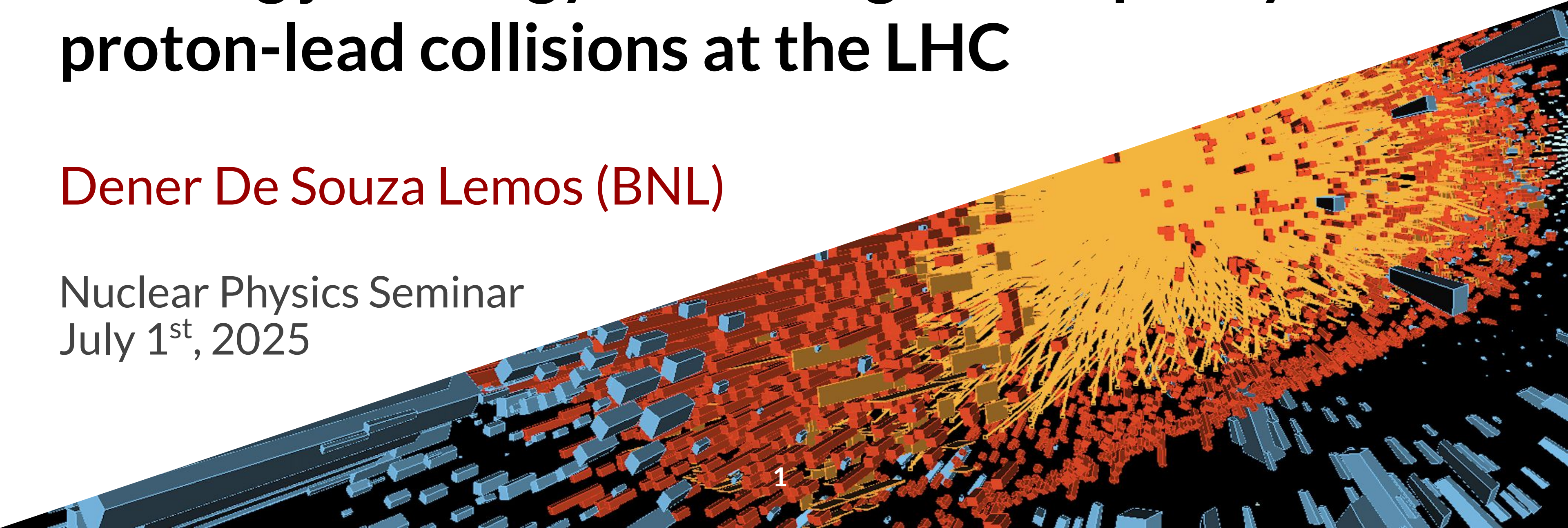
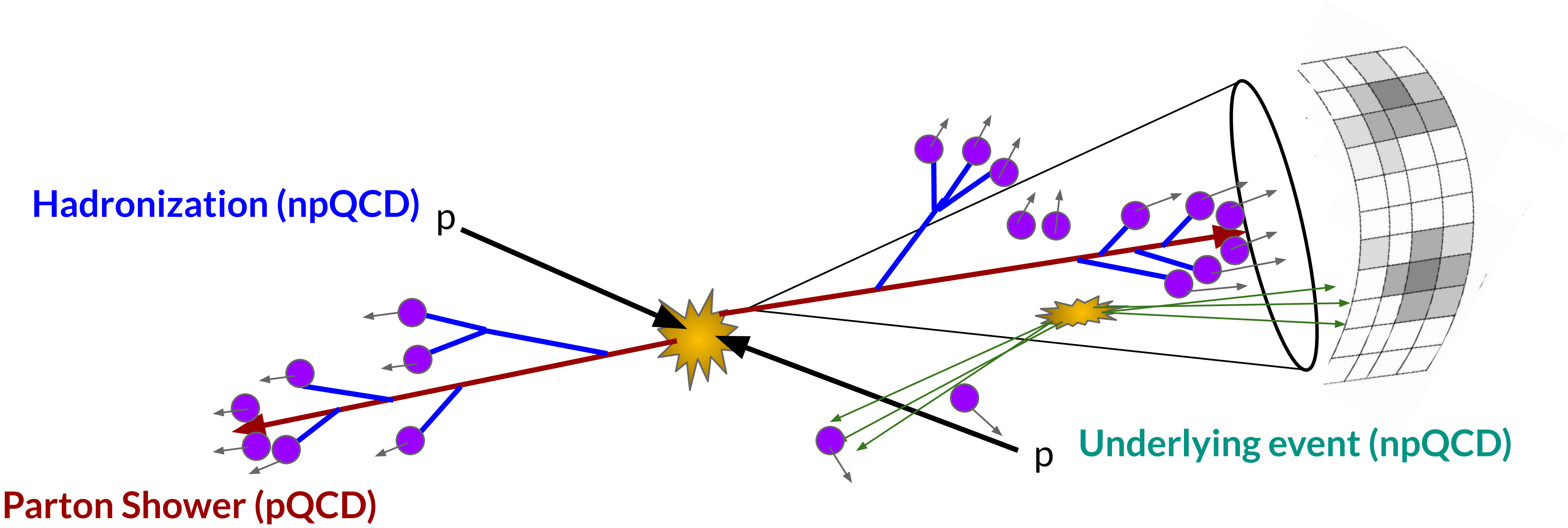
Probing jet energy-loss in high-multiplicity proton-lead collisions at the LHC

Dener De Souza Lemos (BNL)

Nuclear Physics Seminar
July 1st, 2025

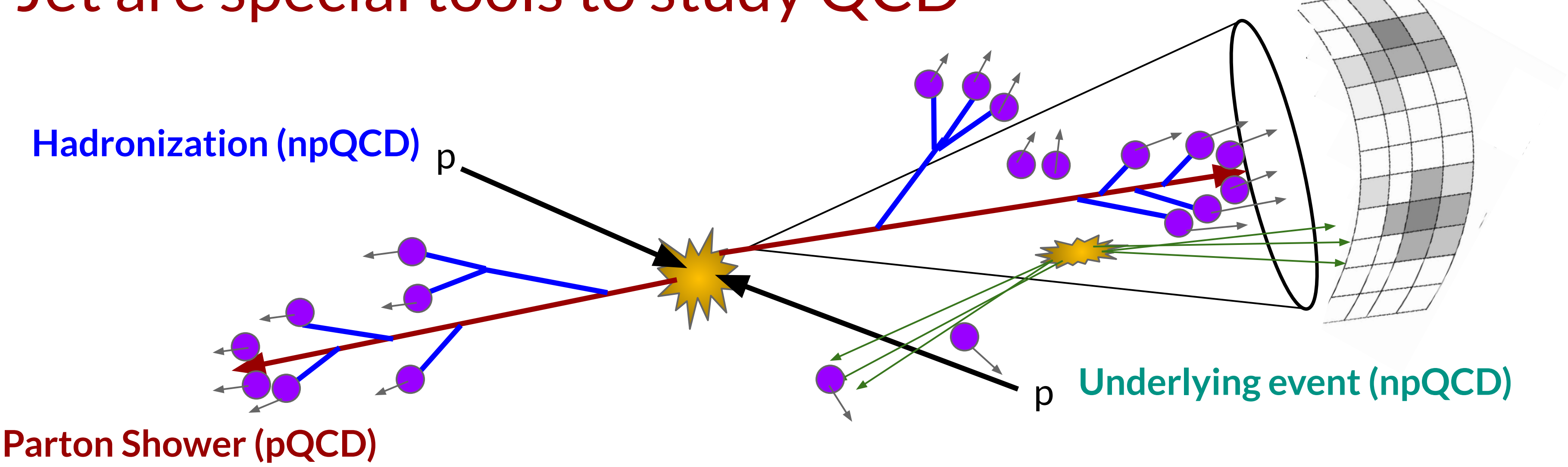


Jet are special tools to study QCD

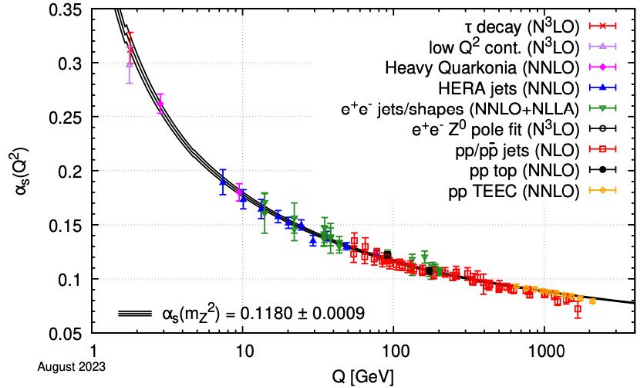


Jets connect unmeasurable partons to measurable hadrons

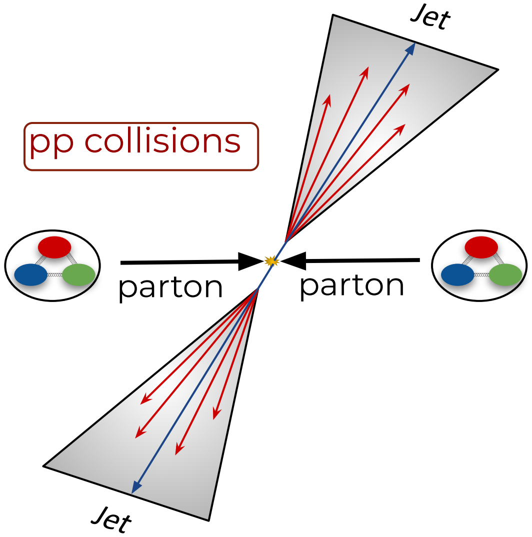
Jet are special tools to study QCD

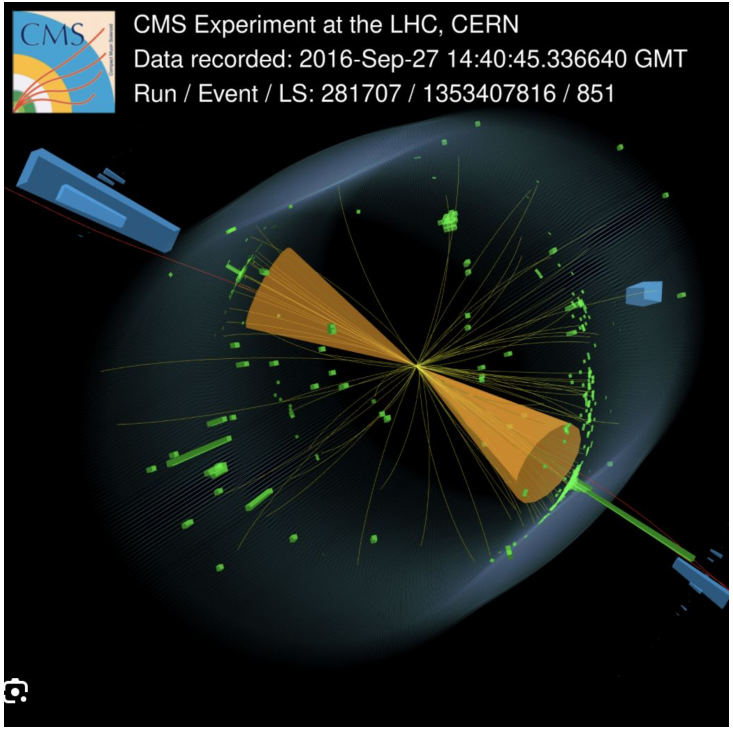


- Measurements of fundamental QCD properties
  - Determination of α_s
  - Spin asymmetries
  - Probe of Quark-Gluon plasma
  - (n)PDF constraints
  - …



pp collisions

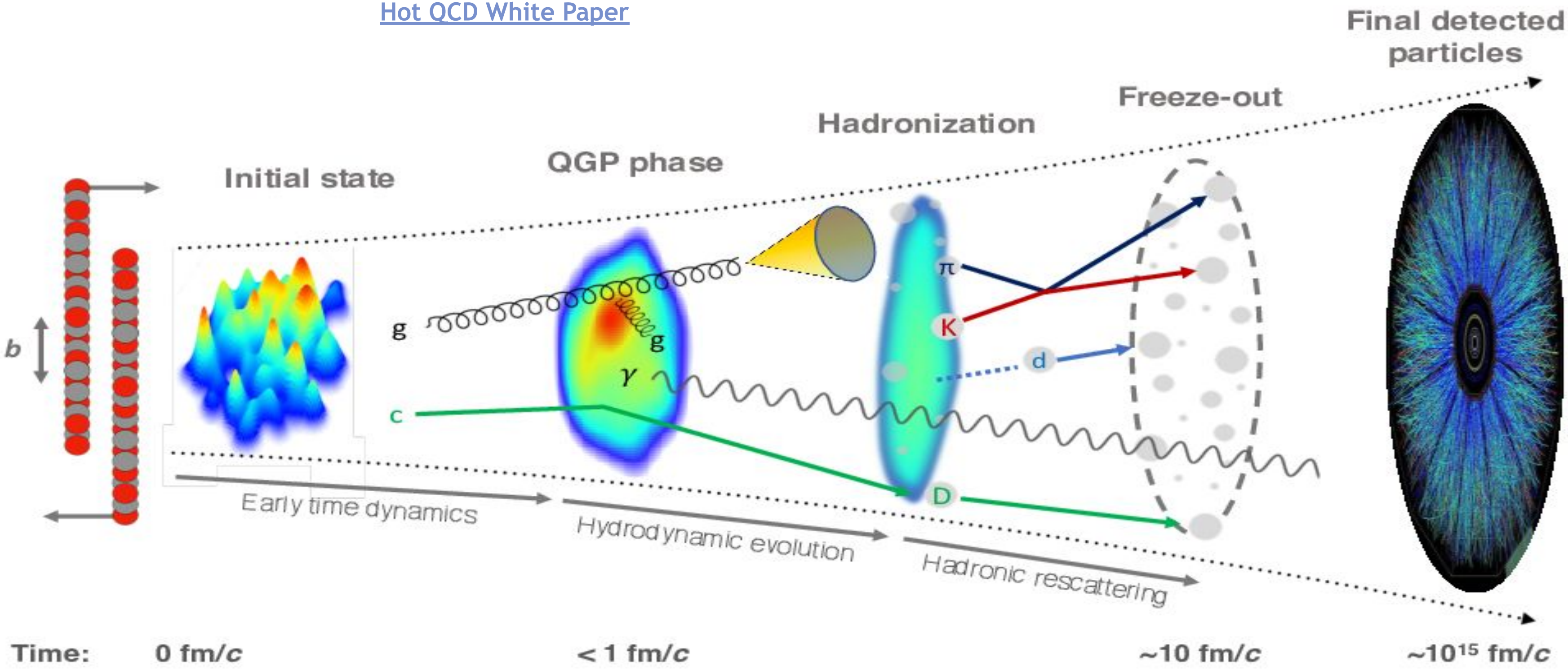




➤ Hard scattering of two quarks produces back-to-back jets

AA collisions

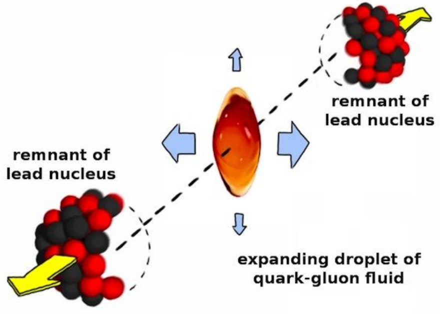
Hot QCD White Paper



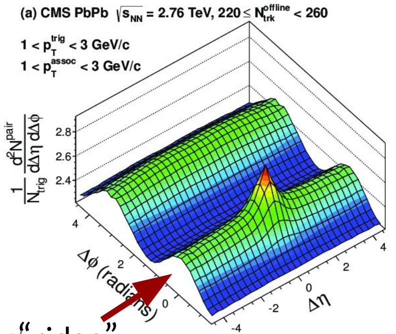
QGP signatures

- Signatures
  - Collective behavior (flow)
  - Strangeness enhancement
  - Quarkonia suppression
  - Electroweak probes
  - Jet quenching
  - …

- Observed at both RHIC/BNL and LHC/CERN



news.vanderbilt.edu/2012/05/16/quark-soup/

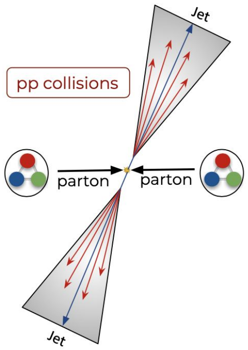


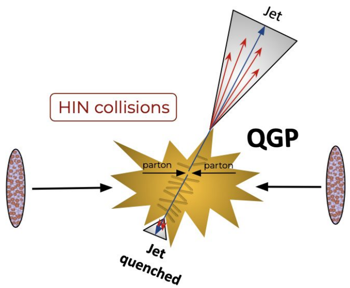
“ridge”

Phys. Lett. B 724 (2013) 213

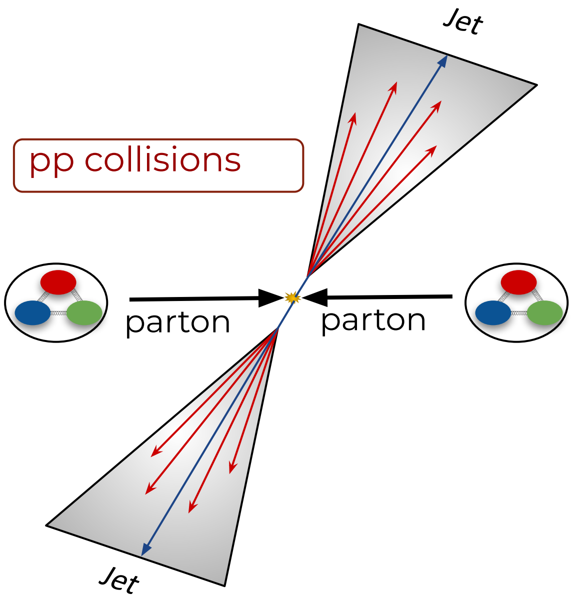
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_{\mathrm{T}}}\frac{d^2N}{dp_{\mathrm{T}}dy}\left(1 + 2\sum_{n=1}^{\infty} v_{\mathrm{n}}\cos[n(\phi - \Psi_n)]\right)$$

