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PHD THESIS

CHARM JET IDENTIFICATION PERFORMANCE
FOR THE ATLAS EXPERIMENT
AND DEVELOPMENT OF FUTURE TRACKING DETECTORS

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Abstract

ATLAS is a particle physics experiment at the Large Hadron Collider (LHC) operating at the CERN laboratory in Geneva. ATLAS is designed to be a general purpose detector: rather than focusing on a particular physical process, it can measure an entire range of signals in order to study many phenomena and search for new particles that could emerge from LHC collisions. During the course of my Ph.D. program, I contributed to several different activities in the context of the ATLAS experiment: from data taking to public outreach, including data quality assessment, b -tagging performance measurement, standard model physics measurement, test beam with detector components and R&D on silicon wafers in view of future tracking detectors. In this thesis, I will mainly focus on the measurement of the charm jet identification performance by specialized b -tagging algorithms, which has been my main contribution, and on the test beam experiments performed on pixel detector modules with unprecedented high energy and intensity proton beam, for beam-loss scenario studies.

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Introduction

In this thesis, several contribution I made to the ATLAS experiment are described, ranging from data taking to public outreach activities. ATLAS is a multi purpose experiment located at the Large Hadron Collider (LHC) operating at the CERN laboratory in Geneva. The ATLAS collaboration is made by more than 3000 physicists coming from 38 different countries. The ATLAS detector was designed to measure a wide range of signals, in order to study many different physical processes and potentially discover new particles.

When I joined the ATLAS collaboration, in Spring 2015, the ATLAS detector was fully operational and the Run 2 data taking was about to start. In such a context, one could imagine that the only possibility to contribute to an already built and operational experiment would be to perform data analysis. From my experience, this is not completely true: there are different fields that can be explored.

During my master degree thesis and along the three years of the Ph.D. program, I had the possibility to contribute to many activities in the context of the ATLAS experiment, with different degrees of commitment. In the meanwhile, the experiment has gone through 4 years of operations (Run 2: 2015-2018) along with the other LHC experiments. The data taking ended in December 2018 with the completion of the Run 2 physics program and the start of a two-years shutdown of the accelerator facilities (Long Shutdown 2). In 2021, the physics program will resume with Run 3, then the LHC should conclude the first part of its physics program at the end of 2023 with an expected integrated luminosity of proton-proton collisions of 300 fb^{-1} . During Long Shutdown 3 the LHC accelerator will be upgraded to achieve a higher instantaneous luminosity: the era of the High-Luminosity LHC (HL-LHC) will start. The ATLAS detector will be upgraded too, in order to cope with the HL-LHC environment. In particular, the tracking system, which has the purpose of reconstructing tracks and vertices, will be completely replaced by a new silicon detector with increased granularity and radiation hardness: the Inner Tracker (ITk).

Beyond the activities related to the current operation of the ATLAS experiment (i.e. detector operations, combined performance, data analysis), I have been involved in laboratory activities focusing on the future tracking system upgrade. The ATLAS Genoa group has a long tradition in silicon detector production and assembly and is going to take part in the ITk detector construction. The building block of the typical silicon detector, the modules, are built assembling silicon tiles (sensor and

microelectronic chip tiles). The tiles are produced by foundries in form of thin round slices (wafers), then the individual components are separated. I contributed to the R&D phase of the Wafer Level Packaging technology, a process developed with the goal of rebuilding a wafer structure starting from previously diced tiles. I performed measurements to assess the quality of the rebuilt wafers and then compared the results with the technical specifications of silicon detector components to be used for high energy physics application (i.e. the ITk pixel detector). Six wafers were produced with this technique by MicroFab Solutions in Trento within the AIDA-2020 framework activities. AIDA-2020 (Advanced European Infrastructures for Detectors at Accelerators) is an European project with the aim of innovating detector technologies and improving testing infrastructures. It is a unique project with a broad field of applications: not only the development of innovative components for future detectors, but also for the upgrade plans of the current detectors. The process flow of the Wafer Level Packaging technique is described in this thesis, together with the results of the measurements of the wafers properties (Chapter 4).

Moreover, I took part in two test beam campaigns at the CERN HiRadMat (High Radiation to Materials) facility. In this experiments, strip and pixel silicon detector modules have been exposed to an unprecedented high energy and intensity proton beam to study the performance degradation of real detector components in case of beam-loss scenarios. In case of a beam-loss event, the particles that make up the beam are deviated from their expected trajectory: a large cascade of particles, from the interaction of the beam with the surrounding material, may hit the detectors. After the accelerator upgrade, the aperture of the HL-LHC quadrupoles in the proximity of the interaction regions will be larger with respect to the current LHC aperture, reducing in this way the shielding potential of this material. The increased intensity of the collisions produced by the HL-LHC accelerator, together with the larger apertures, requires for the measurement of the beam-loss survival threshold of the tracking detector components, both sensors and electronics. After an introduction to the HiRadMat facility, the experimental setup and the beam operations are described, along with the results (Chapter 5).

The ATLAS experiment has a long and wide experience in the data quality assessment, obtained after years of operations, which has guaranteed many successful physics results. The data quality software is continuously updated in order to be ready to assess the quality of the data in any condition: standard proton-proton collisions, high luminosity collisions, low luminosity collisions, special runs, heavy ion collisions. Within this frame, I contributed to the b -tagging data quality software updates during 2018 data taking. The term “ b -tagging” collectively describes the tools developed to identify jets generated from the hadronization of the beauty quarks (b -jets). The correct identification is of fundamental importance for the physics analyses involving b -jets in the final state: top quark and Higgs boson studies, as well as the search for new physics phenomena beyond the Standard Model. With the experience gained in the software updates, I acted as b -tagging data quality ex-

pert, helping in following up the issues and in the organizational aspects of the data quality shifts. After a brief introduction to vertex, tracks and jet reconstruction, the ATLAS b -tagging algorithms are presented (Chapter 7). Thereafter, the ATLAS data quality software is introduced, focusing on b -tagging tools. A detailed description of the improvements to the b -tagging monitoring tools is presented (Chapter 8), along with few examples of relevant issues encountered during 2018 data taking.

As said before, the analysis of the data collected during Run 2 operations was not the only activity I was involved in, but it was my very first contribution to the ATLAS experiment and it is the main part of this thesis (Chapter 10): the measurement of the b -tagging performance on a charm jet sample. The performance of the b -tagging algorithms is calibrated on data, measuring the efficiency to tag a jet originated from a b quark (b -jet tagging efficiency) as a b -jet or to mistakenly tag a jet originated from a charm quark (c -jet tagging efficiency) or from a light quark or a gluon (mistag rate). The c -jet tagging efficiency was measured by the ATLAS experiment with different techniques: the D^* , $W+c$ and $t\bar{t}$ methods (Chapter 9). This thesis work focuses on the $W+c$ method, based on a sample of c -jets produced in association with a W boson, with the c -jet identified by a soft muon coming from a semileptonic c -hadron decay. I used this method to measure the c -jet tagging efficiency of the Run 2 b -tagging algorithms (Chapter 10) on 36 fb^{-1} of proton-proton collision data collected at $\sqrt{s} = 13\text{ TeV}$ by the ATLAS experiment. The same measurement is performed on simulated event samples, then a data-to-simulation scale factor is derived, defined as the ratio of the efficiency on data over the efficiency on simulated event samples. The data-to-simulation scale factors measured on $W+c$ events are finally combined with the results of the measurements performed on $t\bar{t}$ events to reduce total uncertainties.

I am exploiting the experience gained during the measurement of the b -tagging efficiency with a $W+c$ sample to measure the production cross section of this process. The $pp \rightarrow WcX$ production is dominated by the $gs \rightarrow Wc$ process, therefore this measurement is directly sensitive to the s -quark distribution function in the proton at momentum-transfer values on the order of the W -boson mass. The first steps of the measurement of the production of a W boson in association with a single charm quark using 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13\text{ TeV}$ collected with the ATLAS detector at the LHC from 2015 to 2018 are presented (Chapter 11). The events are selected similarly to what done for the b -tagging efficiency measurement, with significant improvements in the statistics, as both electron and muon W -boson decay channels are explored in this measurement.

Finally, during 2018, I contributed to the data taking operations of the ATLAS experiment, taking shifts in the ATLAS Control Room at the Inner Detector desk. I participated as well to outreach activities, in particular to the Genoa Science Festival, which is one of the main science fairs in Italy. Few hints on these activities can be found in Bonus Chapters 6 and 12, respectively.

Chapter 1

The ATLAS experiment at LHC

More than 60 years ago, 12 European countries founded CERN (originally “Conseil Européen pour la Recherche Nucleaire”) to promote international cooperation on scientific research. In the following years, CERN laboratories, based on the particle accelerator technology, addressed many questions and led the scientific community toward the understanding of the atomic, nuclear and sub-nuclear physics. Nowadays, CERN is an intergovernmental organization employing around 2500 people among physicists, engineers, technicians and administratives in its laboratories builded on the border between France and Switzerland. More than 10000 scientists from all over the world operate with its facilities, making the CERN one of the world largest centers for scientific research.

The energy required to study more and more in deep the fundamental constituents of matter often required the building of a new generation of high-energy accelerators. Currently, these accelerators are the constituents of a unique complex (see Figure 1.1), capable of increasing the speed and consequently the energy of a wide range of particles, such as protons, antiprotons, electrons and ions. At the top stage of this accelerator complex stands the Large Hadron Collider: currently the most powerful accelerator in the world.

1.1 Large Hadron Collider at CERN

The Large Hadron Collider (LHC) [1, 2] accelerate particles along their trajectory, in the same tunnel once containing the Large Electron-Positron Collider (LEP) [3]. Within the LHC 27 km length, more than 1200 superconducting dipoles are connected together and cooled at 1.9 K by liquid helium. These magnets generate a 8 T magnetic field that bends the beams along their circular track. Almost 400 quadrupole magnets are used to guide and focus the beams, providing the beams with small transverse sections. Radiofrequency cavities are used to accelerate the beams until they reach the desired energy. LHC accelerates protons or ions to perform collisions at the TeV energy scale, allowing physicists to test the theoretical

predictions of many proposed particle physics models.

After the dismantling of LEP, in the period going from 2000 to 2008, the LHC was built in the tunnel at about 100 m underground. The counter-rotating beams collide at the 4 interaction points, where the ATLAS, ALICE, CMS and LHCb experiments are placed. After accelerator commissioning and cosmic rays studies, LHC begun operations on 10 September 2008. An accidental liquid helium leak due to a broken connection between two magnets caused a long stop to repair more than 50 damaged magnets. After 14 months, the LHC was back in November 2009 with particle collisions at the record energy of $\sqrt{s} = 2.36$ TeV in the center of mass. The energy was then increased in 2011 ($\sqrt{s} = 7$ TeV) and again in 2012 ($\sqrt{s} = 8$ TeV). From September 2013 to March 2015, the LHC underwent the first Long Shutdown: in these months the magnet connections were renewed to get stronger for the new energy level. The LHC resumed operations in April 2015, with both beams circulating at 6.5 GeV energy. In the following years, LHC delivered collisions at the record energy of $\sqrt{s} = 13$ TeV in the center of mass, becoming once again the most powerful accelerator of the world. LHC operated until the end of 2018, when the second Long Shutdown is started.

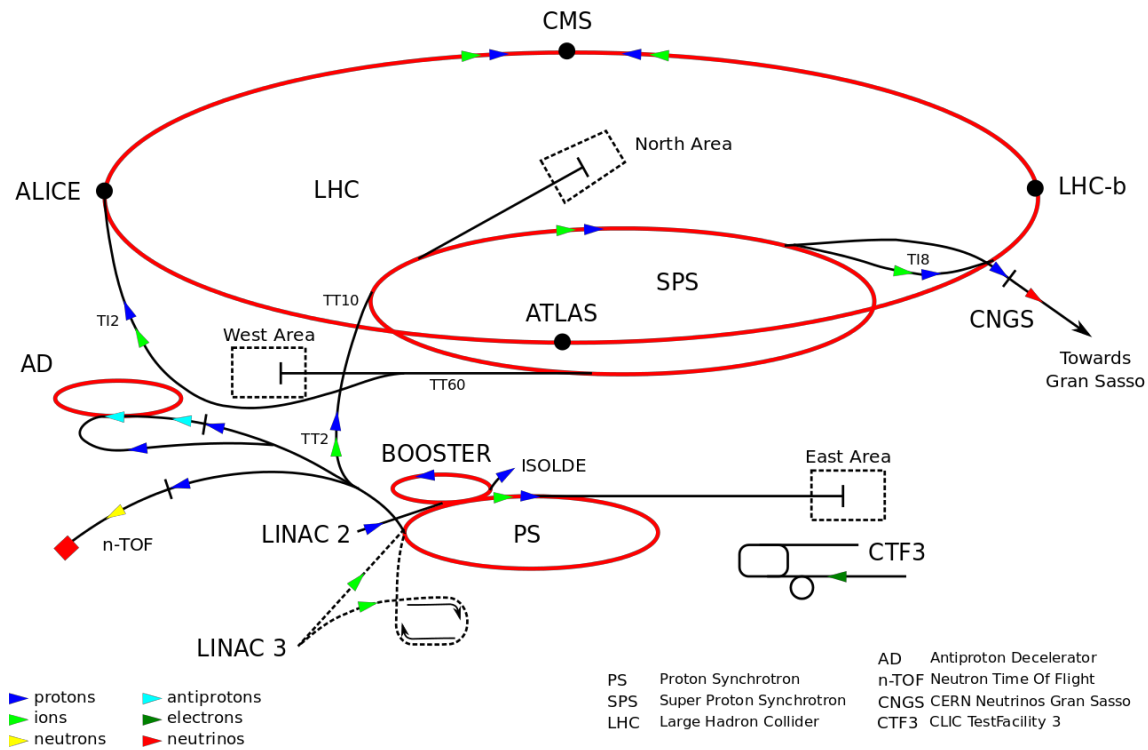


Figure 1.1: CERN accelerator complex: LINAC 2, BOOSTER, PS and SPS operate in the pre-acceleration chain of the LHC. They also accelerate different beams for a wide range of physics experiments: test beams, AD, n-TOF, ISOLDE, CNGS.

Before entering the LHC, the protons extracted from an hydrogen source go through an acceleration chain composed by many stages (see Figure 1.1):

- LINear ACcelerator 2 (LINAC 2): a 36 m long linear accelerator initially increases the energy up to 50 MeV;
- Booster (BOOSTER): four superimposed rings with a 25 m diameter accelerates the protons up to 1.4 GeV;
- Proton Synchrotron (PS): a 628 m long circular accelerator composes bunches of protons and brings them up to 26 GeV;
- Super Proton Synchrotron (SPS): a 2 km diameter ring accelerates the beams up to 450 GeV, before injecting them into LHC.

During the second Long Shutdown, LINAC 2 will be replaced by LINAC 4, a 80 long linear accelerator that will bring protons up to 160 MeV. Booster and PS will be replaced too, by Superconducting Proton Linac and by PS2: these upgrades are the only possible way to reach a higher luminosity level (see Equation 1.1).

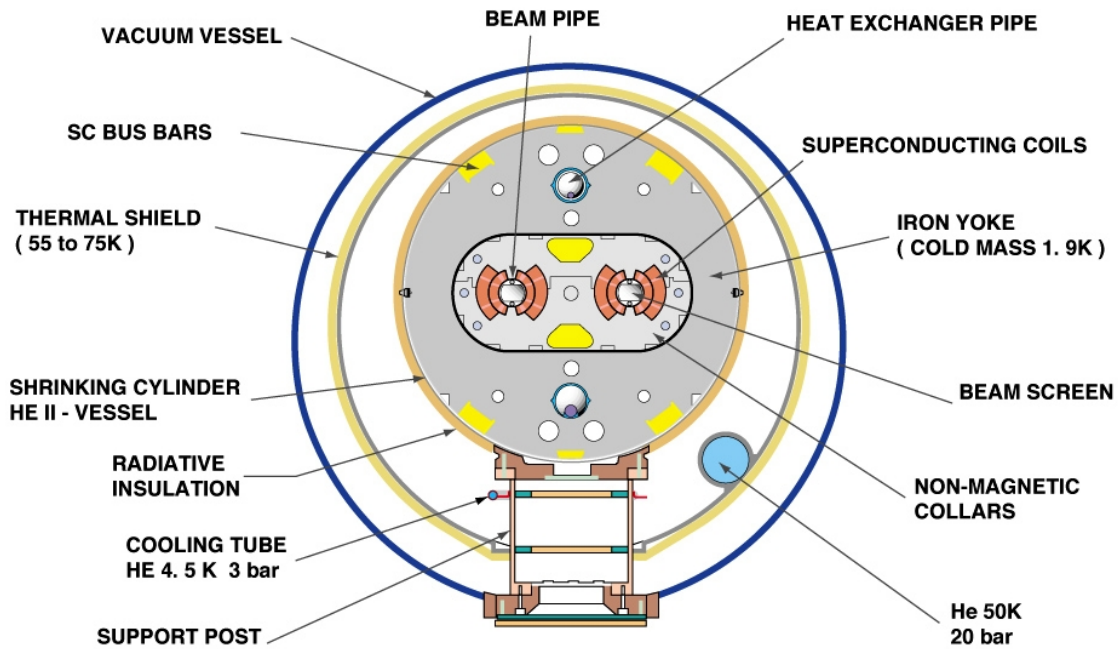


Figure 1.2: Section view of the magnetic dipole of LHC.

Two counter-rotating beams (made by protons or ions) circulate in two separate vacuum chambers contained in a single beam pipe (see Figure 1.2). Each beam is composed by many tiny little bunches of particles (a maximum of 2808 bunches, each one made by about 10^{11} protons). It takes 4 minutes and 20 seconds to accelerate enough protons to fill each LHC ring, then several minutes are needed to reach the final LHC energy. Beams at the established energy circulate for 10 hours or more into LHC, colliding at a rate of 40 MHz (one bunch-crossing event per 25 ns) until the number of protons runs out. Then the beams are dumped, the magnets are

ramped down, the whole system goes through ~ 30 minutes of rest and a new cycle begins.

The variable describing the collider ability to produce collisions is the instantaneous luminosity, defined as:

$$\mathcal{L} = f n_p \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} \quad (1.1)$$

where σ_x and σ_y represent the gaussian transverse profiles of the beams, N_1 and N_2 represents the number of protons in the bunch, f is the revolution frequency of the bunches and n_p is the number of bunches in the beam. To increase the rate of interesting events, the number of collisions needs to be increased. This could be obtained in different ways: increasing the number of bunches in the beam, increasing the number of protons in each bunch, increasing the revolution frequency of the bunches, reducing the transverse sections of the beams.

The number of expected events n for a process having cross section σ is:

$$n = L \sigma, \quad (1.2)$$

where L is the integrated luminosity, defined as the integral of the instantaneous luminosity $\mathcal{L}$ in the time interval from t_1 to t_2 :

$$L = \int_{t_1}^{t_2} \mathcal{L} dt. \quad (1.3)$$

After reaching the final energy, the beams collide in four experimental areas where the particle detectors of the main LHC experiments stand:

- A Large Ion Collider Experiment (ALICE): an experiment with the specific purpose of studying the quark-gluon plasma physics through ion-ion collisions, in order to gain further knowledge on the state of the matter at extreme energy density;
- A Toroidal LHC ApparatuS (ATLAS): a glimpse into the ATLAS experiment physics program is provided in Section 1.4;
- Compact Muon Solenoid (CMS): a general purpose experiment with many different goals as Higgs boson studies, Super Symmetry and Dark Matter searches;
- Large Hadron Collider beauty (LHCb): an experiment focused on beauty physics, aiming toward a better understanding of the rare B hadrons phenomena and a precise measurement of the CP violation parameters.

1.2 Standard Model theory

Nowadays, the most satisfying theory describing particle interaction is the Standard Model (SM) [4–6], born after a century of deep studies over the fundamental constituents of matter. The SM describes the electromagnetic, weak and strong interactions in terms of fields, bringing together the electro-weak theory (also referred as Glashow-Weinberg-Salam Theory) and the Quantum Chromo-Dynamics (QCD). The gravitational interaction is not included in this model: it dominates in the universe on a large scale, but it is not easy to describe it along with SM in terms of a quantum-relativistic field theory. From the theoretical point of view, the Standard Model is a gauge theory based on the symmetry group:

$$U(1) \otimes SU(2) \otimes SU(3) \quad (1.4)$$

where $U(1) \otimes SU(2)$ is the group of unified weak and electromagnetic interactions and $SU(3)$ is the group associated to strong interaction. The interactions are exchanged by means of “messenger particles”, the gauge bosons: the photons (electromagnetic interaction), the gluons (strong interaction) and $W^\pm$ and Z^0 bosons (weak interaction).

Gauge Boson	Mass [GeV]	Interaction	Range [m]
gluon (g)	0	Strong	10^{-15}
photon (γ)	0	Electromagnetic	∞
$W^\pm$	80.4	Weak	10^{-17}
Z^0	91.2	Weak	10^{-17}

Table 1.1: Gauge bosons are mediators of the Strong, Electromagnetic and Weak Interactions. The experimentally measured masses are reported, along with the effective ranges of the interactions.

According to the Standard Model, there are few fundamental particles divided in two main classes: 12 fermions with spin 1/2 (6 leptons and 6 quarks) and 5 bosons with spin 1 (actually, 8 different gluons exist, from the properties of the $SU(3)$ symmetry). Of the three forces, only the weak force affects all fermions; the electromagnetic force is felt only by the charged particles, while only the quarks interact via the strong force.

	Generation			Electric charge
	I	II	III	
Leptons	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$	0 −1
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$	2/3 −1/3

Table 1.2: Leptons and quarks: I, II and III generation.

Lepton	Mass		Quark	Mass
ν_e	$< 2 \text{ eV}$		u	2.3 MeV
e^-	0.511 MeV		d	4.8 MeV
ν_μ	$< 0.19 \text{ MeV}$		c	1.3 GeV
μ^-	105.7 MeV		s	95 MeV
ν_τ	$< 18.2 \text{ MeV}$		t	173 GeV
τ^-	1776.8 MeV		b	4.2 GeV

Table 1.3: Leptons and quarks measured masses.

Since the electroweak theory describes massless fermions and gauge bosons, while evidence tells us that many particles have mass, new parts have to be added to the theory to solve this puzzle: the spontaneous symmetry breaking of the electroweak gauge symmetry and the Higgs mechanism. This introduces a new particle into the theory: the Higgs boson. Since the theory can only indirectly predict favored values for the Higgs boson mass, a long search has been performed at the highest energy colliders: LEP (electron-positron collisions, up to 200 GeV), Tevatron (proton-antiproton collisions, up to 1.96 TeV) and LHC (proton-proton collisions, up to 13 TeV). Finally, the Higgs boson have been discovered: this success opens the field to the era of precision measurements of its properties (further details in Section 1.4.1).

1.3 QCD and PDFs

Proton-proton collisions are well understood and described as parton interactions within the QCD theory. According to the QCD theory, the partons (quarks and gluons) are coloured states that can not exist individually. The quarks usually combine to form colourless states: pairs of quarks-antiquarks bound together (mesons) and triplets of differently coloured quarks or antiquarks (barions). This is the reason why free quarks and gluons always undergo a hadronization process: other quarks and gluons are generated in the so-called “parton shower”, then a tight cone of hadrons (jet) emerges. It is impossible to detect free quarks before the hadronization (except for indirect measurements of the the top quark, which decays before hadronizing because of its very large mass), but it is still possible to identify the quark from which the jet originated.

Jets can be divided in three main categories (flavours): b -jets originating from a beauty quark; c -jets from a charm quark or light jets from a gluon or a up, down or strange quark. The correct identification of jets containing b hadrons (hence b -tagging) is of capital importance for many physics analyses: for top quark studies and Higgs measurements, as well as the search for new physics phenomena beyond Standard Model.

Experimental evidence tell us that the protons are bound states of two up and one down quark (valence quarks) which exchange gluons. In addition there are quark-

antiquark pairs of any flavour which are generated from emitted gluons (sea quarks). Inside the proton, each parton carries a fraction x of the proton momentum. The Parton Density Functions (PDFs) describes the probabilities for a parton to carry a certain momentum fraction in interactions with a given transferred momentum Q^2 : $f(x, Q^2)$.

In Figure 1.3, the proton PDFs and their uncertainties (before the LHC era) are shown: for high x values the valence quarks are dominating, while at low x the sea quarks are giving a relevant contribution. For high values of the transferred momentum, the sea quarks contribution is enhanced. Results from many experiments are combined together as inputs to extract the PDFs: fitting collaborations are providing parametrisations of the PDFs for each of the quark flavours. The LHC experiments have contributed with many studies to improve the PDFs knowledge and understanding [7], reducing uncertainties. The s quark PDF, of particular interest for this thesis, is currently poorly constrained by direct experimental measurements, especially at low Q^2 .

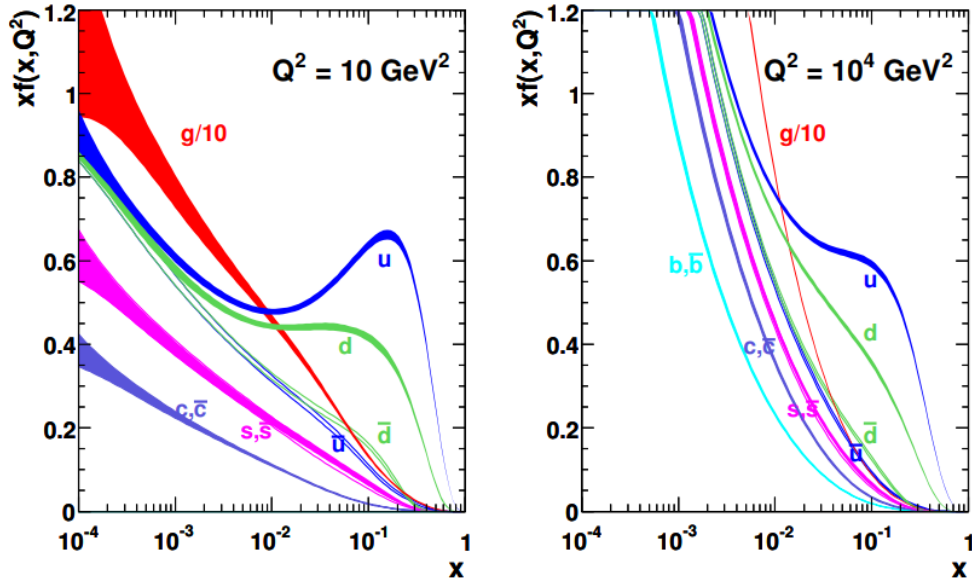


Figure 1.3: Parametrization of the proton PDFs [8] for different momentum transfers.

1.4 ATLAS physics highlights

ATLAS [9] is a multi purpose experiment located at the Interacting Point 1 (IP1) into the LHC tunnel. The ATLAS collaboration is made by more than 3000 physicist coming from 38 different countries. The ATLAS experiment was firstly proposed in 1992, then in 1999 a Tecnical Design Report [10] was defined. The detector assembly was completed in 2008, the physics program started with Run 1 (2011-2012) then a detector upgrade was performed during Long Shutdown 1 (2013-2014) and physics

Run 2 followed (2015-2018). Right now the detector is under maintenance, during Long Shutdown 2 (2019-2020). The physics program will resume in 2021, with Run 3.

During Run 2 operations, the LHC collisions doubled the design instantaneous luminosity, with ATLAS reaching $\mathcal{L} = 2.14 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and mean pile-up values up to 70 (Figure 1.4, right). The total amount of good data for physics analyses collected by the ATLAS detector during Run 2, measured in terms of integrated luminosity L , reaches 140 fb^{-1} (Figure 1.4, left), allowing to study rare phenomena characterized by very low cross section.

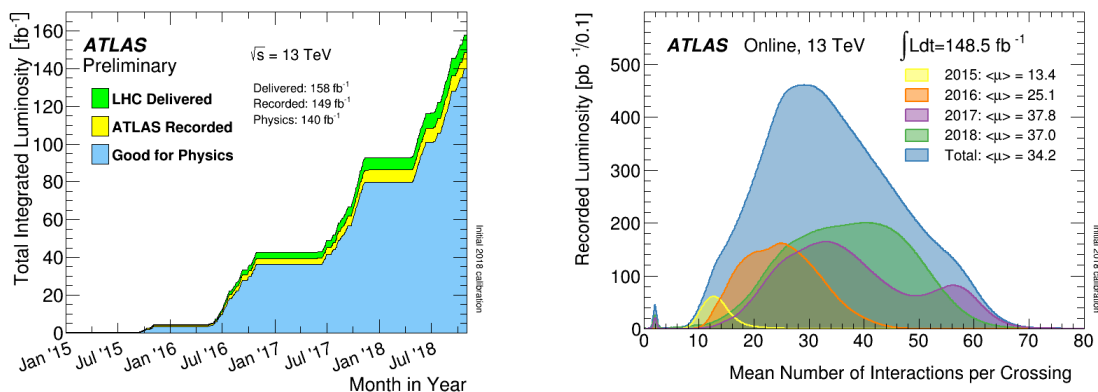


Figure 1.4: ATLAS Run 2 operations: total integrated luminosity of proton-proton collisions (left) and mean number of proton-proton interactions per crossing (right).

Rather than focusing on a particular physics process, the ATLAS detector can measure an entire range of signals, in order to study many phenomena. A field of research of primary interest for the ATLAS experiment is that of Higgs boson measurements, together with the precision Standard Model measurements. Highlights of both research fields are presented in Sections 1.4.1 and 1.4.2, respectively.

After participating to the discovery, the ATLAS community is focusing on the precise measurement of the Higgs boson properties. Among the Higgs boson highlight measurements, there is the observation of its $b\bar{b}$ decay channel. This result has been possible only thanks to the dedicated efforts in the jet flavour tagging expertise, necessary to identify the jets originated from b quarks. Another physics sector where the flavour tagging has a crucial impact is the top physics, due to the exclusive branching ratio of the top: $t \rightarrow Wb$. Within this field, the Higgs boson associated production with top quark pairs has been one of the highlights of the ATLAS physics program in Run 2.

Another aspect of particular importance in the ATLAS physics program is the determination of Standard Model constants through precision measurements. Dedicated efforts are recently focused in particular on the W boson mass, but more in general to W and Z boson production cross sections. Results from cross section measurements are compared to the most up-to-date theory predictions in order to shed light on the proton content in terms of PDFs. W +jets and Z +jets produc-

tion final states represent major backgrounds for many Standard Model and beyond Standard Model processes. An experimental determination of their cross sections and properties is crucial as well for a correct background estimation.

1.4.1 Higgs boson and top measurements

Higgs boson searches have been carried at LEP [11] and at Tevatron [12], but they did not manage to discover the new particle. LEP contributed to exclude the mass region lower than 114.4 GeV, while Tevatron excluded the 147-180 GeV region. Finally, in 2012 the ATLAS [13] and CMS [14] collaborations discovered a neutral boson compatible with the Higgs boson, with a mass value of ≈ 126 GeV. Further studies reached a better precision on the Higgs mass measurement: the current best estimation of the mass value is 125.18 ± 0.16 GeV [15], combining ATLAS and CMS measurements. With this mass value, it is possible to calculate precisely its production cross sections, the decay rates, the branching ratios and the higgs-fermions couplings.

Feynman diagrams of the main production mechanisms are shown in Figure 1.5. The two Higgs boson production mechanisms having the largest cross section are the gluon gluon Fusion (ggF) and the Vector Boson Fusion (VBF). Other important production mechanisms, due to their clean experimental signature, are the production in association with a vector boson (VH) and with a top pair (ttH).

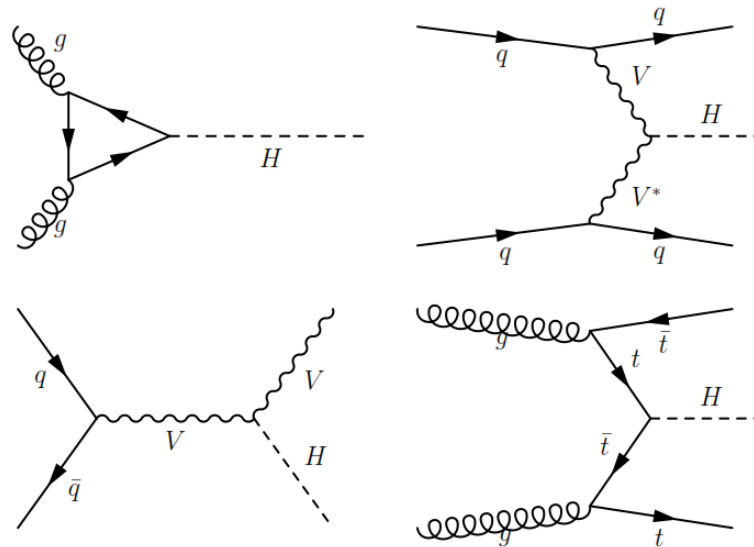


Figure 1.5: Most important Higgs production mechanisms, from top left: gluon-gluon Fusion (ggF), Vector Boson Fusion (VBF), production in association with a vector boson (VH) or with a top pair (ttH).

To study the properties and the couplings of the Higgs boson, it is important to know not only the production rates but also the decay rates (see Figures 1.6 and 1.7). The Higgs boson can decay directly into all possible massive particles, and into pho-

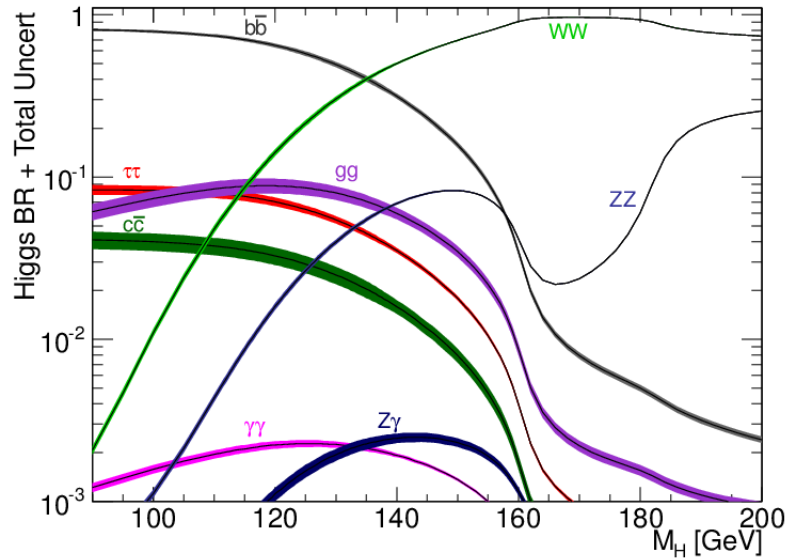


Figure 1.6: Higgs boson decay branching ratios for different mass value: at ≈ 125 GeV the $H \rightarrow b\bar{b}$ is the main channel with about 58%, followed by WW (roughly 20%).

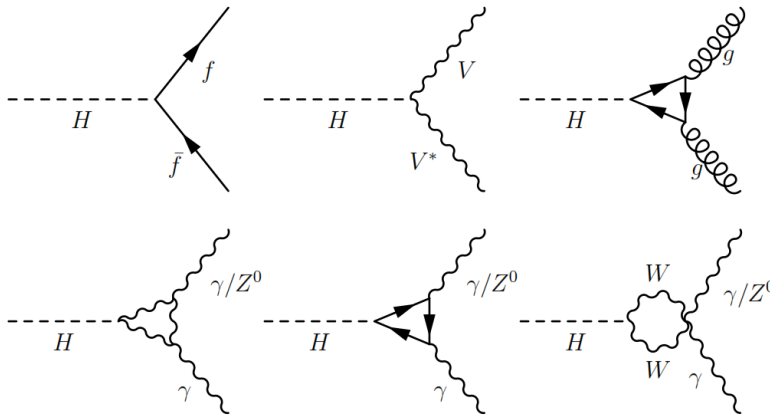


Figure 1.7: Most important Higgs decays channels, from top left: into a fermion pair, a weak vector boson pair, a gluon pair through coupling with a fermion triplet, a $\gamma\gamma$ or a γZ^0 pair through triplets or loop diagrams.

tons and gluons through loop diagrams. With a 125 GeV mass, the main branching ratio is $H \rightarrow b\bar{b}$ (58%) followed by $H \rightarrow WW$ (roughly 20%), with decreasing branching ratio but not minor importance: gg , $\tau\tau$, ZZ , $c\bar{c}$, $\gamma\gamma$, $Z\gamma$.

The Higgs discovery made by the ATLAS and CMS collaborations was performed studying the ZZ and $\gamma\gamma$ decay channels, because these signatures are clearly identified in the detector. On the opposite, at a hadron collider, there is plenty of quark production and this represents a large background for the search in the $H \rightarrow b\bar{b}$ channel. Also for this decay channel, data indicate that the newly discovered particle is compatible with what expected for the SM Higgs boson. In order to measure the Higgs properties, it is essential to measure all the Higgs couplings, included the one with b -quarks.

The b -tagging plays a crucial important role in those searches, especially in the $H \rightarrow b\bar{b}$ channel: this channel has been studied extensively at ATLAS with Run 1 and Run 2 data, with increased energy and luminosity (7 TeV, 8 TeV and 13 TeV results are shown in Figure 1.8). This huge effort led to the evidence of $H \rightarrow b\bar{b}$ [16], announced by the ATLAS collaboration in July 2017, and then to the observation [17], announced in August 2018.

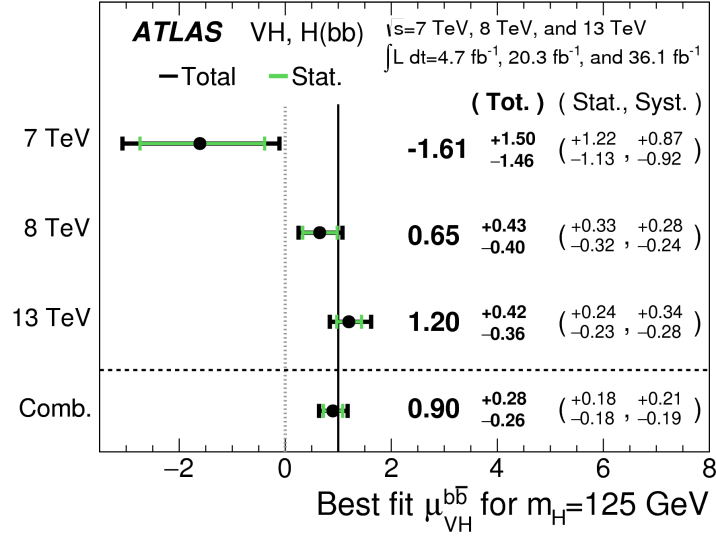


Figure 1.8: Results of the Higgs measurements in the $H \rightarrow b\bar{b}$ channel performed by the ATLAS experiment with 7, 8 and 13 TeV data.

The largest source of Higgs bosons is the production via gluon fusion, but the $gg \rightarrow H \rightarrow b\bar{b}$ channel is not experimentally measurable because of the high background of $b\bar{b}$ events (10^7 more frequent than the signal). The experimental accessible measurements are instead those performed in the more clean associated production of a Higgs with a W or Z vector boson ($VH \rightarrow b\bar{b}$), that allows a easier background rejection, selecting leptons coming from Vector bosons decay. The distribution of the invariant mass of the b -jet pair is presented in Figure 1.9 in data after subtraction of all backgrounds, except for the WZ and ZZ diboson processes.

Top quark is the heaviest particle ever discovered with a measured mass of 173.0 ± 0.4 GeV [15]. It was discovered at Tevatron [18, 19] in 1995, and since then many measurements have been carried out in order to determine its properties. Top quark lifetime is so low ($\sim 10^{-25}$ s) that it is the only quark decaying before the hadronization process occurs. For this reason, no hadrons containing top quark can be observed. The top quark decays almost exclusively into a bottom quark and a W boson via an electro-weak process ($t \rightarrow Wb$ branching ratio being around 99% [15]): the correct identification of a b -jet allows to study in deep the top quark and its properties. The precise measurement of top quark production cross sections and decay channels is important because events having top quarks in the final state

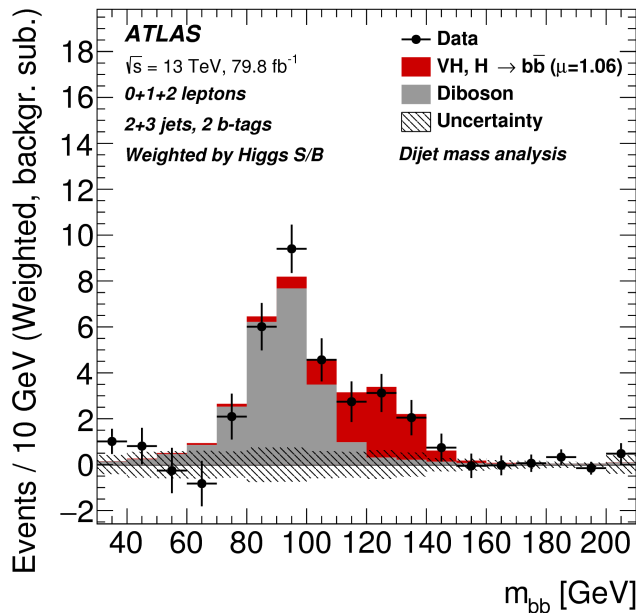


Figure 1.9: Distribution of the invariant mass of the b -jet pair, measured by ATLAS in the $VH \rightarrow b\bar{b}$ channel, after subtraction of all backgrounds, except dibosons.

are one of the dominant backgrounds in many physics analyses searching for new physics beyond Standard Model.

One of the most intriguing measurement in the Higgs sector is the search for Higgs boson associated production with a top pair (ttH). It is one of the most complicated Higgs measurements as well, since the production rate of ttH is very low (about 1% branching ratio) and its final state involves a high number of objects among top and Higgs decay products. There is great interest in this measurement because the top quark has a very large mass; therefore, the strength of its coupling with the Higgs boson is high, higher than any other coupling. The direct measurement of the Higgs-to-top coupling is important to confirm the indirect results, that can be derived starting from other Higgs boson couplings measurements.

The ATLAS collaboration announced to have found statistically significant evidence of the ttH production [20] in 2017 (see Figure 1.10), then the observation was announced in 2018 [22] (see Figure 1.11). Among the studied decay channels, there is also $ttH \rightarrow b\bar{b}$ [21], which involves 4 b -jets in the final states. Due to its complexity, it was categorized into 19 regions as a function of the number of jets and b -jets, and the quality of the b -jet identification.

1.4.2 SM precision measurements

Among recent highlights in ATLAS physics results, there is the precise measurement of the mass of the W boson [23], a parameter closely related to the masses of the top quark and the Higgs boson. Measuring the W mass is a Standard

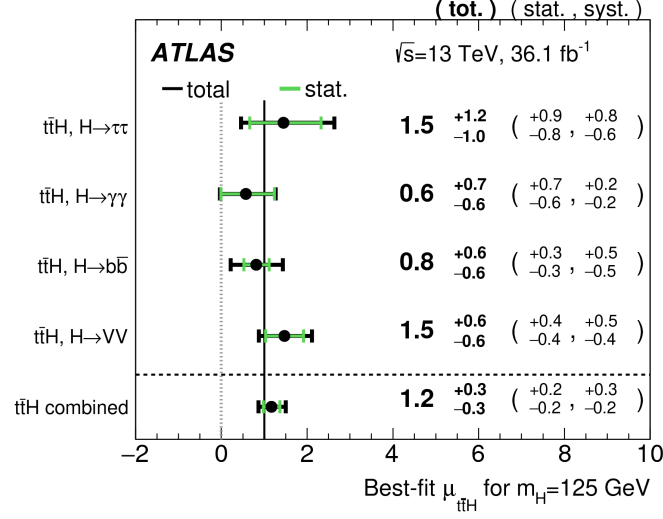


Figure 1.10: Results of the ATLAS measurement of the Higgs boson associated production with top quark pairs, in different Higgs boson decay channel, performed on 13 TeV data.

Model test itself, but also a possible way to look for physics beyond the Standard Model, since any deviation from the theory prediction would be a sign of new physics. The W mass was measured previously at LEP and Tevatron, yielding a world average of 80.385 ± 0.015 GeV, which is consistent with the SM constraints of 80.358 ± 0.008 GeV. The ATLAS collaboration has recently reported the first measurement of the W mass at the LHC [23], based on 4.6 fb^{-1} 7 TeV data, after years of accurate calibrations. The value measured by ATLAS, 80.370 ± 0.019 GeV, matches the precision of the Tevatron CDF experiment and is consistent with both the SM prediction and combined measurements (see Figure 1.12). The value measured by ATLAS is compared to results from the LEP (ALEPH, DELPHI, L3 and OPAL) and the Tevatron experiments (CDF and D0). Measured values of mass for positively and negatively charged W bosons are also shown.

Significant contributions to W production from second-generation quarks (strange and charm) are expected at LHC, compared to LEP and Tevatron: the enhanced amount of W boson produced due to heavy quarks and the ratio of valence and sea quarks in the proton affect the W boson transverse-momentum distribution and its polarisation, which makes the measurement sensitive to the proton PDFs.

Another recent ATLAS result, even more sensitive to proton PDFs, is the $W \rightarrow l\nu/Z \rightarrow ll$ cross section ratio measurement, where W and Z boson production cross sections measured at 7 TeV [24] with high precision are combined into a ratio, allowing to reduce some of the common systematics. The experimental precision reached is comparable and sometimes better than the one on the theoretical predictions. In Figure 1.13, the ATLAS result is compared with predictions obtained adopting different PDFs: in all cases, the predicted cross section ratio values are higher than those measured in data, clearly pointing out the need for improvements in the description of the proton structure.

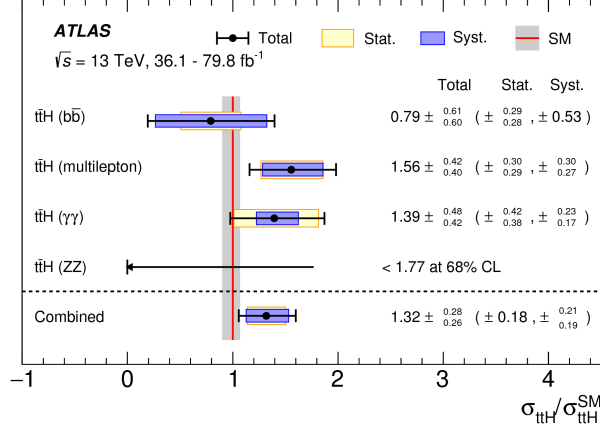


Figure 1.11: Combined ttH production cross section, as well as cross sections measured in the individual analyses (79.8 fb $^{-1}$: $\gamma\gamma$, ZZ; 36.1 fb $^{-1}$: multilepton, $b\bar{b}$), divided by the SM prediction. The black lines show the total uncertainties and the bands indicate the statistical and systematic uncertainties. The red vertical line indicates the SM cross-section prediction and the grey band represents the PDF uncertainties and the uncertainties due to missing higher-order corrections.

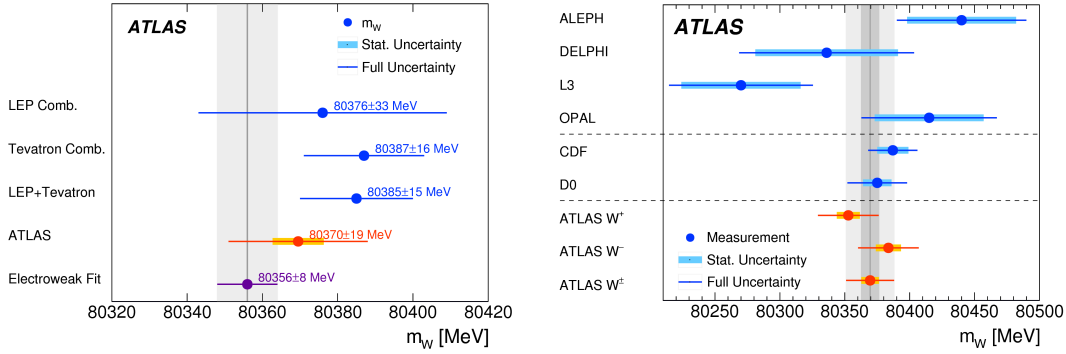


Figure 1.12: W boson mass measured by ATLAS compared with predictions and results from other experiments.

A broad interest in the LHC community is growing towards the strange quark PDF: several measurements are aiming at constraining further and further its values, currently affected by high uncertainties. Cross section measurements both of inclusive W/Z production and of specific W/Z +jets processes (for example $W+c$ production) provide constraints on the proton PDFs. The strange quark PDF is of particular interest due to a tension between experimental results and the predictions [25]. The previous ATLAS W and Z boson cross section measurements and its QCD interpretation suggested that the light quark sea is flavour symmetric. The ratio of the strange-to-anti-down quark densities, r_s , was found to be close to unity within 20% uncertainty, where r_s is calculated as:

$$r_s = \frac{0.5(s + \bar{s})}{\bar{d}}. \quad (1.5)$$

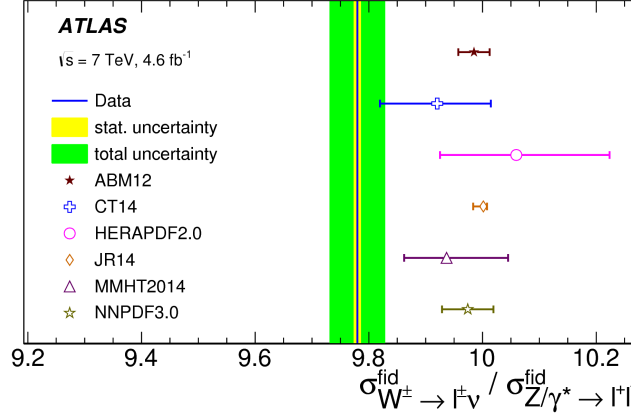


Figure 1.13: Fiducial cross sections times leptonic branching ratios of the $W \rightarrow l\nu/Z \rightarrow ll$ ratio. The data (solid blue line) are shown with the statistical (yellow band) and the total uncertainties (green band). The uncertainties of the theoretical calculations correspond to the PDF uncertainties only.

The recent ATLAS high precision measurement with 7 TeV data has been used to derive a new version of the ATLAS based PDF set, *ATLAS-epWZ16*, that supersedes the previous *ATLAS-epWZ12* set. In the new set, the ratio of strange-to-light sea-quark densities in the proton is determined more accurately and is established to be close to unity in the sensitivity range of the data, suggesting unsuppressed strangeness as a function of x . In particular, the strange-to-light sea-quark ratio, R_s , built as:

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}, \quad (1.6)$$

is found to be higher than unity in the x range considered ($10^{-3} < x < 10^{-1}$), with larger model uncertainties in the high and low x regions (see Figure 1.14). The ATLAS data have the best sensitivity in the region with $Q^2 = 1.9 \text{ GeV}^2$ and $x = 0.023$, where the R_s is measured to be $1.13 \pm 0.05 \text{ (exp)} \pm 0.02 \text{ (mod)} \pm_{-0.06}^{+0.01} \text{ (par)}$. With this high precision measurement, ATLAS is definitely accessing the proton structure. Theoretical predictions, based on calculations accurate to Next-to-Next-to-Leading Order (NNLO) for QCD and to Next-to-Leading Order (NLO) for electroweak processes based on different PDF sets, are compared to the ATLAS result.

Moreover, both the ATLAS [26] and CMS [27] experiments have measured the $W+c$ process cross section, using $\sqrt{s} = 7 \text{ TeV}$ pp collision data collected at the LHC in 2011. The ATLAS result [26] suggested that the ratio of strange-to-down sea-quark distributions r_s is compatible with the unity for a wide range of x (Figure 1.15, left). Recently, an updated measurement performed by the CMS experiment [28], with $\sqrt{s} = 13 \text{ TeV}$ pp collision data collected at the LHC in 2016, has shown that r_s decrease with the increase of x (Figure 1.15, right).

In this context, the preparatory studies for the measurement of the $W+c$ cross section with Run 2 ATLAS data are presented in this thesis (see Chapter 11).

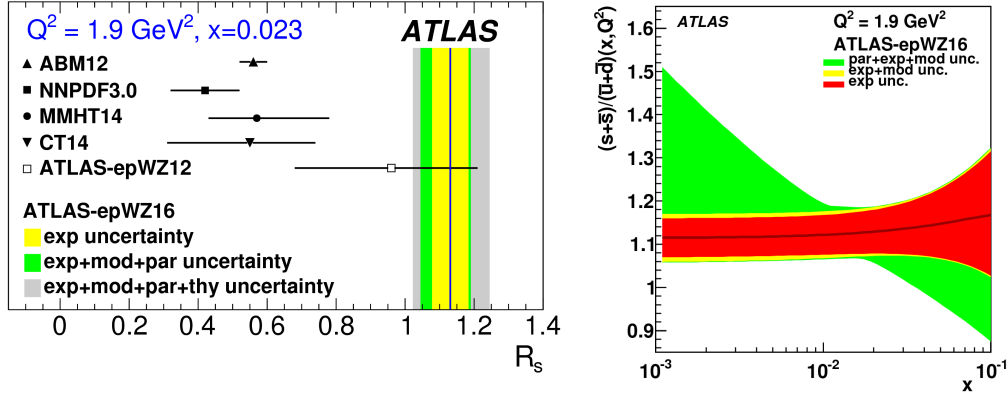


Figure 1.14: Left: R_s ratio of the *ATLAS-epWZ16* PDFs shown in the region of maximum sensitivity of the ATLAS data, $10^{-3} < x < 10^{-1}$. Red, yellow and green bands represent the experimental (exp), model (mod) and parameterization (par) uncertainties, respectively. Right: R_s in the region of ATLAS best sensitivity, $Q^2 = 1.9 \text{ GeV}^2$ and $x = 0.023$. Bands present result and its uncertainties from experimental data, QCD fit, and theoretical uncertainties.

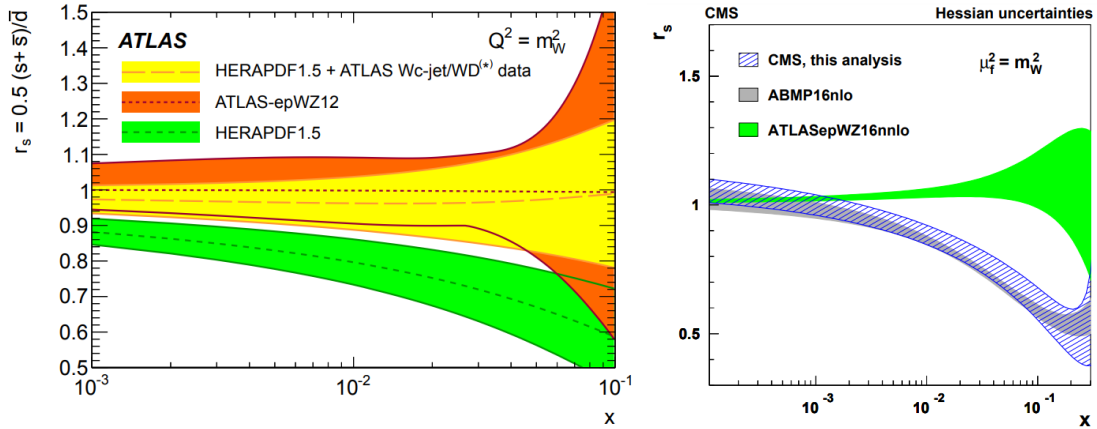


Figure 1.15: Ratio of strange-to-down sea-quark distributions r_s as a function of x at $Q^2 = m_W^2$. Left: HERAPDF1.5 PDF compared to the fit including ATLAS $W+c\text{-jet}/W+D^*$ data, and *ATLAS-epWZ12*. Right: ABMP16 PDF compared to the fit including CMS $W+D^*$ data, and *ATLAS-epWZ16*.

Chapter 2

The ATLAS detector

The ATLAS detector is 46 m long with a 25 m diameter and its overall weight is over 7000 tons (see Figure 2.1). The ATLAS coordinates are reported in Section 2.1. ATLAS is composed by three different sub-detectors: the Inner detector (Section 2.2), the Calorimeters (Section 2.3) and the Muon spectrometer (Section 2.4). These components cover the interacting point, embracing it in the shape of a cylinder: each of the three sub-detectors is divided into a barrel section (around the collision point, in the central region) and two end-caps (at the two sides, in the forward region). In particular, the Inner detector measures charged particles momentum and provides their reconstructed trajectories; the Calorimeters measure the energy of hadrons, electrons, positrons and photons; the Muon spectrometer identifies muons and measures their momentum. To measure properly the particles momentum and their charge sign, ATLAS is equipped with a Magnet system (Section 2.5) composed by a superconducting solenoid (around the Inner detector) and 8 large superconducting toroids (around the Calorimeters). Proton-proton interactions occur at a very high rate: the data acquisition infrastructure (Section 2.6) manages the huge data flow through a dedicated trigger system which selects the most interesting physics events. In the next years the ATLAS detector will undergo several upgrades, including the complete replacement of its tracking system: an introduction to the silicon tracking detectors is presented in Chapter 3, with a focus on the Pixel detectors technology and the future tracker: the Inner Tracker (ITk).

