# Collective anisotropy at high $p_T$ in pPb collisions using subevent cumulants with the CMS at LHC

Prabhat Ranjan Pujahari
(for the CMS collaboration)
Indian Institute of Technology Madras

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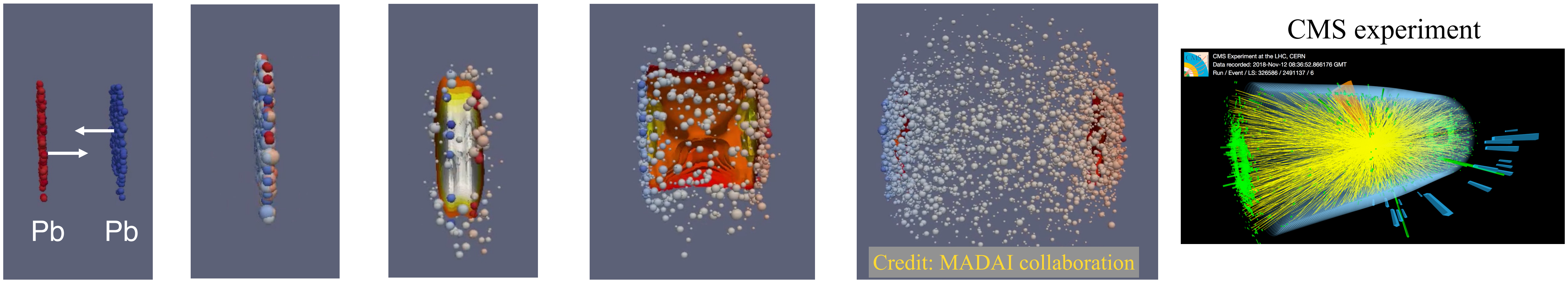
University de Barcelona

# Standard model of heavy-ion physics

Initial state | Hard scatterings | QGP formation | Hydrodynamic expansion | Hadronization and freeze-out | Detection




Time: $\tau = 0$ → $\tau = 1$ fm/c → $\tau = 10$ fm/c → $\tau > 10$ fm/c

Temperature: $T \sim$ 200-800 MeV[1] ← $T \sim$ 155-100 MeV[2]

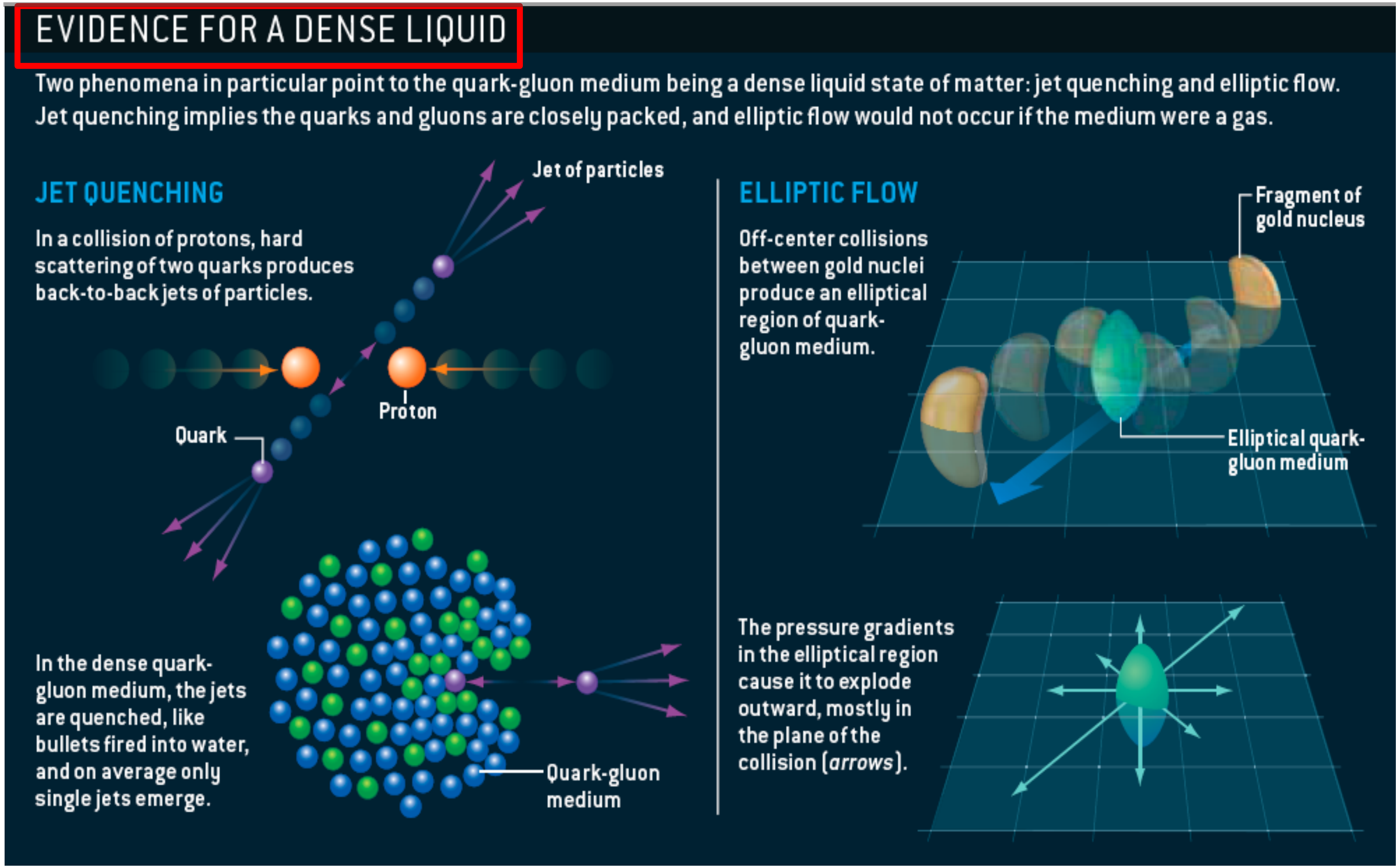
$T_{C,\,LQCD}$ ~ 155 - 159 MeV [3,4]

[1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
[2] A. Andronic et al., Nature 561 (2018) 7723, 321-330
[3] A. Bazavov et al., Phys. Lett. B 795 (2019)
[4] Borsaniy et al. PRL 125 (2020) 5, 052001

Direct observation of the QGP is not possible in an experiment
→ rely on the emerging particles from hadronic collisions as "probes"

- **Probe-I: low-$p_T$ particles, light flavour hadrons (u,d,s + nuclei)**
  - produced from hadronization of the strongly interacting, thermalised QGP constituents bulk of the matter
  - thermodynamical, hydrodynamical and transport properties
- **Probe-II: high-$p_T$ parton (→ jets), heavy flavour hadrons (→ open HF, quarkonia)**
  - produced in the early stages of the collisions
  - traverse through the QGP and interacting with its constituents
  - in-medium interaction (energy loss) and transport properties
  - in-medium modification of the strong force and of fragmentation