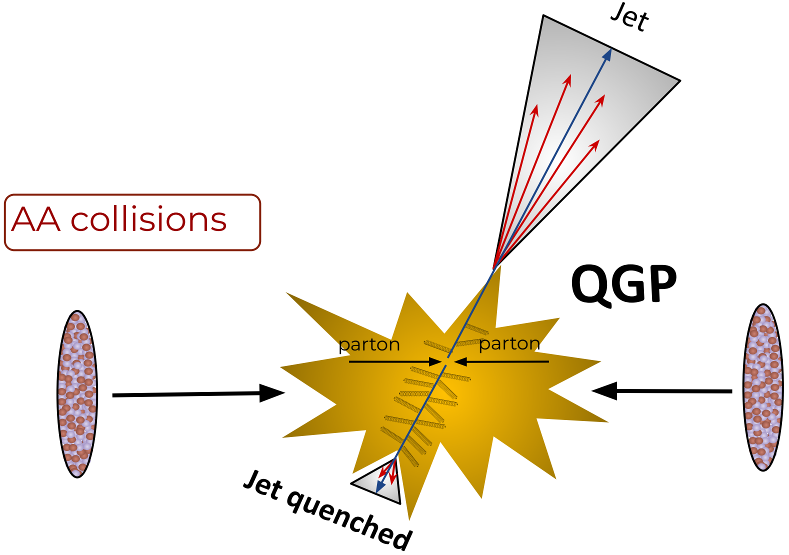
v_n: flow coefficients



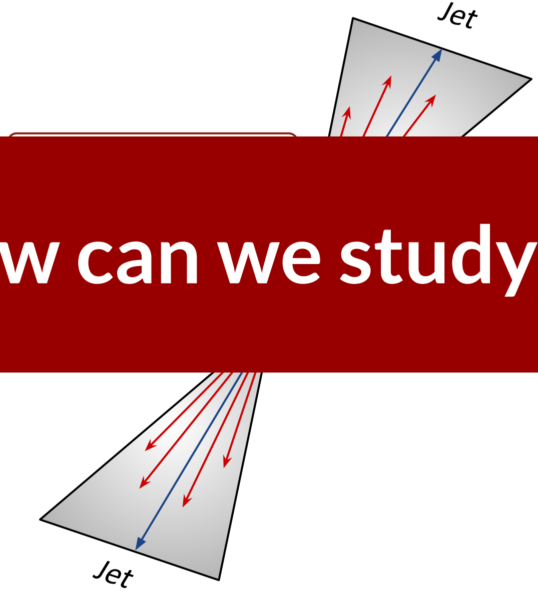


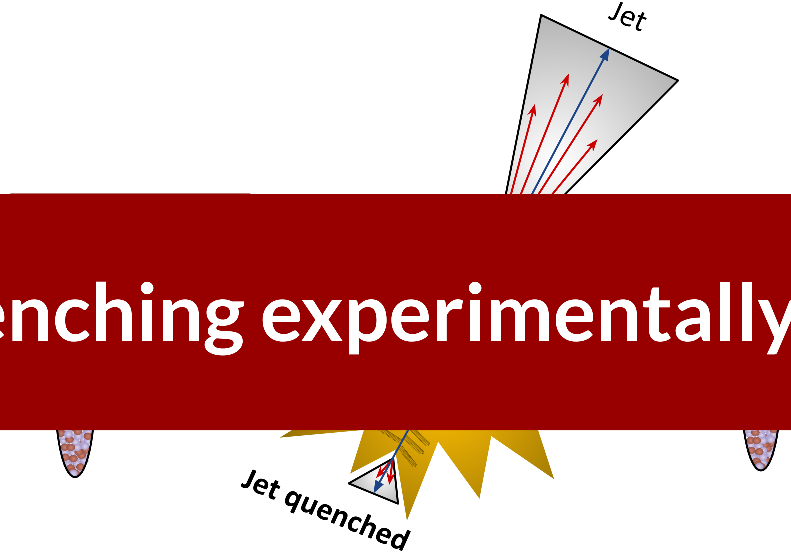
Comparing pp and AA





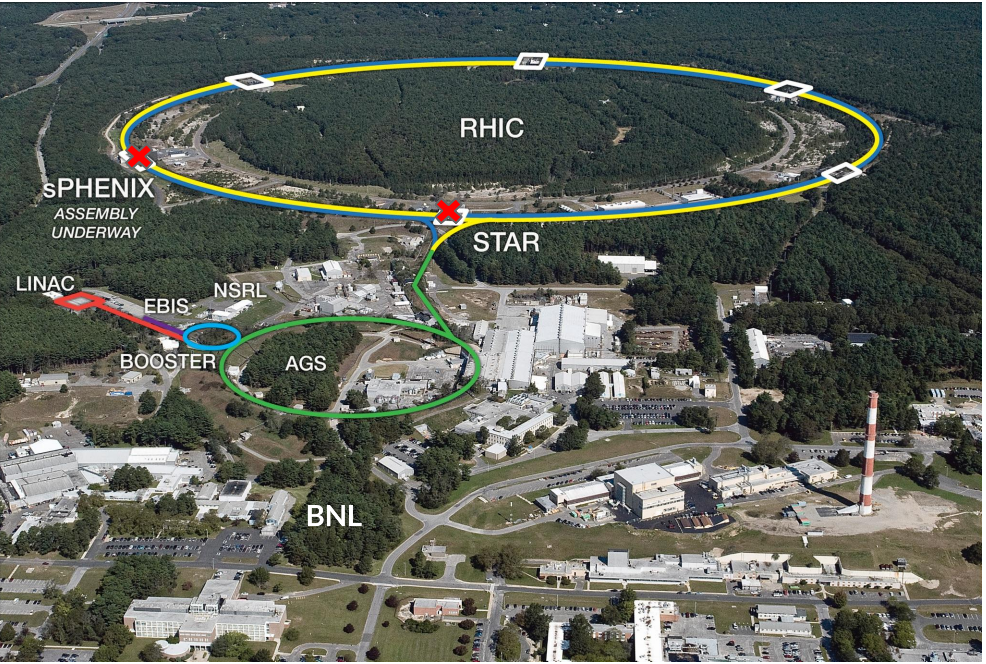
Comparing pp and AA

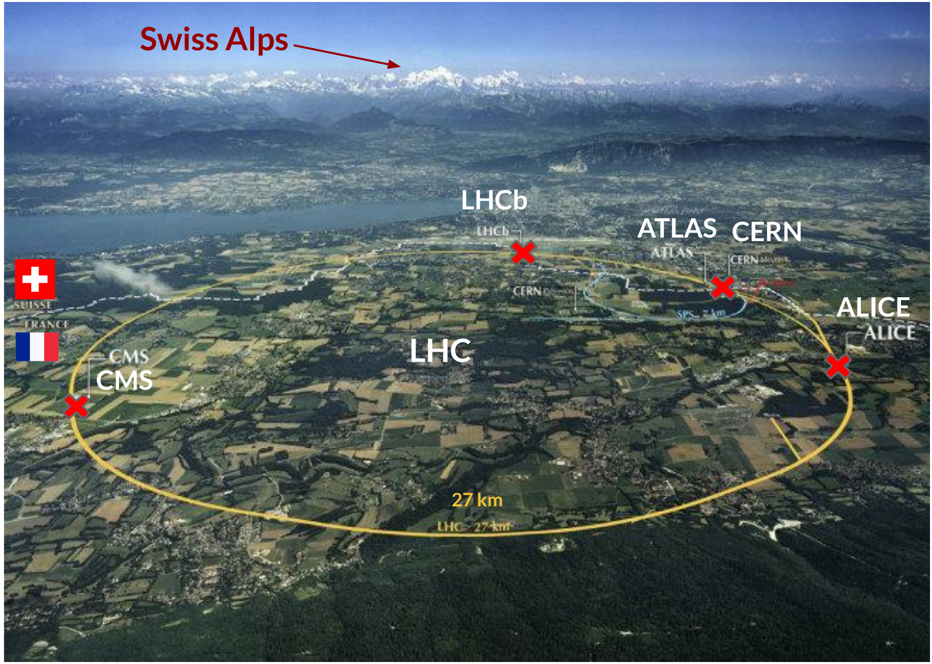




How can we study jet quenching experimentally?

Accelerators and Detectors

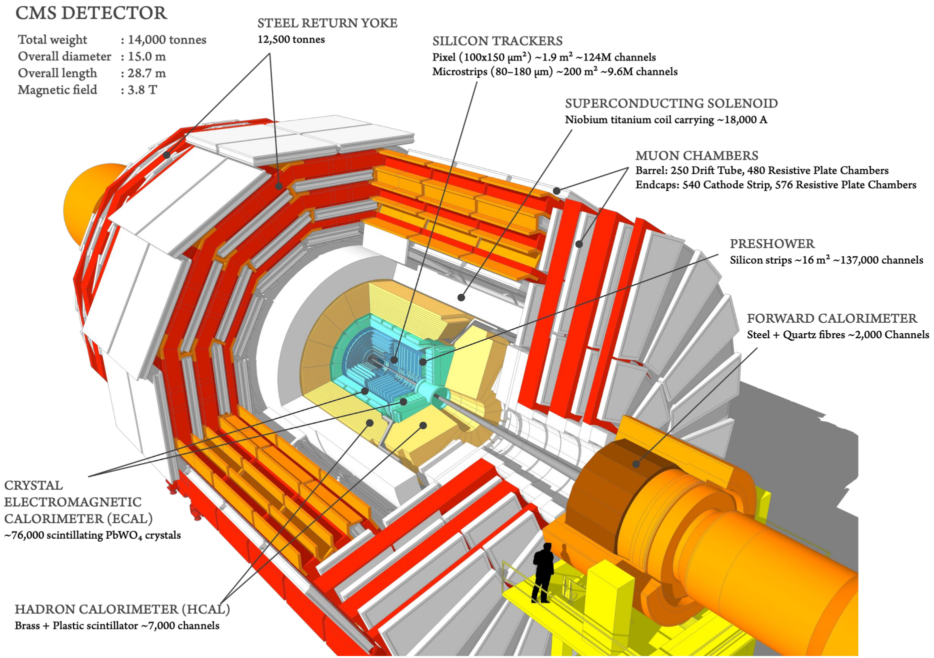


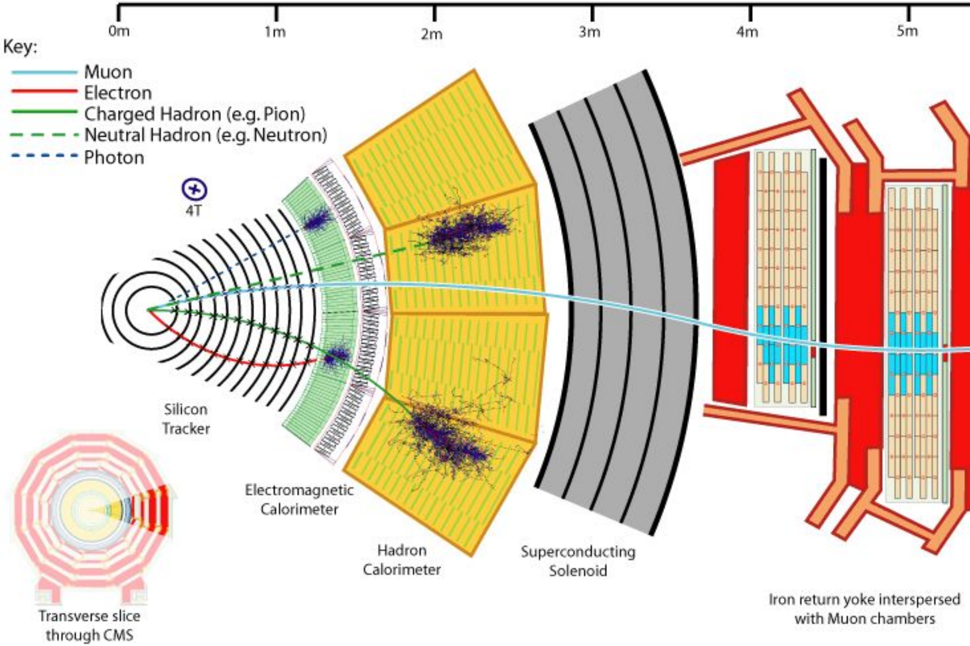


Relativistic Heavy-Ion Collider (RHIC) at BNL
Colliding Particle species: p, d, He^3, O, Au, Al, Cu, Zr, Ru, U
Energies: 7.7 GeV to 510 GeV

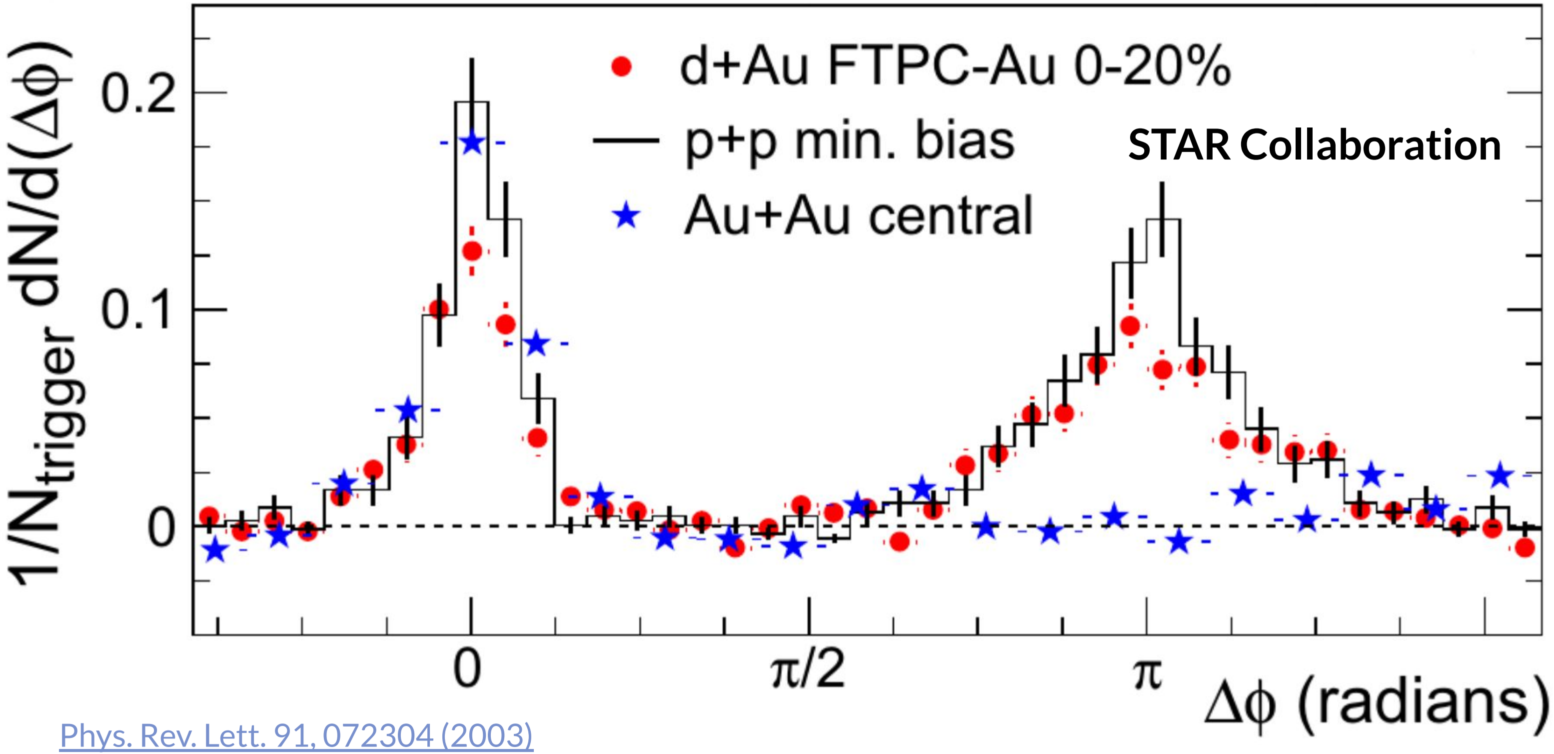
Large Hadron Collider (LHC) at CERN
Colliding Particle species: p, O, Xe and Pb
Energies: 900 GeV to 13.6 TeV

The CMS Detector



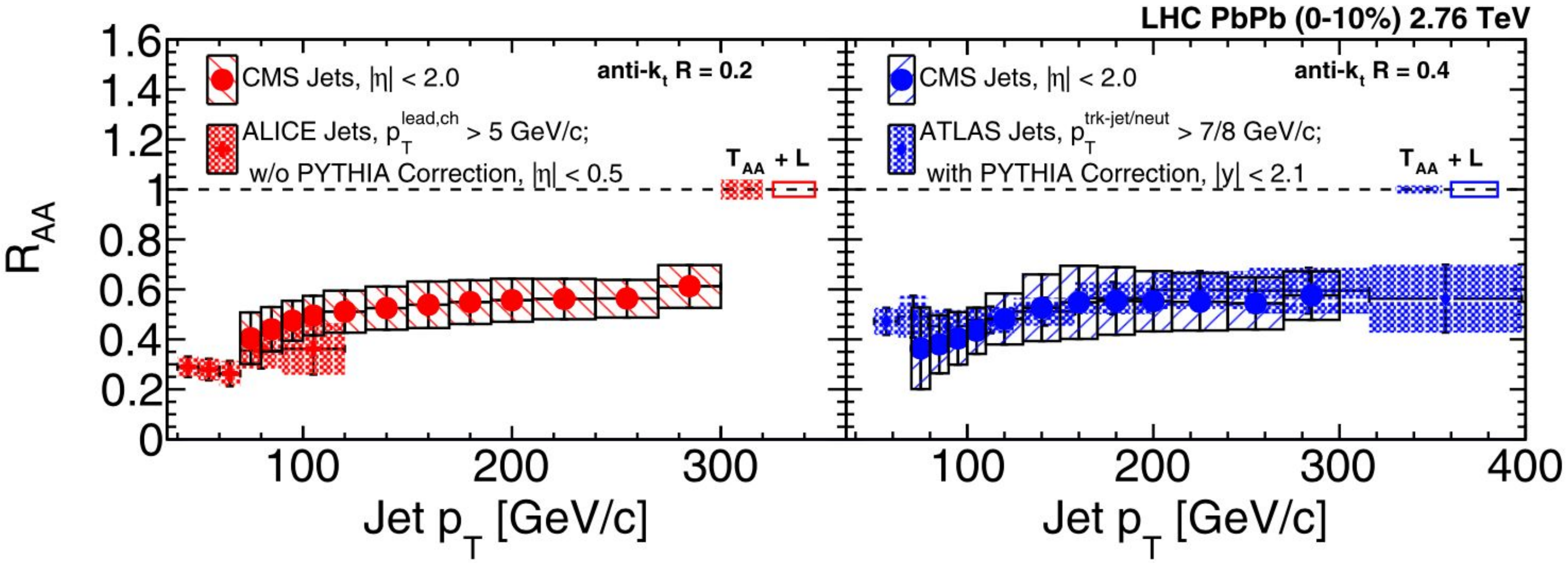


The first measurement of “jet” quenching



Phys. Rev. Lett. 91, 072304 (2003)

