Thermalization and harmonics in CMS

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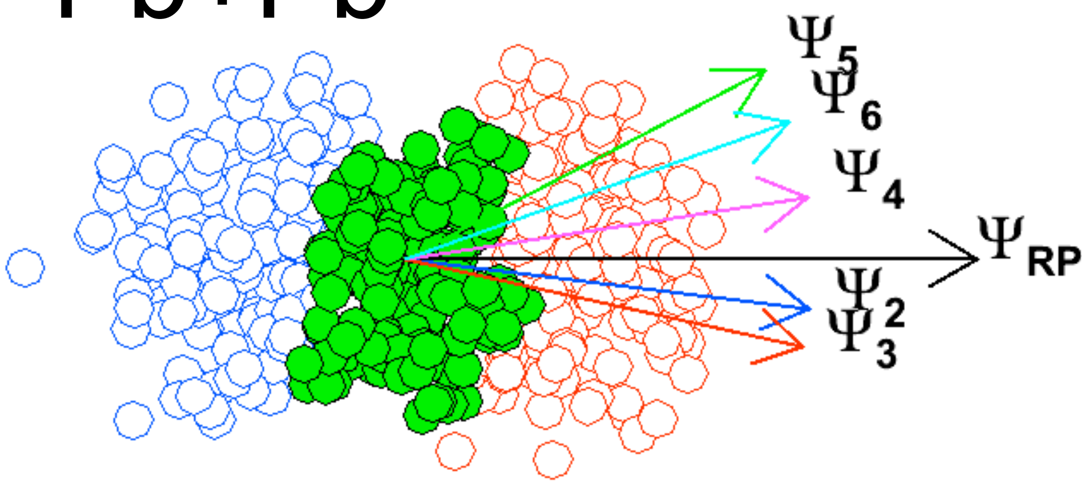
for the CMS Collaboration

International Conference on the Initial Stages in High-Energy Nuclear Collisions
September 8-14, 2013
Illa Da Toxa, Spain

Glauber: Correlations with Participant Plane

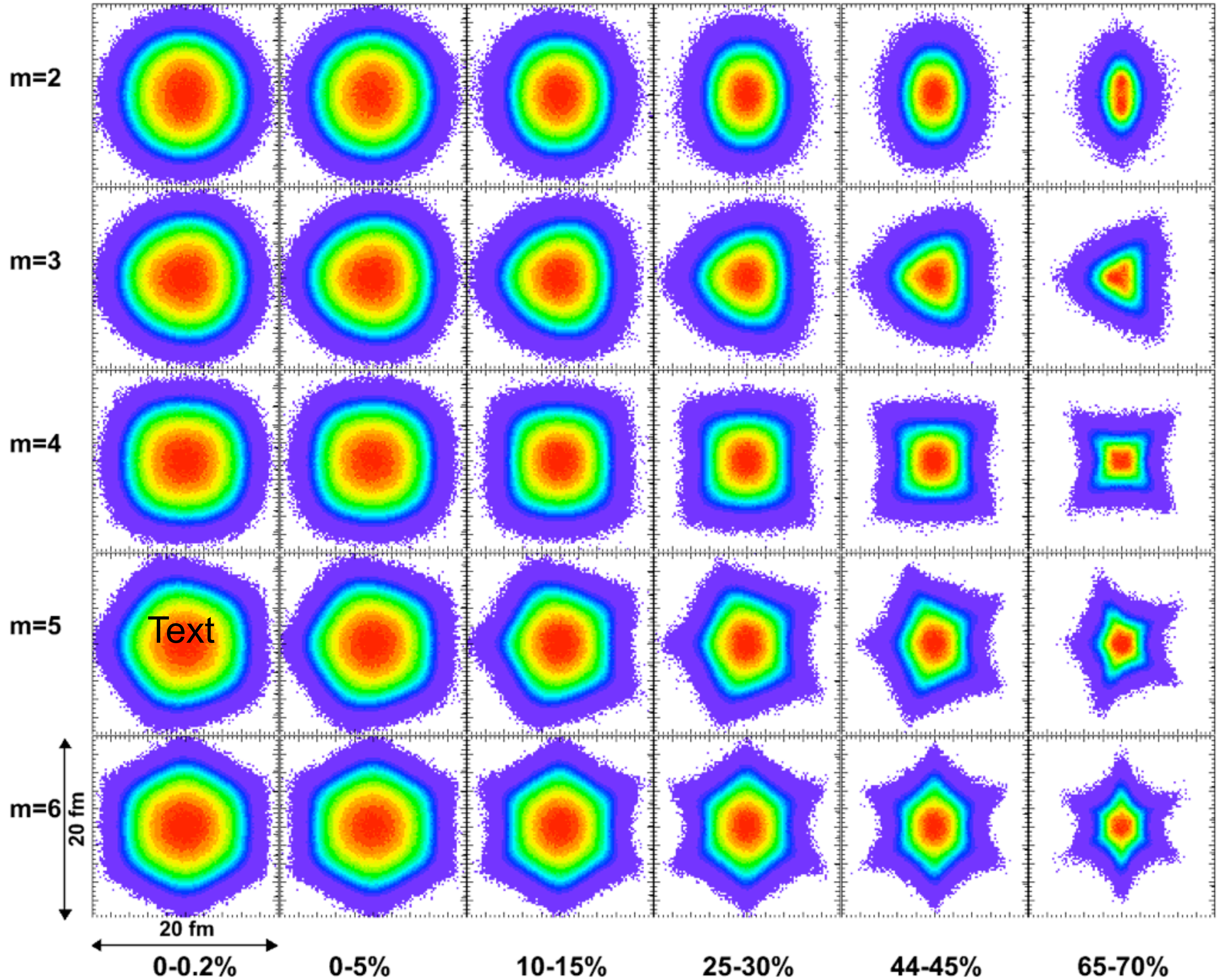
Participant densities with respect to participant plane:

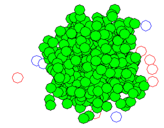
Pb+Pb

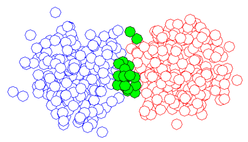


Centrality ∝35%

$$\Psi_m^{pp} = \frac{1}{m}\tan^{-1}\left\{\frac{\sum_{i=1}^{N_{part}} (r_i')^m \sin(m\phi_i')}{\sum_{i=1}^{N_{part}} (r_i')^m \cos(m\phi_i')}\right\} - \frac{\pi}{m}$$







Measure:

$$\frac{dN}{d(\phi-\Psi_m)} \propto 1+\sum_{n\geq m}^{\infty} 2v_n^{obs}\{\Psi_m\}\cos[n(\phi-\Psi_m)]$$

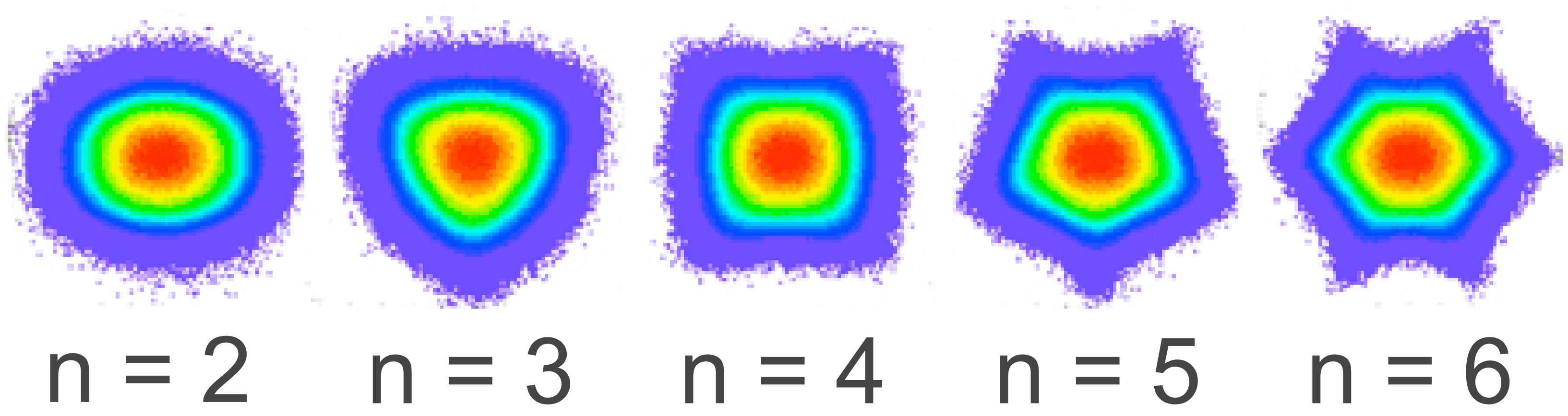
Expectation:

v_n=(medium evolution)×ε_n

$$\Psi_m \approx \Psi_m^{pp}$$

Why Higher Harmonics?

- Explore shorter length scales

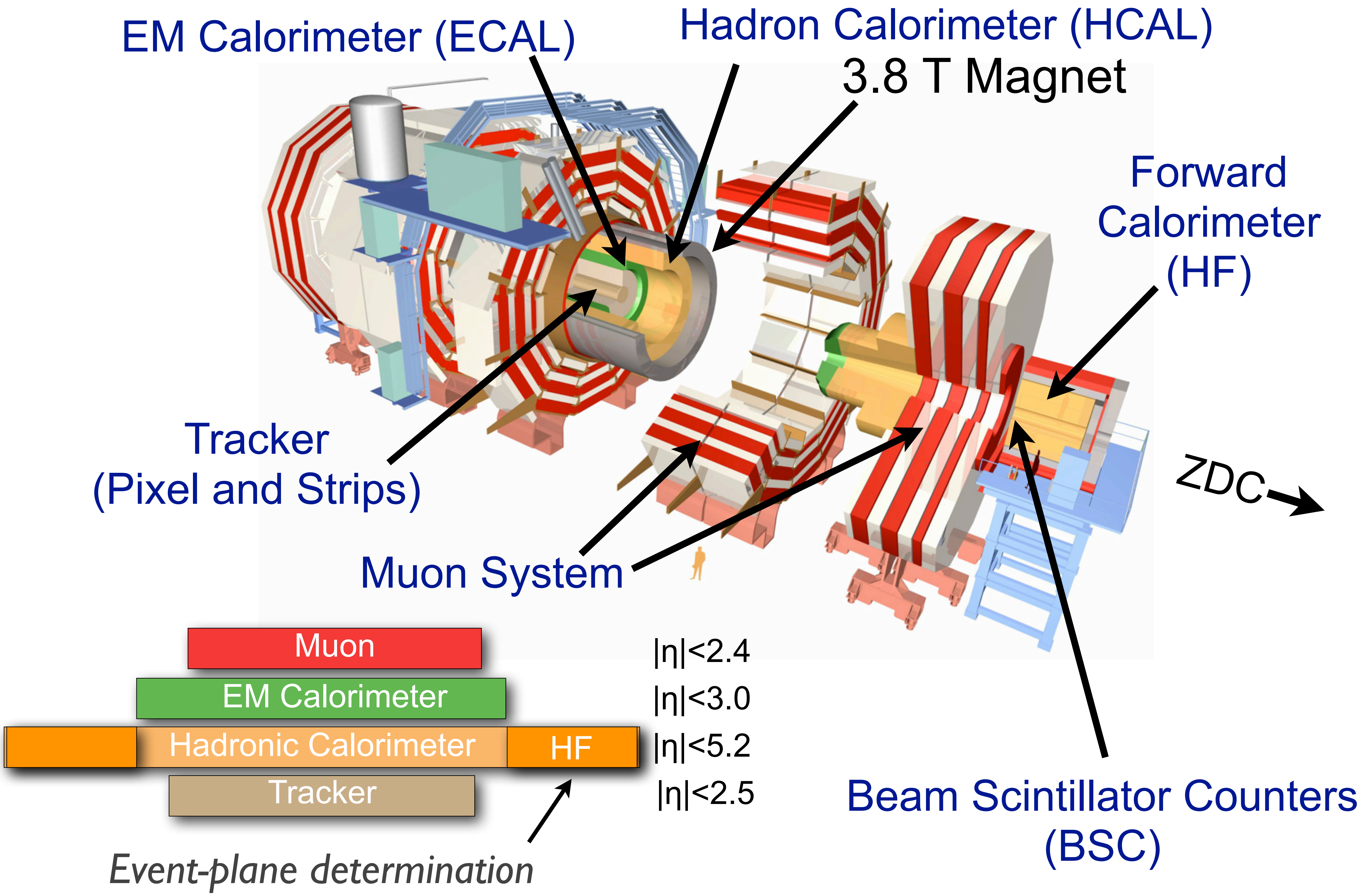


v_2 (elliptic flow)
v_3 (triangular flow)
v_4 (quadrangular flow)
v_5 (pentagonal flow)
v_6 (hexagonal flow)

- Sensitive to IC (Glauber versus CGC) and properties of medium (e.g., EOS, η/s, speed of sound)

- Yields information on participant-geometry fluctuations

CMS Experiment

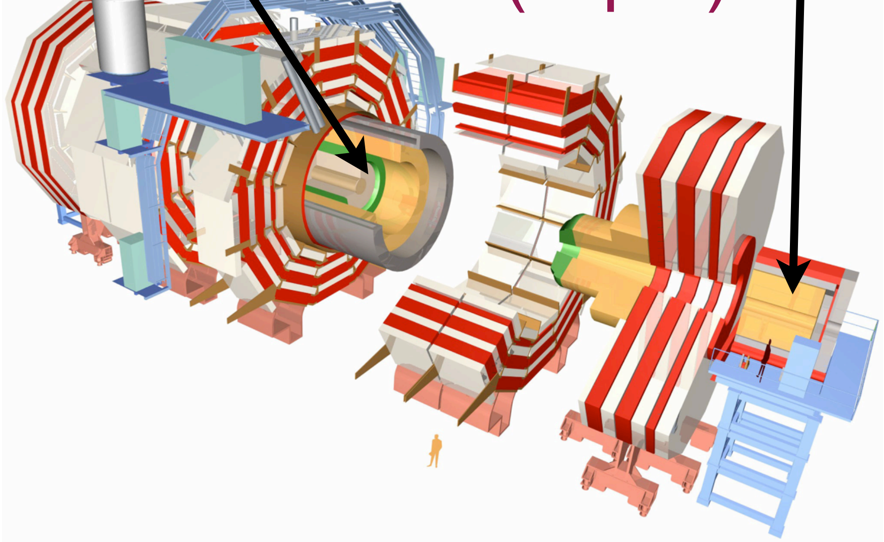


Method Overview

Event Plane

$$v_n\{\Psi_n\}^2 = \langle v_n \rangle^2 + (\alpha - 1)\sigma^2$$

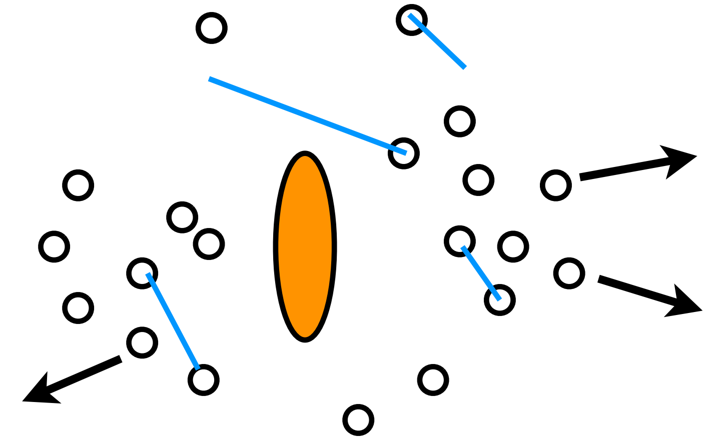
Correlate particles in tracker with those in HF. (Δη>3)



Two-particle Correlations

$$v_n\{2\}^2 = \langle v_n \rangle^2 + \sigma^2$$

Consider all two-particle correlations; require |Δη}>2.

