# News on Collectivity in PbPb Collisions at CMS

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**(Chonnam National University)**
***For the CMS Collaboration***

*International Symposium on Multiparticle Dynamics 2016 @ Seogwipo Jeju*

29th August, 2016

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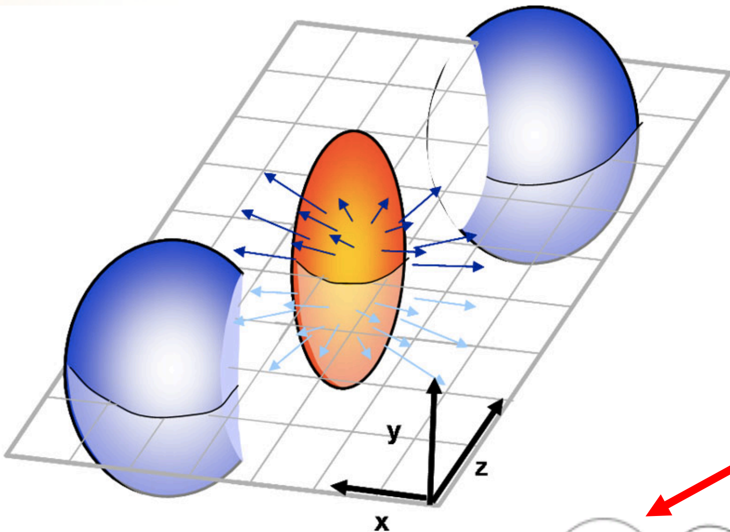
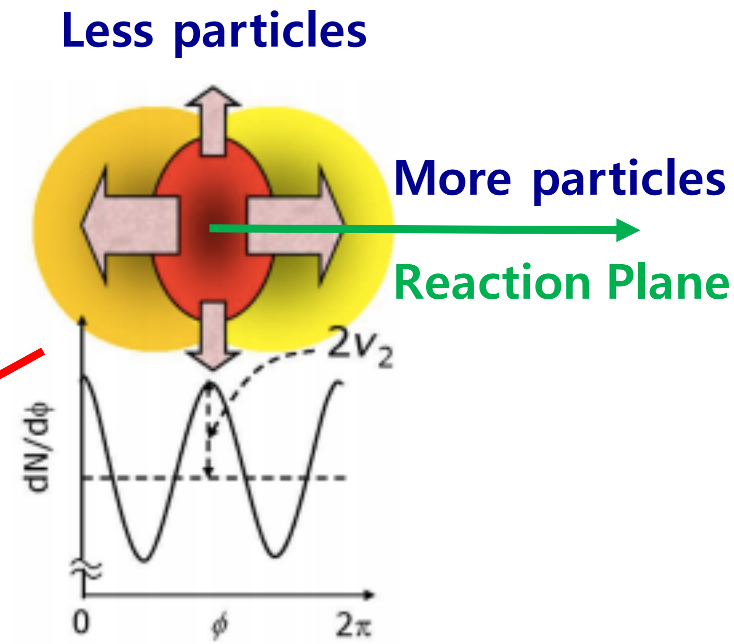
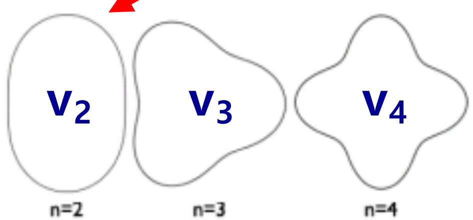
# What is flow ?

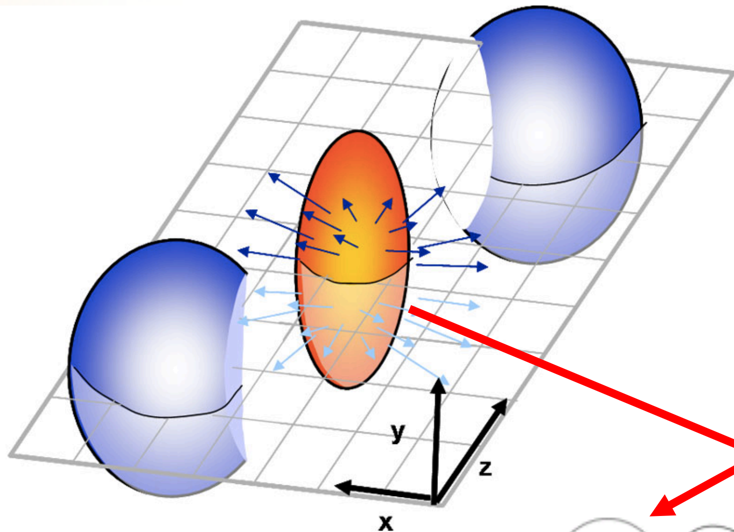


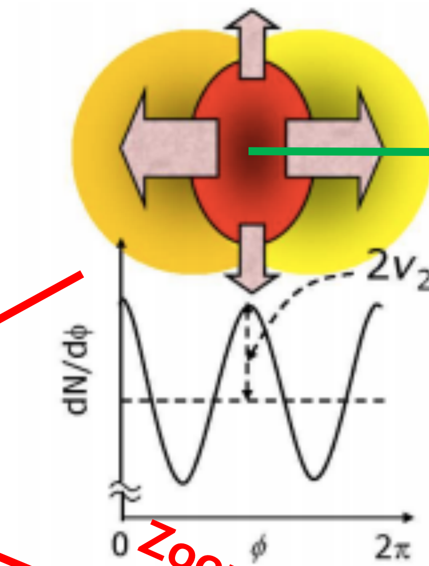



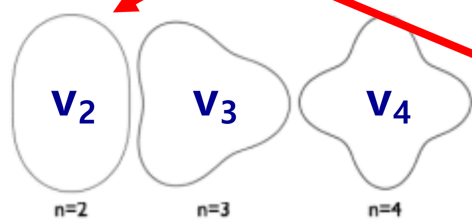



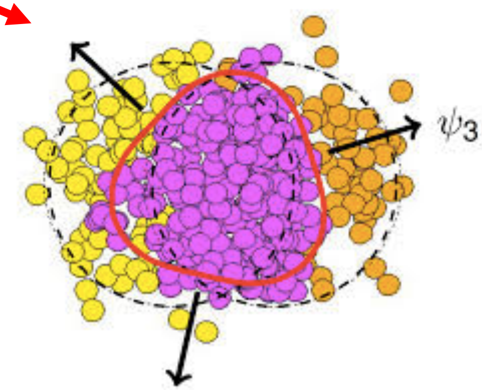

❖ **Flow harmonics $v_n$** $$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

# What is flow ?



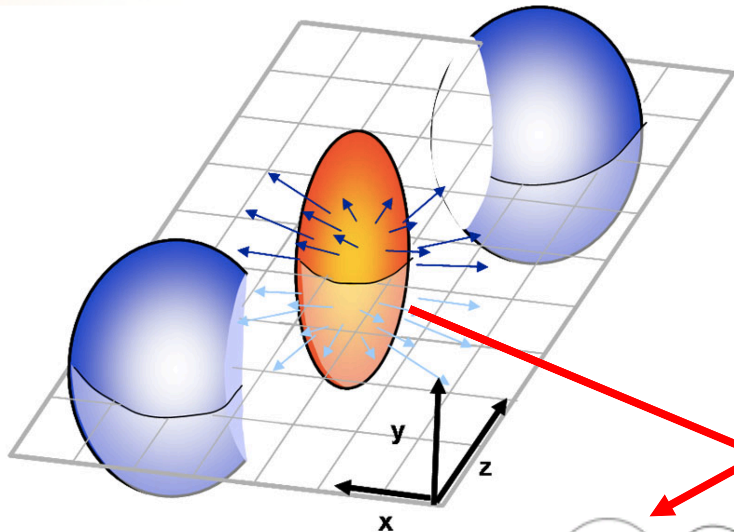



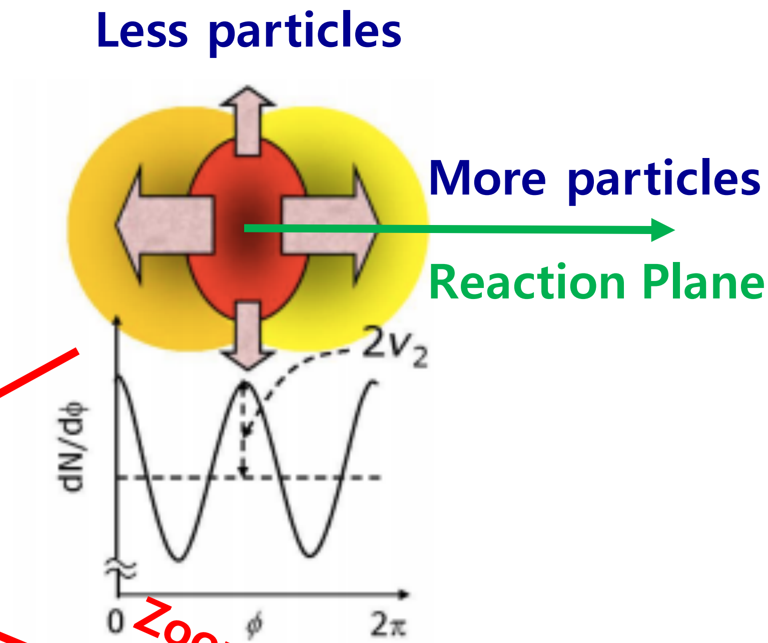



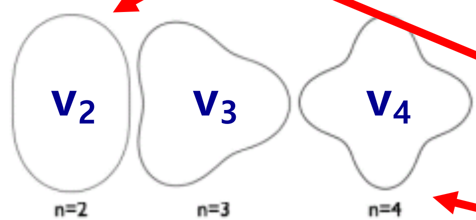



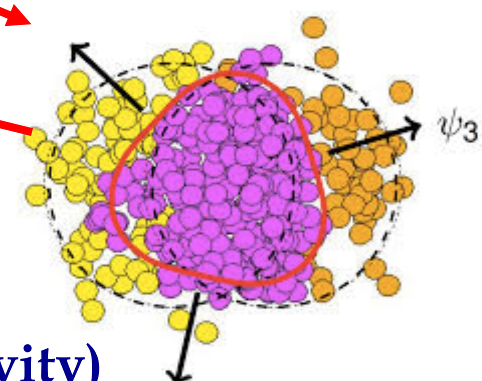

❖ **Flow harmonics $v_n$** $$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

