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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

$t\bar{t}$ production in heavy-ion collisions with the ATLAS and CMS detectors

ATLAS EXPERIMENT

Patrycja Potępa

for the ATLAS and CMS Collaborations

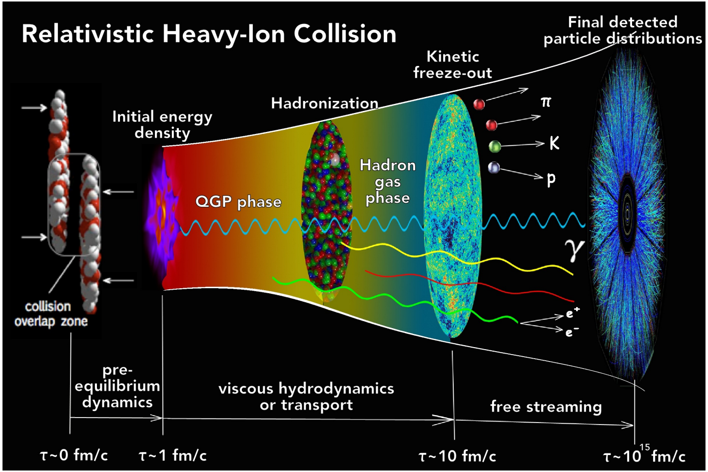
CMS

Outline

Quark-gluon plasma

- **Quark-gluon plasma** (QGP) is created in heavy-ion collisions at LHC and RHIC energies.
- QGP is short-lived with a lifetime of $\sim$ **10 fm/c**.
- QGP is studied via **hard probes** that interact with it.
- Among the elementary particles, only the **top quark** and the **Higgs boson** have not been observed in Pb+Pb collisions.

Nucl.Phys.A 1047 (2024) 122874

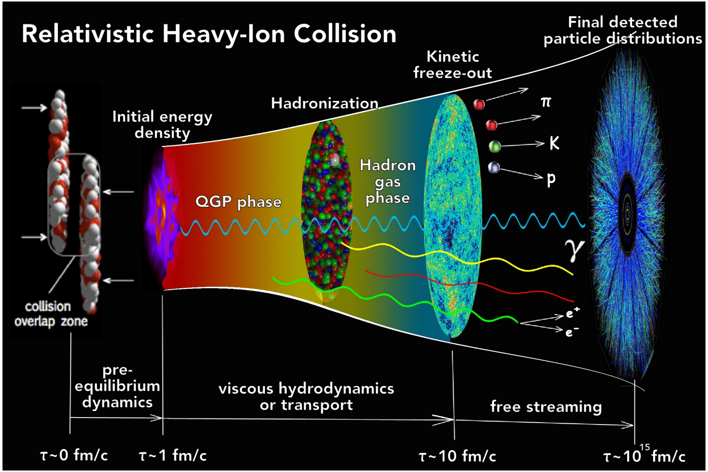


Quark-gluon plasma

Nucl.Phys.A 1047 (2024) 122874

- Top quarks are expected to interact with the **pre-equilibrium stage** of the QGP.
- Differences between *pp* and Pb+Pb systems are quantified via nuclear modification factors.
- The **time structure** of the QGP can be studied via hadronically decaying *W* bosons.

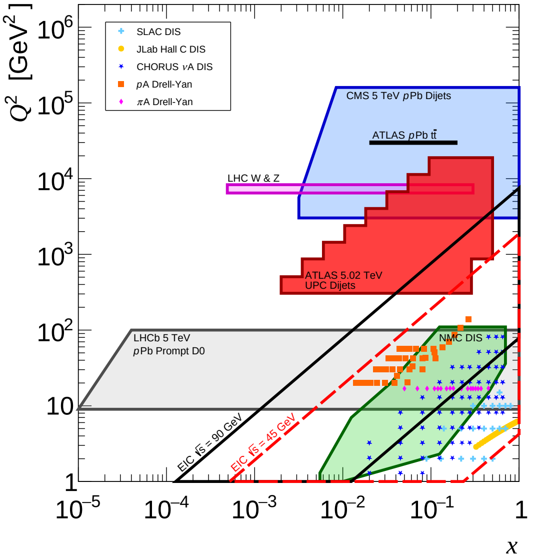
Talk
by **G. Milhano**



Nuclear PDFs

- Top quarks provide novel probes of **nuclear modifications** to parton distribution functions (nPDF).
- Selection of 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),
  - $\boldsymbol{t\bar{t}}$ **8.16 TeV *p*+Pb** (arXiv:2405.05078).