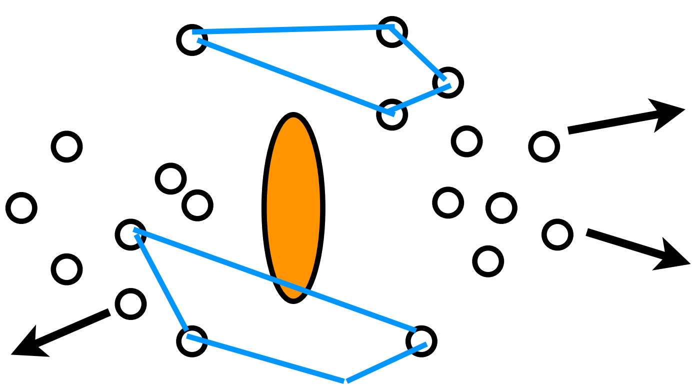


$$\sigma^2 = \langle v^2 \rangle - \langle v \rangle^2$$

Multi-particle Cumulant

$$v_n\{4\}^2 \approx \langle v_n \rangle^2 - \sigma^2$$

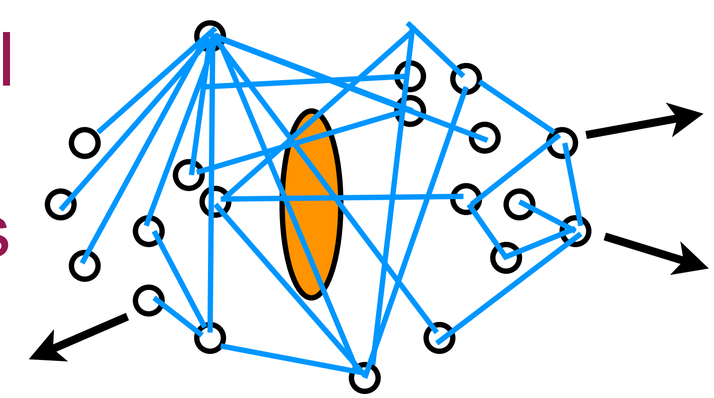
For example, the four-particle cumulant considers all four-particle correlations.



Lee-Yang Zeros

$$v_n\{4\}^2 \approx \langle v_n \rangle^2 - \sigma^2$$

Consider all particle correlations -(Not all shown!).



Correlations with Different Order EP's

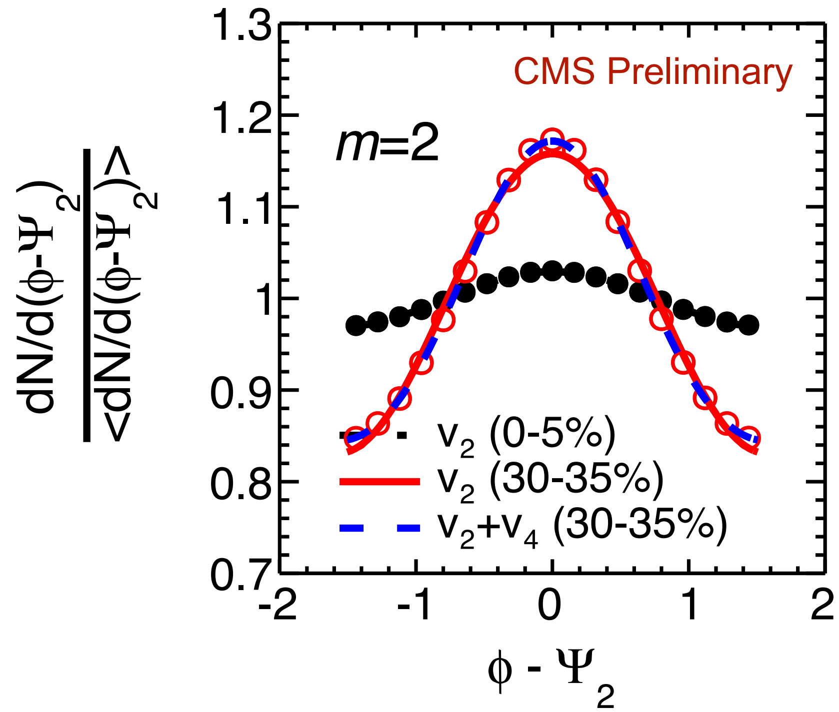
$$\frac{dN}{d(\phi-\Psi_m)} \propto 1+\sum_{n\geq m}^{\infty} 2v_n^{obs}\{\Psi_m\}\cos\left[n(\phi-\Psi_m)\right]$$

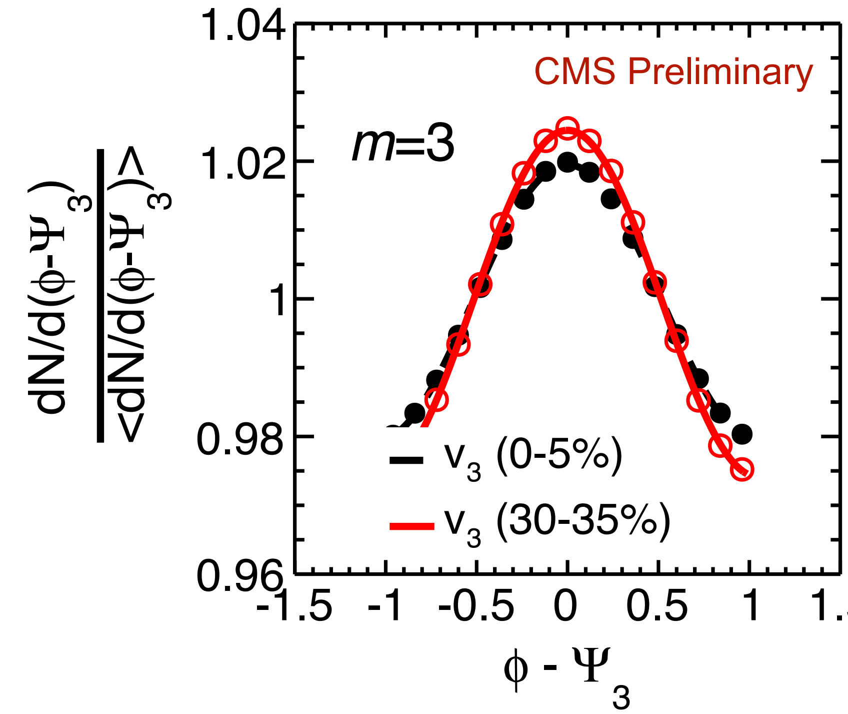
$$|\Psi_m| \leq \frac{\pi}{m}$$

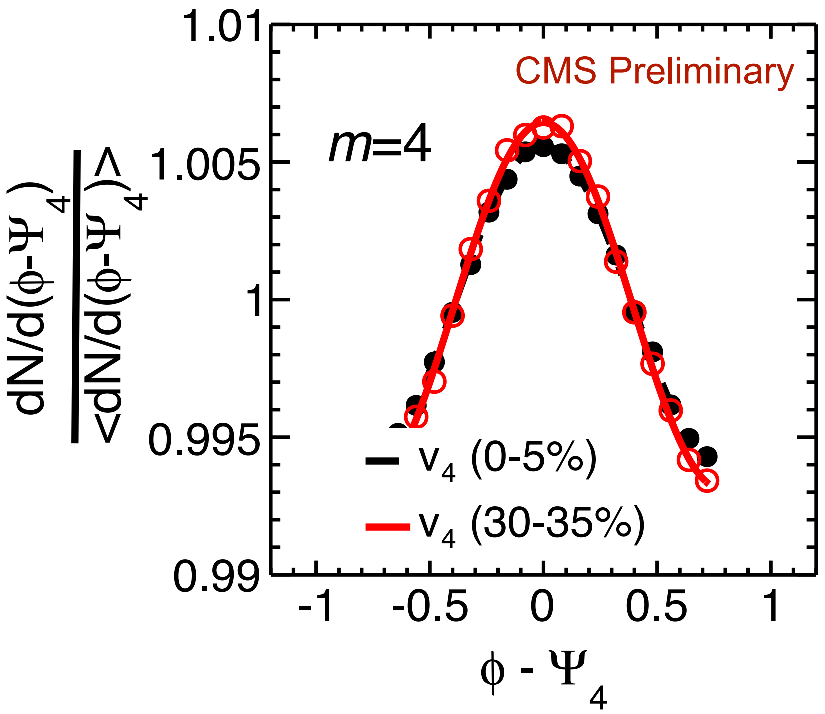
Same events; different orders for event-plane angle...

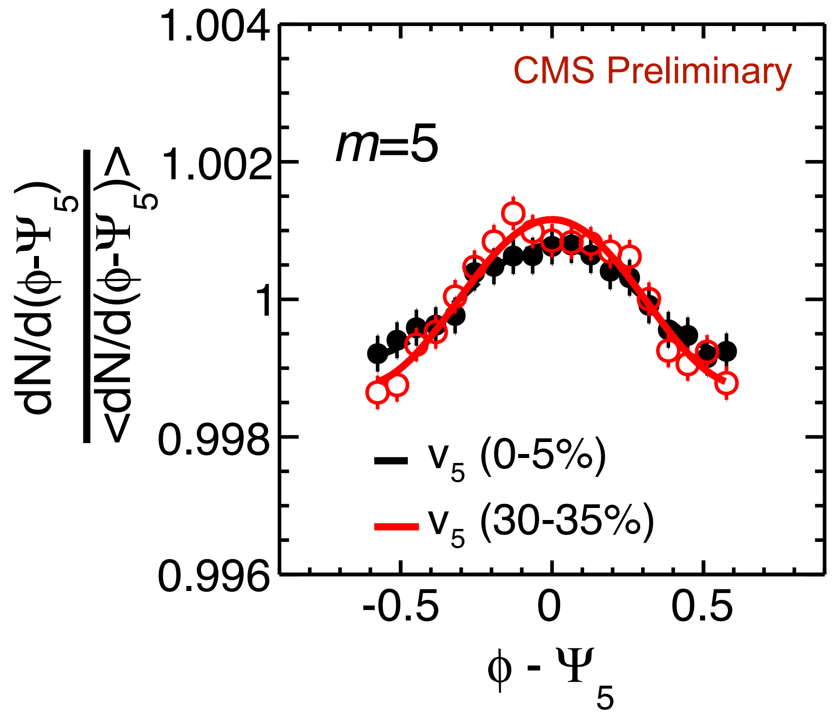
PbPb $\sqrt{s_{NN}}$ = 2.76TeV

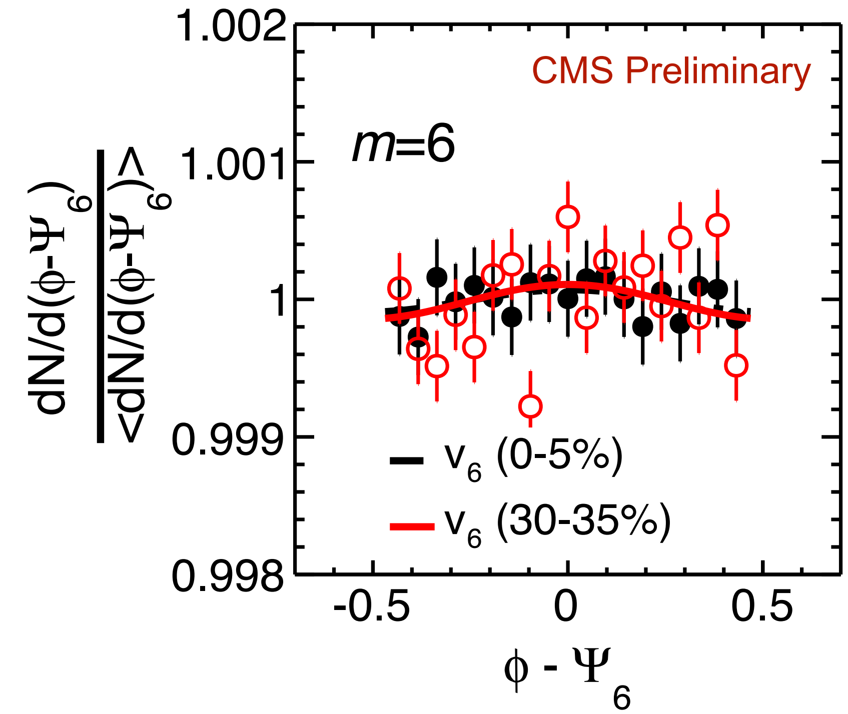
- ● 0-5%
- ○ 30-35%







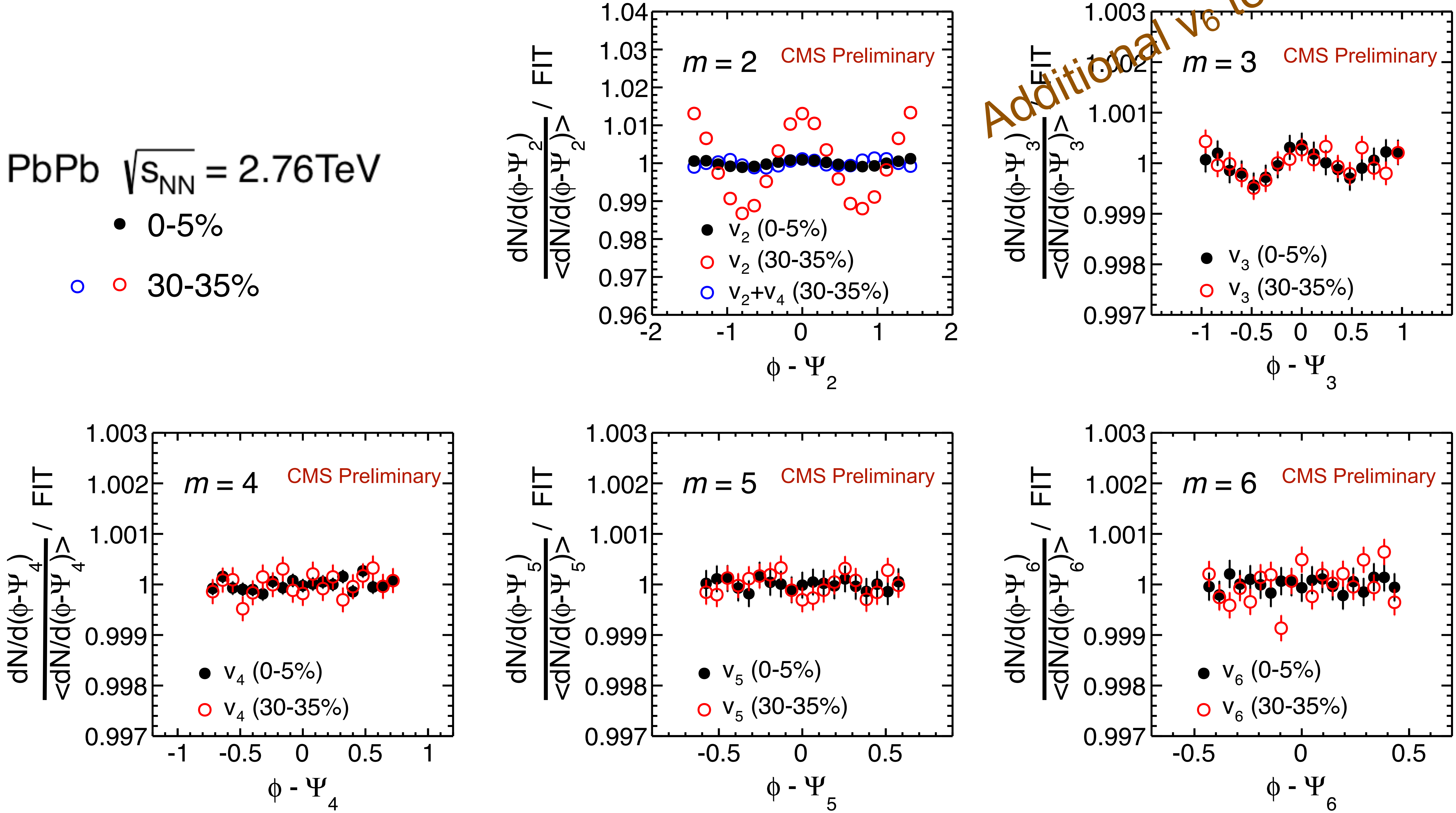




$\Rightarrow v_n$ depends on Ψ_m

Correlations with Different Order EP's

Divide out lowest order behavior:



v_2

Fluctuations *increase* v_2:

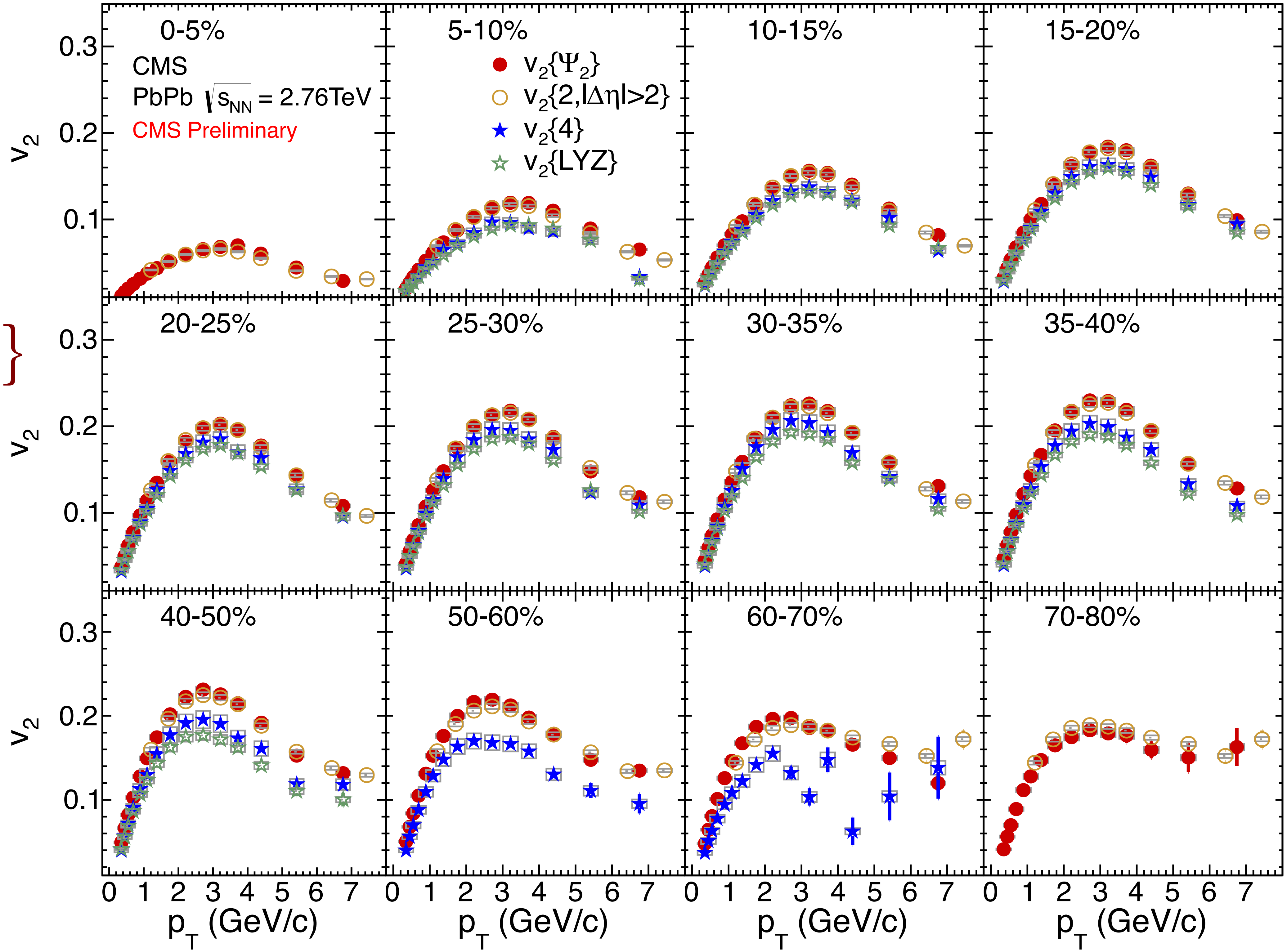
$v_2\{\Psi_2\}$

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

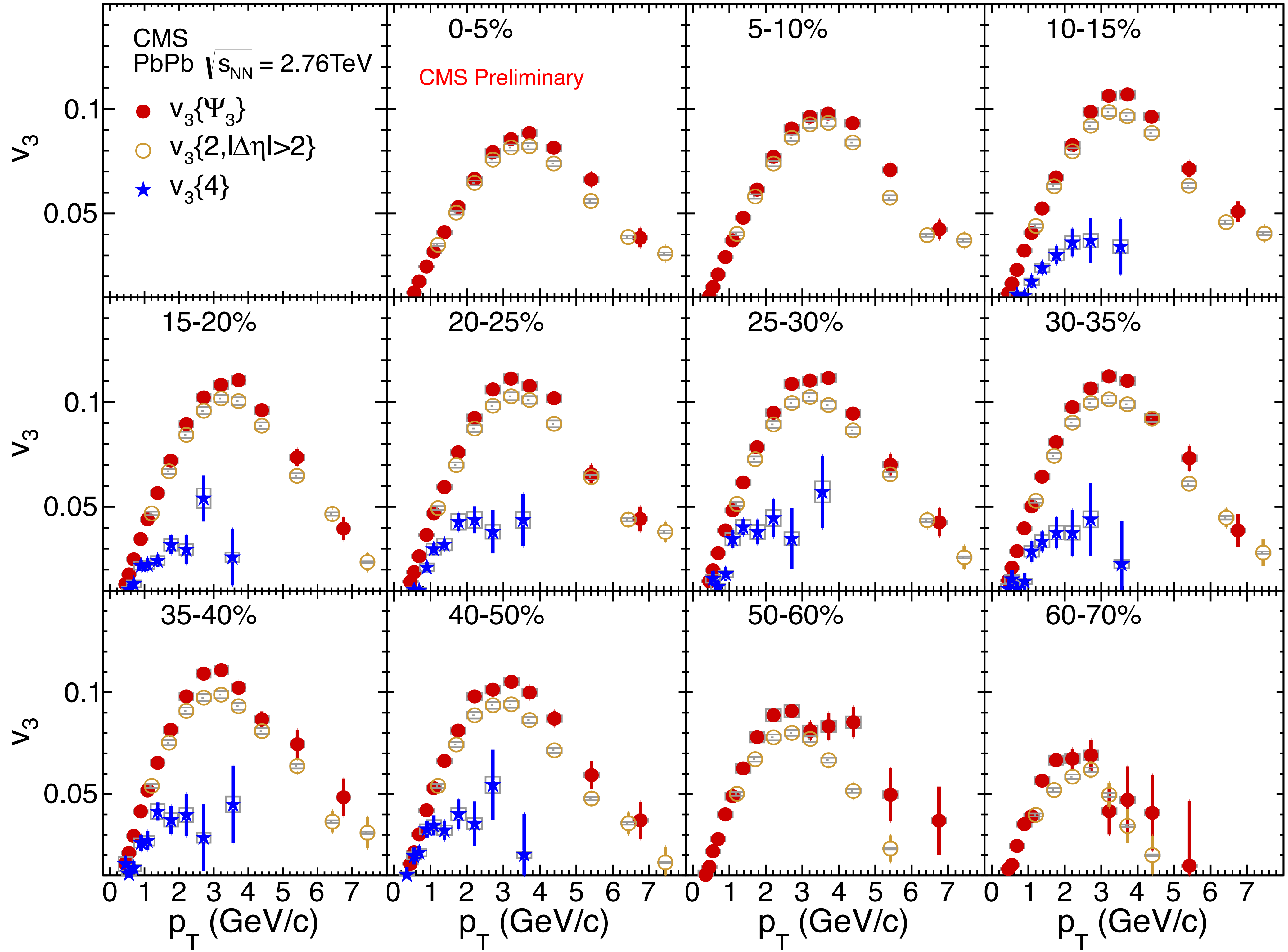
Fluctuations *decrease* v_2:

$v_2\{4\}$

$v_2\{LYZ\}$



v_3



$$v_3\{\Psi_3\} \gg v_3\{4\}$$

Weak centrality dependence

⇒Strong Fluctuations

v_4

Strong centrality dependence:

$v_4\{\Psi_2\}$

$v_4\{5\}$

$v_4\{LYZ\}$

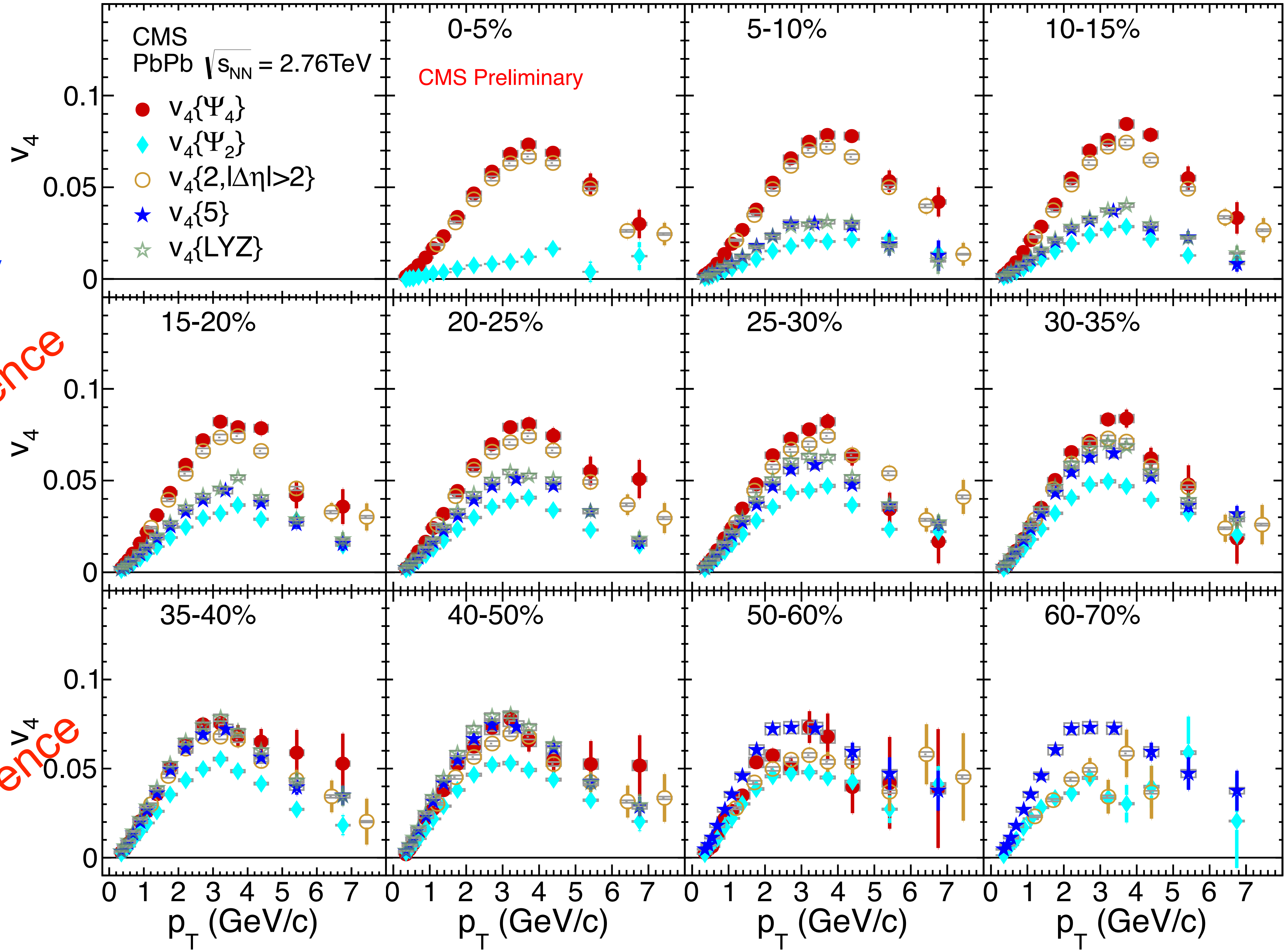
m=2 reference

Weak centrality dependence:

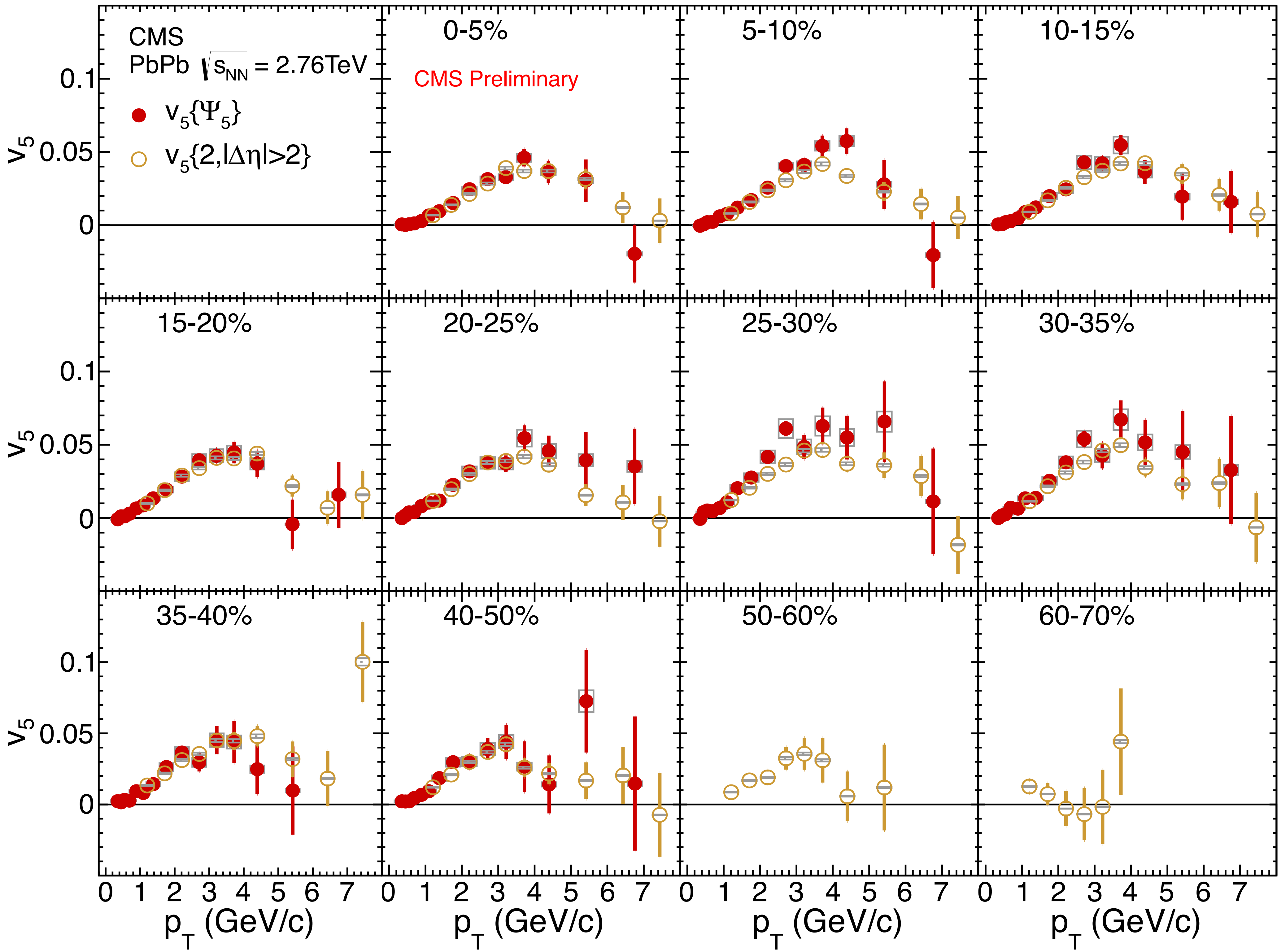
$v_4\{\Psi_4\}$

$v_4\{2,|\Delta\eta|>2\}$

m=4 reference



v_5



Weak centrality dependence:

m=5 reference

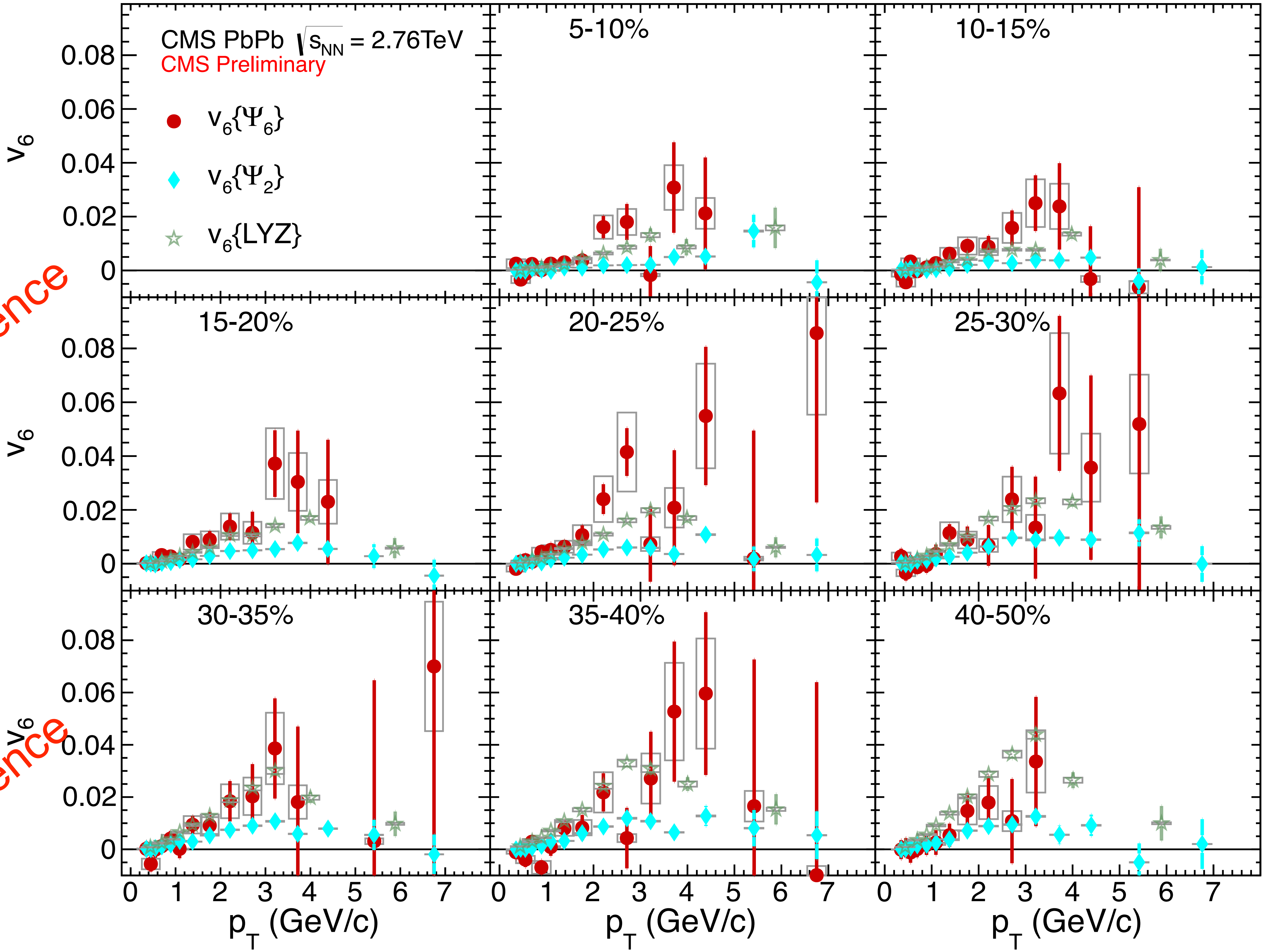
v6

Strong centrality dependence:

$v_6\{\Psi_2\}$

$v_6\{LYZ\}$

m=2 reference



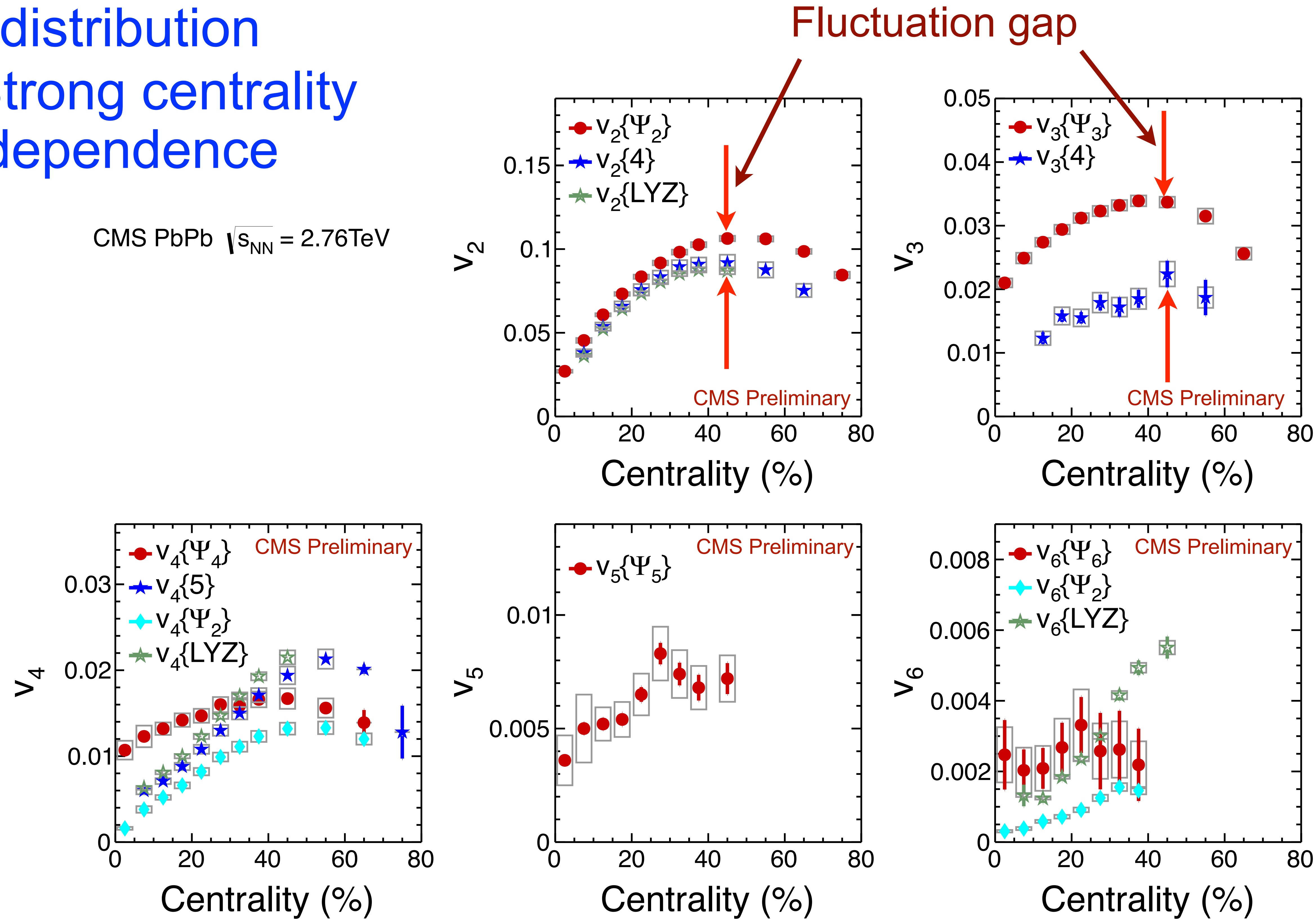
Weak centrality dependence:

$v_6\{\Psi_6\}$

m=6 reference

v_n ($0.3 \le p_T < 3.0$ GeV/c)

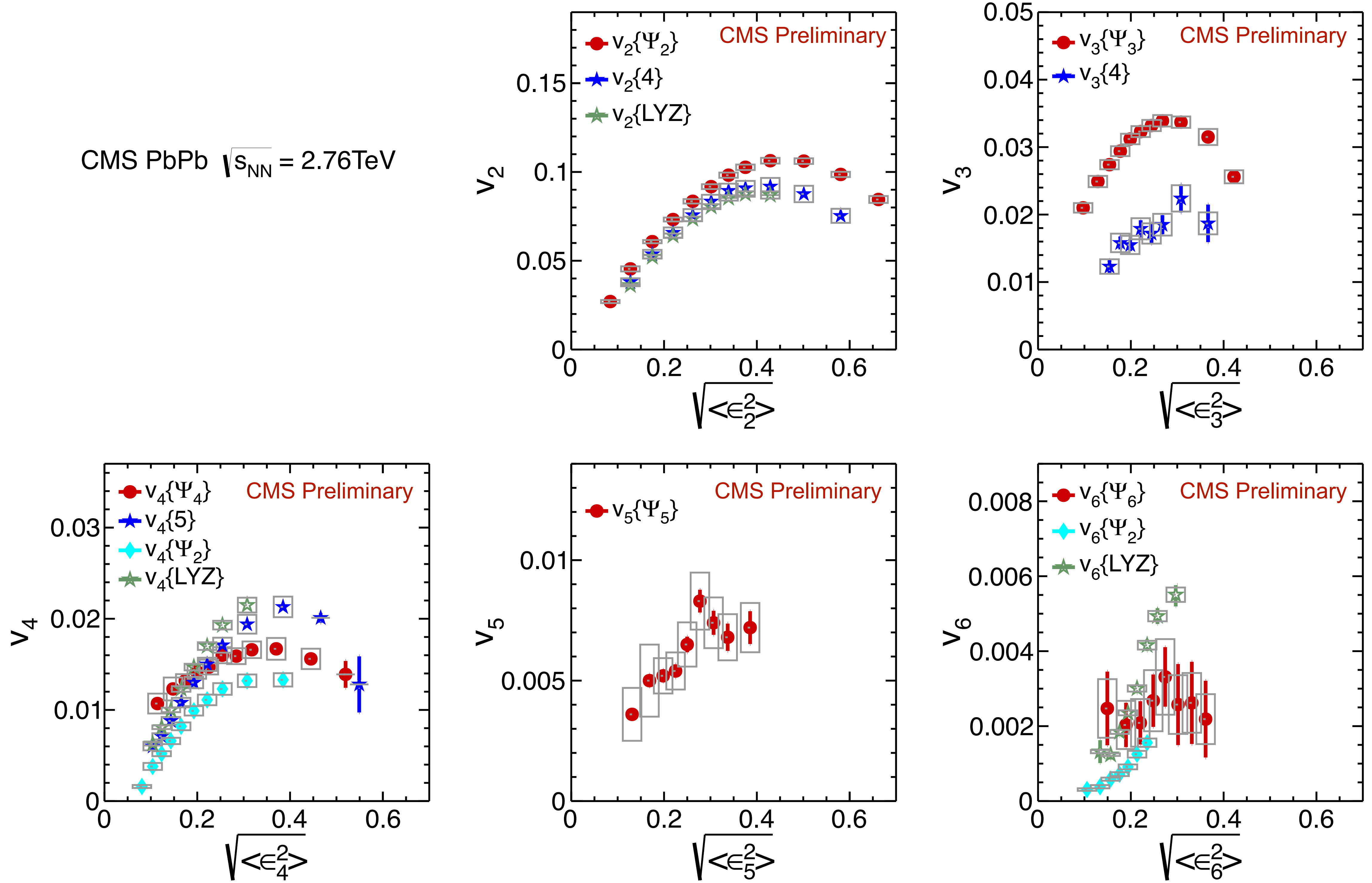
m=2 reference distribution
⇒Strong centrality dependence