# What is flow ?



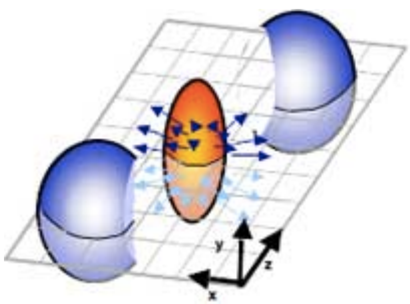



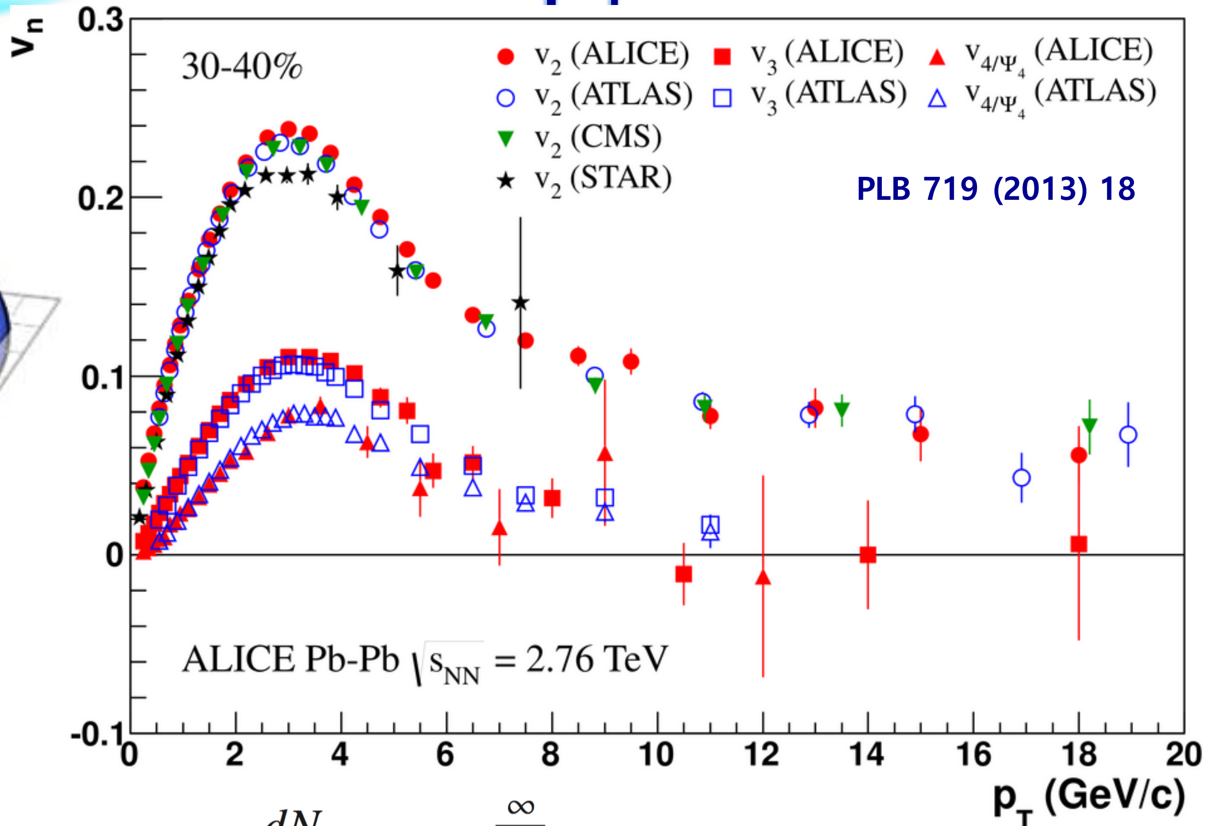

❖ Flow harmonics $v_n$ $\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$

❖ General interpretation

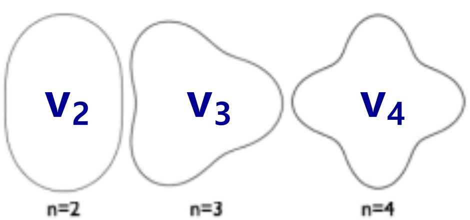
- $v_2$ : hydrodynamic flow phenomena (Collectivity)
- $v_3$ : initial geometrical fluctuations

# Low $p_T$ Flow



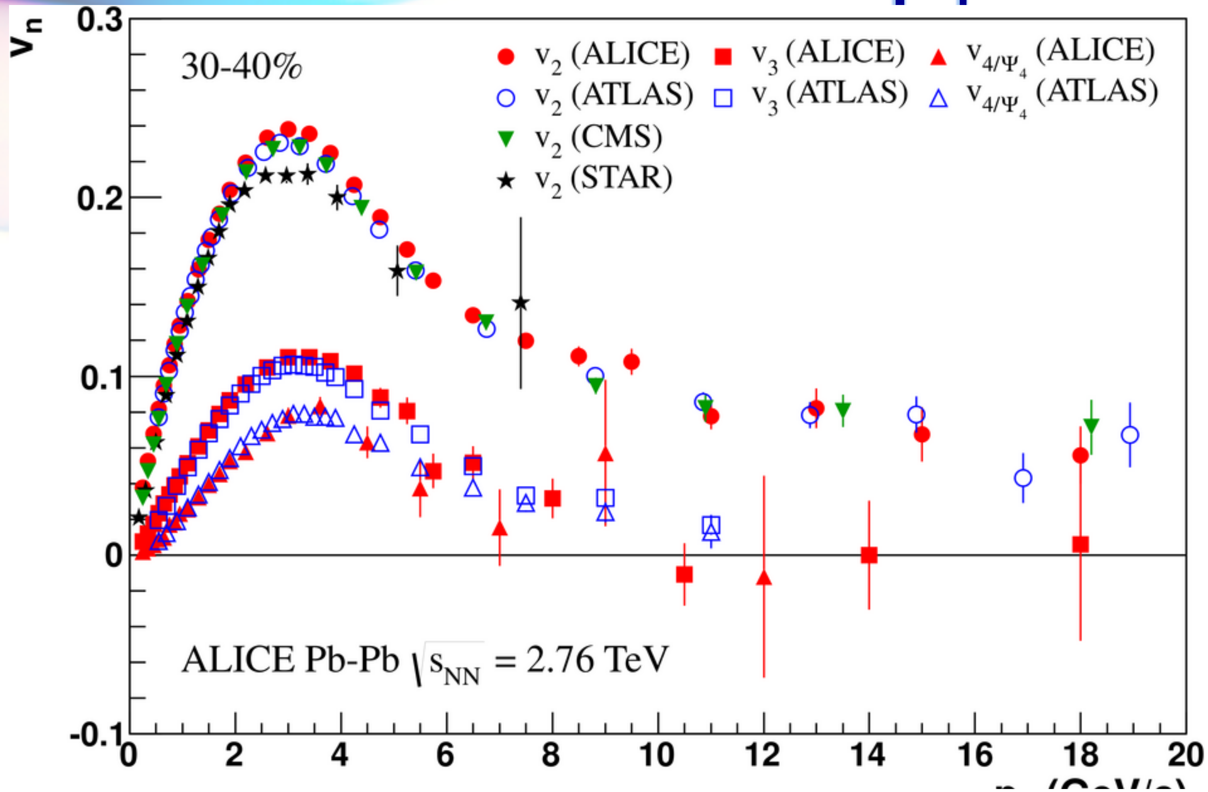



- ❖ Flow harmonics $v_n$ $\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$
- ❖ Good agreements with other experiments

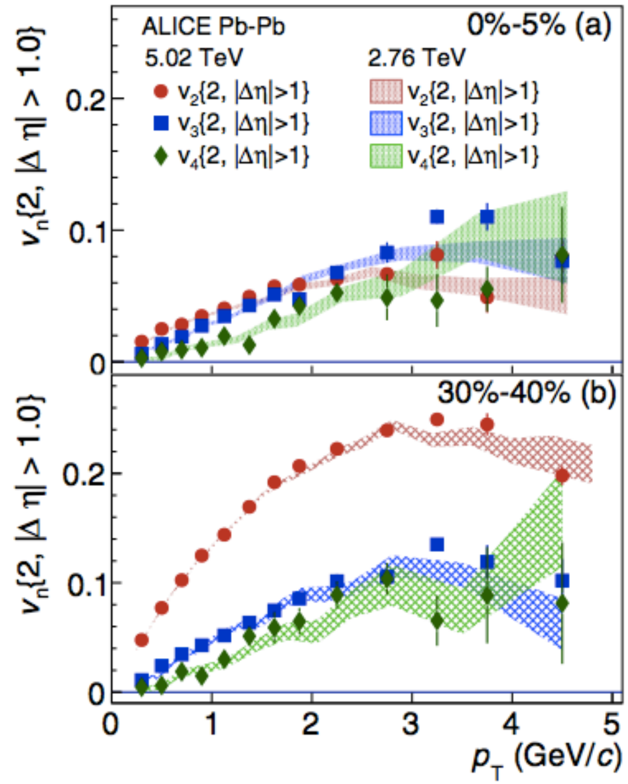



- ❖ $v_2$ : Collectivity (hydrodymics)
- ❖ $v_3$ : Geometrical fluctuations

# Low $p_T$ Flow




PbPb 5.02 TeV

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PLB 719 (2013) 18
PRL 116 (2016) 132302

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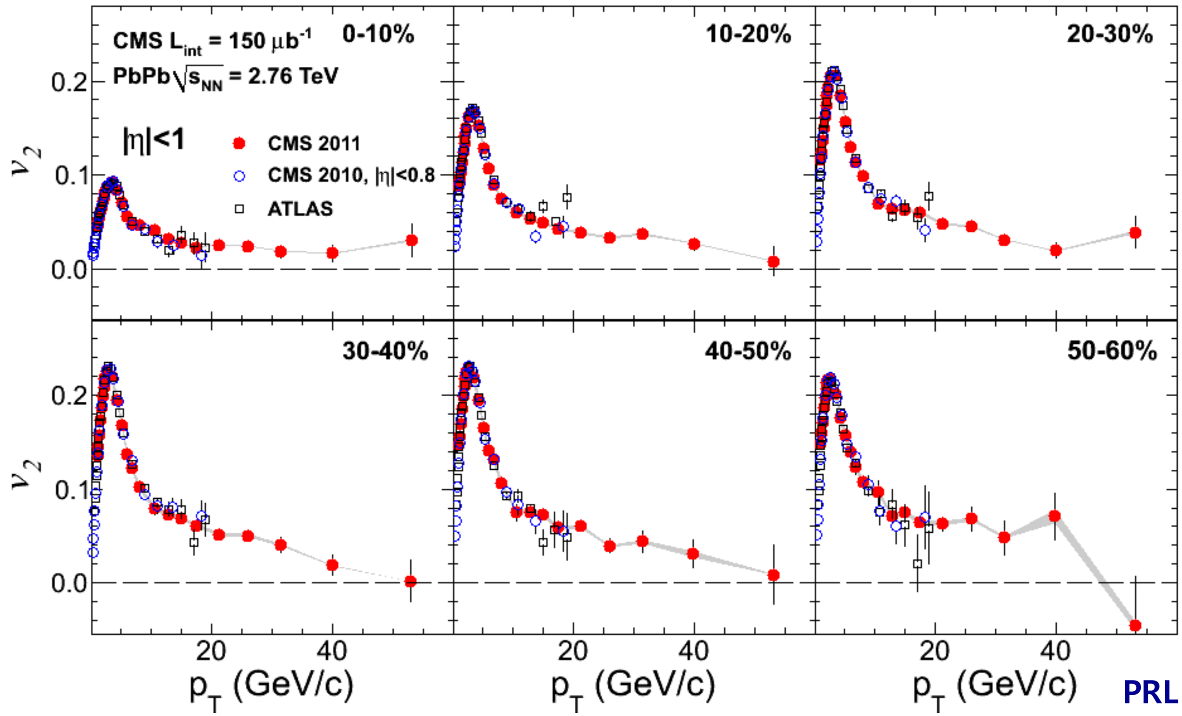
# High $p_T$ Flow

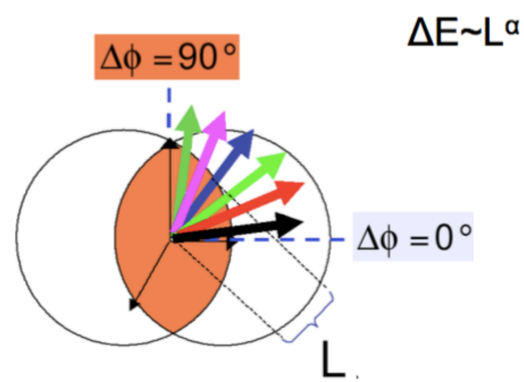



PRL 109 (2012) 022301

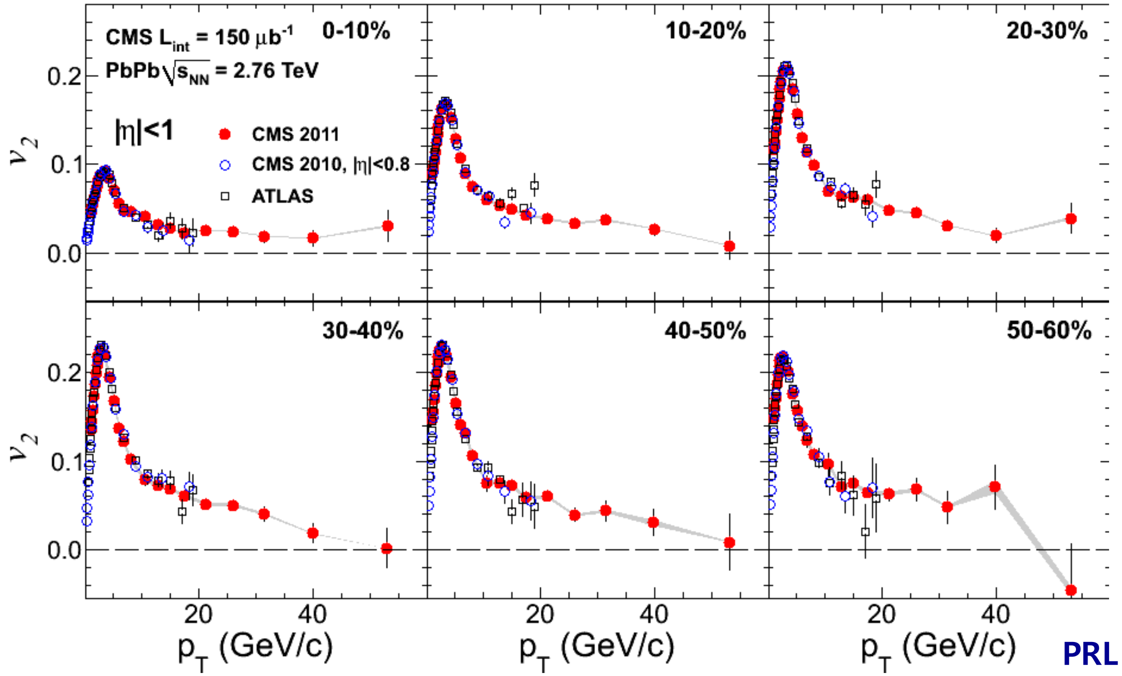
❖ **Flow harmonics $v_n$** $\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$

