Top-quark pair production in heavy-ion collisions

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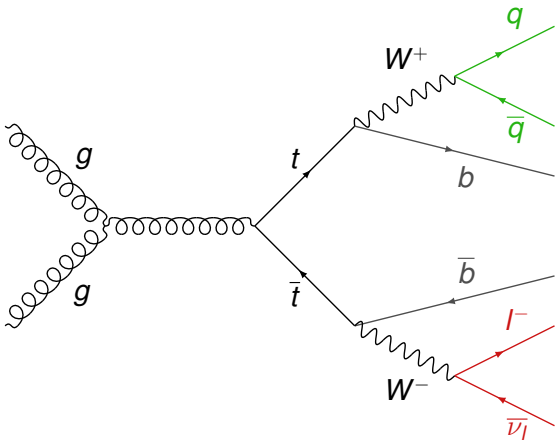
Outline

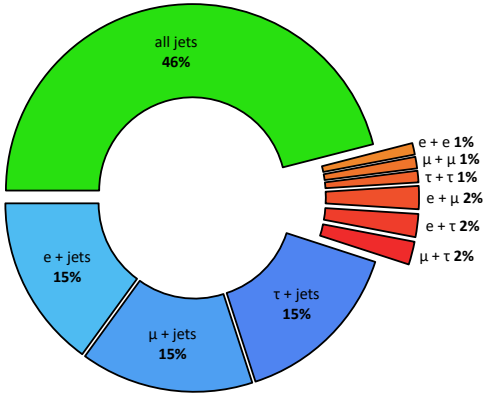
$t\bar{t}$ production

- Top quark is the heaviest elementary particle (175 GeV) and it decays before hadronisation.
- Top quark pair ($t\bar{t}$) is produced mainly via gluon fusion.
- Single top production has a lower cross section compared to $t\bar{t}$.
- $t\bar{t}$ process is sensitive to gluon parton distribution functions (PDFs).
- The final state consists of leptons and jets including two b-jets.



$t\bar{t}$ decay channels

- The $t\bar{t}$ cross section is measured in **ℓ+jets** and **dilepton** channels in p+Pb collisions in ATLAS (ATLAS-CONF-2023-063).
- The first measurement using the **dilepton channel** in p+Pb collisions.
- A measurement in p+Pb collisions using the **ℓ+jets channel** has been reported by CMS (PRL 119, 242001 (2017)).
- An evidence in Pb+Pb collisions using the **dilepton channel** has been reported by CMS (PRL 125 (2020), 222001).



$\ell + \text{jets}: \quad t\bar{t} \to WbW\bar{b} \to \ell\nu_\ell bq\bar{q}'\bar{b}$

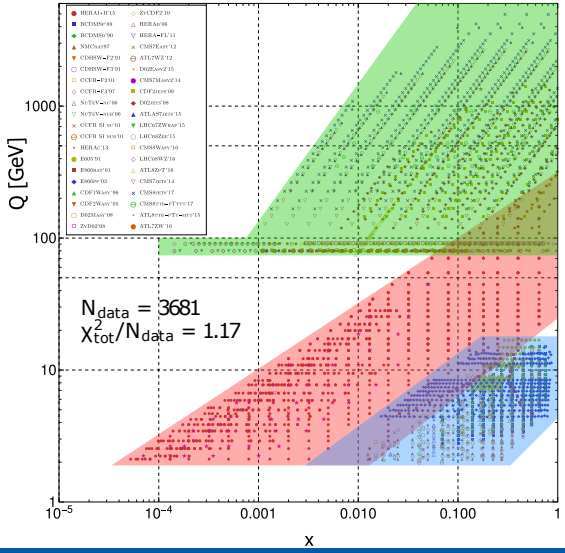
$\text{dilepton}: \quad t\bar{t} \to WbW\bar{b} \to \ell\nu_\ell b\ell\bar{\nu}_\ell\bar{b}$

Proton PDFs

- **Global analysis** - a multi-experiment-multi-observable fit
- **Fixed-target DIS and DY**
  - deep inelastic scattering (DIS) and Drell–Yan (DY) processes,
  - important in setting the large-x quark distributions.
- **HERA DIS**
  - access to a large x, Q^2 range.
- **Hadron colliders**
  - access to new processes: $W^{\pm}$, Z, jets, $t\bar{t}$.

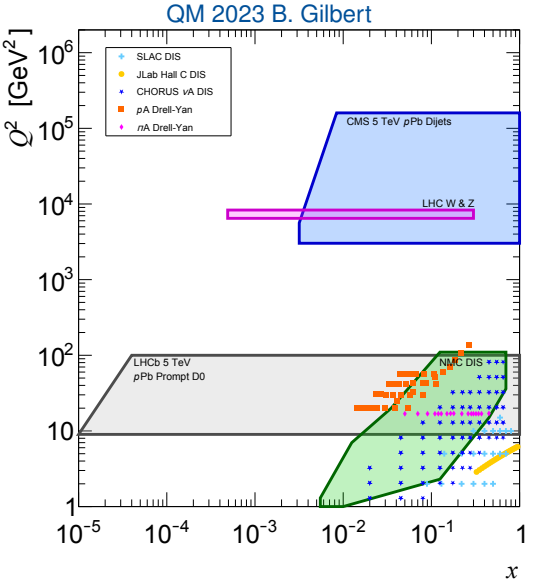
PRD 103, 014013

Experimental data in CT18 PDF analysis



Nuclear PDFs

- World data constraining nuclear Parton Distribution Functions (nPDFs) shown on the (x, Q^2) plane.
- The kinematic coverage of experimental data has expanded massively with contributions from the LHC.
- Gaps still remain in the data determining nPDFs, leaving large stretches of phase space unconstrained.



