Correlation and flow phenomena in pPb and PbPb at CMS

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for the CMS Collaboration

6th International Conference on Hard and EM Probes of High-Energy Nuclear Collisions

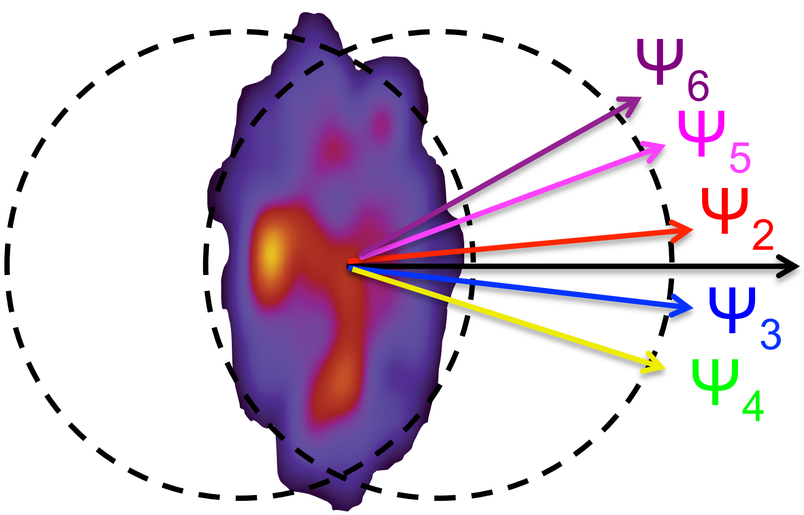
Stellenbosch Institute for Advanced Study
South Africa, November 2013

Outline

Elucidating the role of geometry fluctuations

(I): New results of higher-order flow in PbPb collisions

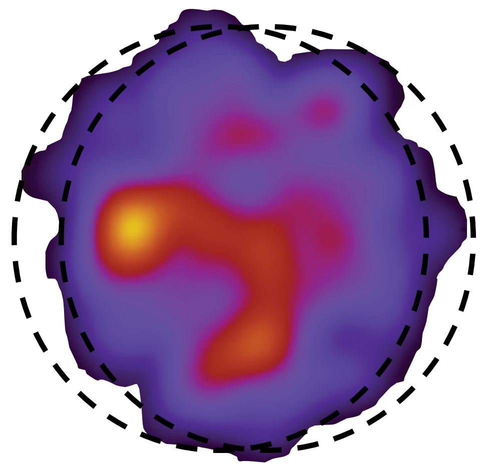
recently submitted to PRC (arXiv:1310.8651)



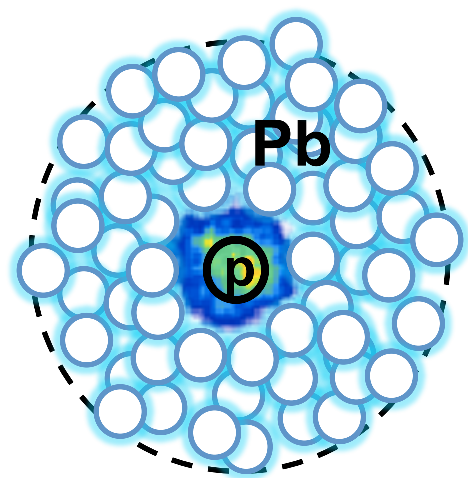
v_2, v_3, v_4, v_5 and v_6 using multiple methods

Flow phenomena in the most violent collisions at the LHC:

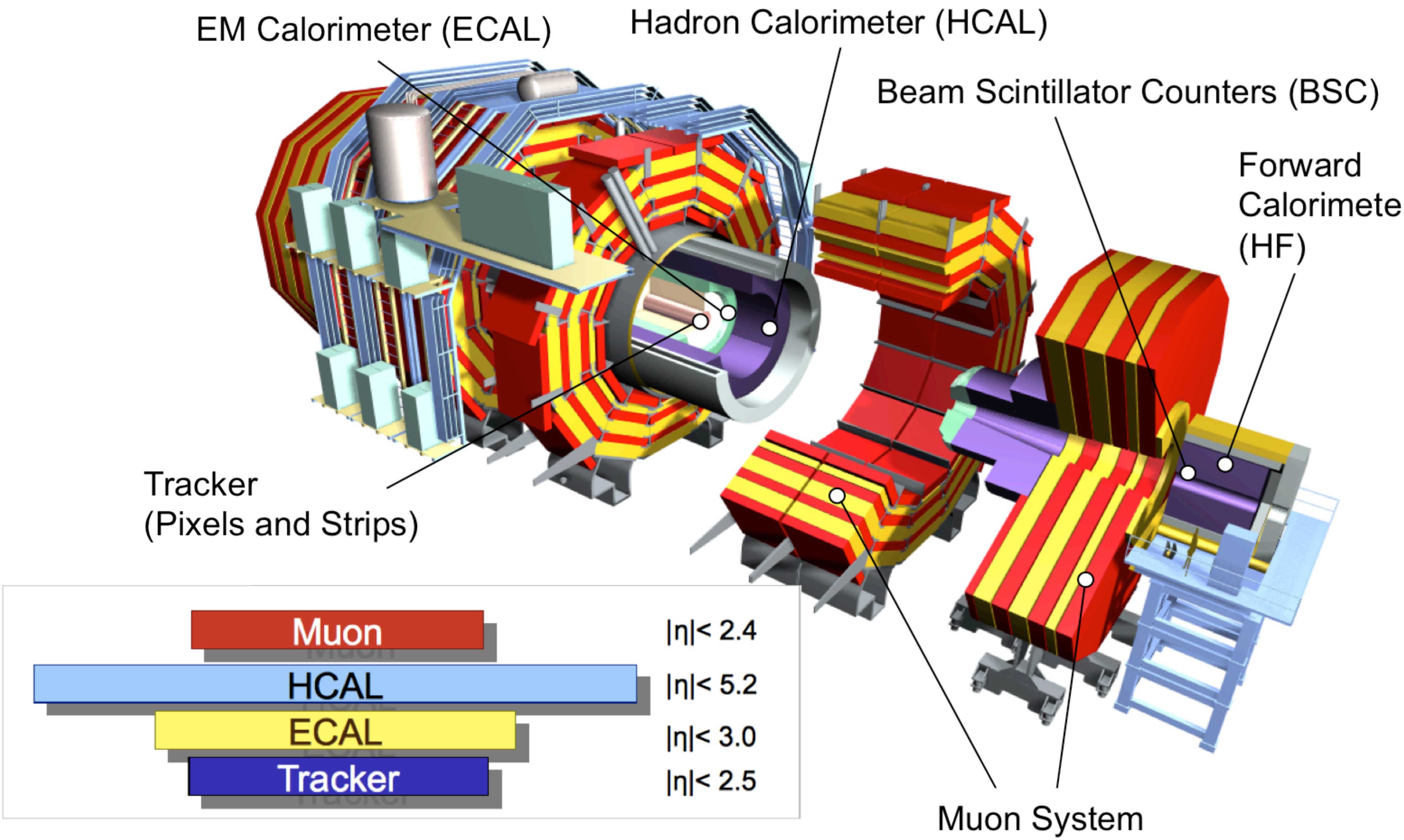
(II): Ultra-central PbPb



(III): High-multiplicity pPb (and pp)



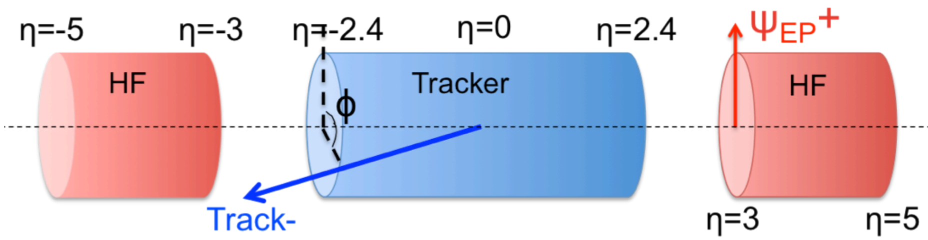
Compact Muon Solenoid (CMS) at the LHC



Large acceptance and wide kinematic coverage!

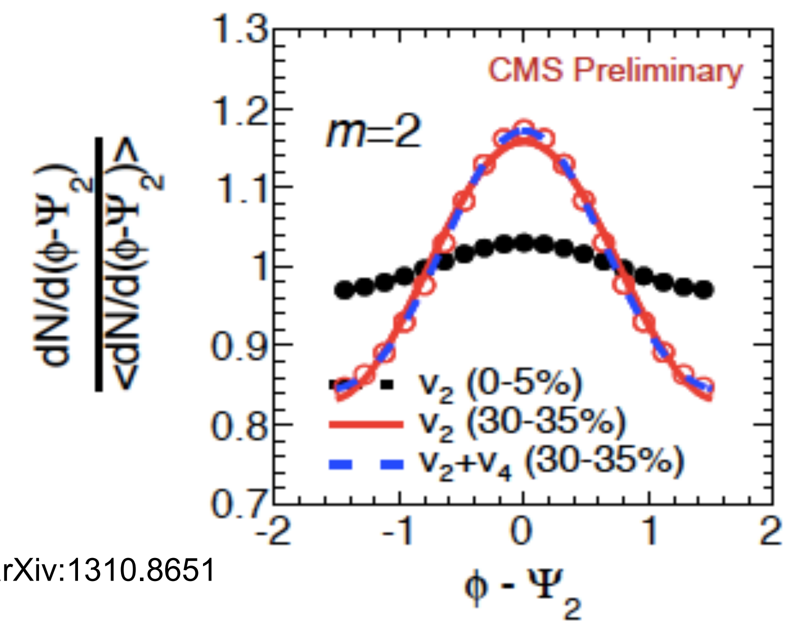
Studies of flow phenomena in CMS

➢ Event plane method:



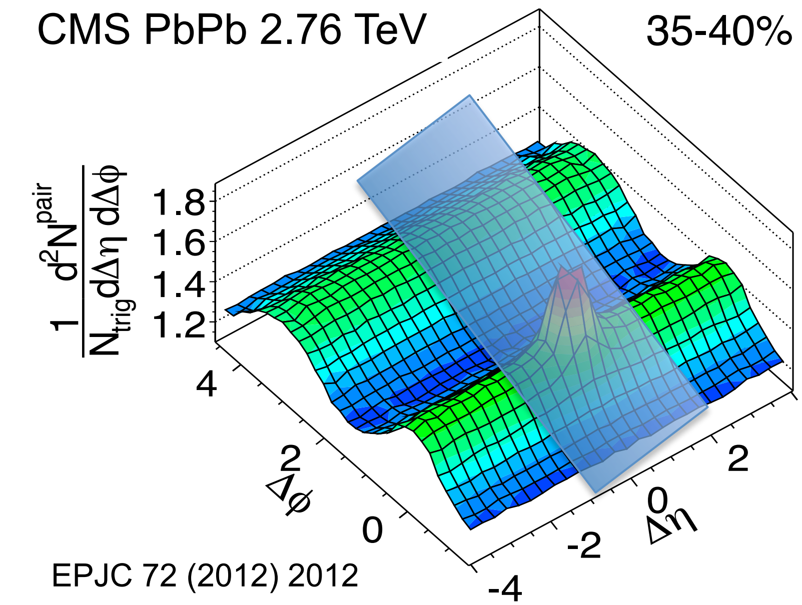
$$\frac{1}{N}\frac{dN}{d\phi} \sim 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\phi - \Psi\right)\right]$$

event plane angle



arXiv:1310.8651

➢ Two-particle Δη-Δϕ correlation:



EPJC 72 (2012) 2012

flow is long-range!

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2\sum_{n=1}^{\infty} V_{n\Delta}\cos(n\Delta\phi)$$

Factorization assumption:

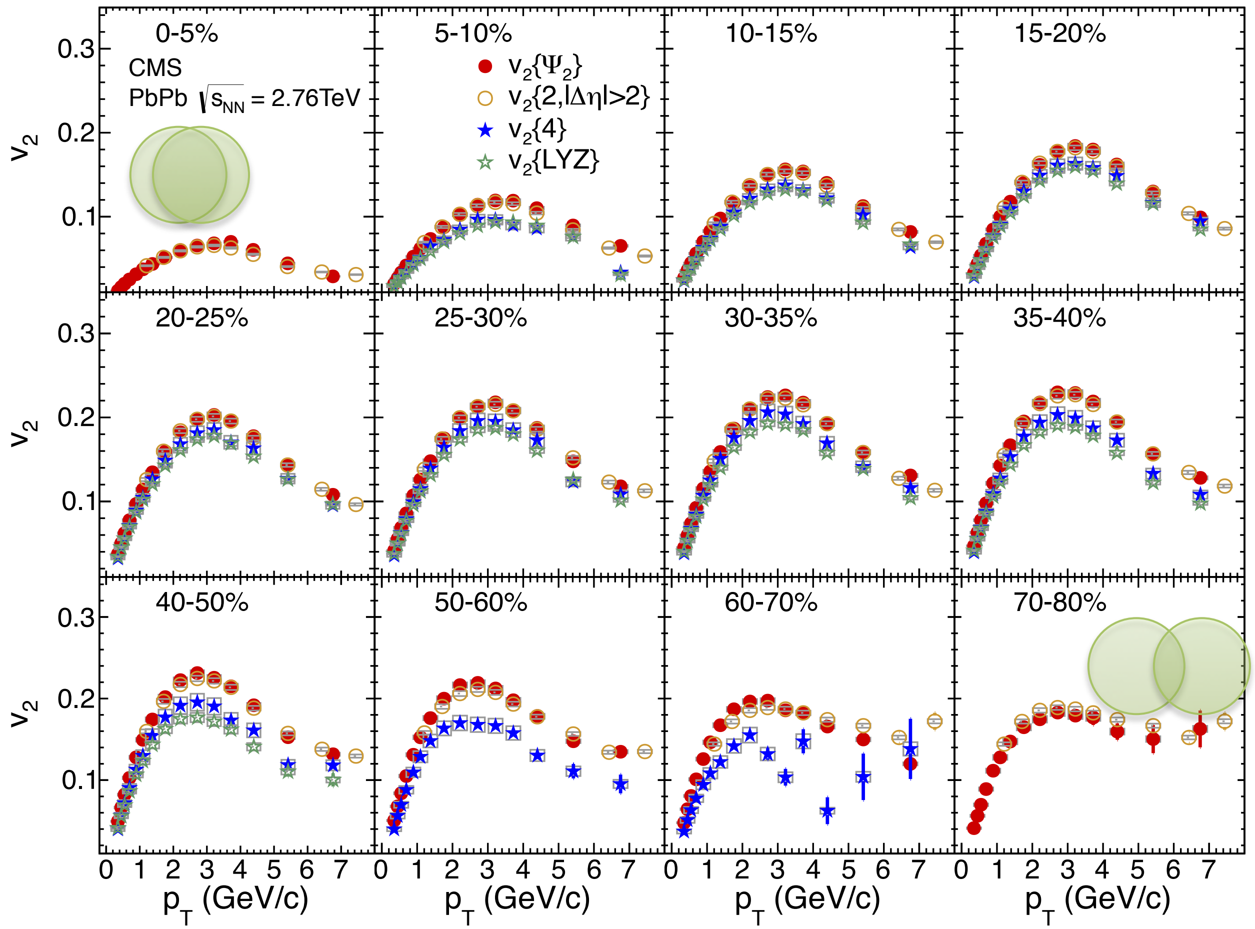
$$V_{n\Delta}(p_T^{trig}, p_T^{assoc}) = v_n(p_T^{trig}) \times v_n(p_T^{assoc})$$

➢ **Multiparticle correlations:** multi-particle cumulants and LYZ

Elliptic flow (v_2) in PbPb at CMS

v_2 vs centrality and p_T

PRC 87(2013) 014902
EPJC 72 (2012) 2012

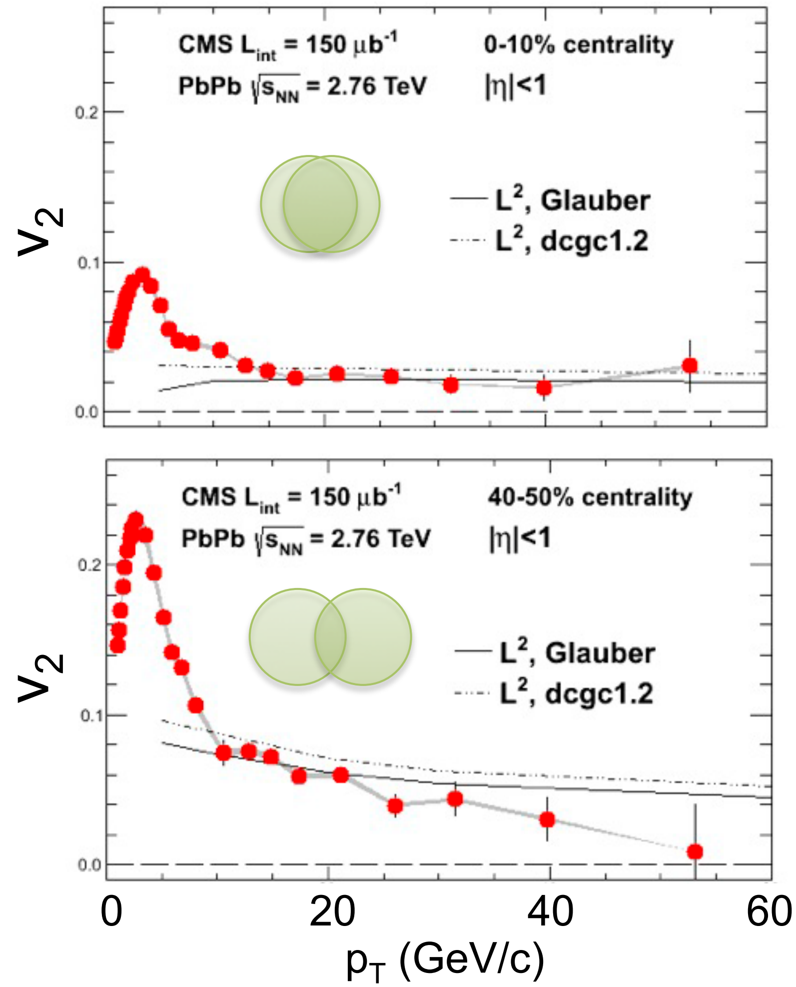


$$v_2(\Psi_2) \approx v_2\{2, |\Delta\eta| > 2\} > v_2\{4\} \approx v_2\{LYZ\}$$

- **Four methods** with different sensitivities to flow fluctuations and non-flow

v_2 at very high p_T

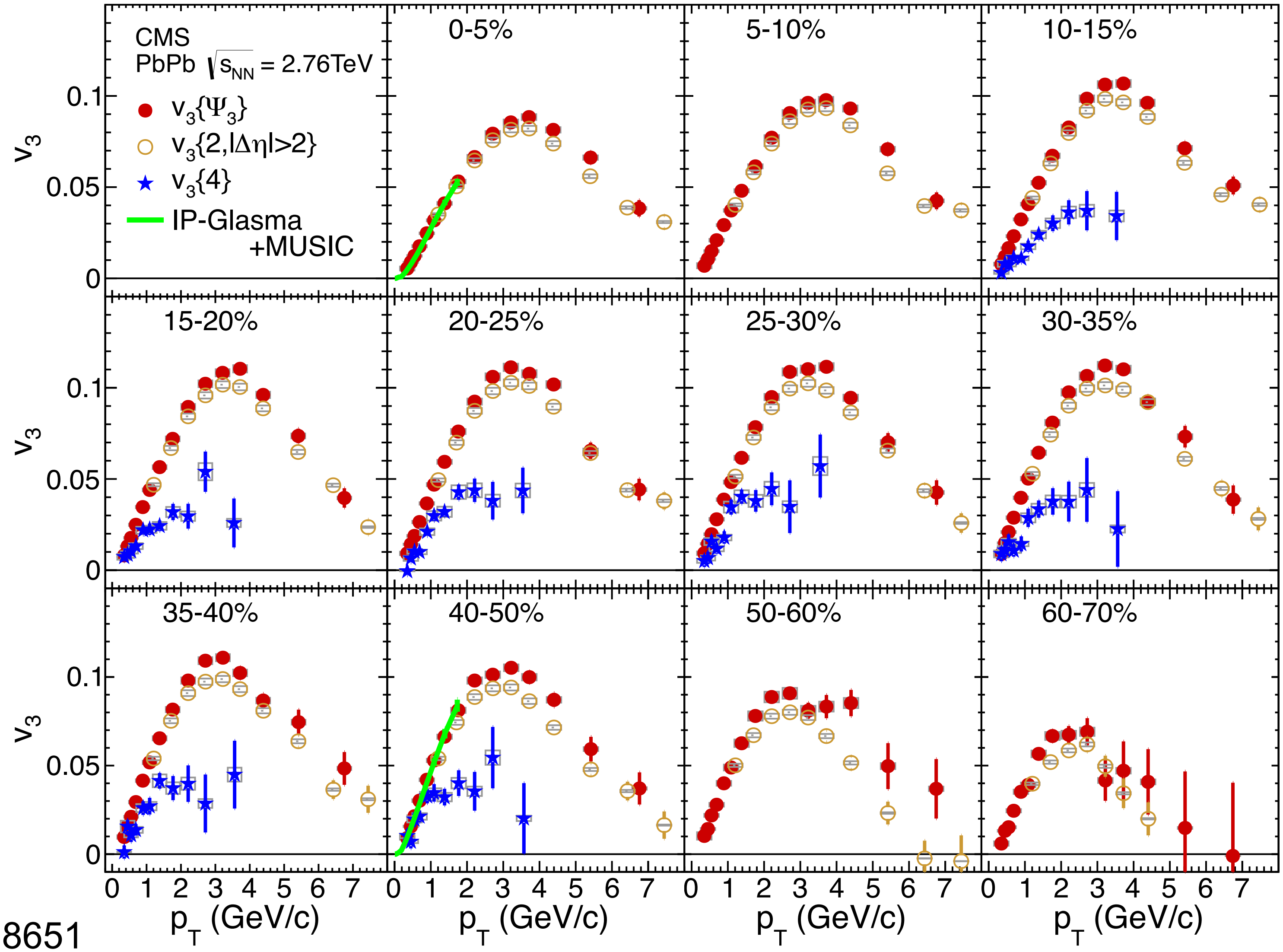
PRL 109, 022301(2012)

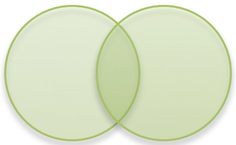


- Geometry is relevant for hard probes!

Higher-order flow (v_n) in PbPb

v_3



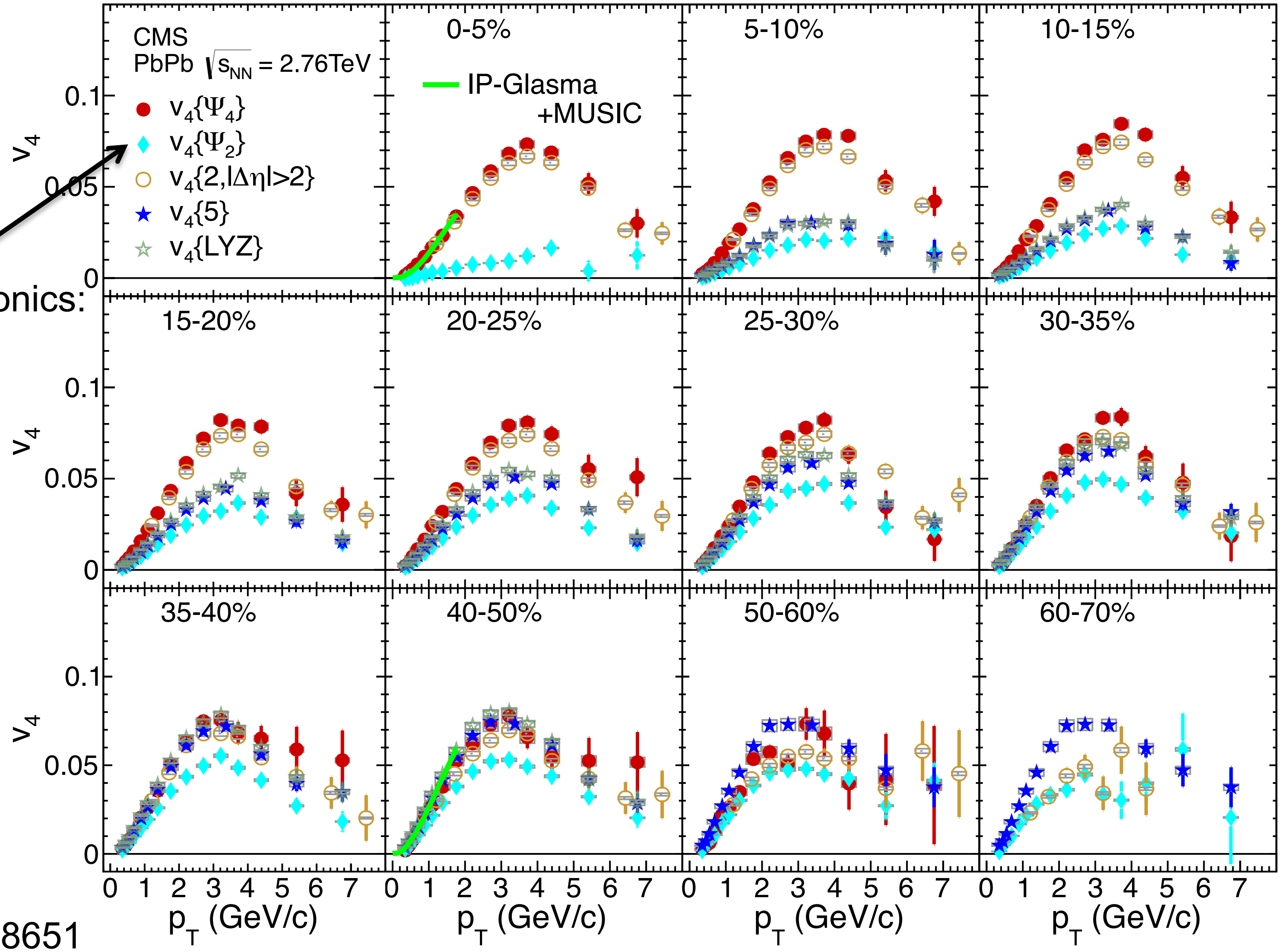


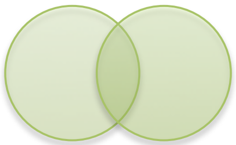
arXiv:1310.8651

$v_3(\Psi_3) \approx v_3\{2, |\Delta\eta| > 2\} >> v_3\{4\}$ with little centrality dependence

➔ Strong effect of fluctuations

Higher-order flow (v_n) in PbPb





arXiv:1310.8651

$v_4(\Psi_4)$ and $v_4\{2, |\Delta\eta| > 2\}$: Ψ_4 ref.

