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Observation of top-quark pair production in heavy-ion collisions with the ATLAS detector

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Introduction

- The top quark is the heaviest known elementary particle, with $m_t = 172.52 \pm 0.33\ GeV$ [ATLAS-CONF-2023-066]
- It decays before hadrons can form via: $t \rightarrow Wb$
- At the LHC, the top quark produced predominantly in $t\bar{t}$ pairs
  - The top quark decays primarily via three channels: **hadronic, lepton+jets, and dilepton modes**
- First measurement of $t\bar{t}$ production in **p+Pb** by ATLAS with $L_{int} = 165\ nb^{-1}$ at $\sqrt{s_{NN}} = 8.16\ TeV$, on **lepton + jets** and **dilepton channels**

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  - Top quarks serve as novel probes of **nuclear Parton Distribution Functions** (nPDFs) in p+Pb collisions
    - Particularly in the anti-shadowing region at **large Bjorken-x values**
- $t\bar{t}$ process is observed for the first time in the $e\mu$ channel in **Pb+Pb** by ATLAS with $L_{int} = 1.9\ nb^{-1}$ at $\sqrt{s_{NN}} = 5.02\ TeV$

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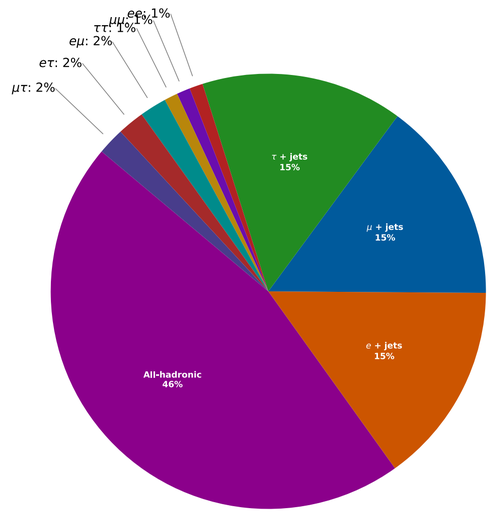
  - Top quarks also provide new insights into the properties of **Quark-Gluon Plasma (QGP)** in Pb+Pb
    - Can indicate information about time evolution of the medium



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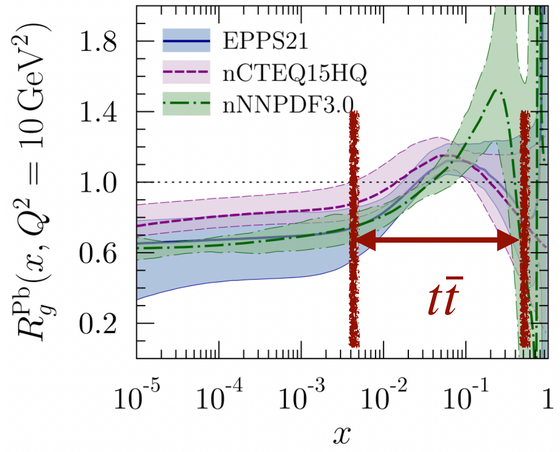
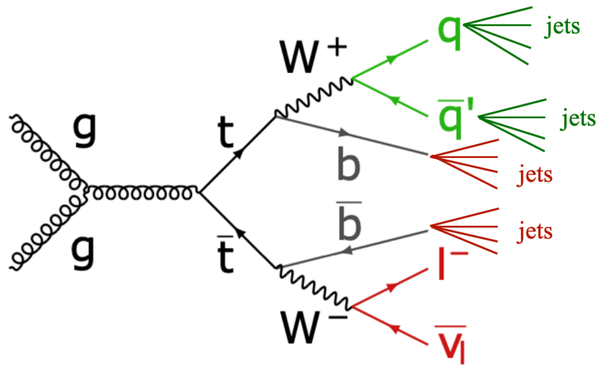


Analysis strategy: p+Pb

- The analysis focuses on **lepton+jets** and **dilepton** channels, with electrons (e) and muons (μ)
  - **Lepton selection:**
    - Transverse momentum $p_T > 18GeV$
    - Pseudorapidity ($|\eta|$) < 2.47 for electrons, and < 2.5 for muons
    - Identification is based on the **'Medium'** likelihood-based criteria, with additional isolation requirements applied
  - **Jets selection:**
    - **HI** jets reconstructed using anti-k_t algorithm, with R= 0.4
    - p_T > 20 GeV and $|\eta|$ < 2.5
    - **Particle Flow (PF)** anti-k_t with R = 0.4 jets used for b-tagging, 85% efficient
    - **HI** jets are matched to PF jets using $\Delta R < 0.3$
  - **Channel-specific requirements:**
    - **Lepton+jets:** ≥ 4 HI jets
    - **Dilepton:** Two opposite-sign leptons with m_{ll}>15 GeV, and ≥ 2 HI jets

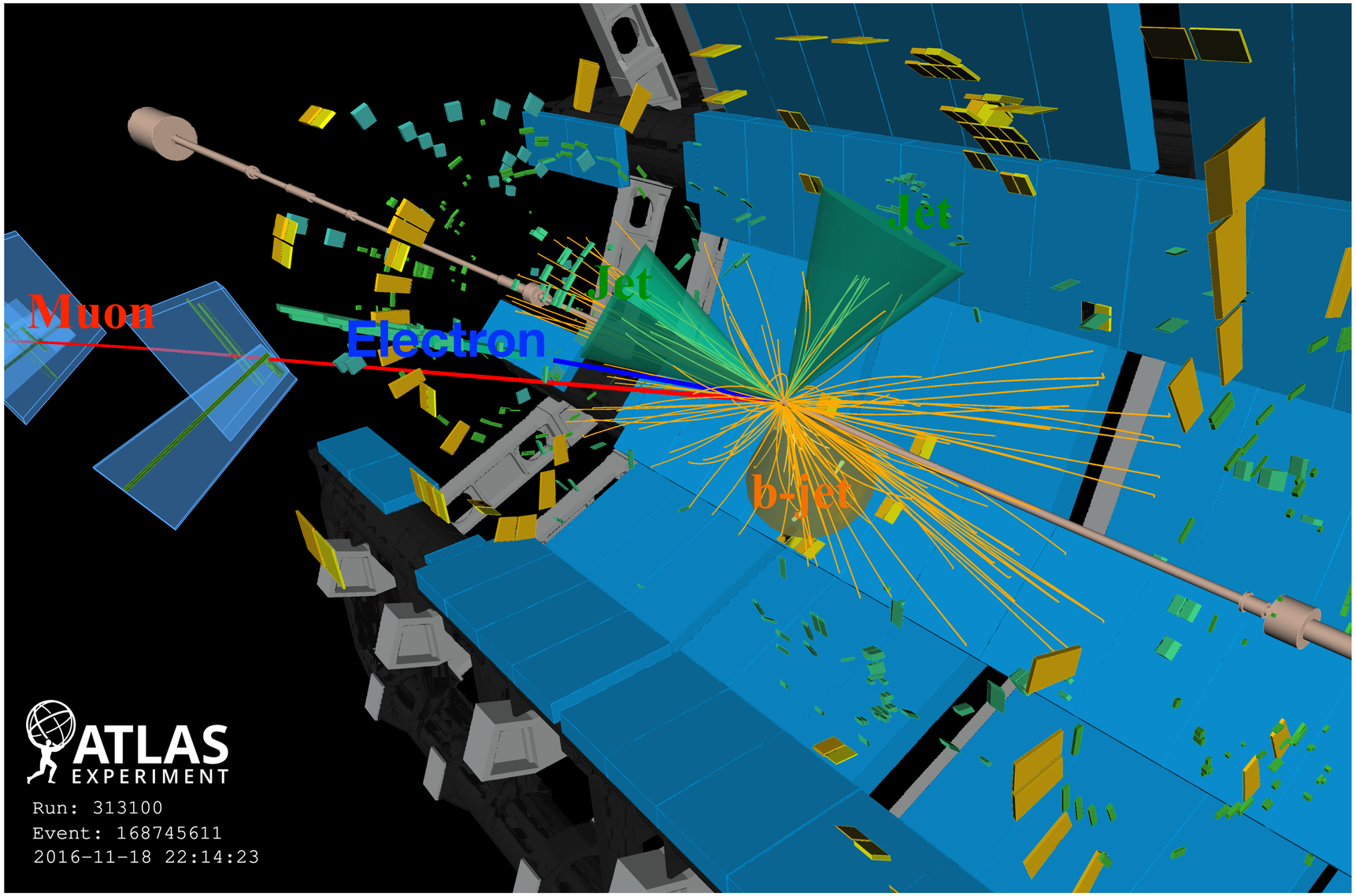


Six signal regions (SR)