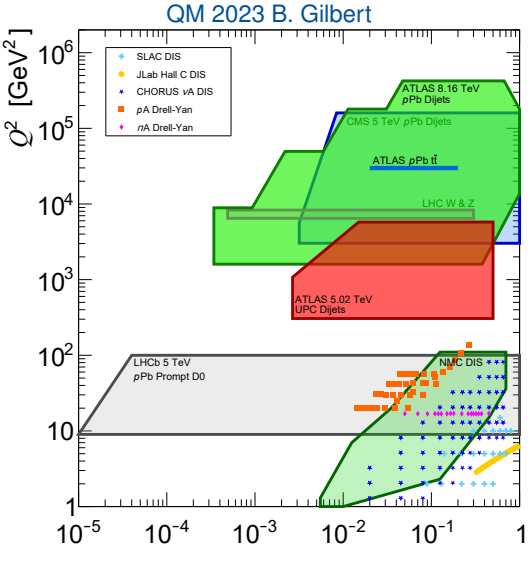
Nuclear PDFs

- Recent **ATLAS** measurements will help to constrain a large phase-space region.

- **UPC dijets 5.02 TeV**
  - ATLAS-CONF-2022-021

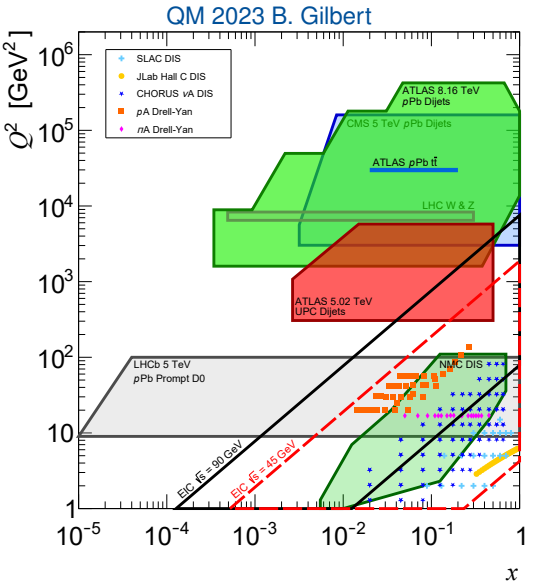
- **dijets 8.16 TeV *p*+Pb**
  - arXiv:2309.00033

- **$t\bar{t}$ 8.16 TeV *p*+Pb**
  - ATLAS-CONF-2023-063



Nuclear PDFs

- **Electron-Ion Collider (EIC)** will help to cover the gap on the (x, Q^2) plane.
- The project is years away, with estimated early completion in 2032.
- Recent ATLAS dijet results are closely related to the early physics goals of the EIC.



nPDF global fits

nPDF	KSASG20 PRD 104, 034010 (2021)	nCTEQ15HQ PRD 105 (2022) 114043	TUJU21 PRD 105 9 (2022), 094031	EPPS21 EPJ C 82, 413 (2022)	nNNPDF3.0 arXiv:2201.12363 (2022)
Order in α_s	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
Free parameters	9	19	16	24	256
Independent flavours	3	5	4	6	6
Free-proton PDFs	CT18	∼CTEQ6M	TUJU own fit	CT18A	∼NNPDF4.0
Data points	4353	940	2410	2077	2188
ℓA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓		✓	✓	✓
***p*A DY**	✓	✓		✓	✓
πA DY				✓	
RHIC *d*Au π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0, $\pi^\pm$, $K^\pm$		✓			
LHC *p*+Pb dijets				✓	✓
LHC *p*+Pb D^0				✓	✓
LHC *p*+Pb *W*, *Z*		✓	✓	✓	✓
LHC *p*+Pb γ					✓

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πA DY				✓	
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LHC pPb π^0, $\pi^\pm$, $K^\pm$		✓			
LHC *p*+Pb dijets				✓	✓
LHC *p*+Pb D^0				✓	✓
LHC *p*+Pb *W*, *Z*		✓	✓	✓	✓
LHC *p*+Pb γ					✓

❖ Four nPDF sets include LHC data.

nPDF global fits

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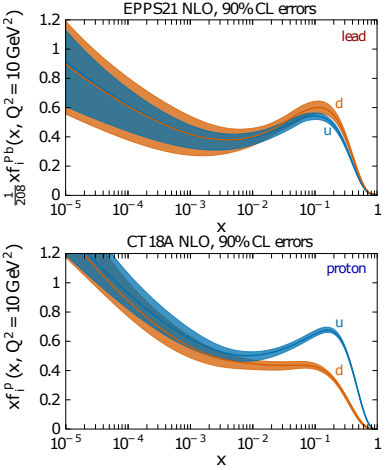
***p*A DY**	✓	✓		✓	✓
πA DY				✓	
RHIC *d*Au π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0, $\pi^\pm$, $K^\pm$		✓			
LHC *p*+Pb dijets				✓	✓
LHC *p*+Pb D^0				✓	✓
LHC *p*+Pb *W*, *Z*		✓	✓	✓	✓
LHC *p*+Pb γ					✓

❖ **KSASG20** and **TUJU21** provide NNLO calculations.