- Weak centrality dependence
- **Fluctuation dominant**

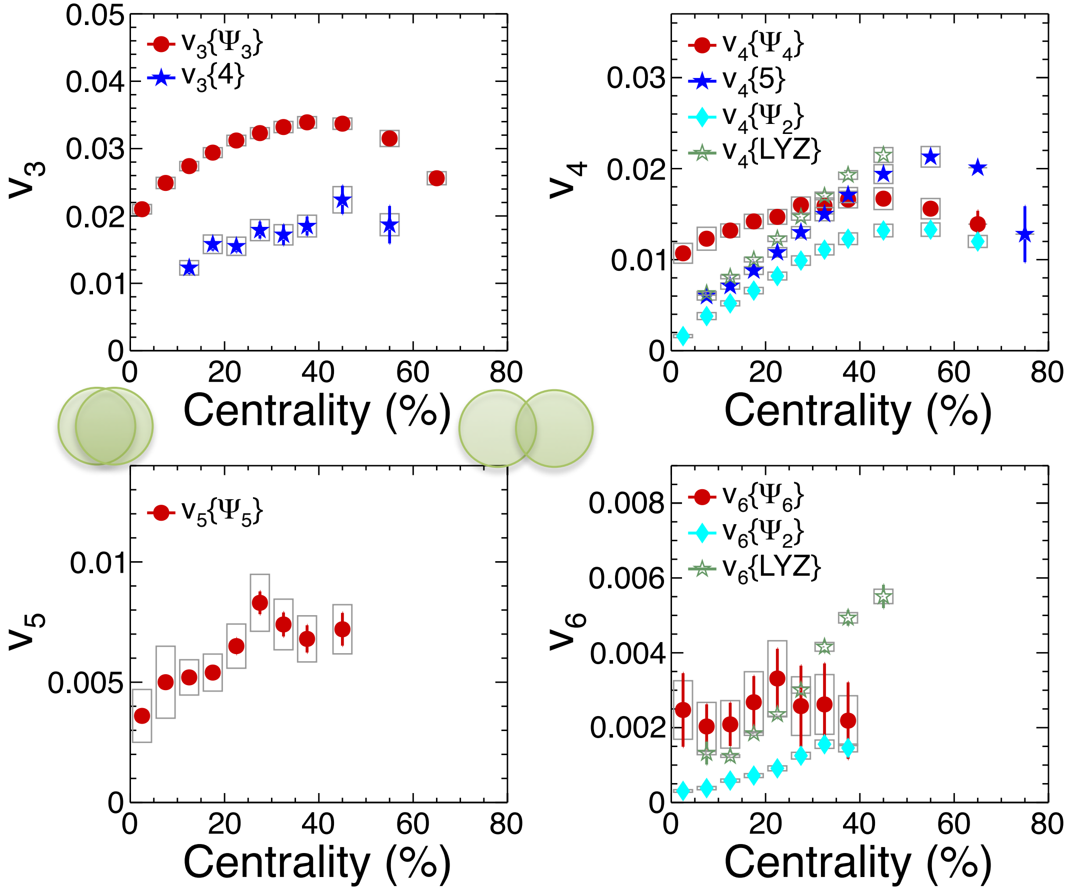
$v_4(\Psi_2)$, $v_4\{5\}$ and $v_4\{LYZ\}$: Ψ_2 ref.

- Strong centrality dependence
- **Elliptic geometry driven**

Higher-order flow (v_n) in PbPb

Averaged over $0.3 < p_T < 3$ GeV/c

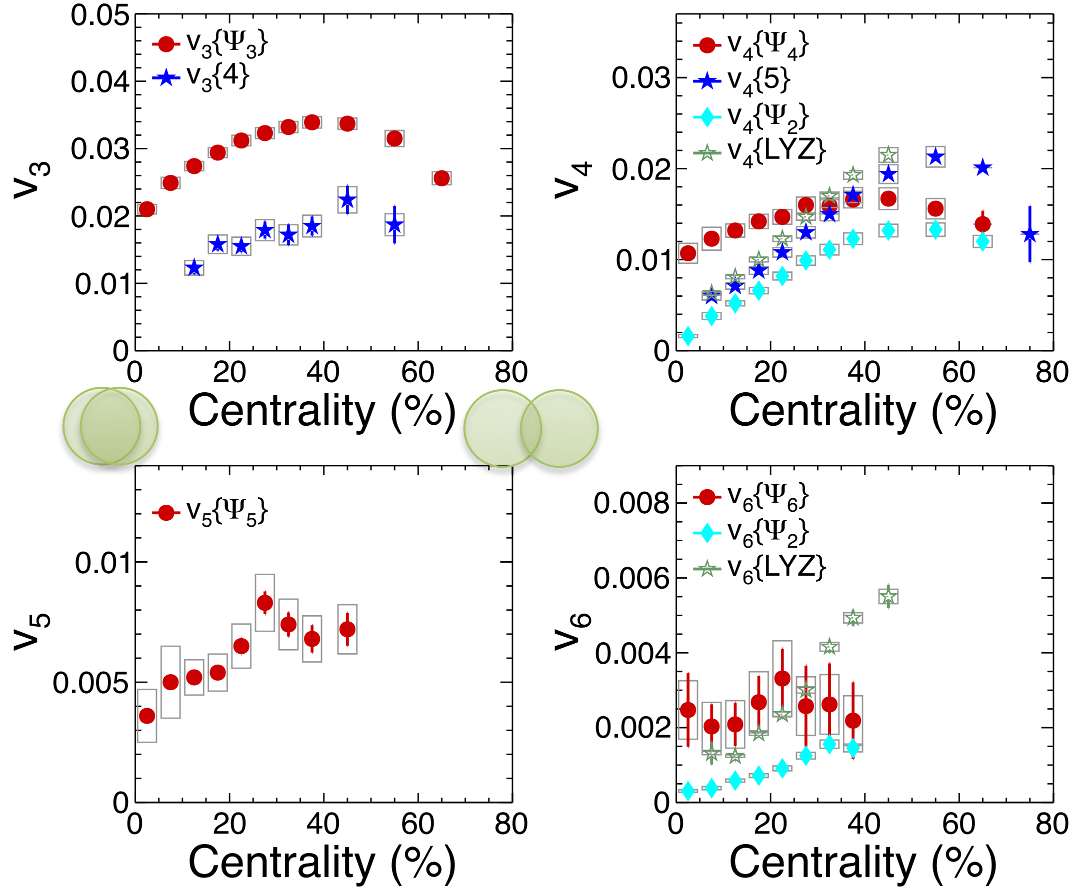
Centrality dependence: arXiv:1310.8651



- Weak centrality dependence for $v_n\{\Psi_n\}$
- Strong centrality dependence of v_4 and v_6 if measured with Ψ_2 reference

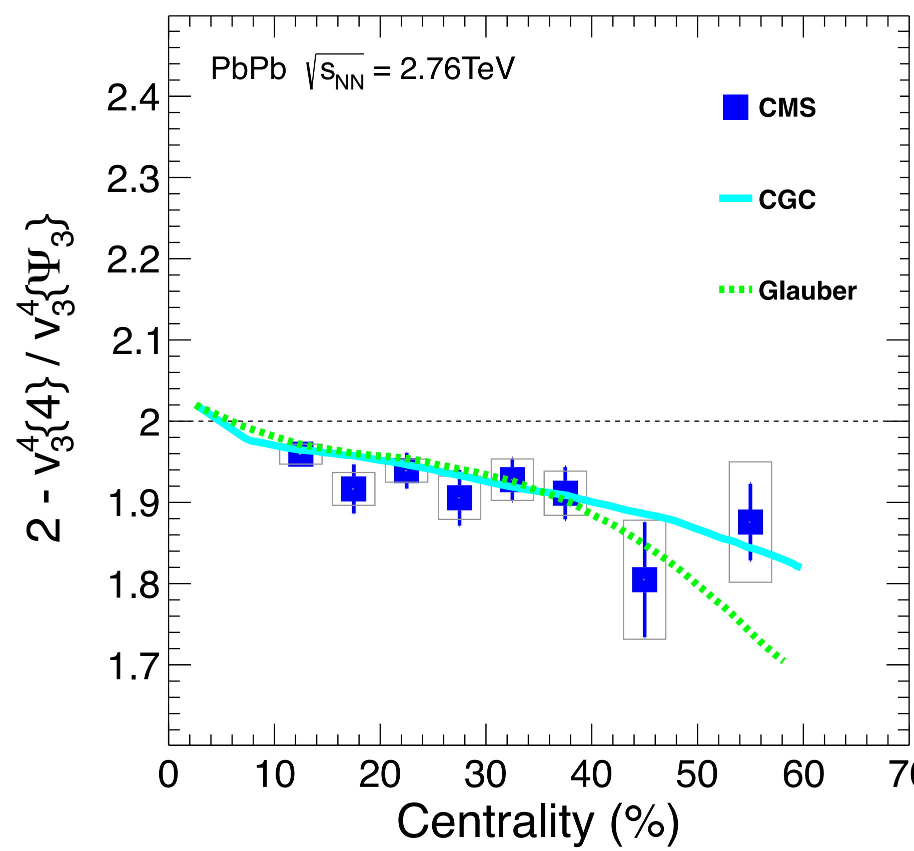
Higher-order flow (v_n) in PbPb

Centrality dependence: arXiv:1310.8651



Averaged over $0.3 < p_T < 3$ GeV/c

Testing initial-state fluctuations



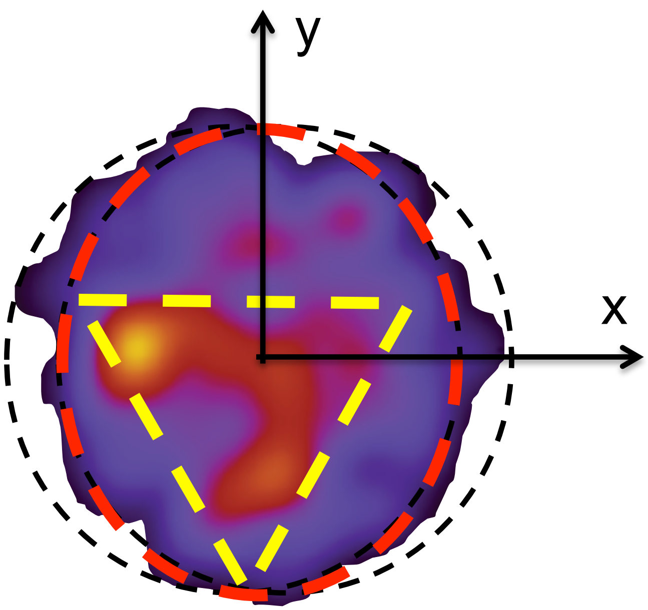
- Weak centrality dependence for $v_n\{\Psi_n\}$
- Strong centrality dependence of v_4 and v_6 if measured with Ψ_2 reference

Less sensitive to medium properties (e.g., η/s)

Bhalerao, Luzum, Ollitrault PRC84, 034910 (2011)

Flow in ultra-central PbPb collisions

Moving to ultra-central events, all v_n are mostly driven by fluctuations:

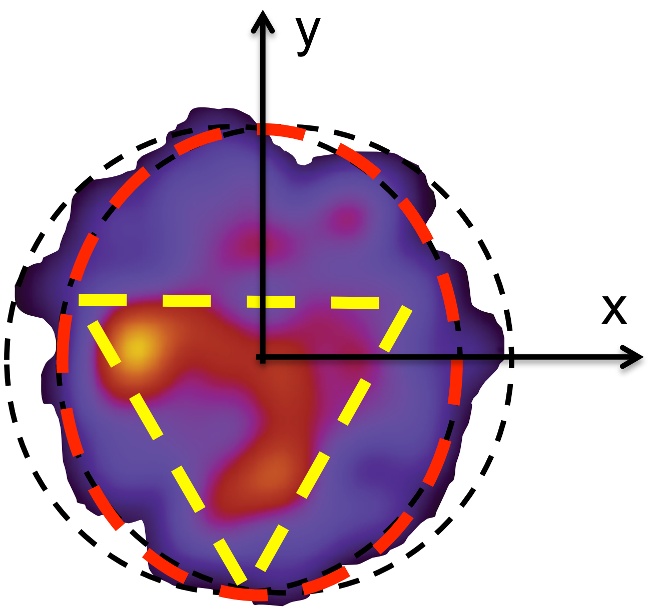


CMS PAS HIN-12-011

Ideal testing grounds for effects due to initial-state fluctuations

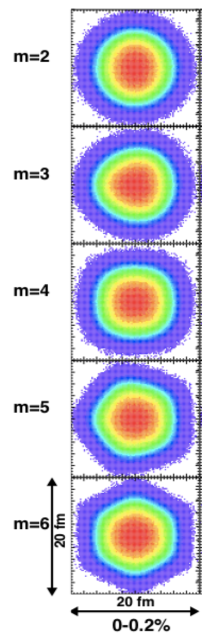
Flow in ultra-central PbPb collisions

Moving to ultra-central events, all v_n are mostly driven by fluctuations:



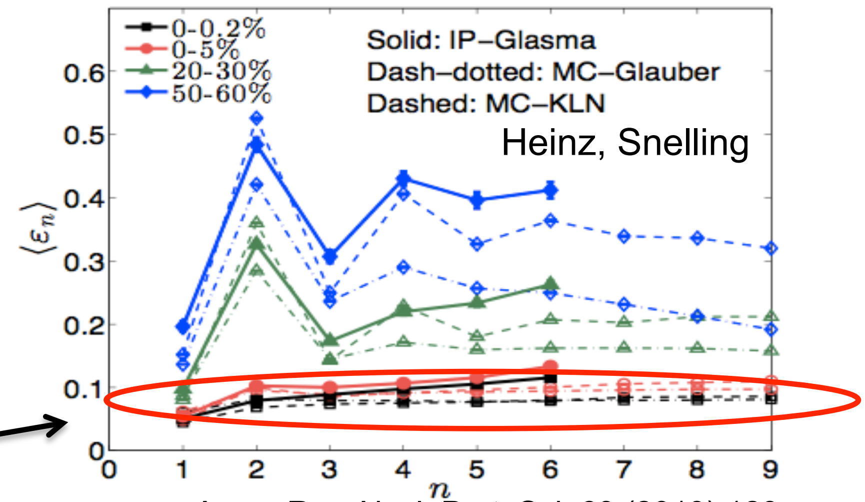
CMS PAS HIN-12-011

0-0.2% central



Participant distribution relative to the n^{th} order participant plane

various order of ε_n converge as collision becomes central

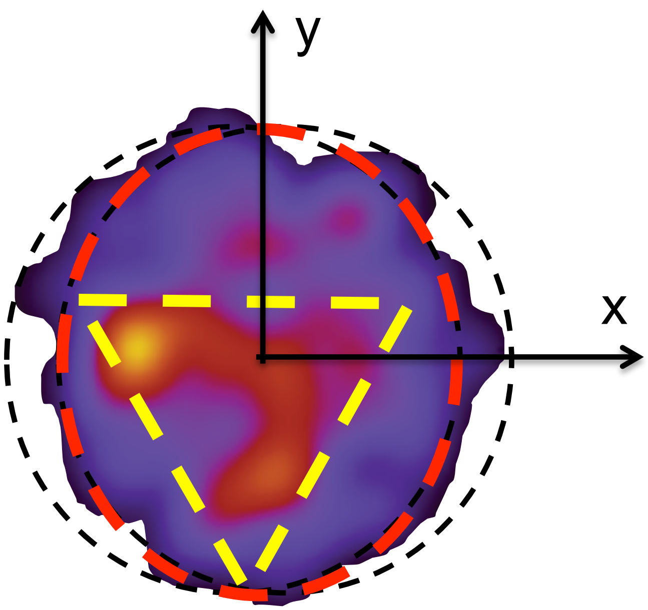


Annu. Rev. Nucl. Part. Sci. 63 (2013) 123

Ideal testing grounds for effects due to initial-state fluctuations

Flow in ultra-central PbPb collisions

Moving to ultra-central events, all v_n are mostly driven by fluctuations:



CMS PAS HIN-12-011

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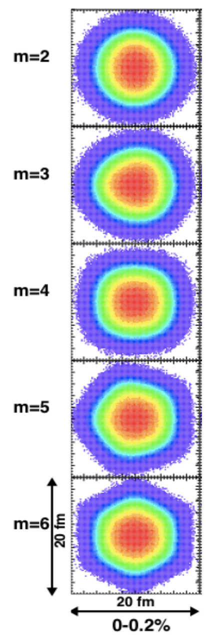

Participant distribution relative to the n^{th} order participant plane

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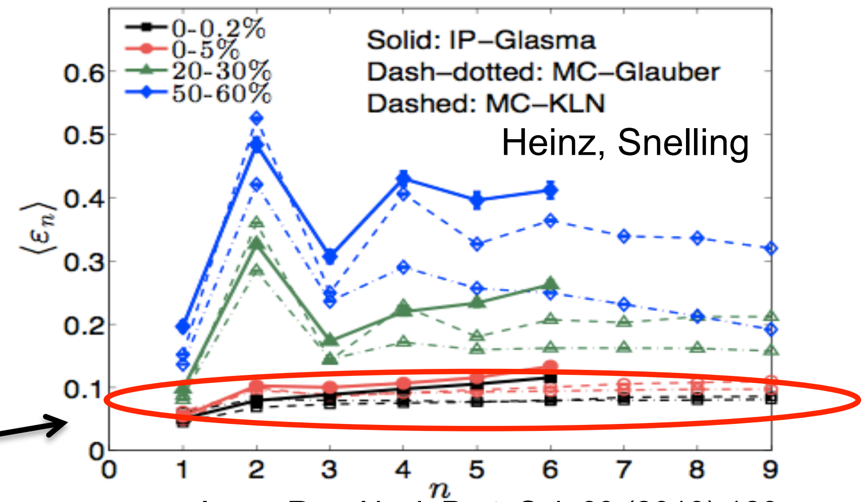
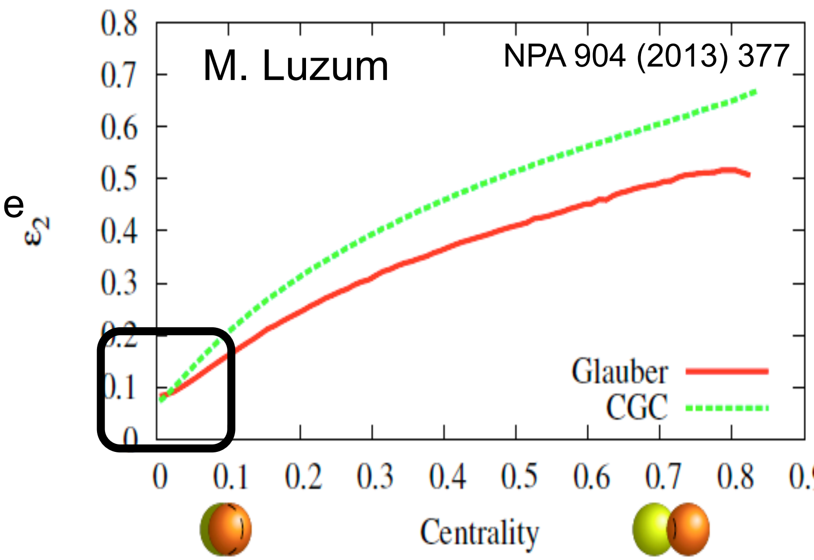


Annu. Rev. Nucl. Part. Sci. 63 (2013) 123

ε_n from various models converge as collision becomes central



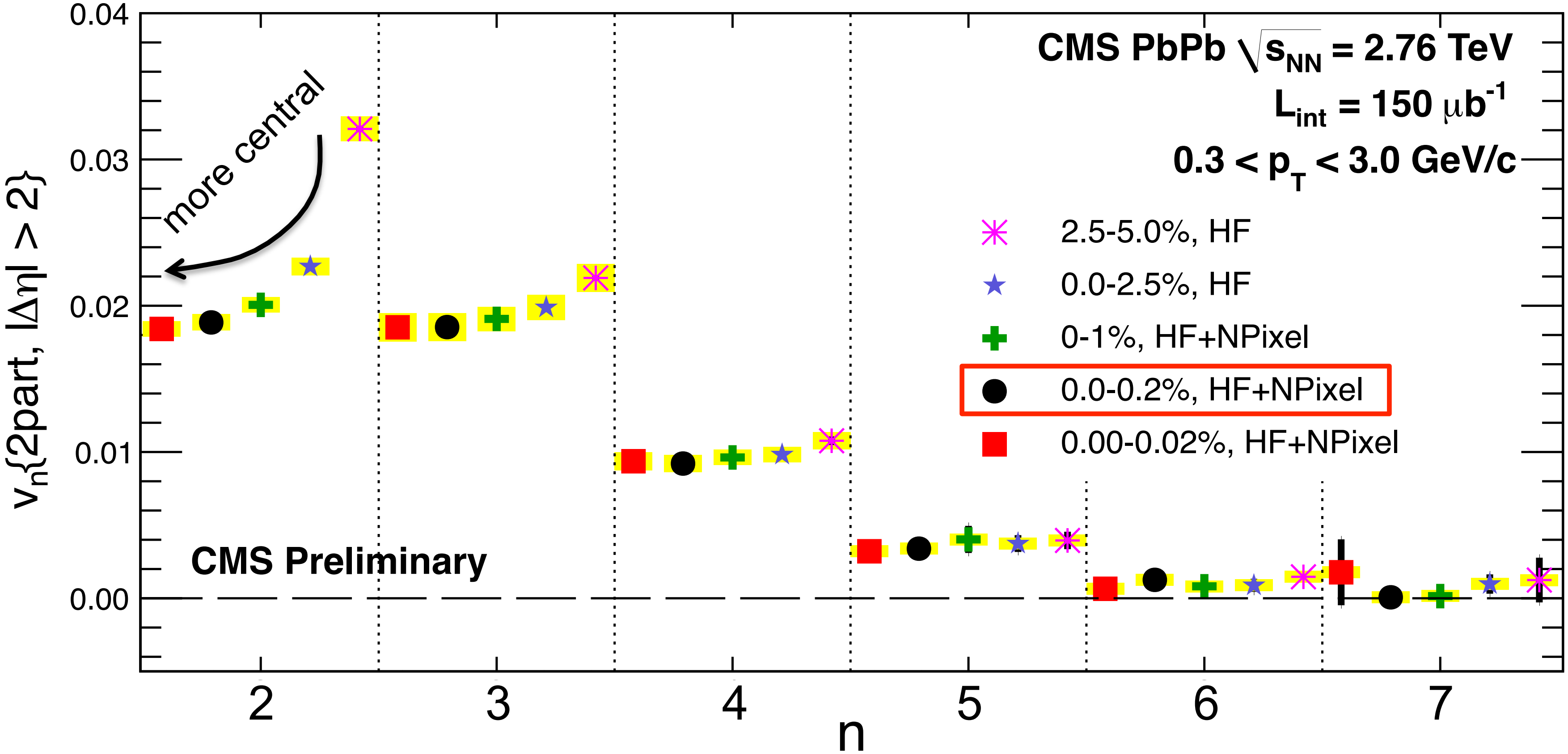
Ideal testing grounds for effects due to initial-state fluctuations

