New insights from CMS pPb data at $\sqrt{s_{NN}}$=8.16 TeV

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SPRACE

Intriguing results in pPb collisions at 8.16 TeV

pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV → large data sample (2016):

- 6.4 billion Min Bias events (Multiplicity range: 10 to 185)

- search for jet suppression due to medium interaction (jet quenching)
  - back-to-back jets
  - jet (im)balance → ratio of jet p_T → $x_j = \frac{p_T^{j_2}}{p_T^{j_1}}$

pPb collisions at 8.16 TeV (2016) & PbPb collisions at 5.02 TeV (2018)

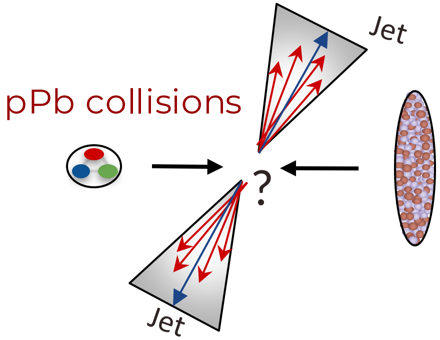
- investigate $v_2\{4\}$ at large p_T in pPb and PbPb collisions
  - cumulant method → using 0, 2 and 3, 4 subevents (reduces non-flow and back-to-back jets)

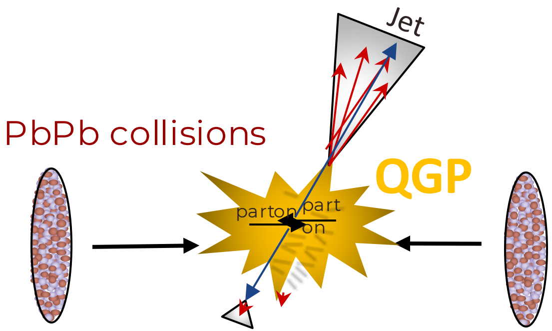
SEARCH FOR JET QUENCHING IN PPB COLLISIONS AT 8.16 TEV

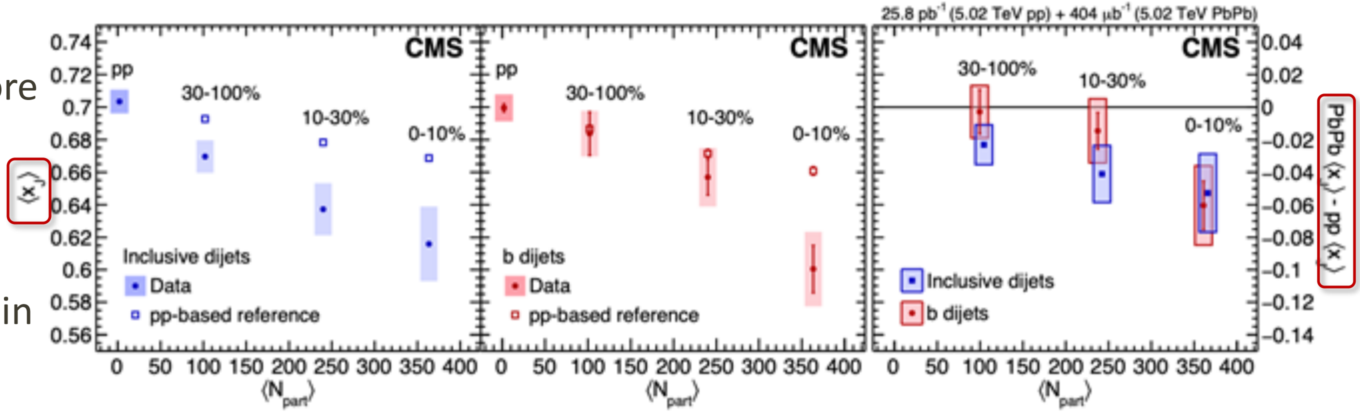
Jet quenching measured as jet imbalance

Measured in CMS thrgough jet imbalance in PbPb collisions at $\sqrt{s_{NN}}$= 5.02 TeV:

- ❑ for inclusive jets
  - quenching increases for more central events (larger multiplicities)
- ❑ for b jets
  - clear quenching in 0-10%







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

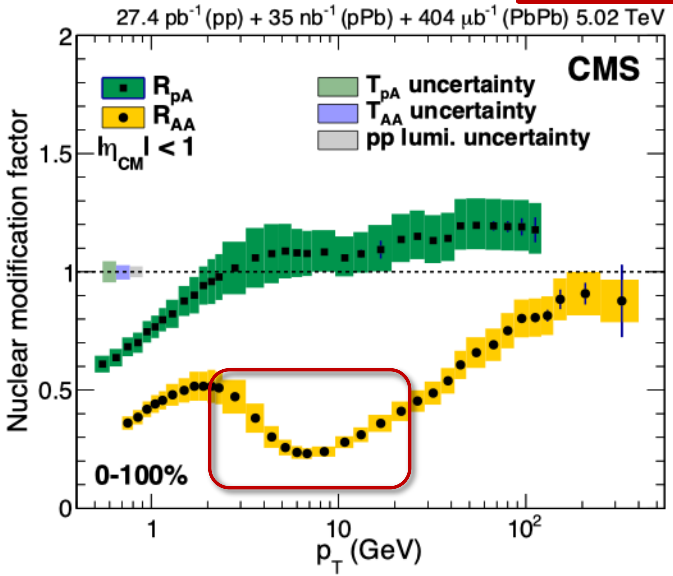
JHEP 03 (2018) 181

CMS R_{AA} and azimuthal anisotropy results

Nuclear modification factors (inclusive centrality class)

- R_{AA} → largest suppression in PbPb for $2 < p_T < 30$ GeV
- R_{pPb} → no suppression in 2-20 GeV region in MinBias pPb

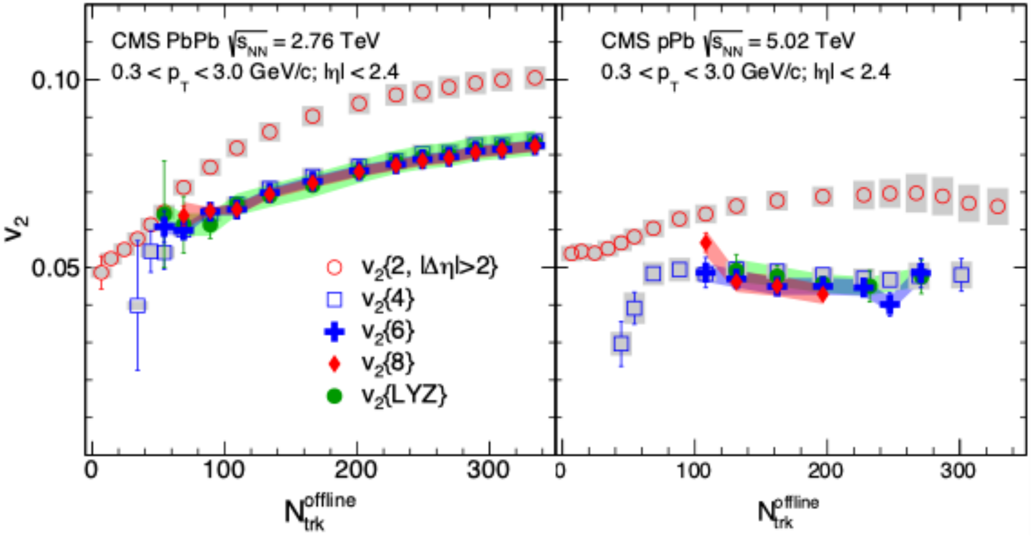
JHEP 04 (2017) 039



Azimuthal anisotropy: low p_T<3 GeV

- observes ridge in pPb
- geometry + fluctuations
- $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$ → collectivity (High Mutliplicity)

PRL 115, (2015) 012301

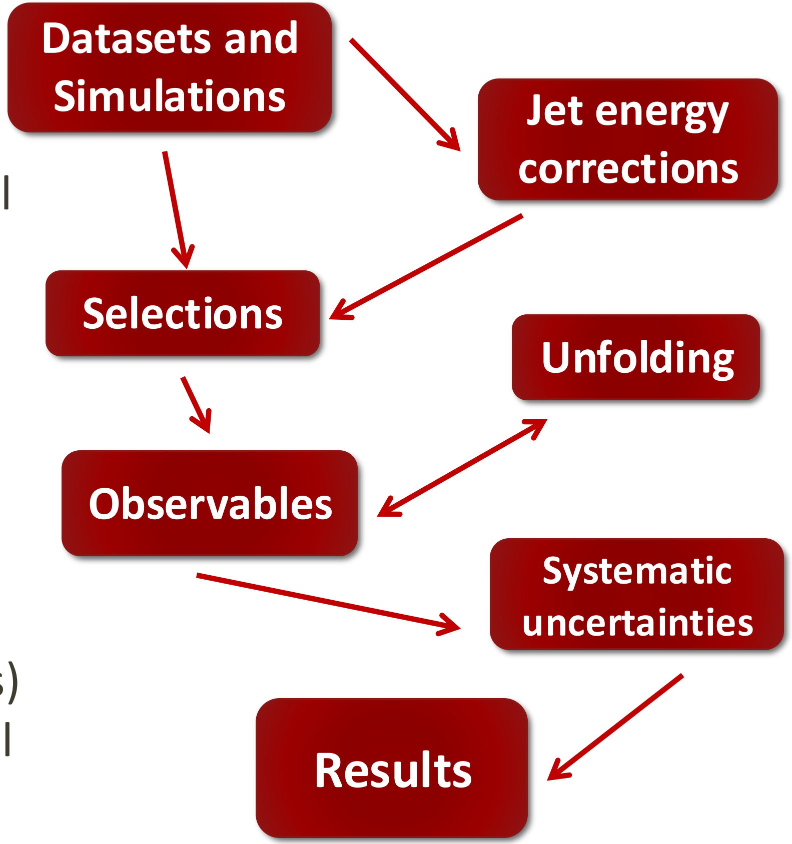


Datasets and MC simulations

pPb@8.16 TeV

- minimum-bias trigger
  - ~ 6.4 billion Minimum Bias 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-model comparison

