

Observation of top-quark pair production in p+Pb collisions with the ATLAS detector



Patrycja Potępa

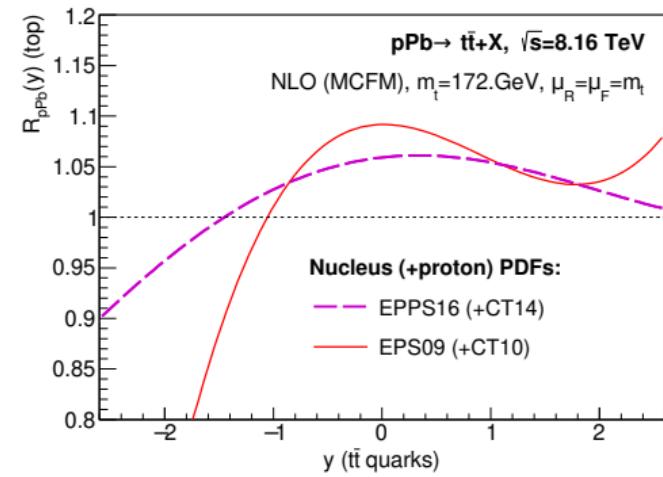
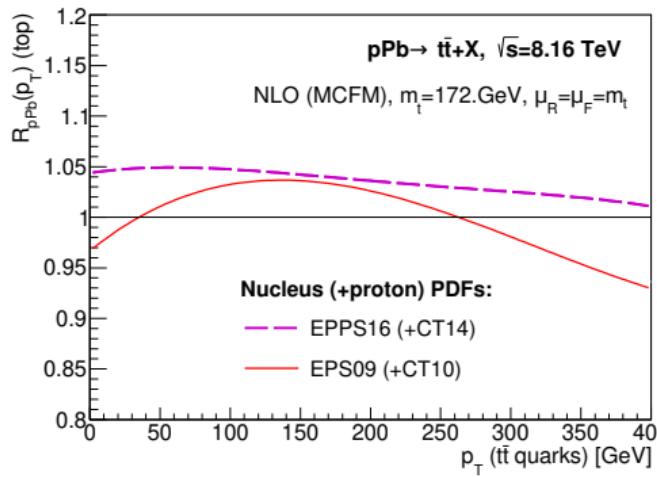
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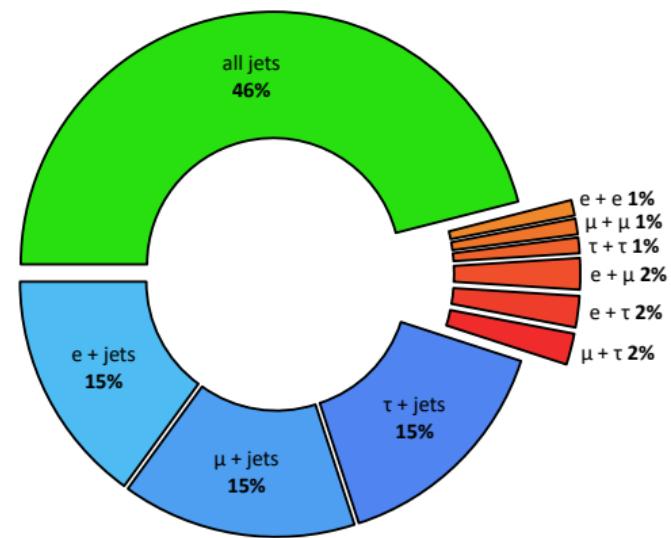
Motivation

- ❖ Top quarks provide novel probes of nuclear modifications to parton distribution functions (nPDF) at high Bjorken- x values ([PRD 93, 014026 \(2016\)](#)).
- ❖ Nuclear modification factor ($R_{p\text{Pb}}$) prediction has been reported in [arXiv:1908.11534](#) as a function of $t\bar{t}$ pair p_T (left) and y (right).