Quark PDFs



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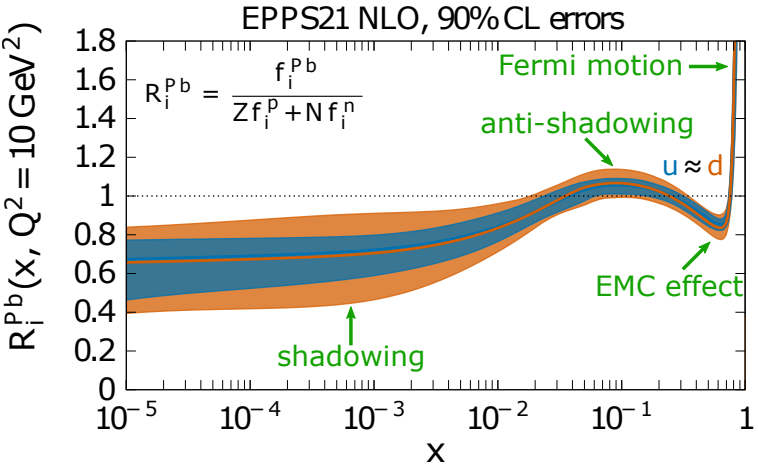

- EPPS21 nuclear modifications of bound protons in lead R_i^{Pb} at the initial scale $Q^2 = 10\ \mathrm{GeV}^2$.
- Similar results for up and down quarks $\boldsymbol{u} \approx \boldsymbol{d}$.

Gluon PDFs

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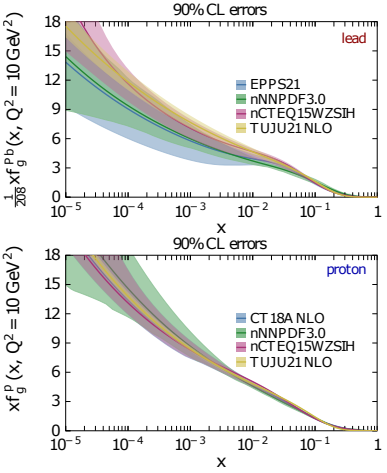
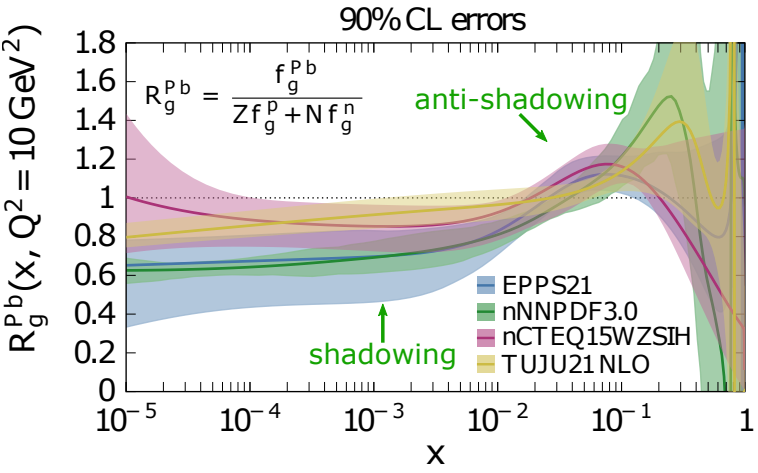
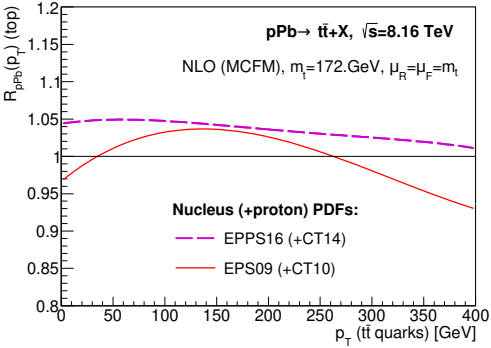


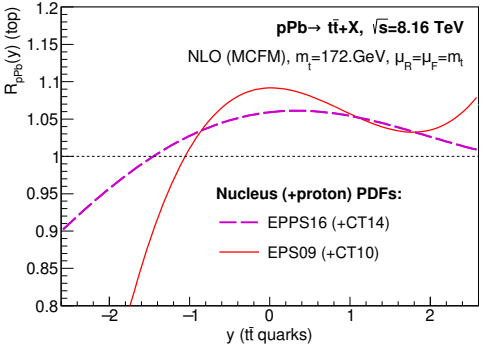


- Nuclear modifications of bound protons in lead R_g^{Pb} for gluons with different nPDFs.
- Large errors and discrepancies between different nPDFs at high Bjorken-x values.

Top-quark probes

- Top quarks provide novel probes of nuclear modifications to nPDFs at high Bjorken-x values (PRD 93, 014026 (2016)).
- Nuclear modification factor ($R_{p\mathrm{Pb}}$) prediction has been reported in arXiv:1908.11534 as a function of $t\bar{t}$ pair p_{T} (left) and y (right).

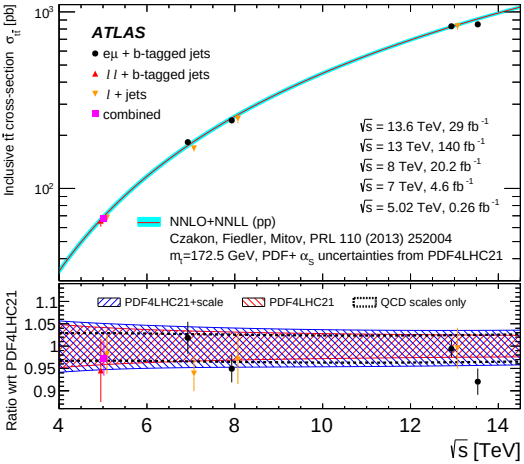




ATLAS *pp* measurements

- ATLAS provides $t\bar{t}$ cross-section measurements in a wide centre-of-mass energy range.
- Measurements were done at **5** centre-of-mass energies:
  - 5.02 TeV
  - 7 TeV
  - 8 TeV
  - 13 TeV
  - 13.6 TeV
- Results are in agreement with theory predictions using the PDF4LHC21 PDF set.

