

# Latest results on anisotropy flow of light and heavy flavors in PbPb collisions at CMS

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# Outline

- ❖ Azimuthal anisotropy and motivation for a deeper insight
  - ✧ Correlations between the higher order  $v_n$  measured with respect to their own plane with the mixed harmonics
  - ✧ Linear and non-linear contribution to higher order  $v_n$  harmonics
  - ✧ Comparison with hydrodynamic predictions with different  $\eta/s$  and initial conditions
- ❖  $v_2$  and  $v_3$  harmonics of prompt  $D^0$  meson
  - ✧ Does c quarks show collectivity as u and d quarks?
  - ✧ Such measurements can complements the measurements of the nuclear modification factor  $R_{AA}$
- ❖ Conclusions

# Mixed harmonics - motivation

- ❖ linear response ( $v_n = k_n \epsilon_n$ ) only for  $n = 2$  and  $3$
- ❖ higher harmonics ( $n > 3$ ) have a non-linear part

$$V_4 = V_{4L} + \chi_{422} (V_2)^2 \quad \text{where} \quad V_n = v_n \cdot e^{in\Psi_n}$$

$$V_5 = V_{5L} + \chi_{523} V_2 V_3$$

$$V_6 = V_{6L} + \chi_{622} (V_2)^3 + \chi_{633} (V_3)^2$$

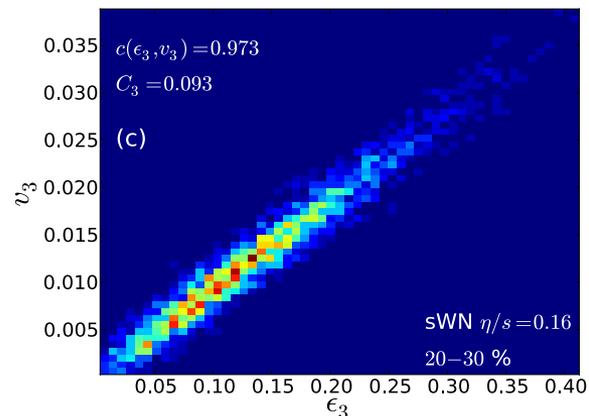
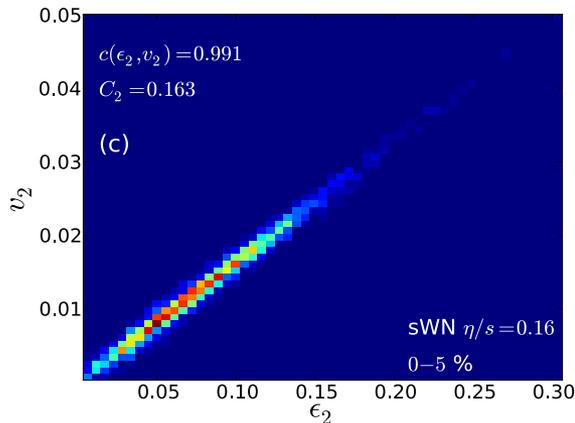
PLB 744(2015)82

$$V_7 = V_{7L} + \chi_{7223} (V_2)^2 V_3$$

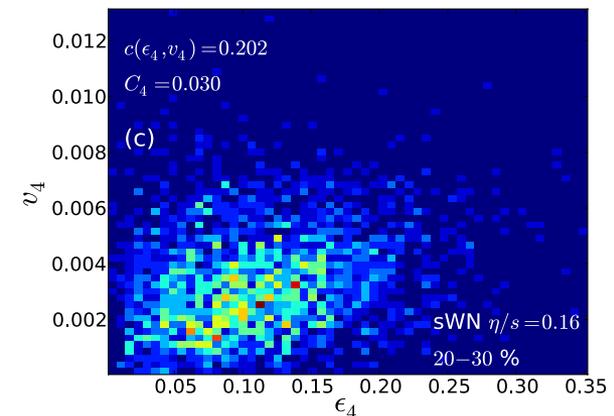
linear

non-linear:  $v_n \sim f(\epsilon_2, \epsilon_3)$

- ❖ Mixed harmonics can separate linear and non-linear part.



PRC87(2013)054901



# Mixed higher order harmonics

$$v_4 \text{ wrt } v_2: \quad v_4 \{\Psi_{22}\} \equiv \frac{\text{Re}\langle V_4 V_2^* V_2^* \rangle}{\sqrt{\langle |V_2|^4 \rangle}} = \frac{\langle v_4 v_2^2 \cos(4\Psi_4 - 4\Psi_2) \rangle}{\sqrt{\langle v_2^4 \rangle}} \quad \chi_{422} = \frac{\text{Re}\langle V_4 V_2^* V_2^* \rangle}{\langle |V_2|^4 \rangle} = \frac{v_4 \{\Psi_{22}\}}{\sqrt{\langle v_2^4 \rangle}}$$

$$v_5 \text{ wrt } v_2 \text{ and } v_3: \quad v_5 \{\Psi_{23}\} \equiv \frac{\text{Re}\langle V_5 V_2^* V_3^* \rangle}{\sqrt{\langle |V_2|^2 |V_3|^2 \rangle}} = \frac{\langle v_5 v_2 v_3 \cos(5\Psi_5 - 2\Psi_2 - 3\Psi_3) \rangle}{\sqrt{\langle v_2^2 v_3^2 \rangle}} \quad \chi_{523} = \frac{\text{Re}\langle V_5 V_2^* V_3^* \rangle}{\langle |V_2|^2 |V_3|^2 \rangle} = \frac{v_5 \{\Psi_{23}\}}{\sqrt{\langle v_2^2 v_3^2 \rangle}}$$

$$v_6 \text{ wrt } v_2: \quad v_6 \{\Psi_{222}\} \equiv \frac{\text{Re}\langle V_6 V_2^* V_2^* V_2^* \rangle}{\sqrt{\langle |V_2|^6 \rangle}} = \frac{\langle v_6 v_2^3 \cos(6\Psi_6 - 6\Psi_2) \rangle}{\sqrt{\langle v_2^6 \rangle}} \quad \chi_{6222} = \frac{\text{Re}\langle V_6 V_2^* V_2^* V_2^* \rangle}{\langle |V_2|^6 \rangle} = \frac{v_6 \{\Psi_{222}\}}{\sqrt{\langle v_2^6 \rangle}}$$

