Top quark pair production in nuclear collisions

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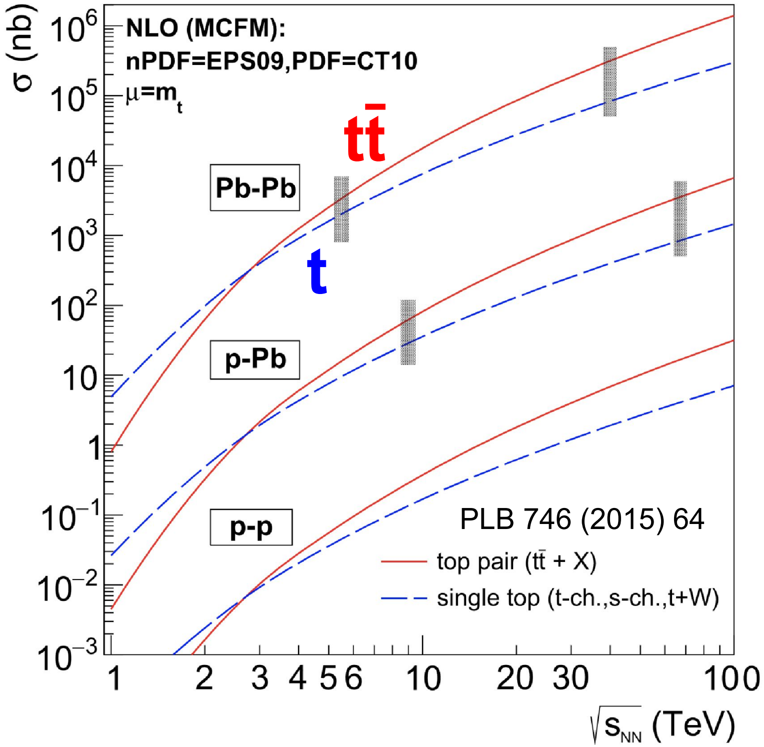
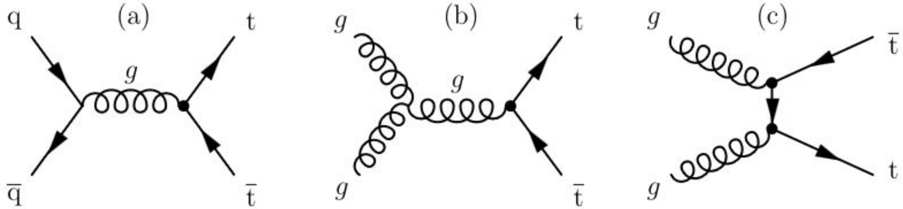
European Organization for Nuclear Research

Emergent QCD Collectivity Across Scales:
From Small Systems Collisions to Jets

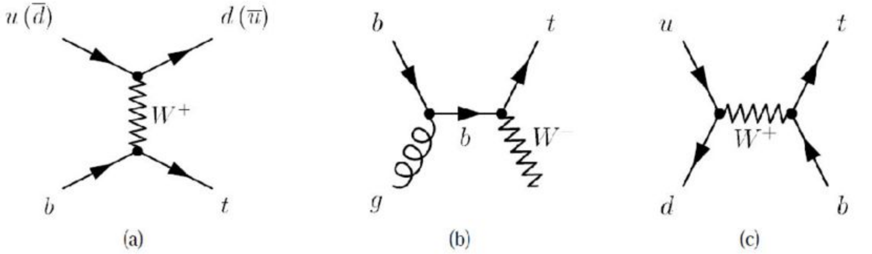
Top quark production in heavy ion

Top quark mainly produced **in pairs** via QCD:





Single top production diagrams:



Top pair production in heavy ion

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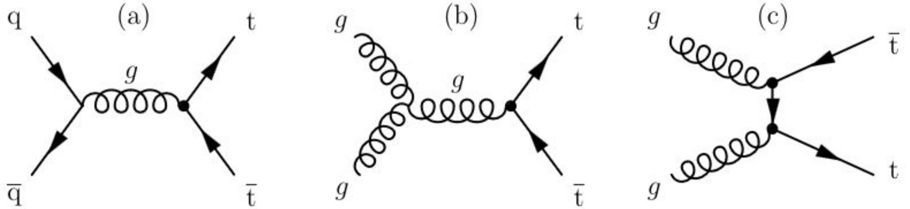
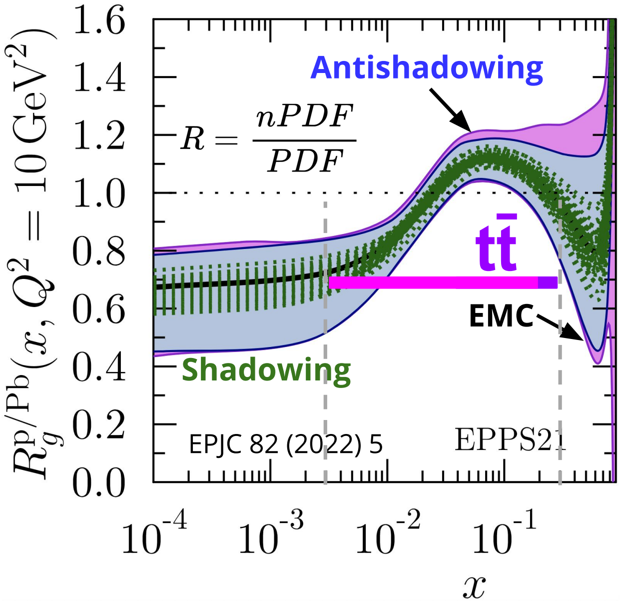
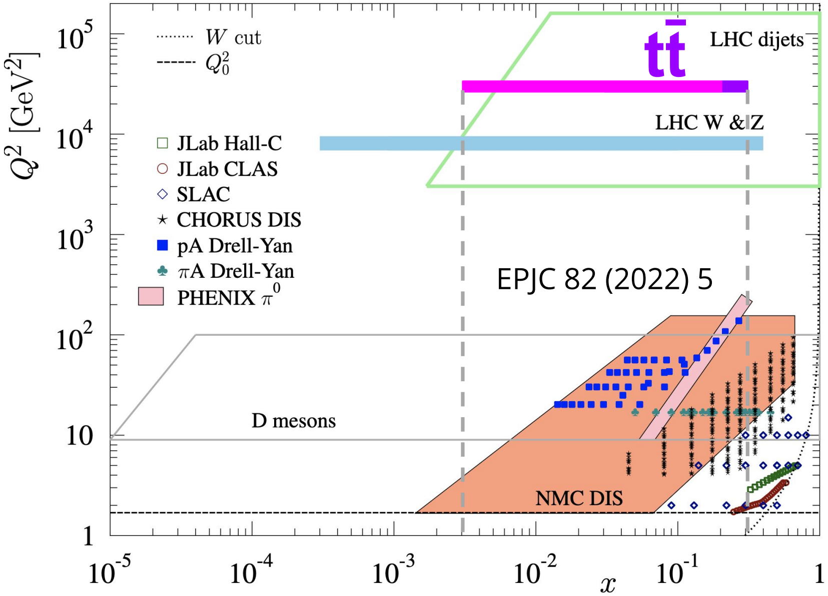


The production of top quarks is sensitive to gluon PDF:

- in HI collisions can probe Pb gluon density at high virtualities.





Top pair production in heavy ion

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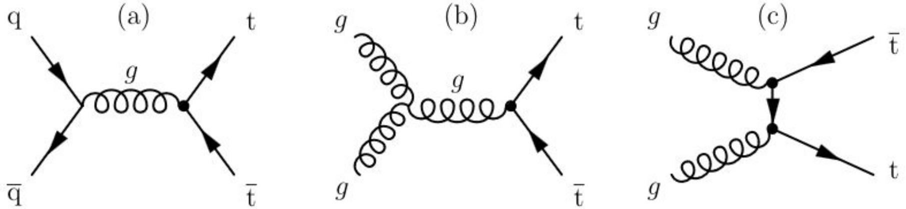
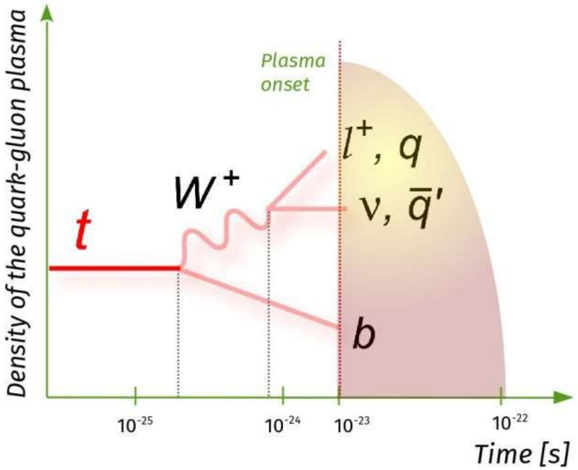


The production of top quarks is sensitive to gluon PDF:

- in HI collisions can probe Pb gluon density at high virtualities.

