High-p_T v_n Harmonics in PbPb Collisions at 5.02 TeV

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for the CMS Collaboration

Hard Probes 2016, Wuhan

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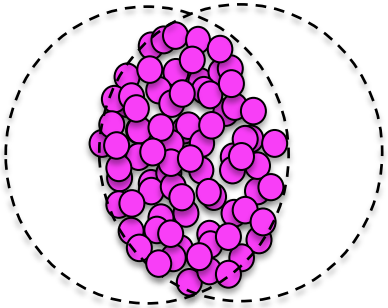
Motivation

- Fourier harmonics v_n

$$\frac{\mathrm{d}N(p_{\mathrm{T}})}{\mathrm{d}\phi} \propto 1 + \sum 2v_n(p_{\mathrm{T}})\cos[n(\phi - \Psi_n)]$$



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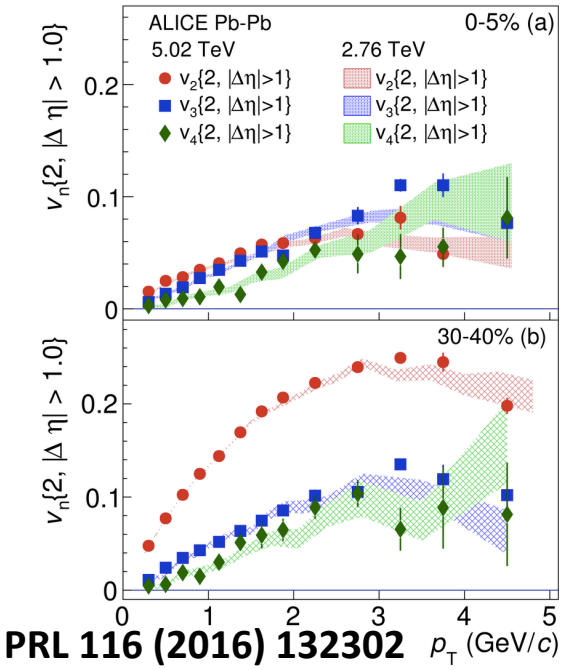
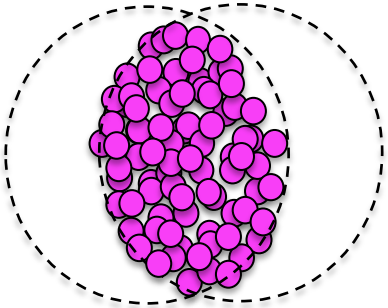
- Low p_T
  - Collectivity, hydrodynamics
  - Geometry(v_2) + fluctuations ($v_{3,4...}$)



PRL 116 (2016) 132302



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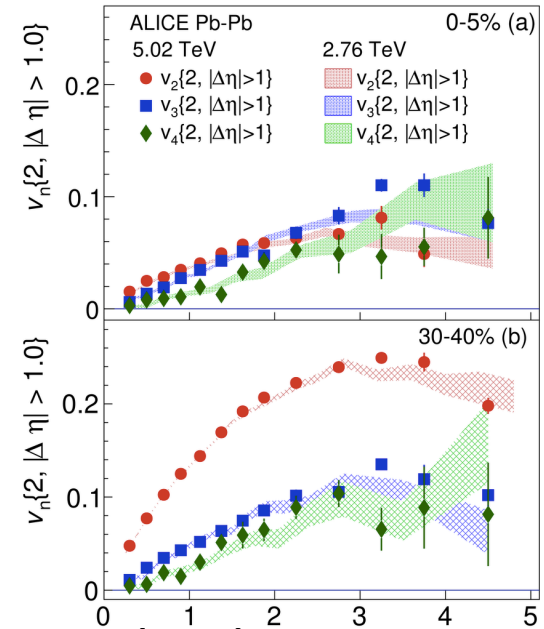
  - Geometry(v_2) + fluctuations ($v_{3,4...}$)
- High p_T
  - Path length dep. energy loss



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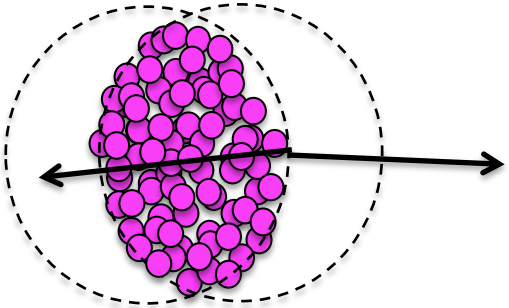

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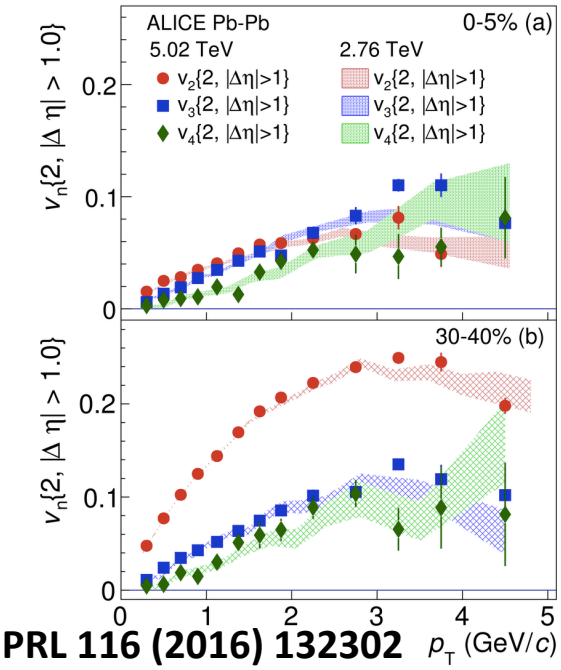

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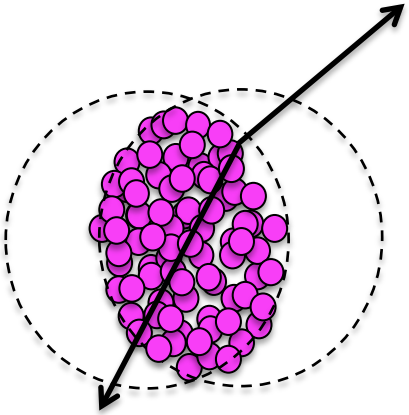
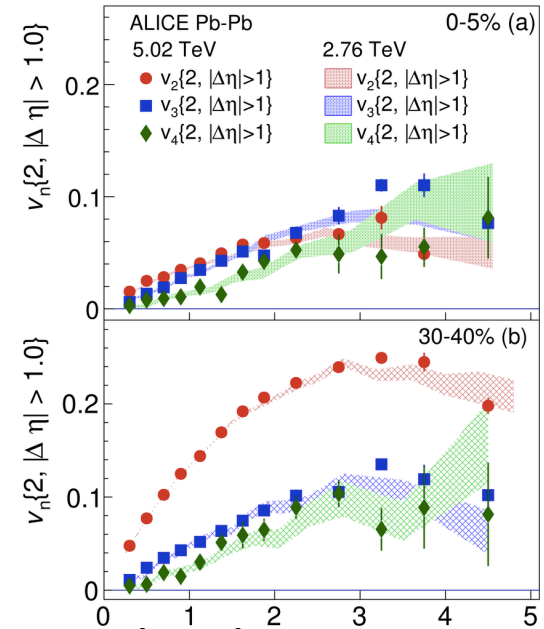


Motivation

- Fourier harmonics v_n

$$\frac{dN(p_T)}{d\phi} \propto 1 + \sum 2v_n(p_T)\cos[n(\phi - \Psi_n)]$$

- Low p_T
  - Collectivity, hydrodynamics
  - Geometry(v_2) + fluctuations ($v_{3,4...}$)
- High p_T
  - Path length dep. energy loss
  - $R_{AA}(p_T)$: average energy loss



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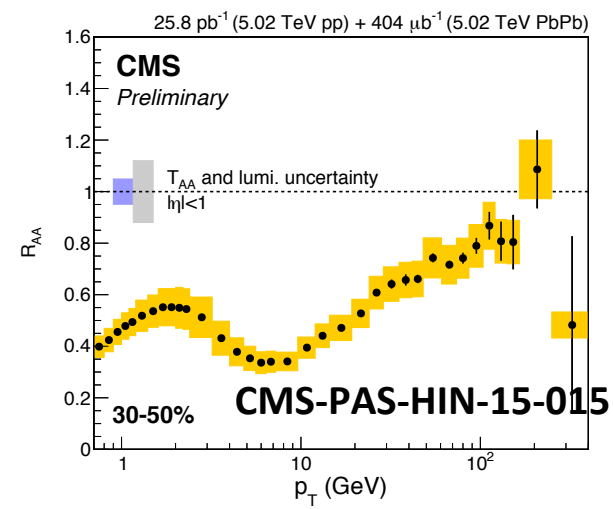
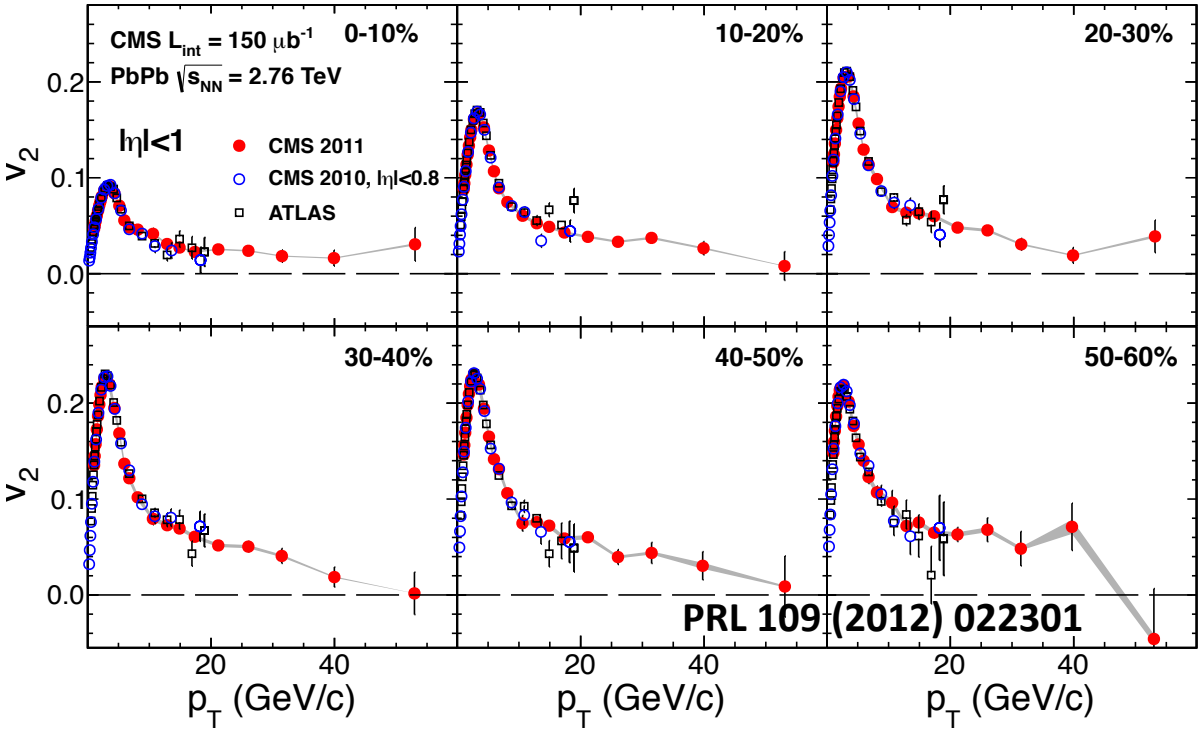
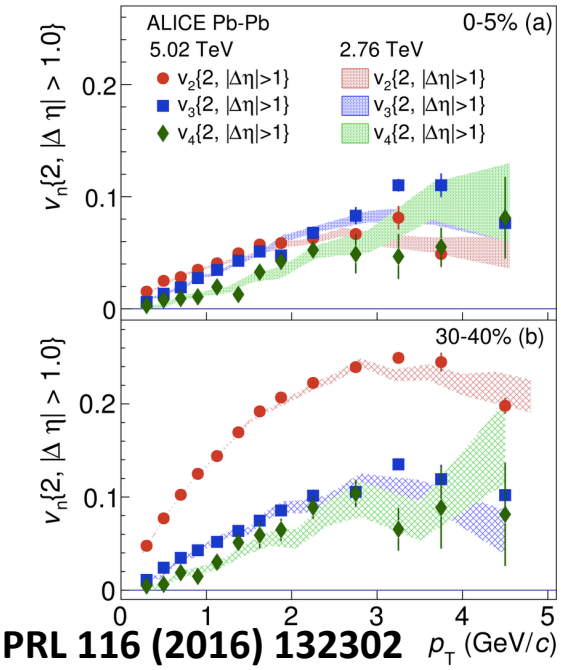
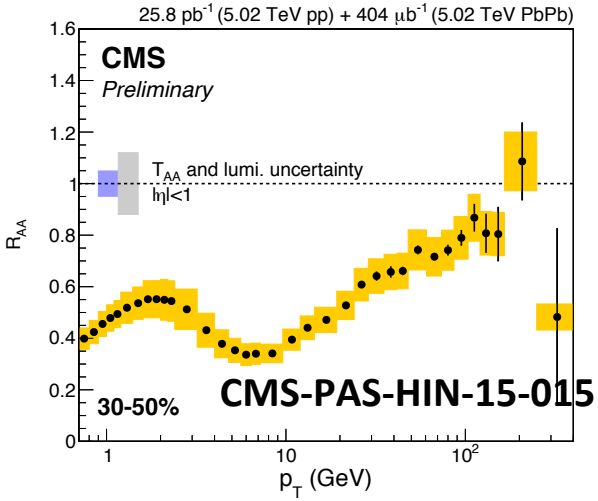


