Hot Jets: Advancing the Understanding of High-Temperature QCD with Jets

Search for Jet Quenching in High-Multiplicity Proton-Lead Collisions at LHC

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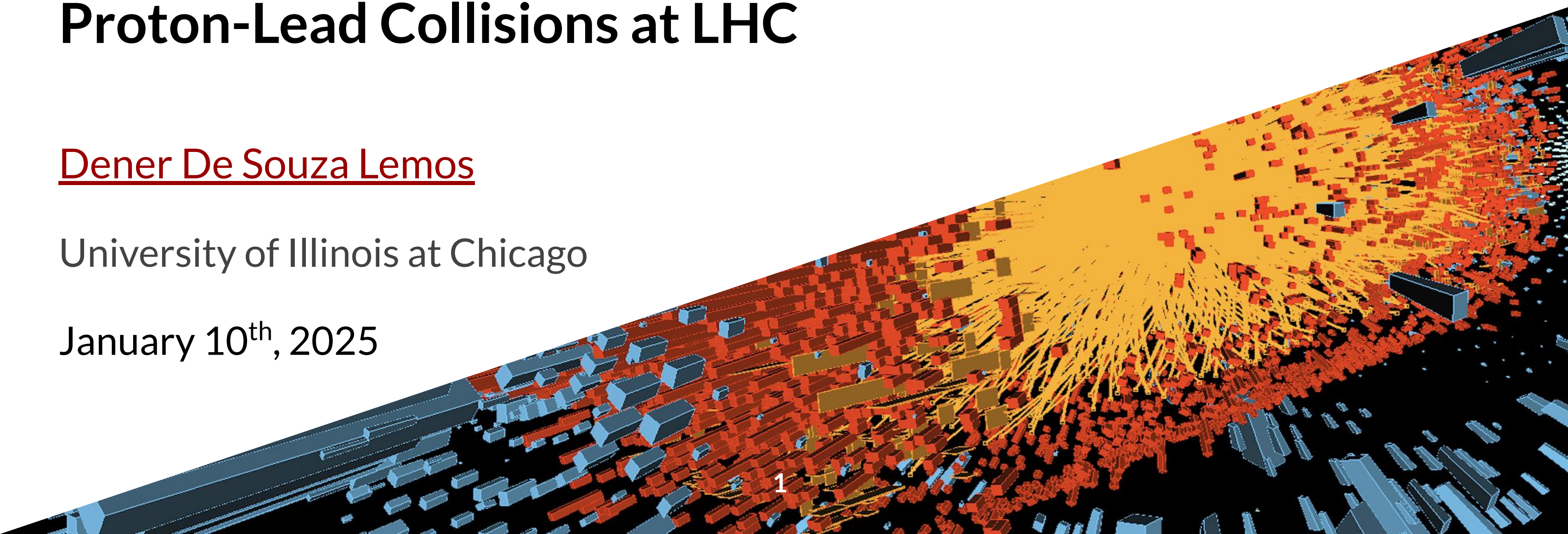
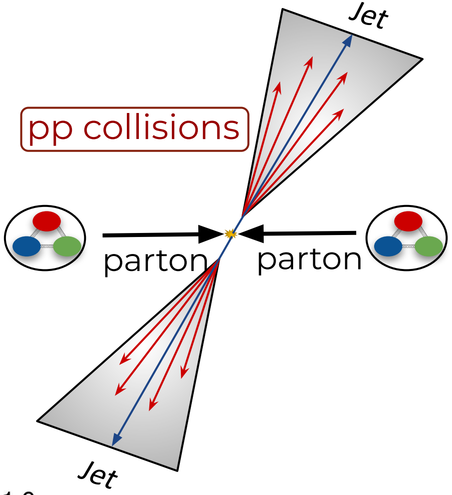
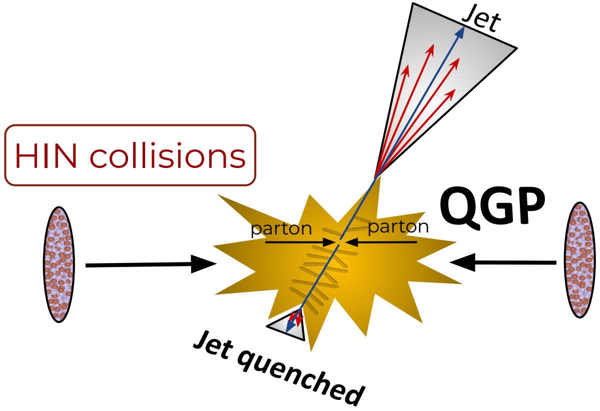
University of Illinois at Chicago

January 10th, 2025

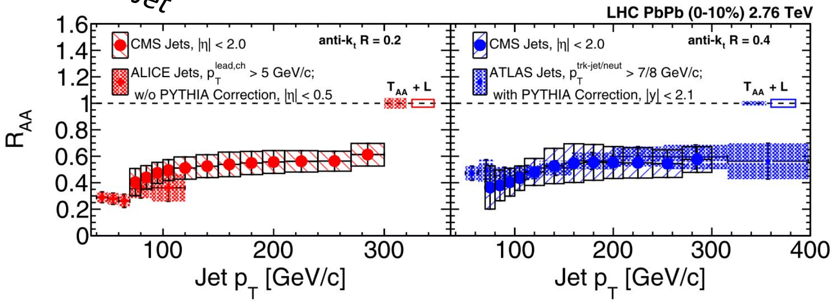


Measurements of jet quenching



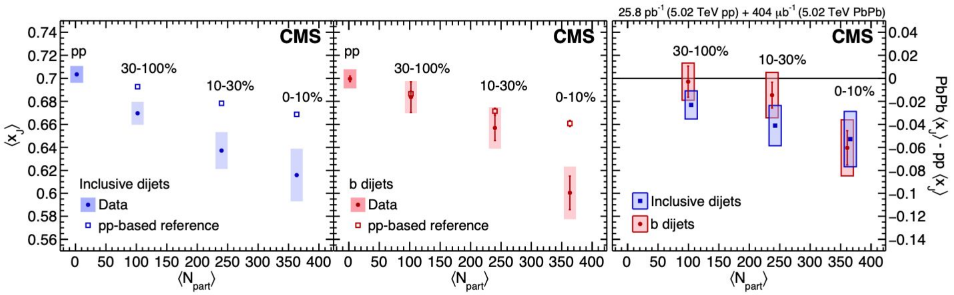


pp used as reference



$$R_{AA} = \frac{d^2N^{AA}_{\text{jets}}/dp_{\text{T}}\,d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}_{\text{jets}}/dp_{\text{T}}\,d\eta}$$

Phys. Rev. C 96 (2017) 015202

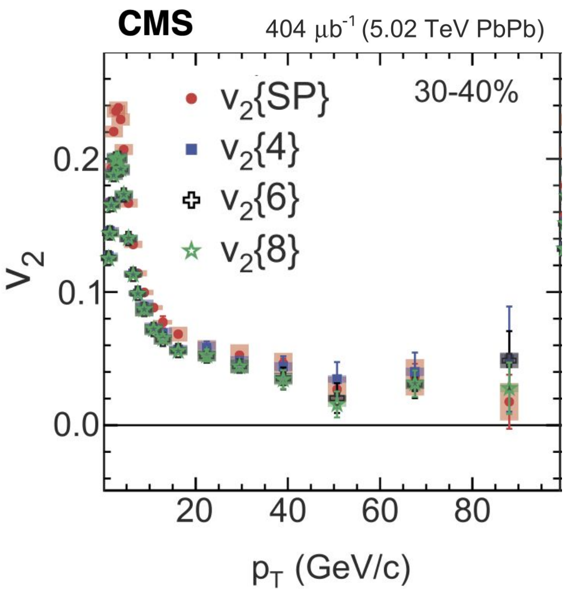


JHEP 03 (2018) 181

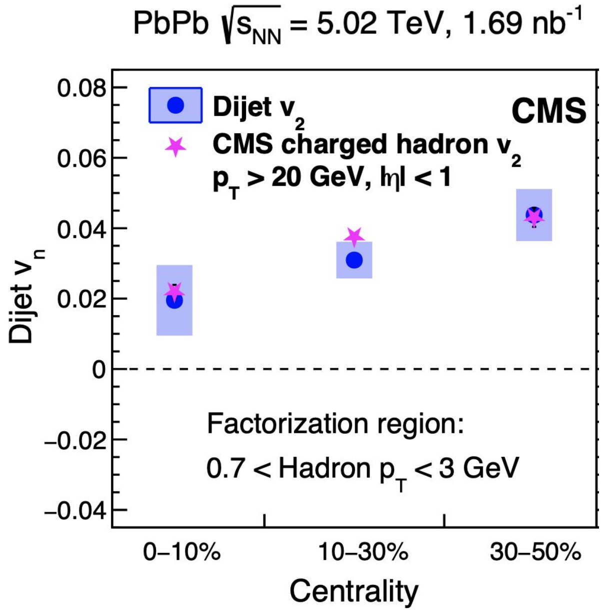
$$x_j = \frac{p_{\text{T}}^{\text{Subleading jet}}}{p_{\text{T}}^{\text{Leading jet}}}$$

Measurements of “jet” flow

- Charged hadron v_2 (left)
  - In high-$p_{T,}$ all methods converge
- Dijet v_2 (right)
  - Good agreement with charged hadrons
  - Consistent with expectations from a path-length dependence of in-medium energy loss

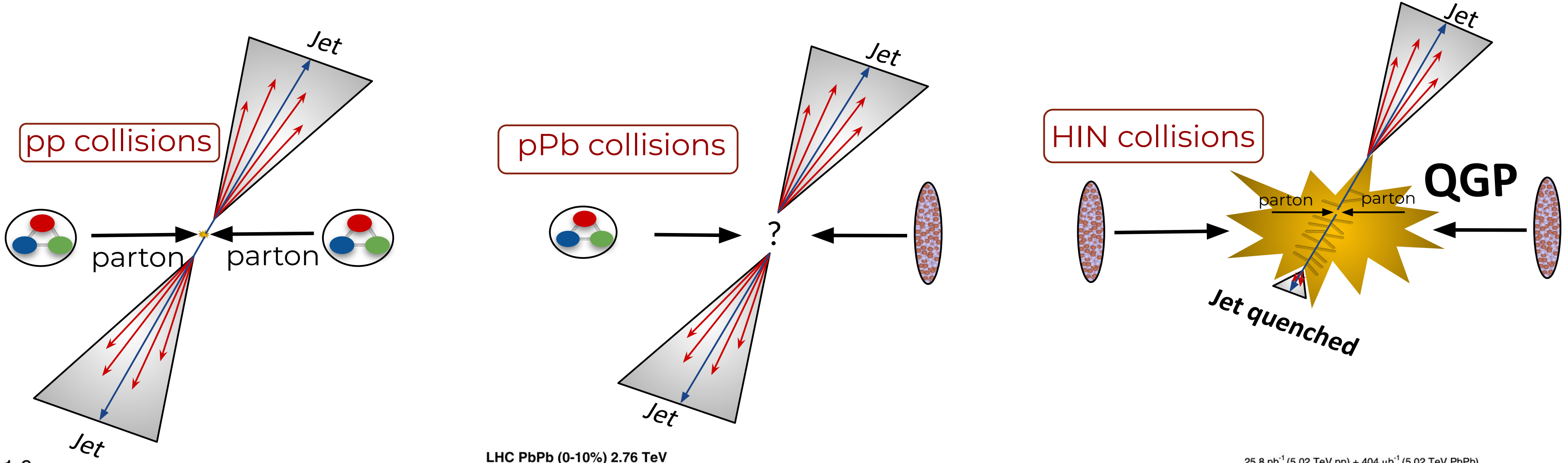


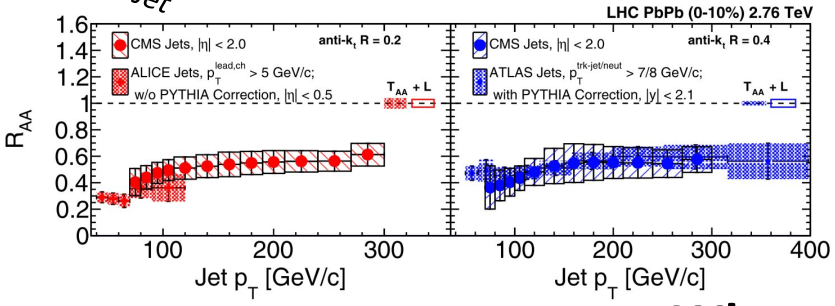
Phys. Lett. B 776 (2017) 195



JHEP 07 (2023) 139

Measurements of jet quenching

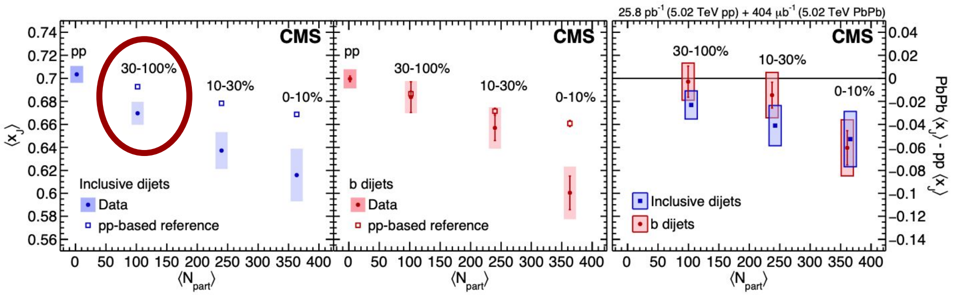




$$R_{AA} = \frac{d^2N^{AA}_{\text{jets}}/dp_T\,d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}_{\text{jets}}/dp_T\,d\eta}$$

Phys. Rev. C 96 (2017) 015202

What about pPb?



