



Resolving medium properties using high- p_T jets with jet and in-jet correlations in PbPb collisions at 5.02 TeV with the CMS detector

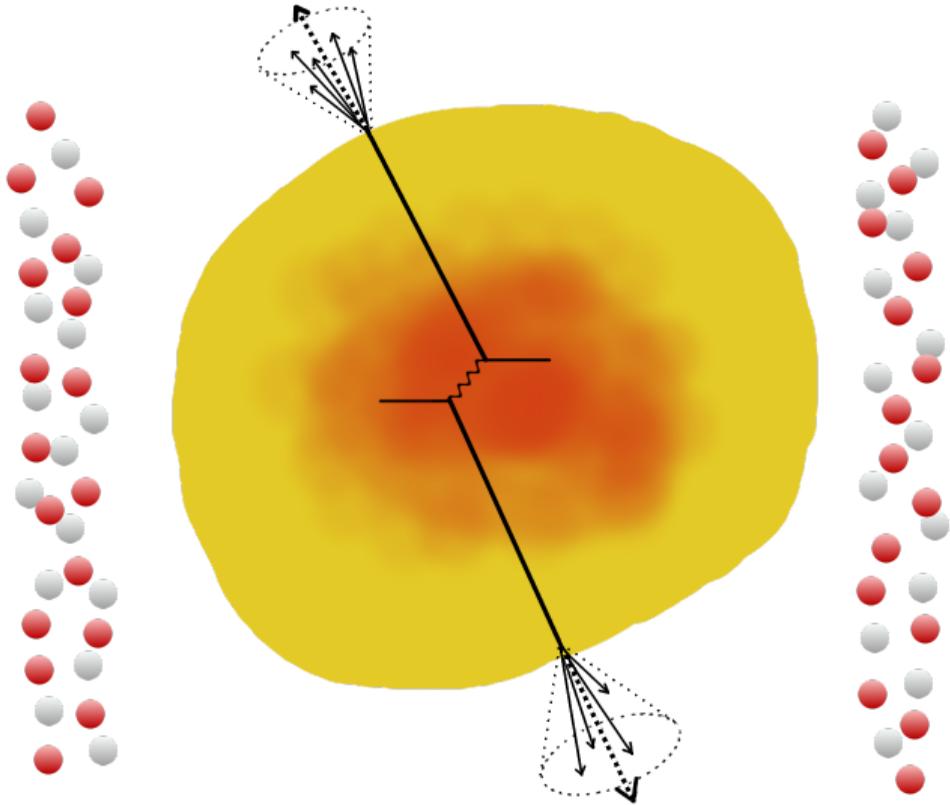
Jussi Viinikainen

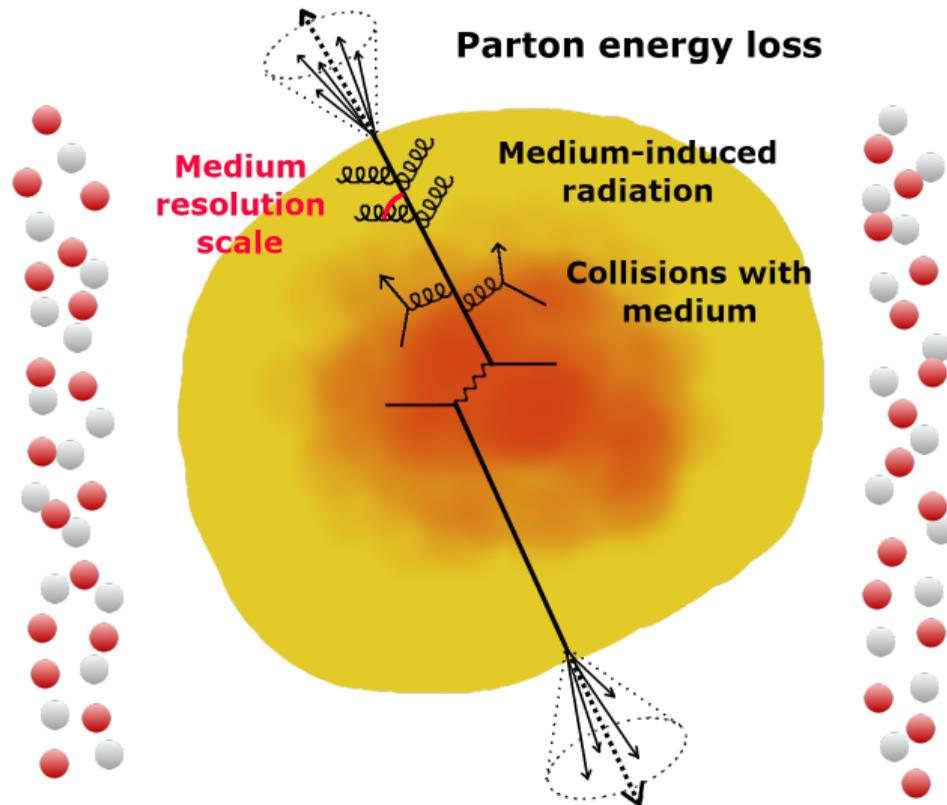
Vanderbilt University

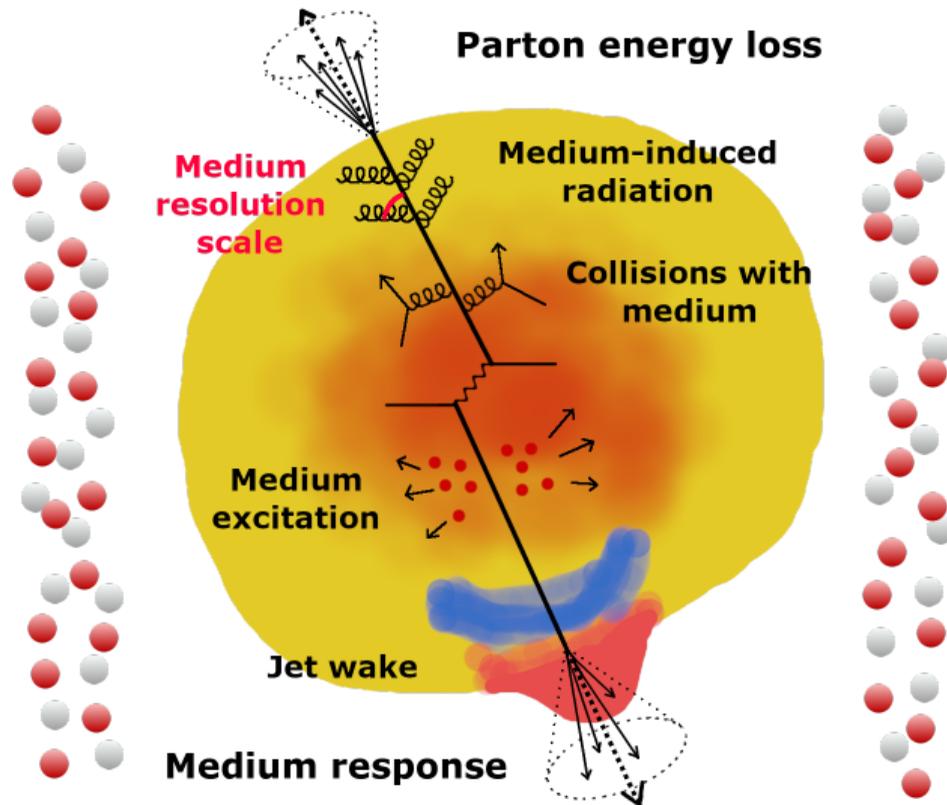
for the CMS collaboration

Quark Matter 2023

Introduction



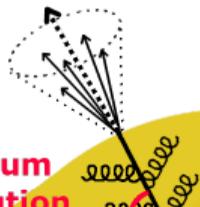
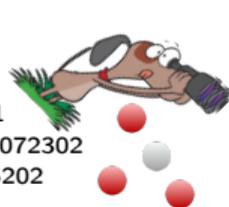




Introduction

Jet R_{AA}

ALICE: PLB 746 (2015) 1
ATLAS: PRL 114 (2015) 072302
CMS: PRC 96 (2017) 015202

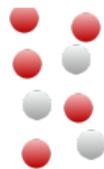
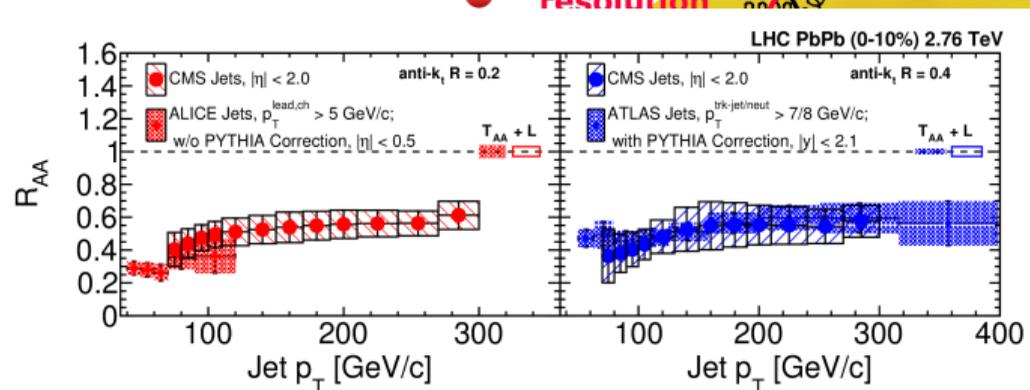


Parton energy loss

Medium resolution

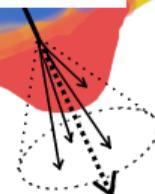
Medium-induced radiation

ions with medium



Jet wake

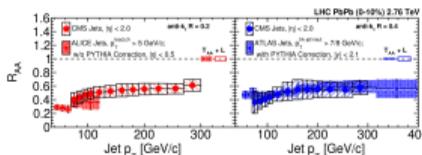
Medium response



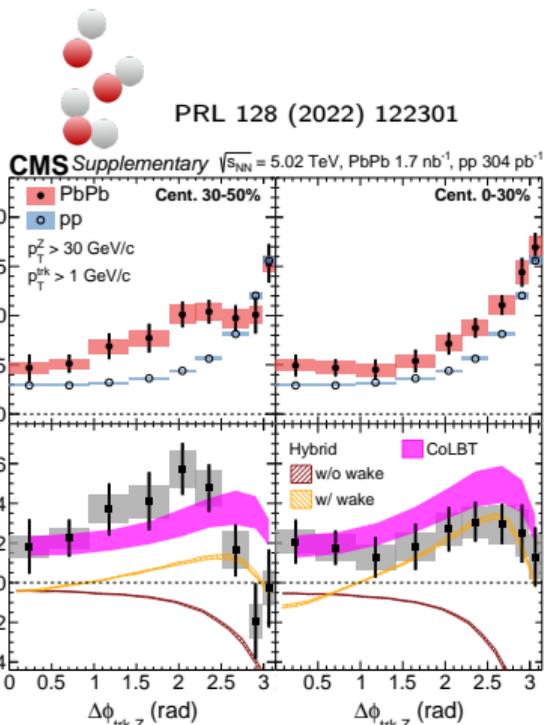
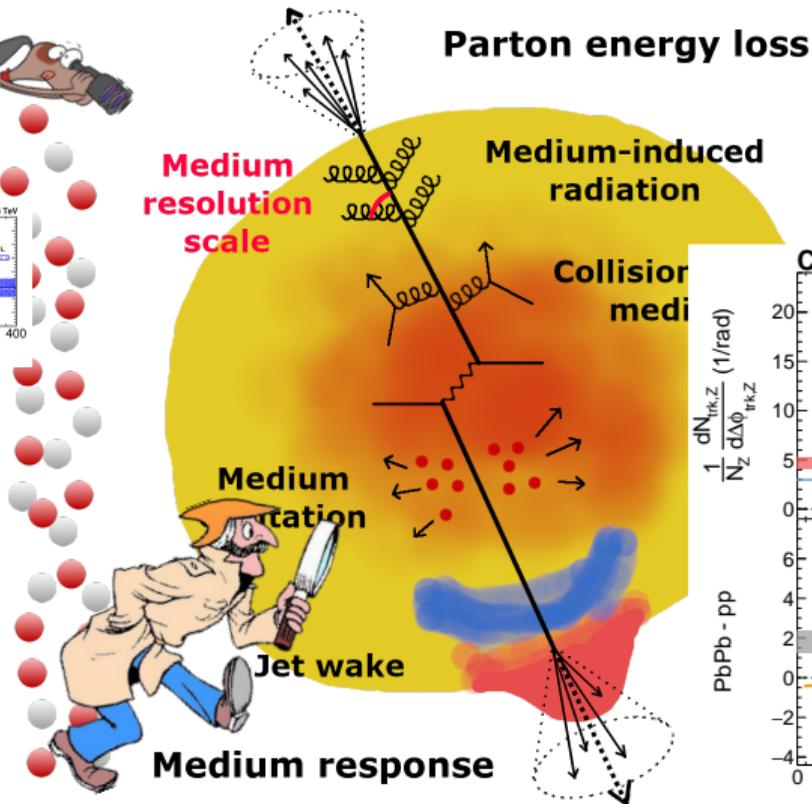
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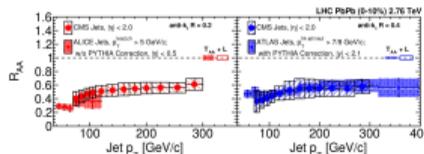
Z-hadron correlation