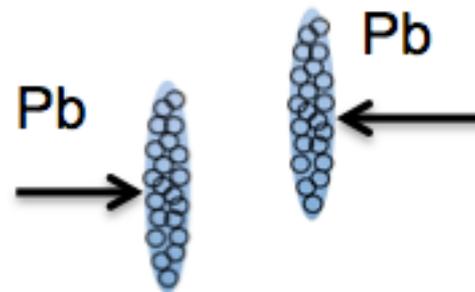
$$v_6 \text{ wrt } v_3: \quad v_6 \{\Psi_{33}\} \equiv \frac{\text{Re}\langle V_6 V_3^* V_3^* \rangle}{\sqrt{\langle |V_3|^4 \rangle}} = \frac{\langle v_6 v_3^2 \cos(6\Psi_6 - 6\Psi_3) \rangle}{\sqrt{\langle v_3^4 \rangle}} \quad \chi_{633} = \frac{\text{Re}\langle V_6 V_3^* V_3^* \rangle}{\langle |V_3|^4 \rangle} = \frac{v_6 \{\Psi_{33}\}}{\sqrt{\langle v_3^4 \rangle}}$$

$$v_7 \text{ wrt } v_2 \text{ and } v_3: \quad v_7 \{\Psi_{223}\} \equiv \frac{\text{Re}\langle V_7 V_2^* V_2^* V_3^* \rangle}{\sqrt{\langle |V_2|^4 |V_3|^2 \rangle}} = \frac{\langle v_7 v_2^2 v_3 \cos(7\Psi_7 - 4\Psi_2 - 3\Psi_3) \rangle}{\sqrt{\langle v_2^4 v_3^2 \rangle}}$$

$$\chi_{7223} = \frac{\text{Re}\langle V_7 V_2^* V_2^* V_3^* \rangle}{\langle |V_2|^4 |V_3|^2 \rangle} = \frac{v_7 \{\Psi_{223}\}}{\sqrt{\langle v_2^4 v_3^2 \rangle}}$$

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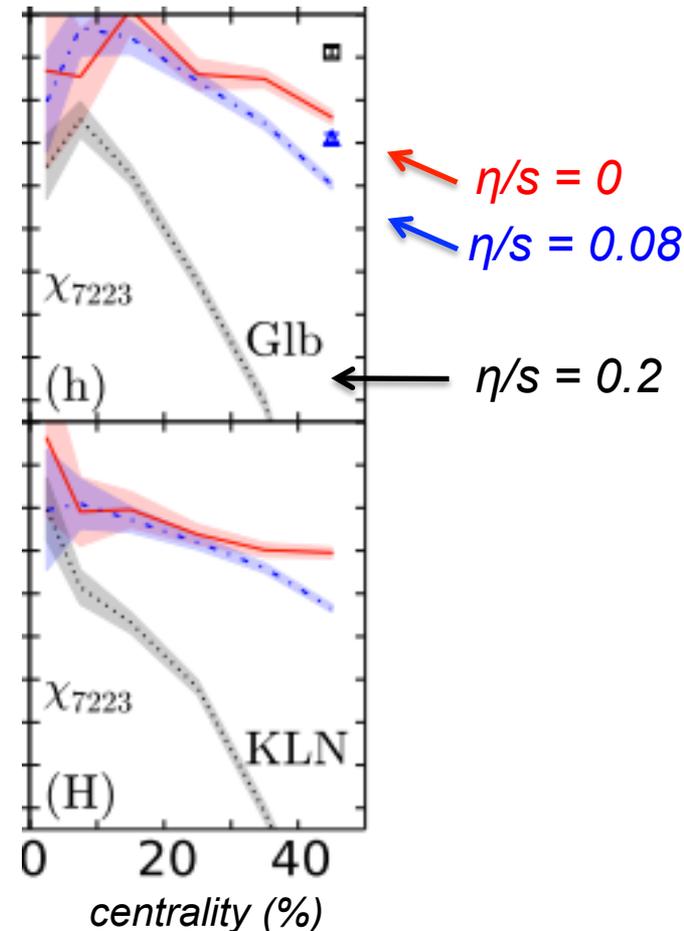
# Mixed harmonics and non-linear contributions in PbPb