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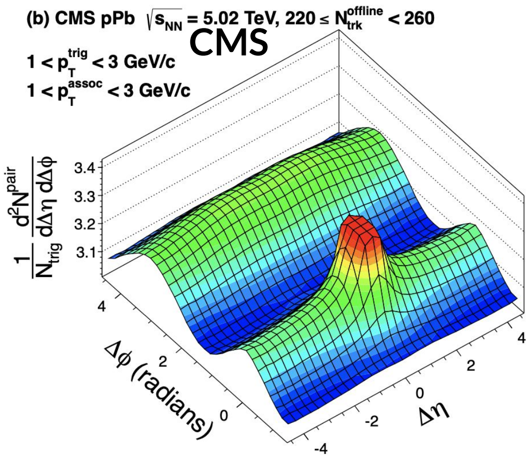
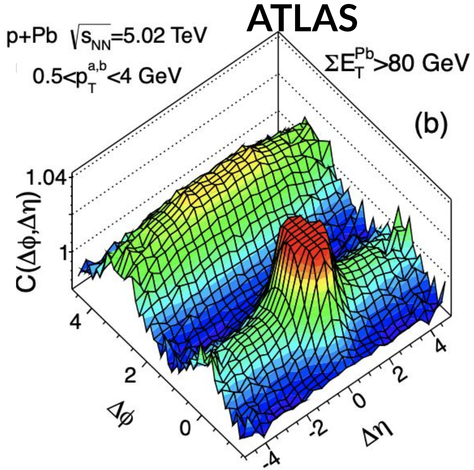
$$x_j = \frac{p_T^{\text{Subleading jet}}}{p_T^{\text{Leading jet}}}$$

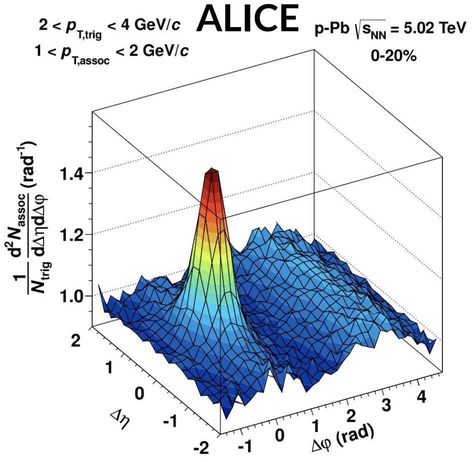
Collectivity in pPb



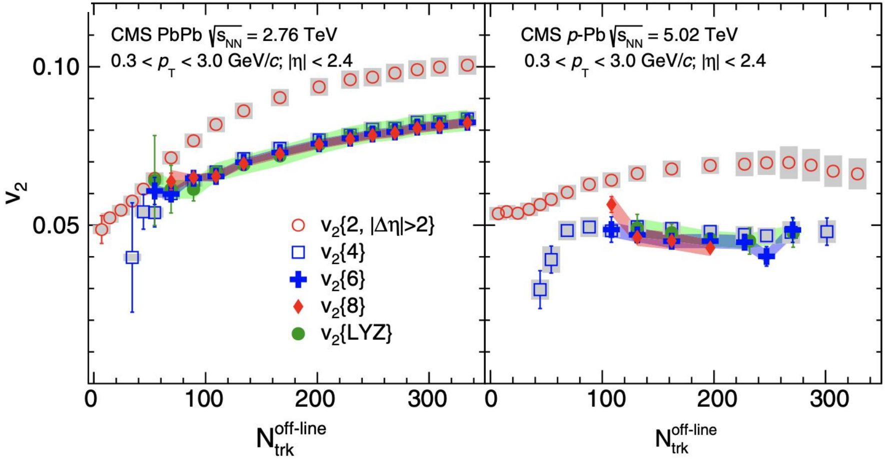
Phys. Lett. B 724 (2013) 213



Phys. Rev. Lett. 110, 182302 (2013)



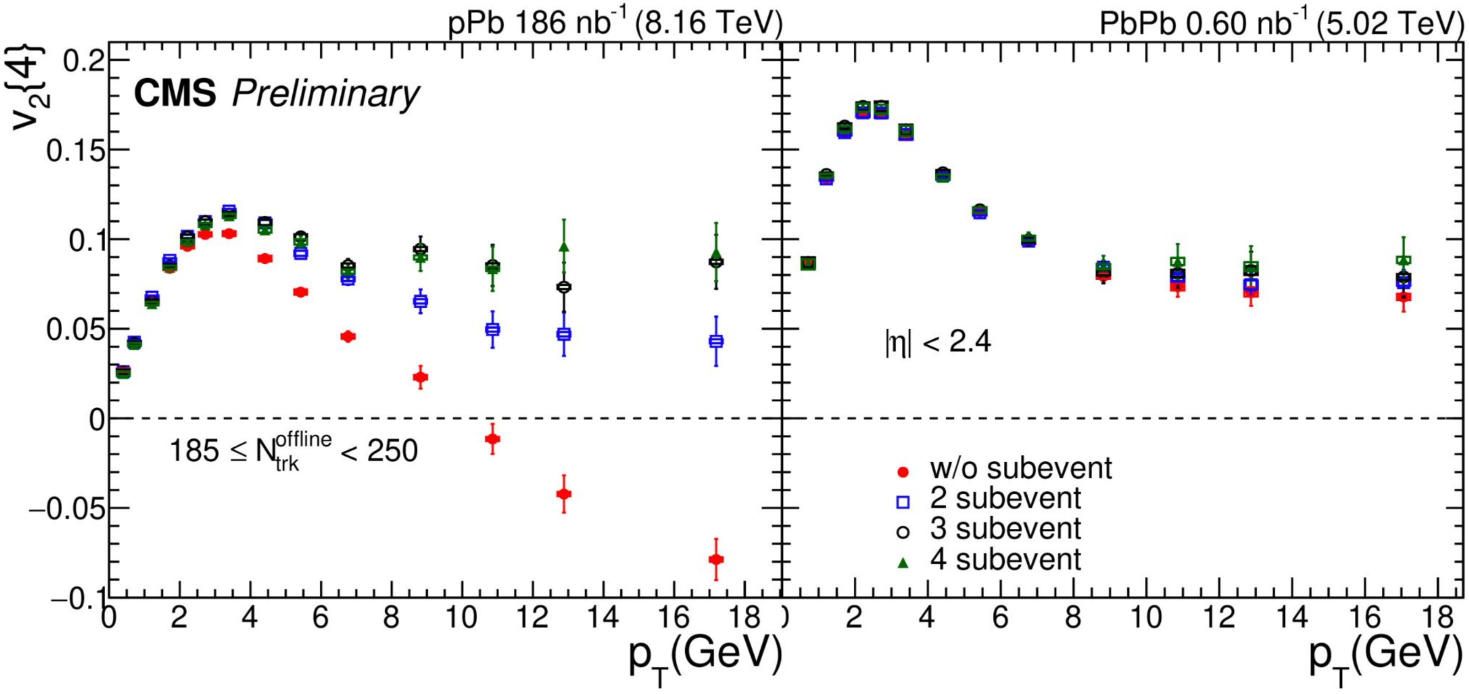
Phys. Lett. B 719 (2013) 29



Phys. Rev. Lett. 115, (2015) 012301

High-p_T flow in pPb? (I)

- Non-zero v_2 observed for high-p_T particles
  - Dealing with non-flow contribution is important



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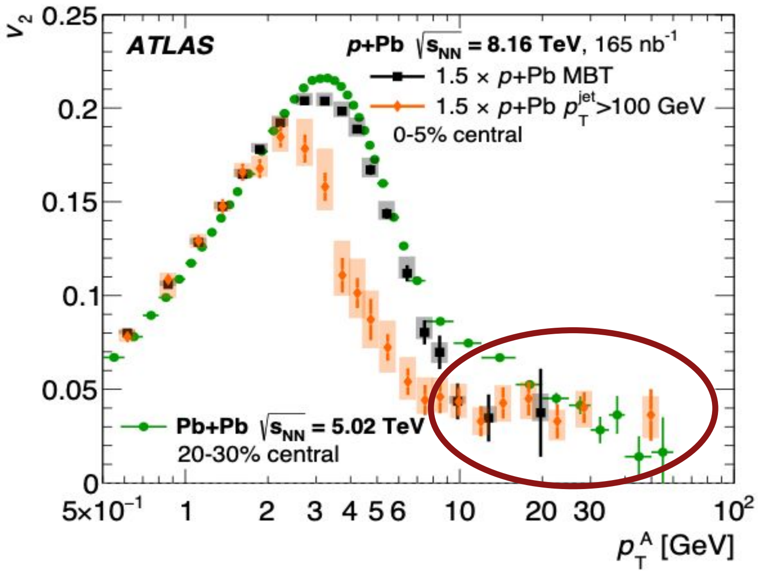
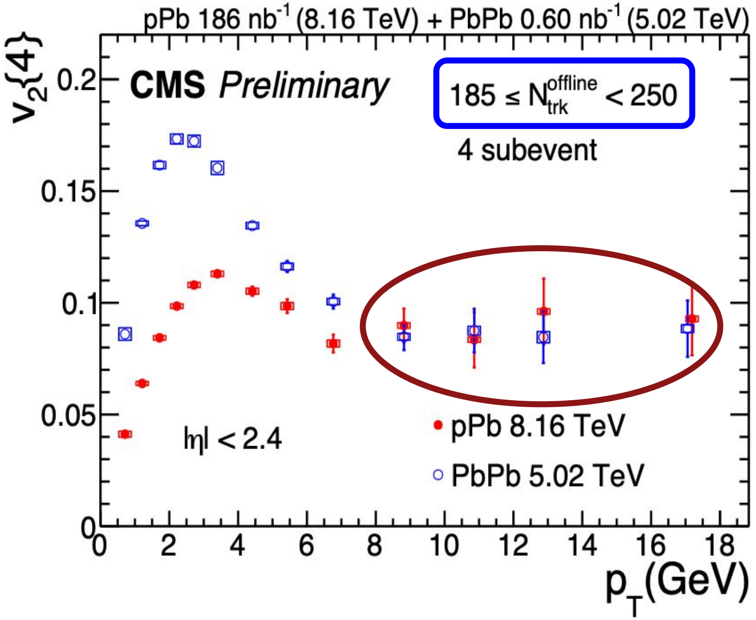
High-p_T flow in pPb? (II)

- Non-zero v_2 observed for high-p_T particles
  - Dealing with non-flow contribution is important
- Similar high-p_T v_2 in pPb and PbPb



