Flow and correlation phenomena measurements in pp, pPb and PbPb collisions at CMS

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Outline

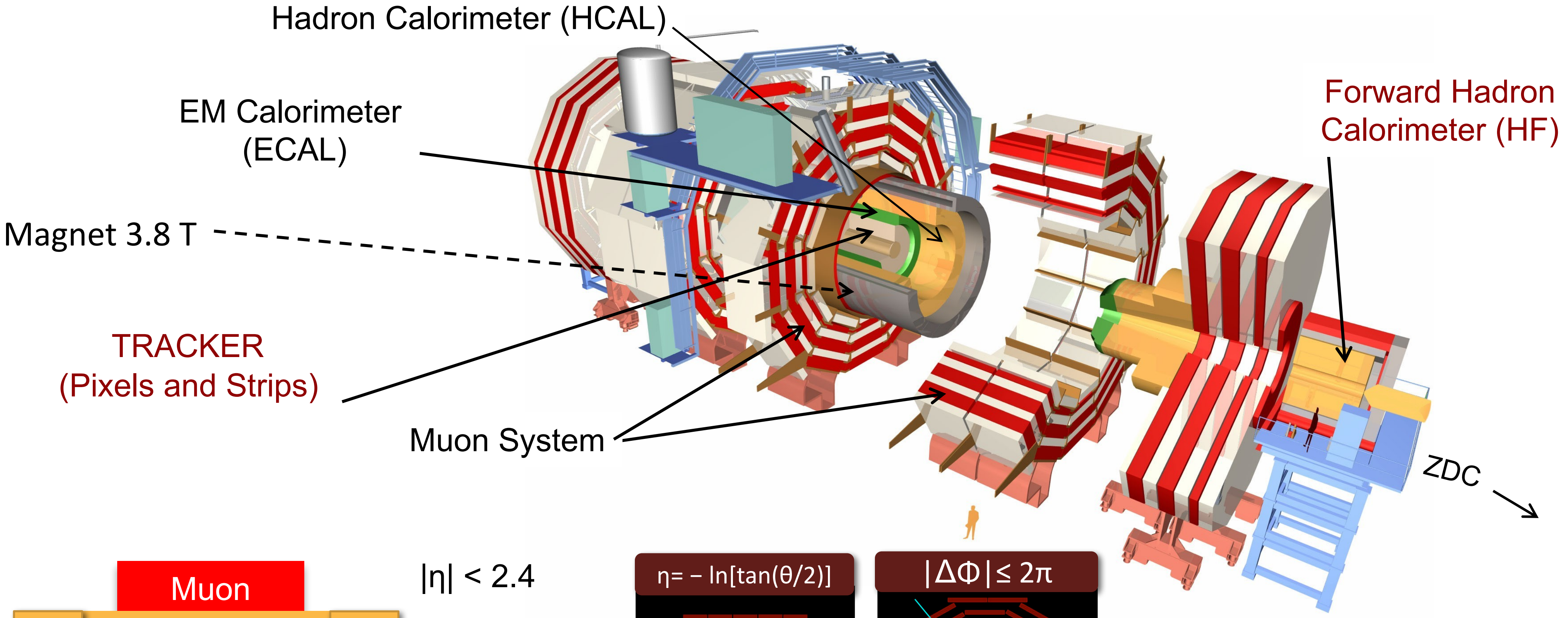
Intriguing similarities in azimuthal correlations and collective flow in different systems

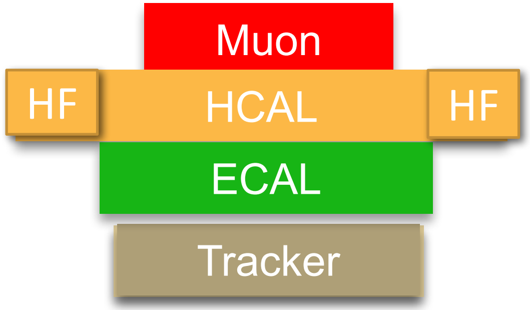
- In AA collisions at RHIC: signature of the QGP as a nearly perfect liquid
- In pA and pp collisions at LHC: collectivity evidence in high multiplicity events

This talk highlights

- Recent results on azimuthal anisotropy up to $p_T \approx 100$ GeV/c
  - Flow harmonics v_n with high p_T tracks in PbPb collisions – path lengths of the energy loss
- Ridge phenomena in pp collisions at 13 TeV
  - v_2 and v_3 harmonics measured
  - $v_2\{4\}$ and $v_2\{6\}$ cumulants: investigating collectivity
- Symmetric cumulant results
  - Scrutinizing further the correlations between azimuthal components

CMS Detector





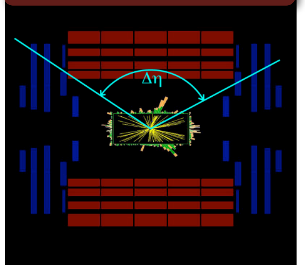
|η| < 2.4

|η| < 5.2

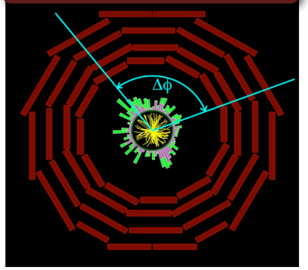
|η| < 3.0

|η| < 2.5

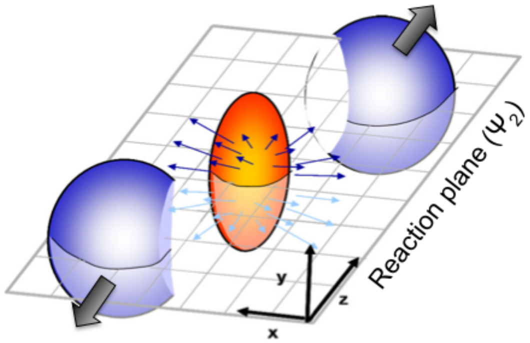
$\eta = -\ln[\tan(\theta/2)]$

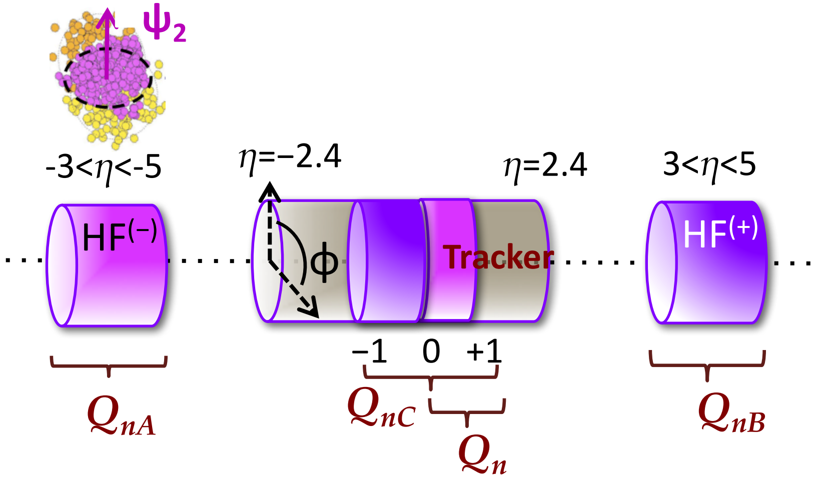


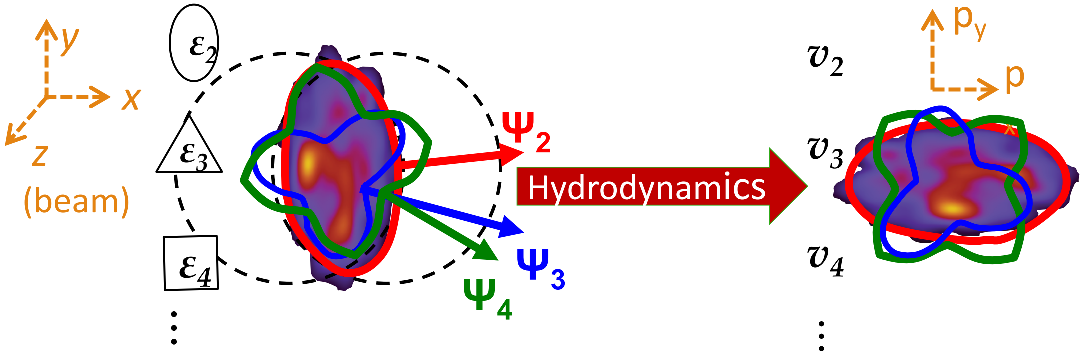
$|\Delta\Phi| \leq 2\pi$



Hydrodynamic flow in A-A collisions





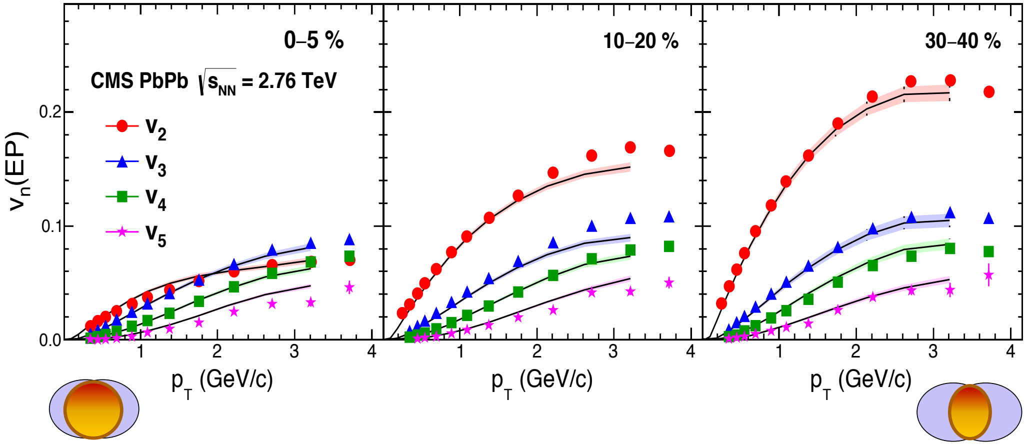


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(\sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{EP})]\right)$$

- v_n depends on:
  - Initial state geometry and its fluctuations
  - Medium transport coefficients (η/s, …)
- v_n well understood in A-A collisions with hydrodynamics
  - Diagonal terms (v_n^2)

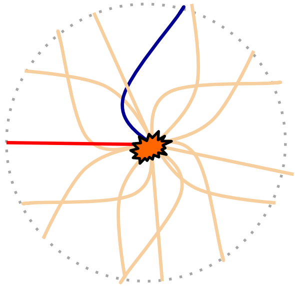
PR C 89 (2014) 044906 (CMS results)

PRL 110 (2013) 012302 (IP Glasma+MUSIC)



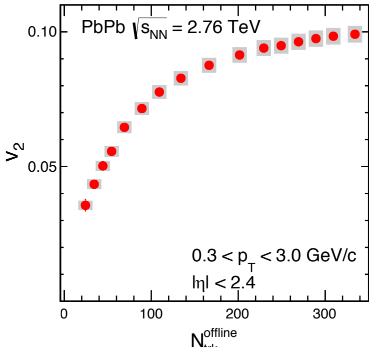
M-particle correlations and collectivity in AA

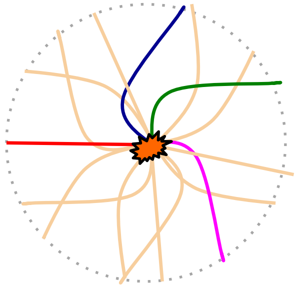
- Sensitive to non-flow (jets induced correlations)
- Several techniques: EP/SP + gap; 2-part. cumulant + gap; 2-part. corr. + gap + low $N_{trk}^{offline}$ subtraction



