Recent Results from CMS HIN

Sayan Chatterjee

1st conference on Physics in Hadronic and Nuclear Collisions - PHANC'25

27th – 30th March 2025

Indian Institute Of Technology, Madras

CMS collaboration, CERN

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(IIT Madras contributions)

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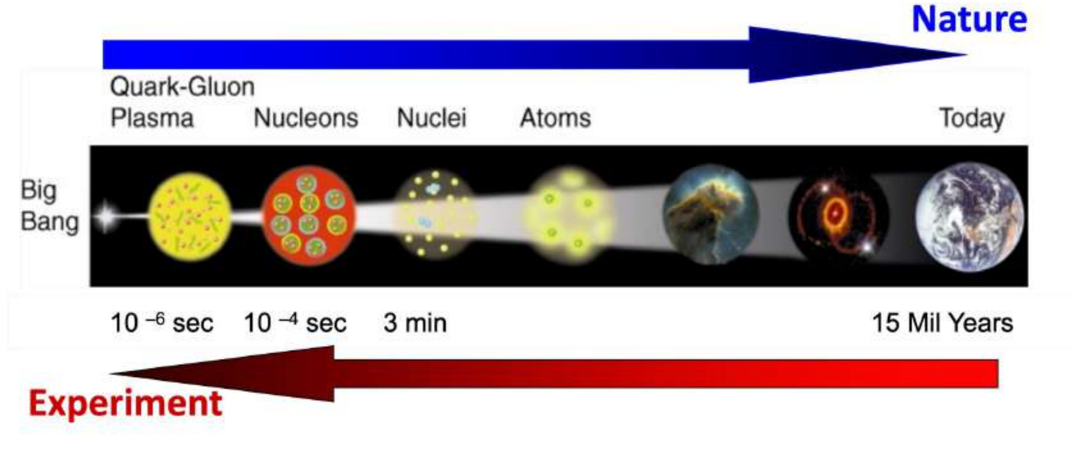
Why heavy ions ?

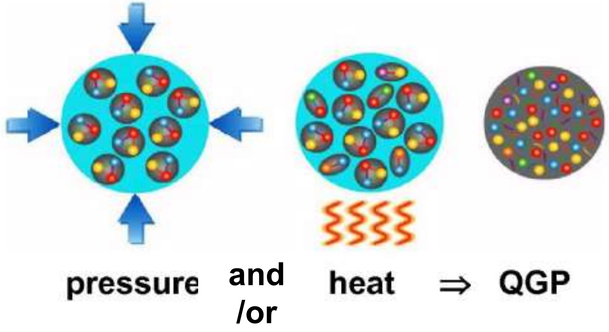
- Heavy ion interactions represent by far the most complex collision system studied in particle physics lab around the world.

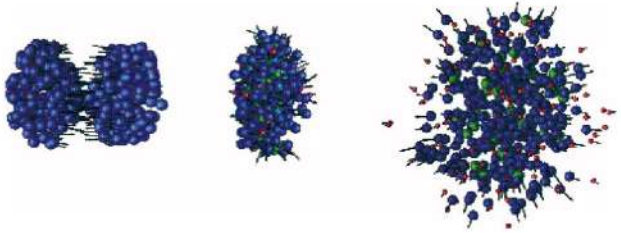
- **So why are people attracted to the study of such a complex system ?**

Heavy ion collision and QGP

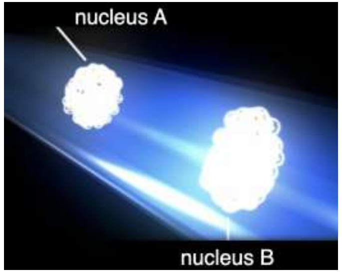
- **Because they can offer an unique way to understand:**
  - The nature of confinement/deconfinement
  - Expansion of the universe after the big bang - origin of our today's world





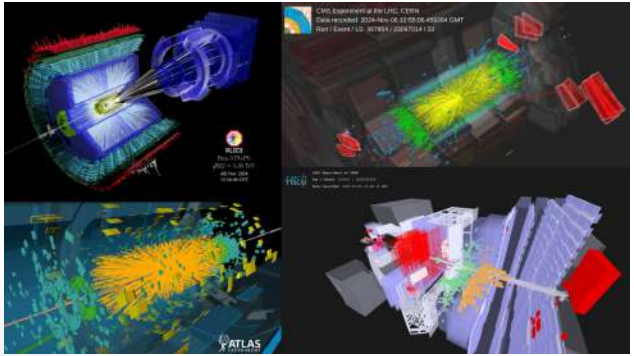


Some of the questions accessible through this talk



Initial State

Final State



What are the properties of the produced medium?

- Does the created medium depend on the structure or shape of the colliding nuclei? Is it thermalized?

- How the hard probes like jet, heavy flavour interact with the medium?

- How are the final state particles correlated?

- Is formation of QGP droplet possible in small colliding systems?

Understanding medium properties

Understanding medium properties

1. Soft probes

Understanding medium properties

1. Soft probes

Collectivity in XeXe & PbPb

Understanding medium properties

Collectivity in XeXe & PbPb

Understanding medium properties

Collectivity in XeXe & PbPb

Jet-medium interaction in PbPb

Understanding medium properties

Collectivity in XeXe & PbPb

Jet-medium interaction in PbPb

Heavy flavour flow in PbPb

Understanding medium properties

Collectivity in XeXe & PbPb

Jet-medium interaction in PbPb

Heavy flavour flow in PbPb

Understanding medium properties

Collectivity in XeXe & PbPb

Jet-medium interaction in PbPb

Heavy flavour flow in PbPb

Collectivity at high-p_T pPb

Understanding medium properties

Collectivity in XeXe & PbPb

Starters

Jet-medium interaction in PbPb

Heavy flavour flow in PbPb

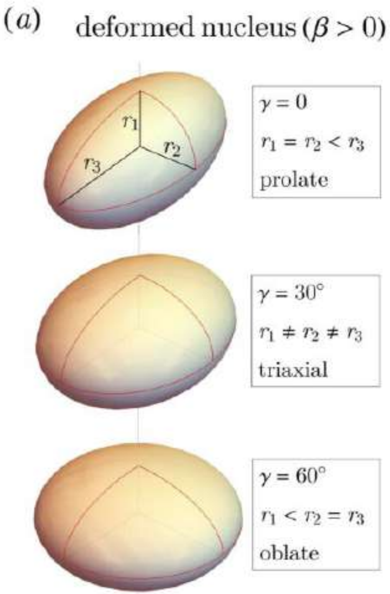
Main course

Collectivity at high-p_T pPb

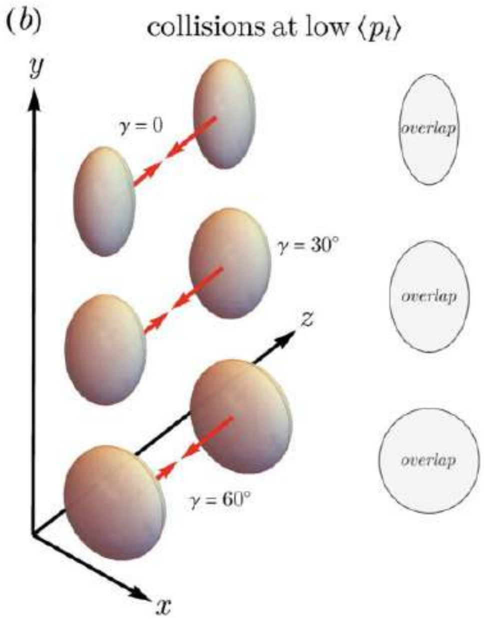
Dessert

Let the feast begin

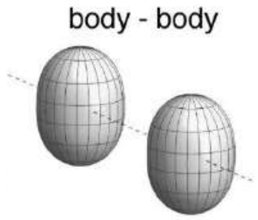
Menu I



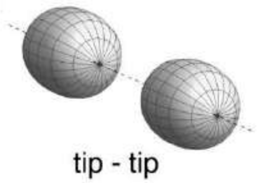
Initial state position to final state momentum anisotropy in XeXe and PbPb collisions



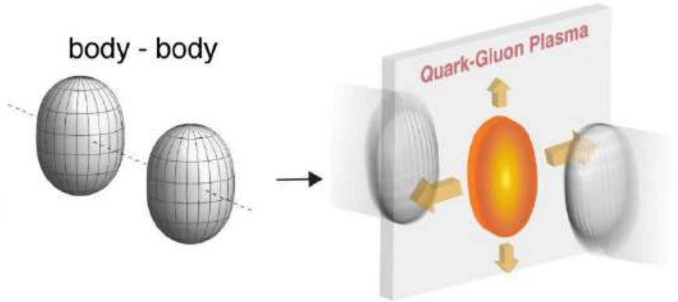
Initial state → Final state (Xe + Xe)



Change in size and initial collision geometry :
change in :

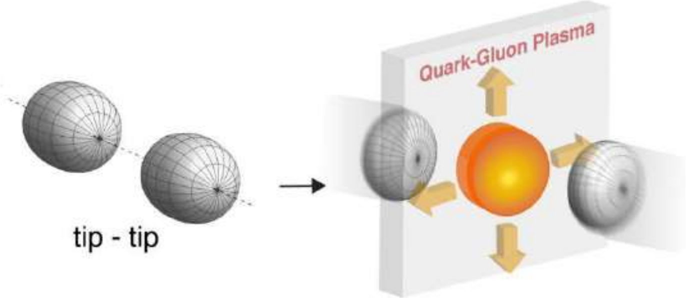


Initial state → Final state (Xe + Xe)

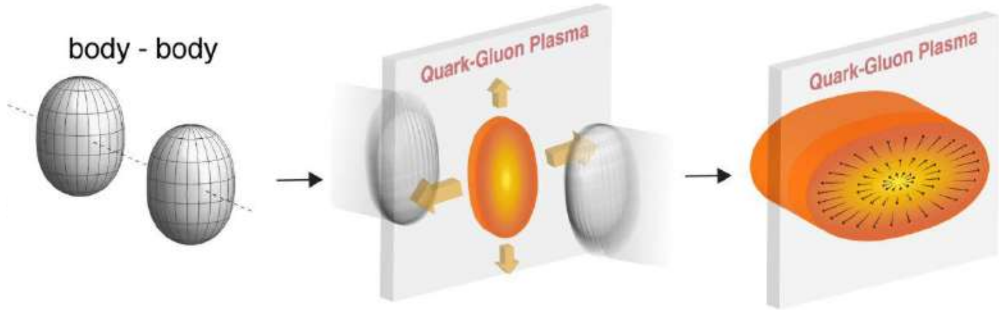


Change in size and initial collision geometry : change in :

- Nuclear overlap

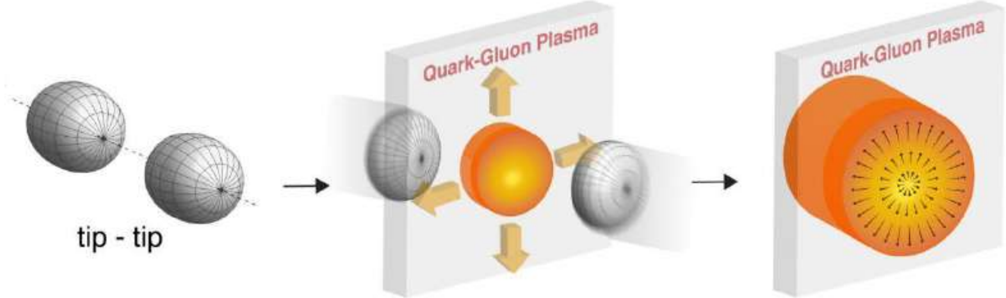


Initial state → Final state (Xe + Xe)