Introduction

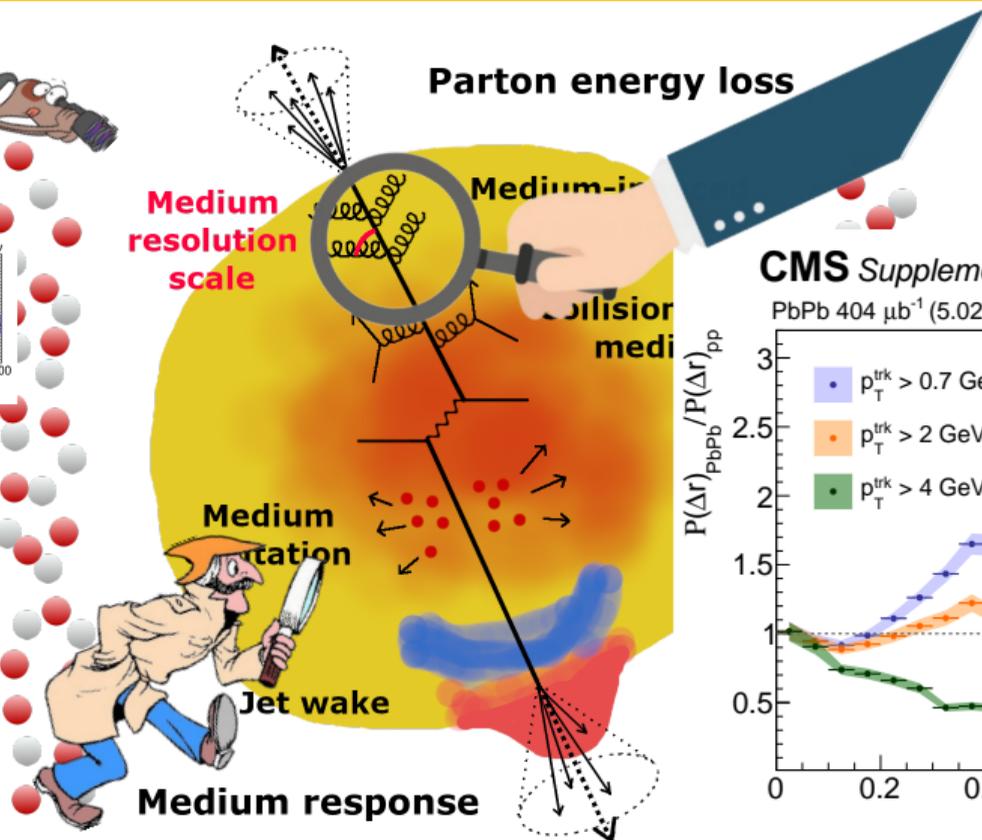
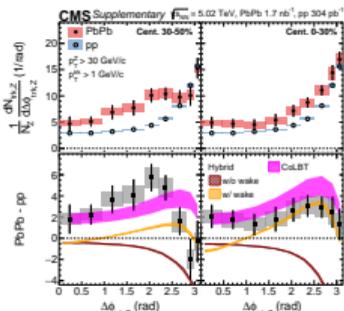
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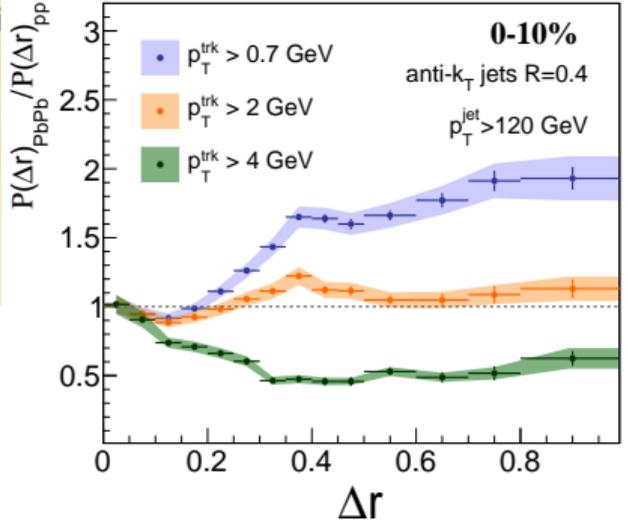
Z-hadron correlation

PRL 128 (2022) 122301



Jet shapes

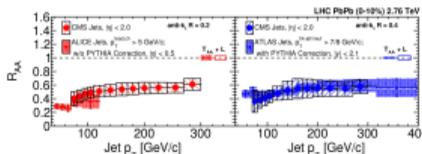
CMS Supplementary JHEP 05(2018) 006
 PbPb 404 μb^{-1} (5.02 TeV) pp 27.4 pb^{-1} (5.02 TeV)



Introduction

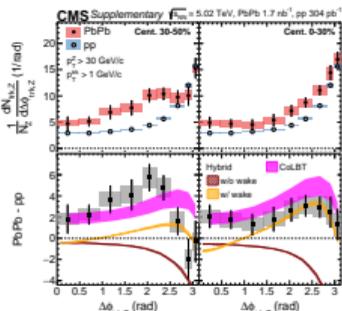
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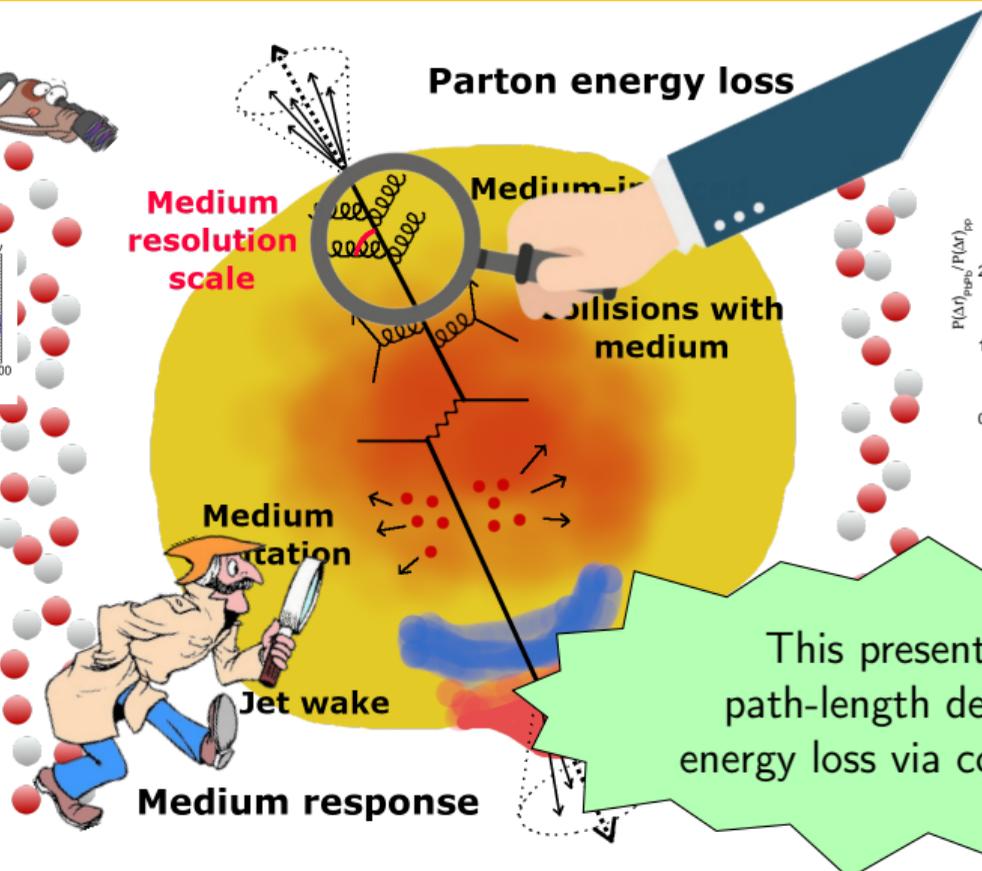


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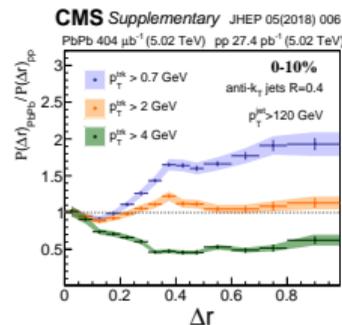
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Parton energy loss



Jet shapes

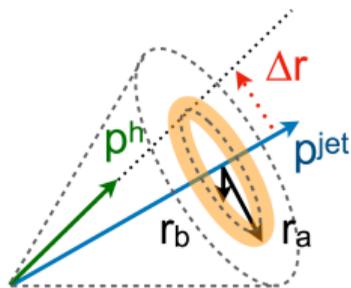


This presentation:
 path-length dependent
 energy loss via correlations!

Correlations between jets and particles

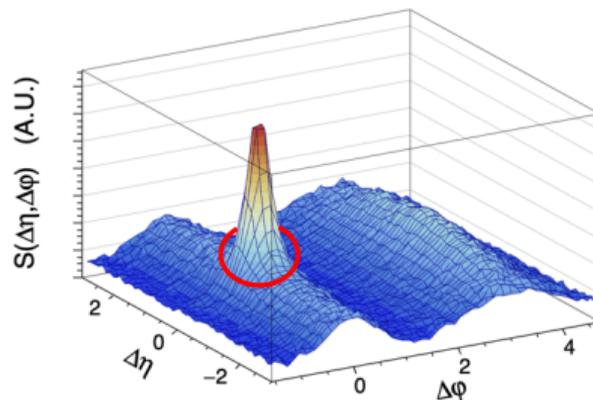
Jet shape and dijet momentum balance definitions

- Jet shape = radial momentum density profile of the jet



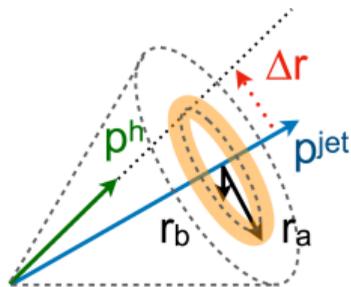
$$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{track} \in (r_a, r_b)} p_T^{\text{track}}}{p_T^{\text{jets}}}$$

$$\Delta r = \sqrt{(\varphi_{\text{jet}} - \varphi_{\text{track}})^2 + (\eta_{\text{jet}} - \eta_{\text{track}})^2}$$



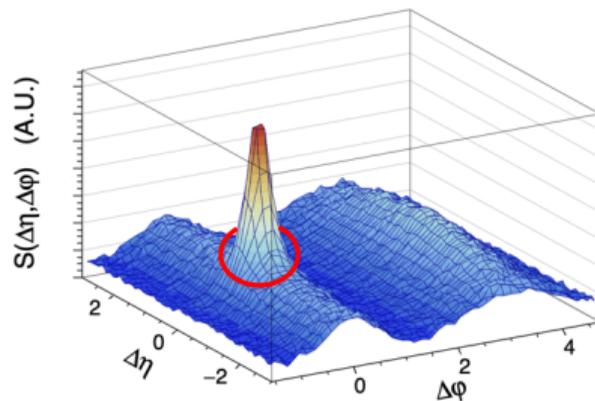
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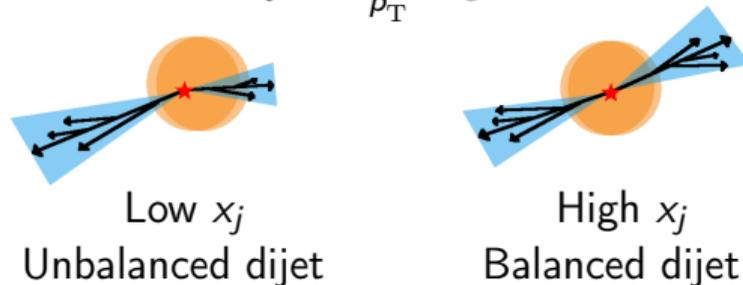


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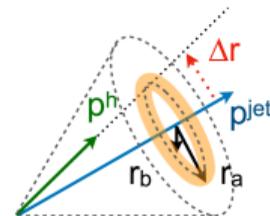
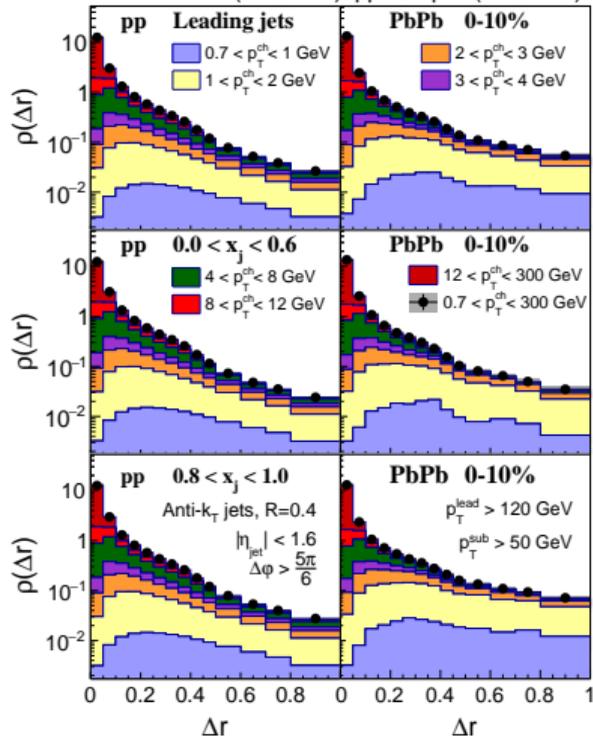
$$x_j = \frac{p_{\text{T}}^{\text{subleading}}}{p_{\text{T}}^{\text{leading}}}$$



Jet shapes for leading jets

CMS Supplementary JHEP 05 (2021) 116

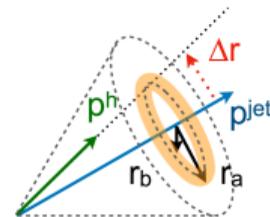
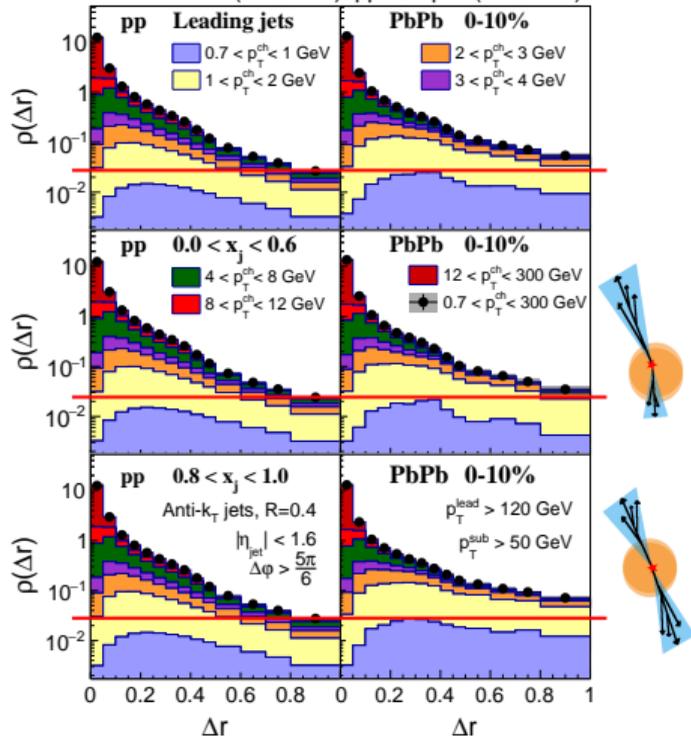
PbPb 1.7 nb⁻¹ (5.02 TeV) pp 320 pb⁻¹ (5.02 TeV)



