CMS Experiment at the LHC, CERN

Probing the Early Stages with Experimental Jet Observables

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EMMI Workshop: Probing the Early Stages with Jets

GSI, Darmstadt, Germany

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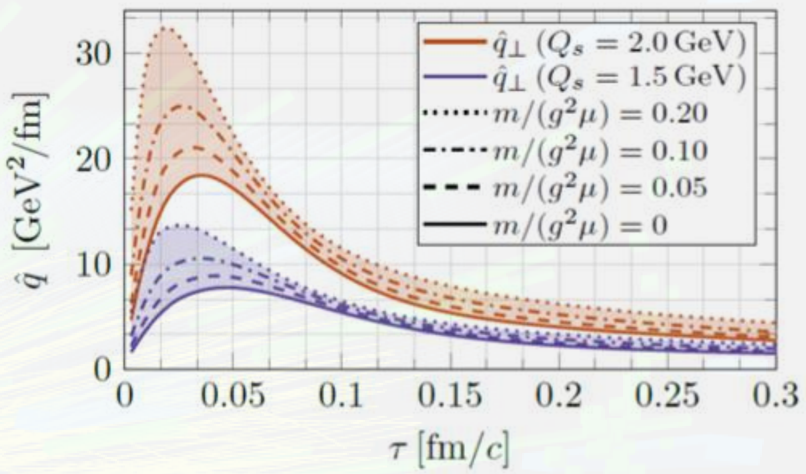
Probing the Early Stages with Jets

Timeline:

- Glasma / classical field: roughly $0 < \tau < 0.1$ fm/c
- Kinetic pre-equilibrium: roughly $0.1 < \tau \leq 0.4$ fm/c
- Hydrodynamic QGP: roughly $\tau > 0.4$ fm/c



Experimental Control:

- **Direction**: beam axis vs. azimuthal angle
- **Production time**: prompt versus delayed probes
- **Shower time**: splitting formation time
- **System lifetime**: OO vs PbPb

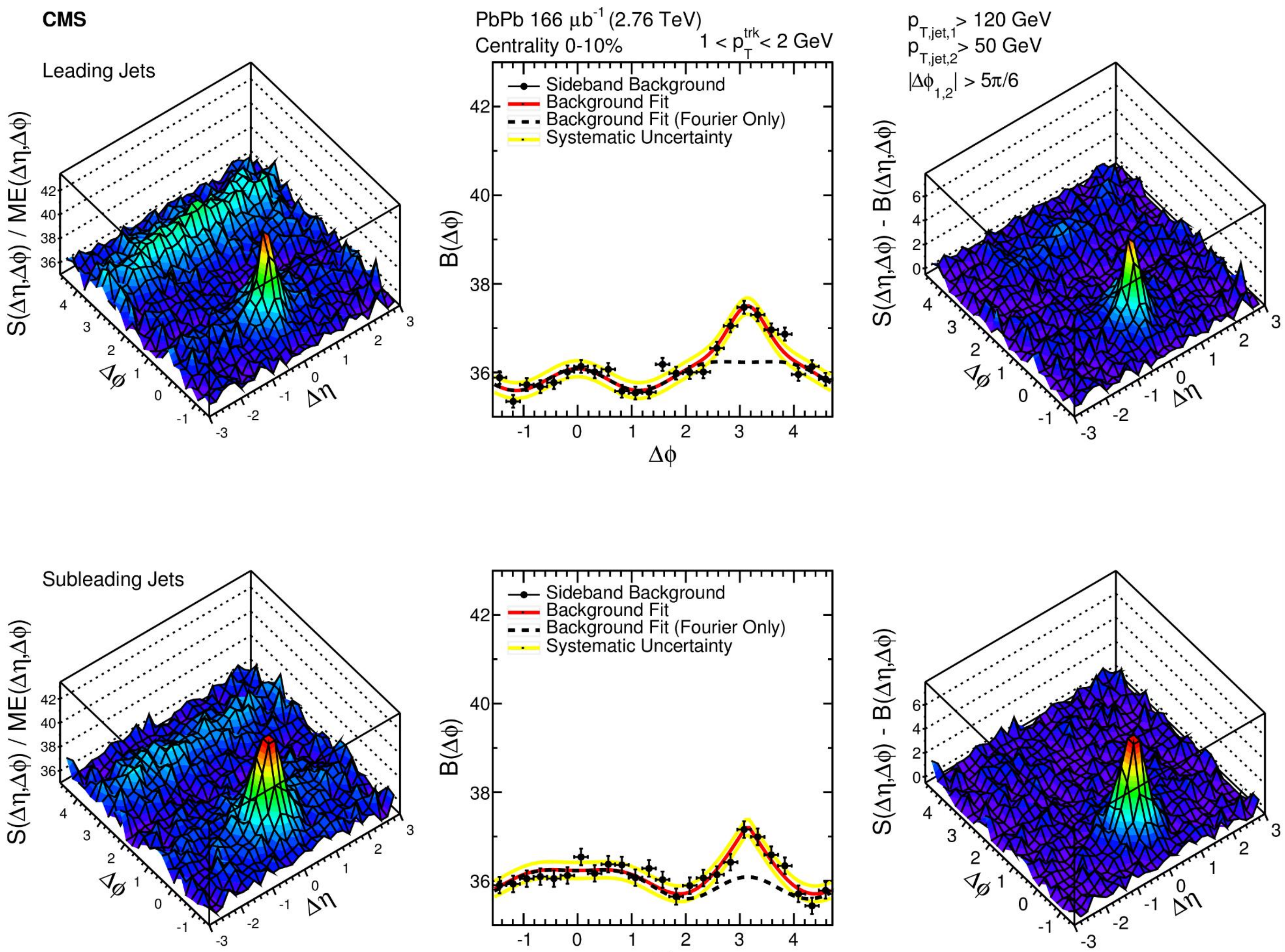
Direction Control: Jet-Hadron Correlation

Hadron spectra tagged by leading and subleading jets have been measured

- Leading jet p_T> 120 GeV
- Subleading jet p_T> 50 GeV

The flow background was subtracted using the data sideband 0.5 <|Δη|< 3.0

- This reveals event-averaged jet-like correlation



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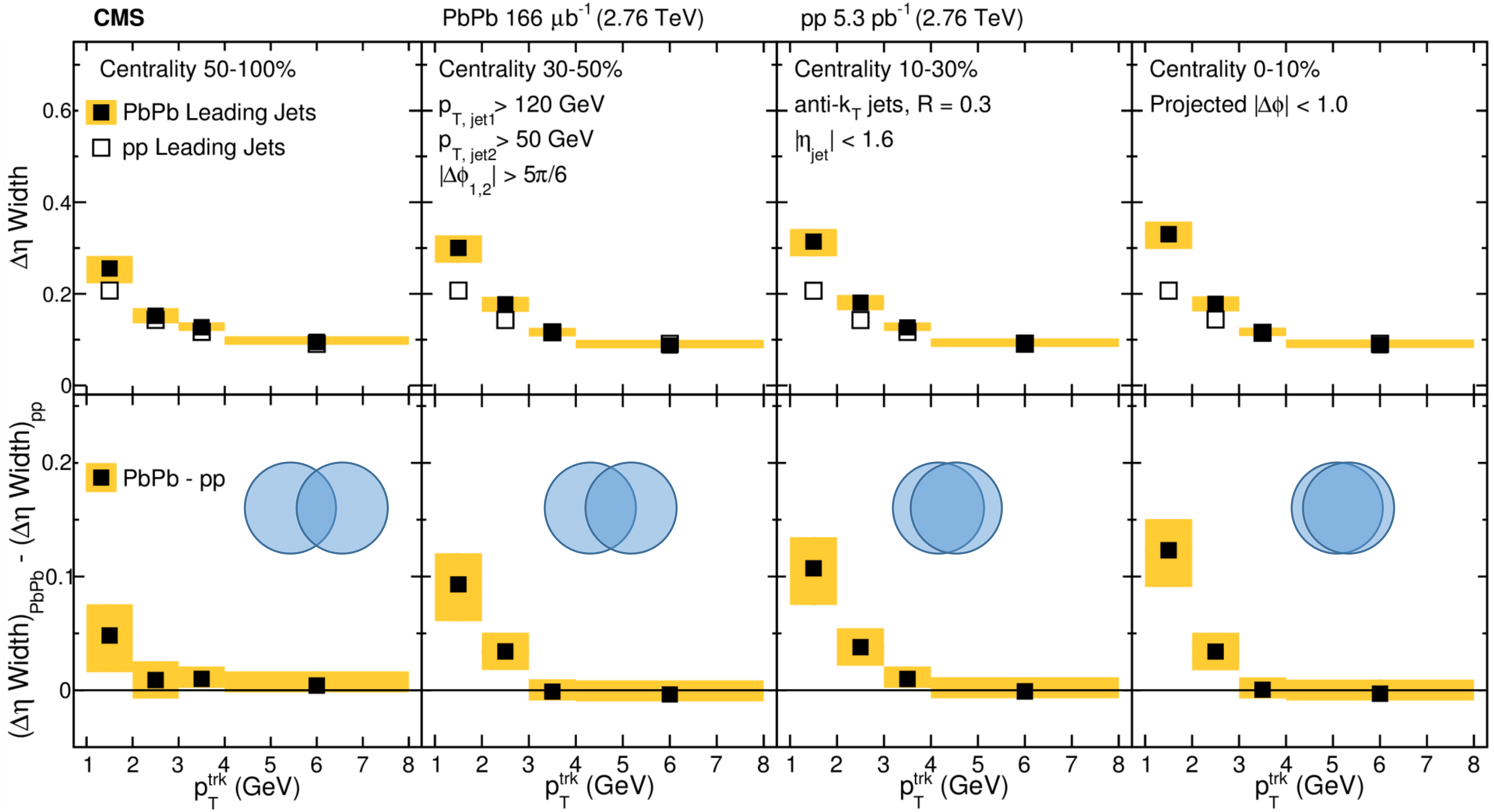
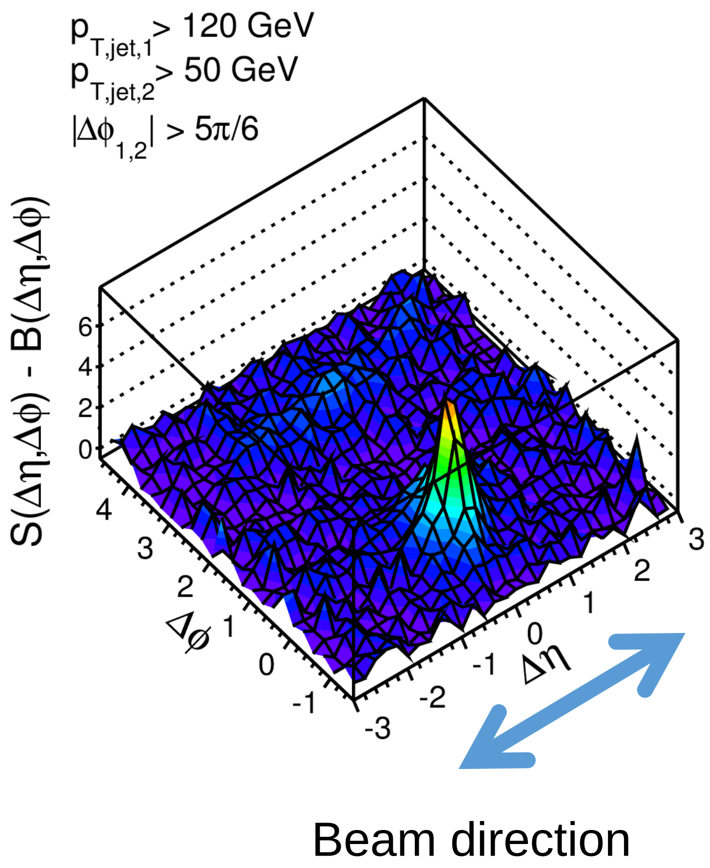
Leading: Δη Width of the Jet-Like Correlation





- At low p_T, significant broadening is observed in central PbPb collisions
- At high p_T, the width between pp and PbPb are consistent

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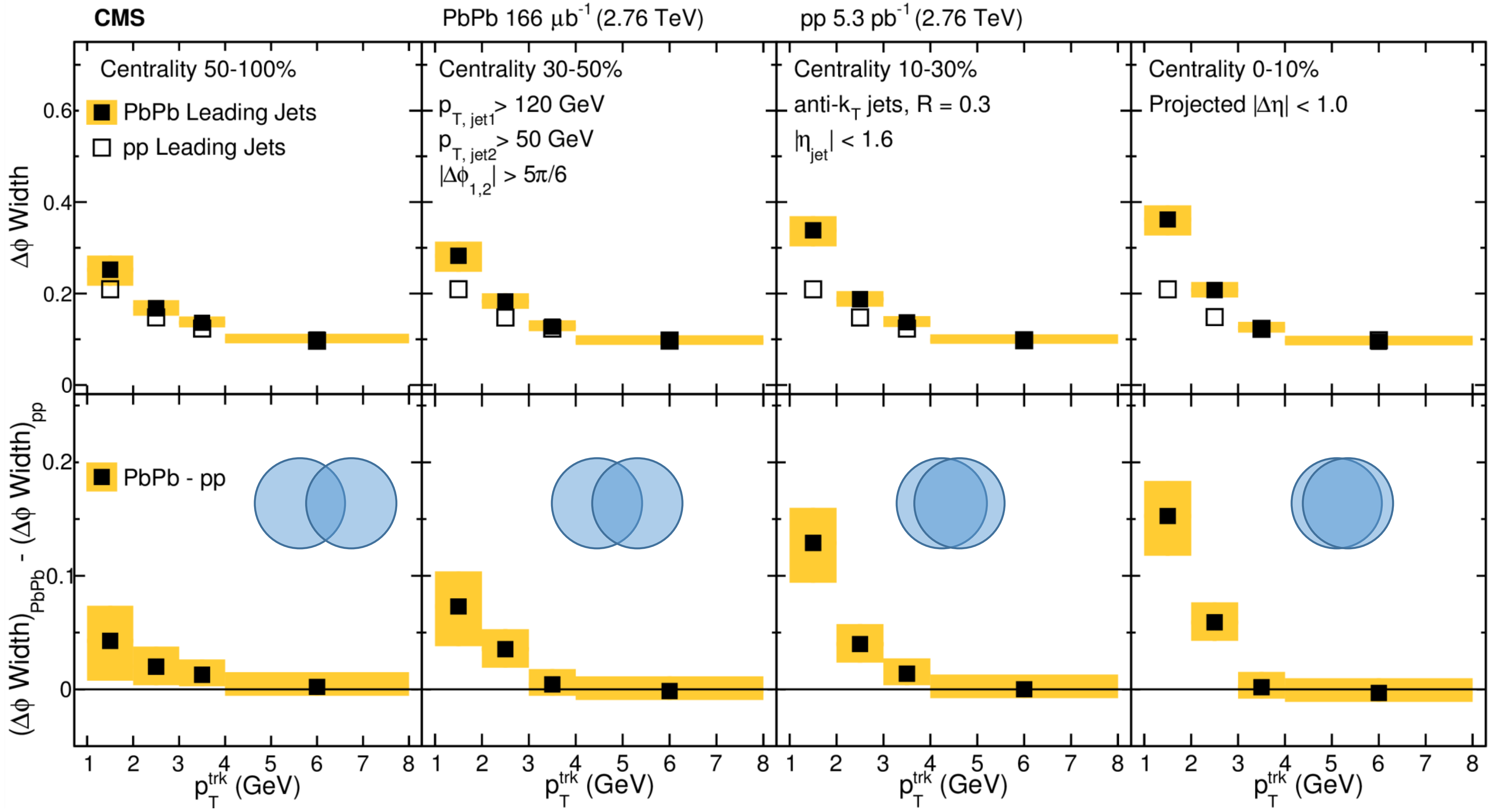
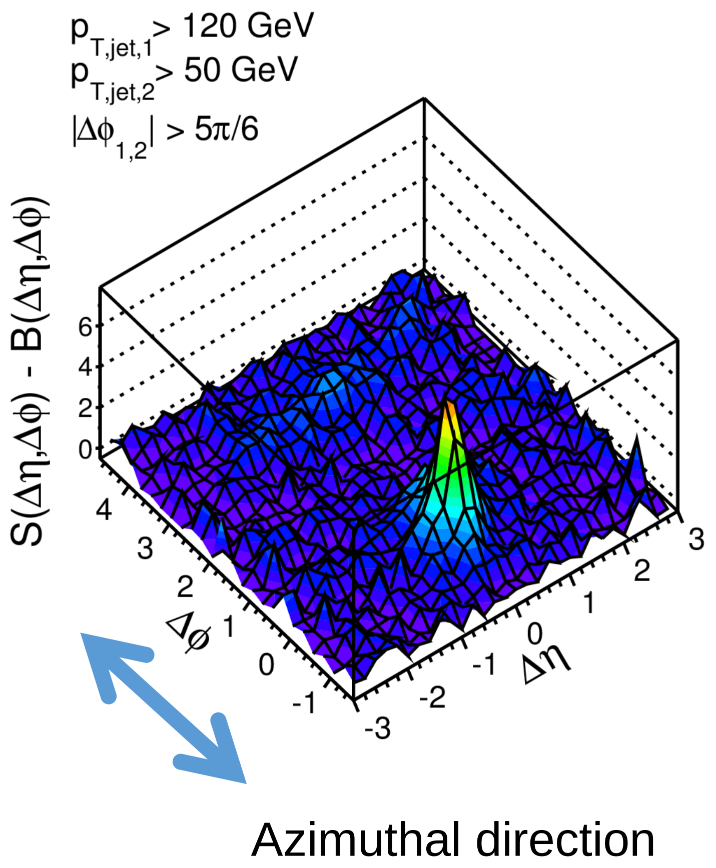
Leading: Δφ Width of the Jet-Like Correlation





- At low p_T, significant broadening is observed in central PbPb collisions, slightly large than Δη
- At high p_T, the width between pp and PbPb are consistent

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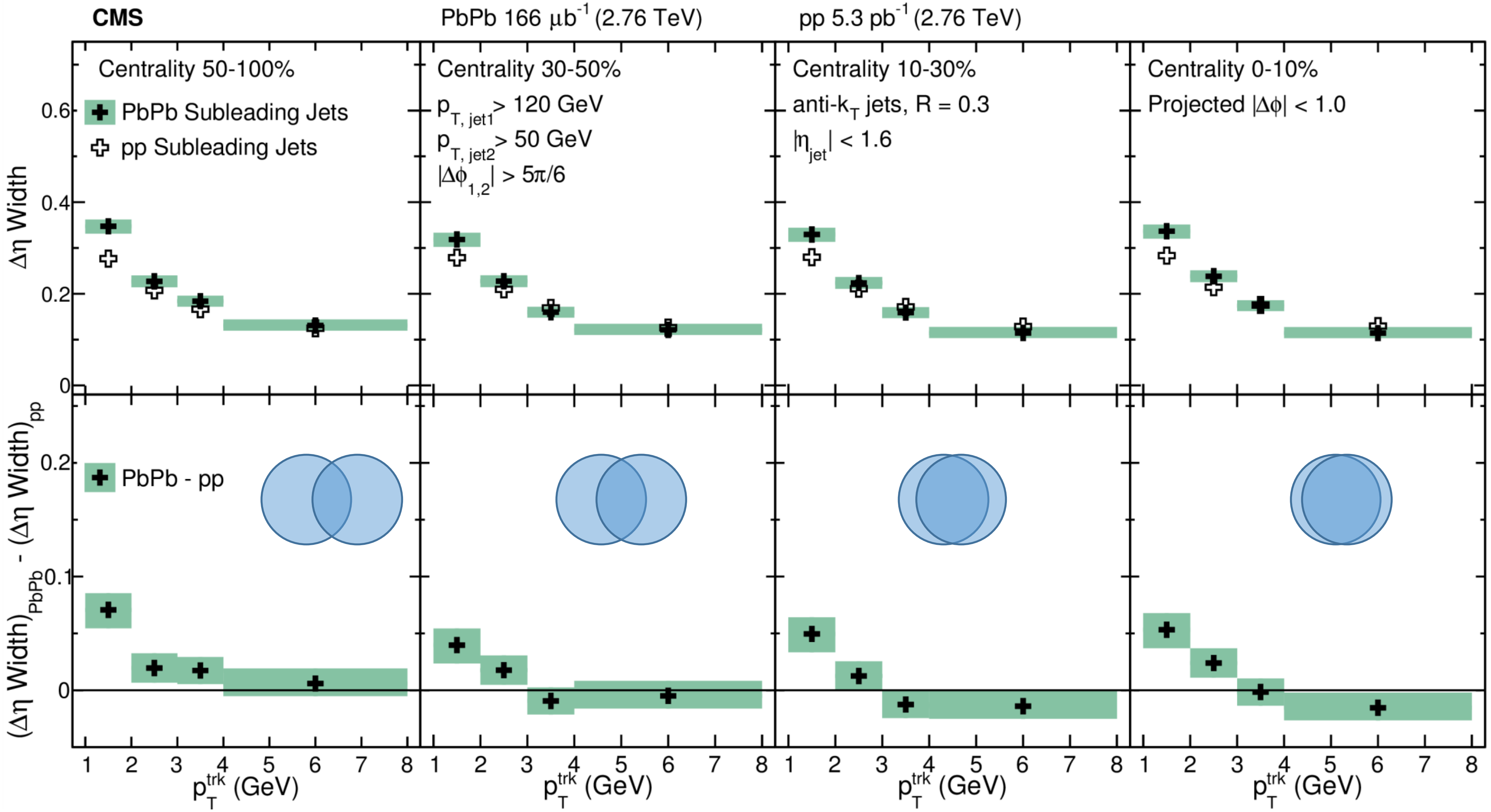
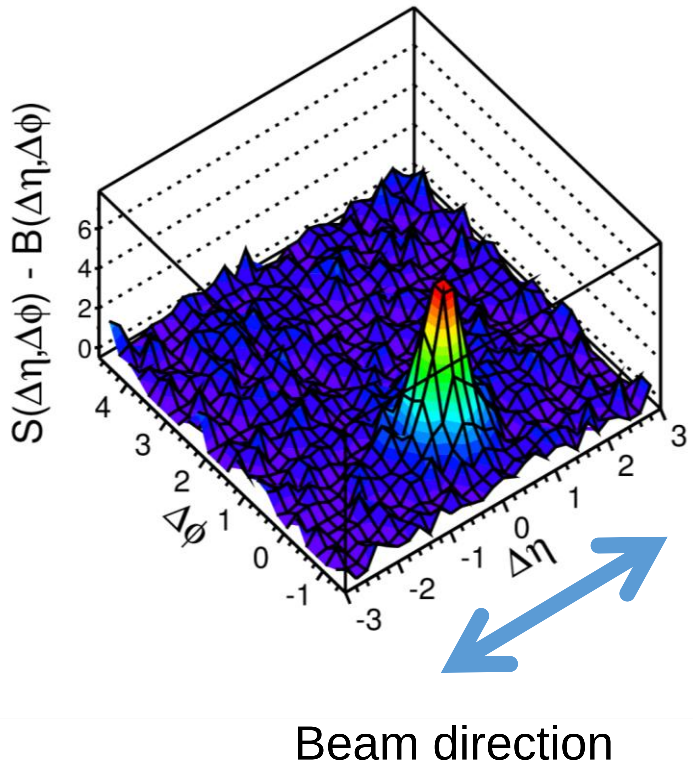
Subleading: Δη Width of the Jet-Like Correlation