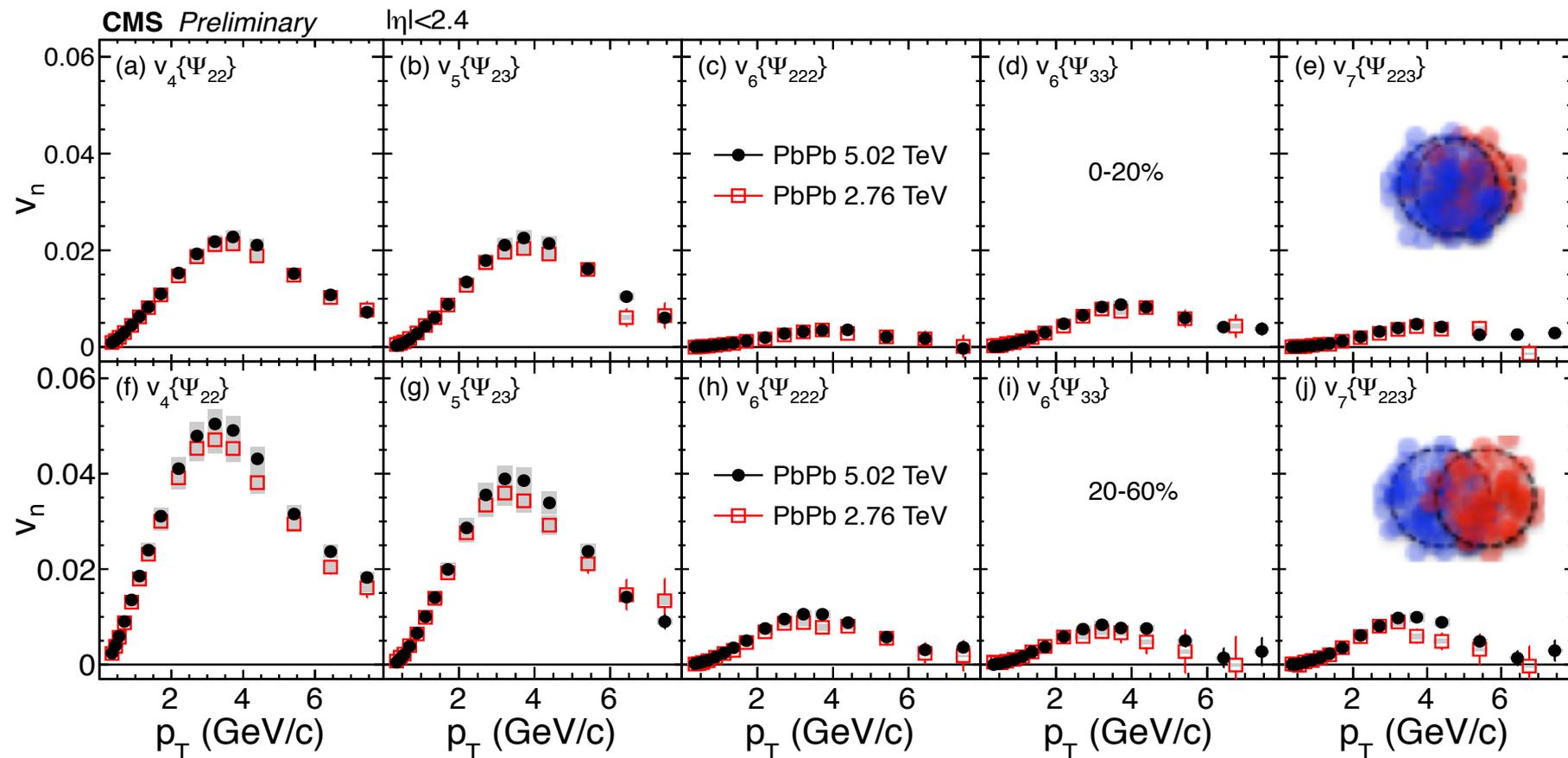
Non-linear part has

- ✧ strong sensitivity to initial-state conditions
- ✧ weak dependence on shear viscosity to entropy density ratio ( $\eta/s$ ) during hydro evolution
- ✧ strong sensitivity to  $\eta/s$  at freeze-out

PRC93(2016)064901



# Mixed harmonics vs $p_T$



CMS PAS HIN-16-018

- ❖ higher order ( $n > 3$ ) mixed harmonics measured wrt lower order harmonics vs  $p_T$
- ❖ first time are measured  $v_5(\Psi_{23})$ ,  $v_6(\Psi_{33})$  and  $v_7(\Psi_{223})$
- ❖ a weak energy dependence