Top quark pair production

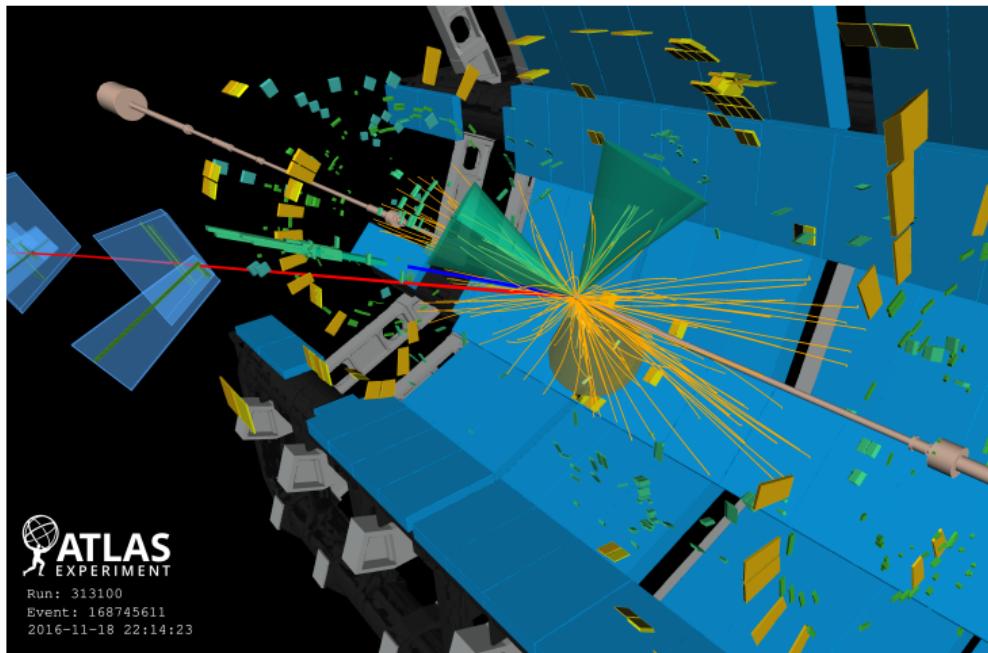
- ❖ Top quark is the heaviest elementary particle and decays before hadronisation.
- ❖ The measurement using the **$\ell + \text{jets}$ channel** has been reported by CMS (PRL 119, 242001 (2017)).
- ❖ The $t\bar{t}$ cross section is measured in the combined **$\ell + \text{jets}$** and **dilepton** channels in $p+\text{Pb}$ collisions (ATLAS-CONF-2023-063).
- ❖ The first measurement using the **dilepton channel** in $p+\text{Pb}$ collisions.



$\ell + \text{jets} : t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell b\bar{q}\bar{q}'\bar{b}$
 $\text{dilepton} : t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell b\ell\nu_\ell \bar{b}$

$p+\text{Pb}$ data in ATLAS

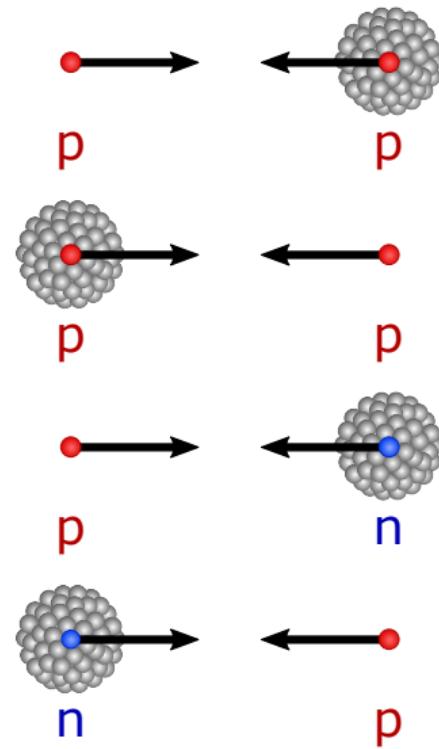
- ❖ $p+\text{Pb}$ data at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ collected in 2016 by ATLAS.
- ❖ The luminosity of **165 nb⁻¹**, split into **57 nb⁻¹** ($p+\text{Pb}$) and **108 nb⁻¹** ($\text{Pb}+\text{p}$).
- ❖ Final luminosity calibration with a relative uncertainty of **2.4%**.



Event display of a $p+\text{Pb}$ collision containing a $t\bar{t}$ candidate.

MC simulation

- ❖ MC samples produced using **Powheg+Pythia 8** and **Sherpa** generators.
- ❖ **Two isospin configurations:**
proton-proton (pp), proton-neutron (pn).
- ❖ **Two beam configurations:**
proton-lead (p+Pb), lead-proton (Pb+p).
- ❖ Events embedded into real p+Pb data forming **data overlay** samples.
- ❖ **Signal:** $t\bar{t}$,
Background: tW (single top), W , Z , diboson.