- At low p_T, significant broadening is observed in central PbPb collisions. Enhancement smaller than leading jet.
- At high p_T, the width between pp and PbPb are consistent

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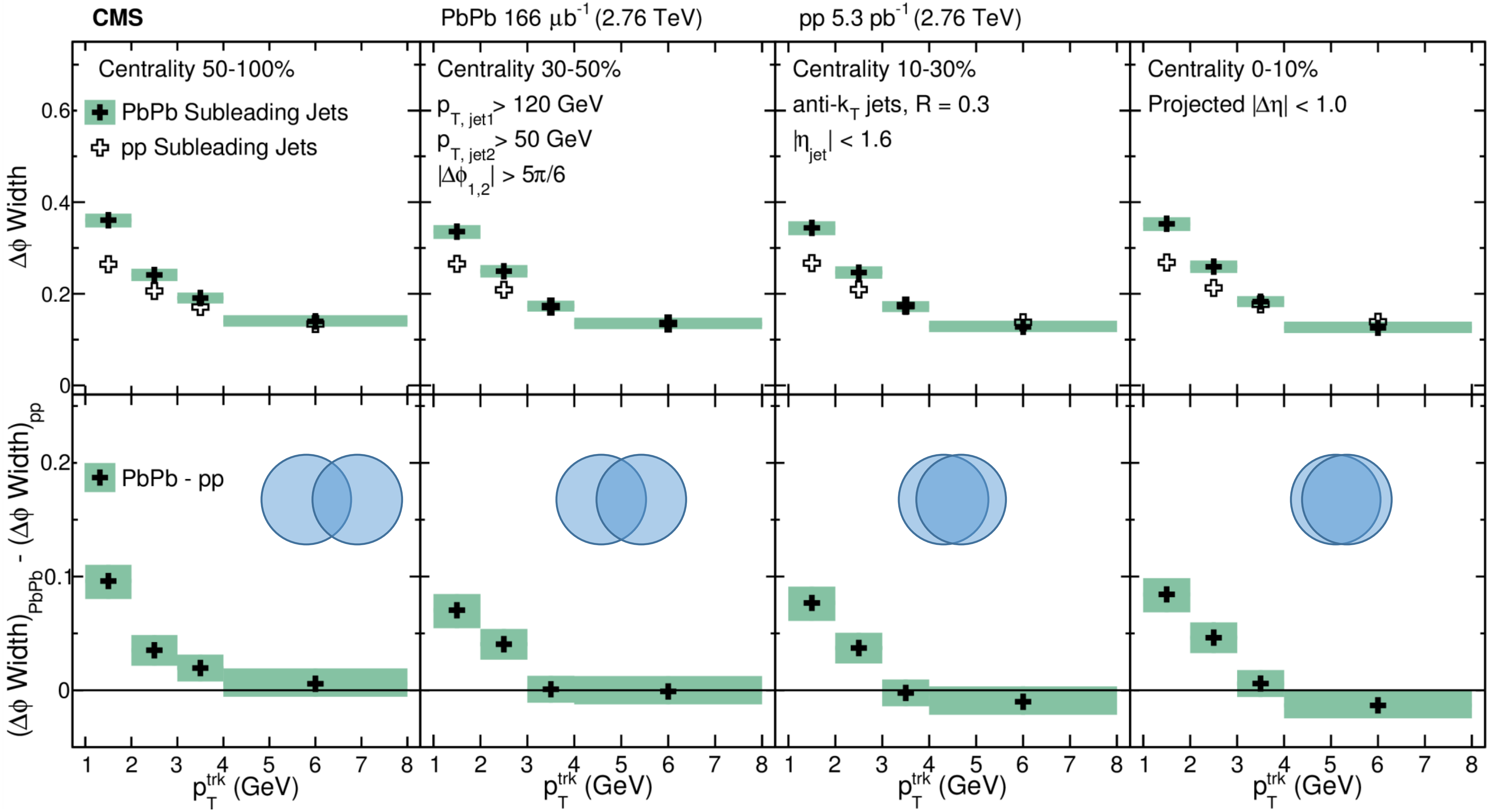
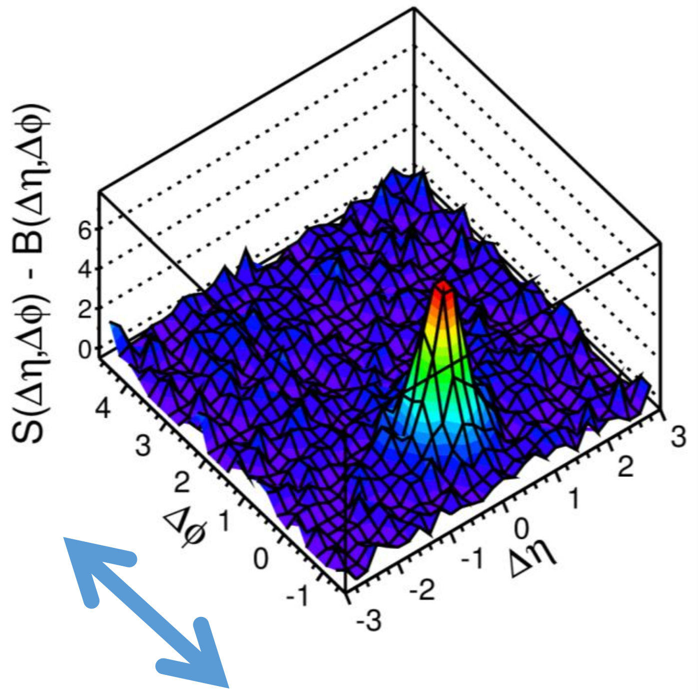
Subleading: Δφ Width of the Jet-Like Correlation





- At low p_T, significant broadening is observed in central PbPb collisions. Enhancement smaller than leading jet.
- At high p_T, the width between pp and PbPb are consistent

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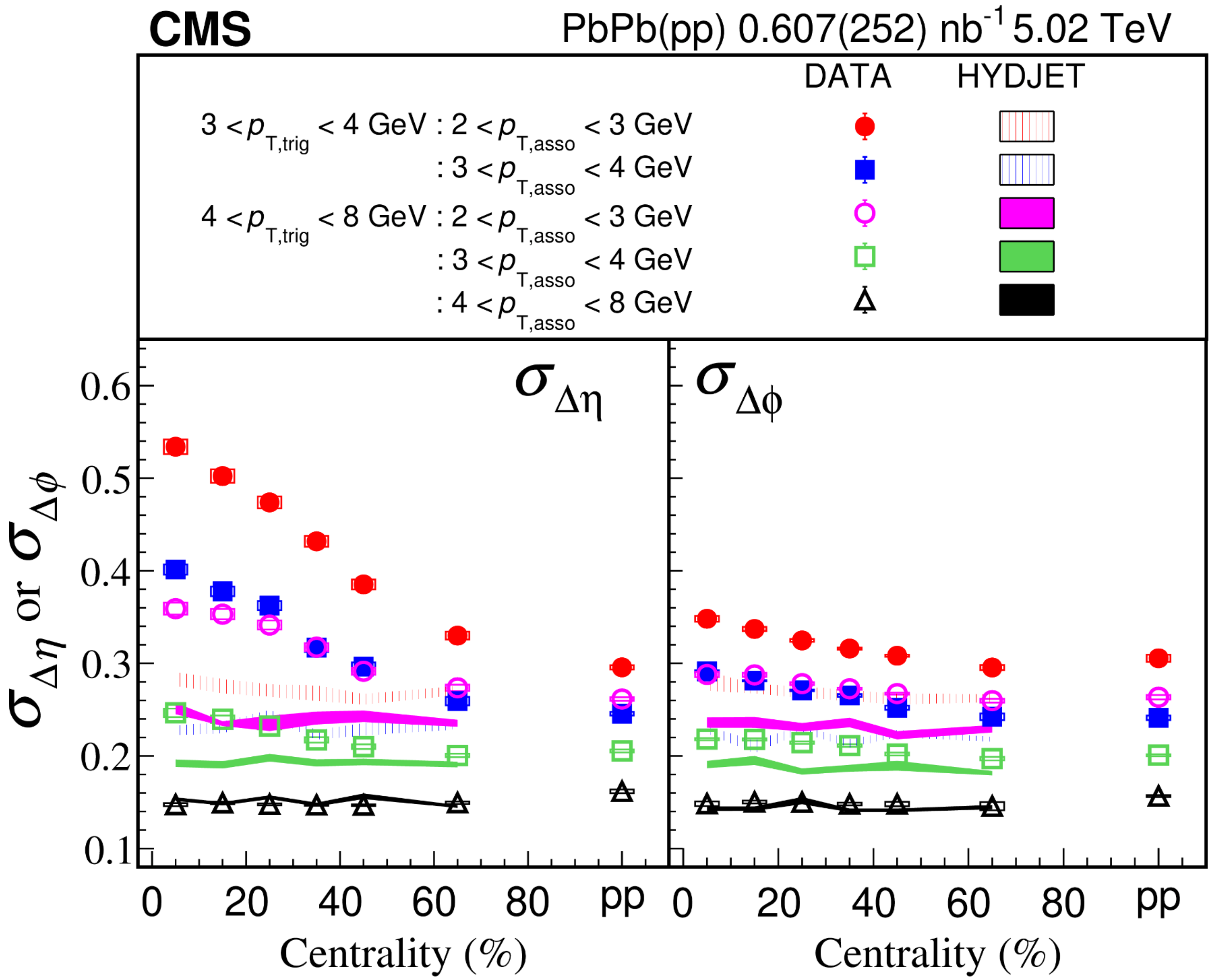
Direction Control: Di-hadron Correlation

- A similar analysis using a hadron trigger was performed
- At **low associated hadron p_T**:
  - Significantly broader η width than φ width is observed in central PbPb collision compared to pp references
- At **high associated hadron p_T**:
  - No significant broadening effect



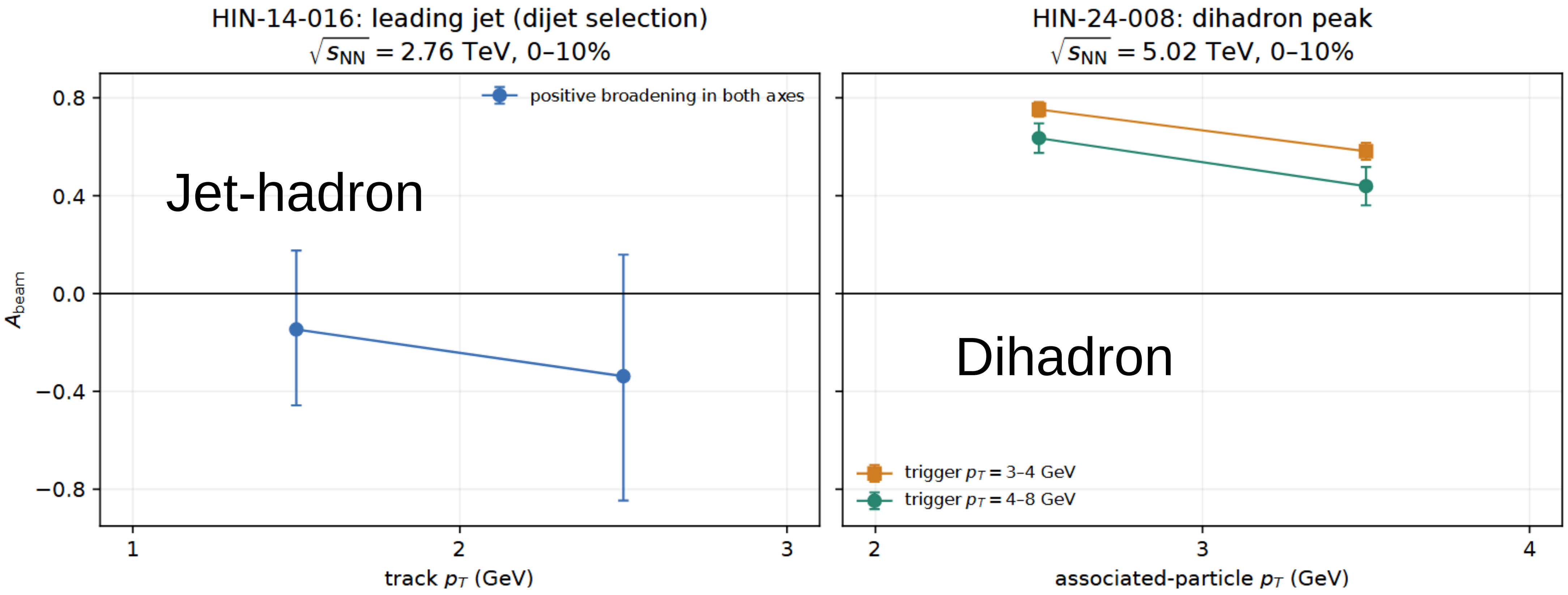
arXiv: 2603:14385

Direction Control: Asymmetry between Δη and Δφ Width

$$A_{\text{beam}}(p_T) = \frac{\Delta\sigma_\eta^2 - \Delta\sigma_\phi^2}{\Delta\sigma_\eta^2 + \Delta\sigma_\phi^2}$$

$$\Delta\sigma_i^2 \equiv \sigma_{i,\text{PbPb}}^2 - \sigma_{i,pp}^2, \qquad i \in \{\eta, \phi\},$$

Minimal anisotropic-glasma expectation: $A_{\text{beam}} > 0$



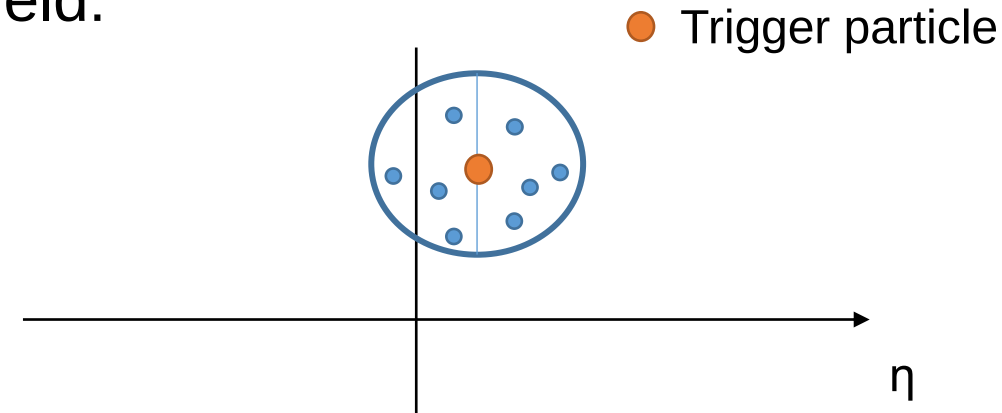
→ Jet-hadron and dihadron correlations give different pictures

However, the result is sensitive to trigger and surface bias, reco jet axis (or hadron) axis response, diffusion wake and medium response, hydro flow subtraction etc.

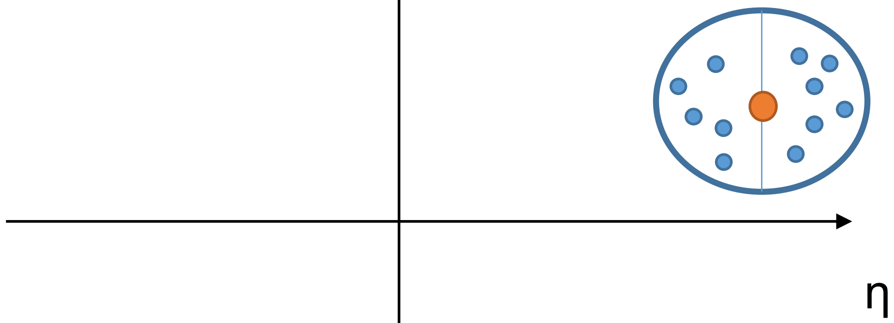
Yield Asymmetry in Positive and Negative Δη

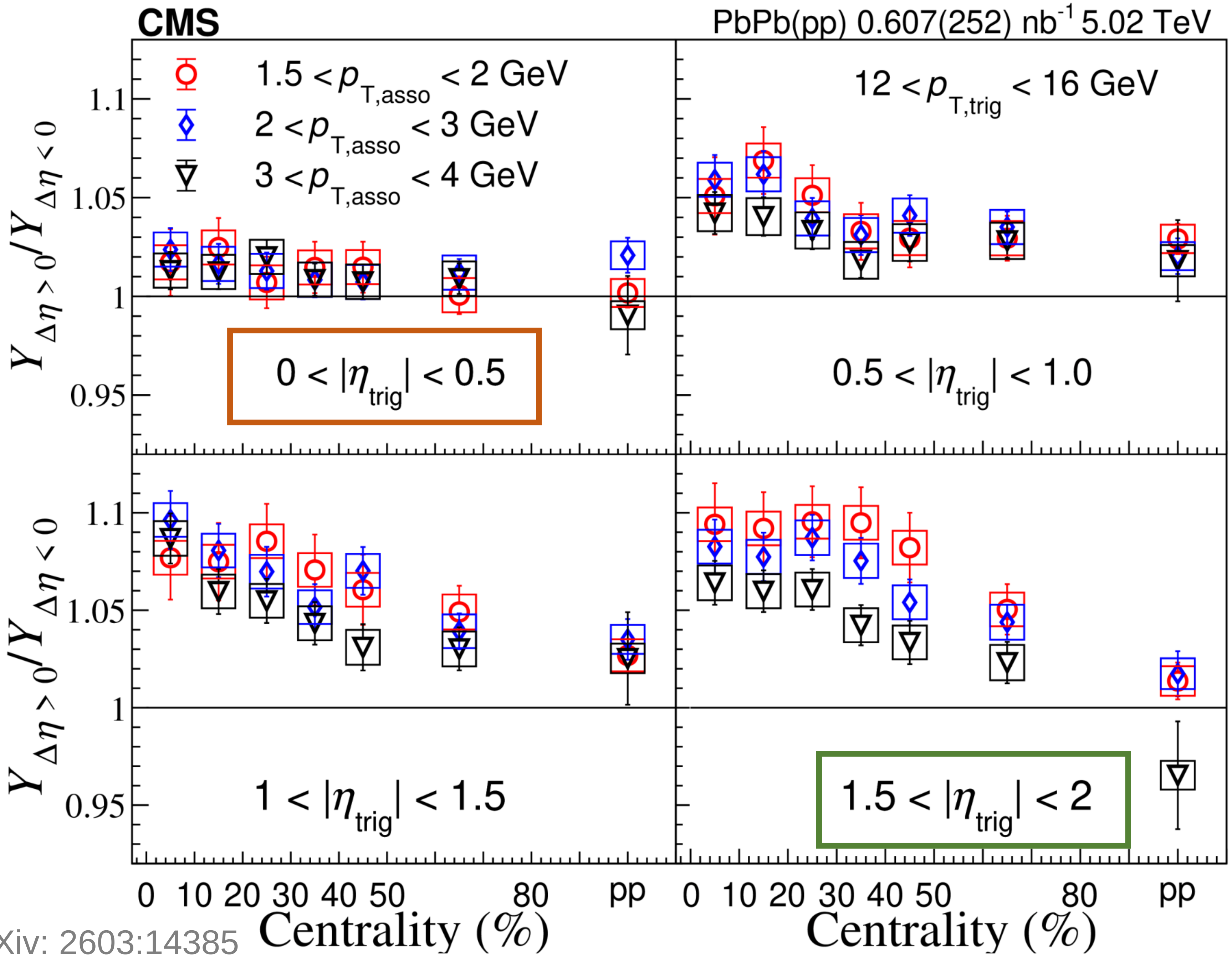
$$R_Y \equiv \frac{Y_{\Delta\eta>0}}{Y_{\Delta\eta<0}}, \qquad 0 < |\Delta\eta| < 0.7$$