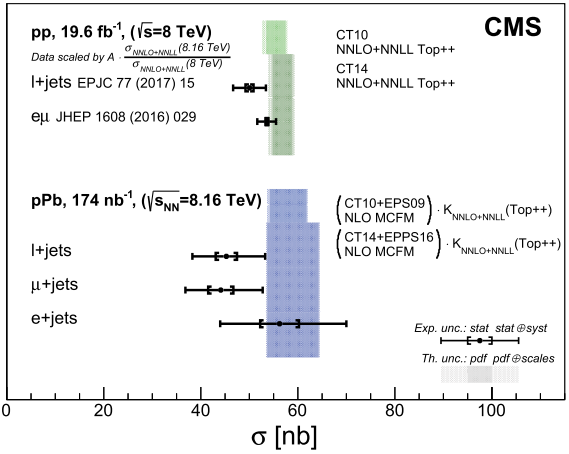
PLB 848 (2024) 138376



CMS p+Pb measurement

- First observation of top-quark production in proton-nucleus collisions by the CMS.
- Total integrated luminosity of **174 nb^{-1}**.
- Measurement done in ℓ+jets channel using a fit to invariant mass distributions of $t \to jj'b$ candidates.
- Combined cross section: $\sigma_{t\bar{t}} = 45 \pm 8$ nb.
- Relative systematic uncertainty of **18%**.

PRL 119, 242001 (2017)



ATLAS and CMS *pp* 7 and 8 TeV measurement

- The most precise $t\bar{t}$ cross-section measurement at 8 TeV scale.
- Two measurements of the $t\bar{t}$ production in the $e\mu$ channel

  ATLAS: EPJ C 74 (2014) 3109,
  CMS: JHEP 08 (2016) 029.
- Measured cross section

  7 TeV: $\sigma_{t\bar{t}} = 178.5 \pm 4.7$ pb,
  8 TeV: $\sigma_{t\bar{t}} = 243.3\ ^{+6.0}_{-5.9}$ pb.
- *pp* $\sigma_{t\bar{t}}$ scaled by lead mass number *A* and extrapolated to 8.16 TeV can be compared to p+Pb $\sigma_{t\bar{t}}$.

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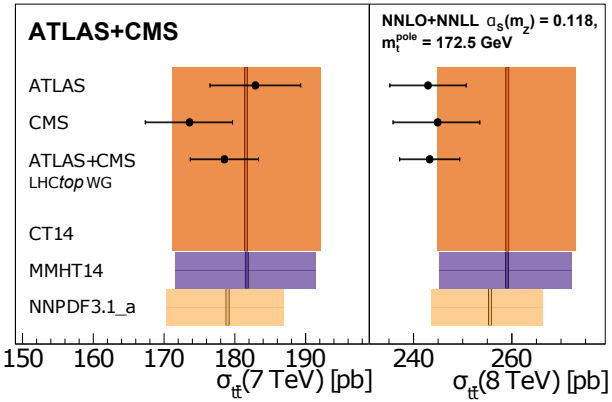
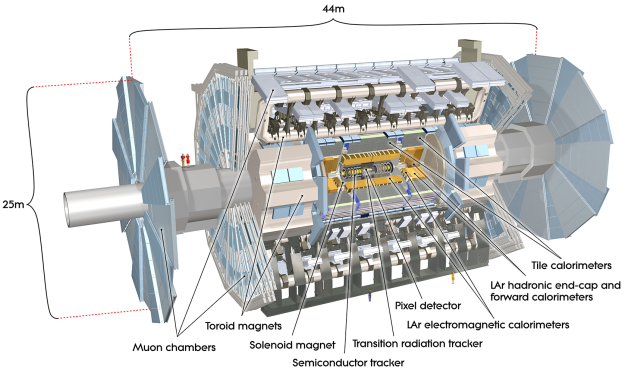


ATLAS detector

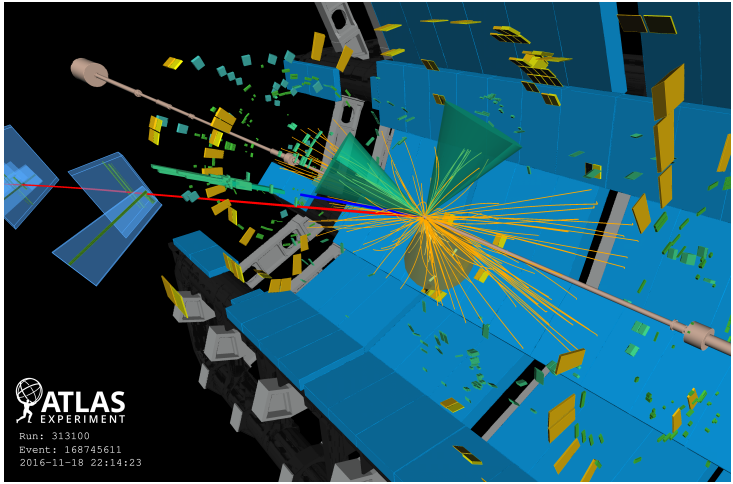
- **A T**oroidal **L**HC **A**pparatu**S** (ATLAS) is the largest, multi-purpose particle detector at the LHC.
- Three main systems are used in reconstruction:
  - inner detector,
  - calorimeter system,
  - muon spectrometer.
- The $t\bar{t}$ analysis uses reconstructed electrons, muons, jets, *b*-jets and missing energy.