Event selection

$\ell + \text{jets}$

$e + \text{jets}$

- 1 electron,
- 0 muons,
- at least 4 jets.

$\mu + \text{jets}$

- 1 muon,
- 0 electrons,
- at least 4 jets.

Dilepton

ee

- 2 electrons,
- 0 muons,
- opposite sign leptons,
- $m_{\ell\ell} > 45 \text{ GeV}$ and $m_{\ell\ell} \notin (80 - 100) \text{ GeV}$,
- at least 2 jets.

$\mu\mu$

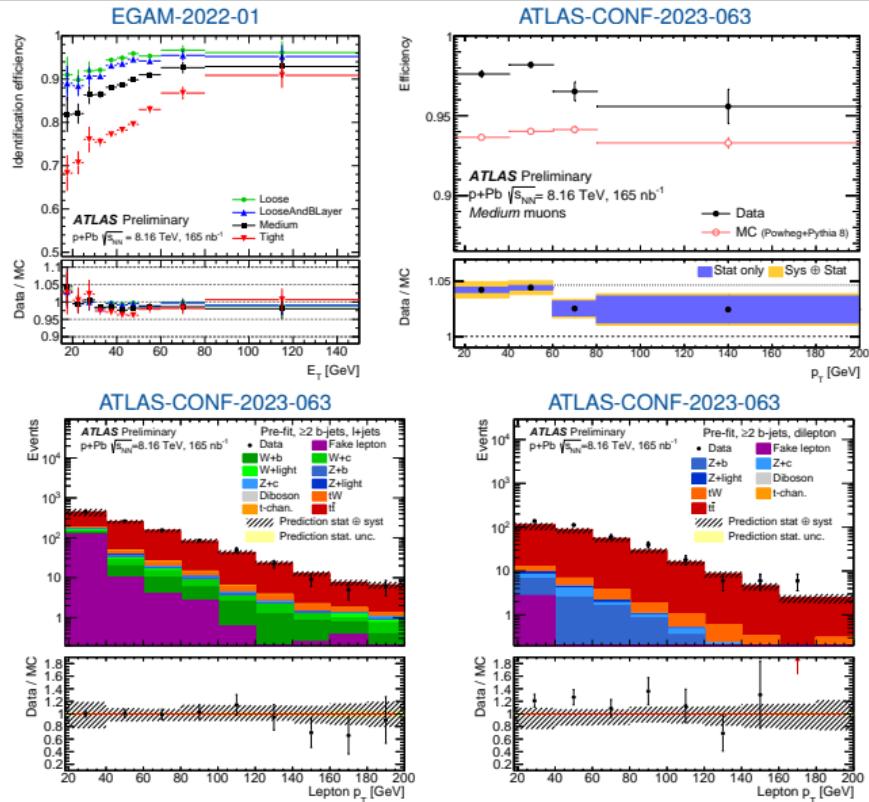
- 2 muons,
- 0 electrons,
- opposite sign leptons,
- $m_{\ell\ell} > 45 \text{ GeV}$ and $m_{\ell\ell} \notin (80 - 100) \text{ GeV}$,
- at least 2 jets.

$e\mu$

- 1 electron,
- 1 muon,
- opposite sign leptons,
- $m_{\ell\ell} > 15 \text{ GeV}$,
- at least 2 jets.

Lepton reconstruction

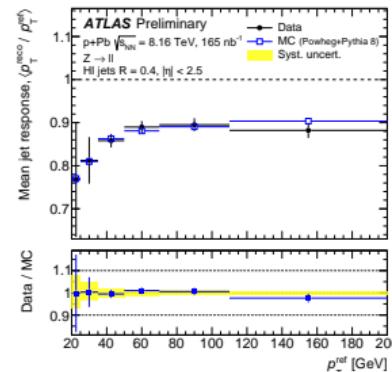
- ❖ Electrons must have $p_T > 18 \text{ GeV}$ and $|\eta| < 2.47$, pass Medium identification and be isolated.
- ❖ Muons must have $p_T > 18 \text{ GeV}$ and $|\eta| < 2.5$, pass Medium requirements and be isolated.
- ❖ Low-pileup egamma calibration and dedicated electron and muon scale factors are applied ([EGAM-2022-01](#)).
- ❖ Fake lepton background is estimated from data using the matrix-method technique.