Flow in ultra-central PbPb collisions

~ 2M events for 0.0-0.2% centrality triggered events

v_n vs n from two-particle correlations

CMS PAS HIN-12-011



All orders of v_n tends to saturate around 0.0-0.2% centrality

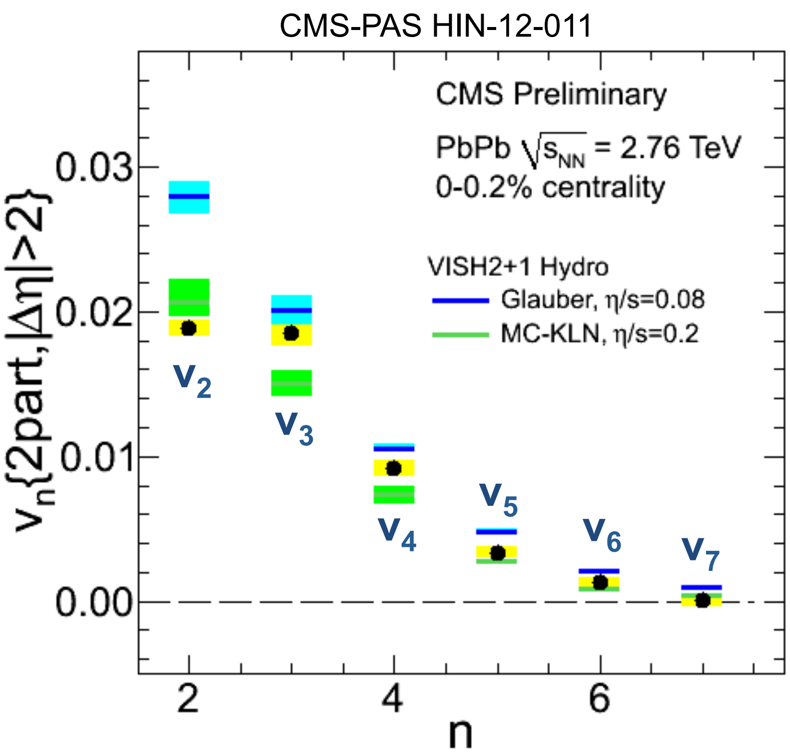
➔ Predominantly induced by participant fluctuations

Flow in ultra-central PbPb collisions

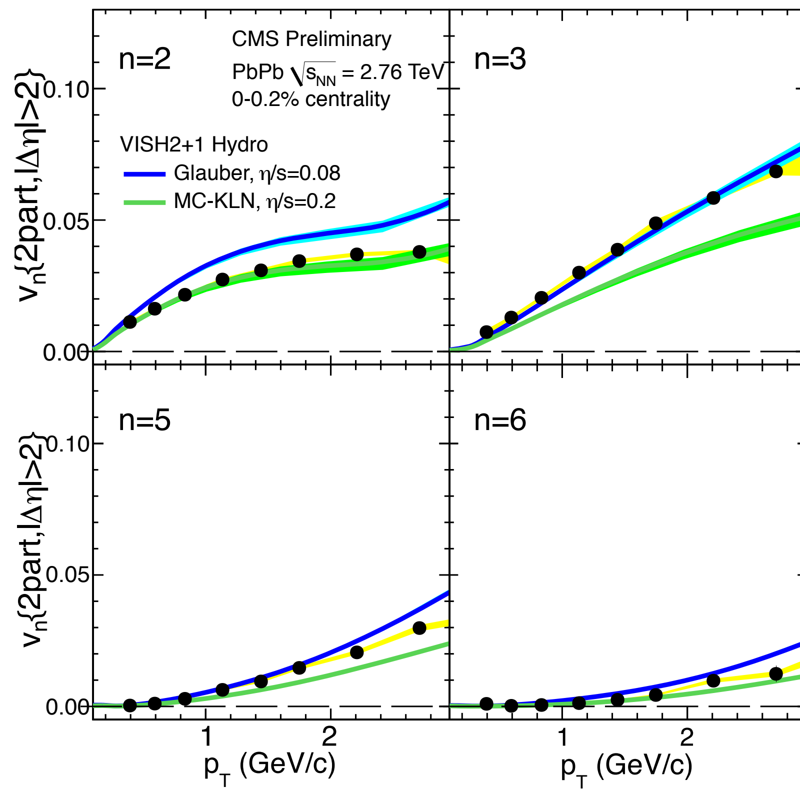
0.0-0.2% centrality

$$v_n(p_T) = \frac{V_{n\Delta}(p_T, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}$$

Calculation by Heinz et al.



p_T dependence of v_n



$1 < p_T^{ref} < 3$ GeV/c

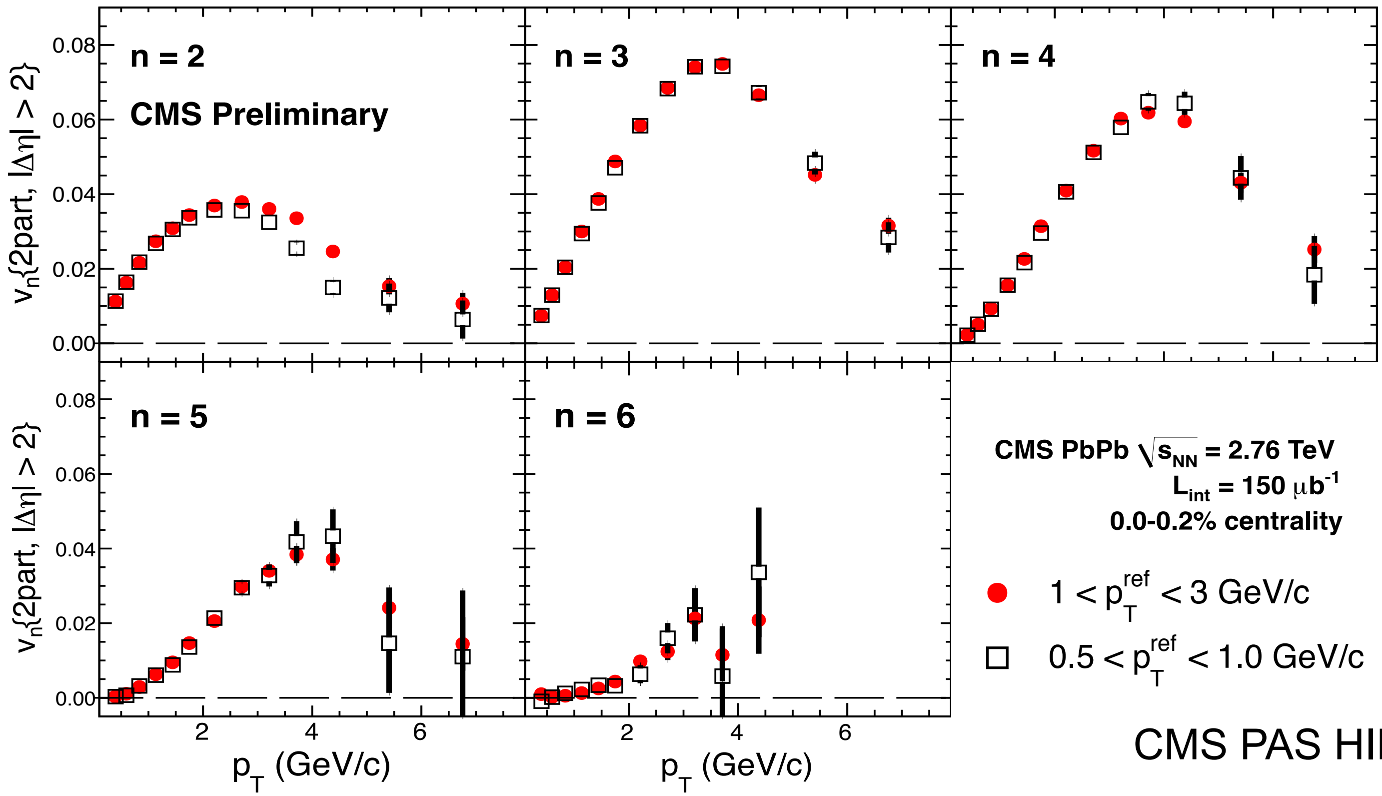
Hierarchy and magnitude of coefficients qualitatively reproduced by viscous hydrodynamics with fluctuating initial conditions

Factorization of $V_{n\Delta}(p_T^{trig}, p_T^{assoc})$

For pure flow-driven correlations,

$$V_{n\Delta}(p_T^{trig}, p_T^{assoc}) \stackrel{?}{=} v_n(p_T^{trig}) \times v_n(p_T^{assoc}) \quad \text{(factorization)}$$

Factorization test: $v_n(p_T)$ derived from different p_T^{ref}



CMS PAS HIN-12-011

Factorization breakdown for v_2 at high p_T → ***onset of non-flow?***

Factorization breakdown in hydrodynamics

Is factorization breakdown really inconsistent with hydro?

$$\frac{2\pi}{N}\frac{dN}{d\phi} \sim 1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos\left[n\left(\phi - \Psi_n(p_T)\right)\right]$$

- It is known that v_n is a function of p_T (also η, PID etc.)
- **Same is true for event plane angle Ψ_n (determined by final-state particles) due to event-by-event fluctuating initial-state geometry**

Gardim et al., PRC 87, 031901(R) (2013), Heinz et al., PRC 87, 034913 (2013)

Proposed to study the ratio:

$$r_n \equiv \frac{V_{n\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n\Delta}(p_T^{trig}, p_T^{trig})}\sqrt{V_{n\Delta}(p_T^{assoc}, p_T^{assoc})}}$$

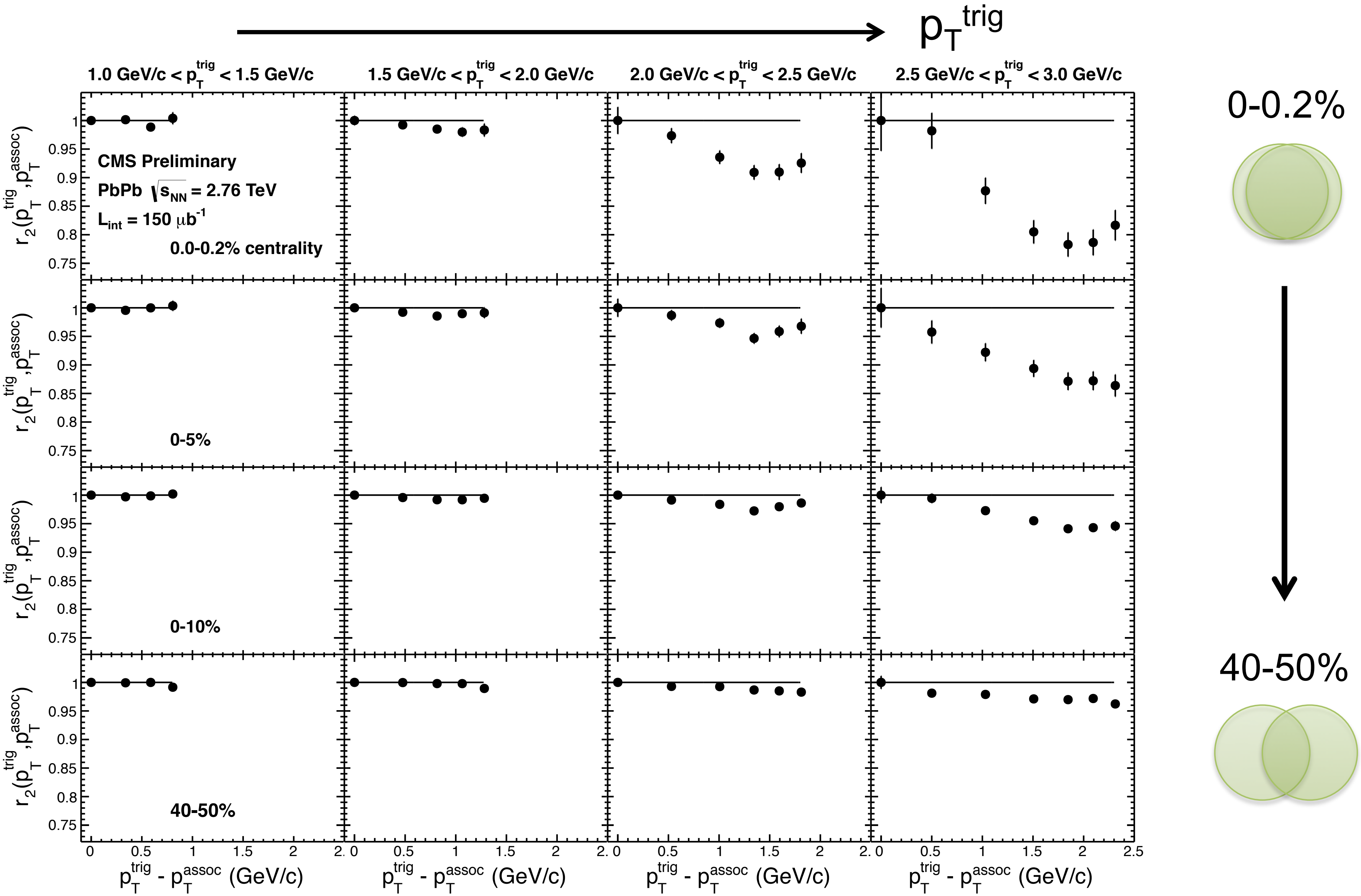
$r_n = 1$ ➔ factorization holds

$$= \frac{\left\langle v_n(p_T^{trig})v_n(p_T^{assoc})\cos[n(\Psi_n(p_T^{trig}) - \Psi_n(p_T^{assoc}))]\right\rangle}{\sqrt{v_n^2(p_T^{trig})v_n^2(p_T^{assoc})}}$$

In general, $r_n \leq 1$, if event-by-event Ψ_n depends on p_T

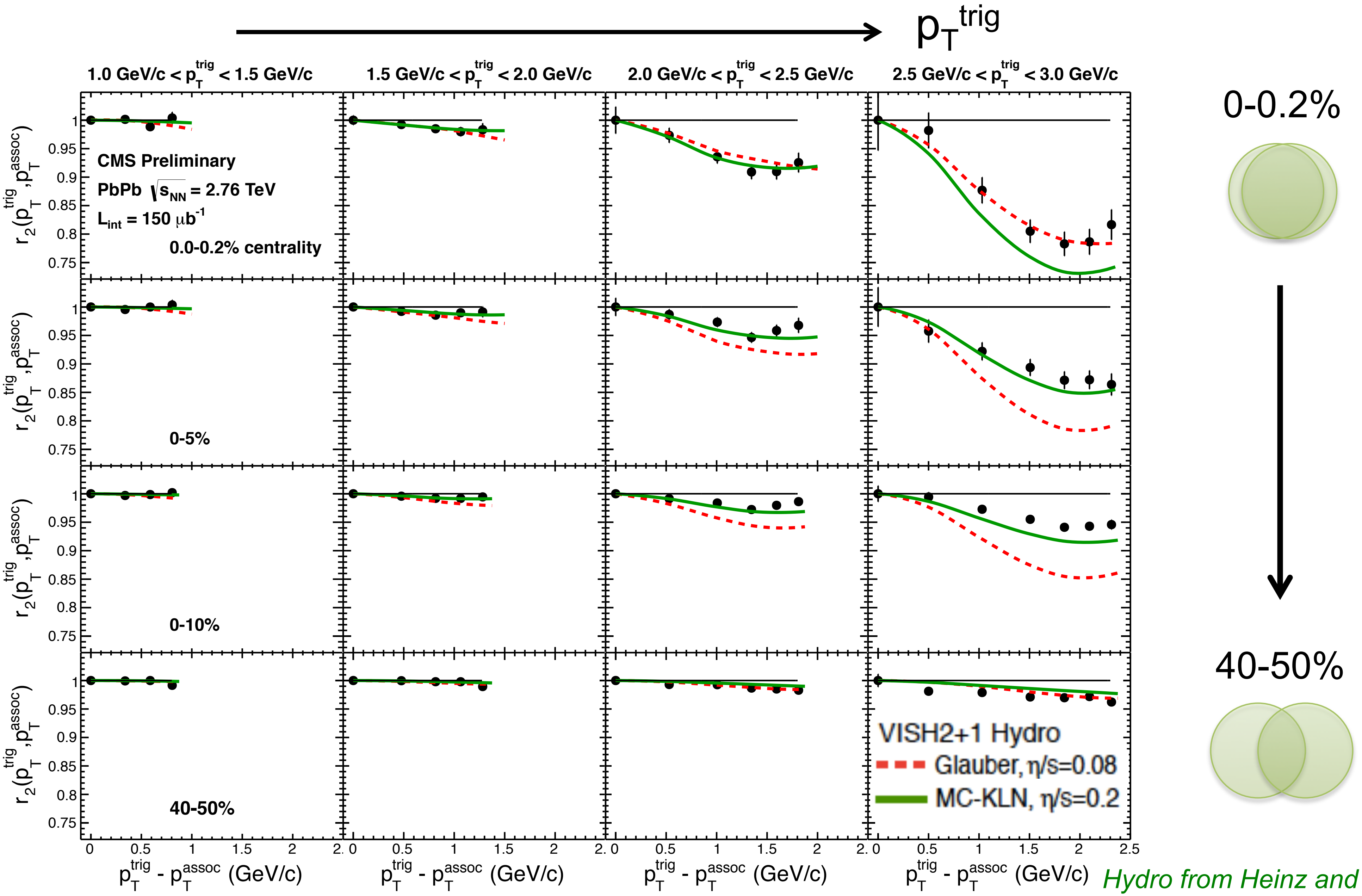
CMS

Factorization breakdown in hydrodynamics



Sizable effect for v_2 in ultra-central events

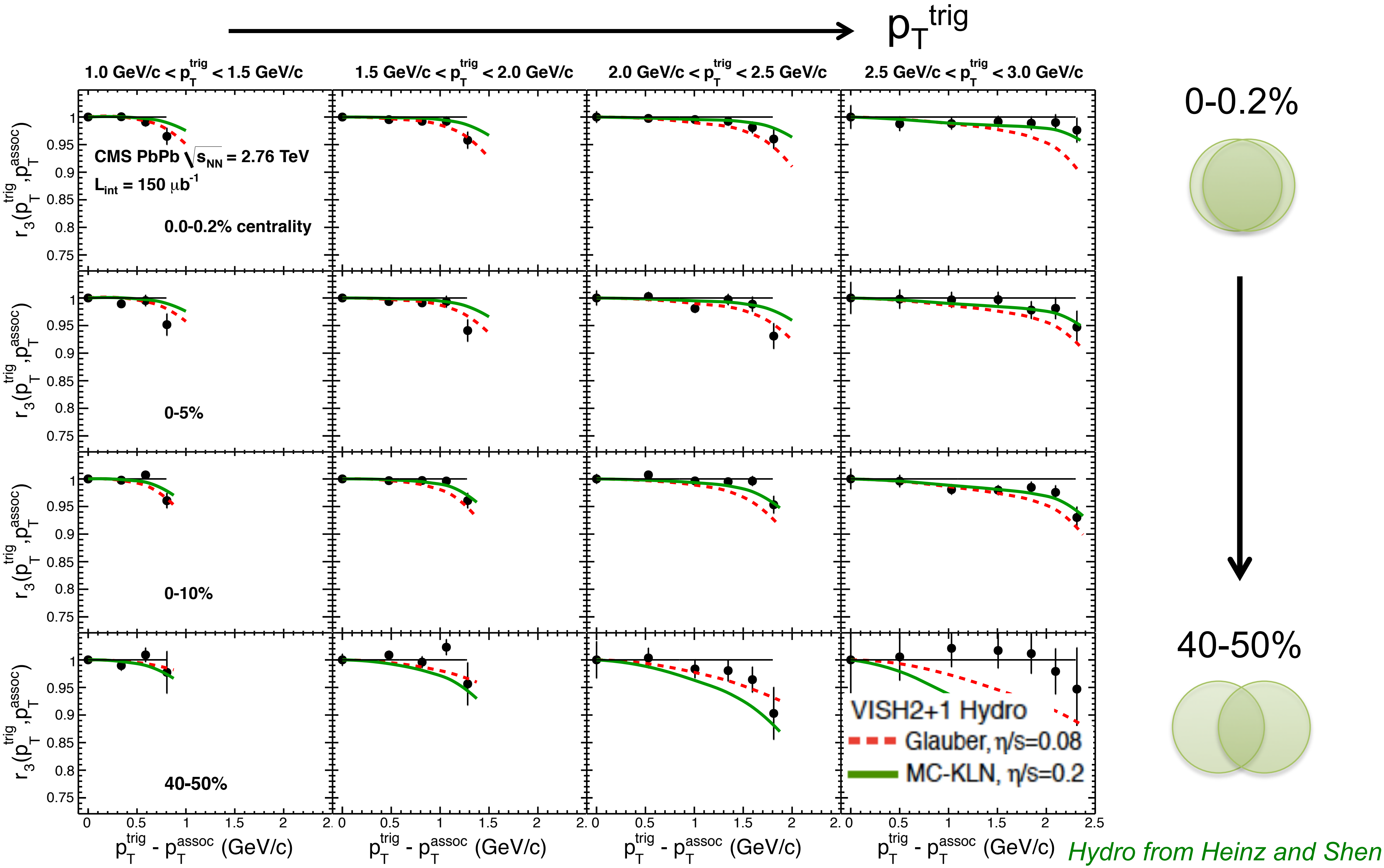
Factorization breakdown in hydrodynamics



Hydro from Heinz and Shen PRC 87, 034913 (2013)

Sizable effect for v_2 in ultra-central events

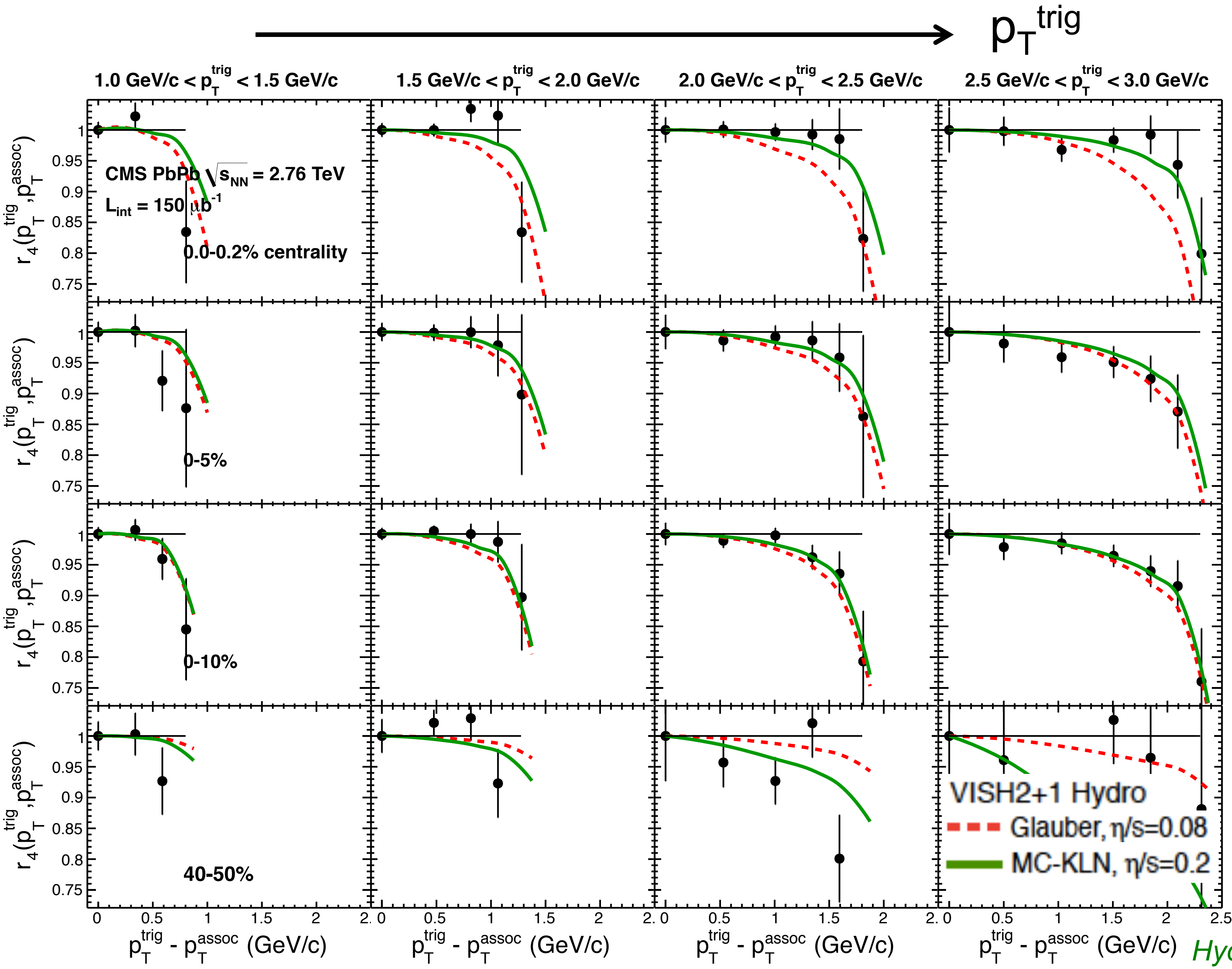
Factorization breakdown in hydrodynamics



Hydro from Heinz and Shen
PRC 87, 034913 (2013)

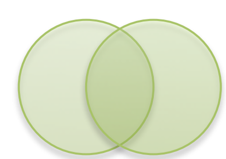
Smaller effect for v_3 ➔ more sensitive to η/s?

