

High- p_T v_n Harmonics in PbPb Collisions at 5.02 TeV



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for the CMS Collaboration

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Motivation

- Flow harmonics v_n

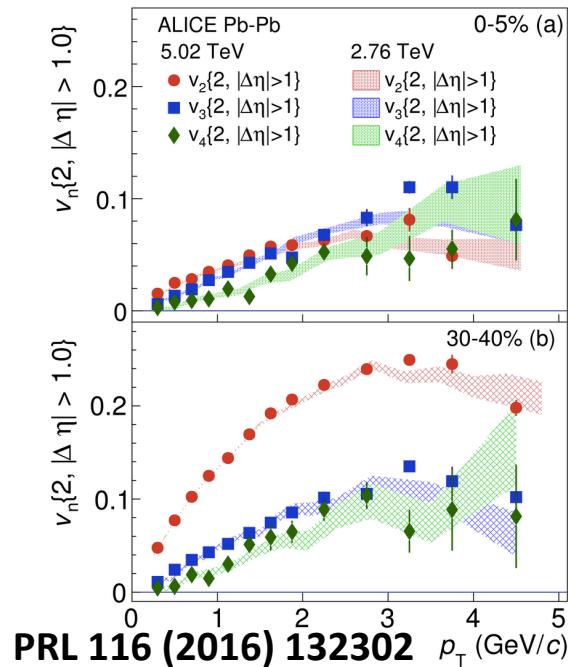
$$\frac{dN(p_T)}{d\phi} \propto 1 + \sum v_n(p_T) \cos[n(\phi - \Psi_n)]$$

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- Low p_T
 - Collectivity, hydrodynamics
 - Geometry + fluctuations

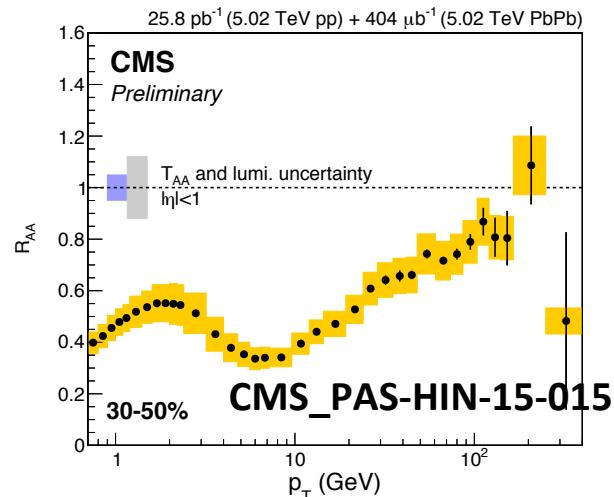
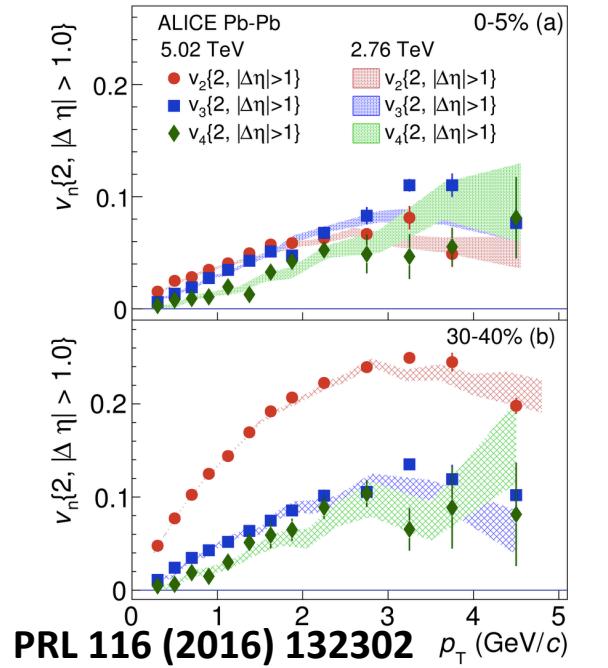


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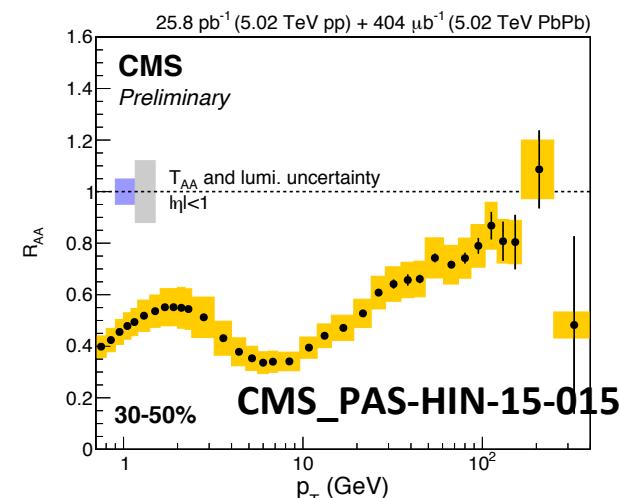
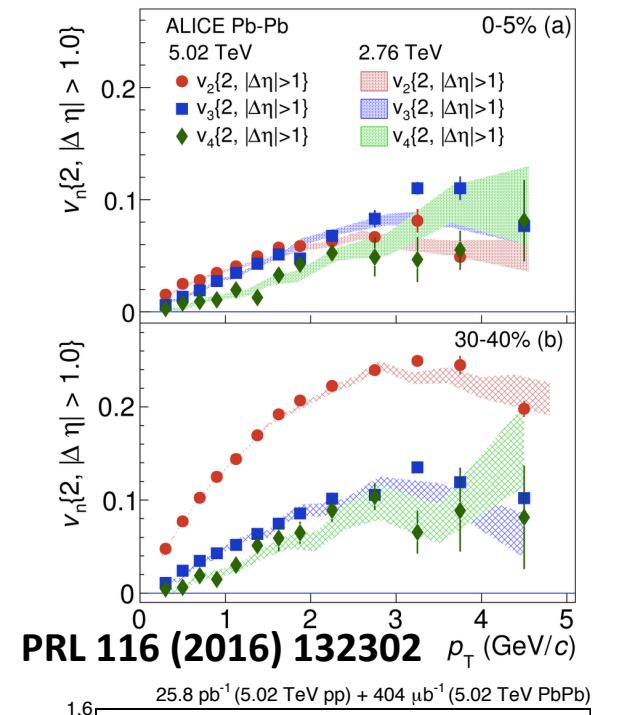
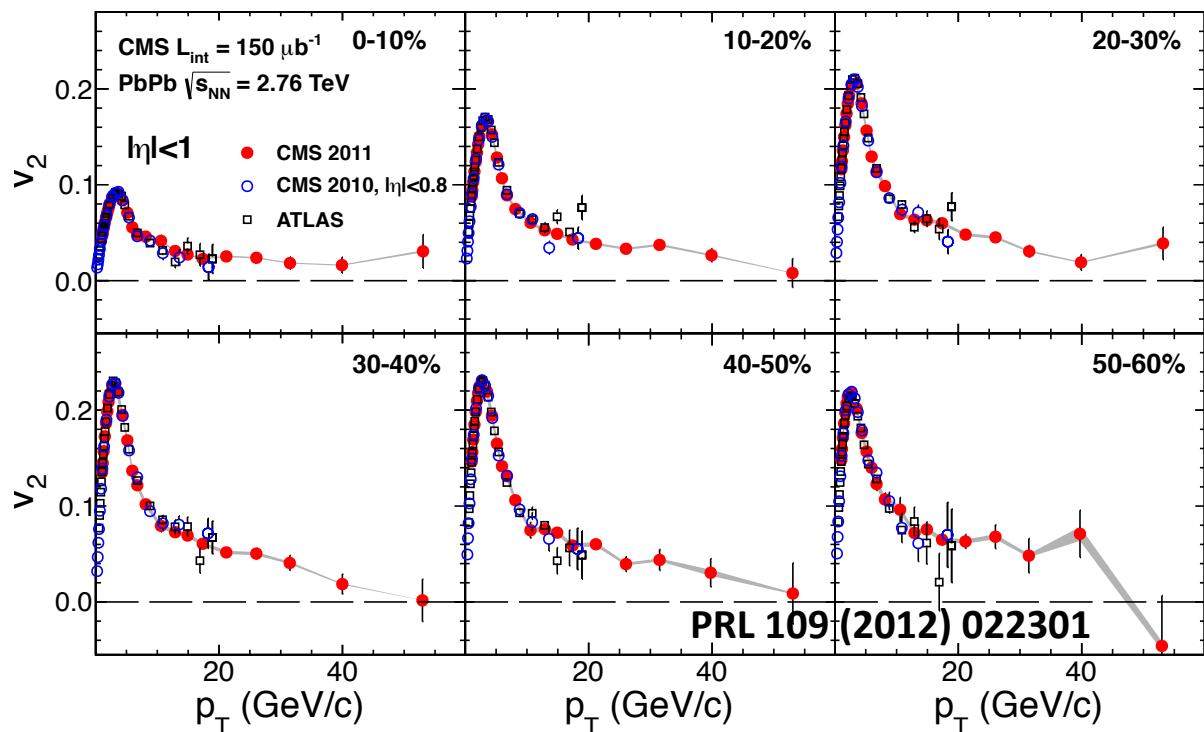
- ## ➤ Flow harmonics v_n