Overview of the ATLAS detector.

p+Pb data in ATLAS

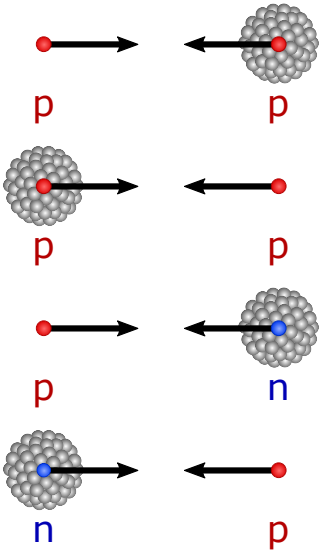
- p+Pb data at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV collected in 2016 by ATLAS.
- The luminosity of **165 nb^{-1}**, split into **57 nb^{-1}** (p+Pb) and **108 nb^{-1}** (Pb+p).
- Final luminosity calibration with a relative uncertainty of **2.4%**.



Event display of a p+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

ℓ+jets

e+jets

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

μ+jets

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

Dilepton

ee

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

$\mu\mu$

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

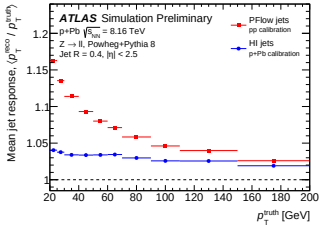
$e\mu$

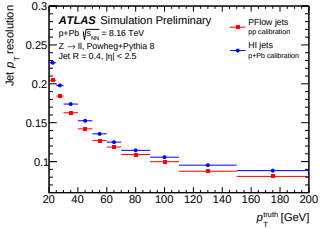
- 1 electron,
- 1 muon,
- opposite sign leptons,
- $m_{\ell\ell} > 15$ GeV,
- at least 2 jets.

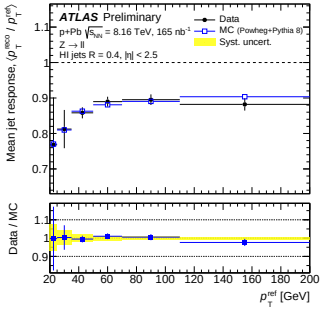
Jet reconstruction

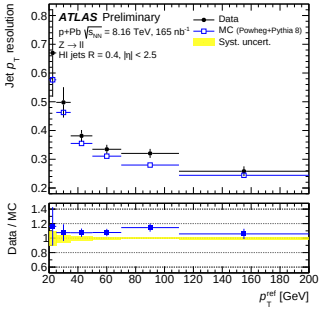
- Jets are required to have $p_{\mathrm{T}} > 20$ **GeV** and $|\eta| < 2.5$.
- Jets are reconstructed using the anti-k_t algorithm with jet radius of $R = 0.4$.
- Two jet definitions are used
  - **heavy-ion (HI)** - dedicated for Pb+Pb collisions including underlying event correction,
  - **particle-flow (PF)** - standard jet definition with available *b*-quark tagging.

JETM-2023-001







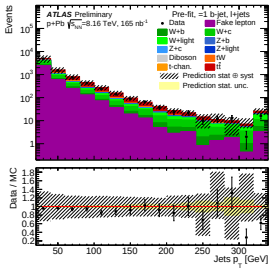


Jet reconstruction

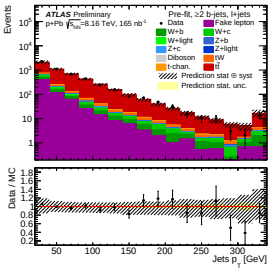
ATLAS-CONF-2023-063

ℓ+jets channel

1 *b*-jet category

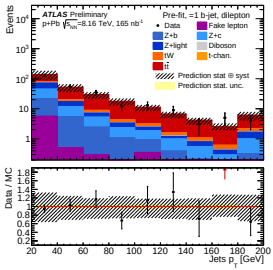


≥2 *b*-jet category

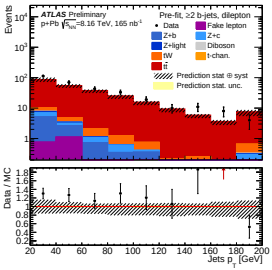


Dilepton channel

1 *b*-jet category



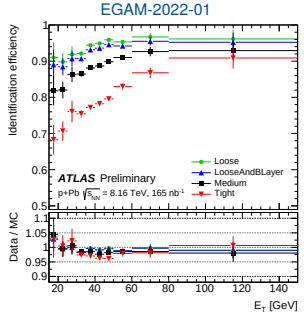
≥2 *b*-jet category

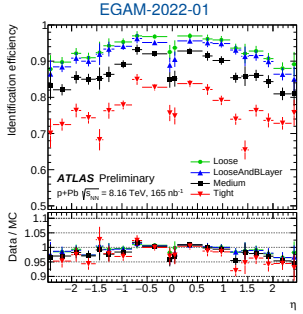


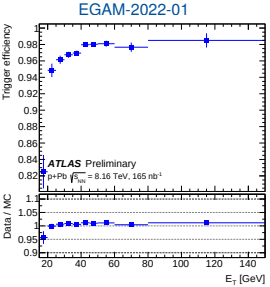
- PF jets with *b*-hadrons are tagged using a recurrent neural network algorithm - DL1r (EPJ C 79 (2019) 970).
- A good aggrement between data and prediction within combined statistical (yellow band) and systematic (hatched band) uncertainties.

