Top quark pair production in Heavy Ion Collisions with the ATLAS experiment

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for the ATLAS Collaboration

Outline

Observation of $t\bar{t}$ production in lepton+jets and dilepton channels in p+Pb collisions

Poster
by **P. Potępa**

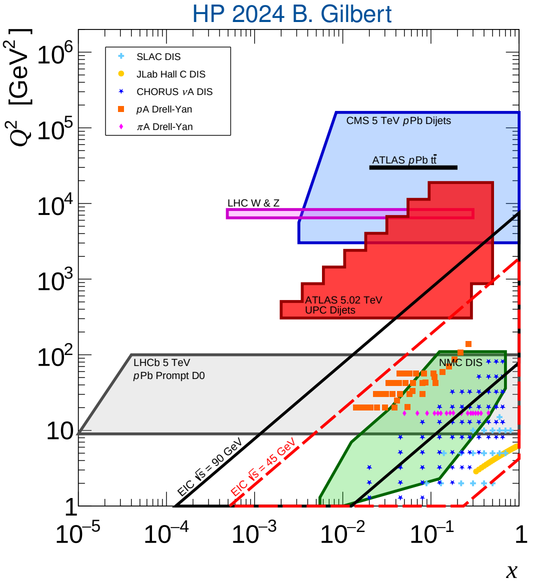
arXiv:2405.05078

Nuclear PDFs

- Top quarks provide novel probes of **nuclear modifications** to parton distribution functions (nPDF).
- **World data** constraining nPDFs are shown on the (x, Q^2) plane.
- Recent **ATLAS measurements** cover a large phase-space region:
  - **UPC dijets 5.02 TeV** (arXiv:2409.11060),
  - **dijets 8.16 TeV *p*+Pb** (PRL 132 (2024) 102301),
  - **$t\bar{t}$ 8.16 TeV *p*+Pb** (arXiv:2405.05078).

Talk by **B. Gilbert**

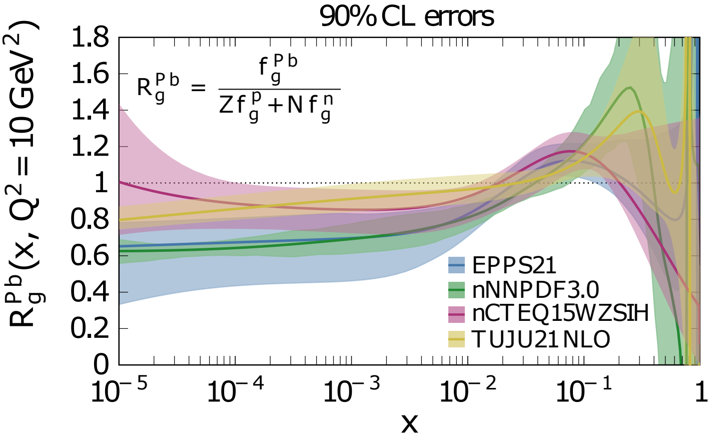
Poster by **M. Hoppesch**



Gluon PDF

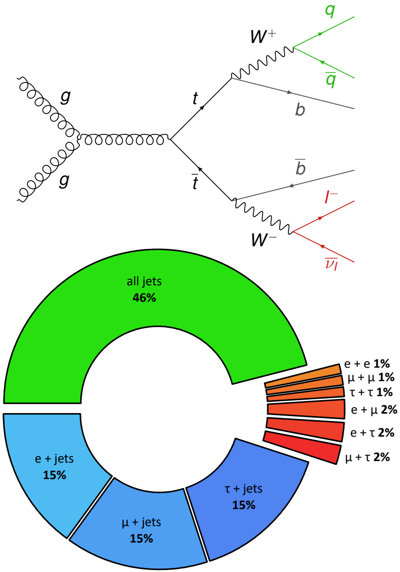
- The gluon nPDF is important for perturbative calculations in **QCD** at LHC energies.
- Large uncertainties for **gluon nPDFs** at high Bjorken-*x* values.
- **Top quarks** are sensitive to gluon nPDFs in the high Bjorken-*x* region.
- An **enhancement** in $t\bar{t}$ production is expected compared to *pp* collisions.