2.1 ATLAS coordinates

The ATLAS coordinate system has the origin in the nominal collision point, with the Y axis pointing vertically upwards, the X axis pointing towards the center of LHC ring and the Z axis pointing towards the direction of the counter-clockwise circulating beam. Actually, the Y axis points upwards with a 0.704° tilt, because of the LHC plane inclination (see Figure 2.2).

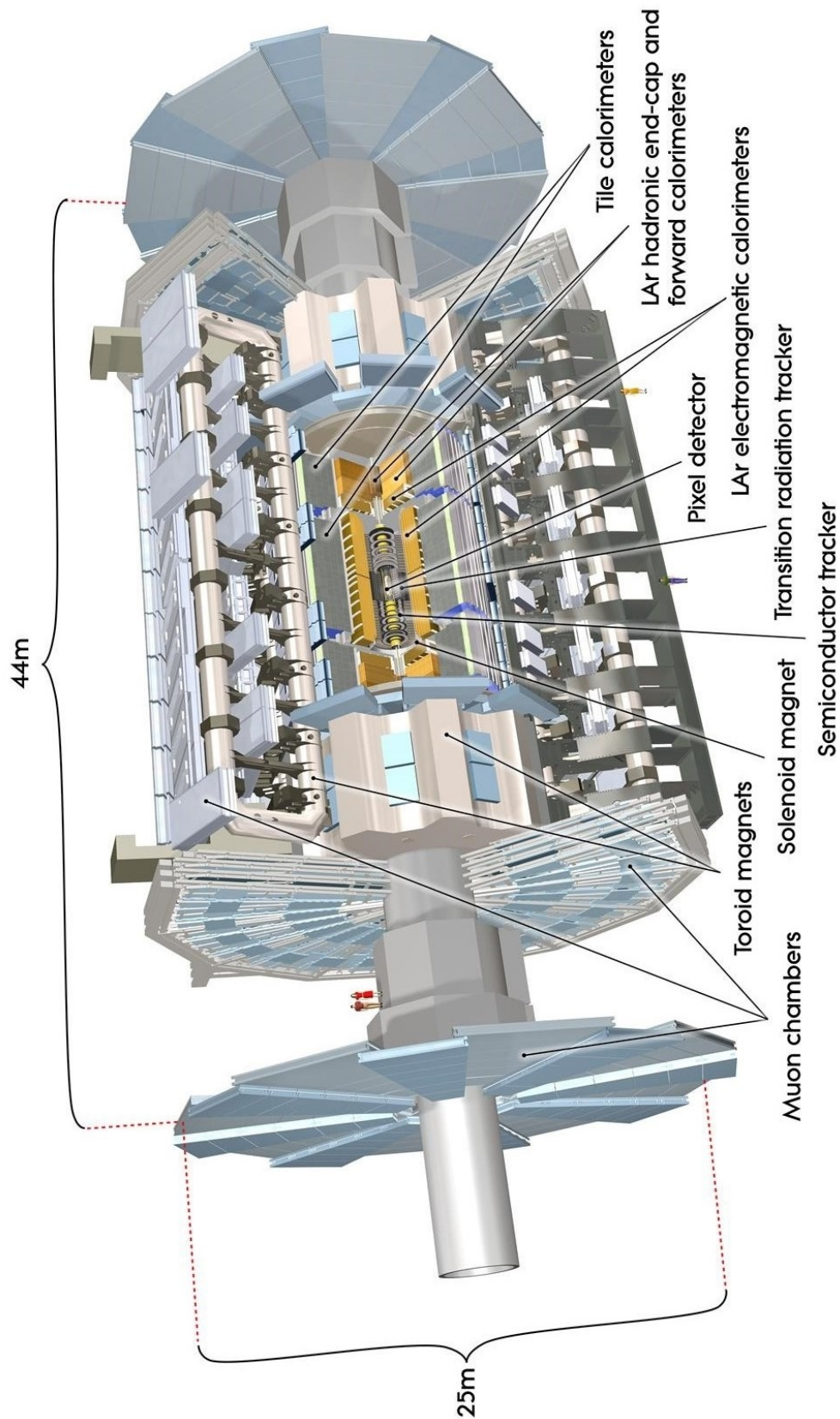


Figure 2.1: Full view image of the ATLAS detector. [29]

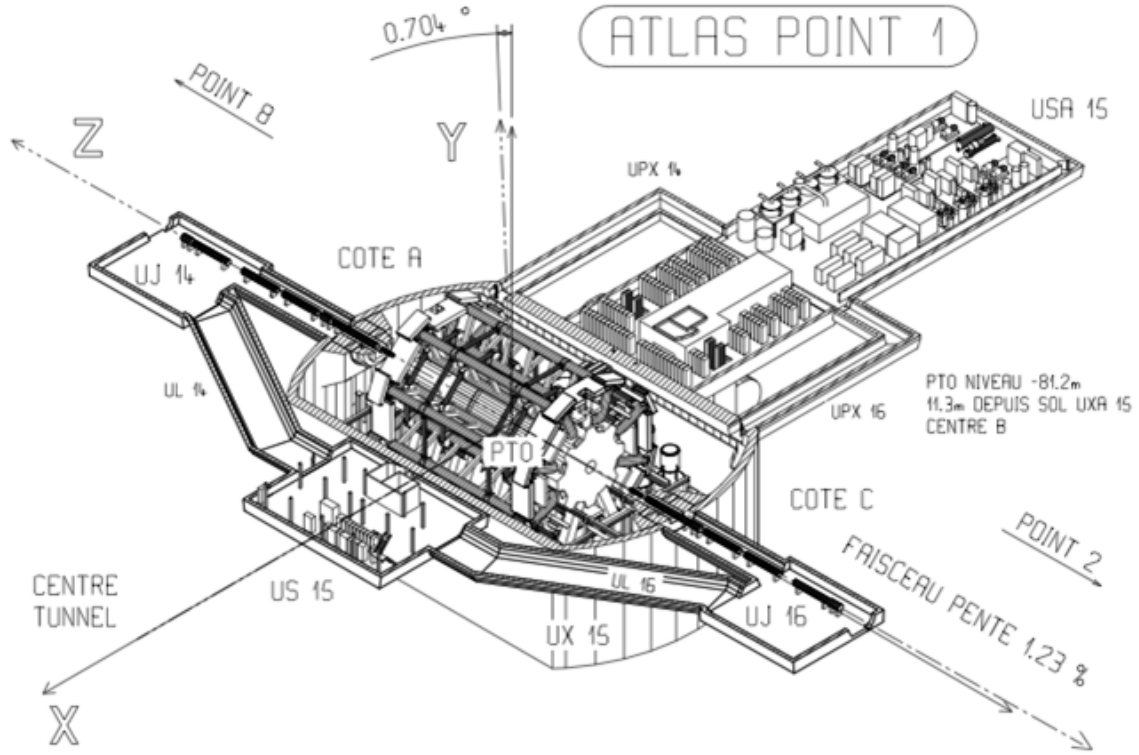


Figure 2.2: Interaction Point 1: ATLAS cavern and coordinate system.

Instead of cartesian coordinates, a system of cylindrical coordinates is preferred:

$$(x, y, z) \rightarrow (r, \phi, \theta). \quad (2.1)$$

The three cylindrical coordinates are: the radial coordinate r , the azimuthal angle ϕ , lying in the transverse plane with respect to the beam, and the polar angle θ , defined as the angle between the particle three-momentum $\mathbf{p}$ and the positive direction of the beam axis. The polar angle coordinate is often expressed in terms of the pseudorapidity η (widely used in high energy physics), where η is defined as a function of the polar angle θ :

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right). \quad (2.2)$$

Many analyses often require a selection on a precise pseudorapidity range ($|\eta| < 2.5$) corresponding approximately to the interval between $\theta = 9.39^\circ$ and $\theta = -9.39^\circ$, since in this region there is a better instrumental coverage.

Starting from the cylindrical coordinates, all vectors, including cinematic vectors, are expressed in these terms (p_T, η, ϕ) , where the transverse momentum p_T is defined as the component of the three-momentum $\mathbf{p}$ perpendicular to the beam axis:

$$p_T = \sqrt{p_x^2 + p_y^2}. \quad (2.3)$$

2.2 Inner detector

The Inner Detector (ID) [30] is the closest to the the interaction point, surrounding the beampipe. It is composed by 4 subdetectors (see Figure 2.3), from the inner to the outer most: the Insertable B-Layer (IBL), the Pixel detector, the Semi Conductor Tracker (SCT) and the Transition Radiation Tracker (TRT). The silicon detectors (IBL, Pixel and SCT) are arranged in cylindrical layers: the barrel layers, made by longitudinal bars covering the interaction region, and the end-cap disks, at the two sides of the barrel. In a similar way, the straw tubes of the TRT are distributed longitudinally in the barrel and radially in the disks. Each layer of the subdetectors provides a 1D coordinate (hit) of the particle transit. Subsequently the hits are connected, reconstructing a 3D track. Immersed into a 2 T magnetic field generated by the solenoid, the ID provides precise charged particle identification, their trajectories and vertex reconstruction. Basic characteristics of the subdetectors are resumed in Table 2.1, more details are provided in the following Sections.

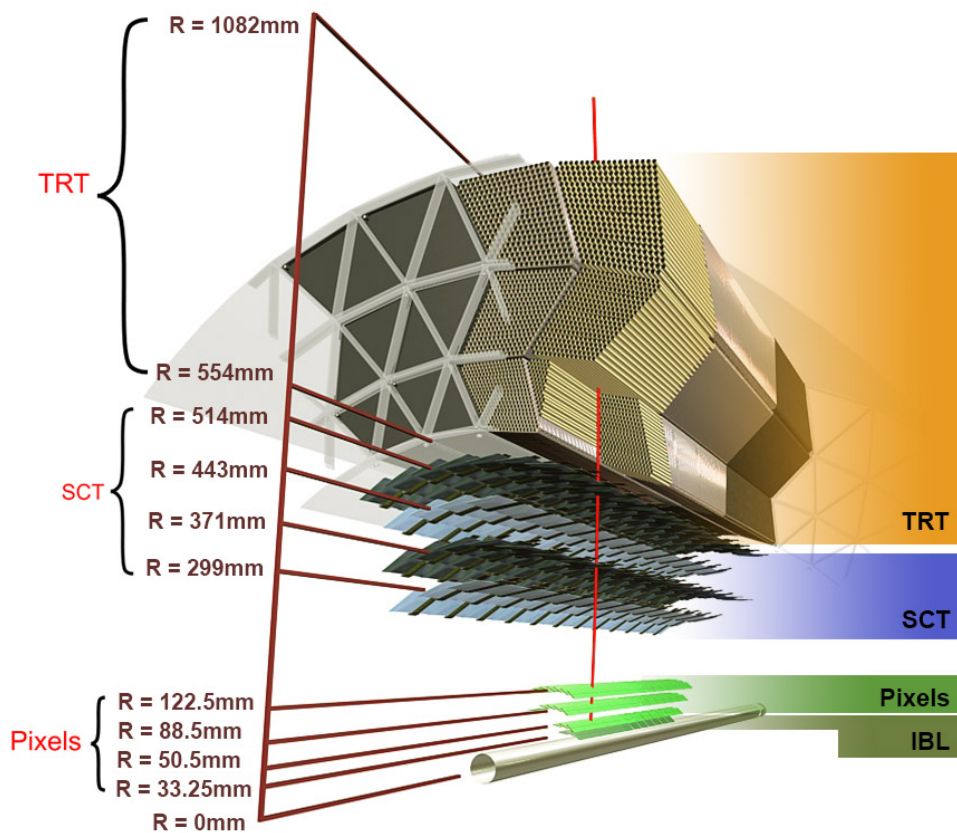


Figure 2.3: Overview of the barrel section of the Inner Detector after the IBL insertion (2015). [29]

Subdetector	Element size	Intrinsic resolution [μm]	Barrel layers radius [mm]
IBL	$50 \mu\text{m} \times 250 \mu\text{m}$	$8 (R - \phi) \times 40 (z)$	33.2
Pixel	$50 \mu\text{m} \times 400 \mu\text{m}$	$10 (R - \phi) \times 115 (z)$	50.5, 88.5, 122.5
SCT	$80 \mu\text{m}$	$17 (R - \phi)$	299, 371, 443, 514
TRT	4 mm	$130 (R - \phi)$	from 554 to 1082

Table 2.1: Basic characteristics of the ID subdetectors: element size, intrinsic resolution and barrel layer radius. For SCT and TRT the element sizes refer to the spacing of the readout strips and the diameter of the straw tubes, respectively.

Insertable B-Layer

The Insertable B-Layer (IBL) [31] has been introduced between the innermost Pixel layer (the B-layer) and the vacuum chamber containing the beams (beampipe) during the first Long Shutdown occurred between Run 1 and Run 2. A new Beryllium beampipe was built (reducing the radius from 29 mm to 25 mm) in order to obtain enough space for the IBL installation. IBL is composed by 14 staves each supporting 20 modules, mounted longitudinally on the beampipe (see Figure 2.4), at about 33 mm from the interaction point. In particular, each staff is equipped with 12 Planar sensors (in the central region of the staff) and 8 3D sensors (in the forward region of the staff, 4 for each side). The Planar sensors are bump-bonded to two Front-End readout chips, while the 3D sensors are connected to a single Front-End chip. In particular, Planar sensors are silicon double chip sensors ($n^+ - in - n$) while 3D sensors are single chip sensors ($n - in - p$).

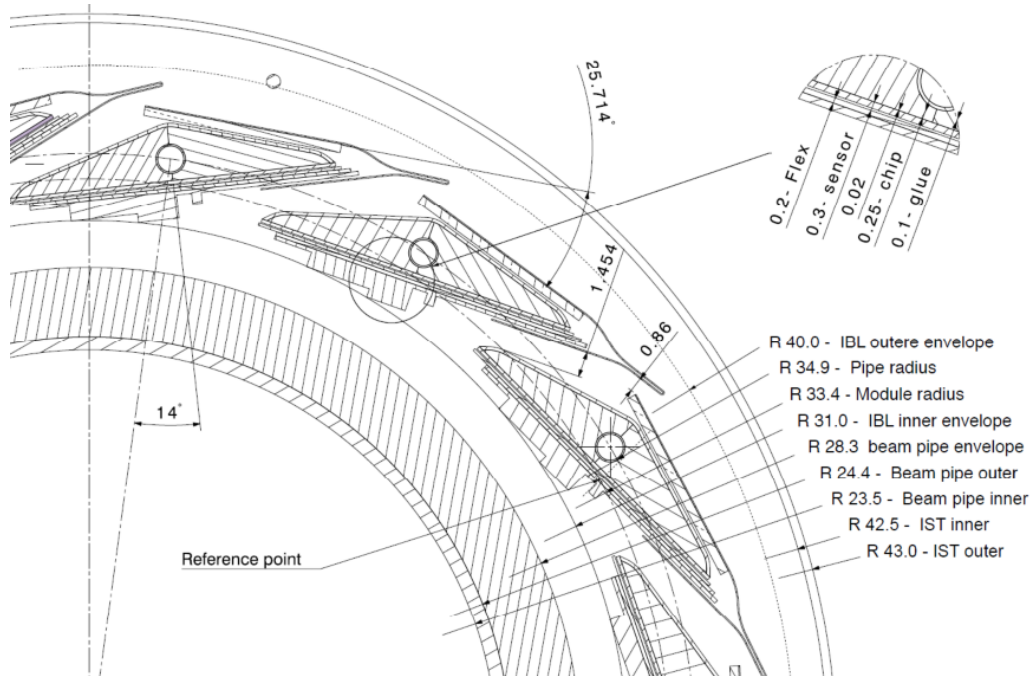


Figure 2.4: Radial view of IBL layout: the staves are mounted between the beampipe and the IBL Support Tube (IST).

Given the fact that semi conductor detectors are quite sensitive to radiation, the main purpose of the IBL is to provide a new additional layer, less sensitive to radiation damage, increasing the robustness of the track reconstruction of the detector. Furthermore, the addition of an extra layer placed closer to the interaction point considerably improves the vertex reconstruction capability of the detector.

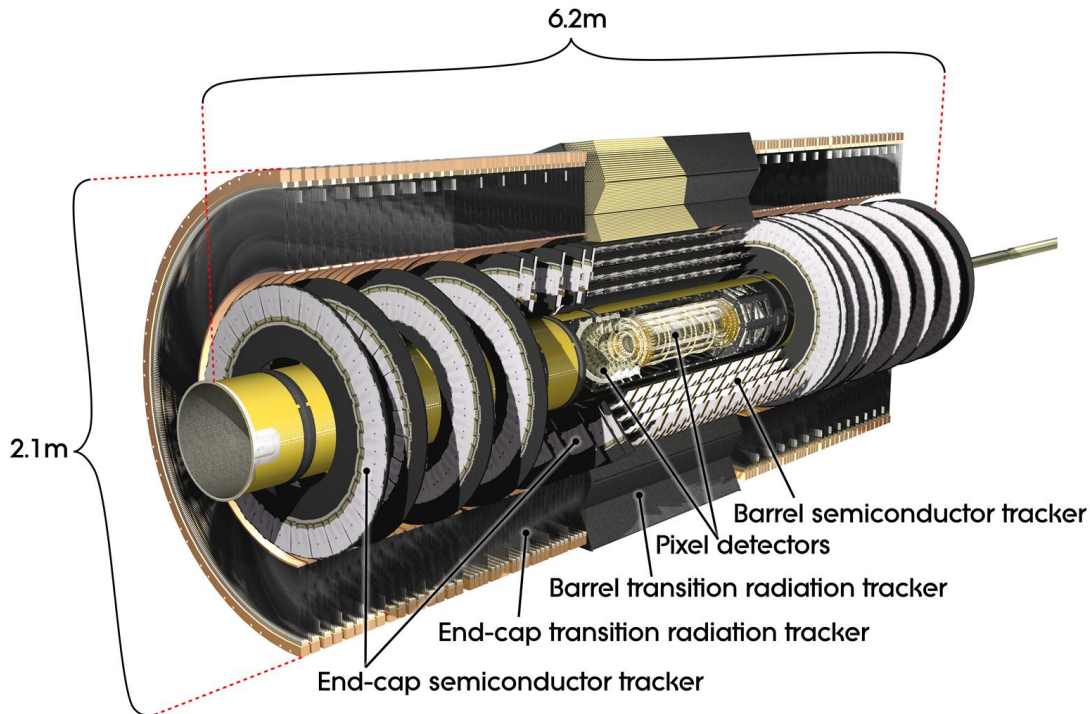


Figure 2.5: Overview of the Inner Detector before introducing IBL: Pixel detector, Semi Conductor Tracker and Transition Radiation Tracker.

Pixel detector

The Pixel detector [32] is located around the interaction point, surrounding IBL. It is composed by three concentric barrel layers (mean radius: 5.05 cm, 8.85 cm and 12.25 cm; length: 80.1 cm) and two end-caps of three disks each (mean radius: 17 cm; distance from the interaction point: 49.5 cm, 58 cm and 65 cm): this allows to provide three hits for a precise track reconstruction. Thanks to Pixel detector it is possible to identify collision vertices and to measure the impact parameters of tracks with high resolution (impact parameters define the distance of closest approach between the track and the primary interaction vertex position, see Section 7.1). With approximately 80 million silicon sensors¹, the Pixel detector covers a pseudorapidity range of $|\eta| < 2.5$ with an extremely high granularity. It reaches an accuracy of 10

¹The Pixel detector channels, together with the IBL channels, reach a total of about 100 million channels, each of them individually calibrated.

μm in $R - \phi$ and $115 \mu\text{m}$ in z in the barrel, $10 \mu\text{m}$ in $R - \phi$ and 115 in R in the disks. Its role is crucial to perform b -tagging as its high spatial resolution allows to measure with high precision the distance between tracks and the primary interaction vertex.

Semi Conductor Tracker (SCT)

The Semi Conductor Tracker (SCT) [33,34] consists of 4088 modules of silicon strips arranged in four concentric barrels and two end-caps of nine disks each, for a total surface of 63 m^2 . The barrel region uses two different micro-strips with one set of strips in each layer parallel to the beam direction and a relative angle of 40 mrad . The end-cap region has a set of strips running radially and a set of stereo strips at an angle of 40 mrad . The SCT is designed to provide a minimum of four three-dimensional position measurements per track: it allows precise measurements of track momenta, vertex position and impact parameter with an accuracy of $17 \mu\text{m}$ in $R - \phi$ and $580 \mu\text{m}$ in z .

Transition Radiation Tracker

The Transition Radiation Tracker (TRT) [35] is both a straw drift-tube tracker and a transition radiation detector. It is divided in two barrel sections and two end-caps. The detector consists of about 300000 proportional drift tubes (straws) with 2 mm diameter; each tube is filled with a gas mixture of Xe , CO_2 and O_2 , with $5\text{-}10 \text{ mbar}$ over-pressure. The barrel sections are composed by 144 cm long straws disposed parallel to the beam direction; the end-caps are composed by radially disposed 37 cm long straws. The accuracy is not high (about $130 \mu\text{m}$ per straw in $R - \phi$), anyway the high number of hits (~ 36 per crossing track) compensates the low precision, providing an accurate momentum measurement.

2.3 Calorimeter

The Calorimeter system [36] surrounds the ID and the 2T solenoid (see Figure 2.6): it is composed by an electromagnetic calorimeter designed to measure the energy and provide identification of electrons/positrons and photons and by an hadronic calorimeter for energy measurement of charged and neutral hadrons. With an overall radius of 4.23 m and a length of 13.3 m , with the hadronic calorimeter surrounding the electromagnetic one, it covers a total range in pseudorapidity $|\eta| < 4.9$. It consists in a barrel section and two end-caps for both electromagnetic and hadronic calorimeter, plus a forward calorimeter in the forward region (the region at small angle with respect to the beam axis). Dedicated sections of the calorimeter have trigger capabilities, exploited for the fast event selection.

In particular the Calorimeter system can measure with high precision the energy, position and shower shape of electrons/positrons, photons and jets. With these

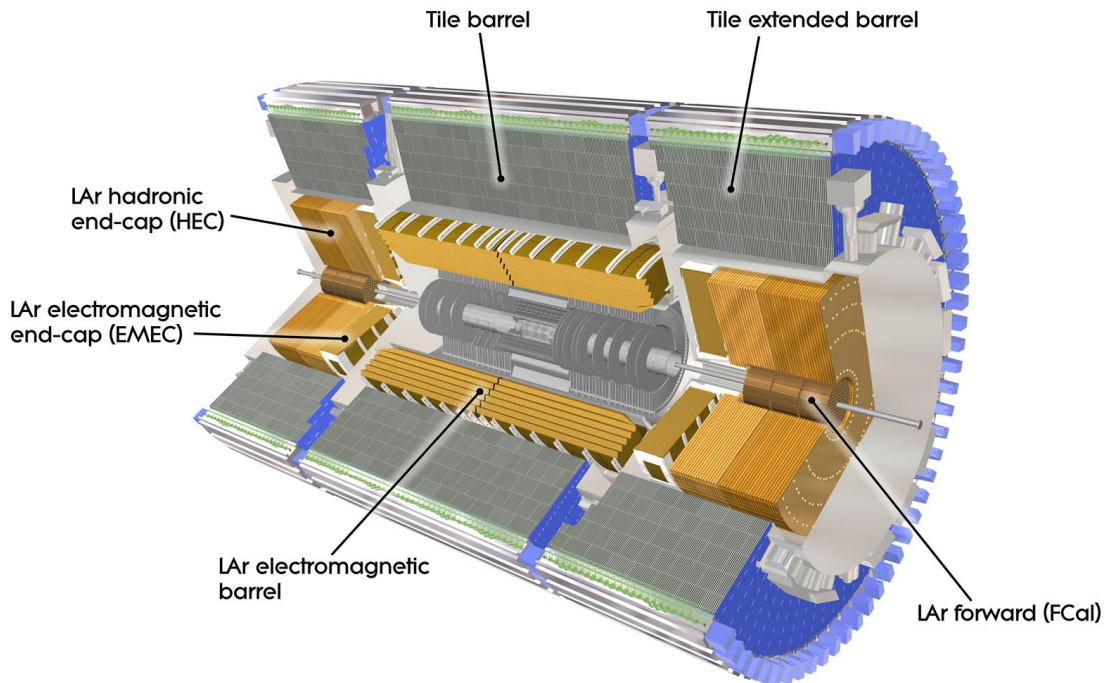


Figure 2.6: The ATLAS Calorimeters system: electromagnetic, hadronic and forward sections. [29]

measurements, it contributes to the definition of missing transverse momentum and to particle identification. It is capable of disentangling electron/positron and photon showers from showers coming from hadrons and tau decays and QCD background up to the TeV energy scale.

Electromagnetic Calorimeter

The electromagnetic calorimeter uses Lead layers as absorber material to generate the particle shower and liquid Argon layers as active material to measure energy and position. It is composed by a barrel section ($|\eta| < 1.475$, more than 26 radiation lengths) and two end-caps ($1.375 < |\eta| < 3.2$, more than 24 radiation lengths). The barrel section is divided in two identical half-barrels, while each endcap is divided into two coaxial wheels. This geometry enhances the η precision measurements and the γ/π_0 and the e/π separation.

Hadronic Calorimeter

The hadronic calorimeter uses different materials for barrel and end-caps: the barrel section uses Iron as absorber material and scintillating tiles as active material, while the end-caps use Argon technology with Copper as absorber material. The barrel section is composed by the central tile barrel ($|\eta| < 1.0$) and by two lateral

tile extended barrel ($0.8 < |\eta| < 1.7$). The hadronic calorimeter end-caps cover a pseudorapidity range $1.5 < |\eta| < 3.2$. This approach contains the hadrons from propagating further in the muon system and provides good measurements of missing transverse momentum.

Forward Calorimeter

The forward calorimeter uses copper and tungsten as absorber materials and liquid argon as active material, covering the forward region between $3.2 < |\eta| < 4.9$, a region with very high level of radiation. It is composed by one electromagnetic and two hadronic calorimeter layers for each side of the interaction point, longitudinally 1.2 m far from the Inner detector.

2.4 Muon spectrometer

The Muon spectrometer [37] is the outermost of the ATLAS sub-detectors (see Figure 2.7). Thanks to the magnetic field produced by the air-core toroid system (described in Section 2.5), it measures the kinematic properties of the muons, through the deflection of their tracks. It is designed to detect charged particles in the pseudorapidity range $|\eta| < 2.7$, measuring the momentum with small uncertainty; it has also trigger capability in the pseudorapidity range $|\eta| < 2.4$. In order to enhance the momentum resolution, the tracks reconstructed in the muon spectrometer can be extrapolated back to the internal region of the ATLAS detector, matching the Inner detector track with the track provided by the Muon spectrometer. The muon system is divided in barrel and end-cap regions, employing four different detector technologies: Monitored Drift Tube chambers (MDT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC). In particular the MDT and the CSC measure with high accuracy the 2D spatial coordinates of the track: they are the tracking core of the muon system because of their high spatial resolution ($80 \mu\text{m}$). The RPC and the TGC are the trigger core of the muon system: they provide a faster but less precise signal, useful for trigger decision.

2.5 Magnet system

The magnet system is made of two different solutions: a central superconducting solenoid and 3 air-core superconducting toroids. The solenoid surrounds the Inner detector and provides a 2 T axial magnetic field that bends particles trajectories. It is 5.3 m long, with a mean radius of 1.25 m; it is cooled at 4.5 K by liquid helium. The toroidal field is generated by 3 huge air-core toroids: one in barrel region and two in the end-cap regions². Each air-core toroid consists of 8 coils mounted symmetrically

²The magnetic field intensity (1 T for the barrel and 0.5 T for the end-cap regions) are indicative, since the field is not uniform across the whole area.

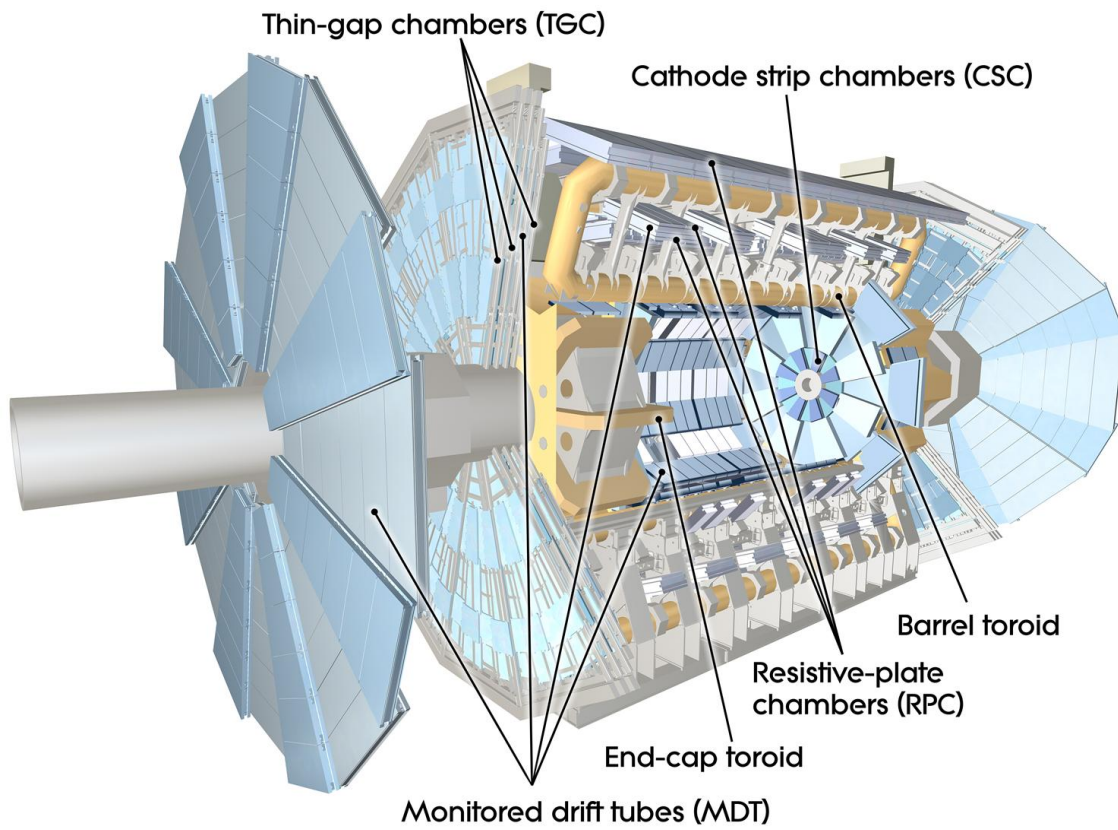


Figure 2.7: Overview of the Muon spectrometer. [29]

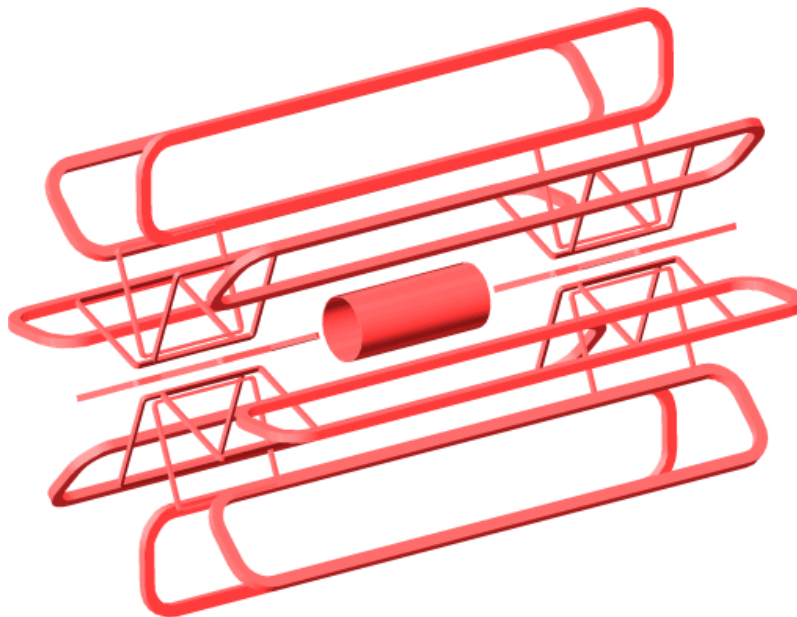


Figure 2.8: The Magnet system: the superconducting solenoid and the toroids.

in ϕ , distanced of 45° around the beam axis. The barrel toroids extend for more than 25 m with an inner diameter of 9.4 m and an outer diameter of 20.1 m. The end-cap toroids have a length of about 5 m, with an inner diameter of 1.6 m and an outer diameter of 10.7 m.

2.6 Trigger and data acquisition

The high event rate produced by LHC collisions is impossible to handle with any available storage technology, while at the same time, the majority of the events are not interesting. The trigger infrastructure performs a drastic selection of the events, reducing the data flow to an acceptable level before transferring it to permanent storage. The data acquisition system (DAQ) reads the data from the detector and manages the data flow until the permanent storage. These two systems are strictly interacting, they are often referred to as a unique system, the TDAQ. A schematic view of the Run 2 ATLAS trigger and DAQ infrastructure is visible in Figure 2.9.

At the design luminosity ($\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$), LHC collisions produce about 23 interactions per bunch crossing: this means a data production of 4000 Gb/s for a bunch crossing rate of 40 MHz (1 bunch crossing event per 25 ns). The ATLAS trigger system [38] is capable to reduce this huge data quantity selecting the interesting events with physics-oriented criteria. During Run 1 the trigger system was divided in 3 levels: Level-1, Level-2 and Event Filter, while from Run 2 the last two levels are merged to form a unique software based trigger, the High Level Trigger.

The Level 1 trigger selects Regions of Interest (RoI) using the Calorimeters and the Muon spectrometer information, searching above all for high transverse momentum particles, the most interesting particles produced in the collisions. Within 2.5 μs , the hardware processors select the events with a roughly 100 kHz accept rate.

The High Level Trigger uses the complete detector information: fine granularity data coming from the Inner detector, the Calorimeters and the Muon spectrometer. It performs ID track reconstruction and searches among fully-built events within 4 s, reducing the rate to a few hundreds of Hz. Adopting offline-like algorithms, in some cases exactly the ones used for final reconstruction, this step can be performed only at the end of the chain, thanks to the previous data reduction.

During the selection, the trigger levels exchange information in the form of RoI and reconstructed events with the data acquisition infrastructure. This information exchange ends with the final permanent data storage of the selected events on the ATLAS software infrastructure.

Since many interactions are produced for each bunch crossing, when saving data for a particular triggered event, also the information coming from all the other bunch crossing interactions is recorded: the events collected in this way are defined pile-up events. The ATLAS experiment developed different solutions to reduce the impact of pile-up contamination on physics analyses (see Section 7.1).

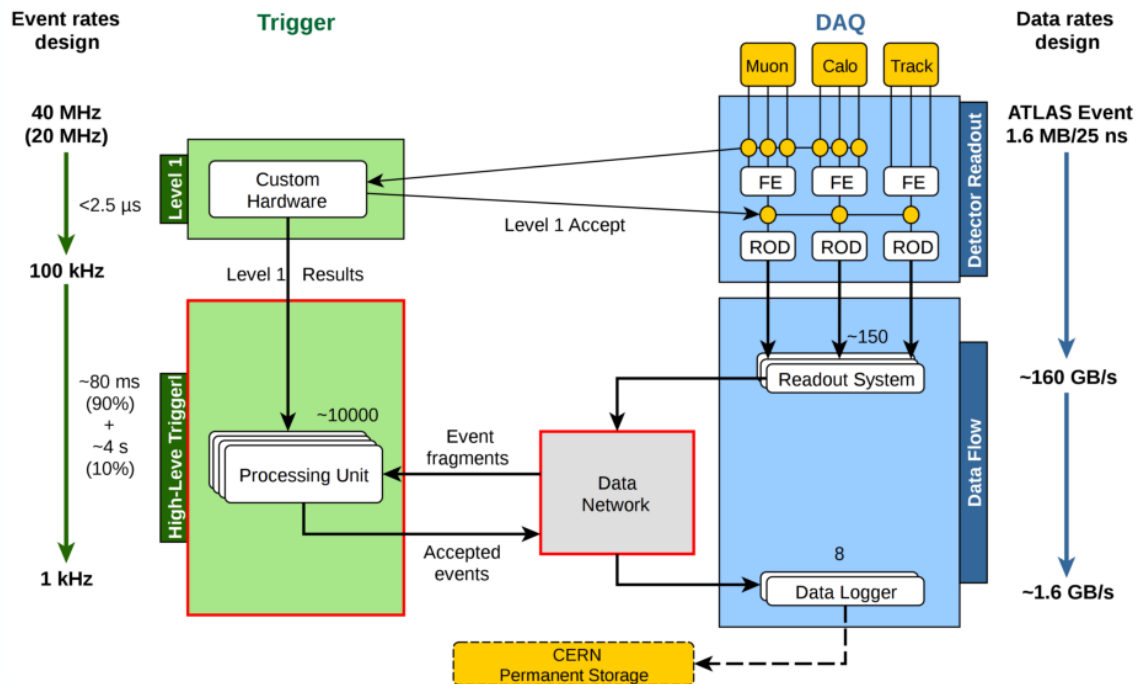


Figure 2.9: Schematic view of the Run 2 ATLAS trigger and DAQ infrastructure.

2.7 Software infrastructure

The ATLAS experiment developed a specific framework for the data analysis, MC simulation and event displaying: the Athena framework [39,40]. Athena is based on Gaudi architecture [41], previously developed for LHCb experiment, with many specific improvements required for ATLAS data analysis. The framework can generate simulated samples and reconstruct both real and simulated events. To perform these tasks, it is possible to run a chain of algorithms in one job or to split the assignment into several jobs.

ATLAS software has a hierarchical structure: Athena is split in Projects and these ones are organized in Packages, a complete collections of projects is identified by an overall release number (i.e. release 21); sometimes sub-release versions are also identified (i.e. release 20.1, release 20.7). Subsequent releases usually include major improvements and optimizations of the available algorithms, as well as new algorithms and tools.

Event generation and detector simulation

The event generation is performed with specific tools, such as Pythia [42], Herwig [43] or Sherpa [44]. In general, the full experimental description of a physics channel, requires the simulation of many different processes, as an example, the background and the signal generation. A typical hadronic process simulation starts from Lagrangian models and matrix elements: the first step is the calculation of the probability for quarks and gluons to produce the parton shower. The next step is

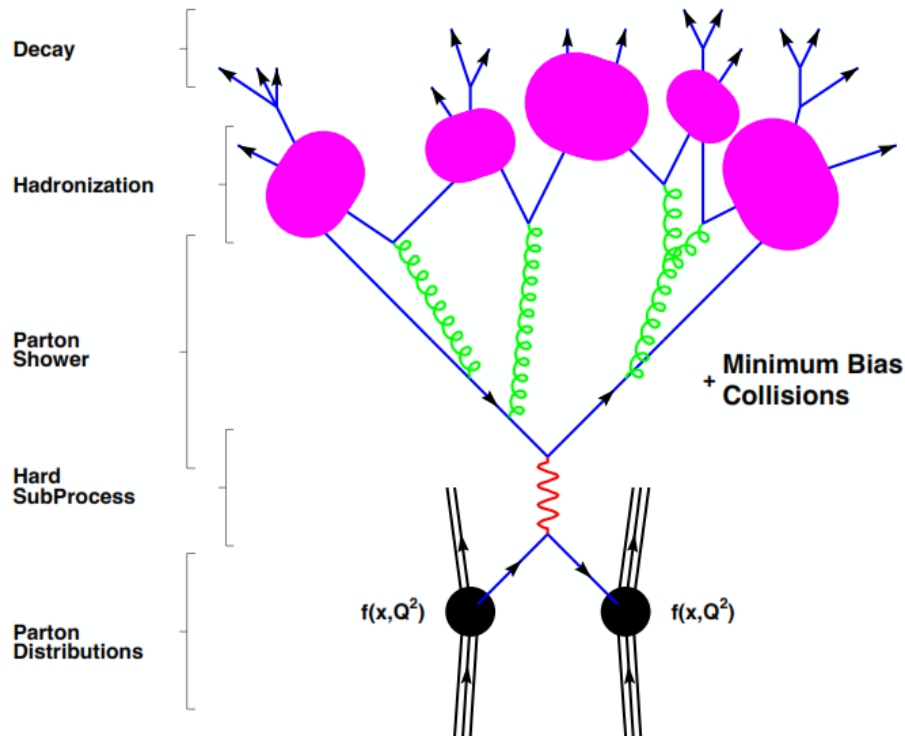


Figure 2.10: Schematic view of the typical hadronic event generation process.

the simulation of the hadronization process: colourless hadrons originate from the coloured partons produced in the shower. The last step of this chain is the simulation of the hadron decay chains towards lighter and more stable states.

After the generation, the events are passed through the simulation of the interaction with the detector material, such as energy loss and scattering. The most important toolkit for detector geometry simulation is GEANT4 [45]: it provides a detailed description of the detector response to the particle interaction, taking into account also the presence of magnetic fields.

Event reconstruction and analysis

The simulated events generated in this way are completely compatible with real data collected by the detector: the reconstruction algorithms can operate both with simulated and real data. During this step, multiple tasks are performed: pattern recognition, track fitting, vertex determination, energy and momentum measurement. Finally, real data and Monte Carlo simulations are used to perform comparative analysis between experimental results and theoretical prediction. Many different analysis techniques are used to look at data from different perspectives. Usually the analysis consists in software programs in C++ language implemented on ROOT [46, 47] software, with additional dedicated libraries, such as RooFit [48].

Chapter 3

Tracking detector technology

The LHC accelerator is going to be upgraded to High-Luminosity LHC (HL-LHC): the instantaneous luminosity will reach $5 \text{ to } 7 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with a pile-up at the level of 200 interactions per crossing. The LHC should conclude the first part of its physics program at the end of 2023 (see Figure 3.1) with an integrated luminosity for proton-proton collisions of 300 fb^{-1} . HL-LHC, with its expected integrated luminosity of 4000 fb^{-1} , will be able to maximize our understanding on SM and maybe it will open new physics scenarios beyond the SM. The ATLAS detector will be upgraded too, in order to cope with the HL-LHC environment. In particular, the current tracking detectors will be completely replaced by a new silicon detector with increased granularity and radiation hardness: the Inner Tracker (ITk) [49, 50].

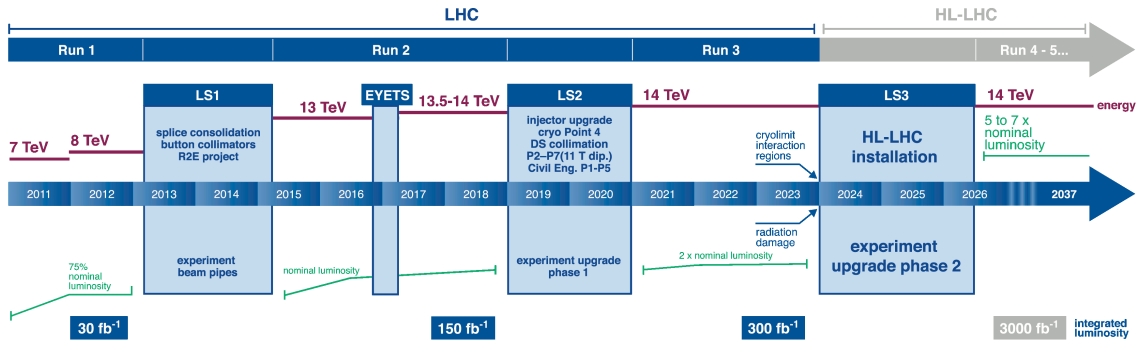


Figure 3.1: LHC physics program will end in 2023, the HL-LHC accelerator will follow.

Tracking and vertexing detectors are essential tools for the study of many phenomena at LHC, since many physics analyses depend on a precise tracking performance. In many cases, the tracking is performed using solid state detectors. In particular, one of the leading edge technology used for tracking and vertexing is the pixel silicon detector. To better understand the contribution I made to the field of future pixel detectors (described in Chapters 4 and 5), which are part of the efforts made in the design and prototyping of the ITk pixel detector, an introduction to the silicon tracking detectors technology is given in this Chapter, along with a brief description of the ITk detector layout.

3.1 Semiconductor detectors

When a charged particle (e.g., electron, pion or proton) penetrates into matter, it interacts with the electrons and nuclei present in the material through the electromagnetic force. Charged particles are sources of electromagnetic fields: a charged particle passing in the neighbourhood of an atom interacts electromagnetically with it as a whole, generating a state excitation or an ionization. More in general, a particle penetrating into a detector produces a uniform ionization along its path. As an example, about 23000 electrons are generated inside a 300 μm thick silicon layer. Actually, in the field of semiconductor detectors, the information carriers are electron-hole pairs, which are produced along the path taken by the charged particle through the detector.

By collecting electron-hole pairs, the detection signal is formed. One of the main advantages of using semiconductor materials instead of gas, is that they require lower energy to produce an electron-hole pair with respect to ionization chambers (3.6 eV for silicon versus 26 eV of argon gas). The mainly used semiconductor is silicon, since it is very cheap and can be found in great abundance. Other semiconductor materials are being investigated (e.g. diamond) which might offer better radiation hardness than silicon, even if they are not currently available in large samples or their performance is not yet as good.

Silicon, as every other semiconductor, has a forbidden region in the energy band structure, the band gap. The amount of free electrons in an intrinsic semiconductor (always equals to the amount of free holes) at ambient temperature ($T = 300\text{ K}$) is of the order of 10^{10} cm^{-3} . The silicon generally shows a low intrinsic conductivity that must be artificially increased in order to be used in devices. Therefore, additional states are inserted in the forbidden band gap so that a lower energy is required for hole or electron excitation. This procedure is known as “doping”.

Silicon has four valence electrons and it is located in the IV Group of the periodic table. In order to modify its conductivity, usually elements from III Group (i.e. boron) or V Group (i.e. phosphorus, arsenic), having respectively one valence electron less (p-type) or more (n-type) than silicon, are used. The latter ones release their extra electron easily into the conduction band and are therefore called donors. Donor levels are very close to the conduction band. In turn materials from III Group are called acceptors as they accept the extra electrons from silicon.

The passage of a charged particle into the typical silicon detector would induce a signal of $2 \cdot 10^4$ electrons, which is very little compared to the larger number of free charge carriers (10^{10} cm^{-3}). Therefore, it is fundamental to reduce them by several orders of magnitude. This is obtained using p-type and n-type doped silicon in combination in a reverse-biased configuration (pn-junction). The reversely biased pn-junction is the basic element of the silicon sensors.

In the junction between the n-doped and p-doped materials, some of the charge carriers will diffuse from one side into the differently doped side. They will then

recombine with the majority carriers producing a region close to the junction which is depleted from free charge carriers. In the vicinity of the junction, donor and acceptor ions are left without their balancing charges, causing this region to be electrically charged with an electrical field counteracting the diffusion. An external voltage applied in the same direction of the electrical field would remove majority carriers from either side and extend the depleted region.

A simple semiconductor diode with only two electrodes can only detect the passage of a particle, but not its position. This information can be obtained by the segmentation of one or both electrodes. There are three main segmentation geometries, shown in Figure 3.2:

- Single side strip;
- Double side strip;
- Pixel.

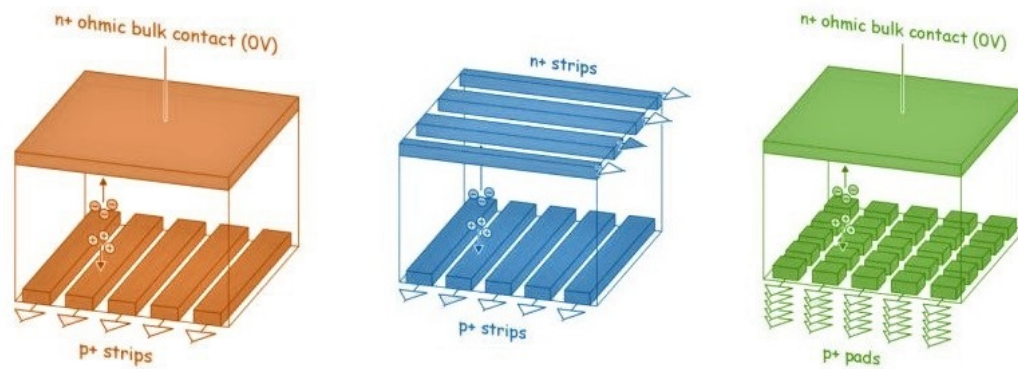


Figure 3.2: Single side (left) and double side (center) strip detectors, along with pixel detectors (right).

A strip detector has (single or double) strip-like implants acting as charge collecting electrodes, while pixel detectors are segmented in both directions. A single sided strip detector can provide only a one dimensional position information. To have a two dimensional position information, both electrodes have to be segmented into non parallel strips. The space resolution improves with a finer segmentation. In the last decades, the total surface and the segmentation level of the tracking and vertexing detectors have increased in order to cope with the increasing track densities due to higher luminosities of colliders. The main limitation to the pixel size usually comes from the electronics, because a large amount of circuitry must be fit in a single read-out pixel.

In trackers and vertex detectors several layers of pixel and strip detectors are used together to reconstruct the tracks of charged particles. Pixel detectors comes with better resolution (and reduced tracking identification ambiguity) but are more

expensive, therefore they are usually used only for the layers closer to the collisions, because of the higher track density.

3.2 Pixel detector technology

Three main different types of pixel detectors may be identified:

- Hybrid pixel detectors: The pixels of the sensor are connected to the Front-End (FE) readout chip through small solder bumps (see Figure 3.3). This technology has many advantages as high radiation hardness and good spatial resolution. The production of an hybrid detector is complex and laborious (involving bump-bonding and flip-chipping processes), as well as expensive. Another disadvantage is the higher material budget.
- Active hybrid pixel detectors: The so-called semi-monolithic detectors, currently under investigation, are still hybrid detectors. In case amplifier stages are implemented in the sensor, the signal size is sufficiently amplified to use different interconnection options, like capacitive mediums (i.e. a glue layer).
- Monolithic pixel detectors: It is possible to integrate parts or the entire electronics in the sensor, obtaining the so-called monolithic detectors. They are the standard devices for the detection of visible light. They are not being used yet in high energy physics due to the slower readout speed and the lower radiation tolerance. A considerable effort is being performed by the silicon detector community to produce and test prototypes that overcome these difficulties. The main advantages of such detectors would be lower production costs, easier assembly and integration.

In the ATLAS Pixel detector, as well as in the IBL, the hybrid pixel detector technology has been used. This technology is the preferred one for the ITk pixel detector too. Nevertheless, there is the possibility to have the external layer (the largest and the more expensive one) done in monolithic pixel technology, in case the prototypes are found to be compatible with the technical specifications. The following Sections are focused on the components of the typical hybrid pixel detector (the readout chip and the sensor) and on the hybridization technique.

3.2.1 Detector readout

The sensor converts the energy deposited by a particle to an electrical signal. This signal is processed by the electronic readout chain that can be located in the same piece of silicon (monolithic approach) or in a different tile of silicon (hybrid approach). The readout electronics usually consist of an analogue part to amplify and shape the signal and a digital data processing logic.

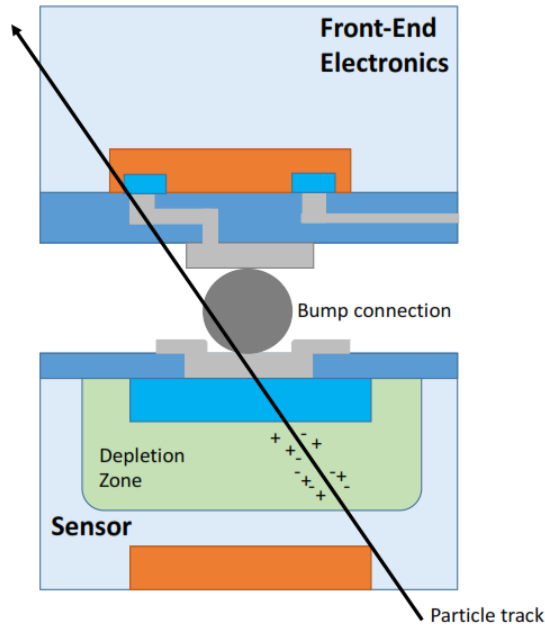


Figure 3.3: Section of a pixel cell after hybridization with a solder bump: the sensor at the bottom (for signal generation), the bump connection in the middle (for the interconnection) and the readout electronics (for the signal amplification and data processing) are shown. When a ionizing particle crosses into the sensor, it generates charges that move in the depletion region under the action of an electric field producing the signal.

As shown in Figure 3.4, the first two basic blocks of the typical front-end are the pre-amplifier and the shaper. The pre-amplifier is needed since the signal charge can be small, in the order of $4 \cdot 10^{-15}$ C. After the amplification stage, a pulse shaper is situated, that is basically a band-pass filter to improve the signal-to-noise ratio. Following the readout chain, the threshold discriminator is found: a discriminator compares the shaper output to a threshold value which is distributed globally to all pixels. Usually the threshold is set to low values in order to maximize the detection efficiency, but high enough to keep the rate of noise hits at an acceptable level. Finally the discriminator output signal is routed to the digital readout chain where the hit information is stored in buffers. In the case of ATLAS pixel modules, the hit information stored consists of a time-stamp to associate the hit to the correct LHC bunch crossing, the pixel address and the digitized Times over Threshold (ToT) information.

3.2.2 Detector sensor

The most common sensor technologies among the hybrid detectors are shown in Figure 3.5: planar (left) and 3D (right) sensors.

Planar sensors are the oldest technology, with proven radiation hardness and well established mass production capabilities. The pixels are obtained through the

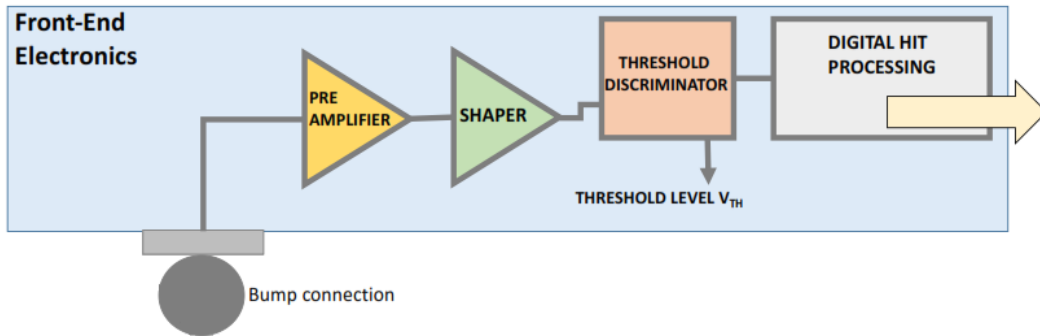


Figure 3.4: Steps of the typical readout chain of a hybrid pixel: the low-level signal, coming through the metallic bump from a pixel sensor cell, is integrated in a pre-amplifier, then fed to a pulse shaper. If the collected charge is higher than a predefined threshold level, the signal is digitized.

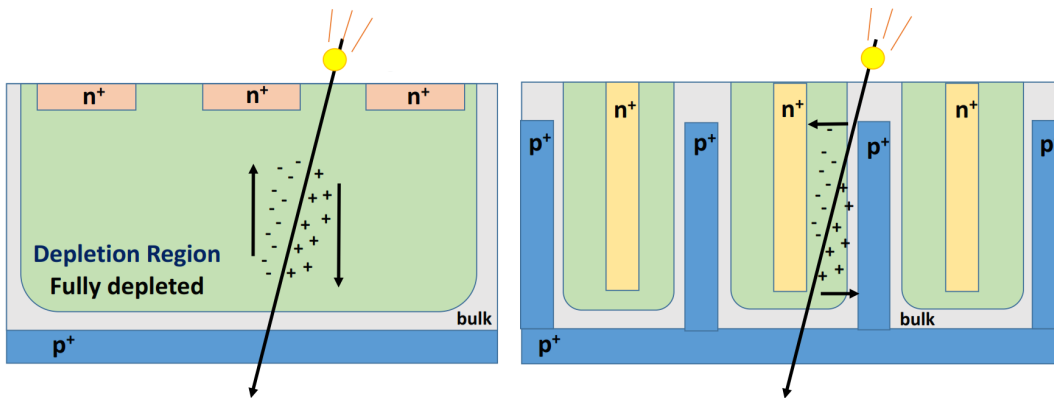


Figure 3.5: Structure of planar (left) and 3D (right) silicon sensors.

segmentation of one of the two electrodes. Planar sensors are made with $p-in-n$ or $n-in-n$ sensor. In Figure 3.5, the cross section of a $n-in-p$ pixel silicon detector is reported with the drift of charge carriers generated by an ionizing particle inside the depleted region.

The 3D sensors architecture was proposed for the first time in 1996 [51]. They are characterized by cylindrical electrodes perpendicular to the surface and etched into the bulk material. To realize this kind of structures micro-machining processes are used. Different processes (single side or double side) have been studied.

The 3D concept preserves the bulk thickness for charge generation while reducing the electrode spacing. In the 3D sensor, the same amount of charge of a planar sensor with the same substrate thickness is generated by a crossing particle. The main difference between the two technologies is that for planar device the inter-electrode distance is equal to the wafer thickness, instead for 3D detectors the distance can be optimized and it is possible to reduce it to very low values (less than 50 μm). Compared to planar detectors, the benefits regarding radiation damage are a shorter drift length for the charge carriers and therefore a much decreased depletion voltage.