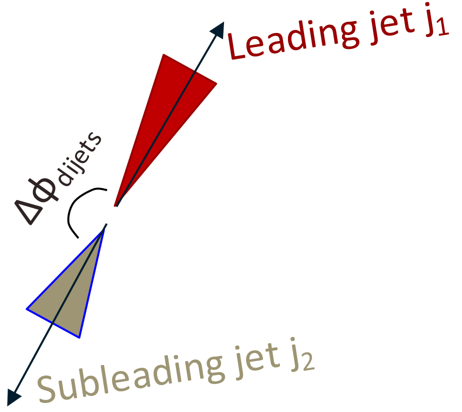
Analysis workflow



Measurement setup

Dijet selection

- ❑ particle Flow
  - anti-k_T jets with R = 0.4
  - p^{j1}_T > 100 GeV
  - p^{j2}_T > 50 GeV
  - $|\Delta\varphi_{dijets}| > 5\pi/6$

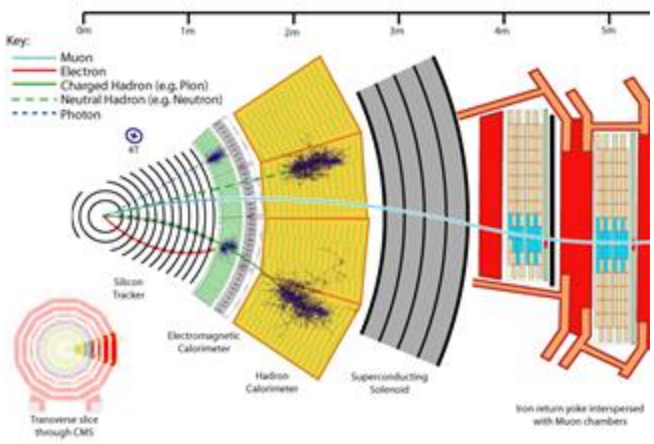


Observable

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

Analysis methods

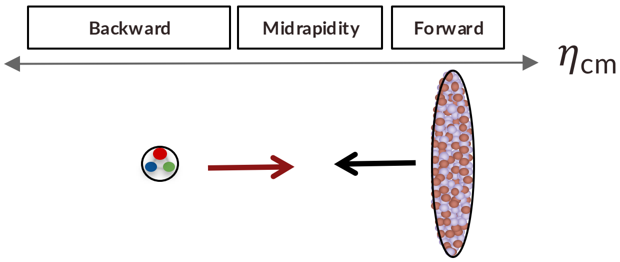
- ❑ ratio high-to-low multiplicity (~ "R_{CP}-like")
- ❑ probe proton and lead directions (check η dependence)
- ❑ apply D'Agostini unfolding to correct for resolution (first x_j unfolding at CMS)



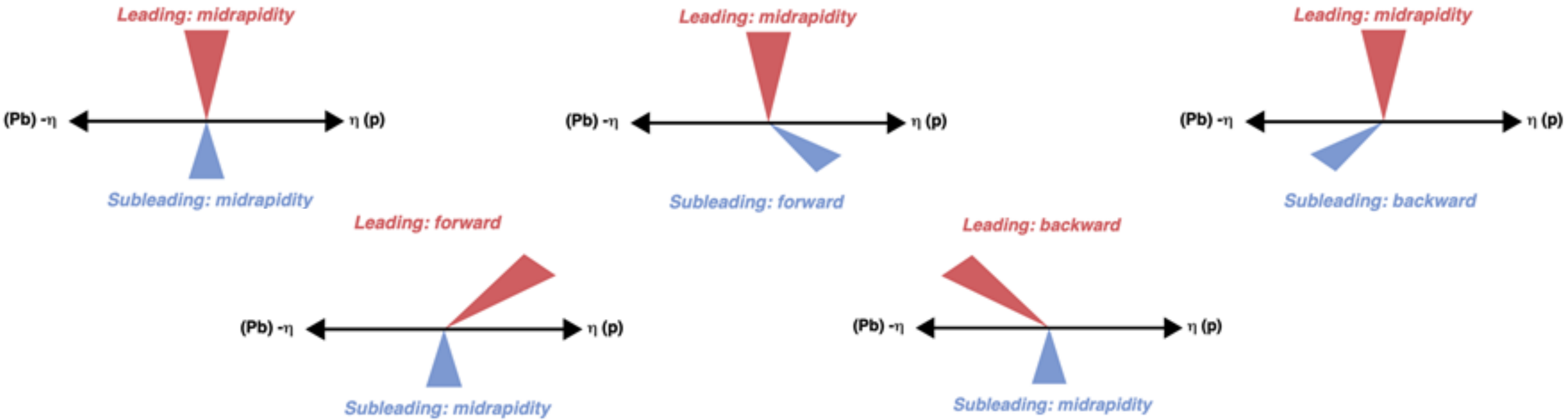
x_j in different multiplicities and η ranges

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): $-3.3 < \eta_{CM} < -1.2$



- Dijet combinations studied:



Unfolding x_j procedure

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]

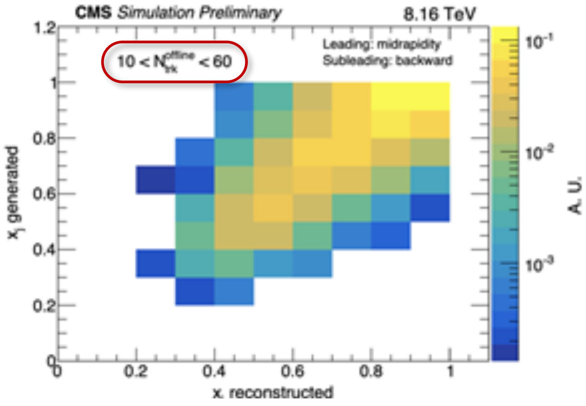
$$x_j = \frac{p_T^{j_2}}{p_T^{j_1}}$$

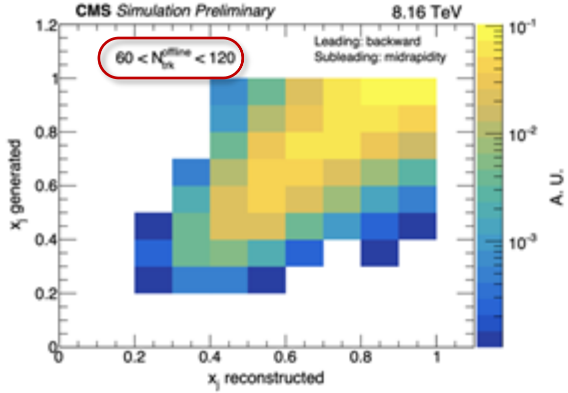
Effects taken into account in the response matrices
- Fakes → Negligible
- Swap → ~ 20%
- Missing → ROOUnfold
- Data/MC differences
  - p^{j1}_T vs p^{j2}_T PDF map applied to the matrices

Performed with D'Agostini unfolding via ROOUnfold

Unfolding procedure → Validation: MC prior (I) and MC Closure (II) (see backup)

Illustration for 2 $N_{trk}^{offline}$ ranges





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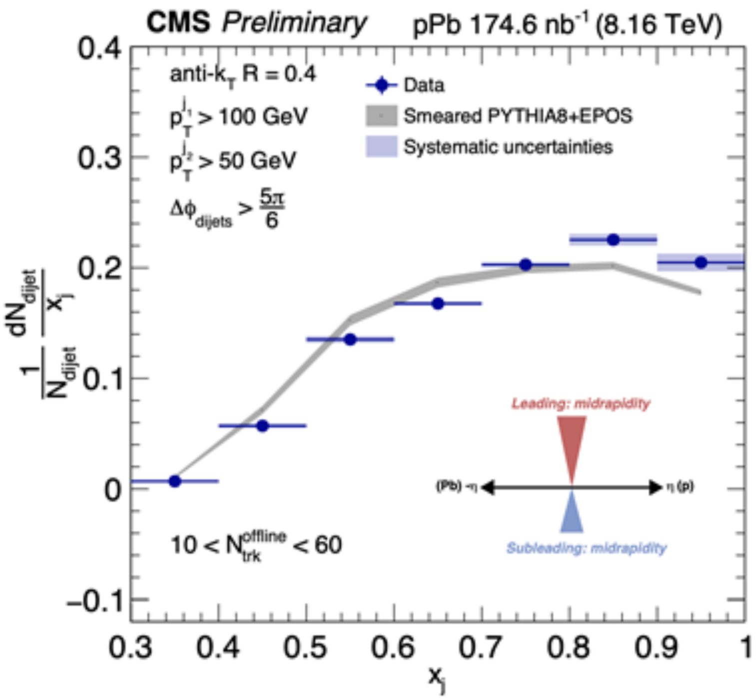
Unfolding x_j – example with data



