



NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF APPLIED MATHEMATICAL AND PHYSICAL SCIENCES
DEPARTMENT OF PHYSICS
HIGH ENERGY PHYSICS LABORATORY

Testing the operation and response with cosmics of the Micromegas detector for the NSW upgrade of the ATLAS experiment and study of the Higgs boson production in the $WW^* \rightarrow \ell \nu \ell \nu$ decay channel through VBF mechanism

A dissertation presented by

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to

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detector for the NSW upgrade of the ATLAS experiment and study of
the Higgs boson production in the $WW^* \rightarrow \ell \nu \ell \nu$ decay channel through
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Ph.D Thesis

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Athens, September 2023

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ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ
ΣΧΟΛΗ ΕΦΑΡΜΟΣΜΕΝΩΝ ΜΑΘΗΜΑΤΙΚΩΝ ΚΑΙ ΦΥΣΙΚΩΝ ΕΠΙΣΤΗΜΩΝ
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**Έλεγχος λειτουργίας και απόκρισης με κοσμικές
ακτίνες των ανιχνευτών Micromegas για την αναβάθμιση
του NSW του πειράματος ATLAS και μελέτη της
παραγωγής του μποζονίου Higgs στο κανάλι $WW^* \rightarrow \ell\nu\ell\nu$
μέσω του μηχανισμού VBF**

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Περίληψη

Η παρούσα διδακτορική διατριβή χωρίζεται σε δύο κύρια μέρη έχοντας ως επίκεντρο το πείραμα ATLAS του Μεγάλου Επιταχυντή Αδρονίων του CERN.

Το πρώτο μέρος αποτελεί αντικείμενο της πιο σημαντικής αναβάθμισης για την περίοδο λήψης δεδομένων κατά το Run-3, του New Small Wheel, και συγκεκριμένα της μίας εκ των δύο τεχνολογιών ανιχνευτών που το απαρτίζουν, τους resistive-strip Micromegas. Παρουσιάζεται η γεωμετρία του ανιχνευτή καθώς και η αναπαράστασή της στο λογισμικό ως βασικό συστατικό της διαδικασίας της ανακατασκευής τόσο των προσομοιωμένων όσο και των πραγματικών δεδομένων. Στη συνέχεια, περιγράφονται τα εργαλεία που αναπτύχθηκαν, και χρησιμοποιούνται ήδη, για τον ποιοτικό έλεγχο των δεδομένων που καταγράφονται από τους ανιχνευτές, σε μη-πραγματικό χρόνο. Με την τοποθέτηση των ανιχνευτών στον ATLAS πραγματοποιήθηκαν σειρές δοκιμών με Micromegas ανιχνευτές του New Small Wheel χρησιμοποιώντας μόνια σε συνδυασμό με ραδιενεργή πηγή με τα τελικώς σχεδιασμένα ηλεκτρονικά προσαρτημένα σε αυτούς. Το πρώτο μέρος λοιπόν ολοκληρώνεται με τη παρουσίαση των κυριότερων αποτελεσμάτων της ανάλυσης των δεδομένων που συλλέχθηκαν με σκοπό το χαρακτηρισμό, όσον αφορά την απόδοση και τη χωρική διακριτική ικανότητα, ενός από τους ανιχνευτές Micromegas.

Το δεύτερο μέρος αφορά τη μέτρηση ενεργών διατομών της παραγωγής του μποζονίου Higgs μέσω του μηχανισμού vector-boson-fusion στο κανάλι διάσπασης $H \rightarrow WW^*$ μελετώντας πλήρως λεπτονικές τελικές καταστάσεις. Η ανάλυση χρησιμοποιεί τα δεδομένα του Run-2 απο συγκρούσεις πρωτονίων ενέργειας κέντρου μάζας στα 13 TeV που καταγράφηκαν από τον ATLAS και αντιστοιχούν σε ολοκληρωμένη φωτεινότητα 139 fb^{-1} . Ιδιαίτερη σημασία δίνεται στην εκτίμηση του υποβάθρου που προέρχεται από πίδακες (jets) οι οποίοι λανθασμένα αναγνωρίζονται ως λεπτόνια και προϊόντα των πρωταρχικών συγκρούσεων. Παρουσιάζονται όλες οι μελέτες που πραγματοποιήθηκαν με στόχο την εισαγωγή συστηματικών αβεβαιοτήτων στη μέθοδο εκτίμησης που βασίζεται στα πραγματικά δεδομένα. Αυτές περιλαμβάνουν την πιθανή διερεύνηση της εξάρτησης της μεθόδου από διεργασίες που συμβαίνουν την ίδια στιγμή με αυτής της σύγκρουσης, γνωστές ως pileup, αλλά και από ιδιότητες που χαρακτηρίζουν τον τρόπο παραγωγής του Higgs που μελετάται, όπως η παρουσία jets. Τέλος, πραγματοποιήθηκε ο έλεγχος της μεθόδου χρησιμοποιώντας μόνο προσομοιωμένα δεδομένα για να αποδειχθεί η αμεροληψία της εκτίμησης που βασίζεται στα πραγματικά δεδομένα.

Σύνοψη στα ελληνικά

Η παρούσα διδακτορική διατριβή έχει ως αντικείμενο τους ανιχνευτές Micromegas της αναβάθμισης New Small Wheel του πειράματος ATLAS. Παράλληλα, μελετάται η παραγωγή του μποζονίου Higgs με τη μέτρηση ενεργών διατομών μέσω του μηχανισμού vector-boson-fusion εξετάζοντας πλήρως λεπτονικές τελικές καταστάσεις στο κανάλι διάσπασης $WW^* \rightarrow \ell\nu\ell\nu$.

Η εργασία αυτή χωρίζεται σε τρεις θεματικές ενότητες.

Η Ενότητα I περιλαμβάνει κεφάλαια που καλύπτουν το θεωρητικό υπόβαθρο. Συγκεκριμένα, στο Κεφάλαιο 1 παρουσιάζεται η θεωρία του Καθιερωμένου Προτύπου των δομικών στοιχείων της ύλης όπως επίσης και η φαινομενολογική περιγραφή συγκρούσεων πρωτονίων. Κύριο αντικείμενο της έρευνας αυτής αποτελεί το πείραμα ATLAS του Μεγάλου Επιταχυντή Αδρονίων, LHC, του Ευρωπαϊκού Εργαστηρίου Σωματιδιακής Φυσικής CERN. Επομένως, το Κεφάλαιο 2 παρουσιάζει τον επιταχυντή LHC με τα πειράματά του, το σχέδιο αναβάθμισής του με στόχο την αύξηση της φωτεινότητάς του, τους υπολογιστικούς πόρους που χρησιμοποιούνται για την αποθήκευση του μεγάλου αριθμού δεδομένων, ενώ ολοκληρώνεται με τους πιθανούς τρόπους παραγωγής και διάσπασης του μποζονίου Higgs. Το Κεφάλαιο 3 αφορά τον ανιχνευτή ATLAS όπου περιγράφονται ενδελεχώς τα υποανιχνευτικά συστήματα που τον απαρτίζουν, το σύστημα σκανδαλισμού και καταγραφής δεδομένων, όπως επίσης και η αλυσίδα που ακολουθείται για την παραγωγή προσομοιωμένων δεδομένων. Επιπλέον, δίνεται βάση στην ανακατασκευή των δεδομένων, τόσο των προσομοιωμένων όσο και των πραγματικών, τα οποία τελικά χρησιμοποιούνται από τις ομάδες ανάλυσης. Το Κεφάλαιο αυτό ολοκληρώνεται με τις αναβαθμίσεις του ATLAS στρέφοντας την προσοχή στην αναβάθμιση New Small Wheel.

Στην Ενότητα II παρουσιάζεται το πρώτο κομμάτι της έρευνας, ο ανιχνευτής Micromegas της αναβάθμισης New Small Wheel. Η γεωμετρία του ανιχνευτή και η περιγραφή της στο λογισμικό που χρησιμοποιείται για την ανακατασκευή των δεδομένων παρουσιάζεται στο Κεφάλαιο 4. Το Κεφάλαιο 5 επικεντρώνεται στην σειρά ελέγχων που υπόκεινται τα δεδομένα ώστε να επιτευχθεί η υψηλή ποιότητά τους. Δίνεται ιδιαίτερη έμφαση στα εργαλεία που έχουν αναπτυχθεί για τον ασύγχρονο έλεγχο των δεδομένων. Τέλος, στο Κεφάλαιο 6 παρουσιάζεται η ανάλυση δεδομένων με στόχο το χαρακτηρισμό της απόδοσης και της χωρικής διακριτικής ικανότητας ενός ανιχνευτή New Small Wheel Micromegas με χρήση της τελικής έκδοσης των ηλεκτρονικών που έχουν σχεδιαστεί χρησιμοποιώντας δέσμη μιονίων αλλά και ραδιενεργή πηγή για την προσομοίωση περιβάλλοντος ανάλογου αυτού που αναμένεται τα επόμενα χρόνια λόγω των αναβαθμίσεων του επιταχυντή.

Η Ενότητα III αφορά το δεύτερο κομμάτι της έρευνας, την ανάλυση δεδομένων με στόχο τη μελέτη του μποζονίου Higgs. Στο Κεφάλαιο 7 δίνεται μια γενική περιγραφή της στρατηγικής της ανάλυσης που ακολουθήθηκε με στόχο τη μέτρηση της ολοκληρωμένης αλλά και διαφορικών ενεργών διατομών της παραγωγής του μποζονίου Higgs μέσω του μηχανισμού vector-boson-fusion στο κανάλι διάσπασης $WW^* \rightarrow \ell\nu\ell\nu$. Το Κεφάλαιο 8 αφιερώνεται στην περιγραφή της τεχνικής για την εκτίμηση του υποβάθρου που προέρχεται από αντικείμενα που λανθασμένα αναγνωρίζονται ως λεπτόνια όπως επίσης και στις μελέτες που διενεργήθηκαν με στόχο την εισαγωγή συστηματικών σφαλμάτων στη μέθοδο.

Το κείμενο της διατριβής ολοκληρώνεται με την παρουσίαση των τελικών συμπερασμάτων στην Ενότητα IV. Υποστηρικτικό υλικό των μελετών καθώς και πρόσθετες μελέτες και ιδέες που αναπτύχθηκαν παρατίθενται στα παραρτήματα της Ενότητας IV.

Ένας από τους κυριότερους στόχους της φυσικής υψηλών ενεργειών αφορά την ενοποίηση των θεμελιωδών αλληλεπιδράσεων της φύσης (ισχυρή, ηλεκτρομαγνητική, ασθενής και βαρυτική). Μέχρι και σήμερα, το Καθιερωμένο Πρότυπο αποτελεί την πιο καλά θεμελιωμένη θεωρία καθώς έχει καταφέρει να προβλέψει επιτυχώς πολλά πειραματικά αποτελέσματα ενώ παράλληλα έχει ανταπεξέλθει πληθώρα πειραματικών ελέγχων.

Σύμφωνα με αυτό το θεωρητικό μοντέλο υπάρχουν δύο είδη στοιχειωδών σωματιδίων, τα λεπτόνια και τα κουάρκ. Αυτά αποτελούν όλα μαζί μία ομάδα δώδεκα σωματιδίων που χωρίζεται σε τρεις οικογένειες-γενιές. Κάθε μία γενιά αποτελείται από δύο λεπτόνια και δύο κουάρκ. Η πρώτη οικογένεια, αποτελείται από τα κουάρκ άνω (up) και κάτω (down) και τα λεπτόνια ηλεκτρόνιο (e^-) και νεutrίνο ηλεκτρονίου (ν_e). Η δεύτερη γενιά αποτελείται από τα κουάρκ χαριτωμένο (charm) και παράξενο (strange) και τα λεπτόνια μόνιο (μ^-) και το αντίστοιχο νεutrίνο του (ν_μ). Τέλος η τρίτη οικογένεια περιλαμβάνει τα κουάρκ κορυφή (top) και πυθμένας (bottom) και τα λεπτόνια ταυ (τ^-) και νεutrίνο του ταυ (ν_τ). Για κάθε ένα από αυτά τα σωματίδια υπάρχει και το αντίστοιχο αντι-σωματίδιο με ιδιότητες ίδιες εκτός από το φορτίο που είναι αντίθετο. Με τα σωματίδια της πρώτης γενιάς μπορούμε να εξηγήσουμε τον ορατό κόσμο. Τα οκτώ σωματίδια των δύο τελευταίων γενιών δεν είναι σταθερά ενώ η διαφορά τους από αυτά της πρώτης γενιάς οφείλεται στη μεγαλύτερη μάζα τους.

Σύμφωνα με το Καθιερωμένο Πρότυπο, τα στοιχειώδη σωματίδια μπορούν να αλληλεπιδρούν μεταξύ τους ανταλλάσσοντας διαφορετικού τύπου σωματίδια-αγγελιοφόρους, χαρακτηριστικό της κάθε θεμελιώδους δύναμης. Τα κουάρκ αλληλεπιδρούν μεταξύ τους ανταλλάσσοντας ένα από τα οκτώ χωρίς μάζα γκλουόνια (g) φορείς της ισχυρής δύναμης ενώ συνδυασμοί κουάρκ συγκροτούν τα σωματίδια που καλούμε αδρόνια. Η ηλεκτρομαγνητική αλληλεπίδραση δρα μεταξύ των φορτισμένων σωματιδίων με αγγελιοφόρο το άμαζο φωτόνιο. Η ασθενής αλληλεπίδραση επιτρέπει μετατροπές των κουάρκ ενός τύπου σε άλλο ανταλλάσσοντας ένα από τα διανυσματικά και με μάζα μποζόνια W και Z .

Η εικόνα του Καθιερωμένου Προτύπου ολοκληρώνεται με το μποζόνιο Higgs με το οποίο εξηγείται η ιδιότητα της μάζας των σωματιδίων. Οι μάζες λοιπόν των σωματιδίων καθορίζονται με το πόσο ισχυρή είναι η σύζευξή τους (coupling) με το πεδίο που δημιουργεί το μποζόνιο Higgs.

Το Καθιερωμένο Πρότυπο απέχει από το να χαρακτηριστεί ως μια πλήρης περιγραφή των θεμελιωδών αλληλεπιδράσεων καθώς απαντήσεις σε πολλά ερωτήματα δεν έχουν δοθεί. Αυτά περιλαμβάνουν την εξήγηση της βαρύτητας και της φυσικής που διέπει τη σκοτεινή ύλη και ενέργεια.

Για να μπορέσουμε να δώσουμε απαντήσεις σε ερωτήματα σχετικά με τη δημιουργία και σύσταση του Σύμπαντος, έχει κατασκευαστεί ο Μεγάλος Επιταχυντής Αδρονίων (LHC). Πρόκειται για έναν κυκλικό επιταχυντή σωματιδίων περιφέρειας 27 χλμ που έχει εγκατασταθεί στα σύνορα Ελβετίας-Γαλλίας. Έχει σχεδιαστεί ώστε να μπορεί να επιταχύνει και να συγκρούει δέσμες σωματιδίων (συνήθως πρωτόνια) σε ταχύτητες που πλησιάζουν την ταχύτητα του φωτός.

Αποτέλεσμα των συγκρούσεων αυτών είναι η δημιουργία βαριών σωματιδίων τα οποία θα επιτρέψουν τον έλεγχο θεωρητικών υποθέσεων αλλά και νέες ανακαλύψεις. Η λειτουργία του επιταχυντή ξεκίνησε επίσημα το 2008.

Σε διάφορα σημεία στην περιφέρεια του επιταχυντή έχουν εγκατασταθεί πειράματα-ανιχνευτές τα οποία λειτουργούν ως μικροσκόπια επιτρέποντας τον ακριβή εντοπισμό των προϊόντων των πρωταρχικών συγκρούσεων. Ένα από αυτά και το μεγαλύτερο είναι το πείραμα γενικού σκοπού ATLAS, κύριο αντικείμενο της παρούσας έρευνας, το οποίο ανακοίνωσε το 2012 ταυτόχρονα με το δεύτερο μεγαλύτερο πείραμα CMS, την ανακάλυψη ενός νέου σωματιδίου μάζας 125 GeV οι ιδιότητες του οποίου ήταν συμβατές με αυτές του μποζονίου Higgs όπως προβλέπει το Καθιερωμένο Πρότυπο.

Ο ανιχνευτής ATLAS έχει κυλινδρικό σχήμα μήκους 45 μ, διαμέτρου 25 μ ενώ ζυγίζει 7000 τόνους. Αποτελείται από τέσσερα κύρια μέρη: α) το σύστημα μαγνητών, β) τον εσωτερικό ανιχνευτή τροχιών, γ) τα καλορίμετρα και δ) το φασματόμετρο μιονίων.

Για τη μέτρηση της ορμής των φορτισμένων σωματιδίων είναι απαραίτητο αυτά να βρίσκονται μέσα σε μαγνητικό πεδίο. Το μαγνητικό σύστημα αποτελείται από έναν κεντρικό σωληνοειδή υπεραγωγίμο μαγνήτη που περιβάλλει τον εσωτερικό ανιχνευτή τροχιών με τιμή μαγνητικού πεδίου 2 T. Τρεις επιπλέον υπεραγωγίμοι τοροειδείς μαγνήτες είναι τοποθετημένοι γύρω από τα καλορίμετρα (έναν στο βαρελοειδές τμήμα (barrel region) και δύο στα καπάκια του βαρελιού (end-cap region)) για την κάμψη των τροχιών των μιονίων. Η μέγιστη τιμή του μαγνητικού πεδίου φτάνει τα 4.1 T.

Ο εσωτερικός ανιχνευτής τροχιών αποτελείται από τους Insertable B-Layer, Pixel Detector, Semiconductor Tracker και Transition Radiation Tracker. Με τη διάταξη αυτή μπορούν να μετρηθούν οι παράμετροι των τροχιών που τη διαπερνά και κατα συνέπεια να οριστεί η ορμή, η διεύθυνση και το πρόσημο του φορτίου των σωματιδίων.

Τα καλορίμετρα ή θερμιδόμετρα μετρούν τις ενέργειες των φορτισμένων και ουδέτερων σωματιδίων και διαχωρίζονται στο ηλεκτρομαγνητικό και το αδρονικό θερμιδόμετρο. Αποτελούνται από εναλλασσόμενα στρώματα απορροφητών και από ενεργά στοιχεία. Οι αλληλεπιδράσεις των σωματιδίων με τον απορροφητή μετατρέπουν την προσπίπτουσα ενέργεια του σωματιδίου σε έναν πίδακα (jet) από σωματίδια τα οποία στη συνέχεια ανιχνεύονται από τα ενεργά στοιχεία μέσω ιονισμού ή σπινθηρισμού.

Τα μόνα σωματίδια που επιβιώνουν χωρίς να επιβραδυνθούν είναι τα μόνια για την ανίχνευση των οποίων έχει σχεδιαστεί το μιονικό φασματόμετρο. Τα ανιχνευτικά συστήματα που χρησιμοποιούνται ανήκουν στην κατηγορία των ανιχνευτών αερίου. Η βαρελοειδής περιοχή αποτελείται από τους Monitored Drift Tubes, οι οποίοι παρέχουν ακριβή μέτρηση των μιονίων, και τους Resistive Plate Chambers οι οποίοι παρέχουν πληροφορία σκανδαλισμού. Από την άλλη, στα καπάκια του βαρελιού είναι εγκατεστημένοι τρεις δίσκοι κάθετοι στον άξονα διέλευσης των συγκρουόμενων σωματιδίων ενώ οι τεχνολογίες ανιχνευτών που έχουν επιλεγεί είναι οι Monitored Drift Tubes, Cathode Strip Chambers και οι Thin Gap Chambers.

Ο επιταχυντής ακολουθεί ένα πρόγραμμα διαδοχικών αναβαθμίσεων με στόχο την αύξηση της φωτεινότητάς του αγγίζοντας τιμές $5-7 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ μετά το 2028 όπου θα επιτευχθούν περίπου 20 φορές περισσότερες συγκρούσεις σε σχέση με την πρώτη περίοδο λειτουργίας, αυξάνοντας

έτσι τη πιθανότητα ανακάλυψης νέων σωματιδίων και Νέας Φυσικής. Παράλληλα, με τις αναβαθμίσεις του επιταχυντή για να μπορέσουν να ανταπεξέλθουν στις νέες συνθήκες ροής σωματιδίων και για την εξασκούθηση της εύρυθμης λειτουργία τους οι ανιχνευτές-πειράματα ακολουθούν το δικό τους σχέδιο αναβαθμίσεων.

Η σημαντικότερη αναβάθμιση του ανιχνευτή ATLAS την περίοδο αναβάθμισεων 2019-2022 αφορά την πλήρη αντικατάσταση των εσωτερικών μιονικών θαλάμων στην περιοχή end-cap με νέους ανιχνευτές. Το κύριο κίνητρο της αναβάθμισης αυτής αφορά την μείωση καταγραφής γεγονότων, συνολικά, από το μιονικό σύστημα τα οποία δεν αντιστοιχούν σε μόνια, παράγωγα, των πρωταρχικών συγκρούσεων.

Η αναβάθμιση αυτή είναι γνωστή ως New Small Wheel (NSW) και υπόσχεται άριστο χωρικό και χρονικό προσδιορισμό των τροχιών σε πραγματικό χρόνο καθώς και πολύ καλό σκανδαλισμό. Το NSW είναι εξοπλισμένο με δύο τεχνολογίες ανιχνευτών αερίου τους small-strip Thin Gap Chambers (sTGC) και τους resistive-strip Micromegas (MMG). Οι sTGC χρησιμοποιούνται πρωταρχικά για τον σκανδαλισμό (παρέχοντας παράλληλα πληροφορία για την ανακατασκευή των τροχιών) και οι MMG για την ανακατασκευή των τροχιών (συμμετέχοντας παράλληλα και στον σκανδαλισμό).

Οι sTGC περιλαμβάνουν δύο καθοδικά επίπεδα αποτελούμενα από πλάκες (pads) ή λωρίδες (strips), που σχηματίζουν ένα διάκενο πάχους 2.8 χιλιοστών το οποίο γεμίζεται με μίγμα αερίου 55% CO₂ και 45% n-πεντάνιο. Το επίπεδο της ανόδου στο μέσο του διακένου αποτελείται από επιχρυσωμένα σύρματα (wires) βολφραμίου.

Οι MMG αποτελούνται από δύο παράλληλα επίπεδα ανόδου και καθόδου ορίζοντας ένα διάκενο πάχους περίπου 5 χιλιοστών το οποίο γεμίζεται με αέριο 93% Ar, 5% CO₂ και 2% ισοβουτάνιο. Ένα μικρο-πλέγμα χωρίζει τον ενεργό όγκο του ανιχνευτή σε δύο ασύμμετρες επιμέρους περιοχές: την περιοχή μετατροπής και την περιοχή πολλαπλασιασμού. Η άνοδος είναι χωρισμένη σε λωρίδες (strips) από χαλκό. Υπάρχουν δύο στρώματα λωρίδων. Πάνω από τις λωρίδες ανάγνωσης έχει τοποθετηθεί ένα επιπλέον στρώμα λωρίδων αντίστασης που χωρίζονται από τις πρώτες από ένα μονωτικό υλικό για την αποφυγή σπινθήρων φαινόμενο το οποίο έχει παρατηρηθεί στους ανιχνευτές αυτού του είδους.

Η λειτουργία και των δύο τύπων ανιχνευτών στηρίζεται στην ίδια αρχή. Με την εφαρμογή κατάλληλων δυναμικών δημιουργούνται ισχυρά ηλεκτρικά πεδία. Έτσι, όταν ένα φορτισμένο σωματίδιο εισέλθει στον ενεργό όγκο του ανιχνευτή ionίζει το αέριο και τα ελεύθερα ηλεκτρόνια ακολουθούν τις δυναμικές γραμμές. Αυτά όταν πλησιάσουν τα σύρματα (για την περίπτωση των sTGC) ή το μικρο-πλέγμα (για την περίπτωση των MMG) λόγω του πολύ ισχυρού ηλεκτρικού πεδίου πολλαπλασιάζονται μέσω του φαινομένου της χιονοστιβάδας. Η κίνηση των ηλεκτρονίων και ιόντων επάγει πολύ γρήγορα σήματα στα ηλεκτρόδια των ανιχνευτών. Συγκεκριμένα για τους sTGC οι συμπτώσεις των pads υποδεικνύουν χοντρικά το σημείο από το οποίο πέρασε το σωματίδιο ενώ παράλληλα υπαγορεύουν τα προς ανάγνωση strips τα οποία παρέχουν πληροφορία για την πρώτη συντεταγμένη. Η ανάγνωση των wires παρέχει πληροφορία της δεύτερης συντεταγμένης. Από την άλλη οι MMG αποτελούνται από επίπεδα τα οποία έχουν τα strips διατεταγμένα παράλληλα (eta strips) έτσι ώστε να μπορούμε να έχουμε μέτρηση της μιάς συντεταγμένης και άλλα (stereo strips) τα οποία είναι στραμμένα υπό μικρή γωνία (1.5°) ως προς τα πρώτα ώστε να είναι δυνατή η ταυτόχρονη μέτρηση δύο συντεταγμένων.

Κάθε NSW είναι ένας δίσκος-τροχός ο οποίος αποτελείται από δεκαέξι συνολικά τομείς (sectors) , οκτώ μεγάλους και οκτώ μικρούς σχήματος τραπεζίου. Κάθε τομέας, αποτελείται από 16 επίπεδα τα οποία είναι οργανωμένα σε δύο πολύ-επίπεδα (multilayers). Κάθε multilayer περιλαμβάνει τέσσερα sTGC και τέσσερα MMG επίπεδα. Η τελική τοποθέτηση κατά μήκος της διεύθυνσης της δέσμης είναι sTGC-MMG-MMG-sTGC. Για την ανάγνωση των σημάτων από όλους τους ανιχνευτές χρησιμοποιούνται 2 εκατομμύρια και 350 χιλιάδες ηλεκτρονικά κανάλια για τους MMG και τους sTGC αντίστοιχα, ο αριθμός των οποίων υποδεικνύει την απαίτηση ενός εξελιγμένου συστήματος ηλεκτρονικών.

Στις επόμενες ενότητες παρουσιάζονται συνοπτικά τα κυριότερα σημεία και αποτελέσματα της διδακτορικής έρευνας.



Ο ανιχνευτής Micromegas της αναβάθμισης ATLAS New Small Wheel

Κάθε MMG αποτελείται από δύο ακτινικά τμήματα, κατασκευασμένα ως ξεχωριστές μονάδες (modules). Υπάρχουν τέσσερα modules τα SM1, LM1 που είναι τοποθετημένα εσωτερικά, εγγύτερα του σημείου σύγκρουσης, και τα SM2, LM2 που βρίσκονται εξωτερικά, σε μεγαλύτερη απόσταση από το σημείο σύγκρουσης. Το L αναφέρεται στους μεγάλους τομείς ενώ το S στους μικρούς. Η κατασκευή τους είχε ανατεθεί μεταξύ τεσσάρων εργαστηρίων της Ιταλίας (SM1), της Γερμανίας (SM2), της Γαλλίας (LM1) και σε συνεργασία μεταξύ Ελλάδας/Ρωσίας (LM2).

Το πείραμα ATLAS έχει αναπτύξει το λογισμικό Athena ώστε να ανακατασκευάζει τα δεδομένα που συλλέγονται από τον κάθε υπο-ανιχνευτή του. Το ίδιο λογισμικό χρησιμοποιείται και για την ανακατασκευή των προσομοιωμένων δεδομένων τα οποία είναι απαραίτητα για κάθε πρόγραμμα ανάλυσης φυσικής.

Για την ορθή επεξεργασία και μετάφραση των σημάτων σε αντικείμενα φυσικής είναι πολύ σημαντική η γνώση και η αναπαράσταση της λεπτομερούς περιγραφής της γεωμετρίας των ανιχνευτών. Ιδιαίτερα σημαντικό ρόλο παίζει η γεωμετρία της ανόδου καθώς απαιτείται ένα-προς-ένα απεικόνιση σύνδεσης με τα ηλεκτρονικά κανάλια. Λόγω περιορισμών κατασκευής οι άνοδοι αποτελούνται είτε από πέντε (SM1, LM1) είτε από τρεις (SM2, LM2) πλακέτες τυπωμένου κυκλώματος (PCB). Επιπλέον, κάθε PCB χωρίζεται στη μέση σε δύο ανεξάρτητες περιοχές για την εφαρμογή υψηλής τάσης. Τέλος, κάθε ένας τύπος ανιχνευτή έχει κατασκευαστεί με μοναδικά χαρακτηριστικά τα οποία και πρέπει να ληφθούν υπόψη.

Η γεωμετρία ωστόσο στην πραγματικότητα δεν είναι στατική ούτε ανταποκρίνεται επακριβώς στα σχέδια κατασκευής.

Κατά την κατασκευή των θαλάμων διάφορες μετρήσεις λήφθηκαν για τη γνώση του ακριβούς εντοπισμού της θέσης των strips για κάθε module. Επιπλέον, λόγω του ότι ήταν η πρώτη φορά που κατασκευαζόταν ανιχνευτής τύπου Micromegas σε μεγάλη κλίμακα, παρατηρήθηκε έντονη η παραγωγή σπινθήρων παρά της εισαγωγής του επιπλέον επιπέδου strips. Ως λύση στο πρόβλημα, αποτέλεσε η εφαρμογή λεπτού στρώματος κόλλας γύρω από τα όρια της ενεργού περιοχής όπου στα σημεία αυτά το πρόβλημα ήταν πιο ορατό και μη αποδεκτό. Αυτή η ενέργεια

κατευθείαν επιφέρει αλλαγή στη γεωμετρία. Όλοι αυτοί οι παράγοντες ανήκουν στην κατηγορία των as-built παραμέτρων.

Με την εγκατάσταση των ανιχνευτών στο ATLAS παράγοντες όπως η θερμοκρασία, η πίεση, η υγρασία αλλά και το μαγνητικό πεδίο, μπορούν να επιφέρουν συνεχώς αλλαγές στη γεωμετρία των θαλάμων. Γι' αυτό το σκοπό το NSW έχει το δικό του σύστημα ευθυγράμμισης των ανιχνευτών του το οποίο είναι προσαρτημένο σε αυτό του ATLAS. Με το σύστημα αυτό λοιπόν οι μετρήσεις μεταφράζονται μέσω ενός ανεξάρτητου λογισμικού, το ARAMyS, και μέσω μετασχηματισμών μπορούν να οριστούν μετατοπίσεις και στροφές (A-line παράμετροι) και παραμορφώσεις (B-line παράμετροι) των θαλάμων στο χώρο. Αυτό το σύνολο παραμέτρων αποθηκεύεται σε μια βάση δεδομένων η οποία ανανεώνεται κάθε λίγες ώρες καθώς καταγράφονται δεδομένα από τους ανιχνευτές. Το Athena στη συνέχεια επικοινωνεί με τη βάση δεδομένων και ανανεώνει αναλόγως τον ορισμό της γεωμετρίας των ανιχνευτών.

Από τη στιγμή που συλλέγονται τα πραγματικά δεδομένα, σειρά ενδεδειγμένων ελέγχων διενεργούνται σε διάφορα στάδια, με σκοπό την εξασφάλιση της υψηλής ποιότητας και χρησιμότητας προς ανάλυση των δεδομένων. Στο δωμάτιο ελέγχου του ATLAS (control room) κάθε ένα υποσύστημα έχει το δικό του γραφείο εξοπλισμένο με πληθώρα εφαρμογές που έχουν αναπτυχθεί ώστε να μπορεί να ελέγχεται η κατάσταση των ανιχνευτών από τον εκάστοτε ερευνητή που έχει αναλάβει βάρδια (shifter).

Έτσι, η κατάσταση λειτουργίας των ανιχνευτών και των εξαρτημάτων που τους αποτελούν ελέγχονται και παρακολουθούνται από το Detector Control System (DCS). Τα δεδομένα από το σύστημα αυτό αρχειοθετούνται σε αντίστοιχη βάση δεδομένων ώστε να ληφθούν υπόψη σε μετέπειτα στάδιο ελέγχων. Ένα άλλο εργαλείο που χρησιμοποιείται σε πραγματικό χρόνο με τη λήψη δεδομένων παρέχει πληροφορία σε μορφή ιστογραμμάτων ενώ αυτόματοι έλεγχοι διενεργούνται σε αυτά για τον εύκολο και άμεσο εντοπισμό προβλημάτων. Τα ιστογράμματα αυτά αποθηκεύονται επίσης. Για οποιοδήποτε θέμα προκύψει ενημερώνεται ο εκάστοτε ειδικός για την άμεση αποκατάσταση του προβλήματος.

Από τη στιγμή που τα δεδομένα έχουν καταγραφεί και ανακατασκευαστεί, περνούν ασύγχρονους ελέγχους σε δύο στάδια. Αρχικά, έλεγχοι διενεργούνται σε ένα αντιπροσωπευτικό δείγμα των δεδομένων (express stream) ενώ αυτοί ξεκινούν μέσα σε λίγες ώρες από την αρχή της καταγραφής των δεδομένων. Σ' αυτό το στάδιο, οι ειδικοί των υποσυστημάτων μπορούν να ανανεώνουν ανάλογα τις βάσεις δεδομένων. Στη συνέχεια, η διαδικασία αυτή επαναλαμβάνεται έως ότου θεωρηθεί βέλτιστη η βαθμονόμηση και ευθυγράμμιση των ανιχνευτών. Η διαδικασία αυτή είναι γνωστή ως calibration loop ενώ έχει διάρκεια περίπου 48 ώρες. Από τη στιγμή αυτή μπορεί να ξεκινήσει η λήψη των δεδομένων προς ανάλυση (main physics stream) σύμφωνα με τα αιτήματα των υπεύθυνων αναλύσεων που παρέχονται σε λίστες επιλογής κριτηρίων (trigger menu). Το σύνολο των δεδομένων ανακατασκευάζεται μέσα σε 48 ώρες από τη λήξη της καταγραφής το οποίο υπόκειται σε τελικούς ελέγχους. Στο στάδιο αυτό ελέγχεται εάν έχουν ληφθεί υπόψη οι αλλαγές που αναμένονται σύμφωνα με τα δεδομένα της βάσης δεδομένων, εντοπίζονται τυχόν προβλήματα που δεν είχαν αντιληφθεί κατά τη διάρκεια της λήψης των δεδομένων όπως επίσης και τυχόν προβλήματα στο λογισμικό (Athena) που χρησιμοποιείται για την ανακατασκευή των γεγονότων.

Για τον ασύγχρονο έλεγχο των ανακατασκευασμένων δεδομένων όπως αυτά συλλέγονται από τους ανιχνευτές MMG έχουν αναπτυχθεί κατάλληλα εργαλεία στο Athena. Πληθώρα ιστογραμμάτων περιλαμβάνει πληροφορία για κάθε ένα από τους 128 ανιχνευτές σε διάφορα στάδια της διαδικασίας ανακατασκευής των δεδομένων. Η πληροφορία των γειτονικών strips που συμμετέχουν σε κάθε γεγονός ομαδοποιείται ορίζοντας τα clusters τα οποία στη συνέχεια χρησιμοποιούνται για τον ορισμό των πιθανών τμημάτων τροχιών ώστε να οδηγηθούμε στην εύρεση των τελικών τροχιών μιονίων. Έτσι ιστογράμματα παρέχονται στα τρία προαναφερόμενα στάδια ενώ αντιστοιχούν για κάθε επίπεδο ανιχνευτή ή και ακόμα για κάθε PCB του. Στη συνέχεια, η πληροφορία μπορεί να ομαδοποιηθεί όπως έχει ή έπειτα από τη διαδικασία εφαρμογής κατάλληλων συναρτήσεων σε αυτά (fitting) ώστε να παραχθούν τελικά συλλογικές εικόνες για τον ευκολότερο εντοπισμό των προβλημάτων. Τέλος, τα κυριότερα ιστογράμματα-γραφήματα επιλέγονται, περνούν μια σειρά αυτομάτων ελέγχων και παρουσιάζονται σε ιστοσελίδα την οποία καλείται να ελέγξει ο shifter. Ένα παράδειγμα της εφαρμογής αυτής παρουσιάζεται στο Σχήμα 0.1.

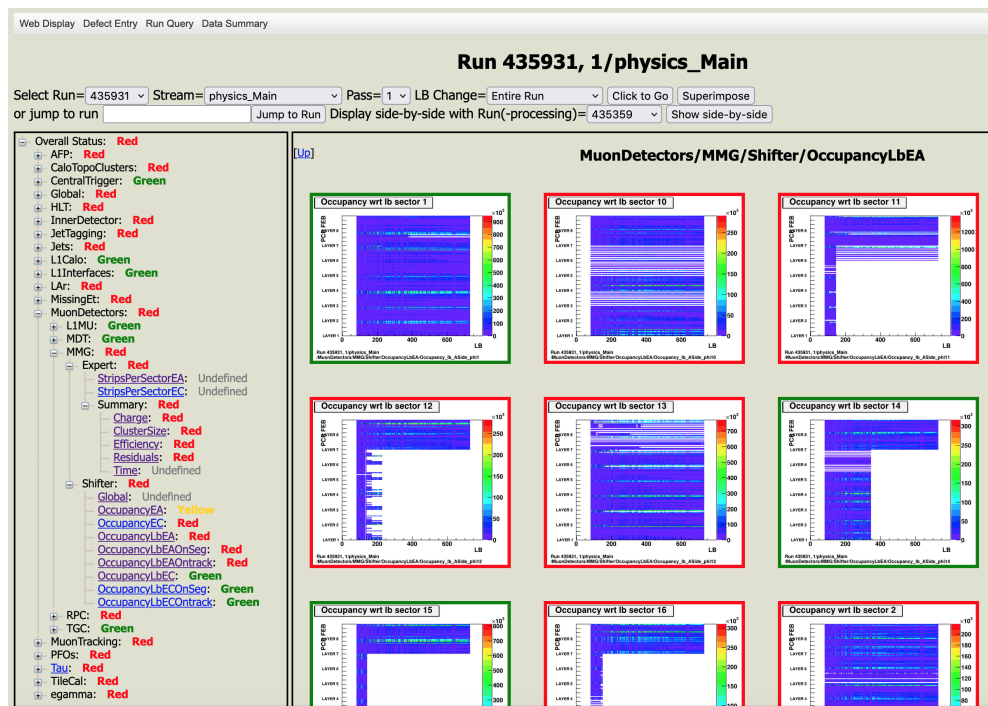


Figure 0.1: Η ιστοσελίδα που καλείται να ελέγξει ο shifter για το μιονικό σύστημα ώστε να ολοκληρωθεί ο ποιοτικός έλεγχος των ανακατασκευασμένων δεδομένων. Συγκεκριμένα, τα ιστογράμματα οργανώνονται σε φακέλους (αριστερά της εικόνας) οι οποίοι πλαισιώνονται με ανάλογο χρώμα το οποίο αντικατοπτρίζει την κατάσταση των ιστογραμμάτων που περιέχει (πράσινο: όλα τα ιστογράμματα έχουν περάσει επιτυχώς τους ελέγχους, κίτρινο: ένα ή περισσότερα ιστογράμματα αξίζουν σημασία, κόκκινο: ένα ή περισσότερα ιστογράμματα είναι προβληματικά και πρέπει να ελεγχθούν περαιτέρω). Δεξιά της εικόνας φαίνεται το περιεχόμενο του φακέλου που έχει επιλεχθεί. Τη στιγμή της συγγραφής, αλλαγές συνεχίζονταν να γίνονται στα εργαλεία οπότε η εικόνα αυτή δεν αντικατοπτρίζει το τελικό προϊόν. Η αναπαράσταση αυτή αντιστοιχεί σε ανακατασκευη δεδομένων του 2022 από συγκρούσεις δεσμών πρωτονίων ενέργειας κέντρου μάζας στα 13.6 TeV.

Με το πέρας της ολοκλήρωσης της εγκατάστασης των ηλεκτρονικών σε όλους τους ανιχνευτές MMG και των δύο τροχών NSW και αφού αυτοί εγκαταστάθηκαν στο ATLAS ξεκίνησε μία σειρά δοκιμών με δέσμη μιονίων και με χρήση ραδιενεργής πηγής με σκοπό το χαρακτηρισμό της απόδοσης και της χωρικής διακριτικής ικανότητας των ανιχνευτών NSW MMG. Τονίζεται ότι είναι η πρώτη φορά που ανιχνευτές NSW MMG δοκιμάζονται με τα τελικώς σχεδιασμένα ηλεκτρονικά. Οπότε παράλληλα έγιναν έλεγχοι και των ηλεκτρονικών.

Στα πλαίσια της παρούσας έρευνας, παρουσιάζεται η ανάλυση των δεδομένων από ανιχνευτή NSW MMG τύπου SM1 από δεδομένα που συλλέχθηκαν τον Ιούλιο 2022.

Οι μελέτες αυτές διενεργήθηκαν στο εργαστήριο Gamma Irradiation Facility (GIF++) στο CERN, όπου είναι δυνατή η ταυτόχρονη ή μη χρήση δέσμης μιονίων, ενέργειας μερικών εκατοντάδων GeV, και ραδιενεργής πηγής 14 TBq ^{137}Cs από την οποία εκπέμπονται φωτόνια ενέργειας 662 keV. Με τη χρήση φίλτρων μπροστά από την πηγή μπορεί να ελεγχθεί η ακτινοβολήση. Η διάταξη περιλαμβάνει όπως αναφέρθηκε παραπάνω τον ανιχνευτή NSW MMG SM1 ο οποίος είναι τοποθετημένος σε ορθή θέση πάνω σε μια πλατφόρμα (με τη μεγάλη βάση κοντά στο πάτωμα) 2 m μακριά από την πηγή. Η δέσμη διαπερνά τον ανιχνευτή σε περιοχή του PCB-3 (η αρίθμηση των PCB ξεκινά από τη μικρή βάση προς τη μεγάλη) και μόνο αυτό εξοπλίστηκε με ηλεκτρονικά.

Στο ATLAS το PCB-1 είναι αυτό που δέχεται τη μεγαλύτερη ροή σωματιδίων σε σχέση με τα υπόλοιπα PCB. Λόγω των διαστάσεων, με την εφαρμογή της υψηλής τάσης στο μισό PCB-3 επιτρέπεται η συσχέτιση των μελετών με αυτή του PCB-1. Τέσσερις μικροί πρωτότυποι ανιχνευτές Micromegas συμπληρώνουν τη διάταξη για τη διευκόλυνση της εύρεσης των τροχιών μιονίων. Εν τέλει, λόγω προβλημάτων, τρεις χρησιμοποιήθηκαν στη διαδικασία εύρεση των τροχιών (ένας από αυτούς ήταν τοποθετημένος εκτός των ορίων ακτινοβολήσης της πηγής και χρησιμοποιήθηκε ως αναφορά, ενώ οι άλλοι δύο τοποθετήθηκαν σε θέση μερικών εκατοστών πίσω από τον ανιχνευτή προς μελέτη).

Η ανάλυση αφορά κάθετες τροχιές μιονίων με τη χρήση της μεθόδου charge centroid. Έχοντας καλά ορισμένες τροχιές μιονίων αναφοράς χρησιμοποιώντας τα δεδομένα από τους μικρούς ανιχνευτές, μελετήθηκε η απόδοση του ανιχνευτή όπως και αναπτύχθηκαν διαφορετικοί τρόποι για την μέτρηση της χωρικής διακριτικής ικανότητάς του.

Για τον υπολογισμό της απόδοσης ελέγχθηκε για κάθε ένα επίπεδο ξεχωριστά ο σχηματισμός cluster σε απόσταση λίγων χιλιοστών από την ευθεία που ορίζει η τροχιά. Ο λόγος του αριθμού των γεγονότων που ικανοποιεί αυτό το κριτήριο προς τον συνολικό αριθμό των ανακατασκευασμένων τροχιών ορίζει την απόδοση του κάθε επιπέδου του ανιχνευτή.

Για τον υπολογισμό της χωρικής διακριτικής ικανότητας του κάθε επιπέδου εξετάστηκαν διαφορετικοί μέθοδοι: Α. υπολογισμός της απόστασης του ανακατασκευασμένου cluster από την τροχιά. Το αποτέλεσμα της τυπικής απόκλισης σ με την εφαρμογή γκαουσιανής συνάρτησης στην κατανομή δίνει μια εκτίμηση της χωρικής διακριτικής ικανότητας. Β. Το ανακατασκευασμένο cluster του επιπέδου που μελετάται εισάγεται στον ορισμό της τροχιάς και το βελτιωμένο αποτέλεσμα ορίζεται ως ο γεωμετρικός μέσος των τυπικών αποκλίσεων των μεθόδων Α και Β. Για τις δύο αυτές μεθόδους υπολογίστηκε το σφάλμα εύρεσης τροχιών χρησιμοποιώντας τους μικρούς ανιχνευτές το οποίο αφαιρέθηκε για τη βελτίωση των αποτελεσμάτων. Τέλος, αναπτύχθηκε η μέθοδος Γ σύμφωνα με την οποία θεωρήθηκε ότι όλα τα επίπεδα

του ανιχνευτή έχουν πανομοιότυπη συμπεριφορά και υπολογίστηκε η διαφορά των θέσεων ανακατασκευασμένων clusters μεταξύ δύο επιπέδων. Αφού εφαρμοστεί στην κατανομή μια γκαουσιανή συνάρτηση η τυπική απόκλιση διαιρεμένη με $\sqrt{2}$ δίνει μια εκτίμηση της χωρικής διακριτικής ικανότητας. Τα αποτελέσματα από όλες τις μεθόδους από την ανάλυση δεδομένων που συλλέχθηκαν μόνο με τη δέσμη (χωρίς τη χρήση πηγής) παρουσιάζονται στον Πίνακα 0.1.

Table 0.1: Χωρική διακριτική ικανότητα για κάθε ένα επίπεδο του υπό μελέτη ανιχνευτή χρησιμοποιώντας διαφορετικές μεθόδους υπολογισμού. Για τη Μέθοδο Α και Β τα αποτελέσματα παρουσιάζονται πριν και μετά την αφαίρεση του σφάλματος εύρεσης τροχιών ϵ^{track} . Τα αποτελέσματα που παρουσιάζονται στη στήλη core αφορούν το fit μόνο της κορυφής της κατανομής, ενώ η στήλη weight είναι αποτέλεσμα του fit όλης της κατανομής, η οποία συμπεριλαμβάνει και φαινόμενα σκέδασης, ακτίνων- δ κ.α.

Method		Spatial Resolution (core) [μm]			Spatial Resolution (weight) [μm]		
		eta out	eta in	stereo	eta out	eta in	stereo
A	w/o ϵ^{track}	129	132	118	187	193	201
	w/ ϵ^{track}	95	99	80	165	172	181
B	w/o ϵ^{track}	114	115	103	170	176	182
	w/ ϵ^{track}	74	75	55	146	153	160
C		67			119		

Στο Σχήμα 0.2 παρουσιάζεται η απόδοση και η χωρική διακριτική ικανότητα του ανιχνευτή υπολογισμένη με τη μέθοδο Β (αριστερά) αφού έχει αφαιρεθεί το σφάλμα της τροχιάς και με

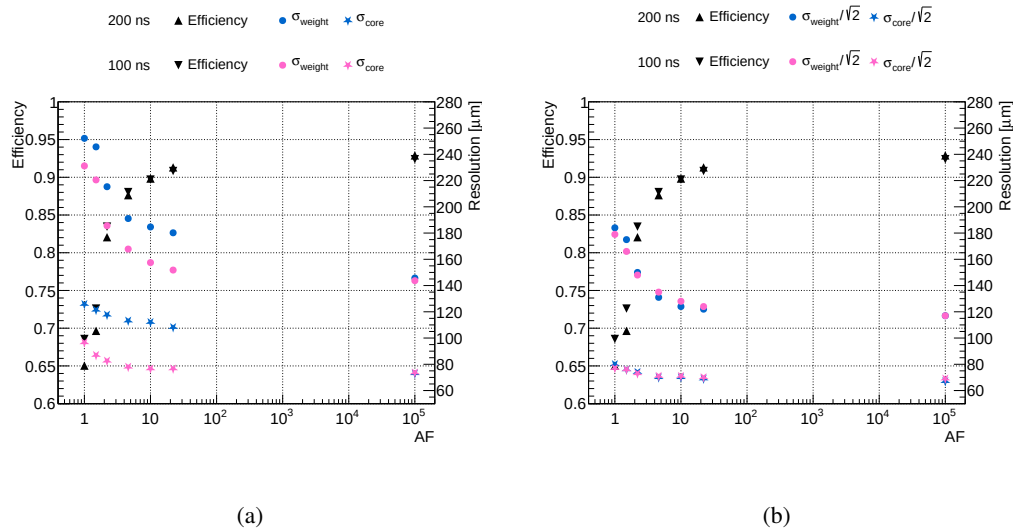


Figure 0.2: Η απόδοση και η χωρική διακριτική ικανότητα υπολογισμένη με τη (a) Μέθοδο Β και με τη (b) Μέθοδο Γ, ως συνάρτηση της έντασης ακτινοβολήσης από τη ραδιενεργή πηγή. Τα διαφορετικά χρώματα/σημεία αντιστοιχούν σε διαφορετική ρύθμιση των ηλεκτρονικών.

τη μέθοδο Γ (δεξιά) για διάφορες τιμές έντασης ακτινοβολήσης από τη ραδιενεργή πηγή (AF)

και για διαφορετικές ρυθμίσεις των ηλεκτρονικών που αφορούν το χρόνο ολοκλήρωσης του σήματος. Το δεξί σημείο και στα δύο γραφήματα αντιστοιχεί σε δεδομένα χωρίς τη χρήση της πηγής, ενώ το σημείο $AF=10$ αντιστοιχεί σε συνθήκες παρόμοιες με αυτές που θα επιβληθούν κατά την περίοδο υψηλής φωτεινότητας του LHC.

Παρατηρείται ότι όσο μεγαλώνει η έκθεση στην πηγή η απόδοση του ανιχνευτή μειώνεται δραματικά φτάνοντας περίπου το 70%. Από μελέτες που είχαν γίνει χρησιμοποιώντας την πηγή μόνο είχε παρατηρηθεί κορεσμός κατά τη ανάγνωση των παλμών από τα ηλεκτρονικά για τις περιπτώσεις μεγάλων ροών σωματιδίων. Βρέθηκε λοιπόν ότι ενεργοποιώντας την παράμετρο των ηλεκτρονικών slh αποκαθίστανται τα κατώφλια που ορίζονται εσωτερικά στα ηλεκτρονικά επιτρέποντας την ανάγνωση μεγάλων παλμών και άρα τη μείωση της απώλειας καταγραφής δεδομένων, βελτιώνοντας σημαντικά το φαινόμενο του κορεσμού. Η βελτίωση αυτή διαφαίνεται στο Σχήμα 0.3. Με την λήψη δεδομένων ενεργοποιώντας την παράμετρο σε μελλοντικές δοκιμές αναμένεται σημαντική βελτίωση στην απόδοση του ανιχνευτή.

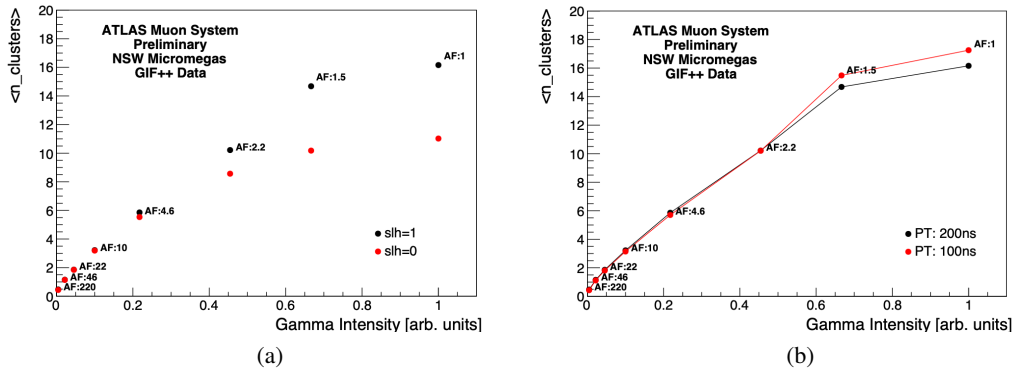


Figure 0.3: Ο μέσος αριθμός των ανακατασκευασμένων clusters μελετώντας ένα επίπεδο του SM1 ως συνάρτηση της έκθεσης στην πηγή (a) ενεργοποιώντας (μαύρα σημεία) και απενεργοποιώντας (κόκκινα σημεία) την παράμετρο slh των ηλεκτρονικών και (b) ενεργοποιώντας τη παράμετρο slh για χρόνο ολοκλήρωσης σημάτων 200 ns (μαύρα σημεία) και 100 ns (κόκκινα σημεία)

Όσον αφορά την εκτίμηση της χωρικής διακριτικής ικανότητας παρατηρείται ότι οι μέθοδοι B και Γ δίνουν συγκρίσιμα αποτελέσματα για την περίπτωση που δεν χρησιμοποιείται η πηγή και για τις δύο ρυθμίσεις ηλεκτρονικών του χρόνου ολοκλήρωσης των σημάτων. Ωστόσο, με την εισαγωγή της πηγής στις μετρήσεις η Μέθοδος Γ εξακολουθεί να δίνει ίδια αποτελέσματα για τις δύο ρυθμίσεις των 200 ns και των 100 ns. Δεν παρατηρείται όμως το ίδιο στην περίπτωση που εξετάζεται η Μέθοδος B. Μια πιθανή εξήγηση για τη διαφορά που παρατηρείται μεταξύ των διαφορετικών ρυθμίσεων των ηλεκτρονικών μπορεί να είναι η εξής: όσο πιο γρήγορος είναι ο χρόνος ολοκλήρωσης των σημάτων, περισσότεροι παλμοί μικρού πλάτους επεξεργάζονται αυξάνοντας τη πιθανότητα φιλτραρίσματος της πηγής και τελικά συμβάλλει στον πιο αποτελεσματικό εντοπισμό των μιονίων. Εάν αυτή η δήλωση είναι σωστή, η Μέθοδος B είναι πιο αξιόπιστη από τη Μέθοδο Γ όταν χρησιμοποιείται σε περιβάλλον υποβάθρου. Συμπερασματικά, εξετάζοντας την περίπτωση των 100 ns τα αποτελέσματα συνάδουν με τις προδιαγραφές που έχει ορίσει η συνεργασία του NSW αφού η απόδοση του ανιχνευτή σε συνθήκες συγκρίσιμες

με αυτές που αναμένονται κατά την περίοδο υψηλής φωτεινότητας του επιταχυντή εκτιμάται στο 90% με χωρική διακριτική ικανότητα λιγότερο από 80 μικρόμετρα ή λιγότερο από 160 μικρόμετρα όταν συνεκτιμάται η συνεισφορά από άλλα φαινόμενα.



Μελέτη παραγωγής του μποζονίου Higgs μέσω του μηχανισμού vector-boson-fusion στο κανάλι διάσπασης $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

Το μποζόνιο Higgs μπορεί να προκύψει μέσω μιας ποικιλίας διαφορετικών διαδικασιών ενώ οι πιθανοί τρόποι διάσπασης είναι κι αυτοί αρκετοί. Η διαδικασία vector-boson-fusion (VBF) είναι η δεύτερη¹ πιο συχνή διαδικασία παραγωγής με ποσοστό παρατήρησης 7%, σύμφωνα με την οποία δύο κουάρκ, ένα από κάθε αλληλεπιδρών πρωτόνιο, εκπέμπουν από ένα διανυσματικό μποζόνιο (W ή Z) και από την αλληλεπίδρασή τους προκύπτει το μποζόνιο Higgs. Τα κουάρκ συνεχίζουν την πορεία τους αφήνοντας τελικά στον ανιχνευτή ίχνη σε μορφή πιδάκων (jets). Έτσι, η διαδικασία χαρακτηρίζεται από την ύπαρξη τουλάχιστον δύο jets. Στη συνέχεια το Higgs μπορεί να διασπαστεί σε δύο διανυσματικά μποζόνια W , διαδικασία η οποία συμβαίνει σε συχνότητα 22% και αποτελεί τη δεύτερη² πιο συχνή σε σειρά.

Σκοπός της ανάλυσης είναι η μέτρηση της ολοκληρωμένης αλλά και διαφορικών ενεργών διατομών (ως συνάρτηση διαφόρων φυσικών ποσοτήτων χαρακτηριστικές του τρόπου παραγωγής και διάσπασης) της παραγωγής του Higgs μελετώντας πλήρως λεπτονικές τελικές καταστάσεις, ενώ τα παρατηρούμενα λεπτόνια απαιτείται να είναι αντίθετου φορτίου και διαφορετικής γεύσης (ηλεκτρόνιο ή μόνιο).

Για την ανάλυση αυτή, χρησιμοποιήθηκαν τα δεδομένα από συγκρούσεις πρωτονίων που συλλέχθηκαν από το ATLAS κατά τα έτη 2015-2018 και αντιστοιχούν σε ολοκληρωμένη φωτεινότητα 139 fb^{-1} .

Ο τρόπος παραγωγής και το κανάλι που μελετάται, δηλαδή το σήμα, θέτει από την αρχή τη δυσκολία/πρόκληση μικρής στατιστικής. Διάφορες περιοχές σχεδιάστηκαν οι οποίες χαρακτηρίζονται από την επιλογή κριτηρίων κατάλληλων για την επίτευξη της αύξησης της ευαισθησίας του σήματος ή κάποιας άλλης συγκεκριμένης διαδικασίας που αφήνει ταυτότητα παρόμοια με αυτή του σήματος στον ανιχνευτή και απαιτείται να διαχωριστεί από αυτό. Η εκτίμηση των υποβάθρων με μεγάλη συνεισφορά (ggF , $Z/\gamma^* + jets$, $VV+Top$) έγινε έπειτα από προσάρτηση κατάλληλης συνάρτησης στα δεδομένα στις περιοχές ελέγχου, χαρακτηριστικές του κάθε υποβάθρου. Συγκεκριμένα, λόγω δυσκολίας διαχωρισμού των διαδικασιών που περιλαμβάνουν δύο διανυσματικά μποζόνια από διαδικασίες σχετικές με την παραγωγή του top quark αναπτύχθηκε μία τεχνική μηχανικής μάθησης (multivariate machine learning technique) χρησιμοποιώντας δέντρα αποφάσεων (boosted decision trees, BDT) τα οποία εκπαιδεύονται χρησιμοποιώντας φυσικές ποσότητες χαρακτηριστικές της παραγωγής και του τρόπου διάσπασης που μελετάται, ενώ γίνεται η κατηγοριοποίηση των γεγονότων ως γεγονότα σήματος ή γεγονότα υποβάθρου. Η αναγωγή των υποβάθρων που υπολογίζονται σε κατάλληλα σχεδιασμένες περιοχές στην περιοχή του σήματος γίνεται έπειτα από την εφαρμογή παραγόντων που

¹ Πρώτη είναι η gluon fusion με ποσοστό παρατήρησης 87%.

² Η πρώτη αφορά τη διάσπαση σε ζεύγη $b\bar{b}$ quark με πιθανότητα 58%.

δρουν πολλαπλασιαστικά στην εκτίμηση. Η εκτίμηση των υποβάθρων με μικρή συνεισφορά στηρίχθηκε αποκλειστικά σε προσομοιωμένα δεδομένα. Τέλος, η εκτίμηση του υποβάθρου που εισάγεται όταν ποσότητες ανακατασκευάζονται λανθασμένα ως λεπτόνια και προέρχονται κυρίως από διαδικασίες που περιλαμβάνουν jets στηρίχθηκε στην ανάπτυξη τεχνικής που βασίζεται σε πραγματικά δεδομένα αφού η προσομοίωση τέτοιων διαδικασιών είναι δύσκολη και όχι ακριβής. Ο αριθμός των γεγονότων που αναμένεται αλλά και μετρήθηκε στις περιοχές που κατασκευάστηκαν παρουσιάζεται στον Πίνακα 0.2.

Table 0.2: Ο αριθμός των γεγονότων που εκτιμάται και παρατηρείται στη περιοχή σήματος (SR) και στις δύο περιοχές ελέγχου ($Z/\gamma^* + jets$ CR, ggF CR).

Sample	SR	$Z/\gamma^* + jets$ CR	ggF CR
Signal (PowHEG + PYTHIA 8)	110	13	86
ggF Higgs	39	4	450
Other Higgs	3	10	78
Top	420	41	11 000
$Z/\gamma^* + jets$	79	320	1 400
VV	280	32	4 300
$V\gamma$	13	14	210
Mis-Id	47	12	810
Total Signal+Background	$1\,000 \pm 120$	450 ± 160	$18\,800 \pm 2\,600$
Data	916	406	18 228

Η εκτίμηση του υποβάθρου που προέρχεται από ποσότητες που λανθασμένα ανακατασκευάζονται ως λεπτόνια των πρωταρχικών συγκρούσεων (fake lepton background, Mis-Id) γίνεται στην περιοχή ελέγχου $W + jets$ CR η οποία ακολουθεί ίδια κριτήρια επιλογής με αυτά που ορίζουν την περιοχή σήματος με τη διαφορά ότι ένα από τα δύο λεπτόνια καλείται να ικανοποιήσει λιγότερο αυστηρά κριτήρια επιλογής. Όπως αναφέρθηκε είναι δύσκολη η προσομοίωση τέτοιων γεγονότων γι' αυτό η εκτίμηση γίνεται αφαιρώντας από τα πραγματικά δεδομένα ηλεκτρασθενείς διαδικασίες που συνιστούν υπόβαθρο για τις $W + jets$ διεργασίες ($V\gamma$, VV , top , $Z + jets$). Η αναγωγή της εκτίμησης αυτής στην περιοχή του σήματος γίνεται με την εφαρμογή παραγόντων που ονομάζονται fake factors (FF).

Οι FF υπολογίζονται σε διαφορετική περιοχή που περιγράφει διαδικασίες $Z + jets$ όπου επιλέγονται τρία λεπτόνια, δύο από τα οποία πρέπει να ικανοποιούν αυστηρά κριτήρια επιλογής και η αναλλοίωτη μάζα τους να είναι πολύ κοντά σ' αυτή του Z μποζονίου. Το τρίτο λεπτόνιο θεωρείται ως το υποψήφιο fake λεπτόνιο και κατηγοριοποιείται με βάση τα αυστηρά ή μη κριτήρια επιλογής που χρησιμοποιούνται για τα λεπτόνια. Οι FF υπολογίζονται ξεχωριστά για ηλεκτρόνια και μύονια σαν συνάρτηση της εγκάρσιας ορμής και της περιοχής της ψευδοωκότητας που καλύπτουν ενώ ορίζονται ως ο αριθμός των fake γεγονότων που ικανοποιούν αυστηρά κριτήρια προς τα fake γεγονότα που ικανοποιούν τα λιγότερο αυστηρά κριτήρια. Τα fake γεγονότα ορίζονται αφαιρώντας από τα πραγματικά δεδομένα προσομοιωμένες ηλεκτρασθενείς διεργασίες που συνιστούν το υπόβαθρο για τις $Z + jets$ διεργασίες. Επειδή η εκτίμηση αυτή γίνεται σε διαφορετική περιοχή, για την εξάλειψη διαφορών στη σύσταση μεταξύ $W + jets$ και $Z + jets$ διεργασιών υπολογίζονται κατά τον ίδιο τρόπο νέοι FF χρησιμοποιώντας μόνο προσομοιωμένα

δεδομένα στις $Z + jets$ και $W + jets$ περιοχές και ο λόγος τους (correction factor, CF) εφαρμόζεται πολλαπλασιαστικά στην τελική εκτίμηση των FF.

Διάφορες μελέτες διενεργήθηκαν σχετικά με τους FF. Αρχικά, ελέγχθηκε η πιθανή εξάρτησή τους από διαδικασίες που συμβαίνουν παράλληλα με τη σύγκρουση (pileup) με σκοπό την εισαγωγή συστηματικού σφάλματος στην εκτίμηση. Στο Σχήμα 0.4 παρουσιάζονται τα

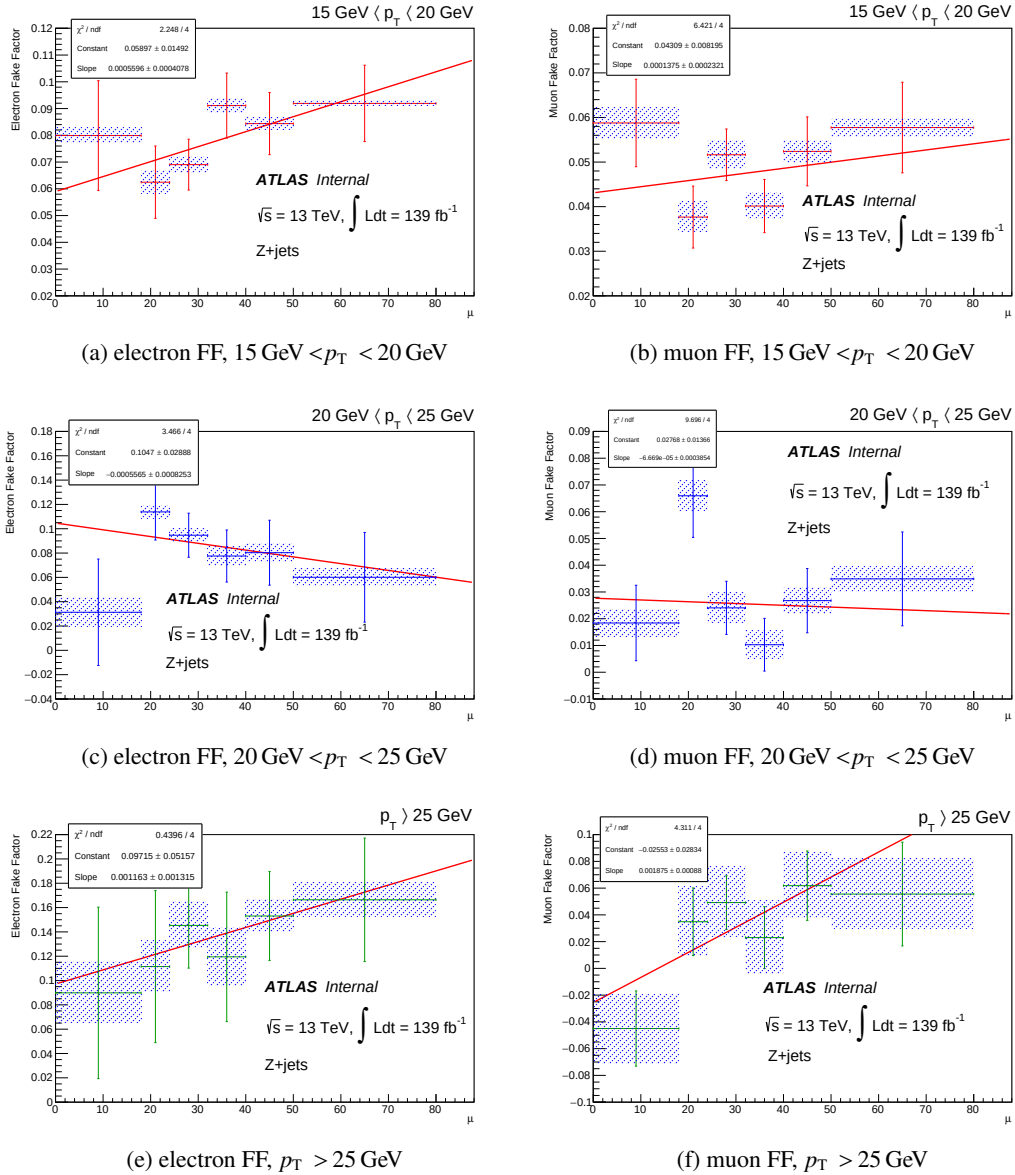


Figure 0.4: Οι FF για (a), (c), (e) ηλεκτρόνια και (b), (d), (f) μόνια ως συνάρτηση του pileup για διαφορετικές περιοχές τιμών της εγκάρσιας ορμής. Οι μπάρες σφαλμάτων αντιστοιχούν στα στατιστικά σφάλματα ενώ οι ζώνες σφαλμάτων αντιστοιχούν στην αβεβαιότητα που προέρχεται από την αφαίρεση των ηλεκτρασθενών διαδικασιών από τα πραγματικά δεδομένα.

αποτελέσματα αυτής της μελέτης για ηλεκτρόνια και μόνια ξεχωριστά σε διαφορετικές περιοχές τιμών της εγκάρσιας ορμής. Μετά την προσαρμογή στα αποτελέσματα αυτά με μια γραμμική συνάρτηση πρώτου βαθμού δεν παρατηρείται κάποια εξάρτηση ώστε να θεωρηθεί απαραίτητη η εισαγωγή σφάλματος στην μέθοδο εκτίμησης του fake lepton background.

Μία άλλη μελέτη, με το ίδιο κίνητρο, αφορά κατά πόσο το fake λεπτόνιο επηρεάζεται από την ύπαρξη κοντά σε αυτό jets. Έτσι λοιπόν υπολογίστηκαν οι FF ως συνάρτηση του αριθμού των jets που υπάρχουν σε κάθε γεγονός όπως επίσης ως συνάρτηση της υπολογισμένης απόστασης του fake λεπτονίου από το εγγύτερο σε αυτό jet. Τα αποτελέσματα παρουσιάζονται στο Σχήμα 0.5 και στο Σχήμα 0.6 ενώ δεν παρατηρήθηκε κάποια ισχυρή εξάρτηση που να οδηγήσει σε εισαγωγή

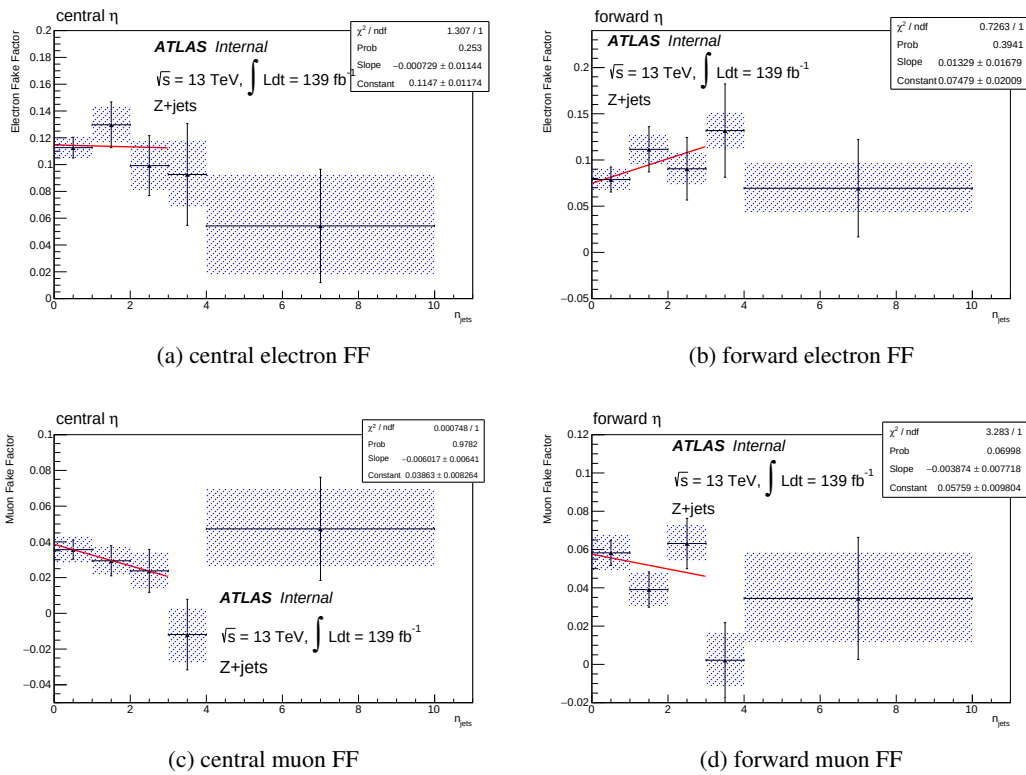


Figure 0.5: Οι FF για (a),(b) ηλεκτρόνια και (c),(d) μόνια ως συνάρτηση του αριθμού των jets που υπάρχουν σε κάθε γεγονός. Οι μπάρες σφαλμάτων αντιστοιχούν στα στατιστικά σφάλματα ενώ οι ζώνες σφαλμάτων αντιστοιχούν στην αβεβαιότητα που προέρχεται από την αφαίρεση των ηλεκτρασθενών διαδικασιών από τα πραγματικά δεδομένα.