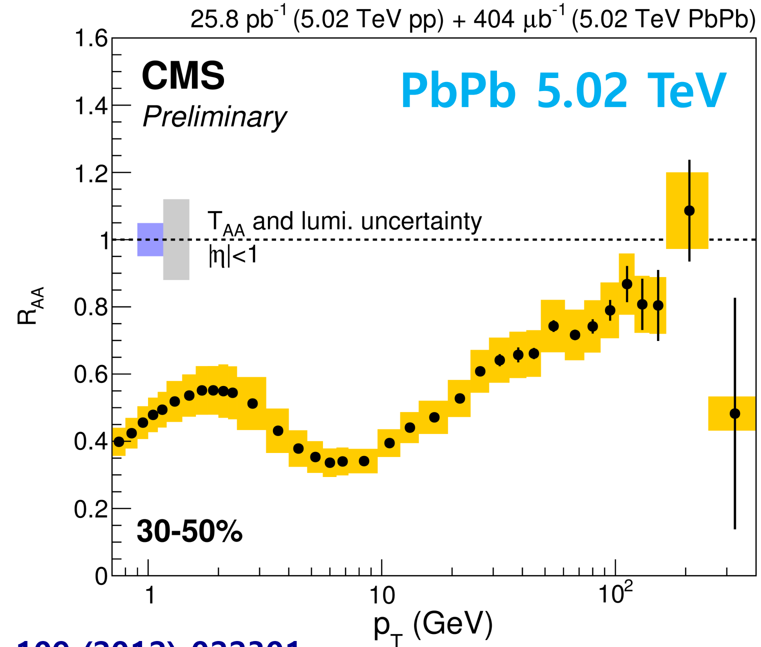
❖ **Good agreements with other experiments**

❖ **Path-length dependence (energy loss)**

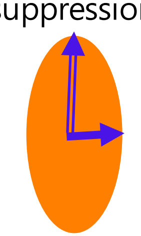


# High $p_T$ Flow



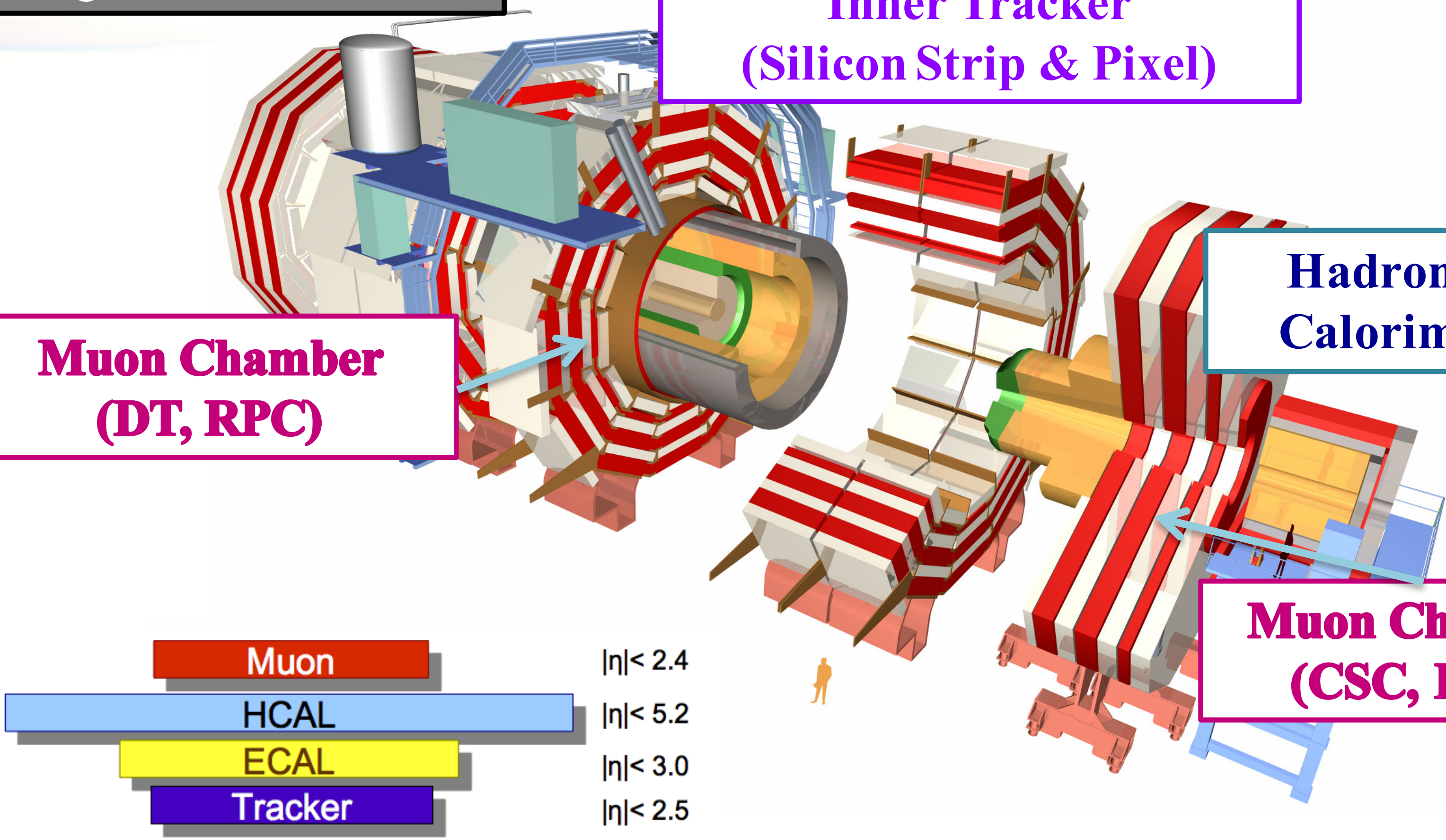

PRL 109 (2012) 022301
CMS-PAS-HIN-15-015




- ❖ **Flow harmonics $v_n$** $$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$
- ❖ **Good agreements with other experiments**
- ❖ **Path-length dependence (energy loss), $R_{AA}$ (average energy loss)**

# CMS Detector

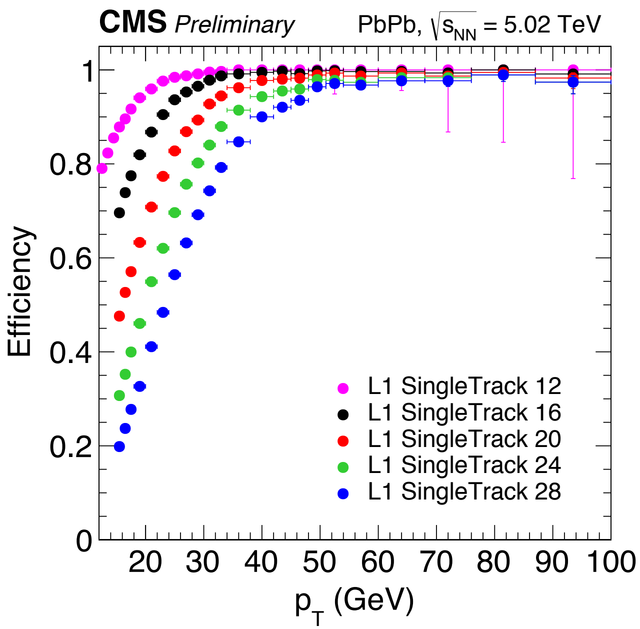
Magnetic Field : 3.8 T

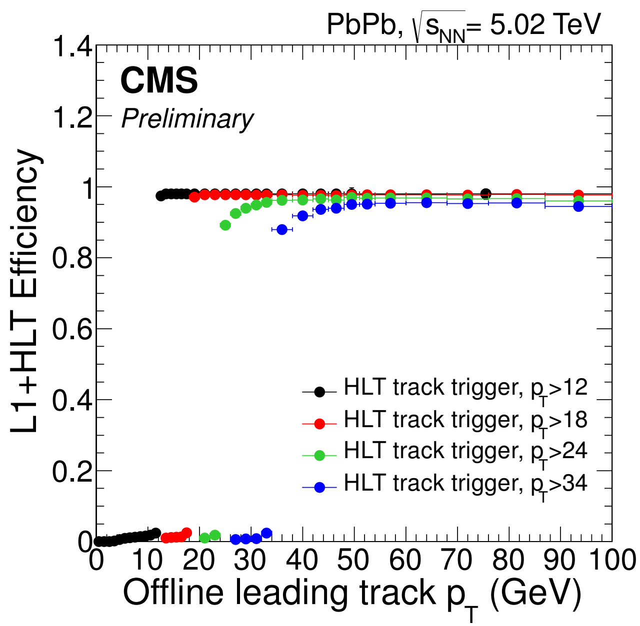


# 2015 Data Taking

❖ **2015 PbPb Run at LHC**
- Collision energy : 5.02 TeV
- Integrated luminosity : 404 μ$b^{-1}$
- Minimum bias ($p_T$ < 14 GeV/c)

❖ **Trigger : high $p_T$ track trigger**
- $|\eta| < 1.0$, $14 < p_T < 100$ GeV/c



# Flow harmonics $v_n$ in PbPb
# - Scalar Product Method

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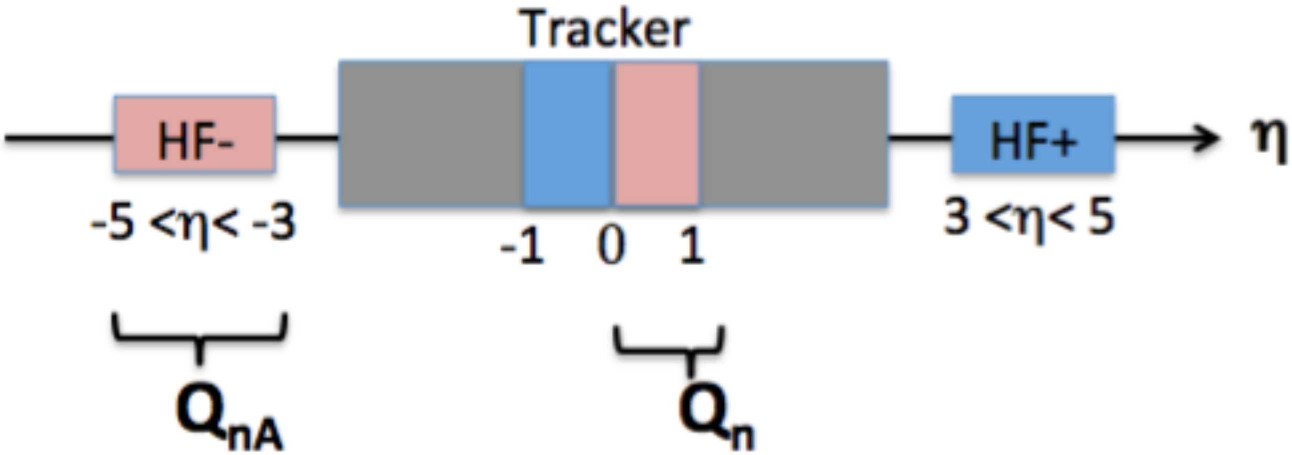



- Q-vector for nth harmonics

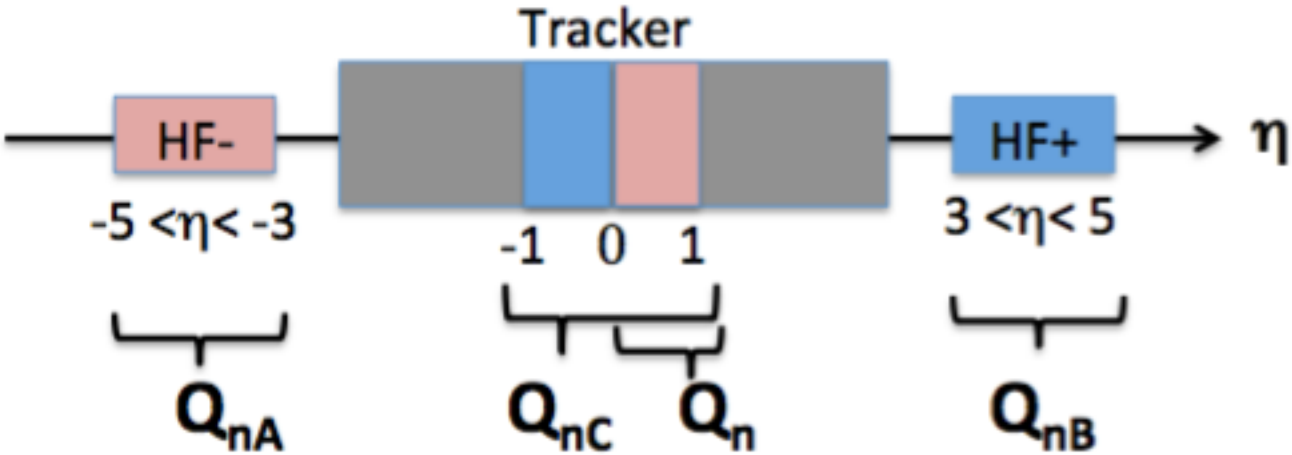
$$Q_n = \sum_j w_j e^{in\phi_j}$$

- $v_n$ measured from scalar product

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

- Applied large η gap ($|\Delta\eta| > 3.0$)