Smeared results

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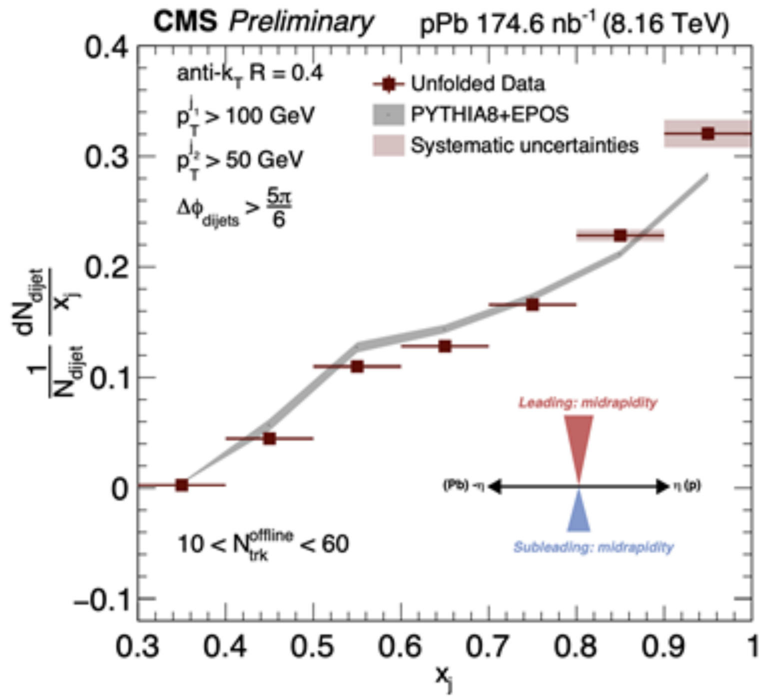

Unfolded results

Results – I: x_j dependence on multiplicity

Changes in shapes seen from low to high multiplicity ranges

- Especially around $x_j \sim 1$
- No simulations for the highest multiplicity range

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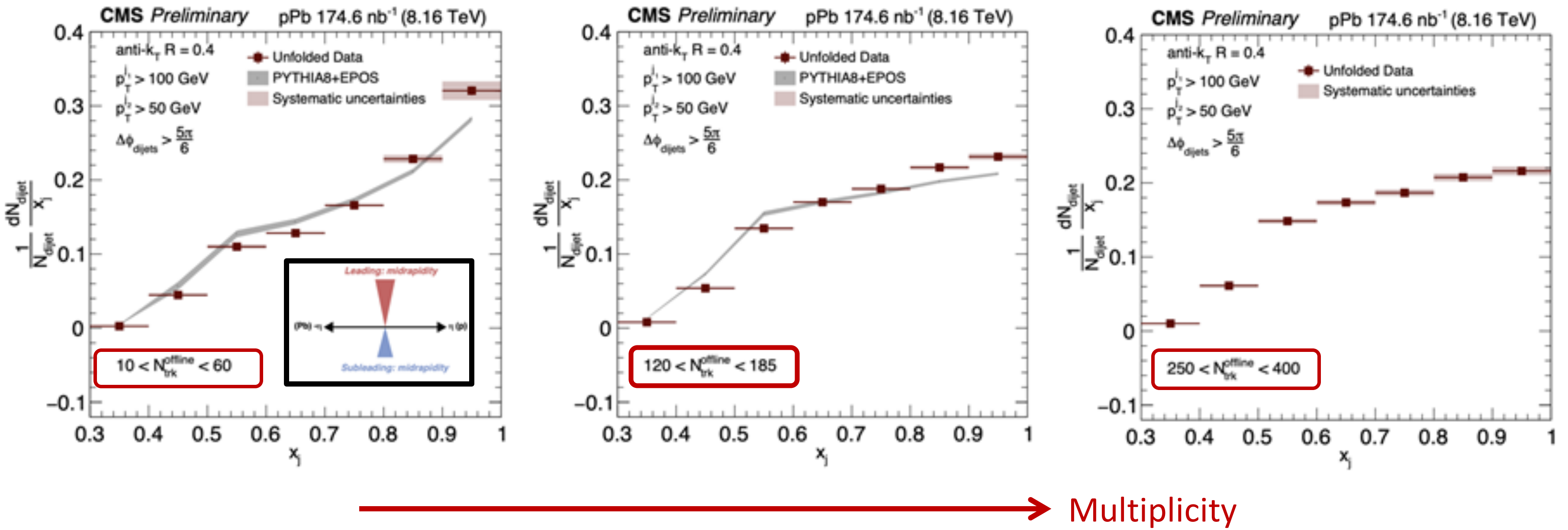

Results – II: x_j dependence on η (forward)

Very similar behavior for all different jet rapidity combinations

- Small changes in shapes
  - results for η backwards are very similar (see backup)

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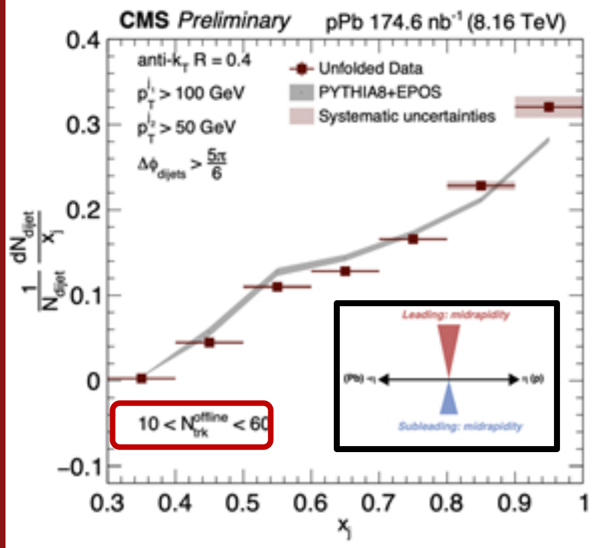

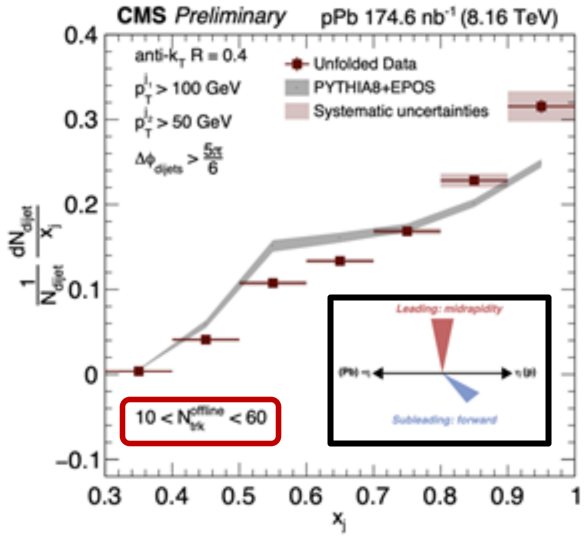

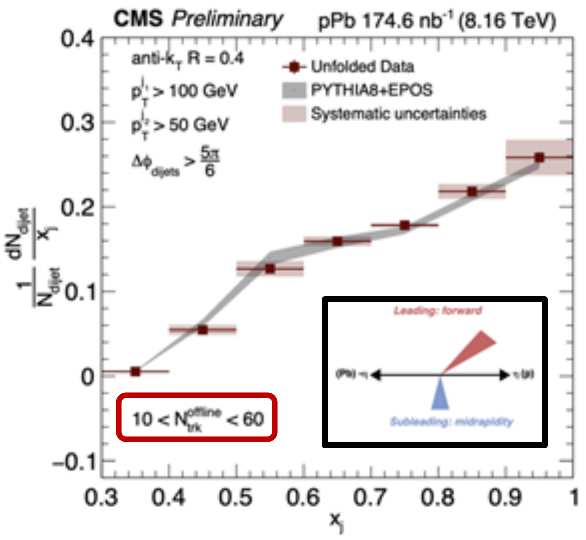

x_j ratios to lowest multiplicity range ($10<N_{trk}^{offline}<60$)

Useful for cancellation of systematic uncertainties

- ❑ Ratio > 1 at low x_j and < 1 for high x_j
- ❑ Data well described by PYTHIA8+EPOS MC in all multiplicities and η combinations!
  - ▪ PYTHIA8+EPOS do not include energy loss mechanism

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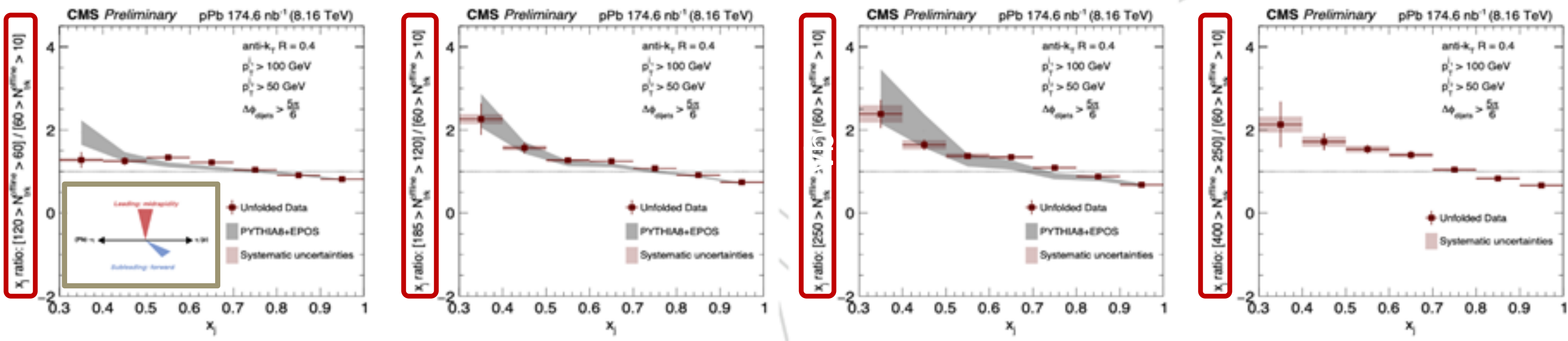
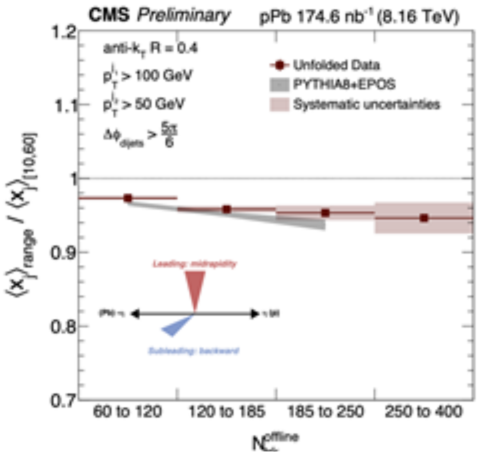
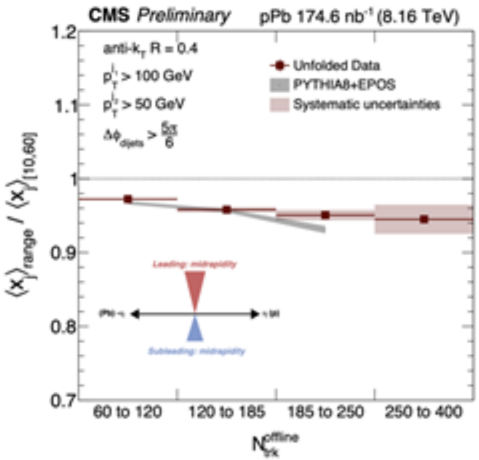


