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

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Outline

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

   JHEP 11 (2024) 101

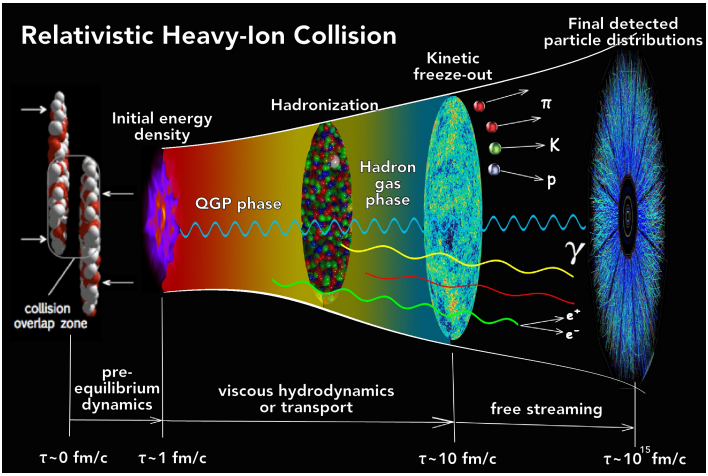
2. Observation of $t\bar{t}$ production in the electron–muon channel in Pb+Pb collisions

   arXiv:2411.10186

Quark-gluon plasma

Nucl.Phys.A 1047 (2024) 122874

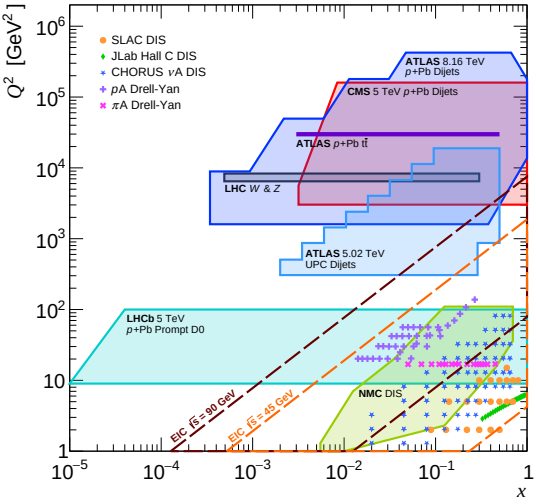
- **Quark-gluon plasma** (QGP) is created in heavy-ion collisions at LHC and RHIC energies.
- QGP is short-lived with a lifetime of $\sim$ **10 fm/c**.
- Top quarks are expected to interact with the **pre-equilibrium stage** of the QGP.
- The **time structure** of the QGP can be studied via hadronically decaying W bosons.



Nuclear PDFs

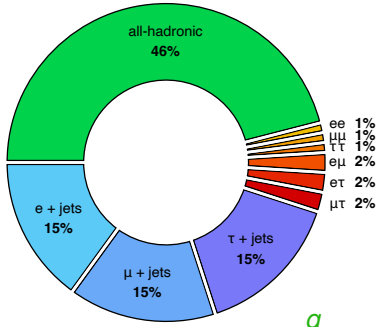
- Top quarks provide novel probes of **nuclear modifications** to parton distribution functions (nPDF).
- Selection of **world data** constraining nPDFs is shown on the (x, Q^2) plane.
- Recent **ATLAS measurements** cover a large phase-space region:
  - **UPC dijets 5.02 TeV** (arXiv:2409.11060),
  - **dijets 8.16 TeV p+Pb** (PRL 132 (2024) 102301),
  - **$t\bar{t}$ 8.16 TeV p+Pb** (JHEP 11 (2024) 101).

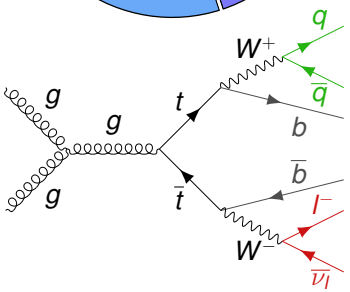
HP 2024 B. Gilbert



Top-quark pair production

- **Top quarks** can serve as novel probes of the QGP and the nPDF.
- $t\bar{t}$ production is measured in the combined **ℓ+jets** and **dilepton** channel in ***p*+Pb** collisions.
- $t\bar{t}$ production is observed for the first time in the **eμ** channel in **Pb+Pb** collisions.
- $t\bar{t}$ measurements by **CMS**:
  p+Pb collisions (PRL 119, 242001 (2017))
  Pb+Pb collisions (PRL 125, 222001 (2020)).





