

THÈSE DE DOCTORAT

Soutenue à Aix-Marseille Université
en cotutelle avec l'Université du Shandong
le 16 septembre 2021 par

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Studies of the Higgs boson properties and search for new
physics beyond the standard model in multilepton final states
with the ATLAS detector at LHC

Discipline

Physique et Sciences de la Matière

Spécialité

Physique des Particules et Astroparticules

École doctorale

ECOLE DOCTORALE 352

Laboratoire/Partenaires de recherche

Centre de Physique des Particules de Marseille
School of Physics of Shandong University

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Résumé

La mesure des propriétés du boson de Higgs est l'un des principaux axes de la physique des hautes énergies. Le couplage de Yukawa entre le Higgs et le quark top - qui est le fermion du modèle standard le plus lourd - est l'une des constantes les plus intéressantes qui puissent être sondées à partir de la mesure de la section efficace de la production associée d'un boson de Higgs avec une paire de quarks top ($t\bar{t}H$).

La mesure de cette section efficace $t\bar{t}H$ dans des états finaux multileptons avec des collisions proton-proton à une énergie dans le centre de masse de $\sqrt{s} = 13$ TeV est présentée dans cette thèse. La mesure a été effectuée sur un ensemble de données, et une luminosité intégrée de 79.9 fb^{-1} , enregistrées par l'expérience ATLAS au grand collisionneur de hadron. Les données sélectionnées sont classées selon six états finaux, en fonction du nombre et de la saveur des leptons chargés candidats, pour rechercher le signal $t\bar{t}H$. La meilleure valeur obtenue de l'ajustement des données est $\hat{\mu} = 0.58^{+0.36}_{-0.33}$, tandis que la section efficace de production $t\bar{t}H$ obtenue est $\sigma_{t\bar{t}H} = 294^{+182}_{-162} \text{ fb}$, en accord avec la prédiction du modèle standard $\sigma_{t\bar{t}H}^S M = 507^{+35}_{-50} \text{ fb}$. La signification observée (attendue) comme excédent au-dessus de l'hypothèse de fond uniquement est de 1.8 (3.1) écarts-types. L'analyse de la mesure de la section efficace $t\bar{t}H$ avec l'ensemble des données ATLAS du Run 2 et une luminosité intégrée de 139.0 fb^{-1} est toujours en cours. Les résultats attendus sont présentés en suivant la méthode utilisée précédemment avec seulement des échantillons nominaux considérés dans le canal avec deux leptons de mêmes signes et aucun tau. La signification attendue dérivée du calcul statistique est de 2.2σ .

La dernière partie de la thèse présente une recherche de résonance neutre lourde X dans un canal $X \rightarrow WW \rightarrow e\nu\mu\nu$ à partir de données collectées par ATLAS en 2015 et 2016. Les données ont été prises à une énergie dans le centre de masse de $\sqrt{s} = 13$ TeV, et une luminosité intégrée de 36.1 fb^{-1} . Sept hypothèses sont testées dans l'analyse : deux scénarios, une approximation de largeur étroite et des hypothèses de grande largeur, qui considèrent les largeurs de désintégration d'un boson de Higgs lourd indépendant du modèle, et cinq modèles de référence, le modèle à deux doublets de Higgs, le modèle Georgi-Machacek, un modèle à triplet vectoriel lourd avec un boson lourd de spin-1, le modèle Randall-Sundrum minimal avec un graviton de spin-2 pour $k/\bar{M}_{Pl} = 0.5$ ou 1, et le modèle de lagrangien effectif avec un graviton spin-2 de fusion vecteur boson. Aucun excès significatif n'a été trouvé au-delà de la prévision du modèle standard dans une gamme de masse comprise entre 200 GeV et 5 TeV. Les limites supérieures à 95% CL sont fixées sur la section efficace de production de résonance multipliée par la fraction de branchement $X \rightarrow WW$.

Mots clés : LHC, ATLAS, Higgs, MS, au-delà du modèle standard, $t\bar{t}H$, $t\bar{t}W$, HWW

Abstract

The measurement of the Higgs boson properties is one of the main focuses of the high energy physics. The Yukawa coupling between Higgs and top quark - which is the heaviest Standard Model (SM) fermion - is one of the most interesting constants which can be probed from the cross section measurement of associated production of a Higgs boson with a top-quark pair ($t\bar{t}H$).

This $t\bar{t}H$ cross section measurement with proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV is presented in this thesis. The measurement was performed in multilepton final states using a dataset corresponding to an integrated luminosity of 79.9 fb^{-1} recorded by the ATLAS experiment at the Large Hadron Collider (LHC). The selected data are categorized in six final states by the number and flavor of charged-lepton candidates to search for the $t\bar{t}H$ signal. The best-fit value obtained is $\mu_{t\bar{t}H}$ is $\hat{\mu} = 0.58^{+0.36}_{-0.33}$, while the corresponding cross section for $t\bar{t}H$ production is $\sigma_{t\bar{t}H} = 294^{+182}_{-162} \text{ fb}$, in agreement with the Standard Model prediction, $\sigma_{t\bar{t}H}^{SM} = 507^{+35}_{-50} \text{ fb}$. The observed (expected) significance as excess above the background-only hypothesis is 1.8σ (3.1σ). The analysis to measure the $t\bar{t}H$ cross section with the full Run 2 ATLAS dataset corresponding to 139.0 fb^{-1} integrated luminosity is in progress. The expectation results are presented following the method used in the previous analysis with only the two same sign leptons and no tau channel. The expected significance derived from the statistical calculation is 2.2σ .

The last part of the thesis presents a search for a heavy neutral resonance X in an $X \rightarrow WW \rightarrow e\nu\mu\nu$ channel using data collected by ATLAS in 2015 and 2016. The 36.1 fb^{-1} integrated luminosity dataset was taken at a center-of-mass energy of $\sqrt{s} = 13$ TeV. Seven hypotheses are tested in the analysis: two scenarios, the narrow width approximation and the large width assumptions, that consider the decay widths of a model-independent heavy Higgs boson, and five benchmark models, the two-Higgs-doublet models, the Georgi-Machacek model, the heavy vector triplet model with a spin-1 heavy boson, the bulk Randall-Sundrum model with a spin-2 graviton at $k/\bar{M}_{Pl} = 0.5$ or 1, and the effective Lagrangian model with a VBF spin-2 graviton. No significant excess was found beyond the Standard Model background prediction in a mass range between 200 GeV and 5 TeV. Upper limits at 95% CL are set on the resonance production cross section times branching fraction $X \rightarrow WW$.

Keywords: LHC, ATLAS, Higgs, SM, BSM, $t\bar{t}H$, $t\bar{t}W$, HWW

Synthèse en français

Le modèle standard est un cadre théorique qui décrit les particules élémentaires et les trois forces fondamentales – interaction électromagnétique, faible et forte – dans une théorie de jauge unifiée. La force gravitationnelle beaucoup plus faible n'est pas incluse. Le modèle standard a été développé et étendu à plusieurs reprises depuis les années 1960. En 2012, la découverte du boson de Higgs par les collaborations d'ATLAS et de CMS annonçait que la dernière pièce manquante du modèle standard avait été corrigée.

Le boson de Higgs occupe une place unique dans le modèle standard, qui est la seule explication des masses des particules à travers le mécanisme de Brout-Englert-Higgs. Les bosons vectoriels d'interaction faible (bosons W et Z) gagnent leurs masses en interagissant avec le champ de Higgs. Les masses de particules de matière (fermions) sont déterminées par les couplages de Yukawa. Le couplage de Yukawa entre le boson de Higgs et le fermion SM le plus lourd, le quark top, est d'un intérêt particulier. L'une des sondes directes du couplage quark top-Yukawa est la mesure de la production associée d'un boson de Higgs avec une paire de quark top. Le processus $t\bar{t}H$ a été observé par les expériences ATLAS et CMS individuellement en 2018, combinant des recherches dédiées exploitant les principaux canaux de désintégration du boson de Higgs en utilisant les données de collision pp à $\sqrt{s} = 13$ TeV. Bien que le modèle standard se soit avéré être le modèle théorique le plus prédictif à ce jour, il existe encore de nombreux problèmes non résolus pour lesquels cette magnifique théorie n'offre aucune explication convaincante, *i.e.* problème de hiérarchie, la matière noire et l'énergie noire, la violation du CP, les masses du neutrino et la gravité. De nombreuses nouvelles théories physiques visent à résoudre les problèmes ci-dessus en étendant le modèle standard actuel. L'une des plus connues est la supersymétrie (SUSY), qui offre à chaque particule un super partenaire.

Le grand collisionneur de hadrons (LHC) est conçu pour tester les prédictions des théories et explorer plus avant la nature fondamentale de la matière. Il se situe à la frontière de la France et de la Suisse et a été approuvé par le Conseil du Centre Européen pour la Recherche Nucléaire (CERN) le 16 décembre 1994. Jusqu'à aujourd'hui, le LHC fonctionne bien et a atteint de nombreux objectifs scientifiques prédéterminés. Lors de l'exécution 1, une luminosité intégrée de 5 fb^{-1} à l'énergie du centre de masse de $\sqrt{s} = 7$ TeV (2011) et de 20 fb^{-1} à $\sqrt{s} = 8$ TeV (2012). La période Run 2 dure trois ans, une luminosité totale d'environ 150 fb^{-1} de données de collision à une énergie centre de masse de $\sqrt{s} = 13$ TeV (2015-2018) a été fournie aux détecteurs. Sept détecteurs, ATLAS, CMS, ALICE, LHCb, LHCf, TOTEM et MoEDAL, sont installés pour collecter les morceaux de particules produits par les collisions dans l'accélérateur.

En tant que l'une des deux expériences à usage général, l'ATLAS est le plus grand détecteur de particules au monde. La structure du détecteur est entraînée par le système d'aimants, qui se compose d'un solénoïde supraconducteur réparti à l'extérieur du détecteur interne et de trois grands tores supraconducteurs autour du calorimètre. Le détecteur interne est immergé dans un champ magnétique de solénoïde de 2 T au cœur du détecteur, le plus proche du tube de faisceau. L'invention concerne un système de calorimètre d'échantillonnage à argon liquide (LAR) pour mesurer l'énergie et la position d'électrons, de photons et de hadrons. Le spectromètre à muons se trouve au niveau de la couche la plus externe. Le champ magnétique puissant à l'intérieur du spectromètre à muons rend possible la mesure précise de l'impulsion muonique. Limités par la bande passante et le stockage, trois niveaux de déclencheurs sont utilisés dans le détecteur ATLAS pour enregistrer uniquement les événements les plus intéressants. Pour fournir une résolution plus élevée au déclencheur L1 après l'exécution 2, 34,000 super cellules sont réorganisées pour avoir une granularité 5 à 10 fois plus fine dans la mise à niveau de phase I du calorimètre LAR. Un démonstrateur a été installé sur l'ATLAS lors de l'exécution 2 et je participe à l'acquisition et à l'analyse des données d'étalonnage du démonstrateur de mise à niveau LAR. La Figure 0.1 montre les relations entre l'ADC et l'énergie convertie à partir du DAC d'entrée dans différentes couches d'une tour de déclenchement. Les dix parcelles ont été regroupées pour couvrir $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$.

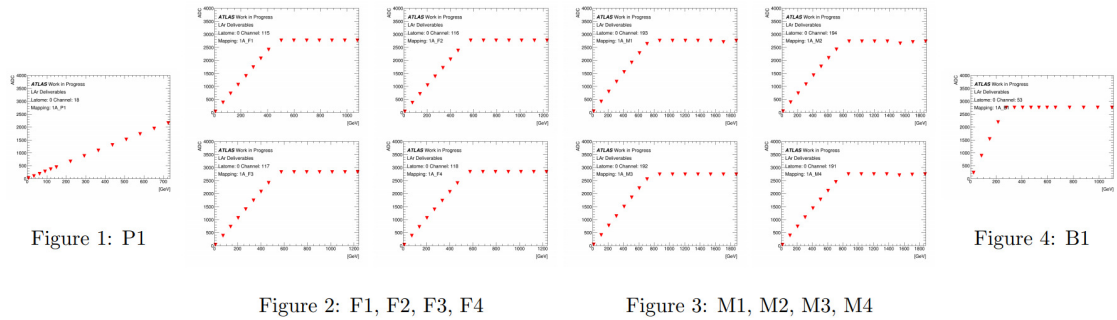


FIGURE 0.1. – ADC versus énergie convertie à partir du DAC d'entrée dans une rampe. 10 tracés correspondent aux signaux reçus par les 4 couches (pré-échantillonneur, couche avant, couche intermédiaire et couche arrière) dans les super cellules provenant d'une tour de déclenchement.

La première partie de cette thèse présente les résultats d'une recherche de $t\bar{t}H$ production dans des états finaux multileptons à partir d'un jeu de données collecté par le détecteur ATLAS en 2015-2017 à une énergie centre de masse de $\sqrt{s} = 13$ TeV avec une luminosité intégrée de 79.9 fb^{-1} . Dans un tel processus, une mesure directe du couplage quark top-Yukawa peut être atteinte. L'analyse est principalement sensible aux signatures de $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ ou $\ell\nu jj$ et $H \rightarrow \tau^+\tau^-$ decays. Six états finaux sont classés par le nombre de leptons légers et de τ_{had} et s'intègrent simultanément dans l'analyse :

- $2\ell\text{SS}$: 2 leptons légers avec la même charge (0 τ_{had})
- 3ℓ : 3 leptons légers (0 τ_{had})
- 4ℓ : 4 leptons légers
- $2\ell\text{SS} + 1\tau_{had}$: 2 leptons légers de même charge et 1 τ_{had}
- $2\ell\text{OS} + 1\tau_{had}$: 2 leptons légers de charge opposée et 1 τ_{had}
- $3\ell + 1\tau_{had}$: 3 leptons légers et 1 τ_{had}

Tous les états finaux sont rendus orthogonaux par des exigences sur le nombre de leptons légers libres et de candidats τ_{had} , comme le montre la figure 0.2 (à gauche). Un diagramme de Feynman montre le processus $t\bar{t}H$, $H \rightarrow WW$ dans un état final de deux leptons de même charge comme exemple dans la figure 0.2 (à droite). J'ai contribué à la classification des événements avec la méthode MVA dans le canal $2\ell\text{SS}$, coopéré sur une fausse estimation de fond et effectué l'analyse statistique combinant tous les états finaux multileptons.

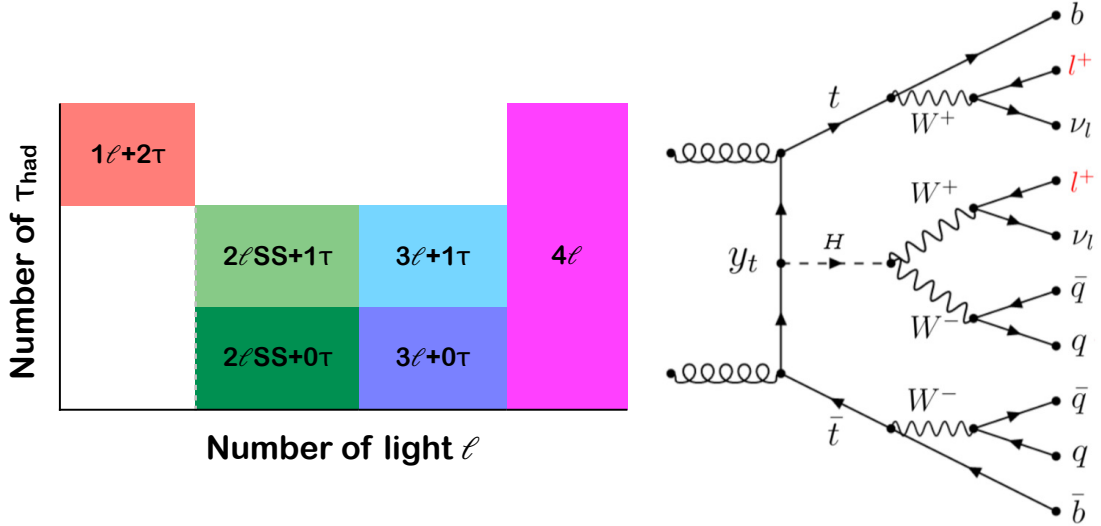


FIGURE 0.2. – Catégorisation des états finaux $t\bar{t}H$ multilepton en termes de multiplicités lepton et τ_{had} (à gauche) et diagramme de Feynman pour $t\bar{t}H$, $H \rightarrow WW$ processus à l'état final $2\ell\text{SS}$ (à droite).

L'échantillon simulé pour le signal $t\bar{t}H$ est normalisé à la section efficace de 507^{+35}_{-50} fb, calculée à NLO dans QCD en considérant les principales corrections électrofaible NLO. Les échantillons $t\bar{t}W$ sont considérés au NLO en QCD avec les principales corrections électrofaible NLO avec une section transversale nominale de 601 ± 76 fb. Un facteur d'échelle supplémentaire à 1.2 est appliqué pour tenir compte des corrections QCD et électrofaible concernant les diagrammes $t\bar{t}W$ +1-jet, ainsi la section efficace $t\bar{t}W$ correspondante est de 727 ± 92 fb.

Les déclencheurs Dilepton sont couramment utilisés dans les canaux avec au moins deux leptons légers. Deux méthodes MVA de lepton, PromptLeptonVeto BDT et charge erronée d'identification BDT, sont développées et optimisées pour réduire da-

vantage les leptons non-prompts et charger des électrons mal identifiés. Les conversions de matériaux sont supprimées par `ambiguityType = 0`. Les régions de contrôle pour les conversions internes et matérielles définies dans les canaux 2ℓ SS et 3ℓ sont requises comme suit :

- Conv. interne CR : $0 < m_{trk-trk,PV} < 100$ MeV, $radius_{CO} < 20$ mm ou $m_{trk-trk,CV} > 100$ MeV
- Matériel Conv. CR : $radius_{CO} > 20$ mm et $0 < m_{trk-trk,CV} < 100$ MeV
- Autres SR et CR dans 2ℓ SS et 3ℓ : !IntCO et !Ext CO

Le fond de lepton non prompt dans 2ℓ SS et 3ℓ est un mélange de leptons provenant de désintégrations de saveurs lourdes et de conversions de photons. La méthode d'ajustement de modèle utilise plusieurs facteurs de normalisation (NF) pour normaliser les faux modèles, donnés par les échantillons MC de tous les processus contribuant au faux arrière-plan, aux données. Comme indiqué ci-dessous, quatre facteurs de normalisation flottants sont attribués à chacune des sources :

- NF_e^{MatC} : facteur de normalisation appliqué sur les événements d'électrons de conversion de matériaux.
- NF_e^{IntC} : facteur de normalisation appliqué sur les événements d'électrons de conversion internes.
- NF_e^{HF} : facteur de normalisation appliqué sur les électrons non-prompt du hadron de désintégration B / C / saveur légère (dominé par la désintégration B).
- NF_μ^{HF} : facteur de normalisation appliqué sur les muons non-prompt de B / C / hadron de désintégration de saveur légère (dominé par la désintégration B).

Les trois CR N_{jets} faibles dans le canal 2ℓ SS sont établis pour mieux contraindre soit les arrière-plans non-prompt de saveur lourde, soit l'arrière-plan $t\bar{t}W$, qui nécessitent $N_{jets} = 2, 3$. Ces CR sont orthogonaux et séparés par des N_{b-jets} et la saveur du lepton sous-lisant.

Afin de mieux distinguer le signal des arrière-plans dans le canal 2ℓ SS, une analyse multi-variée basée sur des arbres de décision à gradient a été optimisée. Le BDT est formé contre l'arrière-plan irréductible ($t\bar{t}W$, $t\bar{t}Z$, conversion interne et diboson) et le fond réductible (processus $t\bar{t}$ avec des leptons provenant de la désintégration des hadrons à saveur lourde, de la conversion des matériaux et de l'affectation des charges). L'arrière-plan non-prompt est estimé par la méthode d'ajustement de modèle en utilisant les facteurs de normalisation obtenus à partir d'un ajustement simultané dans les CR faibles N_{jets} 2ℓ SS et 3ℓ . Les processus $t\bar{t}H$, $t\bar{t}W$ et $t\bar{t}Z$ sont des estimations MC pures. En utilisant le même ensemble de neuf variables d'entrée, y compris N_{jets} , N_{b-jets} , $\min \Delta R_{\ell_0 j}$, $\min \Delta R_{\ell_1 j}$, $\max(|\eta_\ell|)$, $p_T(\ell_1)$, E_T^{miss} , saveur leptonique et $\Delta R_{\ell_0 \ell_1}$, deux scores BDT sont attribués à chaque événement en décrivant la probabilité de celui-ci comme un signal $t\bar{t}H$ sur le fond irréductible et le fond réductible. Six CR et deux SR sont séparés par les scores BDT, les frais de paire de leptons et la saveur de lepton de sous-lecture dans le canal 2ℓ SS high N_{jets} ($N_{jets} \geq 4$). Les performances des deux cas sont comparées sur la Figure 0.3. Le test de surentraînement indique qu'il n'y a pas de surentraînement dans les deux cas, bien qu'un manque d'événements de fond réductibles soit observé.

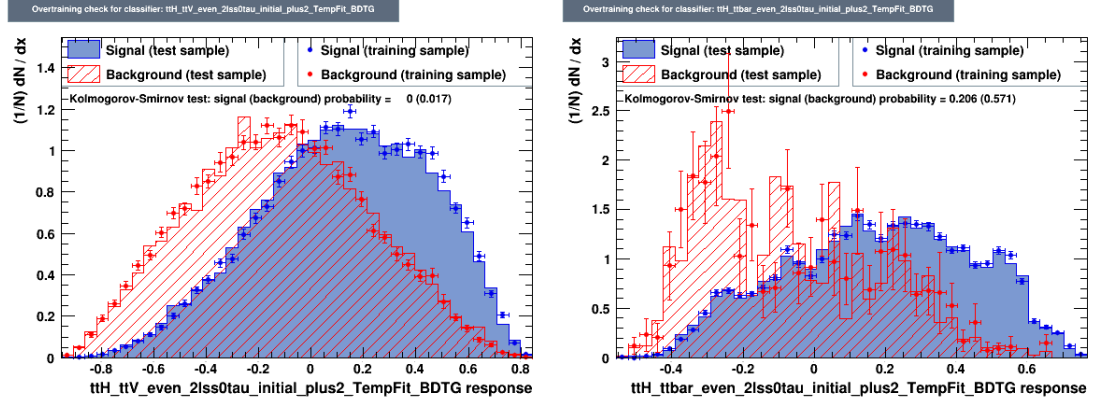


FIGURE 0.3. – Vérifications de surentraînement pour la formation MVA dans le canal $2\ell SS$. Le graphique de gauche montre la réponse du BDTG_irréductible et celui de droite montre la réponse du BDTG_reductible).

Au total, vingt-cinq catégories d'événements dans six canaux définis par leurs états finaux sont impliquées dans un ajustement du maximum de vraisemblance. Les données post-ajustement et les graphiques de comparaison MC sont présentés dans la Figure 0.4 pour les huit SR et pour les dix-sept CR.

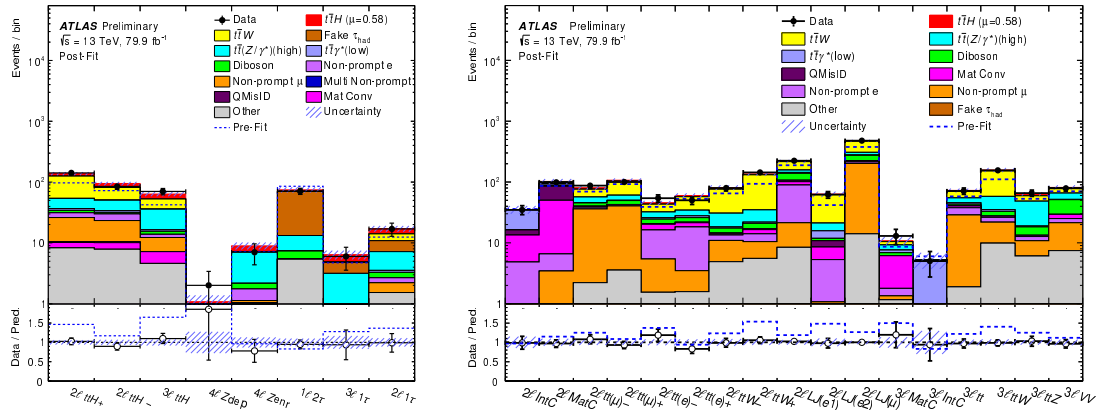


FIGURE 0.4. – Comparaisons entre les données et le CM post-fit dans les catégories 8 $t\bar{t}H$ (en haut) et dans les 17 catégories de régions de contrôle (en bas) [5].

Le faux arrière-plan dans les canaux $2\ell SS$ et 3ℓ est estimé par la méthode d'ajustement de modèle avec des facteurs de normalisation mesurés égaux à $\hat{\lambda}_e^{IntC} = 0.83^{+0.32}_{-0.32}$, $\hat{\lambda}_e^{MatC} = 1.61^{+0.48}_{-0.48}$, $\hat{\lambda}_e^{had} = 1.12^{+0.38}_{-0.38}$, et $\hat{\lambda}_\mu^{had} = 1.20^{+0.18}_{-0.18}$, obtenu à partir de l'ajustement

des données dans toutes les régions de signal et les régions de contrôle. Des facteurs de normalisation indépendants sont associés aux $t\bar{t}W$ arrière-plans dans les 2ℓ SS low N_{jets} , high N_{jets} et 3ℓ régions, et mesurés comme $\hat{\lambda}_{t\bar{t}W}^{2\ell LJ} = 1.56^{+0.30}_{-0.28}$, $\hat{\lambda}_{t\bar{t}W}^{2\ell HJ} = 1.26^{+0.19}_{-0.18}$, et $\hat{\lambda}_{t\bar{t}W}^{3\ell} = 1.68^{+0.30}_{-0.28}$, séparément. Ils sont cohérents les uns avec les autres mais $1.3\sim 1.7\sigma$ au-dessus de la section efficace prévue considérée dans cette analyse. La valeur de meilleur ajustement de $\mu_{t\bar{t}H}$ est $\hat{\mu} = 0.58^{+0.36}_{-0.33}$, correspondant à une section transversale de $\hat{\sigma}(t\bar{t}H) = 294^{+182}_{-162}$ fb. La section efficace mesurée est conforme à la valeur prédite SM de $\sigma(t\bar{t}H) = 507^{+35}_{-50}$ fb calculée à NLO dans les couplages QCD et EW. La Figure 0.5 (à gauche) montre les rendements d'événements en fonction de $\log_{10}(S/B)$ et les valeurs de meilleur ajustement de la force du signal pour chaque canal sont indiquées dans la Figure 0.5 (à droite). La signification observée (attendue) par rapport au fond uniquement l'hypothèse ($\mu = 0$) est de 1.8σ (3.1σ). Les résultats ont été publiés sous forme de note de conférence [5].

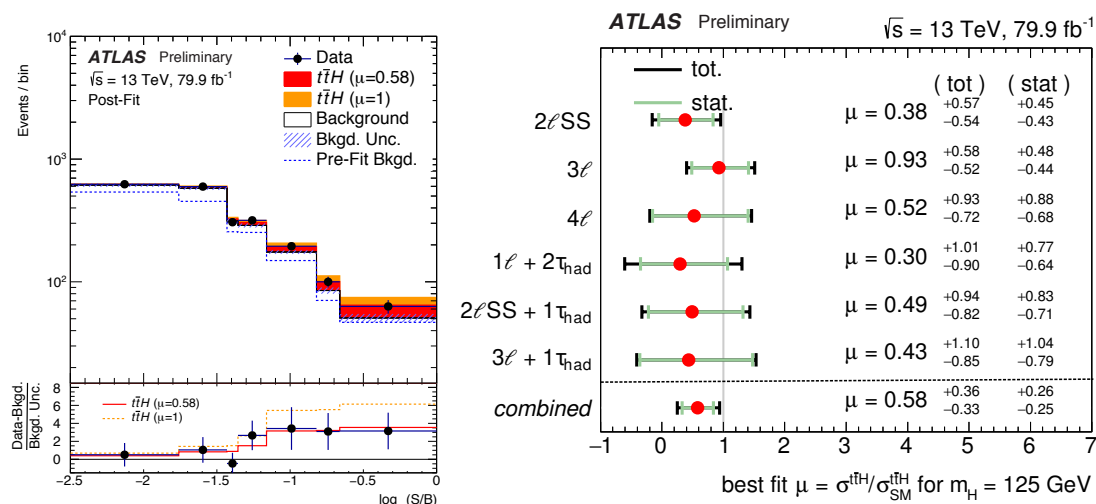


FIGURE 0.5. – Les rendements d'événement en fonction de $\log_{10}(S/B)$ pour les données, l'arrière-plan et un signal de boson de Higgs avec $m_H = 125$ GeV (à gauche) et les valeurs de meilleur ajustement de $\mu_{t\bar{t}H}$ dans chaque canal et la combinaison [5].

Pour mieux estimer le bruit de fond $t\bar{t}W$ lors du prochain cycle de recherche de $t\bar{t}H$ production dans des états finaux multileptons, une mesure de la section efficace de $t\bar{t}W$ est d'abord effectuée. L'analyse en cours est effectuée à l'aide de l'ensemble de données complet de l'analyse 2 correspondant à une luminosité intégrée de 139.0 fb $^{-1}$ à $\sqrt{s} = 13$ TeV enregistrée par l'expérience ATLAS en 2015-2018. Les résultats de la première étape, comme la mesure du signal $t\bar{t}W$, devraient être publiés début 2021. La deuxième étape, une recherche de la production $t\bar{t}H$, devrait être publiée fin 2021. Les deux analyses sont dans un état final de multileptons. En raison de la limitation du calendrier d'analyse, les résultats présentés pour la recherche $t\bar{t}H$ sont effectués

dans le canal $2\ell SS$ et ajustés à un ensemble de données Asimov avec uniquement des incertitudes statistiques. Le faux arrière-plan est estimé par la méthode d'ajustement du modèle avec des facteurs de normalisation extraits des résultats précédents et validés dans les régions de validation de conversion interne et externe de $2\ell SS$. Une approche basée sur la coupure a été utilisée pour séparer la région des jets élevés en douze régions de signal. La valeur la mieux ajustée de $\lambda_{t\bar{t}W}$ et $\mu_{t\bar{t}H}$ est $\hat{\lambda}_{t\bar{t}W} = 1.00^{+0.15}_{-0.14}$ et $\hat{\mu}_{t\bar{t}H} = 1.00^{+0.46}_{-0.45}$ avec les données aveuglées. La signification attendue concernant l'hypothèse d'arrière-plan uniquement ($\mu = 0$) est 2.2σ .

Jusqu'à présent, le SM n'est pas une théorie finale pour décrire tous les résultats expérimentaux. De nombreux problèmes non résolus attendent encore une théorie plus complète. La grande théorie de l'unification, les partenaires de particules supersymétriques et les champs de Higgs supplémentaires sont les théories candidates qui nécessitent plus de preuves expérimentales. La recherche d'une résonance lourde neutre est motivée par les prédictions de certains modèles au-delà des modèles SM, tels qu'un secteur de Higgs étendu, les modèles de Higgs composites et les modèles de dimensions supplémentaires déformés. Des recherches de résonances lourdes ont été effectuées à l'aide d'un jeu de données Run 2 correspondant à une luminosité intégrée de 36.1 fb^{-1} collectée par le détecteur ATLAS à une énergie du centre de masse de $\sqrt{s} = 13 \text{ TeV}$ pour les résonances neutres lourdes se désintégrant en deux bosons W , avec un état final de $e\nu\mu\nu$. Dans cette analyse, j'ai travaillé sur la partie réglage des limites.

Outre les hypothèses indépendantes du modèle pour le boson de Higgs scalaire lourd, la recherche est également sensible aux résonances neutres lourdes prédites par plusieurs modèles de référence dans la gamme de masse de 200 GeV à 5 TeV. Des limites supérieures sont fixées sur les temps de section efficace de production fraction de branchement $X \rightarrow WW$ à un niveau de confiance de 95 %. Aucun excès significatif n'est observé dans les limites supérieures fixées pour les prévisions BSM. Les signaux de boson de Higgs lourds de largeur étroite dans un mode de production ggF (VBF) sont exclus avec des valeurs supérieures à 6.4 pb (1.3 pb) à $m_H = 200 \text{ GeV}$ et supérieures à 0.008 pb (0.006 pb) à $m_H = 4$ (3) TeV, comme le montre la Figure 0.6.

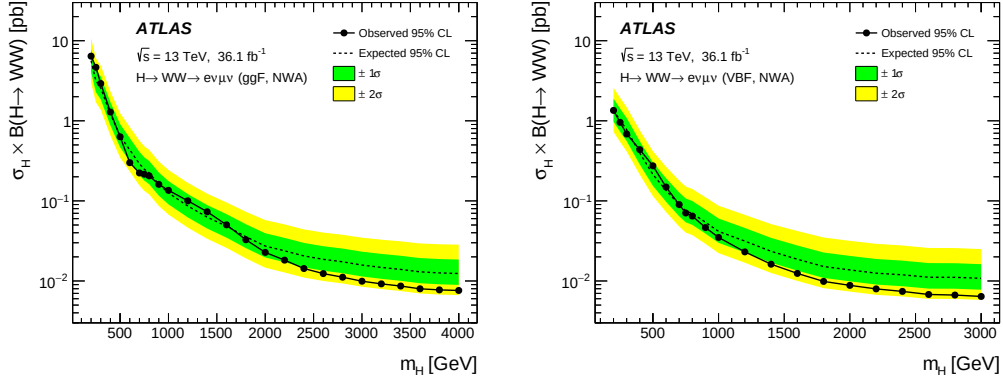


FIGURE 0.6. – Les limites supérieures de 95% CL sur $\sigma_H \times BR(H \rightarrow WW)$ dans le scénario NWA avec l'état final $e\nu\mu\nu$ pour ggF (à gauche) et VBF (à droite) en fonction de la masse de Higgs [14].

Les signaux de triplets de vecteurs lourds recherchés dans la gamme de masse de 250 GeV à 5 TeV (300 GeV à 1 TeV) dans un canal de production de qqA (VBF). Le réglage des limites pour les deux signaux à 95% CL est indiqué sur la Figure 0.7. Les signaux qqA inférieurs à 1.3 TeV sont exclus. Dans le canal VBF, la force de couplage pour jauger les bosons g_V a été mise à 1, tandis que le couplage aux fermions c_F a été mis à 0. Aucune exclusion ne peut être définie pour le signal VBF HVT.

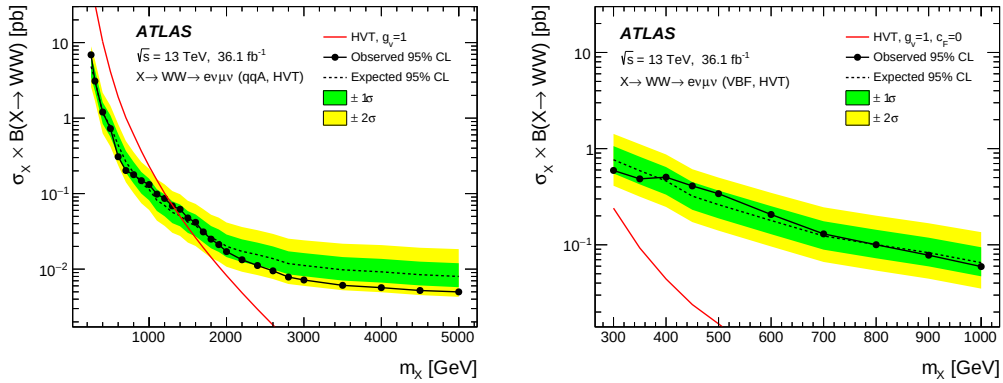


FIGURE 0.7. – Les limites supérieures de 95% CL sur $\sigma_X \times BR(X \rightarrow WW)$ pour les signaux qqA (gauche) et VBF (droite) avec $e\nu\mu\nu$ état final [14].

Pour les signaux prédits par le modèle graviton RS avec $k/\bar{M}_{Pl} = 1$ et 0.5, les valeurs de masse inférieures à 1.1 TeV et 750 GeV sont respectivement exclues. Les graphiques correspondants sont illustrés sur la Figure 0.8. Les résultats ont été publiés sous forme de papier en 2018 [14].

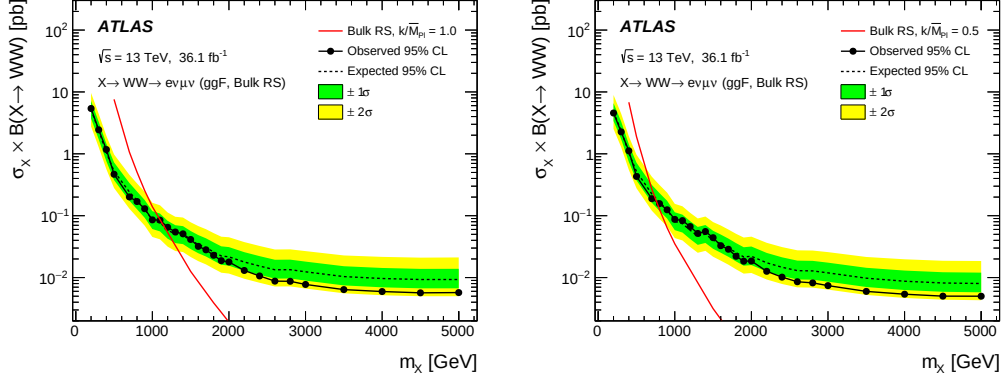


FIGURE 0.8. – Les limites supérieures 95% CL sur $\sigma_X \times BR(X \rightarrow WW)$ pour les signaux graviton avec l'état final $ev\mu\nu$. Les gravitons RS avec des couplages de $k/\bar{M}_{Pl} = 1$ (gauche) et $k/\bar{M}_{Pl} = 0.5$ (droite) et le signal ELM spin-2 VBF (en bas) sont considérés [14].

Avec une énergie au centre de masse de $\sqrt{s} = 14$ TeV, le LHC prévoit d'atteindre une luminosité intégrée de 300 fb^{-1} pendant la phase 3 après la mise à niveau de la phase I. Pour le HL-LHC, un objectif sur 10 ans est de collecter des données de collision pp avec une luminosité intégrée d'environ $3,000 \text{ fb}^{-1}$. L'analyse multilepton actuelle de $t\bar{t}H$ est toujours dominée par des incertitudes statistiques, en particulier dans les canaux τ_{had} à multiplicité élevée de leptons. La méthode basée sur les données pour les fausses estimations dans le canal $2\ell SS$ est également limitée par les faibles statistiques dans la région de contrôle de même signe et la région de contrôle de $N_{b\text{-jets}}$ élevés. Une amélioration est attendue pour l'analyse multilepton $t\bar{t}H$ avec davantage de données collectées par le détecteur ATLAS dans les années à venir. L'analyse pour le processus $X \rightarrow WW \rightarrow ev\mu\nu$ devrait également avoir plus de région d'espace μ_X exclue pour différentes prédictions BSM avec plus de statistiques.

Acknowledgements

While I'm writing the acknowledgements, my doctoral study is coming to an end. Thanks to the financial supports from the Erasmus+ program (2017-2018) and the CSC Grant (2018-2020), I could enjoy three years of fulfilled and fruitful life in the beautiful coastal city, Marseille. Life at Shandong University in the first two years before going abroad and half a year after returning to China is equally important. The former laid a solid foundation for my Ph.D. study, and the latter provided me with a quiet thesis writing environment.

At first, I would give special thanks to my supervisors: Dr. Emmanuel Monnier from CPPM, Prof. Lianliang Ma and Prof. Xueyao Zhang from Shandong University for the opportunities they provided to join the ATLAS experiment, study the project in CPPM, and finish this thesis. Prof. Lianliang Ma is a patient teacher of high academic proficiency. He introduced me to the field of particle physics, guided me in daily research, and provided advice in thesis writing. Dr. Emmanuel Monnier is an outstanding scientist and helped me a lot in both study and life. As a foreigner who speaks no French, I always seek for his help during my three years in Marseille. Prof. Xueyao Zhang is very kind, and he cares about my life and studies a lot. They also support me financially throughout my master's and doctoral studies.

I'd also like to thank Dr. Cristinel Diaconu, Dr. Fabrice Hubaut, and Dr. Pascal Pralavorio, who are very kind and offer helps when I meet difficulties in CPPM. Prof. Cunfeng Feng, Prof. Haifeng Li, Prof. Hui Dong, and many other professors from Shandong University are kind and nice. They taught me a lot during my studies at Shandong University and Aix-Marseille University.

It's been a pleasure to work with the great members of the multilepton and $H \rightarrow WW$ highmass analysis groups. Thanks to convenors of the $t\bar{t}H$ multilepton analysis group, Dr. Tamara Vazquez Schroeder, Dr. Rohin Narayan, and all others, who have done a great job when they lead the group. I would like to thank Chao Wang, Robert Wolff, and Kevin de Vasconcelos, who taught and guided me in running the $t\bar{t}H$ analysis framework hand by hand. My workmates, who are also my friends, Grigore Tarna, Hanlin Xu, Xuan Yang, Zheng Zhi, Shuo Han, Nihal Brahimi, Chenliang Wang, and also Nguyen Hoang Dai Nghia, whom I always discussed with, are all very nice and hard-working people. I want to thank all the convenors and workmates in HWW highmass analysis team, especially Yongke Zhao, who guided me when I was a beginner.

Thanks to my colleagues in Shandong University, Rui Yuan, Zhongyukun Xu, Dongshuo Du, Shuanggeng Wang, Tong Li, Jingyi Han. They always do me favors when I was in need.

At last, I would thank my parents for always standing by me and supporting me.

I would give special thanks to my wife, Hongyan Luo, for her tolerance and understanding of my absence from her side for the past three years. It was her care and encouragement that helped me finish my studies.

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Introduction

The Standard Model (SM) is a theoretical framework that describes the elementary particles and the three fundamental forces – electromagnetic, weak, and strong interaction – in a unified gauge theory. The much weaker gravitational force is not included. The Standard Model has been developed and expanded many times since the 1960s. In 2012, the discovery of the Higgs boson by the collaborations of ATLAS and CMS [1, 2] announced that the last missing piece of the Standard Model had been patched up.

The Higgs boson occupies a unique place in the standard model, which is the only explanation of the masses of the particles through the Brout-Englert-Higgs mechanism. The vector bosons of weak interaction (W and Z bosons) gain their masses by interacting with the Higgs field. The masses of matter particles (fermions) are determined by the Yukawa couplings. The Yukawa coupling between the Higgs boson and the heaviest SM fermion, top quark, is of special interest. One of the direct probes of the top-quark Yukawa coupling is the measurement of associated production of a Higgs boson with a top-quark pair ($t\bar{t}H$). The $t\bar{t}H$ process was observed by the ATLAS and CMS experiments individually in 2018, combined dedicated searches exploiting the main Higgs boson decay channels using pp collision data at $\sqrt{s} = 13$ TeV [3, 4].

The first part of this thesis presents the results of a search for $t\bar{t}H$ production in multilepton final states using a dataset collected by the ATLAS detector during 2015-2017 at a center-of-mass energy of $\sqrt{s} = 13$ TeV with an integrated luminosity of 79.9 fb^{-1} . I contributed to the event classification with MVA method in $2\ell\text{SS}$ channel, cooperated on fake background estimation, and performed the statistical analysis combining all multilepton final states. The results were published as a conference note in 2019 [5]. The on-going search for the SM $t\bar{t}H$ production in multilepton final states is performed with full Run 2 dataset (139.0 fb^{-1}), coming after a measurement of the SM $t\bar{t}W$ production to better estimate the $t\bar{t}W$ background. I worked on group framework development, group ntuple production, object working point validation, muon calibration with an exclusive working point (on-going), and fake estimation (on-going). The measurement on the $t\bar{t}W$ signal is expected to be published in early 2021, and the search for $t\bar{t}H$ is planned to be completed by the end of 2021.

So far, the SM is not a final theory to describe all experimental results. Many unsolved problems are still waiting for a more comprehensive theory. Grand Unification Theory (GUT), Supersymmetric (SUSY) Particle Partners, and additional Higgs fields are the candidate theories that require more experimental proofs. A search for a neutral heavy resonance is motivated by the predictions from some beyond the SM (BSM) models, such as an extended Higgs sector [6, 7], the composite Higgs models [8, 9], and the warped extra dimensions models [10–13]. Searches for heavy resonances have

been performed using a Run 2 dataset corresponding to an integrated luminosity of 36.1 fb^{-1} collected by the ATLAS detector at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ for heavy neutral resonances decaying into two W bosons, with a final state of $e\nu\mu\nu$. Upper limits at 95% CL are set on the resonance production cross section times branching fraction $X \rightarrow WW$ for different BSM predictions. In this analysis, I worked on limit setting part. The results were published as a paper in 2018 [14].

In this doctoral thesis, there are 5 chapters organised as follows. Chapter 1 is an overview of the theory of the SM, as well as the BSM such as the two-Higgs-doublet models and the Randall–Sundrum model. Chapter 2 introduces the LHC and ATLAS experiment, including a brief of the Liquid Argon Calorimeter (LAr) Phase-I upgrade I participated in as service work. Chapter 3 details the analysis of $t\bar{t}H$ production in multilepton final states using an integrated luminosity of 79.9 fb^{-1} dataset, while chapter 4 shows the expectation of the 139.0 fb^{-1} $t\bar{t}W/H$ analysis. A search for BSM predicted resonances in $X \rightarrow WW \rightarrow e\nu\mu\nu$ channel with an integrated luminosity of 36.1 fb^{-1} dataset is presented in Chapter 5.

1. Elementary Particle Physics

Summary

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In this chapter, Some theories based on the Standard Model (SM), as well as Beyond the SM (BSM) will be discussed. Section 1.1 gives a summary of the Standard Model particles and their interactions. Section 1.2 describes the Brout-Englert-Higgs mechanism and how elementary particles gain masses. Section 1.3 discusses some BSM theories which are the extensions of the SM.

1.1. Standard Model

It is generally accepted that the SM was established from the work of Sheldon Glashow [15], Steven Weinberg [16] and Abdus Salam [17] in the 1960s. The Higgs boson, a key prediction of the Standard Model, has been observed by the ATLAS and CMS in 2012 [1, 2], which is the last missing piece for this magnificent framework. So far, the SM has proven to be the most predictive and accurate theoretical model.

1.1.1. Elementary particles

The fundamental particles are grouped into four types: quarks, leptons, gauge bosons, and the scalar Higgs boson. Figure 1.1 shows the generation, mass, charge, and spin of their properties. The three generations (flavors) of quarks and leptons are with a spin of $\frac{1}{2}$ and satisfy the Fermi-Dirac statistics. The masses of these fermions

are increasing in the order of the generations. Six leptons and six quarks are split by the type of interactions they participate in.

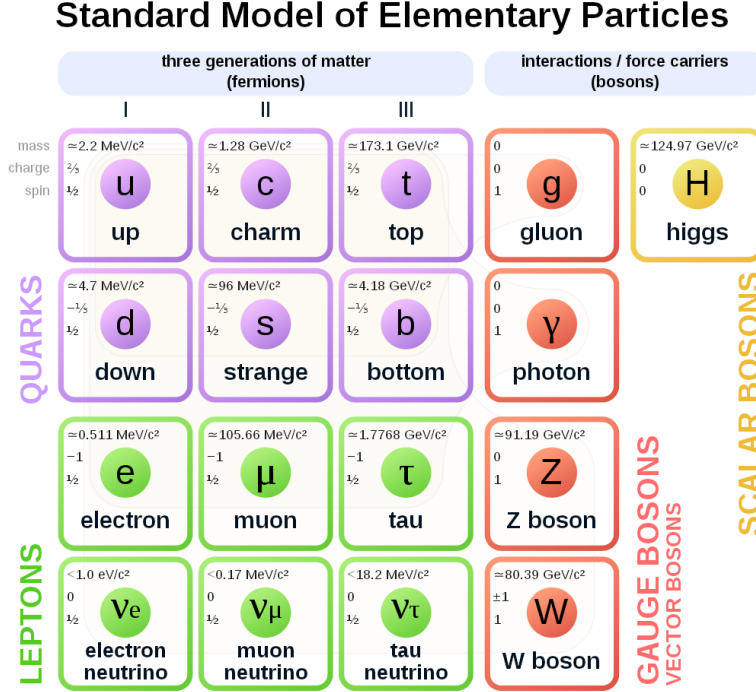


Figure 1.1. – Fundamental particles in the SM [18].

Charged leptons including electron (e), muon (μ), and tau (τ) interact through the electromagnetic as well as the weak interaction. The neutral neutrinos ν_e , ν_μ , and ν_τ have corresponding flavors to the charged leptons but with much smaller masses. These neutral fermions only interact weakly.

Quarks interact through electromagnetic, weak, and strong interactions. Charge $\frac{2}{3}$ quarks u , c and t are known as the "up-type" quarks, while the charge $-\frac{1}{3}$ quarks d , s and b are the "down-type". The intrinsic property color charge of quarks allows them to play roles in strong interactions. The color of a quark can be red, green, or blue. The color is expected to be white when quarks form into hadrons.

Bosons with integer spin, including the vector bosons (spin 1) and the scalar Higgs boson (spin 0). The force carriers - gauge bosons - have spins of 1. Photon (γ) carries the electromagnetic interaction, $W^\pm/Z$ are weak interaction carriers while gluons mediate the strong interactions. All these fundamental particles but photons interact with Higgs field and gain mass through the Brout-Englert-Higgs mechanism.

1.1.2. Electromagnetic interaction

In the Quantum electrodynamics (QED) theory, a particle can be described by a local field $\phi(x)$. A free fermion described by the Dirac Lagrangian density is

$$\mathcal{L}_{Dirac} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi(x), \quad (1.1)$$

here γ^μ are the Dirac matrices and $\psi(x)$ is the Dirac spinor representing the particle's wave function. m is the mass of the particle. The adjoint spinor $\bar{\psi} = \psi^\dagger\gamma^0$. Especially, natural units chose light $c = \hbar = 1$ for simplify.

Considering the Euler-Lagrange equation can:

$$\partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}\right) - \frac{\partial\mathcal{L}}{\partial\phi} = 0, \quad (1.2)$$

We can get

$$(i\gamma^\mu\partial_\mu - m)\psi(x) = 0. \quad (1.3)$$

Since the Lagrangian will not keep invariant under a local $U(1)$ symmetry group transformation

$$\psi(x) \rightarrow U\psi(x) = e^{i\theta}\psi(x), \quad (1.4)$$

we introduce a covariant derivative $D_\mu = \partial_\mu + iqA_\mu$, here A_μ is a vectorial field which transforms as $A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu\theta$. We can obtain the invariant Lagrangian as

$$\begin{aligned} \mathcal{L} &= \bar{\psi}(x)(i\gamma^\mu D_\mu - m)\psi(x) \\ &= \mathcal{L}_{Dirac} - q\bar{\psi}(x)\gamma^\mu A_\mu\psi(x). \end{aligned} \quad (1.5)$$

The second item, as the QED interaction between a charged fermion and an external electromagnetic potential $A_\mu(x)$, the full QED Lagrangian finally is

$$\mathcal{L}_{QED} = \bar{\psi}(x)(i\gamma^\mu\partial_\mu - m)\psi(x) - q\bar{\psi}(x)\gamma^\mu A_\mu\psi(x) - \frac{1}{4}F_{\mu\nu}(x)F^{\mu\nu}(x), \quad (1.6)$$

the last item represents the kinetic energy and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength tensor.

1.1.3. Strong interaction

Strong interaction, also described as quantum chromodynamics (QCD), is the interaction of the quarks and gluons. Colored gluons are exchanged in the strong interaction, thus a transformation of $SU(3)_C$ symmetry must be following. The triple-flavored quarks under $SU(3)_C$ group can be written as

$$q_f = \begin{pmatrix} q_f^R \\ q_f^G \\ q_f^B \end{pmatrix} \quad (1.7)$$

A free quark described by the Dirac Lagrangian density is

$$\mathcal{L} = \sum_f \bar{q}_f (i\gamma^\mu \partial_\mu - m) q_f, \quad (1.8)$$

and the quark's mass is represented as m . The invariance of the Lagrangian under $SU(3)_C$ gauge transformation is

$$q(x) \rightarrow U q(x) = e^{i\frac{\lambda_a}{2}\theta_a} q(x), \quad (1.9)$$

with any unitary 3×3 matrix U , which can be given by a linear combination of 8 Gell-Mann matrices λ_a ($a = 1, \dots, 8$). As done in QED, a covariant derivative

$$D_\mu = \partial_\mu + i g_s \frac{\lambda_a}{2} G_\mu^a(x), \quad (1.10)$$

has to be introduced to achieve the invariant of the Lagrangian. In function Equation 1.10, g_s is the strong coupling constant and $G_\mu^a(x)$ are the gluon fields. Considering the field strength tensors for the gluon-gluon self-interaction

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c, \quad (1.11)$$

where f_{abc} are the structure constants of the $SU(3)_C$ group, and also the kinetic term $\frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$, the final QCD Lagrangian is

$$\mathcal{L}_{QCD} = \sum_f \bar{q}_f (i\gamma^\mu \partial_\mu - m) q_f - g_s \sum_f (\bar{q}_f \gamma^\mu \frac{\lambda_a}{2} q_f) G_\mu^a - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}. \quad (1.12)$$

Required by the gauge invariance, photons and gluons are with no mass.

1.1.4. Electroweak interaction

Electroweak (EW) interaction is a unified description of the electromagnetic interaction and weak interaction. For this work, Glashow [15], Salam [17], and Weinberg [16] won the 1979 Nobel Prize for physics. The weak interaction is described by the $SU(2)_L$ for the left-handed leptons:

$$\psi_1(x) = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L, \quad (1.13)$$

and for the quark terms:

1. Elementary Particle Physics – 1.2. Higgs mechanism and Higgs boson

$$\psi_1(x) = \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L. \quad (1.14)$$

The right-handed terms of the leptons can be described as singlets:

$$\begin{aligned} \psi_2(x) &= \nu_{eR}, \nu_{\mu R}, \nu_{\tau R}, \\ \psi_3(x) &= e_R, \mu_R, \tau_R, \end{aligned} \quad (1.15)$$

and for the quarks:

$$\begin{aligned} \psi_2(x) &= u_R, c_R, t_R, \\ \psi_3(x) &= d_R, s_R, b_R. \end{aligned} \quad (1.16)$$

The Lagrangian for a free fermion can be presented as:

$$\begin{aligned} \mathcal{L}_{free} &= i \bar{u}(x) \gamma^\mu \partial_\mu u(x) + i \bar{d}(x) \gamma^\mu \partial_\mu d(x) \\ &= \sum_{j=1}^3 i \bar{\psi}_j(x) \gamma^\mu \partial_\mu \psi_j(x), \end{aligned} \quad (1.17)$$

which is invariant under the global gauge transformations of $SU(2)_L \otimes U(1)_Y$. To satisfy the local invariant, covariant derivative D_μ is introduced to replacing ∂_μ .

$$\begin{aligned} D_\mu \psi_1(x) &= [\partial_\mu - i g \tilde{W}_\mu(x) - i g' y_1 B_\mu(x)] \psi_1(x), \\ D_\mu \psi_{2,3}(x) &= [\partial_\mu - i g' y_{2,3} B_\mu(x)] \psi_{2,3}(x), \end{aligned} \quad (1.18)$$

$W_{\mu\nu}^i$ and $B_{\mu\nu}$ are the field strength tensors, corresponding to $SU(2)_L$ and $U(1)_Y$ namely.

$$\begin{aligned} W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g \epsilon^{ijk} W_\mu^j W_\nu^k, \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu. \end{aligned} \quad (1.19)$$

The EW Lagrangian finally can be written as:

$$\mathcal{L}_{EW} = \sum_{j=1}^3 i \bar{\psi}_j(x) \gamma^\mu D_\mu \psi_j(x) - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu}. \quad (1.20)$$

1.2. Higgs mechanism and Higgs boson

1.2.1. Higgs mechanism

In Section 1.1.2, 1.1.3 and 1.1.4, the Lagrangian we discussed allows only massless particle fields. The Lagrangian would violate the gauge symmetry with an explicit mass term. However, this is in contradiction with the experimental observation of the massive $W^\pm / Z$ bosons, which were discovered in 1983 by CERN [19]. People were troubled by this question until the Higgs mechanism was raised. The spontaneous

1. Elementary Particle Physics – 1.2. Higgs mechanism and Higgs boson

symmetry breaking (SSB) of the electroweak produces the mass of $W^\pm$ and Z bosons and fermions gain their masses from the Yukawa coupling with the Higgs field.

The Higgs scalar field is introduced as

$$\Phi(x) = \begin{pmatrix} \phi^{(+)} \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_3 + i\phi_4 \\ \phi_1 + i\phi_2 \end{pmatrix}. \quad (1.21)$$

and the corresponding Lagrangian is

$$\begin{aligned} \mathcal{L} &= (D_\mu \Phi)^\dagger D^\mu \Phi - V(\Phi) \\ &= \left| \left(\partial_\mu + i \left(g \frac{\tau_a}{2} W_\mu^a + g' \frac{Y}{2} B_\mu \right) \right) \Phi \right|^2 - V(\Phi), \end{aligned} \quad (1.22)$$

where the first term represents the kinetic energy and the second is the potential of the Higgs field. First look at the potential part:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2. \quad (1.23)$$

Only positive values are permitted for a stable global minimum. If $\mu^2 \geq 0$, the potential reach a minimum value at the point of $\phi_1 = \phi_2 = 0$. For $\mu^2 < 0$, the case is shown in Figure 1.2, the minimum value is

$$|\phi^0| = \sqrt{\frac{\phi_1^2 + \phi_2^2}{2}} = \sqrt{\frac{-\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}} \quad (1.24)$$

where $v = \sqrt{\frac{-\mu^2}{\lambda}}$ is the vacuum expectation value (VEV). The value of v will be given by Equation 1.29. The ground state can be chosen arbitrarily at $\phi_1 = \sqrt{2}v$ and $\phi_2 = 0$, which is not invariant under $SU(2)_L \otimes U(1)_Y$. This is the so-called spontaneous symmetry breaking.

1. Elementary Particle Physics – 1.2. Higgs mechanism and Higgs boson

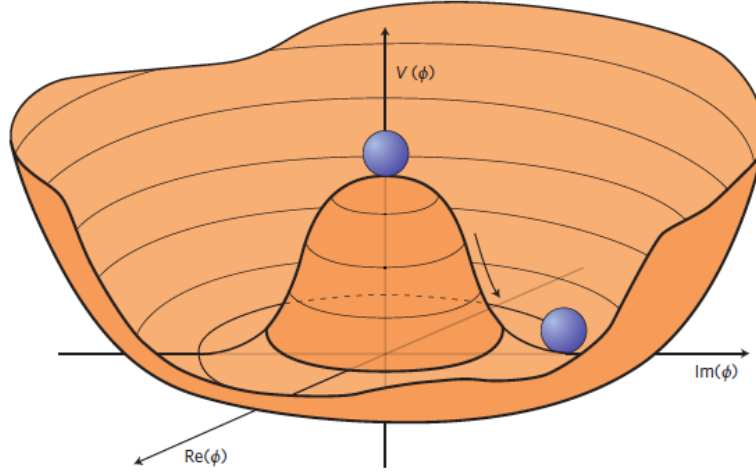


Figure 1.2. – Higgs potential with $\mu^2 < 0$, the x-axis and y-axis are the real and imaginary parts of the $V(\phi^0)$ [20].

The scalar doublet can be written as

$$\Phi(x) = e^{i\frac{\sigma_j}{2}\theta^j(x)} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}, \quad (1.25)$$

where the real fields $\theta^j(x)$ and $H(x)$ are introduced. The kinetic part in Equation 1.22 can be written as:

$$(D_\mu \Phi)^\dagger D^\mu \Phi = \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{1}{8} g^2 (v + H)^2 \left| W_\mu^1 + i W_\mu^2 \right|^2 + \frac{1}{8} (v + H)^2 \left| g W_\mu^3 - g' B_\mu \right|^2, \quad (1.26)$$

thus the final Lagrangian is

$$\mathcal{L}_{Higgs} = \frac{1}{2} \partial_\mu H \partial^\mu H + (v + H)^2 \left(\frac{g^2}{4} W_\mu^\dagger W_\mu + \frac{g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu \right) - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4, \quad (1.27)$$

where

$$\begin{aligned} W_\mu &= \frac{W_\mu^1 + i W_\mu^2}{\sqrt{2}}, \\ Z_\mu &= \frac{g' W_\mu^3 - g B_\mu}{\sqrt{g^2 + g'^2}}, \\ \cos \theta_W &= \frac{g}{\sqrt{g^2 + g'^2}}. \end{aligned} \quad (1.28)$$

The $W^\pm/Z$ can be derived from Equation 1.26

1. Elementary Particle Physics – 1.2. Higgs mechanism and Higgs boson

$$m_W = \frac{gv}{2}, m_Z = \frac{v}{2} \sqrt{g^2 + g'^2} = \frac{m_W}{\cos\theta} \quad (1.29)$$

and thus $v = 246$ GeV is determined from the experimental results.

The mass of a spin-0 scalar boson Higgs is given:

$$m_H = \sqrt{-2\mu^2} = v\sqrt{2\lambda}, \quad (1.30)$$

however, no certain value has been predicted due to a free parameter of the quartic coupling λ is applied.

Fermions obtain their masses through the interaction between fermions and the Higgs field. The interaction term, also known as Yukawa term, is given as:

$$\mathcal{L}_{Yukawa} = -(\Gamma_{i,j}^l \bar{\Psi}_L^l \Phi \psi_R^l + \Gamma_{i,j}^D \bar{\Psi}_L^Q \Phi \psi_R^D + \Gamma_{i,j}^U \bar{\Psi}_L^Q \Phi^\dagger \psi_R^U) + h.c., \quad (1.31)$$

The $\Gamma_{i,j}$ represents the Yukawa coupling matrices for leptons and quarks. The left-handed (doublet) and right-handed (singlet) leptons are represented by Ψ_L^l and ψ_R^l . The left-handed (doublet) up/down-type quarks are represented by Ψ_L^Q while the right-handed (singlet) up and down-type quarks are represented by ψ_R^U and ψ_R^D .

The Yukawa coupling for the up-type quarks can be written as

$$\mathcal{L}_{Yukawa,U} = -m_u \bar{u}u - m_c \bar{c}c - m_t \bar{t}t - \frac{\lambda_u}{\sqrt{2}} \bar{u}Hu - \frac{\lambda_c}{\sqrt{2}} \bar{c}Hc - \frac{\lambda_t}{\sqrt{2}} \bar{t}Ht. \quad (1.32)$$

The coupling between Higgs and the top quark, which is the heaviest quark, is also the largest.

$$\lambda_t = \sqrt{2} \frac{m_t}{v} \sim 1 \quad (1.33)$$

1.2.2. Higgs productions

The Large Hadron Collider (detailed in Chapter 2) provides a variety of ways to observe the Higgs boson. The four main production modes, with center-of-mass energy at $\sqrt{s} = 13$ TeV proton-proton collision, are shown in Figure 1.3, which are gluon-gluon fusion (ggF), vector boson fusion (VBF), associated production with a W or Z (VH), and associated production with a pair of quarks ($t\bar{t}H$).

1. Elementary Particle Physics – 1.2. Higgs mechanism and Higgs boson

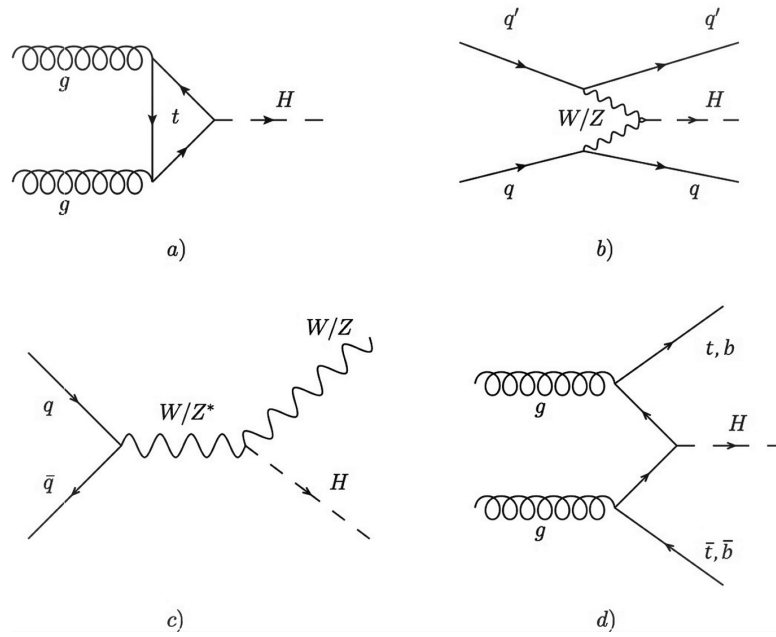


Figure 1.3. – Feynman diagrams for Higgs productions in gluon-gluon fusion (a), vector boson fusion (b), associated production with a vector boson (c), associated production with a pair of top quarks (d) [21].

The ggF is the greatest contribution which accounts for about 87% of the Higgs production. The Higgs boson is produced via a loop of virtual quarks due to there is no coupling between the massless gluons and Higgs boson at tree level. The loop most commonly comes from the top quark because the coupling is proportional to its mass [6].

The VBF provides the second large contribution at a level of 7%. The Higgs boson produced by VBF is from the fusion of two vectors, which are radiated from an incoming quark pair. 1

The VH production with a contribution of ~4% is the third-largest to the total production. The process is also known as Higgs strahlung due to the Higgs boson is a radiation of a vector boson in this mode.

The last ~1% of Higgs cross section is contributed from the associated production with a pair of top quarks ($t\bar{t}H$), which is $\sigma_{t\bar{t}H} = 0.507$ pb. In this process, a top quark and an anti-top quark from two different top-antitop pairs individually are fused and generate the Higgs boson. As a rather rare production mode, $t\bar{t}H$ is still one of the key processes because it gives direct access to the coupling between the top quark and Higgs boson.

Figure 1.4 shows Higgs cross sections in different production modes as a function of $\sqrt{s}$ (left) and Higgs branching ratios as a function of m_H (right).

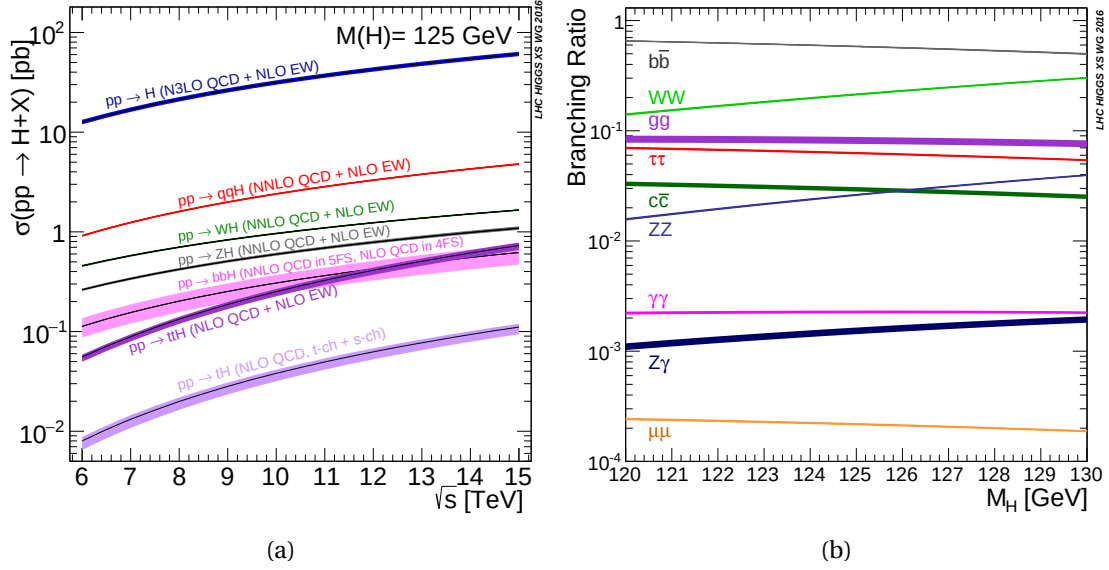


Figure 1.4. – Higgs cross sections (a) for different production modes as a function of the center-of-mass energy $\sqrt{s}$ and Higgs branching ratios (b) for various decay modes as a function of the standard model Higgs mass M_H .

1.2.3. Higgs discovery and measurements

Higgs boson was discovered in 2012 by ATLAS and CMS collaborations [1, 2]. The new particle was announced observed at a mass of 125 GeV with the data taken in 2011 and 2012. The analysis combine the data taken at $\sqrt{s} = 7$ TeV with integrated luminosities of 4.8 fb^{-1} and $\sqrt{s} = 8$ TeV with integrated luminosities of 5.8 fb^{-1} .

Figure 1.5 shows the search for Higgs through channels of $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ with ATLAS. The observed (expected) significance for $H \rightarrow ZZ^* \rightarrow 4\ell$ decay proceeds at $m_H = 125.0$ GeV is 3.6σ (2.7σ), and for $H \rightarrow \gamma\gamma$ decays at $m_H = 125.6$ GeV is 4.5σ (2.5σ). The combination of all the Higgs searching channels at ATLAS gives a significance of 5.9σ (4.9σ expected) at $m_H = 126.5 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})$ GeV. At the same time, CMS gives the result of 5.0σ (5.9σ expected) at $m_H = 125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV.

1. Elementary Particle Physics – 1.2. Higgs mechanism and Higgs boson

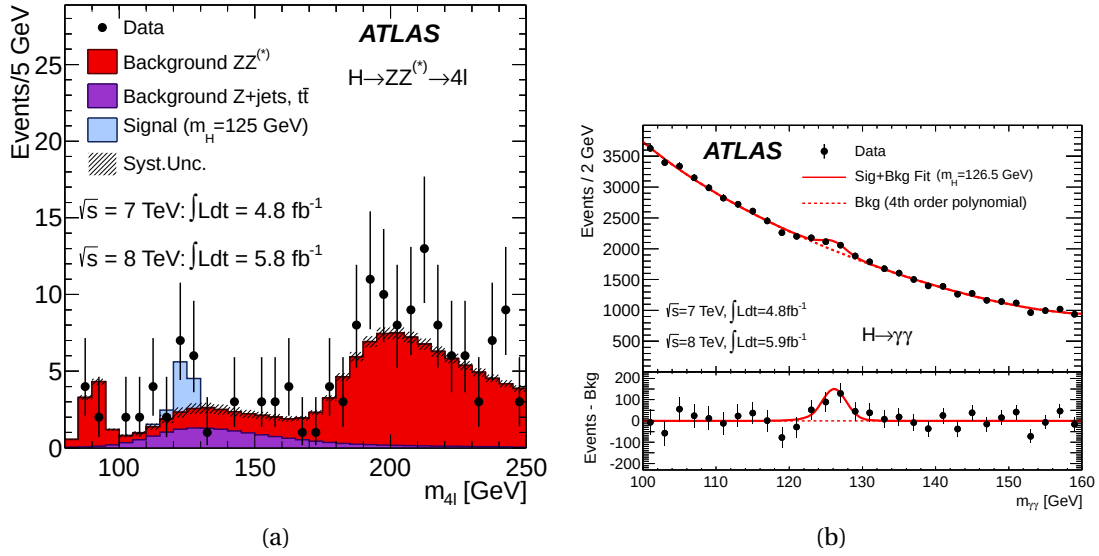


Figure 1.5. – Higgs productions observed in $H \rightarrow ZZ^* \rightarrow 4\ell$ channel (a) and $H \rightarrow \gamma\gamma$ channel (b) the ATLAS detector [1].

The Run 1 combination of ATLAS and CMS gives the Higgs at $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$, still dominated by statistic uncertainties. The latest combination results using the Run 2 data with integrated luminosities of $24.5\text{-}79.8 \text{ fb}^{-1}$ are shown in Figure 1.6.

1. Elementary Particle Physics – 1.3. Theories Beyond the Standard Model

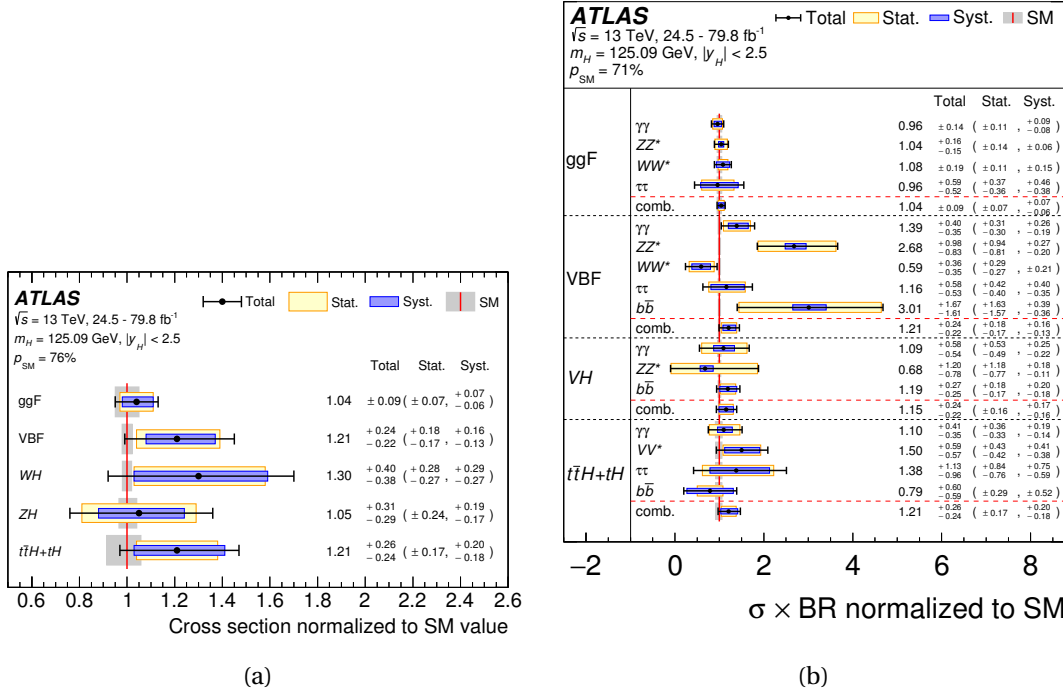


Figure 1.6. – The measured Higgs cross sections (a) and cross sections times branching ratios (b) in ggF, VBF, VH and $t\bar{t}H + tH$ channels [22].