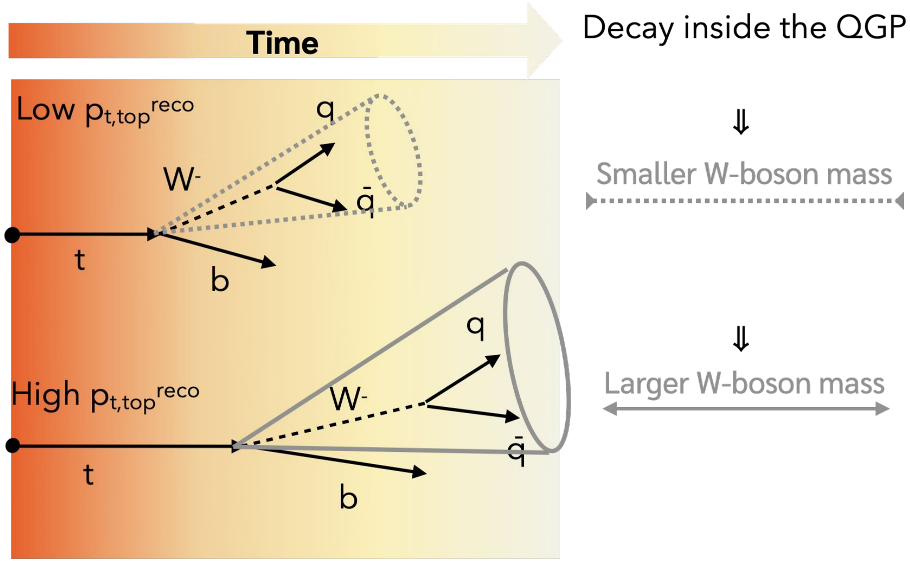
Top quark predominantly decays to a W boson and b quark (before QGP is formed):

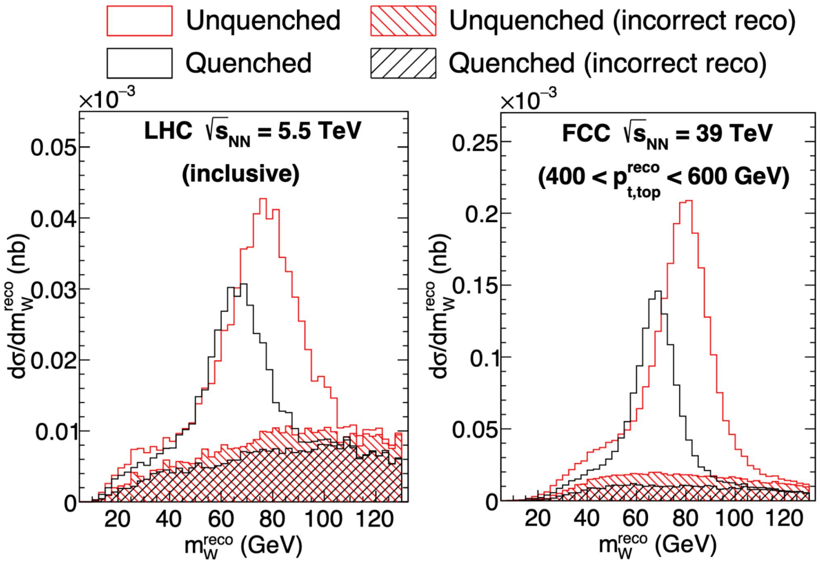


Top pair production in heavy ion

Top quark predominantly decays to a W boson and b quark (before QGP is formed):

- Jets produced from hadronic W decays can probe quark energy loss.





PRL 120, 232301 (2018)

Top pair measurements in nuclear collisions

Feasibility for
pPb/PbPb

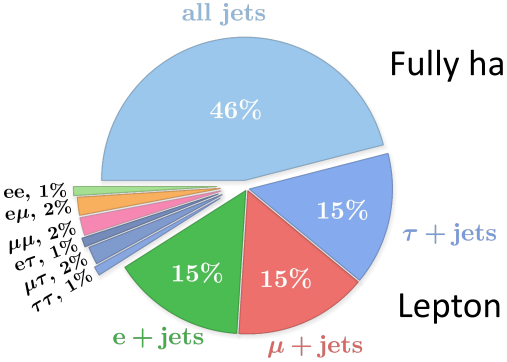
2015

PLB 746 (2015) 64

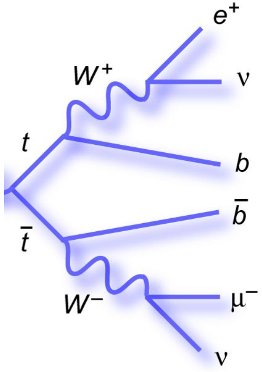
Top pair branching fractions

Fully hadronic

Dileptons



Lepton + jets



Top pair measurements in nuclear collisions

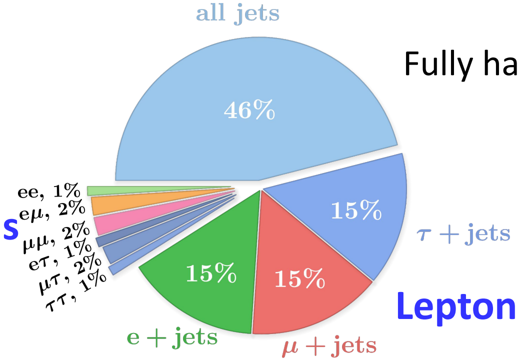
Feasibility for pPb/PbPb

2015	2017	2024
PLB 746 (2015) 64	**PRL 119 (2017) 242001**	**JHEP 11 (2024) 101**
	CMS observation in **pPb 8.16 TeV**	**ATLAS** observation in **pPb 8.16 TeV**

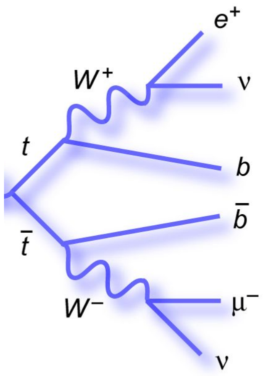
Top pair branching fractions

Fully hadronic

Dileptons

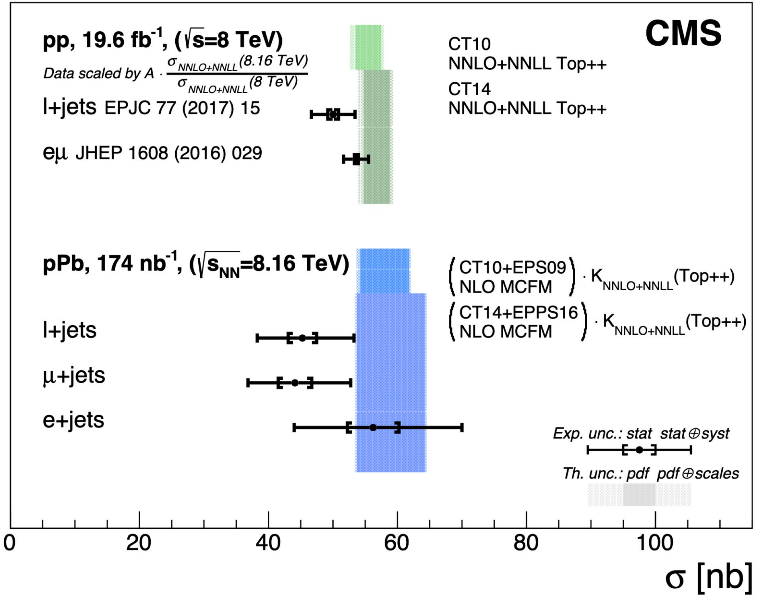


Lepton + jets

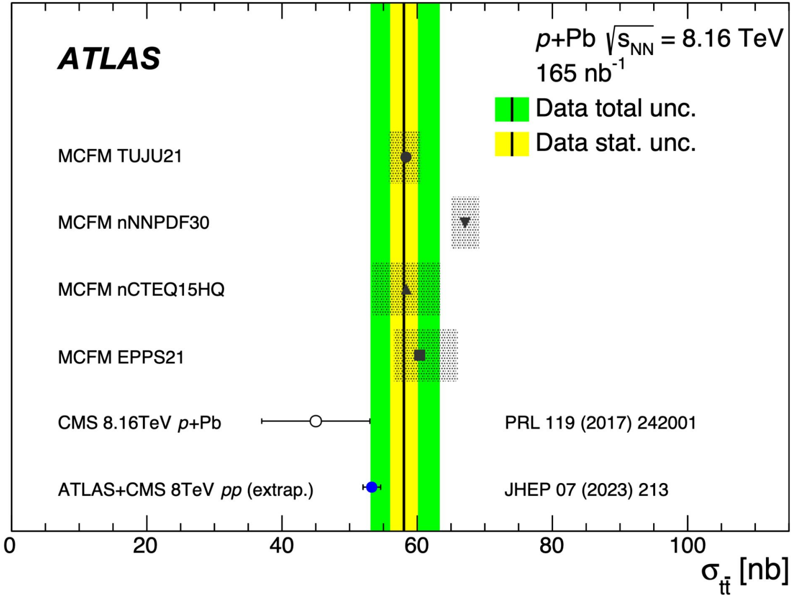


Top pair production in pPb collisions

PRL 119 (2017) 242001



JHEP 11 (2024) 101



Measurement of ttbar production in pPb done on lepton+jets channel.

