New results on collectivity with CMS

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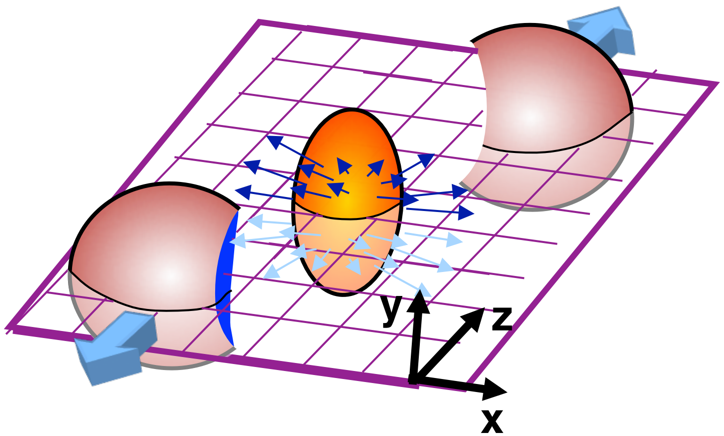
Outline

- 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 η/s and initial conditions
- There is a fine splitting between cumulants of different orders
  - Induces appearance of the negative skewness predicted by hydrodynamics
    - Could help in constraining the initial conditions
  - Comparison with hydro predictions and other experimental results
- Conclusions

Anisotropy harmonics v_n

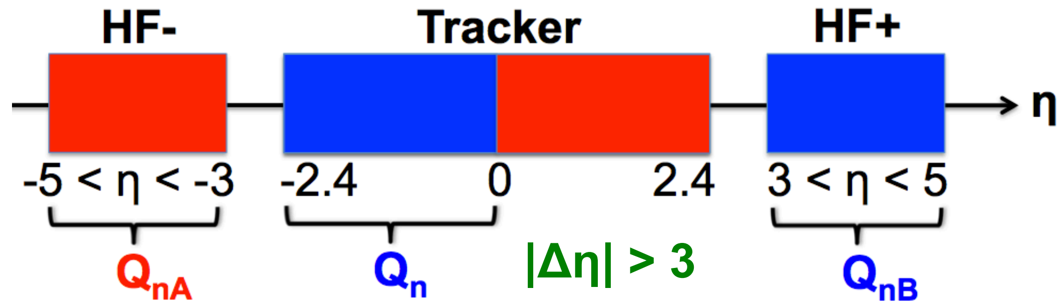
Ideal geometry – only v_2

event plane x-z



2PC $v_n = \langle\langle \cos(n\Delta\phi) \rangle\rangle$

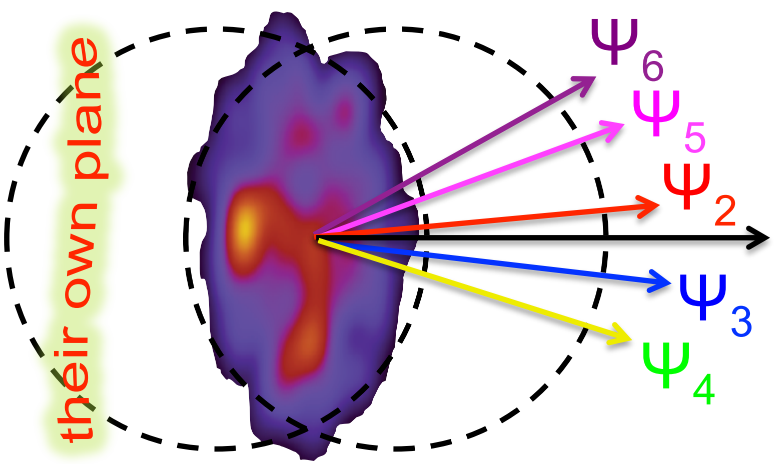
Scalar Product (SP)



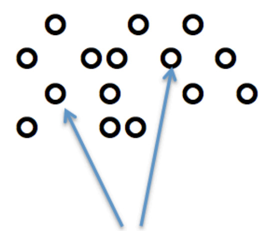
$$v_n\{SP\} = \frac{\langle Q_n Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$$

