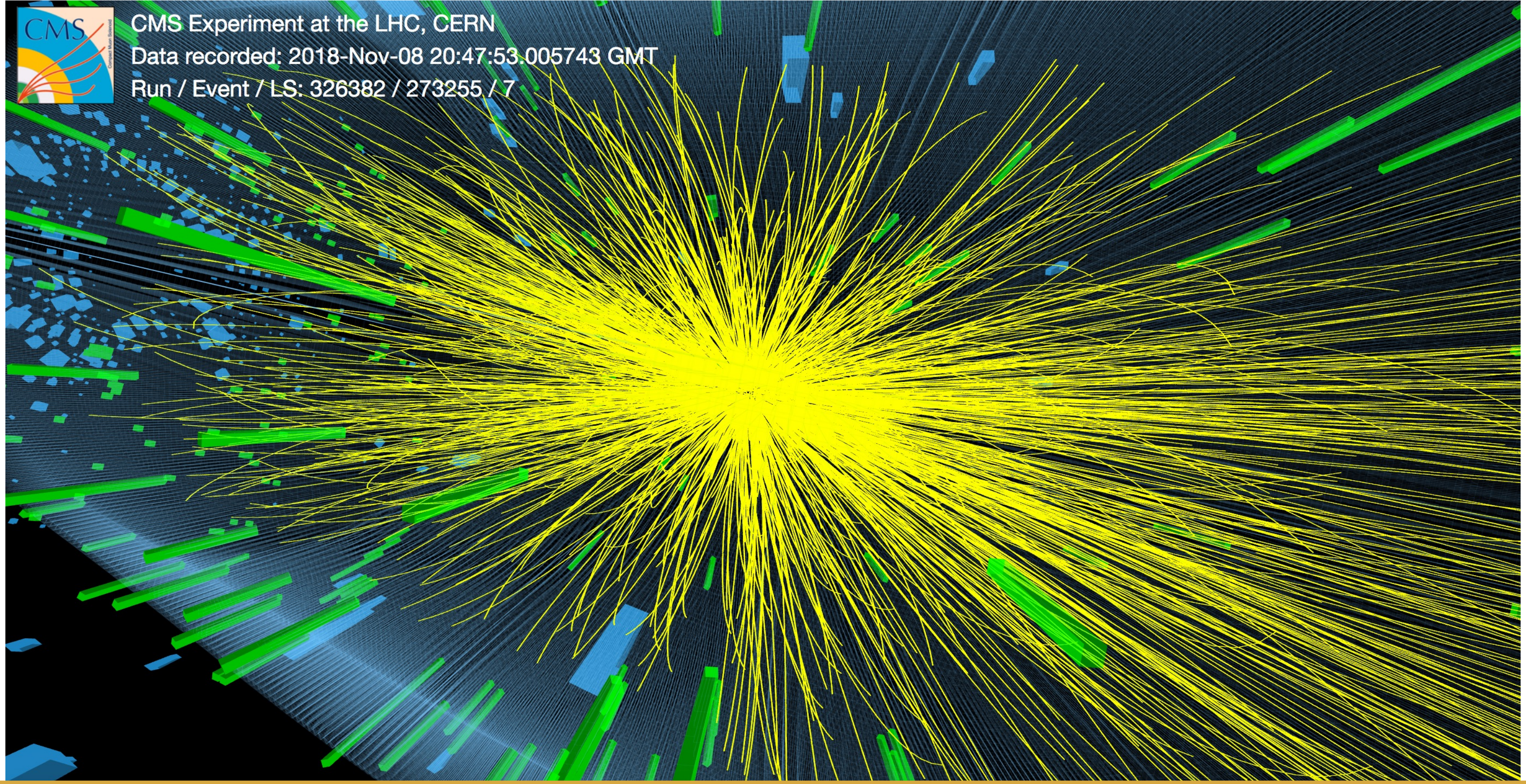

FLOW, NONFLOW, AND FLOW FLUCTUATIONS AT CMS

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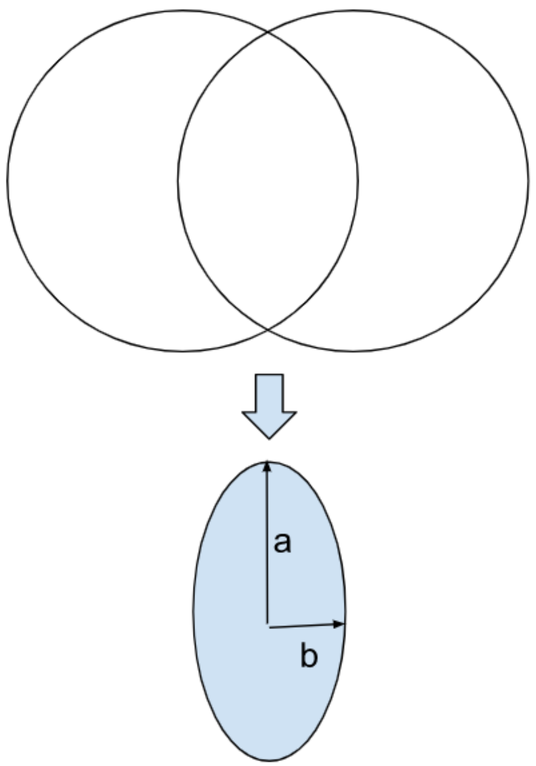
Outline

- Flow, nonflow, and flow fluctuations
- Flow study before CMS
- CMS flow measurements in PbPb collisons
- Flow in small collisions systems
- Recent development
- Summary

Flow, nonflow, and flow fluctuations

Flow in heavy ion collisions

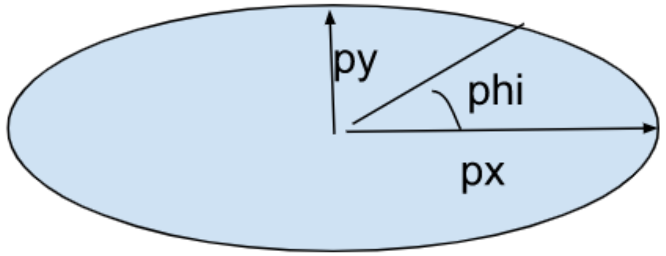
Initial state anisotropy



Reaction plane:
Plane formed by beam axis and impact parameter vector

$e=(a^2-b^2)/(a^2+b^2)$

Final state anisotropy



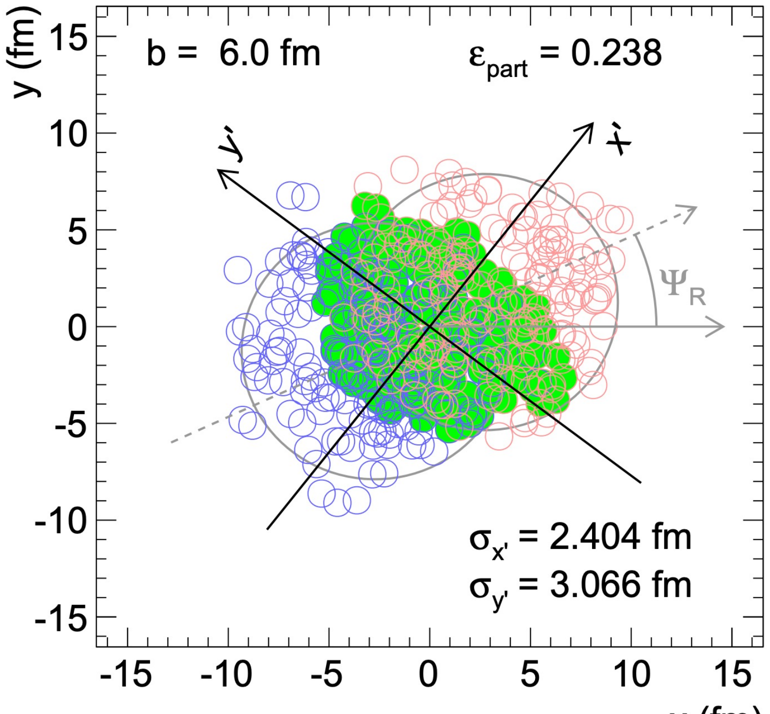
Event plane angle = 0 in this case

$$v2 = ((px)^2 - (py)^2)/((px)^2 + (py)^2)$$
$$= ((pT)^2*(\cos^2(phi) - \sin^2(phi)))/(pT)^2$$
$$= \cos^2(phi) - \sin^2(phi)$$
$$= \cos(2*phi)$$

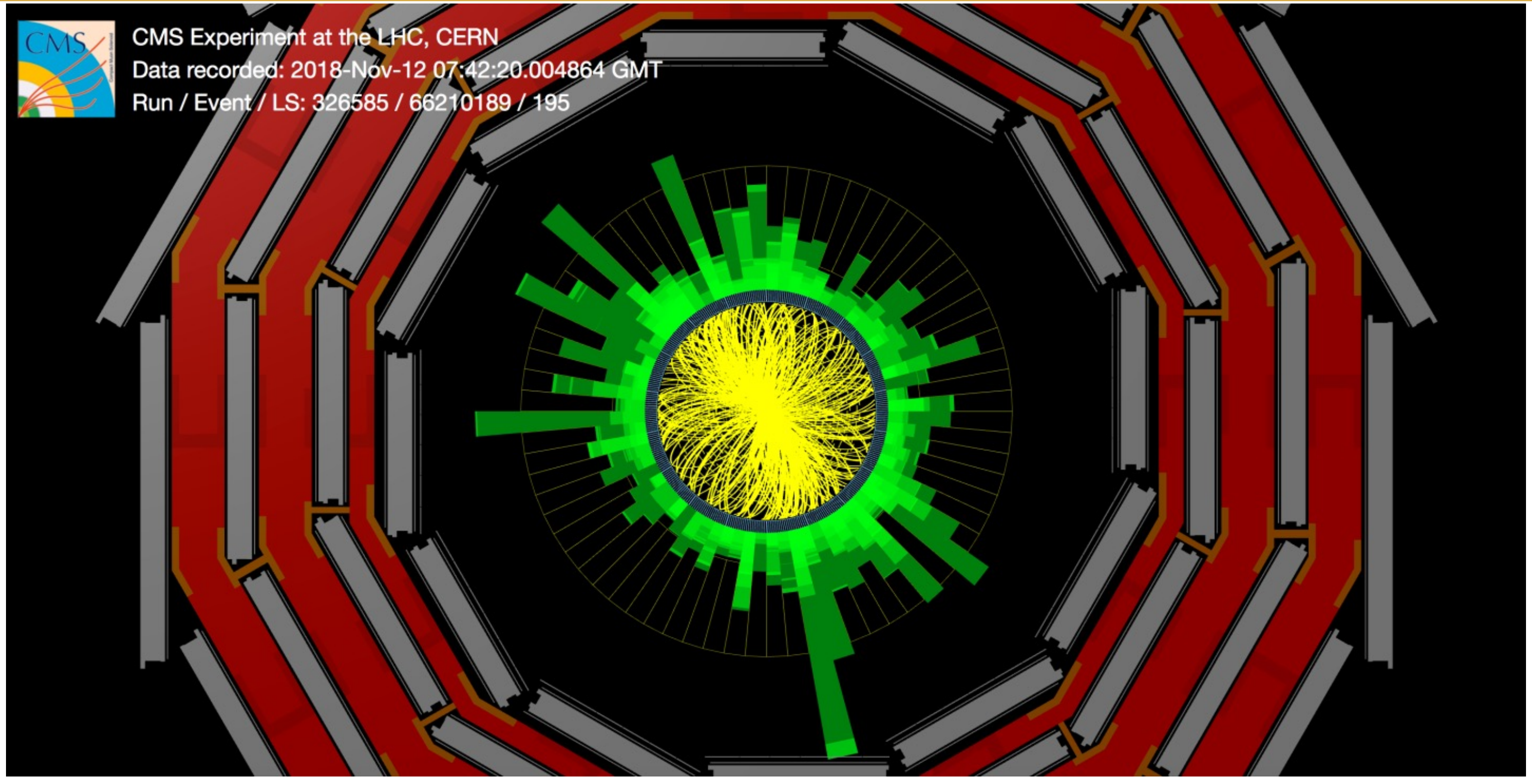
- Initial state anisotropy (ε_2) + hydrodynamics -> final state v_2
- Initial state anisotropy (ε_2) + random streaming of particles (No QGP) -> NO final state v_2
- No initial state anisotropy (ε_2~0) + hydrodynamics -> No final state v_2 or small v_2 from fluctuations

v_2 is sensitive to QGP production

Flow in heavy ion collisions



CMS: Phys. Rev. C 87 (2013) 014902



- One PbPb collision -> hundreds of nucleon-nucleon (NN) collisions
- Particles produced in preferred angles from hundreds of NN collisions at the same time -> collective FLOW of the created medium: Quark-Gluon Plasma
  - ➢ Initial state geometry, fluctuations
  - ➢ Medium properties, parton-medium interactions

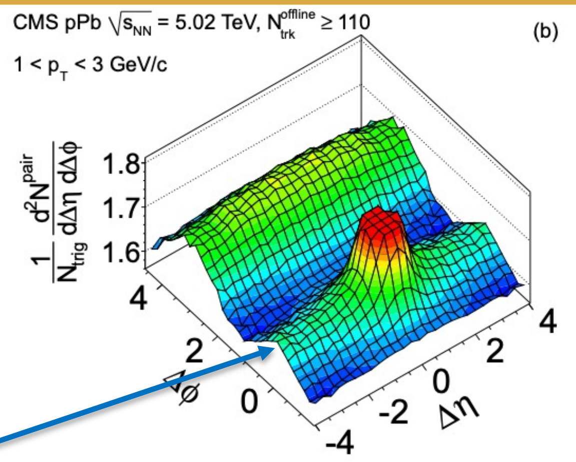
$$dN/d\phi \propto 1 + \sum_n 2v_n \cos(n(\phi - \Psi_n))$$

Elliptic flow: v_2

Triangular flow: v_3

Nonflow and flow

- Nonflow
  - Jets
  - BEC
  - Momentum Conservation
  - …



- Ridge: Near-side long range correlations

v_n

Azimuthal anisotropy

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

v_n analysis method with nonflow removal:

- Two particle correlation method with $v_n\{EP\}$, $v_n\{SP\}$, $v_n^{sub}\{2,|\Delta\eta|>2\}$, …

v_n fluctuations

- Multiparticle correlations with $v_n\{4, 6, 8, 10, …, LYZ\}$
  (Better removing nonflow)

- CGC
- Color Reconnection and Rope Hadronization

Ridge and v_n but not related to FLOW or QGP

- Initial geometry + Hydrodynamics
- Transport models

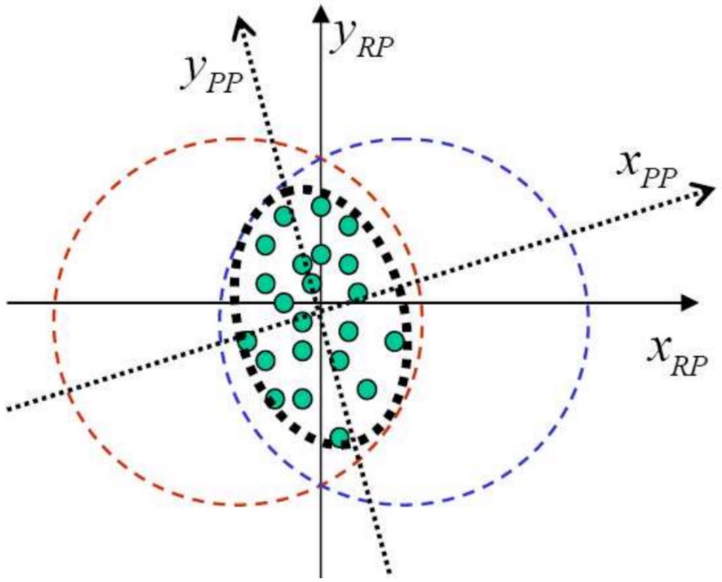
FLOW and QGP

- Path length dependence
  - Jet energy loss
  - Quarkonium suppression

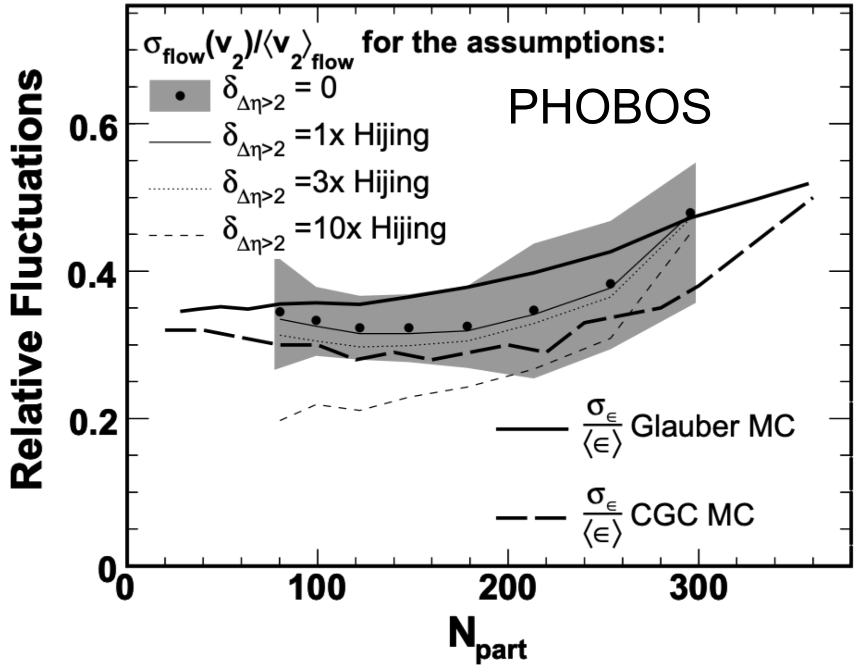
v_n is not hydrodynamic FLOW but probes QGP

Not nonflow, also not flow

Flow fluctuations



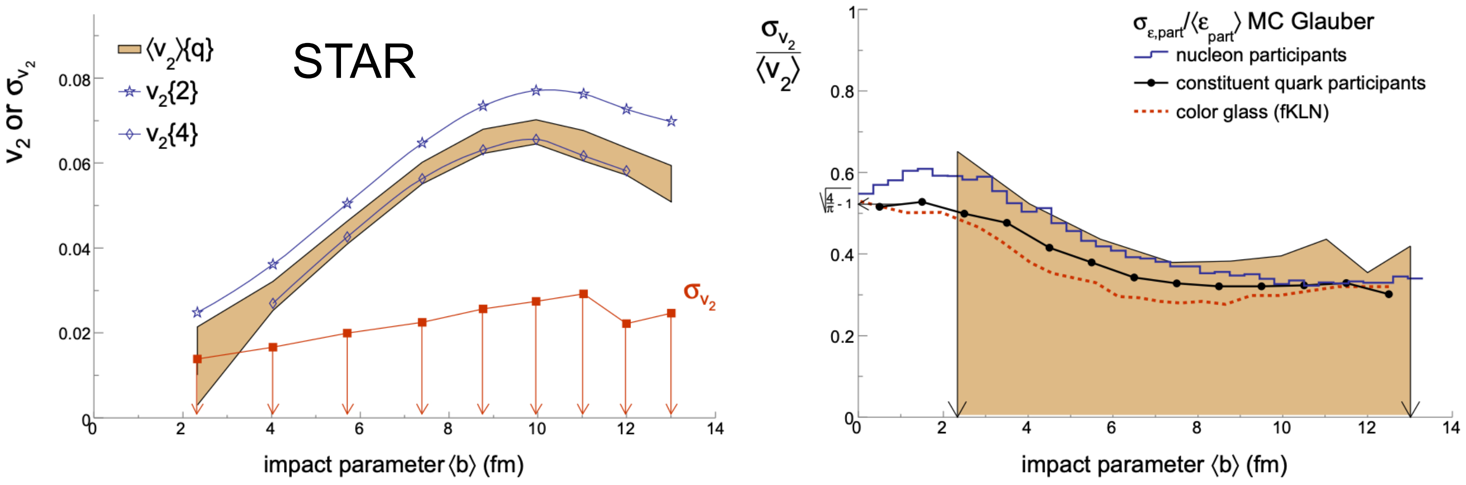
- **RP: the reaction plane**
  - Defined by the impact parameter
  - Initial geometry: ε_{std}
- **PP: the participant plane**
  - Defined by the major axis of the created system
  - Initial geometry: ε_{part}

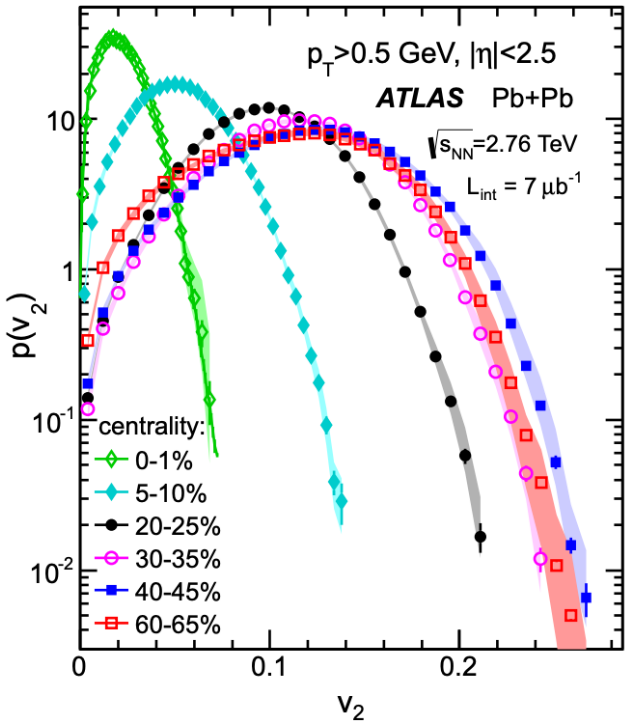


S. A. Voloshin, A. M. Poskanzer, A.Tang and G.Wang, PLB, 659 (2008), 537-541

The fluctuation in initial eccentricity of the participant zone -> flow fluctuations

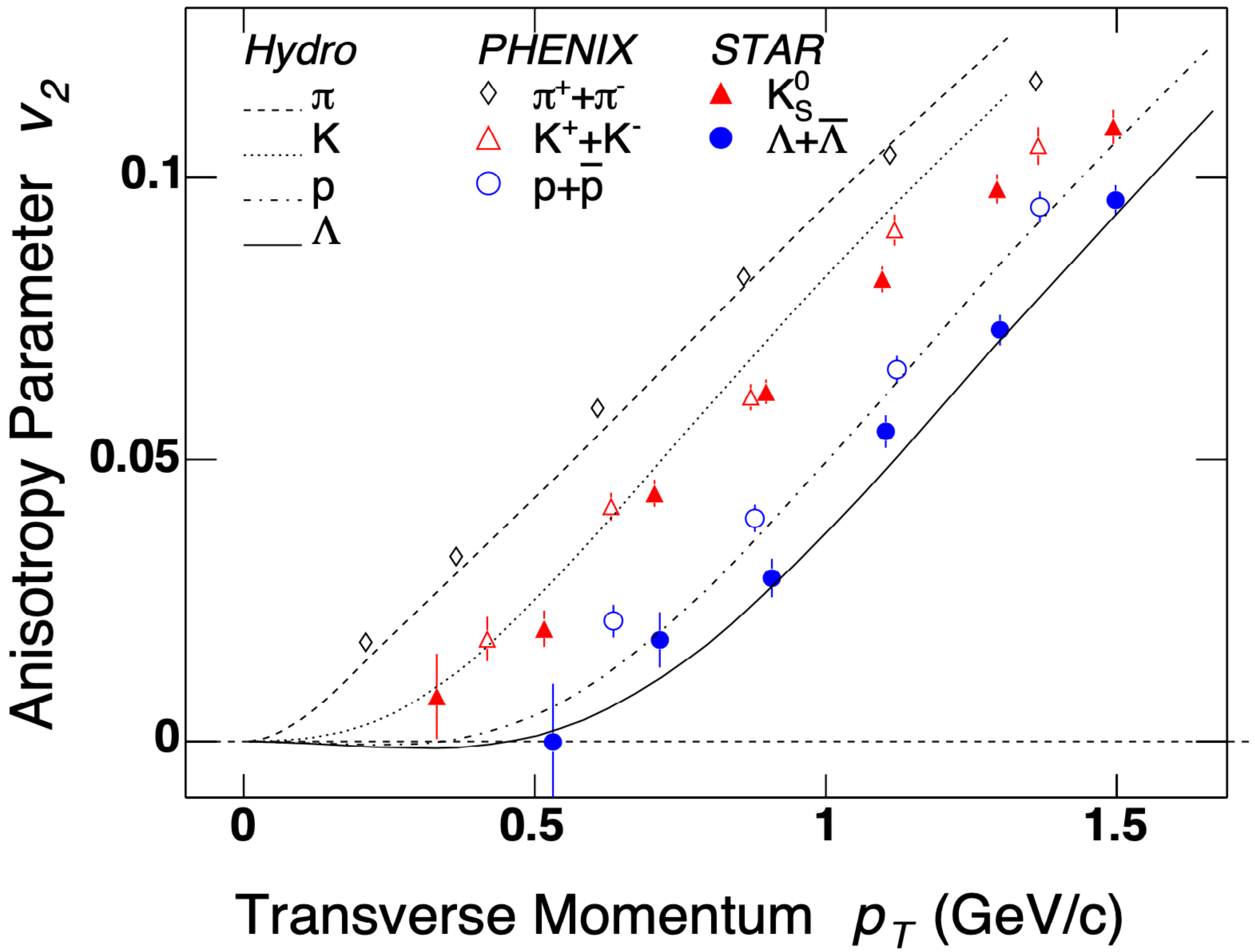
Note: flow fluctuations can be due to different reasons