- Results dominated by systematic uncertainties from b-tagging efficiency and jet energy scale.

Top pair measurements in nuclear collisions

Feasibility for pPb/PbPb

CMS evidence in **PbPb 5.02 TeV**

ATLAS observation in **PbPb 5.02 TeV**

2015 — 2017 — **2020** — 2024 — **2025**

PLB 746 (2015) 64

PRL 119 (2017) 242001

PRL 125 (2020) 222001

JHEP 11 (2024) 101

PRL 134 (2025) 142301

CMS observation in pPb 8.16 TeV

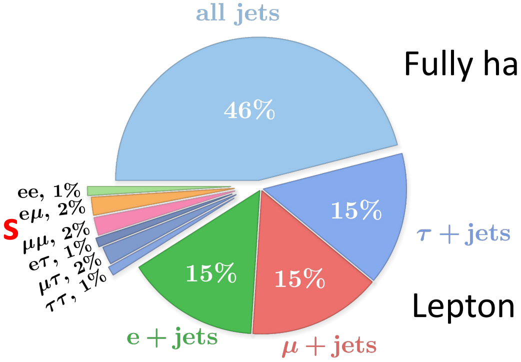
ATLAS observation in pPb 8.16 TeV

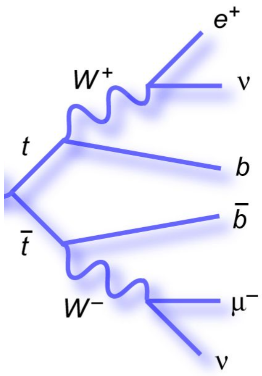
Top pair branching fractions

Fully hadronic

Dileptons

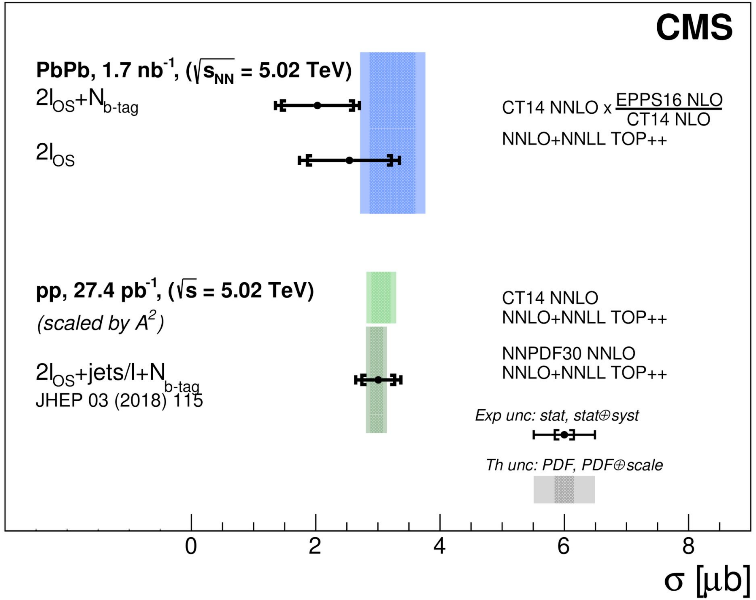
Lepton + jets



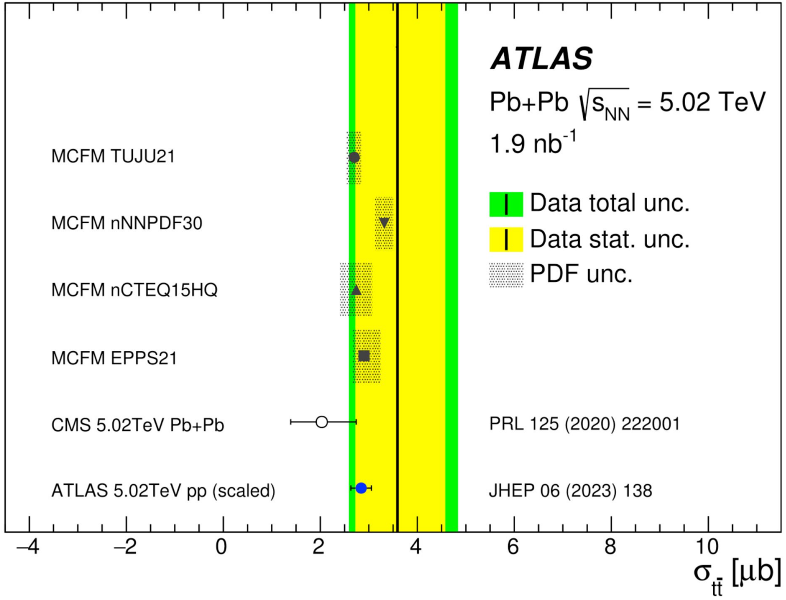


Top pair production in PbPb collisions

PRL 125 (2020) 222001



PRL 134 (2025) 142301



Measurement of ttbar production in PbPb at 5.02 TeV done so far in di-leptonic (e-μ) channel.

- Limited statistical precision has hindered capability to do differential studies.

Top pair measurements in nuclear collisions

Feasibility for pPb/PbPb

2015

PLB 746 (2015) 64

2017

PRL 119 (2017) 242001

CMS observation in pPb 8.16 TeV

CMS evidence in PbPb 5.02 TeV

2020

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JHEP 11 (2024) 101

ATLAS observation in pPb 8.16 TeV

ATLAS observation in PbPb 5.02 TeV

2025

PRL 134 (2025) 142301

CMS observation in **PbPb 5.36 TeV**

2026

arXiv:2604.27091

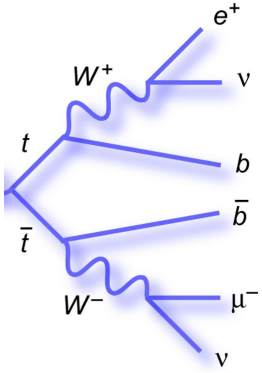
- Run 2 data established feasibility and observation.

Measurement performed using PbPb collisions at 5.36 TeV recorded in 2023:

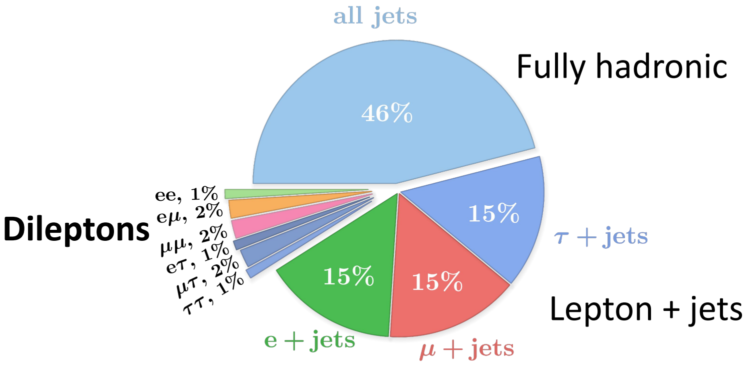
- Though lumi. comparable to Run 2 PbPb at 5.02 TeV, higher beam energy increases production.