Jet shapes for leading jets

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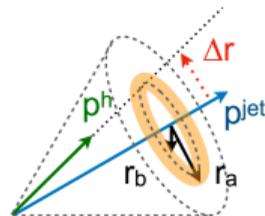
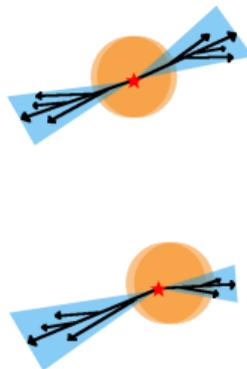
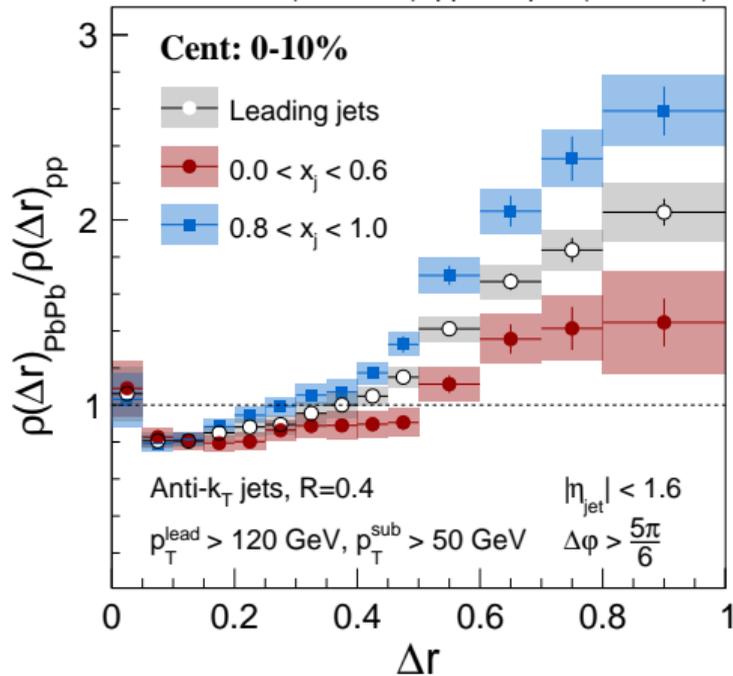


- Shapes wider in central heavy ion collisions compared to pp
- Widening is due to low- p_T particles at large radii
- Differences between x_j bins best seen in a ratio plot

Jet shape ratio for leading jets

CMS Supplementary JHEP 05 (2021) 116

PbPb 1.7 nb⁻¹ (5.02 TeV) pp 320 pb⁻¹ (5.02 TeV)

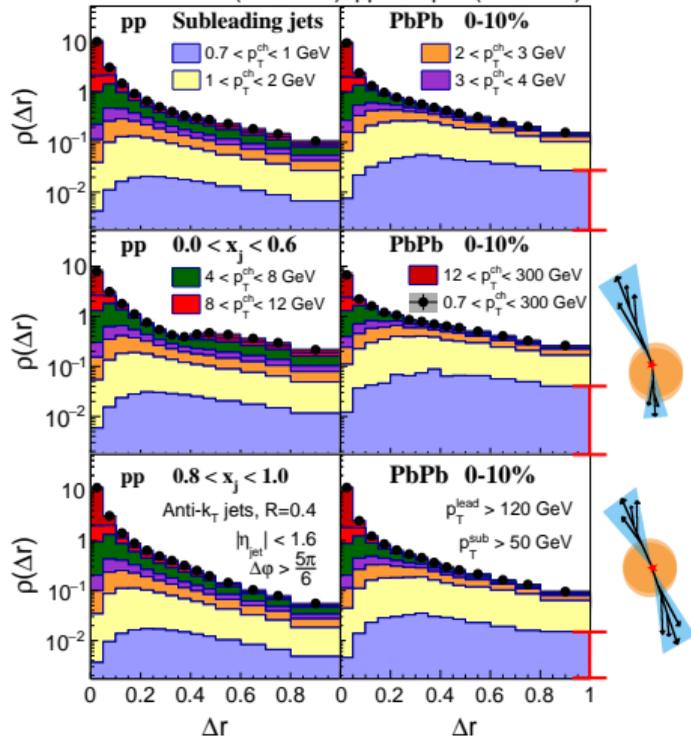


- Modifications are the greatest in balanced events
- Consistent with expectation that unbalanced events caused by energy loss fluctuations or surface bias

Jet shapes for subleading jets

CMS Supplementary JHEP 05 (2021) 116

PbPb 1.7 nb⁻¹ (5.02 TeV) pp 320 pb⁻¹ (5.02 TeV)

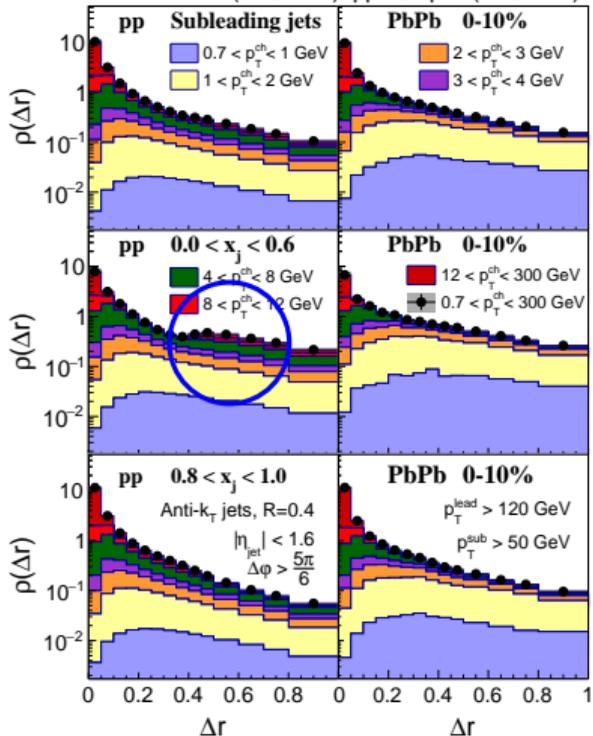


- Widening is greatest in unbalanced events

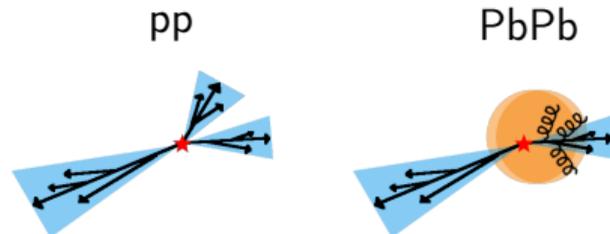
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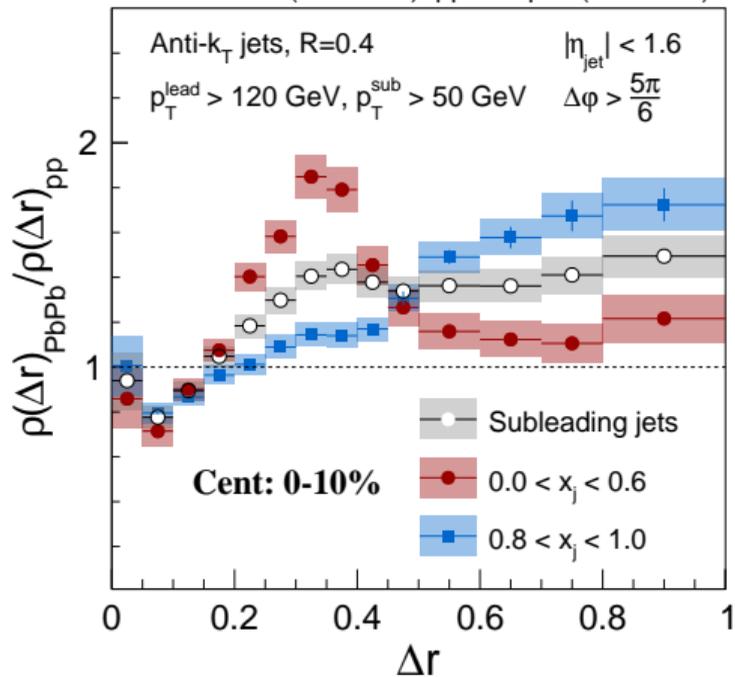
- Widening is greatest in unbalanced events
- Enhancement of high- p_T particles outside of jet cone in unbalanced pp events
 - ⇒ Third jet likely needed to produce the momentum imbalance in pp
 - In PbPb, the energy can be lost to the medium



Jet shape ratio for subleading jets

CMS Supplementary JHEP 05 (2021) 116

PbPb 1.7 nb⁻¹ (5.02 TeV) pp 320 pb⁻¹ (5.02 TeV)

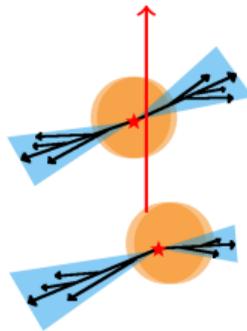
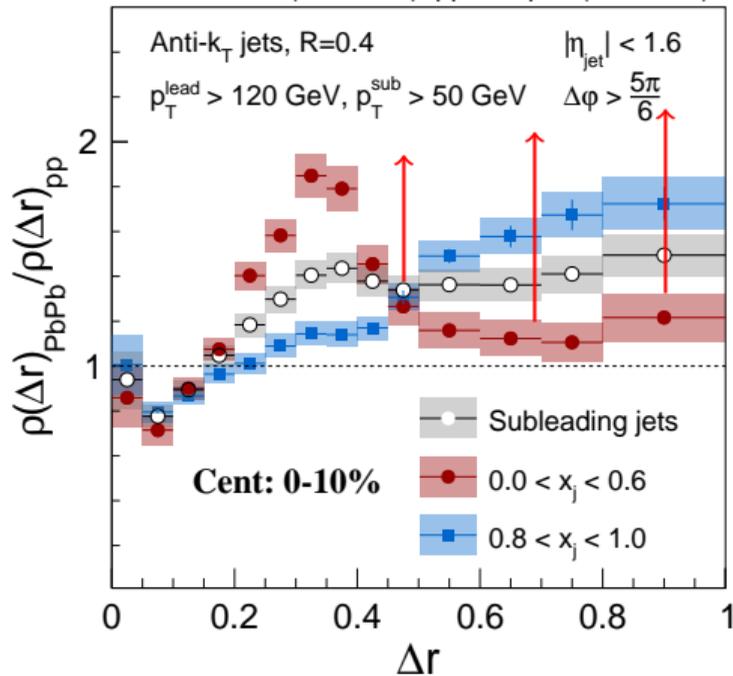


- Unbalanced bin highest around $\Delta r = 0.3$
⇒ Unbalanced events are the most quenched
- Ratio in unbalanced bin close to 1 at high Δr
- Contribution from 3-jet events in pp makes reference wider

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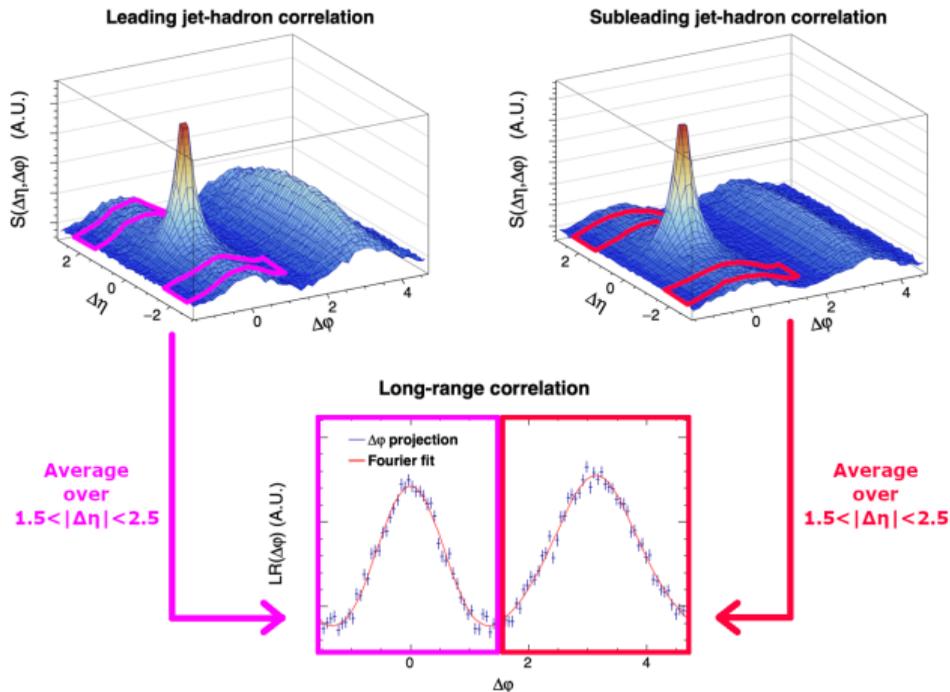


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- Ratio in unbalanced bin close to 1 at high Δr
- Contribution from 3-jet events in pp makes reference wider
 - If compared to x_j integrated pp to mitigate the effect, the ratio would stay high