# Scalar Product Method




- Q-vector for nth harmonics

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

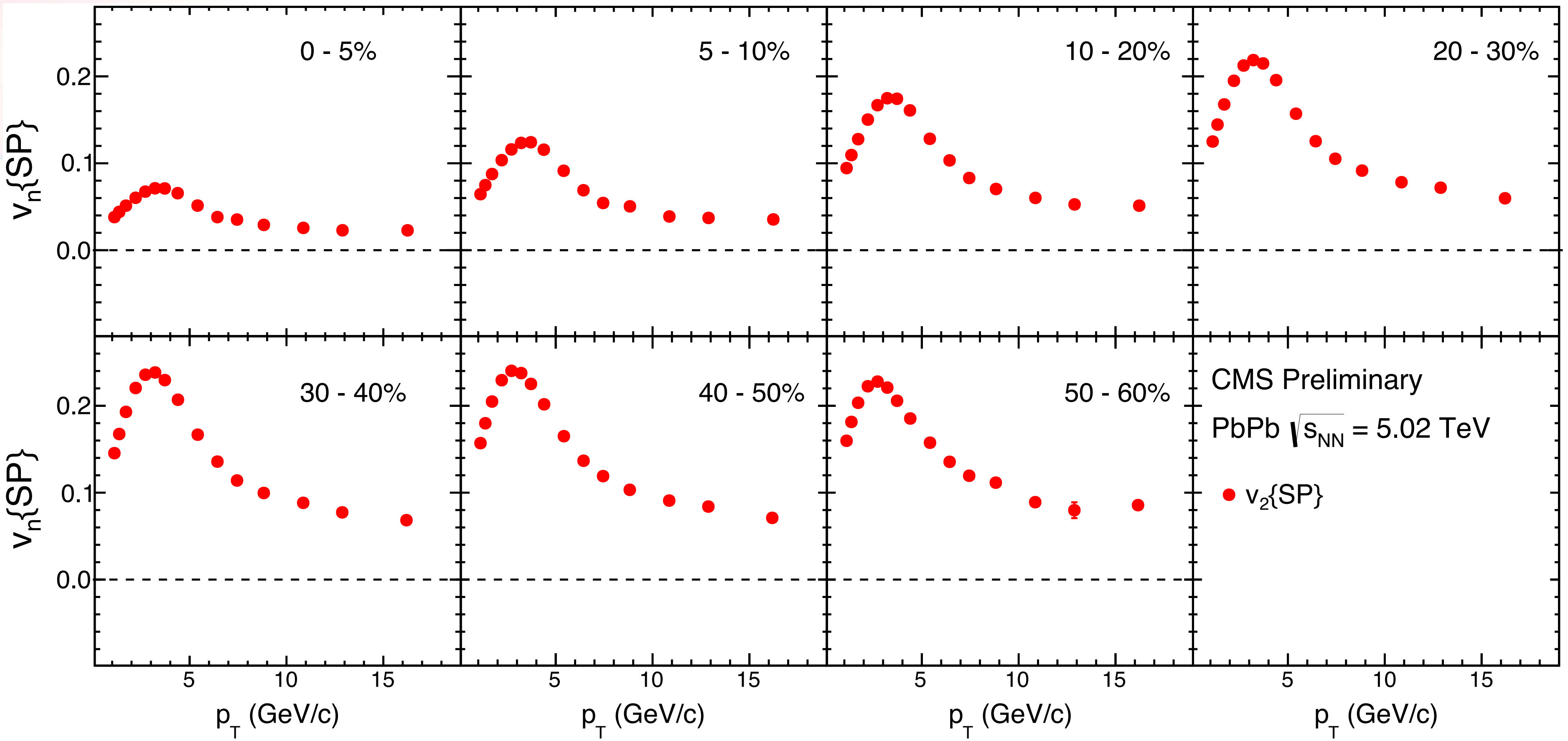
- $v_n$ measured from scalar product

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

- Applied large η gap (|Δη|>3.0)
- Non-ambiguous measure of RMS $v_n$

**Two sub event method**
**PRC 87 (2013) 044907**

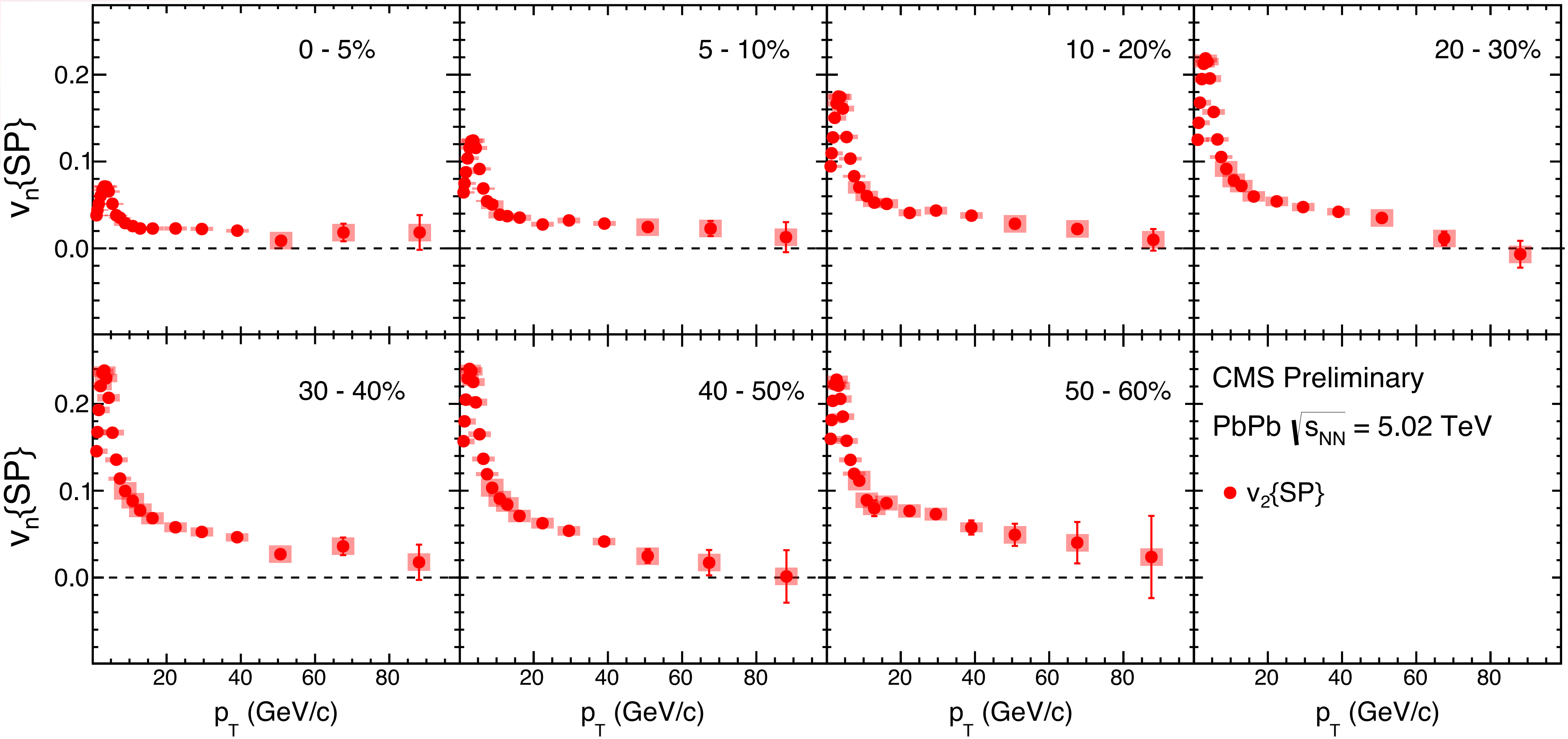
# Results : $v_2\{SP\}$ at Low $p_T$ reigon




PAS HIN-15-014

- ❖ $v_2\{SP\}$ in low $p_T$ increase from most-central to mid-central.
- ❖ $v_2\{SP\}$ increase with $p_T$ .
- ❖ $v_2\{SP\}$ peak at ~3 GeV/c, decrease while increasing $p_T$.

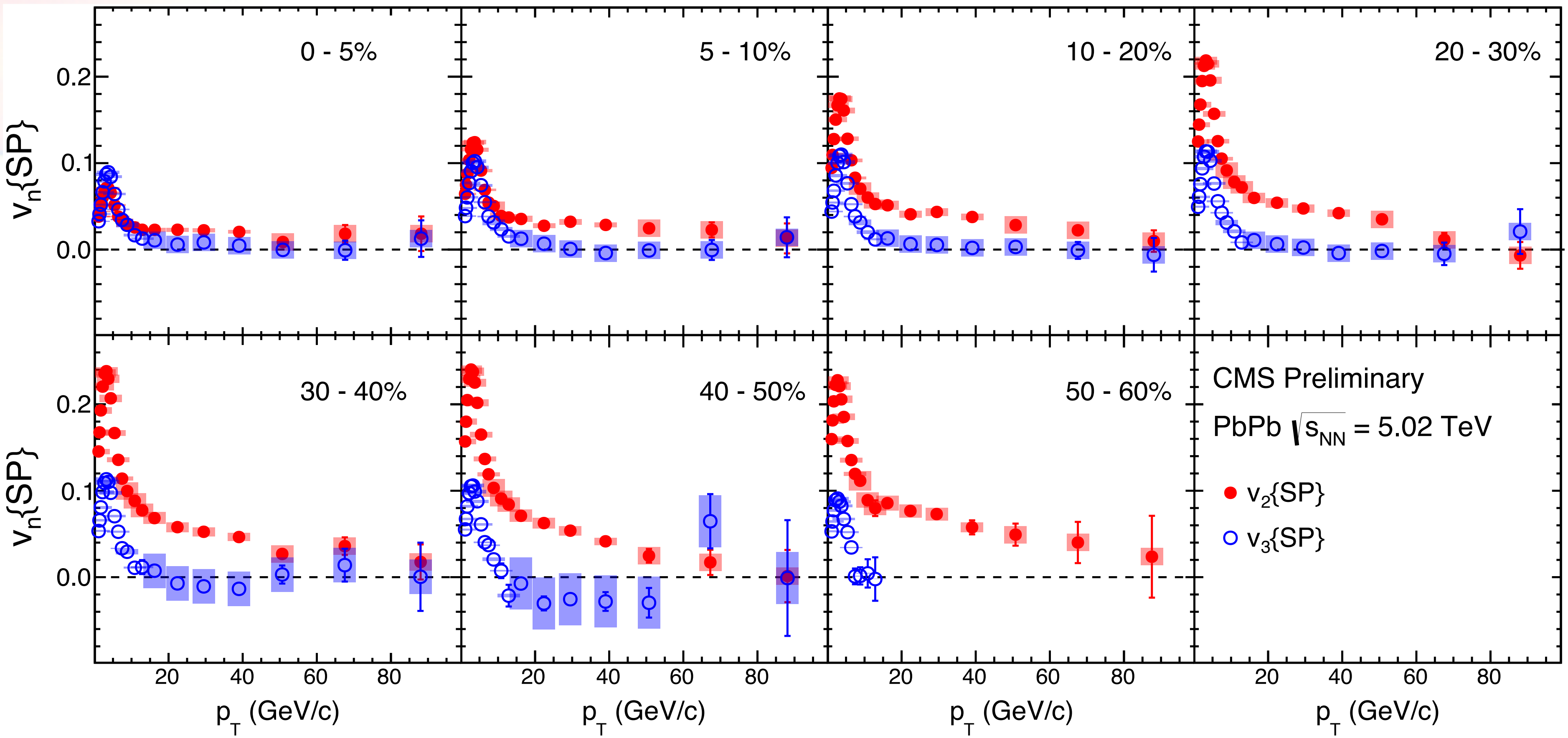
# Results : $v_2\{SP\}$ extended to High $p_T$




PAS HIN-15-014

- ❖ $v_2\{SP\}$ measured up to 100 GeV/c at first time.
- ❖ $v_2\{SP\}$ remains positive at very high $p_T$.