σφάλματος στην τελική εκτίμηση.

Τέλος, διενεργήθηκε μελέτη για τον έλεγχο της αμεροληψίας της μεθόδου λόγω χρήσης πραγματικών δεδομένων στην εκτίμηση. Γι' αυτό το σκοπό υπολογίστηκαν οι FF και οι CF χρησιμοποιώντας αποκλειστικά προσομοιωμένα δεδομένα ελέγχοντας δύο διαφορετικούς γεννήτορες, τον Powheg και MG5_AMC@NLO. Χρησιμοποιώντας $W + jets$ δεδομένα από τον αντίστοιχο γεννήτορα ορίστηκαν δύο διαφορετικές περιοχές: η $W + jets$ SR και η $W + jets$ CR. Τα κριτήρια επιλογής

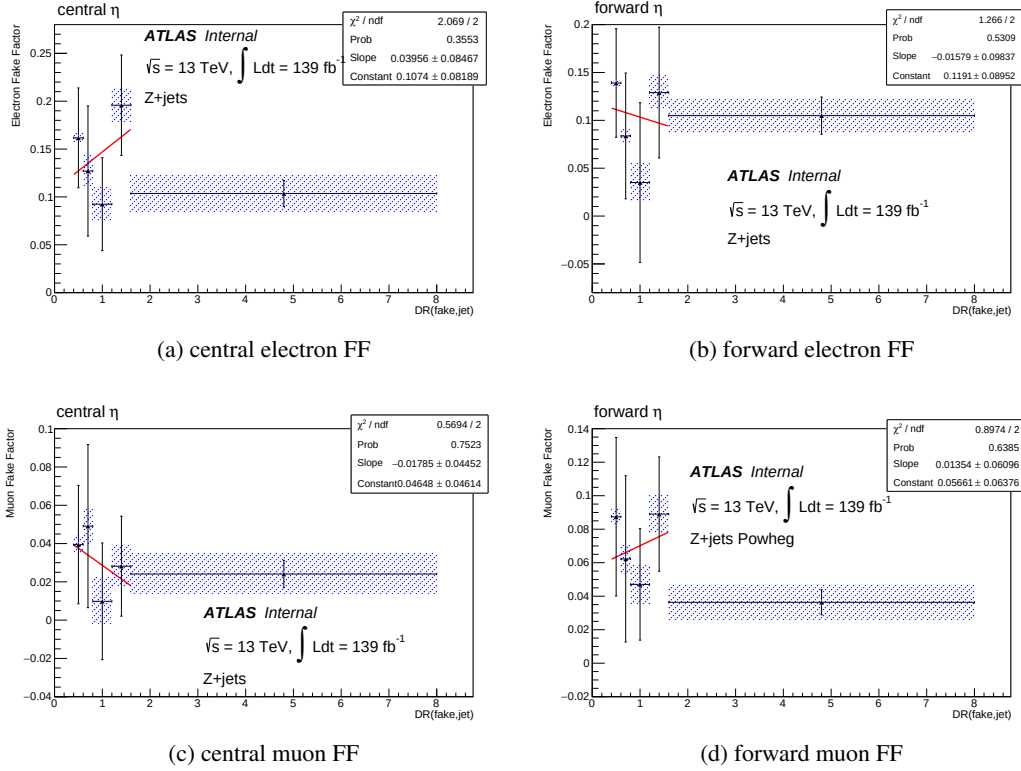


Figure 0.6: Οι FF για (a),(b) ηλεκτρόνια και (c),(d) μόνια ως συνάρτηση της απόστασης μεταξύ του fake λεπτονίου και του εγγύτερου σε αυτό jet. Οι μπάρες σφαλμάτων αντιστοιχούν στα στατιστικά σφάλματα ενώ οι ζώνες σφαλμάτων αντιστοιχούν στην αβεβαιότητα που προέρχεται από την αφαίρεση των ηλεκτρασθενών διαδικασιών από τα πραγματικά δεδομένα.

και των δύο περιοχών είναι παρόμοια με αυτά της περιοχής σήματος που χρησιμοποιείται στην κύρια ανάλυση. Έτσι η πρώτη περιοχή επιλέγει δύο λεπτόνια τα οποία ικανοποιούν αυστηρά κριτήρια επιλογής ενώ η δεύτερη προϋποθέτει το ένα από τα δύο λεπτόνια να περνάει τα αυστηρά κριτήρια, για αυτό το λόγο εφαρμόζονται σε αυτή οι FF. Ο αριθμός των $W + jets$ δεδομένων στις δύο αυτές περιοχές αναμένεται να είναι συγκρίσιμος μέσα στα όρια του σφάλματος για να χαρακτηριστεί η μέθοδος ως αμερόληπτη.

Χρησιμοποιώντας τον γεννήτορα Powheg βρέθηκαν 67.30 ± 24.86 fake γεγονότα στην περιοχή $W + jets$ SR ενώ στην περιοχή $W + jets$ CR ο αριθμός των fake γεγονότων εκτιμήθηκε στα 65.06 ± 10.83 . Η συμφωνία αυτή είναι της τάξης του 3% και βρίσκεται μέσα στα όρια του συνολικού εκτιμώμενου στατιστικού σφάλματος. Με τη χρήση του γεννήτορα MG5_AMC@NLO με τον οποίο το παραγόμενο δείγμα γεγονότων χαρακτηρίζεται από μεγαλύτερη στατιστική βρέθηκαν στην περιοχή $W + jets$ SR 170.81 ± 32.96 fake γεγονότα ενώ 172.77 ± 27.89 εκτιμήθηκαν στην περιοχή $W + jets$ CR. Η συμφωνία αυτή υπολογίζεται στο 1.2% και βρίσκεται μέσα στα όρια του συνολικού εκτιμώμενου στατιστικού σφάλματος.

Τέλος, συγκρίθηκαν οι κατανομές διαφόρων φυσικών κινηματικών ποσοτήτων στις δύο περι-

οχές που σχεδιάστηκαν έτσι ώστε η παρατήρηση όποιων σημαντικών διαφορών να μπορέσει να φανεί χρήσιμη στον έλεγχο της αμεροληψίας. Χρησιμοποιώντας τον γεννήτορα Powheg, η κατανομή της εγκάρσιας ορμής του μποζονίου Higgs και της αναλλοίωτης μάζας των δύο jets παρουσιάζονται ως παράδειγμα αυτής της μελέτης στο Σχήμα 0.7 αφού περάσουν όλα τα

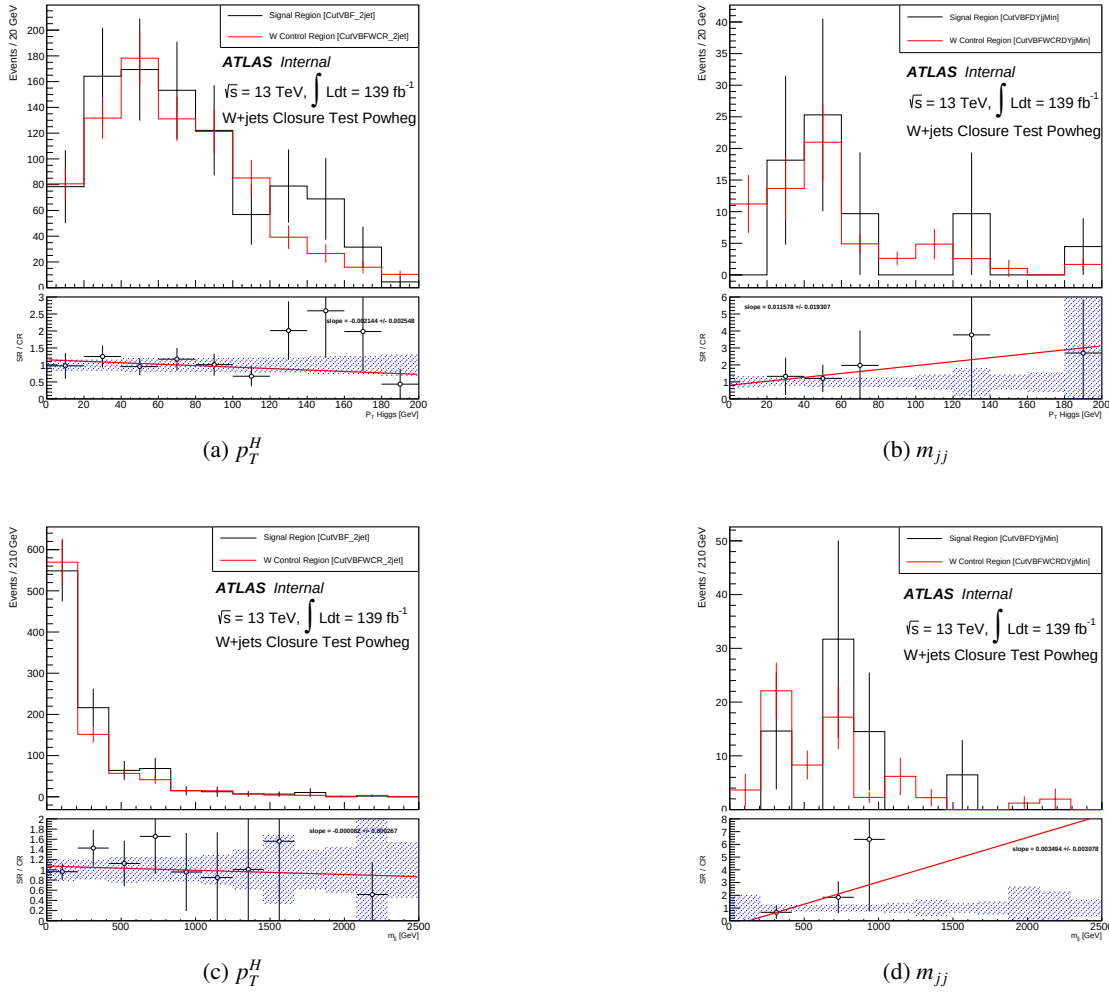


Figure 0.7: Η κατανομή (αριστερά) της εγκάρσιας ορμής του σωματιδίου Higgs και (δεξιά) της αναλλοίωτης μάζας του συστήματος των δύο jets (δεξιά) μετά την πλήρη ικανοποίηση των κριτηρίων και (αριστερά) σε προγενέστερο στάδιο. Οι μπάρες σφαλμάτων αντιστοιχούν στα στατιστικά σφάλματα ενώ οι ζώνες σφαλμάτων αντιστοιχούν στο σφάλμα που έχει υπολογιστεί από τη μέθοδο με χρήση πραγματικών δεδομένων.

κριτήρια που χαρακτηρίζουν τις δύο περιοχές αλλά και σε προγενέστερο στάδιο για να επωφεληθούμε από τη μεγαλύτερη στατιστική. Παρόμοια αποτελέσματα βρέθηκαν και με χρήση του άλλου γεννήτορα. Συνολικά, από τη μελέτη αυτή δεν βρέθηκε υπόνοια προκατάληψης της μεθόδου εκτίμησης του fake lepton background η οποία βασίζεται στη χρήση πραγματικών δεδομένων.

Abstract

This thesis is divided into two main parts with the focus on the ATLAS experiment at the Large Hadron Collider at CERN.

The first part is subject of the most important upgrade for the Run-3 data taking period, the New Small Wheel, and the one of its two constituents, the resistive-strip Micromegas detectors. The detector geometry and its implementation in the software being a key component for the reconstruction of both simulated and real data is presented. Subsequently, the tools that were developed, and are currently in use, for the offline data quality assessment are discussed too. After the installation of the two wheels in ATLAS, series of tests using muons in combination with a radioactive source were carried out for New Small Wheel Micromegas detectors with the final electronics integrated on them. The performance, in terms of efficiency and spatial resolution, of one of the Micromegas detectors was studied with the main results concluding this first part.

The second part concerns the measurement of fiducial cross sections of the Higgs boson production via the vector-boson-fusion in the $H \rightarrow WW^*$ decay channel studying the fully leptonically final states. The analysis uses the full Run-2 proton collision data at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector, corresponding to an integrated luminosity of 139 fb^{-1} . Particular detail is given to the data-driven estimation of the background originating from jets that are misidentified as prompt leptons. Studies conducted with the aim to insert systematic uncertainties to the data-driven method are presented. These include the investigation of dependence on the pileup contamination and on properties characterizing the production mode, such as the presence of jets. Finally, a closure test was performed in order to demonstrate the robustness of the data-driven technique.

Preface

This thesis is based on the experimental apparatus and data of the ATLAS experiment whereas part of it was carried out within the New Small Wheel Collaboration. In this section the author's contributions are going to be clarified.

The manuscript is organised in three parts. An introduction to the theoretical concepts and the experimental setup is given in Part I. Part II discusses the work related to the Micromegas detectors for the New Small Wheel project, whereas Part III presents the analysis for the study of the Higgs boson production using data collected during the previous years of data taking. The conclusions of all conducted studies are presented in Part IV. Finally, supporting material related to the studies presented in the main part of this dissertation as well as additional work that was carried out in parallel and covered a significant part of the author's time is shown in the Appendices.

Chapter 4 presents the geometry description of the individual Micromegas detectors and its implementation in the software, developed by the ATLAS Collaboration, Athena. The author collected from the existing design files the fundamental parameters needed to describe in detail the Micromegas readout geometries. Subsequently, the validity of the parameters already stored in an excel file, known as Parameter book, was checked whereas any found mistakes were incorporated. The correct understanding of the useful parameters was ensured through discussions with the experts. As a second step, the Parameter book content was translated in format readable by Athena. The already developed package responsible for the Micromegas readout geometry description was tested by dumping the positions of the readout elements, i.e strips. The code was corrected and expanded accordingly so as to achieve the as-design description. The alignment group uses its independent software, ARAMyS, to translate the time-dependent measurements taken by the alignment system into translations, rotations and deformations of the chambers. It was of great importance to make sure that Athena and ARAMyS describe the as-design geometry in the same manner. In contact with the alignment group the positions of the Micromegas strips were compared between the two softwares. This work was performed also for the case of strips of the other technology deployed in the New Small Wheel, the small-strip Thin Gap Chambers. Finally, the author contributed to the implementation of the realistic description of the geometry in Athena. During the data-taking the Conditions Database gets updated with parameters that Athena can access and use them to alternate the geometry definition. At the time of the developments such database did not exist for the New Small Wheel. Therefore, a test file following the database format was created whereas a tool with which the file's content could be readable by Athena was developed. A skeleton of the code to incorporate the changes in geometry was implemented in Athena. This work was presented by the author as part in a parallel/short plenary talk at the 40th International Conference on High Energy Physics and published in the conference's proceedings [1].

In Chapter 5 the data quality assessment is being discussed. The author was one of the main developers of the tools that were created and are currently in use for the offline monitoring of the data recorded by the Micromegas detectors. The developments concern all related tools, from the main package that is responsible for the histogram definition and their filling with useful information, to their post-processing till their presentation on the web page which is the main tool used by the shifter during the assessment procedure. Prior to these developments, it was of great importance for

the ATLAS Muon Collaboration to ensure the relevant tools for the offline assessment of the data recorded by the CSC detectors, now replaced by the New Small Wheel, to remain functional and take advantage of the new Athena release capabilities, i.e run in multiple threads. The motivation behind this mandate was the readiness of the tools for the scheduled re-processing campaign of Run-2 held in 2022, prior to the start of Run-3. Nevertheless, all CSC packages including those related to the offline data quality had to be fully functional for the possible scenario the New Small Wheel project could not meet the deadline set for its installation in ATLAS. The author was responsible for the migration of the old packages used during Run-2 to the new needs imposed for Run-3. This work is summarised in Appendix A. In addition, the author has participated since September 2020 in the assessment procedure by checking regularly the web displays created for the CSC subsystem with the aim to catch any software issues that may have been occurred during the developments in the whole Athena.

In Chapter 6 the performance results in terms of efficiency and spatial resolution using muons in combination with a radioactive source are presented. It is the first time a Micromegas module integrated with the final version of the designed electronics to be tested in harsh irradiation conditions. The author has participated in four scheduled test periods, 1) October-December 2021, 2) June 2022, 3) July 2022 and 4) late October-December 2022. The equipment installation and the data-taking were commissioned in collaboration with the members of the group. The author has developed entirely the analysis tool while the techniques followed were carried out after advising the experts. The results presented in the mentioned Chapter correspond to data recorded in July 2022 and have been discussed extensively with the members of the group. Supporting material on the analysis as well as a summary of the studies performed using data collected from other periods are presented in parts of Appendix B. The tool started to be developed using data collected when the detectors were positioned on the cosmic stand, prior to the tests mentioned before. All results that are presented in this thesis are produced with the use of the author's tool. As part of the author's work, preliminary results using data from the first test period were presented by Foteini Kolitsi at the 39th Conference on Recent Developments on High Energy Physics and Cosmology and published in the conference's proceedings [2]. Findings from analysed data recorded during the last test period of late October-December 2022 and subject of the author's work, have been presented at the International Conference on Modern Circuits and System Technologies (MOCASST) on Electronics and Communications by Foteini Kolitsi and published in the conference's proceedings [3].

The simulation studies documented in Appendix B were entirely conducted by the author. These include the geometry definition, the electric field calculation, the gas files and the simulation of the detector response. The Monte Carlo tool is also the author's product. The results were discussed with the members of the group. The studies related to the impact of oxygen contamination in Micromegas detectors were documented in an ATLAS Internal Note [4].

Chapter 7 gives an overview of the analysis for which the author has made significant contributions as member of the analysis team. The author has participated in the ntuple production by using the HWWAnalysisCode that is developed by members of the ATLAS Higgs group. A tool that analyses the ntuples and calculates the contribution of uncertainties (statistical, experimental and theoretical) was built entirely by the author. Moreover, the author has been actively contributing to the analysis optimisation at reconstruction level. All Figures presented in the Chapter are produced with the author's tool except Figure 7.8.

Chapter 8 introduces the method used to estimate the background originating from jets that are misidentified as prompt leptons. The author has used and modified as necessary the HWWAnalysisCode tool but also she has developed independent tools to perform the studies that are reported in the same Chapter. Supporting material is documented in Appendix C.

The analysis presented in Part III has been approved by the ATLAS Collaboration, it has been uploaded to arXiv [5], it has been submitted to Physics Review D. journal and it is in review process.

As member of the broader Higgs Analysis group the author has participated at the 8th Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE 2022) as speaker of the parallel/short talk entitled *Higgs boson property measurements at the ATLAS experiment*. Finally, given the contribution on the fake studies the listings [6] - [9] are subject of the author's work (the papers have been approved by the ATLAS Collaboration, they have been submitted to journals and they are in review process).

The author has been qualified as ATLAS author since November 2019. All publications can be found in inspire record. The list of publications related to the author's work and discussed in this section follows.

1. **C. Kitsaki** on behalf of the ATLAS Muon Collaboration, *The ATLAS New Small Wheel Simulation and Reconstruction Software and Detector Performance Studies*, Proceedings of Science, Vol. 390, 40th International Conference on High Energy Physics (ICHEP 2020) <https://doi.org/10.22323/1.390.0747>.
2. F. Kolitsi, T. Alexopoulos, D. Bitz, G. Iakovidis, **C. Kitsaki**, E. Kyriakis-Bitaros, I. Mesolongitis and K. Zachariadou, *Performance studies of Micromegas electronics in a high radiation environment at the CERN Gamma Irradiation Facility (GIF++)*, Journal of Physics: Conference Series, Vol. 2375, 39th Conference on Recent Developments on High Energy Physics and Cosmology (HEP 2022) <https://doi.org/10.1088/1742-6596/2375/1/012004>.
3. F. Kolitsi, T. Alexopoulos, V. D'Amico, F. Fallavollita, R. Hertenberger, G. Iakovidis, N. Kanellos, **C. Kitsaki**, S. Kompogiannis, E. Kyriakis-Bitaros, I. Mesolongitis, G. Sekhni-aidze, F. Vogel and K. Zachariadou, *Performance of MicroMegas Electronics in a High-Radiation Environment*, in proceedings of the International Conference on Modern Circuits and System Technologies (MOCASST) on Electronics and Communications, 28-30 June 2023 <https://doi.org/10.1109/MOCASST57943.2023.10176380>.
4. T. Alexopoulos, E. Gazis, V. Gkika, **C. Kitsaki**, G. Koutelieris, S. Maltezos, S. Palestini, *Experimental Study of Air/Oxygen Diffusion in the NSW Micromegas Quadruplets*, ATLAS Internal Note, ATL-COM-MUON-2019-031.
5. The ATLAS Collaboration, *Integrated and differential fiducial cross-section measurements for the vector-boson-fusion production of the Higgs boson in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay channel at 13 TeV with the ATLAS detector*, <https://arxiv.org/pdf/2304.03053.pdf>. Approved by Phys.Rev.D.
6. The ATLAS Collaboration, *Measurements of differential cross sections of Higgs boson production through gluon fusion in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ final state at $\sqrt{s} = 13$ TeV with the ATLAS detector*, <https://link.springer.com/article/10.1140/epjc/s10052-023-11873-5>.

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7. The ATLAS Collaboration, *Measurements of Higgs boson production by gluon–gluon fusion and vector-boson fusion using $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decays in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, <https://journals.aps.org/prd/abstract/10.1103/PhysRevD.108.032005>.
 8. The ATLAS Collaboration, *Measurements of gluon fusion and vector-boson-fusion production of the Higgs boson in $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decays using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS Note ATLAS-CONF-2021-014.
 9. The ATLAS Collaboration, *Observation of vector-boson-fusion production of Higgs bosons in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS Note ATLAS-CONF-2020-045.

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Part I

Theoretical Overview and Experimental Setup

1 Theory

This chapter introduces the Standard Model of particle physics in Section 1.1 and concludes with a phenomenological description of the proton-proton collisions in Section 1.2.

1.1 The Standard Model of Particle Physics

The Standard Model (SM) [1] of particle physics has been established as the most accurate and precise scientific model of nature over time. It describes accurately the basic constituents of visible matter along with their interactions into a single powerful equation. The SM is a relativistic quantum field theory which incorporates both special relativity and quantum mechanics. It is based on local gauge symmetries of the composite Lie Group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ ¹.

An overview of the SM particle content is summarized in Figure 1.1. The particles are classified into two main categories: fermions and bosons. The former have the property of half-integer intrinsic spin and are the building blocks for matter in the universe while the latter, have the property of integer intrinsic spin and are the mediators of the fundamental forces.

Fermions come in two types, quarks and leptons. They are arranged in three generations. Each generation consists of particles with identical properties and are sorted by increasing mass. This mass hierarchy causes particles of higher generations to decay to the first generation. Quarks are associated with the color charge under the strong interaction. There are six flavors of quarks: the "up" and the "down" quarks form the first generation, followed by the "charm" and "strange" quarks of the second generation and finally the "top" and "bottom" (or beauty) quarks of the third generation. They are usually observed in combinations of two (namely as mesons) or three (namely as baryons) to compose hadrons [2]. However, they can be combined rarely into four-quark or five-quark particles (namely as exotic hadrons) [3, 4]. Fermions which lack color charge are known as leptons. Similarly to the quarks, there are six flavors of leptons: the electron, the muon and the τ , which are negatively charged, along with their corresponding chargeless neutrinos. Each of the fermions also has an anti-particle whose properties are similar to the original but the electrical charge is of opposite sign.

Bosons are the force carriers for fundamental fermions. The strong nuclear interaction, acting between quarks, is mediated by eight massless gluon fields. The electromagnetic force acts between the electrically charged particles and its mediator is the massless photon. On the other hand, for the weak interactions there are three vector bosons ($W^\pm$ and Z^0), responsible for the β -decays, which are massive. The symmetry imposed by the theory must be spontaneously broken in order to preserve

¹ $SU(3)_C$ group represents the model of strong interactions (see Section 1.1.1) whereas $SU(2)_L \otimes U(1)_Y$ group reflects the unification of the electromagnetic and weak interactions (see Section 1.1.2).

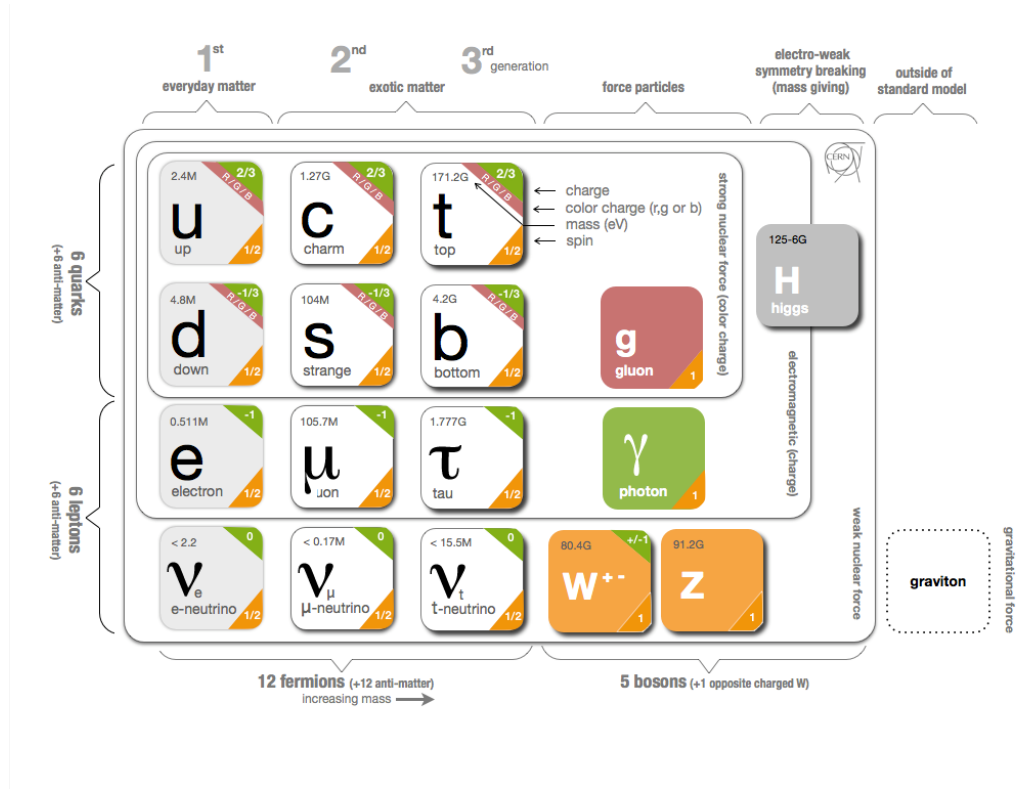


Figure 1.1: Overview of the Standard Model particles [5]. The matter particles are arranged in three families. Four bosons act as the force mediators while the fifth, the Higgs boson, is the key to the origin of mass. Although the model can successfully predict all known particles along with their interactions, the force of gravity has not been included in its description yet.

the gauge symmetry. This happens through the Brout-Englert-Higgs mechanism (see Section 1.1.3), with which the massive Higgs boson is introduced complementing the SM description. At the sub-atomic scale, the gravitational force is way too weak and thus the SM has not succeeded to include its carrier, the graviton, in its definition yet.

1.1.1 Quantum Chromodynamics

The Quantum Chromodynamics (QCD) is the theory of strong nuclear interactions. It is a renormalizable² gauge theory based on the non-Abelian $SU(3)_C$ symmetry group. The "C" index denotes the internal property of particles described in QCD, i.e quarks and gluons, known as color charge. The universe seems to mandate only color neutral quantum states, thus quarks (and gluons) cannot be isolated but are confined inside hadrons.

² The renormalization method is used to absorb the infinities from a theory by redefining these parts using parametrisations or experimentally observed quantities.

The theory implies three colors (red (r), green (g) and blue (b)) for quarks and three anti-colors (anti-red ($\bar{r}$), anti-green ($\bar{g}$) and anti-blue ($\bar{b}$)) for anti-quarks combined in such a way to form colorless states that can be experimentally observed. According to group theory, the 3×3 color combinations form two multiplets of states: a singlet³ and an octet with the latter being the basis from which all other color states can be constructed. The way in which these eight states are derived from colors and anti-colors is a matter of convention and one possible choice is:

$$r\bar{g}, \quad r\bar{b}, \quad g\bar{b}, \quad g\bar{r}, \quad b\bar{r}, \quad b\bar{g}, \quad \sqrt{1/2}(r\bar{r} - g\bar{g}), \quad \sqrt{1/6}(r\bar{r} + g\bar{g} - 2b\bar{b}).$$

The strong interaction between colored particles is mediated by the emission and/or absorption of the eight massless spin-1 gluon combinations. The fundamental diagrams of the strong interaction are presented in Figure 1.2.

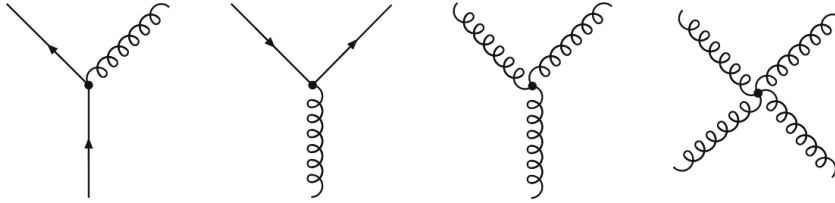


Figure 1.2: The Feynman diagrams of the strong interaction. From left to right: emission of a gluon by a quark, splitting of a gluon into a quark anti-quark pair and the last two diagrams describe the self-coupling of gluons.

The massive spin- $\frac{1}{2}$ quarks can be described as Dirac spinors q_j (the subscript j stands for the flavor). The gluon field tensors are defined by the eight gluon four-potentials g_μ^A and are expressed as $G_{\mu\nu}^A = \partial_\mu g_\nu^A - \partial_\nu g_\mu^A - g_s C_{ABC} g_\mu^B g_\nu^C$ where A, B, C run over the eight color degrees of freedom. The last term is inserted to describe the gluon self-interactions. The quantity g_s (or $a_s = g_s^2/4\pi$) is the strong force coupling constant, the fundamental parameter of QCD. The $SU(3)_C$ structure constants are denoted as C_{ABC} while the group generators, being 3×3 matrices acting on quark spinors, are denoted as t^A obeying the commutation relations $[t^A, t^B] = iC_{ABC}t^C$. The interaction between quarks and gluons is inserted with the covariance derivative expressed as $D_\mu = \partial_\mu + ig_s \sum_A t^A g_\mu^A$.

Therefore, the terms of the SM Lagrangian relevant for QCD are:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{\mu\nu}G_{\mu\nu}^A + \sum_{j=1}^{n_f} \bar{q}_j(i\gamma^\mu D_\mu - m_j)q_j \quad (1.1)$$

where n_f are the different quark flavors and γ^μ are the Dirac matrices.

Vacuum fluctuations of the gluons can appear spontaneously resulting either to virtual $q\bar{q}$ pairs (screening of the strong charge) or to a cloud of virtual gluons (anti-screening of the strong charge), see Figure 1.3. The anti-screening effect dominates and gives rise to the phenomenon of asymptotic freedom.

³ The symmetric colorless combination of the three colors and anti-colors, $\sqrt{1/3}(r\bar{r} + g\bar{g} + b\bar{b})$, is invariant under rotations and therefore has no effect in color space which means that cannot be exchanged between color charges.

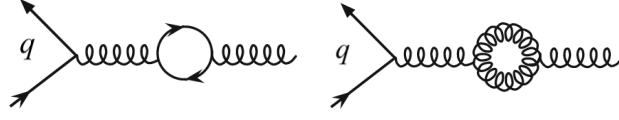


Figure 1.3: Examples of gluon fluctuations. The gluon fluctuates into a $q\bar{q}$ pair (left) and into a virtual gluon (right).

In order to vanish the infinities created by the vacuum fluctuations, perturbative calculations are performed in terms of the renormalised coupling a_s . A first-order perturbation calculation yields:

$$a_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \ln(Q^2/\Lambda^2)} \quad (1.2)$$

where Q represents the energy transferred in the interaction and Λ , being the only free parameter, indicates the energy scale at which the coupling becomes strong and the perturbative approach would fail. Equation 1.2 shows that as the Q increases (at small distances) the interquarks coupling becomes weaker (quarks behave as free particles inside the hadrons and perturbation theory can be used). On the other hand, at lower energies (at large distances) the coupling gets larger (confinement of quarks into hadrons) and the perturbation theory breaks down.

Using data from hadron colliders, the strong coupling constant has been determined at different energy scales and a demonstration of the asymptotic freedom is shown in Figure 1.4. The most up to date world average value of the coupling constant at the Z-boson mass energy scale is $a_s(M_Z^2) = 0.1179 \pm 0.0010$ [6].

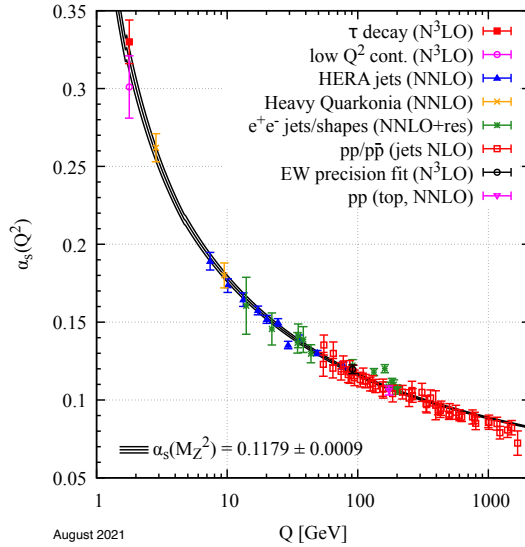


Figure 1.4: Summary of measurements of a_s as a function of the energy scale Q . NLO: next-to-leading order; NNLO: next-to-next-to leading order; NNLO+res: NNLO matched to a resummed calculation; N^3 LO: next-to-NNLO [6].

1.1.2 The Electroweak Interaction

The Quantum Electrodynamics (QED) is the theory of all phenomena involving electrically charged particles, mediated by the massless, chargeless photons and described by the Abelian U(1) symmetry group. It is an extension of the well established classical theory described by Maxwell's equations to the relativistic limit. Therefore, the interaction of a particle of charge e with the photon field is described in Lagrangian formalism as:

$$\mathcal{L}_{QED} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \quad (1.3)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength and $D_\mu = \partial_\mu + ieA_\mu$ is the covariance derivative with its last term describing the interaction of the charged particle in the photon field.

As discussed in Section 1.1.1, an electron can emit spontaneously virtual photons which then emit virtual electron-positron pairs. The virtual positrons are attracted to the electron of interest while the virtual electrons are repelled from it. Due to this polarisation, the electron's charge is "screened". Therefore, at large distances (i.e low energies), the strength of the electromagnetic interaction remains constant at the value measured through the Coulomb force which is proportional to the square of the completely "screened" charge (see Equation 1.4). In contrary, at small distances (i.e large momentum transfers), the screening is partially penetrated and thus the strength of the electromagnetic interaction increases.

QED is among the most stringently tested theories while measurements of its coupling constant, or else called fine structure, have been performed in various physical systems⁴. At low energies, the fine structure is defined as:

$$a_{em} = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137} \quad (1.4)$$

At very short distances (i.e subatomic level), the weak interaction is introduced to describe all particles' decays⁵. In theory, the Lagrangian has to be invariant under any gauge transformations thus, mass terms are not allowed to enter in its description. However, experiments showed that the mediators of the weak interaction are massive, the two electrically charged $W^\pm$ and the one neutrally charged Z^0 bosons. Without violating the gauge symmetry, mass terms can be considered and are explained through the Brout-Englert-Higgs mechanism (discussed in Section 1.1.3).

The weak force is the only interaction that permits the fermion flavor changing when it is mediated by the exchange of the charged $W^\pm$ bosons whereas it is characterized according to the leptonic content of the final state as leptonic, semi-leptonic or hadronic (non-leptonic) process, see Figure 1.5. It was observed that the charged bosons couple only to the left-handed lepton and neutrino within the same generation. In contrary, quarks are allowed to change flavor among generations with a

⁴ 1/137.03599920611 is the most accurate measurement to date with an uncertainty of 81 parts per trillion [7].

⁵ The weak interaction is the only force apart from gravity that interacts with neutrinos. Neutrinos are electrically neutral leptons and thus they do not experience the electromagnetic and/or strong forces. Because of their very small mass the gravitational interaction is extremely weak. Therefore, their study is difficult and their experimental detection is performed indirectly in processes where charged particles are produced.

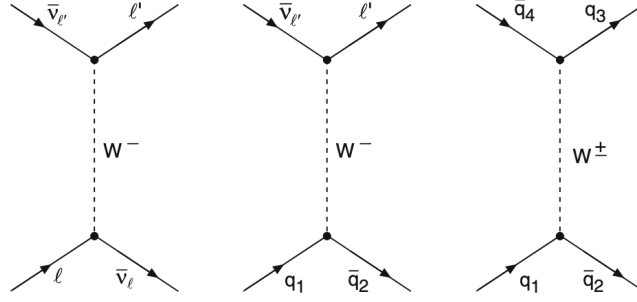


Figure 1.5: The Feynman diagrams for a leptonic (left), a semi-leptonic (middle) and a hadronic process (right).

transition probability being proportional to the square of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements [6]:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.5)$$

$$\rightarrow |V_{CKM}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

The exchange of the neutrally charged Z^0 boson, does not imply any change on the fermion type and both left- and right-handed particles can participate in this interaction.

Another remark of the weak force is that, unlike photons, the carriers of the weak interaction are allowed to self-interact, see Figure 1.6.

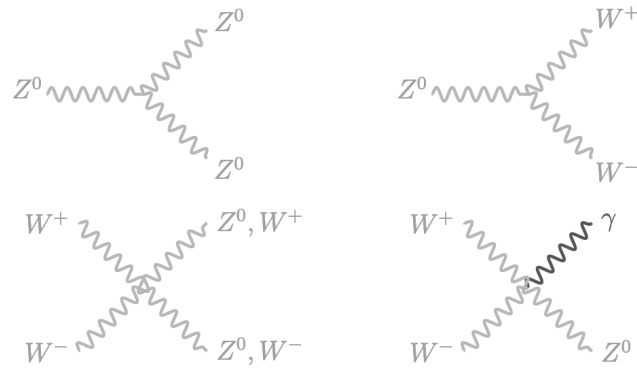


Figure 1.6: The Feynman diagrams of weak bosons self-interactions.

Glashow, Salam and Weinberg proposed a unified model of the electromagnetic and weak interactions into a single force, explained in the electroweak (EW) theory model. This theory is invariant under the $SU(2)_L \times U(1)_Y$ symmetry group which requires four massless boson fields, $W_\mu^1, W_\mu^2, W_\mu^3$ and B_μ . The subscript L refers to the left-handed fermions that are described as doublet states in the $SU(2)_L$ representation. The subscript Y refers to the quantum number of weak hypercharge which relates the electric charge of a fermion Q_f and its third component of the weak isospin (T_f^3) as $Q_f = T_f^3 + \frac{1}{2}Y_f$ while the interacting particles are represented as singlet states.

According to the EW theory, the $W^\pm$ bosons are linear combinations of $W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$. The electromagnetic interaction and the interaction through the neutrally charged Z^0 boson arise from the mixing of the W_μ^3 and B_μ fields and are expressed as $\begin{pmatrix} A_\mu \\ Z_\mu^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}$

where θ_W is the electroweak mixing angle which allows to relate the coupling constants g and g' (associated to the fields W_μ^i and B_μ respectively) to the electric unit charge as $g \sin \theta_W = g' \cos \theta_W = e$.

The resulting electroweak component of the SM Lagrangian is:

$$\mathcal{L}_{EW} = i\bar{\psi}\gamma^\mu D_\mu\psi - \frac{1}{4}W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad (1.6)$$

with $D_\mu = \partial_\mu + ig\vec{T}\vec{W}_\mu + ig'\frac{Y}{2}B_\mu$, $W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon^{ijk}W_\mu^j W_\nu^k$ and $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$. The fermion mass terms as well as those for each vector field are generated through the process of the electroweak symmetry breaking and are not inserted in Equation 1.6.

Since the first detected evidence of the vector bosons, successive experiments at hadron colliders have achieved more precise measurements of their mass aiming the enforcement or a possible extension of the theory. In Figure 1.7, a summary of the heavy electroweak W boson mass measurements performed by different experiments is presented.

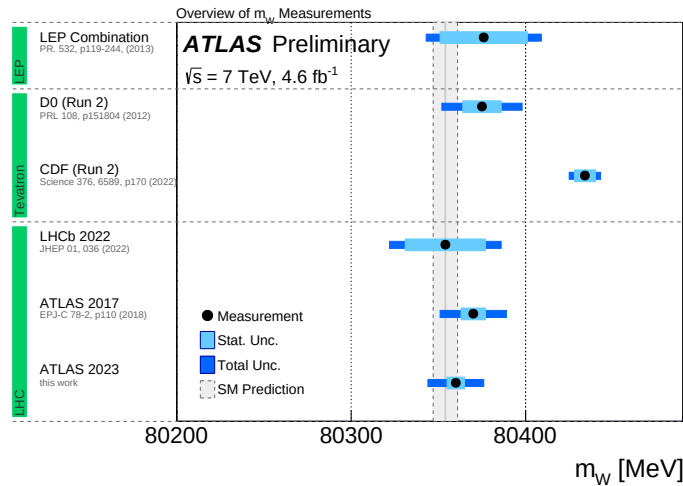


Figure 1.7: W boson mass measurements compared to the SM predictions [8]

1.1.3 The Brout-Englert-Higgs Mechanism

The Brout-Englert-Higgs (BEH) mechanism explains how a field with an asymmetric ground state can be the source of massive particles while preserving the gauge invariance of the theory. It postulates the existence of a complex scalar SU(2) doublet field, $\phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+(x) + i\phi_2^+(x) \\ \phi_1^0(x) + i\phi_2^0(x) \end{pmatrix}$, associated with a potential that is invariant under the transformations of the electroweak symmetry group. The subscripts + and 0 are associated with the electric charge of the components. The corresponding potential has the form

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (1.7)$$

where μ^2 stands for the mass term of the field and λ is the coupling constant of its self-interaction. For vacuum stability the self-coupling constant is required to be positive.

For negative μ^2 values the potential takes the shape of that of a Mexican hat as illustrated in Figure 1.8 whereas it has an infinite number of degenerate minima (asymmetric phase) which are, equivalent in energy, points around the rim of the hat with $|\phi| \equiv \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$ where v is the non-zero vacuum expectation value, as well as a local maximum (symmetric phase) at $|\phi| = 0$.

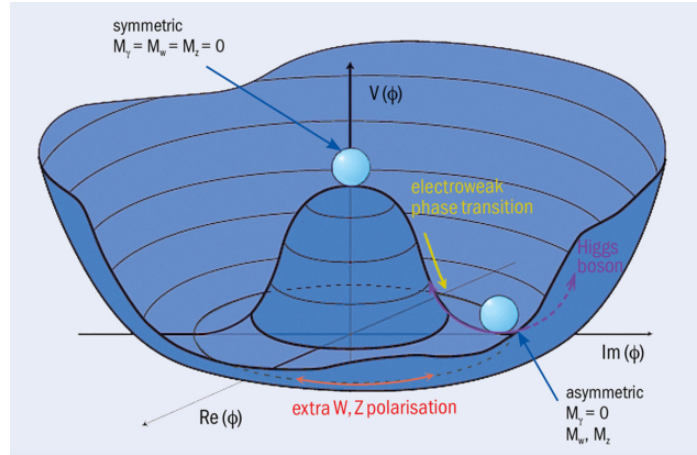


Figure 1.8: The Mexican hat potential of the Higgs field. In the symmetric phase, there is a unique vacuum state at zero which is $U(1)_{em}$ invariant. In the asymmetric phase an infinite number of degenerate vacuum states exist which are described by randomly-chosen points around the bottom of the hat. In a 'global' symmetry, movements around the bottom of the hat corresponds to a massless spin-zero Nambu-Goldstone boson. In the case of a local (gauge) symmetry this boson combines with a massless spin-one boson to yield a massive spin-one particle [9].

The expansion of the scalar fields about the minima generates new terms in the Lagrangian which can be identified as mass terms of the particles and others referred to as interaction terms. The latter can be removed by implying a unitarity gauge transformation. By this procedure, the massless components, the so-called Nambu-Goldstone bosons, are "eaten" through the interaction with the gauge field and transformed into their longitudinal components i.e from massless become massive. Thus, particles acquire the mass property after their interaction with the gauge field.

The shown up in the Lagrangian mass terms for the case of the SM bosons are proportional to the strength of the coupling constants and the vacuum expectation value:

$$m_W = \frac{gv}{2} \quad m_Z = \frac{\sqrt{g^2 + g'^2} v}{2} \quad m_A = 0$$

The fermion masses can be generated in a similar and even easier way by introducing for each fermionic field with left- and right-handed chiralities, gauge invariant interaction terms (Yukawa couplings) with the scalar field of the following form:

$$\mathcal{L} = \lambda_f \bar{f}_L \phi f_R \quad (1.8)$$

where f stands for a particular fermion and λ_f is the associated Yukawa coupling to the gauge field, unique for each fermion type. During the symmetry breaking process the resulting fermion mass is $m_f = \lambda_f \frac{v}{\sqrt{2}}$.

1.2 Description of Proton-Proton Collisions

Experimental measurements are performed at particle level⁶ after correcting for detector effects that are assessed through dedicated detector simulation as discussed in Section 3.1.3. Because of the composite nature of the proton, the event structure when proton beams collide necessitates multi-particle calculations for the full description of the final states [10].

Figure 1.9 illustrates a proton-proton (pp) collision event. The central red blob represents the hard process of interest i.e the constituents of the protons interact with each other at high momentum scale and outgoing particles such as partons, leptons and/or gauge bosons are produced which are perturbatively computable. Then the partons along with all the particles carrying a color, radiate virtual gluons which can emit further gluons or produce quark-antiquark pairs leading to the formation of particle showers shown in light red. The transition (hadronisation process) to the colorless hadrons (hadron decays are shown in dark green) is shown as light green blobs. These hadrons are finally decayed into stable particles that can be observed in detectors. For momenta of the order of 1 GeV the partons are confined and non-perturbatively interactions occur to form final-state hadrons through soft processes. The non-perturbative nature of the soft processes implies their modeling through numerical methods. Furthermore, it is possible to happen in a given collision more than one pair of partons to interact with each other. These multiple parton interactions, namely as the underlying event, can enter into separate but simultaneous scatterings and are depicted as the purple blob. Other beam remnants, are shown in cyan. Finally, the radiation of soft photons is illustrated with the yellow lines.

The inclusive cross-section for the production of the final state X (for instance a Higgs boson) in a pp collision can be expressed as

$$\sigma_{p_1 p_2 \rightarrow X} = \sum_{a,b \in \{q,g\}} \int dx_a \int dx_b f_a^{p_1}(x_a, \mu_F^2) f_b^{p_2}(x_b, \mu_F^2) \int d\Phi_{ab \rightarrow X} \frac{d\hat{\sigma}_{ab}(\Phi_{ab \rightarrow X}, \mu_F^2)}{d\Phi_{ab \rightarrow X}} \quad (1.9)$$

⁶ Particle (or truth) level refers to the stable particles that are produced as a result of a collision.

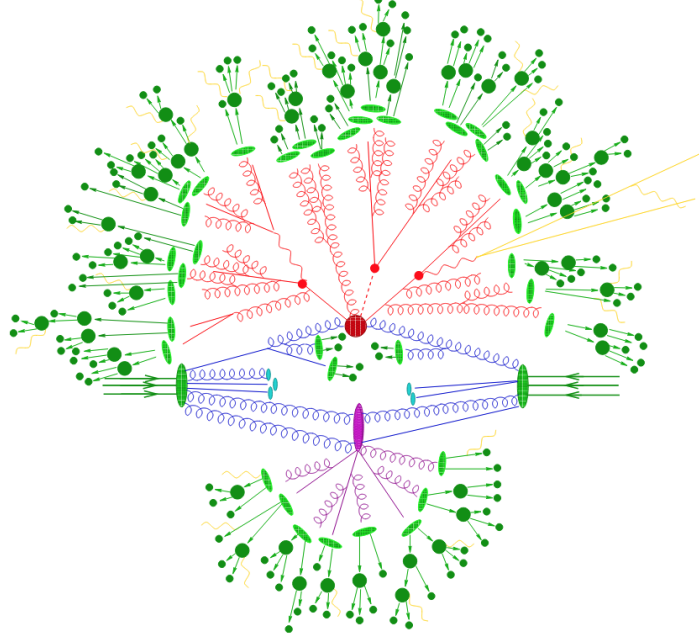


Figure 1.9: The evolution of a pp collision as simulated by a Monte-Carlo event generator [11].

where $f_{a,b}^{p1,2}(x_{a,b}, \mu_F^2)$ are the parton density functions (PDFs) which represent at leading order (LO) perturbative QCD calculations the probability for finding a parton of flavor a (b) with a corresponding momentum fraction x_a (x_b) of the parent proton p_1 (p_2) momentum at the factorization scale μ_F . Finally, $\frac{d\hat{\sigma}_{ab}(\Phi_{ab \rightarrow X}, \mu_F^2)}{d\Phi_{ab \rightarrow X}}$ denotes the differential cross section for the production of the final state X from the partonic initial state whereas $d\Phi_{ab \rightarrow X}$ is the corresponding differential final-state phase-space element.

Experimentally the cross section [12] for a given process is calculated using the following formula:

$$\sigma_{pp \rightarrow X} = \frac{N_X}{\epsilon_{\text{detector}} L} \quad (1.10)$$

where N_X is the number of observed events, $\epsilon_{\text{detector}}$ includes the solid angle coverage, resolution effects, particle detection efficiencies and L stands for the integrated luminosity⁷, characteristic for particle colliders.

⁷ The integrated luminosity is the integral of the instantaneous luminosity with respect to the time $L = \int L_{\text{inst}} dt$. The higher the integrated luminosity, the more data available for analysis is. Thus, collider experiments aim to maximize their integrated luminosity (see Section 2.2).

2 The Large Hadron Collider at CERN

This chapter introduces in Section 2.1 the Large Hadron Collider at CERN along with the experiments along its circumference. Section 2.2 discusses the plan towards the high luminosity phase while the computing resources for the storage of the vast amount of produced data is presented in Section 2.3. Finally, the Higgs boson production modes and decays are presented in Section 2.4.

2.1 The Large Hadron Collider and its Experiments

The Large Hadron Collider (LHC) [13] is the largest and most powerful particle accelerator ever built, operated by the European Organisation of Particle Physics (CERN). It is installed in a circular tunnel, that initially housed the Large Electron-Positron accelerator (LEP) [14], on average 100 meters below the surface with a circumference of 27 km. The LHC machine is designed to accelerate counter-rotating proton beams up to an energy of 7 TeV and collide them at the nominal centre-of-mass energy of 14 TeV, with the aim to reveal the physics at Higgs sector and beyond the SM. Before the injection in the LHC ring, the beams are accelerated in several steps as shown in Figure 2.1.

Protons are extracted by removing electrons from hydrogen atoms which are then accelerated by the LINAC 2 up to the energy of 50 MeV. Afterwards, the protons enter into the Proton Synchrotron Booster which increases their energy to 1.4 GeV¹. Next, they are transferred in the Proton Synchrotron (PS) which accelerates them up to 26 GeV. The resulting beams are boosted in the Super Proton Synchrotron (SPS) reaching an energy of 450 GeV and finally, they are injected in the LHC ring in clockwise or counter-clockwise direction. At full power, the LHC will collide 2808 bunches, each approximately 30 cm long and 16 μm in diameter containing around 1.15×10^{11} protons, leading to billion proton-proton collisions per second. In order to preserve the beam's circular trajectory, 1232 superconducting Niobium-Titanium dipole magnets creating a magnetic field of 8.3 T intensity, are used. Additionally, 392 quadrupole magnets are used to make the protons oscillate around the centre of the vacuum tube, i.e. keeping the beam focused, whereas other magnetic multipoles act to correct any imperfections in the magnetic field at the extremities of the dipoles.

¹ From 2022, the Proton Synchrotron Booster receives protons from LINAC 4 at 160 MeV and accelerates them to 2 GeV for injection into the Proton Synchrotron. These upgrades of the system are the key element in the project to increase the luminosity of the LHC during the next decade.

2 The Large Hadron Collider at CERN

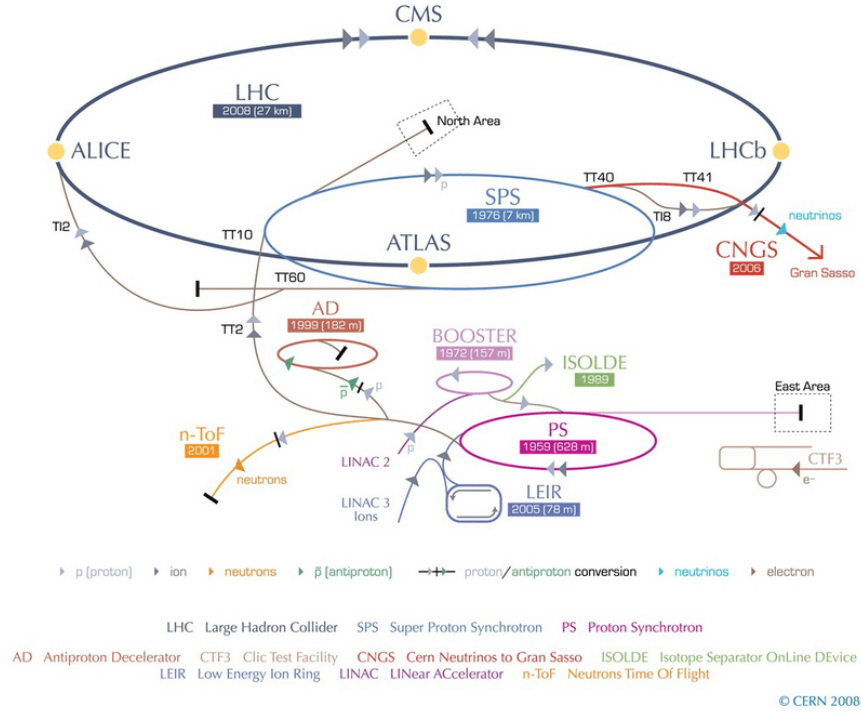


Figure 2.1: Illustration of the LHC injector complex showing the different acceleration steps [15].

The accelerated beams collide every 25 ns at one of the three main interaction points (IP) where the experiments, ATLAS (A Toroidal LHC ApparatuS) [16], CMS (Compact Muon Solenoid) [17] and ALICE (A Large Ion Collider Experiment) [18] are located. The LHCb (Large Hadron Collider beauty) [19] is a forward spectrometer experiment and the fourth largest which studies the beam collisions on fixed targets. The ATLAS and CMS are general purpose experiments aiming to perform precise measurements of SM processes and searches for evidence of new physics. The discovery of the Higgs boson using data recorded during 2011 and 2012 by both experiments [20, 21] for instance, constitutes a landmark achievement opening new horizons for new physics searches. On the other hand, LHCb and ALICE experiments comprise of detectors setups specialized on specific phenomena. LHCb is designed for the study of charm and beauty hadron decay products, whereas ALICE experiment is dedicated to the study of quark-gluon plasma in heavy ion collisions using the Pb ion beams delivered by the LHC. Other smaller dedicated physics experiments are complementary to the general purpose experiments. TOTEM [22] (TOTal Elastic and diffractive cross section Measurement), located on either side of the CMS IP, and LHCf [23] (Large Hadron Collider forward), located on either side of the ATLAS IP, focus on the study of the physics processes in the region very close to the particles beam the so called "forward" region. The former is designed to study the total proton-proton cross-section as well as the in depth study of the proton structure while the latter is used to study the Extremely High-Energy cosmic rays. MoEDAL [24] (Monopole and Exotics Detector At the LHC), located close to LHCb, searches for magnetic monopole and other exotic particles that would indicate new physics beyond the SM. Last, FASER [25] (ForwArd Search ExpeRiment), the newest experiment on the LHC ring is situated 480 m away from the ATLAS IP

and is designed for searches for light and weakly-interacting particles as well as the study of the neutrino interactions.

2.2 The High Luminosity Upgrade Plan

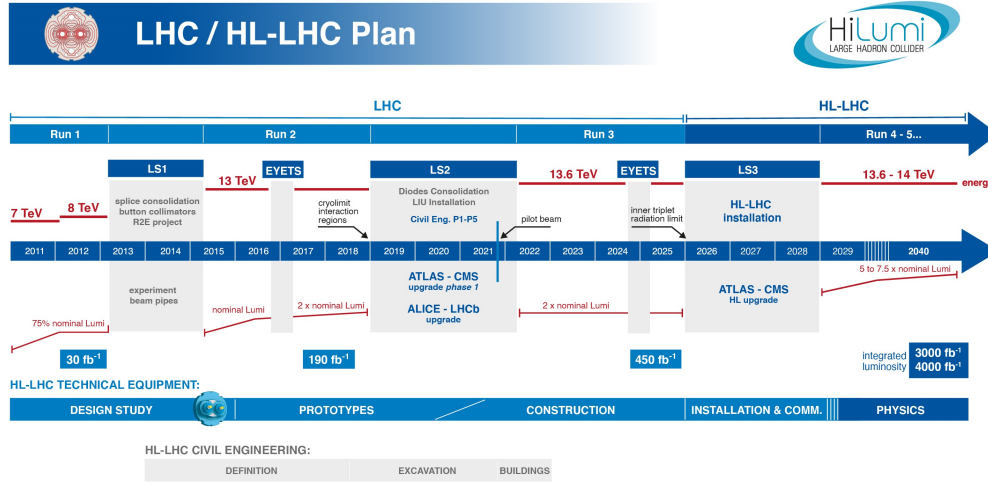


Figure 2.2: The LHC/HL-LHC plan showing the energy of the collisions (upper bold red lines) and peak luminosity (lower red lines) over the years [26].

The first proton beam in LHC launched successfully in September 2008. Very soon, the data-taking had to be suspended though, due to a damage that occurred on the magnet system. In the year 2010 the first collisions took place with the rest of the year to be devoted on commissioning. The data-taking continued in 2011 at a centre-of-mass energy of 7 TeV which was increased to 8 TeV in 2012 reaching the 75% of the nominal luminosity ($1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$). This period is referred to as Run-1. In early 2013, the accelerator stopped its operation for a period of two years (LS1) devoted on maintenance and repair work including improvements on installations connected with the experiments (Phase-0 upgrade). Between 2015 and 2018 (Run-2) the LHC was operated with proton beams at energies of 6.5 TeV and reached a peak luminosity of twice the nominal value. The schedule for the second shutdown period (LS2) which began at the start of 2019 had to be extended for about a year more to early 2022 due to the COVID-19 pandemic. These three years were devoted to preparations for Run-3 (2022-2025) which will deliver an integrated luminosity equals the value of the two previous runs combined. Each proton beam will be accelerated to the energy of 6.8 TeV. In parallel to the accelerator activities, the Phase-1 upgrade related to the experiments were also performed. No changes are foreseen to the schedule beyond 2022. The third long shutdown (LS3) will cover a period of three years from 2026 to 2028 aiming to operate in its high-luminosity phase delivering an instantaneous luminosity of 5-7.5 times the nominal value and reaching the design centre-of-mass energy of 14 TeV during the upcoming data-taking periods (2029 and beyond). The

upgrade plan of the experiments during the LS3 is called Phase-2 upgrade. The detailed upgrade plan is shown in Figure 2.2.

2.3 The Worldwide LHC Computing Grid

In order to store, process and distribute the huge amount of data produced by the LHC experiments, a high performance distributed computing system has been created in 2003. This comprises a network of more than 170 computer centers in more than 42 countries around the world which is arranged in tiers as presented in Figure 2.3.

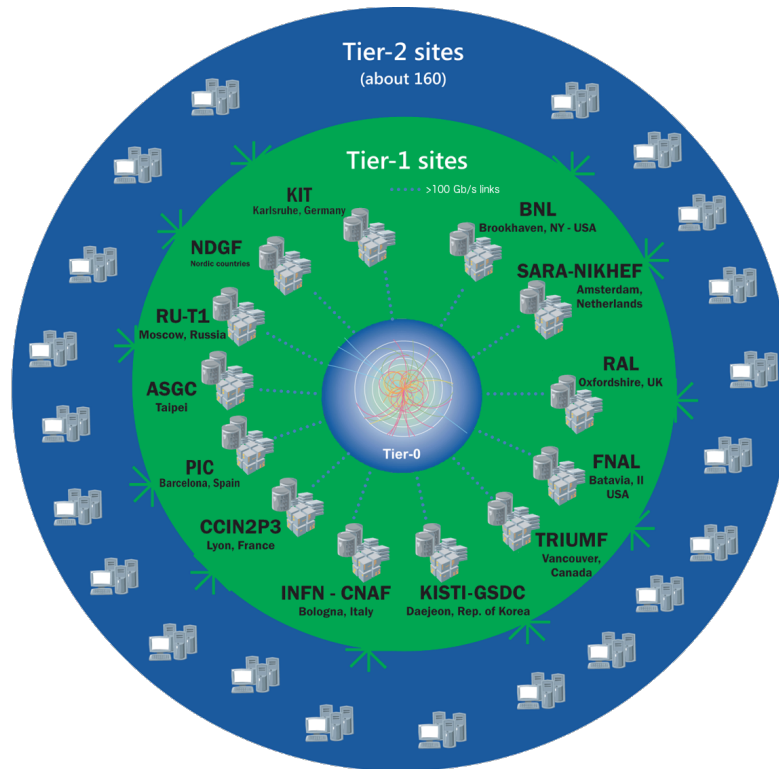


Figure 2.3: The LHC computing structure [27].

Tier-0 is the first contact point between the data and the computing grid while it provides the 20% of the total compute capacity. It is housed in the local CERN Data Center² where a first copy of the raw data is archived and is also responsible to run the initial calibration and reconstruction.

From Tier-0 both raw and reconstructed data are distributed to the Tier-1 sites. These are 13 large computing centers funded by national particle physics communities. They are responsible for the

² Since 2013 Tier-0 was co-located in the CERN Data Center at Meyrin and Wigner Data Center in Budapest. However, the contract with Budapest ended in 2019 and a new facility at CERN Preveessin will be built to house the required computing resources [28].

safe-bookeeping and reprocessing of data. Finally, the distribution of smaller derived datasets to the Tier-2 sites is performed.

Tier-2 consists of about 160 universities and other scientific institutes which can provide adequate computing power for specific analysis tasks, eg. data analyses and Monte-Carlo production. For long-term storage the data are sent back to the Tier-1 sites.

The final layer comprises of the Tier-3 sites which are local computing clusters in universities and institutes or just personal devices. There is no formal engagement between the grid and the Tier-3 resources though.

2.4 The Higgs Boson at the Large Hadron Collider

The Higgs boson is the predicted visible manifestation of the Brout-Englert-Higgs mechanism (see Section 1.1.3). It is a massive scalar boson with zero spin, even parity, without electric and color charge that gives the mass property to the particles it interacts with. The first observation was achieved in 2012 by analysing pp collision data at centre-of-mass energy of $\sqrt{s} = 7-8$ TeV collected by ATLAS and CMS experiments of LHC.

In pp collisions, the Higgs can be produced through a variety of different processes as depicted at the left side in Figure 2.4. The corresponding Feynman diagrams are shown in Figure 2.5 (a-e) in descending order of cross section. The dominant production process is the gluon-gluon fusion (ggF), appearing at a probability of 87% of the Higgs boson production at LHC, where the two gluons are combined forming a loop of virtual fermions with the largest contributor being the heaviest top quark. The second most abundant process (7%) is the vector boson fusion (VBF) where two quarks radiate off a heavy vector boson (W or Z) and then interact with each other emitting a Higgs boson. The initial quarks travel roughly along their initial directions and they leave a signature of two highly energetic particle jets in the detector. Higgs strahlung or else the production of Higgs bosons in association with a vector boson (VH) is observed at a frequency of 4%. When two fermions are combined can form a virtual W or Z boson which if it carries sufficient energy can then emit a Higgs boson. The final process that is commonly considered involves two colliding gluons each of them decaying into a heavy quark-anti-quark pair ($b\bar{b}$ (1%) or $t\bar{t}$ (1%)). A quark and anti-quark can then be combined to form a Higgs boson. The contribution of other $q\bar{q}H$ processes is much smaller and experimentally not accessible. The production of the Higgs boson in association with a single top quark (tH) accounts about the 0.05% of the total Higgs events at LHC with the most dominant contribution to be the Higgs radiation from the W boson and top quark.

After it is produced, the Higgs boson is predicted to decay almost instantly, with a lifetime of 1.6×10^{-22} s. All the possible decay modes are shown at the right side in Figure 2.4 and the corresponding Feynman diagrams are presented in Figure 2.5 (f-i). For a Higgs mass of $125 \text{ GeV}/c^2$ the SM predicts that the most common decay is into a $b\bar{b}$ pair occurring 58% of the time. Because the decay products are purely hadronic it is rather difficult to study this channel due to the large background of b -quark pairs at LHC. Thus, the measurements for this decay mode are done through production processes that are less copious but exhibit features not present in QCD, such as the associated production of Higgs boson with a vector boson [30]. The second most common decay is

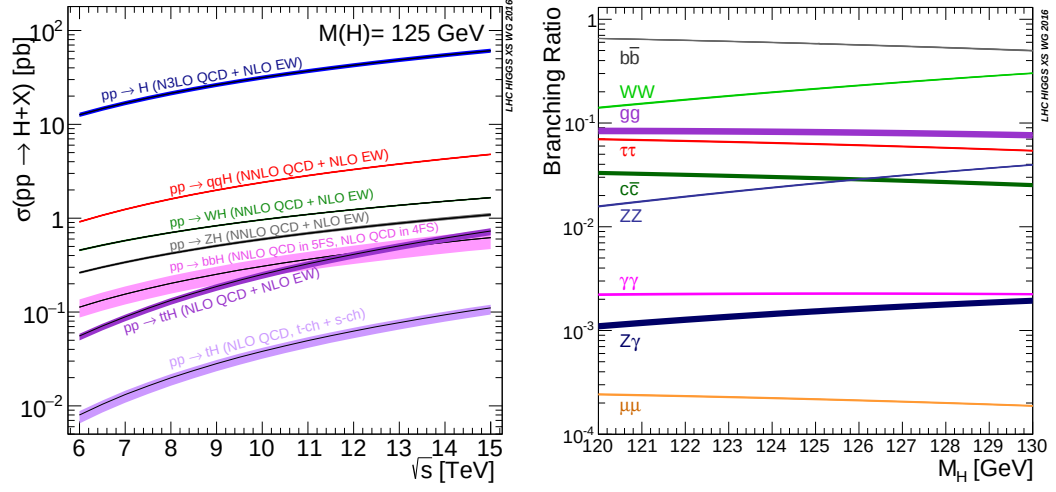


Figure 2.4: The Standard Model Higgs production cross sections (left) and branching ratios of its decay modes (right) at the LHC [29].

$H \rightarrow WW$, occurring 22% of the time. The W bosons can subsequently decay either into a quark-anti-quark pair (not that trivial to distinguish from the background) or into a charged lepton and a neutrino (final states not fully reconstructible because of the E_T^{miss}) with the latter to be the scope of this thesis (more details in Part III). Next, the decay into a pair of gluons through a loop of virtual heavy quarks happens approximately 9% of the time. A branching ratio of 6%, comparable to the gluon pair decay, accounts for the decay to a pair of τ leptons. The decay to c -quarks happens 3% of the time. Despite the small branching fraction of 3% and 0.2% for $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$ respectively, these two channels were the golden channels of the discovery due to their clean signature in the detector. With the increase of the integrated luminosity foreseen, rare decays such as $H \rightarrow Z\gamma$ (0.2%) and $H \rightarrow \mu\mu$ (0.02%) will benefit of better precision measurements.

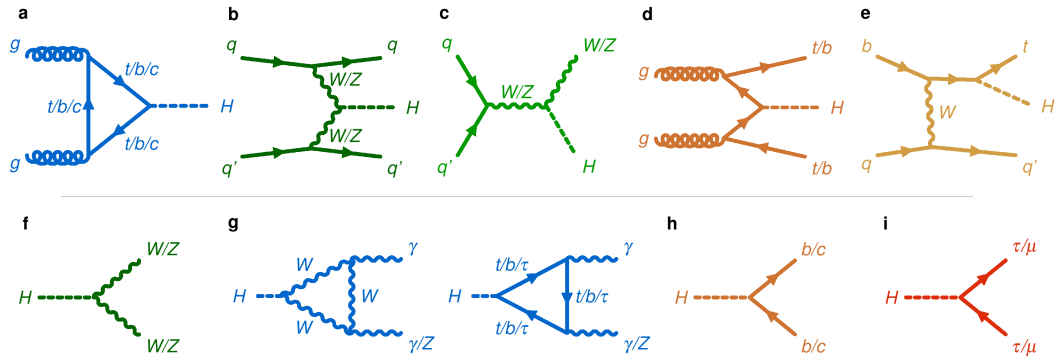


Figure 2.5: The Feynman diagrams for the different production (a-e) and decay modes (f-i) of the Higgs boson at the LHC [31].

3 The ATLAS Experiment

This chapter begins with a description of the ATLAS detector layout and the data processing chain in Section 3.1. Finally, Section 3.2 discusses the ATLAS upgrade plans in order to withstand the new condition standards imposed by the LHC, highlighting the New Small Wheel Project.

3.1 The ATLAS Detector

ATLAS is the largest detector ever constructed for a particle collider. It is cylindrical in shape with a length of 44 m, a diameter of about 25 m and a mass of approximately 7000 t.

ATLAS uses a right-handed coordinate system with its origin interpreted as the interaction point (IP) in the center of the detector, while the beam direction defines the z-axis. The x-axis points from the IP to the centre of the LHC ring and the y-axis points upward, slightly tilted with respect to the vertical. The detector is divided into two sides, A-side and C-side reflecting the positive and the negative z-values respectively. The x-y plane, or else transverse plane, can be expressed in terms of cylindrical coordinates. The azimuthal angle ϕ , is measured around the beam axis ranging from $-\pi$ to $+\pi$, while the radial component measures the distance from the beam line. The polar angle θ ranging from 0 to π , is reported in terms of pseudorapidity, expressed as $\eta = -\ln \tan(\theta/2)$ in the relativistic limit. A graphical representation of ATLAS is shown in Figure 3.1.