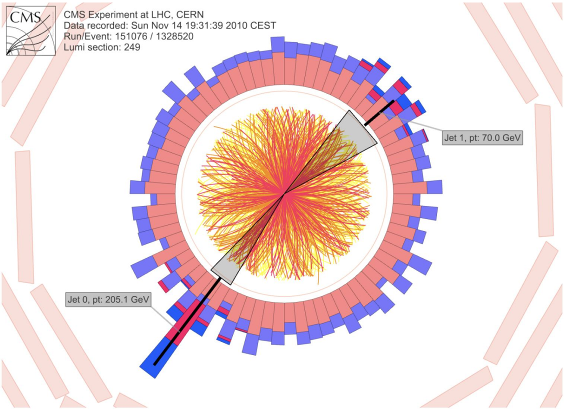
Jet nuclear modification factor

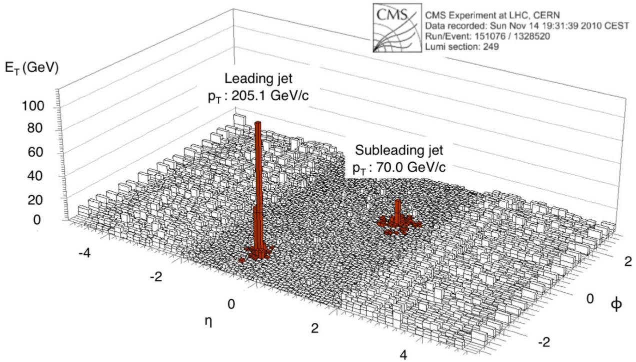


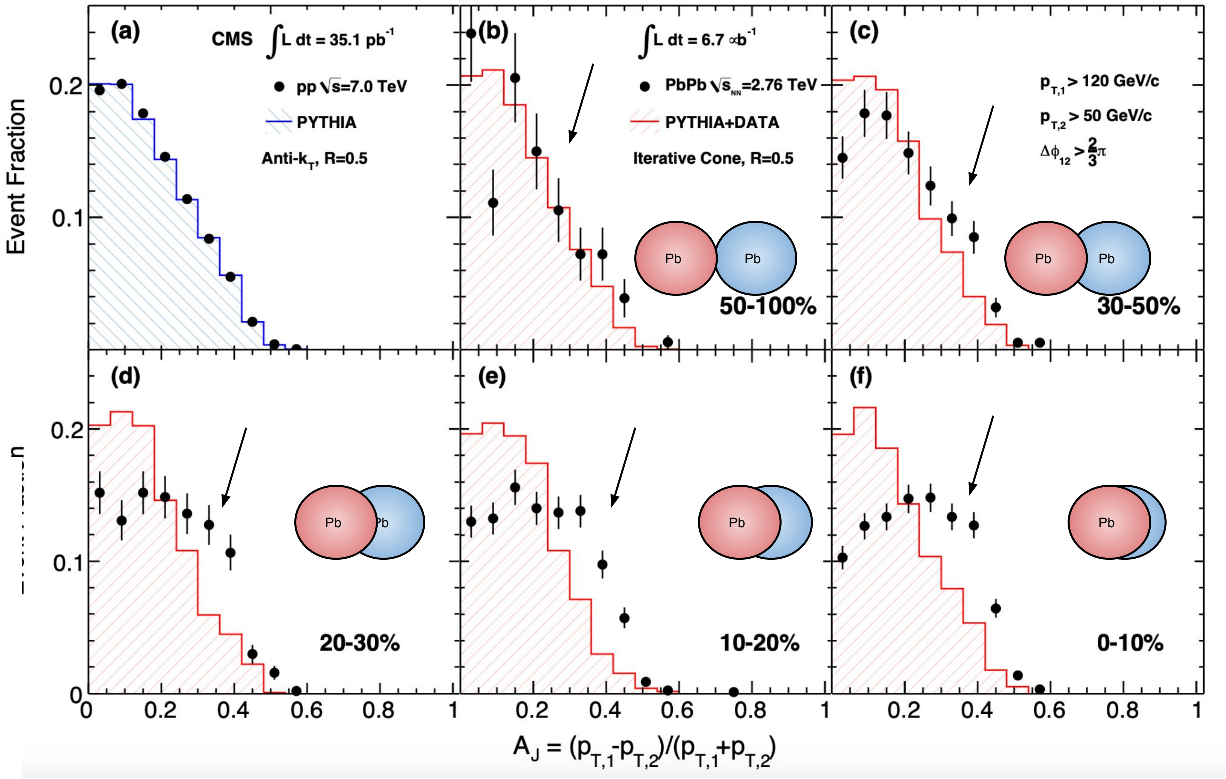
Phys. Rev. C 96 (2017) 015202

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

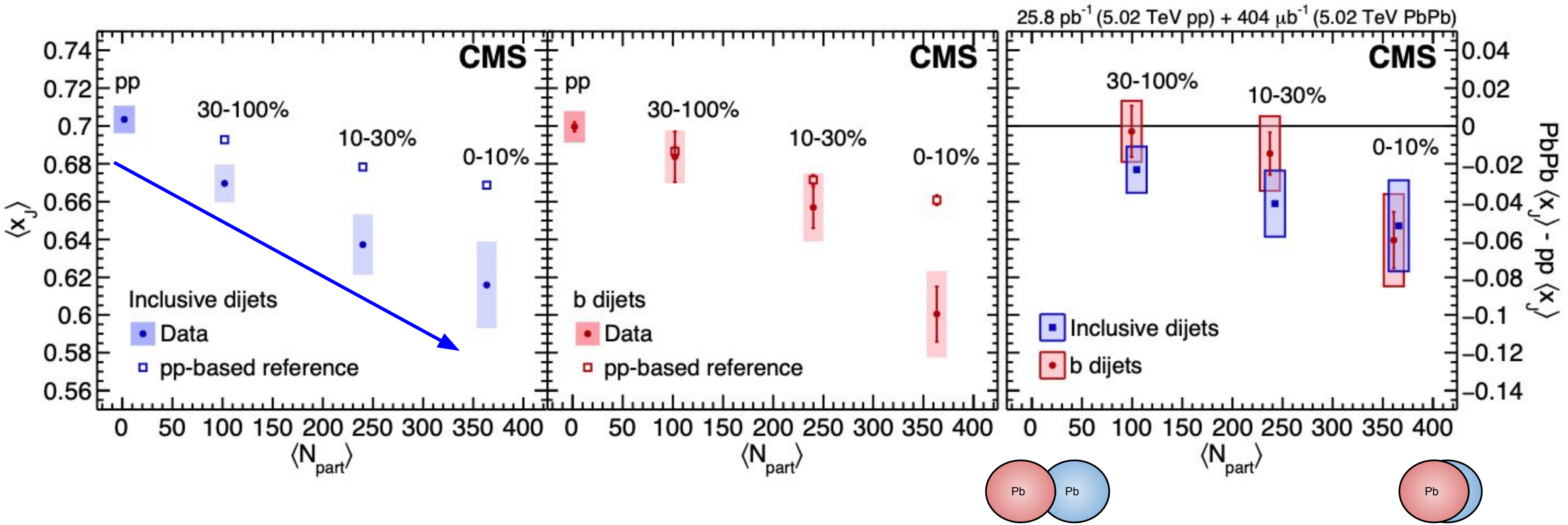
Jet asymmetry







Jet imbalance



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

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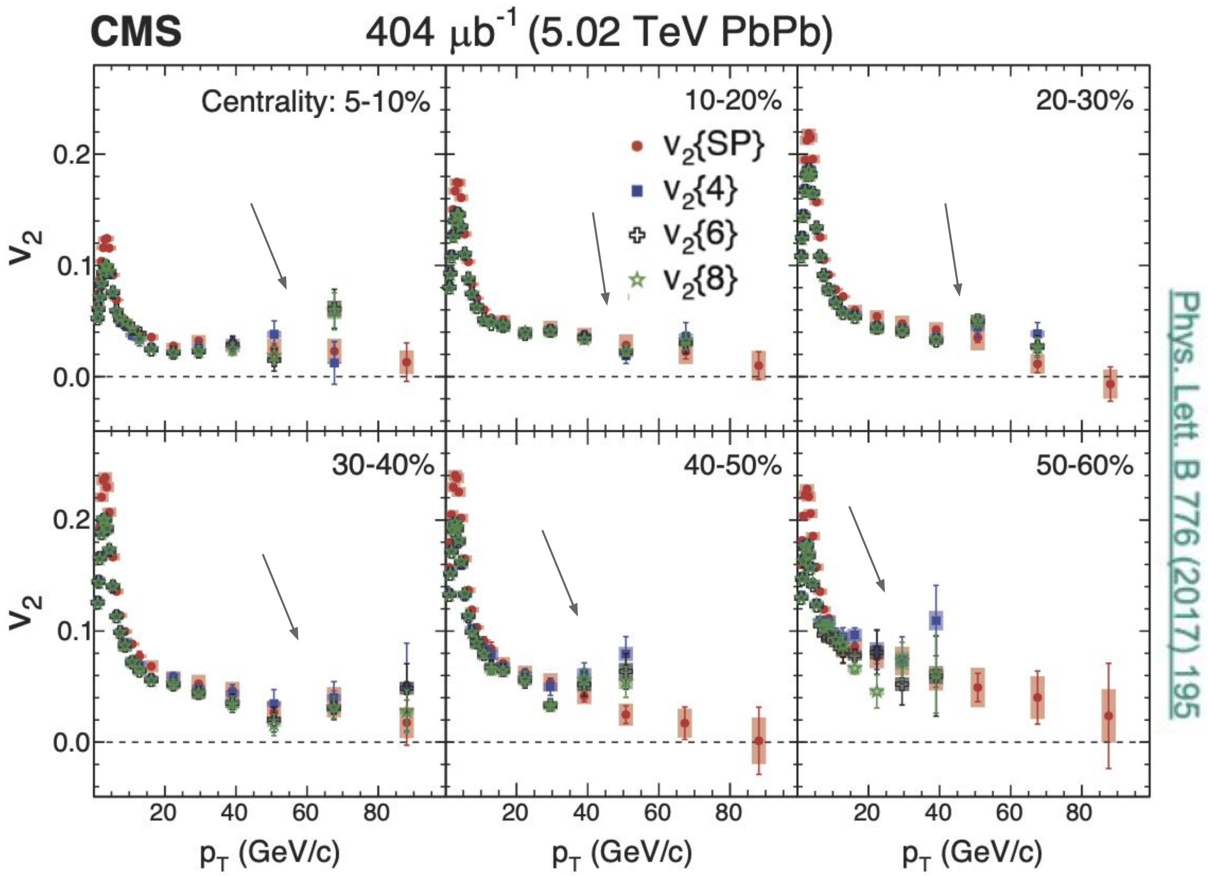
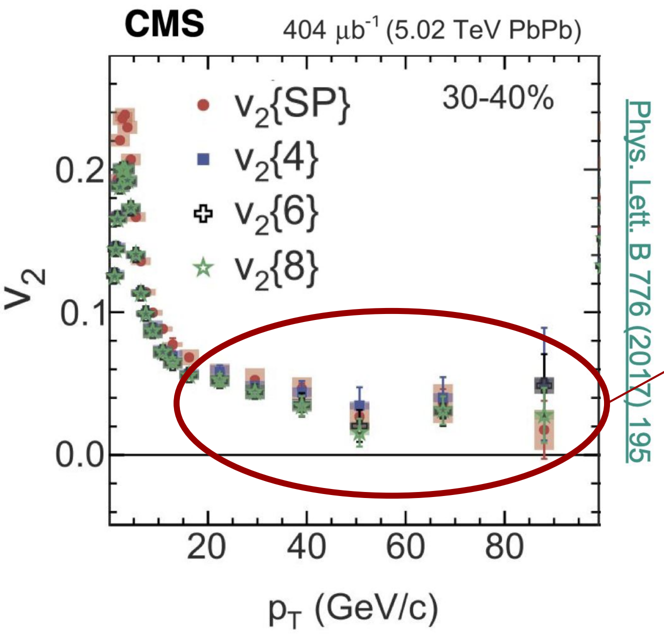
Connection between jet quenching and flow (I)



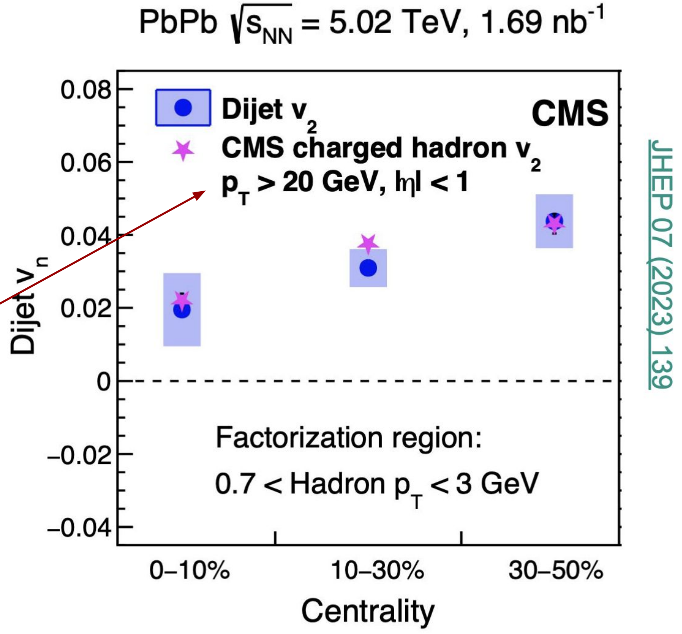
Non-zero High-p_T Hadron v_2

Connection between jet quenching and flow (II)

Hadron v_2

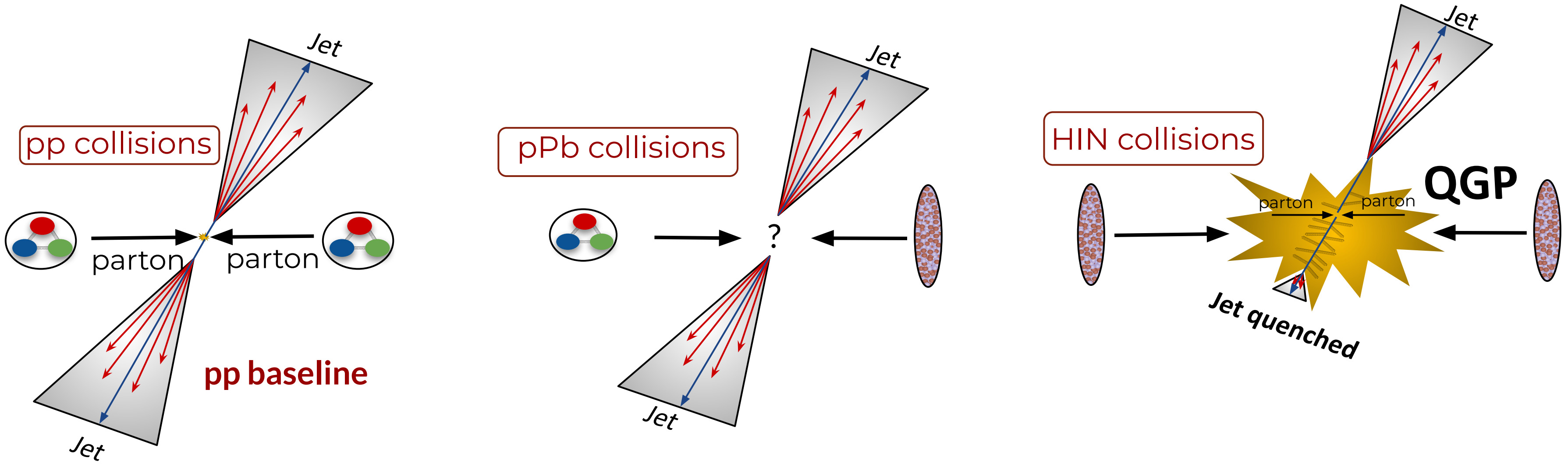


Dijet v_2



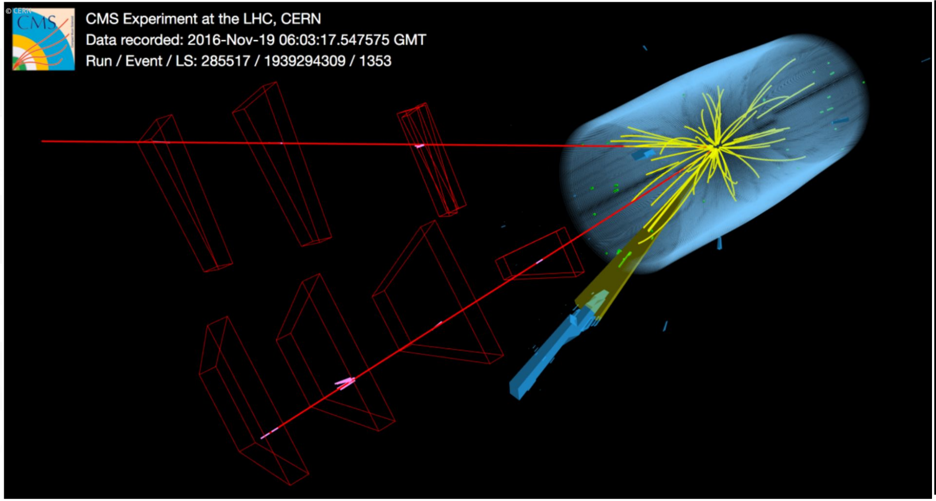
➢ Consistent with expectations from a path-length dependence of in-medium energy loss

What about pPb collisions?

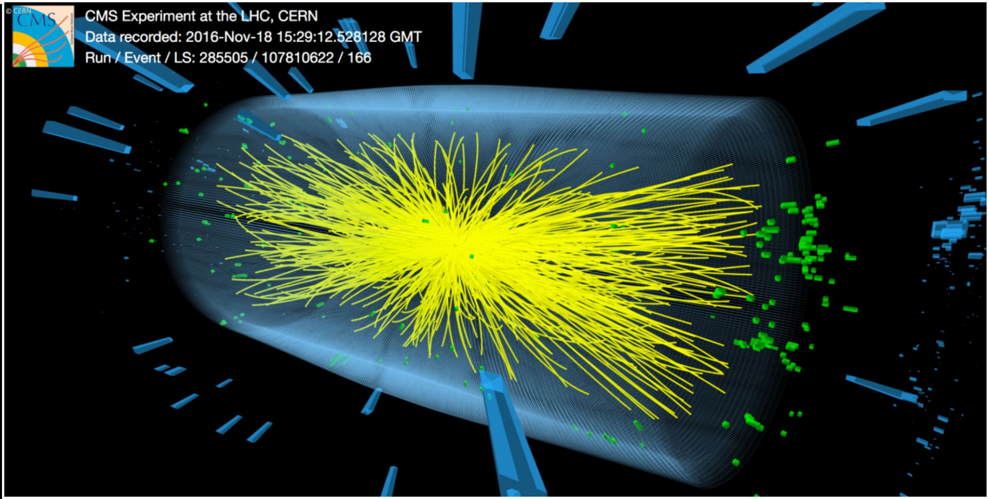


High-multiplicity events

minimum-bias event

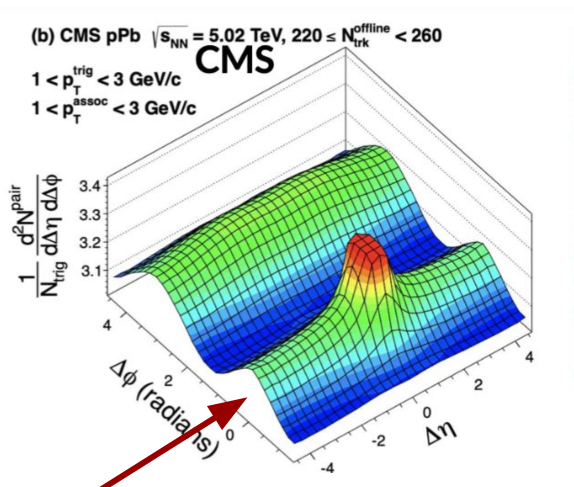


high-multiplicity event



up to 400 tracks

Collectivity everywhere!!