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

- Low p_T
 - Collectivity, hydrodynamics
 - Geometry + fluctuations
 - High p_T
 - Path length dep. energy loss
 - R_{AA} : average energy loss

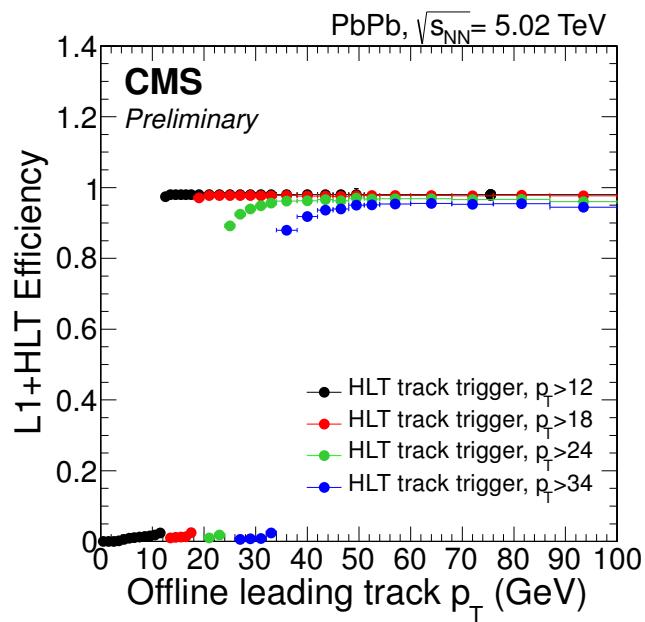
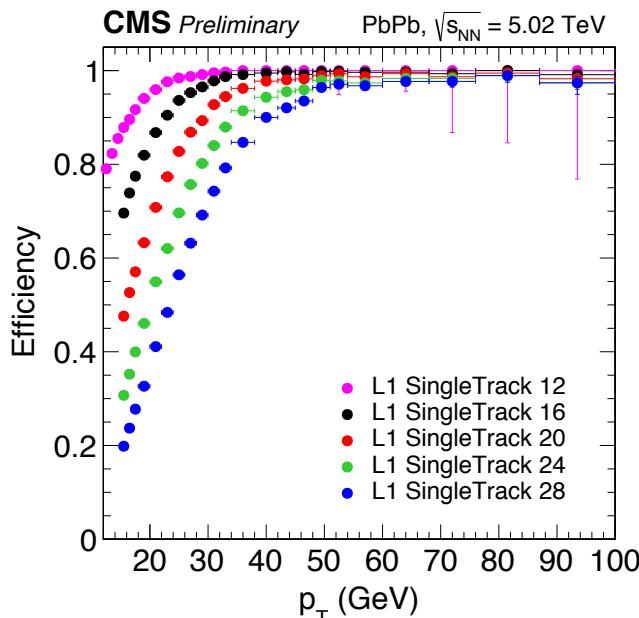


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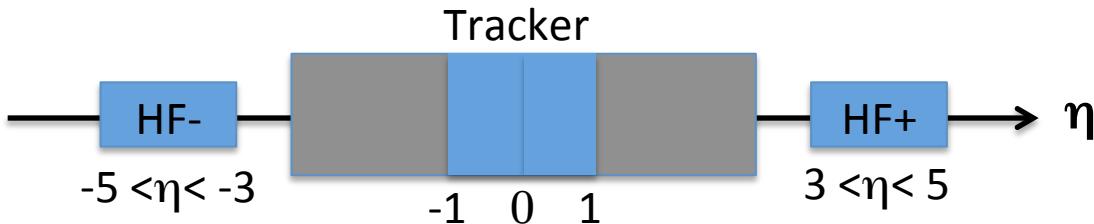


Dataset

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



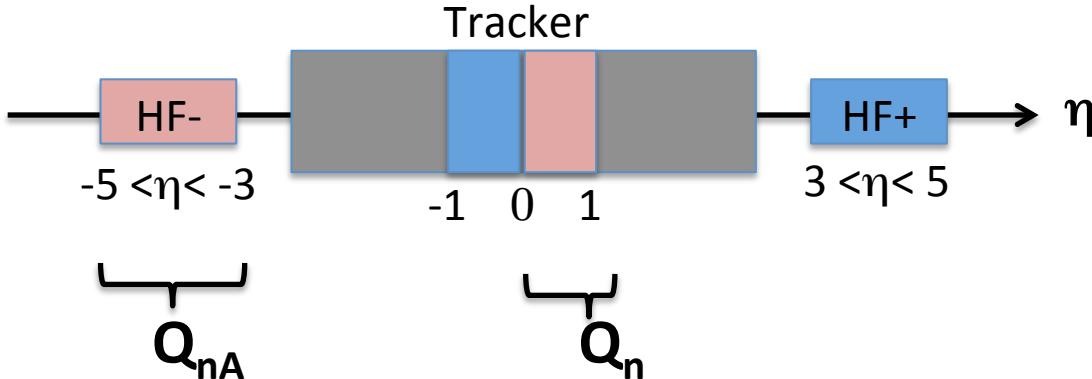
Scalar Product



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

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

Scalar Product



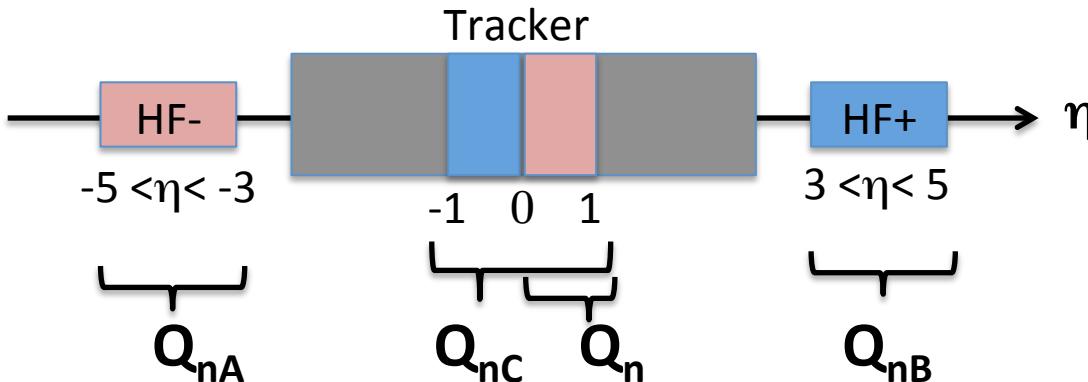
$$Q_n = \sum_j w_j e^{in\phi_j}$$

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

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

- Large η gap applied ($|\Delta\eta| > 3.0$)