3D sensors require a relatively low depletion voltage even after high irradiation dose, but are currently more expensive due to the more complex production processes.

3.2.3 Hybridization technique

Finally the sensors and the electronics are put together to form the hybrid module. Through the bump-bonding and flip-chipping process, each pixel of sensor is connected to the corresponding FE chip. The interconnection between chip and sensor is usually based on soldering, thermo-compression bonding and adhesive bonding. Many different bump metallurgies are used ranging from pure Au, Cu, Sn and In to alloys such as eutectic or high-melting PbSn, AuSn, AgSn, SnCu and AgSnCu, depending on the application. Concerning pixel detectors, two main technologies are well established and developed: electroplated solder bumps or indium bumps deposited by evaporation. The bump deposition is performed at wafer level, instead the flip-chip process is normally carried out on single dices.

Finally, the bare modules (sensor plus front-end chip) are glued to a flex hybrid circuit, which is wire-bonded to the front-end chip. The flex hybrid houses all passive components that are required to operate the front-end chips, like filter capacitors and resistors, and provides the high voltage connection to the backside of the sensor. A pigtail with a connector is used to connect each module to the electrical services of the detector.

3.3 ATLAS tracking detector upgrade

The ATLAS Inner detector was designed for 10 years of operations at the design instantaneous luminosity ($1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, 23 inelastic proton-proton collisions per bunch-crossing). The specifications for radiation tolerance of the current detectors are significantly below to the 4000 fb^{-1} that will be collected at the end of the lifetime of the HL-LHC.

During Long Shutdown 3 (2023-2025) the Inner detector will be removed (both TRT and silicon trackers) and it will be replaced by an all-silicon tracker which fills the existing tracking volume, with pixel sensors within a radius of 362 mm around the beamline, surrounded by microstrip sensors outside of this radius. The ATLAS Inner detector has a pseudorapidity coverage of $|\eta| < 2.5$. The ITk detector will have a coverage of $|\eta| < 4.0$.

Many of the interesting phenomena at the HL-LHC includes jets in the final state. This requires the tracker to cover large pseudo rapidities up to $|\eta| = 4$, to reject pile-up jets through the jet-vertex-association. Despite the significantly higher track density at the HL-LHC with respects to the LHC, the occupancy of the tracking detector needs to be kept at low levels in order to facilitate efficient tracking with a good vertex resolution. This will be achieved by reducing the pixel size significantly with respect to the current Pixel detector. Each pixel will have a

size of either $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$ (ATLAS Pixel detector: $50 \times 400 \mu\text{m}^2$; IBL detector: $50 \times 250 \mu\text{m}^2$).

The layout of the ITk is being finalised. In particular, the ITk pixel detector will consist of 5 layers of modules (see Figure 3.6), which are arranged in three different sections per layer. In the low $|\eta|$ region, the modules are placed in parallel to the beam axis (flat section), while in the high $|\eta|$ region (endcaps) they are placed perpendicular to the beam axis. In the intermediate $|\eta|$ region, the modules will be tilted at an angle with respect to the beam axis (inclined section). The detector will be made by a total of about 10000 hybrid pixel modules, with thin planar sensors in the outermost layers and 3D sensors in the innermost layer. Due to the large number of modules and the high current consumption of the front-end chips, a parallel powering scheme for the modules is not reasonable. A serial powering scheme will therefore be deployed in the ITk pixel detector, with up to four front-end chips per module powered in parallel and up to 13 modules connected in series.

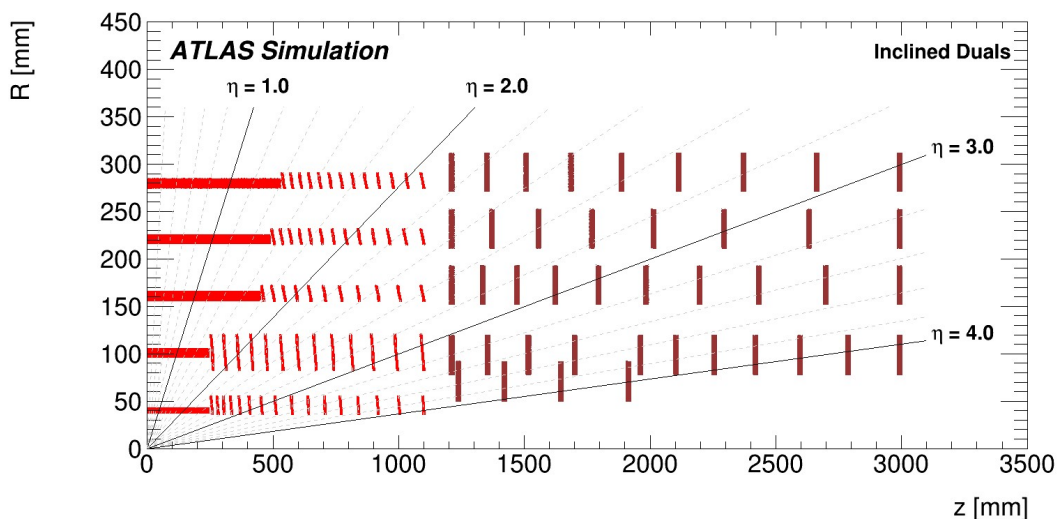


Figure 3.6: Possible layout of the ITk pixel detector with five layers. The layout provides a hermetic coverage for tracks with a pseudorapidity of up to $|\eta| < 4.0$. Each layer is divided into three sections, a flat section, an inclined section and the endcap rings

The new ITk detector should operate under high fluencies (a NIEL¹ up to $1.4 \cdot 10^{16} n_{eq} \text{ cm}^{-2}$), with a correlated high radiation damage. The ITk pixel detector is being designed to sustain a Total Ionizing Dose (TID) of 1 GRad, while the ITK strip detector about 50 Mrad: a lower radiation tolerance is needed for the Strip detector, since it will be farther than the Pixel detector from the interaction point and it will receive a lower amount of radiation. The radiation level of the ITk pixel detector in terms of 1 MeV n_{eq} fluence and TID is shown in Figure 3.7.

¹NIEL: Non Ionizing Energy Loss, where 1 MeV n_{eq} is the number of particles with a non-ionizing energy loss of a 1 MeV neutron.

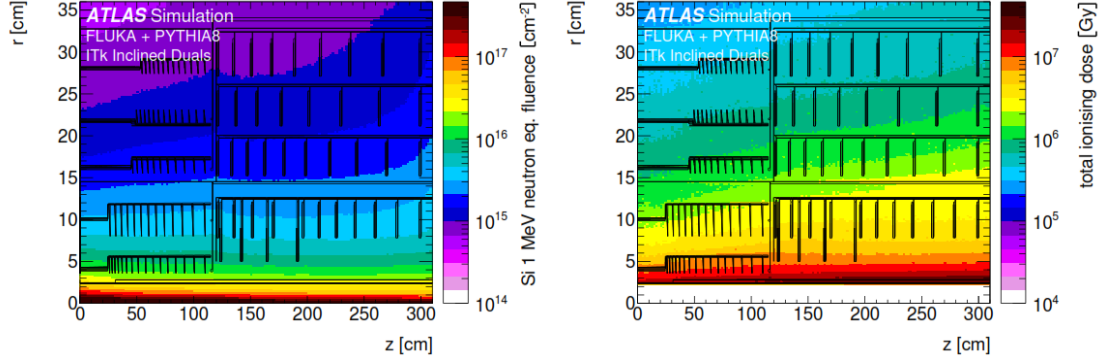


Figure 3.7: ITk pixel detector simulation of radiation level at HL-LHC (4000 fb^{-1}) in terms of 1 MeV n_{eq} fluence (left) and total ionising dose (right).

The pixel detectors modules need a completely new design in the readout electronics, sensors and interconnections. A new 65 nm front-end electronics is being developed by the RD53 collaboration, in a joint effort between the ATLAS and CMS experiments. It will be compatible with smaller pixel sizes than the actual ones to cope with the higher track densities. The ATLAS chip will consist of a pixel matrix of 400×384 pixels. The expected data rates are as high as 5.12 Gbits/s per front-end, being transmitted over up to 4 AURORA lanes running at 1.28 Gbits/s per chip.

The hybrid pixel modules consist of one to four readout chips bump-bonded to a silicon sensor, where each front-end chip has a size of roughly $2 \times 2 \text{ cm}^2$. The innermost layer, Layer 0, will consist of single chip modules with $150 \mu\text{m}$ thick 3D sensors. Layer 1 will consist of quad chip modules with $100 \mu\text{m}$ thick planar sensors, and the outermost layers will consist of quad chip modules with $150 \mu\text{m}$ thick planar sensors.

The sensor prototypes show a hit efficiency of more than 97% after irradiation to 10^{16} 1 MeV n_{eq} at bias voltages of about 400 V / 600 V for the $100 \mu\text{m}$ / $150 \mu\text{m}$ thick planar sensors, and below 200 V for the 3D sensors.

The local supports of the ITk Pixel Detector will be made of low mass carbon structures with thin titanium pipes for CO_2 cooling. In the inner system, the flat section will consist of staves with a single cooling pipe, while there are several different designs for the rings in the innermost two layers: stand-alone rings for L0 and L1; while for the intermediate $|\eta|$ region, coupled rings with single chip modules in the inner ring and quad chip modules on the outer ring. In the outer layers, the endcaps and the inclined section will consist of half-rings, where modules are mounted on both sides to allow the complete coverage of the azimuthal angle, sharing a common cooling pipe per half-ring. The low $|\eta|$ region of the outer layers will be made by “longerons”, carbon truss structures with two coolings lines, supporting two rows of modules which are slightly tilted with respect to each other.

While the final version of the readout chip for the ITk Pixel Detector is not yet

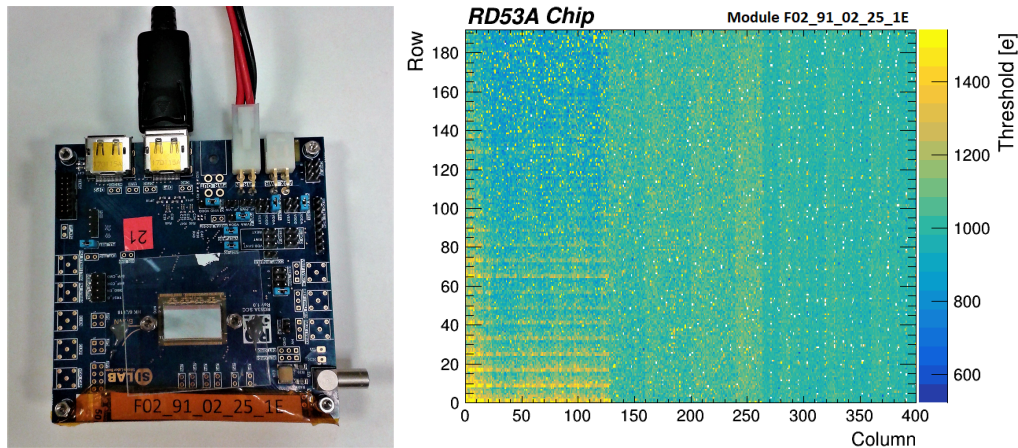


Figure 3.8: First RD53A chip module prototype assembled in the ATLAS Genoa lab on the Single Chip Card (left) and its threshold map (right), after tuning the discriminator values to 1000 electrons.

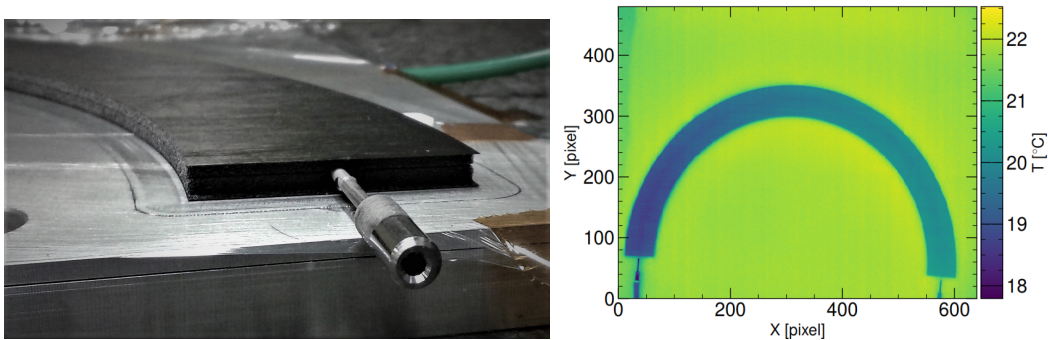


Figure 3.9: Detail of the titanium cooling pipe of the first half-ring prototype assembled in the ATLAS Genoa lab (left) and the thermal profile of the half-ring (right), after the injection of cold water inside the cooling pipe.

available, an extensive prototyping campaign for assembling modules has started to demonstrate several aspects of the new detector layout. Prototypes of local supports have been produced as well, to validate their mechanical properties and thermal performance.

I am currently involved in this effort, within the activities of the ATLAS Genoa group. I am testing in laboratory the first ITk modules prototypes assembled in Genoa (see Figure 3.8), built with 3D sensor connected to the RD53A chip. I am participating to the test beam campaigns, where these modules are tested, before and after irradiation, to measure the hit detection efficiency. I am performing as well thermal tests of the first end-cap half-ring prototypes assembled in Genoa (see Figure 3.9). Since I joined these activities recently (beginning of 2019) and everything is still ongoing, I have not documented them in this thesis.

Chapter 4

Wafer Level Packaging technology

Even for the ATLAS experiment, equipped with a complete and functional detector, the R&D is still an important reality. With the perspective of accelerator upgrades, the research community continues to develop technologies and instruments for future detector components. This has the double goal of improving the performance and maintaining the reliability in harsh environments. Wafer Level Packaging (WLP) is a process developed with the goal of rebuilding a wafer structure starting from previously diced tiles. The aim is to exploit this technique to build larger silicon detectors, reassembling good tiles on a full wafer. Many of the processes involved in the silicon detector module assembly involve steps that are preferably performed at the wafer level to speed up the production (i.e. the bump-bonding and flip-chipping processes). Six wafers were produced with the WLP technique by MicroFab Solutions in Trento within the AIDA-2020 project [52] (as part of the Horizon 2020 european project). The WLP project defined in collaboration between MicroFab Solutions and the INFN Genoa group was focused on the production of wafers with certain standards (thickness, planarity, placement accuracy) compatible with the production of Pixel modules for high energy physics applications (e.g. ITk detector).

After a brief introduction to the AIDA-2020 activities (Section 4.1) and to the motivation of the development of the WLP technology (Section 4.2), the technical details of the process flow are presented in Section 4.3. The wafers produced by the MicroFab Solutions are presented in Section 4.4. I have performed the measurement of their properties in terms of planarity and tiles placement accuracy. The results are presented in Sections 4.4.1 and 4.4.2, respectively.

4.1 AIDA-2020

The AIDA-2020 Advanced European Infrastructures for Detectors at Accelerators project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement n. 654168 [52]. In total, 24 countries and CERN are involved in a coordinated programme in line with the priorities of

the European Strategy for Particle Physics. Fifteen different tasks (namely Working Packages, WP) are defined within the AIDA project. The Wafer Level Packaging is part of the WP 6, together with CMOS active sensors developments.

The main goal of WP6 is to develop novel High Voltage and Resistive (HV/HR) CMOS active sensors for high energy physics applications. Within the WP 6.4 activities, hybridization procedures between depleted CMOS sensors and state-of-the-art readout tiles were investigated. Active CMOS devices can be monolithic, where sensor and electronics are placed in a single substrate, or can be used in hybrid devices, where the active sensor and the readout electronics are two separate substrates interconnected with solder bumps (bump-bonded devices, see Figure 3.3) or through capacitive coupling. The hybridization process is technically demanding since the pixel size is extremely small (tens of micro-meters). The aim of the WP 6.4 activities is to investigate and develop technical solutions for the hybridization procedure, both for capacitive coupled and bump-bonded devices. In both cases the hybridization step requires precise alignment between the active sensor and the tile, so that each pixel is connected.

The capacitive coupling techniques were studied extensively by the INFN Genoa group in collaboration with the University of Geneva. In this case, the coupling is performed gluing both substrates with various glues using a precise pick-and-place process. Several glues (including tape) were investigated for the interconnection. Studies indicated difficulties in achieving uniform capacitive coupling across all the pixels. The use of pillars to aid the hybridization process improved the uniformity of the capacitive coupling. HV/HR CMOS structures developed within the AIDA-2020 project (as part of the WP 6.3 activities) were used as active sensors and interconnected to the readout chip. Several technical difficulties regarding the fabrication process were overcome and assemblies were produced and tested in different institutions.

It should be noted that to industrialize the capacitive coupling procedure a wafer level process would be desirable. With this in mind, the WLP technology was investigated at MicroFab Solutions in order to rebuild wafers from good tiles and carry out the capacitive coupling process at wafer level.

4.2 Motivations and specifications

Wafer Level Packaging is a rather recent technique [53,54] with different applications in many fields of semiconductor technologies [55]. One of the goals of performing WLP in high energy physics is to handle the case of wafers with low yield of working tiles, reassembling good tiles on a full wafer. After rebuilding the wafer according to certain criteria, it is possible to carry out wafer processes (i.e. bump-bonding). Another example is to exploit the WLP to build larger detectors, assembling modules in structures for easier handling and loading on supports.

The WLP process developed at MicroFab Solutions is intended for sensors and

tiles to be used in particle detectors for high energy physics applications. The rebuilt wafers should respect some conditions in order to be usable for wafer processes intended for tracking detectors:

- thickness: thinner tiles (and wafers) have a lower radiation length, being therefore more transparent to particles (less scattering and lower energy loss by particles in tracking detectors);
- planarity: the overall planarity and the maximum bowing of the rebuilt wafer are required to be minimal, within technical specifications of wafers to be used for wafer processes;
- tiles placement: in order to perform wafer processes on pixel cells (dimension: tens of microns) a high accuracy in tiles placement is required.

During the R&D process of the WLP technology, the specifications for wafers used in IBL production were taken into account (planarity better than 10 μm and bowing less than 60 μm) along with the needs for ITk pixel modules production (sensor thickness between 150 μm and 300 μm). The tiles placement precision needs to meet the standards for hybridization: bump deposition processes (bump-bonding) and sensor to front-end chip matching (flip-chip). Due to the high track density in HL-LHC environment, the segmentation of the pixel sensors will increase (from $50 \times 250 \mu\text{m}^2$ of IBL pixels to $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$ of ITk pixels) and the bump density will reach up to $4 \cdot 10^4$ bumps per cm^2 . The tiles placement accuracy needed for hybridization processes is estimated to be about 1 μm .

4.3 Process flow

The WLP process consists of 4 different steps (see Figure 4.1): lamination, tiles placement, molding and de-bonding. The process is performed inside a mold cavity, where high temperatures and pressures are applied.

The first step of the process, the lamination, consists in the application of a thermal release tape on a carrier, in order to protect the electronic components. The carrier is a support wafer which is placed inside the mold cavity. It is possible to regulate the thickness of the final wafer (to produce thinner wafers), by using carrier wafers with different thickness. The choice of the tape is fundamental for the last phase of the process, when the tape is removed from the rebuilt wafer. The use of a carrier facilitates the tiles placement phase: the tiles are placed on the tape by using patterns for the alignment (see Figure 4.2).

Once the carrier is filled with tiles, the compression molding can start. The molding material (a resin) is placed in an open mold cavity (where the tiles were placed). The mold is closed with a top controlled force while heat and pressure are maintained until the molding compound has cured. Then the mold is removed and the molding material is heated (foaming).

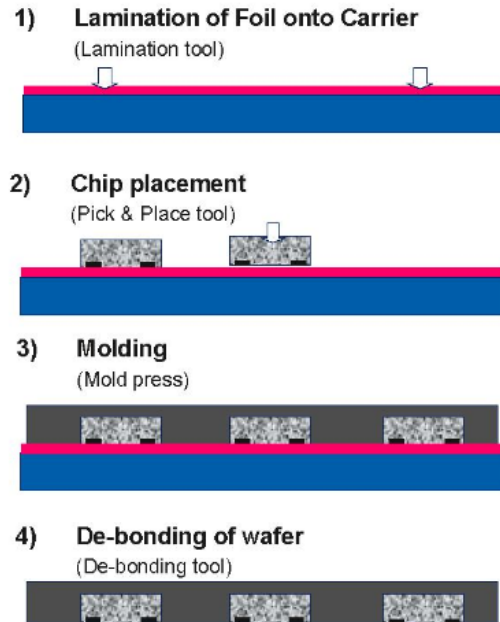


Figure 4.1: Steps of the Wafer Level Packaging process.

Finally, the carrier and the tape are released (de-bonding or peeling, Figure 4.3). The carrier-tape removal operation is a very delicate process, in fact this is the phase with the highest risk to damage the final wafer: the thinner the wafer, the higher is the risk to damage it. The tape-resin combination choice deeply affects the structural integrity of the wafer during the peeling phase. Moreover, the material used in the molding process should be coherent with the tiles material (silicon) and resistant to the handling. After removing the carrier and the tape, the wafer is ready to perform wafer-to-wafer bonding processes.

4.4 Wafer production and test

Six 6-inch wafers were produced by MicroFab Solutions in Trento with the WLP process, their properties are resumed in Table 4.1: two different filling schemes were used (full or cross, see Figure 4.4) for three different wafer thickness values ($675\ \mu\text{m}$, $400\ \mu\text{m}$, $300\ \mu\text{m}$).

Wafer	Thickness [μm]	Filling scheme
1	675	cross
2	675	full
3	400	cross
4	400	full
5	300	cross
6	300	full

Table 4.1: Properties of the six wafers produced by the MicroFab Solutions.

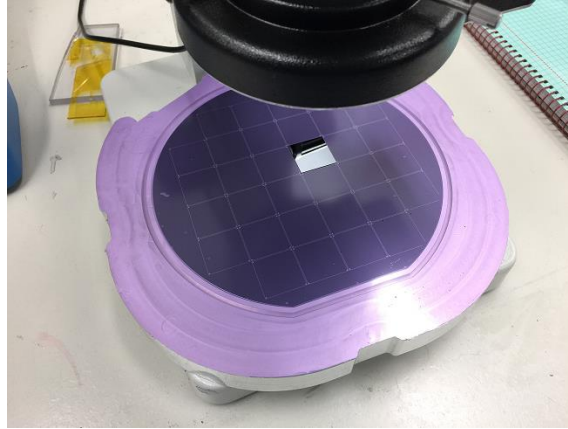


Figure 4.2: Carrier wafer during the placement phase: the first tile has been deposited on the tape.

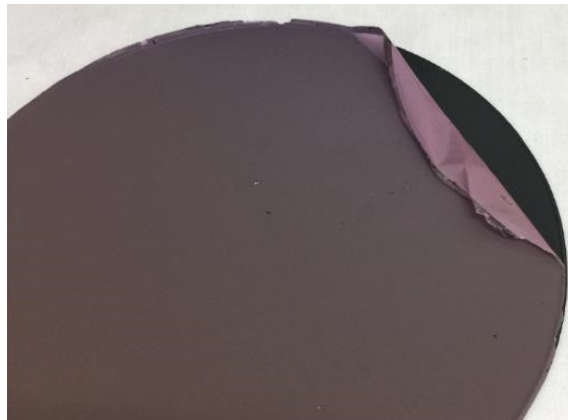


Figure 4.3: The tape is removed from the wafer.

The wafer production plan included 6 wafers. The thickness of the wafers have been reduced step-by-step, from $675\ \mu m$ (1 and 2) to $400\ \mu m$ (3 and 4) and then to $300\ \mu m$ (5 and 6) confirming the solidity of the compound. The first production includes wafers of 675 and $400\ \mu m$, that are strong enough to be handled. The following production includes two more wafers with the minimum achievable thickness, $300\ \mu m$ (the tiles used are $300\ \mu m$ thick).

Two filling schemes were conceived in order to further test the strength of the resin. Wafer 1 and 2 are shown in Figure 4.4: wafer 1 has 32 tiles (full filling scheme) while the wafer 2 has 10 tiles (cross filling scheme). The resin used as molding compound is visible in black.

The WLP process was performed using an aluminum mold specially built for this application. The mold is made of two engraved parts, a bottom side and a top side (see Figure 4.5). The carrier wafer is placed inside the bottom side of the mold, then the tape is added by lamination and the tiles placement is performed. The tiles used in this application are dummy chips of $300\ \mu m$ thickness with alignment crosses. The machine used for the tiles placement has a precision of about $10\ \mu m$

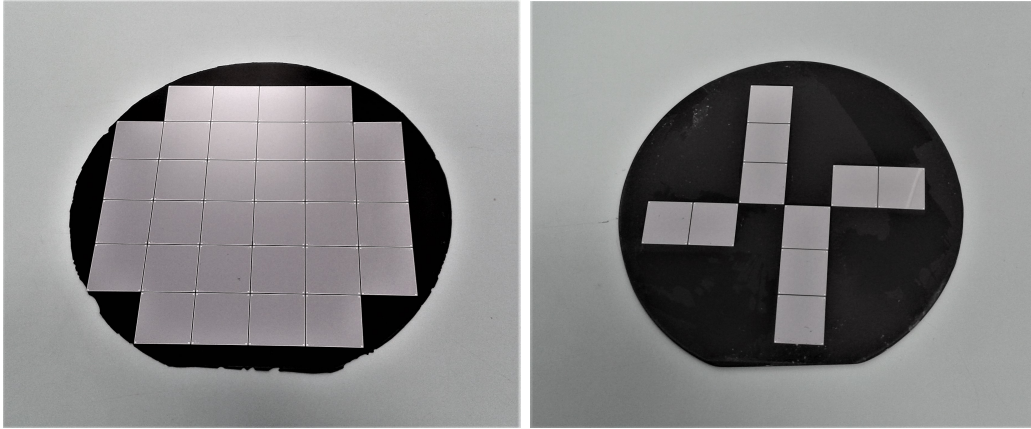


Figure 4.4: Wafer 1 (left) and 2 (right): they have a different filling scheme.

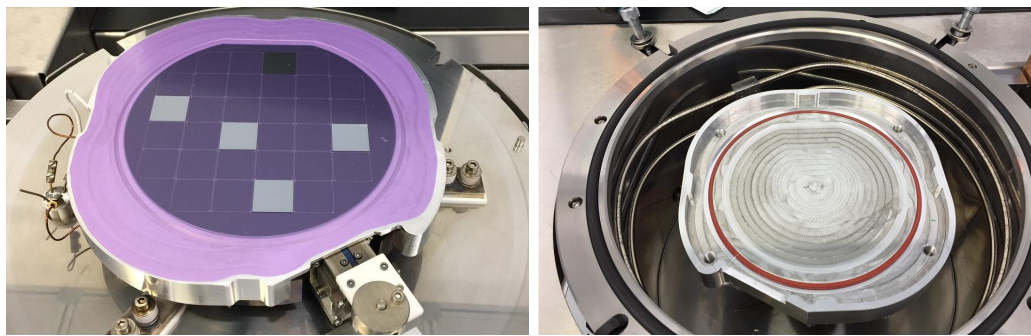


Figure 4.5: The mold is made of two engraved parts: a bottom side (left) and a top side (right).

in the positioning of the tiles, while a typical pick-and-place machine can reach a precision of $0.5 \mu m$.

The molding material used in this application (XV5791S14 Panasonic resin) is made by 81% Silicon with maximum fragment size of $5 \mu m$. The tape (Nitton) used during the production of wafers 1 to 4 is visible in purple in Figure 4.2. Wafer 3 was damaged due to the force applied during the tape removal (see Figure 4.6): the pressure applied has broken twice the resin on the line of separation between tiles. The last two wafers (5 and 6) were produced with a different tape recommended by Panasonic to be compatible with the resin. The new tape has managed to improve the tape removal process.

4.4.1 Planarity measurements

The wafers were sent to the INFN Genoa labs in order to measure their planarity and the precision of the tiles placement. I have performed profile measurements, with a one point per μm precision, to extrapolate the planarity of the wafers. Several measurements were performed with a KLA P-7 mechanical profilometer, on both sides of the wafers (front and back) and on both directions (X and Y axis).

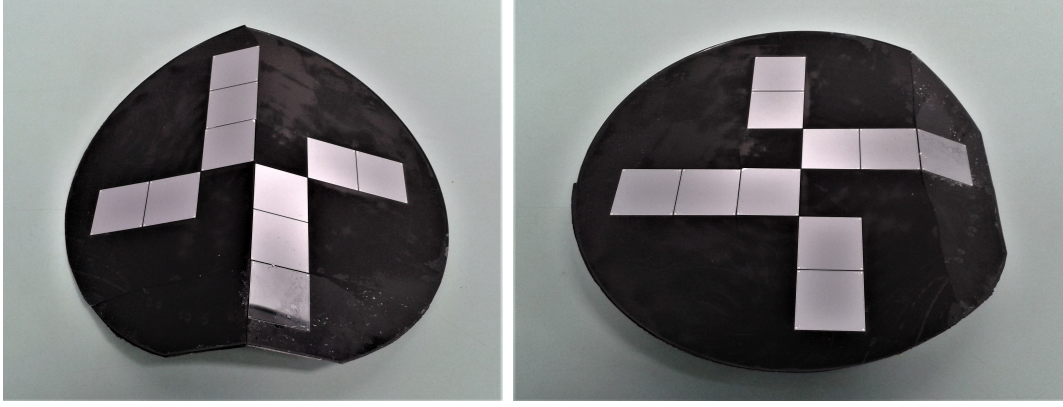


Figure 4.6: Wafer 3, damaged during the tape removal.

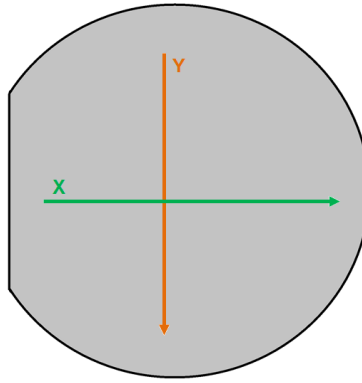


Figure 4.7: Example of X and Y axis profile measurement on wafer.

The results of the profile measurement of the three wafers with the full filling scheme are presented in Figure 4.8. The profiles of wafers 2 ($675\ \mu\text{m}$ thickness, red line) and 4 ($400\ \mu\text{m}$ thickness, blue line) show a bending point in the separation line between two tiles, visible in both X and Y profiles. The wafer 6 profiles ($300\ \mu\text{m}$ thickness, orange line) does not present such a feature and the planarity is improved (overall bowing below $100\ \mu\text{m}$). The improvement is due to a different tape choice. The tape used for wafers 2 and 4 was hard to separate from the molding compound, therefore a high force was applied during the tape removal. The new tape used for the wafer 6 (easily detachable from the molding compound) avoided the formation of bending points and improved the planarity.

Several sequential measurements along X axis, with a $1\ \text{mm}$ pitch along Y, have been taken on wafer 6. The 3D reconstruction of the central part of wafer 6 surface is shown in Figure 4.9: two bending lines are visible along X axis in correspondence of the separation line between tiles, with a slight general deformation of the surface. The overall planarity of wafer 6 is close to the specifications required for IBL pixel modules wafers (planarity better than $10\ \mu\text{m}$ and bowing less than $60\ \mu\text{m}$ was required in IBL wafers): further improvements in the production techniques may result in wafers compatible with the acceptance criteria.

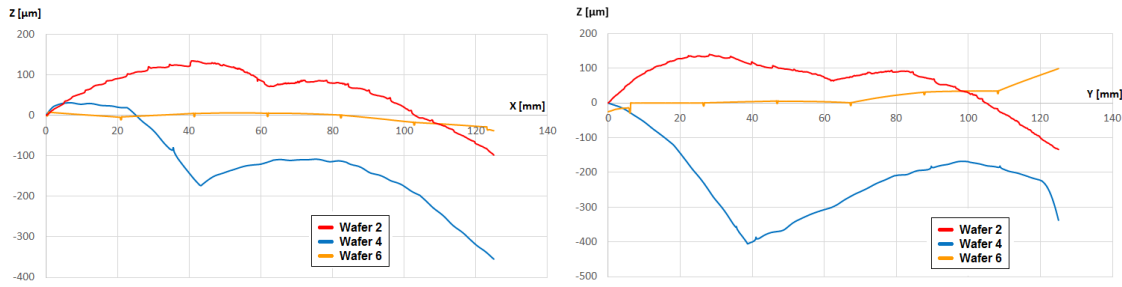


Figure 4.8: Profile measurement of wafers with different thickness (red: $675 \mu m$, blue: $400 \mu m$, orange: $300 \mu m$). Profile X is shown on the left, profile Y on the right.

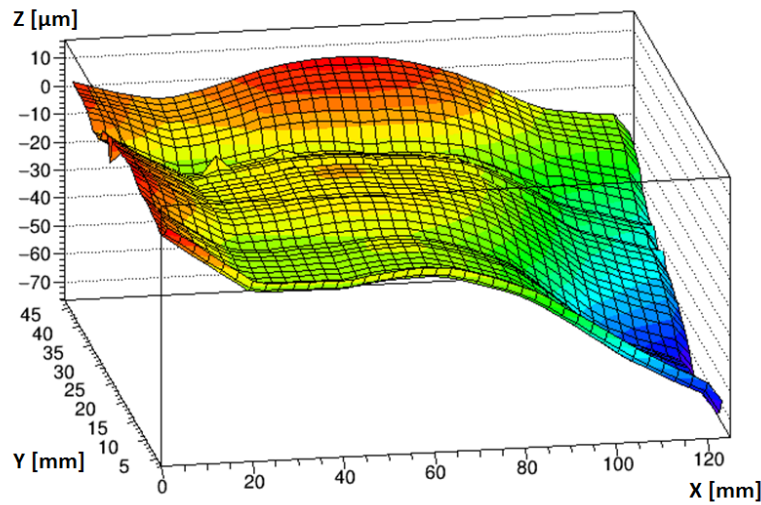


Figure 4.9: 2D reconstruction of the wafer 6 surface.

4.4.2 Tiles placement measurements

The placement of the tiles is performed with the help of alignment crosses: the crosses visible on the carrier wafer are used as reference to place the diced tile on the tape (see Figure 4.10). The cross of the tiles used in the rebuilt wafer are visible in Figure 4.11, the resin between the tiles is visible in black.

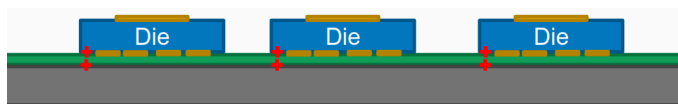


Figure 4.10: Sketch of the positioning of the tiles on the carrier wafer.

The profile measurements performed to assess the wafer planarity have been used as well to extrapolate the tiles placement accuracy. A detail of the profile measurement performed on the separation line between two tiles of wafer 4 is shown in Figure 4.12: the alignment crosses are visible (height: $0.80 \pm 0.05 \mu m$). It can

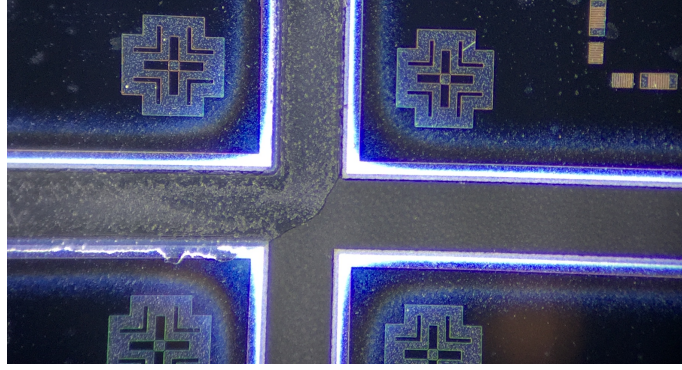


Figure 4.11: Corners of 4 tiles on the rebuilt wafer: the alignment crosses are visible.

be noted that the volume between the tiles is not fully filled by the resin: in many cases $\sim 10 \mu m$ deep wells are observed in between (depth: $12 \pm 1 \mu m$).

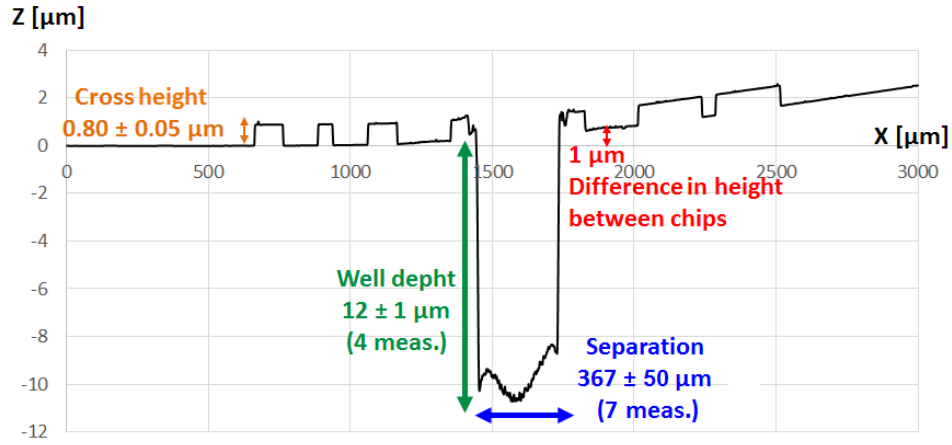


Figure 4.12: Detail of the profile measurement performed on the separation line between two tiles of wafer 4: a small depth well is found between the tiles (average depth: $12 \mu m$), the alignment crosses of both tiles are visible (cross height: $0.8 \mu m$).

The RMS of the wells width has been used to estimate the accuracy of the tiles placement achieved by the WLP process. It seems that the tiles placement accuracy has improved as well thanks to the new tape: the average distance between tiles in wafer 4 was found to be $367 \pm 50 \mu m$ (7 measurements), while the average distance obtained with the same measurement performed on wafer 6 was found to be $336 \pm 10 \mu m$ (5 measurements). The placement accuracy observed on wafer 6 is compatible with the precision of the machine used by MicroFab Solutions for the tiles placement. Therefore, it seems that the overall WLP process has no effect on the tiles placement accuracy. Nevertheless, the achieved accuracy is not yet acceptable for high precision processes like the bump deposition (a placement precision of at least $1 \mu m$ is required for hybridization processes). It is therefore suggested to use a pick-and-place machine to obtain higher accuracy.

4.5 Outlook

The Wafer Level Packaging process has been developed within the AIDA-2020 project in a strict collaboration between the INFN Genoa lab and the MicroFab Solutions industry, with the aim to develop a process to be used to rebuild wafers from previously diced tiles, for the construction of large size silicon detector components with applications in the high energy physics field. This technology was investigated as a first step towards the industrialization of the process. During the R&D phase, precision measurements were performed in order to assess the properties of the output wafers with respects to the specifications and to eventually introduce solutions to optimize the process.

The six 6-inch wafers produced have been found to be strong enough to be handled, even in the case of the $300\ \mu m$ thick wafers (the minimum achievable thickness). I have performed high precision profile measurements with a mechanical profilometer with the goal to assess the wafer planarity and the tiles placement accuracy. The measurements performed on the first four produced wafers highlighted the presence of bending points in the separation line between two adjacent tiles, due to the removal of the Nitton tape. Therefore, the process has been improved introducing a new tape, recommended to be compatible with the Panasonic resin. The wafer planarity has improved substantially: no bending lines are seen through the newly produced wafers. It seems that the tiles placement accuracy has improved too, thanks to the new tape.

The WLP process is close to meet the technical specifications required for wafers to be used in the wafer processing steps for silicon detector production. Further optimizations are required, as an example, it is recommended to use a pick-and-place machine for the tiles positioning in order to achieve the required accuracy. Small productions for future silicon tracking detectors may already profit from the WLP process, but not before having ascertained the functionality of real sensor and chip tiles obtained from wafers produced with this potentially destructive production flow (involving high pressures and temperatures). In case of mass production for large area silicon detectors, a more detailed inspection of the output wafers is recommended, along with further tests that were not performed at this stage (i.e. relative thickness of the wafer, radiation hardness of the resin included in the wafer).

Chapter 5

Beam-loss scenario test beam

The ATLAS detector [9], and in particular the Pixel detector [32] which is the closest to the interaction point, is designed to sustain high dose integrated over several years of operation. The intrinsic radiation hardness of the silicon detectors should also favor the survival in case of accidental beam-losses. These events are very unlikely to happen since several systems (beam monitors, beam dumps, collimators, beam absorbers) are implemented to guarantee safe operations of the accelerator and of the experiments.

In 2006, an experiment [56] established that the pixel modules could survive to beam-losses as large as $1.5 \cdot 10^{10}$ protons/cm² in a single bunch of 42 ns, with minimal or no deterioration of performance. This measurement set a survival threshold well above the worst expected beam-loss scenario at the LHC.

During Long Shutdown 3, LHC will be upgraded to HL-LHC to reach higher instantaneous luminosity. The aperture of the HL-LHC quadrupoles in the proximity of the interaction regions will be larger with respect to the current LHC aperture. The aperture of the quadrupole absorbers (TAS) protecting the magnets from the collision debris will be larger too, from the current 17 mm radius to 30 mm radius, potentially exposing the ATLAS detector to a larger fluence of beam-induced radiation towards the interaction region.

The increased intensity of the collisions produced by the HL-LHC accelerator, together with the larger apertures, requires for new measurements of the beam-losses survival threshold for the tracking detectors, including both sensors and electronics. The components that are being developed for the ITk detector needs to be tested with high energy and intensity beams. The new damage thresholds need to be compared to the level of radiation received in beam-loss scenarios at the HL-LHC, to assess if they are able to survive and to quantify the performance degradation.

In 2017 and 2018, two experiments have been performed on recent silicon modules (IBL pixel, ITk strip) with an unprecedented high energy and intensity beam at the CERN HiRadMat facility. In this Chapter, after an introduction to the HiRadMat facility (Section 5.1), there will be the description of the beam operations (Section 5.2), of the tested devices (Section 5.3) and of the experimental apparatus

(Section 5.4) used in these experiments. Together with the Genoa group, I was involved in the activities regarding IBL pixel modules: the measurements performed on IBL modules will be presented (Section 5.5) along with the results (Section 5.6).

5.1 HiRadMat facility

High-Radiation to Materials (HiRadMat) [57] is a test beam facility at CERN, designed to provide a high-intensity pulsed beam to an irradiation area where material samples can be tested. The facility uses the high-energy 440 GeV proton beam extracted from the CERN Super Proton Synchrotron (SPS). Each pulse is made of 1 to 288 bunches (up to $1.2 \cdot 10^{11}$ protons per bunch) with 25 ns separation or higher, reaching a maximum pulse length of 7.2 μ s. The proton beam can carry up to a maximum pulse energy of 3.4 MJ. The proton beam parameters are resumed in Table 5.1. In addition to protons, ion beams with an energy of 173.5 GeV/nucleon and a total pulse energy of 21 kJ can be used: up to now, no experiment has ever been performed with ion beams at the HiRadMat facility.

Proton Beam Parameters	Value
Beam Energy	440 GeV/ c^2
Pulse Energy	up to 3.4 MJ
Bunch intensity	up to $1.2 \cdot 10^{11}$ protons
Number of bunches	1 to 288
Maximum pulse intensity	$4.0 \cdot 10^{13}$ protons
Bunch length	11.24 cm
Bunch spacing	25, 50, 75 or 150 ns
Maximum pulse length	7.2 μ s
Cycle length	18 s
Beam radius at target	0.5 to 2 mm

Table 5.1: HiRadMat facility proton beam parameters.

Two separate parallel tunnels host the beam line with the experimental tables (TNC tunnel, Figure 5.1, left) and the read-out system (TT61 tunnel, Figure 5.1, right). Long connecting cables (~ 15 m) pass through a concrete screening wall placed between the TNC and the TT61 tunnels. They connect the experimental setup to the powering and read-out systems. Due to the high radiation level, it is not possible to control the setup neither from the TNC tunnel or from the TT61 tunnel: the operations of the modules are remotely controlled from the CERN Control Center.

HiRadMat is not an irradiation facility where large doses on equipment can be accumulated. It is rather a test area designed to perform single experiments in order to evaluate the effect of high-intensity pulsed beams on materials or accelerator components. The facility is open to CERN users and external groups, as all other

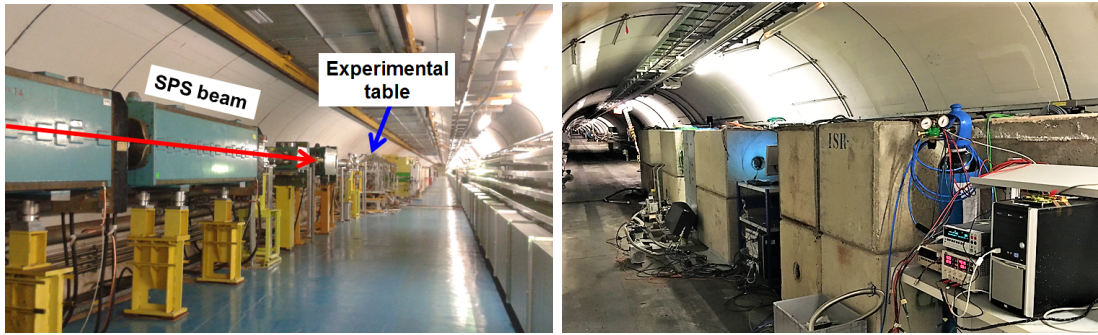


Figure 5.1: HiRadMat experimental area: TNC tunnel (left), hosting the beam line and the experimental table, and TT61 tunnel (right), hosting the powering and readout of the detectors.

experimental areas and test beams at CERN. The first experiments, performed in 2012, included candidate materials and prototype assemblies of LHC collimators foreseen to operate at the ultimate LHC beam powers, as well as beam windows and high-power target materials, such as tungsten powder.

The facility is designed for a maximum of 10^{16} protons per year, distributed among several experiments. This limit allows reasonable cool-down times for the irradiated objects (few months to a year) before they can be analysed in a surface specialized lab. A specific beam pulse list defined by each HiRadMat experiment is exploited during the beam operations. The experimental team decides when to shoot every pulse, according to the experiment recovery time but also to the availability of SPS beam time, which is shared with other users, i.e. for LHC fills.

5.2 Beam operations

ATLAS silicon modules have been exposed to the beam in the HiRadMat facility on July 2017 and on May 2018. Two different beam configurations were used during the test of the silicon modules: wide beam (2 mm radius) to test the global effects of the irradiation on a large part of the module and narrow beam (0.5 mm radius) to test the local effects of the irradiation with higher intensity on a smaller region.

Silicon detectors were never directly exposed to such high intensity proton beams before: in order to correctly evaluate the damage threshold, the number of proton bunches was gradually increased. The performance of the modules has been systematically monitored after each pulse in order to ascertain the survival of the sensor and the electronics to that level of irradiation. Nevertheless, the effects are incremental, since the bunches are delivered subsequently on the same devices. In the first phase, the wide beam was used; after checking the survival of the detectors to the maximum intensity available for wide beams, a second phase was performed with narrow beams. Since it was possible to move the hit point of the beam by few mm, after the first phase the beam position was moved out of the irradiated region

in order to study the effect of narrow beams on a different portion of the modules.

The beam pulses used in the 2017 experiment include:

- wide beam (2 mm radius): 1, 4, 12, 24, 36, 72, 144, 288 bunches ($5 \cdot 10^{10}$ p/bunch)
- narrow beam (0.5 mm radius): 1, 12, 72, 288 bunches ($1 \cdot 10^{11}$ p/bunch)

The beam pulses used in the 2018 experiment include:

- wide beam (2 mm radius): 1, 4, 12, 24, 36, 72, 144, 288 bunches ($1 \cdot 10^{11}$ p/bunch)
- narrow beam (0.5 mm radius): 1, 12 bunches ($1 \cdot 10^{11}$ p/bunch)

In 2017, the 2 mm pulse with 288 bunches was repeated with higher intensity ($1 \cdot 10^{11}$ p/bunch); in 2018, it was repeated three times with the same intensity ($1 \cdot 10^{11}$ p/bunch).

Operations	2006 experiment	2017/2018 experiments
Beam line	Proton Synchrotron	Super Proton Synchrotron
Beam energy	24 GeV	440 GeV
Bunch intensity	$1 \cdot 10^{11}$ protons	$1 \cdot 10^{11}$ protons
Number of bunches	1 to 8	1 to 288
Bunch spacing	256 ns	25 ns
Beam profile	gaussian	gaussian
Beam direction	parallel w.r.t. modules	perpendicular w.r.t. modules
Module tested	Pixel	IBL pixel, ITk strip
Radiation hardness (TID)	50 MRad	250 MRad, 50 MRad
Established limit	$1.5 \cdot 10^{10}$ p/cm ²	$1 \cdot 10^{13}$ p/cm ²

Table 5.2: Summary of the operational parameters of 2006 and 2017/2018 experiments.

During the 2017 test beam, the experimental table with the ATLAS test box was installed downstream of the RotColl experiment [58] for the study of HL-LHC collimator robustness. The first day of operations was entirely dedicated to the ATLAS experiment, with the ATLAS team being the main user of the beam and setting its parameters. Then the ATLAS program was interrupted during the second phase, after 12 bunches, narrow beam. There was one week dedicated to RotColl operations, during which the ATLAS experiment was passively receiving a stream of secondary particles on the sensors. Finally one last day of the ATLAS experiment operations (delivering 72 and 288 bunches, narrow beam). The 2018 beam time was entirely devoted to the ATLAS experiment and the experimental program was completed in one night of operations.

Module	Total size	Sensor type	Sensor thickness	Chip type	Channel (Pitch)	Maximum dose
2017 test						
IBL	$2 \times 2 \text{ cm}^2$	n-in-p, 3D [59]	$230 \mu\text{m}$	FE-I4 [60]	$26680 (50 \times 250 \mu\text{m}^2)$	250 MRad
ITk	$1 \times 1 \text{ cm}^2$	n ⁺ -in-p, ATLAS12 [61]	$320 \mu\text{m}$	ABC130 [62]	104 ($74.5 \mu\text{m}$)	35 MRad
2018 test						
IBL	$2 \times 4 \text{ cm}^2$	n ⁺ -in-n, planar [63]	$200 \mu\text{m}$	FE-I4 [60]	$2 \times 26680 (50 \times 250 \mu\text{m}^2)$	250 MRad
ITk	$0.7 \times 2.6 \text{ cm}^2$	n ⁺ -in-p, PTP [61]	$320 \mu\text{m}$	ABC130 [62]	64/128 ($77 \mu\text{m}$)	35 MRad

Table 5.3: Summary of the modules characteristics used in 2017 and 2018 tests.

5.3 Devices

The HiRadMat test beam campaign started with the objective to test ITk pixel and strip detectors components. A first test was performed in 2017 with two available IBL pixel modules and one ITk strip module. It was expected to have ITk pixel modules in early 2018, therefore a second test was planned at the HiRadMat facility in 2018. Unfortunately the ITk pixel modules production suffered some delays, it was therefore decided to use a different IBL pixel module in the 2018 test beam, along with two ITk strip modules. A detailed description of the IBL and ITk strip devices is presented below. Details on the performed measurements and results for IBL pixels are presented in the following Sections. ITk strip modules measurements are out of the scope of this thesis: a complete overview of the experiment is going to be published. The specifications of the devices, in terms of modules, sensors and chips properties, are resumed in Table 5.3.

5.3.1 IBL pixels

In 2006, a pixel module from the initial Pixel detector was tested [56]. The Pixel detector [32] has been designed to face a Total Ionizing Dose (TID) of 50 MRad (expected at 300 fb^{-1}), a NIEL of $1 \cdot 10^{15} \text{ 1 MeV } n_{eq} \text{ cm}^{-2}$ and a peak luminosity of $1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The Pixel module is made of planar $n-in-p$ sensors bump-bonded to FE-I3 read-out chips.

The new generation of ATLAS pixel modules developed for the IBL, at least a factor 5 more radiation-hard ¹ than the pixel modules used in the 2006 test, has been tested in 2017 and 2018 experiments. The Insertable B-Layer has been built to sustain higher radiation levels, up to a NIEL of $5 \cdot 10^{15} \text{ 1 MeV } n_{eq} \text{ cm}^{-2}$ and a dose of 250 MRad. In the IBL, two different silicon sensor technologies have been used: planar $n^+ - in - n$ (Figure 3.5, left) and 3D with passing through columns (Figure 3.5, right), bump-bonded to FE-I4 read-out chips [60]. The IBL planar module has the double size of a 3D module and it is made by two FE-I4 read-out chips (see Figure 5.2). In the HiRadMat test beam, two IBL modules with 3D silicon sensors and one IBL module with planar sensor have been tested in 2017 and 2018,

¹This was the minimum requirement from the IBL TDR [64]. Some IBL modules have been irradiated with a 25 MeV proton beam to an estimated TID of 750 Mrad [64].

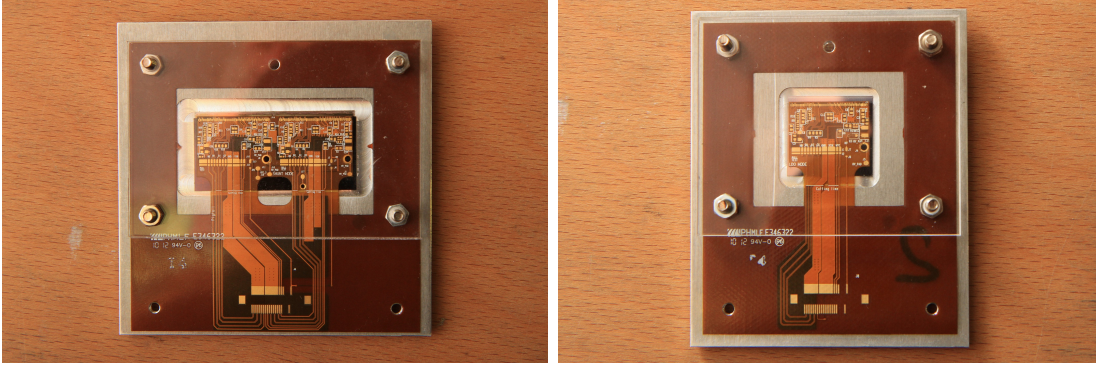


Figure 5.2: Planar (double chip) and 3D (single chip) IBL modules.

respectively.

The IBL read-out chip, FE-I4, was designed in 130 nm CMOS technology to cope with higher radiation levels (250 MRad) and larger occupancies. It has a total size of $20.2 \times 18.8 \text{ mm}^2$ (5 times larger than the FE-I3, Figure 5.3) and consists of 26880 pixel cells organized in a matrix of 80 columns ($50 \mu\text{m}$ pitch) by 336 rows ($250 \mu\text{m}$ pitch).

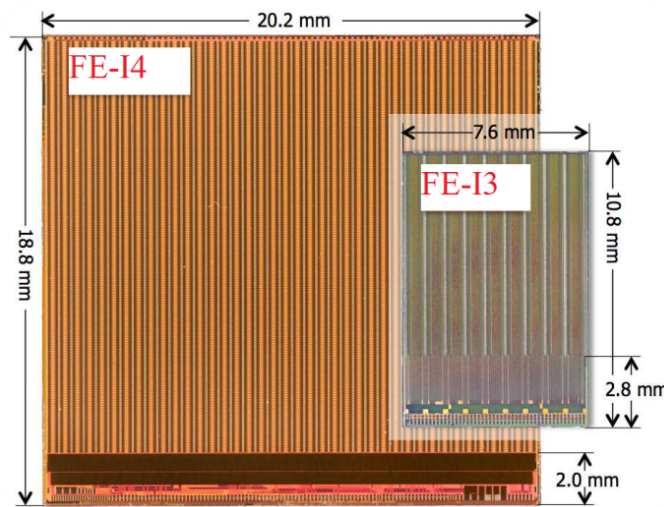


Figure 5.3: Comparison of the FE-I4 and FE-I3.

5.3.2 ITk strip

The ITk strip modules used in 2017 and 2018 tests are made by strip silicon sensors (ATLAS12) wire-bonded to ABC130 readout chip [49] and placed on a DAQLoad test board, from which LV, HV and data transfer is provided. In 2017 a single module with 104 strips was used, while in 2018 two different modules were tested, with (64 strips) and without (128 strips) the Punch-Through Protection structure (PTP). In particular, one of the sensors was a standard strip sensor with standard PTP design (typically $\sim 20 \mu\text{m}$ distance from the implant to the bias ring) while

the second sensor had virtually no PTP (with an unusual long distance from the implant to the bias ring of $70\text{ }\mu\text{m}$). In a beam-loss scenario, silicon strip sensors could accumulate large amounts of charges in the bulk, collapsing the electric field, and producing high voltages in the strip implants. In order to prevent this situation, ITk strip sensors have been equipped with PTP for each strip, reducing the distance between the strip implant and the bias rail. One of the goal of this test is to check the effectiveness of the PTP structure in order to contribute to the choice of a proper PTP design for the ITk strip detectors.

5.4 Setup

The ATLAS silicon modules were mounted on frames, hosted in a dedicated box placed on the experimental table 3 (slot C) in the TNC tunnel (Figure 5.4). The supporting table (aluminum), provided by the HiRadMat facility, was fixed with respect to the beam position. A detailed description of the box and its components is available in the following Sections.