Eur. Phys. J. C 80 (2020) 73



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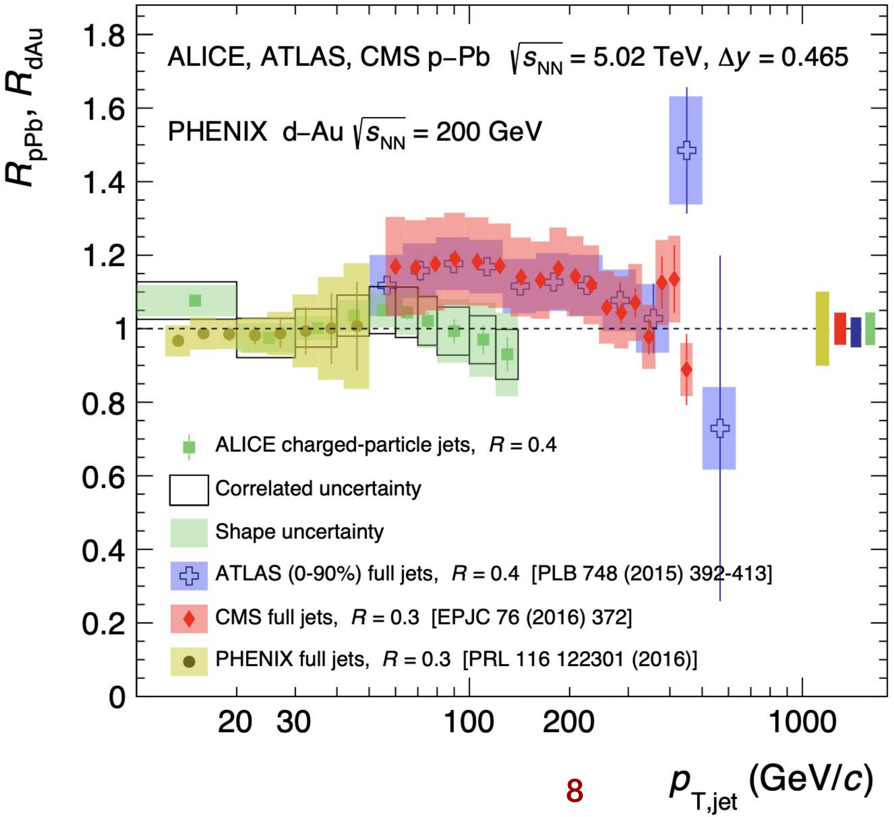
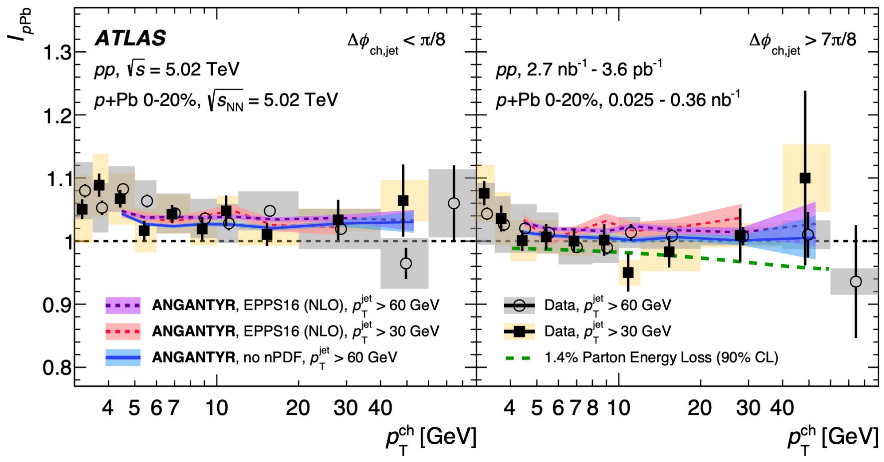
Jet quenching in aA?

Nuclear modification factors consistent with unity

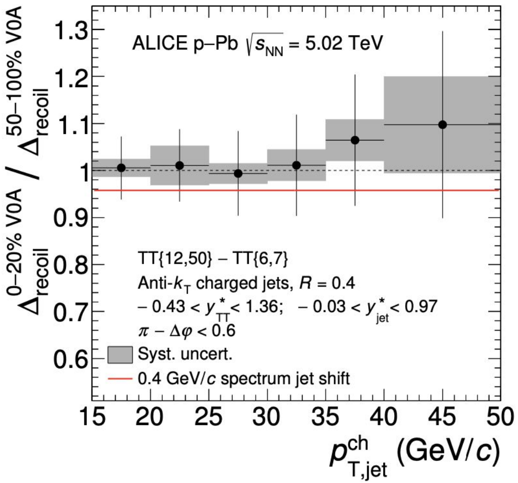


JHEP 05 (2024) 041

Jet quenching constraints in pPb at LHC



Phys. Rev. Lett. 131 (2023) 072301

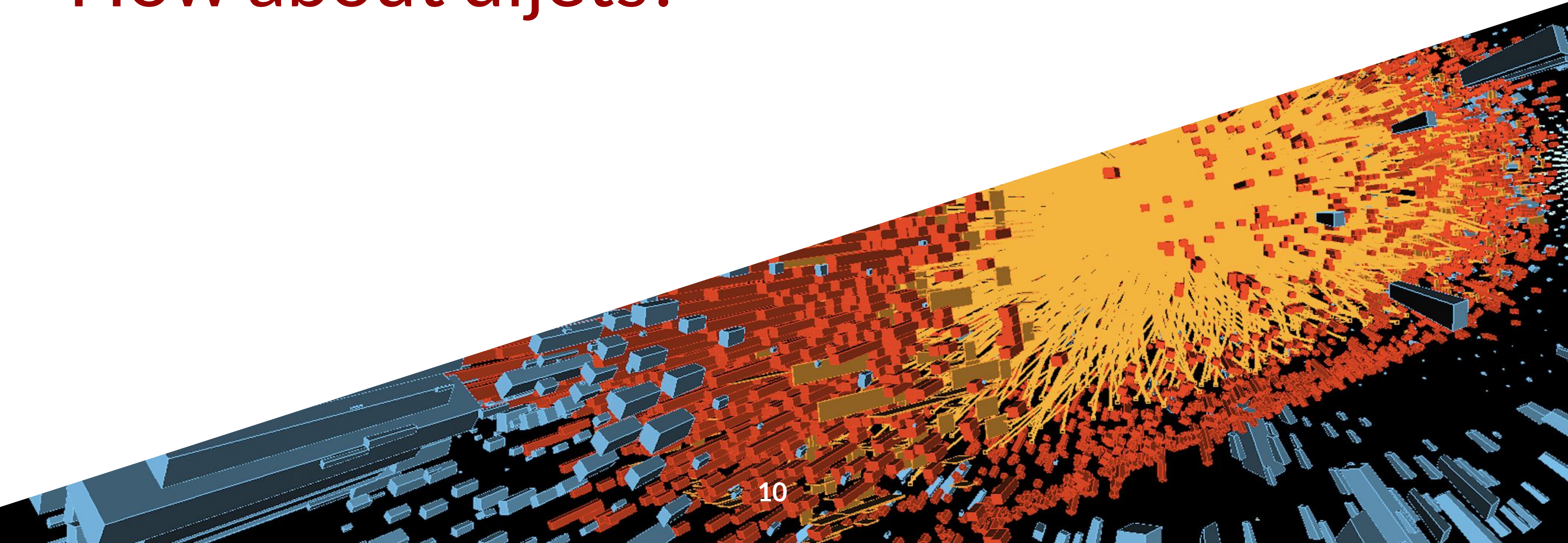


Phys. Lett. B 783 (2018) 95

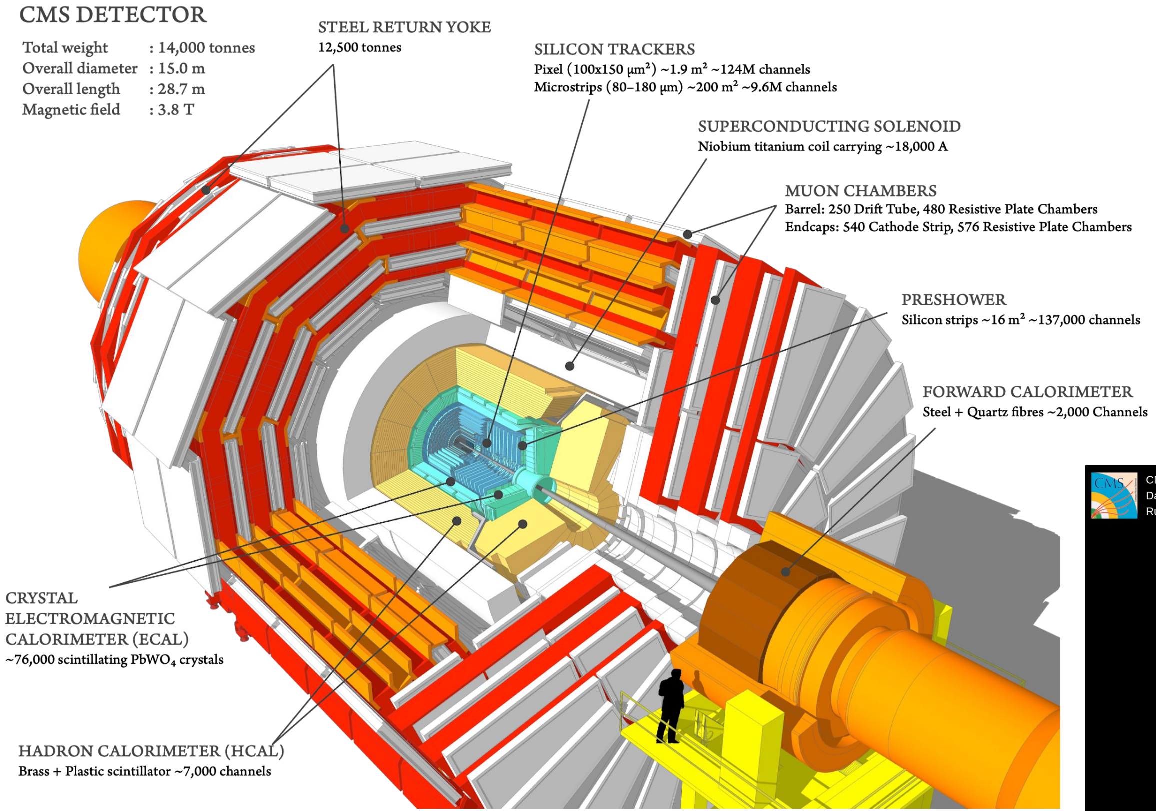
- ➤ Ratio of charged-particle yields per jet
  - ⇨ $I_{pPb} = Y_{pPb}/Y_{pp}$
- ➤ 1.4% Parton E-Loss at 90% C. L.

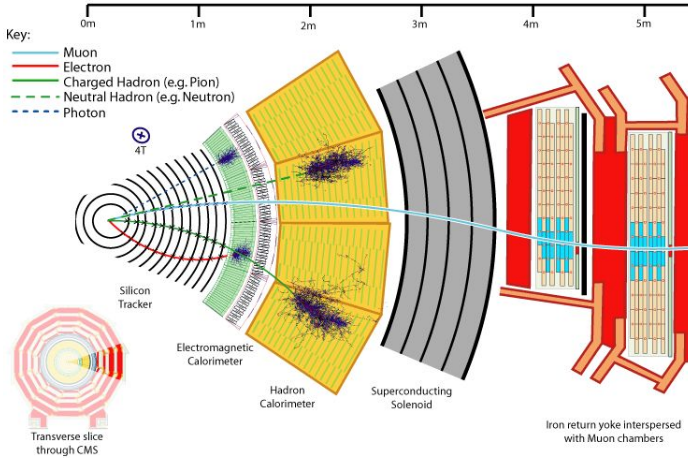
- ➤ Jet-track recoil
- ➤ Limit on out-of-cone energy transport due to jet quenching of < 400 MeV at 90% C. L

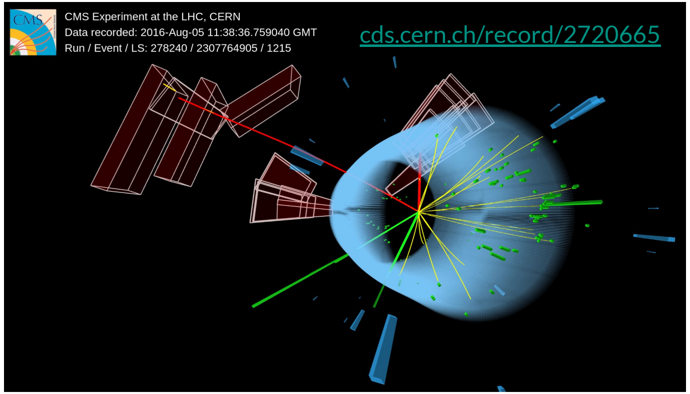
How about dijets?