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

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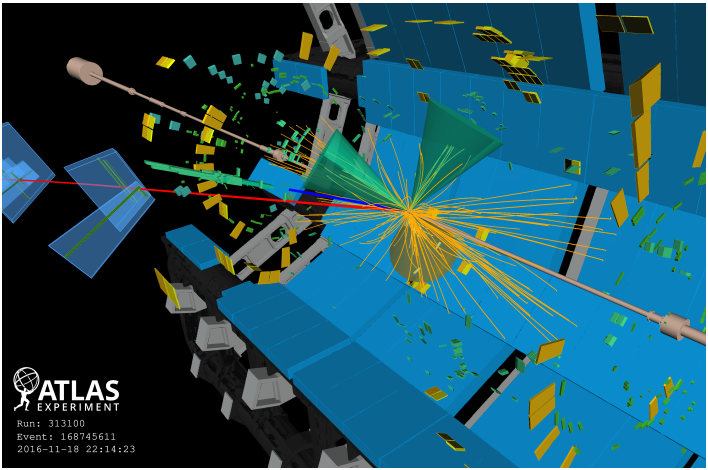
p+Pb data in ATLAS

- 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%**.

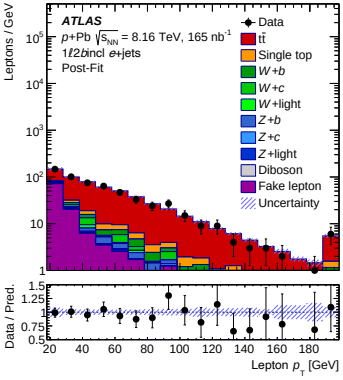


Event display of a p+Pb collision containing a $t\bar{t}$ candidate in the $e\mu$ channel.

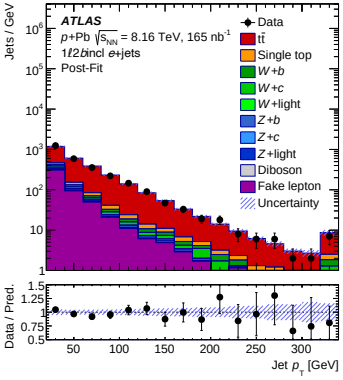
Object reconstruction

- **Electrons** must have $p_{\mathrm{T}} > 18$ GeV and $|\eta| < 2.47$, pass Medium identification and be isolated.
- **Muons** must have $p_{\mathrm{T}} > 18$ GeV and $|\eta| < 2.5$, pass Medium requirements and be isolated.
- **Jets** are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$.
- ***b*-jets** are tagged using the DL1r algorithm (EPJ C 79 (2019) 970).
- **Fake-lepton background** is estimated from data using the matrix-method technique.

Lepton p_{T}



Jet p_{T}



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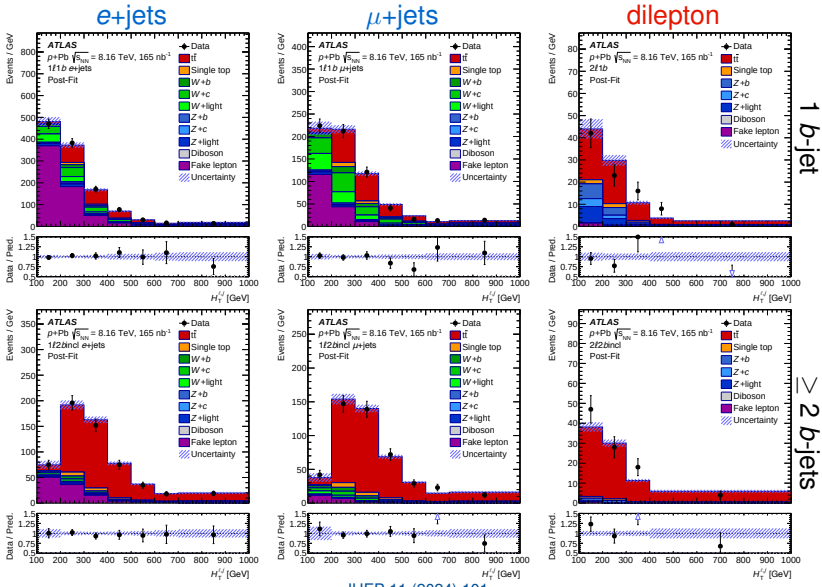
Signal regions

- **Signal strength** $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{\text{measured}} / \sigma_{t\bar{t}}^{\text{theory}}$ is determined by a profile-likelihood fit.
- $H_{\text{T}}^{\ell,j}$ 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.