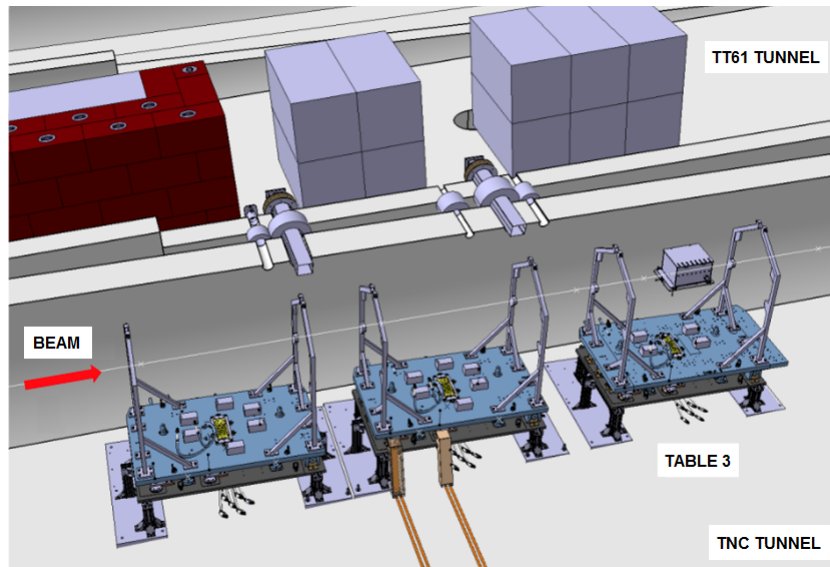


Figure 5.4: ATLAS test box placed on the experimental table 3 in the TNC tunnel.

5.4.1 Box and frames

The test box (epoxy fiber glass, makrolon and aluminum) was designed to host up to 8 modules on dedicated frames. The modules are loaded on fiber glass frames within the test box (Figure 5.7), aligned perpendicularly to the beam, with the beam spot centered on the modules. The same box was used in 2017 and 2018 tests: thanks to the gained experience, several improvements were introduced in the experimental setup in 2018.

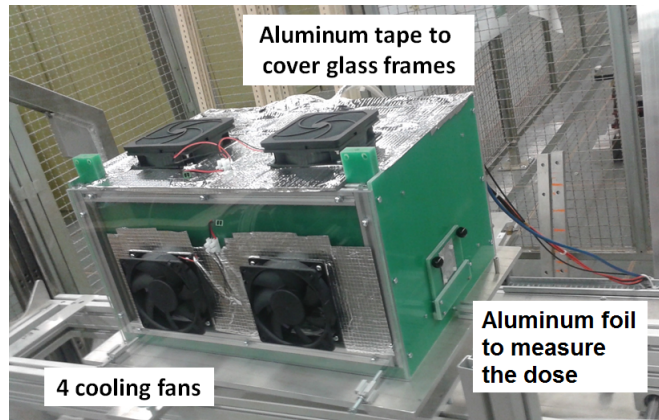


Figure 5.5: Test box (2018): cooling fans, aluminum tape, aluminum foil.

In 2017, the modules were not in a fully dark environment because the box was partly built with glass walls and it was not possible to completely switch off the tunnel lights. Therefore, before the 2018 test beam, the box was covered with aluminum tape in order to have a completely dark environment for the modules, beneficial for the operations (better tuning, reduced noise).

During the 2017 test, the modules received secondary radiation from the RotColl experiment placed in the upstream table. In 2018, it was decided to mount the box on a remotely-controlled motorized system (Figure 5.6), in order to move the box out of the beam in case of spurious beam shots or shots dedicated to other experiments in order to better monitor the received dose.

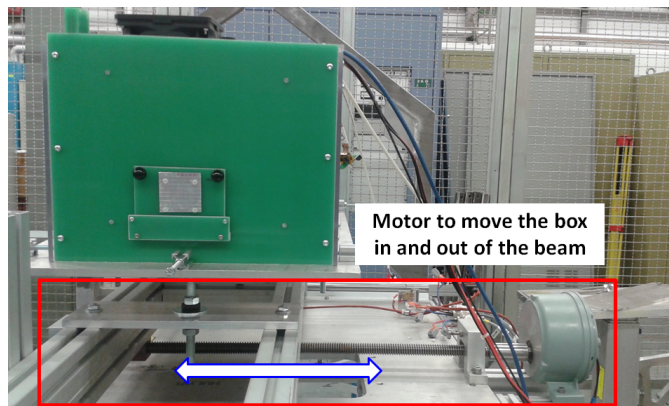


Figure 5.6: Test box (2018) mounted on the motorized system.

5.4.2 Cooling

Due to the high radiation environment, the material of the modules would heat up after the beam impact. To keep the temperature below the damage threshold (i.e. avoid the melting of the silicon), the box was equipped with a simple cooling system: four $12 \times 12 \text{ cm}^2$ fans (Figure 5.5), two for injecting air inside the box and

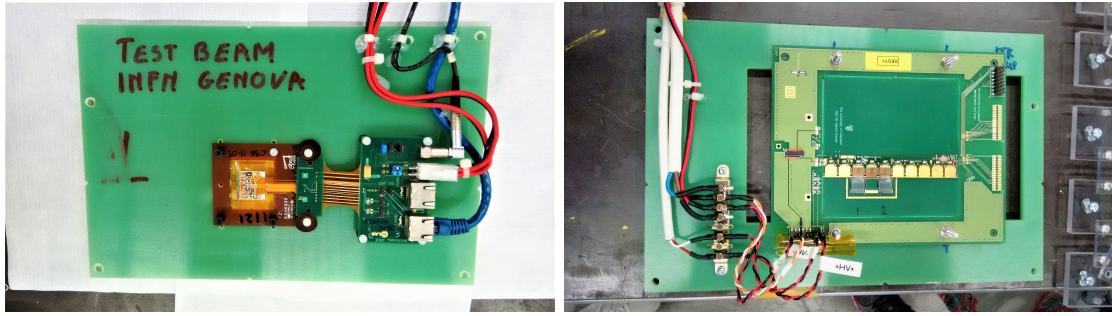


Figure 5.7: 3D IBL module (left) and ITk strip module (right) loaded on the frames for the 2017 test.

two for ejecting air outside it. The fans were equipped with filters to avoid dust and any other possible particle to enter or exit the box because of the air flow. This was required especially to avoid radioactive contamination in case of melting of the silicon detectors during the experiment.

During the 2017 test, the temperature raised up to 60°C on the IBL modules². For the 2018 test, the dissipation was improved for the IBL module. The IBL planar module is made by two FE-I4 chips: it was decided to use only one chip for the irradiation experiment, while the other one served as a metallic contact to transfer the heat to an aluminum foil connected to two aluminum heat sinks (Figure 5.8). Additionally, a heat transfer compound (RS 503-357) was spread between the module, the aluminum foil and the heat sinks, in order to improve the thermal conductivity. The performance of this setup was proved in laboratory with a thermal camera: thanks to the improved dissipation, the operational temperature of the device has decreased from 52°C to 34°C . The chip used as a metallic contact was not powered in order to further reduce the heat production, removing the wire-bonding lines that supply sensors and electronics. The operational temperature of the IBL module was monitored during the 2018 experiment, the value was constant at about 36.5°C .

5.4.3 Dose measurement

As already mentioned, during the 2017 test, the modules received a certain amount of secondary radiation from the beam pulses hitting the RotColl experiment. It was not possible to estimate the amount of radiation received during the week of RotColl operation.

In order to have a direct estimate of the particle fluence deposited in the ATLAS modules during the 2018 test, a separate system to measure the dose was developed (visible in Figure 5.5 and 5.6): two additional insertable and easily removable frames were mounted on the front and on the back of the test box. Each frame supported a passive aluminum foil over the windows where the beam enters or exits the box.

²The temperature was monitored with NTC thermistors embedded in the IBL modules.

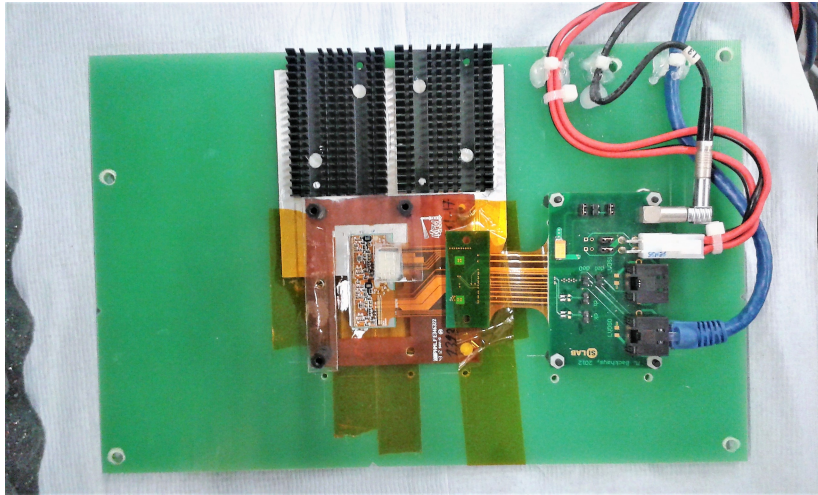


Figure 5.8: Planar IBL module (2018) loaded on the frame, with improved heat dissipation.

The aluminum foil is divided in 100 squares (with a 10×10 grid); the squares are properly numbered in order to know their exact position with respect to the beam and the modules, once singled out for dose measurement. During the irradiation, the aluminum nuclei are activated through the process $\text{Al}^{27}(\text{p},\text{X})\text{Na}^{22}$. Once the experiment is completed, the activity of the Na^{22} isotope³ is measured on each aluminum square using germanium spectrometers at the CERN IRRAD facility. From the front and rear direct measurements, it is possible to interpolate the fluence measurements and to extrapolate the value to the different modules.

5.5 IBL measurements

Differently from the standard HiRadMat experiments, which are performed on passive materials (such as collimators, targets, magnets), the ATLAS setup was made of active sensors. Therefore, the live monitoring of the state of these modules involved the powering and the readout of the signals. Several power supplies were used: low voltage supplies for the front-end electronics, the read-out boards, the fans; high voltage supplies for the bias of the silicon sensors. The whole system was connected to PCs and remotely controlled (see Figure 5.9).

In this Section, the measurements performed on IBL modules are described. The IBL modules were controlled through the USBpix setup [65], via the STControl software. The hardware consists of a Multi-IO board connected to an adapter card (see Figure 5.10). The Multi-IO board, developed at SiLab in Bonn University, is interfaced to the PC with a micro USB controller. The adapter card, dependent to the FE used, receives the signal from the module via ethernet cable and is powered by a low voltage supply. STcontrol, a C++ and ROOT based software application

³Gamma spectroscopy, Na^{22} peak: 1274.53 KeV.

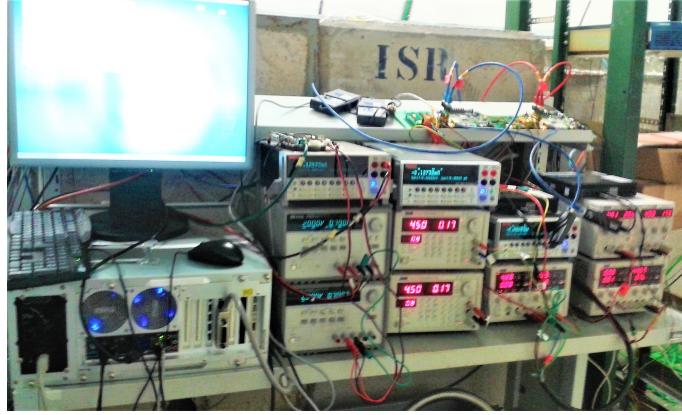


Figure 5.9: PCs, power supplies and readout boards installed in the TT61 tunnel for the 2018 experiment.

based on the ATLAS PixLib package, is used to perform scans. Additional C++ software was used to remotely control the power supplies and to perform IV scans. The IBL modules were configured to specific operational parameters⁴ sent through the USBPix setup.

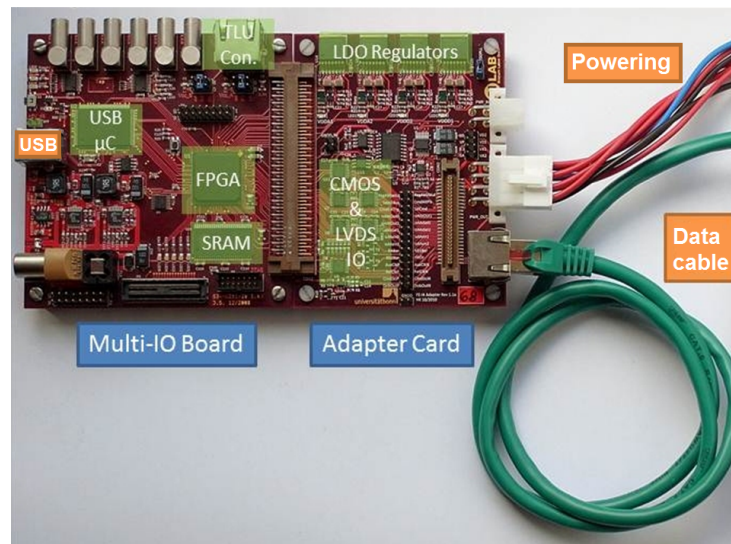


Figure 5.10: USBPix hardware: readout board used for IBL modules during 2017 and 2018 experiments.

The tests on IBL modules were performed between two shots, because the FE was deconfigured after the beam transit. Several different scans were performed:

- digital and analog scan: check the FE analog and digital functionality;
- threshold scan: measure the occupancy at different injected charges for a fixed threshold;

⁴Tuning values: threshold at 3000 electrons, TOT at 10 bunch crossing at 10000 electrons.

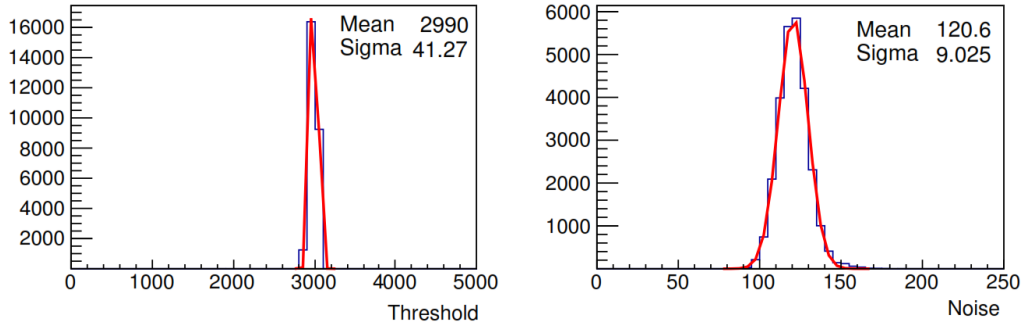


Figure 5.11: Threshold and relative noise distribution for each pixel of 2018 IBL module after tuning to 3000 electrons in a dark environment.

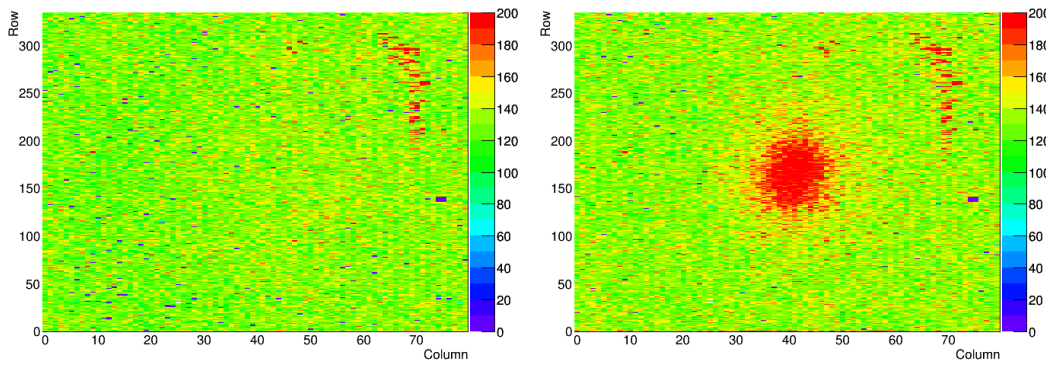


Figure 5.12: Noise measurement from Threshold scans performed before (left) and after (right) the beam: the noise increases in correspondence of the irradiated region.

- self-triggering scan: measure the material activation after irradiation;
- IV scan: measure the leakage current at different bias voltages.

The basic functionality of the IBL module was quickly checked after the beam transit, performing digital or analog scans. In case these scans were not responsive, the supplies were power-cycled and a reconfiguration of the module was performed.

Threshold scans have been performed, with HV on, to measure the noise increase due to the beam irradiation. The response curve of the threshold scan may be fitted with a gauss error function of sigmoid shape. The width of the corresponding gaussian can be identified as the noise. For a non irradiated module, the noise value corresponds to about 130 electrons (ENC): 30 electrons from sensor leakage current and bulk capacitance and 100 from the electronics. After the beam irradiation, the noise increases in correspondence of the irradiated region up to 300 electrons (see Figure 5.12).

The self-triggering scan (also referred to as source scan) is usually performed in laboratory to check the full functionality of the module. A trigger signal is generated with a Hitbus formed by the outputs of the individual pixel comparators ORed together. During the quality assurance, a radioactive source (i.e. Am^{241}) is

placed on top of the module and the signal produced by the gamma rays cascade is registered thanks to the self-triggering.

During the 2017 HiRadMat experiment, a self-triggering scan was performed after the beam: it was noticed that the part of the detector crossed by the beam has become itself a source of radiation, because of the material activation. The hit occupancy per pixel is shown in Figure 5.13: the two spots corresponding to the 2 mm and the 0.5 mm radius beams are visible.

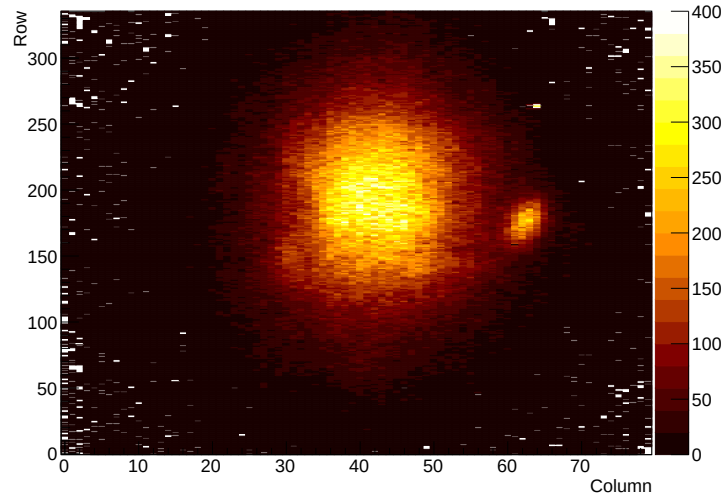


Figure 5.13: Material activation of the 2017 IBL module in terms of hit occupancy after the 2 mm (central big spot) and 0.5 mm (small spot on the right side) beam operations.

The leakage current was measured as a function of the sensor bias voltage (IV characteristic) during the test. During laboratory tests, a current limit of $10 \mu\text{A}$ is used to protect the modules. After the beam irradiation, the leakage current increases and therefore it is necessary to increase the current limit in order to achieve the full depletion of the sensor (see Figure 5.14).

5.6 IBL results

The first and main result of the experiments performed with IBL modules is the survival of the module after the 288 bunches at 2 mm beam radius, with 10^{11} protons per bunch. Both IBL 3D modules survived to this level of radiation in 2017, as well as the IBL planar module in 2018.

Therefore a lower limit on the damage threshold of IBL modules can be conservatively set at $1 \cdot 10^{13}$ protons/cm². The limit is calculated taking into account $288 \cdot 10^{11}$ protons delivered in a single pulse of $7.2 \mu\text{s}$ over an effective irradiated region (square) of $0.5 \times 0.5 \text{ cm}^2$.

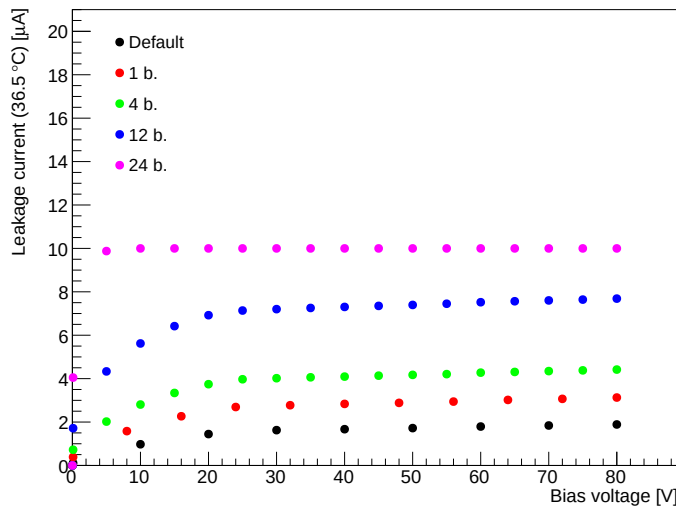


Figure 5.14: IV scans performed on IBL module during 2018 test: the leakage current increases after irradiation, reaching the current limit (set to $10 \mu\text{A}$) after 24 bunches.

The new limit is three orders of magnitude larger than the previous limit [56], however it should be noted that, despite the number of protons and the delivered energy per pixel are higher in the 2017/2018 tests with respect to the 2006 experiment, the total energy deposited in the module is similar in the two tests⁵

During 2017, the modules were tested as well with 0.5 mm radius beam pulses, increasing the intensity up to 288 bunches. After the last shot with 288 bunches, the FE-I4 was irretrievably damaged on both IBL modules. Although a small bump on the Flex-Hybrid is visible under a microscope in correspondence of the spot where the last 288 bunches 0.5 mm beam shot was delivered, the electrical lines of the Flex-Hybrid circuitry are working. Detailed post processing inspections seems to indicate the presence of a short circuit between ground and analog voltage in the read-out chip. Because of this issue, it was not possible to supply the modules anymore, inhibiting any post-experiment measurement.

In order to keep safe the 2018 IBL module for post-experiment measurements, after completing the wide beam tests, it was decided to stop the narrow beam tests at 12 bunches. The IBL module survived and it is now in ATLAS Genoa laboratory for post-experiment measurements.

The damage suffered by the silicon detectors during beam irradiation is well known and studied. Because of the bulk and surface radiation damage, the leakage current increases linearly with the fluence [66]. During the 2018 experiment, the leakage current of the IBL module was systematically measured after each pulse. The full series of measurements is visible in Figure 5.15: the leakage current increases after irradiation, reaching $170 \mu\text{A}$ at 80 V after 228 bunches.

⁵The beam is perpendicular to the modules in 2017/2018 tests, while it goes through the whole module in 2006 experiment (beam parallel with respect to the module).

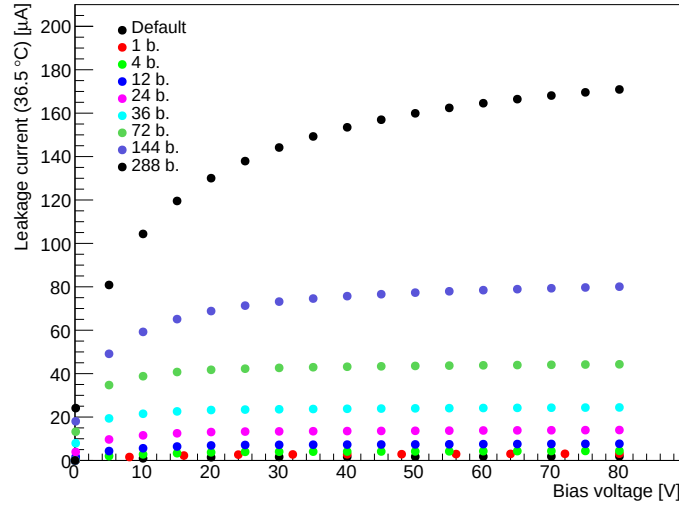


Figure 5.15: IV scans performed on IBL module after the beam irradiation: the leakage current increases after irradiation, reaching 170 μA after 228 bunches.

The linear relation between the leakage current increase and the fluence is summarized by the relation:

$$\Delta I = \alpha \Phi V, \quad (5.1)$$

where ΔI is the increase of the current measured before and after the irradiation, α is the linear coefficient, Φ is the proton fluence and V is the volume. The linear relation between the leakage current, normalized over the sensor volume, and the fluence is verified (see Figure 5.16), taking into account the measurements performed on the 2018 IBL module at 80 V bias and at a constant temperature of about 36.5°C, after each beam pulse.

A detailed analysis was performed to correlate the degradation of the performance of the modules to the proton fluence received. The performance was measured for each pixel in terms of increase of the noise, extracted from threshold scans. The proton fluence per pixel was simulated taking into account the position of the beam, the X and Y width of the beam, assuming a bidimensional gaussian profile, the number of bunches and the number of protons per bunch. The estimated fluence in terms of number of protons per pixel reaches $13 \cdot 10^9$ in the center of the beam spot (see Figure 5.17, left), after the whole series of 2 mm beam pulses, during the 2018 experiment. In the irradiated region, the noise reaches values up to 300 electrons (see Figure 5.17, right), while on the top and left corners the noise remains stable at about 120 electrons. The full series of noise measurements, along with the corresponding simulated proton fluences, is reported in the Appendix 12.

There is a clear correlation between the proton fluence and the noise increase, as can be seen in the distribution in Figure 5.18: each point corresponds to a pixel,

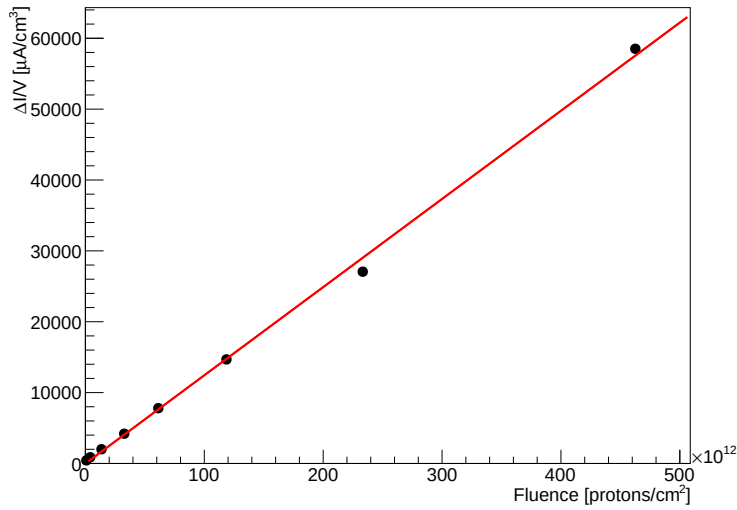


Figure 5.16: Linear relation between the fluence and the leakage current measured on the 2018 IBL module.

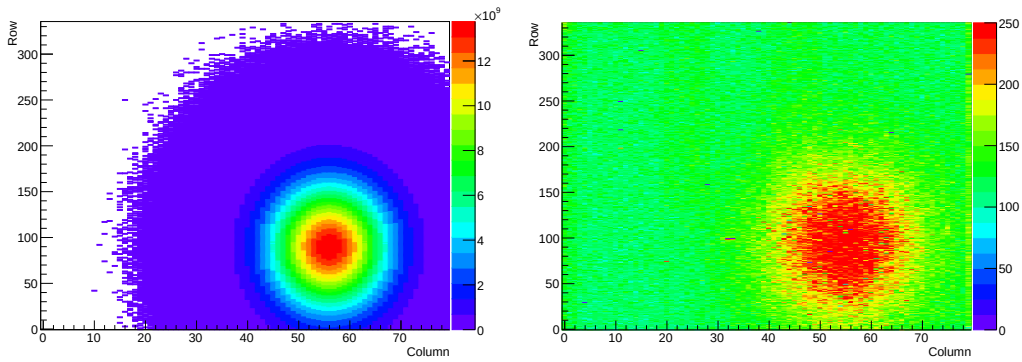


Figure 5.17: Simulated proton fluence per pixel (left) and noise measurement from threshold scan (right) relative to 288 bunches of 2 mm radius beam (2018).

with its value of simulated fluence and measured noise. The correlation is confirmed from the analysis of the noise measurements performed after each beam pulse (see Figure 5.19). The distribution is coloured differently for each measurement. The noise starts to increase after 12 bunches, then constantly increases after each beam pulse following the same trend.

The three IBL modules were operated with different configurations during the beam transit: two configurations were used to reproduce the standard status of the ATLAS detectors when LHC is delivering stable or non-stable beams:

- IBL module 1 (2017), stable beam: sensor bias and FE amplifiers on;
- IBL module 2 (2017), stand-by: sensor bias and FE preamplifier off;
- IBL module 3 (2018), stable beam: sensor bias and FE amplifiers on.

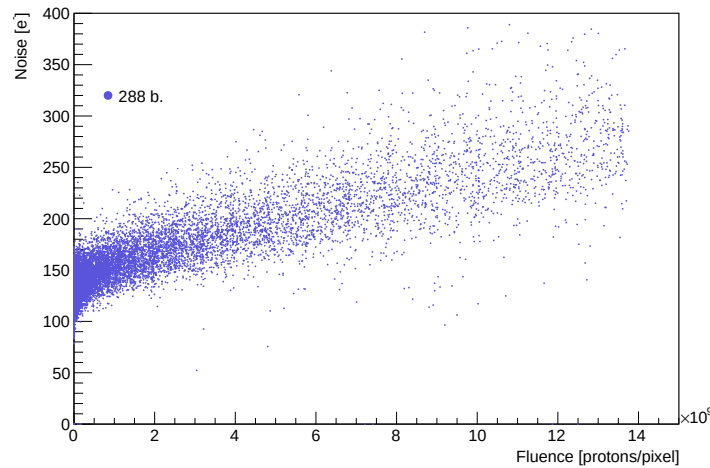


Figure 5.18: Correlation between the proton fluence and the noise increase per pixel, noise values measured after 288 bunches.

The stable beam configuration reflects the configuration used in ATLAS during stable beam operations: the sensor is powered and the FE preamplification is switched on to allow the data acquisition. The stand-by configuration is used instead during non-stable beam conditions to avoid local shorts in the sensors or damages in the electronics due to the heavily ionizing particles.

The noise increases in correspondence of the beam spot in a similar way for the three modules (see Figure 5.20): the modules operating with the stable beam configuration (module 1 and 3) have not experienced additional damage with respect to the module operating in stand-by (module 2). The same conclusion is obtained for the different structure of the silicon sensor: the noise measured on IBL modules with 3D sensor (module 1 and 2) has increased in a similar way to the noise measured on the IBL module with planar sensor (module 3).

The effect of 288 bunches with 2 mm radius beam is visible as a big red spot in the center of the plot for module 1 and 2 and on the right for module 3. The effect of few 0.5 mm radius beam bunches is visible as well: two small spots can be seen on the right of the big spot for module 1 and 2, while 1 spot is visible on top of the big spot for module 3.

5.7 ITk strip measurements and results

A detailed description of the performance degradation of ITk strip modules is out of the scope of this thesis and is being documented in separated publications. On the ITk strip modules, the following measurements were performed:

- leakage current monitoring: continuous online record of the leakage current with the detector under bias;

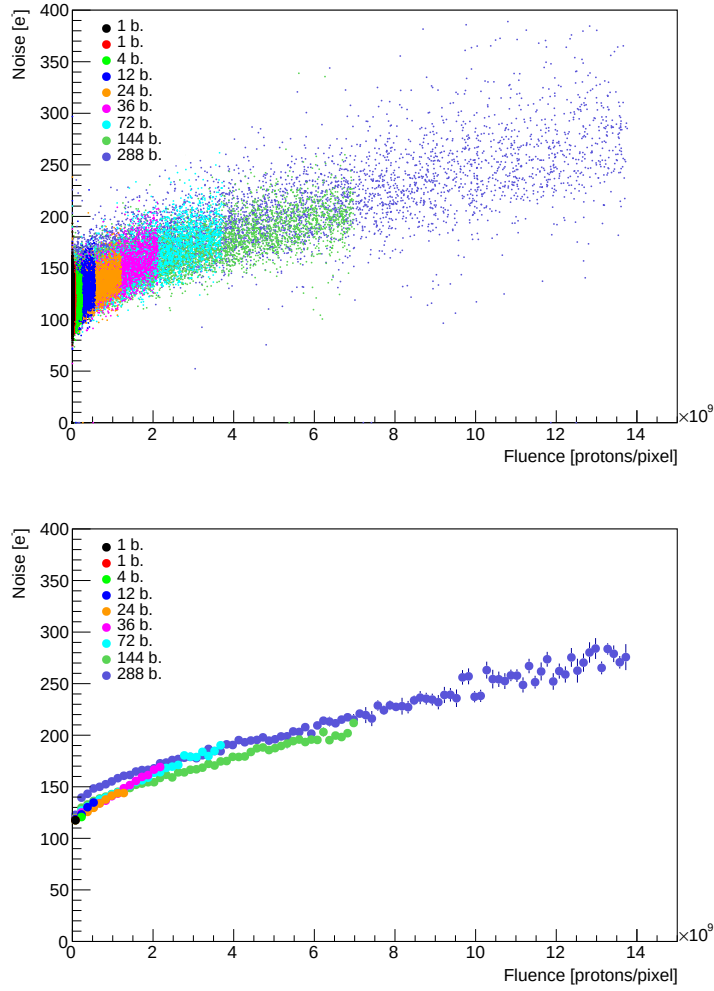


Figure 5.19: Correlation between the proton fluence and the noise increase per pixel: one point per pixel (top) or averaged over the fluence (bottom). The colour of the points corresponds to the beam pulse, the colour code is on the right.

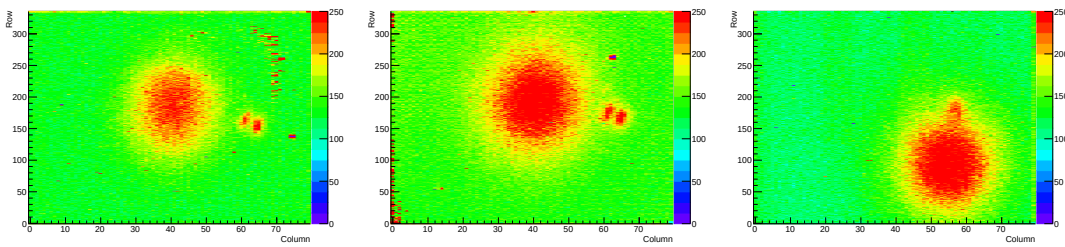


Figure 5.20: Comparison of the noise distribution measured on the three IBL modules after 288 bunches with 2 mm radius and few bunches with 0.5 mm radius.

- three points gain: measurement of the noise and gain injecting three different charges and varying the threshold value.

For the ITk strip modules, it was observed that the increase in leakage current follows the increase of beam intensity and that the noise level increases as a function of the proton fluence. The fraction of fully operating channels decreases significantly with the increase of the dose received by the sensor. A significant amount of channels shows high or low level of noise after the irradiation. The effect is maximal around the beam center and decreases with the distance. Since about 10% of the damaged channels was observed after 1 bunch with wide beam operation, the damage threshold of the ITk strip module is estimated as $\sim 8 \cdot 10^{11}$ protons/cm². The value is calculated using 1 sigma beam spot with the beam hitting the sensor perpendicularly. No macroscopic damages on the sensor and chip were visible after the full irradiation.

Studies are on-going to improve the sensor and chip post-irradiation characterization. The 2018 strip sensors, after the irradiation, show the typical leakage current and depletion voltage for proton irradiated sensors. From preliminary studies, it seems that PTP effectively protects the coupling capacitors of the silicon sensors from large charge accumulation by a beam-loss scenario, but still this could induce damages on the read-out electronics. Further studies are needed to understand the beam-loss effect on read-out electronics for the PTP module.

5.8 Conclusions

The HiRadMat facility was used to irradiate ATLAS pixel and strip modules with beams orders of magnitude more intense compared to previous experiments [56] to test their resistance in case of beam-loss scenarios at HL-LHC.

After the completion of the wide beam program, up to 288 bunches with 10^{11} protons per bunch, both IBL 3D modules survived (2017), as well as the IBL planar module (2018). The ITk strip module, monitored in the 2018 test with a full read-out system, shows a significant performance degradation in terms of not operational channels (high/low level of noise).

Based on the 288 bunches wide beam operations, a lower limit on the damage threshold of IBL modules can be set at $1 \cdot 10^{13}$ protons/cm², taking into account that the beam was hitting perpendicularly a good fraction of the sensitive detector area. In 2017, after the last shot with a 288 bunches narrow beam, the FE-I4 was damaged irretrievably on both IBL 3D modules. Detailed post processing inspections seems to indicate the presence of a short circuit between ground and analog voltage in the read-out chip.

For the ITk strip module tested in 2018, about 10% of the channels was damaged after 1 bunch of wide beam operations, therefore the damage threshold is estimated as $\sim 8 \cdot 10^{11}$ protons/cm². Detailed post-irradiation studies are on-going, separately

for the sensor and the chip, to identify the source of the channel loss. Preliminary studies suggest that PTP effectively protects the coupling capacitors of the silicon sensors from a large amount of charge, but the read-out electronics still might be damaged.

I joined this effort from the beginning, taking part in each of the steps of these experiments. I prepared the experiment proposal to be submitted to the HiRadMat beam committee, together with the other members involved in this test beam campaign. I selected the 3 IBL modules to be used in this potentially destructive test, measuring their properties in the ATLAS Genoa lab. I helped in the design and the finalization of the experimental box (including the IBL frames), in agreement with the strict HiRadMat facility requirement (the experimental area is a tunnel, with extremely high radiation levels). Then I prepared and installed the setup (PCs, cables, powering and read-out) in the HiRadMat facility tunnels. I took part in the data taking, remotely controlling the IBL devices from the CERN Control Center (CCC) at the SPS desk. Finally, I performed the IBL data analysis and presented results at national and international conferences. This is a high interest measurement, since silicon detectors were never exposed directly to such a high energy and intensity proton beam before. The HiRadMat facility is the unique available facility in the world where such experiments may be performed. There are plans to repeat the experiment with the final prototype of the ITk pixel module, along with other different prototypes of ITk strip modules, after the end of Long Shutdown 2, when the HiRadMat facility will resume the operations.

Chapter 6

Bonus: my Good Run List

During the 2018, I contributed to the data taking activities for the ATLAS experiment taking shifts in the ATLAS Control Room at the Inner detector desk. In particular, I did 6 shifts in March 2018 with responsibility on the temperature and environment control of the Inner detector, before the restart of the accelerator complex. Then, in May and June 2018, I did 15 shifts during proton-proton collisions with responsibility on the data taking with the Inner detector. The 2018 runs I contributed to record are listed in Table 6.1. A single run is split into luminosity blocks (LB) which have a fixed duration (approximately five minutes). Taken together, these runs correspond to a statistics of almost 6 fb^{-1} .

Day	Run	LB	Notes
1 st May 2018	349268	500 → End	
1 st May 2018	349309	Fill → 300	
2 nd May 2018	349335	Fill → End	
3 rd May 2018	349451	600 → End	
7 th May 2018	349646	500 → End	
7 th May 2018	349693	Fill	
8 th May 2018	349769	-	ALFA detector run
9 th May 2018	349944	Fill	2018 data reference run
10 th May 2018	350013	Fill	
13 th May 2018	350160	700 → End	
13 th May 2018	350184	Fill	
15 th May 2018	350310	300 → End	Tile module off (LBA29)
15 th May 2018	350361	Fill → 300	Tile modules off (LBA29, LBA30)
25 th May 2018	351160	Fill → End	
26 th May 2018	351223	Fill → 700	
27 th May 2018	351296	Fill → 200	
31 st May 2018	351636	Fill → 500	
1 st June 2018	351671	200 → 700	
2 nd June 2018	-	-	Cryogenic fault in LHC

Table 6.1: My personal 2018 Good Run List

In case defects are spotted in the data, the LB are excluded from the list of data runs used for the physics analyses, namely the Good Run List (GRL). The direct experience I had with the detector control gave me a complete overview of a high energy physics experiment. Moreover, the situations I experienced during data taking (good runs, runs affected by detector issues, special runs) have been very useful for me to fully understand the data quality from the data taking operations point of view. This helped me a lot in my role as b -tagging data quality coordinator (details in Chapter 8).

Chapter 7

Jets and flavour tagging

As outlined in Section 1.3, free quarks and gluons always undergo a hadronization process with the resulting production of a hadronic jet shower. Quarks play an important role within the Standard Model frame: they are the base components of the hadrons (barions and mesons) such as protons, neutrons, pions, kaons. At hadronic machines, such as LHC, plenty of quarks stem from each collision and, moreover, many particles generated in the collisions decay in channels containing quarks.

After a brief introduction to the treatment of tracks, jets and vertices in the ATLAS experiment (Section 7.1), a description of the characteristics of quark flavours and of the corresponding jets is reported (Section 7.2): b -jets have a different topology with respect to jets coming from charm quarks, light quarks or gluons and this allows to separate them from the others.

ATLAS developed its own algorithms for the jet flavour identification [67], exploiting the typical properties of the quarks and the hadrons: the low level and high level b -tagging algorithms are presented in Sections 7.3.1 and 7.3.2, respectively.

7.1 Vertices, jets and tracks reconstruction

Since jets are complex physics objects, particular attention is devoted to their reconstruction: this is mainly based on calorimeter cell data, but also on reconstructed charged tracks, which are used to identify the primary vertex candidate (i.e. the vertex corresponding to the most interesting proton-proton interaction) and are the associated to jets. In this section a brief description of this process is reported, along with the description of techniques meant to reduce the effects of pile-up.

A charged particle generated at the collision point in the presence of the magnetic field produces a track in the Inner detector that can be approximated as a helix. The helix can be represented with 5 parameters in the perigee parametrisation, where the perigee of a track is the point of closest approach to the z axis of the coordinate system. The ATLAS perigee parameters are:

- d_0 : signed transverse impact parameter, defined as the distance of closest approach of the track to the primary vertex point in the transverse plane, signed according to the trajectory of the reconstructed track with respect to the primary vertex and the jet axis;
- z_0 : longitudinal impact parameter, defined as the difference between the z coordinates of the primary vertex position and of the track at this point of closest approach in the transverse plane;
- ϕ : azimuthal angle of the track at the perigee;
- θ : polar angle of the track at the perigee;
- q/p : charge over momentum of the track.

Each vertex (defined as the point where two or more tracks are converging) is required to have two or more tracks; the primary vertex is selected as the vertex that maximises the sum of the square transverse momentum (p_T^2) for the associated tracks. Due to pile-up interactions, the average number of reconstructed primary vertices is larger than one (up to 70 interaction per bunch crossing in Run 2). The determination of the primary vertex is particularly important for b -tagging, because it is the reference point to determine track impact parameters and the vertices corresponding to in-flight decay of hadrons (secondary vertices).

The standard collection of jets are reconstructed by clustering energy deposits in the calorimeter using the anti- k_t algorithm [68] with a radius parameter of 0.4. The clusters are calibrated to the electromagnetic energy response scale prior to jet reconstruction. The reconstructed jets are then calibrated to the jet energy scale (JES) [69] using corrections derived from simulation and in situ corrections based on 13 TeV data.

The tracks associated to the calorimeter jet are required to have small angular separation with respect to the jet axis: $\Delta R(track, jet) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where η is the pseudorapidity and ϕ is the azimuthal angle (see Section 2.1). Greater the jet p_T and narrower is the jet cone, resulting with a smaller cut value of ΔR : a 20 GeV jet has a cone cut value $\Delta R = 0.45$ while a 150 GeV jet has a cone cut value $\Delta R = 0.26$. Tracks are further required to pass some quality criteria in order to reject fake and badly reconstructed tracks.

The Jet Vertex Fraction (JVF) [70], defined as the summed transverse momentum of the tracks associated with the jet and originated from the primary vertex divided by the summed transverse momentum of all the tracks associated with the jet, has been developed during Run 1 to reject pile-up jets. JVF measures the fractional p_T from tracks associated with the primary vertex: its value is bound between 0 and 1, a -1 value is assigned to jets with no associated tracks. A small JVF value corresponds to a large pile-up contamination, so, to reduce the contribution from

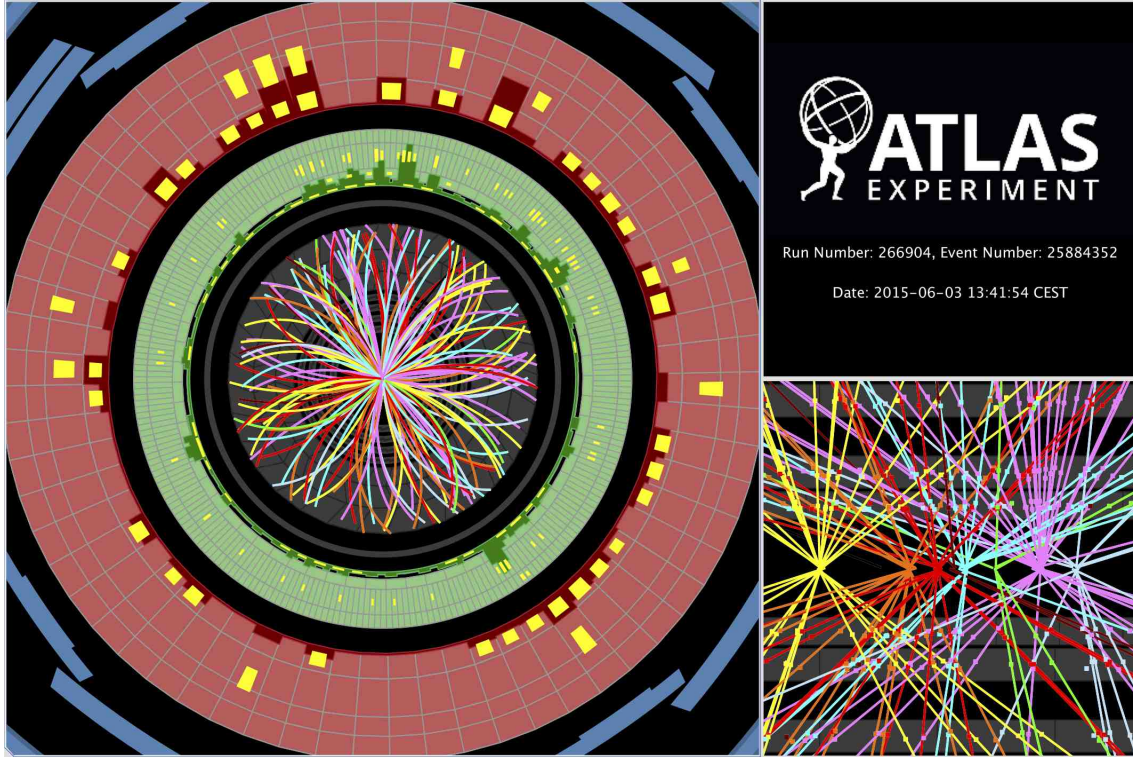


Figure 7.1: Display of a proton-proton collision recorded on 3 June 2015, with the first LHC stable beams at 13 TeV. Transverse plane (left): tracks reconstructed from hits in the Inner Detector are shown as arcs curving in the magnetic field, while the electromagnetic and the hadronic calorimeters are shown in green and red respectively, with bars indicating energy deposits. Longitudinal plane (right): tracks originate from several vertices, indicating multiple proton-proton interactions, also known as pile-up. [29]

jets arising from pile-up, in Run 1 analysis, jets with $p_T < 50$ GeV and $|\eta| < 2.4$ were required to satisfy $JVF > 0.5$.

A new discriminant for pile-up suppression has been developed and is currently used by Run 2 analyses: the Jet Vertex Tagger (JVT) [71], obtained with a 2-dimensional likelihood of R_{p_T} , defined as the p_T sum of the tracks associated with the jet and originated from the primary vertex divided by the fully calibrated jet p_T , and $corrJVF$ defined as JVF , but corrected for the average sum p_T from pile-up tracks associated with the jet. The resulting JVT value is bound between 0 and 1, with -0.1 assigned to jets with no associated tracks. To reduce pile-up contamination, JVT is required to be higher than 0.59 for jets with $p_T < 60$ GeV and $|\eta| < 2.4$, while jets with $p_T > 60$ GeV have a negligible contamination, so no further selection is applied to them.

7.2 Quarks and jet flavour

The b quark is the second heaviest known quark, with a mass around 4 GeV [15]. Jets coming from b quarks (b -jets) will contain one or more B hadrons in their final

state after hadronisation: the properties of B hadrons give to b -jets their special topology: the presence of a secondary vertex, quite separated from the primary vertex and reconstructable in most cases, and tracks with large impact parameters (d_0 and z_0).

The most important B hadrons are the $B^\pm$, B^0 and B_s mesons which decay via electro-weak interactions and have lifetimes of the order of 1.5 ps. With such a relatively long lifetime, the typical B meson with a 50 GeV momentum would travel about 5 mm in the lab frame before decaying, generating in this way a displaced secondary vertex with a high number of tracks (high multiplicity). The tracks coming from the secondary vertex have also larger impact parameters with respect to the tracks from primary vertex. The b -tagging algorithms exploit all of these properties to label a jet as a b -jet, together with other variables (i.e. the jet invariant mass).

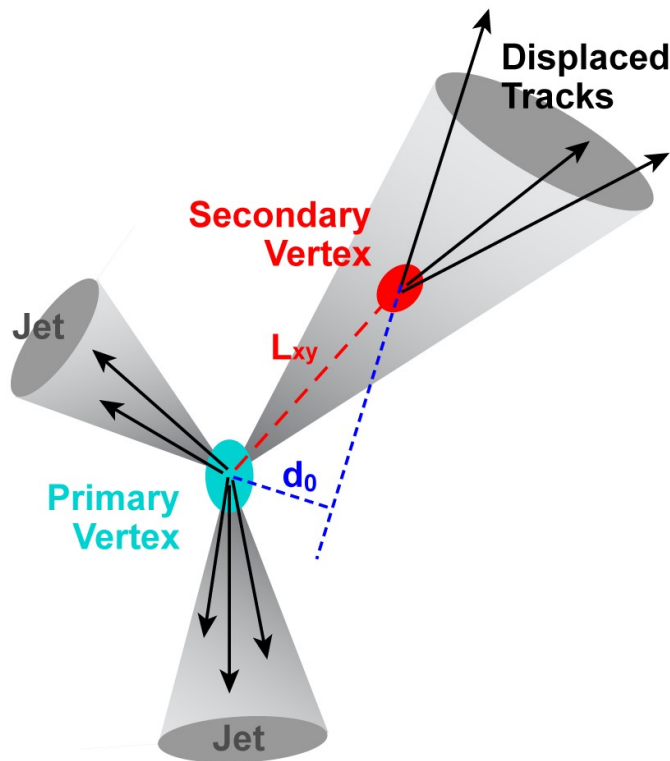


Figure 7.2: Typical structure of a b -jet (or a c -jet) stemming from the primary vertex of the event: while light jets tracks originates in the primary vertex (i.e. the collision point), most of the b -jet tracks originates in the secondary vertex (i.e. the vertex of the hadron decay). Tracks originated in the secondary vertex have higher longitudinal (z_0) and trasversal (d_0) impact parameters.

The light quarks (up, down and strange) with masses in the MeV scale or the massless gluons are much lighter than the b quark: the so-called light jets (l -jets) are quite different with respect to the b -jets in terms of invariant mass and decay length. Lifetime of hadrons containing lighter quarks are several orders of magnitude

shorter (10^{-23} s to 10^{-16} s for strong or electromagnetic decays) or longer (10^{-8} s for electro-weak decays). In case they decay instantly, they will not travel a measurable distance, excluding the possibility to identify a secondary vertex due to the hadron decay. In case they decay out of the Inner detector, meters away from the primary vertex, the possibility to find a secondary vertex in the Inner detector is excluded. In case they decay in the Inner detector, the topology of the decay is such that it can be correctly identified as a hadron containing light quarks, also thanks to the different invariant mass.

The c quarks are slightly lighter than the b quarks, with a mass of about 1 GeV [15], so jets coming from c quarks (c -jets) have intermediate properties: since the hadrons containing c quarks have a lifetime similar to that of the B hadrons, they also produce a separated secondary vertex, characterized by a lower track multiplicity and an invariant mass in the middle between b -jets and l -jets. For this reason c -jets are very hard to identify and they are easily mistaken as b -jets. The most important hadrons containing c quarks are $D^\pm$ and D^0 mesons which decay via the electro-weak force and have lifetimes of the same order of magnitude with B hadrons (about 1 ps), but slightly briefer. The typical D meson decay produces a secondary vertex displaced from the primary vertex of about 3 mm (estimated for a meson with 20 GeV momentum in the laboratory frame) with a topology very similar to that of b -jet.

7.3 Flavour tagging algorithms

The identification of b -jets is performed with several algorithms, exploiting the long lifetime, high mass and decay multiplicity of b hadrons. The tracks originated from b -hadron decay have large impact parameters with respect to the tracks stemming from the primary vertex. The basic ATLAS b -tagging algorithms [72] (or Low Level Taggers) are based on the presence of reconstructed secondary vertices (SV1 and Jet-Fitter), large impact parameters of their tracks (IP3D) and spatial and kinematic correlations between tracks (RRNIP). To obtain an overall variable with more discriminating power, improving the flavour tagging performance, the output of the individual algorithms are combined through multivariate techniques. This is the case of the High Level Taggers, used by analyses for final discrimination: MV1 (for Run 1) and MV2c10 and DL1 (for Run 2).

7.3.1 Low Level Taggers

IP3D

IP3D is the impact-parameter-based algorithm currently used by ATLAS, deriving from JetProb, a previous and simpler algorithm extensively used at LEP and at Tevatron. The impact parameters are computed with respect to the primary vertex.

In particular, the transverse impact parameter d_0 is signed to further discriminate the tracks from the b -hadron decay from tracks originating from the primary vertex. The sign is defined as positive if the track intersects the jet axis in front of the primary vertex, and negative if the intersection lies behind the primary vertex. The jet axis is defined from the calorimeter jet direction or, when a compatible secondary vertex is found, the jet axis is defined as the line joining the primary and the secondary vertex. IP3D uses both the transverse (d_0) and the longitudinal (z_0) impact parameters and their correlations. More precisely, IP3D uses d_0 and z_0 significances defined as the ratio between the impact parameter and its uncertainty on the reconstructed impact parameter: $S_{d_0} = d_0/\sigma_{d_0}$ and $S_{z_0} = z_0/\sigma_{z_0}$. For each track, the significances are compared to the pre-determined 2-dimensional Probability Density Function (PDF) obtained from simulation of the b -jet and light jet. The log-likelihood ratio formalism is used on the jet weight, defined as the sum of the logarithms of the track weights, on their turn defined as the ratio of probabilities (derived from PDFs) of a track to come from a light- or a b -jet.

SV1

SV1 is one of the secondary vertex based algorithms currently used by ATLAS, along with the JetFitter algorithm described later. The secondary-vertex-based algorithms have a much smaller mistag rate (i.e. the probability of mistakenly tagging a light jet as a b -jet) with respect to the impact parameter based algorithms, but they are limited by the relatively small efficiency of finding the secondary vertex ($\approx 60\%$). SV1 searches for the secondary vertex trying to associate every pair of tracks far enough from the primary vertex with a χ^2 fit. Vertices with invariant mass compatible to K_s , Λ and other long lived light hadrons are rejected, as well as vertices with coordinates compatible with a secondary interaction with the detector material. SV1 is based on a likelihood ratio formalism exploiting these properties:

- the invariant mass of all the tracks used to reconstruct the secondary vertex;
- the ratio of the sum of the energies of these tracks to the sum of the energies of all tracks in the jet;
- the number of two-track vertices;
- the ΔR between the jet direction and the line joining the primary and the secondary vertex.

JetFitter

Jet Fitter exploits the topological structure of the weak decays of the b -hadron and the c -hadron inside the jet. A Kalman filter is used to find the line where the primary vertex, the b -hadron and the c -hadron vertices lie, as well as their position on this line. The JetFitter algorithm takes six variables as input of a neural network:

- the number of vertices with at least two tracks;
- the total number of tracks at these vertices;
- the number of additional single track vertices on the b -hadron flight axis;
- the invariant mass of all charged particle tracks attached to the decay chain;
- the energy of these charged particles divided by the sum of the energies of all charged particles associated to the jet;
- the weighted average displaced vertex decay length divided by its uncertainty.

The jet p_T and η are used as additional input nodes in the neural network, since the six input variables depend on them. JetFitter has three output nodes, referred as P_b , P_c and P_l , corresponding to the b -jet, c -jet and light jet hypotheses. The discriminating variable is defined as the logarithm of the ratio between P_b and P_l .

SMT

During Run 2, to further increase the b -jet identification performance, a new Low Level Tagger has been developed to be possibly used as input to High Level Taggers: the Soft Muon Tagger (SMT), based on the reconstruction of muons coming from semileptonic decays of heavy flavour hadrons. Three main inputs used for SMT as discriminant variables: the ΔR separation between the jet and the muon, the d_0 impact parameter of the muon track and $p_{T\text{rel}}$, defined as the relative transverse momentum of the muon with respect to the jet. Finally, six variables are combined as inputs in a dedicated MVA, using a Boosted Decision Tree (BDT), to extract the SMT discriminant weight.