2-particles

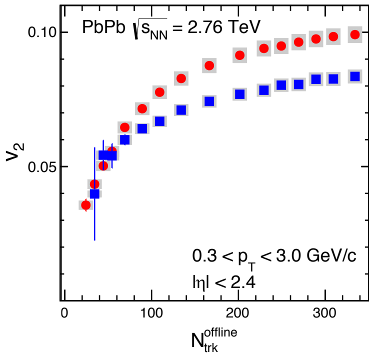
$v_2\{2\}$





4-particles

$v_2\{4\}$



- Less sensitive to non-flow
- Requires larger data sample

M-particle correlations and collectivity in AA

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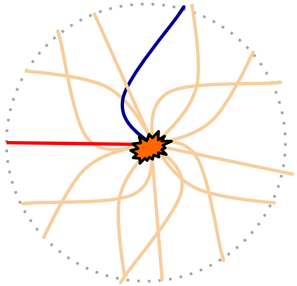
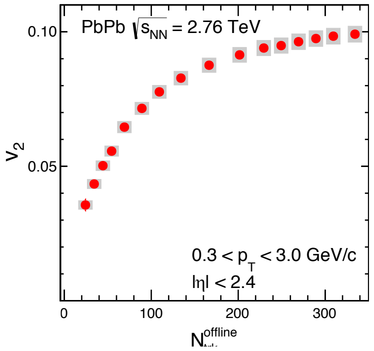
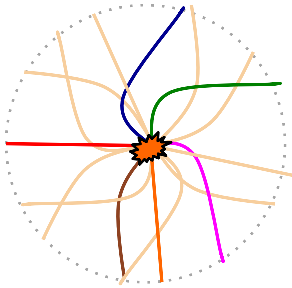
- Several techniques: EP/SP + gap; 2-part. cumulant + gap; 2-part. corr. + gap + low $N_{trk}^{offline}$ subtraction

PRL 115 (2015) 012301

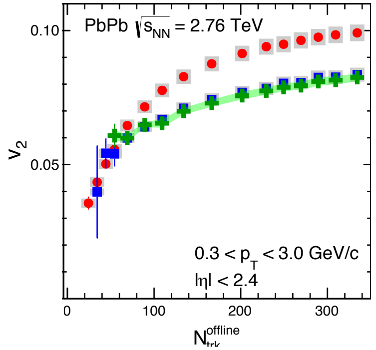


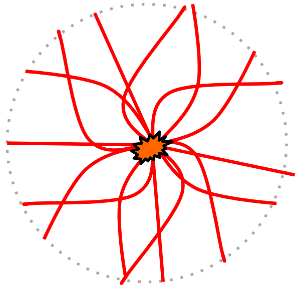
2-particles
$v_2\{2\}$



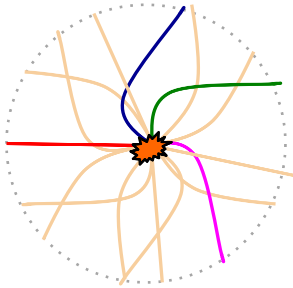


6-particles
$v_2\{6\}$

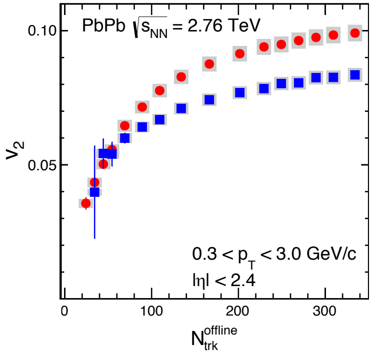


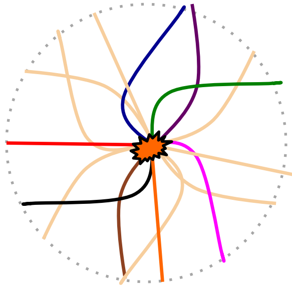


All particles
$v_2\{LYZ\}$

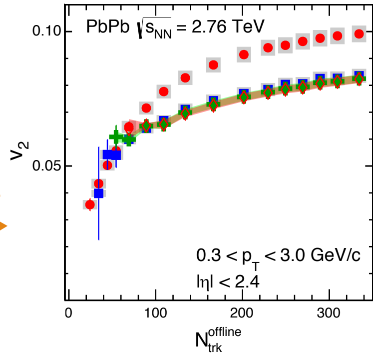


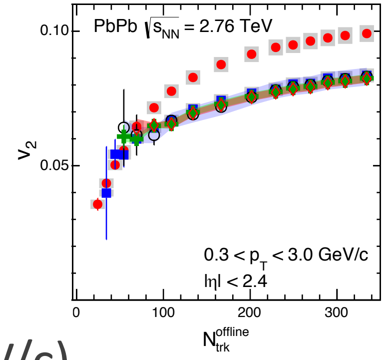
4-particles
$v_2\{4\}$





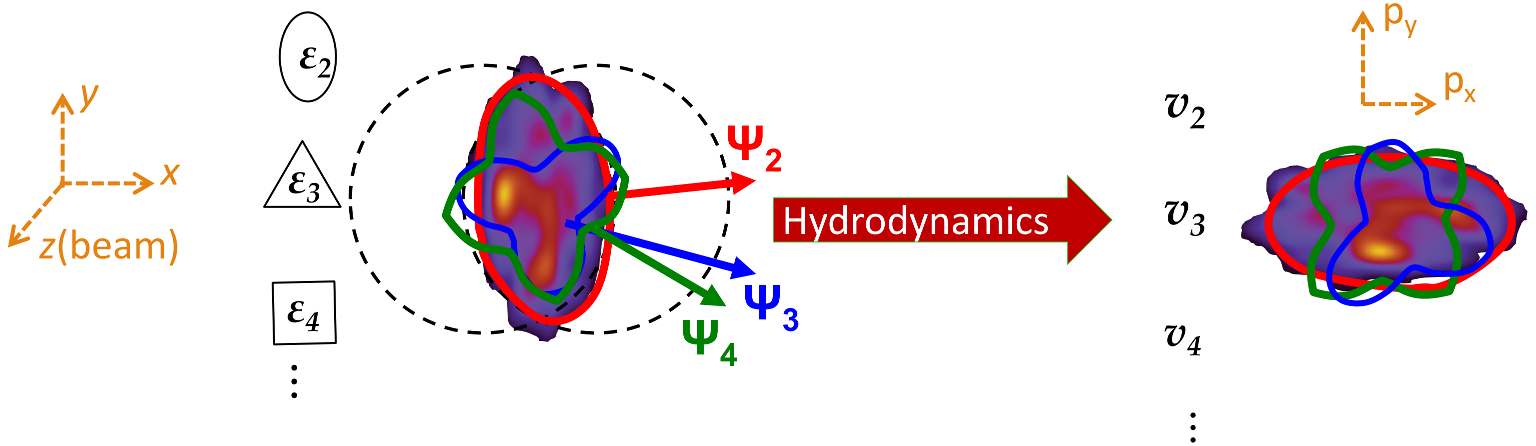
8-particles
$v_2\{8\}$





- v_4: less sensitive to non-flow
- Requires larger data sample
- Collectivity: $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ\}$
- Well described by **hydrodynamics** at low p_T (< 3 GeV/c)

Flow in high energy collisions



- ❑ Hydrodynamical picture of eccentricities (fluctuating initial conditions) and the corresponding flow single particle Fourier harmonics

low pT | intermediate p_T | high p_T

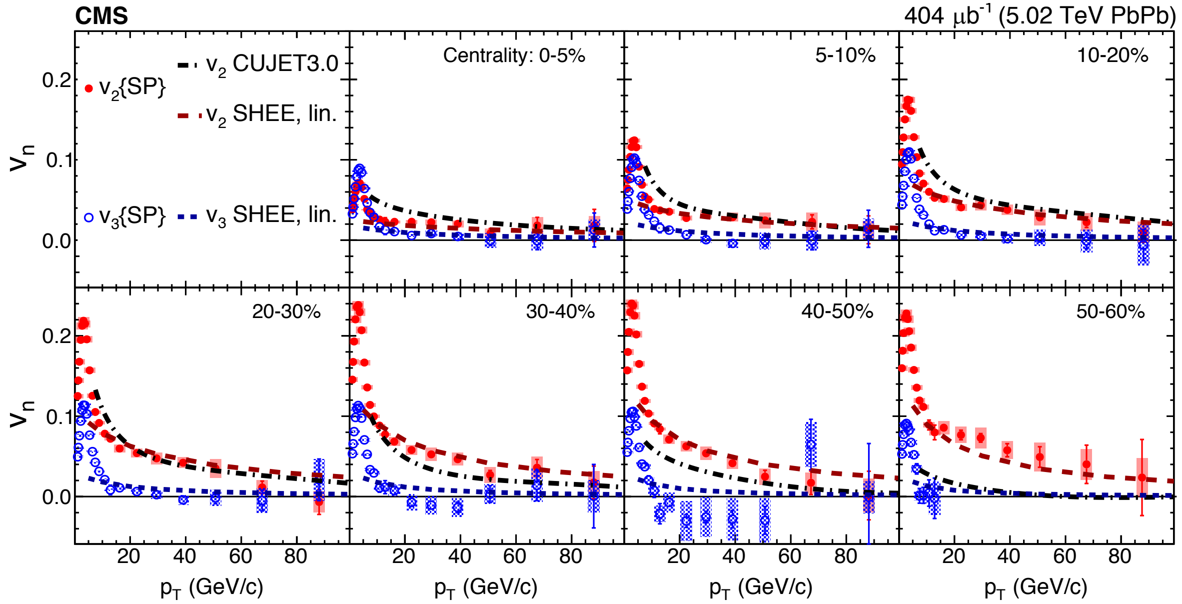
Hydrodynamic flow (asymm. pressure gradients & spatial anisotropies)

Soft-hard interplay (hadrons from thermal quarks + jet fragm.)

Path-length dependent energy loss

High-p_T v_2 and v_3 in PbPb collisions at 5.02 TeV

v_n harmonics from Scalar Product method



arXiv:1702.00630

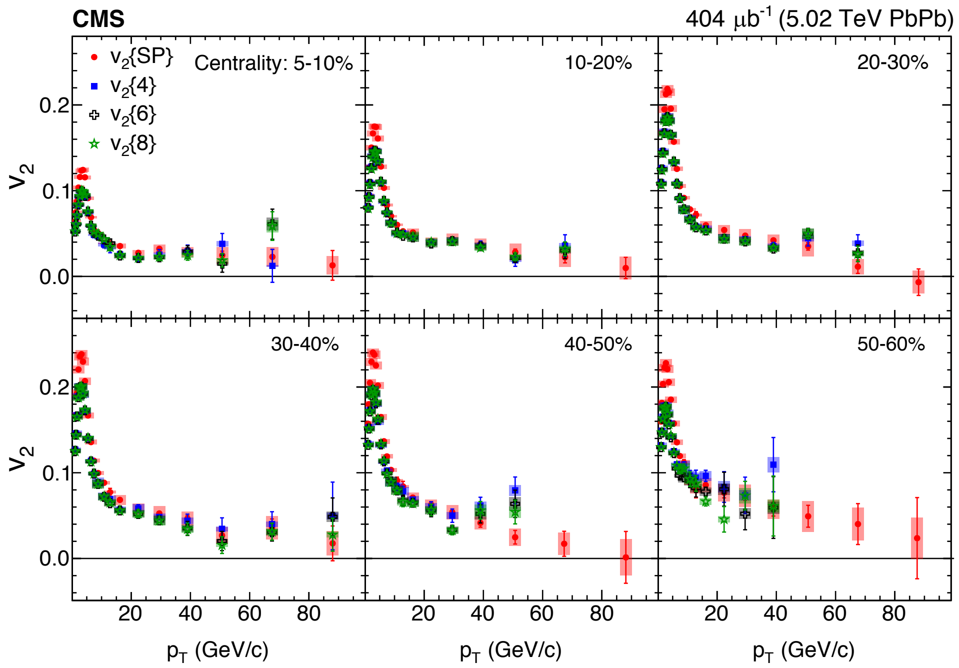
- $v_2 > 0$ up to $p_T \approx 100$ GeV/c ; v_2 increases from central to peripheral collisions; similar p_T behavior
- v_3 are non-zero up to $p_T \approx 20$ GeV/c; v_3 shows similar behavior as v_2, but is centrality independent at low p_T
- Results compared to CUJET3.0[1] (qualitative description only) and SHEE[2] models (good agreement with v_2 and v_3 for $p_T > 10$ GeV/c)

[1] *CUJET3.0, PRL **116** (2016) 252301 [smooth IC + perfect hydro fluid]*

[2] *SHEE, JHEP **02** (2016) 169 [fluctuating IC; viscous hydro with EbyE fluctuations, $(\eta/s) \leq 0.12$]*

High-p_T results for Scalar Product and Cumulants

$v_2\{SP\}$ and $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ in six centrality classes



arXiv:1702.00630

- $p_T < 3$ GeV/c : $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ (consistent with hydrodynamics)
- $p_T > 10$ GeV/c : $v_2\{SP\} \approx v_2\{m\}$ → collective anisotropy till high p_T (related to jet quenching?)
- anisotropies at low and high p_T → likely related to IS anisotropy and EbyE fluctuations