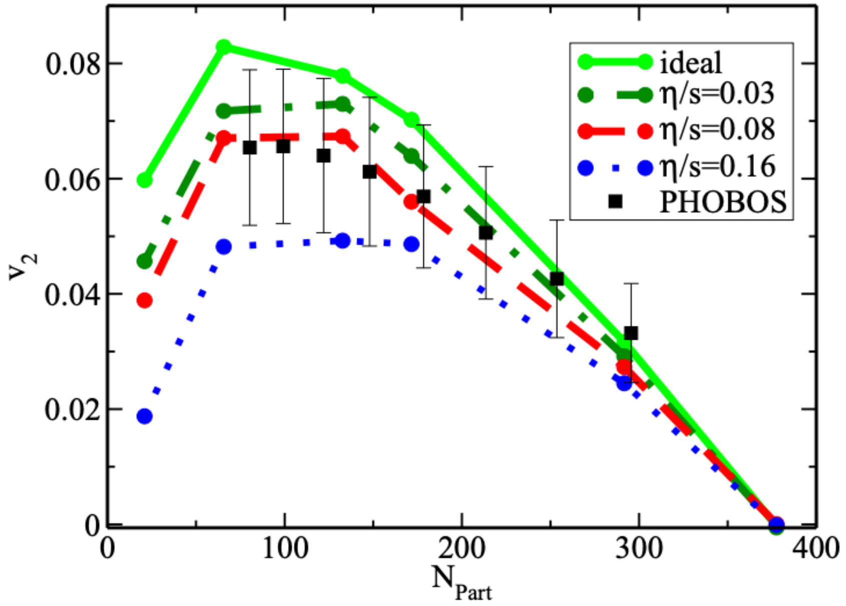


Flow study before CMS

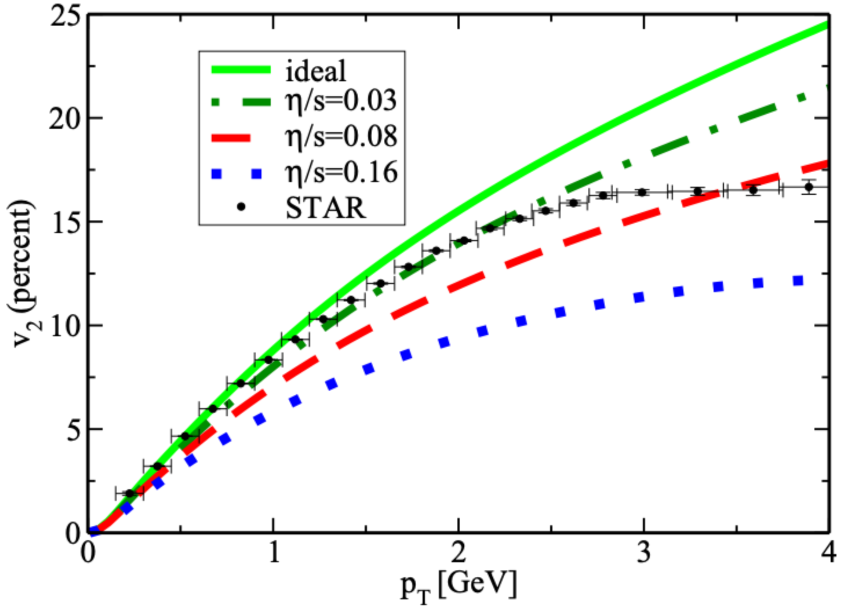
v_2 and properties of QGP



Prog.Part.Nucl.Phys. 54 (2005) 443

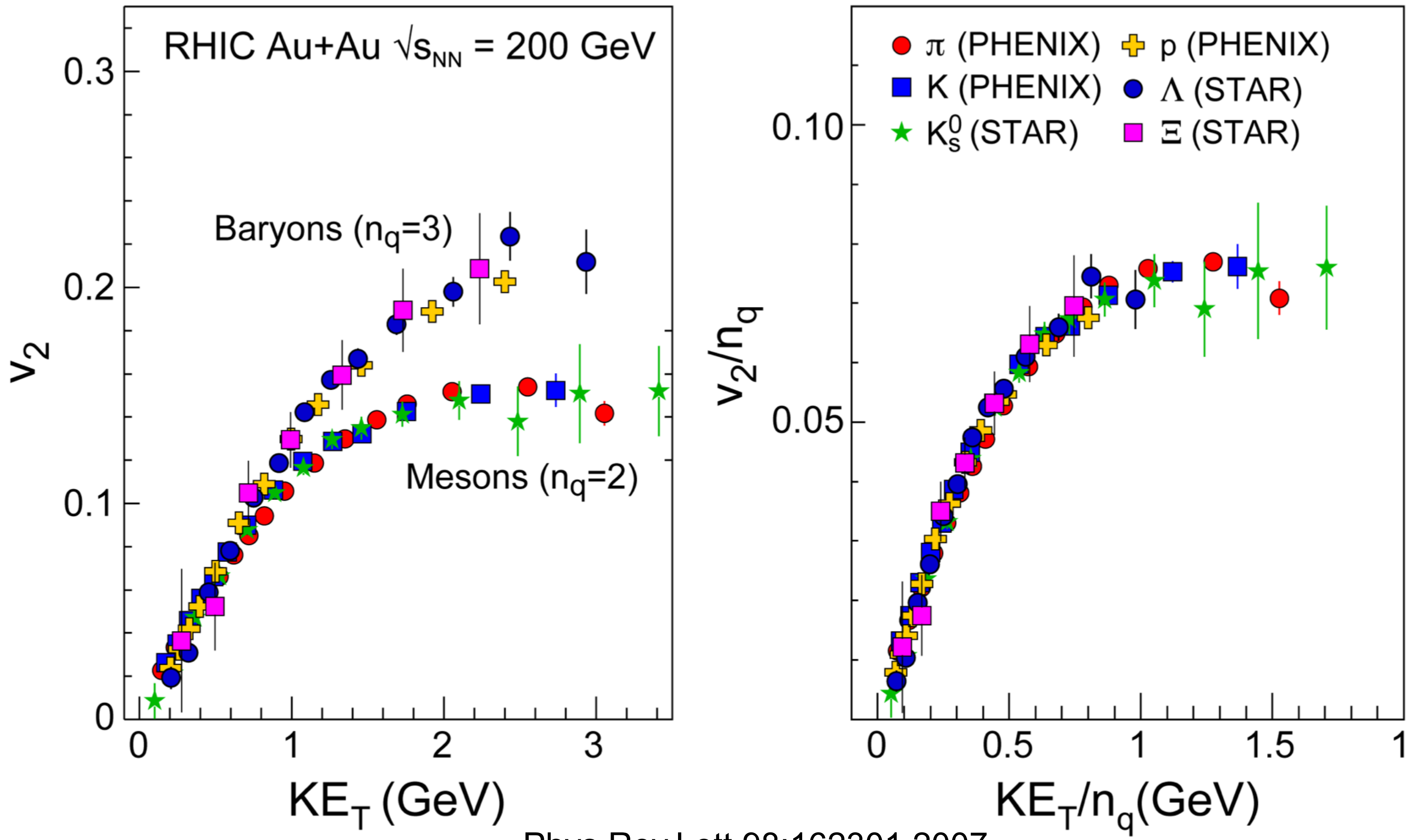


Phys.Rev.Lett.99:172301,2007



Measurements of v_2 provide constraints for the properties of QGP

NCQ scaling



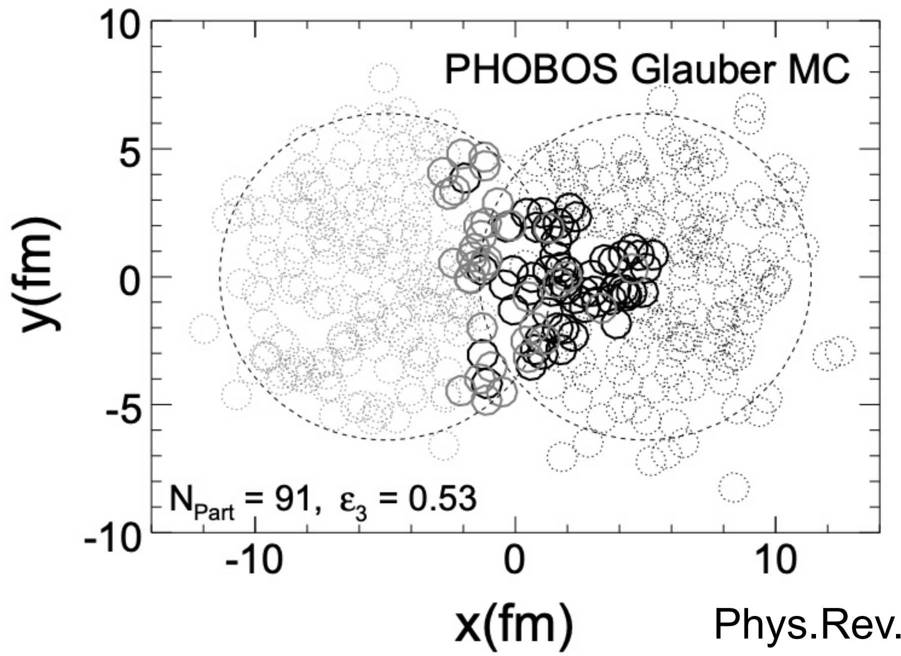
Phys.Rev.Lett.98:162301,2007

Transverse kinetic energy KE_T:

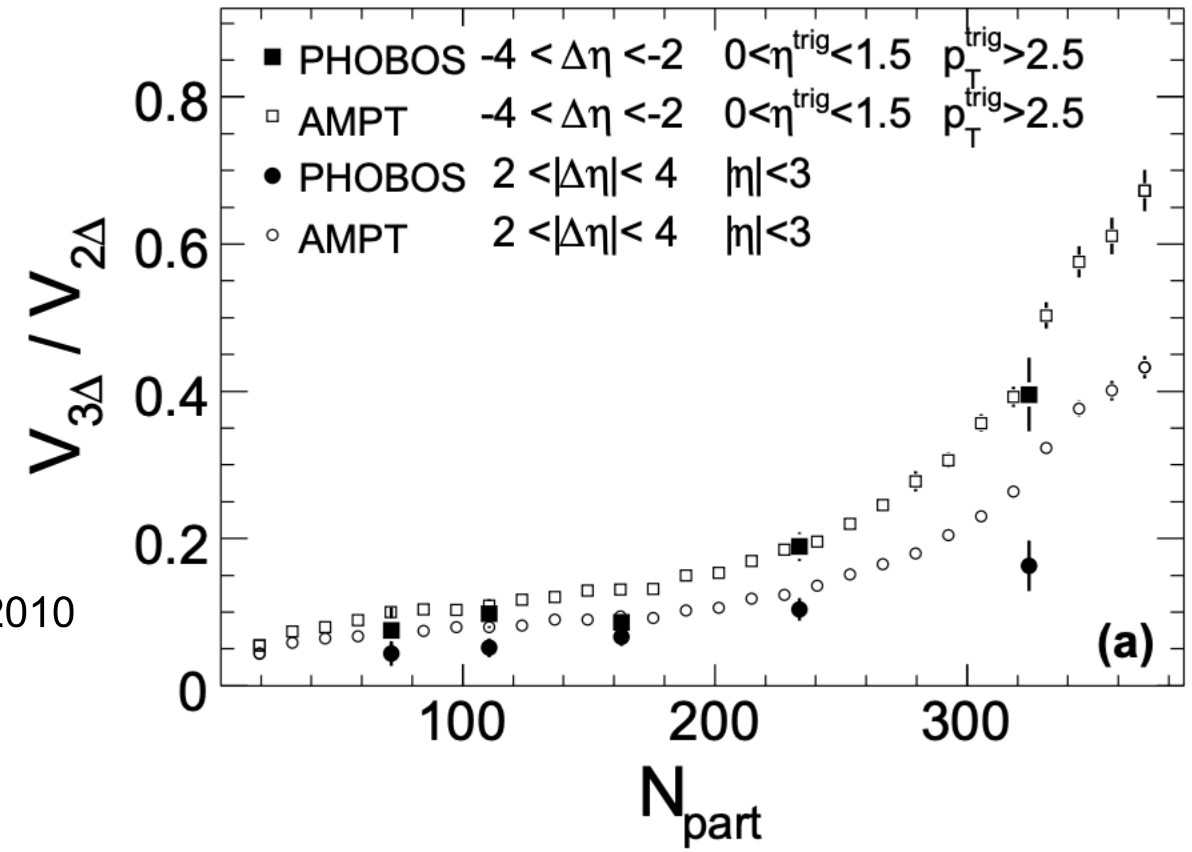
$$\sqrt{p_T^2 + m^2} - m$$

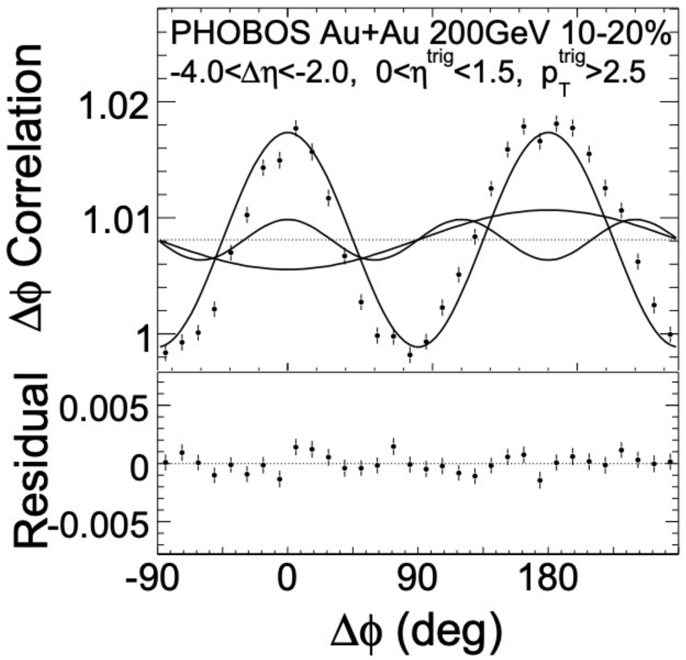
- The flowing could be at the partonic level
- More evidence of QGP

Higher order harmonics



Phys.Rev.C81:054905,2010



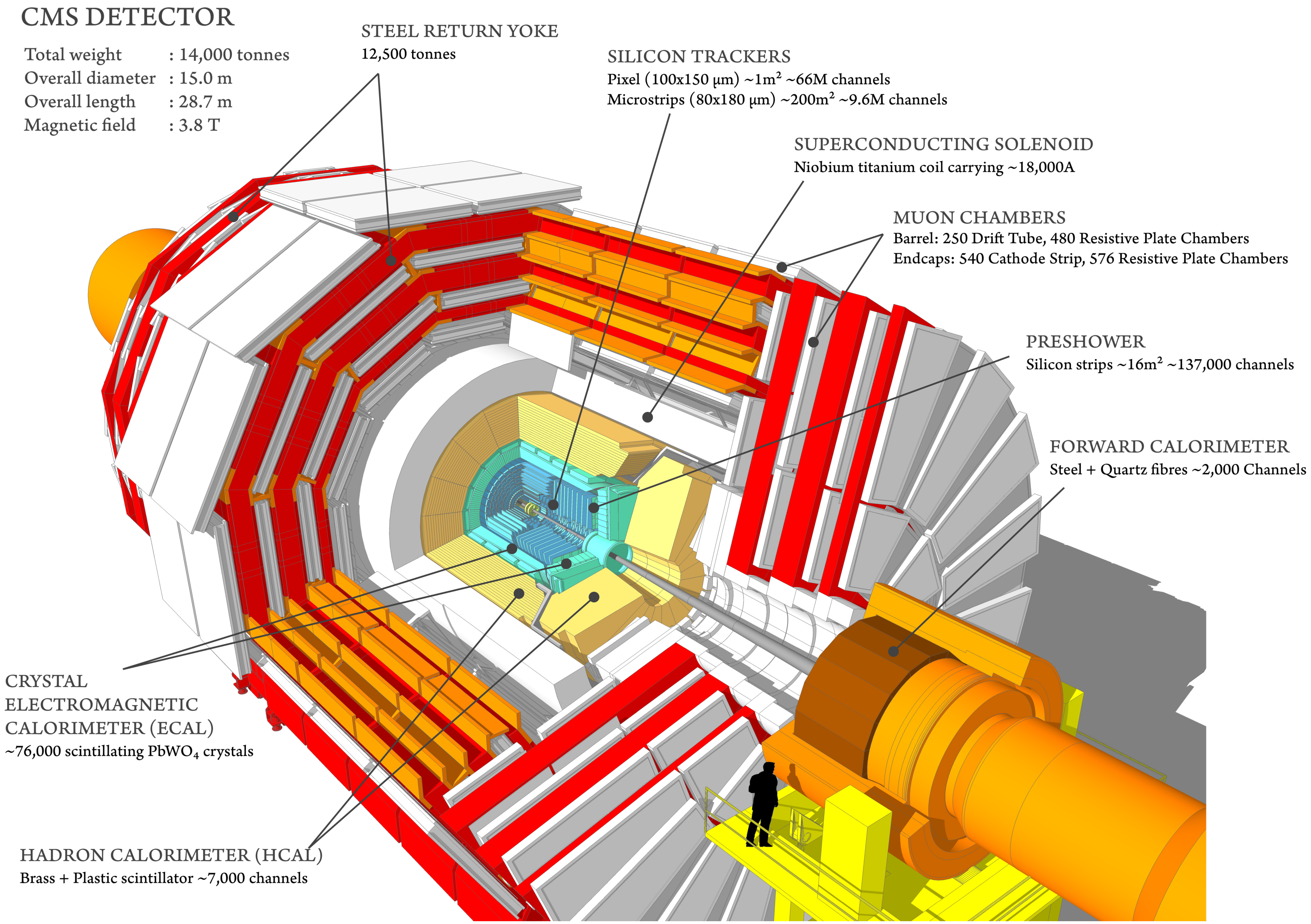


$$\frac{\mathrm{d}N^{\mathrm{pairs}}}{\mathrm{d}\Delta\phi} = \frac{N^{\mathrm{pairs}}}{2\pi}\left(1 + \sum_n 2\mathbf{V}_{n\Delta}\cos(n\Delta\phi)\right)$$

- Higher harmonics due to fluctuations at the initial state

CMS flow measurements in PbPb collisons

CMS detectors

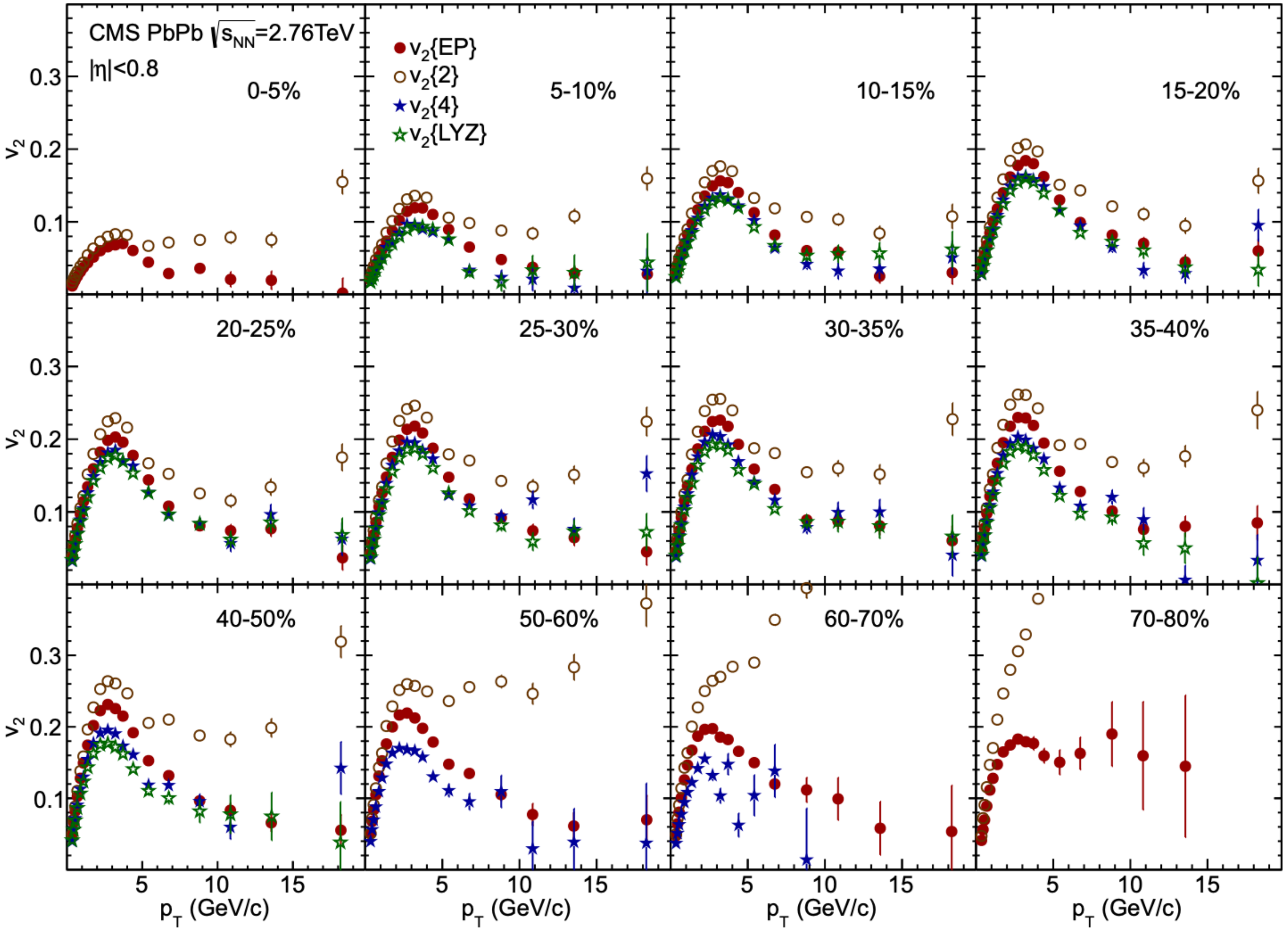


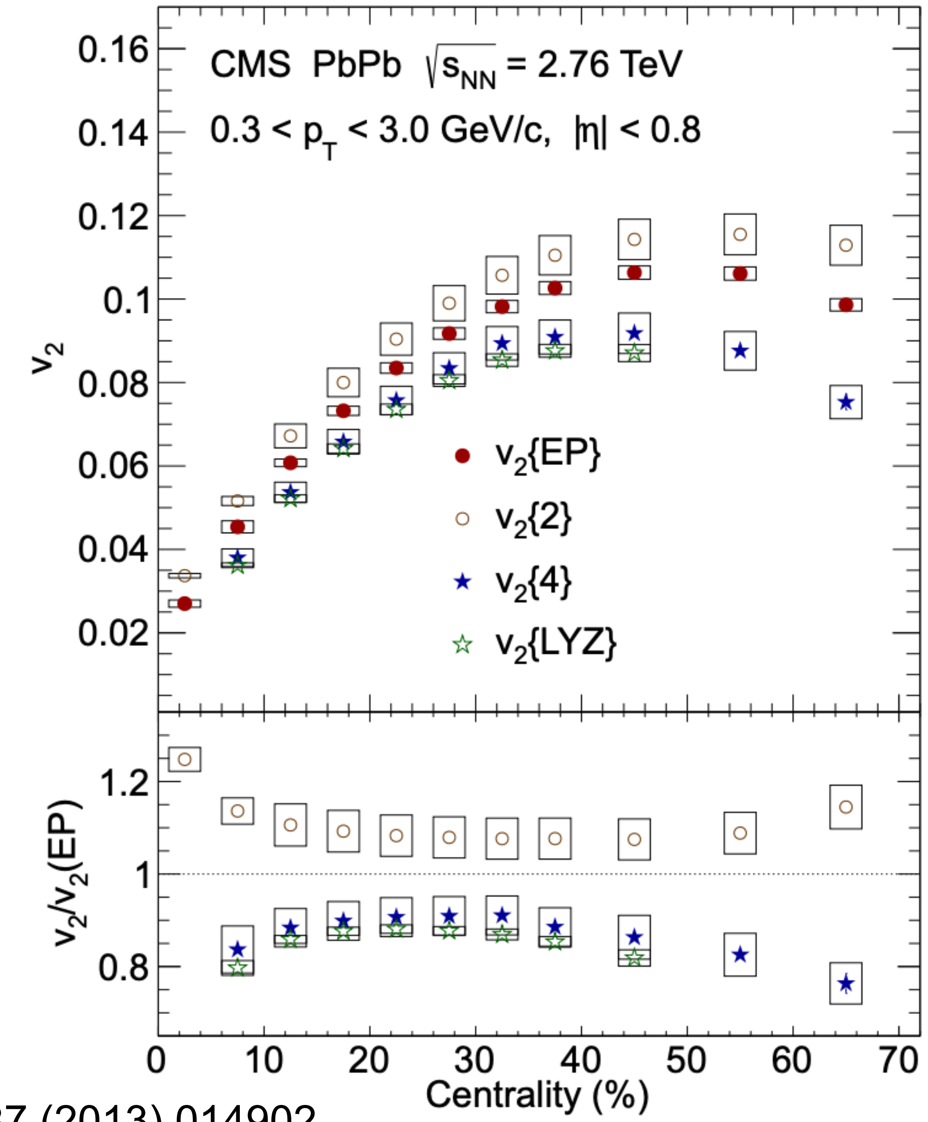
- Tracker with $|\eta|<2.4$
- Hadronic Forward (HF) calorimeter with $2.9<|\eta|<5.2$