Factorization breakdown in hydrodynamics



0-0.2%

40-50%

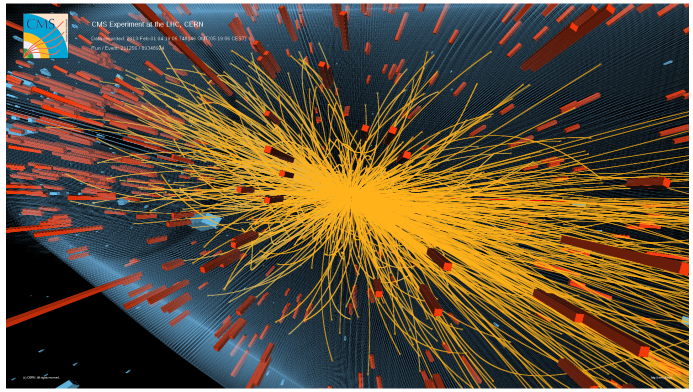


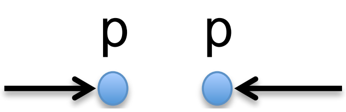
Hydro from Heinz and Shen PRC 87, 034913 (2013)

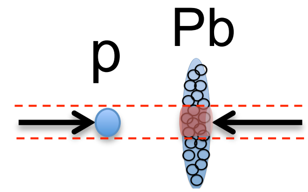
Smaller effect for v_4 ➔ more sensitive to η/s?

"Flow" in tiny collison systems?

High-multiplicity
pPb event
(418 tracks)

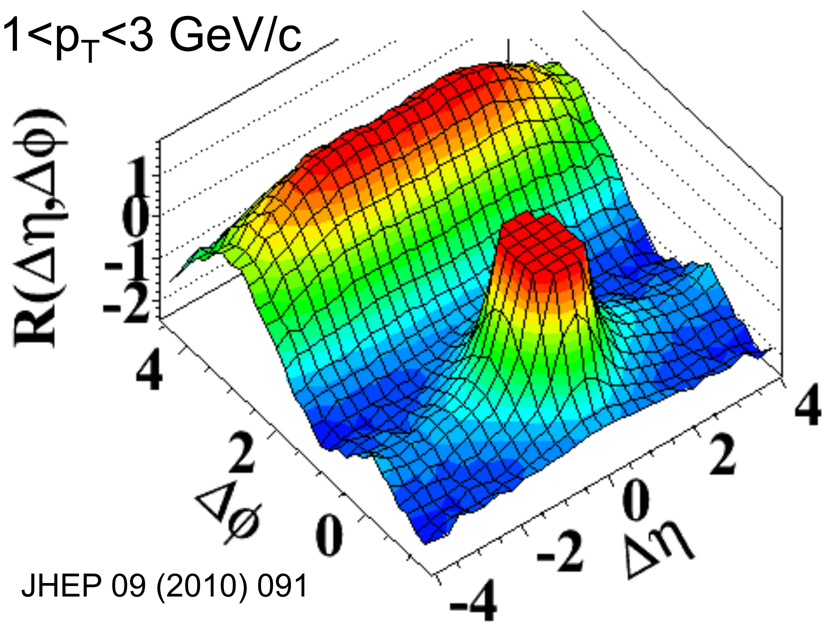






pp 7 TeV, N>=110 **0.0007% central**

$1<p_T<3$ GeV/c

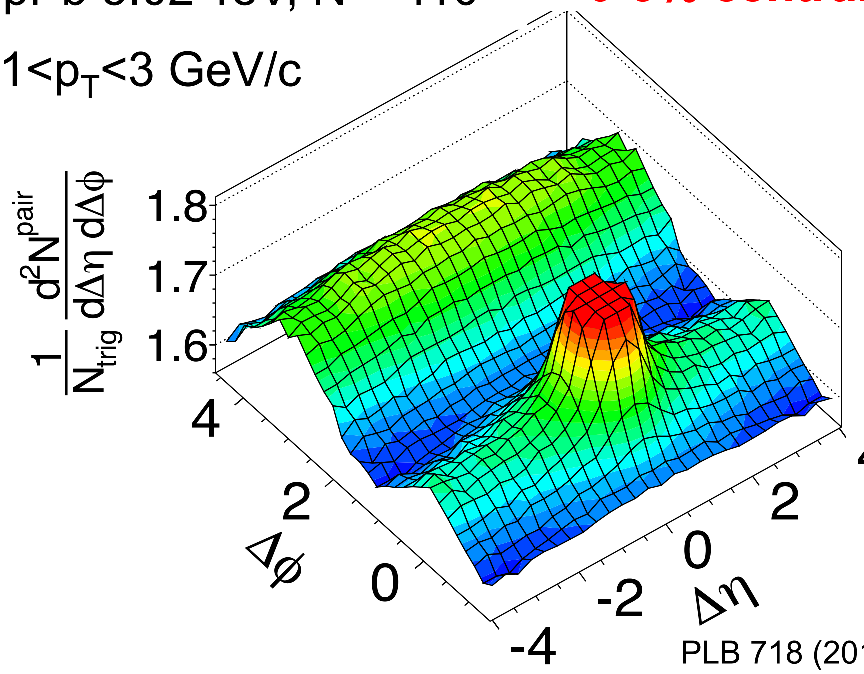


JHEP 09 (2010) 091

Most sensitive to fluctuations inside a nucleon!

pPb 5.02 TeV, N>=110 **0-3% central**

$1<p_T<3$ GeV/c



PLB 718 (2013) 795

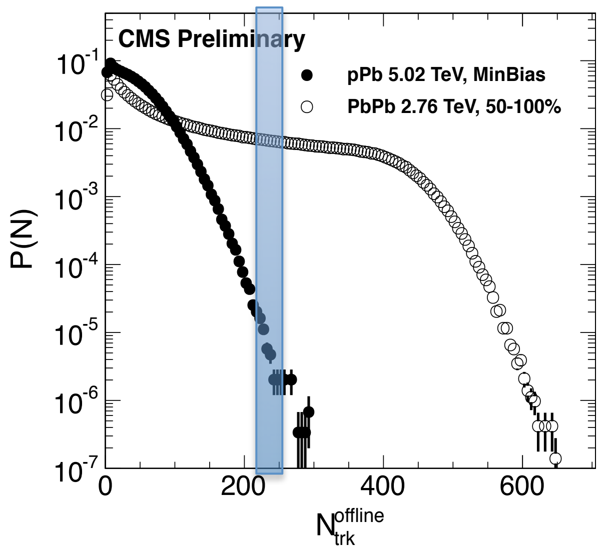
2 million MB events from 2012 pilot run

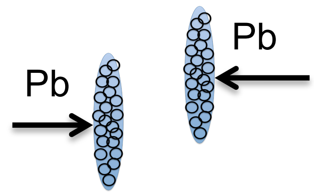
Flow (or QGP) manifests also in pp and pPb?
Or quantum interference of gluon (CGC model)?

New pPb data from 2013 run

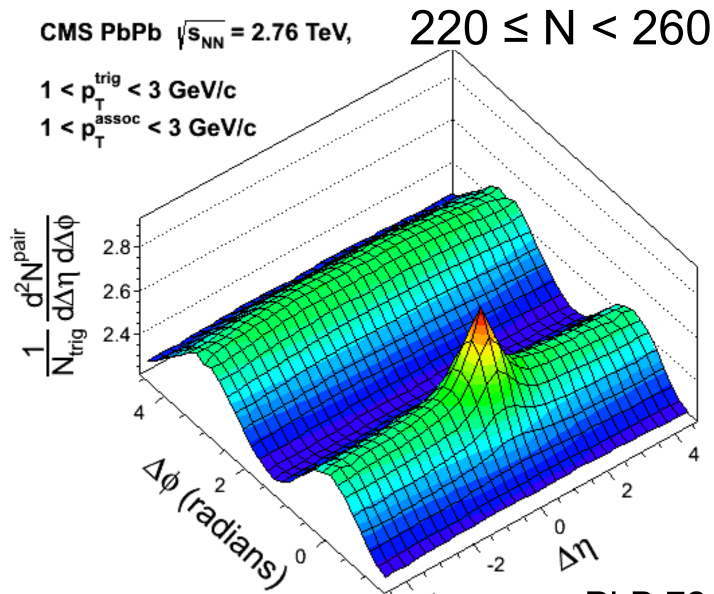
Pushing into very high multiplicity region for pPb

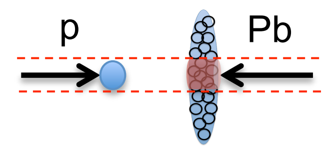
60 billion sampled pPb events at 5 TeV from 2013 run



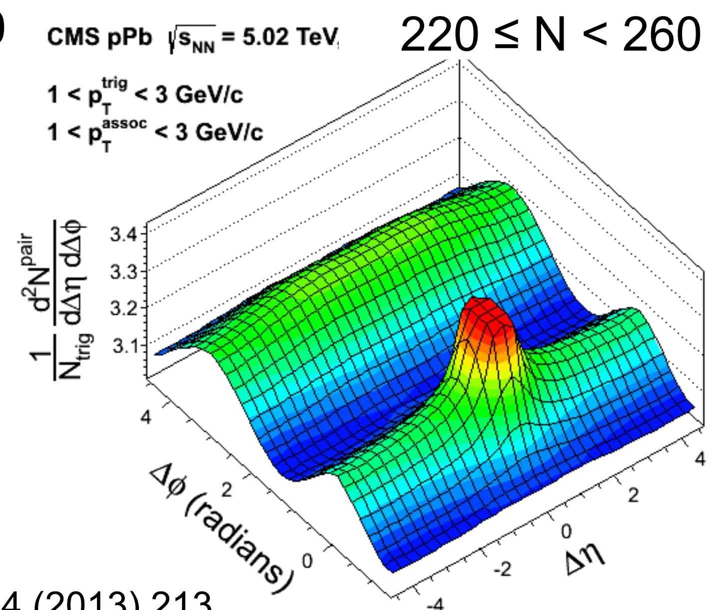


~ 55-60% centrality





0-0.0003% most central



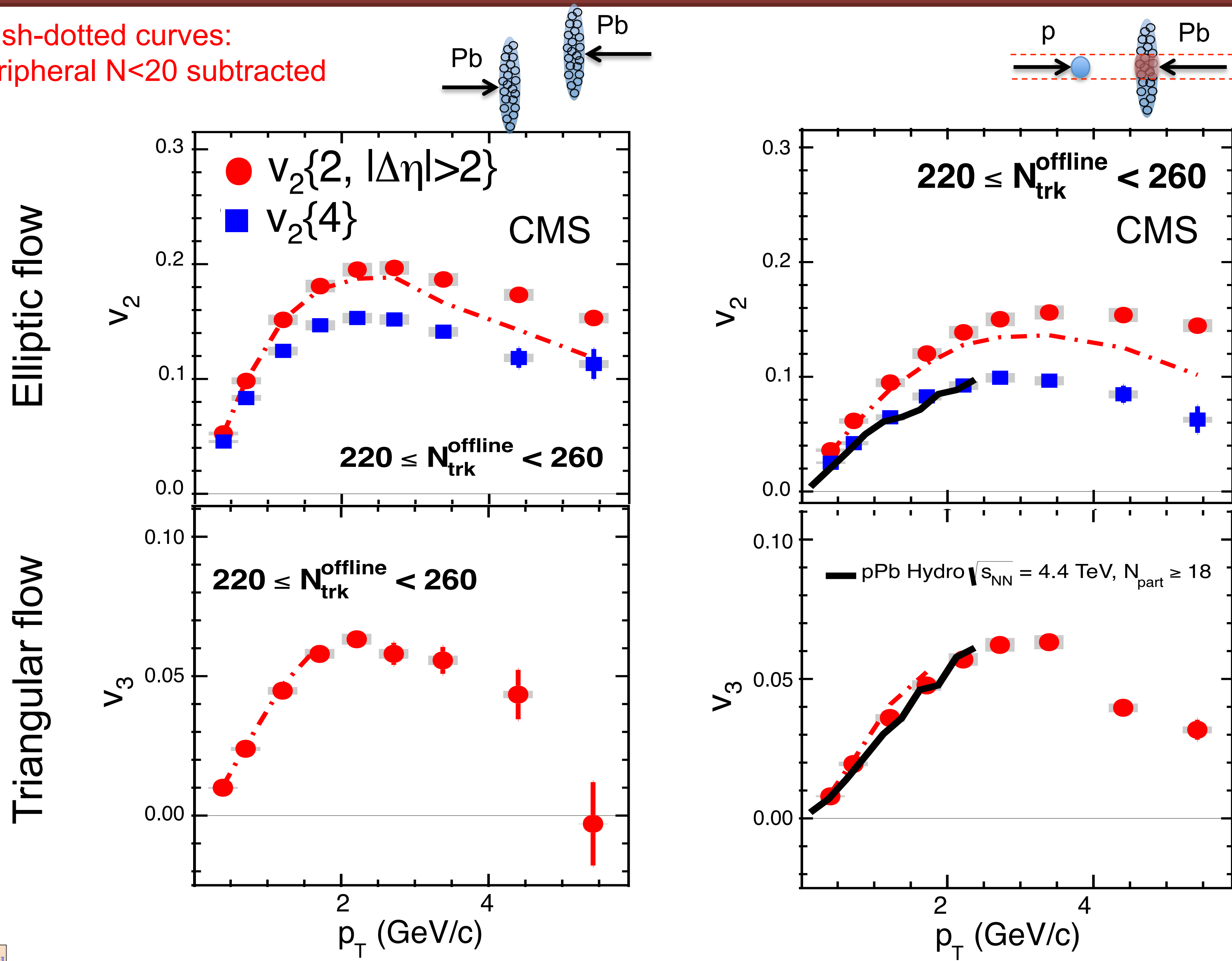
PLB 724 (2013) 213

Hydrodynamics well established

The phenomena is very similar in pPb

p_T dependence of flow (v_n) in pPb

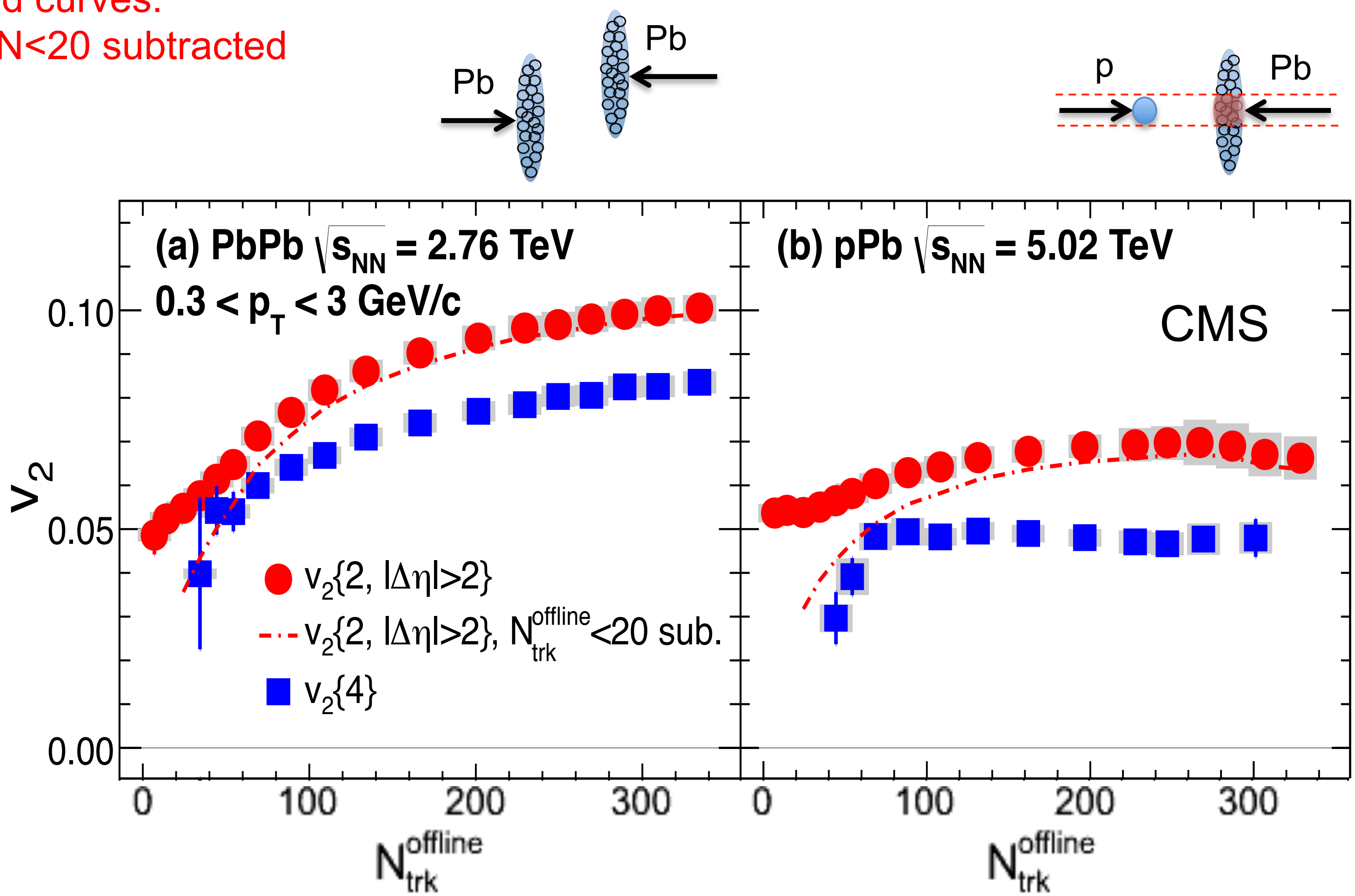
Dash-dotted curves:
peripheral N<20 subtracted



Remarkable similarity of v_n for PbPb and pPb

Multiplicity dependence of elliptic flow (v_2)

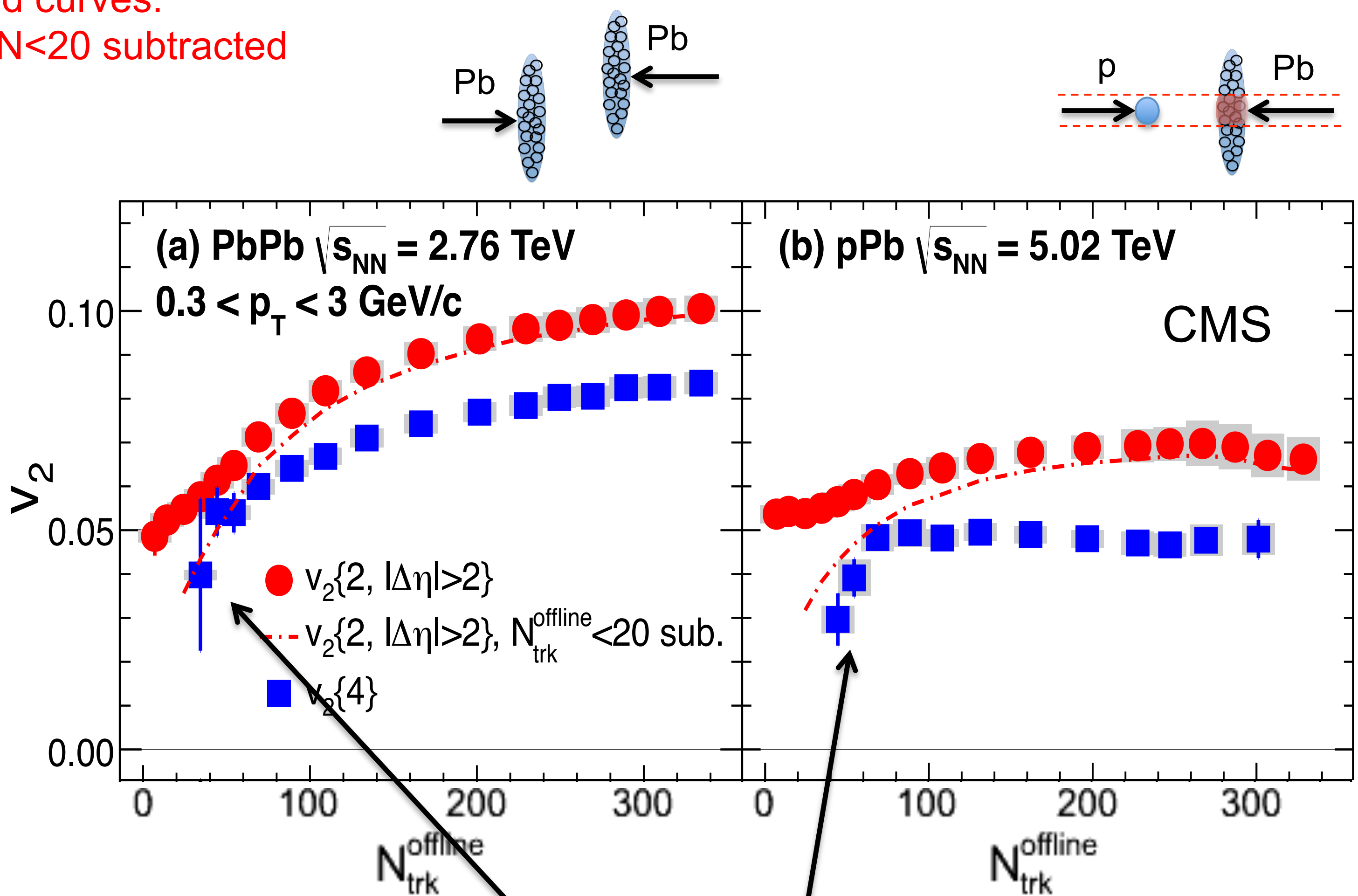
Dash-dotted curves:
peripheral N<20 subtracted



For both systems, v_2 increases with multiplicity

Multiplicity dependence of elliptic flow (v_2)

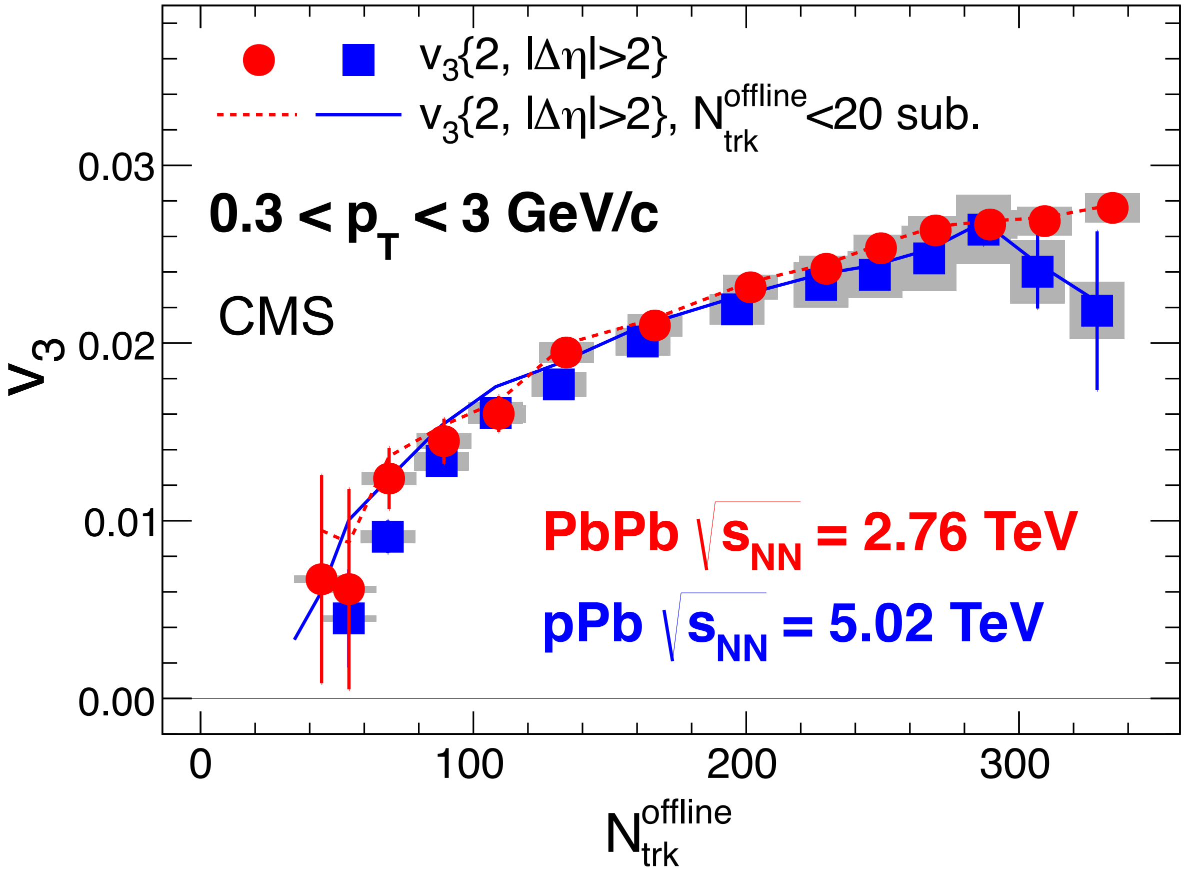
Dash-dotted curves:
peripheral N<20 subtracted