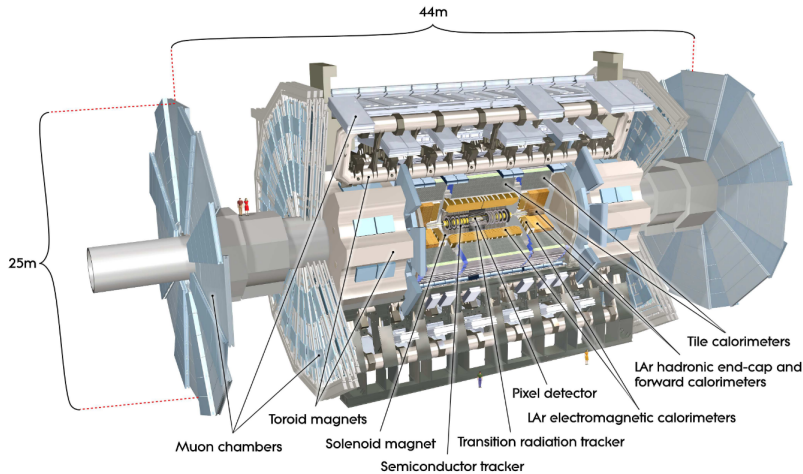


Figure 3.1: Cut-away view of the ATLAS detector [16].

3.1.1 Subsystems

ATLAS is composed of different detector sub-systems, each sensitive to different types of particles covering almost the entire solid angle around the collision. In the central region, or else barrel region, its sub-components are arranged in concentric cylinders while in the forward region, where the two end-caps are located, the detectors are mounted on disks perpendicular to the beam axis.

Magnet System

Particles emerging from charged particles normally travel in straight lines. For precise momentum measurements though, the particles' trajectories need to be bent. Thus, an essential part of the detector is the magnet system providing the bending power required. ATLAS has selected the arrangement of a central superconducting solenoid [32] servicing the inner tracker with a magnetic field of 2 T, surrounded by a system of three large scale superconducting air-core toroids (one in the barrel and two in the end-cap regions) [33, 34] providing a magnetic field with a peak value at 4.1 T for muons. The overall dimensions of the magnet system extend over a length of 26 m, an outer diameter of 20 m with a total volume of 8000 m³ [35].

Inner Detector

Starting from the core of the detector, the innermost sub-system contains the Inner Detector (ID) [36] that provides an excellent tracking reconstruction of the charged particles traversing its volume in the pseudorapidity range of $|\eta| < 2.5$. It consists of three complementary sub-detectors arranged coaxially around the beam pipe. The Pixel Detector is followed by the Semiconductor Tracker (SCT) while at the outermost layers the Transition Radiation Tracker (TRT) complements the tracking system. A cross-section of the ATLAS ID barrel is shown in Figure 3.2. The ID was designed to withstand and operate under the nominal luminosity conditions. However, prior to the Run-2 data-taking the accelerator system was upgraded so that to enable its operation at luminosity higher than the nominal value.

The Pixel Detector is made of three layers of silicon pixels in the barrel region with its first layer positioned at 50.5 mm away from the IP, while 3 disks are mounted in each end-cap. The performance of the innermost layer in the barrel region is critical for the evaluation of physics and at the same time challenging due to the very high radiation environment. For radiation reasons, a replacement of this first layer was foreseen until the total replacement of the ATLAS inner tracker for the HL-LHC era. Instead, during the LS1 a new layer, called the Insertable B-Layer (IBL) [37], was installed reducing the distance from the beam axis to 33.25 mm. Among other benefits, the IBL improved the resolution of track impact parameters as shown in Figure 3.3. The intermediate detector is the SCT which consists of four layers of micro-strip silicon sensors in the barrel and nine disks in each of the end-caps and it plays an important role in measuring the transverse momenta of charged particles. The particle detection in the Pixel and SCT detectors is based on the ionisation happening when charged particles traverse the silicon bulk. The outermost sub-system is the TRT, consisting of 50 layers of gaseous straw tubes. The particle detection is based on the ionisation of the gas when a charge particle traverse its volume. The drift time of electrons originating from the ionisation

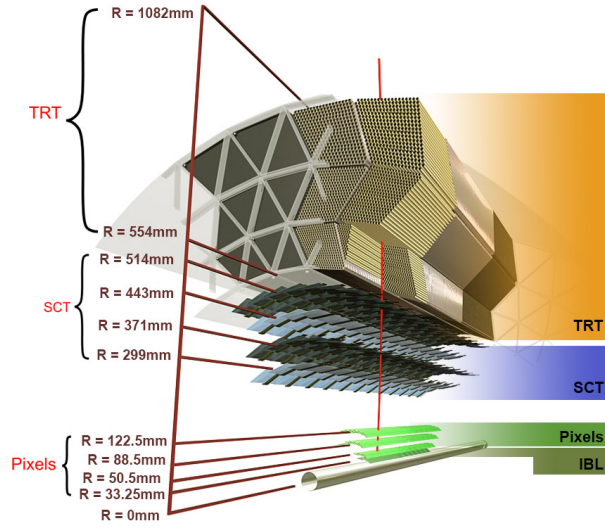


Figure 3.2: Transverse view of the ATLAS Inner Detector in barrel region [16].

provides a discrimination between tracking hits and hits from the transition radiation ¹, enhancing the identification of electrons and their discrimination against pions.

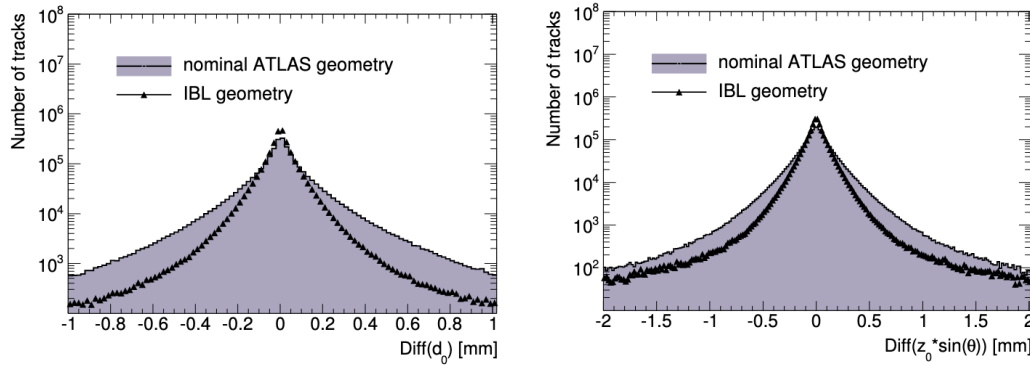


Figure 3.3: The measured d_0 (left) and $z_0 \times \sin \theta$ (right) impact parameter distributions with respect to the Monte-Carlo measurements with and without IBL geometry for tracks in $t\bar{t}$ events without pileup [37].

Calorimeter System

The Calorimeter System [38] is designed to measure the energy deposits of the incoming particles while they stop within its volume. It covers the pseudorapidity range of $|\eta| < 4.9$ and a representation of its constituents is presented in Figure 3.4. The ATLAS Calorimeters were designed to last for the

¹ The transition radiation is produced by relativistic charged particles when they cross the boundary between materials with different dielectric properties.

entire lifetime of the LHC and the detectors themselves require very few modifications to run at higher luminosity.

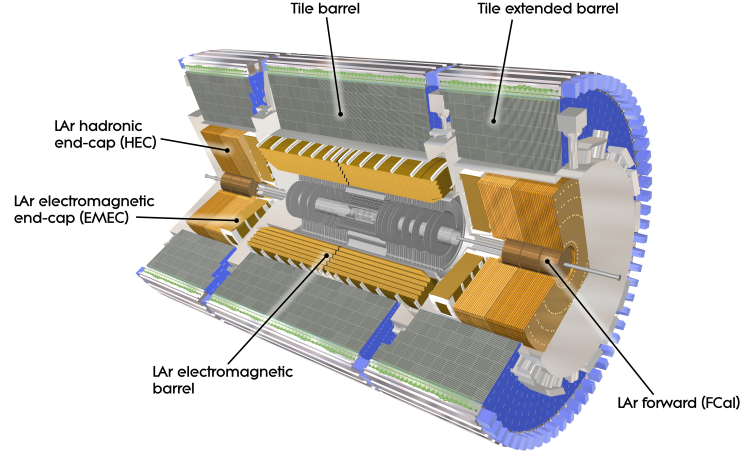


Figure 3.4: Cut-away view of the ATLAS Calorimeter System [16].

The calorimeters closest to the beam are mainly designed to identify electrons and photons (Electromagnetic Calorimeter (ECal)) while the outer layers are designed for the hadronic particles (Hadronic Calorimeter (HCal)) which do not deposit all of their energy on the past layers. Their construction is based on alternating layers of passive material that absorbs the particles and active material that collects their energy via ionisation or scintillation providing a measurable signal.

ECal is divided into a barrel part ($|\eta| < 1.475$) and two end-cap components (EMEC) ($1.375 < |\eta| < 3.2$). It uses liquid Argon (LAr) as the active detector medium and lead (Pb) for the absorber plates. HCal is placed directly outside the ECal envelope. Its barrel part covers the region $|\eta| < 1.0$ while two extended regions are located in the range $0.8 < |\eta| < 1.7$. It uses steel for the absorber parts and scintillating tiles as the active material. The Hadronic End-cap Calorimeters (HEC) slightly overlap with other components of the Calorimeter System covering the range $1.5 < |\eta| < 3.2$. Copper plates are interleaved with liquid Argon gaps, serving as the active medium for this sampling calorimeter. An additional thin LAr layer acting as a presampler detector covers the region $|\eta| < 1.8$ and is used to correct upstream energy losses. The Forward Calorimeter (FCal) complements the Calorimeter System and consists of one electromagnetic and two hadronic components. It is integrated at the end-caps providing coverage over $3.1 < |\eta| < 4.9$. The active material chosen is the LAr while copper and tungsten are the passive material choices for the electromagnetic and hadronic modules respectively. FCal not only minimises the energy losses in cracks between the calorimeter systems but also reduces the radiation background levels in the following detecting system.

Muon Spectrometer

Muons being minimum ionizing particles (MIPs) cross the calorimeters without being absorbed, usually only losing a small fraction of their energy. Thus, their identification is provided by the Muon

Spectrometer (MS) [39], installed at the outer part of the ATLAS detector covering the range $|\eta| < 2.7$ with full ϕ coverage. A graphical representation of the Muon System is shown in Figure 3.5.

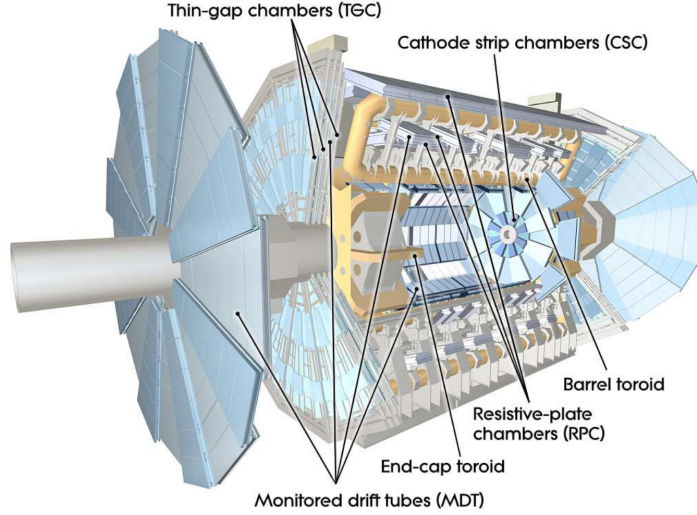


Figure 3.5: Cut-away view of the ATLAS Muon Spectrometer [16].

The MS operation is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets instrumented with separate trigger and high-precision tracking chambers. For $|\eta| < 1.4$, the muon tracks are bent by the barrel toroid while the two end-cap toroids are responsible for the magnetic deflection in the region $1.6 < |\eta| < 2.7$. The combination of barrel and end-cap fields is applicable to $1.4 < |\eta| < 1.6$. This magnet configuration minimises the resolution degradation due to multiple scattering.

In the barrel region, muon stations are arranged in three roughly cylindrical layers around the beam axis. The most part of the barrel is equipped with the multilayered Monitored Drift Tubes (MDTs) responsible for precision measurements. The basic element of the MDTs is a pressurised drift tube with a diameter of 30 mm and a central tungsten-rhenium wire (anode) of 50 μm in diameter. The tube is filled with Ar/CO₂ (93/7) gas at 3 bar and a high voltage is applied on the central wire. Each MDT chamber consists of a stack of tubes organised in layers. Resistive Plate Chambers (RPCs) are installed together with the MDTs in the middle and outer stations to provide the trigger information and measure the second, azimuthal component of the muon tracks. The basic RPC unit is a narrow gas gap of C₂H₂F₄/Iso-C₄H₁₀/SF₆ (94.7/5/0.3) formed by two parallel resistive plates made of phenolic-melaminic plastic laminate.

In the end-cap regions the chambers are installed in three disks perpendicular to the beam pipe. Again, in the middle and outer wheels, the MDTs serve as the precision tracking chambers except of the innermost forward direction ($2.0 < |\eta| < 2.7$) where the particle flux and muon-track density are highest, exceeding the limit for their safe operation. Consequently, the technology chosen for this first innermost layer (nicknamed Small Wheel (SW)) is the Cathode Strip Chambers (CSCs). The whole CSC system consists of two disks, one on each ATLAS end-cap side with 8 small and 8 large

trapezoid chambers consisting of 4 layers each. The CSCs are multi-wire proportional chambers with cathode planes segmented into strips in orthogonal directions to measure both precision and transverse coordinates. The gas mixture consisting of Ar/CO₂ (80/20) is chosen as the detector's active material. Instead of reading out the signal on the wires the position of the track is measured by the interpolation between the charges induced on the neighbouring cathode strips. In this way a spatial resolution of 60 μm is achieved per layer compared with the 80 μm of a MDT tube layer. The middle wheels are occupied along with the MDTs with the Thin Gap Chambers (TGCs) to provide information for the trigger and the second coordinate. They are multi-wire proportional chambers like CSCs, with the characteristic that the wire-to-cathode distance is smaller than the wire-to-wire distance and along with the high electric field applied around the wires this leads to a good performance. The gas used is a mixture of CO₂/n-pentane (55/45).

3.1.2 Trigger & Data Acquisition

The LHC collides protons at a frequency of around 40.079 MHz, i.e every 25 ns. However, this detector particle footprint rate not only exceeds the read-out capabilities of the detector subsystems but also overcomes the bandwidth and the storage capabilities at the CERN computing center.

The ATLAS Trigger and Data Acquisition (TDAQ) [40] system is responsible for deciding in real time whether to record data and store the events of interest for offline analysis. A diagram of all the relevant components for triggering as well as the detector read-out and data-flow used in Run 2 is shown in Figure 3.6. The events are selected using a two-level trigger system. The first level reduces the maximum rate of events to about 100 kHz while the second stage reduces it further to an averaged rate of 1.2 kHz resulting to a throughput to permanent storage of 1.2 GB/s.

The Level-1 (L1) trigger is a hardware-based system that uses custom electronics to dump reduced-granularity information from the calorimeter (L1Calo) and muon detectors (L1Muon). The L1Calo trigger uses signals that are digitised and calibrated by the preprocessor and are sent in parallel to the Cluster Processor (CP), which identifies electron, photon and τ -lepton candidates above a threshold, and Jet/Energy-sum Processor (JEP), which identifies jet candidates and produces sums of total and missing transverse energy. The L1Muon trigger uses hits from the RPCs (in the barrel) and TGCs (in the end-caps). To reduce the rate in the end-cap regions of particles not originating from the IP, coincidence requirements are applied between the outer and inner TGC stations as well as between the TGCs and the tile calorimeter. The L1 trigger decision is made by the Central Trigger Processor (CTP), which receives inputs from the L1Calo and L1Muon through the L1Muon Central Trigger Processor Interface (MUCTPI) and the L1 topological (L1Topo) trigger. It is also responsible for applying the dead time, a mechanism to limit the number of L1 accepts to be within the 2.5 μs time window (latency) permitted by the detector electronics. For each L1-accepted event, the Front-End (FE) detector electronics read out the event. The data are sent first to ReadOut Drivers (RODs), performing the initial processing and formatting and then to the ReadOut System (ROS) to buffer the data which are then sent to the second stage of the trigger when requested. In addition the L1 triggers identify the Regions-of-Interest (RoIs) within the detector to be further investigated by the second trigger stage.

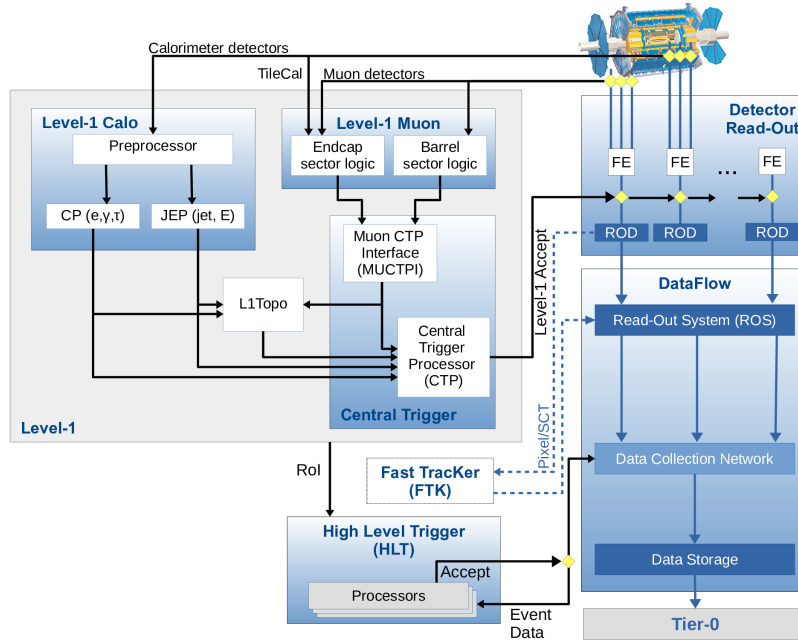


Figure 3.6: Schematic of the ATLAS Trigger² and Data Acquisition system in Run-2 [40].

The second level of the trigger, the High-Level Trigger (HLT) is software based. It makes use of dedicated fast trigger algorithms to provide early rejection, followed by more precise and more CPU-intensive algorithms similar to those used for offline reconstruction to make the final decision. Once an event is accepted by the HLT, the data are sent to permanent storage in RAW (bytestream) format for offline reconstruction and are exported to the Tier-0 facility at CERN's computing center.

3.1.3 Simulation

Monte-Carlo (MC) detector simulations consist a fundamental tool for comparisons of the theoretical models to data among others (e.g testing the performance of the detector, calculation of systematic uncertainties, background modelling, etc.). The ATLAS simulation is integrated into the common software framework, called Athena [41], based on the common Gaudi [42], a framework for data processing for high energy experiments. The main code is written in C++ whereas there is also a configuration layer in Python. The generation of MC datasets consists of several steps [43] that are shown in Figure 3.7 and summarized below.

² The Fast Tracker (FTK) was designed to provide inner detector tracks to the HLT and L1 acceptance rate. It was eventually not approved by the ATLAS Collaboration and thus not implemented.

Event Generation

Event generators run within Athena framework, but most of the generators themselves are written and maintained by authors external to ATLAS. Each generated event contains the particles from a single interaction considering prompt decays with and without accounting the beam properties and the detector effects respectively. The information of the stable and long-lived particles expected to interact within the detector is kept for processing at the next step. Thus, the definition of what is considered as stable particle has to be done at generator level. The output format is called EVNT while the information stored is based on standard HepMC format [44] and contains a full picture of the event history including the parents of unstable particles as well as all particles' data information (i.e PDG particle identifier code, name, charge, mass, lifetime and spin) including their four momenta. This information is called Monte Carlo truth.

Detector Simulation

The simulation of ATLAS relies on the Geant4 [45] particle simulation toolkit and describes the interaction of particles with the active and passive detector materials as well as their deflection in the magnetic field. The output is appended to the Monte Carlo truth information already defined at generator-level which is a record of energy deposits, vertexing, incoming/outgoing particles etc. and its format is called HITS. Very precise simulations cost in terms of CPU and disk-space while the requirements for large-scale MC production are going to be increased significantly the upcoming years with the increase of the luminosity. As an alternative for the most time consuming parts of the simulation (i.e the calorimeters) a parametrisation (the so-called fast simulation) of their response has been deployed and runs in combination with the Geant4 simulation to address the above mentioned issues.

Simulation of Detector Response (Digitisation)

The hits produced by the simulation need to be translated into detector responses, or else digits (inputs to the RODs in the detector electronics). This process is dependent on the detector type as it includes the modelling of effects like the signal collection, pulse shaping, readout scheme, electronic noise etc. Data collected during test-beams or from other tests performed in the lab are used to tune the digitisation algorithms. The output format is written out as Raw Data Objects (RDO). Simulated Data Objects (SDO) can also be produced at this step containing information about all the particles and noise that contributed to the signal. This particular format is mostly used to determine the tracking efficiency and fake track rates. Within the digitisation step, hits from the hard scattering are overlaid with additional interactions, i.e pile-up for a realistic description.

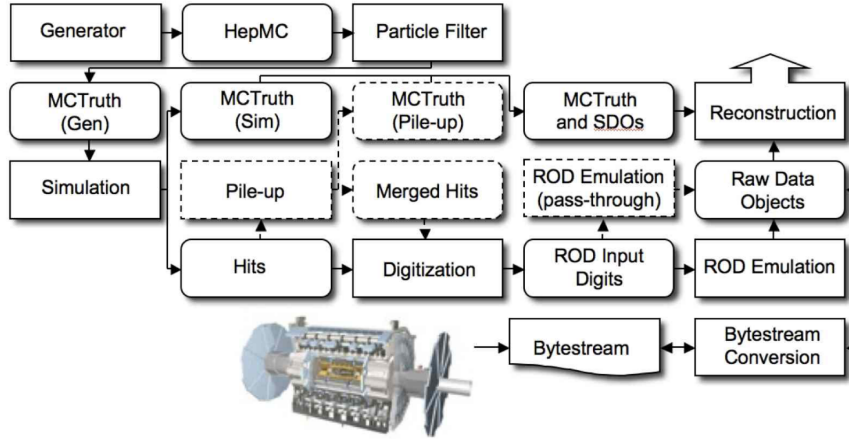


Figure 3.7: Workflow of the ATLAS simulation framework, from event generators (top left) to reconstruction (top right) [43].

3.1.4 Object Reconstruction

The reconstruction procedure is identical for simulation and real data with the exception that truth information can be treated and is available only on simulated data. The ATLAS HLT output is written in bytestream format and a conversion to RDO is needed³ to run the reconstruction step.

Tracks and vertices

Tracks are reconstructed in the ID using a sequence of algorithms [46]. A clustering algorithm is used where pixels and strips in a given sensor are grouped together forming three dimensional space-points. An iterative combinatorial procedure follows to find candidate tracks where sets of three space-points are formed to maximise the possible number of combinations and allow a first estimate of the track momentum. Next, space-points from the remaining layers of the pixel and SCT detectors compatible with the preliminary trajectory are incorporated in the Kalman filter [47]. With this procedure all possible combinations have been made and are used as input to the ambiguity solver whose logic flow is illustrated in Figure 3.8.

A score is assigned to each one of the preliminary trajectories based on criteria defining the track quality and they are sorted in descending order of score. Bad scored tracks are rejected. A neural network is trained to identify the clusters (merged clusters) that are shared among close-by energetic tracks. All tracks fulfilling the requirements are propagated to the final track collection, they are

³ In order to perform HLT simulation studies, the RDO format needs to be converted into bytestream. There is some loss in this conversion but the inverse operation (from bytestream to RDO) is lossless.

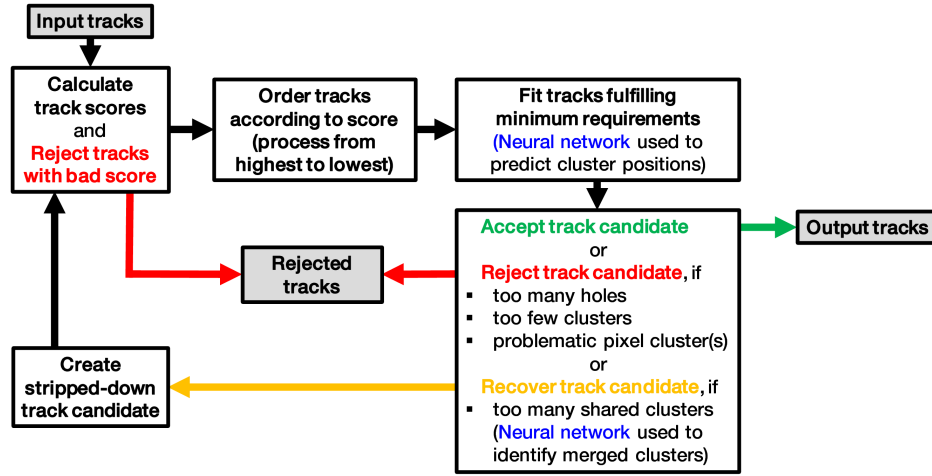


Figure 3.8: The flowchart of tracks through the ambiguity solver [46].

extrapolated to the TRT for the final track parameter estimation⁴ and are used to reconstruct the interaction vertices. The primary interaction vertex is defined to be the one with the highest sum of the squared transverse momenta of its associated tracks.

Electrons and photons

Electrons and photons are particles that initiate electromagnetic showers, i.e providing similar signatures in the detector, and therefore their reconstruction proceeds in parallel, by combining the information from both the ID and the ECal systems [48].

In short, clusters of energy deposits (superclusters) in the calorimeter matched with a track found in the ID define an electron object. A converted photon is a cluster matched to a conversion vertex while an unconverted photon is a cluster matched to neither an electron track nor a conversion vertex.

The superclusters are built starting from a list of EM topo-clusters⁵ sorted by descending E_T . The clusters, or else seed clusters, are tested one by one and are labeled as electrons, prompt and converted photons according to the criteria they pass. Then, the algorithm tries to search for satellite clusters. A satellite cluster for both electrons and photons is considered as any cluster falling within a window of $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$ around the seed cluster barycentre, representing secondary EM showers originating from the same initial particle. In particular for electrons if a cluster falls within a window of $\Delta\eta \times \Delta\phi = 0.125 \times 0.300$ around the seed barycentre and its best-matched track is also the best-matched track for the seed is considered a satellite as well. For photons with conversion vertices made up only of tracks containing silicon hits, a cluster is added as a satellite if its best-matched electron track belongs to the conversion vertex matched to the seed cluster. By this way

⁴ The final reconstructed tracks are described by five parameters. The transverse impact parameter d_0 defined as the shortest distance between the track and the beam line in the transverse plane, the longitudinal impact parameter z_0 defined as the distance in z between the primary vertex and the point on the track used to evaluate d_0 , the η and ϕ of the particle and the track momentum expressed as q/p_T .

⁵ iterative algorithm where clusters are formed in the calorimeters using a set of noise thresholds.

the discrimination between distant radiative photons or conversion electrons from pile-up or other unrelated clusters is achieved. As described above, the superclusters are formed independently for electrons and photons and therefore a given seed cluster can be both labeled as electron and photon. To distinguish such cases the procedure presented in Figure 3.9 is followed. If none of the criteria are satisfied the particle is labeled as ambiguous and its final classification is performed at analysis level.

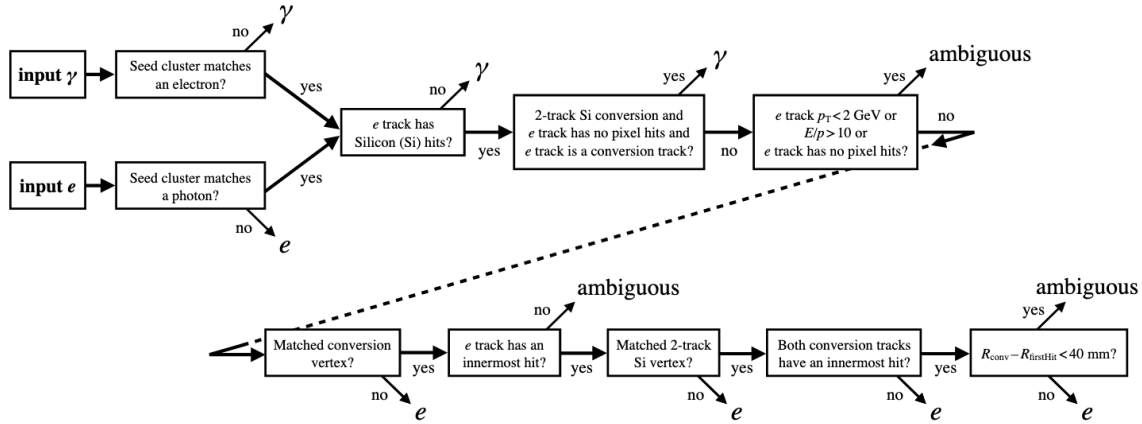


Figure 3.9: The flowchart showing the logic of the ambiguity resolution for particles initially reconstructed both as electrons and photons [48].

Further identification and isolation selections (working points, WP) are used to improve the purity of selected electron and photon objects. Prompt electrons are discriminated against hadronic jets, converted photons and electrons produced in the decays of heavy-flavour hadrons, based on a likelihood (LH) discriminant using information measured in the ID, the calorimeter and the combined ID and calorimeter whereas prompt photons are identified and selected against backgrounds from hadronic jets using a cut-based selection on the shower shapes in the calorimeters.

Muons

The reconstruction of muons is based on information collected by the ID, the MS tracking detectors as well as the calorimeter system [49]. The main reconstruction strategies that are followed are six and thus six muon types are defined: stand-alone (rely only on information from the MS used for the tracks that fall outside the ID coverage), combined (CB, matching MS tracks to ID tracks and accounting the energy loss in the calorimeters), inside-out combined (IO, ID tracks are extrapolated to the MS where at least three loosely-aligned MS hits are required and the energy loss in the calorimeters is accounted in the combined track fit), muon-spectrometer extrapolated (ME, if MS tracks are not matched to an ID track, its parameters are extrapolated to the beamline), segment-tagged (ST, an ID track extrapolated to the MS satisfies tight angular matching requirements to at least one

reconstructed MS segment) and calorimeter-tagged (CT, ID tracks extrapolated to the calorimeters and search for energy deposits consistent with a MIP).

The reconstruction of tracks in the MS starts with the identification of short straight-line track segments found in the different muon stations. The segments are then combined into preliminary track candidates loosely constrained based on the IP and a parabolic trajectory describing the bending in the magnetic field. Precision measurements in the bending plane are combined with measurements of the second coordinate from the trigger detectors providing three-dimensional tracks. Then a global fit is performed. After reconstruction a selection of WPs for each of the muon types is applied for further distinction of prompt and non-prompt muons.

Jets

A jet is a narrow cone of hadrons and other particles, moving along the same direction, produced by the hadronisation of a quark or gluon resulting to colour-neutral states. Several algorithms exist for jet reconstruction with the anti- k_t [50] being the most accurate one and employed in most ATLAS analyses which use the Run 2 dataset.

Topo-clusters are formed in the calorimeter and two main variables expressed as distances between closest-neighbour clusters (i and j), and a cluster (i) and the beam (B) are defined as:

$$d_{ij} = \min \left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2} \right) \frac{\Delta_{ij}^2}{R^2}, \quad d_{iB} = \frac{1}{k_{ti}^2} \quad (3.1)$$

where $\Delta_{ij}^2 = (\gamma_i - \gamma_j)^2 + (\phi_i - \phi_j)^2$ and k_{ti}, γ_i and ϕ_i are the transverse momentum, rapidity and azimuthal angle of the entity i respectively. The parameter R defines the radius of the output jet. The algorithm checks at every step the smallest distance and if it is the d_{iB} , that cluster is considered as a jet and is removed from the list. For the other case, the two clusters are merged into a single larger cluster, and the procedure is repeated until no clusters are left.

Hadronic final-state measurements can be improved when the track information from the ID is combined with the calorimeter systems and is given as input to the particle flow algorithm (PFlow) [51]. Specifically, energy deposits in the calorimeter by charged particles is removed from the observed topo-clusters and the jets are reconstructed with the remaining clusters in the calorimeters. By this way the resulting jet energy and angular resolution are improved while the reconstruction efficiency and pile-up are more stable compared to the jet reconstruction based only on the information provided by the calorimeters.

Reconstructed jets undergo a calibration procedure as described in Figure 3.10 to correct their energy in order to be compatible with the parton which initiated the jet.

First, the excess energy due to in-time (i.e additional pp interactions) and out-of-time (i.e residual gases in the beam pipe) pile-up is removed. Then, the reconstructed jet four-momentum is brought to particle level by comparing the energy of simulated jets between the truth and reconstruction level in order to account for energy losses in passive material, non-compensation of calorimeters, out-of-cone effects etc. After, with the global sequential calibration which is performed using both data and

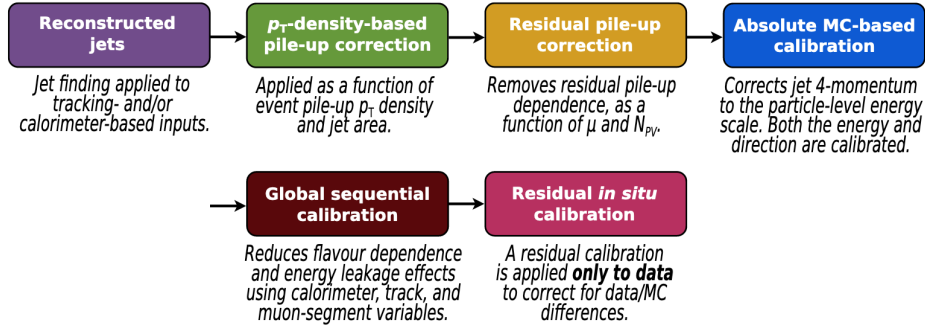


Figure 3.10: Calibration stages for jets [52].

MC, the jet p_T resolution is improved by removing the dependence of the jet response on variables (observables) constructed using information from the ID, calorimeters and MS. At the last step, an in-situ calibration is applied on data only, and corrects the remaining differences on jet response observed between data and MC simulation (i.e imperfect simulation of the detector material and physics processes involved).

The categorisation of jets into b -jets, c -jets and light-flavour jets is done using a two-staged approach [53]. At first level the properties of individual charged-particle tracks associated with a hadronic jet are used while the tracks are combined to explicitly reconstruct displaced vertices⁶. Then these results are passed into high level algorithms which consist of multivariate classifiers.

Missing Transverse Energy (MET)

The presence of non-interacting particles with the detector, i.e neutrinos, can be established through the missing transverse energy [54], E_T^{miss} , defined as the negative of the vectorial momentum sum of all reconstructed objects in the detector. There are two contributions coming from the hard- and soft-event signals. The former comprises all fully reconstructed and calibrated particles and jets while the latter consists of reconstructed charged-particle tracks associated with the primary vertex without being associated to any of the hard-scatter objects.

3.2 The ATLAS Upgrades towards the HL-LHC

For Run-3 an instantaneous luminosity of 2 times the nominal value and an average pileup of about 80 collisions per bunch crossing while for the HL-LHC phase an instantaneous luminosity of 7.5 times the nominal value and an average pileup of about 200 collisions per bunch crossing are foreseen. In order to cope with the new harsh conditions many improvements and upgrades have been planned for ATLAS organised in two phases during the LS2 and LS3, namely Phase-1 and Phase-2 respectively.

⁶ energetic b -hadrons before decaying generally lead to at least one vertex displaced by a few mm away from the hard-scatter collision point

3.2.1 Phase-1 Upgrades & the New Small Wheel Project

The preservation but also the improvement of the low transverse-momentum electron and muon trigger thresholds as well as the maintainance of the machine to be sensitive to electroweak-scale particles that produce hadronically-decaying τ leptons, jets and missing transverse momentum are the main objectives for the Phase-1 upgrade plan. These goals have been accomplished through the following upgrades:

1. installation of new calorimeter trigger electronics [55], providing a finer granularity and a higher energy resolution to the trigger system.
2. new end-cap muon detectors [56] that can withstand the high background radiation environment.
3. new muon chambers in the inner barrel central region, extending the trigger coverage of the muon system (it serves as a test prior to the Phase-2 muon system upgrade [57]).
4. TDAQ system upgrades [58], that take advantage of the calorimeter and muon system upgrades while rejecting background in a high pile-up environment and simultaneously maintaining the same acceptance rate.

Being part of this thesis, a detailed overview of the new end-cap system, the so-called New Small Wheels (NSW), is presented below.

The New Small Wheel Project

Simulation studies alongside with analysis of data collected during 2012, have demonstrated that the performance of the muon tracking chambers (in particular at the inner end-cap region, at the location of SWs, the region with the highest background conditions) both in terms of efficiency and resolution, degrades with the expected increase of the cavern background rate. The potential degradation is expected to have the worst impact for high momentum muons ($p_T > 100$ GeV) while precise measurements require track segments to be found in all three muon stations.

$Z' \rightarrow \mu\mu$ simulated events in different background environments were used to quantify the loss in efficiency of the muon end-cap stations. As presented in the distribution at the left of Figure 3.11, the signal is reduced by 70% for conditions close to HL-LHC (red distribution). Furthermore, during the previous running periods, it was observed that low energy particles can interact with the material that is located between the inner and middle end-cap regions producing fake muon triggers. The right distribution of Figure 3.11 shows the η distribution of the Level-1 muon signal along with the offline well reconstructed muon tracks. More than 80% of the muon trigger rate comes from the end-caps ($|\eta| > 1.0$) while most of the triggered objects are not reconstructible offline.

The latter could be solved by rising the Level-1 trigger threshold for the muon momentum, but this will have a big impact on several physics searches. In order to solve the above mentioned issues together, ATLAS Collaboration proposed to totally replace the inner muon station with the NSW.

The performance of the new detector should be as good as that of the SW. For this reason, the NSW should be able to measure the transverse momentum of passing muons of 1 TeV, with a precision of

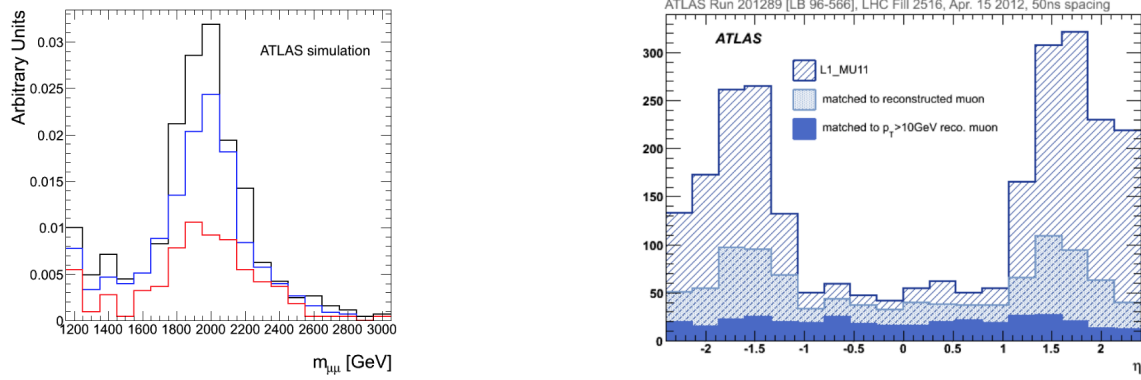


Figure 3.11: Left: Reconstructed di-muon mass using simulated $Z' \rightarrow \mu\mu$ events in three different background conditions. The black, blue and red histograms correspond to luminosities of 0.3, 3 and 5 times the nominal value. Right: η distribution of Level-1 muon signal with $p_T > 10$ GeV (L1_MU11) and of the offline reconstructed muons with $p_T > 3$ GeV and $p_T > 10$ GeV [56].

10%. In order to achieve this, the position resolution in the bending plane of muon track segments should be better than $50\ \mu\text{m}$, to match the performance of the MDT system. This requires a position resolution better than $100\ \mu\text{m}$ per plane for a 4-layer detector. In terms of efficiency, the segment finding should be better than 97% for muons with $p_T > 10$ GeV at the high radiation environment. Moreover, the second coordinate should be measured with a resolution of 1-2 mm to facilitate the combined muon reconstruction. Finally, a good angle resolution of about 1 mrad is required to eliminate and correct effects like the multiple scattering in the calorimeters and the finite size of luminous region of pp collision, improving the p_T resolution.

The NSW is a set of precision tracking and trigger detectors able to work at high rates with excellent real-time spatial and time resolution. Two detector technologies from the family of gaseous detectors are deployed to the system: the small-strip Thin Gap Chamber (sTGC) [59] and the resistive strip Micro-Mesh Gaseous Structure (Micromegas, MMG) [60]. Their internal structure is shown in Figure 3.12.

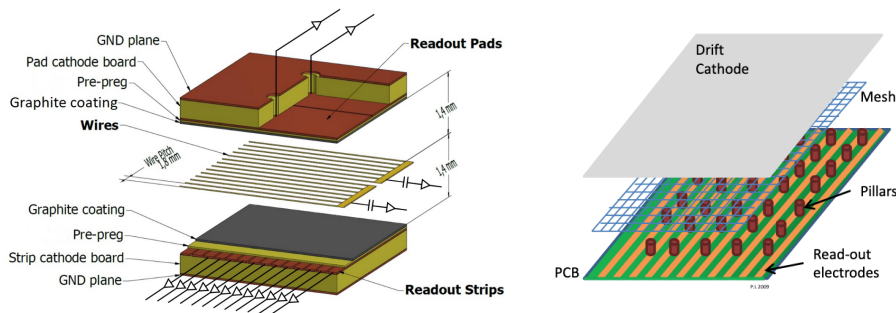


Figure 3.12: The sTGC (left) and MMG (right) internal structure [56, 61].

The sTGC is an extension of TGC technology allowing fast on-line tracking that can be used in the

L1 trigger with sufficient precision for the offline tracking as well. Two FR4 cathodes coated with a resistive graphite-resin mixture form a gap 2.8 mm thick filled with a mixture of 55% CO₂ and 45% n-pentane. The anode plane in the middle of the gap consists of 50 µm in diameter gold-plated tungsten wires with a pitch of 1.8 mm. The direction of the wires is parallel to the radial axis of the chamber and a high voltage of +2.8 kV is applied on them. Signals are capacitively induced on copper readout strips with a direction perpendicular to the wires, 2.7 mm wide with a pitch of 3.2 mm on one side of the gap and on large rectangular copper pads on the other side. The pad coincidence can form a vector pointing at the IP. Moreover, the pads dictate which strips are for readout in order to obtain a precise measurement in the bending coordinate. The read out of the wires provides the information of the azimuthal coordinate.

On the other hand, the Micromegas technology permits the construction of thin wireless detectors. A stainless steel mesh separates a gas gap of about 5 mm thickness into two asymmetric regions. The larger region extending from the mesh plane upwards to the cathode electrode is called conversion or drift gap. The anode electrode is located at a distance of 128 µm below the metallic mesh, and is segmented into strips 0.3 mm wide with a pitch of 425 – 450 µm depending on the type. This region is called amplification gap. The mesh sits on support pillars. Two gas mixtures have been extensively tested; the originally proposed gas mixture⁷ with a composition of 93% Ar and 7% CO₂ and the baseline mixture with a composition of 93% Ar, 5% CO₂ and 2% isobutane. The high voltage potentials are chosen such that the electric field to be a few hundred V/cm in the drift region (adjusted to set the drift velocity close to its local maximum and plateau and at the same time minimise the longitudinal diffusion) and 40-50 kV/cm in the amplification region, to reach a gain close to 10⁴ for MIP muons. On top of the read out strips a layer of resistive strips is inserted being separated by a thin insulator, for the former to not be directly exposed to the charge to minimize the effect of sparking⁸. More details on the detector geometry, its operation and performance for the NSW Project are documented in Part II.

The operation principle for both detectors is quite similar. Energetic charged particles ionize the gas atoms as they pass through the detectors. The liberated primary electrons and ions drift along the electric field lines. The primary electrons are being multiplied in an electron avalanche as they pass through the metallic mesh (approach the anode wires) for MMG (sTGC) due to the strong electric field. The motion of the electron-ion pairs formed in the avalanche induces fast signals in the anode and cathode electrodes. Each detector technology complements the other for their corresponding primary functions with the sTGC to be mainly responsible for the triggering and the MMG for the track reconstruction.

Each NSW is composed of 16 trapezoidal in shape sectors of precision chambers, eight small and eight large. Each sector consists of 16 detector planes organised in two multilayers. Each multilayer comprises four sTGC and four MMG detector planes⁹ with the final arrangement along the z-axis to be sTGC-MMG-MMG-sTGC as to maximise the lever-arm between the two sTGC multilayers and

⁷ now considered as the backup mixture.

⁸ Large-scale Micromegas detectors risk of sparking. Low energy alpha particles or slowly moving charged debris from neutron (or other) interactions with the detector gas or materials can produce high ionisation levels that can damage the detector, the read out electronics and as a consequence lead to large dead times.

⁹ The four detector planes consist of a quadruplet.

achieve an optimal online track reconstruction. A graphical representation of the NSW structure and its arrangement along the z-axis is shown in Figure 3.13.

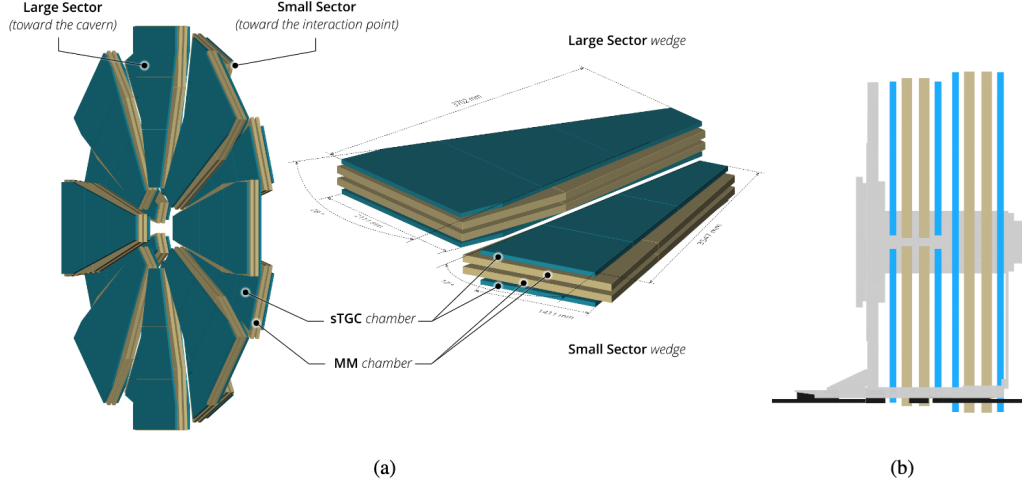


Figure 3.13: (a) The structure of small and large NSW sectors. (b) rz -plane view of NSW. sTGCs are shown in green and MMG in brown [61].

Both NSWs host 128 detectors with approximately 2 million for MMG and 350.000 for sTGC electronic read out channels. The electronics and their connectivity [62] are summarized in Figure 3.14 and are divided into two major categories: the on-detector (front-end boards, Level-1 Data Driver Card (L1DDC) [63], ART (Address in Real Time) Data Driver Card (ADDC) [64], Pad trigger and Router boards) and off-detector (Front End Link eXchange (FELIX) [65], trigger processor, sector logic and services running on commercial server Computers like Read Out Drivers (ROD), Detector Control System (DCS), event monitoring, configuration, trigger monitor and calibration) electronics.

The front-end boards are connected directly to the detectors and the same components are chosen for both technologies wherever possible. The VMM [66] is an ASIC responsible for the read out of the MMG strips as well as of the wires, strips and pads of the sTGC. It performs the amplification, the shaping, the peak finding and the digitisation of the detector signals. The GBT-Slow Control Adapter (GBT-SCA) [67] ASIC can be configured to monitor the temperature and voltage power levels of the MMG front-end boards. The ReadOut Controller (ROC) [68] is used for handling, preprocessing and formatting of the data received from the VMMs. The Trigger Data Serializer (TDS) [69] prepares the trigger data from pad and strips of sTGC with the aim to define the RoIs.

Three different types of front-end boards are designed for NSW: one for the MMG which is called MMFE8 and hosts 8 VMMs, and two for the sTGC which are the pFEB that hosts 3 VMMs (two for the read out of the cathode pads and one of the anode wires) and the sFEB that hosts 8 VMMs (read out of cathode strips). Each front-end board houses the GBT-SCA and ROC ASICs while for sTGCs they are accompanied with the corresponding TDS chip as well. The L1DDC boards serve as an intermediate element collecting the data up to eight front-end boards and transmitting them to

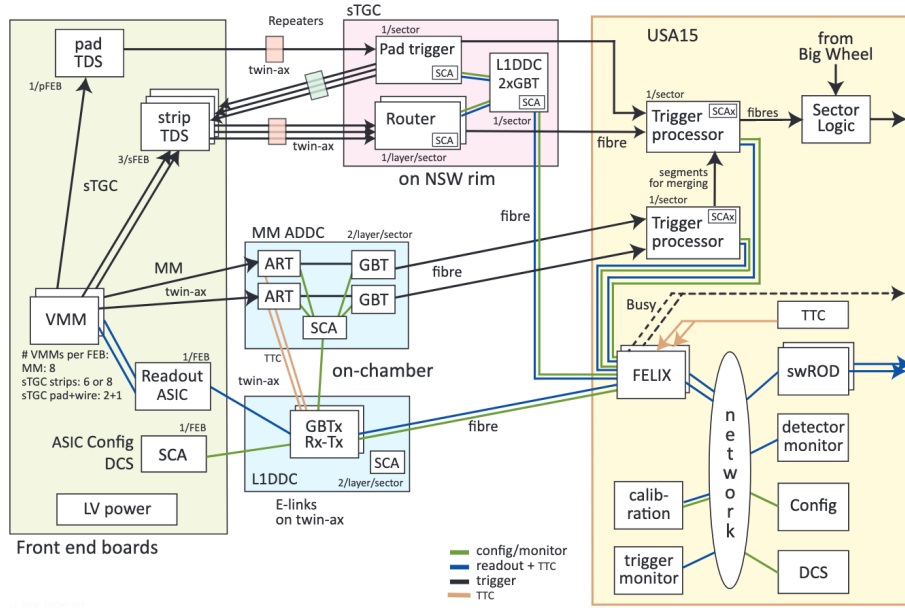


Figure 3.14: Overview of the NSW electronics for the TDAQ and Monitoring paths [62].

FELIX¹⁰ for both MMG and sTGC. It also distributes synchronous clocks, trigger and configuration data coming from the back-end systems to the front-end boards.

Pad signals, coming from the pad TDS, are sent to the pad trigger which looks for hit coincidences within one bunch-crossing. A three out of four logic is used for the two sTGC quadruplets to select a muon candidate. The geometrical information is then sent to the strip TDS ASICs where a selection of strip data is propagated to the router and finally to the NSW Trigger Processor. For MMG the ADDC, is mounted on the detector, receives the ART data (address of the strip of the first hit) from 64 VMMs and propagate them to the NSW Trigger Processor. Finally, the NSW Trigger Processor uses all the information collected to calculate the track segments which are then sent to Sector Logic and are combined with candidate tracks from the Big Wheel.

Despite the tight schedule and the challenges¹¹ the NSW Collaboration had to face during the commissioning, both NSW-A and NSW-C succeeded to be installed in their positions in ATLAS in time and are already collecting the LHC data. An event display of a reconstructed muon track using hits from MMG chambers is shown in Figure 3.15. In Figure 3.16 a photograph of NSW-C taken the moment it was lowering in the cavern is presented.

¹⁰ FELIX is a gateway between dedicated links connecting to detectors and trigger electronics, links providing timing and trigger information and a commodity network (Ethernet or Infiniband). Software running on server PCs will interact via FELIX with on-detector and trigger electronics for configuration, control, monitoring and calibration. Finally, the swROD being part of this network, performs functions to prepare the data facilitating the online selection.

¹¹ construction issues, noise, HV stability etc.

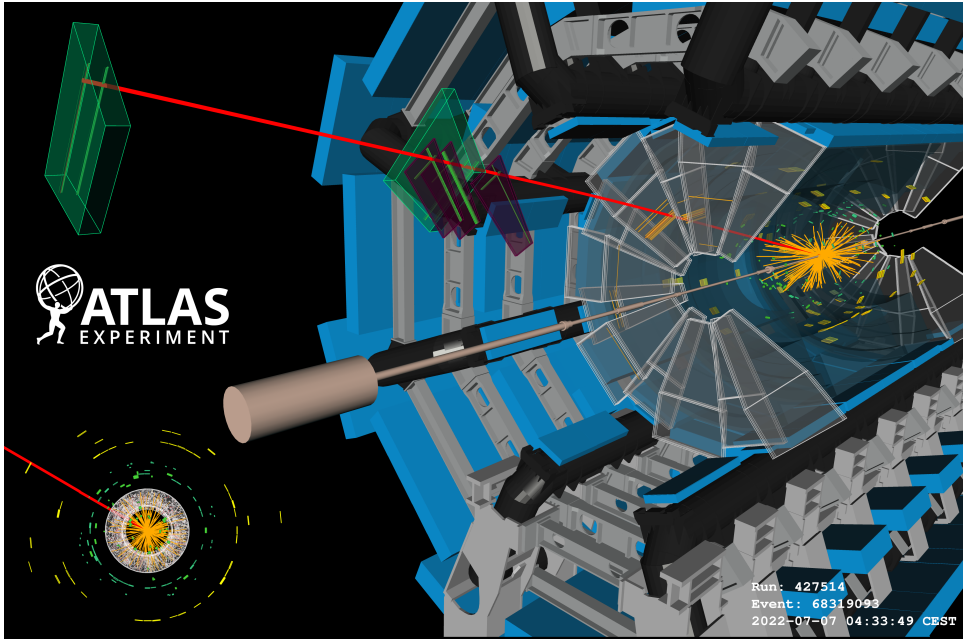


Figure 3.15: Event display of a collision event recorded in ATLAS on 7th July 2022, with stable beams of protons at the energy of 6.8 TeV [70]. The red line represents a muon track that is reconstructed using hits in the MMG chambers (shown in white) of the NSW-C. The other muon chambers used in the track reconstruction, are shown in green (MDT endcap) and purple (TGC endcap) boxes.



Figure 3.16: The second New Small Wheel (NSW-C) ready to be lowered and installed into its position in ATLAS on 4th November 2021 [71].

3.2.2 Phase-2 Upgrades

The Phase-2 upgrades complement the broader ATLAS upgrade program and consist of interventions in the following parts of the detector:

1. replacement of the current ID with the new Inner Tracker (ITk) [72, 73] to augment the radiation hardness and enhance its resolution under the harsh pile-up conditions.
2. High Granularity Timing Detector (HGTD) [74] will be installed to complement the ITk by providing high-precision timing information in order to distinguish between collisions occurring very close in space but well separated in time.
3. new read out electronics for the LAr calorimeter [75] while new front-end boards for the Tile calorimeter [76] are foreseen to be installed.
4. new detectors in the inner barrel region of the MS with the aim to increase the geometrical coverage while others will be replaced to increase the rate capacities. Furthermore, the power system as well as the electronics will be replaced [57].
5. design, build and installation of new TDAQ hardware with its firmware and needed software [77].

Part II

The Micromegas Detector for the ATLAS New Small Wheels

4 Geometry Description

This chapter presents all the useful information related to the layout description of the individual NSW MMG types and the geometry implementation in the common offline software, Athena. Section 4.1 discusses according to the design, the ideal geometry while the realistic one is described in Section 4.2. Finally, Section 4.3 introduces the strategy followed for the geometry description in Athena.

4.1 Nominal Geometry

Each of the 16 NSW sectors per wheel consists of a central spacer frame with two MMG quadruplets attached to either face. The spacer frame serves as the sector's mechanical support with all MMG services [78], i.e. gas pipes and twinax cables, routed through its center. Each MMG is assembled from two radial sections, built as separate modules. There are four modules for MMG: SM1 and SM2 for the inner and outer sections of the small sectors and LM1 and LM2 for the inner and outer sections of the large sectors. The construction of the four different modules has been shared between four laboratory consortia: Italy (SM1), Germany (SM2), France (LM1) and Greece/Russia/CERN (LM2). The integration with services and their assembly in sectors composing the wheel was held at CERN. Figure 4.1 illustrates the constituents of each NSW sector.

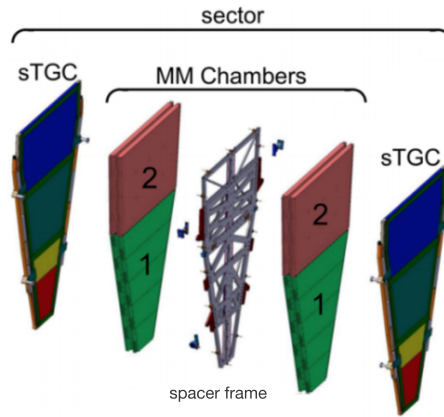


Figure 4.1: Schematic of a disassembled NSW sector. It is made of eight sTGC layers that surround eight MMG layers arranged in two quadruplets. The spacer frame is the sector's mechanical support. Particularly, for MMG two independent modules exist.

Each quadruplet encloses four gas gaps where a Micromegas structure is supported by three drift and two readout (RO) panels. The drift panels hold the drift electrode and the mesh, which is glued on

4 Geometry Description

a frame, and defines a 5.03 mm drift gap. The two external drift panels have an outer skin on one side and support a single cathode electrode ($\sim 20\text{ }\mu\text{m}$ thick) and mesh (with a diameter of $\sim 60\text{ }\mu\text{m}$) on the other side. The central drift panel holds the cathode electrode and mesh on both sides. There are two RO panels with strips and pillars on both sides which are placed between the drift panels. The one RO panel, called eta plane (or layer), hosts strips in the precision direction, η . The other RO panel, called stereo plane, has its strips tilted at opposite angles of $\pm 1.5^\circ$ with respect to the eta plane. With this orientation, both precision (η) and second (ϕ) coordinates can be measured [79, 80, 81]. The electronic amplification occurs between the mesh and the resistive strips plane resulting to an amplification gap of $150\text{ }\mu\text{m}$. A cross-section of the two MMG quadruplets constituents of a NSW sector along with all the useful dimensions is presented in Figure 4.2. The sectors and all their parts, are trapezoidal in shape. The dimensions for each module type are shown in Table 4.1.

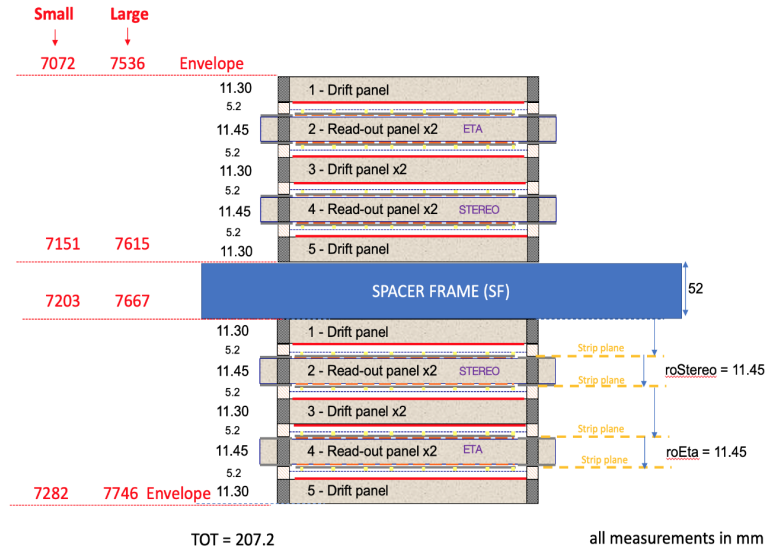


Figure 4.2: A cross-section of a MMG NSW sector. The bold red lines represent the drift copper electrodes of $\sim 0.02\text{ mm}$ thickness which are part of the chamber's active areas. The numbers shown in red indicate the distances from the IP.

Table 4.1: The MMG NSW sectors' dimensions.

	LM1	LM2	SM1	SM2
Small Base (mm)	640	2 022.8	500	1 321.1
Large Base (mm)	2 008.5	2 220	1 319.2	1 821.5
Height (mm)	2 310	1 410	2 210	1 350
Radial Distance (mm)	923	3 238	895	3 110
Opening Angle ($^\circ$)	33	8	21	21

A RO panel is made of five (three) printed circuit boards (PCBs) for the inner (outer) sections of the sector. Each PCB can host 1024 strips in total. However, for the first and last PCB there is a small number of strips at the edges that is not present (these strips are referred to as *missed* strips) due to lack of space to fit in. Furthermore, at the junctions between two PCBs there is always one *missed* strip per PCB left (the last strip of PCB_n and the first strip of PCB_{n+1}). These regions are

less efficient and they cover a distance of 1 pitch. The pitch is set at 450 (425) μm for large (small) modules while the strip width is 300 μm . For the stereo planes, in order to maximise the coverage area of strips at the corners of the modules there is a number of strips with short lengths that are not directly connected to the FE board. These strips are referred to as *routed* strips.

Table 4.2: Overview of strips per module type.

	LM1	LM2	SM1	SM2	LM1	LM2	SM1	SM2
	eta layers				stereo layers			
Missed strips (top)	72	48	41	31	36	43	11	1
Missed strips (bottom)	72	47	42	29	86	42	35	1
Missed strips (between PCBs)	6	2	6	2	6	2	6	2
Routed strips (top)	-	-	-	-	88	64	66	79
Routed strips (bottom)	-	-	-	-	0	58	18	64
Total active strips	4 968	2 973	5 029	3 008	4 990	2 983	5 066	3 066

The number of *missed* and *routed* strips depends on the module type. Table 4.2 gives an overview of the strips for each module type, Table 4.3 presents the dimensions for each of the PCBs and Table 4.4 lists the active areas dimensions.

Table 4.3: Dimensions of RO PCBs.

	LM1	SM1	LM2	SM2
PCB-1			PCB-6	
Small Base (mm)	640	500	2 022.8	1 321.1
Large Base (mm)	914.8	667.7	2 089.2	1 490.7
Height (mm)	463.9	452.3	474.7	457.5
PCB-2			PCB-7	
Small Base (mm)	914.8	667.7	2 089.2	1 490.7
Large Base (mm)	1 187.7	828.9	2 153.6	1 651.9
Height (mm)	460.55	434.925	460.55	434.925
PCB-3			PCB-8	
Small Base (mm)	1 187.7	828.9	2 153.6	1 651.9
Large Base (mm)	1 460.5	990.1	2 220	1 821
Height (mm)	460.55	434.925	474.25	457.025
PCB-4				
Small Base (mm)	1 460.5	990.1		
Large Base (mm)	1 733.3	1 151.3		
Height (mm)	460.55	434.925		
PCB-5				
Small Base (mm)	1 733.3	1 151.3		
Large Base (mm)	2 008	1 319		
Height (mm)	463.45	451.825		

Table 4.4: Dimensions of active area.

	LM1	LM2	SM1	SM2
Radial Length (mm)	2238.7	1339.2	2140.3	1279.7
Small Base (mm)	426.7	1802.5	284.0	1103.1
Large Base (mm)	1753.0	1990.0	1078.4	1579.6

The information reported here is collected from the technical drawings¹ and documented in Excel spreadsheets, in the so-called Micromegas Parameter book².

4.2 Realistic Geometry

In order to ensure that the system will operate within the specifications, at each stage of the construction procedure, series of strict quality control protocols need to be passed [82], in terms of eg. thickness, planarity, gas tightness, relative strip alignment.

Particularly, the alignment of the RO strips is very important for the accurate track reconstruction. For this purpose, chessboard patterns (rasnik masks) are etched on the PCBs, while a lens and a Contact CCD camera are used for the determination of the strip alignment parameters [83]. A light source (LED), transmitted through an optical fiber, back illuminates the pattern which is projected through the lens onto the CCD. The final image can give the rasnik mask displacement which corresponds to a copper strip location. These measurements describe the initial permanent "as-built" conditions whereas they have been collected for all modules and should be accounted for the corrected description of the RO layers in software.

The MMG technology was invented in 1990's [84], and thus the scaling to large surfaces was never tested nor used before the NSW project. The issue of sparks³ in the detector had been extensively studied [85] and the proposed solution was the addition of an insulating layer, made of kapton, of 50 μm thick with resistive strips on top of the copper strip layer. Despite the proposed fix, HV instabilities were persistent in 10% of the first produced RO panels and therefore, in parallel to the module production, studies had been launched to further understand the issue. Detailed measurements had proven that the resistance was decreasing at the boundaries of the active area providing insufficient spark protection. The HV stabilisation was treated by passivating the weak areas along the sides of the RO panels. A thin (up to ~ 10 cm) layer of araldite glue was added while its thickness varies between the different RO layers. The passivation has shrunk the size of the active areas and thus is considered as an "as-built" parameter.

Additionally to the in plane alignment, 16 alignment bars are mounted on each wheel forming a reference alignment grid in the ATLAS coordinate system [56, 86]. This setup is shown in Figure 4.3. On the surface of the outer (η) layer of the quadruplet, a system of light sources is installed in known

¹ The information related to the design, construction and maintenance of the different components is available and accessible through CERN's Engineering Data Management Service EDMS.

² The Parameter books for the NSW detector technologies are accessible in this twiki.

³ A highly ionising particle can be created by hadronic interaction with the detector materials, which can then result a number of charges in the avalanche exceeding the Raether limit, provoking noticeable detector damages.

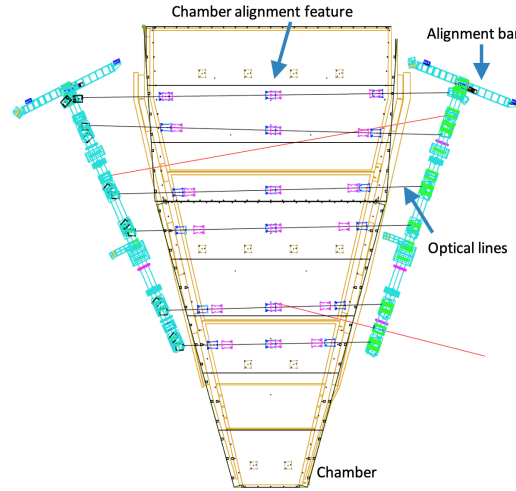


Figure 4.3: Layout of the alignment system for a large NSW MMG. The alignment bars are shown in cyan whereas the BCAMs are shown as the black boxes on them. The light sources are shown as the blue and magenta boxes on the chamber. Six optical lines (shown as black lines) are defined consisting of a BCAM pair and a set of six light sources arranged in pairs. The red lines represent the bar-to-bar alignment. Figure taken from Camila Pazos slides.

locations using a special jig. The light sources are viewed by the Brandeis CCD Angle Monitor (BCAM) cameras that are clamped onto the alignment bars. Following a triangulation process the chamber locations can be monitored at a timescale of some hours, with respect to the bar sensors. Inside the bars, a system consisting of rasnik elements and temperature sensors ensures their well-controlled positioning in space over time. Moreover, the chambers are equipped with an adequate number of sensors that can monitor the environmental conditions, i.e. temperature, humidity, and magnetic field, inside the chambers in real time via the Detector Control System (DCS) [87].

The alignment software, ARAMyS [88], was designed to translate the sensors' data into useful parameters that can describe the chambers' translations, rotations, deformations and expansions as function of the time. The translation and rotation data define the A-line set of parameters while the chambers' deformations and expansions are described by the B-line parameters. Finally, this information is stored in the ATLAS Conditions Database [89] that can be accessed by the Athena geometry and its track reconstruction algorithms.

A representation of the deformation states the NSW MMG chambers experience are depicted in Figure 4.4.

The NSW Large MMG chamber shifts along the global ATLAS z-axis as reconstructed by the ARAMyS software using data collected with the toroid magnet at nominal operation and for the case when it is switched off are shown in Figure 4.5.

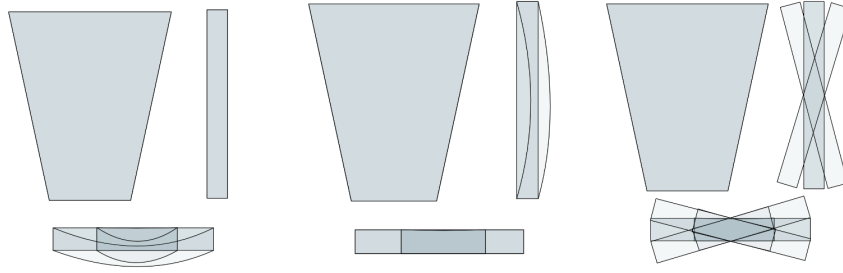


Figure 4.4: NSW MMG deformation states [90]. For each state three different perspectives of view are shown. Left: bowing out of plane. Center: sagging out of plane. Right: twist.

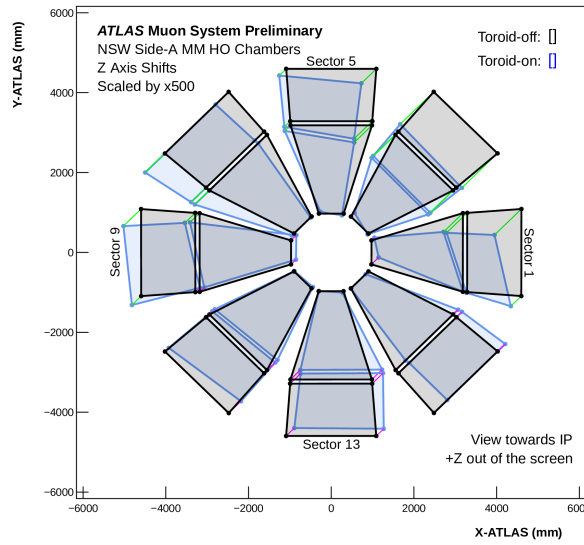


Figure 4.5: The shifts along the ATLAS z-axis of the Large MMG modules of NSW Side-A after switching on the magnet field. The positive shifts, +z, are shown as green lines, whereas the negative shifts, -z, are shown in magenta. The shifts are scaled by a factor of 500 in order to be visible [91].

4.3 Description in the ATLAS Offline Reconstruction Framework

The detailed description of the ATLAS geometry is of great importance for the precise modeling of its response and as a consequence for the accurate calibration and reconstruction of the real data.

The GeoModel toolkit [92] has been developed by the ATLAS Collaboration and it is integrated in the offline software Athena. It is a C++ library of geometrical primitives which allows the description of complex detector systems with minimum memory consumption. As a first step each subsystem's primary numbers are read from tables organised by an Oracle database system, called the ATLAS Detector Description Database. Thereafter, a transient geometry description is built on the fly upon

request⁴, whereas is represented as a tree of geometrical volumes which carries information about the shapes, materials, positions, etc. This description can then be translated in Geant4 representation for the full simulation of the ATLAS response.