# Linear vs non-linear part

$$v_4(2, |\Delta\eta|>2)$$

$$v_5(2, |\Delta\eta|>2)$$

$$v_6(2, |\Delta\eta|>2)$$

$$v_6(2, |\Delta\eta|>2)$$

$$v_7(2, |\Delta\eta|>2)$$

$$v_4(\Psi_{22})$$

$$v_5(\Psi_{23})$$

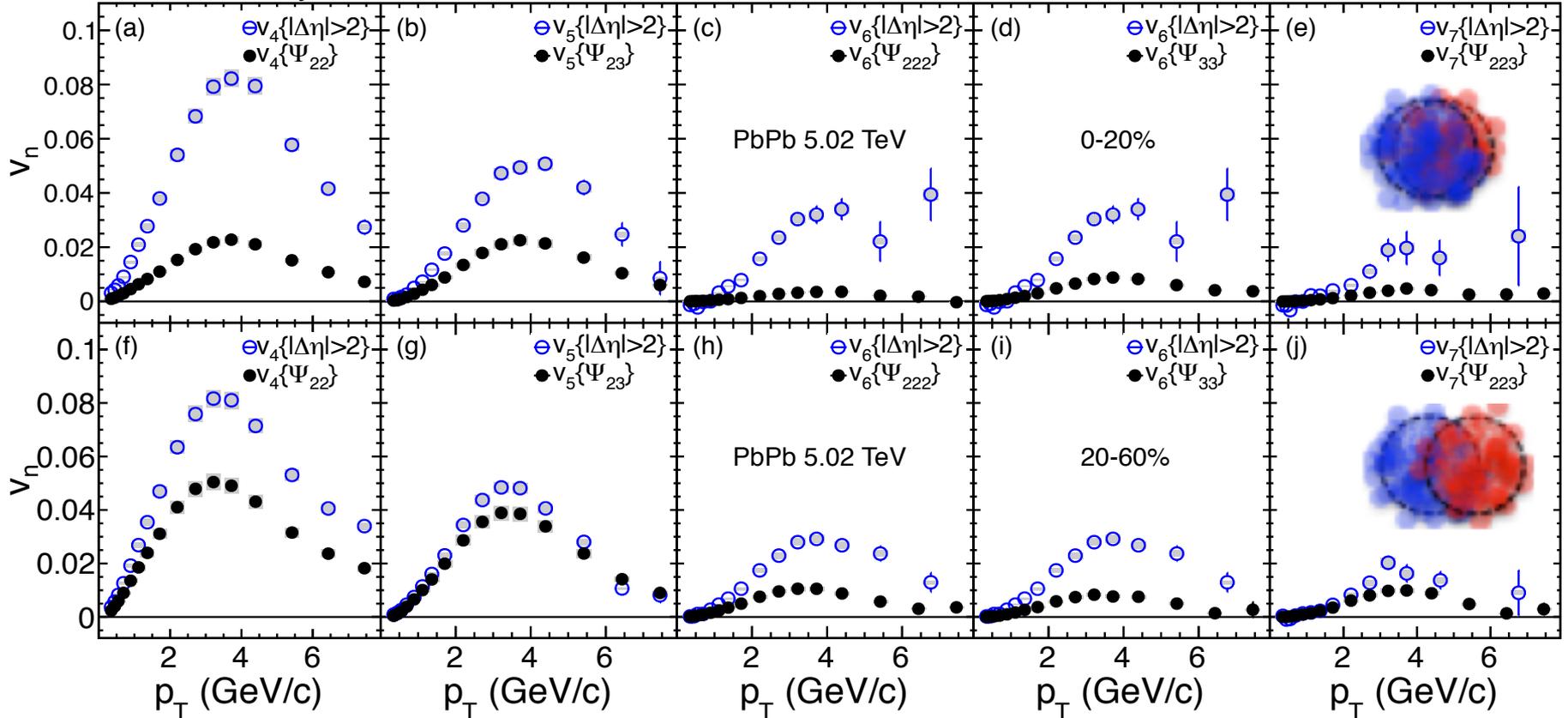
$$v_6(\Psi_{222})$$

$$v_6(\Psi_{33})$$

$$v_7(\Psi_{223})$$

CMS Preliminary

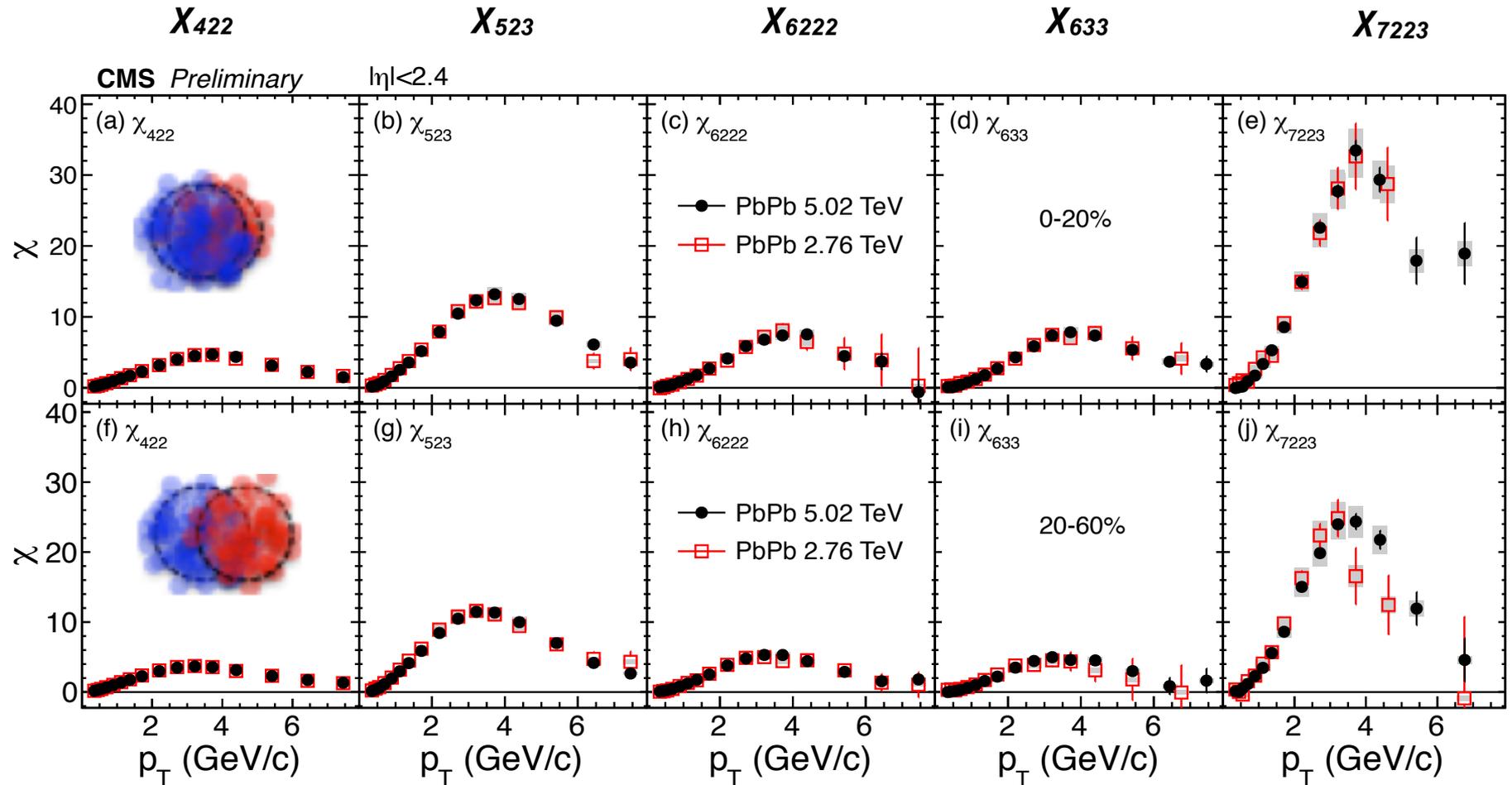
$|\eta|<2.4$



CMS PAS HIN-16-018

- ❖ Larger contribution of non-linear part for odd  $v_5$  and  $v_7$  in 20-60% centrality bin
- ❖ For all  $v_n$  the difference is stronger for central (0-20%) wrt semi-central (20-60%)
- ❖ Smaller statistical uncertainties from mixed harmonics

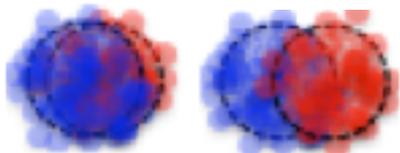
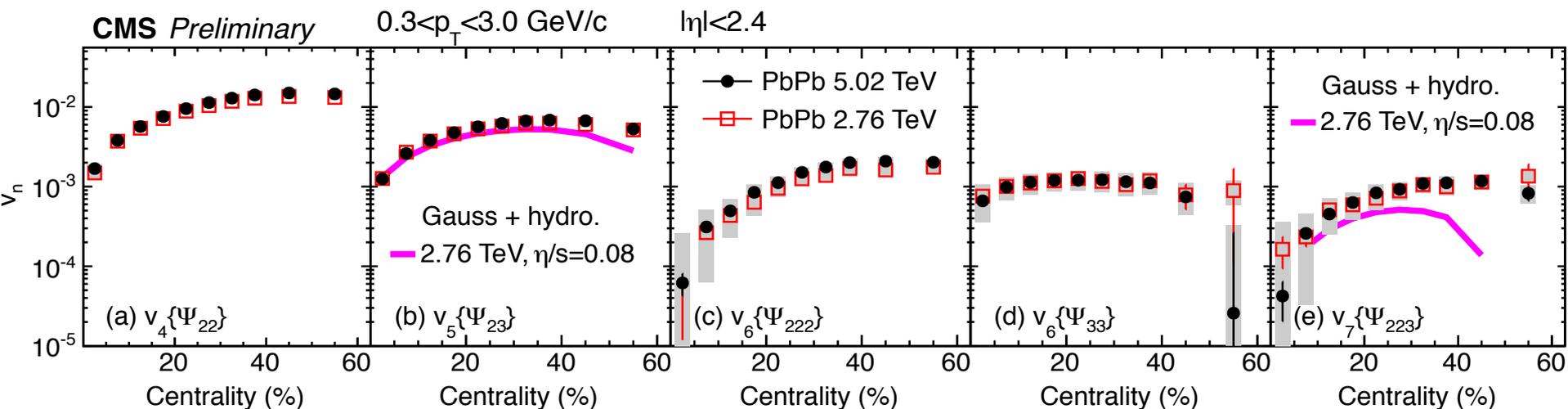
# Non-linear response vs $p_T$