$v_2\{4\}$ becomes significant at N ~ 40

For both systems, v_2 increases with multiplicity

Multiplicity dependence of triangular flow (v_3)

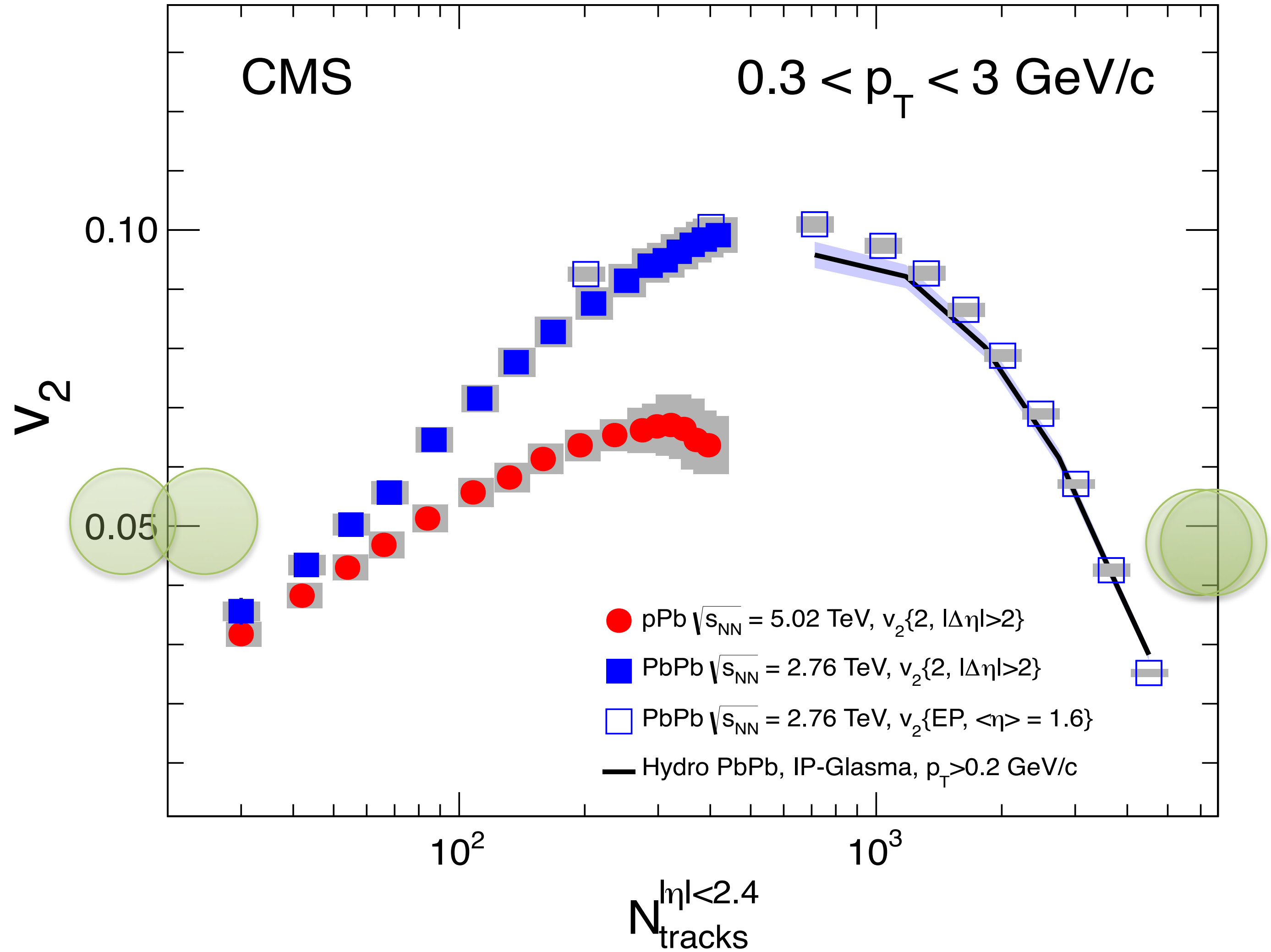


Striking similarity of v_3 for PbPb and pPb systems, although drastically different collision geometry and its fluctuations

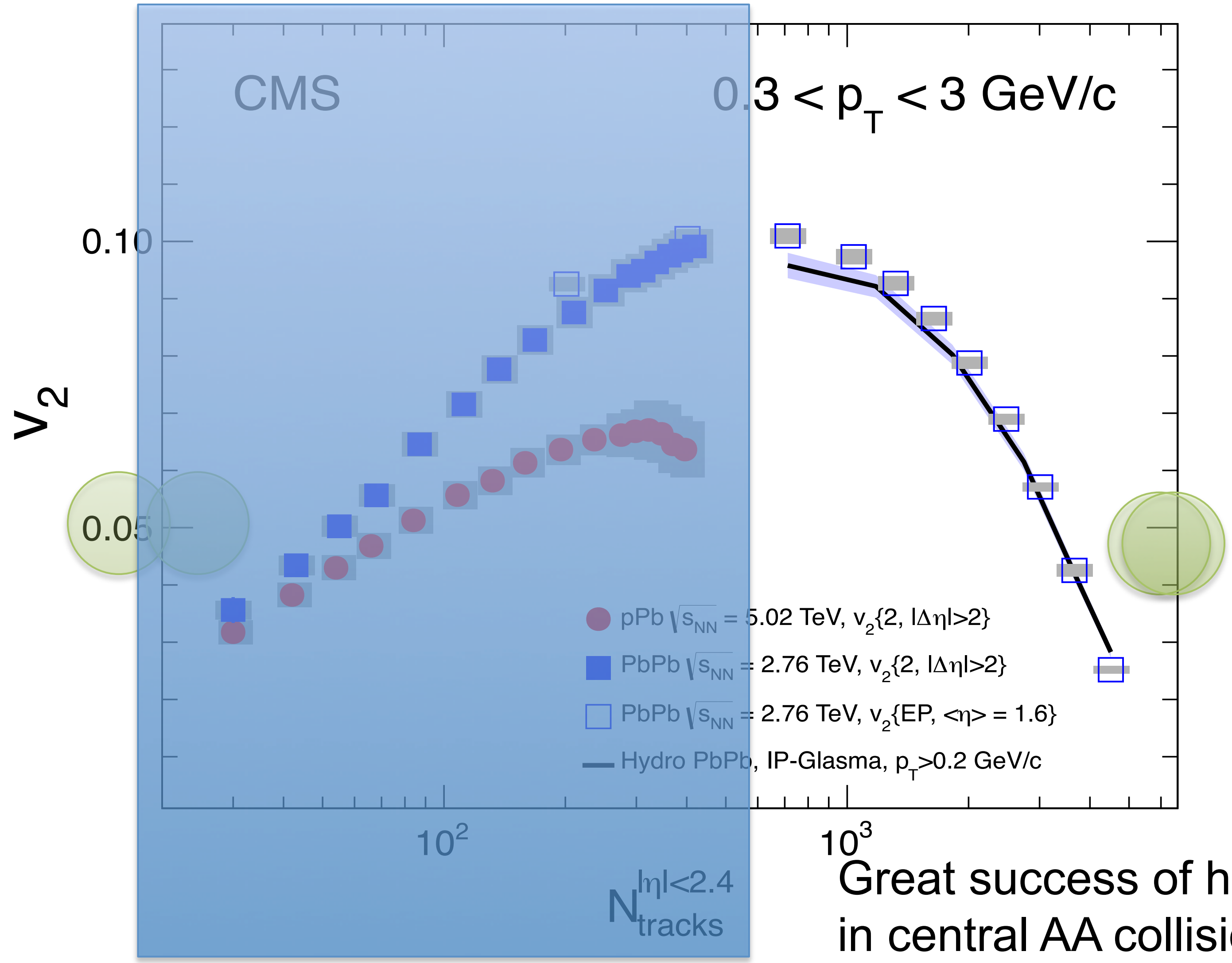
- *Can this be understood in hydrodynamics?*
- *In CGC model, intrinsic gluon correlations predict v_3=0*

v_3 may be a critical challenge to both models

Quest for a coherent picture of flow phenomena



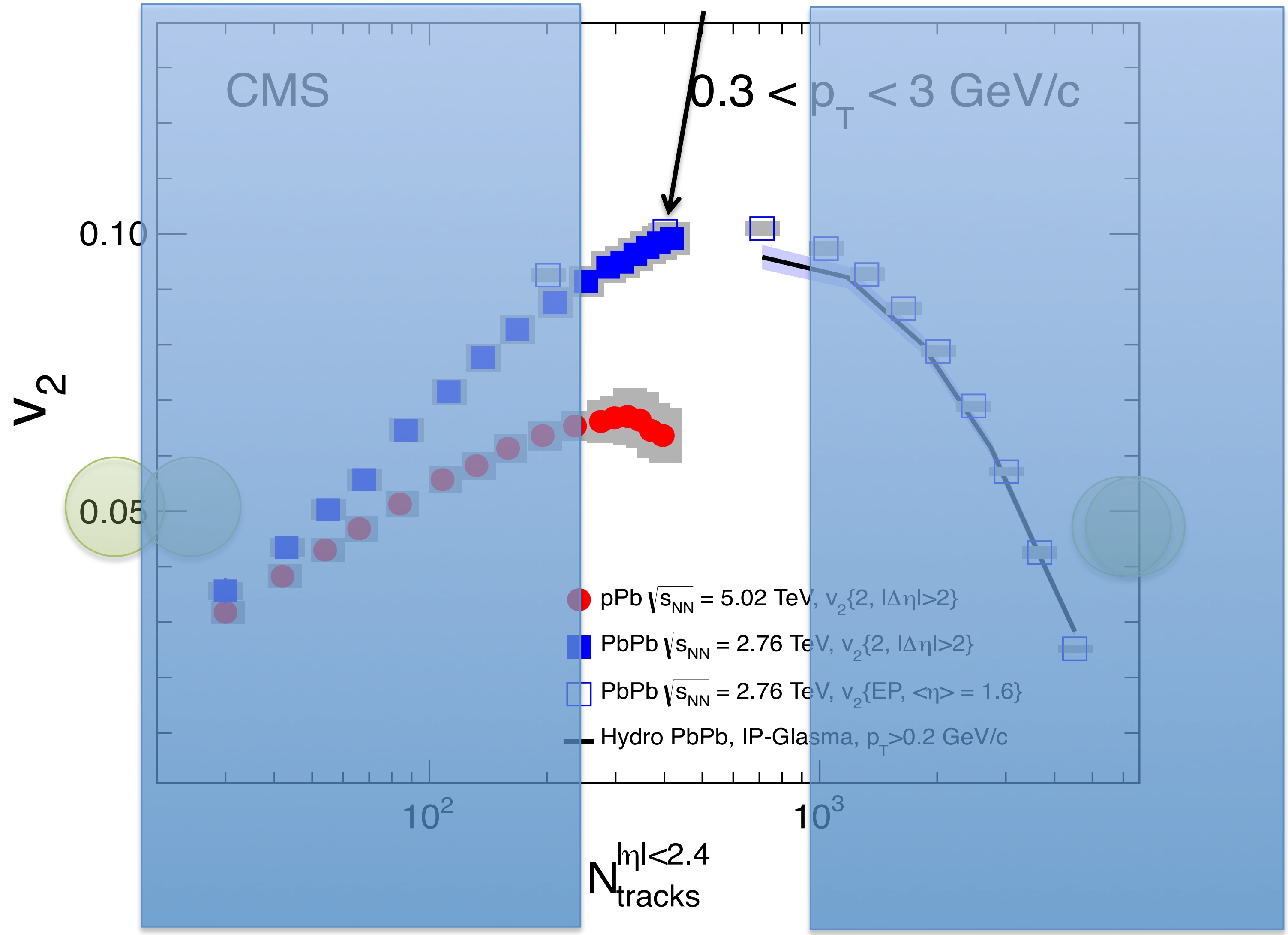
Quest for a coherent picture of flow phenomena



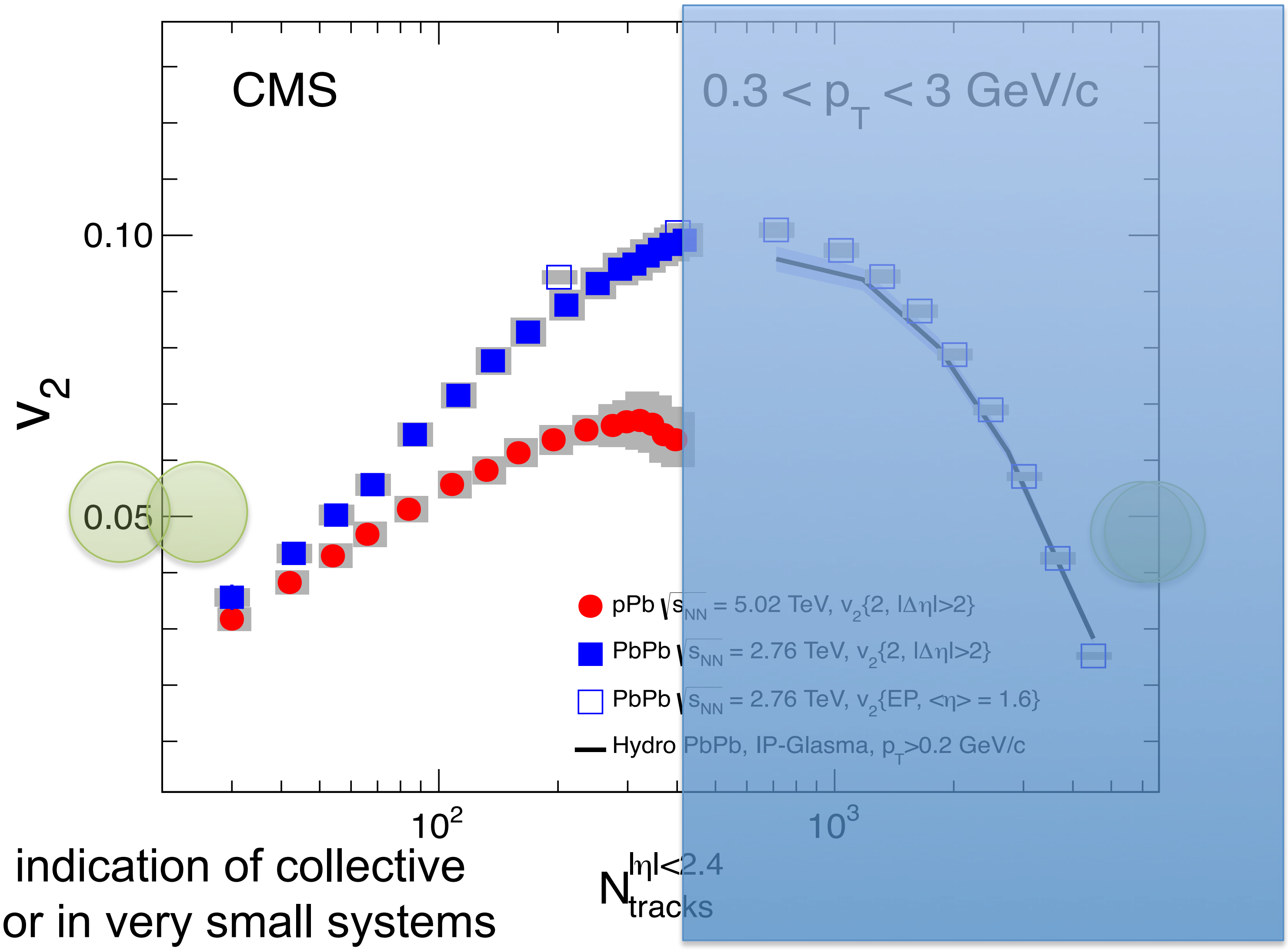
Great success of hydrodynamics in central AA collisions

Quest for a coherent picture of flow phenomena

Breakdown of nearly ideal hydrodynamics
in transition to very peripheral AA collisions



Quest for a coherent picture of flow phenomena

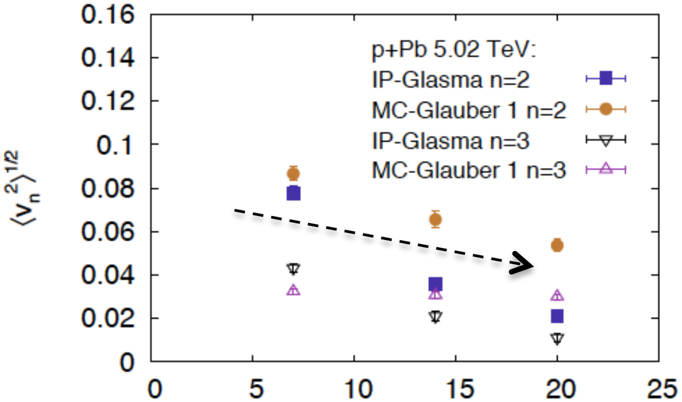


Strong indication of collective behavior in very small systems

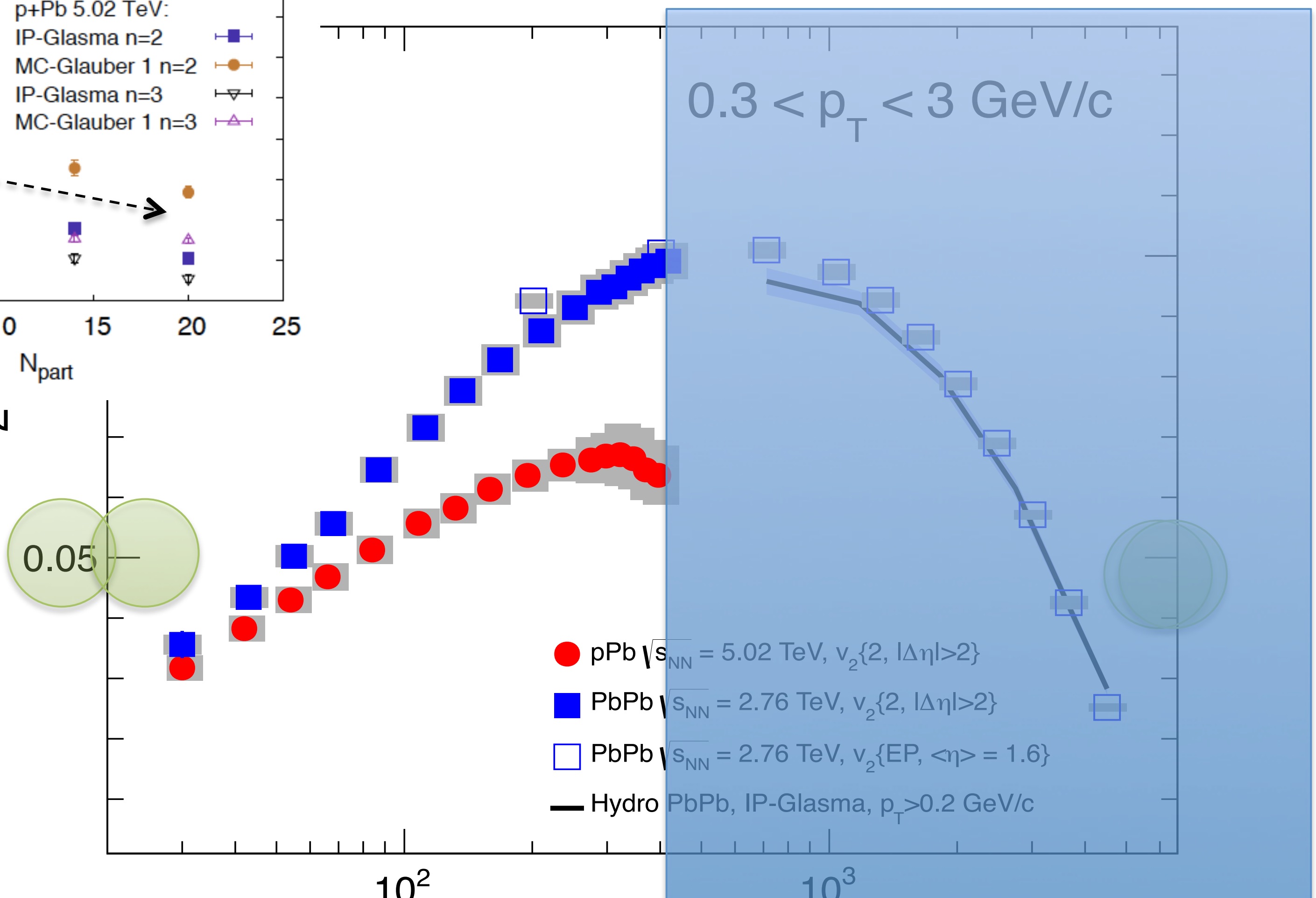
It is imperative to achieve a coherent picture of flow phenomena among various systems

Quest for a coherent picture of flow phenomena

"Incorrect" centrality trend in hydro



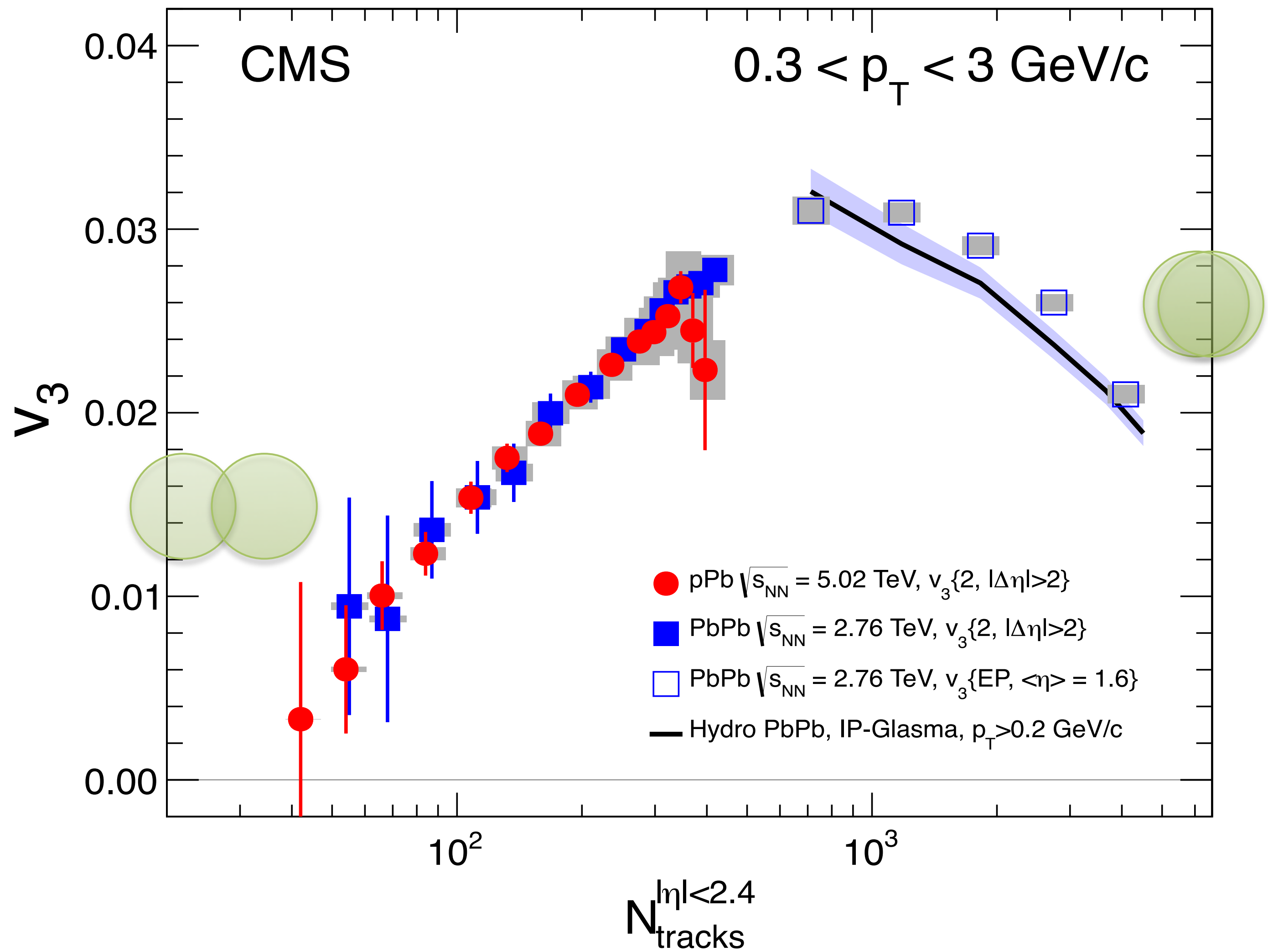
Bzdak et al.,
PRC 87, 064906 (2013)



Strong indication of collective behavior in very small systems

It is imperative to achieve a coherent picture of flow phenomena among various systems

Quest for a coherent picture of flow phenomena



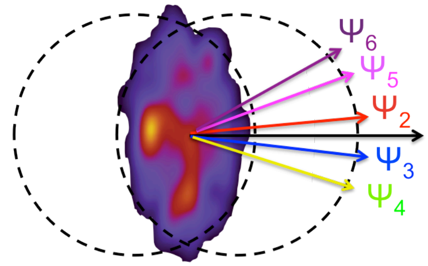
How to understand the almost identical v_3 for pPb and PbPb?