For the event processing of data, the Conditions Database, interfaces to Athena for the realistic description of the detector. Conditions data aim to describe the state of the detector for a given time and include alignment, calibration, monitoring as well as DCS data. A schematic of the full detector description workflow in Athena is shown in Figure 4.6.

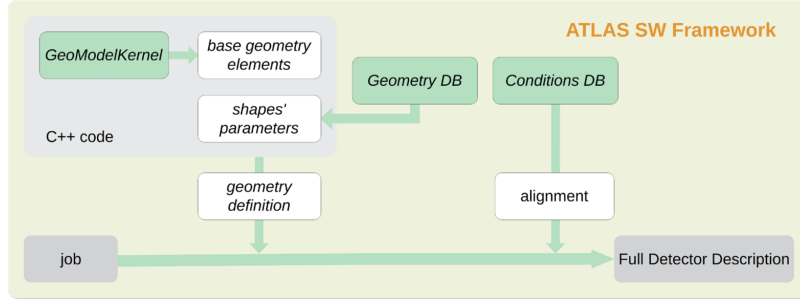


Figure 4.6: The workflow of the full ATLAS geometry description in Athena [93].

Both simulated and real data are processed through a long chain of tools and data formats. At every step of this long process the data can be visualised together with the detector geometry as constructed by the GeoModel, with the use of the Virtual Point 1 (VP1) [94] 3D event display which runs within Athena. The data formats related to the simulation have been discussed in Section 3.1.3. Different data formats are sequentially reconstructed. The ESD format contains all reconstructed objects including low level information and is aimed for detector and reconstruction performance studies. The xAOD files contain the higher level reconstruction objects, i.e. jets, leptons, MET etc. relevant for physics analysis. The TAG format carries the event-level metadata and is used for a fast event selection. The final data format of this long chain is the DxAOD, which is derived from xAOD and stores the filtered and calibrated "good for physics" data. A schematic illustration of this long process is given in Figure 4.7. In order to facilitate the detector description workflow and the debugging, the GeoModel can now be used in a lightweight development environment, outside of the complex ATLAS software framework [93, 95, 96].

The Muon Spectrometer retrieves the fundamental parameters for its description from the general ATLAS Detector Description Database. In principle, the primary numbers for the active parts (i.e. chambers), follow the ATLAS Muon DataBase (AMDB) [97] convention, stored in tables in the database. On the other hand, the passive structures (i.e. shielding, toroid magnets, supporting frames, etc.) follow the ATLAS Generic Detector Description (AGDD) [98] format, stored as a Binary Large Object (BLOB) in the database. The migration of all the detector components to the generic AGDD description will provide a geometry description which can be used independently by the simulation, reconstruction and visualisation packages.

⁴ The relational database model allows the versioning of the primary numbers. This brings as a consequence the versioning of the GeoModel descriptions. A specific version of the ATLAS geometry can be built by providing an ATLAS geometry *tag* as an input parameter to Athena.

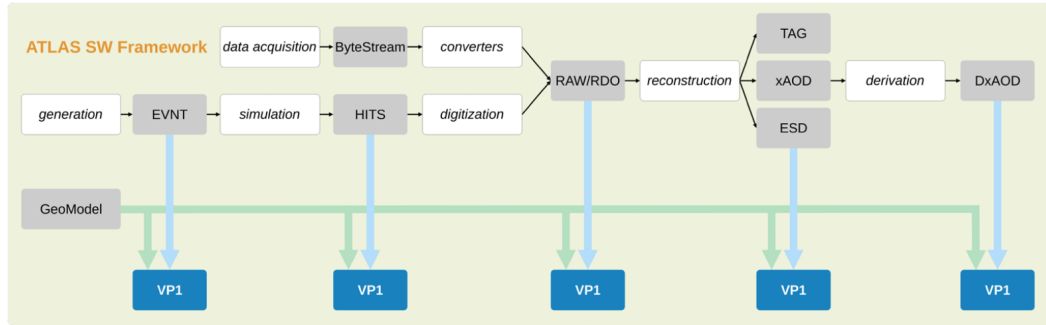


Figure 4.7: The full chain of data flow and the interface with the ATLAS geometry description through GeoModel and the visualisation tool, VP1. All steps are performed within Athena. [93].

The New Small Wheel description is fully implemented in the AGDD format, based on the meta-language, XML (eXtensible Mark-up Language)⁵. For the description of both active and passive components, the useful parameters, i.e. dimensions, positions, strip information etc., are stored in the XML files which can be read and parsed within Athena as a set of AGDD C++ objects.

These objects are then used by GeoModel whose output becomes the input to build the geometry in Geant4 representation used for the simulation. Geant4 simulates the passage and the interactions of particles with matter, i.e. the gas gap volumes for NSW case. The particles are propagated in small steps whereas the information of the starting and ending positions in the corresponding gas gap volumes as well as the energy deposits are stored in the muon hit collection. Each hit is labeled by a specific identifier, i.e. a 32-bit integer, in which the hit geometry information is stored. Therefore, all events are completely decoupled from the geometry and the only communication is established via the Identifiers. Each chamber is first positioned in a local coordinate system with its origin located at the center of the quadruplet⁶ and can then be translated in the global ATLAS reference system. In this local system, the z coordinate points towards the beam direction while the y (x) coordinate describes the direction perpendicular (parallel) to the bases of the trapezoid.

Up to this step, the detailed description of the RO layers is not relevant. However, it becomes important at digitisation step, where the muon hits are converted to digits which are associated to the fired RO strips, aiming for an accurate mitigation of the detector response output. Therefore, the RO description is stored on top of the raw⁷ detector geometry. The MMG RO description is unique and depends on the module type and layer, see Table 4.2. This description is defined in the *MMReadoutElement* class (in the MuonReadoutGeometry Athena package) and should be well centered inside the gas gap volumes. The one-to-one resistive strip to electronic channel mapping scheme has been deployed as it is crucial for the accurate processing of the data. The intersection of the strips with the y axis defines their position in the local RO layer's reference frame. The strip identifier, along with other quantities (eg. charge, time, etc.) that are determined at the digitisation step, represent the digit collection which is the input to the reconstruction algorithms. Table 4.5 lists

⁵ The simplicity of the the structured ASCII format allows the straightforward conversion of the existing databases. Moreover, the XML-syntax can be easily modified and maintained.

⁶ The center of a quadruplet falls at the center of the central drift panel.

⁷ The raw geometry consists of the gas volume and the two planar electrodes (drift and readout).

all the variables that need to be passed as input to the Identifier builders in order to gain access in the desired geometry volume, eg. multilayer, PCB, channel, etc.

Table 4.5: The list of useful variables for the MMG description in Athena.

Variable Name	Values	Short Description
stationName	MML (or 55), MMS (or 56)	Large or Small MMG module
stationEta	-2, -1, 1, 2	module type (positive (negative) sign: side A (C))
stationPhi	[1 – 8]	sector on the wheel in polar direction
multilayer	1, 2	quadruplet (1 for the one closest to IP)
gasgap	[1 – 4]	gas gap of a MMG multilayer
channel	[1 – n]	FE board's channel number (n=5120 for type-1 and n=3072 for type-2)

The *MuonDetectorManager* class provides access to the readout geometry information for the Muon system after request. The readout description is finally stored as a tree on top of the raw geometry by GeoModel in the *MuonDetectorFactory001* class (in the MuonGeoModel Athena package). This class also provides the connection with the databases.

During runtime, the conditions data are passed through the *MuonDetectorFactory001* to the *MuonDetectorManager* where the corresponding containers for the initialisation of the A- and B-lines are being filled. These data are then used by the alignment transformations defined in the *MMReadoutElement* class and the RO strip positions are tweaked. A similar procedure is followed for the as-built corrections with the difference that the models are hosted in the MuonNSWAsBuilt dedicated package.

For NSW the Conditions Database was not in place at the time of the implementation in Athena. Therefore, as a workaround a text file following the Character Large Object (CLOB) data collection stored in the Oracle database for the pre-existing Run 2 muon stations, was created and can be used as input to test the chambers alignment implementation and performance in the software. A dedicated tool, *NSWCondUtils* in the MuonConditions package, was developed to allow the reading of the file while its content feeds the alignment containers. For the as-built case, the input follows the JavaScript Object Notation (JSON) format.

5 Data Quality

First, an introduction of the ATLAS data preparation procedure from raw to "good for physics" data is given in Section 5.1. The data quality assessment is realised in two stages: online and offline. This chapter is oriented towards the offline part. Therefore, the code implementation of the offline data monitoring for the NSW MMG detectors in the offline reconstruction framework, Athena is discussed in Section 5.2. Although, both NSWs have been successfully installed in ATLAS, the offline tools for the former SWs had to be functional for the Run-2 reprocessing campaigns that were launched during LS2. The offline monitoring for the CSC detectors is documented in Appendix A.

5.1 Data Preparation

5.1.1 Definitions

ATLAS records data continuously after LHC enters in "stable beams" conditions. This uninterrupted period with beams is called a LHC fill. At that time, the ATLAS subsystems start ramping up the high voltage (HV). Once the detector configurations for data taking are all set, ATLAS raises the flag "ready for physics". A continuous period of data recording is referred to as an ATLAS run which typically corresponds to a single LHC fill ($\sim$ hours of data taking). Each ATLAS run is divided into luminosity blocks (LB). A LB is defined as the period of time during which the instantaneous luminosity, detector, trigger and data quality conditions are considered constant ($\sim$ 1 min). A group of runs with very similar running conditions constitutes a sub-period which is marked with a capital letter along with a number. Similarly, a group of sub-periods defines a period, marked with a capital letter. Finally, a long period of data taking between LHC shutdowns is known as LHC Run, i.e. Run-1, Run-2, Run-3, Run-4, etc.

5.1.2 Data Streams

The data are recorded in three major streams: physics, calibration and express, which are defined in dedicated trigger menus. A trigger menu contains a list of selection criteria at the L1 and HLT for one or several physics signatures. The menu for the main, physics stream is decided by the physics groups whereas it contains data for physics studies. The calibration stream is used by the detector experts. It refers to data that are triggered by algorithms specific to subdetectors or HLT features, used to define the electronic noise, detector alignment, etc. These data are passed to the Conditions Database and can be used back real time during data taking or later at reconstruction level. Finally, the express stream contains a representative subset (around 10%) of data collected in the physics

and calibration streams. These events are reconstructed in real time at the ATLAS Tier-0 computing facility for the prompt monitoring of all ATLAS sub-detectors.

5.1.3 Data Quality Assessment

The data quality assessment begins immediately with the start of an ATLAS run. A schematic of the operations workflow for the ATLAS data quality control is shown in Figure 5.1.

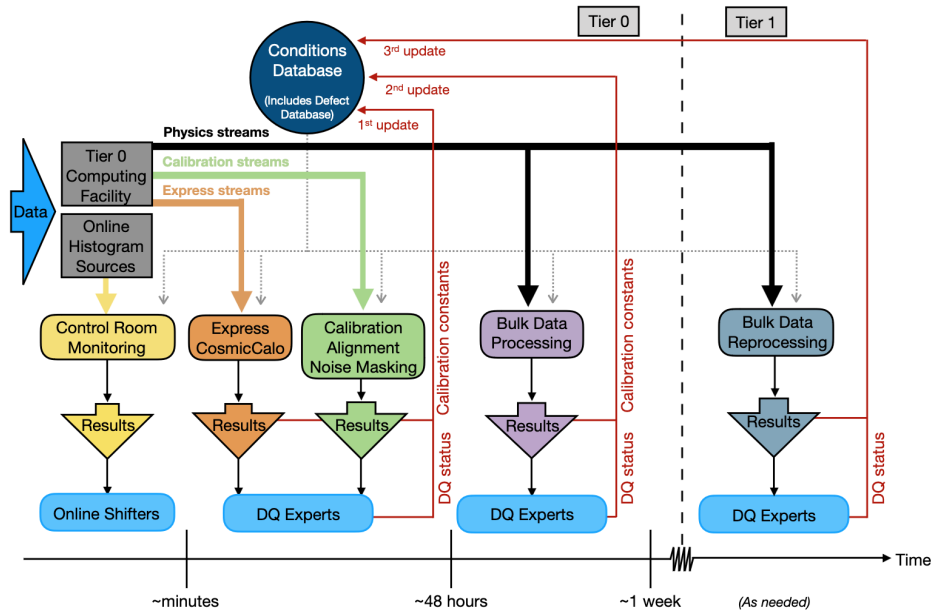


Figure 5.1: The workflow for the ATLAS data quality assessment [99].

For each ATLAS subsystem there is a dedicated desk in the ATLAS control room where online shifters make use of the online monitoring applications to check the detectors' status and notify the detector experts who can take action in case of issues that can arise during run time. A central data quality desk also exists where the shifter has a global view of the ATLAS detector and additionally monitors the reconstructed objects.

The operational status of the hardware components is controlled and monitored with the DCS. The DCS data are archived and are used to assign defects indicating the detectors operation conditions during the data taking. These data are uploaded automatically in the Defect Database, subcomponent of the Conditions Database. A lightweight tool [100] is used to further monitor the low-level detector hardware at different stages of the data flow and key histograms are displayed on the online desks [101]. An automatic data quality assessment on each histogram is performed and a status flag with a colour is assigned to easily identify the problematic histograms. This first assessment aims the mitigation of data losses at trigger level. At the end of the run these flagged histograms along with others produced by the HLT are archived and can be distributed to the offline applications for future reference.

Once the data have been recorded and reconstructed, they pass a two-stage offline quality control. The first control is performed on the reconstructed data from the express and calibration streams. The first express reconstruction starts within few hours of the start of a run. At this stage, the detector experts can update the calibration constants and detector alignment information in the Conditions Database as necessary. Additional reconstruction iterations will occur until the calibrations are approved for the full reconstruction of the run. This process is known as the calibration loop and lasts about 48 hours.

The main physics stream is launched right after the Conditions Database is up-to-date. The reconstructed dataset is usually available within 48 hours after the end of the run. The final assessment is then performed with the high statistics dataset. The detector and the combined performance experts validate the quality of the data and ensure that the conditions data are applied successfully. At this stage a second update to the Conditions Database can be realised to cover any remaining issues. This further update is going to be applied at the time the reconstruction procedure starts again. It is evident that the data reprocessing results in higher data quality efficiency. Therefore, reprocessing can take place as needed. Usually, once a year the data are reprocessed to incorporate the final conditions as well as any important software improvements. These large-scale reprocessings are performed at Tier-1 sites and the validation procedure is repeated.

After the complete data quality validation of a data period, a certified list of LBs that satisfies the "good for physics" conditions is documented in XML files, the so-called Good Run Lists (GRLs). The GRLs are then propagated to the physics analysis groups.

5.1.4 Data Quality Performance

The "good for physics" data efficiency as measured from 2022 Run-3 physics runs at 13.6 TeV centre of mass energy is 93.1% [102]. The overall data quality efficiency of 2022 data is very similar to the measured efficiency of data collected in the beginning of Run-2 (see Figure 5.2).

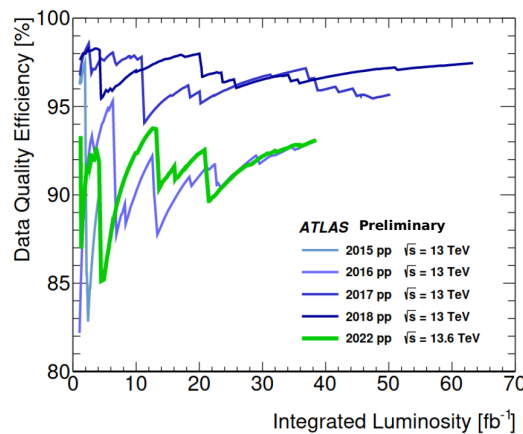


Figure 5.2: The cumulative data quality efficiency versus the total integrated luminosity recorded by ATLAS in Run-2 (2015-2018) and first year of Run-3 (2022) [102].

Particularly, the detectors of the muon system operated with a data quality efficiency at 99.99% for MDTs, 97.95% for RPCs and 99.72% for TGCs [102]. Although both NSWs were installed in the ATLAS cavern before the end of the LS2, the commissioning efforts are still ongoing and thus they were not included in the GRLs this time.

5.2 Micromegas Offline Monitoring in the ATLAS Offline Reconstruction Framework

A first version of the offline monitoring tools for the MMG technology has been developed within Athena. The tools were tested using MC samples during LS2. Currently, the offline monitoring package runs at Tier-0, the histograms are filled with Run-3 data whereas they aid the commissioning by identifying detector and software related problems. However, there are several developments ongoing in the current configuration, e.g. Defect Database, review and add/remove histograms, update the fitting functions, check the algorithms for the automatic histogram assessment etc.

For the scope of this thesis, the description of the current MMG offline monitoring workflow in Athena will be given.

5.2.1 Monitored Histograms

The calculation of the monitored variables is performed in the dedicated for MMG technology *MMRawDataMonAlg* C++ class of the *MMRawDataMonitoring* package, located in *MuonSpectrometer/MuonValidation/MuonDQA/MuonRawDataMonitoring* Athena path. There is a top-level python configuration where the monitoring algorithm is configured and the histograms are defined. The produced histograms are stored in root files¹ and are organised in folders specific for the MMG technology.

As already mentioned (see Section 3.1.4) the reconstruction procedure is similar for both simulated and real data. The data monitoring is performed at different stages of the reconstruction step in order to validate the whole procedure. First, the calibrated hits on the adjacent readout elements are combined to form clusters on the MMG layers. This collection of data is called Prepared Raw Data (PRD). Experience from Run-2 data taking proved that a plot showing the hit occupancy as a function of the LB can validate the data delivery over time and spot any transient hardware issues. Therefore, this kind of information is provided also for the MMG technology and plots for each MMFE8 card of a given sector and detector layer are implemented. An example is given in Figure 5.3. A representative set of key histograms filled with variables at this level of reconstruction are presented in Figure 5.4. The same histograms are provided at lower granularity, i.e. per layer or PCB.

Next, the PRD collection is used to identify all the possible line segments built on the MMG detectors. Finally, the segments are combined with those found on the other ATLAS subsystems to define

¹ The new Athena version enables parallelism thus multiple root files are produced for each running job. A merging procedure follows with the name format of the produced root file to be `<project-Tag>.<00runNumber>.<stream>.merge.HIST.<tags>`.

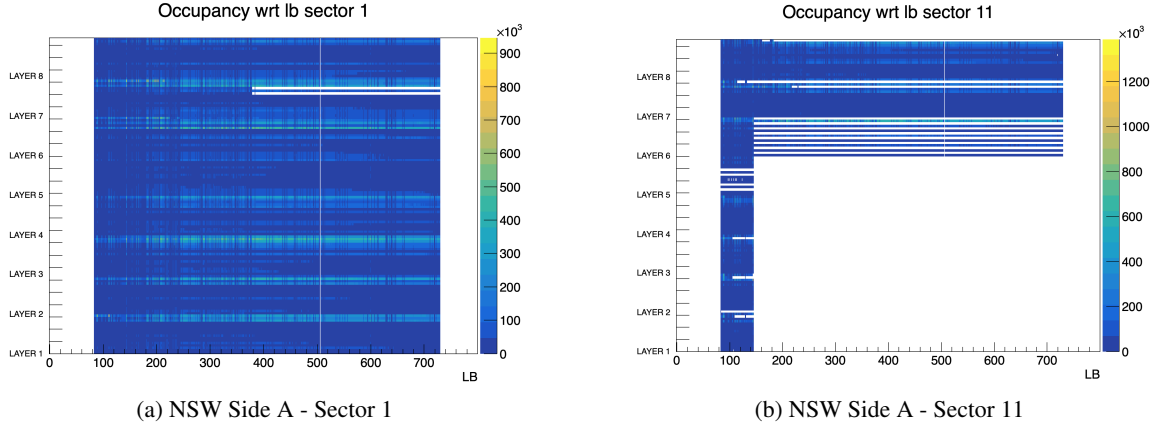


Figure 5.3: Hit occupancy for NSW Side-A (a) Sector 1 and (a) Sector 11 as a function of the LB per layer and MMFE8 card. Each bin of the y-axis corresponds to a MMFE8 card of the specific sector's eight MMG layers. The histograms are produced from run 435931 in the physics stream of 2022 data at 13.6 TeV centre of mass energy.

the final muon tracks [103]. Similar histograms with those already discussed are provided at segment and at track level. Figure 5.5 shows the number of reconstructed segments and tracks found when using the information from the MMG detectors. Moreover, the transverse momentum of the muon track and the residuals defined as the difference between the cluster position on the MMG layer and the corresponding position on track are shown in the same Figure using information recorded by every MMG layer.

Last but not least, the MMG track efficiency is computed and provided in histograms for every MMG layer in a quadruplet. The resulted efficiency is estimated using the tag and probe method. The tag tracks correspond to all the events for which a cluster on track is found on at least three out of four MMG layers in a quadruplet. Then, for each MMG layer the number of probe tracks is defined as the number of occurrences a cluster is found on the under study layer. The ratio of probe (accepted tracks) over the tag (total number of reconstructed MMG tracks) tracks defines the layer's efficiency. The selected granularity for the efficiency plots is the PCB. Typical examples are shown in Figure 5.6.

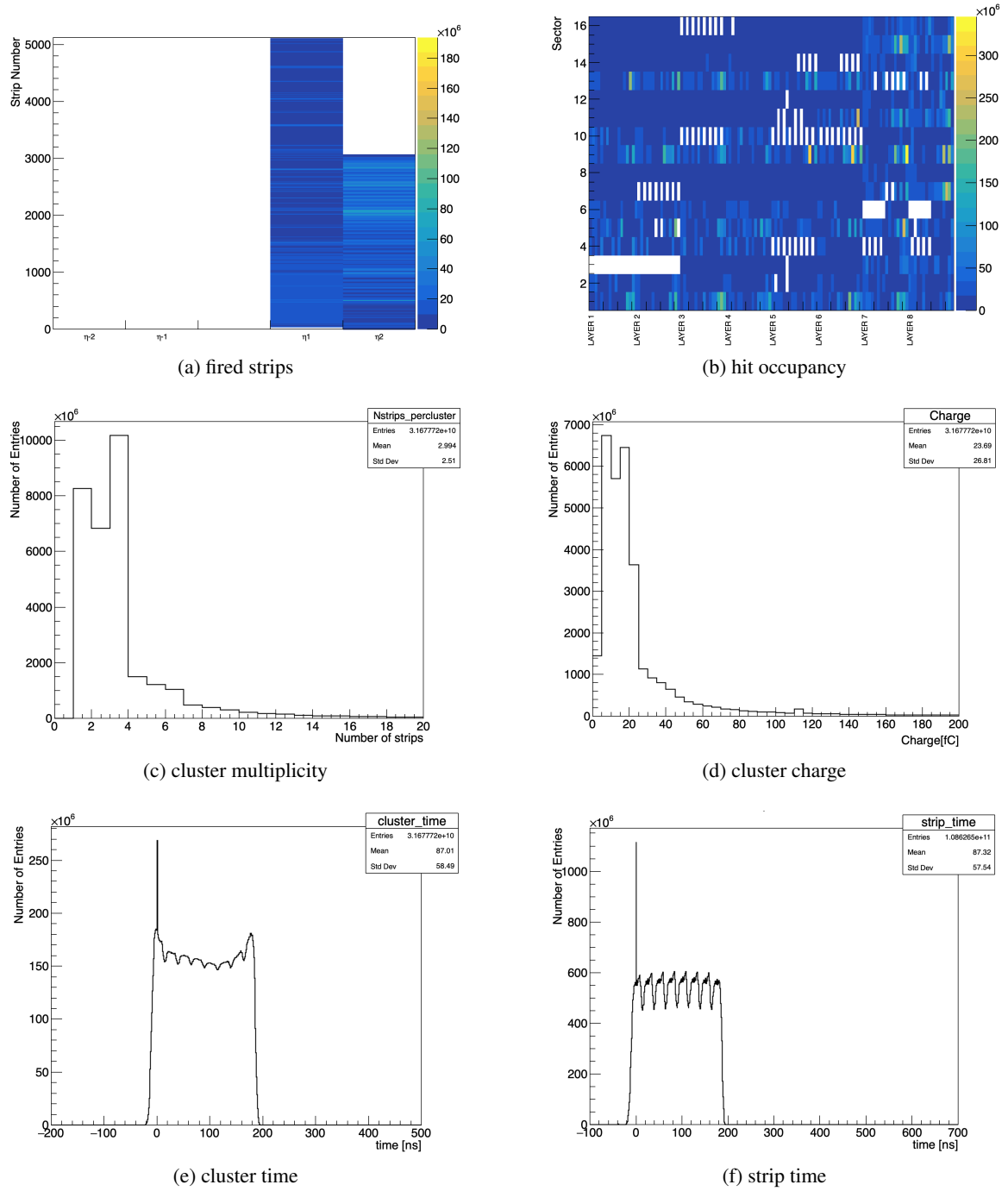


Figure 5.4: (a) The fired strips indices per module, (b) hit occupancy per sector, layer and MMFE8 card, distributions of (c) cluster multiplicity, (d) cluster charge, (e) cluster time, (f) strip time for all chambers collectively at PRD level. The histograms are produced from run 435931 in the physics stream of 2022 data at 13.6 TeV centre of mass energy. The NSW Side-C was not recording data. Despite the empty histograms, it is also visible in (a) where the two first bins (corresponding to Side-C MMG) do not contain any data.

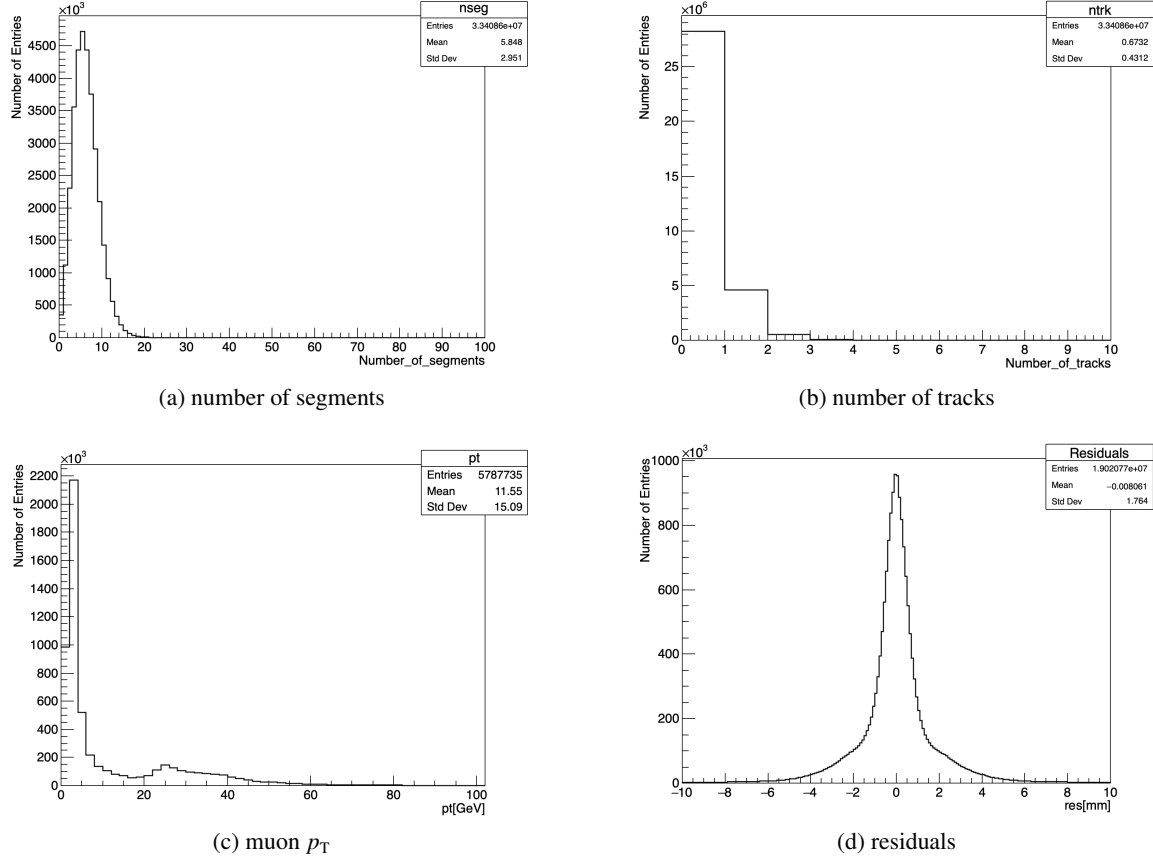


Figure 5.5: The number of reconstructed (a) segments and (b) tracks. (c) The transverse momentum of the reconstructed muon tracks and (d) the track residuals. The histograms are produced from run 435931 in the physics stream of 2022 data at 13.6 TeV centre of mass energy.

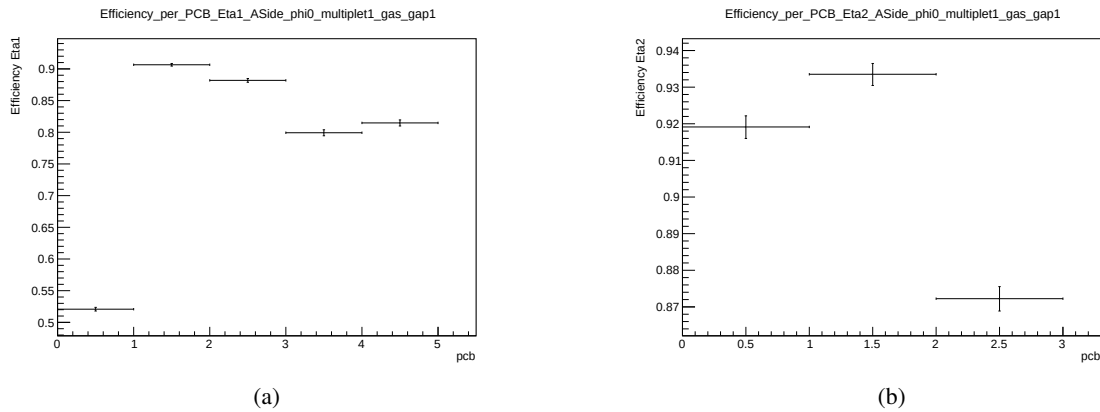


Figure 5.6: The efficiency of the first eta layer of the quadruplet closest to the IP for (a) LM1 and (b) LM2 as a function of the PCB. The efficiencies are produced from run 435931 in the physics stream of 2022 data at 13.6 TeV centre of mass energy.

5.2.2 Post-processing

Hundreds of histograms are provided to monitor the delivered data as well as to check the detector performance. In order to ease the histogram assessment, supplementary algorithms run during the merging process whereas additional summary histograms are saved in the final root file.

The post-processing code includes two components: a python file with the definition of the post-processing functions and a configuration yaml file where histograms are passed as input to the corresponding functions in the python file and the output path of the produced histogram in the root file is also specified. For MMG the post-processing functions are written in the `MMPostProcessing.py` which is located under the python folder of the `MMRawDataMonitoring` Athena package. The configuration file is found in the `DataQuality/DataQualityUtils/data/postprocessing` Athena path.

A summary map filled with the efficiencies as calculated at PCB level is provided for each NSW MMG module type and an example is presented in Figure 5.7. The inefficient PCBs can be easily identified. The specific to the problematic PCBs histograms can be then checked to examine further the possible issue.

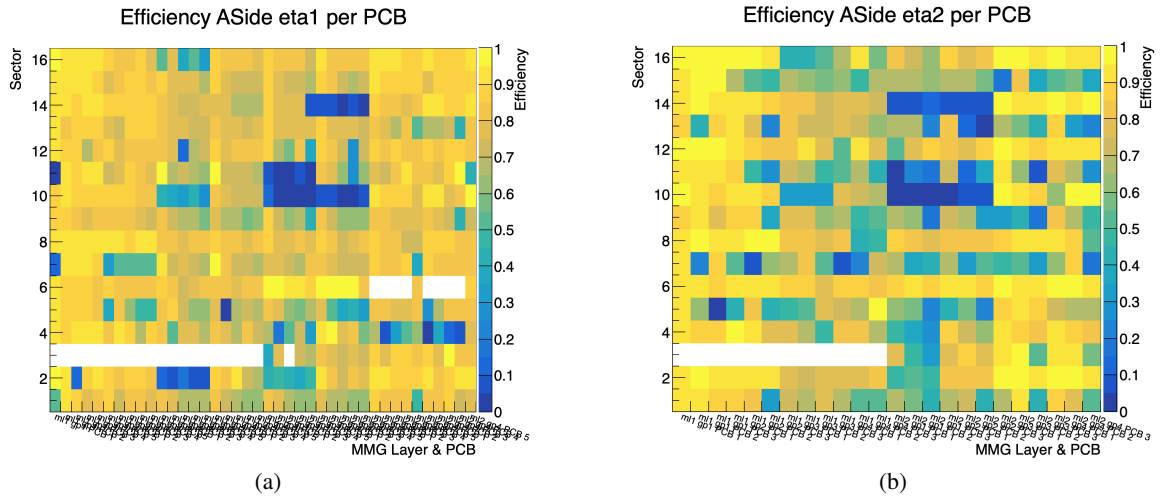


Figure 5.7: The efficiency map of (a) LM1, SM1 and (b) LM2, SM2 MMG as a function of layer and PCB for NSW Side-A. The same plots are provided for NSW Side-C. The plots are produced from run 435931 in the physics stream of 2022 data at 13.6 TeV centre of mass energy.

The mean value of the cluster multiplicity distributions is used to fill summary maps. As concerning the cluster charge distributions a fit with a Landau function is performed. The most probable value (MPV) is presented in summary maps as result of the fit. The alignment of the chambers can be validated and a rough estimation of the spatial resolution is also possible by performing a fit with a simple gaussian function on the residual distributions. Finally, the time distributions are fitted with a double Fermi-Dirac function where the values at half maximum of its rising (t_0) and falling ($t_{\max}$) parts are dumped. The information of the initial time (t_0) and the time difference ($\Delta t = t_{\max} - t_0$) is presented similarly in summary maps.

5.2.3 Webdisplays

The detector experts select the most important histograms to be presented on a web page. Each histogram is automatically checked by using an appropriate algorithm. Threshold values are set and a colour flag is assigned on each histogram. The red flag indicates a problematic histogram, i.e. a potential issue with the detector or the data taking, the yellow flag is just a warning while the green flag signals that the automatic checks have been successfully passed. The histograms are organised in folders. If a histogram is flagged as yellow or red in a folder, the folder inherits that flag. Thus, the navigation in the folder structure for the identification of the problematic histograms becomes easy. A screenshot of a Webdisplay produced for run 435931 in the physics stream of 2022 data collected at 13.6 TeV centre of mass energy is shown in Figure 5.8.

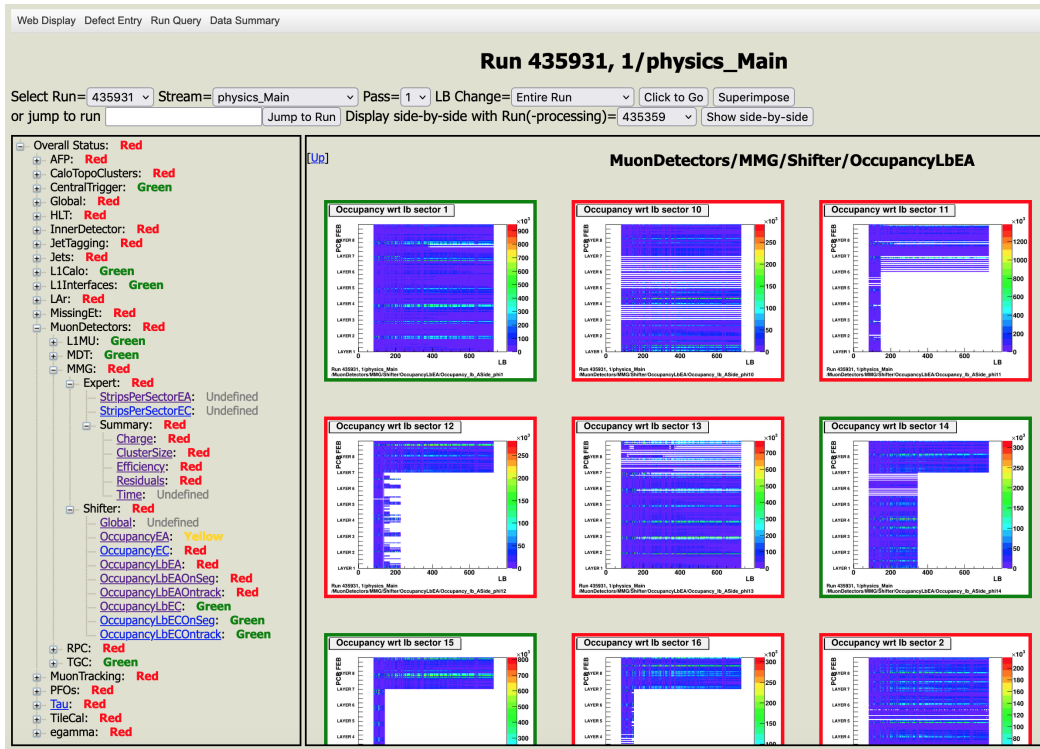


Figure 5.8: A screenshot of the Data Quality Offline Webdisplay for run 435931 in the physics stream of 2022 data at 13.6 TeV centre of mass energy. The histograms are organised in folders. Dedicated algorithms check whether the histograms fulfill certain requirements and a colour flag is assigned to help the shifter identify problems.

A close up of a histogram presented on the Webdisplay is shown in Figure 5.9. Among the details of the automatic assessment are the name of the algorithm used, the configuration parameters and the results whereas they are presented along with the histogram. For the summary maps each bin content is checked whether it falls inside a predefined range. For the hit occupancy distributions the algorithm counts the number of bins for which the content is above a certain percentage of the median value of all bins in the histogram. As concerning the plots that show the occupancy as a function of LB the algorithm identifies the number of empty bins. Finally, an algorithm that checks

whether the histogram is filled with data or not is used for the rest of the distributions shown on the Webdisplay. The colour of the flag is determined by the algorithm's result.

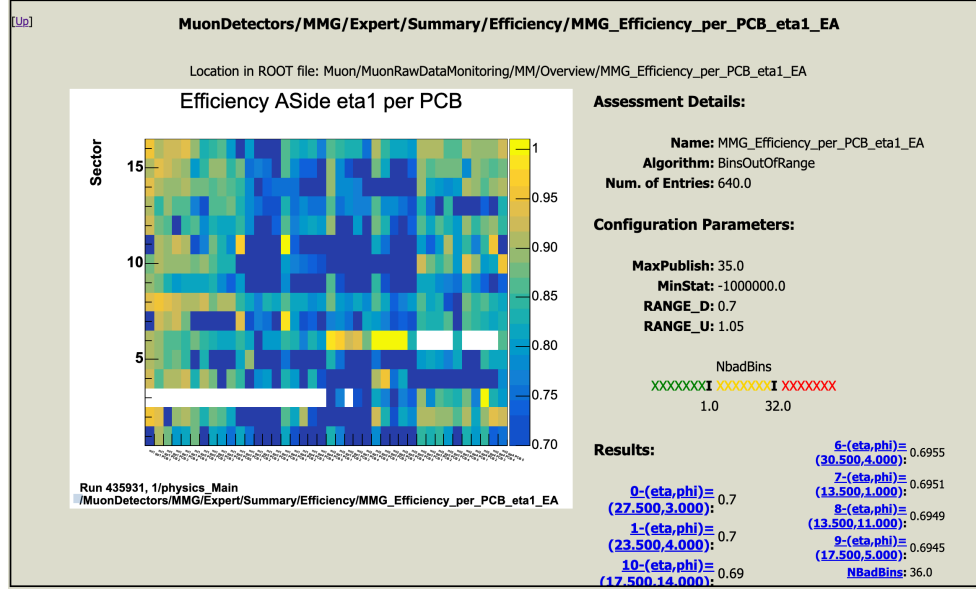


Figure 5.9: A close up view of the efficiency map for NSW Side-A and MMG type 1. The name of the algorithm used for the automatic assessment is shown along with the configuration parameters and the results. The number of "bad" bins found amounts to 36 and thus the red flag is assigned on the histogram. The histogram is part of the Webdisplay produced for run 435931 in the physics stream of 2022 data at 13.6 TeV centre of mass energy.

The algorithms are located in the *DataQuality/dqm_algorithms* Athena path. The folder structure and the choice of the appropriate algorithm for each histogram is defined in a configuration file located in the *DataQuality/DataQualityConfigurations/config* Athena path.

The review of the offline Webdisplays is subject to the final assessment of the data. Prior to the checks, the offline shifter has the responsibility to be well informed about the running conditions of the muon subsystems. Afterwards, the offline Webdisplays are checked and the shifter can relate issues that are present in histograms to problems that have been already detected online. In case of any remaining issues, the shifter must inform the detector expert who can update the Defect Database if deemed necessary. Once the validation of the data is completed and the muon system's defects are considered as tolerable, the shifter signs off the run which will enter in the GRL.

6 Performance Studies

With the completion of the electronics integration on the NSW MMG chambers, series of test beam campaigns are carried out. It is the first time the NSW MMG modules are tested with the final version of the NSW electronics mounted on them in conditions similar to those that will be imposed by the HL-LHC upgrade. The motivation behind these tests lies on a deeper understanding of the data taking system and the detector itself. The results will serve as reference when the NSW will start collecting "good for physics" data. In this chapter the analysis for the characterisation of the detector performance using data collected in July 2022 will be presented. First, the experimental setup will be described in Section 6.1. In Section 6.2 the analysis strategy will be discussed. Finally, the results of the under study detector's performance in terms of efficiency and spatial resolution will be presented in Section 6.3. Additional material on MMG studies are documented in Appendix B.

6.1 Experimental Setup

6.1.1 The Gamma Irradiation Facility

The Gamma Irradiation Facility (GIF++) [104] was designed and built during LS1 whereas it has been operational since April 2015. At GIF++ performance studies and stability tests of detectors designed for the HL-LHC upgrades can be carried out. A 14 TBq ^{137}Cs source is combined with high energy charged particle beams (mostly muons of a few hundreds of GeV) from the secondary SPS beam line H4 in EHN1 (887) building at Preveessin CERN site.

The H4 beam line can transport attenuated primary proton beams, secondary or tertiary particle beams such as electrons, muons or mixed hadrons (i.e pions, protons, kaons) produced when the primary proton beam from SPS impinges onto a beryllium target, T2 [105]. Particularly, for the muon configuration the high-energy, high-intensity pion beam is stopped onto an iron absorber located upstream of GIF++. The pions are stopped and only the surviving muon beam continues downstream, reaching the detectors. Two additional beam dumps are installed at the entrance and exit of the beam passage from the facility, in order to enhance the quality of the muon beam. Finally, two scintillator trigger systems are installed in order to provide trigger information both for the muon beam and cosmic muons.

^{137}Cs decays with a half-life of about 30.05 y through β emission to a metastable isomer of barium which rapidly (~ 153 s) decays to its ground state with the emission of a 662 keV photon. This process happens 94.6% of the time. The remainder directly populates the ground state of ^{137}Ba . The source is located inside a shielded 100 m² bunker where two independent irradiation zones are defined. An attenuator system consisting of movable lead filters is installed on the side of the

irradiator to tune the photon fields. By changing the arrangement of the filters attenuation factors (AF) between 1 (without putting any filter) and 46420 (all filters are placed in a way to achieve the maximum attenuation of the gamma source, else noted in the following as source OFF) can be selected [106]. The layout of the GIF++ facility is depicted in Figure 6.1.

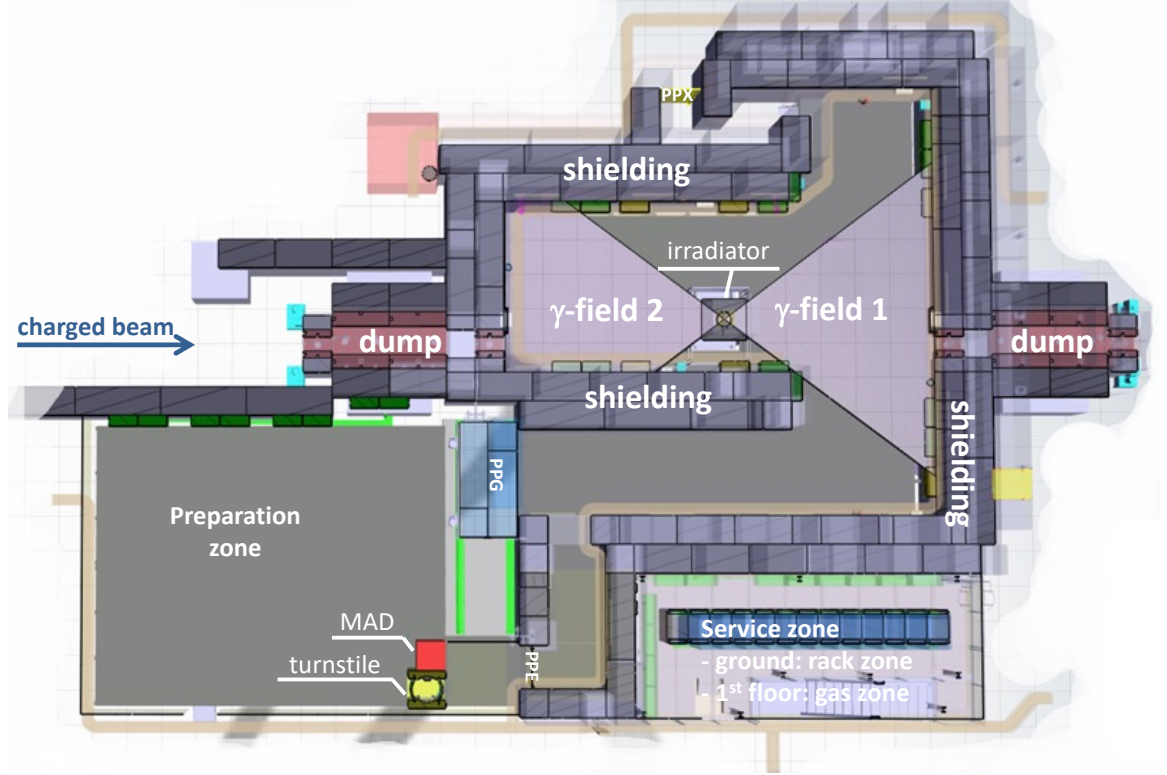


Figure 6.1: The floor plan of the GIF++ facility [107]. The ^{137}Cs source is hosted inside the shielded bunker where two independent regions are defined and shown as the highlighted γ field cones at the upstream (left) and downstream (right) regions. The muon beam passes close to the irradiator and the bunker's wall side, the one towards to the preparation zone. The two beam dumps are used for the beam tuning. There are four access doors (MAD, PPG, PPE, PPX) for personnel and/or material. The preparation zone is a fenced area close to the bunker which serves as an additional space for the detector testing. The service zone is a two floor area with the gas distribution/mixing system and several racks for electronics installed for the users' needs.

6.1.2 Detector Installation

A small NSW MMG module of type 1, labeled as SM1-M40¹, was positioned at the downstream region of the bunker, at a distance of around 2 m away from the irradiator. The module was placed at vertical position with its large trapezoidal base mounted on a rotating platform whereas it operated with the baseline gas mixture. Only PCB-3 was integrated with electronics.

¹ Referred to as SM1. The readout layers are labeled as: eta out (first layer facing the source), eta in, stereo in, stereo out.

The dimensions² of PCB-3 allow to relate its performance to that of PCB-1 (being the one that will experience the highest background rates at the HL-LHC Runs) when the HV is switched on only on the half³ PCB-3. The background environment at HL-LHC is rather complex, comprising of other particles (i.e protons, neutrons, pions, etc) besides photons. At GIF++ the NSW MMG can be efficiently tested by translating the gamma source to particle and readout detector rates. The background rate levels at HL-LHC era are expected to be up to 20 kHz/cm^2 at the first strips of PCB-1 whereas the PCBs closest to the beam line will experience the highest rates. This particle rate corresponds to the AF setting at around 10. This relation is demonstrated in Appendix B.1.

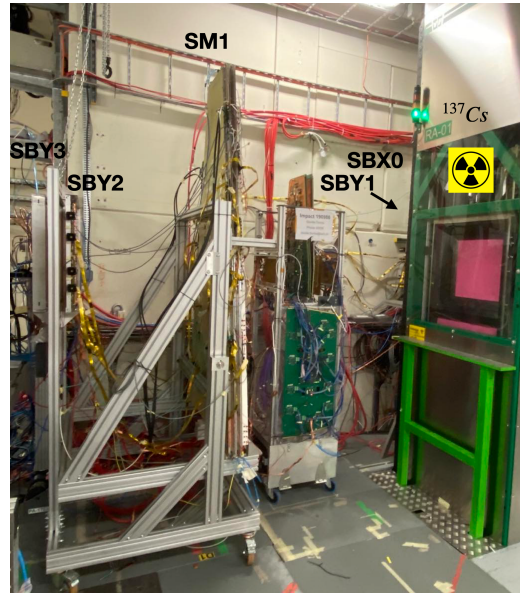


Figure 6.2: The experimental setup at GIF++. The performance of SM1-M40 was tested under HL-LHC conditions with the use of the ^{137}Cs source and the muon beam provided by the H4 beam line. Four prototypes (SBX0, SBY1, SBY2, SBY3) were used as reference tracking chambers.

The setup also includes four other small MMG prototypes which served as reference tracking chambers. They have an active area of $40 \times 40 \text{ cm}^2$ and a strip pitch of $450 \mu\text{m}$. The orientation of strips for those labeled as SBY is identical to that of the NSW MMG eta layers. One chamber labeled as SBX0 has its strips tilted by 90 degrees with respect to the others. Thus, both coordinates can be measured for the reference tracks. The two small chambers (SBY2 and SBY3) were installed on the same platform with the SM1-M40 at a distance of 79 cm away inside the irradiation cone. The distance between them was measured at 13.6 cm. The rest two chambers (SBX0 and SBY1) were positioned along the beam line path, nearby the source but outside the irradiation boundaries. This choice of positioning enables the muon track finding in the presence of gammas for runs where the source is ON. The distance between them was measured at 26.2 cm. The NSW front end boards were used for the readout of the signals. The chambers were operated with a gas mixture with a composition of 93% Ar and 7% CO_2 .

² The length of the strip which is located at the middle of PCB-3 is $\sim 680 \text{ mm}$ whereas for PCB-1 it has a length of $\sim 360 \text{ mm}$.

³ Due to PCB construction limitations each PCB is divided into two HV sections.

A photograph, taken during the beam time in July 2022, showing the detectors installed inside the GIF++ bunker is presented in Figure 6.2. A sketch of the setup is depicted in Figure 6.3.

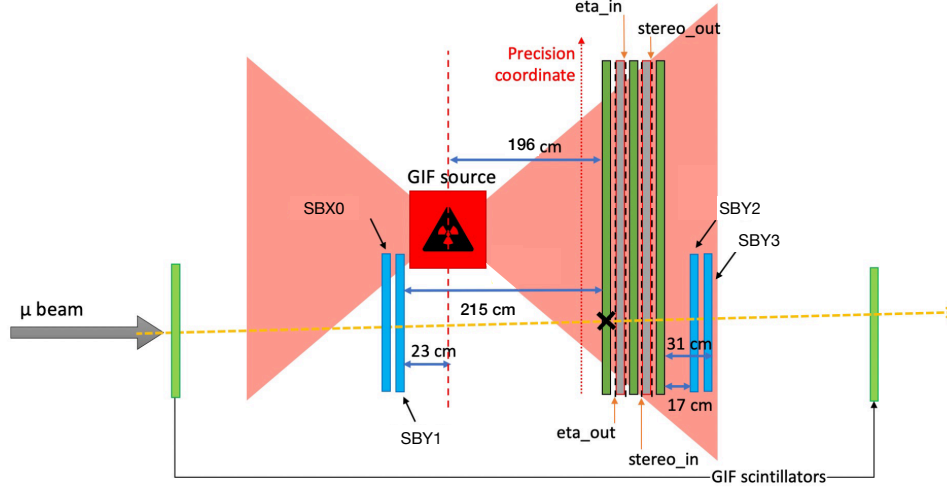


Figure 6.3: A sketch of the experimental setup at GIF++.

6.1.3 The VMM Readout Configurations

The VMM [66] is a 64 channel ASIC which readouts the signals on the MMG anode strips. Eight VMMs are hosted on each of the MMFE8 front end boards, i.e 512 strips/board. For the test beam setup, two MMFE8s per MMG layer were integrated on PCB-3 of SM1 resulting to eight MMFE8. Two MMFE8s were used for the readout of each of the small prototype detectors too.

The fundamental parameters for the MMG track reconstruction are the charge and time depending on the method to be used for the offline data analysis. In short, in VMM there is a discriminator, a threshold trimmer and a peak and time detector for each channel [108]. The VMM has a common reference bunch crossing clock (CKBC) operating at a frequency of 40.079 MHz to coincide with the pp collisions in ATLAS. For the test beam the reference clock was controlled externally by sending the trigger signal. Each VMM channel can find events within eight reference clock cycles (200 ns readout window).

Once a signal above a defined threshold level is detected inside a clock's cycle, the peak detector starts integrating the charge up to the first peak found which is stored in an analog memory as the PDO, measure for the charge. The channel gain is adjustable in eight values: 0.5, 1, 3, 4.5, 6, 9, 12 and 16 mV/fC. A voltage ramp, generated by a time-to-amplitude converter (TAC), starts either at the threshold crossing or at the time of the pulse peak until the falling edge of the next clock cycle. The peak value of the voltage ramp is stored in an analog memory as the TDO, measure for the time. The peaking time, i.e the time for the signal integration, is adjustable in four values: 25, 50,

100 and 200 ns and the ramp duration is also adjustable in four values: 60, 100, 350 and 650 ns. A representation of the overall VMM channel functionality is presented in Figure 6.4.

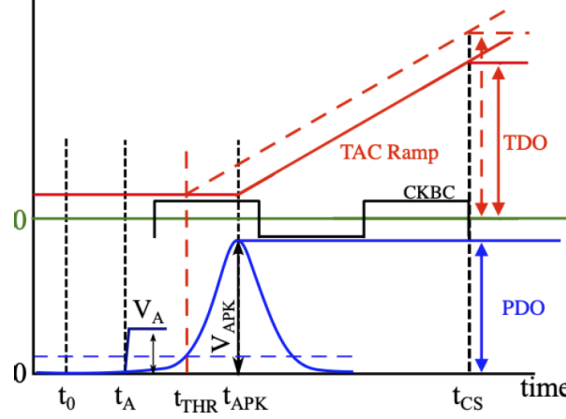


Figure 6.4: The VMM channel functionality [66]. The charge information is provided by the peak amplitude measurement whereas the time information is provided by the peak timing of a configurable time-to-amplitude converter (TAC).

Prior to the actual data taking, the first step is the evaluation of the noise levels. A global threshold common to all channels is set. The electronic noise introduces baseline fluctuations which are superimposed on the signal and alter the peak amplitude. To ensure that each channel's response is the same for the same value of input charge the distance from the baseline to the threshold must be the same for each channel. A baseline holder circuit, set at 160 mV, is implemented in the VMM to provide the stabilisation of each channel's baseline fluctuations. Additionally, each channel features

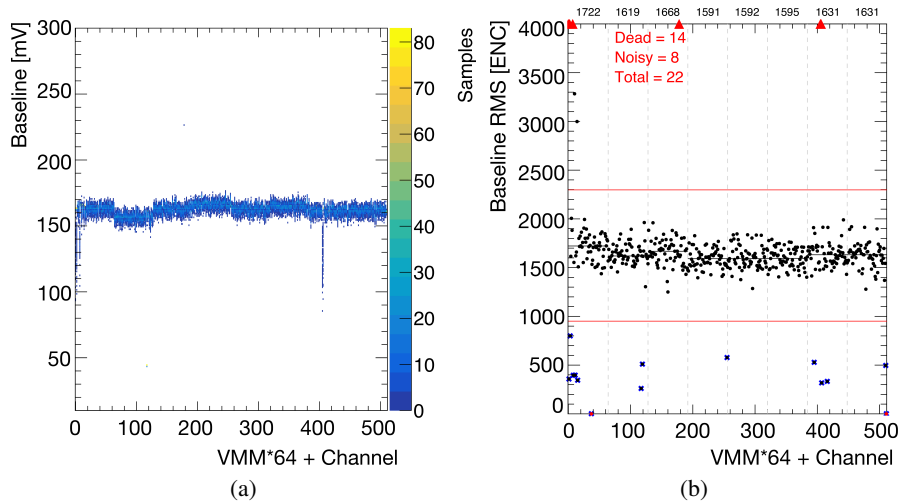


Figure 6.5: (a) The baseline voltage variation and (b) the equivalent noise charge for each VMM channel that reads out the half PCB-3 of SM1 eta layer. The noisy and dead channels are identified and can be masked at the offline analysis.

an individual trimmer which can shift the baseline level at one direction with respect to the global threshold setting. An external test pulser, in 1 V range, is fed to each VMM channel and a sampling on all input voltages is performed. The individual channel's baselines can be directly measured by the oscilloscope through a specific output of VMM, called monitoring output. The equivalent noise charge (ENC) of a channel can then be measured as the root mean square (rms) of its baseline voltage. The baseline variations after the trimmer adjustment across all channels and their corresponding ENC of one MMFE8 mounted on PCB-3 of SM1 eta layer are shown in Figure 6.5.

6.2 Analysis Strategy

The motivation of this analysis is to characterize the SM1 performance, in terms of its efficiency and spatial resolution, in HL-LHC environment. The analysed runs refer to the state when the SM1 was positioned perpendicularly to the beam axis, i.e study of normal tracks. The main VMM configuration settings are summarised in Table 6.1.

Table 6.1: The VMM configuration settings.

gain	9 mV/fC
ramp duration	60 ns
peaking time	200 ns
trimmers threshold	9×rms

The anode HV was set at +520 V for the half PCB-3 of SM1. The operation gas with a consistency of 93% Ar, 5% CO₂ and 2% isobutane was used for SM1. The prototype detectors were operating at +570 V for the operation gas mixture with a consistency of 93% Ar and 7% CO₂. Due to hardware issues during the data taking the HV was set at +560 V for SBX0. Finally, the detector proved to be inefficient due to a gas leak problem and thus it was not included in the search of the reference tracks. However, this issue was resolved in later runs.

The charge centroid method can accurately measure the position of particles when they transverse the detector layers at small incident angles ($< 10^\circ$) while a spatial resolution of better than 100 μm can be reached [80]. This method was employed for the scope of this analysis. The raw hits on the strips were grouped together to form clusters. Each cluster consists of at least two adjacent strips whose PDO recorded value is at least 64 ADC counts. Two holes are allowed between two fired strips in a cluster (without a maximum limit) to account for any dead electronic channels. The cluster position can then be reconstructed as the weighted sum of the fired strip position, that form the cluster, with the signal amplitude (PDO) over the total cluster charge (sum of each strip PDO).

Typical distributions of various parameters, eg. raw hits, number of clusters, cluster multiplicity, cluster position, strip PDO, strip TDO, relative BCID, were measured for each detector individually. These distributions serve as a confirmation that the system provides good data for analysis, whereas they are shown in Figure 6.6 for the SM1 eta out layer. Similar results are produced for the rest readout layers of the setup.

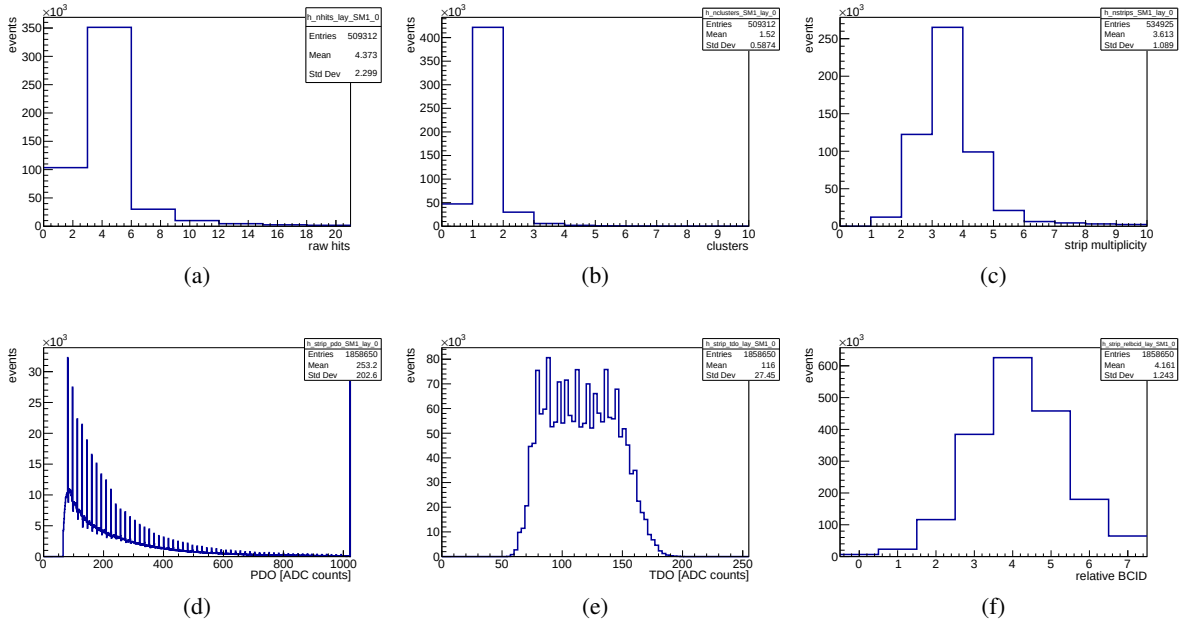


Figure 6.6: The distributions of (a) raw hits, (b) number of clusters, (c) cluster multiplicity, (d) strip PDO, (e) strip TDO and (f) relative BCID for the SM1 eta layer closest to the source. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

The beam profile is presented in Figure 6.7 as recorded from all layers of SM1 and the three small prototype detectors that are used in the analysis.

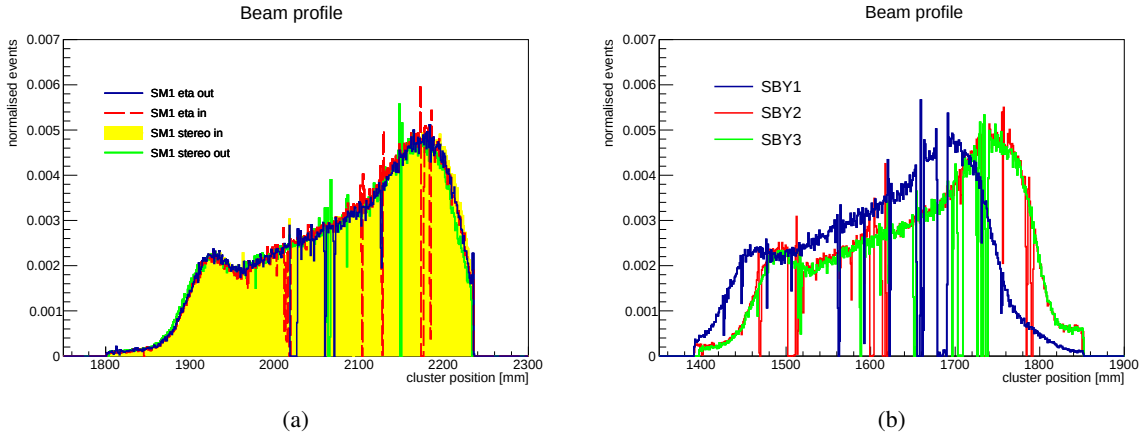


Figure 6.7: The beam profile as reconstructed by (a) SM1 and (b) small prototype MMG layers prior to the alignment. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

In order to ensure precise results, the chambers were aligned using events recorded with the muon beam only. During the alignment procedure a shift by 1-2 strip pitches was observed from MMFE8 to MMFE8 and for some cases between VMMs of a given SM1 layer. After introducing these

shifts as corrections to the strip positions, all chambers were aligned by calculating correlations between all detectors of the setup and the reference detector SBY1. The correlations were fitted with a linear function and the resulting residuals were centered at zero by correcting the strip positions with the insertion of a shift and a slope (results of the linear fit). Several iterations were performed to achieve an optimal alignment of the system and a detailed description of the procedure is presented in Appendix B.3.

The following procedure was followed for the muon tracks detection. The SBY1 detector as the one positioned outside the irradiation cone could facilitate the reconstruction of muon tracks and specifically in the presence of the source. Therefore, only the events for which only one cluster is reconstructed in SBY1 are processed whereas these events amount the 60.7% of the total sample. The breakdown of the events for which more than one clusters are reconstructed in each chamber of the setup, before and after the application of this cut is shown in Table 6.2.

Table 6.2: Breakdown of events and the corresponding fraction of the total events in the run (in percentage) before and after the cut requirement of exactly one cluster found on SBY1. For completeness, the recorded events on SBX0 are shown despite that the chamber is not used in the analysis. These numbers are produced from run 1658081138 with muon beam ON and γ source OFF.

Total events	509 312	100%
Events with clusters ≥ 1		
SBX0	115 058	22.6%
SBY1	339 933	66.7%
SM1 eta out	466 935	91.7%
SM1 eta in	462 187	90.7%
SM1 stereo in	464 976	91.3%
SM1 stereo out	474 344	93.1%
SBY2	453 703	89.0%
SBY3	481 741	94.6%
Cut: Events with exactly 1 cluster on SBY1	309 323	60.7%
Events with clusters ≥ 1		
SBX0	94 151	18.5%
SBY1	309 323	60.7%
SM1 eta out	289 512	56.8%
SM1 eta in	285 527	56.1%
SM1 stereo in	288 107	56.6%
SM1 stereo out	294 732	57.9%
SBY2	283 158	55.6%
SBY3	294 304	57.8%

Even though the system was aligned, the chambers did not reconstruct the same beam spectra. In order to ensure that the reconstructed events in each chamber comes from the same part of the beam a geometrical cut was applied on all chambers. With the application of this cut about the 48.3% of the total events survived. The next step was to look for clusters reconstructed on the other two small chambers, SBY2 and SBY3, within a window of $\pm 1^\circ$. A linear fit on the three reference chambers corresponds to a muon track candidate. The total number of muon track candidates results to the

40.3% of the total events in the run. Because of the initial requirement on SBY1, single track events are processed only. Therefore, the best cluster pair (on SBY2 and SBY3) has to be selected (for the cases where more than one tracks satisfy the requirements)⁴. The single muon track candidates amount to the 40.1% of the total events in the run. Finally, a spread of the reconstructed track angles was observed and in order to augment the quality of the normal tracks, a requirement of $\pm 0.5^\circ$ on the reconstructed tracks should be satisfied. This additional cut results to a decrease of 0.5% of the total muon track candidates. The distribution of the reconstructed track angles before and after the insertion of this cut is presented in Figure 6.8.

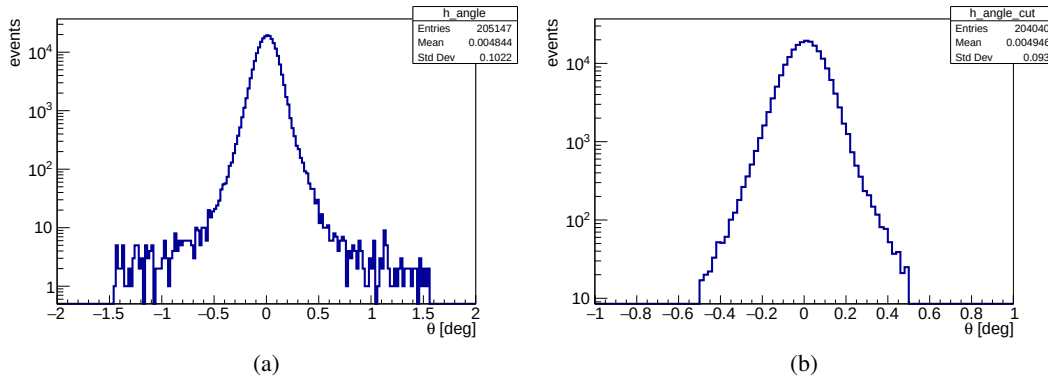


Figure 6.8: The reconstructed muon track angles (a) before and (b) after the insertion of the cut $-0.5^\circ \leq \theta \leq +0.5^\circ$. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

A display of a reconstructed muon candidate is depicted in Figure 6.9.

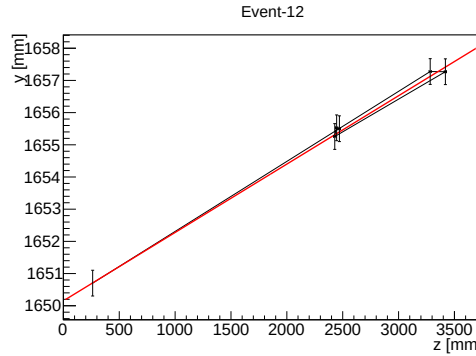


Figure 6.9: An example of a reconstructed muon track candidate. The linear fit (red line) is performed only on the clusters reconstructed by the prototype chambers. The three points in the middle correspond to the clusters as reconstructed by each SM1 layer. An error of ± 10 mm is assigned for the z coordinate (direction of the beam) whereas the error on the y coordinate (points towards the eta strip direction) equals ± 0.4 mm (~ 1 strip pitch) same for all chambers. The track display is produced from run 1658081138 with muon beam ON and γ source OFF.

⁴ The selection of the best track in an event is decided by inspecting how far from it the reconstructed clusters on SM1 layers are found. The track which has the closest distance with the clusters reconstructed by SM1 is selected as the good candidate.

6.2.1 Efficiency

The evaluation of the efficiency was performed for each SM1 layer independently and at different irradiation conditions. For each reconstructed muon track it is checked if a reconstructed cluster on the under study layer is found within a window of some mm (± 1 mm for eta layers, ± 2.5 mm for stereo layers) away from the track. If a cluster is found within the window the under study layer is labeled efficient for the event. Otherwise, the layer is labeled inefficient, i.e the layer did not detect the track. The ratio of the number of occurrences for which a layer is labeled efficient over the total number of reconstructed tracks defines the layer's efficiency. Figure 6.10 shows the number of SM1 layers for which a cluster is reconstructed per track. For the majority of the reference muon tracks there is always a reconstructed cluster in all SM1 layers. Table 6.3 lists the analysed runs.

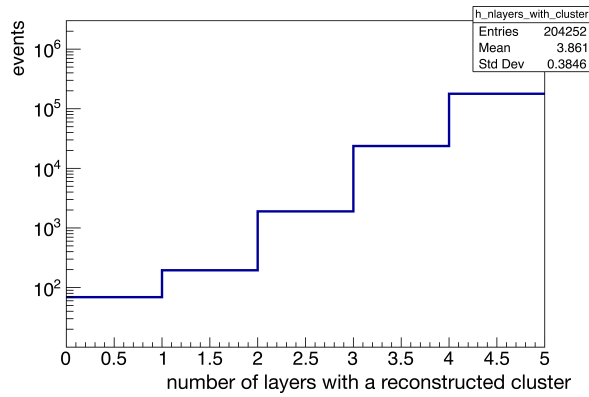


Figure 6.10: The number of SM1 layers for which a cluster is reconstructed per muon track. The plot is produced from run 1658081138 with muon beam ON and γ source OFF.