Scalar Product



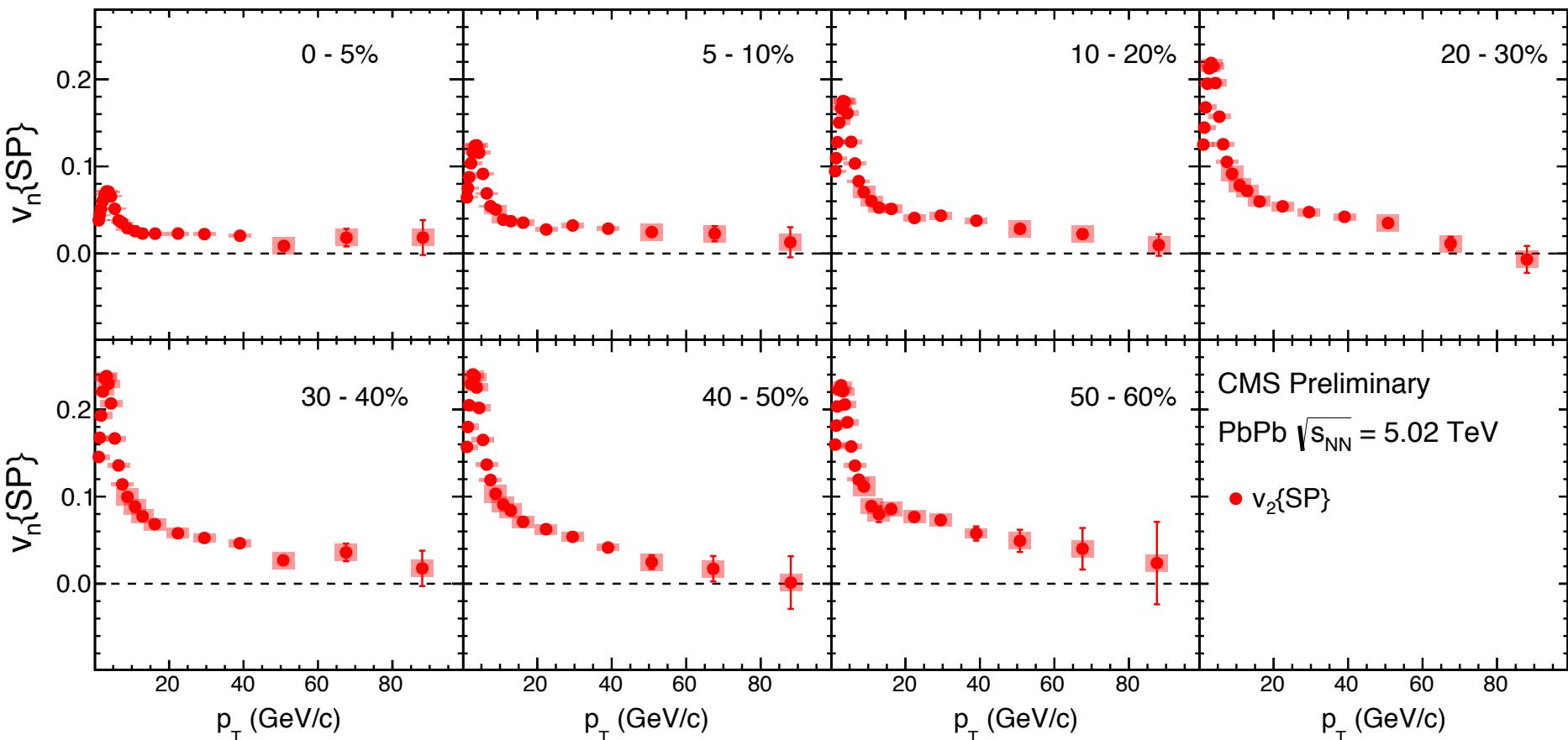
$$Q_n = \sum_j w_j e^{in\phi_j}$$

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

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

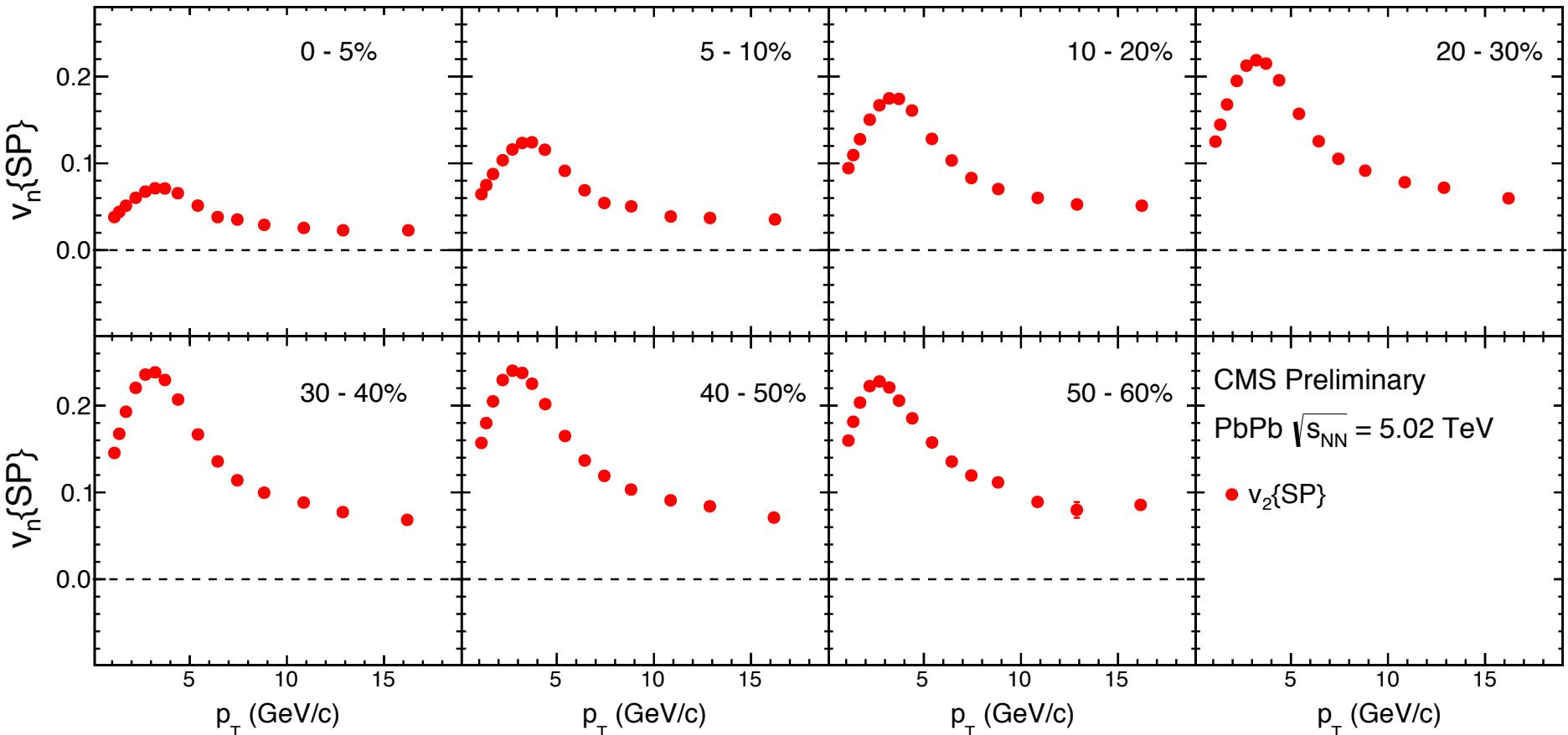
- Large η gap applied ($|\Delta\eta| > 3.0$)
- $\nu_n \{SP\}$, non-ambiguous measure of RMS ν_n

Results (I)



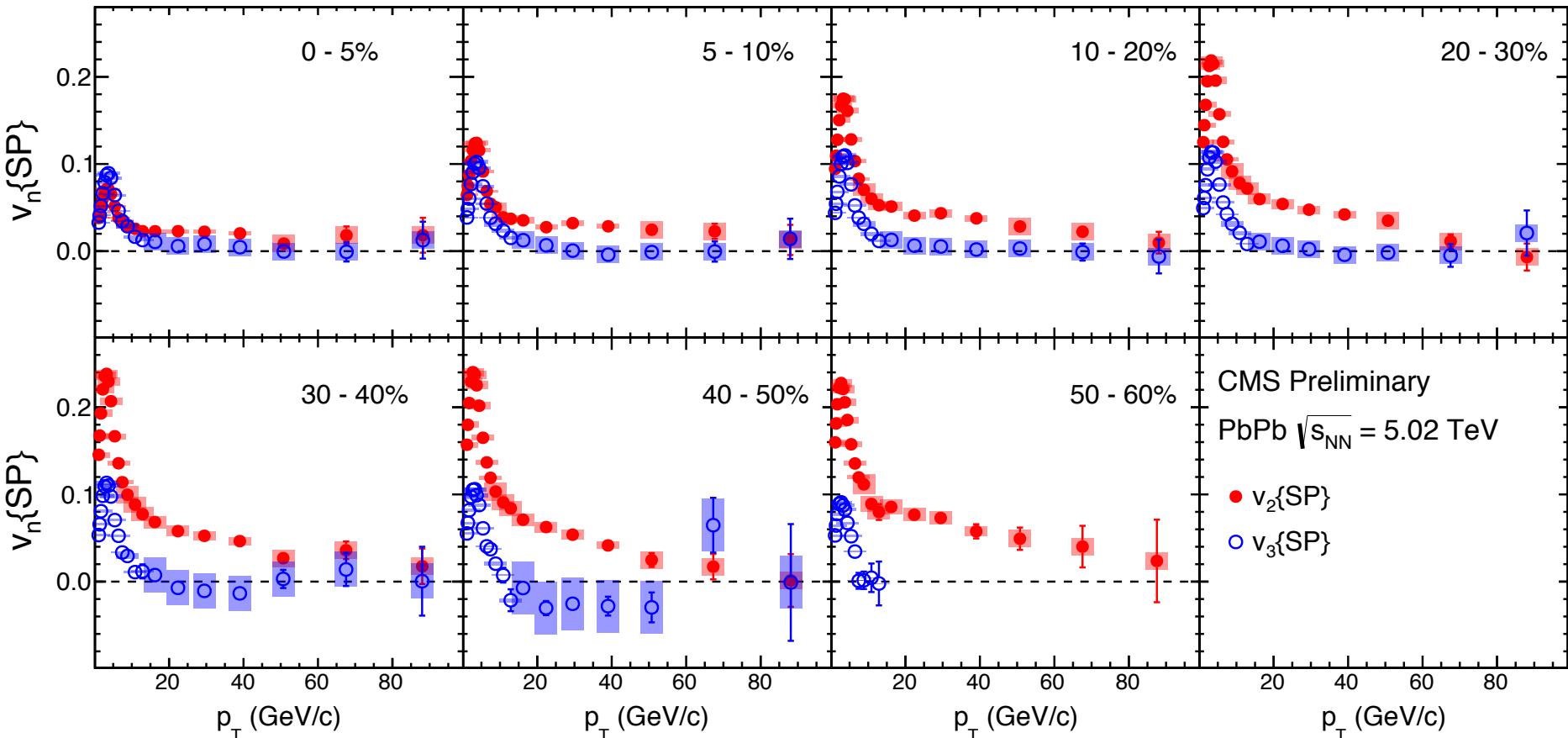
- FIRST time measure of $v_2\{\text{SP}\}$ up to 100 GeV/c
- $v_2\{\text{SP}\}$ remains positive at very high p_T