A typical analysis in CMS

- A very long process with different layers of reviews
  - Proposal an analysis
  - Multiple reports and review in the analysis (Flow/Corr for example) group -> Green light for pre-approval
  - Pre-approval talk and homework
  - Review by analysis review committee, lots of meetings/reports -> Green light for approval
  - Approval talk and homework
  - Collaboration wide review and comments
  - Final reading
  - Submit to a journal
- Could take 6 months – several years to submit

v_2 at LHC energy – first CMS analysis





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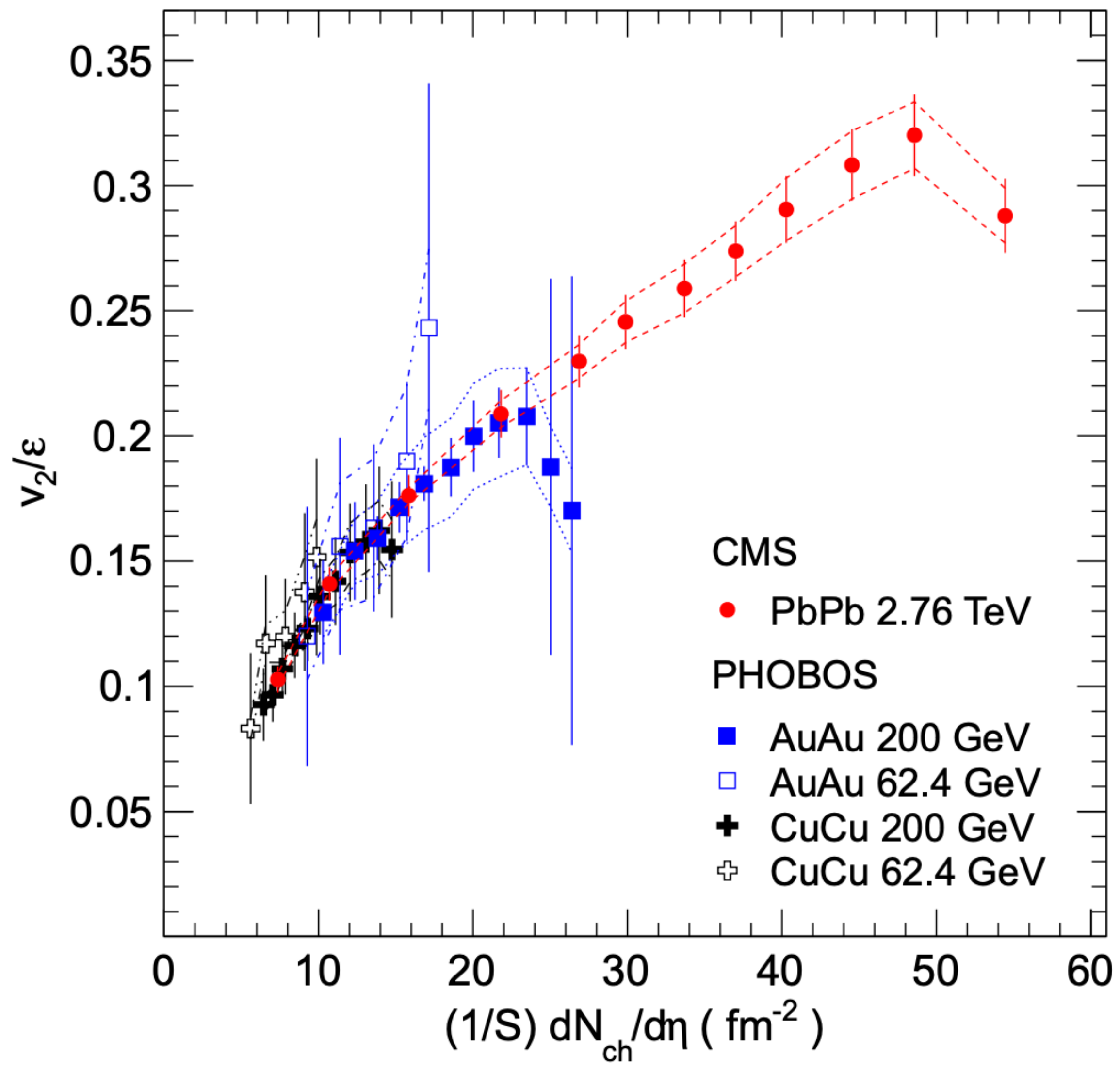
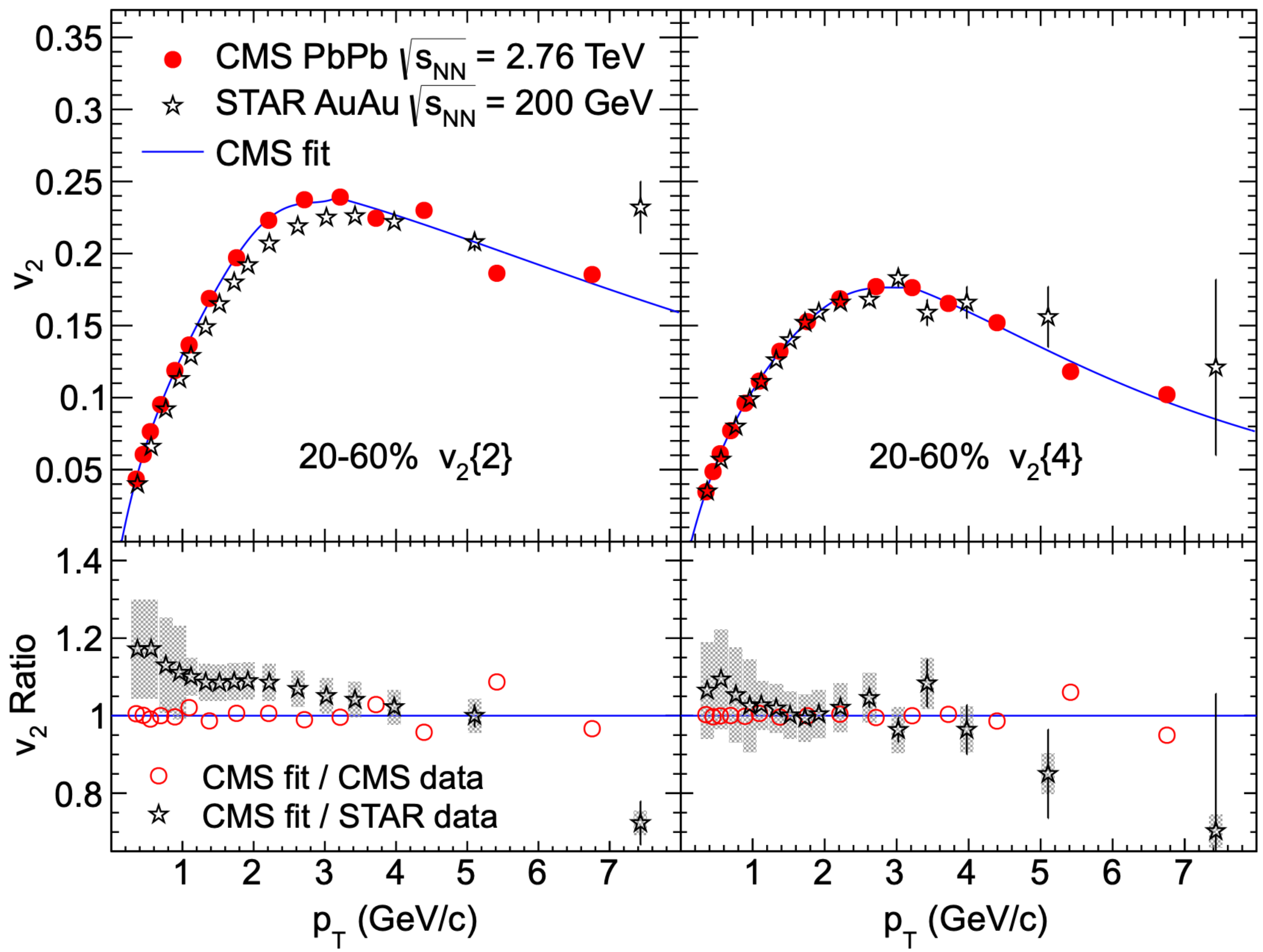
- Strong v_2 signals at LHC energy with different analysis methods

v_2 at LHC energy – first CMS analysis





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- The v_2 values are larger (<20%) at LHC energy compared to RHIC

Example of systematic studies

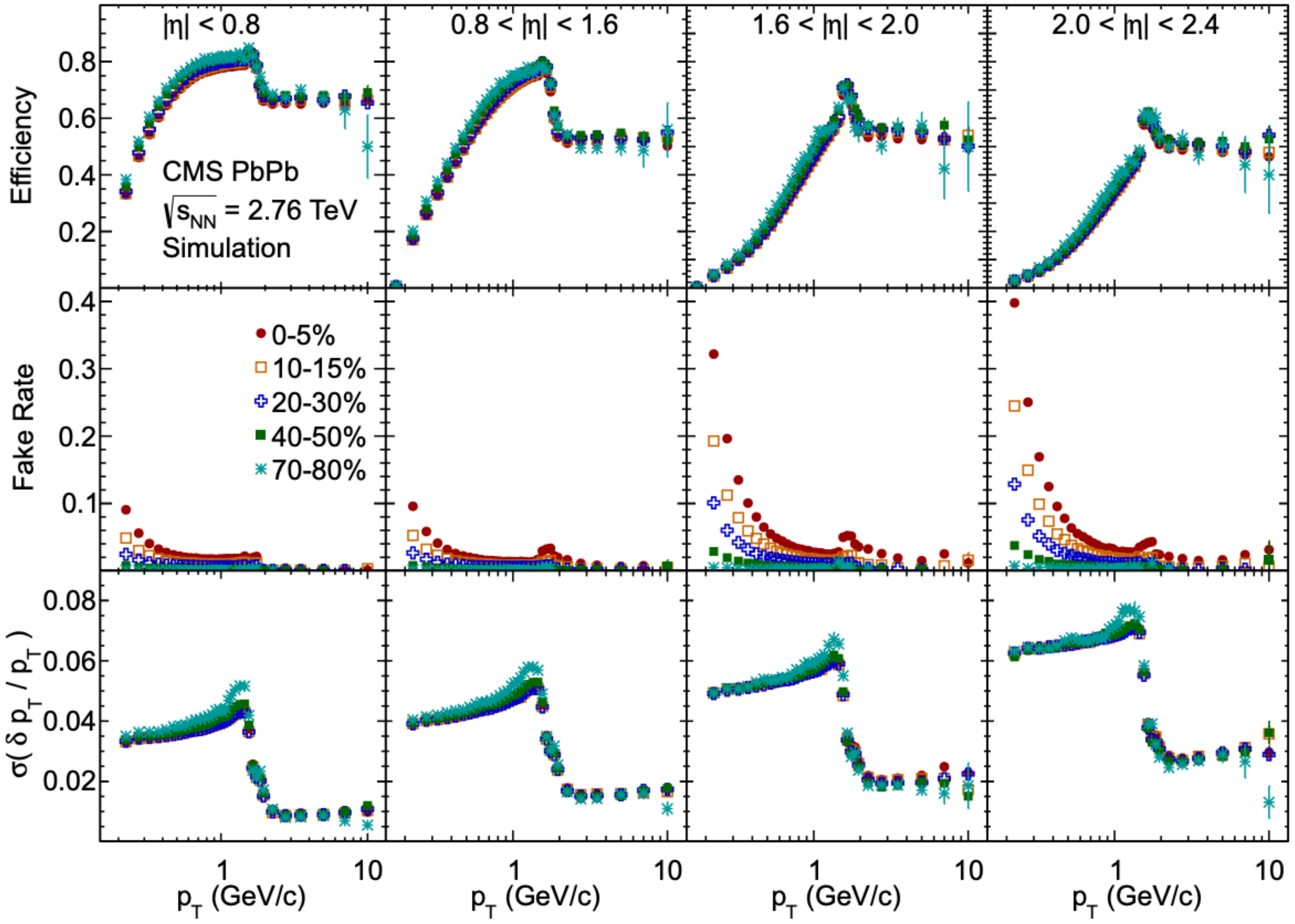

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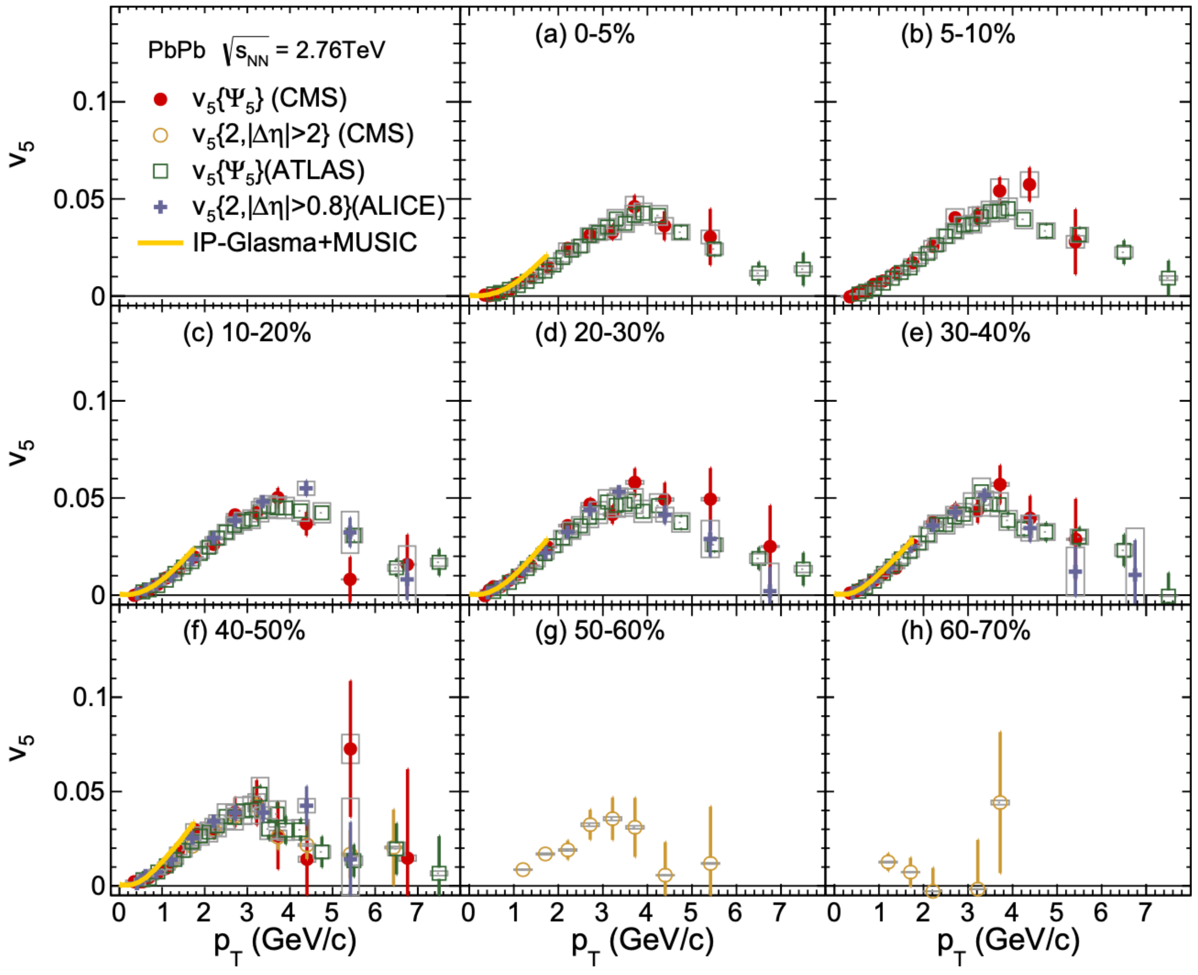
Table 2: Systematic uncertainties in the measurement of $v_2(p_T)$ for $|\eta| < 0.8$ with the event-plane method for different p_T and centrality ranges.

Source	p_T (GeV/c)	Centrality		
		0 – 10%	10 – 70%	70 – 80%
Part. composition	All	0.5%	0.5%	0.5%
Cent. determination	All	1.0%	1.0%	1.0%
Corrections	< 0.3	4.0%	2.0%	3.0%
	0.3 – 0.5	2.0%	< 1.0%	2.0%
	0.5 – 22.0	< 1.0%	< 1.0%	2.0%
Total	< 0.3	4.2%	2.3%	3.2%
	0.3 – 0.5	2.3%	1.5%	2.3%
	0.5 – 22.0	1.5%	1.5%	2.3%

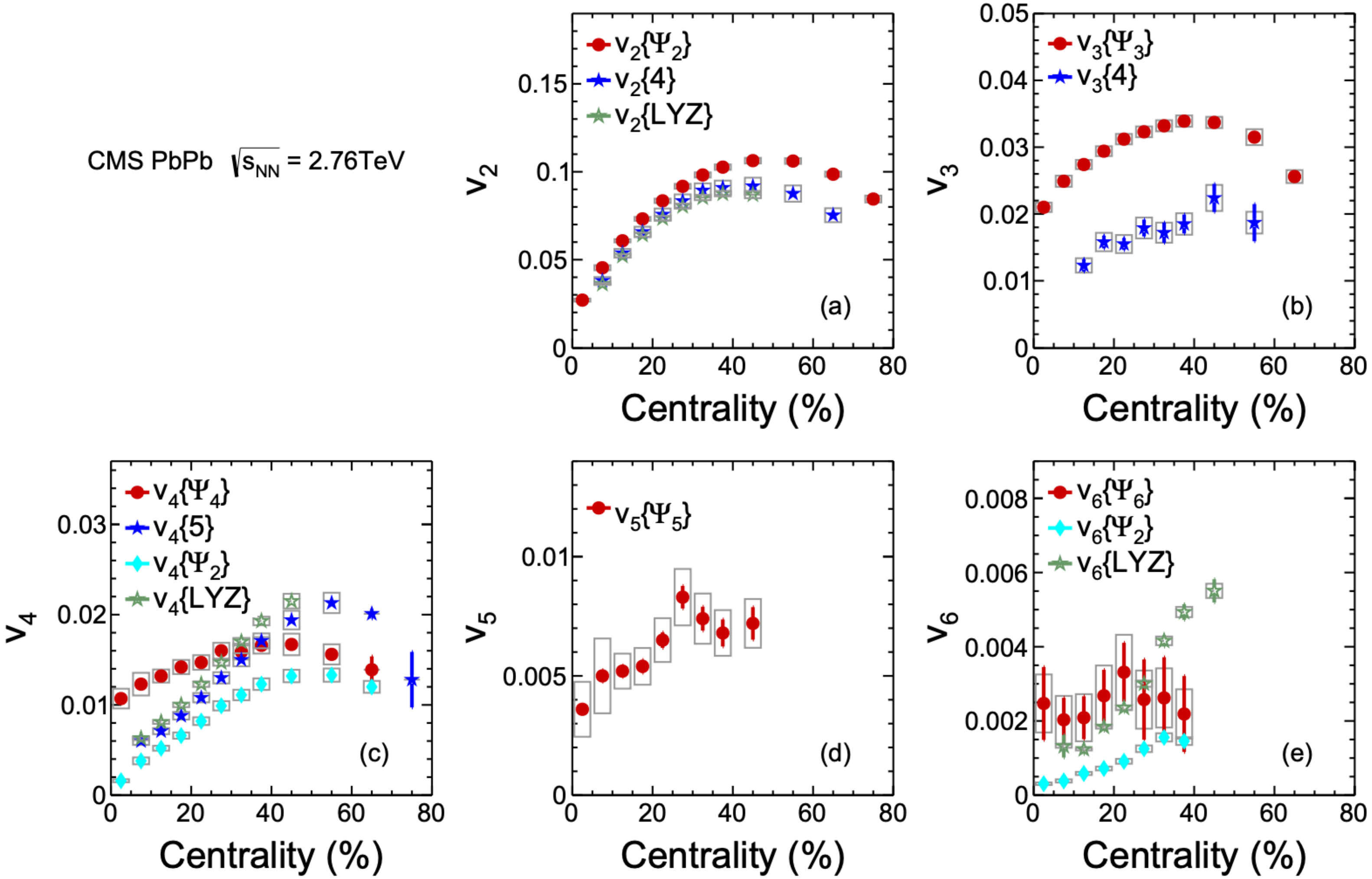
- Other possible sources of systematics:
  - Event selections
  - Trigger efficiency
  - Pileup
  - Track selections
  - …

- Detailed cross check of analysis methods/systematic studies are carefully reviewed

Higher order harmonics

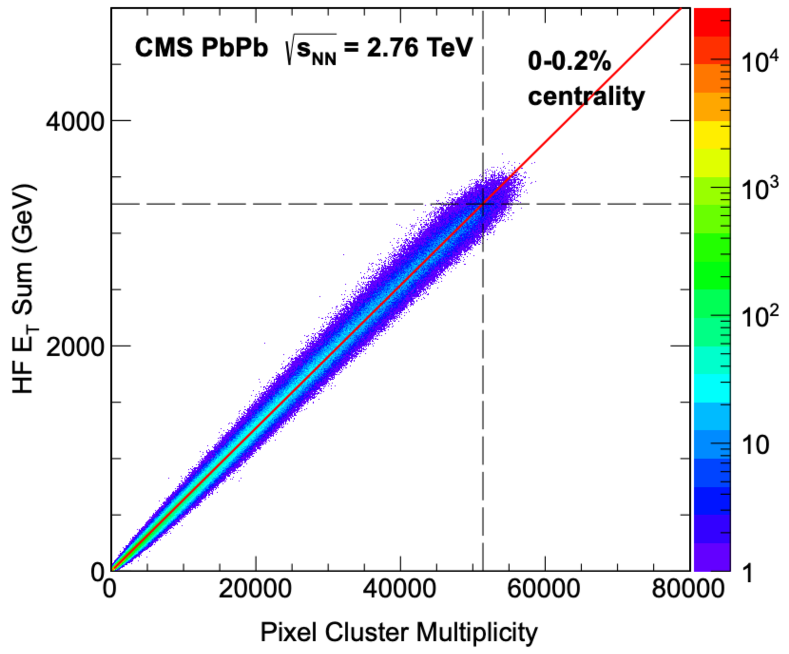


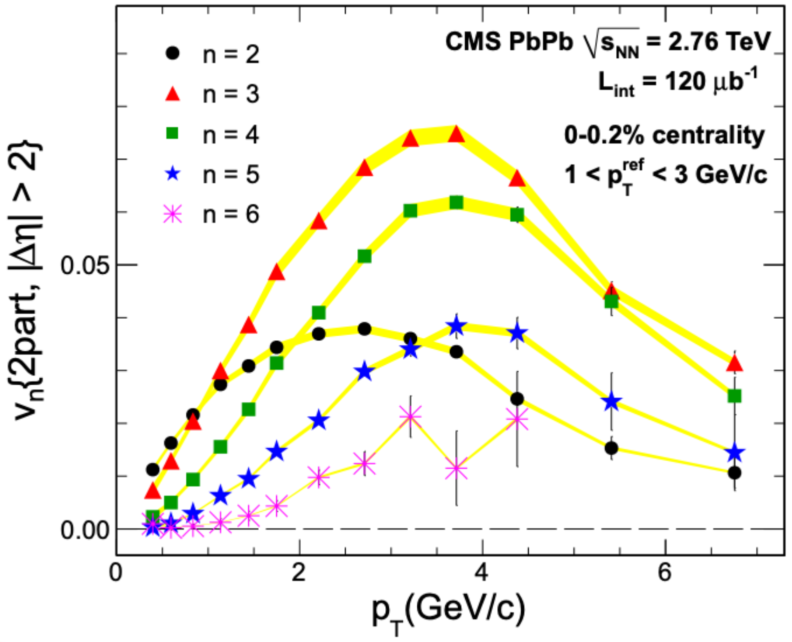
Phys. Rev. C 89 (2014) 044906

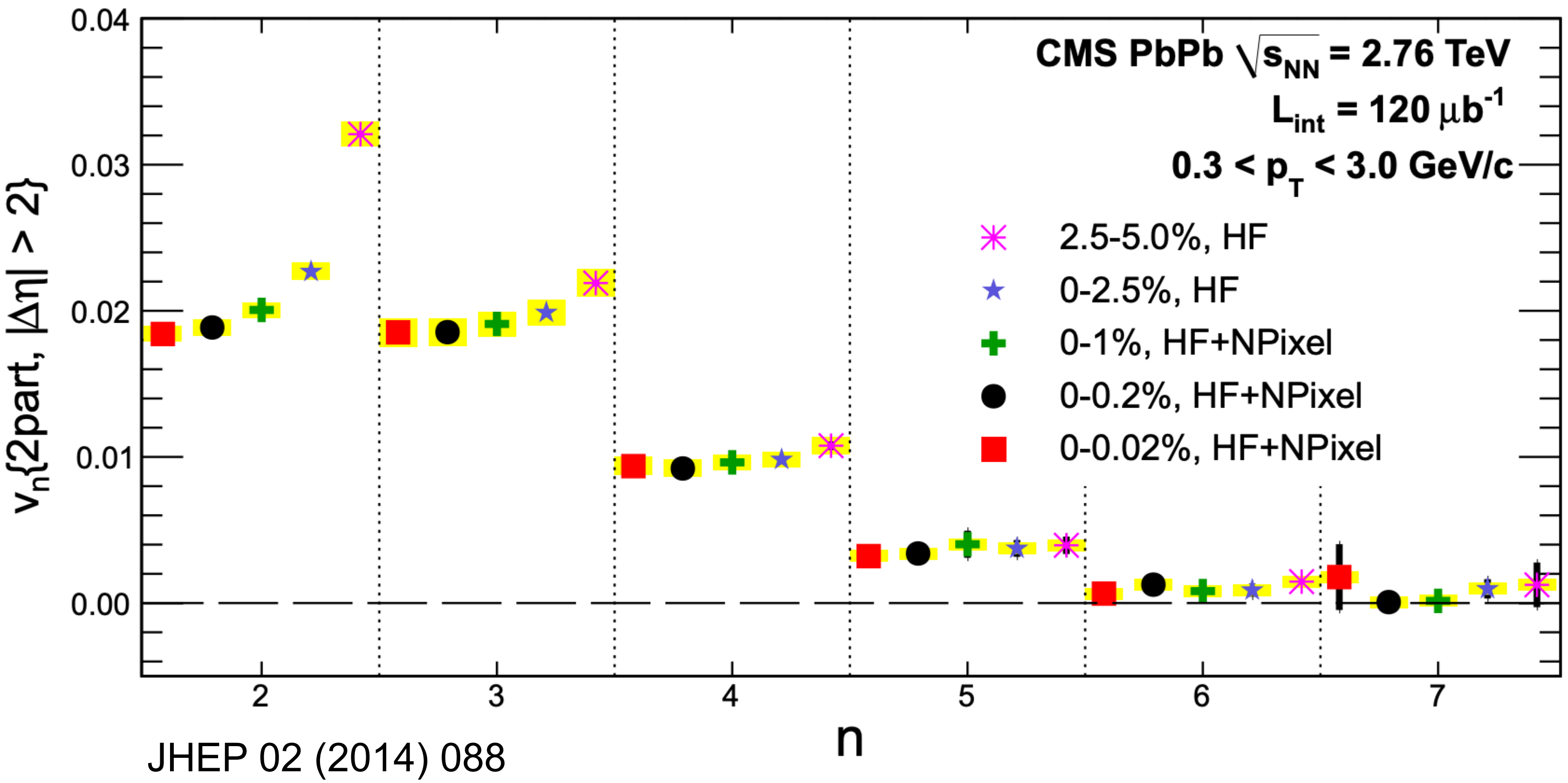


- Higher order harmonics with fluctuation driven confirmed

Ultra-central collisions







JHEP 02 (2014) 088

- v_3 larger than v_2 for p_T larger than 1 GeV in UCC
- p_T integrated v_3 larger than (or close to) v_2 for most central