1.3. Theories Beyond the Standard Model

Though the SM has proven to be the most predictive theoretical model so far, still there are many unsolved problems for which this magnificent theory offers no convincing explanations.

- The fine-tuning problem (hierarchy problem) is always bothering the physicists. Compared to the Planck scale (10^{19} GeV), the SM EW scale (125 GeV) is extremely small. Why Higgs boson's mass is so light, which looks like a fine-tuning in some way.
- The normal matter we have observed accounts for only 5% of the whole energy in the universe. The rest 26% of dark matter and 69% of dark energy has not been observed so far. SM is exhausted and several new models are proposed to provide particle candidates for the dark matter and dark energy [23].
- The CP violation measured is much larger than the SM predicted. Particles and anti-particles are required to be symmetric in SM, however, in the universe, there's a much larger amount of matter than anti-matter.
- Neutrinos must have masses from the neutrino oscillations experiments. However, they are considered to be massless in the SM. Mass terms for neutrinos in SM are hard especially for the right-handed neutrinos.

- Gravity is not included in the SM. Quantum gravity theory is proposed to explain gravitation through the quantum field theory.

Many new physics theories aim to solve the above problems by extending the current SM. One of the most famous ones is supersymmetry (SUSY), which offers each particle a superpartner.

1.3.1. The 2HDM

Two complex scalar doublets are introduced to extend the SM in the two-Higgs-doublet models (2HDM) [24]. From the extending, eight real scalars including two charged Higgs, three neutral scalars, and three generators to give masses to $W^\pm/Z$ are considered.

The 2HDM theory provides a new way to explain the dark matter with the extended singlet. The neutrino masses can also get explained by this theory from an extended triplet without considering a right-handed neutrino. From the Higgs sector extension, A mechanism to explain the CP violation is also offered.

1.3.2. The RS model

One of the solutions for the hierarchy problem is the Randall-Sundrum (RS) model [25–28], which offers a new higher-dimensional mechanism. The SM is set up in (3+1)-dimensional subspace, also known as the weak or TeV brane. A warp factor, which is a function to the additional dimension, is multiplied to the four-dimensional metric. Thus a non-factorized five-dimensional space (bulk) has been established.

$$ds^2 = e^{-2krc|\phi|} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2. \quad (1.34)$$

The space-time interval ds^2 in the RS is represented as Equation 1.34, where k is a scale of the order of the Planck scale. x^μ represents coordinates for the SM four-dimensions, while $0 \leq \phi \leq \pi$ is the coordinate for the extra dimension. The interval of x^μ is finite and its size is set by r_c . The five-dimensional mass parameters and the warp factor, $e^{-2krc|\phi|}$ determine the four-dimensional mass scales together. As an exponential function, it does not require the r_c to be extremely large to reach the Planck scale.

2. The LHC and the ATLAS detector

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The Large Hadron Collider (LHC) is designed to test the predictions of theories and further explore the fundamental nature of matter. Up to today, the LHC has been running smoothly and has achieved many predetermined scientific goals. One of the main achievements was the discovery of the SM predicted Higgs boson in 2012 [1, 2].

In this chapter, the LHC accelerator and the detectors at the LHC are described in Section 2.1. Details for the ATLAS detector are discussed in Section 2.2. Section 2.3 describes the Phase-I upgrade of the Liquid Argon (LAr) Calorimeter. I participate in the acquirement and analysis of the LAr demonstrator calibration data as my qualification task. The ATLAS event simulation and object reconstruction are talked about in Section 2.4 and Section 2.5.

2.1. The LHC

Located at the border of France and Switzerland, the LHC [29, 30] was approved by the European Organization for Nuclear Research (CERN) council on 16 December 1994. The accelerator took the advantage of the existing 26.7 km in circumference, about 100 m deep tunnel constructed from 1984 to 1989 for The Large Electron-Positron collider (LEP) [31], which was closed in 2000.

The LHC accelerator complex and collision production are discussed in Section 2.1.1 and 2.1.2. The experiments at LHC are introduced in Section 2.1.3

2.1.1. Accelerator complex

The complex of the accelerator is shown in Figure 2.1. As a machine built for proton-proton collisions, the protons injected into the accelerators are produced by ionizing the hydrogen gas. A linear accelerator, LINAC2, is the starting of the accelerator chain. The protons can reach an energy of 50 MeV after they leave the LINAC2 to the Proton Synchrotron Booster (BOOSTER), which is a ring accelerator with a radius of 25 m. In BOOSTER, the protons are accelerated to an energy of 1.4 GeV. Then the protons are collected by the Proton Synchrotron (PS) and accelerated to 26 GeV. After that, a Super

2. The LHC and the ATLAS detector – 2.1. The LHC

PS (SPS), which has a circumference of 6.9 km, can accelerate the protons to 450 GeV. Finally, the protons are injected into the LHC through two parallel rings in opposite directions.

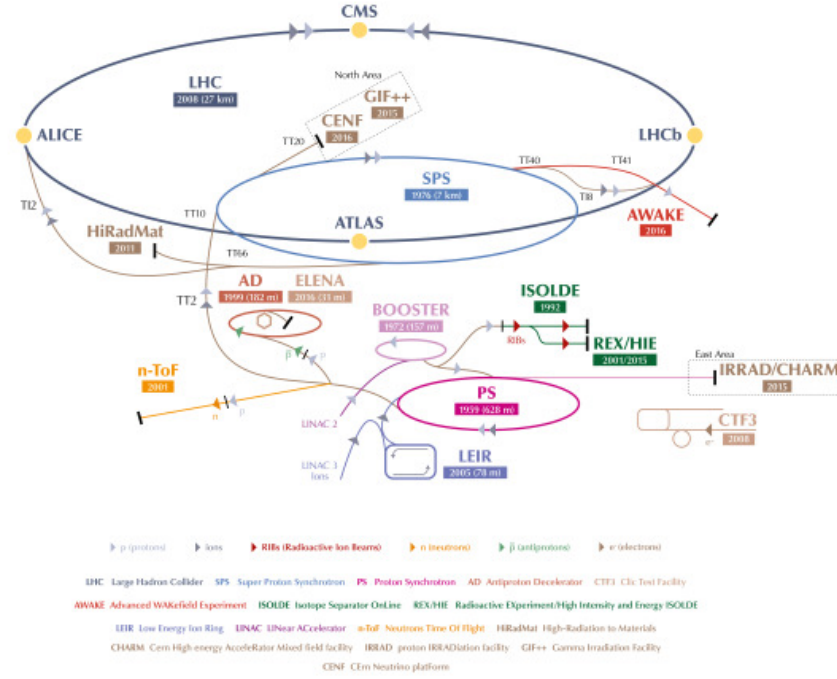


Figure 2.1. – Complex chain of the LHC accelerator [32].

The proton beams are accelerated with an oscillating electromagnetic fields at 400 MHz, obtained by a superconducting cavity system. A system of more than 9,000 magnets surrounds the beam pipe. In total 1,232 superconducting dipole magnets, 1,104 in the arc and 128 in the dispersion suppressor (DS) regions, with the same basic design with 14.3 m length, are built to bend the beams. About 450 quadrupole magnets are used for centering and correcting the beams. For the magnets operate, the cryostat can provide a temperature of either 1.9 K or 4.5 K and diffusion pumps achieve the insulating vacuum environment.

2.1.2. Collision production

The LHC started its operation on 10 September 2008. However, 9 days later, a fault occurs in the electrical connection and thus leads to damage to the machine and helium leakage. After more than a year of repairing and consolidating, the LHC succeeded its first period of operation at 2.36 TeV on 16 December 2009.

2. The LHC and the ATLAS detector – 2.1. The LHC

The first center-of-mass energy at $\sqrt{s} = 7$ TeV collision happened on 30 March 2010, which was recorded by the ATLAS as a milestone achieved (starting of the Run 1). By the end of 2011, $5.46 - 6.10 \text{ fb}^{-1}$ of proton-proton collision data [33] were collected and analysed to search for evidence of new particles. On 5 April 2012, the LHC started to record the center-of-mass energy at $\sqrt{s} = 8$ TeV data [34]. On 4 July 2012, the ATLAS and CMS experiments announced their latest results in a new particle, the Higgs boson, observed at a mass around 125-126 GeV [1, 2]. The Run 1 total integrated luminosity and data quality (DQ) is shown in Figure 2.2 (left).

The first Long Shutdown (LS1) took place on 16 February 2013, which is a 2-year technical stop for repairing, maintenance, and upgrading. The LHC Run 2 started on 03 June 2015 with the center-of-mass energy increased to $\sqrt{s} = 13$ TeV, energy has not been achieved by any other accelerator. This period lasted for three years, a total luminosity of about 150 fb^{-1} collision data [35] has been delivered. The Run 2 total integrated luminosity and data quality are shown in Figure 2.2 (right).

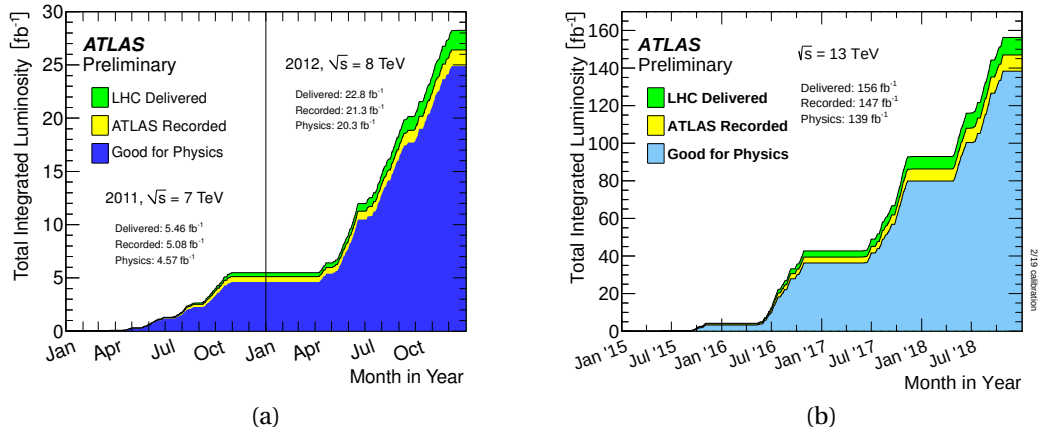


Figure 2.2. – Total integrated luminosity and data quality versus time in Run 1 (a) [36] and Run 2 (b) [37].

Figure 2.3 shows the delivered cumulative luminosities by LHC versus time.

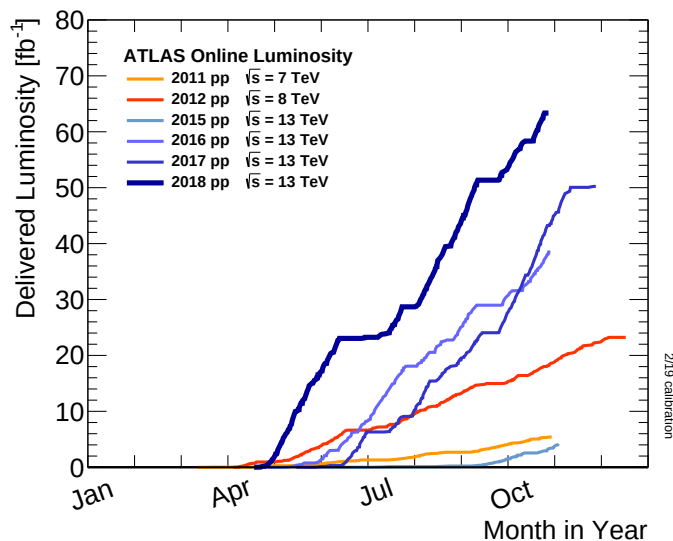


Figure 2.3. – Delivered luminosity versus time [37].

During 2019-2020, the second Long Shutdown (LS2) is going on for Run 3 with upgrading to the center-of-mass energy at $\sqrt{s} = 14$ TeV. Run 3 will last for 3 years and afterward, a plan for High-Luminosity Large Hadron Collider (HL-LHC) [38] is expected to reach an integrated luminosity of $3,000 \text{ fb}^{-1}$.

2.1.3. Detectors at the LHC

Seven detectors (ATLAS, CMS, ALICE, LHCb, LHCf, TOTEM, and MoEDAL) [39] are installed to collect the pieces of particles produced by collisions in the accelerator. The two general purposed detectors, the ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) measure the precise cross sections and particle properties. ALICE (A Large Ion Collider Experiment) and LHCb (Large Hadron Collider beauty) are the specialized detectors, either focus on strong interactions by studying heavy-ion physics or investigate the differences between matter and antimatter via b hadrons. LHCf (Large Hadron Collider forward) and TOTEM (TOTAl cross section, Elastic scattering and diffraction dissociation Measurement at the LHC) are the smallest experiments. The LHCf is motivated to simulate cosmic rays in laboratories with two detectors installed 140 meters at both sides of the ATLAS collision point, locating along the LHC beamline. The TOTEM borrows the forward parts of the CMS detector, measures the protons directly as well as investigate some other phenomena. MoEDAL (Monopole and Exotics Detector at the LHC), the experiment focusing on searching for the magnetic monopole, which is a hypothetical particle with magnetic charge, with detectors near LHCb, was approved in 2010.

2.2. The ATLAS detector

As one of the two general-purpose experiments, the ATLAS is the largest particle detector in the world. The length of this cylindrical detector is 46 m, with 25 m of diameter and 7,000 tons of weight (shown in Figure 2.4). The ATLAS detector is symmetrical to the interaction point. The structure of the detector is driven by the magnet system described in Section 2.2.2, which consists of a superconducting solenoid distributed outside the inner-detector (described in Section 2.2.3) and three large superconducting toroids around the calorimeter. The inner detector immersed in a 2 T solenoid magnetic field at the core of the detector, closest to the beam pipe. A liquid-argon (LAr) sampling calorimeter system (see in Section 2.2.4) for measuring the energy and position of electrons, photons, and hadrons. The muon spectrometer mentioned in Section 2.2.5 is at the outermost layer. The strong magnetic field inside the muon spectrometer makes the precise measurement of muon momentum possible. A brief introduction of the trigger system (see in Section 2.2.6) is presented at the end of this section.

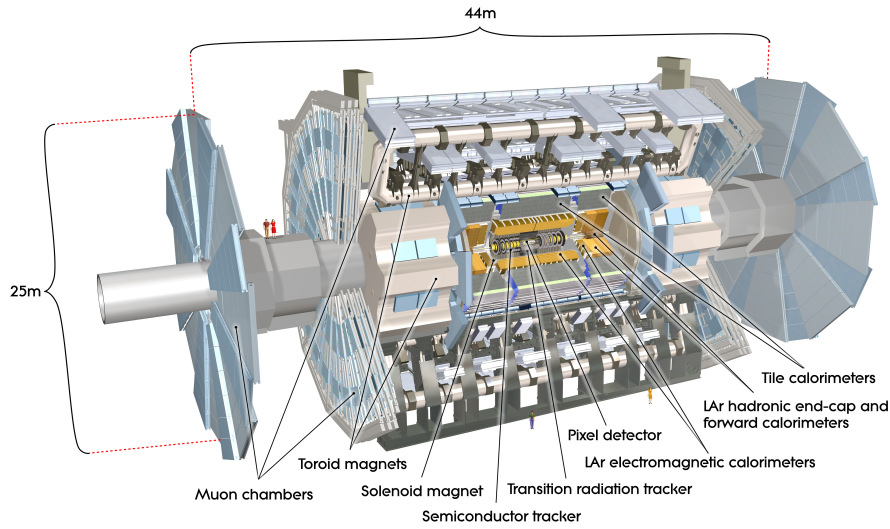


Figure 2.4. – The ATLAS detector layout [40].

Table 2.1 gives the performance goals of each part of the ATLAS detector. E and p_t are in GeV.

2.2.1. The ATLAS coordinates

The ATLAS coordinate system is an approach to describe the particle position and momenta. The origin of the coordinate system is defined by the interaction point (IP). The beam direction is defined as the z -axis and the x - y plane is perpendicular to the beam pipe. The positive x -axis points toward the center of the ring and the positive

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets) barrel and end-cap forward	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	± 3.2 $3.1 < \eta < 4.9$	± 3.2 $3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	± 2.7	± 2.4

Table 2.1. – The performance goals of the ATLAS detector [41].

y-axis points upwards, from the interaction point. Half of the detector at the positive z-axis side is defined as side-A, the other part is called side-C.

The azimuthal angle ϕ is defined as the angle between the positive x-axis and the particle's projection in the x-y plane. The polar angle θ is the angle between the positive z-axis and the particle's position. The pseudorapidity η is defined as

$$\eta = -\ln \tan \frac{\theta}{2}, \quad (2.1)$$

while for the massive objects, the rapidity y is defined as

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}. \quad (2.2)$$

The distance ΔR in $\eta - \phi$ angle space is defined as

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}. \quad (2.3)$$

The transverse energy E_T , the missing transverse energy E_T^{miss} , and the transverse momentum p_T

$$p_T = |p| \sin \theta, \quad (2.4)$$

are defined in the x-y plane.

2.2.2. The magnet system

The ATLAS magnet system consists of a solenoid, a barrel toroid, and two end-cap toroids, the detailed parameters are listed in Table 2.2.

The solenoid lying between the inner detector (described in Section 2.2.3) and the barrel electromagnetic calorimeter (described in Section 2.2.4), provides the inner detector an axial magnetic field at 2 T. The radiation thickness before the barrel electromagnetic calorimeter is also guaranteed to be minimum. Figure 2.5 (left) shows a picture of the solenoid in the factory.

The barrel toroid and the two end-cap toroids lying around the calorimeters are

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

Property	Feature	Unit	Solenoid	Barrel toroid	End-cap toroids
Size	Inner diameter	m	2.46	9.4	1.65
	Outer diameter	m	2.56	20.1	10.7
	Axial length	m	5.8	25.3	5.0
	Number of coils		1	8	2×8
Mass	Conductor	t	3.8	118	2×20.5
	Cold mass	t	5.4	370	2×140
	Total assembly	t	5.7	830	2×239
Coils	Turns per coil		1154	120	116
	Nominal current	kA	7.73	20.5	20.5
	Magnet stored energy	GJ	0.04	1.08	2×0.25
	Peak field in the windings	T	2.6	3.9	4.1
	Field range in the bore	T	0.9-2.0	0.2-2.5	0.2-3.5
Conductor	Overall size	mm ²	30×4.25	57×12	41×12
	Ratio Al:Cu:NbTi		15.6:0.9:1	28:1.3:1	19:1.3:1
	Number of strands (NbTi)		12	38-40	40
	Strand diameter (NbTi)	mm	1.22	1.3	1.3
	Critical current (at 5 T and 4.2 K)	kA	20.4	58	60
	Operating/critical-current ratio at 4.5 K	%	20	30	30
	Residual resistivity ratio (RRR) for Al		>500	>800	>800
	Temperature margin	K	2.7	1.9	1.9
	Number of units×length	m	4×2290	8×4×1730	2×8×2×800
	Total length (produced)	km	10	56	2×13
Heatload	At 4.5 K	W	130	990	330
	At 60–80 K	kW	0.5	7.4	1.7
	Liquid helium mass flow	g/s	7	410	280

Table 2.2. – Details of the ATLAS magnet system [41].

providing toroidal magnetic fields to the muon detectors. The magnetic fields are between 0.5 T and 1 T. Figure 2.5 (right) shows the geometry of the toroids around the calorimeters with an eight-fold azimuthal symmetry.

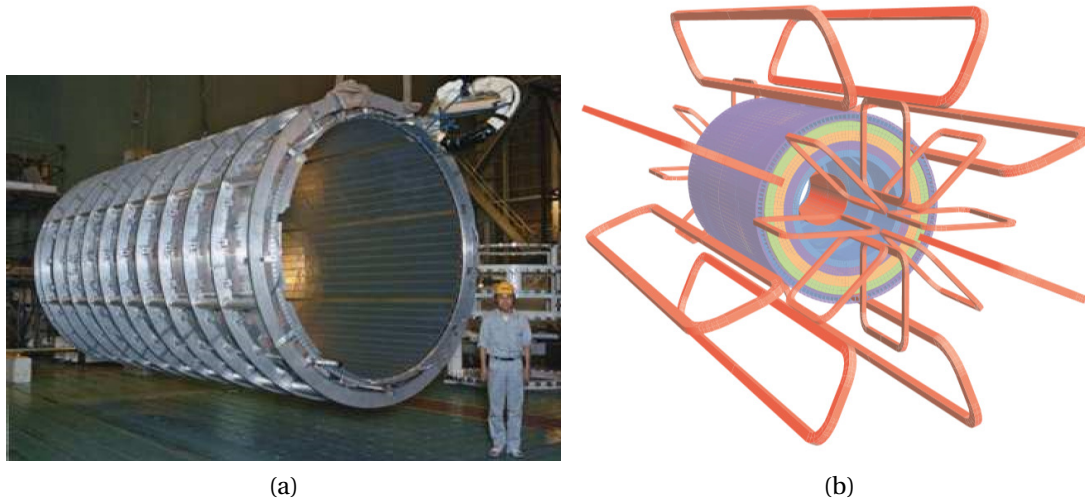


Figure 2.5. – Bare central solenoid in the factory (a) and geometry of toroids around the calorimeter (b) [41].

2.2.3. The inner detectors

More than 1,000 final products are produced in each deep-inelastic-scattering process. As the detector closest to the beam pipe, the Inner Detector (ID) has the responsibility of accurately measuring the particle track and momenta under very intense radiation. As immersed in a 2 T magnetic field, the ID can provide a very precise measurement for the charged tracks above 0.5 GeV and $|\eta| < 2.5$. It can also identify the electrons within $0.5 < E < 150$ GeV and $|\eta| < 2.0$.

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

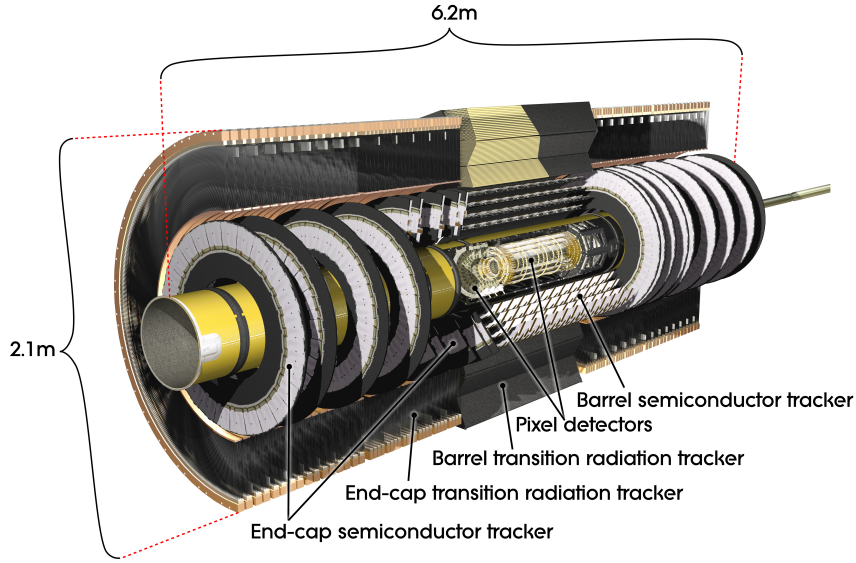


Figure 2.6. – The inner detector layout [42].

The ID consists of three parts: the pixel, the silicon microstrip (SCT), and the Transition Radiation Tracker (TRT), which are laying from the inside out, according to Figure 2.6. The pixel and SCT are with high resolution and TRT would generate and detect the transition radiations. The ID basic parameters are shown in Table 2.3 and a schematic of the ID is shown in Figure 2.7.

Item		Radial extension (mm)	Length (mm)
Overall ID envelope		$0 < R < 1150$	$0 < z < 3512$
Beam-pipe		$29 < R < 36$	
Pixel 3 cylindrical layers 2×3 disks	Overall envelope	$45.5 < R < 242$	$0 < z < 3092$
	Sensitive barrel	$50.5 < R < 122.5$	$0 < z < 400.5$
	Sensitive end-cap	$88.8 < R < 149.6$	$495 < z < 650$
SCT 4 cylindrical layers 2×9 disks	Overall envelope	$255 < R < 549$ (barrel) $251 < R < 610$ (end-cap)	$0 < z < 805$ $810 < z < 2797$
	Sensitive barrel	$299 < R < 514$	$0 < z < 749$
	Sensitive end-cap	$275 < R < 560$	$839 < z < 2735$
TRT 73 straw planes 160 straw planes	Overall envelope	$554 < R < 1082$ (barrel) $617 < R < 1106$ (end-cap)	$0 < z < 780$ $827 < z < 2744$
	Sensitive barrel	$563 < R < 1066$	$0 < z < 712$
	Sensitive end-cap	$644 < R < 1004$	$848 < z < 2710$

Table 2.3. – The inner detector basic parameters [41].

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

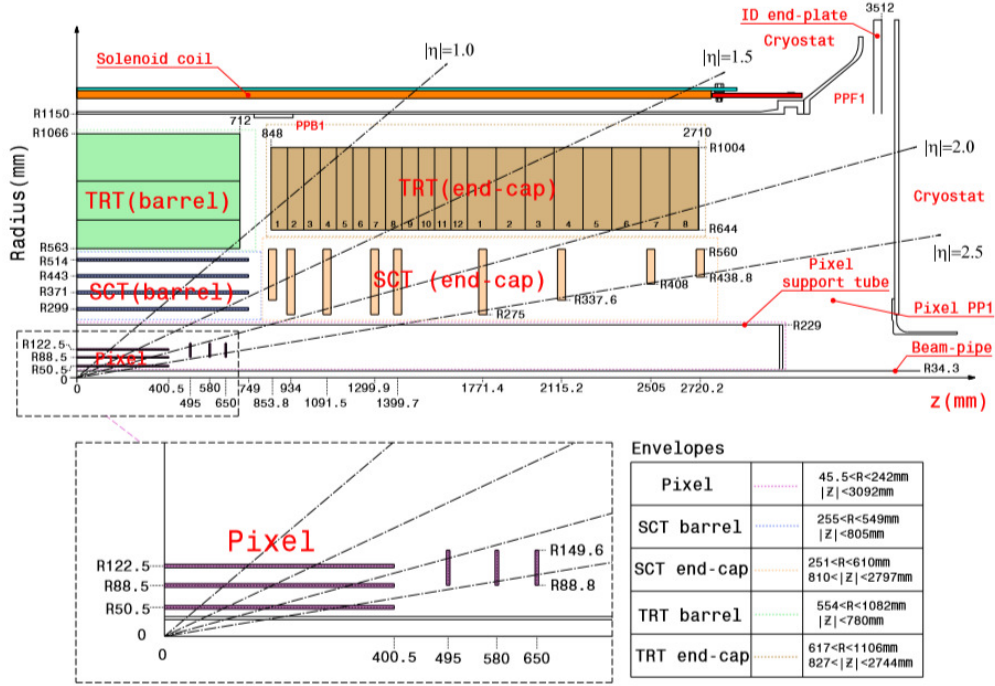


Figure 2.7. – The inner detector schematic [41].

2.2.3.1. The pixel

Three cylindrical layers, B-layer, Layer 1, and Layer 2, and six disks (three on each side) in the end-caps make up the pixel detector. The B-layer is located at a distance of 50.5 mm from the beam pipe center, while 88.5 mm for Layer 1 and 122.5 mm for Layer 2, as shown in Figure 2.7. There are more than 80 million pixels grouped as 1744 modules in the pixel detector. The typical size for a pixel is $50 \times 400 \mu\text{m}^2$ in $R - \phi \times z$. The intrinsic accuracies for the barrel layers are $10 \mu\text{m}$ in $R - \phi$ directions and $115 \mu\text{m}$ in z direction and for the disks in end-caps are $10 \mu\text{m}$ in $R - \phi$ and $115 \mu\text{m}$ in R .

During the LS1, an additional layer was installed on the innermost part, which is called Insertable B-Layer (IBL). The IBL is located at a distance of 33.2 mm to the beam pipe center and about 6 million pixels with a size of $50 \times 250 \mu\text{m}^2$. Thus the IBL can reach a higher granularity with an accuracy of $8 \times 40 \mu\text{m}^2$ per reconstructed point in $R - \phi$.

2.2.3.2. The silicon microstrip

The silicon microstrip contains 4 cylindrical layers in the barrel and 2×9 disks in the end-caps as shown in Figure 2.7 showing the positions. In total, more than 4,000 modules having about 6.3 million readout channels. Two strip layers crossed with an angle of 40 mrad in each module provide 3D measurements. The intrinsic accuracies are $17 \mu\text{m}$ in $R - \phi$ directions and $580 \mu\text{m}$ in z direction for barrel and $17 \mu\text{m}$ in $R - \phi$ and $580 \mu\text{m}$ in R for end-caps. Figure 2.8 shows the modules mounted in the SCT.

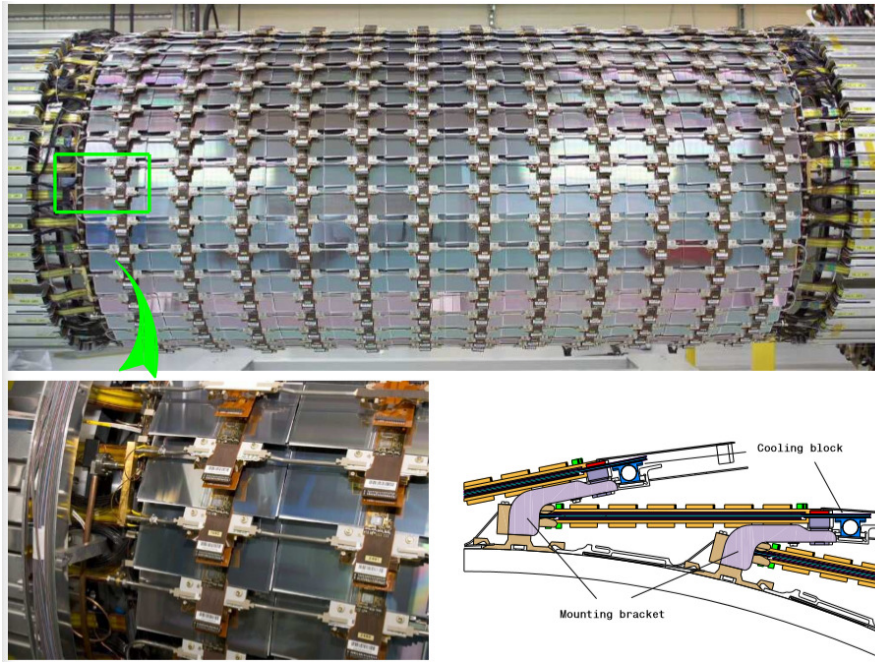


Figure 2.8. – The SCT barrel with modules mounted [41].

2.2.3.3. The Transition Radiation Tracker

The TRT occupies the outer region of the ID. Three module layers (32 modules each) in the barrel and 2×20 wheels in the end-caps link to more than 350,000 readout channels. Abundant hit information is collected by the 4 mm diameter straw tubes in a range of $|\eta| < 2.0$. The Polyimide drift (straw) tubes in TRT only provides information in $R - \phi$ with an intrinsic accuracy of $130 \mu\text{m}$. In barrel regions, the straws are axially oriented and 144 cm long, while in the end-caps, the straws are radially arranged and 37 cm long.

2.2.4. The sampling calorimeters

As an effective containment for electromagnetic and hadronic showers, the calorimeters cover a wide range of $|\eta| < 4.9$. Over the coverage, sections of different regions have different functional orientations, balanced between precise measurements and radiation resistance. In the low η regions matched to the ID, the electromagnetic (EM) calorimeter can give accurate results of electron and photon measurements. In the rest part of the calorimeter, the granularity is also sufficient to meet the needs of jet reconstruction and E_T^{miss} measurement.

As shown in Figure 2.9, the calorimeter system consists of the barrel part and the end-cap parts. The barrel part consists of the LAr electromagnetic barrel (EMB) and the tile barrel, while the end-caps contains the LAr electromagnetic end-cap (EMEC), the LAr hadronic end-cap (HEC), and the LAr forward (FCal). Total thicknesses of

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

more than 22 radiation lengths (X_0) for EM calorimeter and 9.7 interaction lengths (λ) for tile calorimeter in the barrel, more than 24 X_0 for EM calorimeters and 10 λ for tiles in the end-caps are adequate for high-energy jets sampling, as well as reducing the energy level of prompt muons.

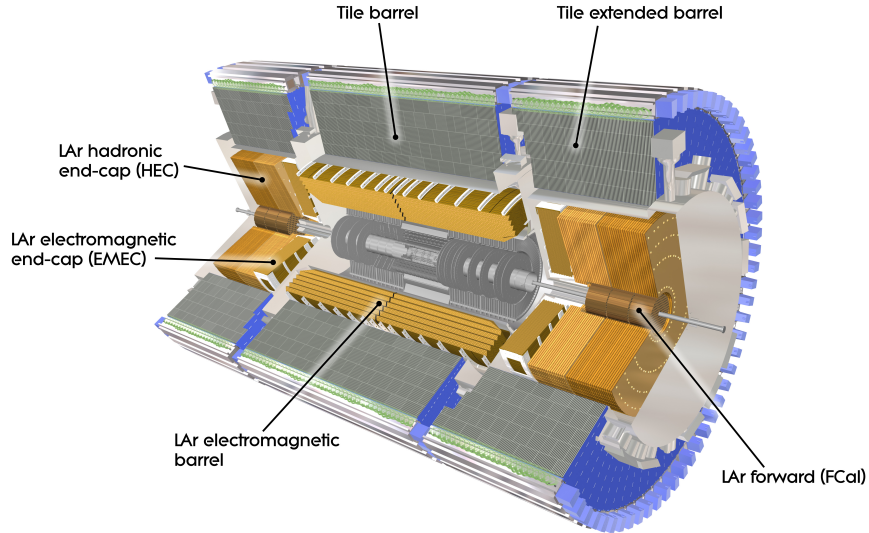


Figure 2.9. – The ATLAS calorimeter system layout [43].

2.2.4.1. The LAr electromagnetic calorimeter

The EM calorimeter includes the barrel part covering a range of $|\eta| < 1.475$ and two end-cap parts covering $1.375 < |\eta| < 3.2$. The central solenoid is smartly designed to minimize the influence on the EM calorimeter's performance. The EM calorimeter stops and measures the particles interact electromagnetically, such as electrons and photons, through lead (Pb) absorbers and liquid argon active medium.

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

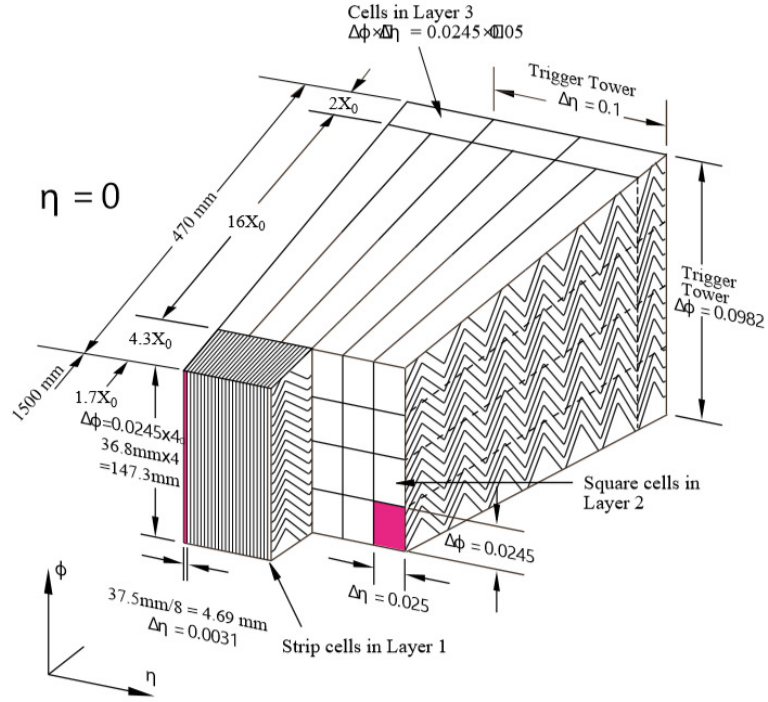


Figure 2.10. – The EM barrel schematic [41].

Figure 2.10 shows the EM barrel geometry. The precision measurement calorimeter ($|\eta| < 2.5$) is composed of three layers together with a pre-sampler. Layer 1 gives accurate position information with its fine granularity in η direction. With layer 1 and layer 2, the η direction of photons can be precisely measured. As the thickest layer, most of the energy in an electromagnetic shower would be absorbed by layer 2. The presampler provides energy loss before the EM calorimeter. The detailed parameters for EM layers are shown in Table 2.4.

There are 1,600 front end boards (FEB) connected to more than 180,000 readout channels. The digital signals are transferred to the back-end readout driver boards (ROD). Signals are summed up into cells over different layers by layer sum boards (LSB) and then combined into the tower builder boards (TBB) used in the level 1 trigger system (details in Section 2.2.6). The phase-I upgrades for LAr front ends will be further discussed in Section 2.3.

2.2.4.2. The hadronic calorimeter

The hadronic calorimeter consists of three parts, which are the tile calorimeter, the LAr hadronic end-cap calorimeter (HEC), and the LAr forward calorimeter (FCal). These sampling calorimeters measure the position and energy deposit of the hadrons.

The tile calorimeter covers $|\eta| < 1.0$ region with its barrel and $0.8 < |\eta| < 1.7$ regions with its extended barrel. The absorber in this calorimeter is made of steel, while the

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

	Barrel		End-cap	
EM calorimeter				
Number of layers and $ \eta $ coverage				
Presampler	1	$ \eta < 1.52$	1	$1.5 < \eta < 1.8$
Calorimeter	3	$ \eta < 1.35$	2	$1.375 < \eta < 1.5$
	2	$1.35 < \eta < 1.475$	3	$1.5 < \eta < 2.5$
			2	$2.5 < \eta < 3.2$
Granularity $\Delta\eta \times \Delta\phi$ versus $ \eta $				
Presampler	0.025×0.1	$ \eta < 1.52$	0.025×0.1	$1.5 < \eta < 1.8$
Calorimeter 1st layer	$0.025/8 \times 0.1$	$ \eta < 1.40$	0.050×0.1	$1.425 < \eta < 1.5$
	0.025×0.025	$1.40 < \eta < 1.475$	$0.025/8 \times 0.1$	$1.5 < \eta < 1.8$
			$0.025/6 \times 0.1$	$1.8 < \eta < 2.0$
			$0.025/4 \times 0.1$	$2.0 < \eta < 2.4$
			0.025×0.1	$2.4 < \eta < 2.5$
			0.1×0.1	$2.5 < \eta < 3.2$
Calorimeter 2nd layer	0.025×0.025	$ \eta < 1.40$	0.050×0.025	$1.375 < \eta < 1.425$
	0.075×0.025	$1.40 < \eta < 1.475$	0.025×0.025	$1.425 < \eta < 2.5$
			0.1×0.1	$2.5 < \eta < 3.2$
Calorimeter 3rd layer	0.050×0.025	$ \eta < 1.35$	0.050×0.025	$1.5 < \eta < 2.5$
Number of readout channels				
Presampler	7808		1536 (both sides)	
Calorimeter	101760		62208 (both sides)	

Table 2.4. – Parameters for the EM calorimeter [41].

2. The LHC and the ATLAS detector – 2.2. The ATLAS detector

active material is a plastic scintillator. There are 64 modules in each barrel leads to a total thickness of 9.7λ . The parameters of the tile calorimeter are given in Table 2.5.

Scintillator tile calorimeter		
	Barrel	Extended barrel
$ \eta $ coverage	$ \eta < 1.0$	$0.8 < \eta < 1.7$
Number of layers	3	3
Granularity $\Delta\eta \times \Delta\phi$	0.1×0.1	0.1×0.1
Last layer	0.2×0.1	0.2×0.1
Readout channels	5760	4092 (both sides)

Table 2.5. – Parameters for the tile calorimeter [41].

The HECs are the two wheels behind EMECs, using copper as the absorber and liquid argon as the active medium. The coverage of the HEC is $1.5 < |\eta| < 3.2$, which is slightly overlapped with the tile calorimeter and FCal for fear of dropping material. The parameters of the LAr hadronic end-caps are given in Table 2.6.

LAr hadronic end-cap		
$ \eta $ coverage	$1.5 < \eta < 3.2$	
Number of layers	4	
Granularity $\Delta\eta \times \Delta\phi$	0.1×0.1	$1.5 < \eta < 2.5$
	0.2×0.2	$2.5 < \eta < 3.2$
Readout channels	5632 (both sides)	

Table 2.6. – Parameters for the LAr hadronic end-caps [41].

The FCal is limited by its depth, copper is used as the absorber in its first module (FCal1) and tungsten is used in the second and third modules (FCal2, FCal3). FCal1 is designed as the electromagnetic module while the other two are designed as hadronic modules. The FCal has a total thickness of 10λ . The parameters of the LAr forward calorimeter are given in Table 2.6.

LAr forward calorimeter			
$ \eta $ coverage	$3.1 < \eta < 4.9$		
Number of layers	3		
Granularity $\Delta\eta \times \Delta\phi$	FCal1: 3.0×2.6	$3.15 < \eta < 4.30$	
	FCal1: $\sim$ four times finer	$3.10 < \eta < 3.15$,	
		$4.30 < \eta < 4.83$	
	FCal2: 3.3×4.2	$3.24 < \eta < 4.50$	
	FCal2: $\sim$ four times finer	$3.20 < \eta < 3.24$,	
		$4.50 < \eta < 4.81$	
	FCal3: 5.4×4.7	$3.32 < \eta < 4.60$	
	FCal3: $\sim$ four times finer	$3.29 < \eta < 3.32$,	
		$4.60 < \eta < 4.75$	
Readout channels	3524 (both sides)		

Table 2.7. – Parameters for the LAr forward calorimeter [41].

2.2.5. The muon spectrometer

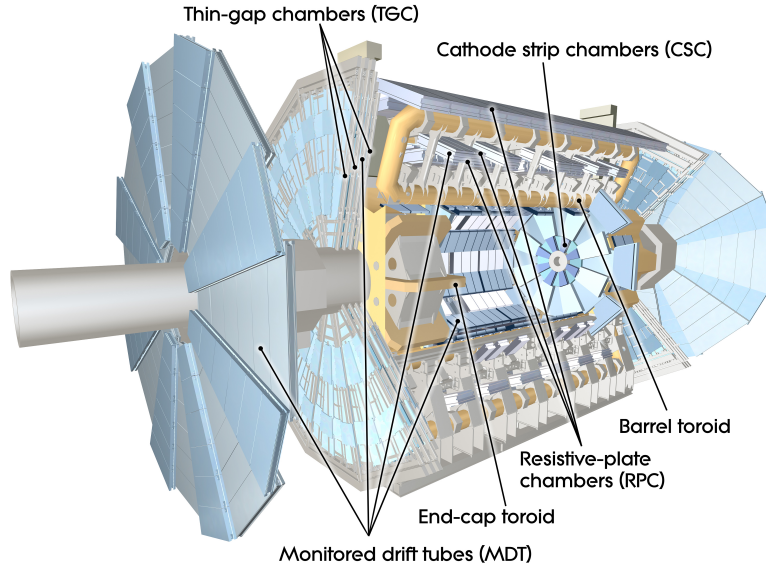


Figure 2.11. – The ATLAS muon spectrometer layout [44].

The muon spectrometer (MS, shown in Figure 2.11) is the outermost part of the ATLAS detector and aims to measure the position and momenta of the muons. Four parts together form the MS. The Monitored Drift Tubes (MDTs) cover the central areas ($|\eta| < 2.7$) and the Cathode Strip Chambers (CSC) cover the end-caps ($2.0 < |\eta| < 2.7$). They measure the muon momentum and provide its track. The other two parts form a fast trigger system (refers to Section 2.2.6). The Resistive Plate Chambers (RPCs)

cover the barrel ($|\eta| < 1.05$) while the Thin-Gap Chambers (TGCs) cover the end-caps ($1.05 < |\eta| < 2.7$). The geometry of the muon spectrometer is shown in Figure 2.12.

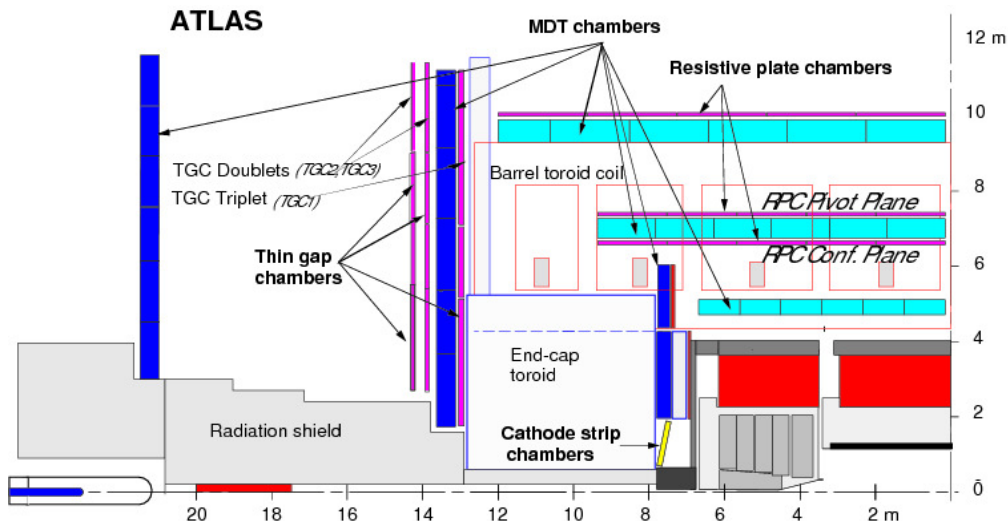


Figure 2.12. – The schematic of the muon spectrometer [45].

2.2.6. The trigger system

Limited by the bandwidth and storage, it is impossible to record all collisions from the LHC with designed luminosity at $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Only events selected by the trigger system are saved. The three levels of triggers [46] used in ATLAS are Level-1 (L1), Level-2 (L2), and the event filter. The L1 trigger is based on hardware. L2 trigger and the event filter are software-based and combined as the high-level trigger (HLT).

The L1 trigger is fired by the events with high transverse momentum particles or large missing transverse energy. The L1 makes fast decisions less than $2.5 \mu\text{s}$ and reduces the event rate to 75 kHz. High energy signatures from leptons (except for muons), photons, jets, and missing transverse energy are identified by calorimeters (described in Section 2.2.4) with reduced-granularity (0.1×0.1) information. High momentum muons fire the trigger system in the MS (described in Section 2.2.5). One or more regions of Interest (RoI) are defined by the L1 trigger and then used by the L2 trigger.

The L2 selection takes into consideration the whole information from the detectors in RoI data and reduces the data rate to 3.5 kHz. The speed for L2 selection is about 40 ms per event. The event filter selection processes offline and reduces the event rate to 200 Hz. For each event, it will take about four seconds to operate.

2.3. Phase-I upgrade of the LAr Calorimeter

An increasing instantaneous luminosity and higher center-of-mass energy are required by many physics process measurements and new particle searches compared to its design value. The LHC accelerator system and detectors will be upgraded in three phases.

The Long Shutdown 1 took place in 2013 and was completed in 2015, which prepared for the accelerator complex and detectors for an operation at center-of-mass energy at $\sqrt{s} = 13$ TeV. The Run 2 period of data taking, from 2015 to 2018, has reached an instantaneous luminosity of $\mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1}$ and an integrated luminosity of $\sim 140 \text{fb}^{-1}$. The Long Shutdown 2 is on-going during 2019-2021, about one year delay on its ending affected by the COVID-19. An upgrade of accelerators and detectors (Phase-I) carries on at the same time, which improves the performance significantly and prepares for center-of-mass energy at $\sqrt{s} = 14$ TeV data taking period (Run 3). The Long Shutdown 3 (LS3) will start after three years of running for Run 3, accompanied by a Phase-II upgrade for detector components. In the following ~ 10 years, an ultimate goal of $3,000 \text{fb}^{-1}$ integrated luminosity proton-proton collision data will be collected by the HL-LHC [38].

With Phase-I upgrade, an instantaneous luminosity up to three times the design value ($\mathcal{L} = 3 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$) and an average number of interactions per bunch-crossing $\langle \mu \rangle = 80$ for the LHC will be achieved. The Phase-II upgrade prepares for the HL-LHC to achieve an instantaneous luminosity of about $\mathcal{L} = 7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ and $\langle \mu \rangle = 200$.

To provide a higher resolution to the L1 trigger, 34,000 super cells are rearranged to have a 5 to 10 times finer granularity in the Phase-I upgrade for the LAr calorimeter. The new system also has an increasing processing rate at 40 MHz and with 12-bit precision. The data are transmitted at 5.12 Gb/s to the back-end system using a custom serialiser and optical transmitter. The readout electronics for LAr Calorimeter Phase-I upgrade are introduced in Section 2.3.1. A demonstrator has been installed on the ATLAS during Run 2. An analysis of the calibration data is discussed in Section 2.3.2. I participate in the LAr upgrade demonstrator calibration data acquiring and analysing.

2.3.1. Phase-I LAr Calorimeter readout electronic upgrades

The current calorimeter trigger system uses the energy deposition in trigger towers in the EMB. Every trigger tower covers an area of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (shown in the left plot of Figure 2.13). The super cells, as shown in the right plot of Figure 2.13, with a 10-fold increase in granularity, would be used to replace the trigger towers during the LAr Calorimeter Phase-I upgrade.

2. The LHC and the ATLAS detector – 2.3. Phase-I upgrade of the LAr Calorimeter

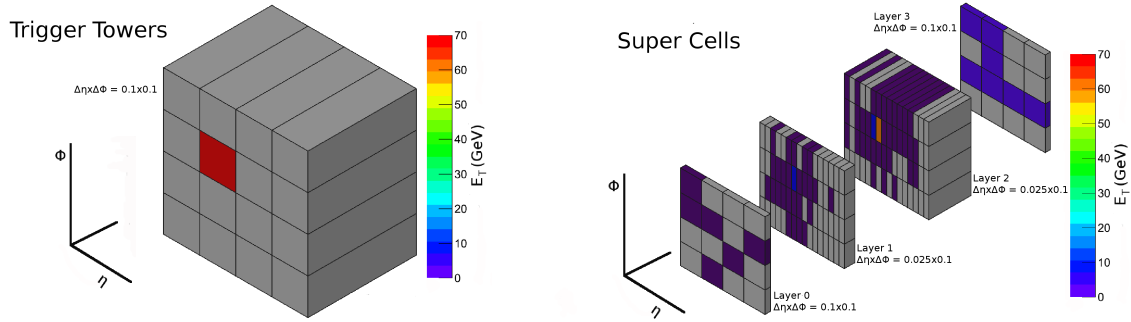


Figure 2.13. – The trigger tower in the existing L1 Calorimeter trigger system (left) and the super cells after Phase-I upgrade with a shower of an electron ($E_T = 70$ GeV) [47].

A fine granularity as $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$ of the front and middle layers of the EMB and EMEC within $|\eta| \leq 2.5$, as well as longitudinal shower information added by separating the four layers improves the efficiencies for selecting electrons, photons, τ leptons, jets, and E_T^{miss} , also enhances the discrimination against backgrounds and fakes. The scheme is shown in Figure 2.14 for the EMB.

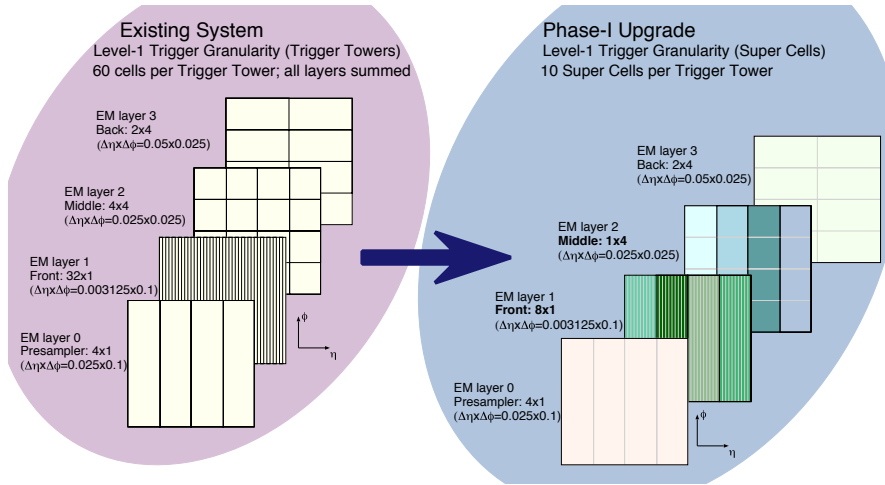


Figure 2.14. – Geometrical representation of an trigger tower (left) and super cells (right) with a coverage of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ [47].

The Phase-I LAr Calorimeter readout electronics upgrade with the new components outlined in red is shown in Figure 2.15. About ten times signal lines are routed to keep compatible between the existing set-up and the new super cells. The LAr Trigger Digitizer Boards (LTDBs) digitize the super cell signals and deliver them to the LAr Digital Processing System (LDPS). Meanwhile, the LTDB feeds back the 0.1×0.1 analog sums to the TBB to maintain the current system, which will keep working as a backup until the Phase-II upgrade. The digitized signals are converted to calibrated energies

2. The LHC and the ATLAS detector – 2.3. Phase-I upgrade of the LAr Calorimeter

in LDPS, then transferred continuously at 40 MHz to the upgraded trigger processors, Feature EXtractors (FEXs).

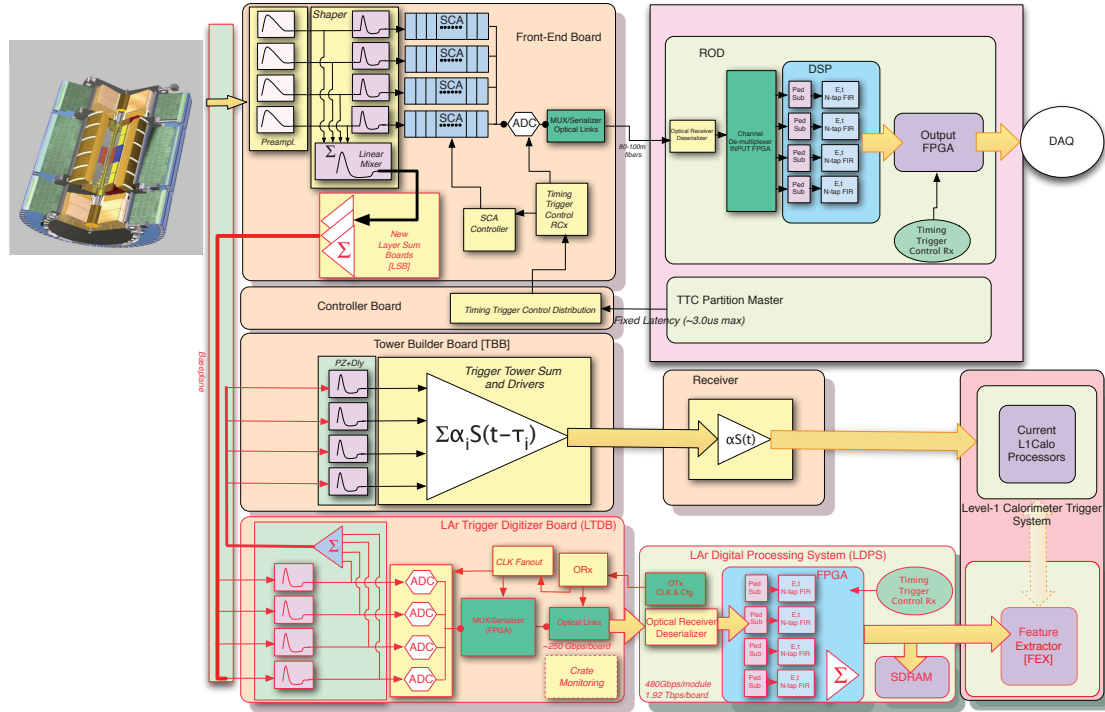


Figure 2.15. – Schematic diagram of the Phase-I upgrade LAr trigger readout electronics. Components with red outlines and arrows are upgraded [47].

2.3.1.1. Front-end electronics

The LSBs will be replaced to cope with the super cell signal summing, while the FEBs remains unchanged. In total, 124 LTDBs will be installed, and each collects 320 super cell signals. The analog-to-digital converters (ADCs) on LTDBs digitize the analog signals with 12 bits at 40 MHz. An LTDB requires 80 custom ADCs, each handles four super cell signals, with a latency less than 200ns. The base-plane is developed to adapt to the new layout, and the whole system is radiation-tolerant.

2.3.1.2. Back-end electronics

The LDPS receives the ADC data from the LTDBs and transmits the computed results to L1Calo. It also feeds back the ATLAS Trigger, Timing and Control (TTC) signal to the LTDBs. About 30 LAr Digital Processing Blades (LDPBs) located on LDPS, carried by three Advanced Telecom Computer Architecture (ATCA) platform that supports the design of high-density, and read the outputs of 124 LTDBs. The main components of the LDPB are four Advanced Mezzanine Cards (AMCs), so-called LATOME (LAr trigger processing mezzanine), which receive the ADC data, and treat them with Intel ARRIA

2. The LHC and the ATLAS detector – 2.3. Phase-I upgrade of the LAr Calorimeter

10 field programmable gate array (FPGA). Those LATOME mezzanines are located on a carrier board equipped with a Xilinx Kintex-7 FPGA used to reorganize and serialize the ADC data.

The LATOME receives super cell data from the LTDBs via 48 optical links in AMCs, with a speed of 5.12 Gb/s, and sends the data to the L1 trigger at 11.2 Gb/s via the 48 output links in AMCs. It treats the transverse energies of super cells with an optimal filtering algorithm (OF) [48] and calculates the energy deposited in the calorimeter from the digitized samples. The LATOME also assigns bunch crossings (BCs) by timing measurement.

2.3.1.3. LAr demonstrator set-up

As a pre-prototype, the LAr demonstrator has been installed to an area of $\eta \times \phi \in [0, 1.4] \times [1.77, 2.16]$ in EMB at the ATLAS experiment. The calibration uses data taken from proton-proton (and heavy-ion) collisions during Run 2 and has been tested at the LAr Electronics Maintenance Facility (EMF) next to ATLAS point 1. The final prototypes were replaced in early 2018. They are tested with 2018 proton-proton collision data.

The ATCA board for a baseline of liquid argon acquisition (ABBA) is the pre-prototype for the LDPS. It receives the digital signals from LTDB and stores them in circular buffers, then sends them to the L1 trigger in a ‘monitoring mode’. It has been set-up in the ATLAS counting room at the end of 2017, then replaced by the new prototypes of LATOME boards in early 2018.

2.3.2. Analysis of the calibration data

The signal waves have been collected from a testbeam [49] by two deliverable LTDB boards. There are 128 calibration lines link to the 4 layers in one calibration board. In different layers, one calibration line could collect the pulses from 8 to 32 cells. The numbers of calibration lines corresponding to cells in different layers are listed in Table 2.8. As an example, Figure 2.16 shows details of the matching between calibration lines and cells in a plane of $i_\phi^{cell} \times i_\eta^{cell}$ in the middle layer.

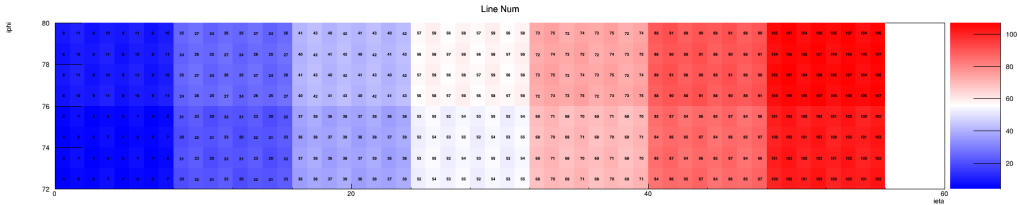


Figure 2.16. – Matching between calibration lines and middle layer cells in a plane of $i_\phi^{cell} \times i_\eta^{cell}$.

The amplitude of the signal pulse is determined by the DAC (digital-to-analog

2. The LHC and the ATLAS detector – 2.3. Phase-I upgrade of the LAr Calorimeter

$ \eta $	PS	Strips	Middle	Back	Barrel-End
0.0-0.2	120	0-3	4-11	12-15	-
0.2-0.4	121	16-19	20-27	28-31	-
0.4-0.6	122	32-35	36-43	44-47	-
0.6-0.8	123	48-51	52-59	60-63	-
0.8-1.0	124	64-67	68-75	76-79	-
1.0-1.2	125	80-83	84-91	92-95	-
1.2-1.4	126	96-99	100-107	108-111	112-119
Number of detector cells pulsed by ONE calibration line	16	32	8	8	8

Table 2.8. – Distribution of the calibration lines link to the LAr demonstrator cells in different layers [50].

converter) value, which can be set between 0 and 65,535 ($2^{16} - 1$). The step for pulse delays are set as 1.04 ns, 1/24 of one clock cycle ($\Delta t_{\text{TTC}} = 24.95$ ns). Signal pulses are collected with 32 samples, corresponding to a time window of 800 ns. The signal for ramp runs (with varying pulse amplitudes) and delay runs (with shifting pulses) loops in a circle of 17 patterns, with 4 patterns test for the stripe layer, 8 for the middle layer and the Barrel-End, 4 for the back layer, and the last pattern for the pre-sampler layer. The analysis of calibration data with pedestal (with no signal pulse) runs is shown in Section 2.3.2.1. Section 2.3.2.2 and 2.3.2.3 describes the analysis of ramp runs and delay runs.

2.3.2.1. Pedestal run

Dedicated runs with no injection beams are used to measure the pedestal and monitor the noise. The mean value of pedestal runs is extracted in each calibration channel and used in noise subtraction for other signal pulse analysis. Figure 2.17 shows the pedestal value in channel 0.

2. The LHC and the ATLAS detector – 2.3. Phase-I upgrade of the LAr Calorimeter

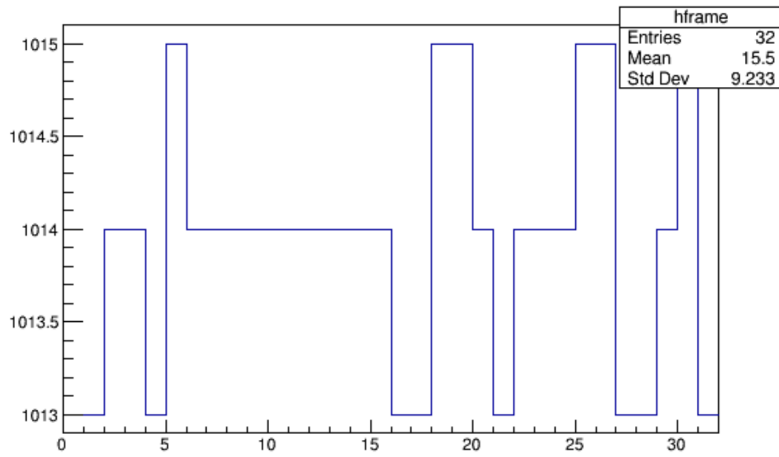


Figure 2.17. – Pedestal in channel 0 with ADCs at about 1014.

2.3.2.2. Ramp run

Tests have been performed with the ramp runs to check the relation of ADC counts to DAC. Figure 2.18 shows the signal pulses in ADC with different input DAC values given. A distortion is observed in the pulse with an input DAC=1500, which indicates a measurable maximum of the calibration board at ADC $\approx$ 2700. Figure 2.19 shows the peak ADC values for each pulse in a ramp run with increasing input DACs in different layers. The ten plots have been grouped as from the same trigger tower.

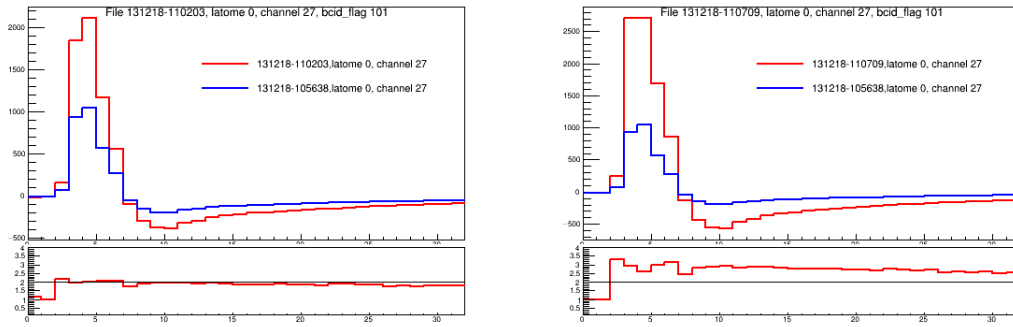


Figure 2.18. – Signal pulses with input DAC=1000 (red) compared to input DAC=500 (blue) is shown in the left plot, while the right plot shows signal pulses with input DAC=1500 (red) compared to input DAC=500 (blue). The pulse with DAC=1500 reaches the measurable maximum of the calibration board.

2. The LHC and the ATLAS detector – 2.3. Phase-I upgrade of the LAr Calorimeter

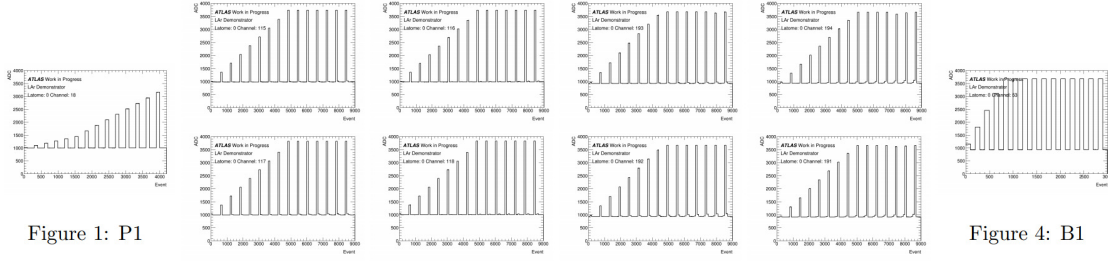


Figure 2: F1, F2, F3, F4

Figure 3: M1, M2, M3, M4

Figure 4: B1

Figure 2.19. – Distribution of peak ADC values extracted from each pulse in a ramp run with increasing input DAC. 10 plots correspond to the signals received by the 4 layers (pre-sampler, front layer, middle layer, and back layer) in super cells originated from one trigger tower.

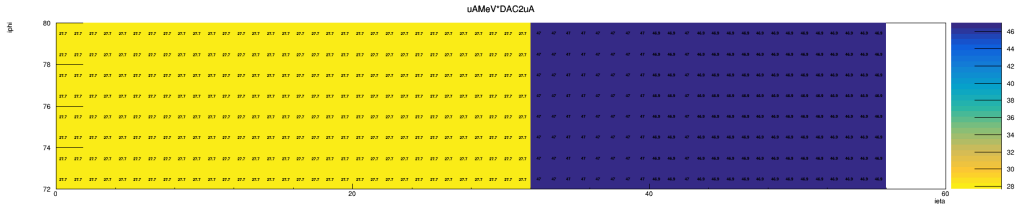
The relation between DAC and energy is measured in the electronic calibration system [50]. The factor $F_{DAC \rightarrow \text{MeV}}$ is derived in two steps: first with a factor

$$F_{DAC \rightarrow \mu A} = \frac{76.295 \mu V}{R_{inj}}, \quad (2.5)$$

where R_{inj} is the injection resistor. Then with

$$F_{\mu A \rightarrow \text{MeV}} = \frac{1}{I/E \times f_{\text{sampl}}}, \quad (2.6)$$

converts the current into energy, where I/E is the current conversion factor and f_{sampl} is a fraction of visible energy deposits in the LAr (E^{act}) over the total deposited energy (E^{tot}) for an electron. Figure 2.20 shows the values of $F_{DAC \rightarrow \text{MeV}}$ in the middle layer cells in a plane of $i_{\phi}^{cell} \times i_{\eta}^{cell}$. Figure 2.21 shows the relations between ADC and energy converted from the input DAC in different layers. The ten plots have been grouped to cover $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$.



2. The LHC and the ATLAS detector – 2.4. Simulations at the ATLAS

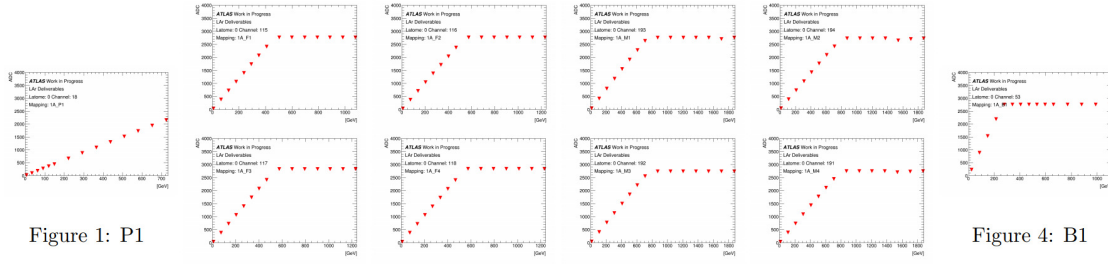


Figure 2.21. – ADC versus energy converted from the input DAC in a ramp run. 10 plots correspond to the signals received by the 4 layers (pre-sampler, front layer, middle layer, and back layer) in super cells originated from one trigger tower.

2.3.2.3. Delay run

The series of pulses in delay runs are overlaid to obtain a full pulse shape, as shown in Figure 2.22. The distortion in the back layer comes from the limit of measurable maximum for the calibration board.

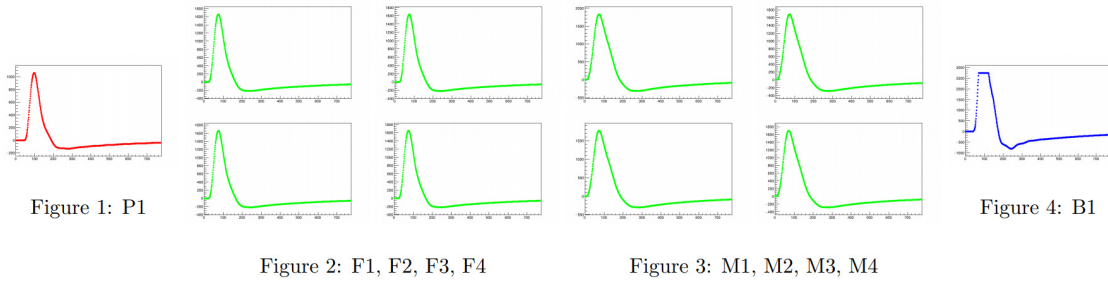


Figure 2.22. – Full pulse shapes obtained by scanning the delay run in different layers. 10 plots correspond to the signals received by the 4 layers (pre-sampler, front layer, middle layer, and back layer) in super cells originated from one trigger tower. The distortion in the back layer comes from the limit of measurable maximum for the calibration board.

2.4. Simulations at the ATLAS

Signals and backgrounds in the analysis are simulated by Monte Carlo (MC) generators according to the SM predicted cross sections by generating events from random numbers. K-factors have been considered as the calculation of higher-order QCD corrections in recent years. Hadronization, parton shower, and underlying events (UE) can be simulated by PYTHIA [51, 52], HERWIG [53, 54] (the UE is implemented by JIMMY [55]), and SHERPA [56]. The underlying event parameters in PYTHIA and JIMMY are tuned to the observed data from Tevatron and other experiments [57]. The matrix

element (ME) used for perturbative QCD calculations in hard-scattering processes can be processed by MADGRAPH [58], POWHEG [59, 60], and SHERPA. The partons calculated by parton distribution functions (PDFs) in deep-inelastic scattering are using the Les Houches accord PDF interface library (LHAPDF) [61, 62] value sets.

A GEANT 4 [63] package was used for detector simulations, which includes the ATLAS geometry, materials, and subsystems. Most MC samples are produced with “full simulation”, which describes the interactions of particles precisely but time-consuming. “Fast simulation” is an alternative way to produce the template samples for uncertainty estimations, cross-check samples with alternative generators, or signals and backgrounds not in popular demand.

2.5. Object reconstructions

This section gives the ideas of how the objects and particles are reconstructed in the ATLAS. Tracks and vertices reconstructions are discussed in Section 2.5.1, followed by the electrons and photons (in Section 2.5.2). The reconstructions of muon and tau are discussed in Section 2.5.3 and 2.5.4, respectively. Topo-cluster jet as well as particle flow jet reconstructions are described in Section 2.5.5. Section 2.5.6 talks about the missing transverse energy.

2.5.1. Tracks and vertices

The hits in the pixel and SCT detectors are collected and formed into clusters. The connected component analysis (CCA) method is employed to record and group the deposited charge energies above a threshold. A cluster is always with the size of about two pixels in the $r - \phi$ plane and 1~3 pixels in η direction. The single-particle cluster and the merged cluster are defined by how many charged particles are deposited in the cluster. Sometimes clusters are not compatible with the definition of merged clusters but used in multiple track reconstructions, which are referred to as shared clusters. Illustrations of single-particle clusters and merged cluster are shown in Figure 2.23. The 3D parameters of these clusters are recorded as space-points.

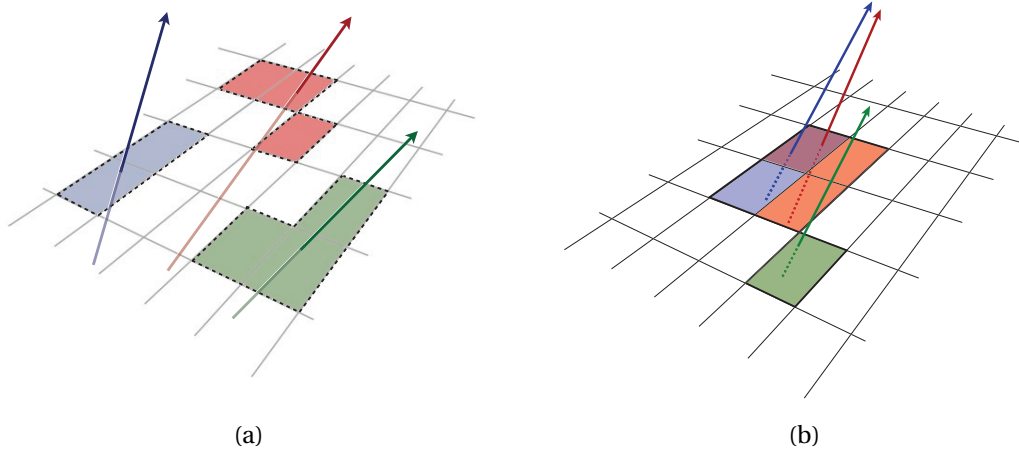


Figure 2.23. – Single-particle clusters (a) and merged cluster (b) in a track reconstruction [64].