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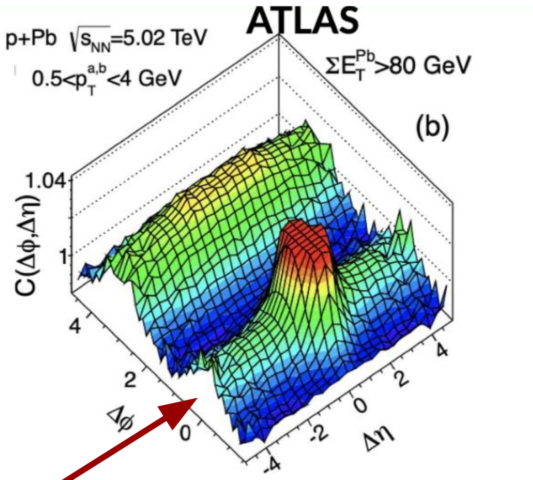
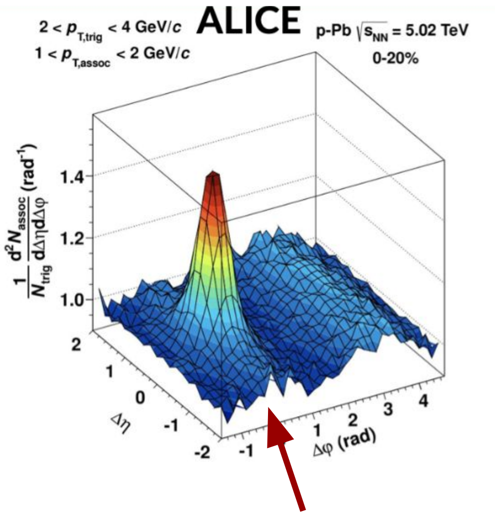
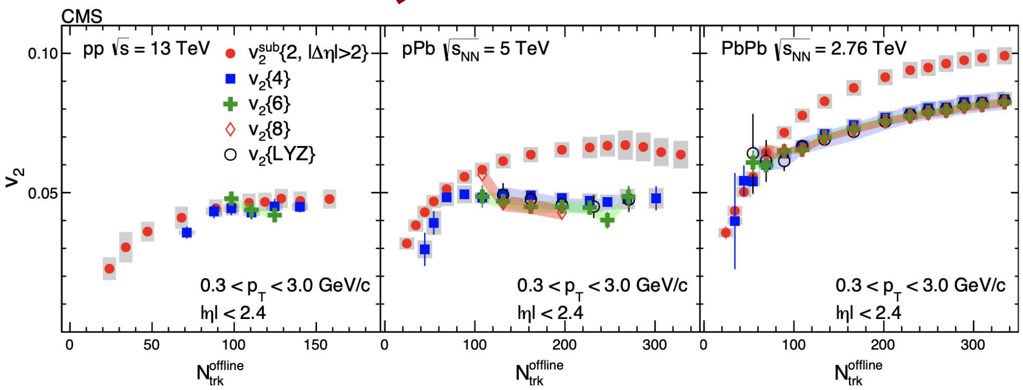


Phys. Rev. Lett. 110, 182302 (2013)



Phys. Lett. B 719 (2013) 29

Phys. Lett. B 765 (2017) 193



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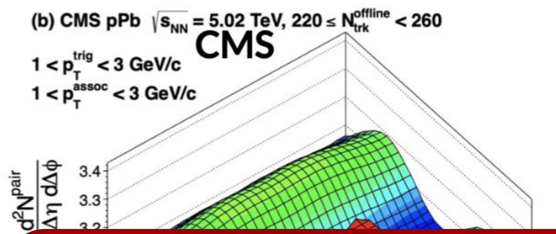
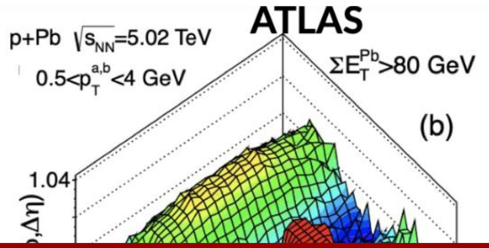
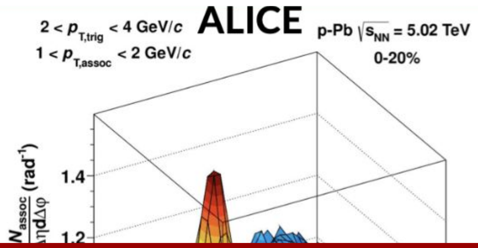


Phys. Lett. B 724



Phys. Rev. Lett. 11



Phys. Lett. B 7

Do we observe high-p_T flow in small systems?

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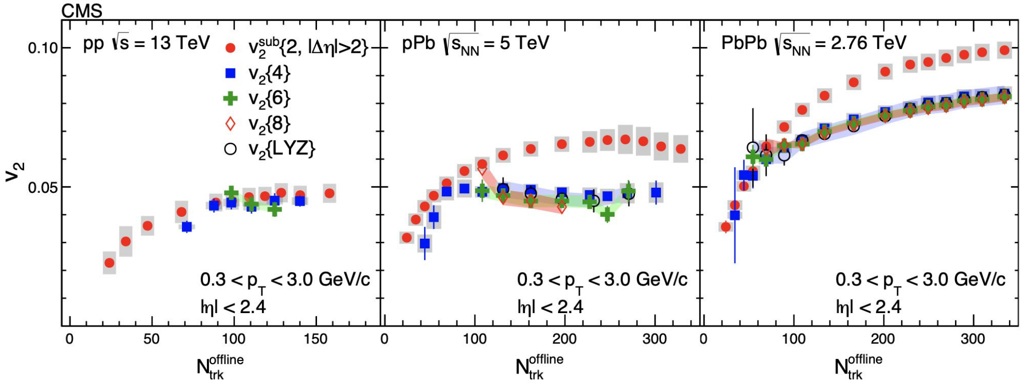
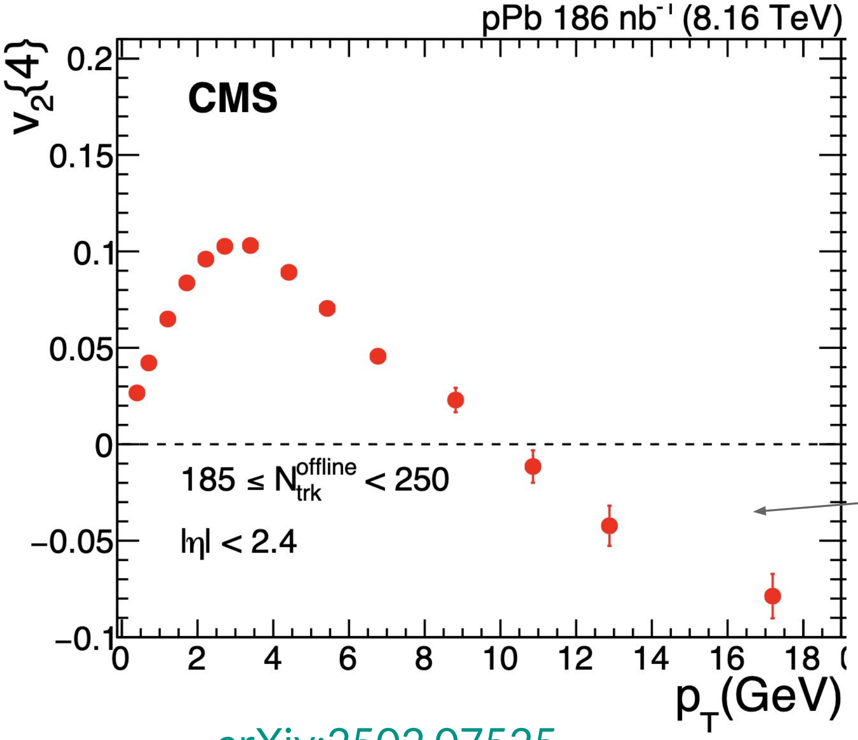
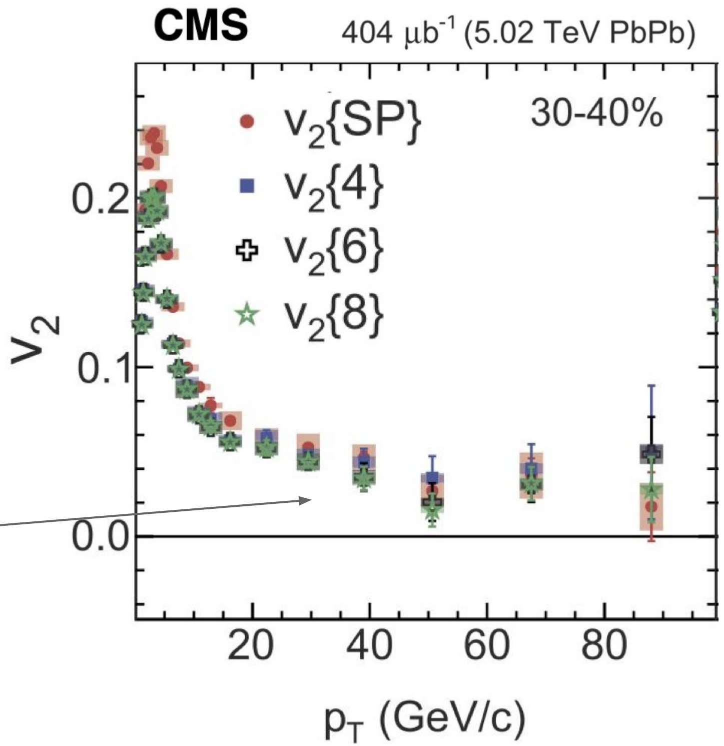


How about high-p_T flow in pPb? (I)



arXiv:2502.07525

?



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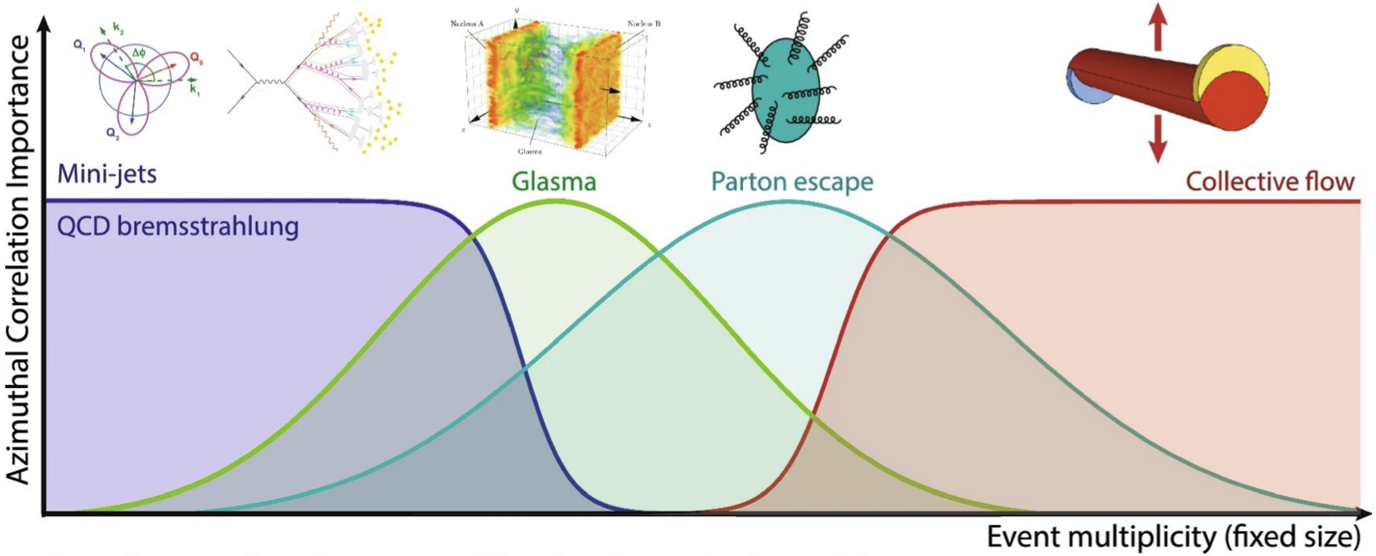
How about high-p_T flow in pPb? (II)

Various sources of anisotropy

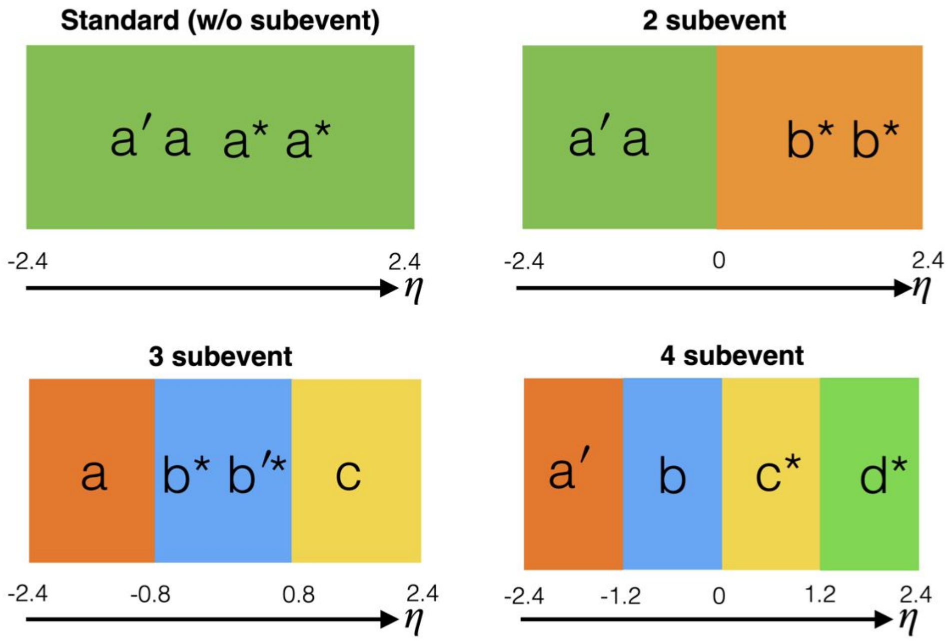


A schematic diagram. Vertical scale is arbitrary

M. Strickland, 1807.0719

How about high-p_T flow in pPb? (II)

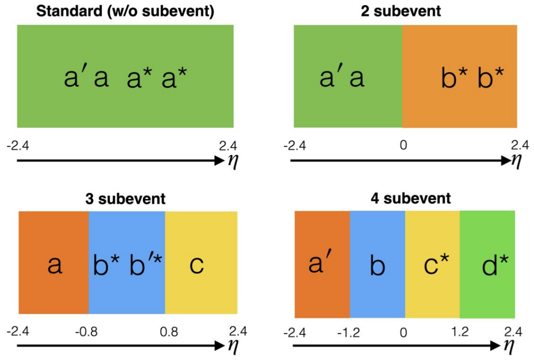
- Non-flow subtracted using subevent method
  - Data-driven method

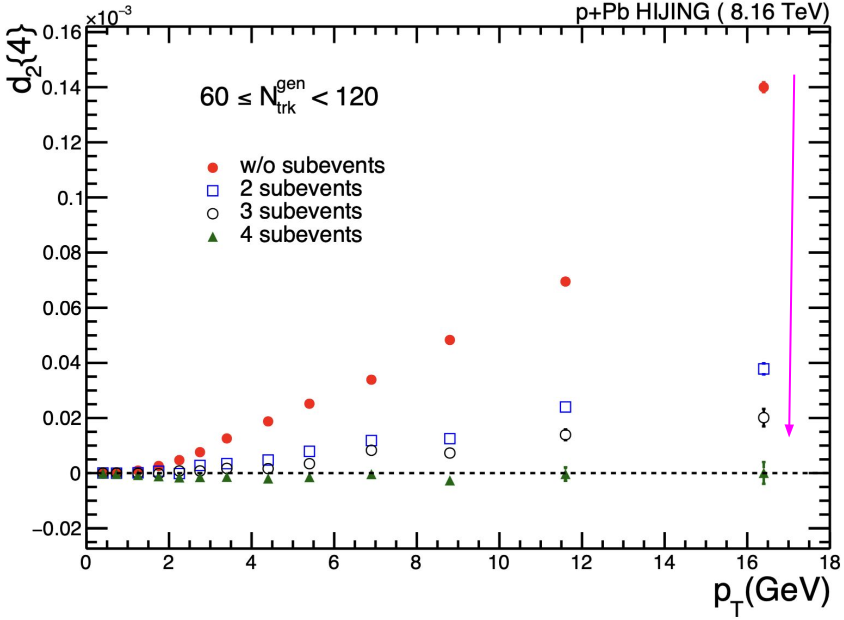


arXiv:2502.07525 (sub. to PRL)

How about high-p_T flow in pPb? (II)

- Non-flow subtracted using subevent method
  - Data-driven method
  - HIJING does not include collectivity: good check





$$v_n\{4\} = -d_n\{4\}/(-c_n\{4\})^{3/4}$$

Rohit's QM2025 slides

How about high-p_T flow in pPb? (II)

- Non-flow subtracted using subevent method
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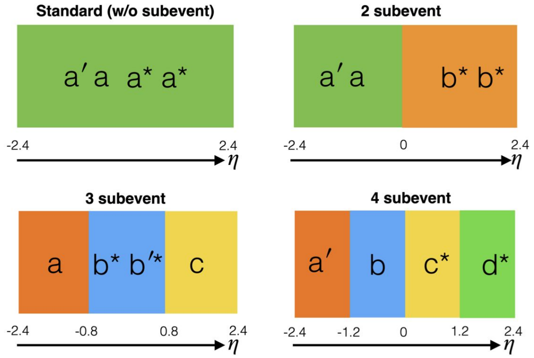