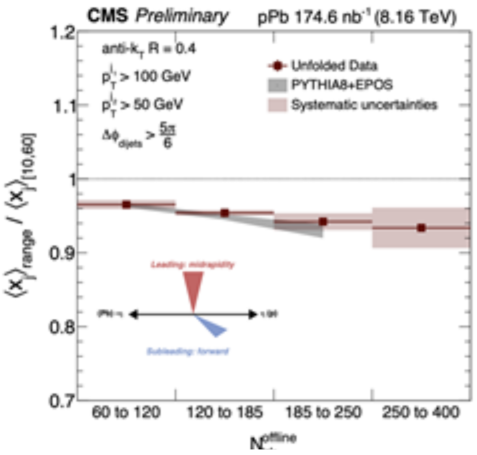
Multiplicity

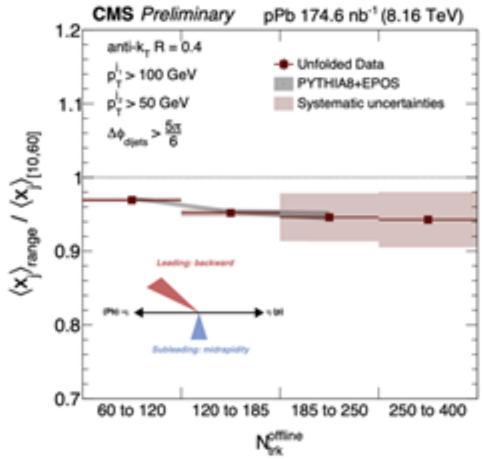
- ❑ Possible effects: multijets contribution, energy-momentum conservation, etc.

$\langle x_j \rangle$ ratios to lowest multiplicity range $(10 < N_{trk}^{offline} < 60)$



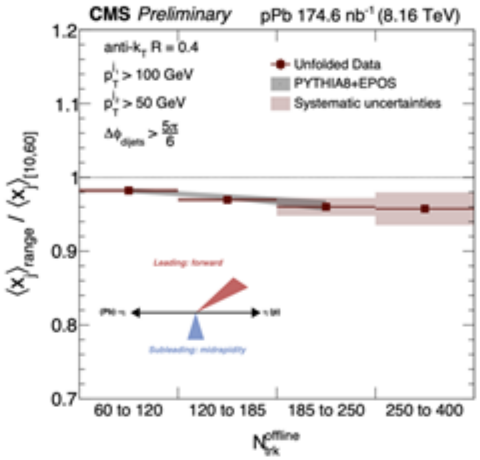






Ratio decrease with multiplicity

- ❑ Overall good data/MC agreement!
- ❑ No clear indication of energy loss!



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Summary – Part I

First measurement of unfolded x_j using high multiplicity up to $N_{\mathrm{trk}}^{\mathrm{offline}} \sim 400$

- No modifications observed at high multiplicity for any configuration of jet-jet geometry
  - ratio deviations from 1 seen → possible effects:
    - Energy-momentum conservation, multijets, among others
    - Well described by PYTHIA8+EPOS (no energy loss)

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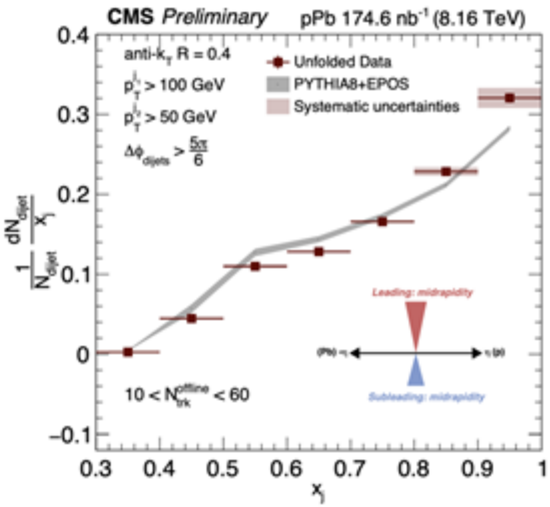
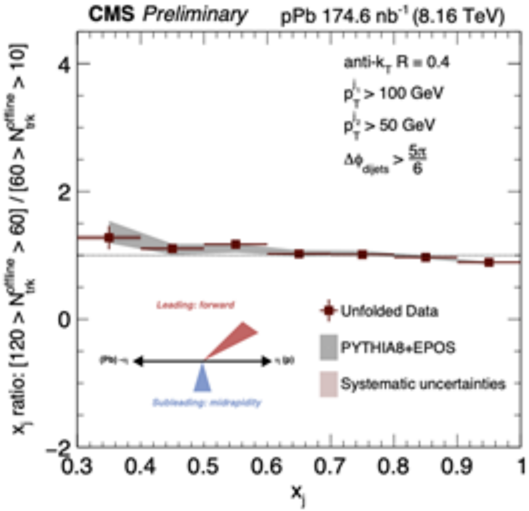
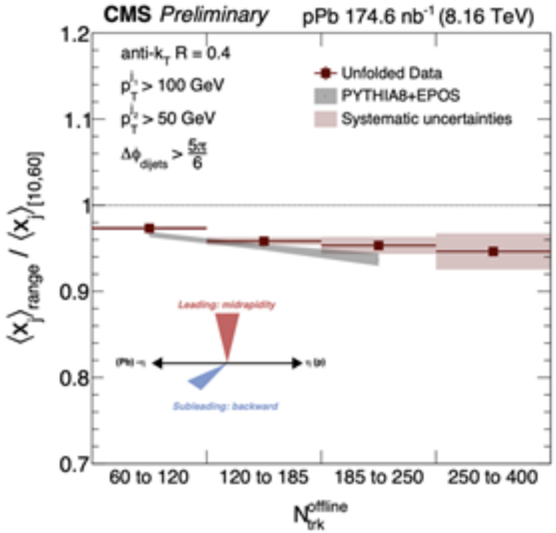




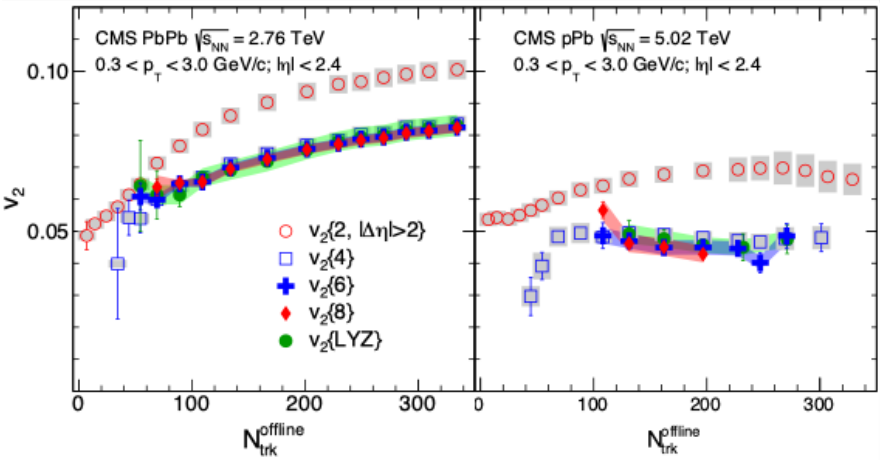


$V_2\{4\}$ → CUMULANT METHOD WITH SUBEVENTS

CMS azimuthal anisotropy results at low and at high p_T

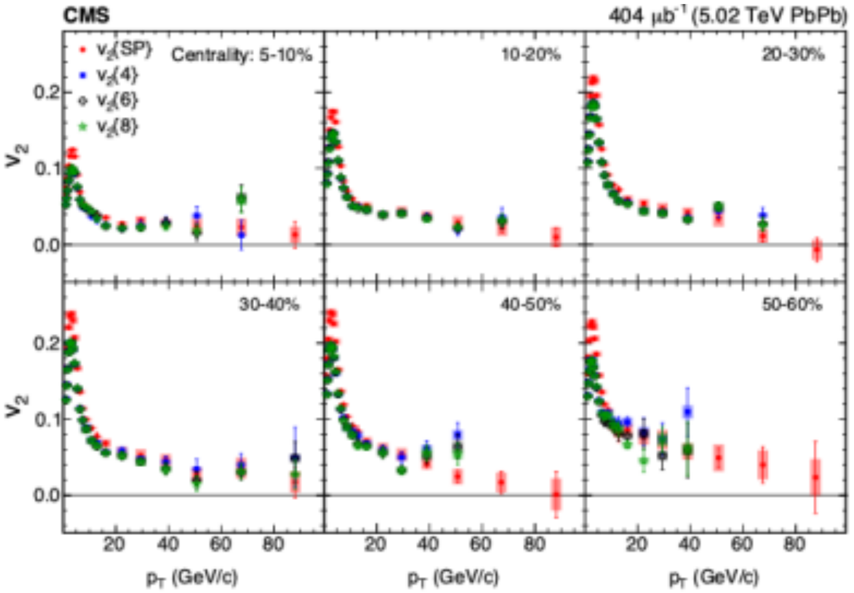
- Azimuthal anisotropy: low p_T<3 GeV
  - observes ridge in pPb
  - geometry + fluctuations
  - well described by hydrodynamics
    - $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$ → collectivity (High Mutliplicity)