Ridge observed in Run-I in pp, pPb and PbPb

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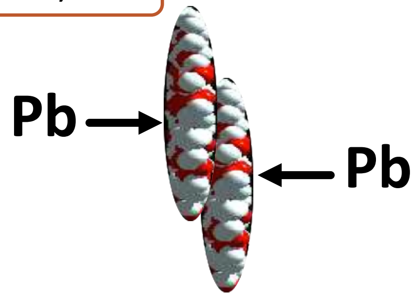
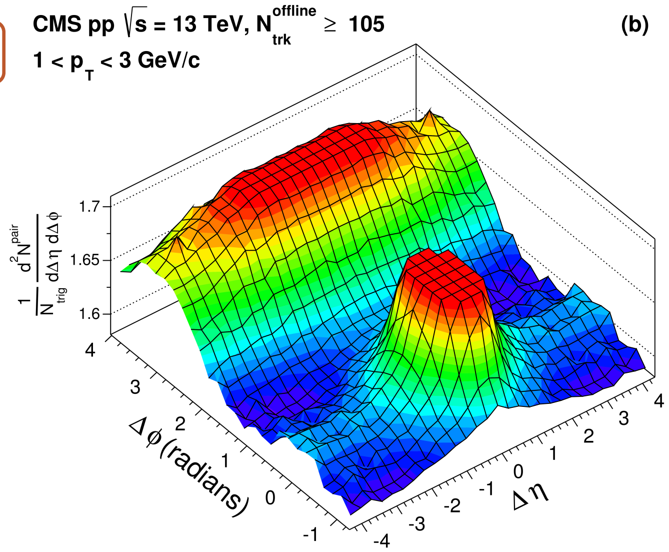
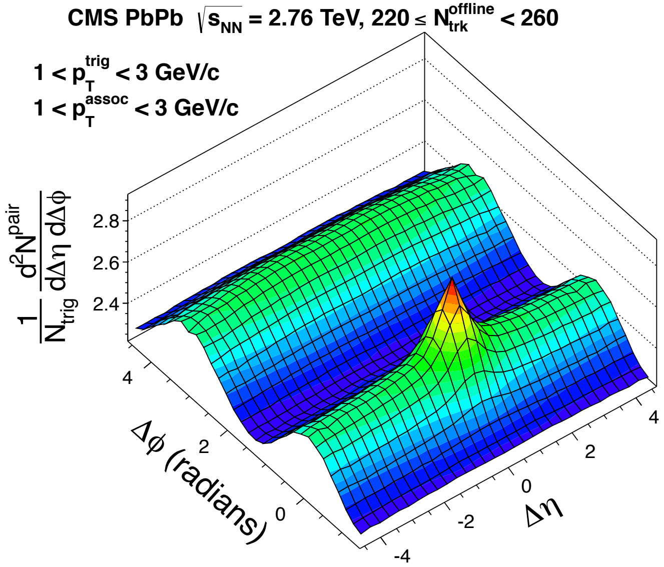
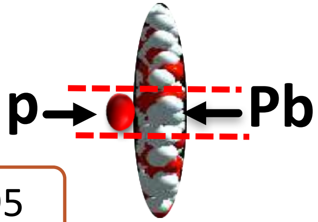


PRL 116 (2016) 172302







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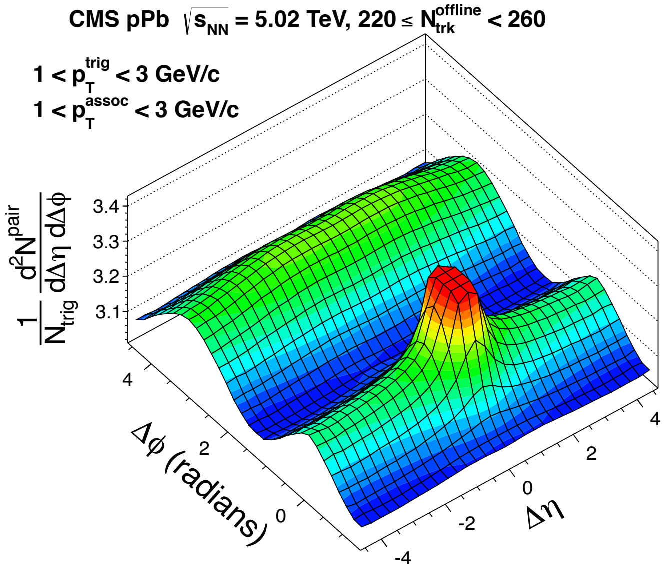
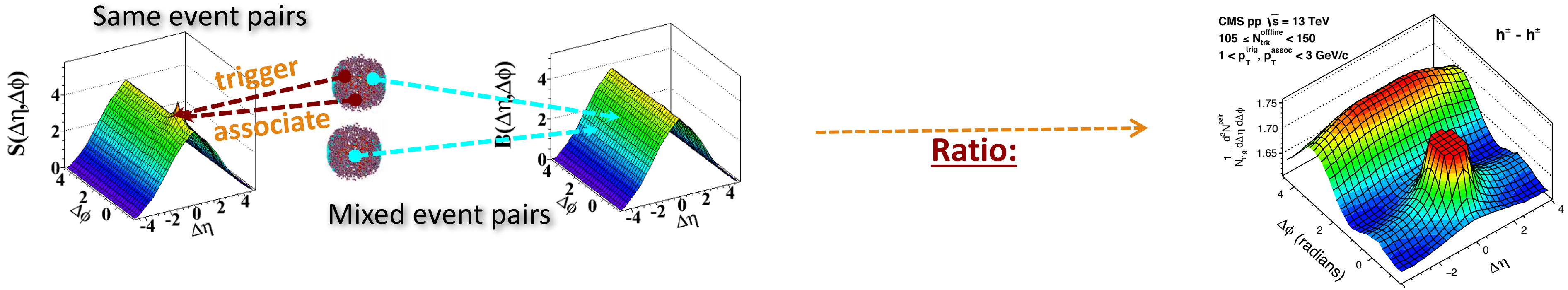


Dihadron correlations technique



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- Quantifying the ridge: average the 2D two-particle correlation function over |Δη| > 2 (avoid jet contamination)

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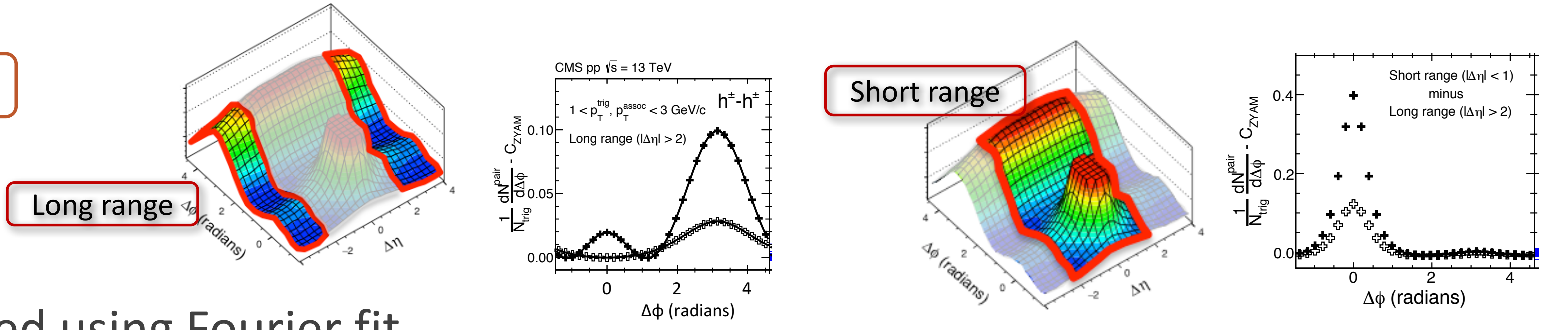

- $V_{n\Delta}$ extracted using Fourier fit

$$\frac{1}{N_{\text{trig}}}\frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left\{1+\sum_n 2V_{n\Delta}\cos\left(n\Delta\phi\right)\right\}$$

- Low multiplicity subtraction applied on $V_{n\Delta}$

  (removes back-to-back jets; assuming $v_2(N_{trk}^{offline} < 20) = 0$)

- Single v_n computed by

$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a) \times v_n(p_T^b)$$

$$v_n\{2, |\Delta\eta| > 2\}(p_T) = \frac{V_{n\Delta}(p_T, p_T^{\text{ref}})}{V_{n\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}$$

Ridge scrutinized in pPb collisions

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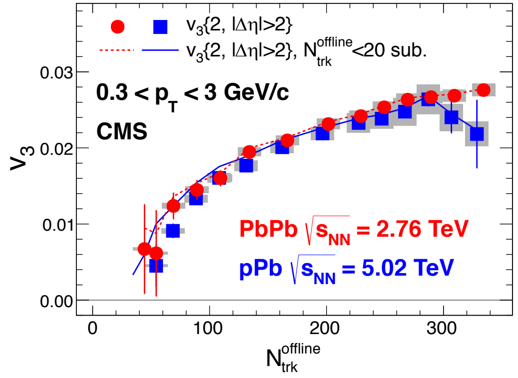
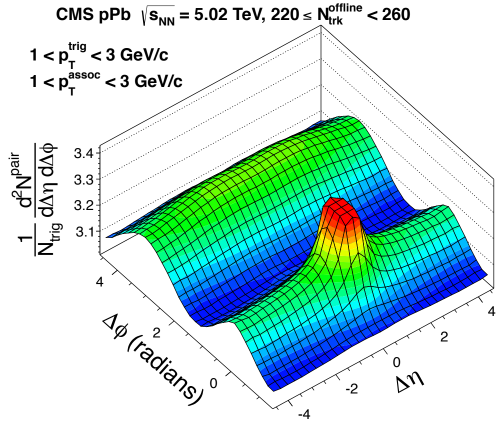
- Higher harmonics: v_3 results in pPb very similar to v_3 in PbPb





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- Higher harmonics: v_3 results in pPb very similar to v_3 in PbPb
- Strong signal of collectivity in pPb, similar to PbPb
  - $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ\}$

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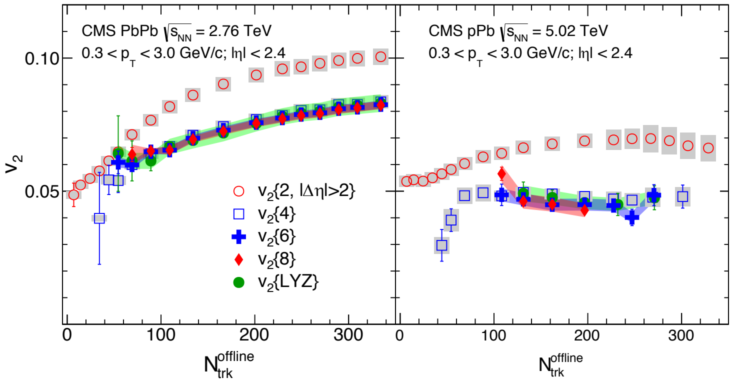

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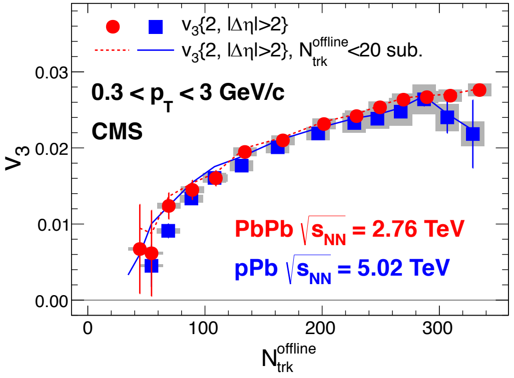

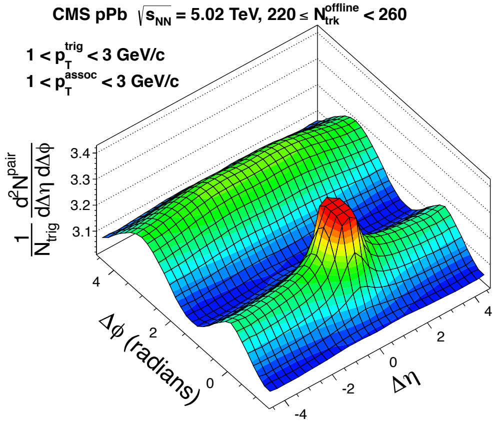

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- Clear mass ordering from ID particles (V^0's) ⟷ radial flow

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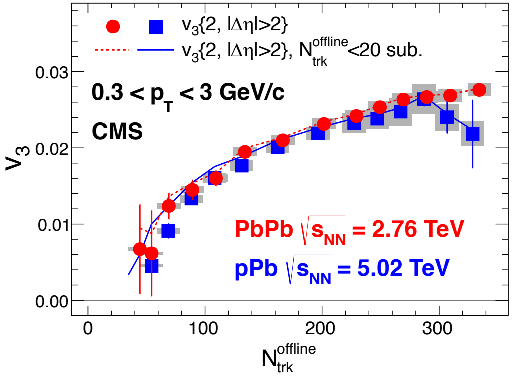