RNNIP

In order to exploit the increasingly powerful Machine Learning techniques applied to high energy physics, another b -jet identification algorithm has been developed, RNNIP [76], based on a Recurrent Neural Network (RNN). It processes charged particle tracks associated to jets without reliance on secondary vertex finding. Differently from IP3D, which assumes that tracks associated to jets are independent from each other, the RNNIP algorithm exploits the spatial and kinematic correlations between tracks which are initiated from the same b -hadron. This new approach includes (with respect to IP3D input variables) also the fraction of transverse momentum carried by the track relative to the jet and the angular distance between the track and the jet axis. The RNNIP algorithm performance is found to be higher with respect to the IP3D algorithm and is able to introduce significant improvements to High Level Taggers, since its performance is mostly orthogonal to secondary-vertex based taggers.

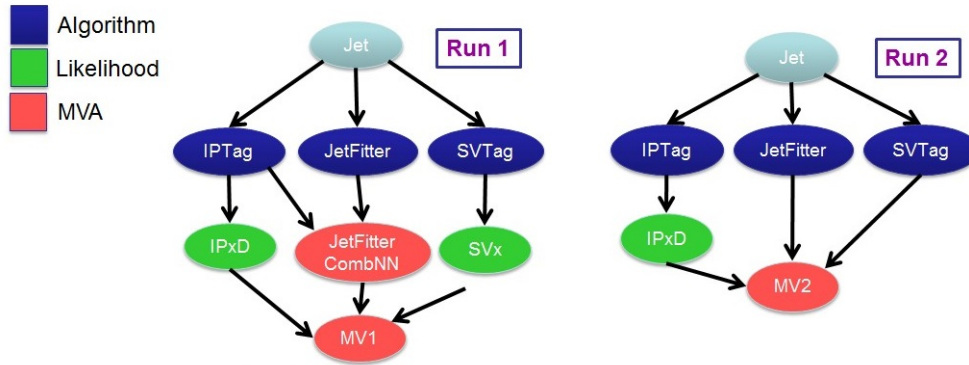


Figure 7.3: Combination of the b -tagging algorithms to build High Level Taggers.

7.3.2 High Level Taggers

MV1

To better improve the performance, during Run 1, the MV1 algorithm was developed as a combination of three of the previously described algorithms: IP3D, SV1 and JetFitter. The MV1 neural network is a perceptron based on the TMVA package [73] with two hidden layers consisting of three and two nodes, respectively, and an output layer with a single node which holds the final discriminant variable. The training relies on a back-propagation algorithm and is based on two simulated samples: b -jets (signal hypothesis) and light jets (background hypothesis).

Jets are divided in ten bins in p_T and four bins in η and the (p_T, η) bin of the jet is used as additional input node in the Neural Network. The MV1 output weight distribution is shown in Figure 7.4 for b -, c -, and light jets in simulated $t\bar{t}$ events: b -jets tend to have high values close to 1 and light jets low values close to 0. The MV1 discriminant variable was used for b -tagging purpose by many Run 1 physics analyses.

MV2c10

A new multivariate b -tagging algorithm was developed for Run 2: MV2c10 [74, 75]. The input variables obtained from the three basic algorithms (IP3D, JetFitter and SV1) are combined using a BDT algorithm to discriminate b -jets from light jets and c -jets. The training is performed on $t\bar{t}$ events and Z' events (to increase the statistics at high jet transverse momentum), controlling the fraction of c -jets added in the training. One of the enhancements is in fact to train the MV2c10 network also against c -jets, introducing a c -jet component in the background hypothesis: the name itself, MV2c10, reflects that the training is performed with b -jets as signal and a mixture of about 90% light jets and about 10% c -jets as background. The 24 input variables used for the training include the jet p_T and η to take advantage of correlations with the other input variables.

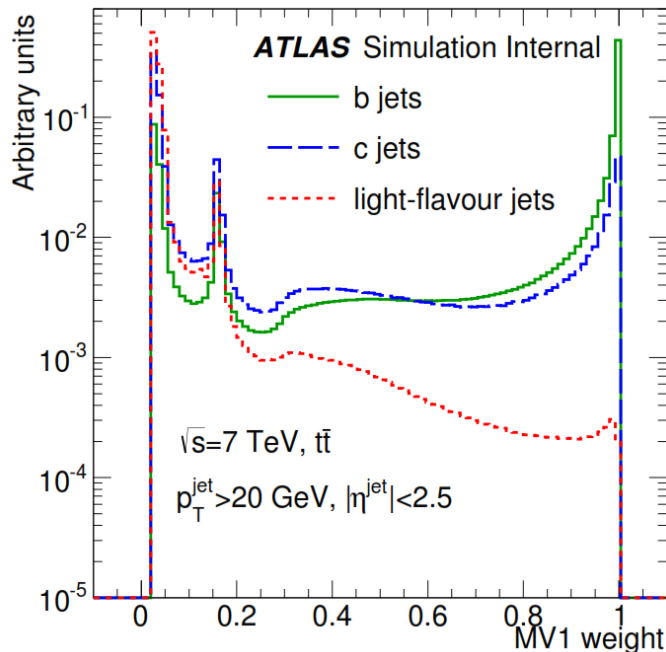


Figure 7.4: Distribution of the tagging weight obtained with the MV1 algorithm, for three different flavours: b -jet, c -jet and light jets. The spike around 0.15 corresponds mostly to jets for which no secondary vertex could be found.

While MV1 was based on a neural network approach using also intermediate multivariate tools (see Figure 7.3), the MV2c10 uses a BDT omitting the intermediate steps: this not only improves the performance, but also significantly simplifies the algorithm by directly using the variables from the basic algorithms.

As can be seen in Figure 7.5, the MV2c10 output weight ranges between -1 and +1, with b -jets tending to have weights close to +1 and light jets close to -1, while the c -jet distribution is broadly spread between -1 and +1.

DL1

A completely new High Level Tagger, and the most promising one in terms of performance, has been developed during Run 2: DL1 [77] (from Deep Learning), based on an artificial Deep Neural Network. Its Neural Network has a multidimensional output corresponding to the probabilities for a jet to be a b -, c - or light jet. The input variables to DL1 are the same of the MV2 BDT, while the parameters of DL1 are optimised in terms of the architecture of the NN, the number of training epochs, the learning rates and training batch sizes. The jet flavours are considered equally during training and multiple output nodes are used, each trained to predict a specific jet flavour, which provides a highly flexible flavour tagging algorithm. The performance for arbitrary background mixtures can be adjusted after the training, according to physics analysis requests.

The final output of the DL1 algorithm is spread between -5 and 10 (see Fig-

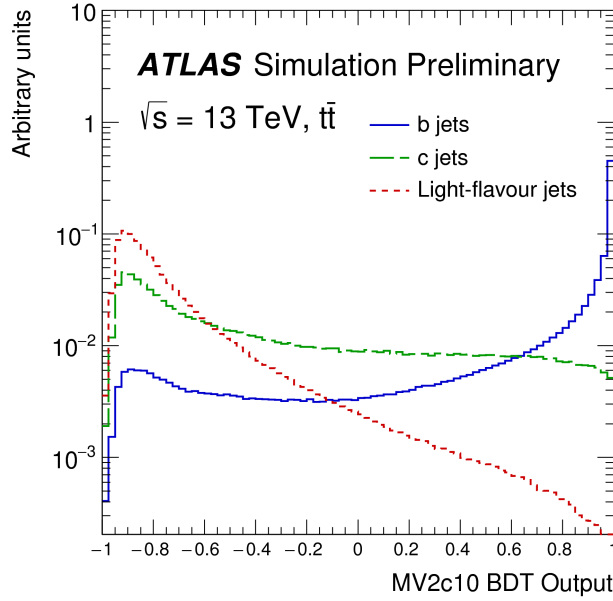


Figure 7.5: Distribution of the tagging weight obtained with the MV2c10 algorithm, for three different flavours: b -jet, c -jet and light jets.

ure 7.6), with b -jets tending to have weights between -2 and 10, light jets between -5 and 2, peaked around -2, while the c -jet distribution is spread between -3 and +5.

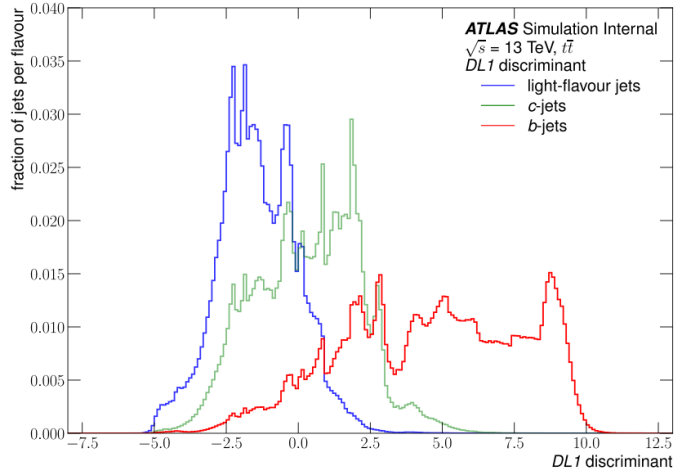


Figure 7.6: Distribution of the tagging weight obtained with the DL1 algorithm, for three different flavours: b -jet, c -jet and light jets.

SMT and RNNIP enhanced High Level Taggers

Given the availability of the new Low Level Taggers, SMT and RNNIP, three variants have been developed for each of the High Level Taggers [78] (MV2c10 and DL1):

- MV2c10 and DL1, baseline taggers with the standard inputs: impact parameter (IP2D and IP3D) and secondary vertex based (SV1 and JetFitter);
- MV2c10mu and DL1mu, baseline tagger plus the introduction of the SMT tagger as input;
- MV2c10rnn and DL1rnn, a full option with the SMT and the RNNIP inputs in addition to the standard variables.

The performance of the different variants of MV2 (MV2, MV2mu and MV2murnn) is shown in terms of the light-flavour and charm rejection, evaluated as a function of the b -jet efficiency (see Figure 7.7, top) or as a function of the jet p_T for a constant b -jet efficiency of 77% (see Figure 7.7, bottom). The rejection is measured as the inverse of the efficiency of selecting quark and gluon jets: a rejection factor of 50 would mean that, if the tagger is applied, the number of background jets is decreased by a factor of 50.

The use of the full set of input variables from the SMT algorithm and the output of the SMT multivariate BDT discriminant have both been tested in the High Level Tagger development. The introduction of SMT is found to introduce significant improvements in the low p_T region of the jet kinematic with respect to the baseline taggers, while the additional input from RNNIP introduce further improvements in the high p_T region.

7.3.3 Working points

For each b -tagging algorithm, working points (WP) are defined as a function of the average b -jet efficiency measured on simulated data. The same algorithm may be optimized through the years and released as new versions of the same algorithm, therefore it is important to report the software release number. In Tables 7.1 to 7.5, the working points of different b -tagging algorithms are reported, along with the corresponding c -jet and light jet rejection factors. Jets originated from τ leptons can be mistakenly tagged as b -jet too: in order to have a good b -tagging performance it is important to take them into account, so τ jets rejection factors are also reported in the tables.

Cut Value	b -jet Efficiency [%]	c -jet Rejection	light jet Rejection	τ jet Rejection
0.9867	60	7.98	651.81	25.21
0.8119	70	4.99	150.00	14.07
0.6065	75	3.96	65.98	9.05
0.1644	85	2.38	10.29	2.93

Table 7.1: Working points for the MV1 b -tagging algorithm (software release 17, 2012), including benchmark numbers for the efficiency and rejections rates. The statistical uncertainties are negligible.

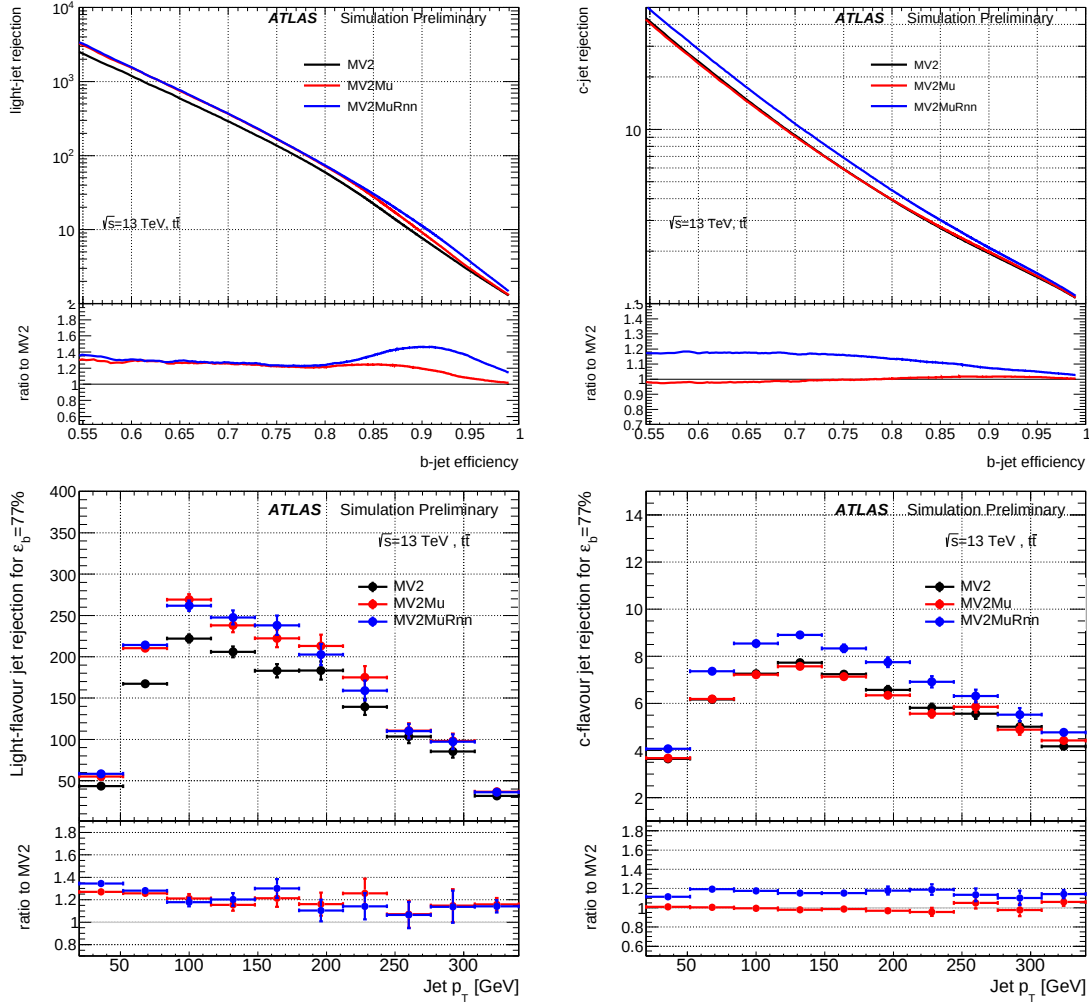


Figure 7.7: The light jet and c -jet rejection versus b -jet efficiency (top) or as a function of the jet transverse momentum for a flat b -jet efficiency of 77% (bottom) for the MV2c10, MV2c10mu and MV2c10rnn algorithms: significant improvements are observed when variables from SMT and RNNIP taggers are included as inputs to enhanced High Level Taggers.

Cut Value	b -jet Efficiency [%]	c -jet Rejection	light jet Rejection	τ jet Rejection
0.4496	60	21.33	1846.27	92.89
-0.0436	70	8.05	442.85	26.19
-0.4434	77	4.53	135.78	9.76
-0.7887	85	2.62	27.51	3.83

Table 7.2: Working points for the MV2c20 b -tagging algorithm (software release 20.1, 2015), including benchmark numbers for the efficiency and rejections rates. The statistical uncertainties are negligible.

Cut Value	b -jet Efficiency [%]	c -jet Rejection	light jet Rejection	τ jet Rejection
0.934906	60	34.54	1538.78	183.98
0.8244273	70	12.17	381.32	54.72
0.645925	77	6.21	134.34	22.04
0.1758475	85	3.10	33.53	8.17

Table 7.3: Working points for the MV2c10 b -tagging algorithm (software release 20.7, 2016), including benchmark numbers for the efficiency and rejections rates. The statistical uncertainties are negligible.

Cut Value	b -jet Efficiency [%]	c -jet Rejection	light jet Rejection	τ jet Rejection
0.94	60	21	1204	155
0.83	70	8	313	39
0.64	77	4	113	16
0.11	85	2	28	6

Table 7.4: Working points for the MV2c10 b -tagging algorithm (software release 21, 2017), including benchmark numbers for the efficiency and rejections rates. The statistical uncertainties are negligible.

Cut Value	b -jet Efficiency [%]	c -jet Rejection	light jet Rejection	τ jet Rejection
2.74	60	26	1320	239
2.02	70	9	395	47
1.45	77	4	137	15
0.46	85	2	32	4

Table 7.5: Working points for the DL1 b -tagging algorithm (software release 21, 2017), including benchmark numbers for the efficiency and rejections rates. The statistical uncertainties are negligible.

Chapter 8

b-tagging data quality in 2018

The ATLAS experiment has a long and wide experience in the data quality assessment, obtained after years of operations, which has guaranteed many successful physics results. The ageing of the detector is posing new challenges to the operation team, since the detector components may introduce faults during data collection that would bias the data. The constant monitoring of the data quality and stability is a key component toward a successful physics program. Nevertheless, the LHC operations are tightening year by year in order to gain as much as possible from the collisions. In 2017 a high increase in the instantaneous luminosity delivered to the LHC experiments has posed many challenges to the experiment operations and to the performance of the collected data. The data quality software needs to be adapted to such changes in order to be ready to assess the quality of the data in any condition: standard proton-proton collisions, high luminosity collisions, low luminosity collisions, special runs, heavy ion collisions. In this context, I contributed updating the *b*-tagging data quality software and with the experience gained, I acted as *b*-tagging data quality expert, helping to follow up the issues and in the organizational aspects of the data quality shifts. I am going to be involved in the documentation of the Run 2 data quality procedures, to maintain the experience and allow a smooth knowledge transfer towards Run 3. I will take care as well of the migration of the *b*-tagging data quality software to release 22: a complete rewriting of the tools is required in order to allow the Athena framework to work in parallel on multiple threads.

After the introduction to the ATLAS data quality software (Section 8.1), a detailed description of the improvements to the *b*-tagging monitoring tools is presented (Section 8.2), along with few examples of relevant issues (Section 8.3).

8.1 Data quality framework

As introduced in Section 2.7, the ATLAS reconstruction software framework, Athena, is used for a variety of purposes, including high-level triggering, simulation, reconstruction, monitoring and analysis. Athena provides a skeleton in which users can

embed their specific analysis code. As usual in particle physics, the framework is oriented to run on input data in event per event steps and make use of Python scripts (known as job options) to initialize and configure run-time algorithms.

As explained in Section 2.6, the data read-out by the ATLAS detector are filtered by a two-levels on-line trigger: Level 1 (LVL1) and High Level Trigger (HLT). The recorded events are stored into different streams depending on purpose (calibrations, monitoring or physics) and trigger hypotheses (minimum bias, muons, calorimetric clusters, ...). The express stream (namely the `express-express`) is a special stream containing a sample of each other trigger stream and it is analysed first to provide a fast feedback of the detector status.

Collision data are recorded from the detector in byte stream format (RAW data) and contain only hits of electronic read-out channels and information about trigger decisions. Those data are decoded and reconstructed by running Athena reconstruction process in various steps. First, data are translated from electronic channels to correspondent detector elements, then are reconstructed particles tracks and clusters (i.e. energy deposits in calorimeter cells). Finally, the particles are identified, along with more complex objects (secondary vertex, b -jets). Detailed output of the detector reconstruction from RAW data is written in ESD (Event Summary Data) files and AOD (Analysis Object Data) files.

The reconstruction is run at the CERN computing farm (the Tier-0 centre) on the express stream as soon as data are available on disk and when the necessary detector conditions information has been replicated to Tier-0, generally within few hours of the start of a run. Detector calibrations, alignment, and basic detector operation have to be verified by rapidly reconstructing a smaller subset of the physics events. Data monitoring is first done online by the DQ shifter in the ATLAS Control Room (ACR) to quickly spot problems and instabilities, on a relatively small number of histograms filled with a subset of the events being recorded (see Figure 8.1).

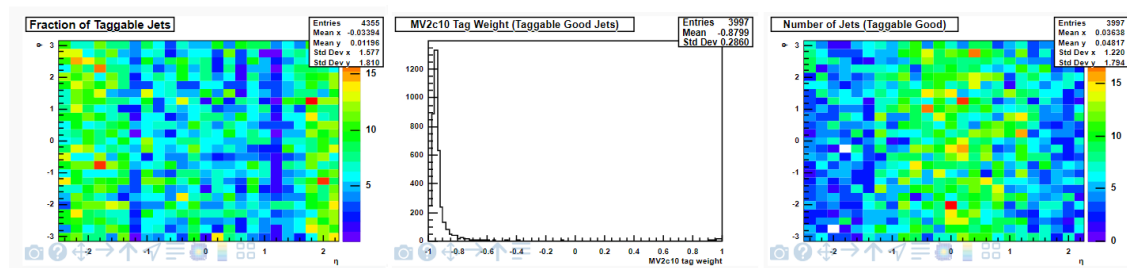


Figure 8.1: Example of three of the few plots monitored online via the Online Histogram Presenter (OHP) for the b -tagging data quality, run 364040.

After that, the reconstruction of the different data streams is performed and data quality is monitored as well offline by offline shifters. Monitoring histograms are checked by shifters with the help of an automatic quality assessment implemented in the Data Quality Monitoring Framework [79]. A first step of calibration and alignment occurs within 24 hours after the data has been taken. The obtained

values are then used for the bulk processing of the data, including the physics stream (namely the physics_Main) which is the main stream used during the assessment of the quality of the collected data. Data are then distributed to the regional (Tier-1) and local (Tier-2) centers for data analysis.

Data quality is a crucial point for physics analyses. The data quality process has been introduced with the aim of marking reconstructed data of every run as usable or not for performance and physics analyses in the ATLAS experiment. Because of the complexity of the detector and of the objects used in analyses, it is necessary to divide the data quality monitoring in sub-groups, each one dedicated to a main detector component or physics object:

- luminosity: assess the correct operation of the luminosity detectors and the related measured quantities;
- trigger: check the application of the correct trigger keys to each specific running condition;
- Pixel, SCT, TRT, LAr, Tile, Muon: assess each sub-detector status in terms of number of working detector components and overall performance of the sub-detector;
- Inner detector global: check the general performance of tracking and the status of the alignment of the tracking detectors;
- b -tagging: assure the quality of tracking and jet reconstruction with a focus on heavy flavour jets;
- Calorimetry combined: check the performance of high level objects (photon, electron, τ , jet, E_T^{miss}).

In particular, the goals of b -tagging offline monitoring are mainly three:

- give information, almost in real-time, about the status and the behaviour of the detector components involved in b -tagging (tracking, vertexing, calorimetry) and spot possible problems which can occur during detector operations;
- monitor the quality of the tracks and jets to ensure that the b -tagging performance is stable across physics runs;
- assess the quality of the recorded data to define whether or not it can be used for physics analysis.

The output of the monitoring application are ROOT histograms, grouped in folders according to level of details. The offline data quality process of ATLAS is based primarily on analysing histograms produced by monitoring tools. The most interesting data quality histograms are automatically presented in a dedicated web

page ¹, namely a Web display. In particular, the histograms used for the offline data quality monitoring of b -tagging are organized in sub-folders within the JetTagging folder:

- Quality control: these histograms are intended to be controlled run by run by non expert shifters; they give a global and complete view of the b -tagging status without too many details.
- Diagnostics: these histograms are related to the global b -tagging status going into details and monitoring high level quantities; they are included to be monitored in case of issues by the b -tagging data quality experts.
- JetInformation: detailed plots on jets, including two dimensional η vs ϕ maps of the step-by-step selection performed on jets, including two dimensional maps of jets after b -tagging application.
- TrackInformation: detailed plots on tracks, including impact parameter distributions and a sub-folder with details on the distribution of tracks failing quality selection cuts.

Figure 8.2 shows a Web display from a 2018 run: on the left, the links to folders in which b -tagging folders are expanded; on the right, the histograms from the Quality control folder which are mainly meant to be checked by human shifters, with the help of automatic checks performed by the he Data Quality Monitoring Framework tool (DQMF) [79].

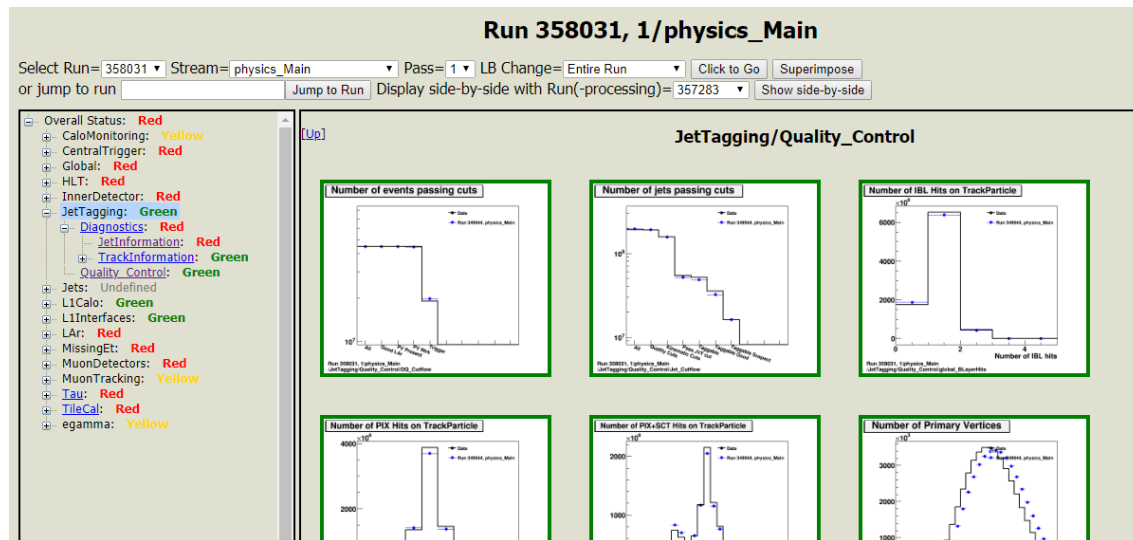


Figure 8.2: Example of plots to be monitored offline via the offline DQ framework. On the left, the ATLAS data quality folders hierarchy is visible, with b -tagging related folders expanded. On the right, the plots from the b -tagging Quality control folder are visible.

¹<https://atlasdqm.cern.ch/webdisplay/tier0/>

The Data Quality Monitoring Framework is a software tool developed to perform automated analysis on monitoring histograms and to encode results in colour flags (green/yellow/red) on the basis of specific algorithms: the evaluation of the mean or the RMS of a histogram, the Kolmogorov test², the counting of the number of bins with content above or below a predefined threshold, a comparison with a predefined histogram used as reference. The numerical result of these operations is compared with the thresholds which define the good (green), acceptable (yellow) and bad (red) intervals. The flags are presented as coloured frames surrounding the histograms in the Web display (see Figure 8.2). The comparison between the run to be monitored (358031, in black) and the reference run (349944, in blue) for the MV2c10 distribution of jets in the $20 \text{ GeV} < p_T < 50 \text{ GeV}$ range is visible in Figure 8.3: a green flag is assigned according to the check performed with a Kolmogorov test.

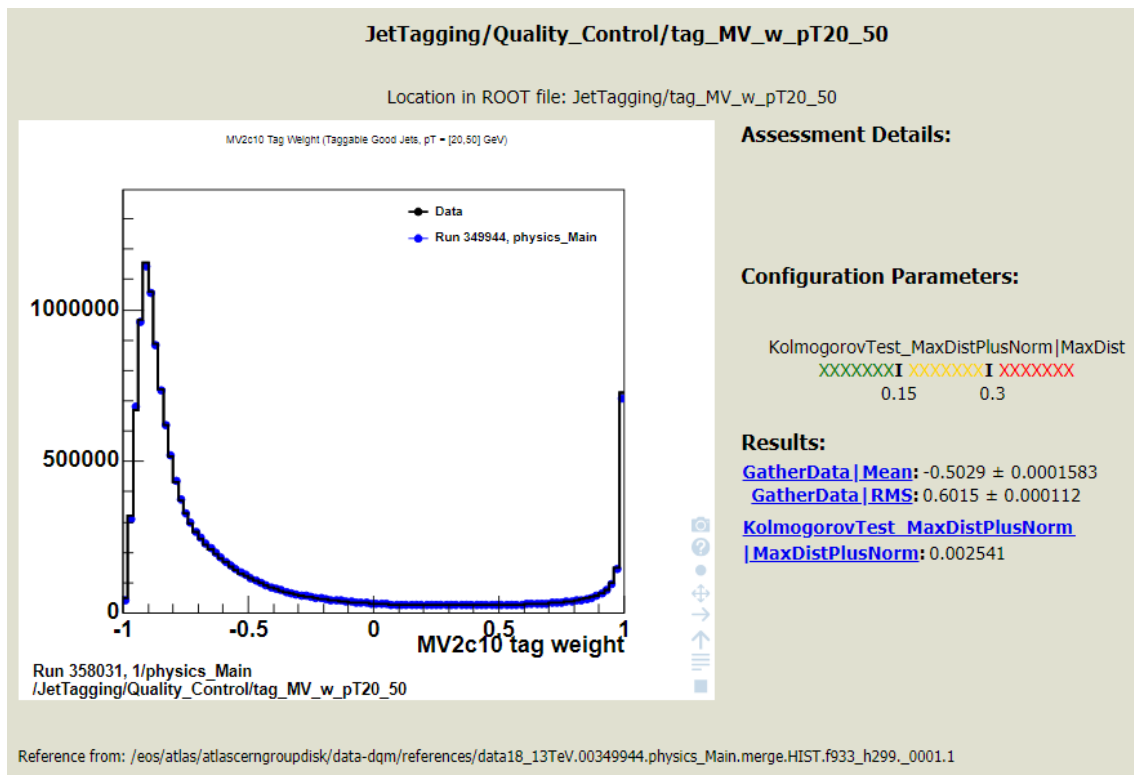


Figure 8.3: Example of comparison between a 2018 run and a reference run for the MV2c10 distribution of jets in the $20 \text{ GeV} < p_T < 50 \text{ GeV}$ range: a green flag is assigned according to the check performed with a Kolmogorov test.

The b -tagging performance is heavily based on the performance of track and jet reconstruction. Any issue related to tracking or calorimetry may in principle affect the jet distributions and the b -tagging performance in general. For the tracking, the goal is to compare track distributions (track parameters, kinematic distributions,

²The Kolmogorov-Smirnov test is a test of the equality of one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution.

multiplicity distributions, hit patterns in the tracking sub-detectors, etc.) with reference distributions from standard reference runs. In case significant discrepancies are found, the origin of the issue can sometimes be tracked down to an issue with one of the tracking sub-detectors. For the calorimetry, the goal is to check kinematic and b -tagging distributions of jets. Additionally, 2D maps distributions (η vs ϕ) of jets after each step of the jet selection, including before and after the application of the b -tagging selection, are monitored. Any discrepancy between the monitored run and the reference run is followed up with the experts. The classical example of defects arising from calorimetry are hotspots.

In case of visible defects in the recorded data (i.e. noisy channels, detector components with wrong configurations, missing data from part of detectors), each sub-group may declare a defect to a full run or a part of a run (in terms of LB range). After collecting the feedback from each of the sub-groups in terms of defects, the official Good Run List is defined and delivered to the ATLAS community for physics analyses. The possible defects to be assigned by the b -tagging sub-group are:

- BTAG_BEAMSPOT_SHIFT (*Tolerable: flag a shift in the beamspot position.*)
- BTAG_BLAYER_PROBLEM (*Tolerable: suspect area in the 2D maps or in other histograms due to a problem with IBL.*)
- BTAG_BLAYER_SERIOUS_PROBLEM (*Intolerable: a fraction or a whole run is affected by IBL issues, large areas of low efficiency in the 2D map.*)
- BTAG_BULK_UNCHECKED (*Tolerable: not yet validated.*)
- BTAG_JET_HOTSPOT (*Tolerable: calorimeter hotspot affecting the b -tagging performance.*)
- BTAG_JET_SEVHOTSPOT (*Intolerable: several or severe calorimeter hotspots affecting the b -tagging performance.*)
- BTAG_LOWSTAT (*Tolerable: statistics too low for reliable assessment.*)
- BTAG_NOJETS (*Tolerable: no jets passing requirements to be considered for b -tagging.*)
- BTAG_SCT_PROBLEM (*Tolerable: drop in the track selection efficiency due to e.g. an insufficient number of SCT hits, in a small region of the detector.*)
- BTAG_SCT_SERIOUS_PROBLEM (*Intolerable: drop in the track selection efficiency due to e.g. an insufficient number of SCT hits, in a large portion of the detector.*)
- BTAG_TAGGABILITY_FLUCTUATIONS (*Tolerable: low statistics cause the 2D maps to look chaotic.*)

- `BTAG_TRT_PROBLEM` (*Tolerable: problem related to the tracking requirements in the TRT which adversely impact b-tagging performance.*)
- `BTAG_TRT_SERIOUS_PROBLEM` (*Intolerable: problem related to the tracking requirements in the TRT which seriously impacts b-tagging performance.*)
- `BTAG_UNCHECKED` (*Intolerable: not yet checked.*)

8.2 Data quality software improvements

In this section, the updates performed to the b -tagging data quality software for the 2018 data taking as presented. They include improvements to the trigger pre-selection of the events (Section 8.2.1), the introduction of histograms to cope with the increase of the instantaneous luminosity (Section 8.2.2), the update of the tools to be compatible with the b -tagging algorithms of the release 21 (Section 8.2.4), the introduction of histograms to monitor jets with soft-muons from semi-leptonic b -hadron decays (Section 8.2.5) and the update of the tools to work with events from heavy ions collisions (Section 8.2.6).

8.2.1 Trigger pre-selection

The instantaneous luminosity has sensibly increased during 2017 data taking. Because of that, the number of pile-up collisions increased as well, raising the number of jets due to pile-up jets contamination. The monitoring histograms which included jet kinematic and b -tagging distributions, but also vertex and tracks variables, are found to be sensitive to the level of pile-up. Therefore the comparison between histograms of different runs (a run and a reference run) was biased due to different pile-up contributions.

In order to limitate this phenomenon, the b -tagging DQ framework was improved during 2017 data taking introducing an additional pre-selection step in the selection of the events used in the monitoring. The pre-selection consisted in requiring the events to pass few HLT chains of single lepton triggers (single muon and electron triggers), with the aim of monitoring events with a stable rate, less affected by pile-up jets contamination.

Between the start of 2018 data taking, the event pre-selection was improved introducing wild cards in the HLT trigger naming convention: in this way the pre-selection was not sensitive to the possible changes of trigger thresholds during the 2018 data taking.

The typical cut flow of the 2018 data event selection performed on events used for the b -tagging data quality monitoring is shown in Figure 8.4. The event selection includes: a veto selection on error flags related to Tile and LAr calorimeters, at least 1 primary vertex, at least 4 tracks associated to the primary vertex, the single lepton

trigger pre-selection. In particular, the wild-cards include all single lepton triggers with p_T threshold included from 20 to 99 GeV.

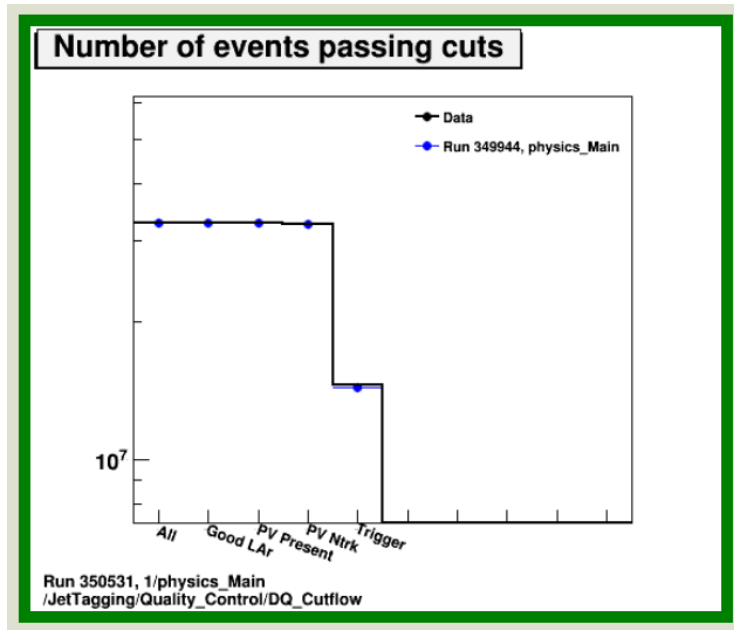


Figure 8.4: Cut flow of the event selection for the b -tagging data quality monitoring.

8.2.2 Pile-up dependency

The pile-up jet contamination is a well known issue in hadron collider physics, the ATLAS experiment has developed the JVT variable to discriminate between jets coming from the hard collision and pile-up jets (see Section 7.1). Within the ATLAS physics analyses, the jets are required to pass the JVT selection. Up to 2017, the b -tagging data quality tools were not including such a selection. The JVT selection has been introduced before the start of 2018 data taking, as an extra step in the selection of the jets used included in the monitoring histograms.

The typical cut flow of the jet selection performed on the events that previously passed the event selection is shown in Figure 8.5. The jet selection includes: basic quality cuts over jet related quantities (i.e. energy, timing, sampling), a kinematic threshold cut ($p_T > 15$ GeV, $|\eta| < 2.5$), the JVT selection (introduced in 2018), the jet quality based on tracks passing basic requirements (Good, Suspect or Bad).

The introduction of the JVT selection within the jet selection has sensibly reduced the pile-up, but a small effect was still visible for runs with different average pile-up distributions $\langle \mu \rangle$ (see Figure 8.6).

To further reduce the dependency of the b -tagging algorithm distributions from the pile-up contamination, three new histograms have been introduced in the 2018 monitoring tools, dividing the events according to the average pile-up value $\langle \mu \rangle$. The three histograms of the MV2c10 b -tagging algorithm distribution of jets for

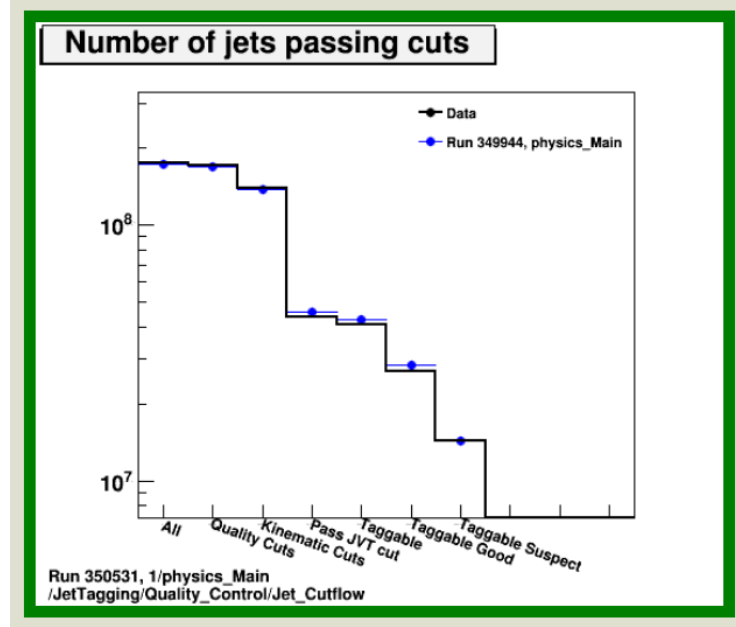


Figure 8.5: Cut flow of the event selection for the b -tagging data quality monitoring.

events classified according to the $\langle \mu \rangle$ value in the $[0, 30]$, $[30, 50]$ and $[50, 70]$ ranges are visible in Figure 8.7. The different shape of the MV2c10 distribution between events from different $\langle \mu \rangle$ ranges is visible in Figure 8.8.

8.2.3 $t\bar{t}$ events

During 2017, a dedicated event selection was introduced with the aim to select $t\bar{t}$ events, in order to monitor events with a high fraction of b -jets (at least two b -jets from the $t \rightarrow Wb$ decay). These events have a relatively high production cross section at 13 TeV. The number of events selected with the di-lepton channel (with the W bosons decaying into an electron and a muon with opposite sign) in a single run is enough to be used for monitoring purpose.

The simplified $t\bar{t}$ event selection used in the data quality monitoring requires two isolated leptons with opposite sign charge. In 2018, the selection was improved (fixing bugs and adapting the selection to the standard used in physics analyses). The improvements allowed to increase the number of $t\bar{t}$ events, with more than 5000 events per run, in standard running conditions. With such a statistics, it is possible to monitor the b -tagging performance on sufficient number of b -jets. The MV2c10 distribution of jets from the selected $t\bar{t}$ events is shown in Figure 8.9: a good fraction of b -jets is visible with the peak of jets in the region close to 1. In Figure 8.10 it is visible the p_T distribution of the jets from $t\bar{t}$ events: on the left the pre-tag distribution, on the right the distribution after the b -tagging selection (70% working point of MV2c10 algorithm).

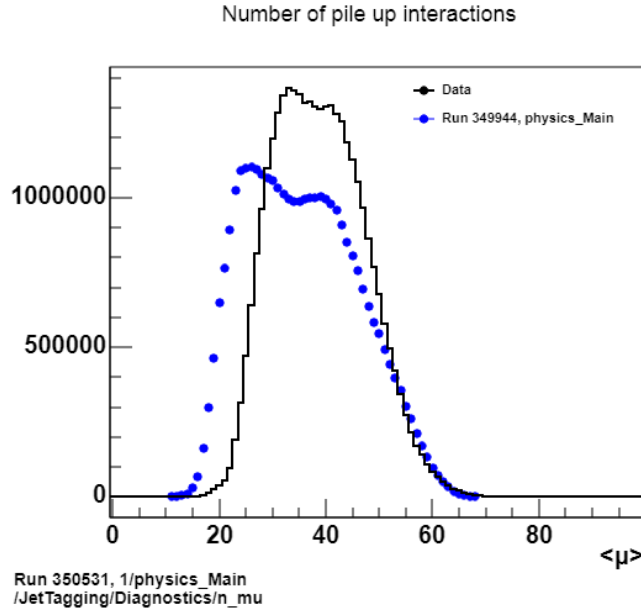


Figure 8.6: Different average pile-up distribution between a 2018 run (350531) and a reference run (349944).

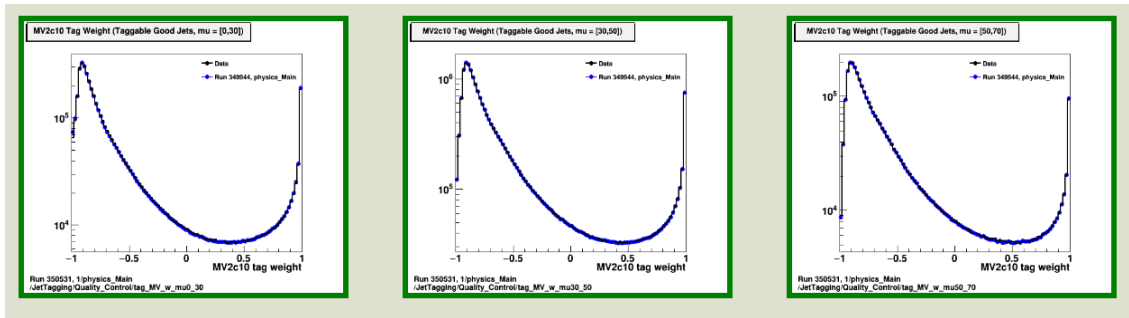


Figure 8.7: Three new monitoring histograms introduced in 2018: the events are classified according to the $\langle \mu \rangle$. From left to right: $[0, 30]$, $[30, 50]$ and $[50, 70]$ $\langle \mu \rangle$ ranges.

8.2.4 Release 21 algorithms

During 2017, a new ATLAS software release has been introduced (release 21) which includes 6 new b -tagging algorithms. The new physics analyses were asked to use data reconstruction performed with the new software release. The 2017 data monitoring was performed with the b -tagging algorithm from release 20 (MV2c10).

In general, the monitoring algorithms are called in the job options files with several parameters that can be easily changed, if necessary, without to change and re-compile the C++ algorithm code. The default value of each parameter is included in the C++ code, and it can eventually be over-written by the value included in the job options file.

Before the start of the 2018 data taking, the selection of the b -tagging algorithm to be used in the monitoring has been included in the job options file, in order to easily switch from one algorithm to another in case a different b -tagging algorithm

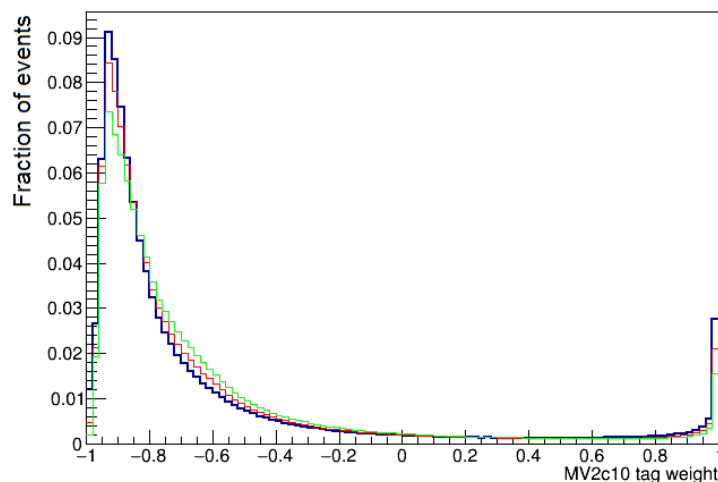


Figure 8.8: Comparison of the shape of the MV2c10 distribution for events classified according to $\langle \mu \rangle$ ranges: $[0, 30]$ $\langle \mu \rangle$ range in blue, $[30, 50]$ $\langle \mu \rangle$ range in red and $[50, 70]$ $\langle \mu \rangle$ range in green.

is recommended in 2018. The MV2c10 b -tagging algorithm from release 21 was used for the 2018 monitoring.

8.2.5 SMT jets

With the release 21, the MV2c10 and DL1 b -tagging algorithms are enhanced with the introduction of soft muon tagging (see Section 7.3.2). In order to monitor the stability of the new algorithm (in view of a possible change in the recommended algorithm), a dedicated selection has been introduced in 2018 to select jets with a soft muon from the semileptonic hadron decay. The selection is focused on the soft muon properties: a combined track (fitted from fragments from the Inner detector and the Muon spectrometer), $p_T > 5$ GeV, $|\eta| < 2.5$, $d_0 < 4$ mm. Only one soft muon is allowed with an angular separation with respect to the jet axis of $\Delta R < 0.4$. The number of soft muons per jet is shown in Figure 8.11, on the left: the number of jets with one soft muon associated is stable, around 7%. The MV2c10 distribution of the soft muon tagged jets is shown in Figure 8.11, on the right: the b -jet component of this sample is much higher than the one available in $t\bar{t}$ events (see Figure 8.9).

8.2.6 Heavy ion collisions

The Large Hadron Collider is designed to accelerate both protons and ions. Together with the standard proton-proton collisions, the LHC has delivered in these years also ion-ion collisions as well as proton-ion collisions. The ATLAS experiment is a general purpose experiment mainly focused on proton-proton collisions, but it is able to collect data from ion-ion collisions too. There is an ATLAS group dedicated to the analysis of heavy ion collision data. Among the main results of the ATLAS

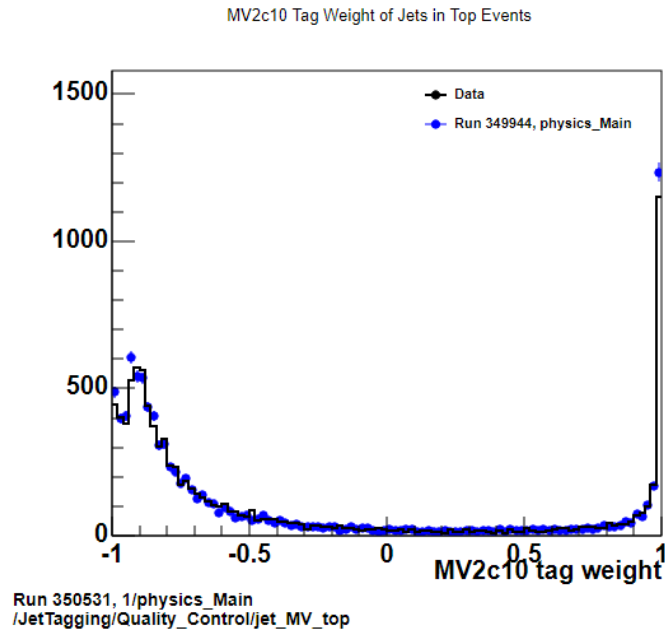


Figure 8.9: MV2c10 distribution of jets from the selected $t\bar{t}$ events: a good fraction of b -jets is visible with the peak of jets in the region close to 1.

experiment in the heavy ion physics field, there is the evidence for light-by-light scattering in heavy ion collisions [80]. The ion-ion collision events are much more complex (in terms of objects) with respect to the events from standard proton-proton collisions. The track multiplicity of Xe-Xe collision jets compared to the proton-proton collision jets is shown in Figure 8.12, on the left: the track multiplicity peaks at 10 for the standard collisions while the average track multiplicity of a Xe-Xe collision is around 25. The level of complexity in the reconstruction of a jet in such an environment is nevertheless minor compared to the complexity of finding a secondary vertex from the b -hadron decay within a b -jet.

In ATLAS there are dedicated jets collection for the jets reconstructed within heavy ion collisions. The b -tagging has never been attempted on jets from heavy ion collision events. During 2018, for the first time, the b -tagging algorithms are introduced in the Athena framework for the heavy ion jet collections; b -jet trigger keys are prepared as well. The b -tagging data quality tools has never monitored before the quality of heavy ion collisions, because of the lack of b -tagging algorithms. I have updated the data quality tools in order to allow the monitoring of the heavy ion jet collections. Preliminary tests have been performed reprocessing events from the 2017 Xe-Xe collisions with the Athena software release 21.0.83, which is the first release to include the b -tagging algorithms for heavy ion jet collisions. A comparison of the MV2c10 distribution between the Xe-Xe run and a 2018 proton proton collision is shown in Figure 8.12, on the right. As expected, the shape of the distributions is different: due to the complexity of the tracking in heavy ion collision environment, the peak of b -jets (close to 1) is not visible in the heavy ion collision jets.

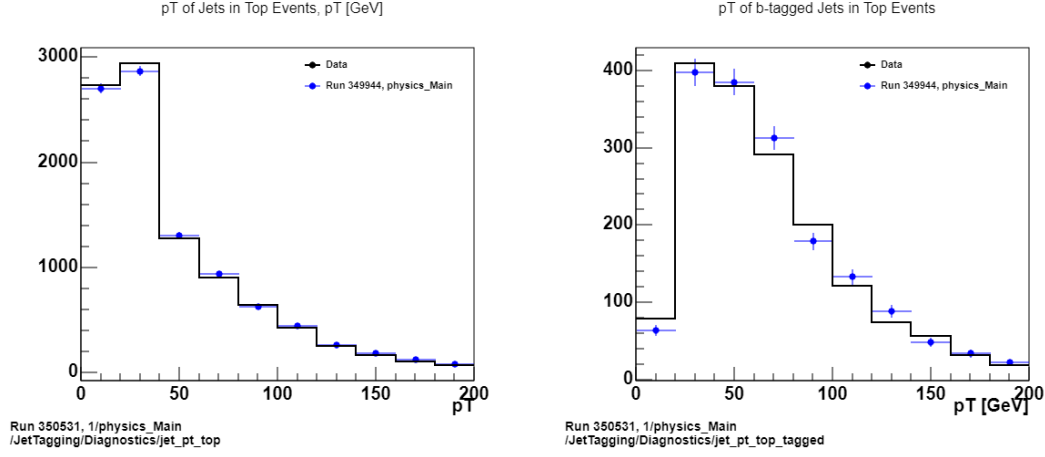


Figure 8.10: p_T distribution of the jets from $t\bar{t}$ events: on the left the pre-tag distribution, on the right the distribution after the b -tagging selection (70% working point of MV2c10 algorithm).

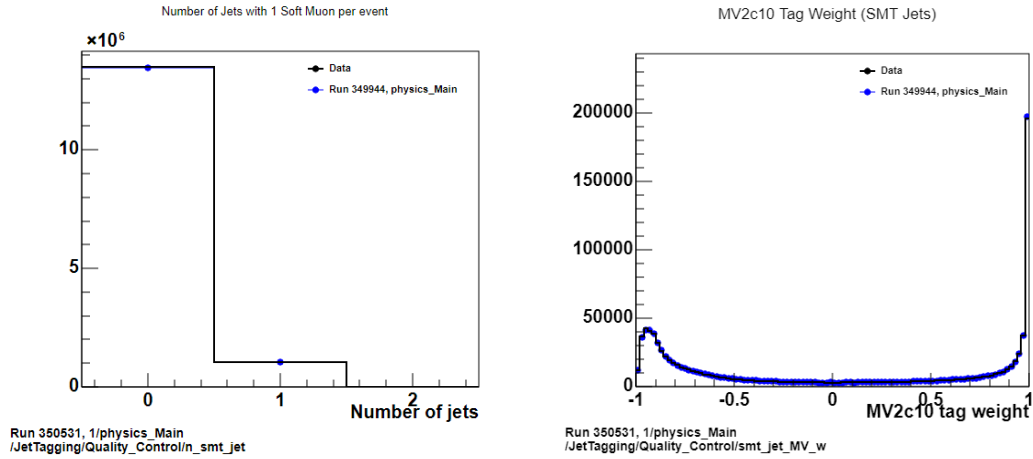


Figure 8.11: Histograms related to soft muon tagged jets, introduced in the 2018 monitoring: on the left, the multiplicity of soft muons per jet; on the right, the MV2c10 distribution of the soft muon tagged jets.

8.3 Data taking performance

The offline b -tagging data quality monitoring is performed by non expert shifters. The 2018 monitoring was performed by shifters from 17 different institutes, organized in weekly shifts for a total of 33 weeks, from 9 April to 6 December (including the heavy ion collision period). During the year, several issues were spotted and flagged according to severity. The MV2c10 b -tagging algorithm (from release 21) has been monitored for the whole 2018 proton-proton collisions period, with a rather stable performance despite the high instantaneous luminosity.

A drop of performance was instead clearly visible during run 364485, a special run taken after the end of the proton-proton collision period. During this run, the number of interactions per bunch crossing was exceptionally raised: up to 110 inter-

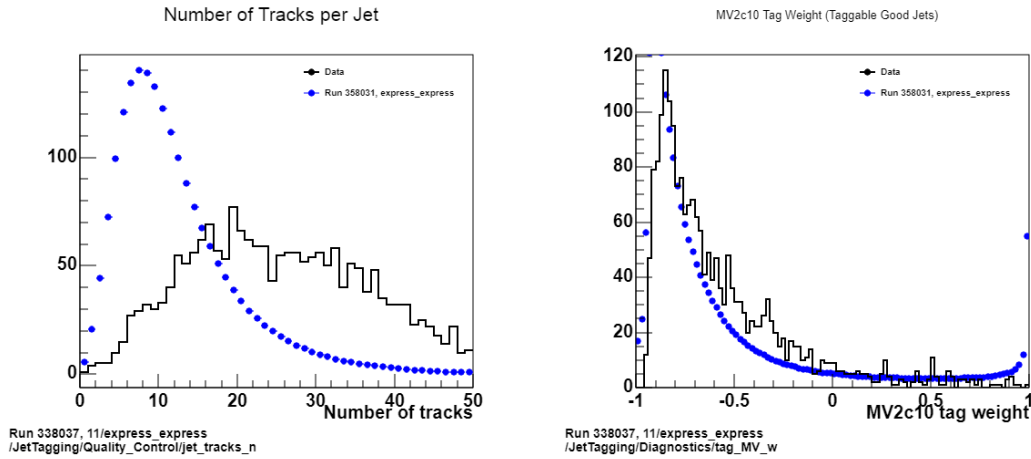


Figure 8.12: Track multiplicity (left) and MV2c10 distributionn (right) of jets from 1000 events from the 2017 Xe-Xe collisions (black) compared to a 2018 proton proton collisions (blue).

actions in the ATLAS detector, much higher than the average number of interactions during standard runs (see Figure 8.13). The data from this special run will not be used for data analyses, but are useful to check the performance of the detector at very high pile-up (in view of the High-Luminosity LHC).