Fully leptonic decays of tt pair:

- Highest purity
- Leptons + b-jets
- Small BR (~5% with e/μ)
- Simulated with POWHEG



Top pair branching fractions



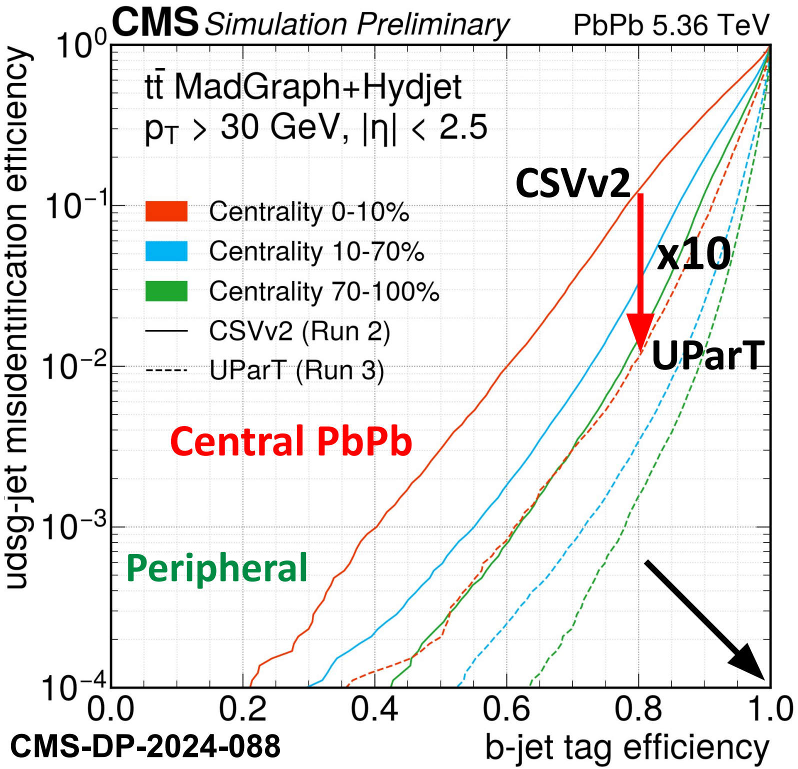
Backgrounds:

- Z/γ*+jets with MadGraph5 FxFx (normalized to Z control region)
- Non-prompt: W+jets and QCD multi-jets with HF decays (from data using event-mixing technique)
- Small contributions from single top and WW processes with POWHEG

Processes simulated at NLO using EPPS21 nPDF and embedded into HYDJET PbPb events.

b jet tagging

A ML model based on the Particle Transformer architecture (UParT) was used performing in an inclusive way both heavy flavour tagging and a flavour-aware jet energy regression.



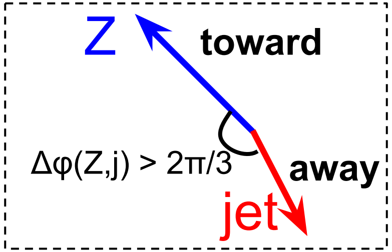
CMS-DP-2024-088

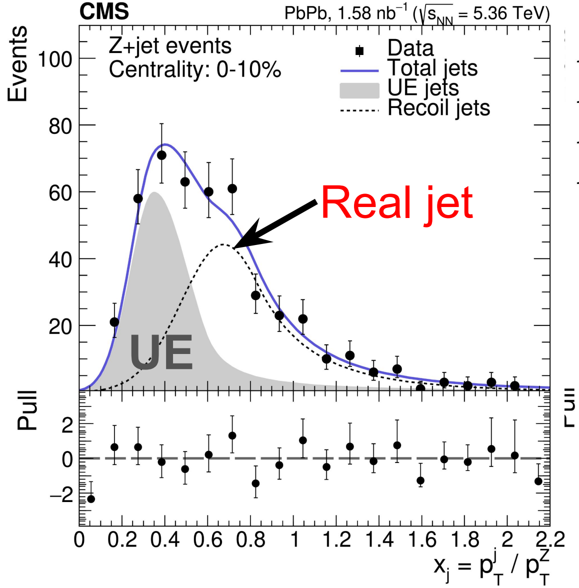
- Performed an adversarial training improving robustness against MC simulation mismodeling.
- Dedicated training on PbPb MC of UParT achieved x10 better light-jet rejection compared to b-tagging methods used in Run 2.
- Working point tuned to yield ~80% efficiency for b-tag jets from hard scattering independent of collision centrality.

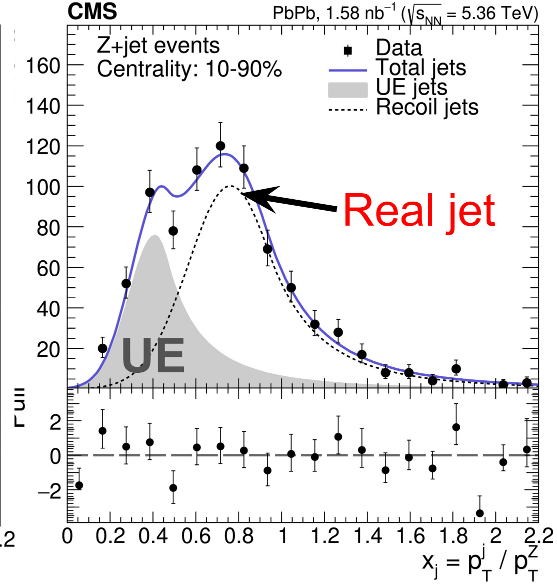
Jet energy residual

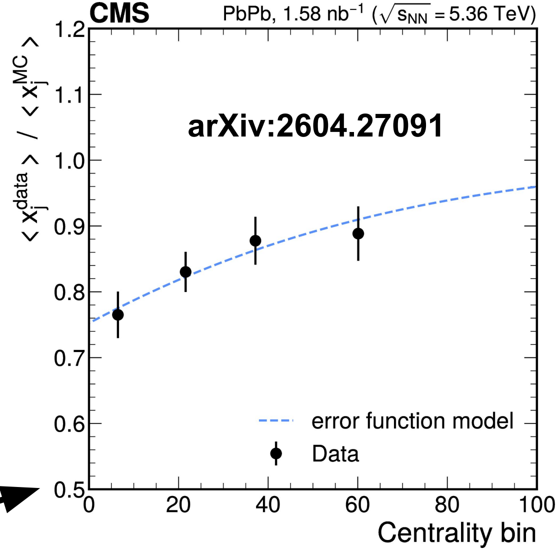
Z candidates with recoiling jet are used to verify residual JES is in data

- Selection requires a **recoil jet** in the opposite (*away*) hemisphere to a Z.
- Expect residual contamination from **UE jets** (in particular for central events).
- Model response of **UE jets** from data in the toward region and **real jets** with a Crystal-Ball.









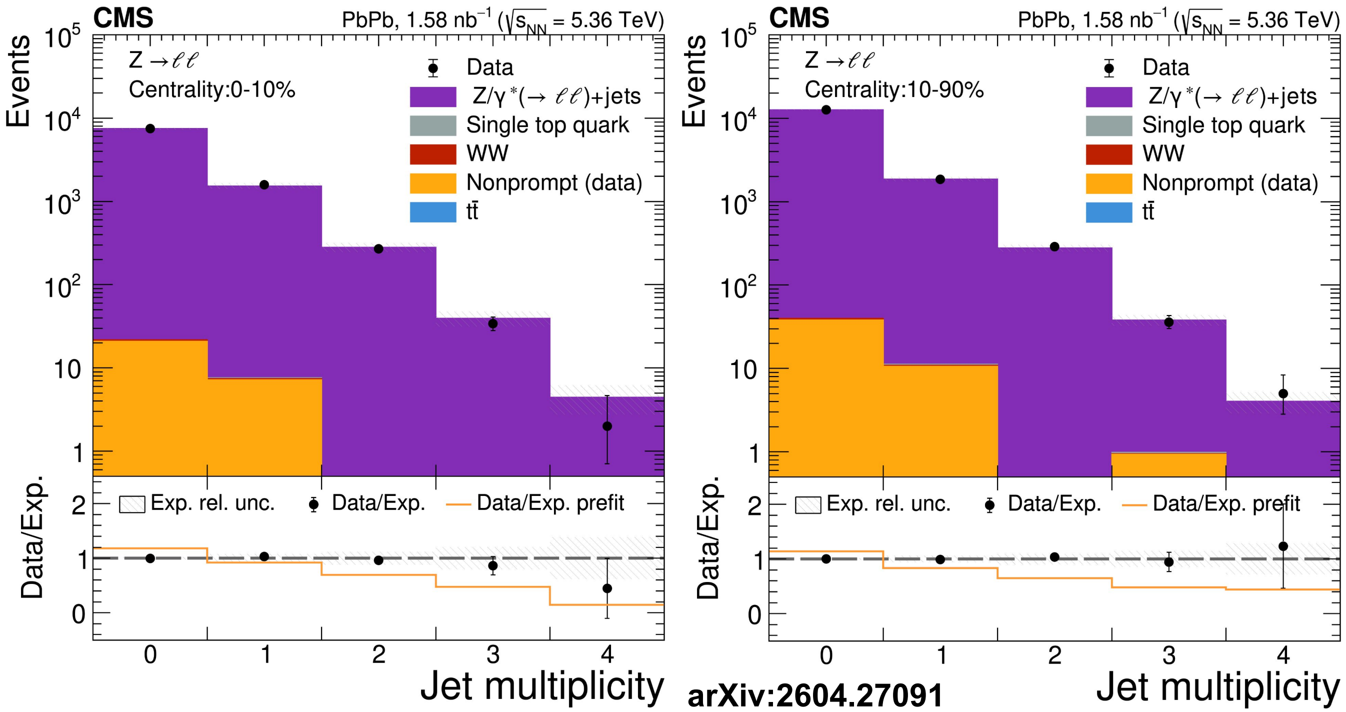
The fit in each centrality bin allows us to estimate:

- the number of **UE** and **real recoil jets**
- the average response (μ of the Crystal-Ball)

Result in a data-based model for Z-jet balance including jet quenching

Jet multiplicity in PbPb

Jet multiplicity checked on Z+jet events including jet energy scale, quenching, efficiency and uncertainties.