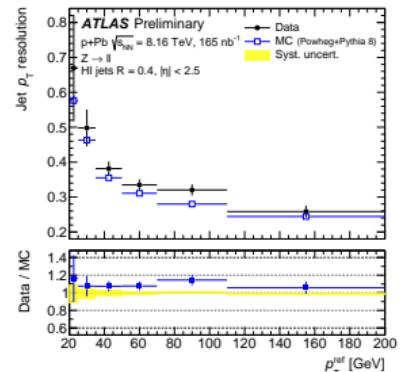
Jet reconstruction

- ❖ Jets are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$.
- ❖ Jets are reconstructed using the anti- k_t algorithm with jet radius of $R = 0.4$.
- ❖ Jet kinematics are corrected event-by-event for the contribution from the underlying event.
- ❖ Jets are calibrated using simulation and in-situ measurements of the absolute energy scale ([JETM-2023-001](#)).
- ❖ Jets with b -hadrons are tagged using the 85% efficiency working point of the DL1r algorithm ([EPJ C 79 \(2019\) 970](#)).

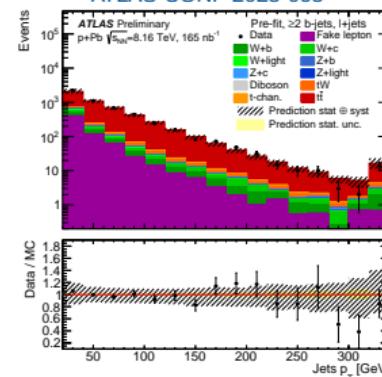
JETM-2023-001



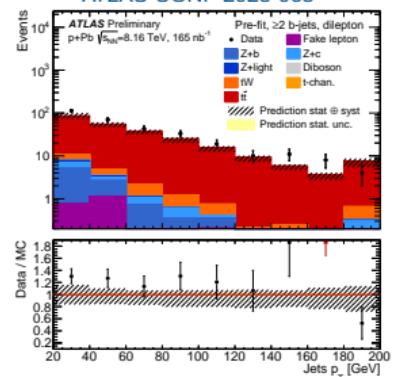
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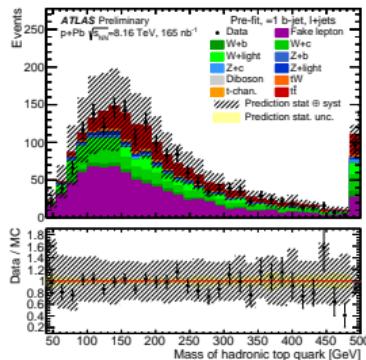
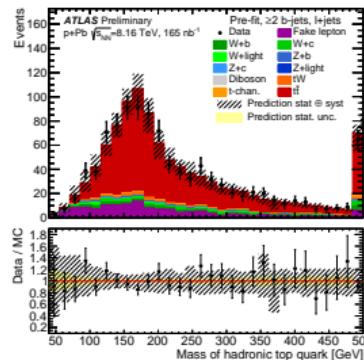


Control plots

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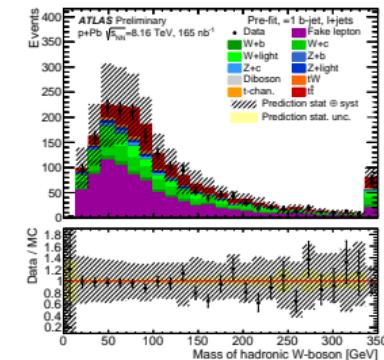
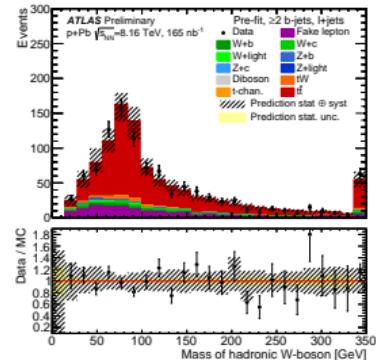
Hadronically decaying top quark