CMS-PAS-HIN-15-015

Motivation



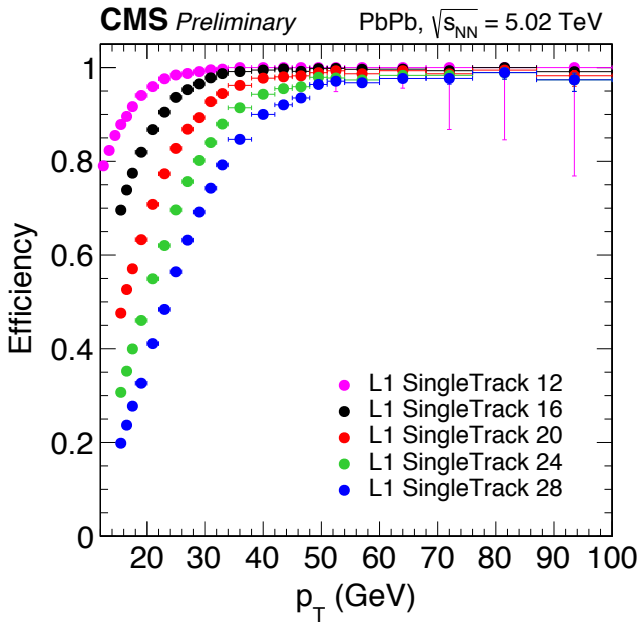


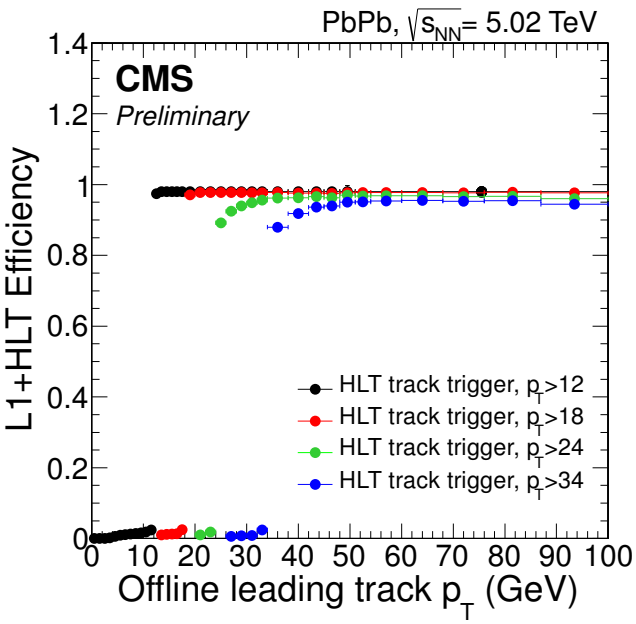


- Measurement of high p_T v_n
  - Complementary to $R_{AA}(p_T,\phi)$
  - Initial state + energy loss

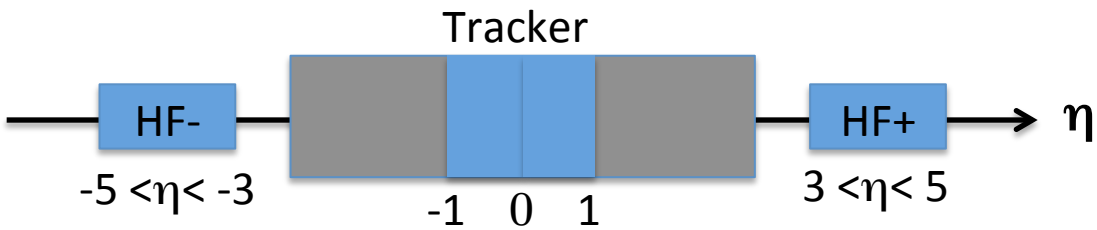
Dataset

- 2015 PbPb run at LHC
  - $\sqrt{s_{NN}}$ = 5.02 TeV, 404 μb^{-1}
  - MinimumBias (p_T < 14 GeV/c)
- High p_T track trigger
  - $|\eta| < 1.0$, $14.0 < p_T < 100$ GeV/c





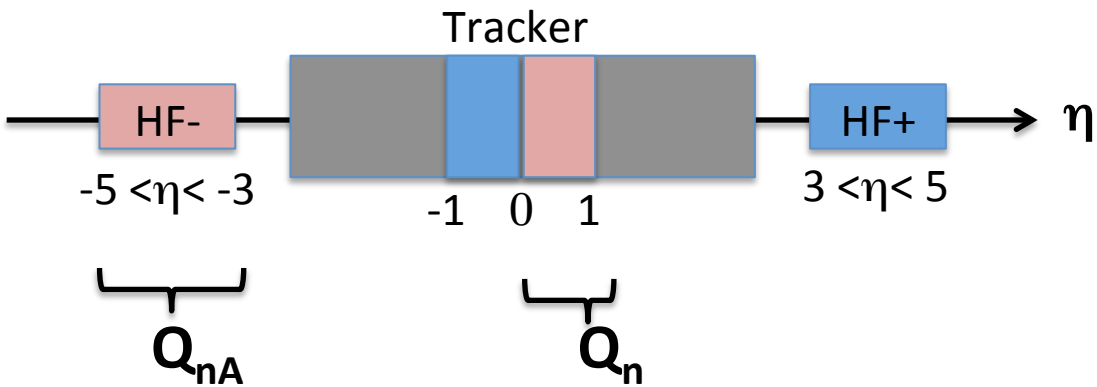
Scalar Product



$$Q_n = \sum_j w_j e^{in\phi_j}$$

Sum over tracks (tracker), or towers (HF)

Scalar Product



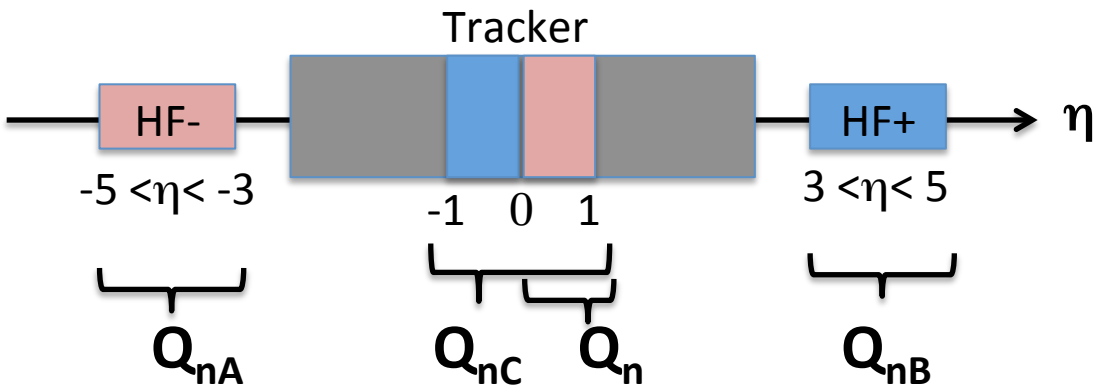
$$Q_n = \sum_j w_j e^{in\phi_j}$$

Sum over tracks (tracker), or towers (HF)

$$v_n\{\mathrm{SP}\} = \frac{\langle Q_n \cdot Q_{nA}^* \rangle}{R}$$

- Large η gap applied (|Δη|>3.0)

Scalar Product



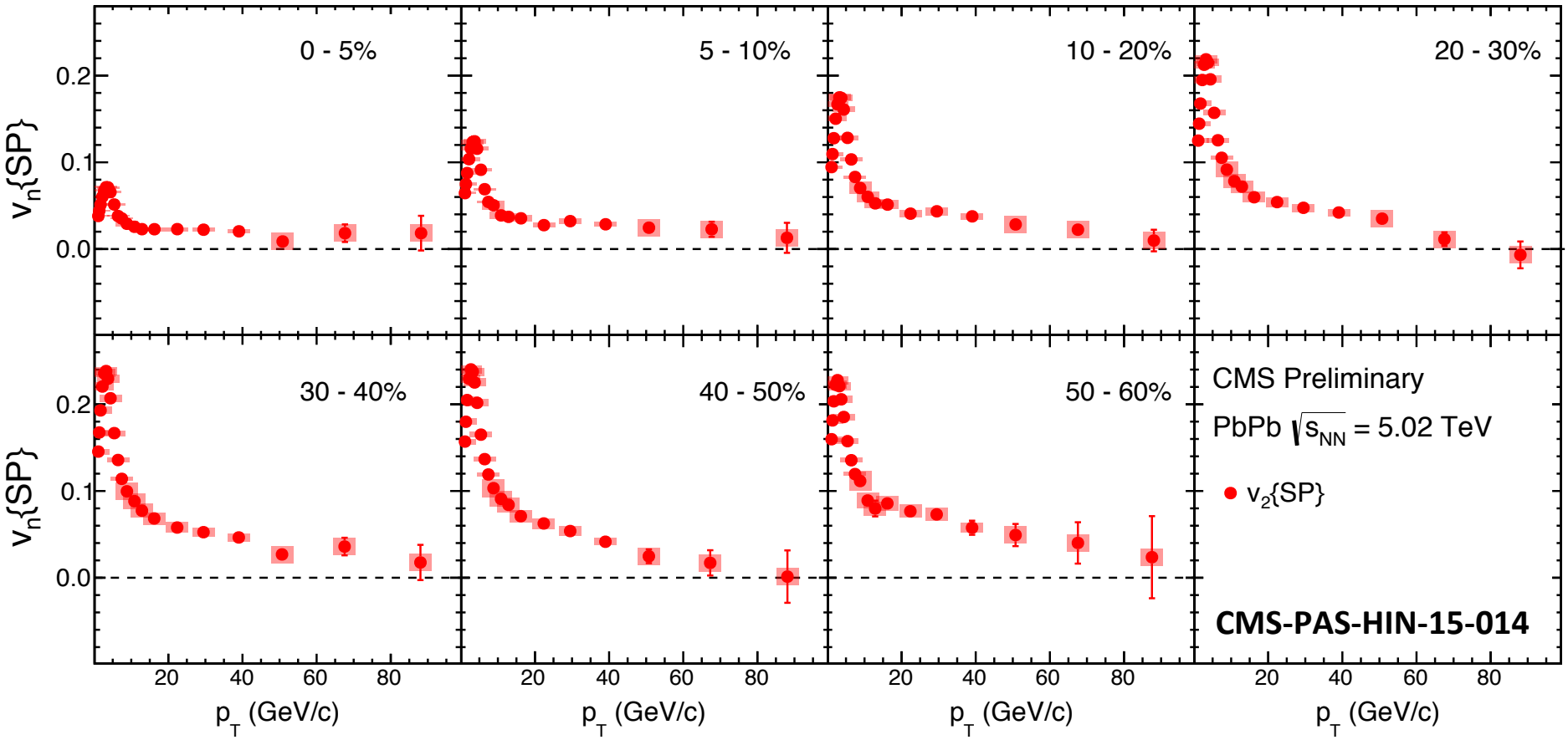
$$Q_n = \sum_j w_j e^{in\phi_j}$$

Sum over tracks (tracker), or towers (HF)

$$v_n\{\mathrm{SP}\} = \frac{\langle Q_n \cdot Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} \cdot Q_{nB}^* \rangle \langle Q_{nA} \cdot Q_{nC}^* \rangle}{\langle Q_{nB} \cdot Q_{nC}^* \rangle}}}$$