- **Lepton + jets**
  - e + jets
  - $\mu + jets$
  - 1b
  - ≥2b
- **Dilepton**
  - 1b
  - ≥2b

b:multiplicity of b-tagged jets

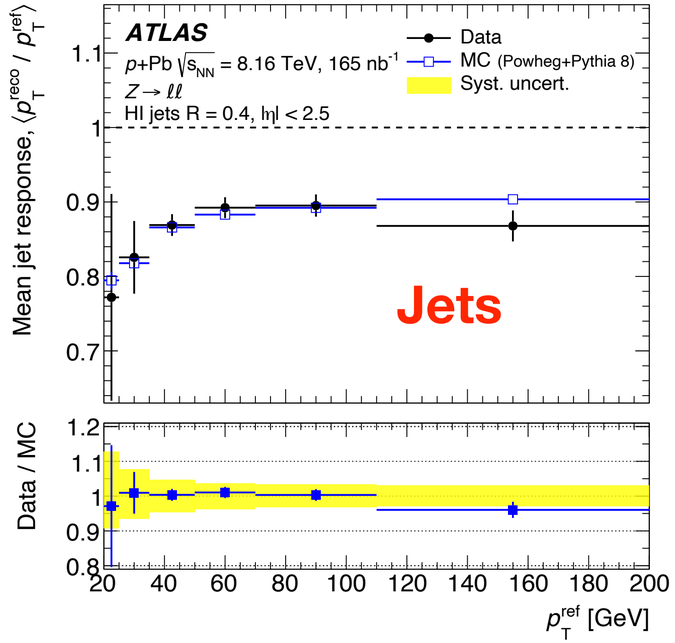
$t\bar{t}$ event candidate: p+Pb



Event candidate from the **dilepton** channel with an **electron** (blue track), **muon** (red track), one **b-jet** (yellow cone) and **two jets** (green cones)

Jet reconstruction

- Jets are reconstructed from calorimeter energy deposit using the **anti-k_t** algorithm with jet radius of **R = 0.4**
  - Jets reconstructed this way are referred to as **heavy-ion (HI)** jets
  - The jet kinematics are corrected event-by-event for the contribution from **underlying event (UE)**
- The second type of jets in **p+Pb** is reconstructed from **particle-flow (PF)** objects that combine information from topological clusters of calorimeter energy deposits and inner detector tracks
  - **The b-tagging** information is inherited from the matched PF jets to HI jets
- **No *b*-tagging** requirements are applied to the jets in **Pb+Pb**



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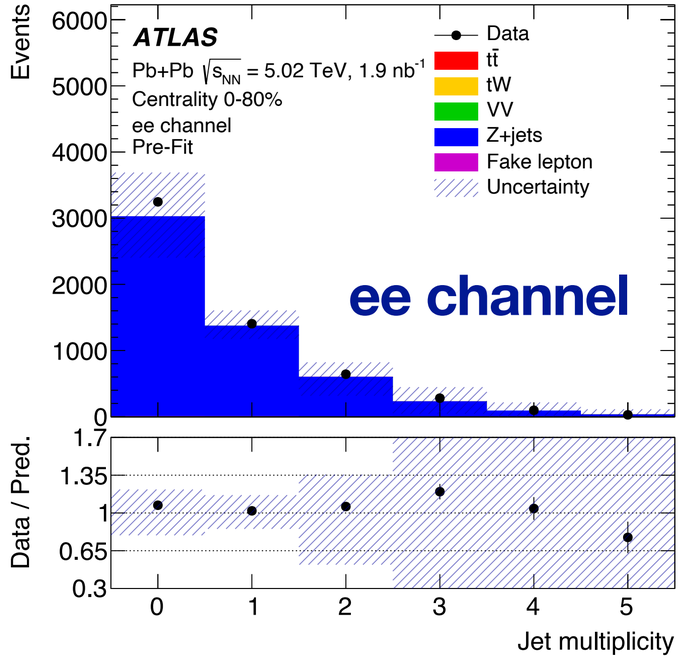

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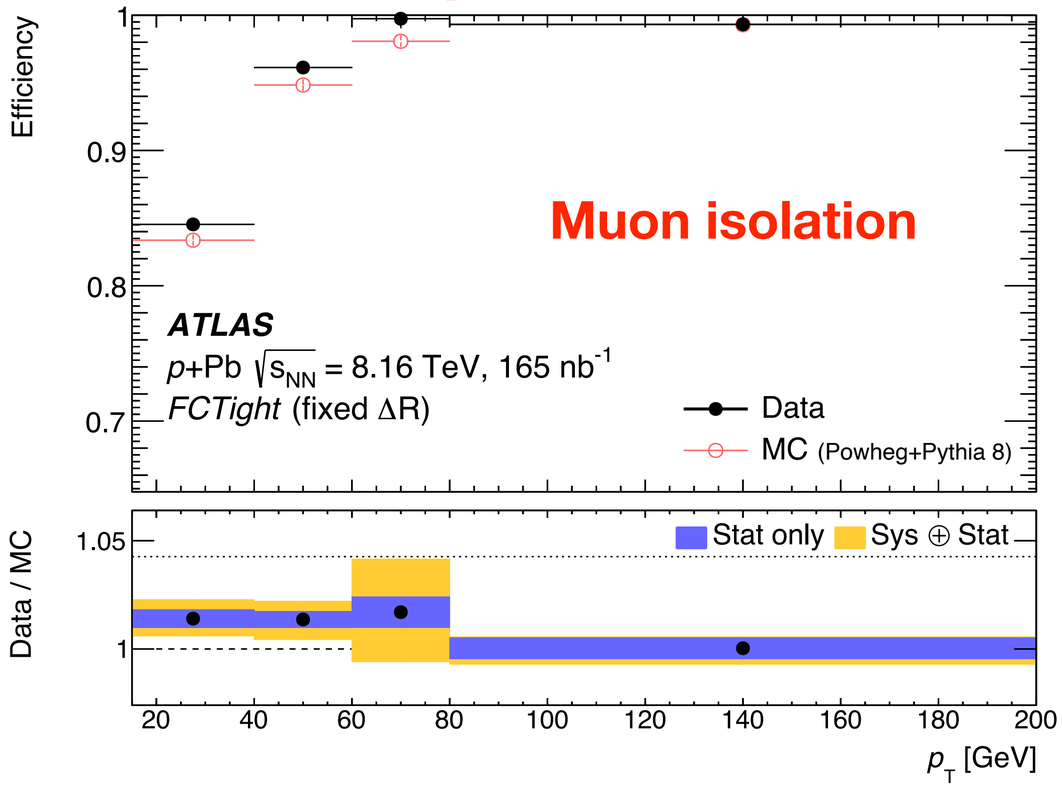
Jet and lepton performance