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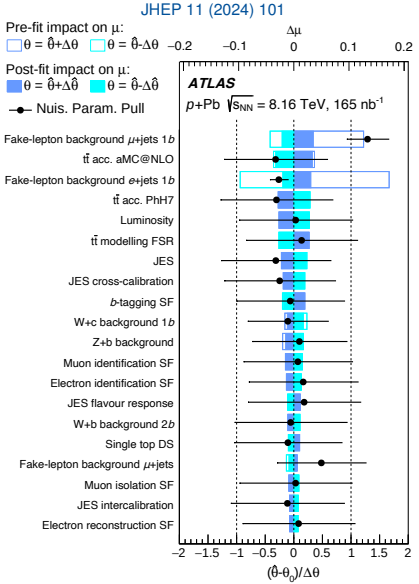
Systematic uncertainties

- The main systematic uncertainties: **jet energy scale** and **signal modelling**.
- The total systematic uncertainty amounts to **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

- The $t\bar{t}$ production cross section is measured to be

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

- The total uncertainty amounts to **9%**, which makes it the most precise $t\bar{t}$ measurement in HI collisions.
- The result is consistent with the CMS measurement and scaled cross section in pp collisions, extrapolated to $\sqrt{s} = 8.16$ TeV.
- The nuclear modification factor is measured to be

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

- Good agreement with **MCFM NNLO calculations** (PRD 94, 093009 (2016)) based on four nPDF sets.

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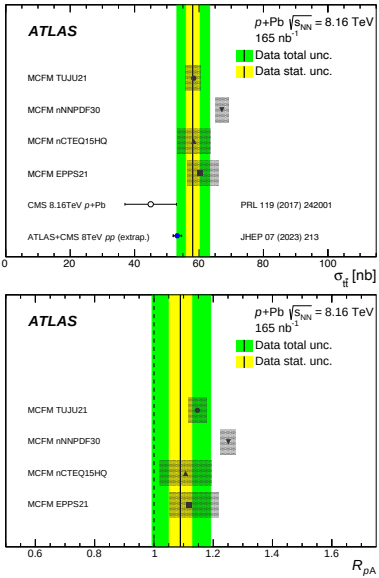
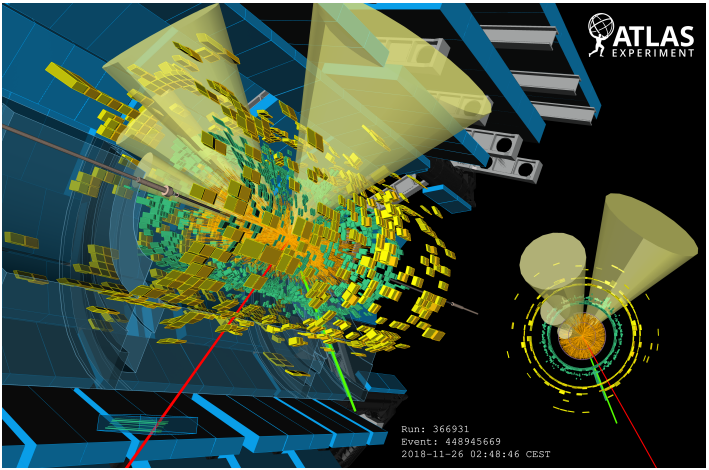


Observation of $t\bar{t}$ production in the electron–muon channel in Pb+Pb collisions

arXiv:2411.10186

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%**.