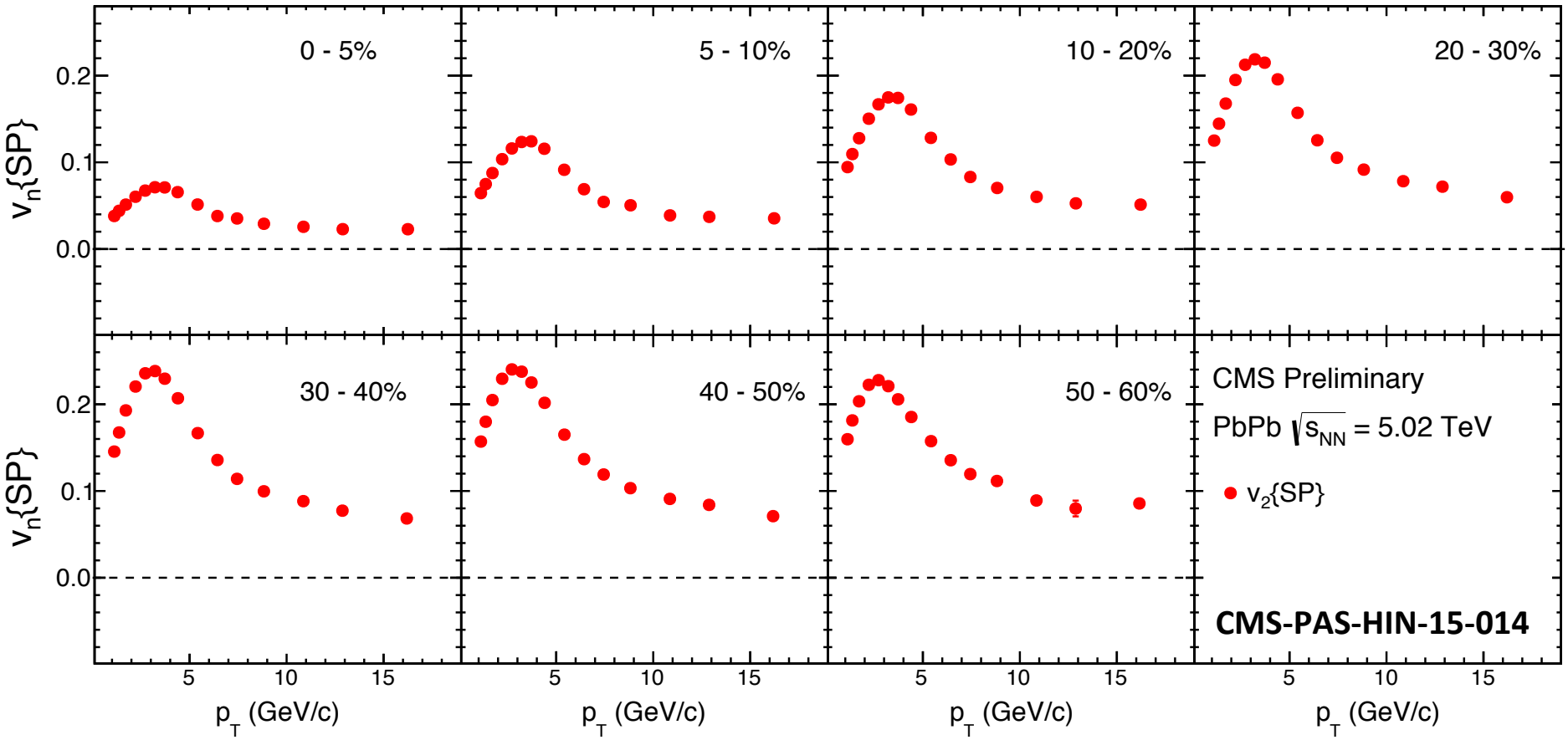
- Large η gap applied (|Δη|>3.0)
- $v_n\{SP\}$, non-ambiguous measure of RMS v_n

Results – $v_2\{SP\}$ high p_T



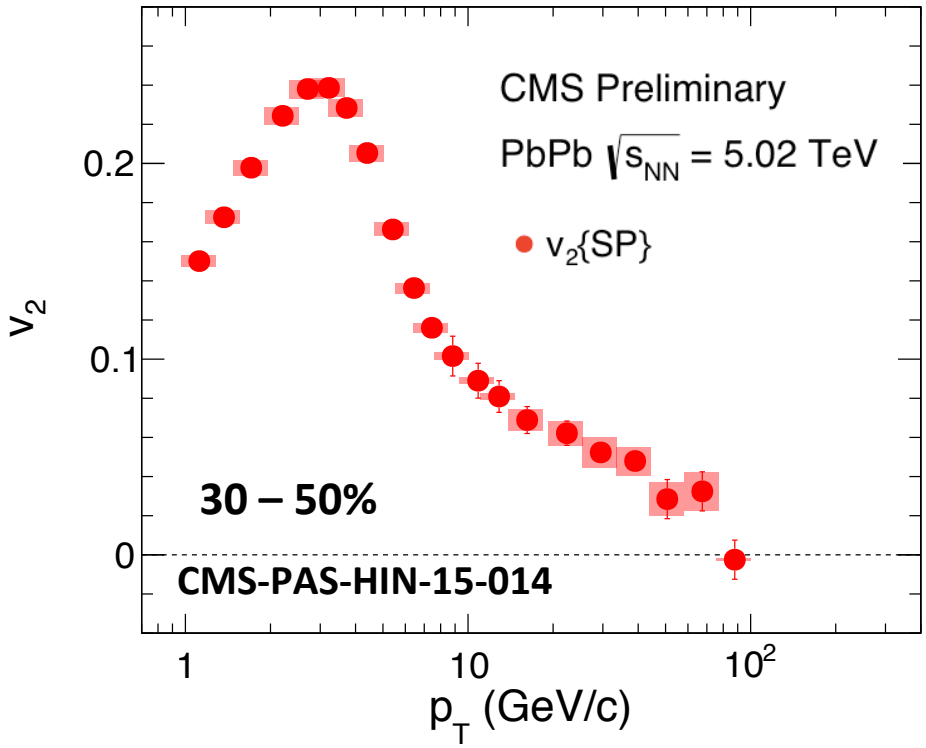
- FIRST time measure of $v_2\{SP\}$ up to 100 GeV/c
- $v_2\{SP\}$ remains positive at very high p_T

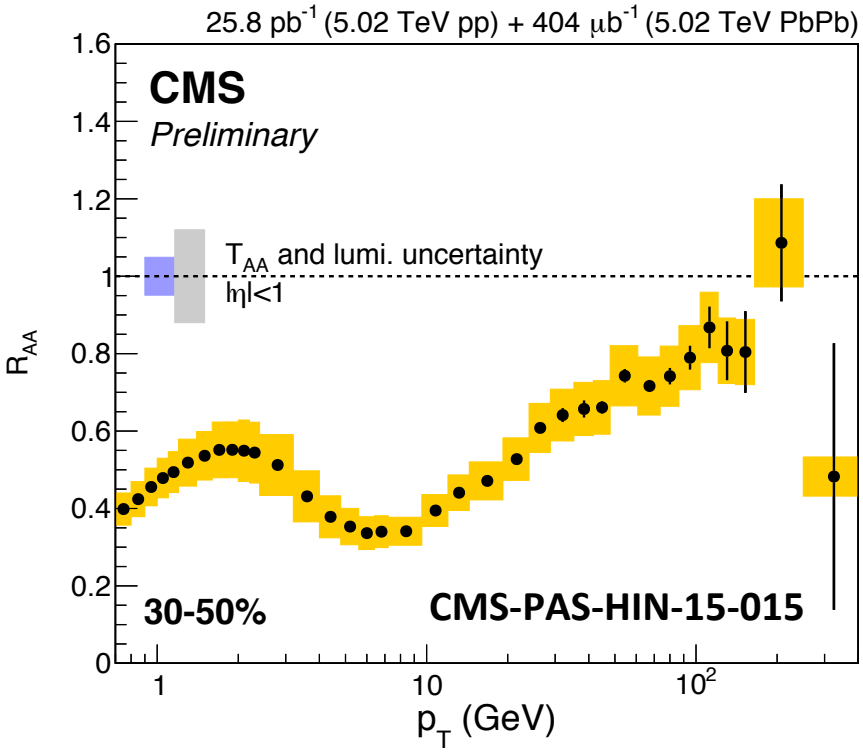
Results – $v_2\{SP\}$ low p_T



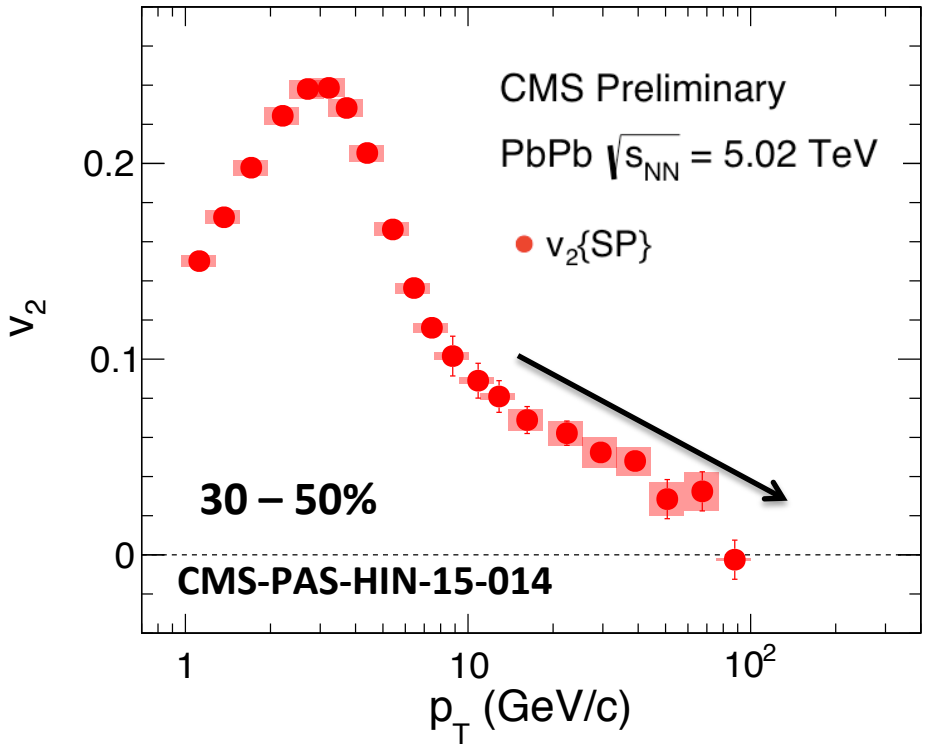
- Low p_T v_2 increase from most-central to mid-central, then decrease
- v_2 increase with p_T, peaked ~ 3 GeV/c, decrease while increasing p_T