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

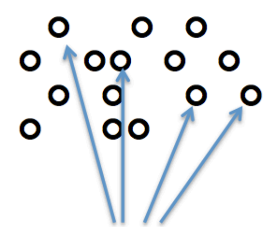
initial-state fluctuations ↓



multi-particle correlations



$$\langle e^{in(\varphi_1 - \varphi_2)} \rangle$$



$$\langle e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle$$

- even higher order cumulants

Mixed harmonics - motivation

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

*PLB **744**(2015)82*

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

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

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

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

linear

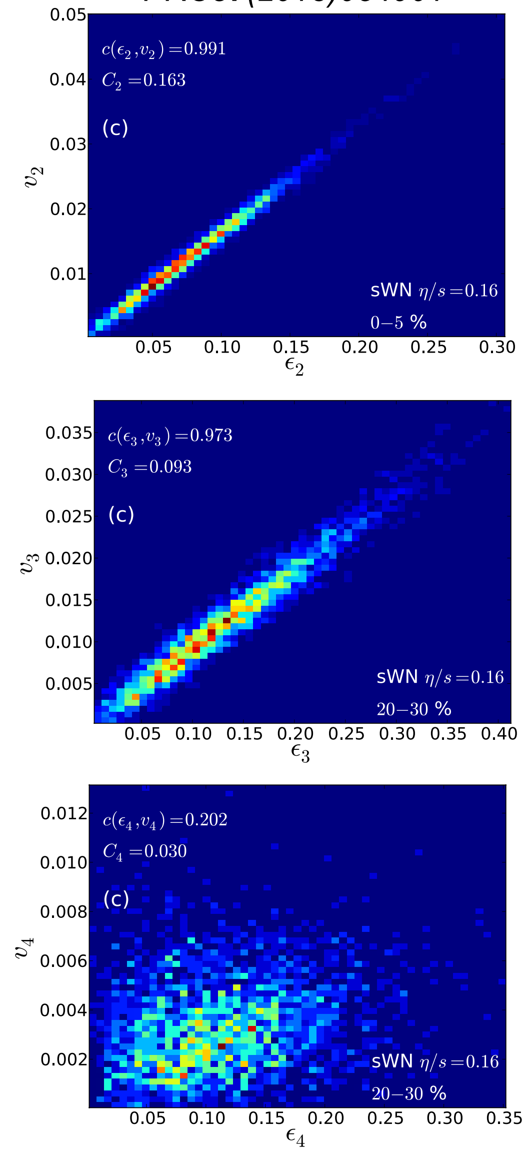
non-linear: $v_n \sim f(\varepsilon_2, \varepsilon_3)$

- Mixed harmonics can separate linear and non-linear part. Example: v_5 wrt direction of v_2 and v_3

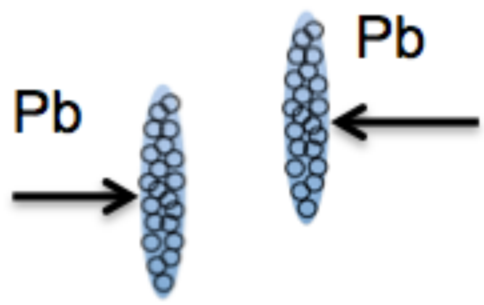
$$v_5\{\Psi_{23}\} \equiv \frac{\mathrm{Re}\langle V_5 V_2^* V_3^* \rangle}{\sqrt{\langle |V_2|^2 |V_3|^2 \rangle}} = \frac{\langle v_5 v_2 v_3 \cos(5\Psi_5 - 2\Psi_2 - 3\Psi_3)\rangle}{\sqrt{\langle v_2^2 v_3^2 \rangle}}$$

$$\chi_{523} \equiv \frac{\mathrm{Re}\langle V_5 V_2^* V_3^* \rangle}{\langle |V_2|^2 |V_3|^2 \rangle} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle v_2^2 v_3^2 \rangle}}$$