QM 2022 P. Paakkinen



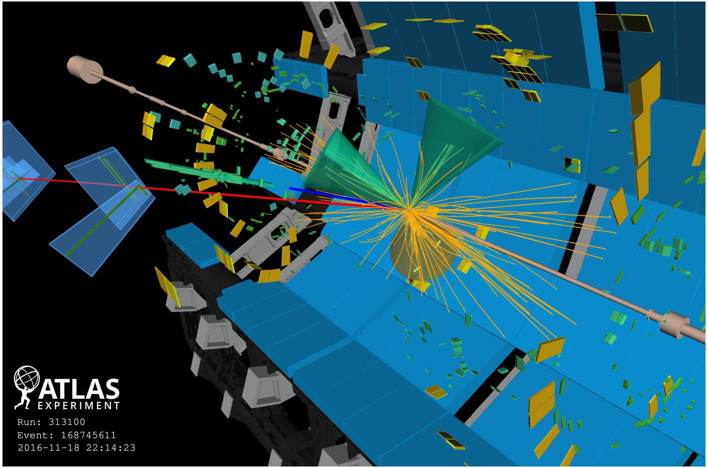
Top-quark pair production

- The top-quark pair ($t\bar{t}$) production is studied in ***p*****+Pb collisions**.
- The $t\bar{t}$ **cross section** is measured in the combined **ℓ+jets** and **dilepton** channel.
- The first measurement of the **nuclear modification factor** R_{pA} for the $t\bar{t}$ process.
- Measurements by CMS:
  p+Pb (PRL 119, 242001 (2017)),
  Pb+Pb (PRL 125, 222001 (2020)).



p+Pb data in ATLAS

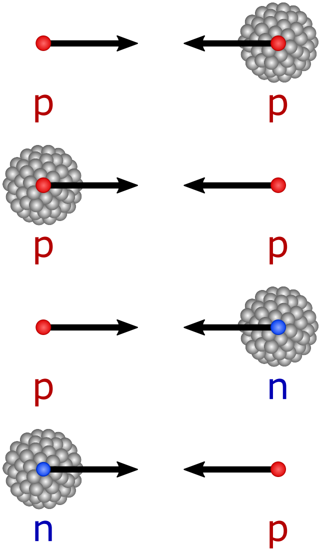
- p+Pb data at $\sqrt{s_{\text{NN}}} = 8.16$ TeV collected in 2016 by ATLAS.
- The luminosity of **165 nb^{-1}**, split into **57 nb^{-1}** (p+Pb) and **108 nb^{-1}** (Pb+p).
- Final luminosity calibration with a relative uncertainty of **2.4%.**



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 overlay samples.
- **Signal:** $t\bar{t}$,
  Background: 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.

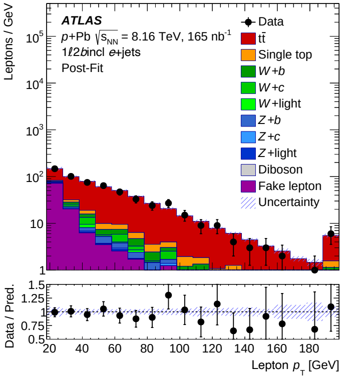
Background

- Single top,
- W+jets,
  - W+b,
  - W+c,
  - W+light,
- Z+jets,
  - Z+b,
  - Z+c,
  - Z+light,
- Diboson,
- Fake lepton.

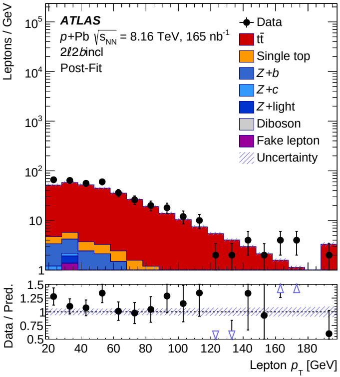
Lepton reconstruction

- **Electrons** must have $p_T > 18$ GeV and $|\eta| < 2.47$, pass Medium identification and be isolated.
- **Muons** must have $p_T > 18$ 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).
- **Fake-lepton background** is estimated from data using the matrix-method technique.

e+jets



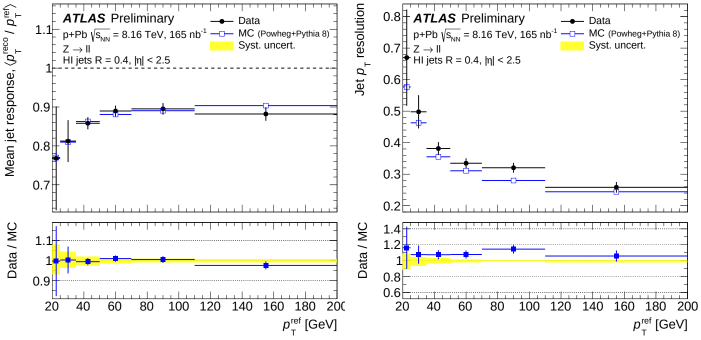
dilepton



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 $R = 0.4$.
- **Jet calibration** uses 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).