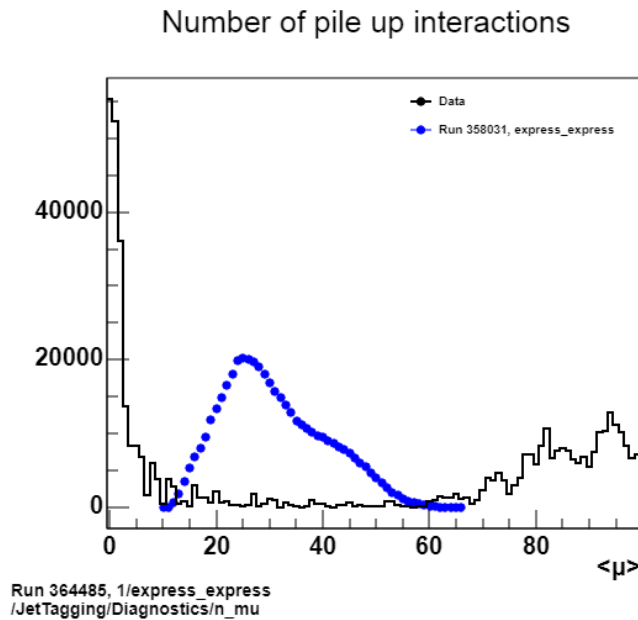


Figure 8.13: Average number of interaction per bunch crossing for the run 364485 (black) compared to a standard 2018 run (blue).

Such a high number of interactions resulted in a high number of tracks and jets. A high number of pile-up jets (jets coming from close-by collisions) is expected in these conditions: this environment has an impact on the b -tagging performance, which is based on track reconstruction and on secondary vertex finding. For jets

with low transverse momentum ($p_T < 50$ GeV) the drop of performance is visible in Figure 8.14 (left): the shape of the MV2c10 distribution is clearly different between the run 364485 (black) and a standard 2018 run (blue). A lower number of b -jets (jets close to -1 score) is identified in high pile-up conditions compared to the nominal 2018 pile-up conditions. The performance is less degraded for medium p_T jets ($50 \text{ GeV} < p_T < 100$ GeV, Figure 8.14, center) and looks to be stable for high p_T jets ($p_T > 100$ GeV, Figure 8.14, right).

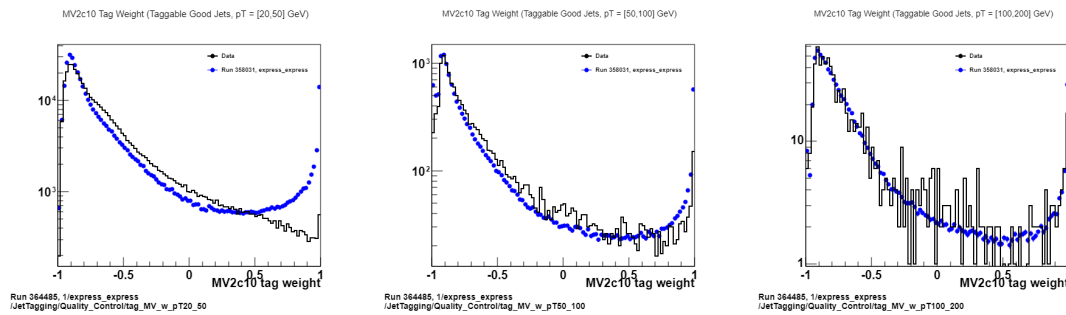


Figure 8.14: Comparison of the MV2c10 distribution of jets collected during the run 364485 (black) and a standard 2018 run (blue): a drop of the performance is visible for the low p_T jets (left); the performance is less degraded for medium p_T jets (center) and looks to be stable for high p_T jets (right).

Besides the performance, several issues may happen. Two main categories of issues may be identified: faulty detector parts during operations and defects from the ageing of the detector components. One example for each of the two categories is presented below: the example of SCT in standby (Section 8.3.1) and the defect due to the disabling of two Tile modules (Section 8.3.2).

8.3.1 Data taking faults

During data taking, complex procedures are performed on the detector in different moments, especially between the end of a run and the start of the following run (check up of the full detector, switch off and on of the high voltages of tracking detectors, set up of different settings for detector calibration between two runs). It is possible that during these operations a component of a sub-detector is disabled or an entire sub-detector is not ready to take data.

During run 348895, three effects were observed in different monitored histograms:

- primary vertex multiplicity: peak of events with low number of vertices;
- track multiplicity of the primary vertices: peak of vertices with few tracks;
- track multiplicity of selected jets: peak of jets with low track multiplicity.

The three observations were clearly connected together: they all pointed to a fault in the tracking detectors. Within the data quality software, there are dedicated

python scripts which are able to find the LB interested by a particular feature in the histogram. The “hotspot” finding script was run on the data of the run 348895, looking for the LB with track multiplicity between 0 and 120 (Figure 8.15, left). It was found that the events with low track multiplicity occurred only in few LB (Figure 8.15, right). These LB were registered right after the declaration of “Stable beam” operations from the ATLAS detector.

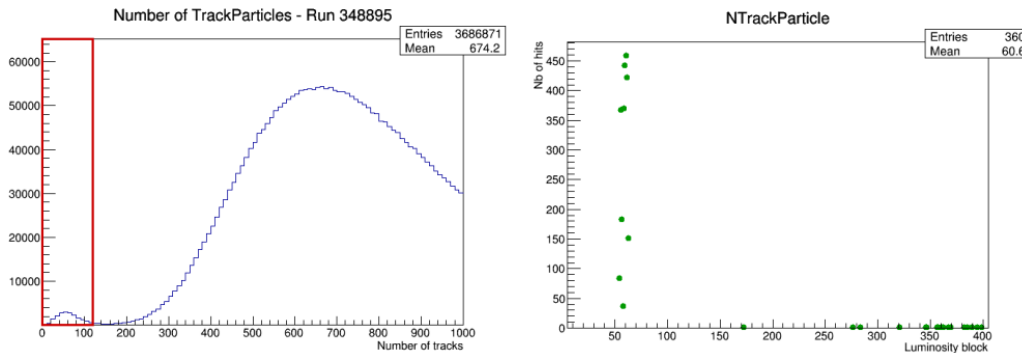


Figure 8.15: Example of a fault during data taking. Left: track multiplicity of the selected jets, the contribution from events with a low number of tracks is highlighted in red on the left side of the histogram. Right: LB from 54 to 62 are interested by events with a number of tracks between 0 and 120.

A closer look into the log entries written by the Control Room shifters helped to understand the problem. The “Stable beams” operations were declared at 03:46, but the High Voltage for the SCT detector was not yet raised to the operational value. For about 13 minutes, the ATLAS detector was taking data without the contribution of the SCT detector: the tracking was heavily affected and therefore a lower number of tracks was reconstructed. The LB interested by this fault are now excluded from the GRL.

From the *e*-log of the ATLAS Control Room:

- [03:46] STABLE BEAMS. Pixel ramped up automatically, but SCT did not.
- [03:59] SCT is now READY.

8.3.2 Detector ageing

The ATLAS detector construction was completed in 2008, with first collisions in 2009. Minor upgrades have been performed during the first Long Shutdown (2013-2014). During 2018, after many years of operations, some components of the ATLAS detector were not working properly due to the ageing of the material. As an example, the cooling loop which serves eight modules of the Tile calorimeter developed an air leak during run 350310. As a consequence, the temperature of some of the Tile modules was raising. Therefore, the Tile tower LBA29 was disabled during run

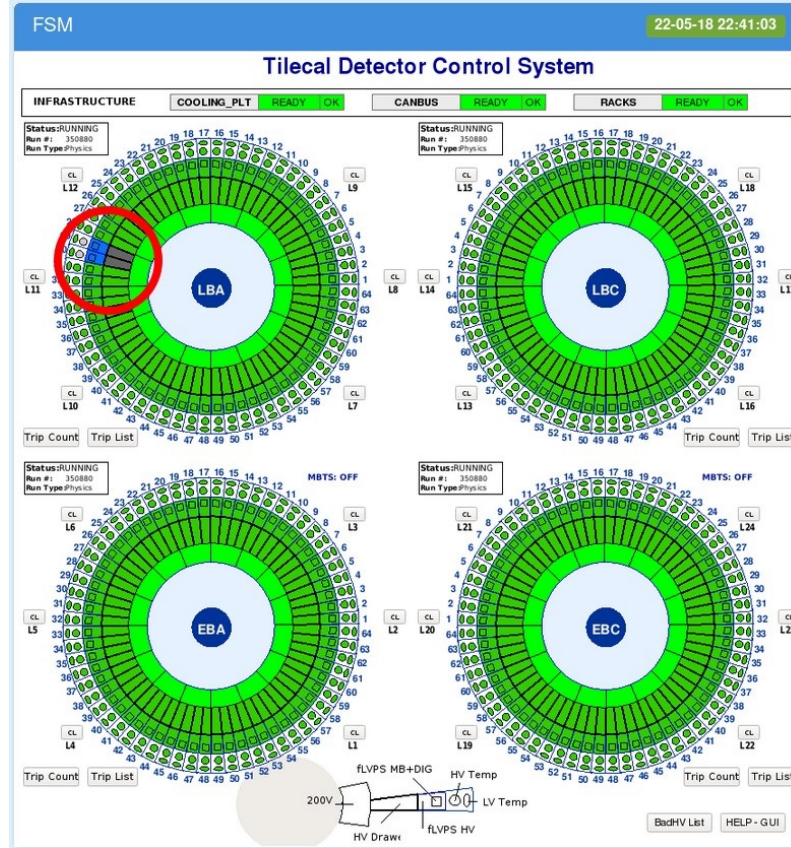


Figure 8.16: Map of the modules of the ATLAS Tile calorimeter: top row, barrel sections (A and C side); bottom row, endcap sections (A and C side). The disabled modules (LBA29 and LBA30) are highlighted in red.

350310. Then the temperature increased further, two modules were disabled (LBA29 and LBA30, see Figure 8.16) from run 350361 over.

The disabling of two modules of the Tile calorimeter in the barrel section introduced a defect in the reconstruction of many physics objects (loss of jets and τ leptons, excess of electrons and photons). The loss of jet and tau candidates is shown in Figure 8.17 for run 350531.

The defect was visible as well in the reconstruction of b -jets. In Figure 8.18 a loss of b -jets is visible in the 2D map (η vs ϕ) of jets tagged by the 70% working point of the MV2c10 algorithm (run 350531). A cold spot (a region with a low number of b -tagged jets) is visible in the region delimited by the η range between 0 and 1 at ϕ around 2.9. This defect was considered a tolerable defect: besides there is a significative loss of performance in the central part of the Tile calorimeter, it was not possible to exclude so many runs from the GRL. The cooling loops of the Tile detector are not easily accessible, therefore the defect persisted for several months until the end of 2018 data taking. The air leak will be possibly repaired during the second Long Shutdown (2019-2020).

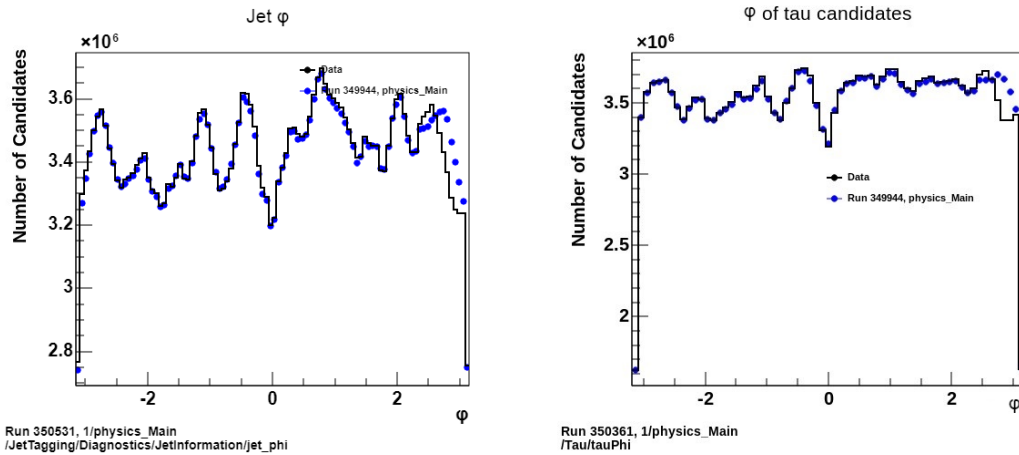


Figure 8.17: Run 350531: distribution of jet candidates (left) and τ candidates (right) as a function of ϕ : a sizable loss of reconstructed objects is visible at ϕ around 2.9.

8.4 Summary and outlook

During 2018, ATLAS has collected a record amount of data from proton-proton collisions with a record 97.5 % efficiency. After the assessment of data quality, these data are now distributed to the collaboration through the 2018 Good Run List, including 59.9 fb^{-1} of proton-proton collision data. A separate GRL has been produced for the heavy ion collision data: it includes $1423.9 \mu\text{b}^{-1}$ of Pb-Pb collisions. The amount reaches $1700.5 \mu\text{b}^{-1}$ if the data taken with the toroid off are included (the toroid accidentally switched off during the last runs of the 2018 Pb-Pb campaign). Moreover, GRL are being issued for special runs: ALFA runs (which includes the ATLAS forward detectors) and low instantaneous luminosity runs (low pile-up data, with the goal of performing vector boson measurements in a cleaner environment).

The experience I had as a shifter at the Inner detector desk during 2018 data taking (see Chapter 6) has proven to be very useful for me in my role as b -tagging data quality expert. I had direct experience with ATLAS detector operations and shifter e -logs and this helped me in the identification of the SCT issue, since I have been an Inner detector desk shifter. Moreover, I was in the ATLAS Control Room during run 350531, when the Tile modules were switched off. I had a clear view of what was happening to the ATLAS detector, in order to judge the severity of the defect propagated to physics objects.

The ATLAS data quality activities are going to be documented in an overview paper, with the aim to describe the improvements with respect to Run 1 and the success achieved in Run 2. As responsible of b -tagging data quality, I am contributing to this effort, documenting the procedures (organization of the sub-group, monitored quantities, assigned defects) and the improvements achieved in Run 2. The document will be a useful guide for a smooth start of data quality activities in Run 3, when the ATLAS detector will be awakened again and the collaboration will

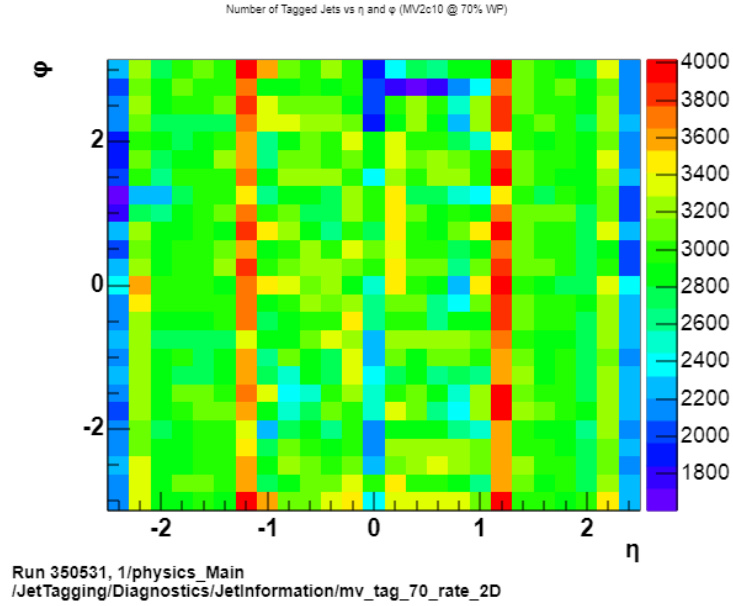


Figure 8.18: Run 350531: 2D map (η vs ϕ) of jets tagged by the 70% working point of the MV2c10 algorithm. A cold spot is visible in the region delimited by the η range between 0 and 1 at ϕ around 2.9.

resume the data taking activities.

In these years, a new ATLAS software version to be used for Run 3 activities is in preparation: release 22. The new Athena release, will be Multi-Threaded: AthenaMT will focus on enabling parallelism by using threads within a single process. The entire Athena code is going to be rearranged to allow the execution of each piece of code simultaneously by more than one thread. This will enable very important improvements in the overall memory footprint of jobs. As a responsible, I will contribute to the migration of the b -tagging data quality software from release 21 to 22: this requires a complete rewriting of the code since the work flow of the monitoring will change. It will be an opportunity to clean up the code, include improvements and remove dismissed features.

Chapter 9

Calibration of the b -tagging efficiency

Any physics measurement adopts several reconstruction tools (e.g. for trigger selection or particle identification), whose behavior is well known from studies on simulated data. But this needs to be compared to what is seen in real data, to take into account possible differences and to validate the reliability of each tool. This process is usually called calibration and the uncertainty of its results is the best way to quantify how well we control each tool. This applies to each algorithm used in any analysis, b -tagging included.

In order to use the b -tagging in physics analyses, it is necessary to measure, on data collected by the detector, the efficiency of the tagger algorithms to correctly identify as a b -jet a jet originated from a b quark (ϵ_b : b -efficiency) or to mistakenly tag a jet originated from a charm quark (ϵ_c : c -efficiency) or from a light quark or a gluon (ϵ_l : l -efficiency or mistag rate). The efficiency is measured for each of the b -tagging working points with different methods, both on data and on Monte Carlo simulation samples, then the results are presented as data-to-simulation Scale Factors (SF) defined as the ratio of the efficiency in data to that in simulation.

The samples used to perform each efficiency measurement must be characterized by a strong predominance of jets having the flavour for which we want to perform the calibration: the first step of each calibration analysis is to select an almost pure sample of the required flavour, estimating the flavour composition in data.

In particular, in ATLAS the c -jet tagging efficiency has been measured on a sample of c -jets associated to D^* charged mesons [81, 82] (see Section 9.1.1) as well as on an sample of c -jets from $W+c$ events [83] (see Section 9.1.2) and on a sample of c -jets from top pair events [84] (see Section 9.1.3).

In this Chapter a detailed description of the D^* , $W+c$ and $t\bar{t}$ methods for the c -jet tagging efficiency determination is reported, while in Chapter 10 the results of the measurement I performed with the $W+c$ method on Run 2 b -tagging algorithms are presented.

9.1 *c*-jet tagging efficiency measurement

The charm tagging efficiency (i.e. the efficiency to mistakenly tag a jet originated from a charm quark as a *b*-jet) was measured with two different techniques in Run 1: using a sample of *c*-jets containing D^{*+} mesons (from now on, referred to as the D^* method) [81,82] and using a sample of *c*-jets produced in association with a *W* boson (referred to as the $W+c$ method) [83].

The D^* method uses a sample of *c*-jets containing D^{*+} mesons, reconstructed within a jet in the $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ final state (see Figure 9.1). Since the *c*-jet sample is strictly exclusive (contains only *c*-jets with a D^{*+} meson decaying in a specific channel), the *c*-jet efficiency measurement must be extrapolated to an inclusive sample, taking into account both the fragmentation fractions and the branching ratios of the various charm hadron species present in a generic *c*-jet.

The $W+c$ method uses a sample of *c*-jets produced in association with a *W* boson, with the *W* boson decaying into an electron and a neutrino, and the *c*-jet identified via a soft muon stemming from a semileptonic *c*-hadron decay. Exploiting the charge correlation of the two leptons (electron and muon) it is possible to extract an almost pure *c*-jet sample. As seen for the D^* method, also the $W+c$ method requires an extrapolation correction of the *c*-efficiency to an inclusive *c*-jet sample.

Due to the extrapolation procedure, the systematic uncertainty of the results increases: the D^* method uncertainties vary depending on the p_T bin, from 10% to 40% in the 7 TeV calibration and from 8% to 15% in the 8 TeV calibration, while the $W+c$ method uncertainties for the 7 TeV calibration are between 5% and 13%.

A third method to measure the *c*-jet tagging efficiency has been developed in Run 2: the $t\bar{t}$ method, using a sample of top pair events, both quarks decaying into Wb channel, with one *W* boson decaying to lepton and neutrino and the other *W* boson decaying hadronically. In this hadronic decay the interesting channel is $W \rightarrow sc$, containing a *c*-jet. Once the events are selected according to this topology, i.e. two *b*-jets and two *W* bosons, one decaying leptonically and the other decaying hadronically, among the jets produced in the hadronic *W* decay, approximately one jet out of four will be a charm jet. The $t\bar{t}$ method does not bias the *c*-jet selection, resulting in a completely inclusive sample of *c*-jets with the advantage of not requiring any extrapolation of the result, eliminating this source of systematic uncertainty.

9.1.1 D^* method

The *c*-jet tagging efficiency measurement with the D^* method was performed almost with the same procedure on 4.6 fb^{-1} of 7 TeV proton-proton collision data recorded by ATLAS during 2011 [81] and on 20.3 fb^{-1} of 8 TeV data recorded in 2012 [82]. The D^* method was the first method to be developed to measure the *c*-jet efficiency and was the reference method during Run 1. The D^* method was employed as

well during Run 2, along with the other methods, for a first estimation of the *c*-jet tagging efficiency. During my master degree thesis, I performed optimization studies of the D^* method fitting procedures.

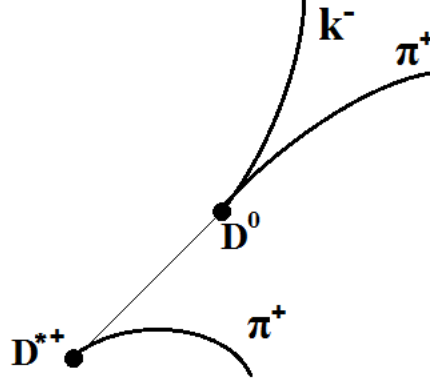


Figure 9.1: D^{*+} decay : $D^{*+} \rightarrow D^0 \pi^+$, with $D^0 \rightarrow K^- \pi^+$

To perform a charm efficiency calibration, the optimal solution would be to have access to a pure sample of *c*-jets: the D^* method uses events with a D^{*+} meson within a jet (implicitly including also the charge-conjugate D^{*-}). In this case, the jet sample selected is mostly made up by *c*-jets, with some contamination of *b*-jets with $b \rightarrow c$ decays, and a modest combinatorial background that can be subtracted by studying the signal sidebands. The contamination from D^* mesons that result from *b*-hadron decays is measured with a fit to the D^0 pseudo-proper time distribution.

After estimating the beauty contamination, the *c*-jet tagging efficiency is measured comparing the yield of D^* mesons before and after applying the *b*-tagging requirement.

The data samples are collected using a logical “OR” of single jet triggers, allowing to populate the entire jet p_T range used in the calibration ($20 \text{ GeV} < p_T < 140 \text{ GeV}$ and $20 \text{ GeV} < p_T < 300 \text{ GeV}$, for the 7 and 8 TeV measurements, respectively). The Monte Carlo samples are generated with PYTHIA6 [85] (7 TeV) or with PYTHIA8 [42] (8 TeV), then re-weighted in terms of jet p_T and average number of interactions to match the data sample.

Event selection

To reconstruct the D^{*+} decay chain ($D^{*+} \rightarrow D^0 \pi^+$, with $D^0 \rightarrow K^- \pi^+$), pairs of opposite sign charged tracks are selected, assigning them kaon and pion mass hypotheses, in order to reconstruct the D^0 decay. These D^0 candidates are then combined with charged particle tracks with opposite sign to that of the kaon candidate, assigning the pion mass to them. The so reconstructed D^{*+} decay chain is then associated with a reconstructed jet requiring its direction to be within $\Delta R = 0.3$ of the jet direction.

Some kinematic conditions are required to select good candidates and reduce the combinatorial background:

- all tracks must have at least 5 hits in the silicon tracking detectors (Pixel and SCT), at least one of them in the Pixel detector;
- the transverse momenta of the kaon and pion candidates from the D^0 decay candidate have to fulfill $p_T > 1 \text{ GeV}$;
- the reconstructed D^0 candidate mass must have $m_{K^-\pi^+} - m_{D^0} < 40 \text{ MeV}$, where m_{D^0} is the world average D^0 mass ($1864.83 \pm 0.14 \text{ MeV}$ [86]);
- the transverse momentum of the D^{*+} candidate has to exceed 4.5 GeV ;
- the momentum of the D^{*+} candidate projected along the jet direction has to exceed 30% of the jet energy (50% in the 8 TeV calibration).

The kinematics of the decay cause the D^{*+} to release only a small fraction of energy to the prompt pion, usually called “slow pion”; for this reason the D^{*+} signal is commonly studied as a function of the mass difference Δm between the D^{*+} and D^0 candidates. D^{*+} mesons are expected to form a peak in the Δm distribution around 145.4 MeV (i.e. the difference between D^{*+} and D^0 mass), while the combinatorial background forms a rising distribution, starting at the pion mass (139.57 MeV [86]). The distributions of the mass difference Δm is divided in four p_T bins: $[20, 30] \text{ GeV}$, $[30, 60] \text{ GeV}$, $[60, 90] \text{ GeV}$, $[90, 140] \text{ GeV}$ (7 TeV calibration) or $[20, 30] \text{ GeV}$, $[30, 60] \text{ GeV}$, $[60, 140] \text{ GeV}$, $[140, 300] \text{ GeV}$ (8 TeV calibration).

Mass fit

In order to determine the yield of the D^{*+} mesons, the mass difference distribution is fitted with a signal part S and a background part B . The signal is described with a modified Gaussian, giving a better description of the signal tails with respect to a simple Gaussian:

$$S = \exp[-0.5 \cdot x^{(1+\frac{1}{1+0.5x})}] \quad (9.1)$$

where $x = |(\Delta m - \Delta m_0)/\sigma|$. Δm_0 and σ are free parameters in the fit and they represent the mean and the width of the Δm peak.

The combinatorial background is fitted with a power function multiplied by an exponential function, with α and β free parameters:

$$B = (\Delta m - m_\pi)^\alpha \cdot e^{-\beta(\Delta m - m_\pi)} \quad (9.2)$$

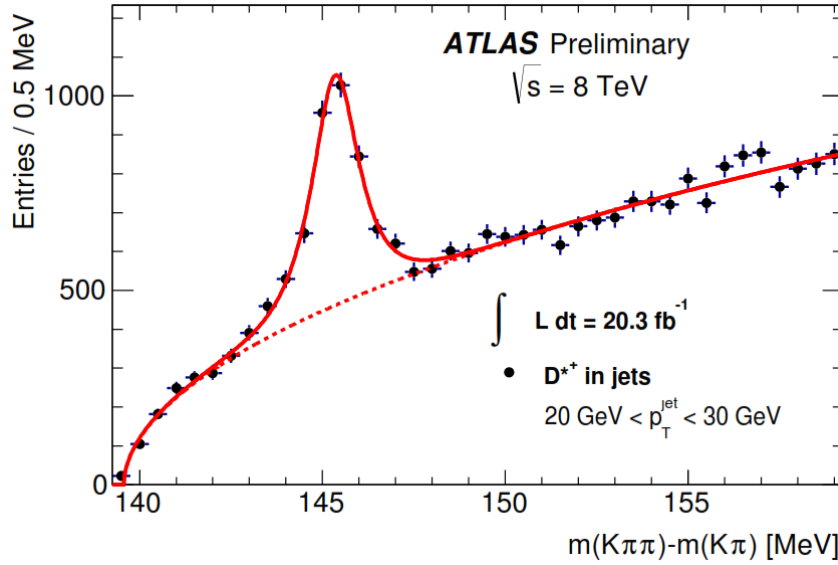


Figure 9.2: Plot of the mass difference distribution Δm of the D^{*+} candidates associated with $20 \text{ GeV} < p_T < 30 \text{ GeV}$: the solid curve shows the total fit to the distribution, the dashed curve shows only the background contribution (8 TeV calibration) [82].

Background subtraction

Signal and background regions are defined as the region within 3σ around the D^{*+} mass peak and the region between 150 MeV and 168 MeV, respectively. This choice of the intervals aims at including almost all the signal events in the signal region and ensuring a negligible fraction of signal events in the background region.

The background fraction $f_B/(f_B + f_S)$ is computed by integrating both the signal S and background B functions in the Signal region (3σ around the Δm peak).

For the variable of interest, the D^0 pseudo-proper time, the distribution of events from the background region, normalised to the fitted background fraction in the signal region, is subtracted from the corresponding distribution in the signal region. The procedure relies on the assumption (verified on MC samples) that the distribution of the variable of interest is the same for the combinatorial background under the peak and in the sideband.

Flavour composition

As pointed out before, the D^{*+} candidates can come directly from original c -jets, but also from c -jets originated in the $b \rightarrow c$ decay in b -jets. The measurement of the flavour composition for the selected D^{*+} sample is of fundamental importance in order to obtain a c -jets pure sample for the c -jet tagging efficiency measurement. The discriminating variable used to identify beauty and charm components is the D^0 pseudo-proper time defined as:

$$t(D^0) = \text{sign}(\mathbf{L}_{xy} \cdot \mathbf{p}_T(D^0)) \cdot m_{D^0} \cdot \frac{L_{xy}(D^0)}{p_T(D^0)} \quad (9.3)$$

where m_{D^0} is the D^0 mass, $p_T(D^0)$ is the transverse momentum of the reconstructed D^0 candidate, $L_{xy}(D^0)$ is the distance in the transverse plane between the D^0 decay vertex and the primary vertex of the event.

Firstly, the charm and beauty D^0 pseudo-proper time distributions, referred as $F_c(t)$ and $F_b(t)$, are extracted from simulated samples originated from charm and beauty quarks respectively. The functional form of $F_c(t)$ and $F_b(t)$ is fixed over the simulated distributions, then their sum is built as follows:

$$F(t) = f_b \cdot F_b(t) + (1 - f_b) \cdot F_c(t) \quad (9.4)$$

where f_b is the beauty fraction of the signal, used subsequently to evaluate the c -jet tagging efficiencies. A binned likelihood fit is performed on the D^0 candidates pseudo-proper time distribution in order to extract the beauty fraction: f_b is a free parameter, while $F(t)$ is normalized to the integral of the fitted histogram. The fit is performed with the variable $ct(D^0)$ in the range $[-1, 2]$ mm after the background subtraction: c is the speed of light in vacuum and $t(D^0)$ is the D^0 pseudo-proper time.

The fit to background-subtracted data, in the jet p_T bin $[30, 60]$ GeV is shown in Figure 9.3 and the results in the four bins of jet p_T are summarised in Table 9.1 for the 7 and 8 TeV calibrations.

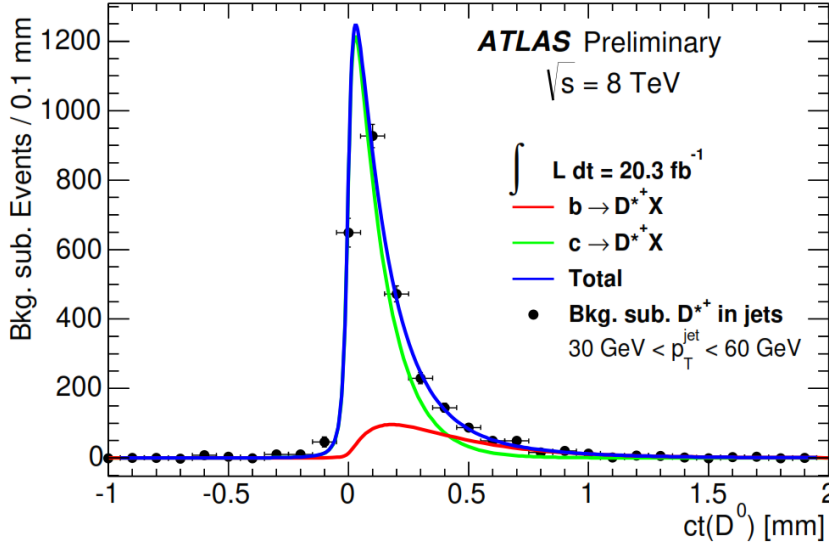


Figure 9.3: Fitted D^0 pseudo-proper time distributions to background-subtracted D^{*+} data samples in the jet p_T bin $[30, 60]$ GeV of 8 TeV calibration. The solid lines show the complete fit (blue), the beauty component (red) and the charm component (green).

p_T bin [GeV]	f_b (7 TeV)		p_T bin [GeV]	f_b (8 TeV)
20 - 30	0.212 ± 0.010		20 - 30	0.193 ± 0.017
30 - 60	0.315 ± 0.010		30 - 60	0.197 ± 0.014
60 - 90	0.303 ± 0.015		60 - 140	0.157 ± 0.014
90 - 140	0.315 ± 0.017		140 - 300	0.171 ± 0.023

Table 9.1: Beauty fractions determined by D^0 pseudo-proper time fits to the data in four jet p_T bins for 7 TeV and 8 TeV calibrations.

Tagging efficiency measurement

To measure the c -jet tagging efficiency over the selected sample, a combined fit to the Δm distribution of D^{*+} mesons in jets is performed before and after applying the b -tagging requirement, introducing an extra parameter $\epsilon_{D^{*+}}$ to describe the D^{*+} tagging efficiency.

This inclusive efficiency $\epsilon_{D^{*+}}$ is then decomposed into the efficiency for b and c -jets containing D^{*+} :

$$\epsilon_{D^{*+}} = f_b \epsilon_b(D^{*+}) + (1 - f_b) \epsilon_c(D^{*+}) \quad (9.5)$$

where f_b is the fraction of D^{*+} from beauty determined by the D^0 pseudo-proper time fit before applying the tagging requirement. The efficiency to tag a b -jet, ϵ_b , is taken from simulation and corrected by the data-to-simulation scale factors obtained from the b -jet efficiency calibration analysis.

The c -jet tagging efficiency determined with a D^{*+} sample is obtained solving the Equation 9.5 with respect to ϵ_c :

$$\epsilon_c = \frac{\epsilon_{D^{*+}} - f_b \epsilon_b}{1 - f_b} \quad (9.6)$$

Extrapolation to inclusive c -jet sample

The obtained result needs to be extrapolated to a inclusive c -jet sample. The efficiency extrapolation factors for data and simulation X are defined as follows:

$$\epsilon_c^{data} = X^{data} \cdot \epsilon_c^{data}(D^{*+}) \quad (9.7)$$

$$\epsilon_c^{sim} = X^{sim} \cdot \epsilon_c^{sim}(D^{*+}) \quad (9.8)$$

where $\epsilon_c(D^{*+})$ is the c -jet tagging efficiency measured over a D^{*+} sample and ϵ_c is the c -jet tagging efficiency on an inclusive sample of c -jets. The inclusive scale factor $SF_c^{data/sim}$ is given by:

$$SF_c^{data/sim} = \frac{\epsilon_c^{data}}{\epsilon_c^{sim}} = \frac{X^{data}}{X^{sim}} SF_c^{data/sim}(D^{*+}) \quad (9.9)$$

While it is possible to evaluate X^{sim} over simulation, it is not currently possible to measure the corresponding factor in data. The extrapolation factor in data is therefore estimated from simulation, after re-weighting both the production fractions and the branching ratios in the simulation to the best experimental values.

Results

The results of the calibrations are expressed in terms of data-to-simulation scale factors, useful to correct the efficiencies in simulated events to those measured in data. The scale factors are compatible with unity within the uncertainties, while no significant p_T dependence is observed. The 7 TeV calibration [81] contains results for MV1 60%, 70%, 75% and 85% working points, while the 8 TeV calibration [82] contains results for MV1 60%, 70% and 80% working points.

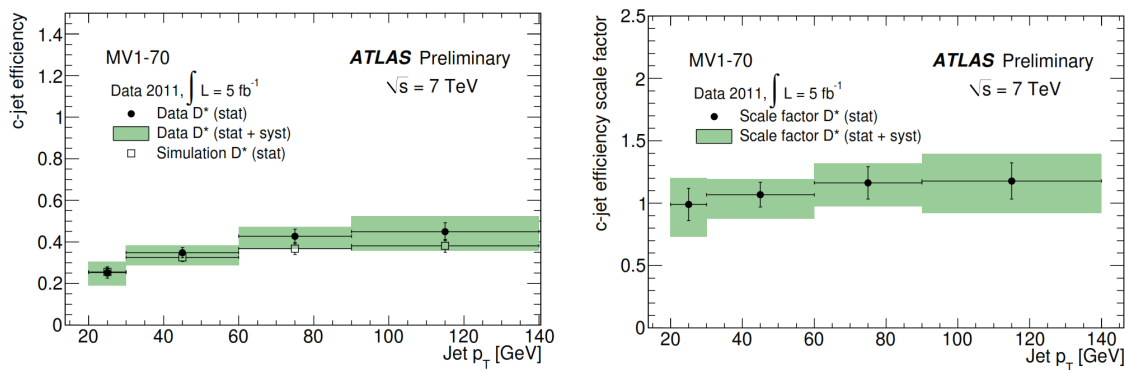


Figure 9.4: The c -jet tagging efficiency measurement results for data and simulation (left) and the corresponding data-to-simulation scale factors (right) for the MV1 tagging algorithm at 70% b -jet efficiency working point (7 TeV calibration).

The uncertainties vary depending on the p_T bin, from 10% to 40% in the 7 TeV calibration and from 8% to 15% in the 8 TeV calibration. The most important systematic uncertainties are those related to the mass fit of D^{*+} mesons, to the extractions of the fraction of D^{*+} mesons originating from beauty hadrons and the extrapolation of the scale factor to that of an inclusive c -jet sample. Other minor systematic uncertainties are from the b -tagging efficiency scale factor, the jet energy scale, the jet energy resolution and the pile-up contamination.

9.1.2 $W+c$ method

The c -jet tagging efficiency measurement with the $W+c$ method was performed on 4.6 fb^{-1} of 7 TeV proton-proton collision data recorded by ATLAS during 2011 [83]. With a similar procedure, studies were performed on 2012 data recorded at 8 TeV. A similar event selection strategy was exploited as well in the $W+c$ production cross section measurement at 7 TeV [26].

To extract a pure c -jets sample, the $W+c$ method selects events with c -jets produced in association with a W boson. The W boson is reconstructed via its decay into an electron¹ and a neutrino, and the c -jet is identified via a soft muon stemming from a semileptonic c -hadron decay. The dominant production mechanism of the $W+c$ signal is $gs \rightarrow W^-c$ and $g\bar{s} \rightarrow W^+\bar{c}$ where the W boson is always accompanied by a c quark with an oppositely signed charge, resulting in two opposite sign leptons (see Figure 9.5). Most of the background processes are evenly populated with events where the charges of the decay leptons are of Opposite Sign (OS) or of Same Sign (SS). The charge correlation of the two leptons is exploited to extract a c -jet sample with high purity, as the difference between the number of events with opposite and with same charge (OS-SS).

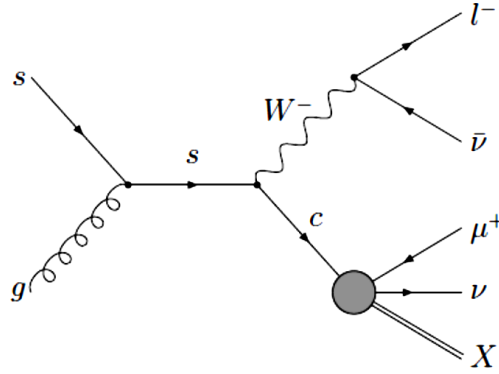


Figure 9.5: The Feynman diagram of the dominant $W+c$ production.

After the determination of the c -jet tagging efficiency using the c -jet sample containing a soft muon produced in association with a W boson, an extrapolation to an inclusive c -jet sample is performed. The results are presented as data-to-simulation scale factors, that are applicable to an unbiased sample of inclusive c -jets.

The data samples are collected using single-electron trigger, selecting events with an electron of pseudorapidity $|\eta| < 2.47$ and $p_T > 20$ GeV. The Monte Carlo samples are generated with PYTHIA [85] or HERWIG [43] with specific configuration for each sample. Besides the $W+c$ sample (i.e. the signal process), many background processes were generated: $W+b$, W +light, top quark pairs, single-top quarks, Z +jets and dibosons samples (WW, ZZ and WZ).

Event selection

To select good events, many requests are applied over all the event components: electrons, missing energy, jets and muons.

¹The first application of the $W+c$ method was focused on the electron channel only of the W boson decay, but the measurement is possible in the muon channel as well.

Firstly, events are required to have at least one primary-vertex candidate: if more than one vertex is found, the vertex with the highest sum of the squared transverse momenta of associated tracks is selected as the primary vertex.

Electrons are required to have a transverse momentum $p_T > 25$ GeV. The pseudo-rapidity range allowed for electrons is $|\eta| < 2.47$, excluding the calorimeter transition region $1.37 < |\eta| < 1.52$. Electrons are required to pass the “tight” identification criteria adopted for 2011 data. Only isolated electrons are selected, with a cut on the calorimeter-based quantity that estimates the transverse energy in the calorimeter cells within a cone of radius $\Delta R < 0.3$ around the electron direction (from now on, referred as ETCone). The ETCone of the electron should be lower than 3 GeV, with this request the electrons coming from hadrons decay within a jet are excluded. Exactly one electron with these qualities is allowed in each event.

The neutrino coming from the W decay is represented by the missing transverse momentum (from now on, referred to as E_T^{miss}). Each event is required to have $E_T^{miss} > 25$ GeV; in addition the W boson transverse mass m_T^W is required to be greater than 40 GeV:

$$m_T^W = \sqrt{2 p_T^{el} E_T^{miss} (1 - \cos(\phi_{el} - \phi_{E_T^{miss}}))} \quad (9.10)$$

where p_T^{el} is the transverse momentum of the selected electron, E_T^{miss} is the missing transverse momentum of the event, ϕ_{el} and $\phi_{E_T^{miss}}$ are the azimuthal angles of the electron and the missing momentum.

Jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are selected. To reduce pile-up contribution, jets are further required to have $JVF > 0.75$ (see Section 7.1). Exactly one jet fulfilling these conditions is allowed for each event.

The selected jet is required to have a “soft” muon inside, with $p_T > 4$ GeV and $|\eta| < 2.5$, coming from the *c*-hadron decay inside the jet. A specific matching procedure between the jet and the muon, defined Soft Muon Tagging (SMT) provided a χ^2 representing the quality of the jet-muon association: a SMT $\chi^2 < 3.2$ is required. Only “combined” muons are accepted, i.e. muons with a track both in the Inner Detector and in the Muon Spectrometer. Two impact parameter conditions are added: $|d_0| < 3$ mm and $|z_0 \sin(\theta)| < 3$ mm. A set of ID hit requirements are required to select high quality tracks, according to 2011 recommendations. The ETCone of the muon is required to be higher than 3 GeV, resulting in a not isolated muon. Exactly one muon with the described quality associated to the selected jet is allowed per each event.

Signal extraction

In order to exploit the charge correlation of the $W+c$ signal events, the sample is extracted as the difference between the number of events with opposite charged leptons and same signed leptons: $N^{OS-SS} = N^{OS} - N^{SS}$. After the subtraction some background events still remains, predominantly from W +light and multijet.

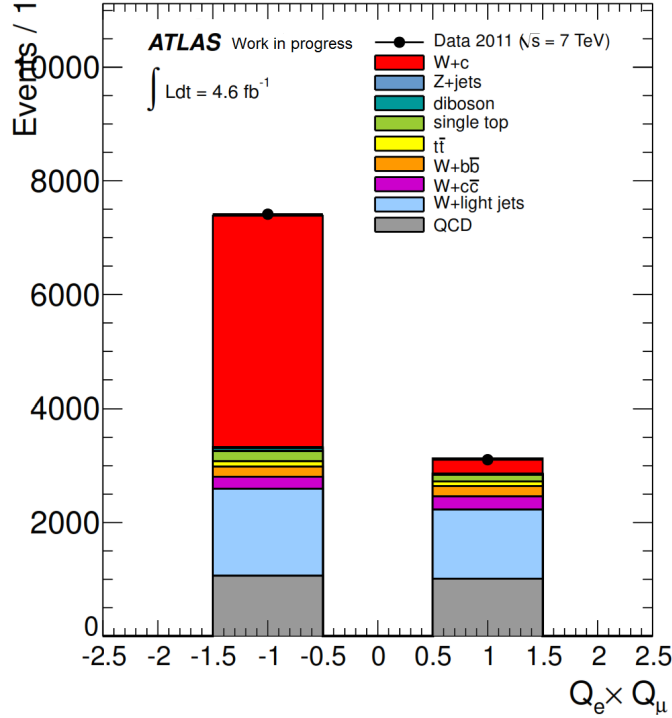


Figure 9.6: Number of Opposite Sign (left) and Same Sign (right) events: the $W+c$ events (red) are dominant in the OS selection, while the most important backgrounds are W +light (blue) and multijet (grey).

Their contribution to the N^{OS-SS} in terms of OS-SS asymmetry is evaluated with data-driven methods. With this procedure, from the 4.6 fb^{-1} 7 TeV data, about 7445 OS events and 3125 SS events were selected, resulting in $N^{OS-SS} = 4320 \pm 100$. Of these events, the estimated SMT $W+c$ events are $3910 \pm 100(stat) \pm 160(sys)$, resulting in a 90% pure c -jet sample.

Tagging efficiency measurement

The high purity of the selected SMT c -jet sample is well suited to measure the c -jet tagging efficiency $\epsilon_{c(\mu)}^{data}$, defined as the fraction of $W+c$ selected events that pass the b -tagging requirement:

$$\epsilon_{c(\mu)}^{data} = \frac{N_{W+c}^{b-tag}}{N_{W+c}} \quad (9.11)$$

where N_{W+c} is the number of $W+c$ events before applying the b -tagging requirement (also referred as pre-tag sample) and N_{W+c}^{b-tag} is the number of $W+c$ events passing the b -tagging requirement. The small background contribution is estimated using MC simulation or data-driven method and subtracted.

The c -jet tagging efficiencies for the MV1 tagging algorithm derived for SMT c -jets measured on 7 TeV data vary between 13% and 50% with the total uncertainty (3% – 10%) increasing with the tightness of the working point. The systematic un-

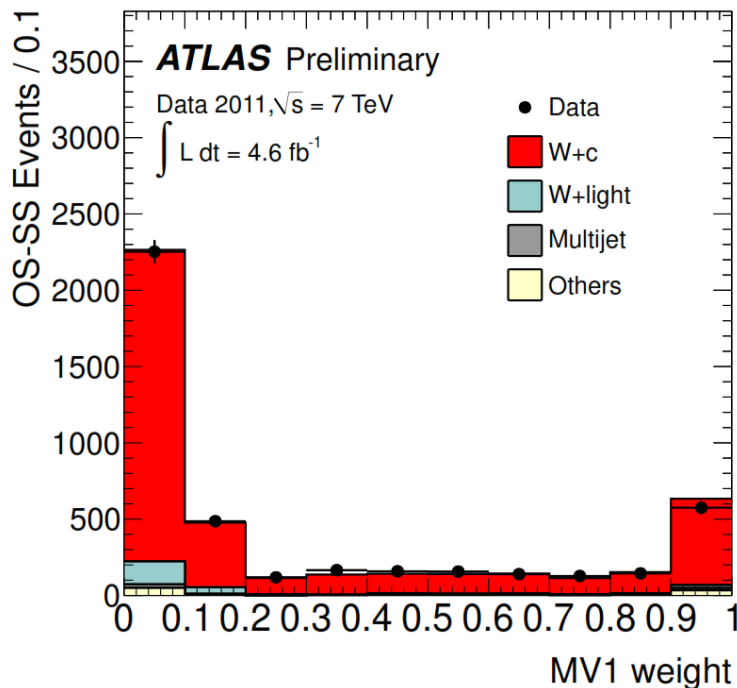


Figure 9.7: MV1 output weight distribution for N^{OS-SS} events: the $W+c$ process is about 90% of the total events, few events from W +light and multijet processes remains.

certainties are dominated by the precision on the W +light and multijet background yields at pre-tag level, the statistical uncertainties are of the same order as the systematic uncertainties. The c -jet tagging efficiency is measured for a simulated sample too and a data-to-simulation scale factor is presented. Due to several differences between an inclusive sample and a sample of semileptonic c -jets, the derived scale factors $SF_{c(\mu)}^{data/sim}$ need to be extrapolated in order to be applicable to samples of inclusive c -jets.

Extrapolation to inclusive c -jet sample

Selecting a sample of c -jets via the semimuonic decays of c -hadrons results in a different composition of c -hadron types with respect to an inclusive sample due to the different semileptonic branching ratios of the c -hadrons. The c -jet tagging efficiency of an inclusive sample of c -jets ϵ_c can be obtained from the one obtained on semileptonic c -jets $\epsilon_{c(\mu)}$ by applying an extrapolation factor α .

$$\epsilon_c = \alpha \cdot \epsilon_{c(\mu)} \quad (9.12)$$

Similarly to the D^* method, the efficiency extrapolation factors for data and simulation α are defined as follows:

$$\epsilon_c^{data} = \alpha^{data} \cdot \epsilon_{c(\mu)}^{data} \quad (9.13)$$

$$\epsilon_c^{sim} = \alpha^{sim} \cdot \epsilon_{c(\mu)}^{sim} \quad (9.14)$$

The inclusive scale factor $SF_c^{data/sim}$ is given by:

$$SF_c^{data/sim} = \frac{\epsilon_c^{data}}{\epsilon_c^{sim}} = \frac{\alpha^{data}}{\alpha^{sim}} SF_{c(\mu)}^{data/sim} \quad (9.15)$$

The α^{sim} extrapolation factor is derived from MC samples, resulting in a value of about 0.8 for the different working points. The corresponding extrapolation factor for data α^{data} is estimated using simulated-corrected sample to minimize differences between data and simulation. The fragmentation fraction of the relevant weakly decaying c -hadrons of simulation are re-weighted to the value measured by many e^+e^- and $e^\pm p$ collision experiments, while the semileptonic branching ratios of c -hadrons are corrected to match the world average values.

Results

The results are presented as data-to-simulation scale factors in Figure 9.8: the values vary between 0.75 and 0.92 with total relative uncertainties of 13% to 5%. The scale factors decrease and the corresponding uncertainties increase with increasing tightness of the working point. Three main sources of uncertainties are of the same order: the statistical uncertainty, the systematic uncertainty on the measured scale factors for the SMT c -jet sample and the systematic uncertainty due to the extrapolation procedure. The main source for the systematic uncertainties due to the performed extrapolation is the limited knowledge of the charged particle multiplicity of c -hadron decays which has a significant impact on the c -jet tagging efficiency.

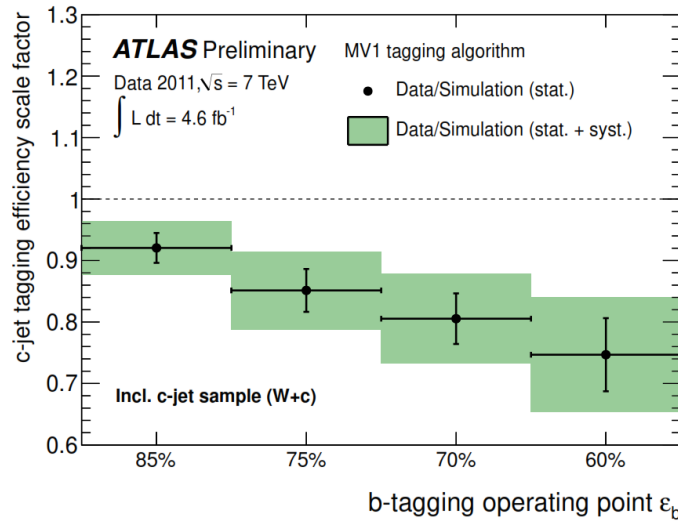


Figure 9.8: The c -jet efficiency data-to-simulation scale factors for different MV1 tagging algorithm working points.

9.1.3 $t\bar{t}$ method

In 2016, a new method to measure the c -jet tagging efficiency was developed: the $t\bar{t}$ method, which soon became the reference method for Run 2 measurements. It is based on a sample of c -jets from $t\bar{t}$ events, where one of the W bosons decays hadronically to a $W \rightarrow cX$ pair ($X = d; s; b$) and the other leptonically to an electron or muon and a neutrino. A schematic diagram can be found in Figure 9.9. The charged lepton is used to trigger the event; events are required to have exactly four jets. A kinematic likelihood fitter, known as the KLFFitter [87], is used to assign the reconstructed jets to the $t\bar{t}$ decay products. The measurement was firstly performed on data collected by the ATLAS experiment in 2015 and 2016 at 13 TeV, corresponding to a total of 36 fb^{-1} .

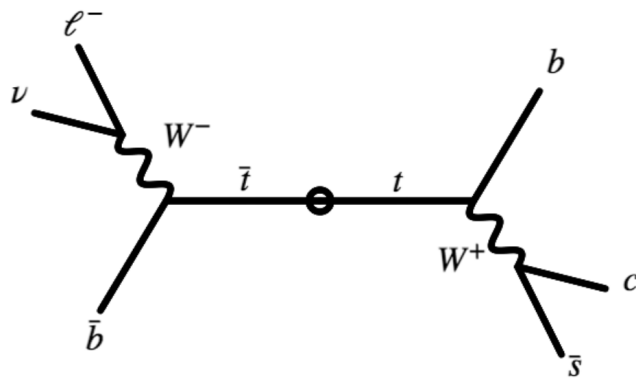


Figure 9.9: A diagram of the $t\bar{t}$ decay system with one W boson decaying hadronically to a c and s quark and one decaying to a charged lepton and a neutrino.

The previously described methods (D^* and $W+c$ methods) achieve a high purity of c -jets in their final selection, but they rely on specific hadron decay topologies: their results have to be extrapolated to an inclusive sample of c -jets by making assumptions that lead to additional uncertainties.

The novelty of the $t\bar{t}$ method is that no extrapolation correction is required: the results are directly applicable to the same inclusive sample of c -jets that is normally present in physics analyses. However, given the final state signature of single lepton $t\bar{t}$ events, two real b -jets and a light-jet are expected along with the c -jet. In addition, 50% of the times, the W decays to a light quark pair; thus, on average, the W hadronic decay products include one charm jet every four jets. Therefore, the kinematic likelihood fitter is used to reduce the combinatorial background arising from the improper assignment of b -jets or additional jets in the event as decay products of the hadronic W boson.

A maximum likelihood fit based on a combinatorial likelihood function is used to extract efficiencies simultaneously for several jet p_T bins, using MC to predict the flavour composition of the jets in the sample. Efficiencies and scale factors are derived for c -jets inclusively and as a function of jet p_T (three jet p_T bins: $[25, 40] \text{ GeV}$, $[40, 65] \text{ GeV}$, $[65, 140] \text{ GeV}$).

The data samples are collected using a logical “OR” of single lepton triggers, populating the jet p_T range between 25 GeV and 140 GeV, which contains the majority of the *c*-jets relevant for top and Higgs physics analyses.

The signal Monte Carlo samples, $t\bar{t}$ +jets, are generated with Powheg-Box v2 NLO [88–90] with a specific filter to select W boson leptonic decays. PYTHIA8 [42] is used to model parton shower, hadronisation, multiparton interactions and underlying-events. The systematic uncertainties on the signal sample generation are measured comparing the default generator (Powheg + PYTHIA8) to $t\bar{t}$ events generated with MadGraph5_aMC@NLO [91, 92] + PYTHIA8, in order to estimate the uncertainty of the matrix element generator, and to MadGraph5_aMC@NLO + Herwig7 [93] for the parton shower uncertainty estimation. Other uncertainties are estimated varying the renormalization and factorization scales, and the shower radiation parameters.

Event selection

Events are required to contain exactly one trigger-matched charged lepton having p_T above 27 GeV and exactly four jets with a p_T above 25 GeV. Reconstructed electrons are required to have p_T higher than 27 GeV and $|\eta| < 2.47$, with tight or medium quality. Electrons are required to be isolated, passing calorimeter and track isolation criteria. Muons, reconstructed from combined tracks, with medium selection criteria, are required to have $p_T > 27$ GeV and $|\eta| < 2.5$. Muons are required to be isolated, passing track isolation criteria. A dedicated selection is applied on the transverse and longitudinal impact parameters of the electron and muon tracks.

The jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. To reduce pile-up contribution, jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are further required to have JVT > 0.59 (see Section 7.1).

Of the selected jets, at least two must be *b*-tagged using the 70% WP of the MV2c10 *b*-tagging algorithm. In addition, events are required to have missing transverse momentum $E_T^{miss} > 20$ GeV, which is assumed to be the result of the neutrino from the leptonically-decaying W boson.

The *b*-tagging efficiency for *b*-jets [94] and light-jets [95] has been measured in data enriched in jets of the respective flavour. The results are used to correct the tagging rate in the simulated samples adopted in the analysis.

For each event, a kinematic likelihood fitter is applied which determines the jet assignment to the various decay products. Events that have a relatively small log likelihood value are more often found to be the ones where the jet-parton combination is incorrectly assigned or that are not $t\bar{t}$ events. In order to reduce the effect of this background on the measurement, a log likelihood cut is applied (value > -48 , see Figure 9.10), accepting 68% of the total selected $t\bar{t}$ events. The resulting leading jet p_T distribution after the full selection is shown in Figure 9.11.

