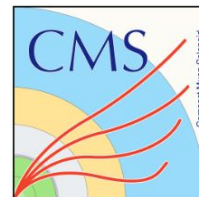


Studies of the nuclear initial state in PbPb with measurements of top quark pair production at CMS

Andre Ståhl
on behalf of the CMS collaboration

European Organization for Nuclear Research

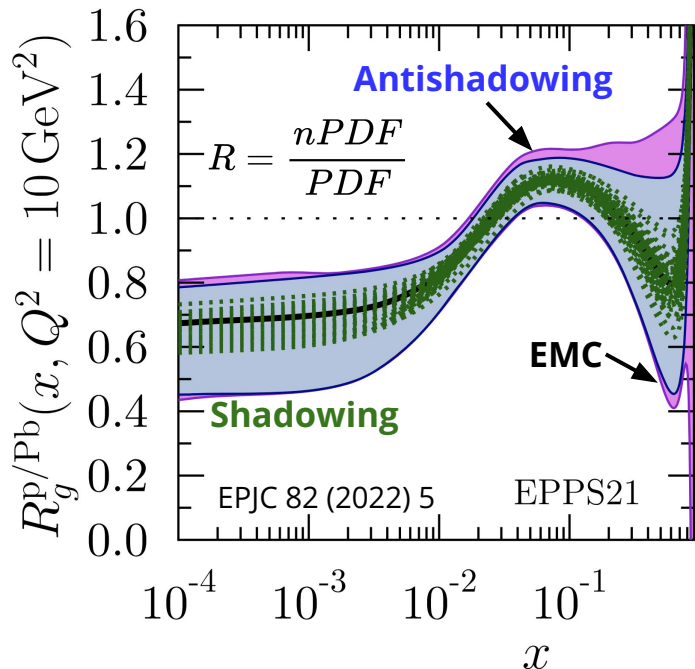
8th International Conference on the
Initial Stages in High-Energy Nuclear Collisions



High p_T particle production in heavy ions

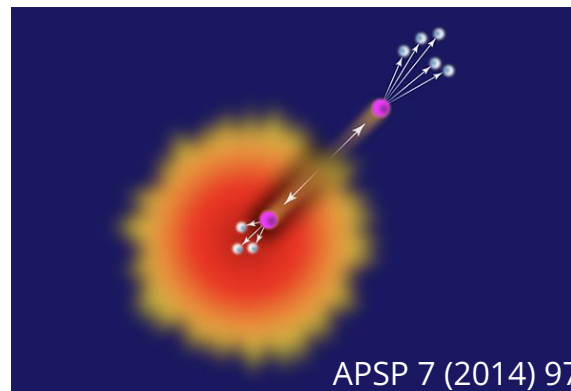
$$d\sigma^{AB \rightarrow X} \sim f_i^A(x_1, \mu_f^2) \otimes f_j^B(x_2, \mu_f^2) \otimes d\hat{\sigma}^{ij \rightarrow kl} \otimes P(\Delta E) \otimes D^{kl \rightarrow X}(z', \mu_F^2)$$

Nuclear parton distribution function



PDFs are modified in the nucleus

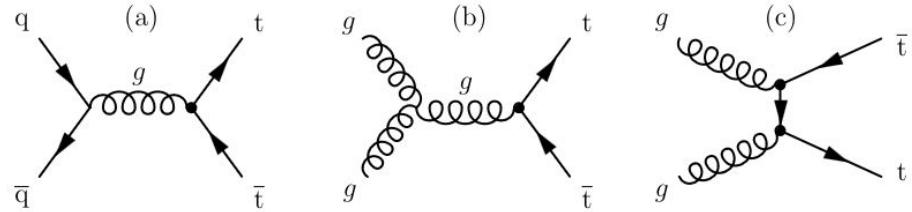
Parton energy loss



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

Top pair production in heavy ion

Top quark mainly produced in pairs via QCD:

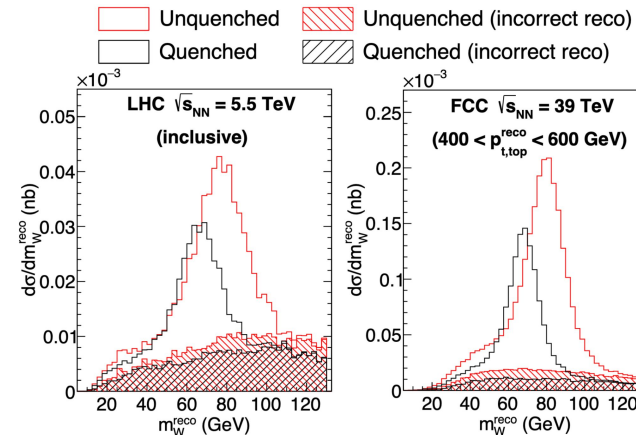
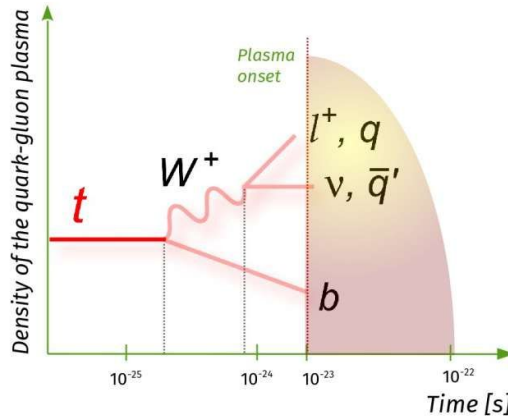


The production of top quarks is sensitive to gluon PDF:

- 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):