Results (I)



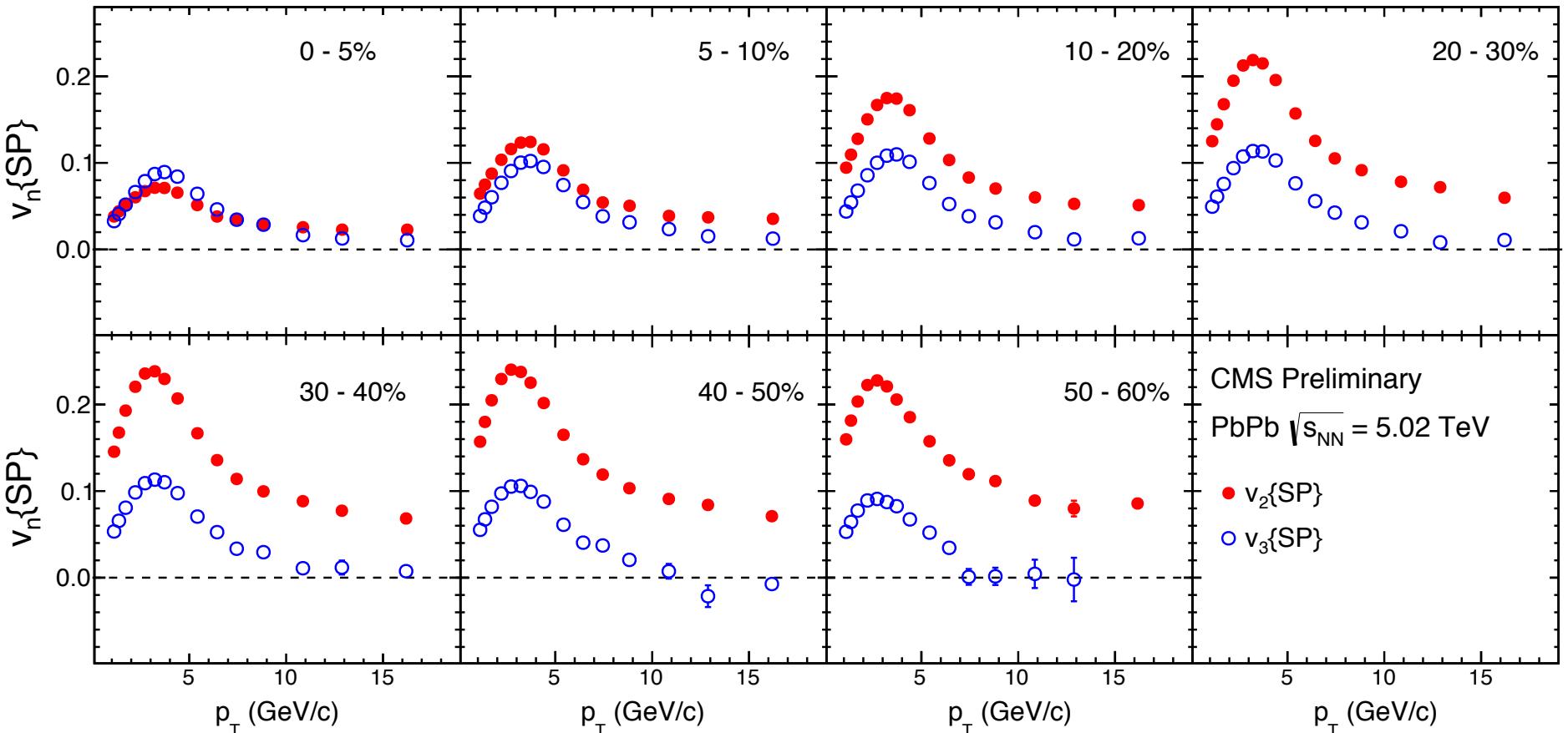
- Low p_T v_2 increase from most-central to mid-central, then decrease
- v_2 increase with p_T , peaked ~ 3 GeV/c, decrease while increasing p_T

Results (I)



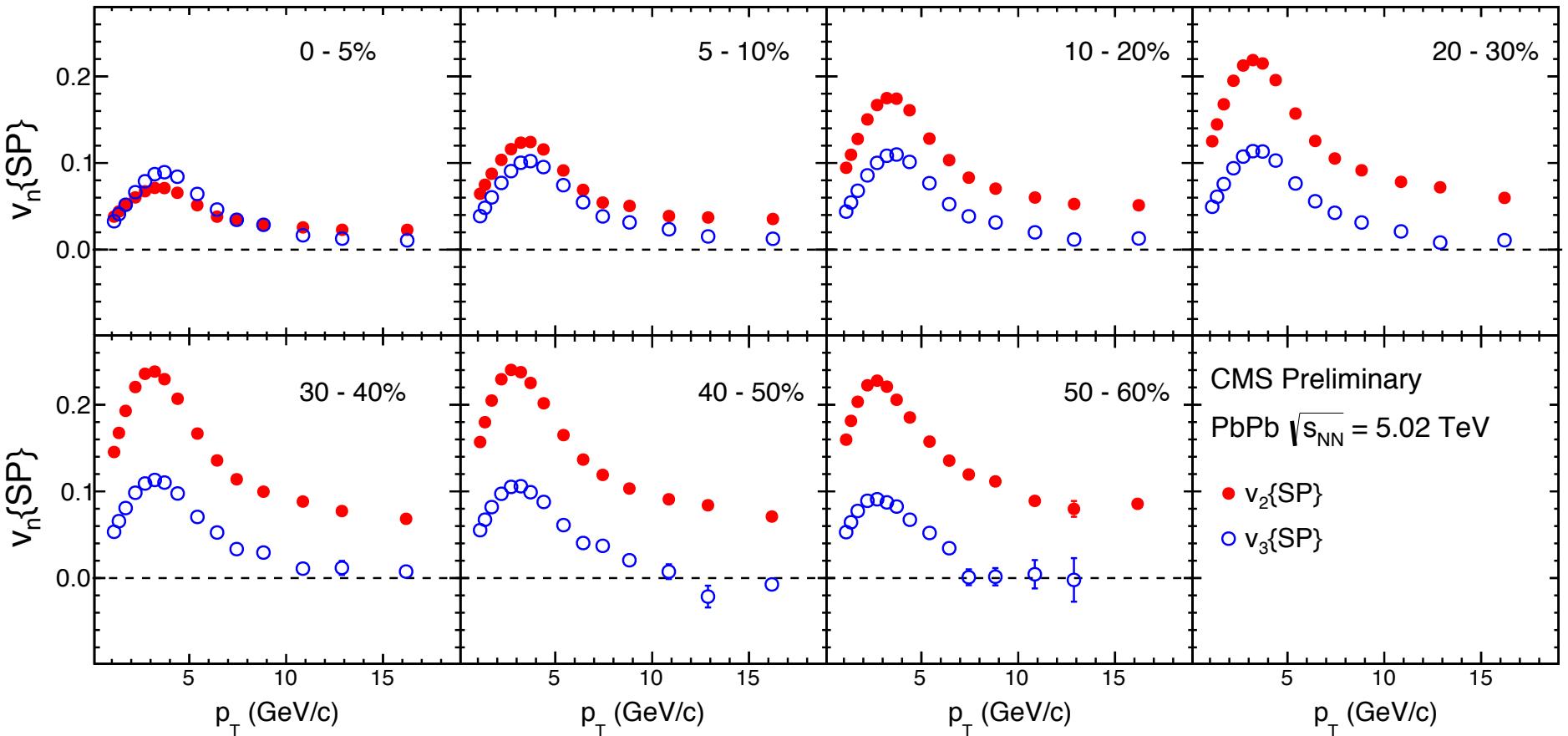
- FIRST time measure of $v_3\{\text{SP}\}$ up to 100 GeV/c
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Results (I)