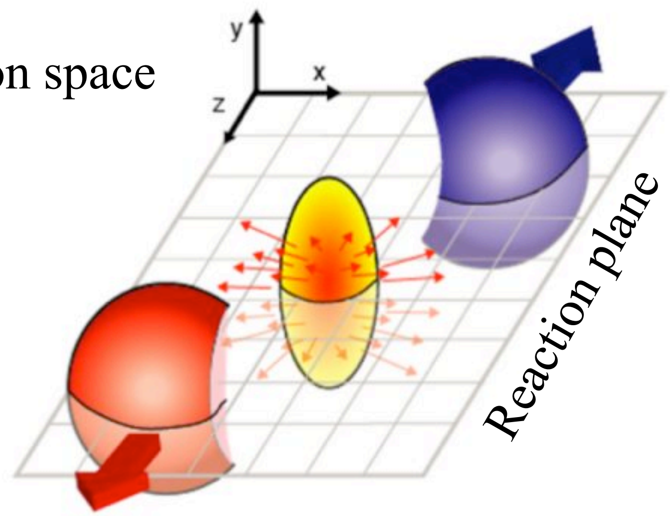
# QGP discovery at RHIC: 2005 - 2006



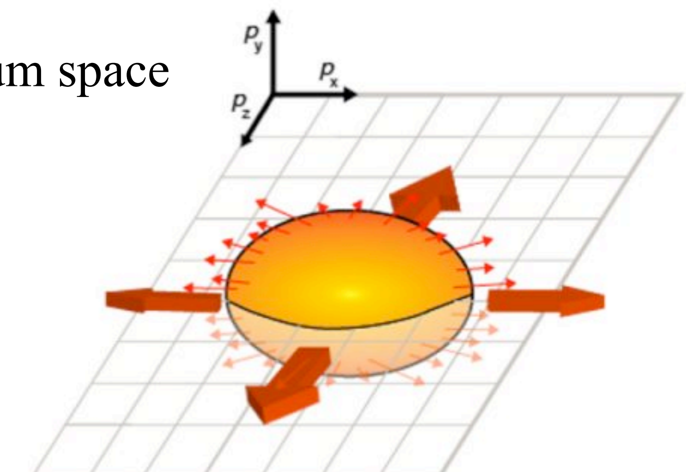

M. Roirdan and W. Zajc, Scientific American, May 2006

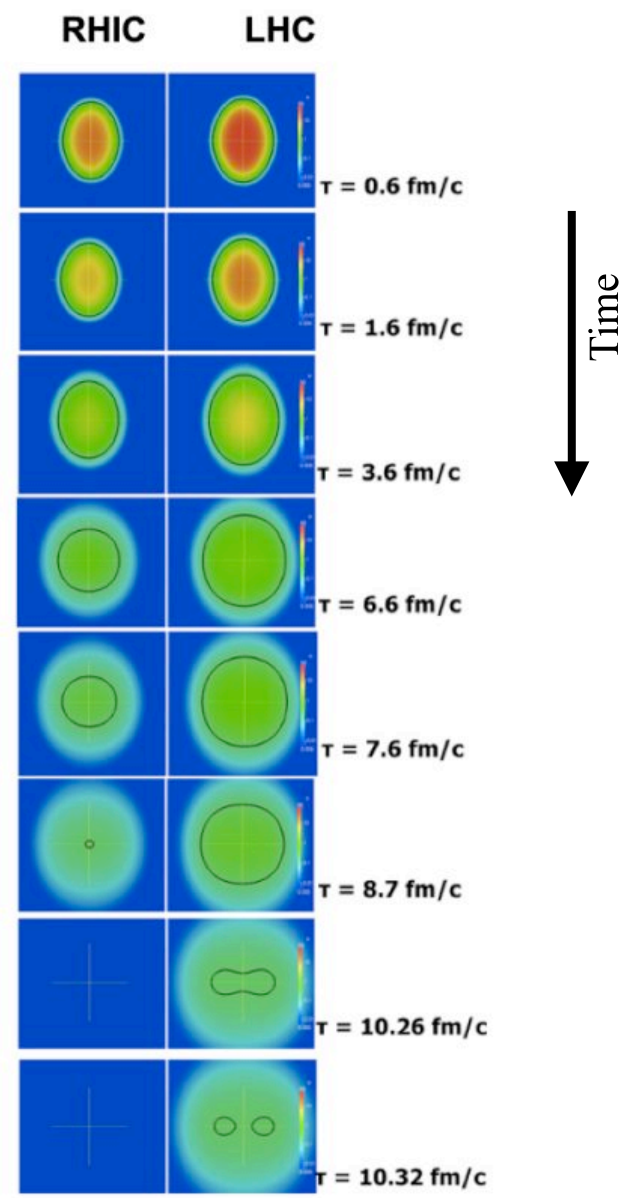
# Collectivity - evidence of QGP fluidity

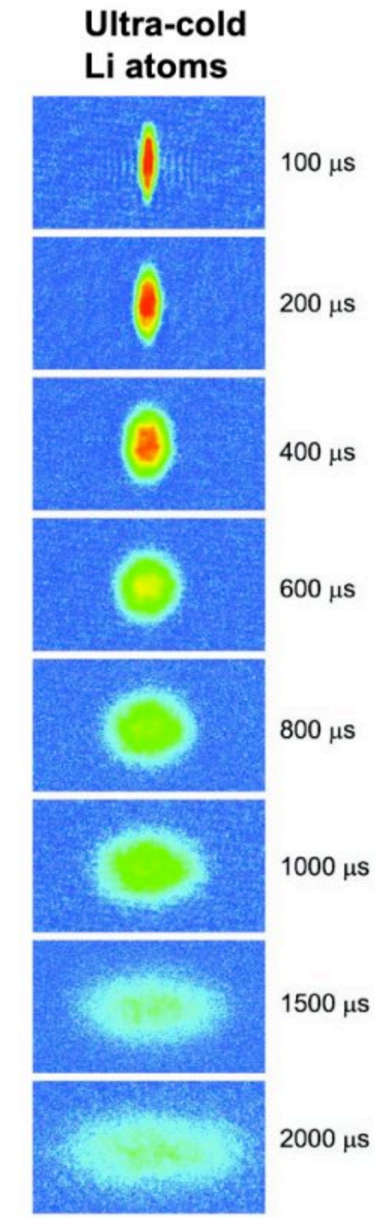
Configuration space




Momentum space



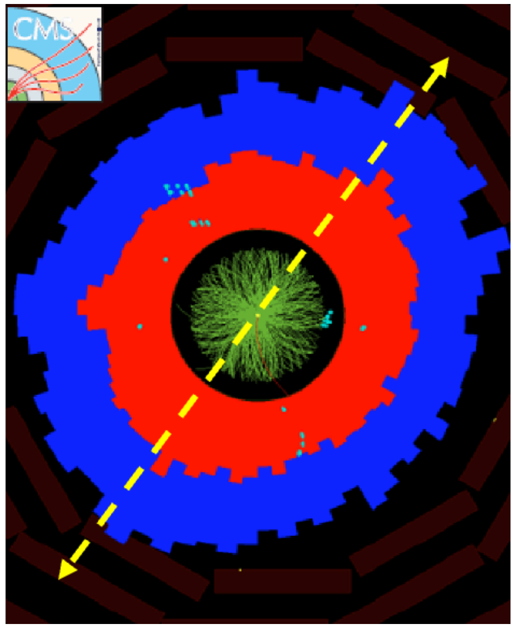




Courtesy: Prof. John Thomas

Particle correlations and Fourier analysis:

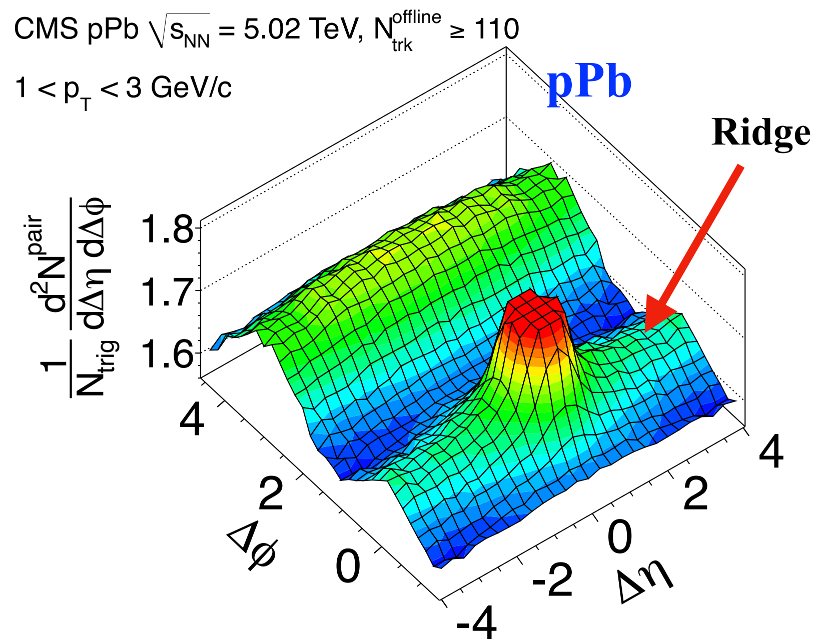
$$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2V_{1\Delta}\cos(\Delta\phi) + 2V_{2\Delta}\cos(2\Delta\phi) + 2V_{3\Delta}\cos(3\Delta\phi) + 2V_{4\Delta}\cos(4\Delta\phi) + \ldots$$

# Ridge - azimuthal anisotropy at low $p_T$

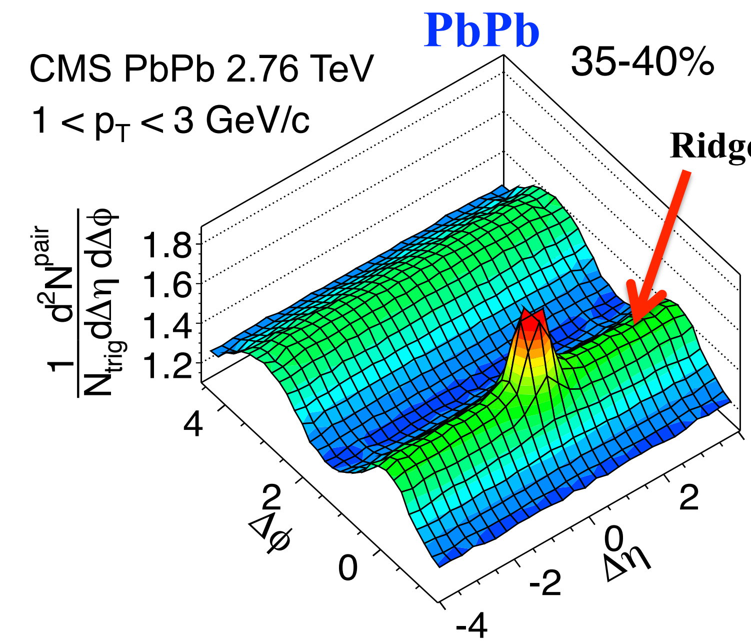


See it by "eyes" event-by-event

Phys. Lett. B 718, 795 (2013)