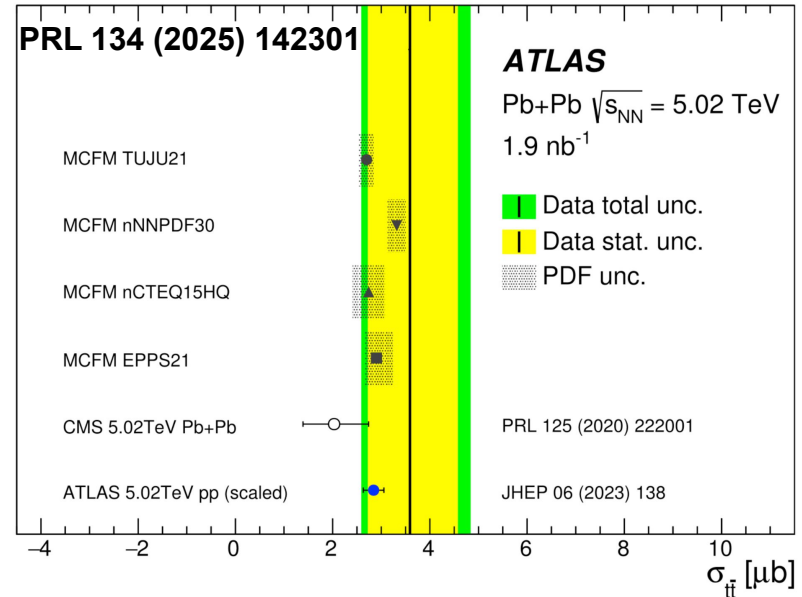
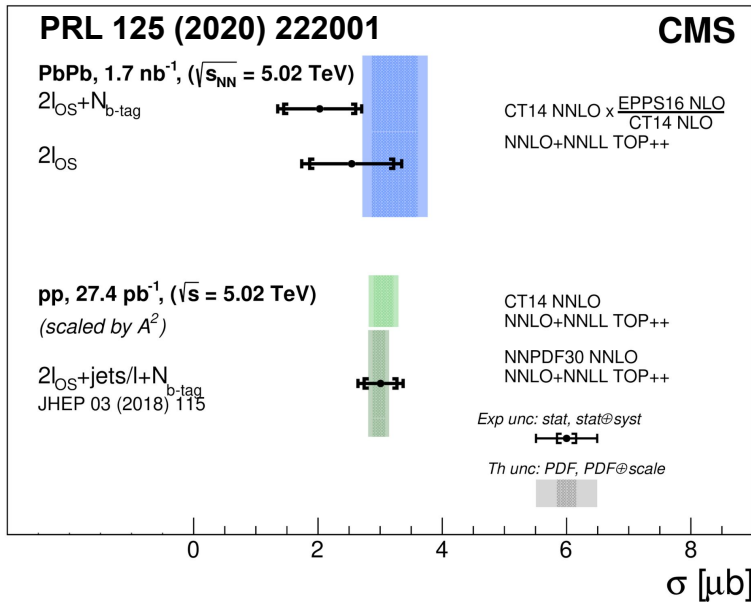
- Jets produced from hadronic W decays can probe quark energy loss.



PRL 120, 232301 (2018)

Top pair production in heavy ion

First measured by CMS in pPb, PbPb and recently also measured by ATLAS.



Measurement of $t\bar{t}$ production in PbPb only done so far in di-leptonic ($e\text{-}\mu$) channel.

- Limited statistical precision and presence of neutrinos has hindered capability to do differential studies.

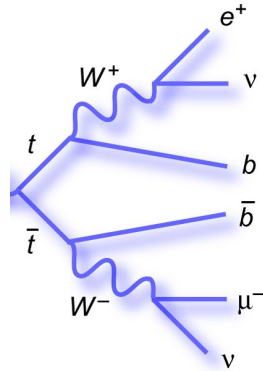
Analysis strategy

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

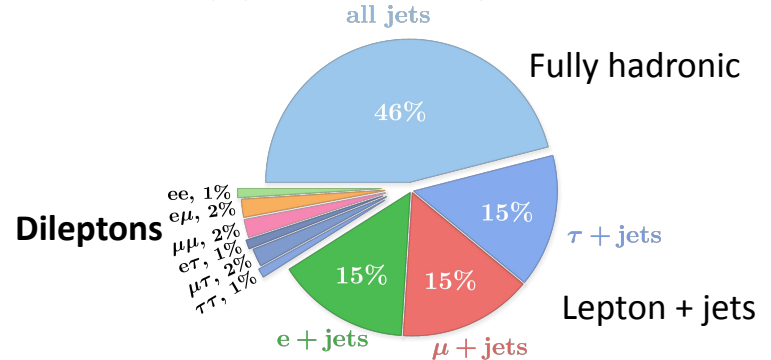
- Though lumi. comparable to Run 2 PbPb at 5.02 TeV, higher beam energy increases production.

Fully leptonic decays of tt pair:

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



Top pair branching fractions



Backgrounds:

- **ee/ $\mu\mu$** : Z/ γ^* +jets with MadGraph5 FxFx (normalized to Z control region)
- **e μ** : Z \rightarrow $\tau\tau$ with POWHEG
- 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.

Lepton identification and isolation BDT

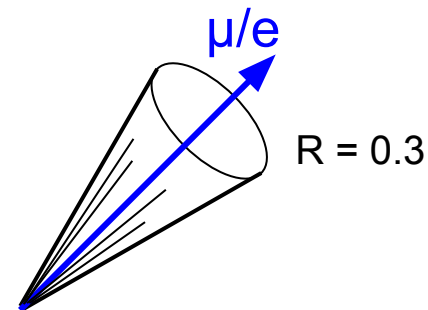
A boosted decision tree (BDT) was used for electron identification and lepton isolation, trained on PbPb simulations to improve the resilience versus collision centrality.