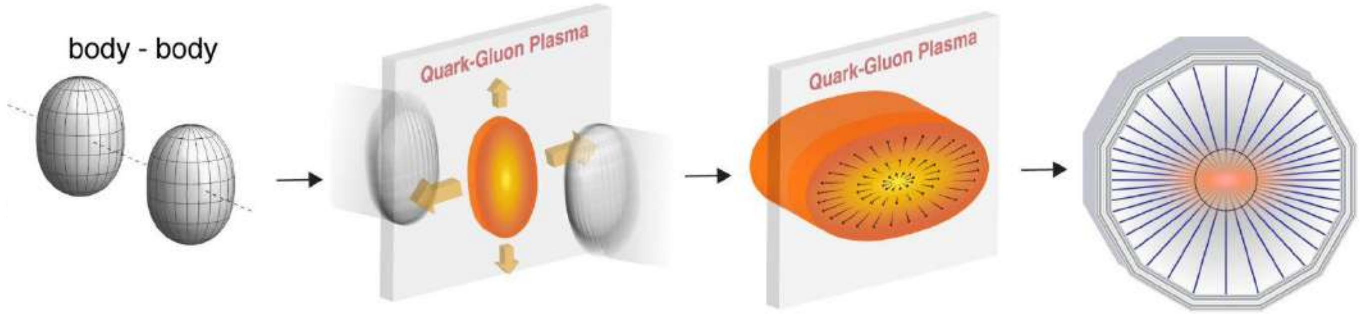


Change in size and initial collision geometry :
change in :

- Nuclear overlap
- Pressure gradient & Number of nucleonic interactions

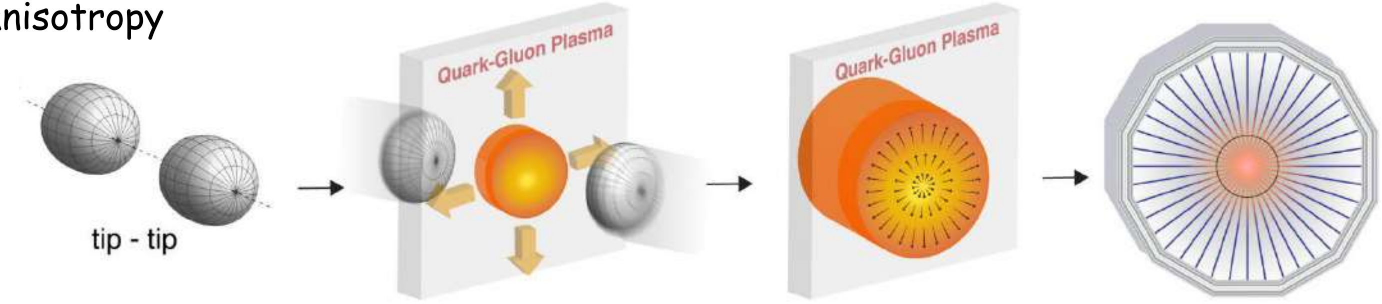


Initial state → Final state (Xe + Xe)

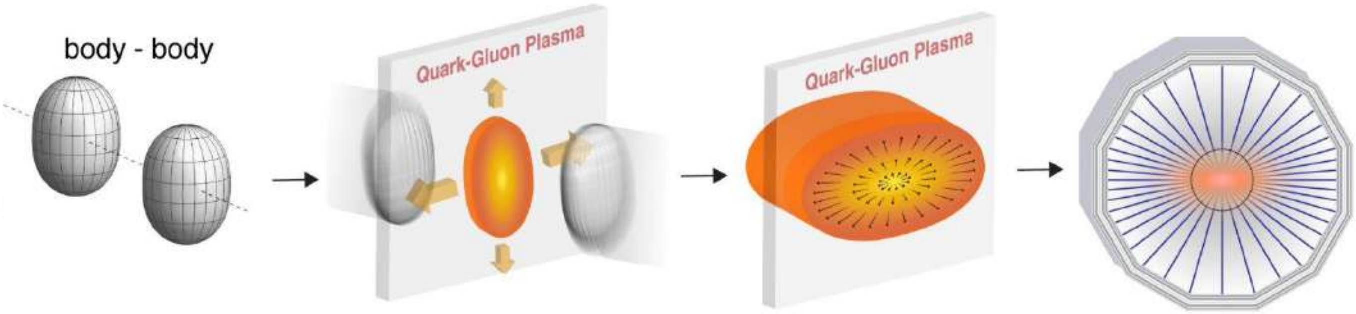


Change in size and initial collision geometry :
change in :

- Nuclear overlap
- Pressure gradient & Number of nucleonic interactions
- Number of particles produced → Momentum anisotropy



Initial state → Final state (Xe + Xe)

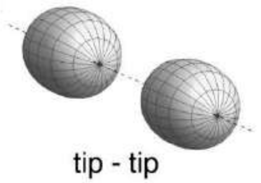


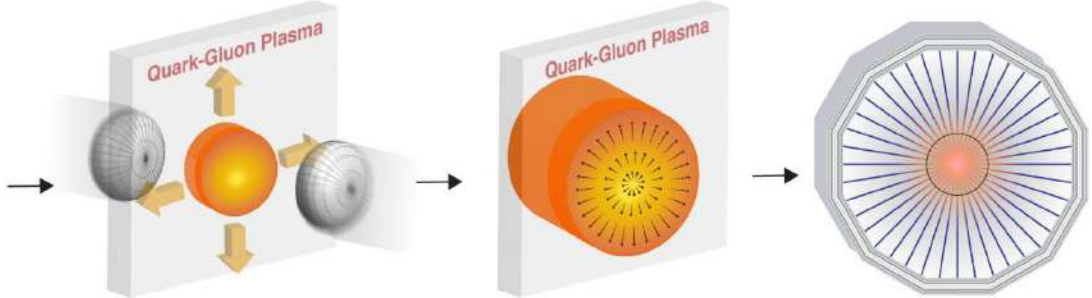
Change in size and initial collision geometry :
change in :

- Nuclear overlap
- Pressure gradient & Number of nucleonic interactions
- Number of particles produced → Momentum anisotropy

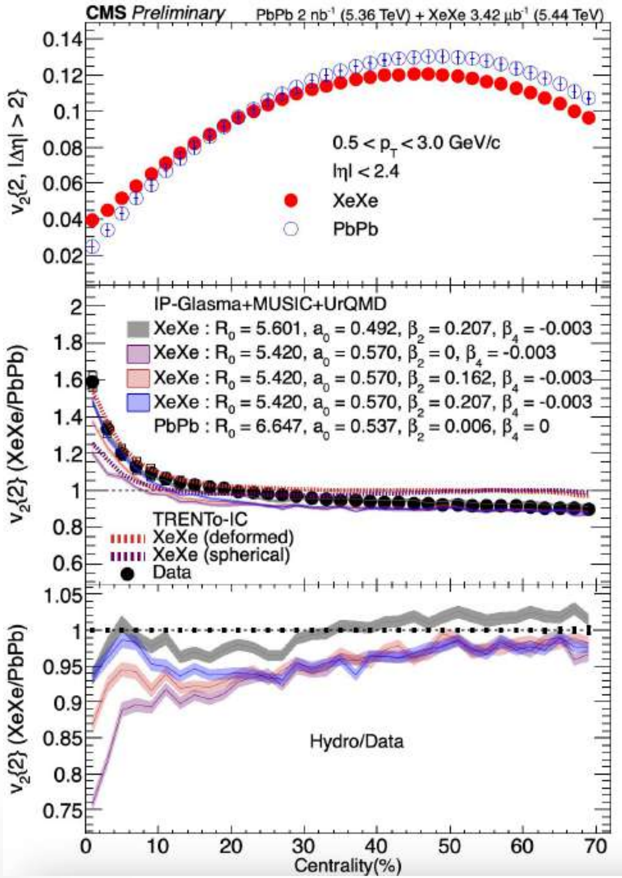
Comparison between XeXe and PbPb :

- Nuclear deformation effect
- System size effect





$v_2\{2, |\Delta\eta| > 2\}$ vs Centrality



- $v_2\{2\}$(XeXe) > $v_2\{2\}$(PbPb) till ~20% centrality
  - More elliptic flow fluctuations [https://arxiv.org/pdf/1711.08499]
- **Hydrodynamic predictions** by IP-Glasma+MUSIC+UrQMD for $v_2\{2\}$(XeXe/PbPb): closest match with parameter set R_0 = 5.601 fm, a_0 = 0.492 fm, β_2 = 0.207, β_4 = -0.003

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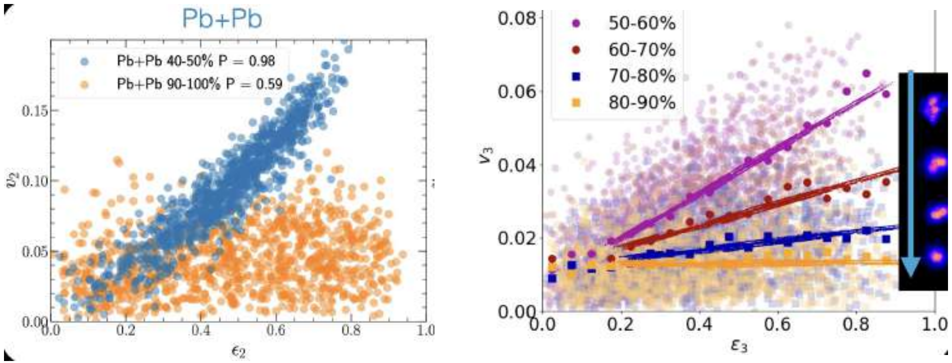
Probing the Initial State through Higher Moments

- Naive expectation :
  - $v_n \propto \varepsilon_n$ for n = 2,3 [Phys. Rev. C **62**, 054909]
- Reality :