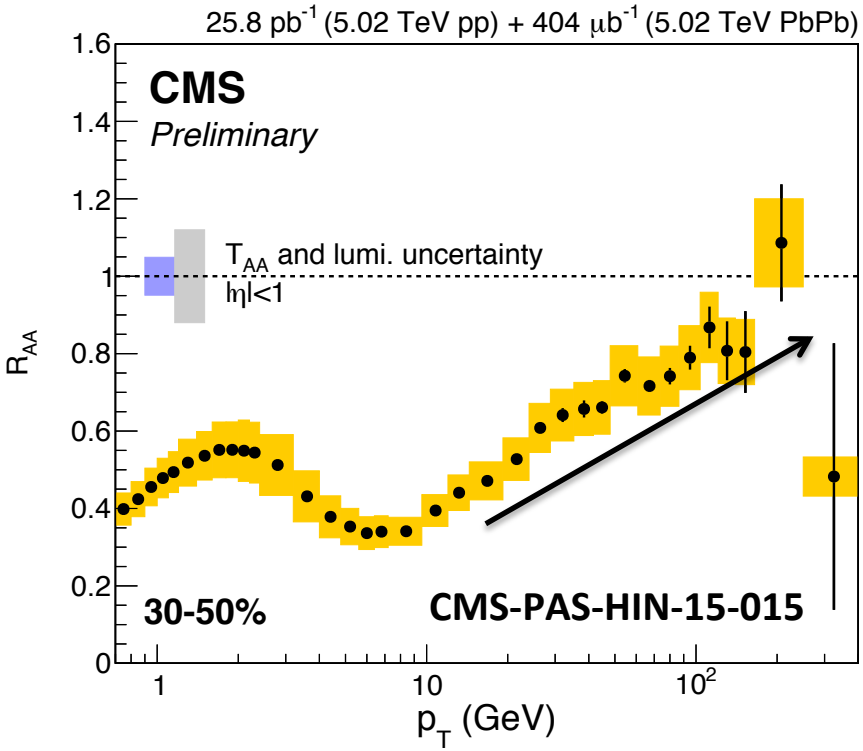
Results – $v_2\{SP\}$





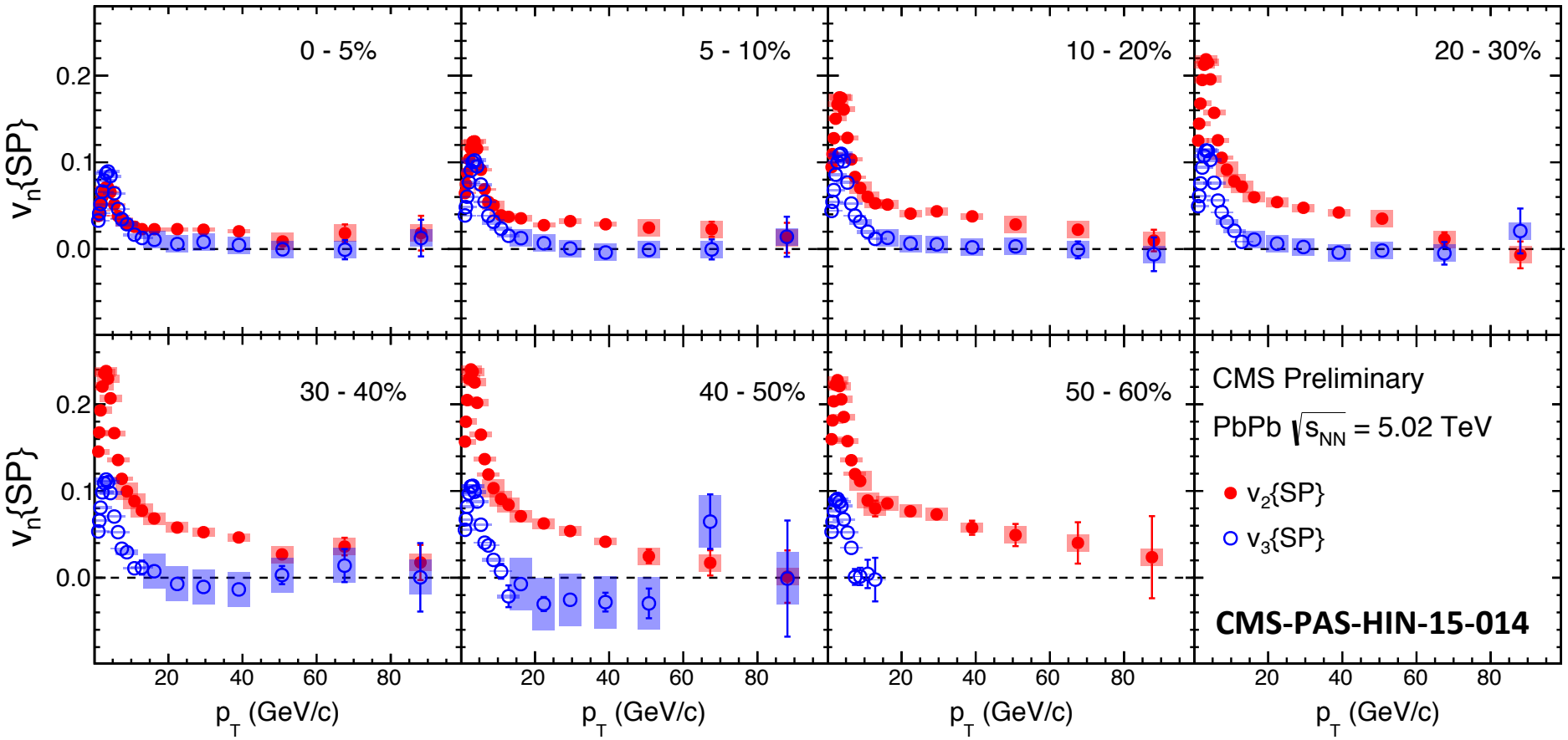
Results – $v_2\{SP\}$





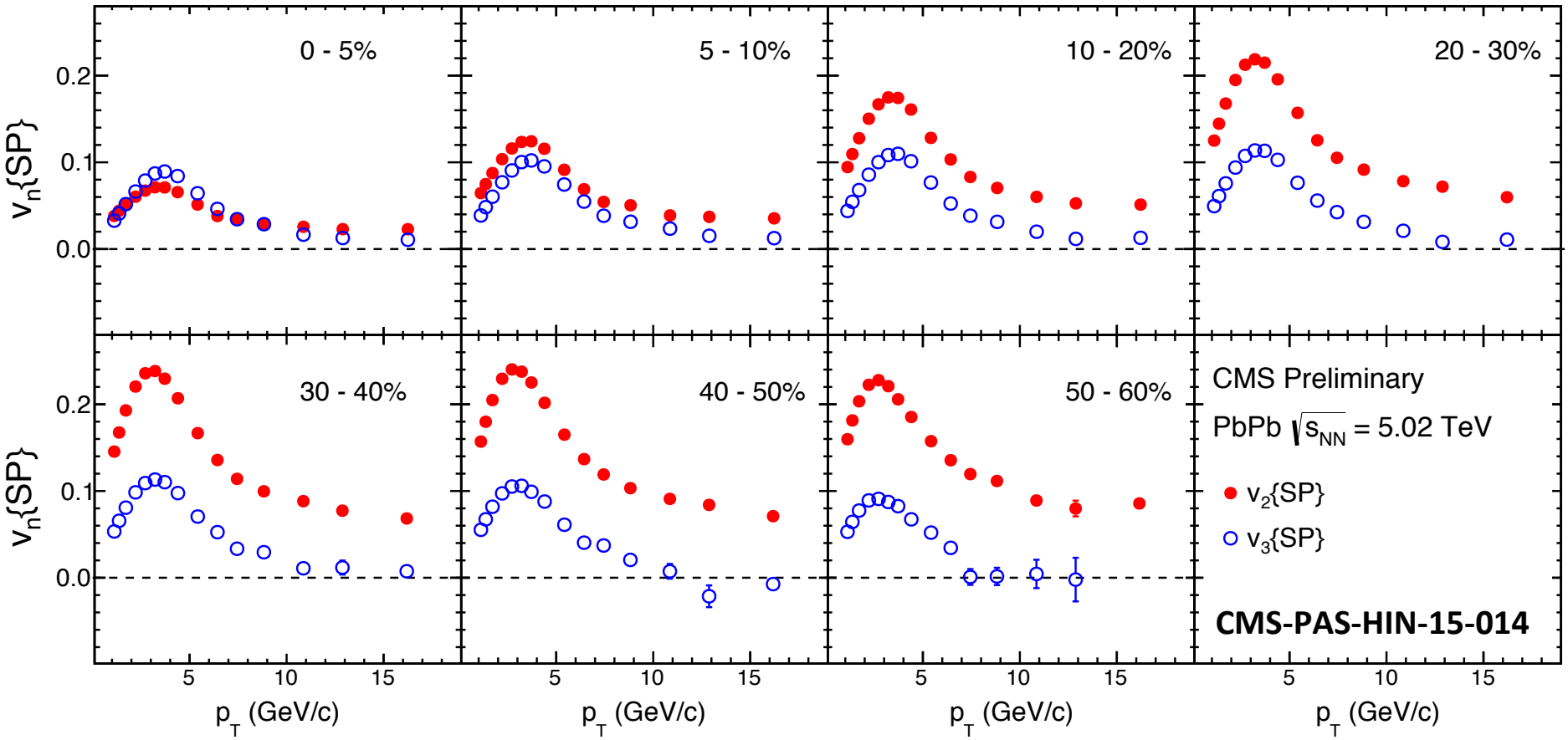
- At high p_T, less suppressed, more isotropic (less v_2)

Results – $v_3\{SP\}$ high p_T



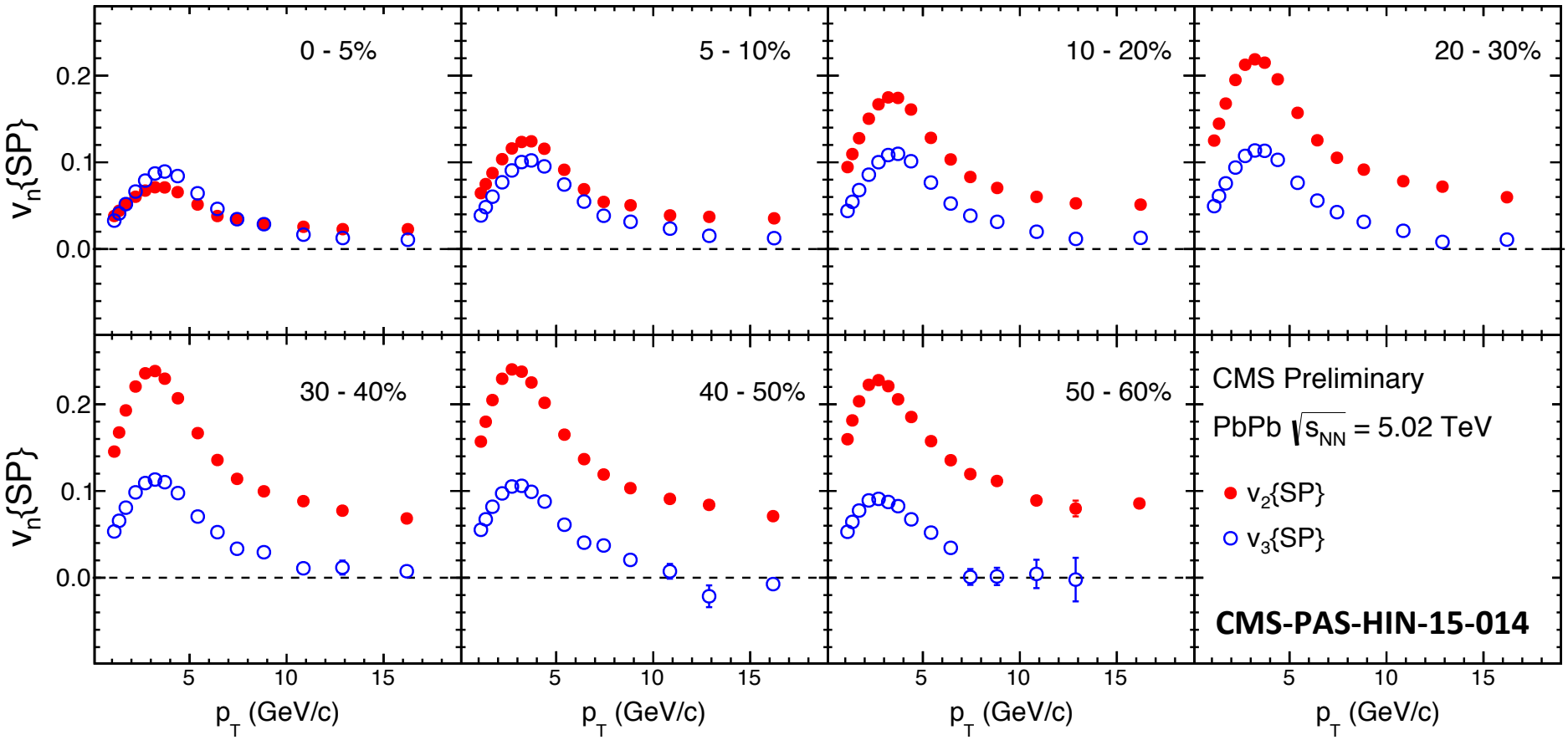
- FIRST time measure of $v_3\{SP\}$ up to 100 GeV/c
- Consistent with 0 for p_T > 30 GeV/c