Table 6.3: List of runs used in the analysis. The higher the attenuation filter value the less exposure to the source.

Run Number	Attenuation Filter (AF)
1658081138	no filter - source OFF
1657876123	22
1657822252	10
1657827799	4.6
1657833031	2.2
1657878807	1.5
1657871992	1

Figure 6.11 presents the efficiency measurement for each SM1 layer as a function of the attenuation filter used. For low photon intensities the SM1 performance in terms of efficiency is found to be higher than 90%. At the expected HL-LHC background conditions (AF = 10) the detector is capable to identify the muon tracks at the same efficiency levels. At higher intensities a drop in efficiency is observed whereas it reaches the $\sim 50\%$ for the stereo layers and $\sim 65\%$ for the eta layers.

Extensive studies, with different VMM settings, have been performed during the past and later test

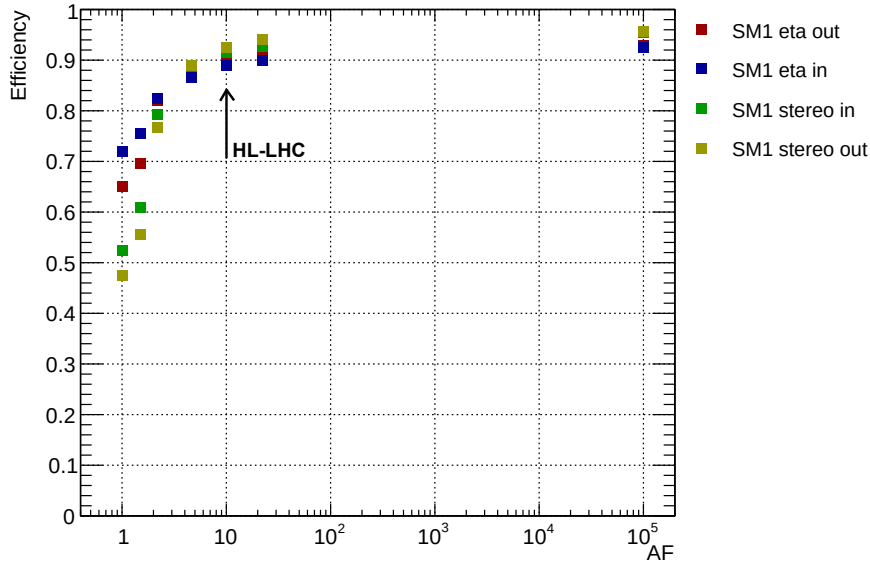


Figure 6.11: The estimated efficiency for each SM1 layer as a function of the AF setting. AF = 1 refers to full exposure to the γ field. As the AF value increases a filter arrangement is embedded in the source resulting to a reduction of the photon flux. In the absence of photons (source OFF, AF $\gg$) the measured efficiency of all SM1 layers is around 95%. At HL-LHC conditions (AF = 10), the efficiency exceeds the 90% for most of layers.

periods at GIF++ with the aim to understand the response of the detector and its electronics under irradiation. A saturation effect had been observed at high photon intensities (AF < 2.2). Looking at the PDO distribution there is always a peak in the last bin, i.e channel 1024 of the analog memory, indicating that high amplitude pulses cannot be processed by VMM. At high photon intensities this effect becomes more prominent, about 2.5 times higher peak (see Figure 6.12).

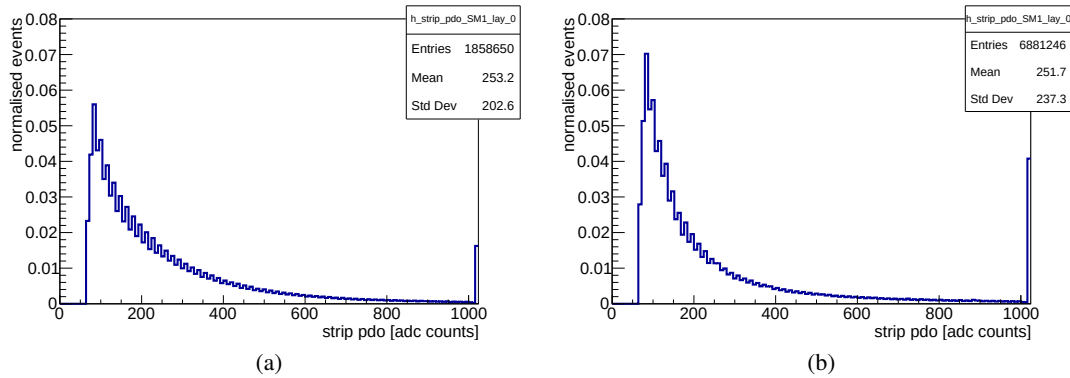


Figure 6.12: The pdo distribution for (a) the typical run 1658081138 with the muon beam and source off and (a) the run 1657871992 with the muon beam and under full irradiation.

The VMM setting `slh` [109], if enabled increases the bias current at input node from nominal 1 nA to 15 nA such that it can compensate with higher input charges from the detector. Figure 6.13 shows the mean number of clusters as reconstructed by SM1 under full irradiation conditions when `slh` is enabled and disabled. Up to $AF = 2.2$ there is a linear behaviour for both settings, as expected, whereas at higher intensities the saturation effect observed when `slh` is disabled is significantly improved when the parameter is enabled. These studies were performed at late 2022 out of muon test beam period. Therefore, by enabling this parameter an improvement of the detector performance with muons at such harsh conditions is expected.

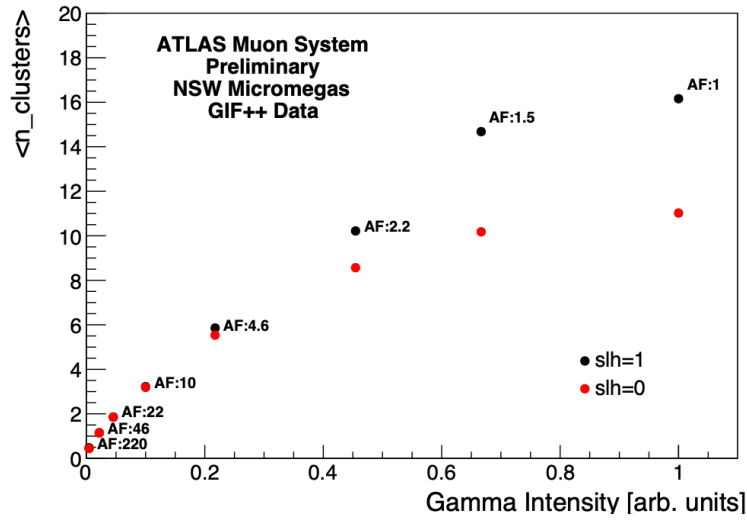


Figure 6.13: The mean number of clusters as a function of the source intensity ($1/AF$) when the `slh` parameter is disabled (red points) and enabled (black points). The plots are produced from runs taken at late 2022 out of the muon test beam period and under irradiation. The peaking time is set at 200 ns, the gain at 9 mV/fC and the trimmers threshold at $9 \times rms$. The HV was set at +530 V for half PCB-3.

6.2.2 Spatial Resolution

Different methods were examined to determine the accuracy, in terms of muon track's position identification, the SM1 layers can achieve.

As a first measure, the distribution of the distance between the reconstructed cluster in the under study layer and the muon track was derived for each layer. The clusters as reconstructed by the two stereo layers were combined to derive the y coordinate [79]. The standard deviation as result of a fit with a double gaussian function gives an estimate of the detector's spatial resolution, accounting also effects⁵ present at the tails. The result of a simple gaussian fit gives the detector's intrinsic spatial resolution. The distributions are presented in Figure 6.14. This method is referred to as Method A.

⁵ i.e multiple scattering, δ -rays, particle showers.

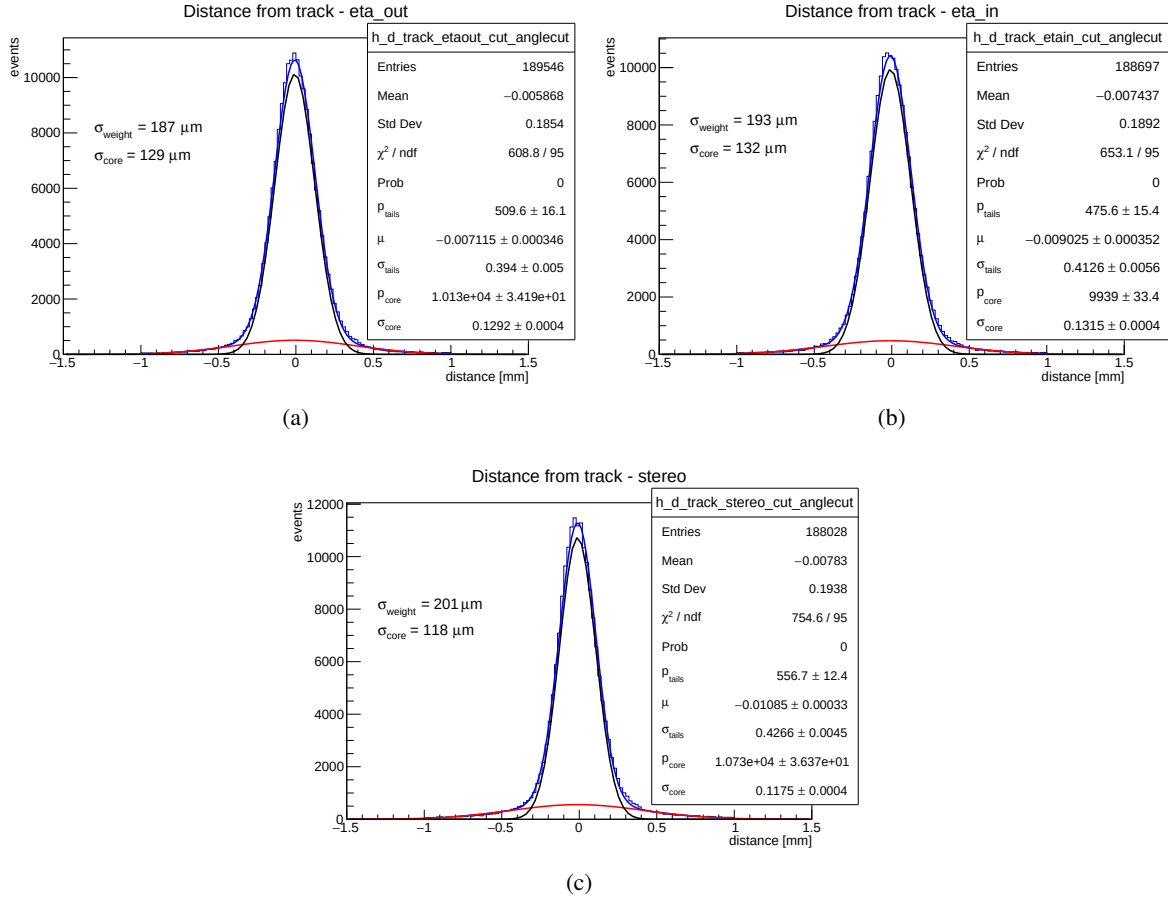


Figure 6.14: The distribution of the distance between the reconstructed cluster in (a) eta out, (b) eta in, (c) the two stereo layers combined and the extrapolated position on track. The extracted resolutions as result of the fit with a double gaussian function (blue line, σ_{weight}) as well as with a simple gaussian function (black line, σ_{core}) are reported. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

The result can be improved if the reconstructed cluster in the under study layer is included in the track definition. The corresponding distributions are shown in Figure 6.15. The improved unbiased result can then be defined as the geometrical mean of results from Figures 6.14, 6.15. This method is referred to as Method B.

Considering that the reference detectors are identical with a measured spatial resolution of $\sigma_{\text{SB}} \sim 150 \mu\text{m}$, the track extrapolation error can be estimated by using the following formula for three reference chambers [80]:

$$\sigma_e^2 = \frac{(z_0 - z_1)^2 + (z_0 - z_2)^2 + (z_0 - z_3)^2}{(z_1 - z_2)^2 + (z_1 - z_3)^2 + (z_2 - z_3)^2} \cdot \sigma_{\text{SB}}^2 \sim 87^2 \mu\text{m}^2 \quad (6.1)$$

where z_i , for $i = 1, 2, 3$, are the positions along the beam direction of the SBY chambers. The spatial resolution after accounting the track extrapolation error can then be defined as $\sqrt{\sigma^2 - \sigma_e^2}$. The results before and after accounting for the track extrapolation error are presented in Table 6.4.

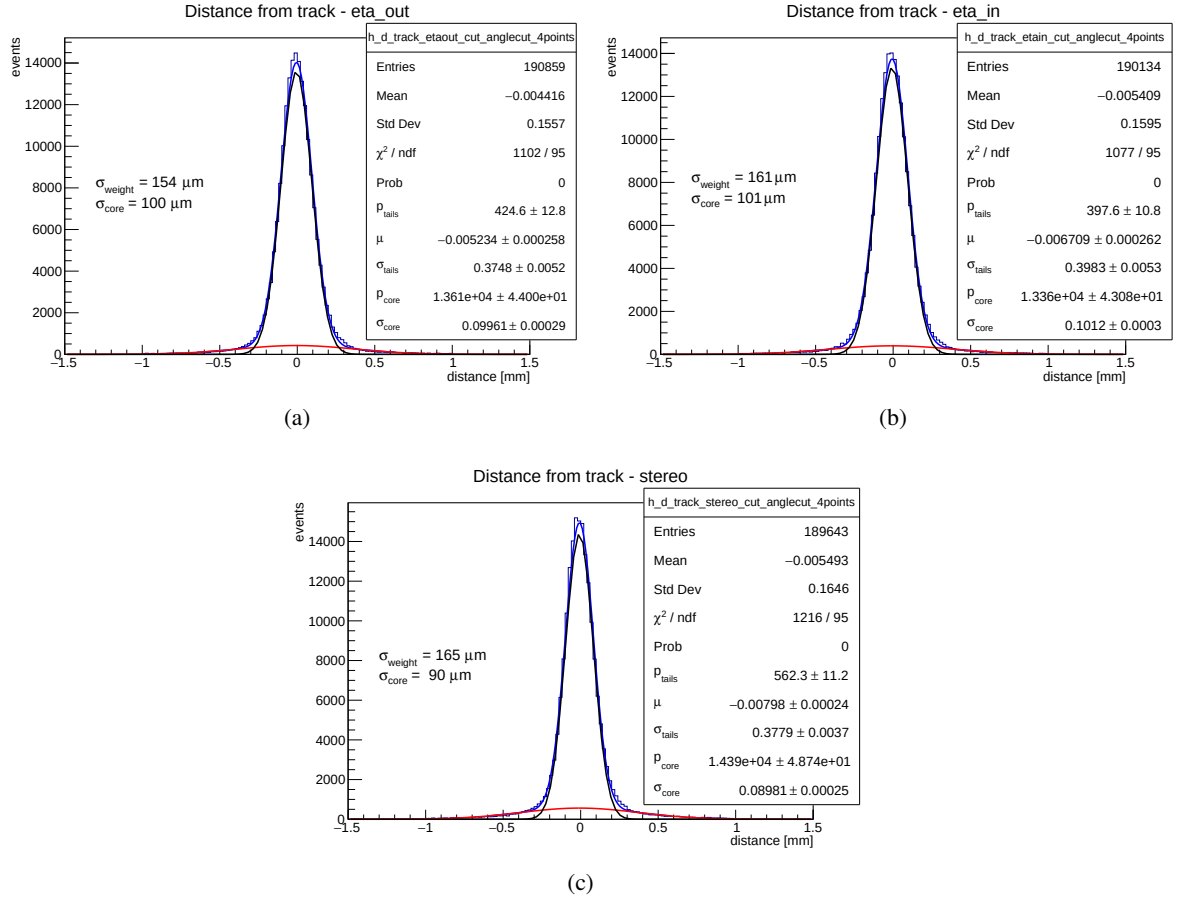


Figure 6.15: The distribution of the distance between the reconstructed cluster in (a) eta out, (b) eta in, (c) the two stereo layers combined and the extrapolated position on track when the reconstructed cluster in the corresponding layer is included in the track definition. The biased extracted resolutions as result of the fit with a double gaussian function (blue line, σ_{weight}) as well as with a simple gaussian function (black line, σ_{core}) are reported. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

An alternative method (Method C) was followed for the spatial resolution measurement. The distributions of the difference between the reconstructed cluster positions, i.e residuals, of all possible layer combinations are presented in Figure 6.16. After a fit with a double gaussian function the spatial resolution⁶ can be expressed by dividing the obtained σ with $\sqrt{2}$.

⁶ The layers are considered identical.

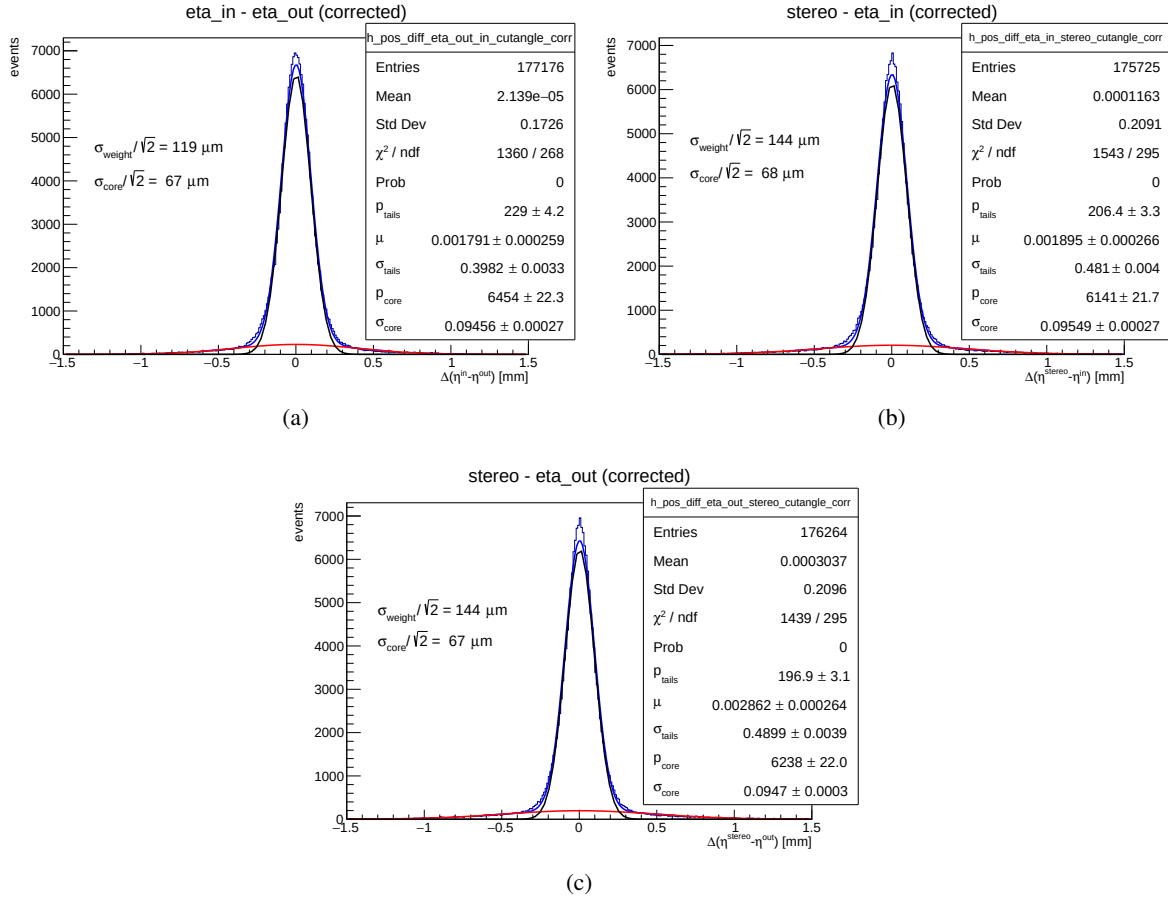


Figure 6.16: The distribution of residuals as calculated between the (a) two eta layers, (b) eta in and combined stereo information and (c) eta in and combined stereo information. The extracted resolutions as result of the fit with a double gaussian function (blue line, $\sigma_{\text{weight}} / \sqrt{2}$) as well as with a simple gaussian function (black line, $\sigma_{\text{core}} / \sqrt{2}$) are reported. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

Table 6.4: Summary of the measured spatial resolutions. The numbers are rounded. For Method A and B the results before and after considering the track extrapolation error, ϵ^{track} , are reported. For Method C the best achieved results are presented considering that all layers behave the same. The reported results are produced from run 1658081138 with muon beam ON and γ source OFF.

Method		Spatial Resolution (core) [μm]			Spatial Resolution (weight) [μm]		
		eta out	eta in	stereo	eta out	eta in	stereo
A	w/o ϵ^{track}	129	132	118	187	193	201
	w/ ϵ^{track}	95	99	80	165	172	181
B	w/o ϵ^{track}	114	115	103	170	176	182
	w/ ϵ^{track}	74	75	55	146	153	160
C		67			119		

The best results are derived by Method C with a core resolution of $\sigma_{\text{core}} \sim 67 \mu\text{m}$ and a weight resolution of $\sigma_{\text{weight}} \sim 119 \mu\text{m}$. Slightly worse results are measured by Method B, while a stricter estimation is provided by Method A. Overall, the detector operating with the final electronics shows a good performance in terms of spatial resolution for normal muon tracks studies.

6.3 Summary Results

The efficiency and spatial resolution were measured for different attenuation filters for the VMM configuration settings shown in Table 6.1 and the run list in Table 6.3. The same analysis was performed for the run list presented in Table 6.5 where the VMM peaking time was set at 100 ns.

Table 6.5: List of runs. VMM peaking time setting is set at 100 ns. The higher the attenuation filter value the less exposure to the source.

Run Number	Attenuation Filter (AF)
1658066066	no filter - source OFF
1658159623	22
1658103127	10
1658100654	4.6
1658096165	2.2
1658093141	1.5
1658064770	1

A summary of the results is presented in Figure 6.17. The spatial resolution was estimated by Method C. For both VMM settings the performance of the detector is similar. The detector is 93% efficient with a core (weight) spatial resolution measured at $\sim 70 \mu\text{m}$ ($\sim 120 \mu\text{m}$) in operation without the source. In HL-LHC conditions (AF = 10) the estimated efficiency is measured at 90% while the spatial resolution has remained at the same level as measured from the run in absence of irradiation field.

The estimation of the spatial resolution when using the track information (see Figure 6.18), as followed by Method B, yields the same results in absence of irradiation and are comparable with those derived by Method C. However, when the detector records data while the source is on the results differ significantly between the two peaking time configurations. Figure 6.19 shows the PDO distributions for the different peaking time settings and irradiation conditions. A possible explanation could be the following: the faster the integration time, the more data are processed corresponding to pulses of lower amplitude and to an increased probability to filter the source and eventually process the muons. If this statement is correct, Method B is more reliable than Method C in background conditions.

Overall, the results of the analysis are promising and prove that the detector's performance in terms of efficiency and spatial resolution fulfill the requirements for operation in the HL-LHC era. In the future test beam periods with the slh setting enabled a better performance is expected. Figure 6.20 shows the number of reconstructed clusters as a function of the source intensity for the two peaking time settings and with the slh parameter enabled.

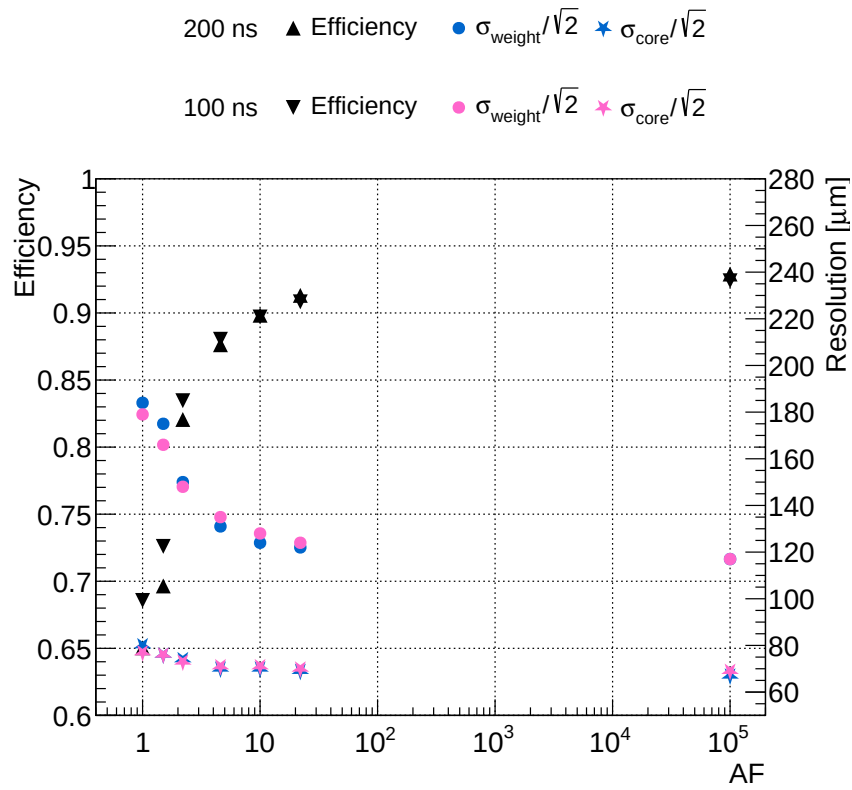


Figure 6.17: Efficiency and spatial resolution as a function of the attenuation filter setting as measured for eta out. The results for different configuration settings of the VMM peaking time, 200 ns and 100 ns, are shown together in the same graph. The spatial resolution is calculated by Method C.

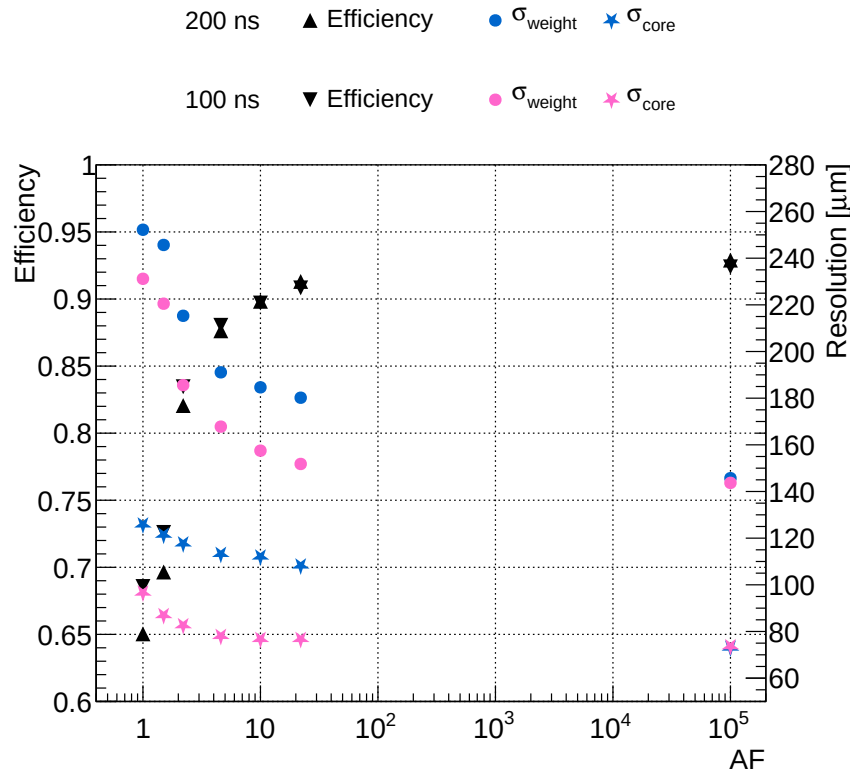


Figure 6.18: Efficiency and spatial resolution as a function of the attenuation filter setting as measured for eta out. The results for different configuration settings of the VMM peaking time, 200 ns and 100 ns, are shown together in the same graph. The spatial resolution is calculated by Method B and by accounting the track extrapolation error.

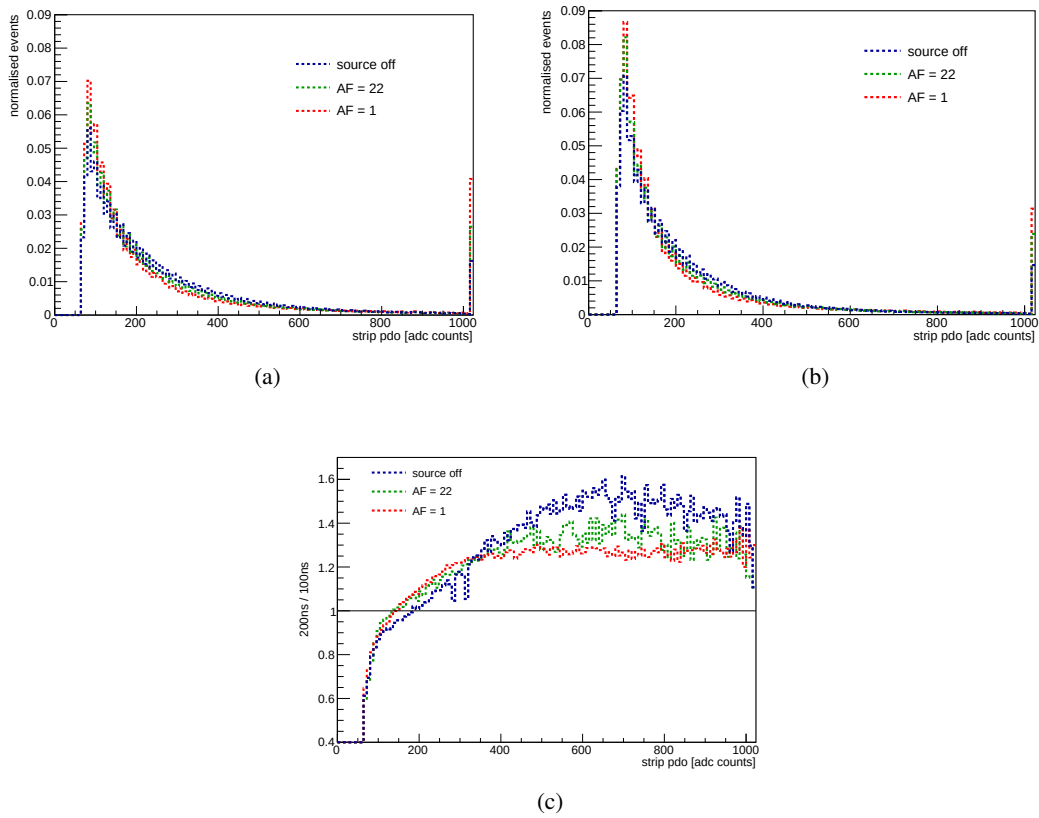


Figure 6.19: The PDO distributions at (a) 200 ns and (b) 100 ns VMM peaking time setting and at different irradiation conditions. The corresponding ratio is presented in (c).

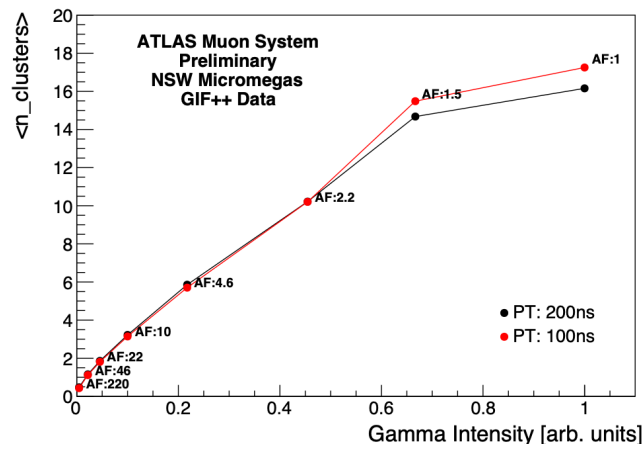


Figure 6.20: The mean number of clusters as a function of the source intensity ($1/AF$) when the slh parameter is enabled for peaking time set at 200 ns (black points) and at 100 ns (red points). The plots are produced from runs taken at late 2022 out of the muon test beam period and under irradiation. The gain is set at 9 mV/fC and the trimmers threshold at $9\times rms$. The HV was set at +530 V for half PCB-3.

Part III

**Study of the Higgs boson production via Vector Boson
Fusion in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel**

7 Analysis Overview

This chapter is structured as follows: First, an introduction of the targeted decay channel and process is given in Section 7.1. The data and the simulated signal and background samples are described in Section 7.2, whereas the physics objects and observables definitions considered in the analysis are presented in Section 7.3. Section 7.4 discusses the event level selections in all designed regions while the background extraction strategies are detailed in Section 7.5. Finally, Section 7.6 demonstrates the method followed to derive the cross section measurements and presents the final results.

7.1 Introduction

This analysis targets the $H \rightarrow WW^*$ decay mode when each of the W vector bosons decays leptonically. Electrons being stable and muons due to their relatively large mean lifetime (2.2×10^{-6} s) can be measured directly by the detector. On the other hand, τ -leptons decay immediately and can only be observed through their products, i.e. electrons or muons. Therefore, in the context of this analysis the W bosons final state refers to either an electron or a muon with the contribution from τ -leptons being included implicitly. Moreover, oppositely charged and of different¹ flavour leptons are identified as signal-like events in order to reduce the background that occur from $Z/\gamma^* + \text{jets}$ processes (known as Drell-Yan) that contaminate the signal.

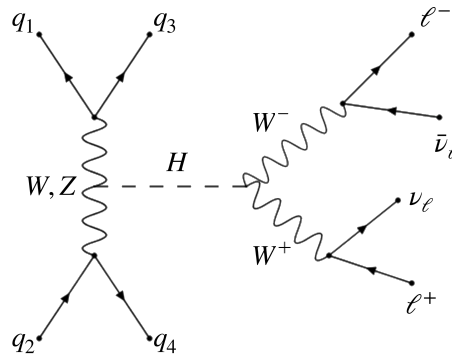


Figure 7.1: Feynman diagram for the Higgs boson production via VBF and decay to two W bosons.

The production of the Higgs boson through the vector-boson-fusion (VBF) process is characterized by the presence of (at least) two energetic jets with large separation in rapidity and a large invari-

¹ The same flavour, opposite charged final states can occur through pair production from $Z/\gamma^* + \text{jets}$ processes. In order to provide a higher sensitivity to the signal these final states are not considered as signal-like events.

ant mass of the di-jet system. An example of a tree-level Feynman diagram for the Higgs boson production via VBF in the $H \rightarrow WW^*$ decay channel is presented in Figure 7.1.

The VBF in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel has previously been studied, but not observed, by the CMS [110, 111] and the ATLAS [112, 113, 114] Collaborations using a partial Run-2 dataset corresponding to an integrated luminosity of approximately 36 fb^{-1} and at lower centre-of-mass energies of 7 TeV and 8 TeV pp collisions recorded in Run-1. The CMS Collaboration has reported the measurement in the form of inclusive and differential cross sections in the simplified template cross section framework [115]. ATLAS has also measured in terms of cross section times the $H \rightarrow WW^*$ branching ratio using the full Run-2 dataset at 13 TeV centre-of-mass energy, corresponding to an integrated luminosity of 139 fb^{-1} [116].

This thesis presents the measurement of fiducial cross sections using the full Run-2 dataset by the ATLAS experiment [117].

7.2 Dataset & Simulated Events

7.2.1 Dataset

This analysis uses the full Run-2 pp collision data at $\sqrt{s} = 13 \text{ TeV}$ with 25 ns bunch crossing recorded by the ATLAS experiment during 2015-2018 year periods of the LHC operation. The data are categorised per year and are subjected to quality requirements. The recommended by the Data Preparation Group "All Good" GRLs are used. The resulting integrated luminosity is 139 fb^{-1} . Figure 7.2 shows the profiles of the average number of simultaneous pp collisions (called pile-up events) and its evolution over the years.

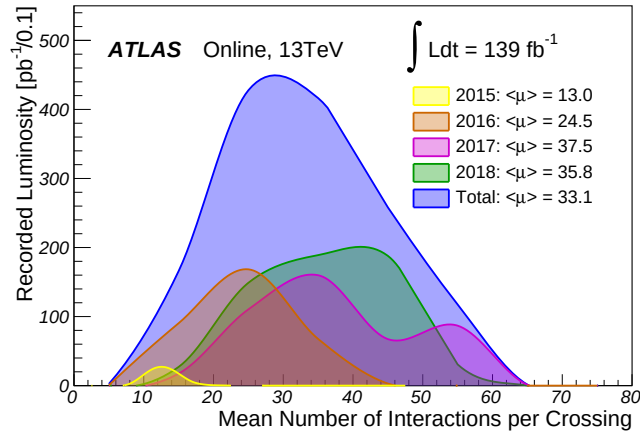


Figure 7.2: The luminosity weighted distribution of the mean number of pp interactions per bunch crossing, $\langle\mu\rangle$, for the analysed dataset.

A combination of single lepton (e, μ) and dilepton ($e\mu$) triggers are used in order to maximise the total trigger efficiency and a summary is given in Table 7.1.

Table 7.1: List of e , μ single-lepton and $e\mu$ dilepton trigger chains, the L1 seed followed by the HLT, used in the analysis. More than one triggers listed as L1 indicate that different seeds have been used in periods within the data-taking years. The number after the lepton symbol refer to the E_T and p_T thresholds on the reconstructed L1- and HLT-level objects, respectively. Keywords “tight”, “medium”, and “loose” refer to identification criteria, while the letter “i” indicates an isolation requirement. Tighter requirements are placed on triggers with lower p_T thresholds.

Lepton	Level-1 Trigger	High Level Trigger
2015		
e	L1_EM20VH	HLT_e24_lhmedium_L1EM20VH
	L1_EM22VHI	HLT_e60_lhmedium
	L1_EM22VHI	HLT_e120_lhloose
μ	L1_MU15	HLT_mu20_iloose_L1MU15
	L1_MU20	HLT_mu50
$e\mu$	L1_EM15VH_MU10	HLT_e17_lhloose_mu14
2016–2018		
e	L1_EM22VHI	HLT_e26_lhtight_nod0_ivarloose
	L1_EM22VHI	HLT_e60_lhmedium_nod0
	L1_EM22VHI	HLT_e140_lhloose_nod0
μ	L1_MU20, L1_MU21	HLT_mu26_ivarmedium
	L1_MU20, L1_MU21	HLT_mu50
$e\mu$	L1_EM15VH_MU10	HLT_e17_lhloose_nod0_mu14

7.2.2 Simulated Events

Six samples that describe the $VBF\ H \rightarrow WW^* \rightarrow e\nu\mu\nu$ process were simulated. Different calculations are performed by the implementation of different approximations in QCD and EW higher-order corrections and different modelling of parton showering (PS), hadronisation and underlying event (UE). The default sample for the signal events was generated with POWHEG-Box v2, interfaced with PYTHIA 8.230 to model the PS, hadronisation and UE. This prediction is accurate to next-to-leading order (NLO) in QCD corrections and is normalised to a cross section calculated up to the full NLO order in QCD and EW couplings with an additional approximate next-to-next-to-leading (NNLO) order QCD correction. Systematic variations were generated on the fly as event weights to account for uncertainties associated to PDFs, α_s and higher order effects. The cross section and branching ratio are simulated assuming a Higgs boson mass of 125 GeV. The alternative samples are used for comparison and/or the evaluation of uncertainties that are not covered by the nominal.

Several processes referred to as background, leave similar signatures to the signal process (i.e. two electrically charged leptons, neutrinos and jets) in the detector. These processes include events from the production of dibosons, top-quark, Z+jets, W+jets and to minor extent, multijet production. Finally, the Higgs boson production and decay into a pair of W bosons were simulated for the rest Higgs boson’s production modes, i.e. ggF and the associated production with a vector boson (VH , $V = W, Z$). Other modes like the Higgs boson production in association with a heavy quark pair ($t\bar{t}H$, $b\bar{b}H$) were examined and found to have a negligible contribution ($< 0.1\%$). Therefore, they are

not included in the analysis. The main simulation tools for the dominant background processes are summarised in Table 7.2.

Table 7.2: Overview of the main simulation tools used to generate the dominant background processes, including the matrix element calculation, the PDF set, the UE and PS models and the order used for the normalisation of the total cross section. The processes are categorised (from the top) as those including a Higgs boson, top quarks, di-bosons and Drell-Yan production.

Process	Matrix element	PDF set	UE and PS models	Calculation Order
$ggF\ H$	POWHEG-Box v2 (NNLOPS)	NNPDF3.0NNLO	PYTHIA 8, AZNLO tune	NLO QCD, N ³ LO QCD + NLO EW norm.
VH	POWHEG-Box v2	NNPDF3.0NNLO	PYTHIA 8, AZNLO tune	NLO QCD up to 1j, NNLO QCD + NLO EW norm.
$t\bar{t}$	POWHEG-Box v2	NNPDF3.0NNLO	PYTHIA 8, A14 tune	NLO QCD, NNLO+NNLL QCD norm.
Wt	POWHEG-Box v2	NNPDF3.0NNLO	PYTHIA 8	NLO QCD
QCD $qq/qg \rightarrow WW$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	NLO QCD up to 1j, LO QCD up to 3j
EW $qq \rightarrow WWqq$	MG5_AMC@NLO	NNPDF3.0NNLO	PYTHIA 8	LO QCD
$gg \rightarrow VV$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	LO QCD up to 1j, NLO QCD norm.
QCD $WZ/\gamma^*, ZZ$	SHERPA 2.2.2 ($4\ell, 3\ell + \nu$)	NNPDF3.0NNLO	SHERPA 2.2.2	NLO QCD up to 1j, LO QCD up to 3j
	POWHEG-Box v2 (other channels)	CT10NNLO	PYTHIA 8	NLO QCD
$V\gamma$	SHERPA 2.2.8 (MEPS@NLO)	NNPDF3.0NNLO	PYTHIA 8	NLO QCD up to 1j, LO QCD up to 3j
QCD Z/γ^*	SHERPA 2.2.1 (MEPS@NLO)	NNPDF3.0NNLO	SHERPA 2.2.1	NLO QCD up to 2j, LO QCD up to 4j, NNLO QCD norm.
EW Z/γ^*	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	LO QCD up to 4j

7.3 Physics Objects & Observables Definitions

The signal signature in the detector includes two electrically charged leptons, their corresponding neutrinos and at least two jets. The reconstruction techniques used by ATLAS are discussed in Section 3.1.4. The physics objects are further selected and calibrated according to the needs of each ATLAS search programme. A brief description of the selections applied to this analysis is given in Sections 7.3.1-7.3.3. From the physics object definition several variables can be derived. A description of the observables employed in this analysis is presented in Section 7.3.4.

7.3.1 Leptons

Leptons are required to originate from the primary vertex that has no less than two associated tracks, each with transverse momentum $p_T > 500$ MeV. Electrons are required to be within $|\eta| < 2.47$, excluding the transition region $1.37 < |\eta| < 1.52$ between the barrel and the end-caps in the LAr calorimeter while muons are required to be within $|\eta| < 2.5$. According to their transverse momenta, different identification Working Points (WP) are applied. Electrons with p_T in the range of 15-25 GeV are required to satisfy the *Tight* WP which has an efficiency of approximately 70% in this energy range and the *Medium* WP is chosen for those with $p_T > 25$ GeV (for electrons with $p_T \sim 40$ GeV the efficiency is around 85%). All muons are required to have $p_T > 15$ GeV and follow the *Tight* WP which results to an efficiency of approximately 93%. The impact parameter requirements are $|z_0 \sin \theta| < 0.5$ mm and $|d_0|/\sigma_{d_0} < 5$ (3) for electrons (muons). Leptons are also required to be

isolated using information from the inner detector tracks and energy clusters in the calorimeters in a cone around the lepton. Finally, at least one of the offline reconstructed leptons must be associated to an online lepton candidate that triggered the recording of the event. In the case where the dilepton trigger is solely responsible for the recording of the event, each lepton must correspond to one of the trigger objects. This trigger matching scheme also requires the p_T of the offline lepton to be at least 1 GeV above the trigger-level threshold.

7.3.2 Jets & Missing Transverse Energy

Jets are required to have a transverse momentum of $p_T > 20$ GeV and fall in the pseudorapidity range up to $|\eta| < 4.5$. The anti- k_t algorithm is used with a radius parameter of $R = 0.4$. The jet-vertex-tagger (JVT) multivariate discriminant selection [118] ($JVT > 0.5$) is used to separate the hard-scatter jets from pileup jets within the acceptance of the inner detector of $|\eta| < 2.5$ for jets with $20 < p_T < 60$ GeV by using the calorimeter and tracking information. Jets containing b-hadrons (referred to as b -jets) are identified using a deep-learning neural network. The chosen operating point has an efficiency of 85% for selecting jets containing b -hadrons, as determined from a sample of simulated $t\bar{t}$ events.

The missing transverse energy is employed in the analysis using the definition discussed in Section 3.1.4.

7.3.3 Overlap Removal

In order to ensure that jets, electrons and muons are not counted twice an overlap removal is incorporated. The following strategy is followed. If two electrons share calorimetric energy clusters or a track, the lower- p_T electron is removed. If a muon shares an ID track with an electron, the electron is removed. For electrons and jets, the jet is removed if $\Delta R(\text{jet}, e) < 0.2$ while for any of the surviving jets the electron is removed if $\Delta R(\text{jet}, e) < \min(0.4, 0.04 + 10 \text{ GeV}/p_T^e)$ is satisfied. For muons and jets, if $\Delta R(\text{jet}, \mu) < 0.2$ the jet is removed if it has less than three associated tracks with $p_T > 500$ MeV or both of the following conditions are met: the p_T ratio of the muon and the jet is larger than 0.5 and the ratio of the muon p_T to the sum of the p_T of the tracks with $p_T > 500$ MeV associated to the jet is larger than 0.7. For any of the surviving jets, if $\Delta R(\text{jet}, \mu) < \min(0.4, 0.04 + 10 \text{ GeV}/p_T^\mu)$ the muon is removed. Finally, the b -tagged jets are always saved from overlap removal.

7.3.4 Observables

This analysis measures 13 observables that are sensitive to the Higgs boson production and decay, its properties (i.e. spin, charge and parity) and that can provide tests of perturbative and non-perturbative QCD calculations, higher-order EW corrections or even reveal beyond the SM physics. In addition, several variables are used to enhance the signal sensitivity, reduce the backgrounds and to discriminate among the processes. The two leptons and jets are generally ordered by their transverse momentum referred to as leading/subleading lepton or jet². A summary of all observables used in the

² The two leading jets are referred to as tagged jets.

analysis is shown in Table 7.3.

Table 7.3: List of the observables used in the analysis.

Observable	Short Description	Motivation
m_{jj}	invariant mass of the two leading jets	Higgs boson prod. & decay, QCD effects, beyond SM physics
$ \Delta y_{jj} $	rapidity difference between the two leading jets	Higgs boson prod. & decay, QCD effects, beyond SM physics
$\Delta\phi_{jj}$	azimuthal angle difference between the forward with higher & the central with lower rapidity jets	Higgs boson prod., decay & properties, QCD effects, beyond SM physics
$p_T^{j_1, j_2}$	leading (j_1) / subleading (j_2) jet transverse momentum	Higgs boson prod. & decay, QCD effects beyond SM physics
$m_{\ell\ell}$	invariant mass of the two charged leptons	Higgs boson prod., decay & properties, beyond SM physics
$ \Delta\phi_{\ell\ell} $	azimuthal angle difference between the two charged leptons	Higgs boson prod., decay & properties, higher-order EW corrections
$ \Delta y_{\ell\ell} $	rapidity difference between the two charged leptons	Higgs boson prod., decay & properties, higher-order EW corrections
$p_T^{\ell\ell}$	transverse momentum of the dilepton system	QCD calculations, Higgs boson interactions
θ_η^*	polar angle defined by the two back-to-back lepton directions relative to the beam	Higgs boson properties, higher-order EW corrections,
$p_T^{\ell_1, \ell_2}$	leading (ℓ_1) / subleading (ℓ_2) lepton transverse momentum	Higgs boson prod., decay & properties, beyond SM physics
p_T^H	Higgs boson transverse momentum	QCD calculations, Higgs boson interactions
$m_{\tau\tau}$	invariant mass of τ pair leptons	background suppression ($Z/\gamma^*, H \rightarrow \tau\tau$)
$n_{b\text{-jet}}$	number of b-jets	background suppression (top-quark induced)
m_T	transverse mass	process discrimination
p_T^{tot}	total transverse momenta of objects	process discrimination
$\sum_\ell C_\ell$	sum of the leptons η centrality	quantifies leptons η -positions w.r.t two jets
$\sum_{\ell, j} m_{\ell, j}$	sum of the invariant masses of lepton-jet pairs	enhance VBF signal

7.4 Event Selection

Several distinct regions were designed by applying appropriate selection requirements that can maximise the sensitivity to the VBF signal or a given background process. Finally, three regions were used for the measurements: the Signal Region (SR), the Drell-Yan Control Region ($Z/\gamma^* + \text{jets}$ CR) and the ggF Control Region (ggF CR), while several others (named as Validation Regions) were designed and served as a cross-check of the MC modelling.

7.4.1 Pre-selection

The SR and the two CRs prior to the final selection share a number of common kinematic cuts (pre-selection). Events are required to consist of exactly two different flavour and opposite sign charged

leptons (*Channel Selection, OS Leptons, Only two Leptons*) and pass the trigger requirements (*Trigger Selection/Matching*) discussed in Section 7.2.1. A cut which selects all jets that pass a loose identification selection (*Jet Cleaning*) is applied too. Another cut that discriminates between $V\gamma$ and $V + \text{jets}$ MC processes where $V = W$ or Z (*Overlap: Vgamma/Vjets*), is used to remove overlaps between MC samples. The leading (subleading) lepton transverse momentum is required to be above 22 (15) GeV ($p_T^{\text{lead}} > 22 \text{ GeV}$, $p_T^{\text{sublead}} > 15 \text{ GeV}$). Some MC events produced with Sherpa generator and some specific $Z + \text{jets}$ events are being removed from the selection as it was found to be highly weighted (*Remove High Eventweight Events, Remove High Eventweight Z+jets Samples*). The invariant mass of the lepton pair is required to be greater than 10 GeV ($M_{\ell\ell} > 10 \text{ GeV}$) to suppress the background contributions from the $Z/\gamma^* + \text{jets}$ and hadronic resonances. Finally, a set of cuts that account for corrections related to the mis-identification of leptons (Mis-Id) are incorporated (discussion in Chapter 8). Table 7.4 lists the requirements in the pre-selection region along with the signal, background and data yields. The resulting ratio of the VBF signal over the total background in the pre-selection region is 0.0004.

7.4.2 Signal Region

The selected events falling in the SR are required to have at least two jets with $p_T > 30 \text{ GeV}$ and $|\eta| < 4.5$. Any event containing b-jets is vetoed in order to suppress the contribution from top-quark production. Events with a third jet with $p_T > 20 \text{ GeV}$ that lies between the two tagged jets are also removed in order to select events with low hadronic activity between the two leading jets, characteristic of the VBF process. In the VBF process the Higgs products should be between the two tagged jets. Therefore, an additional veto (outside-lepton-veto (OLV)) on those leptons that fall outside this η -plane removes those events. The suppression of the Drell-Yan background in the SR is achieved by the requirement $m_{\tau\tau} < m_Z - 25 \text{ GeV}$. To further suppress the background contamination most notably from top-quark production, the invariant mass of the di-jet system should be greater than 450 GeV while their absolute difference in rapidity is required to be greater than 2.1. Finally, a cut on the absolute difference in the azimuthal angles between the two selected leptons must be less than 1.4 rad to reduce the diboson background. The resulting ratio of the VBF signal over the total background after all SR cuts is 0.13.

Figure 7.3 shows the kinematic distributions of several observables in SR for the final state physics objects (i.e. leptons, jets and neutrinos).

Table 7.4: Cutoff in the pre-selection region.

$\sqrt{s} = 13\text{TeV}, \mathcal{L} = 139\text{fb}^{-1}$ (Full Run 2)	H_{IDF}	H_{IDF}	H_{IDF}	Other VV	Top	Zjets	Mis-ID	Total Bkg	Data	Data/MC
Channel Selection	619.73 $\pm$ 0.76	5912.42 $\pm$ 8.09	1869.22 $\pm$ 2.69	132476.46 $\pm$ 121.36	1215040.34 $\pm$ 243.62	273581.31 $\pm$ 471.56	5112304.94 $\pm$ 4305.85	6763333.83 $\pm$ 4342.17	4374979	0.65 $\pm$ 0.00
Trigger Selection	619.73 $\pm$ 0.76	5912.42 $\pm$ 8.09	1869.22 $\pm$ 2.69	132442.59 $\pm$ 121.36	1215040.34 $\pm$ 243.62	273581.31 $\pm$ 471.56	5112304.94 $\pm$ 4305.85	6763299.96 $\pm$ 4342.17	4374979	0.65 $\pm$ 0.00
Trigger Matching	602.71 $\pm$ 0.74	5697.95 $\pm$ 7.82	1809.71 $\pm$ 2.62	130002.21 $\pm$ 119.34	1192099.51 $\pm$ 239.59	260696.26 $\pm$ 447.19	5303655.16 $\pm$ 4230.14	6915048.73 $\pm$ 4264.02	4352644	0.63 $\pm$ 0.00
Jet Cleaning	602.71 $\pm$ 0.74	5697.95 $\pm$ 7.82	1809.71 $\pm$ 2.62	130002.21 $\pm$ 119.34	1192099.51 $\pm$ 239.59	260696.26 $\pm$ 447.19	5303655.16 $\pm$ 4230.14	5530491.75 $\pm$ 3166.81	4352644	0.79 $\pm$ 0.00
Overlap: γ gamma/ γ jets	602.71 $\pm$ 0.74	5697.95 $\pm$ 7.82	1809.71 $\pm$ 2.62	130002.21 $\pm$ 119.34	1192099.51 $\pm$ 239.59	260696.26 $\pm$ 447.19	5303655.16 $\pm$ 4230.14	5530491.75 $\pm$ 3166.81	4352644	0.79 $\pm$ 0.00
Only two Leptons	600.90 $\pm$ 0.74	5693.00 $\pm$ 7.81	1792.12 $\pm$ 2.60	129781.23 $\pm$ 119.29	1177783.16 $\pm$ 238.25	260303.18 $\pm$ 444.93	3914948.92 $\pm$ 3100.14	5509809.07 $\pm$ 3145.74	4323749	0.78 $\pm$ 0.00
$p_{\text{t}}^{\text{lead}} > 22\text{ GeV}$	600.90 $\pm$ 0.74	5693.00 $\pm$ 7.81	1792.12 $\pm$ 2.60	129781.23 $\pm$ 119.29	1177783.16 $\pm$ 238.25	260303.18 $\pm$ 444.93	3914948.92 $\pm$ 3100.14	5509809.07 $\pm$ 3145.74	4323749	0.78 $\pm$ 0.00
$p_{\text{t}}^{\text{sublead}} > 15\text{ GeV}$	598.61 $\pm$ 0.74	5662.30 $\pm$ 7.79	1784.55 $\pm$ 2.60	129453.29 $\pm$ 119.20	1175875.71 $\pm$ 238.06	258912.26 $\pm$ 444.25	3913337.04 $\pm$ 3099.53	5504434.75 $\pm$ 3144.99	4322240	0.79 $\pm$ 0.00
Remove High Eventweight Events	598.61 $\pm$ 0.74	5662.30 $\pm$ 7.79	1784.55 $\pm$ 2.60	129400.80 $\pm$ 115.84	1175875.71 $\pm$ 238.06	258993.22 $\pm$ 431.59	3913285.88 $\pm$ 3095.03	5504424.60 $\pm$ 3138.41	4322240	0.79 $\pm$ 0.00
Remove High Eventweight Zjets Samples	598.61 $\pm$ 0.74	5662.30 $\pm$ 7.79	1784.55 $\pm$ 2.60	129400.80 $\pm$ 115.84	1175875.71 $\pm$ 238.06	253469.93 $\pm$ 312.18	3989048.25 $\pm$ 2888.74	5574663.69 $\pm$ 2920.01	4322240	0.78 $\pm$ 0.00
OS Leptons	598.60 $\pm$ 0.74	5662.30 $\pm$ 7.79	1784.55 $\pm$ 2.60	129371.64 $\pm$ 115.84	1175868.71 $\pm$ 238.06	253469.16 $\pm$ 312.18	3983509.56 $\pm$ 2887.46	5569085.82 $\pm$ 2918.74	4319096	0.78 $\pm$ 0.00
$M_{\ell\ell} > 10\text{ GeV}$	598.45 $\pm$ 0.74	5660.63 $\pm$ 7.79	1784.44 $\pm$ 2.60	129359.63 $\pm$ 115.84	1175831.89 $\pm$ 238.06	253459.69 $\pm$ 312.16	3983236.06 $\pm$ 2887.40	5568746.77 $\pm$ 2918.68	4318965	0.78 $\pm$ 0.00
Leptons ID, singleFakes 1 anti-ID, 1 ID, doubleFakes 2 $\times$ anti-ID	591.57 $\pm$ 0.73	5593.39 $\pm$ 7.74	1763.44 $\pm$ 2.58	127414.86 $\pm$ 115.14	1162127.44 $\pm$ 236.67	250269.90 $\pm$ 310.22	1163533.77 $\pm$ 1482.59	2729885.98 $\pm$ 1541.87	1585575	0.58 $\pm$ 0.00
Apply QCD FF weight	591.57 $\pm$ 0.73	5593.39 $\pm$ 7.74	1763.44 $\pm$ 2.58	127414.86 $\pm$ 115.14	1162127.44 $\pm$ 236.67	250269.90 $\pm$ 310.22	519203.80 $\pm$ 1201.95	2085556.01 $\pm$ 1274.35	1585575	0.76 $\pm$ 0.00
Apply fake factor	591.57 $\pm$ 0.73	5593.39 $\pm$ 7.74	1763.44 $\pm$ 2.58	127414.86 $\pm$ 115.14	1162127.44 $\pm$ 236.67	250269.90 $\pm$ 310.22	35395.54 $\pm$ 222.65	1601747.75 $\pm$ 478.38	1585575	0.99 $\pm$ 0.00

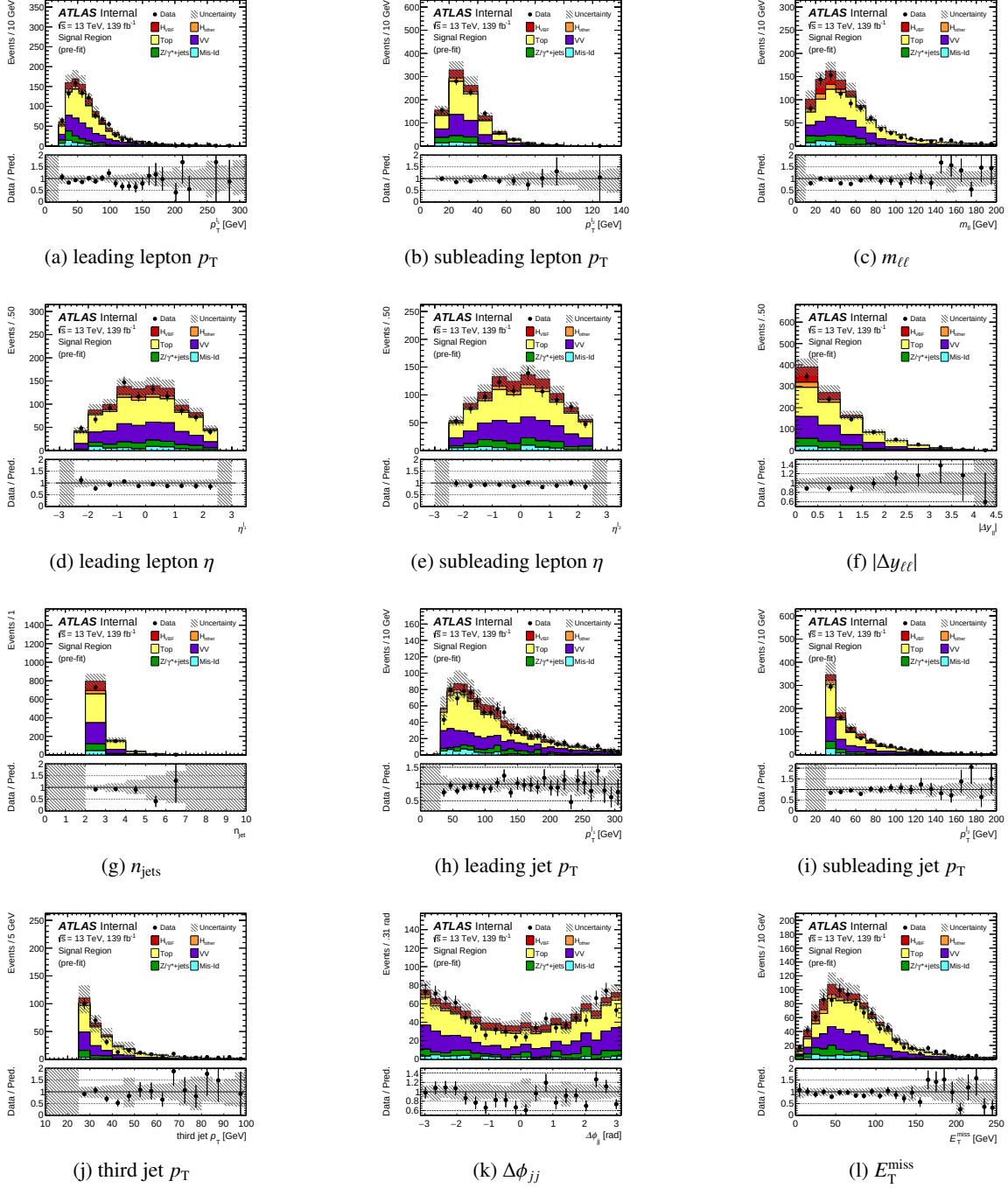


Figure 7.3: Kinematic distributions of (a) leading lepton p_T , (b) subleading lepton p_T , (c) $m_{\ell\ell}$, (d) leading lepton η , (e) subleading lepton η , (f) $|\Delta y_{\ell\ell}|$, (g) n_{jets} , (h) leading jet p_T , (i) subleading jet p_T , (j) third jet p_T , (k) $\Delta\phi_{jj}$ and (l) E_T^{miss} in the Signal Region. The error bars on data indicate the statistical uncertainties and the hatched band includes MC statistical, experimental and theory uncertainties (see Section 7.6).

7.4.3 $Z/\gamma^* + \text{jets CR}$

The Drell-Yan process consists of events in which two incoming partons produce two jets in the final state and a Z boson which decays to two leptons whereas is dominated by $Z \rightarrow \tau\tau$ processes. Contrary to the SR, instead of removing events near the Z-mass window, they are selected with the requirement the invariant mass of the two τ -leptons to be within a 25 GeV window about the Z mass peak. Moreover, the invariant mass of the dilepton system should be less than 80 GeV since the leptons from the Z boson decay tend to have low energy due to the extra neutrinos. In order to minimise the extrapolation of the Drell-Yan background in SR the OLV, CJV and the invariant mass of the dijet system cuts are applied similarly. The cuts on $|\Delta y_{jj}| > 2.1$ and $|\Delta\phi_{\ell\ell}| < 1.4$ rad are not applied to achieve high statistics in the region.

Figure 7.4 shows the distributions for $m_{\tau\tau}$ and the transverse mass m_T in the $Z/\gamma^* + \text{jets CR}$.

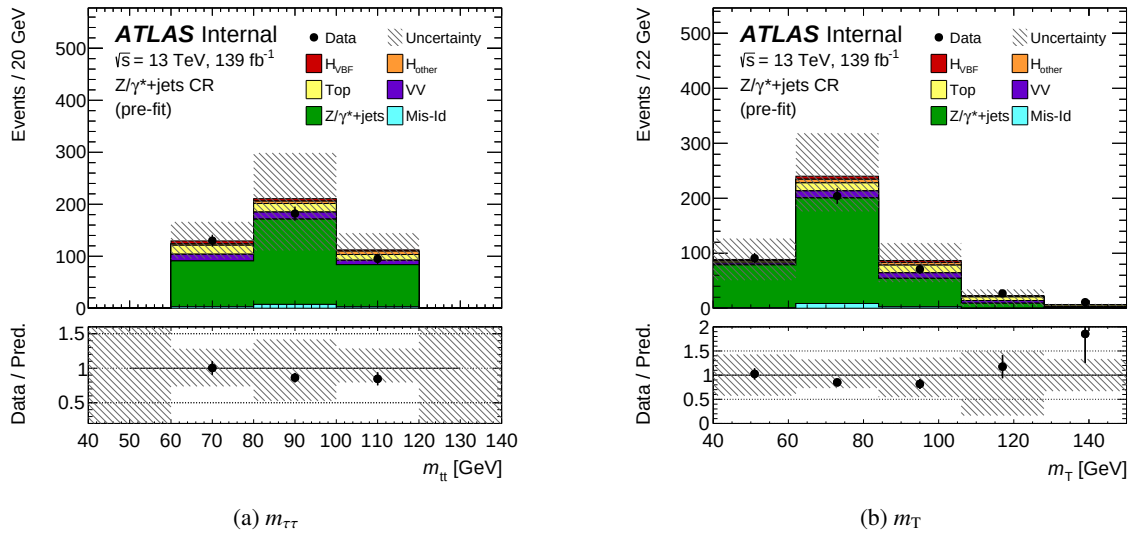


Figure 7.4: The observed and expected (pre-fit) distributions of (a) $m_{\tau\tau}$ and (b) m_T in the $Z/\gamma^* + \text{jets CR}$. The uncertainty bars on the data points indicate the statistical uncertainties, while the uncertainties in the prediction are shown by the hatched band, which includes experimental and theoretical uncertainties of the signal and the backgrounds (see Section 7.6). The H_{other} contribution is dominated by the ggF production. The bottom panel shows the ratio of the data to the expected distributions.

7.4.4 ggF CR

The ggF CR was constructed by inverting the SR selection cuts with the aim to minimise the statistical and modelling uncertainties originating from the modelling of higher order QCD corrections. The selection criteria which define the ggF CR are: at least two jets, b-jets and $Z \rightarrow \tau\tau$ events are vetoed, one of the CJV and OLV requirements should be satisfied and the absolute angular difference of the dilepton system should be less than 1.4 rad.

Figure 7.5 shows the distributions for $|\Delta\phi_{\ell\ell}|$ and m_{jj} in the ggF CR.

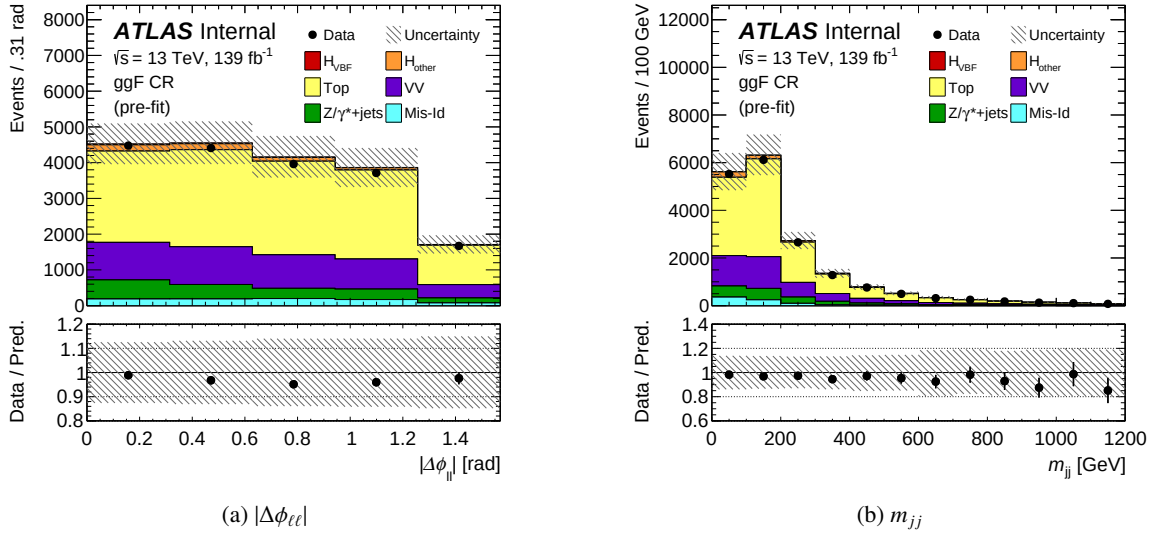


Figure 7.5: The observed and expected (pre-fit) distributions of (a) $|\Delta\phi_{\ell\ell}|$ and (b) m_{jj} in the ggF CR. The uncertainty bars on the data points indicate the statistical uncertainties, while the uncertainties in the prediction are shown by the hatched band, which includes experimental and theoretical uncertainties of the signal and the backgrounds (see Section 7.6). The H_{other} contribution is dominated by the ggF production. The bottom panel shows the ratio of the data to the expected distributions.

7.5 Background Estimation

Backgrounds, such as Drell-Yan and ggF production, are estimated from fit to data in the dedicated CRs, as discussed in Section 7.4. Top-quark production and non-resonant VV processes have very similar properties and final states and their discrimination is very difficult. Thus, their combined contribution is determined from fit to data in a background enriched phase space of the SR, discussed in the following.

The W +jets events constitute the background when a jet is misidentified as a lepton. For this background a purely data-driven technique is used and is described in detail in Chapter 8.

The remaining background processes, considered as minor, are estimated using solely MC modeling.

Table 7.5 gives a summary of the methods used to estimate the background processes along with their relative contributions in the pre-selection and SR. The event yields in the SR and the two CRs are shown in Table 7.6.

7.5.1 Multivariate Discriminants

For a better discrimination between one process type against others, a multivariate machine learning technique using the boosted decision tree (BDT) algorithm of the ROOT TMVA library is implemented in the analysis.

Table 7.5: Background processes, their relative contributions in the pre-selection region and in the SR and the estimation methods.

Background	Relative size Pre-selection	Relative size Signal Region	Estimation
QCD WW	$\sim 8\%$	$\sim 20\%$	MC + fit to data
EW WW	$< 1\%$	$\sim 7\%$	MC + fit to data
Top	$\sim 73\%$	$\sim 48\%$	MC + fit to data
ggF Higgs	$< 1\%$	$\sim 4\%$	MC + fit to data
W +jets	$\sim 2\%$	$\sim 5\%$	Data-driven
$Z \rightarrow \tau\tau$	$\sim 16\%$	$\sim 9\%$	MC + fit to data
$V\gamma, V\gamma^*, ZZ, WZ$	$\sim 1\%$	$\sim 5\%$	MC only
$H \rightarrow \tau\tau, VH$	$< 1\%$	$< 1\%$	MC only

Table 7.6: Expected and observed (pre-fit) event yields in the SR as well as in the Z/γ^* +jets and ggF CRs. The quoted uncertainties correspond to the statistical uncertainty, together with the experimental and theory modeling systematic uncertainties (see Section 7.6). The sum of all the contributions may differ from the total value due to rounding.