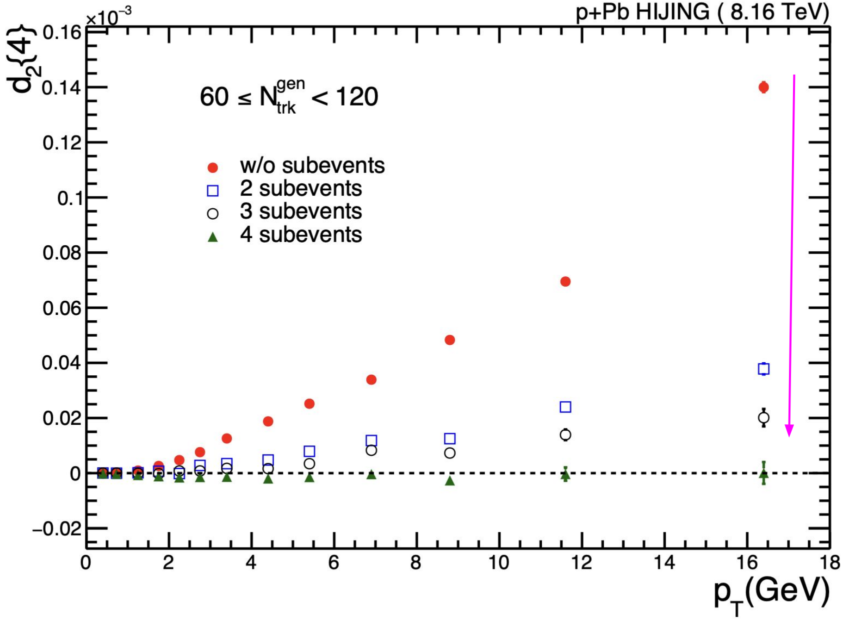

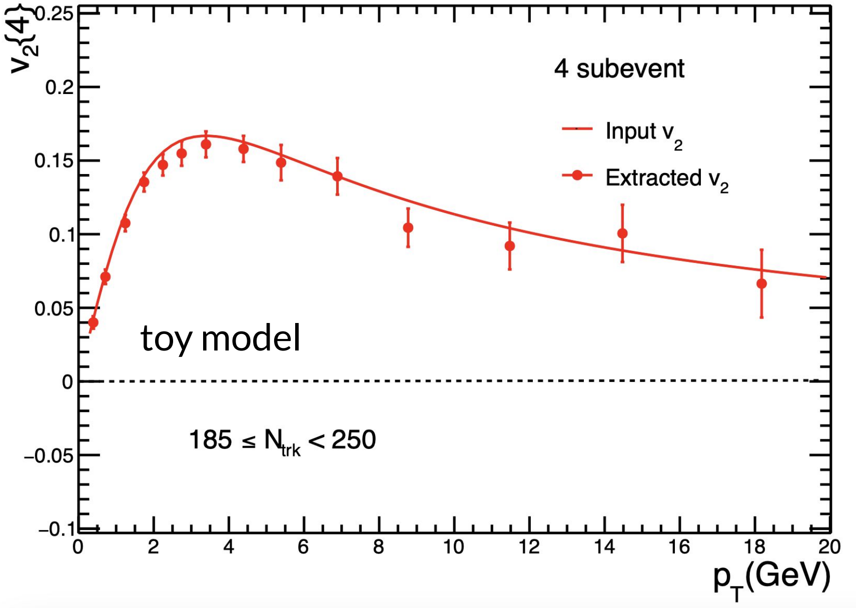

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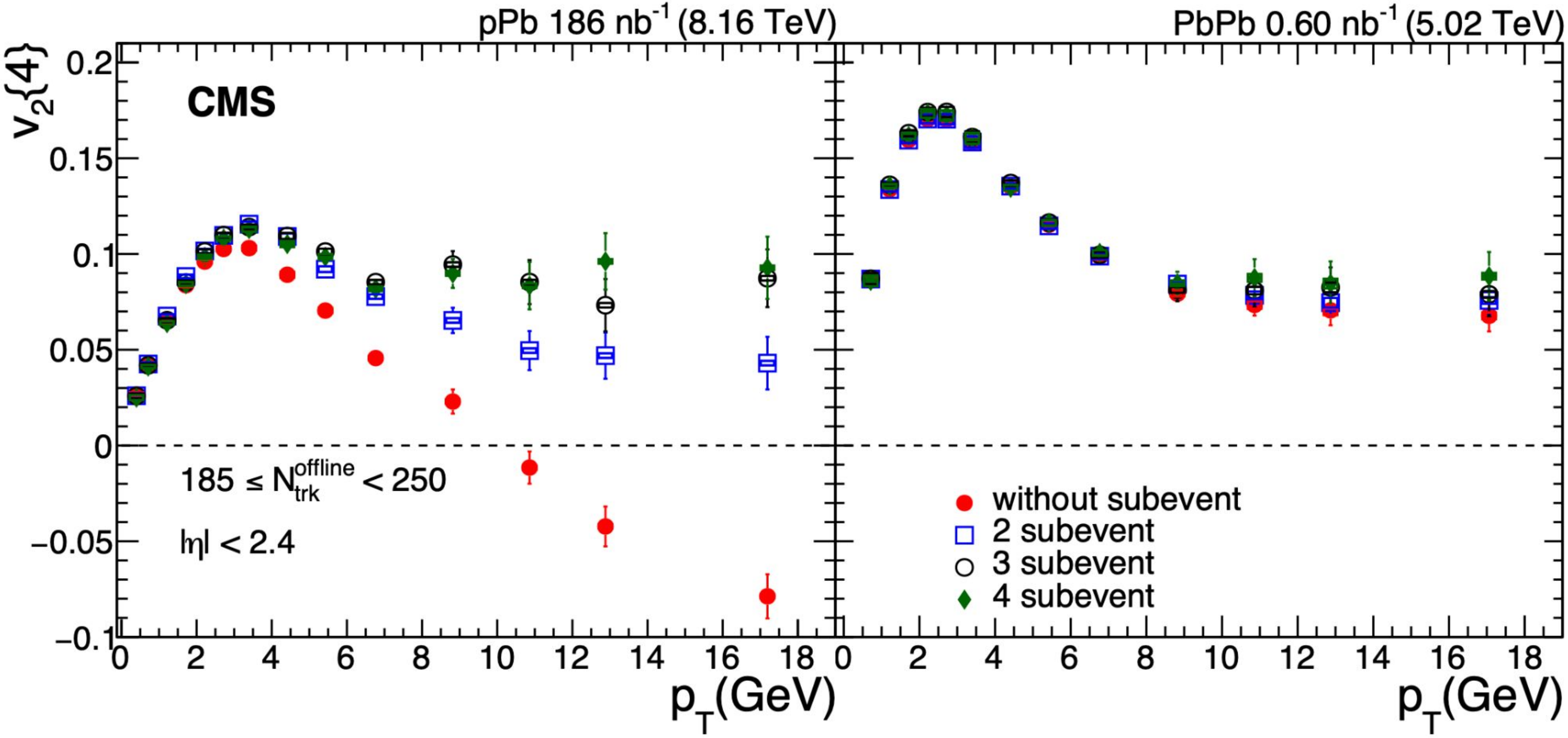
Rohit's QM2025 slides

How about high-p_T flow in pPb? (III)

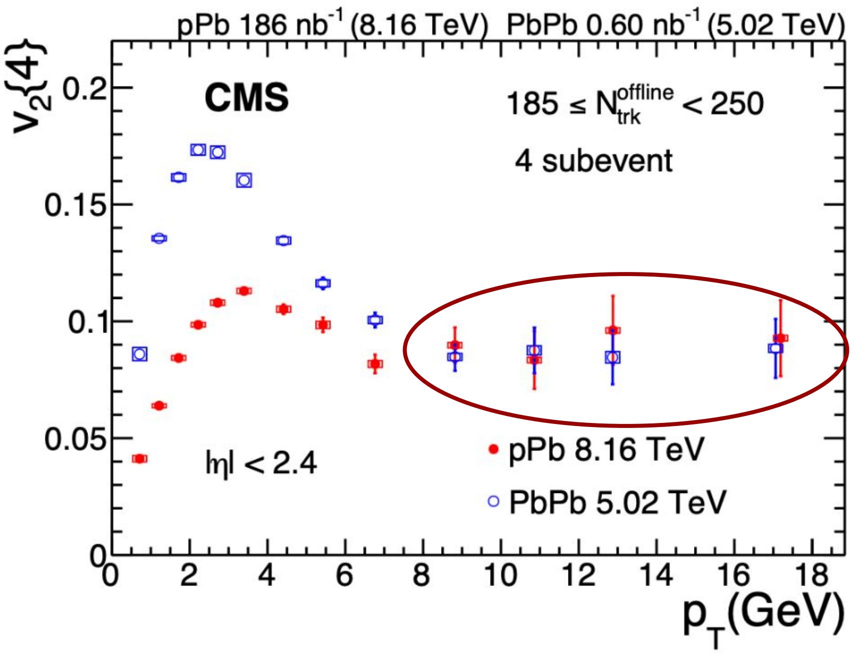


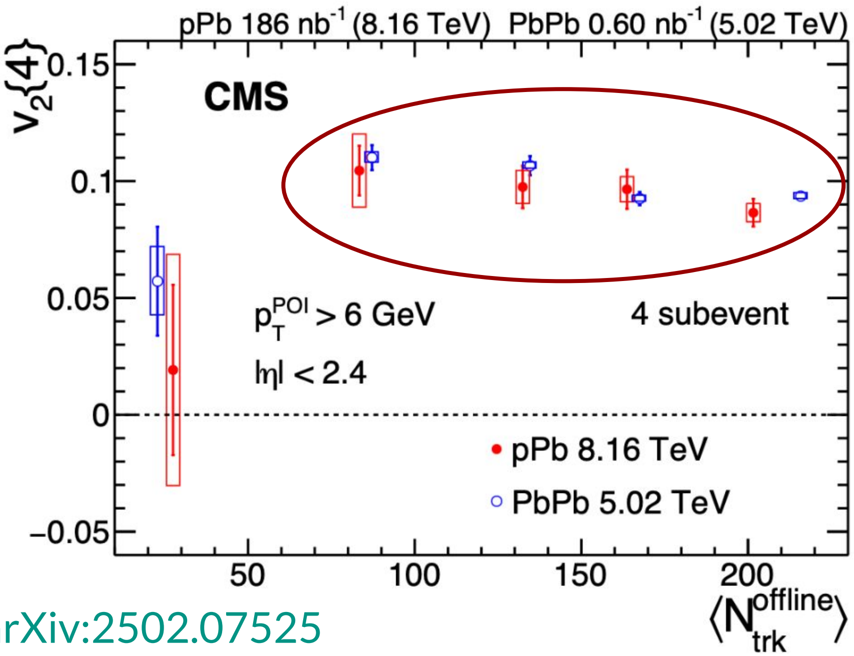
arXiv:2502.07525

Positive pPb $v_2\{4\}$ after non-flow removal

PbPb $v_2\{4\}$ non-sensitive to non-flow

How about high-p_T flow in pPb? (IV)

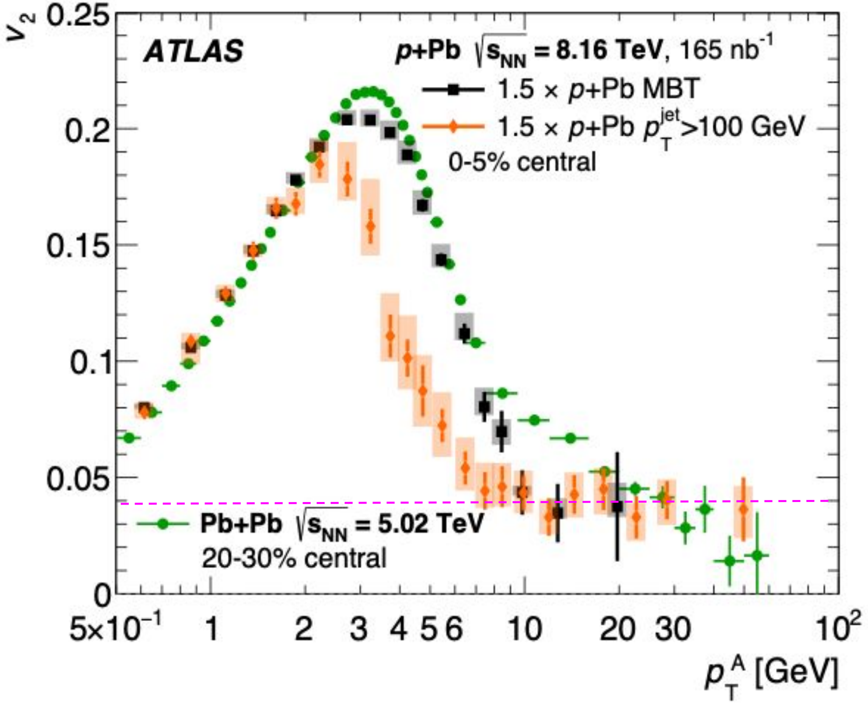




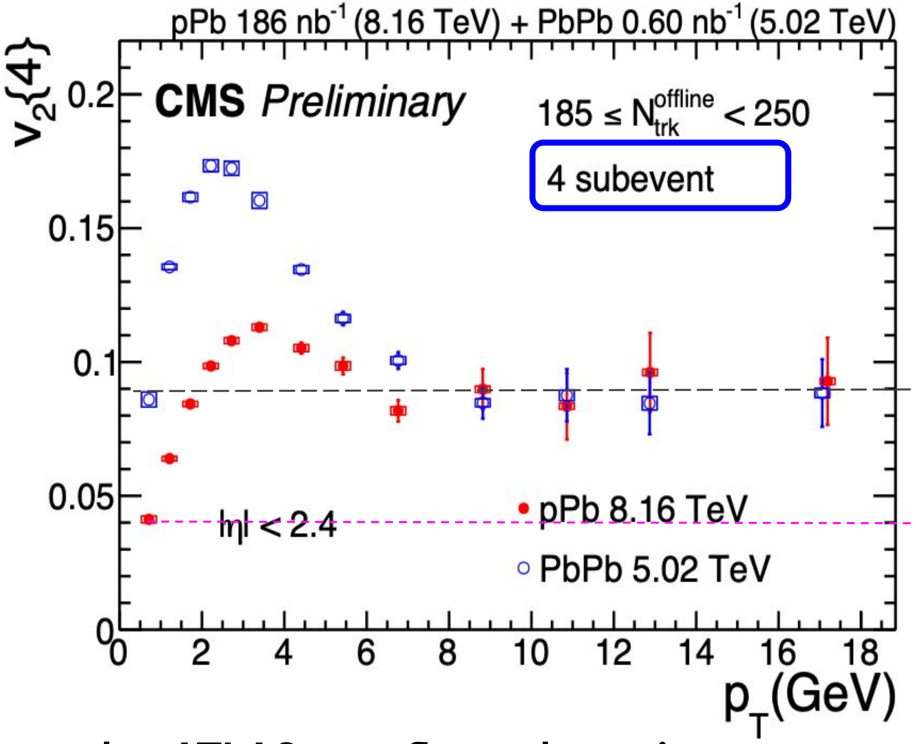
arXiv:2502.07525

Good agreement in PbPb and pPb: path-length dependence of in-medium energy loss?

Comparison between ATLAS and CMS



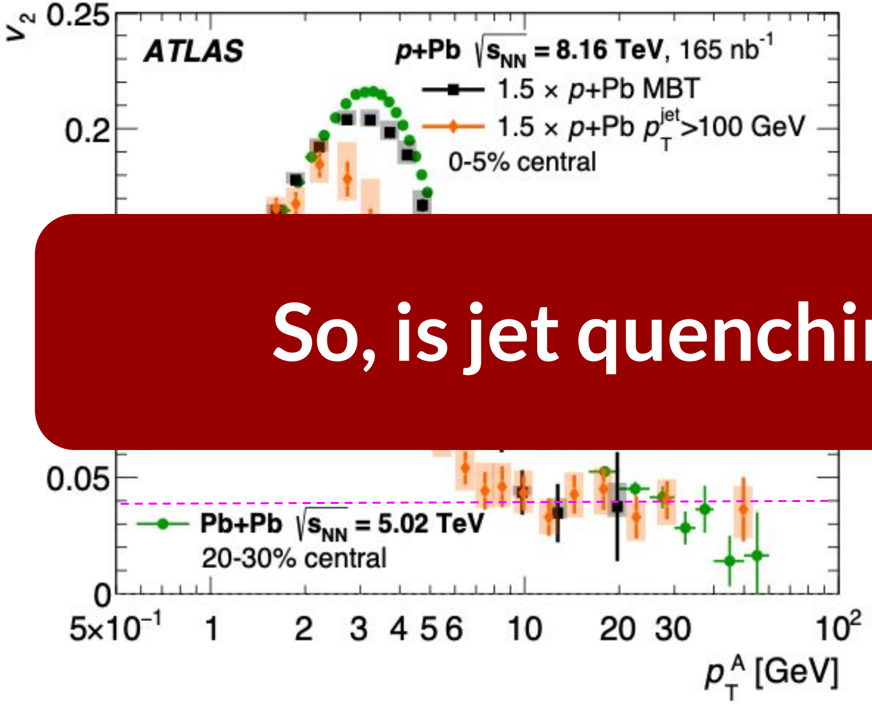
Eur. Phys. J. C 80 (2020) 73



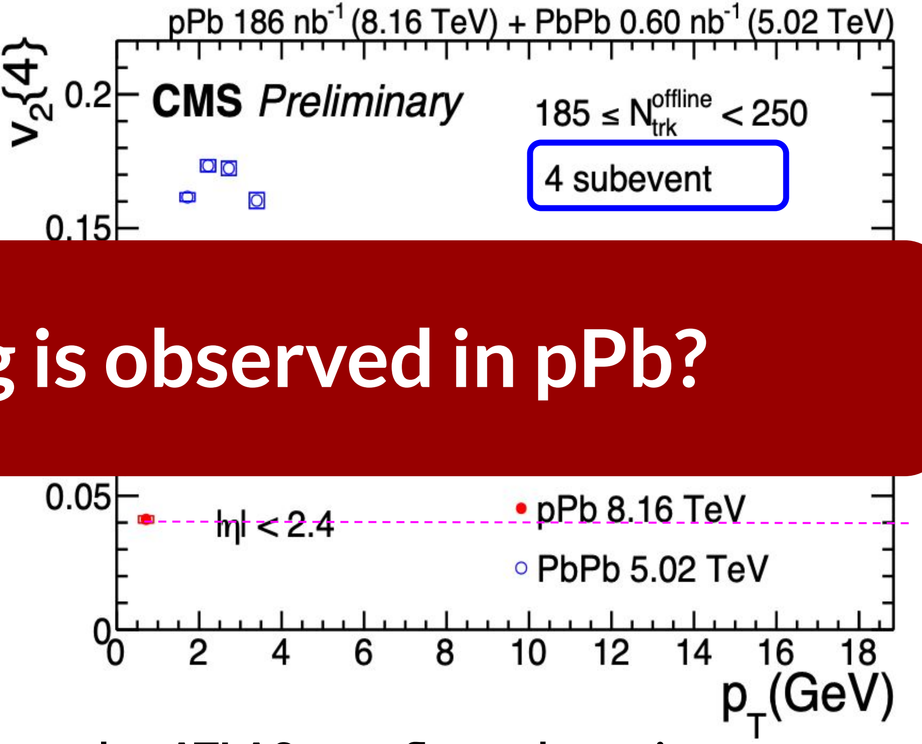
arXiv:2502.07525

Larger v_2 from CMS when compared to ATLAS: non-flow subtraction

Comparison between ATLAS and CMS



Eur. Phys.

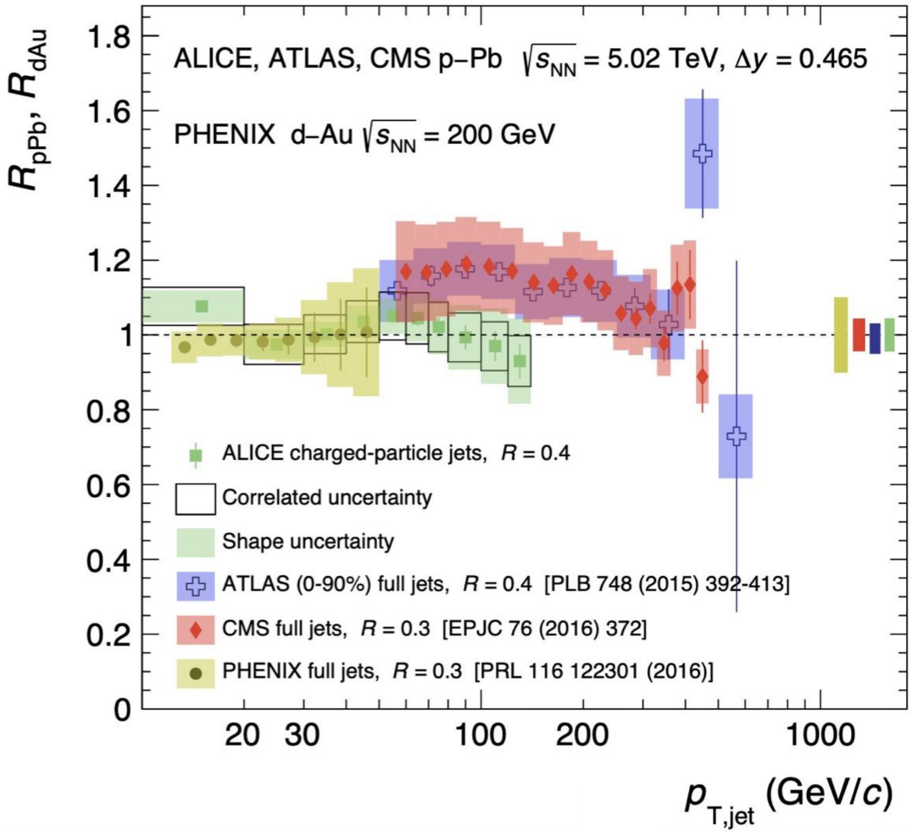


arXiv:250

So, is jet quenching is observed in pPb?