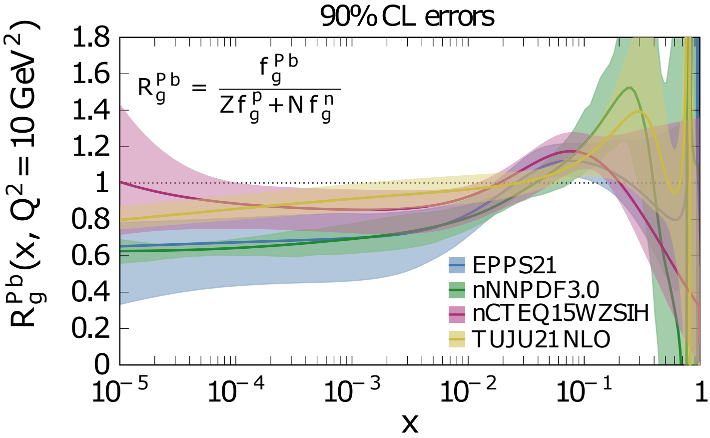
HP 2024 B. Gilbert



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.

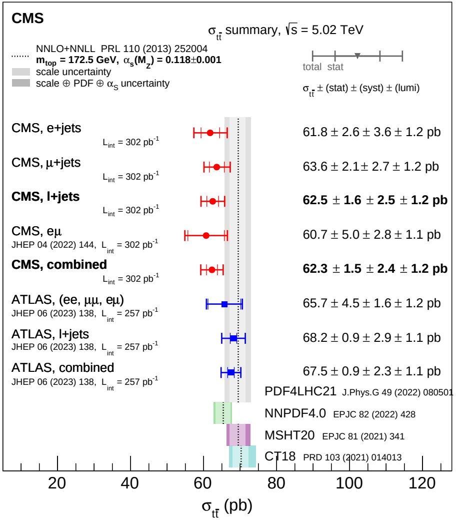
QM 2022 P. Paakkinen



$t\bar{t}$ in 5.02 TeV *pp* collisions by ATLAS and CMS

- *pp* at $\sqrt{s} = 5.02$ TeV is a reference system to Pb+Pb collisions at the same energy.
- Total integrated luminosity of 2017 *p*+Pb data is **257 pb^{-1}** (ATLAS) and **302 pb^{-1}** (CMS).
- Measurements combines ℓ**+jets** and **dilepton** channels.
- Very precise cross-section measurements:
  $\sigma_{t\bar{t}} = \mathbf{67.5 \pm 2.7}$ **pb** (ATLAS),
  $\sigma_{t\bar{t}} = \mathbf{62.3 \pm 3.1}$ **pb** (CMS).
- Total relative uncertainties:
  4% (ATLAS),
  5% (CMS).

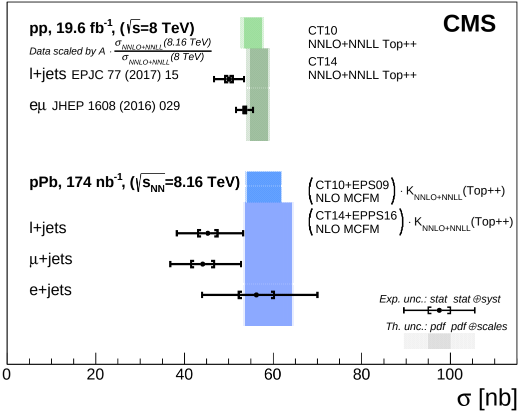
arXiv:2410.21631



$t\bar{t}$ in p+Pb collisions by CMS

- First observation of $t\bar{t}$ production in 2016 ***p*+Pb collisions** by CMS.
- Total integrated luminosity of **174 nb^{-1}**.
- Measurement done in the **ℓ+jets** ($\ell = e, \mu$) channel of $t\bar{t}$ decay.
- Combined cross-section: $\sigma_{t\bar{t}} = 45 \pm 8$ nb.
- Total relative uncertainty of **18%**.