The CMS detector

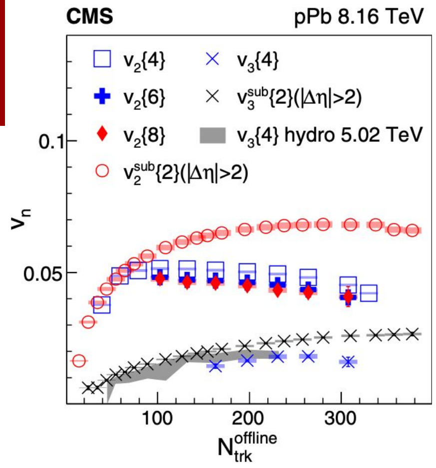




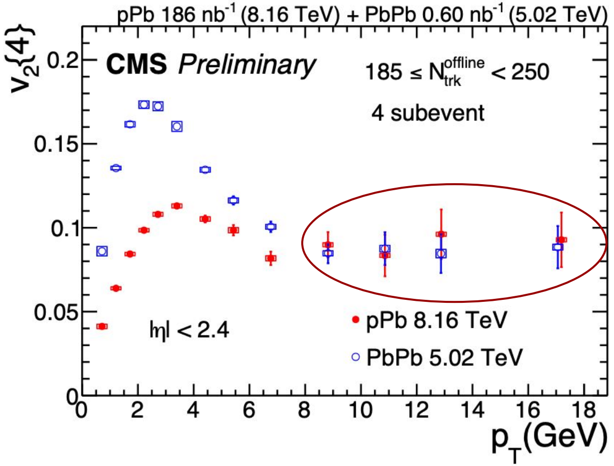


Datasets and Monte Carlo simulations

- pPb@8.16 TeV (L = 174.6 nb^{-1})
  - Minimum-bias trigger
    - ~6.4 Billion events in total
    - Multiplicity range: 10 to 185
  - High multiplicity triggers
    - Multiplicity range: 185 to 250
      - ~ 498 Million events in total
    - Multiplicity range: > 250
      - ~ 32 Million events in total
  - Simulations: **PYTHIA8+EPOS**
    - ~ 22 Million dijet events (all multiplicities)
    - For corrections , unfolding and data comparison



PRC 101, 014912 (2020)



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Analysis workflow

Datasets and Simulations

Jet energy corrections

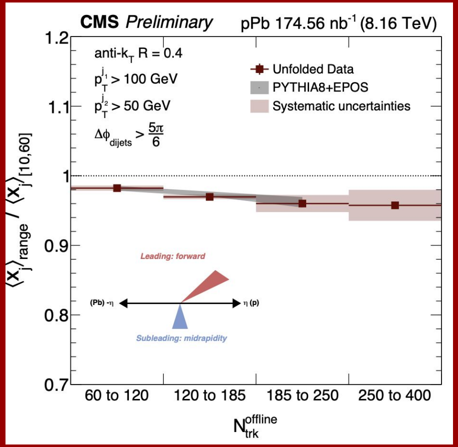
Selections

Unfolding

Observables

Systematic uncertainties

Final results

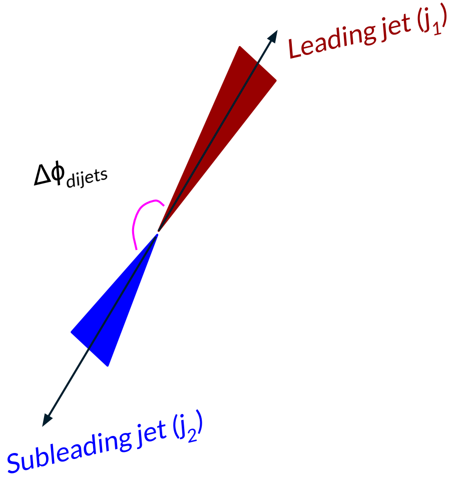


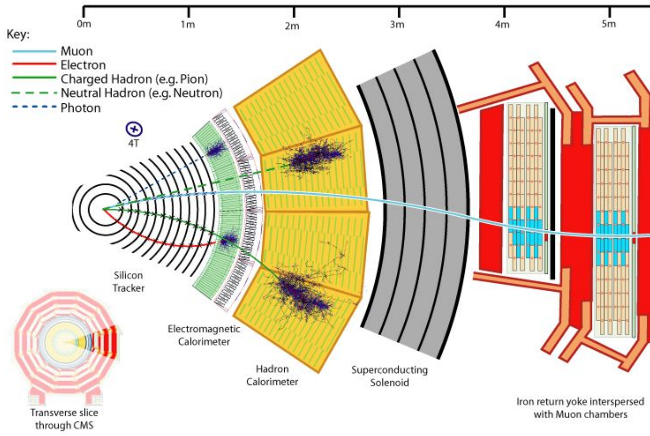
Measurement setup

- Dijet selection
  - Particle Flow
    - anti-k_T jets with R = 0.4
    - $p_T^{j1} > 100$ GeV
    - $p_T^{j2} > 50$ GeV
    - $|\Delta\phi_{dijets}| > 5\pi/6$
- Observable

$$x_j = \frac{p_T^{j_2}}{p_T^{j_1}}$$

- Analysis methods
  - Ratio high-to-low multiplicity (R_{CP}-like)
  - Probe proton and lead directions (η dependency)
  - Apply D'Agostini unfolding to correct for resolution





x_j dependency

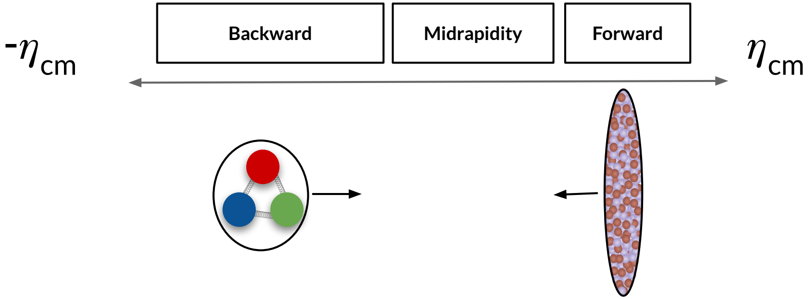
- Study of x_j as function of multiplicity and pseudorapidity
  - Multiplicity ranges: **[10,60]**, [60,120], [120,185], **[185,250] and [250,400]**

Minimum bias trigger

High multiplicity triggers

x_j dependency

- Study of x_j as function of multiplicity and pseudorapidity
  - Multiplicity ranges: **[10,60]**, [60,120], [120,185], **[185,250] and [250,400]**
  - Probe jets in both proton and lead directions
    - Midrapidity: $|\eta_{CM}| < 1$
    - Forward (p direction): $1.2 < \eta_{CM} < 2.4$
    - Backward (Pb direction): $-3.3 < \eta_{CM} < -1.2$



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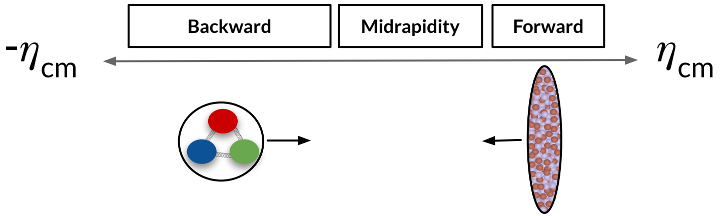
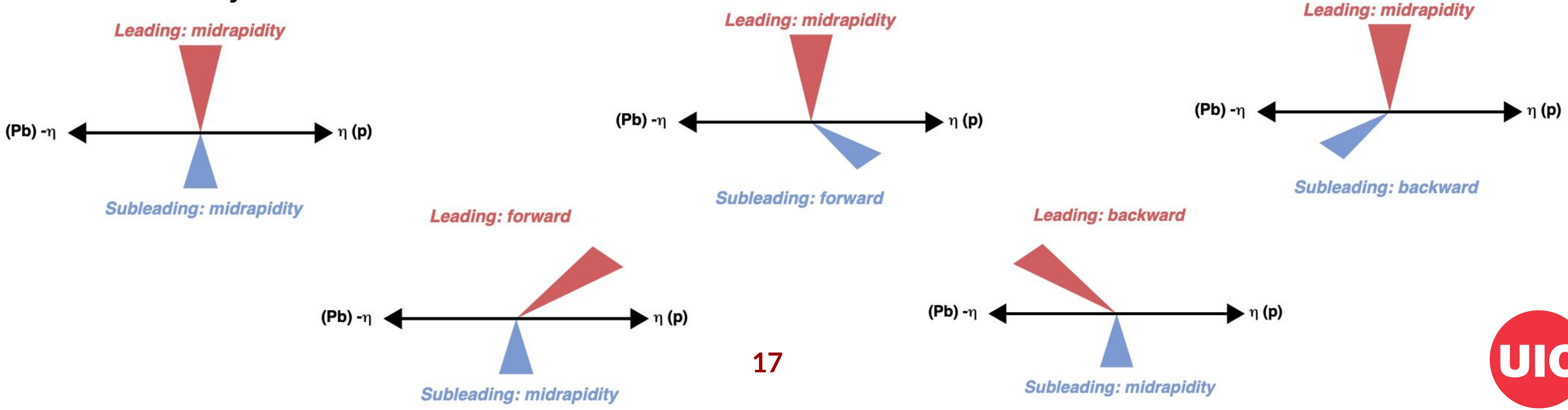


  - Dijet combinations studied:



Unfolding x_j

- First x_j unfolding at CMS
  - x_j reconstructed vs x_j generated
    - For each η_{CM} combination
    - In different multiplicity bins
      - [10,60], [60,120] and [>120]
- Effects taken into account in the response matrices
  - Fakes → Negligible
  - Swap → ~20%
  - Missing → added to ROOUnfold
  - Data/MC differences
    - p_T^{j1} vs p_T^{j2} PDF map applied to the matrices
- Applied with D'Agostini unfolding using ROOUnfold

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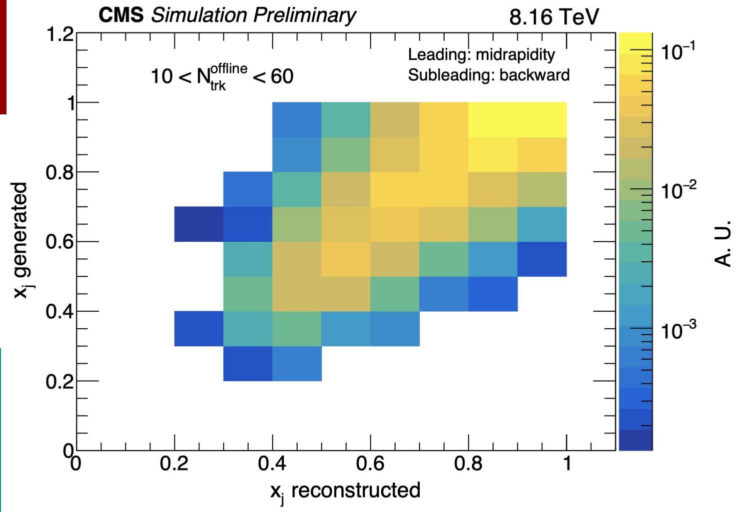
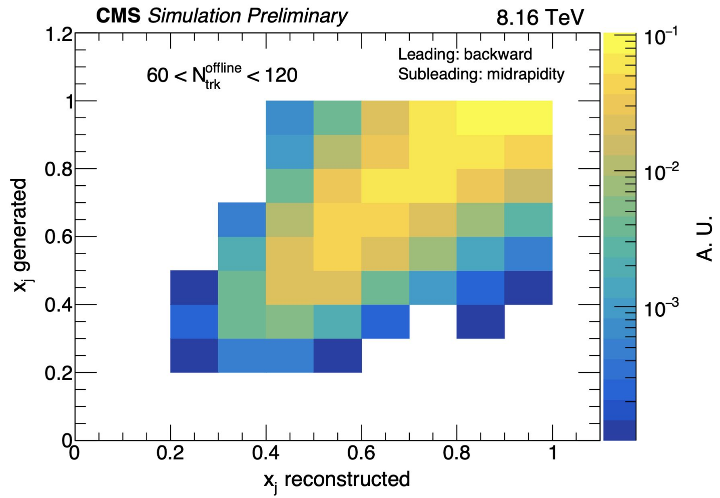
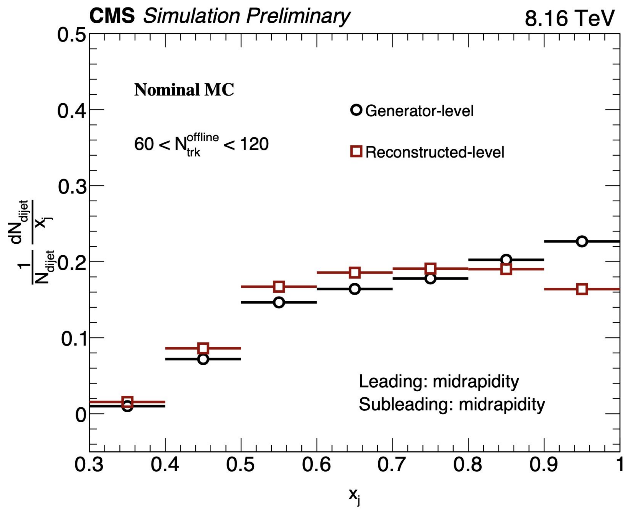