Correlations between jets and event plane



Factorizing dijet v_n



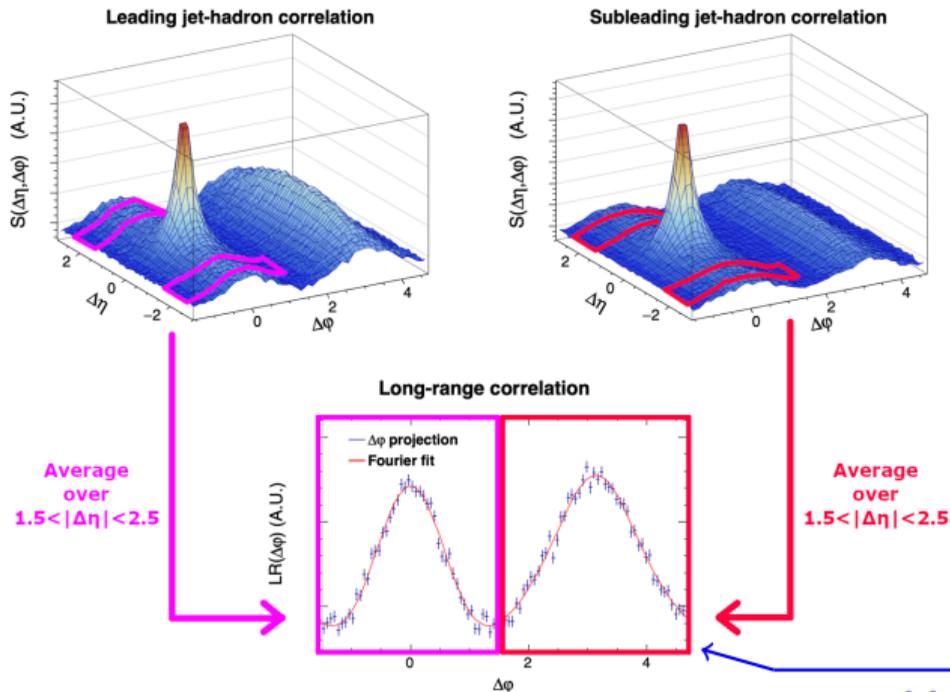
- Fit $\Delta\varphi$ -projection of the long-range distribution with a Fourier fit:

$$f(\Delta\varphi) = A \cdot \left(1 + \sum_{n=1}^4 2V_n \cos(n\Delta\varphi) \right)$$

- Here coefficients V_n are mixture of $v_{n,\text{hadron}}$ and $v_{n,\text{dijet}}$
- Based on [1], dijet v_n can be factorized: $V_n = v_{n,\text{dijet}} \times v_{n,\text{hadron}}$

¹Eur. Phys. C 72 (2012) 10052

Factorizing dijet v_n



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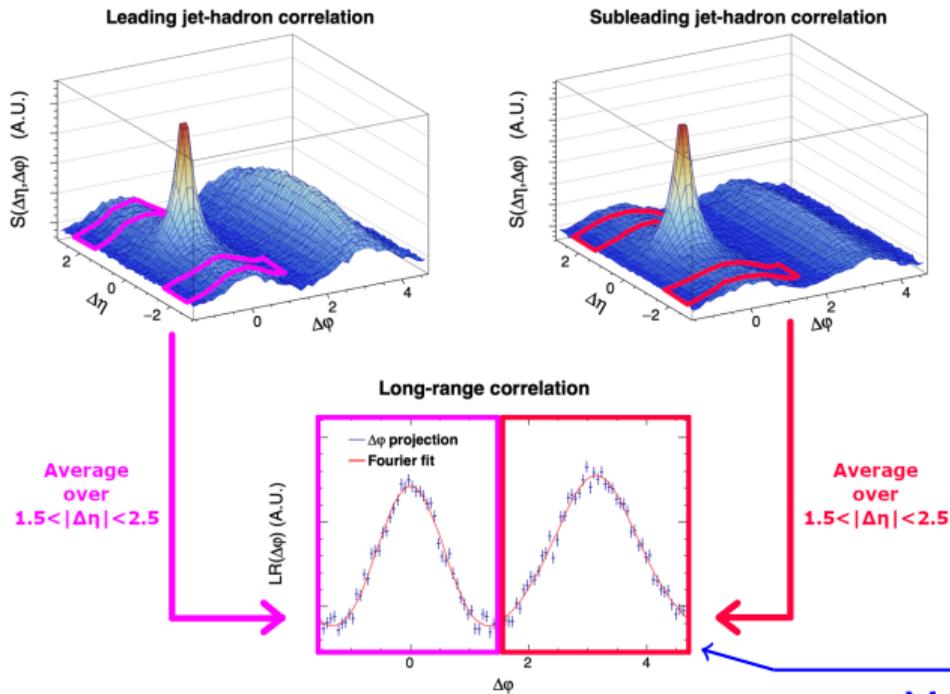
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Measure jet-hadron

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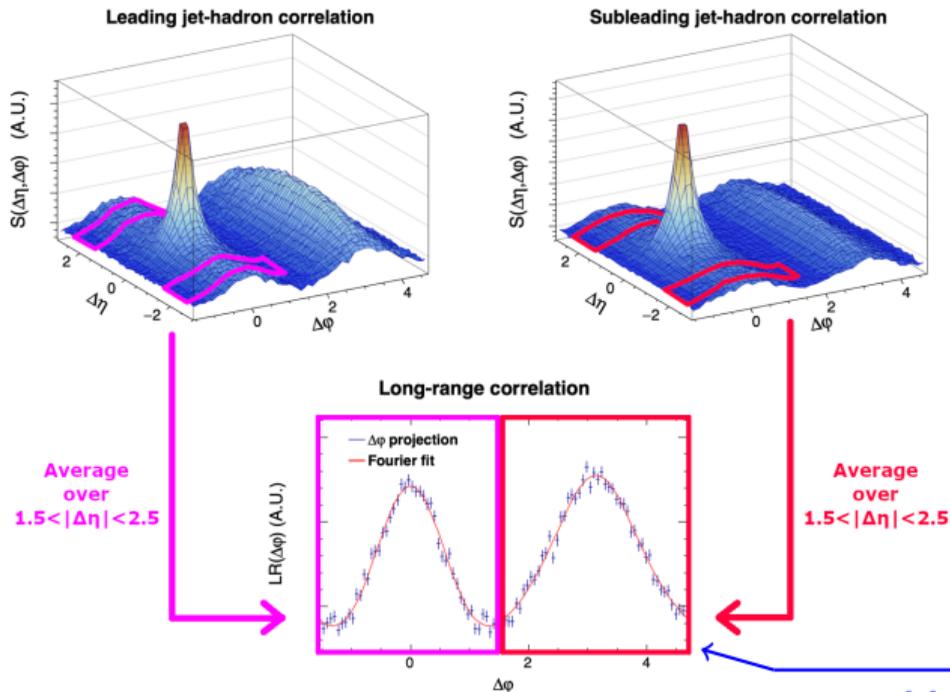
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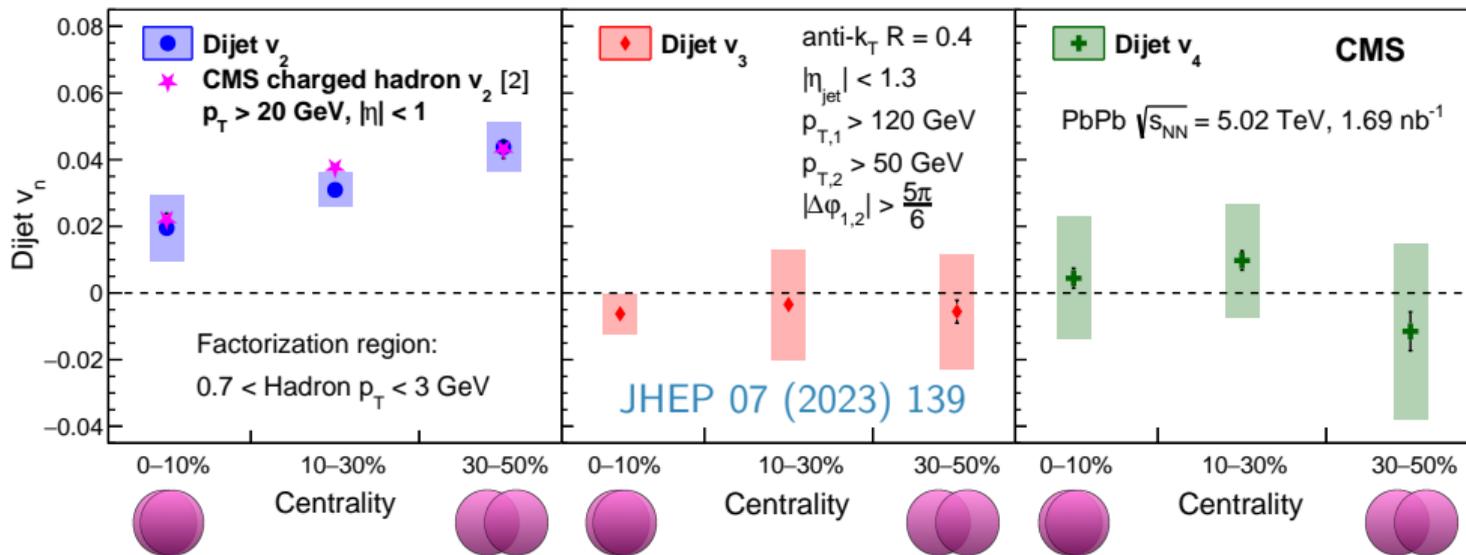
Calculate

Measure dihadron

¹Eur. Phys. C 72 (2012) 10052

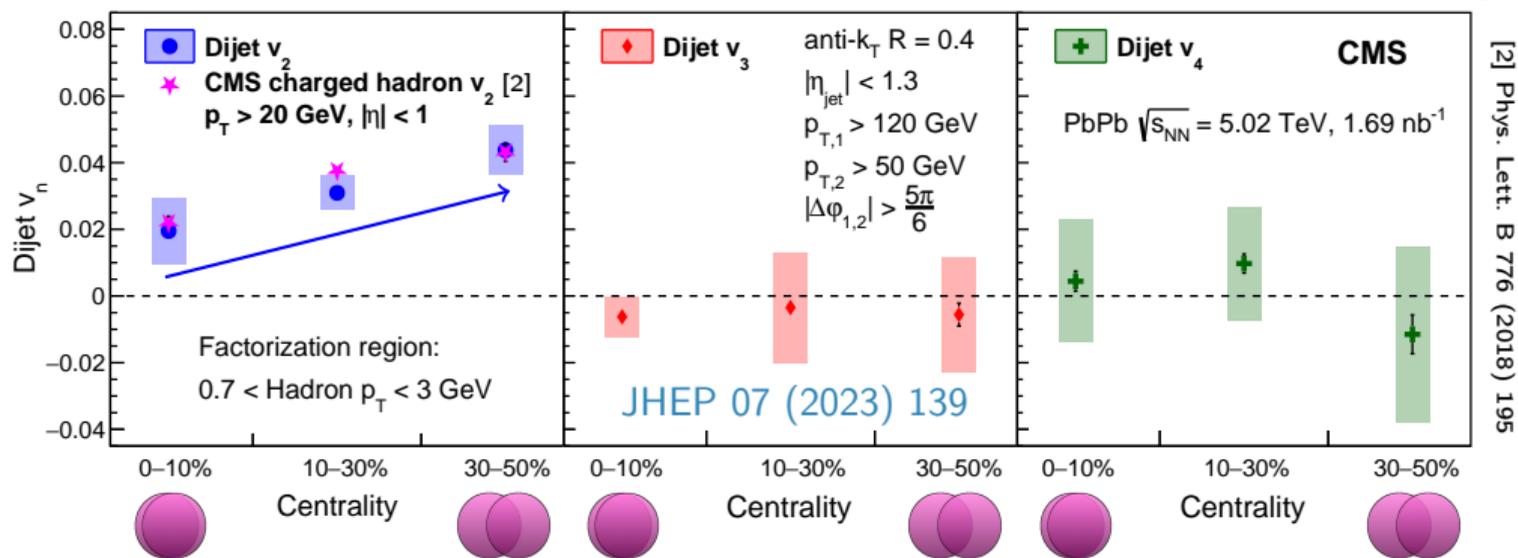
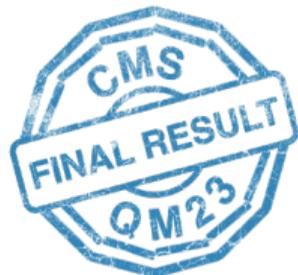
Dijet v_n as a function of centrality

- Final dijet v_n values factorized from one wide $0.7 < p_T^{\text{ch}} < 3$ GeV bin



Dijet v_n as a function of centrality

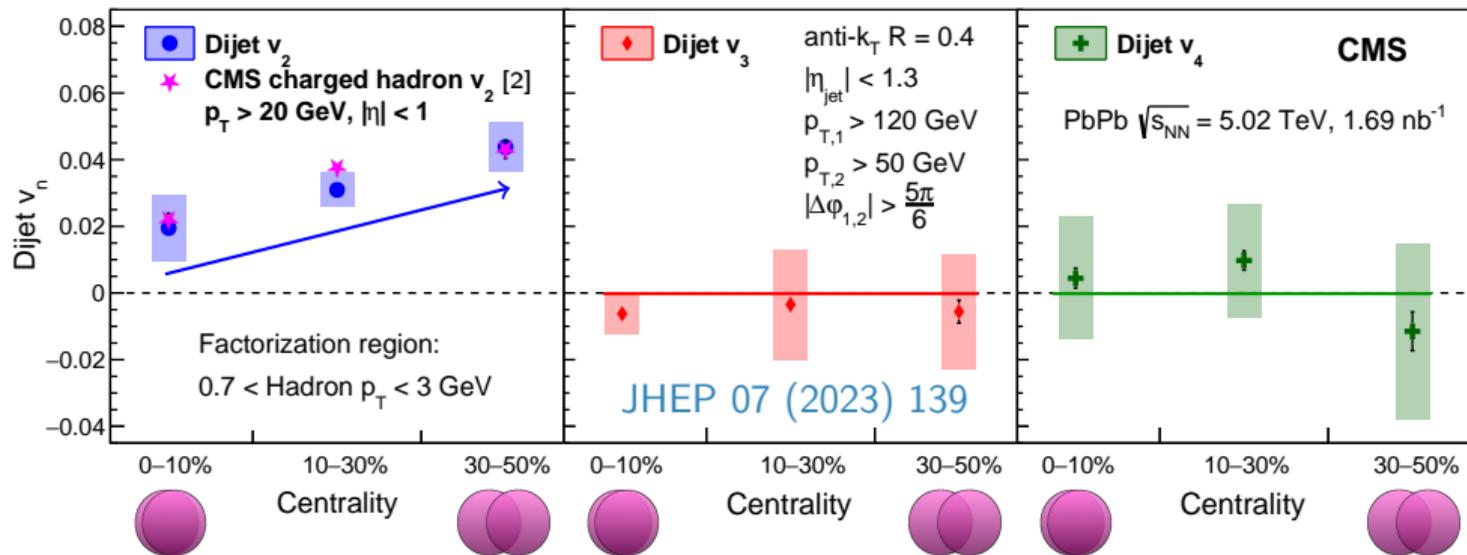
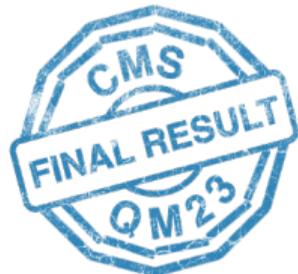
- Final dijet v_n values factorized from one wide $0.7 < p_T^{\text{ch}} < 3$ GeV bin
- Positive dijet v_2 , increasing towards more peripheral events
 \Rightarrow More almond-like initial geometry \Rightarrow bigger short vs. long axis difference