PRL 119, 242001 (2017)



$t\bar{t}$ in p+Pb collisions by ATLAS

- $t\bar{t}$ production cross-section in 2016 p+Pb collisions by ATLAS:

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

- First observation of $t\bar{t}$ production in the **dilepton** (ee, $\mu\mu$, $e\mu$) channel of $t\bar{t}$ decay.

- Nuclear modification factor definition:

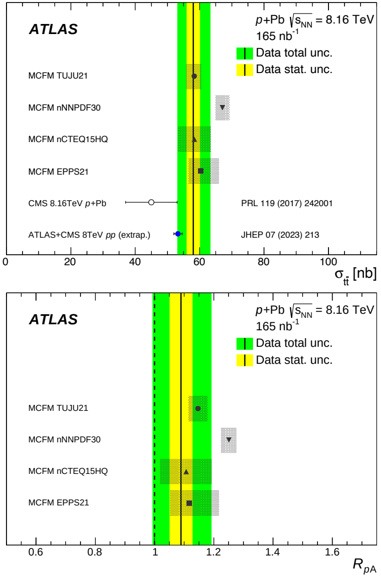
$$R_{pA} = \frac{\sigma^{p+\mathrm{Pb}}_{t\bar{t}}}{A_{\mathrm{Pb}} \cdot \sigma^{pp}_{t\bar{t}}}.$$

- First measurement of the nuclear modification factor:

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

- Good agreement with NNLO calculation for three nPDFs, the largest discrepancy with nNNPDF3.0.

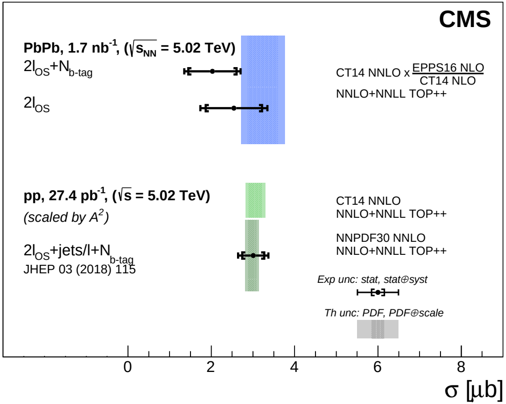
arXiv:2405.05078



$t\bar{t}$ in Pb+Pb collisions by CMS

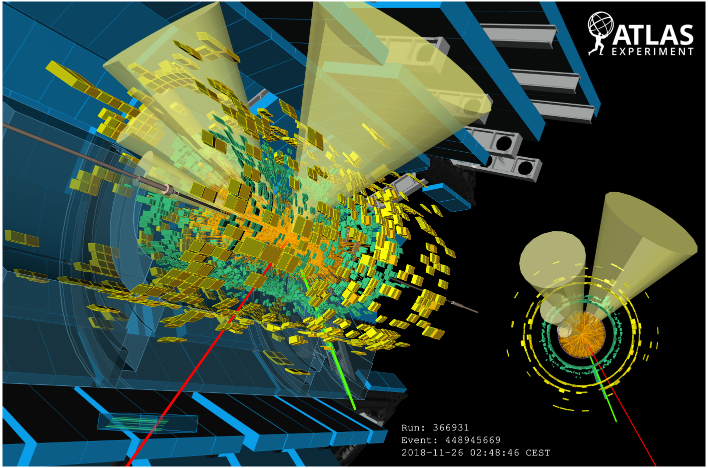
- First evidence of $t\bar{t}$ production in 2018 **Pb+Pb collisions** by CMS.
- Total integrated luminosity of **1.7 nb^{-1}**.
- Measurement done in the **dilepton** channel of $t\bar{t}$ decay.
- Observed significance for two methods:
  3.8 σ (dilepton-only),
  4.0 σ (dilepton + *b*-jets).
- Measured cross-sections:
  $\sigma_{t\bar{t}} = 2.54\ ^{+0.84}_{-0.74}\ \mu\mathrm{b}$ (dilepton-only),
  $\sigma_{t\bar{t}} = 2.03\ ^{+0.71}_{-0.64}\ \mu\mathrm{b}$ (dilepton + *b*-jets).
- Older (available back then) PDF (CT14) and nPDF (EPPS16) used.