CMS PAS HIN-16-018

- ❖ First time are measured  $X_{422}$ ,  $X_{523}$ ,  $X_{6222}$ ,  $X_{633}$  and  $X_{7223}$
- ❖ Odd  $X_{523}$  and  $X_{7223}$  have a stronger non-linear response wrt the other harmonics
- ❖ nearly no energy dependence

# Mixed harmonics vs centrality and hydro predictions

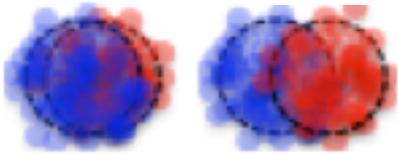
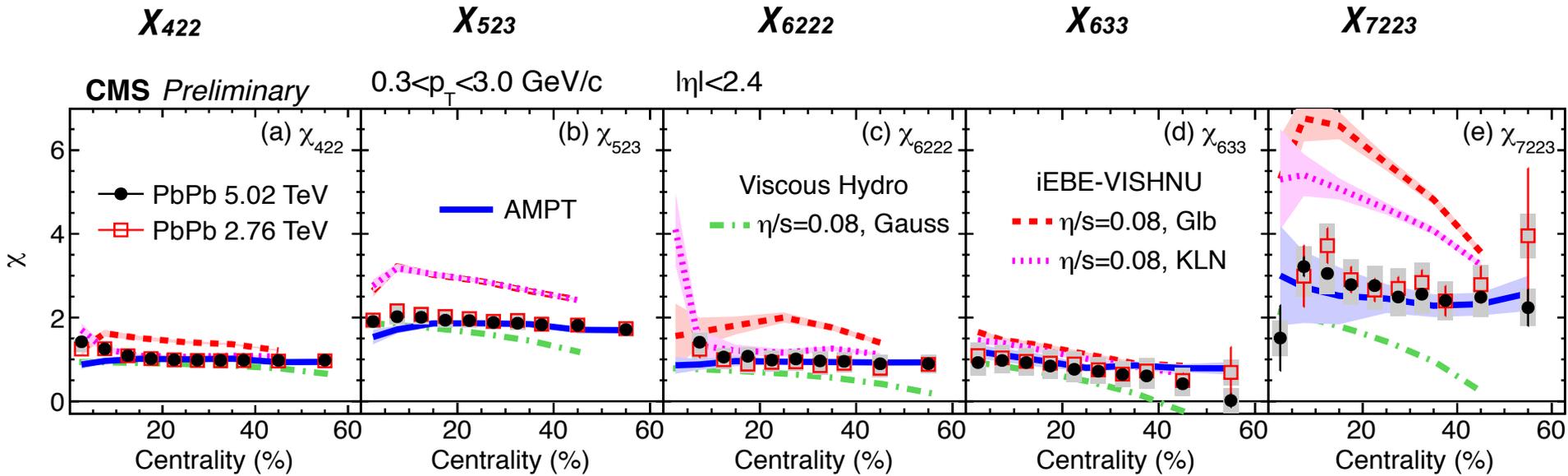


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hydro: PLB 744 (2015) 82

- ❖ Strong centrality dependence for  $v_4(\Psi_{22})$ ,  $v_5(\Psi_{23})$ ,  $v_6(\Psi_{222})$  and  $v_7(\Psi_{223})$
- ❖ Weaker centrality dependence for  $v_6(\Psi_{33})$
- ❖ Again, a weak energy dependence is seen
- ❖ Hydrodynamics predictions with  $\eta/s = 0.08$  at 2.76 TeV describe  $v_5(\Psi_{23})$  data rather well, but not  $v_7(\Psi_{223})$

# Non-linear response vs centrality and comparison with theory predictions

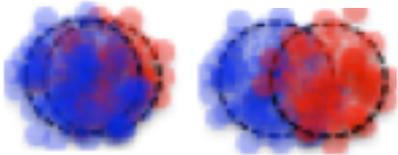
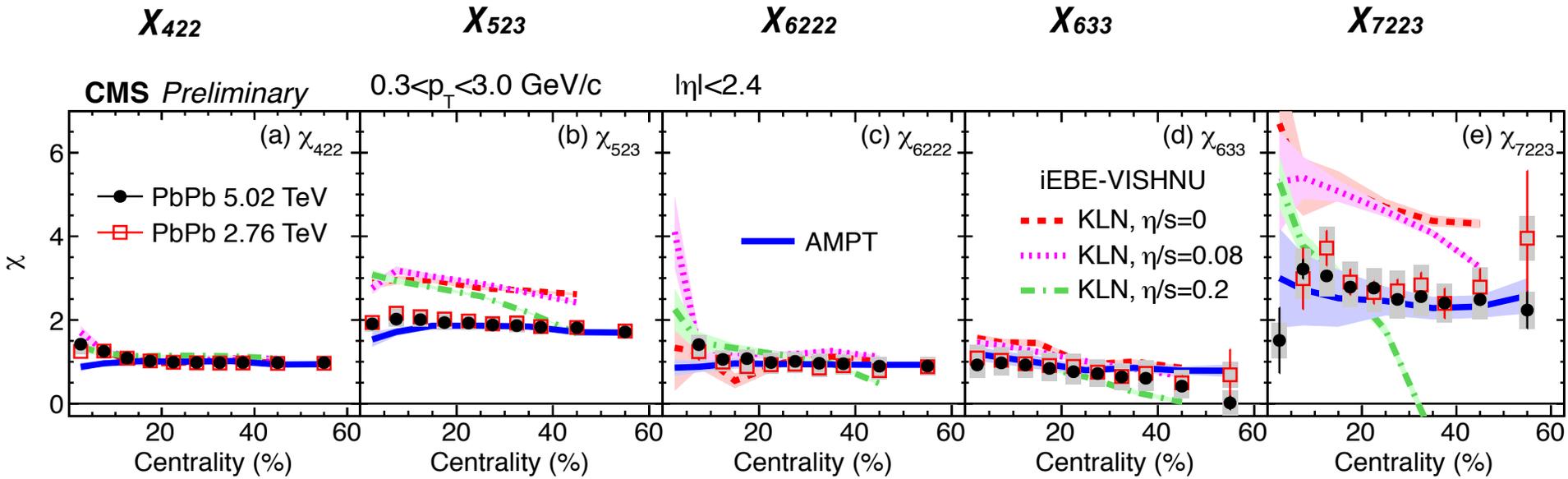