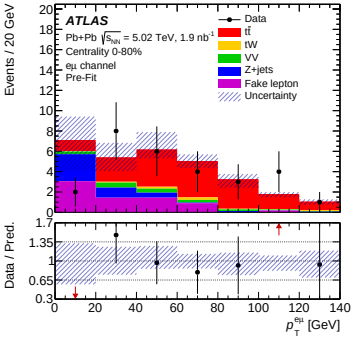


Event display of a Pb+Pb collision containing a $t\bar{t}$ candidate in the $e\mu$ channel.

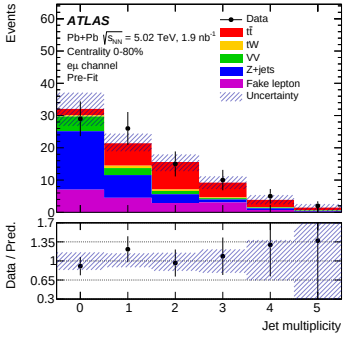
Object reconstruction

- **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.
- **Jets** are required to have $p_{\mathrm{T}} > 35$ GeV and $|\eta| < 2.5$.
- **No *b*-tagging** requirements are imposed on jets.
- **Fake-lepton background** is estimated from data using the ABCD method.

Dilepton p_{T}



Jet multiplicity



arXiv:2411.10186

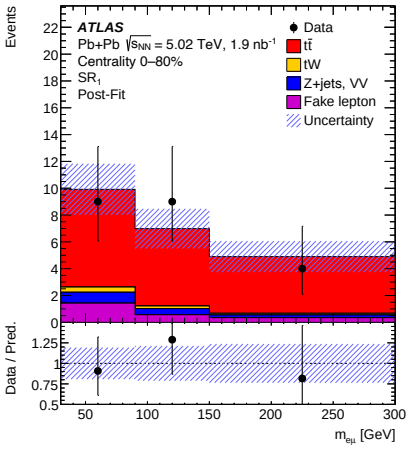
Signal regions

- Two **signal regions** are defined using invariant mass $m_{e\mu}$:
  - **SR1:** $p_{\mathrm{T}}^{e\mu} > 40$ GeV,
  - **SR2:** $p_{\mathrm{T}}^{e\mu} \leq 40$ GeV.

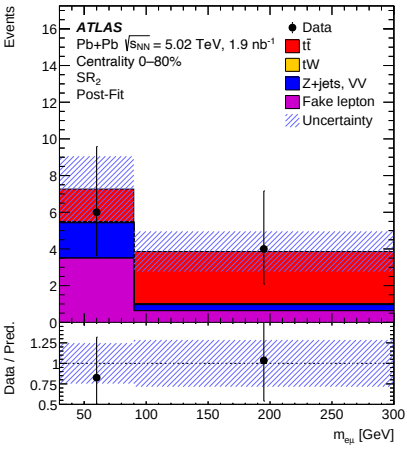
- **Signal strength** definition:
  $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{\mathrm{measured}} / \sigma_{t\bar{t}}^{\mathrm{theory}}$.

- $\mu_{t\bar{t}}$ is determined by a **profile-likelihood fit** to $m_{e\mu}$ data distributions.

Signal region 1



Signal region 2



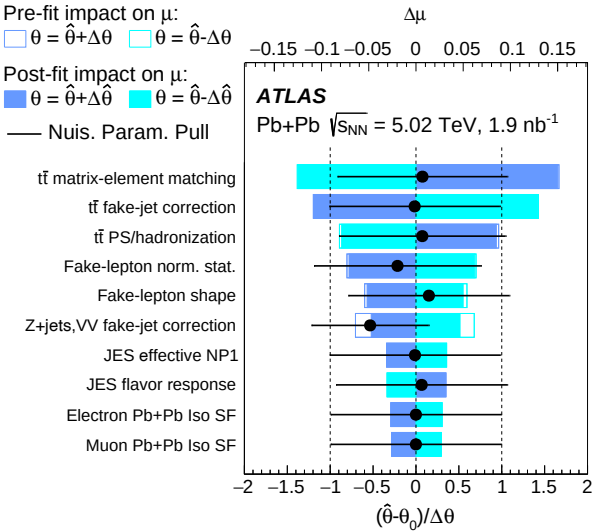
arXiv:2411.10186

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	+14.4	-8.7
Jet	+7.4	-5.3
Fake-lepton	+6.6	-6.7
Electron	+3.6	-2.3
Muon	+3.4	-2.2
Luminosity	+2.3	-1.6
Background modeling	+2.2	-2.2
MC statistics	+1.9	-1.6
Systematic uncertainty	+18.4	-13.2