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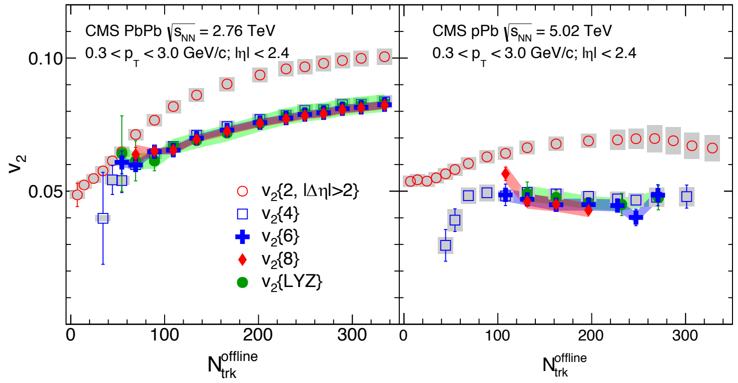

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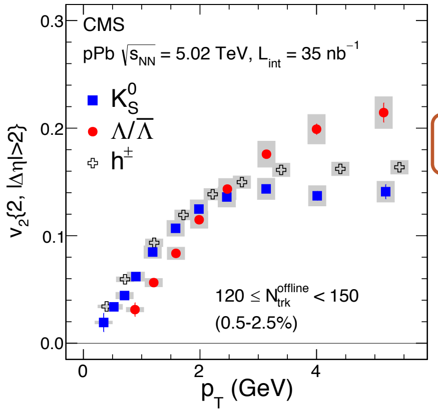

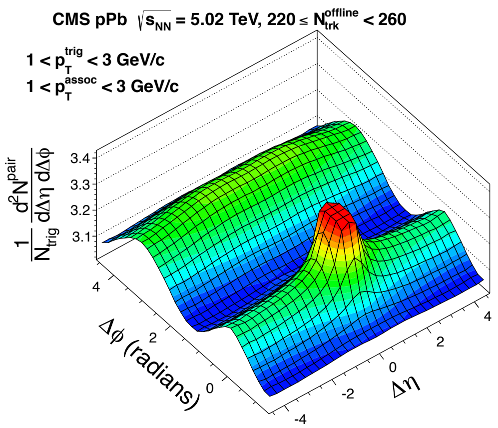

Ridge scrutinized in pPb collisions

- Higher harmonics: v_3 results in pPb very similar to v_3 in PbPb
- Strong signal of collectivity in pPb, similar to PbPb
  - $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ\}$
- Clear mass ordering from ID particles (V^0's) ⟷ radial flow
- In summary, in pPb: collective effects observed!
- Possible origins:
  - IS interactions (e.g., CGC)
  - IS geometry & fluctuations + FS interactions (hydrodynamics)

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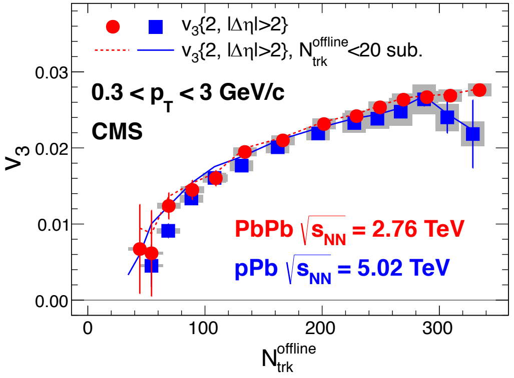

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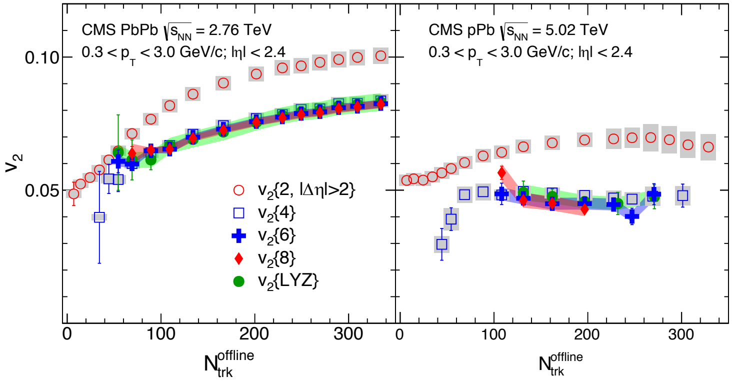

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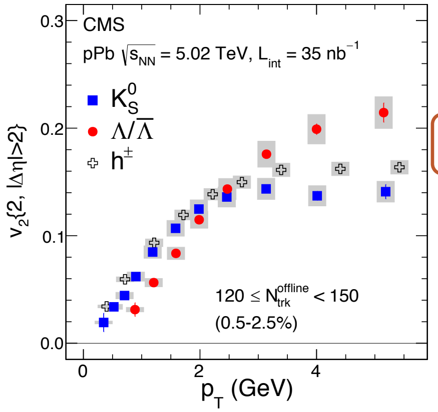

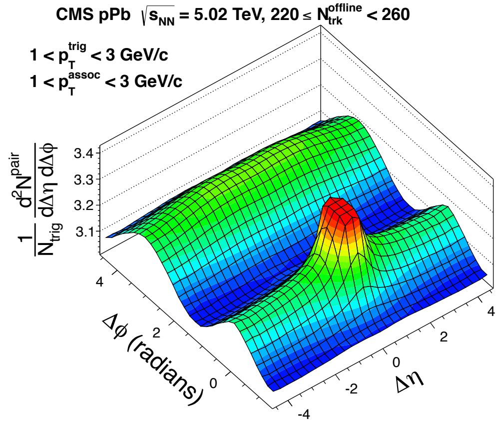

Ridge for $h^{\pm}$ $h^{\pm}$, K^0_s $h^{\pm}$, $\bar{\Lambda}$ /Λ $h^{\pm}$ in HM pp collisions

- Dihadron correlations

  $h^{\pm}$ $h^{\pm}$ hadrons (top)

  K^0_s $h^{\pm}$ (middle)

  Λ /Λ $h^{\pm}$ (bottom)

  - (left) low multiplicity $10 \le N_{trk}^{offline} \le 20$ range: no near-side ridge

  - (right) high multiplicity $105 \le N_{trk}^{offline} \le 150$ range: long-structure near $\Delta\phi$=0

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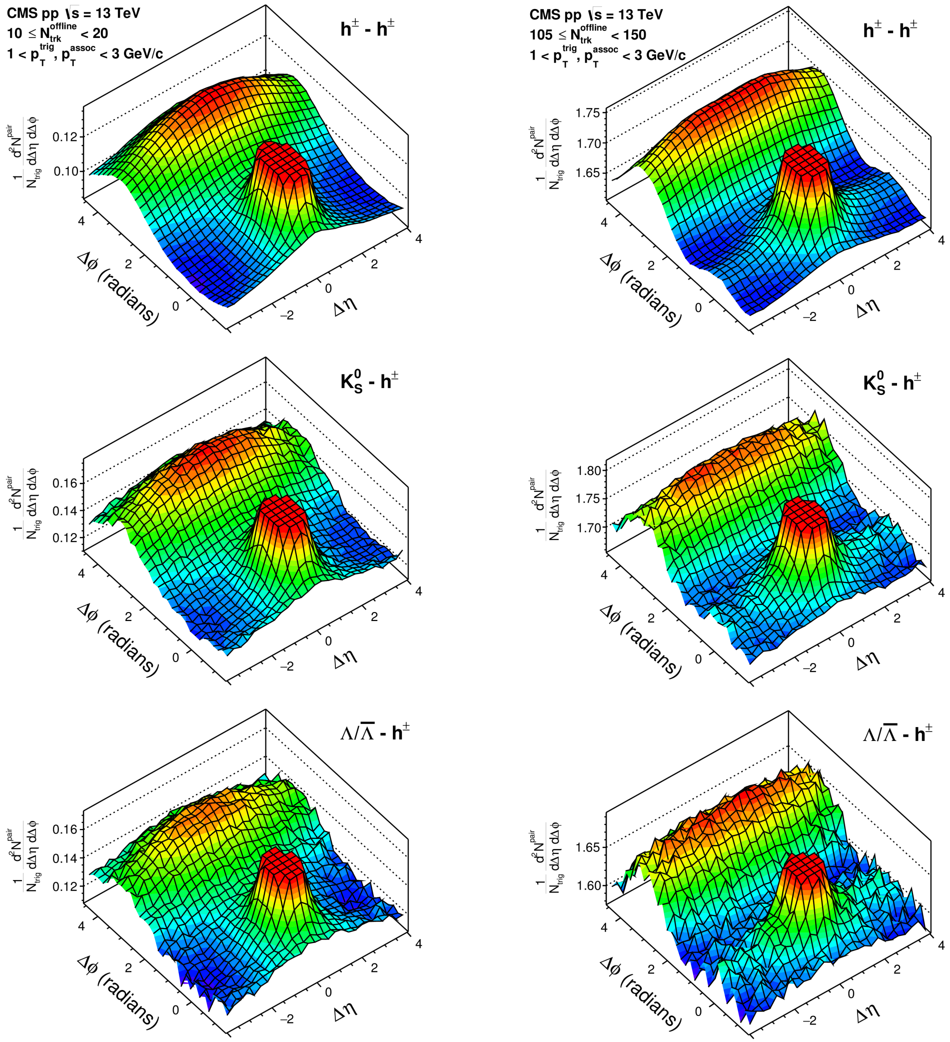

$v_2^{sub}\{2\}$ and $v_3^{sub}\{2\}$ extracted from $V_{2\Delta}, V_{3\Delta}$

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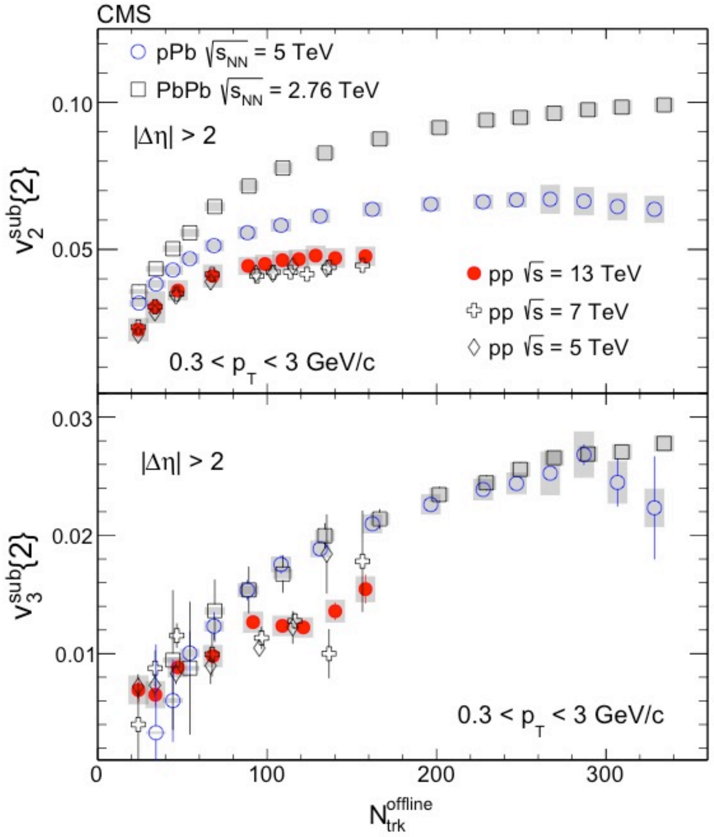
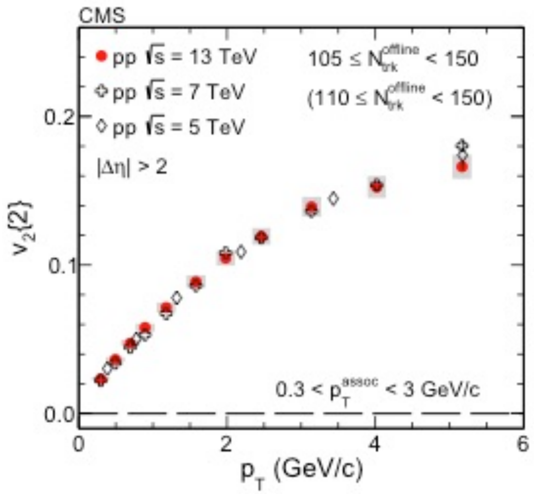
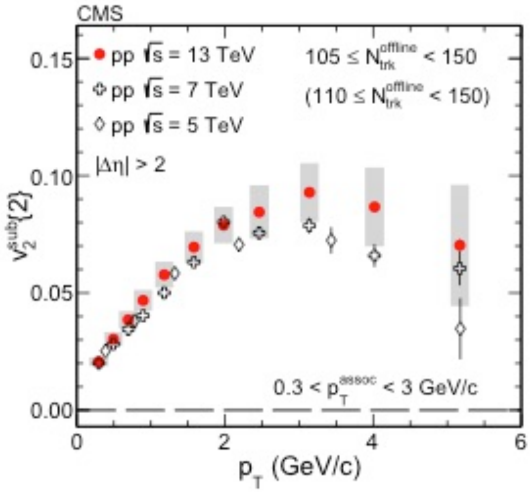