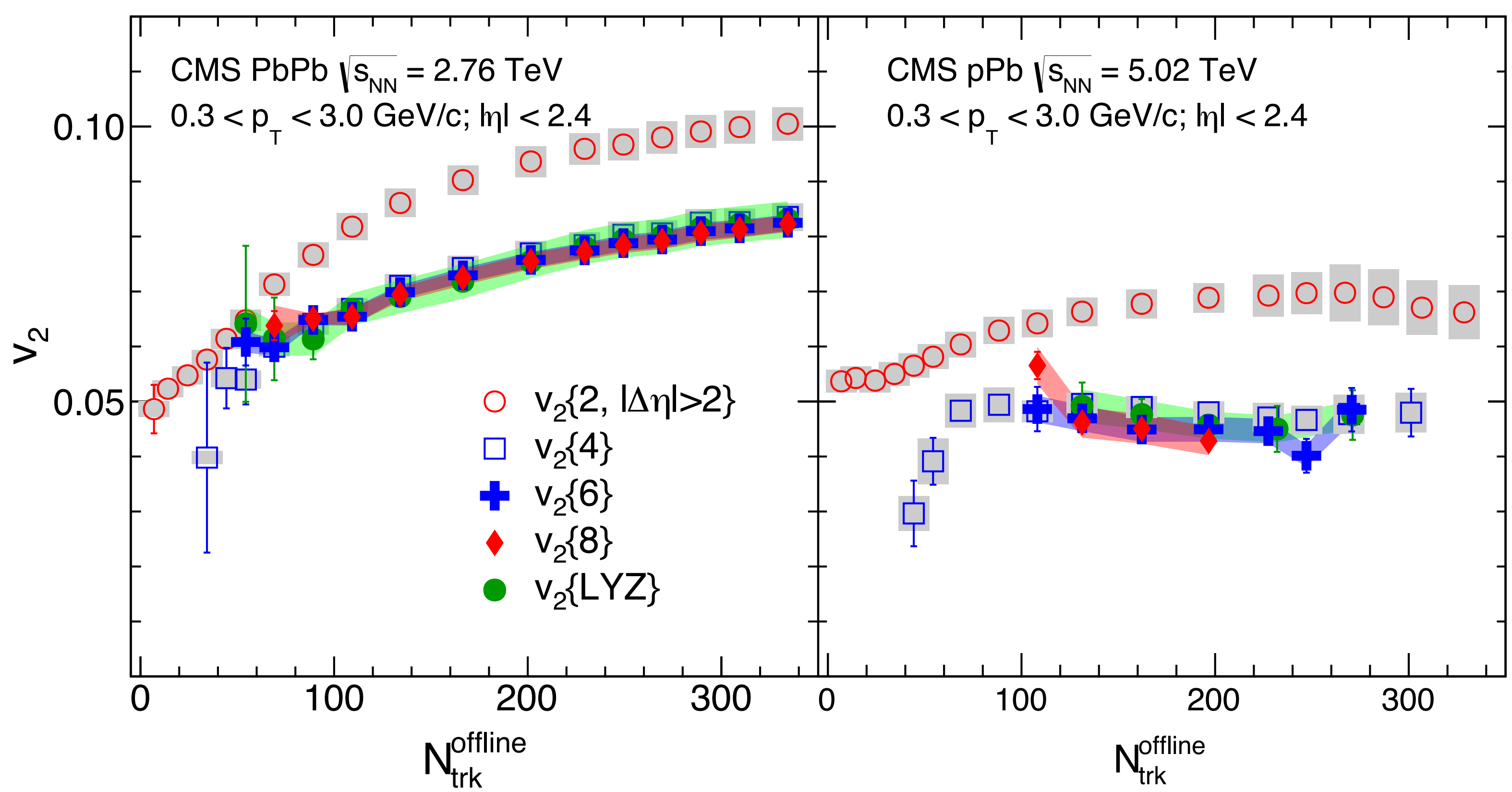

JHEP 07 (2011) 076




Extended structure away from near-side jet peak interpreted as collective effect due to presence of QGP

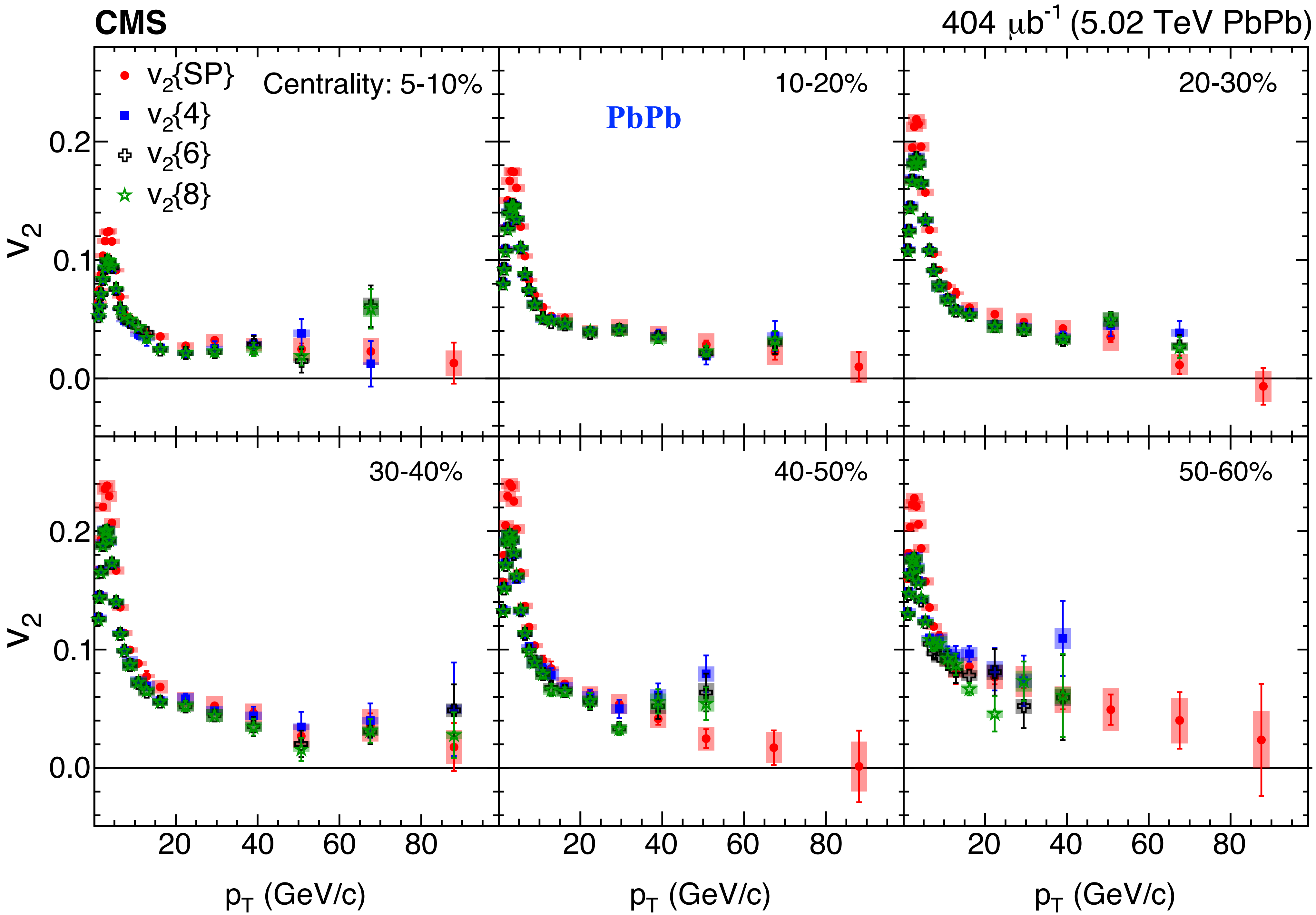
Phys. Rev. Lett. 115, 012301 (2015)

- Azimuthal Anisotropy ($v_n$) at low $p_T$ ( < 3 GeV/c)
  - Discovery of "Ridge" in pPb
  - Geometry + Fluctuations
  - $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$ => sign of collectivity
  - Hydrodynamic provides simultaneous descriptions of $v_2$, $v_3$, $v_4$ in pp, pPb and PbPb collisions



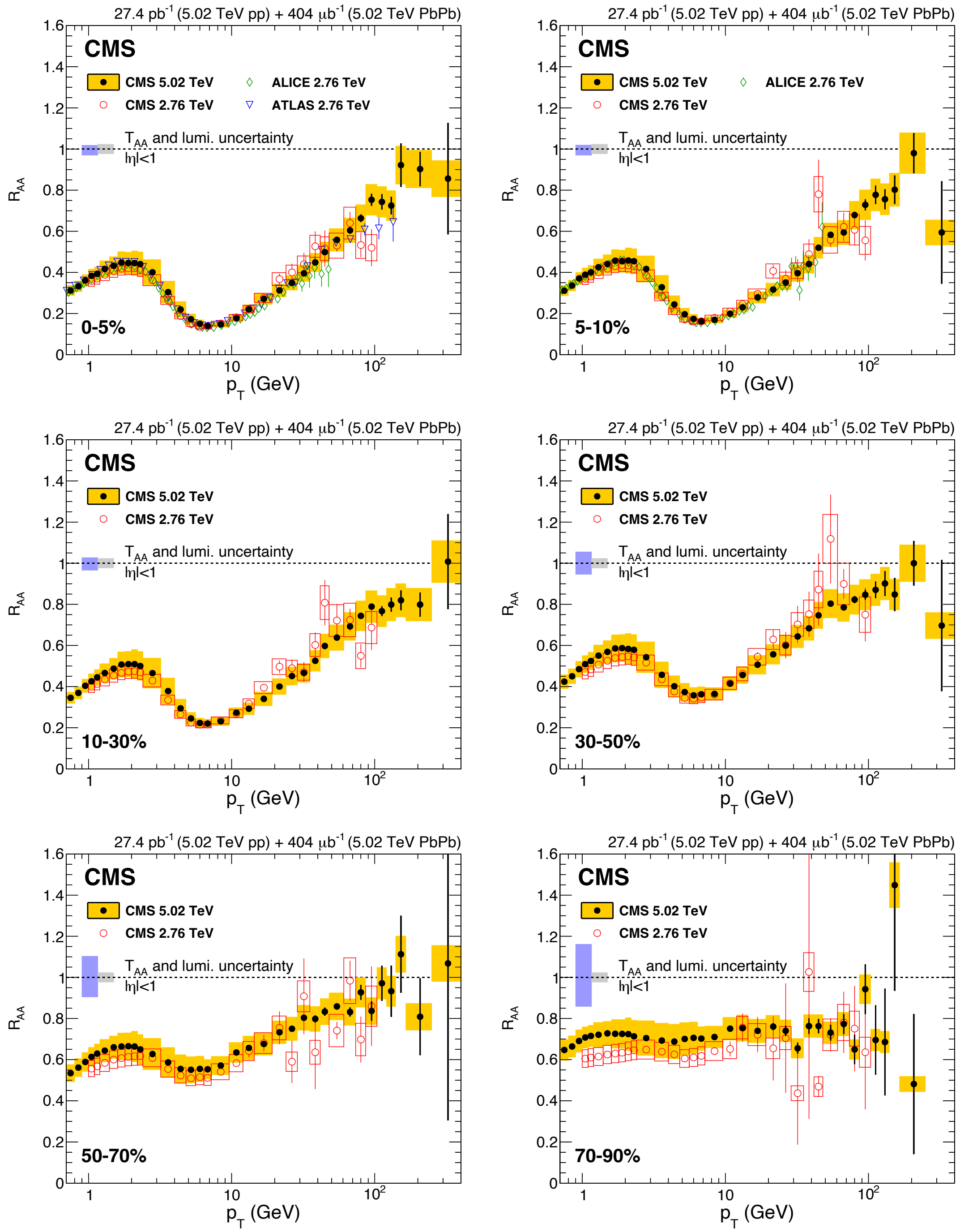
# Azimuthal anisotropy at high $p_T$ in PbPb collisions