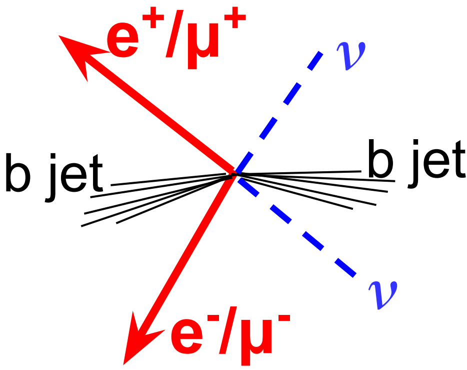
arXiv:2604.27091

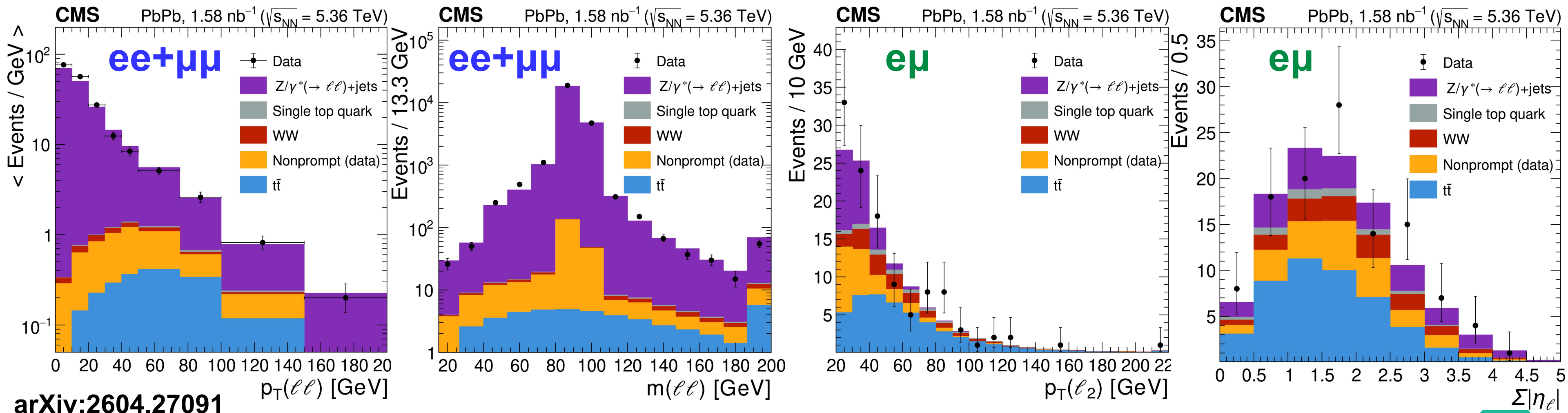
Excellent agreement with post fit expectations reached using both ee and μμ channels.

Measurement of top pairs in the dilepton channel

BDT discriminator used to **separate signal (tt) from background (Z/γ*):**

- Dilepton channel: use **only leptonic variables**
- Most relevant features:
  - **ee/μμ** channels: dilepton p_T (p_T(ll)), and invariant mass
  - **eμ** channel: p_T(ll), subleading lepton p_T and pseudo-rapidity sum





arXiv:2604.27091

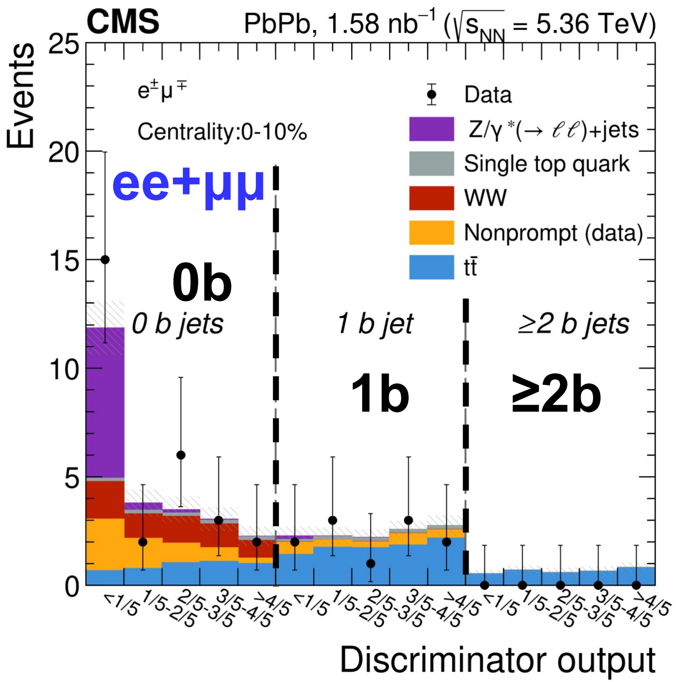
Measurement of top pairs in the dilepton channel

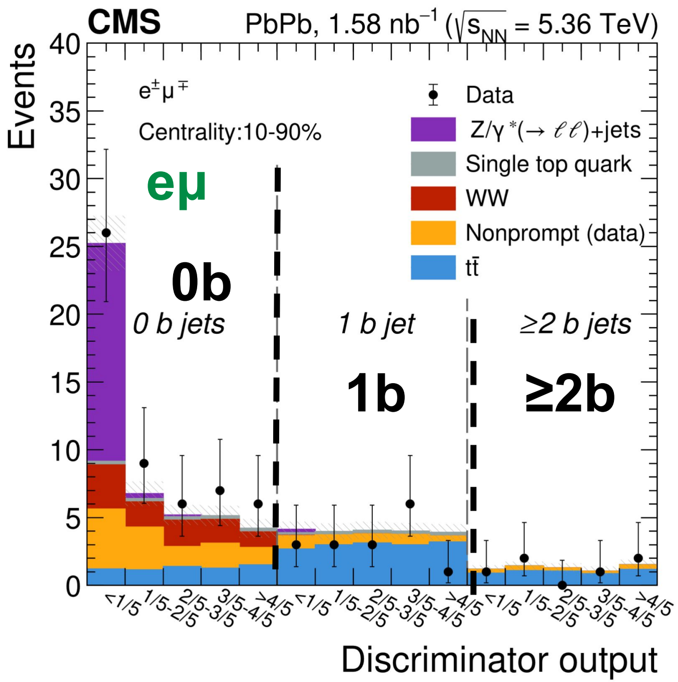
The ttbar cross section is extracted by fitting dilepton BDT score in the **ee, μμ** and **eμ** channels.

- Background separation is improved by fitting the BDT output in **0, 1** and **≥2 b-tag** jet events.

Fit done in two PbPb centrality intervals: **0-10%** and **10-90%**

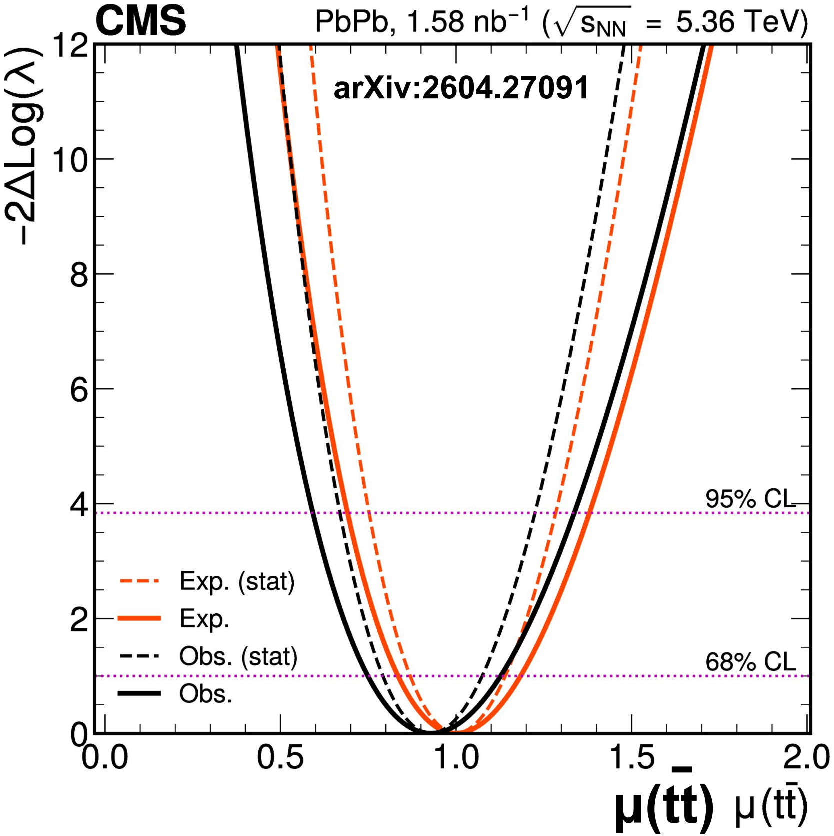
arXiv:2604.27091





Results for PbPb at 5.36 TeV

Log-likelihood scan: $t\bar{t}$ signal strength



Extract the ttbar signal strength: $\mu_{t\bar{t}} = \sigma_{t\bar{t}}/\sigma_{t\bar{t}}^{\mathrm{SM}}$