Electron identification BDT:

- Use same inputs as cut based approach.
- Leading features include the η variance of the ECAL cluster and the $\Delta\eta$ (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:

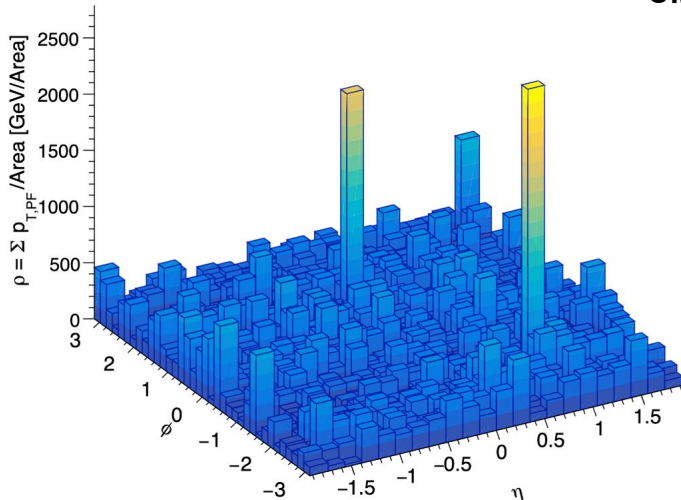
- Muon: $p_T > 20$ GeV and $|\eta| < 2.4$
- Electron: $p_T > 20$ GeV and $|\eta| < 2.5$

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

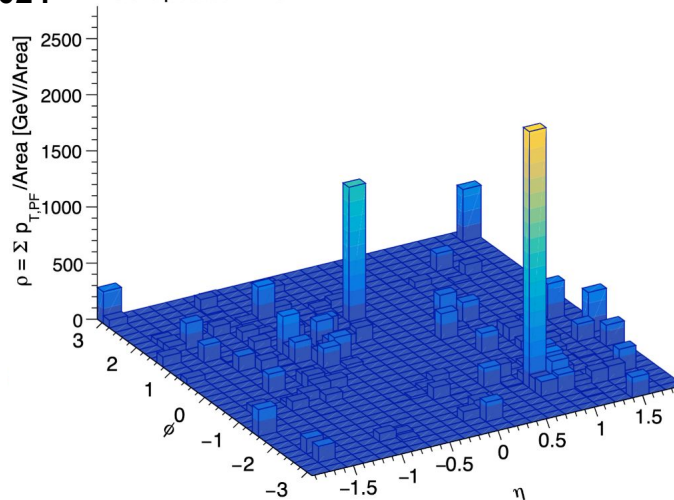
CMS Preliminary 2015 PbPb $\sqrt{s_{NN}}=5.02$ TeV
Single 3.0% Event
Unsubtracted



CMS-DP-2018-024

After UE subtraction

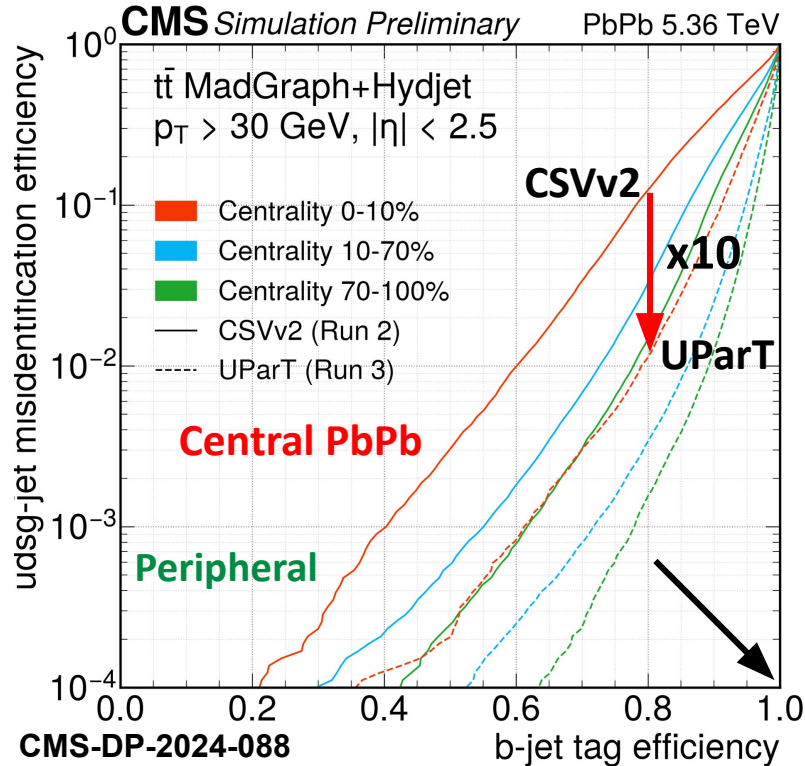
CMS Preliminary 2015 PbPb $\sqrt{s_{NN}}=5.02$ TeV
Single 3.0% Event
CS Updated + Flow



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

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.