Track seeds are referred to as the sets of three space-points. Experience shows that good-quality tracks are more likely to be reconstructed from the seeds in SCT only, then in pixel only, and mixed-detector seeds at last. To maximize the fraction of seeds that result in good-quality tracks, the requirement of impact parameters and seed-type-dependent momentum, as well as other requirements, are considered. Finally, a combinatorial Kalman filter [65] is employed to effectively reconstruct track candidates originated from the selected seeds to its space-point extensions (including the hits in the TRT) if exist.

Track score is evaluated to rank the tracks with its probability of representing a truth particle trajectory. Clusters are weighted by their intrinsic resolutions in track score calculations. Holes, defined as when no matched clusters found at the space-points where the extensions of seeds pass, would reduce the scores. Track candidate fitting results evaluated by χ^2 are considered by track score as well. Track scores also prefer the tracks with large momentum. If a track candidate is composed of more than two shared clusters, or a cluster is shared by more than two tracks, the cluster will be removed from a track and the score will be calculated again. An ambiguity solver only accepts the track candidates satisfying the following quality criteria:

- $p_T > 400$ MeV,
- $|\eta| < 2.5$,
- Clusters ≥ 7
- In a layer, shared pixel cluster ≤ 1 and shared SCT cluster ≤ 2
- Hole_{pixel+SCT} ≤ 2 and hole_{pixel} ≤ 1
- $|d_0^{BL}| < 2.0$ mm
- $|z_0^{BL} \sin \theta| < 3.0$ mm

where d_0^{BL} is the transverse impact parameter according to the beam-line and z_0^{BL} is

the longitudinal distance to the primary vertex. An artificial neural network (NN) is introduced to further identify merged clusters, which can reach an efficiency of 90% for two charged particle cases and 85% for three-particle clusters. A high-resolution track fit is performed to the remaining tracks and gives the final track collections. Additional NNs are employed to predict the positions and the number of particles and uncertainties of clusters.

The vertices are then decided with a set of good-quality tracks and selected seed positions (seed pool). An iterative fit with a minimized χ^2 is performed to give the best positions of the vertices one by one. The track weights are calculated as

$$\omega(\hat{\chi}^2) = \frac{1}{1 + \exp\left(\frac{\hat{\chi}^2 - \chi_{\text{cutoff}}^2}{2T}\right)}, \quad (2.7)$$

where χ_{cutoff}^2 is a constant which ensures the track weight threshold at 0.5 and is set as nine, corresponding to three standard deviations. The low weighted tracks are not removed immediately from the vertex but have less impact on the position determination. When the iterative fit is done, the incompatible tracks are removed from the vertex and become candidates for other vertices. The iteration is then started again looking for new vertices until all tracks are associated or no new vertex can be found. Among all these vertices, the one with the highest sum of transverse momenta squares (Σp_T^2) is considered as the only primary vertex in this event [66].

2.5.2. Electrons and photons

The electrons and photons deposit all their energy in the EM calorimeter, while the electrons show curved tracks in the ID. In this section, only electron reconstruction is detailed since the photons are not required in the presented analyses. The schematic in Figure 2.24 shows an illustration of the electron pass through the detector.

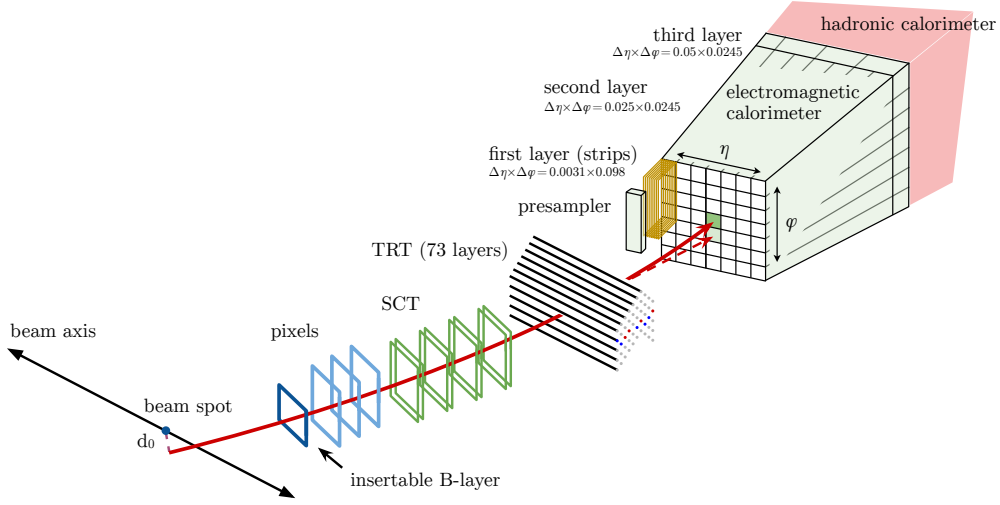


Figure 2.24. – The schematic of an electron pass through the ID and deposit in the EM calorimeter [67].

The total electron efficiency can be calculated as

$$\epsilon_{total} = \epsilon_{EMclus} \times \epsilon_{reco} \times \epsilon_{id} \times \epsilon_{iso} \times \epsilon_{trig}. \quad (2.8)$$

The reconstruction of the EM cluster is described in Section 2.5.2.1 as well as the reconstruction of its matching to tracks in the ID, the corresponding efficiencies ϵ_{EMclus} and ϵ_{reco} are discussed in Section 2.5.2.2. In Section 2.5.2.3 and 2.5.2.4, the ϵ_{id} and ϵ_{iso} are introduced. The ϵ_{iso} and ϵ_{trig} are specific in $t\bar{t}H$ multilepton analysis by its standalone tight lepton working point and will be discussed in Section 3.3.3.

2.5.2.1. Reconstruction

The ATLAS electron reconstruction [67] follows a step of observing energy deposits in the EM calorimeter, finding tracks in the ID, and matching the energy deposits and charged tracks in $\eta \times \phi$ phase space.

Cluster reconstruction in the EM calorimeter In the early Run 2 period, the seeds of energy deposits in the EM calorimeter are identified with a sliding-window algorithm [68]. Towers are defined as the elements with a size of 0.025×0.025 in $\eta \times \phi$ directions. The first layer, the second layer, the third layer, and presampler (in a range of $|\eta| < 1.8$) collects energy deposits in a unit of 3×5 towers in $\eta \times \phi$ and sums up. If the summed transverse energy is above 2.5 GeV, the cluster is selected as a candidate seed. The same process repeated until the cluster of 3×5 scans over the whole precision measurement region ($|\eta| < 2.5$) with a step length of one tower in both η and ϕ directions. An overlap removal is considered between two candidates within $\Delta\eta \times \Delta\phi = 5 \times 9$ towers area. If one candidate has transverse energy (E_T) of 10%

higher than the other, the lower one will be removed. If the difference between the E_T of the two candidates is less than 10%, the candidate with the highest E_T central tower is kept. A high reconstruction efficiency can be reached as 96% at $E_T = 7$ GeV and 99% at $E_T = 15$ GeV.

The topo-cluster reconstruction algorithm [69, 70], implemented during Run 2, which enables irregular, variable-size superclusters benefit for the reconstructions of bremsstrahlung photons and electrons from photon conversions could reach similar stability as the fixed-size cluster algorithm. The topo-cluster reconstruction follows a ‘4-2-0’ principle, which started with the proto-clusters requiring a significance $|\zeta_{cell}^{EM}| \leq 4$ in both EM and hadronic calorimeters. The ζ_{cell}^{EM} is defined as

$$\zeta_{cell}^{EM} = \frac{E_{cell}^{EM}}{\sigma_{noise,cell}^{EM}}, \quad (2.9)$$

where E_{cell}^{EM} is the energy of the cell and $\sigma_{noise,cell}^{EM}$ is the expected noise of the cell. The noise includes the electronic noise and the pile-up noise evaluated from the average instantaneous luminosity of Run 2. Neighbours to the proto-clusters meeting the requirement of $|\zeta_{cell}^{EM}| \geq 2$ are added to the proto-clusters. If two proto-clusters are linked by a $|\zeta_{cell}^{EM}| \geq 2$ cell, they are merged into one. The iteration continues until no neighbours of $|\zeta_{cell}^{EM}| \geq 2$ found. In a proto-cluster, if two or more maxima found with $E_{cell}^{EM} > 500$ MeV and all their neighbours (at least four neighbours required) are not signal liked, the proto-cluster will be separated.

The EM energy is defined as the energy collected by the cells in the EM calorimeter, except for the transition region ($1.37 < |\eta| < 1.63$), which also counts for the energy measured by the presampler and scintillator. The EM fraction (f_{EM}) is defined as the fraction between the EM energy and the total cluster energy. The threshold set on the EM energy is 400 MeV. In Figure 2.25, distributions of the f_{EM} (left) and the efficiency of various f_{EM} working points (right) are shown. As a conclusion, a cut on $f_{EM} > 0.5$ has been taken as could reject about 60% of the pile-up clusters.

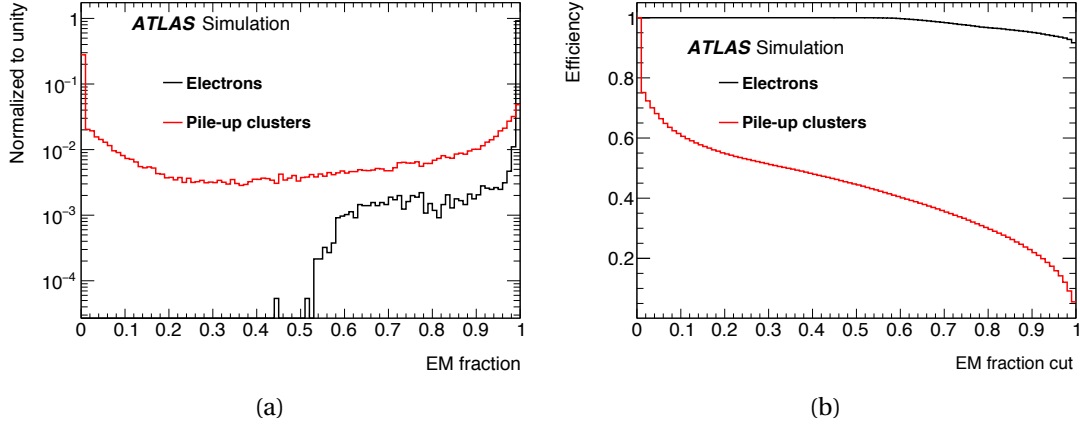
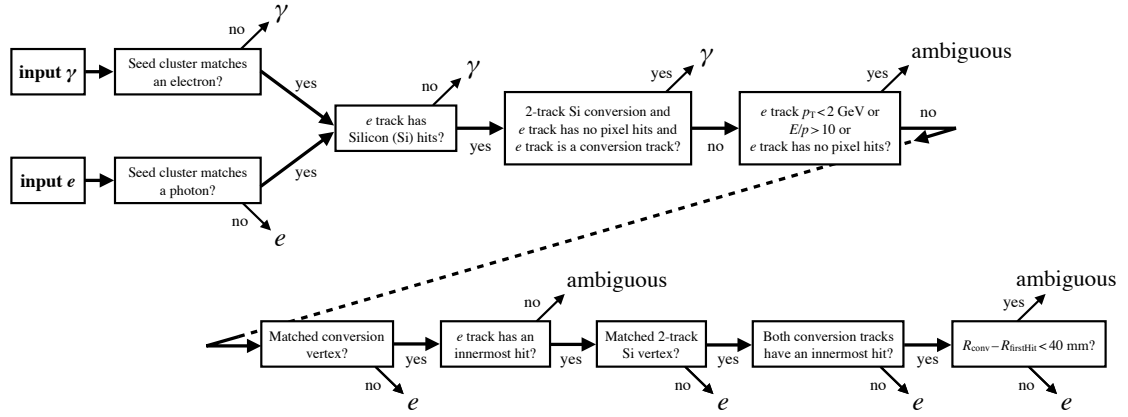


Figure 2.25. – Distributions of the f_{EM} (a) and the reconstruction efficiency with a various f_{EM} selection cut (b) [70].

Track reconstruction and track-cluster matching The track reconstruction follows the strategy described in Section 2.5.1. The fitting procedure Gaussian-sum filter (GSF) is then processed to match the tracks and EM clusters. The GSF is processed between the tracks and the EM clusters within $|\eta_{cluster} - \eta_{track}| < 0.05$ and either $-0.20 < -q \times (\phi_{cluster} - \phi_{track}) < 0.05$ or $-0.10 < -q \times (\phi_{cluster} - \phi_{track}) < 0.05$ ($\phi_{cluster}$ and ϕ_{track} rescaled to the energy of cluster), where q is the charge of the particle. The GSF method is based on the Kalman filter with the implementation of the non-linear bremsstrahlung effects. Multiple weighted sums of Gaussian functions are adopted by the GSF to estimate the track parameters, material effects, and experimental noise.

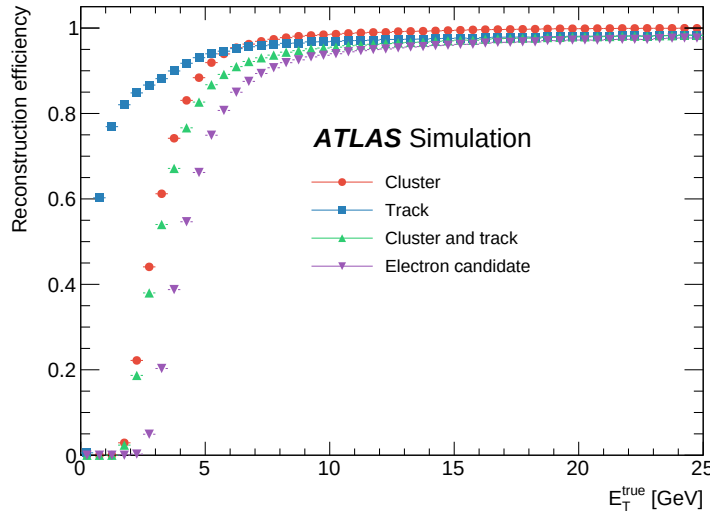
Electron reconstruction The topo-clusters satisfied $E_T > 1$ GeV and matched to a track with at least four hits in the SCT are identified as seed cluster candidates for superclusters. Clusters near the seed clusters (in a window of $\Delta\eta \times \Delta\phi = 0.125 \times 0.300$) are considered to be the satellite clusters from bremsstrahlung radiation or cluster splitting. The matched track of the satellite clusters is required to be the same as the seed cluster.

The reconstructions for electrons and photons are independent, thus there are cases with electrons and photons created by the same superclusters. These cases are remarked as ambiguous and will be determined later in the analysis. A flow chart is shown below (Figure 2.26) for the e/γ reconstructions.


 Figure 2.26. – The flow chart of e/γ reconstruction [70].

2.5.2.2. Calibration

Figure 2.27 shows the reconstruction efficiencies as a function of E_T . The inefficiency is caused by the E_T threshold introduced by the GSF method.


 Figure 2.27. – The reconstruction efficiencies of clusters, tracks, track matched clusters, and electron candidates on the distribution of E_T [70].

One of the advantages brought by the topo-cluster reconstruction algorithm is a better energy resolution gained from more deposit energy collected by the superclusters. To quantify the resolution of the energy, an effective interquartile range is defined as

$$\text{IQE} = \frac{Q_3 - Q_1}{1.349}, \quad (2.10)$$

where Q_n are the n quartiles of the distribution of E_{calib}/E_{true} . A normalisation factor selected as 1.349 makes the Gaussian distribution equals to its standard deviation. Figure 2.28 shows the performance differences between the superclusters and fixed-size clusters.

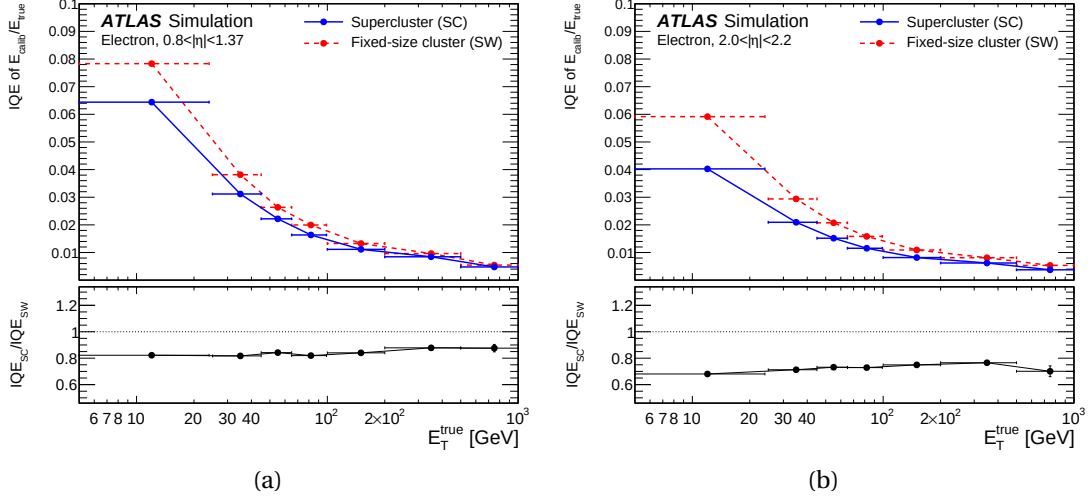


Figure 2.28. – The IQE value comparisons between superclusters (full line in blue) and fixed-size clusters (dash line in red) in low η regions (a) and high η regions (b) in as a function of the simulated electron E_T [70].

2.5.2.3. Identification

The identification of electrons is based on a likelihood (LH) discriminant technique. The values of the products for signal (L_S) and background (L_B) are given by probability density functions (pdfs). The pdfs (P) are created with an adaptive kernel density estimator (KDE) [71] in 9 bins of $|\eta|$ and 7 bins of E_T .

$$L_{S(B)}(x) = \prod_{i=1}^n P_{S(B),i}(x_i), \quad (2.11)$$

The pdfs are derived from the 36.9 fb^{-1} data recorded in 2015 and 2016, in $Z \rightarrow ee$ ($E_T > 15 \text{ GeV}$) and $J/\Psi \rightarrow ee$ ($E_T < 15 \text{ GeV}$) channels. A tag-and-probe method is introduced to calculate the identification efficiency. The tag electron in an electron pair is required to meet a tight selection, while the other electron, served as the probe, is for the efficiency measurement. Probes are required to satisfy very loose selection criteria to reduce the background contamination. LH operation points are defined as the loose, medium, and tight, with the background rejection from low to high. Efficiencies of the three operation points are at an average of 93%, 88%, and 80%. The identification efficiency for electron at different operation points as functions of E_T (left) and $|\eta|$ (right) is shown in Figure 2.29.

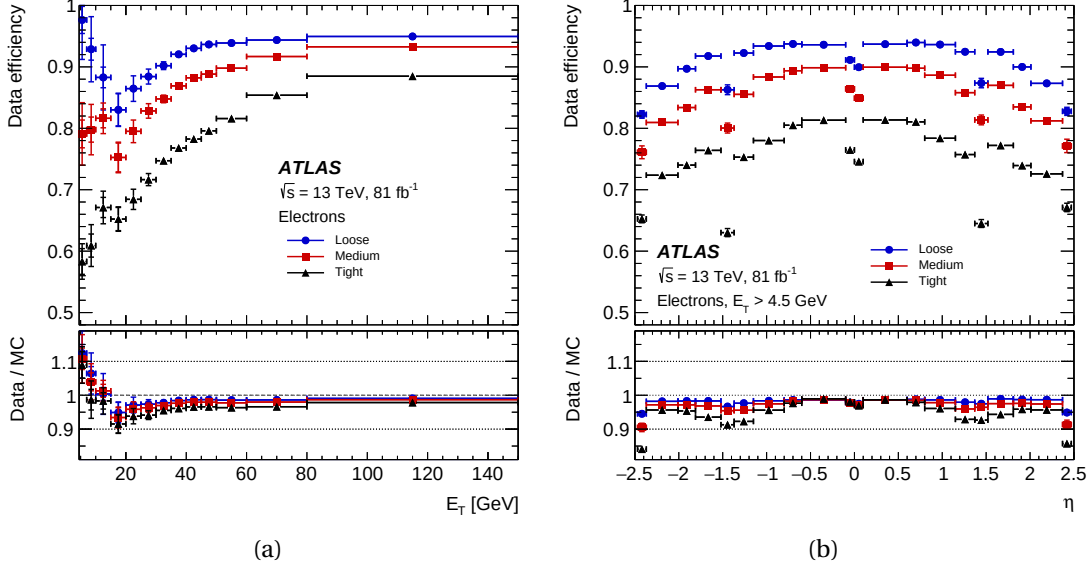


Figure 2.29. – The identification efficiency for electron at different operation points on distributions of E_T (a) and $|\eta|$ (b) in $Z \rightarrow ee$ channel [70].

2.5.2.4. Isolation

Raw calorimeter isolation ($E_{T,raw}^{isol}$) is defined as the summed transverse energy of the clusters within a certain cone size ΔR , which is centered at the barycenter of the particle cluster. The EM particle energy ($E_{T,core}$) is the energy of a rectangular cluster with a size of $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$ at the barycenter of the particle cluster, as a coarse estimation of the particle energy. The corrections for leakage energy ($E_{T,leakage}$) and pile-up energy ($E_{T,pile-up}$) are estimated in the range of ΔR . The final calorimeter isolation variable is given as

$$E_T^{cone} = E_{T,raw}^{isol} - E_{T,core} - E_{T,leakage} - E_{T,pile-up}, \quad (2.12)$$

The cone size as $\Delta R = 0.2$ is used as the electron isolation working point.

Track isolation ($p_T^{varcone}$) is defined as the summed transverse momentum of selected tracks within a variable-size cone

$$\Delta R = \min\left(\frac{10}{p_T[\text{GeV}]}, \Delta R_{max}\right), \quad (2.13)$$

where ΔR_{max} is the maximum size of the cone. The tracks are required to satisfy a sequence of requirements including:

- $p_T > 1$ GeV,
- $|\eta| < 2.5$,
- Hits_{pixel+SCT} ≥ 7 ,
- Shared hits_{pixel+SCT} ≤ 1 ,

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- $\text{holes}_{\text{pixel+SCT}} \leq 2$,
- Matched to a loose vertex (only for electrons).

Four working points are defined and shown in Table 2.9. Corresponding efficiencies to the isolation working points are shown in Figure 2.30.

Working point	Calorimeter isolation	Track isolation
Gradient	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with E_T^{cone20})	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with $p_T^{\text{varcone20}}$)
HighPtCaloOnly	$E_T^{\text{cone20}} < \max(0.015 \times p_T, 3.5 \text{ GeV})$	-
Loose	$E_T^{\text{cone20}}/p_T < 0.20$	$p_T^{\text{varcone20}}/p_T < 0.15$
Tight	$E_T^{\text{cone20}}/p_T < 0.06$	$p_T^{\text{varcone20}}/p_T < 0.06$

Table 2.9. – Definations of the 4 electron isolation working points under $\Delta R = 0.2$ and $\Delta R_{\text{max}} = 0.2$ [70].

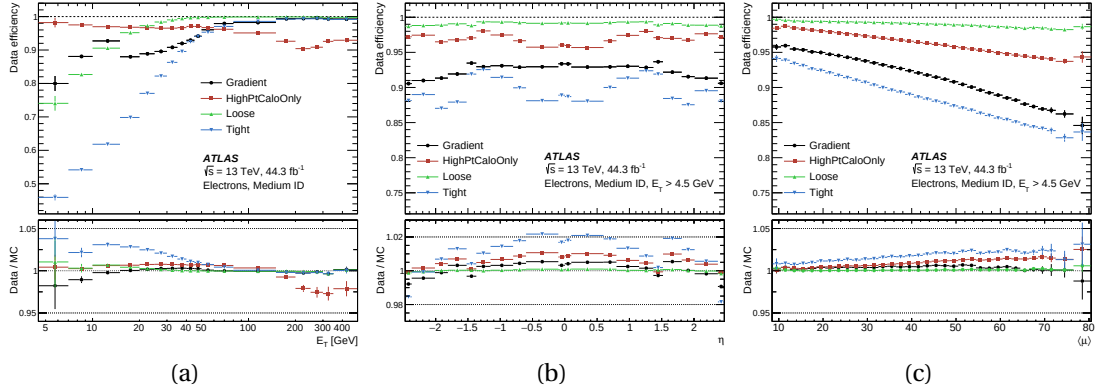


Figure 2.30. – The isolation efficiencies for electron at different working points on distributions of E_T (a), η (b), and bunch crossing $\langle \mu \rangle$ (c) in $Z \rightarrow ee$ channel [70].

A standalone working point (details in Section 3.3.3) is calibrated for the $t\bar{t}H$ multilepton analysis. The working point is based on the standard FixedCutLoose and includes more strict isolation criteria. The following trigger efficiency is also calibrated exclusively for the analysis. I calibrated this combined working point together with the trigger efficiency for electrons with 2018 data and record this work in Appendix A.

2.5.3. Muons

A muon could leave tracks in both ID and MS [72]. The muon reconstruction in the ID has been discussed in Section 2.5.1 as other charged tracks. The reconstruction of muons in the MS has introduced in Section 2.5.3.1 as well as the combination of the ID and MS tracks. The efficiency for muon reconstruction is described in Section 2.5.3.2

2.5.3.1. Reconstruction in the MS and combination

Muons are searched individually in each chamber in the beginning. Segments are formed with hits in each chamber with different fitting algorithms. The muon track candidates are built by combining the segments collected in each layer. Only segments which are high-quality are selected for track building, decided by their positions and angles, also their hit multiplicities. Two or more matching segments are required for a track, except for the barrel–endcap transition region, in which only one high-quality segment is needed. Segments are shared by track candidates if the hits in the outermost layer are different. Then a global χ^2 fit is performed to all track candidates. The track not passing the fit criteria still has a chance through a hit recovery procedure as changing its hits formation.

Then the information from the ID, MS, and also calorimeters are combined for the muon reconstruction. Four types of muons are defined:

- **Combined (CB) muon:** Tracks in the ID and MS matched with a global fit. The most common and popular type of muon.
- **Segment-tagged (ST) muon:** A track in the ID matched to a segment in the MDT or CSC. These muons are either with a low p_T or in a $|\eta|$ region with reduced MS acceptance.
- **Calorimeter-tagged (CT) muon:** A track in the ID and matched to an energy deposit for muon’s minimum-ionization. This is the type of muons with the lowest purity but it allows reconstruction of muons in a region of cabling and services. The CT muons are with an optimised identification criteria in the range $|\eta| < 0.1$ and $15 < p_T < 100$ GeV.
- **Extrapolated (ME) muon:** A high-quality track (at least two hits in chambers, especially three hits are required in the forward region) in MS extrapolated to the primary vertex. ME muons are the main implements to a region of $2.5 < |\eta| < 2.7$ which is not covered by the ID.

All these muons are with a priority order of CB, ST, CT, and ME in final during an overlap removal procedure which deals with the overlaps between the different types of muons.

2.5.3.2. Efficiency measurement for muons

Similar to the electron reconstruction, four working points are defined (Loose, Medium, Tight, and High- p_T). Loose, Medium, and Tight are inclusive selections with different background rejections. High- p_T is optimised for the track $p_T > 100$ GeV.

A tag-and-probe method is employed for muon reconstruction and identification efficiency calculation. $Z \rightarrow \mu\mu$ events for muon $p_T > 10$ GeV and $J/\Psi \rightarrow \mu\mu$ events for $5 < p_T < 15$ GeV are used for reconstruction efficiency calibration. Figure 2.31 shows the Medium muon reconstruction efficiency as a function of p_T .

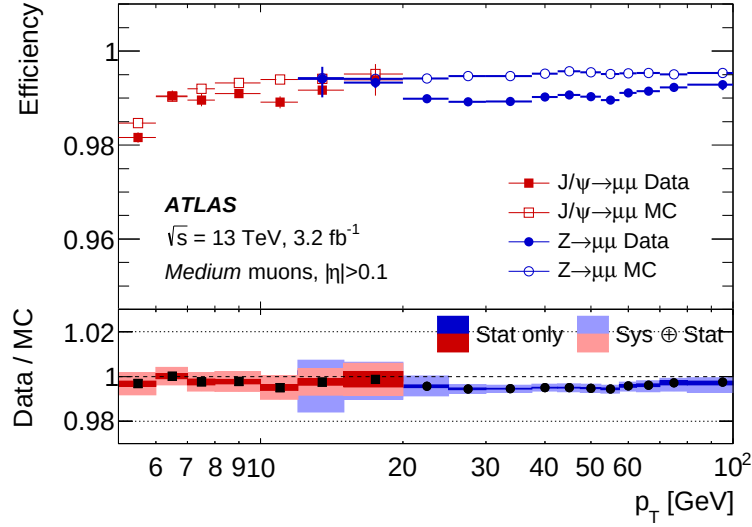


Figure 2.31. – The reconstruction efficiency of Medium muon on the distribution of p_T [72].

The efficiency for muon identification selection is shown in Table 2.10, which is measured with $t\bar{t}$ samples. Low p_T muons are separated from high p_T muons.

Selection	$4 < p_T < 20$ GeV		$20 < p_T < 100$ GeV	
	$\epsilon_{\mu}^{\text{MC}} [\%]$	$\epsilon_{\text{Hadrons}}^{\text{MC}} [\%]$	$\epsilon_{\mu}^{\text{MC}} [\%]$	$\epsilon_{\text{Hadrons}}^{\text{MC}} [\%]$
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11
High- p_T	78.1	0.26	80.4	0.13

Table 2.10. – Identification efficiency for muon selection measured with $t\bar{t}$ samples [72].

The muon isolation efficiency is also calculated using a tag-and-probe method. In total seven working points are defined, details are shown in Table 2.11. The isolation efficiency is calibrated with $\Delta R_{\mu\mu} > 0.3$ $Z \rightarrow \mu\mu$ events, and is shown in Figure 2.32 with Loose (left) and FixedCutLoose (right) selections.

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Isolation WP	Discriminating variable(s)	Definition
<i>LooseTrackOnly</i>	$p_T^{\text{varcone30}}/p_T^\mu$	99% efficiency constant in η and p_T
<i>Loose</i>	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	99% efficiency constant in η and p_T
<i>Tight</i>	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	96% efficiency constant in η and p_T
<i>Gradient</i>	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$\geq 90(99)\%$ efficiency at 25 (60) GeV
<i>GradientLoose</i>	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$\geq 95(99)\%$ efficiency at 25 (60) GeV
<i>FixedCutTightTrackOnly</i>	$p_T^{\text{varcone30}}/p_T^\mu$	$p_T^{\text{varcone30}}/p_T^\mu < 0.06$
<i>FixedCutLoose</i>	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$p_T^{\text{varcone30}}/p_T^\mu < 0.15, E_T^{\text{topocone20}}/p_T^\mu < 0.30$

Table 2.11. – Muon isolation working points [72].

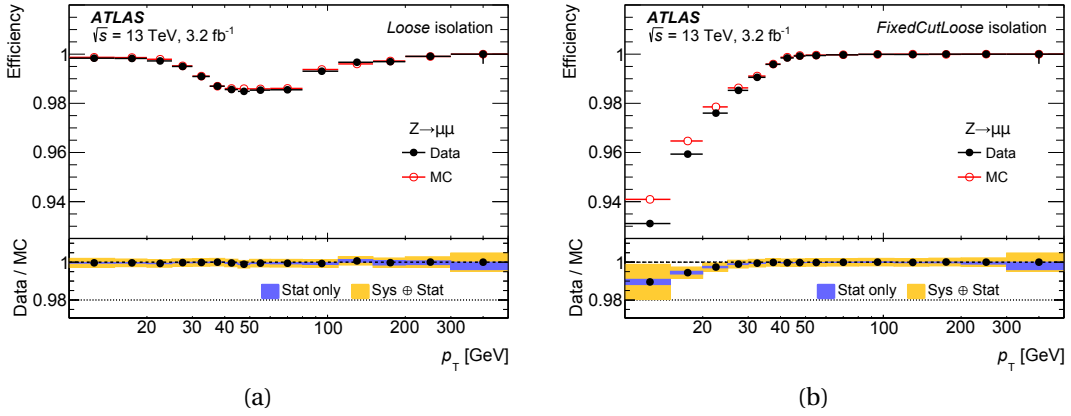


Figure 2.32. – Isolation efficiencies for muons at working points of Loose (a) and Fixed-CutLoose (b) on distributions of p_T with $Z \rightarrow \mu\mu$ events [72].

Similar to electron isolation working point calibration, a special working point is calibrated for muon isolation definitions in $t\bar{t}H$ multilepton analysis as described in Section 3.3.3.

2.5.4. Taus

The tau lepton with a mass of 1.78 GeV and life of 2.9×10^{-13} s [73]. The decay mode of τ includes leptonically decay (35%) and hadronically decay (65%). The former results in charged light leptons and neutrinos, while the latter leads to pions and a tau neutrino. The leptonically decaying taus are always reconstructed as light leptons. The latter products include one charged pions (one-prong, 72%) and three charged pions (three-prong, 22%). Thus the signature of hadronically decaying taus (τ_{had}) is similar to the hadrons originated from the primary interaction.

The reconstruction of τ_{had} seeds from the anti- k_t jets ($R = 0.4$) and clusters in calorimeters [74, 75]. Additional requirements as $p_T > 10$ GeV and $|\eta| < 2.5$ are con-

sidered, and also the candidates in the transition region ($1.37 < |\eta| < 1.52$) are rejected. The reconstruction efficiency is shown in Figure 2.33. Two BDTs are employed to further reject the jets and electrons, namely.

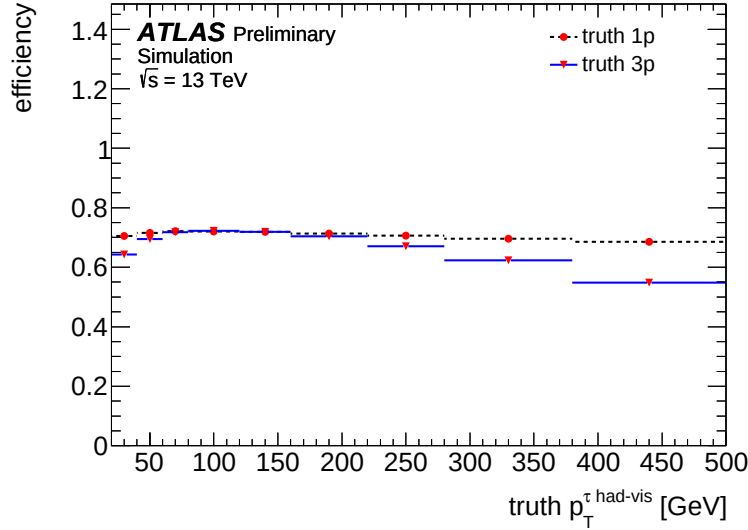


Figure 2.33. – The reconstruction efficiencies of one-prong and three-prong taus on the distribution of p_T [74].

During Run 2, a recurrent neural network (RNN) has been developed to separate true visible hadronic taus from the misidentified ones instead of the BDT method used in the past [76]. Similar to BDT, the RNN reads in the low-level input variables for tracks and clusters as well as high-level observables calculated from track and calorimeter quantities. The performances compared between the BDT and RNN are shown in Figure 2.34. Four working points have been optimised with different signal efficiencies. The Medium working point is defined with a signal efficiency at 75% for one-prong taus and 60% for three-prong taus. Corresponding rejection powers compared to the BDT at the same working point are shown in Figure 2.35.

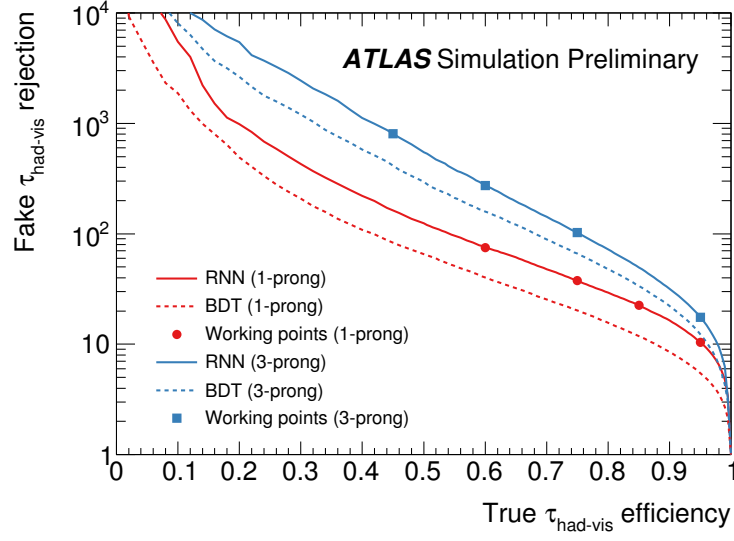


Figure 2.34. – Rejection powers compared between the RNN (full line) and BDT (dashed line) for one-prong (red) and three-prong (blue) visible hadronic tau misidentifications. [76]

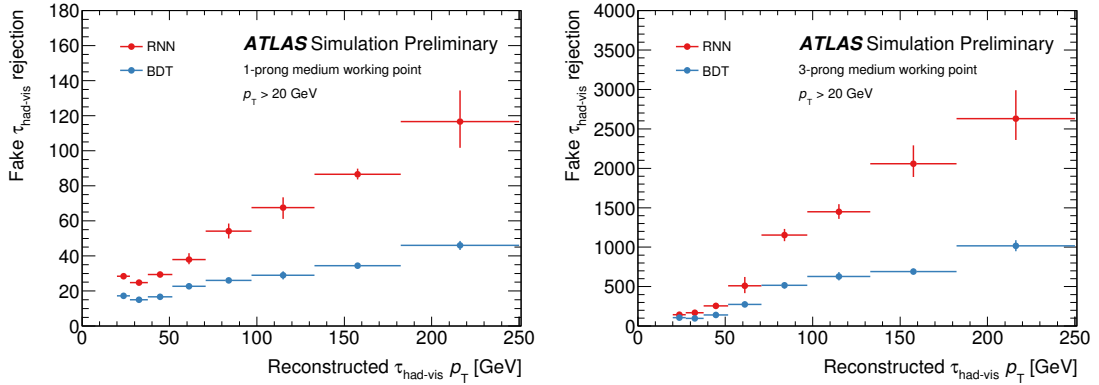


Figure 2.35. – Rejection powers compared between the RNN (red) and BDT (blue) for one-prong (left) and three-prong (right) visible hadronic tau misidentifications using the Medium working point on a distribution of reconstructed p_T [76].

The BDT τ_{had} leptons are used in the 79.9 fb^{-1} $t\bar{t}H$ multilepton analysis mentioned in Chapter 3, while the taus identified using the RNN at a medium working point are considered in the on-going analysis for $t\bar{t}W/H$ productions in multilepton final states presented in Chapter 4.

2.5.5. Jets

Jets are the showers of particles that originated from the quarks and gluons hadronization. Jets reconstruction with calorimeter energy deposits only is introduced in Section 2.5.5.1, while jets reconstruction with particle flow algorithm is described in Section 2.5.5.2. Section 2.5.5.3 and 2.5.5.4 describes the jet energy scale calibration and flavor the tagging algorithm.

2.5.5.1. Calorimeter jets reconstruction

The topo-cluster jets reconstruction is based on energy deposits in the calorimeters, together with associate tracks in the ID. An anti- k_t algorithm [77] with radius parameter $R = 0.4$ [78] has been employed to reconstruct jets if they have a p_T above 7 GeV. The input is a collection of topo-clusters [79] built in the calorimeters.

A Jet Vertex Tagger (JVT) is used to further distinguish the hard-scatter jets and pile-up jets. The JVT borrows a k-nearest neighbour (kNN) algorithm implemented by the TMVA toolkit to categorise the origination of a jet from either the hard-scatter vertex or pile-up vertices (shown in Figure 2.36).

The topo-cluster jets are used in the $t\bar{t}H$ multilepton analysis mentioned in Chapter 3 and the search for $X \rightarrow WW$ described in Chapter 5.

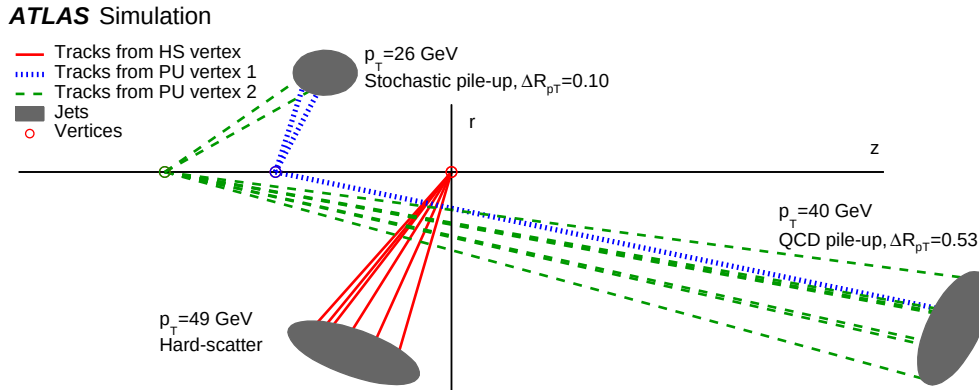


Figure 2.36. – Schematic of a hard-scatter jet from two pile-up jets in a view of $r - z$ plane [80].

2.5.5.2. Particle flow jets reconstruction

The particle flow algorithm takes account of the charged particle momenta obtained from the ID, then removes the charged particle energy deposits in calorimeters to enable a measurement of neutral particle energies. In Figure 2.37, a flow chart shows how the particle flow (PFlow) algorithm proceeds.

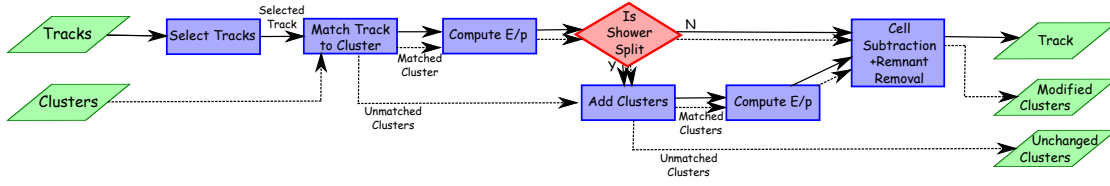


Figure 2.37. – A work flow chart of the particle flow algorithm [81].

After the ID tracks and topo-clusters are selected, a matching among the tracks and topo-clusters is processed considering two criteria:

- Consistency between the track momentum p^{trk} and topo-cluster energy E^{clus} :

$$E^{\text{clus}}/p^{\text{trk}} > 0.1. \quad (2.14)$$

The cut rejects about 10% of incorrect matches for low p_T particles and above 30% in high p_T . The efficiency loss for correct matches is less than 1%. The performance is shown in Figure 2.38.

- Distance between tracks and topo-clusters:

$$\Delta R' = \sqrt{\left(\frac{\Delta\phi}{\sigma_\phi}\right)^2 + \left(\frac{\Delta\eta}{\sigma_\eta}\right)^2} < 1.64, \quad (2.15)$$

where σ_ϕ and σ_η are the angular topo-cluster widths. The numerical value 1.64 is derived from a one-sided Gaussian confidence interval of 95%, which is well performed as shown in Figure 2.39.

The tracks associated with a topo-cluster satisfying both criteria will be used for energy subtractions.

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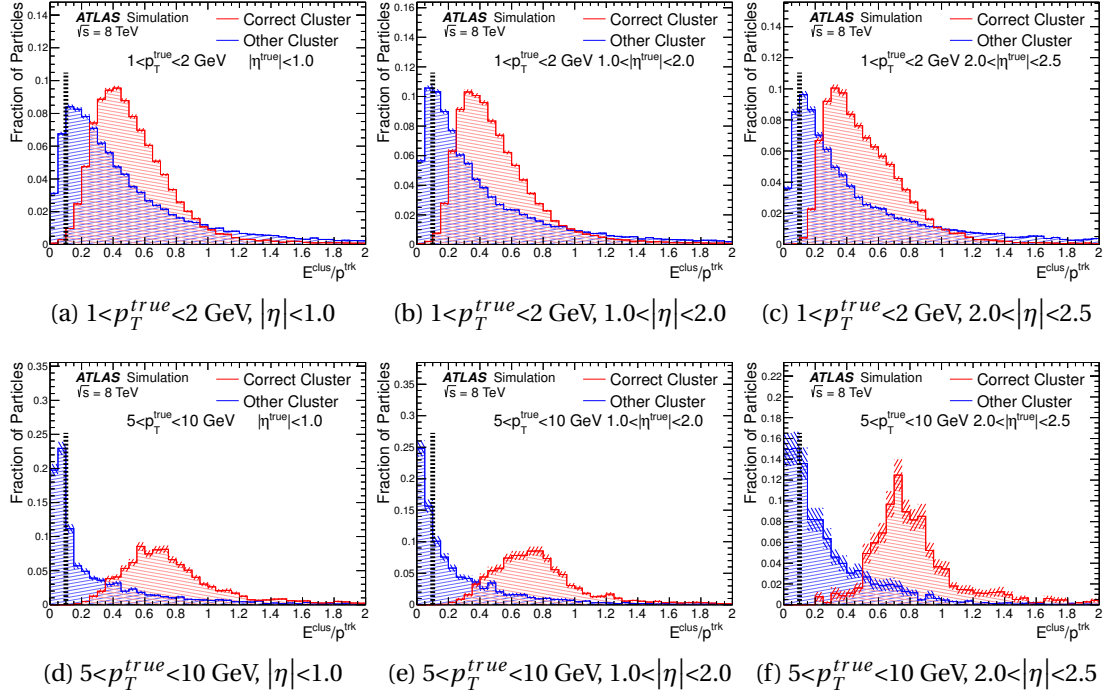


Figure 2.38. – Distribution of $E^{\text{clus}}/p^{\text{trk}}$. The correct cluster is referred to as $E_{\text{topo-cluster}}/E_{\text{true particle}} > 90\%$, while other cluster is the closest cluster [81].

2. The LHC and the ATLAS detector – 2.5. Object reconstructions

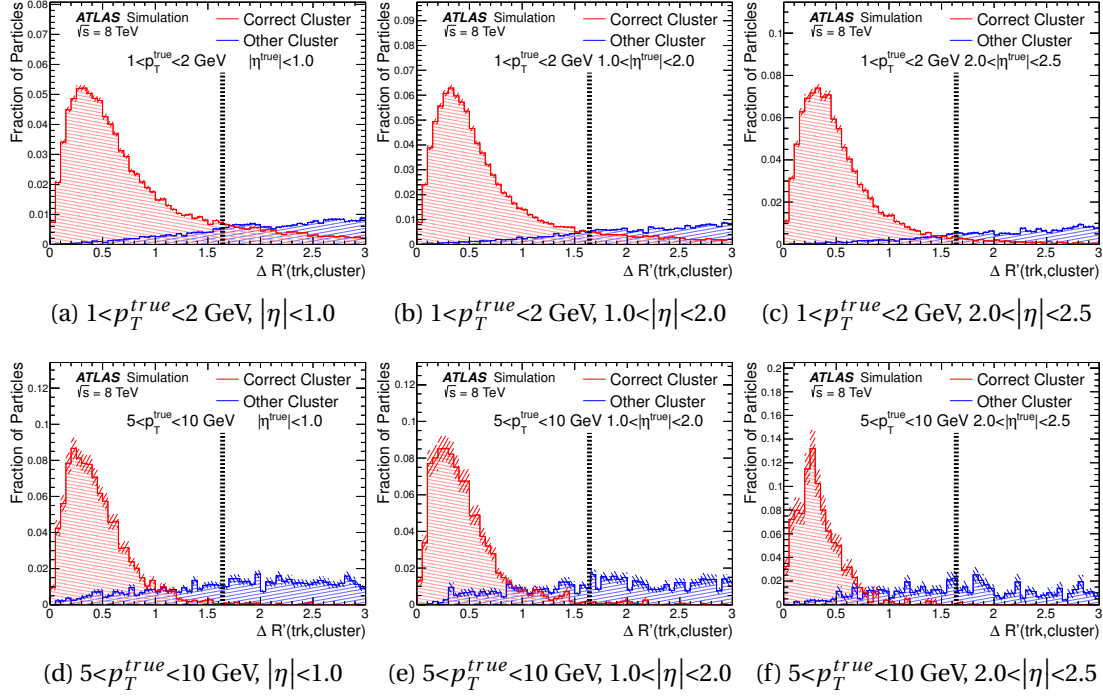


Figure 2.39. – Distribution of $\Delta R'(\text{track}, \text{cluster})$. The correct cluster is referred to as $E_{\text{topo-cluster}}/E_{\text{true particle}} > 90\%$, while other cluster is the closest cluster. Both clusters satisfying $E^{\text{clus}}/p^{\text{trk}} > 0.1$ [81].

An expected value of $\langle E_{\text{ref}}^{\text{clus}}/p_{\text{ref}}^{\text{trk}} \rangle$ has been measured using single particle samples without pile-up. Then it is varied considering the detector geometry and shower development, as well as the layer of highest energy density (LHED), which gives the layer with the largest energy density increasing rate.

The significance of the difference between the expected and matched topo-cluster energies is defined as:

$$S(E^{\text{clus}}) = \frac{E^{\text{clus}} - \langle E_{\text{dep}} \rangle}{\sigma(E_{\text{dep}})}, \quad (2.16)$$

where E^{clus} and $\langle E_{\text{dep}} \rangle$ are the track matched topo-cluster energy and expected deposit energy estimated from $\langle E_{\text{ref}}^{\text{clus}}/p_{\text{ref}}^{\text{trk}} \rangle$, while $\sigma(E_{\text{dep}})$ is the standard deviation of $E^{\text{clus}}/p^{\text{trk}}$ measured with single-pion samples. $S(E^{\text{clus}})$ is observed to have a clear relation to the fraction of the energy deposited in the topo-cluster and the total energy deposited in all clusters (ϵ^{clus}). More than 90% of $\epsilon^{\text{clus}} > 90\%$ clusters also satisfy $S(E^{\text{clus}}) > -1$. The clusters with $S(E^{\text{clus}}) < -1$ are considered with a $\epsilon^{\text{clus}} < 70\%$ and as part of a split cluster. A split shower recovery procedure is performed on these clusters: all topo-clusters within $\Delta R < 0.2$ are considered to match the track.

A cell-based energy subtraction algorithm is performed to best remove the charged track associated topo-clusters. The topo-clusters with an energy less than $\langle E_{\text{dep}} \rangle$ are

simply removed, otherwise the process will be performed cell-by-cell. The subtraction starts from the extrapolated track position located according to the LHED, then follows a set of concentric rings built in $\eta - \phi$ plane centered at the track position, from inside out. Rings in different layers are ordered by the energy density. The subtraction continues until $\langle E_{\text{dep}} \rangle$ reached. The outermost ring will be partially subtracted if the energy exceeded. Figure 2.40 gives the idea how the subtraction acts. The energy removed from the subtraction in the cells and topo-clusters are removed if consistent with $\sigma(E_{\text{ref}}^{\text{clus}}/p_{\text{ref}}^{\text{trk}})$ from remnant removal before the combination of the ID tracks for the charged particles and remained topo-clusters represents the neutral particles as the final step.

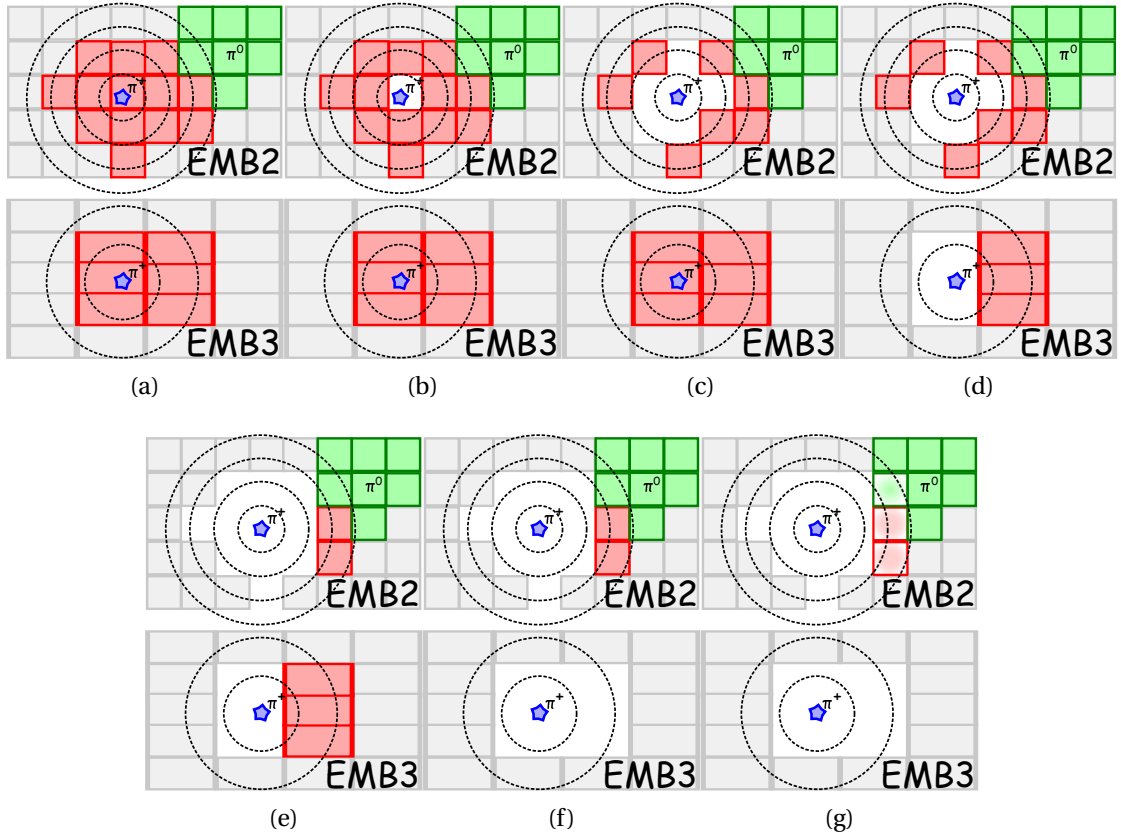


Figure 2.40. – Example of a charged $\pi^\pm$ (red) subtracted from a neutral π^0 (green) cell-by-cell in EMB2 and EMB3. The star represents the extrapolated track position and the lighter shading in the outermost ring is partially subtracted in (g) [81].

The particle flow jets are used in the on-going $t\bar{t}W/H$ multilepton analysis presented in Chapter 4.

2.5.5.3. Jet energy scale calibration

Truth jets are reconstructed from the MC simulations, at the particle-level. Inputs for the $R = 0.4$ anti- k_t are final-state particles with a lifetime of $c_\tau > 10$ mm and muons. Truth jets are used to calibrate the jet four-vector to particle-level energy scale from the EM scale. This process is referred to as the jet energy scale (JES) [82]. The JES consists of several corrections, including pile-up correction, absolute jet energy scale correction, η calibration correction, global sequential calibration (GSC), which processes corrections to five observables, and in situ calibration, which correct jets in data referred to as the well-measured objects such as photons and Z bosons. Figure 2.41 gives the flow chart showing how JES calibration works.

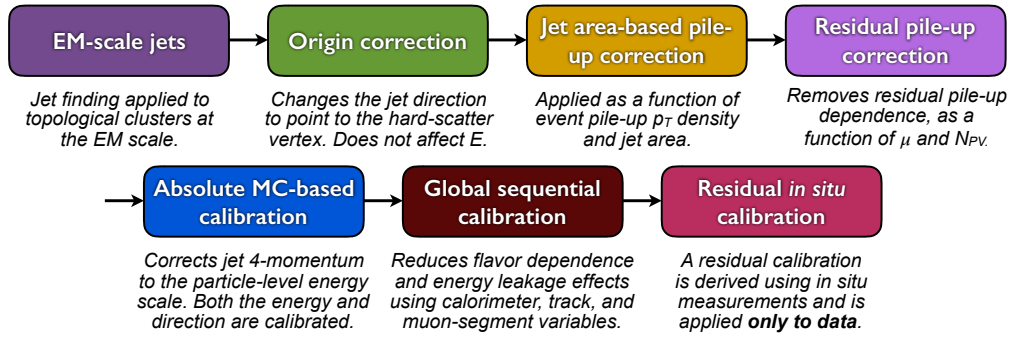
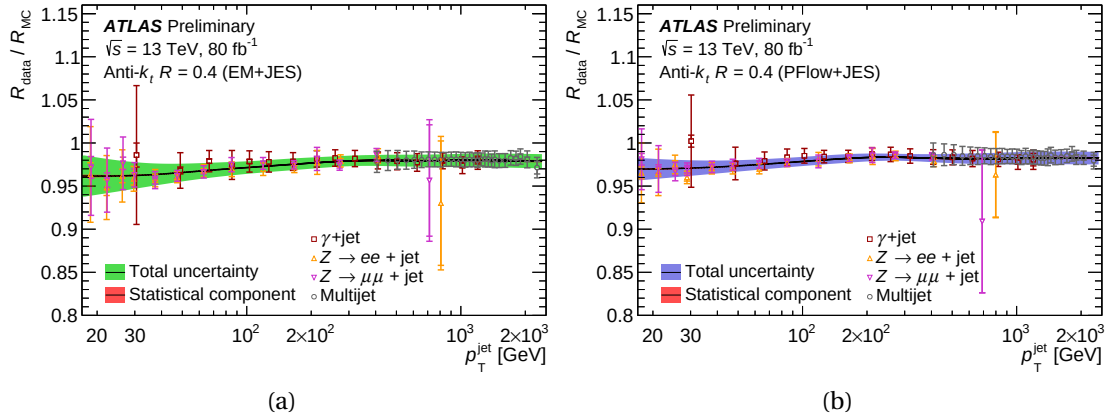


Figure 2.41. – A flow chart for JES calibration stages [82].

In Figure 2.42 shows data to MC ratio of the average p_T response for EM topo-cluster jets (left) and particle flow jets (right) on a distribution of jet p_T .


 Figure 2.42. – Data to MC ratio of the average p_T response for EM topo-cluster jets (a) and particle flow jets (b) as a function of jet p_T [83].

2.5.5.4. Flavor tagging

The b-jets are tagged [84] from their long transverse flight length about 5 mm with a b-hadron $p_T = 50$ GeV. Algorithms are built to identify b-jets from different approaches in Run 1:

- **IP2D/IP3D** [85] are the impact parameter based algorithms. The IP2D focuses on the track transverse impact parameter significance with charge, while the IP3D takes an additional longitudinal impact parameter significance into account. Log-likelihood ratio (LLR) discriminants are employed to separate b-jets, c-jets, and light-jets.
- **SV1** [86] is a secondary vertex tagging algorithm. Vertex candidates are reconstructed from tracks rejected by decaying of other long-lived particles, photon conversions, or material interactions. The best secondary vertex is selected from a χ^2 fit.
- **JETFITTER** [87] is a topological multi-vertex algorithm, which attempts to reconstruct the full b-quark decay chain. It borrows and modifies the Kalman filter to reconstruct a weak decay chain like $b \rightarrow c \rightarrow s$. Multiple vertices, even with only one track, are built during the reconstruction.

In Run 2, these algorithms, referred to as low-level algorithms, are improved and included in two high-level algorithms, the MV2 and the DL1. Both of the high-level algorithms are using outputs of the low-level algorithms as inputs for the intrinsic multivariate classifiers. The MV2 [85] takes an advantage of the boosted decision tree (BDT), and the DL1 [85] uses a deep feed-forward neural network (NN).

Input variables for the MV2 and the DL1 are summarised in Table 2.12. Both methods are sharing the same operating points (OPs) with a b-tagging efficiency at 85%, 77%, 70%, and 60%. The DL1 and MV2 gives similar performance. Benefits from the JETFITTER c-tagging variables, the DL1 algorithm have a 30% and 10% better rejection of light-flavor jet and c-jet to MV2, at a 70% OP. The performances of the two methods against light-flavor jets (left) and c-jets (right) are shown in Figure 2.43.

2. The LHC and the ATLAS detector – 2.5. Object reconstructions

Input	Variable	Description
Kinematics	p_T η	Jet p_T Jet $ \eta $
IP2D/IP3D	$\log(P_b/P_{\text{light}})$ $\log(P_b/P_c)$ $\log(P_c/P_{\text{light}})$	Likelihood ratio between the b -jet and light-flavour jet hypotheses Likelihood ratio between the b - and c -jet hypotheses Likelihood ratio between the c -jet and light-flavour jet hypotheses
SV1	$m(\text{SV})$ $f_E(\text{SV})$ $N_{\text{TrkAtVtx}}(\text{SV})$ $N_{2\text{TrkVtx}}(\text{SV})$ $L_{xy}(\text{SV})$ $L_{xyz}(\text{SV})$ $S_{xyz}(\text{SV})$ $\Delta R(\vec{p}_{\text{jet}}, \vec{p}_{\text{vtx}})(\text{SV})$	Invariant mass of tracks at the secondary vertex assuming pion mass Energy fraction of the tracks associated with the secondary vertex Number of tracks used in the secondary vertex Number of two-track vertex candidates Transverse distance between the primary and secondary vertex Distance between the primary and the secondary vertex Distance between the primary and the secondary vertex divided by its uncertainty ΔR between the jet axis and the direction of the secondary vertex relative to the primary vertex.
JETFITTER	$m(\text{JF})$ $f_E(\text{JF})$ $\Delta R(\vec{p}_{\text{jet}}, \vec{p}_{\text{vtx}})(\text{JF})$ $S_{xyz}(\text{JF})$ $N_{\text{TrkAtVtx}}(\text{JF})$ $N_{2\text{TrkVtx}}(\text{JF})$ $N_{1\text{-trk vertices}}(\text{JF})$ $N_{\geq 2\text{-trk vertices}}(\text{JF})$	Invariant mass of tracks from displaced vertices Energy fraction of the tracks associated with the displaced vertices ΔR between jet axis and vectorial sum of momenta of all tracks attached to displaced vertices Significance of average distance between PV and displaced vertices Number of tracks from multi-prong displaced vertices Number of two-track vertex candidates (prior to decay chain fit) Number of single-prong displaced vertices Number of multi-prong displaced vertices
JETFITTER c -tagging	$L_{xyz}(2^{\text{nd}}/3^{\text{rd}}\text{vtx})(\text{JF})$ $L_{xy}(2^{\text{nd}}/3^{\text{rd}}\text{vtx})(\text{JF})$ $m_{\text{Trk}}(2^{\text{nd}}/3^{\text{rd}}\text{vtx})(\text{JF})$ $E_{\text{Trk}}(2^{\text{nd}}/3^{\text{rd}}\text{vtx})(\text{JF})$ $f_E(2^{\text{nd}}/3^{\text{rd}}\text{vtx})(\text{JF})$ $N_{\text{TrkAtVtx}}(2^{\text{nd}}/3^{\text{rd}}\text{vtx})(\text{JF})$ $\gamma_{\text{trk}}^{\text{min}}, \gamma_{\text{trk}}^{\text{max}}, \gamma_{\text{trk}}^{\text{avg}}(2^{\text{nd}}/3^{\text{rd}}\text{vtx})(\text{JF})$	Distance of 2^{nd} or 3^{rd} vertex from PV Transverse displacement of the 2^{nd} or 3^{rd} vertex Invariant mass of tracks associated with 2^{nd} or 3^{rd} vertex Energy fraction of the tracks associated with 2^{nd} or 3^{rd} vertex Fraction of charged jet energy in 2^{nd} or 3^{rd} vertex Number of tracks associated with 2^{nd} or 3^{rd} vertex Min., max. and avg. track rapidity of tracks at 2^{nd} or 3^{rd} vertex

Table 2.12. – Input variables used in the MV2 and the DL1 are displayed. JETFITTER c -tagging variables are used only in DL1 [84].

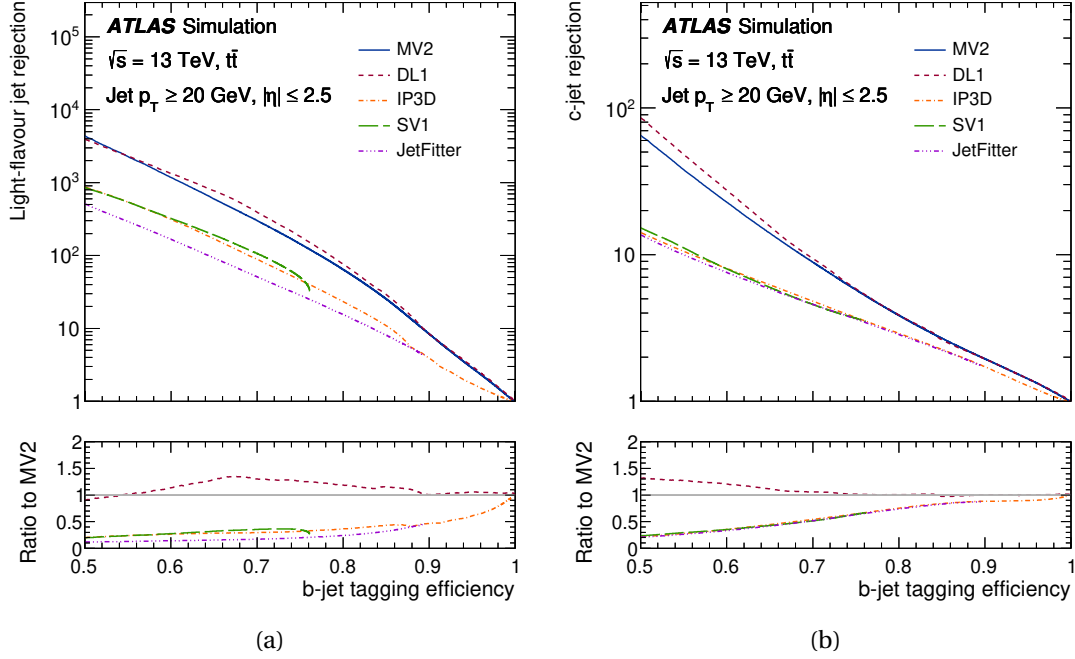


Figure 2.43. – The rejection rates of light-flavour jet (a) and c-jet (b) versus b-jet tagging efficiency with different b-tagging algorithms [84].

The presented analyses for $t\bar{t}H$ multilepton with an integrated luminosity of 79.9 fb^{-1} dataset (mentioned in Chapter 3) and highmass resonances search in $X \rightarrow WW$ mode with an integrated luminosity of 36.1 fb^{-1} dataset (described in Chapter 5) are using the tagger MV2c10 [88, 89], which is a variant of MV2, tuning the background c-jet (light-jet) fraction at 10% (90%). Only the flavour algorithms DL1 and DL1r support the particle flow jets, while DL1r is also calibrated for charm and light jets. The analysis in progress on the $t\bar{t}W/H$ measurement in multilepton final states is using the DL1r tagger as recommended.

2.5.6. Missing transverse momentum

The missing transverse momentum (E_T^{miss}) [90, 91] represents the particles which are not detected by ATLAS directly. The $E_{x(y)}^{\text{miss}}$ can be calculated from a sum of the transverse momentum of particles equates to zero in $x(y)$ direction:

$$E_{x(y)}^{\text{miss}} = - \sum_{\text{hard objects}} p_{x(y)} - \sum_{\text{soft signals}} p_{x(y)}, \quad (2.17)$$

and E_T^{miss} is calculated as:

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}. \quad (2.18)$$

The hard objects are the reconstructed and selected particles (electrons, muons, photons, and hadronic taus) and accepted jets, while the soft term represents the unused ID tracks. Both in-time pile-up and out-of-time pile-up are taken into account in the final reconstructions [92]. The Root Mean Square (RMS) resolutions obtained from the combined distributions of EMTopo E_x^{miss} and E_y^{miss} comparing between data with EMTopo jets, data with PFlow jets, and MC with EMTopo jets at Loose and Tight working points in a $Z \rightarrow ee$ selection are shown in figure 2.44.

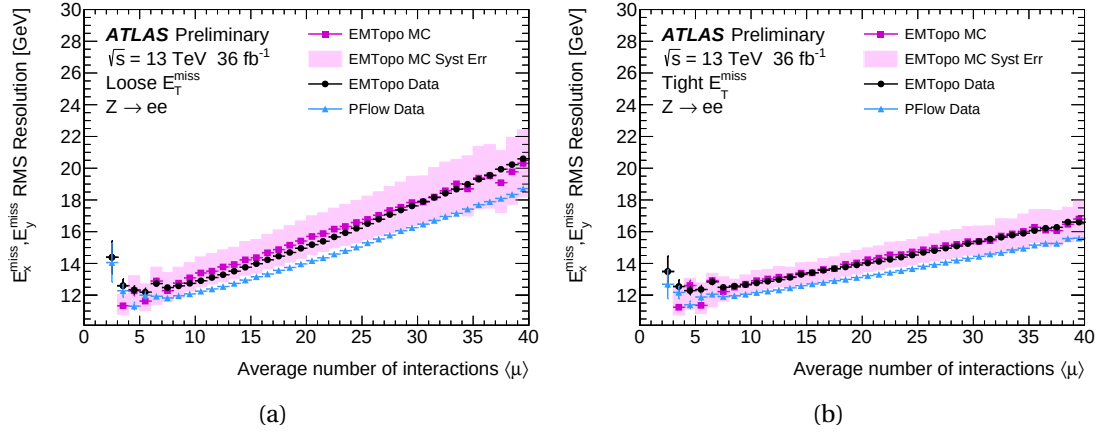


Figure 2.44. – The RMS resolutions obtained from the combined distributions of EMTopo E_x^{miss} and E_y^{miss} comparing between data with EMTopo jets, data with PFlow jets, and MC with EMTopo jets at Loose (a) and Tight (b) working points in a $Z \rightarrow ee$ selection [90].

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset

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3.1. Introduction

Since the Higgs discovery in 2012 [1, 2], the interest in measuring the properties of the Higgs boson is growing. One of the most interesting key parameters is the Yukawa coupling of the Higgs to the top quark, λ_t (determined by Equation 1.33), which is also by far the largest. It can be measured directly from a tree-level process of $gg/qq \rightarrow t\bar{t}H$.

The $t\bar{t}H$ process has been observed by the ATLAS and CMS collaborations in 2018 [3, 4]. The published result for $t\bar{t}H$ observation by the ATLAS is a combination of several Higgs channels. In $H \rightarrow \gamma\gamma$ [3, 93] and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell = e, \mu$) [3, 94] channels, up to 79.9 fb^{-1} integrated luminosity data are used. Channels with multilepton [95] and all hadronic [96] final states are performed with a dataset corresponding to an integrated luminosity of 36.1 fb^{-1} . The $t\bar{t}H$ measurements performed in Run 1 [97–101] are also considered in this combination.

The combination assumes the Higgs boson mass corresponding to a measured value of $125.09 \pm 0.24 \text{ GeV}$. The corresponding cross sections and significances in each channel are shown in Table 3.1. The total cross section measured with 13 TeV data only is $670 \pm 90(\text{stat.})^{+110}_{-100}(\text{syst.}) \text{ fb}$, which is in agreement with the SM prediction value of $507^{+35}_{-50} \text{ fb}$ calculated to NLO within uncertainties. The fitted $\mu_{t\bar{t}H}$ for the SM $t\bar{t}H$ production in each final state (left plot) and measured cross section compared to the SM prediction (right plot) are shown in Figure 3.1.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.1. Introduction

Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \rightarrow \gamma\gamma$	79.8	710^{+210}_{-190} (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \rightarrow \text{multilepton}$	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	36.1	400^{+150}_{-140} (stat.) ± 270 (syst.)	1.4σ	1.6σ
$H \rightarrow ZZ^* \rightarrow 4\ell$	79.8	< 900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ

Table 3.1. – $t\bar{t}H$ cross sections and significances measured by individual analyses and combinations [3].

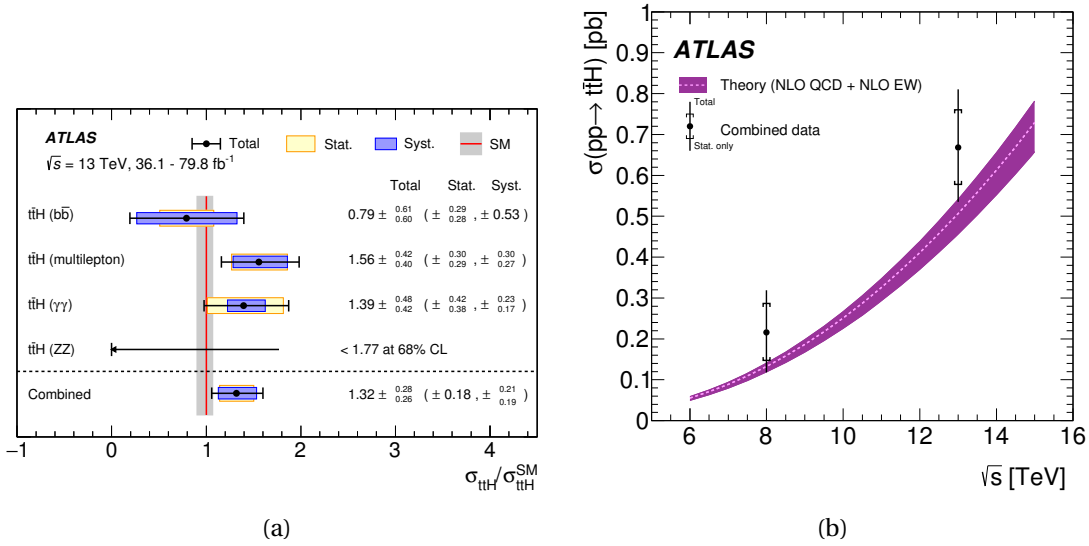


Figure 3.1. – The best-fit $\mu_{t\bar{t}H}$ in each final state (a) and the measured $t\bar{t}H$ cross sections at $\sqrt{s} = 8 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$ compared to the SM prediction [3].