PRL 125, 222001 (2020)



Pb+Pb data in ATLAS

- Pb+Pb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV collected in Run 2 (2015, 2018) by ATLAS.
- The luminosity of **1.9 nb^{-1}**: **0.49 nb^{-1}** (2015) **1.4 nb^{-1}** (2018).
- Final luminosity calibration with a relative uncertainty of **1.5%.**
- **Collision centrality** varies from 0% (the most central) to 100% (the most peripheral).

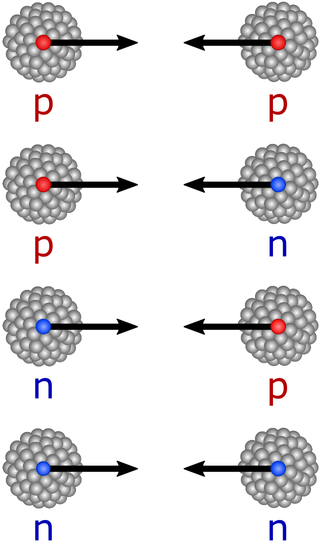


Event display of a Pb+Pb collision containing a $t\bar{t}$ candidate in the $e\mu$ channel.

MC simulation

- Samples produced using **`PowHeg + Pythia8`** and **`Sherpa`** MC generators.
- **Four isospin configurations:** proton-proton (pp), proton-neutron (pn) neutron-proton (np), neutron-neutron (nn).
- Events embedded into HIJING min-bias Pb+Pb collisions forming **HIJING overlay** samples.
- **Signal process:**
  - $t\bar{t}$

  Background processes:
  - tW
  - VV
  - Z



Event selection

Dilepton

- 0–80% collision centrality
- primary vertex

ee (control region)

- 2 electrons,
- 0 muons,
- opposite sign leptons,
- $m_{ee} \in$ (66-116) GeV,
- no jet requirement.

$\mu\mu$ (control region)

- 2 muons,
- 0 electrons,
- opposite sign leptons,
- $m_{\mu\mu} \in$ (66-116) GeV,
- no jet requirement.

$e\mu$ (signal region)

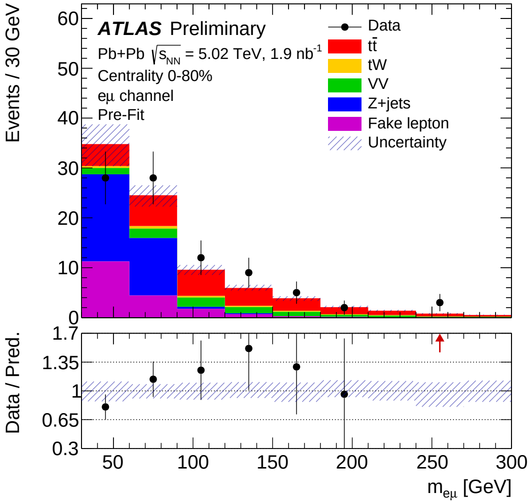
- 1 electron,
- 1 muon,
- opposite sign leptons,
- $m_{e\mu} > 30$ GeV,
- at least 2 jets.

Background

- Single top (tW),
- Diboson (VV),
- Z+jets,
  - $Z \to ee$,
  - $Z \to \mu\mu$,
  - $Z \to \tau\tau$,
- Fake lepton.

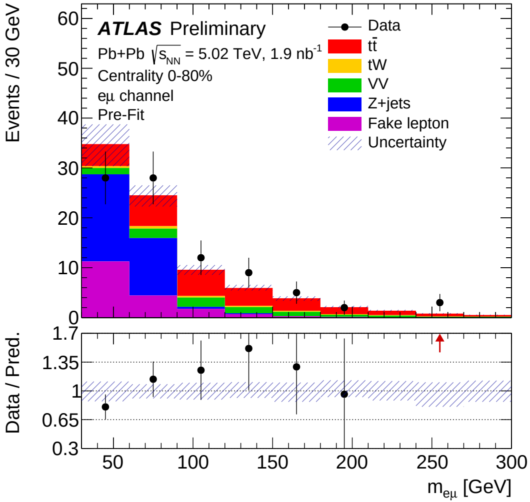
Lepton reconstruction

- Electrons must have $p_\mathrm{T} > $ **18 GeV** and $|\eta| < 2.47$, pass Loose identification and be isolated.
- Muons must have $p_\mathrm{T} > $ **15 GeV** and $|\eta| < 2.5$, pass Loose requirements and be isolated.
- Low-pileup electron calibration and dedicated electron and muon scale factors are applied.
- **Fake-lepton background** is estimated from data using the ABCD method.