Flow decorrelations

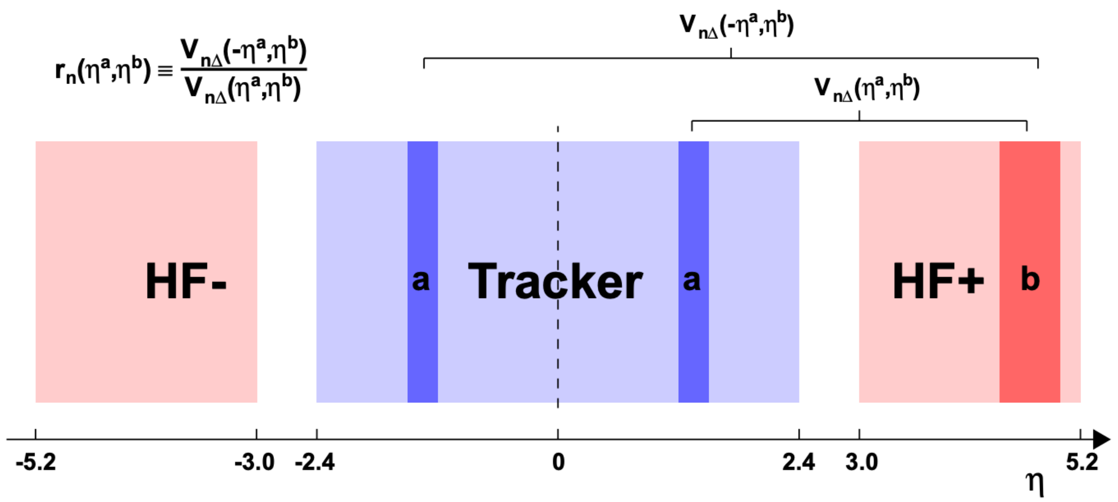
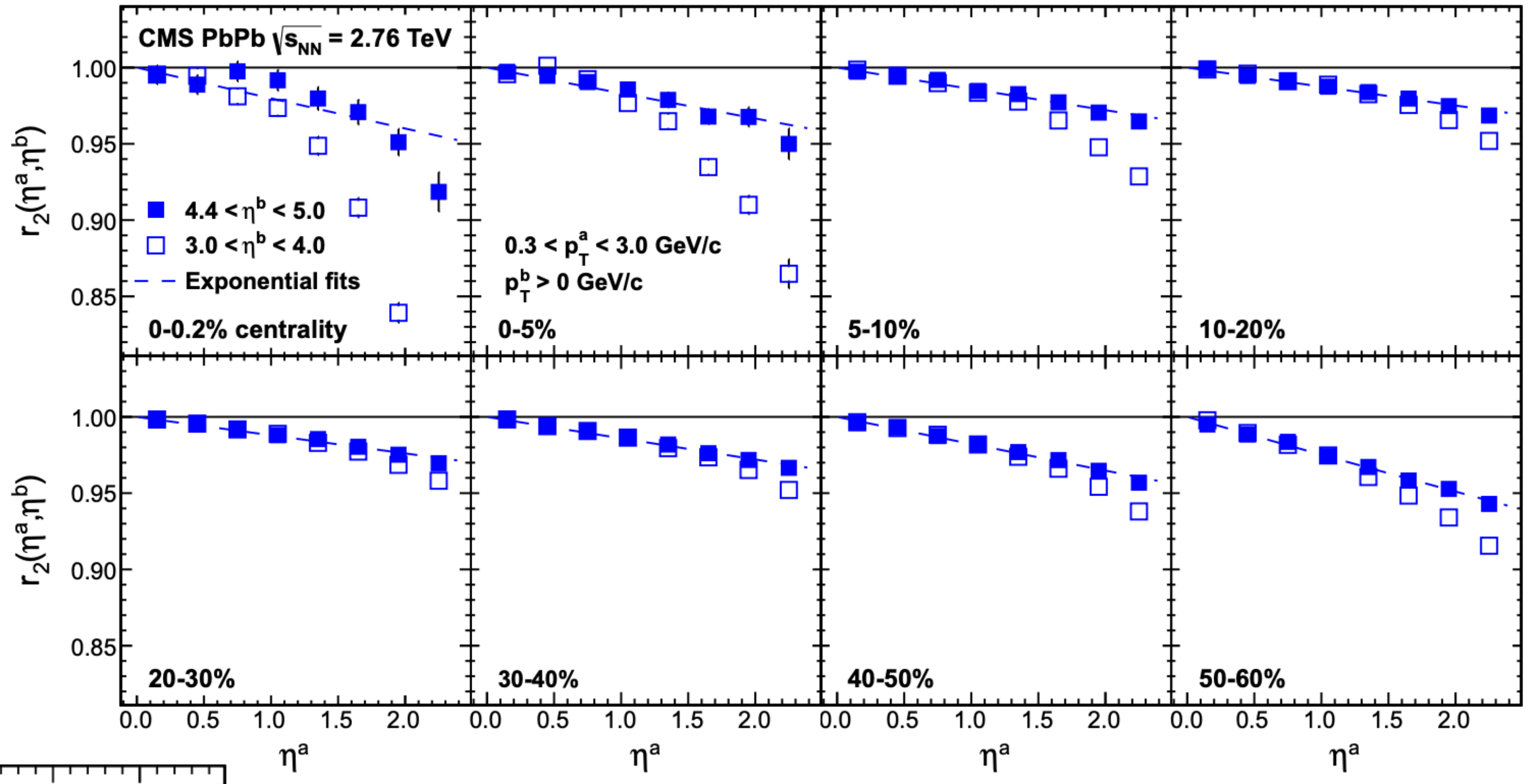
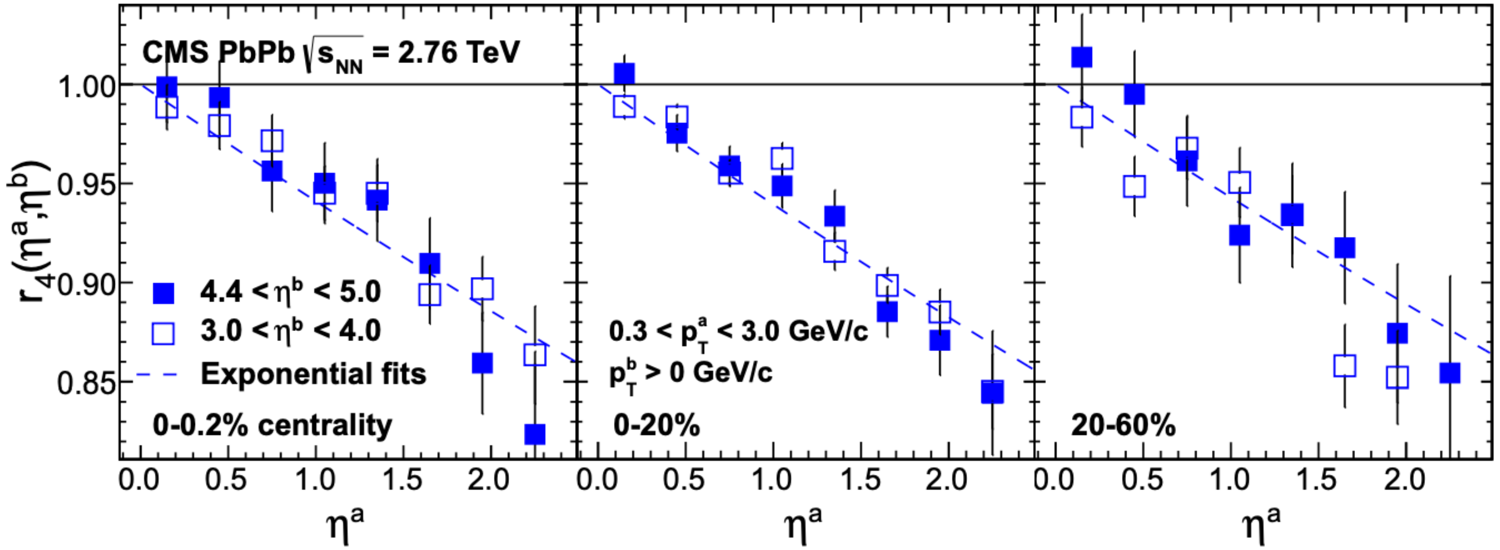


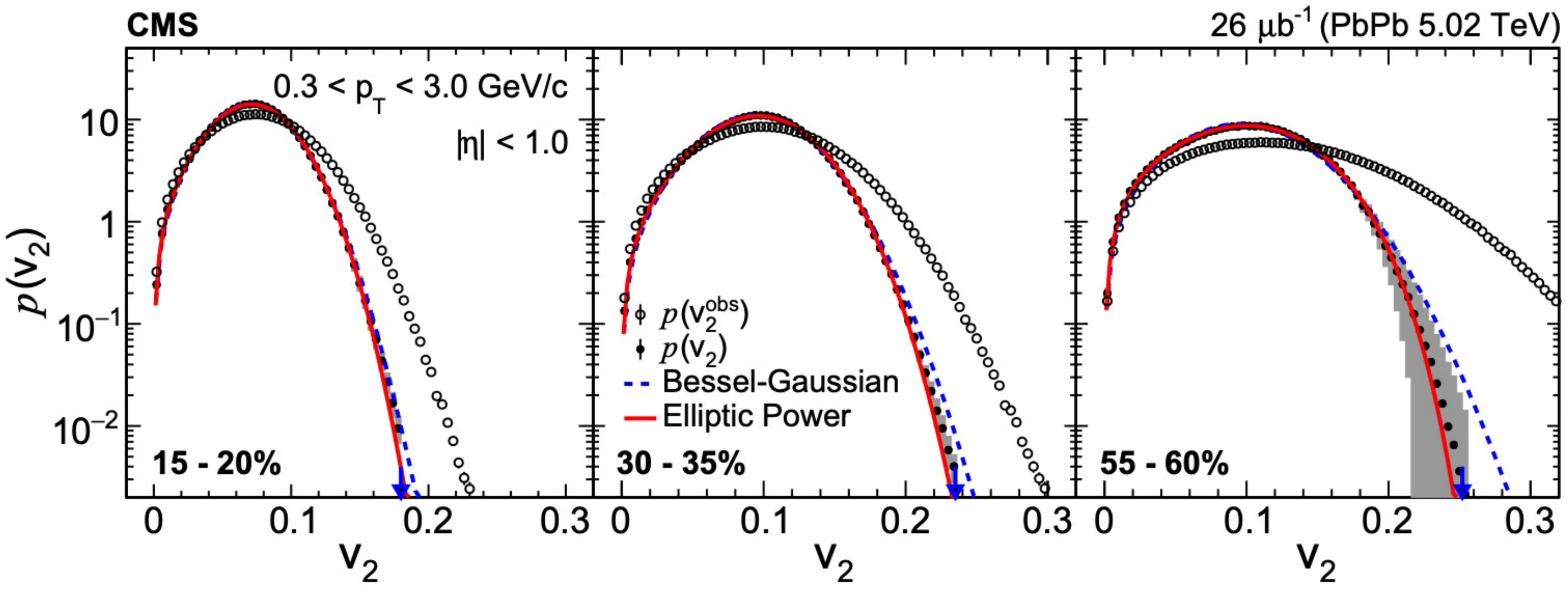
Figure 8: (Color online) A schematic illustrating the acceptance coverage of the CMS tracker and HF calorimeters, and the procedure for deriving the η-dependent factorization ratio, $r_n(\eta^a, \eta^b)$.



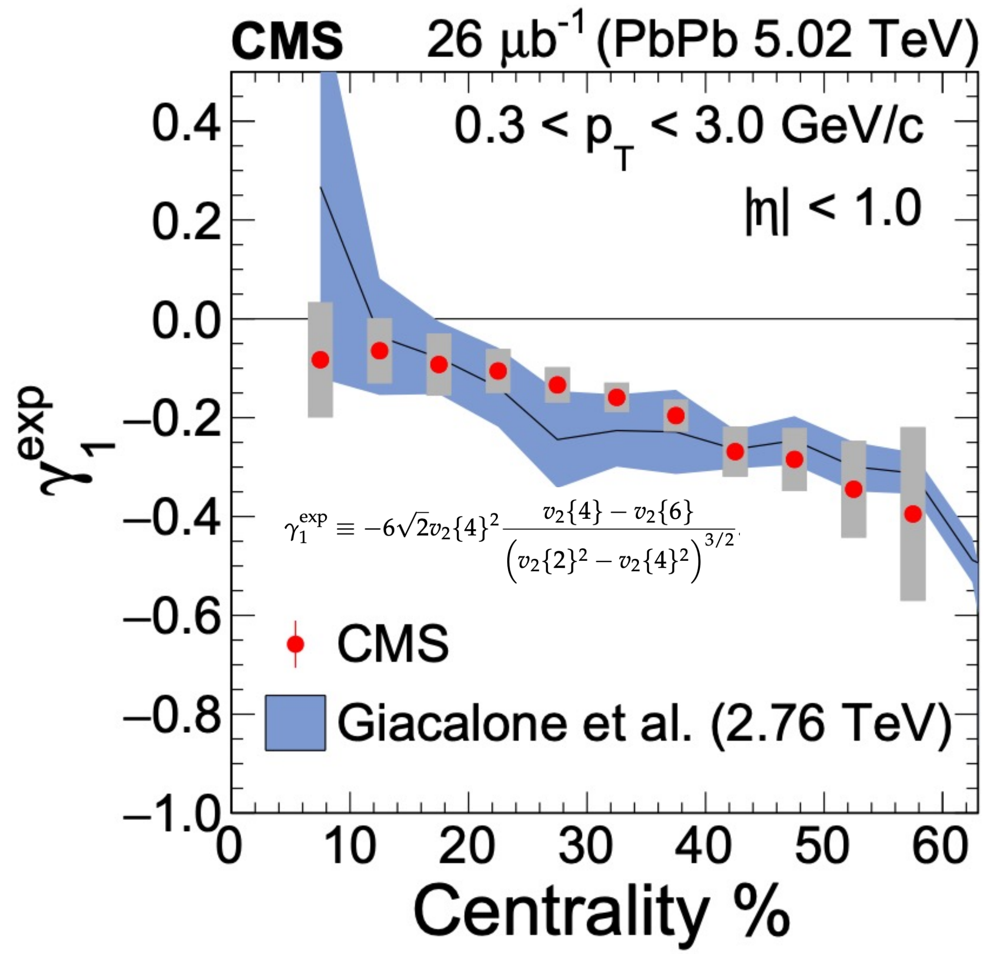


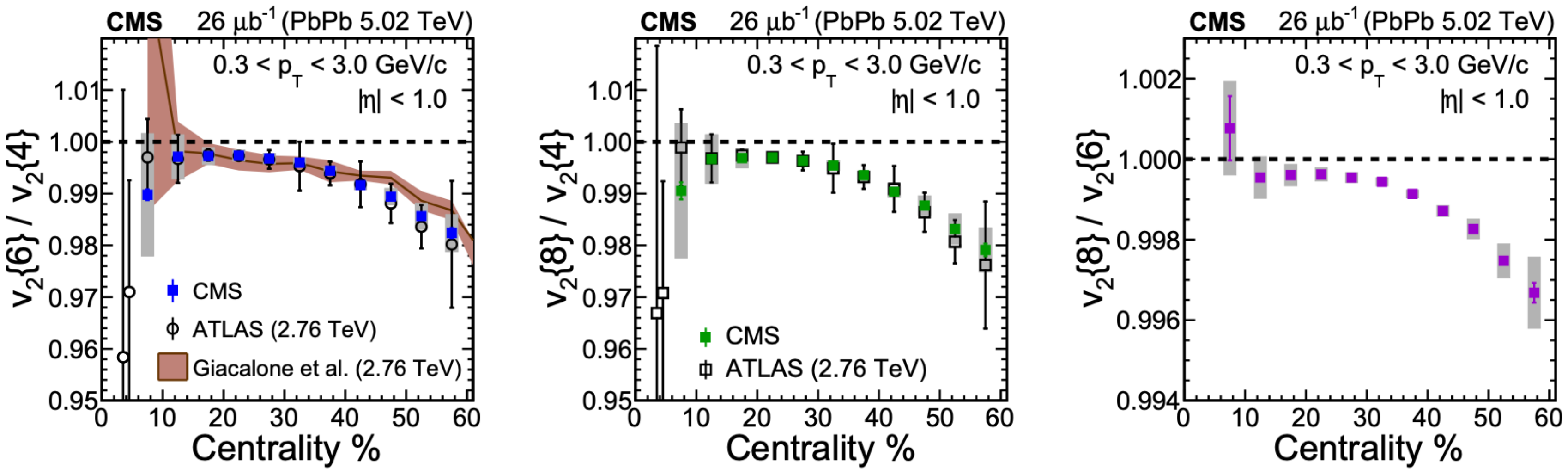
- Factorization break down
- Clear evidence of η dependence event plane fluctuations

Flow fluctuations



Phys. Lett. B 789 (2019) 643

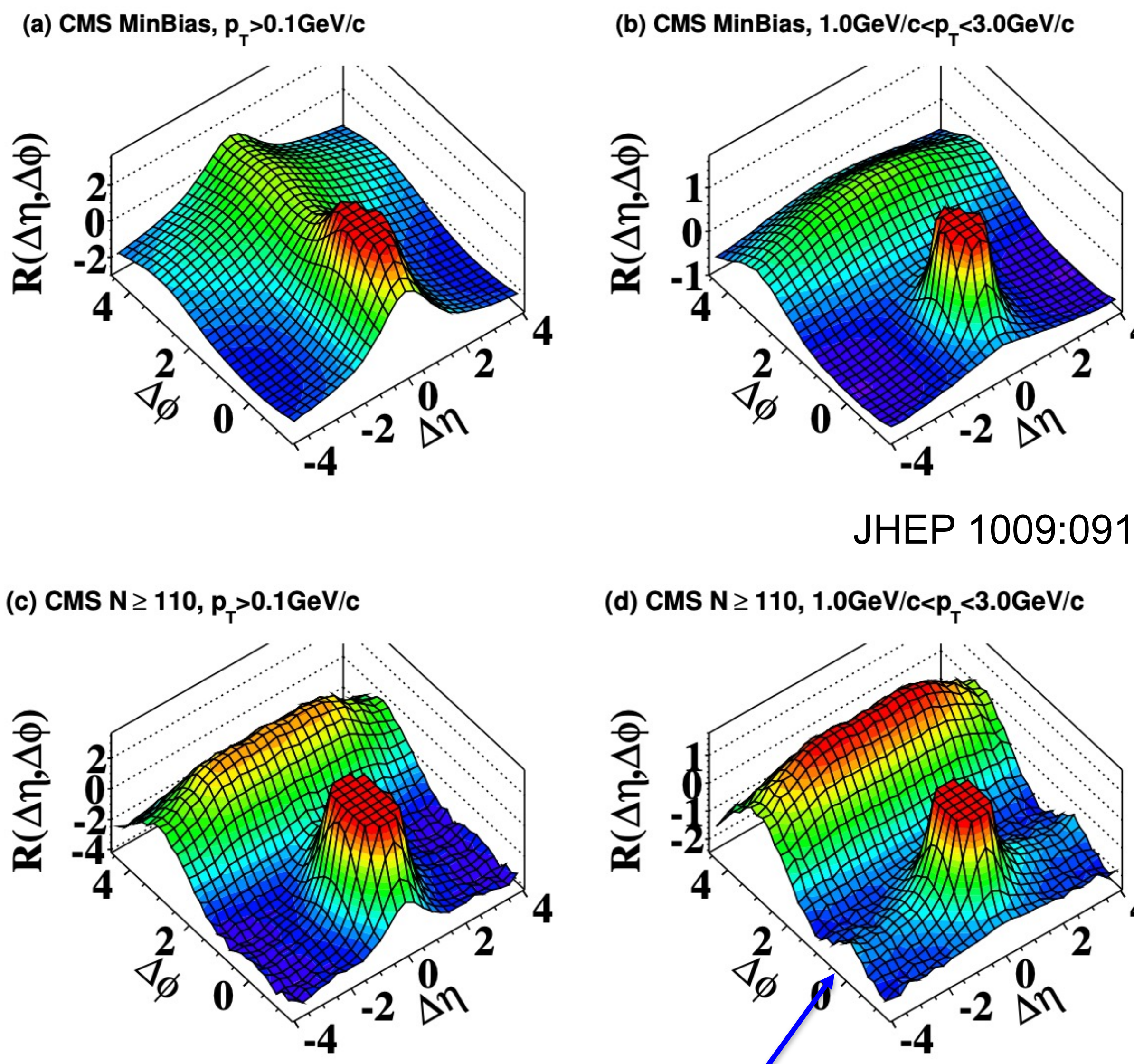




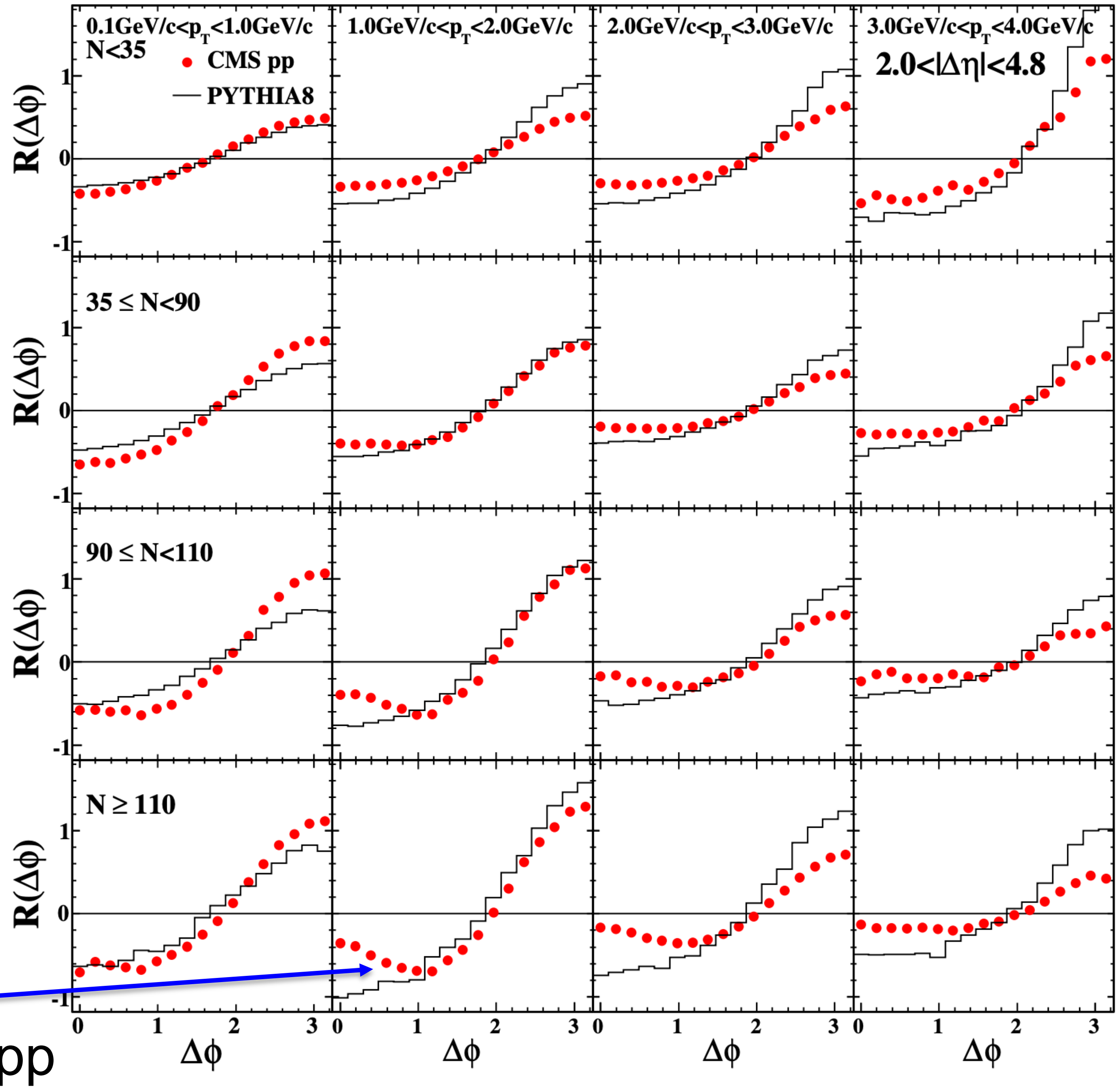
- Event-by-event flow fluctuations with unfolding method
- Evidence of non-Gaussian fluctuations