[2] Phys. Lett. B 776 (2018) 195

Dijet v_n as a function of centrality

- Final dijet v_n values factorized from one wide $0.7 < p_T^{\text{ch}} < 3$ GeV bin
- Positive dijet v_2 , increasing towards more peripheral events
 - ⇒ More almond-like initial geometry ⇒ bigger short vs. long axis difference
- Dijet v_3 and v_4 consistent with zero
 - ⇒ No measurable impact from medium density fluctuations



[2] Phys. Lett. B 776 (2018) 195

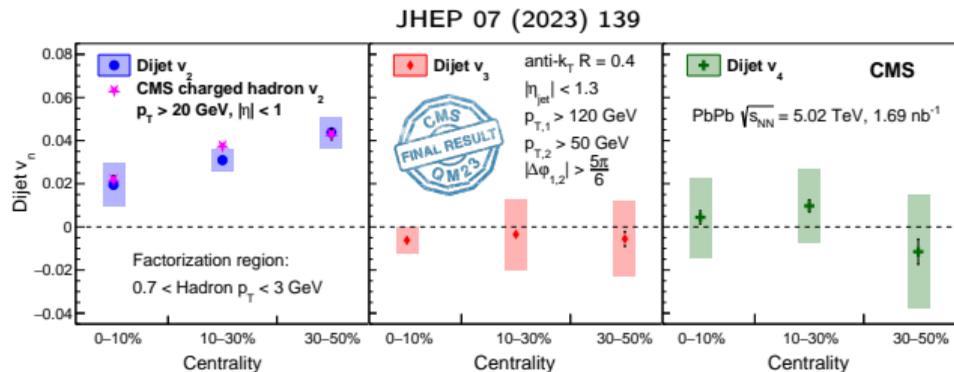
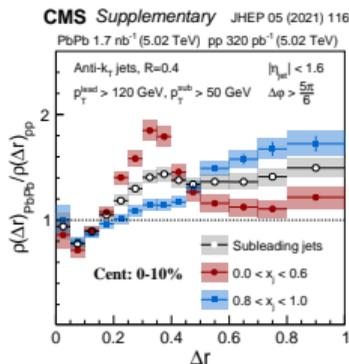
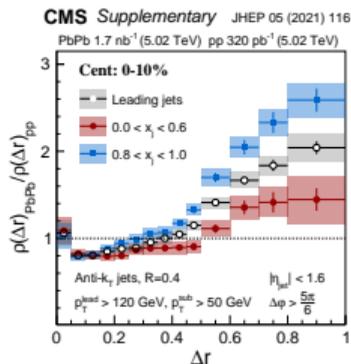
Teaser: energy-energy correlators

Stay tuned!

Results
coming soon!

Summary

- Measured jet shapes for leading and subleading jets in dijet events as a function of x_j
 - Leading jets are the broadest in balanced events
 - Subleading jets show biggest modifications in unbalanced events
 - Observations are consistent with energy loss fluctuation and surface bias interpretations
- Measured jet azimuthal anisotropies from dijet events
 - Positive and centrality dependent dijet $v_2 \Rightarrow$ path-length dependence
 - Dijet v_3 and v_4 consistent with zero



This work is supported by the grant DE-FG05-92ER40712 from the US Department of Energy

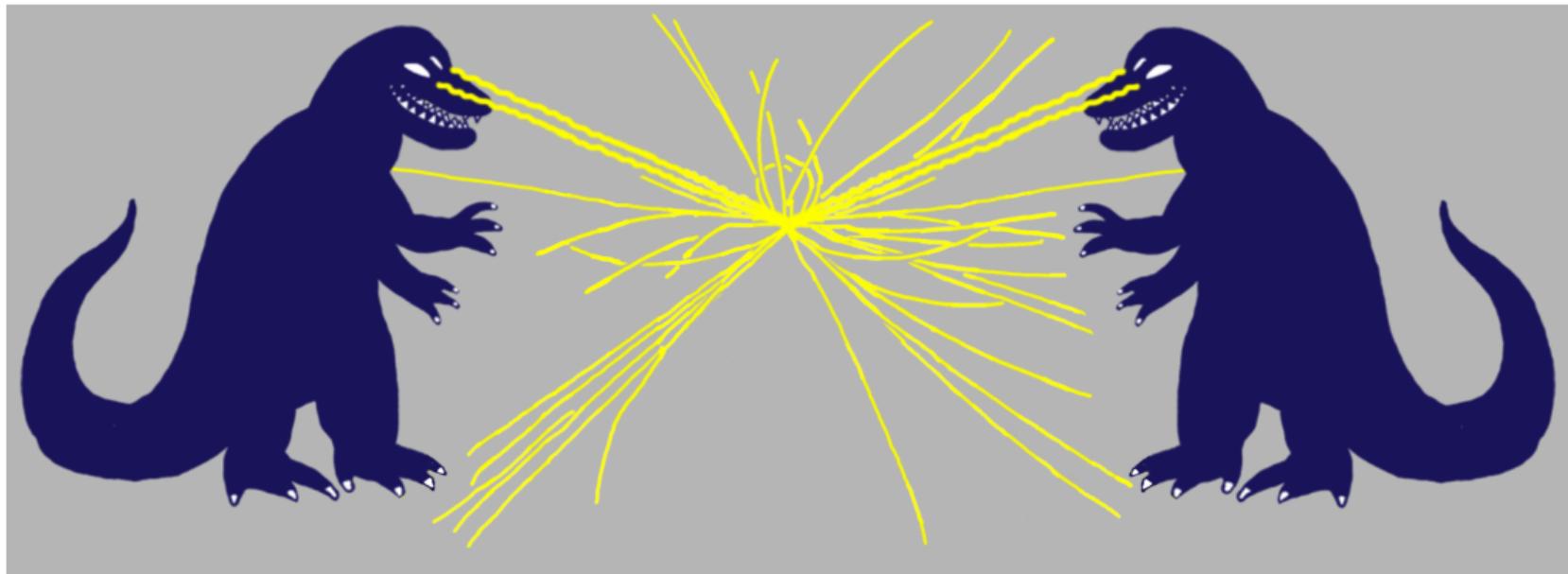
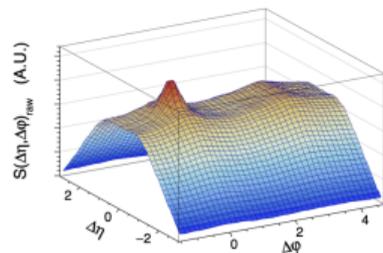


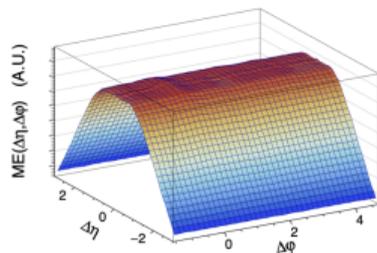
Image credit: BOOST 2022 conference logo

Jet-hadron correlation ($\Delta\varphi, \Delta\eta$) distribution

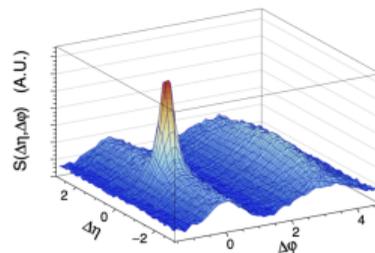
Same event



Mixed event



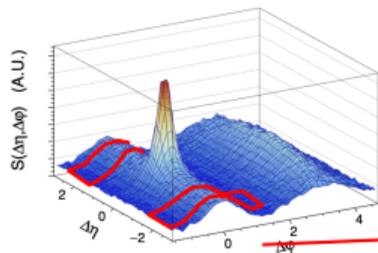
ME Corrected



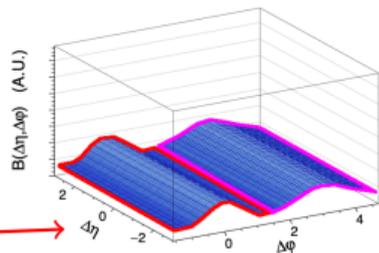
- Select dijet events with back-to-back leading and subleading jets
- Pair charged particle tracks with leading and subleading jet axes
- Limited detector acceptance in beam direction ($\Delta\eta$)
 - ⇒ More likely to see pairs with small $\Delta\eta$
- Mixed event: take jet from one event and particles from another
 - No correlations, only acceptance effects
- Divide same event with mixed event to correct for acceptance

Short- and long-range ($\Delta\varphi$, $\Delta\eta$) correlations

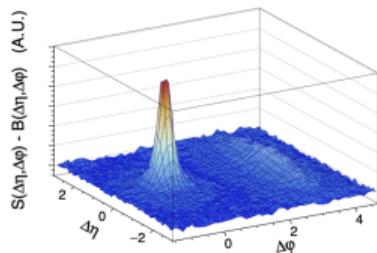
Acceptance corrected



Long-range correlation

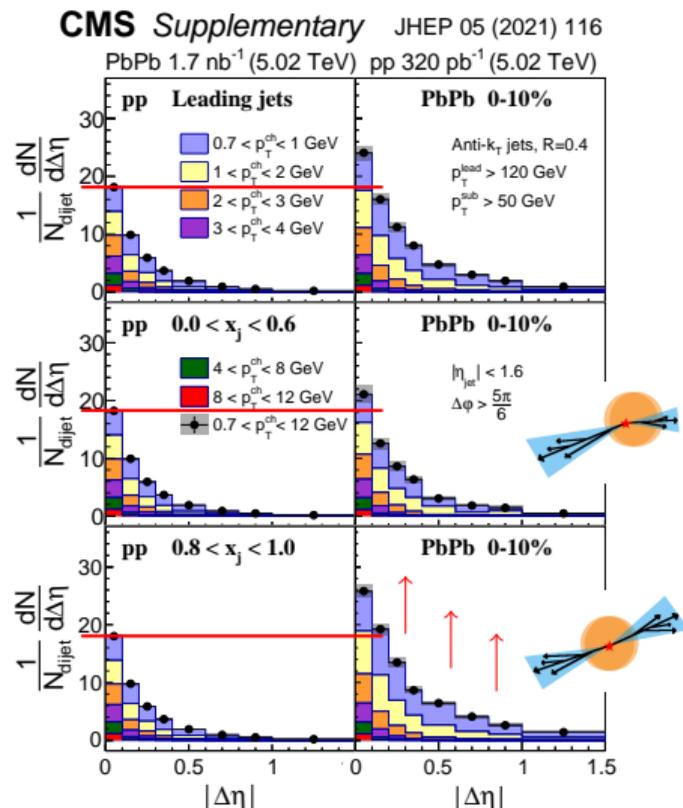


Short-range correlation



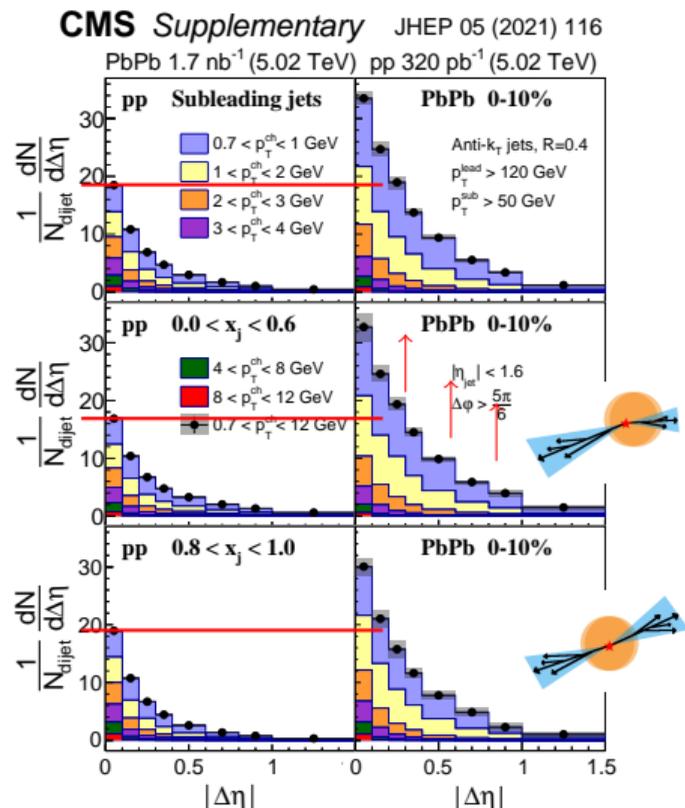
- Jet correlations are small-angle correlations
 - Estimate long-range correlations from $1.5 < |\Delta\eta| < 2.5$ "side band"
 - Avoid prolonged away-side peak
- Combine **leading** and **subleading** side bands to fill long-range correlation distribution in whole $(\Delta\eta, \Delta\varphi)$ region
- Subtract long-range correlation distribution from acceptance-corrected distribution to extract jet signal