$v_2^{sub}\{2\}$ (elliptic) and $v_3^{sub}\{2\}$ (triangular) Fourier coefficients vs. $N_{trk}^{offline}$

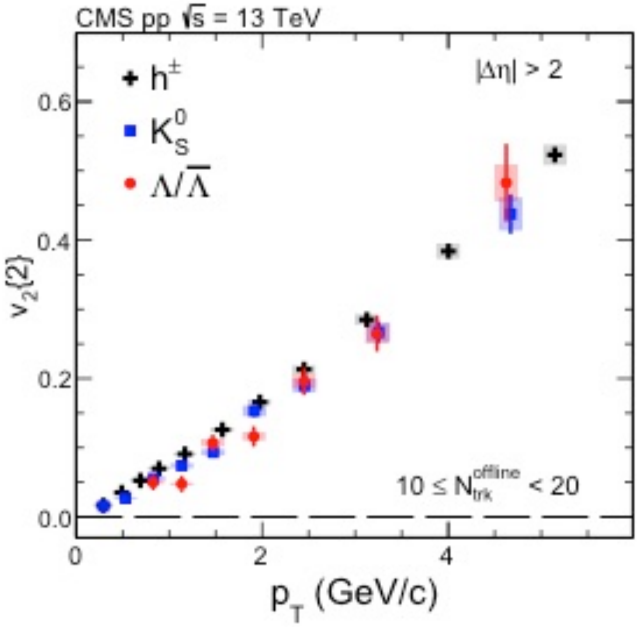
- for $h^{\pm}h^{\pm}$ in pp collisions at √s=13, 7, 5 TeV (earlier results from pPb and PbPb added)
  - weak or almost no energy dependence in $v_2^{sub}\{2\}$
  - $v_2^{sub}\{2\}$ → similar pattern as in pPb: grows with $N_{trk}^{offline}$ and then flattens
  - $v_3^{sub}\{2\}$ → very similar to $v_3^{sub}\{2\}$ in pPb and PbPb collisions; increase at a lower rate

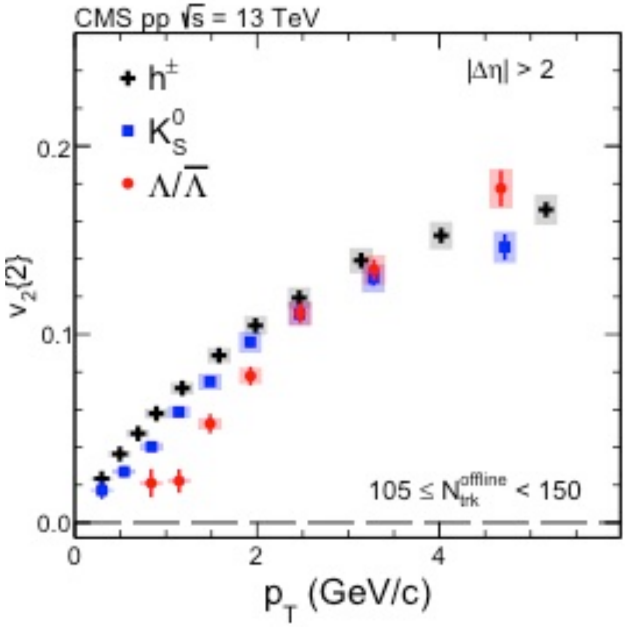
$v_2^{sub}\{2\}$ versus p_T before and after applying jet corrections





v_2 for $h^{\pm}$, K^0_s and $\Lambda/\bar{\Lambda}$ as trigger particles





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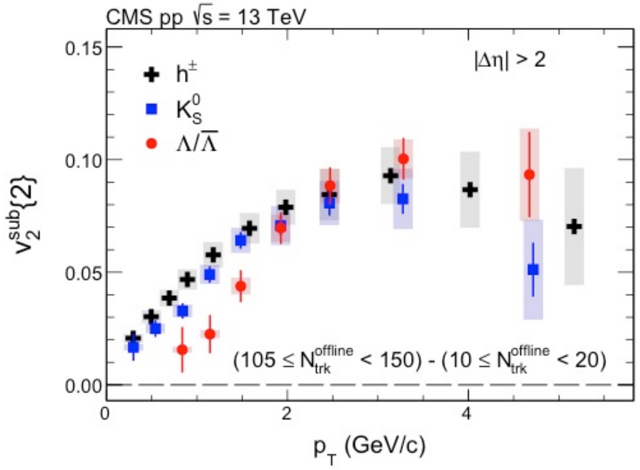
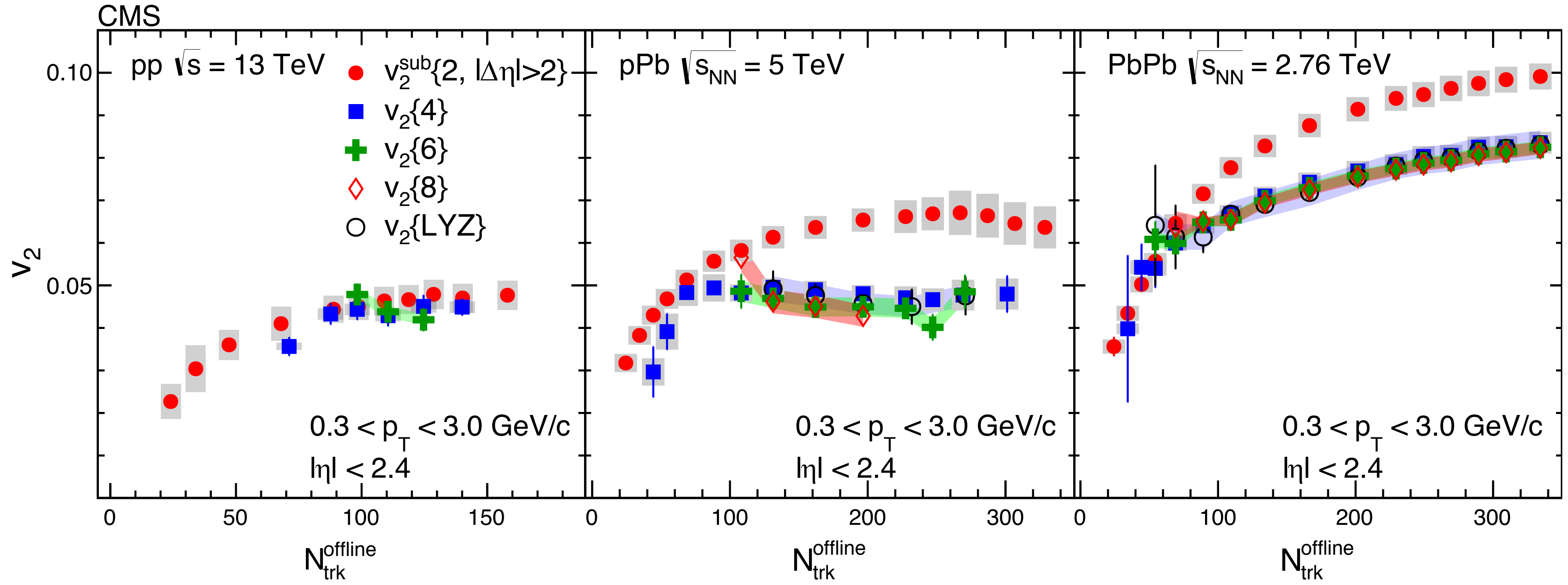


- no clear mass-ordering for low $N_{trk}^{offline}$
- high multiplicity $N_{trk}^{offline}$ range: mass-ordering observed (radial flow)
- $v_2^{sub}\{2\}$ increase with p_T (up to 2-3 GeV/c) then decrease
- particle mass ordering: K^0_s higher than $\Lambda/\bar{\Lambda}$ at low p_T

Evidence of collectivity in pp collisions at 13 TeV



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Similar to the observations in pPb and PbPb collisions, except $v_2\{2\}$

- smaller $v_2\{2\}/v_2\{4\}$ → fewer fluctuating sources in the IS in pp collisions? [PRL 112 (2014) 082301]

Higher-order cumulant analysis in pp: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$ → **collectivity in pp collisions!**

Correlations between flow harmonics (Looking into more details)

CMS-PAS-HIN-16-022

Correlation between harmonics:

$$SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

Symmetric Cumulant (SC) – developed by ALICE Collab.

- New observable
- Base on 4-particle cumulant technique
- Non-flow free at first order

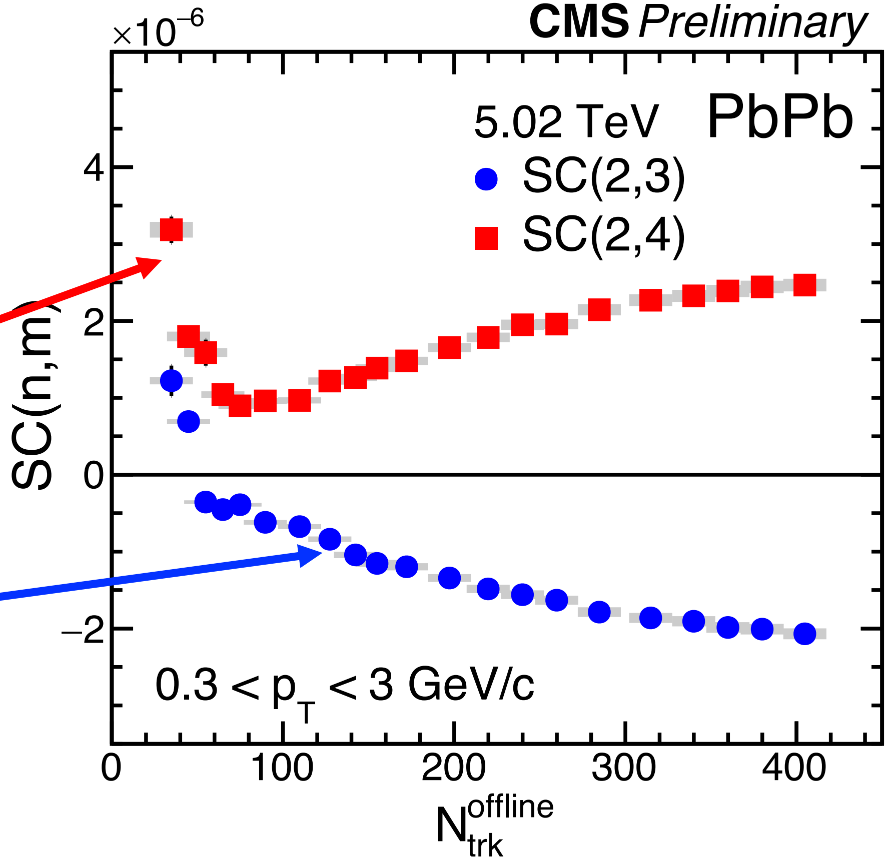
SC(2,4) > 0 → v2 and v_4 are correlated

- Medium response + IS fluctuations

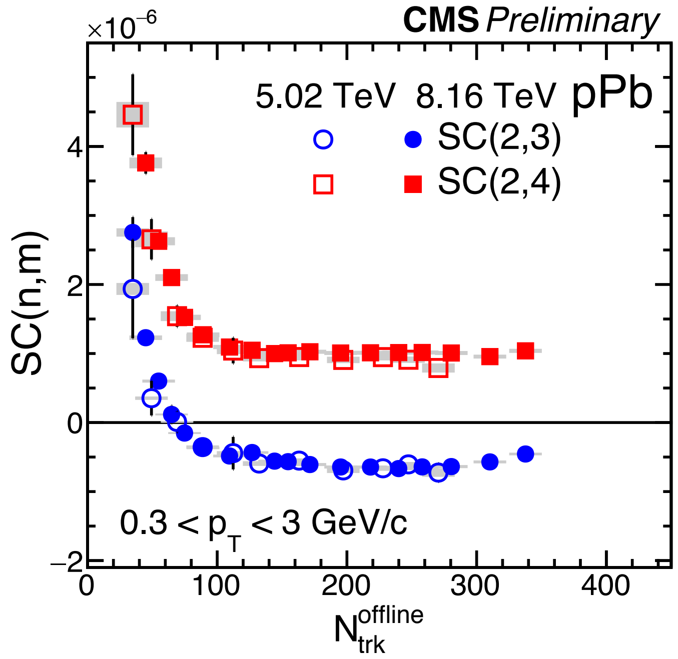
SC(2,3) < 0 → v_2 and v_3 are anti-correlated