Results – $v_3\{SP\}$ low p_T



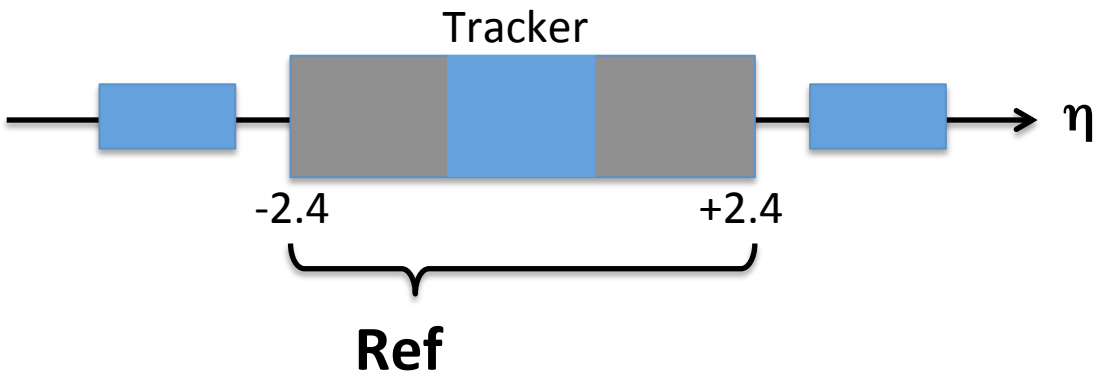
- FIRST time measure of $v_3\{SP\}$ up to 100 GeV/c
- Consistent with 0 for p_T > 30 GeV/c
- Little centrality dependence for v_3

Results – $v_3\{SP\}$ low p_T



- FIRST time measure of $v_3\{SP\}$ up to 100 GeV/c
- Consistent with 0 for p_T > 30 GeV/c
- Little centrality dependence for v_3 **Multi-particle or few particle?**

Cumulant



- Reference: $|\eta| < 2.4$, $1 < p_T < 5$ GeV/c

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

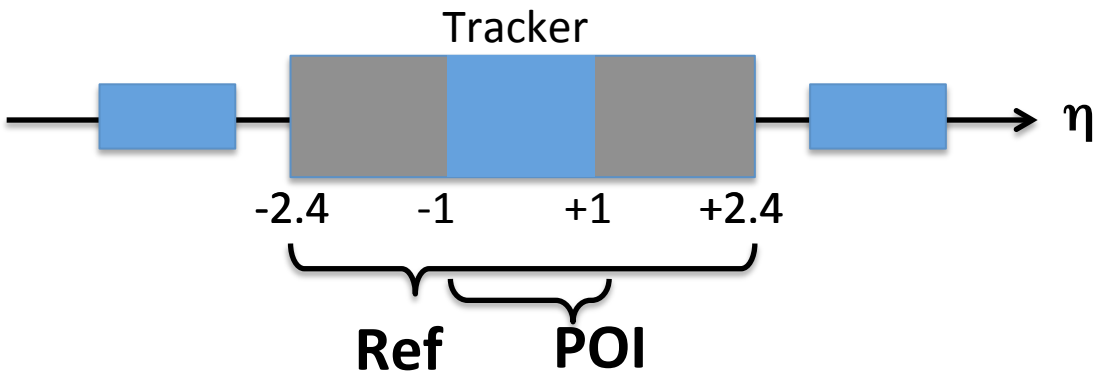
$$v_n\{6\} = \sqrt[6]{c_n\{6\}/4}$$

$$v_n\{8\} = \sqrt[8]{-c_n\{8\}/33}$$

- 4-, 6-, 8-particle Q-Cumulant

[A. Bilandzic et.al., PRC 83 (2011) 044913]

Cumulant



- Reference: $|\eta| < 2.4$, $1 < p_T < 5$ GeV/c
- Particle of interest (POI): $|\eta| < 1.0$

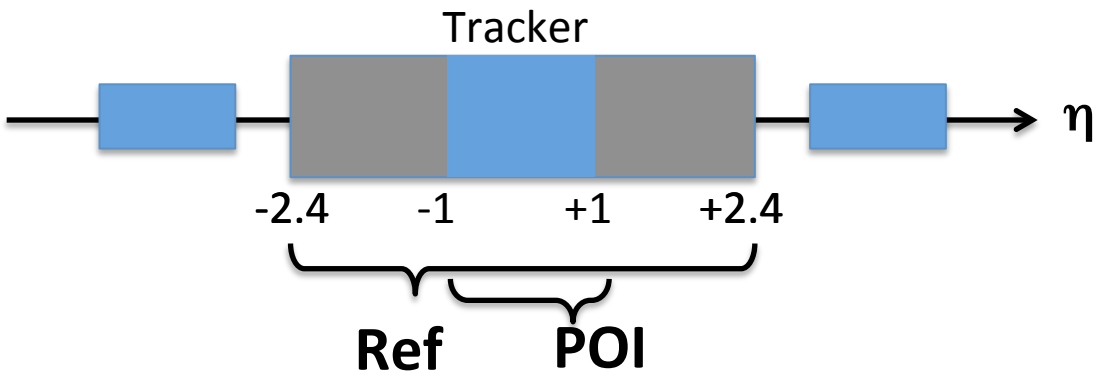
$$v_n\{4\}(p_T) = -d_n\{4\}/(-c_n\{4\})^{3/4}$$

$$v_n\{6\}(p_T) = \frac{d_n\{6\}}{4} \Big/ \left(\frac{c_n\{6\}}{4}\right)^{5/6}$$

$$v_n\{8\}(p_T) = \frac{-d_n\{8\}}{33} \Big/ \left(\frac{-c_n\{8\}}{33}\right)^{7/8}$$

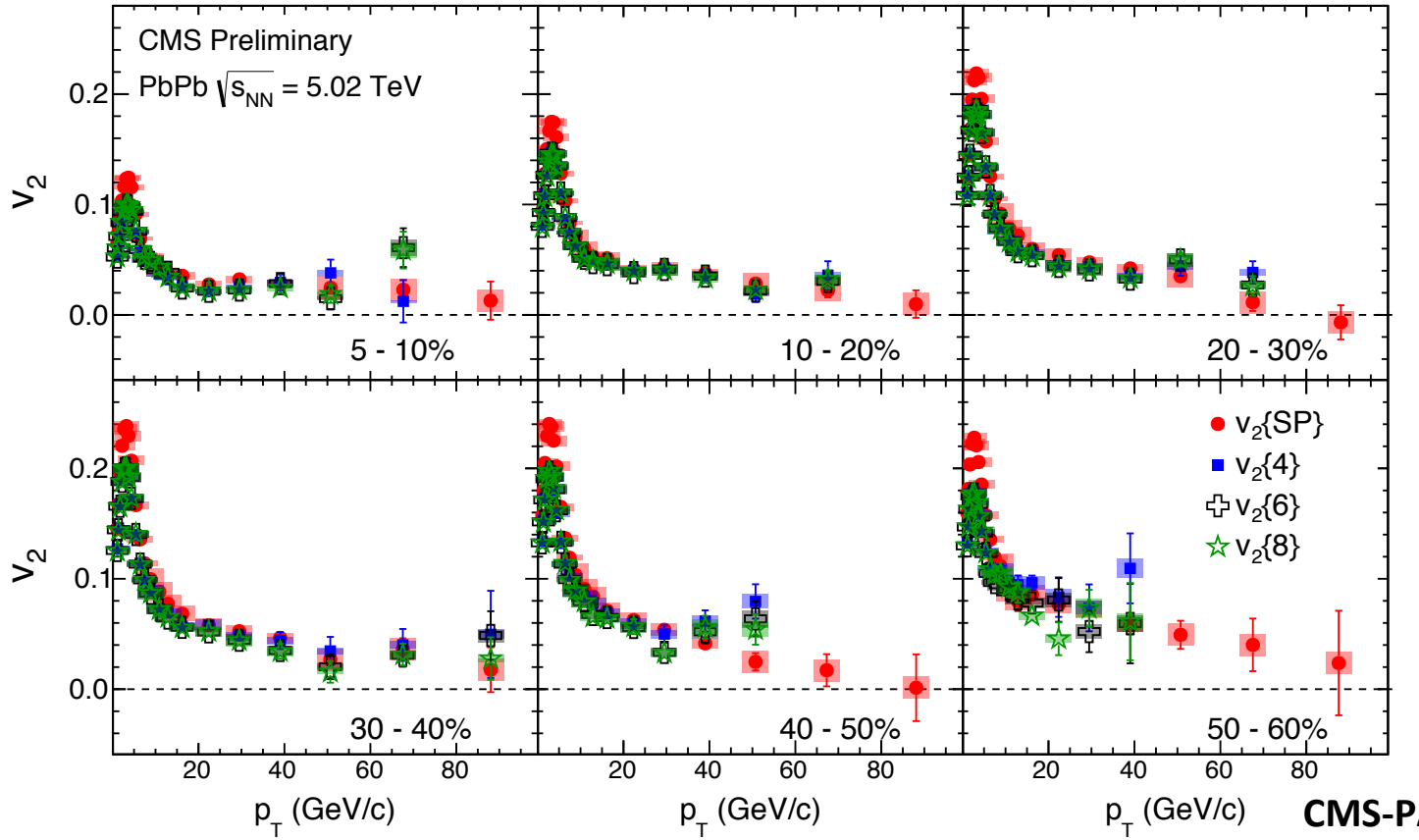
$\boldsymbol{d_n\{m\}}$: 1 particle from POI within given p_T range, m-1 particles from Ref.