Phys. Lett. B 776 (2017) 195

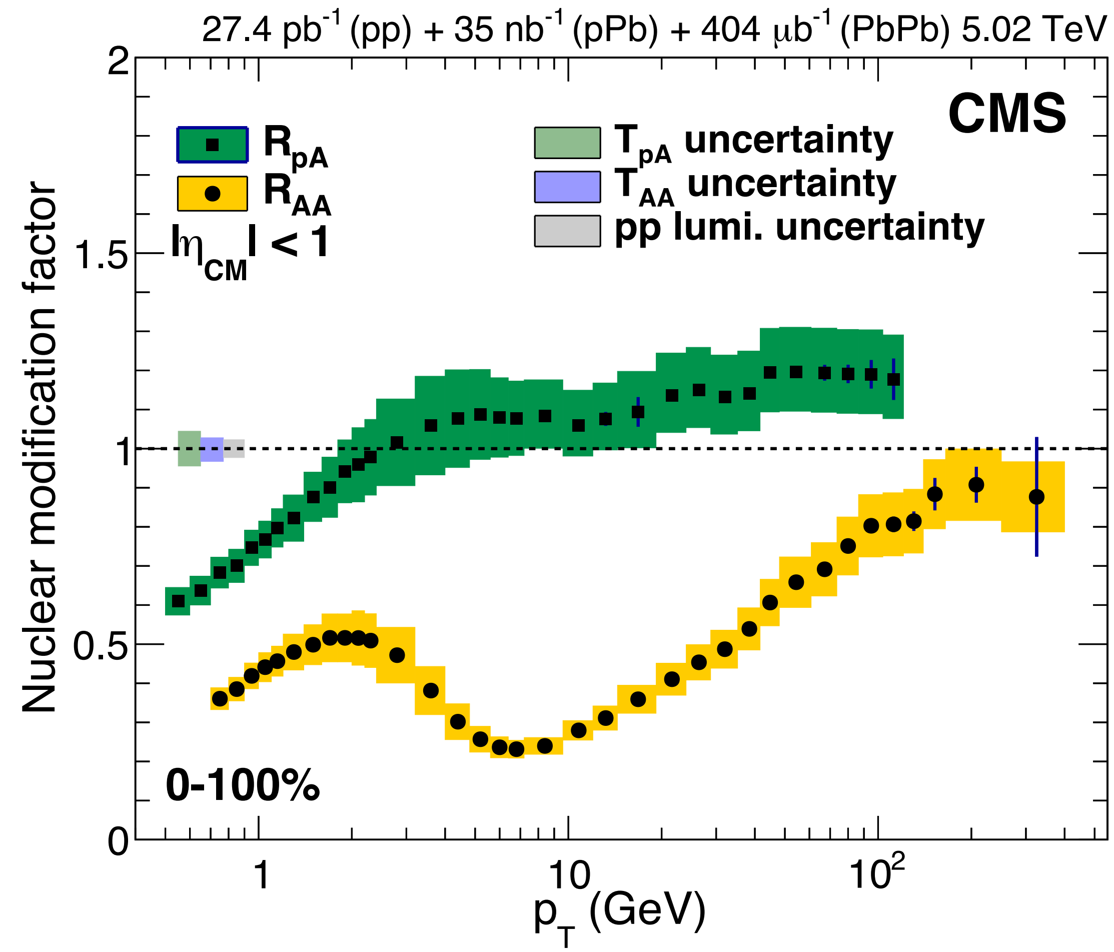



- Azimuthal Anisotropy ($v_n$) at high $p_T$ ( > 10 GeV/c) in AA:
  - Energy loss + Fluctuations, no hydrodynamics at such high-$p_T$
  - Sensitive to the path length of high $p_T$ parton in QGP medium (Jet Quenching)

# Nuclear modification factor in small to large system




JHEP 04 (2017) 039




$$R_{AA} = \frac{N^{A+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$$

- $R_{AA} < 1$ => particles are suppressed
- Bigger system → more suppression

- Charged hadron yield at high $p_T$ suppressed in Pb-Pb central collisions ($R_{AA} < 1$)
- Suppression decreases from central to peripheral Pb-Pb collisions
  - lower medium density, small path length in peripheral collisions
  - suppression in peripheral Pb-Pb could be entirely due to selection bias
- No evidence of jet quenching in p-A collisions
  - $R_{pA} \sim 1$ at higher-$p_T$ in minimum bias p-Pb collisions
  - Suppression in central Pb-Pb is due to the hot and dense QCD medium

**Open question: collectivity in small system (p-Pb) without energy loss?**
**→ when does energy loss turn on?**

# Review of the story on hard probes

**Hard scattering and connection with flow:**

- Hard scattering => large momentum transfer $Q^2$ between partons
- Leads to final state particle with large pT
- Probe small distance scales $d \approx 1/Q$
- Probe early times because scattering occur during nuclear crossing $\tau = 2R/\gamma$
- Jet quenching allows to observe process of equilibrium
- Energy loss is connected to elliptic flow: relationship between jet suppression ($R_{AA}$) and initial nuclear geometry

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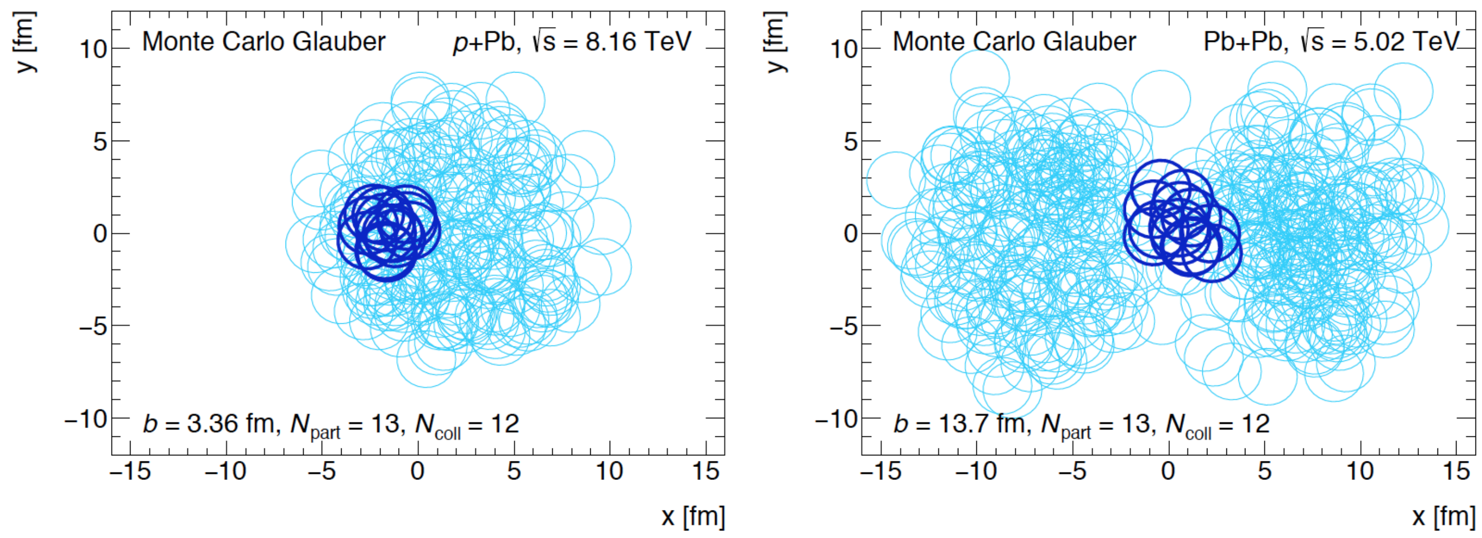
**What about small system?**

Figure credit: D.V. Perepelitsa




**Which is which?**

# Review of the story on hard probes

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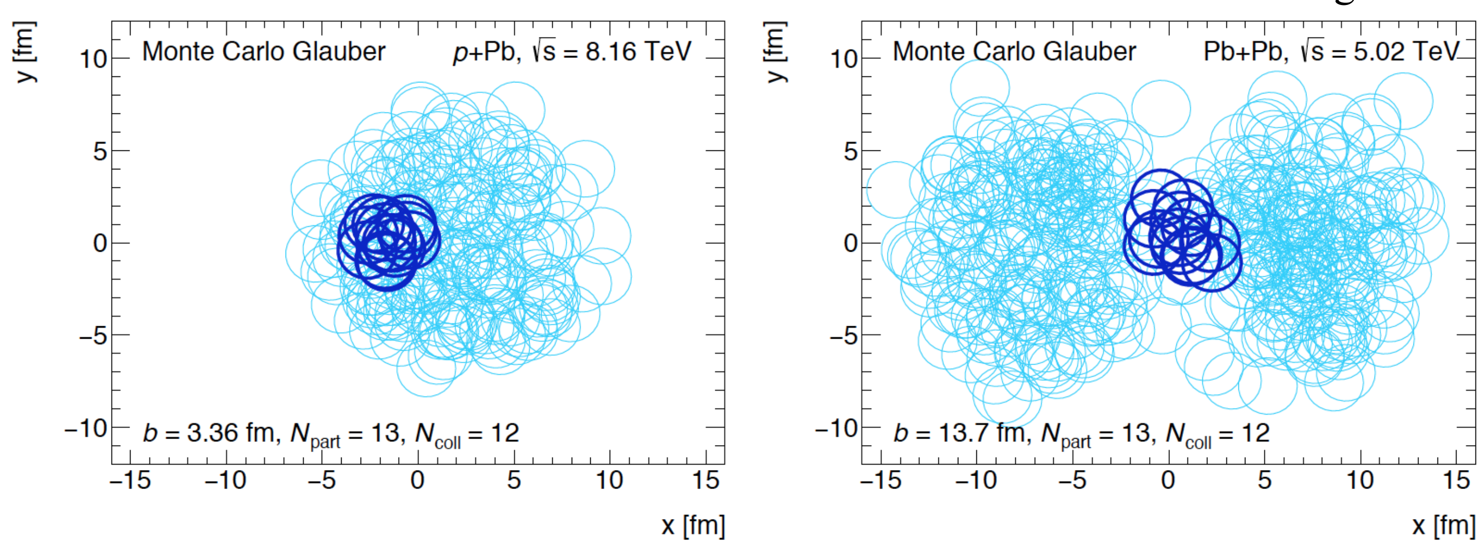
**What about small system?**