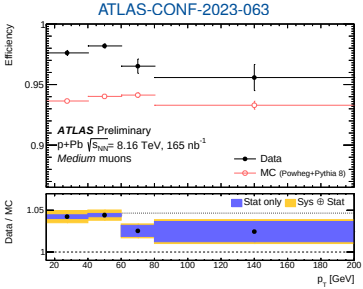
Lepton reconstruction

- Electrons must have $\boldsymbol{p_T} > \mathbf{18\ GeV}$ and $|\eta| < 2.47$, pass Medium identification and be isolated.
- Muons must have $\boldsymbol{p_T} > \mathbf{18\ GeV}$ 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).







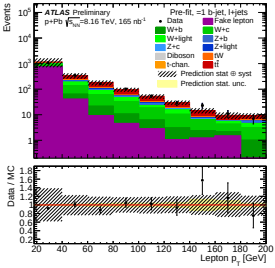


Lepton reconstruction

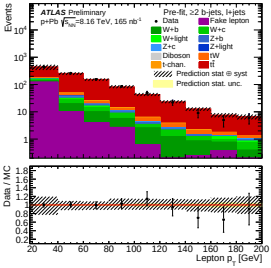
ATLAS-CONF-2023-063

ℓ+jets channel

1 *b*-jet category

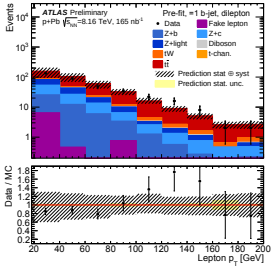


$\geq$2 *b*-jet category

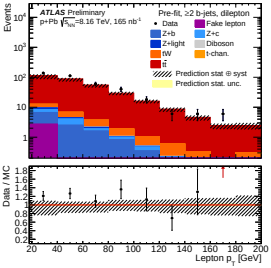


Dilepton channel

1 *b*-jet category



$\geq$2 *b*-jet category



- Fake lepton background is estimated from data using the matrix-method technique (arXiv:2211.16178).
- A good aggrement between data and prediction within combined statistical (yellow band) and systematic (hatched band) uncertainties.

Top quark and W boson

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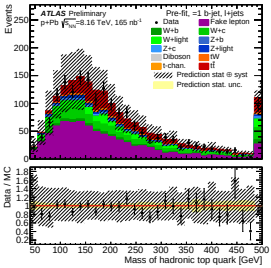
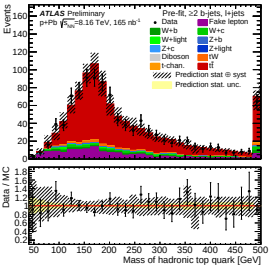
Hadronically decaying top quark

1 *b*-jet category

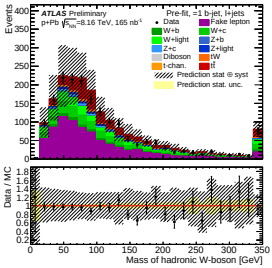


$\geq$2 *b*-jet category

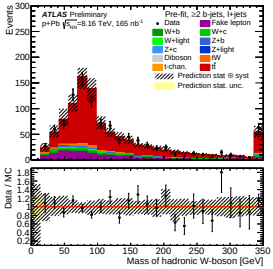


Hadronically decaying W boson

1 *b*-jet category



$\geq$2 *b*-jet category



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

Signal regions

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

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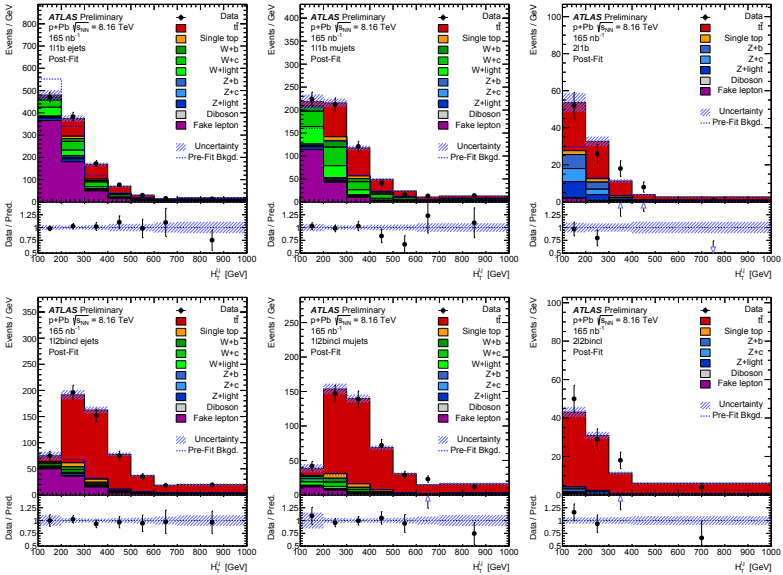

Fitting procedure

- The **signal strength** is defined as $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{\text{measured}} / \sigma_{t\bar{t}}^{\text{theory}}$
- $\mu_{t\bar{t}}$ is determined using a profile-likelihood method with $H_{\text{T}}^{\ell,j}$ data distributions.
- The most signal events are found in the ℓ+jets regions with $\geq$2 *b*-jets.
- The dilepton channel with $\geq$2 *b*-jets forms the cleanest signal region.