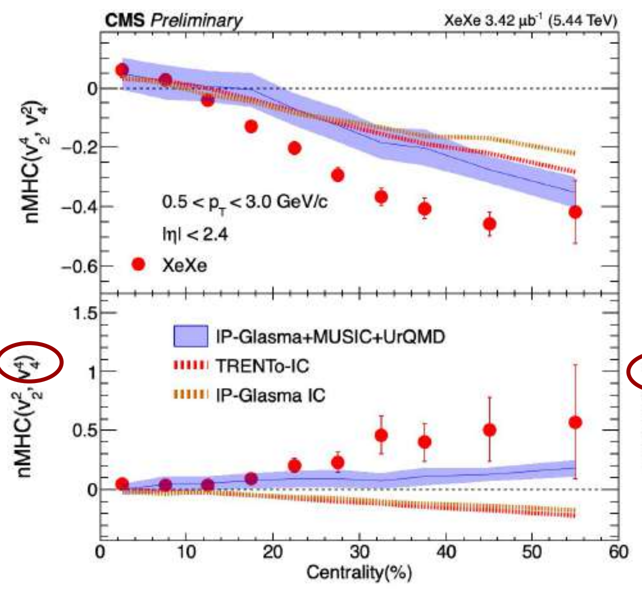
Link

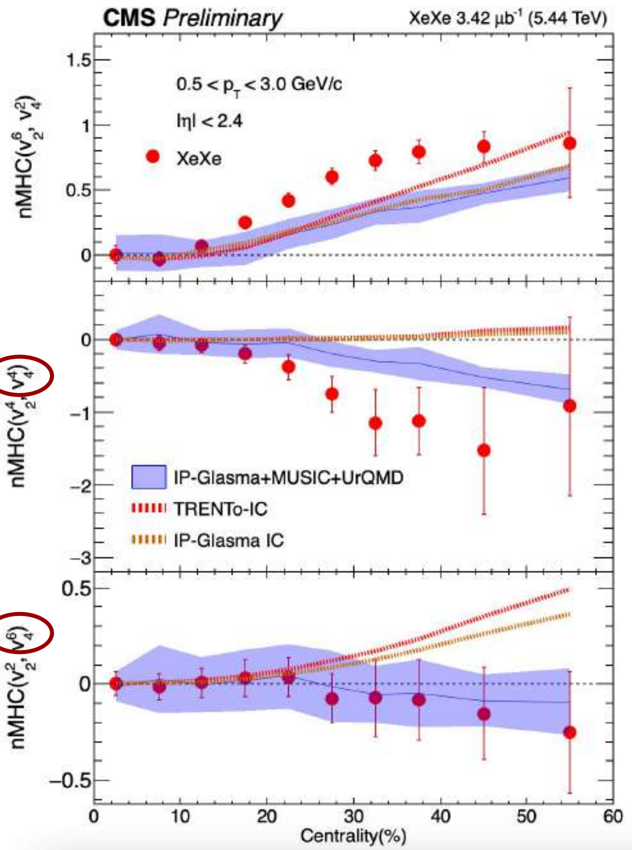


- Non-linear response (v_2, v_3) from semi-peripheral collisions
- n > 3 : Non-linear response observed right from semi-central collisions

- **Higher-order moments of $\langle v_n^k \rangle$** (n = 4; k = 2, 4, 6) : **probe increasing non-linearity** [Phys. Rev. C **92**, 034903]
- For this we used mixed harmonic cumulants which correlate different moments of v_2 and v_4
- **Through this we can Study the effects of different initial-state model conditions**

Initial vs final-state predictions for nMHC(v_2^k, v_4^l)





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$v_2 \approx a\varepsilon_2$, $v_3 \approx b\varepsilon_3$
$v_4 \approx c\varepsilon_4 + d(\varepsilon_2)^2$

- **Higher-order moments of v_4^k** (k=4,6) : **completely different results from IC models**
- **Increasing non-linearity of v_4 with increase in k,** moving from central to peripheral regions
- *Goes way beyond the naive expectations of "v_2 and v_4 being positively correlated", as suggested by just NSC(2,4)*

Menu I → Outcome

- First systematic study of 2-, 4-, 6- and 8-particle mixed harmonic cumulants in XeXe and PbPb collisions at 5.44 TeV and 5.36 TeV respectively

- Best match of XeXe using IP-Glasma+MUSIC+UrQMD hydrodynamic prediction with parameter set :
    - **(R_0 = 5.601 fm, a_0 = 0.492 fm, β_2 = 0.207, β_4 = -0.003)**

- Study of higher-order mixed harmonic cumulants :
    - Harmonics involving higher-order moments of $\mathbf{v_4}$ - has non-linear effects .
    - Responsible to different predictions as compared to initial-state models

- XeXe - SC(2,3,4), SC(2,3,5), SC(3,4,5), SC(2,4,6), nMHC(v_2^k, v_3^l), nMHC(v_2^k, v_4^l)

- PbPb - nMHC(v_2^k, v_4^l)

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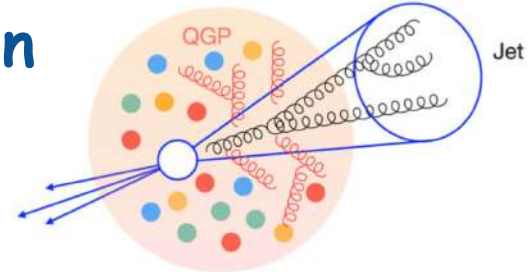
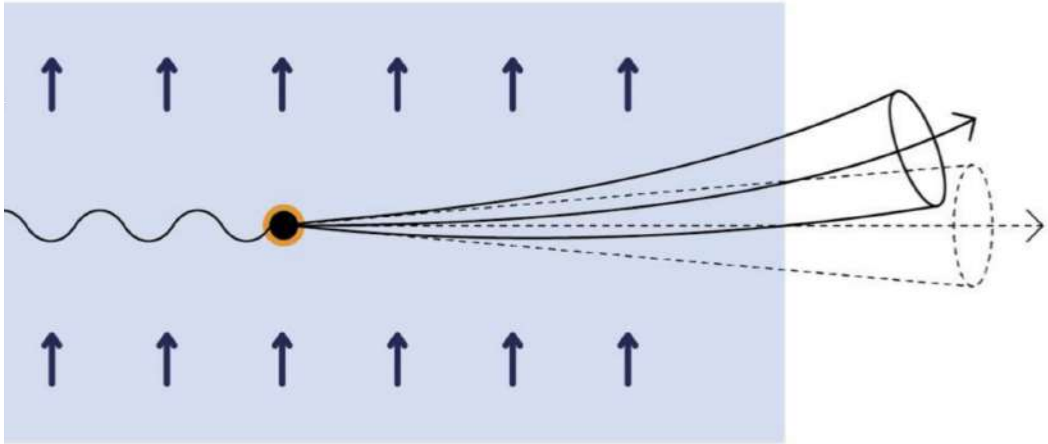
Menu II

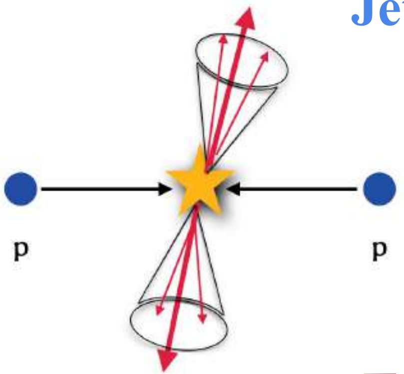
Jet transport in QGP and jet-medium interaction

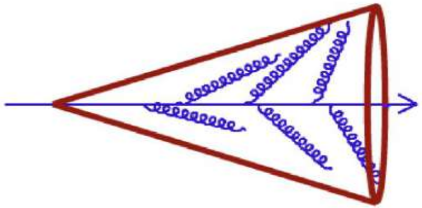




Jet-like correlations in heavy ion collision

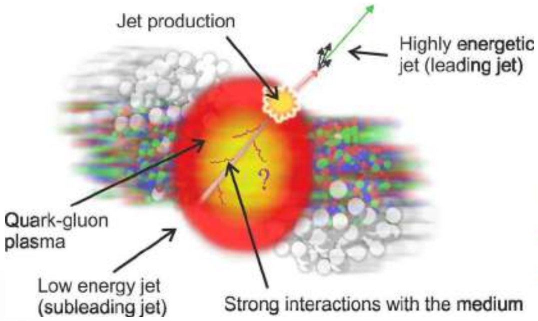
Jet shower in vacuum

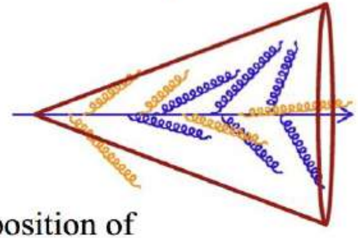




Evolution of highly virtual parton via gluon radiation

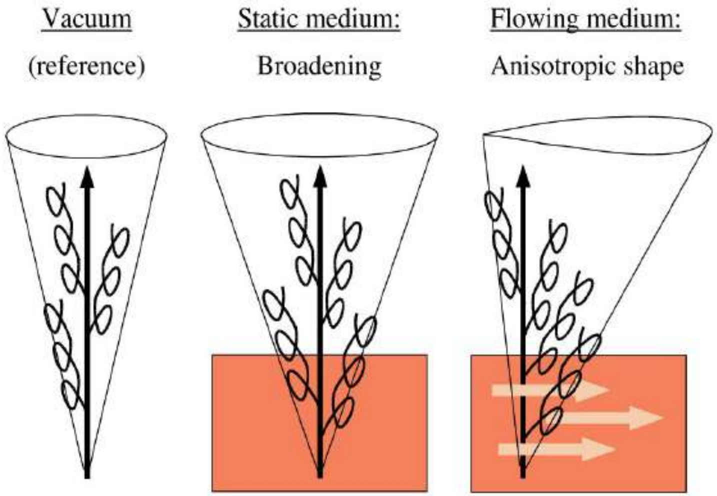
Jet shower in medium



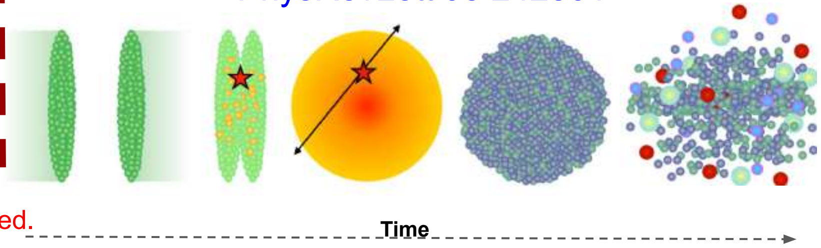


Superposition of
- vacuum shower
- medium-induced gluon emission

Jet shape in flowing medium



PhysRevLett.93.242301



These process happen simultaneously and interfere. Angle ordering is modified or destroyed.