As one of the combined channels, seven categories are defined in the $t\bar{t}H$ multilepton analysis using the Run 2 dataset with an integrated luminosity of 36.1 fb^{-1} . Figure 3.2 shows the post-fit data/MC comparison in eight signal regions together with four control regions for the seven categories. The best-fit values of the signal strength $\mu_{t\bar{t}H}$ is $1.6^{+0.5}_{-0.4}$. The corresponding significance is calculated as 4.1σ (2.8σ) in observation (expectation) with respect to the SM background-only hypothesis. Details are given in Table 3.2.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1}
dataset – 3.1. Introduction

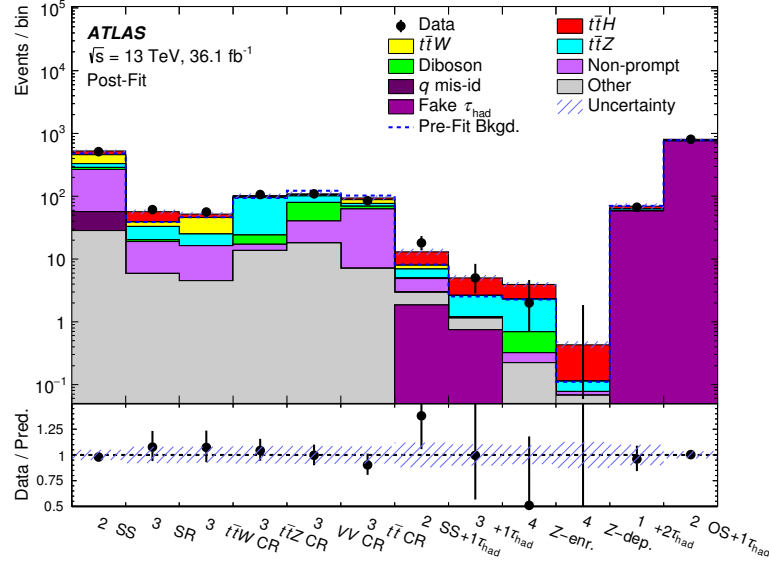


Figure 3.2. – Post-fit data/MC comparisons in eight signal regions and four control regions using the Run 2 dataset with an integrated luminosity of 36.1 fb^{-1} . The pre-fit MC values are shown in dash blue lines [95].

Channel	Best-fit μ				Significance	
	Observed		Expected		Observed	Expected
$2\ell\text{OS}+1\tau_{\text{had}}$	1.7	$^{+1.6}_{-1.5}$ (stat.) $^{+1.4}_{-1.1}$ (syst.)	1.0	$^{+1.5}_{-1.4}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	0.9σ	0.5σ
$1\ell+2\tau_{\text{had}}$	-0.6	$^{+1.1}_{-0.8}$ (stat.) $^{+1.1}_{-1.3}$ (syst.)	1.0	$^{+1.1}_{-0.9}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	—	0.6σ
4ℓ	-0.5	$^{+1.3}_{-0.8}$ (stat.) $^{+0.2}_{-0.3}$ (syst.)	1.0	$^{+1.7}_{-1.2}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	—	0.8σ
$3\ell+1\tau_{\text{had}}$	1.6	$^{+1.7}_{-1.3}$ (stat.) $^{+0.6}_{-0.2}$ (syst.)	1.0	$^{+1.5}_{-1.1}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	1.3σ	0.9σ
$2\ell\text{SS}+1\tau_{\text{had}}$	3.5	$^{+1.5}_{-1.2}$ (stat.) $^{+0.9}_{-0.5}$ (syst.)	1.0	$^{+1.1}_{-0.8}$ (stat.) $^{+0.5}_{-0.3}$ (syst.)	3.4σ	1.1σ
3ℓ	1.8	$^{+0.6}_{-0.6}$ (stat.) $^{+0.6}_{-0.5}$ (syst.)	1.0	$^{+0.6}_{-0.5}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	2.4σ	1.5σ
$2\ell\text{SS}$	1.5	$^{+0.4}_{-0.4}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	1.0	$^{+0.4}_{-0.4}$ (stat.) $^{+0.4}_{-0.4}$ (syst.)	2.7σ	1.9σ
Combined	1.6	$^{+0.3}_{-0.3}$ (stat.) $^{+0.4}_{-0.3}$ (syst.)	1.0	$^{+0.3}_{-0.3}$ (stat.) $^{+0.3}_{-0.3}$ (syst.)	4.1σ	2.8σ

Table 3.2. – Fit results for each channel and combined in 36.1 fb^{-1} $t\bar{t}H$ multilepton analysis [95].

In this chapter, a measurement with ATLAS data corresponding to an integrated luminosity of 79.9 fb^{-1} has been performed as a search for the $t\bar{t}H$ productions in multilepton final states at $\sqrt{s} = 13 \text{ TeV}$. The analysis is primarily sensitive to the signatures of $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ or $\ell\nu jj$ and $H \rightarrow \tau^+\tau^-$ decays. In Figure 3.3, a Feynman diagram shows the $t\bar{t}H$, $H \rightarrow WW$ process in a two same-charge leptons final state as an example.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.1. Introduction

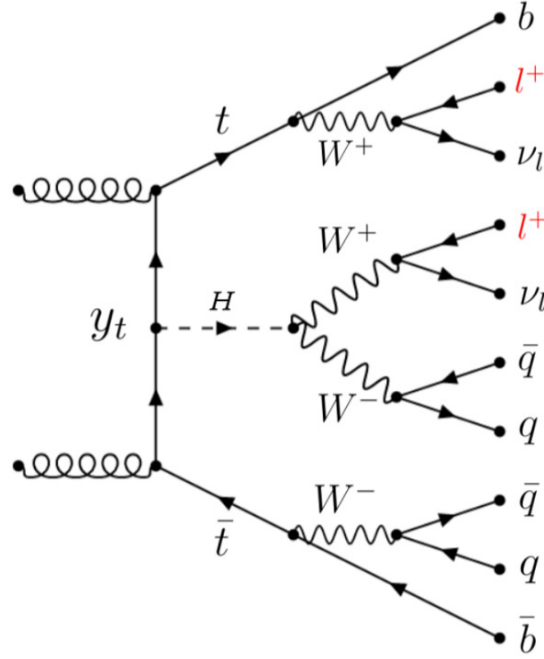


Figure 3.3. – A Feynman diagram for $t\bar{t}H$, $H \rightarrow WW$ process in $2\ell\text{SS}$ final state.

Six final states are made orthogonal through requirements on the number of loose light leptons and τ_{had} candidates, as shown in Figure 3.4.

The six channels are:

- $2\ell\text{SS}$: 2 light leptons with same-charge (0 τ_{had})
- 3ℓ : 3 light leptons (0 τ_{had})
- 4ℓ : 4 light leptons
- $2\ell\text{SS} + 1\tau_{had}$: 2 same-charge light leptons and 1 τ_{had}
- $2\ell\text{OS} + 1\tau_{had}$: 2 opposite-charge light leptons and 1 τ_{had}
- $3\ell + 1\tau_{had}$: 3 light leptons and 1 τ_{had}

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.2. Data and MC samples

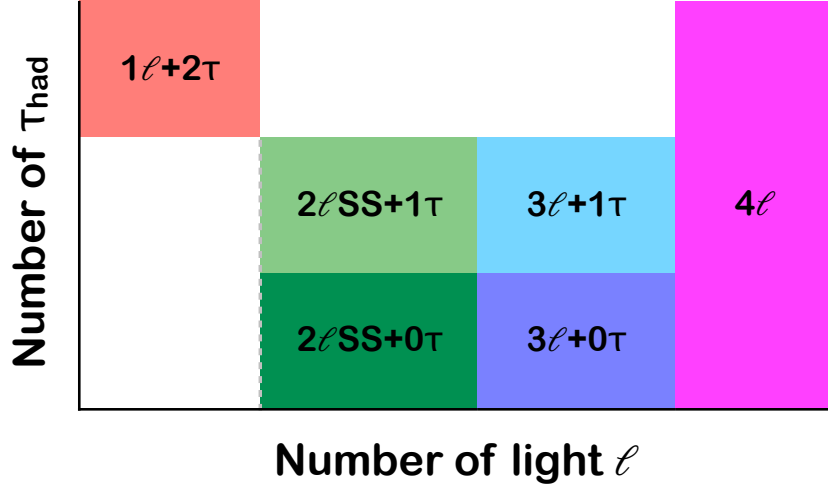


Figure 3.4. – Categorization of $t\bar{t}H$ multilepton final states in terms of lepton and τ_{had} multiplicities.

This chapter is organised as follows. Section 3.2 describes the data and MC samples used in this analysis. General selections, including the tight lepton definitions, are introduced in Section 3.3. Section 3.4 shows how the fake backgrounds are estimated in $2\ell SS$ and 3ℓ channels. Section 3.5 describes an event MVA to discriminate signals from backgrounds in $2\ell SS$ channel. The systematic uncertainties considered in the analysis are introduced in Section 3.6. In Section 3.7, the setups and results of a simultaneous fit combined all multilepton final states are shown.

My main contributions in this analysis are performing the event classification using an MVA method in $2\ell SS$ channel, cooperating on fake background estimation with a template fit (TF) method, and working on the simultaneous fit with all the six channels, as well as some post-fit checks.

3.2. Data and MC samples

In total, an integrated luminosity of $79.9 \pm 1.6 \text{ fb}^{-1}$ [37] pp collision data collected during 2015-2017 by the ATLAS detector at center-of-mass energy at $\sqrt{s} = 13 \text{ TeV}$ is used in this analysis. An average of 34 additional pp interactions (pile-up) happen in each bunch crossing of 25 ns. The overall uncertainty on the luminosity calibration is considered as 2.0% [37]. Only datasets recorded in the Good Run List (GRL) are used. Datasets are first prepared with xAOD format. Through the HIGG8D1 framework, datasets are derived into DxAOD format with a reduction in the size. This DxAOD has

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.3. General selections

specified for the $t\bar{t}H$ multilepton events and is of 0.1% collision dataset size.

MC samples are simulated by generators with different configurations. Details for the generator decisions and configure settings for signal and background estimation are listed in table 3.3. Taking the ATLAS detector geometry and response into consideration, the generated events also go through by the GEANT4 [63]. These generators have been discussed in Section 2.4. MC16a (representing 2015 and 2016 datasets) and MC16d (representing 2017 dataset) sets of MC samples are used considering different years.

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}H$	POWHEG-BOX [59, 60]	NLO	PYTHIA 8 [52]	NNPDF3.0 NLO [62]/ NNPDF2.3 LO [61]	A14 [102]
	(POWHEG-BOX)	(NLO)	(HERWIG7 [53])	(NNPDF3.0 NLO/ MMHT2014 LO [103])	(H7-UE-MMHT)
$tHq\bar{b}$	MG5_AMC [58]	LO	PYTHIA 8	CT10 [104]	A14
tHW	MG5_AMC	NLO	HERWIG++ [54]	CT10/ CTEQ6L1 [105, 106]	UE-EE-5
$t\bar{t}W$	SHERPA 2.2.1 [56] (MG5_AMC)	MEPs@NLO [107–110] (NLO)	SHERPA (PYTHIA 8)	NNPDF3.0 NNLO (NNPDF3.0 NLO/ NNPDF2.3 LO)	SHERPA default (A14)
$t\bar{t}(Z/\gamma^*)$	MG5_AMC	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
	(SHERPA 2.2.0)	(LO multileg)	(SHERPA)	(NNPDF3.0 NLO)	(SHERPA default)
$t\bar{t} \rightarrow W^+bW^-\bar{b}l^+l^-$	MG5_AMC	LO	PYTHIA 8	NNPDF3.0 LO	A14
tZ	MG5_AMC	LO	PYTHIA 6 [51]	CTEQ6L1	Perugia2012
tWZ	MG5_AMC	NLO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}t, t\bar{t}\bar{t}$	MG5_AMC	LO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_AMC	LO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
Single top (t^- , Wt^- , s -channel)	POWHEG-BOX [111–113]	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
$VV, qqVV, VVV$	SHERPA 2.2.2	MEPs@NLO	SHERPA	NNPDF3.0 NNLO	SHERPA default
$Z \rightarrow l^+l^-$	SHERPA 2.2.1	MEPs@NLO	SHERPA	NNPDF3.0 NLO	SHERPA default

Table 3.3. – The generators and configurations used for signal and background productions [5].

The simulated sample for the $t\bar{t}H$ signal is normalised to the cross section of $507^{+35}_{-50} \text{ fb}$, computed at NLO in QCD considering the leading NLO electroweak corrections [114–119]. The $t\bar{t}W$ samples are considered at NLO in QCD with the leading NLO electroweak corrections with a nominal cross section of $601 \pm 76 \text{ fb}$. Additional scaling factors are applied to account for missing QCD and electroweak corrections, which will be discussed in Section 3.7.3.1.

3.3. General selections

In this section, the general settings of this analysis are talked about. Object reconstructions are already mentioned in Section 2.5. Topo-cluster jets (see Section 2.5.5.1) and MV2c10 tagged b-jets (see Section 2.5.5.4) are used. Trigger decisions are introduced in Section 3.3.1. Section 3.3.2 describes the details of light lepton selections for multilepton final states. Tight and very tight lepton working points are defined to

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.3. General selections

better reject the non-prompt backgrounds. Section 3.3.3 describes the calibrations of the standalone electron and muon isolation working point considering the tight lepton definitions. Section 3.3.4 shows the overlap removal between leptons and jets. Selection criteria and analysis strategy in $2\ell\text{SS}$ channel are discussed in Section 3.3.5.

3.3.1. Trigger decisions

The trigger decision in $2\ell\text{SS}$ and 3ℓ channels is made concerning the isolation requirement in the single-lepton trigger (SLT) [120] introduces additional complexity and potential biases in non-prompt lepton estimation, while only gains negligible improvement in the analysis significance. Dilepton triggers (DLT) are commonly used in the channels with at least two light leptons and have been listed in Table 3.4.

Dilepton triggers (2015)	
$\mu\mu$ (asymm.)	HLT_mu18_mu8noL1
ee (symm.)	HLT_2e12_lhloose_L12EM10VH
$e\mu, \mu e$ ($\sim$ symm.)	HLT_e17_lhloose_mu14
Dilepton triggers (2016)	
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1
ee (symm.)	HLT_2e17_lhvloose_nod0
$e\mu, \mu e$ ($\sim$ symm.)	HLT_e17_lhloose_nod0_mu14
Dilepton triggers (2017)	
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1
ee (symm.)	HLT_2e24_lhvloose_nod0
$e\mu, \mu e$ ($\sim$ symm.)	HLT_e17_lhloose_nod0_mu14

Table 3.4. – Dilepton trigger used for 2015-2017 data in channels with at least two light leptons.

3.3.2. Object selections

Electrons are reconstructed from energy deposits in the EM calorimeter associated with charged tracks in the ID (see Section 2.5.2.1). They are required to satisfy the requirements of $p_T > 10 \text{ GeV}$ and $|\eta| < 2.47$, while the candidates in the transition region $1.37 < |\eta| < 1.52$ are rejected. A loose working point has been adopted for electron identification with no requirement for isolation. The transverse impact parameter significance ($|d_0|/\sigma_{d_0}$) and the longitudinal impact parameter ($|\Delta z_0 \sin\theta_\ell|$) are also required to better reject the non-prompt electrons.

Muons are reconstructed by associating the tracks in the ID and MS (see Section 2.5.3). The basic requirements for muon reconstruction are $p_T > 10 \text{ GeV}$ and

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.3. General selections

$|\eta| < 2.5$. Similar to electron, muon also has requirements on loose identification, transverse impact parameter significance, and longitudinal impact parameter.

Tight and very tight isolation lepton working points are optimised to further reduce the non-prompt leptons. The very tight working point is defined with dedicated control regions separated exclusively for internal and material conversions in the template fit. They are based on the standard lepton isolation working point of FixedCutLoose. Two lepton MVA methods, PromptLeptonVeto BDT (discussed in Section 3.3.2.1) and charge misidentification BDT (see Section 3.3.2.2), are developed to further reduce the non-prompt leptons and charge misidentified electrons. Their working points are optimised in Section 3.3.2.3 and implemented to the tight and very tight lepton definitions. The variable used to distinguish electrons and photon conversions (see Section 3.3.2.4) is also involved. A full list summarising the isolation lepton working points is shown in Table 3.5.

	e				μ		
	L	L*	T	T*	L	L*	T/T*
Identification	Loose		Tight		Loose		Medium
Isolation	No	Yes			No	Yes	
Non-prompt lepton veto	No		Yes		No		Yes
Charge misidentification veto	No		Yes		N/A		
Material/internal conversion veto	No			Yes	N/A		
Lepton $ \eta $	< 2.47			< 2	< 2.5		
$ d_0 /\sigma_{d_0}$	< 5				< 3		
$ z_0 \sin \theta $	$< 0.5 \text{ mm}$						

Table 3.5. – Light lepton definitions as loose (L), minimally-isolated loose (L*), tight (T), and very tight(T*) [5].

Hadronically decaying tau reconstructions are discussed in Section 2.5.4. Tau candidates are selected with criteria of $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$. The transition region candidates are also rejected. A medium working point for tau ID has been chosen.

Jets reconstruction from topological clusters are detailed in Section 2.5.5. Requirements of $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$ are applied to jets as the basic selection. The b-tagged jets, as described in Section 2.5.5.4, are selected by the MV2c10 method at 70% OP. the basic selection criteria for b-jets are $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$.

3.3.2.1. PromptLeptonVeto BDT

The $t\bar{t}H$ multilepton analysis has a particularly strict requirement on lepton isolation due to the signature of the final state is very sensitive to the $t\bar{t}$ background with misidentified heavy flavour decays as prompt light leptons. PromptLeptonVeto is thus developed to better reject the non-prompt leptons than the standard cut-based selection.

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PromptLeptonVeto is a gradient BDT that originated from the PromptLeptonIso (PLI) method used in the last round [95]. The PLV takes advantages of additional information from the lepton associated track jet to identify non-prompt leptons. Among the eight variables used by the PLV, three of them are also used as taggers to b-jets. Two variables are concerning the relations between the lepton and the track jet. The last three variables are on the isolation of the lepton. The input variables are listed in Table 3.6.

Variable	Description
$N_{\text{track in track jet}}$	Number of tracks collected by the track jet
rnnip	Recurrent Neural Network with additional impact parameter information of tracks inside the track-jet
DL1mu	DL1 (deep learning tagger) extended with Soft Muon Tagging information
p_T^{rel}	lepton p_T projected on the track jet direction
$p_T^{\text{track lepton}} / p_T^{\text{track jet}}$	The ratio of the track lepton p_T and the track jet p_T
$\Delta R(\text{lepton, track jet})$	ΔR between the lepton and the track jet axis
$p_T \text{VarCone30} / p_T$	Lepton track isolation, with track collecting radius of $\Delta R < 0.3$
$E_T \text{TopoCone30} / p_T$	Lepton calorimeter isolation, with topological cluster collecting radius of $\Delta R < 0.3$

Table 3.6. – List of the PLV input variables.

The ROC curves in Figure 3.5 shows the performance of the PLV method compared to the PLI and a FixedCutTight working point.

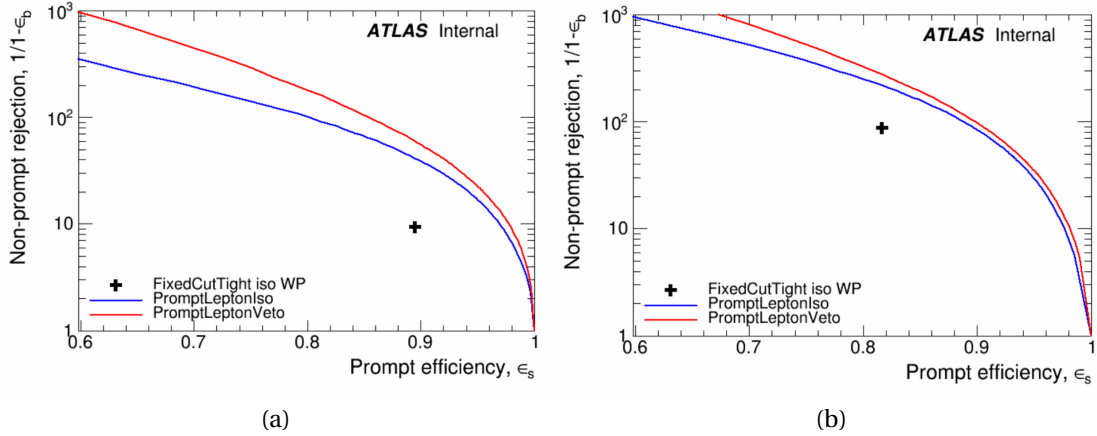


Figure 3.5. – Performance of the PLV compared to PLI and FixedCutTight working point for elections (a) and muons (b).

3.3.2.2. Electron charge misidentification BDT

Another dedicated BDT that aims to suppress the electron charge misidentification (QMisID) has been developed for the dilepton same-sign analysis, with the name of ElectronChargeIDSelectionTool (ECIDS). Eight variables (shown in Table 3.7) are introduced to distinguish the events with their electrons reconstructed with a wrong charge. Electrons with $|\eta| > 2.0$ are removed for very tight working point due to a large rate of charge flips in this region with a limited number of hits in ID.

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dataset – 3.3. General selections

Variable	Description
p_T	Transverse momentum
η	Pseudo-rapidity
charge $\times d_0$	Electric charge times the transverse impact parameter
E/p	Ratio of the cluster energy to the track momentum
R_ϕ	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centred at the electron cluster position
$\Delta\phi_1$	$\Delta\phi$ between the cluster position in the strip layer and the extrapolated track
$\Delta\phi_{rescaled}$	$\Delta\phi$ between the cluster position in the middle layer and the extrapolated track, where the track momentum is rescaled to the cluster energy before extrapolating the track to the middle layer
$\frac{q/p}{\sigma_{q/p}}$	Significance of the curvature of the track defined as the ratio of the reconstructed charge to the track momentum

Table 3.7. – List of the QMisID BDT input variables.

3.3.2.3. PLV and QMisID WP optimisation

The PLV working point for muon is kept at -0.5 from the PLI working point in the last round [95]. The correlation has been considered between the PLV and QMisID BDT scores in working point optimisation for tight electron definitions. The signal efficiencies and S/B values are scanned in a 2D plane of QMisID BDT Cut versus PLV BDT Cut in the ee channel of $2\ell\text{SS}$. A final working point has been chosen as $\text{PLV} < -0.7$ and $\text{QMisID} > 0.7$ taking into account the balance between remaining statistics and the goal to get as close to the sensitivity of muons as possible ($S/B \approx 0.12$). Event yields and S/B values are shown in Table 3.8 as a comparison between the performance of the new working points and the old ones (from PLI in the last round). For ee events, the new working point has a 33% increasing value of S/B , but 14% less signal efficiency than the old working point. With all channels combined, the overall improvement is expected to be 17% for the S/B , while losing 7% of the signal.

	$t\bar{t}H$	MC fake	S/B
$\text{PLV} < -0.5 + \text{QMisID} > 0.1 - ee$	23.69	239.68	0.0736
$\text{PLV} < -0.5 - \mu\mu$	35.87	164.20	0.1225
old PLV WPs - inclusive	117.56	846.74	0.0932
$\text{PLV} < -0.7 + \text{QmisID} > 0.7 - ee$	20.28	137.57	0.098
$\text{PLV} < -0.5 - \mu\mu$	35.87	164.20	0.1225
new PLV WPs - inclusive	108.87	616.62	0.1087

Table 3.8. – Event yield and S/B comparisons between the new working points and the old ones (from last round [95]) for $\text{PLV} + \text{QMisID}$ for e and PLV for μ .

3.3.2.4. Photon conversion suppression

One of the sources of fake electrons is photon conversion. It has been divided into two types by the radius of the conversion vertex reconstructed by a pair of tracks in ID with respect to the beamline ($\text{radius}_{\text{CO}}$):

- Internal conversion: Photon converts to a pair of electrons with a vertex near the interaction point. ($\text{radius}_{\text{CO}} < 20 \text{ mm}$)

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- Material conversion: Photon conversion happens in the detector material, which is also known as external conversion. ($\text{radius}_{\text{CO}} > 20 \text{ mm}$)

The variable `ambiguityType` from the electron and photon reconstruction (described in Section 2.5.2.1), has been required to equal to 0 to reduce the material conversions. The invariant masses of the electron associated track and the closest track with an opposite charge calculated at the conversion vertex ($m_{\text{trk-trk,CV}}$) and calculated at the primary vertex ($m_{\text{trk-trk,PV}}$) are used to better define the photon conversion candidates:

- Internal conversion candidates: $0 < m_{\text{trk-trk,PV}} < 100 \text{ MeV}$, $\text{radius}_{\text{CO}} < 20 \text{ mm}$ or $m_{\text{trk-trk,CV}} > 100 \text{ MeV}$
- Material conversion candidates: $\text{radius}_{\text{CO}} > 20 \text{ mm}$ and $0 < m_{\text{trk-trk,CV}} < 100 \text{ MeV}$
- Very tight electron candidates: `!IntCO` and `!ExtCO`

3.3.3. Lepton isolation calibration

The total electron efficiency has been discussed in Section 2.5.2. However, due to the standalone PLV and QMisID isolation working points used in $t\bar{t}H$ multilepton analysis, independent calibrations have to be done for ϵ_{iso} and ϵ_{trig} . The corresponding total electron efficiency is thus defined as

$$\epsilon_{\text{total}} = \epsilon_{\text{EMclus}} \times \epsilon_{\text{reco}} \times \epsilon_{\text{id}} \times \epsilon_{\text{PLV}} \times \epsilon_{\text{trig}}. \quad (3.1)$$

The latter terms are calculated as

$$\epsilon_{\text{PLV}} \times \epsilon_{\text{trig}} = \frac{N_{\text{PLV}}}{N_{\text{id}}} \times \frac{N_{\text{trig}}}{N_{\text{PLV}}}. \quad (3.2)$$

The ϵ_{PLV} is an exclusive tight isolation working point represents the efficiency of a combination of several working points specifically for $t\bar{t}H$ multilepton analysis. It includes the following working points:

- Pass identification: `TightLH` (required by both numerator and denominator)
- pass isolation: `FixedCutLoose`
- Pass `PromptLeptonVeto`: `PLV < -0.7`
- Pass charge misidentification BDT: `QMisID > 0.7`
- Pass ambiguity selection: `ambiguityType = 0`

The calibration has been performed using a tag-and-probe method with $Z \rightarrow ee$ samples. The tag electron is required to satisfy $E_T > 25 \text{ GeV}$ and $|\eta| \leq 2.47$ removing the transition area ($1.37 \leq |\eta| \leq 1.52$), while the probe electron needs $E_T > 10 \text{ GeV}$ and $|\eta| \leq 2.47$. The combined tight isolation efficiency shows a clear dependency on the distributions of η and E_T . The efficiency and corresponding scale factor (SF) on distributions of η in different E_T ranges have been calculated and shown in Figure 3.6.

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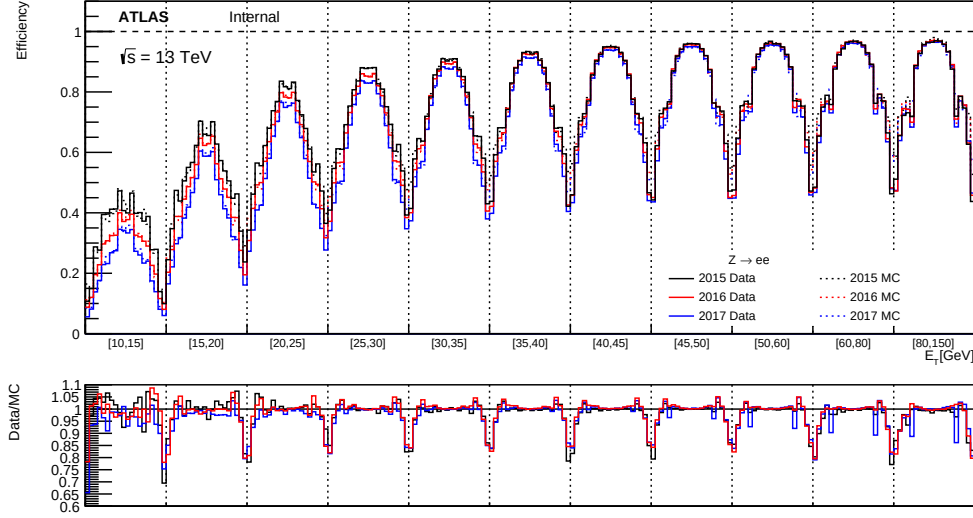


Figure 3.6. – Calibrated efficiencies for data and MC at a combined tight electron isolation working point and corresponding SF calculated from data/MC, versus η distribution in different E_T bins for 2015-2017 data.

In total 18 variations are considered for systematic uncertainty estimation:

- Variations on the tag identification: Tight, Tight with $E_T^{\text{cone } 40} < 5 \text{ GeV}$, and Medium with $E_T^{\text{cone } 40} < 5 \text{ GeV}$.
- Variations on Z -mass peak window: Excluding (80,100), (75,105), and (70,100) GeV.
- Two background template variations.

The final efficiencies and statistical uncertainties are computed as the average of the variations, and the corresponding systematic uncertainty is the root mean square (RMS) value of the 18 values for the efficiency. The systematic and statistical uncertainties are shown in figure 3.7 separated by different years.

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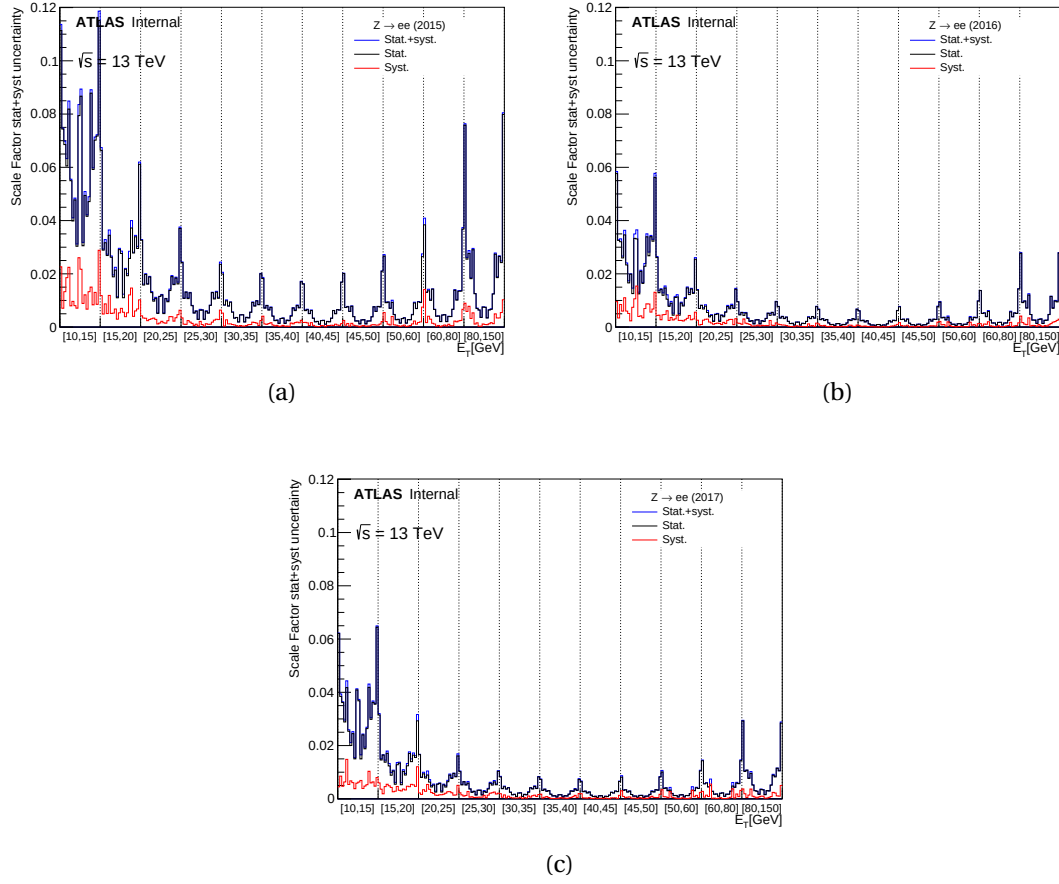


Figure 3.7. – Systematic, statistical, and total uncertainties associated to the scale factors for 2015 (a), 2016 (b), and 2017 (c).

For muon calibration, a tag-and-probe method has been performed with $Z \rightarrow \mu\mu$ samples, requiring $Z_0 \sin\theta < 0.5$ and $D_0^{sig} < 3$. The calibrated efficiencies are derived in the 2017 dataset and validated in the 2015-2016 dataset. The efficiency and data/MC rate calculated for the muon combined working point used in this analysis (FixedCutLoose+PromptLeptonVeto<-0.5) is shown in Figure 3.8, on distributions of η (left) and p_T (right).

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.3. General selections

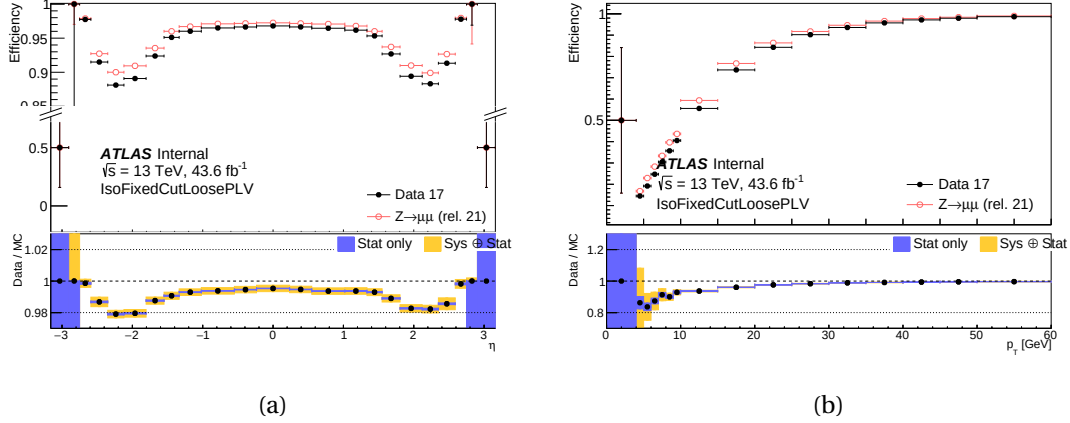


Figure 3.8. – The combined tight isolation working point efficiency and data/MC rate as a function of η (a) and p_T (b).

The trigger efficiencies are calculated similarly as for isolation working points but for a working point concerning the trigger decision listed in Table 3.4. I calibrated this combined working point for electrons with the 2018 dataset as well as the following electron trigger efficiency. This work has been presented in Appendix A.

3.3.4. Overlap removal

The overlap removal (OR) strategy is shown in Table 3.9. The OR processes in an order of from the top to the bottom. It removes the double-counted particles and solves the ambiguities. Light leptons are preferred in this overlap removal procedure.

Keep	Remove	Cone size (ΔR)
electron	electron (low p_T)	0.1
muon	electron	0.1
electron	jet	0.3
jet	muon	$\min(0.4, 0.04 + 10[\text{GeV}]/p_T \text{ (muon)})$
electron	tau	0.2
muon	tau	0.2
tau	jet	0.3

Table 3.9. – The overlap removal strategy in $t\bar{t}H$ multilepton analysis.

3.3.5. Selection criteria and analysis strategy in $2\ell\text{SS}$ channel

Selection criteria for the six channels categorised by the number and flavour of loose leptons (shown in Figure 3.4) are listed in Table 3.10. The $2\ell\text{SS}$ channel requires

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at least two N_{jets} and one $b - \text{jet}$. Two same-sign very tight leptons are asked with $p_T > 20 \text{ GeV}$ and no τ_{had} matched. Minor cuts on $M_{\ell_0\ell_1}$, $\Delta R_{\ell_0\ell_1}$, and $|\eta|$ for leptons with certain flavour are applied to reject the non-prompt and charge misidentified backgrounds in these regions with negligible effect on the signal.

Channel	Selection criteria
2 ℓ SS	Two same-charge (SS) very tight (T*) leptons, $p_T > 20 \text{ GeV}$ No τ_{had} candidates $N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$ $M_{\ell_0\ell_1} > 12 \text{ GeV}$ for all SF pairs $\Delta R_{\ell_0\ell_1} > 0.5$ for ee and $e\mu$ channels $ \eta < 2.0$ for e 13 categories: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}$, mat. conv, int. conv., split by lepton flavour, charge, jet and b -jet multiplicity

Table 3.10. – Selection criteria in 2 ℓ SS channel.

The analysis strategy used in 2 ℓ SS channel is summarised in Table 3.11. The $t\bar{t}H$ signal and $t\bar{t}V$ background are estimated by the MC samples (described in Section 3.2). The non-prompt lepton background (contributed by $t\bar{t}$, $t\bar{t}\gamma^*$, and $V + \text{jets}$) is estimated using a template fit (TF) method (described in Section 3.4). A 2-dimensional (2D) MVA has been applied in 2 ℓ SS channel to better select $t\bar{t}H$ signal from backgrounds (described in Section 3.5).

Channel	Non-prompt lepton strategy	MVA trained against	Discriminant
2 ℓ SS	Template fit (semi-DD)	$t\bar{t}$ and $t\bar{t}V$	2D BDT

Table 3.11. – Summary of strategies in 2 ℓ SS channel.

3.4. Fake estimation

In this section, non-prompt light lepton backgrounds and charge misassignments are discussed. Two methods have been practiced for non-prompt leptons, which are the data-driven matrix method (MM) and the semi-data-driven template fit (TF) method. The latter method is approved by this analysis and described in Section 3.4.1. The electron charge misassignments, which are also known as charge misidentifications and charge flips, are introduced in Section 3.4.2.

3.4.1. Non-prompt leptons

The non-prompt lepton background in 2 ℓ SS and 3 ℓ discussing in this section is a mixture of leptons from heavy-flavour decays and photon conversions. Efforts have

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been done with different approaches to estimate the true fake background and end up with a TF method. This is a method of semi-data-driven, which makes use of multiple normalisation factors (NFs) to normalise the fake templates, given by the MC samples of all processes contributing to the fake background, to data. In this method, the truth information from $t\bar{t}$ and $t\bar{t}\gamma^*$ defining types of fakes are trusted, while the MC estimation of non-prompt leptons is corrected by the normalisation factors free-floating in a simultaneous fit to data.

3.4.1.1. Classifications at truth level

Non-prompt background mainly comes from $t\bar{t}$ and $t\bar{t}\gamma^*$ processes, followed by a much smaller contribution from V+jets and single-top-quark processes. The $t\bar{t}$ and $t\bar{t}\gamma^*$ samples are divided into different types with truth level information:

- Prompt: Top decay leptons (truth origin=10), bremsstrahlung radiation (truth origin=5, truth parent id=particle id, and truth type=2), or rare top decay (muon truth origin=0).
- Material conversion (MatC): truth origin=5 and $\text{radius}_{\text{CO}} > 20 \text{ mm}$.
- Internal conversion (IntC): truth origin=5 and $\text{radius}_{\text{CO}} < 20 \text{ mm}$.
- Heavy flavour (HF) B-decay: truth origin=26,29,33.
- Heavy flavour C-decay: truth origin=25,27,28,32.
- Light flavour (LF) decays and others.

The contribution from prompt leptons is very small and can be ignored. Heavy and light flavour sources are studied individually and were combined after discussions due to their similar behavior and composition. Two normalisation factors are assigned to the flavour of the non-prompt lepton (e, μ) originated from the B/C/light flavour decays.

3.4.1.2. Normalisation factors

As listed below, four free-floating normalisation factors are assigned to each of the sources:

- $\text{NF}_e^{\text{MatC}}$: normalisation factor applied on material conversion electron events.
- $\text{NF}_e^{\text{IntC}}$: normalisation factor applied on internal conversion electron events.
- NF_e^{HF} : normalisation factor applied on non-prompt electron from B/C/light flavour decay hadron (dominated by B-decay).
- $\text{NF}_\mu^{\text{HF}}$: normalisation factor applied on non-prompt muon from B/C/light flavour decay hadron (dominated by B-decay).

An additional normalisation factor concerning the modelling of MC $t\bar{t}W$ samples ($\text{NF}_{t\bar{t}W}$) apart from the TF method has been applied on $t\bar{t}W$ samples. As a result, there are in total six free-floating normalisation factors in fit.

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3.4.1.3. Region settings

Figure 3.9 gives the idea of the region settings in the TF. There are in total seventeen CRs defined for the simultaneous fit.

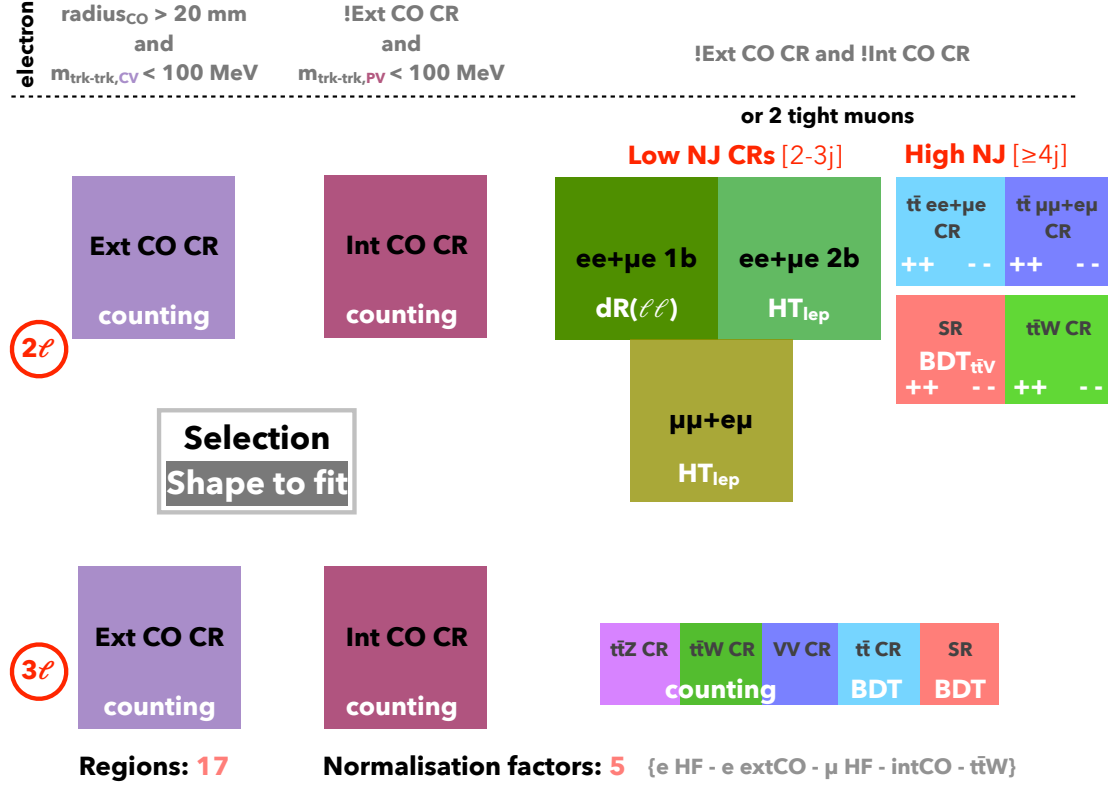


Figure 3.9. – A sketch showing the region settings in 2ℓ SS and 3ℓ channels.

A material (external) CR and an internal CR are set in 2ℓ SS and 3ℓ channels individually. The definitions for these conversion dedicated CRs can be referred to as in Section 3.3.2.4. The four regions are with one bin only and give no shape information in the fit.

The three low N_{jets} CRs in 2ℓ SS channel are established to better constrain either heavy flavour non-prompt backgrounds or $t\bar{t}W$ background, which require $N_{\text{jets}} = 2, 3$. These CRs are orthogonal and separated by $N_{b\text{-jets}}$ and the flavour of the subleading lepton. A region with subleading lepton as μ is established first, with a combined number of b-jets, on the distribution of a scalar sum of leptons (HT_{lep}). Then the events with subleading lepton as e are separated by their b-jets multiplicity ($N_{b\text{-jets}} = 1$ or $N_{b\text{-jets}} \geq 2$). Two CRs are established on distributions of $\Delta R_{\ell_0\ell_1}$ and HT_{lep} individually. The first region is rich of heavy flavour μ , while the latter two are abundant of heavy flavour e ($N_{b\text{-jets}} = 1$) and $t\bar{t}W$ ($N_{b\text{-jets}} \geq 2$). The two regions containing $N_{b\text{-jets}} = 1$ events are with four bins, while the region with $N_{b\text{-jets}} \geq 2$ is set with a binning of two. Plots are shown in Figure 3.10 gives the distributions of these three CRs.

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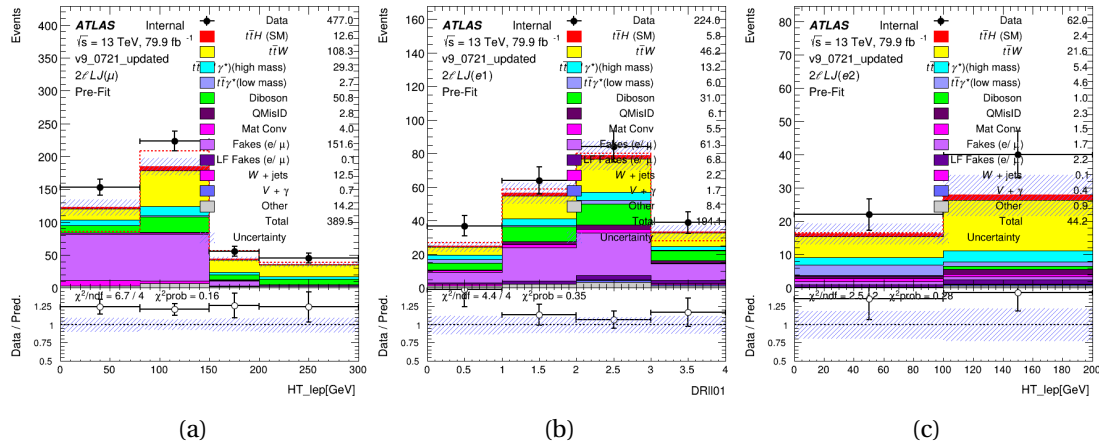


Figure 3.10. – Distributions for the pre-fit low N_{jets} ($N_{\text{jets}}=2,3$) $2\ell\text{SS}$ CRs. HT_{lep} distribution for events with subleading lepton as μ is shown in (a). Events with μe and ee are in plots (b) and (c), separated by $N_{b\text{-jets}} = 1$ or $N_{b\text{-jets}} \geq 2$, distributed as functions of $\Delta R_{\ell_0 \ell_1}$ and HT_{lep} for each.

Regions in 2ℓ SS high N_{jets} and 3ℓ channels are separated by their BDT scores. As a result, six (four) dedicated CRs and two (one) SRs are built in 2ℓ SS high N_{jets} (3ℓ) channel. Further details for 2ℓ SS high N_{jets} region definitions will be discussed in Section 3.5.5.

3.4.1.4. Template fit results

Fit has been done twice as an iterate to cooperate with the MVA classification in 2ℓ SS. At the first time, a simultaneous fit has been performed in low N_{jets} 2ℓ SS and 3ℓ CRs. The NFs obtained (shown in Table 3.12) are then applied to the 2D BDT for weighting the irreducible and reducible backgrounds. Then the BDT scores are fed back to separate SRs from CRs in the 2ℓ SS high N_{jets} region. With all the CRs available in 2ℓ SS channel and 3ℓ channel, a simultaneous fit is performed to obtain the final NFs for different sources of non-prompt background before unblinding. Figure 3.11 and Table 3.13 show the post-fit summary plot and best-fitted NF values. Only one $t\bar{t}W$ NF is considered in the template fit.

Parameter	NF_{tiW}	NF_e^{ExtCO}	NF_e^{IntCO}	NF_e^{HF}	NF_μ^{HF}
Stat-Only	1.63 ± 0.14	2.41 ± 0.98	1.26 ± 0.60	0.81 ± 0.29	1.14 ± 0.15
Syst.+ Stat.	1.64 ± 0.21	2.55 ± 1.02	1.18 ± 0.61	0.69 ± 0.32	1.10 ± 0.17

Table 3.12. – NFs from a template fit with 2ℓ SS low N_{jets} CRs and 3ℓ CRs.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.4. Fake estimation

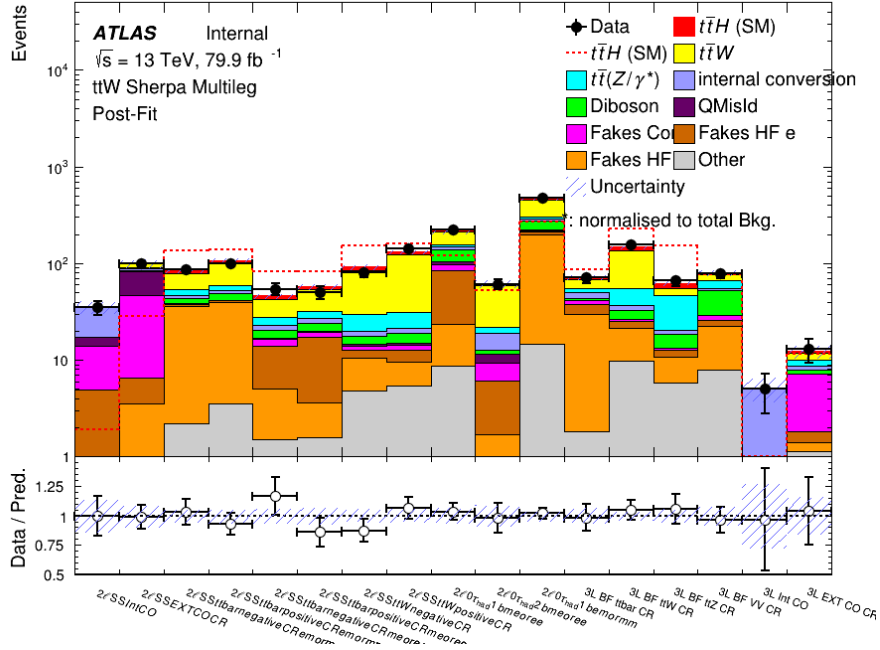


Figure 3.11. – Post-fit summary plot of the template fit with all CRs in 2ℓ SS and 3ℓ .

Parameter	$NF_{t\bar{t}W}$	NF_e^{ExtCO}	NF_e^{IntCO}	NF_e^{HF}	NF_μ^{HF}
Stat-Only	1.51 ± 0.12	1.67 ± 0.45	0.75 ± 0.25	1.11 ± 0.27	1.31 ± 0.14
Syst.+ Stat.	1.44 ± 0.18	1.70 ± 0.51	0.75 ± 0.26	1.09 ± 0.32	1.28 ± 0.17

Table 3.13. – NFs from a template fit with all low and high N_{jets} 2ℓ SS CRs and 3ℓ CRs.

3.4.2. Electron charge misidentifications

The electron charge misidentification (QMisID) is one of the main sources of the backgrounds in loose regions of 2ℓ SS channel. It can be dramatically suppressed by a dedicated BDT mentioned in Section 3.3.2.2. The remaining QMisID events are estimated by a data-driven likelihood-based method. The contribution from charge misidentification for muons is negligible.

The QMisID events are originated mainly from $t\bar{t}$ processes. Electrons in ee and $e\mu/\mu e$ channels are wrongly measured with track curves or having a bremsstrahlung ($e^\pm \rightarrow e^\pm \gamma^* \rightarrow e^\pm e^+ e^-$). The charge flip rate, ϵ_{misid} , is measured from a process of $Z \rightarrow ee$ reconstructed as a same-sign electron pair shown in Figure 3.12. The event weight for QMisID is calculated as

$$\epsilon_{QMisID} = \frac{\epsilon_{misid,1} + \epsilon_{misid,2} - 2\epsilon_{misid,1}\epsilon_{misid,2}}{1 - (\epsilon_{misid,1} + \epsilon_{misid,2} - 2\epsilon_{misid,1}\epsilon_{misid,2})}. \quad (3.3)$$

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell\text{SS}$ channel

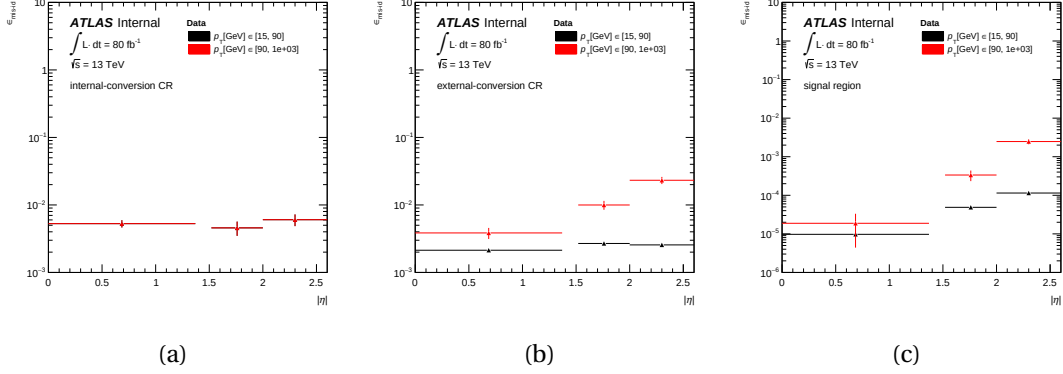


Figure 3.12. – Charge flip rates measured from $Z \rightarrow ee$ events as a function of $|\eta|$ for internal conversions (a), material conversions (b), and prompt (c) candidates.

3.5. Event MVA in $2\ell\text{SS}$ channel

As to better discriminate the signal from the backgrounds in $2\ell\text{SS}$ channel, a Multi-Variate Analysis (MVA) [121] based on Gradient Boosted Decision Trees (BDTG) [122] has been optimised. A pre-MVA selection has been performed and shown in Table 3.10. Additionally, a requirement on jet multiplicity ($N_{\text{jets}} \geq 4$) has also been applied in BDT training.

The event MVA in $2\ell\text{SS}$ has been developed as we learn more about the non-prompt background. At first, the BDT was trained against $t\bar{t}$ (estimated from matrix method) and $t\bar{t}V$ ($t\bar{t}W$ and $t\bar{t}Z$ from MC) following a strategy used in the last round [95]. In the study of the template fit method (see Section 3.4.1), a better knowledge of the non-prompt background composition has been acquired at truth level. Thus the strategy of event MVA in $2\ell\text{SS}$ channel has been changed.

In the updated MVA method, the backgrounds are no more grouped by their sample sets. The non-prompt backgrounds are further separated into heavy flavour decays and photon conversions, in which the internal conversion is considered as an irreducible background, while the heavy flavour decays and material conversion are reducible backgrounds. So two BDTs are trained against the irreducible backgrounds and reducible backgrounds independently. The region for MVA training is with internal and material conversion CRs excluded.

3.5.1. Signals and backgrounds

The $t\bar{t}H$ signal in MVA training is using the next-to-leading-order POWHEG [59, 60] +PYTHIA 8 [52] MC samples.

The irreducible background consists of a large fraction of $t\bar{t}W$ and $t\bar{t}Z$ backgrounds, together with internal conversion, diboson (VV), and other rare backgrounds in $2\ell\text{SS}$

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channel. The main contributions, $t\bar{t}W$, $t\bar{t}Z$, and internal conversion are considered as the irreducible background in MVA training. $t\bar{t}W$ and $t\bar{t}Z$ are simulated by MADGRAPH5_AMC@NLO [58] +PYTHIA 8 and internal conversion is estimated from $t\bar{t}$ samples simulated by POWHEG+PYTHIA8 and $t\bar{t}\gamma^*$ samples by MADGRAPH5_AMC@NLO + PYTHIA 8 after the overlap events removed. All these samples are weighted to the normalisation scale obtained from the template fit.

The reducible background is dominated by the $t\bar{t}$ process with leptons from heavy flavour hadron decay, followed by material conversion and charge misassignment. The heavy flavour hadron decay and material conversion are considered as the main background trained by MVA. Both of them are estimated from the overlap removed $t\bar{t}$ and $t\bar{t}\gamma^*$ samples, but with different truth selection criteria.

An alternative way to estimate the non-prompt lepton background is using the matrix method, which is a data-driven method to measure the real/fake efficiencies in an OS/SS (low N_{jets}) control region for electrons and muons separately. Then the events are assigned with weight as being non-prompt leptons, which derives from the real/fake efficiencies applying to the $2\ell\text{SS}$ loose regions. The matrix method fake background is generally used in MVA optimisations and tests. However, it is not used in the final result due to an MC modelling problem found in a few kinematic variable distributions, which we will see later.

3.5.2. MVA configuration

BDTG is one of the most robust MVA methods so far, with its kernel, the GradientBoost algorithm, developed from the most popular boosting algorithm, Adaptive Boost (AdaBoost), by fixing its weakness in noisy settings [121]. The final configurations in training for $t\bar{t}H$ signal against MC $t\bar{t}V$ and TF $t\bar{t}$ backgrounds are shown below.

For $t\bar{t}H$ vs $t\bar{t}V$ together with internal conversion (irreducible background):

- NTrees=1000
- MaxDepth=2
- MinNodeSize=1.5%
- nCuts=20
- BoostType=Grad
- Shrinkage=0.10
- UseBaggedBoost
- BaggedSampleFraction=0.5

For $t\bar{t}H$ vs heavy flavour decay and external conversion (reducible background):

- NTrees=1000
- MaxDepth=1
- MinNodeSize=1.5%
- nCuts=10
- BoostType=Grad
- Shrinkage=0.10

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell SS$ channel

- UseBaggedBoost
- BaggedSampleFraction=0.5

The parameter `NTrees` represents the number of binary trees (as shown in Figure 3.13) used in the classifier. `MaxDepth` sets the max depth of a decision tree. `MinNodeSize` is the minimum percentage of training events required in a leaf node. `nCuts` defines the number of grid points to find optimal cut in variable range. `BoostType` is chosen as `Grad` to encourage a GradientBoost algorithm which works best on weak classifiers, corresponding to small individual decision trees with a depth of often just 2 to 4. The learning rate `shrinkage` is set as small as 0.1 to improve the accuracy of the prediction in difficult settings. `UseBaggedBoost` enables a bagging-like resampling procedure, using individual classifiers to train random subsamples of events repeatedly. The final classifier is combined as their average. In such a way, the stability of the classifier is enhanced by using the statistics of training data effectively. `BaggedSampleFraction` controls the sample fraction used in each iteration.

To make better use of the statistics, the BDTs are trained with even and odd events separately then tested with events with the opposite parity. The configuration parameters and options are optimised and fine-tuned according to the dimension of input variables and signal/background statistics in each training.

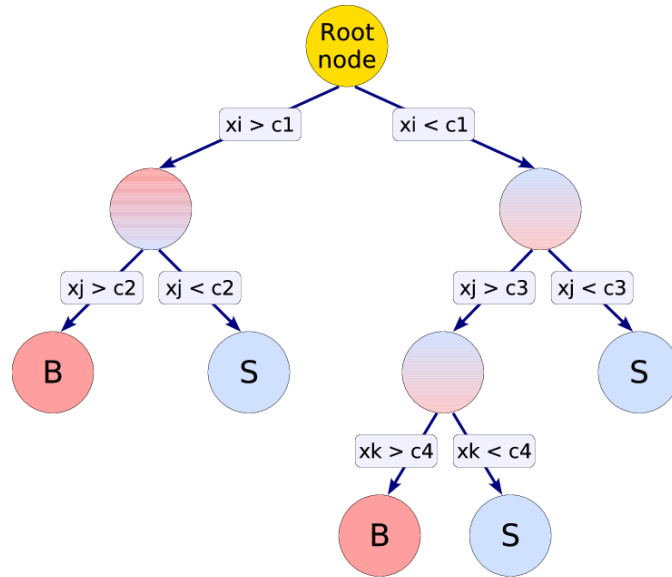


Figure 3.13. – Schematic view of a decision (regression) tree. Starting from the root node, signal and background are split using the variable that gives the best separation at each nodes. The leaf nodes at the bottom end of the tree are labeled “S” for signal and “B” for background [121].

3.5.3. MVA optimisation attempts

The MVA attempts are performed with the data-driven fake background before the template fit method comes into service. These tests aim to optimise the $2\ell\text{SS}$ BDTs and are presented in the appendices. A tight lepton working point is considered. Appendix B shows the results of optimising the input variables from a pool of 35 variables. Appendix C describes the trainings against fake backgrounds split by lepton flavours ($ee + e\mu + \mu e, \mu\mu$) and $t\bar{t}V$ inclusively. An effort is shown in Appendix D to replace the input variable $M_{\ell_0\ell_1}$ with $\Delta R_{\ell_0\ell_1}$ due to the bad modelling on $M_{\ell_0\ell_1}$ distribution.

3.5.4. Performance of MVA against template fit fakes

Due to the modelling problem cannot be solved by the matrix method, an alternative fake estimator, the template fit, has been introduced and studied in the presented analysis. Cooperative work is carried out between the template fit and MVA classification, as mentioned in Section 3.4.1.4.

The BDTs are trained in the $2\ell\text{SS}$ high N_{jets} region at the very tight lepton working point. Sources of backgrounds have been described in Section 3.5.1. In MVA training, the backgrounds are scaled by the normalisation factors extracted from the template fit to data in $2\ell\text{SS}$ low N_{jets} and 3ℓ control regions. The irreducible background is considered as a combination of $t\bar{t}Z$, $t\bar{t}W$, and internal conversion, while the reducible background is consists of heavy-flavor decay and material conversion.

As have been checked in Appendix D, $\Delta R_{\ell_0\ell_1}$ is considered to take the place of $M_{\ell_0\ell_1}$ because it has a better modelling. A similar check has been performed on the TF estimated fake background to see if this is still the case. Case 1 in this check uses the nine variables inherited from last round [95], and case 2 replace $M_{\ell_0\ell_1}$ by $\Delta R_{\ell_0\ell_1}$. Definitions of all ten variables considered in the check are listed below:

- Number of jets with $p_T > 25 \text{ GeV}$, N_{jets} ;
- Number of b -jets with $p_T > 25 \text{ GeV}$, $N_{b\text{-jets}}$ — MV2c10 algorithm is used with 70% b -tag efficiency;
- lepton flavour, $ee, e\mu, \mu e$ and $\mu\mu$ where the first lepton corresponds to the one with the highest p_T , $lFlav = 2 \times N_{\mu_0} + N_{\mu_1}$;
- Distance between leading lepton and its closest jet, $\min \Delta R_{\ell_0 j}$;
- Distance between sub-leading lepton and its closest jet, $\min \Delta R_{\ell_1 j}$;
- Maximum between lepton $|\eta_{\ell_0}|$ and $|\eta_{\ell_1}|$, $\max(|\eta_\ell|)$;
- Sub-leading lepton p_T , $p_T(\ell_1)$;
- Missing transverse energy, E_T^{miss} ;
- Invariant mass of two leptons, $M_{\ell_0\ell_1}$ (only in case 1);
- Distance between the two same-sign leptons, $\Delta R_{\ell_0\ell_1}$ (only in case 2).

The modellings of $M_{\ell_0\ell_1}$ and $\Delta R_{\ell_0\ell_1}$ are checked and shown in Figure 3.14, while the other eight variable distributions are shown in Figure 3.15. Data in the bins with signal purity larger than 15% are blinded because the set of NFs used in MVA training

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and modelling checks is obtained from the intermediate template fit only contains low $2\ell\text{SS } N_{\text{jets}}$ CRs and 3ℓ CRs (according to Section 3.4.1.4) and was not approved by the ATLAS.

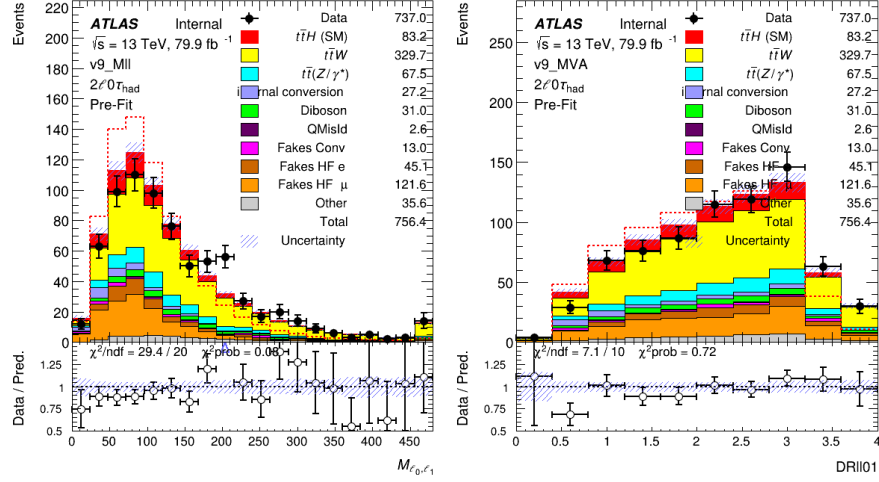


Figure 3.14. – Modelling of $M_{\ell_0\ell_1}$ and $\Delta R_{\ell_0\ell_1}$ in the very tight region. Fake background is estimated by the TF.

There is a clear trend that we can see in the distribution of $M_{\ell_0\ell_1}$. In the bins with $M_{\ell_0\ell_1} < 120 \text{ GeV}$, there is an excess in the MC simulation, while in the bins around $M_{\ell_0\ell_1} = 200 \text{ GeV}$, data overshoot the MC. The agreement between data and MC on the distribution of $\Delta R_{\ell_0\ell_1}$ is much better than $M_{\ell_0\ell_1}$. The other eight variables have fair data and MC agreement in the bins in which data is not blinded.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell\text{SS}$ channel

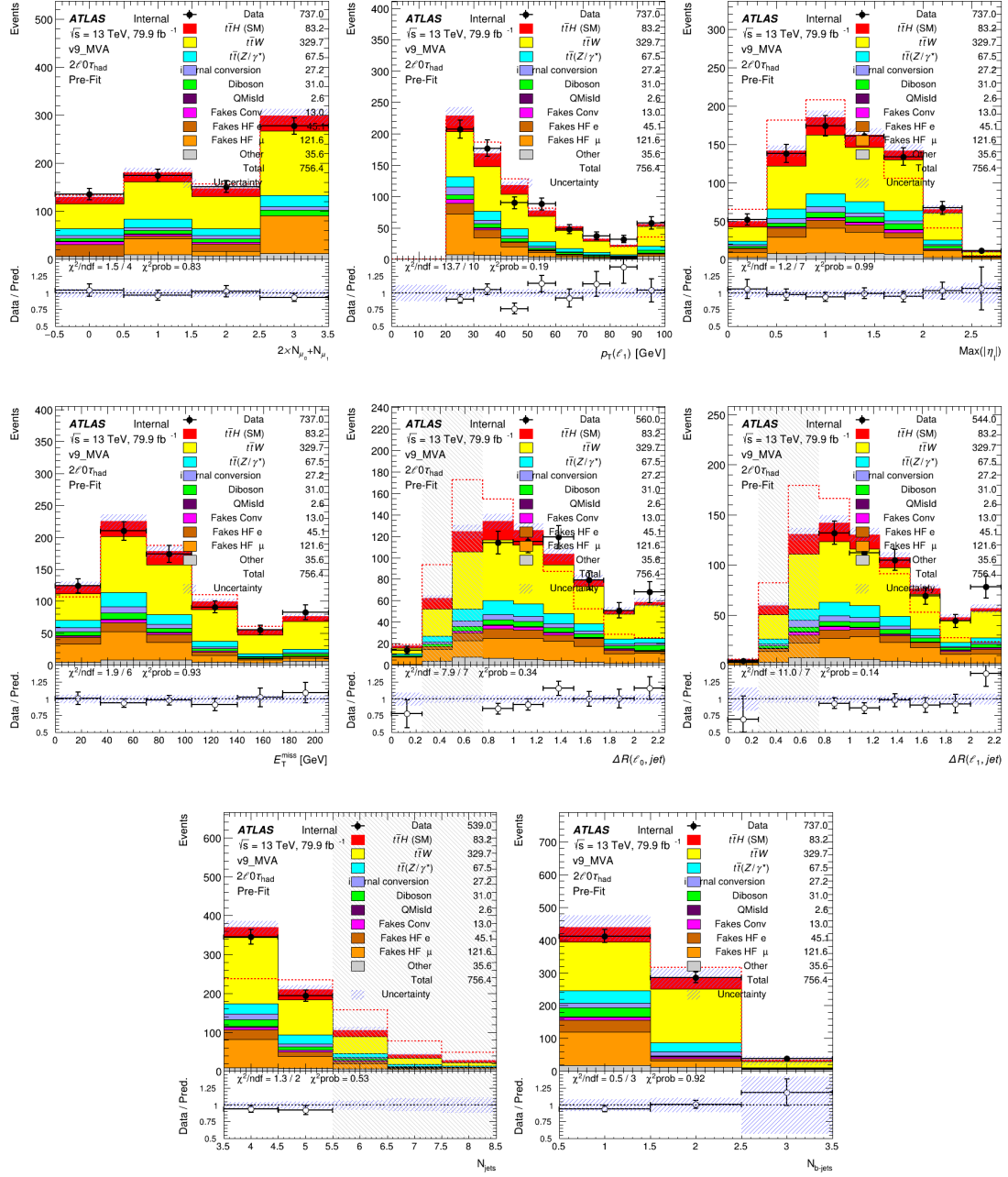


Figure 3.15. – Modelling of the other eight input variables for BDTG in the very tight region. Fake background is estimated by the TF. Data in the bins with signal purity larger than 15% are blinded due to the NFs used in fake estimation for modelling checks have not been approved by ATLAS.

The matrices of correlations are shown in Figure 3.16. Large correlations only observed between $M_{\ell_0\ell_1}$ and $p_T(\ell_1)$ without surprise. Figure 3.17 and 3.18 show the

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separation power between $t\bar{t}H$ and the two types of backgrounds.