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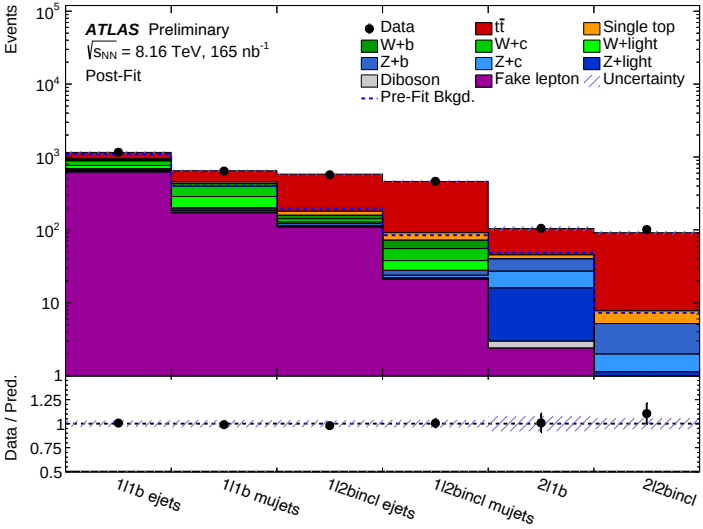
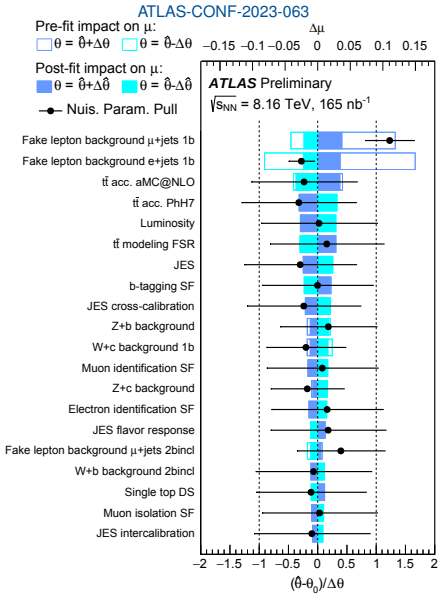


Systematic uncertainties

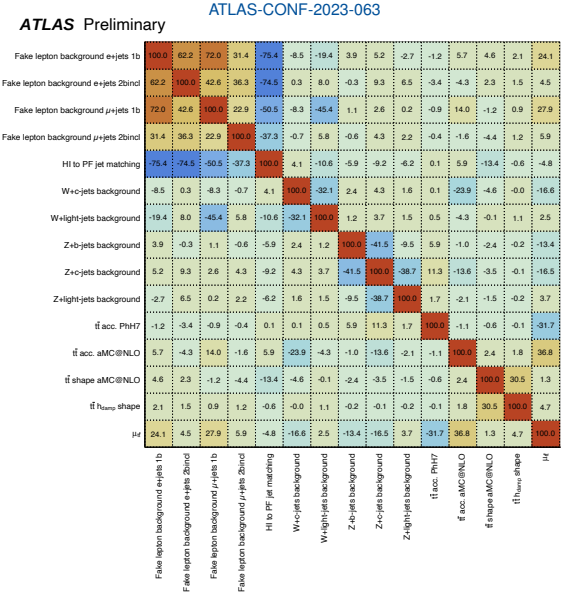
- Systematic uncertainties arise from the lepton and jet reconstruction, *b*-tagging, fake-lepton background, the signal and background modeling, and luminosity.
- The main systematic uncertainties include **jet energy scale** and **signal modelling**.
- The total systematic uncertainty amounts to **9%**.

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



Correlations

- Correlations beetween all systematic components have been studied.
- Components with $\geq$ 30% correlations are presented in a form of the correlation matrix.
- The largest **correlation** of $\sim$ 70% is found between fake-lepton background estimation in *e*+jets and μ+jets channels.
- The largest **anticorrelation** of $\sim -75\%$ is observed between fake-lepton background estimation and matching two jet definitions heavy-ion (HI) and particle-flow (PF).



Cross-section measurement

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

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

- The total uncertainty amounts to **9%**, which makes it the most precise $t\bar{t}$ measurement in HI collisions.

- The significance is well over $\mathbf{5}\,\sigma$ in the ℓ+jets and dilepton channels separately.

- First observation of top-quark pair production in the **dilepton channel** in p+Pb collisions.

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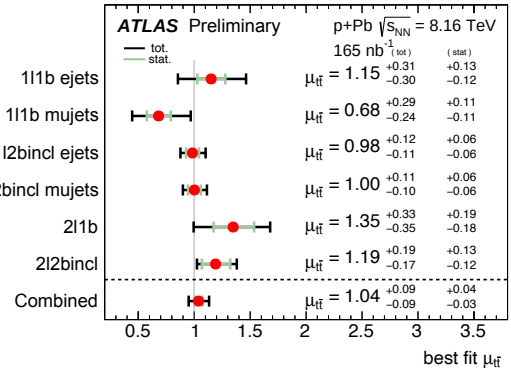

Comparison to other experimental results and theory

- The cross section is compared to the **CMS measurement** in the *p*+Pb system.
- The result is consistent with the cross section in ***pp* collisions**, scaled by $A = 208$ and extrapolated to $\sqrt{s} = 8.16$ 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 $2\,\sigma$ significance.
  - A good agreement is found with NNLO calculation based on other nPDF sets.