Sample	SR	Z/γ^* +jets CR	ggF CR
Signal (PowHEG +PYTHIA 8)	110	13	86
ggF Higgs	39	4	450
Other Higgs	3	10	78
Top	420	41	11 000
Z/γ^* +jets	79	320	1 400
VV	280	32	4 300
$V\gamma$	13	14	210
Mis-Id	47	12	810
Total Signal+Background	$1\,000 \pm 120$	450 ± 160	$18\,800 \pm 2\,600$
Data	916	406	18 228

A decision tree is a collection of criteria (cuts) designed to classify events as signal-like or background-like. A given signal event is correctly identified if it is placed in a signal-dominated leaf and vice-versa for background events. After the initial tree is built another classifier is grown to better separate the signal and background events misidentified by the first tree. This proceeds iteratively until there is a collection of a specified number of trees, in a process known as boosting. A weighted average is taken from all these trees to form a BDT output discriminant with values ranging in $[-1,1]$.

A bi-dimensional discriminant is formed in the SR by utilising two distinct BDTs, i.e. D_{VBF} and $D_{\text{top+VV}}$, both trained in a slightly larger phase space than the SR³. The former was trained to discriminate the VBF signal events against the backgrounds from diboson and top processes together, while the latter was trained to discriminate the sum of top-quark and VV processes against VBF, ggF, Z +jets and $V\gamma$ events. A bi-dimensional plane is defined with the D_{VBF} score on the one axis

³ The m_{jj} cut is relaxed to 200 GeV and the $|\Delta\phi_{\ell\ell}| < 1.4$ rad cut is removed. This selection was made with the aim to increase the sample statistics.

and the $D_{\text{top}+\text{VV}}$ on the other axis.

The data that are contained in the $[+0.5, +1.0]$ range of D_{VBF} define a subset of the SR that is denoted as SR1. Similarly, those that fall into $[-1.0, +0.5)$ define the SR2. The boundaries were defined such as to maximise the statistical sensitivity on both the signal and backgrounds. For events in the SR1 the D_{VBF} score is used as a discriminant and along this axis 4 bins of variable size are defined in the range $[+0.5, +1.0]$. For events in the SR2 the $D_{\text{top}+\text{VV}}$ score is used as a discriminant and 4 equal bins are defined in the range $[-1.0, +1.0]$.

Another BDT was trained in a phase space slightly larger than the ggF CR⁴, named $D_{\text{ggF-CR}}$, with the aim to discriminate the ggF process against the VBF signal and all other background processes. The score of this BDT is split into 4 equal bins in the range $[-1.0, +1.0]$.

Various observables were tested as inputs to the BDTs and only those that demonstrated the highest discrimination were considered. At the same time, it was ensured that none of those dominated the discrimination, thus any bias is being minimised.

Figure 7.6 shows the comparisons between the test and training samples of the three BDTs used in the analysis. There are not big differences observed between the training and test distributions which indicates that any model over-training is well controlled.

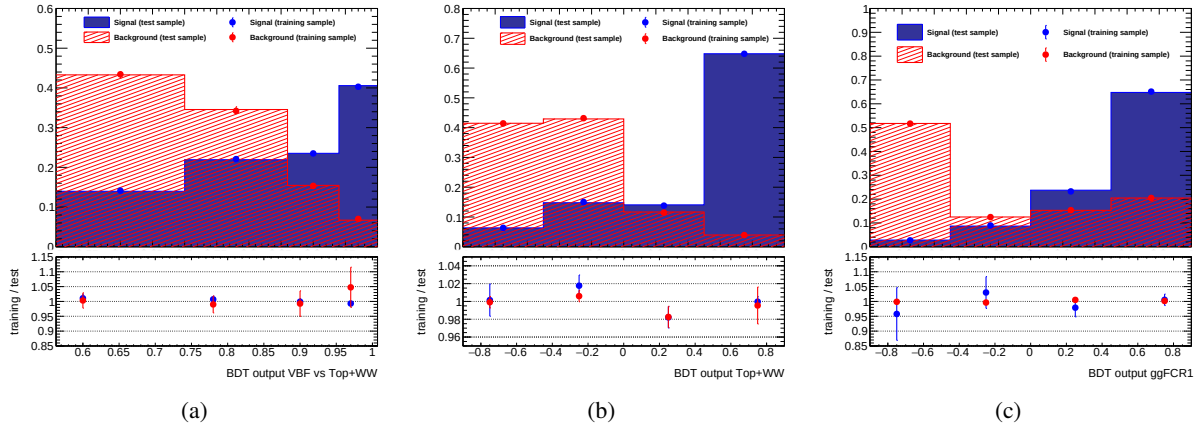


Figure 7.6: The BDT scores of unweighted, normalised processes for test and training samples for (a) D_{VBF} , (b) $D_{\text{top}+\text{VV}}$ and (c) $D_{\text{ggF-CR}}$.

The weighted distributions of the three BDTs in the corresponding designed regions are presented in Figure 7.7.

The same definitions and training of the $D_{\text{top}+\text{VV}}$ and $D_{\text{ggF-CR}}$ are used for the differential cross section measurements. The D_{VBF} was re-trained in the SR for each of the differential cross section measurements with a reduced set of input variables. To be more precise, the highly correlated variables of the measured distributions as well as the measured variable were excluded from the input set to avoid biasing the result towards the SM prediction used for the training. In each bin of the

⁴ With the $|\Delta\phi_{\ell\ell}| < 1.4$ rad cut removed.

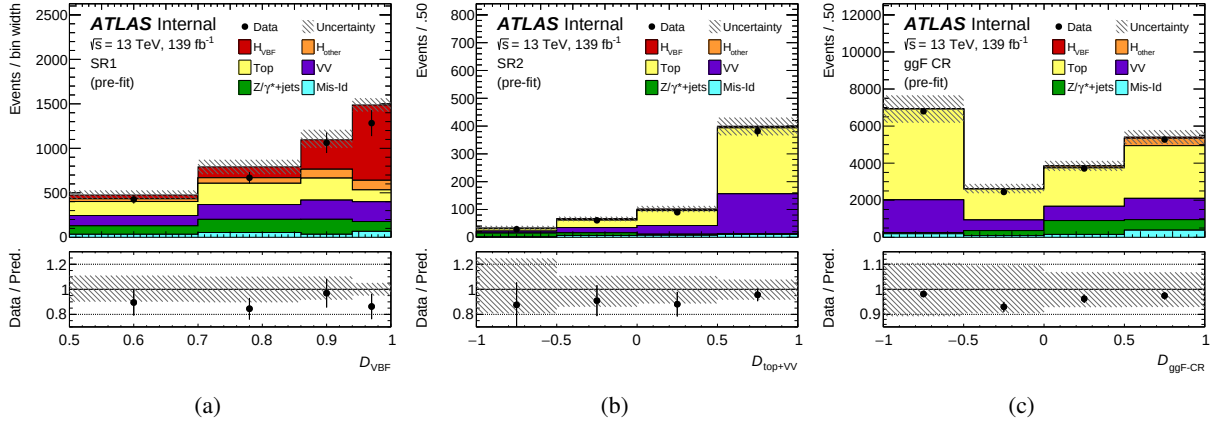


Figure 7.7: The weighted distributions of (a) D_{VBF} in SR1, (b) D_{top+VV} in SR2, and (c) D_{ggF-CR} in ggF CR. The uncertainty bars on the data points indicate the statistical uncertainties, while the uncertainties in the prediction are shown by the hatched band, which includes experimental and theoretical uncertainties of the signal and the backgrounds (see Section 7.6). The H_{other} contribution is dominated by the ggF production. The bottom panel shows the ratio of the data to the expected distributions.

kinematic distribution that is measured, 4 bins of variable size were chosen for the D_{VBF} in the range $[+0.5, +1.0]$ and 2 (4) equal bins for the D_{top+VV} (D_{ggF-CR}) in the range $[-1.0, +1.0]$.

7.6 Cross Section Measurements

A fiducial phase space (using objects at truth level) which closely follows the kinematic criteria applied in the SR event selection (using objects at reconstruction level) is used to perform the cross section measurements. Therefore, the results are corrected for detector inefficiency and resolution effects. This method allows the minimisation of the model dependence in the extrapolation from one phase space to the other and is known as unfolding.

The results are derived by minimising the negative logarithm of a binned profile-likelihood L which consists of a product of likelihood functions ($\mathcal{P}$ s) of the SR yield and those of the two CRs, and is defined as:

$$L = \mathcal{P}(N_{data}^{SR} | N_{signal}^{SR} + \sum_{k=1}^{n_{bkg}} \mu_{bkg-k} \cdot N_{bkg-k}^{SR} + \sum_{j=1}^{m_{bkg}} N_{bkg-j}^{SR}) \cdot \prod_{n=1}^2 \mathcal{P}(N_{data}^{CR-n} | N_{signal}^{CR-n} + \sum_{k=1}^{n_{bkg}} \mu_{bkg-k} \cdot N_{bkg-k}^{CR-n} + \sum_{j=1}^{m_{bkg}} N_{bkg-j}^{CR-n}) \cdot \prod_{i=1}^{n_{\theta_i}} \mathcal{N}(\tilde{\theta}_i | \theta_i) \quad (7.1)$$

where N_{data}^{SR} (N_{signal}^{SR}) and N_{data}^{CR-n} (N_{signal}^{CR-n}) are the numbers of events observed (expected) in the SR and CR- n (ggF CR or Z/γ^*+jets CR), respectively. The parameter μ_{bkg-k} is the normalization of back-

ground process k , and $N_{\text{bkg}-k}^{\text{SR}}$ ($N_{\text{bkg}-j}^{\text{SR}}$) and $N_{\text{bkg}-k}^{\text{CR}-n}$ ($N_{\text{bkg}-j}^{\text{CR}-n}$) are the expected yields of the background contribution k (j) in the SR and CR- n , respectively. The parameter n_{bkg} is the number of background processes whose normalizations are left floating in the likelihood functions and are determined from the fit to data, while m_{bkg} is the number of background processes whose yields are obtained from MC simulation or from data-driven techniques that are not included in the simultaneous fit. The $\mathcal{N}$ term is a normal function that parameterizes the systematic effect of type i as a function of a constrained nuisance parameter θ_i and the associated estimate of the corresponding effect $\tilde{\theta}_i$. The parameter n_{θ_i} represents the number of parameters modelling systematic uncertainties considered in the analysis.

The systematic uncertainties are estimated from experimental and theoretical sources. The former are relevant to the reconstructed leptons, their energy (for electrons) and momentum (for muons) scale as well as their identification, isolation and trigger efficiency. Furthermore, uncertainties coming from the jets energy scale and resolution and others relevant to the suppression of jets originating from pile-up interactions, the jet-vertex association and the flavour tagging efficiency are considered too. A variation in the pile-up modelling is included to account for the uncertainty in the ratio of the predicted and measured inelastic cross-sections. The uncertainty in the $E_{\text{T}}^{\text{miss}}$ measurement is estimated by propagating the uncertainties in the transverse momenta of reconstructed objects and applying the momentum scale and resolution uncertainties to the track-based soft term. Finally, the uncertainty in the integrated luminosity is obtained using the LUCID-2 detector and applied to the background processes that are normalised to SM theoretical predictions and to the signal cross section parameters in the simultaneous fit. This set of experimental systematics uses 102 nuisance parameters in the analysis. The modelling uncertainties are calculated per-sample for the VBF signal and the major backgrounds, i.e. ggF, top, diboson and $Z \rightarrow \tau\tau$, and include those originating from renormalisation and factorisation scale choices, PDF, α_s , those associated with UE, PS, hadronisation modelling and differences in the matrix element calculations and PS matching schemes are also considered. For the minor backgrounds no modelling uncertainties are assigned as their contribution is negligible on the final estimate.

The likelihood functions in the SR and CRs are defined as Poisson probability density functions built from binned histograms of discriminant distributions (templates) using MC events for signal and backgrounds. The signal and background templates are also functions of the nuisance parameters such that systematic uncertainties can affect the discriminator distribution shapes for the signal process and irreducible backgrounds whose yields are extracted from the fit, and the normalization for the backgrounds whose yields are fixed to SM predictions. This methodology accounts for correlations of systematic uncertainties between signal and background estimates and between bins of the measured observables.

The fit is performed simultaneously in the SR and the two CRs. Each of the regions included in the fit uses a different discriminant. For the estimation of $Z/\gamma^* + \text{jets}$ background the transverse mass distribution is used in the $Z/\gamma^* + \text{jets}$ CR as the discriminant template. For the ggF contribution the $D_{\text{ggF-CR}}$ is used in the ggF CR while the bi-dimensional BDT is used in SR to extract the VBF signal as well as the contribution from top and diboson processes, as described in Section 7.5.1. A diagram that describes the simultaneous fitting scheme is illustrated in Figure 7.8.

The measured cross section for the VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ production in the fiducial phase space is: $\sigma^{\text{fid}} = 1.68 \pm 0.40 \text{ fb} = 1.68 \pm 0.33 \text{ (stat)} \pm 0.23 \text{ (syst)} \text{ fb}$. The overall relative precision is about 23%, dominated by the statistical uncertainty in data. The systematic uncertainty is dominated by

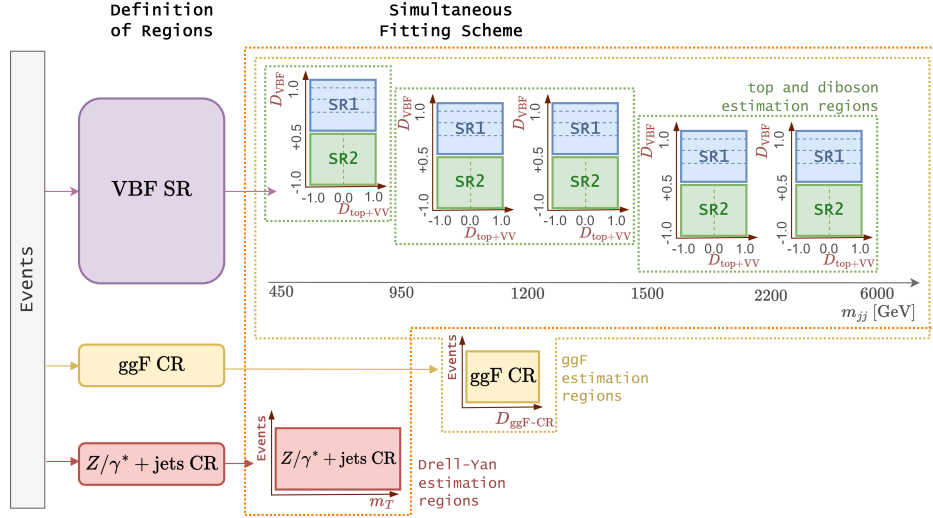


Figure 7.8: A diagrammatic illustration of the procedure used in the simultaneous fit to the data in the SR and in two CRs to measure the differential cross section as a function of m_{jj} . The dotted frames aim to describe the background normalisation factors used in each region and bin of the differential measurement.

the theory uncertainties, most notably due to shape differences that cannot be absorbed by the background normalisation uncertainties. The background normalisation parameters constrained by data in the designed regions along with the correlations between them and the fiducial cross section are shown in Figure 7.9. The comparison between the measurement and the SM theoretical predictions obtained at different orders in QCD and different matrix element and PS calculations⁵ is shown in Figure 7.10. The measured cross section is found to be consistent (at the level of approximately one standard deviation) with the SM predictions that implement parton shower and the SM prediction calculated at parton level and at NLO accuracy in the strong and electroweak couplings. Particularly, the prediction at LO order QCD calculation with the parton shower calculated at particle level, despite the LO approximation shows the importance of parton shower for a good description. Finally, the fixed order LO calculation at parton level without the parton shower modeling overestimates all other predictions by approximately 24%.

The measured differential fiducial cross sections for a representative subset of the 13 observables that were unfolded to particle-level are presented in Figure 7.11. Overall the compatibility with the SM predictions is good with the data statistical uncertainty dominating the systematic uncertainties for all the measured observable bins. The predictions at LO and NLO QCD interfaced to parton shower provide good description of the data in most regions of phase space showing a small impact of the parton shower model while the fixed order NLO calculation overestimates the measured cross sections beyond the experimental uncertainties with discrepancies that range between one and two standard deviations.

⁵ The predictions are obtained from the parton shower generators POWHEG + PYTHIA8, POWHEG + HERWIG7, MG5 + HERWIG7 and VBFNLO@LO + PYTHIA8 at particle level. The predictions obtained at parton-level calculations refer to VBFNLO@LO and VBFNLO@NLO.

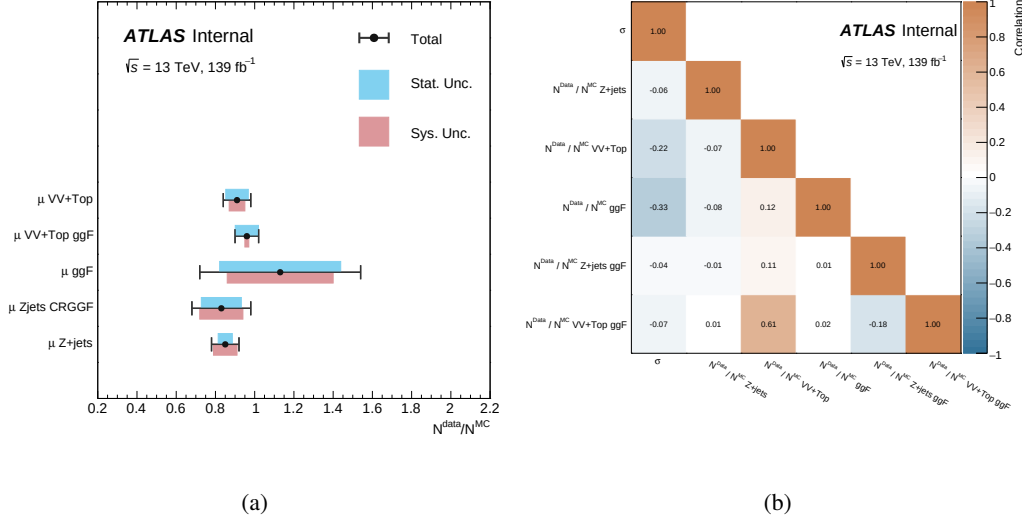


Figure 7.9: (a) The measured background normalisation factors and the (b) correlations among them and the fiducial cross section measurement. The parameter μ Z+jets is the normalisation factor of the Z+jets background in SR1, SR2 and $Z/\gamma^* + \text{jets}$ CR, while the μ Z+jets CRGGF refers to the normalisation of the same background process in the ggF CR. μ ggF is the normalisation of the ggF process in ggF CR, SR1 and SR2. The parameter μ VV+Top ggF refers to the normalisation of the combined contribution from top and diboson processes in the ggF CR, whereas μ VV+Top corresponds to the normalisation of the same backgrounds in SR1 and SR2.

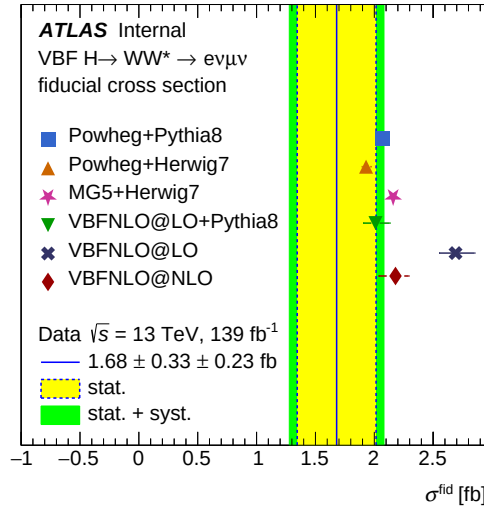


Figure 7.10: The measured fiducial cross-section in comparison with the SM theoretical predictions in the fiducial phase space. The vertical bands around the measurement indicate the statistical uncertainty (inner band) and the sum in quadrature of statistical, systematic and luminosity uncertainties (outer band).

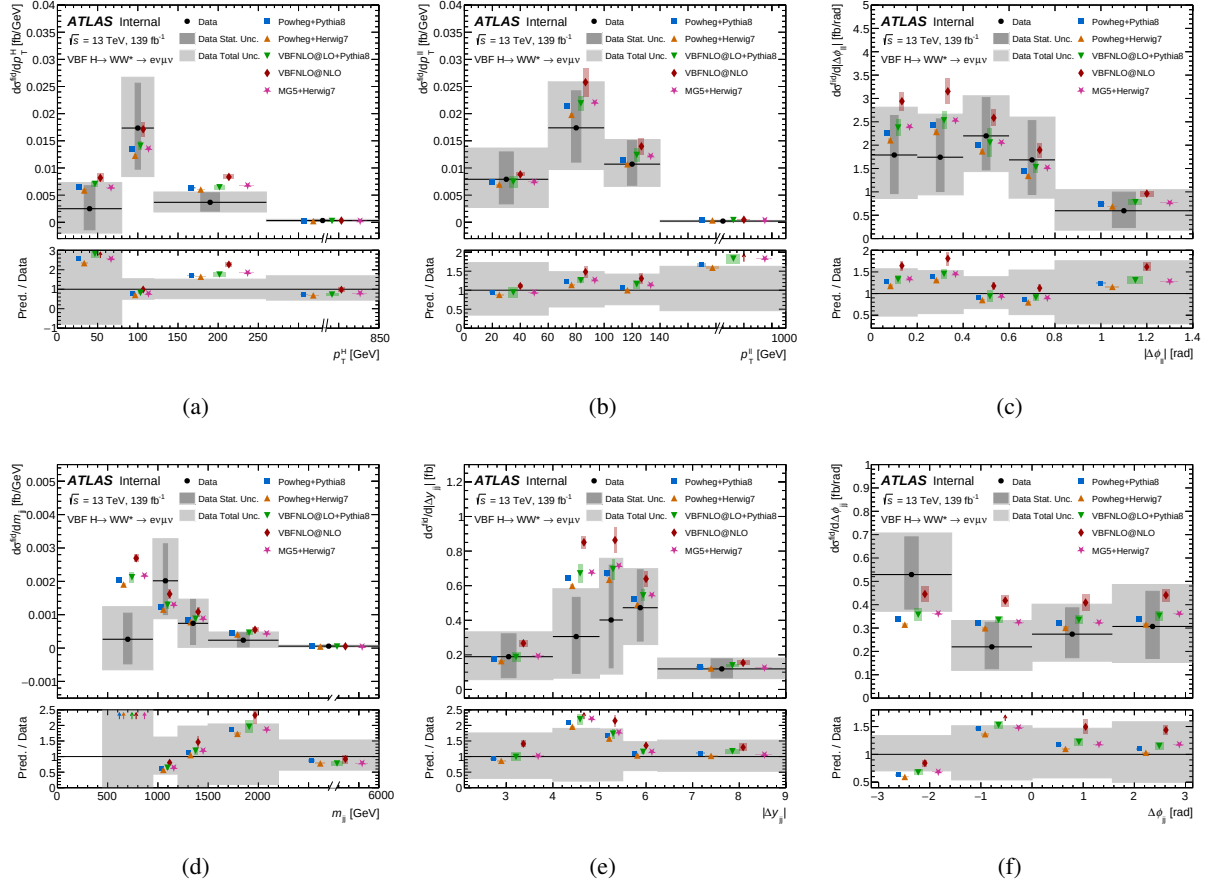


Figure 7.11: The measured differential fiducial cross sections for (a) p_T^H , (b) p_T^ℓ , (c) $|\Delta\phi_{\ell\ell}|$, (d) m_{jj} , (e) $|\Delta y_{jj}|$, and (f) $\Delta\phi_{jj}$ compared with the SM theoretical predictions. The inner boxes on the data points show the statistical uncertainties, while the total uncertainties are indicated by the outer boxes. The uncertainties on the expected cross-sections indicate the PDF and scale systematic uncertainties. The bottom panel shows the ratio of different predictions to the data, and the band represents the total uncertainty of the measurement.

8 Contribution from Mis-identified Leptons

This chapter is dedicated to the estimation of the background originating from jets that are misidentified as prompt leptons and which enter in the analysis. Section 8.1 discusses the data-driven technique used to estimate this background. The W +jets Control Region which is designed to provide the W +jets contribution in the Signal Region is defined in Section 8.2. Section 8.3 presents some studies on the fake factors aiming to assess if there are other sources of uncertainties that affect the overall uncertainty. Finally, a closure test based solely on Monte Carlo simulation is presented in Section 8.4 to assess any potential bias in the fake estimation method.

8.1 The Fake Factor Method

The fake lepton background (else fakes or Mis-Id) arises from non-prompt leptons produced either by the decay of hadrons containing a heavy flavor quark or by the fragmentation of a quark or gluon. The dominant processes, relevant to this analysis, which contain fake leptons appear from W +jets events in which one prompt lepton originates from the W boson which decays leptonically in association with one or more jets, when one of them is misidentified as a second prompt lepton. These events are classified as single-fakes. A contribution from QCD multi-jet processes in which two jets are simultaneously misidentified as prompt leptons can also be present. These events are classified as double-fakes. However, V +jets and multi-jet processes are hard to be modelled with high perturbative accuracy and sufficient statistical precision [119], thus this background is treated by a data-driven approach.

The leptons falling in the SR pass from stringent lepton identification selections (as discussed in 7.3) and are referred to as *identified* (or just *id*) leptons in the following. The events in the SR can be expressed as

$$N_{id+id} = N_{id+id}^{EW} + N_{id+id}^{W+jets} + N_{id+id}^{QCD} \quad (8.1)$$

where the N_{id+id}^{EW} term denotes all processes with two real leptons (including the VBF signal) and the last two terms denote the single and double fake backgrounds respectively.

In order to handle the fakes, MC V +jets control samples are generated with *id* leptons as well as with leptons that pass looser identification and isolation requirements which are referred to as *anti-identified* (or just *anti-id*) leptons in the following. A summary of the selection criteria for both electrons and muons is given in Table 8.1.

The fakes are estimated in the enhanced with fake leptons W +jets CR (described in Section 8.2), which constitutes of events that can be expressed as

$$N_{id+anti-id} = N_{id+anti-id}^{W+jets} + N_{id+anti-id}^{EWMC} + N_{id+anti-id}^{QCD} \quad (8.2)$$

8 Contribution from Mis-identified Leptons

Table 8.1: Requirements for fully identified and anti-identified leptons. Note: The FF were computed using a slight different isolation and quality working points for the *id* leptons compared to those shown here. The fake factor studies (Section 8.3) and the closure test (Section 8.4) were performed using the same requirements as presented in Section 7.3.1.

Electron		Muon	
identified	anti-identified	identified	anti-identified
$p_T > 15 \text{ GeV}$ $ \eta < 2.47, \text{excluding } 1.37 < \eta < 1.52$ $ z_0 \sin \theta < 0.5 \text{ mm}$ $ d_0 /\sigma(d_0) < 5$		$p_T > 15 \text{ GeV}$ $ \eta < 2.45$ $ z_0 \sin \theta < 0.5 \text{ mm}$ $ d_0 /\sigma(d_0) < 3$	
Pass	Pass LHLoose	Pass Quality Medium	Pass Quality Medium
LooseAndBLayerLH if			
$p_T < 25 \text{ GeV}$		Pass FCLoose isolation	Veto against identified muon
Pass			
LooseAndBLayerLH if			
$p_T > 25 \text{ GeV}$			
Pass FCLoose isolation			
AUTHOR = 1			
	Veto against identified electron		

where $N_{id+anti-id}^{EWMC}$ term denotes processes with two real leptons which contaminate the W +jets CR. The subtraction of the EW processes using MC from data will result to the fake background estimate. Thereafter, the contribution in the SR is estimated by scaling the fake yields by the fake factor which is defined as the ratio of *id* and *anti-id* leptons.

The fake factors (FF) are derived separately for electrons and muons by using a jet enriched sample (other than W +jets) in a dedicated fake factor Control Region (see Section 8.1.1). They are then corrected based on predictions from MC to assess any difference between the samples composition (see Section 8.1.2) and finally they are applied to the fake estimate in all designed regions.

8.1.1 Fake Factor Definition

The analysis for the FF measurement is performed by using a sample of Z +jets¹ events and a dedicated Z +jets CR is defined. The CR is designed by selecting events with final states of three loosely identified reconstructed leptons (electrons or muons), each with $p_T > 15 \text{ GeV}$ (*Channel Selection, lll final state, All lep $p_T > 15 \text{ GeV}$*). Two of the leptons are required to be tagged as Z boson candidates, i.e. need to be of the same flavour and opposite charge, while the invariant mass of the dilepton system should be in the range of $[80 (70), 110] \text{ GeV}$ for electrons (muons)² (*Z-tagging*). The two Z -tagged leptons should fulfill the *id* requirements as listed in Table 8.1 and at least one of them should be matched to one of the single lepton triggers presented in Table 7.1. If multiple lepton combinations satisfy this requirement, the pair with the invariant mass closest to the Z boson is chosen. The remaining third lepton is classified as the fake candidate.

¹ POWHEG generator is used for the simulation of the Z +jets process because it demonstrated the best statistical precision among others.

² The ranges were chosen such as reducing the $Z + \gamma$ background.

The set of backgrounds considered includes $V + \gamma$, diboson (WW , WZ , ZZ), top production and triboson processes. A cut for the discrimination of $V + \gamma$ and V +jets processes is used (*Overlap: $V_{\gamma}/V_{\text{jets}}$*). The major contribution comes from the WZ processes. Therefore, a cut on $m_T^W = \sqrt{2E_T^{\text{miss}} E_T^{\text{fake cand.}} (1 - \cos \phi)} < 50 \text{ GeV}$ is added to reject the events with leptonic WZ decays (*TransMassW*). Then two distinct regions are constructed depending on whether the fake lepton passes the *id* or *anti-id* cuts (see Table 8.1). These regions are split depending on the fake lepton type, i.e. electron or muon. The full cutflow is presented in Table 8.2.

In order to better handle the WZ prediction, a control region is created. This region is defined for all the fake candidates passing the *id* criteria and when the transverse mass is $m_T^W > 50 \text{ GeV}$. A normalisation factor of 0.99 ± 0.01 is computed and then applied to the WZ yields.

The fake factor is then measured for each fake lepton type as the ratio

$$FF = \frac{N_{\text{data}}^{i,i} - N_{\text{non-Z+jets}}^{i,i}}{N_{\text{data}}^{i,a} - N_{\text{non-Z+jets}}^{i,a}} \quad (8.3)$$

where subscripts i and a correspond to *id* and *anti-id* leptons respectively. The lepton properties that commonly affect the fake factor are the transverse momentum and pseudorapidity and are shown for both fake candidate types which pass the *id* and *anti-id* requirements in Figures 8.1- 8.2. The fake estimate for the high transverse momenta is small (close to zero). The fake factors are derived as a function of these two properties, binned such as to gain enough statistical precision. Particularly for the electron fake factors it was found to be the same across η , thus the estimation was performed integrating the whole η range for this lepton type. For muons the fake factors are calculated as a function of those falling in the central ($|\eta| < 1.05$) and forward ($1.05 < |\eta| < 2.50$) regions of the detector. Four p_T bins [15, 20, 25, 35, 10 000] GeV were chosen for electrons and muons. The fake factors are presented in Figure 8.3.

The uncertainties on the fake factors have contributions from systematic and statistical sources. The systematic uncertainty comes from the non-Z+jets MC processes, which are subtracted from the data yield. Theoretical uncertainties were computed for the major backgrounds, i.e. WZ , ZZ , $Z + \gamma$ by varying their normalisations in both *id* and *anti-id* regions. For the rest processes an uncertainty of 10% was assigned. The relative contribution of the uncertainties on the fake factors is shown in Figure 8.4.

Table 8.2: Cutflow of the Z+jets fake factor analysis.

$\sqrt{s} = 137 \text{ eV}, \mathcal{L} = 139 \text{ fb}^{-1}$ (Full Run 2)	Z+jets Powheg	V + γ	WW	WZ	ZZ	Top	VVV	Total Bkg	Data	fakes	ZFake purity(%)
Channel Selection	243999.56 $\pm$ 265.69	103576.26 $\pm$ 733.79	990.92 $\pm$ 8.35	48878.83 $\pm$ 1712.65	14773.62 $\pm$ 113.44	85411.82 $\pm$ 61.84	238.23 $\pm$ 0.93	253869.68 $\pm$ 1867.72	605458	351588.32 $\pm$ 2023.33	58.07 $\pm$ 0.34
Ill final state	243999.56 $\pm$ 265.69	103576.26 $\pm$ 733.79	990.92 $\pm$ 8.35	48878.83 $\pm$ 1712.65	14773.62 $\pm$ 113.44	85411.82 $\pm$ 61.84	238.23 $\pm$ 0.93	253869.68 $\pm$ 1867.72	605458	351588.32 $\pm$ 2023.33	58.07 $\pm$ 0.34
All lep $p_T > 15 \text{ GeV}$	243999.56 $\pm$ 265.69	103576.26 $\pm$ 733.79	990.92 $\pm$ 8.35	48878.83 $\pm$ 1712.65	14773.62 $\pm$ 113.44	85411.82 $\pm$ 61.84	238.23 $\pm$ 0.93	253869.68 $\pm$ 1867.72	605458	351588.32 $\pm$ 2023.33	58.07 $\pm$ 0.34
Overlap: $V_{\text{gamma}}/V_{\text{jets}}$	243999.56 $\pm$ 265.69	103576.26 $\pm$ 733.79	990.92 $\pm$ 8.35	48878.83 $\pm$ 1712.65	14773.62 $\pm$ 113.44	85411.82 $\pm$ 61.84	238.23 $\pm$ 0.93	253869.68 $\pm$ 1867.72	605458	351588.32 $\pm$ 2023.33	58.07 $\pm$ 0.34
Z-tagging	109854.17 $\pm$ 175.42	14440.44 $\pm$ 275.36	97.13 $\pm$ 2.55	26433.12 $\pm$ 38.89	4798.93 $\pm$ 23.79	7677.51 $\pm$ 17.49	71.41 $\pm$ 0.40	53518.54 $\pm$ 279.67	169539	116020.46 $\pm$ 497.75	68.43 $\pm$ 0.34
TransMassW	99115.01 $\pm$ 166.56	12335.41 $\pm$ 257.66	35.63 $\pm$ 1.65	8344.58 $\pm$ 20.89	3414.15 $\pm$ 19.70	3009.26 $\pm$ 11.05	18.38 $\pm$ 0.20	27157.42 $\pm$ 259.49	127820	100662.58 $\pm$ 441.77	78.75 $\pm$ 0.41
all three leptons ID or AntiID	49785.61 $\pm$ 120.79	3589.51 $\pm$ 144.71	15.63 $\pm$ 1.06	8020.26 $\pm$ 20.58	3231.23 $\pm$ 18.68	2595.07 $\pm$ 10.21	17.68 $\pm$ 0.19	17469.38 $\pm$ 147.71	68057	50587.62 $\pm$ 299.79	74.33 $\pm$ 0.52
fake type: electron	27114.88 $\pm$ 86.05	3032.25 $\pm$ 128.88	9.38 $\pm$ 0.86	3632.34 $\pm$ 14.64	1508.23 $\pm$ 10.24	570.31 $\pm$ 4.41	7.95 $\pm$ 0.13	8760.46 $\pm$ 130.19	32627	23866.54 $\pm$ 222.66	73.15 $\pm$ 0.79
fake el η cut	21365.18 $\pm$ 76.58	2703.91 $\pm$ 122.21	7.04 $\pm$ 0.82	3430.76 $\pm$ 14.36	1418.90 $\pm$ 9.36	526.99 $\pm$ 4.23	7.54 $\pm$ 0.12	8095.13 $\pm$ 123.48	26946	18850.87 $\pm$ 205.41	69.96 $\pm$ 0.87
Scale factors	1823.04 $\pm$ 22.64	619.48 $\pm$ 56.81	0.37 $\pm$ 0.19	2759.50 $\pm$ 12.98	1026.22 $\pm$ 6.11	167.46 $\pm$ 1.67	6.22 $\pm$ 0.11	4579.25 $\pm$ 58.61	6349	1769.75 $\pm$ 98.92	27.87 $\pm$ 1.60
ID cuts	19542.13 $\pm$ 73.15	2084.43 $\pm$ 108.21	6.67 $\pm$ 0.80	639.93 $\pm$ 5.83	392.69 $\pm$ 7.09	359.53 $\pm$ 3.89	1.32 $\pm$ 0.05	3484.56 $\pm$ 108.67	20597	17112.44 $\pm$ 180.02	83.08 $\pm$ 1.05
Anti-ID cuts	22670.73 $\pm$ 84.77	557.27 $\pm$ 65.81	6.25 $\pm$ 0.61	4387.92 $\pm$ 14.47	1723.00 $\pm$ 15.63	2024.75 $\pm$ 9.21	9.73 $\pm$ 0.15	8708.93 $\pm$ 69.78	35430	26721.07 $\pm$ 200.75	75.42 $\pm$ 0.69
fake type: muon	21968.08 $\pm$ 83.41	508.03 $\pm$ 64.45	6.06 $\pm$ 0.61	4285.76 $\pm$ 14.28	1684.04 $\pm$ 15.47	1962.13 $\pm$ 9.04	9.51 $\pm$ 0.14	8455.52 $\pm$ 68.40	34232	25776.48 $\pm$ 197.26	75.30 $\pm$ 0.71
fake mu η cut	1063.43 $\pm$ 18.21	7.20 $\pm$ 3.58	0.50 $\pm$ 0.17	3510.44 $\pm$ 13.06	1074.96 $\pm$ 10.34	212.44 $\pm$ 1.99	7.90 $\pm$ 0.13	4813.44 $\pm$ 17.16	5800	986.56 $\pm$ 78.07	17.01 $\pm$ 1.36
Scale factors	20904.65 $\pm$ 81.39	500.83 $\pm$ 64.35	5.55 $\pm$ 0.59	736.18 $\pm$ 5.45	609.08 $\pm$ 11.51	1749.69 $\pm$ 8.82	1.61 $\pm$ 0.06	3602.95 $\pm$ 66.19	28432	24829.05 $\pm$ 181.14	87.33 $\pm$ 0.82
ID cuts											
Anti-ID cuts											

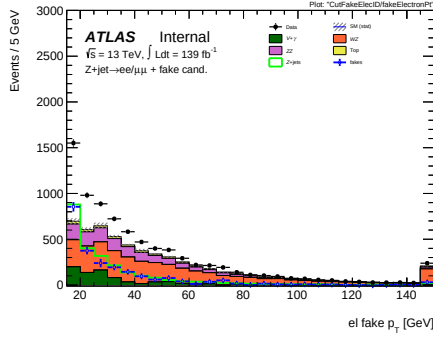
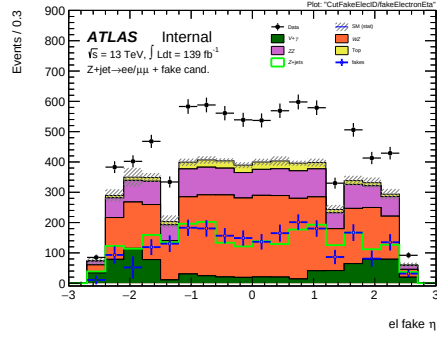
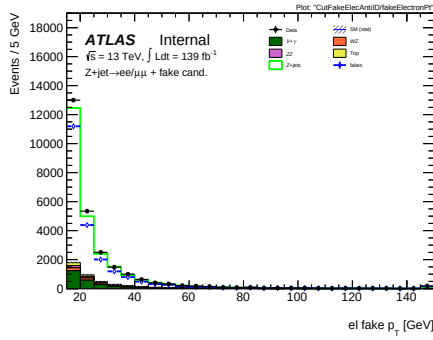
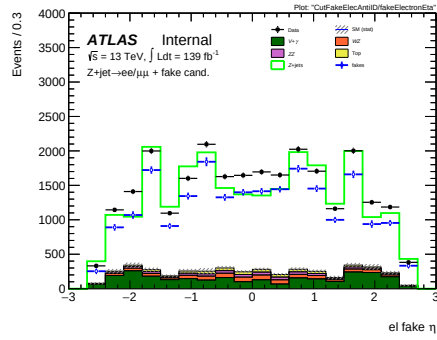

 (a) *id* electron p_T

 (b) *id* electron η

 (c) *anti-id* electron p_T

 (d) *anti-id* electron η

 Figure 8.1: Transverse momentum and pseudorapidity distributions of the fake (a)-(b) *id* and (c)-(d) *anti-id* electron candidate.

8 Contribution from Mis-identified Leptons

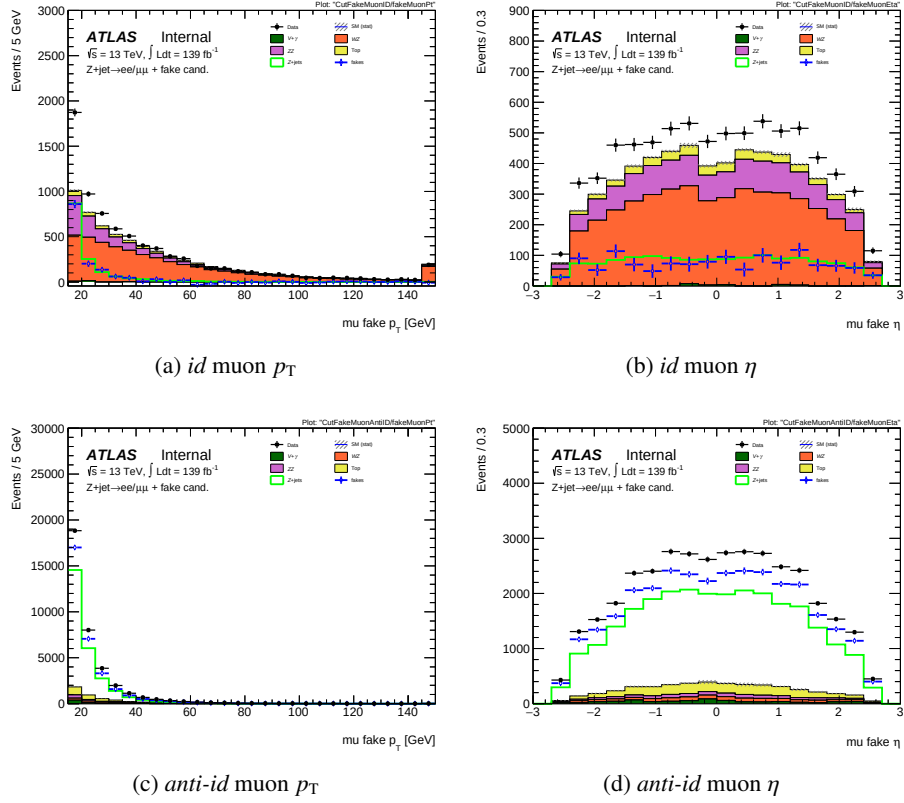


Figure 8.2: Transverse momentum and pseudorapidity distributions of the fake (a)-(b) *id* and (c)-(d) *anti-id* muon candidate.

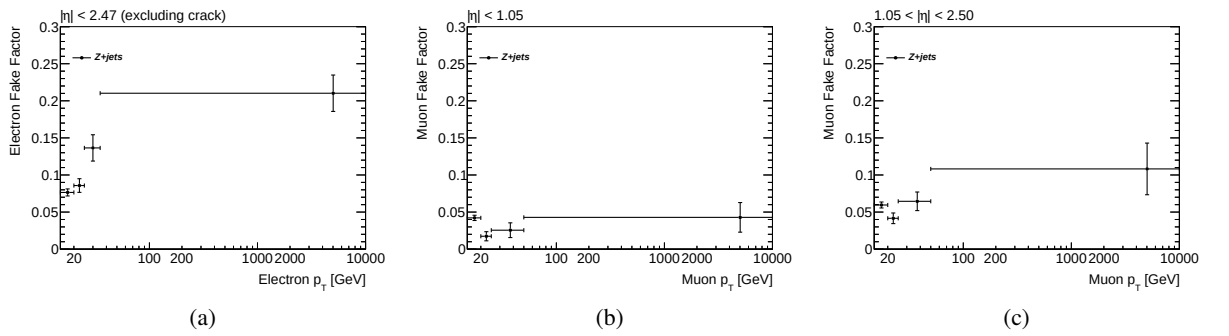


Figure 8.3: The fake factors estimated in the Z+jets CR as a function of p_T and η . (a) The fake factor integrated in η for fake electrons. (b) The fake factor for fake muons falling in the central region and (c) those falling in the forward region. The error bars show the statistical uncertainty.

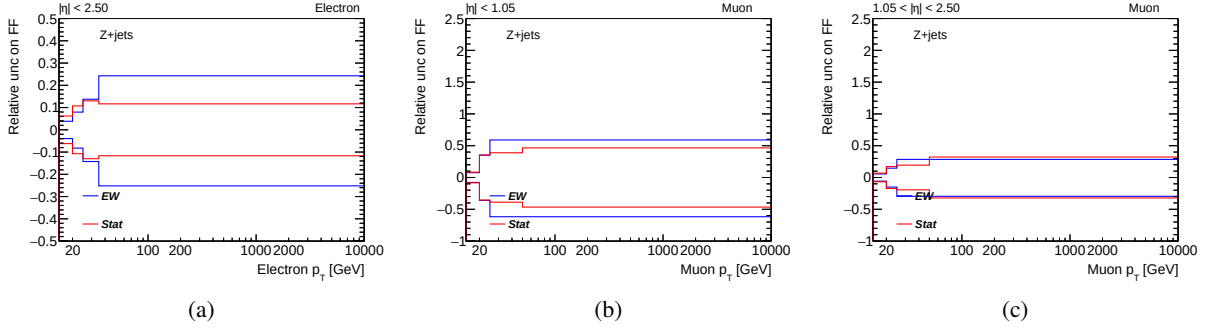


Figure 8.4: The relative contribution of the statistical and systematic uncertainties on the fake factors for (a) fake electrons, (b) fake muons falling in the central region and (c) fake muons falling in the forward region.

8.1.2 Fake Factor Corrections

Correction Factors

The fake factor method described in Section 8.1.1 is derived in a three lepton selection (Z+fake in Z+jets CR) whereas is supposed to be applicable to a two lepton selection (W+fake in W+jets CR) described in Section 8.2 for the fake lepton background estimation in the VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ analysis (see Chapter 7). In order to absorb any discrepancy due to the different control samples and regions, the fake factors must be corrected. The correction is made by comparing the fake factors measured using solely MC³ in Z+jets and W+jets CRs, using the same selection cuts as used in data⁴. The ratio of these fake factors gives the correction factor ($CF = FF_{MC}^W / FF_{MC}^Z$) which is then multiplied by the data-driven fake factor in Z+jets CR to finally get the fake factor that can be applied to the W+jets CR (with the FF applied).

The CFs are calculated separately for electrons and muons. For electrons the same choice of the p_T binning is made as used for the FFs. For muons the two highest bins were consistent between each other, thus they are combined into one bin to enhance the statistics. The dependence on η was found to be negligible thus they are not derived as a function of this kinematic variable. The CFs for electrons and muons are shown in Figure 8.5.

The uncertainties on the CFs have contributions from statistical and systematic sources. The evaluation of the systematic uncertainty was made by computing the CFs using a different generator (MG5_AMC@NLO) and was taken as the central value difference of the CFs as derived with the two generators. Table 8.3 gives a summary of the final results by splitting the overall uncertainty into the statistical and systematic components.

³ POWHEG generator is used for the simulation of Z+jets and W+jets processes because of the high statistical precision.

⁴ Additionally, one (two) leptons in the event are truth-matched to the W (Z) boson and the remaining lepton is determined as the fake.

8 Contribution from Mis-identified Leptons

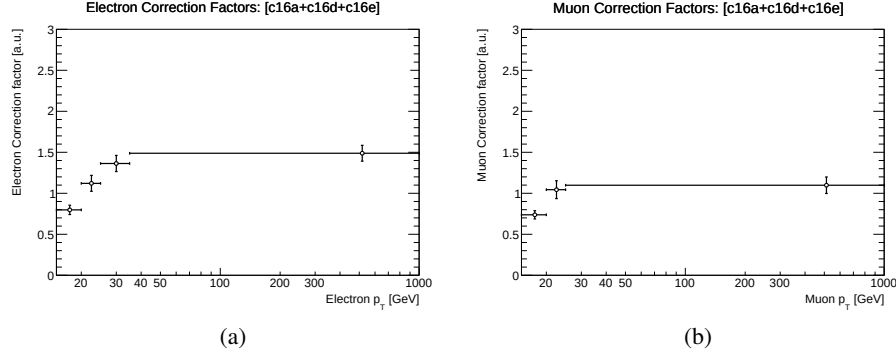


Figure 8.5: The corrections factors for (a) electrons and (b) muons. The error bars show the statistical uncertainty.

Table 8.3: The correction factor central values with the overall uncertainty split into the statistical and systematic components for electrons and muons in each p_T bin.

Electron Correction Factor			
15 – 20 GeV	20 – 25 GeV	25 – 35 GeV	35 – 1000 GeV
$0.80 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$	$1.12 \pm 0.10(\text{stat}) \pm 0.33(\text{syst})$	$1.36 \pm 0.10(\text{stat}) \pm 0.01(\text{syst})$	$1.49 \pm 0.10(\text{stat}) \pm 0.30(\text{syst})$
Muon Correction Factor			
$0.74 \pm 0.05(\text{stat}) \pm 0.02(\text{syst})$	$1.04 \pm 0.11(\text{stat}) \pm 0.01(\text{syst})$	$1.10 \pm 0.10(\text{stat}) \pm 0.12(\text{syst})$	

Double Fakes

The W +jets CR (discussed in Section 8.2) is designed to select events with one prompt lepton and the other being classified as fake. As discussed in Section 8.1 there is a contribution from double fake events too. The method described so far, overestimates this contribution. In order to avoid the overcounting a double-fake control region is used where both of the leptons in the event are required to pass the *anti-id* criteria while MC processes with two real leptons are then subtracted. Fake factors corresponding to two *anti-id* leptons in the selection are then applied. The size of the correction and the fake yields in the SR before and after the correction are shown in Table 8.4.

Table 8.4: Fake yields in SR before and after the double-fake correction.

$\sqrt{s} = 13\text{TeV}$, $\mathcal{L} = 139\text{fb}^{-1}$, V21	e Wjets	μ Wjets	e+ μ Wjets	Double Fakes Corr.	Double Fakes Relative Contribution (%)	MisID (double-fake corrected)
VBF SR ($e\mu$)	18.52 ± 4.37	14.77 ± 1.05	33.29 ± 4.49	-6.57 ± 0.42	24.58 ± 4.44	26.73 ± 4.51
VBF SR (μe)	17.62 ± 3.96	7.10 ± 1.29	24.72 ± 4.16	-4.46 ± 0.32	22.01 ± 4.80	20.26 ± 4.18

Trigger Bias

Most of the events entering in the analysis are collected by the dilepton triggers that have looser identification and isolation criteria compared to those for *id* and *anti-id* definitions. On the other hand, single lepton triggers have tighter (looser) requirements than the *anti-id* (*id*) definition. Therefore, in

the case that an *id* lepton fires the trigger there is no loss in the event yield. But, in the case when an *anti-id* lepton fires the trigger, the tighter requirements result to a bias in the event yield. The proportion of the fake lepton candidates which fired a single lepton trigger is shown in Table 8.5. The highest percentage of fake events that fire a single lepton trigger refer to when the fake candidate is a muon and the leading lepton in the event.

Table 8.5: Events in the W +jets control region for which only the fake candidate fired a single-lepton trigger.

	$e\mu$	μe
e-fakes	5.6%	2.2%
μ -fakes	0.0%	15.5%

In order to account for this scenario, separate fake factors are derived by requiring the *anti-id* lepton to fire one of the single lepton triggers used in the analysis. This requirement does not yield sufficient statistics for a reliable estimation using a Z +jets sample and therefore the calculation is performed in a di-jet selection. More details can be found in Ref. [120].

To sum up, the FF application in the VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ analysis is performed on the fake estimate and is based on which of the leptons fires the trigger. When a dilepton trigger fires in an event, for the fake lepton (or leptons if both are matched to the dilepton trigger) the FF as estimated in the Z +jets sample is applied. On the other hand, when the prompt (fake) lepton fires one of the single lepton triggers the FF as estimated in the Z +jets (di-jet) selection is applied. For the case where both of the leptons in the event are fakes and a single lepton trigger is fired, the di-jet FF is used for the lepton that fired the trigger whereas for the remaining fake lepton the Z +jets FF is applied.

8.2 W +jets CR

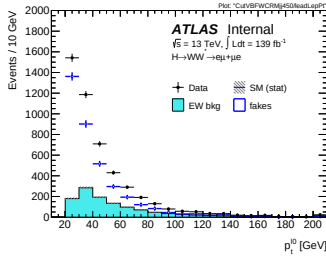
The W +jets CR is used to estimate the contribution of jets from W +jets processes that are misidentified as prompt leptons. The same kinematic requirements as those used in the SR, except for the $|\Delta\phi_{\ell\ell}| < 1.4$ rad cut are applied. Unlike the SR, this region requires one *id* and one *anti-id* lepton instead of two well-identified⁵. The cutflow is shown in Table 8.6 where fakes are defined by subtracting $V\gamma$, diboson, top and Z +jets MC processes from data. Once fake factors and correction factors are applied these events constitute the fake background estimate in the SR. The kinematic distributions for several variables in the W +jets CR are shown in Figure 8.6.

⁵ The fake factors are not applied in this region as it is used to estimate the fake yields on which the FF are meant to be applied for the fake background extrapolation in the designed regions of the analysis described in Section 7.4.

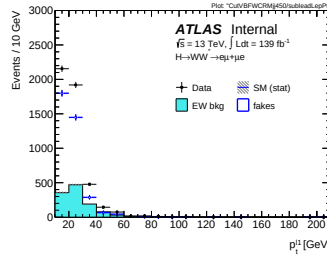
8 Contribution from Mis-identified Leptons

Table 8.6: Cutflow in the W +jets control region.

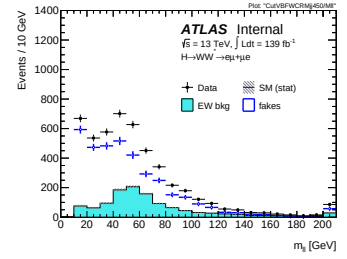
$\sqrt{s} = 13\text{TeV}$, $\mathcal{L} = 139\text{fb}^{-1}$ (Full Run 2)	Total Bkg	data	fakes	fake purity(%)
Channel Selection	8012632.06 $\pm$ 2327.10	13124937	5112304.94 $\pm$ 4305.85	38.95 $\pm$ 0.03
Trigger Selection	8012632.06 $\pm$ 2327.10	13124937	5112304.94 $\pm$ 4305.85	38.95 $\pm$ 0.03
Trigger Matching	7754276.84 $\pm$ 2199.12	13057932	5303655.16 $\pm$ 4230.14	40.62 $\pm$ 0.03
W +jets flavour split muon	5672759.42 $\pm$ 1876.51	10572340	4899580.58 $\pm$ 3754.15	46.34 $\pm$ 0.04
W +jets flavour split electron	3498327.82 $\pm$ 1524.29	7417426	3919098.18 $\pm$ 3121.04	52.84 $\pm$ 0.05
Jet Cleaning	3498327.82 $\pm$ 1524.29	7417426	3919098.18 $\pm$ 3121.04	52.84 $\pm$ 0.05
Overlap: $V_{\text{gamma}}/V_{\text{jets}}$	3498327.82 $\pm$ 1524.29	7417426	3919098.18 $\pm$ 3121.04	52.84 $\pm$ 0.05
Only two Leptons	3448417.08 $\pm$ 1499.17	7363366	3914948.92 $\pm$ 3100.14	53.17 $\pm$ 0.05
$p_t^{\text{lead}} > 22\text{ GeV}$	3448417.08 $\pm$ 1499.17	7363366	3914948.92 $\pm$ 3100.14	53.17 $\pm$ 0.05
$p_t^{\text{sublead}} > 15\text{ GeV}$	3447273.96 $\pm$ 1498.83	7360611	3913337.04 $\pm$ 3099.53	53.17 $\pm$ 0.05
Remove High Eventweight Events	3447325.12 $\pm$ 1489.49	7360611	3913285.88 $\pm$ 3095.03	53.17 $\pm$ 0.05
Remove High Eventweight Zjets Samples	3371562.75 $\pm$ 992.08	7360611	3989048.25 $\pm$ 2888.74	54.19 $\pm$ 0.04
OS Leptons	3370094.44 $\pm$ 991.88	7353604	3983509.56 $\pm$ 2887.46	54.17 $\pm$ 0.04
$M_{\ell\ell} > 10\text{ GeV}$	3370035.94 $\pm$ 991.87	7353272	3983236.06 $\pm$ 2887.40	54.17 $\pm$ 0.04
SF: Z Veto	3370035.94 $\pm$ 991.87	7353272	3983236.06 $\pm$ 2887.40	54.17 $\pm$ 0.04
Leptons ID, singleFakes 1 anti-ID, 1 ID, doubleFakes 2*anti-ID	764479.23 $\pm$ 519.68	1928013	1163533.77 $\pm$ 1482.59	60.35 $\pm$ 0.09
2-jet (30,30); no FF	385167.42 $\pm$ 196.07	656338	271170.58 $\pm$ 833.53	41.32 $\pm$ 0.14
b-veto	63869.88 $\pm$ 142.74	197677	133807.12 $\pm$ 466.96	67.69 $\pm$ 0.28
CJV (20GeV)	44256.34 $\pm$ 121.29	137560	93303.66 $\pm$ 390.22	67.83 $\pm$ 0.34
OLV bool	9437.81 $\pm$ 59.38	27999	18561.19 $\pm$ 177.55	66.29 $\pm$ 0.75
$Z \rightarrow \tau\tau$ veto	5237.79 $\pm$ 42.66	18022	12784.21 $\pm$ 140.86	70.94 $\pm$ 0.94
$M_{jj} > 200\text{ GeV}$	3269.09 $\pm$ 32.93	11883	8613.91 $\pm$ 113.88	72.49 $\pm$ 1.17
$DY_{jj} > 2.1$	2851.94 $\pm$ 32.06	10879	8027.06 $\pm$ 109.12	73.78 $\pm$ 1.23
$M_{jj} > 450\text{ GeV}$	1162.08 $\pm$ 19.87	4821	3658.92 $\pm$ 72.22	75.90 $\pm$ 1.85



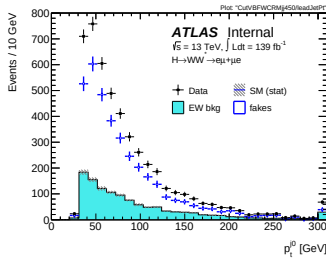
(a) leading lepton p_T



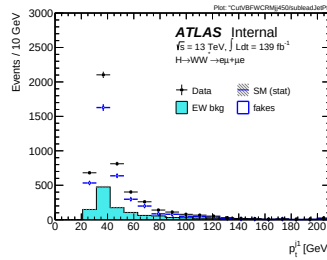
(b) subleading lepton p_T



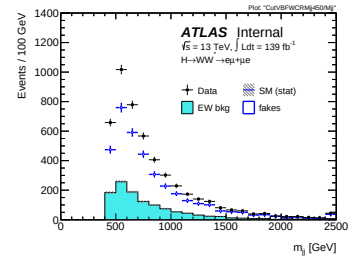
(c) $m_{\ell\ell}$



(d) leading jet p_T



(e) subleading jet p_T



(f) m_{jj}

Figure 8.6: Kinematic distributions of (a) leading lepton p_T , (b) subleading lepton p_T , (c) $m_{\ell\ell}$, (d) leading jet p_T , (e) subleading jet p_T and (f) m_{jj} in the W +jets control region. The data (black markers) are shown together with the electroweak processes in MC (cyan histograms). Their difference (blue markers) represents the estimate of the fake background. The fake factors are not applied in this region.

8.3 The Fake Factor studies

A possible dependence on the pileup contamination and on properties that characterize the VBF signal was investigated for the data-driven fake factor method. Any evidence of dependence should contribute as an additional systematic error in the total uncertainty.

8.3.1 Pileup

The high luminosity delivered by the LHC leads to multiple pp interactions per beam crossing. This effect, known as pileup, complicates the reconstruction of the objects in the final state.

There are two different techniques to measure the pileup in a given event. The first method uses the averaged pileup value across all bunch crossings in the lumiblock (average number of interactions per bunch crossing) which takes into account the out-of-time pileup⁶. The other method describes better the in-time pileup⁷ by using the averaged pileup value per bunch crossing across the lumiblock (actual number of interactions).

Each detector condition has a corresponding reference pileup distribution, which is used to determine the μ value that should be used for the event simulation in MC samples⁸. For an accurate mitigation of the pileup conditions there is need to reweight the MC to match the data. Due to the discrete nature of the pileup values used in MC, it is practical to scale the pileup conditions in data by the inverse scale factor prior to the pileup weights calculation [121].

For the data collected during 2015-2016 the reweighting of the MC samples was performed by using the average number of interactions per bunch crossing. For the data taken in 2017 and 2018 years, the actual number of interactions were chosen to simulate the pileup conditions. The scale factor $1/1.03$ was applied on data prior to the reweighting procedure.

The distributions of pileup are shown in Figure 8.7 at the Z -tagging cut. The data/MC agreement is good for the data taking periods of 2015-2016. For 2017 data an excess of $\sim 10\%$ in data is observed whereas at high pileup values there is a deficit in data reaching $\sim 30\%$. For 2018 data, a strong increase appears at $\mu > 45$ region. These imperfections are not inserted as an additional systematic uncertainty for this study.

In order to investigate whether the fake factors are affected by pileup, six pileup bins were used [0, 18, 24, 32, 40, 50, 80]. This binning choice resulted to a stable fake purity across the various pileup regions (bins). The event yields at the *id* and *anti-id* selection cuts are presented in Appendix C.1.1. The fake factors were computed with the data-driven method as a function of pileup in each fake lepton p_T region⁹. The results are shown in Figure 8.8 for electrons and muons. For completeness

⁶ The out-of-time pileup is referred to when there is a signal overlap from neighbouring bunch crossings.

⁷ The in-time pileup is referred to the number of interactions in the same bunch crossing.

⁸ The simulated values of pileup form a discrete set, unlike the pileup in data which represents a continuous spectrum.

⁹ For this study three p_T bins instead of four are defined (the last two bins are merged) in order to increase the statistics in the high p_T region. The dependence on η was found to be negligible, thus the fake factors were integrated in the full η range.

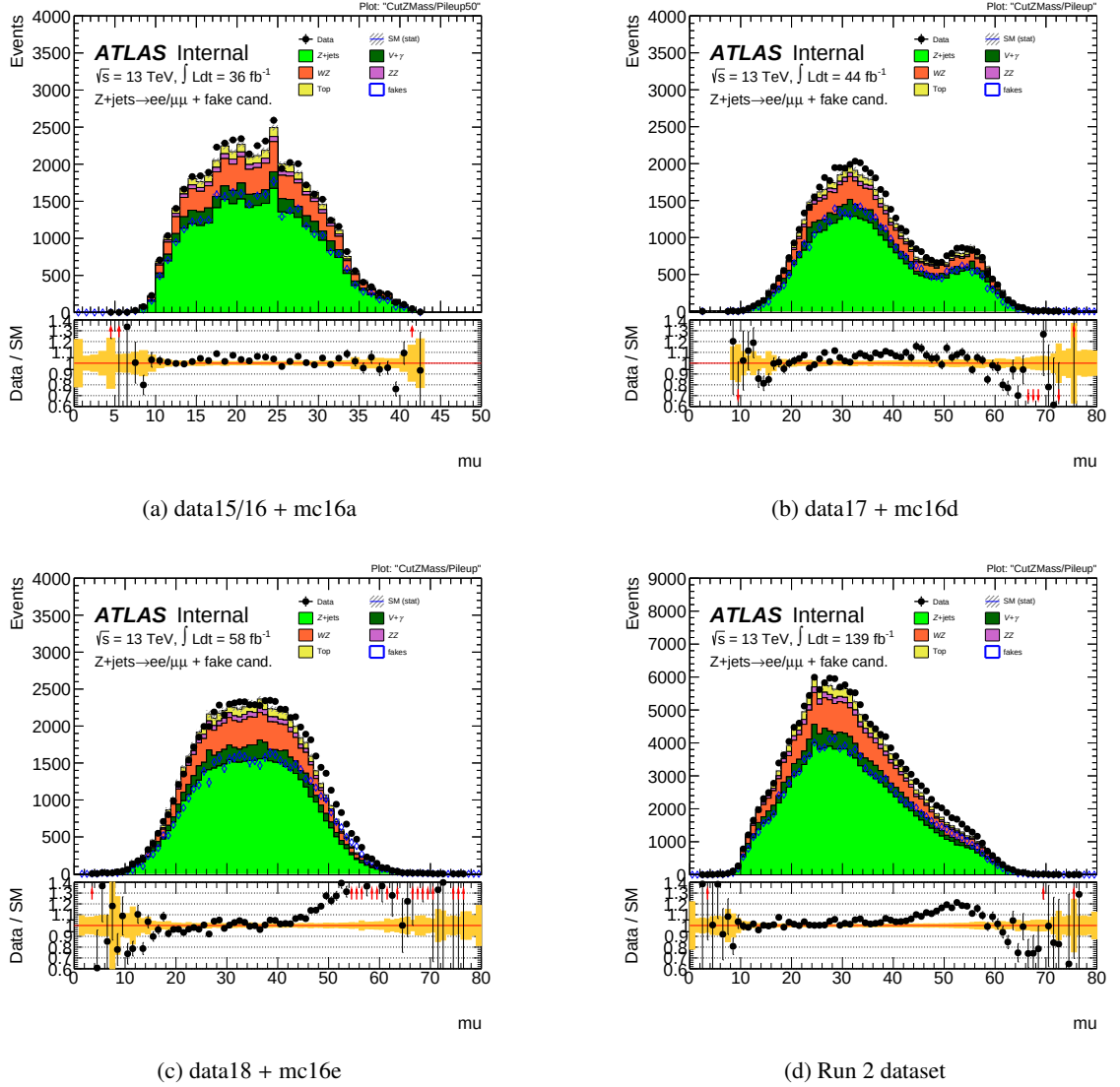


Figure 8.7: The pileup distributions in data and MC for (a) 2015-2016 data, (b) 2017 data, (c) 2018 data and (d) collectively for Run 2.

and to check the validity of the method, the same study was performed based only on MC and the results are documented in Appendix C.1.2.

A fit with a linear function was performed on the results to assess whether is needed to introduce a systematic error in the overall fake factor uncertainty. For the low p_T regions ($p_T < 25$ GeV) the fake factors for both leptons remain stable across pileup. For the high p_T values ($p_T > 25$ GeV) the fake factors are dominated by the statistical uncertainties. This study does not show any strong evidence of pileup dependence.

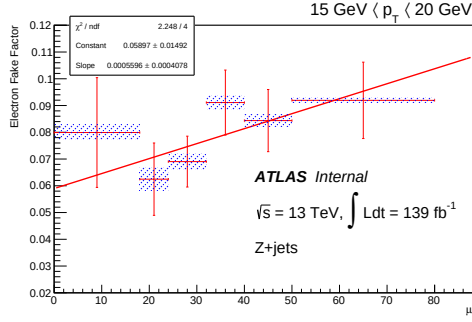
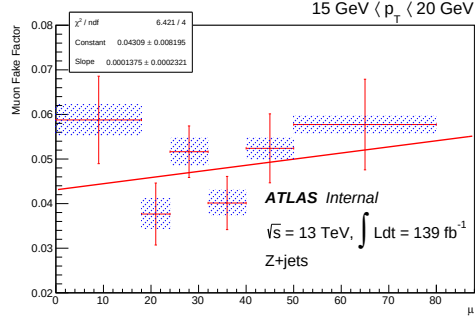
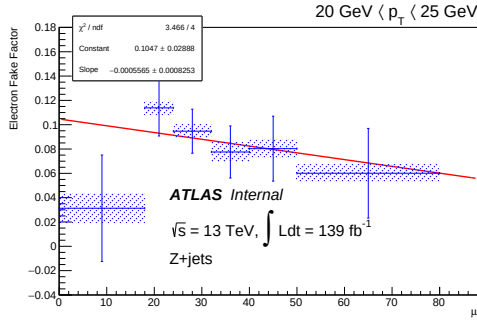
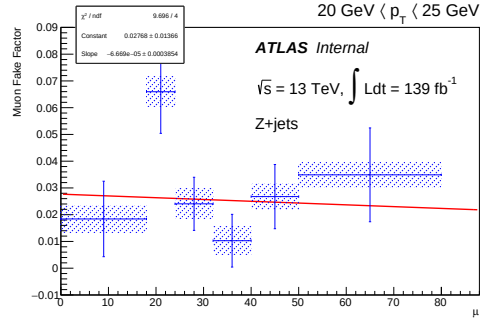
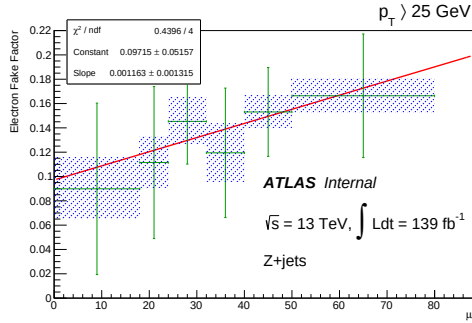
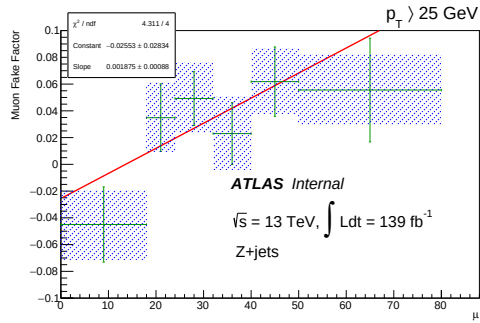
(a) electron FF, 15 GeV < p_T < 20 GeV(b) muon FF, 15 GeV < p_T < 20 GeV(c) electron FF, 20 GeV < p_T < 25 GeV(d) muon FF, 20 GeV < p_T < 25 GeV(e) electron FF, p_T > 25 GeV(f) muon FF, p_T > 25 GeV

Figure 8.8: (a), (c), (e) Electron and (b), (d), (f) muon fake factors in data as functions of the pileup for each p_T bin, while integrated in η . Statistical uncertainties are shown as error bars. The EW subtraction uncertainties are shown as error bands. A polynomial fit is performed and the fit parameters are displayed in the insets to assess any possible pileup dependence.

8.3.2 Jets

The final state of the VBF signal constitutes of two leptons, their corresponding neutrinos and two jets. The fake factors are measured in a three-lepton selection without any requirement on jets. A new cut which selects events with at least one jet ($p_T > 30$ GeV and $|\eta| < 4.5$) is inserted in the event selection. The aim of this study is to check whether there is any detector activity near the fake lepton that can have an impact on the data-driven fake factor estimation.

Due to the nature of the Z+jets sample, the cut on jets resulted to significant discrepancies between data and MC on the kinematic distributions. A reweighting technique of the Z+jets MC sample to data was performed. The weights that were applied per event and the kinematic distributions before and after the reweighting procedure are presented in Appendix C.2.1.

The fake factors are derived as a function of the number of jets in the event and are shown in Figure 8.9 separately for central and forward electrons and muons. A fit with a linear function up to two jets was performed on the results. The fake factors do not show any dependence with the presence of jets in the events.