Jet reconstruction

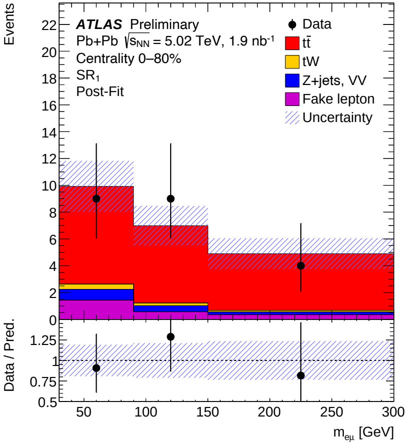
- Jets are required to have $p_{\mathrm{T}} > 35$ GeV and $|\eta| < 2.5$.
- Jets are reconstructed using the anti-k_t algorithm with jet radius of $R = 0.4$.
- The background energy from the **underlying event** is subtracted on an event-by-event basis.
- Jets are calibrated using simulation and in-situ measurements.
- **No *b*-tagging** requirements are imposed on jets.



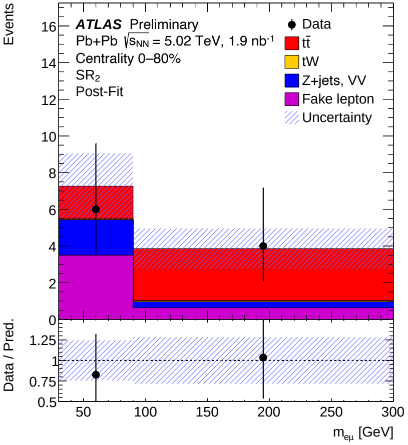
Signal regions

- Two **signal regions** are defined using invariant mass $m_{e\mu}$:
  - **SR1:** $p_T^{e\mu} > 40$ GeV,
  - **SR2:** $p_T^{e\mu} \leq 40$ GeV.
- **Signal strength** definition: $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{\text{measured}} / \sigma_{t\bar{t}}^{\text{theory}}$.
- $\mu_{t\bar{t}}$ is determined by a **profile-likelihood fit** to $m_{e\mu}$ data distributions.

Signal region 1



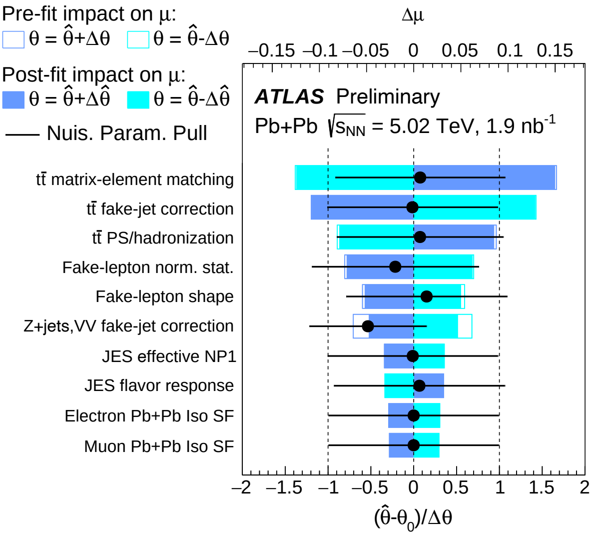
Signal region 2



Systematic uncertainties

- Main systematic uncertainties: **signal modelling** and **jet reconstruction**.
- The total systematic uncertainty of **18%**.