arXiv:2411.10186



Cross-section measurement

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

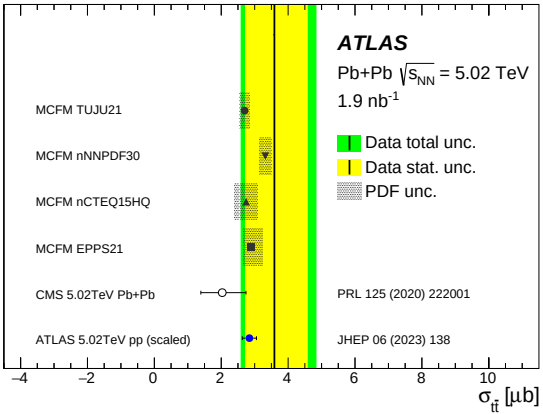
$$\sigma_{t\bar{t}} = \mathbf{3.6}\ ^{+\mathbf{1.0}}_{-\mathbf{0.9}}\ \mathbf{(stat.)}\ ^{+\mathbf{0.8}}_{-\mathbf{0.5}}\ \mathbf{(syst.)}\ \boldsymbol{\mu}\mathbf{b}.$$

- The total uncertainty of **31%** is 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 **MCFM NNLO calculations** (PRD 94, 093009 (2016)) based on four nPDF sets.

arXiv:2411.10186



Summary

1 Observation of $t\bar{t}$ production in p+Pb collisions

- The first $t\bar{t}$ observation using the dilepton channel in p+Pb collisions at the LHC.
- The $t\bar{t}$ cross section is measured to be $\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\text{stat.})\ ^{+4.8}_{-4.4}\ (\text{syst.})\ \text{nb}$.
- The most precise $t\bar{t}$ cross-section measurement in HI collisions at the LHC.

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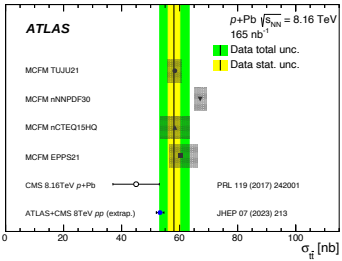
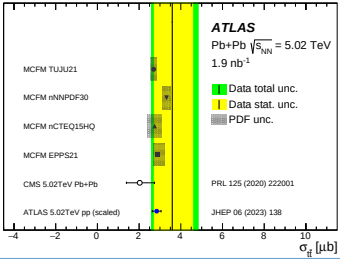


2 Observation of $t\bar{t}$ production in Pb+Pb collisions

- The first observation of $t\bar{t}$ production in Pb+Pb collisions at the LHC.
- The $t\bar{t}$ 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 observed significance in the $e\mu$ channel amounts to $5.0\,\sigma$.

arXiv:2411.10186



Acknowledgements

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Backup slides

Event selection in p+Pb collisions

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.

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.

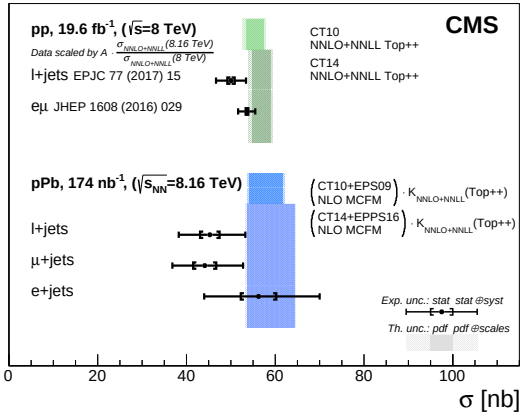
Background

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

$t\bar{t}$ 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 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** ($ee, \mu\mu, e\mu$) 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:
  $\sigma_{t\bar{t}} = 2.54\ ^{+0.84}_{-0.74}\ \mu$b (dilepton-only),
  $\sigma_{t\bar{t}} = 2.03\ ^{+0.71}_{-0.64}\ \mu$b (dilepton + *b*-jets).
- Available back then PDF (CT14) and nPDF (EPPS16) used.

PRL 125, 222001 (2020)