Charged-particle yield with respect to leading jets



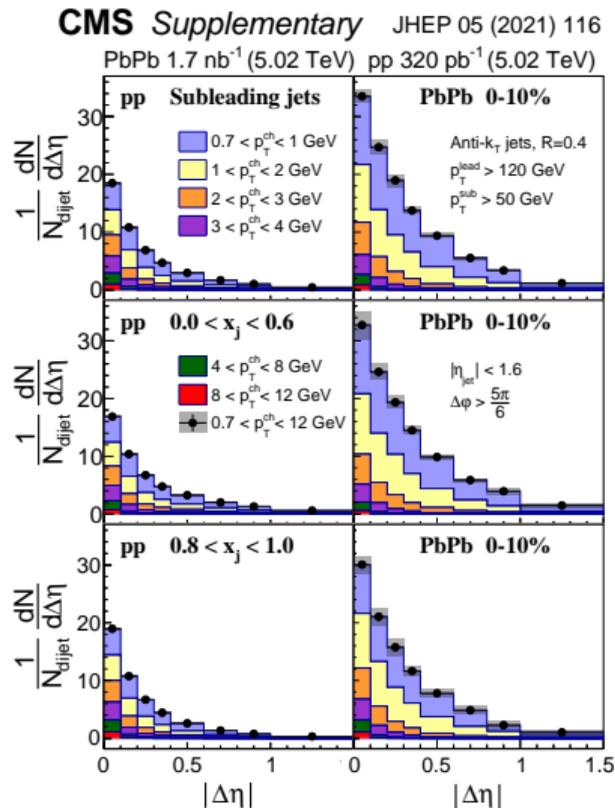
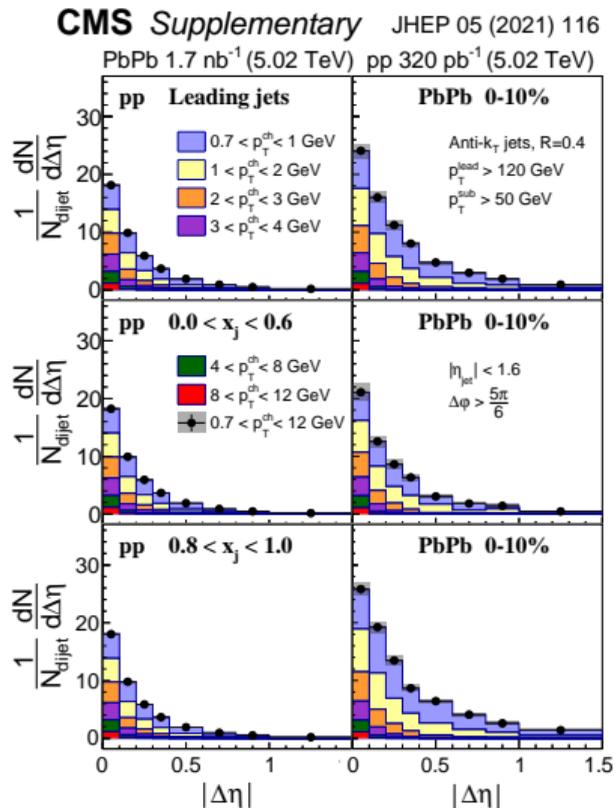
- Low- p_T yield enhanced in central heavy ion collisions
- Biggest modifications when dijet momentum is balanced
- Consistent with energy loss fluctuations and surface bias

Charged-particle yield with respect to subleading jets



- Modifications larger than for leading jets
- Conversely to leading jets, **modifications are the largest in unbalanced events**
- As expected from energy loss fluctuations and surface bias

Charged-particle yields leading-subleading comparison



- Modifications much larger for subleading jets

Extra studies for third jet in pp

- Make a cut based on the third highest jet p_T in the event
 - Three jet event = Third jet $p_T > \frac{\text{Subleading jet } p_T}{2}$
 - Two jet event = Third jet $p_T < \frac{\text{Subleading jet } p_T}{2}$
- The table below shows the numbers of dijets following this categorization in the used x_j bins for pp data

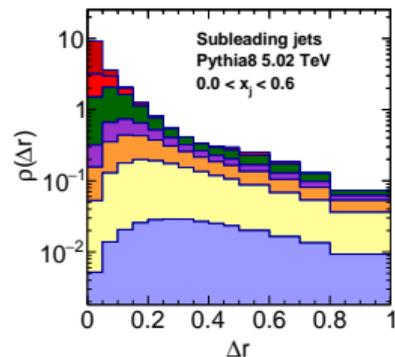
Event type	$0 < x_j < 0.6$	$0.6 < x_j < 0.8$	$0.8 < x_j < 1$
Three jet event	1391651 (52 %)	582004 (15 %)	131811 (3 %)
Two jet event	1298405 (48 %)	3331967 (85 %)	4259981 (97 %)
All events	2690056	3913971	4391792

- From the table it can be seen that unbalanced events are likely to have high p_T third jet, but balanced very unlikely

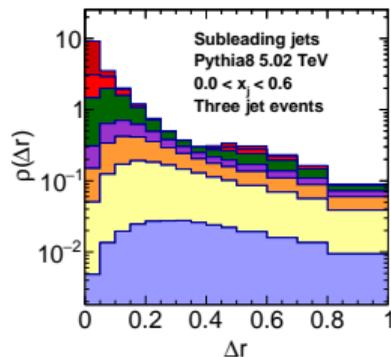
Jet shape in Pythia8 for $0 < x_j < 0.6$ bin for subleading jet



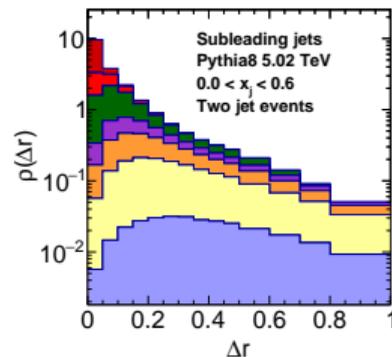
All dijets



Three jet events



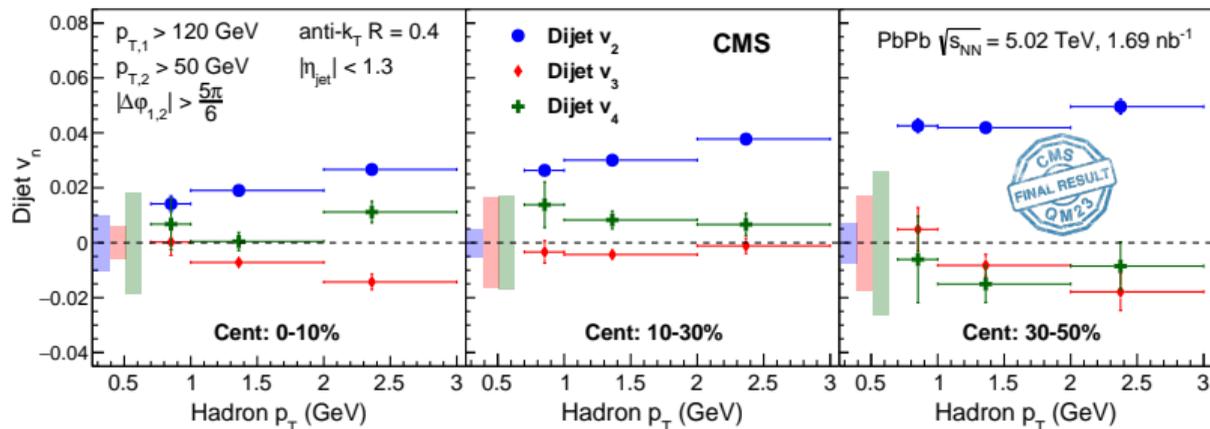
Two jet events



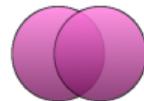
- Similar enhancement of high- p_T particles as in data
- Three jet events enhance the effect
- No effect visible in two jet events

Dijet v_n as a function of hadron p_T

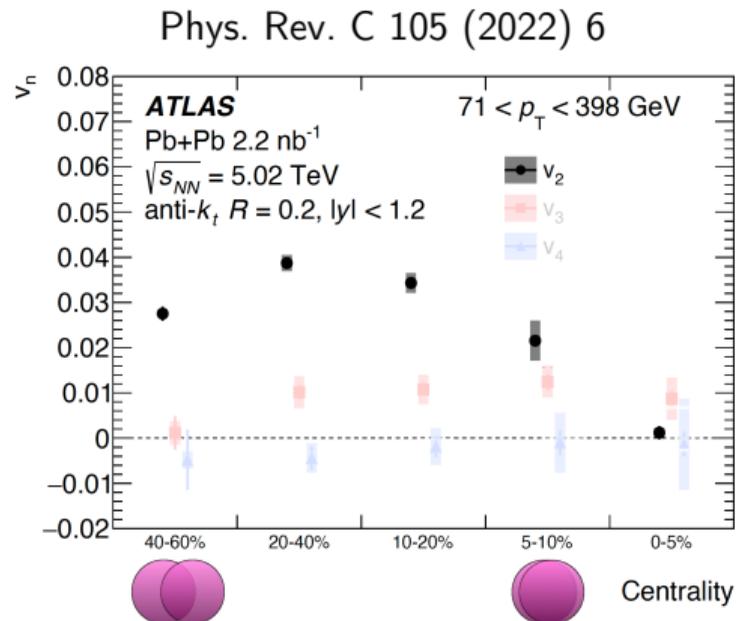
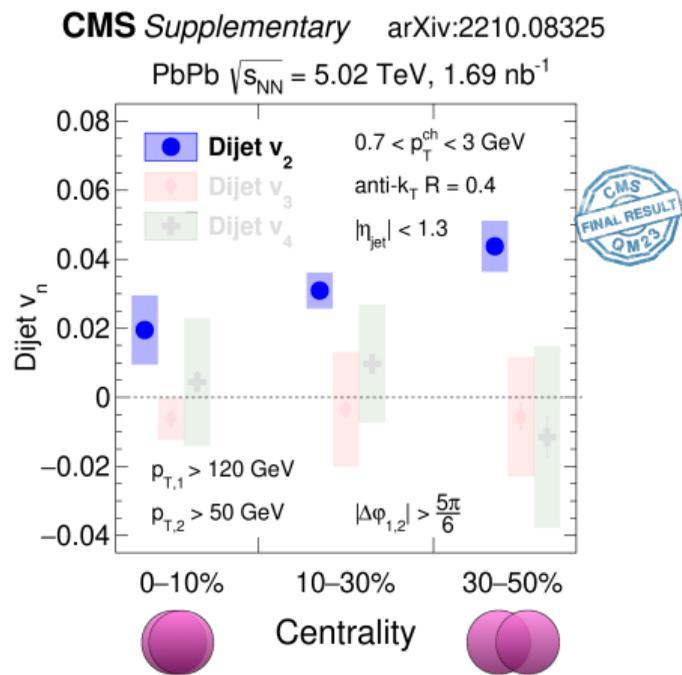
- Jet-hadron correlations are free from away-side jet bias
- To mitigate the bias for dihadron correlations, analysis limited to region $0.7 < p_T < 3 \text{ GeV}$
- Dijet v_n values factorized from different hadron p_T bins shown below
⇒ No significant p_T dependence, can extract one value



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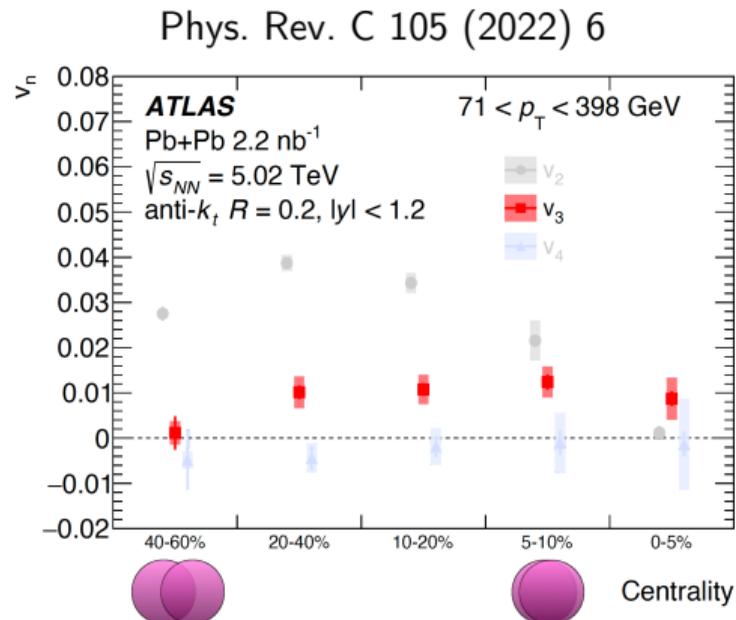
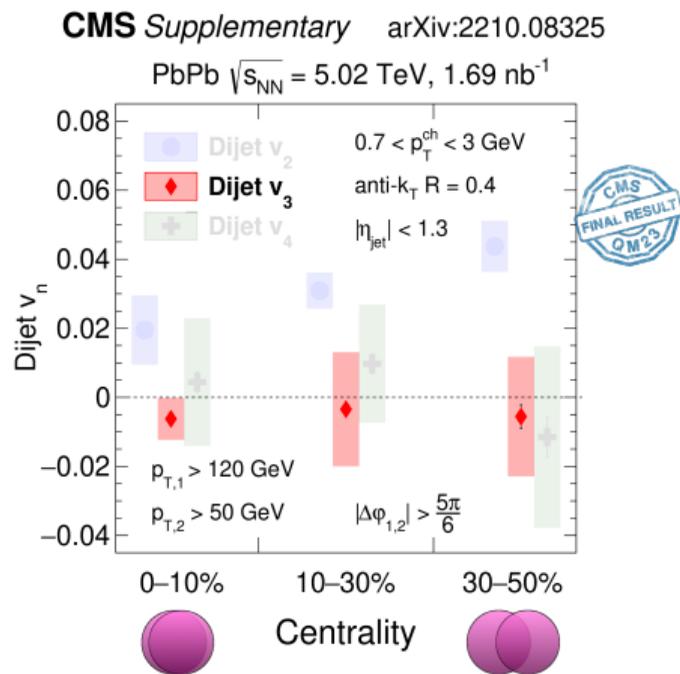