PLB **744** (2015) 82  
 PRC **93** (2016) 064901

CMS PAS HIN-16-018  
 NPA **956** (2016) 340

- ❖ No strong centrality and energy dependence
- ❖ Data for all harmonics are described well with AMPT predictions
- ❖ Strong sensitivity to the initial-state conditions
- ❖ Sensitivity increases with an increase of the harmonic order  $n$

# Non-linear response vs centrality and comparison with theory predictions



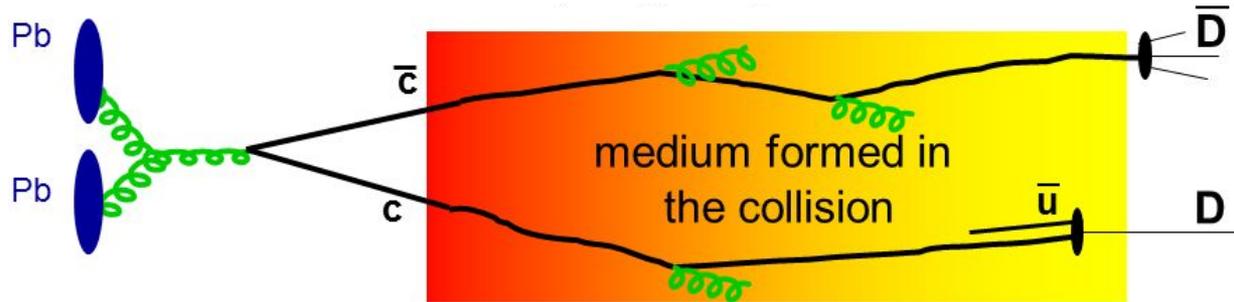
PLB **744** (2015) 82  
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CMS PAS HIN-16-018  
 NPA **956** (2016) 340

- ❖ No strong centrality and energy dependence
- ❖ Data for all harmonics are described well with AMPT predictions
- ❖ Strong sensitivity to the initial-state conditions
- ❖ Sensitivity to  $\eta/s$

# Prompt $D^0$ $v_2$ and $v_3$ flow

- Does c quarks flow as u and d?
- $D^0$   $v_n$  complements  $R_{AA}$  measurements