1 b-jet region

 ≥ 2 b-jet region

Hadronically decaying W boson

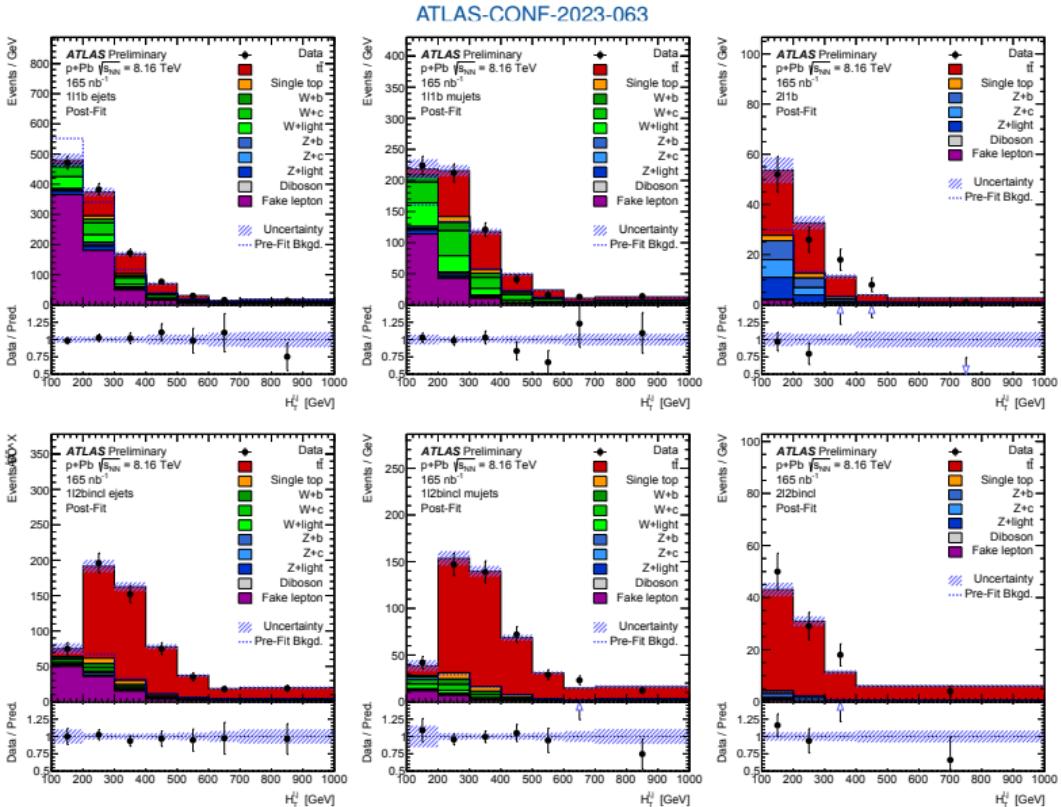
1 b-jet region

 ≥ 2 b-jet region

- ❖ Invariant mass distributions of hadronically decaying top quark and W boson have been studied in 1 and ≥ 2 b-jet regions.
- ❖ A good agreement is observed between data and prediction within statistical and systematic uncertainties.