The data and MC efficiencies are extracted from the minimization of a log like-

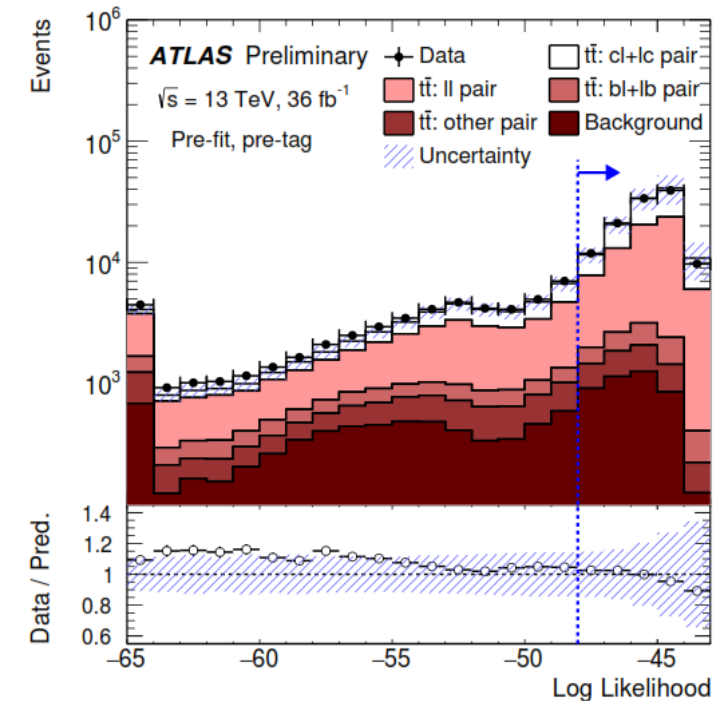


Figure 9.10: Data and MC distribution for the event log likelihood given by the KLFFitter after the full event selection. $t\bar{t}$ events are shown in different colours according to the flavour composition. The dashed blue line indicates the position of the likelihood cut.

likelihood function defined as the sum over all jet p_T bins of the two selected jets, the leading and the subleading jets. In particular, the likelihood formalism is based on the observed and expected number of events with exactly 0 or 1 tagged jets in each p_T bin. A likelihood fit is performed separately for each of the b -tagging efficiency working points. Within the terms, apart from the c -jet efficiency which is the main fitting parameter, there are the b - and light-jet efficiencies (calibrated with scale factors measured by separate b -tagging analyses) and the flavour composition of jets from the W decay, expressed as fraction of all hadronic W decays in top event (estimated from MC).

Results

In the software release 20.7, the efficiency measured in data is significantly higher than in MC for the tightest working points, due to a poor modeling of the impact parameter resolution in the simulation. In Figure 9.12, a trend is visible on the measured c -jet tagging scale factor integrated over p_T for the four considered working points: the differences between data and MC progressively reduce as looser operating points are considered, from 60% for the 60% WP to 10% for the 85% WP.

For the loosest working point, the dominant systematic uncertainty is represented by the uncertainty on the b -tagging efficiency of light-jets; this component decreases as the working point gets tighter due to the increased light-jet rejection.

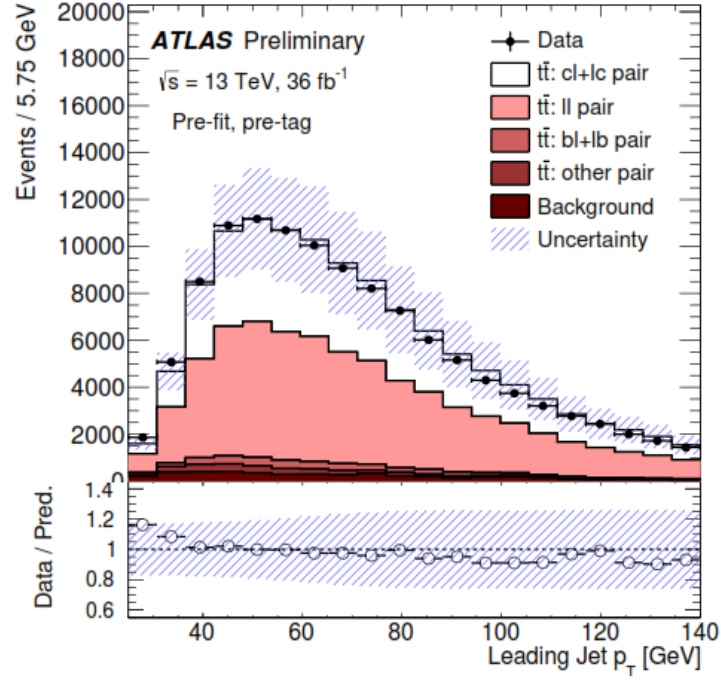


Figure 9.11: Data and MC distribution of the leading jet p_T for the jets assigned to the hadronic W boson.

For the rest of the working points, the leading uncertainties on the measurement are from $t\bar{t}$ modelling uncertainties, in particular through their impact on the flavour composition of the jet pairs from the hadronic W -boson decays.

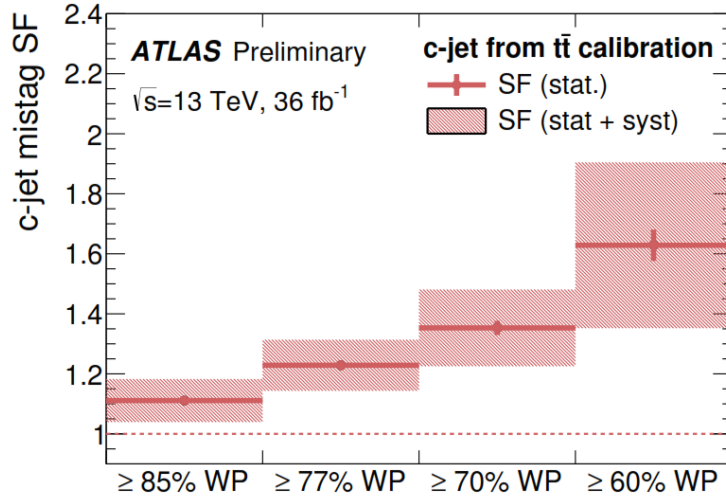


Figure 9.12: Measured c -jet efficiency scale factors determined for the four working points of the MV2c10 tagging algorithm (release 20.7) integrated over p_T .

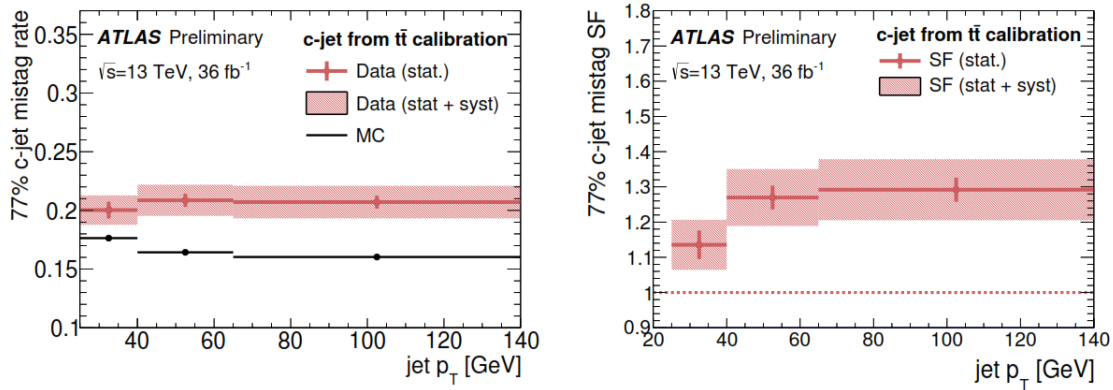


Figure 9.13: The c -jet tagging efficiency measurement results for data and simulation (left) and the corresponding data-to-simulation scale factors (right) for the MV2c10 tagging algorithm (release 20.7) at 77% b -jet efficiency working point.

Chapter 10

c -jet calibration with $W+c$ events

The main part of my thesis work is focused on the measurement of the c -jet tagging efficiency with the $W+c$ method (see Section 9.1.2) on Run 2 data: the first tests on 13 TeV data samples were performed in 2015 with the b -tagging algorithms available in the software release 20.1; then a full measurement was performed on the release 20.7 b -tagging algorithms based on 2015 and 2016 data. The performance measurement of the release 21 b -tagging algorithms is ongoing on the full Run 2 dataset (2015, 2016, 2017 and 2018 data).

In this chapter, a detailed review of the calibration performed on the release 20.7 algorithm (MV2c10) is presented in Section 10.1, along with the preliminary studies on the release 21 algorithms (MV2c10 and DL1) in Section 10.2.

10.1 Release 20.7 calibration

In this Section, the $W+c$ method is adopted to measure the c -jet tagging efficiency on a data sample of pp collision events collected at $\sqrt{s} = 13$ TeV. After extrapolation to an inclusive c -jet sample using simulation, a data-to-simulation scale factor is derived, defined as the ratio of the efficiency on data over the efficiency on simulated event samples, which can be applied to any unbiased sample of c -jets. Results [96] are presented for the four working points of the release 20.7 MV2c10 algorithm, integrated and as a function of jet p_T , for jets reconstructed from topological clusters in the calorimeter by the anti- k_t algorithm [68] with a radius parameter R of 0.4.

The final results of the c -jet tagging efficiency data-to-simulation scale factors are obtained by the combination of the results measured by two different methods: $W+c$ and $t\bar{t}$ methods [84]. The two methods have different advantages and nicely complement each other: the $W+c$ analysis allows a clean extraction of c -jets containing semileptonic decays of the charm hadron while the $t\bar{t}$ analysis is targeting the inclusive c -jet sample profiting of the high statistics provided by W hadronic decays.

10.1.1 Data and MC samples

The release 20.7 analysis is based on data recorded by the ATLAS detector in LHC pp collisions at the center of mass energy $\sqrt{s} = 13$ TeV in 2015 and 2016, corresponding to integrated luminosities of 3.2 fb^{-1} and 32.9 fb^{-1} , respectively.

The $W+c$ signal and all background sources containing W or Z bosons or top quarks are modeled using simulated event samples. The additional multijet background, important due to the presence of misidentified reconstructed electrons, is estimated with a data-driven method described in Section 10.1.3.

The default W +jets and Z +jets simulated event samples (including the $W+c$ signal) are produced with MADGRAPH v1.15 [97] interfaced to PYTHIA8 [42] with A14 general-purpose high- p_T tunes [98]. As a crosscheck, these are compared with samples produced adopting different generators: SHERPA v2.2.0 [44] using the NNPDF 3.0 PDF set [7] in conjunction with dedicated parton-shower tuning developed by the SHERPA authors; POWHEG-BOX v2.2 [88–90] interfaced to PYTHIA8; ALPGEN v2.14 [99] interfaced to PYTHIA6 [85].

Diboson (ZZ , WZ and WW) samples are generated using SHERPA 2.1.1, while single-top t -channel and $W+t$ events are generated using POWHEG-BOX v1 and $t\bar{t}$ events are generated using POWHEG-BOX v2, both interfaced to PYTHIA6.

All samples, except for those generated with SHERPA, use the EVTGEN [100] package to describe the b - and c -hadron decay processes.

All generated samples are passed through the simulation of the ATLAS detector based on GEANT4 [45]. The same offline reconstruction methods used with data events are applied to the simulated events samples. Minimum-bias events generated by PYTHIA8 [42] are used to simulate multiple pp interactions in the same and nearby bunch crossings (pile-up).

10.1.2 Event selection

The final state for this analysis is defined by the presence of an isolated electron, coming from the W boson decay, accompanied by sizeable missing transverse energy E_T^{miss} , and a jet containing a muon. The criteria used to select candidates for each of these objects are given below and summarized in Table 10.1.

Events in which the W boson decays to a $e\nu$ pair are selected by a set of single-electron triggers [101, 102]. During 2015 data acquisition, the triggers selected an electron with $p_T > 24$ GeV passing medium quality criteria and a veto against energy deposited in the hadronic calorimeter (hadronic isolation selection), or $p_T > 60$ GeV passing medium quality criteria or $p_T > 120$ GeV passing loose quality criteria. During 2016 data acquisition, the triggers selected an electron with $p_T > 26$ GeV passing tight quality criteria and a hadronic isolation selection, or $p_T > 60$ GeV passing medium quality criteria or $p_T > 140$ GeV passing loose quality criteria.

The event must contain a primary vertex with at least three tracks having p_T higher than 400 MeV. If more than one primary vertex is found, the one with

1 electron candidate with: $p_T > 30 \text{ GeV}$ $ \eta < 2.47 \text{ and } 1.37 < \eta < 1.52$ $ d_0 /\sigma(d_0) < 5$ $ z_0 \sin\theta < 0.5 \text{ mm}$ Tight ID quality Tight calorimeter and track isolation
Missing energy and W boson transverse mass: $E_T^{\text{miss}} > 25 \text{ GeV}$ $m_T^W > 60 \text{ GeV}$
1 jet candidate with: $p_T > 20 \text{ GeV}$ $ \eta < 2.5$ JVT < 0.59 (jets with: $p_T < 60 \text{ GeV}$ and $ \eta < 2.4$)
1 muon candidate with: $p_T > 4 \text{ GeV}$ $ \eta < 2.5$ Tight ID quality $\Delta R(\text{jet, muon}) < 0.4$
Extra requirement to reduce multijet background contamination: electron $p_T > 70 \text{ GeV}$ or $\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.8$

Table 10.1: Summary of the event selection.

the highest $\sum p_T^2$ of associated tracks is chosen. The simulated event samples are reweighted so that their distribution of number of pile-up interactions per bunch crossing, μ , reproduces the one measured in data.

The reconstructed isolated electron is identified by requiring a track to match an electromagnetic calorimeter energy cluster, subject to several criteria on the shape of the shower, the quality of the track, and the consistency between the shower and the track. Electrons selected for this analysis must satisfy the tight identification requirement using a likelihood discriminant that combines many individual variables [103]. Furthermore, good candidates are required to match the online electron that triggered the event with a ΔR criteria and to be compatible only with the electron hypothesis and not with the photon one. The track associated with an electron must have a transverse impact parameter with respect to the beamline, d_0 , that satisfies $|d_0|/\sigma(d_0) < 5$, where $\sigma(d_0)$ is the uncertainty on d_0 . The difference between the longitudinal position of the track along the beam line at the point where d_0 is measured and the longitudinal position of the primary vertex, z_0 , must satisfy $|z_0 \sin\theta| < 0.5 \text{ mm}$. The electron is required to have $p_T > 30 \text{ GeV}$, while the calorimeter energy cluster associated with the electron must fall in the range $|\eta| < 2.47$, excluding the barrel/end-cap transition region $1.37 < |\eta| < 1.52$. Electron candidates are further selected by applying tight calorimeter and track isolation criteria that accept real isolated electrons from Z boson decay with an efficiency of

95%, while rejecting fake electron candidates.

The E_T^{miss} [104], expected due to the presence of a neutrino coming from the W boson decay, is calculated as the negative of the vector sum of the transverse momenta of all identified physics objects (electrons, photons, muons, jets), and an additional soft term constructed from tracks associated with the primary vertex, but not associated with any physics objects. Each event must satisfy the requirement $E_T^{\text{miss}} > 25$ GeV. In addition, the W boson transverse mass m_T^W (see Equation 9.10) is required to be higher than 60 GeV. Moreover, events with $p_T^W > 20$ GeV are selected, with p_T^W being the p_T of the W boson four-vector, built as the sum of electron and E_T^{miss} terms.

For the selection of muons coming from the semileptonic c -hadron decay, only combined muons are considered, *i.e.* muons for which a track was reconstructed both in the inner detector and in the muon spectrometer. A minimal requirement on muon transverse momentum is applied, $p_T > 4$ GeV, along with requiring $|\eta| < 2.5$. Finally, in order to select only good-quality muons, candidates are required to pass tight identification criteria [105].

Jets are reconstructed by clustering energy deposits in the calorimeter using the anti- k_t algorithm [68] with a radius parameter of 0.4. Clusters are calibrated at the electromagnetic energy scale¹, then the hadronic scale is obtained through p_T - and $|\eta|$ -dependent correction factors. Jets with $p_T > 20$ GeV and $|\eta| < 2.5$ are selected. To reduce the amount of jets originating from pile-up interactions, the jets are required to pass the JVT requirement (see Section 7.1). Jets are not removed if overlapping with leptons, in order to keep all possible b - and c -jet candidates, but they are not accepted if overlapping with the selected electron. Exactly one jet passing this selection is allowed in each event.

The identification of the c -jet by the semileptonic c -hadron decay is performed requiring the selected jet to contain exactly one reconstructed muon with an angular separation between the muon and the jet axis $\Delta R < 0.4$. In order to take into account the contribution of the selected muon to the jet, the jet p_T is re-calculated with the muon regarded as a part of the jet. The re-calculated jet p_T is required to be higher than 25 GeV.

Events with misidentified electrons can pass the selection, mainly from non-prompt decays of the heavy flavour hadrons or photon conversions (*i.e.* $\pi^0 \rightarrow \gamma\gamma$). To reduce these background events (referred to as multijet background events), an additional dedicated selection is applied: events are accepted in the signal region if the electron $p_T > 70$ GeV or the $\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.8$. This additional selection reduces the number of multijet background events, while keeping about 80% of the $W+c$ signal events.

Jets in simulated event samples are labeled according to their flavour, using particle-level information by matching jets to weakly decaying b - and c -hadrons

¹The electromagnetic scale correctly measures the energy deposited by electromagnetic showers in the calorimeter, and needs to be corrected to the jet energy scale for hadronic showers.

with $p_T > 5$ GeV and angular distance from the jet axis $\Delta R < 0.3$. The flavour labeling is exclusive, with the hadron matched only to the closest jet. If a b -hadron is found within the cone, the jet is labeled as a b -jet. If no b -hadron is found, the search is repeated for c -hadrons, then for τ leptons. If no match is found for b , c or τ , the jet is labeled as a light-flavoured jet.

10.1.3 Signal and backgrounds

Exploiting the charge correlation between the electron and the muon of the $W+c$ events, a highly pure signal sample can be extracted as the difference between the number of events in which the selected electron and muon have opposite charges and those in which they have the same charge: $N^{\text{OS-SS}} = N^{\text{OS}} - N^{\text{SS}}$. Some background contributions are not charge-symmetric, so still give residual contributions after the subtraction procedure. Therefore, a careful modelling of all background sources is mandatory.

One of the main backgrounds remaining after the OS–SS subtraction consists of W +light-jet events, which show some OS/SS asymmetry due to the correlation of the charge of the W boson and the fragmentation products of the associated light quark. Another large contribution comes from multijet production, which is characterized by large normalisation uncertainties and is asymmetric in sign correlation.

A smaller number of background events comes from diboson production, from Z +jets events and from single-top and top-pair production. Backgrounds from $W+b\bar{b}$ and $W+c\bar{c}$ events are included in the $W+b$ and $W+c$ yields; their contribution is almost negligible after subtraction, since they both show a symmetric distribution of OS and SS events.

In the following, the procedure adopted to estimate the background contributions is described, and the resulting extraction of OS–SS event yield is then presented.

Simulated background estimation

Since the cross-section of all the relevant background processes, except for the multijet production, are sufficiently precisely described by the MC simulation, their contribution is estimated from the simulated event samples described in Section 10.1.1. Simulated events are weighted according to theory cross-section, filtering efficiency at event-generation level, individual event weight assigned by the generator, overall integrated luminosity and pile-up distribution.

Multijet background estimation

Jets misidentified as electrons are the main source of the multijet background in this analysis. This background is estimated from data using the so-called fake-factor method [106]. The number of OS and SS multijet background events is estimated separately, thereafter the number of OS–SS events is derived.

Two selections are defined, differing in the electron identification criteria: the standard selection with tight identification, corresponding to that adopted in the analysis and described in Section 10.1.2, and the inverted selection, where electron candidates are required to pass the medium but fail the tight identification selection, allowing more fake electron candidates to be selected.

A control region is defined, enriched in fake electron candidates: events containing one candidate electron and one jet are selected. The electron is required to pass the standard or the inverted selection and to match the online-reconstructed electron that triggered the event. The reconstructed jet is required to pass the jet selection adopted in the analysis and described in Section 10.1.2, without the requirement of a muon inside the jet. To reduce the impact of real electrons from W and Z boson decays, no cut on E_T^{miss} is applied and the events included in the region of electron-jet invariant mass between 80 and 130 GeV or in the region of $m_T^W > 60$ GeV are excluded (to be orthogonal to the signal region); the remaining contribution from real electrons from W and Z boson decays is subtracted using estimates from simulated event samples. Minor background contributions from di-boson, single-top and top-pair productions are also estimated from simulated event samples and subtracted.

The fake factor is measured in the control region enriched in fake electron candidates as a function of the electron p_T and η ; it is defined as the ratio of the number of events with the standard electron selection to the number of events with the inverted electron selection.

The number of multijet background events in the signal region (events with a fake electron candidate) $N_{\text{standard}}^{\text{SR}}$ is estimated as a function of the variables of interest adopting the following relation:

$$N_{\text{standard}}^{\text{SR}} = f \times N_{\text{inverted}}^{\text{SR}}, \quad (10.1)$$

where f is the fake factor and $N_{\text{inverted}}^{\text{SR}}$ is the number of events passing the inverted electron selection in the signal region.

Extraction of signal with OS–SS subtraction

All signal and background contributions so far described are summed and compared with the yield measured in data, separately for the case in which the two selected leptons have the same or opposite sign. Figure 10.1 shows the two yields for the events passing the selection. Numerical details on the signal and background contributions are available in Table 10.2.

By performing the OS–SS subtraction, a sample with a 80% c -jet purity is obtained. The residual discrepancy in the total number of OS–SS events estimated with the prediction and measured on data is covered by the total uncertainties on the yield. Background events, predominantly from W +light jet and multijet processes, are observed even after subtraction. Events with a W boson decaying to τ lepton

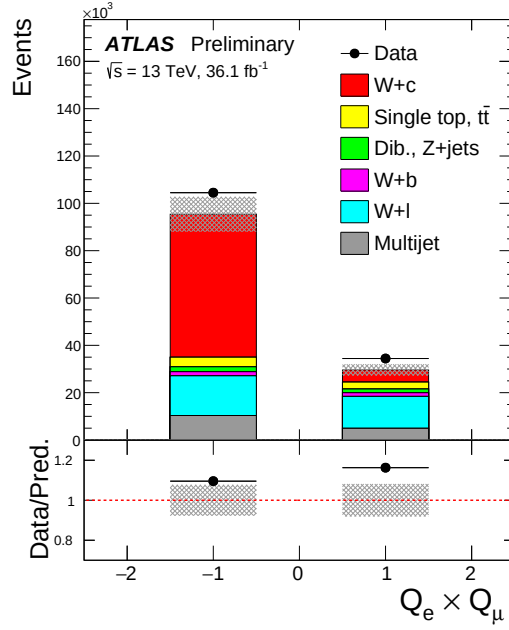


Figure 10.1: Comparison of the yield of events passing the selection adopted for the analysis, as measured in data and estimated with simulated event samples and data-driven background estimation, separately for the case in which the two selected leptons have the same or opposite sign; data statistical uncertainties are included as error bars (invisible, due to the data bullet size), while grey bands include the statistical and systematical uncertainties on the simulated event samples and multijet estimate derived in data.

and consequently to an electron are counted as $W \rightarrow e\nu$ events and are assigned to $W+c$, $W+b$ or $W+\text{light}$ according to the flavour of the jet.

The distributions of the MV2c10 tagger discriminant and of the jet and muon transverse momentum obtained after OS–SS subtraction, as measured in data and as predicted by simulated event samples and data-driven background estimates, are shown in Figure 10.2 and Figure 10.3, respectively. Reasonable agreement between data and prediction is visible for the shown distributions, within the uncertainties, except for the MV2c10 region close to +1: as a consequence of this mismodeling, the c -jet tagging efficiency measured on data is higher than the one measured on simulated event samples, resulting in data-to-simulation scale factor being higher than one.

10.1.4 Semileptonic efficiency

The c -jet tagging efficiency is measured as the ratio between the number of OS–SS signal events passing a given b -tagging selection and the total number of OS–SS events. Simulated efficiency is measured using simulated $W+c$ events with c -jets identified via truth c -hadron matching, while data efficiency is measured on data events after the subtraction of background events estimated by MC simulation and

Process	N^{OS}	N^{SS}	$N^{\text{OS-SS}}$
Single top	2400 ± 200	1500 ± 100	850 ± 70
$t\bar{t}$	1700 ± 100	1400 ± 100	290 ± 40
Diboson	600 ± 40	170 ± 10	430 ± 40
Z +jet	1500 ± 100	1400 ± 100	70 ± 100
W + b	1700 ± 200	1600 ± 200	200 ± 300
W +light	17000 ± 1000	13000 ± 1000	3300 ± 900
Multijet	10000 ± 5000	5000 ± 2000	5000 ± 3000
Total background	35000 ± 5000	24000 ± 2000	11000 ± 3000
W + c	60000 ± 5000	5000 ± 500	55000 ± 5000
Total estimate	95000 ± 7000	30000 ± 2000	66000 ± 6000
Data	104501	34432	70069

Table 10.2: Selected events yield, separately for the case of opposite sign and same sign lepton content and after the OS–SS subtraction. A comparison between predicted yield and the one measured in data is also provided; statistical and systematic uncertainties are included.

data-driven approach. In both cases, jets are required to contain a soft muon coming from the c -hadron semileptonic decay. The procedure is repeated for the four MV2c10 b -tagging efficiency working points: 85%, 77%, 70% and 60%.

The efficiencies measured on semileptonic c -jet samples for data, $\epsilon_{Wc(\mu)}^{\text{data}}$, and simulated event samples, $\epsilon_{Wc(\mu)}^{\text{sim}}$, are used to calculate the c -jet tagging scale factor, $k_{Wc(\mu)}$, as:

$$k_{Wc(\mu)} \equiv \frac{\epsilon_{Wc(\mu)}^{\text{data}}}{\epsilon_{Wc(\mu)}^{\text{sim}}} \quad (10.2)$$

Results are shown in Figure 10.4: for all the working points, the data efficiencies are higher than the ones measured on simulated event samples, as a consequence of the MV2c10 distribution mismodelling. The scale factors are higher than one, with a growing linear trend with the increase of the tightness of the working point. The efficiencies measured for semileptonic c -jets on the simulated W + c event samples are found to be compatible with the ones measured on simulated $t\bar{t}$ events.

In addition, efficiencies and scale factors are derived as a function of jet p_{T} for three jet p_{T} bins: $25 \text{ GeV} < p_{\text{T}} < 40 \text{ GeV}$, $40 \text{ GeV} < p_{\text{T}} < 65 \text{ GeV}$ and $65 \text{ GeV} < p_{\text{T}} < 140 \text{ GeV}$. Results for the 77% working point are shown in Figure 10.5. While the efficiencies are decreasing with the increase of jet p_{T} , no trend is visible for the scale factors within the uncertainties.

10.1.5 Extrapolation correction

The selection described in Section 10.1.2 allows a pure sample of c -jets to be identified, but at the same time, requiring the jets to contain a soft muon coming from the c -hadron semileptonic decay, introduces a bias on the hadron composition with

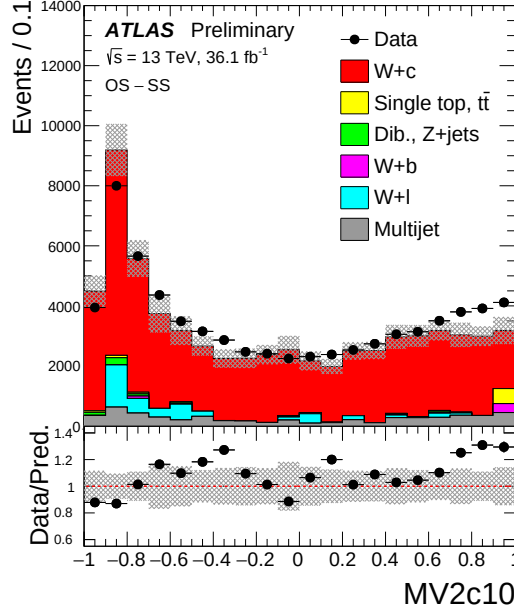


Figure 10.2: Comparison of the distribution after OS–SS subtraction for the MV2c10 tagger discriminant, as measured in data and as predicted by simulated event samples and data-driven background estimation; data statistical uncertainties are included as error bars (invisible, due to the data bullet size), while grey bands include the statistical and systematical uncertainties on the simulated event samples and multijet estimate derived in data.

respect to the case of the fully inclusive c -jet sample.

As an example, the dominant c -hadron species expected to be found in an inclusive c -jet sample is the D^0 meson ($\sim 60\%$), while the D^+ meson fraction is strongly enhanced in the semileptonic c -jet sample, due to its relatively large branching ratio for final states including leptons. More quantitatively, the semileptonic c -jet sample consists of a similar amount ($\sim 43\%$) of D^0 and D^+ mesons. In addition to this, the c -hadron production fractions and semileptonic branching ratios predicted by simulation do not fully agree with the values measured, with limited precision, by experiments. All these effects have an impact on the measured efficiencies, as different hadron species correspond to different lifetimes and average charged track multiplicities of the decay, thus biasing the b -tagging selection of the corresponding jet.

As a consequence, the efficiencies measured in Section 10.1.4 need to be corrected, deriving extrapolation factors relating them to the efficiencies that would be measured in an inclusive c -jet sample. Two different extrapolation factors, for MC simulation (α_{sim}) and data (α_{data}), are then defined by the relations:

$$\epsilon_{Wc}^{\text{sim}} = \alpha_{\text{sim}} \cdot \epsilon_{Wc(\mu)}^{\text{sim}}, \quad \epsilon_{Wc}^{\text{data}} = \alpha_{\text{data}} \cdot \epsilon_{Wc(\mu)}^{\text{data}}, \quad (10.3)$$

where $\epsilon_{Wc(\mu)}^{\text{data}}$ and $\epsilon_{Wc(\mu)}^{\text{sim}}$ are the c -jet tagging efficiencies measured on the semileptonic

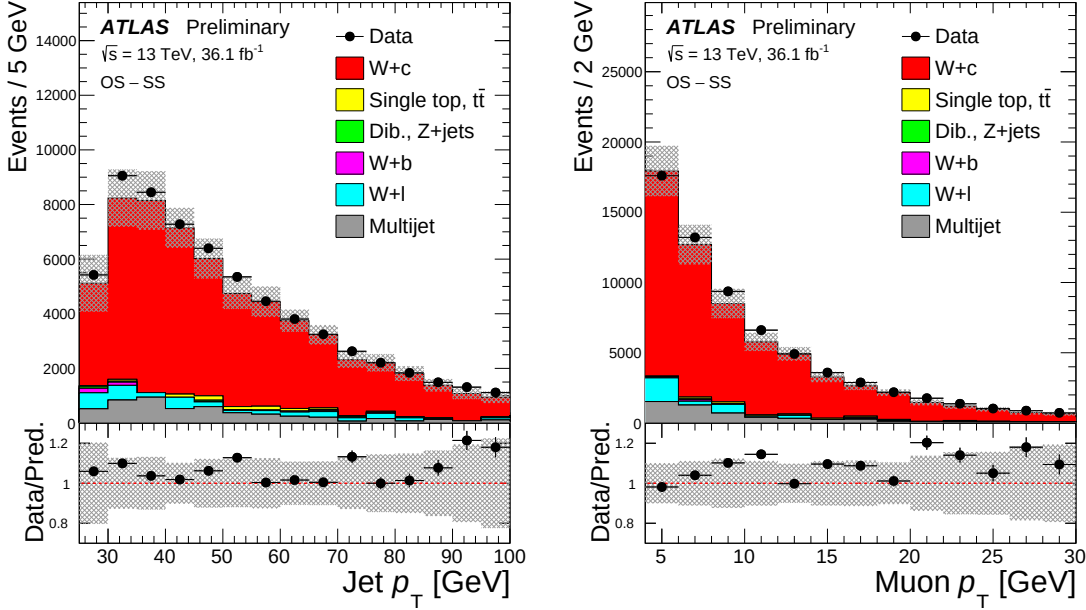


Figure 10.3: Comparison of the distribution after OS–SS subtraction for the jet (left) and the muon (right) transverse momentum, as measured in data and as predicted by simulated event samples and data-driven background estimation; data statistical uncertainties are included as error bars (invisible, due to the data bullet size), while grey bands include the statistical and systematical uncertainties on the simulated event samples and multijet estimate derived in data.

sample in Section 10.1.4, while $\epsilon_{Wc}^{\text{data}}$ and $\epsilon_{Wc}^{\text{sim}}$ are the corresponding efficiencies that would be measured on an inclusive sample.

The extrapolation factor for simulated event samples is derived as the ratio of the inclusive efficiency, measured on a simulated c -jet sample dropping the requirement of a soft muon inside the selected jet, and the already measured semileptonic efficiency:

$$\alpha_{\text{sim}} = \frac{\epsilon_{Wc}^{\text{sim}}}{\epsilon_{Wc(\mu)}^{\text{sim}}}. \quad (10.4)$$

To derive the extrapolation factor in data in a similar way, since an inclusive sample of c -jets is not directly accessible, a corrected simulated event sample is used instead, in which the events of the MADGRAPH $W+c$ sample are reweighted in order to rescale the c -hadron properties (fragmentation fractions and branching ratios) to those experimentally measured in data [86, 107]²; with the assumption that α_{data} can be replaced by:

²The values used in the reweighting procedure are relative to the 2014 PDG publication [86]. The 2018 PDG publication [15] includes recent improvements in the uncertainties of the branching ratios of the D^0 and D^+ exclusive semileptonic decays: these improvements would have a minor impact on the final extrapolation uncertainty.

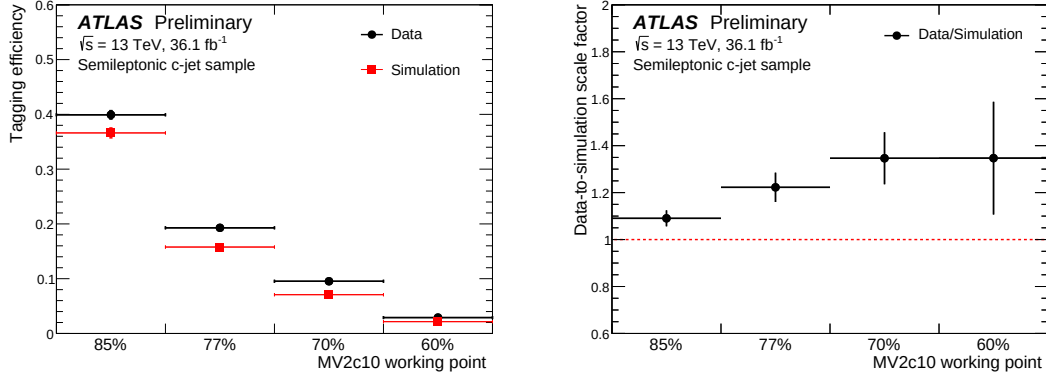


Figure 10.4: Tagging efficiencies (left) and corresponding scale factors (right) for semileptonic c -jet samples measured for different MV2c10 working points; statistical uncertainties are shown.

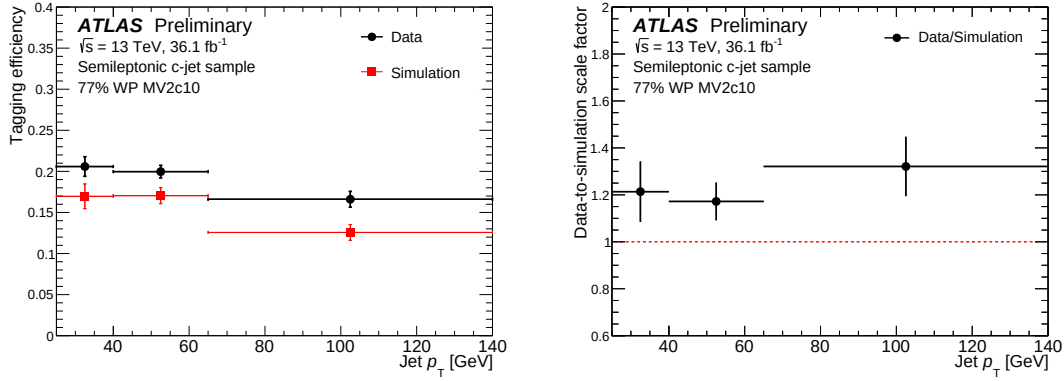


Figure 10.5: Tagging efficiencies (left) and corresponding scale factors (right) for semileptonic c -jet samples measured as a function of jet p_T for the 77% MV2c10 working point; statistical uncertainties are shown.

$$\alpha_{\text{sim}}^{\text{corr}} = \frac{\epsilon_{Wc}^{\text{corr sim}}}{\epsilon_{Wc(\mu)}^{\text{corr sim}}}, \quad (10.5)$$

where $\epsilon_{Wc(\mu)}^{\text{corr sim}}$ and $\epsilon_{Wc}^{\text{corr sim}}$ are the efficiencies measured, respectively with and without the soft muon requirement, on the corrected simulated event sample.

Figure 10.6 shows the comparison between fragmentation fractions (the probability a given c -hadron emerges from the c -quark fragmentation process) predicted by various MC generators and measured by experiments. Fragmentation fractions predicted by SHERPA 2.2.0 are not in agreement with data and other MC generators, due to a not optimal parameter setting.

In detail, the events are reweighted according to the following c -hadron properties:

- D^0 , D^+ , D_s , Λ_c^+ : fragmentation fraction;

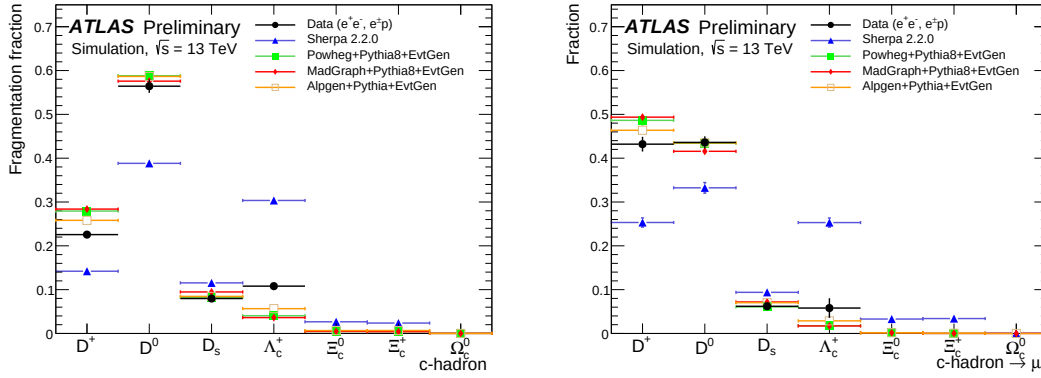


Figure 10.6: Comparison of the fragmentation fractions of c -hadrons predicted by different generator choices and with those experimentally measured [86,107]; results are presented separately for inclusive (left) and semileptonic (right) c -jet samples; data total uncertainties and simulation statistical uncertainties are reported as error bars.

- D^0 , D^+ , D_s , Λ_c^+ : semileptonic branching ratio;
- D^0 , D^+ : exclusive semileptonic decays;
- D^0 : hadronic n -prongs decays.

In the case of fragmentation fractions and semileptonic branching ratios, the most important c -hadrons types (D^0 , D^+ , D_s and Λ_c^+) are considered, while the less frequent c -hadrons (Ξ_c^0 , Ξ_c^+ and Ω_c^0) are only reported, but not reweighted for the analysis purpose due to their very low impact. In the case of exclusive semileptonic branching ratios only D^0 and D^+ mesons are considered, since they constitute most of the c -hadron content after fragmentation. Only D^0 mesons are considered in the reweight procedure regarding topological branching ratios of hadronic n -prongs decays, due to the lack of experimental measurements for the other c -hadrons.

The effect of the impact parameter resolution on the extrapolation correction have been studied on a sample of c -jets from simulated $t\bar{t}$ events, recalculating the MV2c10 output value after the application of the systematic variation of the impact parameter (smearing). The difference between the effect measured on an inclusive and on a semileptonic sample of c -jets is found to be negligible compared to the final measurement uncertainties. Assuming that any other difference seen between data and simulation in the semileptonic c -jet sample is present also in the inclusive c -jet sample (apart from the considered fragmentation fractions and branching ratios), a correction to obtain the inclusive c -jet scale factor, k_{Wc} , can be then computed using the derived extrapolation factors:

$$k_{Wc} \equiv \frac{\epsilon_{Wc}^{\text{data}}}{\epsilon_{Wc}^{\text{sim}}} = \frac{\alpha_{\text{data}} \cdot \epsilon_{Wc(\mu)}^{\text{data}}}{\alpha_{\text{sim}} \cdot \epsilon_{Wc(\mu)}^{\text{sim}}} \equiv \frac{\alpha_{\text{data}}}{\alpha_{\text{sim}}} \cdot k_{Wc(\mu)} \simeq \frac{\alpha_{\text{sim}}^{\text{corr}}}{\alpha_{\text{sim}}} \cdot k_{Wc(\mu)}. \quad (10.6)$$

If the ratio of the extrapolation factors, δ , is defined as:

$$\delta \equiv \frac{\alpha_{\text{data}}}{\alpha_{\text{sim}}} \simeq \frac{\alpha_{\text{sim}}^{\text{corr}}}{\alpha_{\text{sim}}}, \quad (10.7)$$

then Equation 10.6 can be expressed as:

$$k_{Wc} = \delta \cdot k_{Wc(\mu)}. \quad (10.8)$$

The extrapolation factors $\alpha_{\text{sim}}^{\text{corr}}$ (0.82–1.09) are systematically lower than α_{sim} (0.85–1.23), both showing a growing linear trend with the increase of the tightness of the working point. Therefore, the resulting ratios δ , shown in Figure 10.7, are systematically lower than unity with a decreasing trend towards tighter working points. The total systematic uncertainties due to the c -hadron corrections are shown, while statistical uncertainties can be neglected since the nominal and corrected simulation samples contain approximately the same MC seed events.

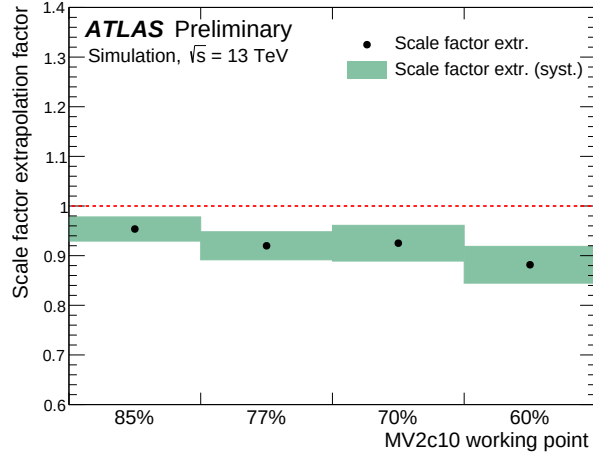


Figure 10.7: Scale factor extrapolation factors for different MV2c10 working points; systematic uncertainties are shown, while statistical uncertainties are omitted since the measurement is performed using the same events.

10.1.6 Systematic uncertainties

The resulting systematic uncertainty contributions to the c -jet tagging efficiency scale factor extrapolated to an inclusive c -jet sample are discussed further below and summarised in Table 10.3. These include event reconstruction effects for the efficiency measured on simulated event samples, uncertainties on both simulated and multijet backgrounds, which affect the efficiency measured on data and the uncertainties coming from the inclusive sample extrapolation procedure discussed in Section 10.1.5.

Source	MV2c10 working point			
	85%	77%	70%	60%
Event reconstruction	2.6	4.8	9.4	6.4
↪ Jet	2.3	3.7	9.2	6.3
↪ Electron	0.1	0.3	0.4	0.3
↪ Muon	0.0	0.0	0.0	0.1
↪ E_T^{miss}	1.3	2.7	1.4	1.4
↪ Pile-up re-weighting	0.1	1.4	0.4	0.2
Simulation and backgrounds	0.5	1.8	4.9	16.9
↪ MC statistics	0.1	1.6	4.2	15.6
↪ MC normalisation	0.2	0.1	0.4	2.4
↪ Multijet method	0.4	0.7	2.4	5.7
↪ Fake factor	0.1	0.4	0.4	2.3
Inclusive extrapolation	2.6	3.0	4.0	4.1
↪ c -hadron fragmentation	0.2	0.4	0.6	0.7
↪ c -hadron semilept. b.r.	1.8	2.0	2.2	2.5
↪ D^+ and D^0 semilept. decays	1.1	1.5	2.6	2.4
↪ D^0 n -prongs hadronic decays	1.5	1.7	1.9	2.1
Systematic	3.7	6.0	11.3	18.5
Statistics	3.3	5.5	8.9	20.2

Table 10.3: Summary of the systematic uncertainty contributions to the c -jet tagging efficiency scale factor (k_{Wc}) for inclusive c -jets; the values are listed in percent for the different MV2c10 working points, integrated in p_T . The breakdown of the three main categories is shown: the systematic uncertainty for each category is calculated adding in quadrature the corresponding sources. The total systematic and statistical uncertainties are shown too.

The corresponding effect on individual jet p_T bins for the different working points is shown in Table 10.4 for the systematic uncertainties on event reconstruction, simulation and backgrounds. The extrapolation scale factors and their systematic uncertainties are measured directly for the different MV2c10 working points; the corresponding measurements in jet p_T bins are not used, due to the limited statistics of the simulated event sample.

Source	Jet p_T bin for 85% / 77% / 70% / 60% MV2c10 working point					
	25–40 GeV		40–65 GeV		65–140 GeV	
Ev. reconstruction	9.8 / 14.0 / 25.5 / 30.5		3.8 / 7.9 / 4.8 / 16.4		5.6 / 6.8 / 12.2 / 10.3	
Sim. and backgrounds	1.1 / 2.3 / 9.6 / 58.2		1.3 / 3.7 / 6.7 / 20.4		0.4 / 3.3 / 8.5 / 26.7	

Table 10.4: Summary of the systematic uncertainty contributions to the data-to-simulation scale factor extrapolated to an inclusive c -jet sample; the values are listed in percent for the different MV2c10 working points and jet p_T bins.

Event reconstruction

Event reconstruction uncertainties are taken into account separately for all the physics objects used in the analysis, to evaluate their impact on the data-to-simulation scale factor. For the jets, the contribution of jet energy scale (JES) [69] and resolution (JER) [108] uncertainties are evaluated for inclusive jets and specifically for b -jets [109] (closure of the JES calibration relative to MC15 simulation, JES uncertainty for b -jets, effective JES uncertainty components, eta intercalibration uncertainties from MC generator modelling uncertainty and statistical uncertainty, overall JER uncertainty, high- p_T resolution term, systematic-shifted resolution); in addition, the contributions from pile-up, punch-through, jet area and jet flavor composition (flavor composition and response uncertainty, dominated by gluon response, pile-up offset effects, ρ topology uncertainty for jet areas, punch-through correction uncertainty) are estimated. For the electrons, contributions for energy scale and resolution [110] and for electron triggering and identification [103] uncertainties are taken into account. For the muons, detector effects [105] are treated separately for the inner tracking system and the outer muon spectrometer; in addition, contributions for the energy scale, reconstruction efficiency and isolation uncertainties are calculated, taking into account both statistical and systematic sources. Other uncertainties include the E_T^{miss} measurement uncertainties [111] (scale, parallel and perpendicular soft terms), the effect of JVT selection [71] on jets and the pile-up re-weighting procedure.

Table 10.5 shows the systematic uncertainty on the inclusive c -jet tagging efficiency scale factor, coming from these event reconstruction effects.

Source	MV2c10 working point			
	85%	77%	70%	60%
Jet Resolution (JER) single NP	-1.8	-2.3	-7.6	5.4
JES uncertainty for b -jets	-0.1	0.0	-0.4	-0.5
Effective JES Uncertainty Component 1	0.0	0.1	-2.0	-1.8
Effective JES Uncertainty Component 2	0.0	-0.3	0.6	0.2
Effective JES Uncertainty Component 3	0.1	0.2	0.1	0.0
Effective JES Uncertainty Component 4	-0.1	-0.2	-0.1	0.0
Effective JES Uncertainty Component 5	-0.0	0.0	0.0	-0.1
Jet Eta intercalibration: MC modelling	0.4	1.1	0.8	-0.2
Jet Eta intercalibration: non-closure	-0.2	-0.2	0.2	-0.6
Jet Eta intercalibration: statistical and method	-0.1	-0.2	-0.7	0.1
Jet Flavor composition	1.0	2.3	3.4	0.1
Jet Flavor response	-0.0	-0.4	0.7	-0.6
Jet Pile-up: Offset, μ term	-0.4	-0.7	-1.1	-1.8
Jet Pile-up: Offset, NPV term	0.5	0.4	0.1	-0.9
Jet Pile-up: p_T term	-0.3	-0.5	-0.1	-0.5
Jet Pile-up: ρ topology uncertainty (jet areas)	0.1	-0.0	-2.9	-0.9
Muon efficiency stat.	0.0	0.0	0.0	0.0
Muon efficiency sys.	0.0	0.0	-0.0	0.1
EGamma resolution	0.0	0.0	-0.2	0.3
EGamma scale	0.1	0.3	0.3	0.2
MET soft-track scale	-0.2	-0.0	0.2	0.0
MET soft-track parallel resolution	-0.3	-1.6	-0.9	1.2
MET soft-track perpendicular resolution	-1.2	-2.1	-1.1	0.8
JVT efficiency	-0.0	-0.0	0.0	-0.0
Pile-up re-weighting	0.1	-1.4	-0.4	0.2
Total	2.6	4.8	9.4	6.4

Table 10.5: Summary of the systematic uncertainty contribution, from event reconstruction, to the c -jet tagging efficiency scale factor extrapolated to an inclusive c -jet sample; the values are listed in percent for the different MV2c10 working points.

Simulated and data-driven backgrounds

The uncertainties coming from background modelling affect the measurement of the c -jet tagging efficiency on data, because this is performed on data events after the subtraction of background events. The backgrounds event yields estimated using simulated event samples, are varied within the statistical uncertainty of the simulated event sample, yielding a large effect, due to the limited amount of simulated events available in each bin of jet p_T and of the MV2c10 distribution. For W +jets, Z +jets, single-top, $t\bar{t}$ and diboson samples, the normalisation uncertainty due the uncertainty on the integrated luminosity (3.2% uncertainty) and to the theoretical prediction of the cross-section are also taken into account (corresponding to 5% for W +jets and Z +jets samples, and to 6% for single-top, $t\bar{t}$ and diboson samples).

For the multijet background, which is predicted using the fake-factor method, the measured fake factors are varied within the statistical uncertainty (fake factor unc. 1). Furthermore, systematic variations on the multijet background are measured varying the MC background components predicted in the control region used to measure the fake factors, with variations on the MC statistics (fake factor unc. 2), MC cross-sections and luminosity uncertainty (fake factor unc. 3). An extra uncertainty due to the method (multijet method) is estimated assuming the matrix method [112] as an alternative method to predict multijet events.

The resulting systematic uncertainties on the inclusive c -jet tagging efficiency data-to-simulation scale factor are shown in Table 10.6.

Source	MV2c10 working point			
	85%	77%	70%	60%
MC statistics	0.1	−1.6	−4.2	−15.6
MC cross-section	0.1	−0.1	−0.4	−2.1
Int. luminosity	0.1	−0.0	−0.2	−1.2
Fake factor unc. 1	−0.0	−0.1	−0.1	−0.5
Fake factor unc. 2	0.0	0.0	0.0	0.1
Fake factor unc. 3	0.1	0.4	0.4	2.3
Multijet method	−0.4	−0.7	−2.4	−5.7
Total	0.5	1.8	4.9	16.9

Table 10.6: Summary of the systematic uncertainty contribution, from background modelling, to the c -jet tagging efficiency data-to-simulation scale factor extrapolated to an inclusive c -jet sample; the values are listed in percent for the different MV2c10 working points.

10.1.7 Extrapolation to inclusive c -jet sample

The scale factors evaluated on the selected semileptonic c -jet sample are corrected to extrapolate the result to a fully inclusive c -jet sample, as explained in Section 10.1.5.

The systematic uncertainty on the extrapolation factor is evaluated varying, within the experimental uncertainty, the corrections for specific fragmentation and decay properties of c -hadrons applied to the corrected simulated event sample. In the correction of fragmentation fraction and semileptonic branching ratio, the largest effect arises from the D^0 hadron, having predicted fractions far from the measured ones, and from the Λ_c hadron, because of the large experimental uncertainty on its fractions. Due to large experimental uncertainties, large contributions to the extrapolation systematic are due to the D^0 specific semileptonic decay ($D^0 \rightarrow \bar{K}^0 \pi^- \mu^+ \nu_\mu$) and the n -prongs hadronic decays.

The resulting uncertainties on the inclusive c -jet tagging efficiency data-to-simulation scale factor are shown in Table 10.7.

Source	MV2c10 working point			
	85%	77%	70%	60%
Fraction D^+	−0.1	−0.3	−0.4	−0.4
Fraction D^0	0.1	0.2	0.4	0.4
Fraction D_s	0.1	0.1	0.0	0.1
Fraction Λ_c	−0.2	−0.2	−0.2	−0.3
BR D^+	−0.3	−0.4	−0.5	−0.6
BR D^0	0.1	0.2	0.2	0.3
BR D_s	0.1	0.1	0.0	0.1
BR Λ_c	1.7	2.0	2.1	2.4
D^+ decay bin 1	−0.1	−0.1	−0.1	0.1
D^+ decay bin 2	−0.1	−0.2	−0.3	−0.5
D^0 decay bin 1	0.0	0.1	0.1	0.2
D^0 decay bin 2	1.1	1.5	2.6	2.3
D^0 n -prongs 0	−1.5	−1.7	−1.9	−2.1
D^0 n -prongs 2	0.0	−0.0	−0.0	−0.1
D^0 n -prongs 4	0.0	0.1	0.2	0.2
Total	2.6	3.0	4.0	4.1

Table 10.7: Summary of the systematic uncertainty contribution, from extrapolation factor, to the c -jet tagging efficiency data-to-simulation scale factor extrapolated to an inclusive c -jet sample; the values are listed in percent for the different MV2c10 working points.

10.1.8 Data-to-simulation scale factors

The c -jet tagging efficiency scale factors k_{Wc} valid for an inclusive sample of c -jets are obtained as the product of the scale factor extrapolation factors δ times the scale factors measured on semileptonic c -jets $k_{Wc(\mu)}$, as reported in Equation 10.8. The integrated scale factors are shown in Figure 10.8, while the scale factors measured as a function of jet p_T are shown in Figure 10.9. The values, including statistical and systematic uncertainties, are reported in Tables 10.8 (integrated) and 10.9 (as

a function of jet p_T).

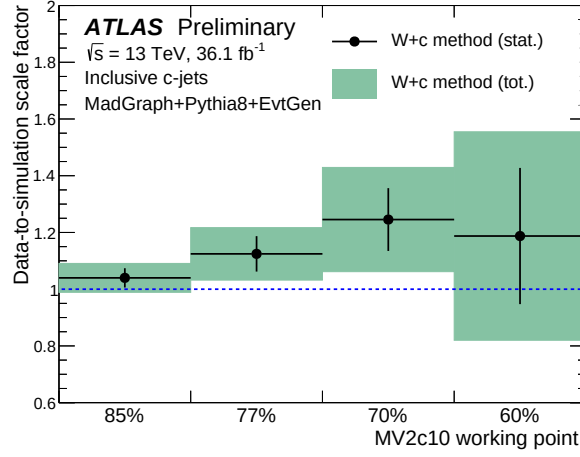


Figure 10.8: Inclusive scale factors measured for the analysed MV2c10 working points; statistical and systematic uncertainties are included.

MV2c10	k_{Wc}
85% working point	1.04 ± 0.03 (stat) ± 0.04 (syst)
77% working point	1.13 ± 0.06 (stat) ± 0.07 (syst)
70% working point	1.25 ± 0.11 (stat) ± 0.15 (syst)
60% working point	1.19 ± 0.24 (stat) ± 0.28 (syst)

Table 10.8: Scale factor for inclusive c -jet samples measured for different MV2c10 working points; statistical and systematic uncertainties are shown.

MV2c10	Jet p_T		
	25–40 GeV	40–65 GeV	65–140 GeV
85% WP	1.07 ± 0.08 (stat) ± 0.11 (syst)	1.01 ± 0.04 (stat) ± 0.05 (syst)	1.07 ± 0.07 (stat) ± 0.07 (syst)
77% WP	1.12 ± 0.13 (stat) ± 0.17 (syst)	1.08 ± 0.08 (stat) ± 0.11 (syst)	1.22 ± 0.13 (stat) ± 0.10 (syst)
70% WP	1.20 ± 0.24 (stat) ± 0.36 (syst)	1.27 ± 0.15 (stat) ± 0.12 (syst)	1.20 ± 0.19 (stat) ± 0.20 (syst)

Table 10.9: Scale factors for inclusive c -jet samples measured for different MV2c10 working points, as a function of jet p_T ; statistical and systematic uncertainties are shown.

10.1.9 Combination with $t\bar{t}$ method results

The final c -jet tagging efficiency scale factors are obtained through the combination of the results obtained with two different methods: the $W+c$ method, described above, and the $t\bar{t}$ method [84], which measures the c -jet scale factors on $t\bar{t}$ events, where one of the W bosons decays leptonically into a charged lepton and neutrino and the other decays to a c - and s -quark.