Larger v_2 from CMS when compared to ATLAS: non-flow subtraction

Jet measurements: nuclear modification factor



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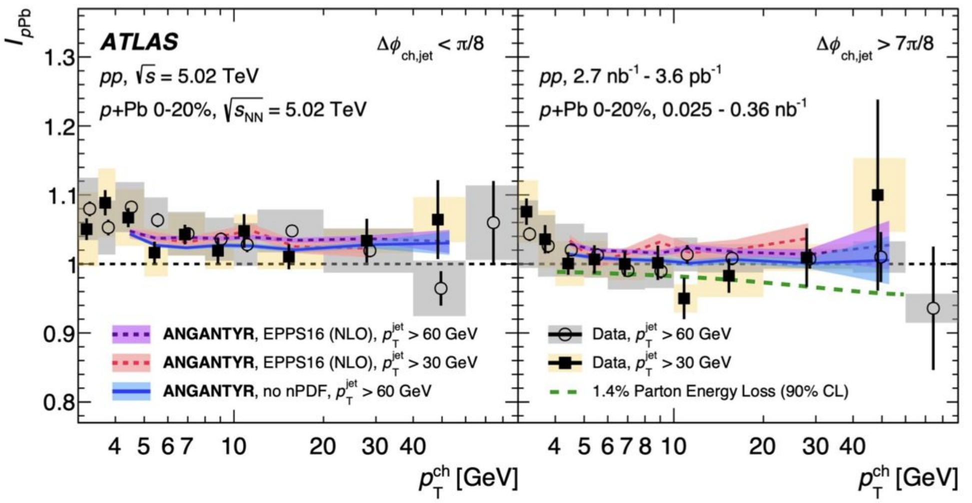
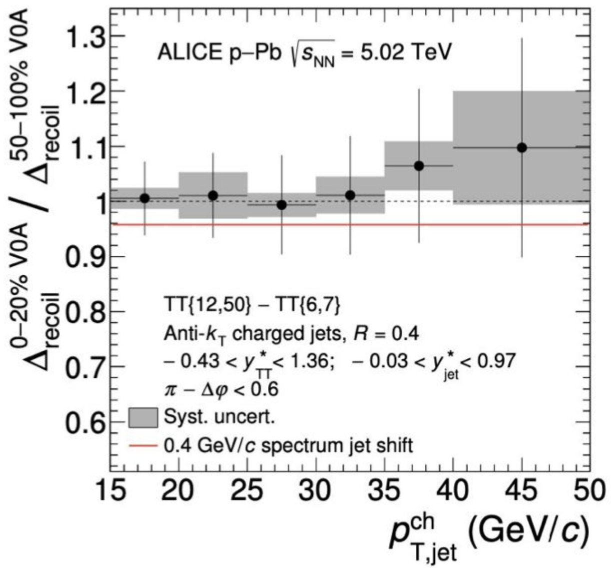
No suppression observed in R_{aA}

Jet quenching constraints at LHC



Phys. Rev. Lett. 131 (2023) 072301



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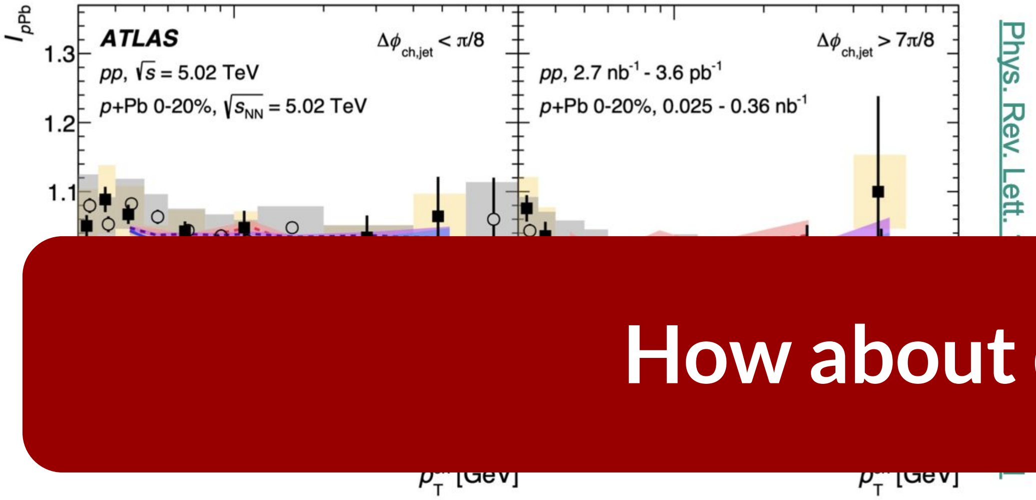
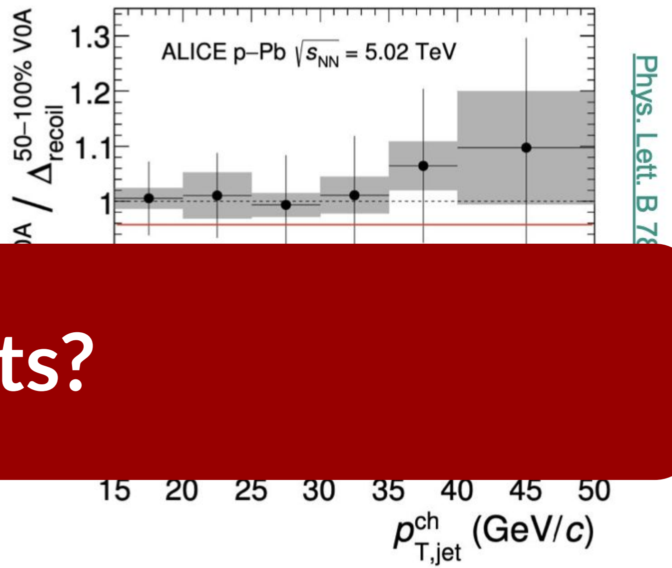
- ➤ Ratio of charged-particle yields per jet
  - ⇨ $I_{pPb} = Y_{pPb}/Y_{pp}$
- ➤ 1.4% Parton E-Loss at 90% C. L.

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

Jet measurements: nuclear modification factor





How about dijets?

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

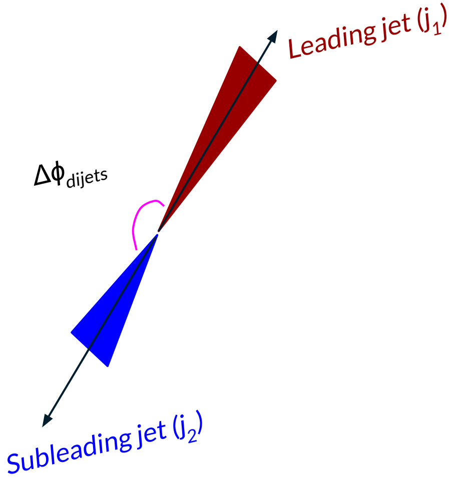
- ➢ Jet-track recoil
- ➢ Limit on out-of-cone energy transport due to jet quenching of < 400 MeV at 90% C.L.

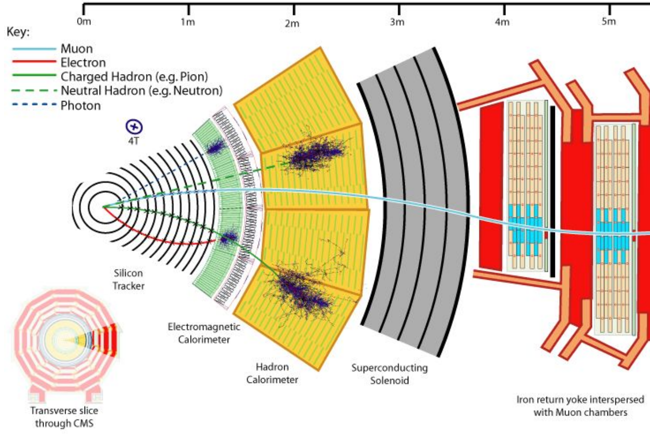
Measurement setup

- 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 (dijet momentum balance)

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

- 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





arXiv:2504.08507
(accepted for pub in JHEP)

x_j dependency

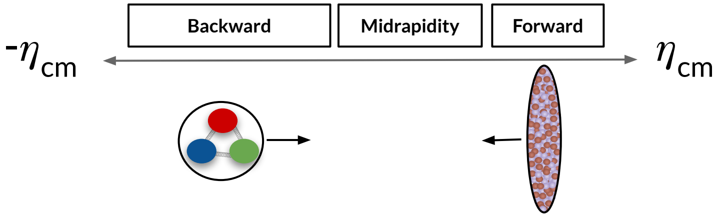
- Study of x_j as function of multiplicity and pseudorapidity
  - Multiplicity ranges: **[10,60]**, [60,120], [120,185], **[185,250] and [250,400]**

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 (***x* between ~0.03 and ~0.28**)
    - Midrapidity: $|\eta_{CM}| < 1$
    - Forward (p direction): $1.2 < \eta_{CM} < 2.4$
    - Backward (Pb direction): $-3.3 < \eta_{CM} < -1.2$



x_j dependency

- Study of x_j as function of multiplicity and pseudorapidity
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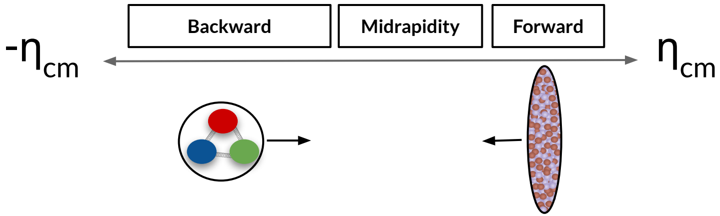
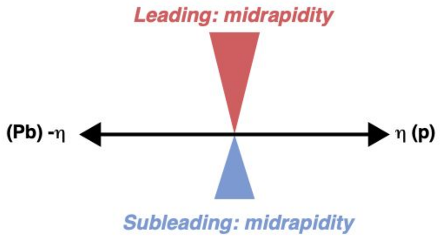
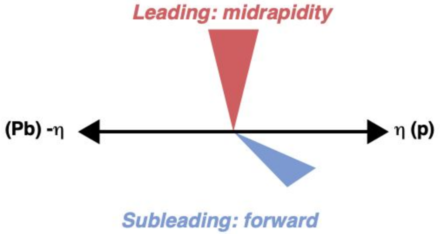
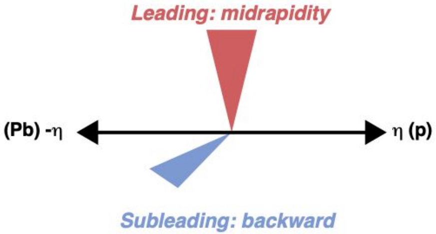
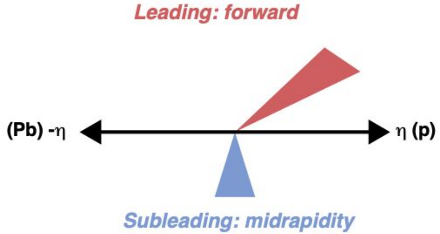


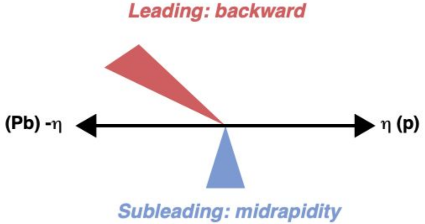
  - Dijet combinations studied:



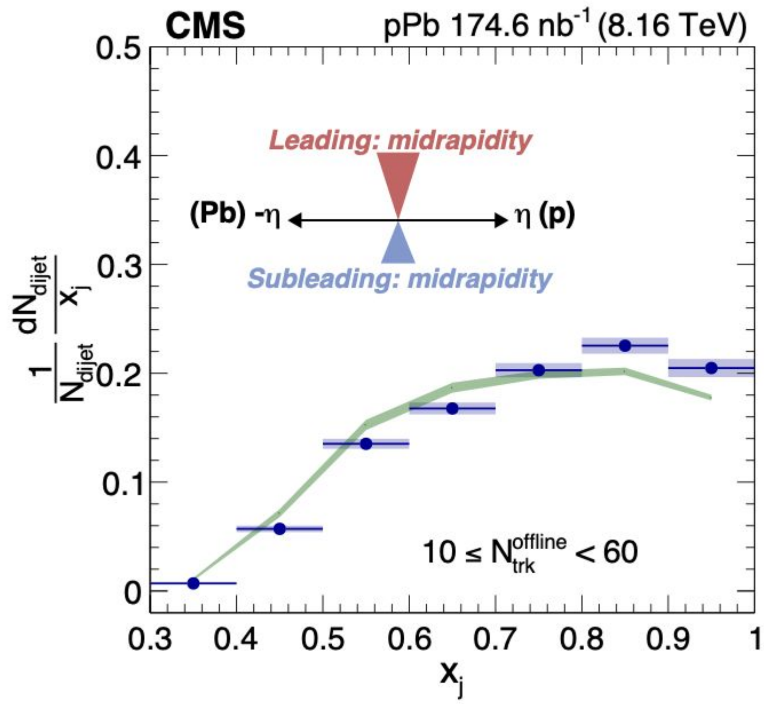






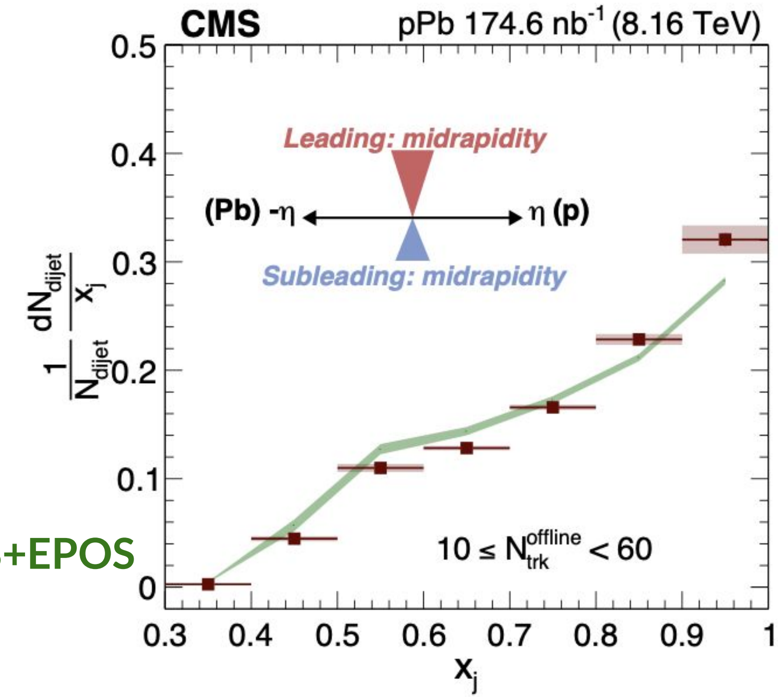


Example of x_j unfolding in data



Smeared results

Data
PYTHIA8+EPOS

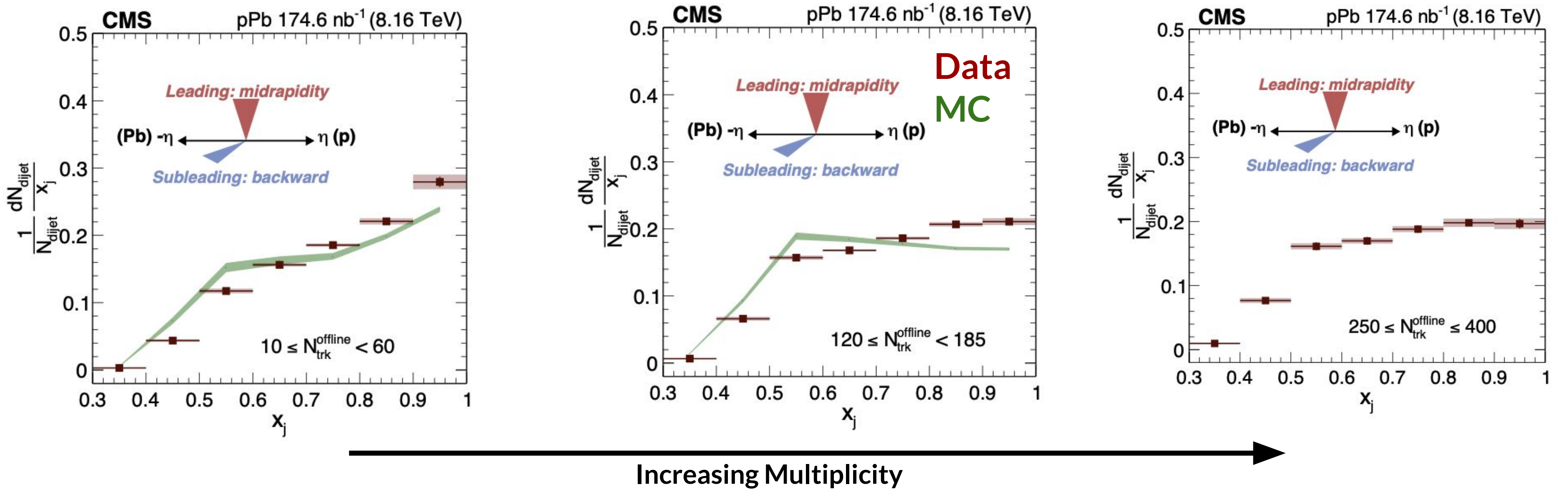


arXiv:2504.08507

Unfolded results

x_j results: multiplicity dependency

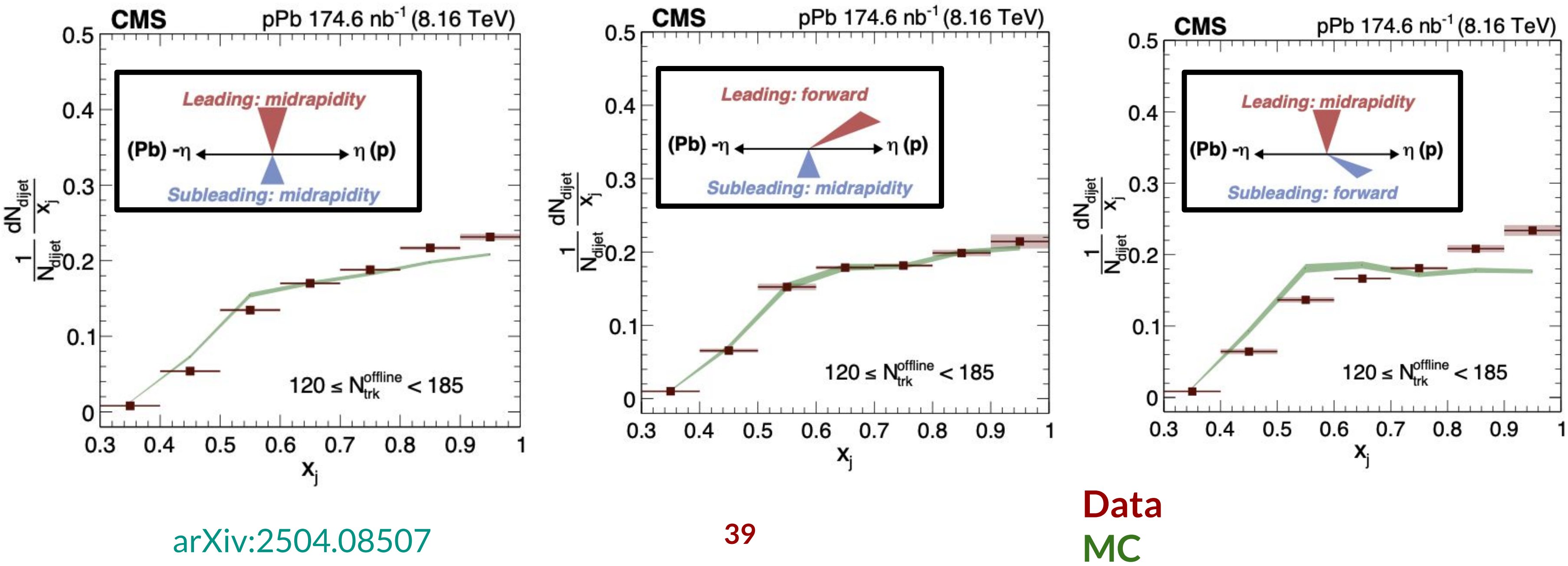
- Changes observed in the shapes from low to high multiplicity ranges
  - Especially in x_j ~ 1 (imbalance?)
    - Same behavior for all η combinations
  - Simulations cannot be performed for the highest multiplicity range



arXiv:2504.08507

x_j results: η dependency (forward)