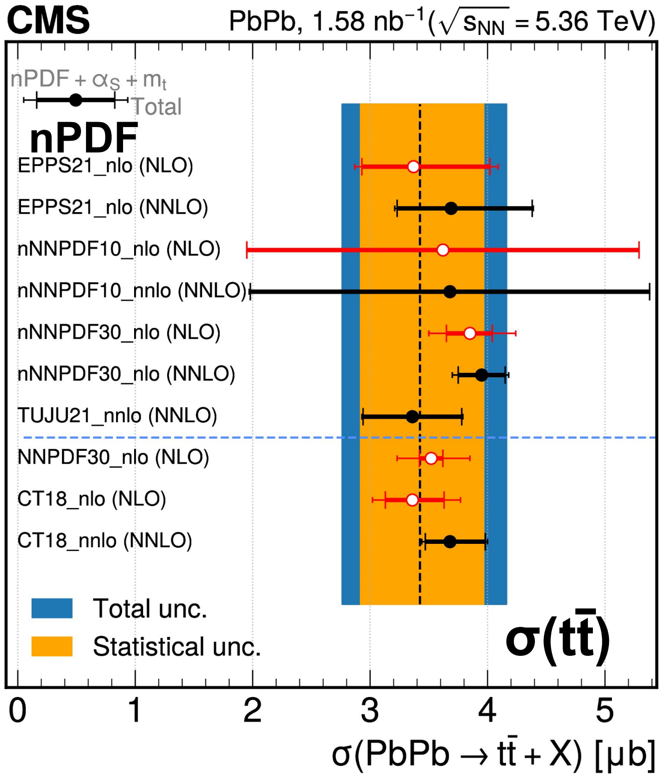
Theory cross section: $\sigma_{t\bar{t}}^{\mathrm{SM}} = 3.69\,^{+0.71}_{-0.48}\,\mu\mathrm{b}$ (*NNLO+NNLL*)

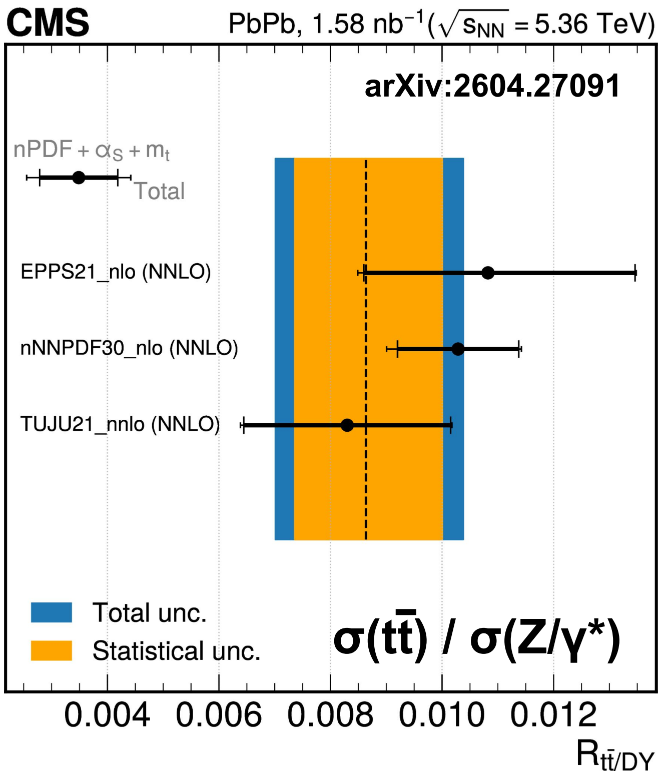
Results obtained:

$$\sigma_{t\bar{t}} = 3.42\,^{+0.54}_{-0.51}\,(\mathrm{stat})\,^{+0.50}_{-0.43}\,(\mathrm{syst})\,\mu\mathrm{b}$$

reached **>5** significance (stat. unc. dominates)

Comparison with theory for PbPb at 5.36 TeV



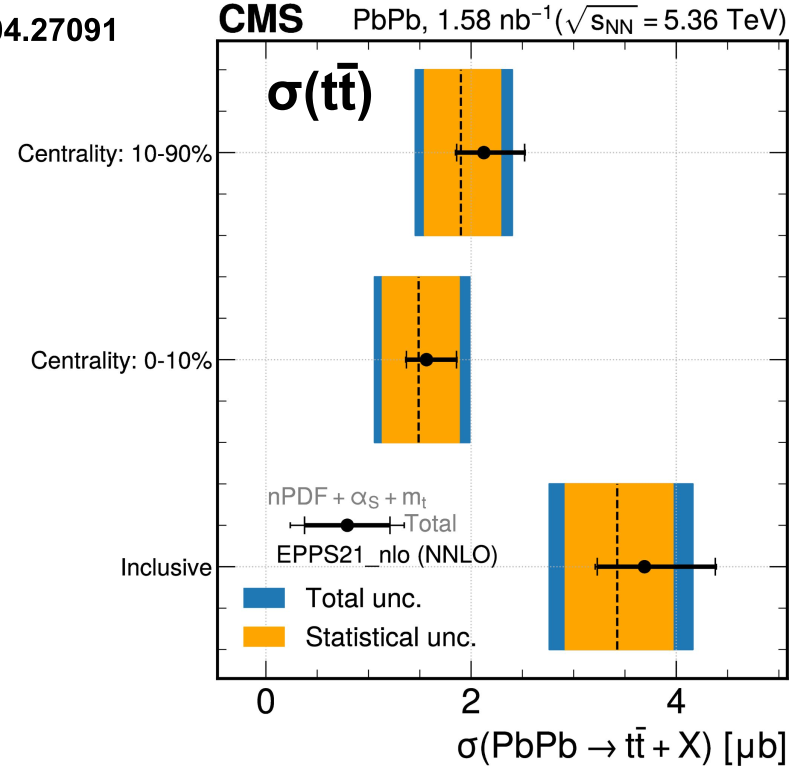


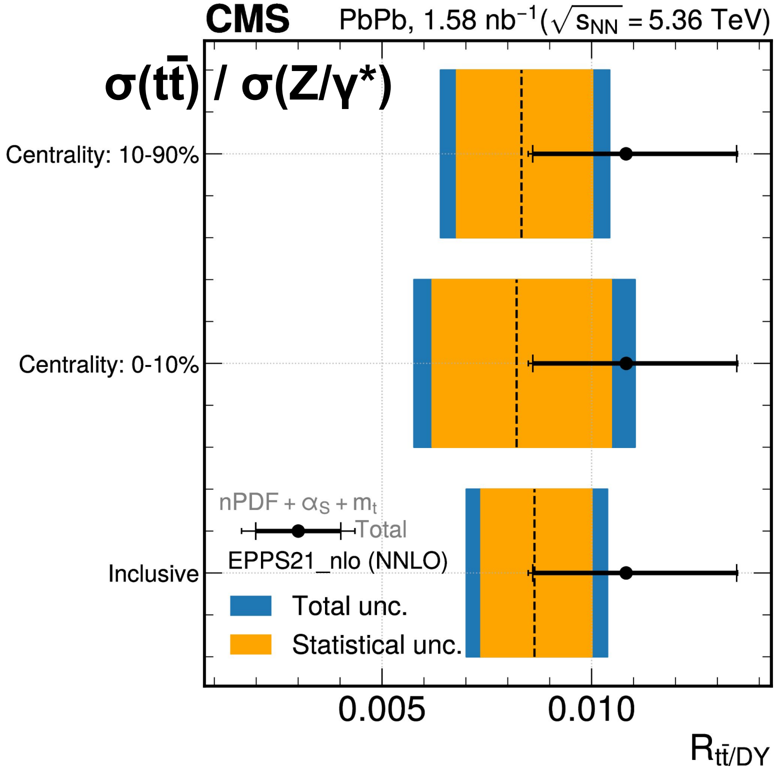
Good agreement between nPDF calculations and measured σ(tt) and σ(tt)/σ(Z/γ*).

- Measurement uncertainty similar to theory → will **improve** with **full Run 3** data (~x4 lumi).

Results vs centrality for PbPb at 5.36 TeV

arXiv:2604.27091





- First centrality differential measurement of the tt cross section in PbPb.