At midrapidity, asymmetric associated yield:



At **large η**, the asymmetry grows:





Sensitive to medium response
Demonstration of experimental feasibility

arXiv: 2603:14385

Direction Control: Possible New Observable

- To reduce selection bias: use a photon-tag and/or a Z-tag:
  - One shower is a lot easier than 2 showers

- Use a winner-take-all jet axis for a recoil-free axis tagging

- Consider using energy weighting to be less sensitive to flow and wake effect

- Observable based on **tracks** and **WTA jet axis**: $C_{ab} = \frac{\sum_{i\in\text{tracks}} p_{T,i}\,\Delta x_{i,a}\Delta x_{i,b}}{\sum_{i\in\text{tracks}} p_{T,i}} \qquad a,b\in\{\eta,\phi\},$

Where $\Delta x_i = (\eta_i - \eta_{\text{WTA}},\, \phi_i - \phi_{\text{WTA}})$

Charged track and WTA jet axis provide high angular resolution and less sensitive to UE background in heavy ion collisions

[Alternatively, one could also choose E-scheme axis for momentum balance]

Direction Control: Possible New Observable

Example Observable:

$$C^{\mathrm{ch}}_{ab} = \frac{\sum_{i\in\mathrm{tracks}} p_{T,i}\,\Delta x_{i,a}\Delta x_{i,b}}{\sum_{i\in\mathrm{tracks}} p_{T,i}} \qquad a,b \in \{\eta,\phi\},$$

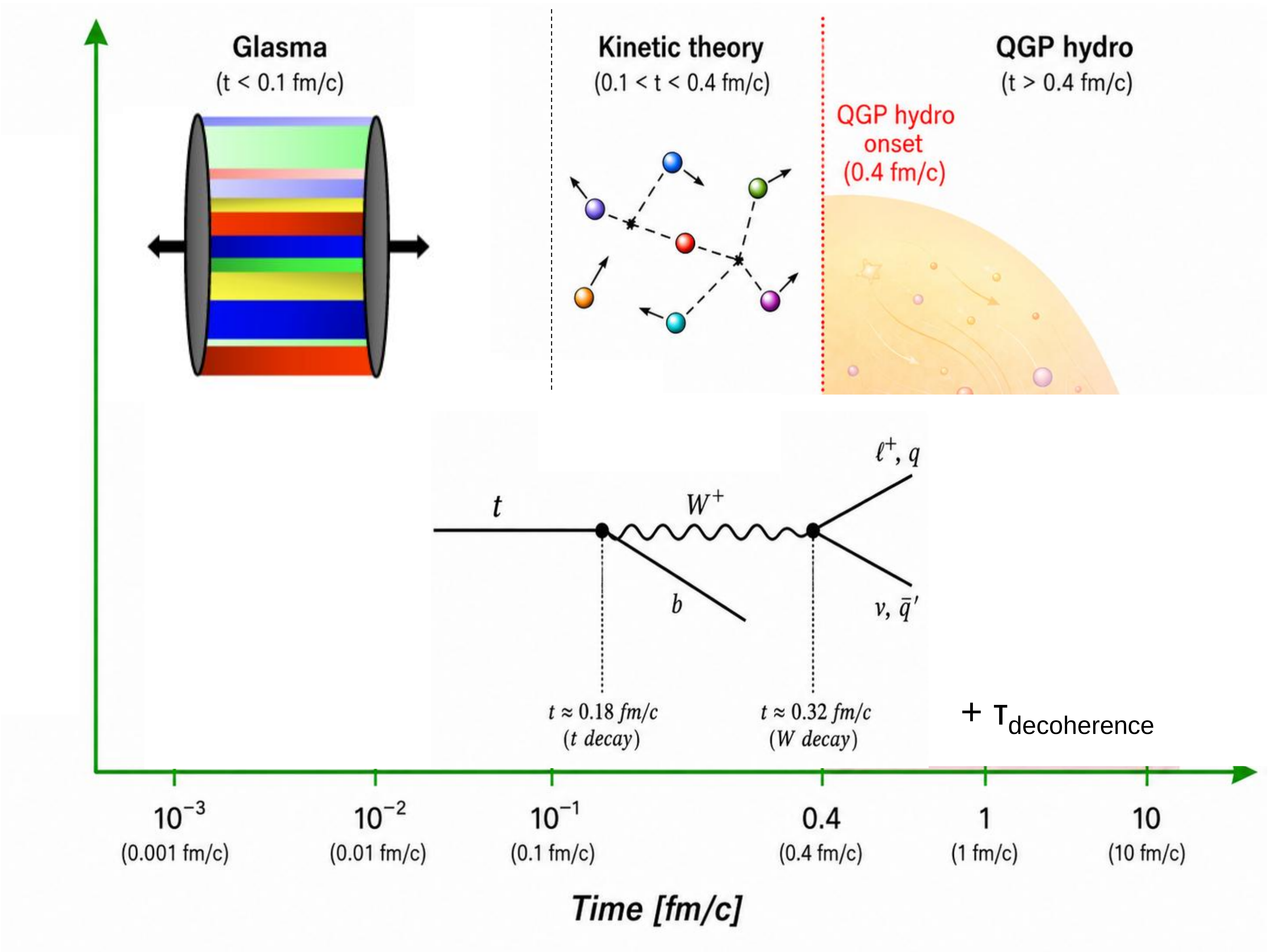
$$\Delta x_i = (\eta_i - \eta_{\mathrm{WTA}},\, \phi_i - \phi_{\mathrm{WTA}})$$

$$\Delta C_{ab} \equiv C^{\mathrm{PbPb}}_{ab} - C^{pp}_{ab}$$

Expectation:

- Medium response and medium induced radiation in isotropic medium: $\Delta C_{\eta\eta} - \Delta C_{\varphi\varphi} \sim 0$ and $\Delta C_{\eta\eta} + \Delta C_{\varphi\varphi} > 0$
- Glasma momentum kicks **after** early splitting: $\Delta C_{\eta\eta} > \Delta C_{\varphi\varphi}$
- Glasma momentum kicks **before** early splitting: $\Delta C_{\eta\eta} \sim \Delta C_{\varphi\varphi} \sim 0$, sensitivity moves to boson-jet acoplanarity
- Cross-terms as additional checks

Production Control: $t\bar{t}$ Production



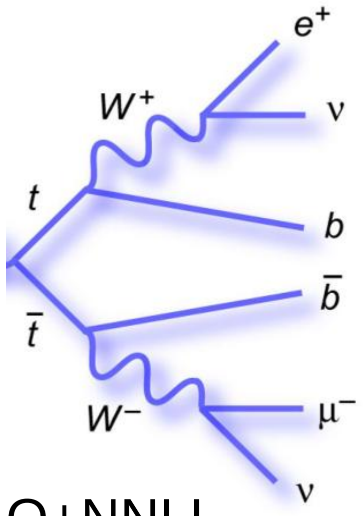
Production Control: $t\bar{t}$ analysis with Run 3 PbPb

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

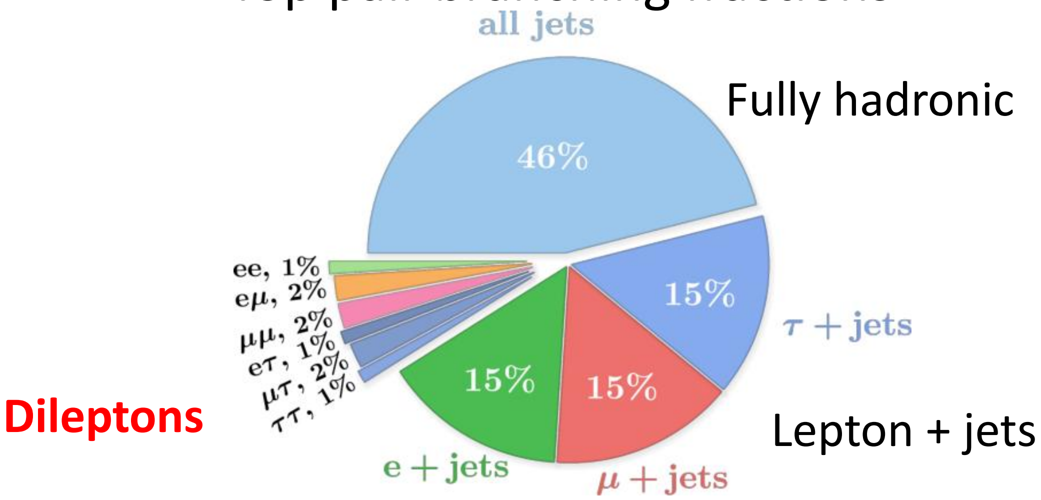
- Though lumi. comparable to Run 2 PbPb at 5.02 TeV, higher beam energy increases production.

Fully leptonic decays of tt pair:

- Highest purity
- Leptons + b-jets
- Small BR (~5% with e/μ)
- Simulated with MG5_aMC@NLO and POWHEG normalized to NNLO+NNLL



Top pair branching fractions



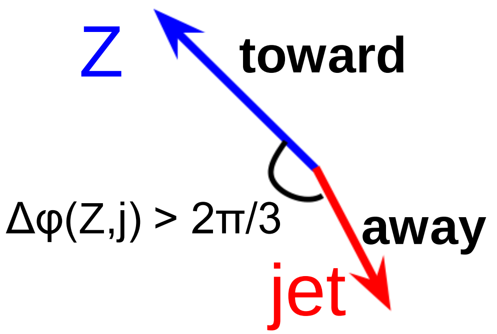
Backgrounds:

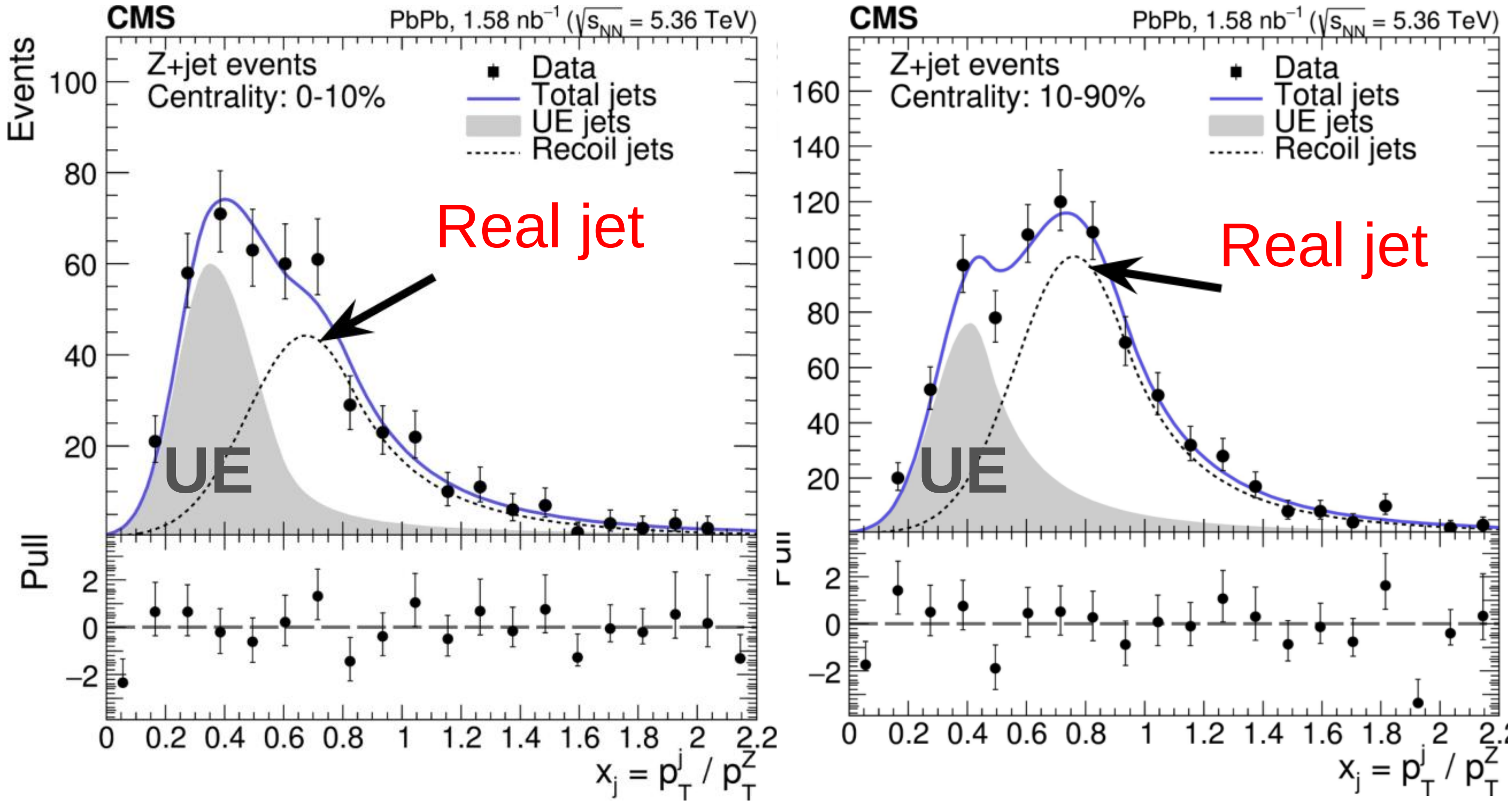
- Z/γ*+jets with MadGraph5 FxFx (normalized to Z control region)
- Non-prompt: W+jets and QCD multi-jets with HF decays (from data using event-mixing technique)
- Small contributions from single top and WW processes with POWHEG

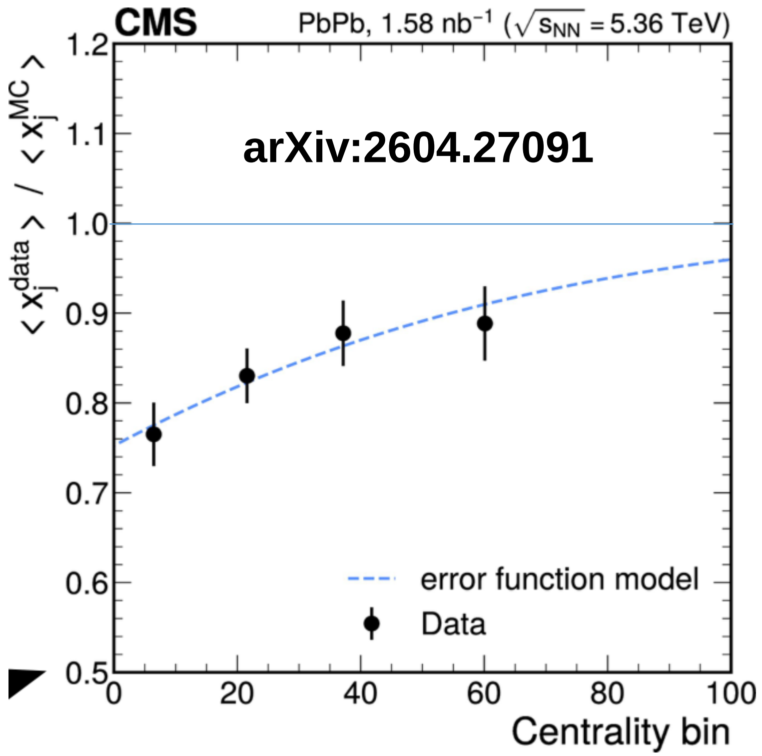
Processes simulated at NLO using EPPS21 nPDF and embedded into HYDJET PbPb events.

Jet Energy Residual Correction to Monte Carlo

- Z bosons with recoiling jet are used to verify residual JES is in data
  - Z p_T> 30 GeV, Z+jet pair with $\Delta\varphi(Z,j) > 2\pi/3$ are selected
  - Contamination from **UE jets** are subtracted in the toward hemisphere (Z direction) and **Real jets** are modeled with a Crystal-Ball function





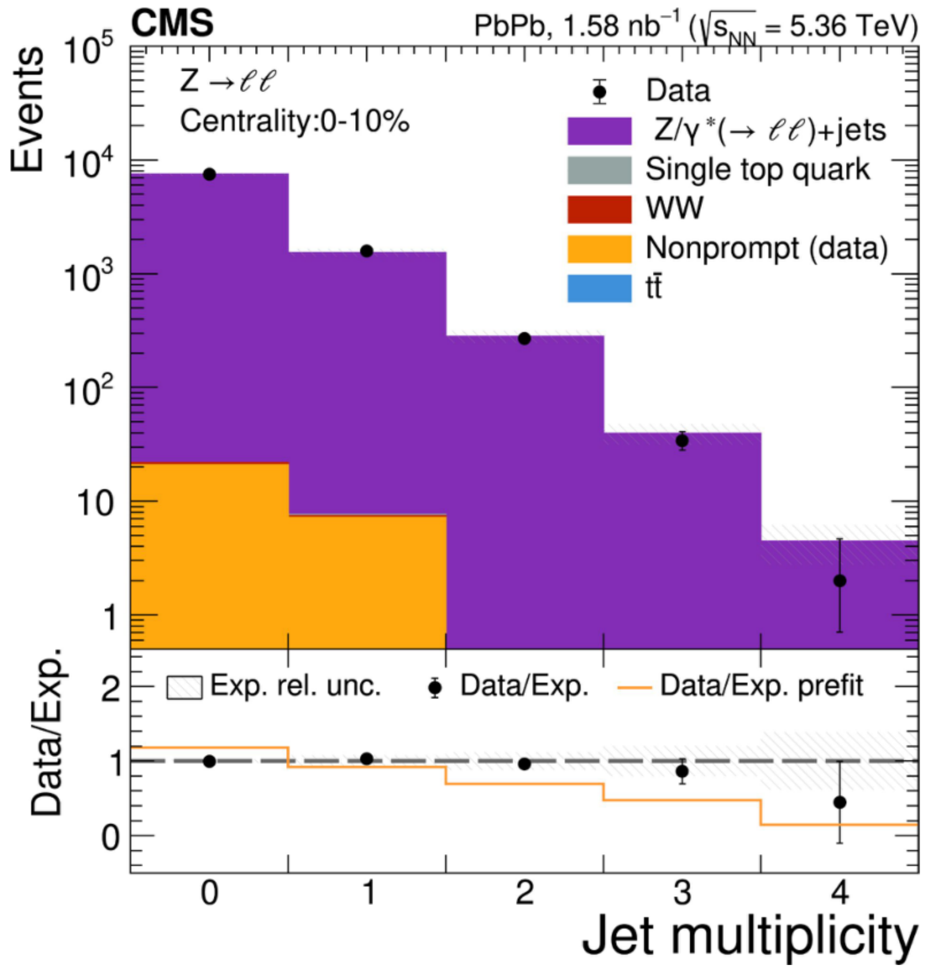


Quenching effects are included in the MC using data-driven jet-energy response from Z+Jet events