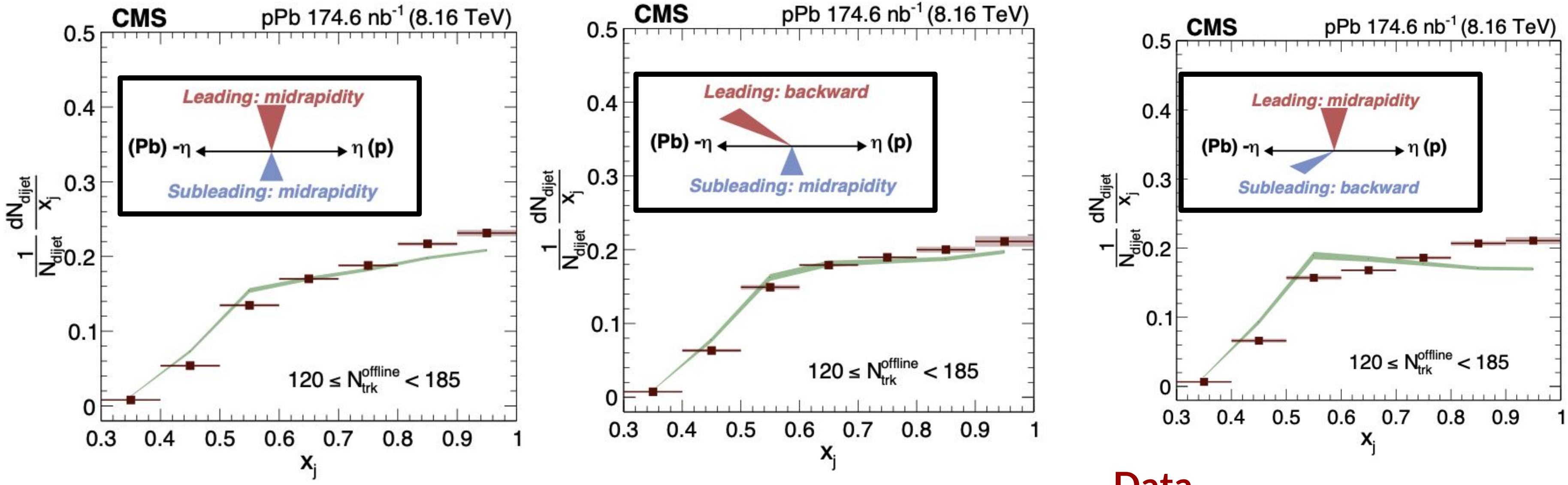
- Very similar behavior across all different jet combinations
  - Small changes in shapes
    - Indicates weak *x* dependency



arXiv:2504.08507

x_j results: η dependency (backward)

- Very similar behavior across all different jet combinations
  - Small changes in shapes
    - ➔ Indicates weak *x* dependency

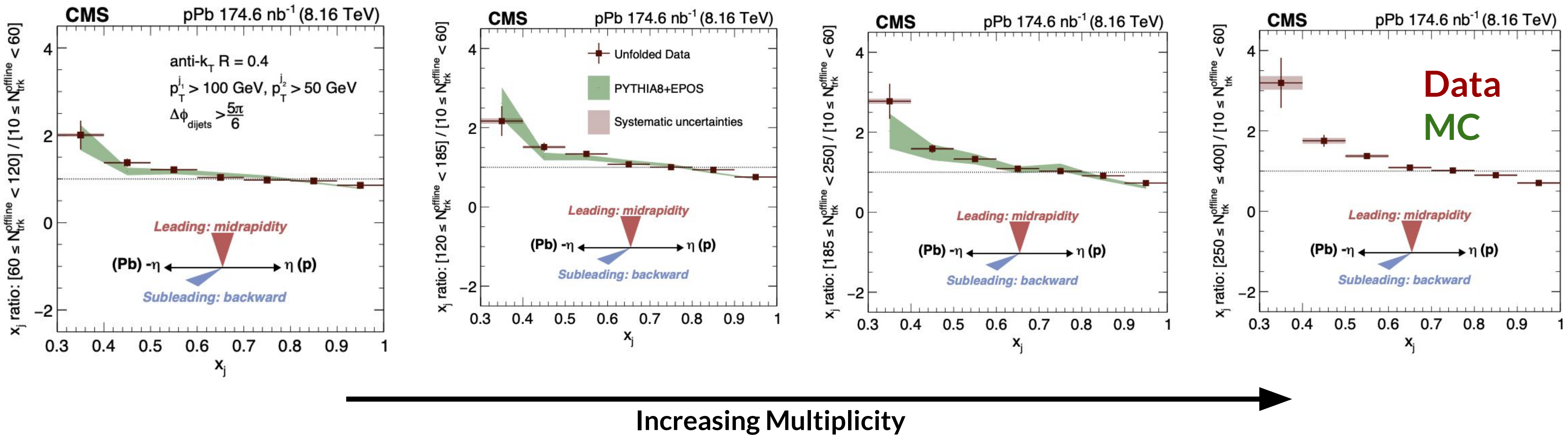


Data
MC

arXiv:2504.08507

x_j ratio to lower multiplicity range (I) – R_{CP}-like

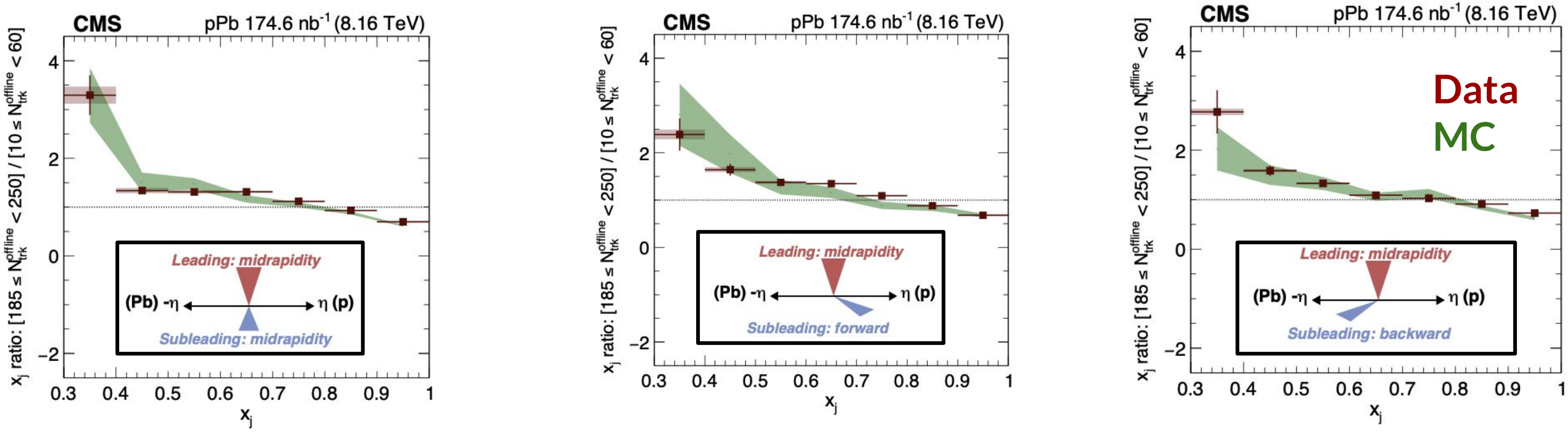
- Ratio > 1 at low x_j and < 1 for high x_j
  - Possible effects: multijets contribution, energy-momentum conservation, …
- Data well described by PYTHIA8+EPOS MC in all multiplicities and η combinations
  - **PYTHIA8+EPOS do not include energy loss mechanism nor nPDF effects**



arXiv:2504.08507

x_j ratio to lower multiplicity range (II) – R_{CP}-like

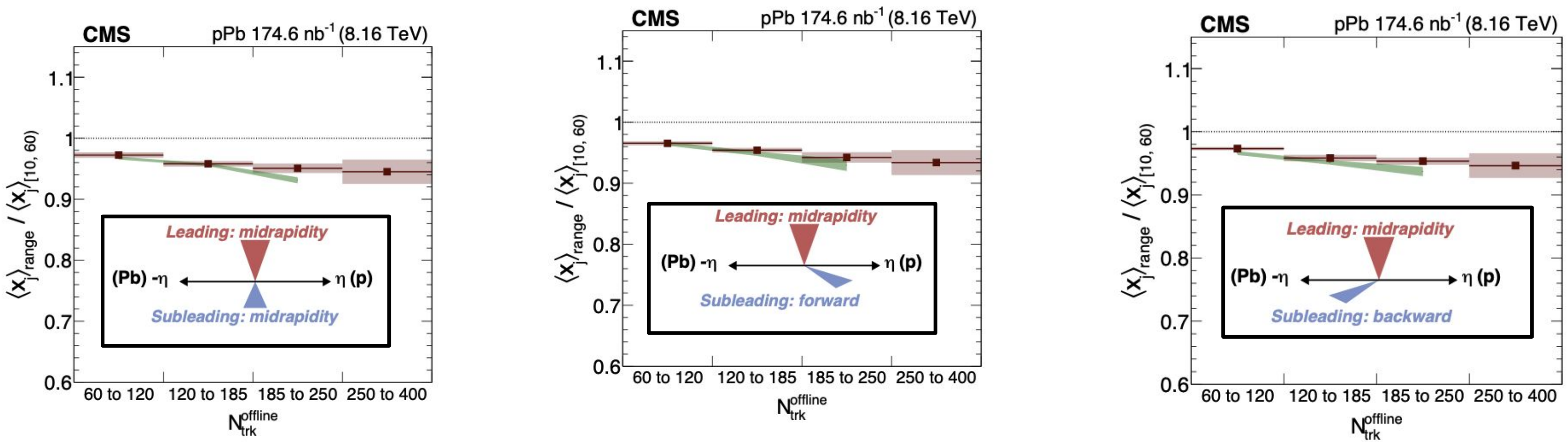
- Ratio > 1 at low x_j and < 1 for high x_j
  - Possible effects: multijets contribution, energy-momentum conservation, …
- Data well described by PYTHIA8+EPOS MC in all multiplicities and η combinations
  - **PYTHIA8+EPOS do not include energy loss mechanism nor nPDF effects**



Similar behavior observed for all η combinations

arXiv:2504.08507

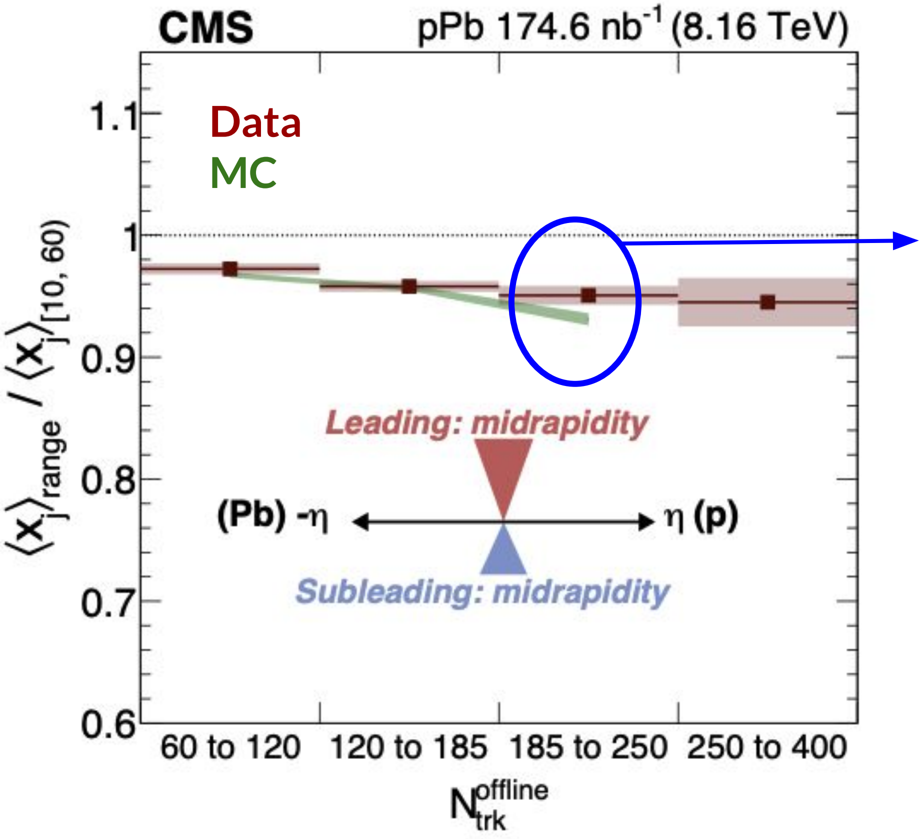
Average x_j : ratio high-to-low multiplicities



- ➤ Ratio high to low multiplicity for average x_j decreases (similar to PbPb collisions)
- ➤ Deviations from unity can come from different sources
  - ➪ **Energy-momentum conservation, multi jets, ...**
- ➤ Great agreement between data and MC (without energy-loss mechanism)
  - ➪ **Indicates no presence of quenching**

arXiv:2504.08507

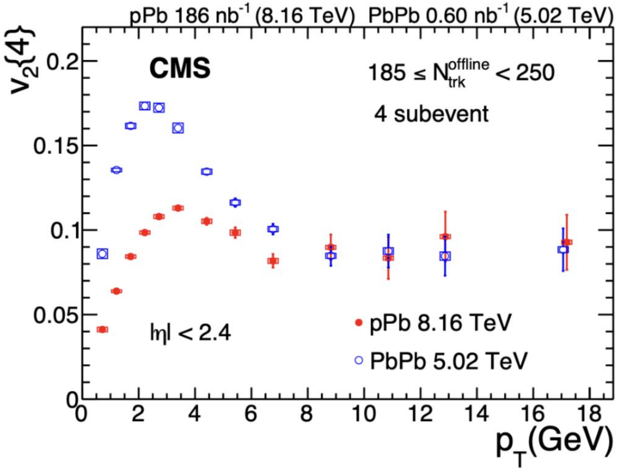
Jet quenching in pPb collisions? (VI)

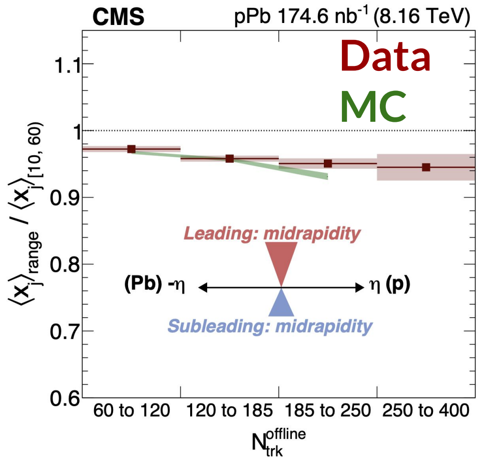


- ➤ **Constraining subleading quenching**
  - ⇨ **Based on data/MC difference**
    - ➔ **1.26% at 90% C. L.**

Summary

- Intriguing results using high-multiplicity triggers (strongest flow regime)
  - Similar high-p_T flow magnitude for pPb and PbPb
    - ➔ Is the path-length dependence of in-medium energy loss valid?
  - No modifications observed in x_j for any configuration of jet-jet geometry
    - ➔ Deviations from 1 observed, possible effects:
      - Energy-momentum conservation, multijets, among others
    - ➔ Well described by PYTHIA8+EPOS
      - Constraining E-Loss of subleadjet in **1.26% at 90% C.L.**





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рахмат
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謝謝
teşekkür ederim
Баярлалаа
mersi
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barka
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spas
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tapadh leat
спасибо
faafetai lava
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blagodaram
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matondo
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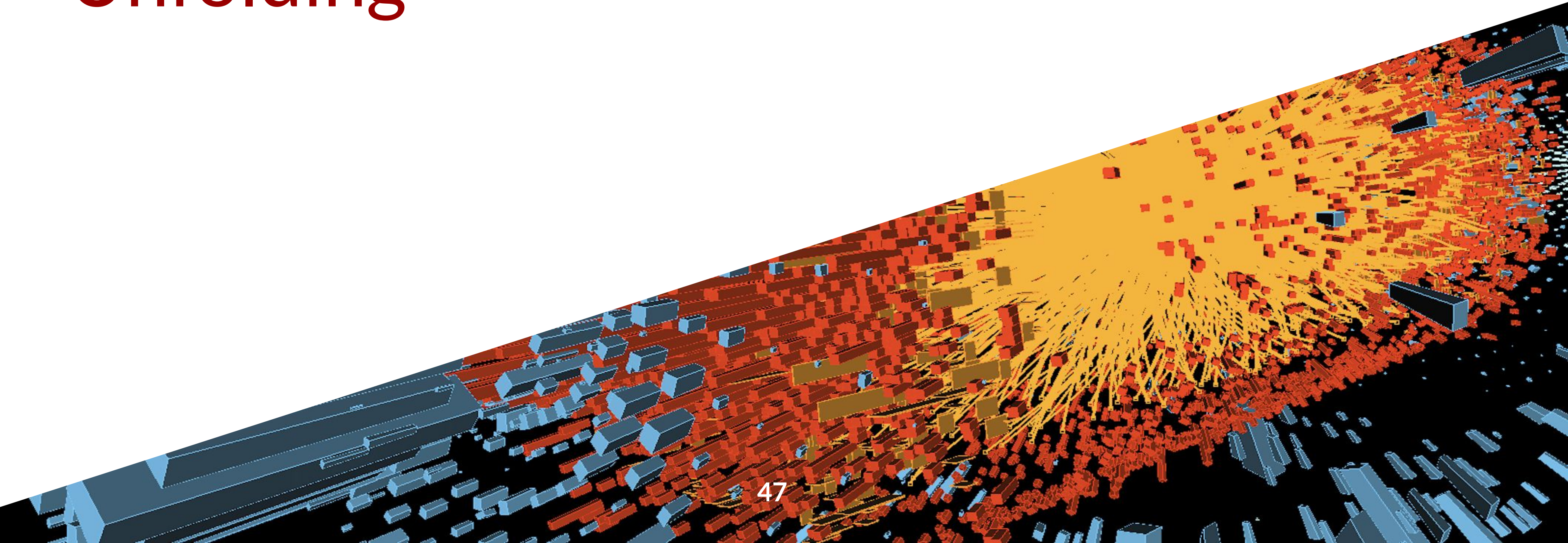
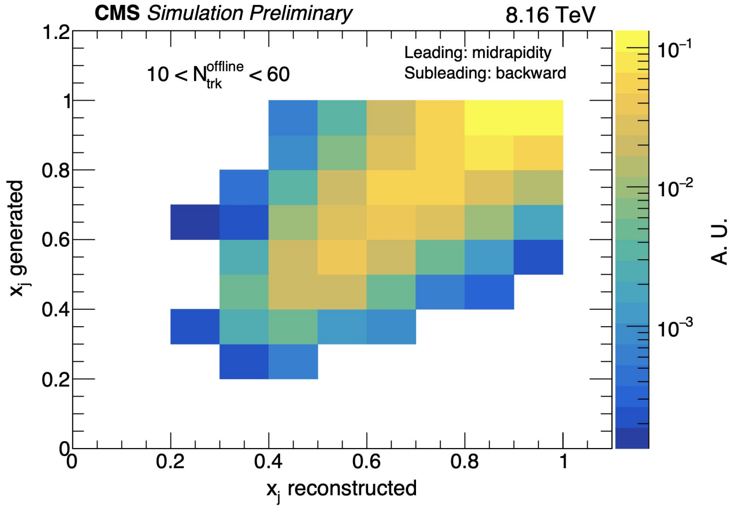
Unfolding

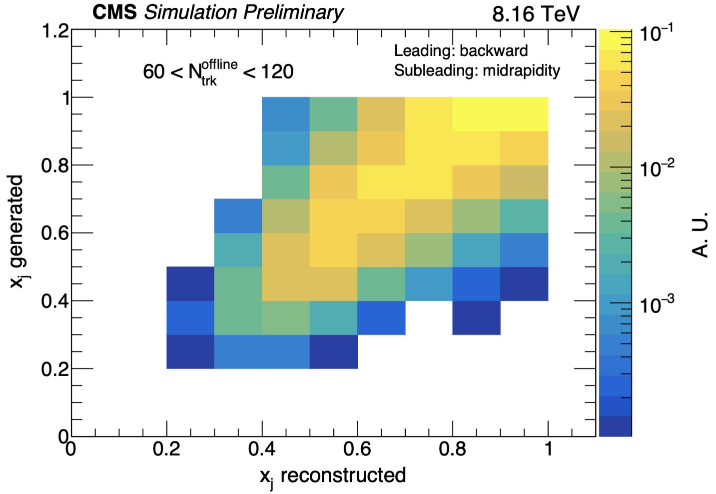


Unfolding x_j

- 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 → ROOUnfold
  - Data/MC differences
    - p_T^{j1} vs p_T^{j2} PDF map applied to the matrices
- Applied with D'Agostini unfolding using ROOUnfold