*PRC**87**(2013)054901*

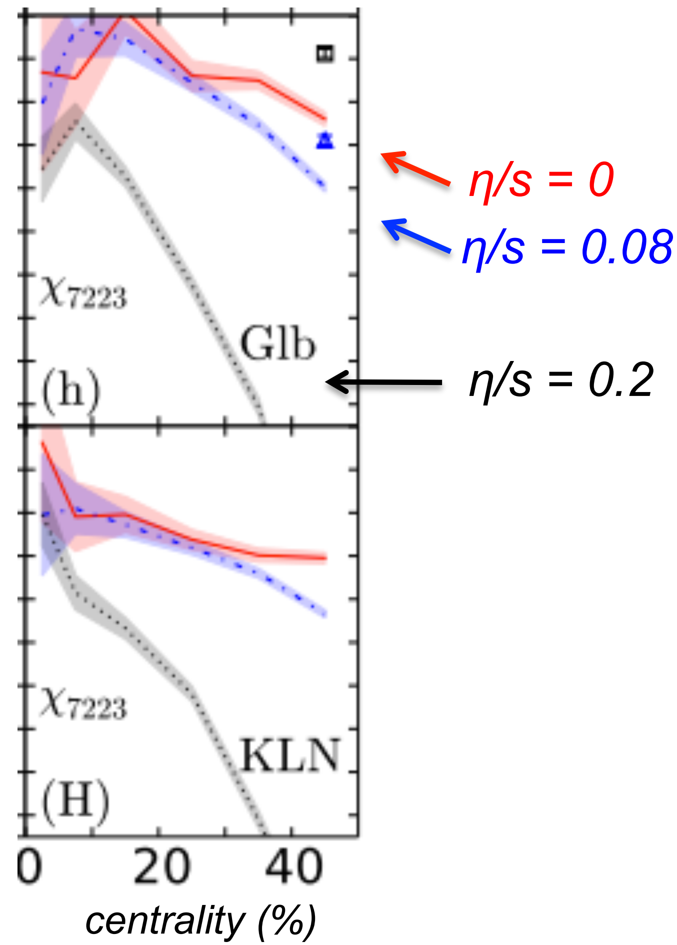


Mixed harmonics and non-linear contributions in PbPb

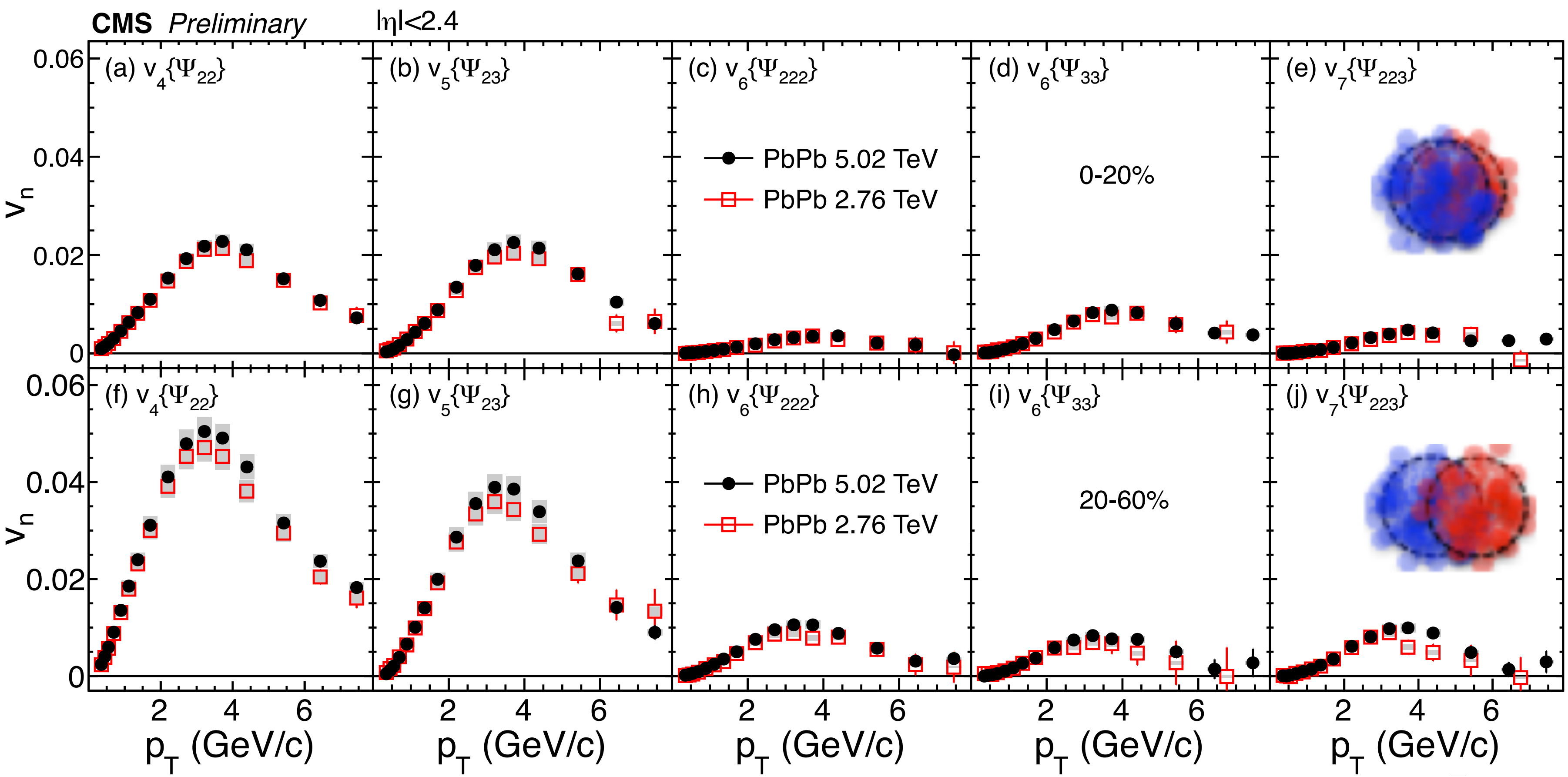


Non-linear part has
✧ strong sensitivity to initial-state conditions
✧ weak dependence on shear viscosity to entropy density ratio (η/s) during hydro evolution
✧ strong sensitivity to η/s at freeze-out