Analysis method: Near-side width

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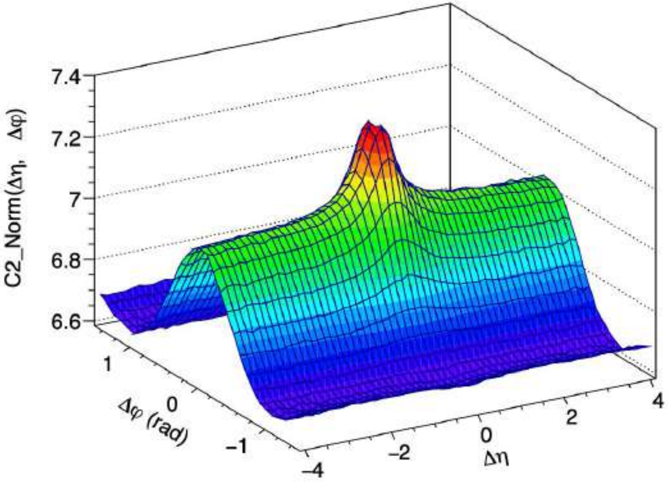
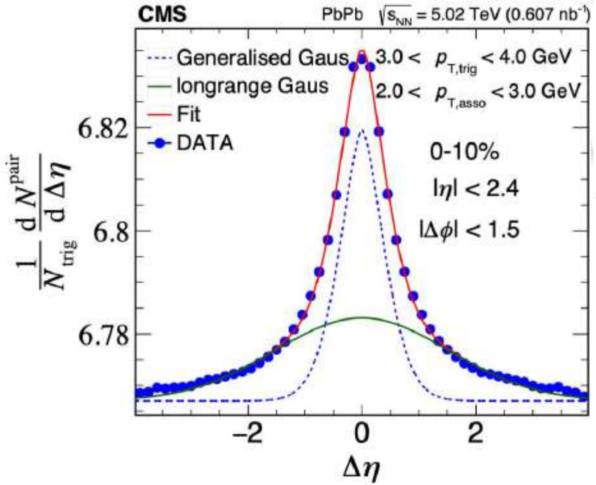
$$G_{\gamma_x, w_x}(x) = \frac{\gamma_x}{2 w_x \Gamma(1/\gamma_x)} \exp\left[-\left(\frac{|x|}{w_x}\right)^{\gamma_x}\right]$$

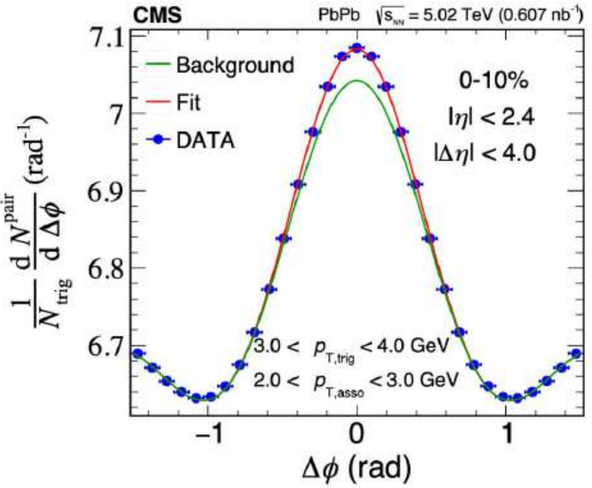
$$F(\Delta\phi) = c_1\left[1 + \sum_{n=2}^{4} 2V_{n\Delta}\cos(n\Delta\phi)\right] + c_2\, G_{\gamma_{\Delta\phi},\omega_{\Delta\phi}}$$

Width, $\sigma_x = \sqrt{\frac{\omega_x^2\,\Gamma(3/\gamma_x)}{\Gamma(1/\gamma_x)}}$

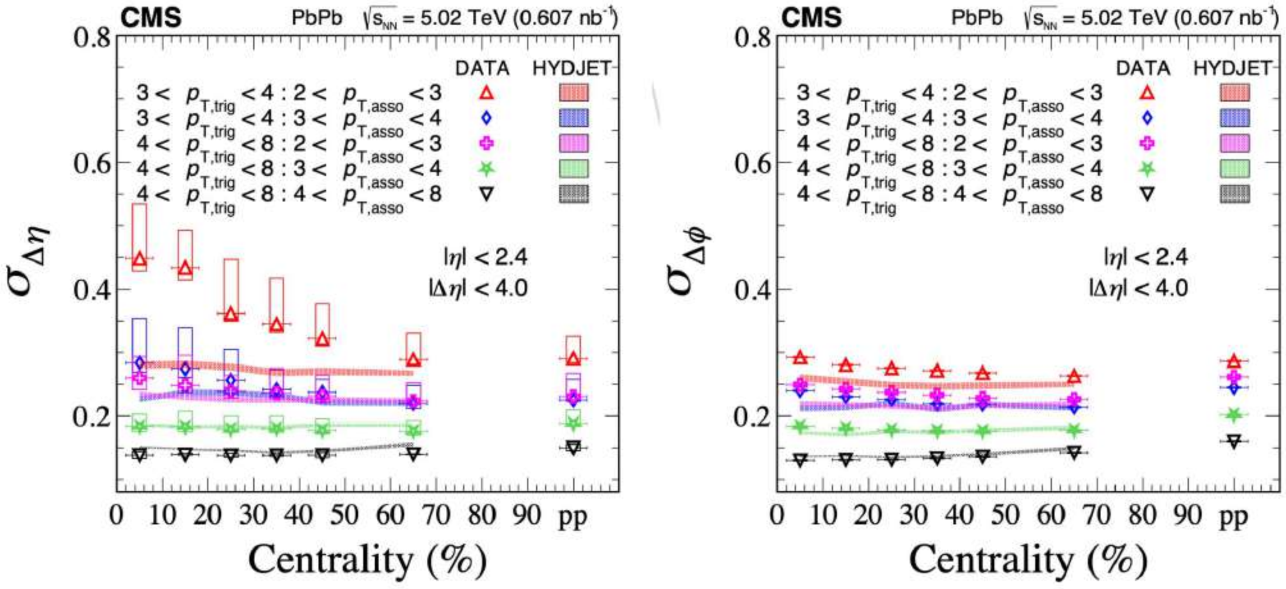
$$F(\Delta\eta) = c_1 + c_2\, G_{\gamma_{1,\Delta\eta},\omega_{1,\Delta\eta}} + c_3\, G_{\gamma_{2,\Delta\eta},\omega_{2,\Delta\eta}}$$







Results: Width of the near-side peak ($\sigma_{\Delta\eta}$ & $\sigma_{\Delta\varphi}$)



- The near-side peak has a similar shape in pp and PbPb peripheral (50-80%) collisions, where it is approximately symmetric in Δφ and Δη.
- This symmetric trend vanishes in longitudinal widths (Δη) towards central collisions.
- The centrality dependent longitudinal broadening is mostly effective in low-p_T regions.
- Whereas, Hydrojet behaves almost independently with centrality for both longitudinal (Δη) and transverse (Δφ) directions.

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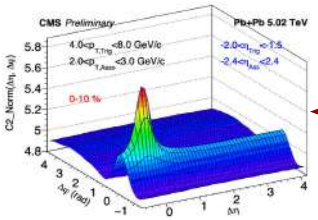
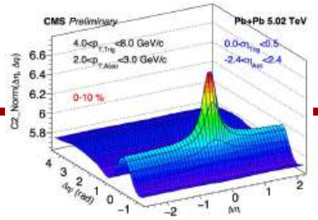
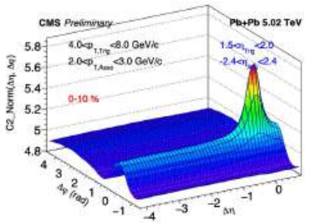
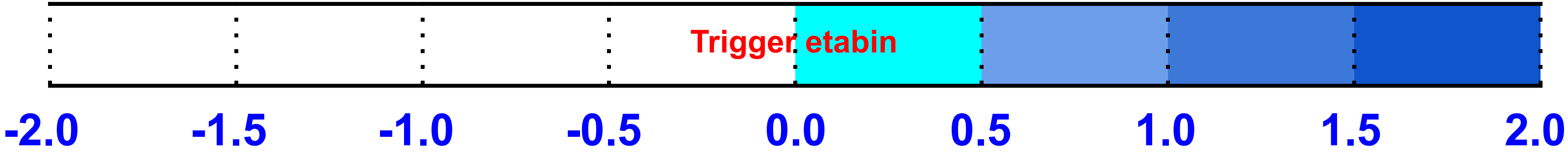
Boost invariance study of near-side jet peak

- Mid-rapidity refers to the region around zero-rapidity, notable for its observed boost invariance.
- Whether boost invariance also applies in forward rapidity regions ??









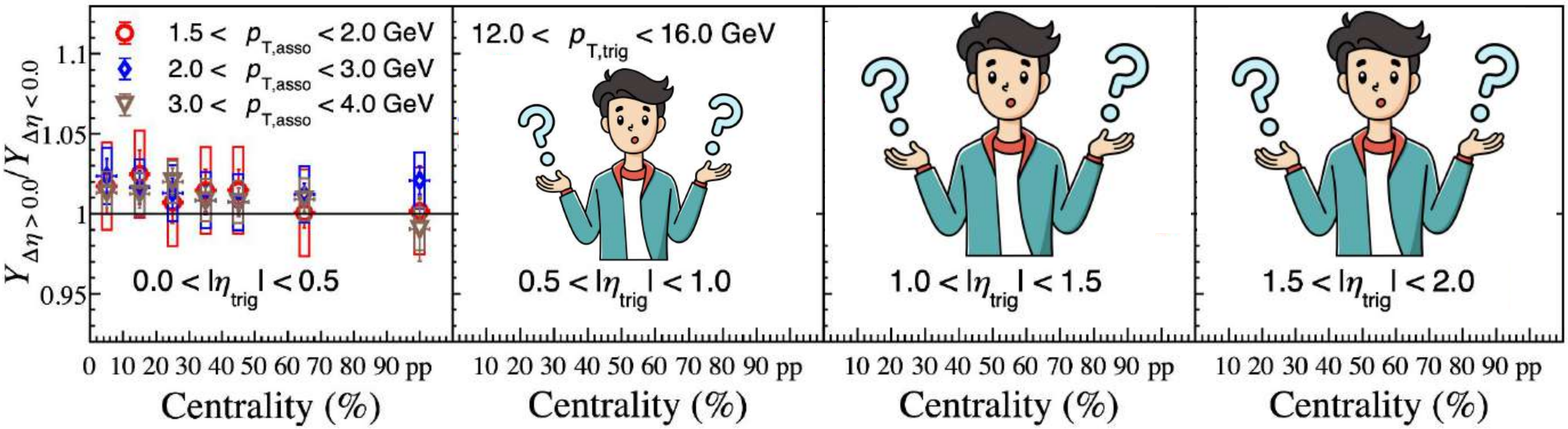
Forward rapidity boost invariant ? ?

Mid-rapidity boost invariant (Symmetric system)

$-2.4 < \eta_{asso} < 2.4$

Forward rapidity boost invariant ? ?

Result: Boost invariance study of near-side peak



❖ At mid η_{trig}, the associated yield ratio is consistent with one and almost independent of $p_{T,asso}$ within their uncertainties.