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- Little centrality dependence for v_3

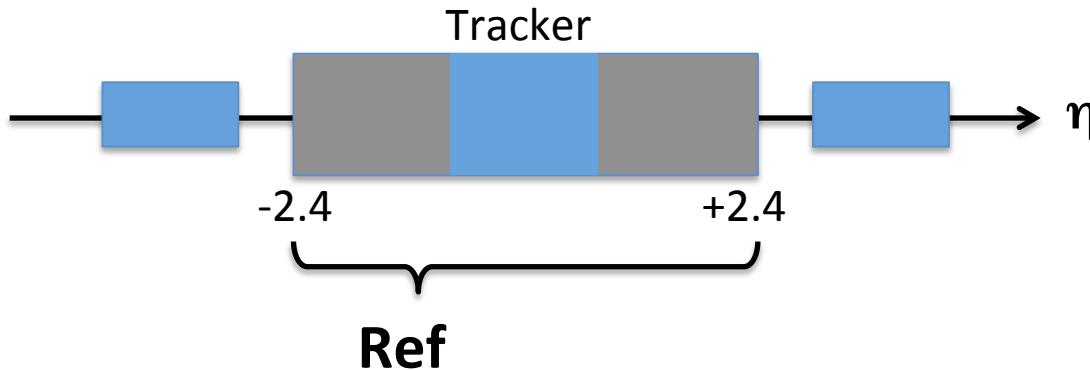
Results (I)



- FIRST time measure of $v_3\{\text{SP}\}$ up to 100 GeV/c
- Consistent with 0 for $p_T > 20 \text{ GeV}/c$
- Little centrality dependence for v_3

Collective at high p_T ?

Cumulant



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

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

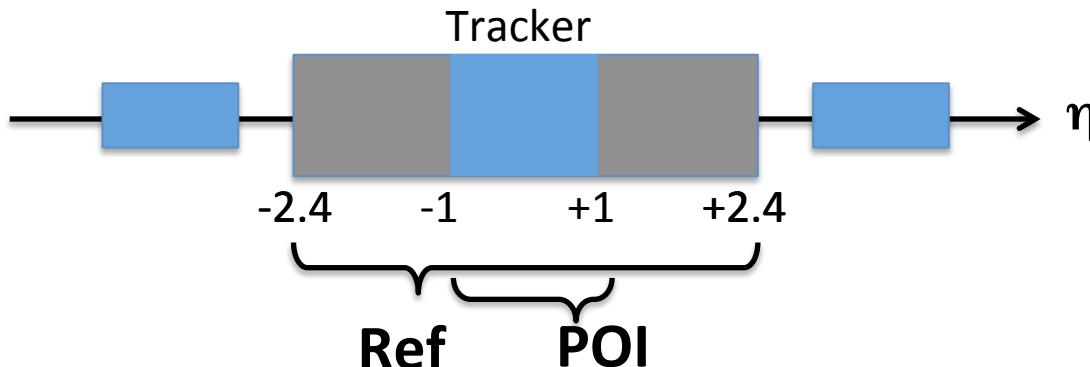
$$v_n\{6\} = \sqrt[6]{c_n\{6\} / 4}$$

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

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

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

Cumulant



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

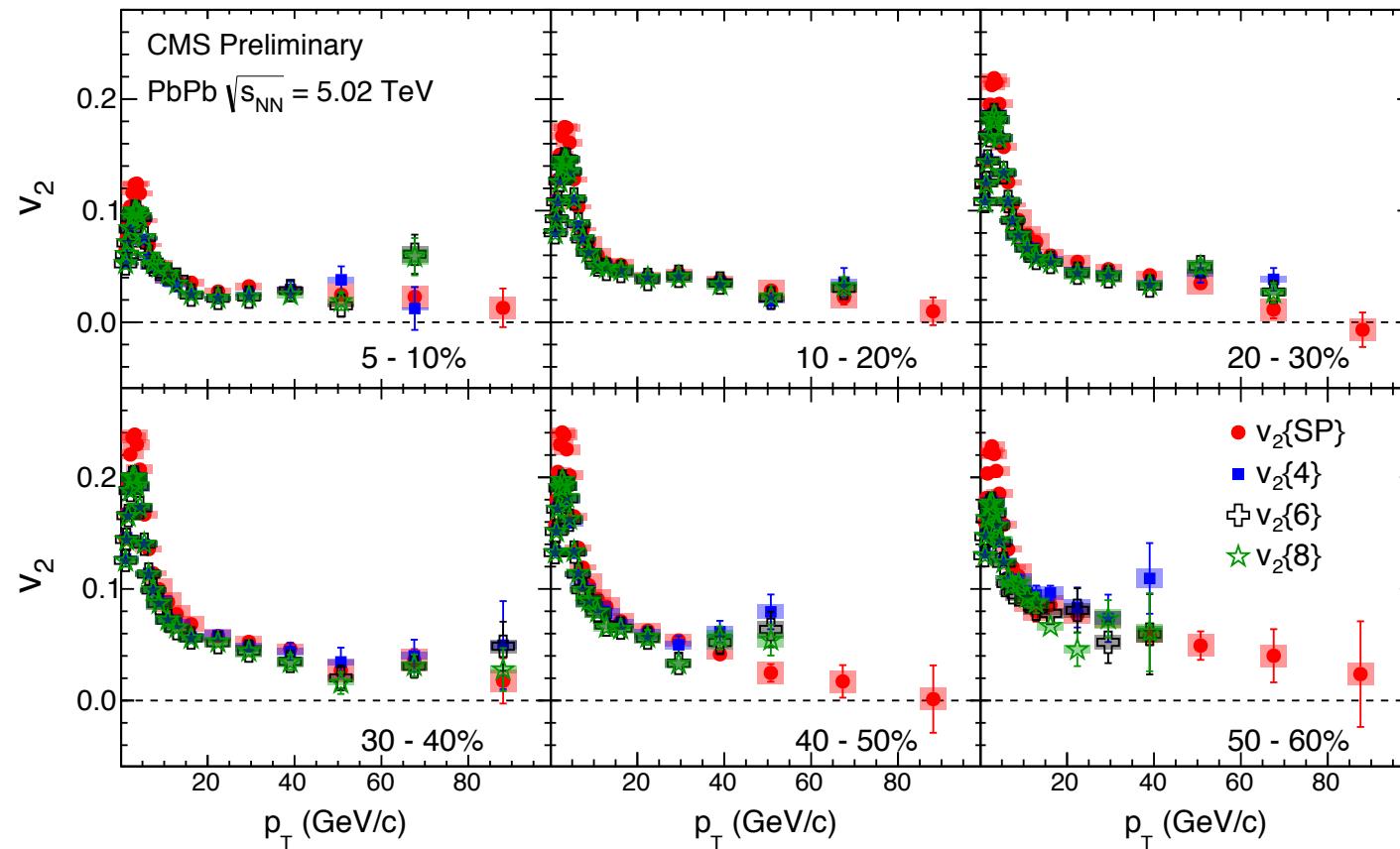
$$v_n\{4\}(p_T) = -d_n\{4\} / (-c_n\{4\})^{3/4}$$