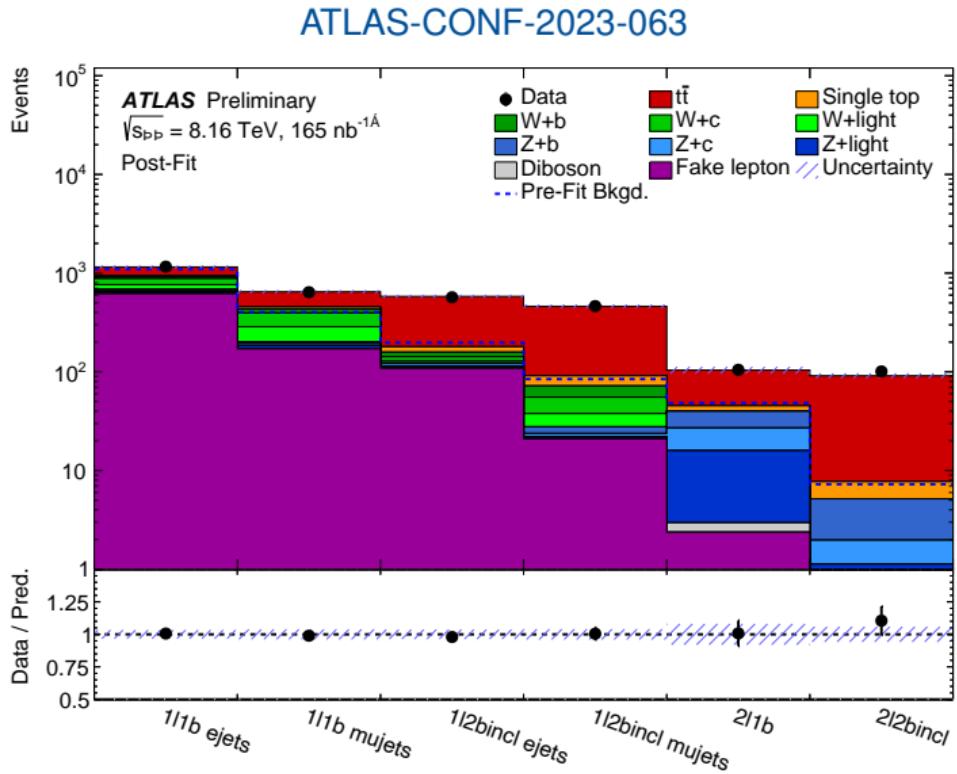
Signal regions

- ❖ Six signal regions are defined using $H_T^{\ell,j}$ distributions.
- ❖ $H_T^{\ell,j}$ is the scalar sum of all lepton and jet p_T .
- ❖ Six signal regions:
 - $4j1b1\ell$ ejets,
 - $4j2b\text{incl}1\ell$ ejets,
 - $4j1b1\ell$ mujets,
 - $4j2b\text{incl}1\ell$ mujets,
 - $2j1b2\ell$,
 - $2j2b\text{incl}2\ell$.



Fitting procedure

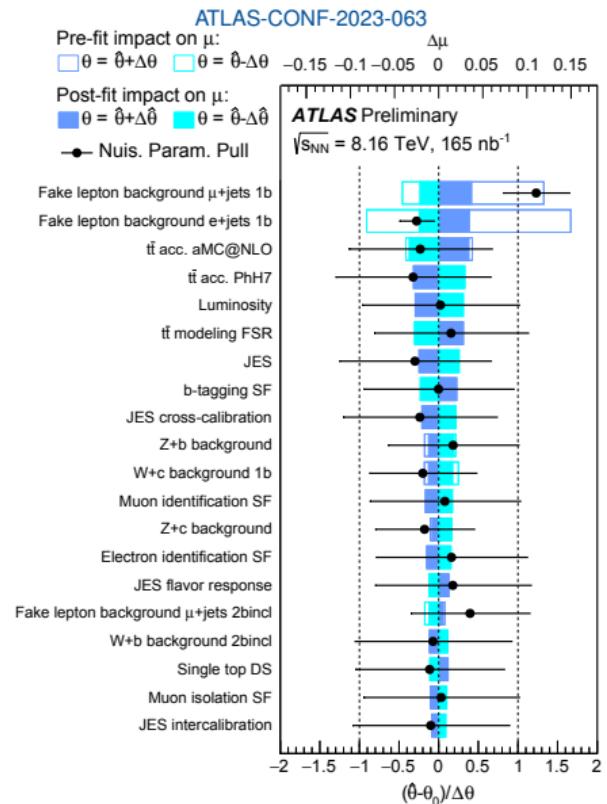
- ❖ The **signal strength** $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{\text{measured}} / \sigma_{t\bar{t}}^{\text{theory}}$ is determined by the fit to $H_T^{\ell,j}$ data distributions.
- ❖ The most signal events are found in the $\ell + \text{jets}$ regions with $\geq 2 b\text{-jets}$.
- ❖ The dilepton channel with $\geq 2 b\text{-jets}$ forms the cleanest signal region.



Systematic uncertainties

- ❖ Systematic uncertainties arise from the lepton and jet reconstruction, b -tagging, fake-lepton background, the signal and background modeling, and luminosity.
- ❖ The main systematic uncertainties include **jet energy scale** and **signal modelling**.
- ❖ The total systematic uncertainty amounts to **9%**.