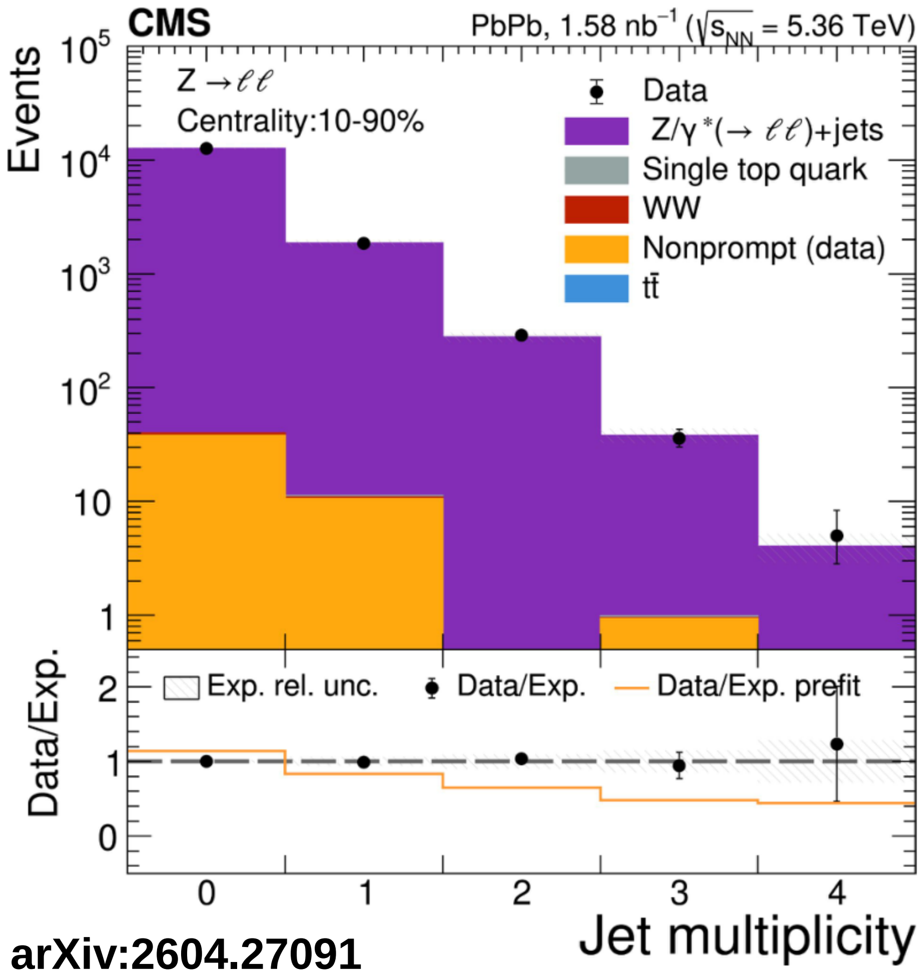
Jet multiplicity in PbPb

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

0-10%



10-90%

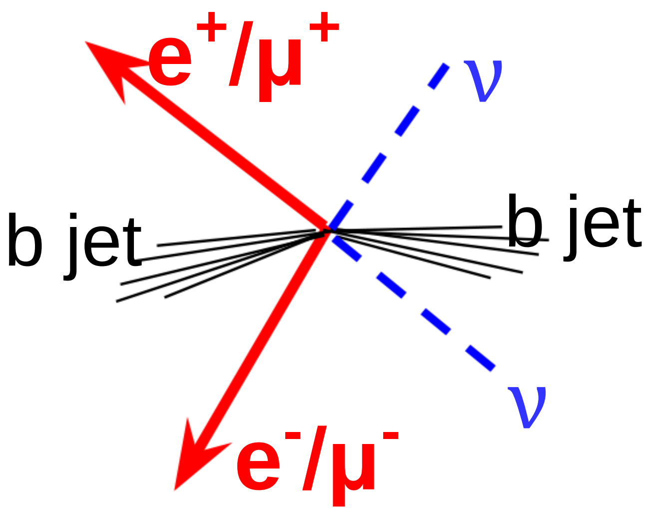


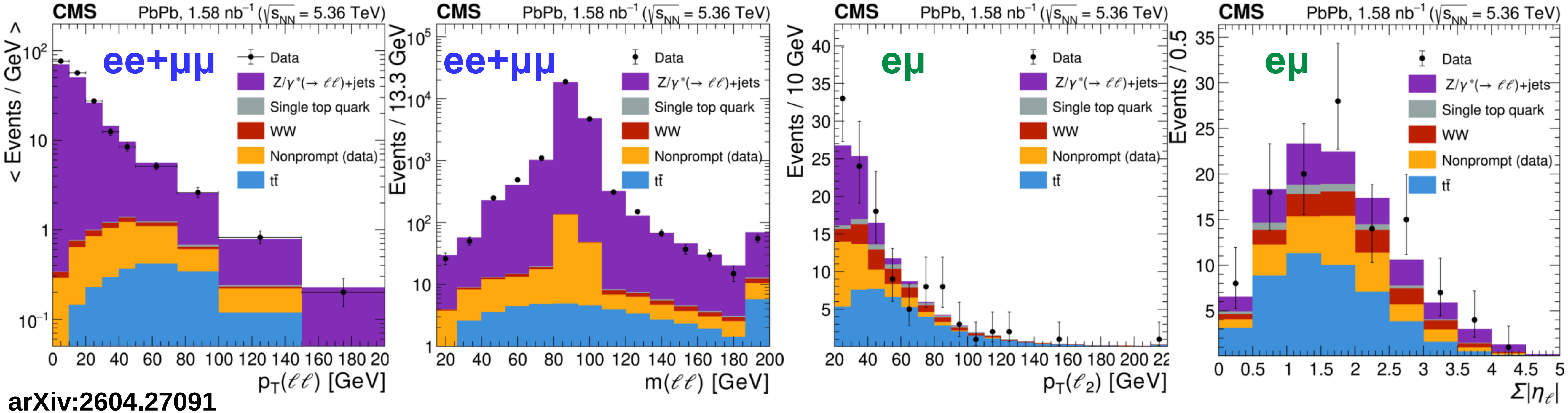
arXiv:2604.27091

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

Measurement of Top Pairs in the Dilepton Channel

- **BDT discriminator is used to separate $t\bar{t}$ signal and background (Z/γ*)**
  - Dilepton channel: use only leptonic variables
  - ee/μμ channels: dilepton p_T (p_T(ll)) and invariant mass
  - eμ channel: p_T(ll), subleading lepton p_T and lepton pseudorapidity sum





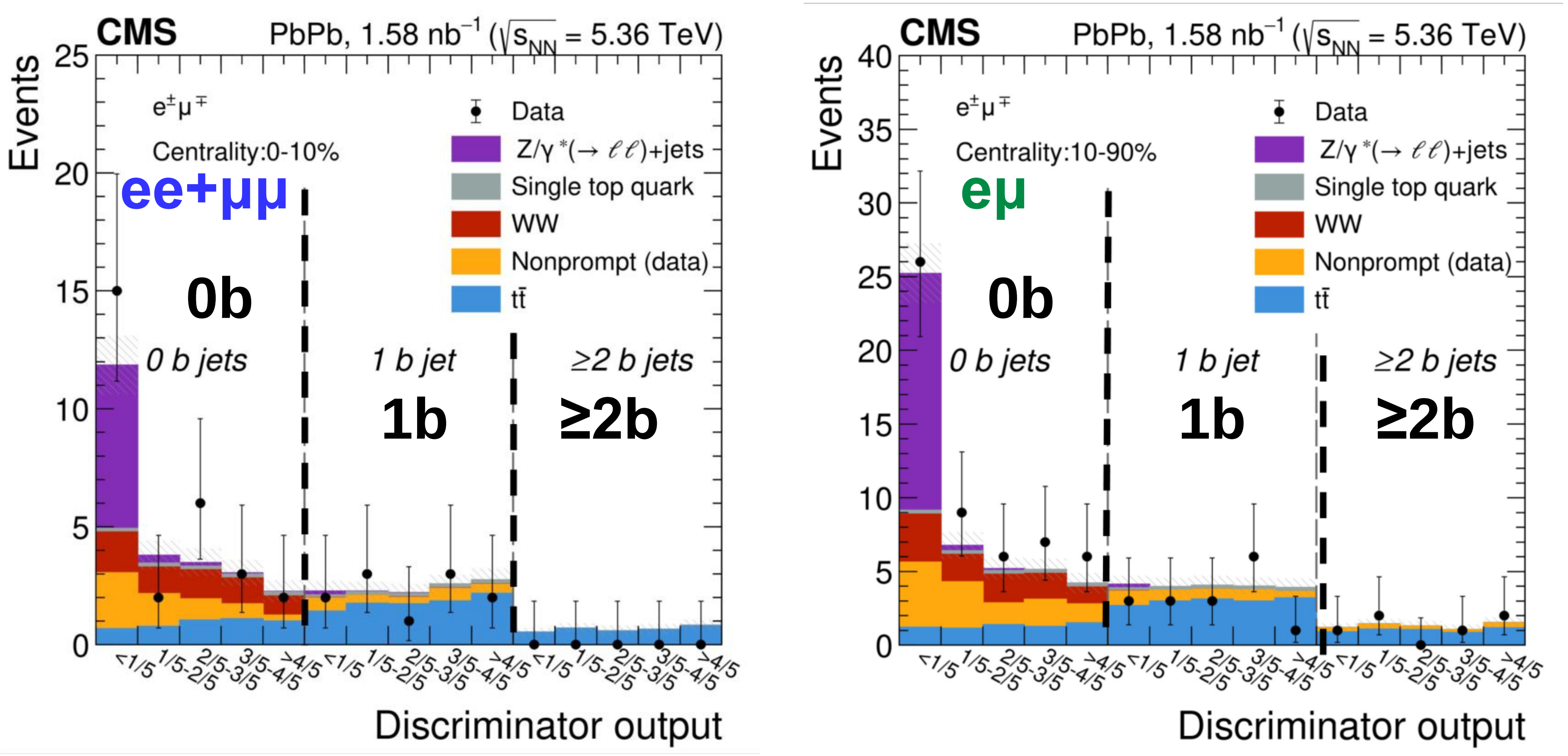
arXiv:2604.27091

Measurement of Top Pairs in the Dilepton Channel

The $t\bar{t}$ cross section is extracted by fitting dilepton BDT score in the **ee, μμ** and **eμ** channels.

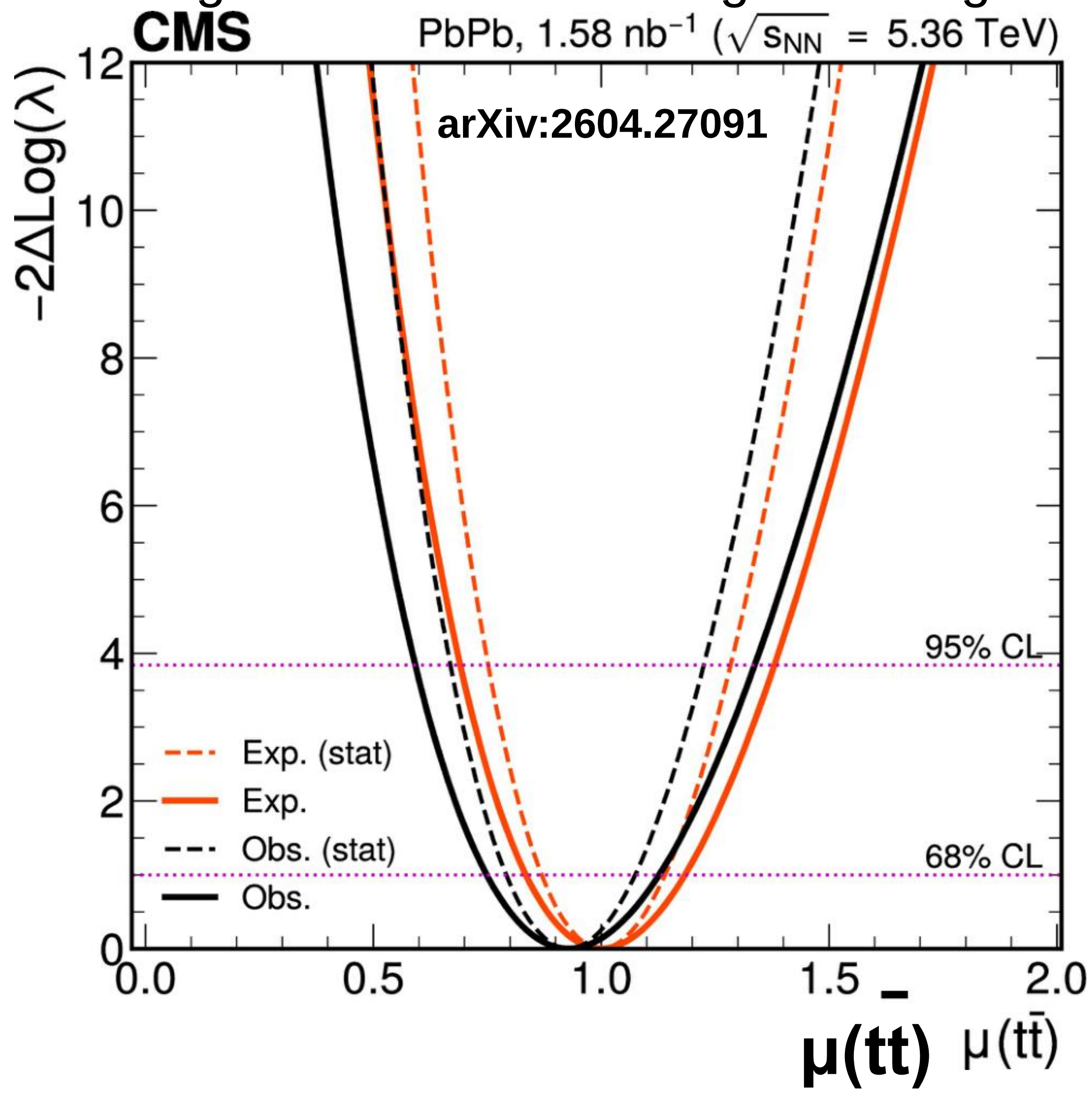
- Background separation is improved by fitting the BDT output in **0, 1** and **≥2 b-tag** jet events.

0-10% **10-90%** **arXiv:2604.27091**



$t\bar{t}$ Cross-Section in PbPb at 5.36 TeV

Log-likelihood scan: tt signal strength



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

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

Results obtained:

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

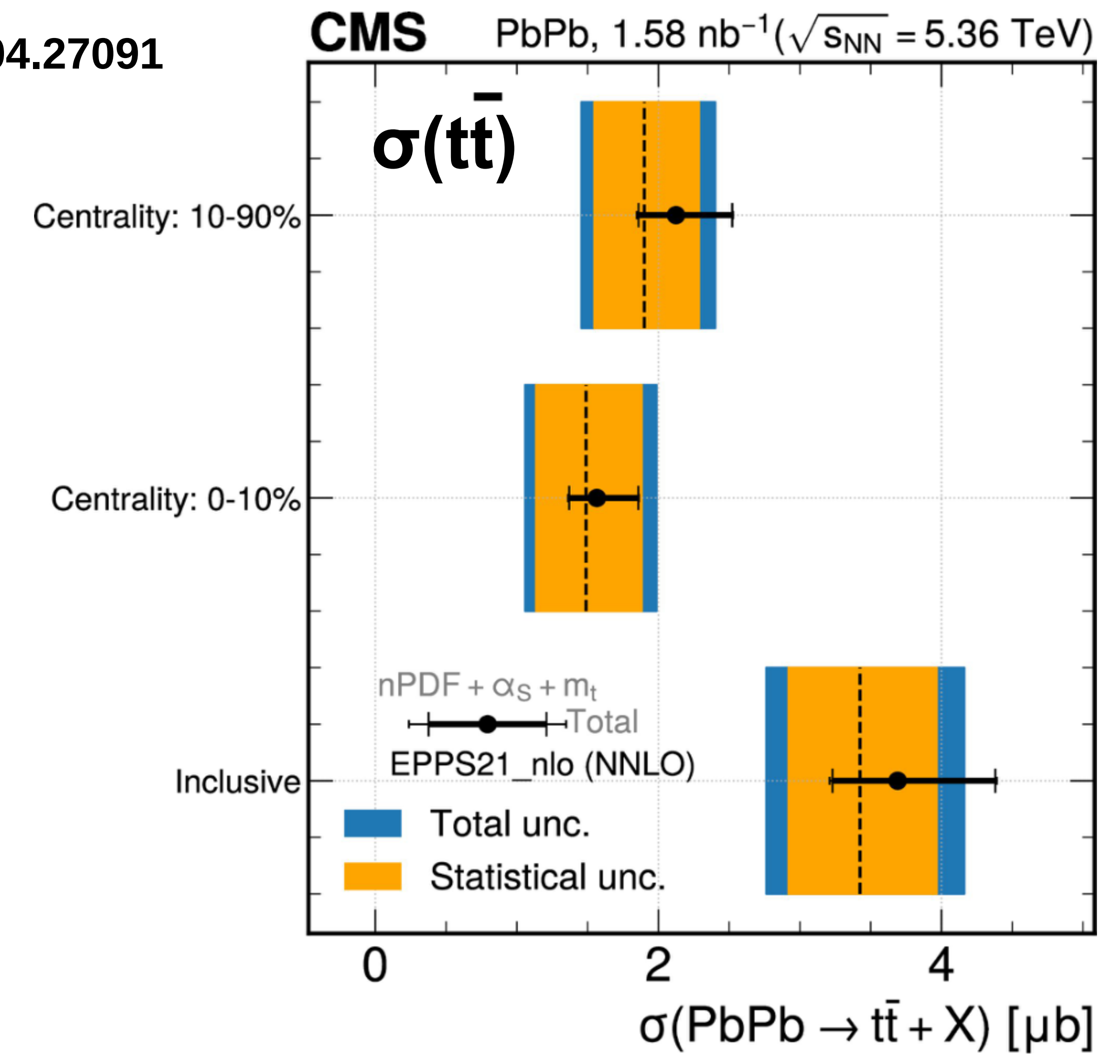
The observed significace exceeds 5σ

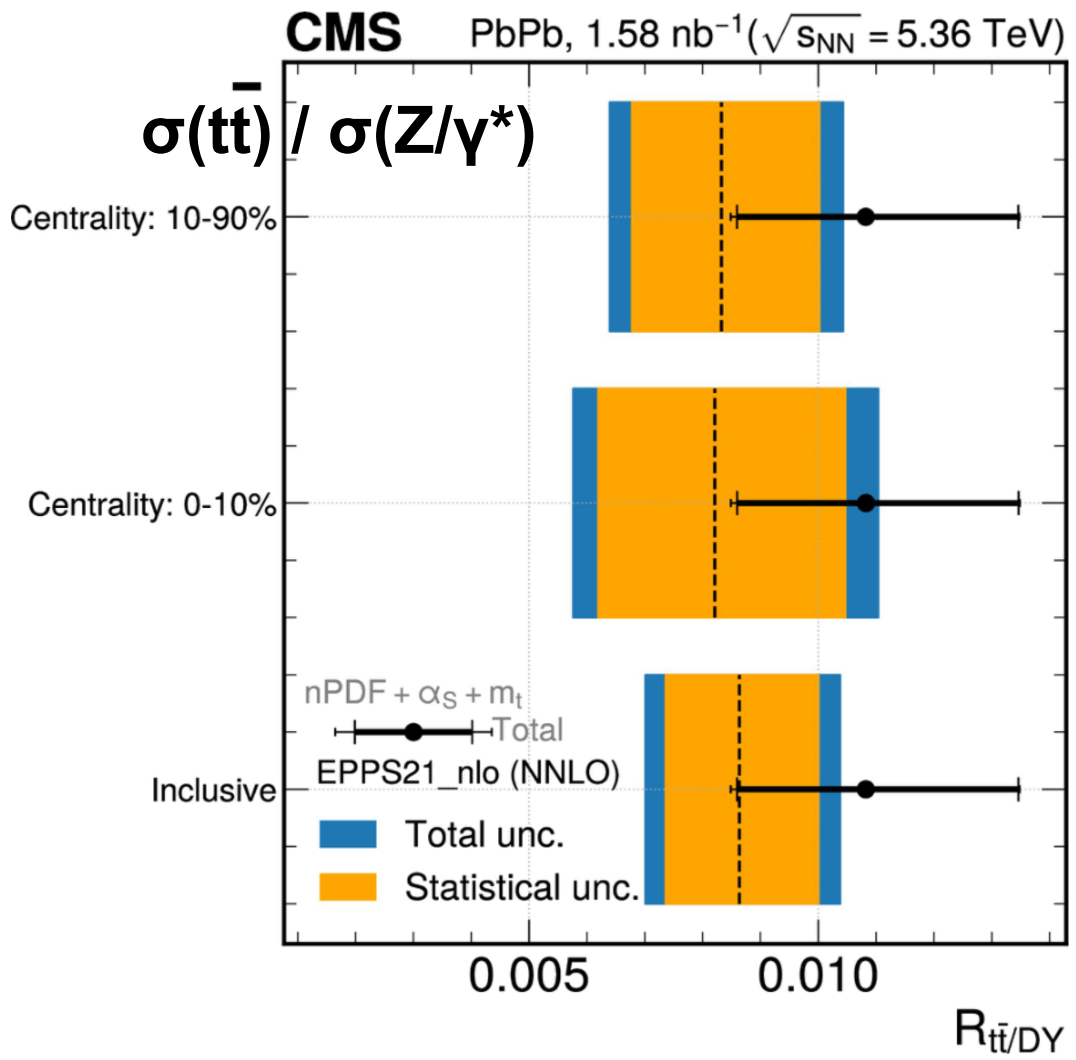
(stat. unc. dominates)

4-5x data on tape!