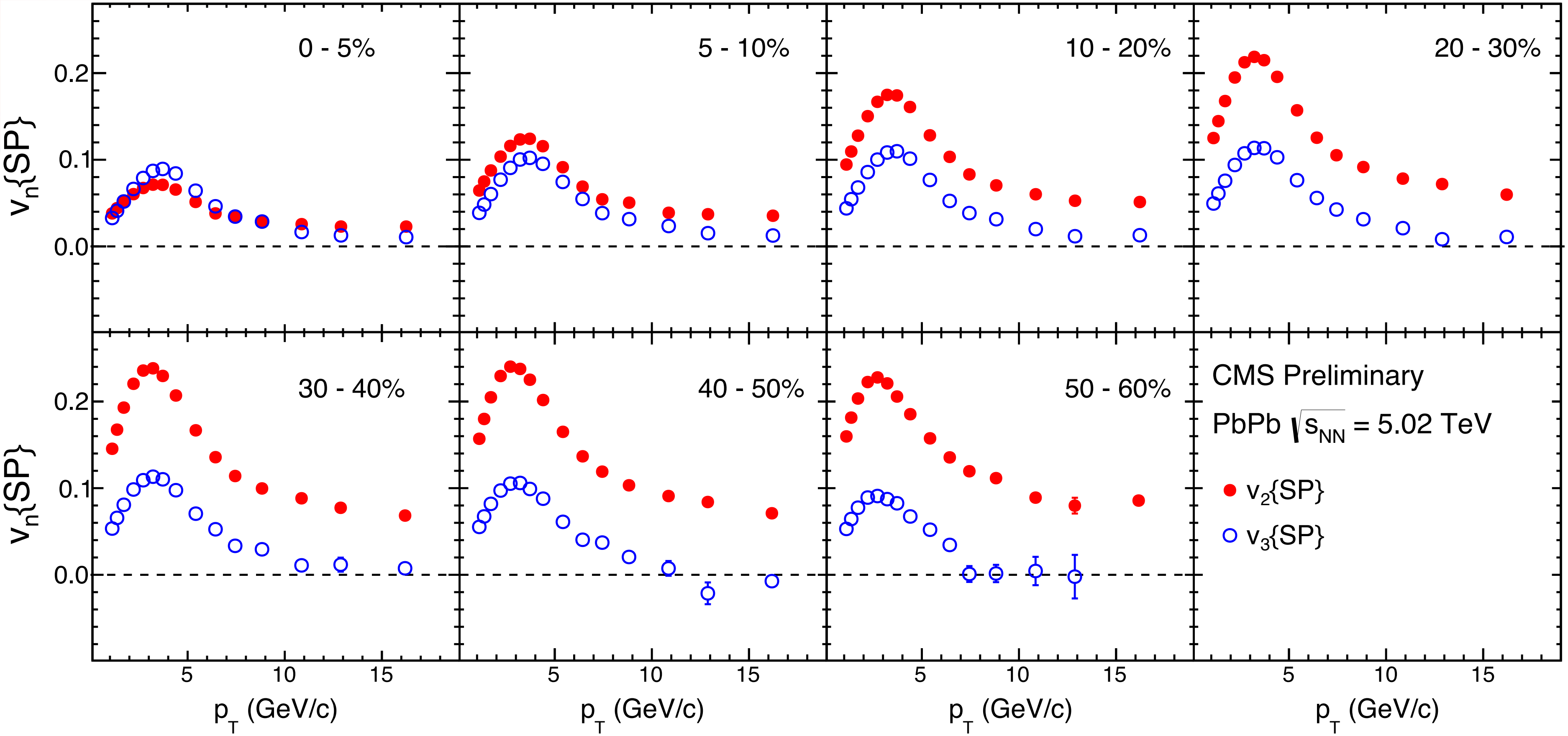
# Results : $v_2\{SP\}$ vs $v_3\{SP\}$ at High $p_T$




PAS HIN-15-014

- $v_3\{SP\}$ measured up to 100 GeV/c at first time.
- $v_3\{SP\}$ doesn't depend on centrality.
- $v_3\{SP\} \sim 0$ consistently for $p_T > 20$ GeV/c.

# Results : $v_2\{SP\}$ vs $v_3\{SP\}$ at Low $p_T$

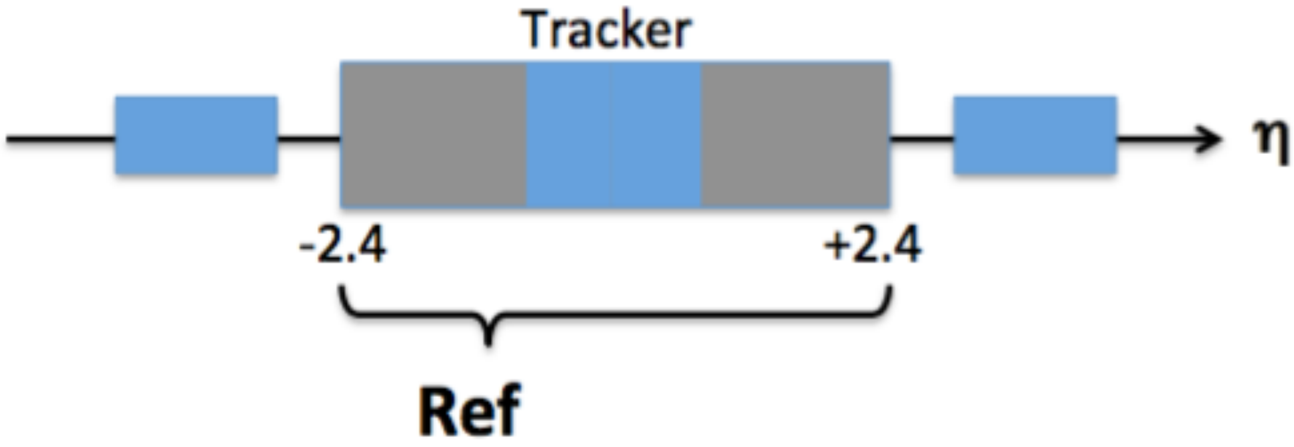



PAS HIN-15-014

❖ $v_3\{SP\}$ has little dependency on centrality in low $p_T$ region.


# Flow harmonics $v_n$ in PbPb
# - Cumulant Method

# Cumulant Method

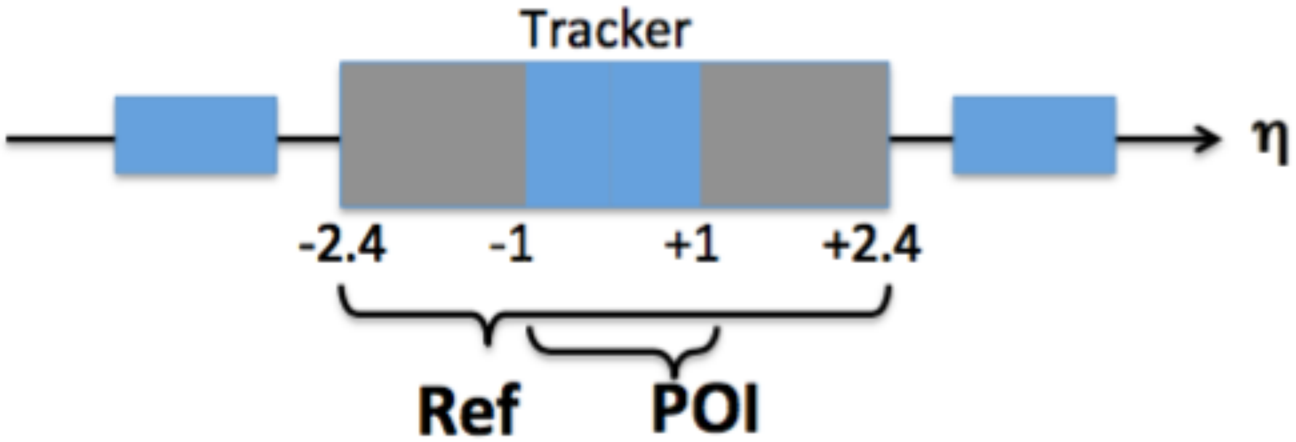



- **4-, 6-, 8-particle Q-cumulant** — PRC 83 (2011) 044913
- **Reference particles in |η| < 2.4, 1 < $p_T$ < 5 GeV/c** — *$C_n$ is in BackUp*

$$\langle\langle 2\rangle\rangle \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle$$
$$\langle\langle 4\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle$$
$$\langle\langle 6\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\rangle\rangle$$
$$\langle\langle 8\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3+\phi_4-\phi_5-\phi_6-\phi_7-\phi_8)}\rangle\rangle$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$
$$v_n\{6\} = \sqrt[6]{c_n\{6\}/4}$$
$$v_n\{8\} = \sqrt[8]{-c_n\{8\}/33}$$

# Cumulant Method




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

Cumulant Method
- No need Event plane
- Remove non-flow contribution

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

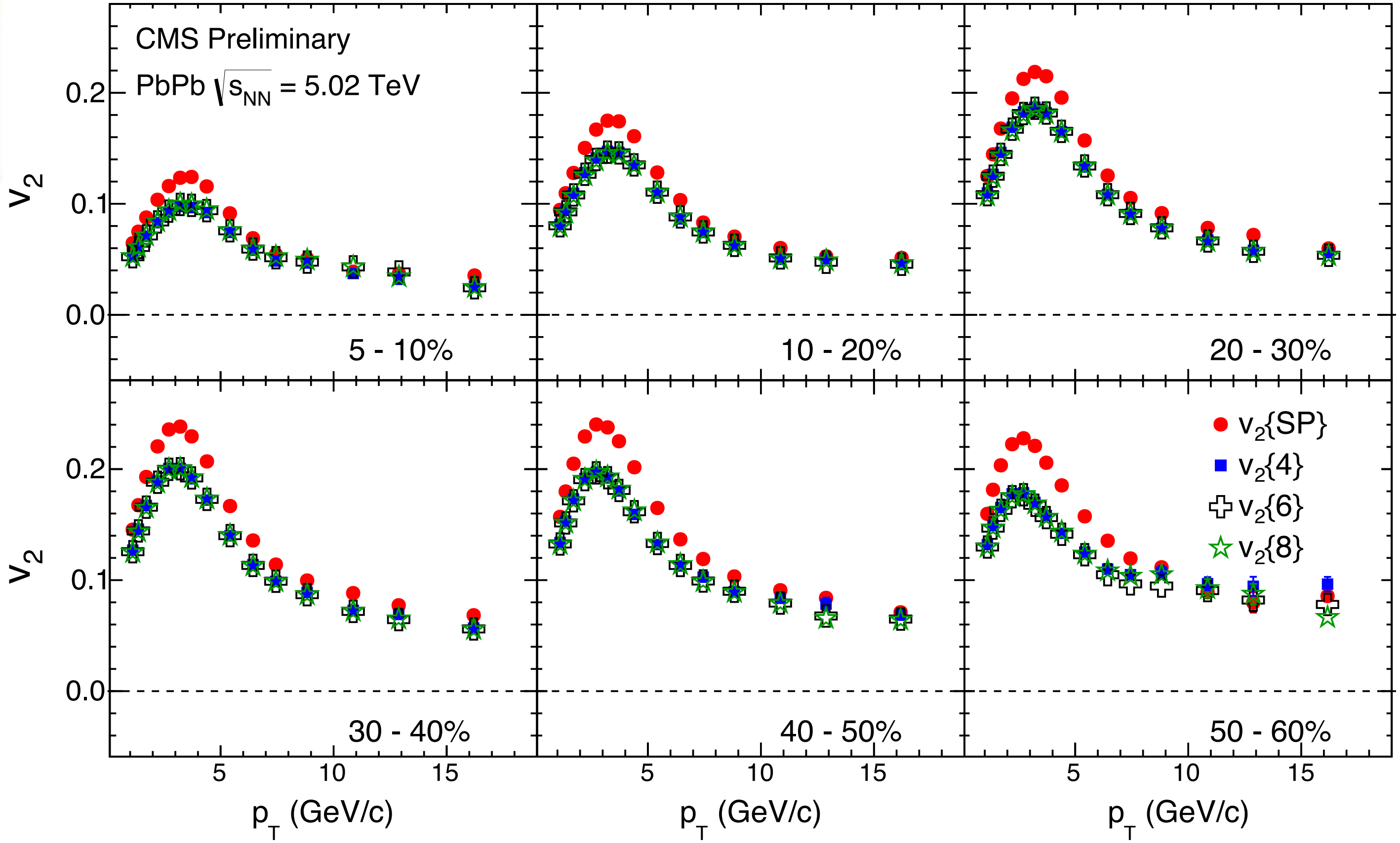
$$v_n\{6\}(p_T) = \frac{d_n\{6\}}{4} \Big/ \left(\frac{c_n\{6\}}{4}\right)^{5/6}$$