Flow in small collisions systems

Ridge in proton-proton collisions

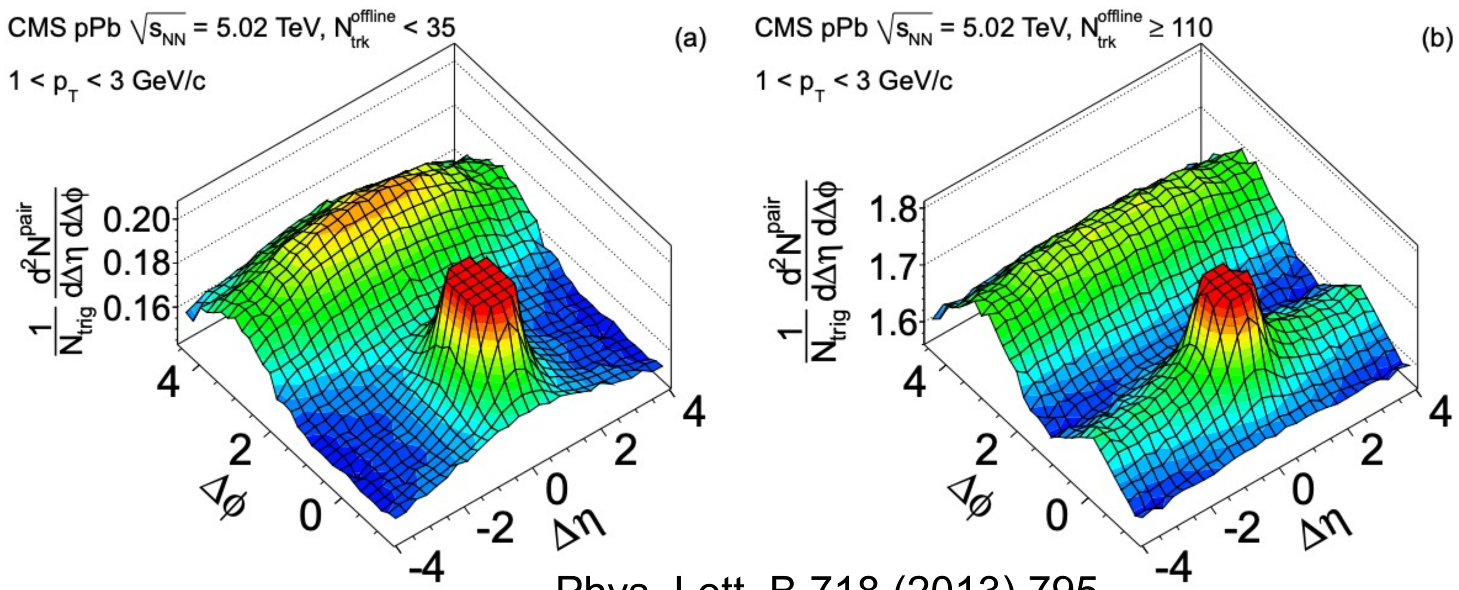


JHEP 1009:091,2010



- Clear evidence of ridge in high multiplicity pp

Ridge in pPb collisions



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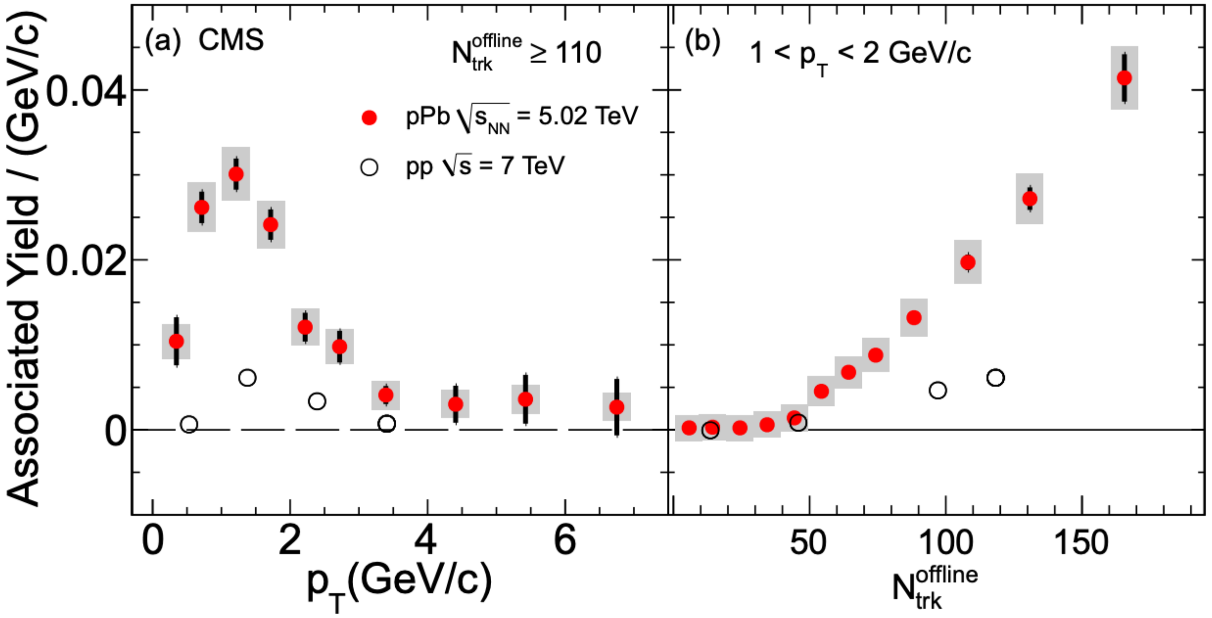
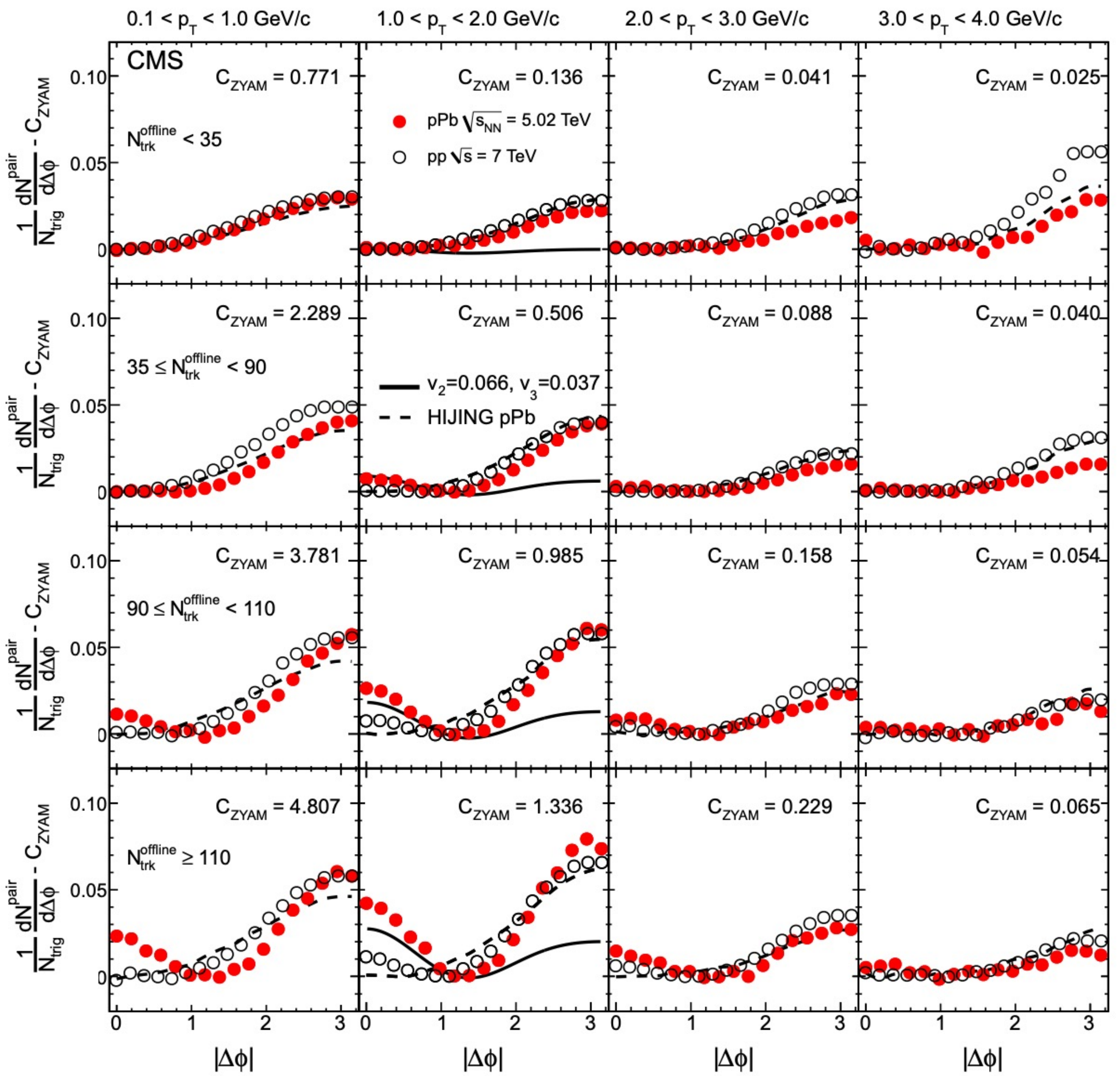
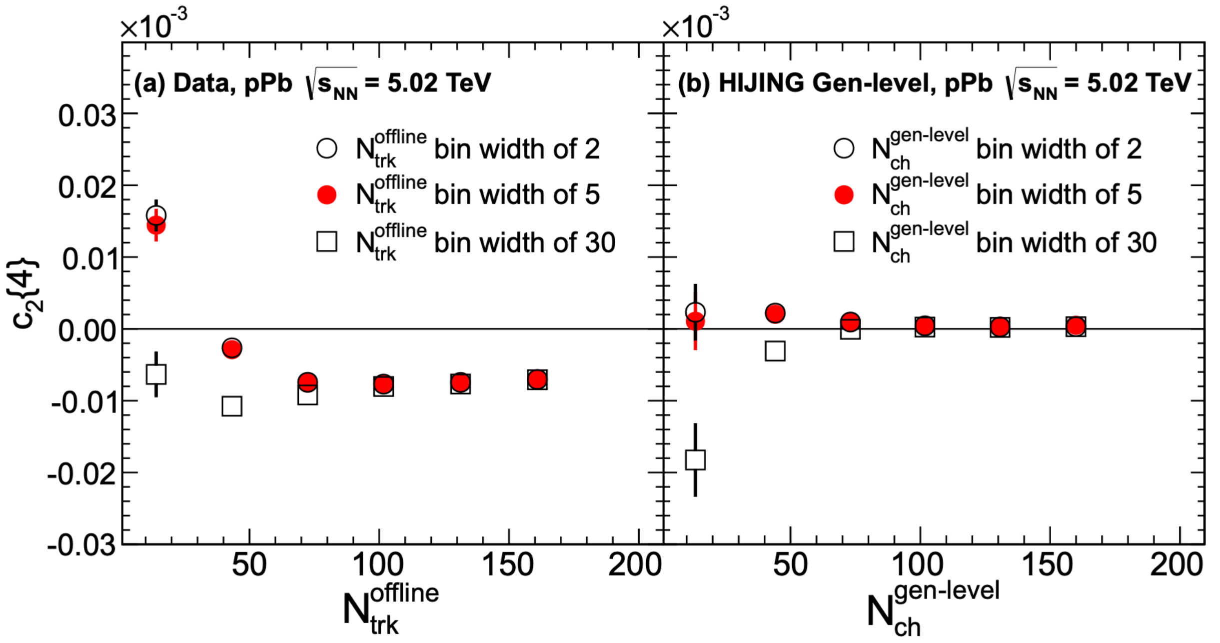
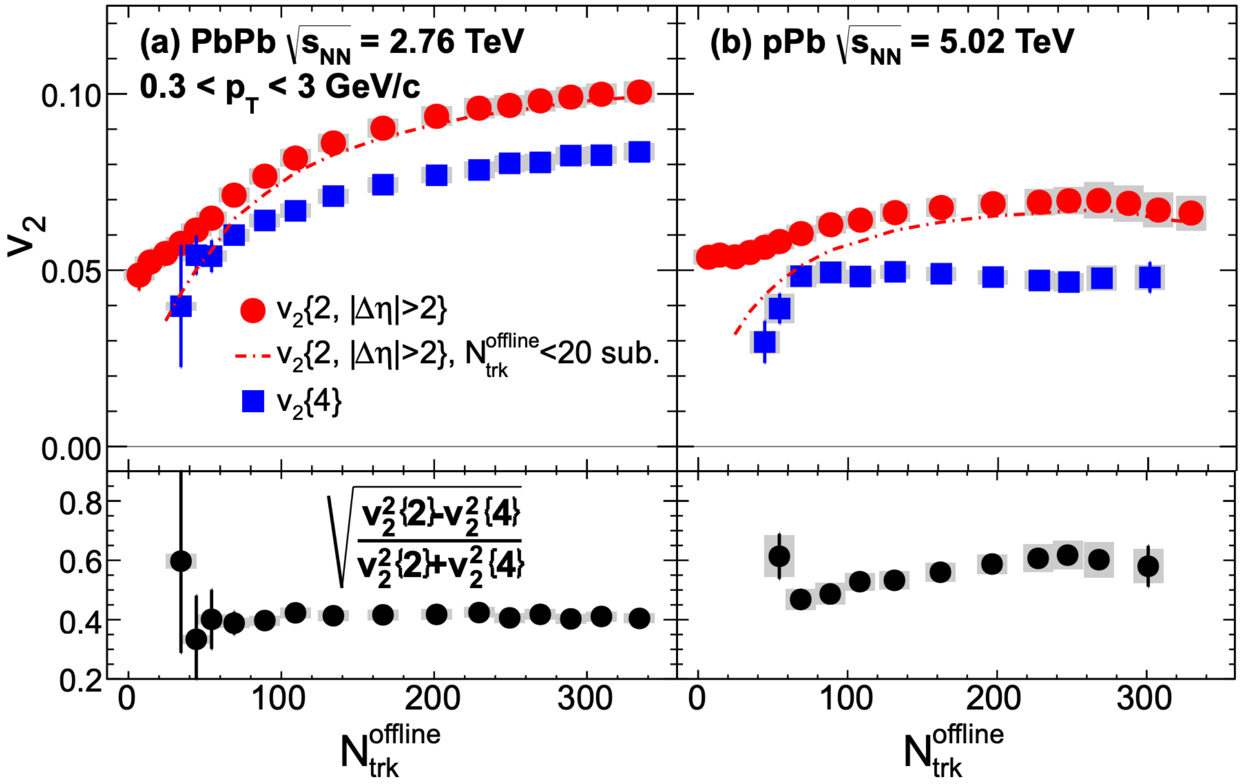


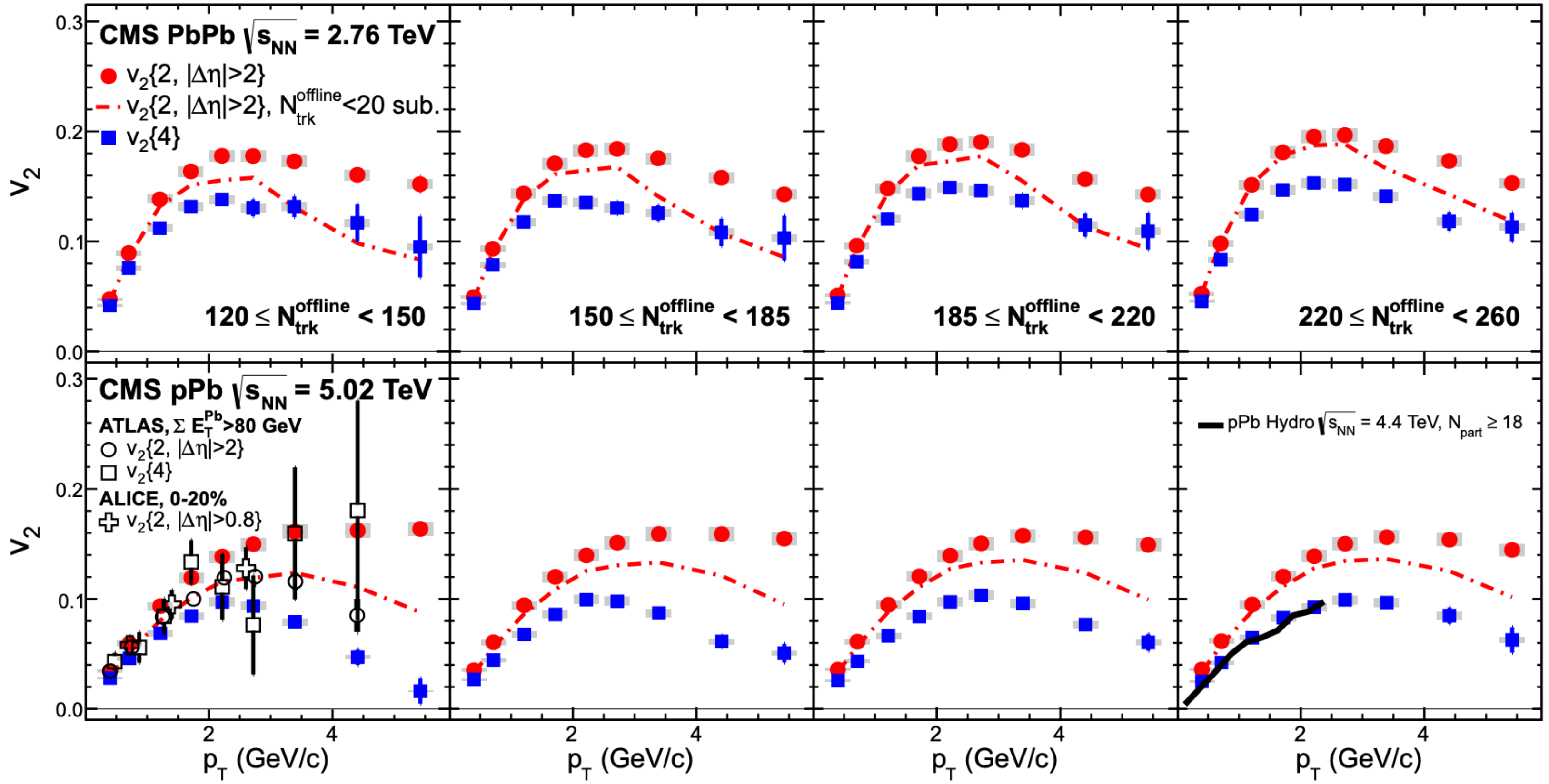


- Clear evidence of ridge also in pPb collisions

Multiparticle correlations in pPb collisions







- Need to carefully consider the multiplicity fluctuation effect for multiparticle correlations
- Fluctuations larger in pPb compared to PbPb
- Hydrodynamic predictions agree with data

More details of two particle correlations at CMS

Reconstructed tracks with $|\eta|<2.4$

Signal pair distribution:

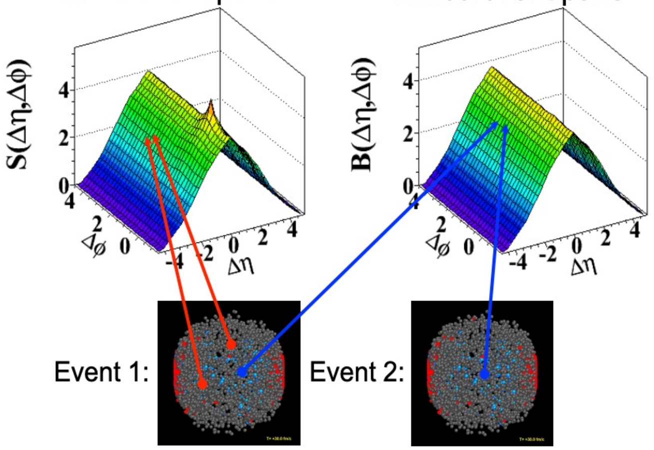
$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

Background pair distribution:

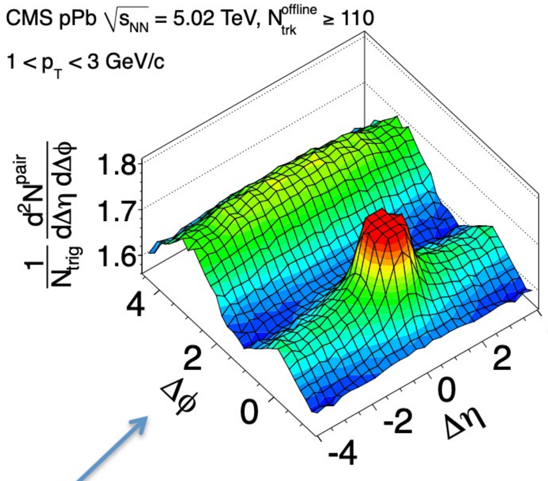
$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$

same event pairs

mixed event pairs



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



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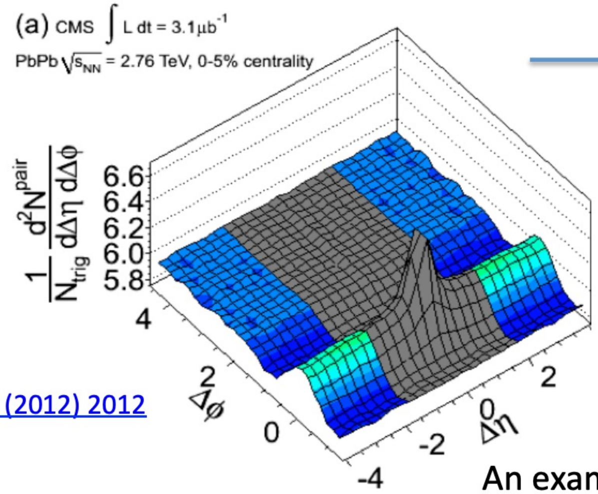
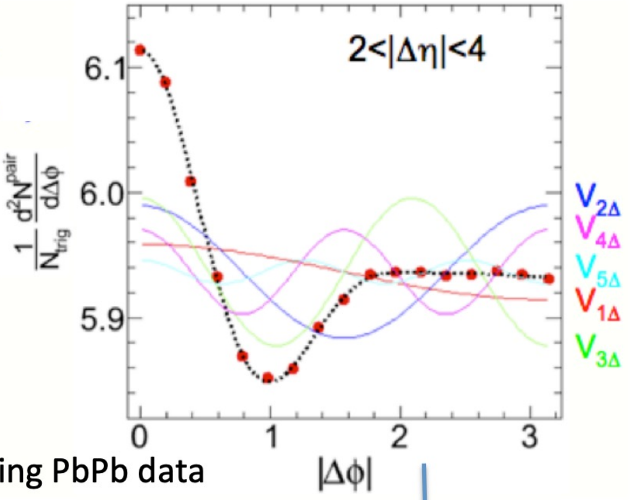
Associated hadron yield per trigger:

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

Long-range: $|\Delta\eta|>2$
Short-range: $|\Delta\eta|<1$
Near-side: $\Delta\phi \sim 0$
Away-side: $\Delta\phi \sim \pi$



EPJC 72 (2012) 2012



An example using PbPb data

Fourier decomposition:

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

Assuming factorization:

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

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

Take low reference p_T bin (0.3-3 GeV/c)

Reducing nonflow with peripheral subtraction

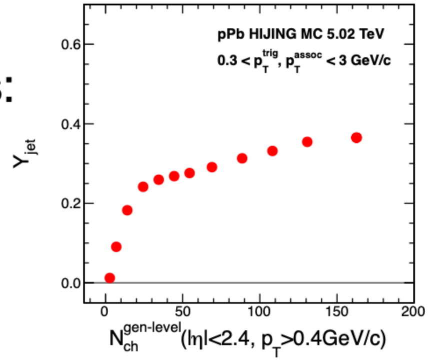
- Away-side correlations contain non-flow effects
- Subtract the data for high multiplicity by low multiplicity to correct for this

Fourier decomposition:

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

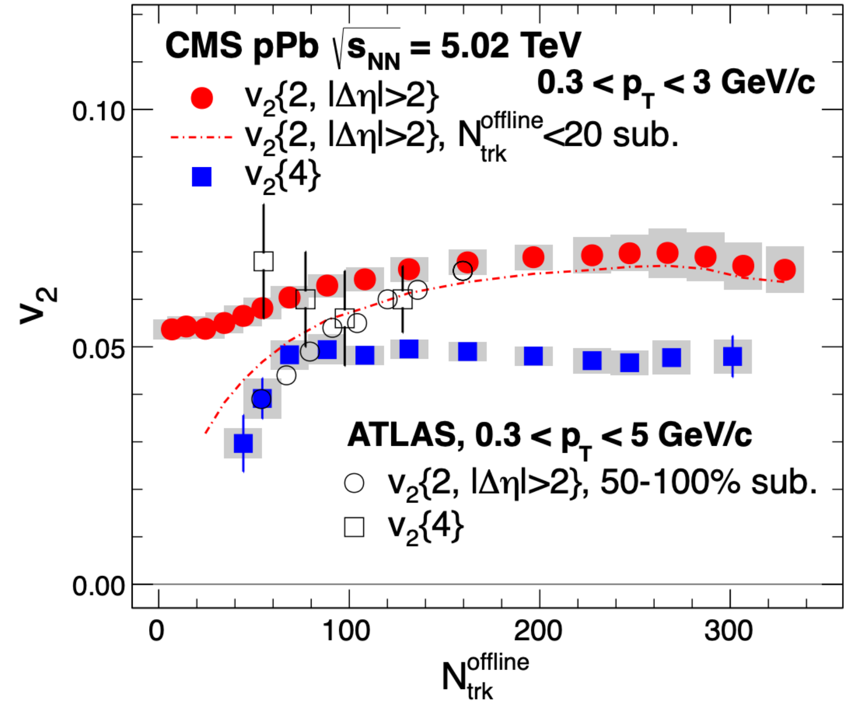
Subtracting peripheral correlations in v_2, v_3 calculations:

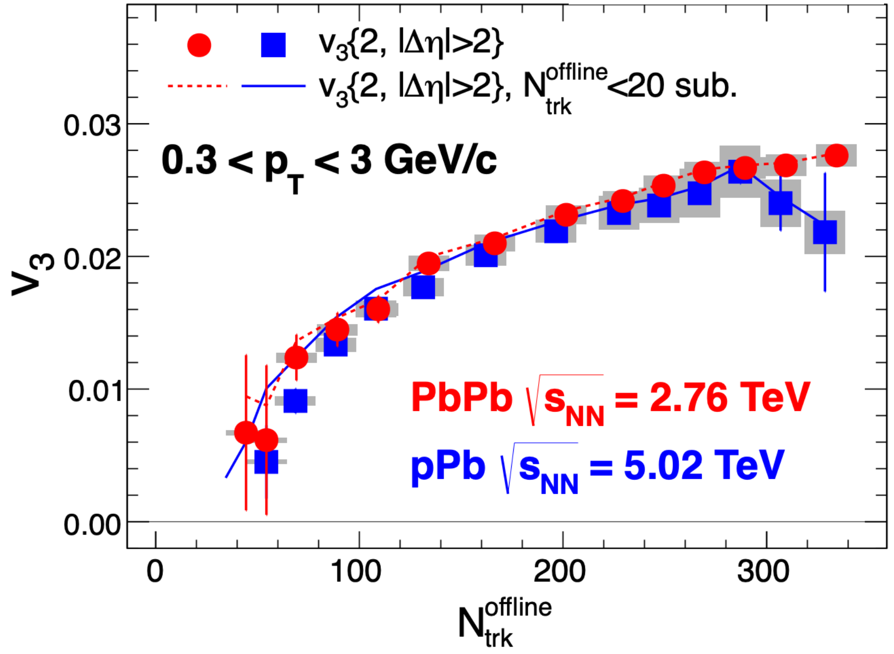
$$V_{n\Delta}(\text{cent}) - V_{n\Delta}(\text{peri}) \times \frac{N_{assoc}(\text{peri})}{N_{assoc}(\text{cent})} \times \frac{Y^{jet}(\text{cent})}{Y^{jet}(\text{peri})}$$



Subtract $N_{trk}^{offline}<20$ (70-100%) to avoid removing signal ($N_{trk}^{offline}\sim 40$)