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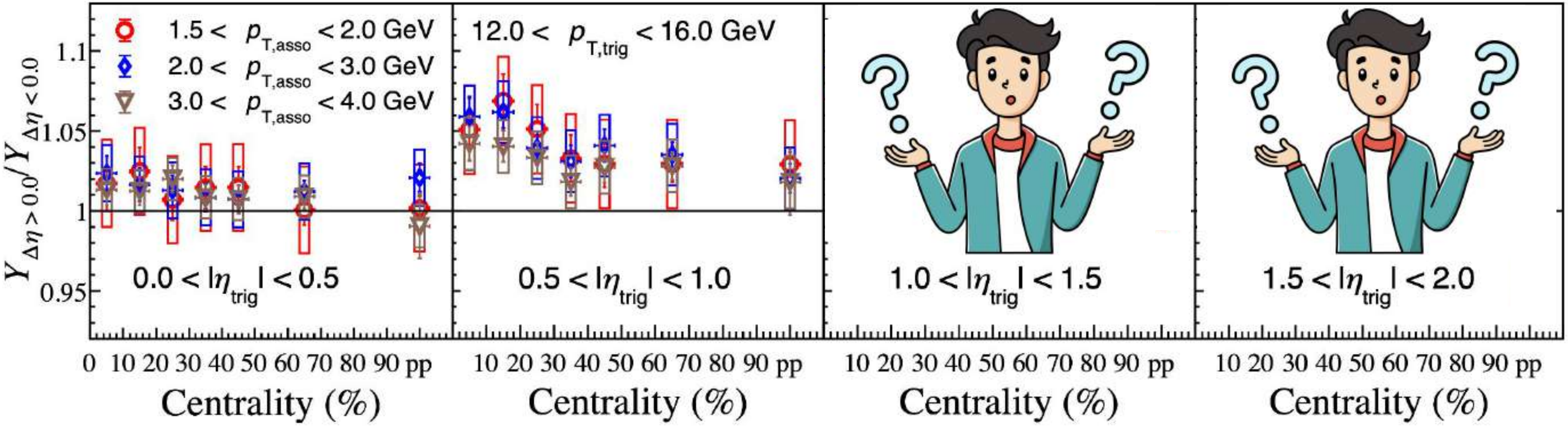
Result: Boost invariance study of near-side peak



❖ At mid η_{trig}, the associated yield ratio is consistent with one and almost independent of $p_{T,asso}$ within their uncertainties.

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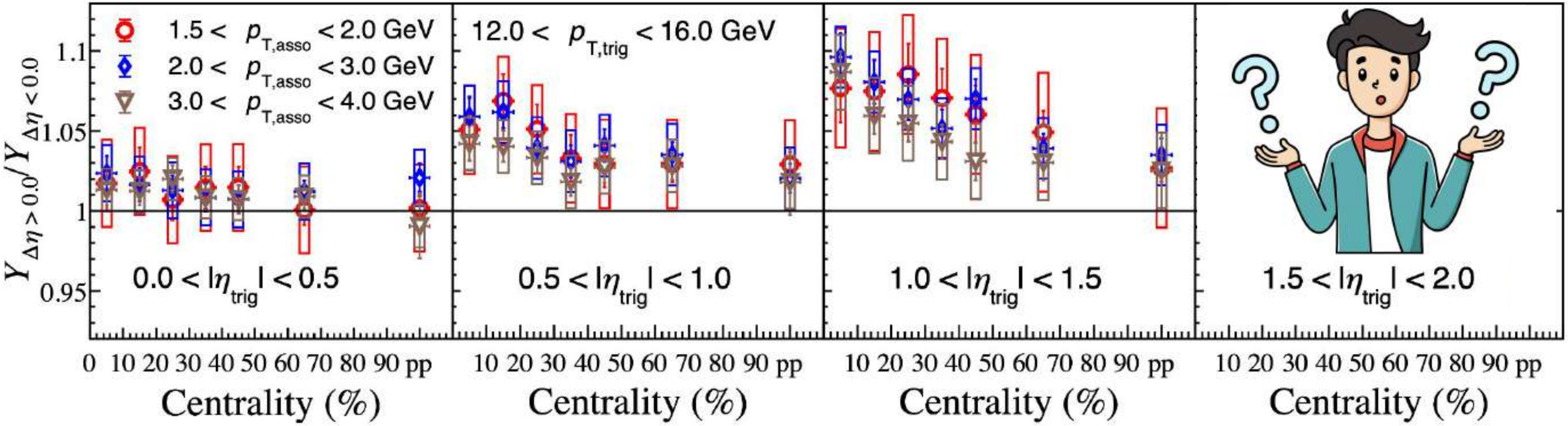
Result: Boost invariance study of near-side peak



- ❖ At mid η_{trig}, the associated yield ratio is consistent with one and almost independent of $p_{T,asso}$ within their uncertainties.
- ❖ A significant increase in the associated yield ratio is observed when we move toward forward η_{trig}.

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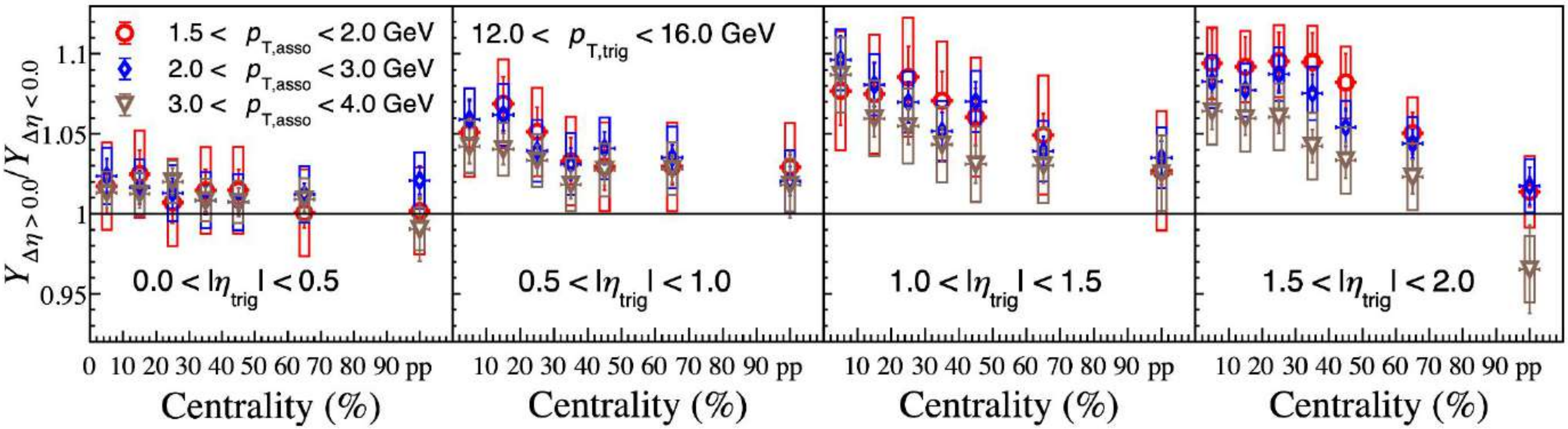
Result: Boost invariance study of near-side peak



- At mid η_{trig}, the associated yield ratio is consistent with one and almost independent of $p_{T,asso}$ within their uncertainties.
- A significant increase in the associated yield ratio is observed when we move toward forward η_{trig}.
- However, at high η_{trig} , a significant dependence of $p_{T,asso}$ is observed across centrality, where asymmetry increases towards central region.

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Menu II - Outcome

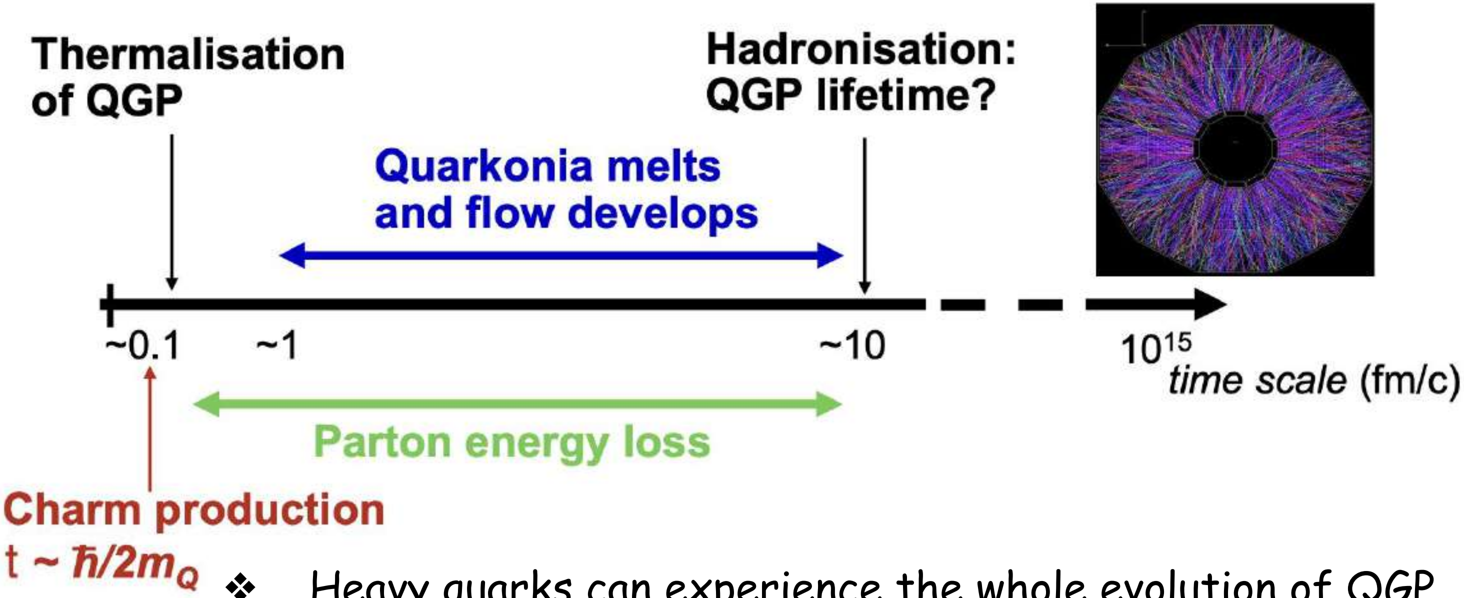
- Longitudinal hydrodynamic flow deform initially conical jets, leading to a ($\Delta\varphi$ – $\Delta\eta$) asymmetry.
- $\Delta\varphi$ – $\Delta\eta$ asymmetry could be explained by the path length dependent energy loss of the progenitor parton of the trigger hadron.
- **Longitudinal boost invariance measurement of near-side peak for the first time in CMS, and even in LHC.**
- Mid-rapidity holds boost invariance, whereas boost invariance phenomena started violating towards forward rapidity.
- Also forward rapidity shows $p_{T,asso}$ as well as system-size dependencies.

Menu III

Heavy Quark Flow -> How b and c flow in QGP ?