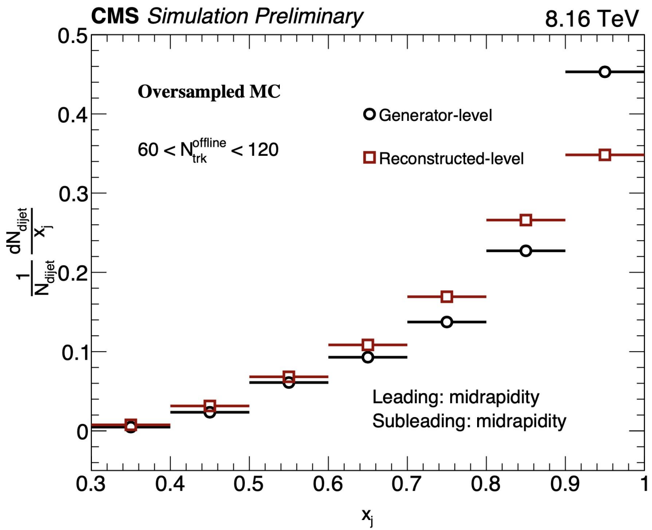
Validate the unfolding procedure at MC (I): prior

- Data/MC reconstructed pdf(p_T^{j1} , p_T^{j2}) is applied to remove sensitivity to prior shape
- Procedure is tested using an "oversampled MC"
  - Very different prior between the nominal and oversampled test-MC

Nominal MC (PYTHIA+EPOS)



Oversampled MC (PYTHIA+EPOS, no invariant p_T rescale)



very different distributions

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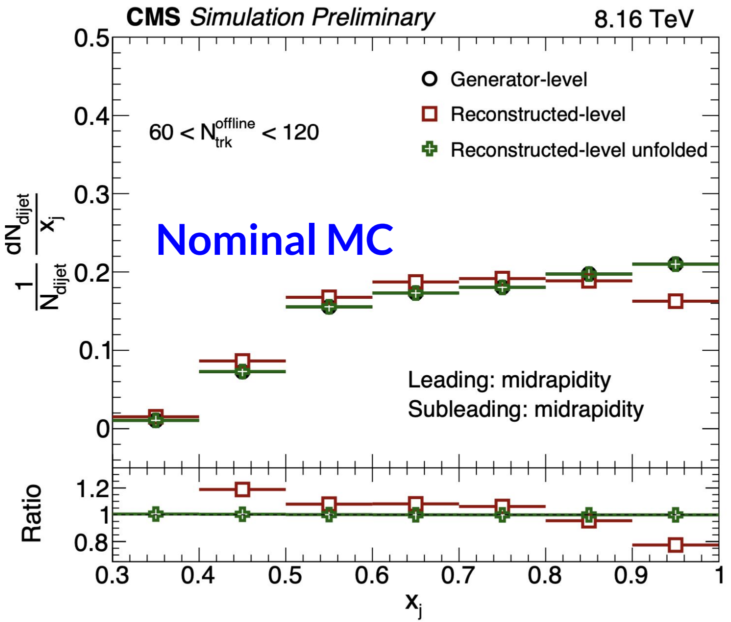
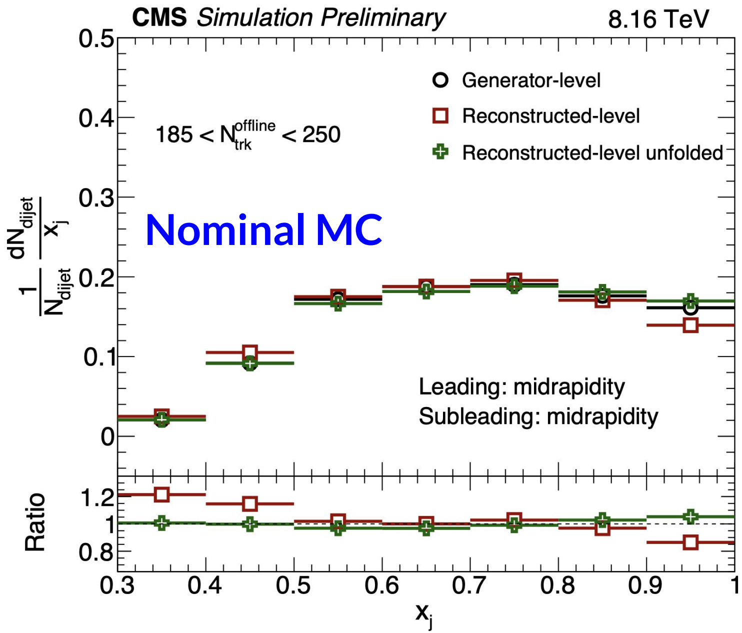
Validate the unfolding procedure at MC (II): closures

- Closures achieved despite drastically different priors
  - Demonstrate the advantage of using the pdf-convoluted response matrices for cases when no reliable Monte Carlo exists





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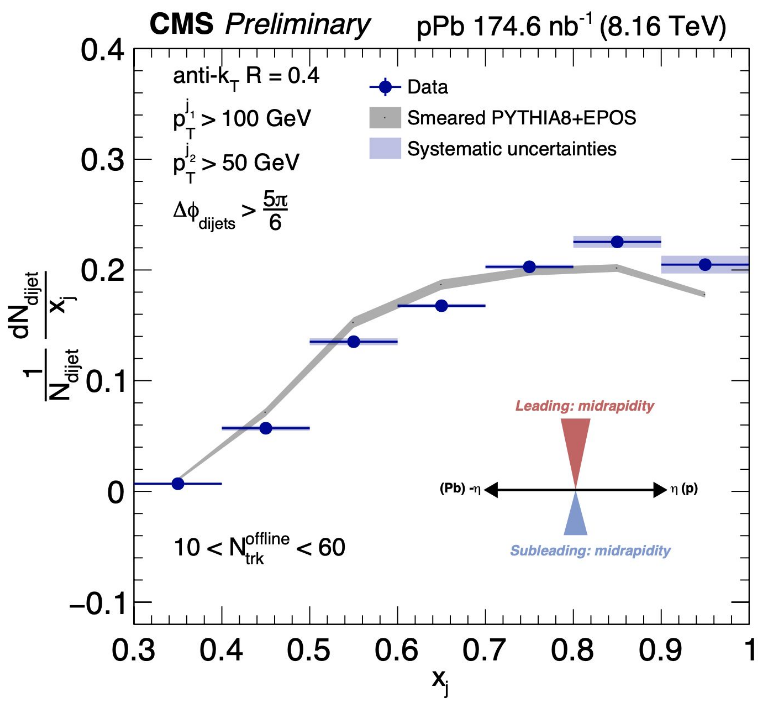
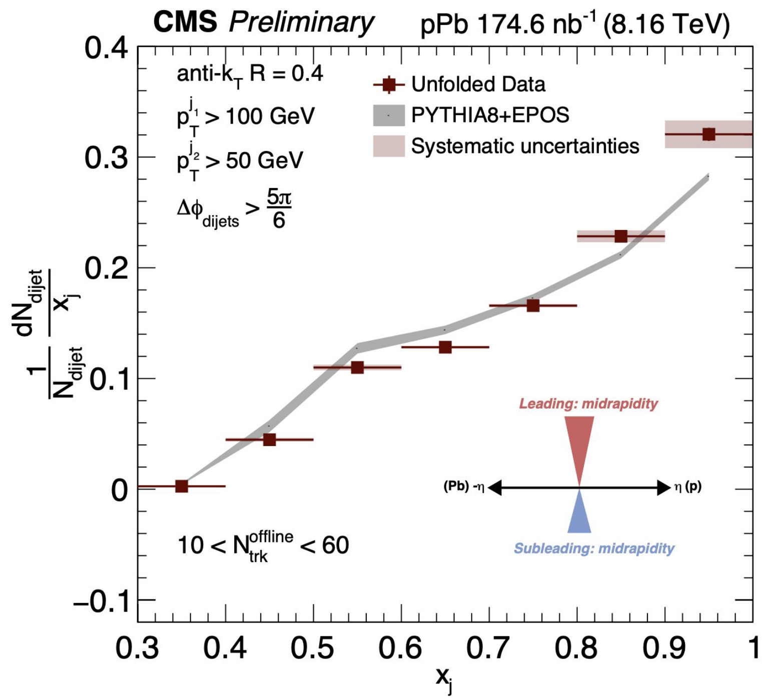
Unfolding x_j – example in data





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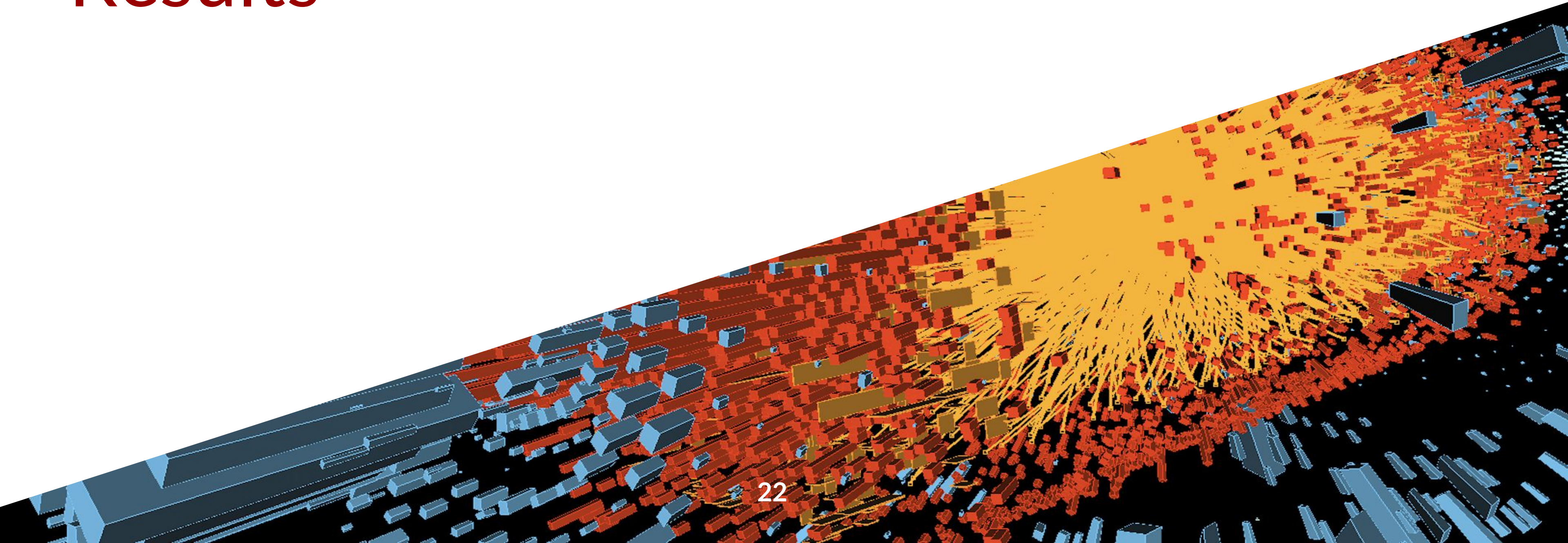
Smeared results