v_n ($0.3 \le p_T < 3.0$ GeV/c): Relation to Glauber-Model ε_n

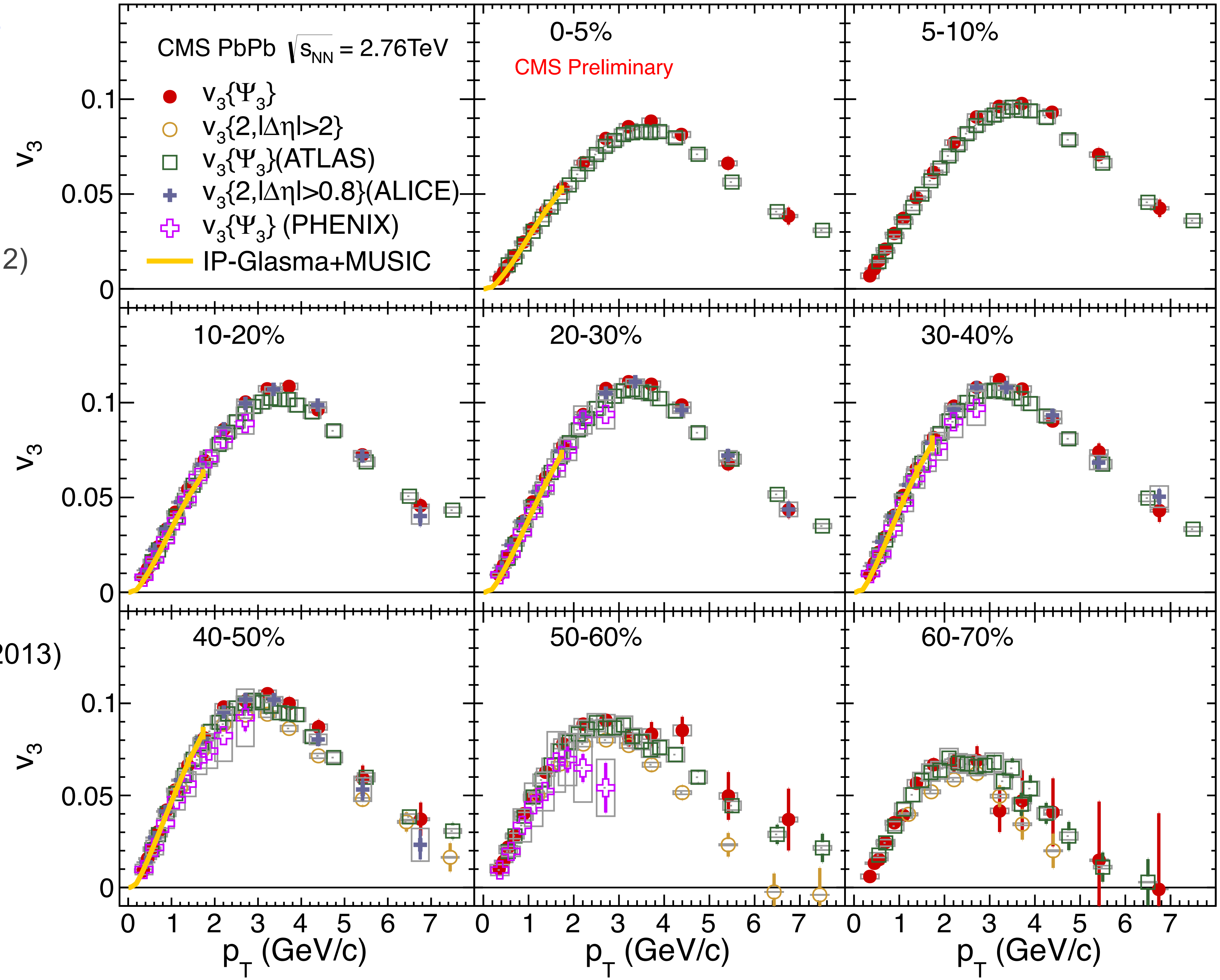
Scaling with $\sqrt{\langle \varepsilon_{n,m}^2 \rangle}$ found for central events

CMS PbPb $\sqrt{s_{NN}}$ = 2.76TeV



Comparisons

V_3



ATLAS:
Phys. Rev. C 86, 014907 (2012)

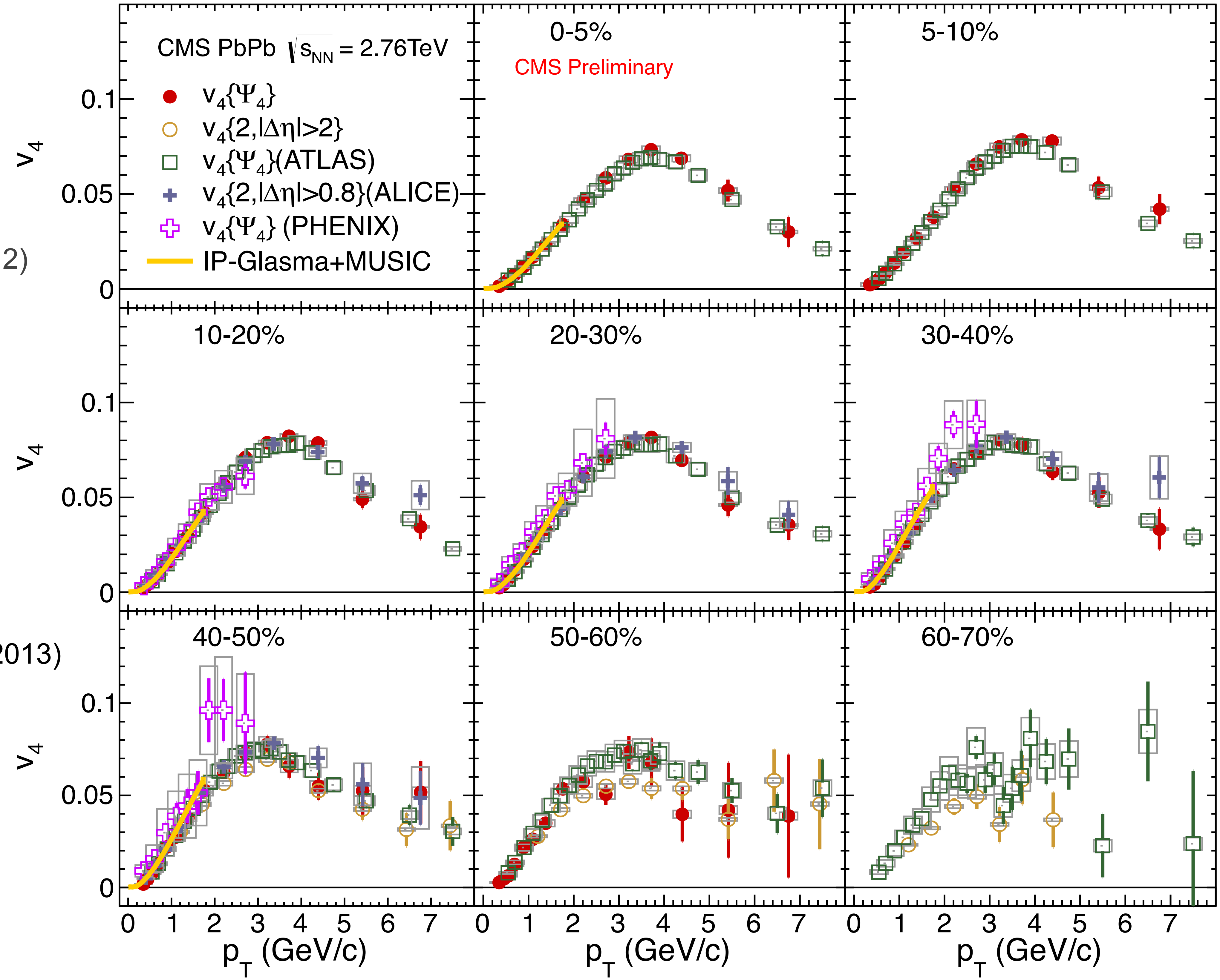
ALICE:
Phys. Lett. B 708, 249 (2012)

PHENIX:
PRL 107, 252301 (2011)

IP-Glasma+MUSIC
Gale et al.,
Phys. Rev. Lett. 110,012302(2013)

Comparisons

v_4



ATLAS:
Phys. Rev. C 86, 014907 (2012)
ALICE:
Phys. Lett. B 708, 249 (2012)
PHENIX:
PRL 107, 252301 (2011)

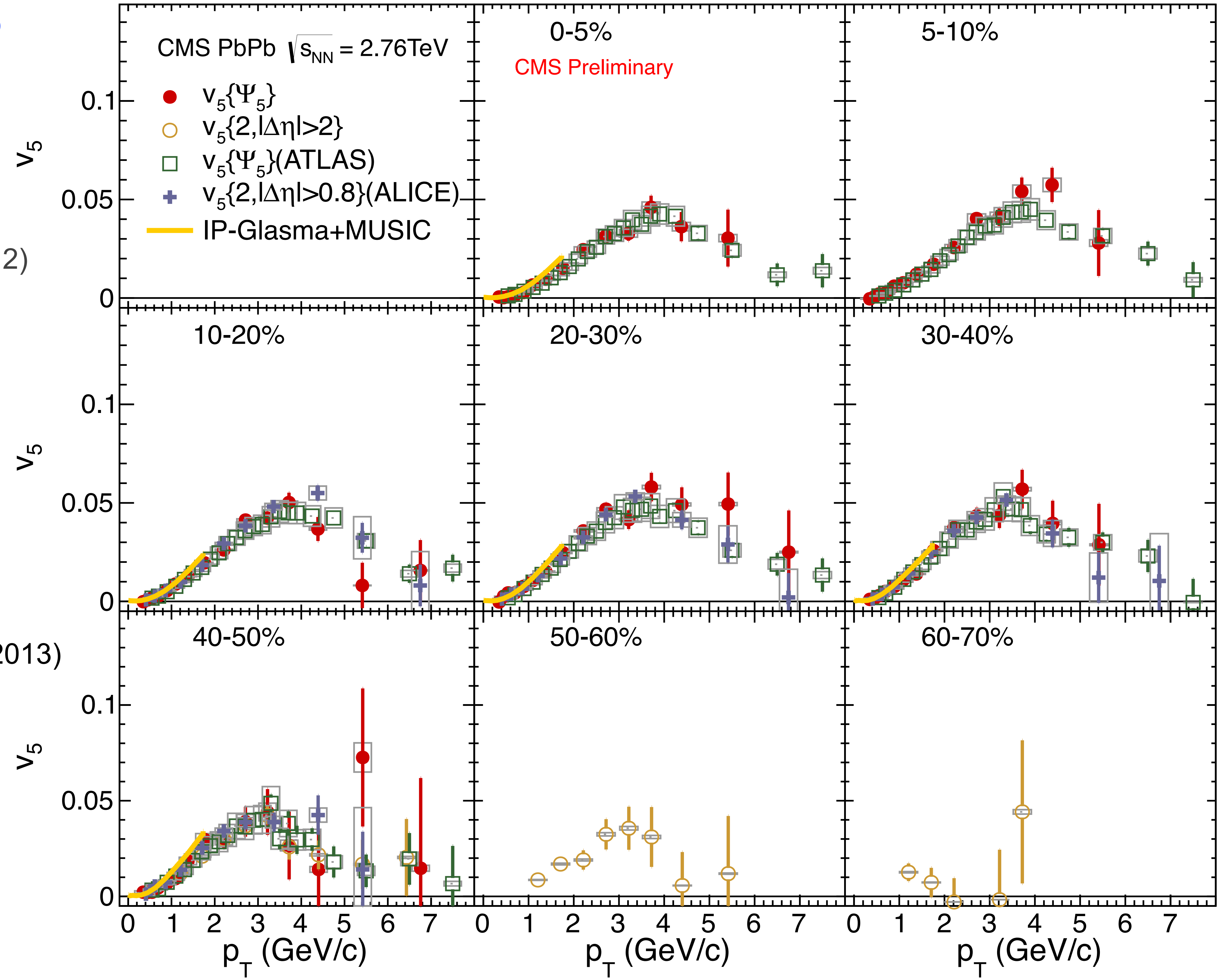
IP-Glasma+MUSIC
Gale et al.,
Phys. Rev. Lett. 110,012302(2013)

Comparisons

V_5

ATLAS:
Phys. Rev. C 86, 014907 (2012)
ALICE:
Phys. Lett. B 708, 249 (2012)
PHENIX:
PRL 107, 252301 (2011)

IP-Glasma+MUSIC
Gale et al.,
Phys. Rev. Lett. 110,012302(2013)



Harmonic Order Dependence

$$\frac{v_n}{\sqrt{\langle \varepsilon_n^2 \rangle}} \sim \exp\left[-\beta n^{\alpha}\right]$$

with

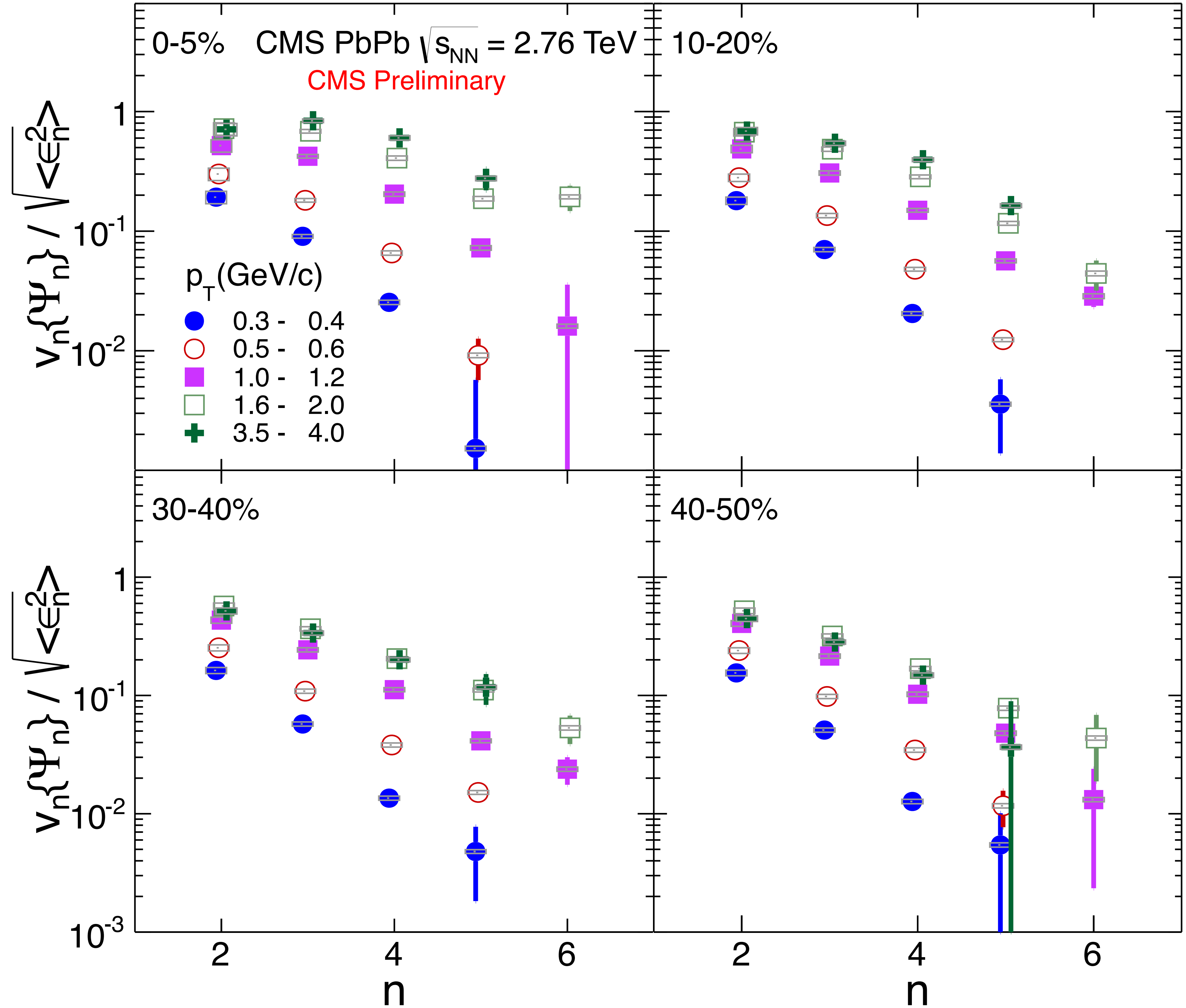
$$\alpha \geq 1$$

For acoustic flow

(Lacey et al.,arXiv:1301.0165)

$$\alpha = 2$$

$$\beta \propto \frac{\eta}{s}$$



Harmonic Order Dependence

$\exp\left[-\beta n^2\right]$ fits

$$\frac{v_n}{\sqrt{\left\langle \varepsilon_n^2 \right\rangle}} \sim \exp\left[-\beta n^{\alpha}\right]$$

with

$$\alpha \geq 1$$

For acoustic flow

(Lacey et al.,arXiv:1301.0165)