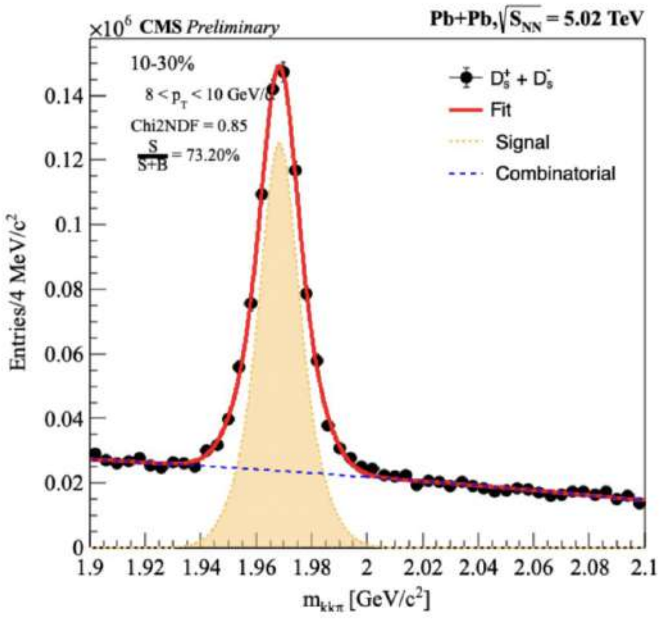
A heavy duck flows with Duck Duck Plasma

Heavy quarks as a probe to QGP



- ❖ Heavy quarks can experience the whole evolution of QGP.
- ❖ Heavy quarks traverse through the QCD medium and interact strongly with it → energy loss
- ❖ Path-length dependent energy loss leads to final state momentum anisotropy

$D_S^{\pm}$ mass spectrum



$$\boxed{D_S^{\pm} \to \phi(1020)\pi^{\pm} \to (K^+K^-)\pi^{\pm}}$$

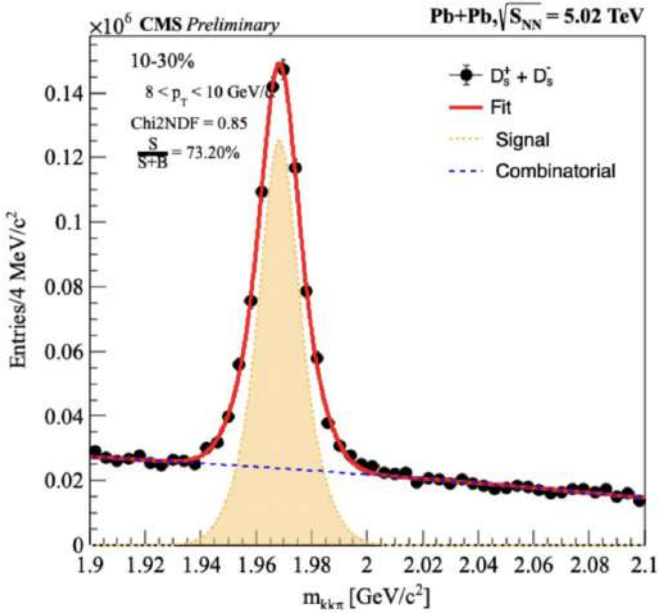
BR: 2.27 ± 0.08 %

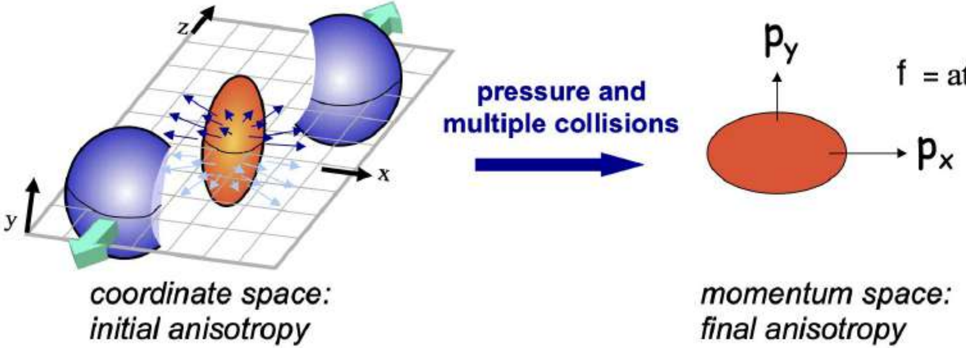
How do heavy quarks couple with the bulk medium?

What about it's transport properties?

- ❖ Signal mass spectrum → Double norm gauss
- ❖ Signal Background → 2nd order Chebyshev poly

Momentum anisotropy





$$f = \text{atan}\frac{p_y}{p_x}$$

Anisotropy coefficient, vn

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_n)$$

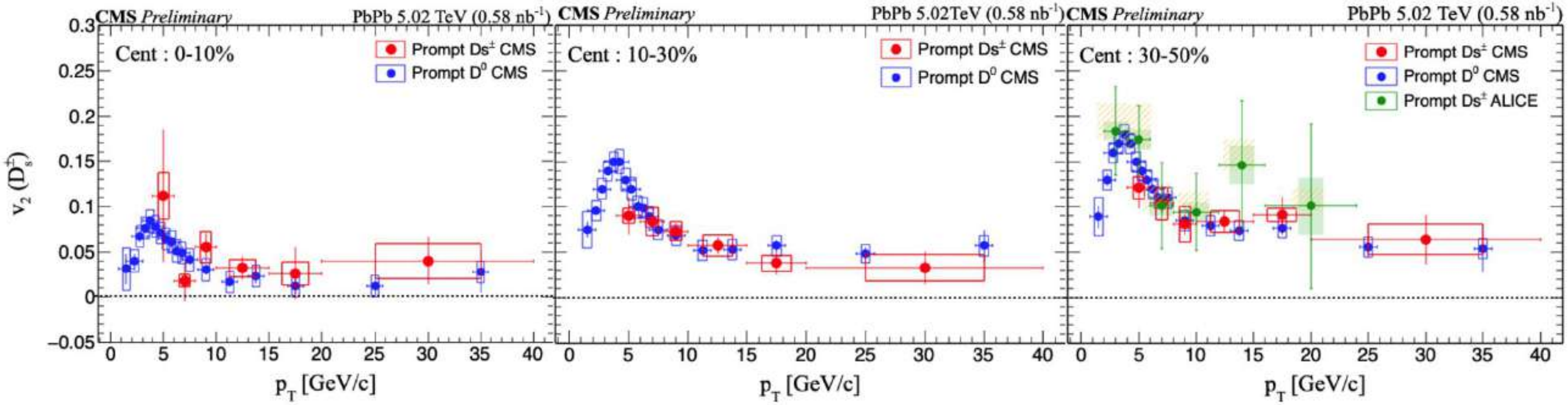
$$v_n = <\ \cos n(\phi - \psi_n) >$$

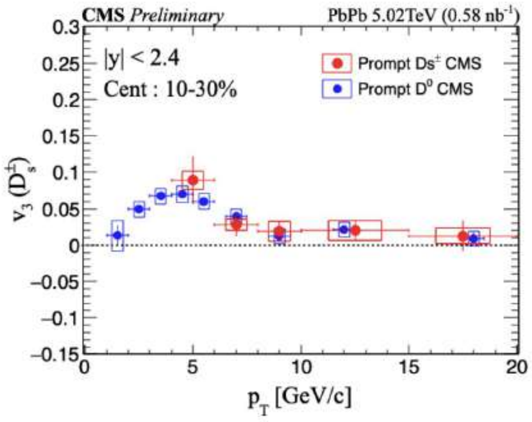
v2 → Elliptic flow → Initial state geometry
v3 → Triangular flow → Initial state fluctuation

- Signal mass spectrum → Double norm gauss
- Signal Background → 2nd order Chebyshev poly

We can probe → Path-length dependent parton energy loss
→ Hadronization mechanism

$D_s^{\pm}$ flow results





- Consistent with prompt D_0 meson flow in the measured p_T range.
- Consistent with ALICE v_2 results in 30-50% centrality within uncertainty.
- Non-zero v_3 for $4 < p_T < 15$ GeV is observed in 10-30% centrality, considering uncertainties.
- Minimal effect of hadronization on D_s flow in the measured p_T range.

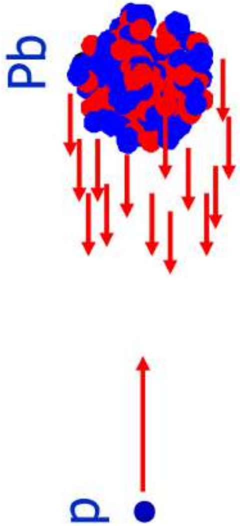
CMS-PAS-HIN-24-006

Menu III - Outcome

- Non zero v_2 for measured in centrality and p_T ranges indicate that charm quark flow is mostly driven by initial state geometry.
- Consistent with ALICE v_2 measurement in 30-50%, and precision has increased significantly as compared to ALICE.
- Minimal effect of hadronization on D_s flow in the measured p_T ranges.

Menu IV

Final state momentum anisotropy in small system

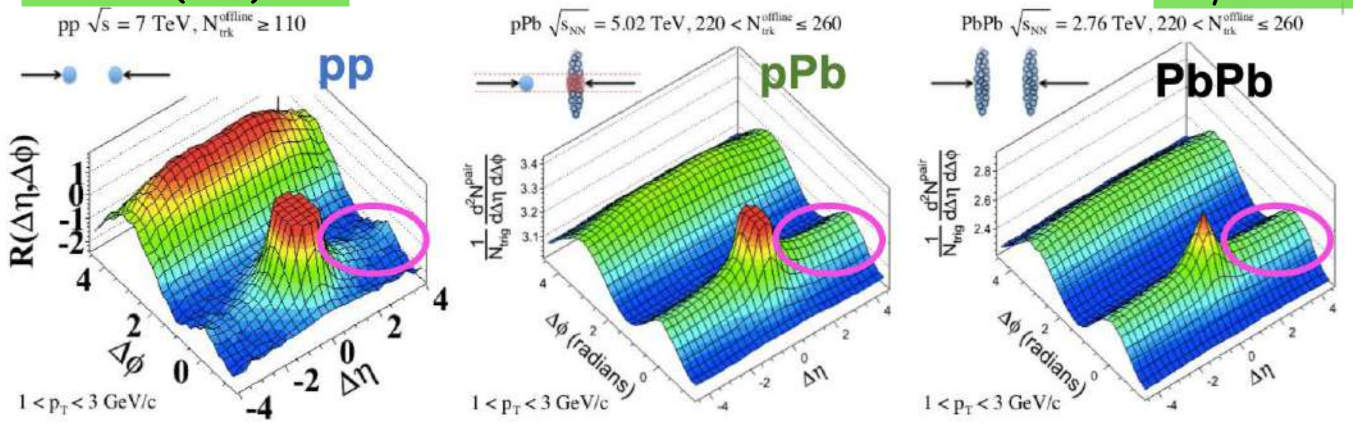


Dream comes true!!