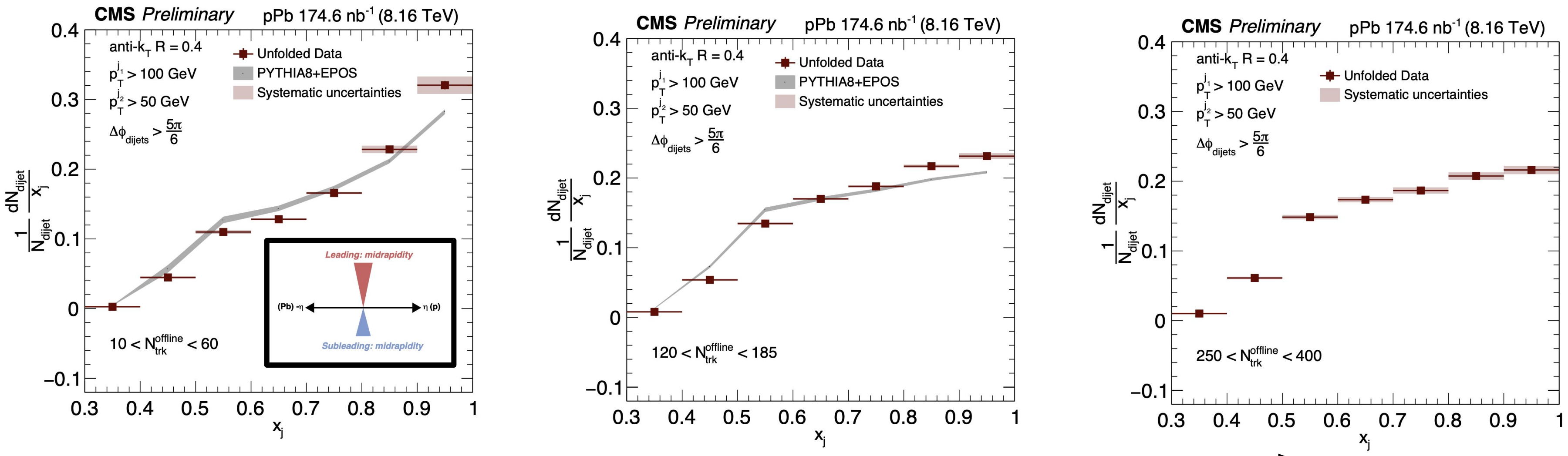
Unfolded results

Results



x_j results: multiplicity dependency

- Changes observed in the shapes from low to high multiplicity ranges
  - Especially in $x_j \sim 1$
    - Same behavior for all η combinations
  - Simulations cannot be performed for the highest multiplicity range



Increasing Multiplicity

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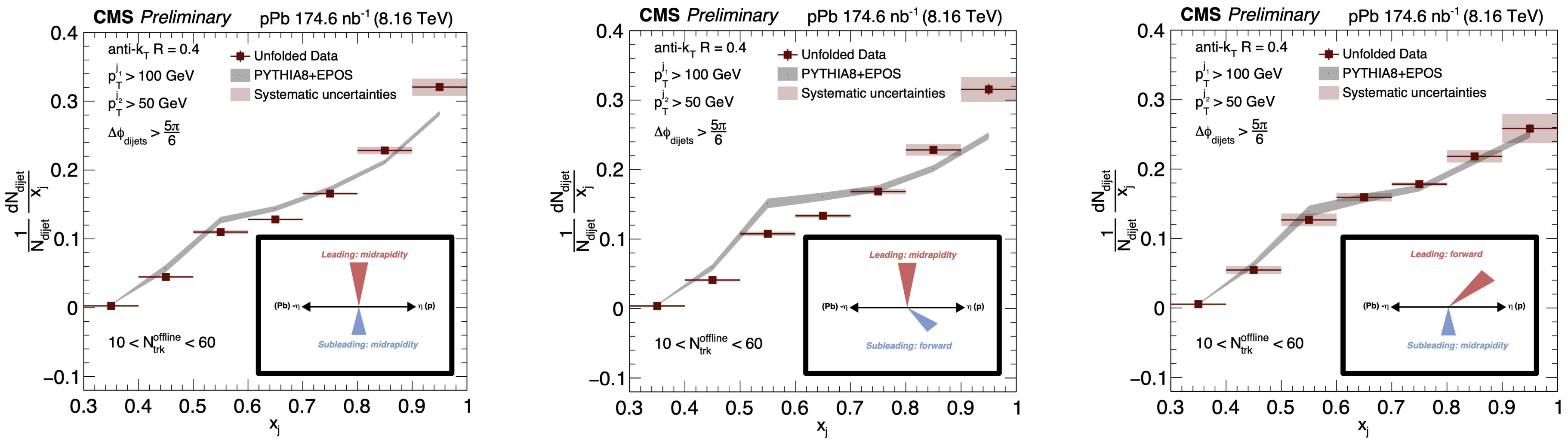
x_j results: η dependency (forward)

- Very similar behavior for all different jet combinations
  - Small changes in shapes



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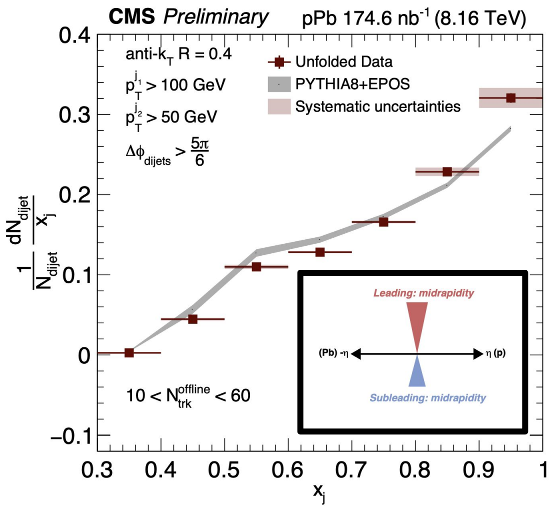
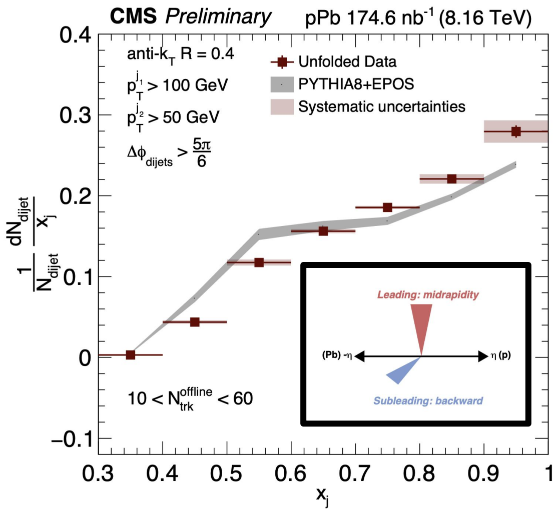
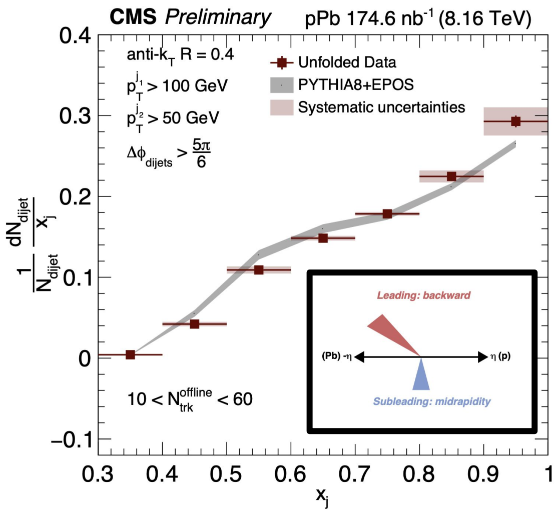
x_j results: η dependency (backward)

- Very similar behavior for all different jet combinations
  - Small changes in shapes







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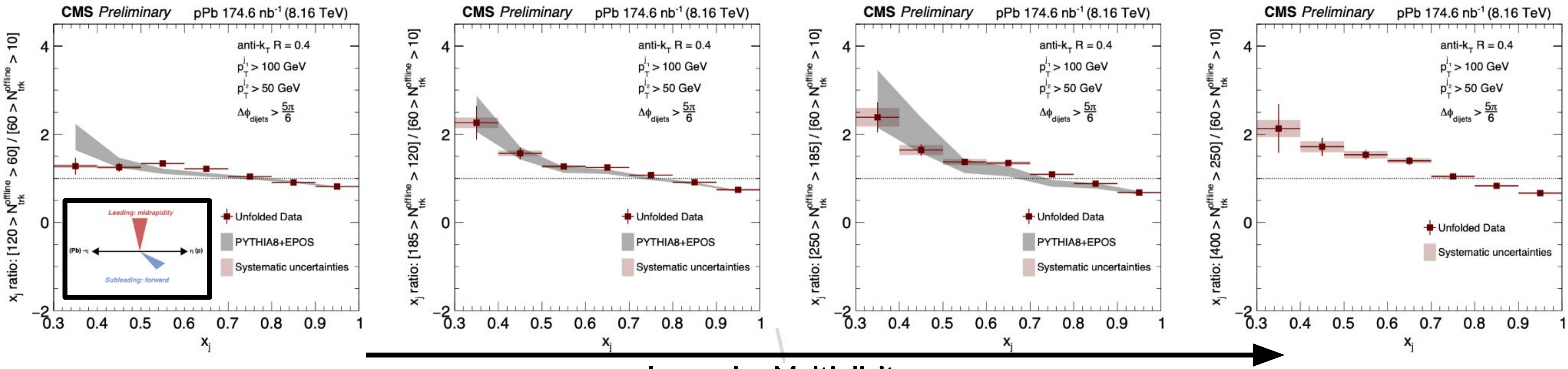
x_j ratio to lower multiplicity range

- Useful for cancellation of systematics
- Ratio > 1 at low x_j and < 1 for high x_j
  - Possible effects: multijets contribution, energy-momentum conservation, among others
- Data well described by PYTHIA8+EPOS MC in all multiplicities and η combinations
  - **PYTHIA8+EPOS do not include energy loss mechanism**



Increasing Multiplicity

Other η combinations in the backup

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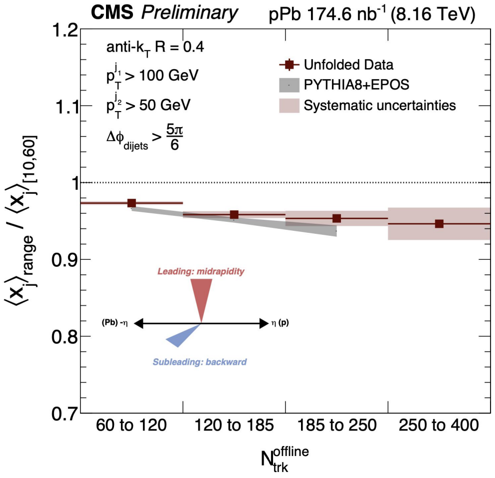
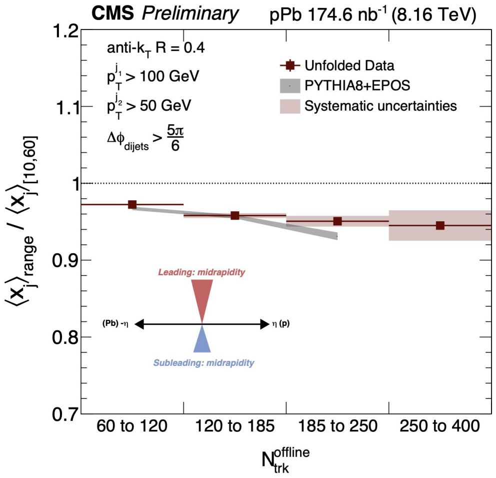
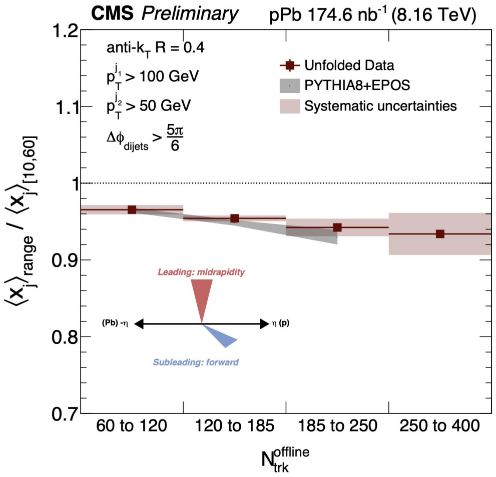
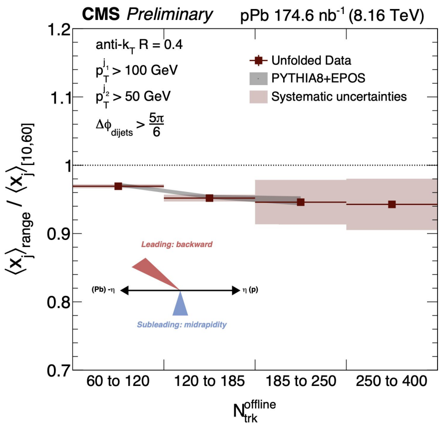
Average x_j : ratio high-to-low multiplicities