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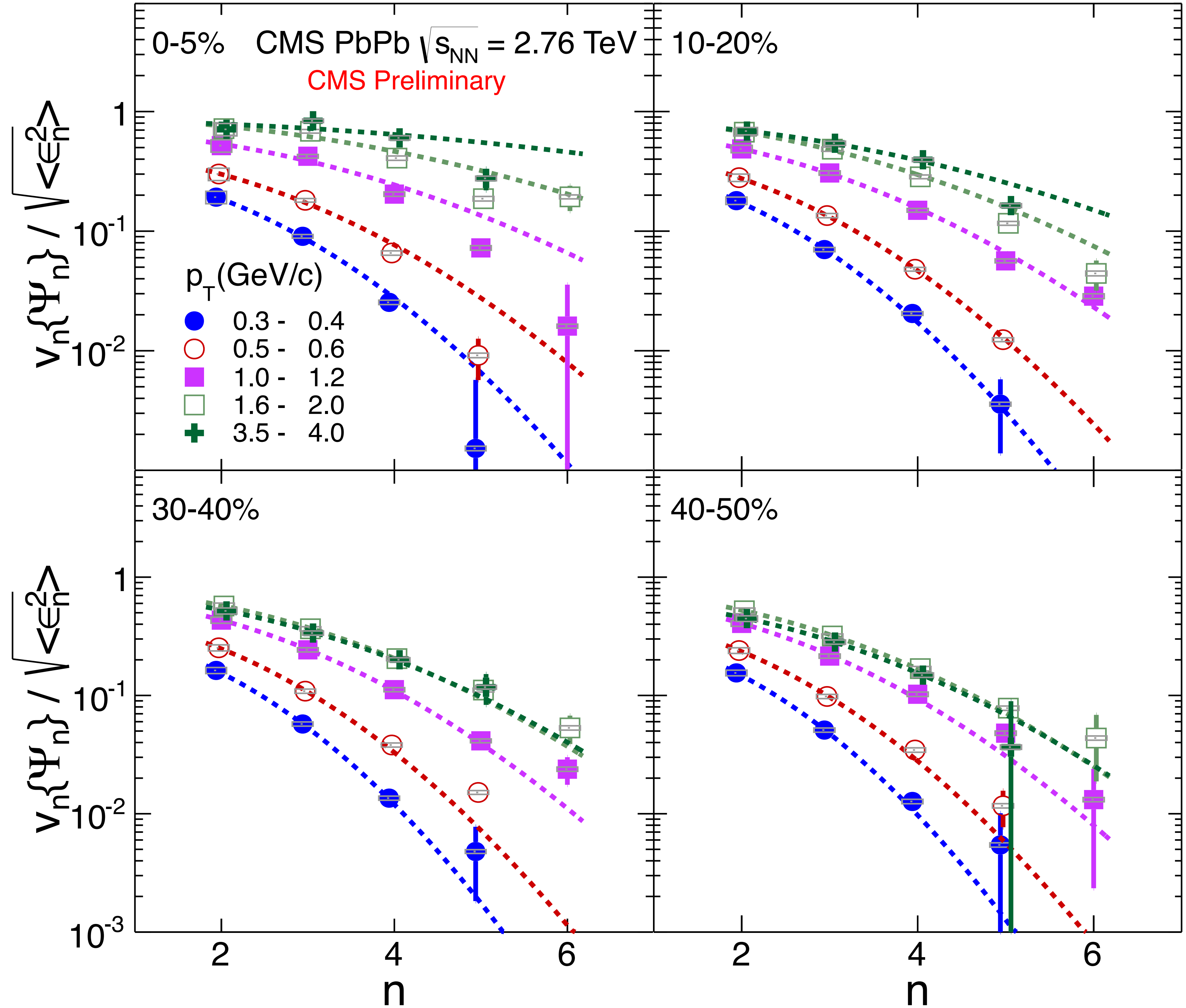


Fluctuations

Ollitrault, Poskanzer, Voloshin,
Phys. Rev. C 80(2009) 014904.

$$v_n\{2\}^2 = \langle v_n^2 \rangle = \langle v_n \rangle^2 + \sigma_n^2$$

$$v_n\{4\}^2 = \left(2\langle v_n^2\rangle^2 - \langle v_n^4 \rangle\right)^{1/2}$$

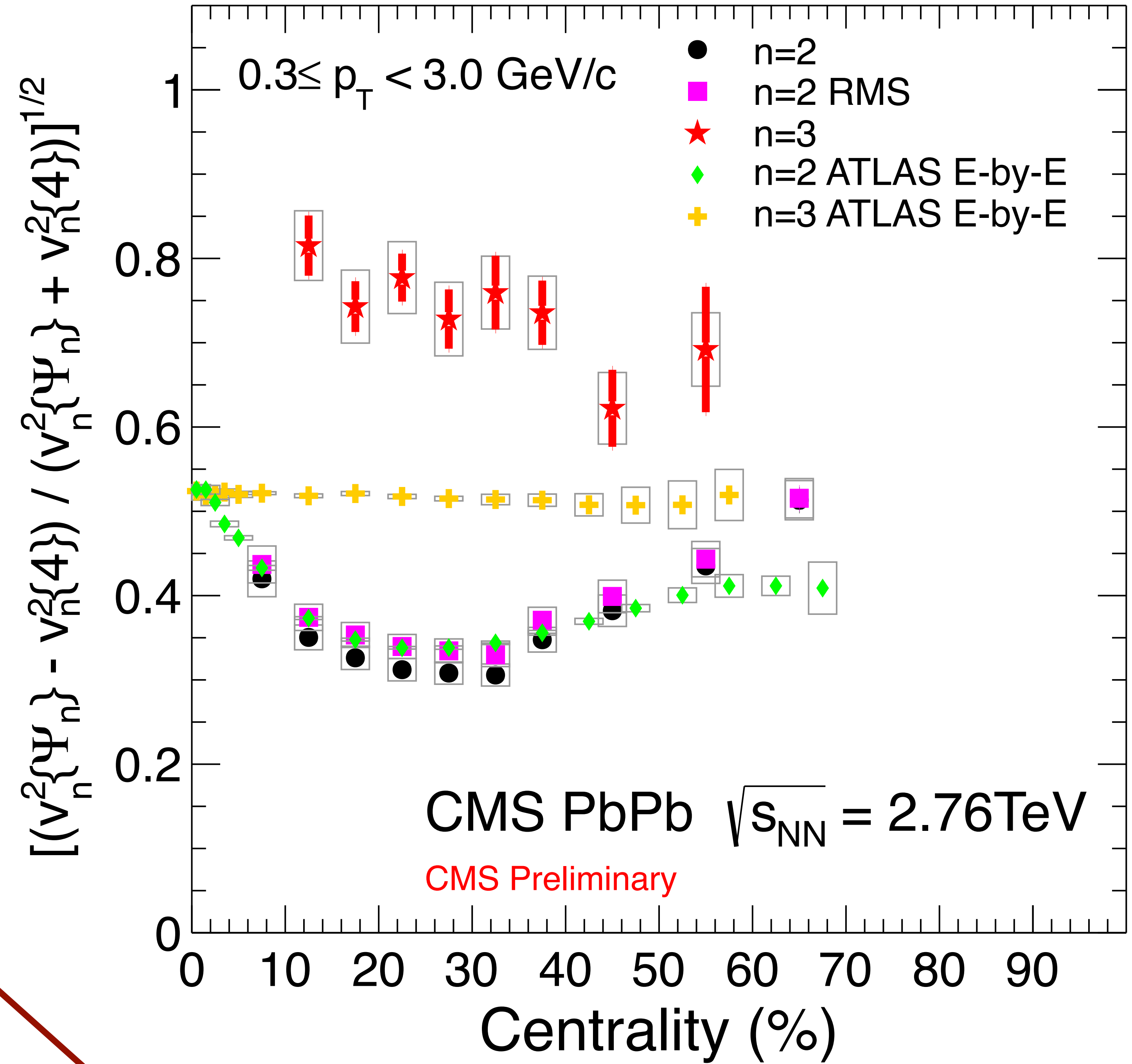
$$\approx \langle v_n \rangle^2 - \sigma_n^2$$

$$v_n^2\{\Psi_n\} = \langle v_n \rangle^2 + (\alpha - 1)\sigma_n^2$$

(α can be found knowing R_n)

Then $$\frac{\sigma_n}{v_n} \approx \left[\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}\right]^{1/2}$$

n=2 RMS results found using one-step iteration with $\sigma_2/\langle v_2 \rangle$ assuming $v_2\{\Psi_2\} \approx v_2\{2\}$



Formalism may not be appropriate for n=3 where σ comparable to <v>

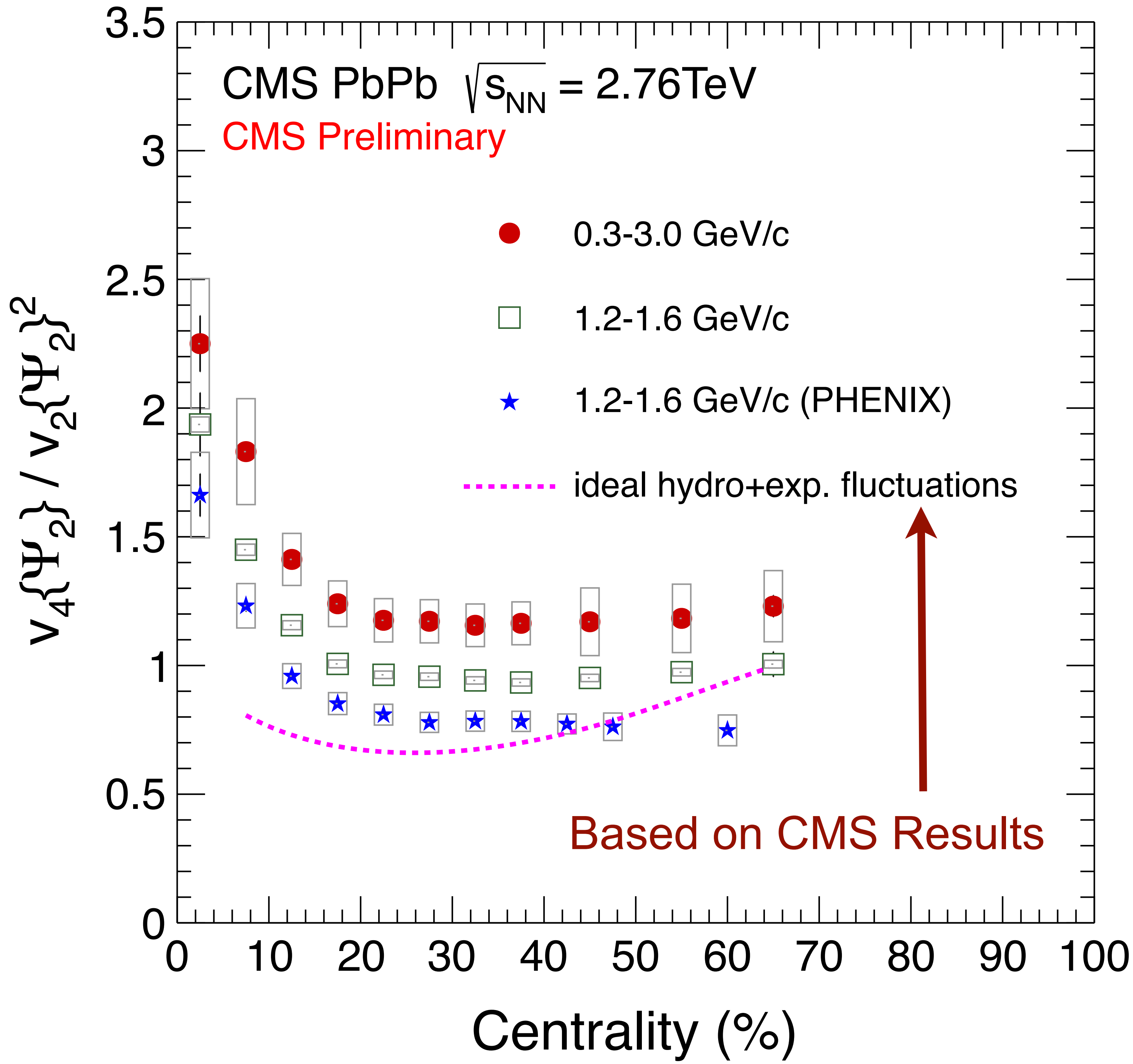
Shape of Overlap Region

$$\frac{v_4\{\Psi_2\}}{v_2\{\Psi_2\}^2} = \frac{1}{2}\left[1+\beta\left(\frac{\sigma_v}{\langle v\rangle}\right)^2\right]$$