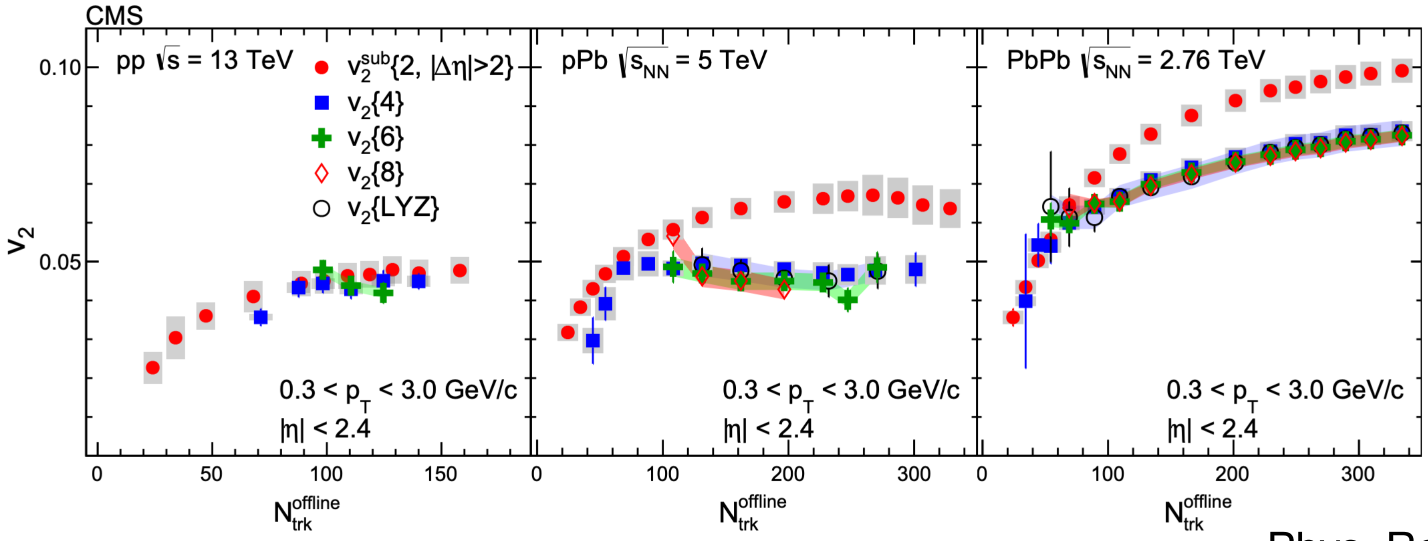
Account for the fact that jet correlation increases with multiplicity





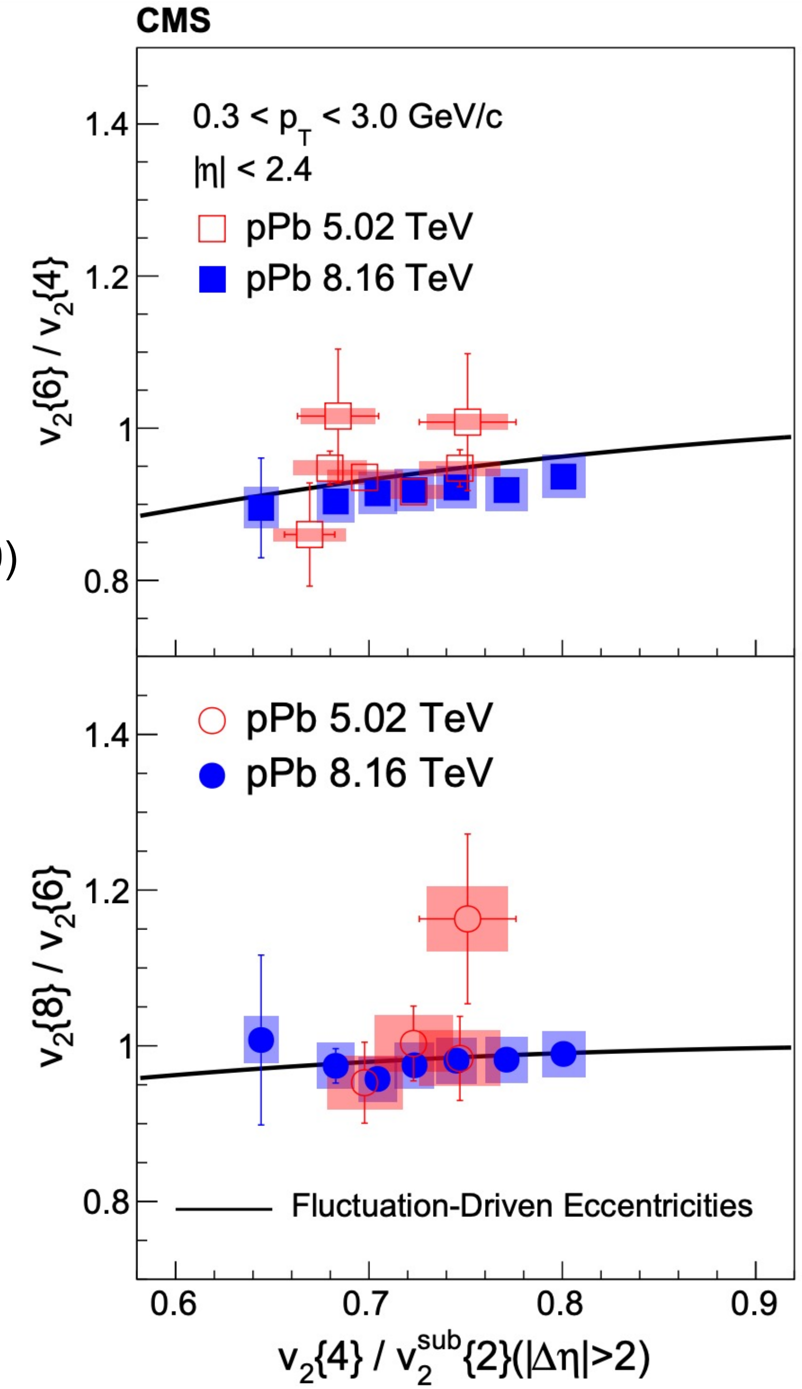
- The method reduce nonflow at low multiplicities

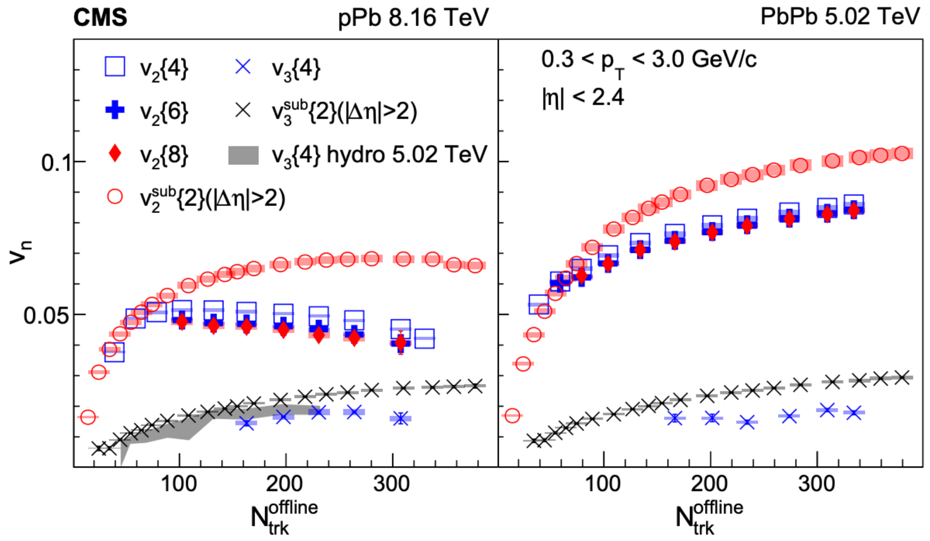
More evidence of small system flow

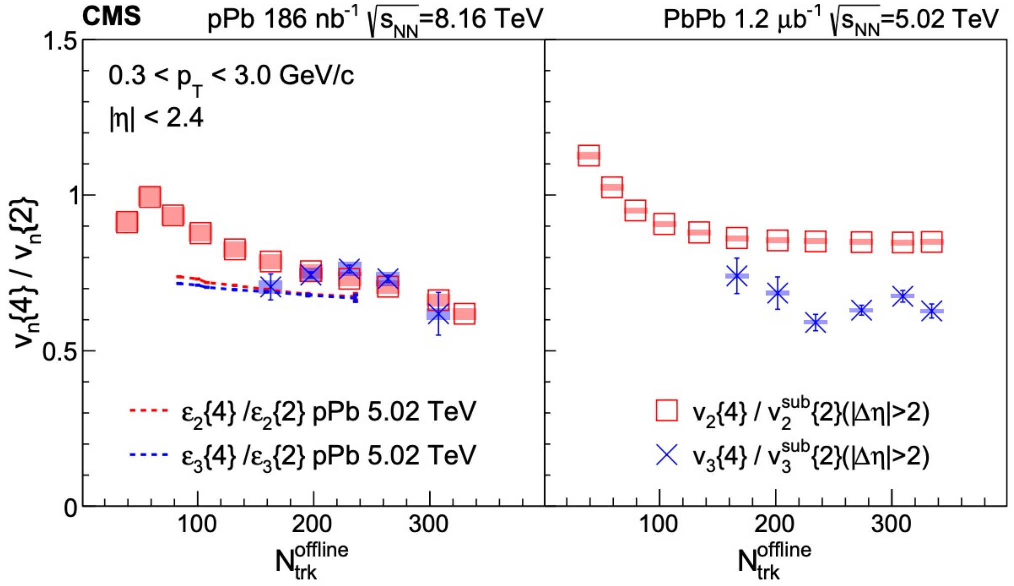


Phys. Lett. B 765 (2017) 193

Phys. Rev. C 101, 014912 (2020)

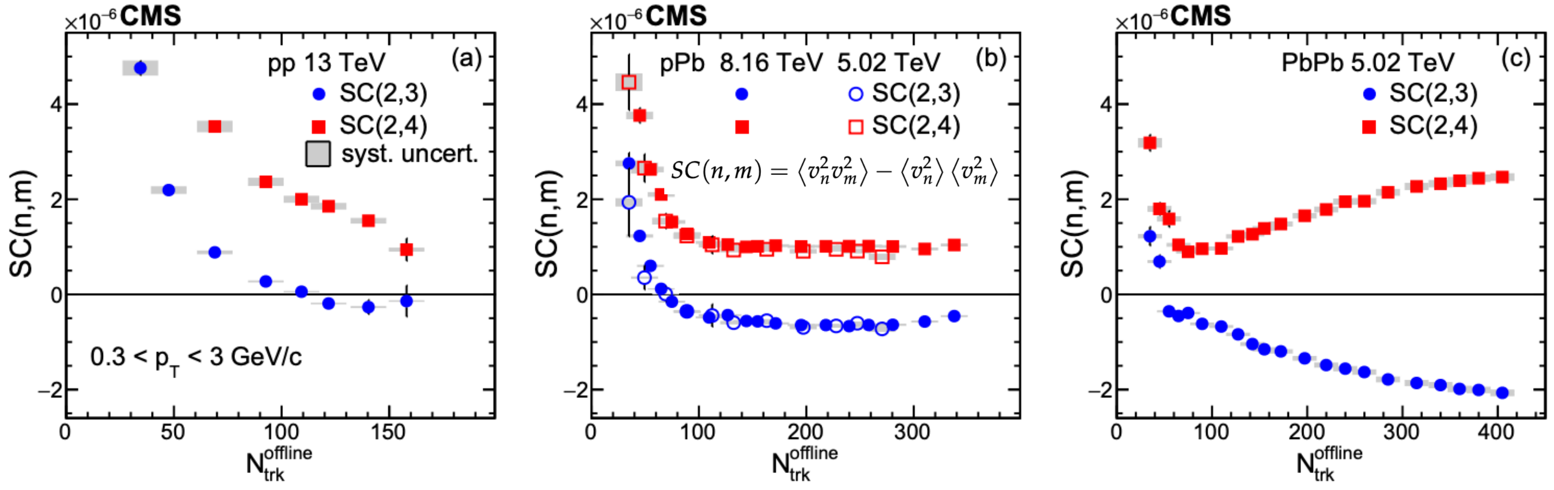


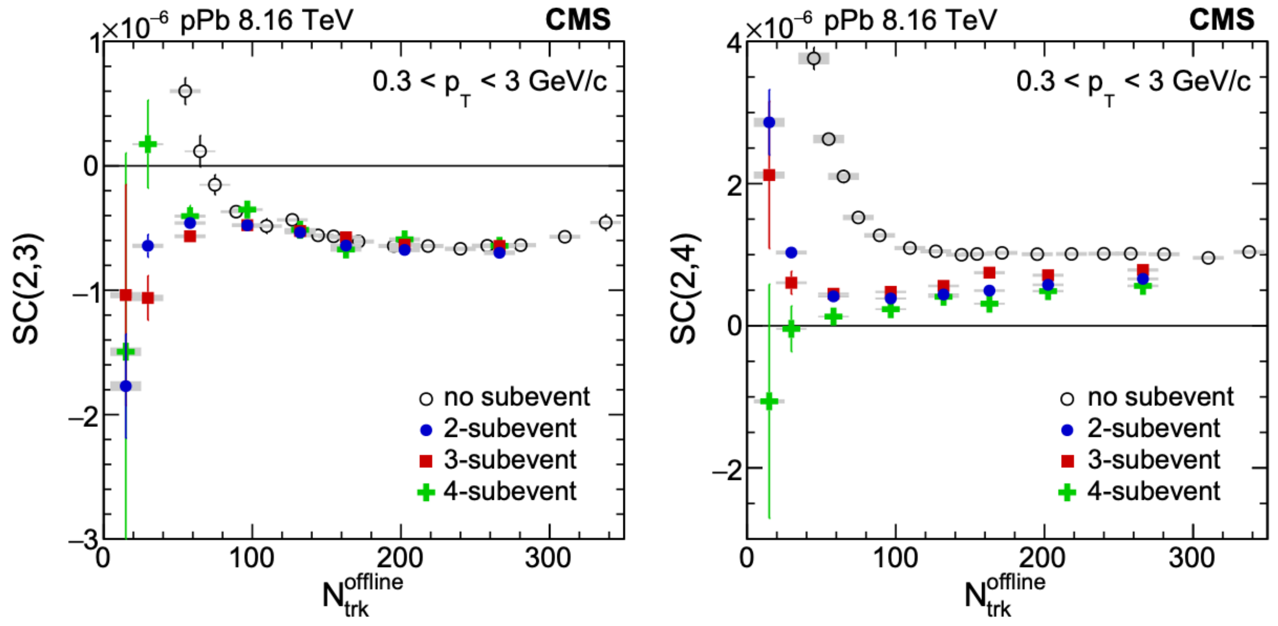


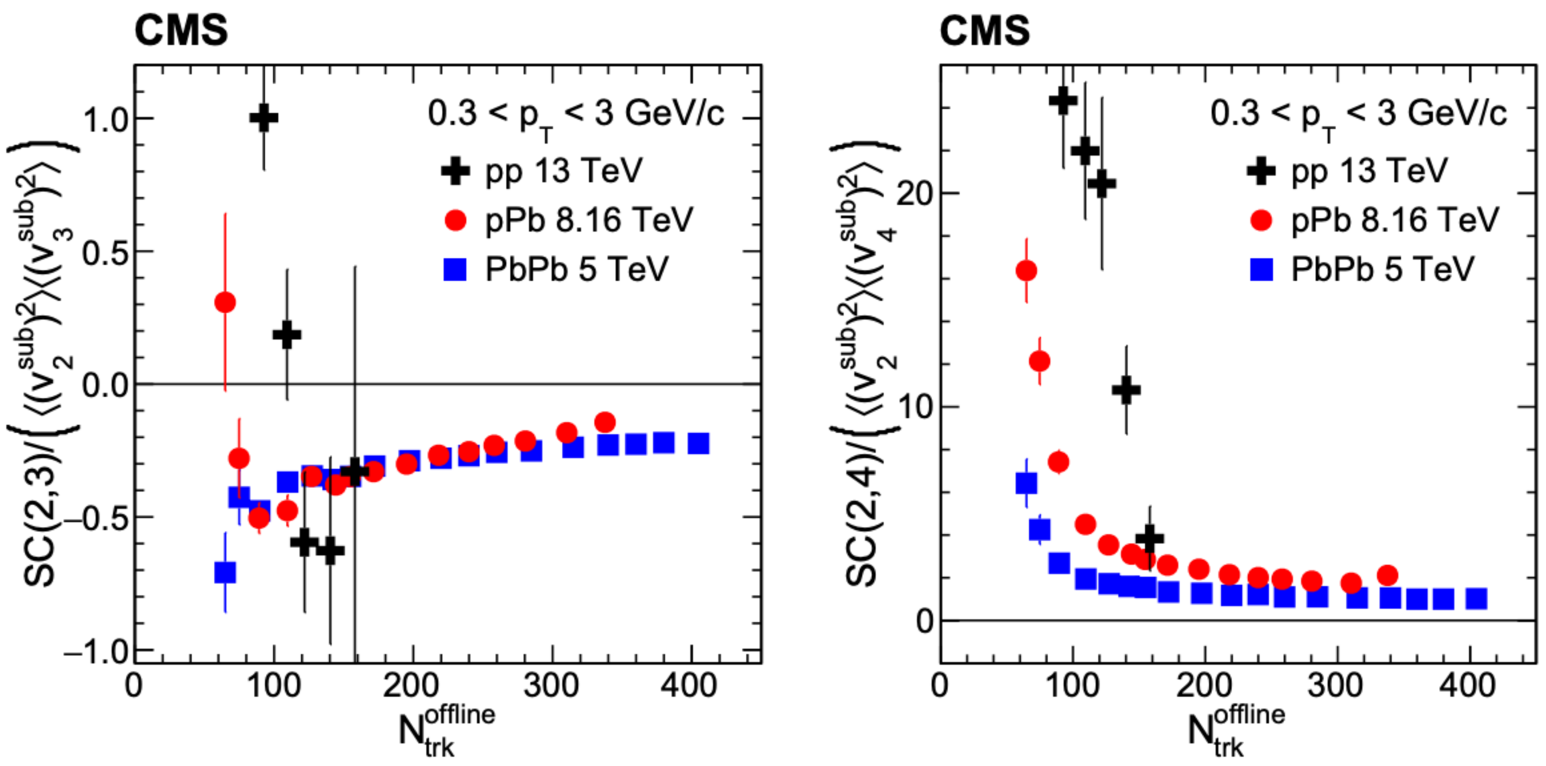


- The evidence of small system flow is more clear

Symmetric cumulant





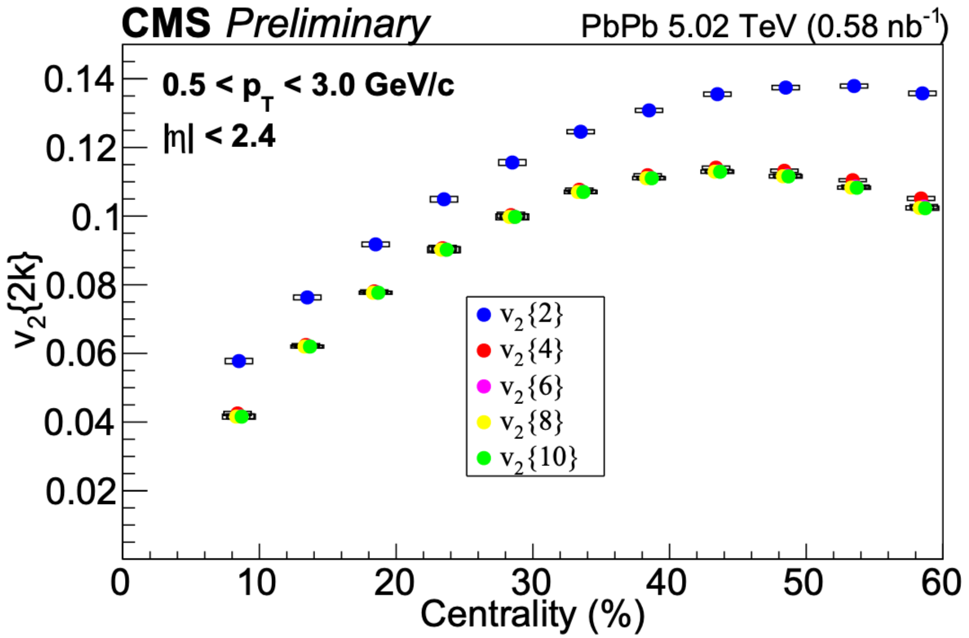


- Anti-correlation between v_2 and v_3
- Positive correlation between v_2 and v_4
- Subevent method remove more nonflow
- Another evidence of flow in small systems

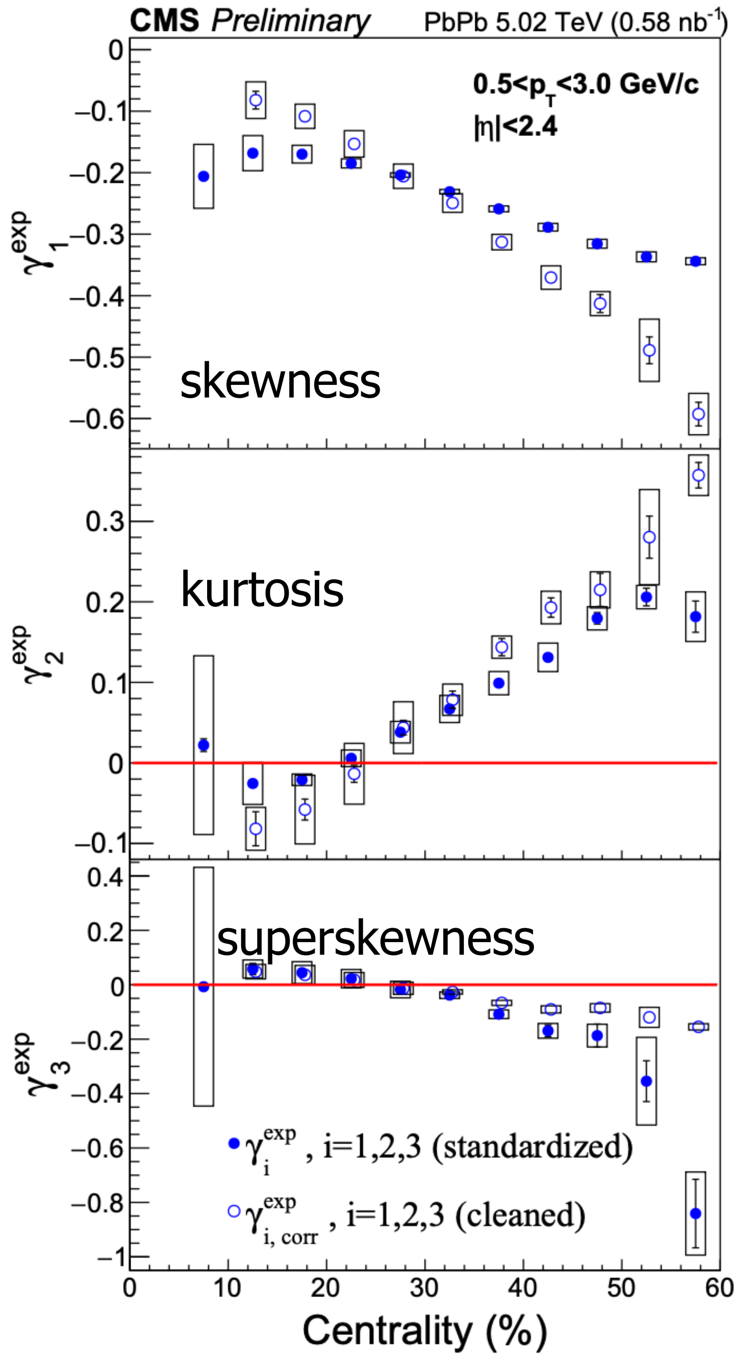
Recent development

CHARGED HADRONS – CUMULANTS IN PBPB

CMS-PAS-HIN-21-010



- Measurements of v_2 with up to 10 particle correlations from the cumulant method
- Splittings between cumulant of different orders are sensitive to non-Gaussian fluctuations of v_2
- Hydrodynamics and initial state models can be tested with the moments: skewness, kurtosis, and superskewness