Comparison between dijet v_n and inclusive jet v_n



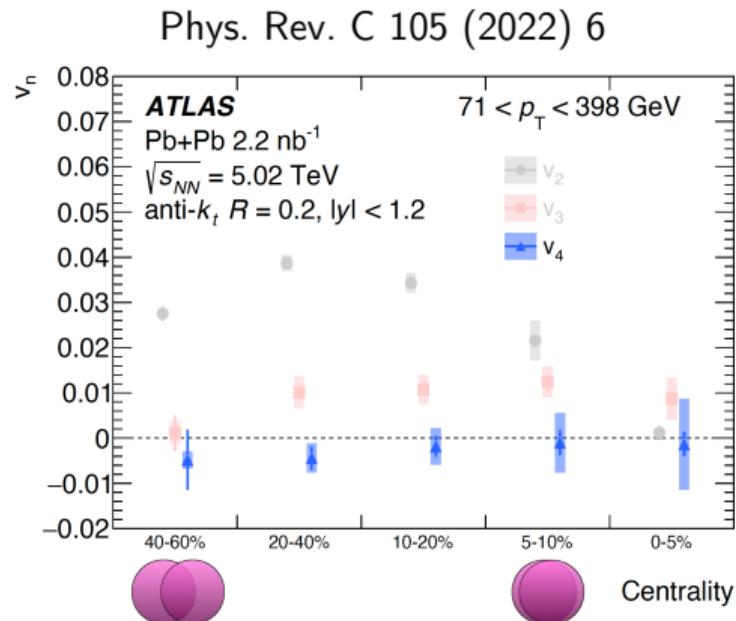
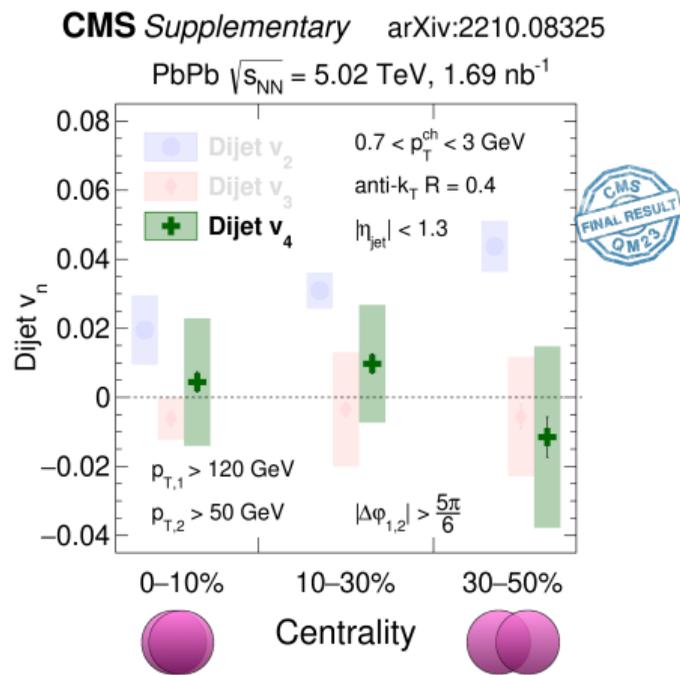
- Dijet and inclusive jet v_2 both similar

Comparison between dijet v_n and inclusive jet v_n



- Dijet and inclusive jet v_2 both similar
- Dijet v_3 zero, inclusive jet v_3 positive. Different sensitivity to medium density fluctuations?

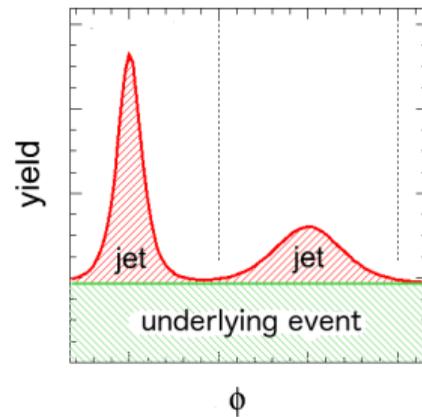
Comparison between dijet v_n and inclusive jet v_n



- Dijet and inclusive jet v_2 both similar
- Dijet v_3 zero, inclusive jet v_3 positive. Different sensitivity to medium density fluctuations?
- Dijet and inclusive jet v_4 consistent with zero

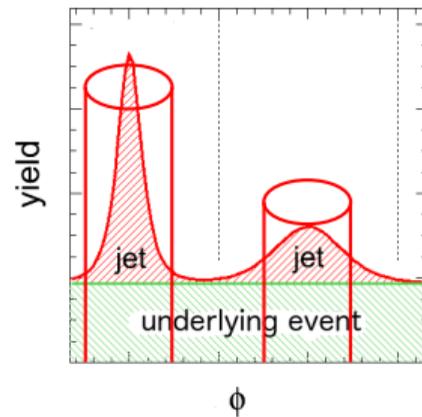
Jet reconstruction bias

- The background subtraction method for jet energy does not have φ dependence



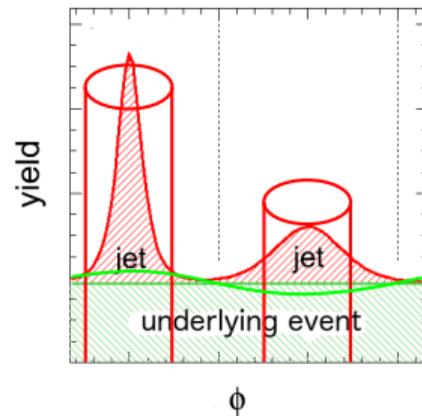
Jet reconstruction bias

- The background subtraction method for jet energy does not have ϕ dependence



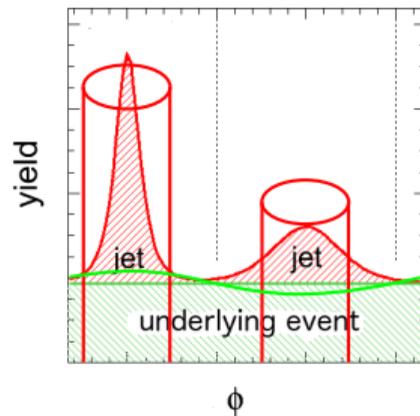
Jet reconstruction bias

- The background subtraction method for jet energy does not have φ dependence
- Underlying event is not flat, but flow contribution changes event by event



Jet reconstruction bias

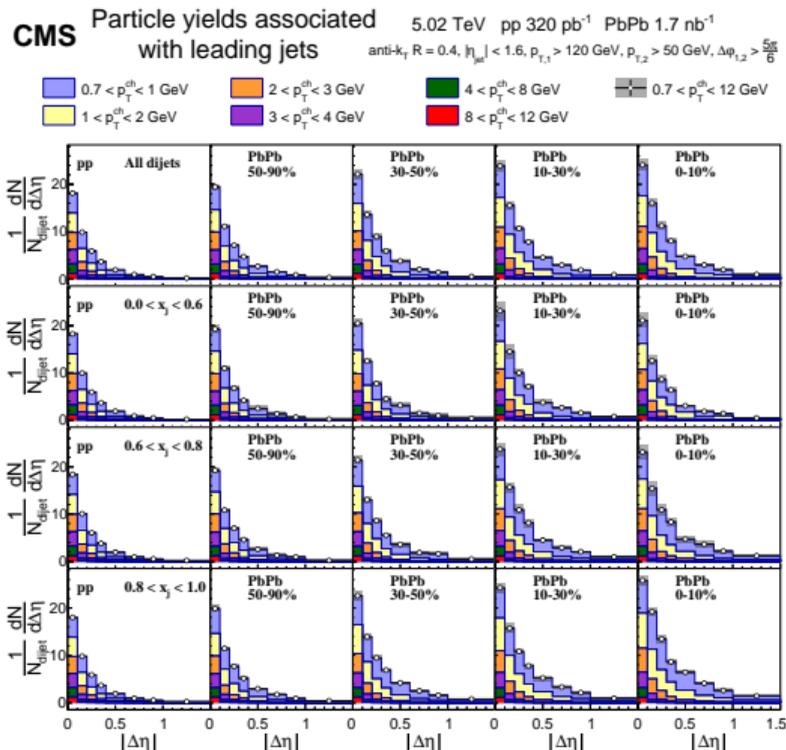
- The background subtraction method for jet energy does not have φ dependence
- Underlying event is not flat, but flow contribution changes event by event



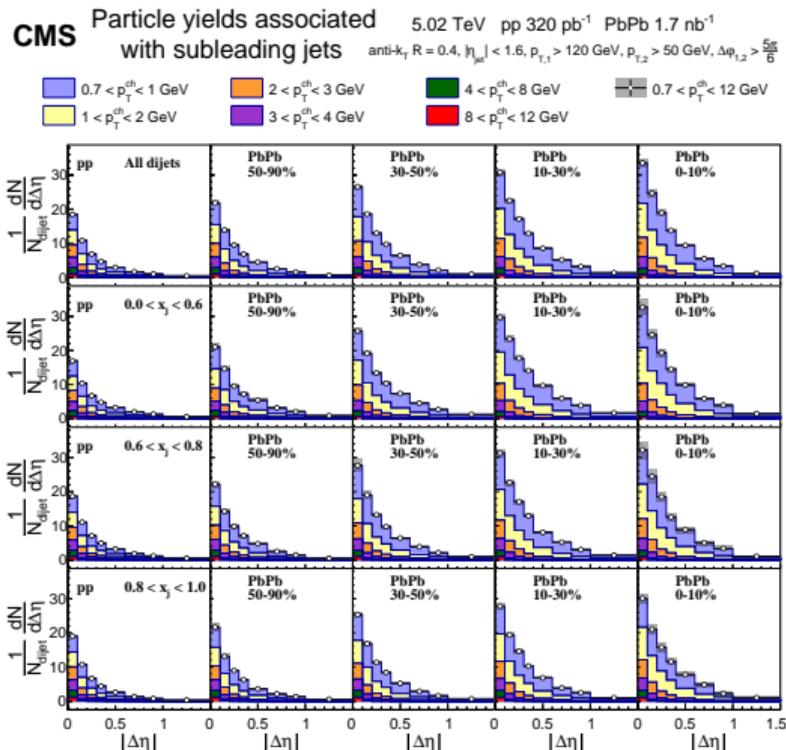
- If hadron flow not taken into account, the left jet will be reconstructed with too much energy and the right jet with too little energy
 - ⇒ More jets aligned with reaction plane ⇒ fake jet v_2 !
- To properly estimate the effect from MC, need to match both shape and magnitude of underlying event with data

- To correct for remaining bias, calculate apparent jet v_n from MC and subtract this from the v_n value obtained from the data
- Strategy 1: Match hadron v_2 , scale for remaining dihadron yield difference
 - Use Q-vector cut/weight in each event to obtain matching hadron v_2
 - $Q_x = \sum_i \cos(2\varphi_i)$, $Q_y = \sum_i \sin(2\varphi_i)$
 - $Q = \sqrt{Q_x^2 + Q_y^2}$
- Strategy 2: Match dihadron yield, scale for remaining hadron v_2 difference
 - Weight the multiplicity distribution in MC to match that in data for the most accurate yield matching
- Extensive MC studies performed to validate both strategies

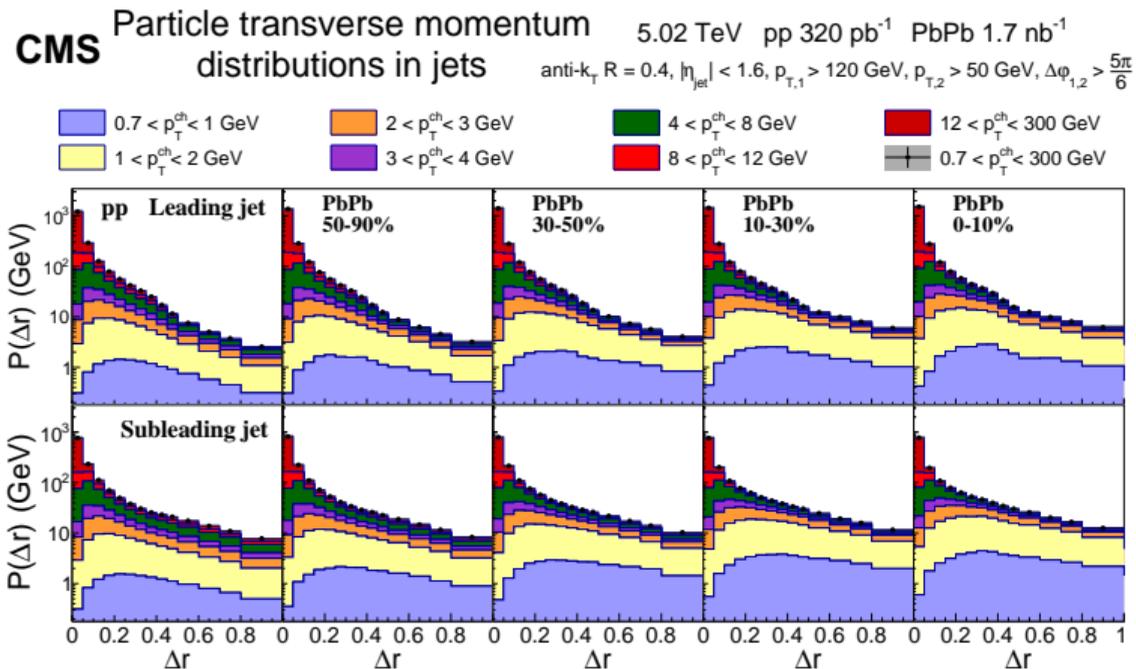
Particle yields w.r.t. leading jet - JHEP 05 (2021) 116