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

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

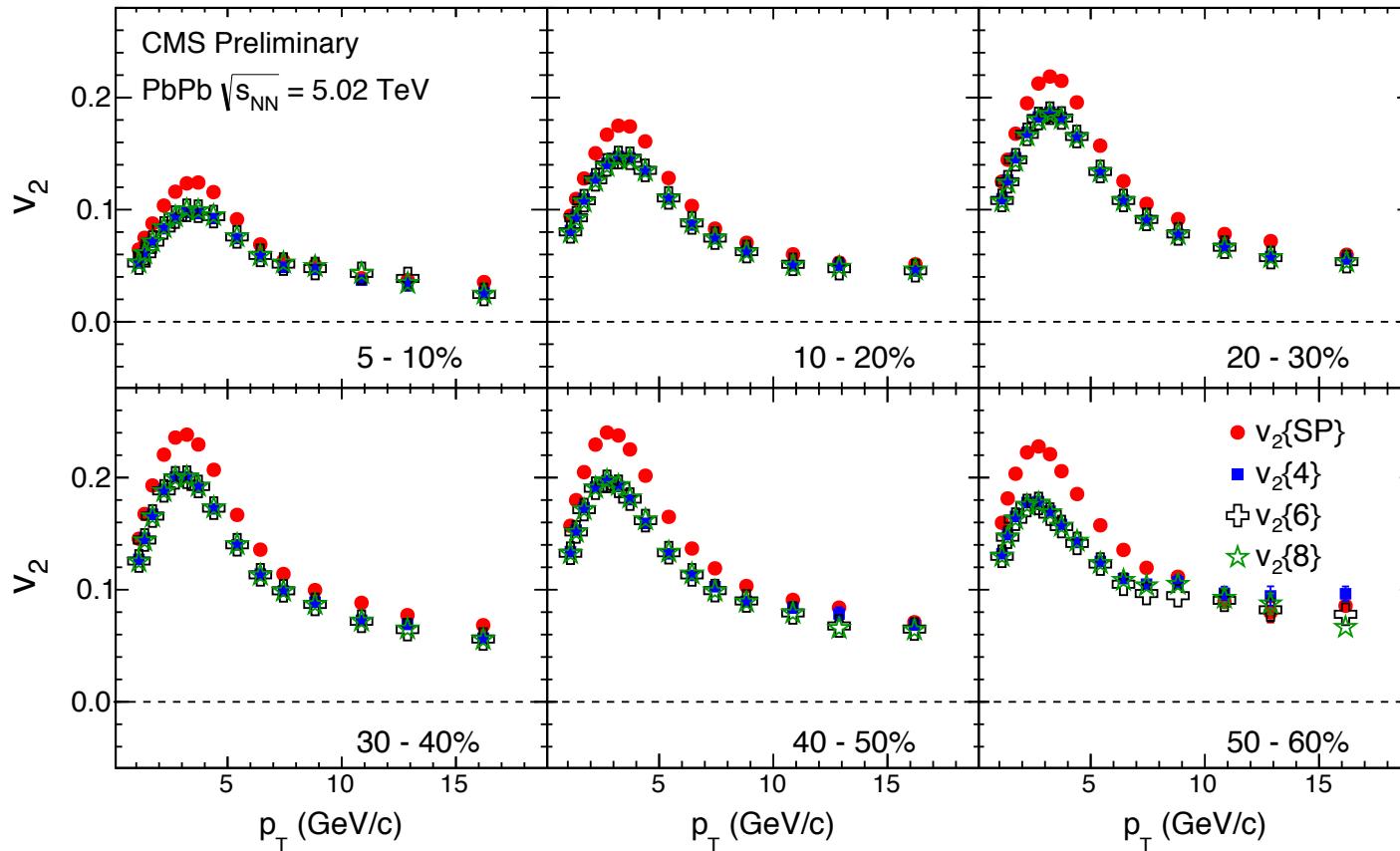
$d_n\{m\}$: 1 particle from POI
within given p_T range,
 $m-1$ particles from Ref.

Results (II)



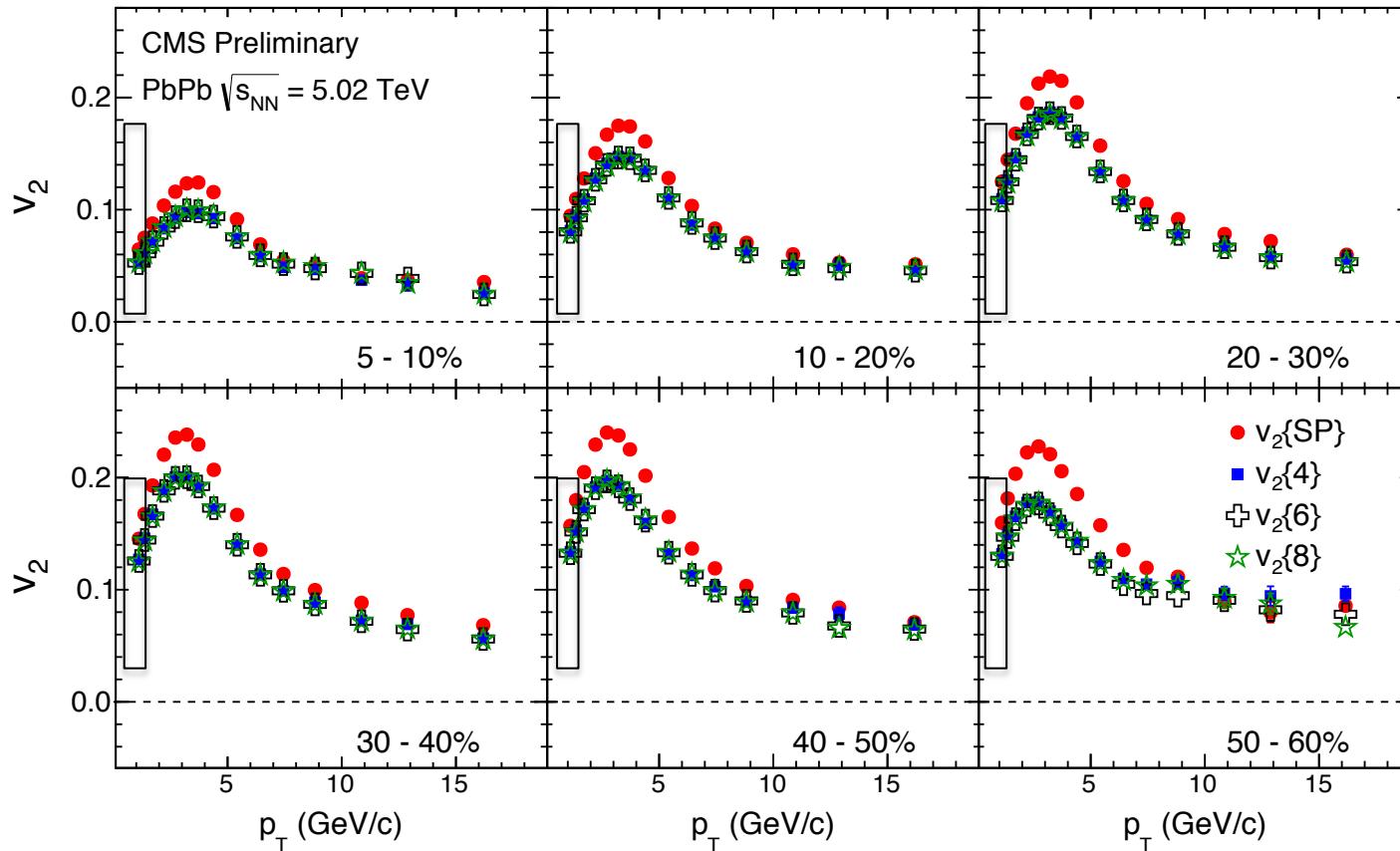
- FIRST time measure multi-particle $v_2\{4,6,8\}$ up to 100 GeV/c
- Multi-particle $v_2\{4,6,8\}$ seems converge with $v_2\{\text{SP}\}$ at high p_T
- Collective nature of high p_T particles

Results (II)