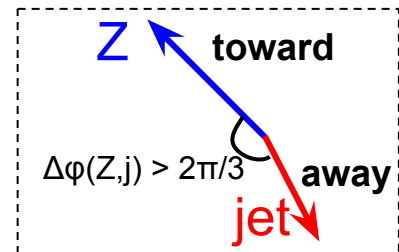


- Performed an adversarial training improving robustness against MC simulation mismodeling.
- Dedicated training on PbPb MC of UParT achieved x10 better light-jet rejection compared to b-tagging methods used in Run 2.
- Working point tuned to yield ~80% efficiency for b-tag jets from hard scattering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

Jet energy residual

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

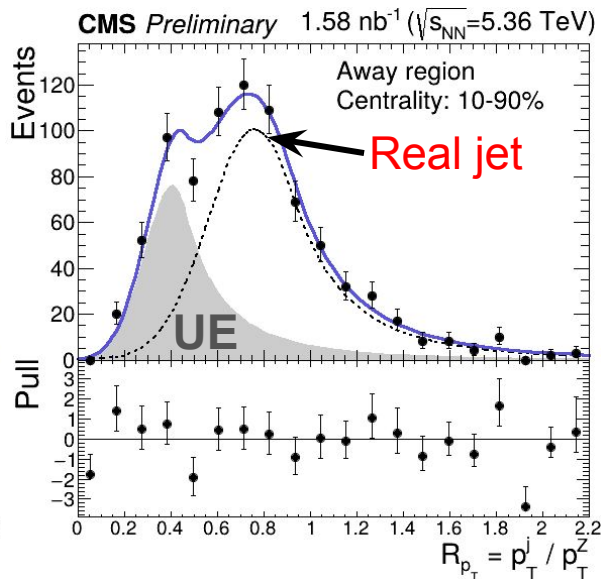
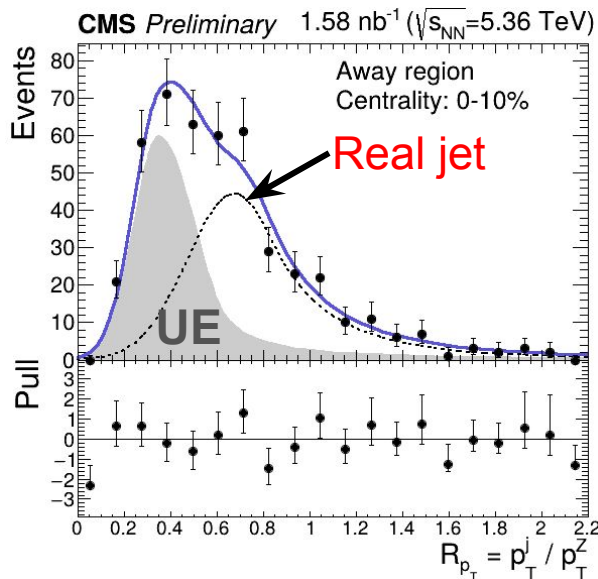
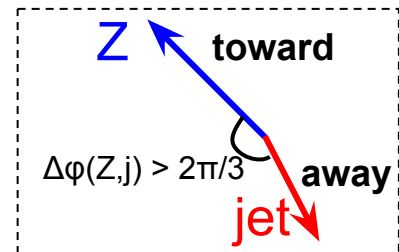
- Selection requires a **recoil jet** in the opposite (*away*) hemisphere to a Z.
- Expect residual contamination from **UE jets** (in particular for central events).
- Model response of **UE jets** from data in the toward region and **real jets** with a Crystal-Ball.



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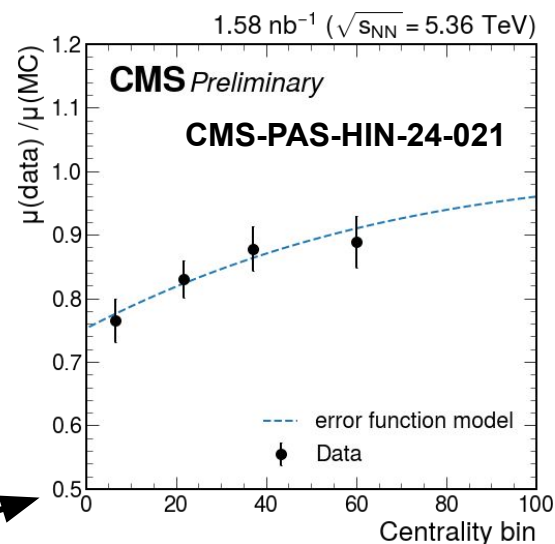
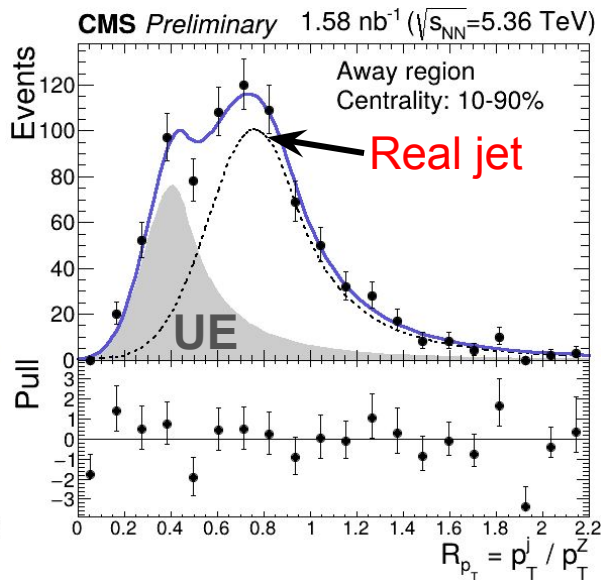
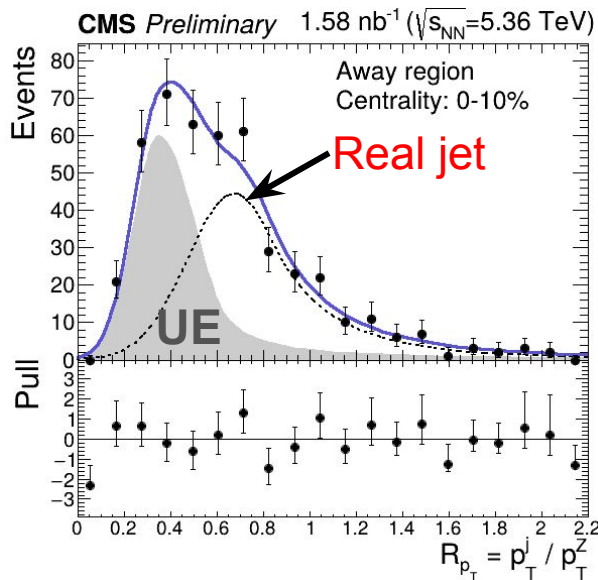
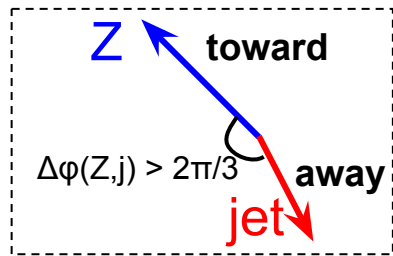
The fit in each centrality bin allows us to estimate:

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

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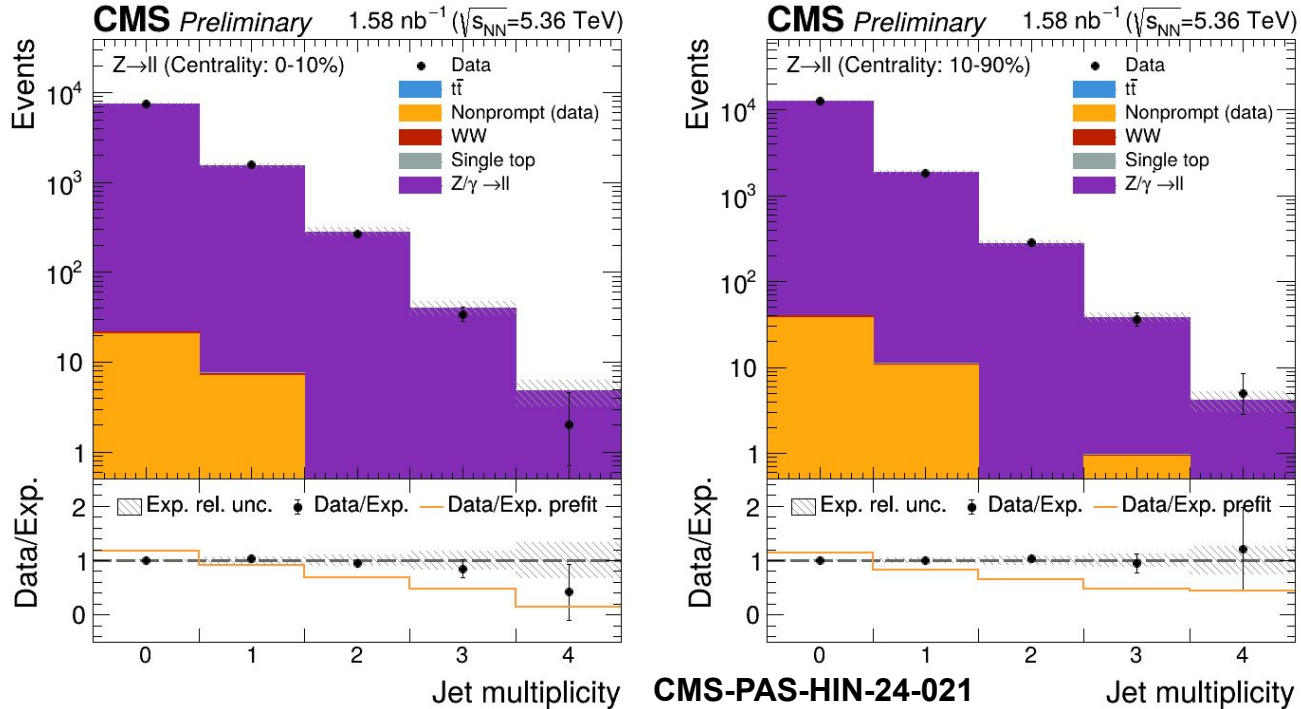
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Result in a data-based model for Z-jet balance including jet quenching