Production Control: Results vs Centrality for PbPb at 5.36 TeV

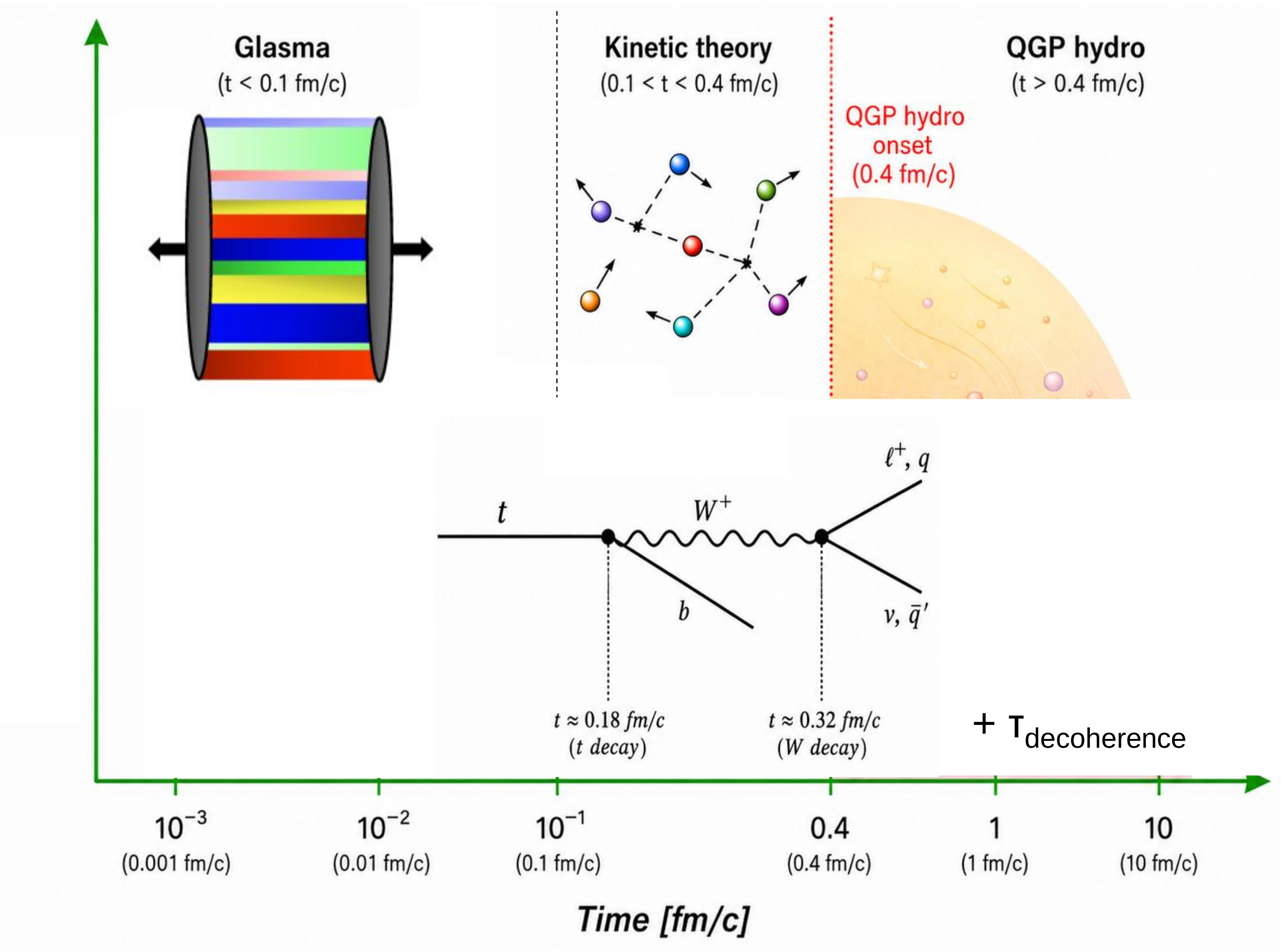
arXiv:2604.27091

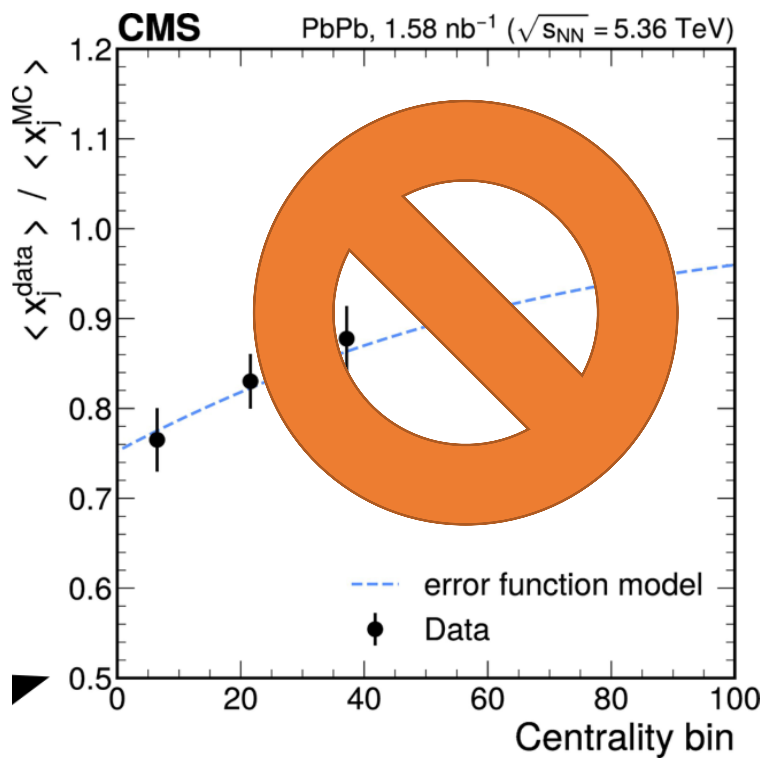




- First centrality differential measurement of the $t\bar{t}$ cross section in PbPb!
- No significant centrality dependence is observed within the current uncertainties

Production Control: $t\bar{t}$ Production





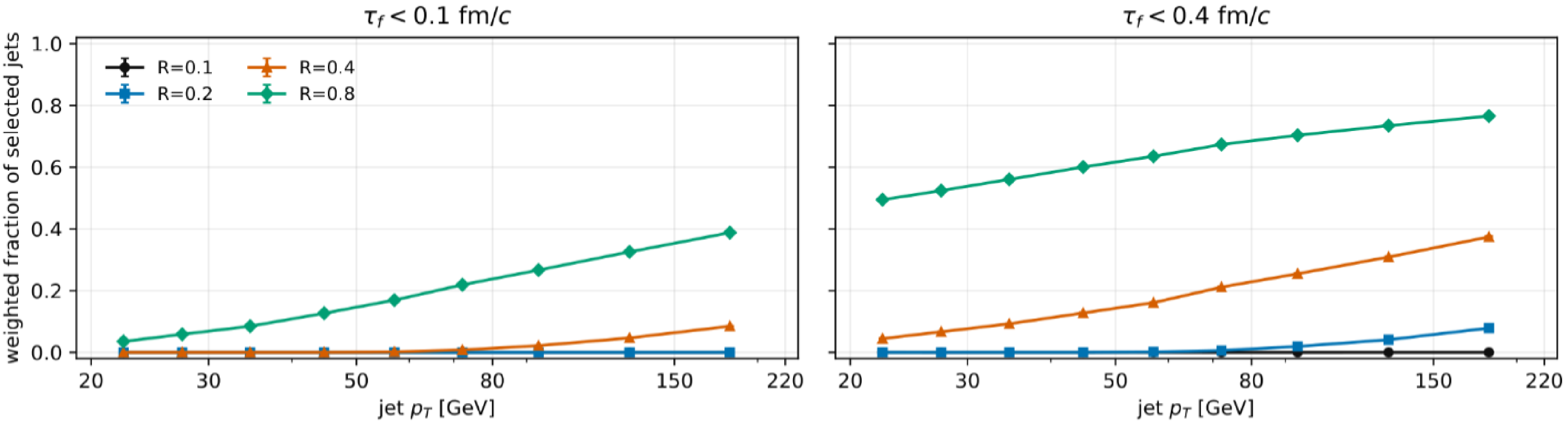
- One could remove the Z+jet correction and use hadronic-W daughter jets as a sensitive probe such as jet counts, m_{jj}, p^{jj}_T …
- Compare to **prompt control**: inclusive b-jets or Boson-tagged jets

Shower Control: Formation Time

Anti-k_T jets with R=0.1, 0.2, 0.4, 0.8. $|\eta|<2$, Recluster with C/A algorithm

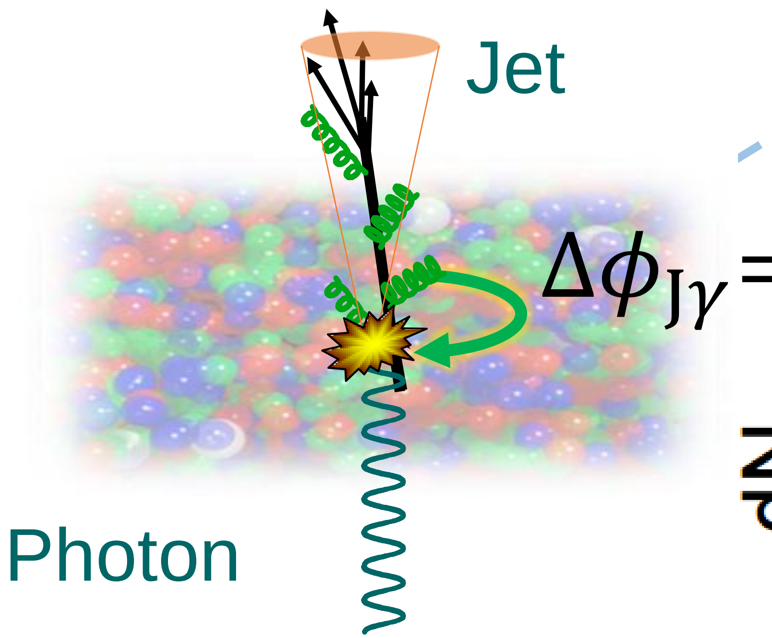
for formation time tagging :

$$\tau_f = \frac{0.19732698 \text{ GeV fm}}{2E_{\text{parent}} z_1 z_2 [1 - \cos(\theta_{12})]}$$

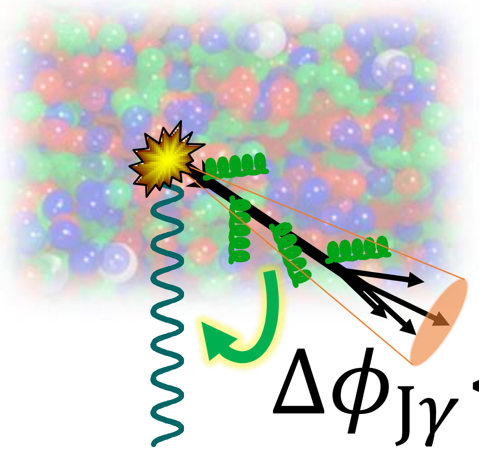


- To access small formation time τ_f jets, we need to use high p_T jet or large area jet.
- The early time momentum broadening of the parton before first splitting will not directly contribute to in-jet observable modification

Shower Control: Photon-Jet Angular Correlation

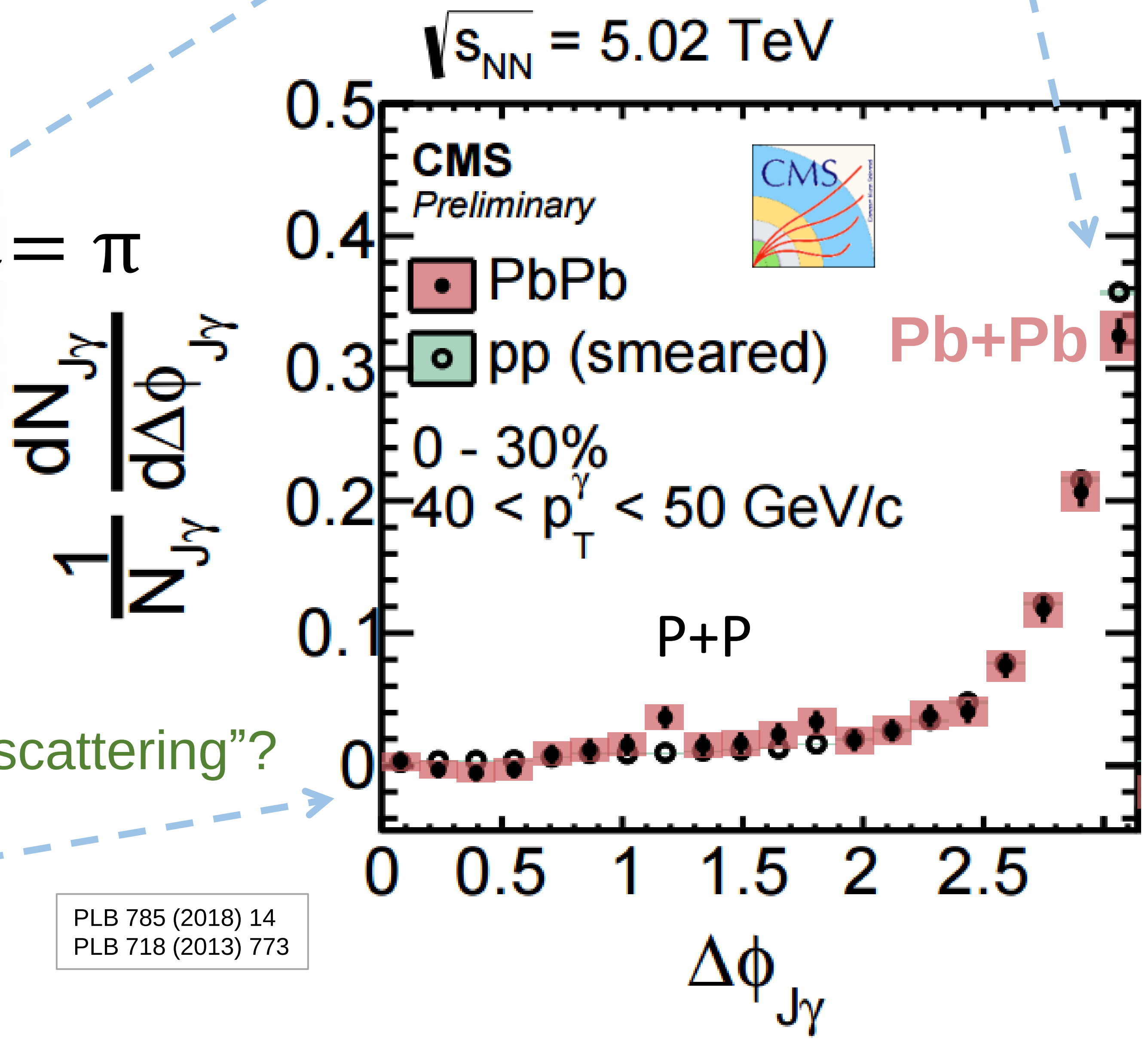


$\Delta\phi_{J\gamma} = \pi$

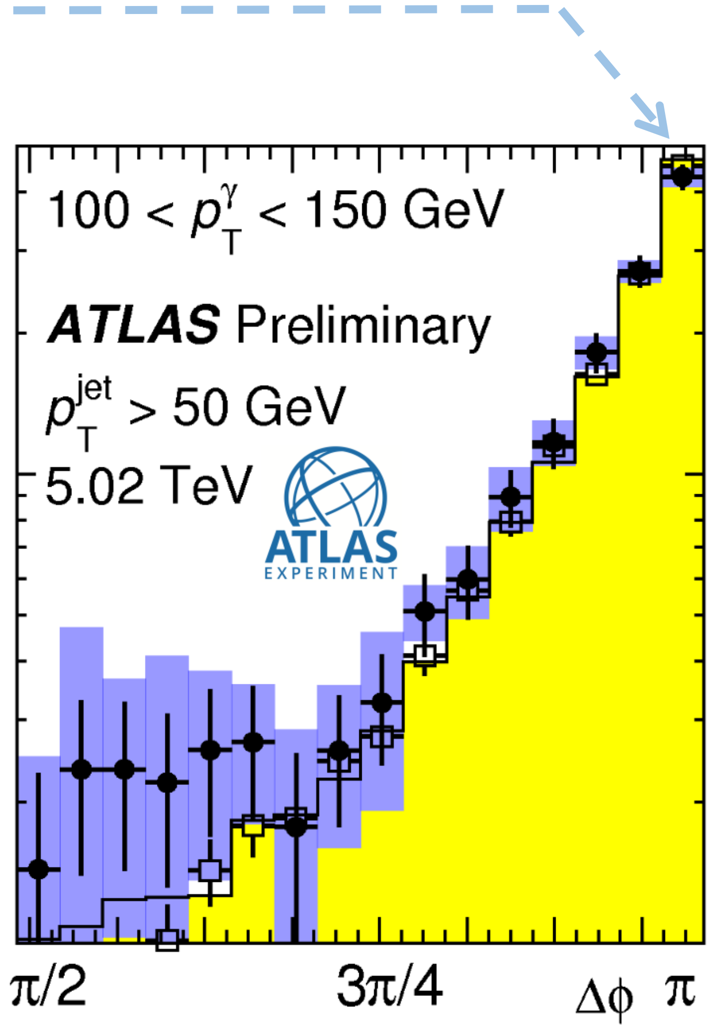


"Backscattering"?