PRL 115, (2015) 012301



- Azimuthal anisotropy: high p_T >10 GeV
  - geometry + fluctuations → different path lengths of high-p_T parton energy loss in QGP medium
  - v_n at high p_T in PbPb

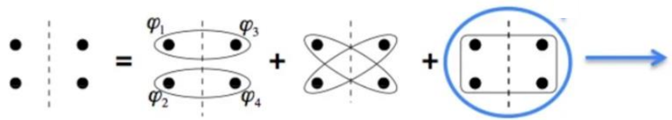
PLB 776 (2017) 195



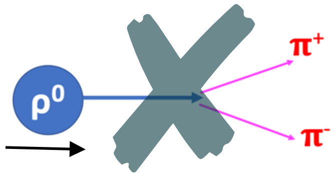
Analysis technique: cumulant method

- Multiparticle correlation technique
- Non-flow suppression

PRC 83 (2011) 044913



$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle\langle\langle 2\rangle\rangle$$



Q-cumulant

PRC 89 (2014) 064904

- Q-vector: $Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$

$$\langle\langle 2\rangle\rangle = \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle, \quad \text{and} \quad \langle\langle 4\rangle\rangle = \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle$$

- cumulants
  - $c_n\{2\} = \langle\langle 2\rangle\rangle$
  - $c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle\cdot\langle\langle 2\rangle\rangle$
- flow
  - $v_n\{2\} = \sqrt{c_n\{2\}}$
  - $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$
- differencial cumulant :

$$d_n\{4\} = \langle\langle 4'\rangle\rangle - 2\,\langle\langle 2'\rangle\rangle\cdot\langle\langle 2\rangle\rangle$$

1 POI **3 RFPs**

differential flow:

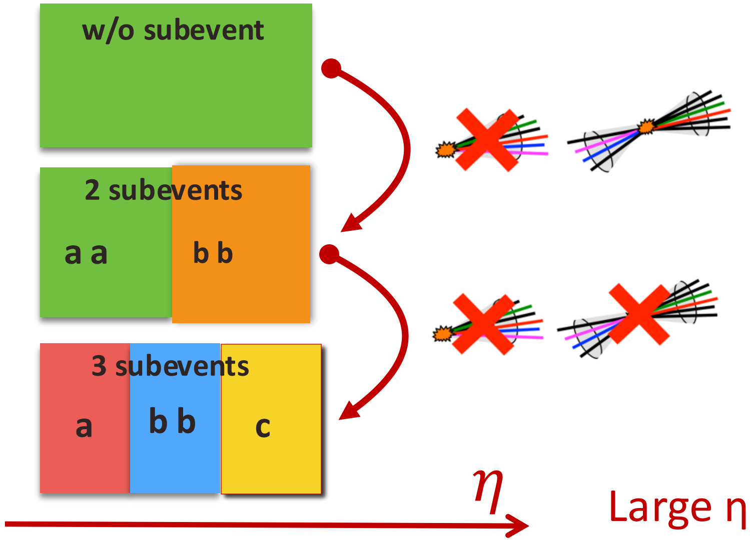
$$v'_n\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}$$

(final observable)

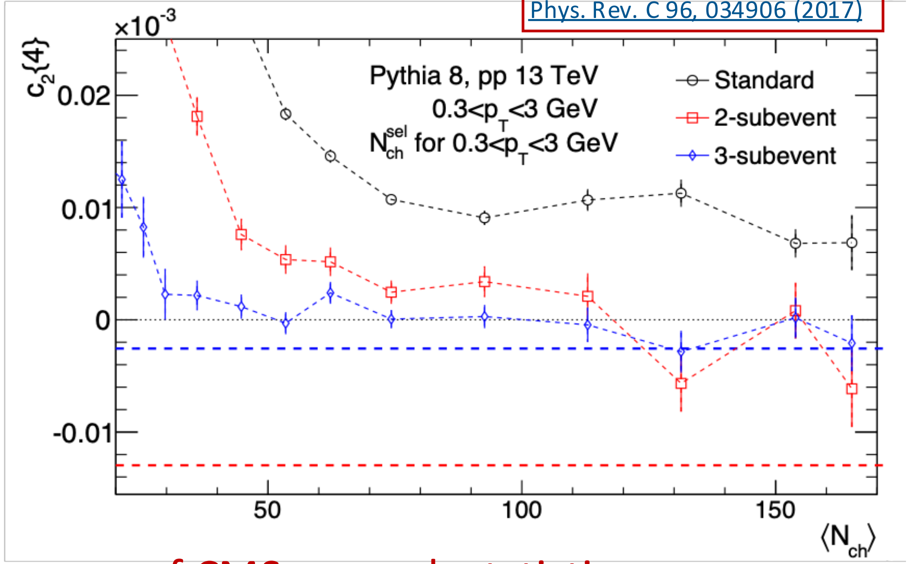
Analysis Method

Subevent cumulant techniques

- ❑ suppress few-particle correlations for exploring collective correlation signals
- ❑ uses subevent cumulant techniques → rapidity gaps among the particles
  - 2 subevents → can reduces non-flow contribution within the Jets
  - 3 & 4 subevents → can remove back-to-back contributions



Phys. Rev. C 96, 034906 (2017)

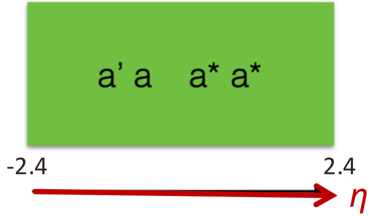


Large η coverage of CMS: enough statistics

Analysis method – I

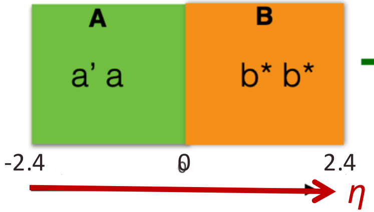
Differential cumulant $d_2\{4\}$: standard and 2 subevent methods

- ❑ standard (no subevents) method

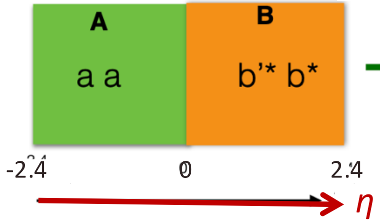


$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle \cdot \langle\langle 2 \rangle\rangle$$

- ❑ 2-subevent method



$$d_n\{4\}_{2sub} = \langle\langle 4\rangle^{a'a\,bb}\rangle - 2\langle\langle 2\rangle^{a'\,b}\rangle \cdot \langle\langle 2\rangle^{a\,b}\rangle$$

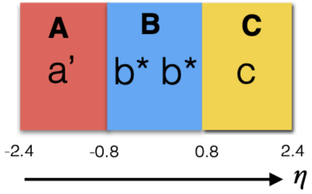


$$d_n\{4\}_{2sub} = \langle\langle 4\rangle^{aa\,b'b}\rangle - 2\langle\langle 2\rangle^{a\,b'}\rangle \cdot \langle\langle 2\rangle^{a\,b}\rangle$$

Analysis method – II

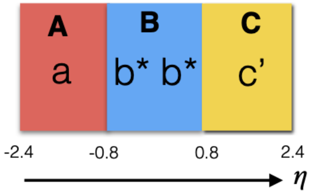
Differential cumulant $d_2\{4\}$: 3 and 4 subevent methods

- 3-subevent method



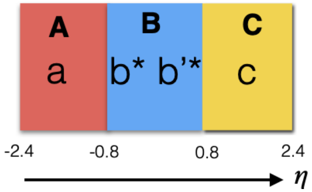
POI : (-2.4<η<0.8)

- $d_n\{4\}_{3sub} = \langle\langle 4\rangle^{a'\,bb\,c}\rangle - 2\langle\langle 2\rangle^{a'\,b}\rangle \cdot \langle\langle 2\rangle^{b\,c}\rangle$



POI : (0.8<η<2.4)

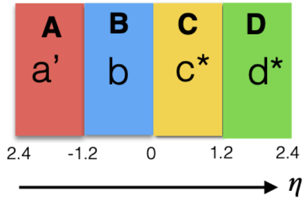
- $d_n\{4\}_{3sub} = \langle\langle 4\rangle^{a\,bb\,c'}\rangle - 2\langle\langle 2\rangle^{a\,b}\rangle \cdot \langle\langle 2\rangle^{b\,c'}\rangle$



POI : (-0.8<η<0.8)

- $d_n\{4\}_{3sub} = \langle\langle 4\rangle^{a\,bb'\,c}\rangle - \langle\langle 2\rangle^{a\,b'}\rangle \cdot \langle\langle 2\rangle^{b\,c}\rangle - \langle\langle 2\rangle^{a\,b}\rangle \cdot \langle\langle 2\rangle^{b'\,c}\rangle$