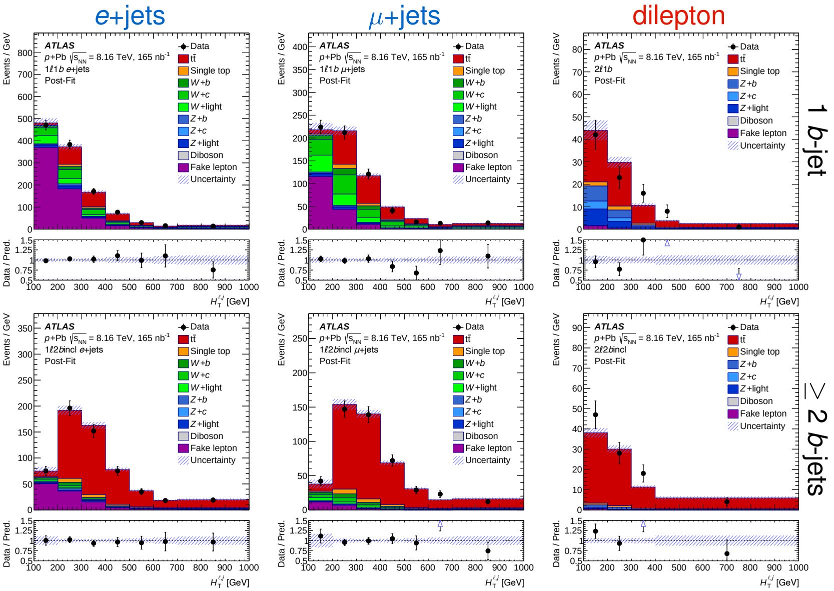
Mean jet response   Jet p_T resolution



JETM-2023-001

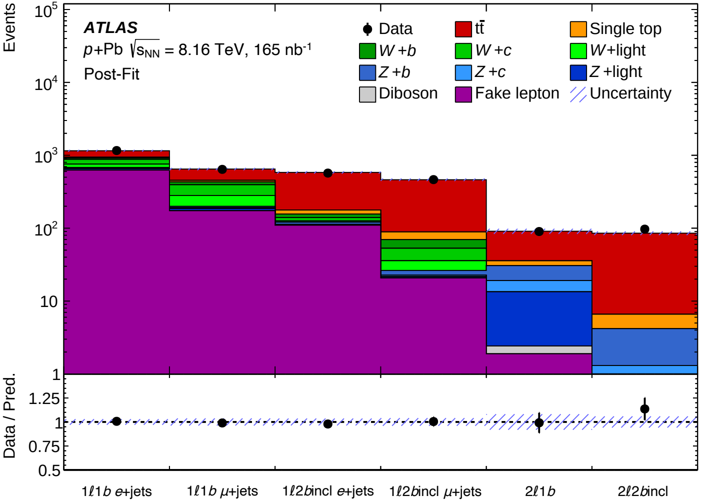
Signal regions

- **Signal regions** are defined using $H_{\mathrm{T}}^{\ell,j}$ distributions.
- $H_{\mathrm{T}}^{\ell,j}$ is the scalar sum of lepton and jet p_{T}.
- Six signal regions:
  - $1\ell 1b$ e+jets,
  - $1\ell 2b$incl e+jets,
  - $1\ell 1b$ μ+jets,
  - $1\ell 2b$incl μ+jets,
  - $2\ell 1b$,
  - $2\ell 2b$incl.



Fitting procedure

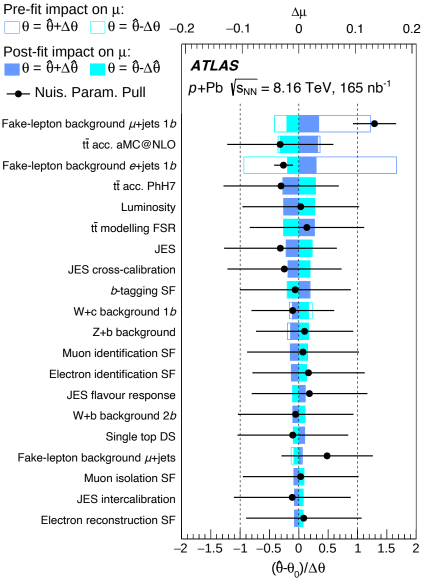
- **Signal strength** definition: $\mu_{t\bar{t}} = \sigma^{\text{measured}}_{t\bar{t}} / \sigma^{\text{theory}}_{t\bar{t}}$.
- $\mu_{t\bar{t}}$ is determined by a **profile-likelihood fit** to $H_{\mathrm{T}}^{\ell,j}$ data distributions.
- The **highest signal statistics** in the ℓ+jets regions with $\geq$2 b-jets.
- The **cleanest signal region** in the dilepton channel with $\geq$2 b-jets.