*PRC**93**(2016)064901*



Mixed harmonics *vs* p_T

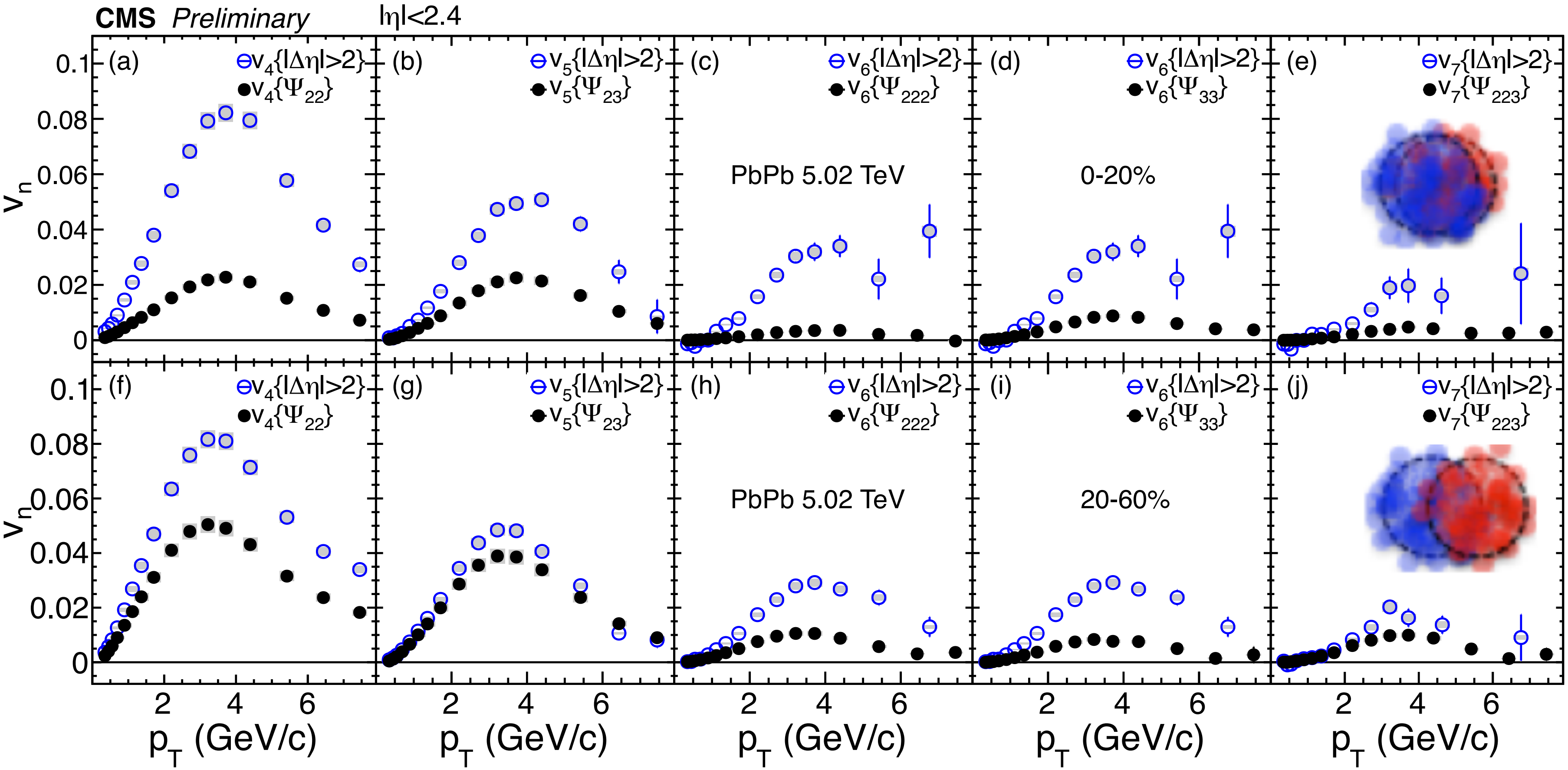


CMS PAS HIN-16-018

- 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

$v_4(2, \|\Delta\eta\|>2)$	$v_5(2, \|\Delta\eta\|>2)$	$v_6(2, \|\Delta\eta\|>2)$	