Summary

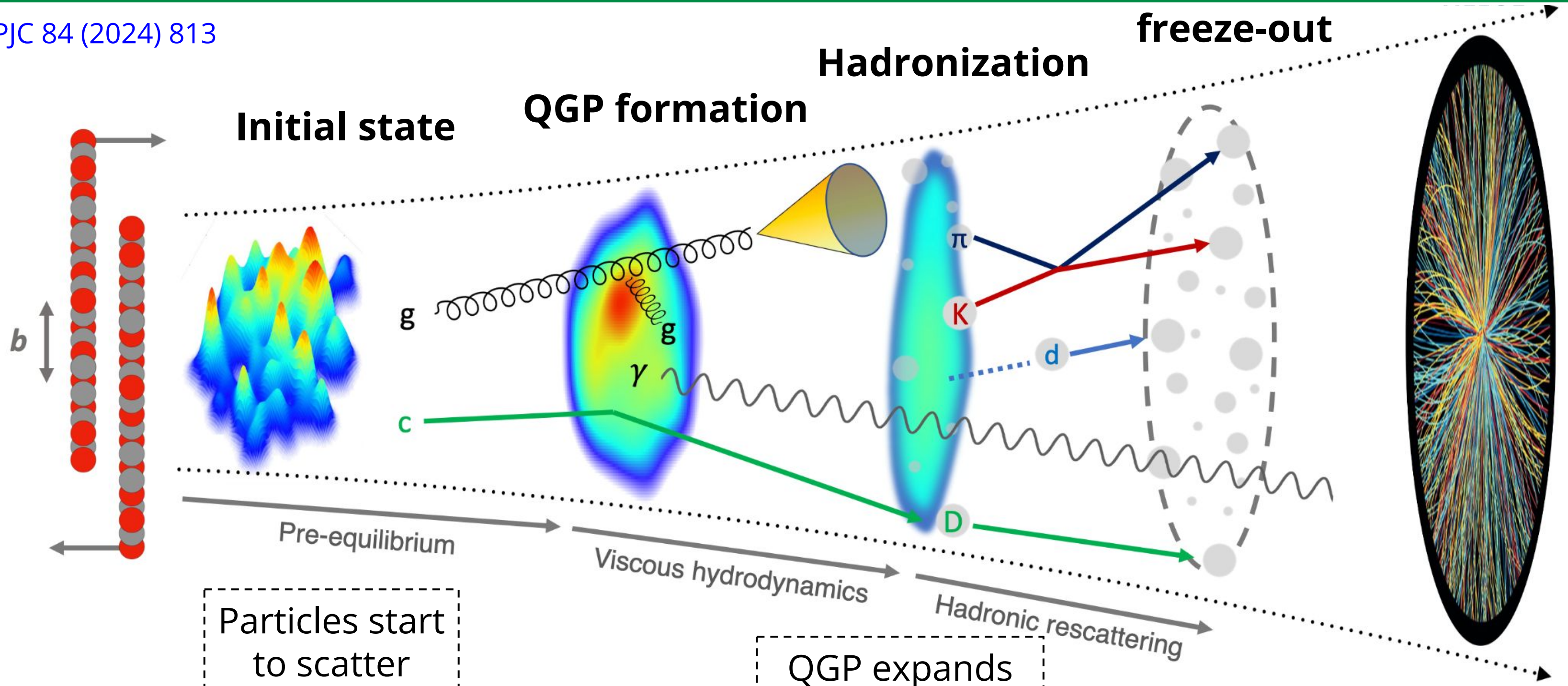
- Run 2 data established feasibility and observation.
- Run 3 **PbPb** data at **5.36 TeV** allows to start performing ttbar differential measurements.
- Measurements **compatible** with **theory** calculations in PbPb within uncertainties.
- Full Run 3 data will help establish top quark physics as a tool to constrain nPDFs and probe QGP.

Thank you for your attention!

BACKUP

The standard model of heavy-ion collisions

ALICE, EPJC 84 (2024) 813



Particles start to scatter

QGP expands and cools down

Time: 0 fm/c **< 1 fm/c** **~10 fm/c** **~10^{15} fm/c**

Relativistic nuclei are Lorentz contracted

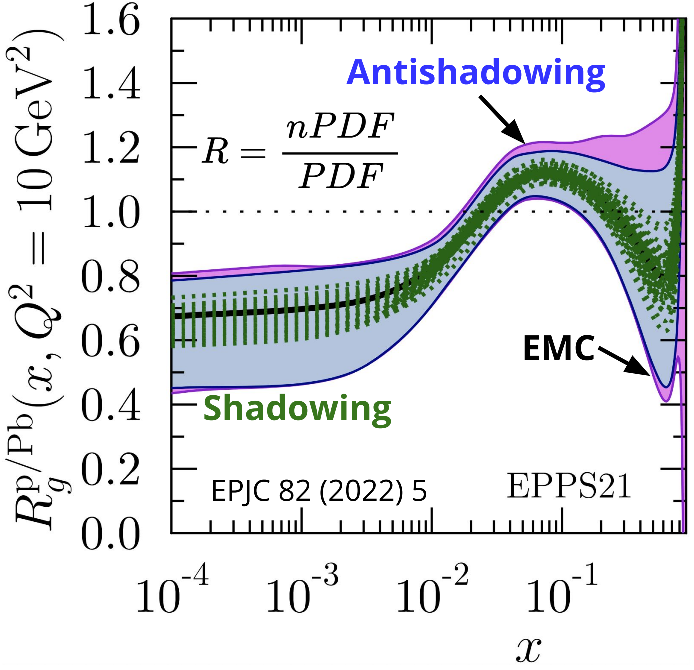
Equilibrium reached, form thermalized QGP

Particles stop interacting

High p_T particle production in heavy ions

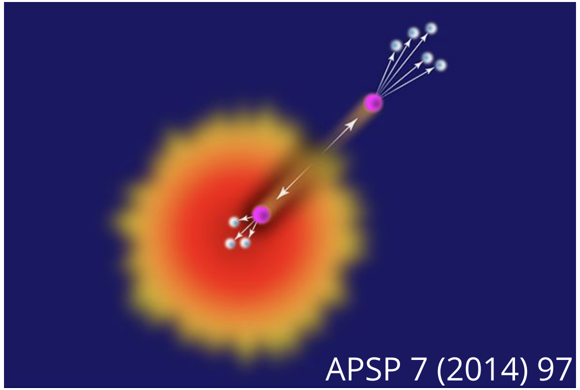
$$d\sigma^{AB\to X} \sim f_i^A(x_1,\mu_f^2) \otimes f_j^B(x_2,\mu_f^2) \otimes d\hat{\sigma}^{ij\to kl} \otimes P(\Delta E) \otimes D^{kl\to X}(z',\mu_F^2)$$

Nuclear parton distribution function



PDFs are modified in the nucleus

Parton energy loss



Outgoing partons traverse and interact with a colored medium (Quark Gluon Plasma, QGP)
→ Jet "quenching" (energy loss)

Lepton identification and isolation BDT

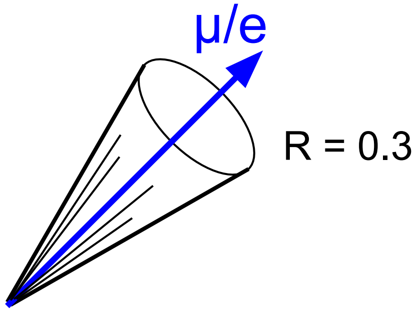
A boosted decision tree (BDT) was used for electron identification and lepton isolation, trained on PbPb simulations to improve the resilience versus collision centrality.

Electron identification BDT:

- Use same inputs as cut based approach.
- Leading features include the η variance of the ECAL cluster and the Δη(track, ECAL cluster).

Lepton isolation BDT:

- Features include isolation sums corrected by UE median energy density and 3D displacement.
- Better linearity versus centrality and heavy flavour rejection.



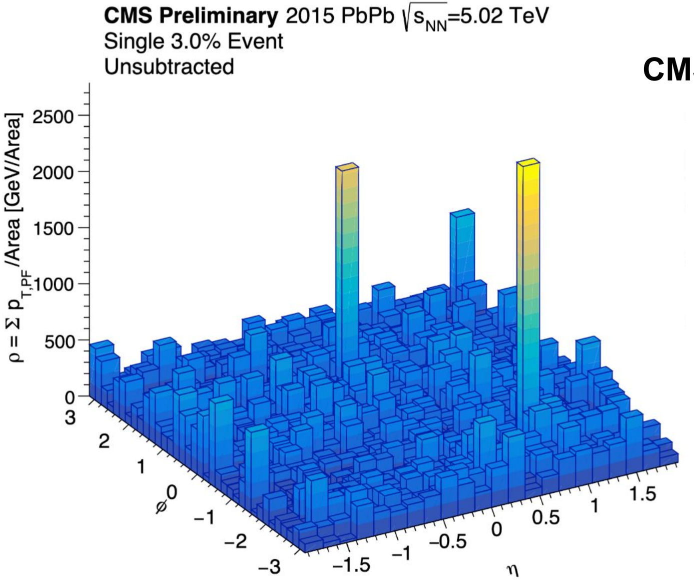
Kinematic selection:

- Muon: p_T > 20 GeV and $|\eta|$ < 2.4
- Electron: p_T > 20 GeV and $|\eta|$ < 2.5

Jet reconstruction in PbPb

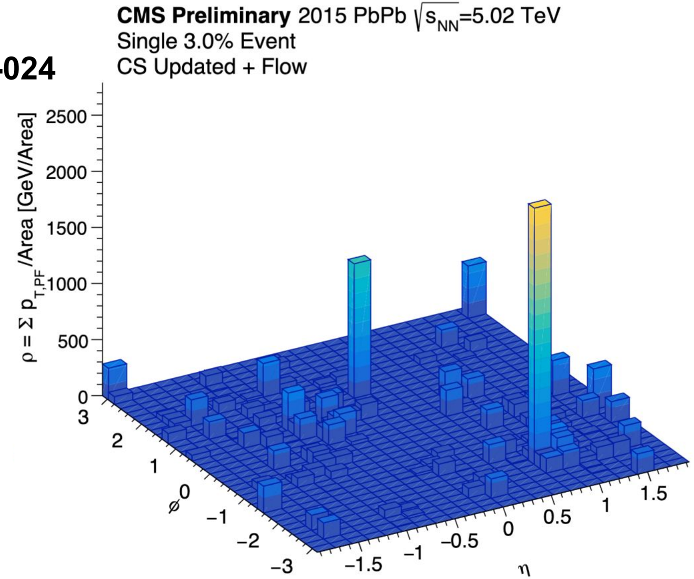
Jets clustered using anti-k_T algorithm and underlying event (UE) contamination mitigated using charged subtraction (CS) method.

Before UE subtraction



CMS-DP-2018-024

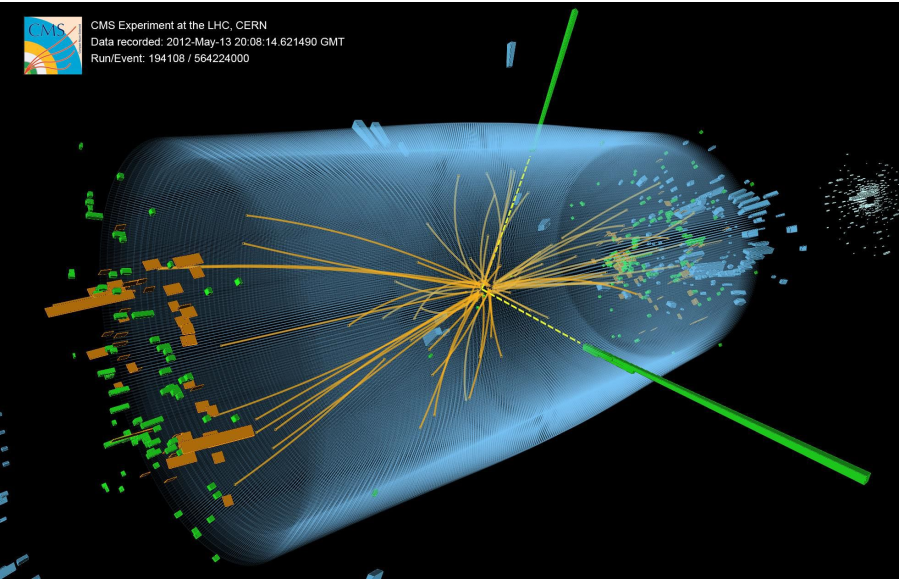
After UE subtraction



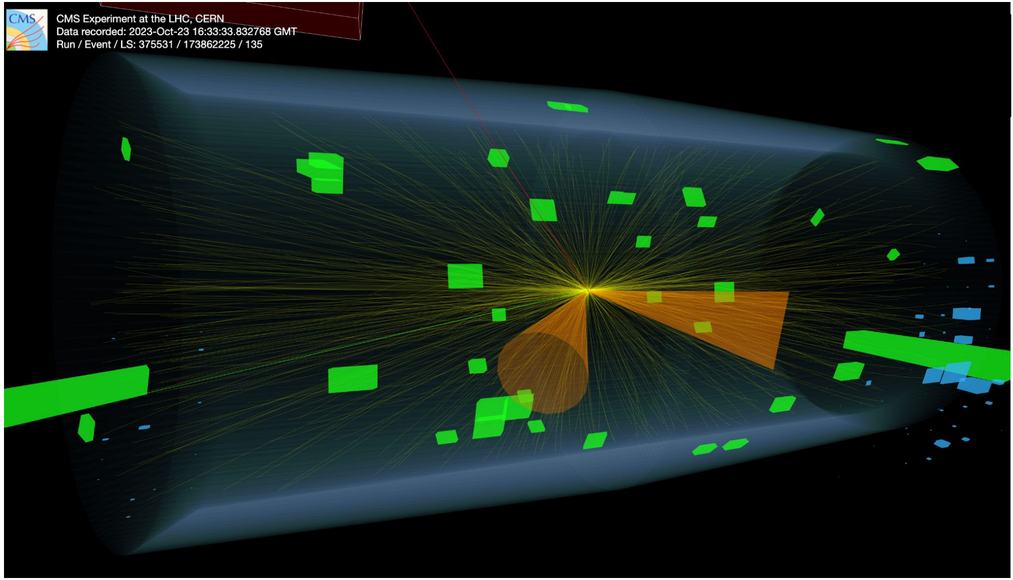
- Jet selected within p_T > 30 GeV and $|\eta|$ < 2.1, and ΔR(jet, lepton) > 0.4
- The jet radius is required to be 0.3 to further reduce the impact of UE.

Event display of collisions at LHC

Proton-Proton collision at CMS



Lead-Lead collision at CMS

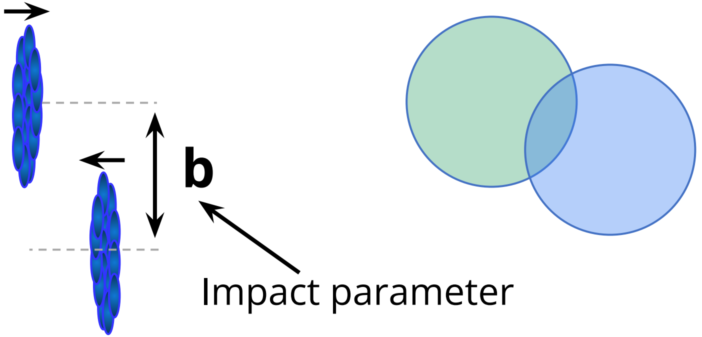


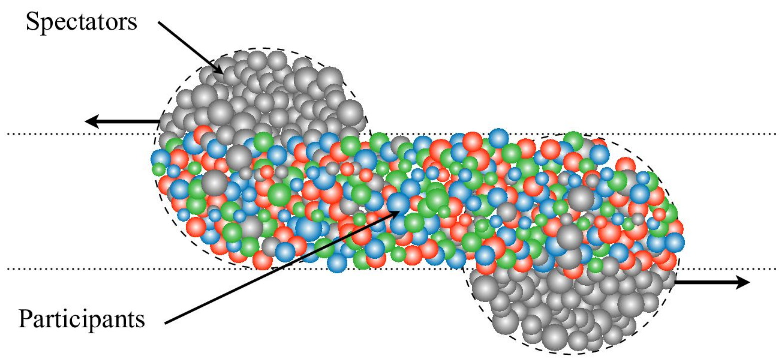
Collision geometry

Not all heavy-ion collisions are created equal, but rather vary in *centrality*

Some are head-on or "central"
(centrality → 0%)

Some are glancing or "peripheral"
(centrality → 100%)





Energy density achieved depends on # of participants

Collision centrality determined from total HF E_T

Nuclear PDF fits

Summary of recent nPDF global fits

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ*
Order in α_s	NLO & NNLO	NLO & NNLO	NLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA DY	✓		✓	✓	✓
πA DY			✓		
RHIC dAu π^0,$\pi^\pm$			✓		✓
LHC pPb π^0,$\pi^\pm$,$K^\pm$					✓
LHC pPb dijets			✓	✓	
LHC pPb HF			✓ GMVFN	✓ FO+PS	✓ ME fitting
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ				✓	
Q, W cut in DIS	1.3, 0.0 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV	2.0, 3.5 GeV
p_T cut in inc.-h,HF	N/A	N/A	3.0, 3.0 GeV	N/A, 0.0 GeV	3.0, 3.0 GeV
Data points	4353	2410	2077	2188	1484
Free parameters	18	16	24	256	19
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
Free-proton PDFs	CT18	own fit	CT18A	~NNPDF4.0	~CTEQ6M
Free-proton corr.	no	no	yes	yes	no
HF treatment	FONLL	FONLL	S-ACOT	FONLL	S-ACOT
Indep. flavours	3	4	6	6	5
Reference	PRD 104, 034010	PRD 105, 094031	EPJC 82, 413	EPJC 82, 507	PRD 105, 114043

Reconstructed W-boson for different QGP sizes