And will this trend continue for more central pPb ?

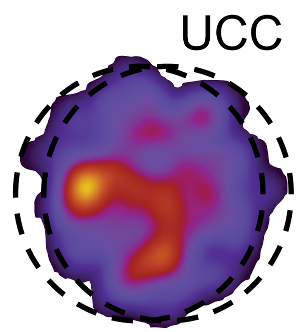
Summary

CMS have performed comprehensive measurements of flow phenomena over various collision systems of ***pp***, ***pPb*** and ***PbPb***

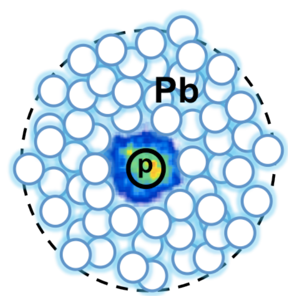
- Differential measurements of higher-order v_n provide new insight on initial-state fluctuations



- Ultra-central PbPb collisions are new testing grounds of initial-state fluctuations and provide stringent constraints to η/s of the QGP

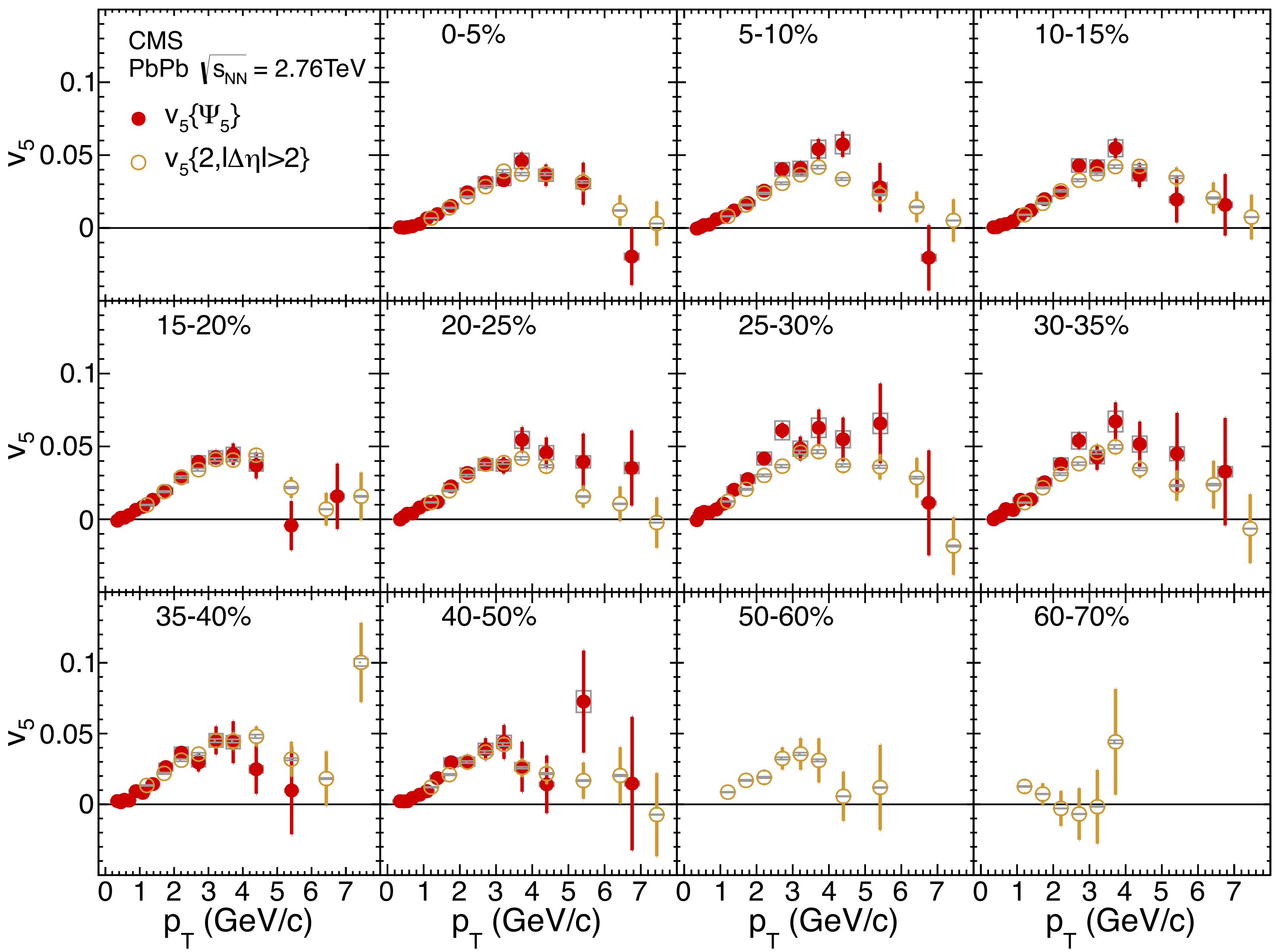


- Factorization breakdown of two-particle correlations is consistent with hydro with event-by-event p_T-dependent event plane angle
- Observation of strong collective behavior in pPb (pp) that is remarkably similar to PbPb: *manifestation of tiny QGP droplet?*