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

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

PRC 83 (2011) 044913

# Results : $v_2$\{SP\} and Cumulant at Low $p_T$

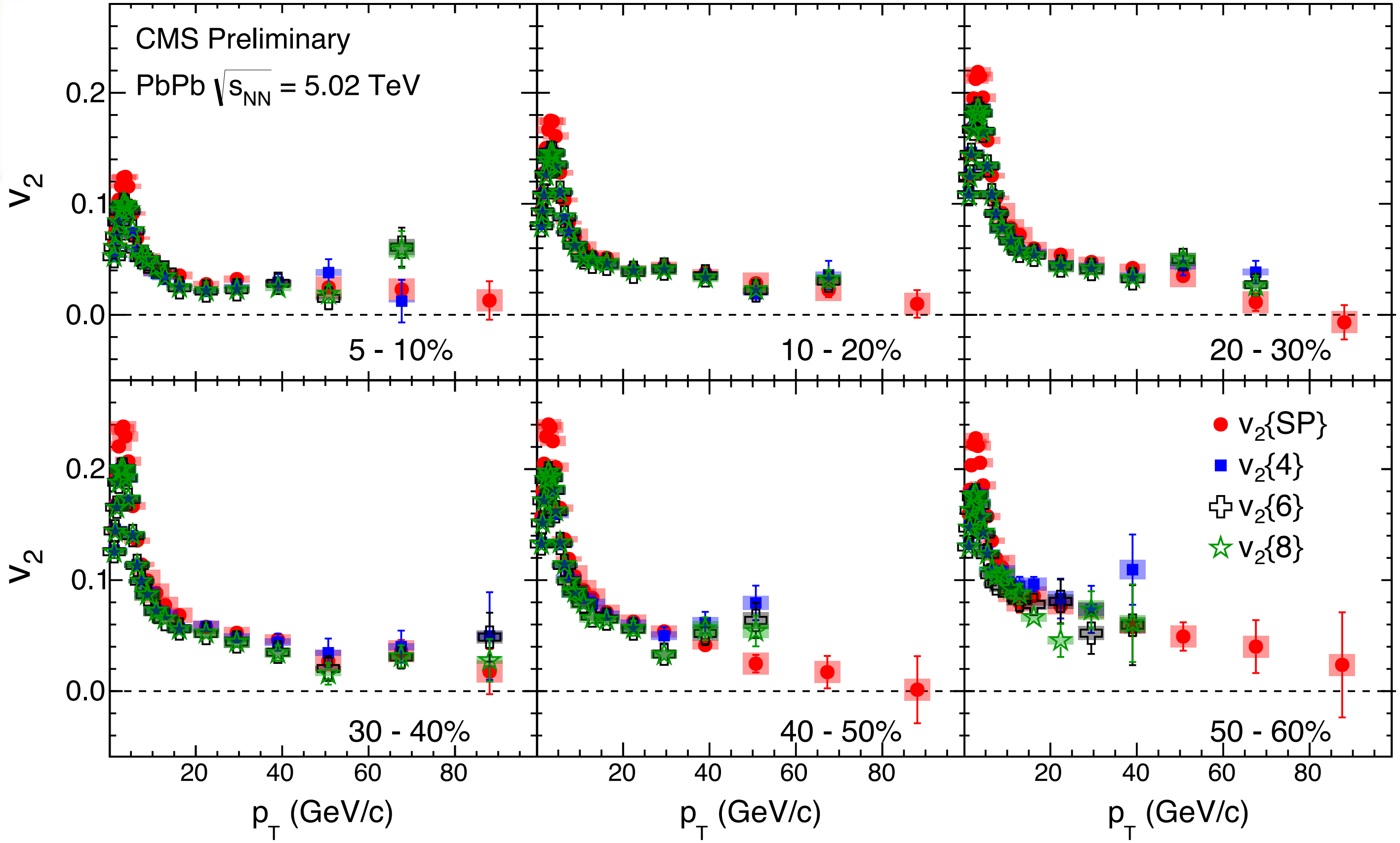



PAS HIN-15-014

- $v_2$\{SP\} in low $p_T$ slightly higher than $v_2$\{4, 6, 8\}.
- Expected in hydrodynamics.

$$v_2\{2\} = v_2 + \sigma^2/(2v_2)$$
$$v_2\{4,6,8\} = v_2 - \sigma^2/(2v_2)$$

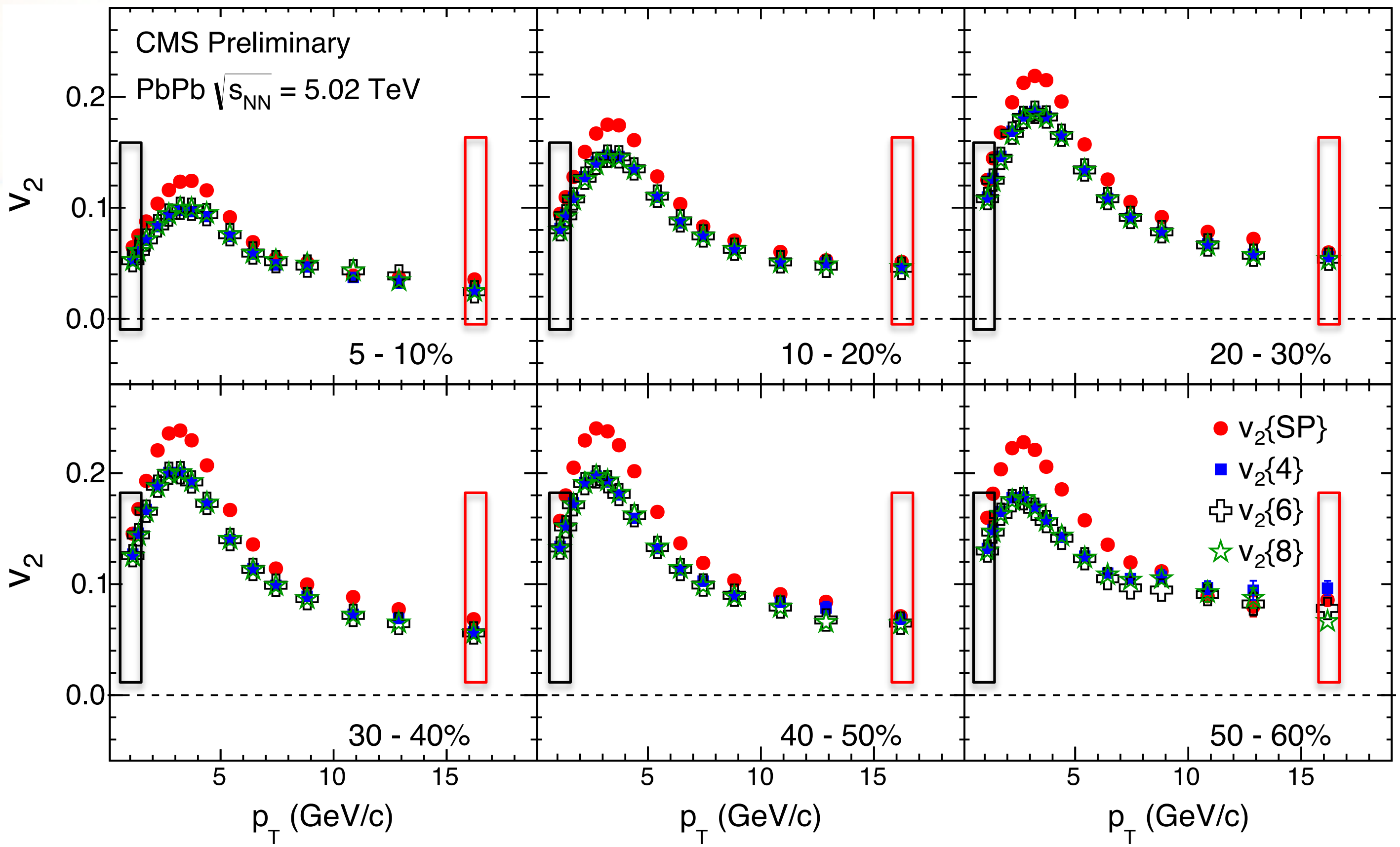
# Results : $v_2$ {SP} and Cumulant at High $p_T$




PAS HIN-15-014

- Multi-particle $v_2${4,6,8} measured up to 100 GeV/c at first time.
- Multi-particle $v_2${4,6,8} are good agreement in high $p_T$ region.
- Indicate collective nature of high $p_T$ particles.
  (Maybe low and high $p_T$ $v_2$ have same origin ?)

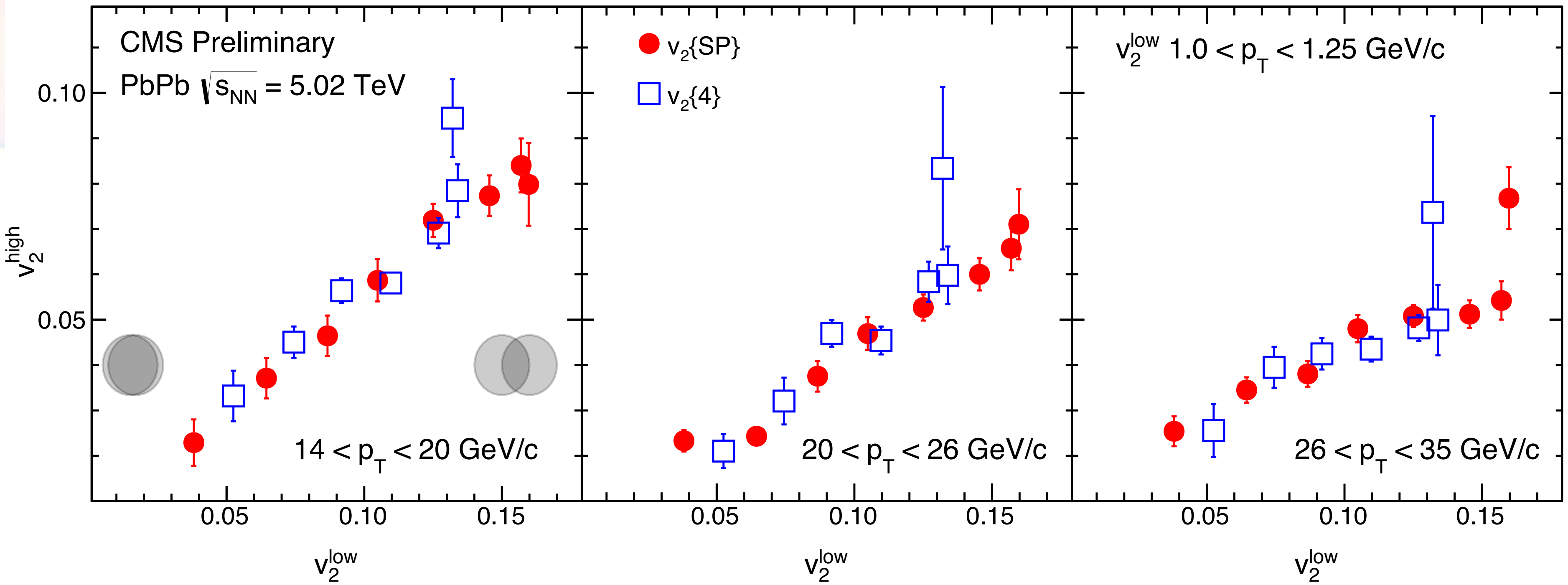
# Results : $v_2\{SP\}$ and Cumulant at Low $p_T$




PAS HIN-15-014

❖ For further investigation, let's have a correlation between the low $p_T$ (dominated by hydrodynamics) and high $p_T$ (dominated by jet quenching) $v_2$.