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 statistics	+2.1	-1.6
Background modeling	+1.5	-1.6
Systematic uncertainty	**+21**	**-14**

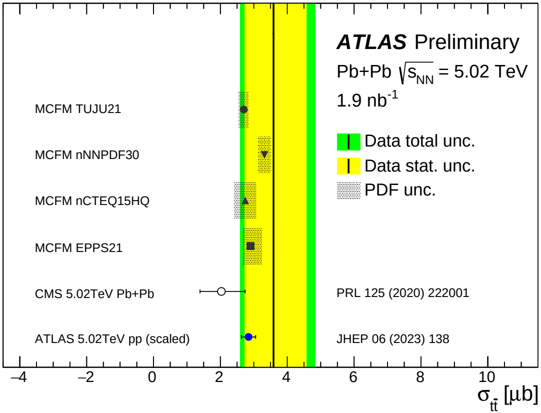


Cross-section measurement

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

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

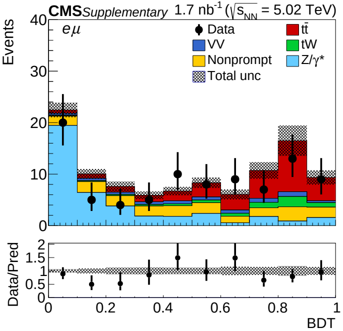
- The total uncertainty amounts to **31%**, dominated by the statistical component of 26%.
- The first observation of $t\bar{t}$ production in Pb+Pb collisions with **5.0** σ significance.
- Good agreement with NNLO predictions based on **four nPDFs** and other measurement.



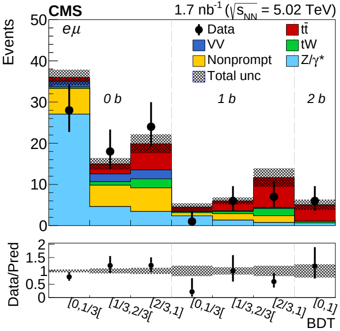
Comparison of analysis strategy

- CMS reported the **evidence** for $t\bar{t}$ production in Pb+Pb collisions (PRL 125, 222001 (2020)).
- **Boosted decision tree** (BDT) classifier trained on $t\bar{t}$ vs Z/γ^* simulation.
- **Profile-likelihood fits** to binned BDT discriminator distributions.
- Two methods:
  - **dilepton-only** uses only lepton kinematics,
  - **dilepton + *b*-jets** uses also *b*-tagging.

dilepton-only



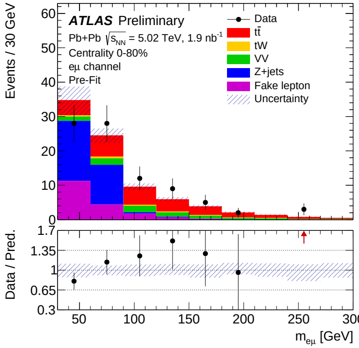
dilepton + *b*-jets



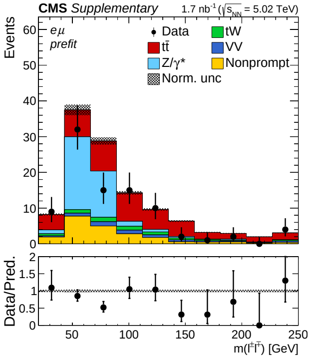
Comparison of event selection

ATLAS	CMS
Luminosity	
1.9 nb^{-1}	1.7 nb^{-1}
Channels	
$e\mu$	$e\mu$, ee, $\mu\mu$
Electrons	
$p_{\mathrm{T}} > 18$ GeV	$p_{\mathrm{T}} > 25$ GeV
$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.1$
Muons	
$p_{\mathrm{T}} > 15$ GeV	$p_{\mathrm{T}} > 20$ GeV
$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.4$
Jets	
$p_{\mathrm{T}} > 35$ GeV	$p_{\mathrm{T}} > 30$ GeV
$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.0$

ATLAS
HION-2022-10



CMS
PRL 125, 222001 (2020)



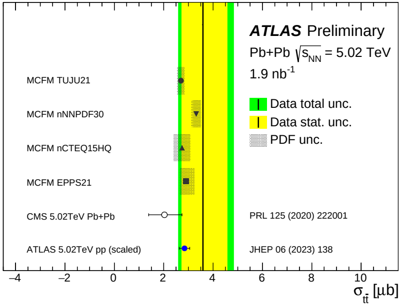
Comparison of uncertainties

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%] ATLAS	CMS dilepton-only	CMS dilepton+*b*-jets
Statistical	26	27	28
Luminosity	2	5	5
Signal and background	13	14	14
Lepton	4	6	6
Jet	12	–	2
b-tagging	–	–	6
Total systematic	18	17	19
Total	**31**	**32**	**34**