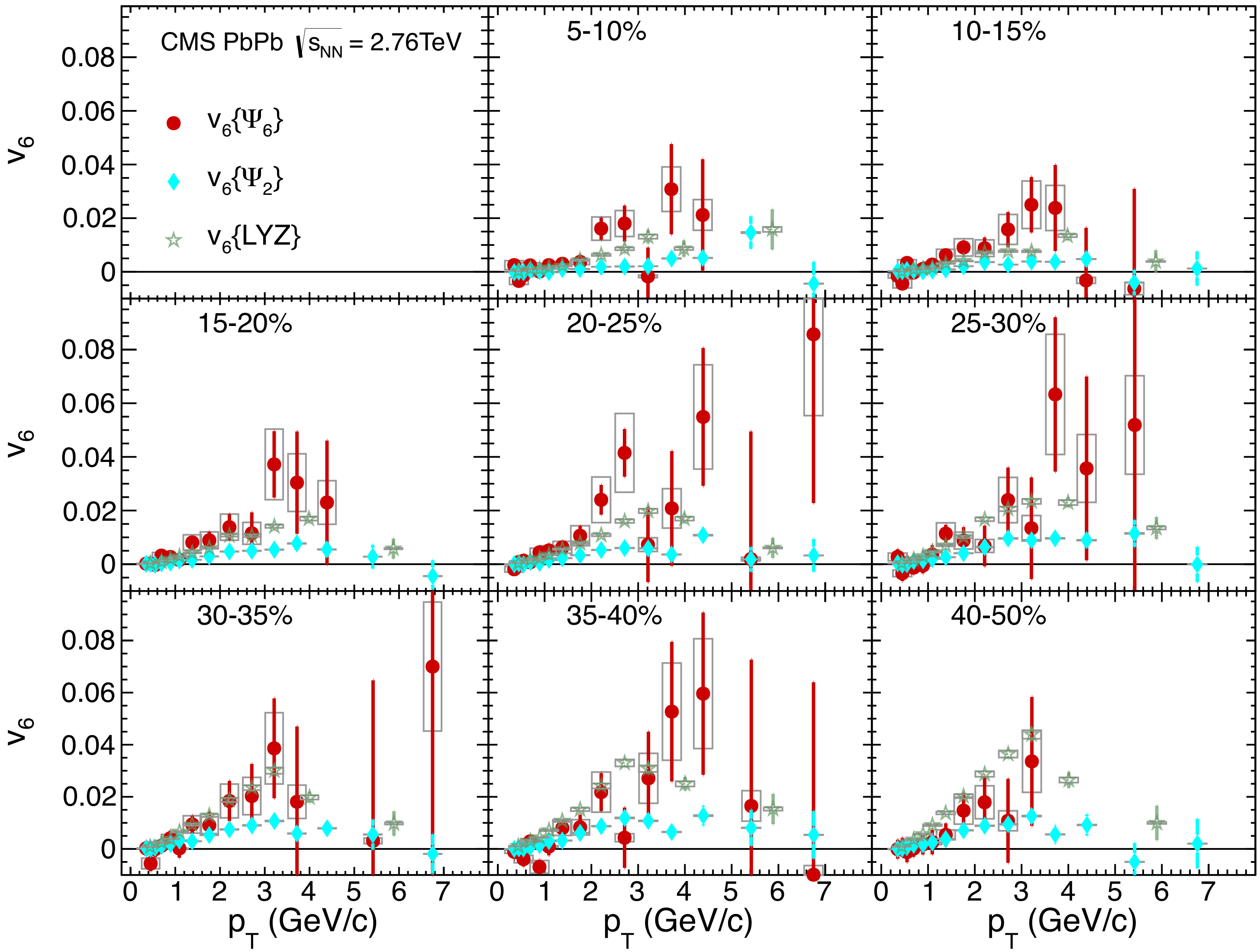


Backup

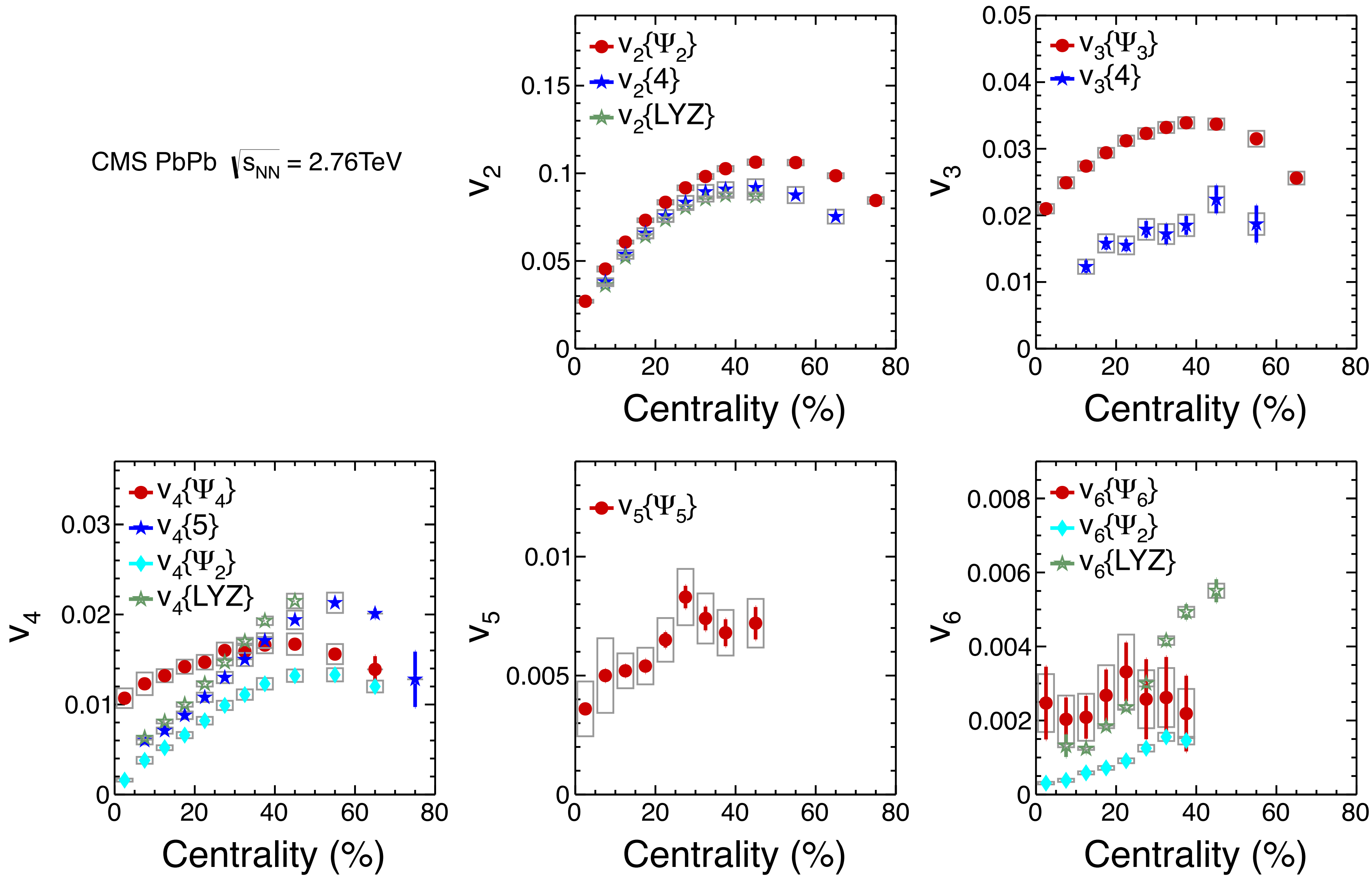
Higher-order flow (v_n) in PbPb



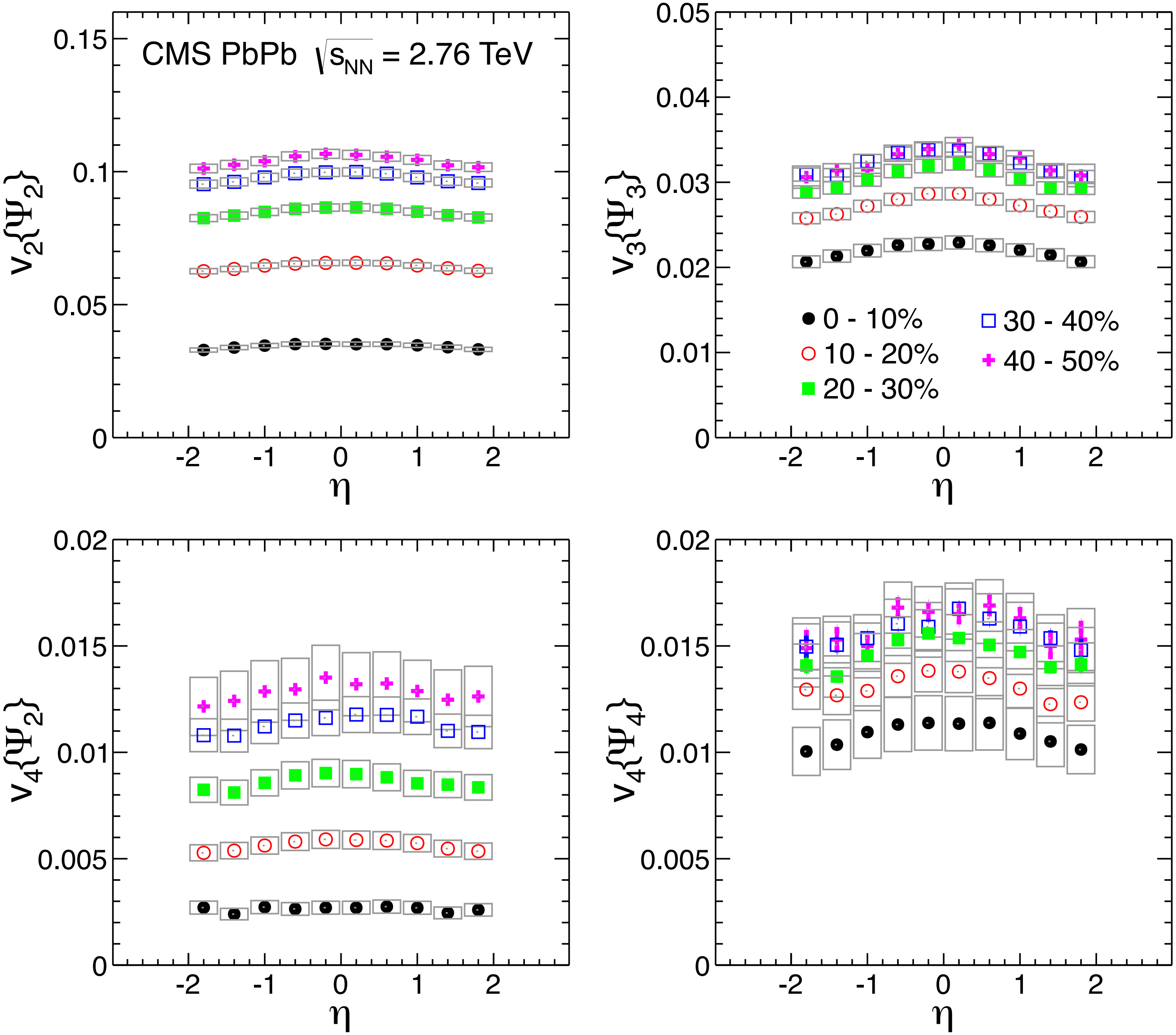
Higher-order flow (v_n) in PbPb



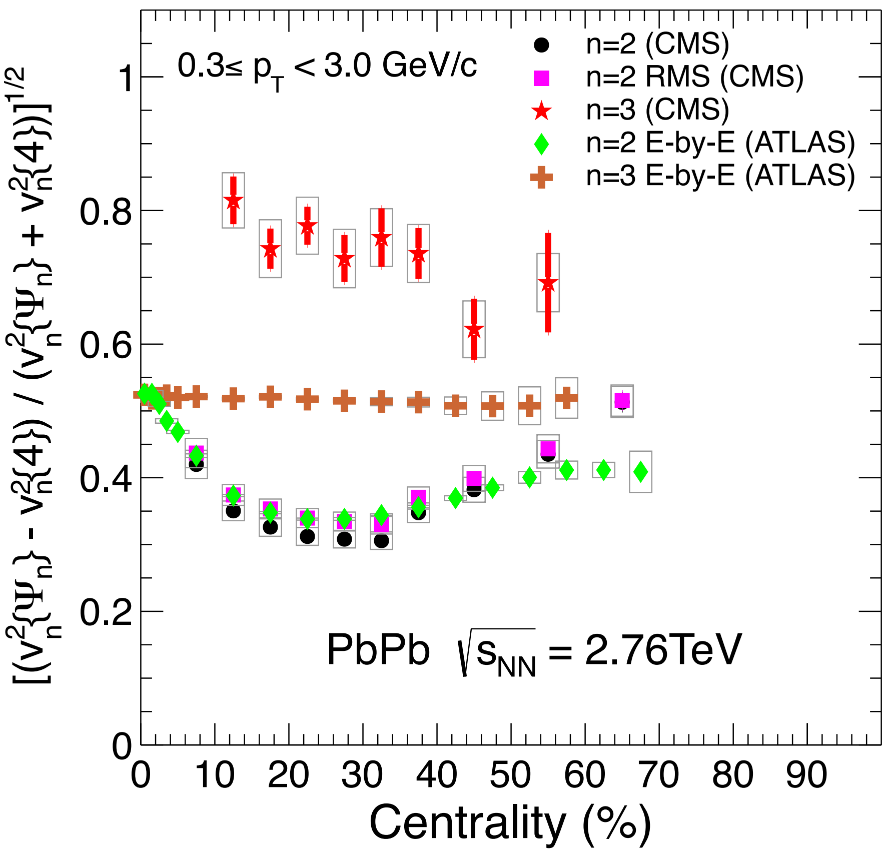
Higher-order flow (v_n) in PbPb

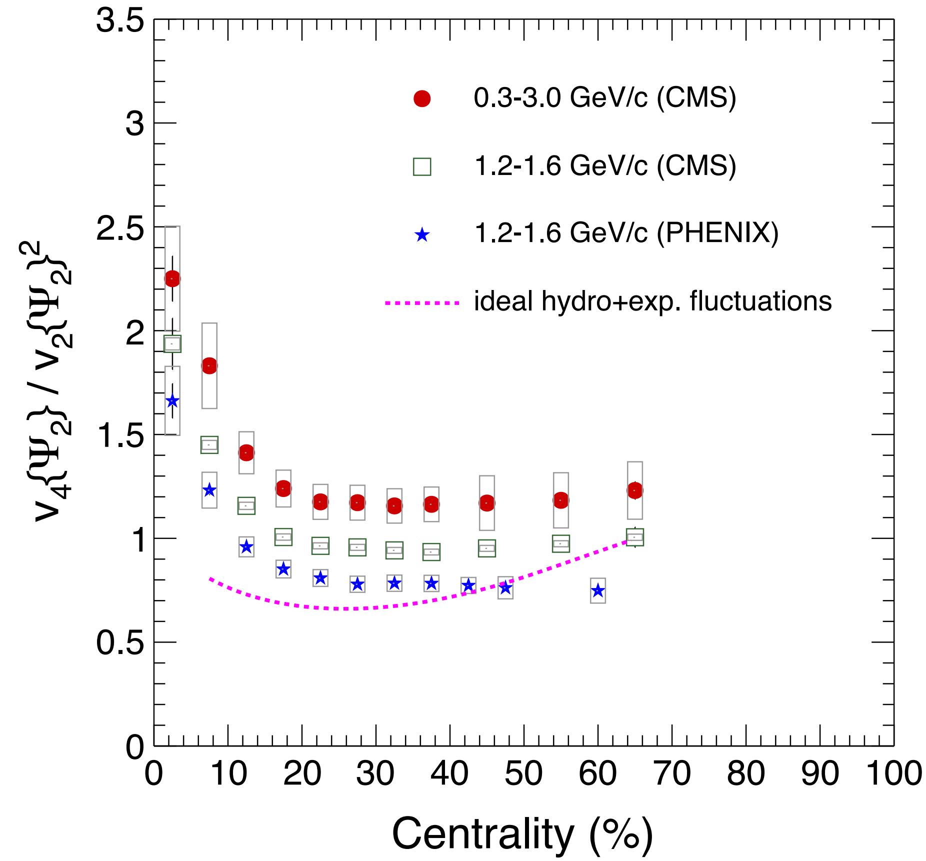


Higher-order flow (v_n) in PbPb



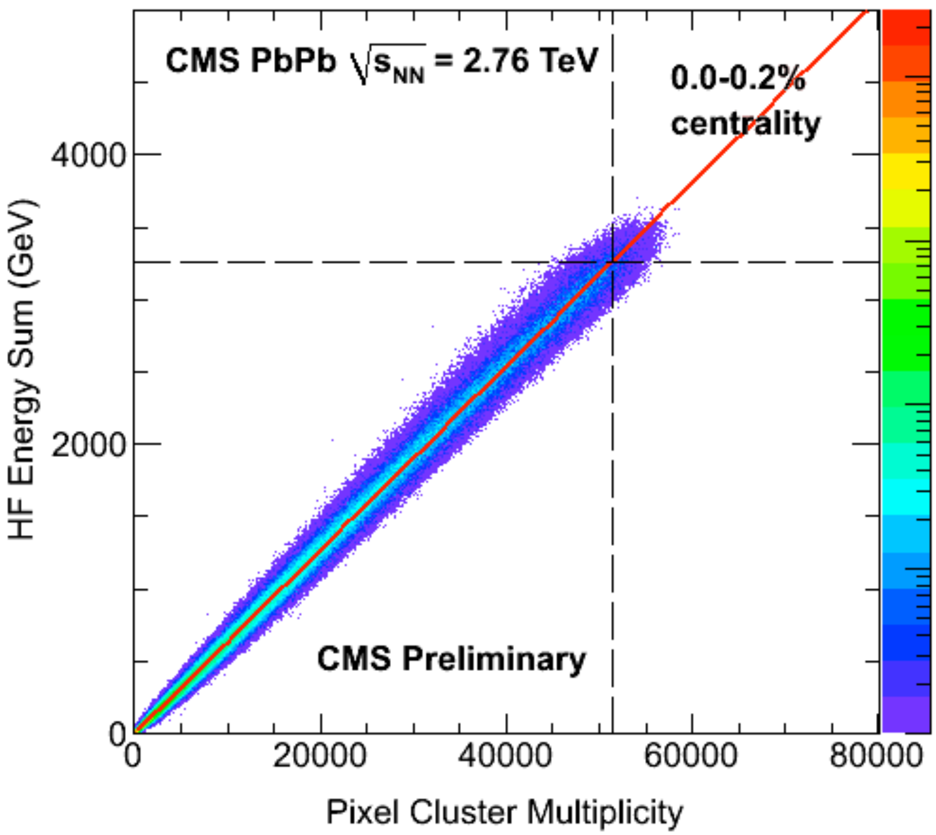
Higher-order flow (v_n) in PbPb



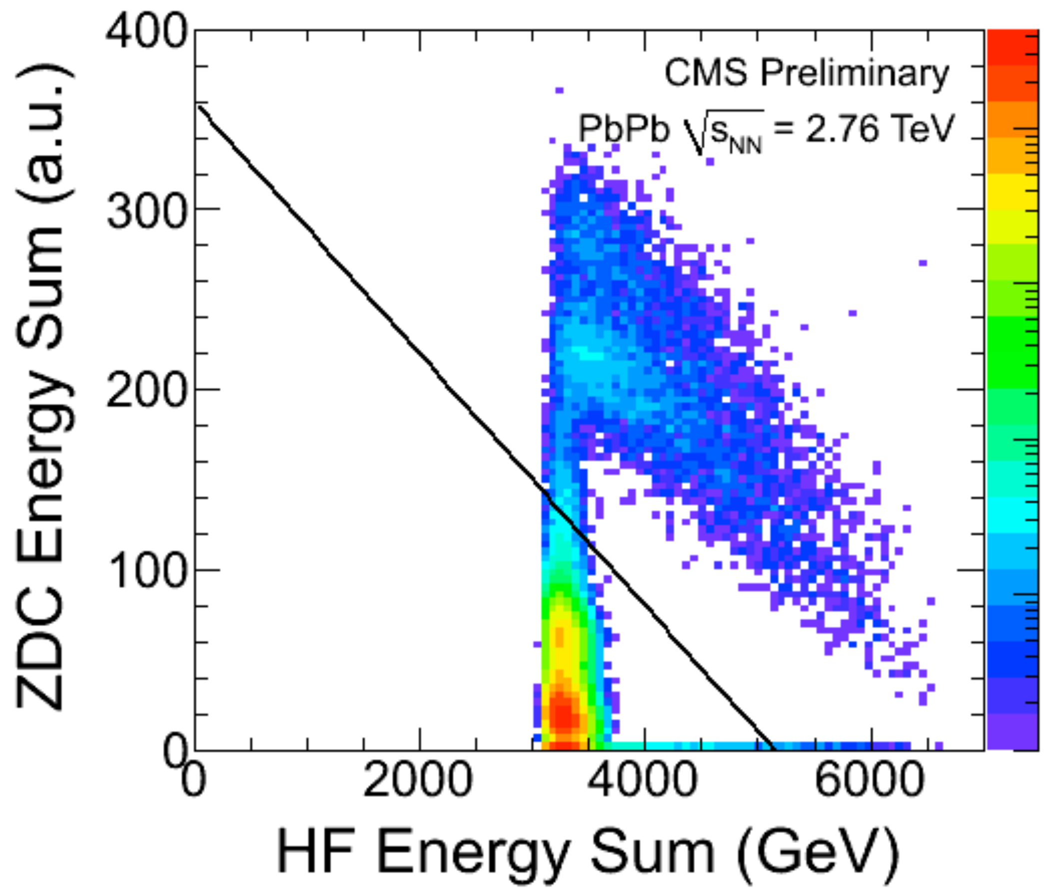


Flow phenomena in UCC events

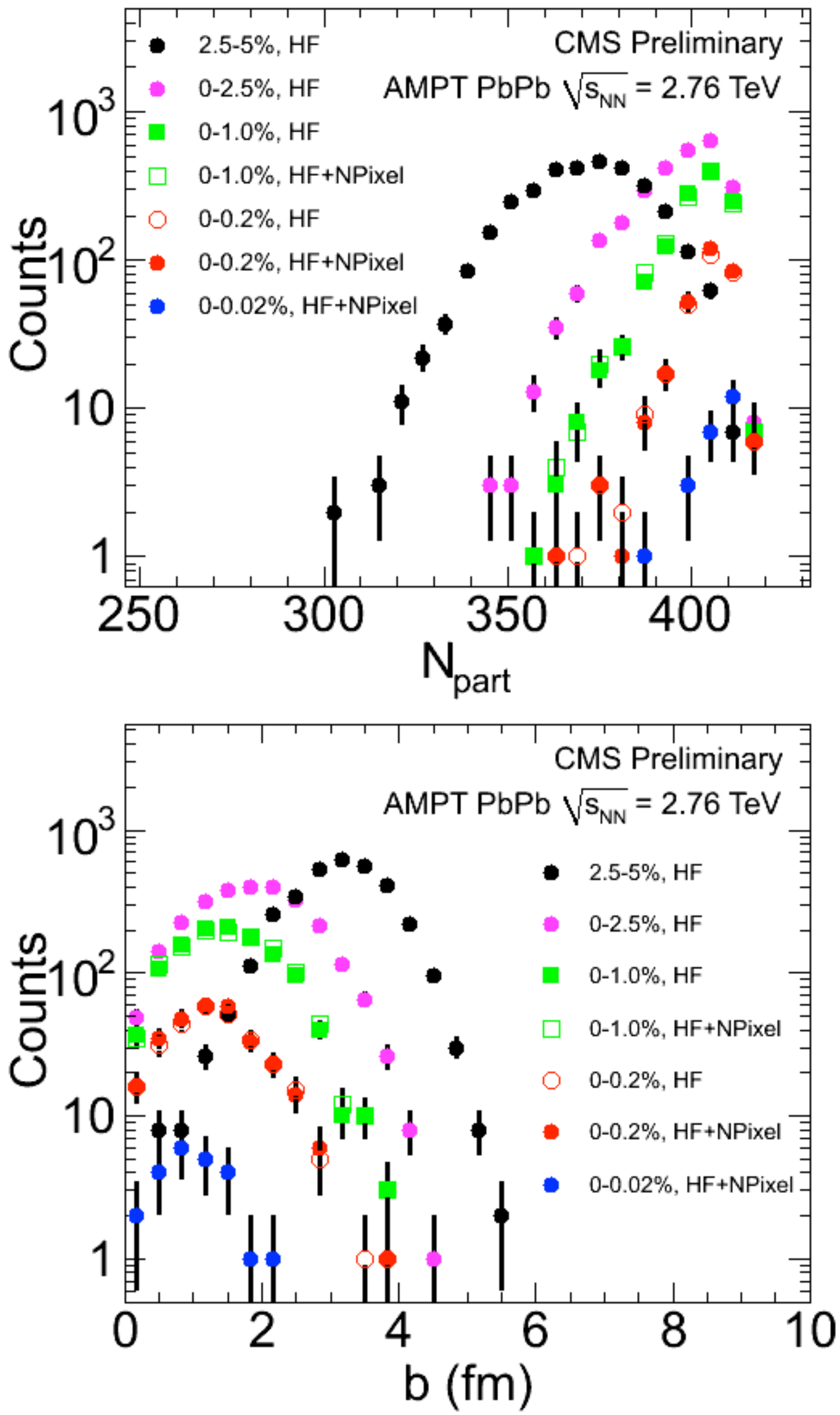
UCC selection



Pileup rejection

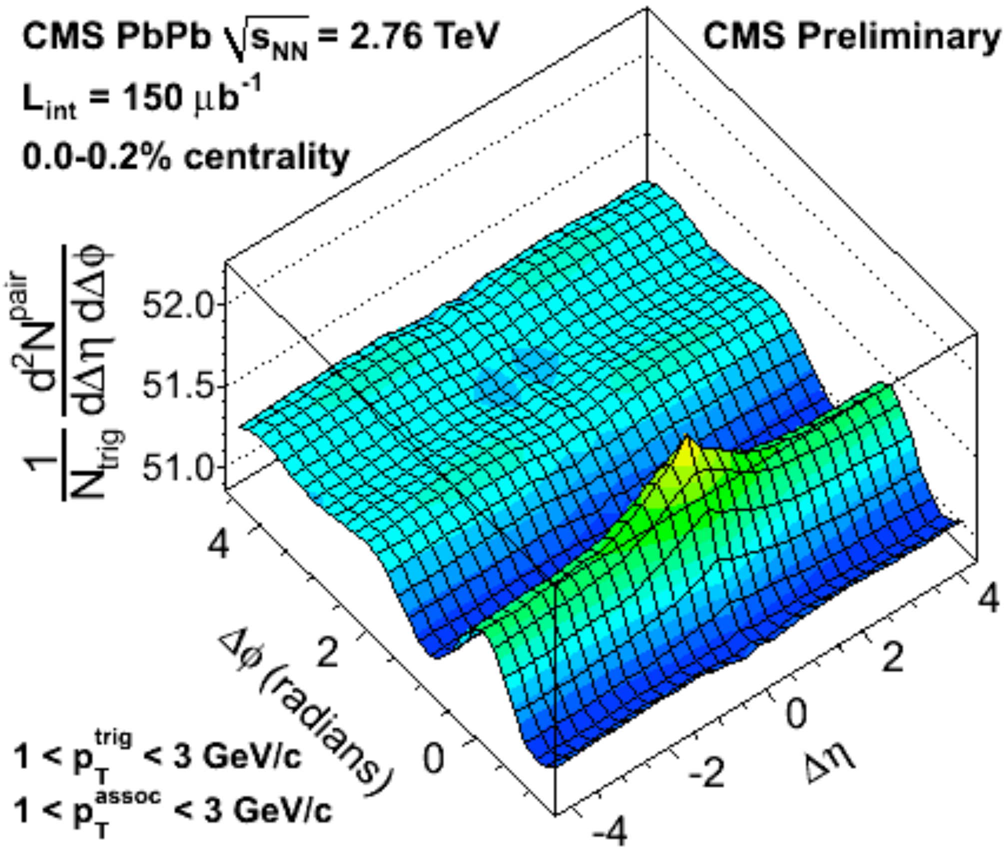


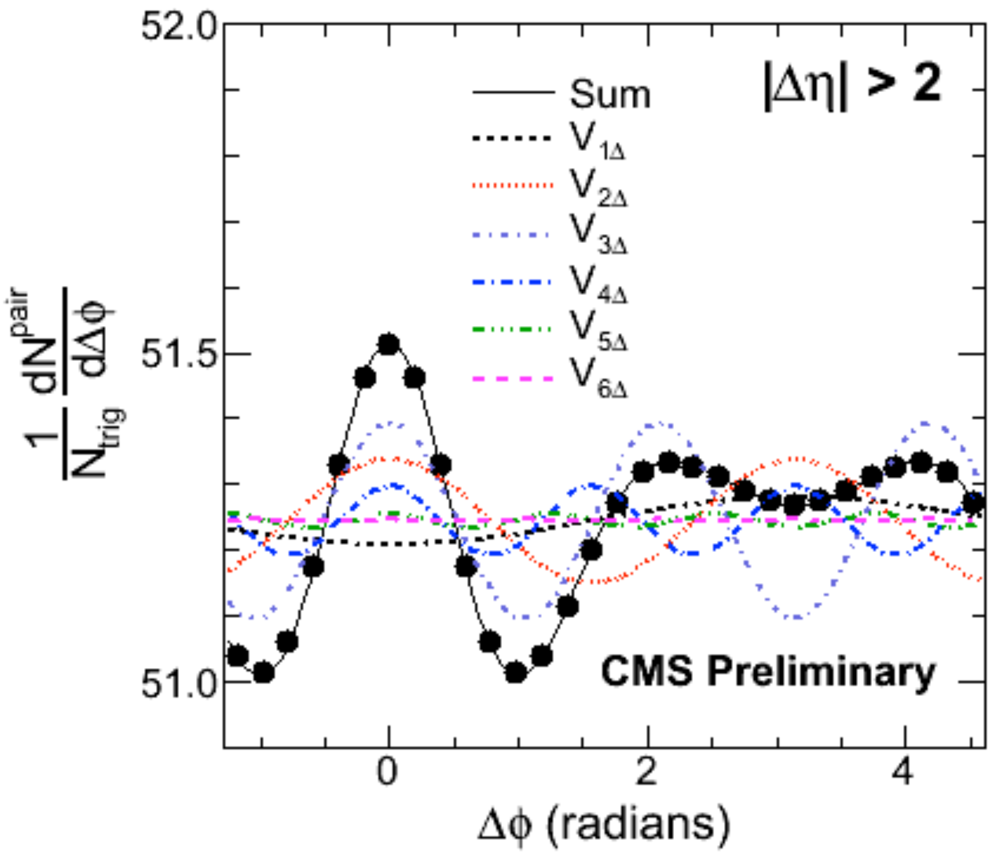
Flow phenomena in UCC events



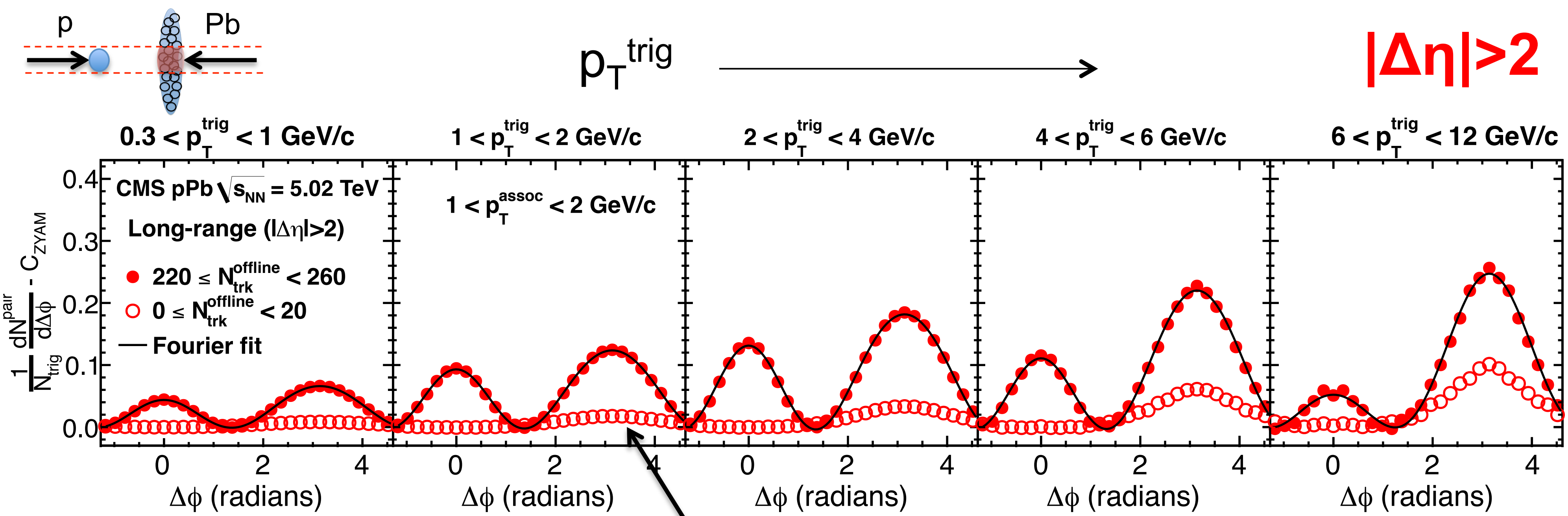
Centrality	N_{part}	RMS
0.00–0.02%	406.2	3.6
0.0–0.2%	404.0	6.9
0.0–1.0%	401.1	8.3
0.0–2.5%	395.8	11.3
2.5–5.0%	381.3	19.5

Flow phenomena in UCC events

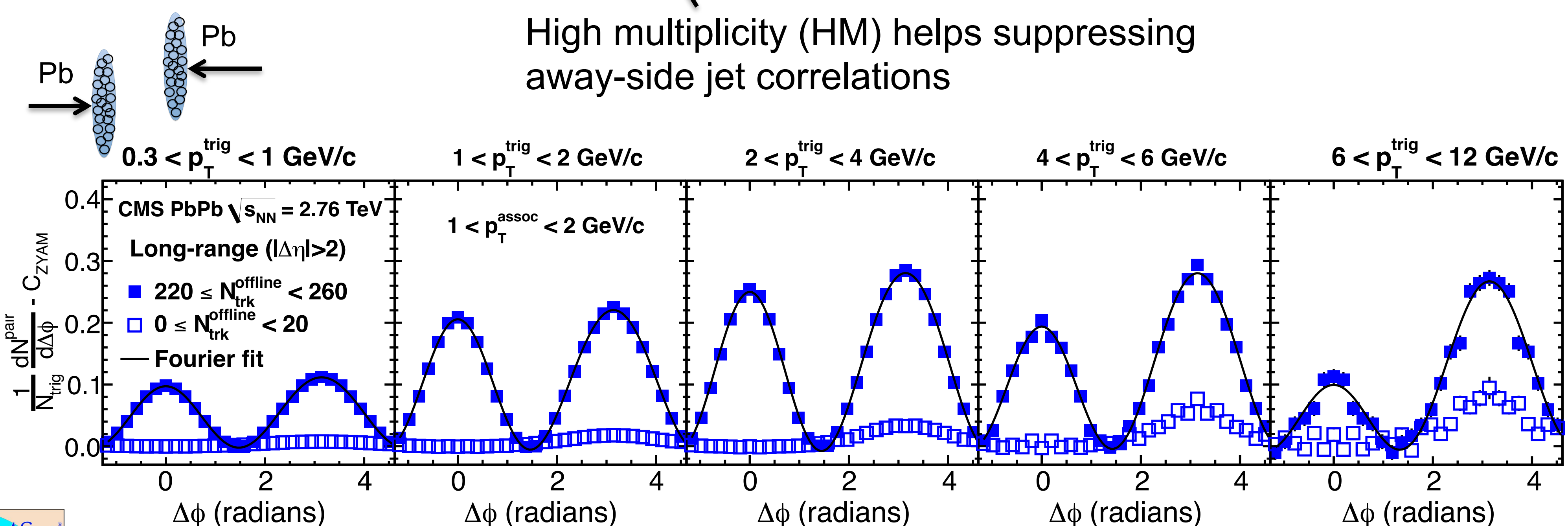




New pPb data from 2013 run



High multiplicity (HM) helps suppressing away-side jet correlations



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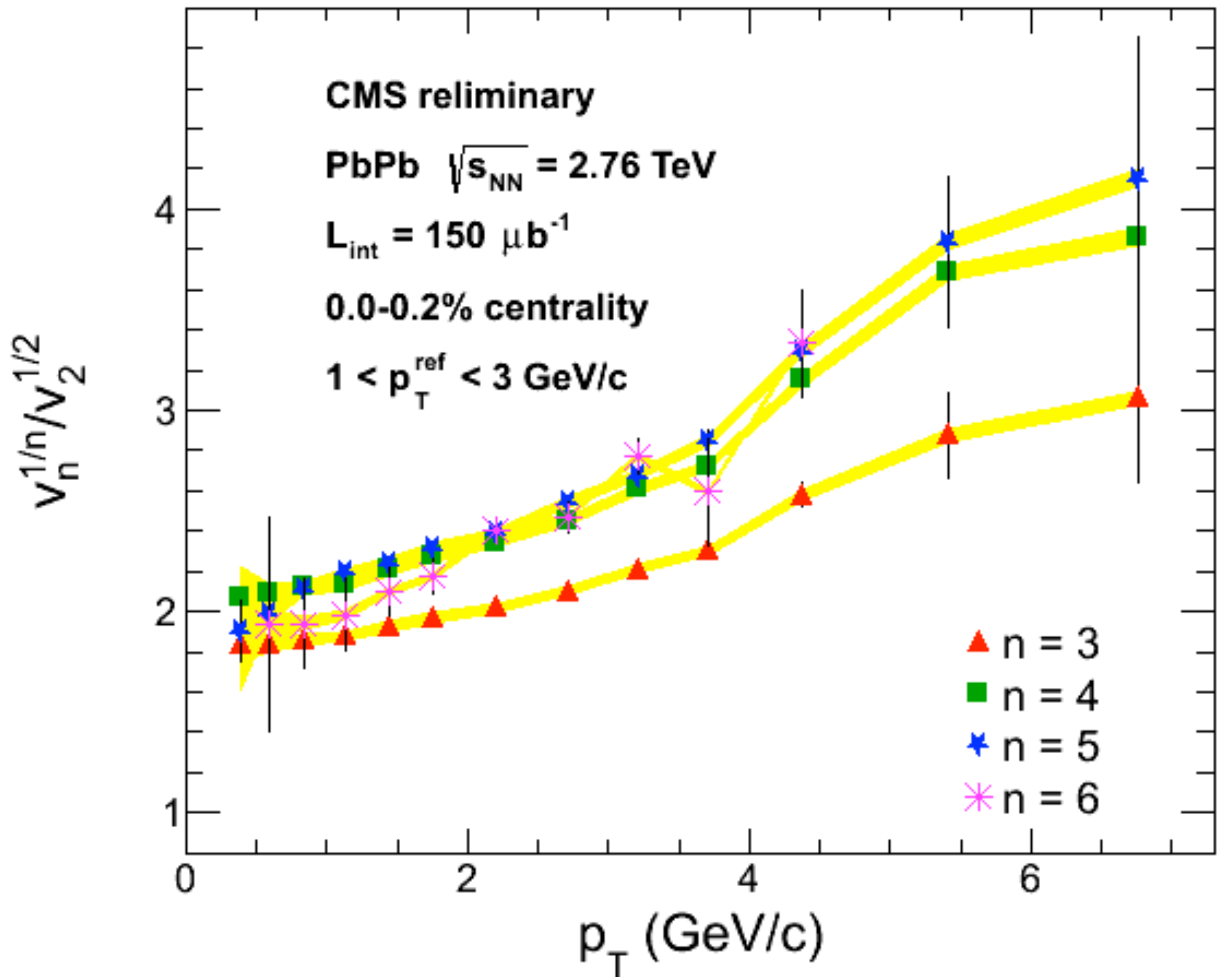
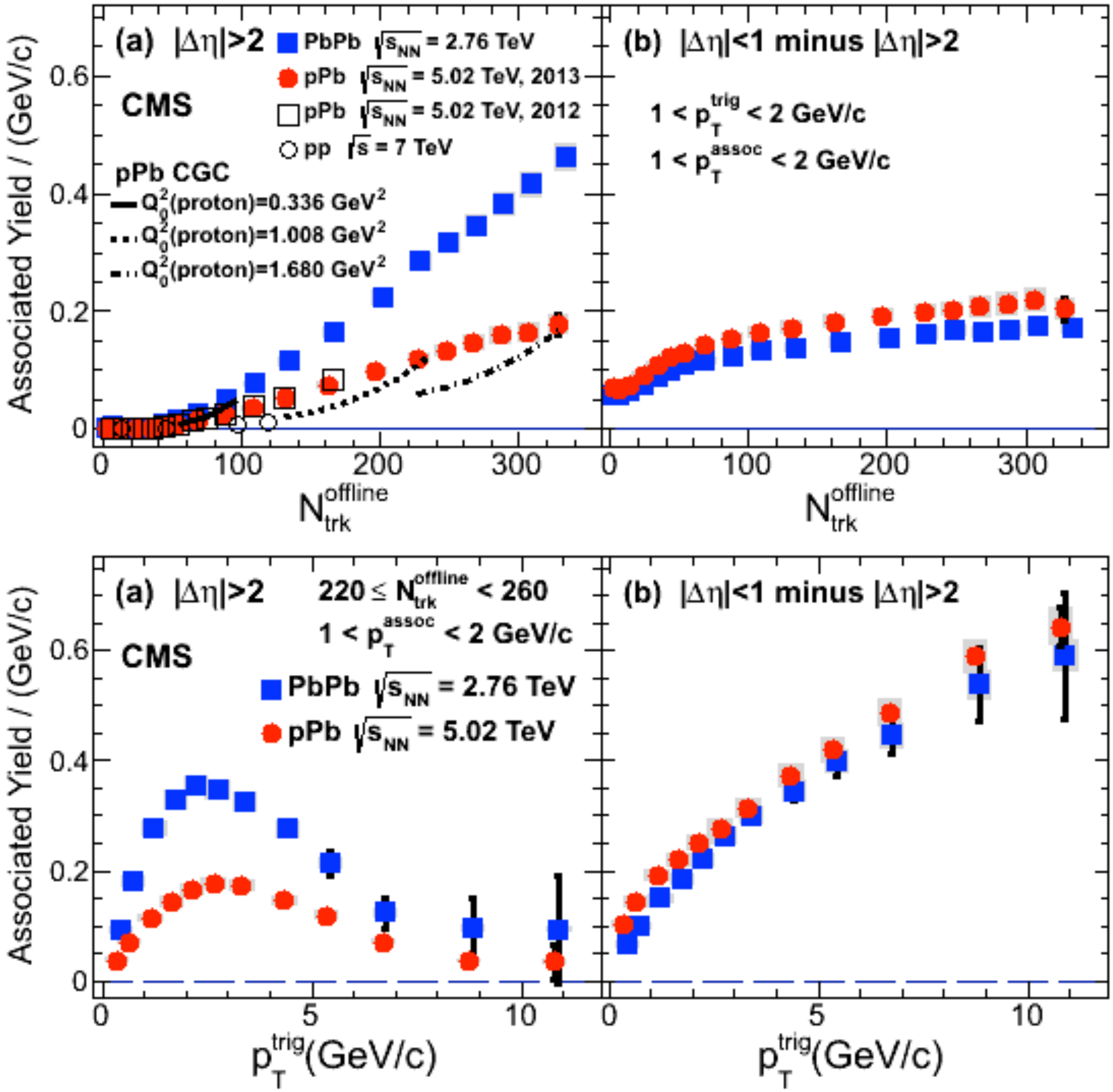