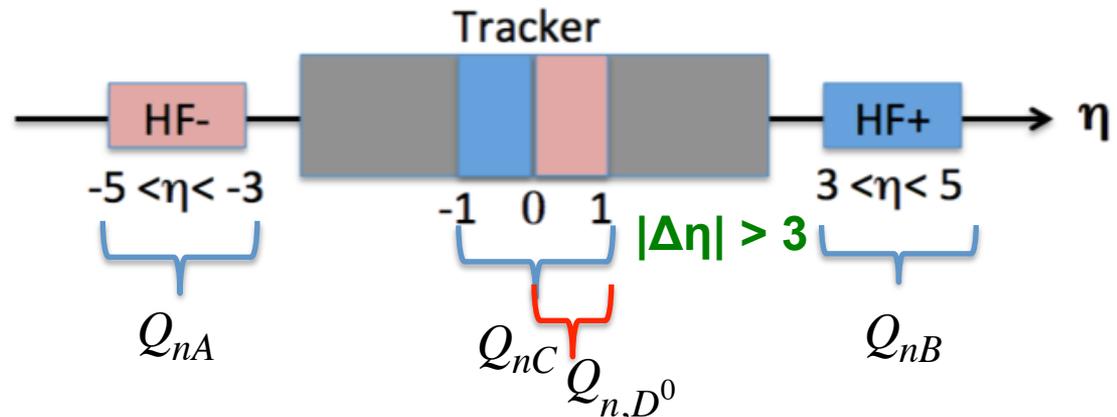


low- $p_T$  – thermalization  
 high- $p_T$  – path length dep.  $R_{AA}$

## Scalar-product method

$$Q_n \equiv \sum_{k=1}^M \varpi_k e^{in\phi_k}$$

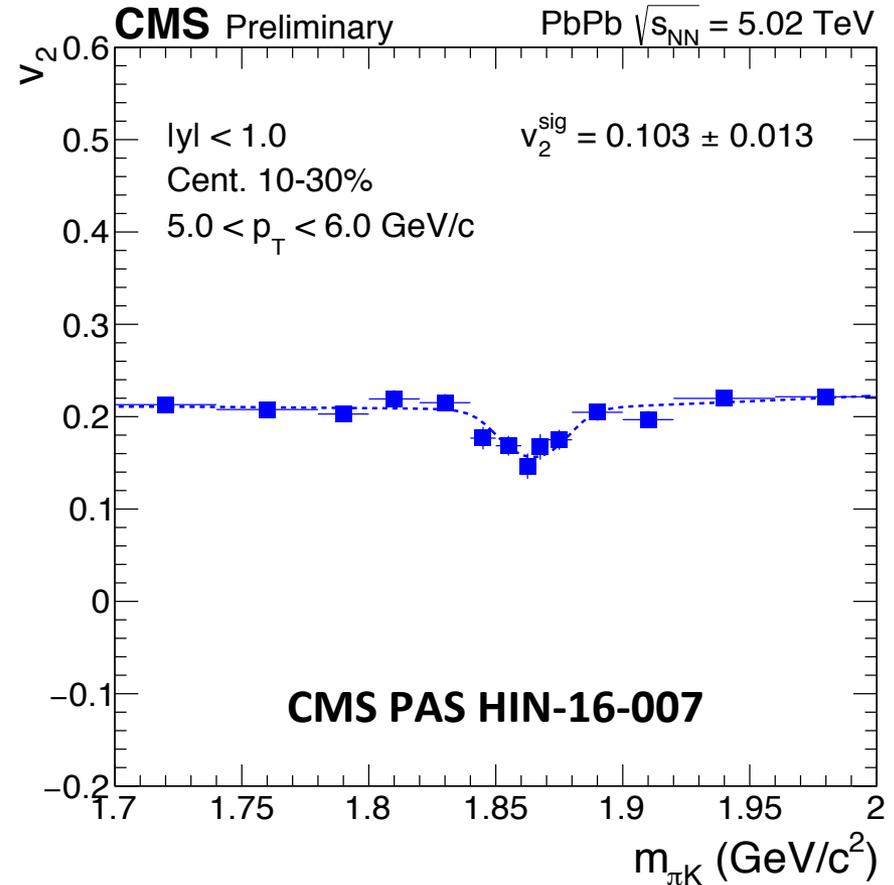
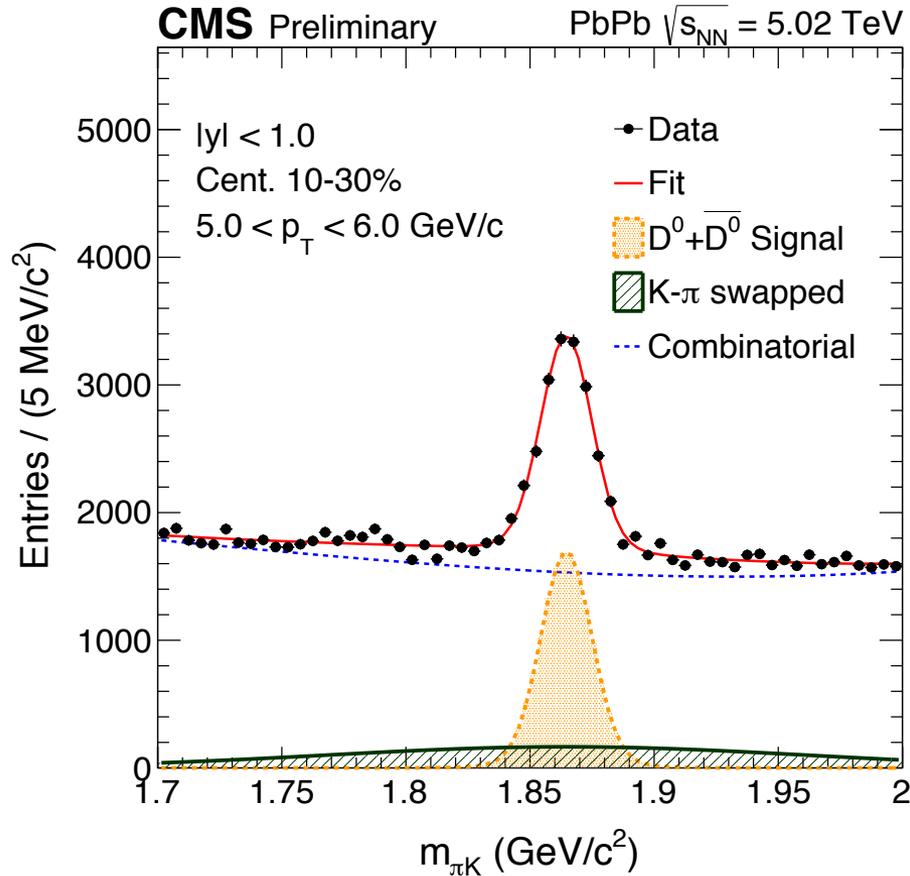
$$v_n \{SP\} = \frac{\langle Q_{n,D^0} Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$$



$$v_n^{S+B}(m) \equiv \alpha(m) v_n^S + [1 - \alpha(m)] v_n^B(m)$$

$$\alpha(m) \equiv \frac{S(m) + SW(m)}{S(m) + SW(m) + B(m)}$$

# Simultaneous fit on invariant mass and $v_n$



- ❖  $D^0(c\bar{u}) \rightarrow K^- \pi^+$  and  $\bar{D}^0(\bar{c}u) \rightarrow K^+ \pi^-$  included. BR  $\approx 4\%$
- ❖ Analysis performed in 3 centrality classes
- ❖  $p_T$  range extended up to 40 GeV/c
- ❖ Crosscheck with  $\Delta\phi$  bins method