p+Pb



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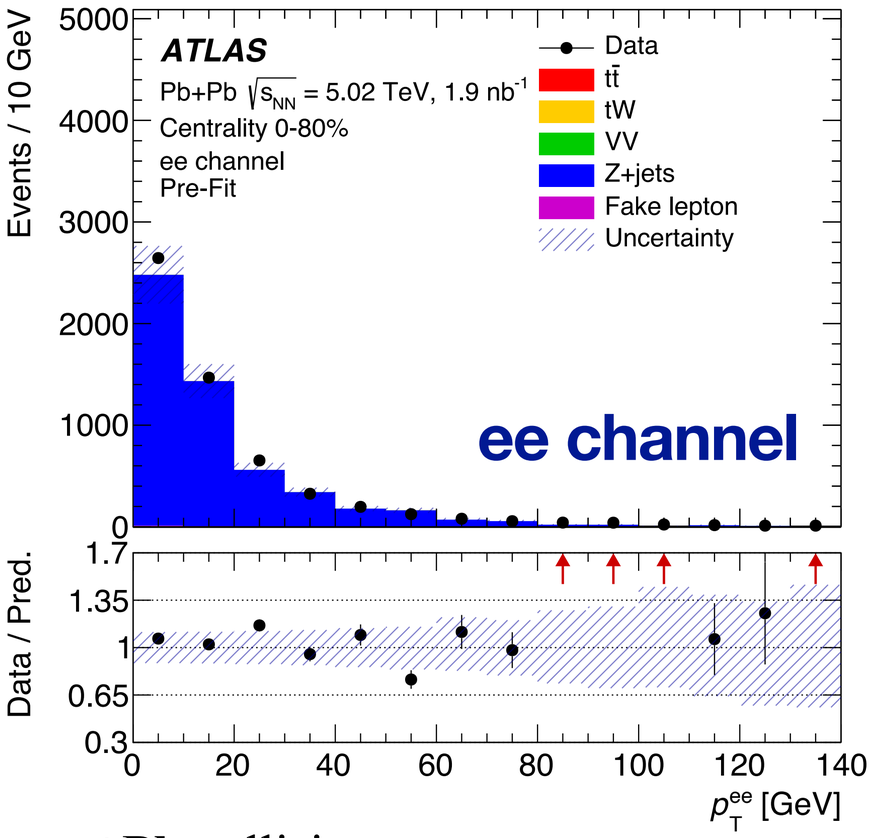
Pb+Pb



HION-2022-10

- Dedicated calibration and performance studies in low-pileup **p+Pb** collisions
  - Identified MC mismodelling applied as a set of scale factors $SF = \frac{\epsilon_{data}}{\epsilon_{MC}}$
- Corrections are implemented to account for **jet quenching** and **fake jets** contributions
- **Low-pileup electron-photon** calibration and dedicated electron and muon scale factors are applied

Analysis strategy: Pb+Pb

- The analysis focuses on **dilepton** channels, with electrons (e) and muons (μ)
  - **Electrons selection:**
    - Transverse momentum $p_T^e > 18\text{GeV}$
    - Pseudorapidity ($|\eta|$) < 2.47
    - Loose identification and isolation criteria applied
  - **Muons selection:**
    - $p_T >$ 15 GeV and $|\eta| < 2.5$
    - Loose identification and isolation criteria applied
  - **Jets selection:**
    - **HI** jets reconstructed using anti-k_t algorithm, with R= 0.4
    - $p_T >$ 35 GeV and $|\eta| < 2.5$
  - **Dilepton:**
    - 0-80% collision centrality
    - Primary vertex

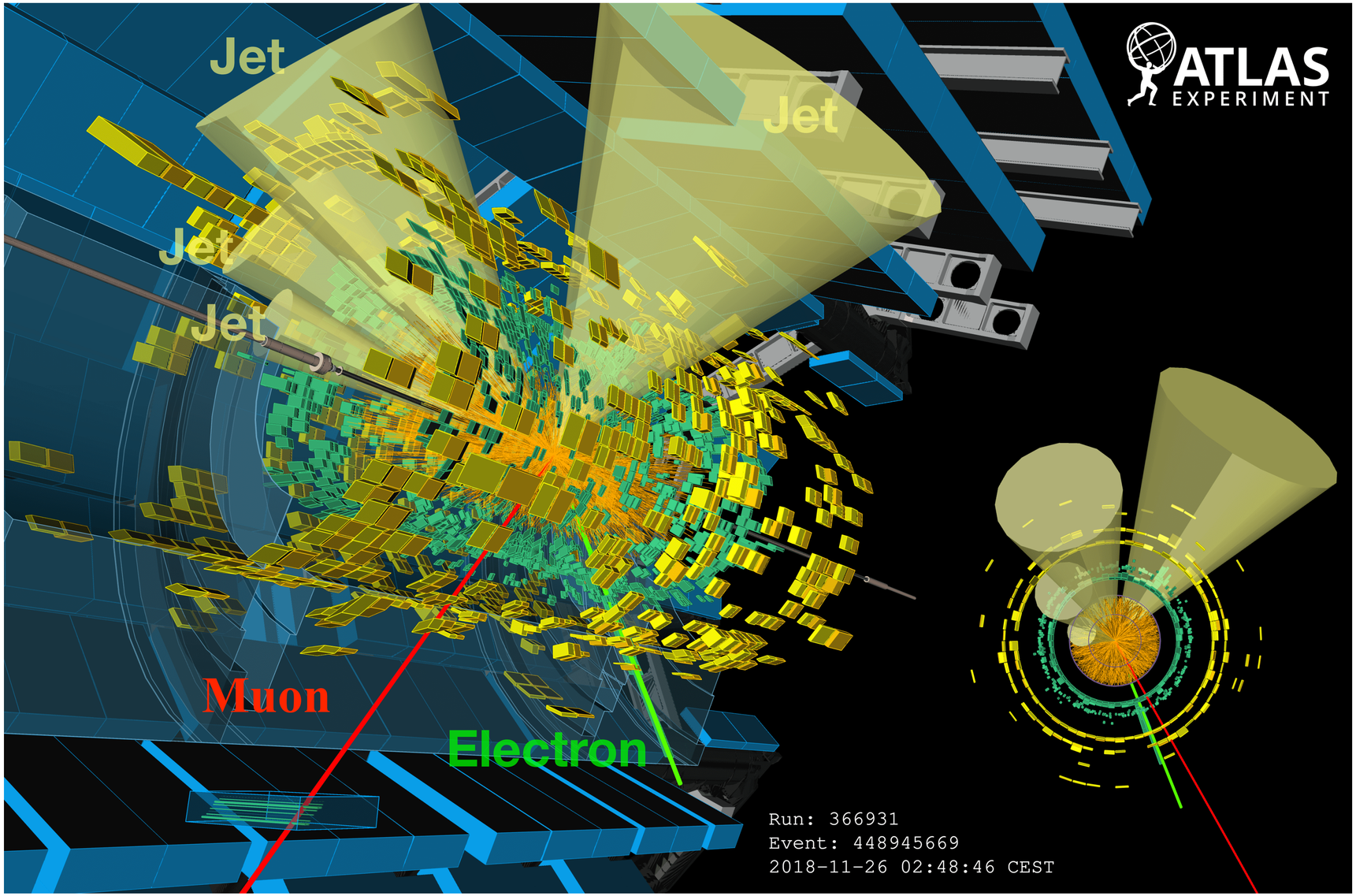
- **Signal region selections: eμ**
  - 1 electron,
  - 1 muon,
  - Opposite sign leptons,
  - $m_{e\mu} \geq 30\text{GeV}$,
  - At least 2 HI jets

Two signal regions (SR)

Events are divided based on the transverse momentum of the lepton pair $p_T^{e\mu}$

- **SR1:** $p_T^{e\mu} > 40\ GeV$,
- **SR2:** $p_T^{e\mu} \leq 40\ GeV$

$t\bar{t}$ event candidate: Pb+Pb



Event candidate from $e\mu$ channel with an **electron** (green track), **muon** (red track), and **four jets** (yellow cones)