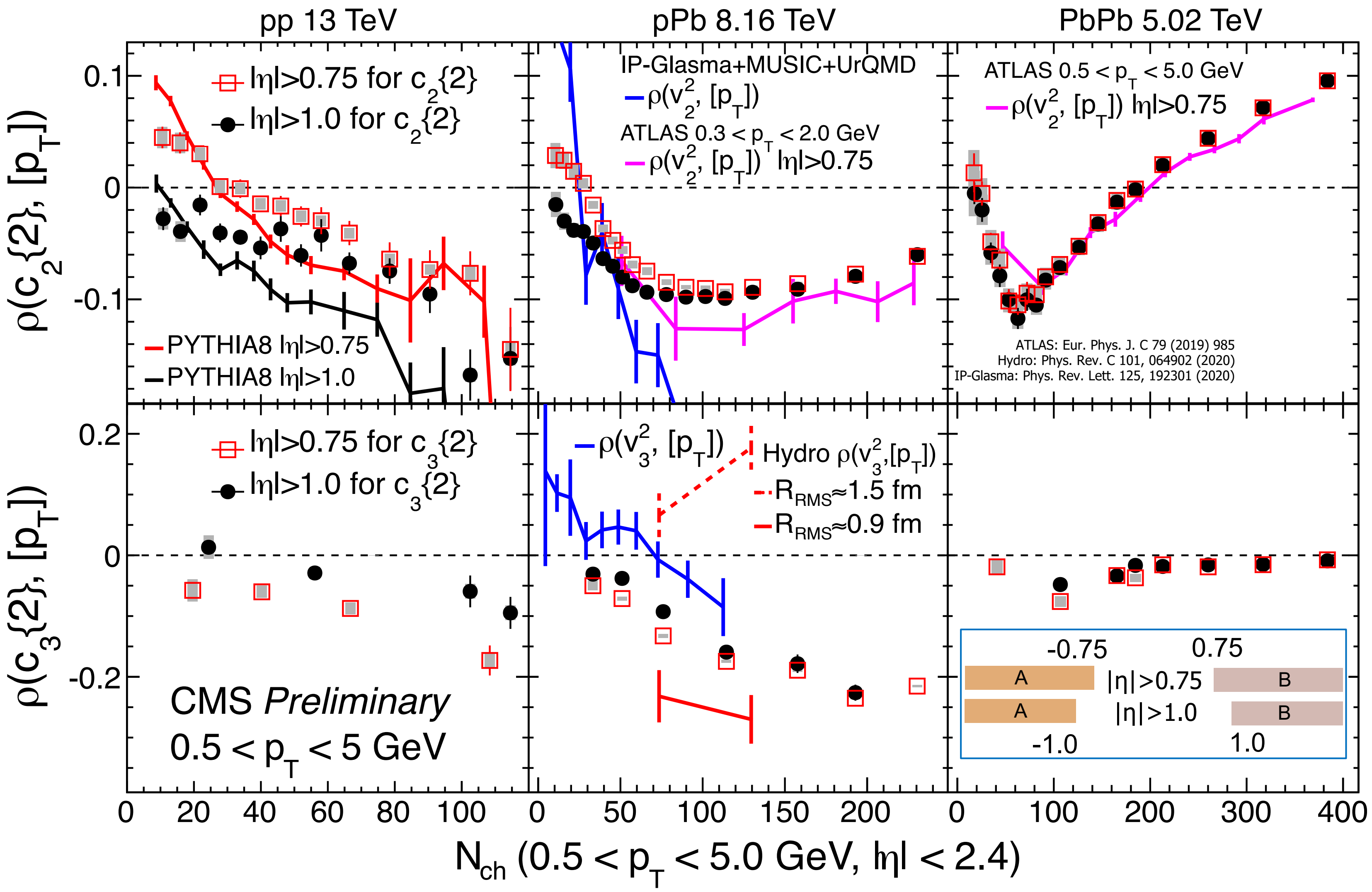
FLOW-MEAN PT CORRELATIONS

CMS-PAS-HIN-21-012

$$\rho(v_2^2, [p_T]) = \frac{\mathrm{cov}(v_2^2, [p_T])}{\sqrt{\mathrm{Var}(v_2^2)_{dyn}}\sqrt{\mathrm{Var}([p_T])_{dyn}}}$$

n=2

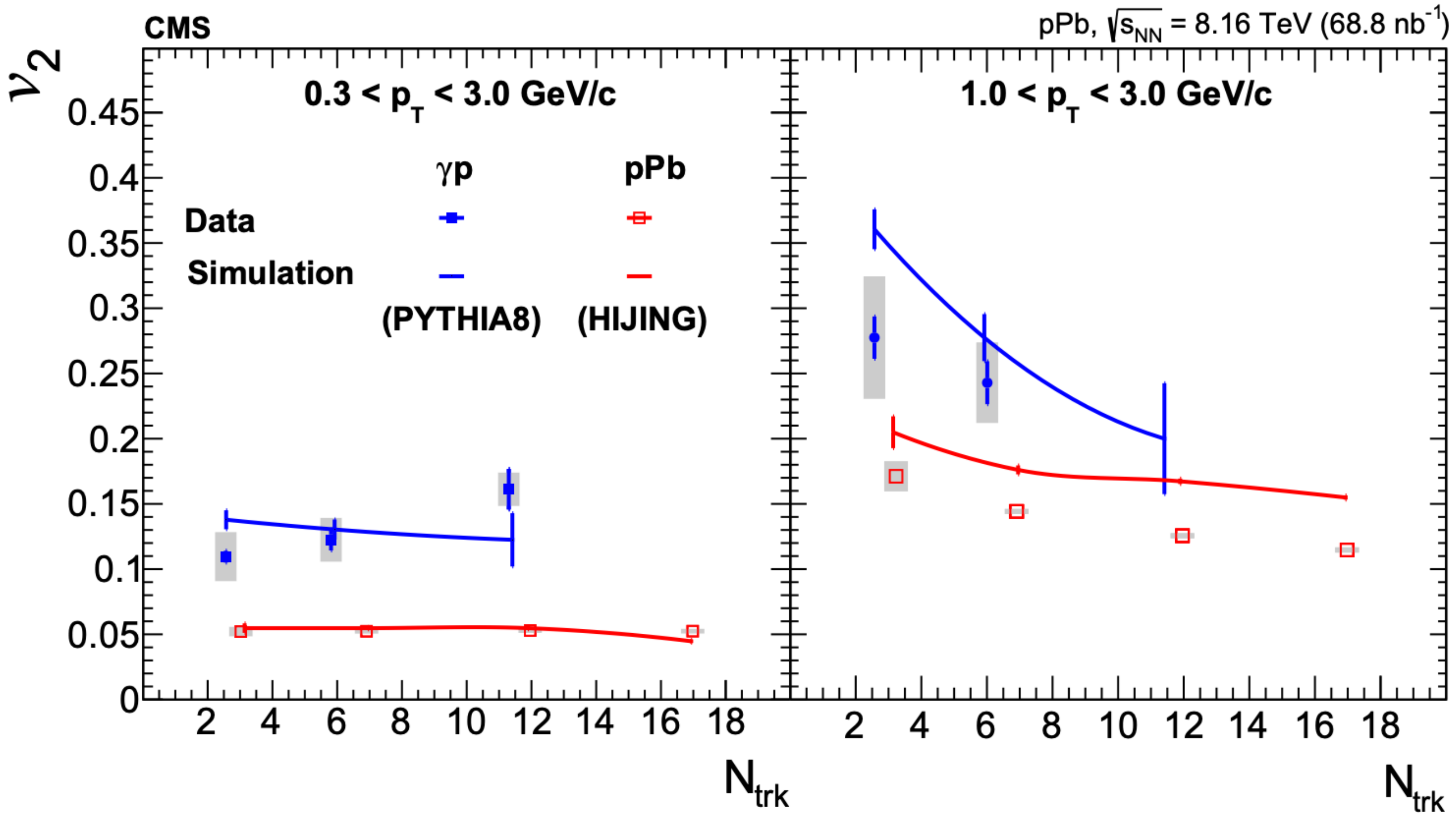
n=3



- Apparent sign change for $\rho(c_2\{2\}, [p_T])$ in pPb -> agree with IP-Glasma+hydrodynamics
- However, no sign change is observed when using $|\eta|>1.0$ for $c_2\{2\}$
- After removing nonflow with larger η gap, no evidence of CGC in data
- Data better described by the smaller initial fireball R_{RMS}=0.9 fm in hydrodynamics

FLOW IN PHOTON-P COLLISIONS

arXiv:2204.13486



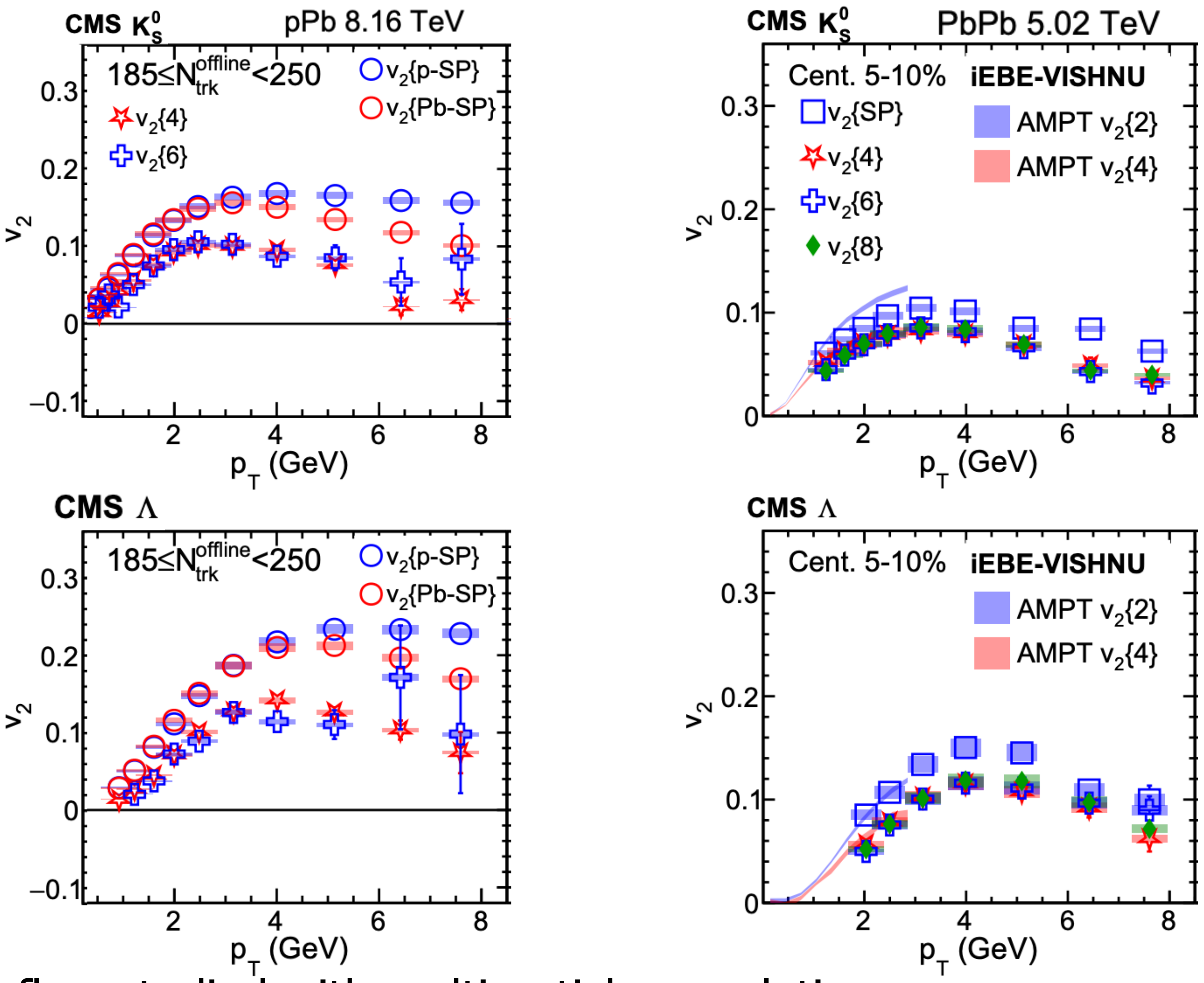
- Search for azimuthal anisotropy in γp interactions with pPb UPC
- Nonflow peripheral subtraction not applied
- Consistent with simulations without collective effects for both γp and pPb in the N_{trk} range

STRANGE PARTICLE FLOW

arXiv:2205.00080

K^0_S

Λ



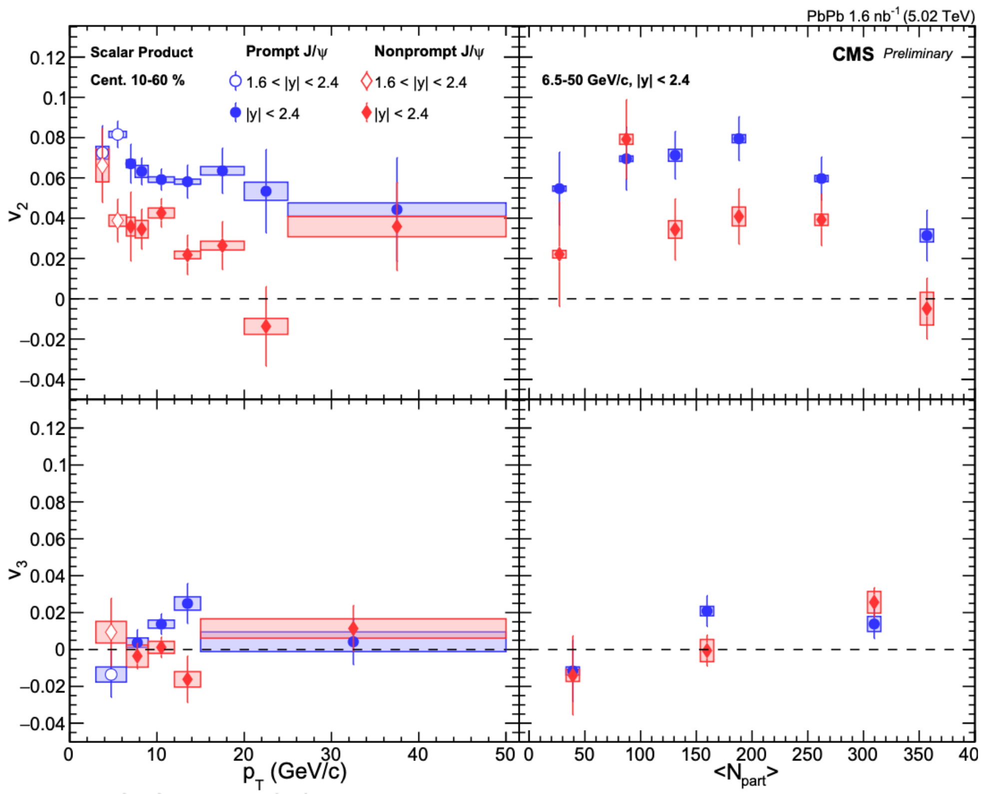
- K^0_s and Λ flow studied with multiparticle correlations
- Four and six particle correlations are nearly identical
- Compared with PbPb to illustrate the system size dependence of event-by-event fluctuations

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Υ(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

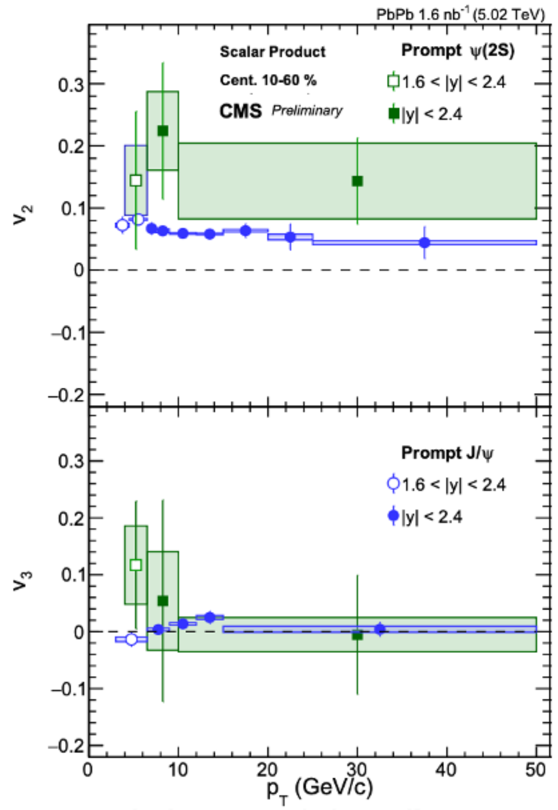
J/Ψ AND Ψ(2S) FLOW IN PBPB

CMS-PAS-HIN-21-008

Prompt J/ψ and b→J/ψ



Prompt Ψ(2S)

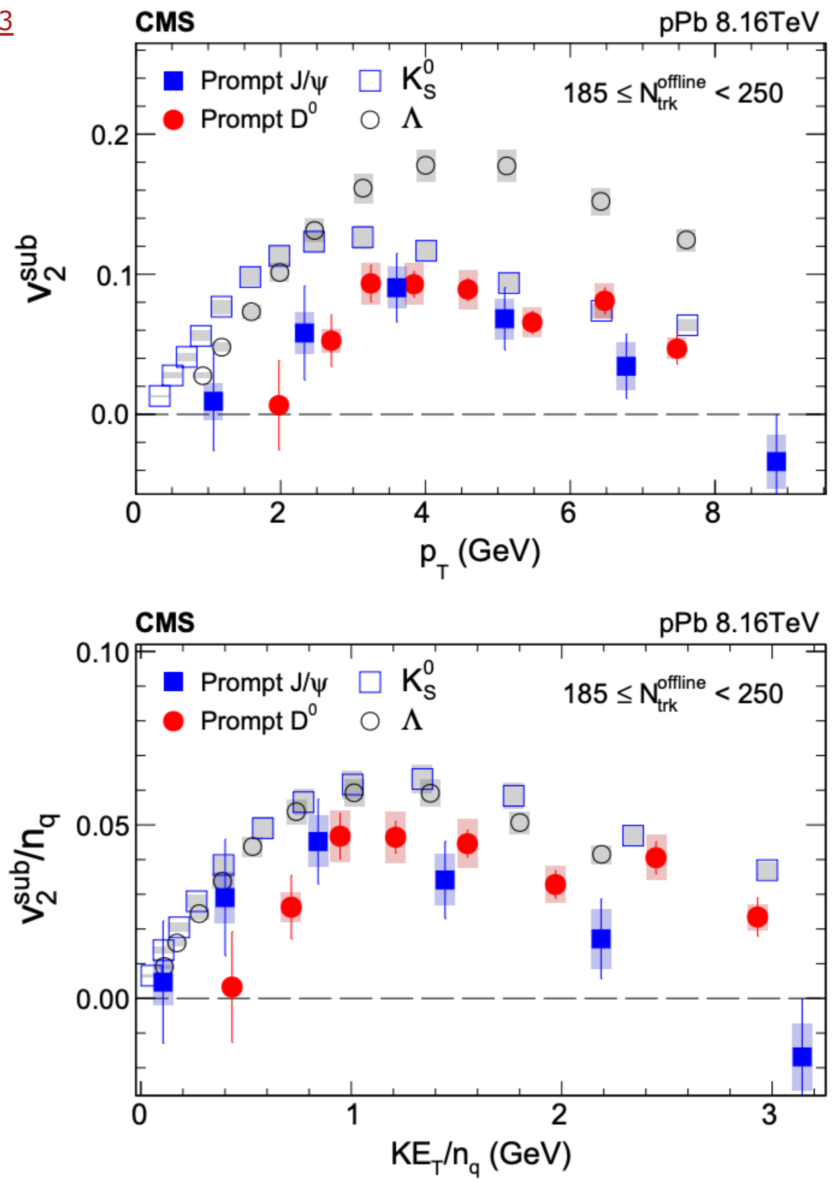


- Significant v_2 for Prompt J/ψ and b→J/ψ
  - Different dynamics for c and b quark
- First separation of v_3 for prompt and b→J/ψ
- First Ψ(2S) with v_2>0; consistent with 0 for v_3

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Υ(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

J/PSI AND D^0 IN PPB

arXiv:1810.01473

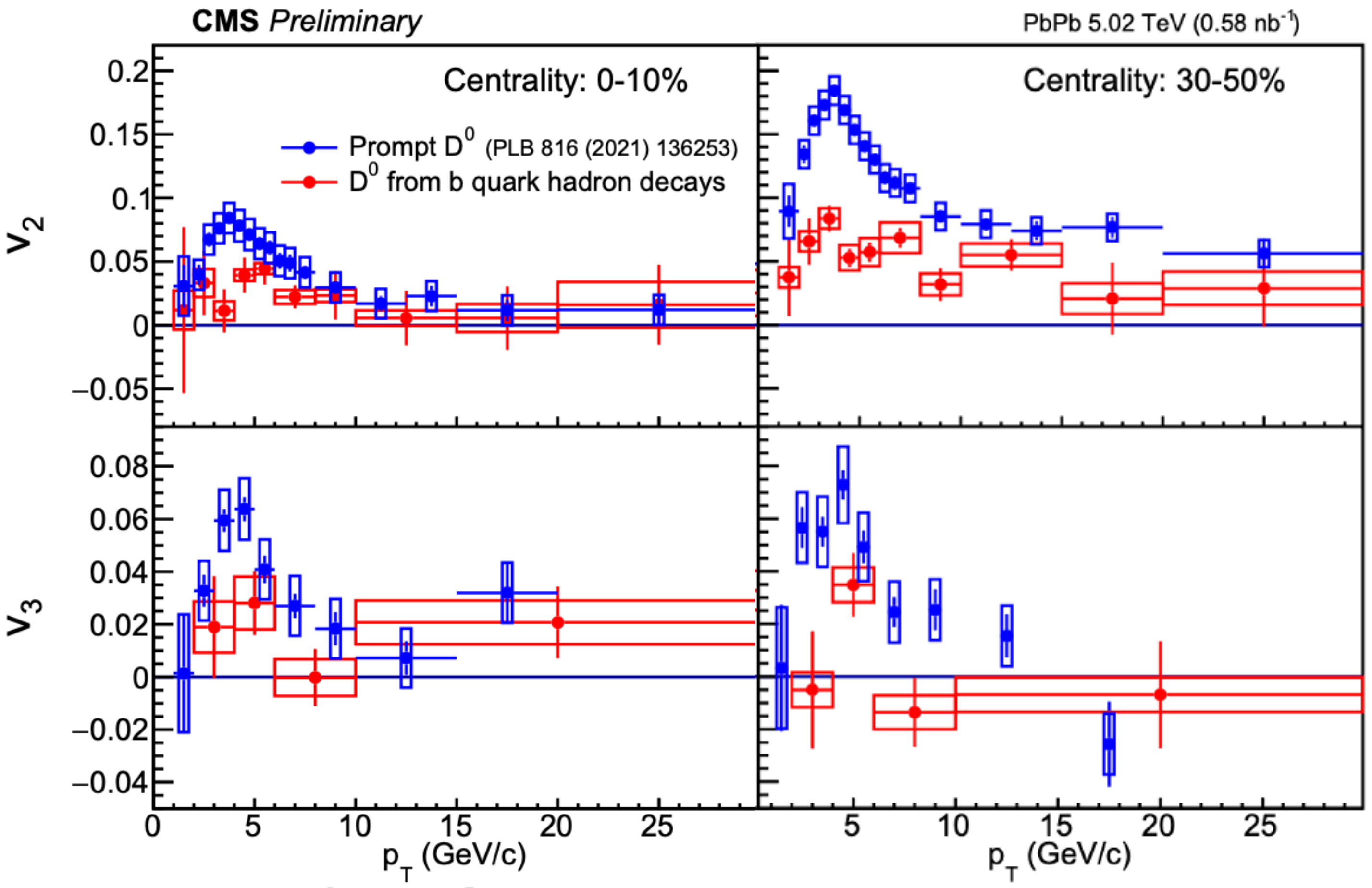


- Evidence of charm quark collectivity in high multiplicity pPb
- Heavy quarks exhibit weaker collective behavior

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Υ(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

PROMPT D⁰ AND B→ D⁰ FLOW IN PBPB

CMS-PAS-HIN-21-003

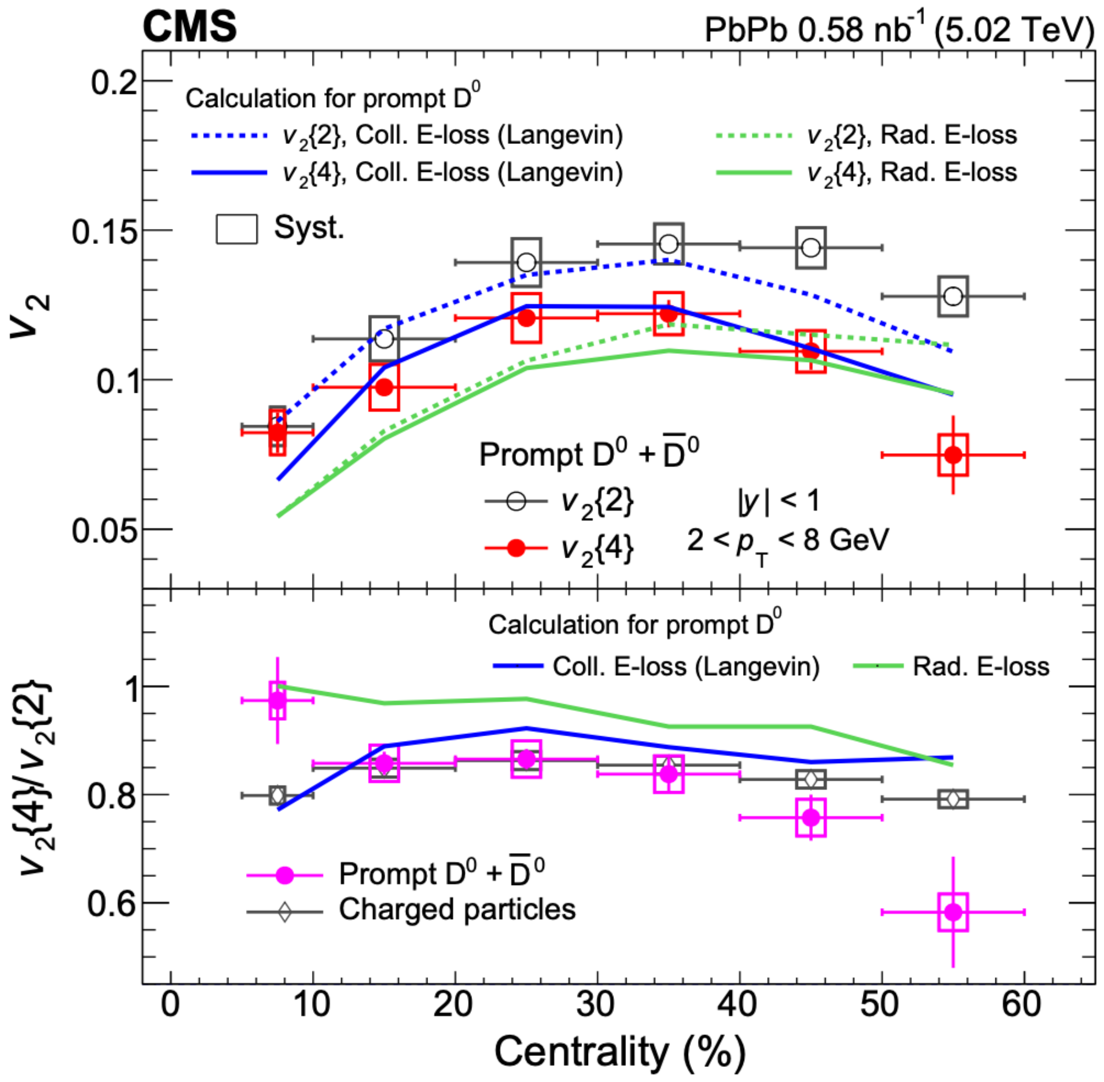


- ($b \to D^0$) v_n significantly lower than prompt D^0 v_n
- ($b \to D^0$) v_2, less centrality dependence compared to prompt D^0 v_2
  - b quark collectivity affected by fluctuations

K^0_S/Λ
pPb/PbPb
↓
J/Ψ
PbPb
pPb
↓
D^0
PbPb
pp/pPb
↓
Υ(1S/2S)
pPb/PbPb
↓
Dijet
PbPb
↓
Z boson
PbPb