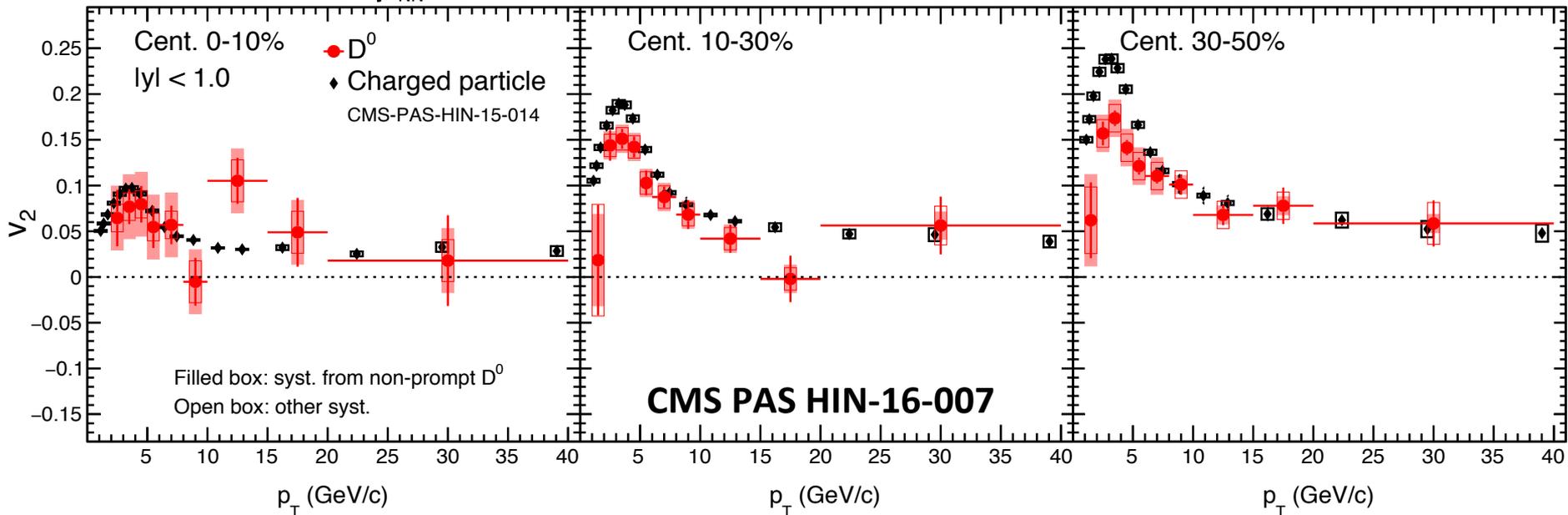
# $v_2$ of prompt $D^0$ meson

0-10%

10-30%

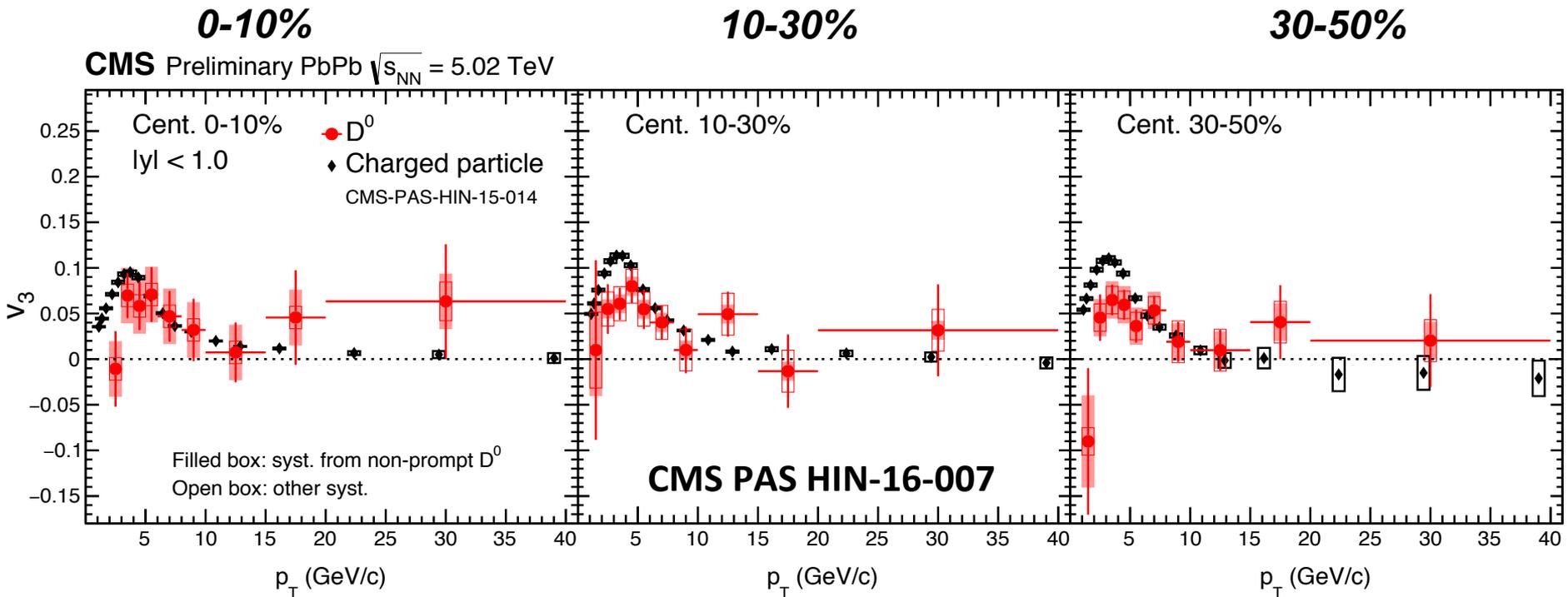
30-50%

CMS Preliminary PbPb  $\sqrt{s_{NN}} = 5.02$  TeV



- ❖ Typical  $p_T$  dependence: a fast increase at low- $p_T$ ; maximum  $\approx 3$  GeV/c and then decrease. Positive up to 40 GeV/c
- ✧ low  $p_T$ : c quark collective motion
- ✧ high- $p_T$ : path length dependence of collective motion
- ✧ shape similar to the one seen for charged particles
- ❖ Typical centrality dependence: increases going from central to peripheral collisions
- ❖ low- $p_T$ :  $v_2(\text{prompt } D^0) < v_2(\text{charged})$  while at high- $p_T$   $v_2(\text{prompt } D^0) \approx v_2(\text{charged})$

# $v_3$ of prompt $D^0$ meson



- ❖ First measurement of prompt  $D^0$   $v_3$
- ❖ Typical  $p_T$  dependence: an increase at low- $p_T$ ; maximum  $\approx 3$  GeV/c and then decrease. At high- $p_T$  close to zero
- ❖ Shape similar to the one seen for charged particles
- ❖ Centrality dependence much weaker than in the  $v_2$  case
- ❖ low- $p_T$ :  $v_3(\text{prompt } D^0) < v_3(\text{charged})$ ; high- $p_T$ :  $v_3(\text{prompt } D^0) \approx v_3(\text{charged})$

# Conclusions

- ❖ The mixed higher-order flow harmonics  $v_4(\Psi_{22})$ ,  $v_5(\Psi_{23})$ ,  $v_6(\Psi_{222})$ ,  $v_6(\Psi_{33})$  and  $v_7(\Psi_{223})$  and non-linear response coefficients  $X_{422}$ ,  $X_{523}$ ,  $X_{6222}$ ,  $X_{633}$  and  $X_{7223}$  are measured in 5.02 TeV PbPb collisions
- ❖ These results are sensitive to initial conditions and  $\eta/s$  at freeze-out, providing constraints on the theoretical description of heavy ion collisions
- ❖ First measurement of  $D^0$   $v_3$
- ❖  $v_2$  positive up to 40 GeV/c
- ✧ low- $p_T$ :  $v_n(\text{prompt } D^0) < v_n(\text{charged})$
- ✧ high- $p_T$ :  $v_n(\text{prompt } D^0) \approx v_n(\text{charged})$
- ❖ important input for theoretical predictions