Backgrounds estimation

p+Pb

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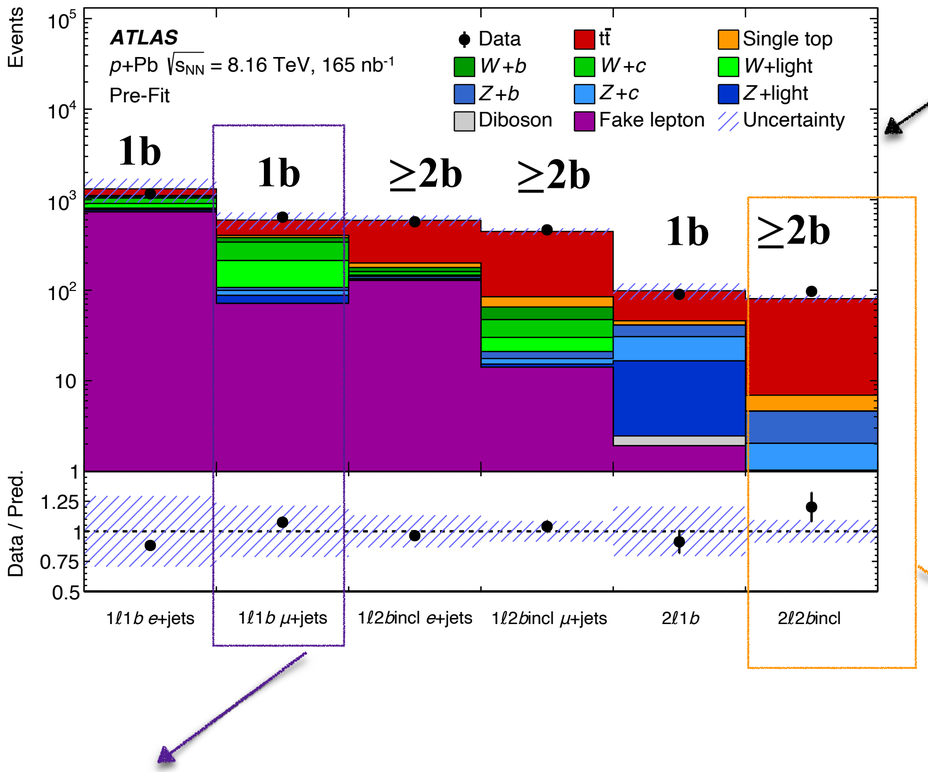

Good agreement between data event yields in each SR and a sum of $t\bar{t}$ signal and backgrounds components

Large contributions from **fake leptons** and **W+jets**

Large contributions from **Z+jets** and **tW**

Pb+Pb

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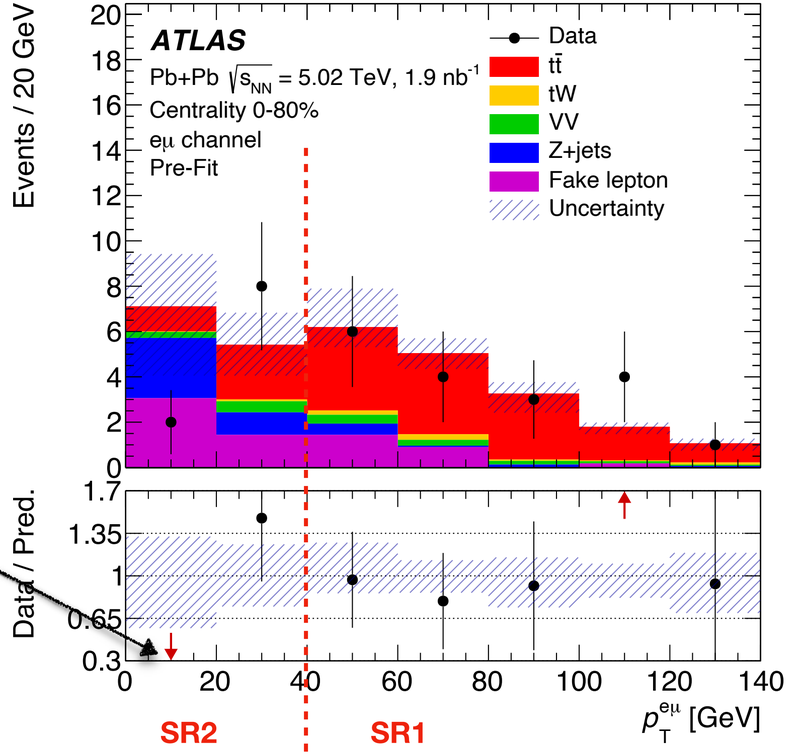


Indicate bins with entries which are outside the ratio range

Large contributions from **Z+jets** and **fake lepton**

Large contributions from **VV** and **tW**

- Background estimated using:
  - Data-driven techniques (Matrix method in **p+Pb**) and (ABCD method in **Pb+Pb**) for **fake leptons**
  - MC simulation for **W+jets, Z+jets**, **single top** and **diboson**