Jet multiplicity in PbPb

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

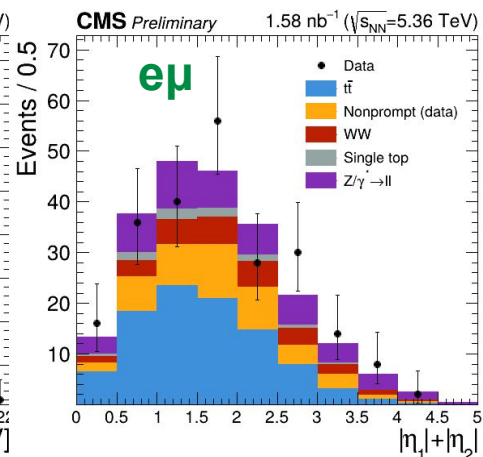
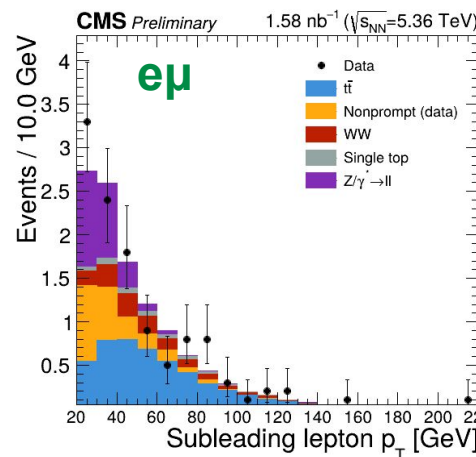
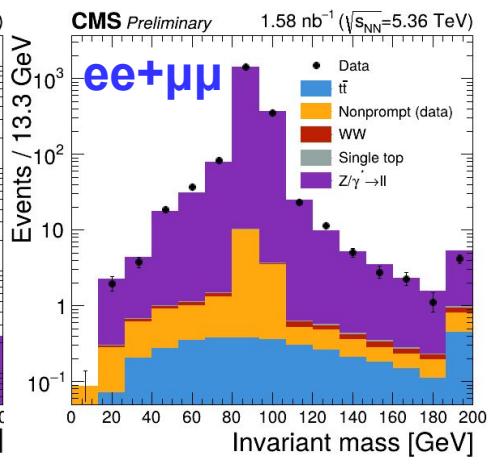
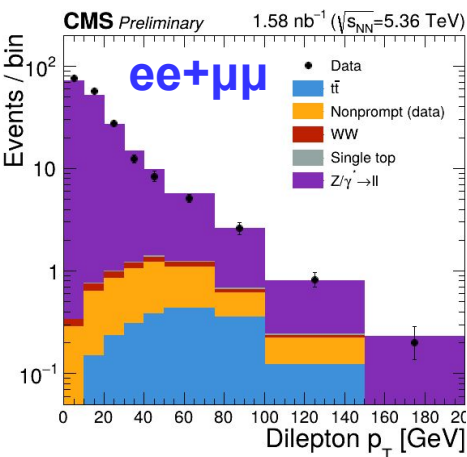
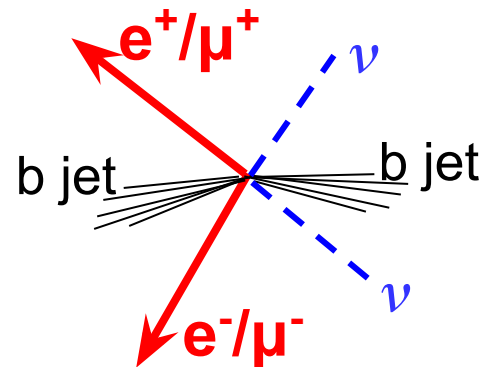


Excellent agreement with post fit expectations reached using both ee and $\mu\mu$ channels.

Measurement of top pairs in the dilepton channel

BDT discriminator used to separate signal ($t\bar{t}$) from background (Z/γ^*):

- Dilepton channel: use **only leptonic variables**
- Most relevant features:
 - $ee/\mu\mu$ channels: dilepton p_T ($p_T(\ell\ell)$), and invariant mass
 - $e\mu$ channel: $p_T(\ell\ell)$, subleading lepton p_T and pseudo-rapidity sum