CMS PAS-HIN-23-010

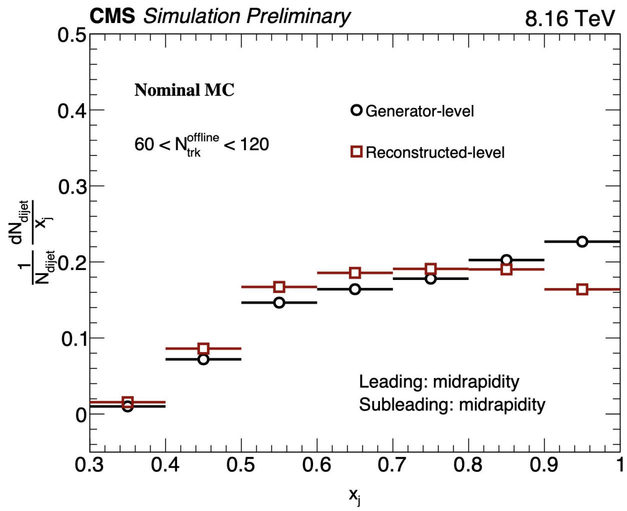




Validate the unfolding procedure at MC (I): prior

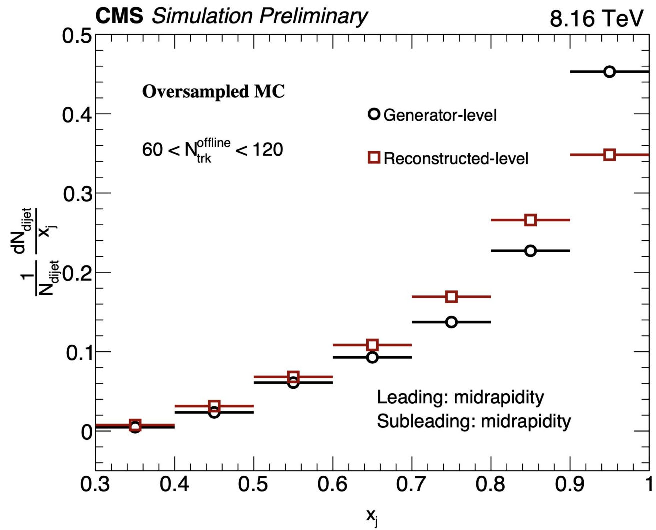
- Data/MC reconstructed pdf(p_T^{j1} , p_T^{j2}) is applied to remove sensitivity to prior shape
- Procedure is tested using an "oversampled MC"
  - Very different prior between the nominal and oversampled test-MC

Nominal MC
(PYTHIA+EPOS)



very different distributions

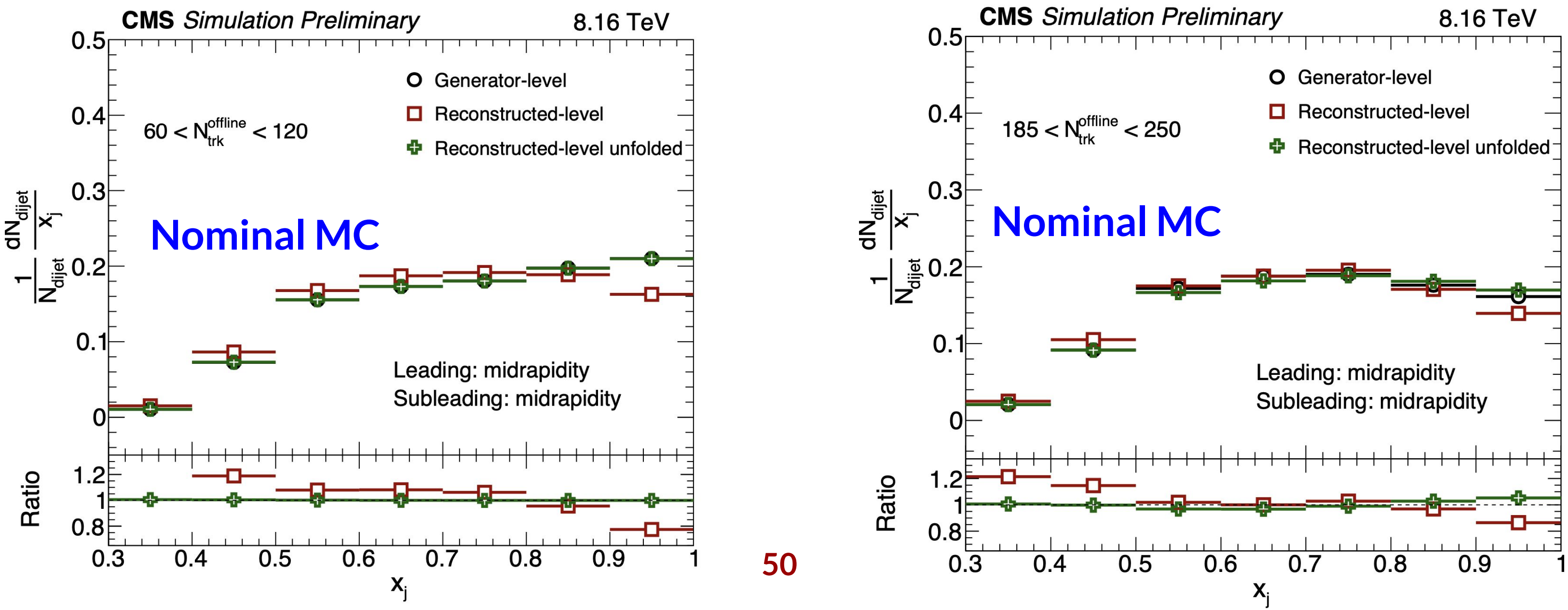
Oversampled MC
(PYTHIA+EPOS, no invariant p_T rescale)



CMS PAS-HIN-23-010

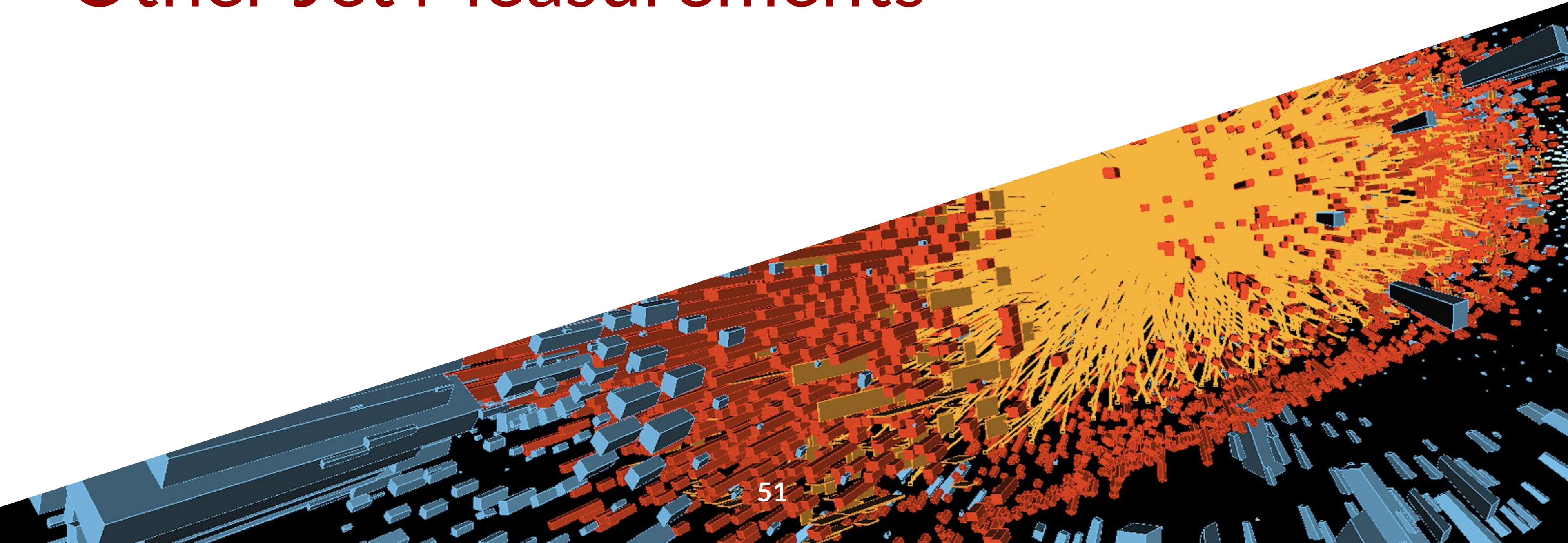
Validate the unfolding procedure at MC (II): closures

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

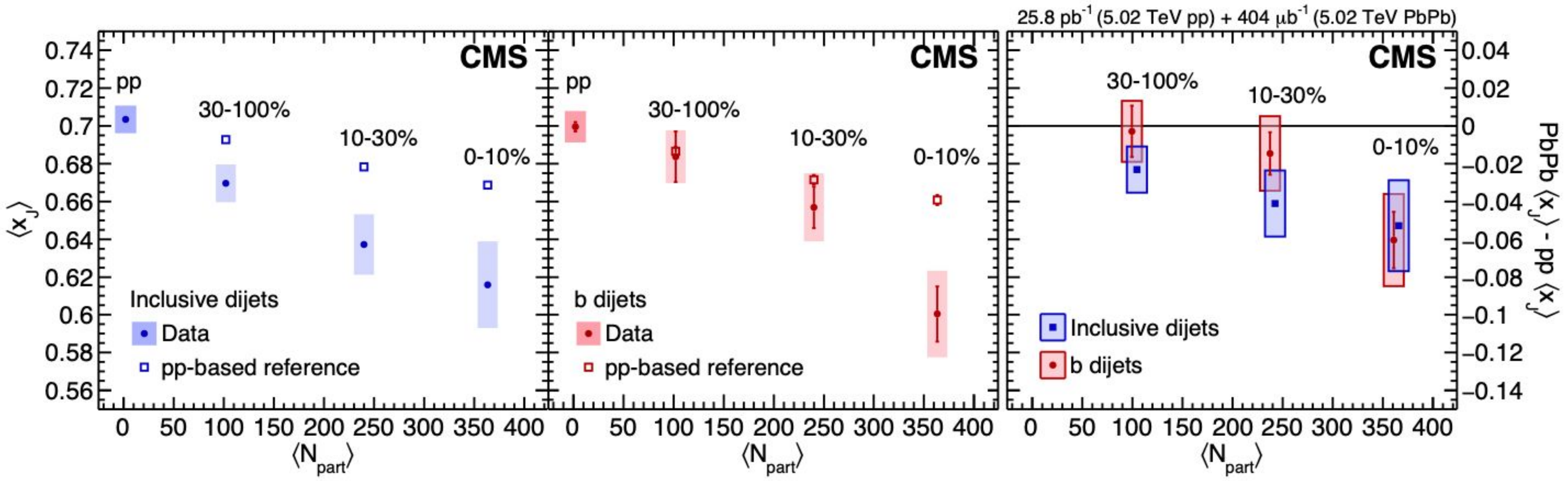


CMS-PAS-HIN-23-010

Other Jet Measurements



Jet momentum balance



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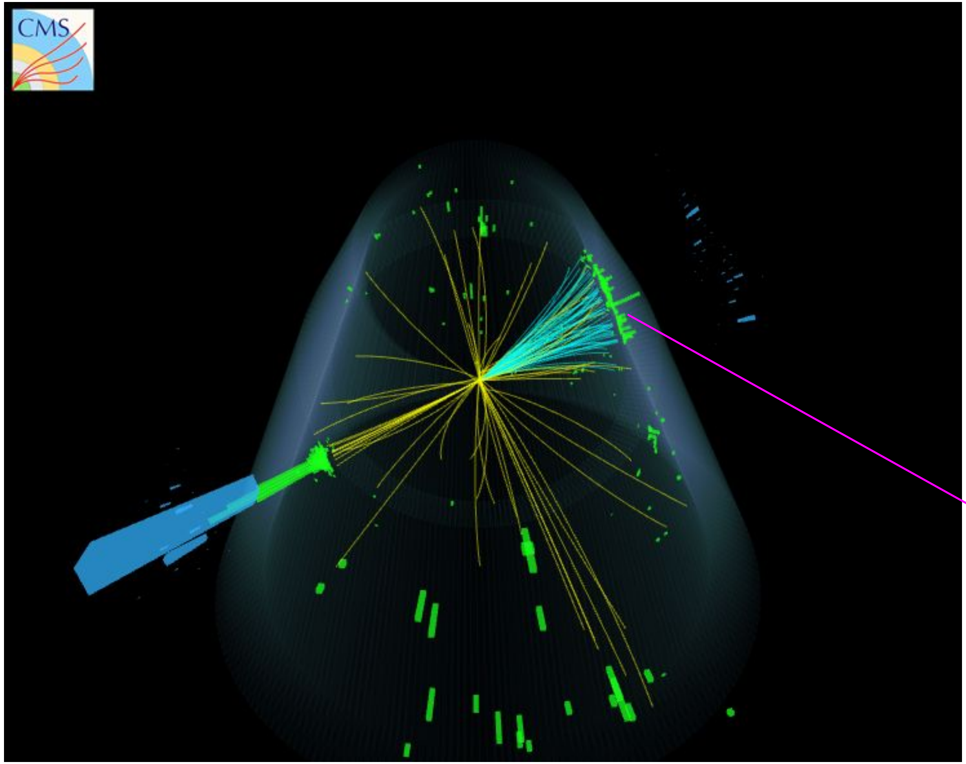
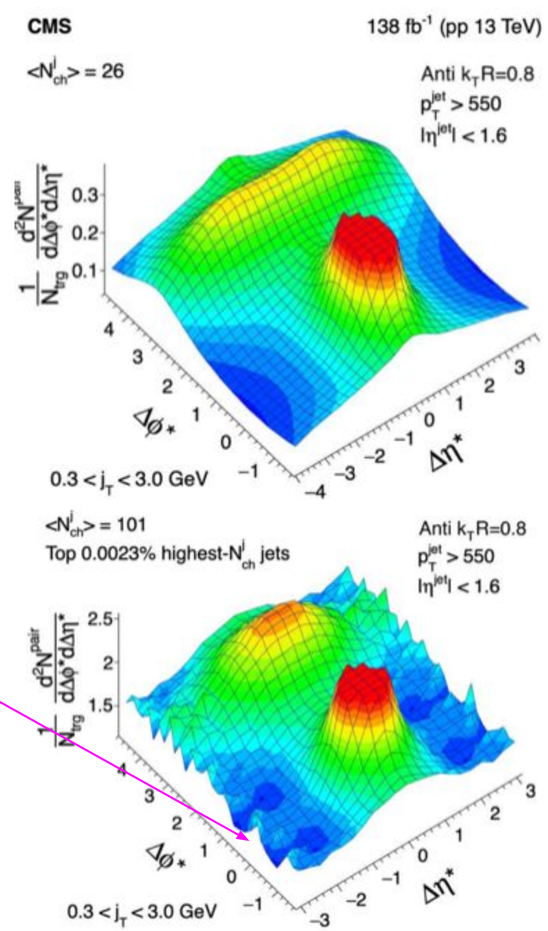
$$x_j = \frac{p_T^{\text{Subleading jet}}}{p_T^{\text{Leading jet}}}$$

Collectivity in high-multiplicity jets (I)

➤ What if we study correlations of in-jet particles?

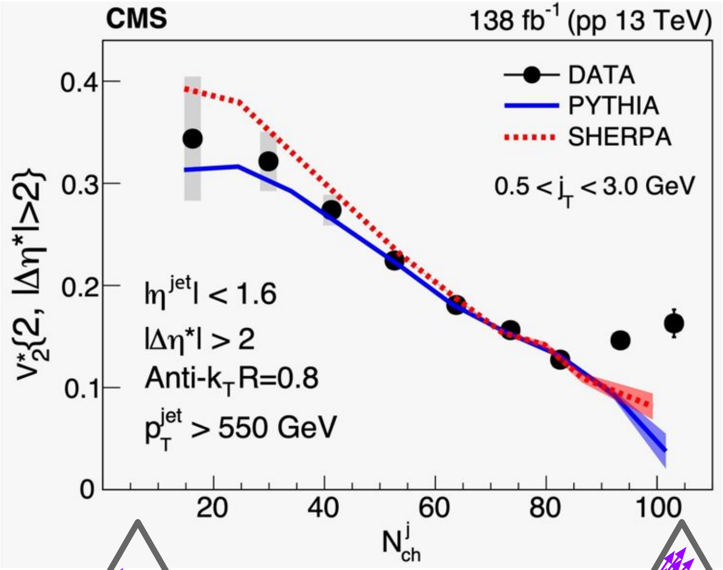


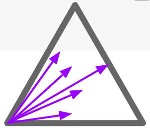


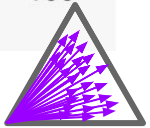
Accepted for pub. at PRL

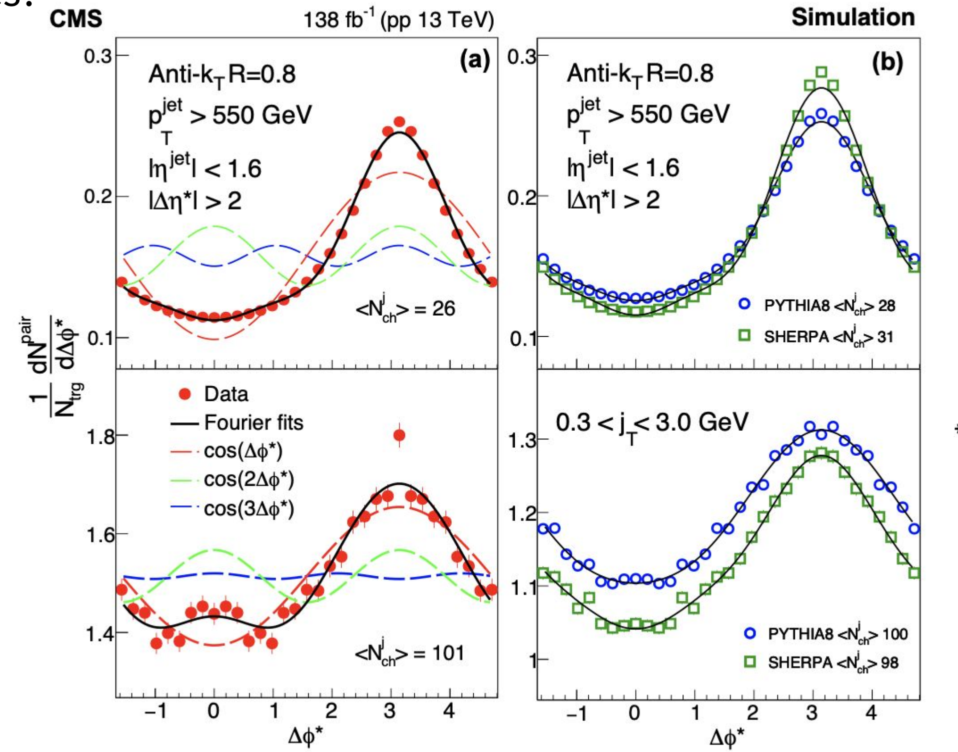
Collectivity in high-multiplicity jets (II)

- What if we study correlations of in-jet particles?
  - Measured as function of jet multiplicity
  - Good agreement with MC for N <~ 80
  - v_2 enhances for N > 90









Accepted for pub. at PRL