# Low & High $p_T$ $v_2$

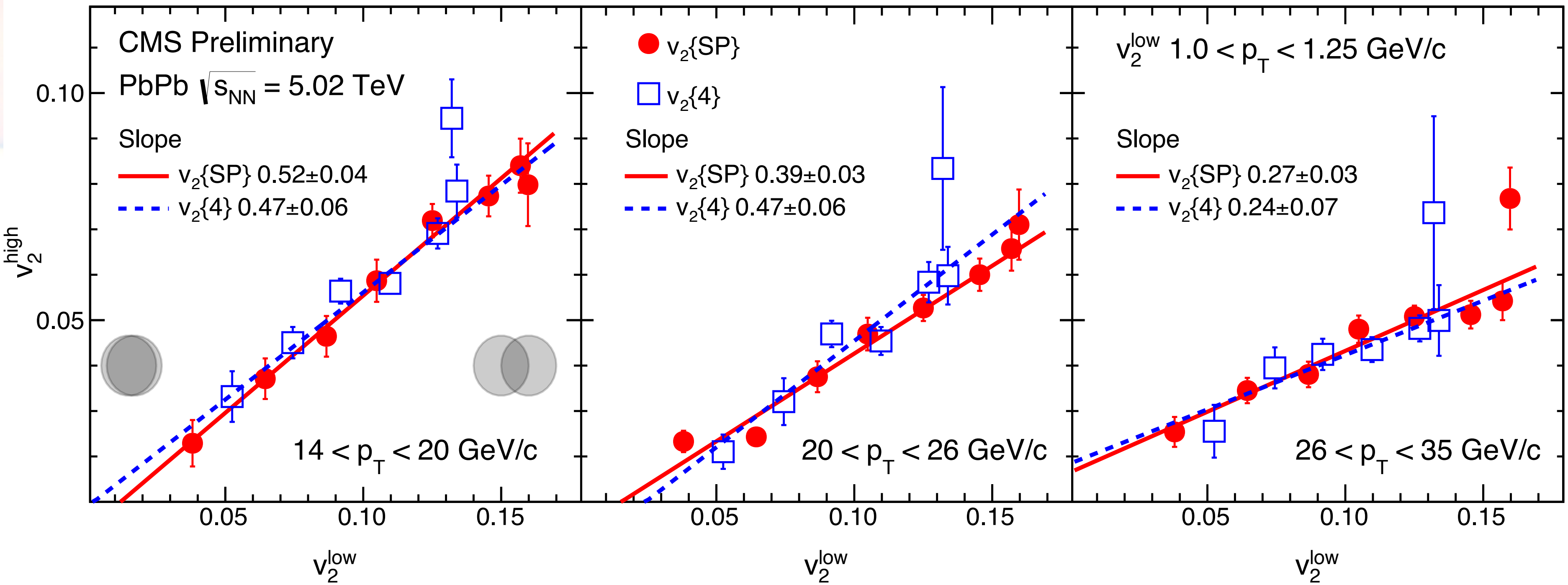



**Low $p_T$ : 1.0 < $p_T$ < 1.25 GeV/c**

**PAS HIN-15-014**

- ❖ **High $p_T$ $v_2$ is strongly correlated to low $p_T$ $v_2$.**
- ❖ **Hint of same origin of the correlations**

# Low & High $p_T$ $v_2$




**Low $p_T$ : 1.0 < $p_T$ < 1.25 GeV/c**

PAS HIN-15-014

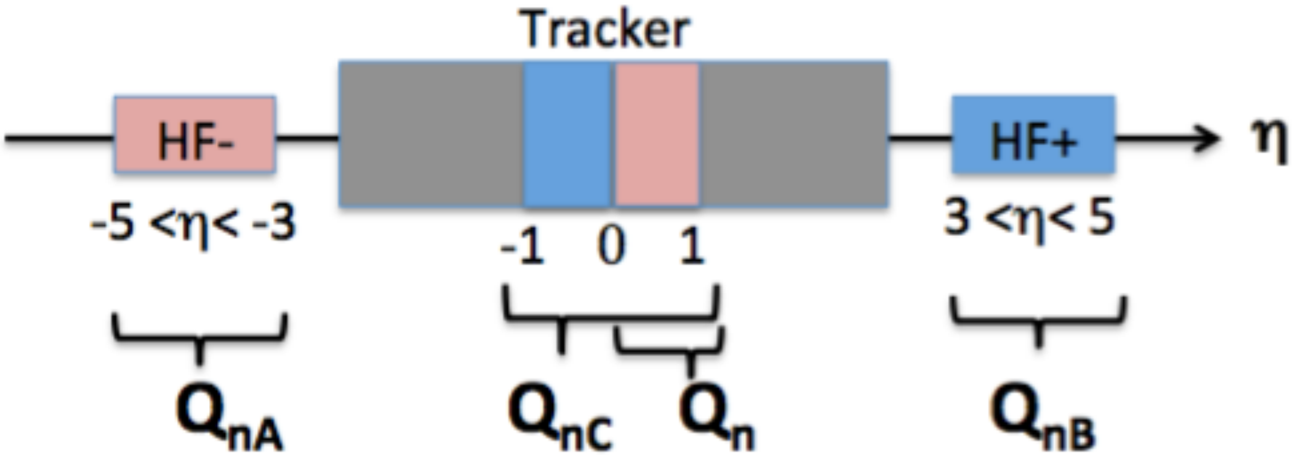
- High $p_T$ $v_2$ is strongly correlated to low $p_T$ $v_2$.
- Hint of same origin of the correlations
- Slope decrease while increasing $p_T$.

# Summary

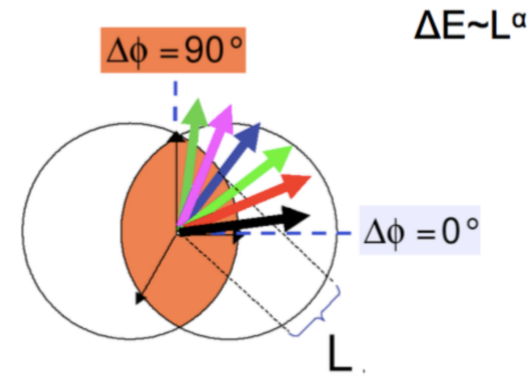
- Measured $v_2\{SP\}$, $v_3\{SP\}$ and $v_2\{4,6,8\}$ up to $p_T$ of 100 GeVc in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for the FIRST time.
- Non-zero $v_2$ still remain at very high $p_T$ region.
- Multi-particle $v_2\{4,6,8\}$ show collective nature of high $p_T$ particles.
- Observed zero $v_3\{SP\}$ in $p_T$ > 20 GeV/c.
- High $p_T$ $v_2$ is strongly correlated with low $p_T$ $v_2$.
  - ✓ Suggestion of same origin for the correlation.
- For more detail information
  - ✓ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

# THANK YOU!!!

# Scalar Product Method




- **Q-vector for nth harmonics**

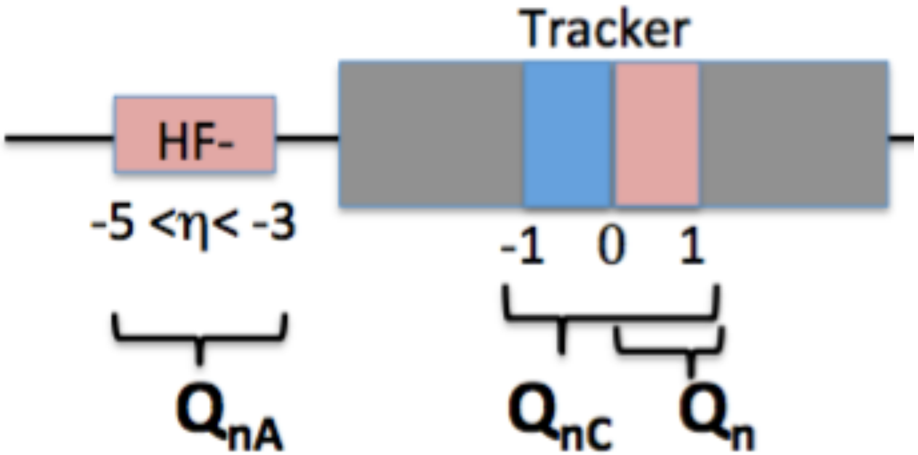


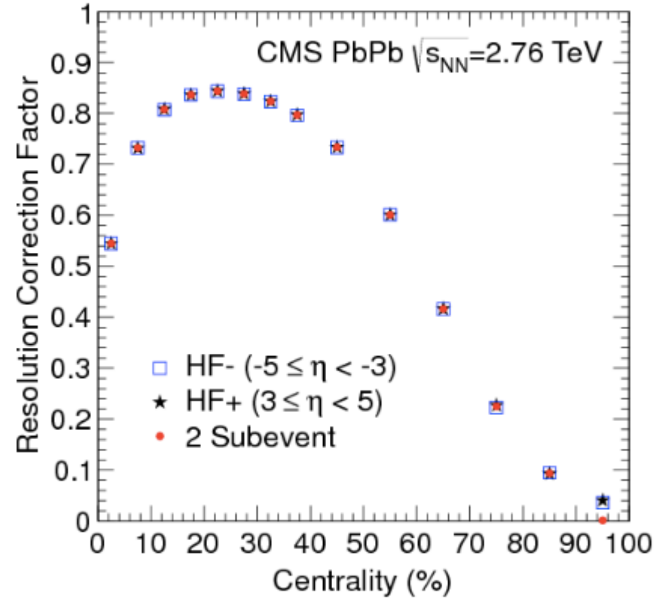

$$Q_n = \sum_j w_j e^{in\phi_j}$$

$$\vec{Q}_m = (Q_{mx}, Q_{my}) = \left(\left|\vec{Q}_m\right| \cos(m\Psi_m), \left|\vec{Q}_m\right| \sin(m\Psi_m)\right) = \left(\sum_{i=1}^{M} w_i \cos(m\phi_i), \sum_{i=1}^{M} w_i \sin(m\phi_i)\right)$$

$$\Psi_m = \frac{1}{m} \tan^{-1}\left(\frac{Q_{my}}{Q_{mx}}\right)$$

# Scalar Product M

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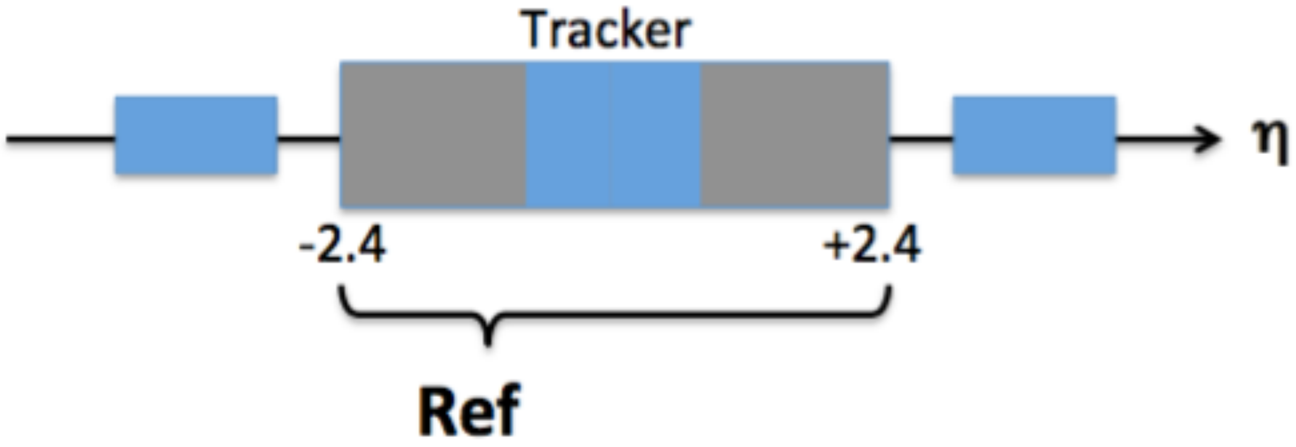
- Applied large η gap (|Δη|>3.0)
- Non-ambiguous measure of RMS $v_n$