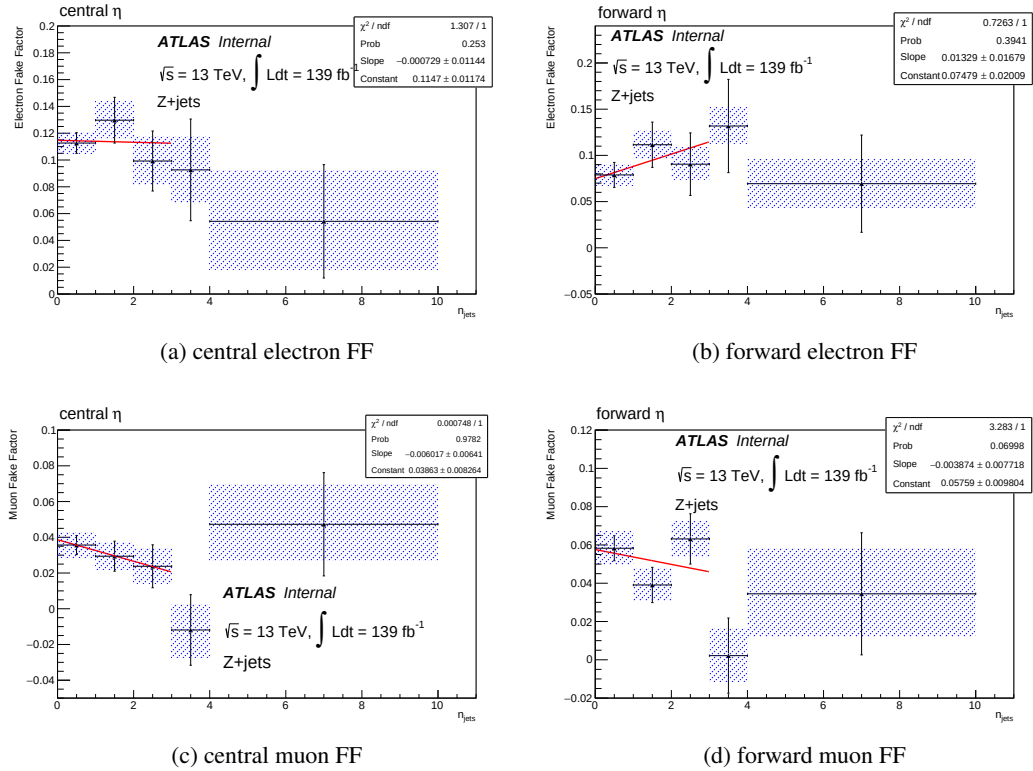


Figure 8.9: (a),(b) Electron and (c),(d) muon data-driven fake factors as a function of the number of jets in the event. Statistical uncertainties are shown as error bars. The EW subtraction uncertainties are shown as error bands. A polynomial fit is performed and the fit parameters are displayed in the insets to assess any possible dependence on jets.

The jets study was extended by measuring the fake factors as a function of the distance between the fake lepton and the leading jet, $\Delta R(\text{fake}, \text{jet})$ in the event. The aim for this study is to investigate if there is any overlap between the lepton tagged as fake and its closest jet. Thus, low ΔR values are of particular interest. The results are shown in Figure 8.10 for central and forward electrons and muons. A linear fit was performed on the results and given the low statistics a conclusion for a possible dependence cannot be made.

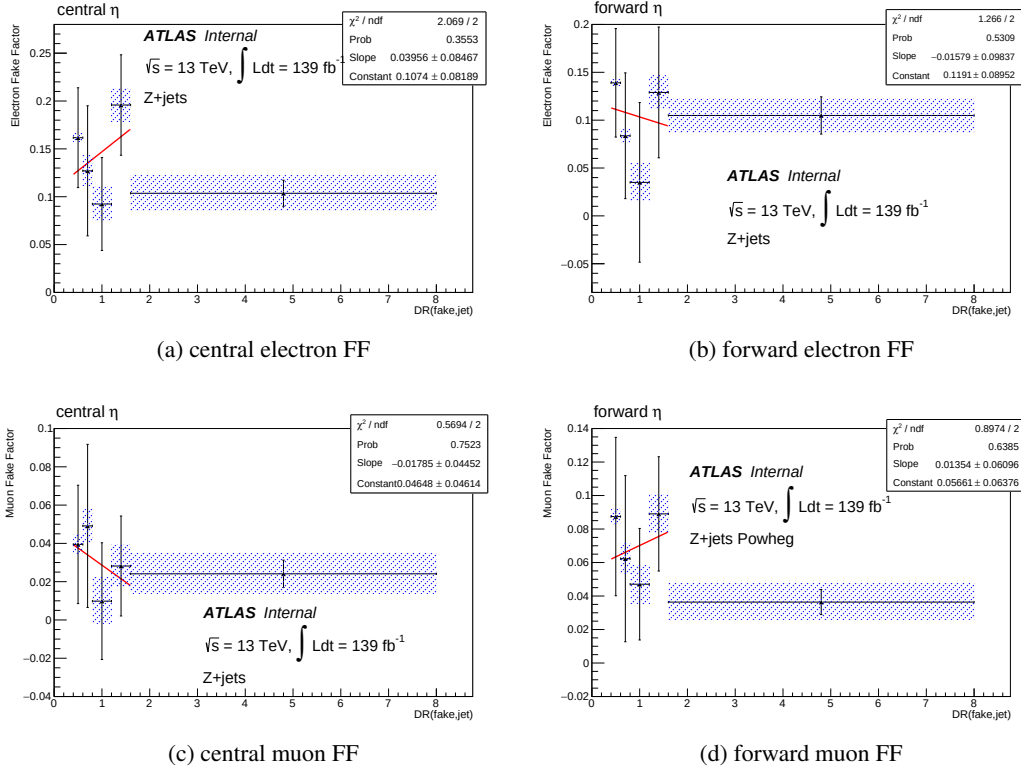


Figure 8.10: (a),(b) Electron and (c),(d) muon data-driven fake factors as a function of the distance between the fake lepton and its closest jet. Statistical uncertainties are shown as error bars. The EW subtraction uncertainties are shown as error bands. A polynomial fit is performed and the fit parameters are displayed in the insets to assess any possible dependence on jets.

For completeness, the studies were performed using MC only and the results are documented in Appendix C.2.2.

8.4 Closure test for the Fake Estimation Method

In order to demonstrate the robustness of the data-driven technique used for the fake lepton background estimation, closure tests were performed using only MC samples. Any non-closure effects would serve as an additional uncertainty in the analysis.

The closure was tested¹⁰ by comparing W +jets events in the SR, to W +jets events in a control region (W +jets CR). In general, the fake factors translate the $id/anti-id$ events selected in the W +jets CR (see Section 8.2) to id/id events selected in the SR (see Section 7.4). Therefore, for the closure tests the SR selects two well identified leptons in the W +jets sample. These events are then compared to the fake events estimated using the W +jets MC events with the FF applied.

Two different MC generators were used for the simulation of W +jets and Z +jets events: PowHEG and MG5_AMC@NLO. For each study, the fake factors were derived from the same MC programme as the one used for the W +jets process. The same applies for the correction factors extraction.

In the SR selection using PowHEG W +jets MC events, the total number of estimated fakes amount to 67.30 ± 24.86 , while in the W +jets CR (with the FF and CF applied) 65.06 ± 10.83 fake events are estimated. The closure is within $\sim 3\%$ and falls well within the total statistical uncertainties. In the SR selection using MG5_AMC@NLO W +jets MC events the total number of estimated fakes amount to 170.81 ± 32.96 , while in the W +jets CR 172.77 ± 27.89 fake events are estimated. The closure is within $\sim 1.2\%$ and falls well within the total statistical uncertainties.

The distributions for several kinematic variables after the full selection are compared between PowHEG MC events in SR and in the W +jets CR and are shown in Figure 8.11. The same distributions are shown at an earlier selection stage in Figure 8.12 to profit from higher statistics.

The cutflows for SR and W +jets CR for both MC generator choices along with the kinematic distributions using MG5_AMC@NLO are presented in sections of Appendix C.3.

Overall, no significant non-closure effects beyond the data-driven fake factor uncertainties have been observed. Therefore, there was no need to insert an additional systematic uncertainty which accounts for non-closure bias.

¹⁰ These tests were performed in a broader phase space, compared to the SR described in Section 7.4, which is differentiated from the absence of cuts on $m_{jj} > 450$ GeV and $\Delta\phi_{\ell\ell} < 1.4$ rad.

8.4 Closure test for the Fake Estimation Method

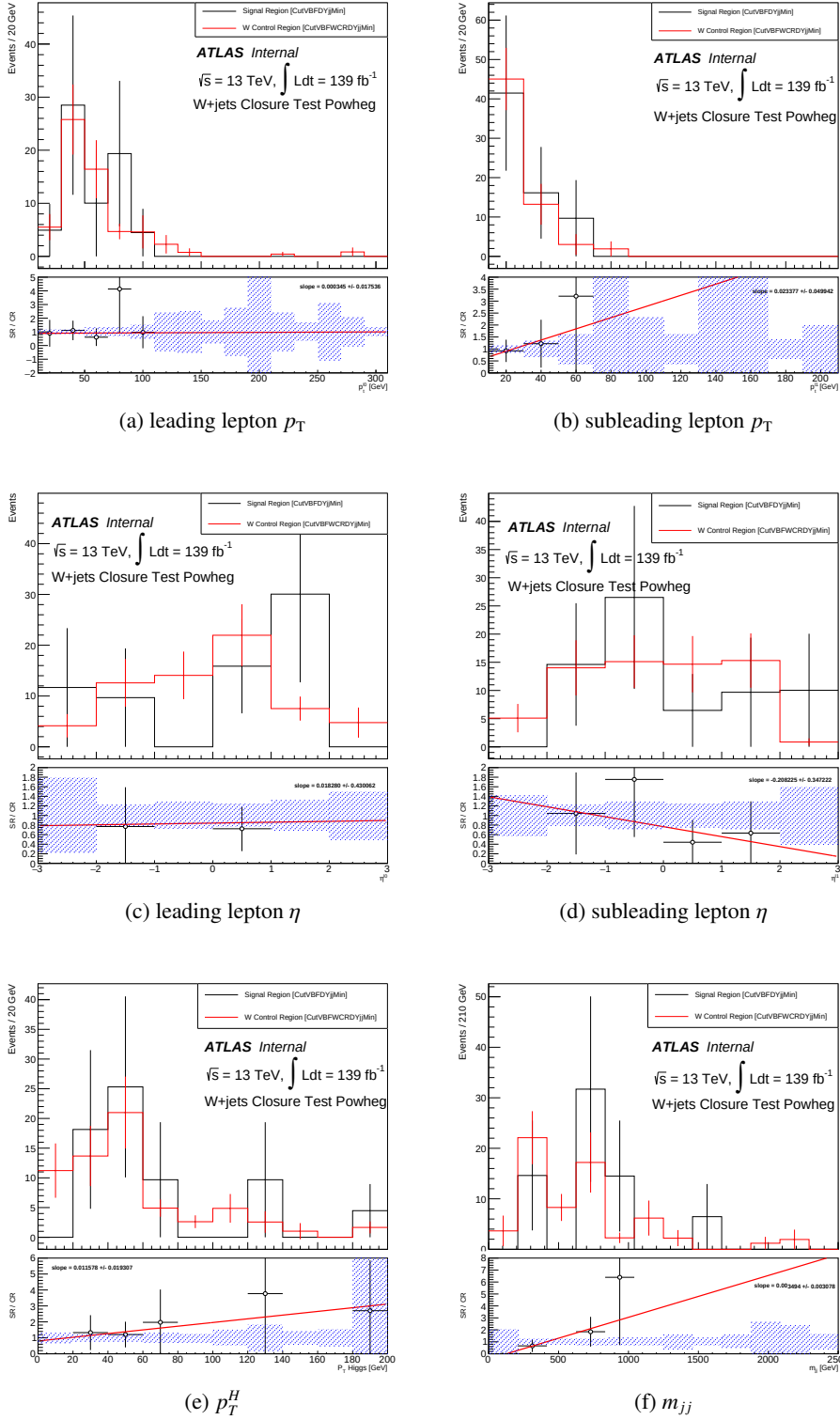
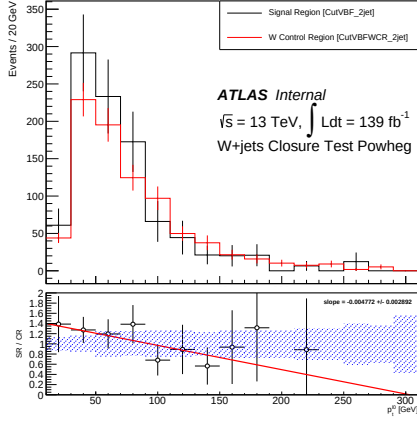
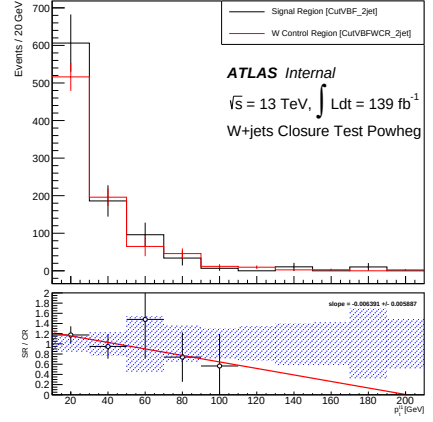


Figure 8.11: Distributions after the full selection for W+jets MC samples in the SR (black) and W+jets CR with FFs and CFs applied (red) using POWHEG MC. Statistical uncertainties are shown as error bars. The uncertainties estimated in the data-driven method are shown in error bands. The results of the linear fit of the ratio of the two distributions are shown for each observable.

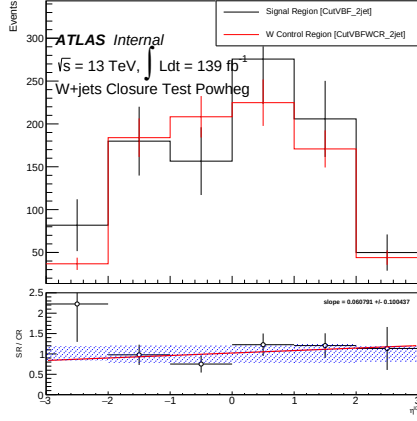
8 Contribution from Mis-identified Leptons



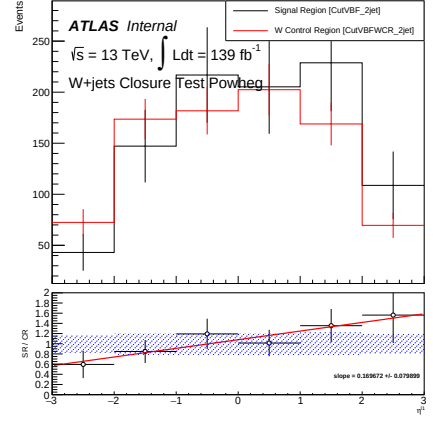
(a) leading lepton p_T



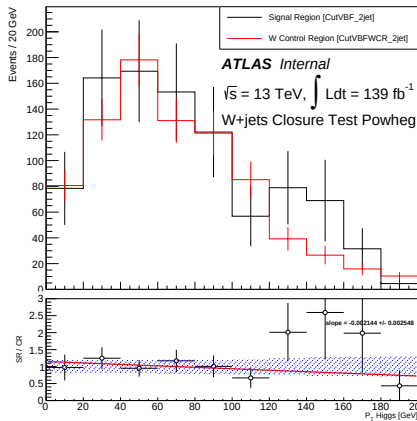
(b) subleading lepton p_T



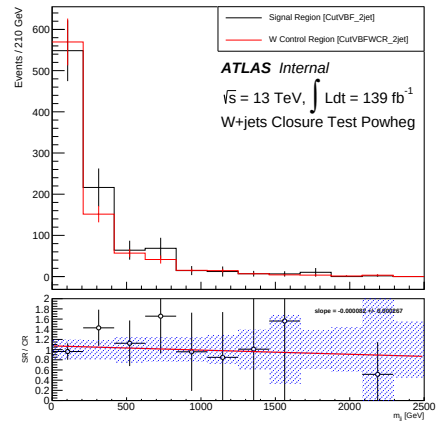
(c) leading lepton η



(d) subleading lepton η



(e) p_T^H



(f) m_{jj}

Figure 8.12: Distributions at pre-selection level for W+jets MC samples in the SR (black) and W+jets CR with FFs and CFs applied (red) using Powheg MC. Statistical uncertainties are shown as error bars. The uncertainties estimated in the data-driven method are shown in error bands. The results of the linear fit of the ratio of the two distributions are shown for each observable.

Part IV

Conclusions

After a few years of the LHC operation, in 2012 the ATLAS and CMS experiments announced the discovery of the SM last missing piece, the Higgs boson. Since then owing to the rapidly growing dataset various physics programmes have been launched which allowed Standard Model precision measurements as well as an improved sensitivity to physics beyond the SM. At the HL-LHC era an instantaneous luminosity of up to 7.5 times the nominal value is expected to be delivered to the experiments. Apart from the higher precision measurements, the larger dataset will increase the sensitivity of rare processes offering a deeper understanding of our Universe.

To cope with the increased number of interactions, the experiments follow an upgrade plan taking advantage of new technologies. The largest upgrade for ATLAS Run-3 was the NSW project. The NSW replaced the pre-existing system located at the innermost part of the endcaps muon spectrometer and it was successfully integrated in ATLAS in November 2021. It consists of two novel detector technologies, the resistive-strip Micromegas and the small-strip Thin Gap Chambers both with good trigger and tracking capabilities. The first part of this thesis aims to characterise the NSW MMG performance in harsh background conditions. It is the first time a Micromegas detector in large-scale is studied. The analysis conducted presents results for normal tracks and different electronics configuration settings. The detector's efficiency has been reported and its spatial resolution has been studied using different methods. In absence of background an efficiency of $\sim 95\%$ has been calculated and a core (weighted) resolution of $67 - 99 \mu\text{m}$ ($119 - 181 \mu\text{m}$) has been achieved depending on the layer tested. The results are similar for the different VMM settings used for the pulse integration time among the different estimation techniques. In background conditions similar to those that will be occurred during the HL-LHC phase the efficiency was found at the level of 90%. The spatial resolution results are not fully consistent among the techniques used for the different electronics configurations. A core (weighted) resolution well below $80 \mu\text{m}$ ($160 \mu\text{m}$) has been estimated for the pulse integration time of 100 ns and around $100 \mu\text{m}$ ($180 \mu\text{m}$) for 200 ns. The detector performance has also been tested in even worse conditions with the efficiency reaching no less than 65% and the core (weighted) resolution was found to be $80 - 120 \mu\text{m}$ ($180 - 250 \mu\text{m}$) depending on the technique used. By testing the different electronics configuration settings, the performance of the detector is expected to be significantly improved with the VMM parameter `slh` enabled at the upcoming test periods. The analysis is presented in Chapter 6. Moreover, the relevant contribution to the NSW project technical tasks for the smooth operation in Run-3 has been reported in Chapters 4 and 5.

The analysis for the fiducial cross-section measurements of the Higgs boson production through the VBF process in the $H \rightarrow WW^*$ channel using the fully leptonic final states has been reported in Chapter 7. The analysed data correspond to the full Run-2 dataset at 13 TeV centre-of-mass energy recorded by ATLAS during 2015-2018 and corresponding to an integrated luminosity of 139 fb^{-1} . The measured fiducial cross section is $1.68^{+0.33}_{-0.32} \text{ (stat)}^{+0.23}_{-0.21} \text{ (sys)} \text{ fb}$ and is consistent with several SM predictions. The big challenge of this analysis is the low statistics of VBF Higgs events that are expected to be increased at the HL-LHC era. In Chapter 8 the data-driven estimation of the background originating from jets that are falsely considered as prompt leptons was presented. Several studies have been performed with the aim to assess the impact of other sources of uncertainties to the data-driven technique. The pileup contamination as well as the presence of jets in the event selection were examined but given the low statistics no evidence was found within the large statistical uncertainties. Finally, in order to demonstrate any bias that may come from the data-driven technique a closure test based solely on MC was performed. The results did not give any evidence of non-

closure effects. The precision of the measurements will be further enhanced the upcoming data-taking periods.

Appendices

A CSC Offline Data Quality: Code Development & Maintenance

In preparation for the LHC Run-3, the ATLAS experiment had to revise its offline software in order to take advantage of the data processing in multiple cores. The package used during Run-2 for the offline monitoring of the data collected by the SW CSC detectors had to be migrated in the new software release.

The motivation behind this mandate relied on the readiness of the offline tools to reprocess the Run-2 data with the new software release. In this way, the new release could be tested and validated while the new derived datasets would benefit from the software improvements, including bug fixes. Moreover, the corresponding packages had to be fully functional for the scenario the NSW detectors could not meet the deadline set for their installation in the ATLAS cavern.

The main difference between the new framework and the old one, is the separation of the user C++ code from the histogram handling [122]. The variables are monitored in C++ algorithms while the list of the produced histograms is part of the python job configuration step. Concerning the post-processing step the histgrinder [123] package is adopted. It is a generic system that provides common libraries to simplify the user code for the histogram post-processing. It uses a yaml configuration file where the input and output histogram name patterns, the name of the python function to carry out the operation on the input histograms as well as any additional parameters to be passed as arguments to the python function must be provided.

The offline monitoring package for the SW CSC detectors is found in the *MuonSpectrometer/MuonValidation/MuonDQA/MuonRawDataMonitoring/CscRawDataMonitoring* Athena path. Similarly to the procedure described in Section 5.2 for the NSW MMG, the offline monitoring for the SW CSC detectors is performed at different stages of the reconstruction step. Therefore, the monitoring of the recorded hits before and after the calibration and their formation in clusters is followed. In addition, variables at segment level are also monitored.

All algorithms are fully migrated to the new multithread-safe configuration framework. The histograms produced with the use of the new framework had been checked one by one against to the old version's output during the migration of the package. Minor changes were implemented as the package was well maintained. Among those, a missing cut of 50 ADC counts was inserted in order to reject the noise that had been detected in some sectors. All other changes were related to histogram visualisation issues.

The most important histograms are presented on the Webdisplays. A typical example is shown in Figure A.1 with all CSC folders being flagged green. From time to time, when a new release of both new and old softwares was published, the Webdisplays were checked and compared against to the

Webdisplay that has been produced using the previous latest already validated version. In this way, possible issues that may have affected the CSC system were spotted and fixed as necessary. The multithread version of the package was finally tested by comparing the histograms produced after running the software with one and eight threads. At the end, nearly 18 PB of Run-2 collision data were reprocessed using the updated version of the ATLAS offline analysis software.

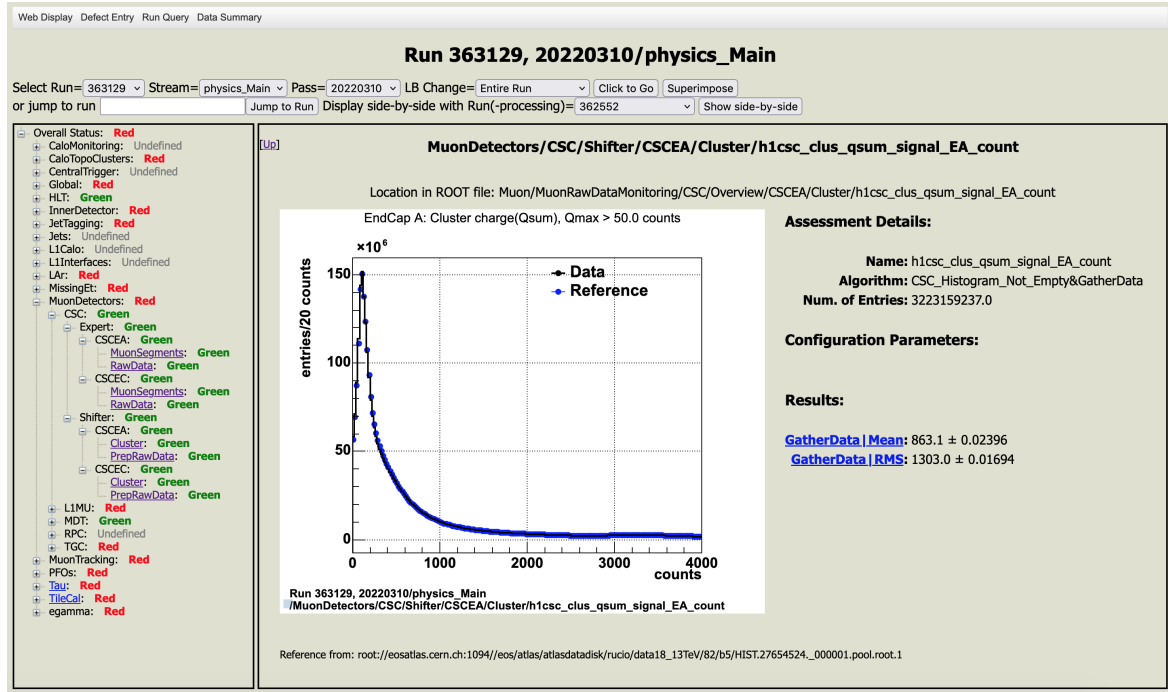


Figure A.1: A typical Webdisplay for the reprocessing at Tier-1 of run 363129 recorded in 2018 from pp collisions at 13 TeV centre of mass energy. The original from Tier-0 run 358031 is used as the reference.

B Additional Material on NSW MMG

B.1 SM1 PCB-1,3 dimensions & expected hit occupancy

The strip length, ℓ_s , can be calculated by the following formula:

$$\ell_s = dL_activeArea_bottom + \frac{(dL_activeArea_top - dL_activeArea_bottom) \cdot (strip - nMissedStrip_bottom) \cdot pitch}{dr_activeArea} \quad (B.1)$$

where $dL_activeArea_bottom/top$ is the length of bottom/top trapezoid bases of the module's active area, $nMissedStrip_bottom$ is the number of strips in PCB-1 that are not connected to the front-end board channels, $dr_activeArea$ is the radial length of the module, $strip$ is the strip index for which the length is calculated and $pitch$ is the distance between two consecutive strips. The exact numbers are documented in Chapter 4.

The middle strip for PCB-3 has the index 2560, therefore its length is about 681 mm. For PCB-1, the middle strip has the index 512 and its length is found to be about 358 mm. The dimensions allow to relate the performance of PCB-3 to that of PCB-1 when the high voltage is set on one side of PCB-3.

The simulated particle flux at a distance of 1 m away from the source is $5 - 7 \cdot 10^7 \frac{\text{photons}}{\text{cm}^2\text{s}}$ [106]. Assuming that the detector sensitivity to photons is $\sim 5 \cdot 10^{-4}$ the expected particle rate under full irradiation ($A.F = 1$) is $25 - 35 \text{ kHz/cm}^2$. A relation between the particle rate and the recorded hits (i.e accepted events) on the detector can be given as:

$$(\text{particle rate}) \cdot (\text{area}) \cdot (\text{time window}) \cdot (\text{number of triggers}) = \frac{(\text{accepted events})}{(\text{cluster multiplicity})} \quad (B.2)$$

The particle rate is presented in Figure B.1 as function of the different attenuation filters used.

The expected hit occupancy, i.e number of hits per strip, can be estimated by using the following formula:

$$\langle \text{hit occup} \rangle = (\text{read out rate}) \cdot (\text{area}) \cdot (\text{strips/cluster}) \cdot (\text{time window}) \quad (B.3)$$

For a time window of 200 ns (i.e 8 BC) the expected hit occupancy on the middle strip of PCB-3 and PCB-1 is presented in Table B.1 for different values of readout rate. These values can be compared to the experimental results of the hit occupancy presented in Appendix B.2 in order to relate the results to what expected at HL-LHC.

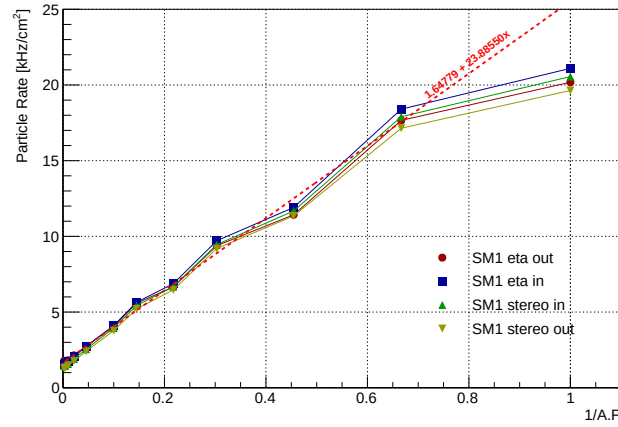


Figure B.1: The particle rate as function of the inversed value of the attenuation filter (A.F) used. A linear fit (red line) is performed upon 0.1. The time window considered is 200 ns (i.e 8 BC, the effect of electronics, dead time and integration time was not considered). The VMM peaking time is set at 100 ns whereas the HV is set on the right side of PCB-3 and its value is set accordingly in order to achieve equal currents among the layers. The operation gas mixture with a consistency of 93% Ar and 7% CO₂ is used. The VMM gain is set at 9 mV/fC. The data were recorded on 16th December 2021 out of the beam period.

Table B.1: Expected hit occupancy on SM1 PCB-1,3 for different readout rates.

SM1 expected hit occupancy		
Readout Rate	PCB-3	PCB-1
5 kHz/channel	0.011	0.006
10 kHz/channel	0.023	0.012
15 kHz/channel	0.034	0.018
20 kHz/channel	0.046	0.024

B.2 Results with the source only or in combination with the muon beam

Several studies were performed with SM1-M40 since October 2021 at GIF++ either during the muon test beam periods or out of the beam period collecting data using only the ¹³⁷Cs source. The aim was to understand the performance under irradiation. Here the results with different gas mixtures, HV and VMM settings are summarised.

B.2 Results with the source only or in combination with the muon beam

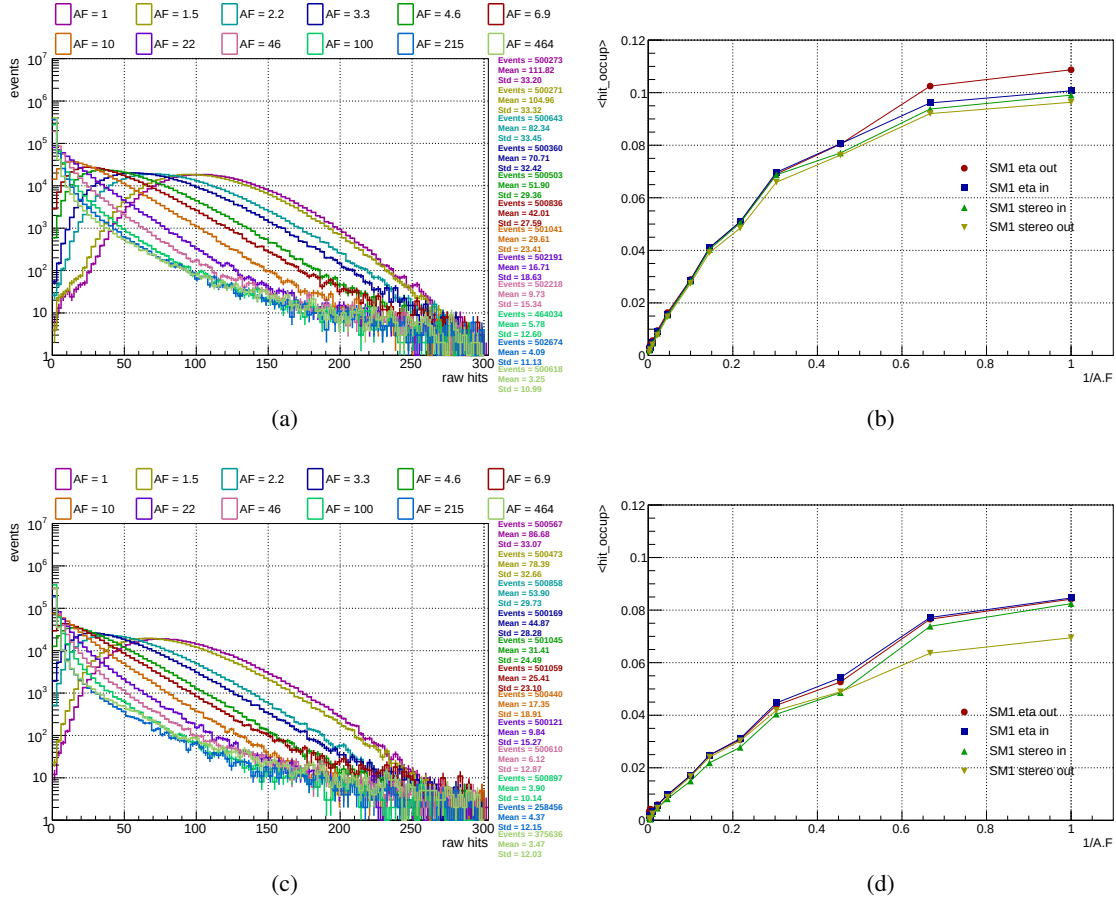


Figure B.2: The distribution of raw hits when the high voltage is set on (a) both sides and (c) on right side of PCB-3. The mean hit occupancy as function of the inversed value of the attenuation filter (A.F) used when the high voltage is set on (b) both sides and (d) on right side of PCB-3. The HV value is set at +570 V for the operation gas mixture with a consistency of 93% Ar and 7% CO₂. The VMM parameters for the peaking time is set at 100 ns and the gain at 9 mV/fC. The data were recorded on 14th and 15th December 2021 out of the beam period.

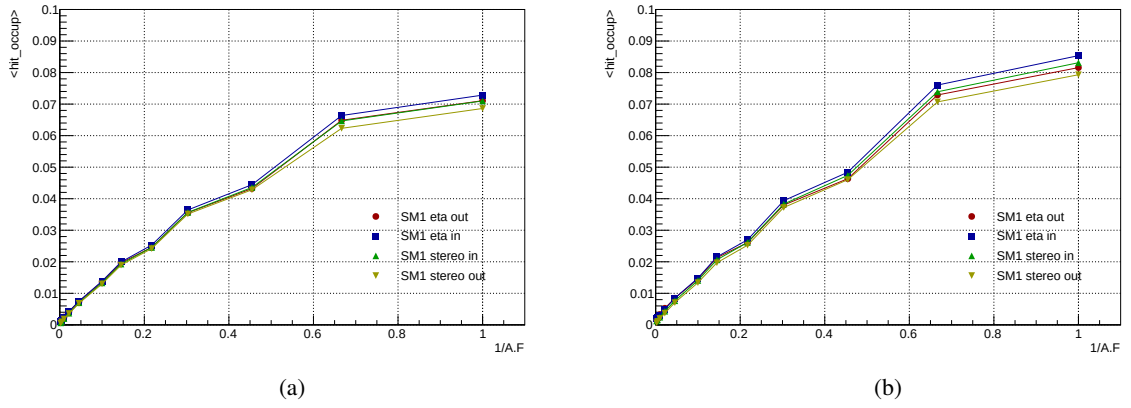


Figure B.3: The mean hit occupancy as function of the inversed value of the attenuation filter (A.F) used for VMM peaking time (a) 200 ns and (b) 100 ns. The high voltage is set on the right side of PCB-3 whereas the value is set in order to achieve equal currents among the layers. The operation gas mixture with a consistency of 93% Ar and 7% CO₂ is used. The VMM gain is set at 9 mV/fC. The data were recorded on 16th December 2021 out of the beam period.

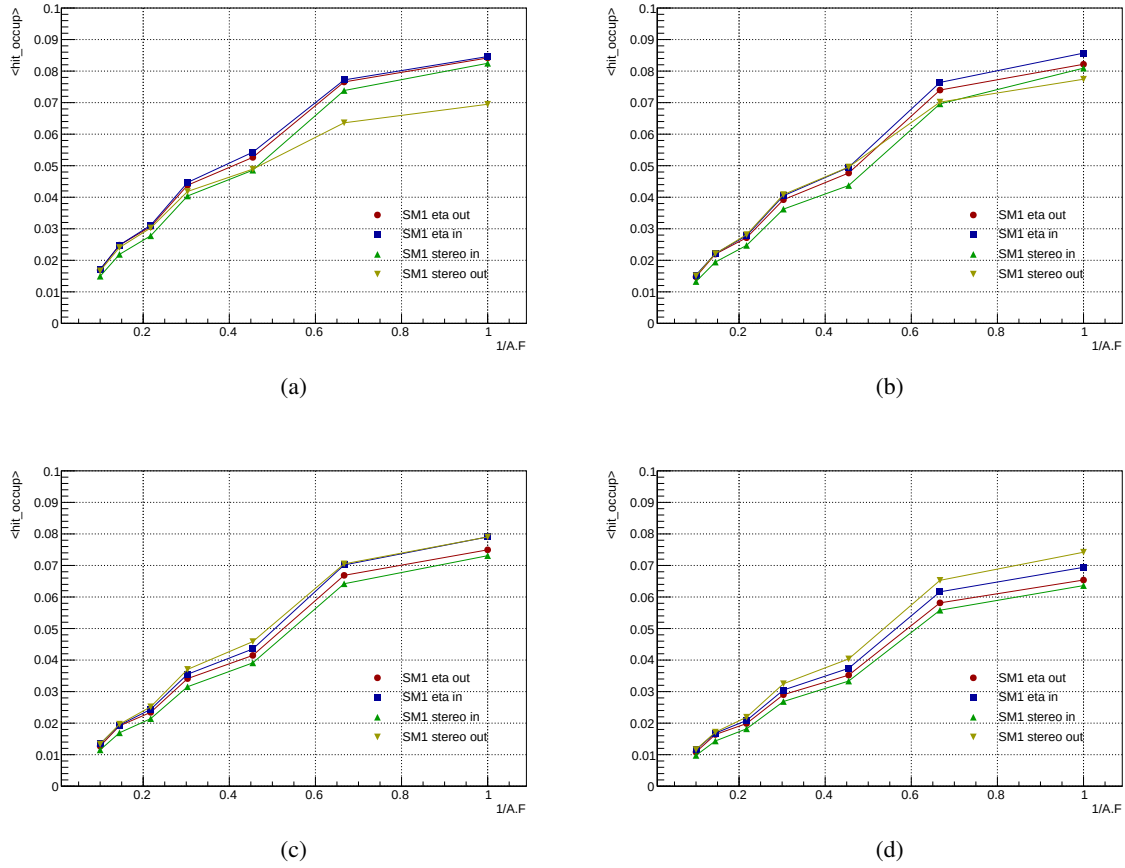
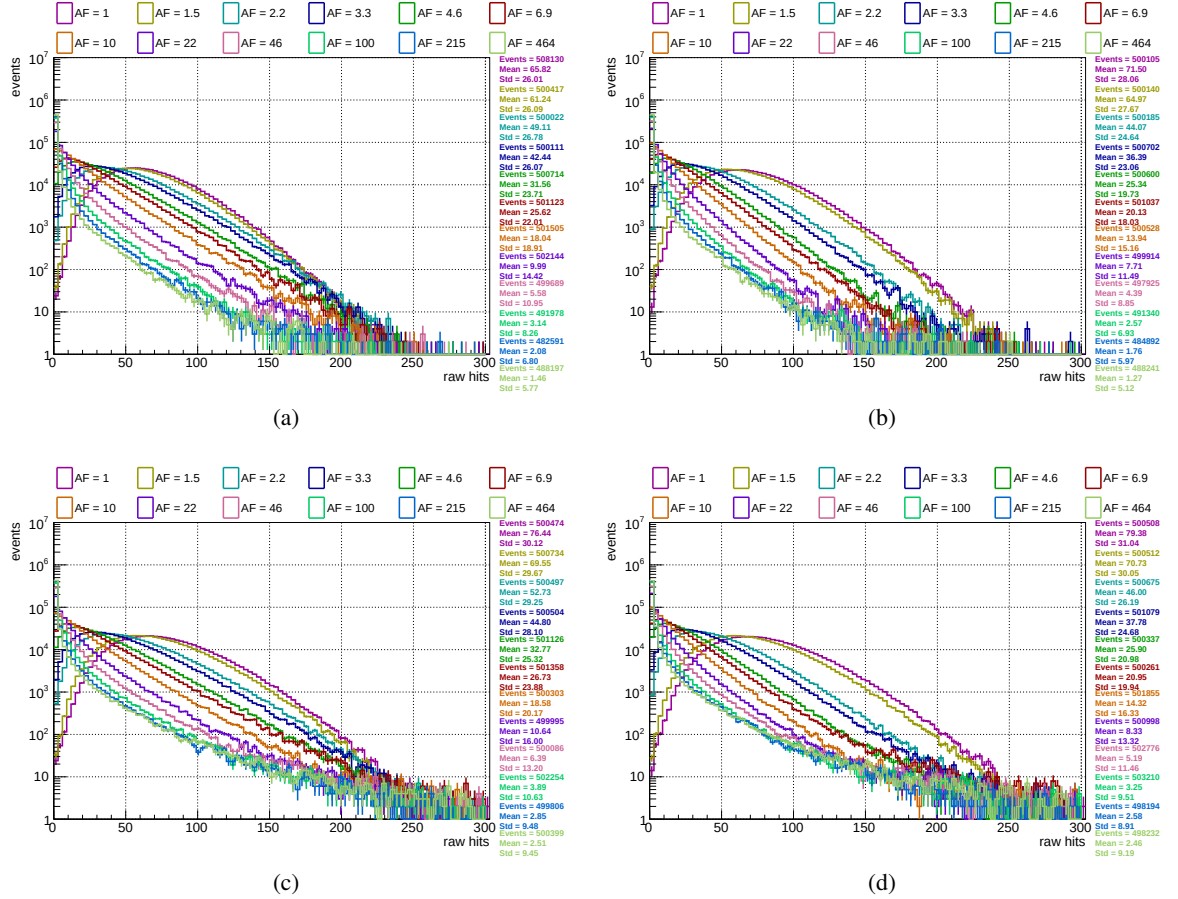


Figure B.4: The mean hit occupancy as function of the inversed value of the attenuation filter (A.F) used when the high voltage is set on half PCB-3 at (a) +570 V, (b) +560 V, (c) +550 V and (d) +540 V. The operation gas mixture with a consistency of 93% Ar and 7% CO₂ is used. The VMM parameters for the peaking time is set at 100 ns and the gain at 9 mV/fC. The data were recorded on 15th December 2021 out of the beam period.



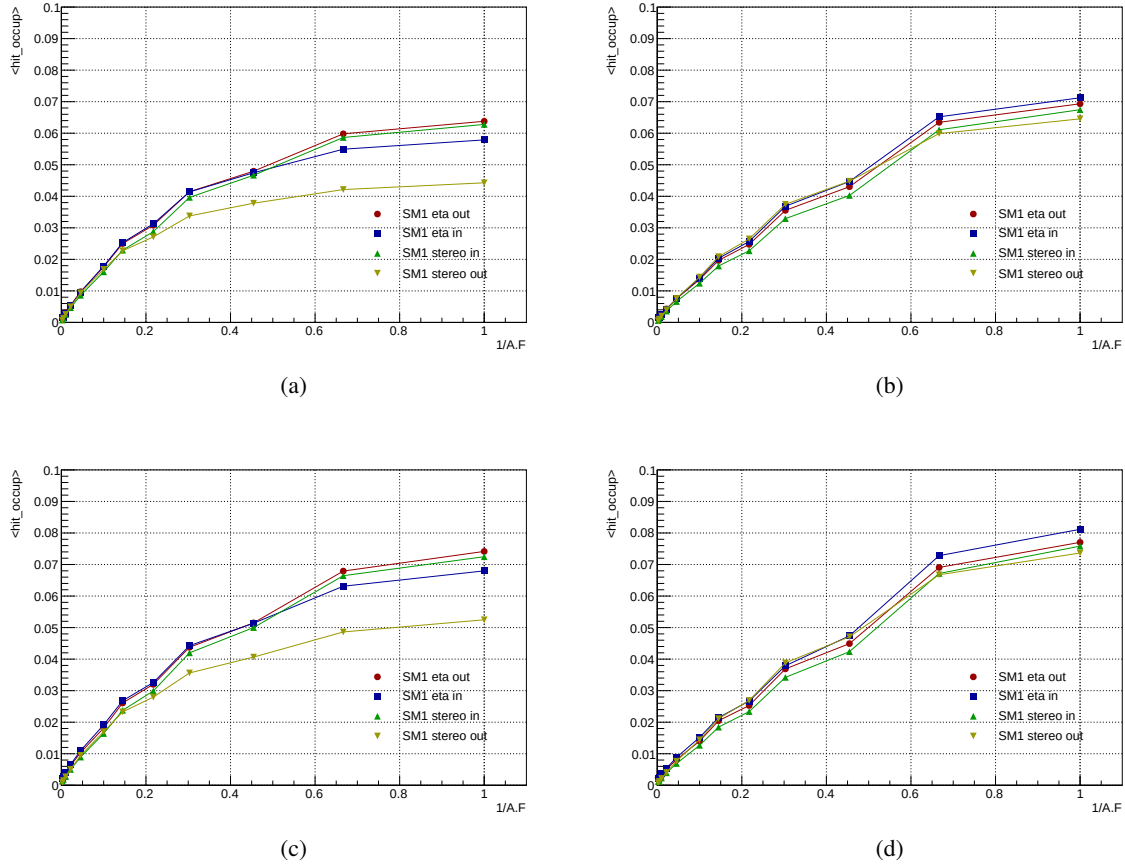


Figure B.6: The mean hit occupancy as function of the inversed value of the attenuation filter (A.F) used when the high voltage is set on half PCB-3 and the VMM peaking time is set at (a) +520 V and 200 ns, (b) +500 V and 200 ns, (c) +520 V and 100 ns and (d) +500 V and 100 ns. The operation gas mixture with isobutane is used. The VMM gain is set at 9 mV/fC. The data were recorded on 8th and 10th December 2021 out of the beam period.

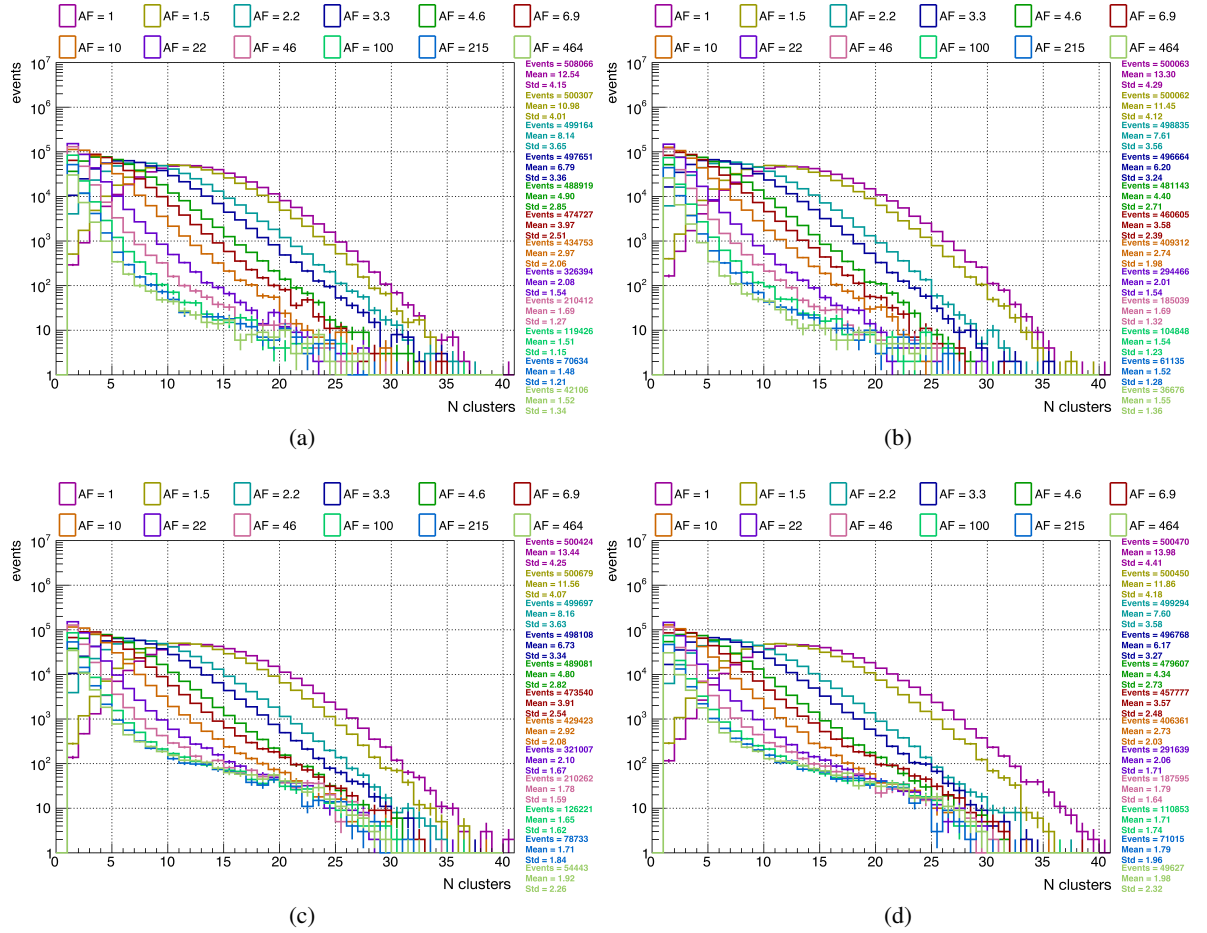


Figure B.7: The distribution of the number reconstructed clusters for different values of the attenuation filter (A.F) used when the high voltage is set on half PCB-3 and the VMM peaking time is set at (a) +520 V and 200 ns, (b) +500 V and 200 ns, (c) +520 V and 100 ns and (d) +500 V and 100 ns. The operation gas mixture with isobutane is used. The VMM gain is set at 9 mV/fC. The data were recorded on 8th and 10th December 2021 out of the beam period.

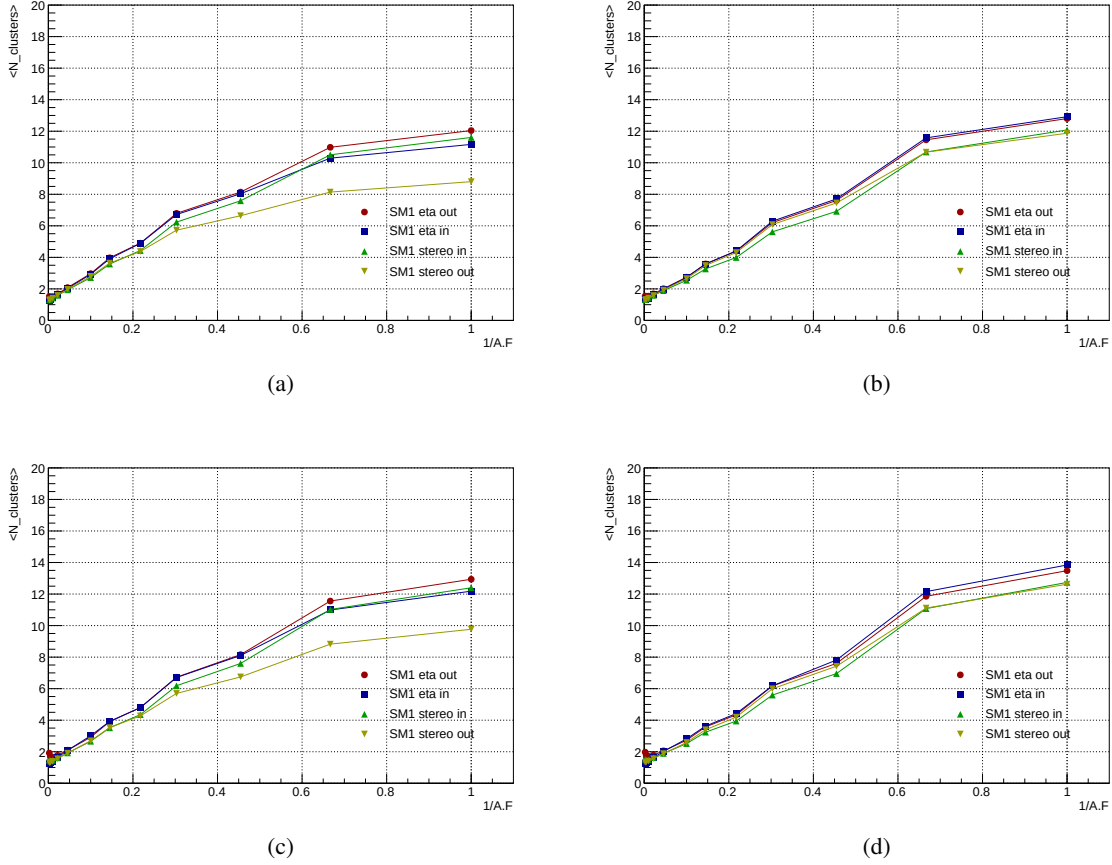


Figure B.8: The mean number of reconstructed clusters as function of the inversed value of the attenuation filter (A.F) used when the high voltage is set on half PCB-3 and the VMM peaking time is set at (a) +520 V and 200 ns, (b) +500 V and 200 ns, (c) +520 V and 100 ns and (d) +500 V and 100 ns. The operation gas mixture with isobutane is used. The VMM gain is set at 9 mV/fC. The data were recorded on 8th and 10th December 2021 out of the beam period.

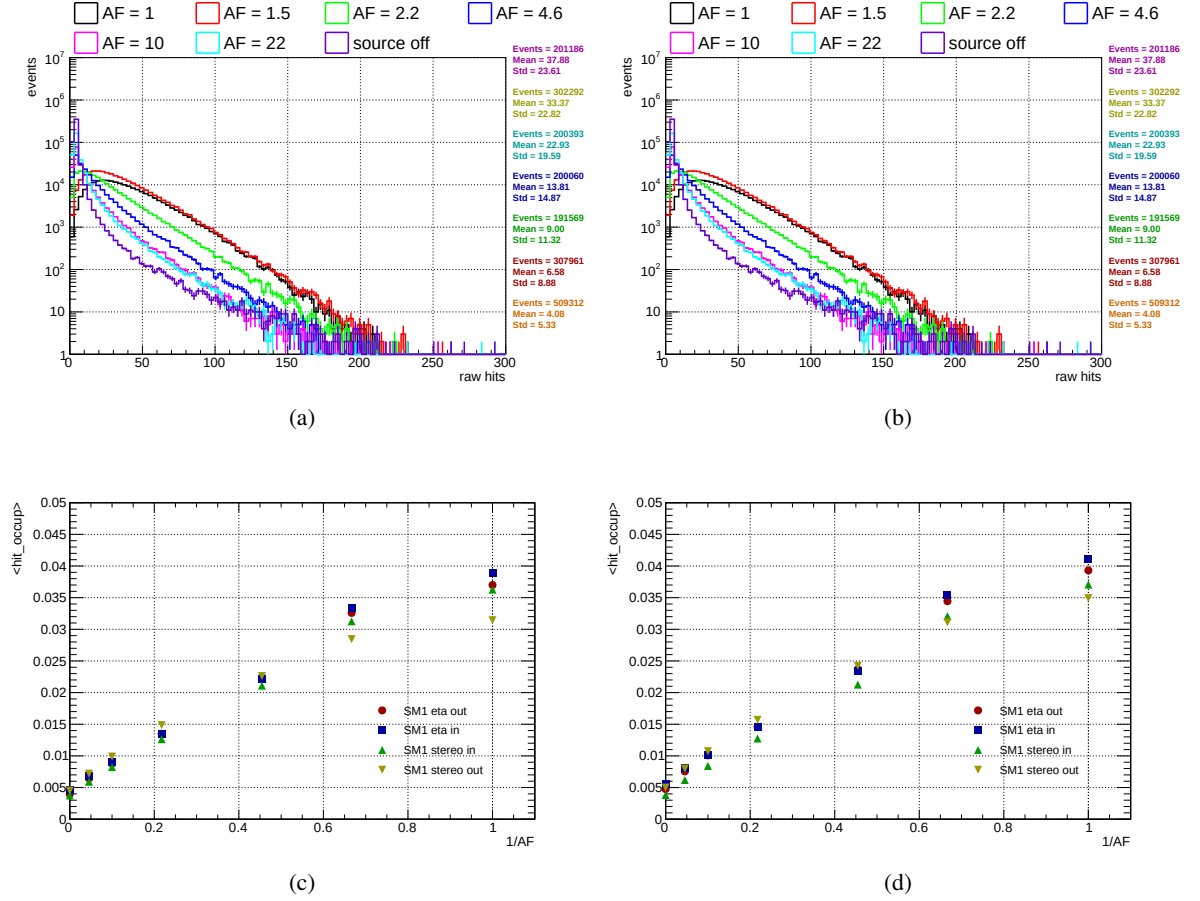


Figure B.9: The distribution of the raw hits for different attenuation filter (A.F) values used for VMM peaking time (a) 200 ns and (b) 100 ns. The mean hit occupancy as function of the inversed value of the A.F used for VMM peaking time (c) 200 ns and (d) 100 ns. The high voltage is set on the right side of PCB-3 at +520 V. The operation gas mixture with isobutane is used. The VMM gain is set at 9 mV/fC. The data were recorded on July 2022 with muon beam and source on and the run details are documented in Chapter 6.

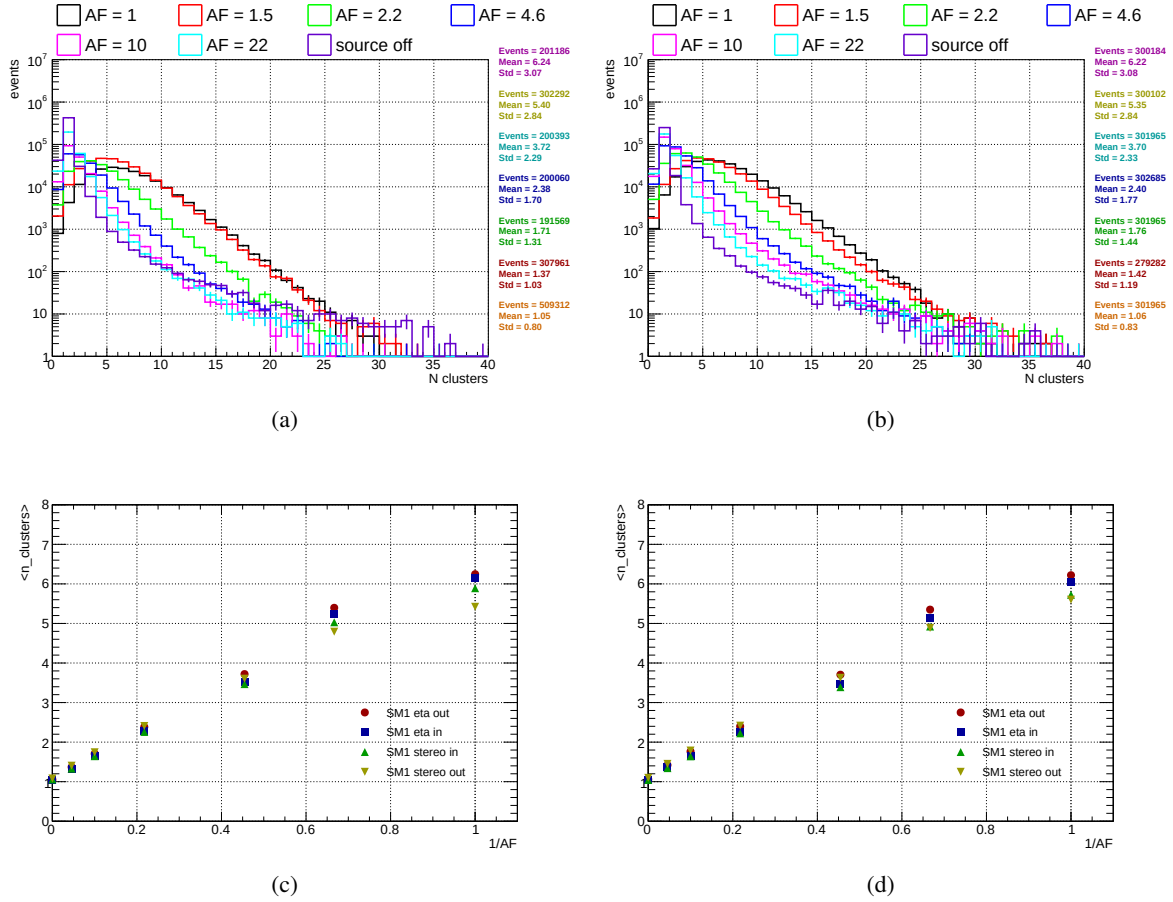


Figure B.10: The distribution of the reconstructed clusters for different attenuation filter (A.F) values used for VMM peaking time (a) 200 ns and (b) 100 ns. The mean number of reconstructed clusters as function of the inversed value of the A.F used for VMM peaking time (c) 200 ns and (d) 100 ns. The high voltage is set on the right side of PCB-3 at +520 V. The operation gas mixture with isobutane is used. The VMM gain is set at 9 mV/fC. The data were recorded on July 2022 with muon beam and source on and the run details are documented in Chapter 6.

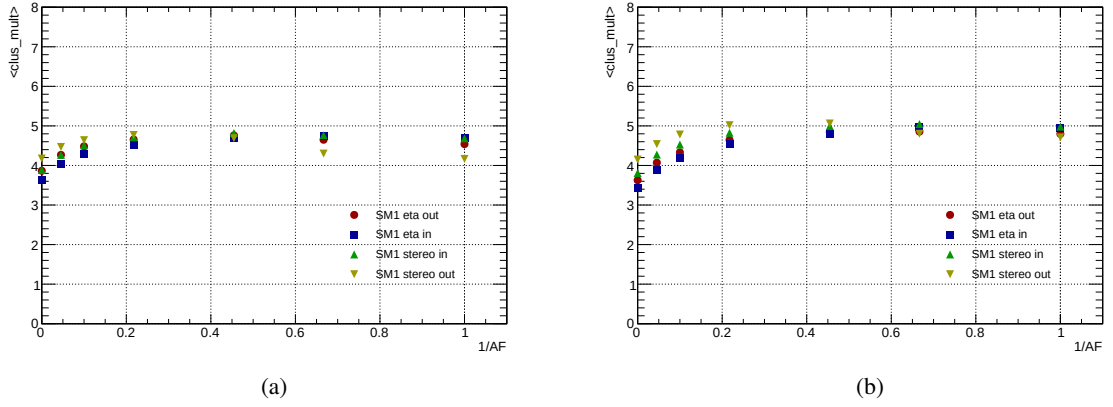


Figure B.11: The mean number of strips per reconstructed cluster as function of the inversed value of the A.F. used for VMM peaking time (a) 200 ns and (b) 100 ns. The high voltage is set on the right side of PCB-3 at +520 V. The operation gas mixture with isobutane is used. The VMM gain is set at 9 mV/fC. The data were recorded on July 2022 with muon beam and source on and the run details are documented in Chapter 6.

B.3 Chamber alignment & corrections

Several checks and iterations were performed to align the test beam's setup presented in Section 6.2. All chambers were aligned with respect to the prototype chamber that was positioned outside the irradiation field, i.e SBY1. Therefore correlations between the SBY1 and all other chambers were calculated. A linear fit was performed and the results of the fit were passed as corrections to the corresponding layer's strip positions. Figure B.12 shows an example for the attempt to align the SBY2 chamber.

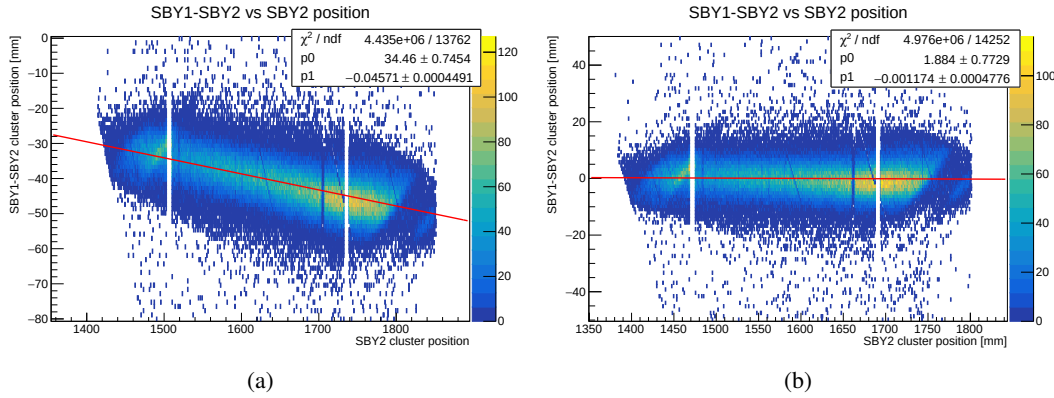


Figure B.12: Correlations between the reconstructed cluster positions in SBY1 and SBY2 (a) before and (b) after the alignment. The result after a linear fit (red line) of (a) are used to correct the chamber's strip position. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

Particularly, for SM1, the eta out layer was aligned with respect to SBY1 and the results from the fit were used to align the other SM1 layers. To a second order, by checking the residuals between the layers an additional shift was inserted as a correction to the strip position as necessary.

Due to geometry imperfections of the large scaled MMG there is not always one to one correspondence of MMFE8 channel to the readout element. These imperfections were observed during the alignment procedure as shifts of the order of $\sim 1 - 2$ strip pitch. Examples showing these shifts between MMFE8 card and for some cases between VMMs are presented in Figure B.13. These imperfections were corrected prior to the alignment of the whole chamber. However, it was not obvious for which of the layers these corrections had to be applied. Therefore, the alignment was checked and corrected again as necessary using information by the reconstructed muon tracks.

For the spatial resolution study, a hidden component had been observed in the shape of the residual distributions leading to slightly worse results (Figure B.14) than those discussed in Chapter 6. A correlation (Figure B.15) between the residuals and the reconstructed track angle was observed and corrected.

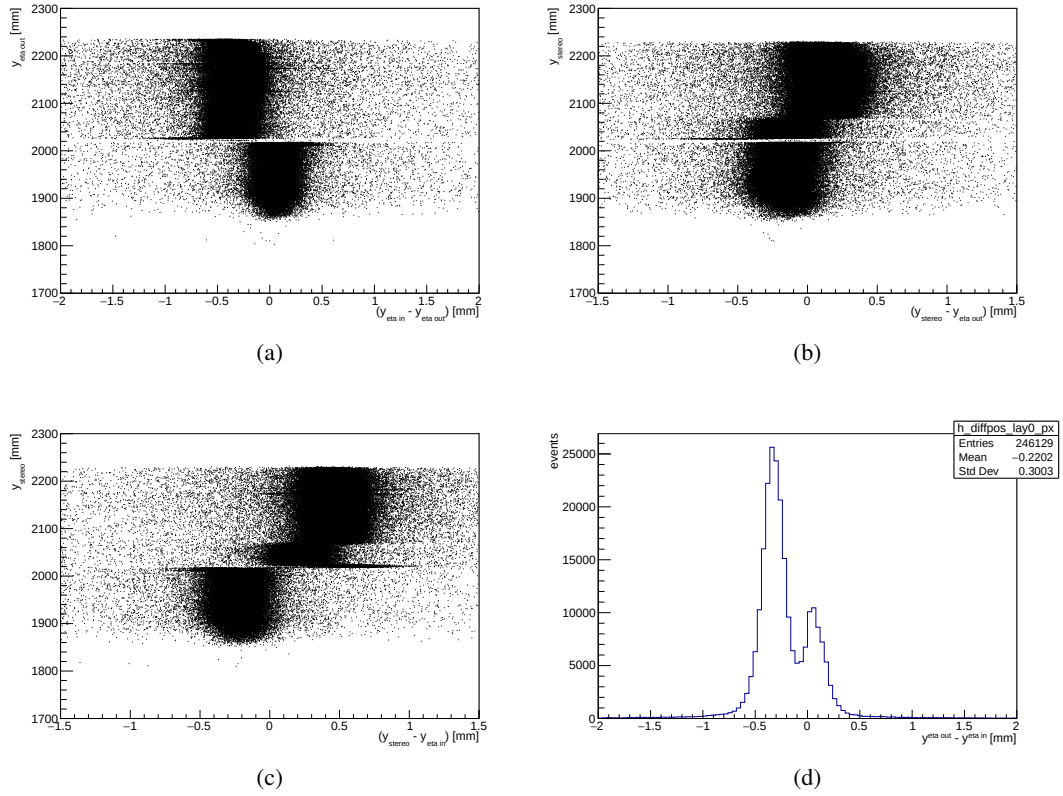


Figure B.13: (a)-(c) Example cases showing the misalignment of the connected MMFE8s. In (c) a misalignment at VMM level is also visible. This kind of misalignment results to residual distributions, like (d), that are not centered at zero whereas an additional peak is observed at the tails. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

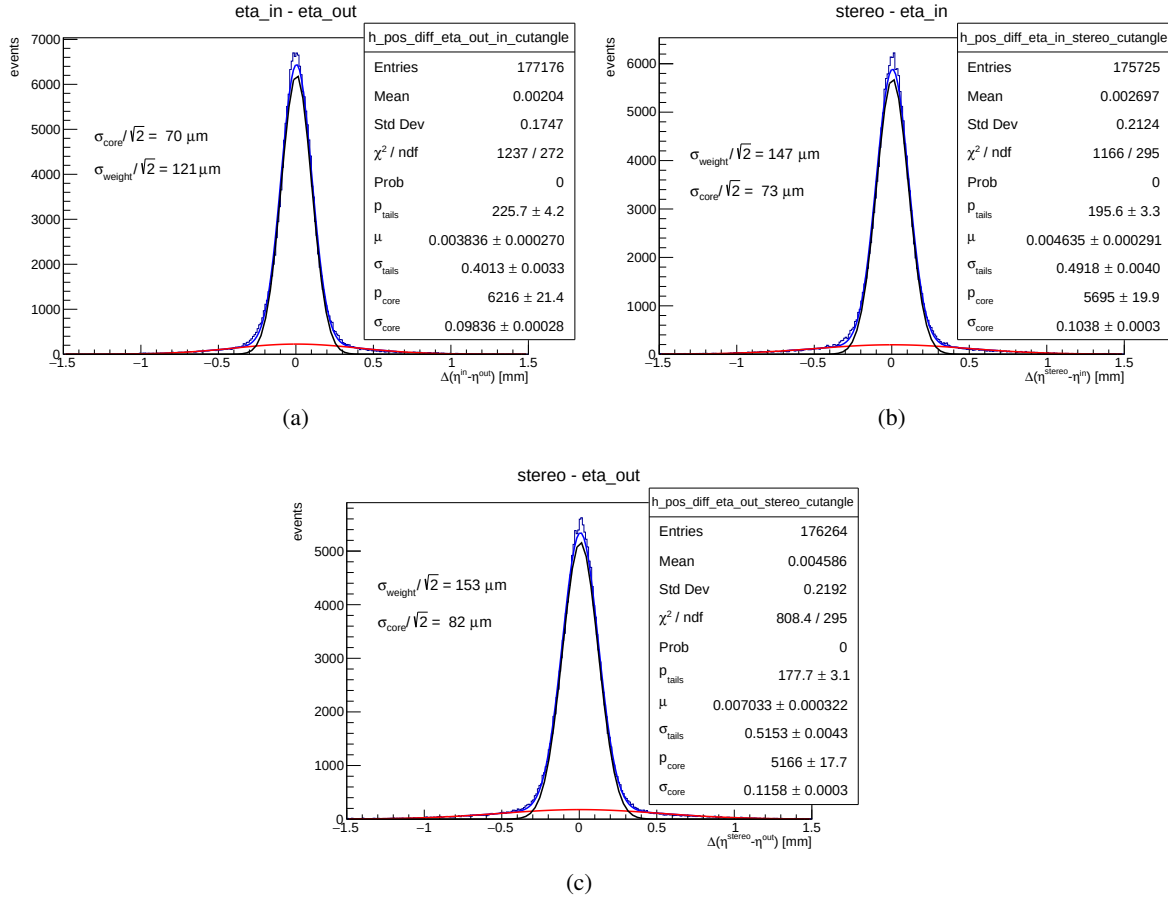


Figure B.14: The distribution of residuals as calculated between the (a) two eta layers, (b) eta in and combined stereo information and (c) eta in and combined stereo information. The extracted resolutions as result of the fit with a double gaussian function (blue line, $\sigma_{\text{weight}} / \sqrt{2}$) as well as with a simple gaussian function (black line, $\sigma_{\text{core}} / \sqrt{2}$) are reported. A hidden component coming from the reconstructed track angle is present. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

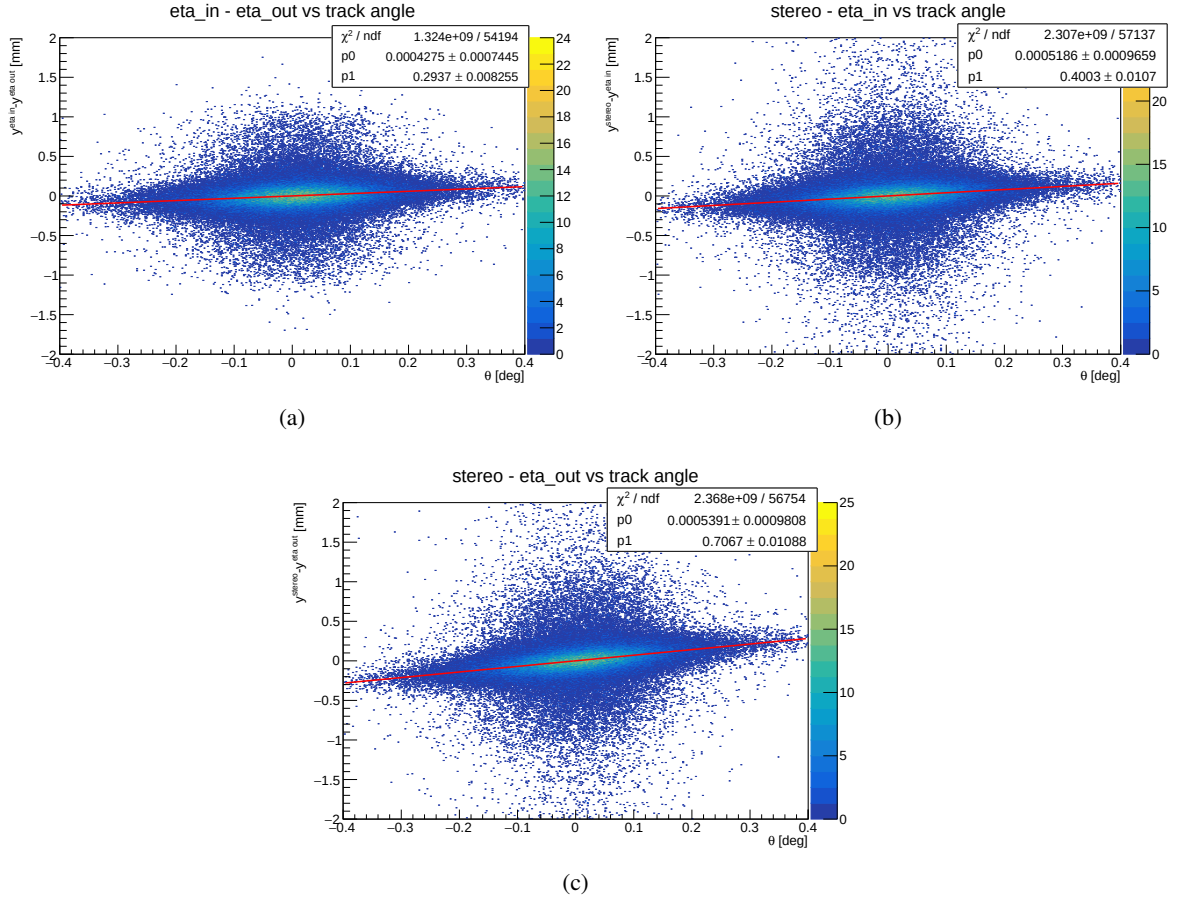


Figure B.15: Observed correlations between the residuals of (a) two eta layers, (b) eta in and combined stereo information and (c) eta in and combined stereo information and the reconstructed track angle. The plots are produced from run 1658081138 with muon beam ON and γ source OFF.