- 4-subevent method

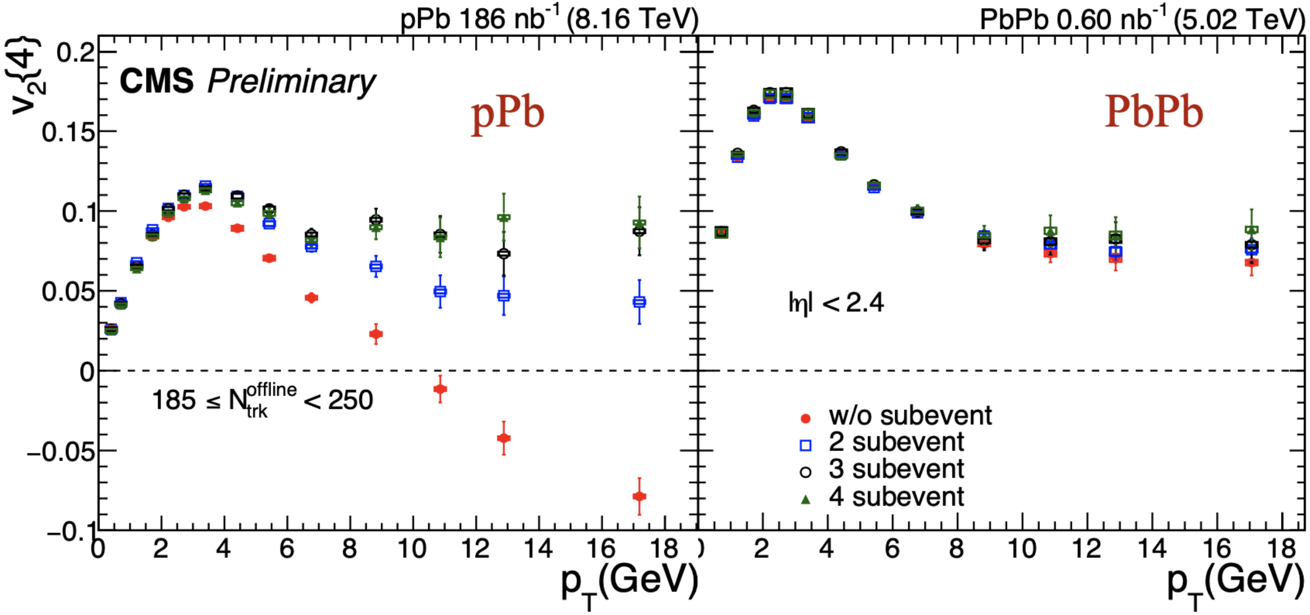


$$d_n\{4\}_{4sub} = \langle\langle 4\rangle^{a'\,b\,c\,d}\rangle - \langle\langle 2\rangle^{a'\,c}\rangle \cdot \langle\langle 2\rangle^{b\,d}\rangle - \langle\langle 2\rangle^{a'\,d}\rangle \cdot \langle\langle 2\rangle^{b\,c}\rangle$$

Results

$v_2\{4\}$ in $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ as a function of p_T

CMS-PAS-HIN-23-002

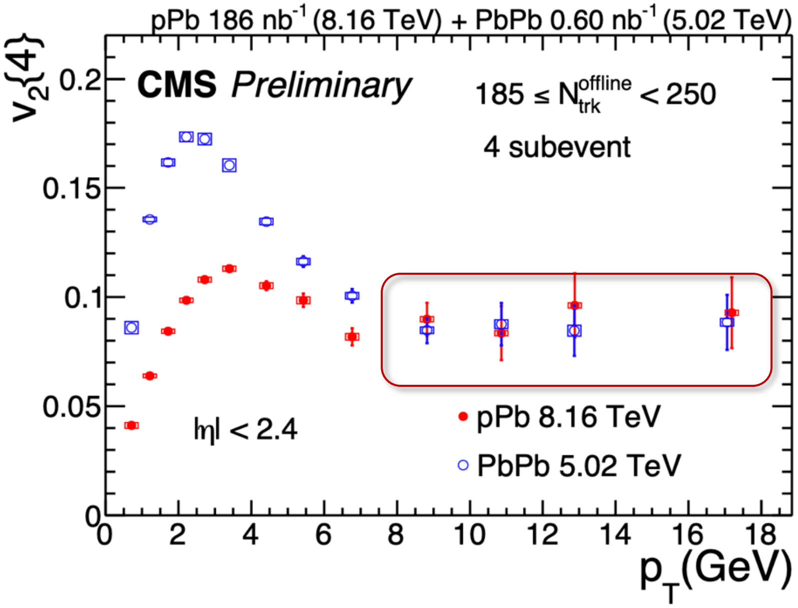


- At low p_T: PbPb has larger $v_2\{4\}$ than pPb
- At high p_T: similar magnitude and similar trend of subevents $v_2\{4\}$

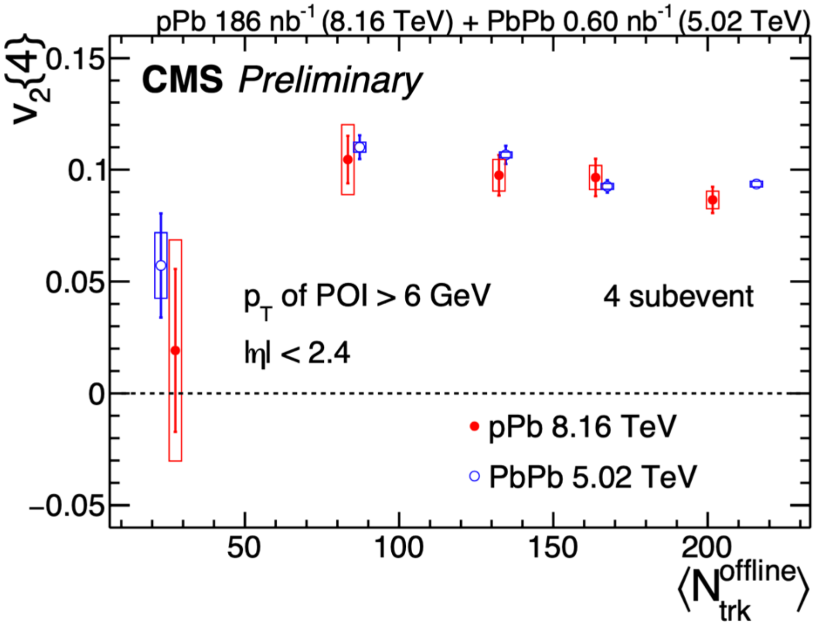
Results: 4-subevent $v_2\{4\}$…

CMS-PAS-HIN-23-002

… for $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ versus p_T



… for $p_T^{\mathrm{POI}} > 6$ GeV versus $< N_{\mathrm{trk}}^{\mathrm{offline}} >$

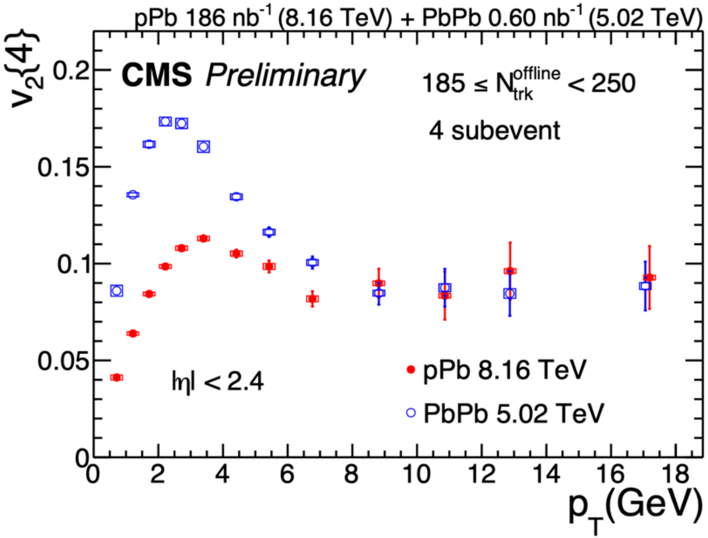


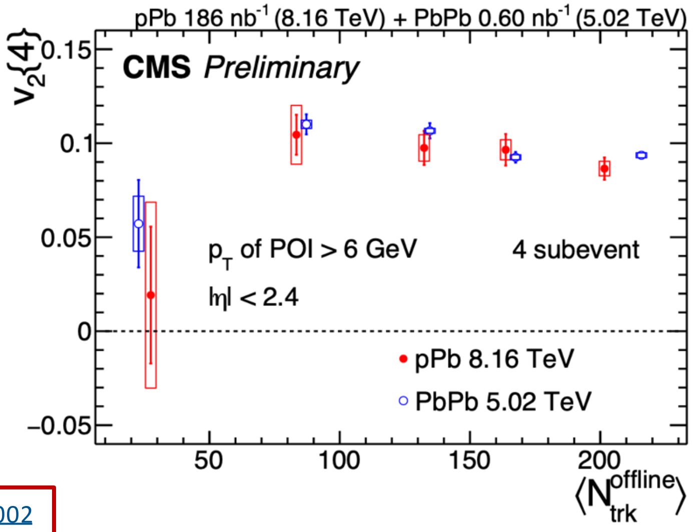
Summary – part II

$v_2\{4\}$: subevents for pPb at $\sqrt{s_{NN}}$ = 8.16 TeV & PbPb collisions $\sqrt{s_{NN}}$ = 5.02 TeV

- Extended phase space investigated for the first time in small systems
  - insights into potential indication of high-p_T parton energy loss
- significant positive value for $v_2\{4\}$ at high p_T in pPb collisions after removing nonflow with subevent methods
- striking similarity of high multiplicity pPb and peripheral PbPb collisions→ similar mechanism?

These results provide new information on the interaction of high-p_T partons with the medium in collisions of small system





CMS-PAS-HIN-23-002

Thank you!!

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BACK UP SLIDES

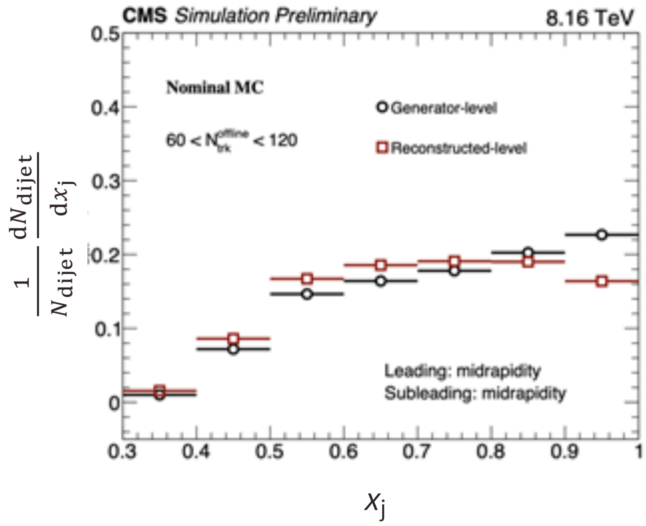
Validate the unfolding procedure at MC (I): prior

Data/MC reconstructed pdf (p^{j1}_T , p^{j2}_T) → 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!)