D^0 WITH MULTIPARTICLE CORRELATIONS

arXiv:2112.12236



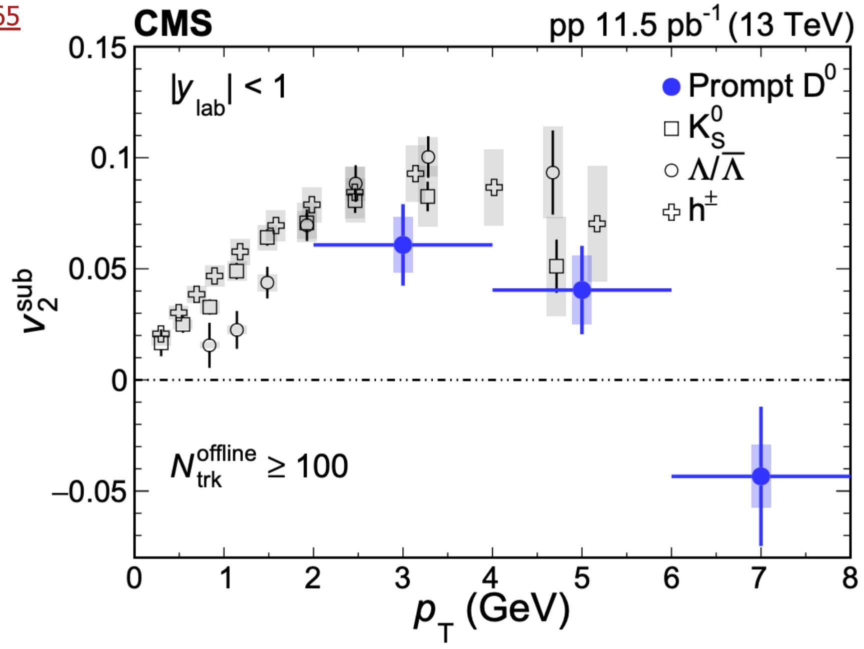
- Probe event-by-event fluctuations
- $v_2\{4\} < v_2\{2\}$ for D^0
- Indications of possible differences in energy loss fluctuations between D^0 and charged hadrons

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Υ(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

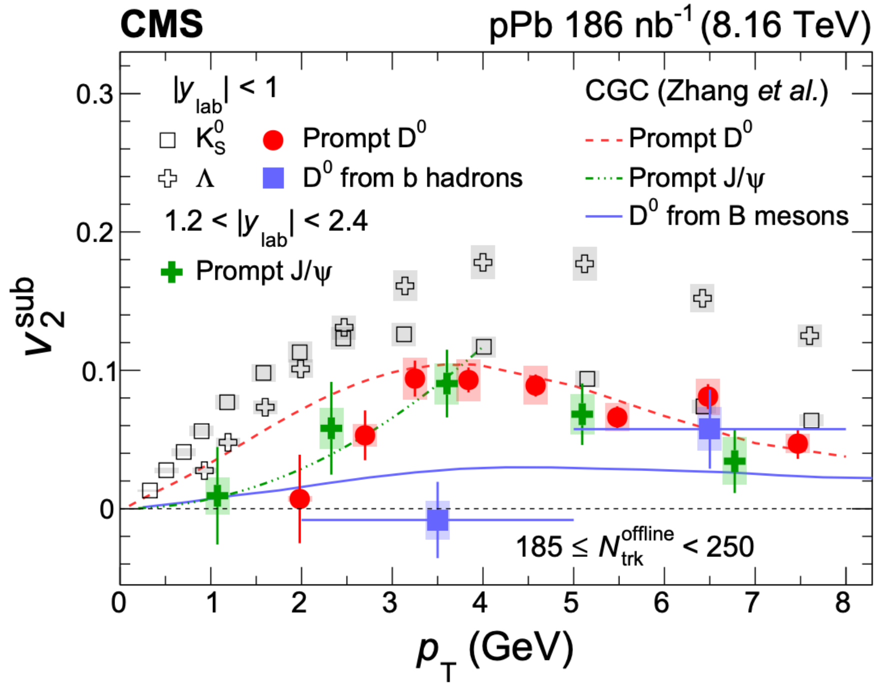
D^0 FLOW IN PP AND PPB

arXiv:2009.07065

pp



pPb



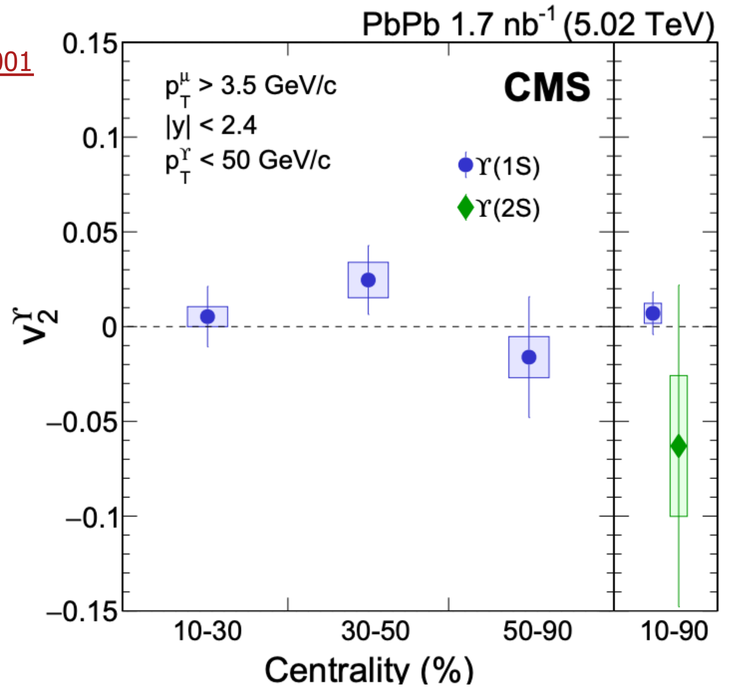
- Indications of positive D^0 v_2 in pp
- ($b \rightarrow D^0$) has much smaller v_2 compared to prompt D^0 in pPb
  - mass dependent v_2

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Υ(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

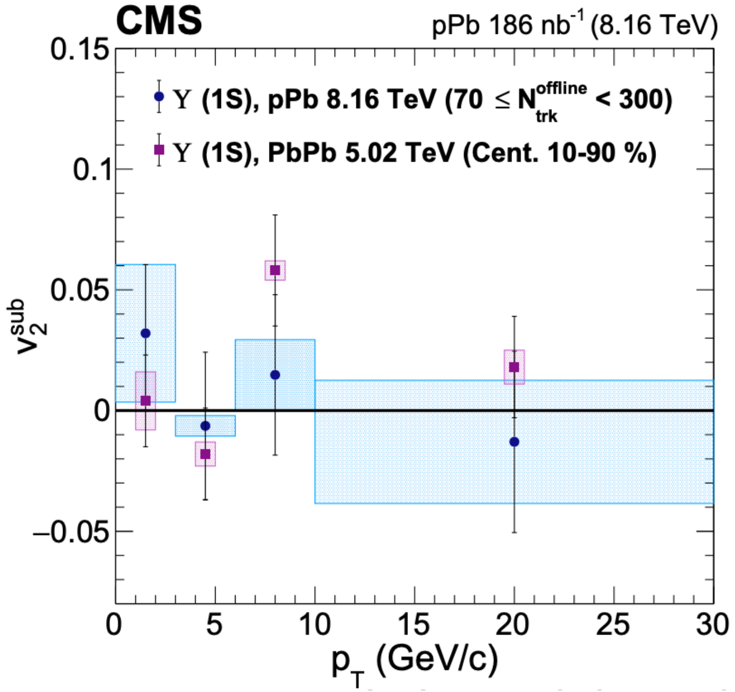
Υ(1S) AND Υ(2S) FLOW

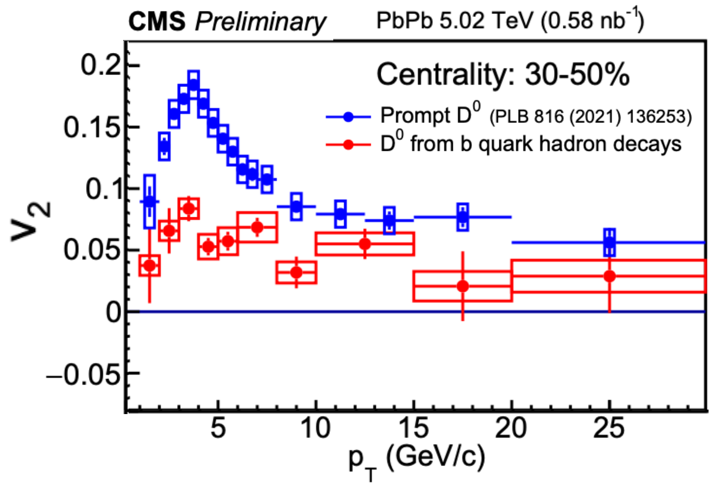
arXiv:2006.07707
CMS-PAS-HIN-21-001

PbPb



pPb



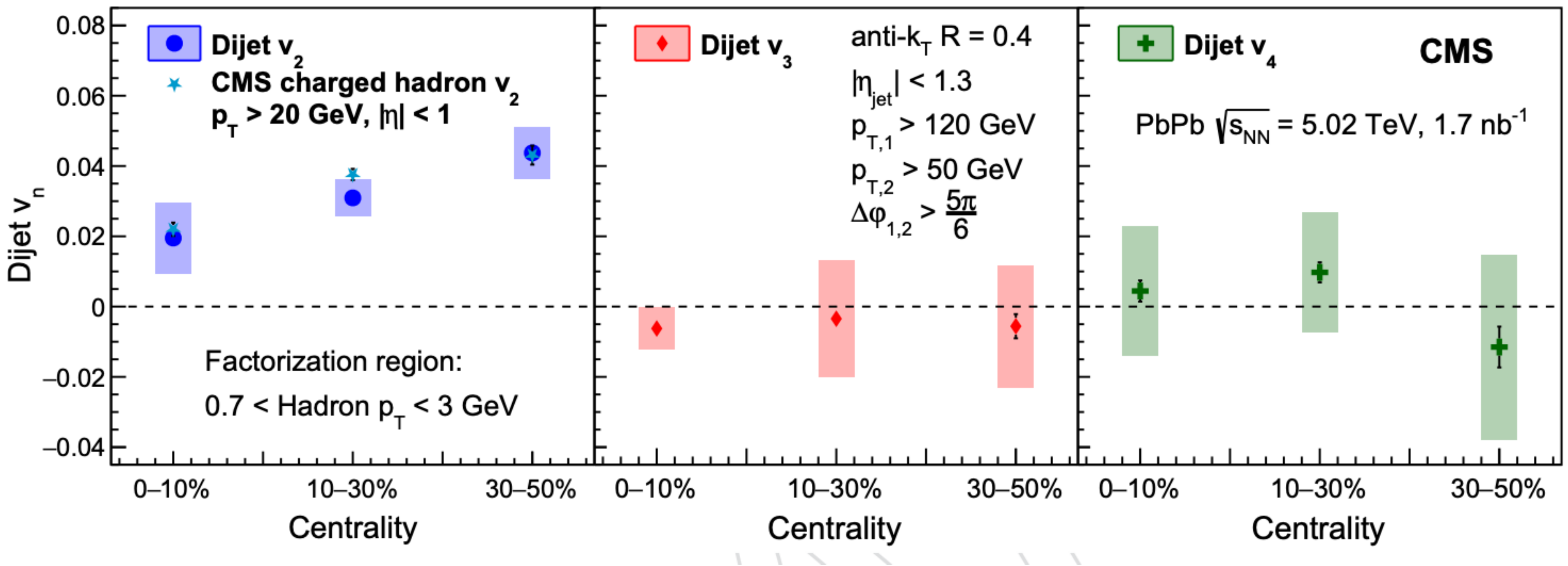


- v_2 of Υ(1S) and Υ(2S) are both consistent with 0 in PbPb
  - But non-zero (b→D⁰) v_2 in PbPb
- Υ(1S) v_2 consistent with 0 in pPb

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Υ(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

DIJET FLOW IN PBPB

CMS-PAS-HIN-21-002

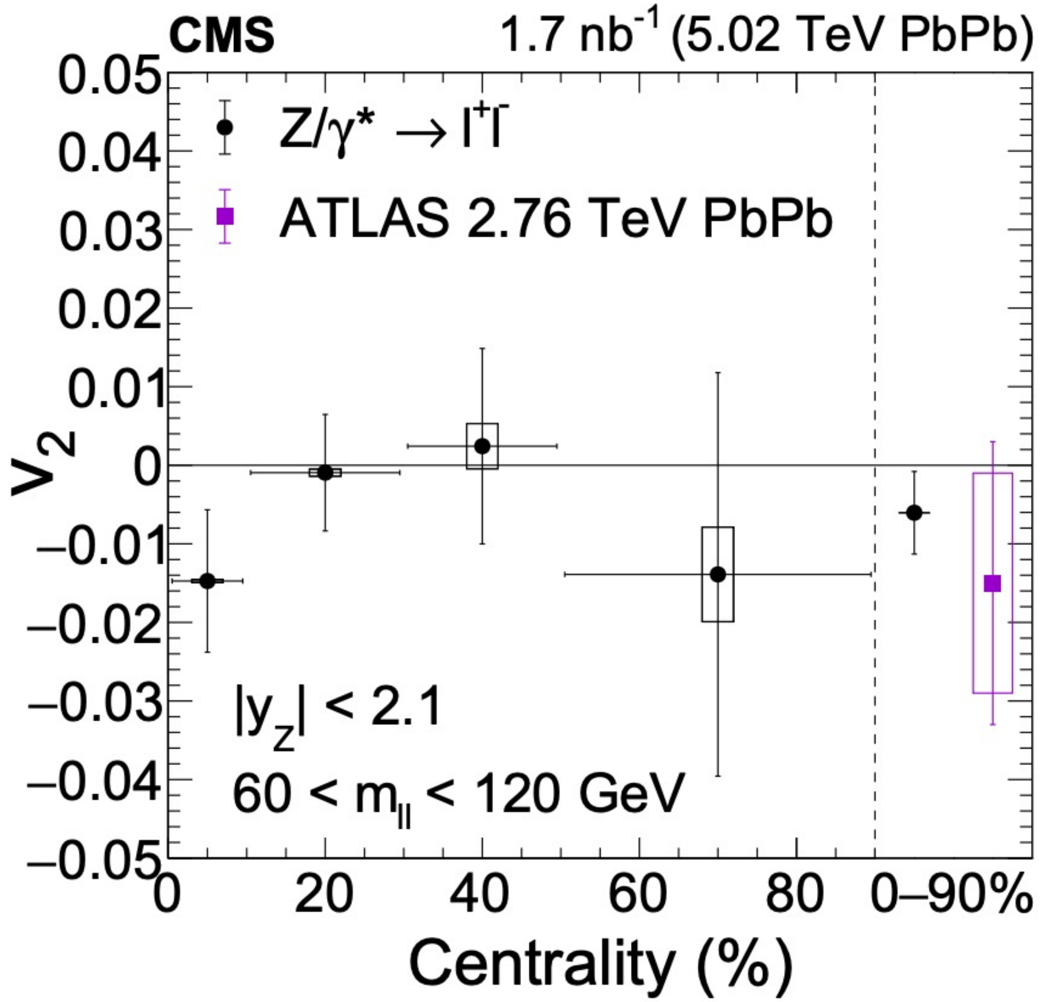


- Significant v_2 for dijet -> path length dependence of energy loss
- Dijet v_3 and v_4 are consistent with 0 -> need better precision to constraint initial state effect

K^0_S/Λ pPb/PbPb
⬇
J/Ψ PbPb pPb
⬇
D^0 PbPb pp/pPb
⬇
Υ(1S/2S) pPb/PbPb
⬇
Dijet PbPb
⬇
Z boson PbPb

Z BOSON FLOW IN PBPB

arXiv:2103.14089



- v_2 is consistent with 0 for Z bosons in PbPb
  - Z bosons do not experience significant final-state interactions in the medium

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Υ(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

Summary

Flow measurements in CMS with

- Collision system size scan: PbPb, pPb, pp, γp collisions
- Particle species scan: Charged hadrons, strange/charm/bottom hadrons, Jets, Z boson

Do we see flow signals?

	Charged hadron	Strange	Prompt J/Ψ	b→ J/ψ	Prompt D^0	b→ D^0	Υ(1S/2S)	Dijet	Z boson
PbPb	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**
pPb	**Yes**	**Yes**	**Yes**		**Yes**	**No**	**No**		
pp	**Yes**	**Yes**			**Yes**				

- We provided a large amount of data with various methods for different particles

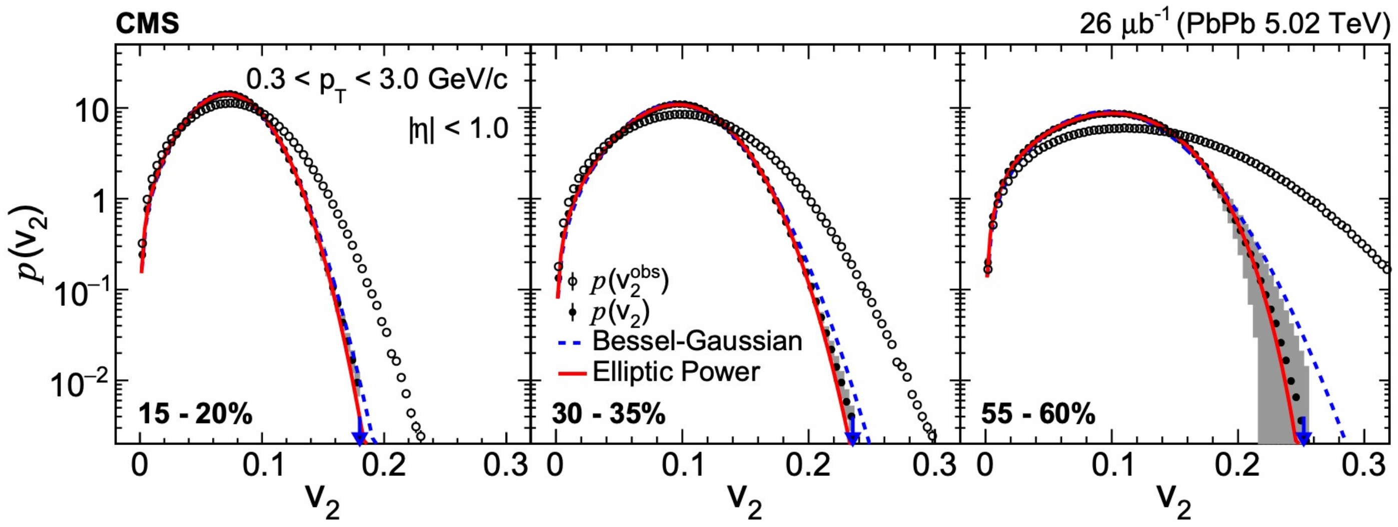
Challenges and future measurements at CMS

Two particle correlations

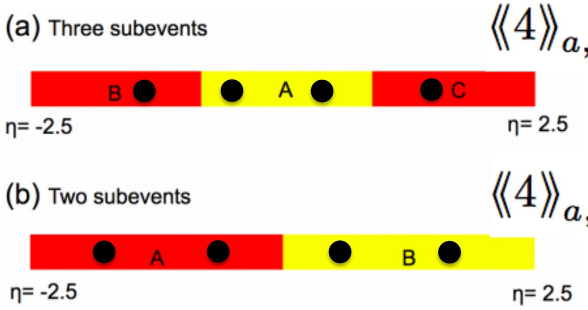
- Peripheral subtraction needed, assumption of no v_2 signal at some low N_{ch}

Multiparticle particle correlations

- Still affected by nonflow, need subevent event method
- 2-sub, 3-sub, 4-sub, …



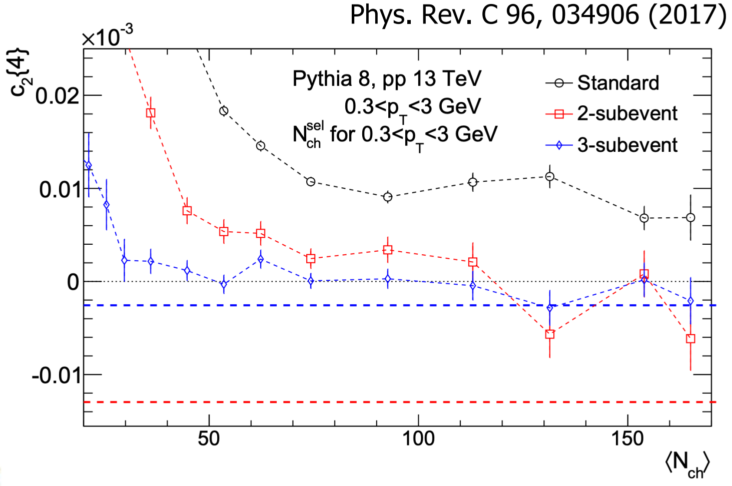
- True v_n distribution without statistical fluctuations not measured yet at small systems
- Challenging for unfolding to work



$$\langle\langle 4\rangle\rangle_{a,a|b,c} \equiv \left\langle\left\langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)}\right\rangle\right\rangle$$

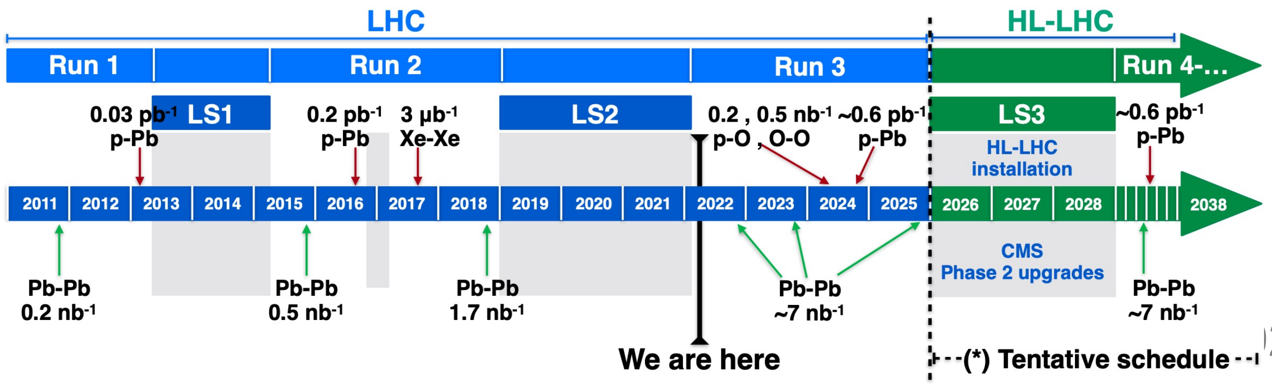
$$\langle\langle 4\rangle\rangle_{a,a|b,b} \equiv \left\langle\left\langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^b)}\right\rangle\right\rangle$$

Phys. Rev. C 96, 034906 (2017)



Questions:

- What are properties of QGP?
- What is the smallest possible QGP droplet?
- What are the origin of flow in small systems

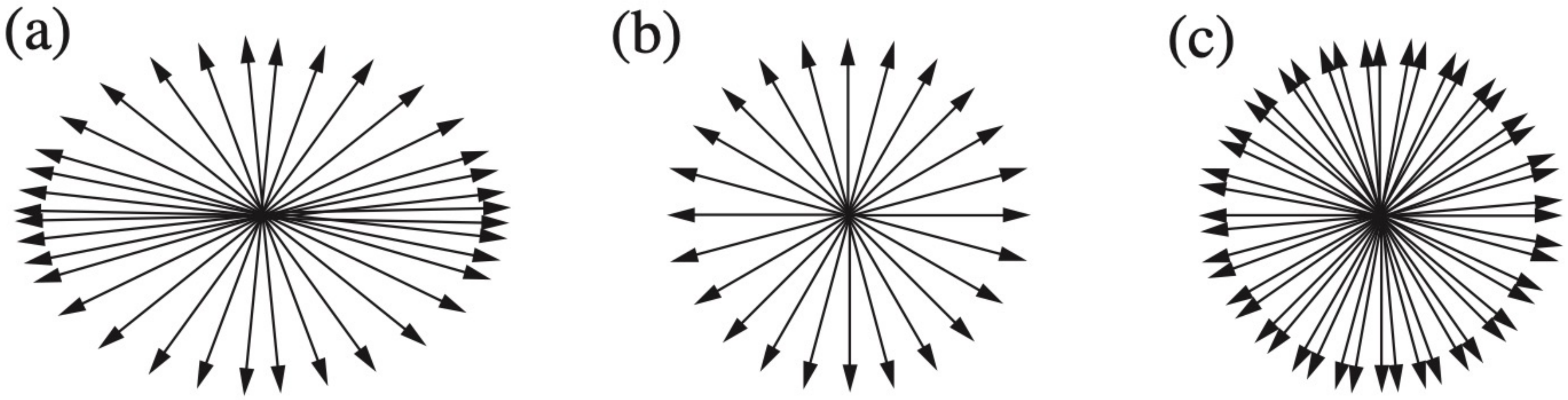


CMS future upgrade

- Particle identification
- Larger η coverage

Backup

Nonflow example



The particle distributions in the transverse plane, where for a) $v_2 > 0, v_2\{2\} > 0$, b) $v_2 = 0, v_2\{2\} = 0$, c) $v_2 = 0, v_2\{2\} > 0$.

Flow fluctuations

$$v\{2\}^2 = \langle v^2 \rangle = \langle v \rangle^2 + \sigma_v^2$$

Neglecting nonflow

$$v\{4\}^2 = \left(2\langle v^2\rangle^2 - \langle v^4 \rangle\right)^{1/2} \approx \langle v \rangle^2 - \sigma_v^2 \,.$$

Phys.Rev.C80:014904,2009

$$v_2\{4\}^2 \approx \langle v_2 \rangle^2 - \sigma_{v_2}^2$$

When $\sigma_{v_2}/\langle v_2 \rangle \ll 1$

Nonflow Flow fluctuations

$$v_2\{2\}^2 - v_2\{4\}^2 \approx \delta_2 + 2\sigma_{v_2}^2$$

$$R_{v(2-4)} = \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$

by setting $\delta_2 = 0$. → An upper limit to $\sigma_{v_2}/\langle v_2 \rangle$

$$R_{\varepsilon(2-4)} = \sqrt{\frac{\varepsilon\{2\}^2 - \varepsilon\{4\}^2}{\varepsilon\{2\}^2 + \varepsilon\{4\}^2}}$$

$\sigma_\varepsilon \ll \varepsilon$ → $\sigma_\varepsilon/\langle \varepsilon \rangle$