Flow phenomena in pPb



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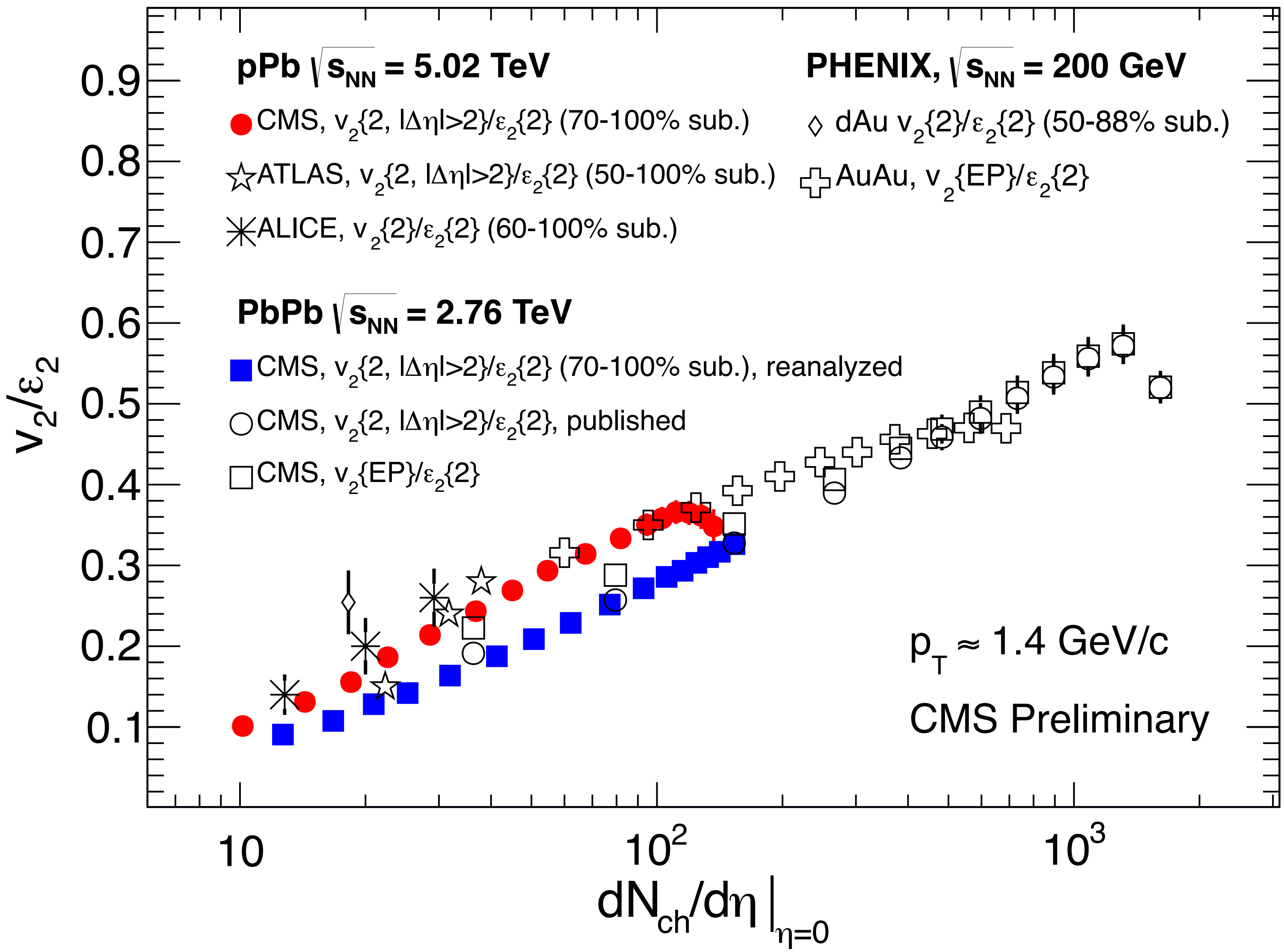
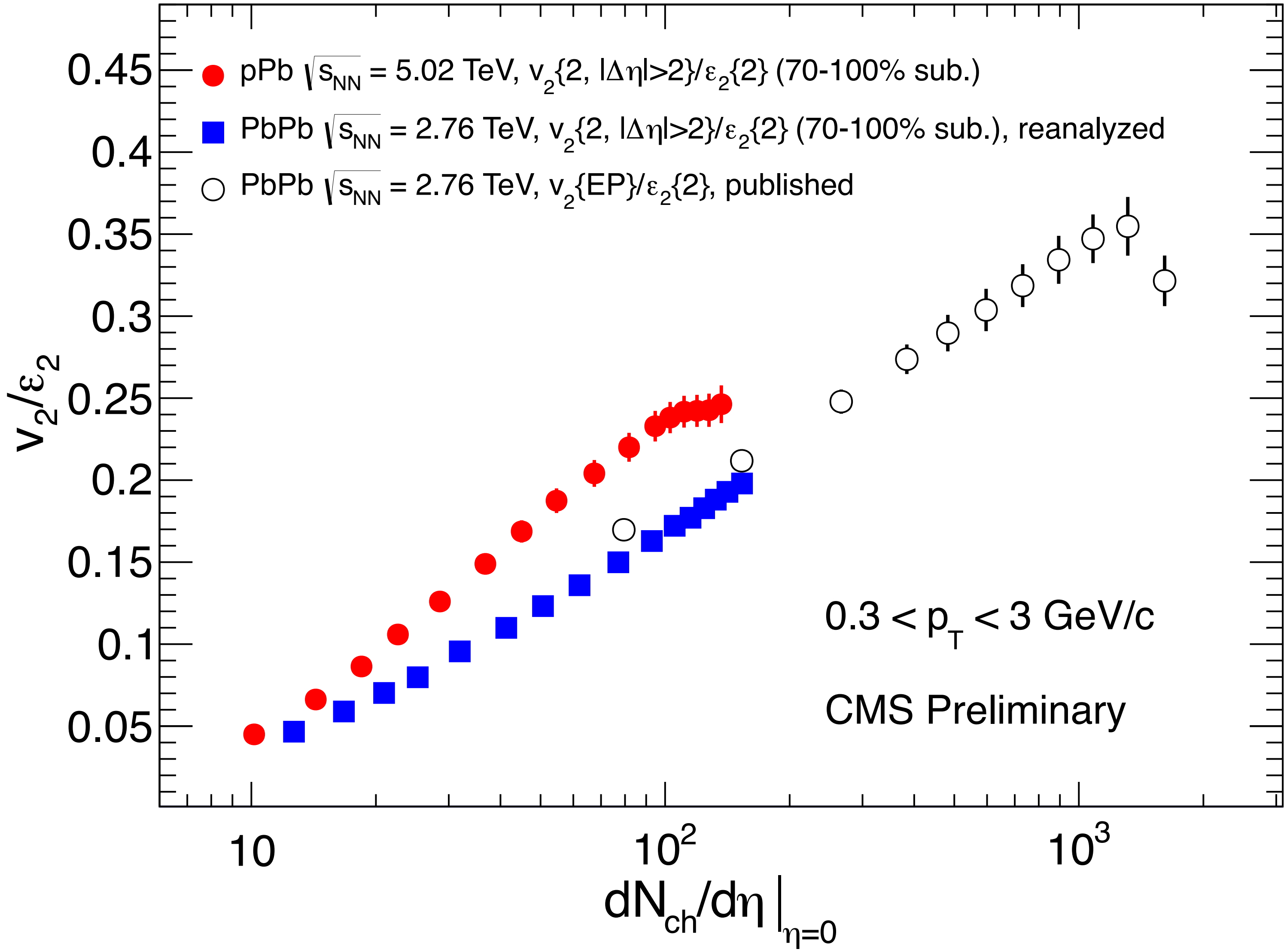
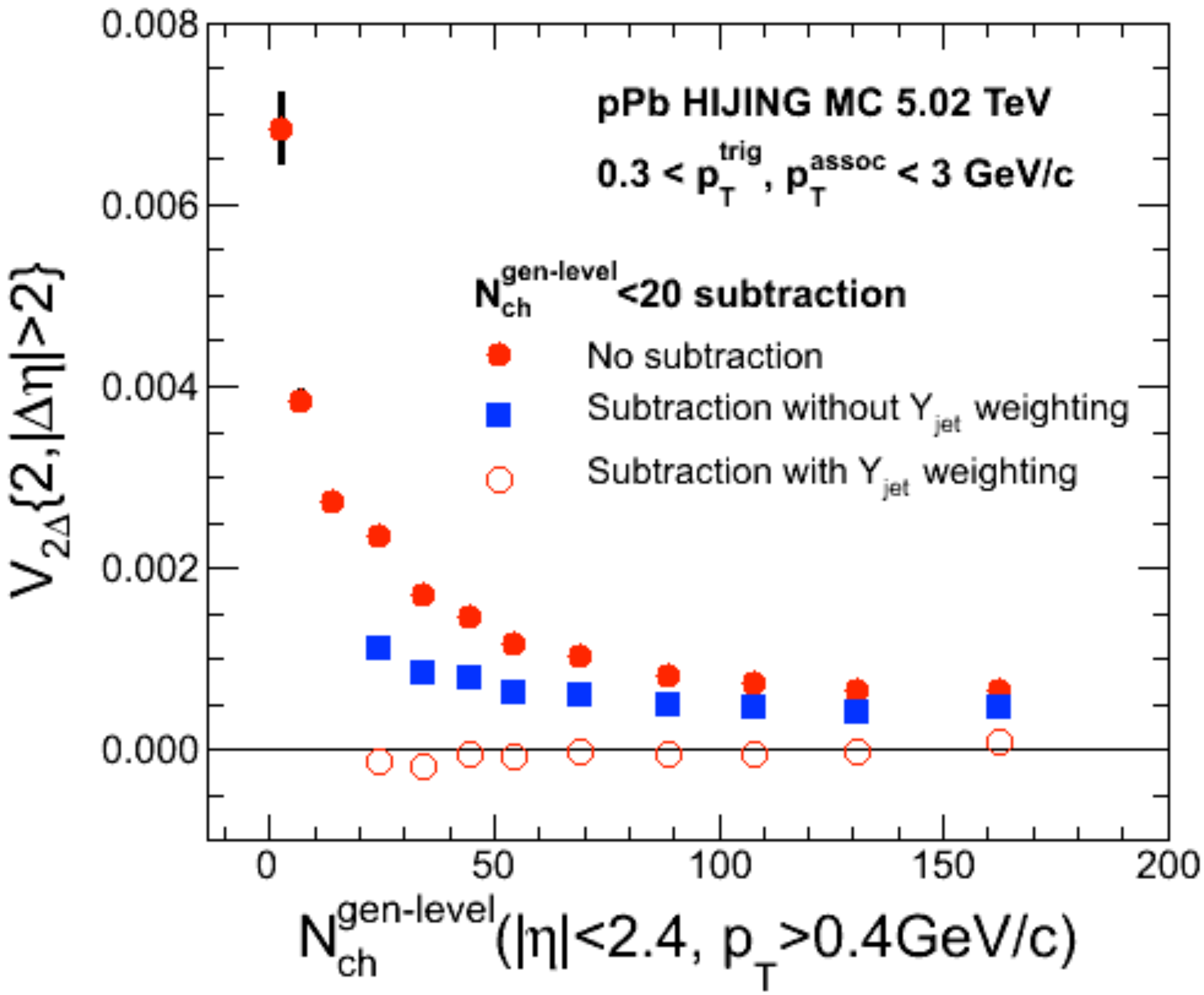


Flow phenomena in pPb



Flow phenomena in pPb



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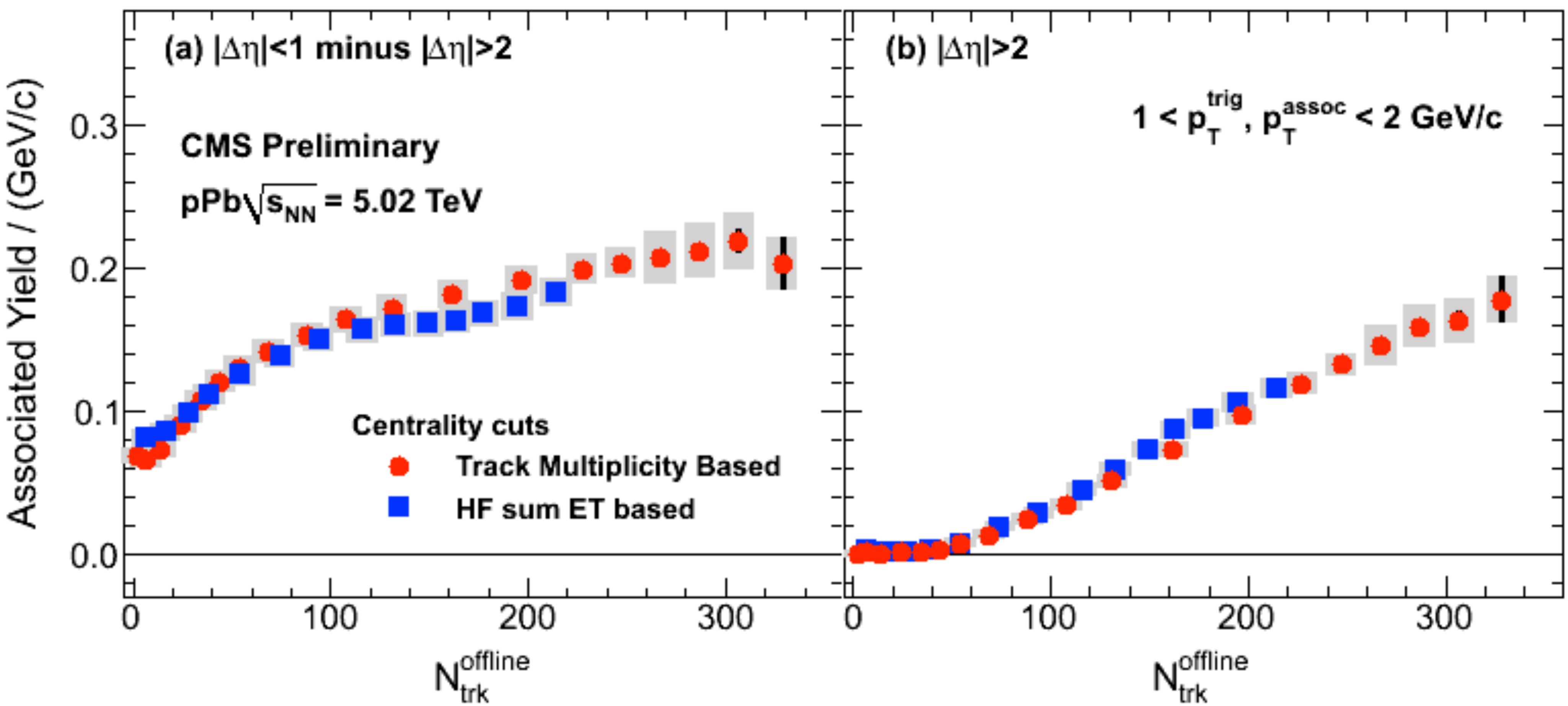

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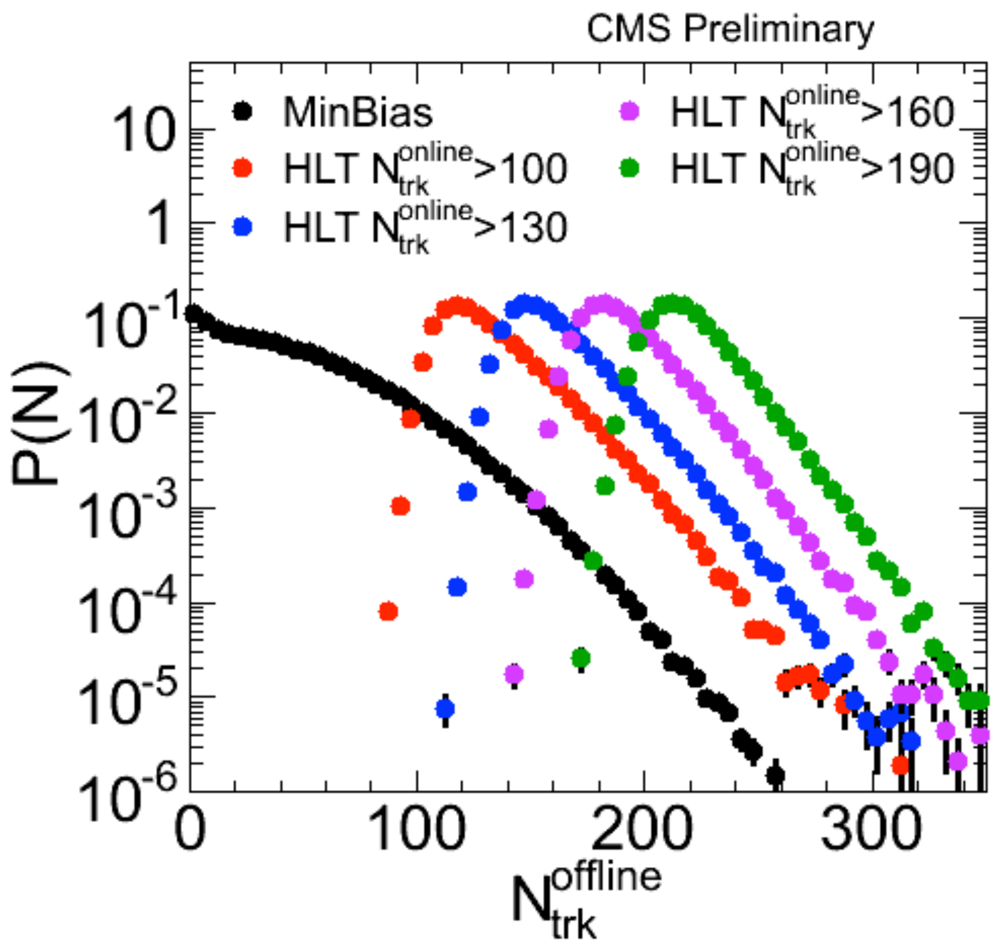

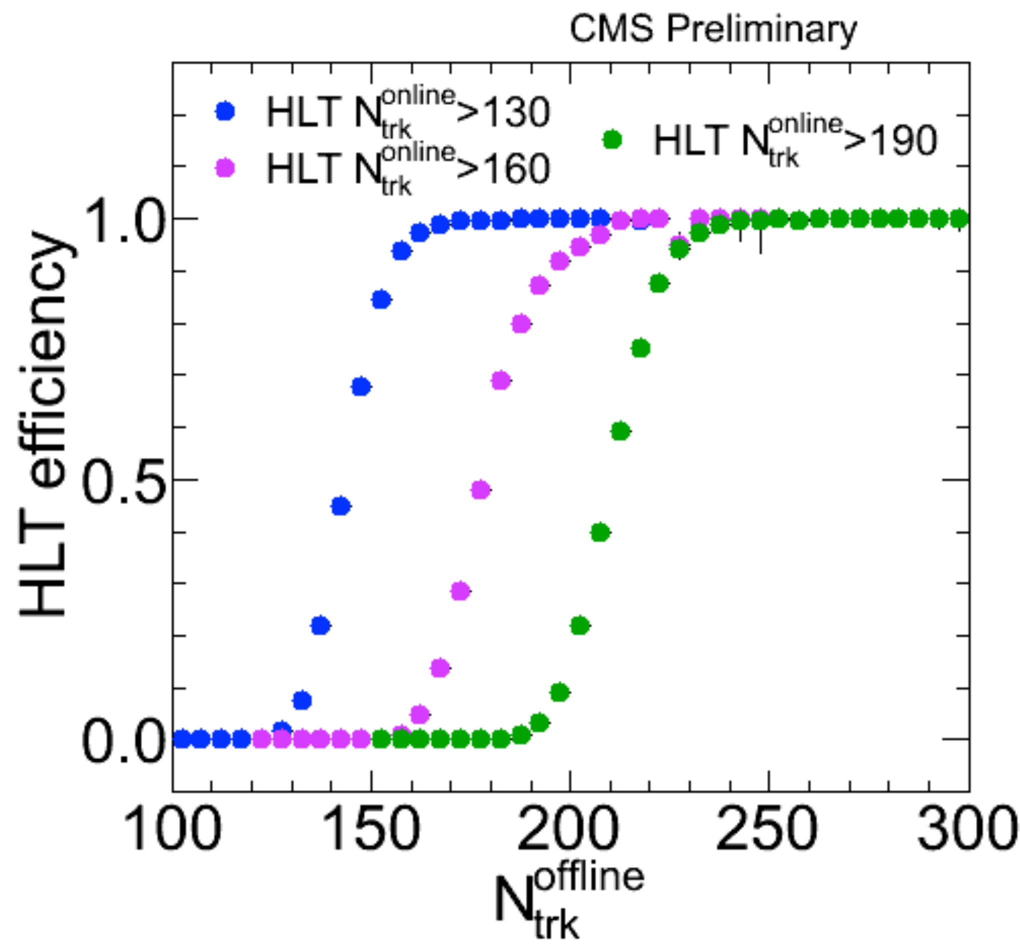

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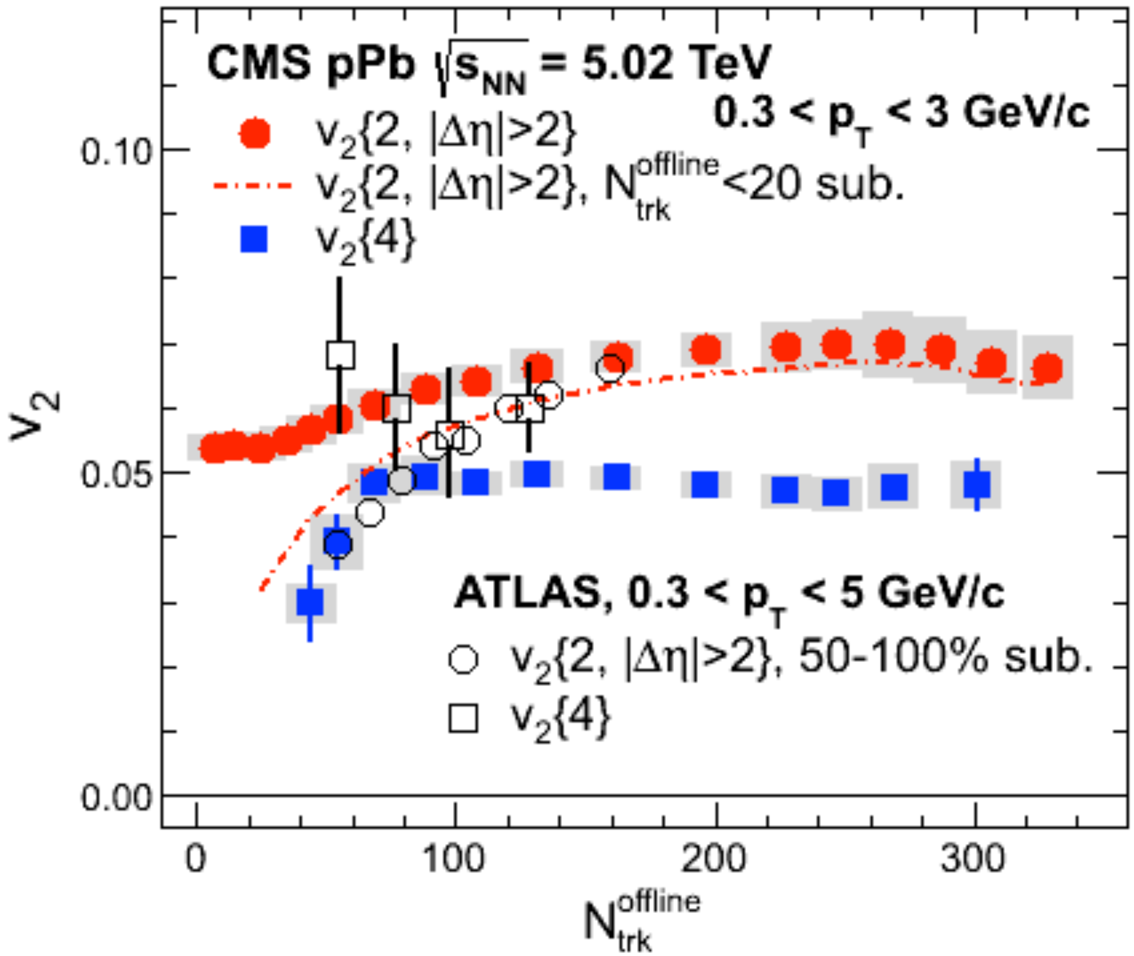

Flow phenomena in pPb