Systematic uncertainties

- Main systematic uncertainties:
  jet energy scale, signal modelling.
- The total systematic uncertainty: **8%.**

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**



Cross-section measurement

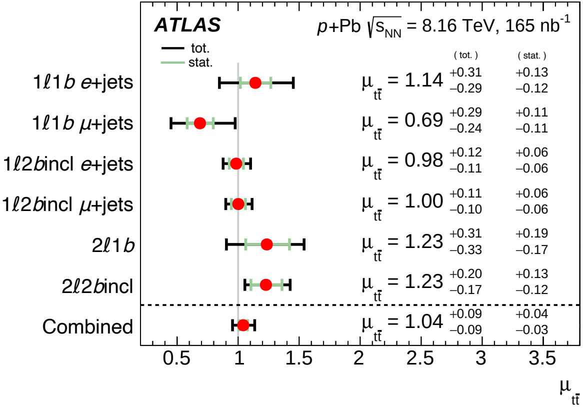
- Signal strength is translated to the cross section:

$$\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{\mathrm{Pb}} \cdot \sigma^{th}_{t\bar{t}}.$$

- Measured $t\bar{t}$ cross section:

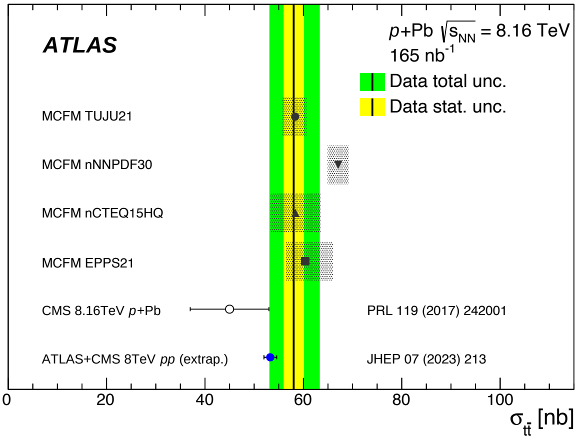
$$\boldsymbol{\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\mathrm{stat.})\ ^{+4.8}_{-4.4}\ (\mathrm{syst.})\ \mathrm{nb}}.$$

- The first observation of $t\bar{t}$ production in the **dilepton channel** in p+Pb collisions.
- The total uncertainty amounts to **9%**, the most precise $t\bar{t}$ measurement in heavy-ion collisions.



Comparison to theory and other measurements

- Consistent with the **CMS result** in p+Pb collisions (PRL 119, 242001 (2017)).
- Consistent with the cross section in ***pp* collisions** (JHEP 07 (2023) 213), scaled by $A_{\mathrm{Pb}} = 208$ and extrapolated to $\sqrt{s} = 8.16$ TeV.
- Good agreement with **NNLO+nPDFs predictions**.



Nuclear modification factor

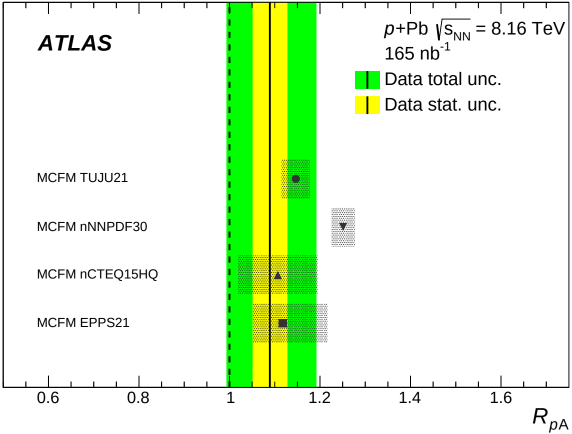
- Nuclear modification factor definition:

$$R_{pA} = \frac{\sigma_{t\bar{t}}^{p+\mathrm{Pb}}}{A_{\mathrm{Pb}} \cdot \sigma_{t\bar{t}}^{pp}}.$$

- Measured nuclear modification factor:

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

- The largest difference for the nNNPDF30 prediction.



Summary

ATLAS HI public results

Observation of $t\bar{t}$ production in lepton+jets and dilepton channels in *p*+Pb collisions

- Measured $t\bar{t}$ **cross section**: $\sigma_{t\bar{t}} = 58.1 \pm 2.0\,(\text{stat.})\,^{+4.8}_{-4.4}\,(\text{syst.})$ nb.
- Measured **nuclear modification factor**: $R_{pA} = 1.090 \pm 0.039\,(\text{stat.})\,^{+0.094}_{-0.087}\,(\text{syst.})$.
- The first $t\bar{t}$ observation in the **dilepton channel** in *p*+Pb collisions at the LHC.
- The **most precise** $t\bar{t}$ cross-section measurement in heavy-ion collisions.