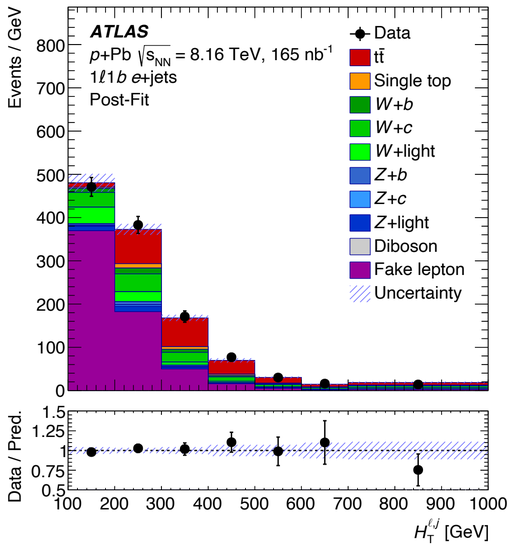
Signal regions in p+Pb

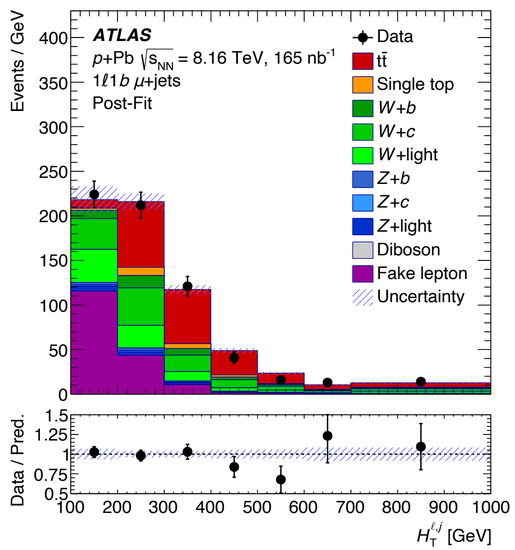
e+ jets

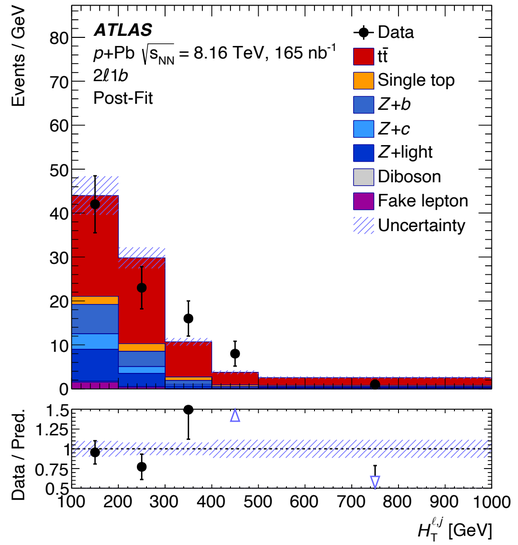
μ+ jets

dilepton

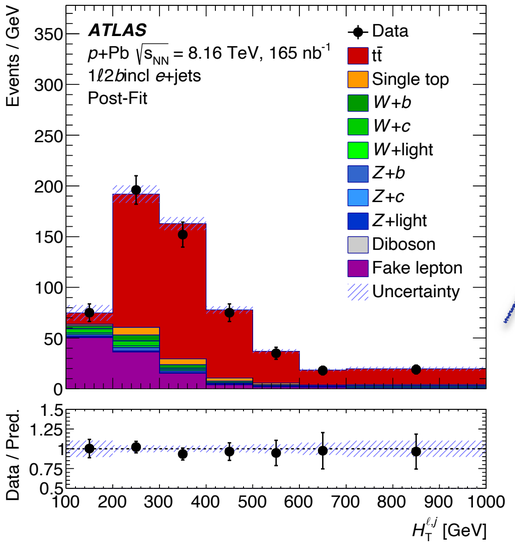
1b-jet



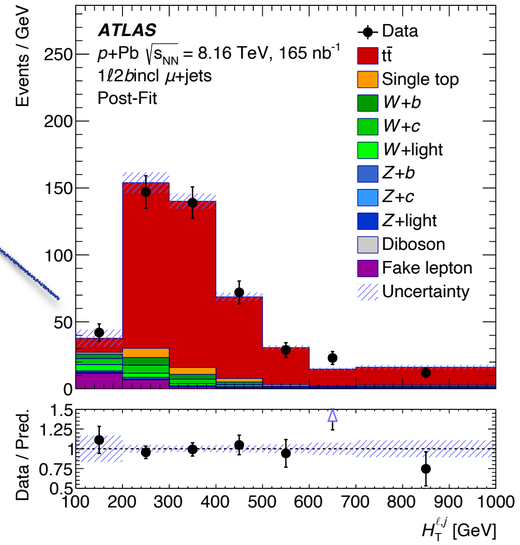


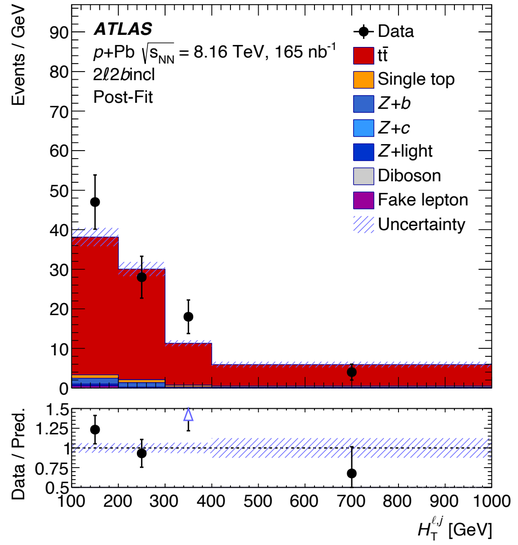


≥ 2 b-jet



Z+jets contribution is negligible





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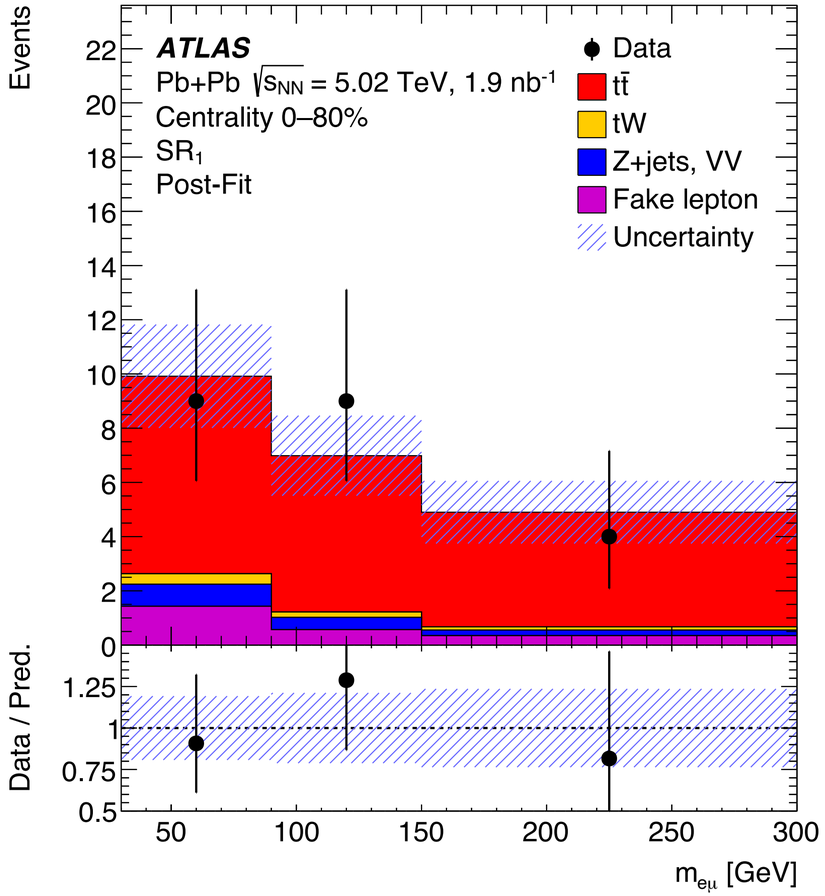
- A **profile-likelihood fit** is performed using $H_T^{lj} = \sum (p_T^j + p_T^l)$ in the six signal regions

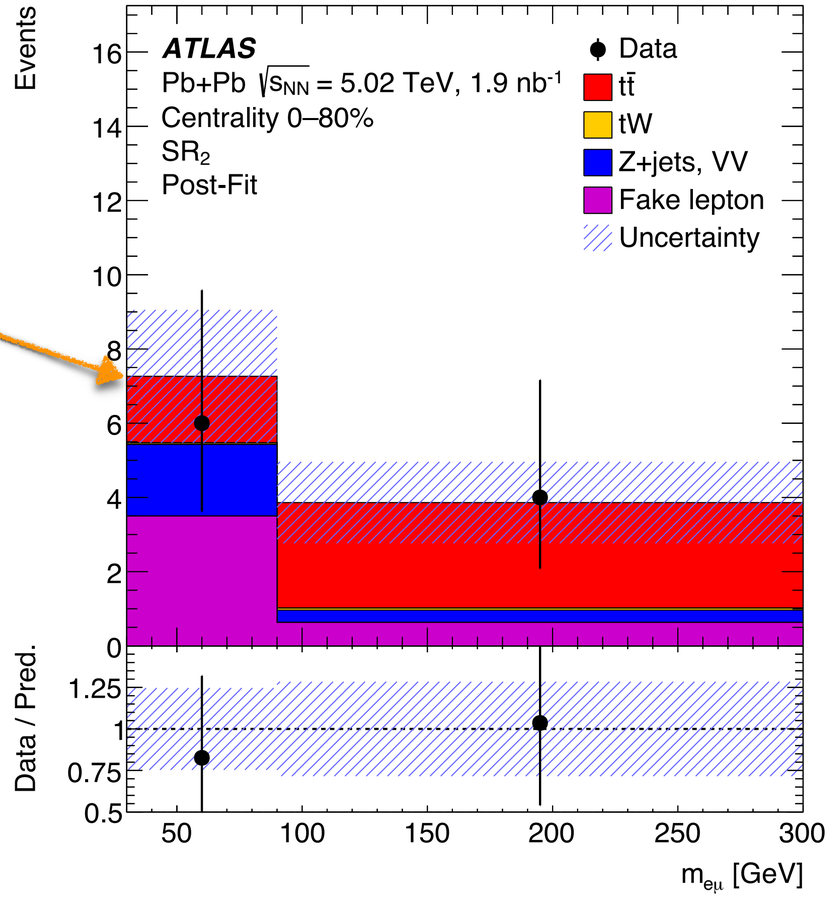
Signal regions in Pb+Pb

eμ Signal region 1 (SR1)



tW contribution is negligible

eμ Signal region 2 (SR2)



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- A **profile-likelihood fit** is performed using distributions of invariant mass of lepton pairs ($m_{e\mu}$)
- Two signal regions are fitted simultaneously: **SR1 and SR2**

Systematic uncertainties

p+Pb

- Main systematic uncertainties:
  - **Jet energy scale, $t\bar{t}$ generator** → group sources
  - **Fake lepton** and **signal modeling** → individual sources
- The total systematic uncertainty of **8.3%**

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. up [%]	unc. down [%]
Jet energy scale	+4.6	-4.1
$t\bar{t}$ generator	+4.5	-4.0
Fake-lepton background	+3.1	-2.8
Background	+3.1	-2.6
Luminosity	+2.8	-2.5
Muon uncertainties	+2.3	-2.0
W+jets	+2.2	-2.0
b-tagging	+2.1	-1.9
Electron uncertainties	+1.8	-1.5
MC statistical uncertainties	+1.1	-1.0
Jet energy resolution	+0.4	-0.4
$t\bar{t}$ PDF	+0.1	-0.1
Systematic uncertainty	+8.3	-7.6