$\Delta\phi_{J\gamma} < \frac{\pi}{2}$



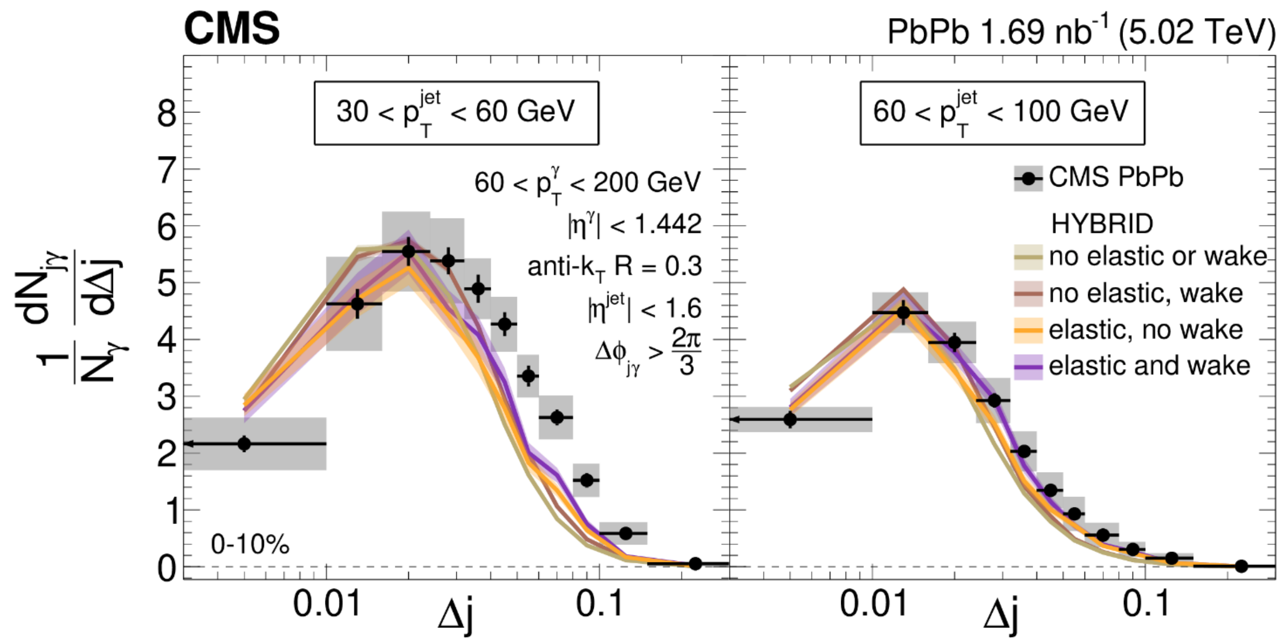
PLB 785 (2018) 14
PLB 718 (2013) 773

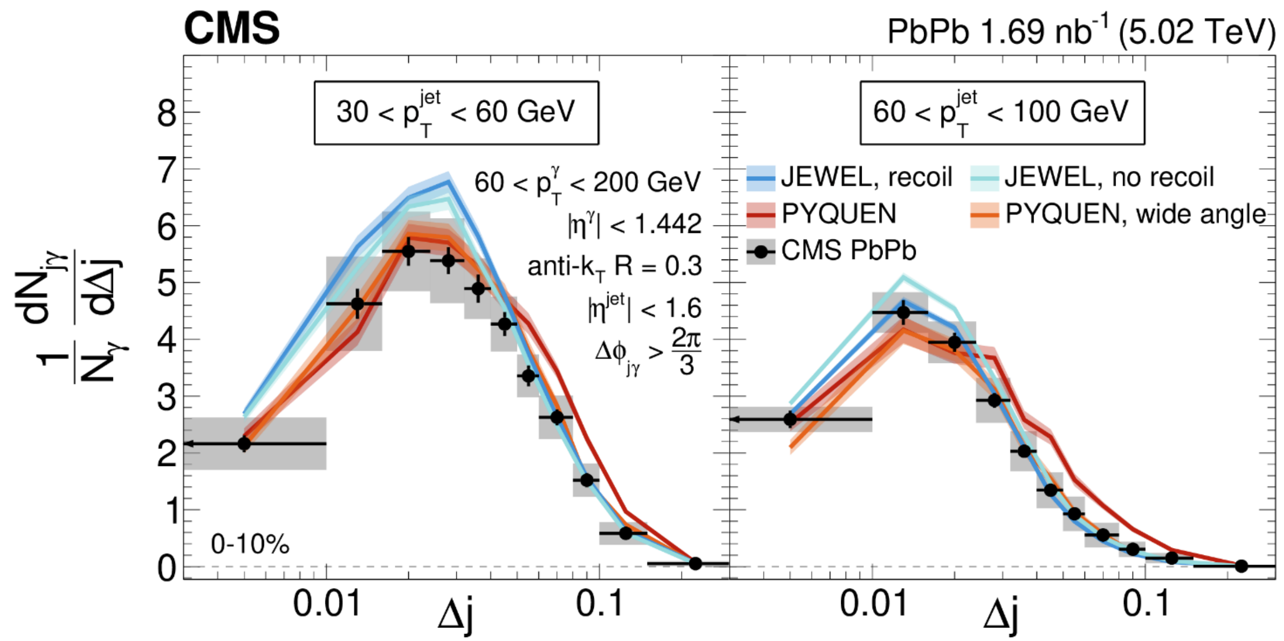


Is there room for large p_T kick? Disfavor very large random transverse kicks

Shower Control: Axis Decorrelation Variable

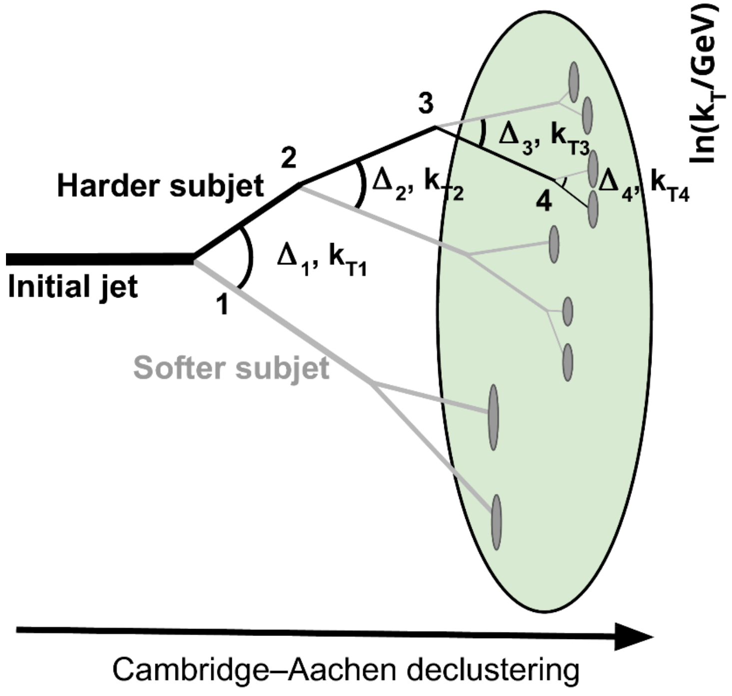
- Jet axis decorrelation Δj, between WTA and E-scheme, has been measured in photon-tagged jets.
- Relatively insensitive to recoil or medium response effect
- Observables: Extension to work on more differential measurements (correlate with beam axis). Study the radius and momentum dependence

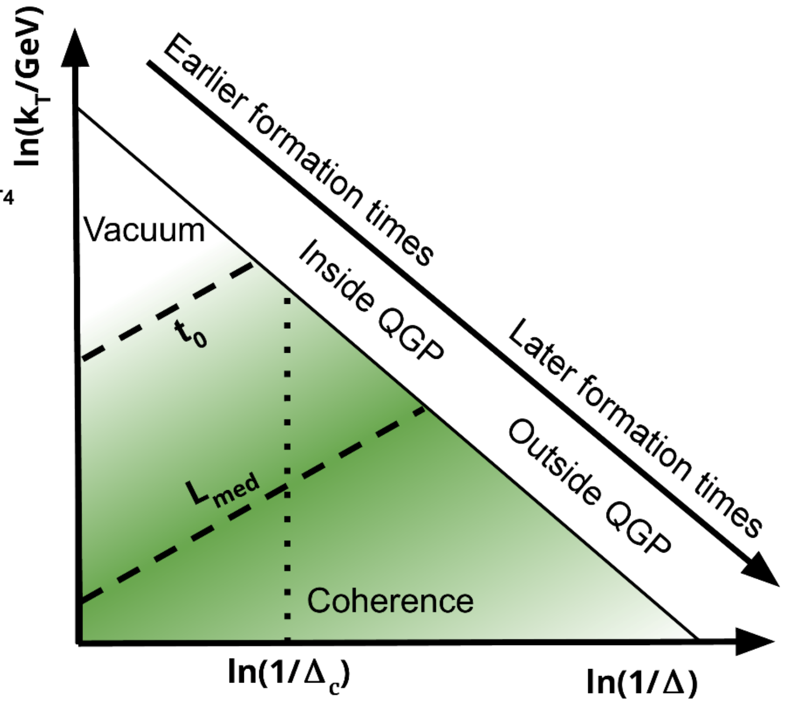


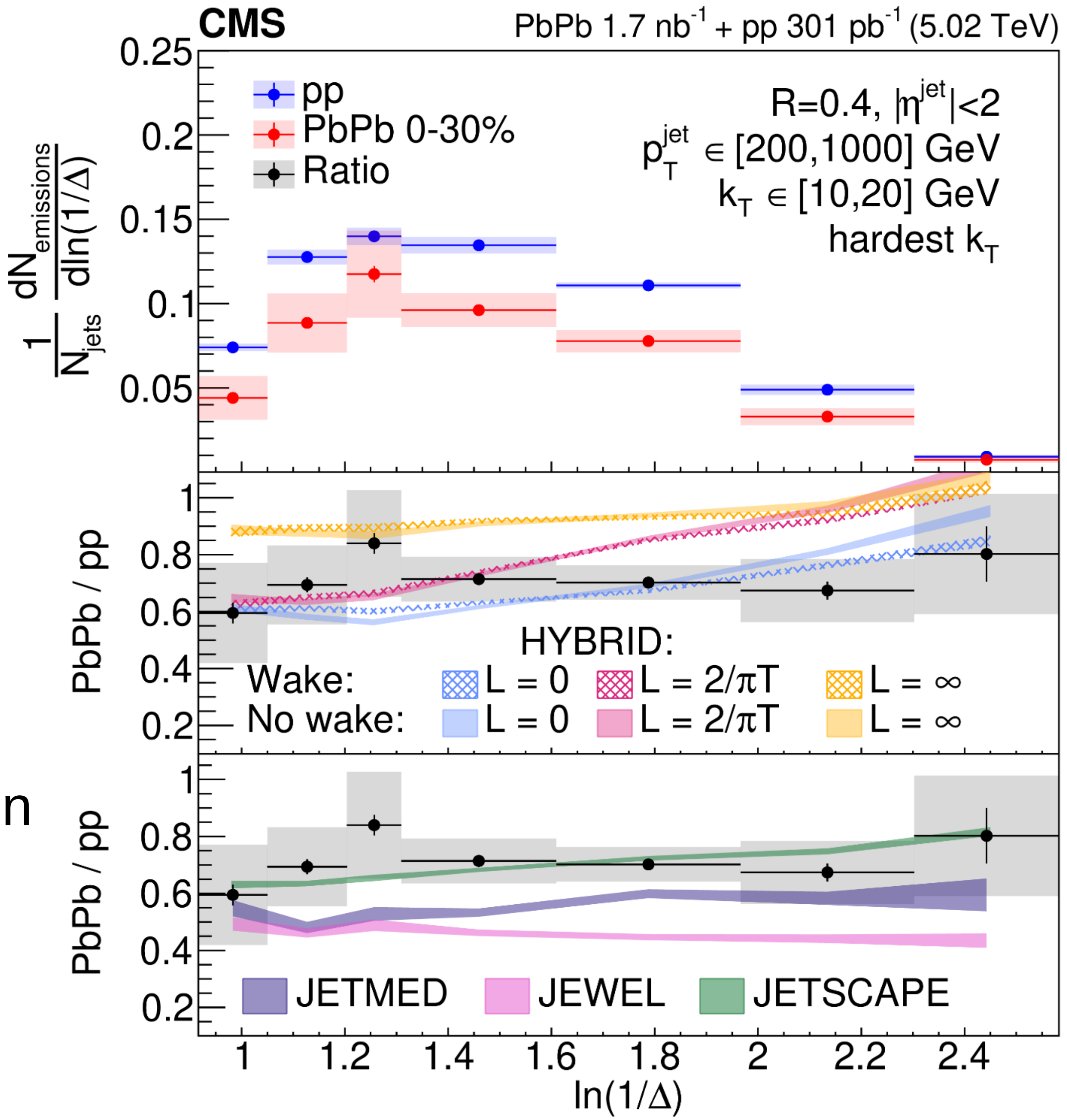


arXiv: 2602.18279
Submitted to PLB

Shower Control: Largest k_T selection







- Angular distribution Δ of the large k_T jet has been measured in PbPb
- Within uncertainties, no significant angular modification is observed for the high-kT emission studied, **consistent with an early vacuum-like origin**
- Observable: Use the largest k_T selection to compare jets with different hardest splitting

arXiv:2602.09271, submitted to PRL

What Have We Learned from Experimental Data?

- Existing jet-hadron and dihadron broadening is striking. However, selection bias, flow and medium response prevent a unique Glasma interpretation
- Experimental controls become possible:
  - beam versus azimuth, prompt versus delayed probes, before versus after splitting and OO vs. PbPb
- Current boson-jet data **disfavor extremely large net random kicks**, but still allow a short-lived early broadening stage

Summary

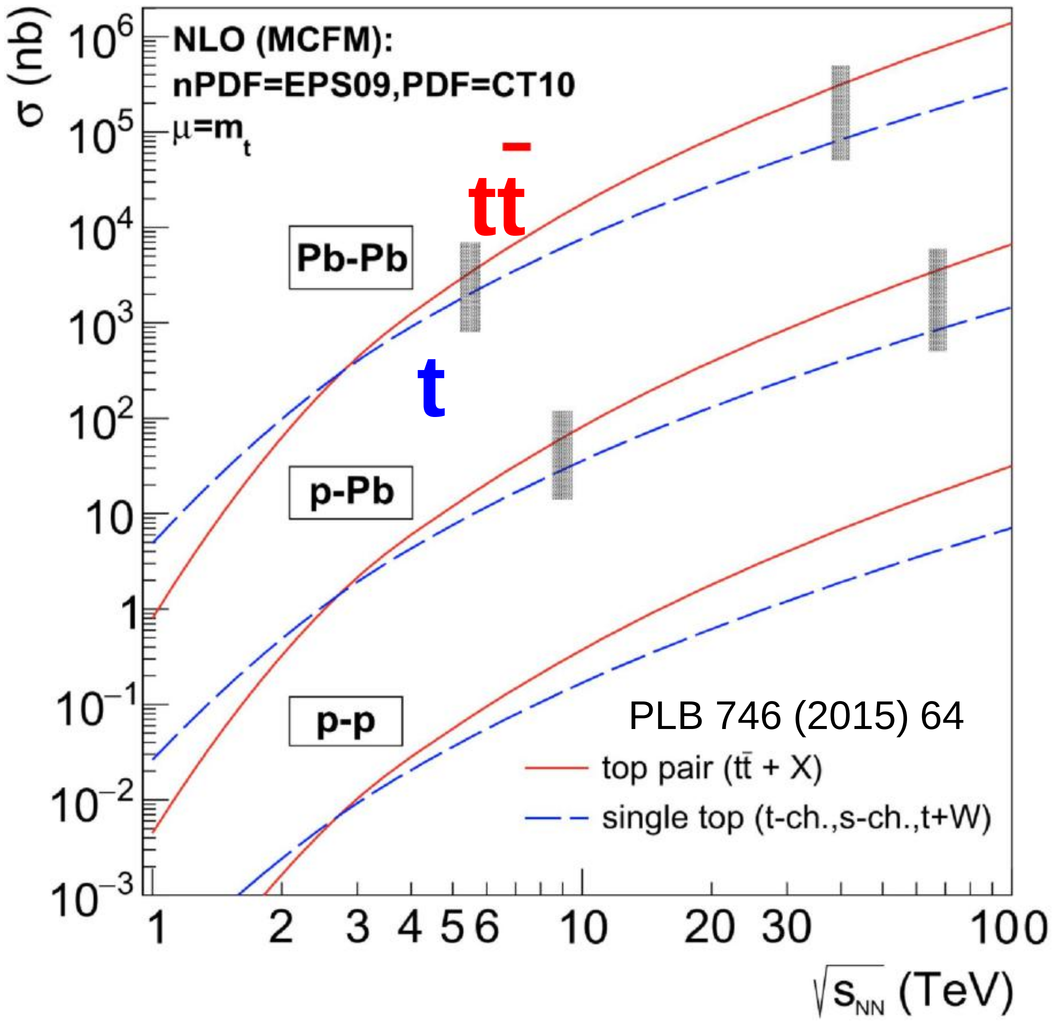
- Early stages require better **experimental control** on direction, production time, shower time and system lifetime.
  - Direction Control: photon/Z-tagged recoil jet + WTA axis + energy-weighted C_{ab} or beam-oriented EEC.
  - Timing Control: prompt photon/Z jets vs delayed hadronic-W jets from $t\bar{t}$.
  - Shower Control: Large k_T jet and Photon-jet acoplanarity already constrain very large random early p_T kicks.
  - OO vs PbPb: shorter hydro phase in OO

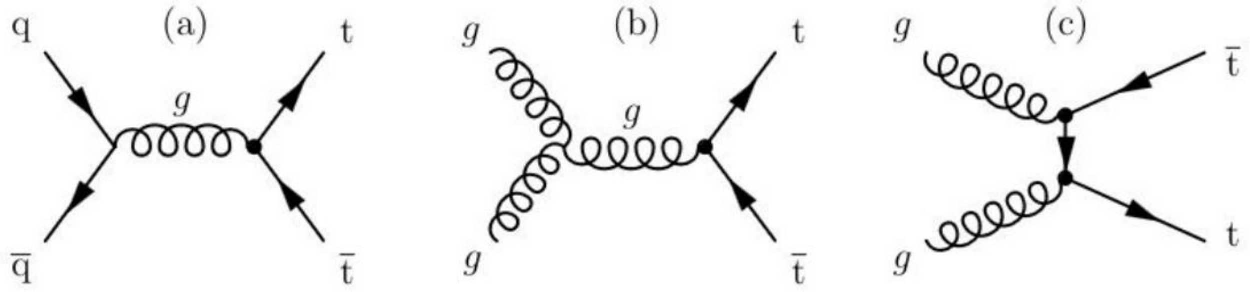
- Possible path forward: **OO/PbPb scans** + improved phenomenology to separate Glasma, kinetic pre-equilibrium and hydrodynamics-stage energy loss and broadening

Backup Slides

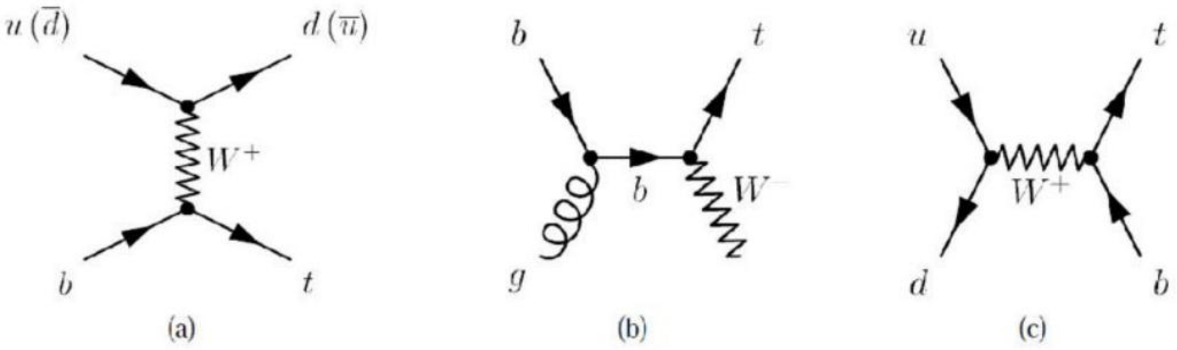
Top quark production in heavy ion

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





Single top production diagrams:



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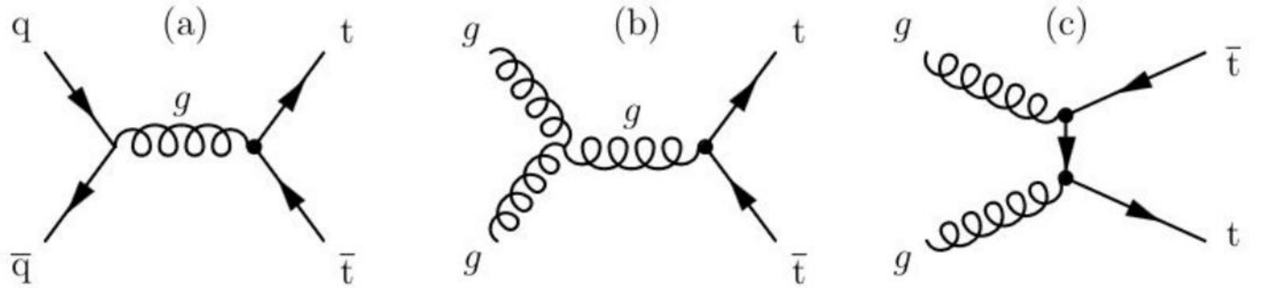
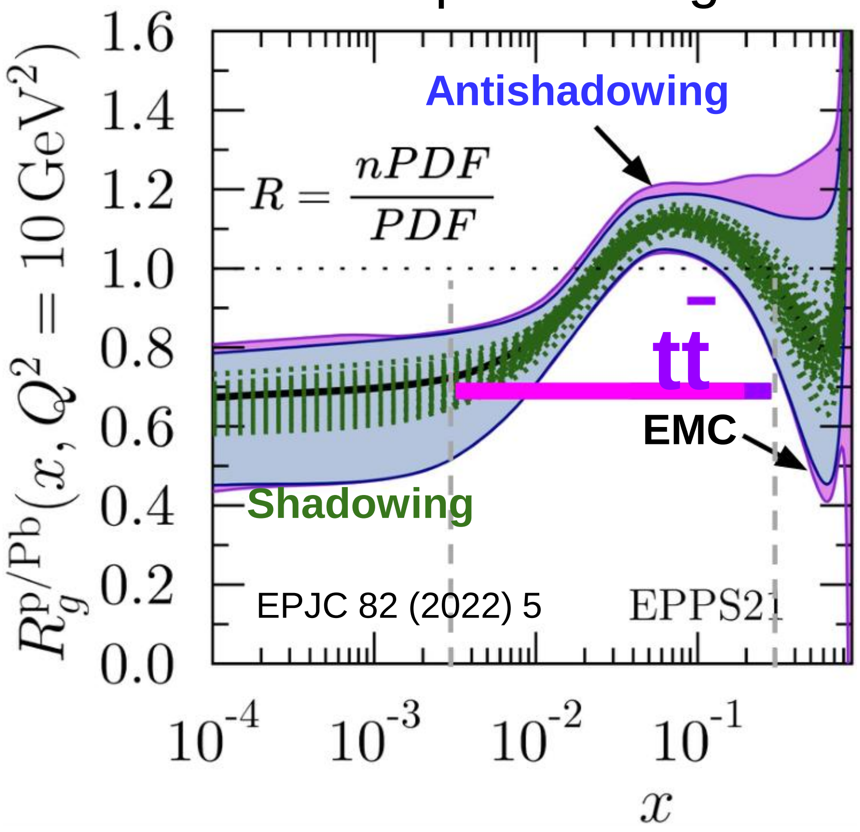
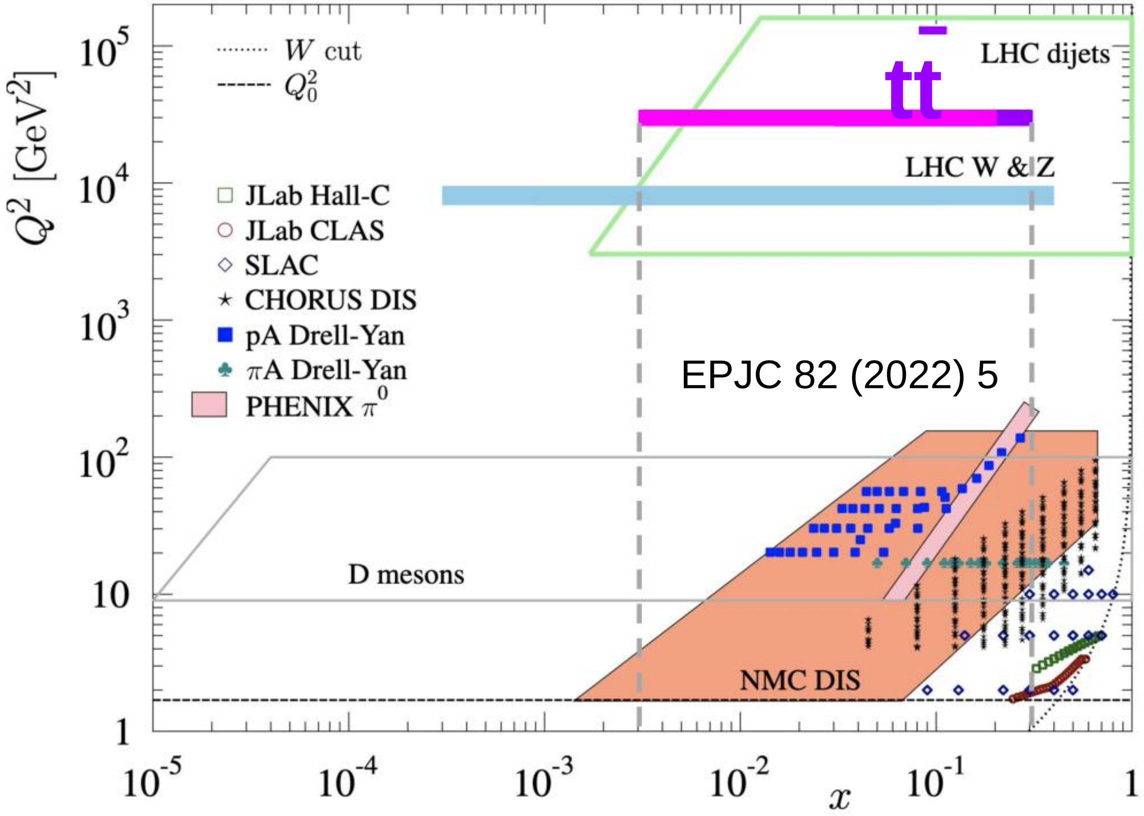


The production of top quarks is sensitive to gluon PDF:

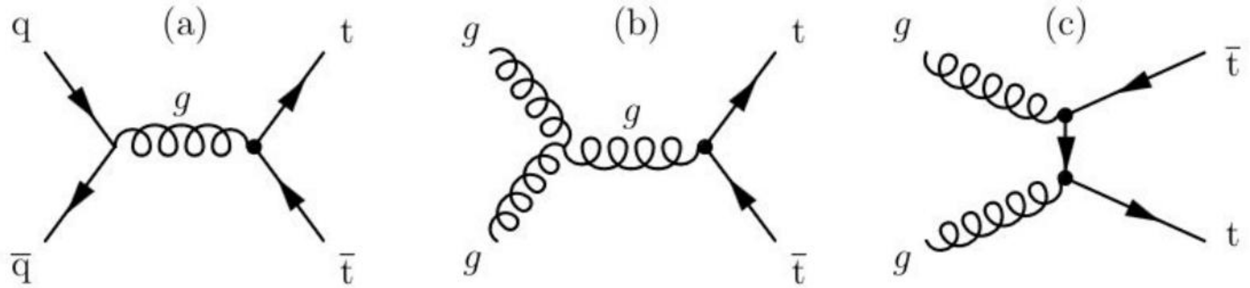
- in HI collisions can probe Pb gluon density at high virtualities.





Top pair production in heavy ion

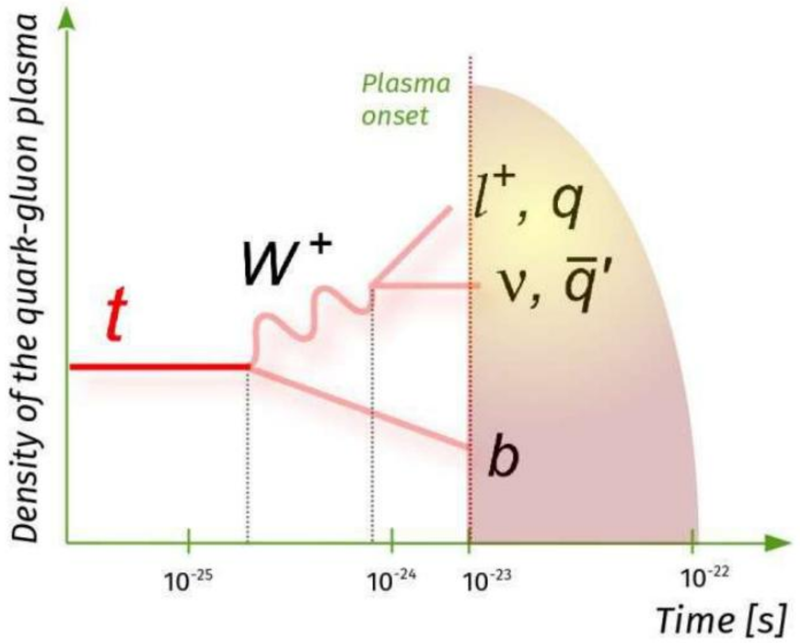
Top quark mainly produced in pairs via QCD:



The production of top quarks is sensitive to gluon PDF:

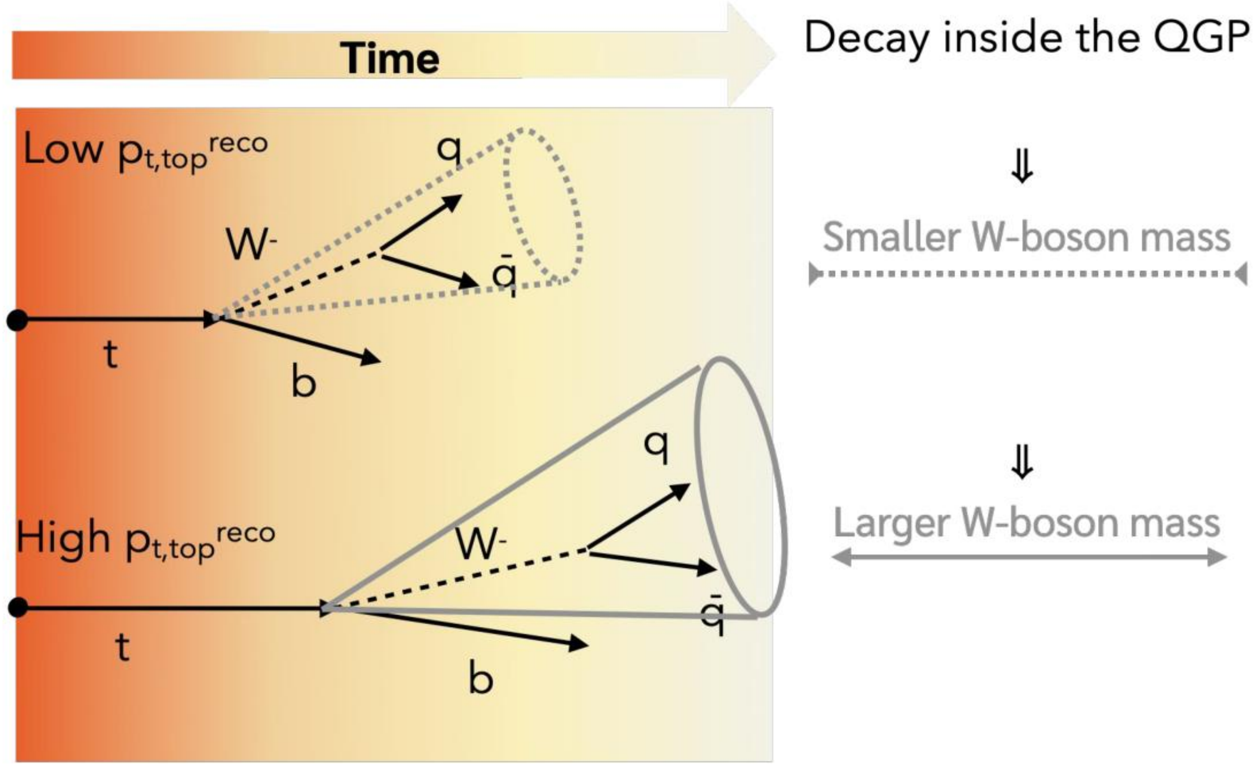
- in HI collisions can probe Pb gluon density at high virtualities.

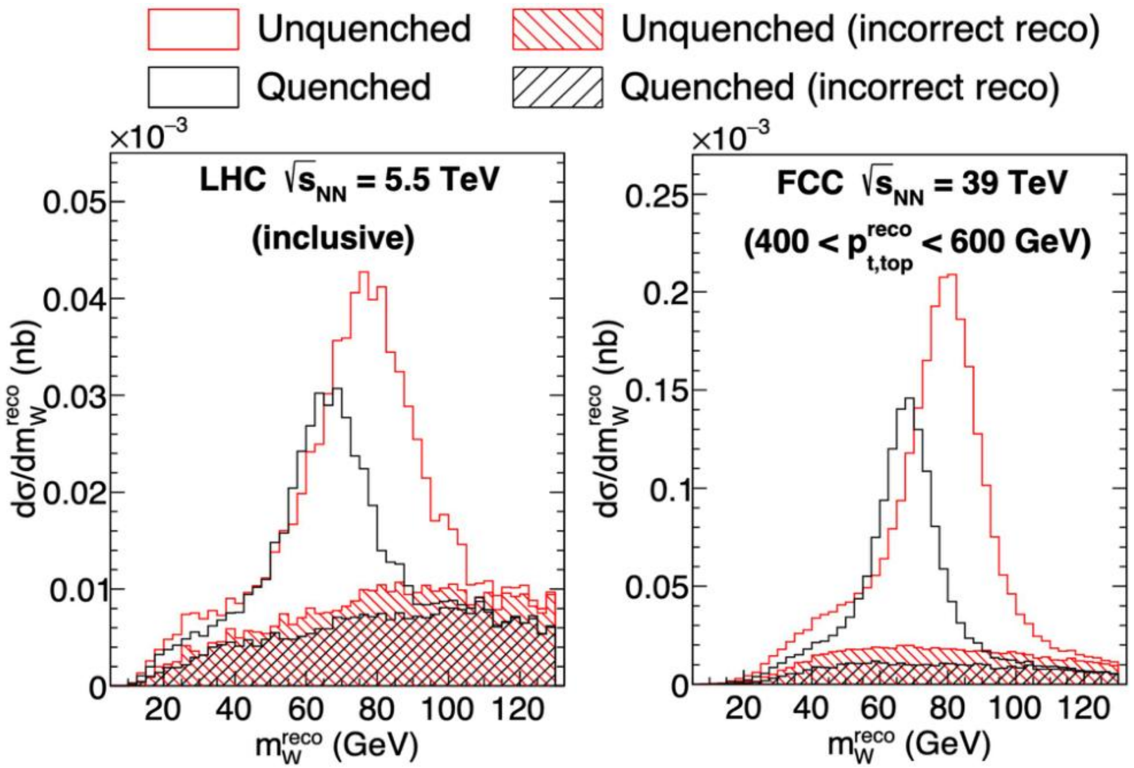
Top quark predominantly decays to a W boson and b quark (before QGP is formed):



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)

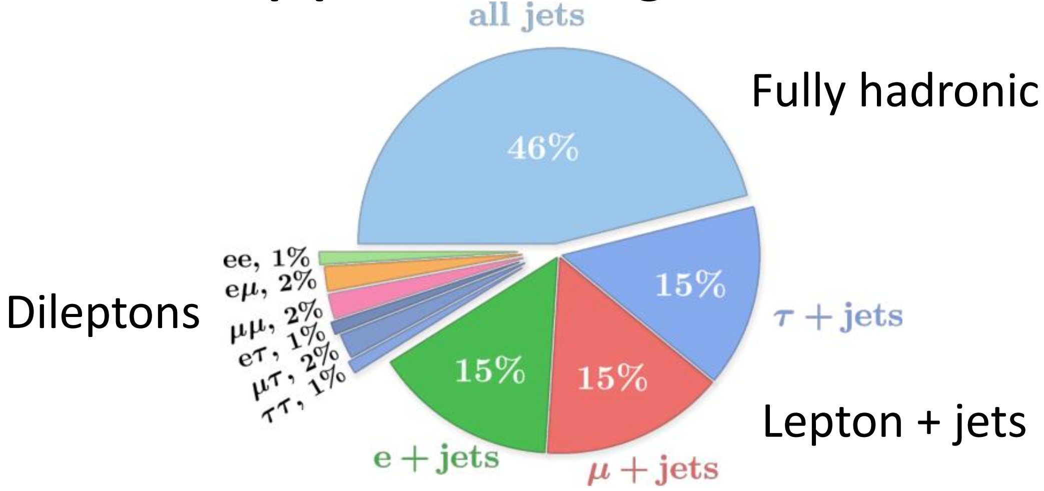
Top pair measurements in nuclear collisions