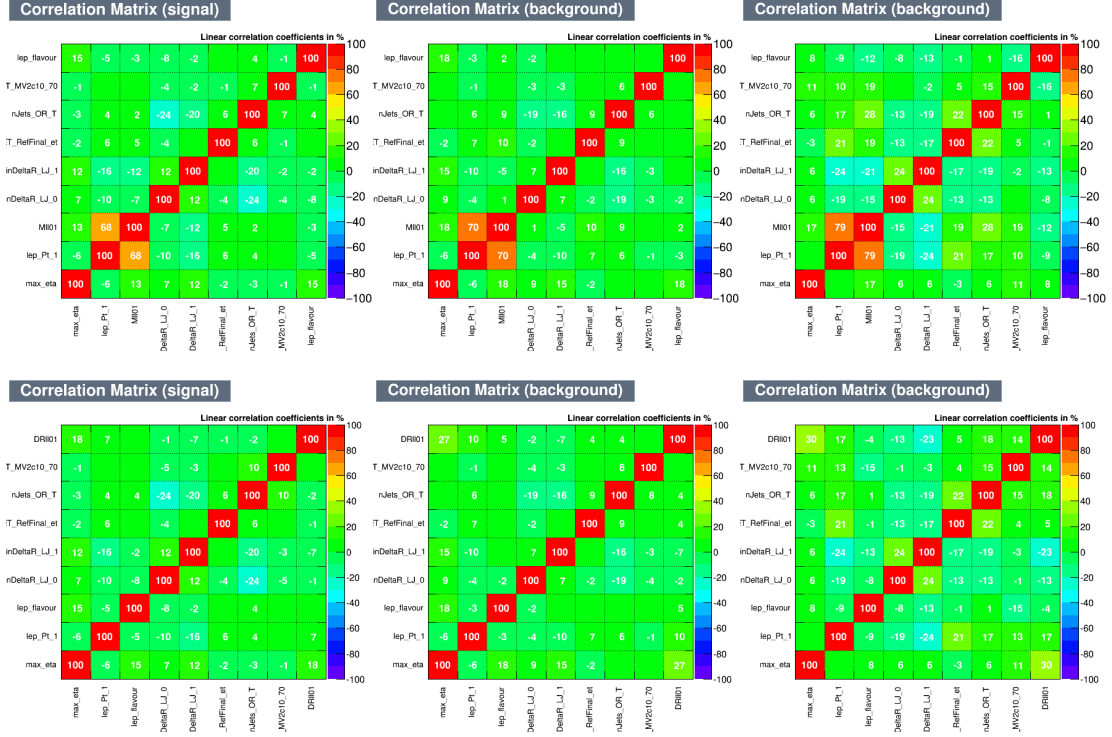


Figure 3.16. – Correlation matrices for the two cases. Correlations between the input variables including $M_{\ell_0\ell_1}$ for case 1 is shown in the upper row, while the correlations between the input variables including $\Delta R_{\ell_0\ell_1}$ for case2 is shown in the lower row. Correlations shown for $t\bar{t}H$, irreducible, and reducible backgrounds are in an order of from the left to the right.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell\text{SS}$ channel

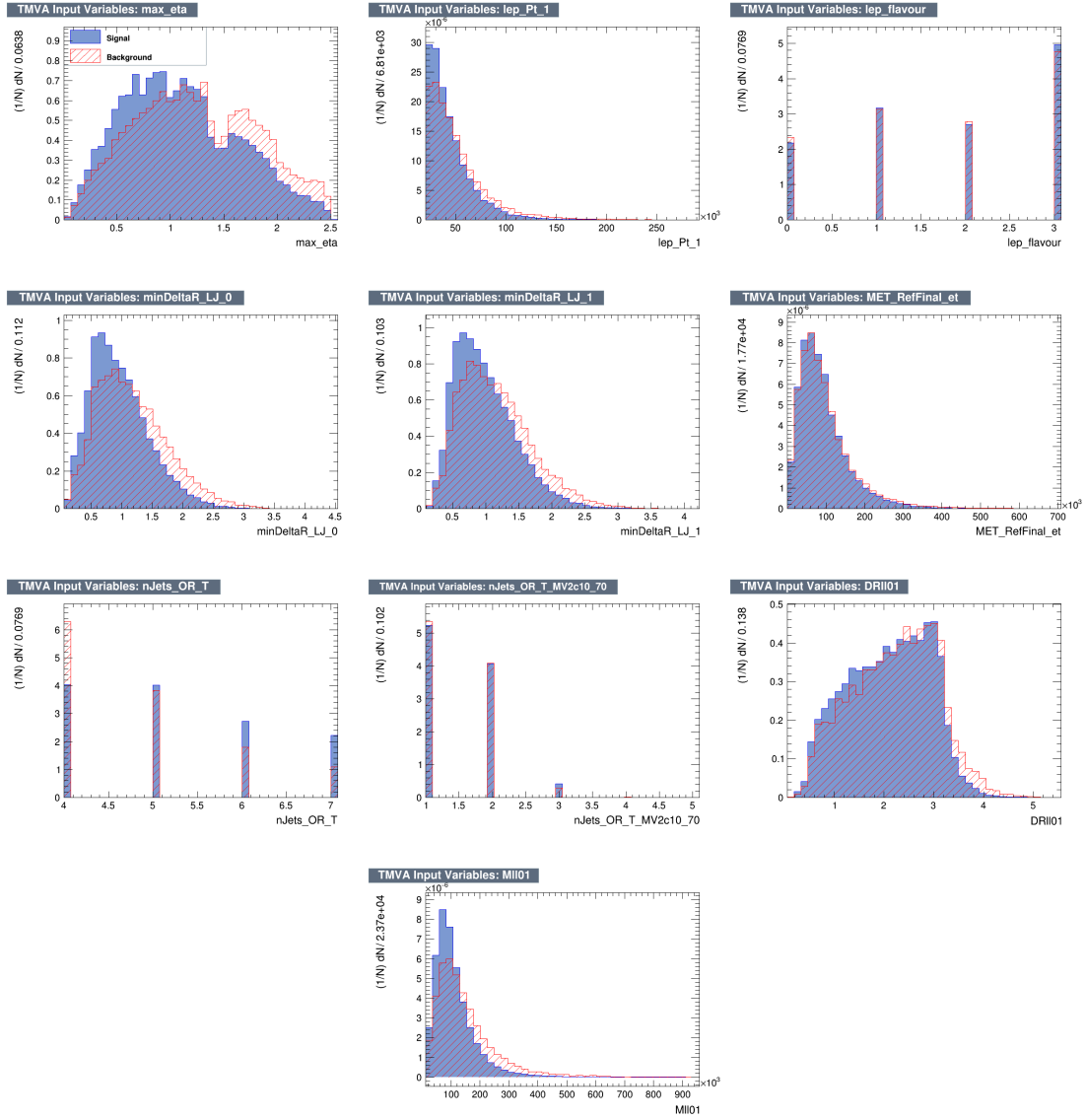


Figure 3.17. – Separation power between $t\bar{t}H$ and irreducible backgrounds. Ten variables are shown, including $M_{\ell_0\ell_1}$ and $\Delta R_{\ell_0\ell_1}$.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell\text{SS}$ channel

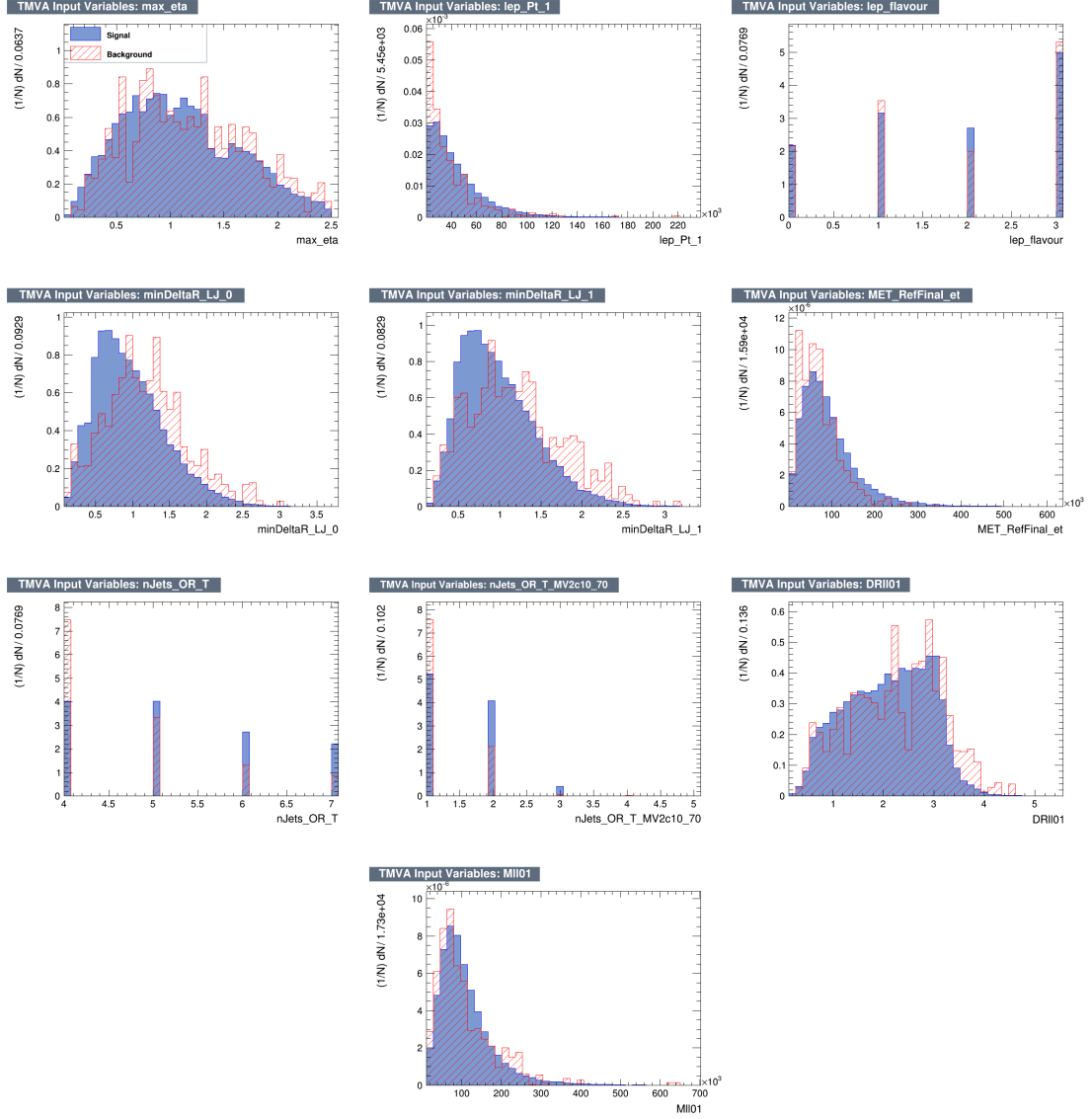


Figure 3.18. – Separation power between $t\bar{t}H$ and reducible backgrounds. Ten variables are shown, including $M_{\ell_0\ell_1}$ and $\Delta R_{\ell_0\ell_1}$.

The performances of both cases are compared in Figure 3.19 and 3.20. The overtraining test indicates no overtraining in both cases, though a lack of reducible background events is observed. The ROC (Receiver Operating Characteristic) curves are in agreement between training and testing for all cases.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell\text{SS}$ channel

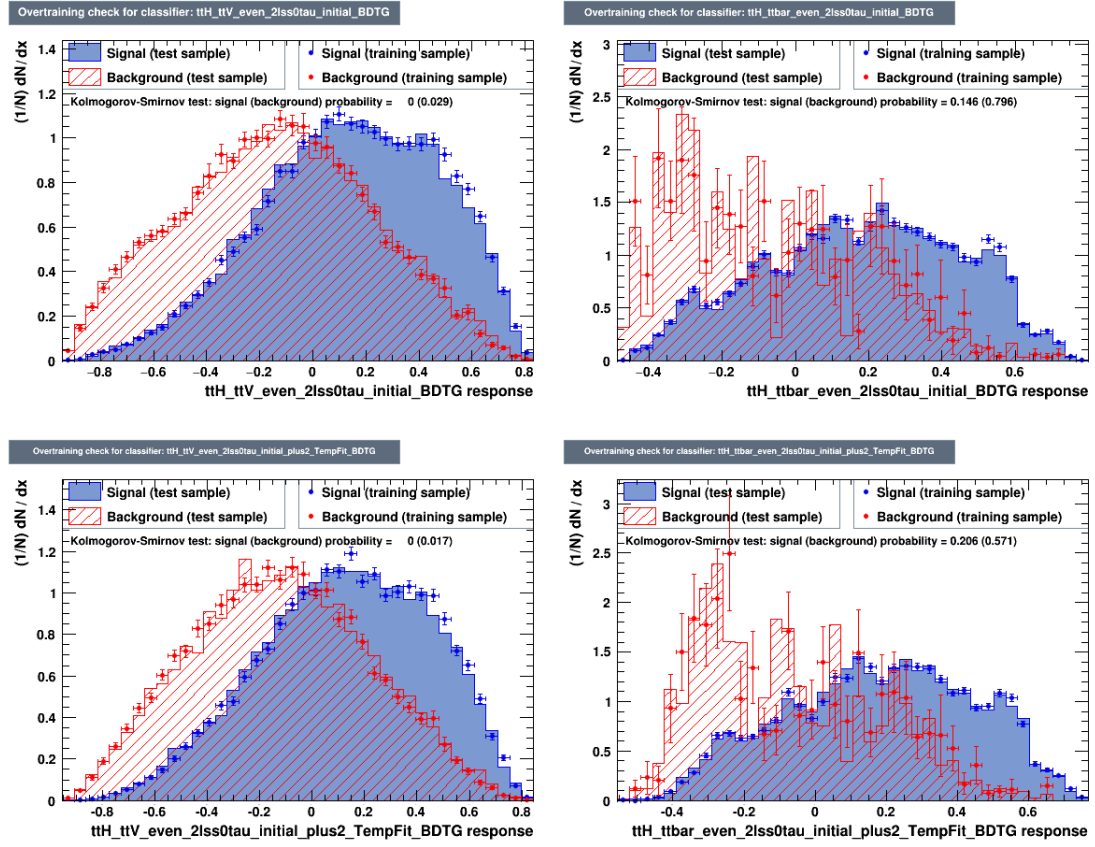


Figure 3.19. – Overtraining checks for case 1 (up) and case 2 (down). Plots in the left (right) column show the responses of the BDTG_irreducible (BDTG_-reducible).

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell\text{SS}$ channel

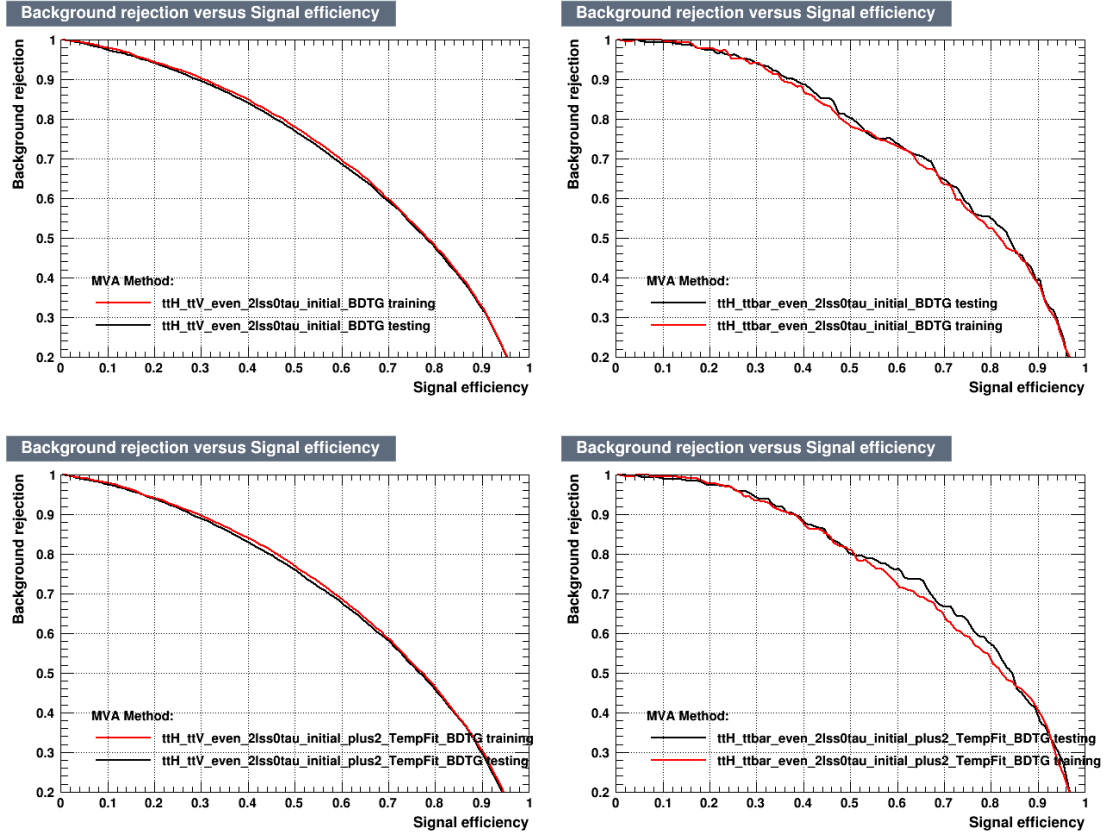


Figure 3.20. – ROC curves compared between training (red) with testing (black) for case 1 (up) and case 2 (down). Plots in the left (right) column show the ROC for BDTG_irreducible (BDTG_reducible).

A table summarised the performance of both BDTGs is shown in Table 3.14. It shows the signal efficiency at a background rejection rate of 70%. Case 1 is slightly better than case 2 in the BDT against the irreducible background, but the opposite is true in the BDT against the reducible background. In final, Case 2 is chosen because of the good modelling of its input variables.

@B=0.3	$t\bar{t}H$ vs irreducible	ttH vs reducible
case 1 (with $M_{\ell_0\ell_1}$)	0.59	0.66
case 2 (with $\Delta R_{\ell_0\ell_1}$)	0.58	0.68

Table 3.14. – Signal efficiencies at background rejection rate 70% for case1 and case2.

Unblinded distributions of the BDTG scores are shown in Figure 3.21 with NFs extracted from the template fit with all $2\ell\text{SS}$ and 3ℓ CRs (refer to Table 3.13).

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.5. Event MVA in $2\ell\text{SS}$ channel

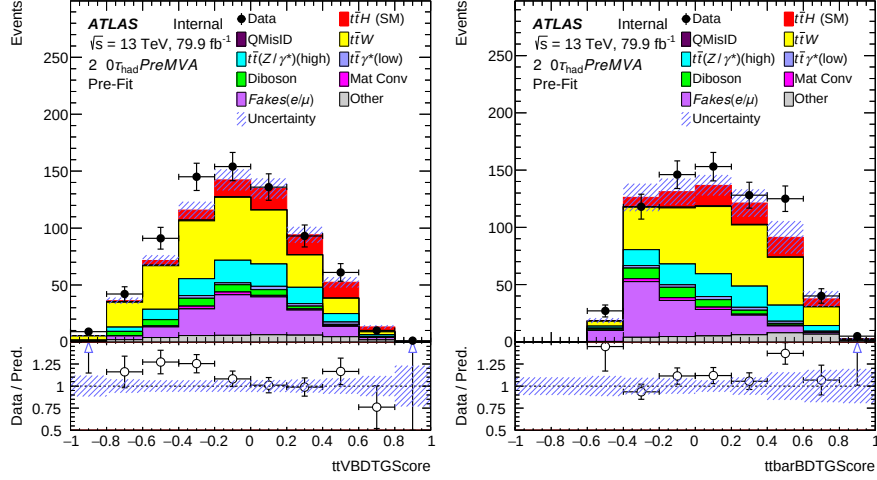


Figure 3.21. – BDTG score distributions for $t\bar{t}H$ against the irreducible background (left) and against the reducible background (right) in $2\ell\text{SS}$ high N_{jets} inclusive region. Non-prompt background is estimated by the template fit performed in all $2\ell\text{SS}$ and 3ℓ CRs.

3.5.5. SR separation by BDTG scores

The SRs and CRs in $2\ell\text{SS}$ high N_{jets} region are separated by the BDTG scores in two dimensions. The idea is given by Figure 3.22. With $\text{BDTG_reducible} < 0$, $t\bar{t}$ CRs are established and further separated into four by the charge of lepton pairs ($++/-$) and subleading lepton flavour ($ee + \mu e / \mu\mu + e\mu$). The SRs and $t\bar{t}W$ CRs are both satisfied with $\text{BDTG_reducible} > 0$ and separated by the BDTG_irreducible score above or below 0. The SRs and $t\bar{t}W$ CRs are further divided into two by the lepton pair charges ($++/-$). As a result, eight regions have been set in $2\ell\text{SS}$ high N_{jets} region. Further details are discussed in Section 3.7.5.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.6. Systematic uncertainties

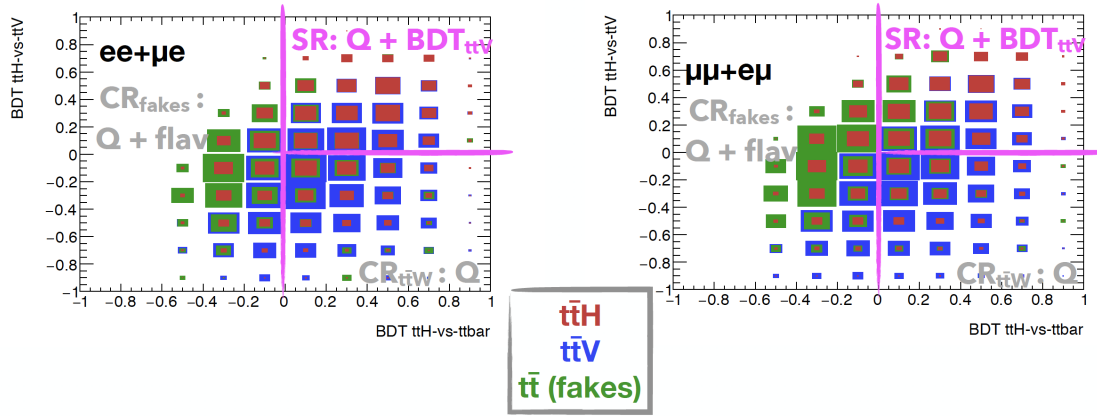


Figure 3.22. – Distributions of $t\bar{t}H$ (red box) compared to $t\bar{t}V$ (blue box) and fake (green box) backgrounds in a 2D BDT distribution. Q represents charge and flav represents lepton flavors.

Figure 3.23 shows the discriminant power of $t\bar{t}H$ against the MC estimated QMisID background for the 2D BDT, which indicates the BDTs also have a discriminant between $t\bar{t}H$ and QMisID events.

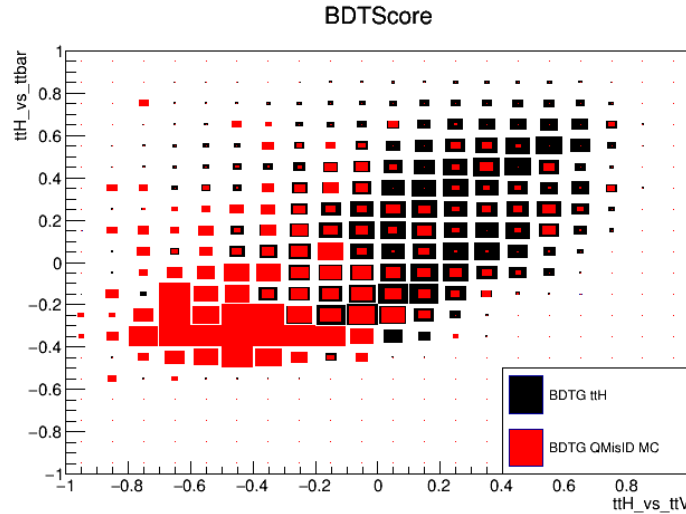


Figure 3.23. – Distributions of $t\bar{t}H$ signal (red box) compared to MC QMisID events (black box) in a 2D BDT distribution.

3.6. Systematic uncertainties

The systematic uncertainties are summarised in the Table 3.15 shown below. Experimental uncertainties related to the trigger efficiency, lepton reconstruction and

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.6. Systematic uncertainties

Systematic uncertainty	Components	Systematic uncertainty	Components
Luminosity (normalisation-only)	1	Cross section (normalisation-only)	27
Pileup modelling	1	$t\bar{t}H$ modelling	
Physics objects		Renormalisation and factorisation scales	3
Electron	8	Parton shower and hadronisation model	1
Muon	11	Higgs boson branching ratio	4
Tau	7	Shower tune	1
Jet energy scale and resolution	28	PDF	32
Jet vertex fraction	1	$t\bar{t}W$ modelling	
Jet flavour tagging	17	Renormalisation and factorisation scales	1
E_T^{miss}	3	Generator	1
Total (Experimental)	77	PDF	32
Data-driven background estimates		Extrapolation	4
Non-prompt light-lepton estimates ($3\ell, 3\ell + 1\tau_{had}$)	1	$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	
Fake τ_{had} estimates	6	Generator	1
Electron charge misassignment	2	Renormalisation and factorisation scales	3
Total (Data-driven reducible background)	9	Shower tune	1
Template fit uncertainties		$t\bar{t}$ modelling	
Material conversions	1	Radiation	1
Internal conversions	1	Z+jets modelling	
HF non-prompt leptons	18	Generator	1
LF non-prompt leptons	2	Total (Signal and background modelling)	113
Total (Template fit)	22	Total (Overall)	211

Table 3.15. – Sources of systematic uncertainty considered in the analysis.

identification, jet calibration, continuous b-tagging, and the global event activity are evaluated by the ATLAS performance groups as an overall event reweighting or a rescaling of the object energy and momentum. Efficiency associated uncertainties for lepton isolation and trigger working point calibrations are described in Section 3.3.3. The uncertainty in the combined 2015-2017 integrated luminosity is 2.0%, derived from a calibration of the luminosity [35].

Systematic uncertainties on non-prompt sources are derived from the shape differences between MC fake templates and data. These systematics are correlated in signal regions and control regions. Shape uncertainties assigned on the lepton associated with heavy flavour decays are distributed in dimensions of 2ℓ SS and 3ℓ BDT scores, HT_{lep} , and $\Delta R_{\ell_0\ell_1}$. Due to the light flavour decays are combined with the heavy flavour, a relative uncertainty is set on the light flavour fake background as 100%, conservatively. The systematic uncertainty on QMisID is a total of four sources considering the variation of Z mass window, statistical size of the control region, rate asymmetry between electron and positron, and the difference between rate measured by likelihood method and truth matching with $Z \rightarrow ee$ events.

Theoretical systematic uncertainties on cross section [6] and acceptance modelling for each process are assessed in all categories. The cross section uncertainties are evaluated by varying the cross section of each process within their uncertainty. The modelling uncertainties are evaluated by comparing samples to the ones simulated by alternative generators. Branching ratio uncertainties for Higgs are considered for $t\bar{t}H$, $tHjb$, and WtH processes using the values recorded in [6]. Variations of renormalisation and factorisation scales (varRF) are introduced to $t\bar{t}H$, $t\bar{t}W$, and $t\bar{t}(Z/\gamma^*)$ (high mass) processes. Parton shower (PS), radiation, generator, and tuning

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.6. Systematic uncertainties

systematics are constructed for signal and main backgrounds to cover the modelling variations. The $t\bar{t}W$ extrapolation uncertainties will be discussed in Section 3.7.3.3. The PDF uncertainties are correlated between the $t\bar{t}H$ signal and $t\bar{t}W$ background. Detailed discussions are followed in the next section.

3.6.1. The PDF uncertainty

For the sake of changing $t\bar{t}H$ and $t\bar{t}W$ samples from MG5_AMC [58] +PYTHIA 8 (0j@NLO) [52] to LO multileg SHERPA (0,1,2j@LO) [56], additional sets of PDF weights [61, 62] and uncertainties have been calculated using the NNPDF3.0 pdfset with a tool of LHAPDF6 [123, 124].

The event weights are calculated according to the function

$$w = \frac{PDF(x1, f1, Q) \times PDF(x2, f2, Q)}{PDF_{\text{nominal}}(x1, f1, Q) \times PDF_{\text{nominal}}(x2, f2, Q)}, \quad (3.4)$$

where $x1, x2$ are the Bjorken x for the incoming partons, $f1$ and $f2$ are the PDF functions, Q^2 is the factorisation scale. The calculation uses a pdfset of PDF4LHC15_nlo_30_pdfas for $t\bar{t}W$ and PDF4LHC15_nlo_30_pdfas for $t\bar{t}H$. There are 33 nominal+variations in each pdfset. The $X0$, as the nominal, is the mean of all variations from $X1$ to $X32$. A common value of $\alpha_s(m_Z^2) = 0.118$ has been used in eigensets $X1$ to $X30$, while the values of 0.1165 and 0.1195 are considered in $X31$ and $X32$.

The uncertainty estimation for the PDF is calculated by

$$\Delta X = \sqrt{\frac{1}{N} \sum_i (X_i - X0)^2}, \quad (3.5)$$

which gives the standard deviation of the NNPDF set. The denominator N here refers to the number of variations in the pdfset. The whole set of the PDF uncertainties has been considered in the simultaneous fit. Figure 3.24 shows an example of the effect of one PDF eigen on the $t\bar{t}W$ event yields in all regions.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

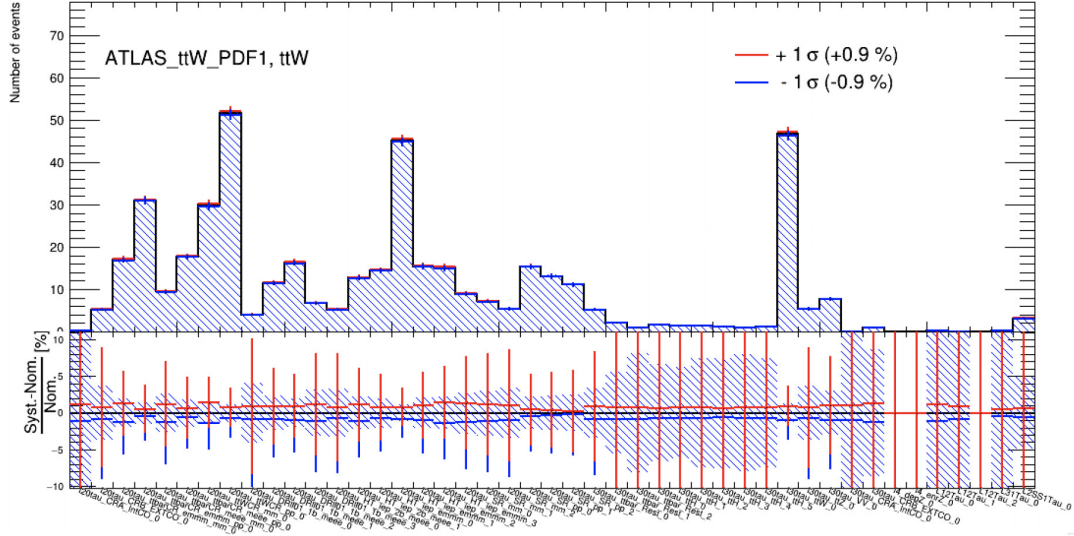


Figure 3.24. – Example of the effect of one PDF eigen on the $t\bar{t}W$ event yields in all regions.

3.7. Statistical analysis

A simultaneous fit has been performed to derive the significance for the $t\bar{t}H$ productions in multilepton final states in all signal regions and control regions. The analysis hired a framework of TRexFitter to generate the workspace for the profiled likelihood fit. The parameter of interest (POI) in the fit is the signal strength

$$\mu_{t\bar{t}H} = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}. \quad (3.6)$$

The nuisance parameters (NP), as normalisation factors and uncertainties, are constrained by the fit model.

3.7.1. Likelihood function

The likelihood $\mathcal{L}(\mu, \theta)$ is a function of the POI (μ) and sets of NPs [125, 126]. A likelihood function contains two Poisson terms for event numbers in bins of SRs and CRs, and a Gaussian term represents the systematic uncertainties, as follows:

$$\begin{aligned} \mathcal{L} &= P_{SR} \times P_{CR} \times C_{syst} \\ &= \prod_{i=1}^{N_{SR}} \prod_{j=1}^{N_{bins}} P(n_{SR}^{ij} | \lambda_{SR}(\mu_{sig}, \vec{b}, \vec{\theta})) \times \prod_{i=1}^{N_{CR}} \prod_{j=1}^{N_{bins}} P(n_{CR}^{ij} | \lambda_{CR}(\mu_{sig}, \vec{b}, \vec{\theta})) \times \prod_{k=1}^{N_{\theta}} G(\theta_j). \end{aligned} \quad (3.7)$$

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

The $n_{SR,CR}^{ij}$ represents the number of events in signal regions and control regions, while the indices i, j are the numbers of SRs (CRs) and bins in each region. The function $\lambda_{SR,CR}$ represents the expectation event yield in an SR (CR), which can be further written as

$$\lambda_{SR,CR}(\mu_{sig}, \vec{b}, \vec{\theta}) = \mu_{sig} n_{sig}^{ij}(\vec{\theta}) + n_{bkg}^{ij}(\vec{\theta}, \vec{b}), \quad (3.8)$$

where the parameter $\vec{b} = \Sigma_i b_i$ denotes the background normalisation factors and $\vec{\theta} = \theta_1, \dots, \theta_N$ are the nuisance parameters representing the systematic uncertainties.

3.7.2. Hypothesis testing

A hypothesis should be set before the analysis. The common hypotheses used in the analysis [125, 126] are:

- A background-only hypothesis for new resonance discovery requires $\mu = 0$.
- A signal and background hypothesis for limit setting corresponds to $\mu > 0$.
- A special hypothesis with background plus signal present at the SM rate matches to $\mu = 1$.

To test a hypothesis, a profile likelihood has been constructed as

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}. \quad (3.9)$$

The numerator is maximized with μ at a hypothesized value, and thus the value of $\hat{\hat{\theta}}$ is decided by the conditional-fit. The $\hat{\hat{\theta}}$ here is referred to as a conditional maximum-likelihood estimator (MLE). In the denominator, an unconditional-fit has been performed to reach a maximum value. Both $\hat{\mu}$ and $\hat{\theta}$ are MLEs.

To better evaluate the hypothesized value of μ , a quantity is defined as

$$q_\mu = -2\ln\lambda(\mu). \quad (3.10)$$

A poor agreement between the data and the hypothesized μ would lead to a high value of q_μ . The $f(q_\mu|\mu')$ is the sampling distribution of q_μ , and μ' is the value used to define the data generated to obtain the distribution. For $\mu' \neq \mu$, the distribution $f(q_\mu|\mu')$ shifts to higher values, which indicates an incompatibility between the data and the hypothesis tested by q_μ . When it comes to $\mu' = \mu$, the pdf $f(q_\mu|\mu)$ approaches a distribution of χ^2 [127].

The p -value, defined as

$$p_\mu = \int_{q_{\mu,obs}}^{\infty} f(q_\mu|\mu) dq_\mu, \quad (3.11)$$

quantifies the compatibility between data and a hypothesized value of μ . The observed value $q_{\mu,obs}$ is obtained from data for q_μ , under the assumption of μ .

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Hypothesis for discovery A hypothesis with $\mu = 0$ is established and then rejected while aiming for a discovery. The p -value for the no-signal hypothesis is

$$p_0 = \int_{q_{0,obs}}^{\infty} f(q_0|0) dq_0, \quad (3.12)$$

with an observed value $q_{0,obs}$. A small value is interpreted as evidence against $\mu = 0$. The significance is defined as the number of standard deviations corresponding to a given p -value:

$$\Phi(Z) = 1 - p, \quad (3.13)$$

where Φ is the cumulative distribution for the standard Gaussian. A significance of $Z = 5$ corresponds to $p = 2.87 \times 10^{-7}$. However, the Higgs group is using a two-sided fluctuation of a Gaussian variable, where the 5σ significance corresponds to a p -value at 5.7×10^{-7} .

Hypothesis for limit setting An alternative hypothesis with $\mu > 0$ is established for limit setting and an attempt is made to reject it. The p -values are computed for different μ , and the set of μ with a p -value above a fixed value 1-CL (confidence level) forms a confidence interval. The upper end of this interval μ_{up} is the upper limit. A typical value for the confidence level used in the analysis is 95%.

The circumstance of $\hat{\mu} > \mu$ is not considered in limit setting for the sake of the data with $\hat{\mu} > \mu$ are less considered in finding the smallest μ_{up} . Therefore the q_μ defined in a limit setting is

$$q_\mu = \begin{cases} -2\ln\lambda(\mu) & \hat{\mu} \leq \mu, \\ 0 & \hat{\mu} > \mu. \end{cases} \quad (3.14)$$

For the case $\hat{\mu} \leq \mu$, q_μ no longer approaches a χ^2 distribution. It falls off more steeply and can be described by

$$f(q_\mu|\mu) = w f_{\chi_1^2}(q_\mu) + (1 - w)\delta(q_\mu), \quad (3.15)$$

if it comes with a large enough μ and $\hat{\mu} > 0$. The value of w is often considered as 0.5. Therefore a half χ^2 distribution is superimposed to the $f(q_\mu|\mu)$, as the study shows in Section 5.6.4.

Two hypotheses, B-only and S+B, are considered in a special procedure to prevent spurious exclusion when there is a downward fluctuation in data, which is referred to as the CL_s method [125]. The corresponding p -values are written as

$$p_{s+b} = \int_{q_{obs}}^{\infty} f(q|s+b) dq \equiv \text{CL}_{s+b}, \quad (3.16)$$

$$p_b = \int_{-\infty}^{q_{obs}} f(q|b) dq \equiv 1 - \text{CL}_b. \quad (3.17)$$

The exclusion μ is set on the ratio

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b} = \frac{p_{s+b}}{1 - p_b}, \quad (3.18)$$

rather than on the p -value for S+B hypothesis only. The S+B hypothesis is excluded when $\text{CL}_s < 0.05$ in the CL_s method. Since $\text{CL}_s \geq \text{CL}_{s+b}$, the μ space region excluded by CL_s is not as large as on the p -value for S+B hypothesis. If the hypothesis $\mu = 1$ has been rejected at $\text{CL}=95\%$, the corresponding signal is regarded as excluded.

3.7.3. $t\bar{t}W$ modelling

As the agreement between data and MC is not as good as expected in $t\bar{t}W$ CRs, the $t\bar{t}W$ background is believed as mismodelled. Steps are taken to minimize the dependence of the $t\bar{t}H$ signal extraction on the $t\bar{t}W$ prediction:

- Normalising the current $t\bar{t}W$ sample to a level of $t\bar{t}W$ +1-jet at NLO by scaling a theoretical correction at ~ 1.2 .
- Decorrelating the free-float $t\bar{t}W$ normalisation factors in $2\ell\text{SS}$ low N_{jets} , high N_{jets} , and 3ℓ regions.
- Constructing $t\bar{t}W$ extrapolation uncertainties to absorb the tension.

3.7.3.1. $t\bar{t}W$ correction factors

The nominal $t\bar{t}W$ sample is generated with a cross section of $601 \pm 76 \text{ fb}$, computed at NLO QCD with the leading NLO electroweak corrections. A previous work [58] shows the NLO QCD corrections to $t\bar{t}W$ +1-jet is larger than what we are using. A factor of 1.11 has been considered for this correction estimated from a SHERPA 2.2.5 generator [56] using the MEPS@NLO [107–110] prescription simulation cross-checked with MADGRAPH5_AMC@NLO 2.2.1 [58] using the FxFx [128] prescription. Another correction concerning an NLO_3 term driven by the $t\bar{t}W$ +1-jet diagrams with a t-channel Higgs [129]. Starting from the NLO_2 , an electroweak correction of 1.09 is considered. Thus a normalisation factor of 1.2 combining the two correction factors has been applied. The corresponding cross section is $727 \pm 92 \text{ fb}$.

3.7.3.2. $t\bar{t}W$ free-floating normalisation factors

Three normalisation factors are assigned to $t\bar{t}W$ background in the likelihood fit, instead of one in the old model as used in the template fit. Three decorrelated $t\bar{t}W$ normalisation factors are introduced into the $2\ell\text{SS}$ low N_{jets} , high N_{jets} regions, and 3ℓ channel because we do not trust the N_{jets} shape estimated by MC. The new fit model enables a better data/MC agreement as well as relieves the tension between low and high N_{jets} regions. Post-fit data/MC comparison plots between fit with one $t\bar{t}W$ NF and three $t\bar{t}W$ NFs are shown in Figure 3.25.

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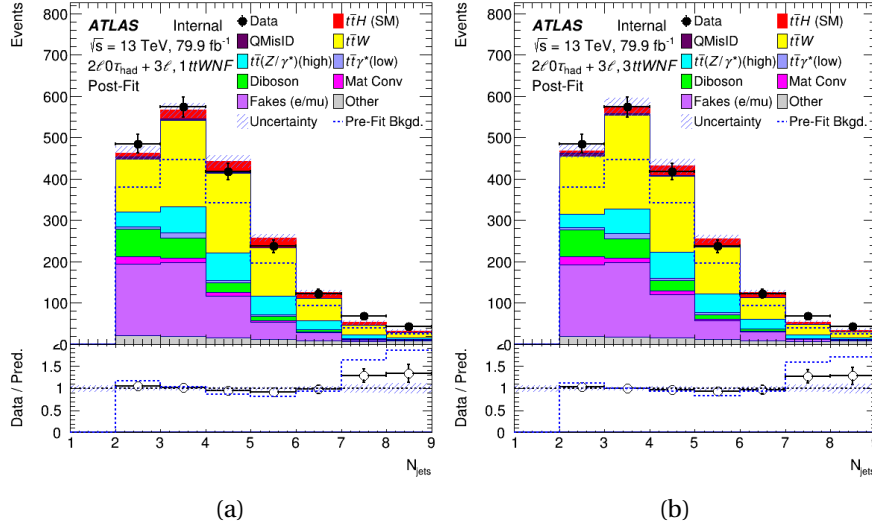


Figure 3.25. – Post-fit data/MC comparisons between fit with 1 $t\bar{t}W$ NF (a) and 3 $t\bar{t}W$ NFs (b) [5].

3.7.3.3. $t\bar{t}W$ modelling uncertainties

Additional extrapolation uncertainties are also considered to reduce the tension of $t\bar{t}W$ without pulling nuisance parameters. The major tensions between data and MC are from the charge asymmetry and b-jet multiplicity disagreement.

The uncertainties are calculated from the differences between the data and MC in corresponding bins. They are applied in $2\ell\text{SS}$ and 3ℓ channels. The size of the uncertainties are derived from

$$1\sigma = \frac{\text{data} - MC_{\text{non-}t\bar{t}W}}{2MC_{t\bar{t}W}}. \quad (3.19)$$

The extrapolation uncertainties affect only the shape. The final uncertainty associated with b-jet multiplicity is $\pm 25\%$ ($\mp 35\%$) for events with $N_{b\text{-jets}} = 1$ (≥ 2), while the uncertainty associated with charge is $\pm 20\%$ ($\mp 35\%$) for events with positive (negative) charge. The systematic shapes are shown in Figure 3.26.

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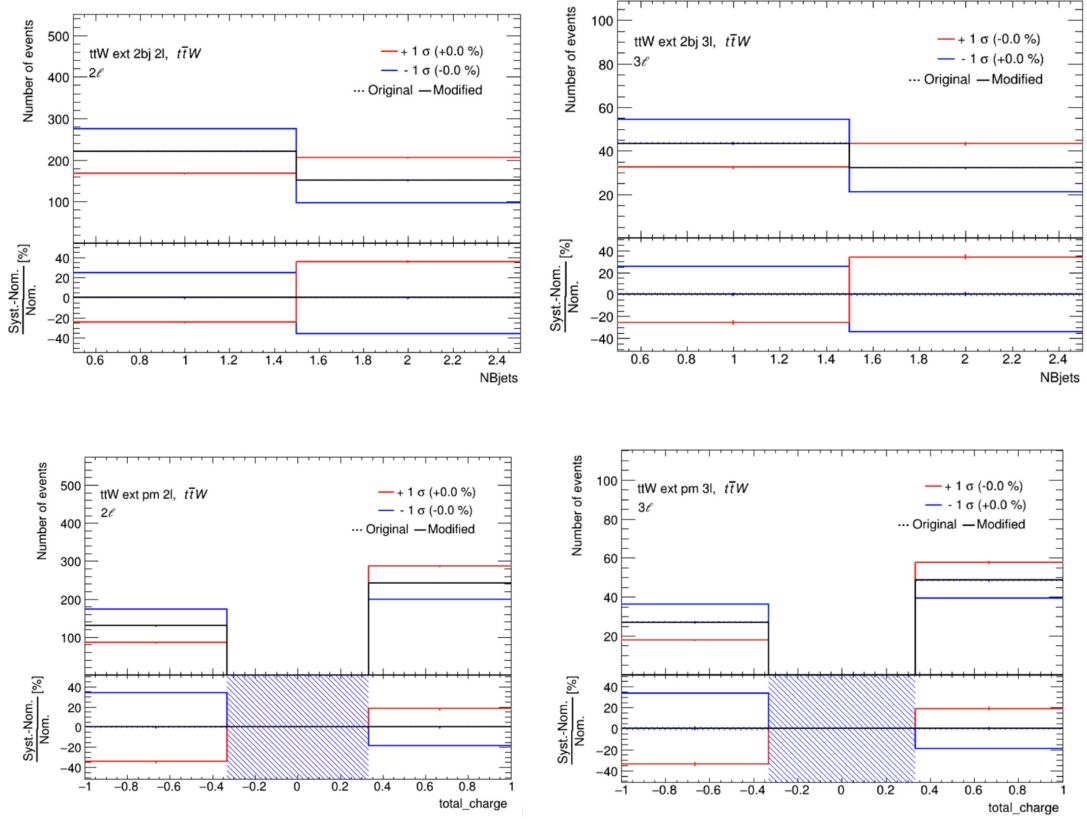


Figure 3.26. – Extrapolation systematic uncertainties on b-jet multiplicity (up) and total charge (down) in 2ℓ SS (left) and 3ℓ (right).

With these shape uncertainties, some of the NPs are relieved from ~ 1 sigma pulling. They also reduce the tension in the fit. The absolute value of negative likelihood (NLL) function with the additional extrapolation uncertainties has decreased to 7299.6438 from 7301.096989. The post-fit data/MC comparisons are displayed in Figure 3.27 for with or without the additional extrapolation uncertainties in 2ℓ SS channel and 3ℓ channel.

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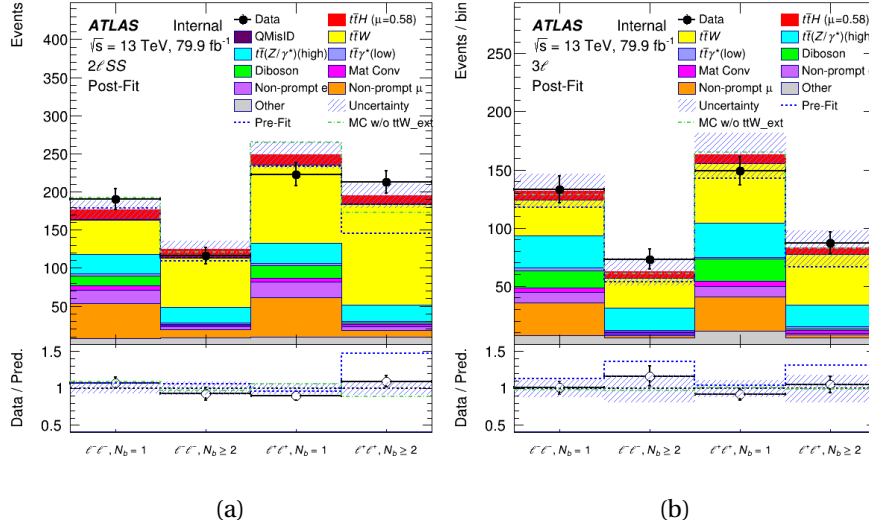


Figure 3.27. – Post-fit data/MC comparisons in $2\ell\text{SS}$ channel (a) and 3ℓ channel (b). Bins are separated by $N_{b\text{-jets}}$ and lepton charges. The pre-fit MC is shown as a dashed blue histogram, and the post-fit MC without $t\bar{t}W$ extrapolation uncertainties are shown as a dashed green histogram.

3.7.3.4. Fit results compared between old and new models

The fit results comparisons have been made between the old fit model:

- with no action on $t\bar{t}W$ modelling;
- with only one $t\bar{t}W$ normalisation factor,

and the new fit model:

- with $t\bar{t}W$ +1-jet QCD+EWK correction (1.2);
- with $t\bar{t}W$ NFs free-floating in low and high N_{jets} $2\ell\text{SS}$ and 3ℓ channels independently;
- with $t\bar{t}W$ extrapolation systematic uncertainties.

The fitted signal strength and normalisation factors are shown in Figure 3.28. The pulls and constraints are also checked between the two cases. Fewer nuisance parameters are pulled in the new fit model, which indicates the tensions are relieved in different dimensions in the fit.

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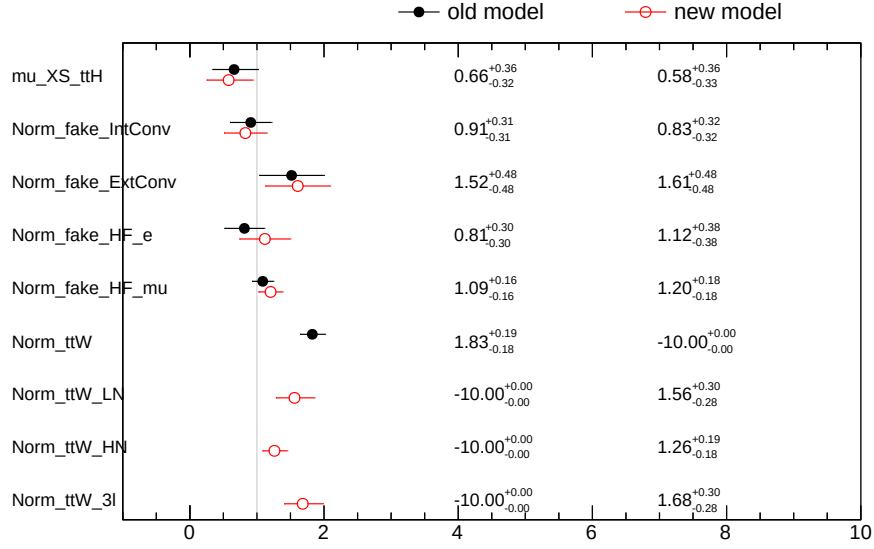


Figure 3.28. – Normalisation factors compared between the old fit model (with no $t\bar{t}W$ +1-jet QCD+EWK correction, only one $t\bar{t}W$ NF, and no extrapolation systematics) and new fit model (with $t\bar{t}W$ +1-jet QCD+EWK correction, $t\bar{t}W$ free-floating in 2ℓ SS and 3ℓ independently, and extrapolation systematics).

3.7.4. $t\bar{t}Z$ modelling

The modelling of $t\bar{t}Z$ background has been checked by free-floating the $t\bar{t}Z$ normalisation factor in 2ℓ SS, 3ℓ , and 4ℓ channels. The study is motivated by the mismodelling observed in $t\bar{t}W$ samples. Three options have been considered in this study:

- Option 1: Default setup in 2ℓ SS and 3ℓ with no dedicated $t\bar{t}Z$ CRs
- Option 2: Default+two 3ℓ Z-peak CRs
- Option 3: Default+two 3ℓ Z-peak CRs+ 4ℓ low BDT Z-enriched region

The first option is close to the template fit setups but includes the 2ℓ SS high N_{jets} regions and 3ℓ regions, with $t\bar{t}Z$ NF free-floating. Figure 3.29 summarises the regions used in this option. The addition $t\bar{t}Z$ dedicated CRs in option 2 and option 3 are shown in Figure 3.30. The 3ℓ low N_{jets} region refers to the Z-peak region with $N_{\text{jets}} = 3, 4, 5$, while the high N_{jets} region refers to a Z-peak region with $N_{\text{jets}} \geq 6$. All these $t\bar{t}Z$ dedicated CRs are with a purity above 50%. The limited statistic in the 4ℓ Z-enriched region leads to a minor impact on the results.

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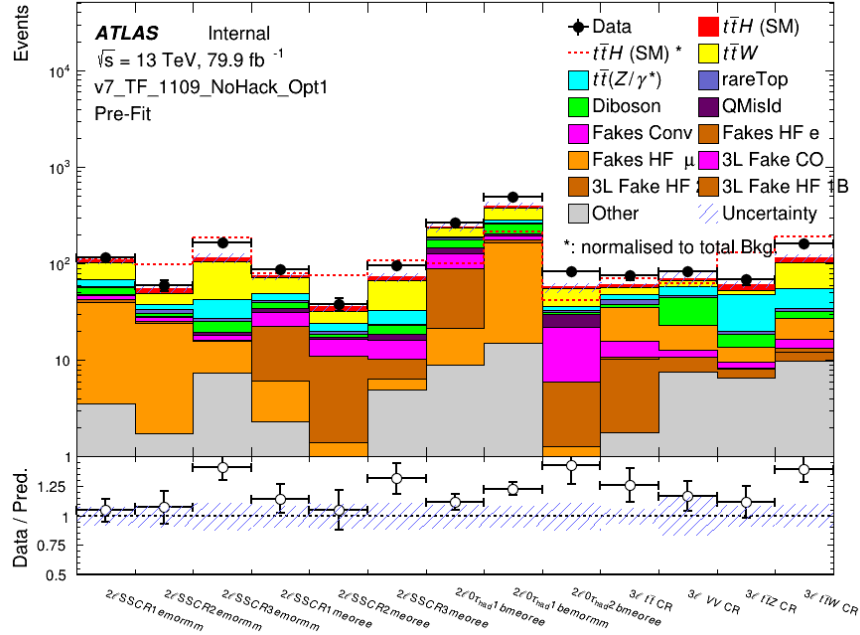


Figure 3.29. – Pre-fit data/MC comparisons in $2\ell\text{SS}$ channel and 3ℓ channel for the $t\bar{t}Z$ free-floating fit option 1.

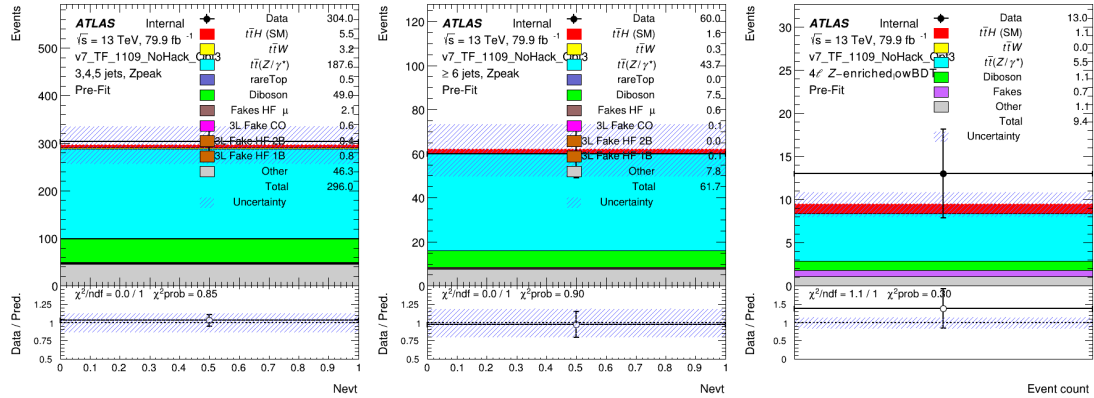


Figure 3.30. – Pre-fit data/MC comparisons in 3ℓ Z-peak low N_{jets} region (left) and 3ℓ Z-peak high N_{jets} region (middle) for option 2 and 3, 4ℓ low BDT Z-enriched region (right) for option 3.

The post-fit summary plots for the three options are shown in Figure 3.31, and the corresponding fitted normalisation factors and significance for $t\bar{t}Z$ measurement are summarised in Table 3.16. Good data and MC agreements have been observed among

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all the three options. The best-fitted NF values on fake background sources are hardly affected by free-floating $t\bar{t}Z$. An anti-correlation has been observed between $NF_{t\bar{t}W}$ and $NF_{t\bar{t}Z}$.

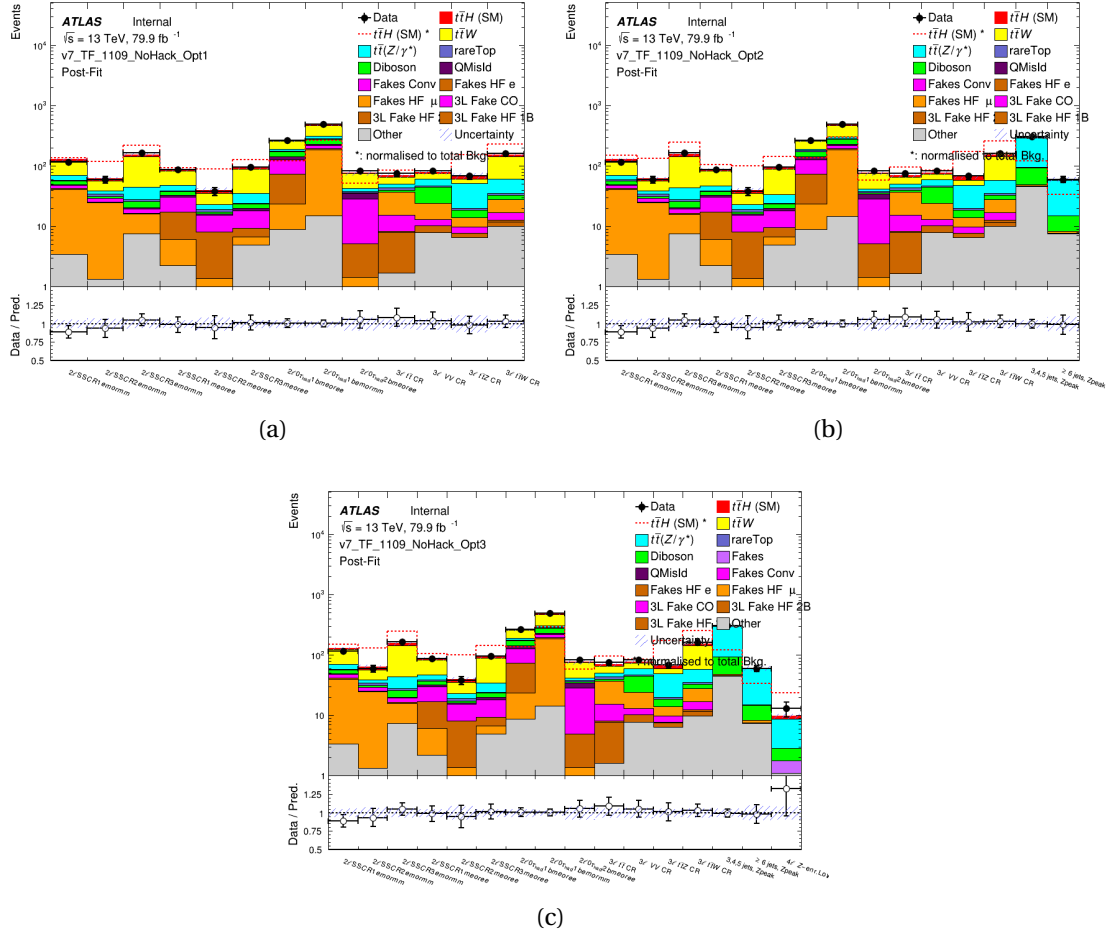


Figure 3.31. – Post-fit data/MC comparisons for option 1 (a), option 2 (b), and option 3 (c).

	NF_{μ}^{HF}	NF_e^{HF}	NF_e^{CO}	$NF_{t\bar{t}W}$	$NF_{t\bar{t}Z}$	$Z(t\bar{t}Z)$
$2lSS+3l \ t\bar{t}Z$ fixed	1.08 ± 0.17	0.70 ± 0.37	1.42 ± 0.56	1.63 ± 0.30	1 ± 0.00	–
Opt1: $2lSS+3l \ t\bar{t}Z$ floating	1.08 ± 0.17	0.73 ± 0.38	1.43 ± 0.57	1.60 ± 0.30	1.18 ± 0.40	3.49
Opt2: $2lSS+3l + 3l \ (Z\text{-peak})$	1.08 ± 0.17	0.73 ± 0.38	1.42 ± 0.57	1.64 ± 0.29	1.04 ± 0.20	5.75
Opt3: $2lSS+3l + 3l \ (Z\text{-peak})$ + $4l \ (Z\text{-enriched})$	1.08 ± 0.17	0.72 ± 0.38	1.42 ± 0.57	1.63 ± 0.29	1.06 ± 0.20	5.88

Table 3.16. – Summary of best-fitted NFs and measured $t\bar{t}Z$ significance in 3 options.

Option 3 gives the most accurate fit result for $t\bar{t}Z$ NF measurement. The best-fitted

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$NF_{t\bar{t}Z}$ is at $1.06^{+0.20}_{-0.20}$ and the measured $t\bar{t}Z$ significance is at 5.88. The result shows the $t\bar{t}Z$ cross section measured in this study is consistent with the SM prediction, and the NF on $t\bar{t}Z$ has a minimal impact on the measurement of $t\bar{t}H$. As a conclusion of this test, $t\bar{t}Z$ is fixed at the SM predicted value in the $t\bar{t}H$ measurement.

3.7.5. Fit categorisation

In total, twenty-five event categories in six channels defined by their final states are involved in a maximum-likelihood fit. Seventeen of them are used as control regions to constrain the backgrounds, including $t\bar{t}W$, $t\bar{t}Z$, VV , and $t\bar{t}$ with non-prompt leptons (heavy/light flavor decay, internal conversion, and material conversion), and the other eight signal regions are used to measure the $t\bar{t}H$ signal strength. Region separations in 2ℓ SS and 3ℓ channels have been mentioned in template fit (Section 3.4.1.3, for 2ℓ SS low N_{jets} and 3ℓ regions) and MVA (Section 3.5.5, for high N_{jets} regions).

The signal purity in each region is shown in Figure 3.32. Due to the low statistic and high signal purity in 4ℓ Z-depleted region, the ratio of S/B there is high, while $S/\sqrt{B}$ is low. The SRs in 2ℓ SS and 3ℓ are true with the opposite. With low signal purity and high statistic, the S/B rate is low, while $S/\sqrt{B}$ is high.

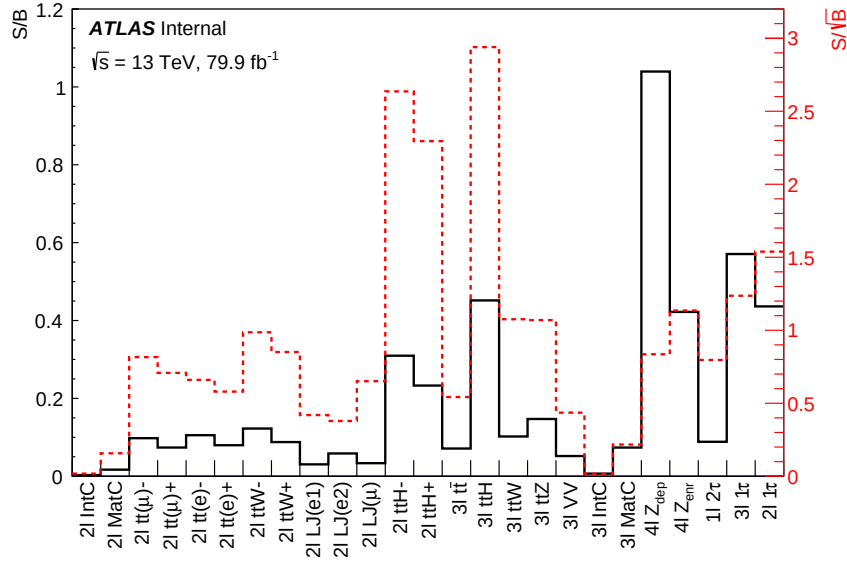


Figure 3.32. – Pre-fit S/B (black) and $S/\sqrt{B}$ ratios in each event category.

The background fractional compositions are shown in Figure 3.33. Two individual CRs for internal conversion and material conversion are established with events selected from 2ℓ SS inclusive region. Similar selection criteria have been applied in

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3ℓ channel, and thus two conversion CRs are built there, with rather low statistics. Non-prompt lepton background originated from heavy flavour decay is abundant in $2\ell\text{SS}$ low N_{jets} CR with 1 b-jet and $2\ell\text{SS}$ high N_{jets} $t\bar{t}$ CRs, both required the subleading lepton as an electron. The $2\ell\text{SS}$ low N_{jets} CR, $2\ell\text{SS}$ high N_{jets} $t\bar{t}$ CRs with subleading lepton required as a muon, and the 3ℓ $t\bar{t}$ CR, are enriched with the heavy flavour decay associate with muons. CRs with the highest rate of $t\bar{t}W$ background are $2\ell\text{SS}$ high N_{jets} $t\bar{t}W$ CRs, 3ℓ $t\bar{t}W$ CR, and $2\ell\text{SS}$ low N_{jets} CR with 2 b-jets and flavour required as $\mu e+ee$. The dominant background in $2\ell\text{SS}$ $t\bar{t}H$ signal regions is $t\bar{t}W$, while in 3ℓ $t\bar{t}H$ signal region is $t\bar{t}Z$.

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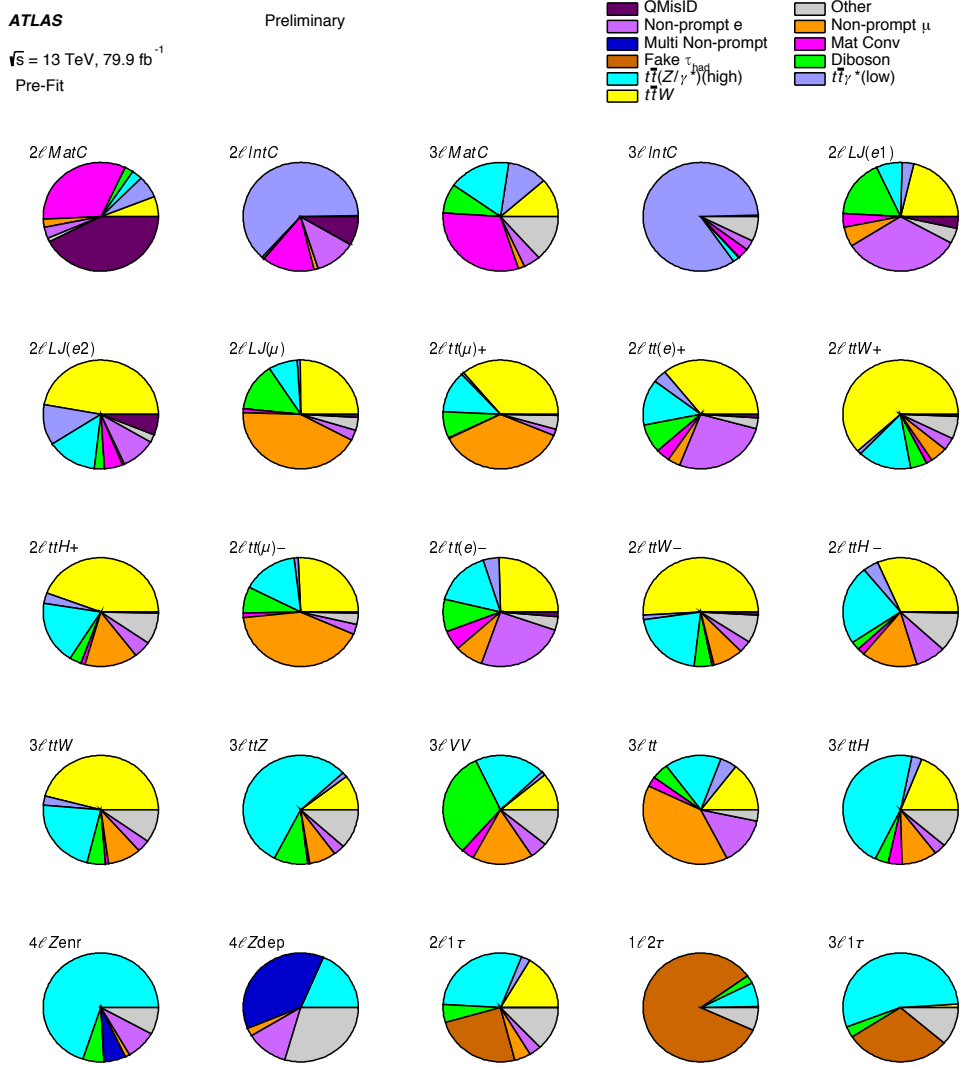


Figure 3.33. – The fractional contribution of backgrounds in each event category.

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All of the control regions are distributed in $2\ell\text{SS}$ channel and 3ℓ channel. Thirteen of them are used only with their yield information. The three control regions in $2\ell\text{SS}$ low N_{jets} together with one $t\bar{t}$ control region in 3ℓ are used both yield and shape information. They are distributed on $\Delta R_{\ell_0\ell_1}$, HT_{lep} , or BDT score. Pre-fit plots for all control regions are shown in Figure 3.34 (with shape) and 3.35 (only yield).

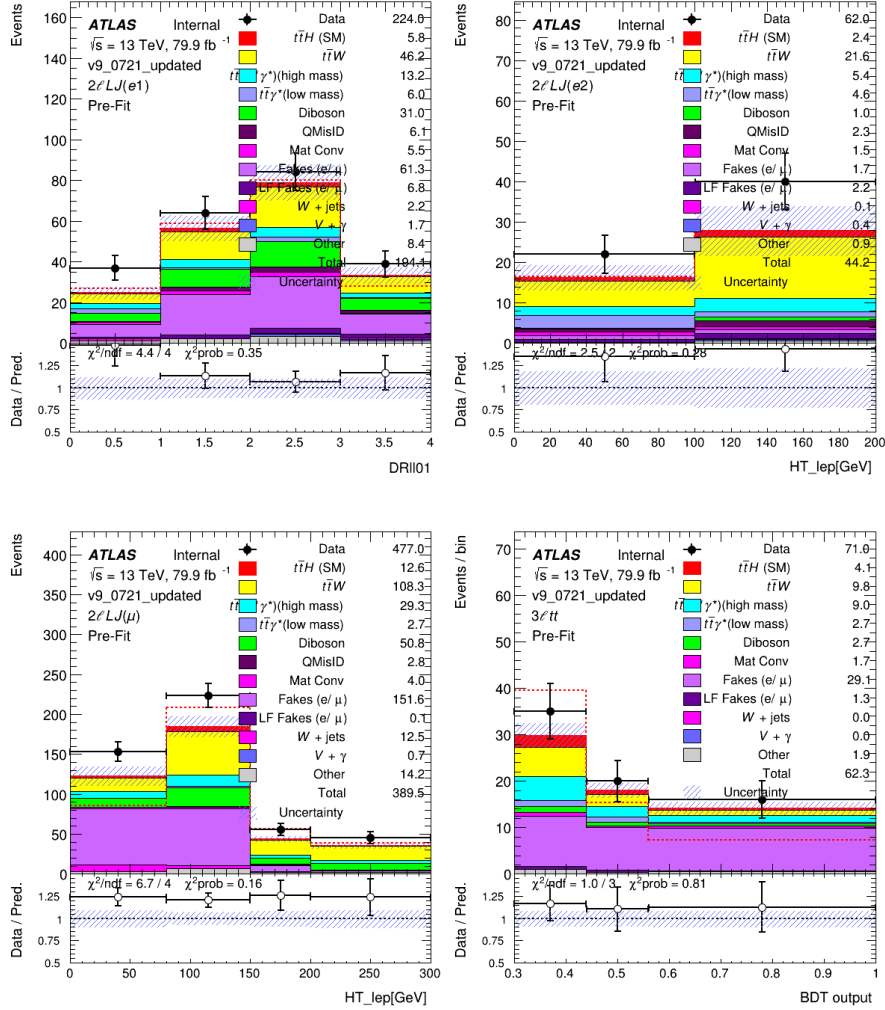


Figure 3.34. – Pre-fit CRs in $2\ell\text{SS}$ channel with low N_{jets} , subleading lepton as an electron (top) or muon (bottom left), and in 3ℓ channel (bottom right).

In most of the regions abundant with $t\bar{t}W$, a situation of data overshoot the MC is observed, which indicates a tension to pull up the $\text{NF}_{t\bar{t}W}$. From a good agreement has already been achieved between data and MC in internal conversion dedicated control regions, we expect the fitted $\text{NF}_e^{\text{IntCO}}$ is not far from 1.

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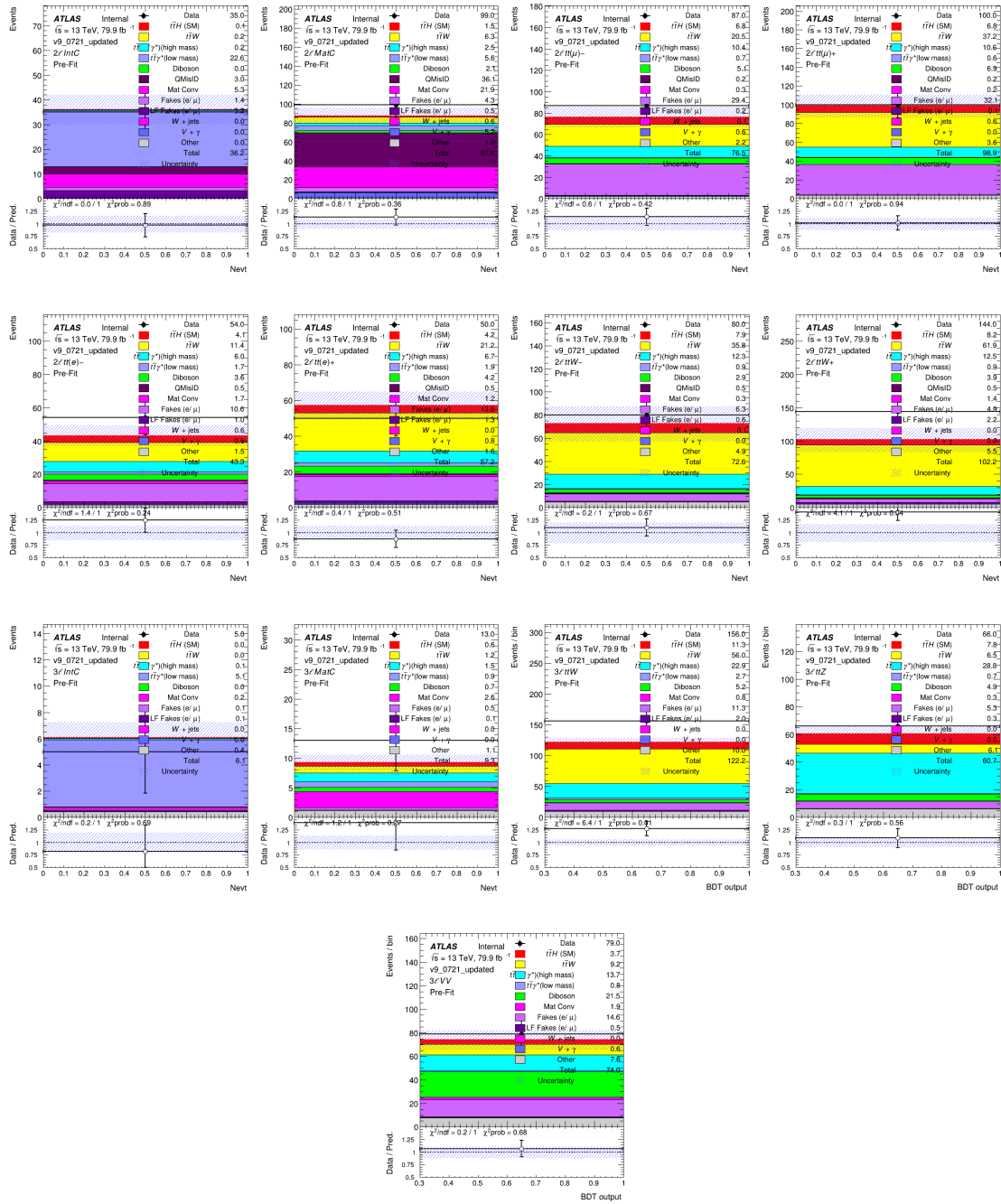


Figure 3.35. – Pre-fit CRs with event yield only.

Two signal regions in $2\ell\text{SS}$, one in 3ℓ , and one in $1\ell + 2\tau_{had}$ are distributed on a BDT discriminant, while the rest four signal regions are using their total event yields. Figure 3.36 displays the pre-fit data/MC comparisons in all the eight signal regions. The τ_{had} channels are with either a low signal purity ($1\ell + 2\tau_{had}$) or a low statistic

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$(2\ell\text{SS} + 1\tau_{\text{had}}, 3\ell + 1\tau_{\text{had}})$, which limits their sensitivity to the $t\bar{t}H$ signal.