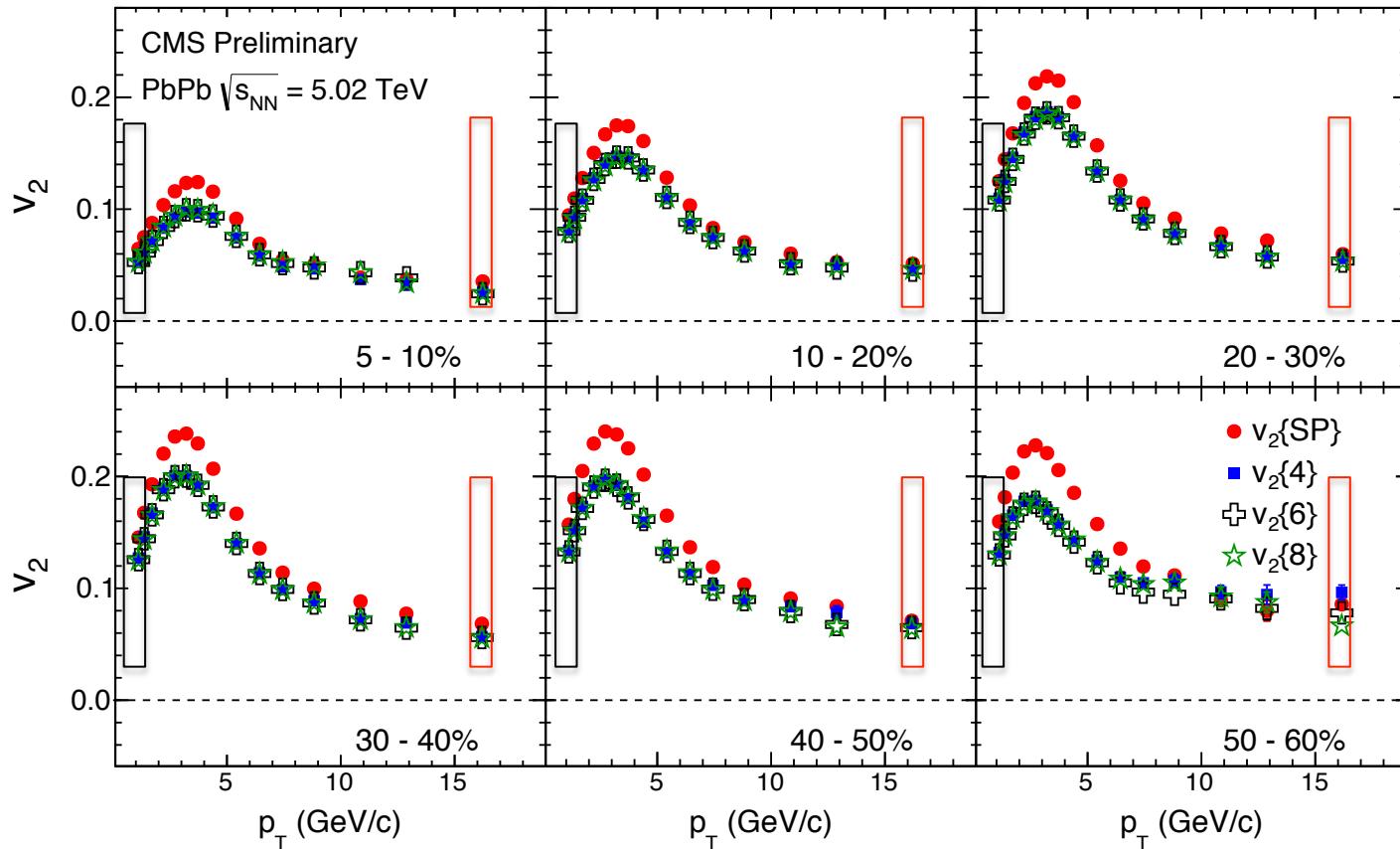
- Low p_T , $v_2\{\text{SP}\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Expected in hydrodynamics

Results (II)



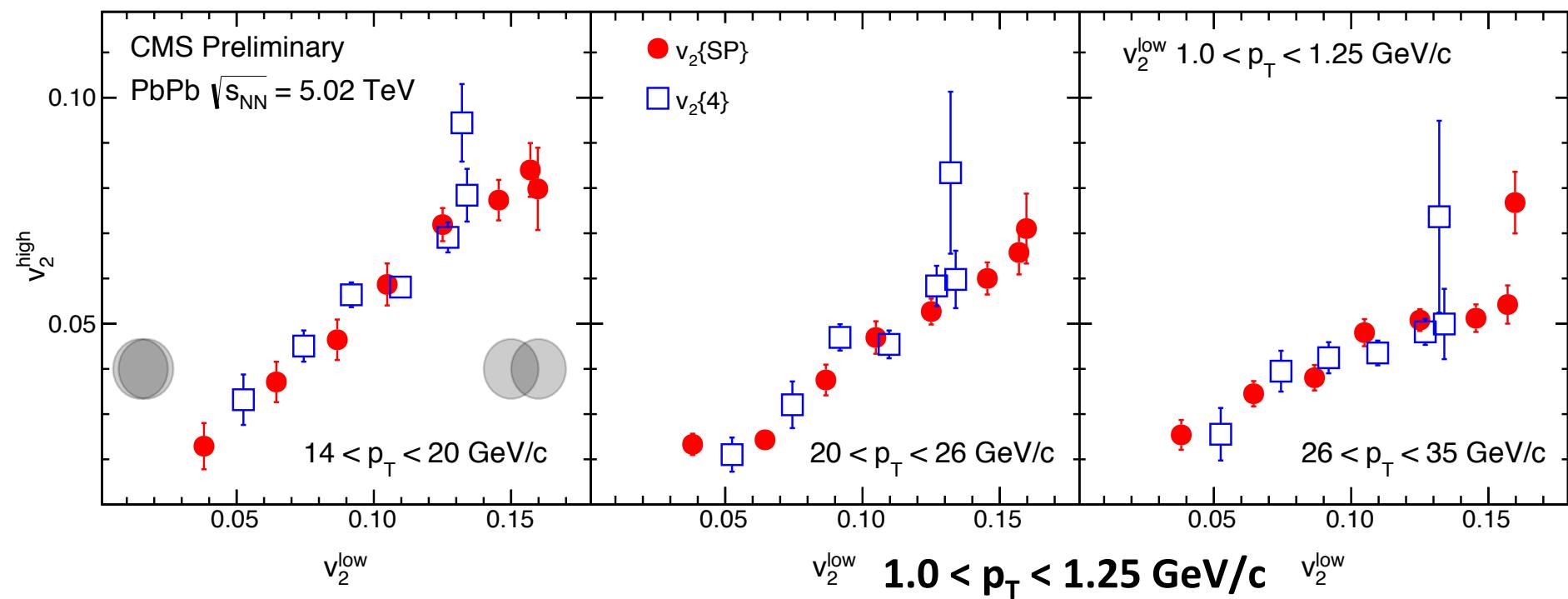
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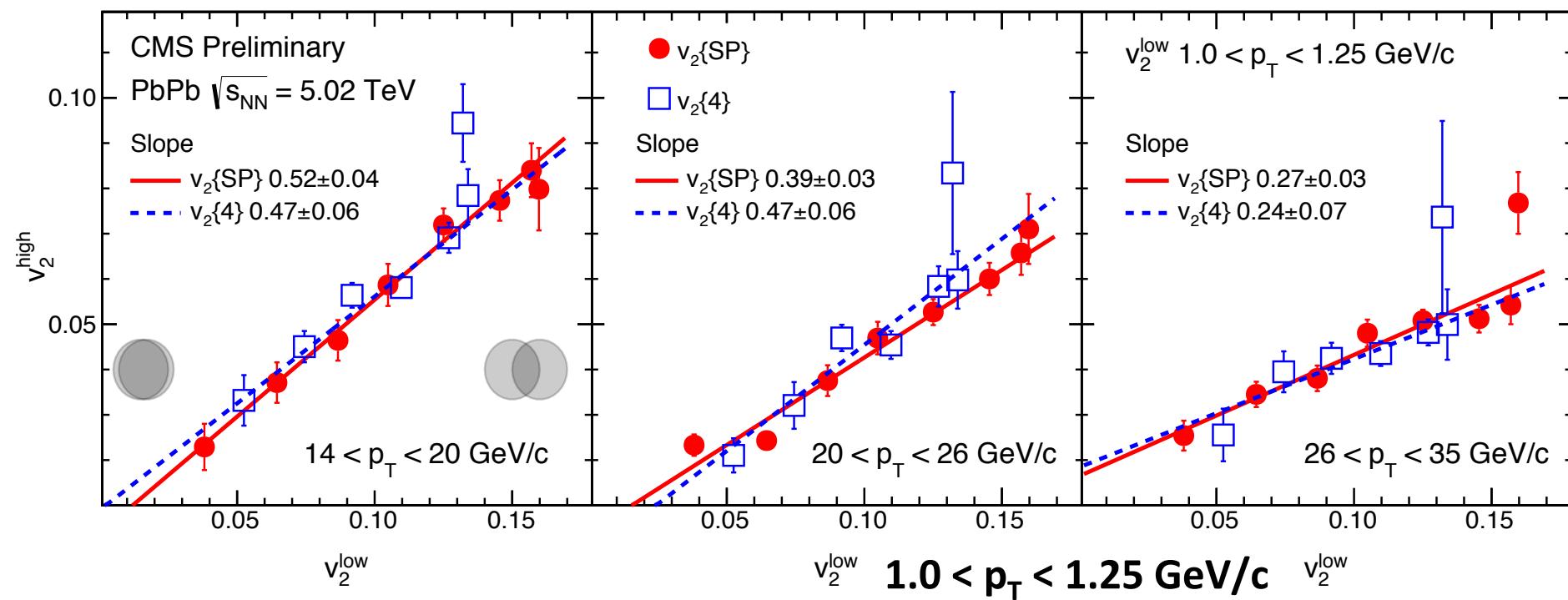
- Low p_T , $v_2\{\text{SP}\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
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Results (III)