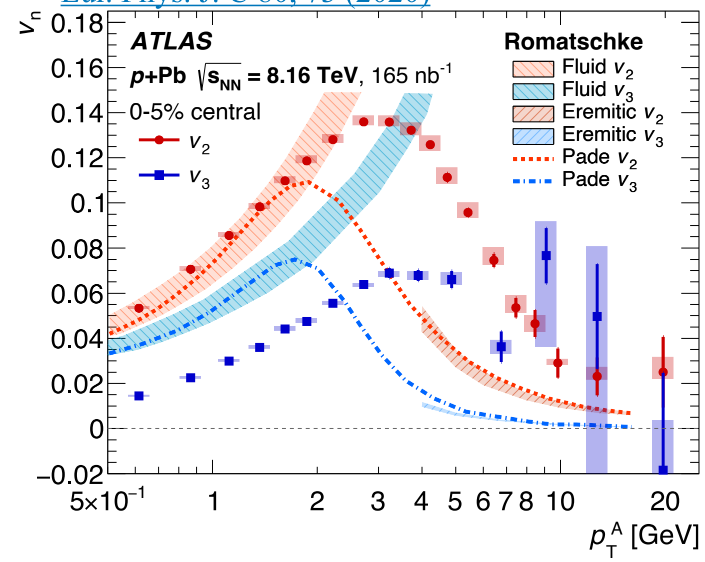
Figure credit: D.V. Perepelitsa




- Observation of absence of particle suppression in small systems despite strong evidence for QGP formation
- Major issue? Apparent similarities between central small systems and peripheral large systems
- Perceived presence of particle suppression in peripheral PbPb collisions may be an event selection artefact, not a physics effect
- Where in system size is the onset of suppression?

# Previous measurements - how are we doing better?

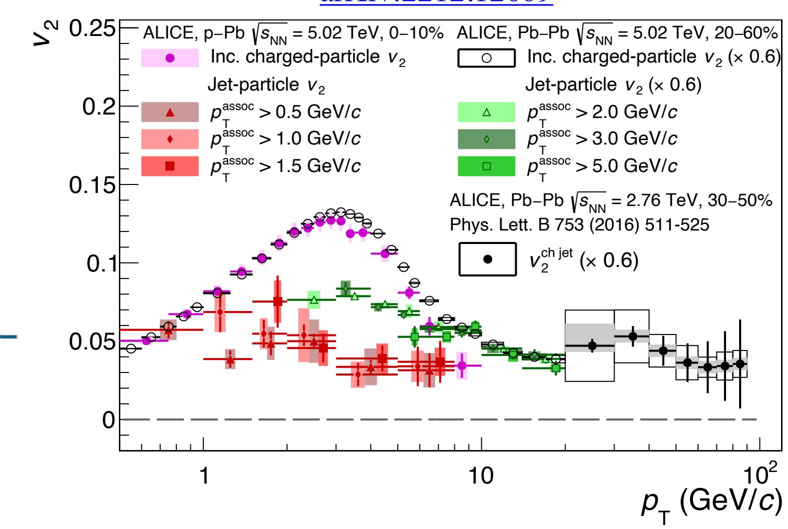
Eur. Phys. J. C 80, 73 (2020)



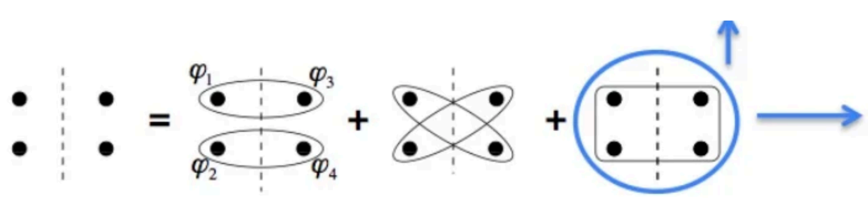

## Previous measurements and limitations:

- ❖ 2-particle correlation technique (Non-flow contamination)
- ❖ Template fit method or peripheral subtraction method to remove non-flow
- ❖ Based on assumptions
- ❖ Could be biased and model dependent
- ❖ Difficult to draw finite conclusion for high-$p_T$ flow due to possible non-flow contamination

arXiv:2212.12609




## Cumulant method and its advantage:



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

**A. Bilandzic, R. Snellings, and S. Voloshin**

Phys. Rev. C 83 (2011) 044913

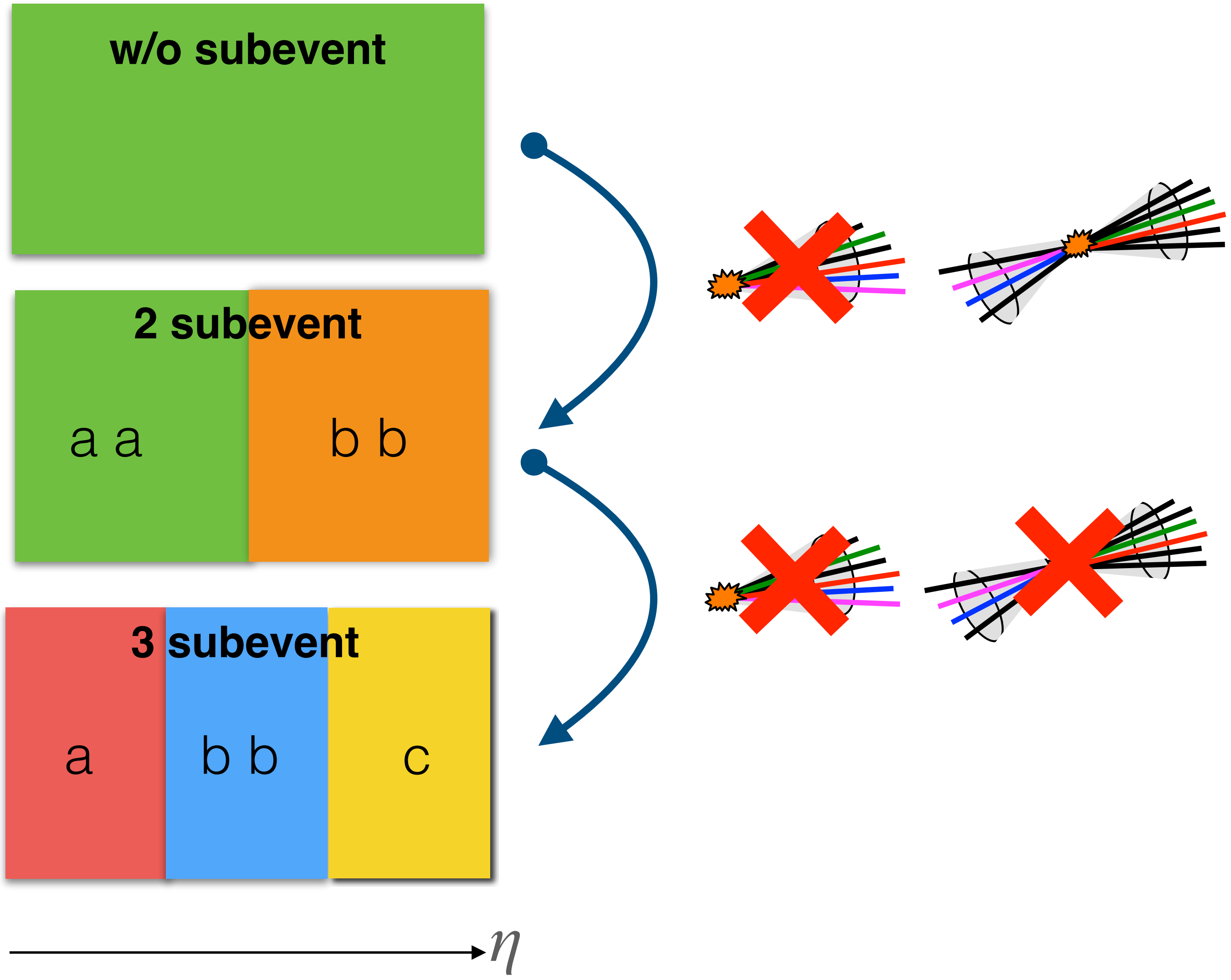
- ❖ Multiparticle correlation technique
- ❖ Non-flow suppression in a data-driven way

# Motivation for using subevent method

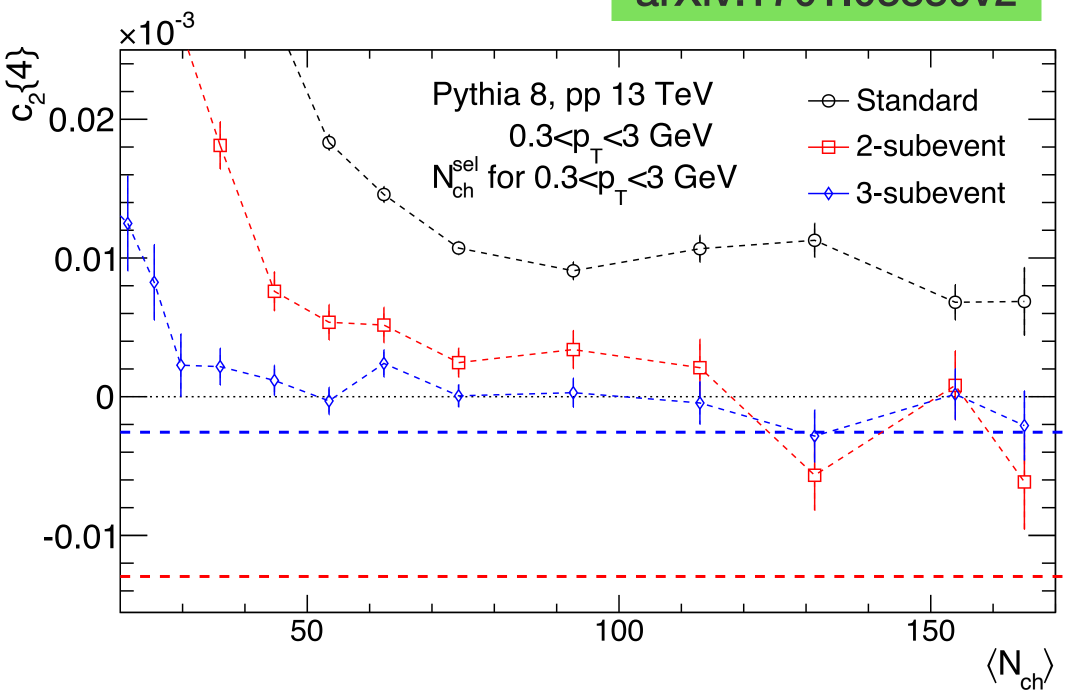
**Subevent method:** Phys. Rev. C 95 (2017) 044911