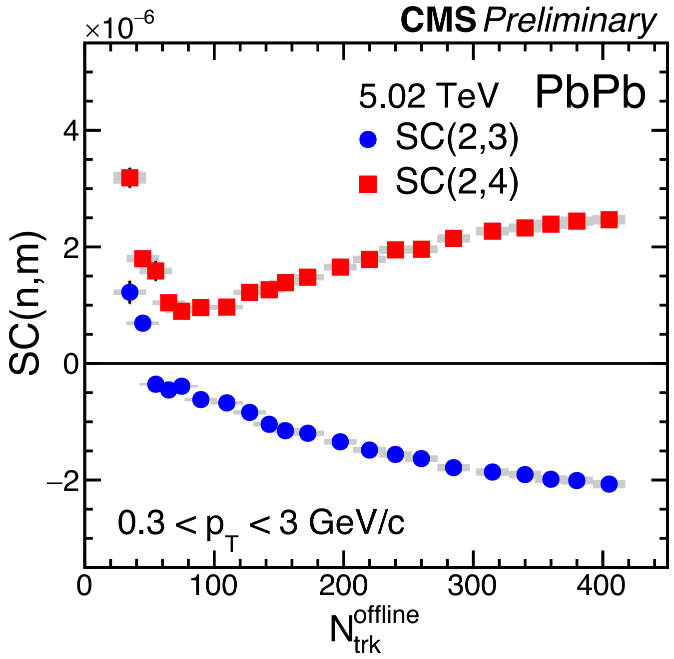
- IS fluctuations

Well understood with hydro calculations in PbPb



Correlation between v_n coefficients: pPb vs. PbPb results





Similar qualitative trend in pPb and PbPb

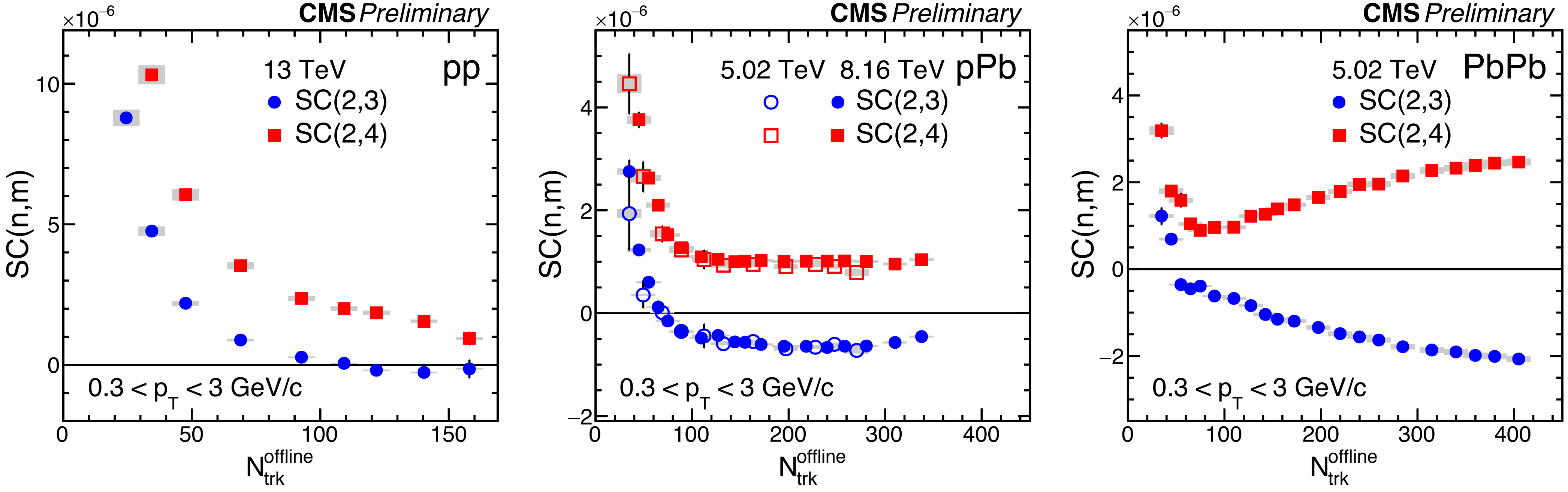
- SC(2,4) always positive
- SC(2,3) positive for $N_{trk}^{offline}$ <60, negative beyond that

Very small energy dependence observed in p-Pb results

→ And in pp collisions?

CMS-PAS-HIN-16-022

Correlation between v_n coefficients: pp, pPb and PbPb results



Similar qualitative trend in pPb and PbPb

- SC(2,4) always positive
- SC(2,3) positive for $N_{trk}^{offline}$ <60, negative beyond that

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Very small energy dependence observed in p-Pb results

In pp collisions SC(2,4) > 0 always ; behavior of SC(2,3) in high multiplicity not conclusive

Non-symmetric cumulants in all systems

SC normalized by $<v_n^2>.<v_m^2>$

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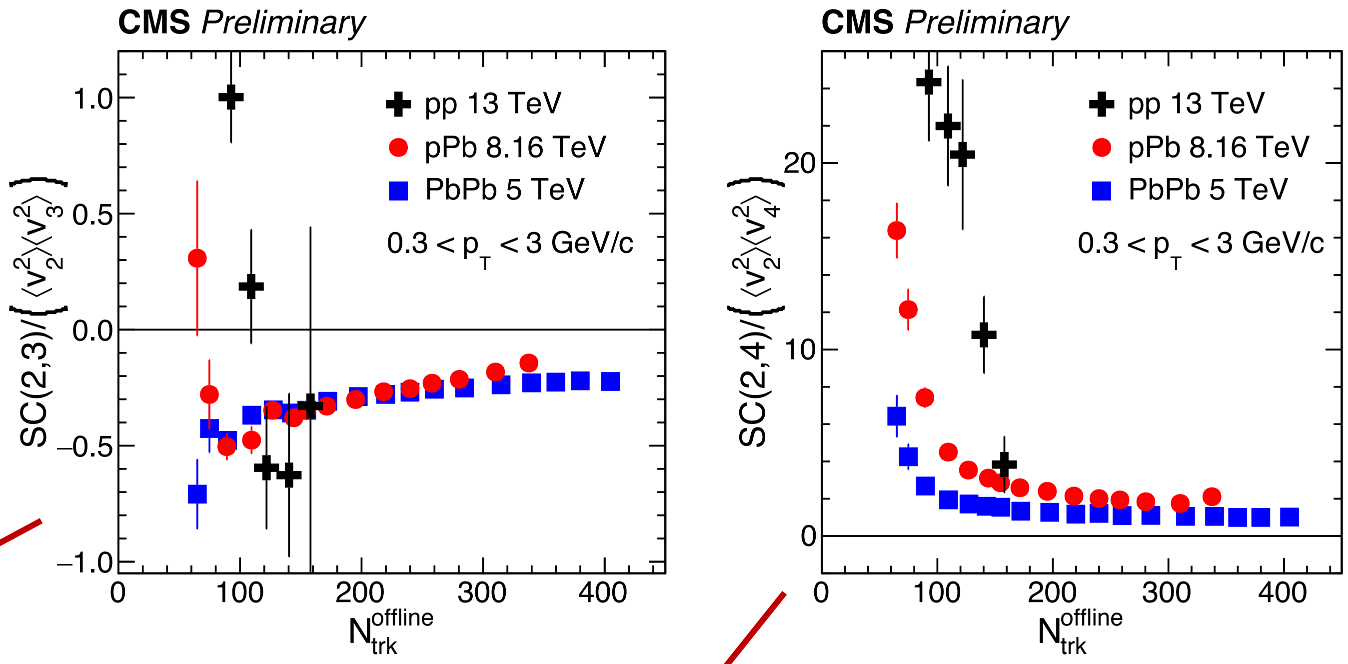


Similar behavior in p-Pb and PbPb

- Points to similar IS fluctuations
- First calculations (ε_n correlations only)
  - Right sign
  - Magnitude is off

- Ordering observed: p-p > p-Pb > Pb-Pb
- May point to different transport properties

Summary and Conclusions

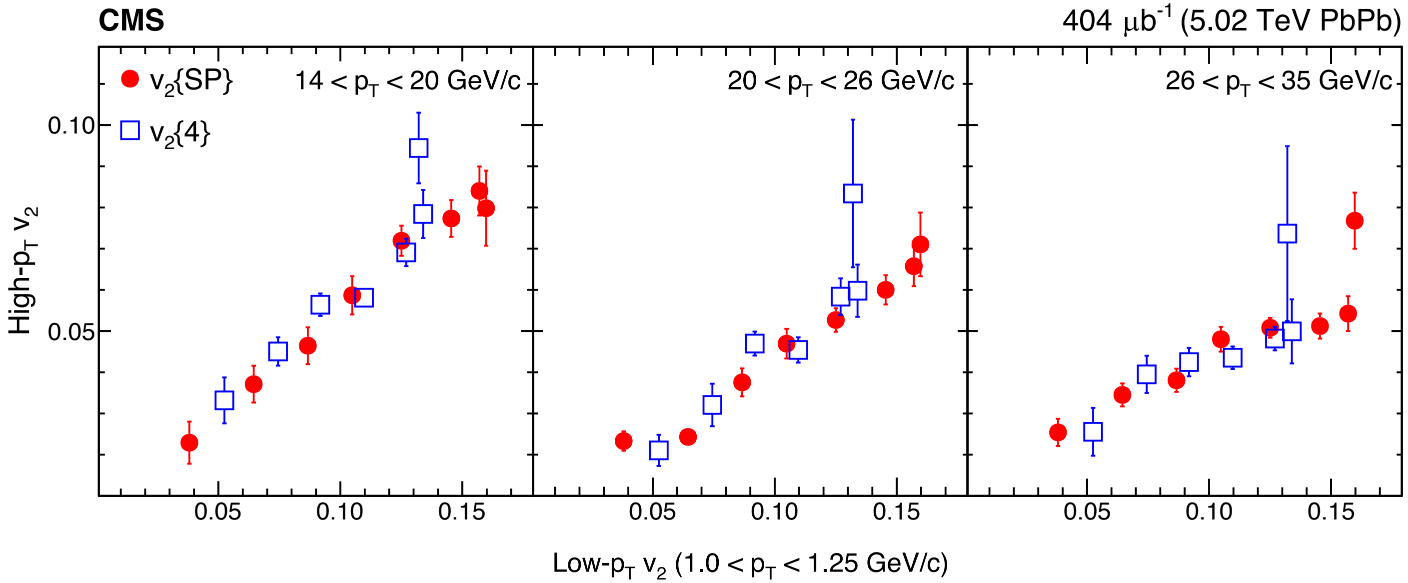
- Azimuthal anisotropy in PbPb collisions up to $p_T \approx 100$ GeV
  - $p_T < 3$ GeV/c: $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ → consistent with hydrodynamics
  - $p_T > 10$ GeV/c: $v_2\{SP\} \approx v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ → collective anisotropy till high p_T: path lengths of the in-medium jet energy loss
  - v_2 results at low and high p_T → IS anisotropy and EbyE fluctuations

- Ridge phenomena in pp collisions at 13 TeV
  - $v_2\{2\}$ and $v_3\{2\}$ flow harmonics for $\sqrt{s}$ = 5, 7 and 13 TeV
    very similar to pPb and PbPb cases, but with smaller intensity
    nearly energy independent
  - Mass-ordering observed in $v_2\{2\}$ of $h^{\pm}$, K^0_s and $\Lambda/\bar{\Lambda}$
  - Cumulant results: $v_2\{4\} \approx v_2\{6\}$ → **collectivity in pp collisions!**
  - Symmetric cumulants: correlations between harmonic coefficients → additional similarities in pp, pPb and PbPb
  - Similarities in results in PbPb, pPb and pp → may be important hint to search for unique paradigm to describe all
  - Challenge to theoretical models!