**Two sub event method**
**PRC 87 (2013) 044907**

# Cumulant Method




- 4-, 6-, 8-particle Q-cumulant

PRC 83 (2011) 044913

- Reference particles in |η| < 2.4, 1 < $p_T$ < 5 GeV/c

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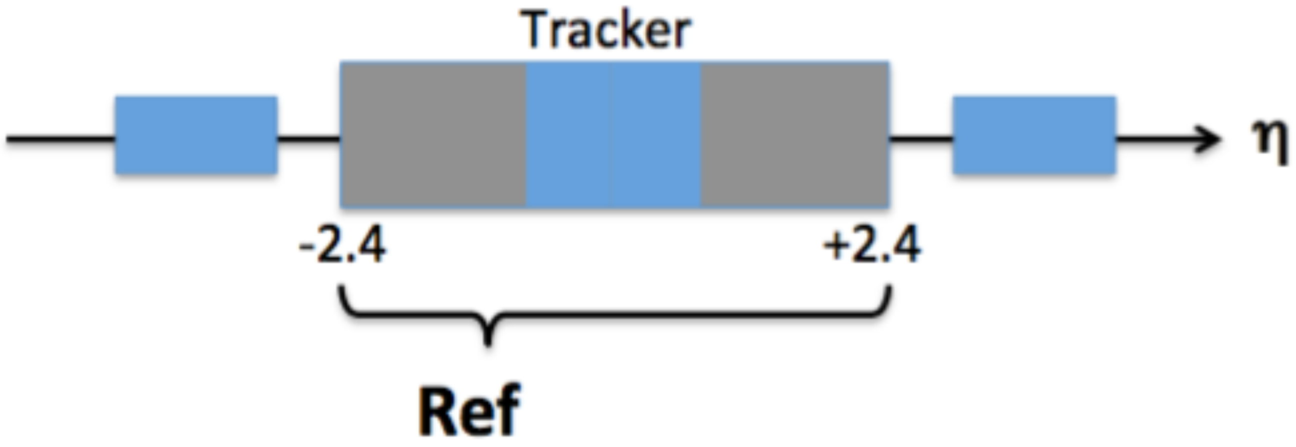
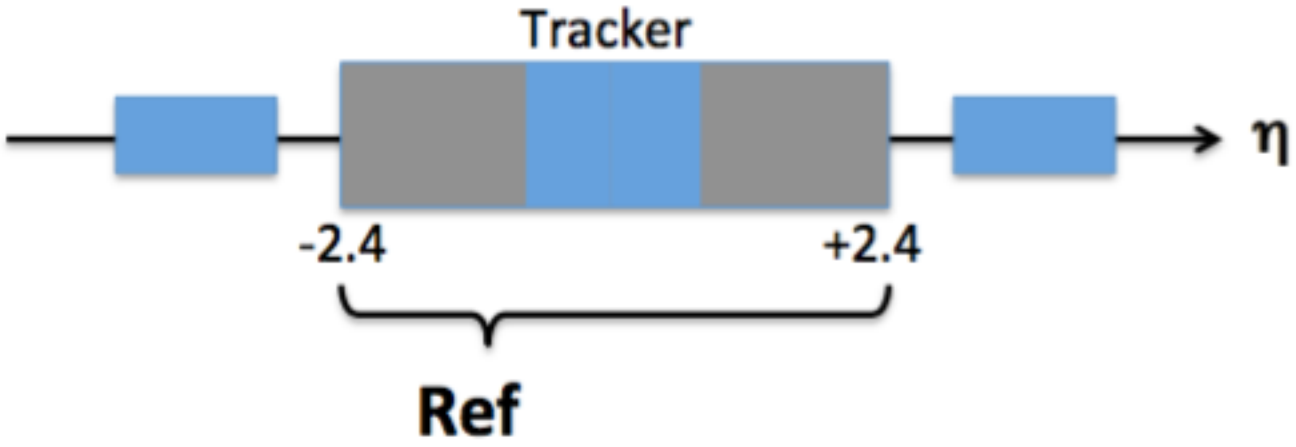



- 4-, 6-, 8-particle Q-cumulant — PRC 83 (2011) 044913

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

$$
\begin{aligned}
c_n\{4\} &= \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2, \\
c_n\{6\} &= \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3, \\
c_n\{8\} &= \langle\langle 8\rangle\rangle - 16\cdot\langle\langle 6\rangle\rangle\langle\langle 2\rangle\rangle - 18\cdot\langle\langle 4\rangle\rangle^2 + 144\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle^2 - 144\langle\langle 2\rangle\rangle^4.
\end{aligned}
$$

# Cumulant Method




- 4-, 6-, 8-particle Q-cumulant

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- Reference particles in |η| < 2.4, 1 < $p_T$ < 5 GeV/c

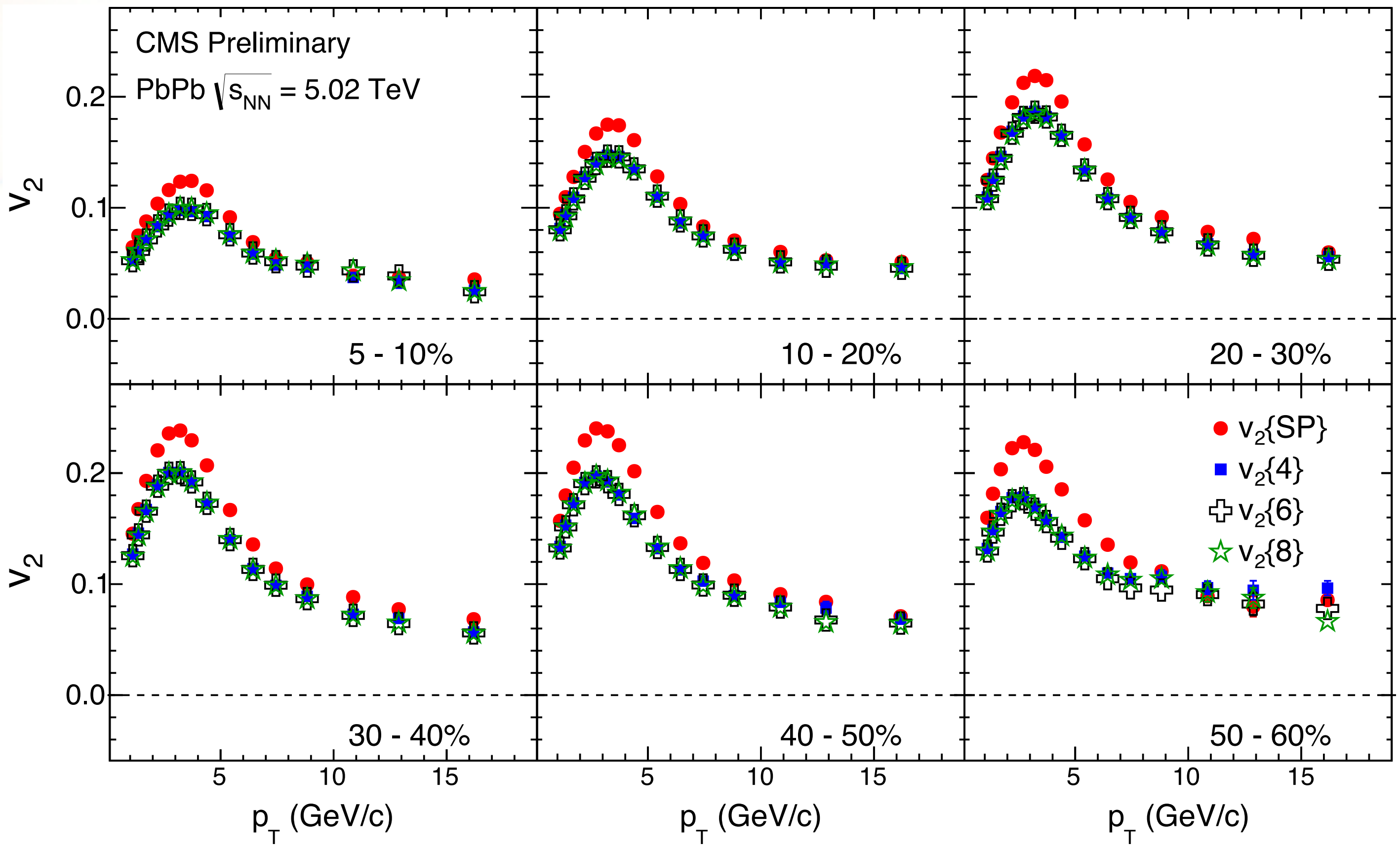
$$v_n\{4\}(p_T) = -d_n\{4\}/(-c_n\{4\})^{3/4}$$

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

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

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

# Results : $v_2$ {SP} and Cumulant at Low $p_T$

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- ❖ $v_2$ {SP} in low $p_T$ slightly higher than $v_2${4, 6, 8}.
- ❖ But expected in hydrodynamics.

$$v_2\{2\} = v_2 + \sigma^2/(2v_2)$$
$$v_2\{4,6,8\} = v_2 - \sigma^2/(2v_2)$$

# Systematics

Table 1: Sources of systematic uncertainties and range of uncertainties in percent.

| Source | $v_2\{SP\}$ | $v_3\{SP\}$ | $v_2\{4\}$ | $v_2\{6\}$ | $v_2\{8\}$ |
|---|---|---|---|---|---|
| Vertex Position | $< 1$ | $< 1$ | $< 1$ | $< 1$ | $< 1$ |
| Tracking Efficiency | $< 1$ | $< 1$ | $< 1$ | $< 1$ | $< 1$ |
| Track Quality Cuts | $2-50$ | $2-50$ | $2-12$ | $2-12$ | $2-12$ |
| Non-flow contribution | $1-50$ | $1-100$ | - | - | - |

# Theory Comparison

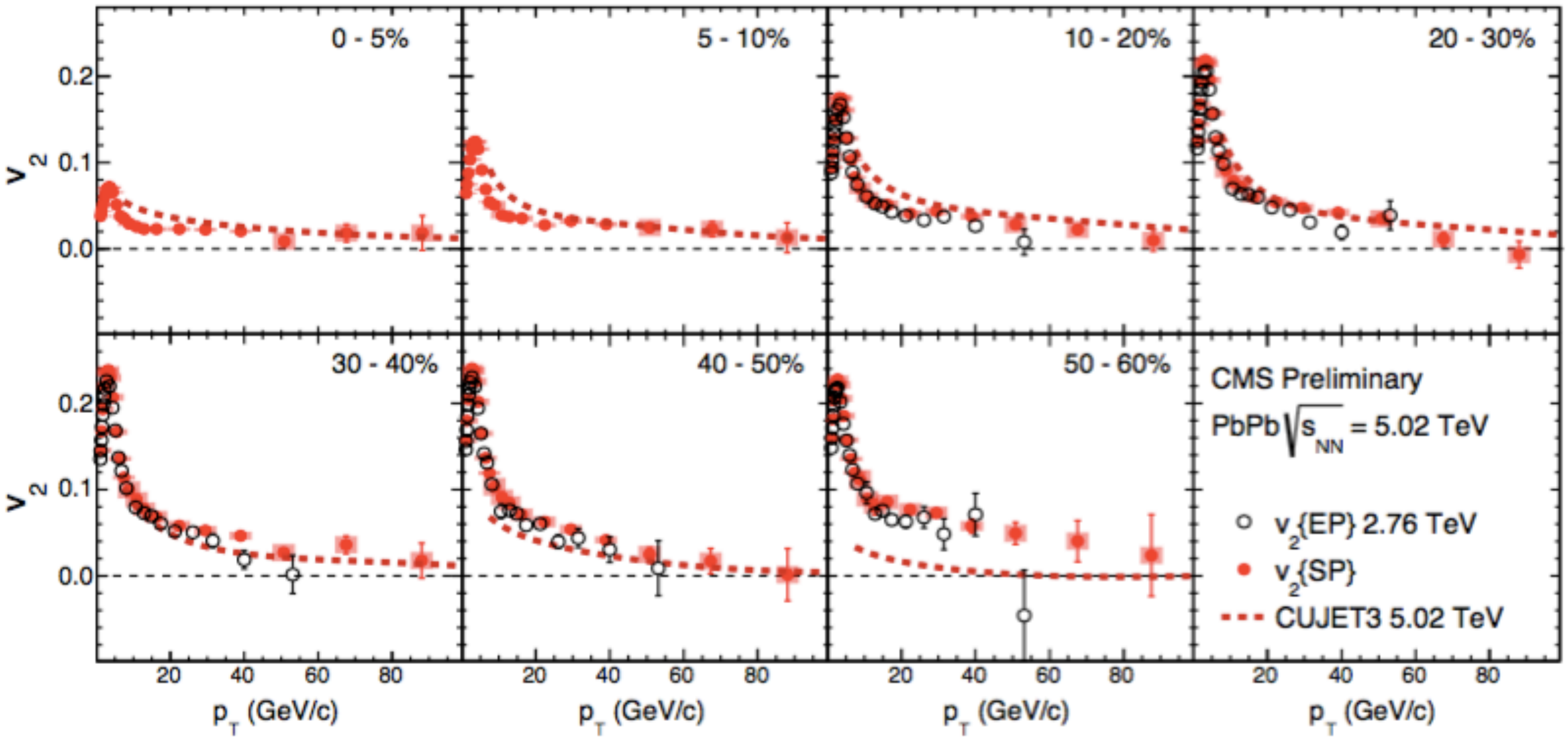


Figure 2: The $v_2$ results from SP and EP method as a function of $p_T$ in seven centrality ranges of PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV respectively. Shaded boxes represent systematic uncertainties and dashed lines are predictions from CUJET3.0 model [26, 27].

- **CUJET3.0 model**