In order to further suppress few-particle correlations and to explore possible collective correlation signals, we are using subevent cumulant techniques to require rapidity gaps among the particles

- 2 subevent can reduce non-flow contribution from within the Jets
- 3 and 4 subevents can remove back to back contribution




arXiv:1701.03830v2



# Analysis method

## ❋ Q-cumulant: Phys. Rev. C 83 (2011) 044913

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

• $|Q_n|^2 = Q_n Q_n^* = \sum_{i,j=1}^{M} e^{in(\phi_i-\phi_j)} = M + \sum_{i,j}^{i\neq j} e^{in(\phi_i-\phi_j)}$ $\Rightarrow \langle 2\rangle = \frac{|Q_n|^2 - M}{M(M-1)}$

• $|Q_n|^4 = Q_n Q_n Q_n^* Q_n^* = \sum_{i,j,k,l}^{M} e^{in(\phi_i+\phi_j-\phi_k-\phi_l)}$ $\Rightarrow \langle 4\rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2Re[Q_{2n}Q_n^*Q_n^*]}{P_{M,3}} - 2\frac{2(M-2)\cdot|Q_n|^2 - M(M-3)}{P_{M,3}}$

=> All-event averaged : • $\langle\langle 2\rangle\rangle \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle = \frac{\sum_{events}(W_{(2)})_i\langle 2\rangle_i}{\sum_{events}(W_{(2)})_i}$ • $\langle\langle 4\rangle\rangle = \frac{\sum_{events}(W_{(4)})_i\langle 4\rangle_i}{\sum_{events}(W_{(4)})_i}$

$where\ W_{(2)} = M(M-1)\ ,\ W_{(4)} = M(M-1)(M-2)(M-3)$

=> 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 : • $v_n\{2\} = \sqrt{c_n\{2\}}$ • $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$

## ❋ Differential Q-cumulant:

• $\langle 2'\rangle \equiv \frac{1}{m_pM - m_q}\sum_{i=1}^{m_p}\sum_{j=1}^{M} cos[n(\psi_i - \phi_j)]$

• $\langle 4'\rangle \equiv \frac{1}{(m_pM - 3m_q)(M-1)(M-2)}\sum_{i=1}^{m_p}\sum_{j,k,l=1}^{M} cos[n(\psi_i + \phi_j - \phi_k - \phi_l)]$

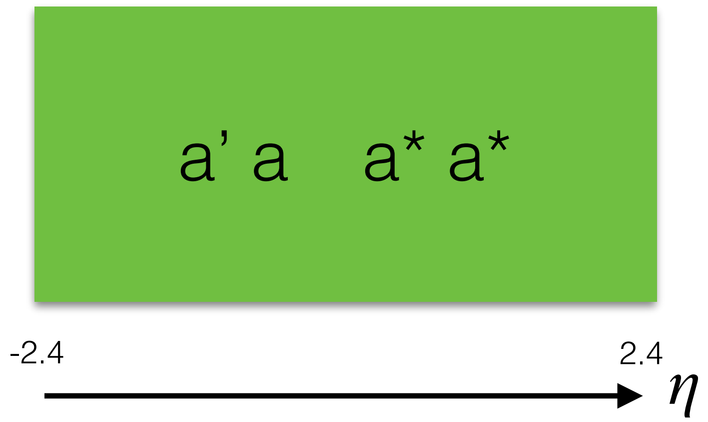
- $P_T$ range of $\phi$ ={0.3 to 3} => RFP
- $P_T$ range of $\psi$ ={small $P_T$ bins} => POI

=> Differential cumulant : $d_n\{4\} = \langle\langle 4'\rangle\rangle - 2\langle\langle 2'\rangle\rangle\cdot\langle\langle 2\rangle\rangle$

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

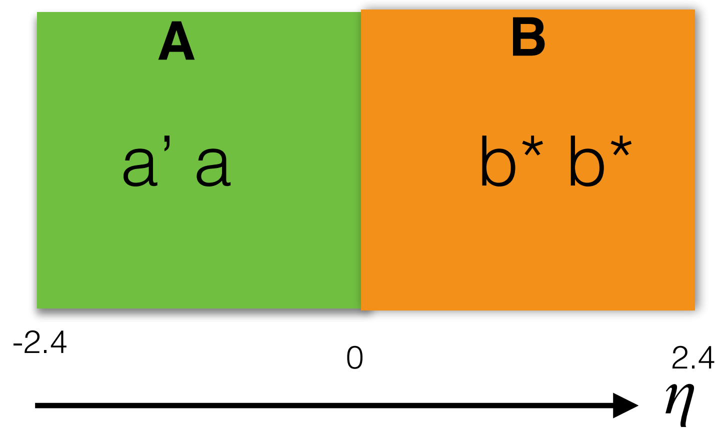
# Analysis method (continue…)

- Differential cumulant $d_2\{4\}$ calculation in standard and 2 subevent method
  - Standard (w/o subevent)

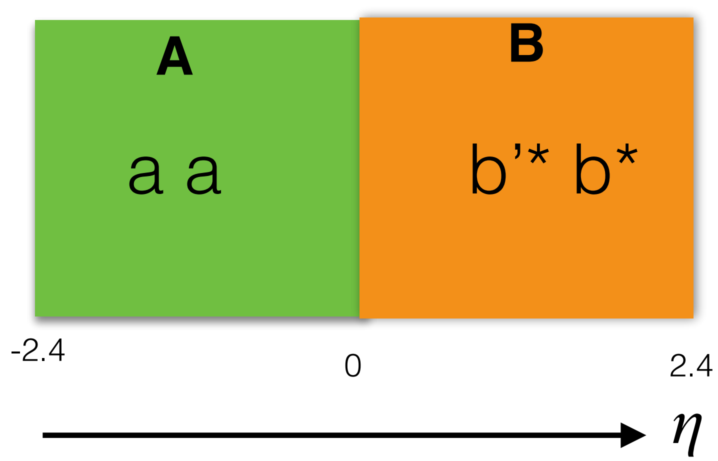



$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle \cdot \langle\langle 2 \rangle\rangle$$

  - 2 subevent



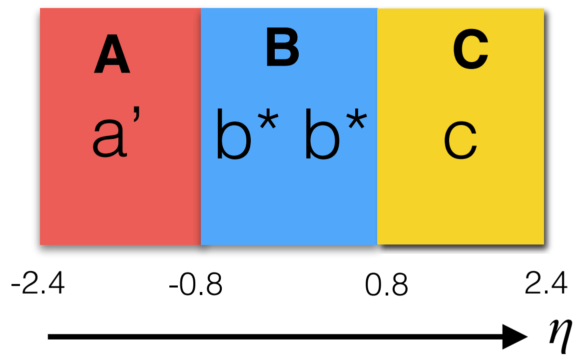

$$d_n\{4\}_{2sub} = \langle\langle 4 \rangle^{a'a|bb} \rangle - 2\langle\langle 2 \rangle^{a'|b} \rangle \cdot \langle\langle 2 \rangle^{a|b} \rangle$$




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

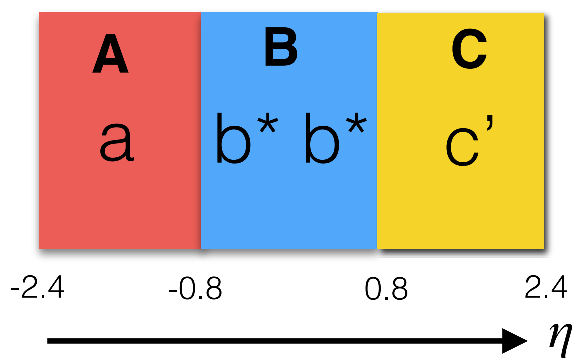
# Analysis method (continue…)

- Differential cumulant $d_2\{4\}$ calculation in 3 & 4 subevent method
  - 3 subevent



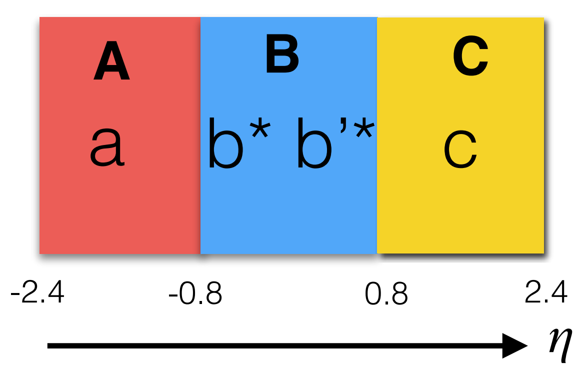

**POI : (-2.4<$\eta$<0.8)**

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




**POI : (0.8<$\eta$<2.4)**

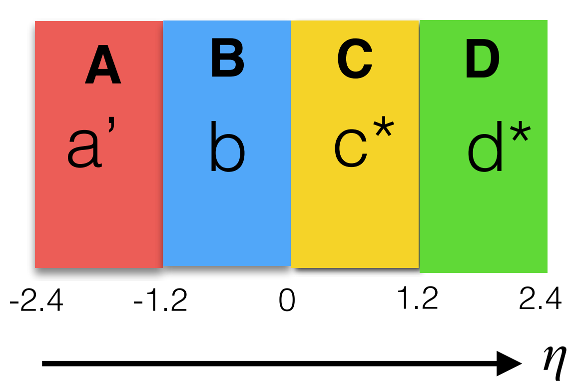
- $d_n\{4\}_{3sub} = \langle\langle 4\rangle^{a|bb|c'}\rangle - 2\langle\langle 2\rangle^{a|b}\rangle \cdot \langle\langle 2\rangle^{b|c'}\rangle$