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Pb+Pb

- Main systematic uncertainties:

signal modeling and **jet reconstruction**

- The total systematic uncertainty of **21%**

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. up [%]	unc. down [%]
Signal modeling	+16	-9.6
Jet	+14	-8.8
Fake-lepton background	+7.3	-6.6
Electron	+3.5	-2.1
Muon	+3.3	-2.0
Luminosity	+2.3	-1.5
MC sample size	+2.1	-1.6
Background modeling	+1.5	-1.6
Systematic uncertainty	+21	-14

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Systematic uncertainties

p+Pb

- Main systematic uncertainties:
  - **Jet energy scale, $t\bar{t}$ generator** → group sources
  - **Fake lepton** and **signal modeling** → individual sources
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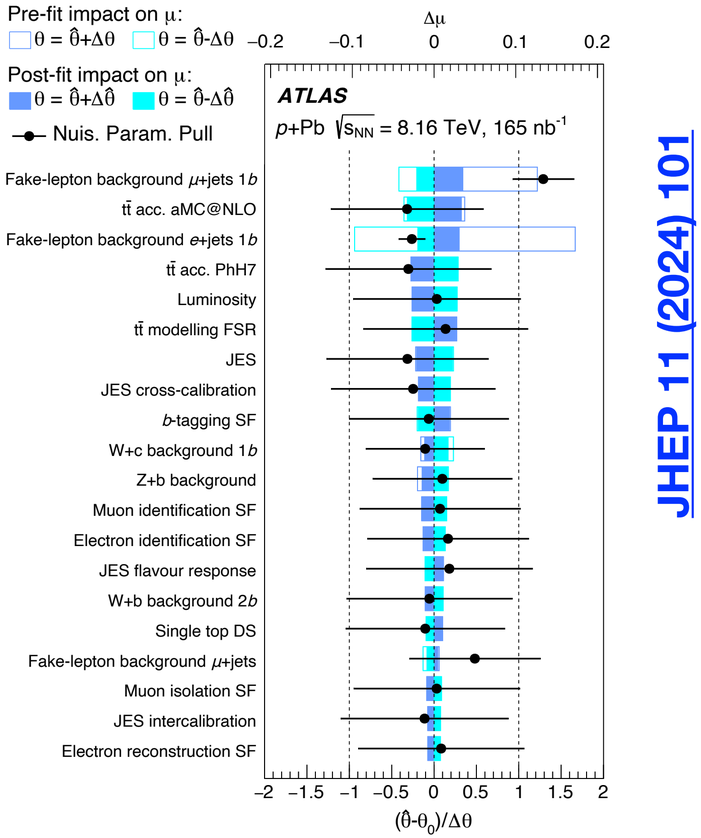

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Pb+Pb

- Main systematic uncertainties:

  signal modeling and **jet reconstruction**
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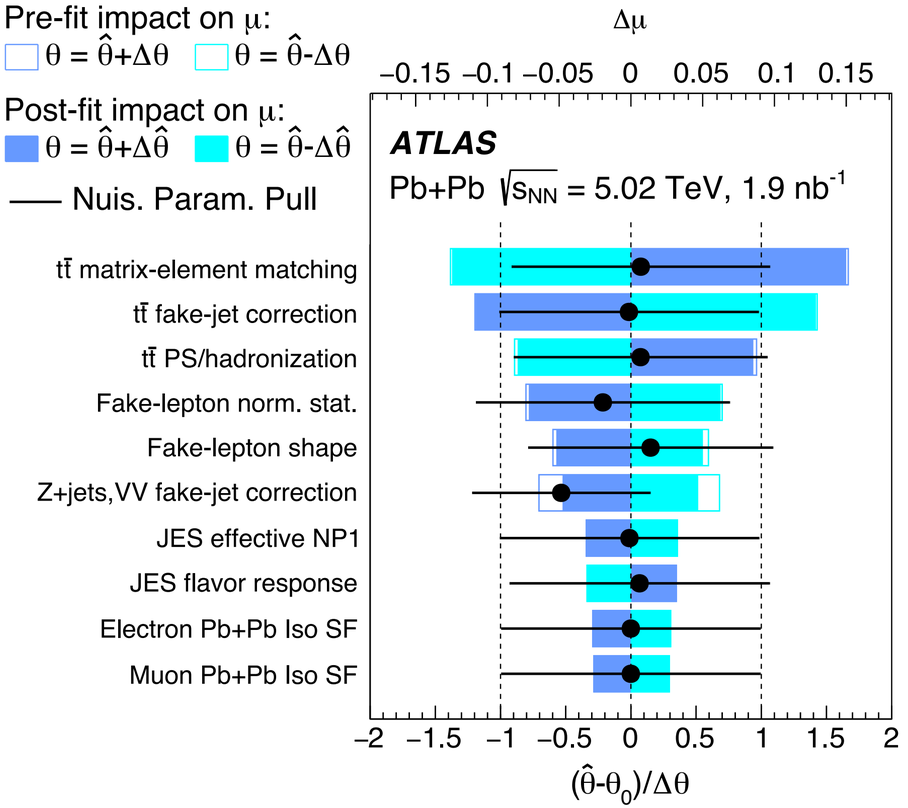

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Cross section measurements in p+Pb

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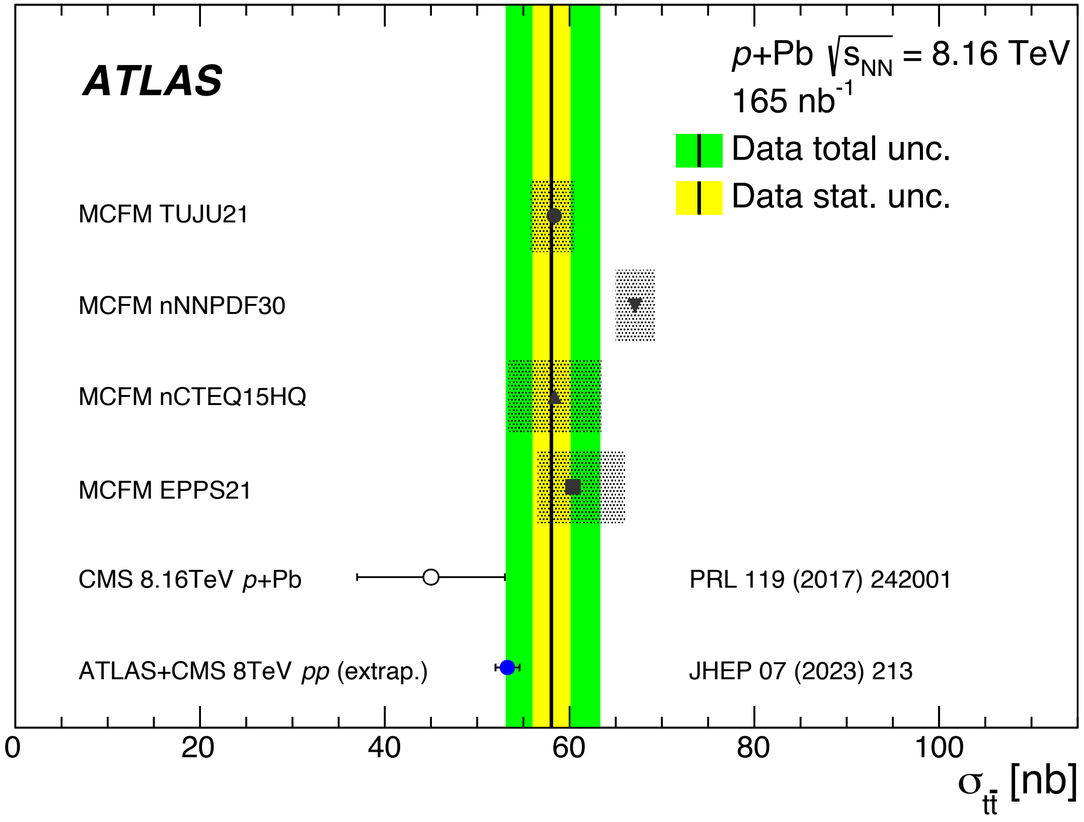
- The **cross section** of $t\bar{t}$ production is measured in p+Pb collisions at $\sqrt{s_{NN}} = 8.16\ TeV$ to be:

$$\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (stat.)\ ^{+4.8}_{-4.4}(syst.)\ nb$$