Cumulant



- Reference: $|\eta| < 2.4$, $1 < p_T < 5$ GeV/c
- Particle of interest (POI): $|\eta| < 1.0$
- Multi-particle cumulant $v_n\{m\}$
  - Suppress correlations with few particle (<m)

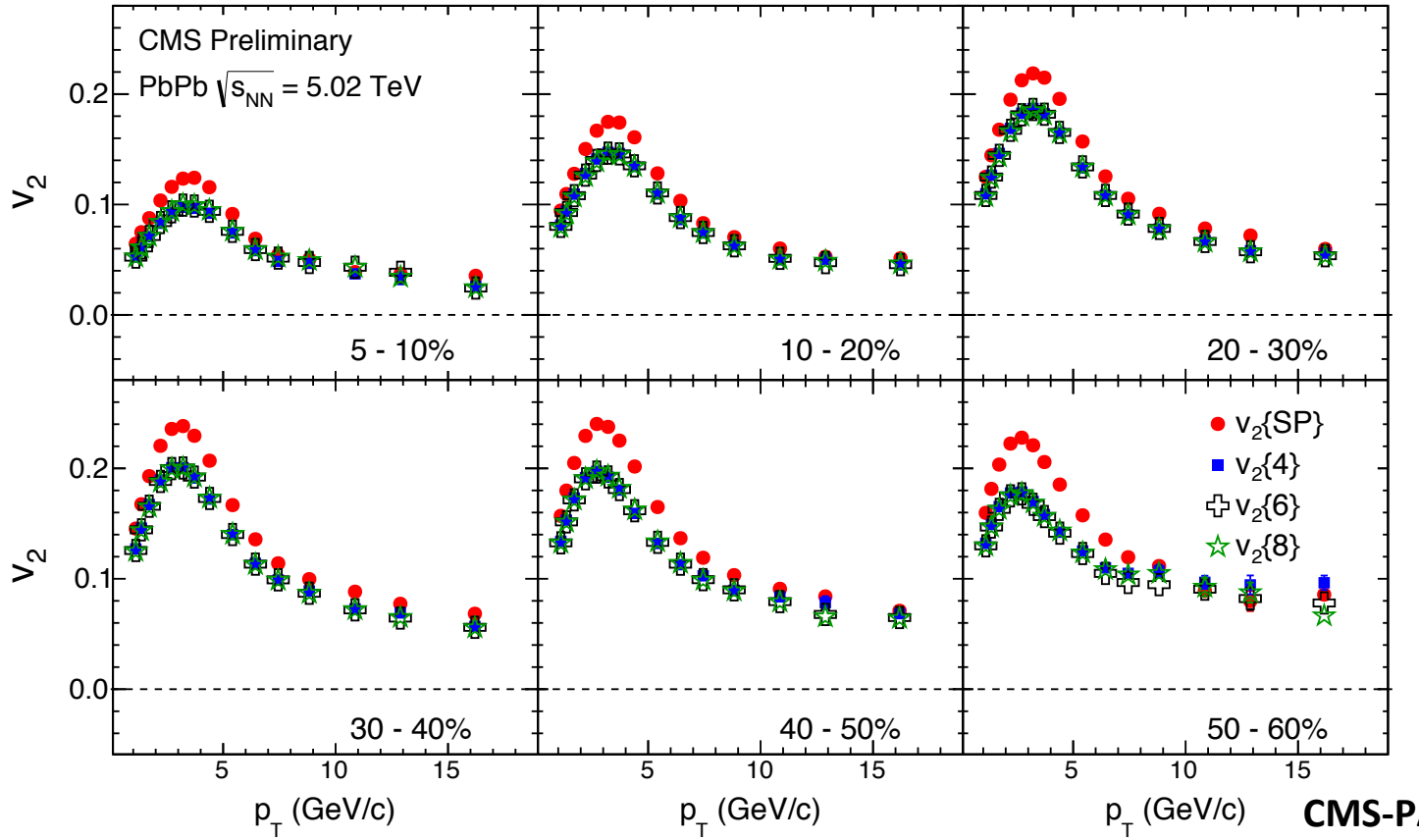
Results – $v_2\{4,6,8\}$



CMS-PAS-HIN-15-014

- FIRST time measure multi-particle $v_2\{4,6,8\}$ up to 100 GeV/c
- Multi-particle $v_2\{4,6,8\}$ seems converge with $v_2\{SP\}$ at high p_T
- Multi-particle nature of high p_T particles – Initial state effect

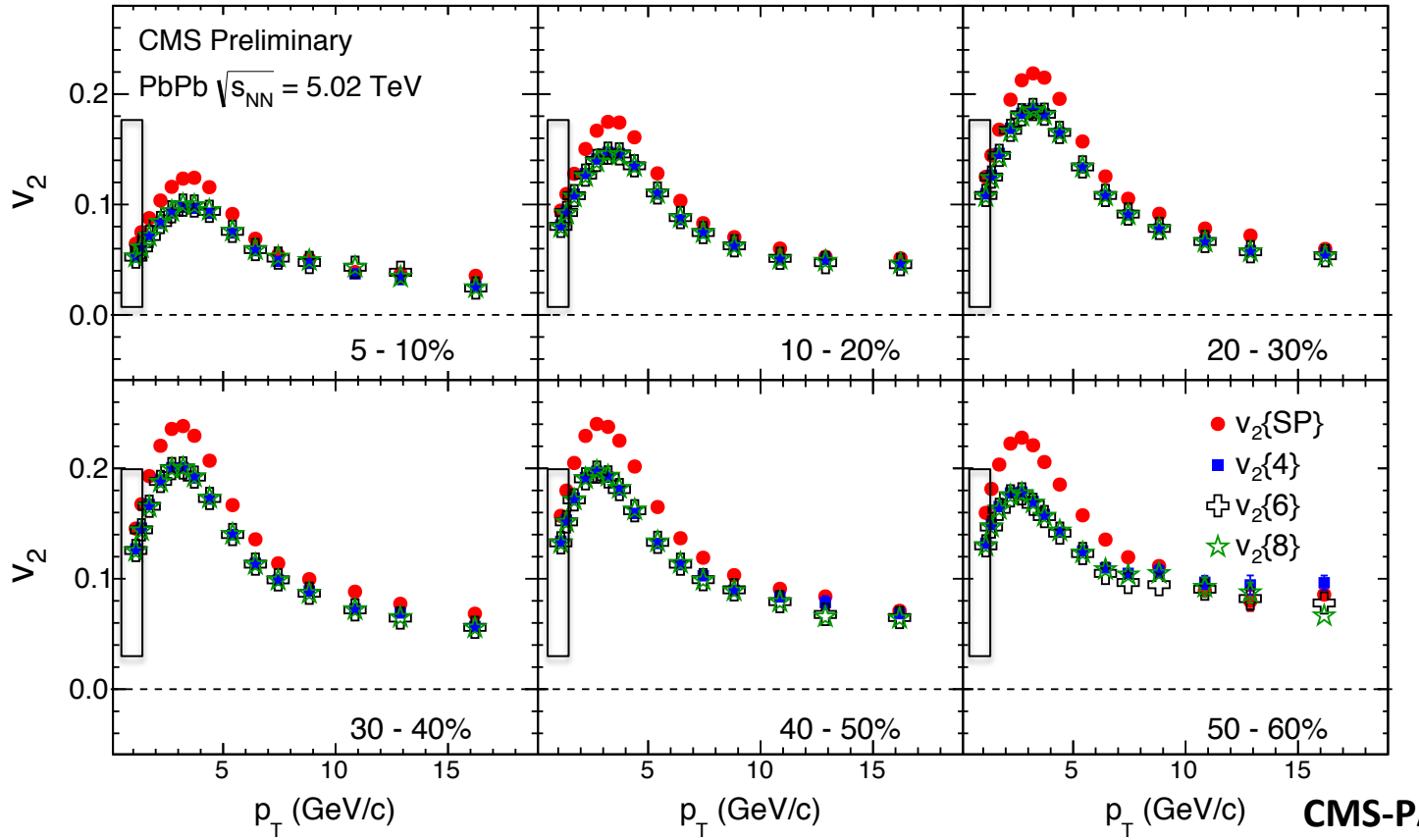
Results – $v_2\{4,6,8\}$



CMS-PAS-HIN-15-014

- Low p_T, $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Expected in hydrodynamics

Results – $v_2\{4,6,8\}$



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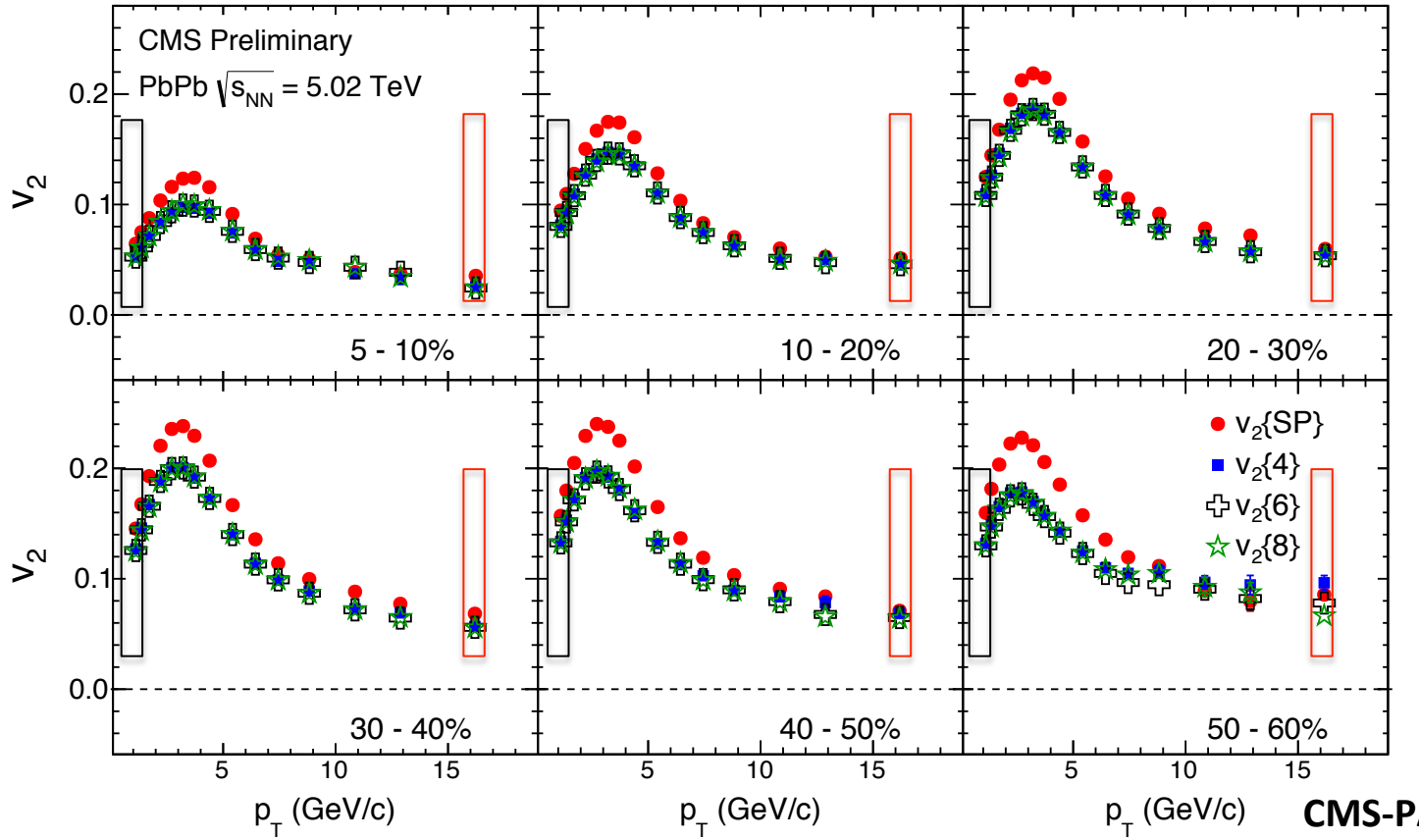