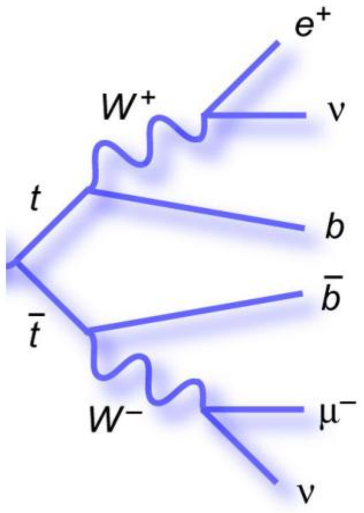
Feasibility for pPb/PbPb

2015

PLB 746 (2015) 64

Top pair branching fractions





Top pair measurements in nuclear collisions

Feasibility for pPb/PbPb

2015 — PLB 746 (2015) 64

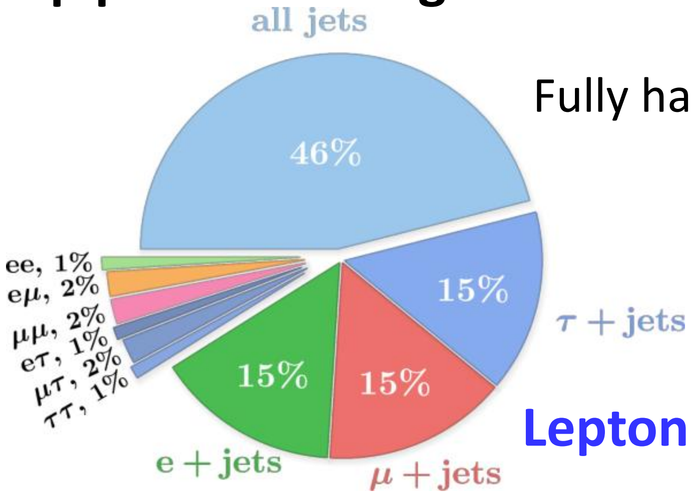
2017 — **PRL 119 (2017) 242001**

CMS observation in **pPb 8.16 TeV**

2024 — **JHEP 11 (2024) 101**

ATLAS observation in **pPb 8.16 TeV**

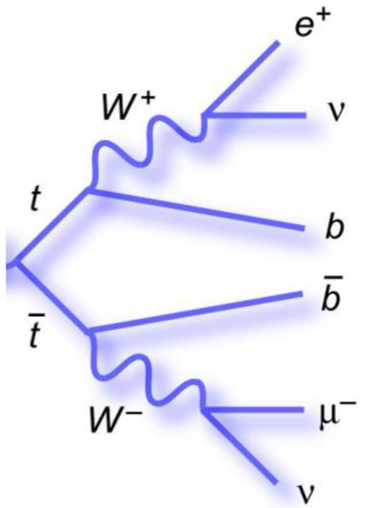
Top pair branching fractions



Fully hadronic

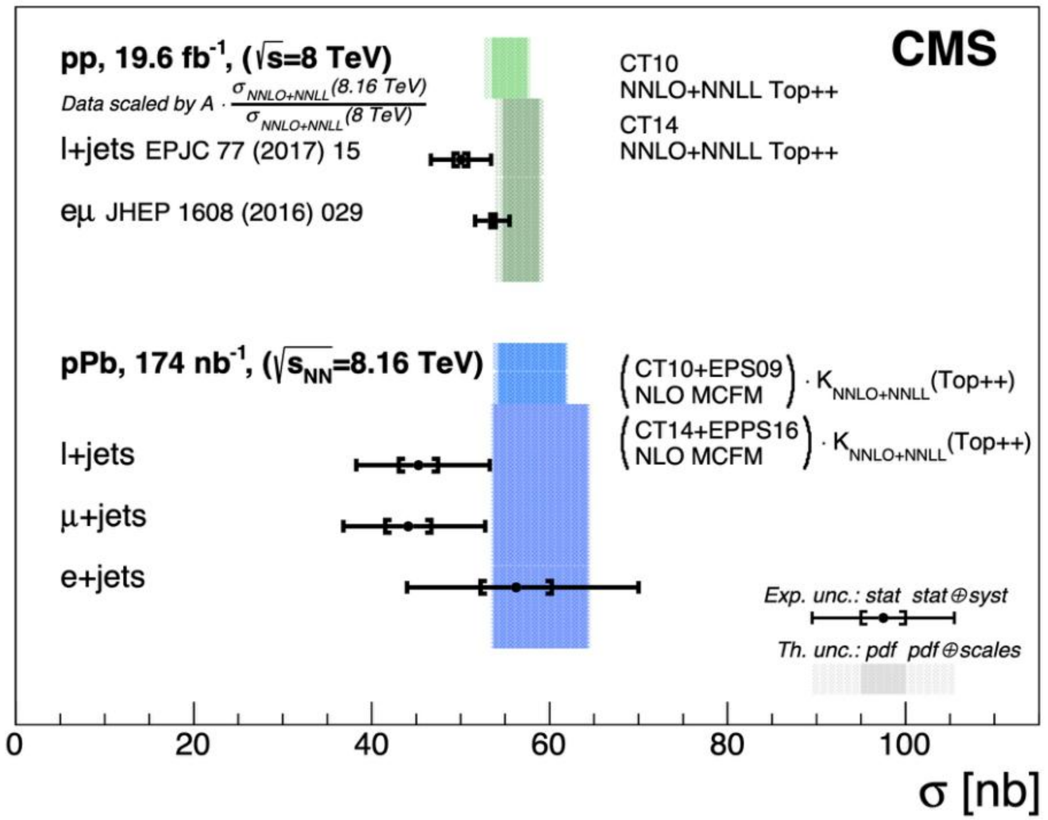
Dileptons

Lepton + jets

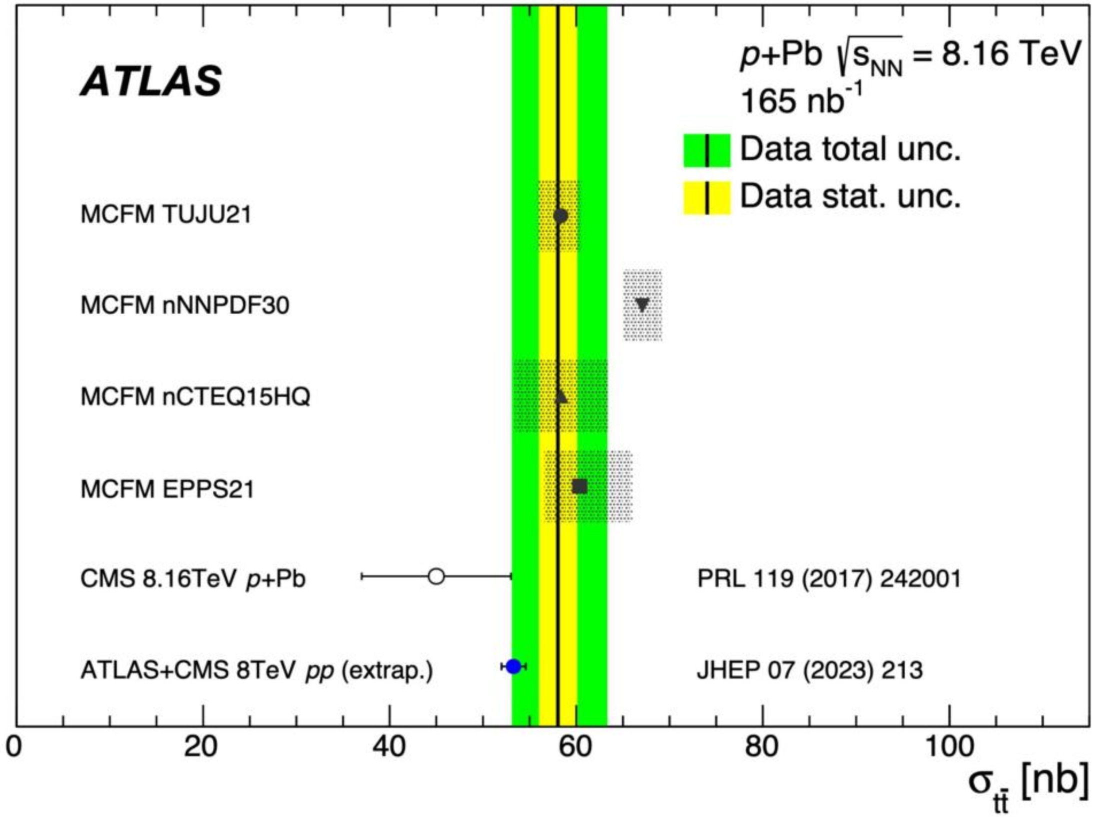


Top pair production in pPb collisions

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 — 2015 — PLB 746 (2015) 64

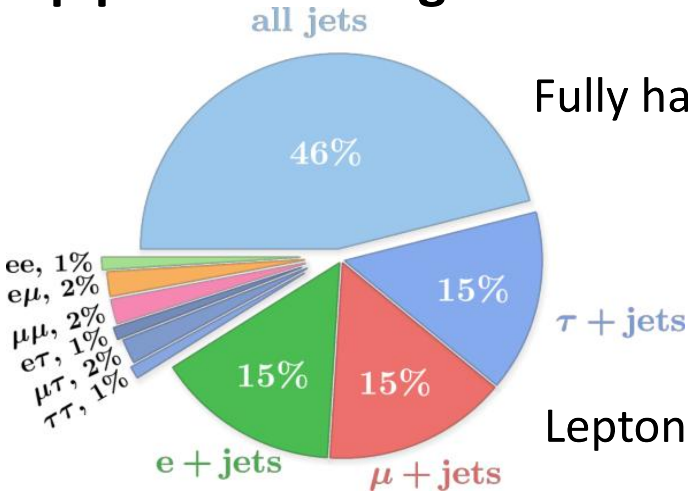
2017 — PRL 119 (2017) 242001 — CMS observation in pPb 8.16 TeV

2020 — **PRL 125 (2020) 222001** — **CMS** evidence in **PbPb 5.02 TeV**

2024 — JHEP 11 (2024) 101 — ATLAS observation in pPb 8.16 TeV

2025 — **PRL 134 (2025) 142301** — **ATLAS** observation in **PbPb 5.02 TeV**

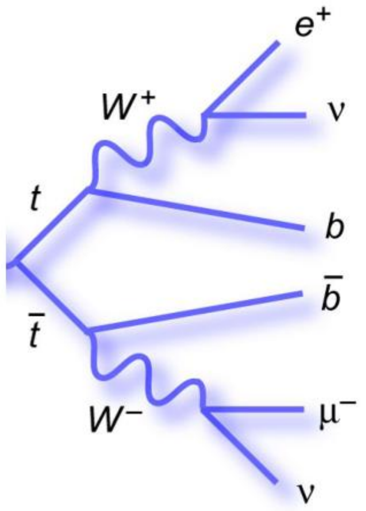
Top pair branching fractions



Fully hadronic

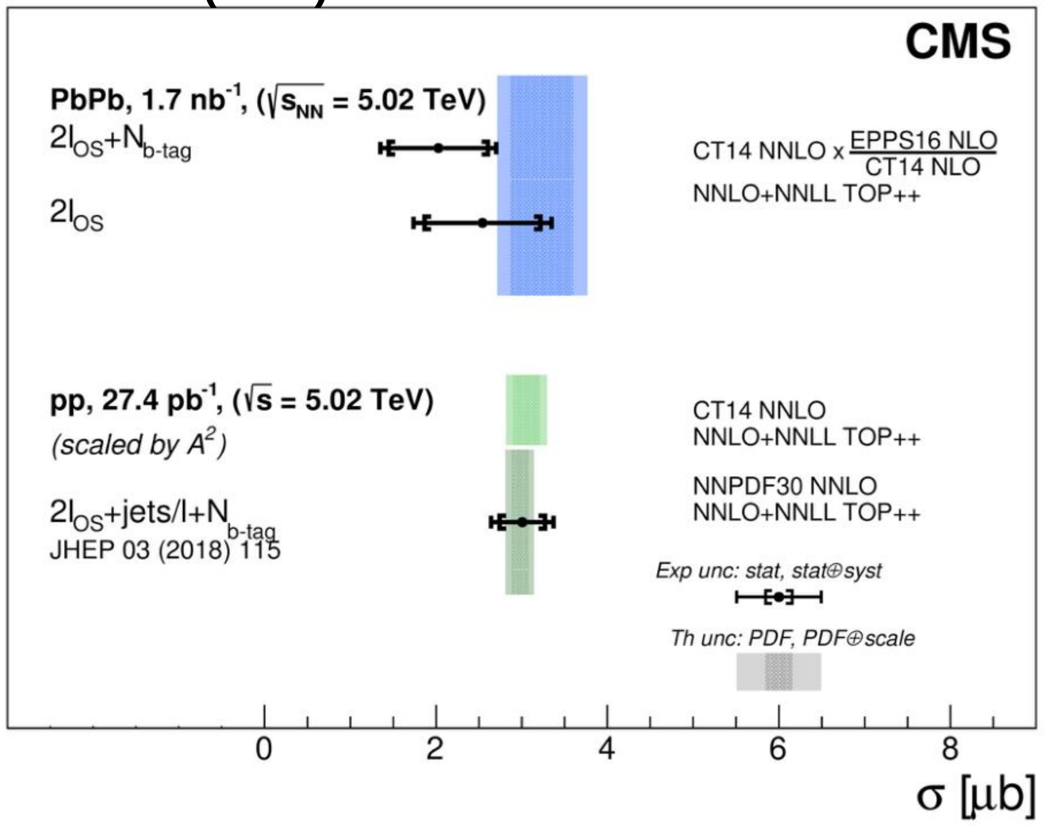
Dileptons

Lepton + jets

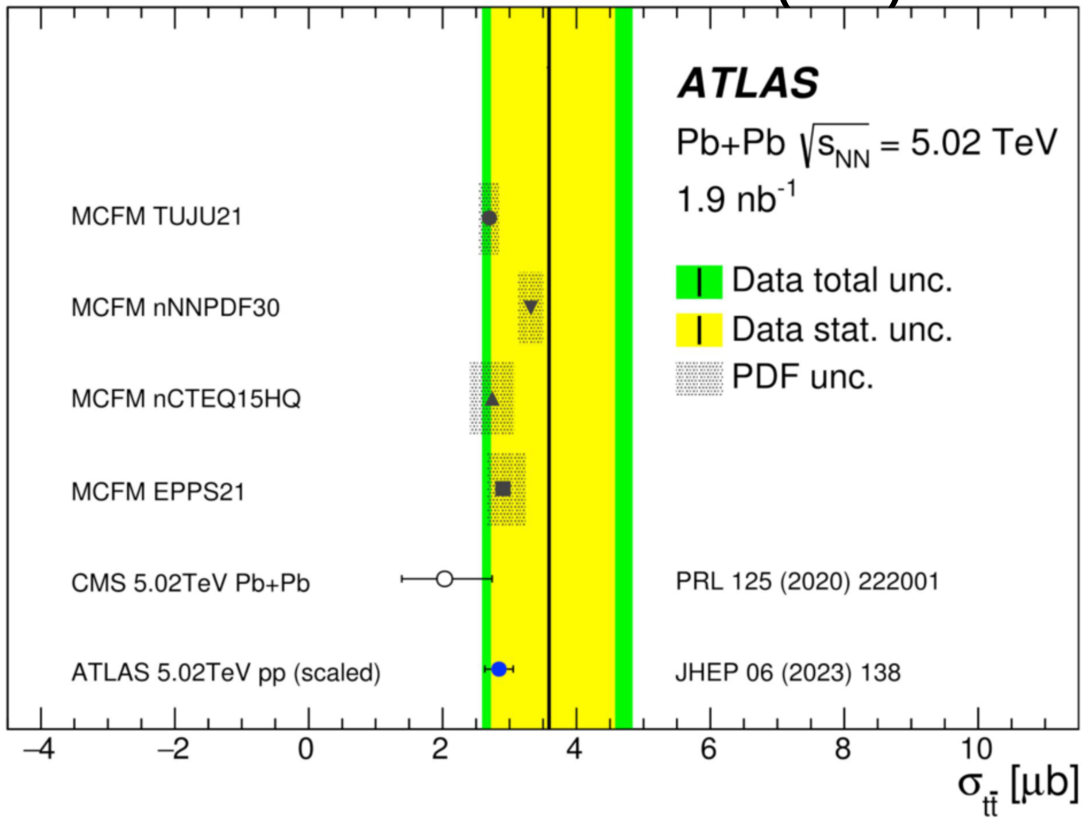


Top pair production in PbPb collisions

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
PRL 125 (2020) 222001

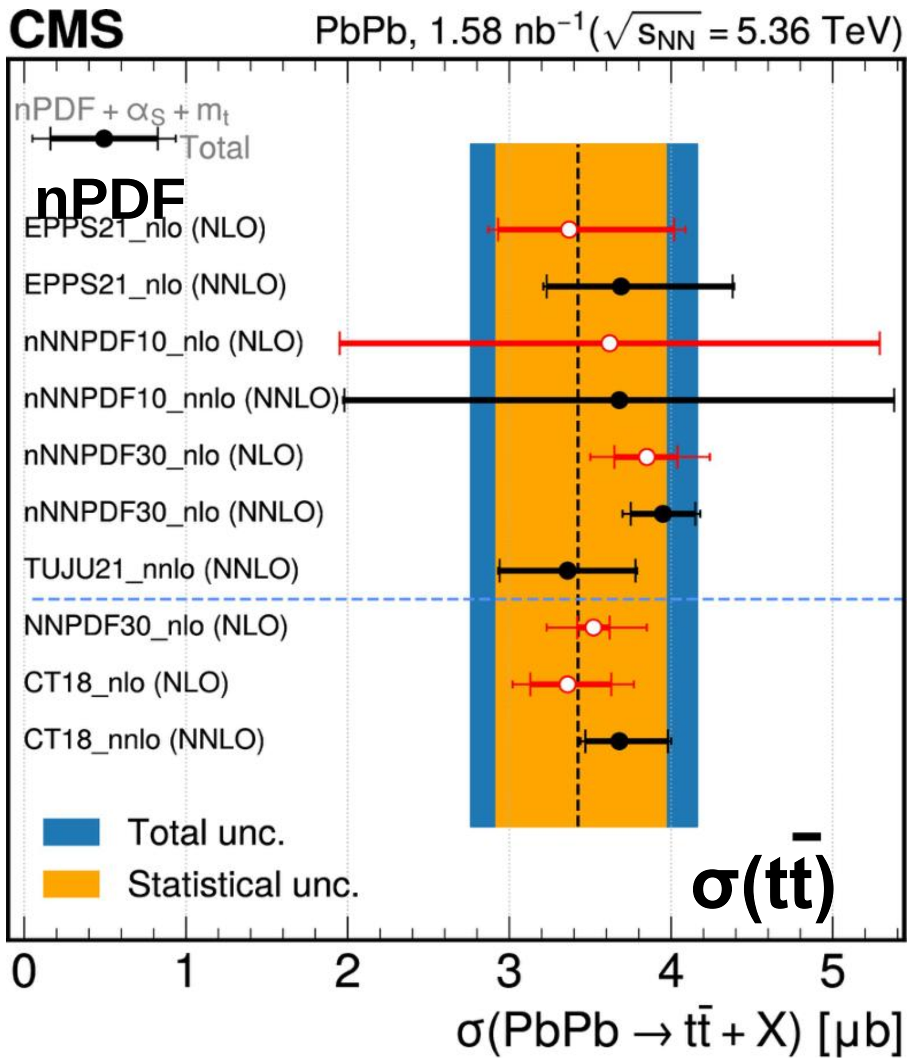
2024
JHEP 11 (2024) 101
ATLAS observation in pPb 8.16 TeV

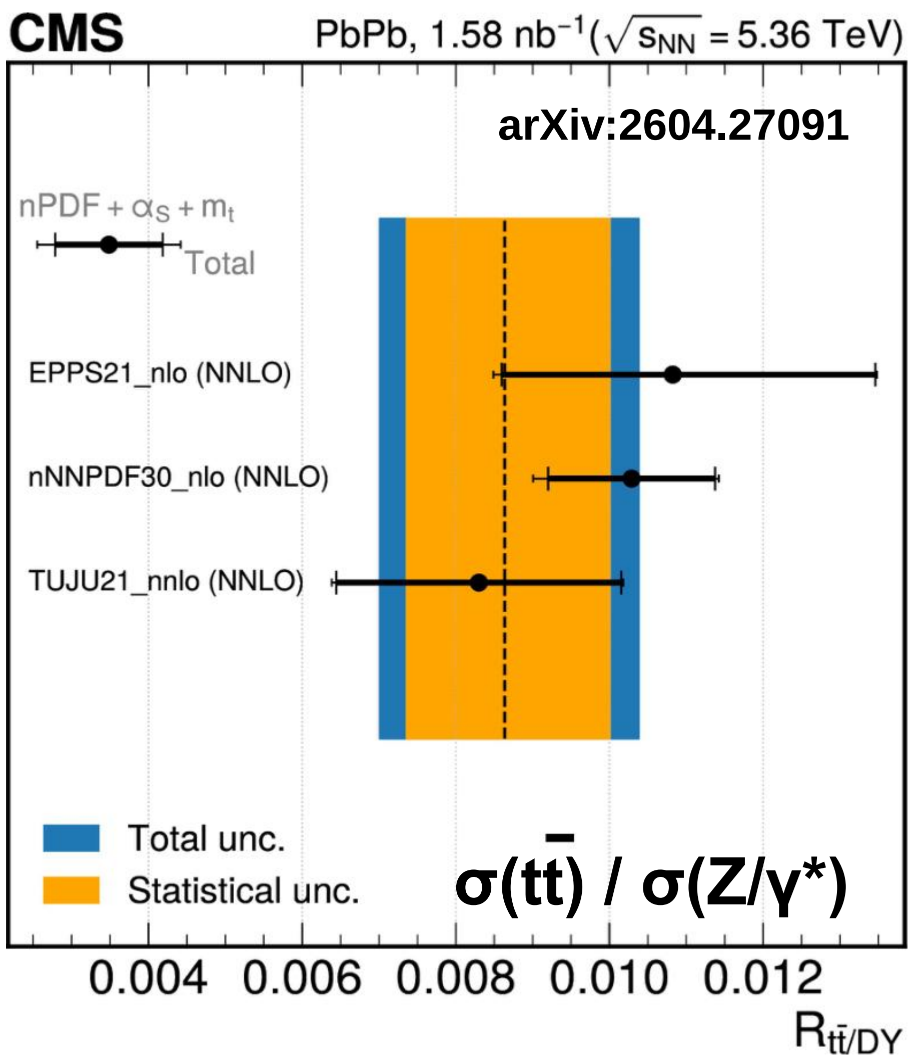
ATLAS observation in PbPb 5.02 TeV
2025
PRL 134 (2025) 142301

CMS observation in **PbPb 5.36 TeV**
2026
arXiv:2604.27091

- Run 2 data established feasibility and observation.

Comparison with theory for PbPb at 5.36 TeV





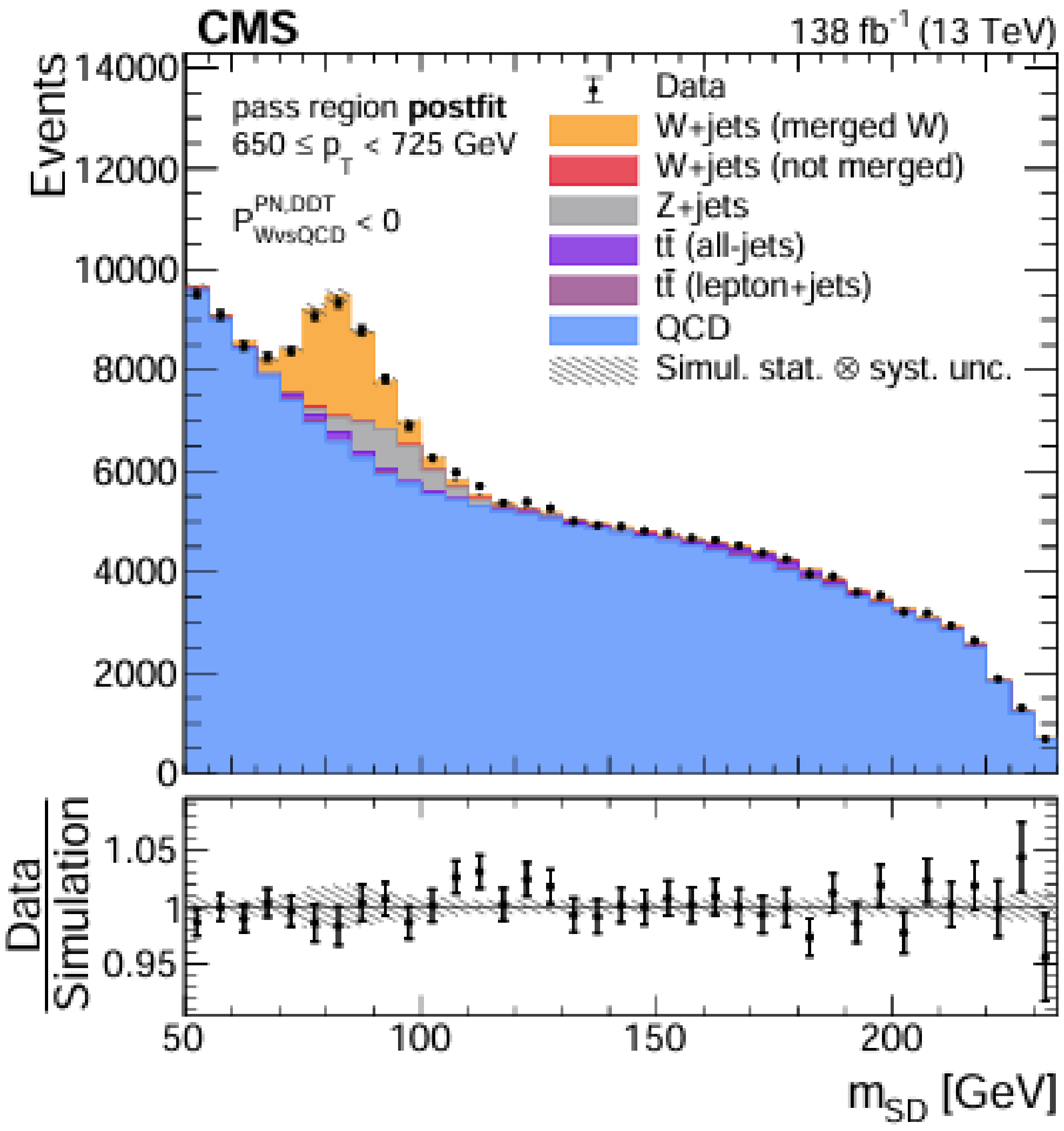
Good agreement between nPDF calculations and measured σ(tt) and σ(tt)/σ(Z/γ*).

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

W Jet Mass

pp benchmark at 13 TeV (**JHEP 07 (2026) 054**)

W jet mass (R=0.8) remain difficult due to the limited PbPb statistics



Shower Control: Formation Time

Generator level in jet splitting using PYTHIA generator shower tree

$t_{split} = \sum 2\hbar c E/Q^2$