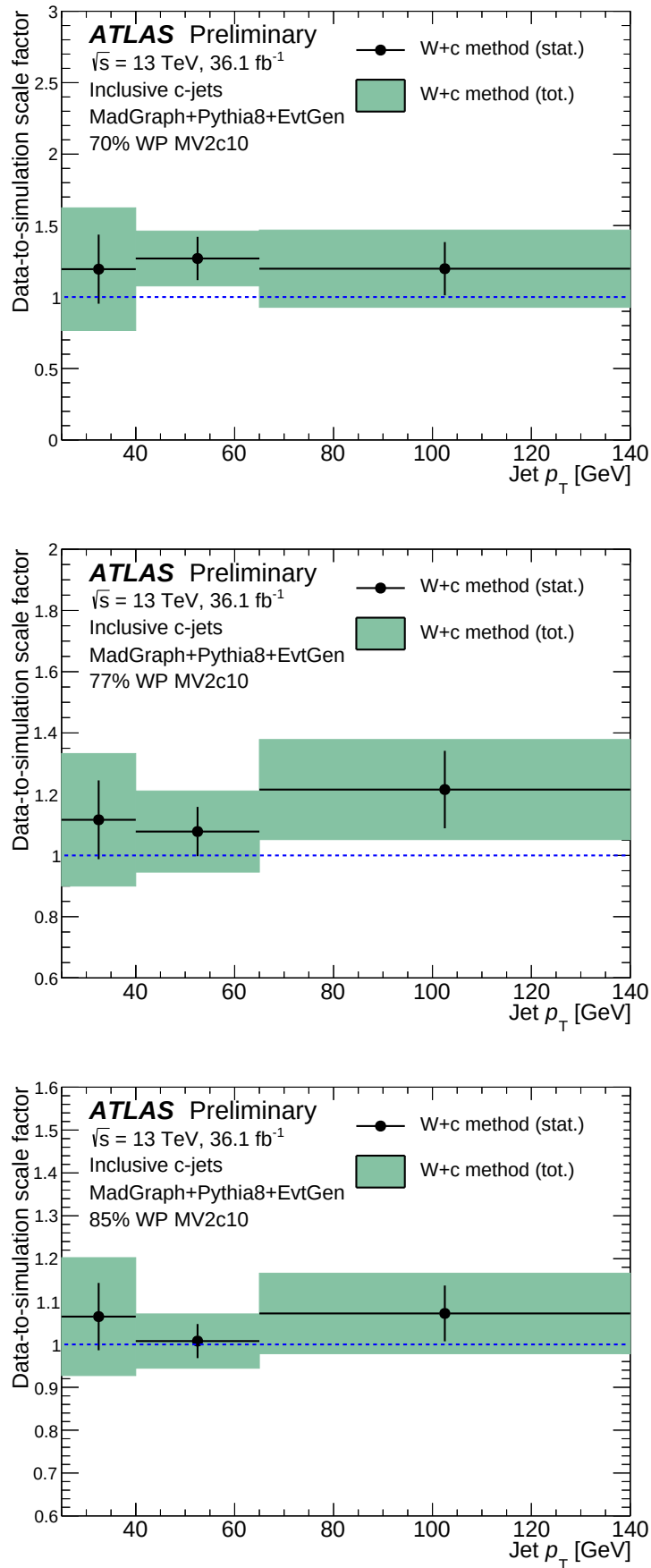


Figure 10.9: c -jet tagging scale factors for the analyzed MV2c10 working points, measured as a function of jet p_T ; statistical and systematic uncertainties are shown.

The $t\bar{t}$ method profits for the high statistics of $t\bar{t}$ events and accesses an inclusive sample of c -jets but it has a worse signal over background ratio with respect to the $W+c$ analysis. The two analyses are then complementary and their combination, besides improving the precision of the final result, is useful to cross-check the compatibility of scale factors determined in different c -hadron final states and production topologies.

To obtain the best overall precision for the c -jet tagging efficiency measurements, a combination of the two set of scale factors (binned in p_T) is performed using a profile likelihood.

The combination takes into account four different types of uncertainty: statistical uncertainty (uncorrelated between analyses and different p_T bins), systematic uncertainty of statistical origin (uncorrelated among p_T bins), systematic uncertainty specific for each analysis (correlated between p_T bins, but uncorrelated between analyses) and common systematic uncertainty (correlated through p_T bins and analyses). The systematic uncertainties in common among the two analyses are those related to the jet energy scale, jet energy resolution, muon and electron identification efficiencies, missing energy and pile-up effects.

The result of scale factor combinations for the MV2c10 tagging algorithm at the 70%, 77% and 85% working points are shown in Figure 10.10, along with the individual scale factors obtained adopting the $W+c$ and $t\bar{t}$ methods.

The fit quality and hence the overall compatibility between the different measurements is evaluated by computing the global χ^2 . For all the combined results the χ^2 probability is above 30%, indicating that the spread between measurements is commensurate with the assigned uncertainties. The combination results have also been compared with those obtained with the “Best Linear Unbiased Estimates” (BLUE) method [113]. The two sets of results are essentially identical, including χ^2 estimates. The precision of the combined results is dominated by the $t\bar{t}$ method; for the jet p_T bins where the precision of the $W+c$ results is competitive, the combination is able to reduce the total uncertainty up to the 30%.

10.1.10 Conclusion

The measurement of the c -jet tagging efficiency has been performed on $W+c$ events [96], with the c -jet identified by a soft muon coming from a semileptonic c -hadron decay. The efficiency is measured on pp collision data collected at $\sqrt{s} = 13$ TeV by the ATLAS experiment. The same measurement is performed on simulated event samples, then a data-to-simulation scale factor is derived, defined as the ratio of the efficiency on data over the efficiency on simulated event samples.

Due to the different c -hadron composition between data and simulation, a correction is derived to extrapolate the data-to-simulation scale factors measured on a semileptonic c -jet sample. After this extrapolation correction, the resulting data-to-simulation scale factors can be applied to an unbiased sample of c -jets.

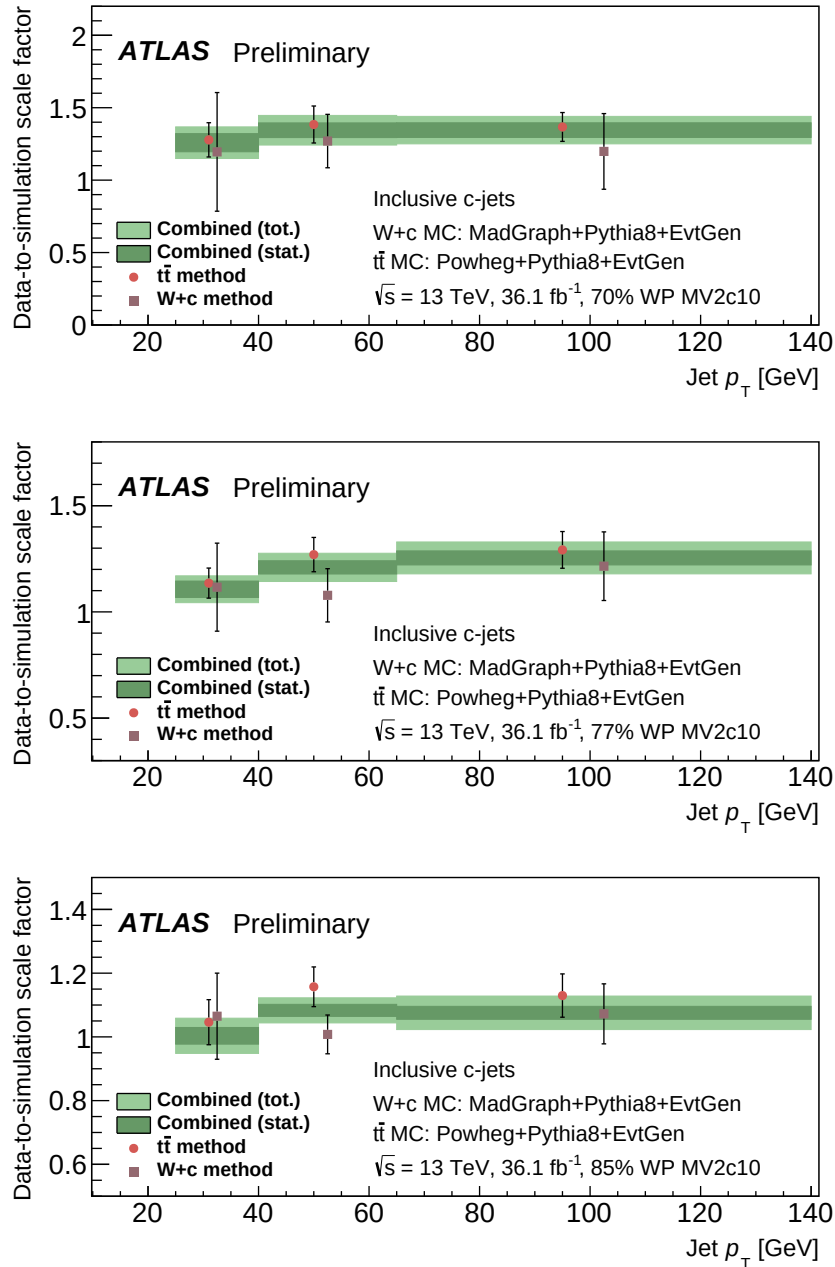


Figure 10.10: c -jet tagging efficiency data-to-simulation scale factors for the MV2c10 tagging algorithm at 70%, 77% and 85% efficiency, obtained by combining the results of the $W+c$ and $t\bar{t}$ methods. The dark green band represents the statistical uncertainty of the combined scale factor while the light green band shows the total uncertainty. The red points indicates $t\bar{t}$ method results, while brown squares indicates $W+c$ method results.

Results are presented for the 60%, 70%, 77% and 85% efficiency working points of the MV2c10 b -tagging algorithm: integrated and as a function of jet p_T . The integrated data-to-simulation scale factors show a growing linear trend between 1.0 and 1.2 as the working point is tightened from 85% to 60%.

The data-to-simulation scale factors measured on $W+c$ events are found to be compatible with the results of the measurements performed on $t\bar{t}$ events [84]. The combination of the results is able to reduce the uncertainties on the final data-to-simulation scale factors up to the 30% for the jet p_T bins where the two methods results have competitive precision.

The $W+c$ and $t\bar{t}$ methods have been deployed for the Run 2 measurements of the b -tagging performance on c -jet samples. Their results are compatible, with competitive precision. These methods will be maintained (and improved) for the performance measurements of new software releases b -tagging algorithms (see Section 10.2). The scale factors measured on $W+c$ and $t\bar{t}$ events are used by ATLAS analyses to calibrate the b -tagging efficiency on c -jets. Among the main results of the recent ATLAS physics analyses based on b -tagging, there is the discovery of the Higgs boson decay to $b\bar{b}$.

10.2 Release 21 calibration

The efficiency on data and simulation needs to be measured as well for the six release 21 b -tagging algorithms. Performance studies have been performed with the $W+c$ method. These studies show that the SMT enhanced algorithms (MV2c10mu, MV2c10rnn, DL1mu, DL1rnn) have different shapes in output distributions compared to the basic algorithms (MV2c10 and DL1) due to the correlations with the soft muon based event selection exploited in the $W+c$ method (see Section 10.2.1).

The MV2c10 and DL1 algorithms are now recommended to be used by ATLAS physics analyses. The $W+c$ method has been used to check the response of the improvement in the simulation of the impact parameters resolution. The preliminary results of the studies performed on 36 fb^{-1} of 2015 and 2016 data are reported in Section 10.2.2: compatible results are obtained by the measurements performed with $W+c$ and $t\bar{t}$ methods.

The $W+c$ method is not the only calibration method to exploit the soft muon topology. Other b -tagging calibration measurements may be affected by SMT or will become excessively complex in order to cope with SMT enhanced algorithms. For these and other motivations, four new algorithms have been recently developed: MV2c10r and DL1r, which includes only RNNIP inputs (contrary to MV2c10rnn and DL1rnn, which included also SMT inputs) and MV2c10rmu and DL1rmu, including both RNNIP and SMT inputs (likely MV2c10rnn and DL1rnn). The ATLAS b -tagging community is starting to study in deep the new algorithms in order to deliver to the ATLAS collaboration the best option in terms of higher discriminating performance and lower related uncertainties.

The $t\bar{t}$ method, based on an inclusive sample of c -jets, is not sensitive to soft muon variables exploited in the SMT algorithm, showing no bias in SMT enhanced algorithms. It is now being used as reference method for the b -tagging efficiency measurements on charm jet samples in release 21.

10.2.1 Bias on SMT enhanced algorithms

As described in Section 7.3.2, along with a revised version of MV2c10 and the new algorithm DL1, there are enhanced algorithms that benefit from the introduction of SMT and RNNIP as inputs to the multivariate tools. The $W+c$ calibration method, based on a sample of c -jets selected exploiting the soft muon from the semileptonic c -hadron decay, is sensitive to the introduction of the SMT contribution inside the release 21 High Level Taggers. This is confirmed by the output distribution of software release 21 b -tagging algorithms shown in Figure 10.11. Simulated events are used to populate a inclusive c -jet sample (top left: Sherpa 2.2.1, bottom left: Powheg+Pythia8+EvtGen), while ATLAS data events (top right: 2016 data, bottom right: 2015 and 2016 data) with the $W+c$ topology are used for the sample of c -jets with semileptonic c -hadron decay. The shape of the ordinary algorithms (MV2c10 and DL1) is similar to the one of the enhanced algorithms (MV2c10mu, MV2c10rnn, DL1mu, DL1rnn) for the case of inclusive c -jets (Figure 10.11, left). The shapes are instead different in case of c -jets selected with the $W+c$ topology, which includes the requirement of a soft muon from the semileptonic c -hadron decay inside the c -jet (Figure 10.11, right). This bias is preventing the application of the $W+c$ method to measure the scale factors on c -jet tagging efficiency for the SMT enhanced algorithms.

10.2.2 Preliminary results

An estimation of the data-to-simulation scale factors for software release 21 MV2c10 b -tagging algorithm has been performed with the $W+c$ method on 2015 and 2016 data. The scale factors, integrated on jet p_T , are shown in Figure 10.12: the results show a growing linear trend between 0.95 and 1.15 as the working point is tightened from 85% to 60%. The improvement in the simulation of the impact parameters resolution has reduced the difference in the efficiency measured on data versus the efficiency measured on simulated samples, therefore reducing the scale factors, which now appear to be close to the unity with respect to the scale factors measured on release 20.7 algorithms (see Figure 10.8).

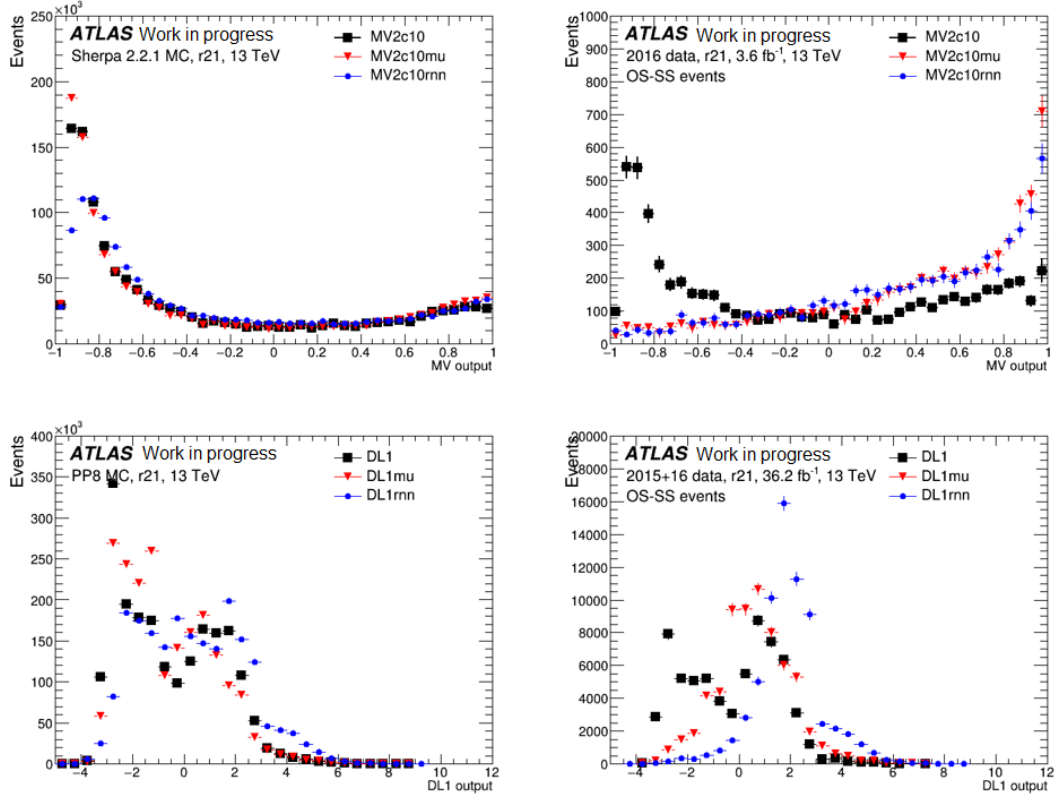


Figure 10.11: Output distribution of software release 21 b -tagging algorithms from a inclusive c -jets sample (left) and from a sample c -jets with semileptonic c -hadron decay (right) from $W+c$ events. Simulated events are used to populate a inclusive c -jet sample (top left: Sherpa 2.2.1, bottom left: Powheg+Pythia8+EvtGen), while ATLAS data events (top right: 2016 data, bottom right: 2015 and 2016 data) with the $W+c$ topology are used for the sample of c -jets with semileptonic c -hadron decay. Top row: the shape of the MV2c10 distribution is very similar to the enhanced algorithms (MV2c10mu and MV2c10rnn) in the case of inclusive c -jet sample, while significant discrepancies are visible in the case of c -jets with semileptonic c -hadron decay. Bottom row: the shape of the DL1 distribution differs from the DL1mu and DL1rnn shapes.

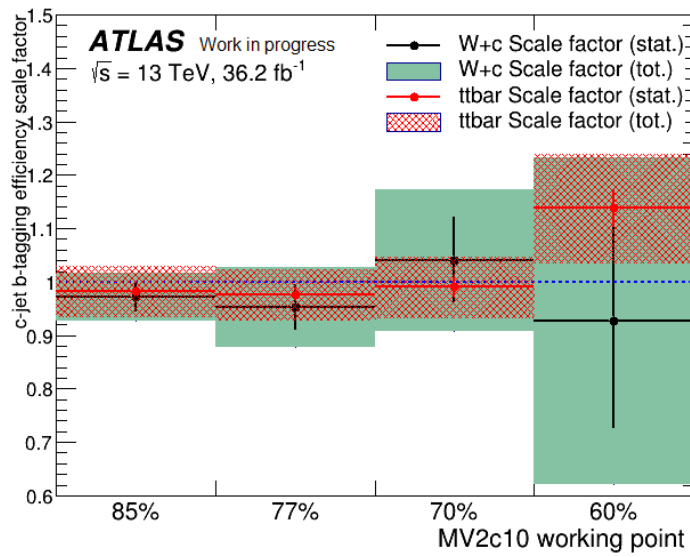


Figure 10.12: Inclusive scale factors measured for the analysed MV2c10 working points (software release 21) with the $W+c$ method and the $t\bar{t}$ methods: the results from the two methods are compatible within the uncertainties. Statistical and systematic uncertainties are shown as error bars and coloured contours. Systematic uncertainties for the $W+c$ method are extrapolated from the release 20.7 measurement.

Chapter 11

Preparatory studies on the $W+c$ cross section at 13 TeV

The experience I gained during the measurement of the b -tagging efficiency on a charm jet sample, selected via the associated production of W boson and c -jet, is being exploited to measure the production cross section of this process. The production of a W boson in association with a single charm quark in proton-proton collisions is described at the Leading Order (LO) accuracy in QCD by the scattering of a gluon and a down-type quark (d , s , b). The relative contribution from each of the three families in the initial state is determined by the proton PDFs and by the quark-mixing matrix elements V_{cd} , V_{cs} and V_{cb} . At the LHC the dominant production channels are $gs \rightarrow W^-c$ and $gs \rightarrow W^+\bar{c}$ (see Figure 9.5). The contribution of diagrams containing d - and b -quarks is instead respectively about 10% [114] or negligible, given the suppression introduced by the corresponding quark-mixing matrix elements V_{cd} and V_{cb} . The Next-to-Leading-Order (NLO) QCD terms [115] are dominated by one-loop corrections to the dominant channels and by the tree-level $gg \rightarrow sWc$ and $qs \rightarrow qWc$ diagrams.

Given the fact that the $pp \rightarrow WcX$ production is dominated by the $gs \rightarrow Wc$ process and corresponding higher-order corrections, this measurement is directly sensitive to the s -quark distribution function in the proton at momentum-transfer values on the order of the W -boson mass. Previous measurements of the s -quark PDF have been provided by neutrino-nucleon deep inelastic scattering (DIS) experiments [116, 117], and by the joint analysis of inclusive W and Z production data from ATLAS and DIS data from HERA [118].

The idea to use $W+c$ events as probes of the strange-quark distribution function has been discussed already for Tevatron experiments, but was limited by the large uncertainty on the cross section measurement. The large production rates available at the LHC provided the first opportunity for a measurement with sufficient precision to constrain the s -quark PDF at x around 0.01, as highlighted in Section 1.4.2.

In this Chapter, the preparatory studies towards the measurement of the production of a W boson in association with a single charm quark using 140 fb^{-1} of pp

collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the LHC from 2015 to 2018 will be presented. In events where a W boson decays to an electron or muon, the charm quark is tagged by the presence of a jet of particles containing its semileptonic decay to a soft muon. Similarly to what done for the b -tagging efficiency measurement (see Section 10), the signal is extracted by the subtraction of events with opposite-sign and same-sign charge leptons (OS–SS).

11.1 Data and MC samples

This analysis is based on data recorded by the ATLAS detector in LHC pp collisions at the center of mass energy $\sqrt{s} = 13$ TeV in 2015, 2016, 2017 and 2018, corresponding to integrated luminosities of 3.2 fb^{-1} , 32.9 fb^{-1} , 44.3 fb^{-1} and 59.9 fb^{-1} , respectively.

The $W+c$ signal and all backgrounds sources containing W or Z bosons or top quarks are modeled using simulated event samples. The additional multijet background, important due to the presence of misidentified reconstructed leptons, is going to be estimated with a data-driven method.

The default W +jets and Z +jets simulated event samples (including the $W+c$ signal) are produced with MADGRAPH v1.15 [97] interfaced to PYTHIA8 [42] with A14 general-purpose high- p_T tunes [98]. As a crosscheck, these are compared with samples produced adopting different generators: SHERPA v2.2.0 [44] using the NNPDF 3.0 PDF set [7] in conjunction with dedicated parton-shower tuning developed by the SHERPA authors; POWHEG-BOX v2.2 [88–90] interfaced to PYTHIA8 with AZNLO tunes [119]; All samples, except for those generated with SHERPA, use the EVTGEN package [100] to describe the b - and c -hadron decay processes.

Diboson (ZZ , WZ and WW) samples are generated using SHERPA 2.2.2 using the NNPDF 3.0 PDF set [7]. Top-pair and single-top (t -channel, s -channel and $W+t$) events are generated using POWHEG-BOX v2 [88–90], interfaced to PYTHIA8, with the EVTGEN package and the PERUGIA 2012 tunes [120].

Main results are obtained with MADGRAPH W +jets and Z +jets simulated event samples. The comparison between MADGRAPH and other MC generators (SHERPA, POWHEG) is then used to derive systematic uncertainties coming from signal and background modeling.

All generated samples are passed through the simulation of the ATLAS detector [121] based on GEANT4 [45]. The same offline reconstruction methods used with data events are applied to the simulated events samples. Minimum-bias events generated by PYTHIA8 [42] are used to simulate multiple pp interactions in the same and nearby bunch crossings (pile-up).

11.2 Object reconstruction and event selection

The final state for this analysis is defined by the presence of an isolated lepton (electron or muon), coming from the W boson decay, accompanied by sizeable missing transverse energy E_T^{miss} , and a jet containing a muon. Finally, the signal is extracted as the difference between events with OS charged leptons and events with SS charged leptons. The criteria used to select object candidates has already been described in Section 10.1.2 (for the electron channel only). In particular, the criteria used to select the electron, the soft muon and the jet, as well as the selections on the missing energy and W -boson transverse mass are in common with the b -tagging performance measurement. The improvements achieved with respect to that event selection strategy are outlined in the followings.

Since both electron and muon W -boson decay channels are explored, the available statistics is doubled with respect to the strategy used in the b -tagging performance measurement. Data used for this analysis are triggered either by single-muon or by single-electron triggers [101, 102] with minimum p_T threshold of 24 or 26 GeV, depending on the data-taking period.

Only one signal W -lepton (electron or muon) with $p_T > 27$ GeV is allowed in the event. A veto is applied to events with any further lepton, based on a looser lepton selection. These leptons are defined as having $p_T > 15$ GeV and passing loose isolation criteria.

For the $W \rightarrow \mu\nu$ channel, the reconstructed isolated muon is identified by matching two tracks in the inner detector and in the muon spectrometer. Medium quality muons candidates are accepted, requiring to pass medium identification criteria [105]. Muons selected for this analysis are required to satisfy tight calorimeter and track isolation criteria that accept real isolated muons, with an efficiency of 90% at 20 GeV and 99% at 60 GeV, while rejecting muons coming from hadrons decay within a jet. Furthermore, good candidates are required to match the online muon that triggered the event with a ΔR criteria. Similarly to the electron track, the inner detector track of the muon must satisfy $|d_0|/\sigma(d_0) < 3$ and $|z_0 \sin\theta| < 0.5$ mm. The muon is required to have $p_T > 27$ GeV and must fall in the range $|\eta| < 2.5$.

Two additional requirements, with minor impact on the signal, are applied in the muon channel to suppress the Z +jets and the Υ backgrounds. First, the event is discarded if the invariant mass of the two muons (the soft muon and the muon from the decay of the W -boson candidate) is close to either the Z -boson mass (*i.e.* 80-100 GeV) or the Υ mass (*i.e.* 8-11 GeV). Second, the angular p_T balance of the two muons is required to be higher than 0.6, with the angular balance variable defined as the ratio of the module of the 4-vector sum of the two muons p_T over the sum of the modules of the two muons p_T .

Differently to the event selection described in Section 10.1.2, in this measurement events are allowed to have either one or two jets with $p_T > 25$ GeV and $|\eta| < 2.5$. The identification of the c -jet by the semileptonic c -hadron decay is performed requiring

one and only one of the two selected jets to contain exactly one reconstructed muon with an angular separation between the muon and the jet axis $\Delta R < 0.5$. Allowing one additional jet in the event, grants about 30% more statistics in the signal events, with a minor increase in background events.

11.2.1 Preliminary kinematic distributions

While the processing of the data samples and MC samples for the simulation of the signal and backgrounds is in progress, it is possible to check the kinematic distributions of the $W+c$ events selected from MadGraph+Pythia8+EvtGen W +jets simulated sample. The results, normalized to the statistics of the full Run 2 data sample (140 fb^{-1}) are shown in Figure 11.1. About $0.8 \cdot 10^6$ signal events are expected after OS–SS subtraction, considering both electron and muon channels ($0.9 \cdot 10^6$ OS and $0.1 \cdot 10^6$ SS events).

11.3 Cross section measurement

The integrated and differential cross sections as a function of the pseudorapidity of the lepton from the W -boson decay are going to be measured for the fiducial region defined in Table 11.1.

The fiducial cross section measures the cross sections times the branching ratio $W \rightarrow \ell\nu$ and it is determined in a fiducial region defined in MC simulation in terms of the W -boson kinematics: $p_T^\ell > 27 \text{ GeV}$, $|\eta^\ell| < 2.5$, $p_T^\nu > 25 \text{ GeV}$ and $m_W^T > 40 \text{ GeV}$, where ℓ and ν are the charged lepton and the neutrino from the decay $W \rightarrow \ell\nu$. The charm quark is identified by a muon from the semileptonic decay of a charmed hadron embedded in a particle-level jet with $p_T^{\text{jet}} > 25 \text{ GeV}$ and $|\eta^{\text{jet}}| < 2.5$. The cross section is measured for events with exactly one c -jet and one possible additional non- c -jet. Particle-level jets are constructed in simulation from stable particles, including muons and neutrinos, using the anti- k_t algorithm with a radius parameter R of 0.4. The particle-level c -jet is defined as the one containing a weakly decaying c -hadron with $p_T > 5 \text{ GeV}$, within $\Delta R < 0.3$.

The signal yield is defined as the number of events where the c -hadron originates from a c -quark with charge sign opposite to the charge of the W boson, minus the number of events where the c quark and W boson have the same charge sign.

1 charged lepton from W -boson decay with: Electron/muon $p_T > 27$ GeV Electron/muon $ \eta < 2.5$
1 neutrino from W -boson decay with: Neutrino $p_T > 25$ GeV
W -boson with: W -boson $m_T > 60$ GeV
1 or 2 jets with: jet $p_T > 25$ GeV jet $ \eta < 2.5$
Exactly 1 c -jet identified by a c -hadron with: c -hadron $p_T > 5$ GeV $\Delta R(c\text{-hadron}, \text{jet}) < 0.3$ W -boson and c -hadron charge: OS–SS
Exactly 1 muon inside the c -jet with: soft muon $p_T > 4$ GeV soft muon $ \eta < 2.5$ $\Delta R(\text{soft muon}, c\text{-jet}) < 0.5$ W -boson and soft muon charge: OS–SS

Table 11.1: Fiducial region phase space to be used for the $W+c$ cross section measurement.

The production cross section in the fiducial region, σ_{fid} , is calculated as:

$$\sigma_{\text{fid}} = \frac{N - B}{C \cdot \int \text{Ldt}}, \quad (11.1)$$

where N is the number of candidate events observed in data, B is the number of background events and $\int \text{Ldt}$ is the integrated luminosity of the dataset. The correction factor C is determined from MC simulation and accounts for detector efficiency, acceptance and resolution effects.

The differential cross sections are determined in intervals of $|\eta^\ell|$ from the same procedure used to determine the total fiducial cross section, but with yields and acceptance corrections determined separately for each $|\eta^\ell|$ bin.

11.4 Outlook

The strategy for the $W+c$ cross section measurement is set. The ATLAS experiment has collected a considerable amount of data during Run 2 operations. The full Run 2 statistics (140 fb^{-1}) is going to be used for this measurement. According to preliminary studies, about $0.8 \cdot 10^6$ events are selected on signal MC samples after the OS–SS subtraction, including both electron and muon channels of the W -boson decay. The processing of the data and MC samples for the simulation of the signal and backgrounds is in progress, meanwhile the analysis group is defining the strategy

for the unfolding.

The integrated and differential cross sections are going to be measured for the fiducial region defined in Table 11.1, as a function of the pseudorapidity of the lepton from the W -boson decay. Other kinematic variables are being considered as well for the differential cross section measurement. The amount of selected OS–SS events is a sufficient statistics to allow a differential cross section measurement in many $|\eta^\ell|$ bins.

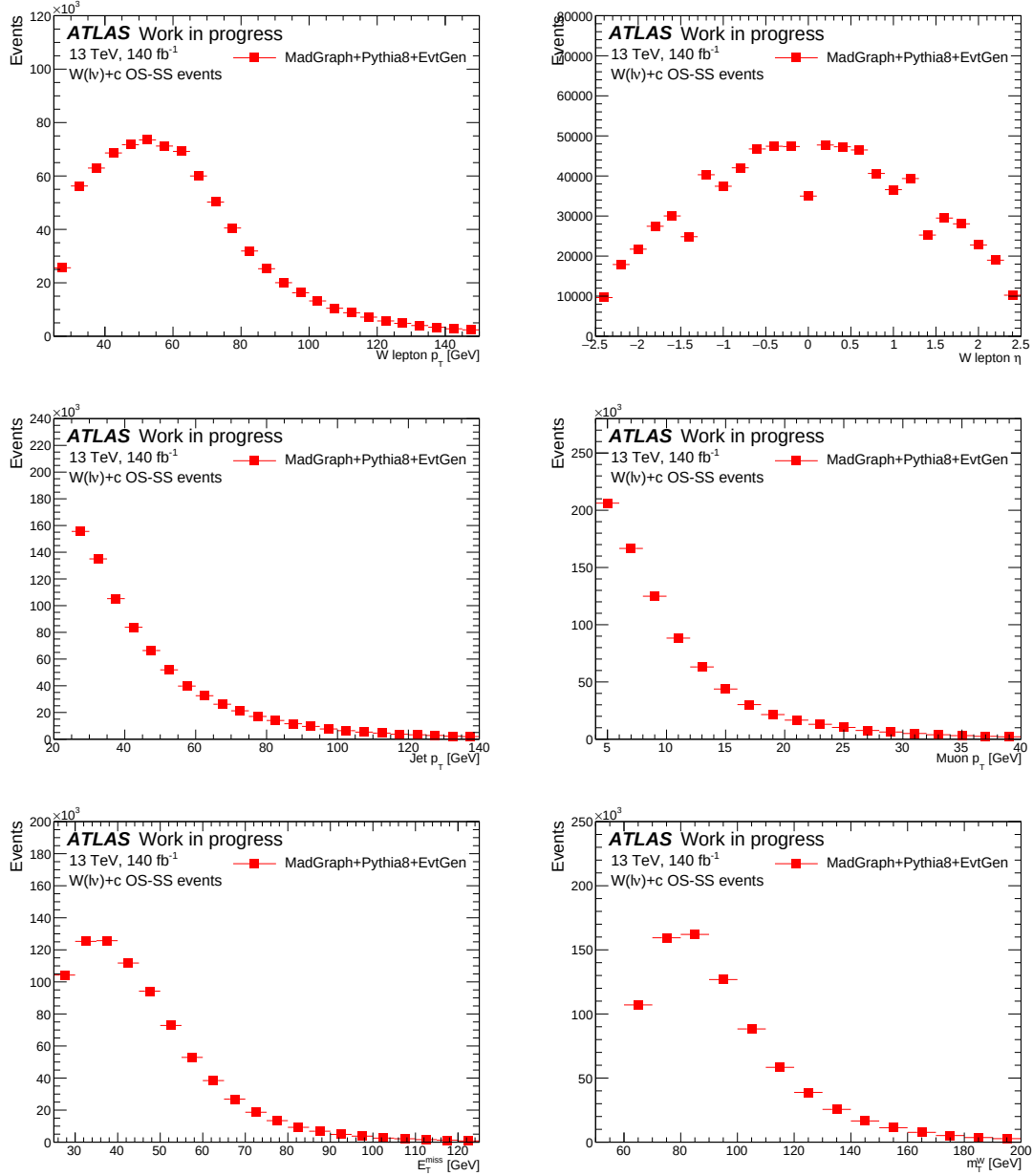


Figure 11.1: Kinematic variables distributions of $W+c$ events after OS-SS subtraction, from MadGraph+Pythia8+EvtGen W +jets simulated sample, normalized to 140 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV. Events from both the electron and muon channels of the W -boson decay are added together.

Chapter 12

Bonus: outreach activities

In these years, I devoted part of my time to outreach activities. During a one-year research period at CERN (July 2017 - June 2018), I joined the CERN visit service and I attended the training to be an official CERN guide. In particular, as an ATLAS official guide, I guided tours to the ATLAS visitor center and to the underground ATLAS experimental cavern.

I participated to outreach activities in Genoa as well, in particular to the Genoa Science Festival, which is one of the main science fairs in Italy, reaching up to 200000 visitors each year, spread in 10 days of activities (conferences, shows, hands-on laboratories). The ATLAS Genoa group has already participated to the 2015 and 2017 editions, proposing hands-on activities on particle physics topics.

The 2018 activity, “A caccia di particelle” (“Hunting for particles”), is based on the tracking detectors. We decided to propose such an activity because the ATLAS Genoa group has a high expertise in tracking detectors:

- Title: A caccia di particelle - Uniamo i puntini per scoprirne le proprietà!
- When: 25th October - 5th November 2018
- Location: Piazza delle Feste, Porto Antico, Genoa, IT
- Attendance: about 1400 visitors

In each 60 minutes session, we explained to the general public the tracking detectors, starting with an introduction on the particle physics experiments. The main part of the activity is based on three games developed in python and pygame libraries:

1. Tracking: find the best matching tracks over 8 silicon ID hits from $Z\mu\mu$ events;
2. Triggering: save or skip events looking for $Z\mu\mu$ events, based on the reconstructed tracks;
3. Template fitting: extract mass and yields of particles from template fit to invariant mass distributions.



Figure 12.1: Setup of the outreach activity presented at the 2018 Genoa Science Festival.

I took part in the technical proposal, preparing the material for the call and following the selection steps. Then I prepared the equipment and the contents of the activity together with the ATLAS Genoa group, assembled the setup (see Figure 12.1) and welcomed the visitors as a scientific explainer. The activity has been attended by about 1400 visitors in 10 days.

Conclusions

In the last four years, the ATLAS experiment has gone through the Run 2 physics program, collecting about 140 fb^{-1} of proton-proton collisions data at the record energy of $\sqrt{s} = 13 \text{ TeV}$. In these years, I have contributed in several ways to the ATLAS experiment. The details of these efforts have been documented in this thesis.

In the context of the ATLAS flavour tagging group, I have performed the measurement of the c -jet tagging efficiency on a sample of c -jets produced in association with W bosons, with the c -jet identified by a soft muon coming from a semileptonic c -hadron decay. The b -tagging performance of MV2c10, the recommended b -tagging algorithm of the ATLAS software release 20, has been calibrated with c -jets in its 60%, 70%, 77% and 85% efficiency working points, integrated and as a function of the jet p_T . The measurement is performed on 13 TeV data and simulated event samples, then a data-to-simulation scale factor is derived, defined as the ratio of the efficiency on data over the efficiency on simulated event samples. Due to the different c -hadron composition between data and simulation, a correction is derived to extrapolate the data-to-simulation scale factors measured on a semileptonic c -jet sample. After this extrapolation correction, the resulting data-to-simulation scale factors can be applied to an unbiased sample of c -jets. The results of the $W+c$ method are found to be compatible with the results of the measurements performed on $t\bar{t}$ events. The combination of the results of the two measurements has reduced the uncertainties on the final data-to-simulation scale factors up to the 30%. The integrated data-to-simulation scale factors of MV2c10 (release 20.7) show a growing linear trend between 1.0 and 1.2 as the working point is tightened from 85% to 60%. Thanks to the constant efforts of the algorithm development group, 6 new b -tagging algorithms have been deployed for the software release 21. The measurement of the c -jet data-to-simulation scale factors of these new algorithms is ongoing. The $W+c$ and $t\bar{t}$ methods have been deployed for the Run 2 measurements of the b -tagging performance on c -jet samples. Their results are compatible, with competitive precision. These methods will be maintained (and improved) for the performance measurements of new software releases b -tagging algorithms. The scale factors measured on $W+c$ and $t\bar{t}$ events are used by ATLAS analyses to calibrate the b -tagging efficiency on c -jets. Among the main results of the recent ATLAS physics analyses based on b -tagging, there is the discovery of the Higgs boson decay to $b\bar{b}$.

The involvement in the ATLAS flavour tagging group led me to join the activities

of the b -tagging data quality. I have updated the software used for the monitoring in order to be ready for the 2018 data taking and followed this throughout the year. The updates include improvements to the trigger pre-selection of the events, the introduction of histograms to cope with the instantaneous luminosity increase, the compatibility with the b -tagging algorithms of the release 21, the introduction of histograms to monitor jets with soft-muons from semi-leptonic b -hadron decays. Thanks to these updates, we have been able to assess the quality of the b -tagging performance during 2018 proton-proton collisions. The performance have been stable through the year, compatible with the 2017 data taking performance, despite the increase in instantaneous luminosity and the ageing of the detector. For the first time, the b -tagging tools have been enabled on events from heavy ion collisions. I have updated the monitoring tools in order to be able to assess the quality of the b -tagging performance in events from heavy ions collisions. With the experience gained in software updates, I acted as b -tagging data quality expert during 2018, helping in following up the issues and in the organizational aspects of the data quality shifts. After collecting the feedback from each of the data-quality sub-groups, the official good run lists of 2018 data taking (59.9 fb^{-1} of proton-proton and $1423.9 \mu\text{b}^{-1}$ of Pb-Pb collisions) have been finalized and delivered to the ATLAS collaboration for physics analyses. I will continue my role as b -tagging data quality maintaining and migrating the software towards the software release 22.

Thanks to the experience with $W+c$ events topology gained during the measurement of the b -tagging efficiency, I have started the measurement of the production cross section of $W+c$ events. The goal of this measurement is to compare results with different PDF models, since the $pp \rightarrow WcX$ production is directly sensitive to the s -quark PDF (dominated by the $gs \rightarrow Wc$ process). The software developed for the b -tagging efficiency measurement has been adapted to the software release 21 to proceed with this measurement using 140 fb^{-1} of pp collision data collected at $\sqrt{s} = 13 \text{ TeV}$. The events with a W boson in association with a single charm quark are selected similarly to what done for the b -tagging efficiency measurement, with significant improvements in the statistics. Events with an additional jet are allowed, granting about 30% more statistics in the signal events. Both electron and muon W -boson decay channels are explored, doubling therefore the available statistics with respect to the strategy used in the b -tagging performance measurement. The basis are established, the measurement is in progres, along with the documentation of the results.

I have been involved as well in laboratory activities within the ATLAS Genoa group, which has a long tradition in silicon detectors. In particular, I played a crucial role to two test beam experiments at the CERN HiRadMat facility in July 2017 and May 2018. In these tests, recent silicon modules (IBL pixel, ITk strip) have been exposed to a high energy and intensity beam (440 GeV proton beam) to study the performance degradation of real detector components in case of beam-loss scenarios. I joined this effort from the beginning, taking part in each of the

steps of these experiments. I selected the 3 IBL modules to be used in the tests, measuring their properties in the lab. Then I prepared and installed the setup (PCs, cables, powering and read-out) in the HiRadMat facility tunnels. I took part in the data taking and, finally, I performed the data analysis. The first and main result of these experiments is the survival of the IBL modules after the transit of 288 bunches at 2 mm beam radius, with 10^{11} protons per bunch. Both IBL 3D modules survived to this level of radiation in 2017, as well as the IBL planar module in 2018. The three IBL modules were operated with different configurations during the beam transit: two configurations were used to reproduce the standard status of the ATLAS detectors when LHC is delivering stable or non-stable beams. Therefore a lower limit on the damage threshold of IBL modules has been set at $\sim 10^{13}$ protons/cm², well above the irradiation that ITk pixel modules may receive in the worst case of possible beam-loss scenarios at the High-Luminosity LHC. This is a high interest measurement, since silicon detectors were never exposed directly to such a high energy and intensity proton beam before. There are plans to repeat the experiment with the final prototype of the ITk pixel module, along with other different prototypes of ITk strip modules, after the end of Long Shutdown 2, when the HiRadMat facility will resume the operations.

Within the laboratory activities, I have been involved in the R&D process of the Wafer Level Packaging technology, measuring the properties (planarity, placement accuracy) of six 6-inch wafers rebuilt starting from previously diced tiles by MicroFab Solutions in Trento, within the AIDA-2020 european project. The quality assessment of these wafers has been performed to compare the properties with the standard requirements of pixel detector modules production for high energy physics applications. The thickness of the wafers have been reduced step-by-step, from 675 μm (1 and 2) to 400 μm (3 and 4) and then to 300 μm (5 and 6) confirming the solidity of the compound. The first four wafers produced show a significant bending in the separation line between two tiles, visible in both X and Y profiles. The planarity has improved thanks to a different tape choice, the wafer 6 profiles does not present bending lines (overall bowing below 100 μm). The tiles placement accuracy seems to be improved as well thanks to the new tape. The WLP process is close to meet the technical specifications required for wafers to be used in the wafer processing steps for silicon detector production. Further optimizations are required towards the industrialization of this process. Small productions for future silicon tracking detectors may already profit from the WLP process. In case of mass production for large area silicon detectors, a more detailed inspection of the output wafers is recommended, along with further tests that were not performed at this stage.

During my Ph.D., I had the possibility to spend one year at CERN, thanks to a CERN-INFN fellowship. I exploited this period to be in close contact with the ATLAS detector operations. I contributed to the 2018 data taking activities with shifts at the Inner Detector desk in the ATLAS Control Room. I participated as

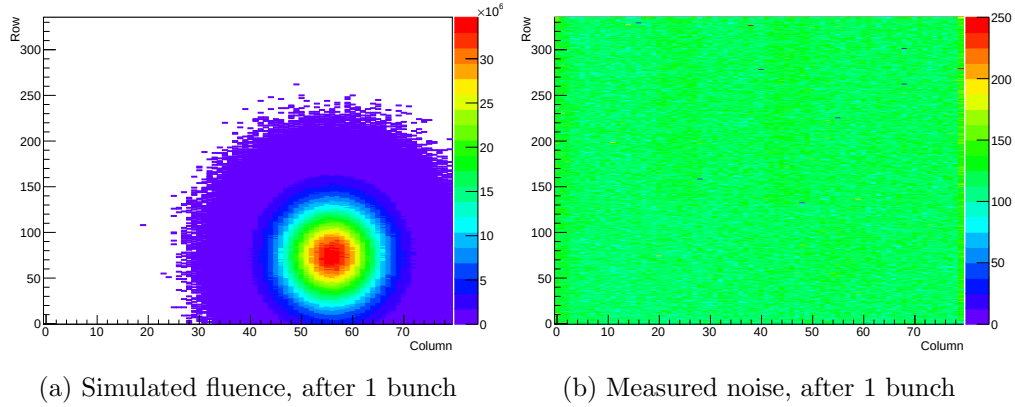
well to outreach activities, leading guided tours to the ATLAS visitor center and inside the underground experimental cavern. The hands-on activity presented at the 2018 Genoa Science Festival, to which I have contributed in the proposal and contents preparation, has welcomed a total of 1400 visitors in 10 days.

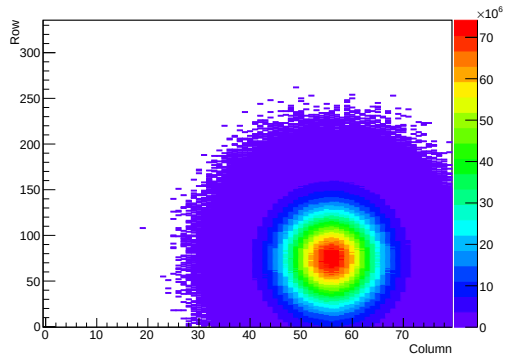
It might seem that all these activities are disconnected from one another, instead they are closely connected. They are all fundamental steps of a high energy physics experiment: from the R&D on wafer production processes, to test beam activities on detector components, from data taking operations to data quality assessment, from physics objects performance calibration to data analysis and, finally, to public outreach activities. Nowadays, it is not easy to participate to all the phases of a high energy physics experiment. This is still possible in big collaborations like the ATLAS experiment.

Appendix: noise evolution during beam-loss scenario test beam

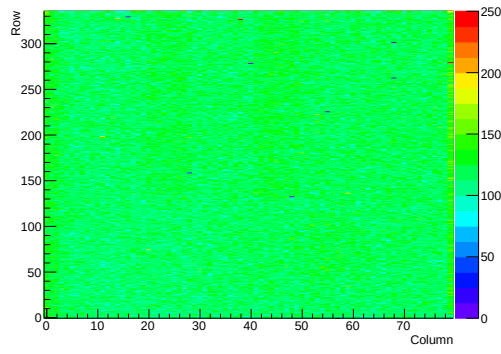
With the goal of estimating the performance loss of pixel detector modules in case of beam-loss scenario (see Chapter 5), a IBL planar pixel module has been exposed to an unprecedented high energy and intensity beam during the 2018 test beam experiment at the HiRadMat facility. The 2 mm radius beam pulses includes 1, 4, 12, 24, 36, 72, 144 and 288 bunches delivered on the same spot. The module has survived the complete beam program. The effect of the high instantaneous irradiation is shown in terms of the increase of the noise value per pixel obtained from threshold scan measurements.

The full series of noise maps, along with the corresponding simulated proton fluences, are shown in Figure 0. The estimated fluence in terms of number of protons per pixel reaches 13×10^9 in the center of the beam spot after the last beam pulse. The noise starts to increase after 12 bunches, then costantly increases after each beam pulse in the irradiated region, reaching values up to 300 electrons (Figure 0, right), while on the top and left corners it remains stable at about 120 electrons.

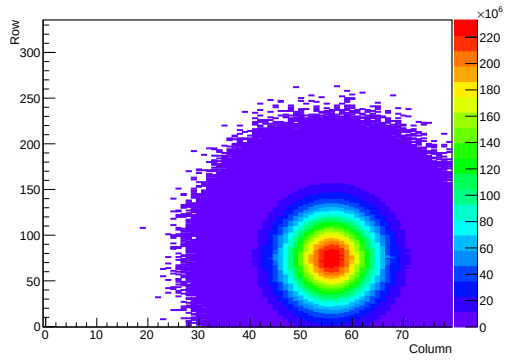




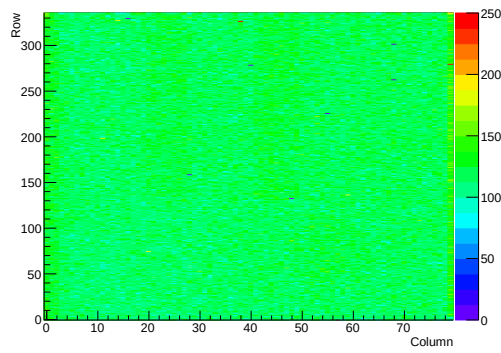
(c) Simulated fluence, after 1+1 bunches



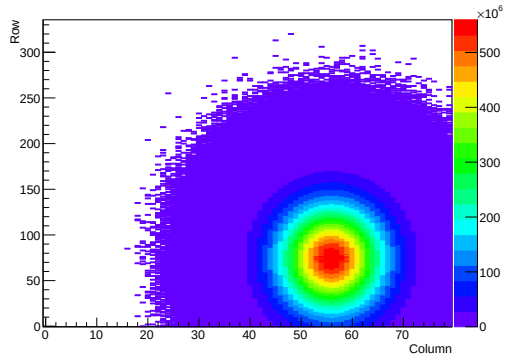
(d) Measured noise, after 1+1 bunches



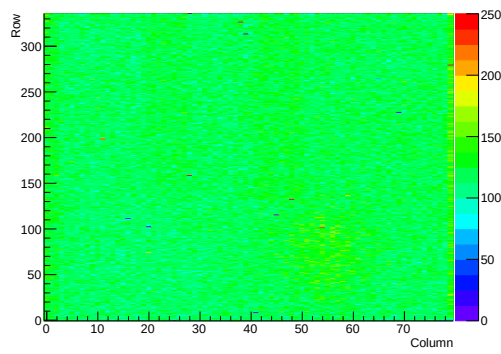
(e) Simulated fluence, after 4 bunches



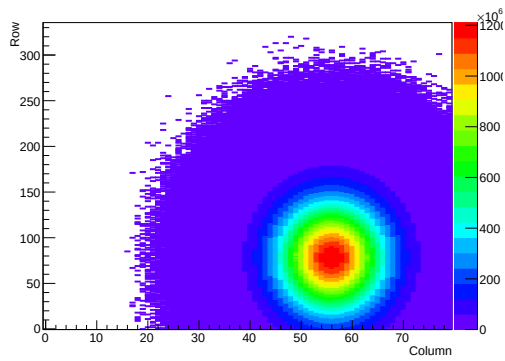
(f) Measured noise, after 4 bunches



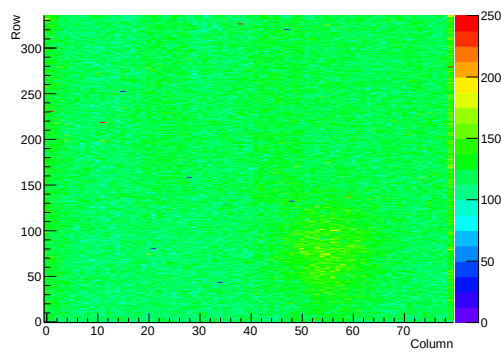
(g) Simulated fluence, after 12 bunches



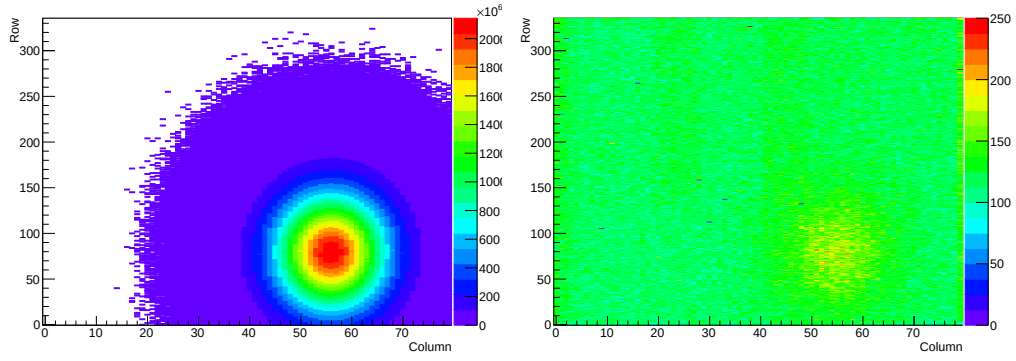
(h) Measured noise, after 12 bunches



(i) Simulated fluence, after 24 bunches

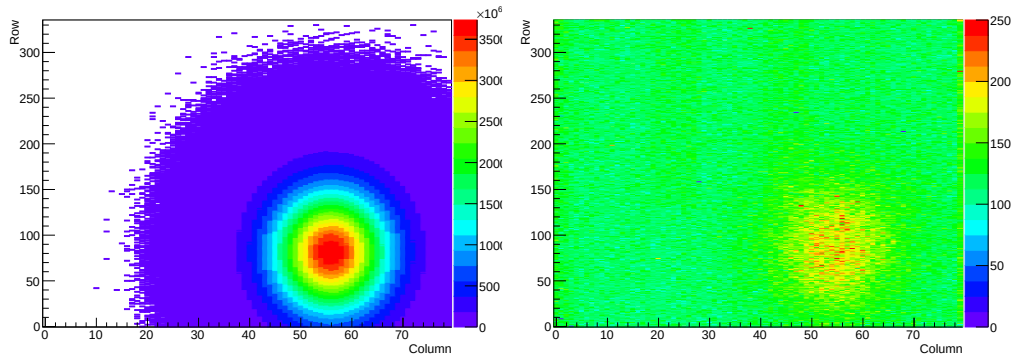


(j) Measured noise, after 24 bunches



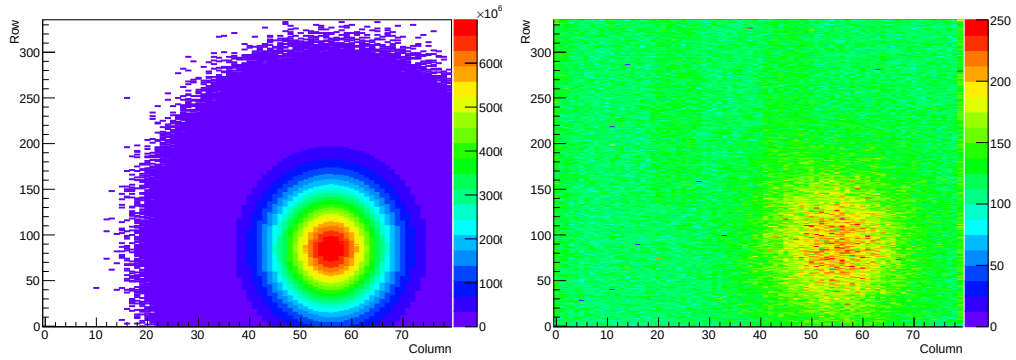
(k) Simulated fluence, after 36 bunches

(l) Measured noise, after 36 bunches



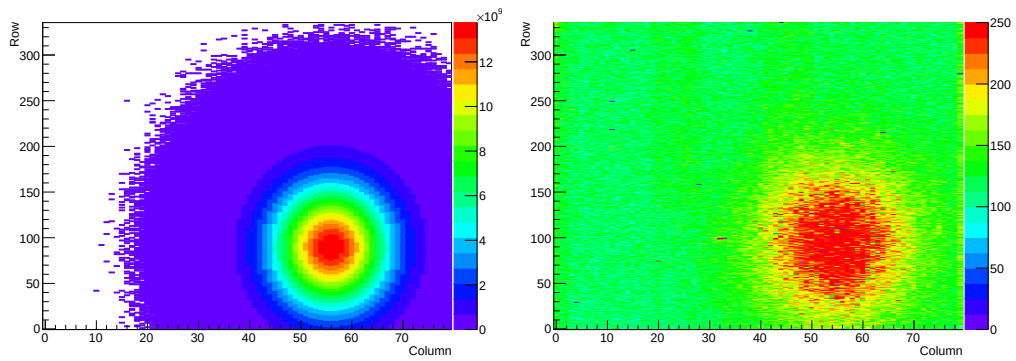
(m) Simulated fluence, after 72 bunches

(n) Measured noise, after 72 bunches



(o) Simulated fluence, after 144 bunches

(p) Measured noise, after 144 bunches



(q) Simulated fluence, after 288 bunches

(r) Measured noise, after 288 bunches

Figure 0: Simulated proton fluence per pixel (left) and noise measurement from threshold scan (right) relative to the complete program of 2 mm radius beam (2018).

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