- High p_T v_2 strongly correlated with low p_T v_2
- Suggestion of same origin of the correlations

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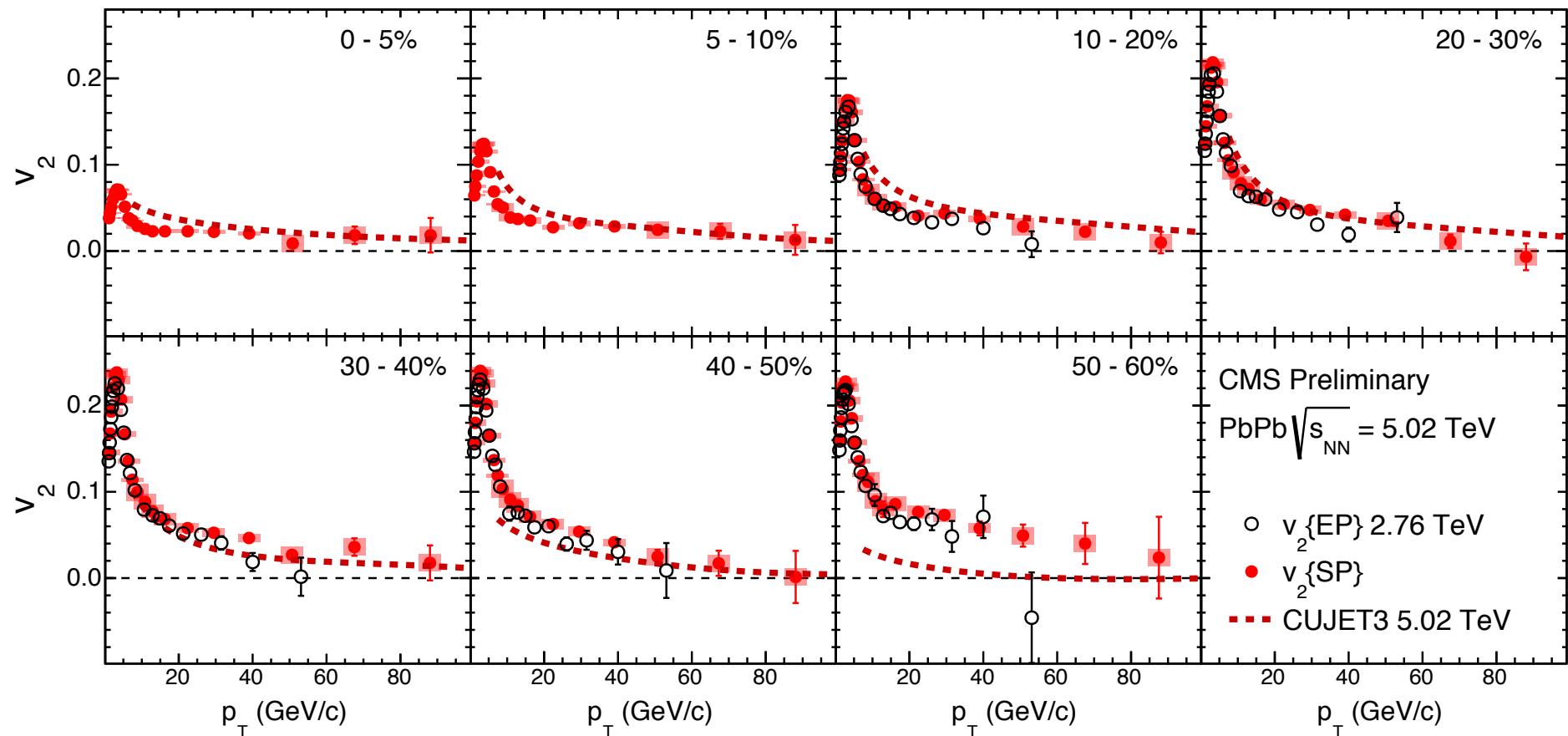
- High p_T v2 strongly correlated with low p_T v_2
 - Suggestion of same origin of the correlations
 - Slope decrease while increasing p_T

Summary

- For the first time, $v_2\{\text{SP}\}$, $v_3\{\text{SP}\}$ and $v_2\{4,6,8\}$ are measured p_T up to 100 GeV/c in PbPb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
- Non-zero v_2 observed at very high p_T
- Multi-particle $v_2\{4,6,8\}$ show collective nature of high p_T particles
- $v_3\{\text{SP}\}$ is consistent with zero for $p_T > 20 \text{ GeV/c}$
- High $p_T v_2$ strongly correlated with low $p_T v_2$ suggesting same origin of the correlation
- ✓ <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN>

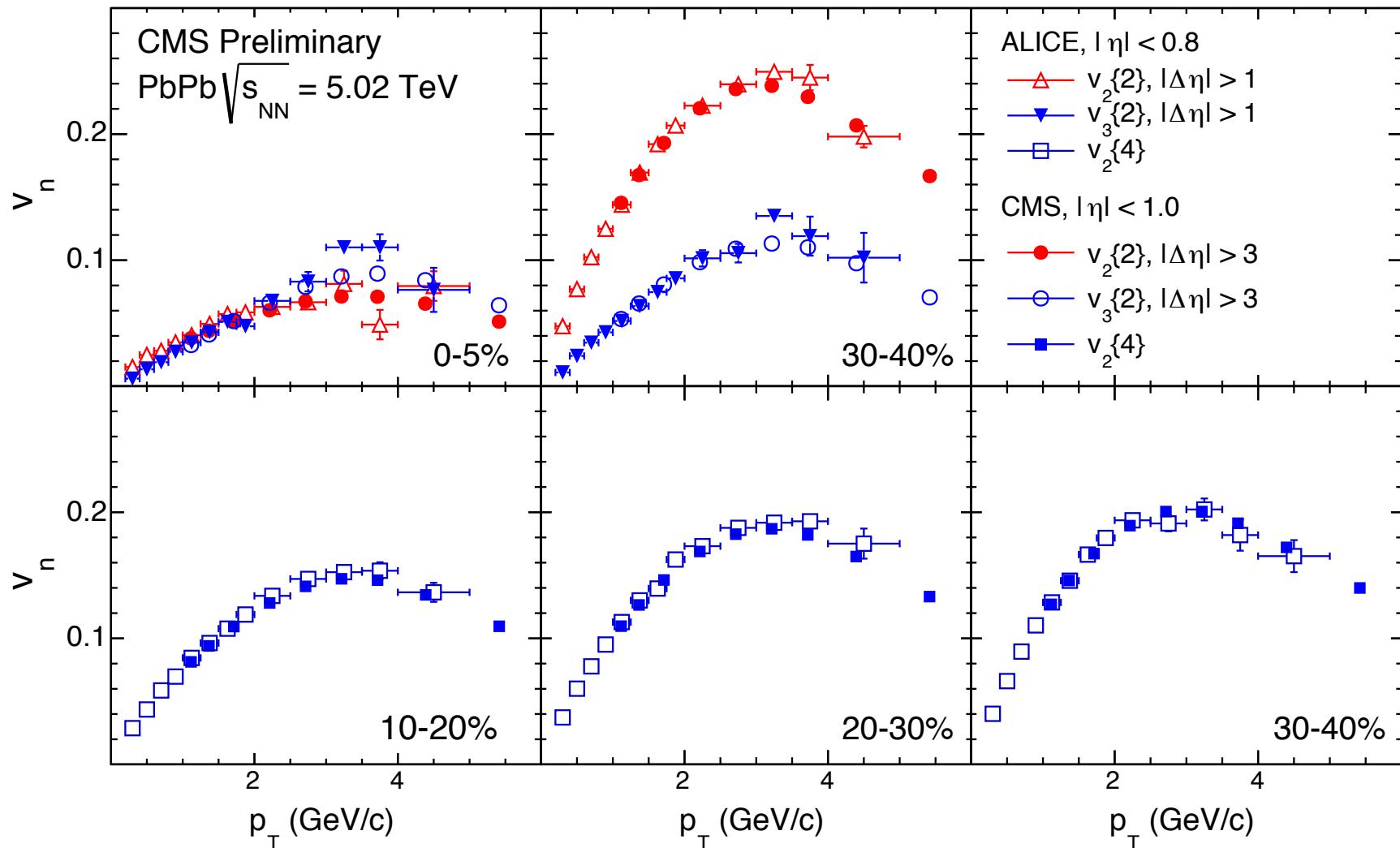
Backup

Theory Comparison



$v_2^{\{\text{EP}\}} 2.76 \text{ TeV}: \text{PRL 109 (2012) 022301}$
 CUJET3: JHEP 1602 (2016) 169

Compare to ALICE



Phys.Rev.Lett. 116 (2016) 132302

Ratio