Comparison of results

ATLAS

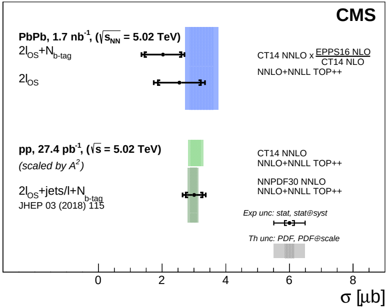
HION-2022-10



- cross-section: $\sigma_{t\bar{t}} = 3.6\ ^{+1.2}_{-1.0}\ \mu$b.
- Expected significance: **4.1** σ.
- Observed significance: **5.0** σ.

CMS

PRL 125, 222001 (2020)

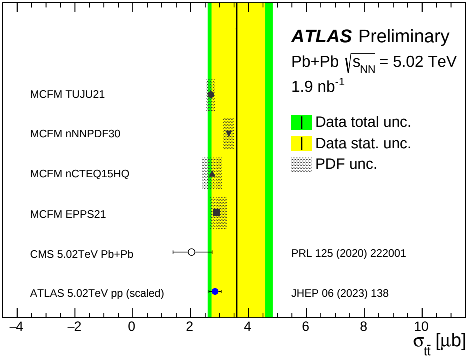


- cross-section (dilepton-only / dilepton + *b*-jets): $\sigma_{t\bar{t}} = 2.54\ ^{+0.84}_{-0.74}\ \mu$b / $\sigma_{t\bar{t}} = 2.03\ ^{+0.71}_{-0.64}\ \mu$b.
- Expected significance: **4.8** σ / **5.8** σ.
- Observed significance: **3.8** σ / **4.0** σ.

Summary

1. **First observation** of $t\bar{t}$ production in Pb+Pb collisions at the LHC by ATLAS.
2. The observed signal significance of **5.0** $\boldsymbol{\sigma}$.
3. $t\bar{t}$ cross-section:
   $\sigma_{t\bar{t}} = 3.6\ ^{+1.0}_{-0.9}\ \text{(stat.)}\ ^{+0.8}_{-0.5}\ \text{(syst.)}\ \mu\text{b}.$
4. Good agreement with theory and other measurements.
5. ATLAS+CMS combination might be useful due to high statistical uncertainties.
6. This result paves the way for further studies of the QGP.

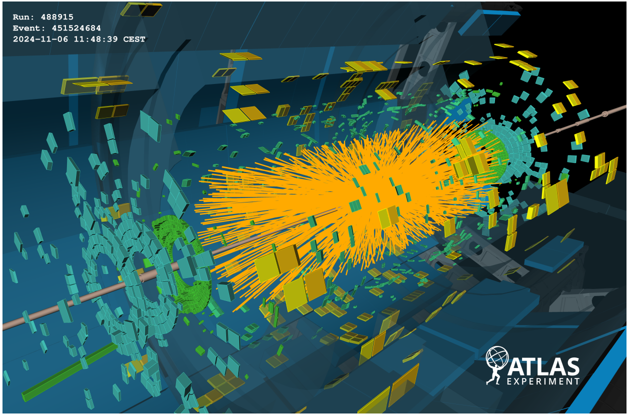
HION-2022-10



Backup slides

New data in Run 3

- **2023 Pb+Pb** at $\sqrt{s_{\text{NN}}} = 5.36$ TeV, luminosity of $1.7\ \text{nb}^{-1}$.
- **2024 Pb+Pb** at $\sqrt{s_{\text{NN}}} = 5.36$ TeV, luminosity of $\sim 1.5\ \text{nb}^{-1}$ (expected).
- **2024 *pp*** at $\sqrt{s} = 5.36$ TeV: luminosity of luminosity of $\sim 400\ \text{pb}^{-1}$.



Event display of a Pb+Pb collision event recorded in ATLAS in November 2024.