Ridge is everywhere

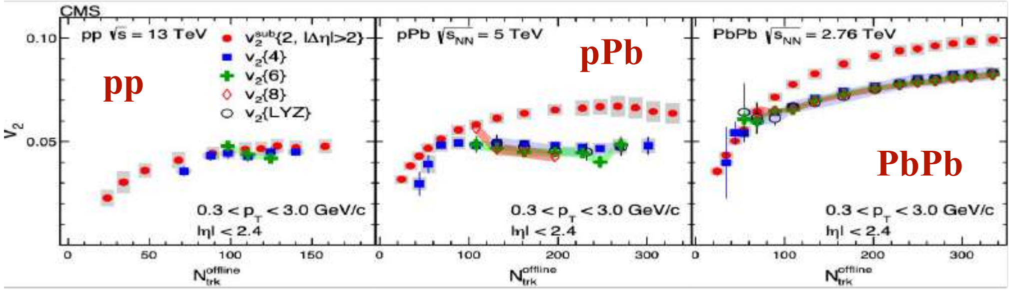
JHEP 09 (2010) 091

Phys. Lett. B 724 (2013) 213



The first unexpected discovery at LHC: Ridge in high multiplicity pp & pPb collisions from CMS

- Discovery of "Ridge" in pp & pPb => sign of collectivity? same origin?
- Geometry + Fluctuations
- Well described by hydrodynamics
- Similar trend of in three systems

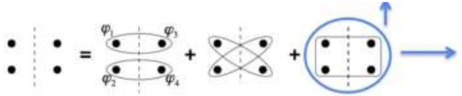


Phys. Rev. Lett. 115, 012301 (2015)

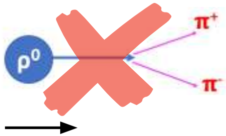
Removing non-flow using subevent cumulant

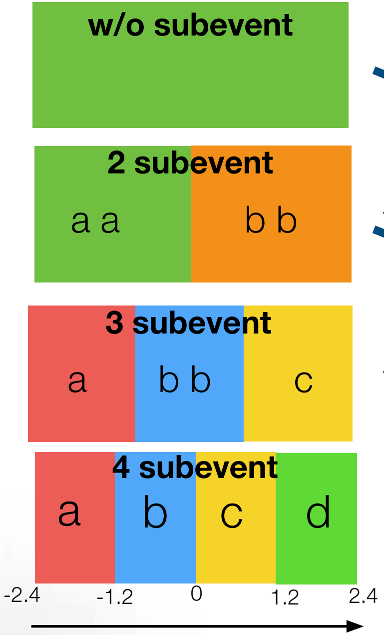
- **Cumulant method:**
  - Multiparticle correlation technique
  - Non-flow suppression in a data-driven way

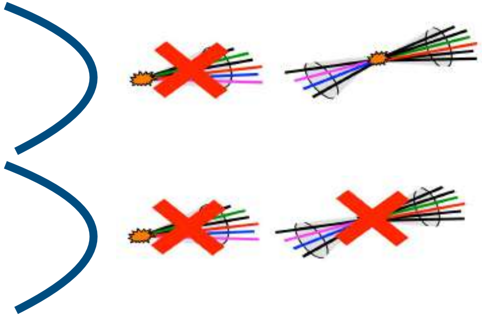
Phys.Rev.C83:044913,2011



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





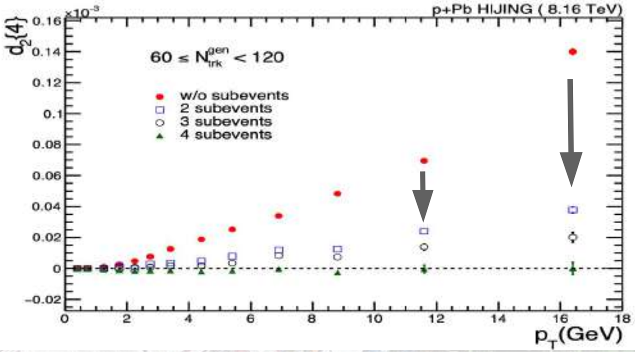


=> Differential cumulant : $d_n\{4\} = \langle\langle 4'\rangle\rangle - 2\langle\langle 2'\rangle\rangle\cdot\langle\langle 2\rangle\rangle$

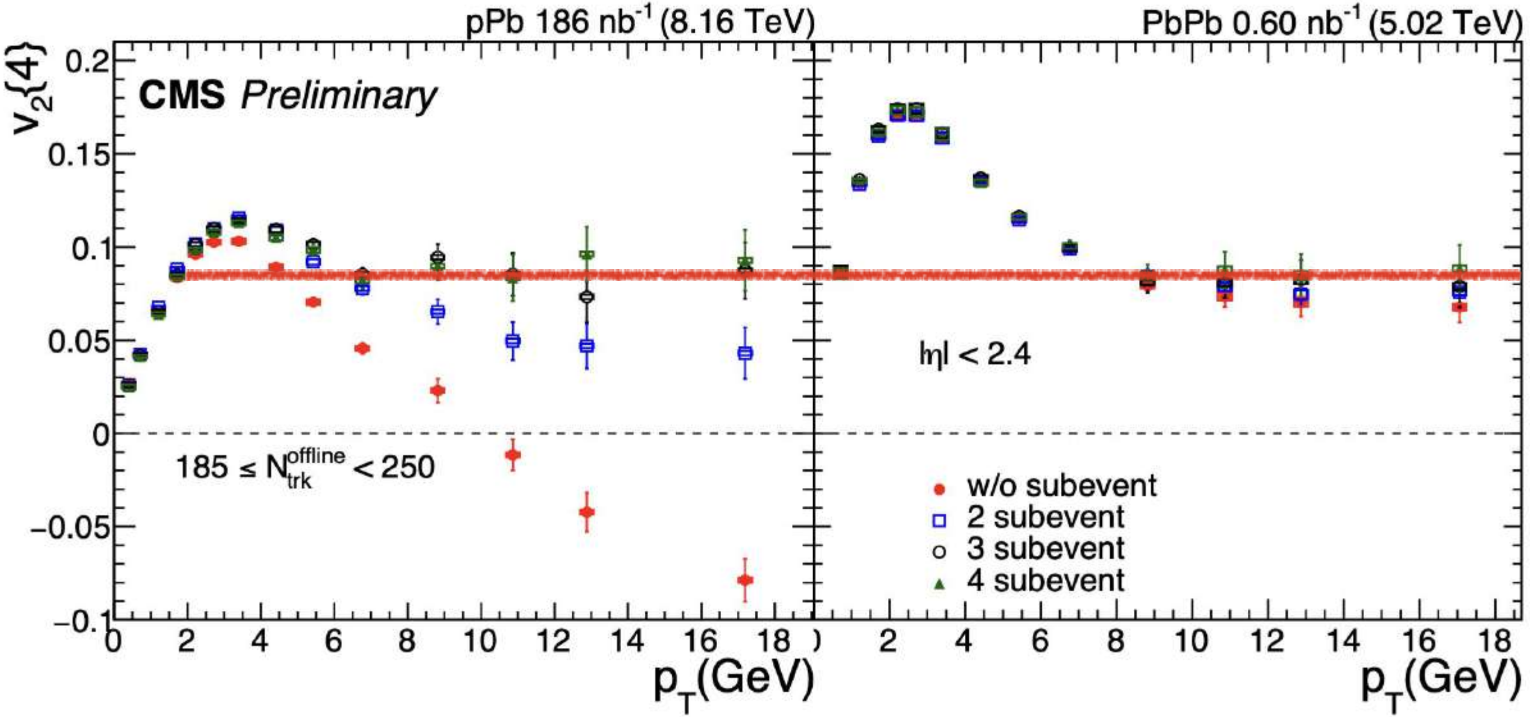
1 POI   3 RFPs

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

- In standard cumulant, nonflow from jets contribute to four-particle correlation
- Subevent method removes these nonflow correlations
- Large coverage of CMS: enough statistics



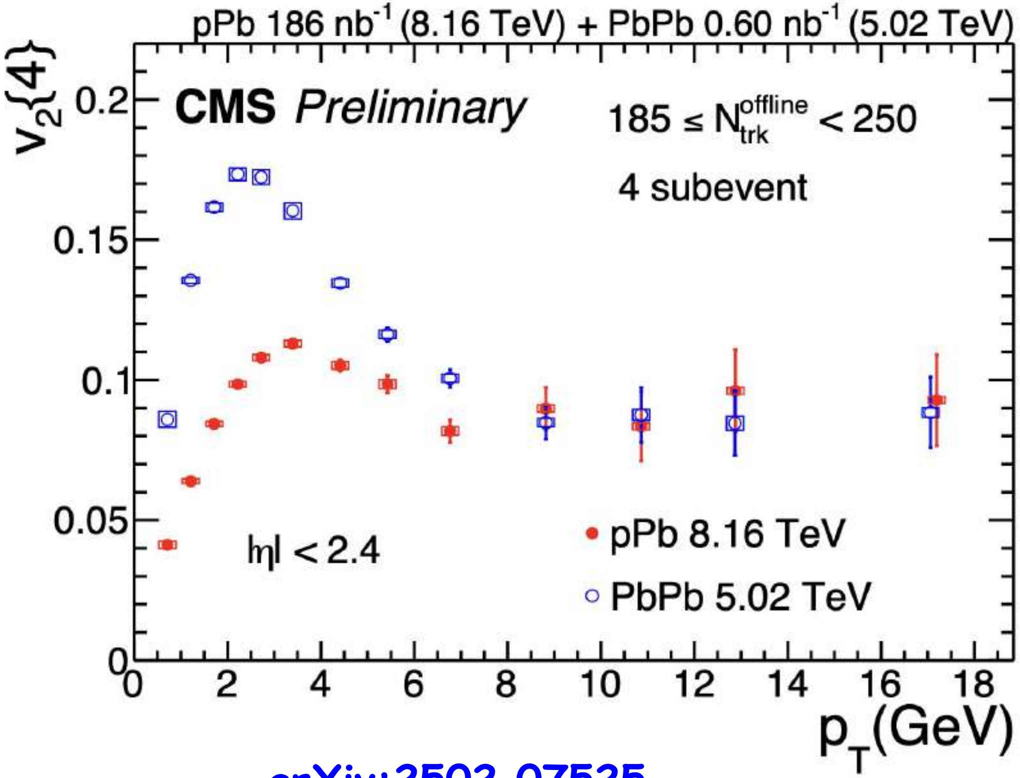
$v_2\{4\}$ in $185 \leq N_{trk}^{Offine} < 250$ vs p_T



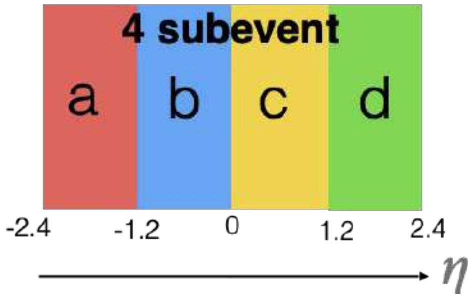
- At low p_T, PbPb has larger $v_2\{4\}$ than pPb
- At high p_T, similar magnitude and similar trend of subevent $v_2\{4\}$