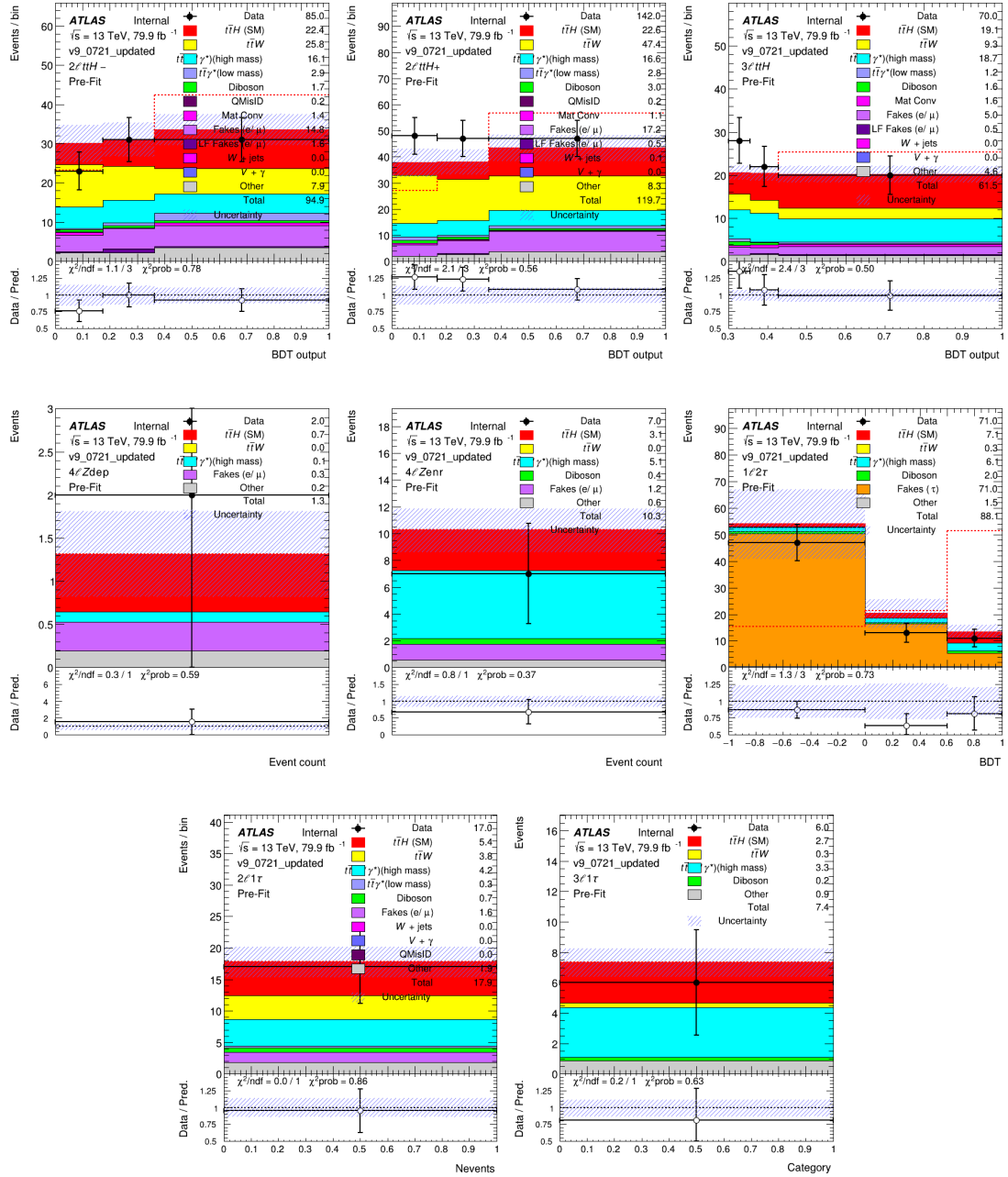


Figure 3.36. – Pre-fit data/MC comparisons in SRs.

3.7.6. Fit results

In this section, fit results of twenty-five event categories with seven normalisation factors are shown. The categorisation for all fit regions has already discussed in last section. The post-fit data and MC comparison plots are shown in Figure 3.37 for all eight SRs (up) and for all seventeen CRs (down). Data and MC are agree with each other in all fit regions within the uncertainties. Shapes of the categories with bins used in the fit are shown in Figure 3.38 and 3.39 for SRs and CRs, respectively. With $t\bar{t}H$ at 0.58 to the SM predicted cross section and $t\bar{t}W$ at over 1σ above the SM prediction, the MC is agree to data in all of signal region and control region bins.

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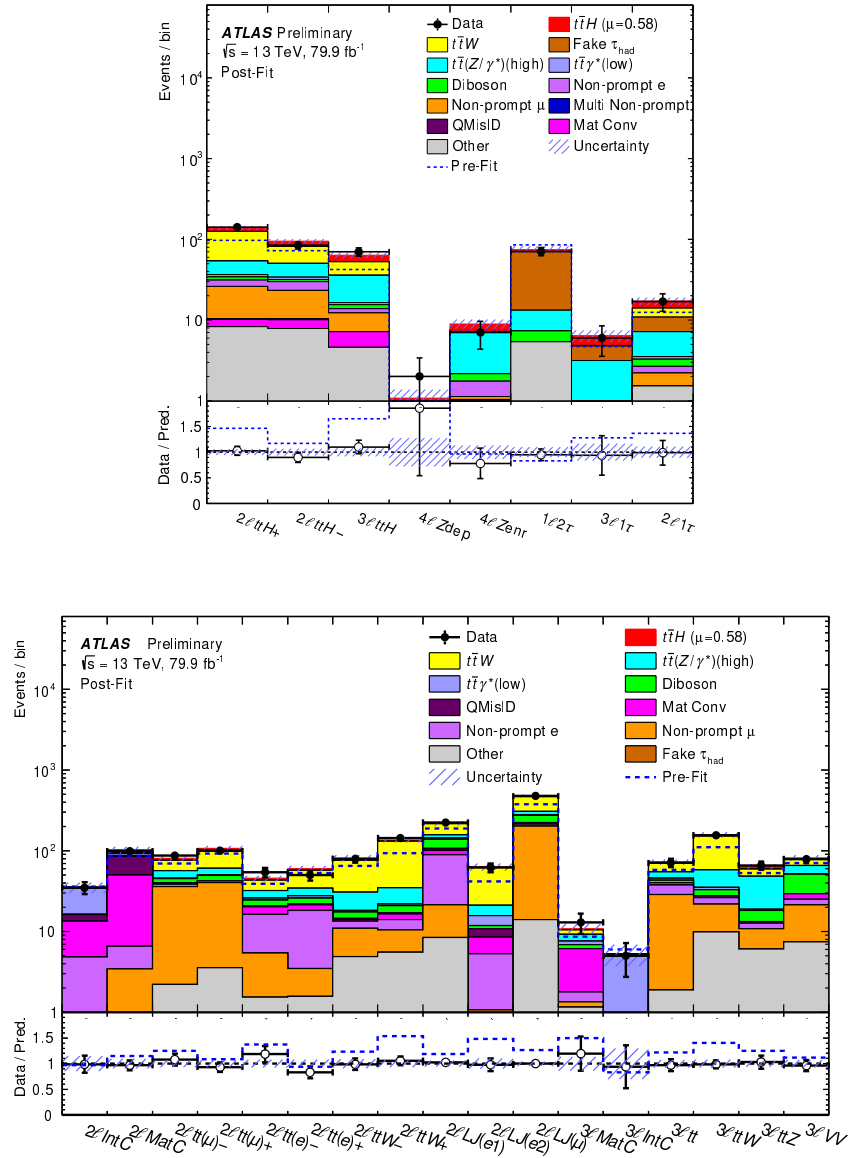


Figure 3.37. – Comparisons between data and the post-fit MC in the 8 $t\bar{t}H$ categories (up) and in the 17 control region categories (down).

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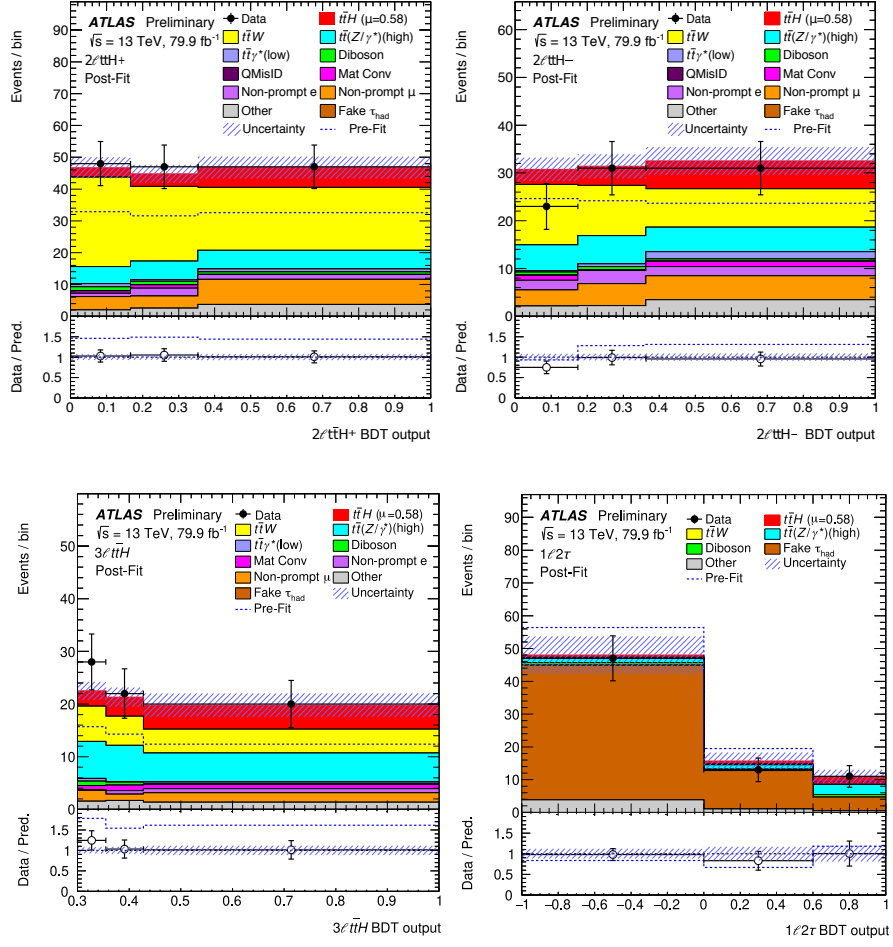


Figure 3.38. – The post-fit distributions for shape SRs. SRs in $2\ell\text{SS}$ channels are shown in the upper row. SRs in 3ℓ and $1\ell + 2\tau_{\text{had}}$ channels are shown in the lower row.

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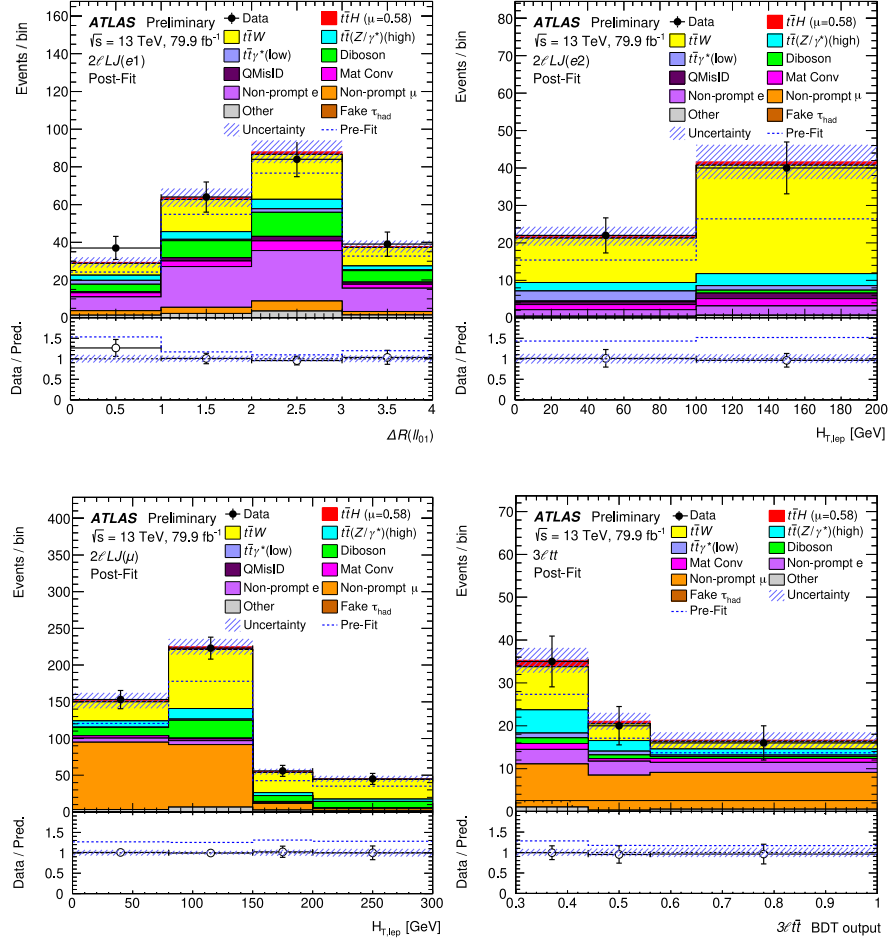


Figure 3.39. – The post-fit distributions for shape CRs. CRs in 2ℓSS channel with subleading lepton as an electron are shown in the upper row. CRs for 2ℓSS low N_{jets} with subleading lepton as a muon and 3ℓ $t\bar{t}$ are shown in the lower row.

The pulls and correlation matrix for nuisance parameters are shown in Figure 3.40. The extrapolation systematics and varRF on $t\bar{t}W$ are largely pulled and constrained. The formers are pulled to relieve the tensions inside the $t\bar{t}W$ and between $t\bar{t}W$ and fakes, and constrained due to a rather conservative value given. The latter, as a systematic on $t\bar{t}W$ renormalisation and factorization scale, is sensitive to the high jet multiplicity region, whose events are more likely to be selected to signal regions by BDTs, while the $t\bar{t}W$ normalisation factors are more sensitive to $t\bar{t}W$ control regions. Thus the fit prefers a pull in $t\bar{t}W$ varRF.

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Among the correlations between the ~ 200 nuisance parameters and POI, only three coefficients are larger than 40%. The coefficient between $t\bar{t}W$ extrapolations for b-jet multiplicity in $2\ell\text{SS}$ and heavy flavour associated electron normalisation factor is the largest, at 51.3%. With the $t\bar{t}W$ extrapolations for $N_{b\text{-jets}}$ and $t\bar{t}W$ normalisation factor in $2\ell\text{SS}$ high N_{jets} , the coefficient is -48%. The third largest is the coefficient between the internal conversion normalisation factor and a 100% overall uncertainty assigned to the light flavour associated non-prompt lepton in conversion control regions at -45.6%. The large correlation between the $t\bar{t}W$ extrapolation systematic and the heavy flavour electron normalisation factor is positive, while between the same systematic and $t\bar{t}W$ normalisation factor is negative. Both indicate that the tensions have been relieved by this $t\bar{t}W$ shape uncertainty, either between $t\bar{t}W$ and heavy flavour fake or between the $t\bar{t}W$ high and low $N_{b\text{-jets}}$ regions. The theoretical uncertainty assigned to a rare light flavour fake process with a conservative value at 100% has a large anti-correlation with the heavy flavour background in conversion control regions is within the expectation, while hardly affect the measurement.

The Figure 3.41 (left) shows event yields as a function of $\log_{10}(S/B)$ and the best-fit values of signal strength for each channel are shown in Figure 3.41 (right). Details of multi- μ fit are discussed in Section 3.7.7.1.

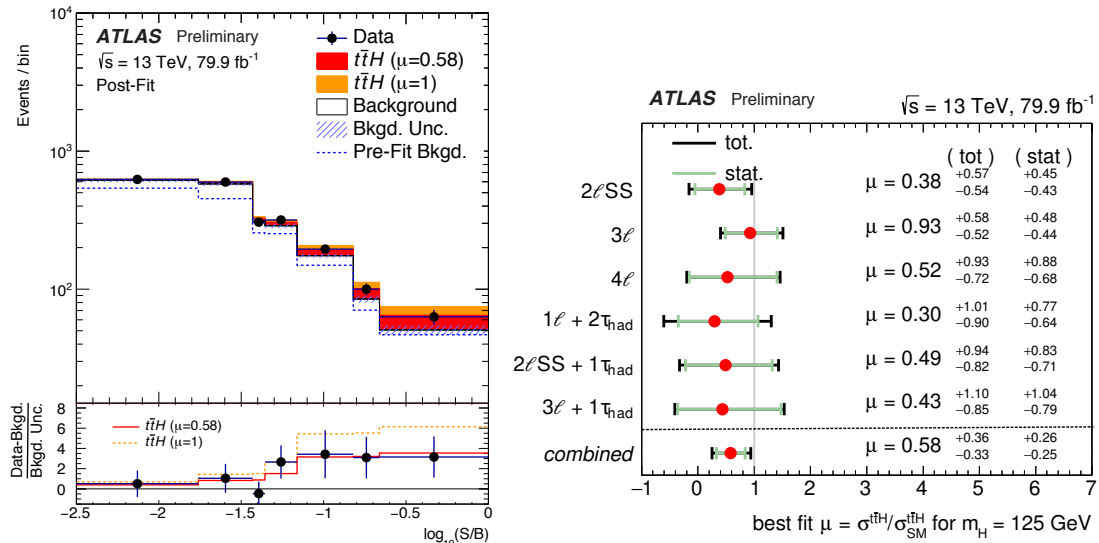


Figure 3.41. – Event yields as a function of $\log_{10}(S/B)$ for data, background and a Higgs boson signal with $m_H = 125 \text{ GeV}$ (left) and best-fit values of $\mu_{t\bar{t}H}$ in each channel and the combination.

The best fitted POI and NFs are shown in Figure 3.42 (left), while the top ranking of nuisance parameters are shown in Figure 3.42 (right).

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

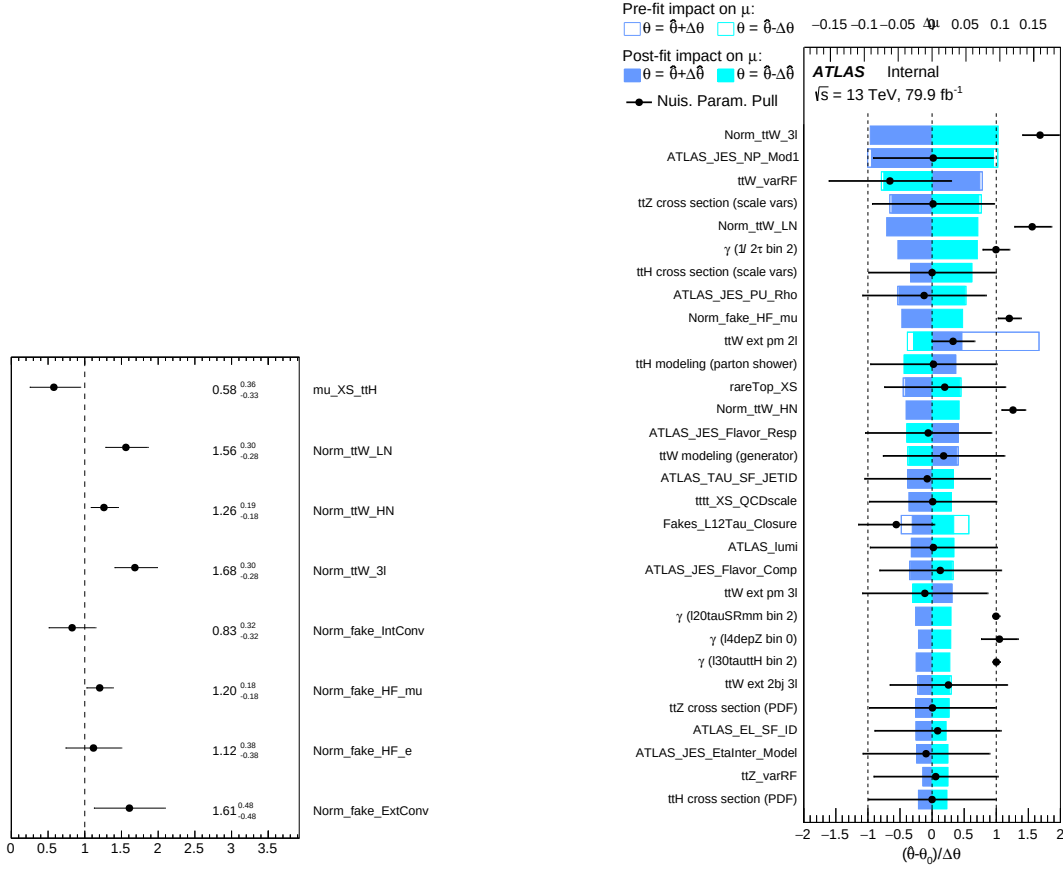


Figure 3.42. – The best fitted POI and NFs (left) and the ranking of the nuisance parameters in terms of its impact on the fitted signal strength (right).

The measured values for $t\bar{t}W$ normalisation factors are a bit above the SM prediction (according to Section 3.7.3.1) at $1.3 \sim 1.7\sigma$. The best-fit value of μ is:

$$\hat{\mu} = 0.58^{+0.26}_{-0.25} (\text{stat.})^{+0.19}_{-0.15} (\text{exp.})^{+0.13}_{-0.11} (\text{bkg. th.})^{+0.08}_{-0.07} (\text{sig. th.}) = 0.58^{+0.36}_{-0.33}. \quad (3.20)$$

The corresponding $t\bar{t}H$ production cross section in this measurement

$$\hat{\sigma}(t\bar{t}H) = 294^{+132}_{-127} (\text{stat.})^{+94}_{-74} (\text{exp.})^{+73}_{-56} (\text{bkg. th.})^{+41}_{-39} (\text{sig. th.}) \text{ fb} = 294^{+182}_{-162} \text{ fb}, \quad (3.21)$$

is consistent with the SM prediction at NLO in QCD and EW couplings [6], $\sigma(t\bar{t}H) = 507^{+35}_{-50} \text{ fb}$, within uncertainties. An observed (expected) significance excess above the background-only expectation ($\mu = 0$) is derived as 1.8σ (3.1σ).

The top three nuisance parameters in the ranking are $t\bar{t}W$ normalisation factor in 3ℓ channel, jet energy scale (JES) model 1, and $t\bar{t}W$ varRF, which correspond to groups of NFs, experimental systematic uncertainty, and theoretical systematic uncertainty.

3.7.7. Post-fit checks

A few checks after the fit are shown in this section and appendices. In Section 3.7.7.1 and 3.7.7.2, results for a multi- μ fit and separate-year fit are shown. Appendix E shows the modelling of post-fit MVA variables in 2ℓ SS high and low N_{jets} regions. Likelihood value scans around the best-fit values for POI and NFs are shown in Appendix F. At last, a comparison with 2015-2016 data between the new analysis and R20.7 results has been performed and shown in Appendix G. The comparisons are made in event yields and the best-fitted values in each channel.

3.7.7.1. Multi- μ fit

A check on multi- μ fit has been performed in two ways:

- Six μ fit: with μ set in the six channels individually
- Two μ fit: with μ set in non-tau and tau channel individually

Figure 3.43 shows the normalisation factors with best fitted μ . The two fittings give sets of NFs with similar values, which indicates the fit model is stable. According to the six μ fit, 2ℓ SS and 3ℓ channels give the most accurate μ estimations, which are at $0.38^{+0.57}_{-0.54}$ and $0.93^{+0.58}_{-0.52}$. A smaller error is observed on μ fitted with non-tau channels compared to tau channels. The fitted signal strengths in all channels are consistent.

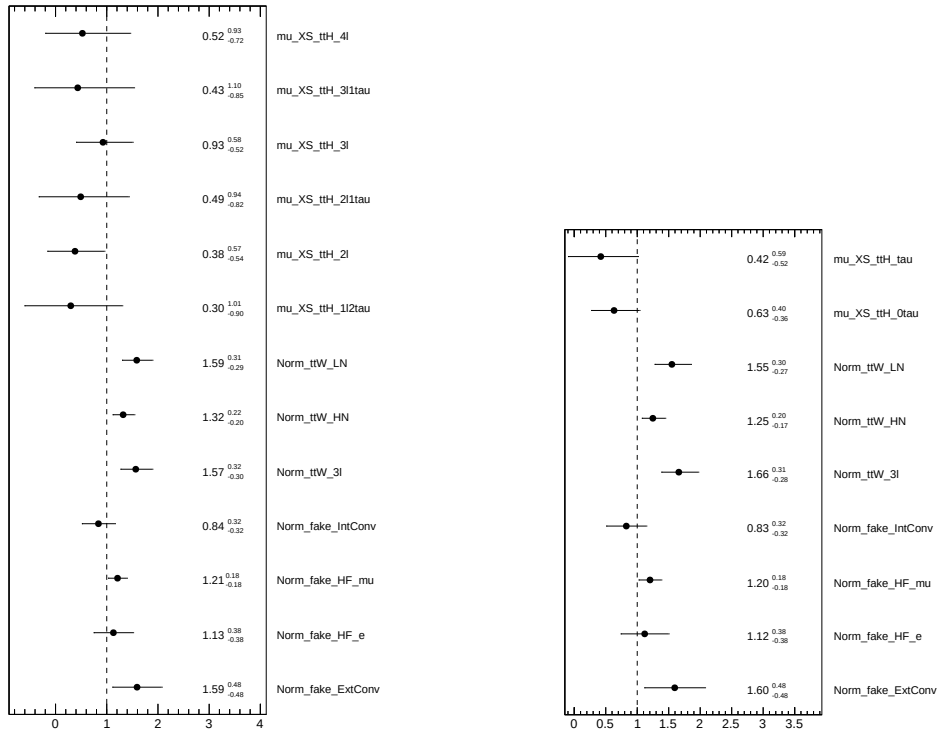


Figure 3.43. – NFs for the 6 μ individual fit (left) and the 2 μ non-tau/tau fit (right).

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

3.7.7.2. Separate-year fit

A study on fit with data separated by years has been performed. The whole dataset has been split into:

- 2015+2016 data with 36.1 fb^{-1} .
- 2017 data with 43.8 fb^{-1} .

Fit comparisons are made between the two fits. The correlation matrices between nuisance parameters and the signal strength whose coefficients above 20% are shown in Figure 3.44. The basic correlations between $t\bar{t}W$ extrapolation systematics and NFs are similar in the two fits, while behaviors of some NPs with low impact on μ are changed (*i.e.* uncertainties on light flavour fakes).

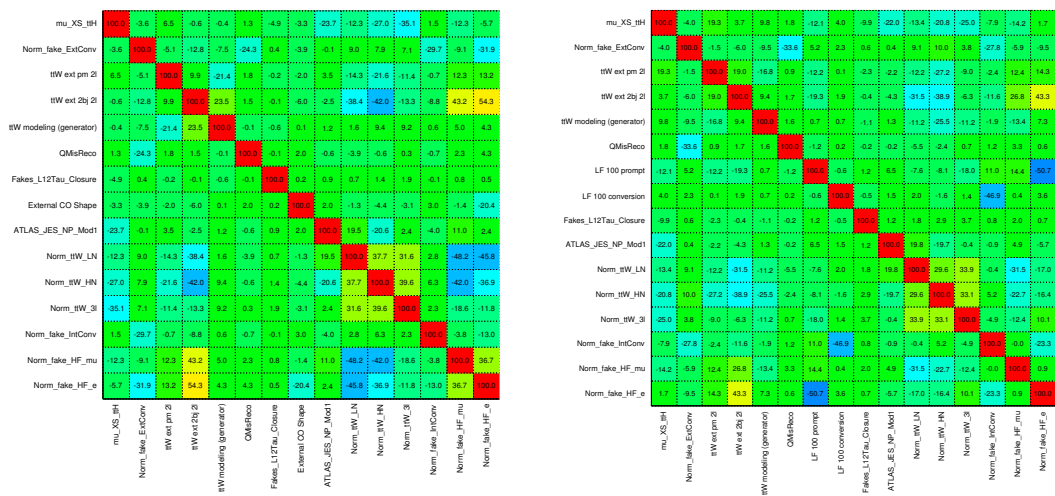


Figure 3.44. – Correlations between NPs and POI for fit with 2015+2016 data (left) and 2017 data (right).

The pulls of nuisance parameters are presented in Figure 3.45. The $t\bar{t}W$ extrapolation systematics are pulled and constraint in the two fits, but in different ways, which indicates the tensions in the two fits are different.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

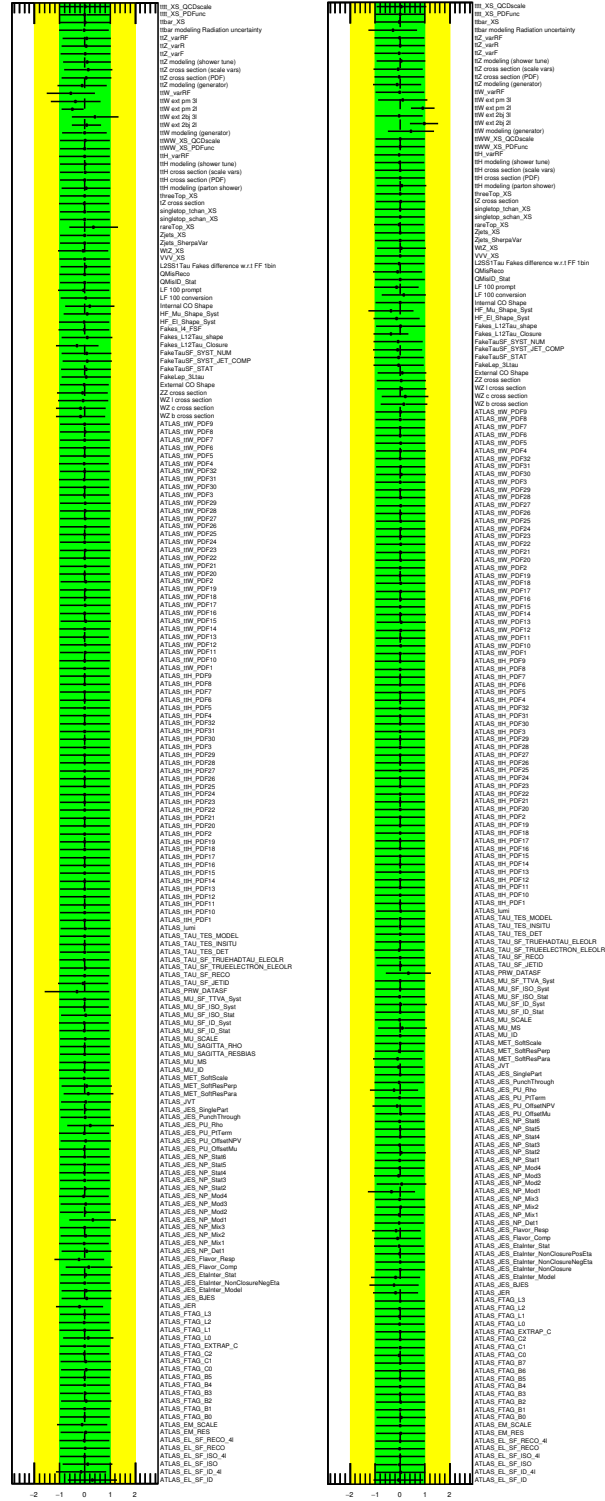


Figure 3.45. – Nuisance parameter pulls and constraints for fit with 2015+2016 data (left) and 2017 data (right).

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

Figure 3.46 shows the normalisation factors with best fitted μ .

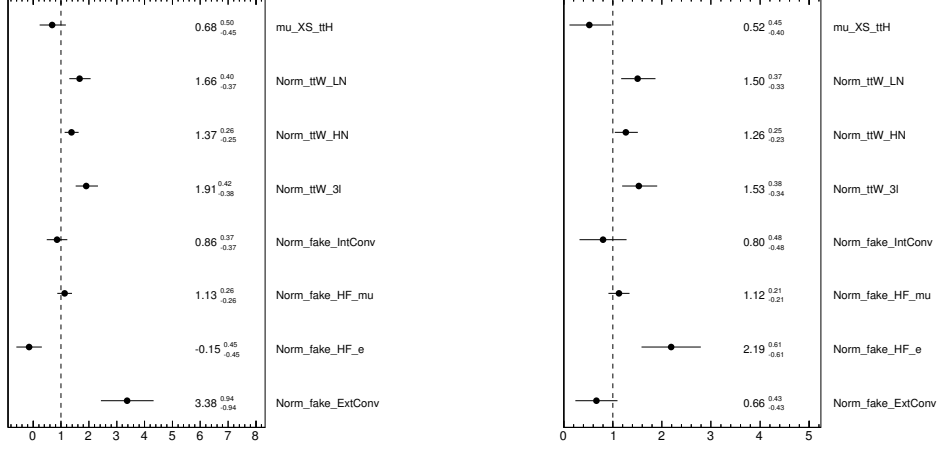


Figure 3.46. – NFs for fit with 2015+2016 data (left) and 2017 data (right).

The fit results are consistent except for the normalisation factors of material conversion and electron heavy flavour fakes. Clues can be found in material conversion control regions and heavy flavour associated non-prompt lepton control regions compared between 2015+2016 data and 2017 data, which are shown in Figure 3.47 and 3.48. Tensions have been observed in different directions according to the data/MC comparison in bins of CRs with different dataset. Statistical uncertainties are dominated in these control region bins, and thus the statistical fluctuation leads to a discrepancy observed in fit results.

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

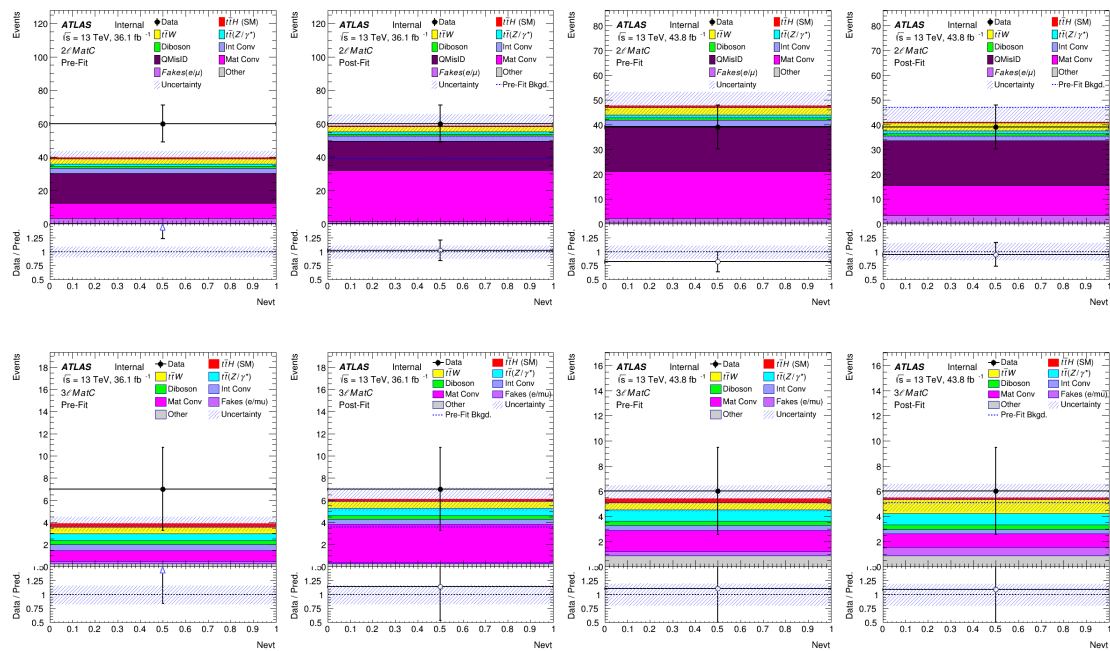


Figure 3.47. – Material conversion CRs in 2ℓ SS channel (upper row) and 3ℓ channel (lower row) for pre- and post-fit data/MC comparisons with 2015+2016 dataset (left 2 columns) and pre- and post-fit data/MC comparisons with 2017 dataset (right 2 columns).

3. The measurement of $t\bar{t}H$ production in multilepton final states with 79.9 fb^{-1} dataset – 3.7. Statistical analysis

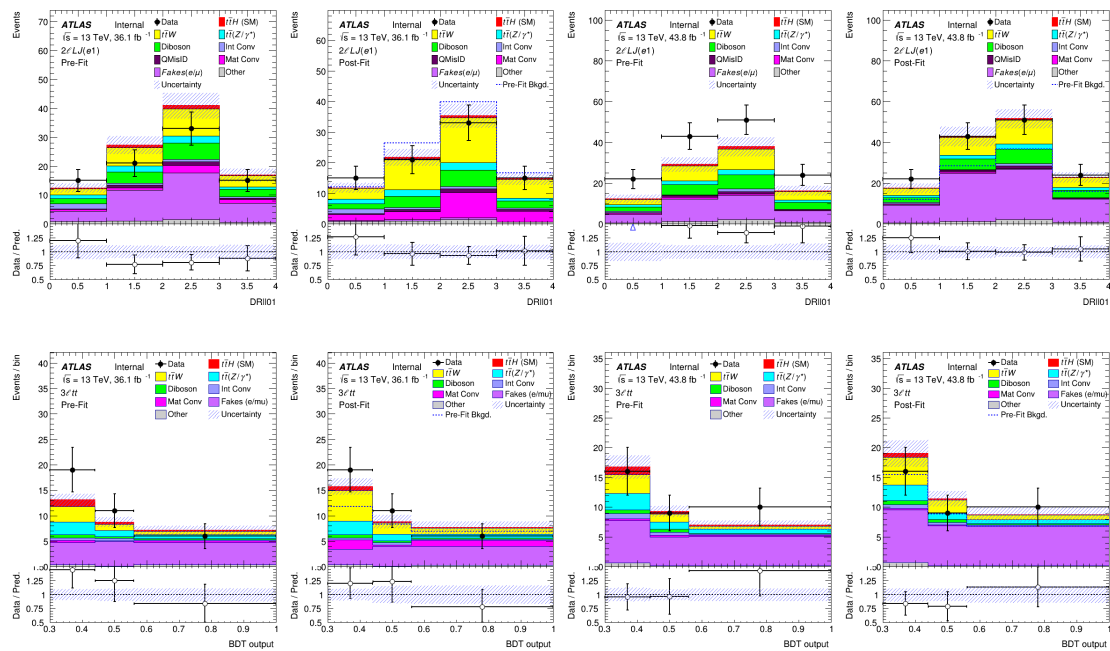


Figure 3.48. – HF(e) CRs in 2ℓ SS low N_{jets} (upper row), and 3ℓ channels (lower row) for pre- and post-fit data/MC comparisons with 2015+2016 dataset (left 2 columns) and pre- and post-fit data/MC comparisons with 2017 dataset (right 2 columns).

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset

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4.1. Introduction

The full Run 2 analysis for a top quark pair associated with a W or Higgs boson uses the data corresponding to an integrated luminosity of 139.0 fb^{-1} collected by the ATLAS detector at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ in multilepton final states. The analysis is performed in two steps. In the first step, the analysis on $t\bar{t}W$ is performed as a differential measurement. In the second step, a search for the $t\bar{t}H$ signal is performed based on a fixed $t\bar{t}W$ background. The first step is motivated by an excess of $t\bar{t}W$ background (see in Figure 3.42) observed in the 79.9 fb^{-1} $t\bar{t}H$ multilepton analysis. The result of the first step is expected to be published in early 2021, and the second step, the search $t\bar{t}H$ in multilepton final states, is planned to be finished by the end of 2021.

In this chapter, only expected results for the two measurements using a simultaneous fit in $2\ell\text{SS}$ channel are presented. The analysis estimates the non-prompt background using a template fit method with normalisation factors extracted from the last round (see in chapter 3) and analyses with a cut based approach. Only systematic uncertainty on luminosity and statistical uncertainties are included in this

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.2. Data and MC samples

measurement. Section 4.2 describes the dataset and MC samples used in this analysis. Section 4.3 introduces the main updates in object selections and tight lepton definitions. Fake estimation by template fit method is described in Section 4.4 with normalisation factor extracted from last round. The region settings in the cut based method are described in Section 4.5. Finally, A fit to the Asimov dataset has been performed in the last section (Section 4.6), which shows the expected best-fit signal strength $\mu_{t\bar{t}H}$, together with a normalisation factor on $t\bar{t}W$. Expected significance will be calculated on the $t\bar{t}H$ signal.

In the $t\bar{t}W$ measurement in progress, I contributed to the group framework developing, group ntuple production, object validation, overlap removal, and the on-going non-prompt background estimation using the data-driven matrix method.

4.2. Data and MC samples

A dataset of pp collisions collected by the ATLAS experiment at $\sqrt{s} = 13 \text{ TeV}$ during 2015-2018 is used in this analysis. The total delivered integrated luminosity recorded by the LUCID2 Cherenkov detector [130] is 156.1 fb^{-1} , while the data ready for the analysis is 139.0 fb^{-1} . The relative error on the total luminosity considering the correlations between all years is calculated as 1.7% [35].

MC simulation samples are produced by different generators given by Table 4.1. The signal samples for $t\bar{t}H$ are using POWHEG-BOX [59, 60]+PYTHIA 8 [52] with an A14 tuning [102] with negative weighted events fixed. The generator for producing the $t\bar{t}W$ ($t\bar{t}Z$) background is switched to the SHERPA2.2.8 [56] (SHERPA2.2.1) with a cross section at $589.2^{+91.3}_{-86.6}$ ($130.6^{+10.2}_{-12.0}$) fb [131], while the $t\bar{t}$ background still uses a POWHEG-BOX+PYTHIA 8. The GEANT4 [63] has been used to simulate the geometry and response in the ATLAS detector. Different sets of MC samples are used for different year, including MC16a (representing 2015 and 2016 datasets), MC16d (representing 2017 dataset), and MC16e (representing 2018 dataset).

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}H$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0 NLO [62]/ NNPDF2.3 LO [61]	A14
$t\bar{t}W$	SHERPA 2.2.8	MEPs@NLO	SHERPA	NNPDF3.0 NNLO	SHERPA default
$t\bar{t}(Z/\gamma^*)$	SHERPA 2.2.1	NLO multileg	SHERPA	NNPDF3.0 NNLO	SHERPA default
$t\bar{t}$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14

Table 4.1. – Generators and configurations used in productions of signals and main backgrounds. Changes have been made adopting the most advanced generator in producing the $t\bar{t}V$ backgrounds from the last round. Generators and configurations are remained for other background samples.

4.3. Event selections

In this section, the basic selections and settings for the on-going analysis will be discussed. Changes and upgrades from the last round [5] are detailed. In Section 4.3.1, the trigger decision in $2\ell\text{SS}$ channel is discussed comparing between the dilepton trigger (DLT), single-lepton trigger (SLT), and a combined choice for DLT or SLT (DLT||SLT). Section 4.3.2 describes the validation of the upgraded τ_{had} reconstruction working point, jet reconstruction, and b-tagging working point. Section 4.3.3 introduces the new overlap removal strategy. The tight lepton definitions after an improved PLV (PLIV) method and a new QMisID working point applied are described in Section 4.3.4.

4.3.1. Trigger decision

Two sets of lepton triggers, the DLT and SLT, are summarised in Table 4.2 for the 2015-2018 dataset.

Dilepton triggers (2015)		Single lepton triggers (2015)	
$\mu\mu$ (asymm.)	HLT_mu18_mu8noL1	μ	HLT_mu20_iloose_L1MU15, HLT_mu50
ee (symm.)	HLT_2e12_lhloose_L12EM10VH	e	HLT_e24_lhmedium_L1EM20VH, HLT_e60_lhmedium, HLT_e120_lhloose
$e\mu, \mu e$ (~symm.)	HLT_e17_lhloose_mu14		
Dilepton triggers (2016)		Single lepton triggers (2016, 2017, 2018)	
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1	μ	HLT_mu26_ivarmedium, HLT_mu50
ee (symm.)	HLT_2e17_lhvloose_nod0	e	HLT_e26_lhtight_nod0_ivarloose, HLT_e60_lhmedium_nod0, HLT_e140_lhloose_nod0
$e\mu, \mu e$ (~symm.)	HLT_e17_lhloose_nod0_mu14		
Dilepton triggers (2017, 2018)			
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1		
ee (symm.)	HLT_2e24_lhvloose_nod0		
$e\mu, \mu e$ (~symm.)	HLT_e17_lhloose_nod0_mu14		

Table 4.2. – DLT and SLT for 2015-2018 data.

The trigger decision in $2\ell\text{SS}$ channel was made to keep compatible with the fake estimation by matrix method in the on-going $t\bar{t}W$ measurement. The bias from the loose lepton used in a tag-and-probe pair with no isolation requirement is minimized if the signal region uses the DLT instead of the SLT. To prove the DLT can provide a similar sensitivity as the SLT, checks have been made and shown below. Three cases of trigger decisions are considered: DLT||SLT, DLT, and SLT. Figure 4.1 shows the sensitivity for a signal of $t\bar{t}W$ as a function of the leading lepton p_T for two cases: DLT and DLT||SLT. The plot indicates that the case with DLT achieves a better significance in the low lepton p_T regions, while the case DLT||SLT shows a better performance in the high lepton p_T area. The performance of SLT is close to DLT||SLT.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.3. Event selections

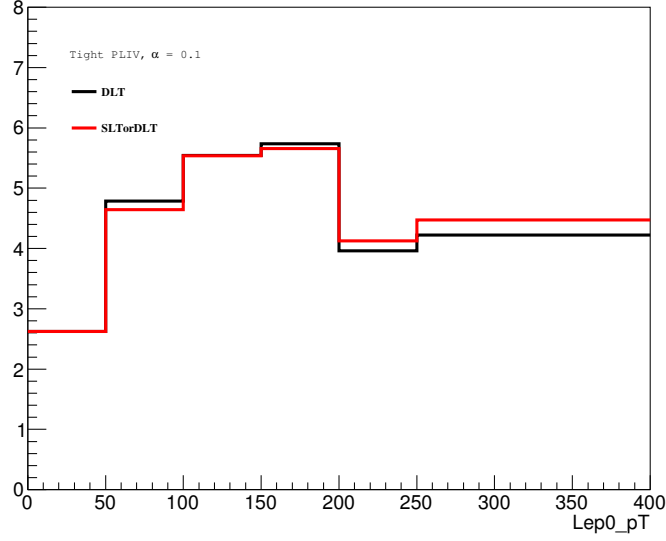


Figure 4.1. – Sensitivity evaluated for $t\bar{t}W$ signal at a tight PLIV working point with DLT (black) and DLT||SLT (red) in a distribution of leading lepton p_T . The significance is calculated bin by bin with a function $\frac{S}{\sqrt{B+\alpha B^2}}$, where $\alpha = 0.1$.

In the measurement of $t\bar{t}H$ productions, a plan is to use the template fit method to estimate the non-prompt backgrounds, and thus the SLT is brought back to consideration. Therefore, sensitivities calculated for different trigger decisions have been checked and shown in Table 4.3. Sensitivity is given by $S/\sqrt{B}$. All three trigger decisions are tested in tight and very tight regions according to the PLIV working points (refer to Section 4.3.4). An optimised working point for BDT with respect to R20.7 QMisID is also applied in this test. As expected, cases DLT||SLT and SLT have a similar trigger efficiency, which leads to a similar significance. According to the significances calculated for each case, SLT is chosen as the trigger used in this practice.

	ttH (signal)	ttW	ttbar	background sum	$S/\sqrt{B}$
DLT SLT (PLIV very tight)	187.2	720.4	466	1773.1	4.45
DLT (PLIV very tight)	163.0	631.0	382.9	1515.3	4.19
SLT (PLIV very tight)	182.5	708.5	445.0	1726.3	4.39
DLT SLT (PLIV tight)	234.3	822.0	784.1	2327.7	4.72
DLT (PLIV tight)	203.8	719.5	656.2	1993.9	4.56
SLT (PLIV tight)	227.5	806.1	741.7	2250.4	4.80

Table 4.3. – Event yields and overall significance ($\frac{S}{\sqrt{B}}$) are checked in 2ℓ SS channel for different trigger decisions (DLT||SLT, DLT, and SLT) with PLIV working points at very tight and tight. QMisID rejection working point with R20.7 is also applied.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.3. Event selections

4.3.2. Object selection

Reconstructions of τ_{had} , jet, and b-tagged jet have been upgraded during Run 2, and new working points are validated in this analysis. A Medium working point is chosen for the RNN τ_{had} (introduced in Section 2.5.4) with $p_T > 25\text{ GeV}$. A particle flow algorithm is used to replace the topo-cluster jet reconstruction. The particle flow jets are reconstructed based on the charged particle tracks in the ID, then derives the neutral particle energies by removing the charged particle energy deposits in calorimeters. The details are stated in Section 2.5.5.2. Validations on p_T distributions τ_{had} and jets are shown in Figure 4.2 with a $t\bar{t}H$ sample. Shape comparisons have been made between RNN taus (v10) and BDT taus (v9), as well as particle flow jets (v10) and topo-cluster jets (v9).

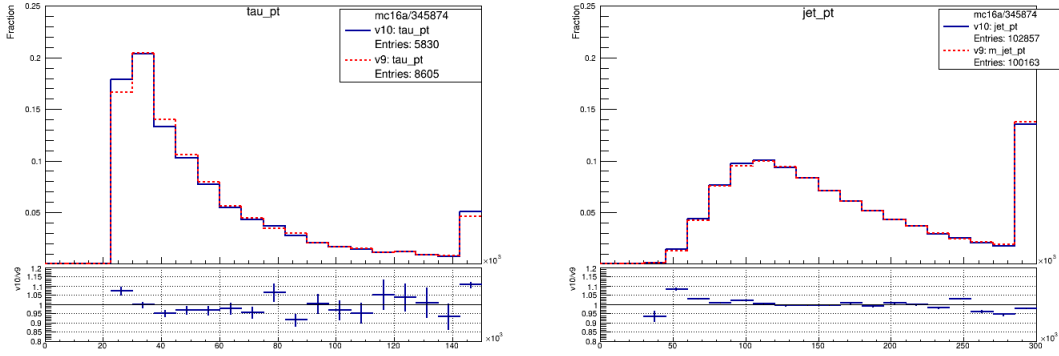


Figure 4.2. – Validations of $t\bar{t}H$ sample compared between the RNN taus (full line in blue) and the BDT taus (dash line in red) on the distribution of p_T (left) and between particle flow jets (full line in blue) and topo-cluster jets (dash line in red).

The shape discrepancy between the RNN taus and BDT taus in the distribution of p_T can be explained by a higher fake τ_{had} rejection with RNN in high p_T regions than BDT (see in Figure 2.35). No significant change has been observed between particle flow jets and topo-cluster jets in jet p_T validation.

The b-tagging algorithm has been changed from MV2c10 to DL1r in this round but with the same operation point at 70% (see in Section 2.5.5.4). Validation plots for jet multiplicity and b-jet multiplicity are shown in Figure 4.3. A trend of more events with lower jet multiplicity has been observed with the particle flow algorithm. No significant discrepancies were found in $N_{b\text{-jets}}$ distribution.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.3. Event selections

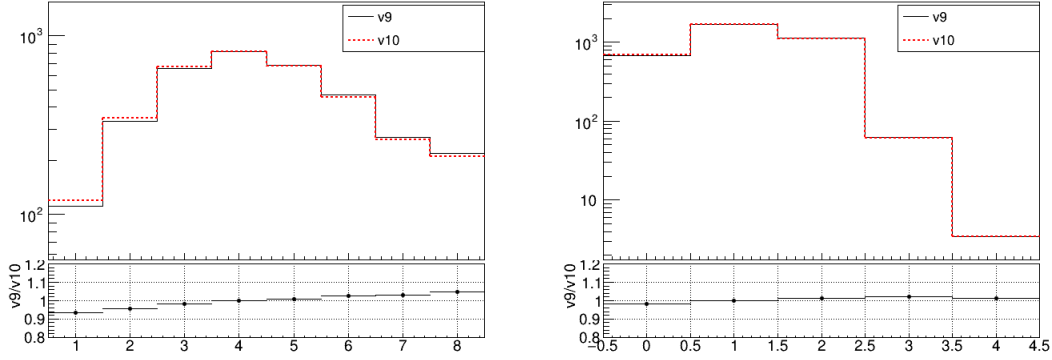


Figure 4.3. – Validations of $t\bar{t}W$ sample on a distribution of N_{jets} (left) compared between particle flow jets (full line in black) and topo-cluster jets (dash line in red) and on a distribution of $N_{b\text{-jets}}$ compared between a DL1r b-tagger (full line in black) and MV2c10 b-tagger (dashed line in red).

The cut flow for $t\bar{t}H$ and $t\bar{t}W$ samples is shown in Table 4.4, which indicates a close cut efficiency between the old and new samples used in the last round and this round.

	$t\bar{t}H$				$t\bar{t}W$			
	last round		this round		last round		this round	
	yield	efficiency	yield	efficiency	yield	efficiency	yield	efficiency
2LSS	229304	–	245690	–	160459	–	167255	–
no τ_{had}	202152	88.1%	213518	86.9%	154961	96.5%	161155	96.3%
$N_{\text{jets}} \geq 4$	144137	71.3%	151408	79.9%	82966	53.5%	87328	54.1%
$N_{b\text{-jets}} \geq 1$	123684	85.8%	130758	86.3%	70225	84.6%	74202	84.9%

Table 4.4. – Cut flow table for $t\bar{t}H$ and $t\bar{t}W$ with raw event numbers in 2 ℓ SS channel.

4.3.3. Overlap removal

The new overlap removal strategy with b-jet aware in the $t\bar{t}W/H$ analysis is shown in Table 4.5. Validation has been done between the old (see in Table 3.9) and new OR working points. The efficiencies for muons and jets to pass the overlap removal are close to what we have in the last round. The efficiency for an electron to pass the overlap removal is $\sim 5\%$ lower than in the previous analysis due to electrons are considered to be removed in more overlap cases. The b-jet is preferred when it is overlapped with an electron. Overlap removal associated with taus is not considered in the current stage.

4.3.4. Tight lepton definition

To further improve the non-prompt lepton rejection, a PromptLeptonImprovedTagger (PLIV) has been developed using isolation and lifetime observables. Classifications

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.3. Event selections

Keep	Remove	Criteria
electron	electron (low p_T)	share track
electron	calorimeter muon	share ID track
muon	electron	share ID track
electron	jet ($p_T < 200 \text{ GeV}$, not b-tagged)	$\Delta R < 0.2$
jet	electron	$\min(0.4, 0.04 + 10[\text{GeV}]/p_T \text{ (electron)})$
muon	jet (not b-tagged)	$\Delta R < 0.4$
jet	muon	$\min(0.4, 0.04 + 10[\text{GeV}]/p_T \text{ (muon)})$

Table 4.5. – List of the overlap removal strategy in $t\bar{t}W/H$ multilepton analysis.

between prompts and non-prompts for electron and muon are trained separately. Training input variables are listed for electrons and muons in Table 4.6 and 4.7.

Variable	Description
PromptLeptonRNN	RNN with track impact parameters and relationship between track jet and lepton
$l_{SV \text{ to PV}}^{\text{longitudinal}}/\sigma$	Secondary vertex longitudinal significance with tracks $p_T > 500 \text{ MeV}$
$p_T \text{VarCone30}/p_T$	Lepton track isolation, with track collecting radius of $\Delta R < 0.3$
$E_T \text{TopoCone30}/p_T$	Lepton calorimeter isolation, with topological cluster collecting radius of $\Delta R < 0.3$
$\sum_{\text{cluster}}^{\Delta R < 0.15} E_T/p_T$	sum of cluster energy over lepton p_T
N_{track} in track jet	Number of tracks collected by the track jet
p_T^{rel}	lepton p_T projected on the track jet direction
$p_T^{\text{track lepton}}/p_T^{\text{track jet}}$	The ratio of the track lepton p_T and the track jet p_T
$\Delta R(\text{lepton, track jet})$	ΔR between the lepton and the track jet axis
p_T^{lepton} bin number	Index of the bin of lepton p_T

Table 4.6. – List of the PLIV input variables for e .

Variable	Description
PromptLeptonRNN	RNN with track impact parameters and relationship between track jet and lepton
$l_{SV \text{ to PV}}^{\text{longitudinal}}/\sigma$	Secondary vertex longitudinal significance with tracks $p_T > 500 \text{ MeV}$
$p_T \text{VarCone30TTVA}/p_T$	similar as $p_T \text{VarCone30}/p_T$, $p_T > 0.5 \text{ GeV}$, Loose vertex association
$E_T \text{TopoCone30}/p_T$	Lepton calorimeter isolation, with topological cluster collecting radius of $\Delta R < 0.3$
$E_{\text{cluster}}^{\mu}/E_{\text{expected}}$	Relative muon calorimeter cluster energy
$p_T^{\text{track lepton}}/p_T^{\text{track jet}}$	The ratio of the track lepton p_T and the track jet p_T
$\Delta R(\text{lepton, track jet})$	ΔR between the lepton and the track jet axis
p_T^{lepton} bin number	Index of the bin of lepton p_T

Table 4.7. – List of the PLIV input variables for μ .

Working points for electron PLIV are further optimised for Barrel electron ($|\eta| < 1.37$) and End-cap electron ($|\eta| > 1.52$). Electrons in the transition regions are rejected. Figure 4.4 shows the performances of the PLIVs. Two sets of working points have been optimised for Barrel electrons and muons (tight and very tight), while only one optimised for End-cap electrons (tight). The working points are developed pseudo-continuous with a dependency on lepton p_T . Different efficiencies are considered in different p_T bins.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.3. Event selections

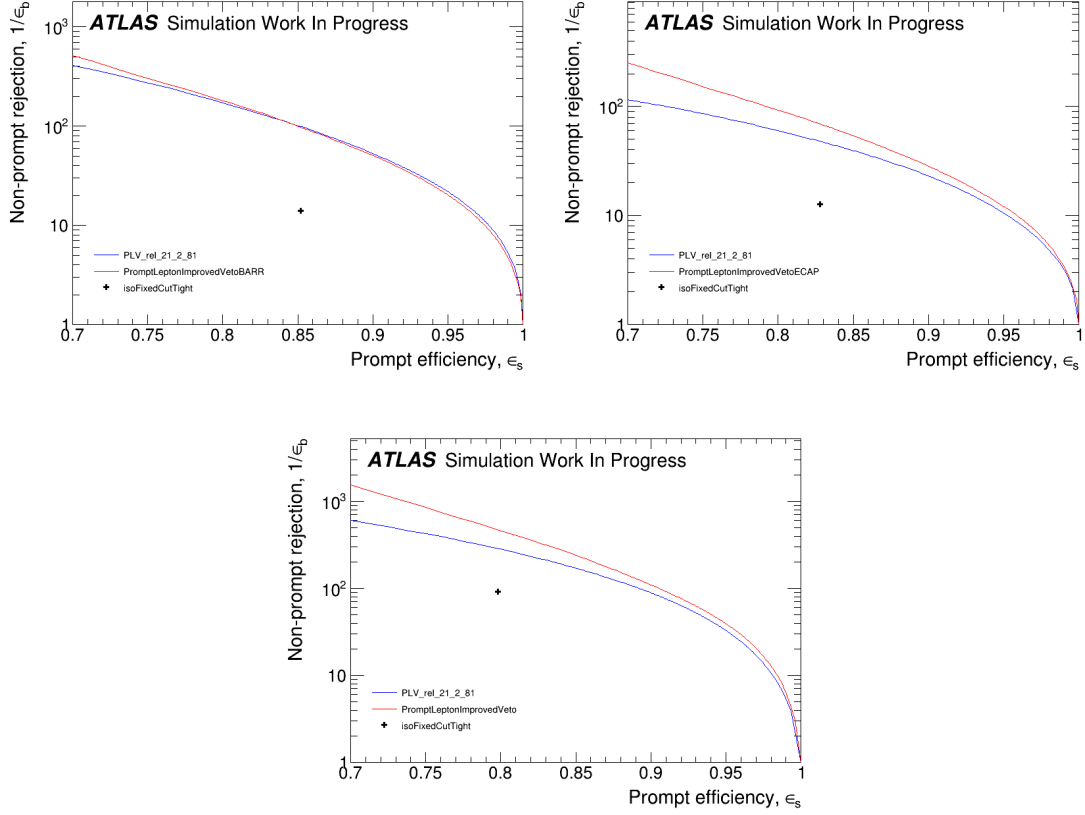


Figure 4.4. – PLIV performances for Barrel electron (top left), End-cap electron (top right), and muon (bottom).

QMISID BDT working points are optimised with $t\bar{t}$ samples in 2ℓ SS channel. Unfortunately, the distribution of ChargeIDBDTResult estimated by the latest Release 21 (R21) ElectronChargeIDSelectorTool (ECIDS) does not meet the expectation. A re-calculated QMISID score using the old ECIDS of R20.7 has been brought back and validated together with the PLIV working points. Comparisons are made between the loose lepton and different tight lepton working points and listed in Table 4.8. The loose working point refers to a baseline lepton selection criteria with no QMISID or non-prompt veto. The case PLV+R21 ECIDS refers to the working point has been used in last round, while the last two cases are the options for this round and are found much better performed in fake rejection.

In the $t\bar{t}W$ measurement, a better sensitivity is given by the case PLIV very tight+R20.7 ECIDS with $S/\sqrt{B} = 19.5$ compared to $S/\sqrt{B} = 18.7$ given by PLIV tight+R20.7 ECIDS, thus a working point at very tight is chosen. However, in an estimation of the $t\bar{t}H$ measurement, a better sensitivity is given by PLIV at tight as shown in Table 4.3. The expected results by fitting to the $t\bar{t}H$ signal will be given with a tight PLIV working point.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.4. Fake estimation

	$t\bar{t}H$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}$	total MC
Loose	299.2	908.3	266.7	12509.1	17709.1
PLV+R21 ECIDS	179.9	595.2	162.5	1402.7	3061.5
PLIV tight+R20.7 ECIDS	203.8	719.5	194.8	656.2	2197.7
PLIV very tight+R20.7 ECIDS	163.0	631.0	163.9	382.9	1678.3

Table 4.8. – Event yield comparisons with loose and tight leptons at different working points.

4.4. Fake estimation

Fake estimations are still on-going in the $t\bar{t}W/H$ analysis. In this $t\bar{t}H$ expectation, fakes are estimated by a template fit method with normalisation factors extracted from the last round. The non-prompt sources are normalised by fixed values equal to what has been shown in Figure 3.42 in a simultaneous fit. Different sources of non-prompt background are defined by the MC truth origin and $\text{radius}_{\text{CO}}$ (details in Section 3.4.1.1). Dedicated control regions for internal and material conversion backgrounds inherited from the last round are considered as validation regions. These two regions defined by $m_{\text{trk-trk,PV}}$, $\text{radius}_{\text{CO}}$, and $m_{\text{trk-trk,CV}}$ (detailed in Section 3.3.2.4) are shown in Figure 4.5. The data and MC agreements are still good in this round.

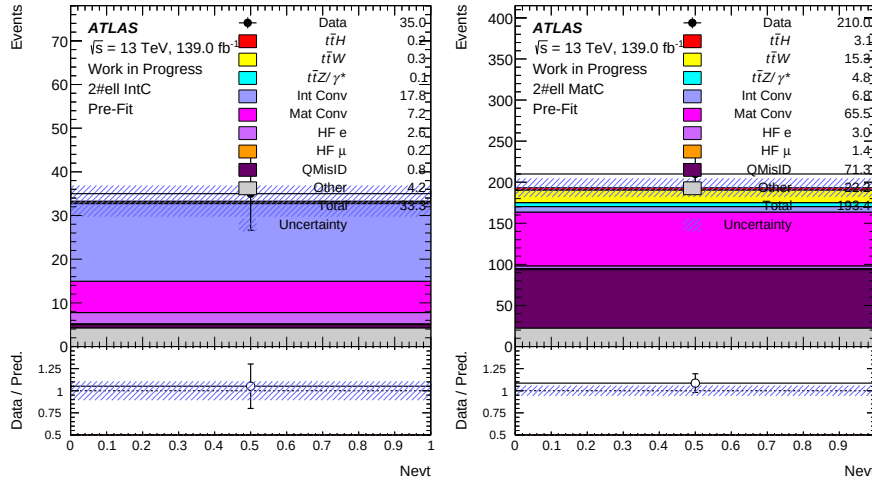


Figure 4.5. – Internal conversion (left) and material conversion (right) validation regions with normalisation factors on non-prompt background extracted from last round.

There are three low jet multiplicity regions with $2 \leq N_{\text{jets}} \leq 3$, enriched with heavy flavour associated muons ($N_{b\text{-jets}} = 1, \mu\mu + e\mu$), heavy flavour associated electrons ($N_{b\text{-jets}} = 1, ee + \mu e$), and $t\bar{t}W$ ($N_{b\text{-jets}} \geq 2$), respectively. These regions will be included in the simultaneous fit as control regions for $t\bar{t}W$ and are blinded at current stage.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.5. The cut based approach

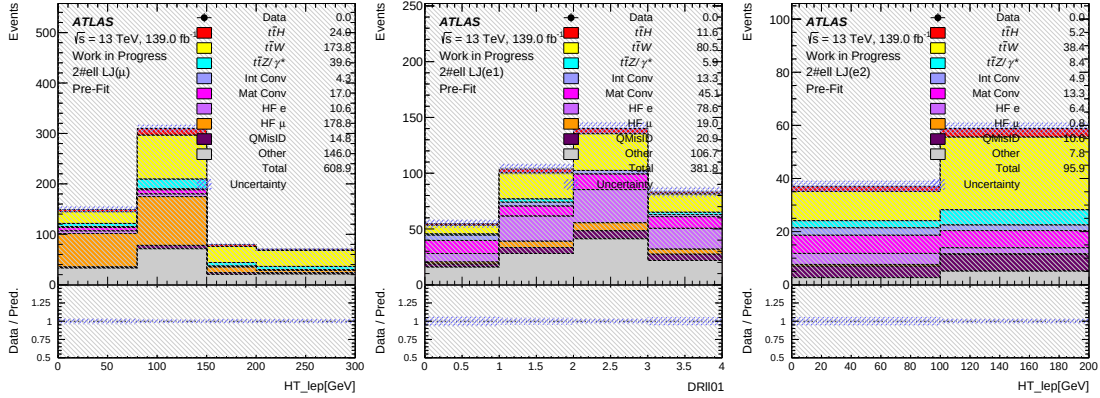


Figure 4.6. – Distributions low N_{jets} ($N_{jets}=2,3$) $2\ell SS$ CRs with normalisation factors on non-prompt background extracted from last round. Heavy flavour muon CR with $N_{b-jets} = 1, \mu\mu + e\mu$ on a distribution of HT_{lep} , Heavy flavour electron CR with $N_{b-jets} = 1, ee + \mu e$ distributed as functions of $\Delta R_{\ell_0\ell_1}$, and $t\bar{t}W$ CR with $N_{b-jets} \geq 2$ on a distribution of HT_{lep} are shown in an order from left to right. Data is blinded in all bins.

4.5. The cut based approach

Due to the fact that the analysis is going on with a differential measurement performing on the $t\bar{t}W$ signal, a cut based method is considered instead of the MVA method. The expected result for $t\bar{t}H$ measurement also bases on a cuts-and-count method for signal and background classifications. The strategy follows the idea of the alternative cut based approach in the previous round. Only in a high N_{jets} ($N_{jets} \geq 4$) region in $2\ell SS$ channel, the cut based method is employed to separate the inclusive region into twelve by jet multiplicity ($N_{jets} = 4$ or $N_{jets} \geq 5$), b-tagged jet multiplicity ($N_{b-jets} = 1$ or $N_{b-jets} \geq 2$), and lepton flavour ($ee, e\mu + \mu e, \mu\mu$).

Signal purity and background composition are shown in Figure 4.7. Signal purity is higher in signal regions with high jet and b-jet multiplicities. The $t\bar{t}V$ becomes the dominant source of background in signal regions due to the PLIV suppressing the non-prompt background dramatically.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.5. The cut based approach

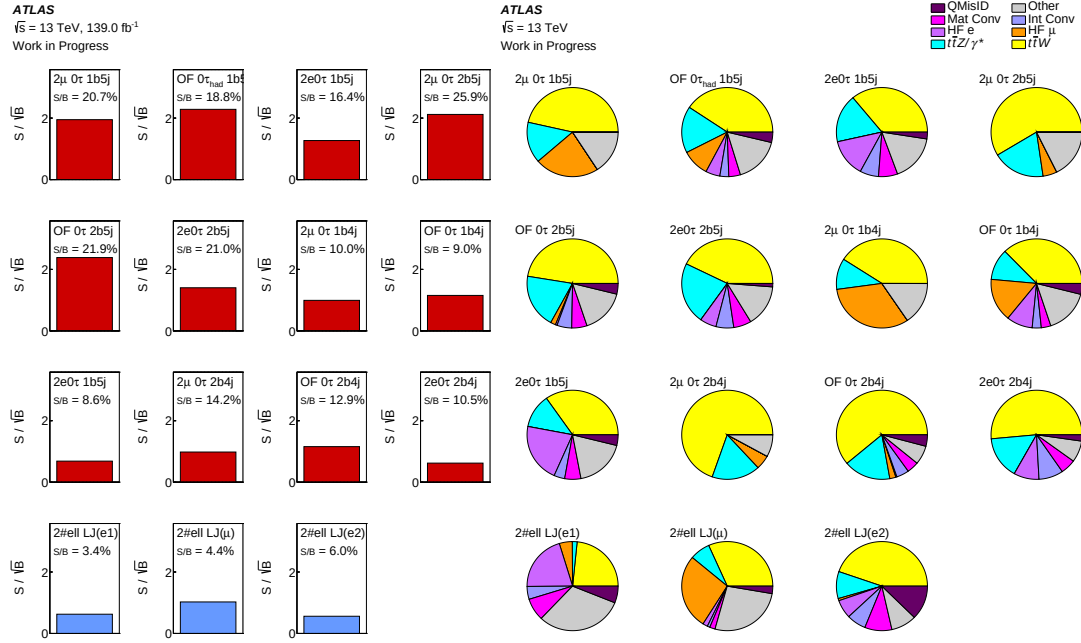


Figure 4.7. – Signal purities (left) and background compositions (right) in SRs and CRs.

Blinding is applied to all signal region bins as shown in Figure 4.8. Twelve signal regions are shown in the sequence of from top to bottom following high $N_{b\text{-jets}}$ and N_{jets} to low $N_{b\text{-jets}}$ and N_{jets} , from left to right following ee , $e\mu + \mu e$, $\mu\mu$.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.5. The cut based approach

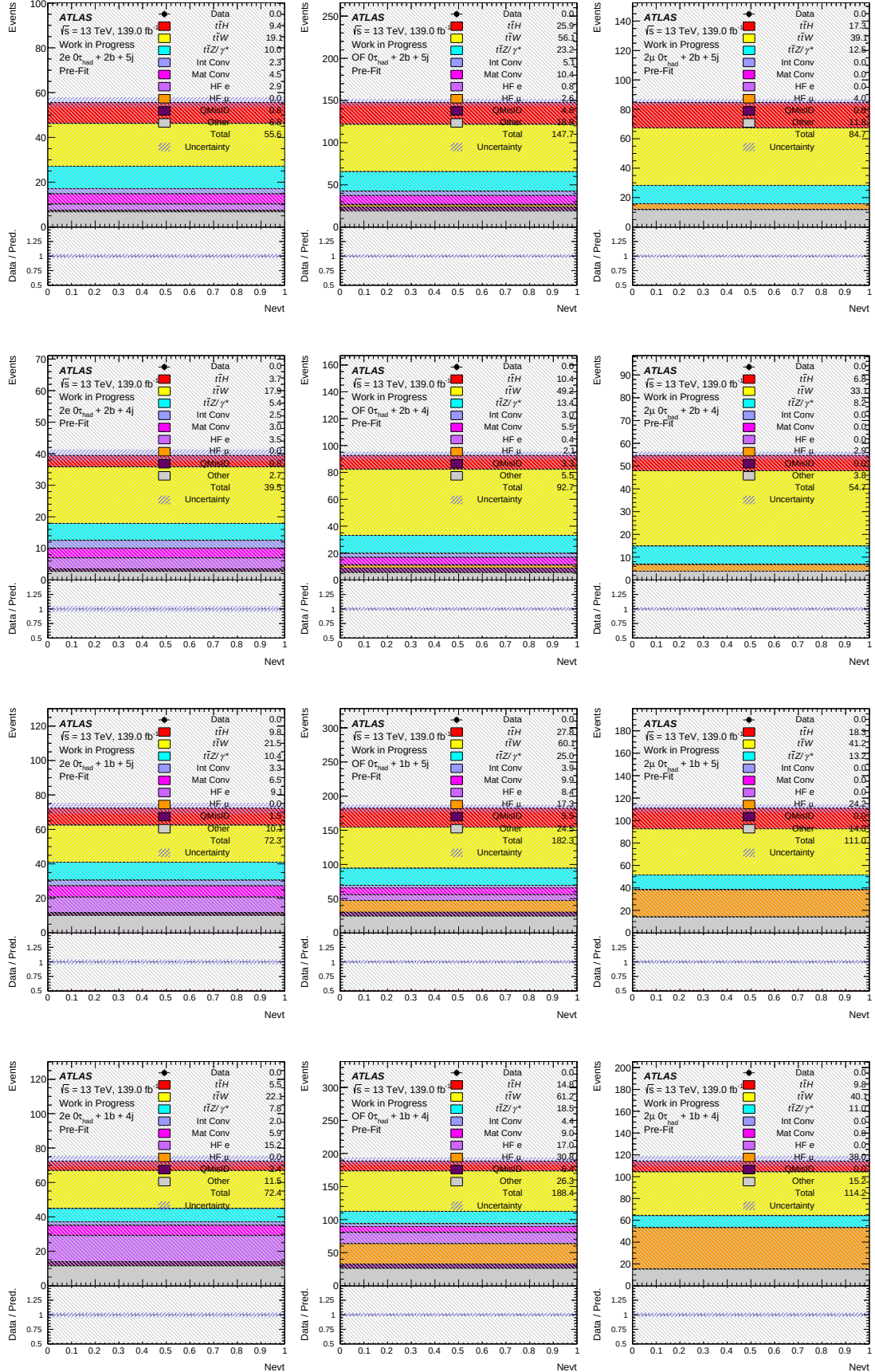


Figure 4.8. – Twelve SRs shows in an order of from top to bottom following high $N_{b\text{-jets}}$ and N_{jets} to low $N_{b\text{-jets}}$ and N_{jets} , from left to right following ee , $e\mu + \mu e$, $\mu\mu$. Data is blinded in all SRs.

4. The measurement of $t\bar{t}W/H$ production in multilepton final states with 139.0 fb^{-1} dataset – 4.6. Fit

4.6. Fit

Expected fit results are derived from a fit to the Asimov dataset with data blinded. Only luminosity and statistic uncertainties are considered. All signal and control regions involved in the simultaneous fit are summarised in Figure 4.9. Twelve signal regions with high jet multiplicity ($N_{\text{jets}} \geq 4$) separated by lepton flavours (ee , $e\mu + \mu e$, $\mu\mu$), jet multiplicity ($N_{\text{jets}} = 4$, $N_{\text{jets}} \geq 5$), and b-jet multiplicity ($N_{b\text{-jets}} = 1$, $N_{b\text{-jets}} \geq 2$) and three low N_{jets} ($N_{\text{jets}} = 2, 3$) control regions inherit from the previous round are considered in the fit.