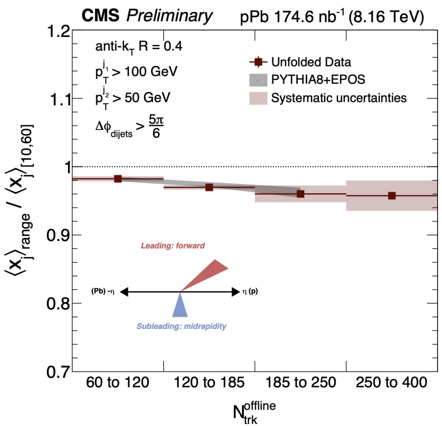








- ➢ **Ratio decrease with multiplicity**
- ➢ **Overall good data/mc agreement**



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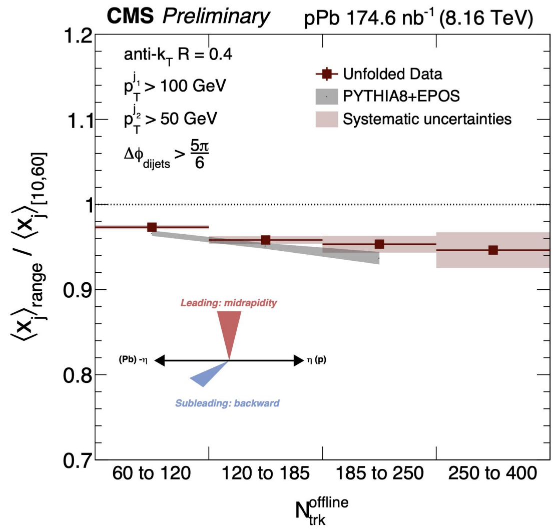
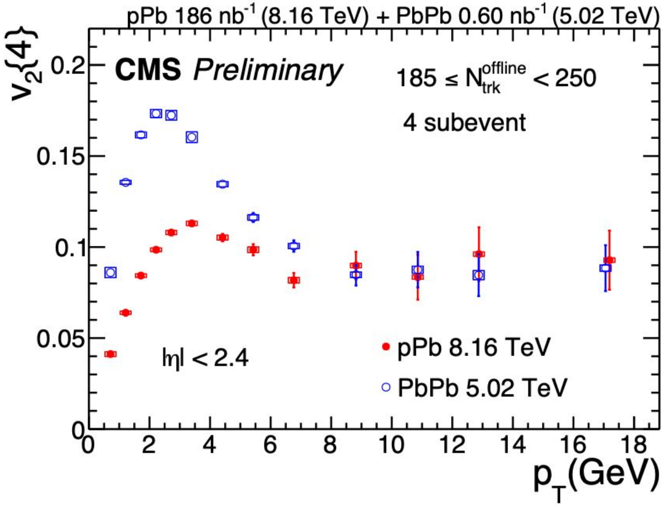
Summary

- ➤ Intriguing results using high multiplicity triggers (strongest flow regime)
  - ⇨ Similar high-p_T flow magnitude for pPb and PbPb
  - ⇨ No modifications observed in x_j for any configuration of jet-jet geometry
    - ➔ Well described by PYTHIA8+EPOS (no energy loss)





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Thank You

The work of the UIC HENP group is supported by the DOE-NP grant


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-08 10:22:07.828203 GMT(11:22:07 CEST)
Run / Event: 150431 / 541464
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Backup

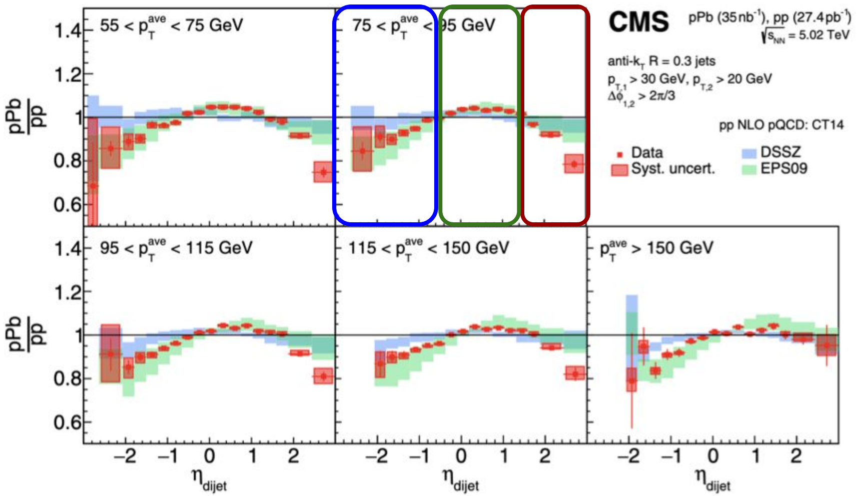
Nuclear PDF's

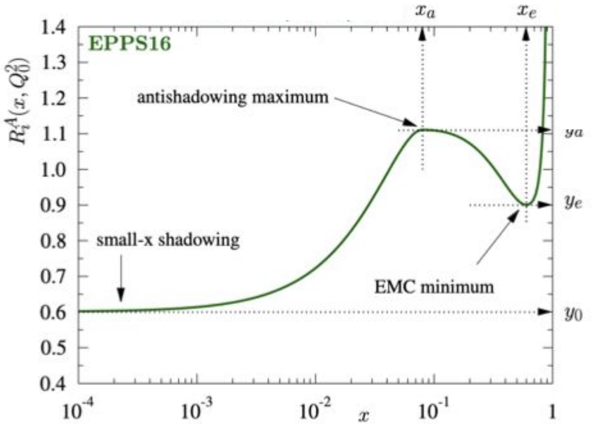
- Nuclear effects
  - Shadowing, antishadowing, EMC
- Dijets can be employed to
  - Map: $(x, Q) \leftrightarrow (\eta_{dijet}, p_T^{ave})$
  - Constraints of gluon nPDFs

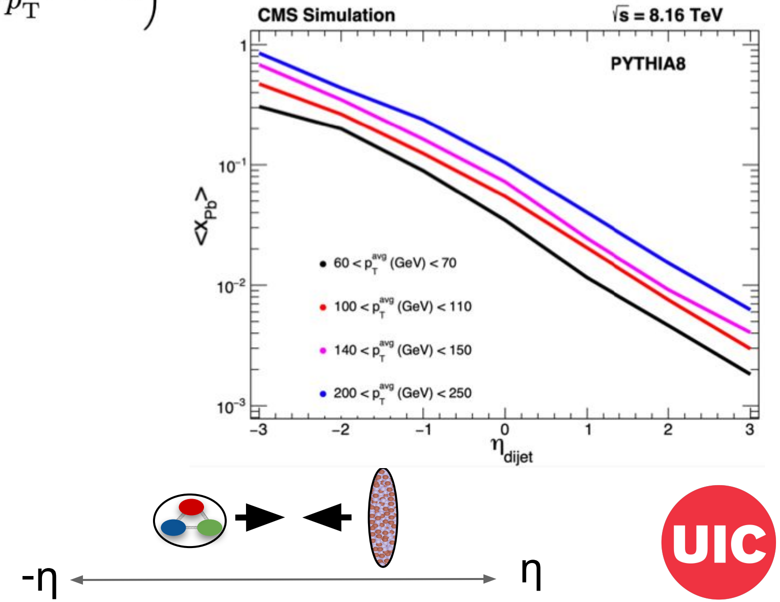
$$\eta_{\text{dijet}} = \frac{1}{2}\left(\eta^{\text{leading}} + \eta^{\text{subleading}}\right)$$

$$p_T^{\text{ave}} = \frac{1}{2}\left(p_T^{\text{leading}} + p_T^{\text{subleading}}\right)$$

PRL121 (2018) 062002



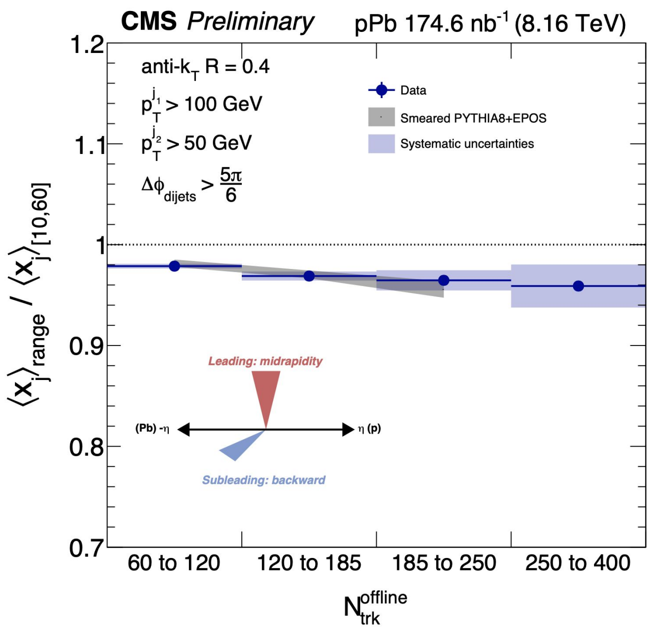


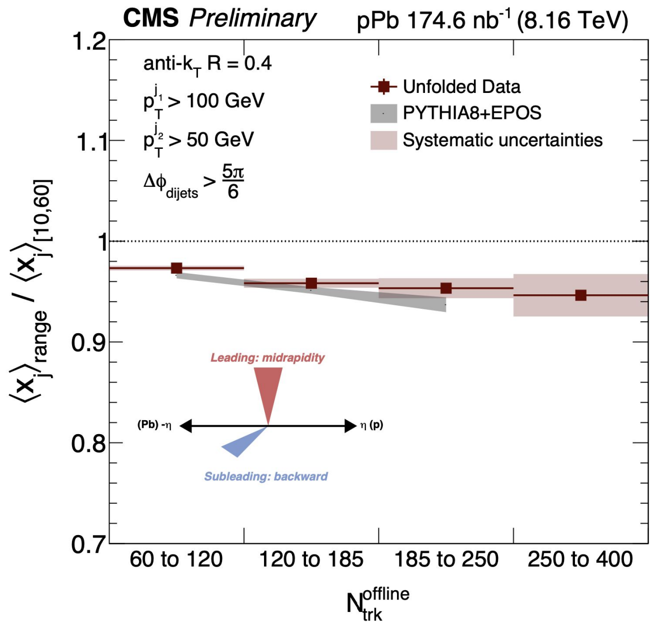


Sources of systematic uncertainties

- Sources of systematics accounted here
  - *Trigger bias:* comparison of distributions between MB and HM triggers
  - *Pileup removal:* different PU rejection event selection criteria are used as systematics
  - ***JES***: shift jet p_T in data based on the uncertainties of jet energy corrections
  - ***JER***: jet p_T is smeared in MC to account for the uncertainties in data-to-simulation differences.
  - *Underlying events:* a jet-area-based background subtraction method is applied As an alternative to the constituent subtraction method
  - *Unfolding*: Five iterations were used to perform the unfolding. Four and six iterations are used as the systematic uncertainty.
- JER and JES are dominant sources of systematics

Average x_j : ratio high-to-low multiplicities





- **Similar behavior between reconstructed and unfolded**
- **Ratio decrease with multiplicity**
- **Overall good data/mc agreement**

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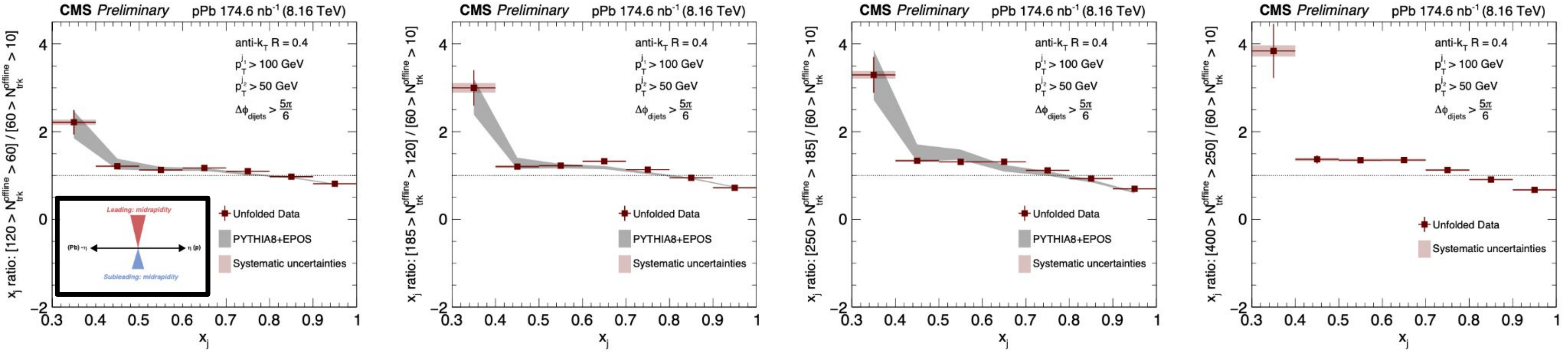
x_j ratio to lower multiplicity range (I)