arXiv:2502.07525

4- subevent $v_2\{4\}$ in $185 \leq N_{trk}^{Offine} < 250$ vs p_T

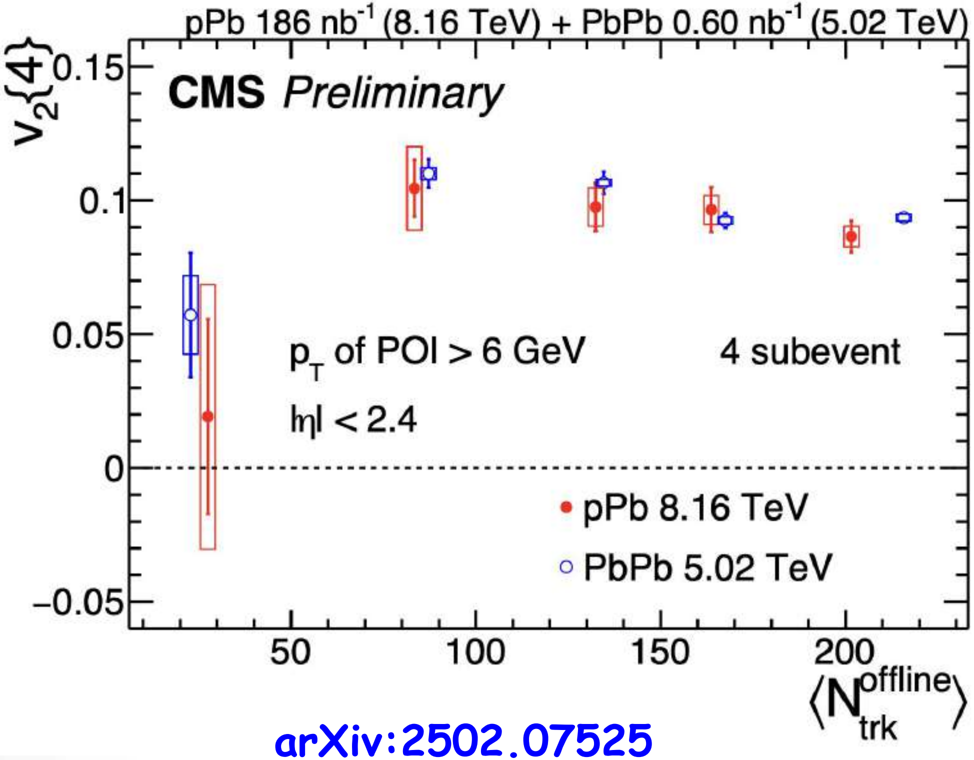


arXiv:2502.07525

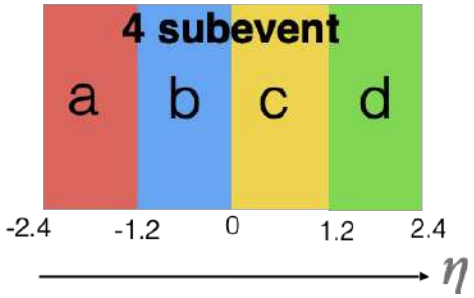


- At low p_T, PbPb has larger $v_2\{4\}$ than pPb
- At high , similar magnitude and similar trend of 4 subevent values

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



arXiv:2502.07525



Similar magnitude and trend for both PbPb and pPb when > 6 GeV across all multiplicity bins

Menu IV - Outcome

- The results of with subevents for pPb & PbPb collisions at = 8.16 TeV & = 5.02 TeV, resp.

- After using subevent to remove nonflow, we have obtained a significant positive value for at high-p_T in pPb

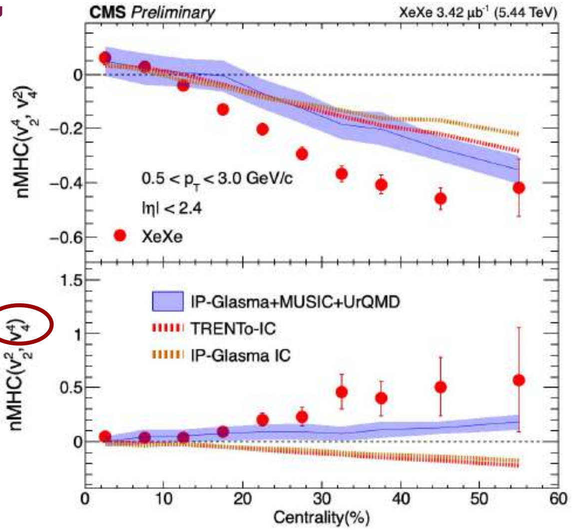
- A remarkable similarity in high multiplicity pPb and peripheral PbPb collisions

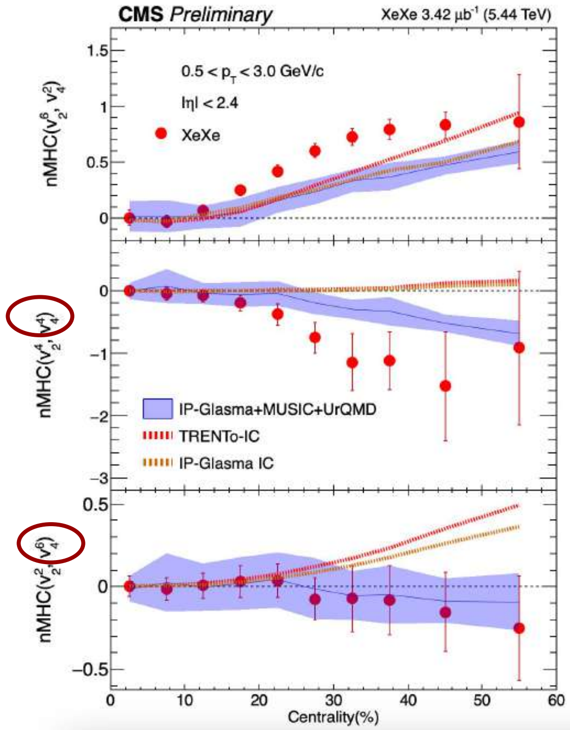
Feast summary

- First time nonlinearity effect observed in higher order moment of v_4 in XeXe and PbPb (Using 6 and 8 particle nMHC observable).

Accepted in QM'25

Starters



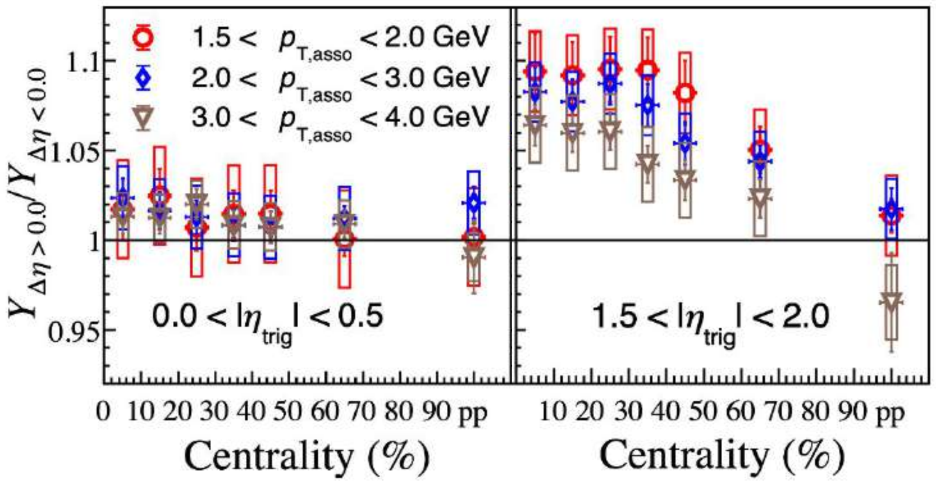


Feast summary

❖ First time experimentally observed that boost invariance phenomena starts violating towards forward rapidity region.

Accepted in QM'25

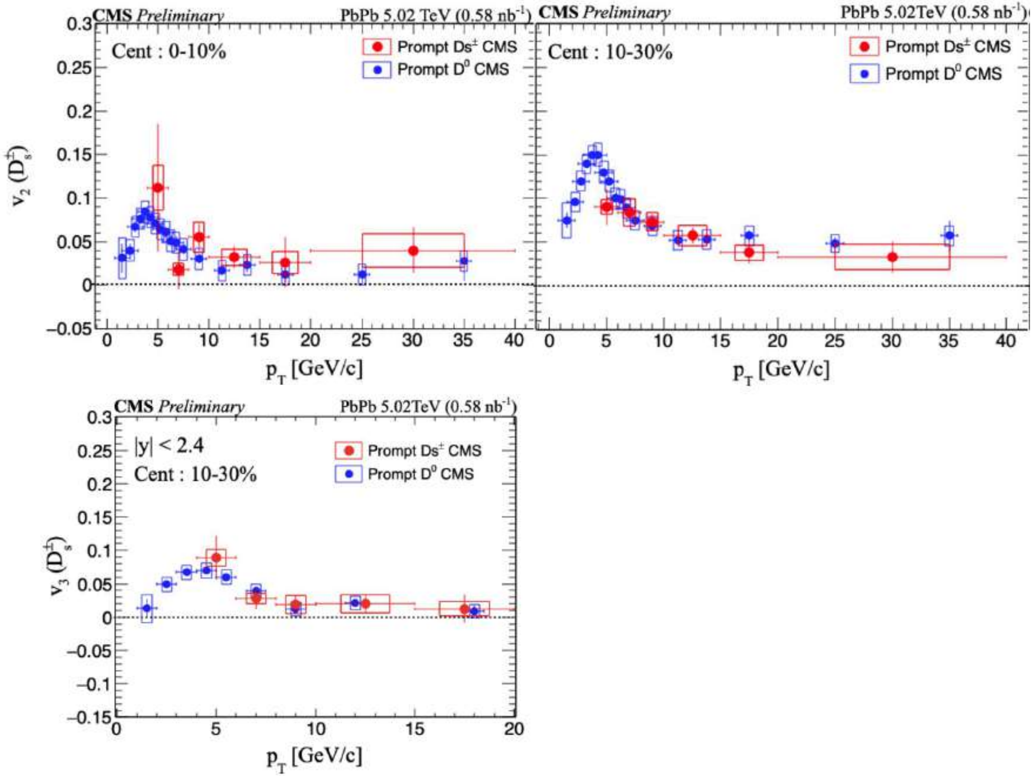
Main Course-I



Feast summary

❖ First time v_2 in 0-10% and 10-30% centrality and v_3 in 10-30% explored for D_s heavy flavour.

Accepted in QM'25

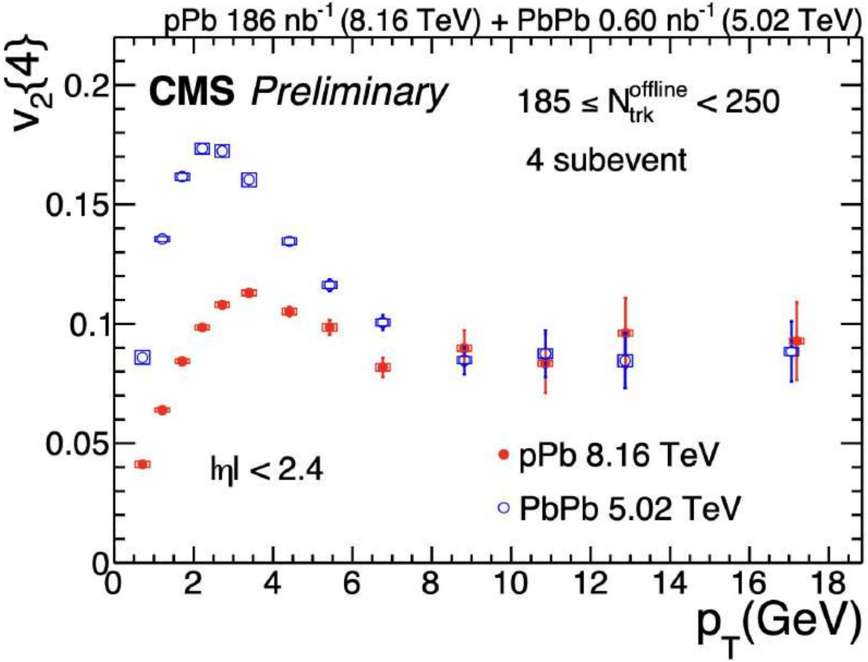


Feast summary

- A remarkable similarity in high multiplicity pPb and peripheral PbPb collisions

Accepted in QM'25

Dessert



Feast ends

Hope you enjoyed the feast and presentation !!

Jai Jagannath !!