Source	unc. up	unc. down
Jet energy scale	+0.048	-0.044
$t\bar{t}$ generator	+0.048	-0.043
Fake-lepton background	+0.030	-0.027
Background	+0.030	-0.025
Luminosity	+0.029	-0.025
Muon systs.	+0.024	-0.021
$W+jets$	+0.023	-0.020
b -tagging	+0.022	-0.021
Electron systs.	+0.018	-0.017
MC statistical uncertainties	+0.011	-0.010
Jet energy resolution	+0.005	-0.004
$t\bar{t}$ PDF	+0.001	-0.001
Total syst.	+0.088	-0.081



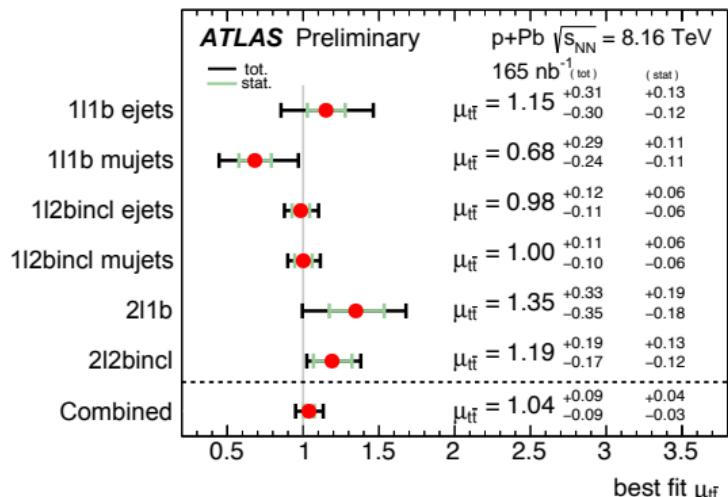
Cross-section measurement

- ❖ The top-quark pair production cross section is measured to be

$$\sigma_{t\bar{t}} = 57.9 \pm 2.0 \text{ (stat.)} {}^{+4.9}_{-4.5} \text{ (syst.) nb.}$$

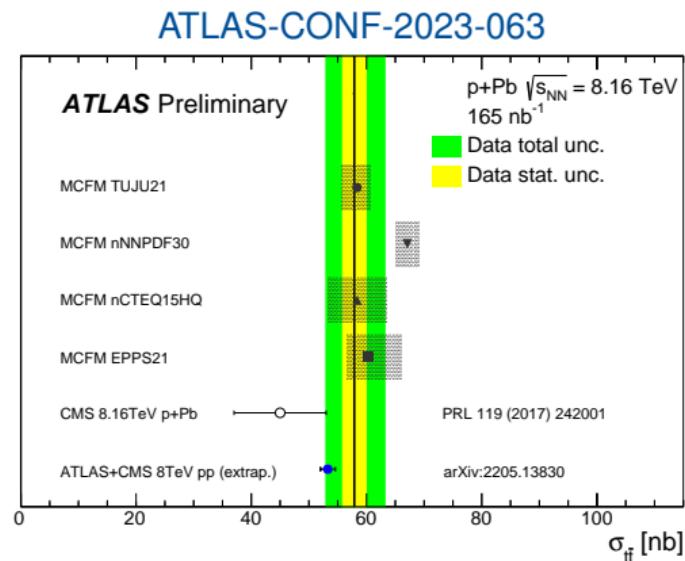
- ❖ The total uncertainty amounts to **9%**, which makes it the most precise $t\bar{t}$ measurement in HI collisions.
- ❖ The significance is well over **5σ** in the $\ell+$ jets and dilepton channels separately.
- ❖ First observation of top-quark pair production in the **dilepton channel** in $p+\text{Pb}$ collisions.

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Comparison to other experimental results and theory

- ❖ The cross section is compared to the **CMS measurement** in the $p\text{+Pb}$ system.
- ❖ The result is consistent with the cross section in **pp collisions**, scaled by $A = 208$ and extrapolated to $\sqrt{s} = 8.16 \text{ TeV}$.
- ❖ The measured $t\bar{t}$ cross section is compared to the **MCFM NNLO calculation** ([PRD 94, 093009 \(2016\)](#)) for four nPDF sets.
 - The largest deviation is observed for the nNNPDF3.0 set with 2σ significance.
 - A good agreement is found with NNLO calculation based on other nPDF sets.



Summary

- 1 The top-quark pair production cross section has been measured to be

$$\sigma_{t\bar{t}} = 57.9 \pm 2.0 \text{ (stat.)} {}^{+4.9}_{-4.5} \text{ (syst.) nb.}$$

- 2 The total uncertainty amounts to 9%, which makes it the most precise $t\bar{t}$ measurement in HI collisions.
- 3 The significance is well over 5σ in the dilepton channel, resulting in the first observation of $t\bar{t}$ production in the dilepton channel in $p+Pb$ collisions.
- 4 The result is consistent with the CMS measurement, the scaled cross section in pp collisions and NNLO calculation based on several nPDF sets.