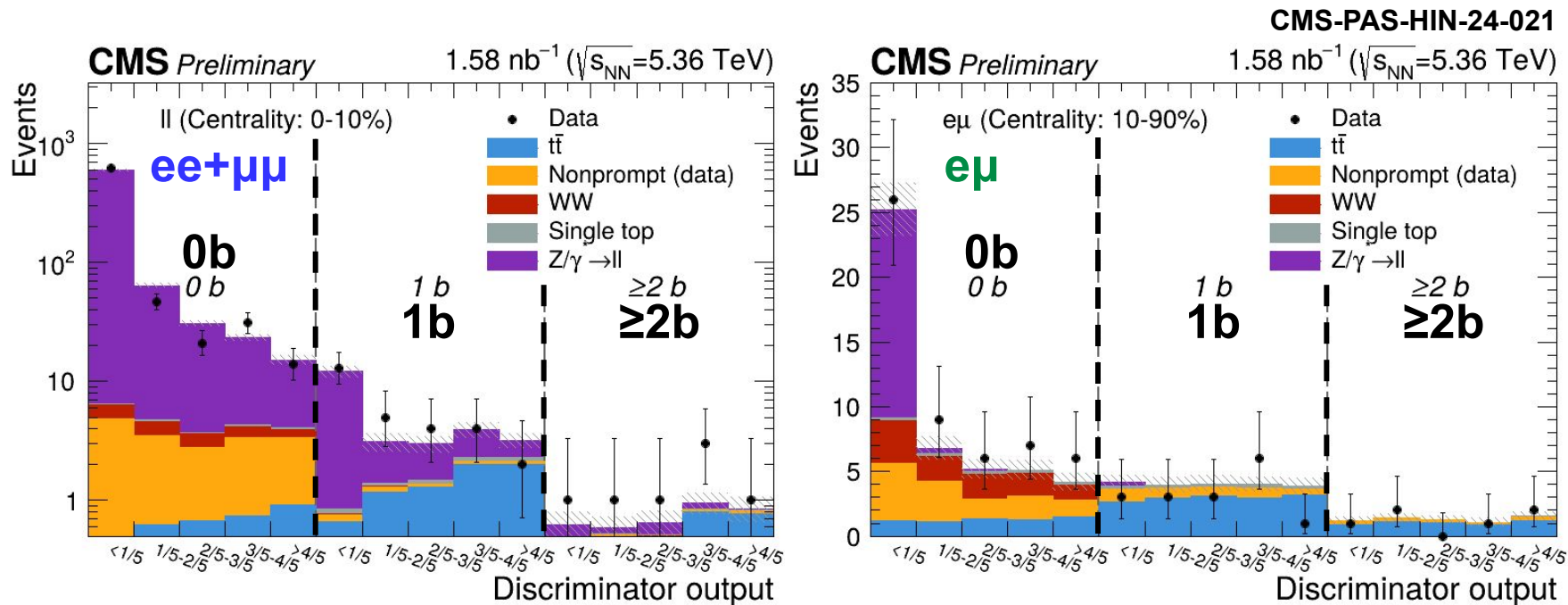
CMS-PAS-HIN-24-021

Measurement of top pairs in the dilepton channel

The $t\bar{t}$ cross section is extracted by fitting dilepton BDT score in the ee , $\mu\mu$ and $e\mu$ 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%**

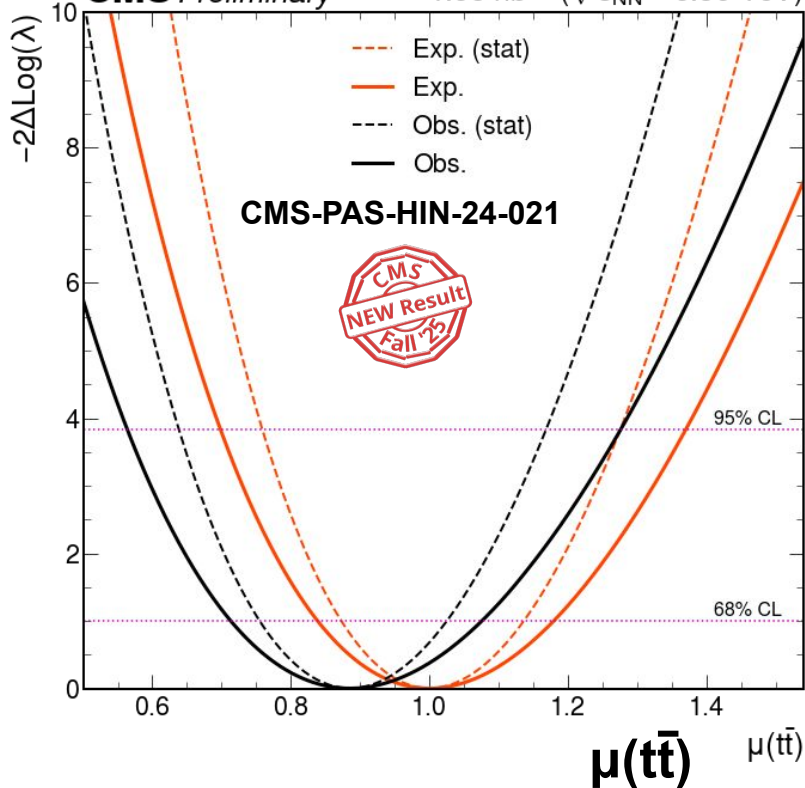


Fit results

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

CMS Preliminary

1.58 nb^{-1} ($\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV}$)



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

Theory cross section: $\sigma_{t\bar{t}}^{\text{SM}} = 3.86^{+0.69}_{-0.62}$ (NNLO+NNLL)

Results obtained:

$$\mu_{t\bar{t}} = 3.42^{+0.54}_{-0.50} \text{ (stat)}^{+0.50}_{-0.43} \text{ (syst)}$$

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

Also fitted the ratio of $\sigma(t\bar{t}) / \sigma(Z/\gamma^*)$:

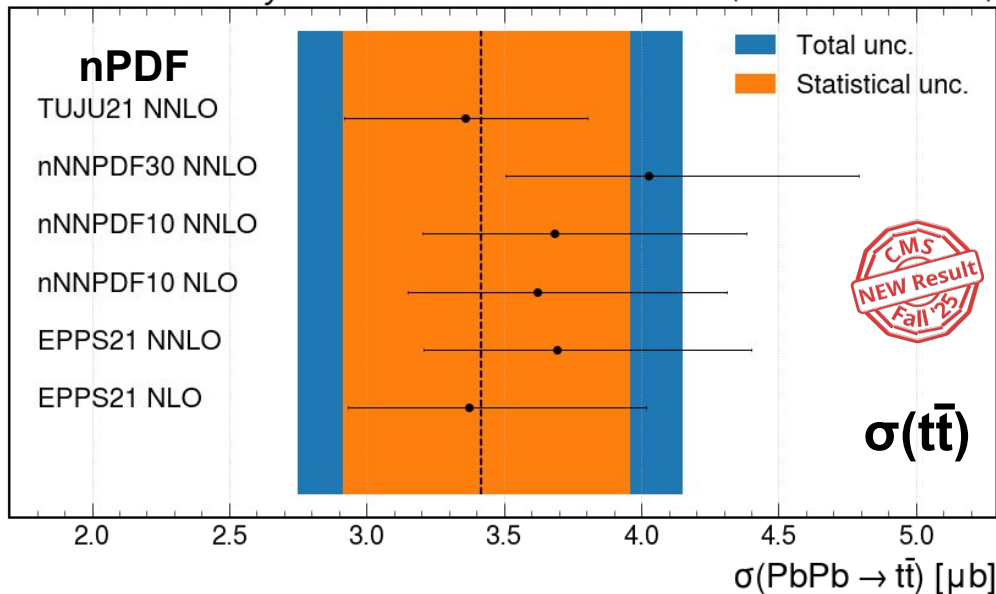
- Cent. 0-10%: $0.0082^{+0.0023}_{-0.0020}$ (stat) $^{+0.0017}_{-0.0014}$ (syst)
- Cent. 10-90%: $0.0083^{+0.0017}_{-0.0015}$ (stat) $^{+0.0012}_{-0.0011}$ (syst)