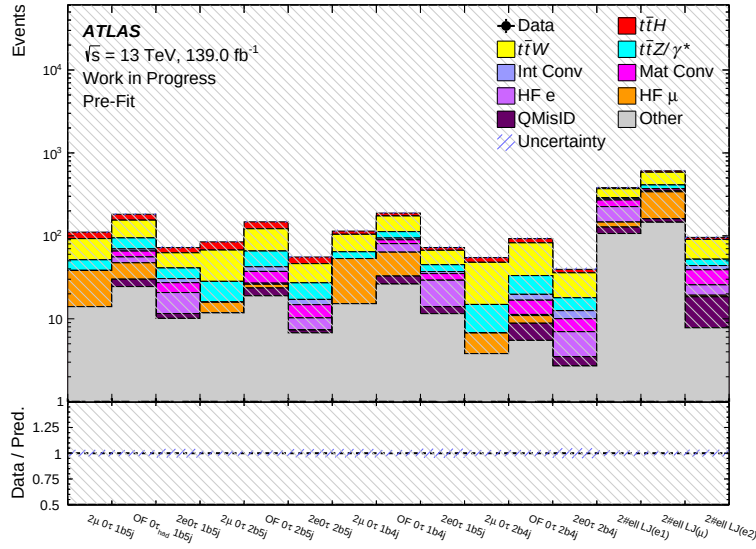


Figure 4.9. – Summary of 12 SRs and 3 CRs in $2\ell\text{SS}$ channel. Data is blinded in all regions

Expected value of $\mu_{t\bar{t}H}$ obtained from the fit is $1^{+0.46}_{-0.45}$, the fitted value of $\text{NF}_{t\bar{t}W}$ is $1^{+0.15}_{-0.14}$. The corresponding expected significance is 2.2σ .

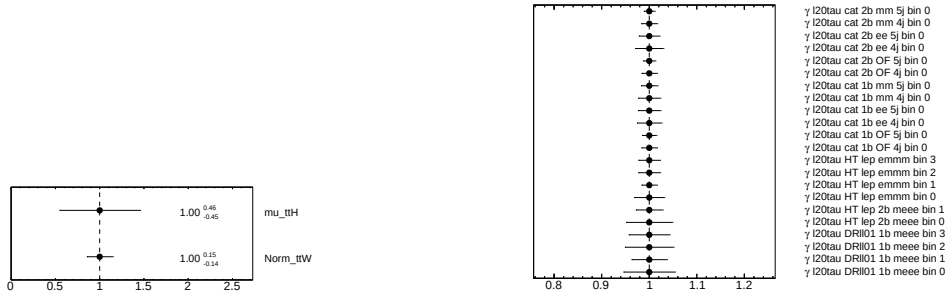


Figure 4.10. – Expected $\mu_{t\bar{t}H}$ and $\text{NF}_{t\bar{t}W}$ (left) as well as gamma pulls (right) extracted from the fit to an Asimov dataset.

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset

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5.1. Introduction

In this chapter, results of a search using the dataset corresponding to an integrated luminosity of 36.1 fb^{-1} collected by the ATLAS detector at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ for heavy neutral resonances decaying into two W bosons, with a final state of $e\nu\mu\nu$ [14] has been presented. The W pair decays either directly or via leptonic tau with additional neutrinos.

Besides the heavy scalar Higgs boson with narrow width approximation (NWA) and large width assumption (LWA), the search also sensitive to the heavy neutral resonances predicted by several different benchmark models, including the two-Higgs-doublet models (2HDM) [24] the Georgi–Machacek (GM) model [132, 133], heavy vector triplet (HVT) interpretation [134, 135], bulk Randall–Sundrum (RS) model [10, 136, 137], and effective Lagrangian model (ELM) [138].

Signal models are detailed in Section 5.2, while the main backgrounds are described in Section 5.3. Section 5.4 and 5.5 introduce the fit models and fit results. Finally, post-fit checks have been done in Section 5.6. I contribute to the upper limits set for all signals as well as the post-fit checks.

5.2. Signal models

All signal models are summarised in Table 5.1.

Model	Resonance spin	Production mode		
		ggF	qqA	VBF
NWA	Spin-0	x		x
2HDM		x		x
LWA		x		x
GM				x
HVT	Spin-1		x	x
Bulk RS ELM	Spin-2	x		x

Table 5.1. – Summary of signal models, spins, and production modes [14].

NWA/LWA The NWA assumes the heavy scalar is with a width much smaller than the detector resolution, while the LWA assumes with larger widths of 5%, 10%, and 15% of the heavy Higgs boson mass. The most relevant BSM predictions with widths above 15% are already excluded by indirect limits [139].

2HDM Two types of 2HDM [24] are considered in the presented analysis. In type I, one Higgs doublet couples to vector bosons and the other to fermions, while in Type II, one Higgs doublet couples to up-type quarks and the other to down-type quarks and charged leptons. Several parameters used are listed below:

- $m_h, m_H, m_A, m_H^\pm$: The masses for the Higgs with two CP-even neutral states, as a pseudo-scalar, and with charge.
- α : The mixing angle between the CP-even neutral Higgs fields.
- $\tan \beta$: the ratio of the two Higgs doublets vacuum expectation values (v_2/v_1).

GM The GM model includes a fermiophobic fiveplet, H_5^0 , $H_5^\pm$, and $H_5^{\pm\pm}$, as an extension of SM Higgs with a triplet of $SU(2)_L$. The value of

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} \quad (5.1)$$

has been preserved as 1 at tree level, where θ_W is the weak mixing angle [140]. The new Higgs boson can only be produced by VBF when its mass is larger than the H_5 multiplet as predicted by the GM model. The proportion to a single parameter, $\sin^2 \theta_H$, determines the cross section and decay width into VV . Its value has been chosen as $\sin \theta_H = 0.4$ in this analysis [141].

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.3. Backgrounds

HVT The HVT model allows a new spin-1 heavy boson couple to the SM particles. The production mechanism for the heavy gauge boson in s -channel is dominated by $q\bar{q}$ annihilation (qqA). The heavy vector bosons couple to the Higgs and SM gauge bosons with a coupling strength of $c_h g_V$, while they couple to fermions with a coupling strength of $g^2 c_F / g_V$. The factors, c_h and c_f control the heavy vector triplet interactions with Higgs bosons and fermions, g_V represents its coupling strength to the SM bosons, and g refers to the SM $SU(2)_L$ gauge coupling. The value of g_V has been chosen as 1 according to the extended gauge symmetry model A [135]. For the VBF productions, it is assumed that there is no coupling to fermions. The samples are generated using the same g_V value but with couplings to the fermions set to 0.

RS A spin-2 graviton (G_{KK}) is predicted as the first graviton Kaluza–Klein (KK) excitation in the RS model with a warped extra dimension, which has been briefly mentioned in Section 1.3.2. There is a chance for the LHC to produce the gravitons at $\sim 1 \text{ TeV}$ for $k/\bar{M}_{Pl} \geq 0.1$, where $\bar{M}_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck scale. In this analysis, scale parameter $k/\bar{M}_{Pl}$ are considered as either 0.5 or 1 [142].

ELM The ELM [138] describes an approach to the spin-2 signal in the VBF production mode. The couplings to fermions and gluons are not included in the Lagrangian, which is different from the RS model. The parameters setting for the ELM are $\Lambda_{ff} = 3 \text{ TeV}$, $n_{ff} = 4$, $\Lambda = 1.5 \text{ TeV}$, and $f_1 = f_2 = f_5 = 1$.

5.3. Backgrounds

The dominant backgrounds are the events with top quarks and SM WW events, followed by the contributions from V +jets and $VZ/V\gamma/V\gamma^*$. The top quark background is estimated as a mixture of $t\bar{t}$ and single-top-quark events scaled to their cross sections and relative acceptances respectively, from 10% to 30% of the contribution comes from the single-top-quark, varies depending on the signal event category. A fake-factor (FF) method based on data-driven has been developed to estimate the W +jets background, while other backgrounds are estimated with a pure MC.

Dedicated CRs have been established for the two main sources of backgrounds in ggF and VBF categories separately. Selections criteria for the CRs are listed in Table 5.2. Rather high purity for the top quark control regions has been accomplished as above 95%, and the purity for WW CRs is about 50%.

Normalisation factors assigned to these two backgrounds are discussed in the next section.

5.4. Fit model

A profiled likelihood function (see in Section 3.7.1) has been established to set the upper limits (see in Section 3.7.2) for signals predicted by the model independent

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.4. Fit model

WW CR _{ggF}	Top CR _{ggF}	WW CR _{VBF1J}	Top CR _{VBF}
$N_{b\text{-tag}} = 0$ $ \Delta\eta_{\ell\ell} > 1.8$ $m_{\ell\ell} > 55\text{GeV}$ $p_T^{\ell,\text{lead}} > 45\text{GeV}$ $p_T^{\ell,\text{sublead}} > 30\text{GeV}$ $\max(m_T^W) > 50\text{GeV}$	$N_{b\text{-tag}} = 1$ $ \Delta\eta_{\ell\ell} < 1.8$	$N_{b\text{-tag}} = 0$ $(\Delta\eta_{\ell\ell} > 1.8 \text{ or } 10\text{GeV} < m_{\ell\ell} < 55\text{GeV})$ $p_T^{\ell,\text{lead}} > 25\text{GeV}$ $p_T^{\ell,\text{sublead}} > 25\text{GeV}$ $-$	$N_{b\text{-tag}} \geq 1$ $-$ $m_{\ell\ell} > 10\text{GeV}$
Excluding VBF1J and VBF2J phase space		VBF1J phase space	VBF1J and VBF2J phase space

Table 5.2. – Selection criteria for the four CRs [14].

scenarios and benchmark models. Three signal regions and four control regions are built to better measure the signal strength and constrain the backgrounds. Selections used in control regions and signal regions are shown in Table 5.2 and 5.3.

SR _{ggF}	SR _{VBF1J}	SR _{VBF2J}
Common selections		
$N_{b\text{-tag}} = 0$ $ \Delta\eta_{\ell\ell} < 1.8$ $m_{\ell\ell} > 55\text{GeV}$ $p_T^{\ell,\text{lead}} > 45\text{GeV}$ $p_T^{\ell,\text{sublead}} > 30\text{GeV}$ veto if $p_T^{\ell,\text{other}} > 15\text{GeV}$ $\max(m_T^W) > 50\text{GeV}$		
ggF phase space	VBF1J phase space	VBF2J phase space
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{\text{jet}} = 1$ and $ \eta_j > 2.4, \min(\Delta\eta_{j\ell}) > 1.75$	$N_{\text{jet}} \geq 2$ and $m_{jj} > 500\text{GeV}, \Delta y_{jj} > 4$

Table 5.3. – Selection criteria for the three SRs [14].

The signal regions are categorised into ggF, VBF1J, and VBF2J. Cuts $N_{b\text{-jets}}$, $|\Delta\eta_{\ell\ell}|$, and $m_{\ell\ell}$ are reversed in defining the control regions so that they are orthogonal to signal regions. In ggF categories, N_{jets} are inclusive in both signal and control regions. In VBF categories, two signal regions are separated by $N_{\text{jets}} = 1$ or $N_{\text{jets}} \geq 2$. The WW VBF control region has been required as $N_{\text{jets}} = 1$ due to a low purity in $N_{\text{jets}} \geq 2$ category and top control region is inclusive for $N_{\text{jets}} = 1$ and $N_{\text{jets}} \geq 2$.

Normalisation factors have been assigned to the top quark and WW backgrounds in signal regions and control regions. The $\text{NF}_{WW}^{\text{ggF}}$ and $\text{NF}_{WW}^{\text{VBF}}$ are assigned on WW backgrounds in ggF and VBF categories, respectively, correlating WW backgrounds in signal regions and control regions. The $\text{NF}_{\text{Top}}^{\text{ggF}}$ and $\text{NF}_{\text{Top}}^{\text{VBF}}$ are set on top quark backgrounds signal regions and control regions, according to the same logic.

5.5. Fit results

The fitted values for the normalisation factors on top quark background are $\text{NF}_{\text{Top}}^{\text{ggF}} = 0.96^{+0.05}_{-0.05}$ and $\text{NF}_{\text{Top}}^{\text{VBF}} = 1.12^{+0.13}_{-0.12}$, on WW background are $\text{NF}_{WW}^{\text{ggF}} = 1.14^{+0.09}_{-0.09}$ and $\text{NF}_{WW}^{\text{VBF}} = 1.0^{+0.2}_{-0.2}$. The post-fit data-MC comparisons are shown in Figure 5.1 for signal regions and 5.2 for control regions.

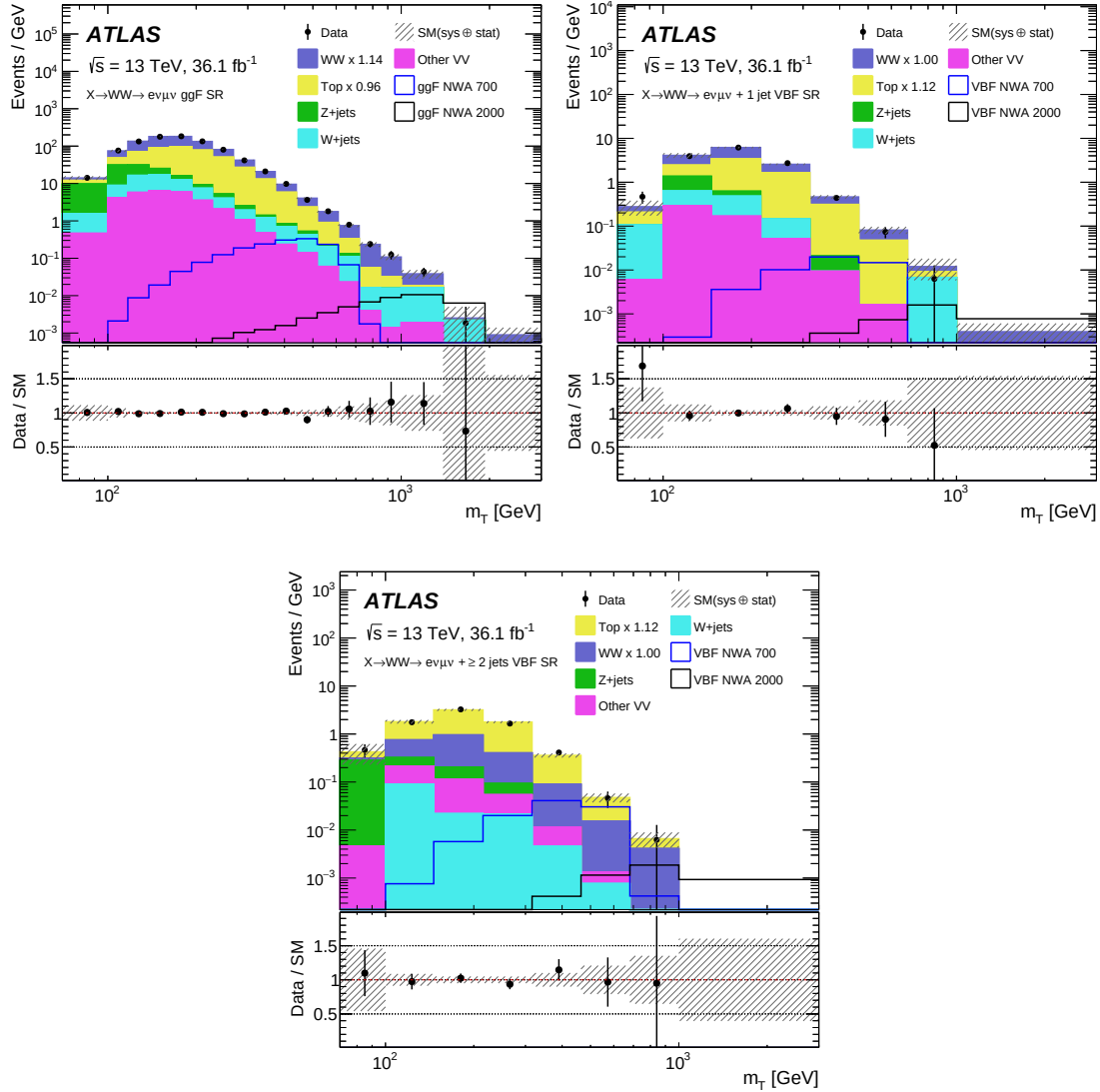


Figure 5.1. – Post-fit distributions of the transverse mass m_T in SR_{ggF} (top left), SR_{VBF1J} (top right), and SR_{VBF2J} (bottom) [14].

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.5. Fit results

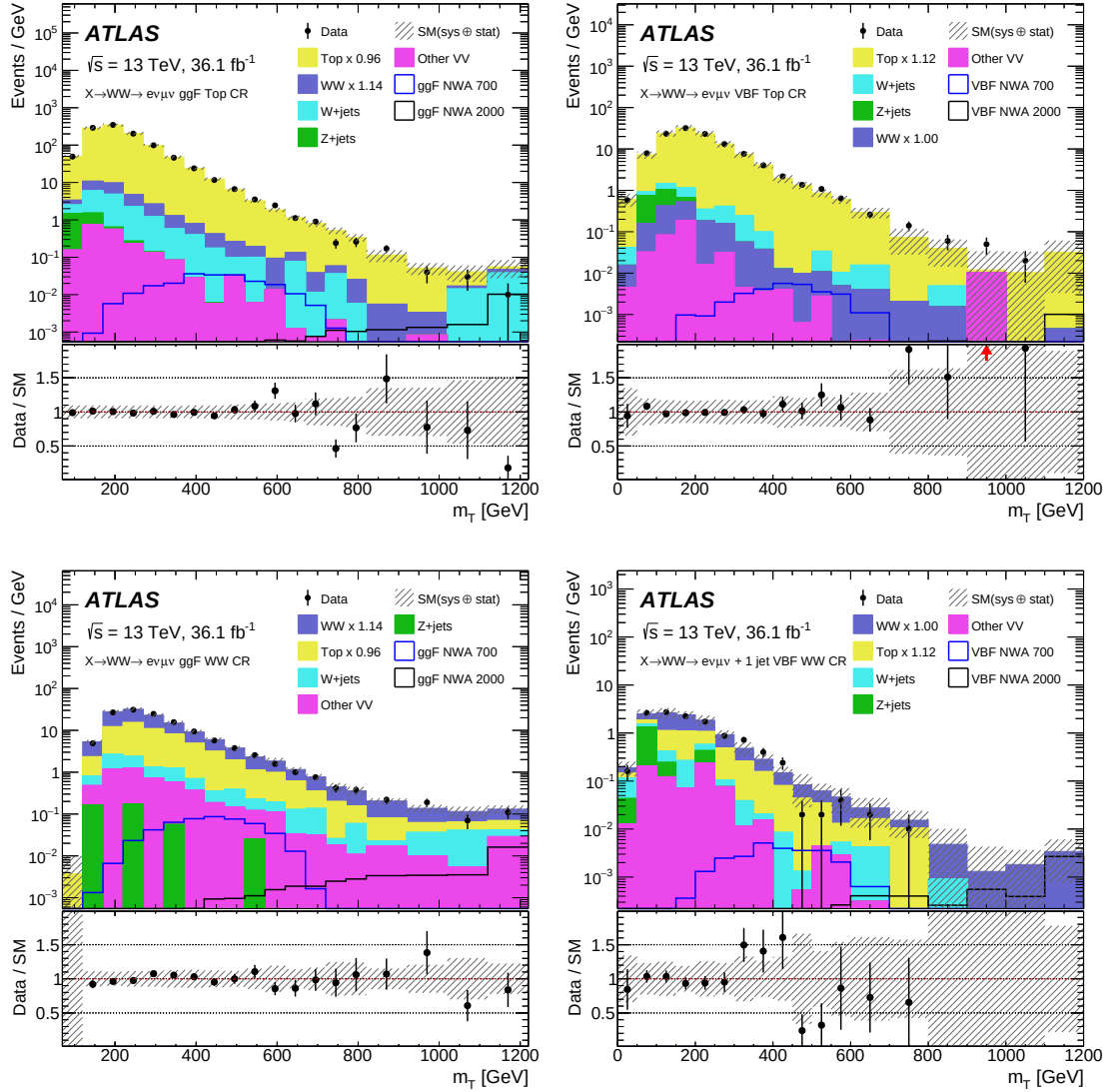


Figure 5.2. – Post-fit distributions of the transverse mass m_T in Top CR_{ggF} (top left), Top CR_{VBF} (top right), WW CR_{ggF} (bottom left), and WW CR_{VBF1J} (bottom right) [14].

The 95% CL upper limits on $\sigma_H \times BR(H \rightarrow WW)$ have been calculated with the signals at different m_H . In the NWA scenario, limits on the ggF (VBF) production in a mass range of 200 GeV to 4 (3) TeV have been shown in Figure 5.3. The limits set on a signal as the total ggF and VBF production at 800 GeV with varying fractions of ggF and VBF are shown in the Figure 5.3 as well. The limits exclude signals above 6.4 pb (1.3 pb) at 200 GeV and above 0.008 pb (0.006 pb) at 4 (3) TeV with a CL at 95% for the ggF (VBF) NWA production. A more stringent limit observed than expected in the high m_T area can be explained by the data deficit in Figure 5.1. Better limits are achieved for VBF signals thanks to the pure signal regions, especially in the $N_{b\text{-jets}} \geq 2$ category.

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.5. Fit results

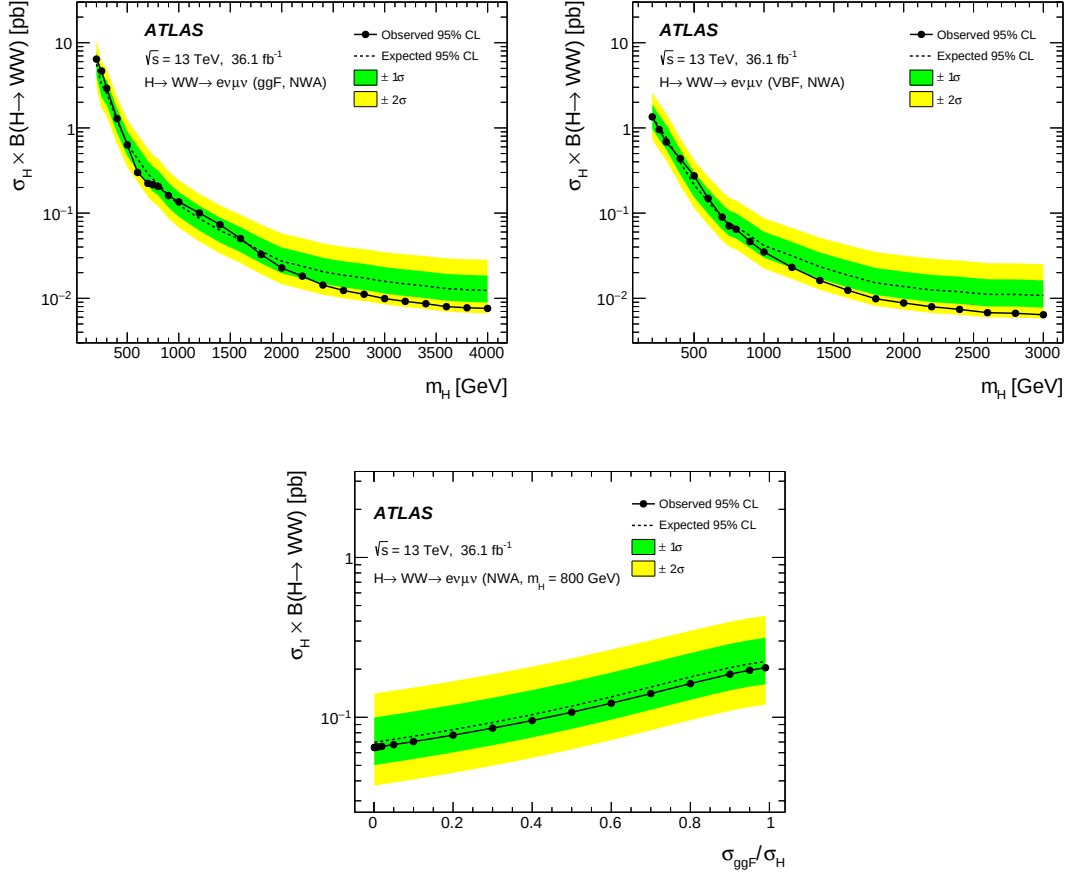


Figure 5.3. – The 95% CL upper limits on $\sigma_H \times BR(H \rightarrow WW)$ in the NWA scenario with $e\nu\mu\nu$ final state for ggF (top left) and VBF (top right) productions as a function of the Higgs mass, and on the total ggF and VBF production at 800 GeV (bottom) as a function of the fraction $\sigma_{ggF}/\sigma_{total}$ [14].

Correlations between the nuisance parameters for ggF and VBF signals at 800 GeV are shown in Figure 5.4. Only correlations between PDF on top quark background and NF_{Top}^{ggF} , Matrix Element+Parton Shower (MEPS) uncertainty on top quark background and NF_{Top}^{VBF} are larger than 50%. Rankings of nuisance parameter impacts on μ are shown in Figure 5.5, which also give the pulls and constraints. The left and right plots show the rankings for ggF and VBF Higgs at 800 GeV, respectively.

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.5. Fit results

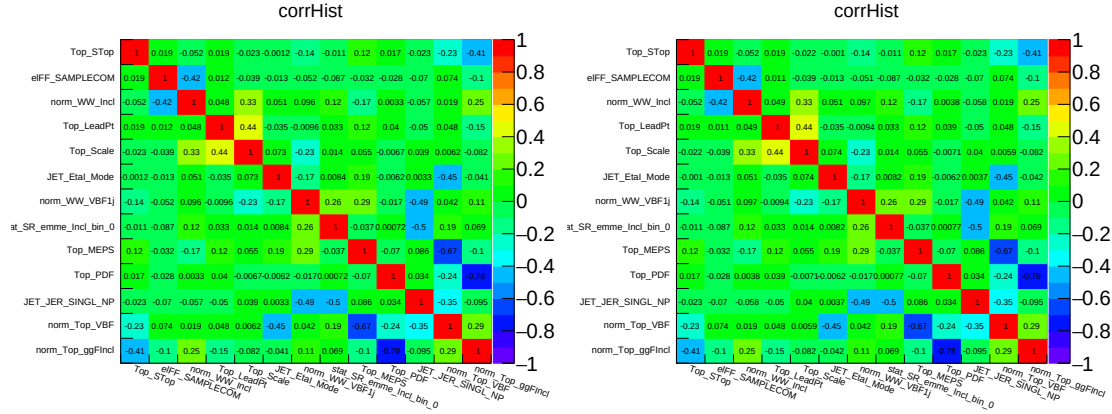


Figure 5.4. – The correlation matrices for ggF (left) and VBF (right) productions at 800 GeV with NWA assumption. Only NPs with coefficients above 40% are shown [14].

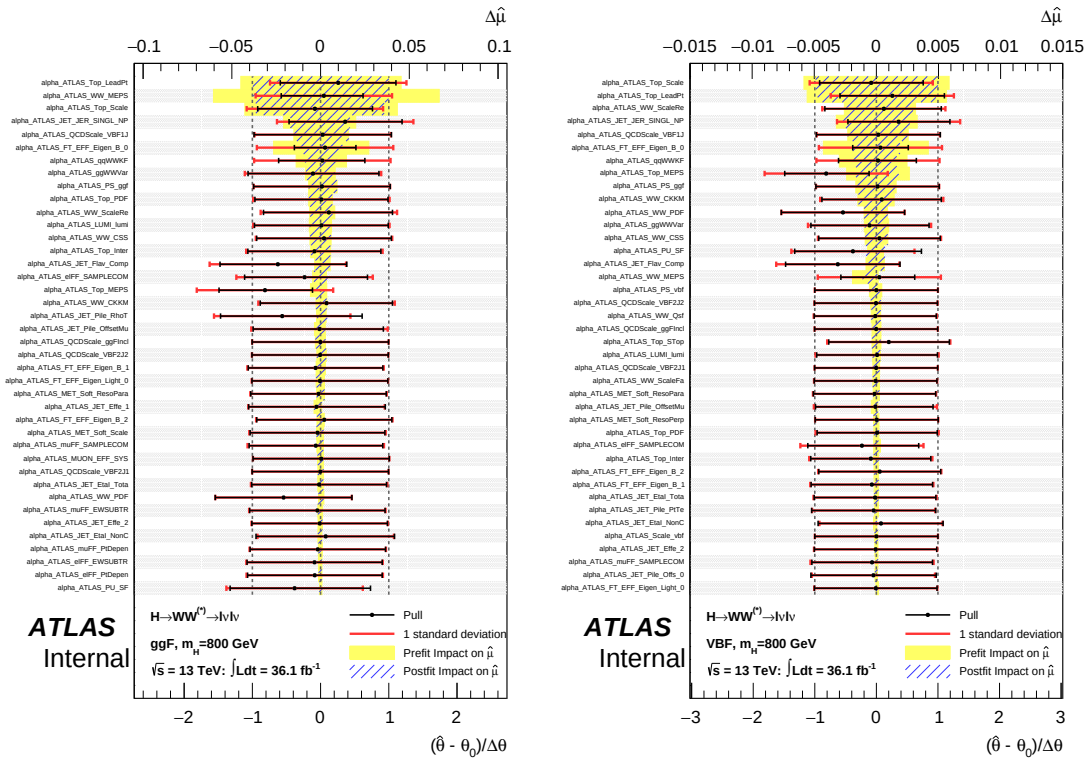


Figure 5.5. – The rankings of nuisance parameter impacts on μ for ggF (left) and VBF (right) productions at 800 GeV with NWA assumption [14].

A few theoretical and experimental uncertainties, which are largely

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.5. Fit results

pulled or constrained, are carefully studied. The main uncertainties affecting the limits are the leading lepton p_T correction (LeadPt) and scale variations on top quark background. The shapes of these theoretical systematic uncertainties are checked in Section 5.6.1. The flavour tagging efficiency systematic uncertainty on b-jets, which has an about 10% variation on top quark background, has been constraint thanks to the very pure Top CRs.

In Figure 5.6, the 95% CL limits set for the LWA scenario are shown for the ggF and VBF productions. The interference effects among the heavy boson, the light Higgs boson at 125 GeV, and the SM WW background have been studied and found negligible (see in Section 5.6.3). For the LWA 15% case, the limit exclude the signal above 5.2 pb (1.3 pb) at $m_H = 200$ GeV and 0.02 pb (0.006 pb) at $m_H = 4(3)$ TeV in ggF (VBF) channel.

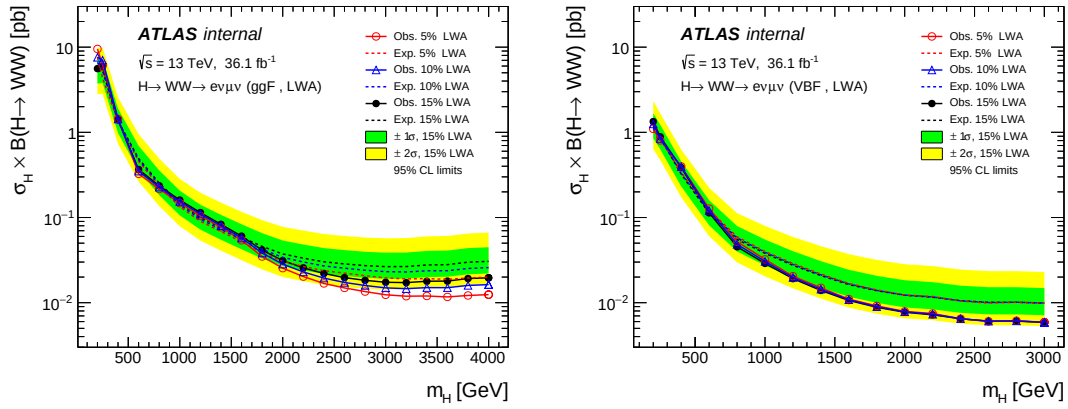


Figure 5.6. – The 95% CL upper limits on $\sigma_H \times BR(H \rightarrow WW)$ in the LWA scenario with $e\nu\mu\nu$ final state for ggF (left) and VBF (right) productions as a function of the Higgs mass. The assumptions with 5%, 10%, and 15% signal widths are compared in each plot [14].

The 95% CL exclusion contours for Type I and Type II 2HDM are shown in Figure 5.7. The limits set in the 2D plane of $\tan \beta$ and $\cos(\beta - \alpha)$ are translated from the NWA exclusion limits at 200, 300, and 500 GeV. In Figure 5.8, 95% CL exclusion limits on $\tan \beta$ have been set as a function of the heavy Higgs mass, with $\cos(\beta - \alpha)$ fixed at -0.1.

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.5. Fit results

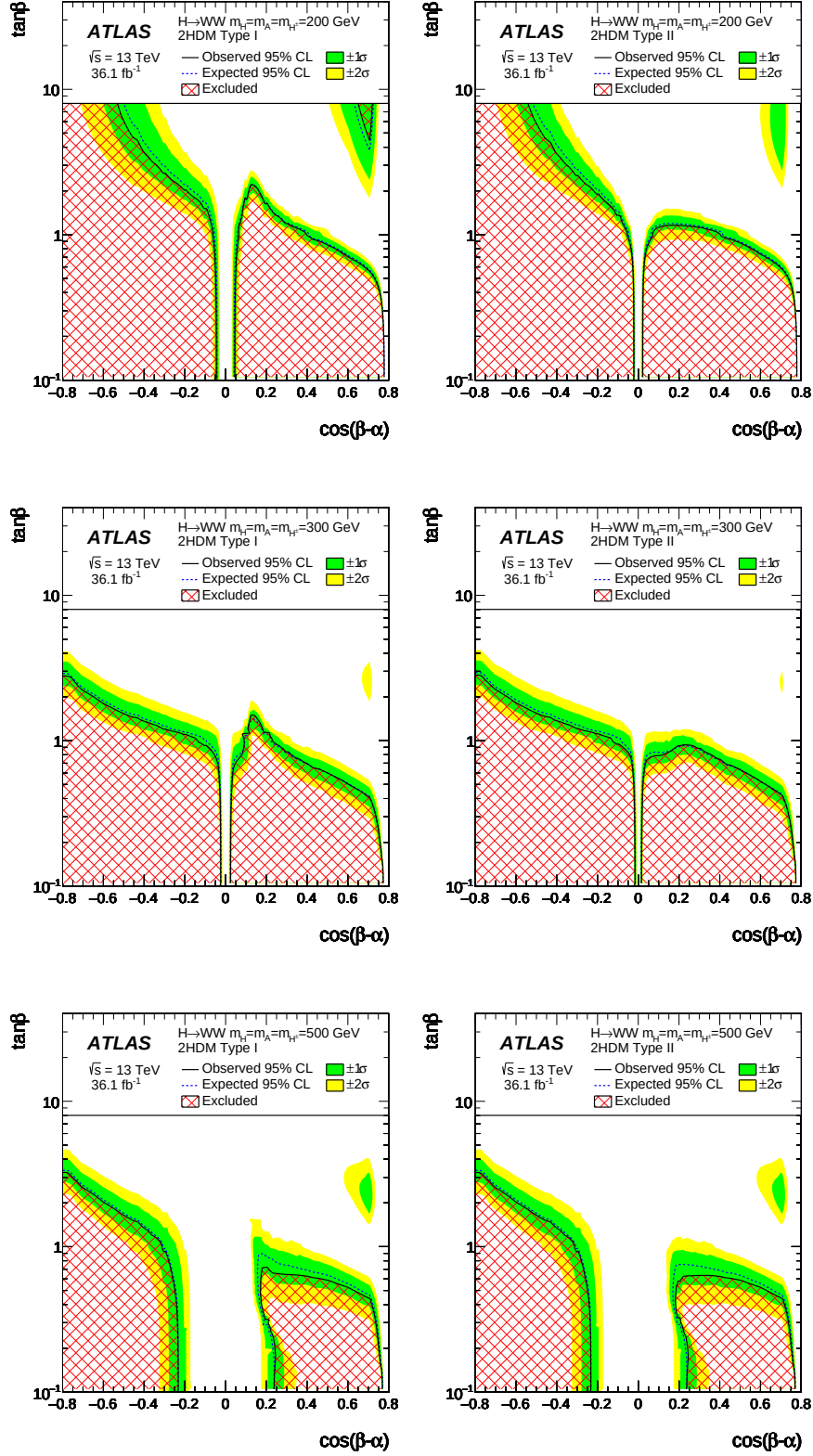


Figure 5.7. – Exclusion contours at 95% CL in the plane of $\tan\beta$ and $\cos(\beta-\alpha)$ for Type I (left) and Type II (right) 2HDM. Signals are chosen at 200 GeV (top), 300 GeV (middle), and 500 GeV (bottom) in the NWA scenario [14].

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.5. Fit results

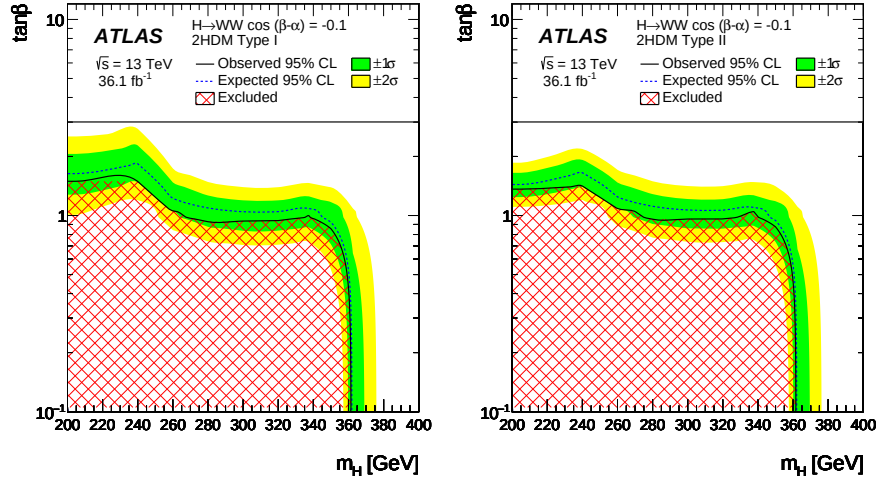


Figure 5.8. – Exclusion contours at 95% CL in the plane of $\tan\beta$ and m_H for Type I (left) and Type II (right) 2HDM with $\cos(\beta - \alpha) = 0.1$. A and $H^\pm$ are assumed to have the same mass as H [14].

Figure 5.9 shows the 95% CL upper limits setting on $\sigma_X \times BR(X \rightarrow WW)$ and $\sin\theta_H$ searching for a VBF GM signal with spin-0. No exclusion can be set compared to the predicted theoretical cross section calculated with $\sin\theta_H = 0.4$ in the mass range between 200 GeV and 1 TeV.

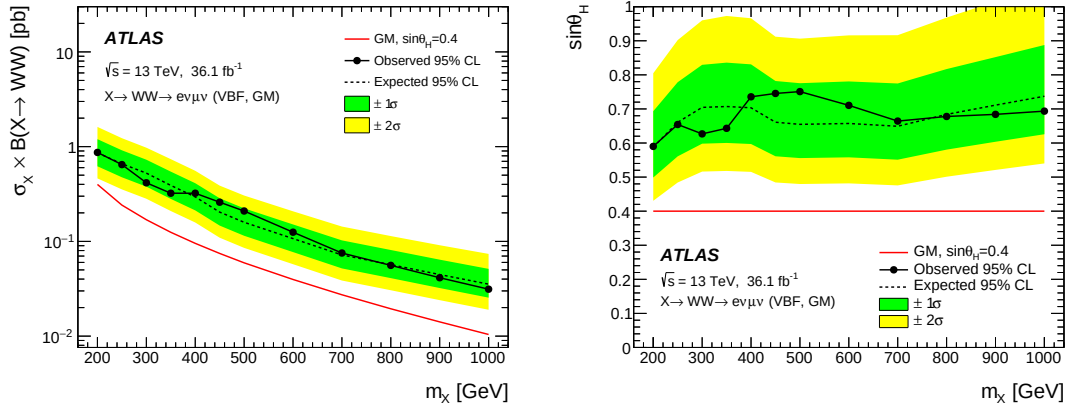


Figure 5.9. – The 95% CL upper limits on $\sigma_X \times BR(X \rightarrow WW)$ (left) and $\sin\theta_H$ (right) for GM signal with $e\nu\mu\nu$ final state [14].

HVT signals are searched in the mass range from 250 GeV to 5 TeV (300 GeV to 1 TeV) in a qqA (VBF) production channel. The limits setting for both signals at 95% CL are shown in Figure 5.10. The qqA signals below 1.3 TeV are excluded. In the VBF channel,

5. Search for $X \rightarrow WW \rightarrow e\nu\mu\nu$ with 36.1 fb^{-1} dataset – 5.5. Fit results

the coupling strength to gauge bosons g_V has been set to 1, while the coupling to fermions c_F has been set to 0. No exclusion can be set for the VBF HVT signal.

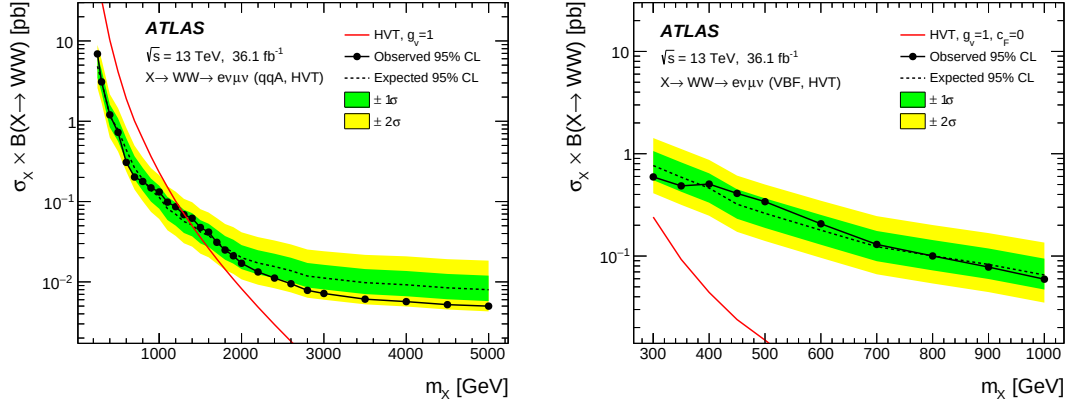


Figure 5.10. – The 95% CL upper limits on $\sigma_X \times BR(X \rightarrow WW)$ for qqA (left) and VBF (right) signals with $e\nu\mu\nu$ final state [14].

Figure 5.11 shows the limits set for the spin-2 ggF production predicted by the RS model and the VBF production predicted by the ELM. Two different couplings, $k/\bar{M}_{Pl} = 1$ and $k/\bar{M}_{Pl} = 0.5$, have been considered for G_{KK} in the mass range from 200 GeV to 5 TeV. The mass range sets for ELM spin-2 VBF signal searching is from 200 GeV to 1 TeV. The KK graviton signal has been excluded when its mass below 1.1 TeV (750 GeV) with a coupling at $k/\bar{M}_{Pl} = 1$ (0.5). The current sensitivity is not sufficient for the ELM spin-2 VBF signal excluding.

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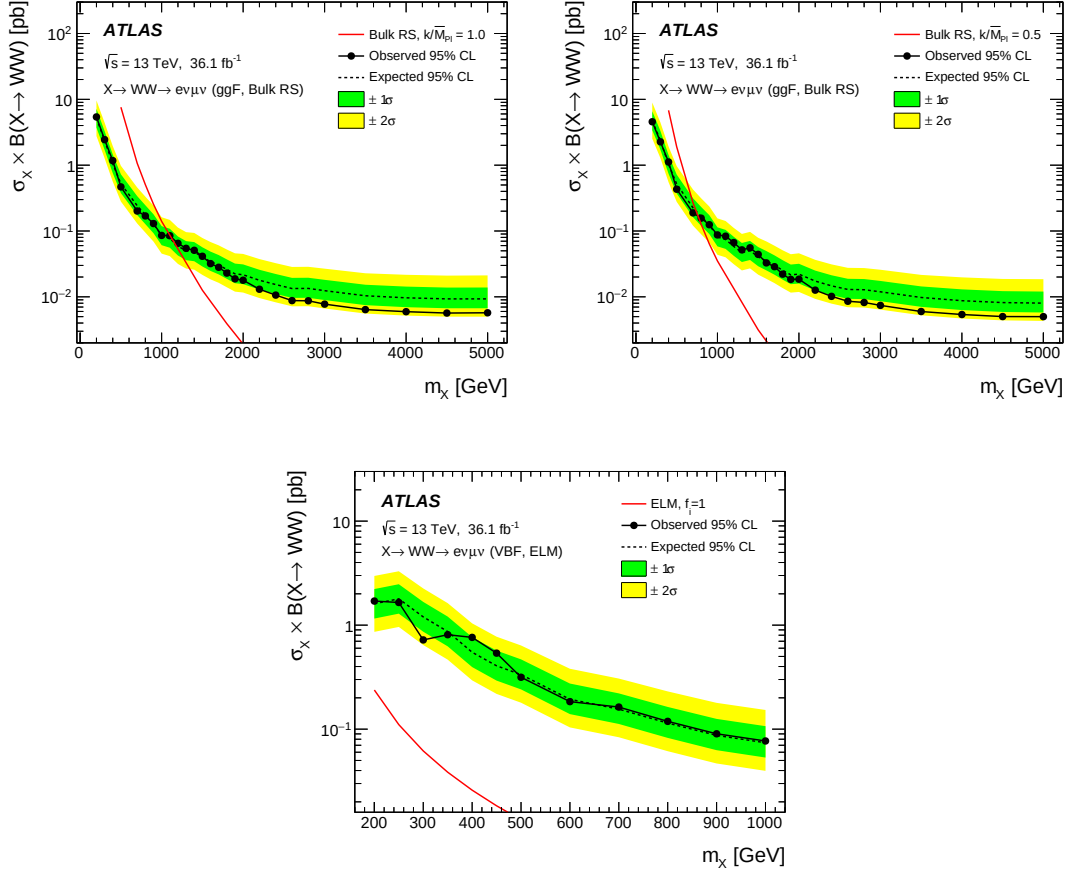


Figure 5.11. – The 95% CL upper limits on $\sigma_X \times BR(X \rightarrow WW)$ for graviton signals with $e\nu\mu\nu$ final state. The RS gravitons with couplings of $k/\bar{M}_{Pl} = 1.0$ (left) and $k/\bar{M}_{Pl} = 0.5$ (right) and the ELM spin-2 VBF signal (bottom) are considered [14].

5.6. Post fit checks

5.6.1. Shapes of theoretical systematics

According to the rankings in Figure 5.5, theoretical systematic uncertainties in both normalisation and m_T distribution shapes are the dominant sources for the impact on μ . The shapes of the highly ranked systematics have been checked in the ggF signal region and shown in Figure 5.12. The two theoretical systematic uncertainties for top quark are sensitive to the high m_T bins from their shapes, and the MEPS systematic for WW background is sensitive to both low mass and high mass ends.

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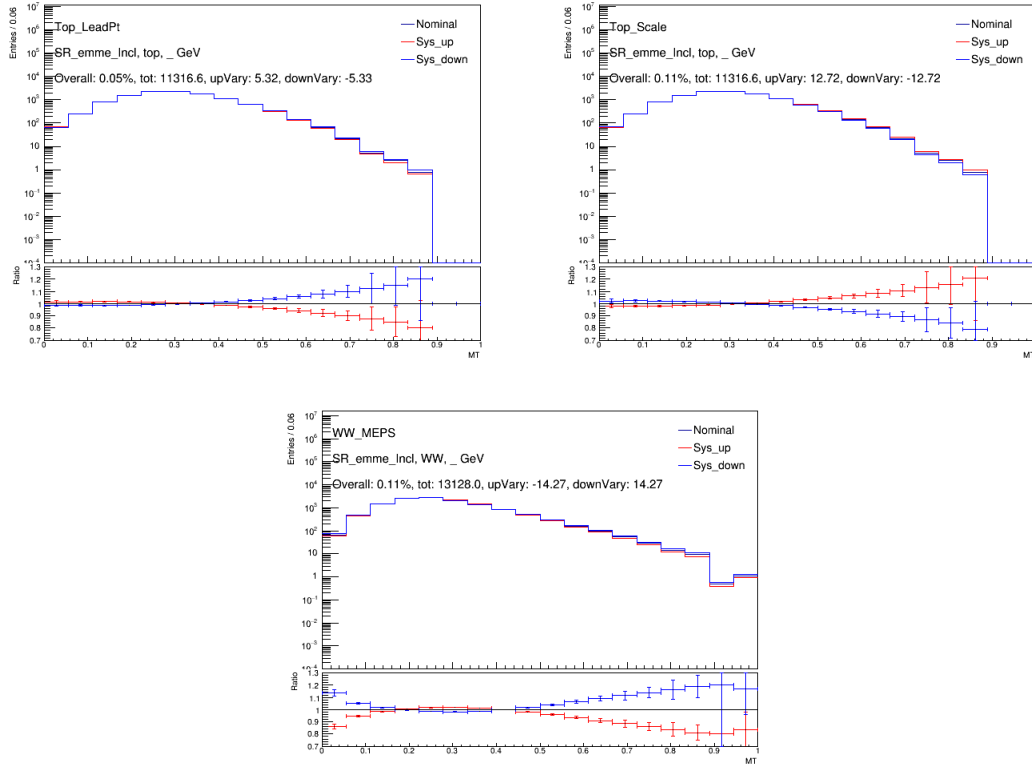


Figure 5.12. – The leading systematic uncertainties on the distribution of a mapped m_T binning. Shapes are shown for leading lepton p_T correction (top left) and scale variations (top right) for top quark background and Matrix Element + Parton Shower uncertainties (bottom) for WW in SR_{ggF} [14].

5.6.2. Signal injection study

A test on limit setting on MC with signal injections has been performed to study the effects from the input signal yield. The input signal samples are normalised to 1 pb for all mass points in the presented searching, while the corresponding cross section times branching ratio at 800 GeV is 0.22 pb with an NWA assumption. The signal injection test aims to tell if the fit model is sensitive enough to a signal at a benchmark model predicted scale, while the statistical input is at a scale of 1 pb.

The study has been performed at $m_H = 800 \text{ GeV}$, with NWA signal at scales of 5.5%, 11%, and 22% injects to the MC. The results have been summarised in Table 5.4. The fitted values for each signal strength show a high sensitivity to the scale of signal injected, and the growth of the signal is also reflected in the pseudo-observed limits.

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Signal injection at	0.055 pb	0.11 pb	0.22 pb
Fitted μ value	0.048 ± 0.11	0.10 ± 0.11	0.22 ± 0.12
Pseudo-observed limit	0.26	0.31	0.42
Expected limit	0.22	0.22	0.23

Table 5.4. – Signal injection test at 800 GeV with an NWA assumption.

5.6.3. Interference effects

The interference effects have been considered between a heavy resonance and the SM Higgs boson, as well as the SM WW continuum background. Distributions of the heavy resonance and interference are obtained with generator gg2VV [143]. Later, a reweighting is performed in the following way:

$$I^{derived} = I_{gg2VV}^{truth} \times \frac{S_{LWA}^{rec}}{S_{gg2VV}^{truth}} \quad (5.2)$$

where S_{LWA}^{rec} is the reconstructed m_T distribution of a LWA signal, while I_{gg2VV}^{truth} and S_{gg2VV}^{truth} are the m_T distributions of signal and interference term at truth level. The fit model can be written as

$$\mu n_{signal} + \sqrt{\mu} n_{interference} + n_{background} \quad (5.3)$$

taking the interference term into consideration. Limits at 95% CL have been set to study the impact of the interference effects with width=15% LWA signal. The results are summarised in the Table 5.5 and the impact is found negligible.

m_H [GeV]	600	1000	2000	3000
Without interference	0.485	0.151	0.0383	0.0283
With interference	0.488	0.149	0.0383	0.0282

Table 5.5. – Interference effects on the expected limits.

5.6.4. Toy MC

As a cross-check for the asymptotic approximation [125, 126], toy MCs have been produced to derive the upper limits μ_{up} for the NWA ggF signals at 800 GeV and 2 TeV. 4,000 sets of toys have been generated for both B-only and μ S+B hypotheses in each mass level.

The hypothesized μ in a model of μ S+B has been fine-tuned to have the p -values slightly above or below the $(1-\text{CL}_s)=5\%$ (see in Section 3.7.2), corresponding plots are shown in Figure 5.13. The solid line shows the observed value for q_μ in collision data. A $\frac{1}{2}\chi^2$ distribution is superimposed, showing the validity of the asymptotic

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approximation. The μ obtained from the toys at a 95% CL for 800 GeV signal is between 0.182 and 0.185, and between 0.025 and 0.026 for 2 TeV, while the asymptotic approximation computed μ is 0.174 (0.0214) for a signal mass at 800 GeV (2 TeV). The limits derived from the two methods are close.

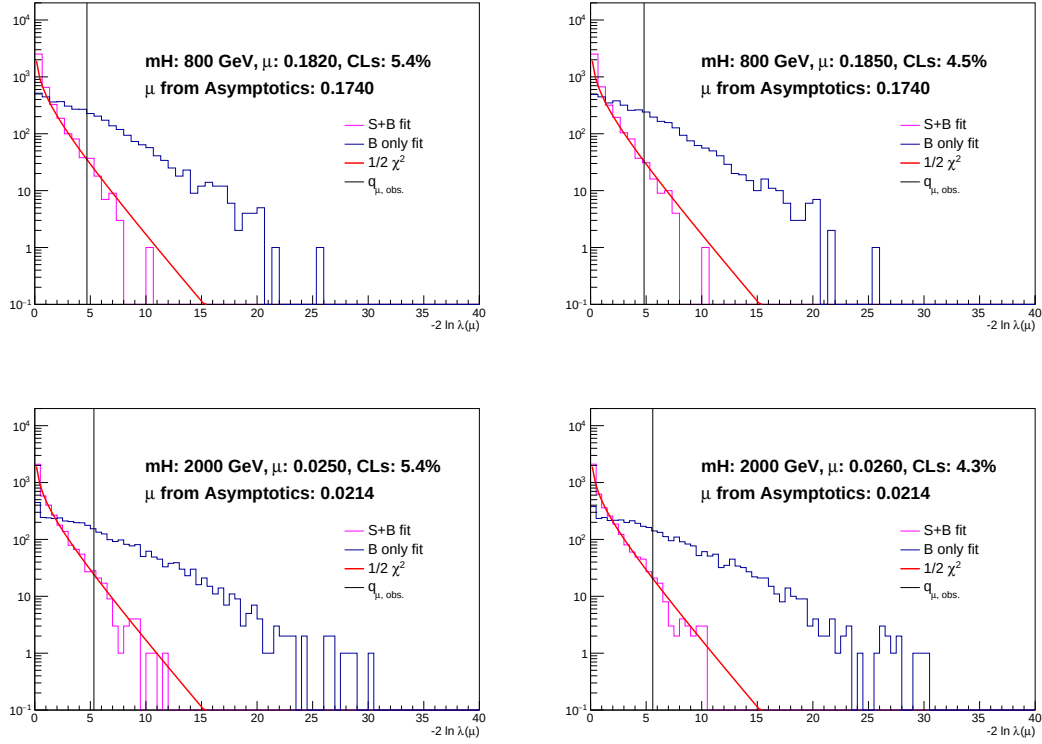


Figure 5.13. – The distribution of the test statistic q_μ under the hypothesis of $\mu s + b$ for $\sigma_H \times BR(H \rightarrow WW)$ in the NWA scenario with $e\nu\mu\nu$ final state. The ggF signals at 800 GeV with $\mu = 0.182$ (top left) and $\mu = 0.185$ (top right) and the ggF signals at 2 TeV with $\mu = 0.025$ (bottom left) and $\mu = 0.026$ (bottom right) are shown. The corresponding signal strengths computed by asymptotic approximation are 0.174 (at 800 GeV) and 0.0214 (at 2 TeV). The solid line gives the observed value for q_μ in a collision data. A $\frac{1}{2}\chi^2$ distribution is superimposed.

Conclusion

The SM, which describes the elementary particles and their interactions, is proved to be the most successful theoretical framework after the key particle in its prediction (the Higgs boson) was discovered by the ATLAS and CMS in 2012 [1, 2]. The ATLAS experiment measures the properties of more SM particles using the Run 1 and Run 2 pp collision data, while the search for BSM particles never stops.

In this thesis, a search for associated production of a Higgs boson with a top-quark pair in multilepton final states performed using an integrated luminosity of 79.9 fb^{-1} data collected by the ATLAS detector at the LHC during 2015-2017 at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ is presented. In such a process, direct measurement of the top-quark Yukawa coupling can be reached. Six final states are categorised by the number of light leptons and τ_{had} and fit simultaneously in the analysis. The fake background in $2\ell SS$ and 3ℓ channel is estimated by the template fit method with measured normalisation factors equal to $\hat{\lambda}_e^{IntC} = 0.83^{+0.32}_{-0.32}$, $\hat{\lambda}_e^{MatC} = 1.61^{+0.48}_{-0.48}$, $\hat{\lambda}_e^{had} = 1.12^{+0.38}_{-0.38}$, and $\hat{\lambda}_\mu^{had} = 1.20^{+0.18}_{-0.18}$, obtained from the data fit in all signal regions and control regions. The $t\bar{t}W$ background is estimated by the MC sample at NLO with QCD and EW corrections to $t\bar{t}W+1\text{-jet}$. Independent normalisation factors are assigned to $t\bar{t}W$ backgrounds in $2\ell SS$ low N_{jets} , high N_{jets} , and 3ℓ regions, and measured as $\hat{\lambda}_{t\bar{t}W}^{2\ell LJ} = 1.56^{+0.30}_{-0.28}$, $\hat{\lambda}_{t\bar{t}W}^{2\ell HJ} = 1.26^{+0.19}_{-0.18}$, and $\hat{\lambda}_{t\bar{t}W}^{3\ell} = 1.68^{+0.30}_{-0.28}$, separately. They are consistent with each other but $1.3\sim 1.7\sigma$ above the predicted cross section considered in this analysis (727 ± 92). The best-fit value of $\mu_{t\bar{t}H}$ is $\hat{\mu} = 0.58^{+0.36}_{-0.33}$, corresponding to a cross section of $\hat{\sigma}(t\bar{t}H) = 294^{+182}_{-162} \text{ fb}$. The measured cross section is consistent with the SM predicted value of $\sigma(t\bar{t}H) = 507^{+35}_{-50} \text{ fb}$ computed at NLO in QCD and EW couplings. The observed (expected) significance with respect to the background only hypothesis ($\mu = 0$) is 1.8σ (3.1σ). The results have been published as a conference note [5].

To better estimate the $t\bar{t}W$ background in the next round of $t\bar{t}H$ production in multilepton final states search, a measurement of $t\bar{t}W$ cross section is carried out first. The on-going analysis is performed using the full Run 2 dataset corresponding to an integrated luminosity of 139.0 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS experiment during 2015-2018. The first step results as measuring the $t\bar{t}W$ signal are planned to be published in early 2021. The second step, a search for the $t\bar{t}H$ production is expected to be published at the end of 2021. Both analyses are in a final state of multileptons. Due to the limitation of the analysis schedule, the presented results for the $t\bar{t}H$ searching is performed in $2\ell SS$ channel and fitted to an Asimov dataset with only statistical uncertainties. The fake background is estimated by the template fit method with normalisation factors extracted from the previous results and validated

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in $2\ell\text{SS}$ internal and external conversion validation regions. A cut based approach has been employed to separate the $2\ell\text{SS}$ high N_{jets} region into twelve signal regions. The best-fitted value of $\lambda_{t\bar{t}W}$ and $\mu_{t\bar{t}H}$ are $\hat{\lambda}_{t\bar{t}W} = 1.00^{+0.15}_{-0.14}$ and $\hat{\mu}_{t\bar{t}H} = 1.00^{+0.46}_{-0.45}$ with data blinded. The expected significance concerning the background-only hypothesis ($\mu = 0$) is 2.2σ .

A search for the BSM heavy neutral resonances decaying into WW pair in the $e\nu\mu\nu$ channel is performed using pp collision data collected at $\sqrt{s} = 13 \text{ TeV}$ corresponding to an integrated luminosity of 36.1 fb^{-1} by the ATLAS. Besides the model-independent assumptions for the heavy scalar Higgs boson, the search also sensitive to the heavy neutral resonances predicted by several benchmark models in the mass range from 200 GeV to 5 TeV. Upper limits are set on the production cross section times $X \rightarrow WW$ branching fraction at a confidence level of 95%. No significant excess is observed in the upper limits set for BSM predictions. The narrow-width heavy Higgs boson signals in a ggF (VBF) production mode are excluded with values above 6.4 pb (1.3 pb) at $m_H = 200 \text{ GeV}$ and above 0.008 pb (0.006 pb) at $m_H = 4 \text{ (3) TeV}$. The heavy vector triplet signals produced by a qqA process are excluded with m_X below 1.3 TeV. For the signals predicted by the RS graviton model with $k/\bar{M}_{Pl} = 1$ and 0.5, mass values below 1.1 TeV and 750 GeV are excluded, respectively. The results have been published as a paper [14].

With a center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$, the LHC plans to reach an integrated luminosity of 300 fb^{-1} during Run 3 after the Phase-I upgrade. For the HL-LHC, a goal for 10 years is collecting pp collision data with an integrated luminosity of about $3,000 \text{ fb}^{-1}$. The current $t\bar{t}H$ multilepton analysis is still dominated by statistical uncertainties, especially in high lepton multiplicity and τ_{had} channels. The data-driven method for fake estimations in $2\ell\text{SS}$ channel is also limited by the low statistics in the same-sign control region and high $N_{b\text{-jets}}$ control region. An improvement is expected for the $t\bar{t}H$ multilepton analysis with more data collected by the ATLAS detector in the coming years. The analysis for the process $X \rightarrow WW \rightarrow e\nu\mu\nu$ is also expected to have more μ_X space region excluded for different BSM predictions with more statistics.

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Appendix

A. Electron isolation and trigger efficiency calibrations for 2018 dataset

A preliminary result of electron calibration for the $t\bar{t}H$ multilepton standalone isolation working point as well as the trigger working point has been derived with the 2018 dataset. The corresponding efficiencies for the two calibrations are calculated by Equation 3.2 using a tag-and-probe method. The denominator follows the selection criteria used in defining the numerator of the upper stream efficiency. The numerator implements the testing working point on the base of the denominator.

The lepton isolation calibration took place before the PLIV working points optimised, which calibrates the same combined working point as shown in Section 3.3.3. The PLV is optimised with 2015-2017 data and applied to the 2018 dataset. For the QMisID working point, a continuous BDT result at 0.7 instead of the previous tight QMisID score at 0.7 is used in data analysis for 2018. The FixedCutLoose and ambiguityType are kept in this calibration practice.

The dependence of the data and MC efficiencies on electron interacts with the detector, namely on the amount of detector material and geometry (parametrized by η) and on the electron energy E_T has been considered in the measurement. The binning for (E_T, η) is listed in Table A.1.

Bin boundaries in E_T [GeV]														
4	7	10	15	20	25	30	35	40	45	50	60	80	150	∞
Bin boundaries in $ \eta $														
0	0.1	0.6	0.8	1.15	1.37	1.52	1.81	2.01	2.37	2.47				

Table A.1. – Bin boundaries in E_T and η directions in measurement of electron efficiencies using $Z \rightarrow ee$ events.

The tag-and-probe lepton pairs used in the measurement are from $Z \rightarrow ee$ process, in a range of $10 < E_T < 150$ GeV. The extrapolation efficiency is used for electron E_T out of this range. These $Z \rightarrow ee$ events are required to fire the single electron trigger, match to at least one primary vertex with two tracks, and have at least 2 electrons. A tag-and-probe pair must satisfy $60 < m_{ee} < 250$ GeV and with an opposite sign charge.

Selections for the tag are shown in the list:

- tight identified;

- $E_T > 25$ GeV;
- $|\eta| < 2.47$ excluding the transition region $1.37 < |\eta| < 1.52$;
- trigger matched;
- isolated from tracks in the ID and EM Calorimeter;
- truth matching (only for MC).

And selections for the probe are:

- not a tag electron;
- $E_T > 10$ GeV;
- $|\eta| < 2.47$;
- no associated jet ($p_T > 20$ GeV) with $\Delta R(\text{probe}, \text{jet}) < 0.4$;
- truth matching (only for MC).

Only a narrow mass window of 20~40 GeV centered on the Z boson mass peak is used as the signal region. The complementary regions are used for background estimation. In Figure A.1, Two plots show the efficiency comparisons between data and MC for the combined electron isolation working point. The left plot shows the efficiencies in the distribution of electron E_T in a range of $0 < \eta < 0.1$, while the right plot shows the efficiencies in the distribution of electron η in a range of $20 < E_T < 25$ GeV. Low efficiencies have been observed in low E_T and high η regions as expected.

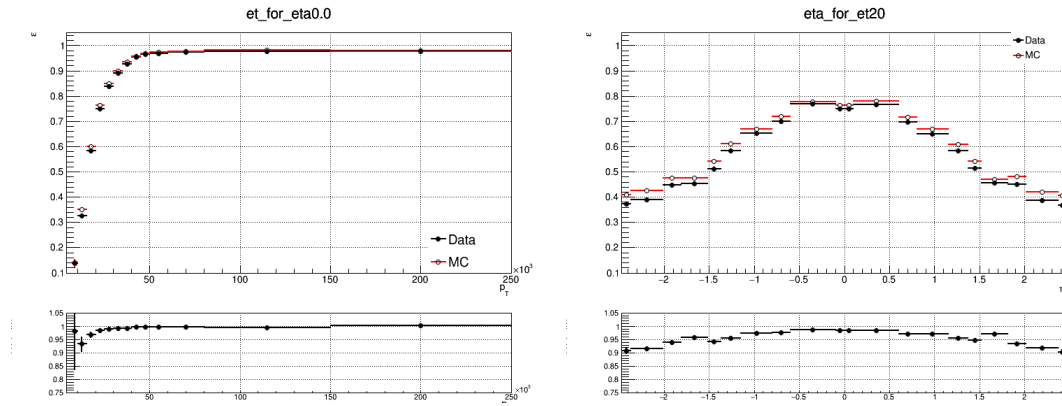


Figure A.1. – Probe electron efficiency in passing the combined isolation working point for data (black) and MC (red) in a distribution of E_T with $0 < \eta < 0.1$ (left) and η with $20 < E_T < 25$ GeV (right) for 2018 data.

Scale factor calculated by data/MC is shown in Figure A.2 on distributions of η in different E_T ranges. Bin to bin variation is large in low E_T regions due to low statistics. The statistical uncertainty is dominated in $E_T < 20$ GeV bins. Higher efficiency for MC in the high η range comes from the QMisID BDT.

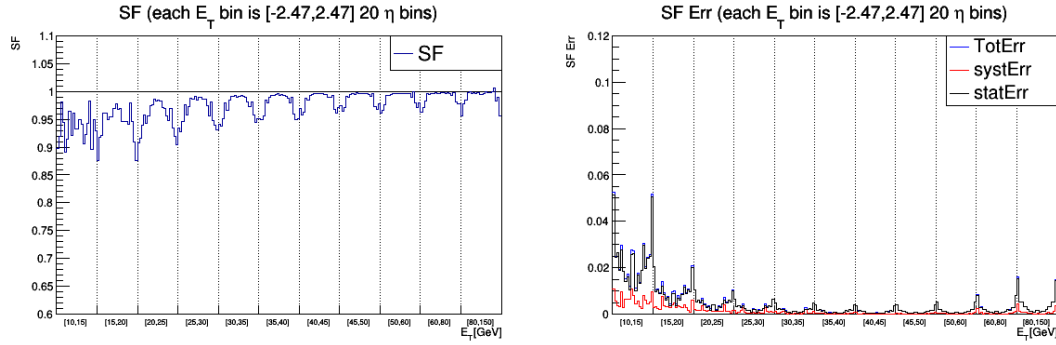


Figure A.2. – SF (left) and uncertainty (right) for the electron combined isolation working point calibration on distributions of η in different E_T ranges for 2018 data.

Calibrated efficiencies for data and MC and corresponding SFs in comparisons between different years are shown in Figure A.3. Higher efficiency for 2018 data in high electron η and E_T regions can be explained by the different QMisID working points used.

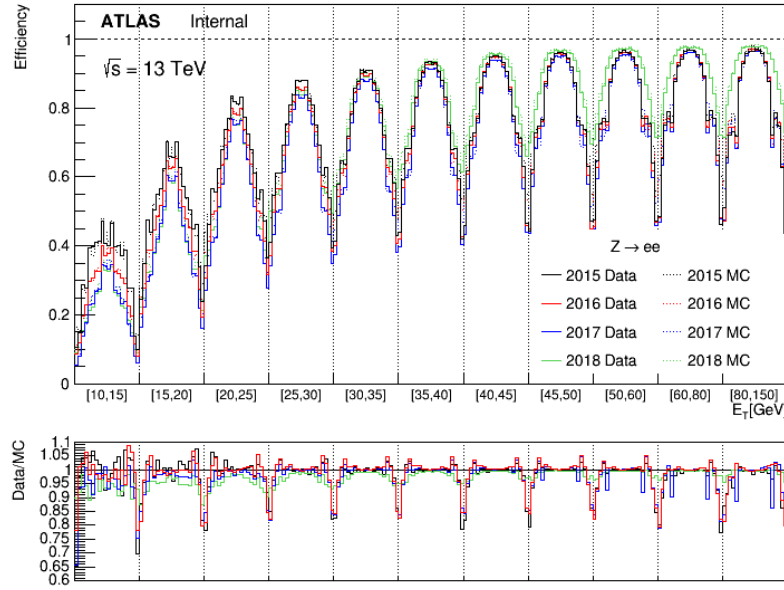


Figure A.3. – Calibrated efficiencies for data and MC at a combined tight electron isolation working point and corresponding SF calculated from data/MC, versus η distribution in different E_T bins. The efficiencies and SFs are calculated for 2015, 2016, 2017, and 2018 separately.

The lepton trigger efficiency is calibrated for different trigger strategies. Trigger decisions for 2015-2018 dataset are listed in Table 4.2. In this section, only the calibration

result for SLT is shown. The scale factor as data/MC and corresponding uncertainties are shown in Figure A.4. The SFs derived are close to 1 in $E_T > 30$ GeV bins. The efficiency drop in data in low E_T could be explained by too few entries coming in.

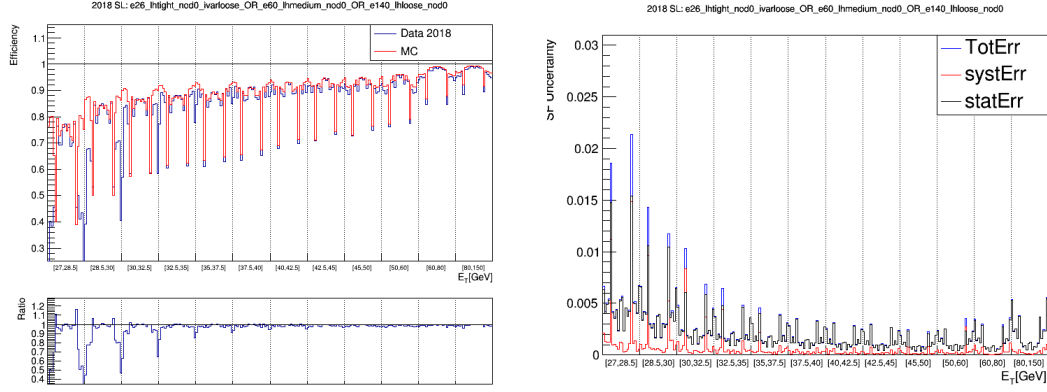


Figure A.4. – SF (left) and uncertainty (right) for DLT efficiency calibration on distributions of η in different E_T ranges for 2018 data.

B. Test on input variables

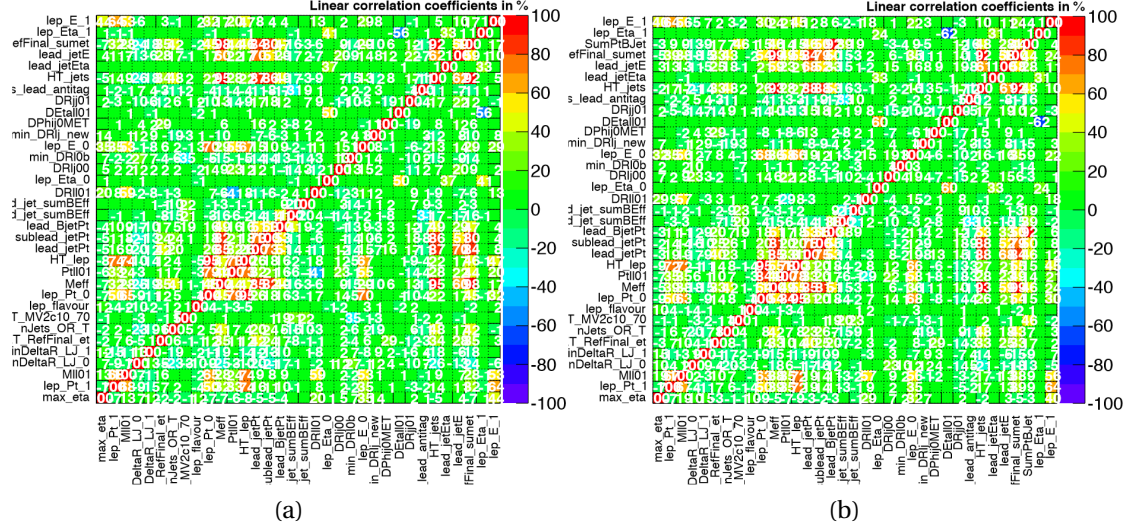
A test for varying the input variables has been performed to find the best set of discriminant variables against the two main backgrounds. The optimisation starts with a pool of 35 variables listed here:

$\Delta\eta_{\ell_0\ell_1}$	E_T^{miss}	E_{j_0}	η_{ℓ_0}	$\min \Delta R_{\ell_1 j}$
$\Delta\phi_{j_0, \text{MET}}$	ΣE_T	η_{j_0}	η_{ℓ_1}	$\min \Delta R_{\ell_0 b}$
$\Delta R_{j_0 j_1}$	M_{eff}	$p_T(j_0)$	$p_T(\ell_0)$	$\min \Delta R_{\ell j}$
$\Delta R_{l_0 j_0}$	$M_{\ell_0 \ell_1}$	$j_0^{not\ b-tag}$	$p_T(\ell_1)$	N_{jets}
$\Delta R_{\ell_0 \ell_1}$	$p_T(\ell_0, \ell_1)$	$\text{sum } j_0(b\text{-tag})$	lep_flavour	$N_{b\text{-jets}}$
HT_{jet}	$\text{sum } p_T(b - \text{jets})$	E_{ℓ_0}	$\max(\eta_\ell)$	$p_T(j_1)$
HT_{lep}	$p_T(b_0)$	E_{ℓ_1}	$\min \Delta R_{\ell_0 j}$	$\text{sum } j_1(b\text{-tag})$

Table B.2. – A pool of 35 MVA input variables.