- Total relative uncertainty of **9%**
- The most precise $t\bar{t}$ cross section measurement achieved at the LHC to date in p+Pb
- **Consistent** with the previous CMS measurement [PRL 119 (2017) 242001] and nPDF predictions at NNLO



Nuclear modification factor in p+Pb

- A nuclear modification factor is defined as:

$$R_{pA} = \frac{\sigma_{t\bar{t}}^{pPb}}{A_{Pb} \cdot \sigma_{t\bar{t}}^{pp}}$$

- It is measured for the first time using the ATLAS and CMS combined $t\bar{t}$ cross section in pp at 8 TeV extrapolated to 8.16 TeV [JHEP 07 (2023)213]
- It is measured to be:

$$R_{pA} = 1.090 \pm 0.039\ (stat.)\ ^{+0.094}_{-0.087}\ (syst.)$$

  - One standard deviation above unity
  - Consistent with NNLO nPDF predictions calculations
- It can be used to further constrain the nPDFs

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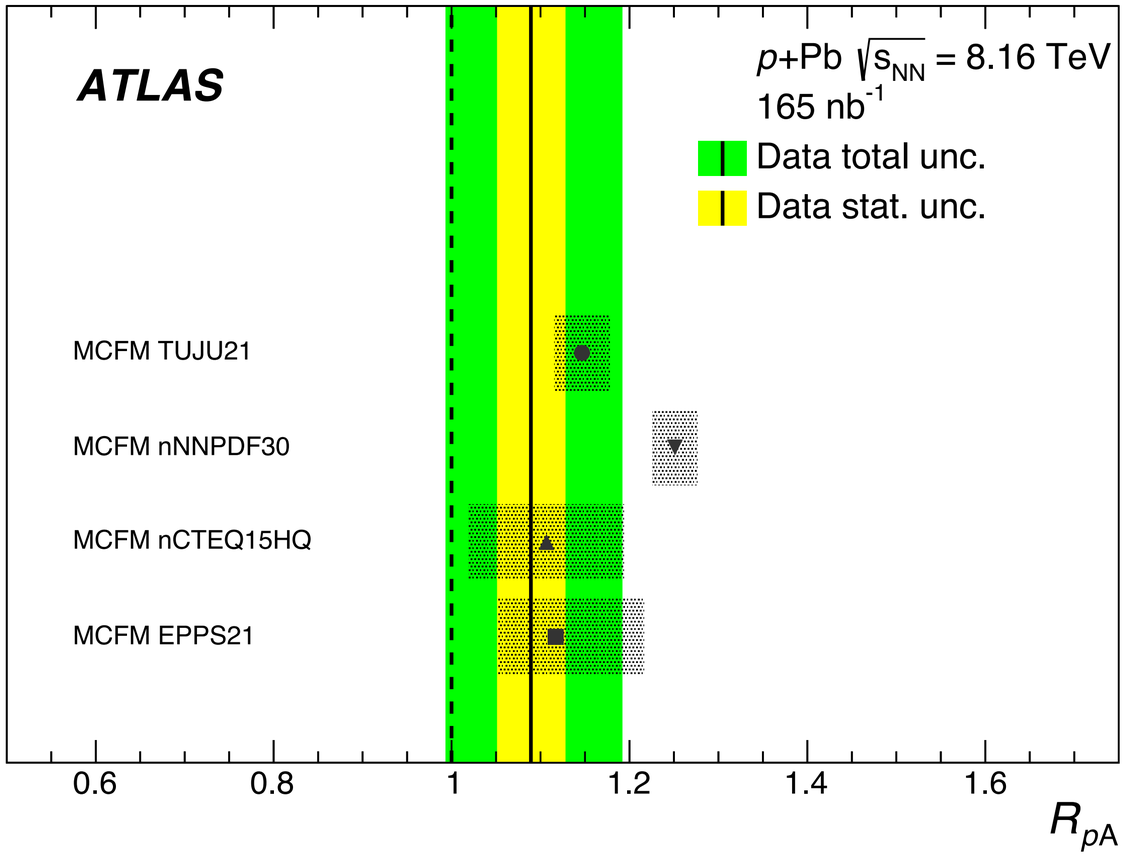

Cross section measurements in Pb+Pb

- The cross section of $t\bar{t}$ is measured in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02\ TeV$ to be:

$$\sigma_{t\bar{t}} = 3.6\ ^{+1.0}_{-0.9}\ (stat.)\ ^{+0.8}_{-0.5}\ (syst.)\ \mu b$$

- The observed (expected) significance in the eμ channel amounts to **5.0** (4.1) standard deviations
- Total relative uncertainty of **31%** dominated by statistical uncertainty
- **The first observation** of $t\bar{t}$ in Pb+Pb collisions with ATLAS detector
  - **Consistent** with the previous CMS measurement [PRL 125 (2020) 222001] and nPDF predictions
  - **New probe** of QGP at the LHC

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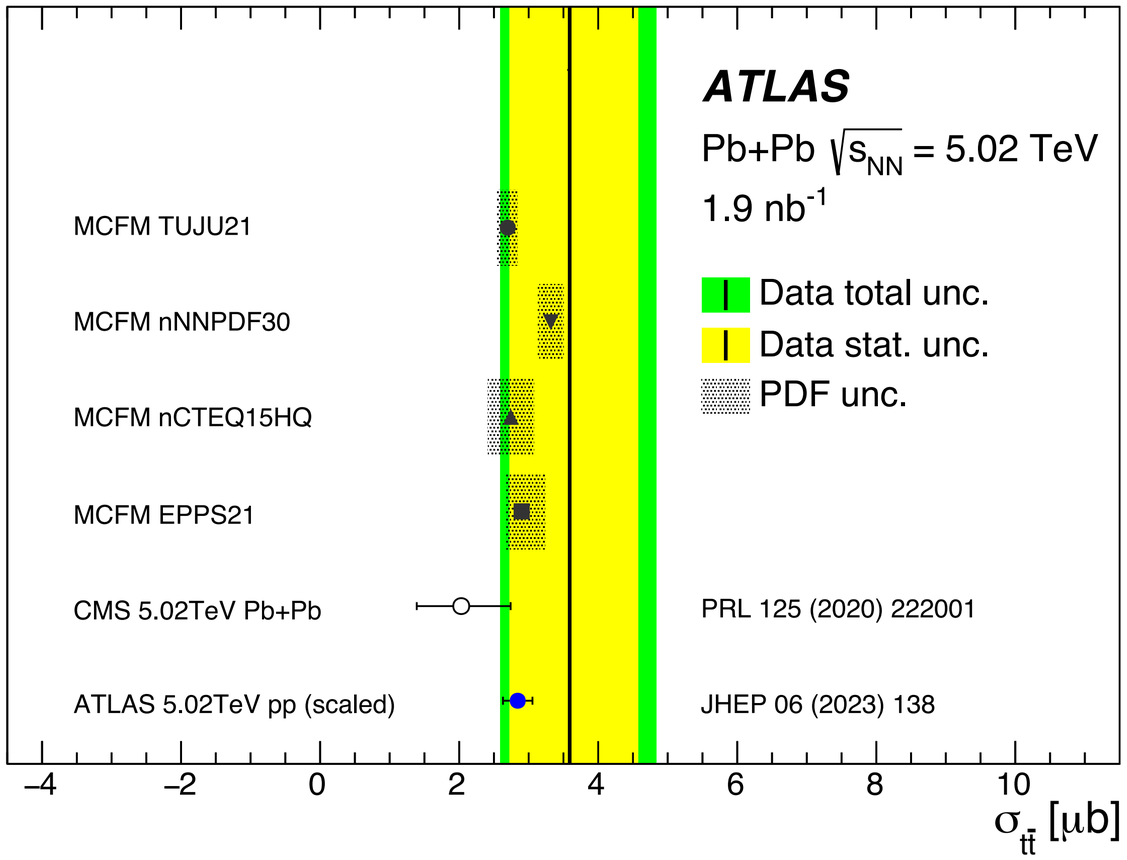