BACKUP SLIDES

Azimuthal correlations (v_2): low p_T vs. high p_T

- Exploring connection of low p_T (hydro dominated) with high p_T (jet quenching dominated) with v_2 data



arXiv:1702.00630

- Centrality bins: 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50, and 50–60% (for SP; not 0-5% for cumulants)
- v_2 in three high p_T ranges vs. low p_T ($1 < p_T < 1.25$ GeV/c) for all centralities
  0-20% divided in four bins of 5% bin width; above 20%, bin width of 10%
- strong correlation of low and high p_T values in full centrality range
  → Indication: initial geometry and its fluctuations → likely to be common origin of anisotropies at low- and high-p_T

Two-particle Fourier coefficients vs. multiplicity

- $V_{2\Delta}$ and $V_{3\Delta}$ before and after jet correction procedure compared to PYTHIA 8 tune CUETO8M1 MC results (back-to-back jets only)
  - before subtraction: $V_{2\Delta}$ flat in N^{off}_{trk} and $V_{3\Delta} < 0$ from PYTHIA (b-to-b jets, $\Delta\phi \approx 0$)
  - after subtraction: $V_{2\Delta}$ grows w/ N^{off}_{trk} and flattens; $V_{3\Delta} > 0$ in full N^{off}_{trk}

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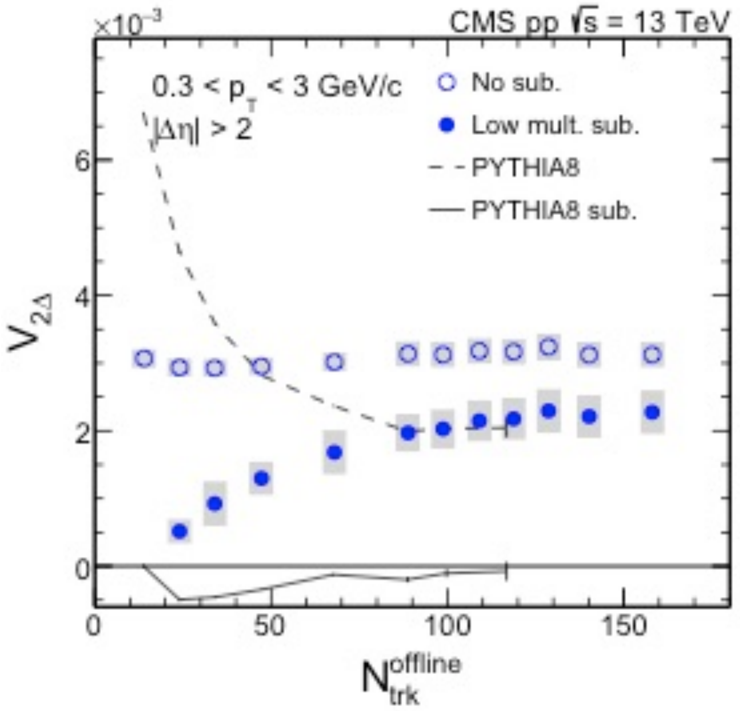
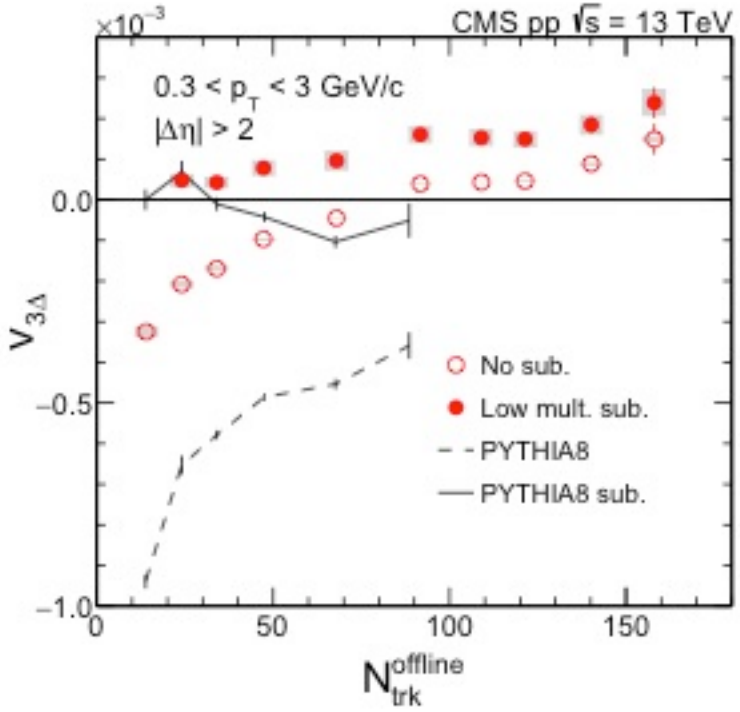
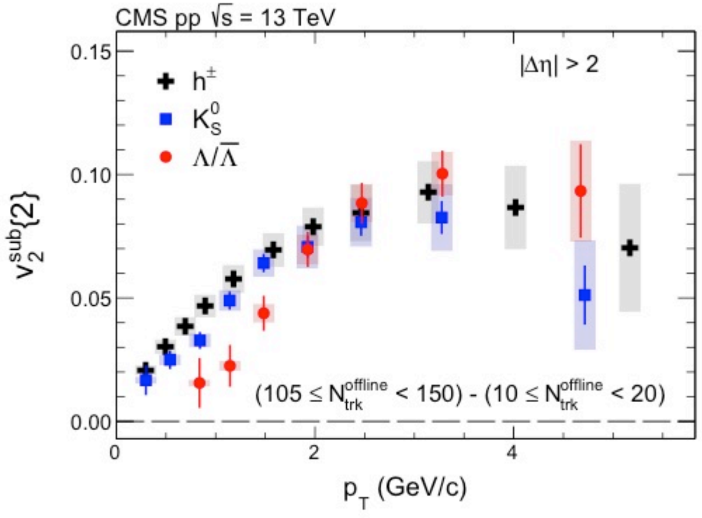




Mass-ordering in $v_2^{sub}\{2\}$ of $h^{\pm}$, K^0_s and $\bar{\Lambda}/\Lambda$

- After subtracting jet contributions (top)
  - $v_2^{sub}\{2\}$ increase with p_T (up to 2-3 GeV/c) then decrease
  - particle mass ordering: K^0_s higher than $\Lambda/\bar{\Lambda}$ at low p_T then reverse at high p_T



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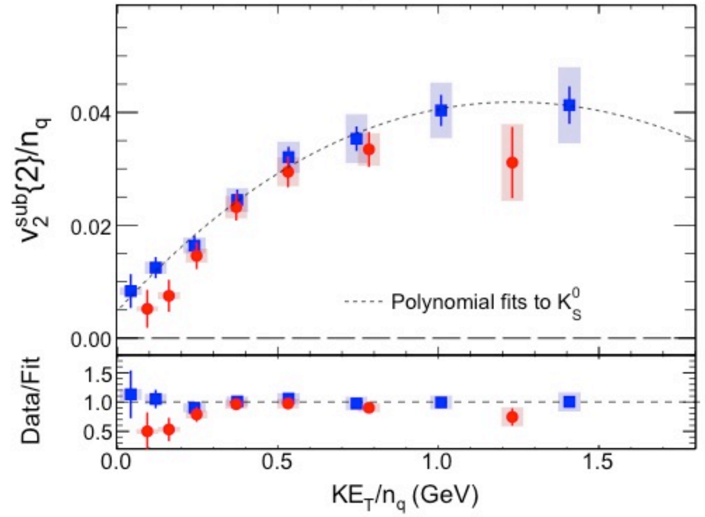
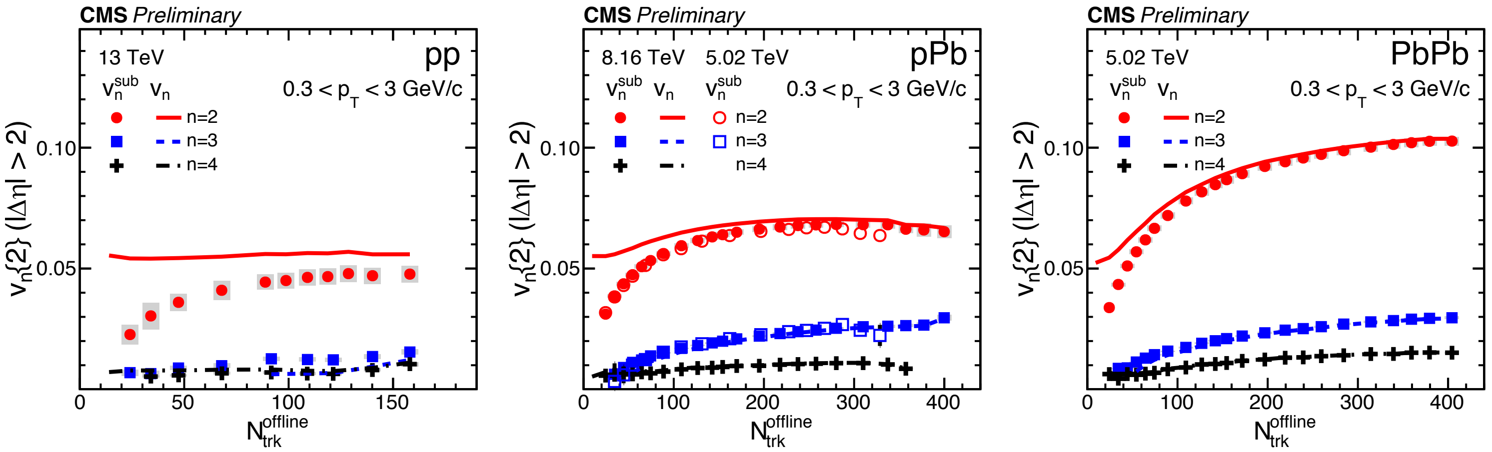
- Scaling with number of constituent quarks
  - $v_2^{sub}\{2\}/n_q$ vs. KE_T/n_q (trans. kin. energy/quark)
  - dashed curve: polynomial fit to K^0_s data
  - ratio of $v_2^{sub}\{2\}/n_q$ results for K^0_s and $\Lambda/\bar{\Lambda}$ particles divided by this polynomial fit

  approximate scaling for $KE_T/n_q > 0.2$ GeV





- Correlations (back-to-back jets) from very low-multiplicity events (v^{sub}) are subtracted
  - plays a larger role in low multiplicity, in particular for pp collisions (dijet correlations expected to be the main source of correlations)
- Results corrected by low-multiplicity subtraction are denoted as v_{sub}
- Lines show the v_n results before subtraction of low-multiplicity v_n correlations
- Note: the correctness of subtraction procedure is under discussion

Comparing $v_2\{m\}$ for different systems

- Comparison between $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ in p-p and p-Pb:
  - $v_2\{2\}/v_2\{4\}$ (p-p) ≤ $v_2\{2\}/v_2\{4\}$ (p-Pb) → related to IS fluctuations
- One possible explanation: PRL 112 (2014) 082301
  - smaller $v_2\{2\}/v_2\{4\}$ → Less IS fluctuating sources
- Still true before subtraction → Upper limit