CMS-PAS-HIN-15-014

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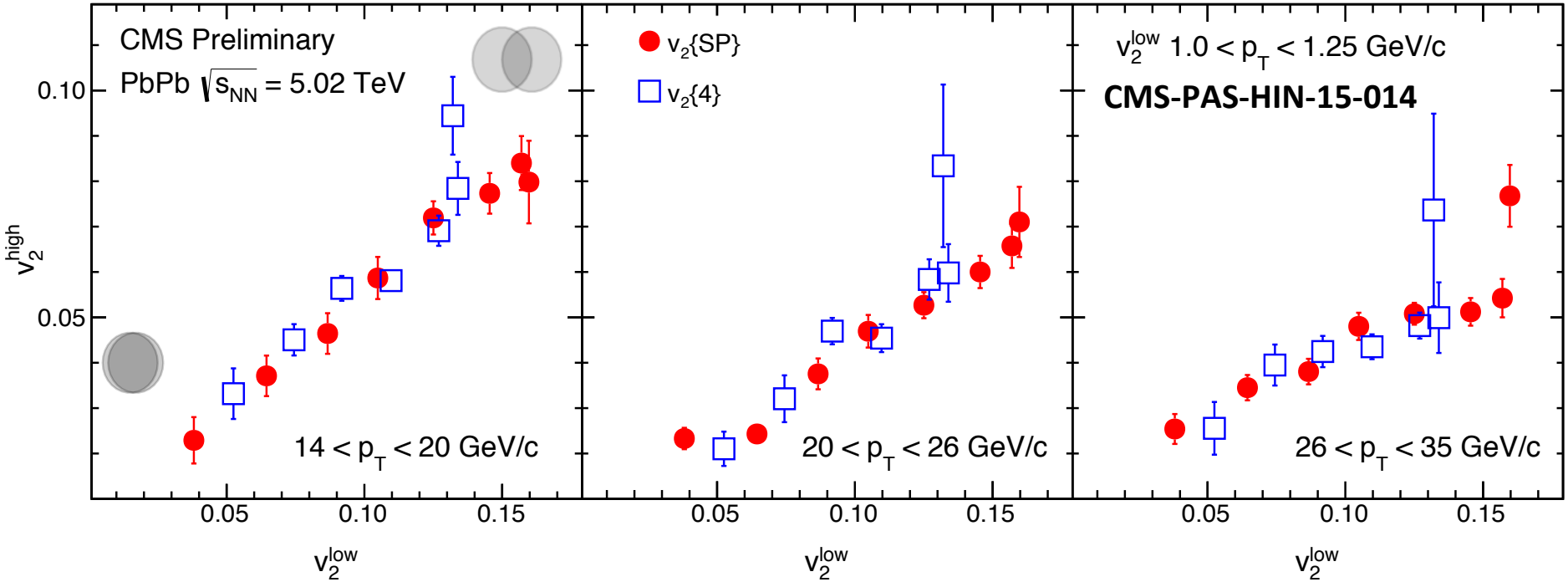
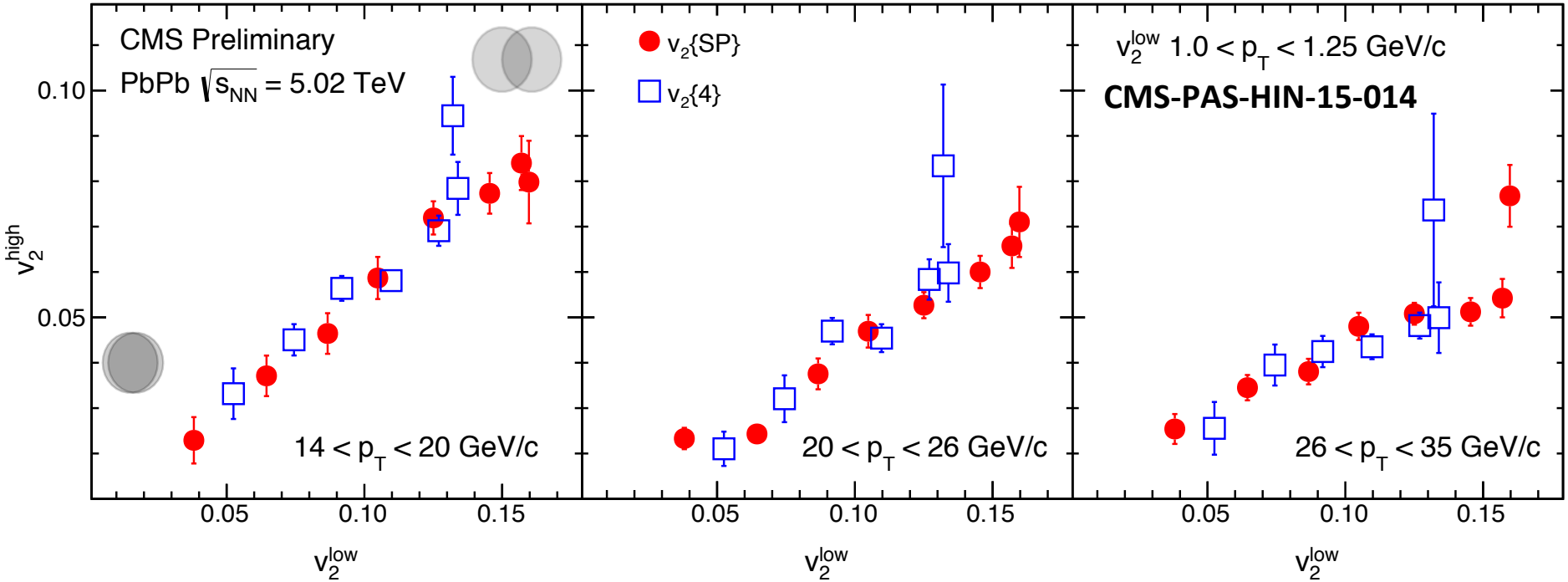
- Expected in hydrodynamics

Results – $v_2\{high\}$ vs $v_2\{low\}$

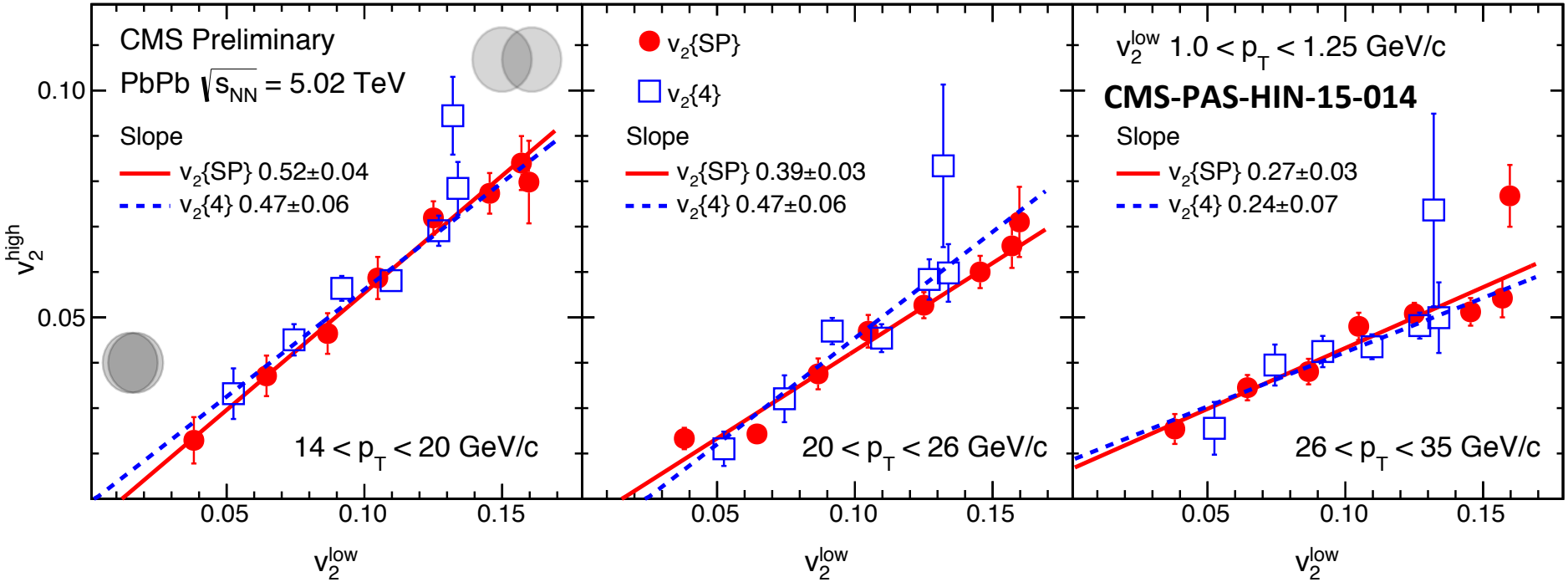


Results – $v_2\{high\}$ vs $v_2\{low\}$



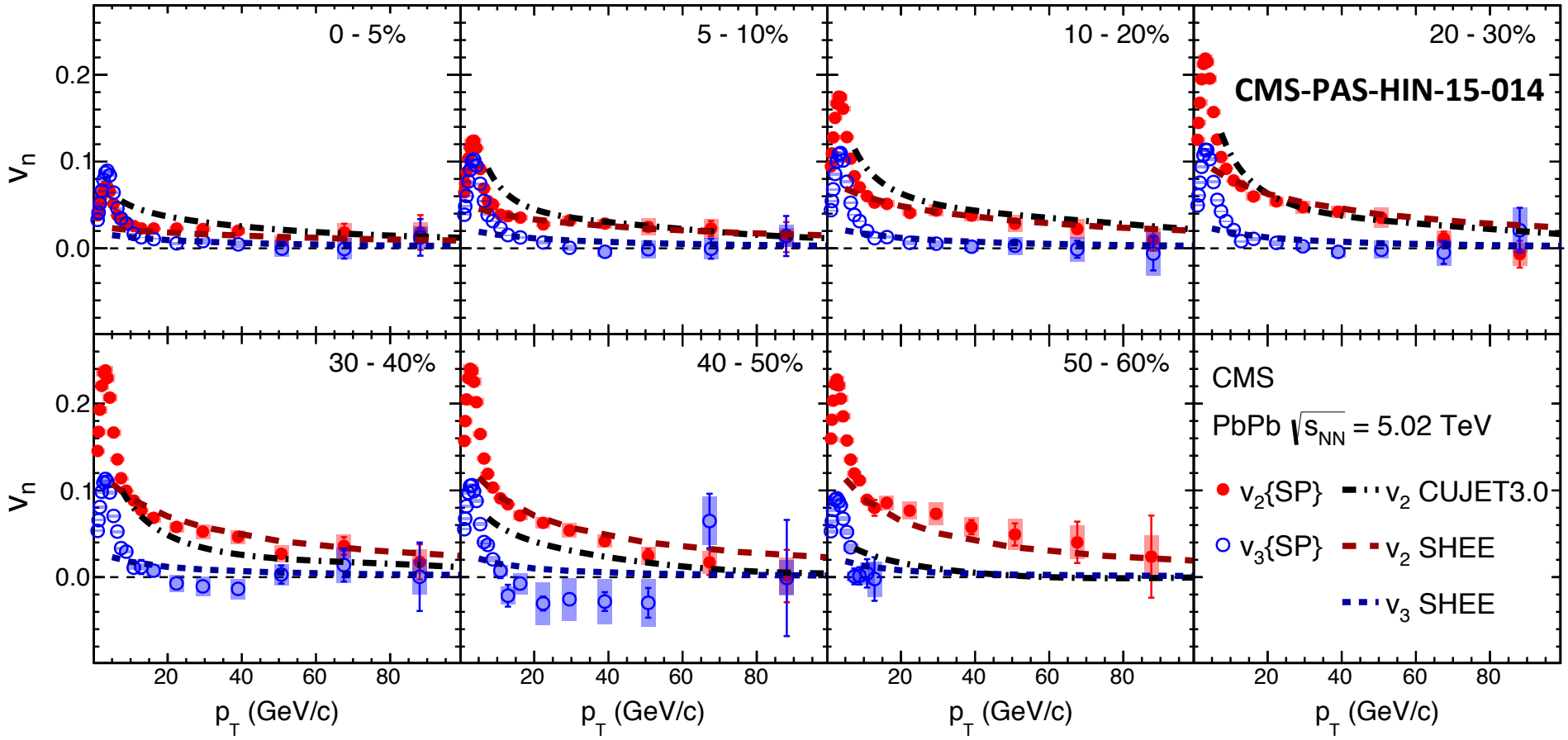
- High p_T v_2 strongly correlated with low p_T v_2
- Suggestion of initial state effect