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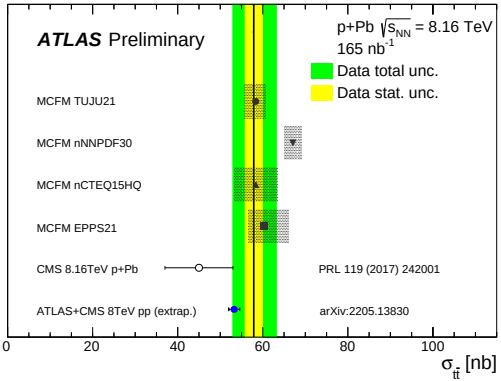
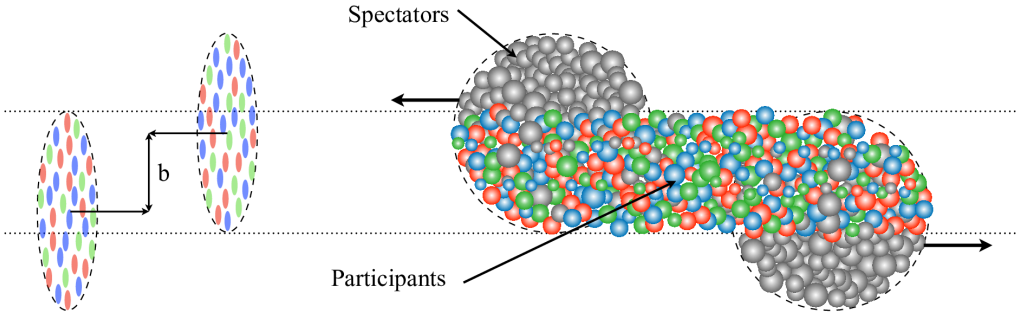


Prospects of $t\bar{t}$ in Pb+Pb



- Pb+Pb data collected by ATLAS:
  - **Run 2:** 1.4 nb^{-1} at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in 2018,
  - **Run 3:** 1.7 nb^{-1} at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV in 2023.

- Centrality varies from ultra-peripheral $\rightarrow$ peripheral $\rightarrow$ central,
  top quarks are expected to be produced with higher probability in central collisions.

CMS Pb+Pb measurement

- First evidence of $t\bar{t}$ production in dilepton final states in heavy-ion collisions in CMS.
- Total integrated luminosity of **1.7 nb^{-1}**.
- Measurement uses a fit to Boosted Decision Tree discriminator distributions.
- Observed significance:
  3.8 σ (dilepton-only),
  4.0 σ (dilepton + *b*-jets).
- Measured cross sections for two methods:
  $\sigma_{t\bar{t}} = 2.54\ ^{+0.84}_{-0.74}$ µb (dilepton-only),
  $\sigma_{t\bar{t}} = 2.03\ ^{+0.71}_{-0.64}$ µb (dilepton + *b*-jets).

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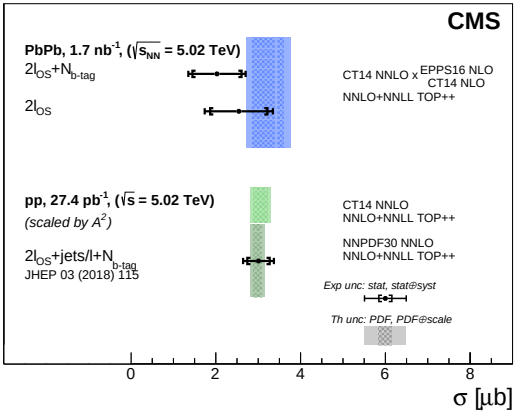

ATLAS *pp* 5.02 TeV measurement

- *pp* at $\sqrt{s} = 5.02$ TeV represents a reference system to Pb+Pb collisions at the same energy.
- Total integrated luminosity of **257 pb^{-1}**.
- Measurement combines ℓ+jets and dilepton decay modes.
- Very precise $t\bar{t}$ cross-section measurement: $\sigma_{t\bar{t}} = 67.5 \pm 0.9$ (stat.) ± 2.3 (syst.) ± 1.1 (lumi.) ± 0.2 (beam) pb.
- *pp* $\sigma_{t\bar{t}}$ scaled by A^2 can be compared to Pb+Pb $\sigma_{t\bar{t}}$.

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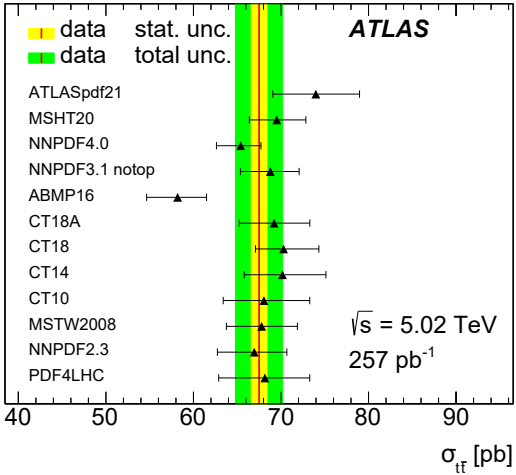

Summary

1. The top-quark pair production cross section has been measured to be
$$\sigma_{t\bar{t}} = 57.9 \pm 2.0\ (\text{stat.})\ ^{+4.9}_{-4.5}\ (\text{syst.})\ \text{nb}.$$

2. The significance is well over 5 σ in the dilepton channel, resulting in the first observation of $t\bar{t}$ production in the dilepton channel in p+Pb collisions.

3. The result is consistent with the CMS measurement, the scaled cross section in pp collisions and NNLO calculation based on four nPDF sets.

4. A combination with the CMS measurement could further improve $t\bar{t}$ cross-section precision in p+Pb collisions.

5. A $t\bar{t}$ measurement in Pb+Pb collisions by ATLAS is also envisaged.

Acknowledgements

Research project partly supported by the National Science Centre of Poland under grant number UMO-2020/37/B/ST2/01043 and by PL-GRID infrastructure.

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