B.4 Impact of oxygen contamination in Micromegas detectors

Once an electron passes through the metallic mesh into the amplification region, due to the strong electric field an avalanche of electron-ion pairs is formed. The number of the electron-ion pairs define the avalanche size or gas gain. In other words, the avalanche size distribution can be described in terms of a probability that an electron with initial momentum created at a position in the drift region reaches the metallic mesh, passes in the amplification region and produces through the avalanche process a readable signal by the detector electronics. Therefore, it consists an important parameter for the detector performance.

The properties of the gas mixture, the electric field, the environmental conditions inside the detector's active volume as well as the initial momentum and position of the electron are subjects to the avalanche size distribution [124].

It is of particular interest to study the impact of air in the gas mixture. The oxygen existing in the air can be inserted by diffusion mechanism in the detector. Because it is electronegative it tends to capture electrons and a degradation in the gas gain is expected. Although a qualitative estimate of the effect can be made by theoretical approaches [125], a detailed simulation, using the microscopic tracking algorithms in Garfield++ toolkit [126], could give more accurate results as the particular detector's geometry characteristics could be considered.

For the detailed geometry description and the electric field calculation, Garfield++ interfaces to applications like gmsh [127] and ElmerFEM [128]. Moreover, it shares functionality with Magboltz [129] for the definition of the electron transport parameters in gas mixtures.

The drift gap is defined by a planar drift electrode positioned 5 mm above the metallic mesh, i.e a grid made by cylindrical wires of radius 15 μm and a pitch of 100 μm . The anode is defined by a planar electrode positioned 128 μm below the metallic mesh whereas it is segmented in strips of 300 μm wide, 20 μm in height and with a pitch of 400 μm . The drift cathode plane was set at -300 V and the anode plane at +540 V. The metallic mesh was kept at ground. This voltage configuration results to an electric field of around 600 V/cm and 42 kV/cm in the drift and amplification regions respectively. Finally, the gas mixture Ar/CO₂:93/7 was simulated. Keeping the two components of the gas mixture at the same ratio, different fractions of N₂/O₂:79/21 were introduced in the gas mixture (neglecting the other components of air). These fractions correspond to 0.005%, 0.02%, 0.25%, 0.5%, 1%, 2% and 5% of air contamination in the under study gas mixture.

A thousand electrons were released at different positions above the metallic mesh with an initial energy of 0 eV. Figure B.16 shows the calculated probability of the electrons reaching the metallic mesh as a function of the air contamination in the gas mixture. As expected, the presence of air leads to a strong attachment preventing the electrons from reaching the metallic mesh and depends on the distance the electron has to cover. A similar effect is expected in the amplification region. However, experimental measurements of the mole fraction of air inside NSW MMG modules were performed and a contamination of air of 80 ppm for LM1 and 90 ppm for SM1 in average were reported [130]. These levels of oxygen detection in the gas mixture are negligible to make impact on the detector's performance.

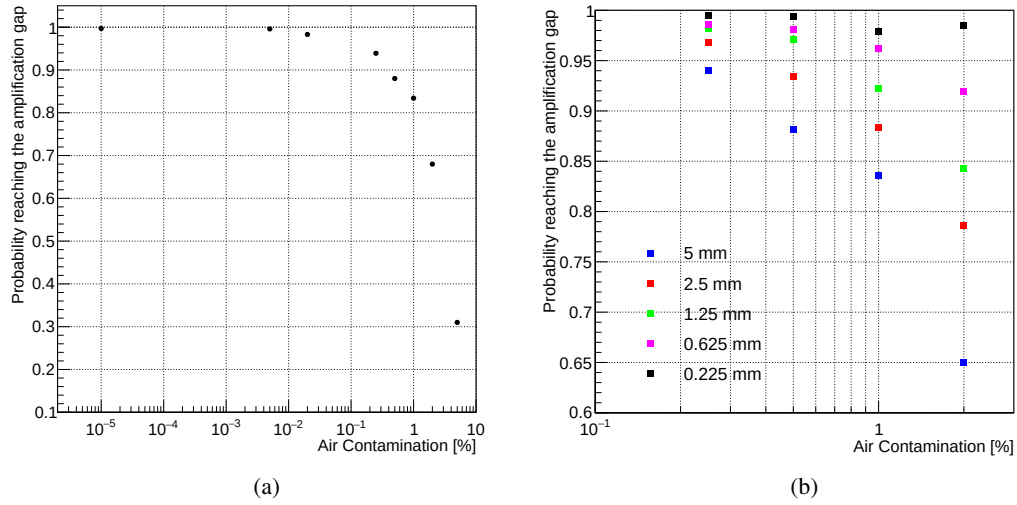


Figure B.16: The probability reaching the amplification region for a single electron released from (a) 5 mm (cathode) and (b) different positions above the metallic mesh as a function of air fractions that contaminate the operating gas mixture.

B.5 Prediction of perpendicular tracks position in Micromegas detectors

This study hasn't reached final conclusions yet. The workflow is documented for future investigation.

A thousand normal muon tracks, with initial energy of 4 GeV, were transported inside the Micromegas geometry discussed in Appendix B.4 using the gas mixture Ar/CO₂:93/7. Each track was initiated above the middle of a strip, at the level of the cathode electrode. The electrons as products of the gas ionisation were drifting inside the drift region while their positions at the mesh level were filled in a histogram, representing their diffusion. The distribution was fitted with an exponential and a gaussian function and is shown in Figure B.17.

Random numbers, x_i , uniformly distributed in a chamber consisting of n strips represent the muon tracks position. By using the fitting function and the generated random number the charge distribution on the strips can be described. The aim of this study is to make predictions of the tracks position, x_i , in the chamber based on the charge information induced on the anode strips.

The strip with the highest charge is called as the middle strip. For a chamber that consists of $n = 20$ strips, with a pitch of 0.4 mm, the cluster multiplicity as function of the cut value imposed on each strip's charge compared to the charge deposited on the middle strip is presented in Figure B.18.

Several predictions of the track position inside the chamber can be made based on the charge deposits on the strips. First, the total charge induced on the strips that are found at the left side of the middle

strip is compared to the charge induced on the strips placed at its right side. If x_0 is the position of the strip with the highest charge (middle strip), the following predictions can be made:

- $Q_{\text{left}} > Q_{\text{right}}$

$$x_a = x_0 - (\text{pitch}) \frac{Q_{\text{left}}}{Q_{\text{middle}}}$$

$$x'_a = x_0 - (\text{pitch}) \frac{Q_{\text{left}}}{Q_{\text{left}} + Q_{\text{middle}} + Q_{\text{right}}}$$

$$x_b = x_0 - (\text{pitch}) \frac{Q_{\text{right}}}{Q_{\text{middle}}}$$

$$x'_b = x_0 - (\text{pitch}) \frac{Q_{\text{right}}}{Q_{\text{left}} + Q_{\text{middle}} + Q_{\text{right}}}$$

- $Q_{\text{left}} < Q_{\text{right}}$

$$x_a = x_0 - (\text{pitch}) \frac{Q_{\text{right}}}{Q_{\text{middle}}}$$

$$x'_a = x_0 - (\text{pitch}) \frac{Q_{\text{right}}}{Q_{\text{left}} + Q_{\text{middle}} + Q_{\text{right}}}$$

$$x_b = x_0 - (\text{pitch}) \frac{Q_{\text{left}}}{Q_{\text{middle}}}$$

$$x'_b = x_0 - (\text{pitch}) \frac{Q_{\text{left}}}{Q_{\text{left}} + Q_{\text{middle}} + Q_{\text{right}}}$$

- $Q_{\text{left}} = Q_{\text{right}}$

$$x_a = x'_a = x_b = x'_b = x_0$$

Similar predictions can be made after accounting the charge sharing ($\alpha = 16\%$) between the strips. Therefore the charges are redefined as:

$$Q'_{\text{left}} = (1 - \alpha)Q_{\text{left}} + \alpha Q_{\text{middle}}$$

$$Q'_{\text{middle}} = (1 - 2 \cdot \alpha)Q_{\text{middle}} + \alpha Q_{\text{left}} + \alpha Q_{\text{right}}$$

$$Q'_{\text{right}} = (1 - \alpha)Q_{\text{right}} + \alpha Q_{\text{middle}}$$

Finally, the prediction of the track position can be made according to the charge centroid method:

$$x_c = \frac{\sum_i Q_i x_i}{\sum_i Q_i}$$

where x_i is the strip's position and Q_i its charge.

Some examples of the best predictions are presented in Figure B.19 and Figure B.20 for a cut value set at 0.02 and 0.05 respectively.

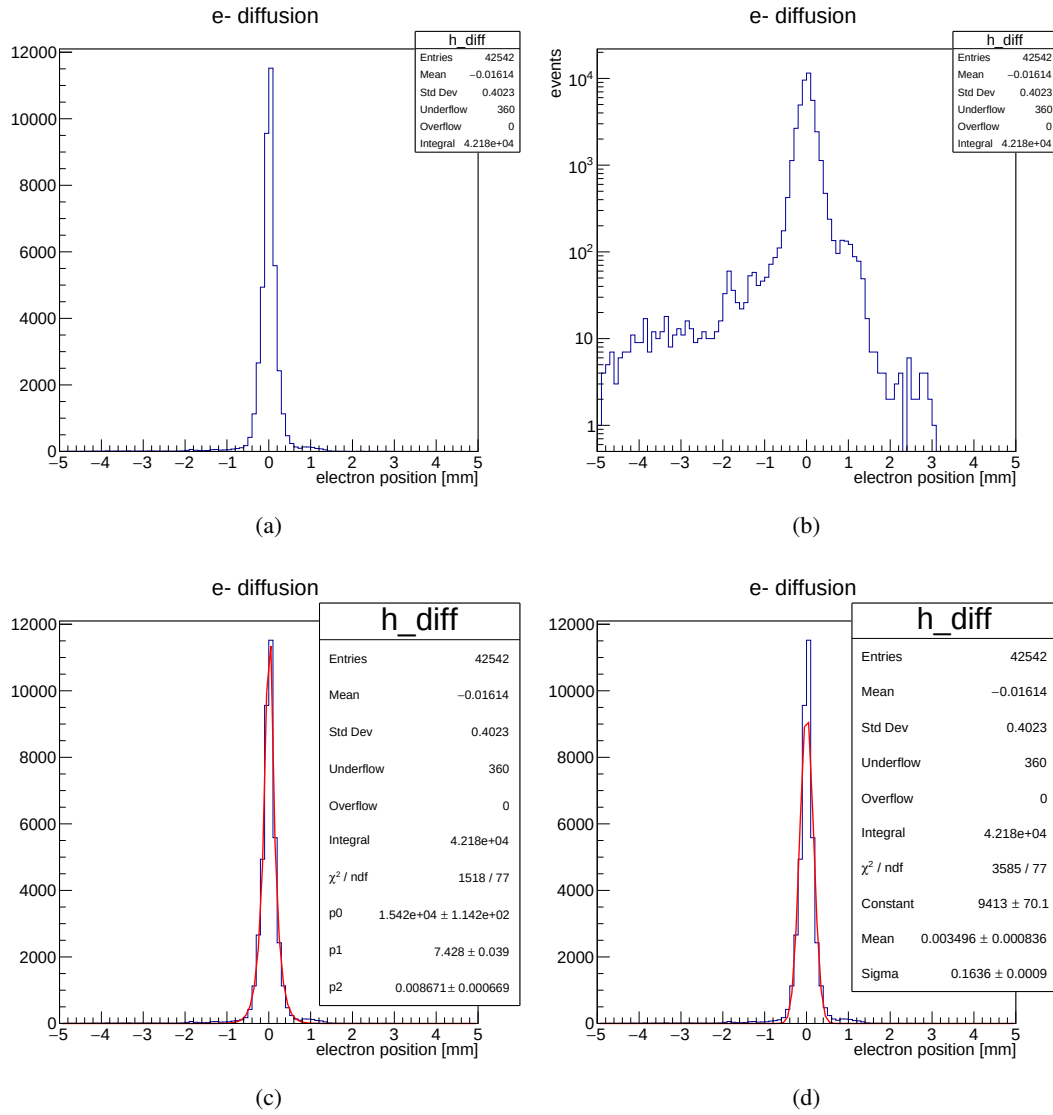


Figure B.17: The electron position at mesh level shown in (a) linear and (b) logarithmic scale. The distribution is fitted with (c) an exponential function ($[0] * \text{TMath::Exp}(-[1] * \text{TMath::Abs}(x - [2]))$) and (d) a simple gaussian function.

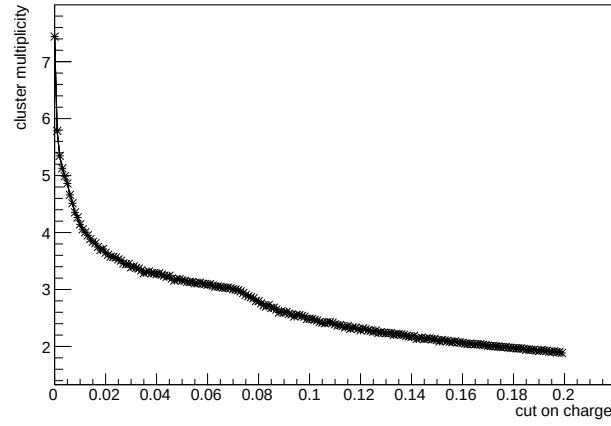


Figure B.18: The strip multiplicity as function of the cut value imposed on each strip's charge.

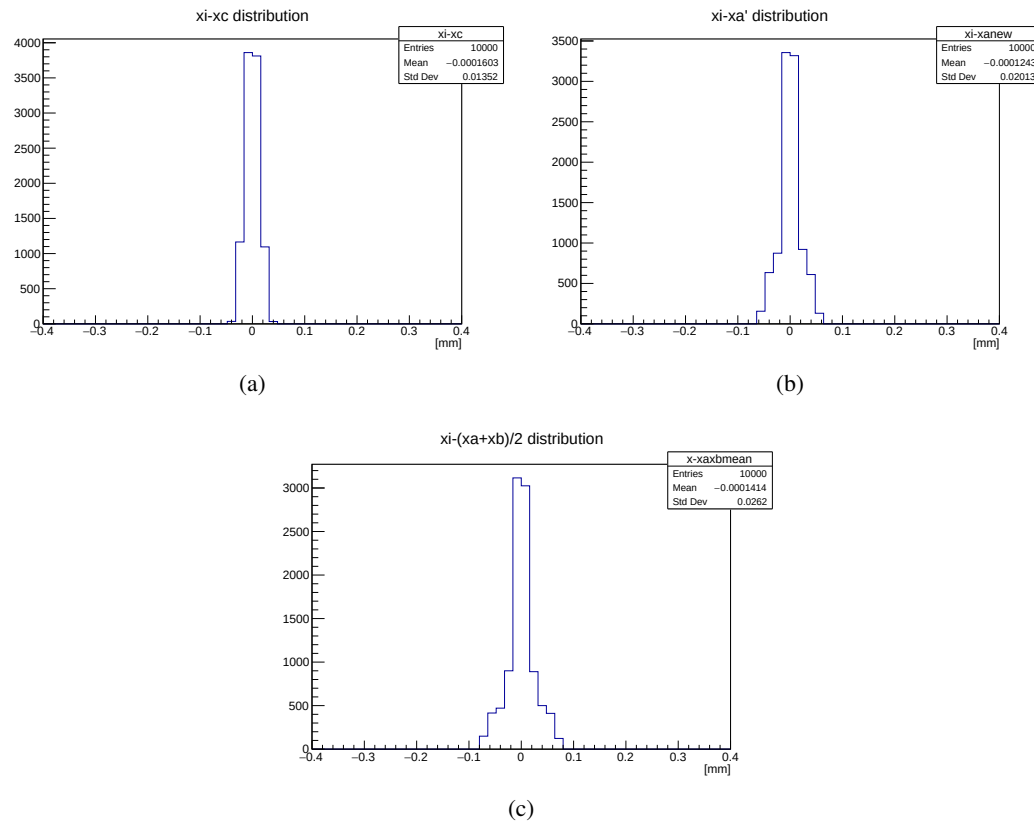


Figure B.19: The predictions compared to the real track position x_i for the (a) charge centroid method, (b) x'_a and (c) $(x_a + x_b)/2$. The cut value on the strip charge is set at 0.02.

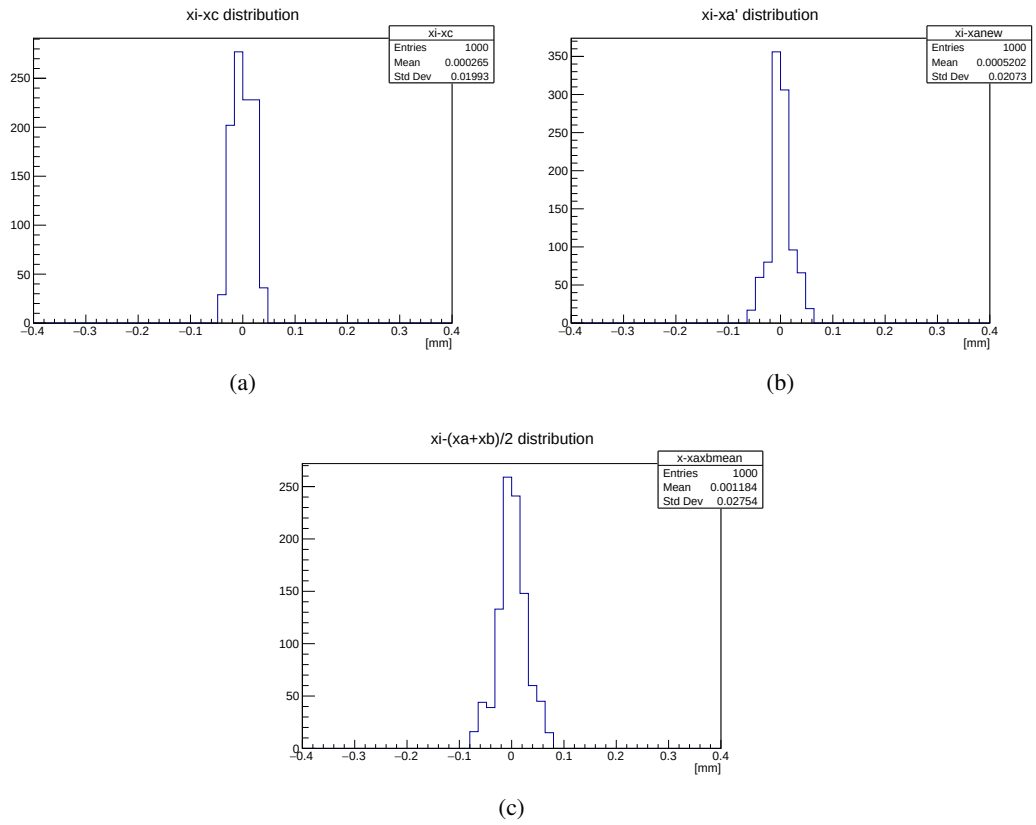


Figure B.20: The predictions compared to the real track position x_i for the (a) charge centroid method, (b) x'_a and (c) $(x_a + x_b)/2$. The cut value on the strip charge is set at 0.05.

C Additional Material on the Fake Factor Method

C.1 Fake Factor pileup study

This section serves as auxiliary material for the studies presented in Section 8.3.1.

The event yields at the selection cuts for the fake leptons in each of the pileup regions defined are shown in Table C.1.

The MC fake factors measured in bins of pileup are presented in Figure C.1.

C.1.1 Event yields

Table C.1: Event yields in the Z+jets CR for the full Run 2 dataset. For each fake lepton type at the selection cuts, the yields are shown for different bins of pileup (μ).

$\sqrt{s} = 13\text{TeV}$, $\mathcal{L} = 139\text{fb}^{-1}$ (Full Run 2)	Z+jets Powheg	V + γ	WW	WZ	ZZ	Top	VVV	Total Bkg	Data	fakes	ZFake purity(%)
fake type: electron	27114.88 $\pm$ 86.05	3032.25 $\pm$ 128.88	9.38 $\pm$ 0.86	3632.34 $\pm$ 14.64	1508.23 $\pm$ 10.24	570.31 $\pm$ 4.41	7.95 $\pm$ 0.13	8760.46 $\pm$ 130.19	32627	23866.54 $\pm$ 222.66	73.15 $\pm$ 0.79
fake el η cut	21365.18 $\pm$ 76.58	2703.91 $\pm$ 122.21	7.04 $\pm$ 0.82	3430.76 $\pm$ 14.36	1418.90 $\pm$ 9.36	526.99 $\pm$ 4.23	7.54 $\pm$ 0.12	8095.13 $\pm$ 123.48	26946	18850.87 $\pm$ 205.41	69.96 $\pm$ 0.87
Scale factors				NF = 0.99 $\pm$ 0.01				NF = 0.99 $\pm$ 0.01		NF = 0.99 $\pm$ 0.01	
ID cuts	1823.04 $\pm$ 22.64	619.48 $\pm$ 56.81	0.37 $\pm$ 0.19	2759.50 $\pm$ 12.98	1026.22 $\pm$ 6.11	167.46 $\pm$ 1.67	6.22 $\pm$ 0.11	4579.25 $\pm$ 58.61	6349	1769.75 $\pm$ 98.92	27.87 $\pm$ 1.60
0 < μ < 18	188.40 $\pm$ 7.40	66.88 $\pm$ 22.16	0.06 $\pm$ 0.05	292.33 $\pm$ 5.42	114.26 $\pm$ 2.11	17.62 $\pm$ 0.56	0.68 $\pm$ 0.04	491.83 $\pm$ 22.91	635	143.17 $\pm$ 34.06	22.55 $\pm$ 5.44
18 < μ < 24	303.21 $\pm$ 9.31	123.53 $\pm$ 28.09	-0.11 $\pm$ 0.10	474.31 $\pm$ 4.80	178.22 $\pm$ 2.61	27.12 $\pm$ 0.64	1.04 $\pm$ 0.05	804.12 $\pm$ 28.62	1077	272.88 $\pm$ 43.55	25.34 $\pm$ 4.12
24 < μ < 32	518.87 $\pm$ 12.28	140.96 $\pm$ 27.68	0.06 $\pm$ 0.02	779.85 $\pm$ 6.42	288.49 $\pm$ 3.25	46.89 $\pm$ 0.91	1.73 $\pm$ 0.06	1257.97 $\pm$ 28.61	1705	447.03 $\pm$ 50.24	26.22 $\pm$ 3.01
32 < μ < 40	385.84 $\pm$ 10.53	165.44 $\pm$ 29.00	0.16 $\pm$ 0.10	605.04 $\pm$ 7.08	223.17 $\pm$ 2.98	36.42 $\pm$ 0.77	1.40 $\pm$ 0.05	1031.62 $\pm$ 30.01	1421	389.38 $\pm$ 48.18	27.40 $\pm$ 3.47
40 < μ < 50	286.01 $\pm$ 8.44	92.57 $\pm$ 16.27	0.22 $\pm$ 0.11	428.76 $\pm$ 4.67	151.86 $\pm$ 2.23	26.69 $\pm$ 0.67	0.91 $\pm$ 0.04	701.01 $\pm$ 17.09	1023	321.99 $\pm$ 36.26	31.48 $\pm$ 3.68
μ > 50	140.72 $\pm$ 6.19	30.11 $\pm$ 8.68	-0.02 $\pm$ 0.02	204.64 $\pm$ 2.44	70.22 $\pm$ 1.28	12.71 $\pm$ 0.46	0.46 $\pm$ 0.03	318.13 $\pm$ 9.12	488	169.87 $\pm$ 23.90	34.81 $\pm$ 5.14
Scale factors				NF = 0.99 $\pm$ 0.01				NF = 0.99 $\pm$ 0.01		NF = 0.99 $\pm$ 0.01	
Anti-ID cuts	19542.13 $\pm$ 73.15	2084.43 $\pm$ 108.21	6.67 $\pm$ 0.80	639.93 $\pm$ 5.83	392.69 $\pm$ 7.09	359.53 $\pm$ 3.89	1.32 $\pm$ 0.05	3484.56 $\pm$ 108.67	20597	17112.44 $\pm$ 180.02	83.08 $\pm$ 1.05
0 < μ < 18	2023.59 $\pm$ 24.17	153.61 $\pm$ 32.13	0.44 $\pm$ 0.37	50.73 $\pm$ 1.76	35.78 $\pm$ 2.33	38.03 $\pm$ 1.37	0.12 $\pm$ 0.02	278.72 $\pm$ 32.30	2025	1746.28 $\pm$ 55.39	86.24 $\pm$ 3.34
18 < μ < 24	3229.48 $\pm$ 29.70	356.28 $\pm$ 40.59	1.06 $\pm$ 0.26	94.73 $\pm$ 2.21	63.79 $\pm$ 3.16	59.24 $\pm$ 1.64	0.16 $\pm$ 0.02	575.25 $\pm$ 40.80	3344	2768.75 $\pm$ 70.77	82.80 $\pm$ 2.56
24 < μ < 32	5395.31 $\pm$ 39.21	668.80 $\pm$ 61.35	1.19 $\pm$ 0.41	178.25 $\pm$ 3.20	110.36 $\pm$ 4.26	101.82 $\pm$ 2.12	0.35 $\pm$ 0.03	1060.77 $\pm$ 61.62	5576	4515.23 $\pm$ 96.81	80.98 $\pm$ 2.05
32 < μ < 40	4306.87 $\pm$ 34.84	415.06 $\pm$ 56.52	2.07 $\pm$ 0.36	146.72 $\pm$ 2.40	86.51 $\pm$ 2.82	77.57 $\pm$ 1.77	0.30 $\pm$ 0.03	728.23 $\pm$ 56.67	4474	3745.77 $\pm$ 87.67	83.72 $\pm$ 2.33
40 < μ < 50	3079.54 $\pm$ 27.27	321.78 $\pm$ 36.36	1.13 $\pm$ 0.30	113.62 $\pm$ 2.97	62.72 $\pm$ 2.35	55.39 $\pm$ 1.42	0.25 $\pm$ 0.02	554.88 $\pm$ 36.58	3420	2865.12 $\pm$ 68.98	83.78 $\pm$ 2.47
μ > 50	1507.35 $\pm$ 19.74	168.90 $\pm$ 27.34	0.78 $\pm$ 0.20	61.78 $\pm$ 1.36	33.53 $\pm$ 1.82	27.47 $\pm$ 0.97	0.13 $\pm$ 0.02	292.59 $\pm$ 27.45	1758	1465.41 $\pm$ 50.12	83.36 $\pm$ 3.48
fake type: muon	22670.73 $\pm$ 84.77	557.27 $\pm$ 65.81	6.25 $\pm$ 0.61	4387.92 $\pm$ 14.47	1723.00 $\pm$ 15.63	2024.75 $\pm$ 9.21	9.73 $\pm$ 0.15	8708.93 $\pm$ 69.78	35430	26721.07 $\pm$ 200.75	75.42 $\pm$ 0.69
fake mu η cut	21968.08 $\pm$ 83.41	508.03 $\pm$ 64.45	6.06 $\pm$ 0.61	4285.76 $\pm$ 14.28	1684.04 $\pm$ 15.47	1962.13 $\pm$ 9.04	9.51 $\pm$ 0.14	8455.52 $\pm$ 68.40	34232	25776.48 $\pm$ 197.26	75.30 $\pm$ 0.71
Scale factors				NF = 0.99 $\pm$ 0.01				NF = 0.99 $\pm$ 0.01		NF = 0.99 $\pm$ 0.01	
ID cuts	1063.43 $\pm$ 18.21	7.20 $\pm$ 3.58	0.50 $\pm$ 0.17	3510.44 $\pm$ 13.06	1074.96 $\pm$ 10.34	212.44 $\pm$ 1.99	7.90 $\pm$ 0.13	4813.44 $\pm$ 17.16	5800	986.56 $\pm$ 78.07	17.01 $\pm$ 1.36
0 < μ < 18	113.05 $\pm$ 6.13	0.00	0.02 $\pm$ 0.02	364.40 $\pm$ 4.39	118.92 $\pm$ 3.02	22.27 $\pm$ 0.70	0.86 $\pm$ 0.04	506.48 $\pm$ 5.37	569	62.52 $\pm$ 24.45	10.99 $\pm$ 4.32
18 < μ < 24	190.96 $\pm$ 7.61	1.37 $\pm$ 1.16	0.17 $\pm$ 0.10	593.04 $\pm$ 5.11	188.46 $\pm$ 4.55	35.99 $\pm$ 0.84	1.31 $\pm$ 0.05	820.34 $\pm$ 6.99	990	169.66 $\pm$ 32.23	17.14 $\pm$ 3.30
24 < μ < 32	283.24 $\pm$ 9.67	5.56 $\pm$ 3.37	0.23 $\pm$ 0.13	1003.66 $\pm$ 6.49	301.82 $\pm$ 5.68	58.11 $\pm$ 1.05	2.15 $\pm$ 0.07	1371.53 $\pm$ 9.33	1667	295.47 $\pm$ 41.88	17.72 $\pm$ 2.55
32 < μ < 40	236.39 $\pm$ 8.76	0.00	0.05 $\pm$ 0.02	763.20 $\pm$ 5.85	229.05 $\pm$ 5.27	47.11 $\pm$ 0.97	1.79 $\pm$ 0.06	1041.20 $\pm$ 7.94	1187	145.80 $\pm$ 35.36	12.28 $\pm$ 3.00
40 < μ < 50	164.42 $\pm$ 6.66	0.00	0.03 $\pm$ 0.02	549.87 $\pm$ 6.40	160.42 $\pm$ 3.41	33.42 $\pm$ 0.71	1.20 $\pm$ 0.05	744.96 $\pm$ 7.29	925	180.04 $\pm$ 31.28	19.46 $\pm$ 3.44
μ > 50	75.37 $\pm$ 4.65	0.27 $\pm$ 0.27	0.00 $\pm$ 0.00	268.62 $\pm$ 3.31	76.28 $\pm$ 2.34	15.54 $\pm$ 0.46	0.58 $\pm$ 0.03	361.29 $\pm$ 4.09	462	100.71 $\pm$ 21.88	21.80 $\pm$ 4.84
Scale factors				NF = 0.99 $\pm$ 0.01				NF = 0.99 $\pm$ 0.01		NF = 0.99 $\pm$ 0.01	
Anti-ID cuts	20904.65 $\pm$ 81.39	500.83 $\pm$ 64.35	5.55 $\pm$ 0.59	736.18 $\pm$ 5.45	609.08 $\pm$ 11.51	1749.69 $\pm$ 8.82	1.61 $\pm$ 0.06	3602.95 $\pm$ 66.19	28432	24829.05 $\pm$ 181.14	87.33 $\pm$ 0.82
0 < μ < 18	2161.26 $\pm$ 26.88	35.31 $\pm$ 31.19	0.23 $\pm$ 0.14	69.72 $\pm$ 1.86	56.33 $\pm$ 3.32	182.87 $\pm$ 3.07	0.16 $\pm$ 0.02	344.62 $\pm$ 31.57	3030	2685.38 $\pm$ 63.46	88.63 $\pm$ 2.64
18 < μ < 24	3569.29 $\pm$ 33.53	83.57 $\pm$ 30.62	1.44 $\pm$ 0.27	113.19 $\pm$ 2.10	105.72 $\pm$ 5.73	295.00 $\pm$ 3.70	0.26 $\pm$ 0.02	599.18 $\pm$ 31.47	4672	4072.82 $\pm$ 75.24	87.18 $\pm$ 2.05
24 < μ < 32	5923.75 $\pm$ 44.08	119.86 $\pm$ 30.40	1.75 $\pm$ 0.34	201.60 $\pm$ 2.93	170.89 $\pm$ 6.46	490.66 $\pm$ 4.76	0.42 $\pm$ 0.03	985.18 $\pm$ 31.58	7797	6811.82 $\pm$ 93.78	87.36 $\pm$ 1.56
32 < μ < 40	4520.36 $\pm$ 38.39	101.65 $\pm$ 21.82	0.87 $\pm$ 0.28	164.64 $\pm$ 2.50	139.00 $\pm$ 5.27	381.79 $\pm$ 4.12	0.36 $\pm$ 0.03	788.30 $\pm$ 22.96	6142	5353.70 $\pm$ 81.67	87.17 $\pm$ 1.73
40 < μ < 50	3208.22 $\pm$ 29.99	113.54 $\pm$ 21.97	0.91 $\pm$ 0.22	124.44 $\pm$ 2.40	93.53 $\pm$ 3.66	267.90 $\pm$ 3.22	0.24 $\pm$ 0.02	600.56 $\pm$ 22.63	4518	3917.44 $\pm$ 70.92	86.71 $\pm$ 2.03
μ > 50	1521.78 $\pm$ 21.48	46.91 $\pm$ 18.63	0.35 $\pm$ 0.11	69.37 $\pm$ 1.33	43.61 $\pm$ 2.37	131.48 $\pm$ 2.17	0.16 $\pm$ 0.02	291.89 $\pm$ 18.95	2273	1981.11 $\pm$ 51.31	87.16 $\pm$ 2.90

C.1.2 Monte Carlo Fake Factors

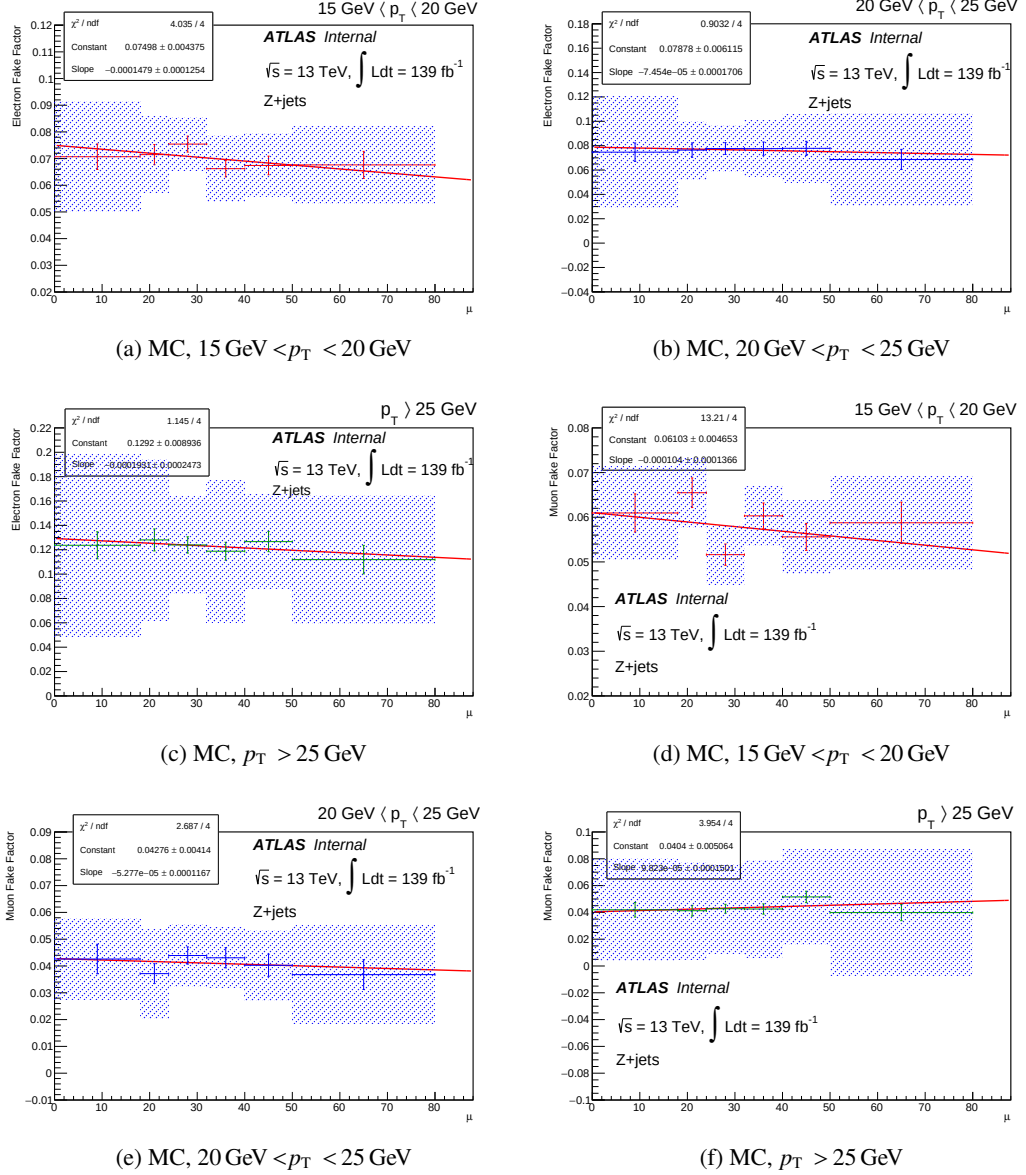


Figure C.1: (a)-(c) Electron and (d)-(f) muon fake factors in MC as functions of the pileup for each p_T bin, while integrated in η . Statistical uncertainties are shown as error bars. The error bands represent the total uncertainties of the data-driven technique for a direct comparison. A polynomial fit is performed and the fit parameters are displayed in the insets to assess any possible pileup dependence.

C.2 Fake Factor jet study

The requirement on jets in the Z+jets event selection lead to significant discrepancies between MC and data on the kinematic variables (see the distributions presented at the left side in Figures C.3, C.4). In order to overcome the jet mis-modeling, a reweighting procedure of the MC events to data was followed. Particularly, the data driven fakes were compared to the Z+jets MC fakes in order to extract the weights that were applied to the Z+jets MC event-by-event. The weights were calculated using the distribution of jets at the cut where the two of the three leptons are matched to the Z boson candidate and thus they pass the strict *id* requirements (*Z-tagging*). Such a MC reweighting procedure only affects the MC modeling of jet production and the fake factor estimation in MC but does not affect the data-driven estimate of the fake factors. The weights measured in bins of number of jets in the event are presented in Figure C.2 and the data/MC improvement on kinematic variables is visible in Figures C.3, C.4 after the weights application.

Figure C.5 shows the MC fake factors as function of the number of jets in the event whereas Figure C.6 presents the MC fake factors as function of the distance between the fake lepton and its closest jet. These results aim to complement the studies based on data as presented in Section 8.3.2.

C.2.1 Z+jets Monte Carlo reweighting

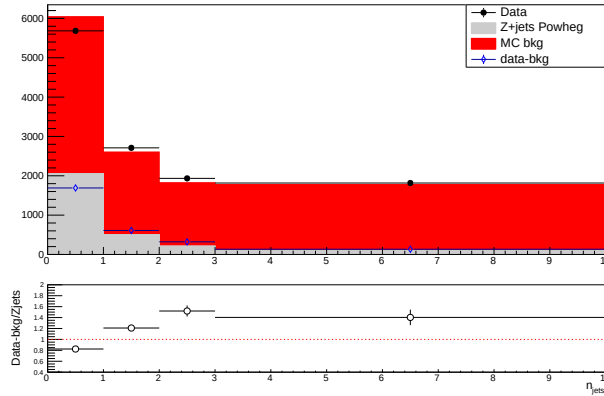


Figure C.2: Number of jets in selected Z+jets events in MC and in data. Their ratios are used to calculate the weights that correct the MC distributions for the jet mismodeling.

C Additional Material on the Fake Factor Method

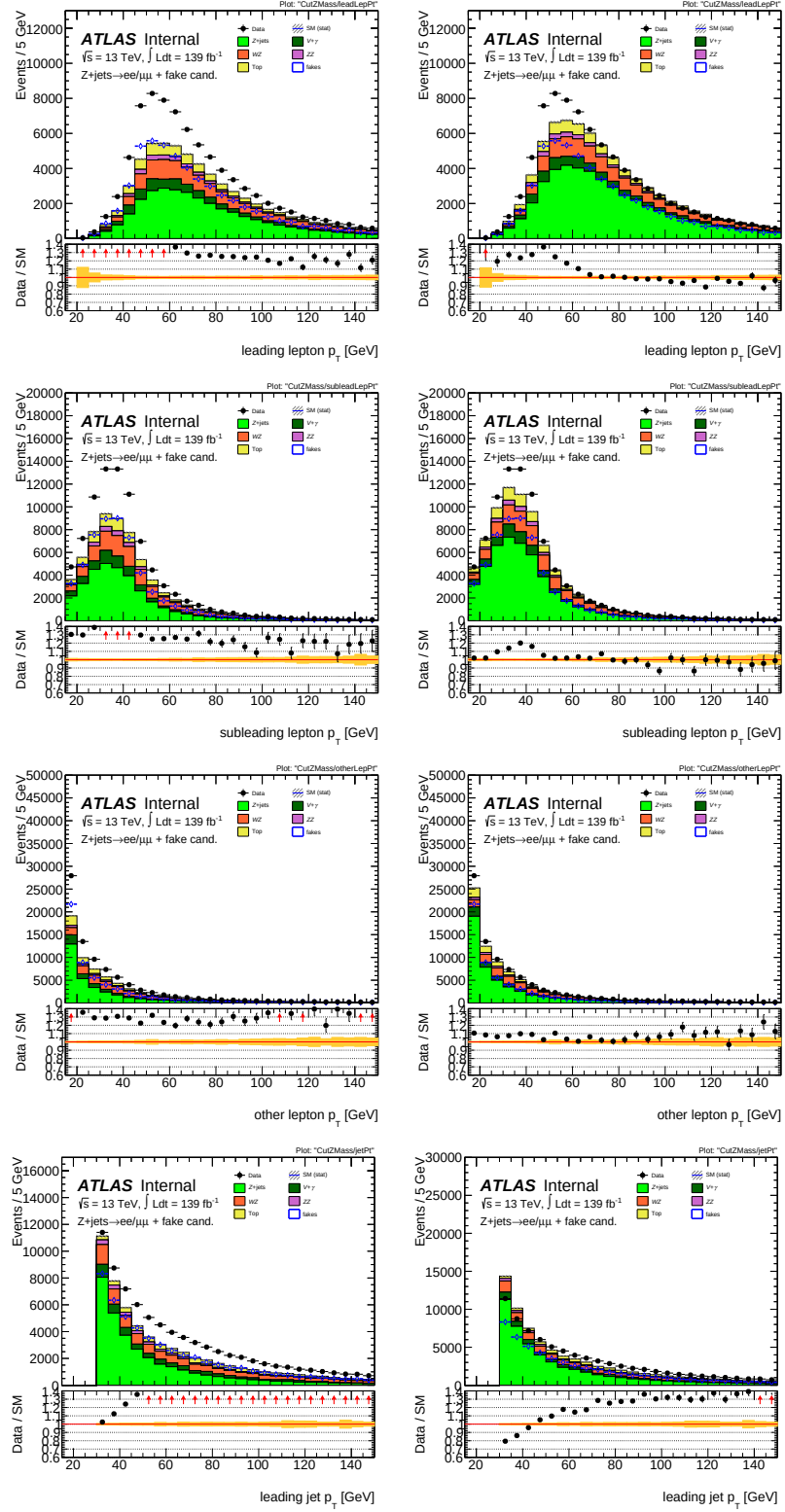


Figure C.3: Leptons and leading jet p_T distributions after the Z-tagging cut (where the fake lepton is selected). Left: before the MC-reweighting, Right: after the MC-reweighting

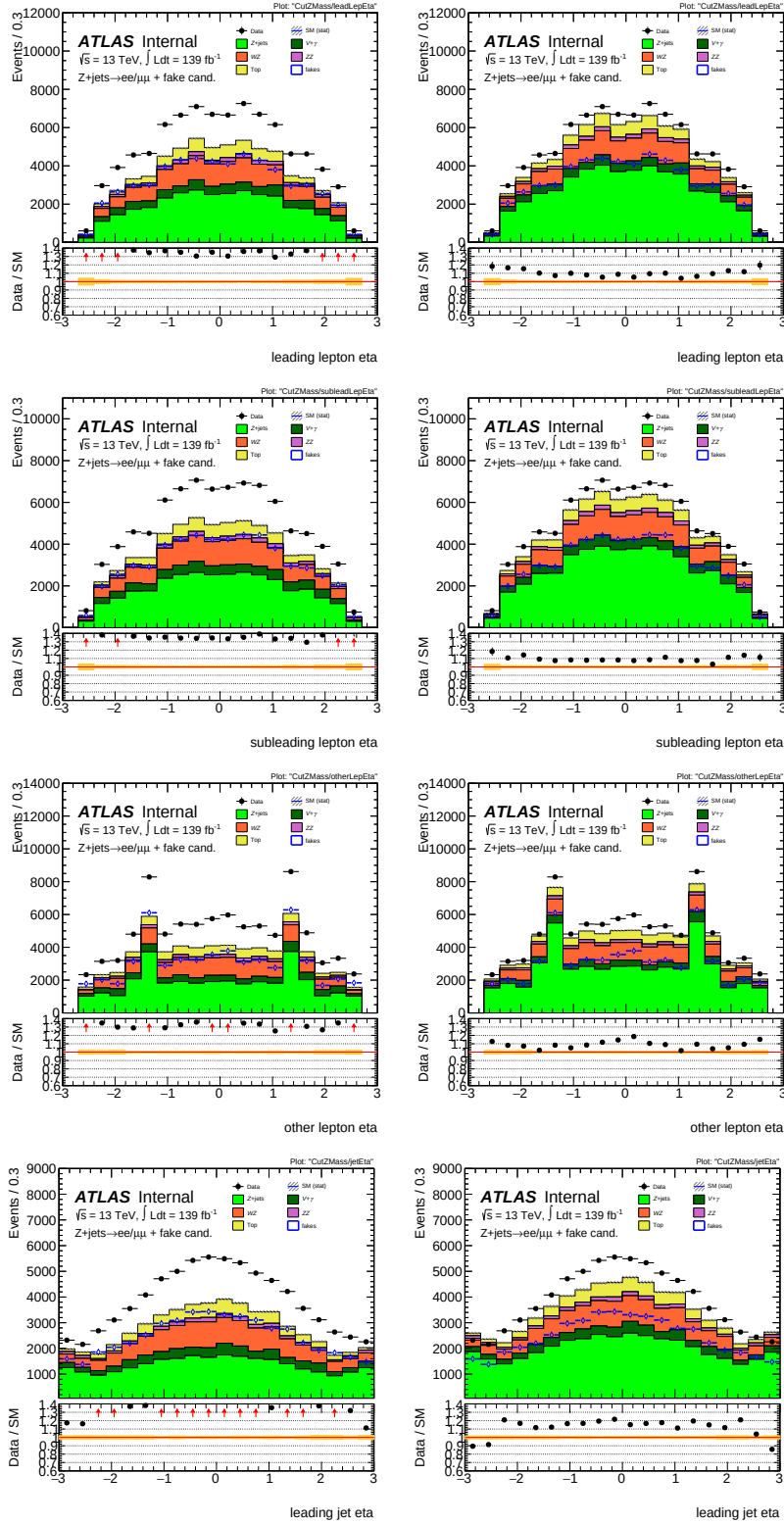


Figure C.4: Leptons and leading jet η distributions after the Z-tagging cut (where the fake lepton is selected). Left: before the MC-reweighting, Right: after the MC-reweighting

C.2.2 Monte Carlo Fake Factors

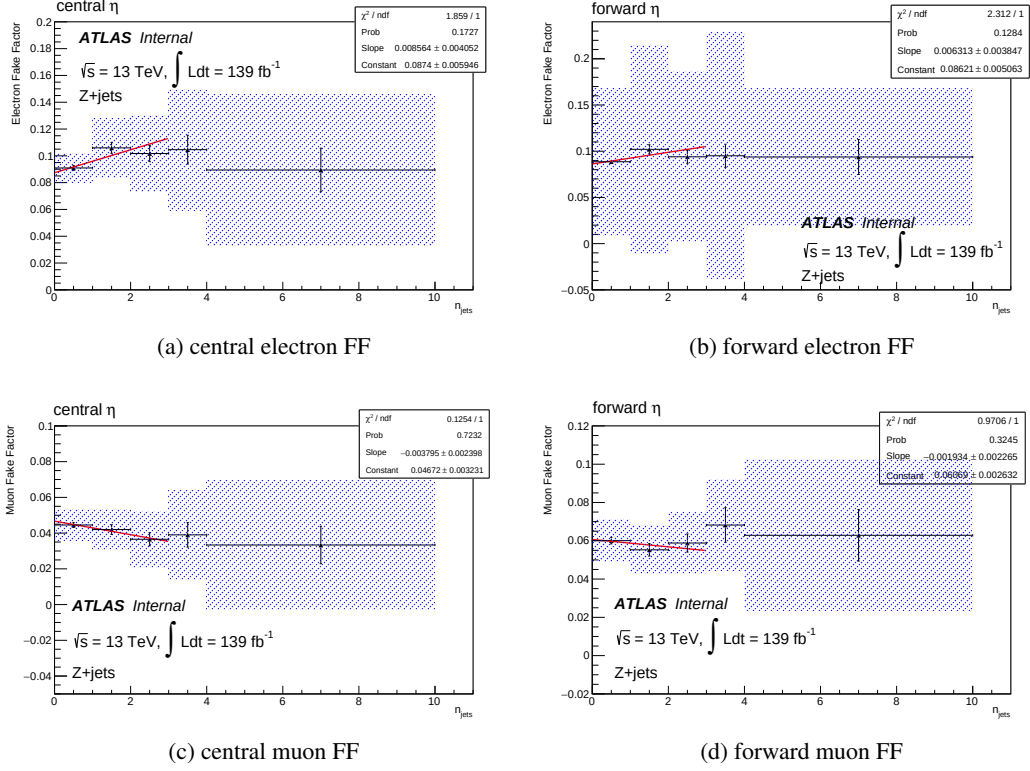


Figure C.5: (a),(b) Electron and (c),(d) muon fake factors in MC as a function of the number of jets in the event. Statistical uncertainties are shown as error bars. The error bands represent the total uncertainties of the data-driven technique for a direct comparison. A polynomial fit is performed and the fit parameters are displayed in the insets to assess any possible dependence on jets.

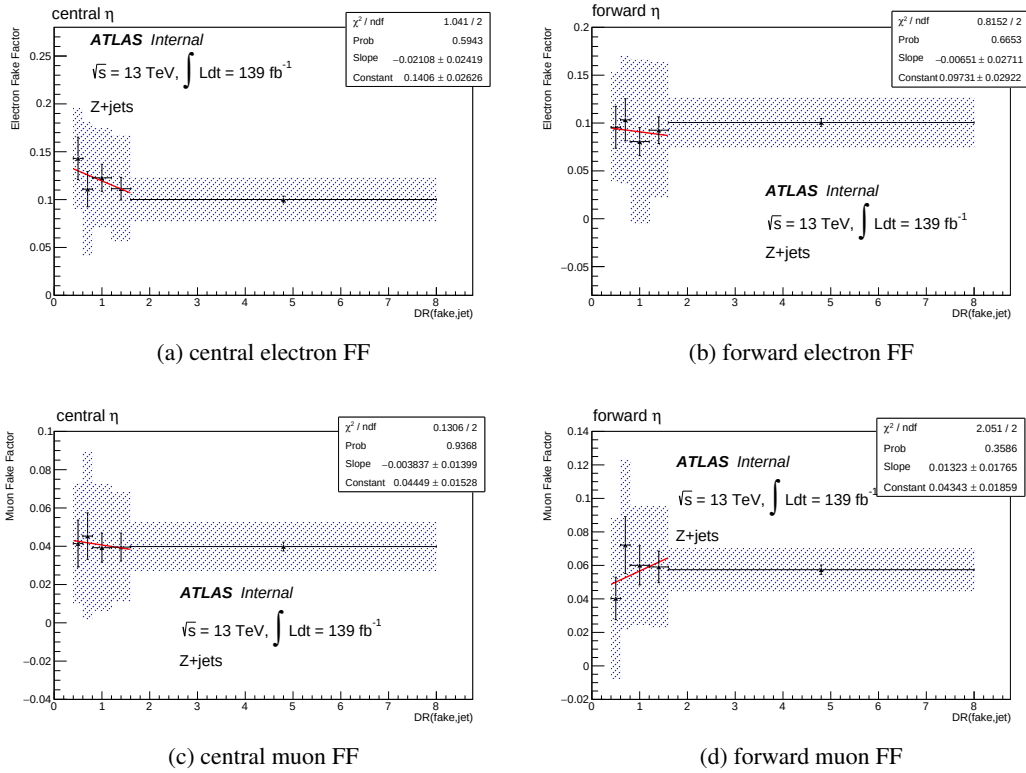


Figure C.6: (a),(b) Electron and (c),(d) muon fake factors in MC as a function of the distance between the fake lepton and its closest jet. Statistical uncertainties are shown as error bars. The error bands represent the total uncertainties of the data-driven technique for a direct comparison. A polynomial fit is performed and the fit parameters are displayed in the insets to assess any possible dependence on the nearby to the fake lepton jet.

C.3 Closure test

This section serves as auxiliary material for the closure test of the data-driven fake factor method described in Section 8.4. The full event selection cuts in the two defined regions are presented in Table C.2 for W +jets Powheg events and in Table C.3 for W +jets Madgraph events. The comparison of the kinematic distributions between the two regions using W +jets Madgraph events are shown at different stages of the event selection in Figures C.7, C.8.

C.3.1 Cutflows

Table C.2: Cutflow for W +jets Powheg MC events in the SR (left) and in W +jets CR (right). Uncertainties are statistical including those from the fake factors and correction factors.

$\sqrt{s} = 13TeV, \mathcal{L} = 139fb^{-1}$ (Full Run 2)	Wjets Powheg	$\sqrt{s} = 13TeV, \mathcal{L} = 139fb^{-1}$ (Full Run 2)	Wjets Powheg
Channel Selection	429029.54 $\pm$ 2088.97	Channel Selection	429029.54 $\pm$ 2088.97
Trigger Selection	429029.54 $\pm$ 2088.97	Trigger Selection	429029.54 $\pm$ 2088.97
Trigger Matching	414966.14 $\pm$ 2024.45	Trigger Matching	414966.14 $\pm$ 2024.45
Jet Cleaning	414966.14 $\pm$ 2024.45	Jet Cleaning	414966.14 $\pm$ 2024.45
Overlap: Vgamma/Vjets	414966.14 $\pm$ 2024.45	Overlap: Vgamma/Vjets	414966.14 $\pm$ 2024.45
Only two Leptons	414915.22 $\pm$ 2024.34	Only two Leptons	414915.22 $\pm$ 2024.34
$p_t^{lead} > 22$ GeV	414915.22 $\pm$ 2024.34	$p_t^{lead} > 22$ GeV	414915.22 $\pm$ 2024.34
$p_t^{sublead} > 15$ GeV	414783.01 $\pm$ 2023.96	$p_t^{sublead} > 15$ GeV	414783.01 $\pm$ 2023.96
OS Leptons	414736.98 $\pm$ 2023.76	OS Leptons	414736.98 $\pm$ 2023.76
$M_{\ell\ell} > 10$ GeV	414718.18 $\pm$ 2023.72	$M_{\ell\ell} > 10$ GeV	414718.18 $\pm$ 2023.72
SF: Z Veto	414718.18 $\pm$ 2023.72	SF: Z Veto	414718.18 $\pm$ 2023.72
Leptons ID	14757.01 $\pm$ 381.36	SingleFakes 1 anti-ID, 1 ID	194343.95 $\pm$ 1357.06
2-jet (30,30) fJVT	949.68 $\pm$ 96.08	Apply fake factor	15288.07 $\pm$ 1039.00
b-veto	820.17 $\pm$ 88.07	2-jet (30,30) fJVT	868.63 $\pm$ 82.45
blinding (2-jet)	820.17 $\pm$ 88.07	b-veto	757.13 $\pm$ 72.01
CJV (20GeV)	618.70 $\pm$ 76.42	CJV (20GeV)	562.89 $\pm$ 57.07
OLV bool	121.78 $\pm$ 33.08	OLV bool	140.20 $\pm$ 19.45
$Z \rightarrow \tau\tau$ veto	85.51 $\pm$ 27.96	$Z \rightarrow \tau\tau$ veto	95.04 $\pm$ 13.45
Mjj>200	67.30 $\pm$ 24.86	Mjj>200	69.01 $\pm$ 11.27
DYjj>2.1	67.30 $\pm$ 24.86	DYjj>2.1	65.06 $\pm$ 10.83

Table C.3: Cutflow for W +jets **MADGRAPH** MC events in the SR (left) and in W +jets CR (right). Uncertainties are statistical including those from the fake factors and correction factors.

$\sqrt{s} = 13TeV, \mathcal{L} = 139fb^{-1}$ (Full Run 2)	Wjets MadGraph	$\sqrt{s} = 13TeV, \mathcal{L} = 139fb^{-1}$ (Full Run 2)	Wjets MadGraph
Channel Selection	576388.36 $\pm$ 2447.50	Channel Selection	576388.36 $\pm$ 2447.50
Trigger Selection	576388.36 $\pm$ 2447.50	Trigger Selection	576388.36 $\pm$ 2447.50
Trigger Matching	558441.72 $\pm$ 2354.41	Trigger Matching	558441.72 $\pm$ 2354.41
Jet Cleaning	558441.72 $\pm$ 2354.41	Jet Cleaning	558441.72 $\pm$ 2354.41
Overlap: Vgamma/Vjets	558441.72 $\pm$ 2354.41	Overlap: Vgamma/Vjets	558441.72 $\pm$ 2354.41
Only two Leptons	558329.53 $\pm$ 2354.37	Only two Leptons	558329.53 $\pm$ 2354.37
$p_t^{lead} > 22$ GeV	558329.53 $\pm$ 2354.37	$p_t^{lead} > 22$ GeV	558329.53 $\pm$ 2354.37
$p_t^{sublead} > 15$ GeV	557872.38 $\pm$ 2353.94	$p_t^{sublead} > 15$ GeV	557872.38 $\pm$ 2353.94
OS Leptons	557580.25 $\pm$ 2353.73	OS Leptons	557580.25 $\pm$ 2353.73
$M_{\ell\ell} > 10$ GeV	557564.30 $\pm$ 2353.72	$M_{\ell\ell} > 10$ GeV	557564.30 $\pm$ 2353.72
SF: Z Veto	557564.30 $\pm$ 2353.72	SF: Z Veto	557564.30 $\pm$ 2353.72
Leptons ID	22108.58 $\pm$ 529.18	SingleFakes 1 anti-ID, 1 ID	243273.90 $\pm$ 1460.28
2-jet (30,30) fJVT	3209.79 $\pm$ 95.94	Apply fake factor	22684.74 $\pm$ 3484.24
b-veto	2675.45 $\pm$ 90.34	2-jet (30,30) fJVT	3297.59 $\pm$ 476.78
blinding (2-jet)	2675.45 $\pm$ 90.34	b-veto	2761.77 $\pm$ 403.51
CJV (20GeV)	1939.87 $\pm$ 75.44	CJV (20GeV)	2045.10 $\pm$ 298.37
OLV bool	367.08 $\pm$ 36.99	OLV bool	394.47 $\pm$ 59.13
$Z \rightarrow \tau\tau$ veto	229.30 $\pm$ 34.36	$Z \rightarrow \tau\tau$ veto	244.64 $\pm$ 37.90
Mjj>200	186.59 $\pm$ 33.21	Mjj>200	182.80 $\pm$ 29.23
DYjj>2.1	170.81 $\pm$ 32.96	DYjj>2.1	172.77 $\pm$ 27.89

C.3.2 Kinematic distributions using MADGRAPH generator

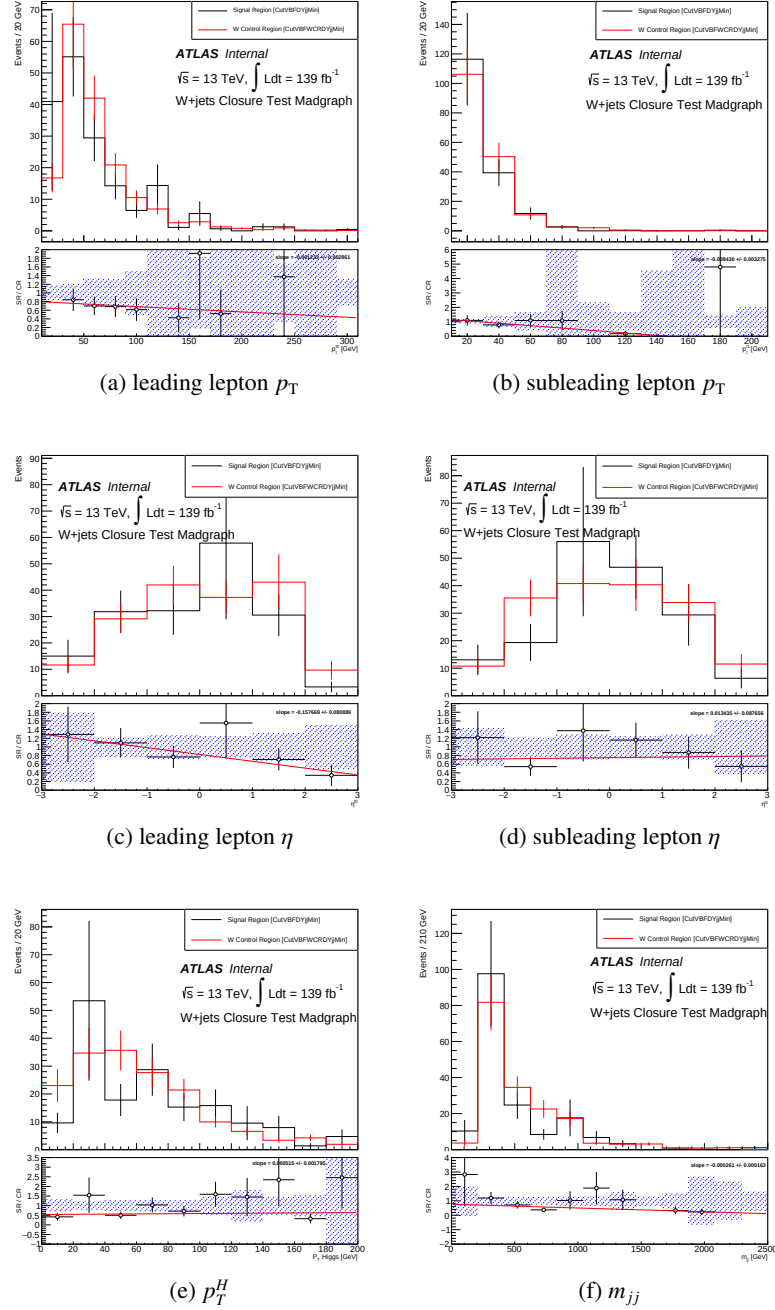


Figure C.7: Distributions after the full selection for W +jets MC samples in the SR (black) and W +jets CR with FFs and CFs (red) using MADGRAPH MC. Statistical uncertainties are shown as error bars. The uncertainties estimated in the data-driven method are shown in error bands to facilitate the comparison. The results of the linear fit of the ratio of the two distributions are shown for each observable.

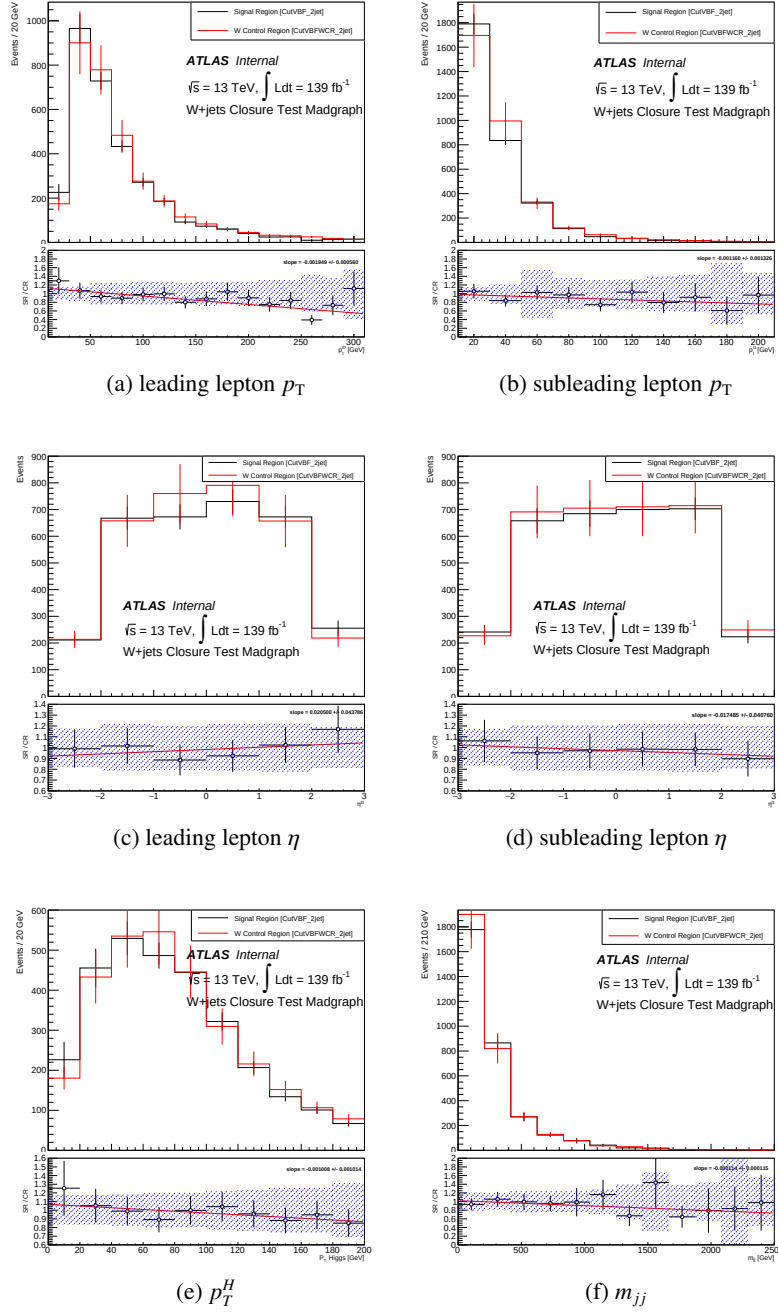


Figure C.8: Distributions at pre-selection level for W+jets MC samples in the SR (black) and W+jets CR with FFs and CRs (red) using MadGraph MC. Statistical uncertainties are shown as error bars. The uncertainties estimated in the data-driven method are shown in error bands to facilitate the comparison. The results of the linear fit of the ratio of the two distributions are shown for each observable.

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