Comparison with theory

CMS-PAS-HIN-24-021

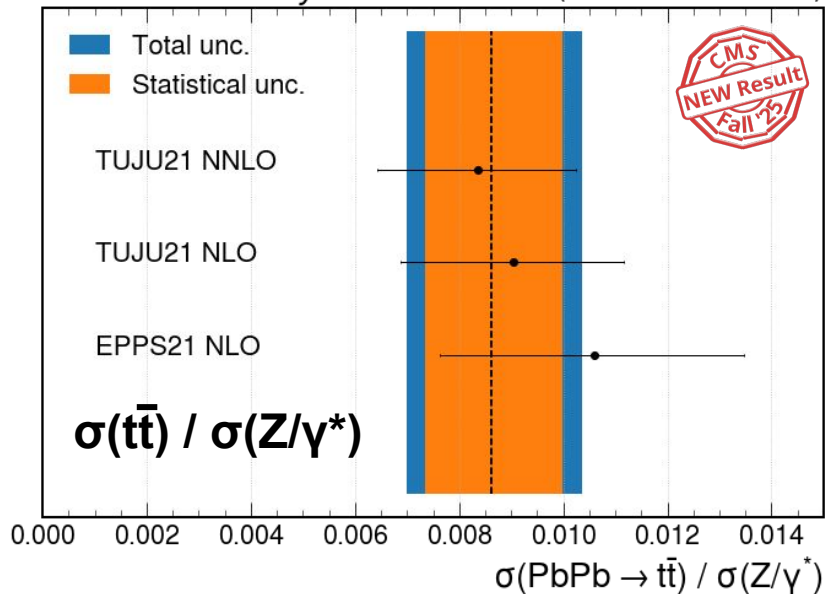
CMS Preliminary

$1.58 \text{ nb}^{-1} (\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV})$



CMS Preliminary

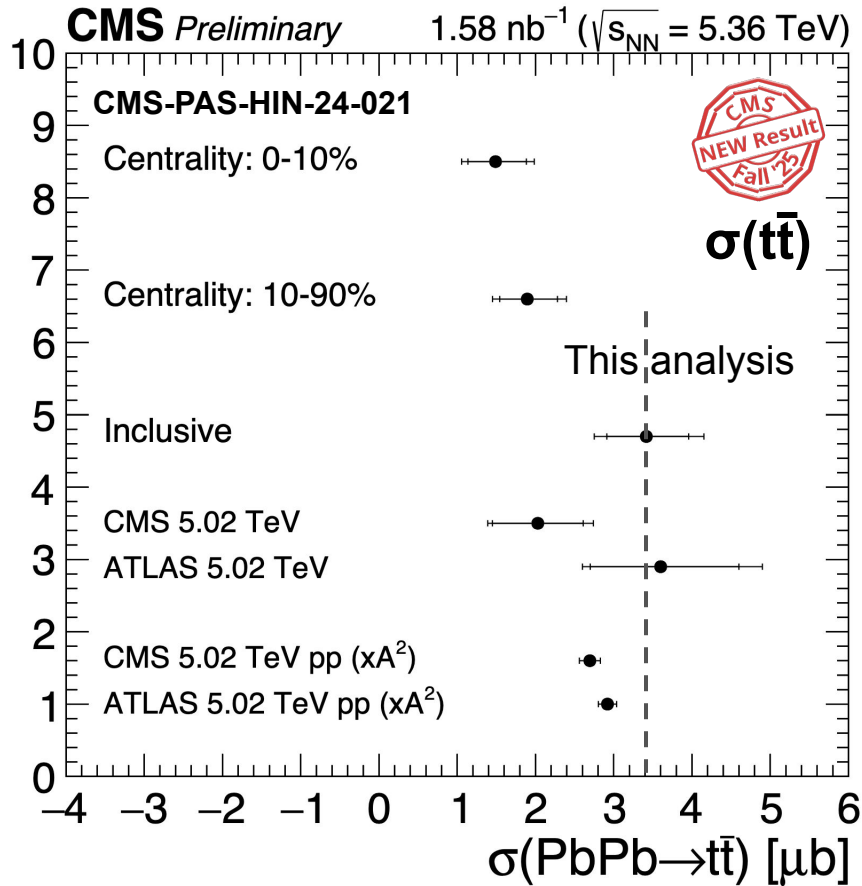
$1.58 \text{ nb}^{-1} (\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV})$



Good agreement between nPDF calculations and measured $\sigma(t\bar{t})$ and $\sigma(t\bar{t})/\sigma(\text{Z}/\gamma^*)$.

- Measurement uncertainty similar to theory \rightarrow will **improve** with **full Run 3** data ($\sim x4$ lumi).

Comparison with other PbPb measurements



- First centrality differential measurement of the $t\bar{t}$ cross section in PbPb.
- New techniques achieve more precise results than previous measurements.
- Central value at 5.36 TeV slightly larger than past results at 5.02 TeV, as expected from \sqrt{s} difference.

Summary

- Presented **first** results of $\sigma(t\bar{t})$ in **PbPb** at **5.36 TeV**, its ratio to $\sigma(Z/\gamma)$ and **centrality** dependence.
- Measurements **compatible** with **theory** calculations in PbPb within uncertainties.
- Full Run 3 data will establish top quark physics as a tool to constrain nPDFs and probe QGP.



Stay tuned for more CMS results!