- Useful for cancellation of systematics
- Ratio > 1 at low x_j and < 1 for high x_j
  - Possible effects: multijets contribution, energy-momentum conservation, among others
- Data well described by PYTHIA8+EPOS MC in all multiplicities and η combinations
  - **PYTHIA8+EPOS does not include energy loss mechanism**



Increasing Multiplicity

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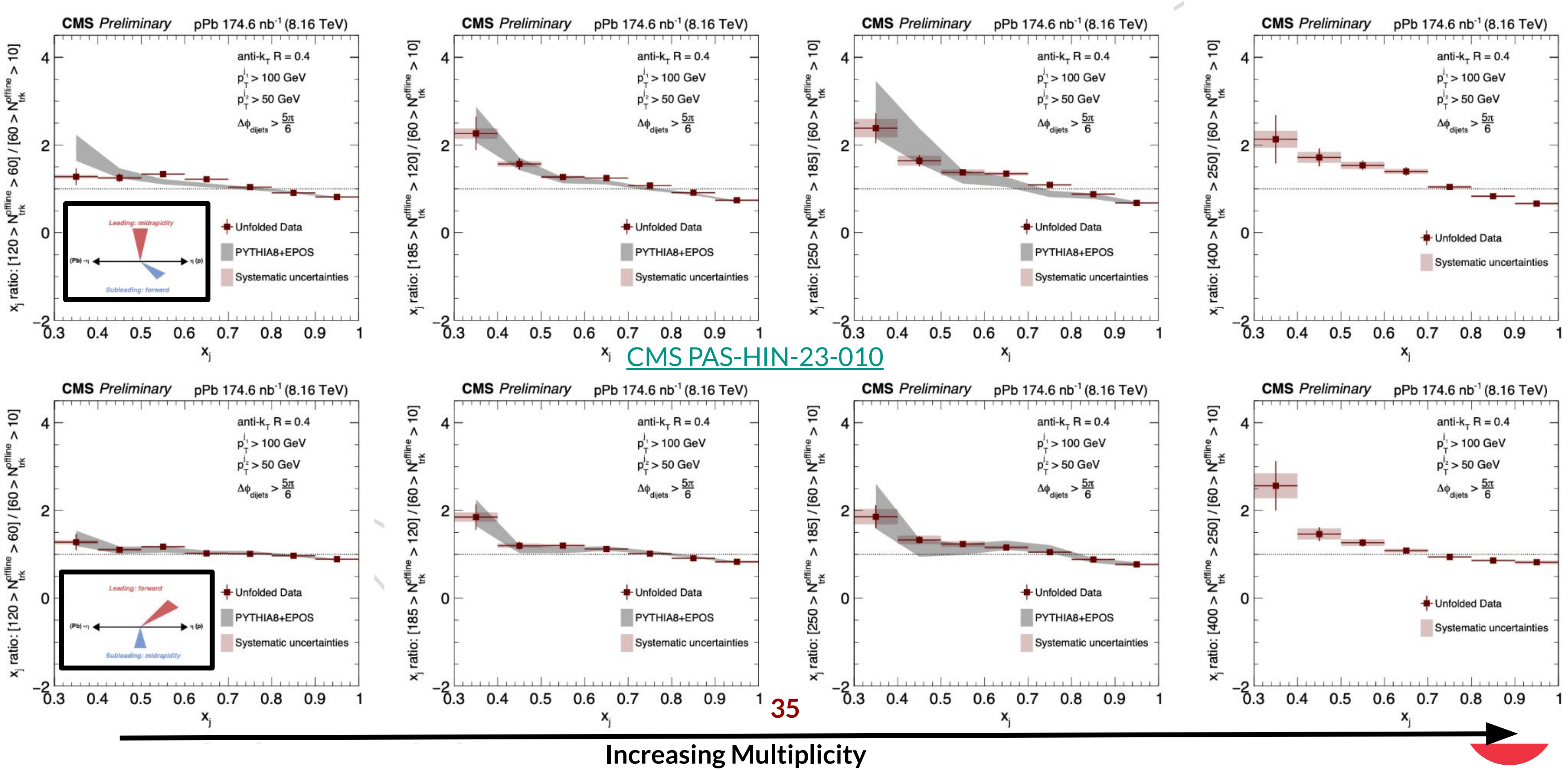
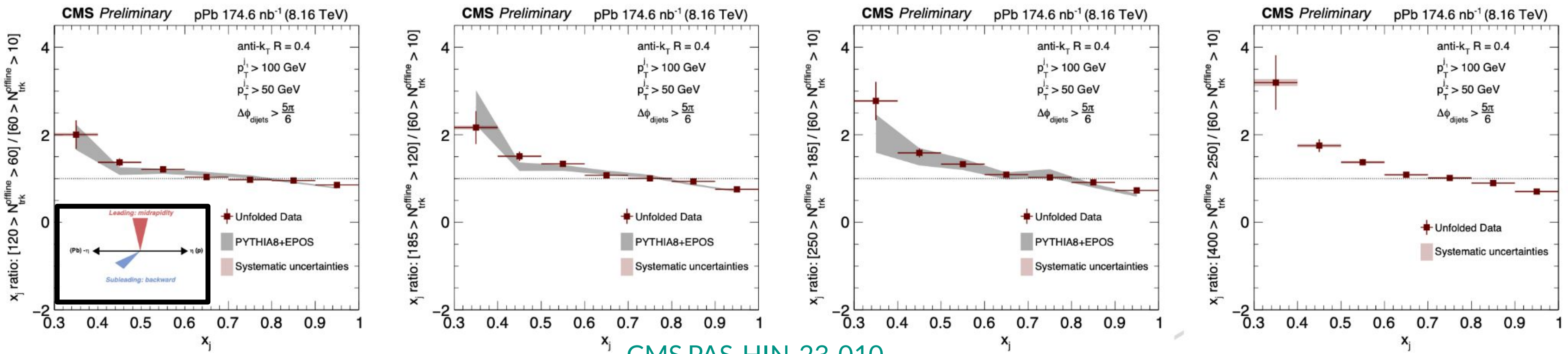
x_j ratio to lower multiplicity range (II)



x_j ratio to lower multiplicity range (III)



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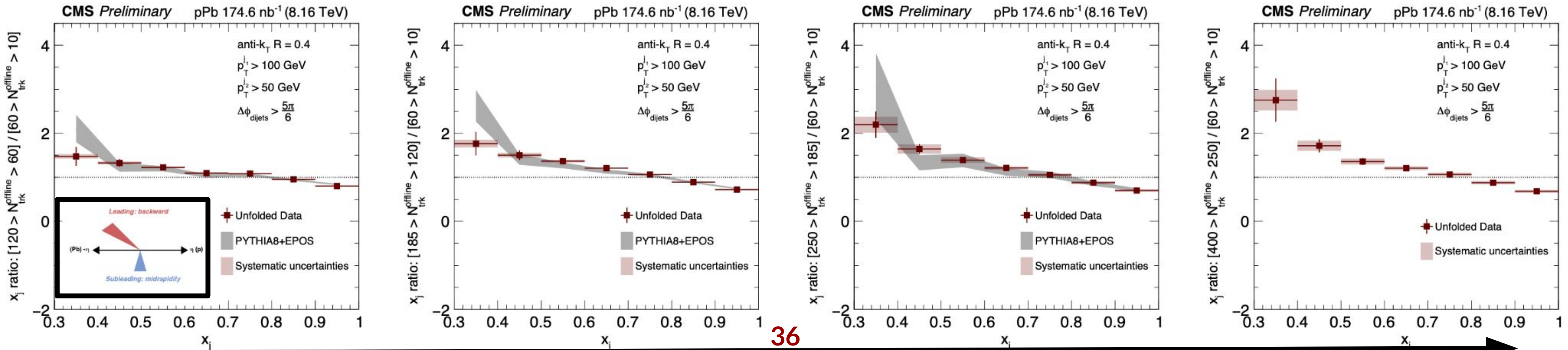
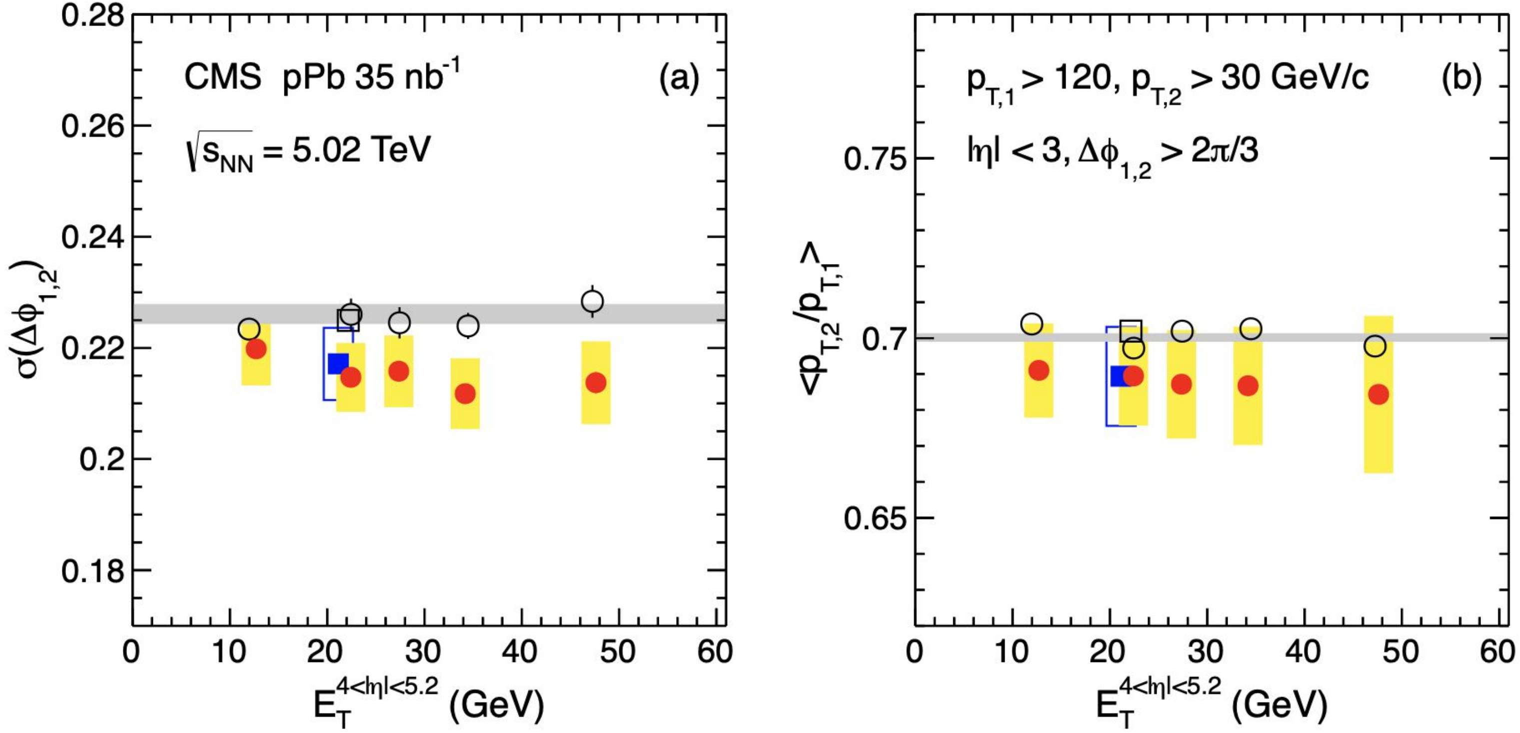


Increasing Multiplicity

CMS Run I search for quenching



Eur. Phys. J. C 74 (2014) 2951