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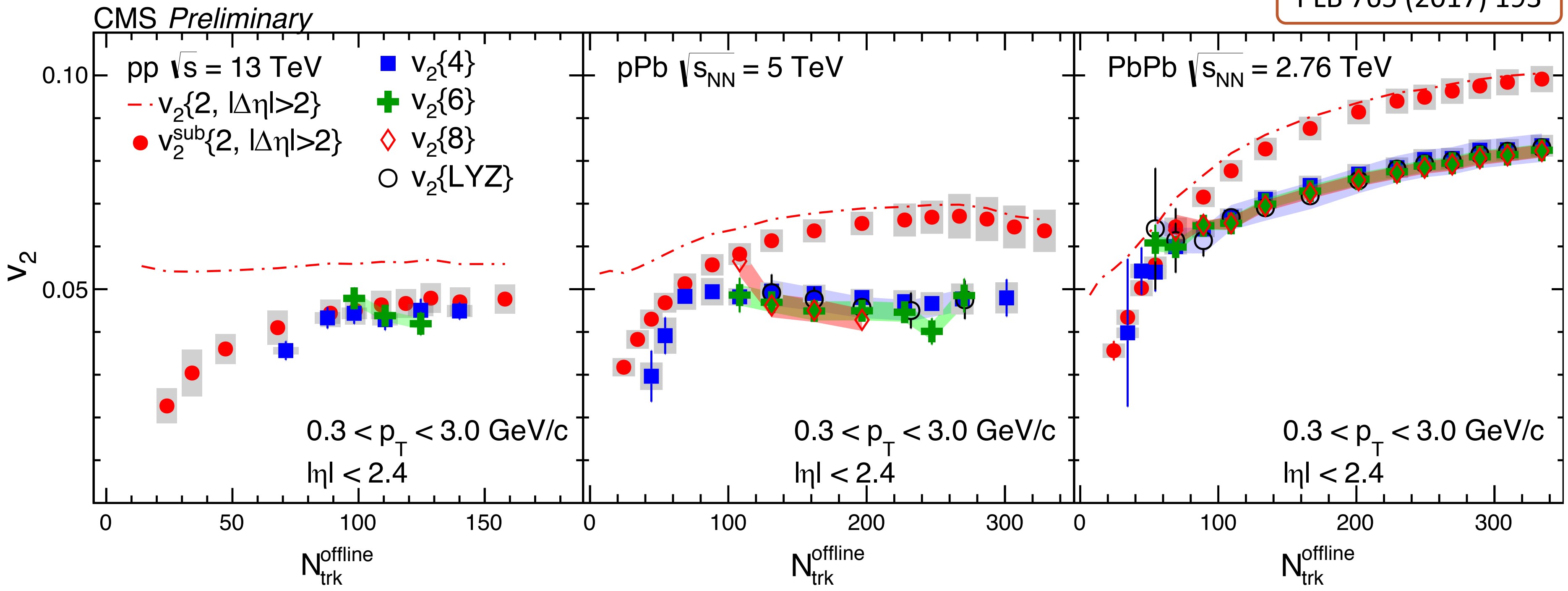
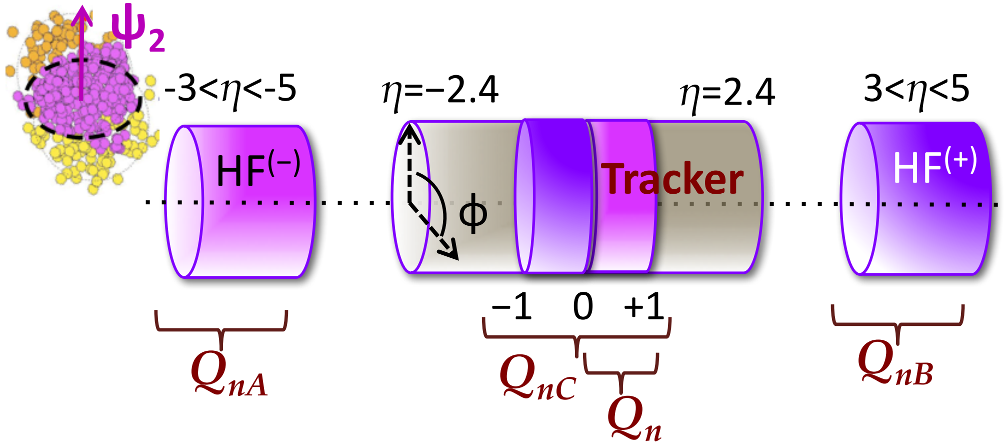


Flow methods: Q-vectors, SP and $v_2\{m\}$

- Scalar Product (Event Plane) Method

$$Q_n = \sum_j^M \omega_j e^{in\phi_j}$$



$$v_n(SP) = \frac{\langle Q_n . Q^*_{nA} \rangle}{\sqrt{\frac{\langle Q_{nA} . Q^*_{nB} \rangle \langle Q_{nA} . Q^*_{nC} \rangle}{\langle Q_{nB} . Q^*_{nC} \rangle}}}$$

Resolution

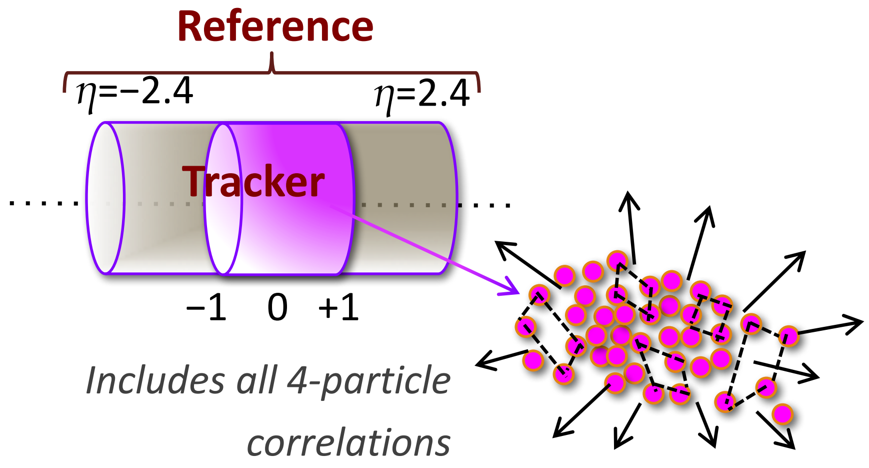
- Particle cumulants
  - m-particle correlations in $v_n\{m\}$ (illustration for m=4 → $v_n\{4\}$)

$$\ll 2 \gg = \ll e^{in(\phi_1 - \phi_2)} \gg$$

$$\ll 4 \gg = \ll e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \gg$$

$$c_n\{4\} = \ll 4 \gg - 2 \times \ll 2 \gg^2 \rightarrow v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Suppresses 2-particle correlations

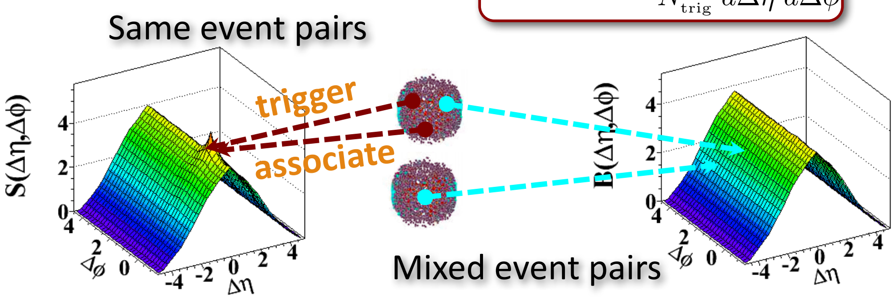


Dihadron correlations technique

$$S(\Delta\eta,\Delta\phi)=\frac{1}{N_{\rm trig}}\frac{d^2N^{\rm same}}{d\Delta\eta\, d\Delta\phi}$$

$$\Delta\eta=\eta^{\rm assoc}-\eta^{\rm trig}$$
$$\Delta\phi=\phi^{\rm assoc}-\phi^{\rm trig}$$

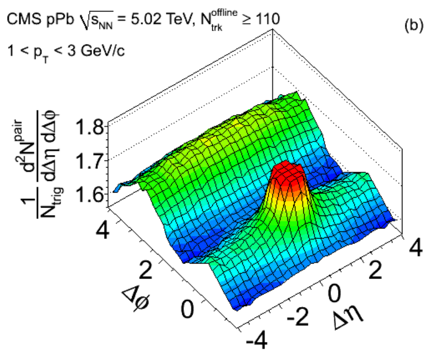
$$B(\Delta\eta,\Delta\phi)=\frac{1}{N_{\rm trig}}\frac{d^2N^{\rm mix}}{d\Delta\eta\, d\Delta\phi}$$



Ratio:

$$\frac{1}{N_{\rm trig}}\frac{d^2N^{\rm pair}}{d\Delta\eta\, d\Delta\phi}=B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Associated hadron yield per trigger



- Quantifying the ridge: average the 2D two-particle correlation function over |Δη| > 2 (avoid jet contamination)

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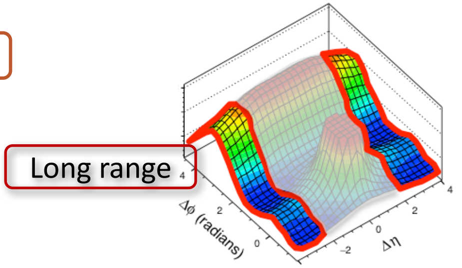

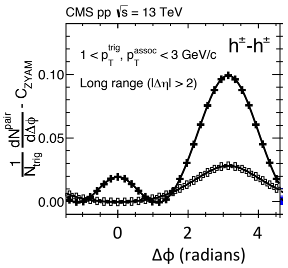

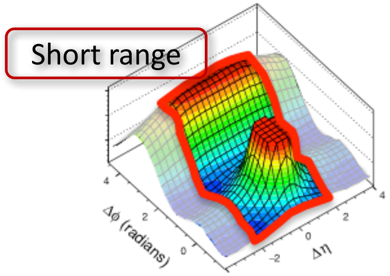

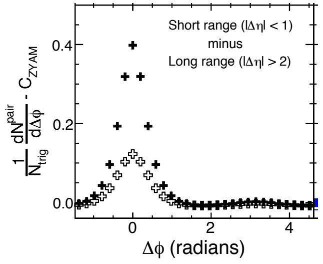

- $V_{n\Delta}$ extracted using Fourier fit
  - $$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi}=\frac{N_{\rm assoc}}{2\pi}\left\{1+\sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

- Plus low multiplicity subtraction applied on $V_{n\Delta}$ (assuming $v_2(N_{trk}^{offline} < 20) = 0$)

- Single v_n computed by $V_{n\Delta}(p_T^a,p_T^b)=v_n(p_T^a)\times v_n(p_T^b)$

$$v_n\{2,|\Delta\eta|>2\}(p_T)=\frac{V_{n\Delta}(p_T,p_T^{\rm ref})}{\sqrt{V_{n\Delta}(p_T^{\rm ref},p_T^{\rm ref})}}$$

Dihadron correlations-III: subtraction

- Low multiplicity subtraction applied on $V_{n\Delta}$
  - Remove jet correlation contribution

    bottom plot used to estimate jet correlation part
  - Assume jet-induced correlations invariant with multiplicity
  - $v_2(N_{trk}^{offline} < 20) = 0$, by construction ??

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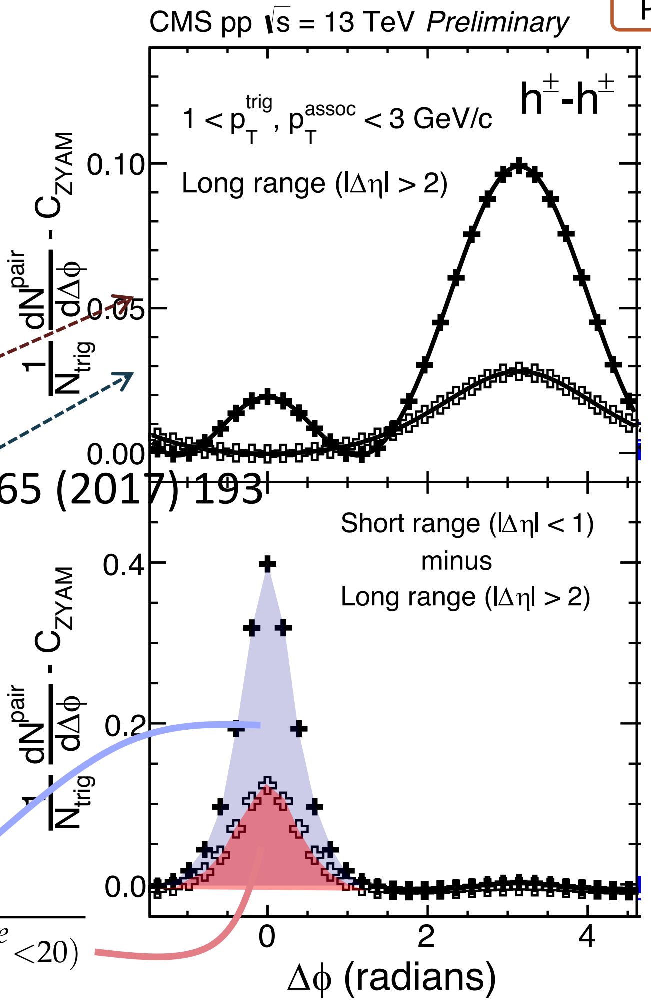

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$$V_{n\Delta}^{sub} = V_{n\Delta} - V_{n\Delta}^{(10<N_{trk}^{offline}<20)} \times \frac{N_{assoc}^{(10<N_{trk}^{offline}<20)}}{N_{assoc}} \times \frac{Y_{jet}}{Y_{jet}^{(10<N_{trk}^{offline}<20)}}$$