Summary

- **First observation of $t\bar{t}$ production** by ATLAS is reported in **p+Pb** collisions at $\sqrt{s_{NN}} = 8.16\ TeV$
  - Measurements were performed in both **lepton+jets** and **dilepton** decay channels
  - The cross section and nuclear modification factor were extracted with a **9% relative uncertainty**
  - Showing good agreement with NNLO predictions using various nPDF sets
  - This constitutes a novel probe of nuclear PDFs (nPDFs), paving the way for future differential measurements
- **First observation of top-quark production** in **Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02\ TeV$ is also reported**
  - The observed signal significance of **5.0 standard deviations**
  - The measured cross-section aligns well with other experimental results and predictions across four nPDF sets
  - These results pave the way for future studies of the **quark-gluon plasma (QGP)**
- **New data Run3,** 2023-2024 Pb+Pb collected at $\sqrt{s_{NN}} = 5.36\ TeV$ with Int. Lumi of **3.2** nb^{-1}
- **HL-LHC** enables **high-statistics** for $t\bar{t}$ studies with possibly improved b-tagging in the heavy-ion environment

THANK YOU FOR YOUR ATTENTION !

BACKUP SLIDES

Measurement methodology

- **Signal strength** extracted using the following formula:

$$\mu_{t\bar{t}} = \frac{\sigma_{t\bar{t}}^{meas}}{\sigma_{t\bar{t}}^{SM}}$$

- $\mu_{t\bar{t}}$ Measurement is consistent with unity and with SM predictions across the individual channels
- In both the lepton+jets and dilepton channels, the background-only hypothesis is rejected with a significance greater than **5**
  - **First observation** of $t\bar{t}$ production in the **dilepton channel**
  - **Highest precision** achieved in the **lepton+jets** channel with **≥2b jets**

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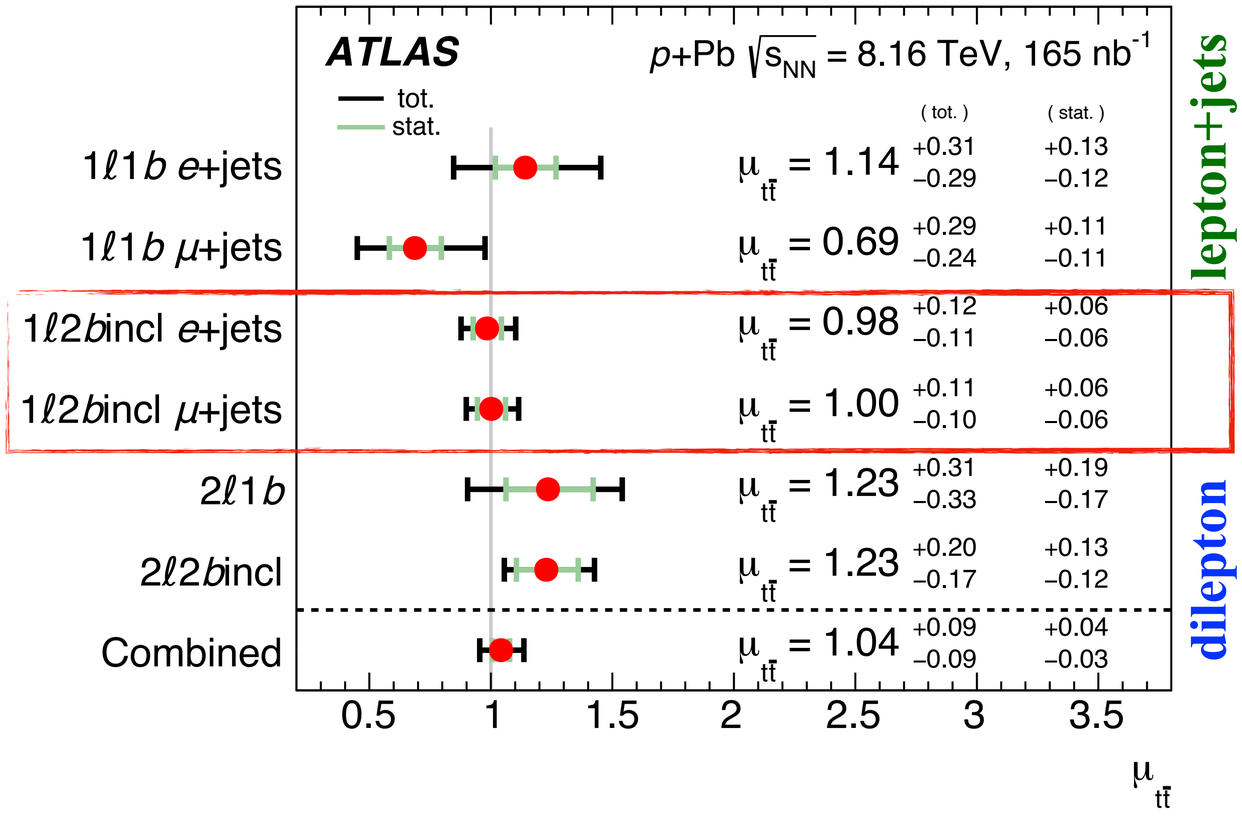
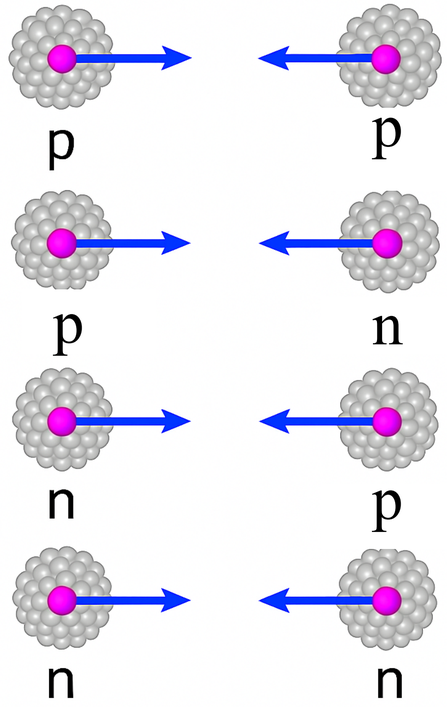


MC simulation

- Samples produced using the following MC generators :
  - **Powheg + Pythia8**
  - **Sherpa**
- **Isospin configurations:**
  - 2 configurations for **p+Pb**: proton-proton(p-p) and proton-neutron(p-n)
  - 4 configurations for **Pb+Pb**: proton-proton(p-p), proton-neutron(p-n), neutron-proton (n-p) and neutron-neutron (n-n)
- **Signal process ($t\bar{t}$)**
- **Background samples:**
  - Z + jets (Z +b, Z+c, Z +light)
  - Single top (tW)
  - Dibsons (VV)
  - Fake lepton
  - W + jets (W +b, w+c, W+light)

Pb+Pb

p+Pb



- Simulated events are embedded into **minimum-bias** Pb+Pb events sampled using **Hijing**
- Events are embedded in real **p+Pb** forming overlay samples

Quark-gluon plasma

- The quark-gluon plasma **(QGP)** is a new state of matter, created in the collisions of nuclei at RHIC and LHC (hot QCD research).
- QGP is short-lived, with lifetime of the order of **10 fm/c**
- **Top quark** is expected to interact with the early,
  - Pre-equilibrium phase of the QGP.
- The time structure of QGP probed via:
  - hadronic W decays from top quark.
  - The time delay between the decay of top quark and subsequent decay of W boson.

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