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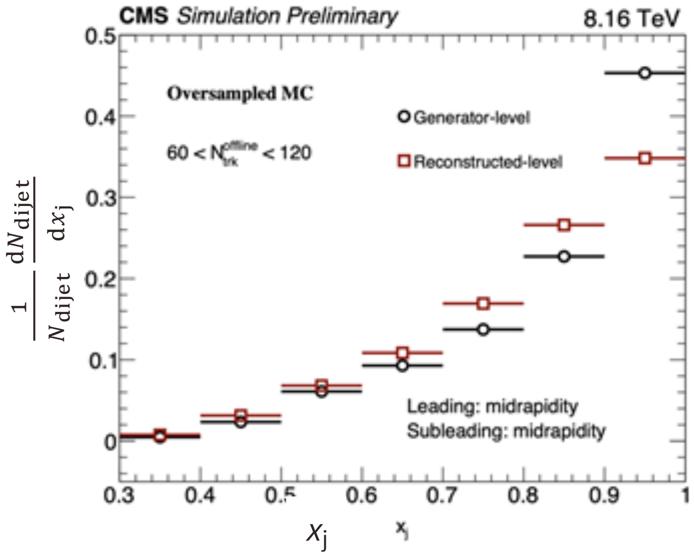
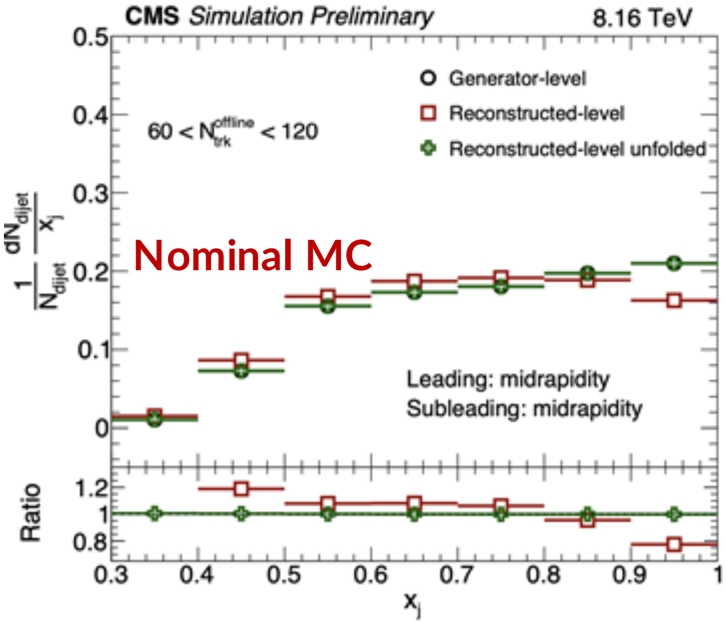
Oversampled MC
(PYTHIA+EPOS, no invariant p_T rescale)

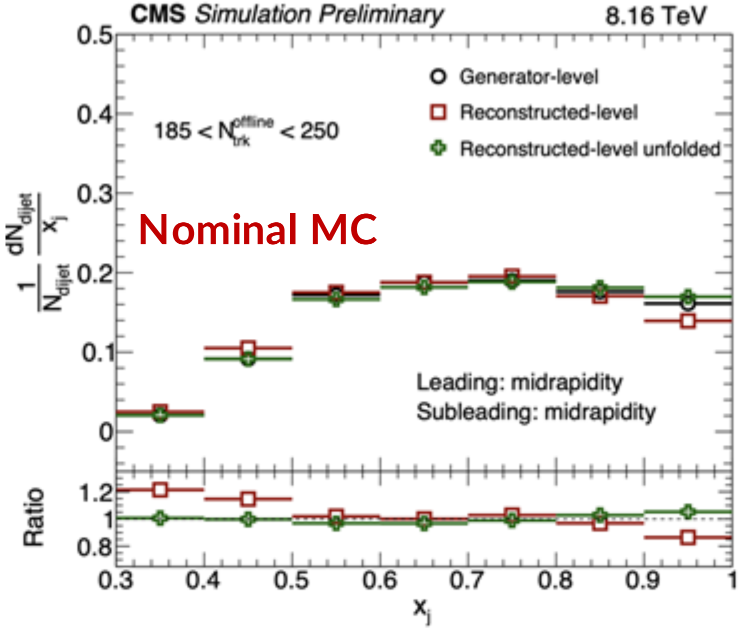


Validate the unfolding procedure at MC (II): closures

Closures achieved even with drastically different priors!

- Shows advantage of using the pdf-convoluted response matrices for cases when no reliable Monte Carlo exists





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Results – III: x_j dependence on η (backward)

Very similar behavior for all different jet combinations

- ❑ Small changes in shapes
  - results for η backwards are very similar (see backup)

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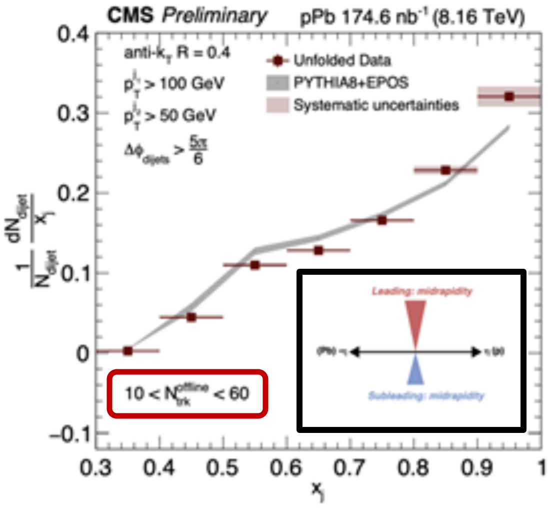