Ideal hydro ratio = 1/2

β can be found knowing the EP resolution correction factor R_n

Gombeaud and Ollitrault, Phys. Rev. C 81 (2010) 014901



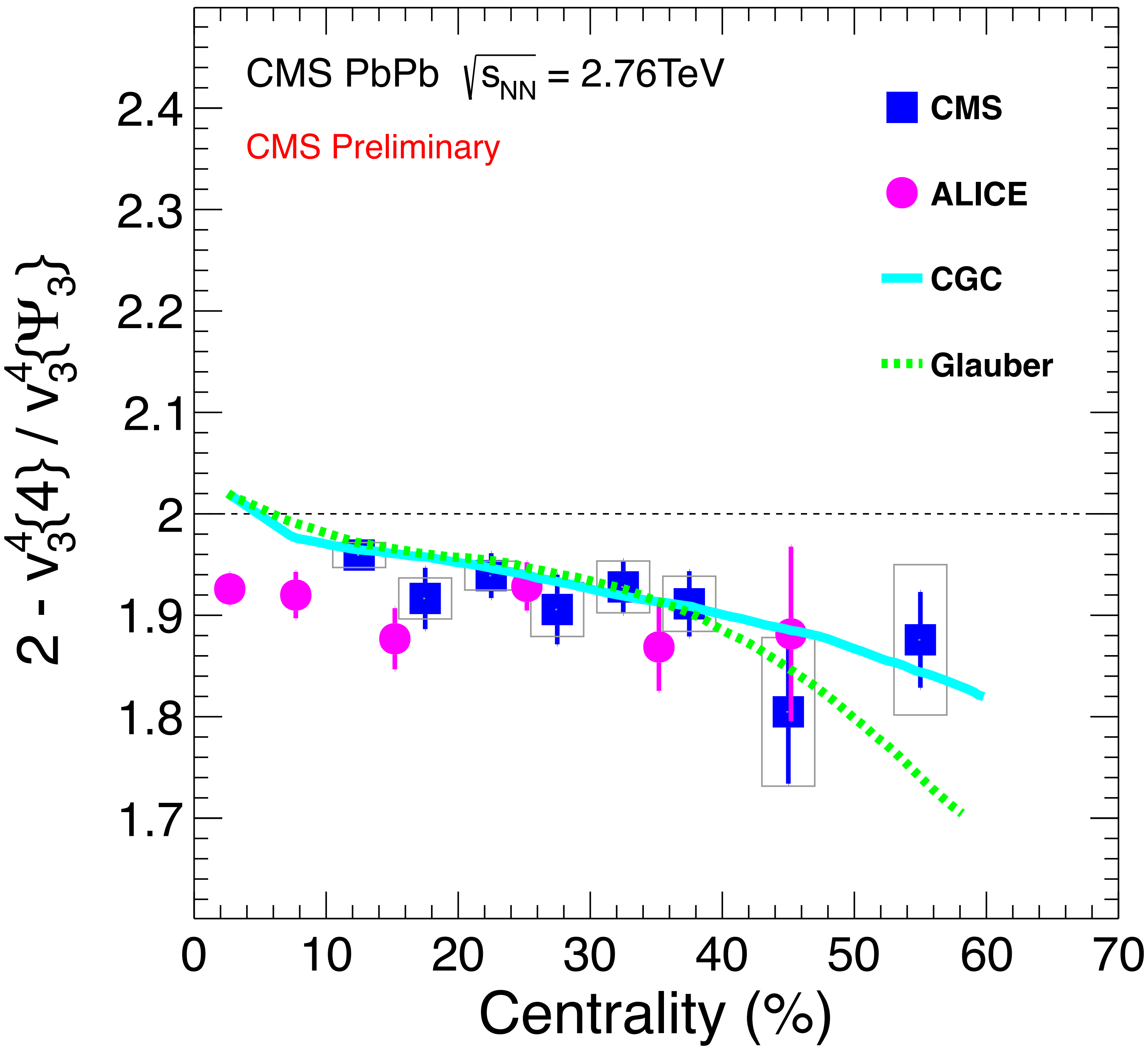
Sensitivity of Ratios to IC

Premise:

If

v_n=(medium evolution)×ε_n ,

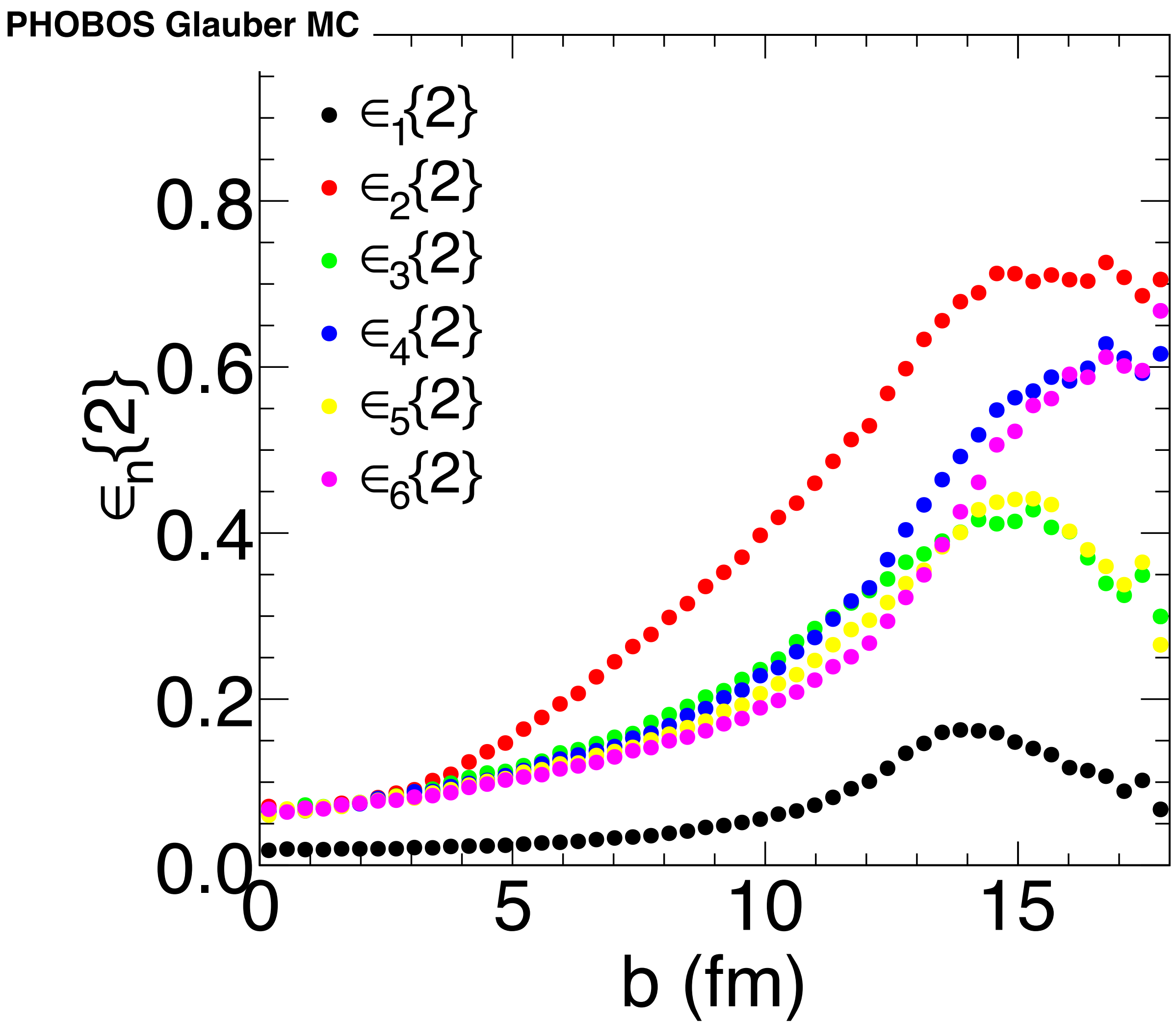
then sensitivity to (medium evolution) reduced by dividing v_n values based on different particle correlations.



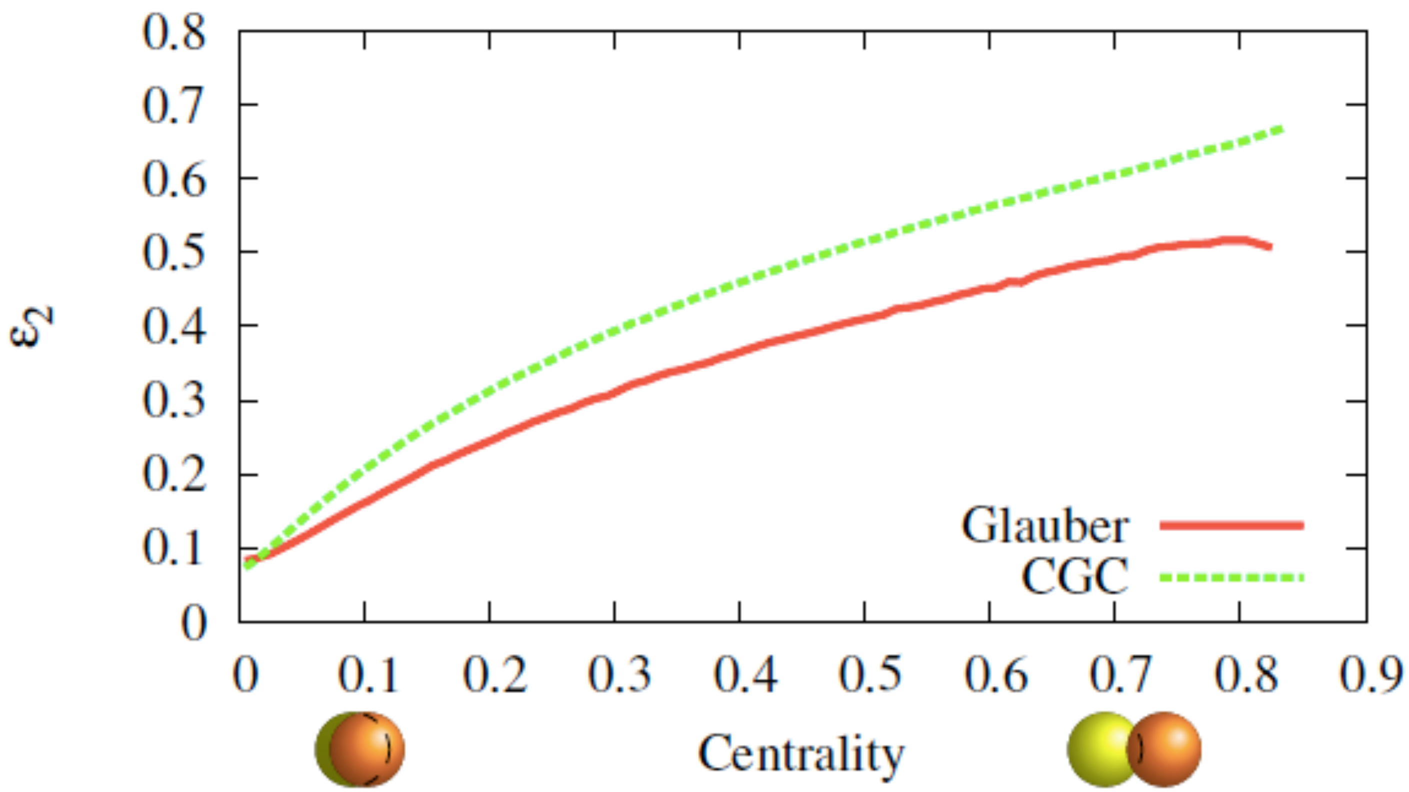
ALICE: Phys. Rev. Lett. 107 (2011) 032301.
Theory: Bhalerao, Luzum, Ollitrault, Phys. Rev. C. 84 (2011) 034910.

Ultra-Central Collisions

Why Ultra Central? Another way to isolate fluctuations....



Matt Luzum, QNP 2012



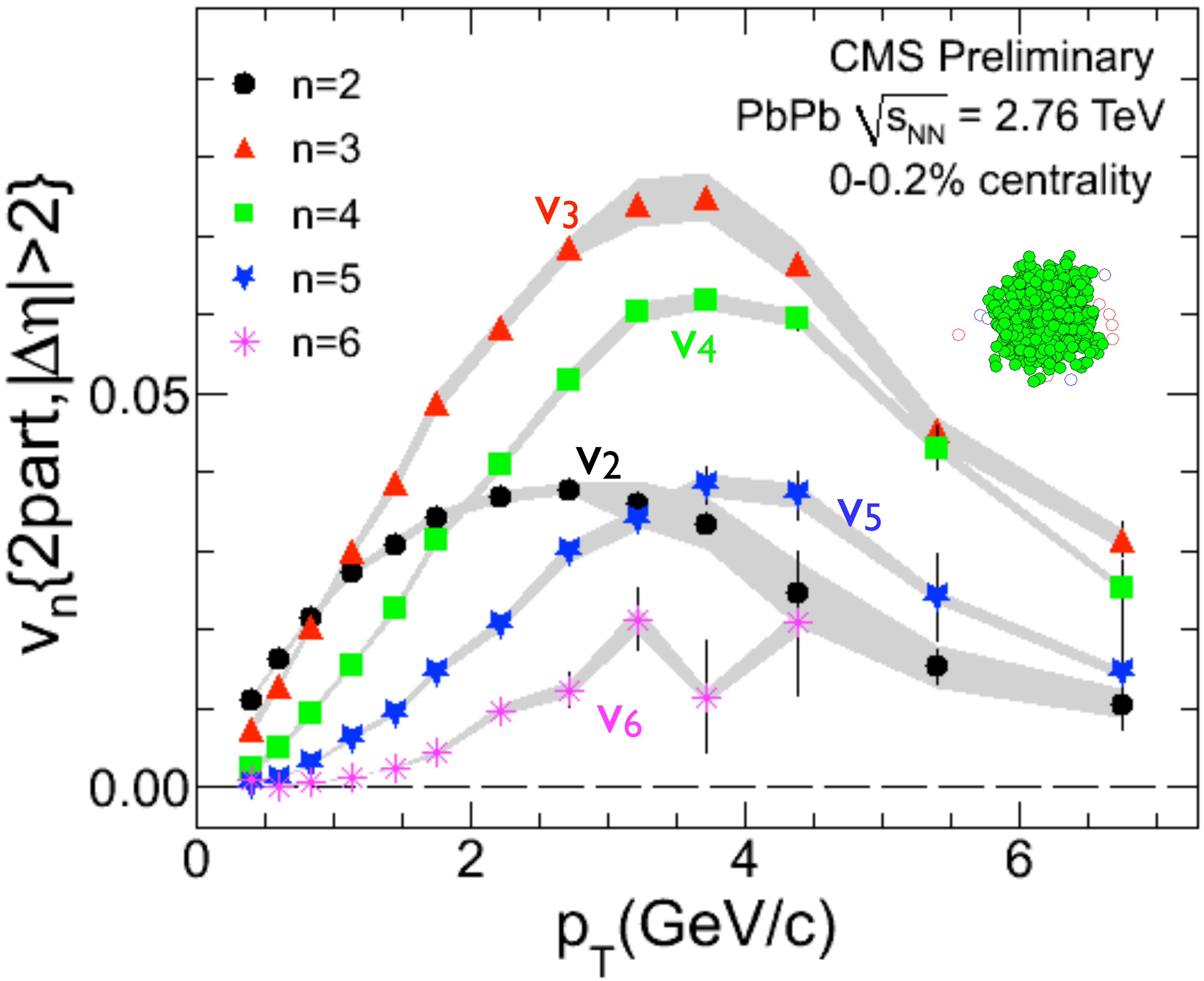
- Comparable excitation of all harmonics >1.

- Influence of initial conditions minimized.

Ultra-Central Collisions

Centrality<0.2%
Dihadron-correlation results

- Higher harmonics strongly excited.
- v_3-v_5 rise above elliptic flow (v_2) value.



Fluctuations dominate!