**POI : (-0.8<$\eta$<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



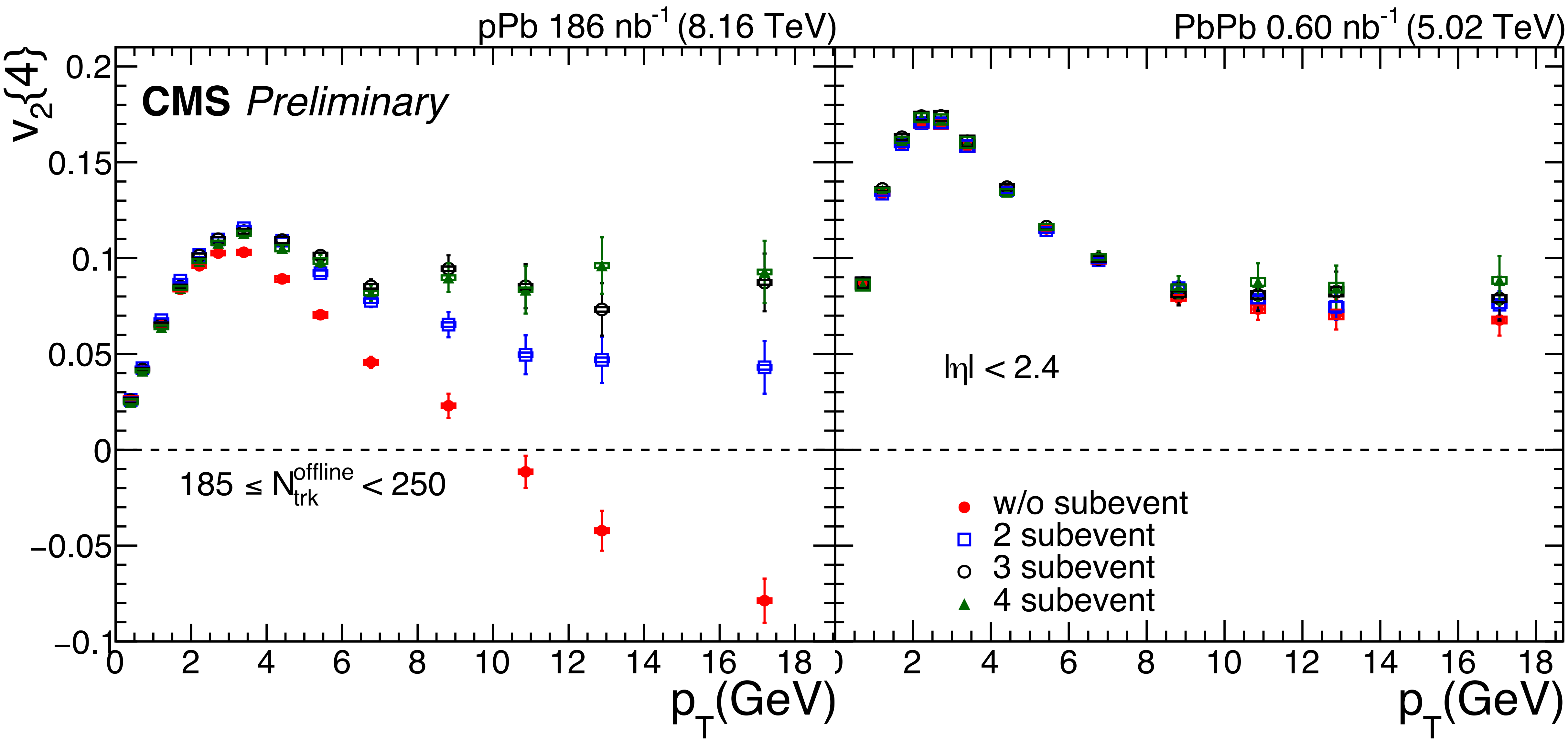

$$d_n\{4\}_{4sub} = \langle\langle 4\rangle^{a'|b|c|d}\rangle - \langle\langle 2\rangle^{a'|c}\rangle \cdot \langle\langle 2\rangle^{b|d}\rangle - \langle\langle 2\rangle^{a'|d}\rangle \cdot \langle\langle 2\rangle^{b|c}\rangle$$

# Results-I: differential $v_2$ vs. $p_T$ in pPb and PbPb

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

CMS-PAS-HIN-23-002

pPb PbPb

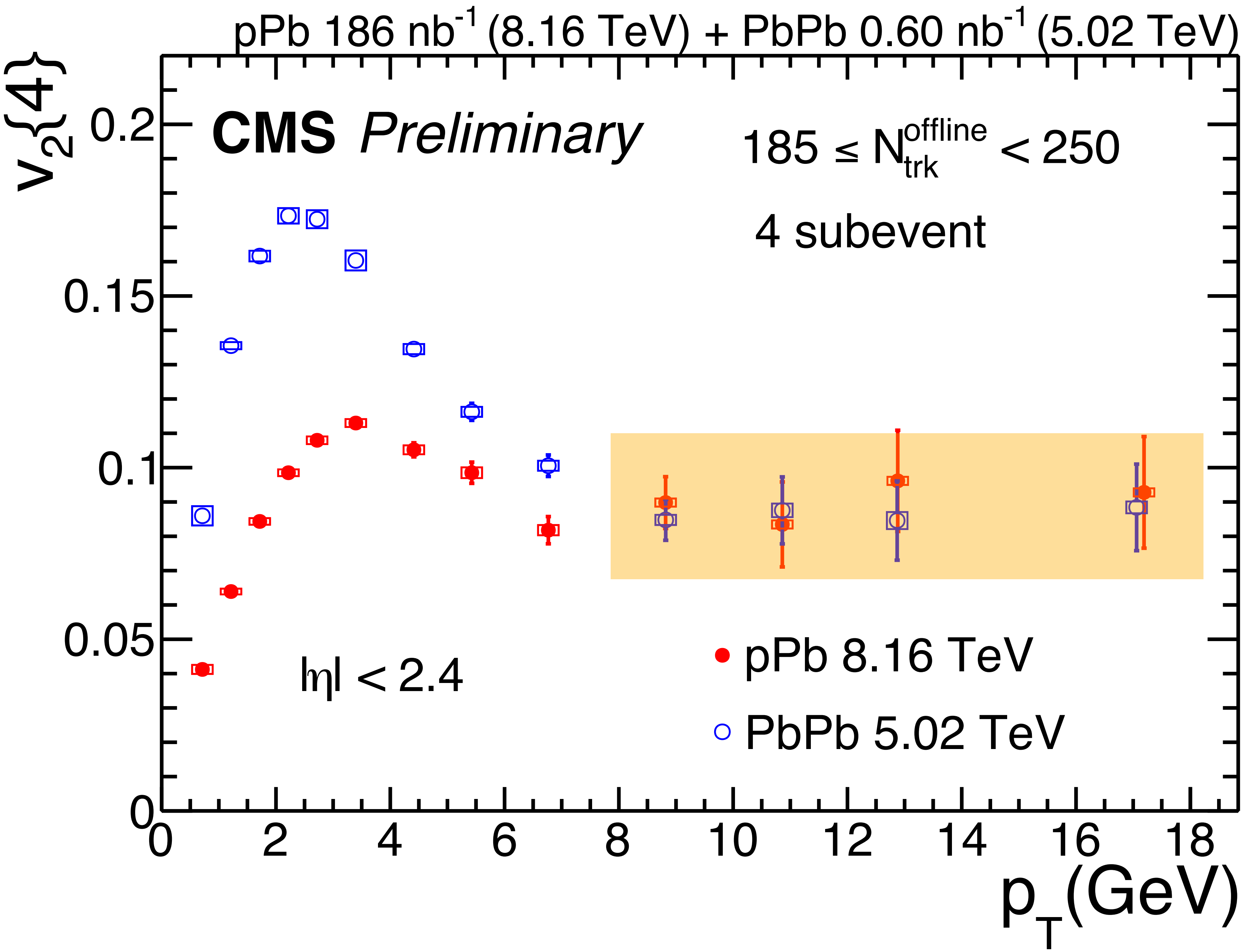



- At low $p_T$, PbPb has larger $v_2\{4\}$ than pPb
- At high $p_T$, similar magnitude and similar trend of subevent $v_2\{4\}$