Results – $v_2\{high\}$ vs $v_2\{low\}$



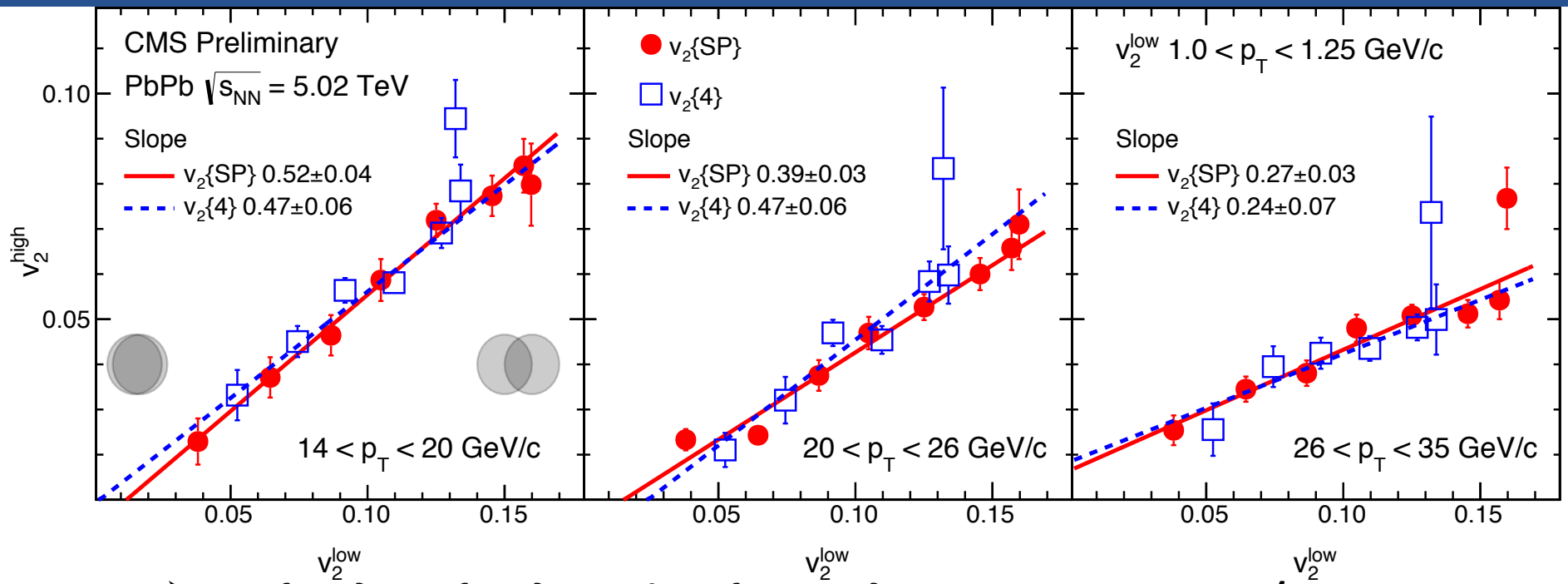
- High p_T v_2 strongly correlated with low p_T v_2
- Suggestion of initial state effect
- Slope decrease while increasing p_T

Results – Compare to Models



- CUJET3.0 fails over full p_T and centrality dependence
  - JHEP **02** (2016) 169
- SHEE with linear energy loss has good agreement
  - arXiv:1609.05171

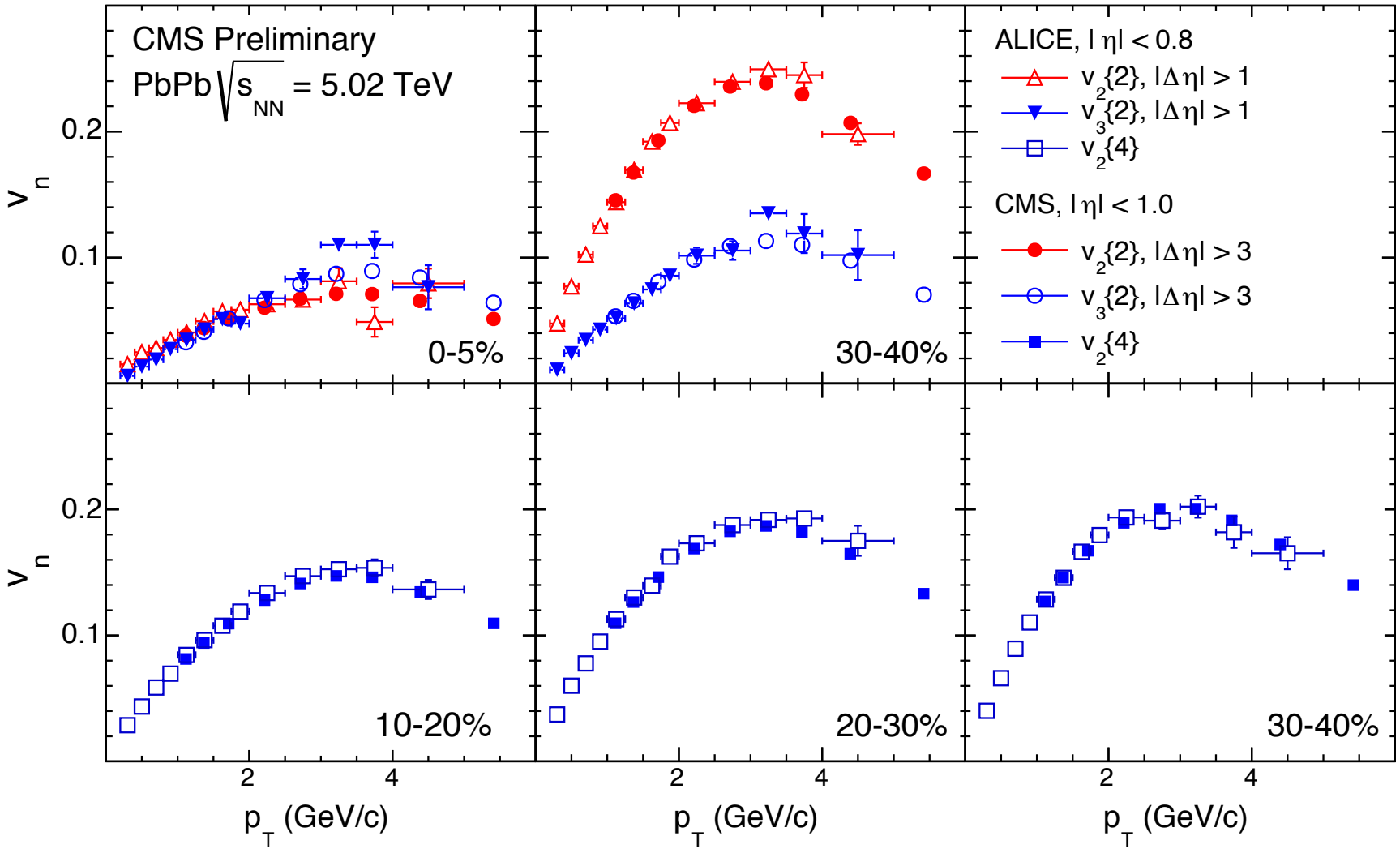
Summary



- $v_2\{SP\}$, $v_3\{SP\}$ and $v_2\{4,6,8\}$ up to 100 GeV/c
- Non-zero v_2 observed at very high p_T
- $v_2\{4,6,8\}$ show multi-particle nature at high p_T
- $v_3\{SP\}$ is consistent with zero for $p_T > 30$ GeV/c
- Strongly correlated high p_T v_2 and low p_T v_2

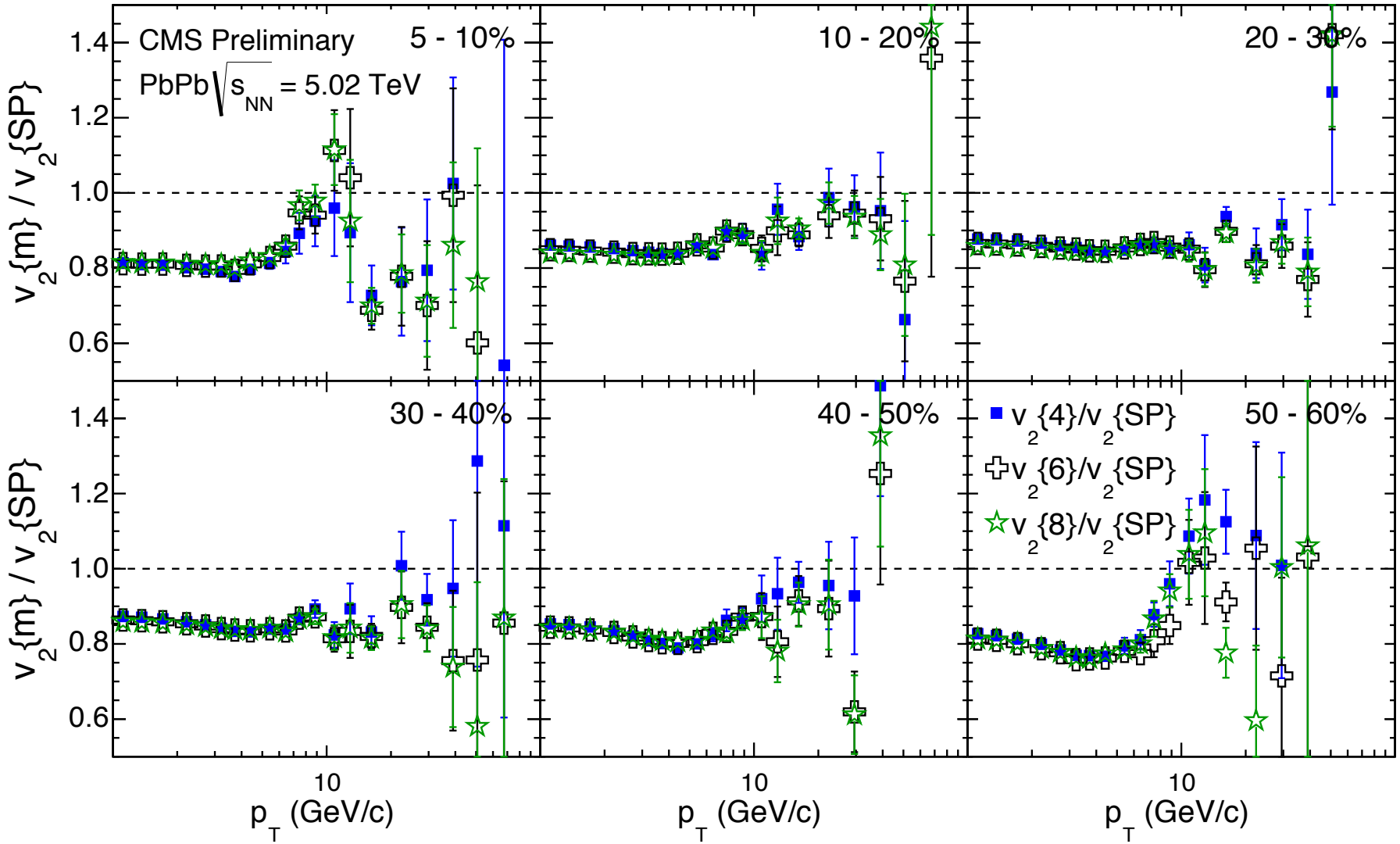
Backup

Compare to ALICE



Phys.Rev.Lett. 116 (2016) 132302

Ratio


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
5 - 10%
10 - 20%
20 - 30%
30 - 40%
40 - 50%
50 - 60%
$v_2\{4\}/v_2\{SP\}$
$v_2\{6\}/v_2\{SP\}$
$v_2\{8\}/v_2\{SP\}$
$v_2\{m\} / v_2\{SP\}$
p_T (GeV/c)
1.4
1.2
1.0
0.8
0.6
10