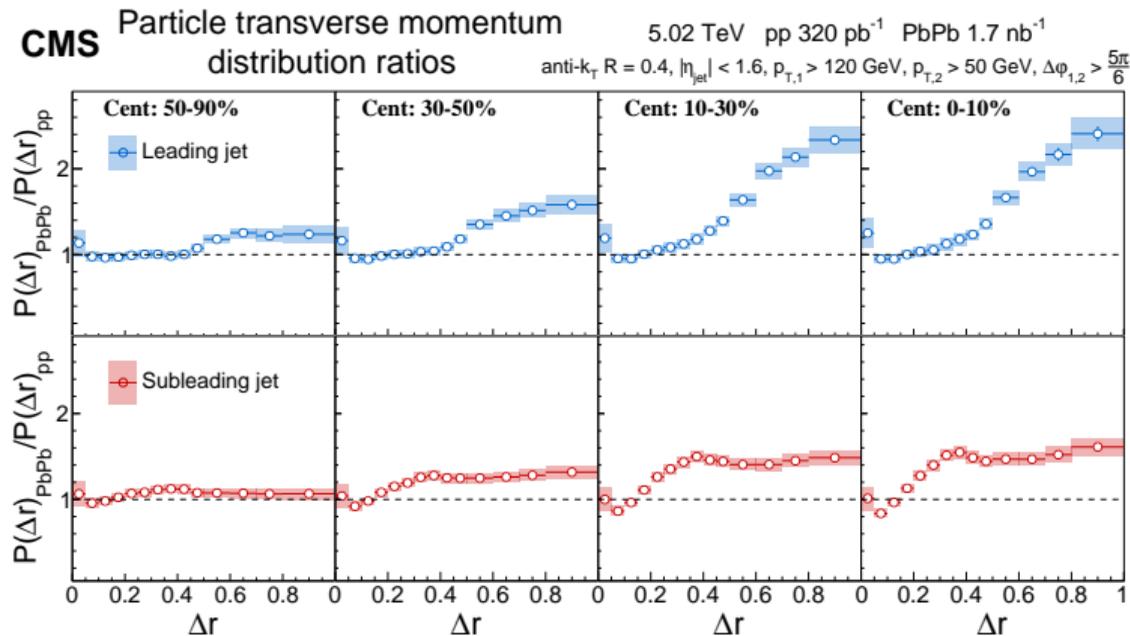
- PbPb over pp excess largest in central and balanced events



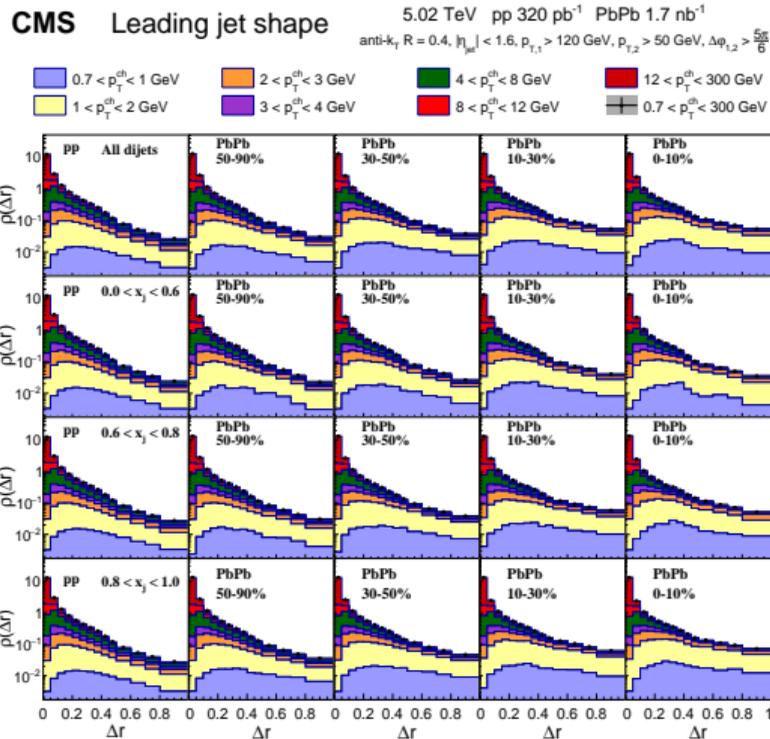
- More excess compared to leading, largest in unbalanced events



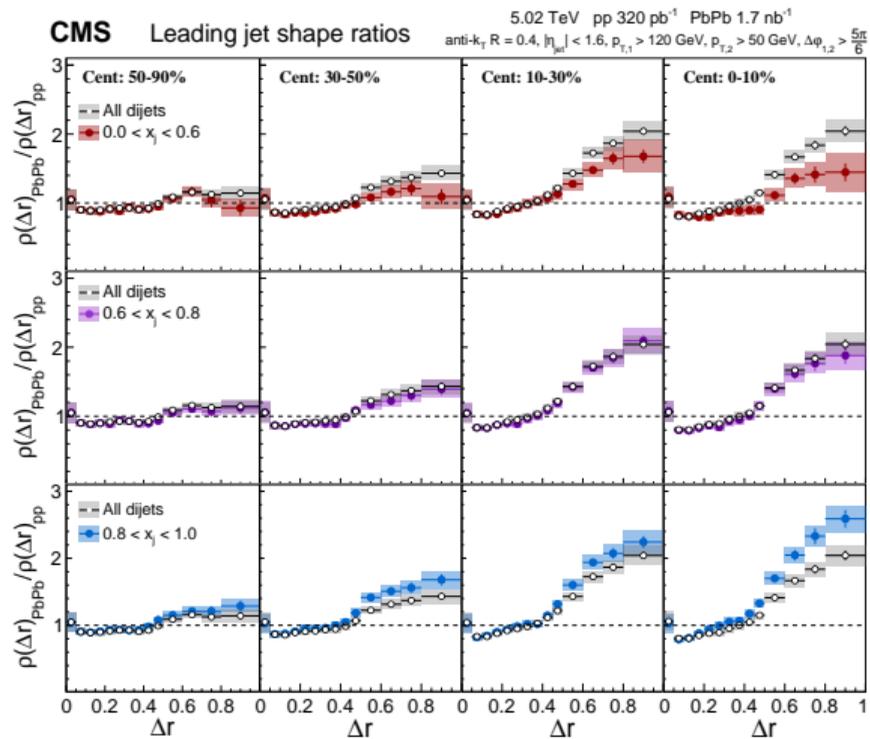
- Subleading side is broader than leading side



- Excess not as big in subleading side due to widening of pp reference



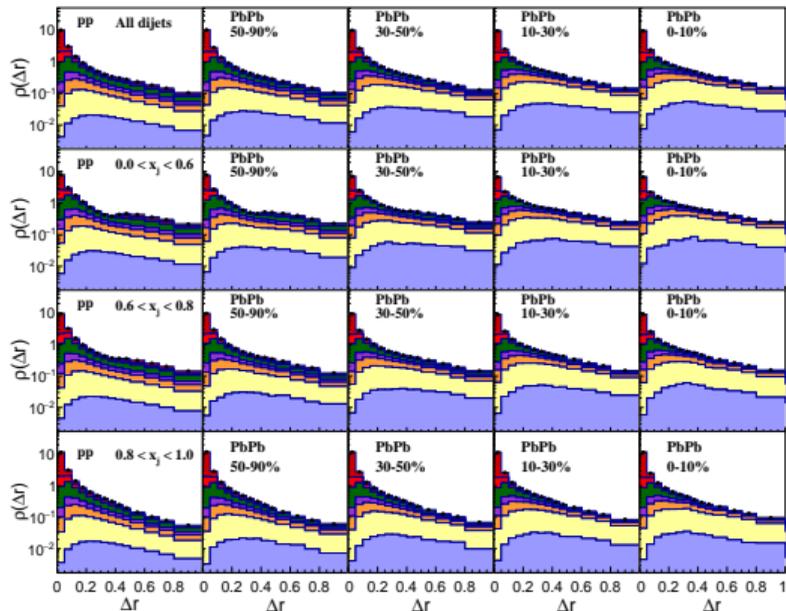
- The balanced PbPb events are the broadest



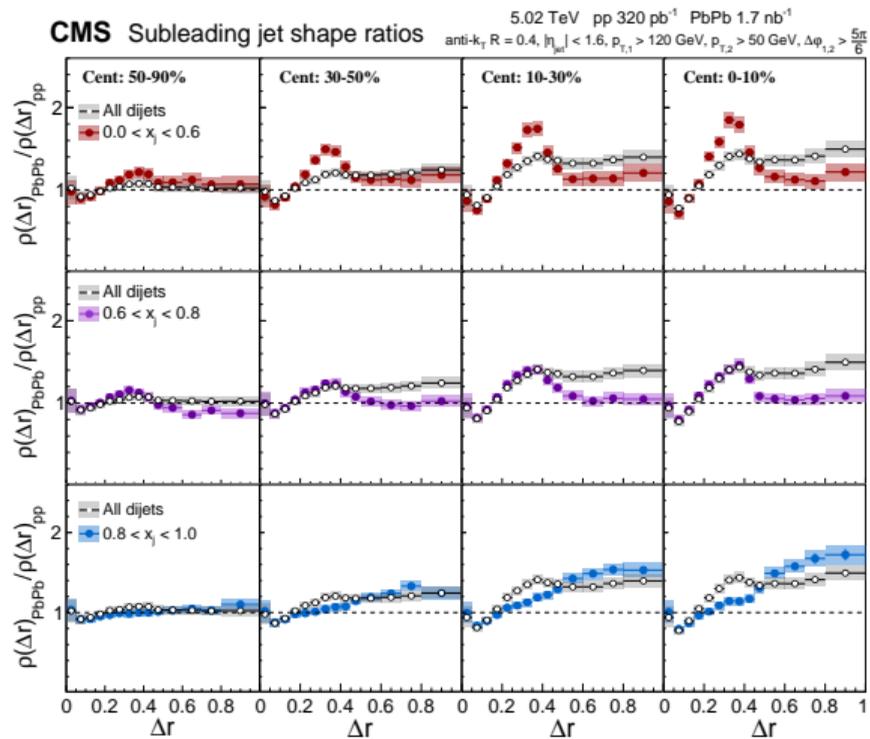
- PbPb jet shape broader than pp, balanced events are the broadest

CMS Subleading jet shape

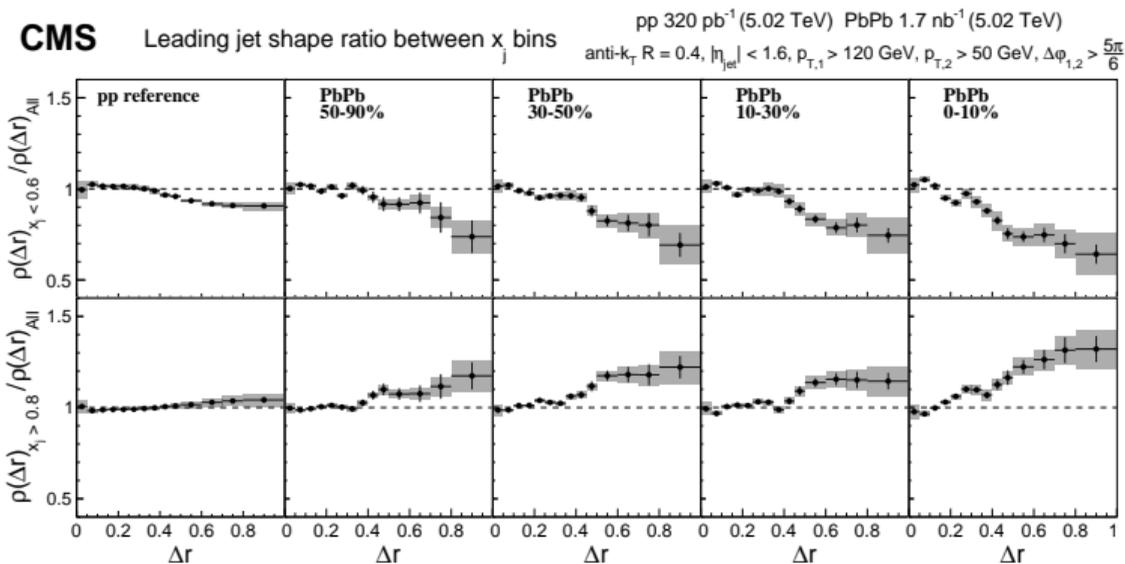
5.02 TeV pp 320 pb⁻¹ PbPb 1.7 nb⁻¹
 anti- k_T , $R = 0.4$, $|\eta_{jet}| < 1.6$, $p_{T1} > 120$ GeV, $p_{T2} > 50$ GeV, $\Delta\phi_{1,2} > \frac{5\pi}{6}$



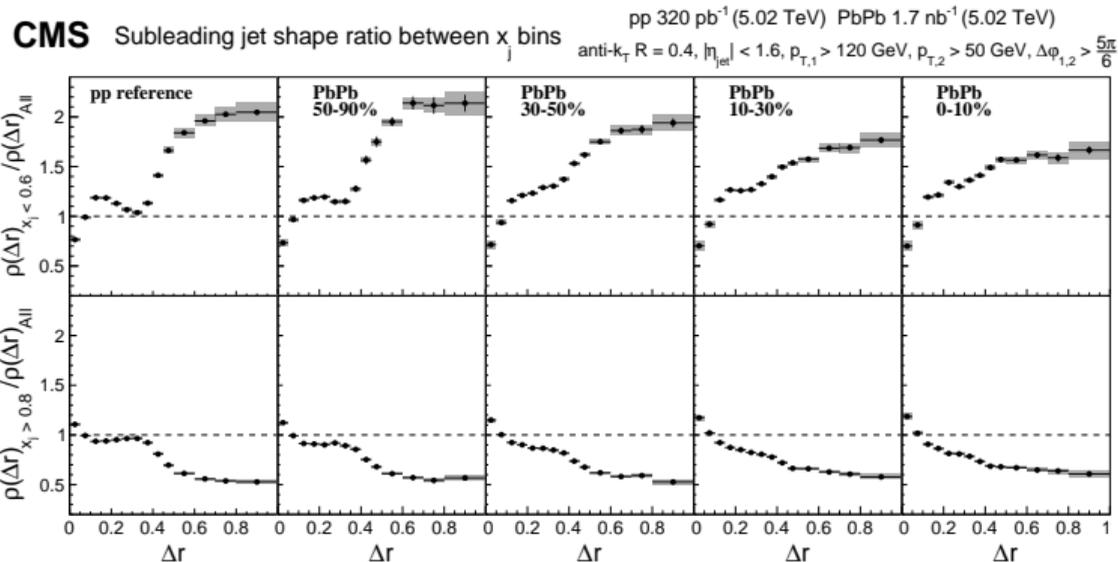
- There is a hump in unbalanced pp and peripheral \Rightarrow third jet



- The ratio at low x_j and high Δr affected by third jet in pp



- Leading jets more broadened in balanced events
 - To create a balanced event in PbPb, also leading jet is quenched



- Subleading jets much more broadened in unbalanced events
 - Consistent with simple hypothesis: leading jet has short path length within plasma while subleading has large path length within plasma