Summary and Conclusions

- Harmonic components up to n=6 significant
- Differences in method (EP, two-particle correlations, cumulant, LYZ) dependence on fluctuations can be used to study this behavior
- Good agreement achieved among LHC experiments
- No dramatic difference going from RHIC to LHC
- IP-Glasma+MUSIC model reproduces low-p_T behavior well
- Ratios of v_n from different methods may increase sensitivity to IC
- UCC data show strong excitations of higher harmonics

BACKUP

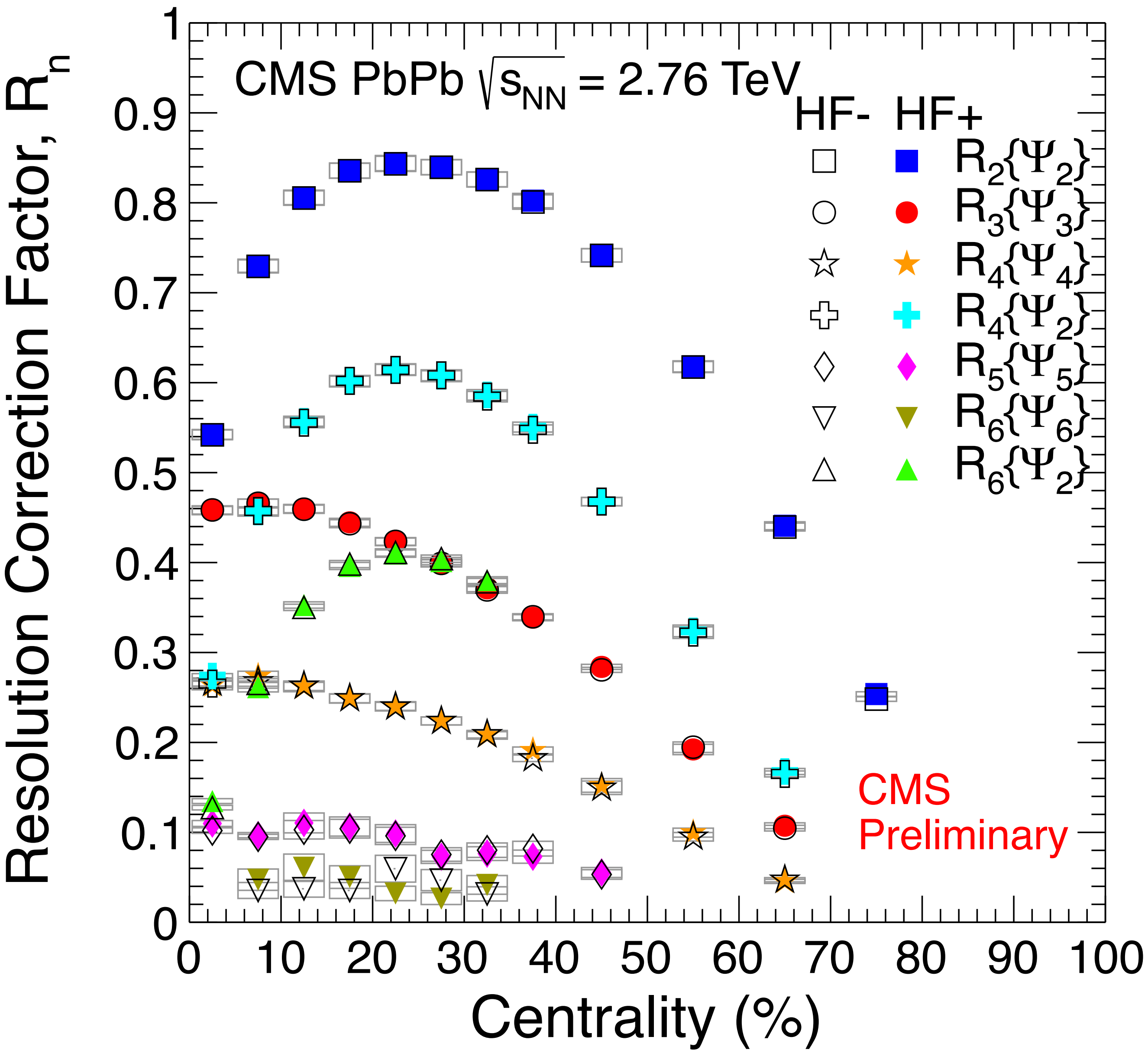
Relating EP to Two-Particle Correlations

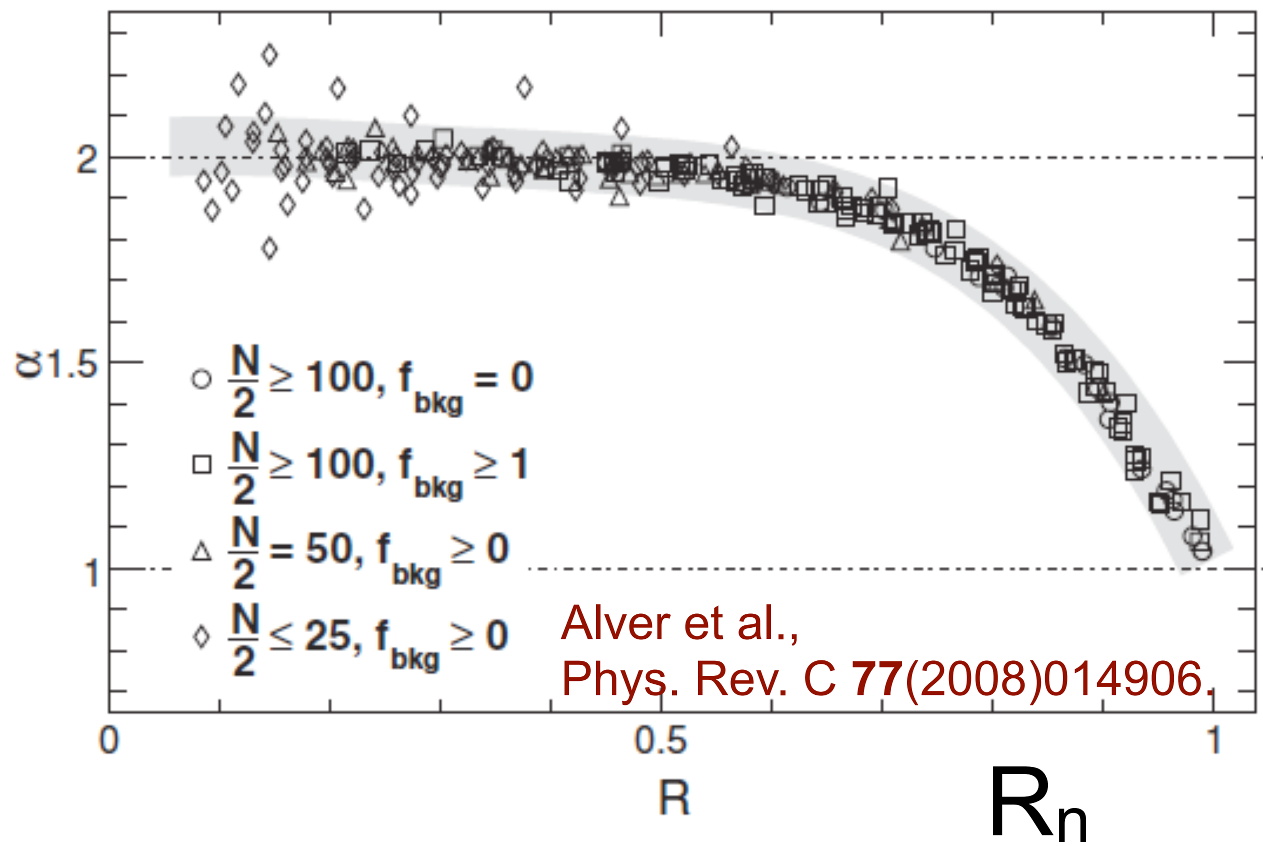
$$\sigma^2 = \langle v^2 \rangle - \langle v \rangle^2$$

Ollitrault, Poskanzer, and Voloshin, Phys. Rev. C **80**(2009)014904.

$$v_n\{\Psi_n\}^2 = < v^\alpha >^{1/\alpha} \approx \langle v_n \rangle^2 + (\alpha - 1)\sigma^2$$

$$v_n\{2\}^2 = \langle v_n \rangle^2 + \sigma^2$$





$$\Rightarrow v_n\{\psi_n\} \approx v_n\{2\} \quad (n > 2)$$

(Consistent with comparison of experimental results for two methods.)

Integral→Differential→Integral

Integral → **Differential**

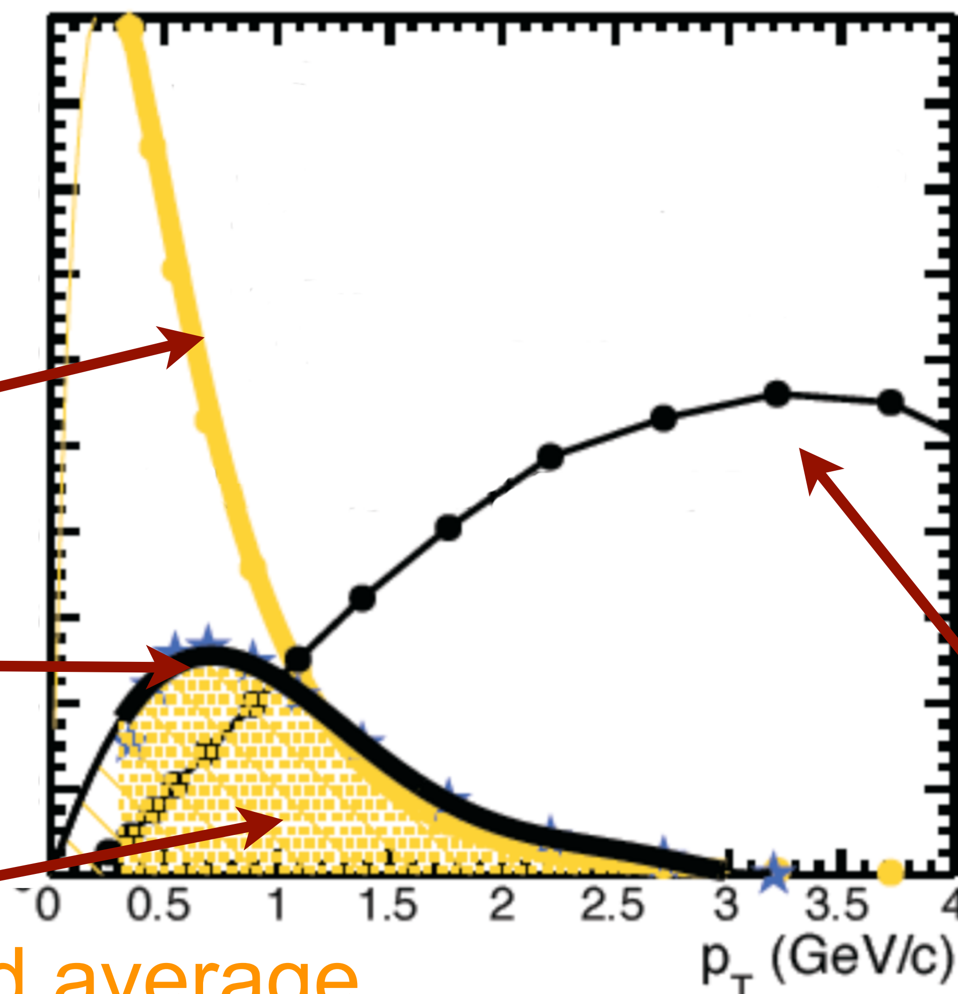
EP: Event-plane angle
2PartCorr: Extended p_T^{ASSOC} range
Cumulant: Integral Generating Function
LYZ: Integral Generating Function

EP : $\langle \cos[n(\Phi-\Psi)] \rangle (p_T)$
2PartCorr: Factorization
Cumulant: Differential Generating Function
LYZ: Differential Generating Function

→ **Integral**

$\frac{dN}{dp_T}$

$\frac{dN}{dp_T} \times v_n(p_T)$



$v_n(p_T)$

Shaded region ∝ spectrum-weighted average

Glauber-model eccentricities

Centrality (%)	$\langle N_{part} \rangle$	$\sqrt{\langle \epsilon_2^2 \rangle}$	$\sqrt{\langle \epsilon_3^2 \rangle}$	$\sqrt{\langle \epsilon_4^2 \rangle}$	$\sqrt{\langle \epsilon_5^2 \rangle}$	$\sqrt{\langle \epsilon_6^2 \rangle}$	$\sqrt{\langle \epsilon_{4,2}^2 \rangle}$	$\sqrt{\langle \epsilon_{6,2}^2 \rangle}$
0 - 5	381 ± 2	0.084 ± 0.010	0.097 ± 0.010	0.114 ± 0.010	0.131 ± 0.010	0.149 ± 0.010	0.081 ± 0.041	0.106 ± 0.065
5 - 10	329 ± 3	0.127 ± 0.010	0.129 ± 0.010	0.148 ± 0.010	0.169 ± 0.010	0.190 ± 0.010	0.104 ± 0.064	0.134 ± 0.081
10 - 15	283 ± 3	0.175 ± 0.011	0.154 ± 0.010	0.174 ± 0.010	0.198 ± 0.010	0.220 ± 0.010	0.123 ± 0.059	0.156 ± 0.092
15 - 20	240 ± 3	0.219 ± 0.016	0.177 ± 0.010	0.199 ± 0.010	0.225 ± 0.010	0.248 ± 0.011	0.143 ± 0.049	0.176 ± 0.081
20 - 25	204 ± 3	0.262 ± 0.016	0.199 ± 0.010	0.225 ± 0.010	0.250 ± 0.010	0.274 ± 0.013	0.165 ± 0.049	0.194 ± 0.073
25 - 30	171 ± 3	0.301 ± 0.019	0.221 ± 0.010	0.254 ± 0.010	0.277 ± 0.010	0.302 ± 0.014	0.193 ± 0.038	0.213 ± 0.062
30 - 35	143 ± 3	0.339 ± 0.022	0.245 ± 0.010	0.284 ± 0.011	0.307 ± 0.011	0.331 ± 0.015	0.221 ± 0.039	0.235 ± 0.062
35 - 40	118 ± 3	0.375 ± 0.022	0.268 ± 0.011	0.317 ± 0.013	0.337 ± 0.012	0.361 ± 0.015	0.254 ± 0.041	0.257 ± 0.067
40 - 50	86.2 ± 2.8	0.429 ± 0.024	0.308 ± 0.013	0.370 ± 0.016	0.385 ± 0.016	0.410 ± 0.017	0.307 ± 0.035	0.297 ± 0.070
50 - 60	53.5 ± 2.5	0.501 ± 0.026	0.366 ± 0.015	0.445 ± 0.020	0.454 ± 0.018	0.475 ± 0.018	0.385 ± 0.039	0.355 ± 0.075
60 - 70	30.5 ± 1.8	0.581 ± 0.027	0.422 ± 0.016	0.520 ± 0.023	0.513 ± 0.018	0.534 ± 0.020	0.466 ± 0.039	0.417 ± 0.069
70 - 80	15.7 ± 1.1	0.662 ± 0.026	0.460 ± 0.012	0.596 ± 0.026	0.559 ± 0.015	0.609 ± 0.023	0.549 ± 0.035	0.497 ± 0.063

|η| dependence