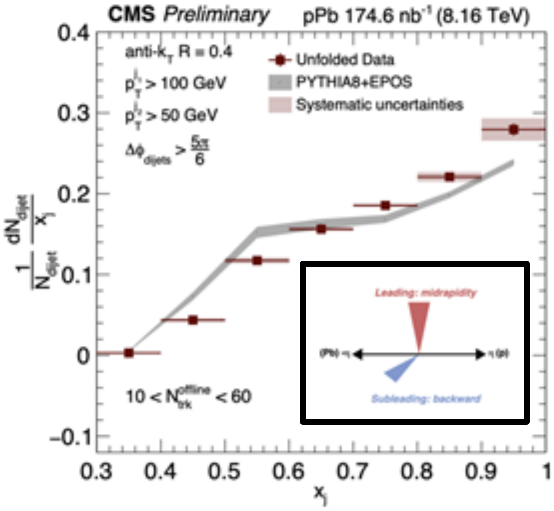

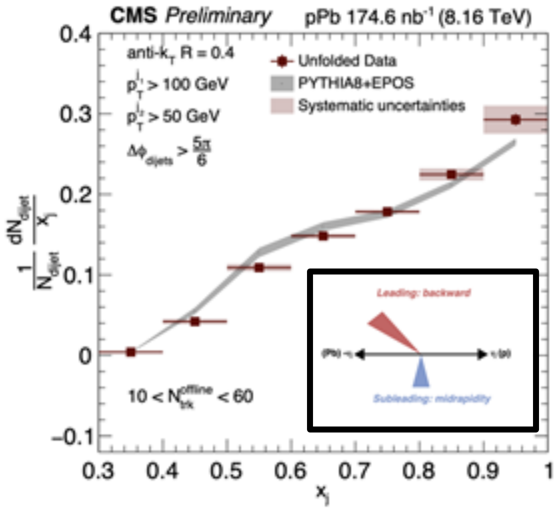

$\langle x_j \rangle$ ratio high-to-low multiplicities: reco vs. unfolded

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

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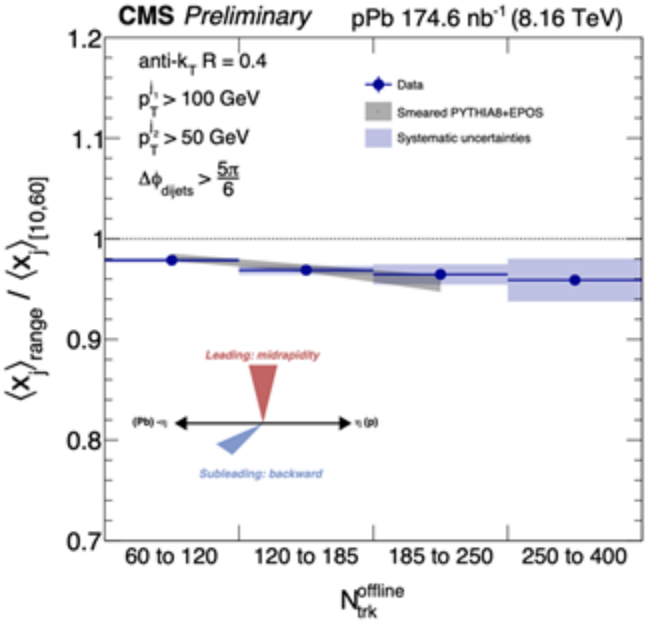
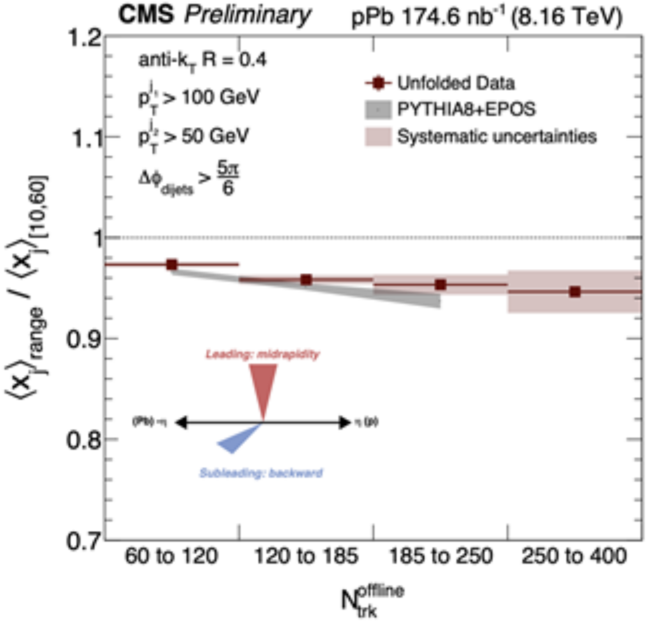
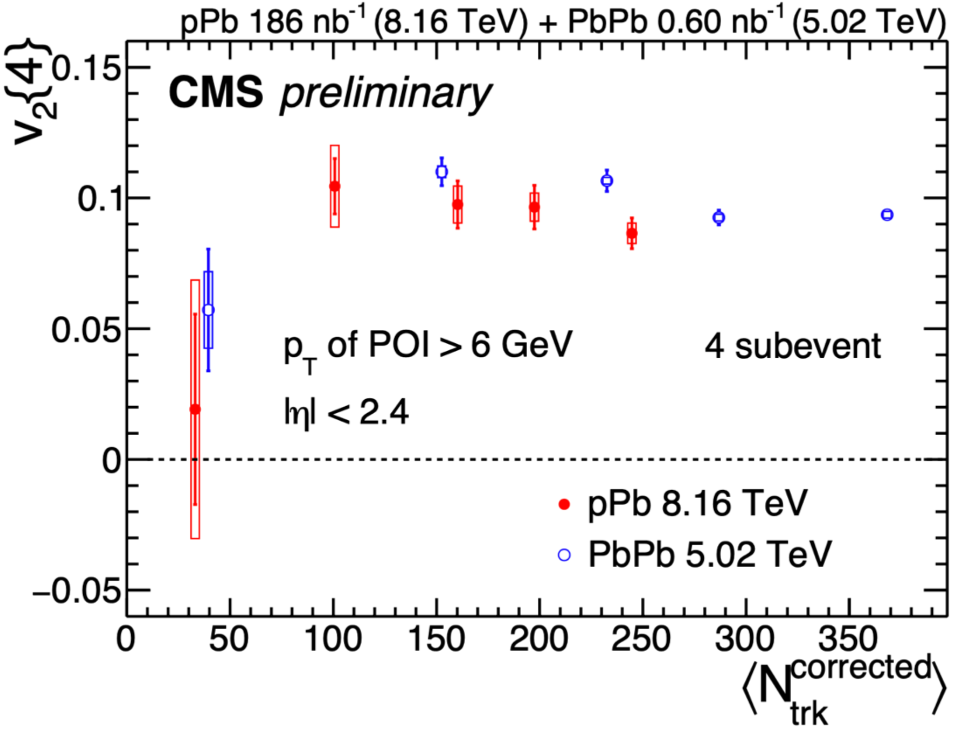




Supplement: $v_2\{4\}$ cumulant with subevents

$v_2\{4\}$ in different $<N_{trk}^{corrected}>$ bins with POI $p_T > 6$ GeV



$N_{trk}^{offline}$ range	pPb $\langle N_{trk}^{offline} \rangle$	pPb $\langle N_{trk}^{corrected} \rangle$	PbPb $\langle N_{trk}^{offline} \rangle$	PbPb $\langle N_{trk}^{corrected} \rangle$
$(0, 60)$	27	33 ± 1	23	39 ± 2
$[60, 120)$	83	101 ± 4	87	152 ± 6
$[120, 150)$	132	160 ± 6	135	233 ± 10
$[150, 185)$	164	198 ± 7	168	287 ± 12
$[185, 250)$	202	245 ± 10	216	368 ± 16

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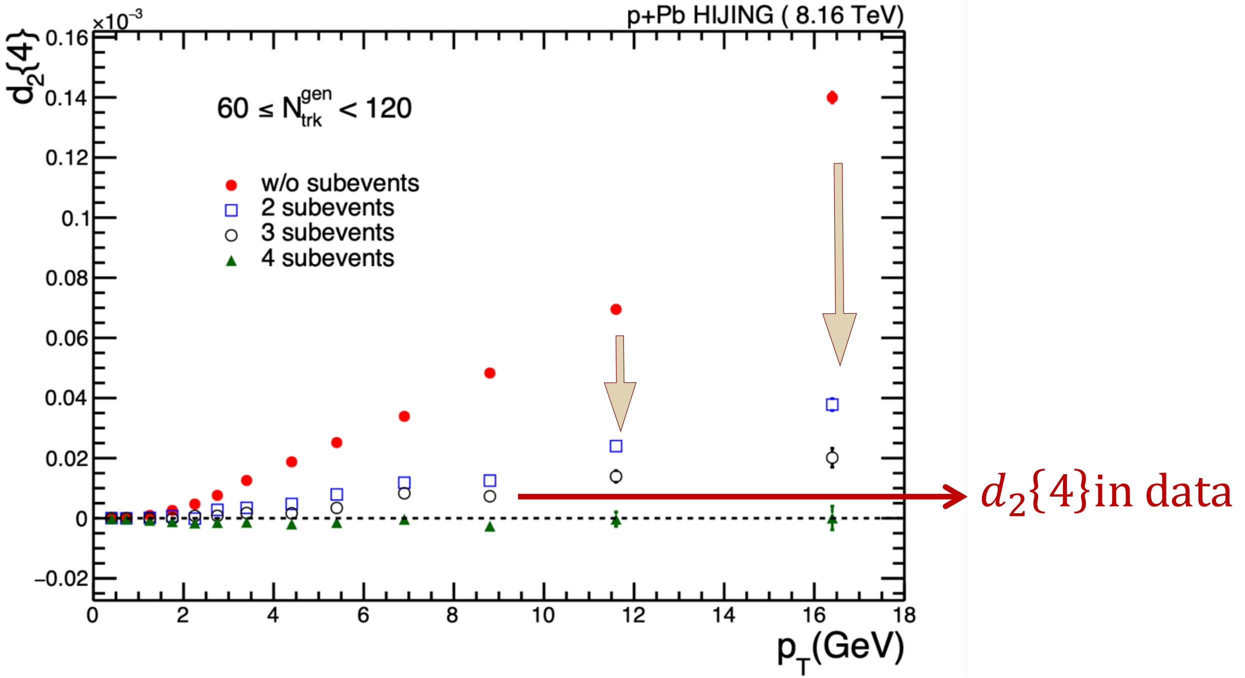
Cross-check with simulation

$d_2\{4\}$ in HIJING in $60 \leq (N_{trk}^{gen}) < 120$

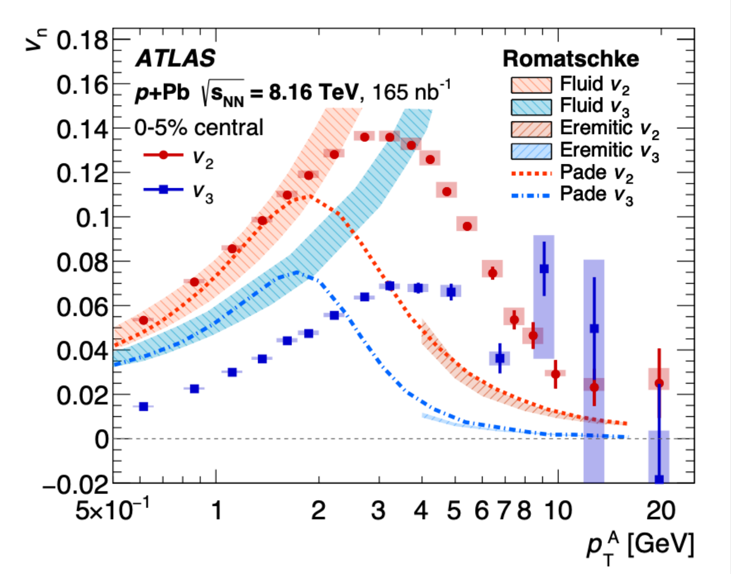


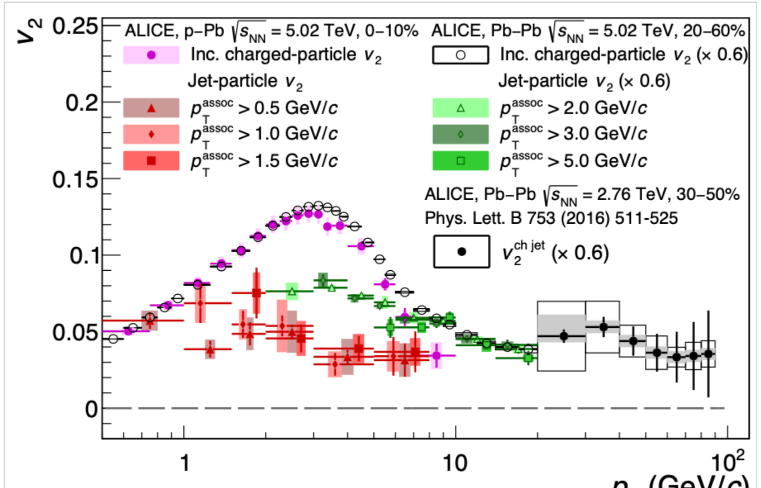
HIJING

- ❑ no collectivity
- ❑ employed to cross check non-flow subtraction of subevent cumulant

Previous Measurements of v_n in pPb at High p_T

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





arXiv:2212.12609

- 2-particle correlation technique (nonflow contamination)
- Template fit method for nonflow subtraction
- Based on strong assumptions