The numeric value of Lepton flavour is defined as $2 \times N_{\mu_0} + N_{\mu_1}$. Variables for the leading jet and subleading jet, $\text{sum } j_0(b\text{-tag})$ and $\text{sum } j_1(b\text{-tag})$, represents how many b-tagging efficiency OP (60%, 70%, 77%, 85%) has it passed. For $j_0^{not\ b-tag}$, if its value is 1, the leading jet is b-tagged. Otherwise, $j_0^{not\ b-tag} = 0$.

In this pool, kinematic variables for leptons, jets, and E_T^{miss} are included, as well as the angular and distance variables between these objects. Jet/b-jet multiplicities and lepton flavour are also considered. The correlations between these input variables are shown in Figure B.5 for the signal and backgrounds.



The rankings of separation powers are shown in Table B.3 and B.4 for all 35 variables in the pool. Figure B.6 displays the distribution of the BDTG response.

$M_{\ell_0\ell_1}$	4.369×10^{-2}	$\Delta R_{\ell_0\ell_1}$	1.115×10^{-2}	$p_T(b_0)$	1.43×10^{-3}
E_{ℓ_0}	3.833×10^{-2}	η_{ℓ_0}	1.03×10^{-2}	sum $p_T(b - \text{jets})$	1.118×10^{-3}
min $\Delta R_{\ell_0 j}$	3.4×10^{-2}	η_{ℓ_1}	7.729×10^{-3}	$\Delta R_{j_0 j_1}$	1.007×10^{-3}
HT _{lep}	3.023×10^{-2}	min $\Delta R_{\ell_0 b}$	6.613×10^{-3}	$j_0^{not\ b\text{-tag}}$	7.916×10^{-4}
$\Delta\eta_{\ell_0\ell_1}$	2.879×10^{-2}	min $\Delta R_{\ell j}$	5.917×10^{-3}	sum $j_0(b\text{-tag})$	6.452×10^{-4}
$p_T(\ell_0)$	2.746×10^{-2}	HT _{jet}	4.483×10^{-3}	$N_{b\text{-jets}}$	3.147×10^{-4}
min $\Delta R_{\ell_1 j}$	2.633×10^{-2}	ΣE_T	3.704×10^{-3}	η_{j_0}	1.742×10^{-3}
E_{ℓ_1}	2.495×10^{-2}	M_{eff}	3.571×10^{-3}	E_T^{miss}	1.603×10^{-3}
$p_T(\ell_0, \ell_1)$	2.478×10^{-2}	$\Delta R_{l_0 j_0}$	3.095×10^{-3}	$p_T(j_0)$	1.587×10^{-3}
max ($ \eta_\ell $)	1.916×10^{-2}	$p_T(j_1)$	2.926×10^{-3}	sum $j_1(b\text{-tag})$	1.406×10^{-4}
$p_T(\ell_1)$	1.725×10^{-2}	E_{j_0}	2.008×10^{-3}	lepton flavour	3.04×10^{-5}
N_{jets}	1.709×10^{-2}	$\Delta\phi_{j_0, \text{MET}}$	1.951×10^{-3}		

Table B.3. – Ranking on separation power of input variables in the BDT training against the $t\bar{t}V$ background.

N_{jets}	8.485×10^{-2}	$\Delta\eta_{\ell_0\ell_1}$	3.325×10^{-2}	E_{j_0}	1.303×10^{-2}
HT _{jet}	7.428×10^{-2}	η_{ℓ_1}	2.877×10^{-2}	E_{ℓ_1}	1.261×10^{-2}
M_{eff}	6.735×10^{-2}	$\Delta R_{\ell_0\ell_1}$	2.56×10^{-2}	$\Delta R_{j_0 j_1}$	1.199×10^{-2}
max ($ \eta_\ell $)	6.194×10^{-2}	HT _{lep}	2.53×10^{-2}	$M_{\ell_0\ell_1}$	1.186×10^{-2}
ΣE_T	5.86×10^{-2}	$p_T(b_0)$	2.451×10^{-2}	$N_{b\text{-jets}}$	1.184×10^{-2}
min $\Delta R_{\ell_0 j}$	5.81×10^{-2}	min $\Delta R_{\ell j}$	2.296×10^{-2}	η_{j_0}	1.116×10^{-2}
min $\Delta R_{\ell_1 j}$	4.877×10^{-2}	$p_T(\ell_0)$	1.935×10^{-2}	sum $j_1(b\text{-tag})$	6.249×10^{-3}
lepton flavour	4.57×10^{-2}	E_{ℓ_0}	1.872×10^{-2}	$\Delta\phi_{j_0, \text{MET}}$	6.013×10^{-3}
η_{ℓ_0}	4.444×10^{-2}	$p_T(\ell_1)$	1.741×10^{-2}	sum $j_0(b\text{-tag})$	5.568×10^{-3}
$p_T(j_1)$	4.182×10^{-2}	$\Delta R_{l_0 j_0}$	1.686×10^{-2}	$j_0^{not\ b\text{-tag}}$	5.445×10^{-3}
$p_T(j_0)$	3.778×10^{-2}	$p_T(\ell_0, \ell_1)$	1.569×10^{-2}		
E_T^{miss}	3.71×10^{-2}	min $\Delta R_{\ell_0 b}$	1.367×10^{-2}		

Table B.4. – Ranking on separation power of input variables in the BDT training against the fake background.

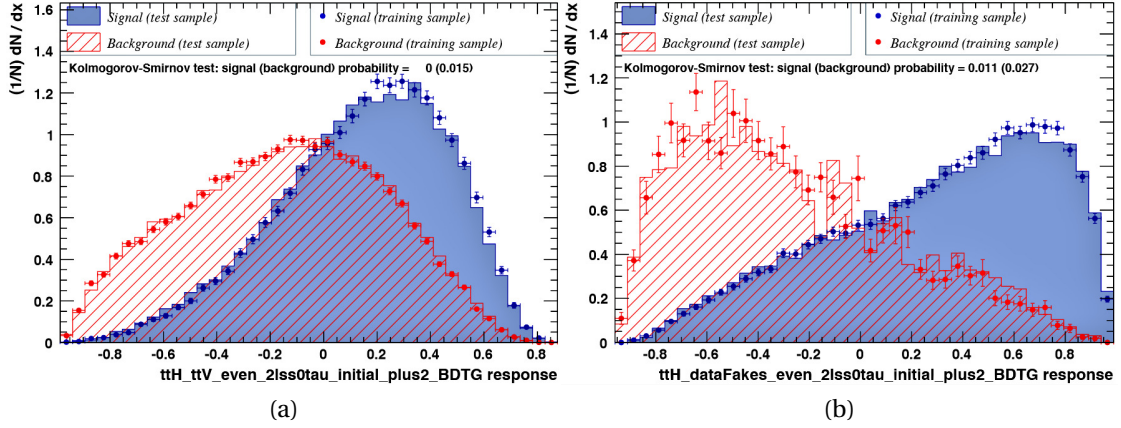


Figure B.6. – BDTG response distribution for $t\bar{t}H$ vs $t\bar{t}V$ (a) and $t\bar{t}H$ vs fakes (b) with 35 input variables.

As the BDTG evaluation result shows, some variables have low separation powers for discriminating signal and backgrounds, while some are largely correlated with others. A slim has been performed on the 35 variables, and 13 variables are selected against each background in the final.

The input variables selected are:

- Against $t\bar{t}V$: $M_{\ell_0\ell_1}$, E_{ℓ_0} , $\min \Delta R_{\ell_0j}$, $\min \Delta R_{\ell_1j}$, $p_T(\ell_0)$, $\Delta\eta_{\ell_0\ell_1}$, E_{ℓ_1} , $p_T(\ell_0, \ell_1)$, $\max(|\eta_\ell|)$, N_{jets} , $\Delta R_{\ell_0\ell_1}$, η_{ℓ_0} , and $\min \Delta R_{\ell_0b}$;
- Against fakes: N_{jets} , HT_{jet} , $\max(|\eta_\ell|)$, $\min \Delta R_{\ell_0j}$, $\min \Delta R_{\ell_1j}$, leptonic flavour, η_{ℓ_0} , E_T^{miss} , $\Delta\eta_{\ell_0\ell_1}$, η_{ℓ_1} , $\Delta R_{\ell_0\ell_1}$, HT_{lep} , $p_T(b_0)$.

The modelling of these input variables are shown in Figure B.7. Data in bins with signal purity larger than 15% are blinded due to the fake background estimated by matrix method has not been approved by the ATLAS. The agreement between data and MC is not so good as expected. The MC modelling issue on $M_{\ell_0\ell_1}$, $p_T(\ell_1)$, and E_T^{miss} exists until we switch to the TF method.

Bibliography – B. Test on input variables

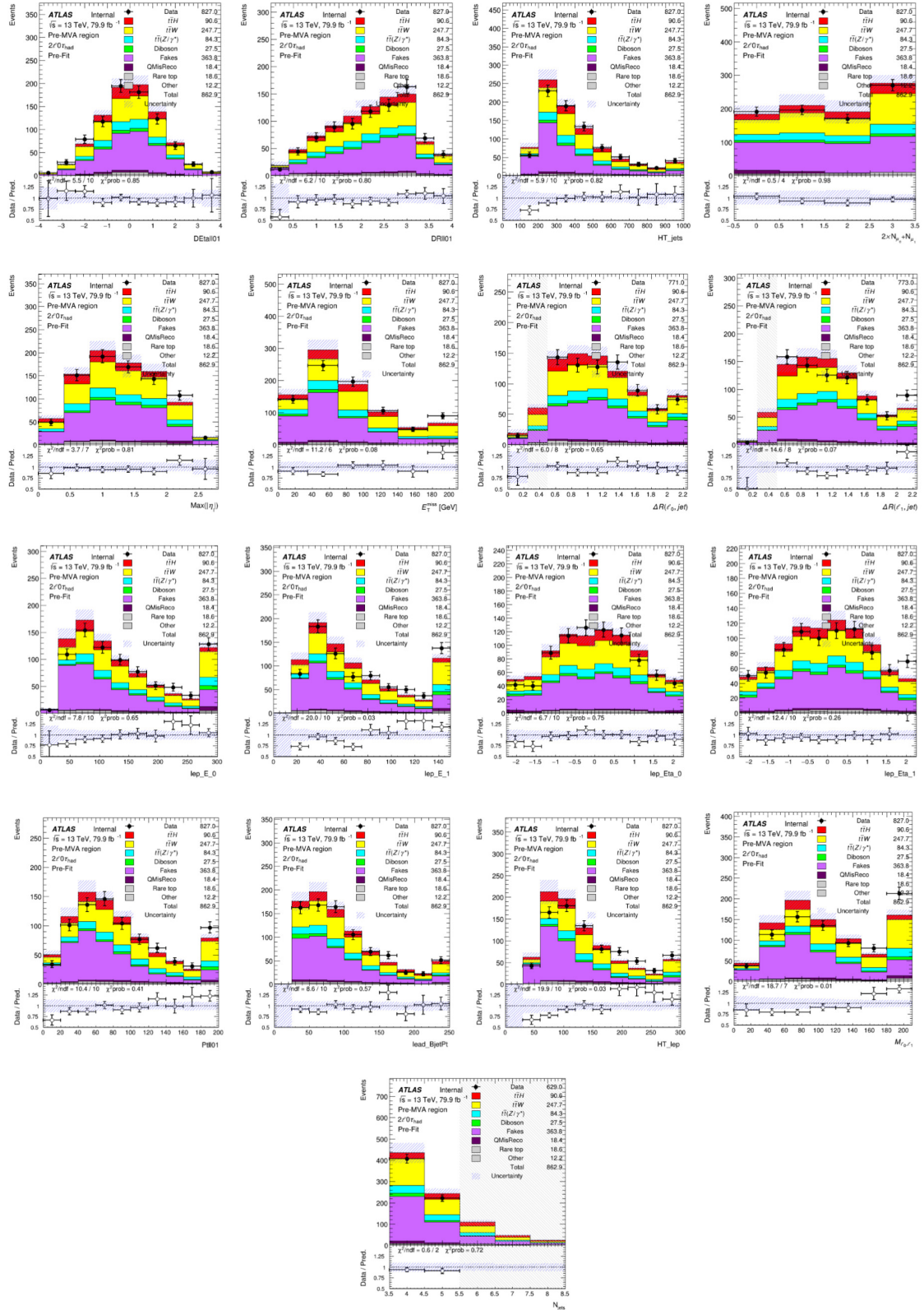


Figure B.7. – Modellings for all 13 input variables in 2ℓ SS high N_{jets} inclusive region. Data in the bins with signal purity larger than 15% are blinded due to the fake background estimated by MM in this modelling check have not been approved by ATLAS.

The distributions of separation power between $t\bar{t}H$ and $t\bar{t}V$ (fakes) of each input variables are shown in Figure B.8 and B.9).

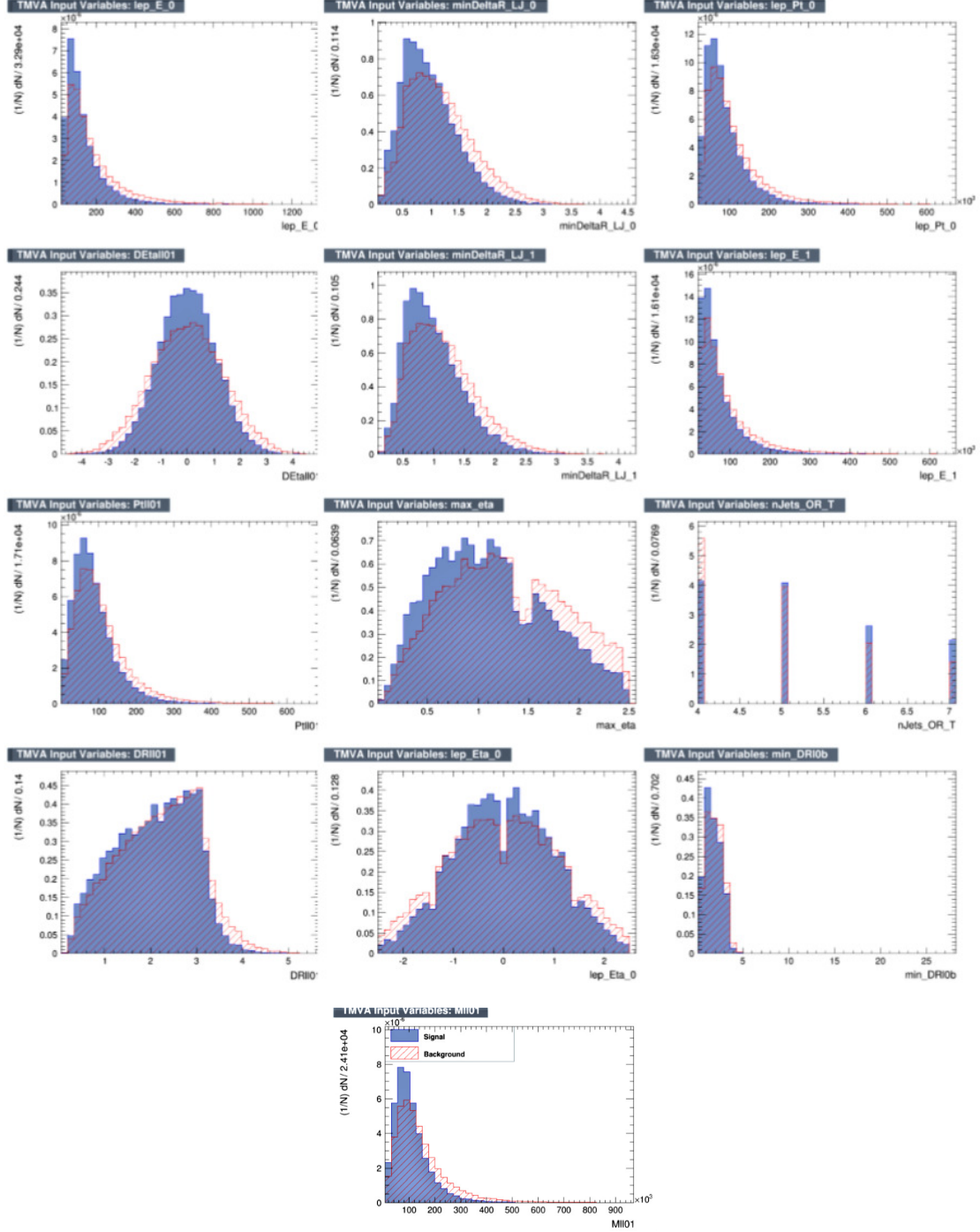


Figure B.8. – Separation power of the 13 input variables in the BDTG training for $t\bar{t}H$ signal against the $t\bar{t}V$ background.

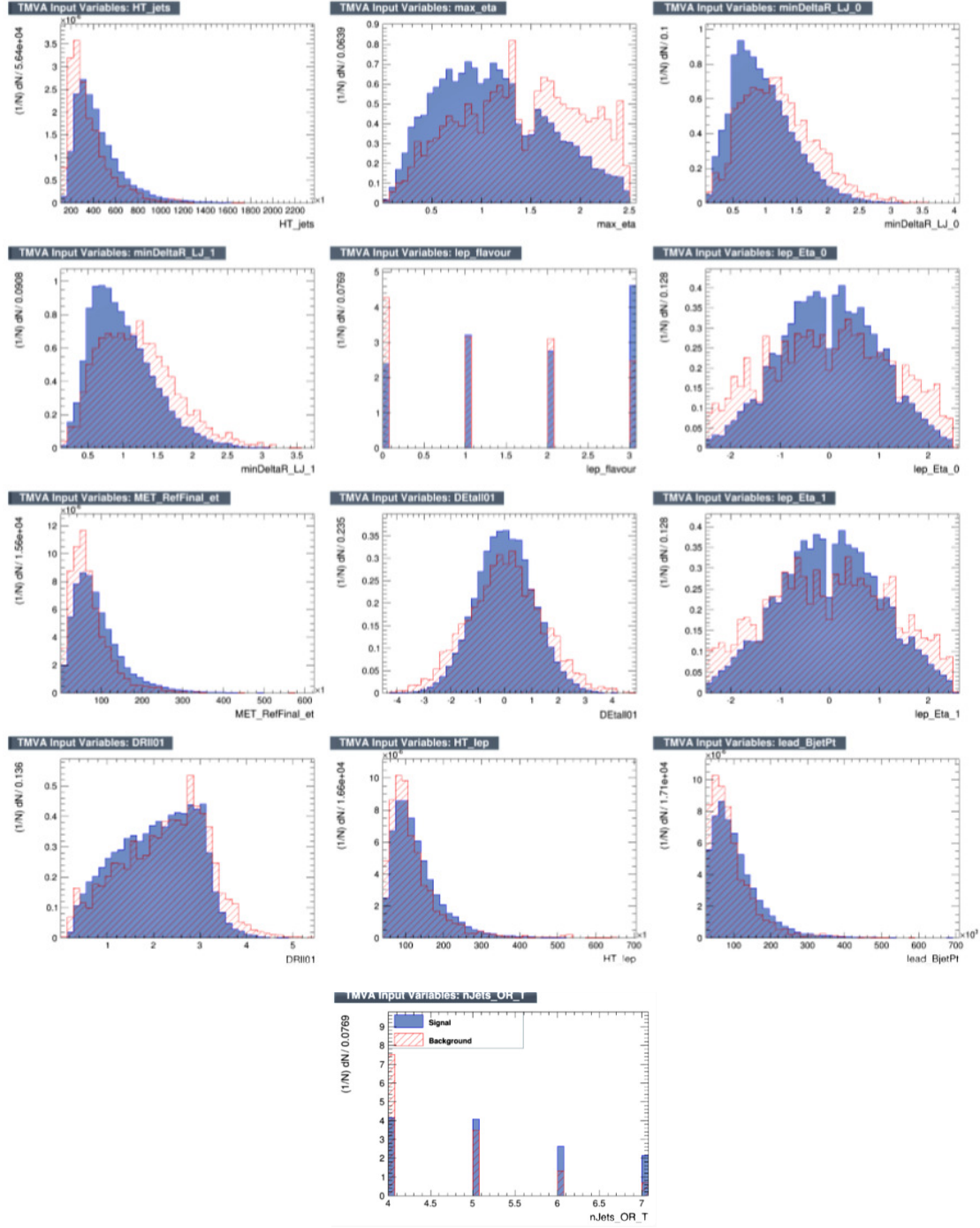


Figure B.9. – SSeparation power of the 13 input variables in the BDTG training for $t\bar{t}H$ signal against the data-driven fake background.

Performances of the two test BDTGs are shown in Figure B.10. The upper two plots are the response and ROC (Receiver Operating Characteristic) curves for BDTG trained against $t\bar{t}V$ background, while the lower two are the same plots for against fakes.

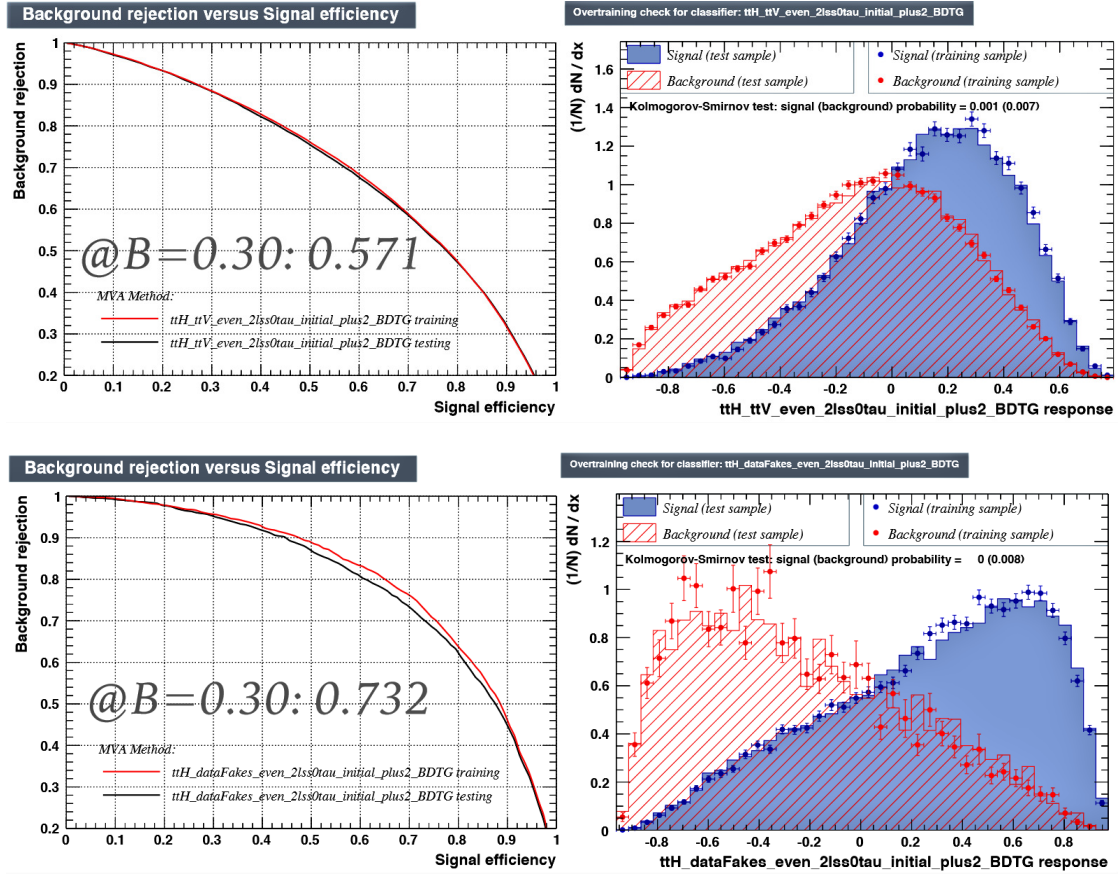


Figure B.10. – ROC curves (left) and BDT responses (right) for the BDTG training for $t\bar{t}H$ signal against the $t\bar{t}V$ background (up) and the data-driven fakes (down) with 13 input variables.

Comparing the new MVA to the previous MVA [95] retrained with new MC samples, we found the results as shown in Table B.5. The referred input variables in last round [95] are: $\max(|\eta_\ell|)$, $p_T(\ell_1)$, $M_{\ell_0\ell_1}$, $\min \Delta R_{\ell_0j}$, $\min \Delta R_{\ell_1j}$, E_T^{miss} , N_{jets} , N_{b-jets} , leptonic flavour.

The BDTG scores with a full set of 35 input variables have a distinct better performance for about 5~10% compared to the retraining results. Using 13 inputs, a subset of the 35 variables, the BDTG reaches the same level of results as in the last round. Concerning the modelling issues among the input variables and the tight publish schedule, the set of input variables close to the one used in the last round [95] is chosen.

@B=0.3	$t\bar{t}H$ vs $t\bar{t}V$	$t\bar{t}H$ vs fakes
Retraining with last round's variables	0.565	0.741
35 input variables	0.596	0.772
13 input variables	0.571	0.732

Table B.5. – MVA with new input variables compared to the retraining MVA with variables from the last round [95].

C. MVA classification with flavour split backgrounds

Considering the compositions are different in channels with different flavours of leptons, a test BDTG training with flavour split fake background has been performed. The event yields have been checked before the study. The BDTG are trained with $t\bar{t}H$ against:

- $t\bar{t}V$: eight input variables.
- ee + opposit flavour (OF) fakes: eight input variables.
- $\mu\mu$ fakes: seven input variables (no leptonic flavour).

The eight input variables are N_{jets} , $N_{b\text{-jets}}$, $\min \Delta R_{\ell_0 j}$, $\min \Delta R_{\ell_1 j}$, $\max(|\eta_{\ell}|)$, $p_T(\ell_1)$, E_T^{miss} , leptonic flavour (not used in MVA training against fake $\mu\mu$ events). The modellings of input variable in three BDTs are shown in Figure C.11, C.12, and C.13. Data in bins with signal purity larger than 15% are blinded due to the fake background estimated by matrix method has not been approved by the ATLAS. The modelling issue still exists as slopes observed in some of the distributions shown, though the variable $M_{\ell_0 \ell_1}$ with the worst modelling among all the inputs has already been removed in this test.

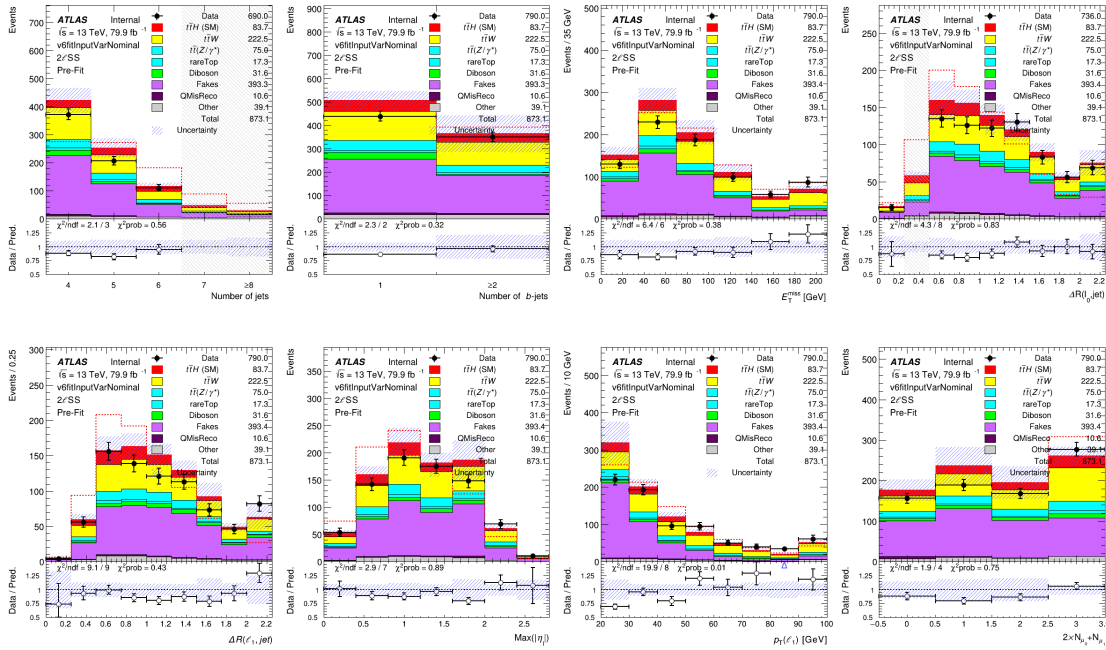


Figure C.11. – Pre-fit distributions of the eight input variables for BDTG against $t\bar{t}V$ background in a flavour inclusive channel. Data in the bins with signal purity larger than 15% are blinded due to the fake background estimated by MM in this modelling check have not been approved by ATLAS.

Bibliography – C. MVA classification with flavour split backgrounds

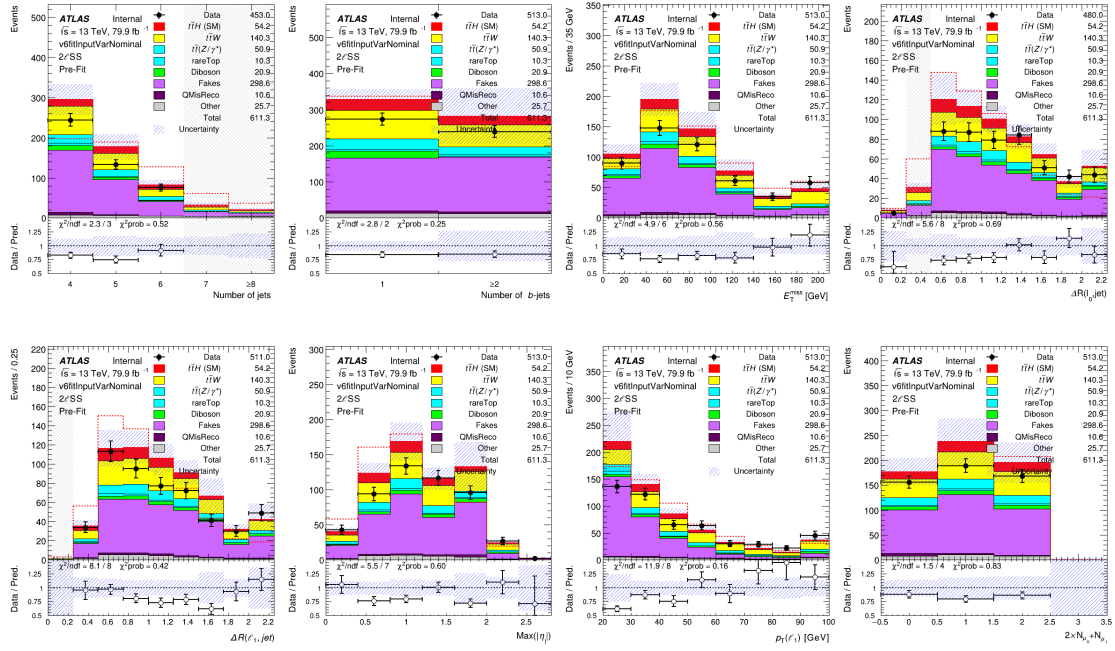


Figure C.12. – Pre-fit distributions of the eight input variables for BDTG against fake background in $ee+OF$ channel. Data in the bins with signal purity larger than 15% are blinded due to the fake background estimated by MM in this modelling check have not been approved by ATLAS.

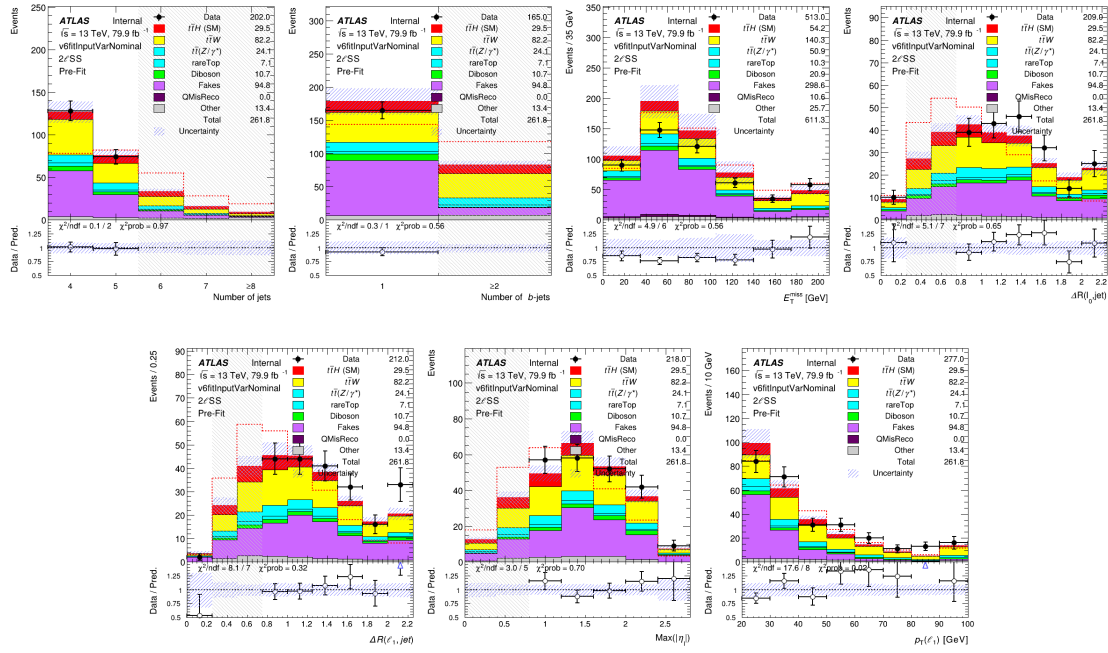


Figure C.13. – Pre-fit distributions of the eight input variables for BDTG against fake background in $\mu\mu$ channel. Data in the bins with signal purity larger than 15% are blinded due to the fake background estimated by MM in this modelling check have not been approved by ATLAS.

Correlation matrices are shown in Figure C.14, which indicate there are no large correlations between the input variables, as expected. Overtraining tests for the three channels are shown in Figure C.15. The training and test fake samples are not in good agreement, but still consistent with each other considering the statistics in these channels.

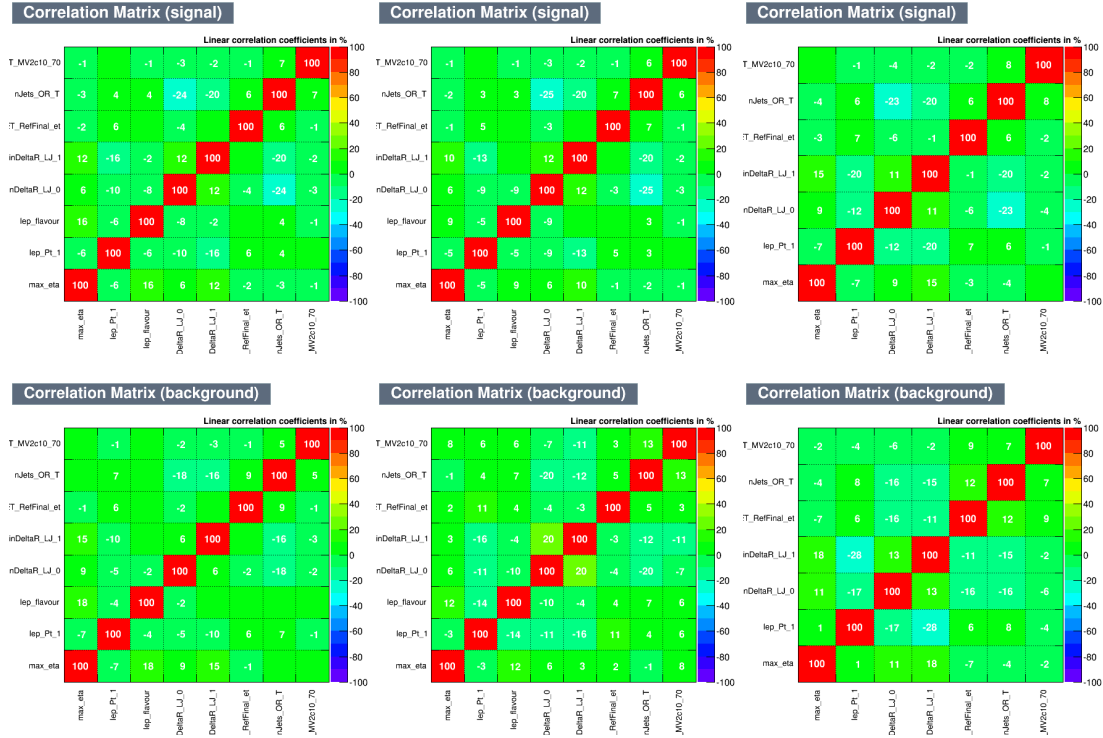


Figure C.14. – Correlation matrices for signal (up) and backgrounds (down). The left, middle, and right columns of plots show the correlations in $t\bar{t}H$ against $t\bar{t}V$ inclusive, ee +OF fake, and $\mu\mu$ fake channels.

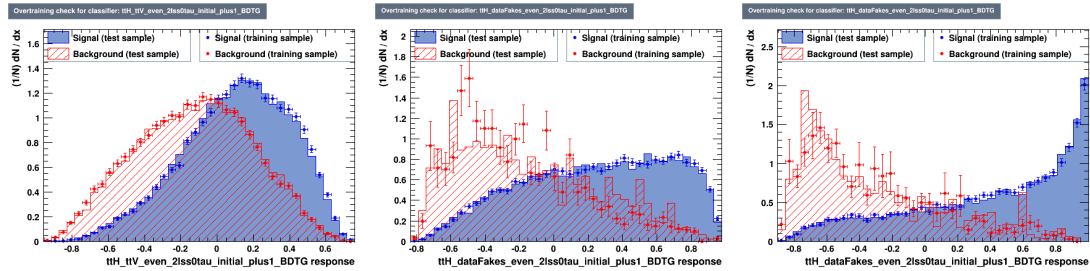


Figure C.15. – Overtraining tests for the inclusive flavour BDT_ $t\bar{t}V$ response and BDT_fake responses in ee +OF channel (middle) and $\mu\mu$ channel (right).

ROC curves in Figure C.16 show the performance of the BDTGs in three channels. Though with the lowest statistic, the fake $\mu\mu$ channel gains the best MVA discriminant power in the three channels. As expected, the BDTG against an irreducible background dominated by $t\bar{t}V$ has the lowest signal efficiency, at about 55% with a background rejection rate of 70%.

The same test has also been performed on TF non-prompt backgrounds. However, no clear improvement was observed by separating the flavours of leptons after balancing the gain from an extra BDT and the statistical reduction.

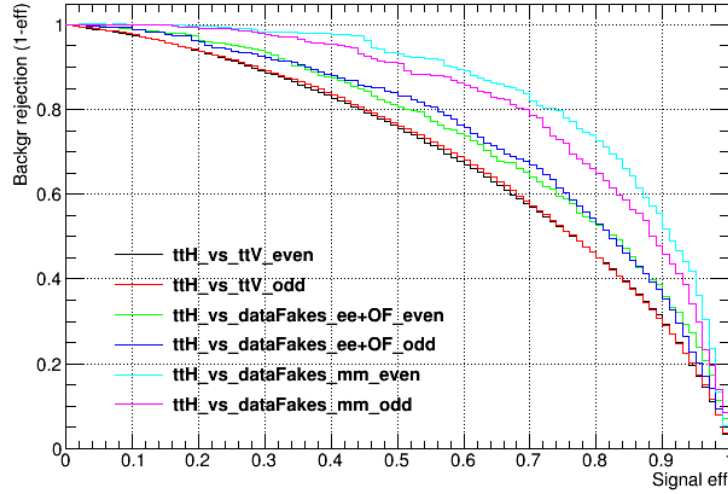


Figure C.16. – Background rejection versus signal efficiency for BDTs in all 3 channels.

D. Test on replacing the input variable $M_{\ell_0\ell_1}$ by $\Delta R_{\ell_0\ell_1}$

Concerning the bad MC modelling in the distribution of $M_{\ell_0\ell_1}$, an attempt was taken to replace or remove this variable from the MVA training. An alternative variable with good MC modelling is $\Delta R_{\ell_0\ell_1}$. Figure D.17 shows the modellings of $M_{\ell_0\ell_1}$ and $\Delta R_{\ell_0\ell_1}$. According to Figure B.5, the coefficient between $M_{\ell_0\ell_1}$ and $\Delta R_{\ell_0\ell_1}$ is 57% for signal $t\bar{t}H$ and 59% for backgrounds.

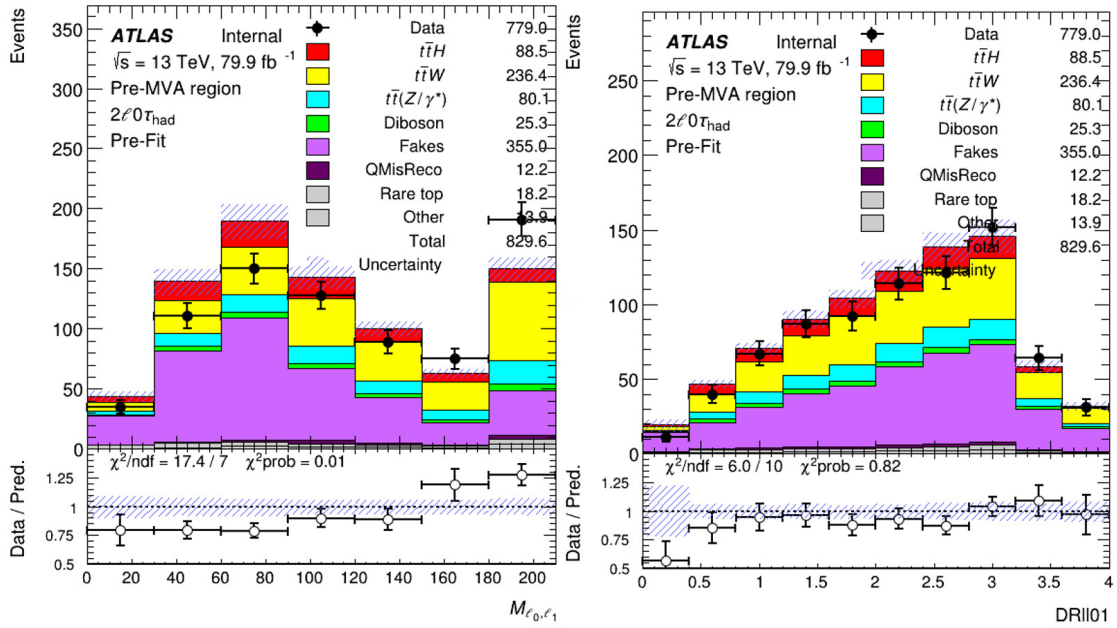


Figure D.17. – Modelling of $M_{\ell_0\ell_1}$ and $\Delta R_{\ell_0\ell_1}$ in 2ℓ SS high N_{jets} flavour inclusive region.

A test between the three cases is performed in this section. The three cases are:

- Case1 with nine variables: N_{jets} , $N_{b\text{-jets}}$, $\min \Delta R_{\ell_0 j}$, $\min \Delta R_{\ell_1 j}$, $\max(|\eta_\ell|)$, $p_T(\ell_1)$, E_T^{miss} , leptonic flavour, $M_{\ell_0\ell_1}$
- Case2 with nine variables: N_{jets} , $N_{b\text{-jets}}$, $\min \Delta R_{\ell_0 j}$, $\min \Delta R_{\ell_1 j}$, $\max(|\eta_\ell|)$, $p_T(\ell_1)$, E_T^{miss} , leptonic flavour, $\Delta R_{\ell_0\ell_1}$
- Case3 with eight variables: N_{jets} , $N_{b\text{-jets}}$, $\min \Delta R_{\ell_0 j}$, $\min \Delta R_{\ell_1 j}$, $\max(|\eta_\ell|)$, $p_T(\ell_1)$, E_T^{miss} , leptonic flavour

The correlation matrices are shown in Figure D.18 for the three cases. By replacing $M_{\ell_0\ell_1}$ with $\Delta R_{\ell_0\ell_1}$, the large coefficient between $M_{\ell_0\ell_1}$ and $p_T(\ell_1)$ disappeared. The variable $\Delta R_{\ell_0\ell_1}$ shows no large correlations with other variables. The rank on separation powers is displayed in Table D.6, which shows $M_{\ell_0\ell_1}$ plays an important role in BDTG_ $t\bar{t}V$, while $\Delta R_{\ell_0\ell_1}$ has a better performance in BDTG_fakes.

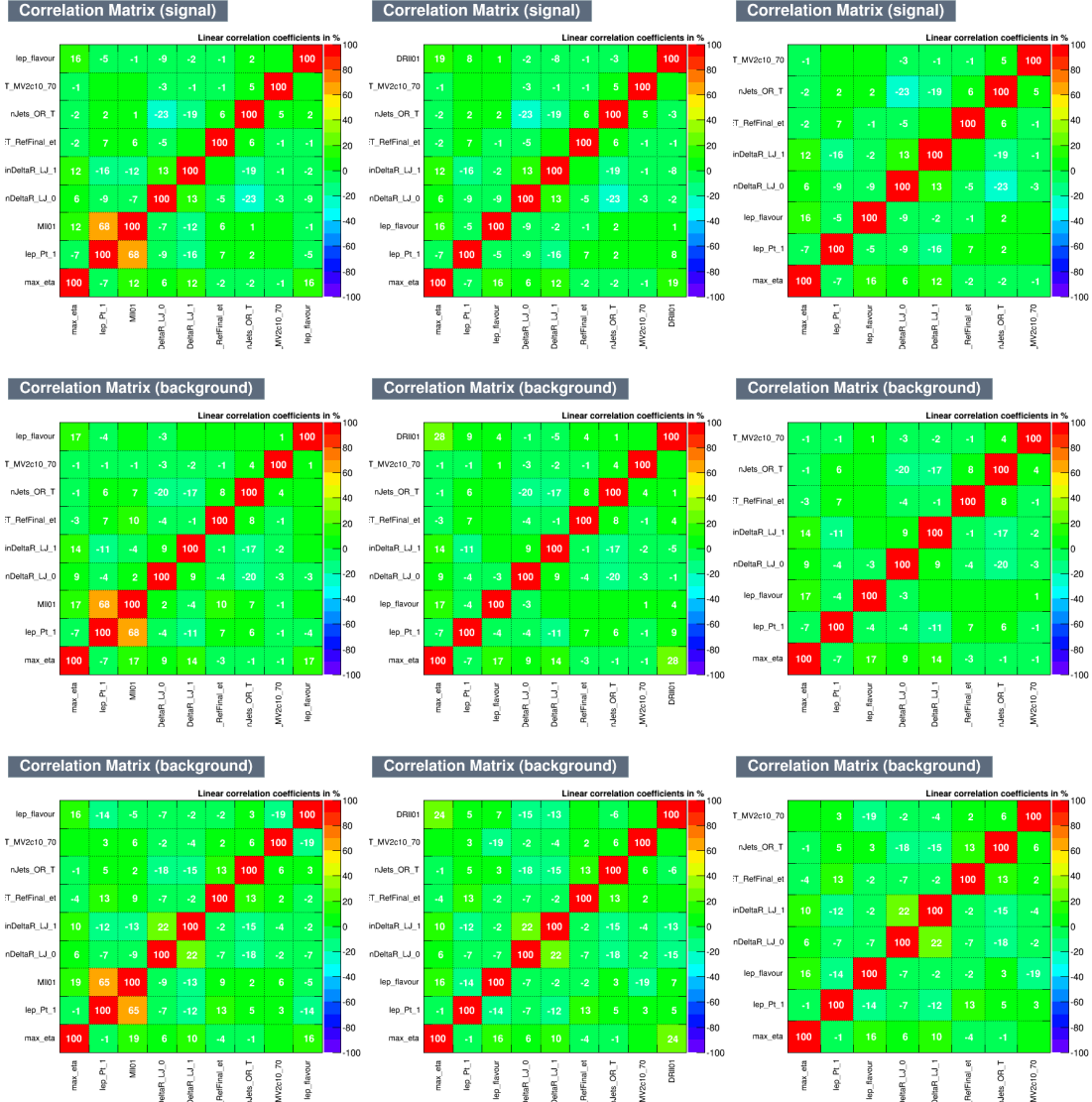


Figure D.18. – The correlation matrices for the 3 cases (case1, case2, and case3 displayed from left to right). The upper row of plots shows the correlations for $t\bar{t}H$, the middle and lower rows for $t\bar{t}V$ and fake backgrounds.

The performances of the three cases are shown below in Figure D.19 and D.20. The response distributions and ROC curves show the parameters in the three cases are fine-tuned without over-training issues. A numeric table gives the signal efficiency at a background rejection rate at 70% (in Table D.7). Better performance has been achieved with $\Delta R_{\ell_0\ell_1}$ in $t\bar{t}H$ against fakes, while the discriminant power is a bit dropped in $t\bar{t}H$ against $t\bar{t}V$ compared to the BDT with $M_{\ell_0\ell_1}$. A similar check has been performed with TF backgrounds in Section 3.5.4.

Bibliography – D. Test on replacing the input variable $M_{\ell_0\ell_1}$ by $\Delta R_{\ell_0\ell_1}$

Separation power for case 1			Separation power for case 2		
$t\bar{t}H$ against $t\bar{t}V$		$t\bar{t}H$ against $t\bar{t}$	$t\bar{t}H$ against $t\bar{t}V$		$t\bar{t}H$ against $t\bar{t}$
$M_{\ell_0\ell_1}$	4.20×10^{-2}	N_{jets}	$\min \Delta R_{\ell_0j}$	3.33×10^{-2}	N_{jets}
$\min \Delta R_{\ell_0j}$	3.33×10^{-2}	$\min \Delta R_{\ell_0j}$	$\min \Delta R_{\ell_1j}$	2.52×10^{-2}	$\min \Delta R_{\ell_0j}$
$\min \Delta R_{\ell_1j}$	2.52×10^{-2}	$\min \Delta R_{\ell_1j}$	$p_T(\ell_1)$	1.73×10^{-2}	$\min \Delta R_{\ell_1j}$
$p_T(\ell_1)$	1.73×10^{-2}	E_T^{miss}	N_{jets}	1.72×10^{-2}	E_T^{miss}
N_{jets}	1.72×10^{-2}	$\max(\eta_\ell)$	$\max(\eta_\ell)$	1.67×10^{-2}	$\max(\eta_\ell)$
$\max(\eta_\ell)$	1.67×10^{-2}	leptonic flavour	$\Delta R_{\ell_0\ell_1}$	9.76×10^{-3}	leptonic flavour
E_T^{miss}	1.61×10^{-3}	$p_T(\ell_1)$	E_T^{miss}	1.61×10^{-3}	$\Delta R_{\ell_0\ell_1}$
$N_{b\text{-jets}}$	2.88×10^{-4}	$N_{b\text{-jets}}$	$N_{b\text{-jets}}$	2.88×10^{-4}	$p_T(\ell_1)$
leptonic flavour	3.95×10^{-5}	$M_{\ell_0\ell_1}$	leptonic flavour	3.95×10^{-5}	$N_{b\text{-jets}}$

Table D.6. – Ranks of input variable separation power against $t\bar{t}V$ and $t\bar{t}$ backgrounds for case1 and case2.

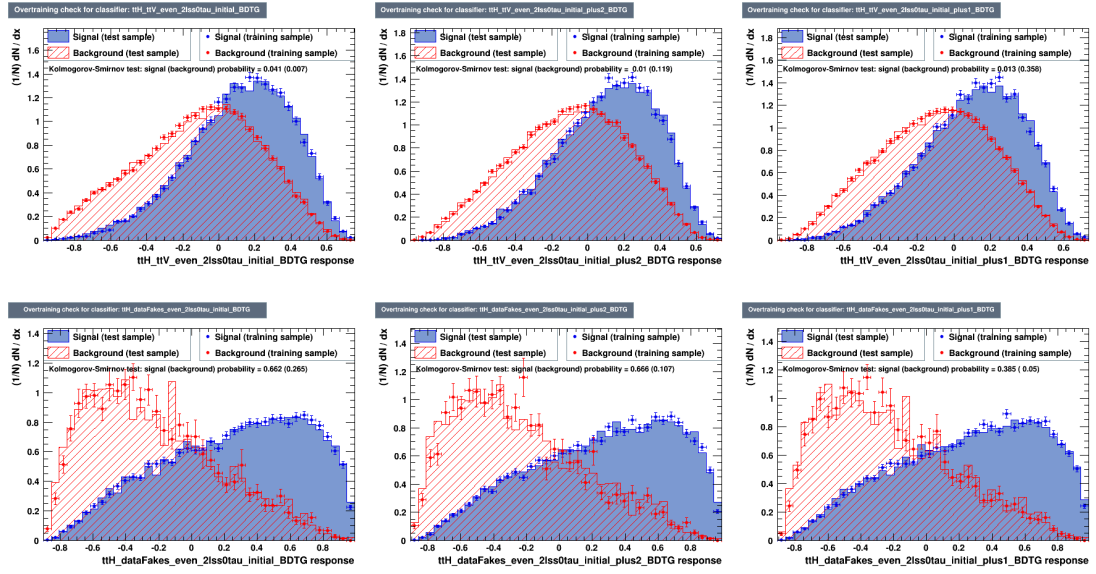


Figure D.19. – The overtraining test on BDTG response distributions shown for the 3 cases (case1, case2, and case3 displayed from left to right). The upper row shows for BDTG against $t\bar{t}V$, and the lower row for fakes.

Bibliography – D. Test on replacing the input variable $M_{\ell_0\ell_1}$ by $\Delta R_{\ell_0\ell_1}$

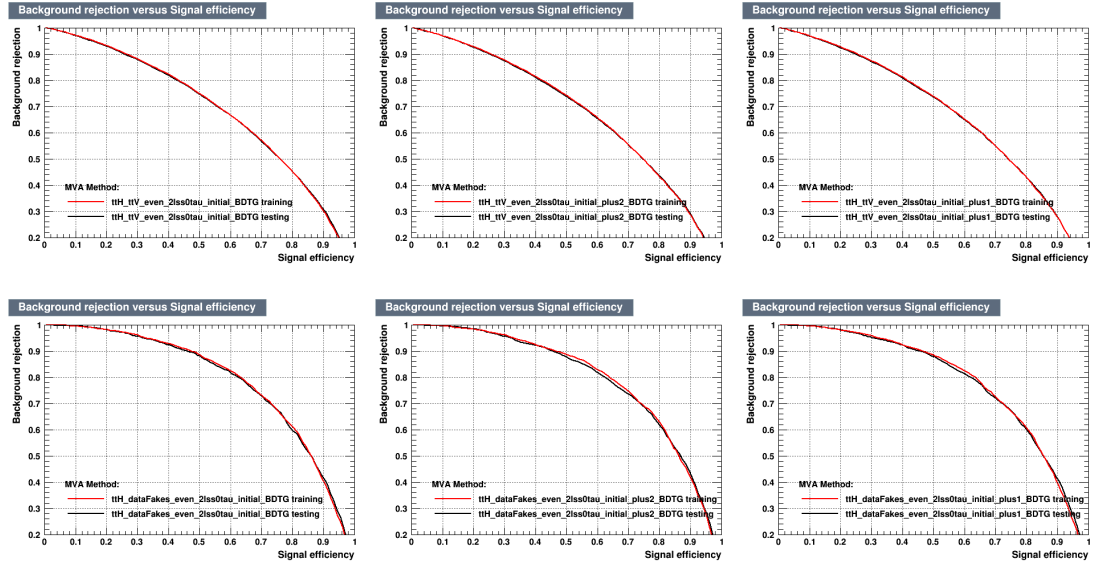


Figure D.20. – The ROC curves shown for the three cases (case1, case2, and case3 displayed from left to right). The upper row shows for BDTG against $t\bar{t}V$, and the lower row for fakes.

@B=0.3	$t\bar{t}H$ vs $t\bar{t}V$	$t\bar{t}H$ vs fakes
case 1	0.560	0.723
case 2	0.548	0.733
case 3	0.545	0.714

Table D.7. – Signal efficiencies at background rejection rate 70% compared between the 3 cases.

E. Post-fit MVA variable distributions

Post-fit distributions of BDT input variables and scores have been checked in 2ℓ SS. Data and MC are in good agreement in most bins. Plots for 2ℓ SS high N_{jets} and low N_{jets} are shown in Figure [E.21](#) and [E.22](#). In each figure, the nine plots in the upper three rows correspond to the nine discriminant variables used in the BDT, and the two plots in the bottom row show the distributions on the two output BDT scores.

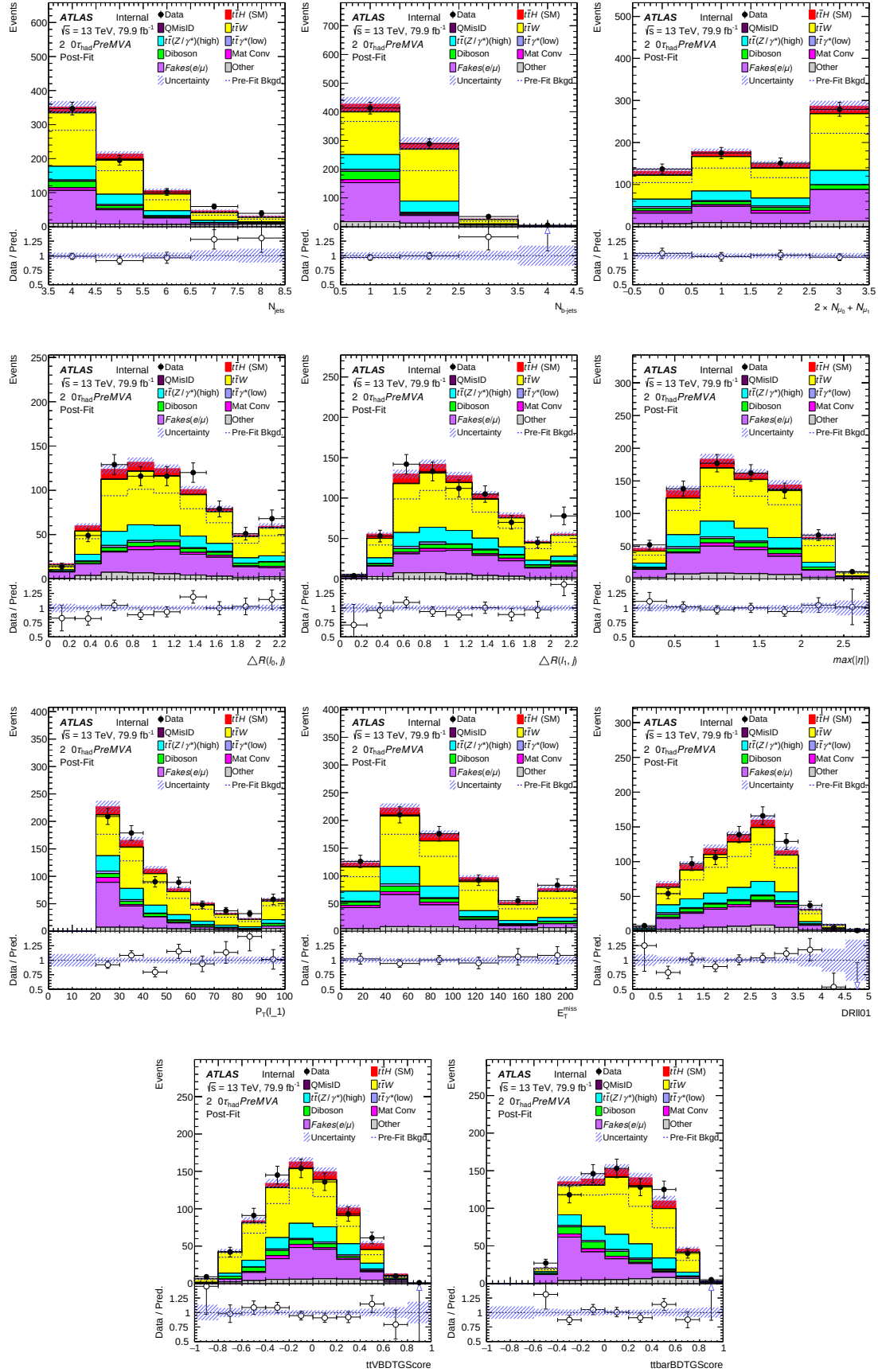


Figure E.21. – Post-fit data/MC comparisons of BDT input variables and BDT scores in 2ℓ SS high N_{jets} region.

Bibliography – E. Post-fit MVA variable distributions

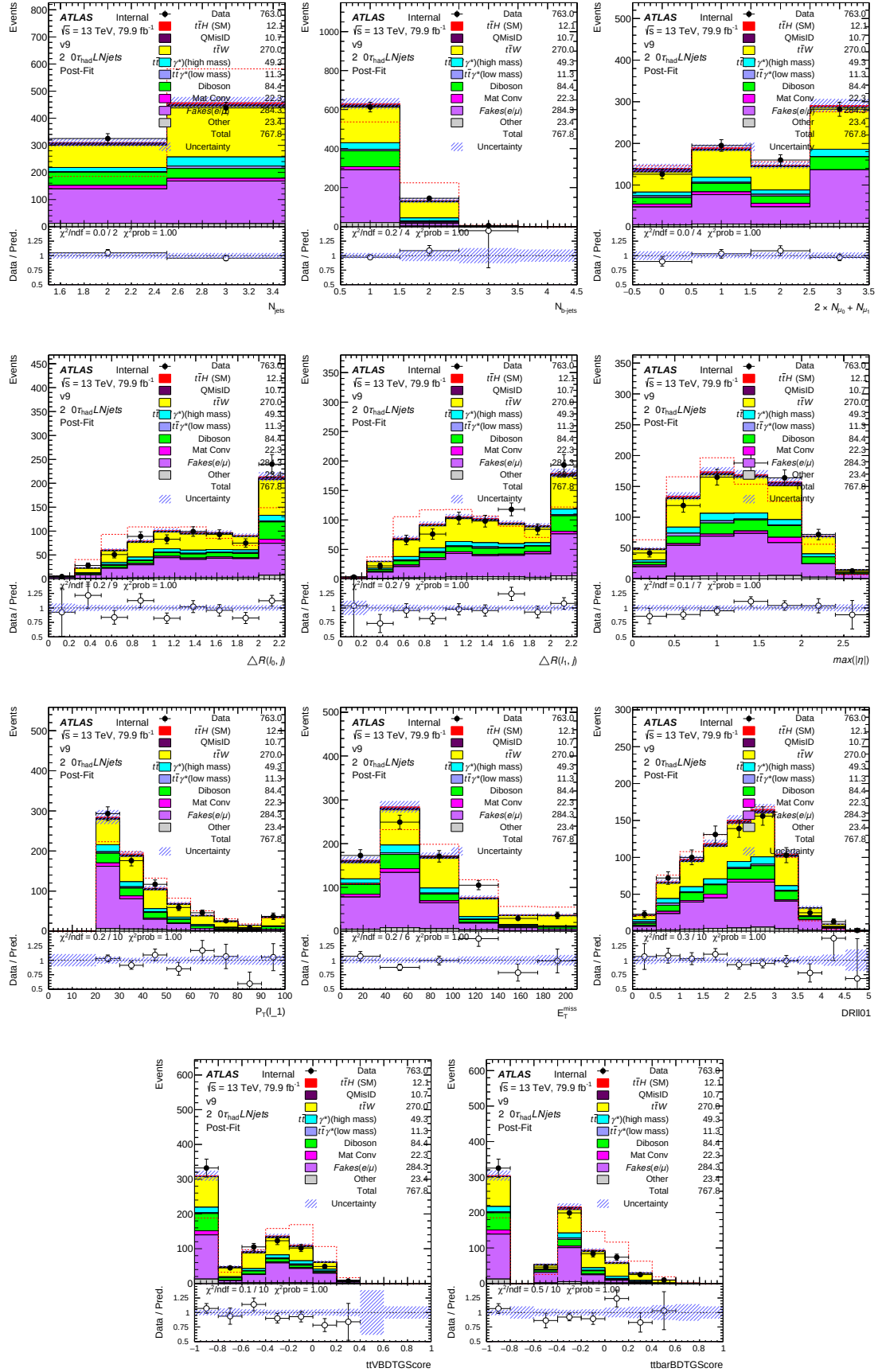


Figure E.22. – Post-fit data/MC comparisons of BDT input variables and BDT scores in 2ℓ SS low N_{jets} region.

F. Likelihood scan

Scans on likelihood values around the test statistics for the signal strength μ and NFs have been performed during the fit. The results show smooth behaviour and no weird features, which indicates a stable fit model. The study performed on the fit considering only one $t\bar{t}W$ NF. The likelihood scans are shown in Figure F.23.

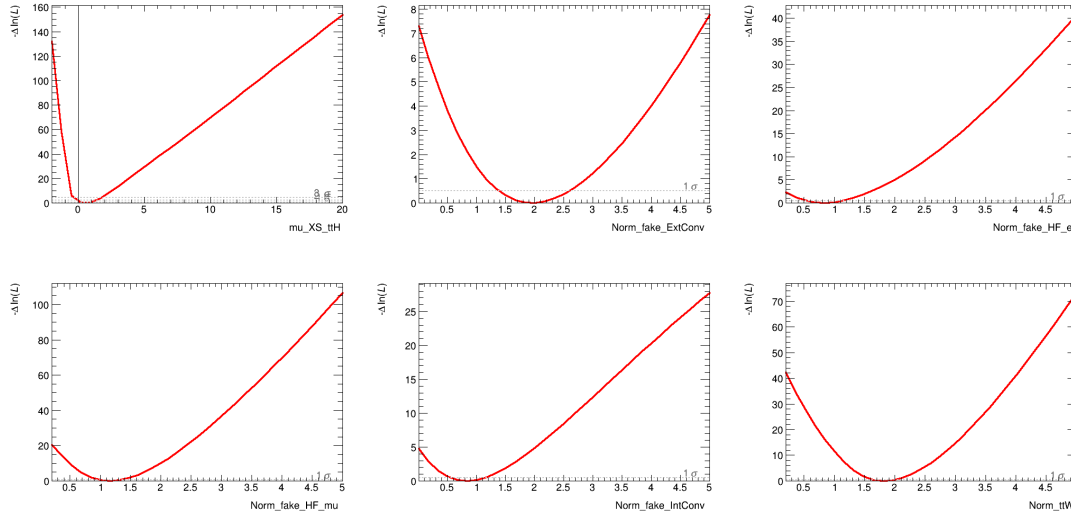


Figure F.23. – Likelihood scan for the POI and NFs in a fit model with one $t\bar{t}W$ normalisation factor.

G. Comparisons to previous results with same statistics

A comparison to the previous paper [95] has been made to understand the changes and improvements. The study only considers the 2015+2016 data which has been used in the previous result.

Quite a lot of changes have been made between the two analysis, among which, the two major differences are the treatment of the background estimations. In the previous analysis with Release 20.7 (R20.7), the $t\bar{t}W$ background was fixed at the SM predicted cross section. The $t\bar{t}W$ has been set free-floating and decorrelated between the three different channels from its bad MC modelling found with more $t\bar{t}W$ dedicated CRs established and studied in this round with Release 21 (R21). For non-prompt lepton background, it was estimated by a data-driven matrix method in the past, whereas the new analysis using the template fit. The change is motivated by the better fake lepton rejection in PLV (compared to PLI used in the last round), which leads to an increased rate of conversions in the non-prompt background. The MM is also affected by the mis-modelling issue of $t\bar{t}W$ in its background subtraction. Region separations are also different in the two analyses.

For yield comparison between the old and new analysis is with reverse several changes to trace back to the R20.7 setup. The changes between each option are highlighted in bold:

- **Opt 0a:** Old PLV cuts; Old QMisID MVA cuts; No $m_{trk,trk}$ cuts; No ambiguity type; Trigger: SLT || DLT; Loose muon; **Remove** $m(\ell\ell) > 12 \text{ GeV}$, $|\eta(e)| < 2.0$, $\Delta R(ee, e\mu, \mu\mu) > 0.5$ cuts.
- **Opt 0b:** Old PLV cuts; Old QMisID MVA cuts; No $m_{trk,trk}$ cuts; No ambiguity type; Trigger: SLT || DLT; **Loose muon**.
- **Opt 1:** Old PLV cuts; Old QMisID MVA cuts; No $m_{trk,trk}$ cuts; No ambiguity type; Trigger: SLT || DLT.
- **Opt 2:** Old PLV cuts; Old QMisID MVA cuts; No $m_{trk,trk}$ cuts; No ambiguity type; Trigger: **DLT**.
- **Opt 3:** Old PLV cuts; Old QMisID MVA cuts; No $m_{trk,trk}$ cuts; **With ambiguity type**; DLT.
- **Opt 4:** **New PLV cuts**; Old QMisID MVA cuts; No $m_{trk,trk}$ cuts; With ambiguity type; DLT.
- **Opt 5:** New PLV cuts; **New QMisID MVA cuts**; No $m_{trk,trk}$ cuts; With ambiguity type; DLT.
- **R21 final:** New PLV cuts; New QMisID MVA cuts; **With** $m_{trk,trk}$ cuts; With ambiguity type; DLT.

The 10% decreasing in the yields for $t\bar{t}H$ and $t\bar{t}W$ and 20% for fakes from R20.7 to option 0a is thought to be the efficiency changing between different release versions, at the same time, data is also observed with a reduction. The PLI has been retrained in R21 thus cannot be reverted to its performance in R20.7.

Another check for fit models have been performed on R20.7 dataset and R21 data

Option	$t\bar{t}H$	$t\bar{t}W$	Fakes (Fakes+Ext/IntConv)	QMISID MC
R20.7 published	42.6	123.2	MM = 232.9 (MC = 134)	
Opt 0a	38.2	109.8	103.4 (70.9+16.2+16.3)	9.4
Opt 0b	36.7	103.0	92.2 (66.2+12.2+13.8)	7.8
Opt 1	36.5	102.7	92.2 (66.2+12.2+13.8)	7.8
Opt 2	36.1	101.7	91.9 (66.1+12.2+13.6)	7.8
Opt 3	36.0	101.5	89.1 (66.0+9.7+13.4)	7.6
Opt 4	39.7	105.3	92.6 (69.0+9.6+14.0)	8.1
Opt 5	39.7	105.3	92.6 (69.0+9.6+14.0)	8.1
R21 final	39.1	103.7	80.4 (67.2+6.1+7.1)	4.6

Table G.8. – Pre-fit yields for $t\bar{t}H$, $t\bar{t}W$, fake lepton, and QMisID compared between the R20.7 and R21 analyses.

with 2015-16 only. The test with options considering the $t\bar{t}W$ normalisation factor (see Section 3.7.3.2) and extrapolation uncertainties (see Section 3.7.3.3), while no higher order QCD and EWK corrections (see Section 3.7.3.1) considered in all circumstances.

- **R20.7 (Published)**: Result from the last published paper [95]
- **R20.7 (Fakes/2, ttW float)**: More R21-like setup where fakes are halved (to make MC-based estimate) and the $t\bar{t}W$ normalisation is floating.
- **R21 (ttW float)**: Baseline fit for this version but only one $t\bar{t}W$ NF considered.
- **R21 (ttW fix)**: R21 fit but with $t\bar{t}W$ fixed to the SM prediction.
- **R21 (ttW fix, w/o ttW syst)**: Same as above but with $t\bar{t}W$ systematics, including the extrapolation uncertainties.

Channel	R20.7 (Published)	R20.7 (Fakes/2, $t\bar{t}W$ float)	R21 ($t\bar{t}W$ float)	R21 ($t\bar{t}W$ fix)	R21 ($t\bar{t}W$ fix, w/o $t\bar{t}W$ syst)
$2\ell SS$	1.5 +0.7/-0.6	1.4 +0.8/-0.8	0.2 +0.7/-0.7	1.0 +0.8/-0.7	1.6 +0.8/-0.7
3ℓ	1.8 +0.9/-0.7	1.8 +0.8/-0.8	1.9 +0.8/-0.7	2.3 +0.7/-0.7	2.5 +0.8/-0.7
4ℓ	-0.5 +1.3/-0.9	-0.5 +1.4/-0.9	-0.4 +0.6/-1.4	-0.4 +0.6/-1.4	-0.4 +0.6/-1.5
$2\ell SS + 1\tau_{had}$	3.5 +1.7/-1.3	3.4 +1.7/-1.4	1.5 +1.6/-1.2	1.7 +1.6/-1.2	1.8 +1.6/-1.4
$3\ell + 1\tau_{had}$	1.6 +1.8/-1.3	1.6 +1.8/-1.3	1.3 +1.9/-1.3	1.3 +1.8/-1.3	1.3 +1.8/-1.3
$1\ell + 2\tau_{had}$	-0.6 +1.6/-1.5	-0.6 +1.3/-1.1	-1.6 +1.3/-1.3	-1.6 +1.3/-1.3	-1.7 +1.3/-1.3
Combined	1.6 +0.5/-0.4	1.5 +0.5/-0.5	0.8 +0.5/-0.4	1.2 +0.5/-0.5	1.5 +0.5/-0.5

Table G.9. – Fitted $\mu(t\bar{t}H)$ values for different scenarios with the R20.7 and R21 analyses.

The largest difference comes from the $2\ell SS$ channel between the $t\bar{t}W$ background free-float and fixed. When the R21 fit with a model close to the R20.7 fit setup, the $2\ell SS$ results are rather compatible (1.5 +0.7/-0.6 vs 1.6 +0.8/-0.7).