# Results-I: differential $v_2$ vs. $p_T$ in pPb and PbPb

- 4 subevent $v_2\{4\}$ in $185 \leq (N_{trk}^{offline}) < 250$

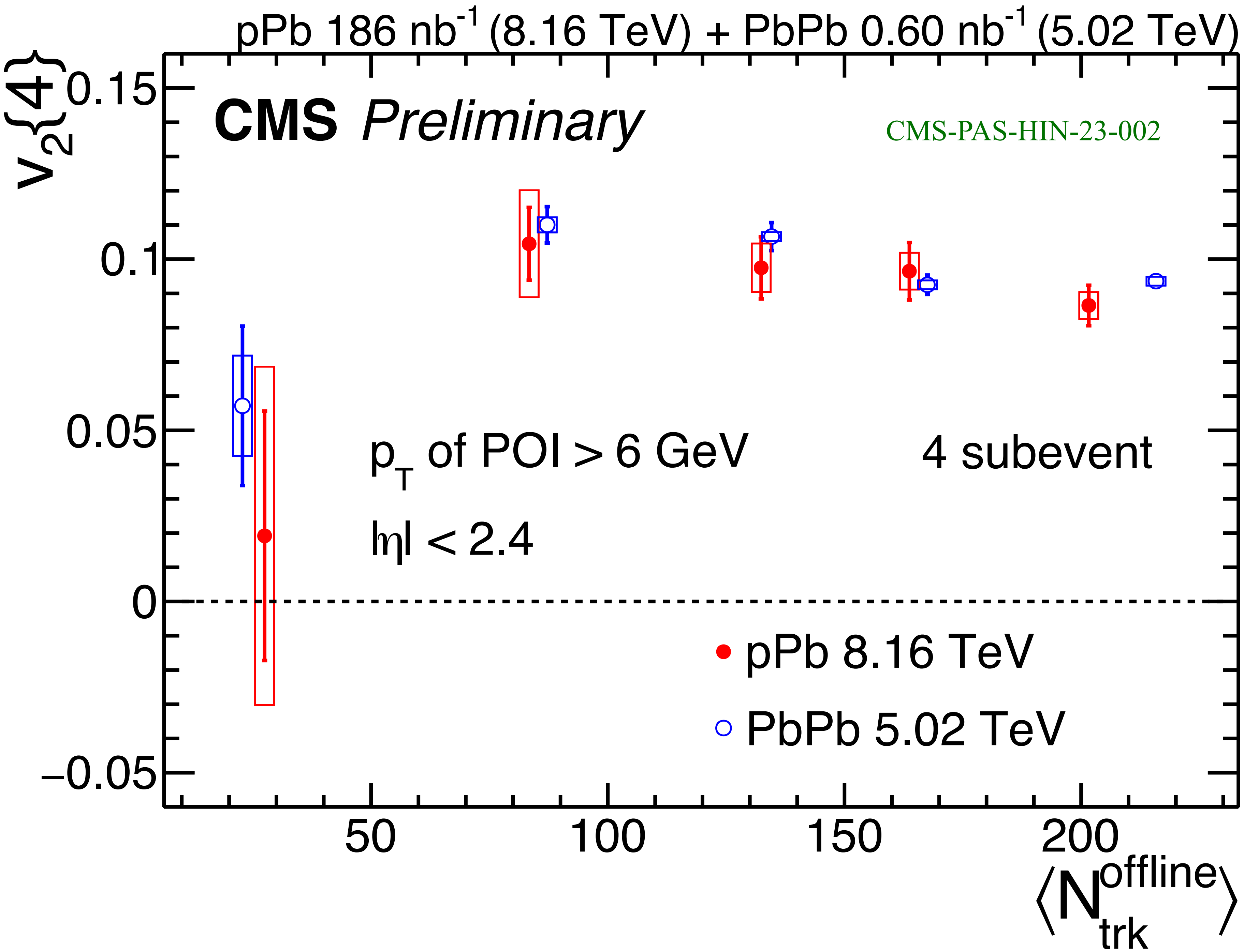
CMS-PAS-HIN-23-002




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

# Results-II: $v_2$ vs. multiplicity in pPb and PbPb

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

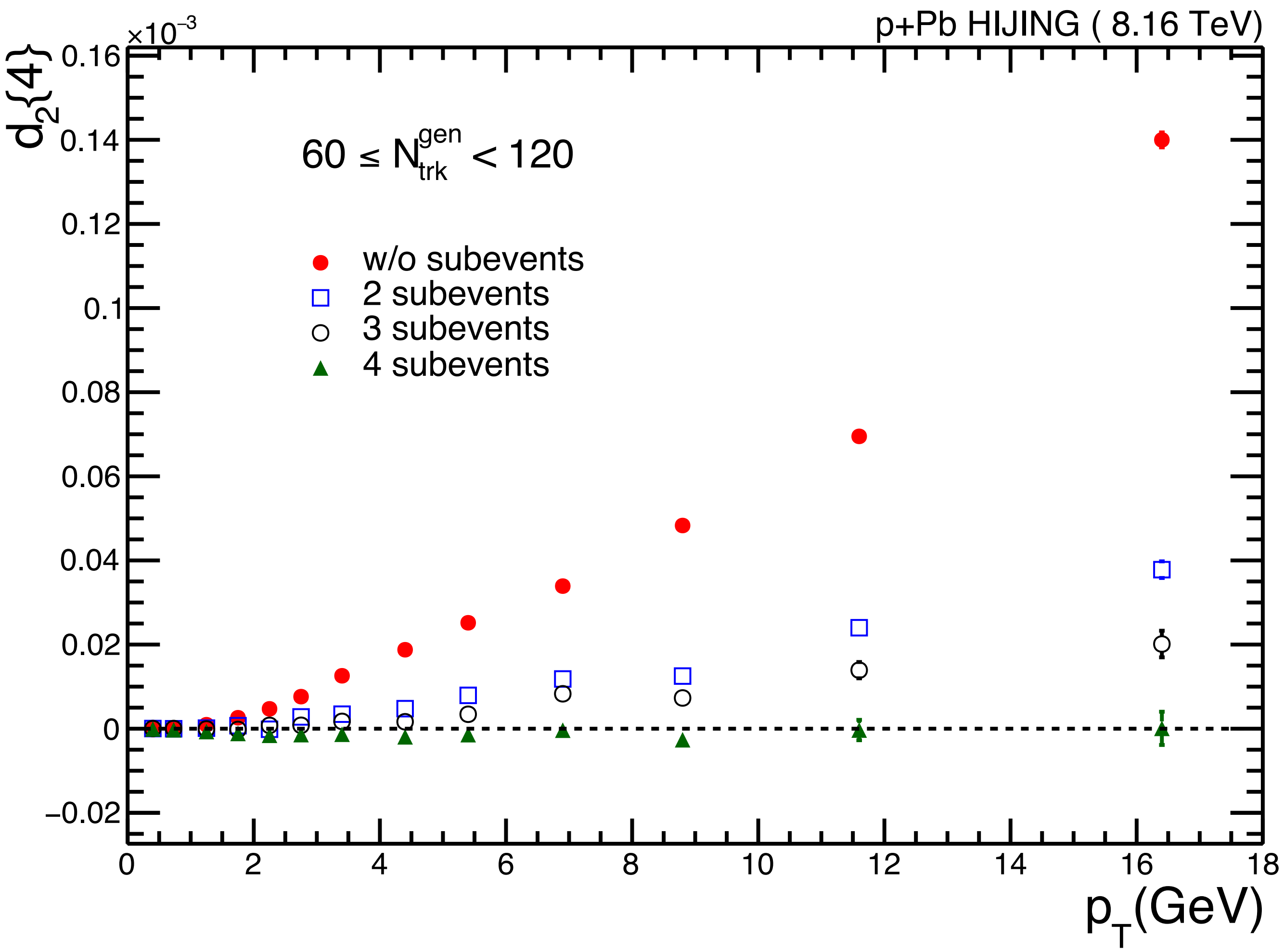



- Similar magnitude and similar trend for both PbPb and pPb when $p_T^{POI} > 6$ GeV across all multiplicity bins

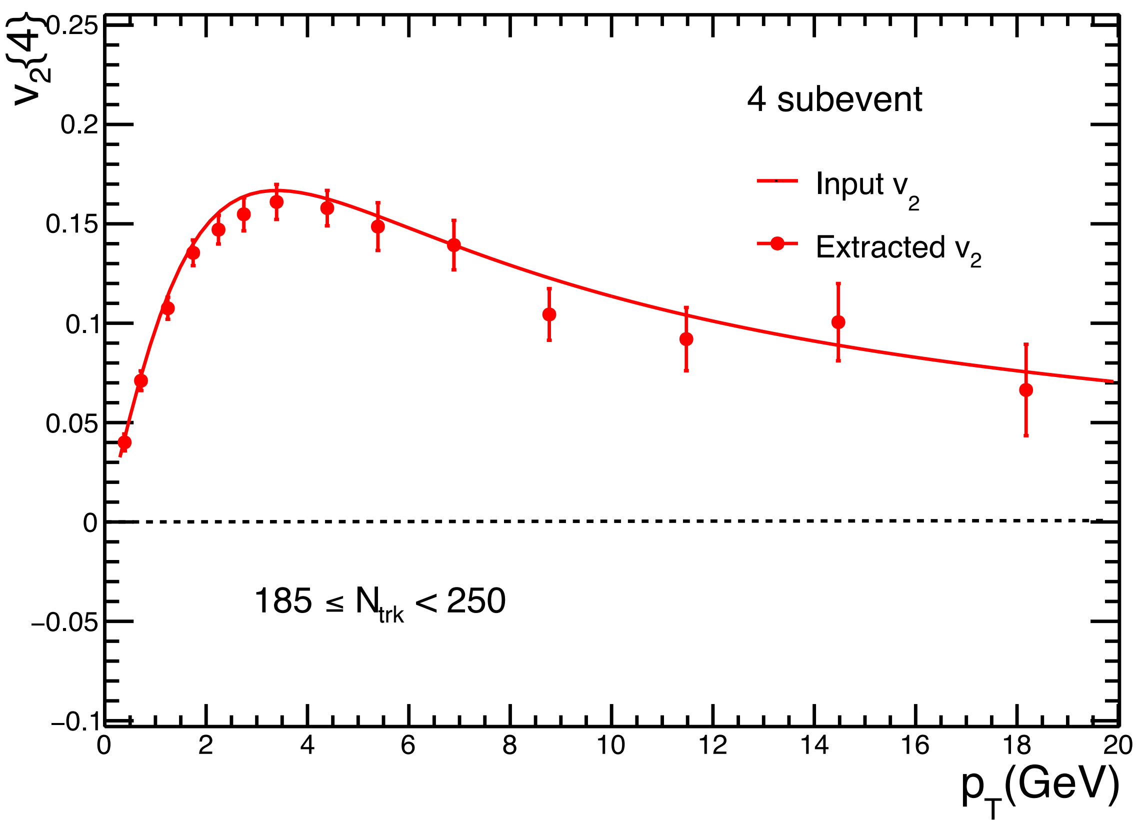
# Results-III: method robustness check

❋ $d_2\{4\}$ in HIJING in $60 \leq \langle N_{trk}^{offline} \rangle < 120$

CMS-PAS-HIN-23-002




Toy Model test




- HIJING lacks collectivity => used to cross check non-flow subtraction of subevent cumulant
- Toy model => successfully recover the input v2 using 4-subevent

# Summary/Conclusion

❖ The results of $v_2\{4\}$ with subevents for pPb & PbPb collisions at $\sqrt{S_{NN}}$ = 8.16 TeV & $\sqrt{S_{NN}}$ = 5.02 TeV, resp.

❖ This analysis investigates an extended momentum space for the first time in small systems, aiming to provide insights into the potential indications of high-$p_T$ parton energy dissipation

❖ Significant positive value for $v_2\{4\}$ at high-$p_T$ in pPb with subagent to remove non-flow

❖ A striking similarity in high multiplicity pPb and peripheral PbPb collisions → ***could be a similar mechanism***

❖ These results provide new information on the interaction of high-$p_T$ partons with the medium in small collision systems

CMS-PAS-HIN-23-002