$v_6(2, \|\Delta\eta\|>2)$	$v_7(2, \|\Delta\eta\|>2)$
$v_4(\Psi_{22})$	$v_5(\Psi_{23})$	$v_6(\Psi_{222})$	$v_6(\Psi_{33})$	$v_7(\Psi_{223})$



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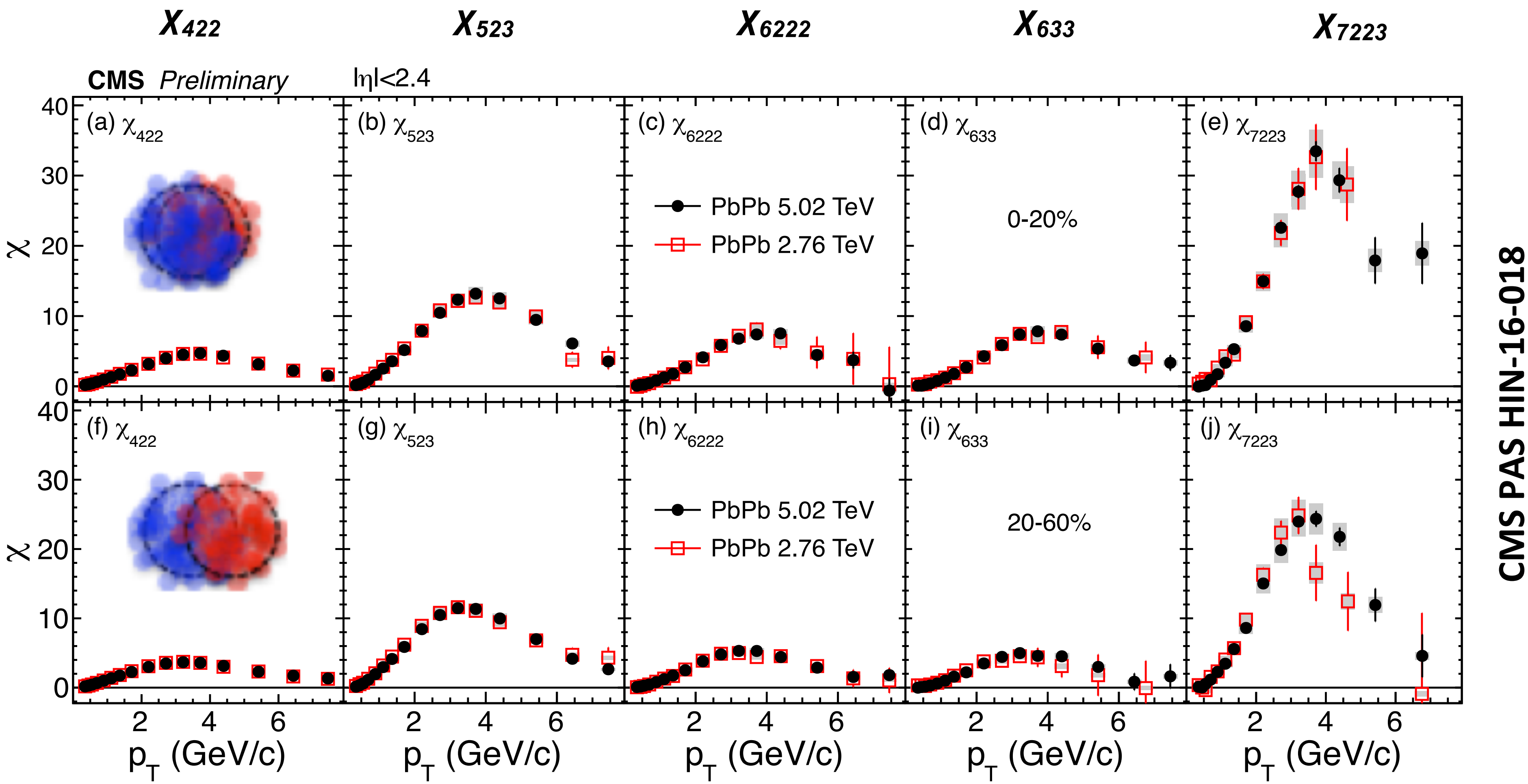
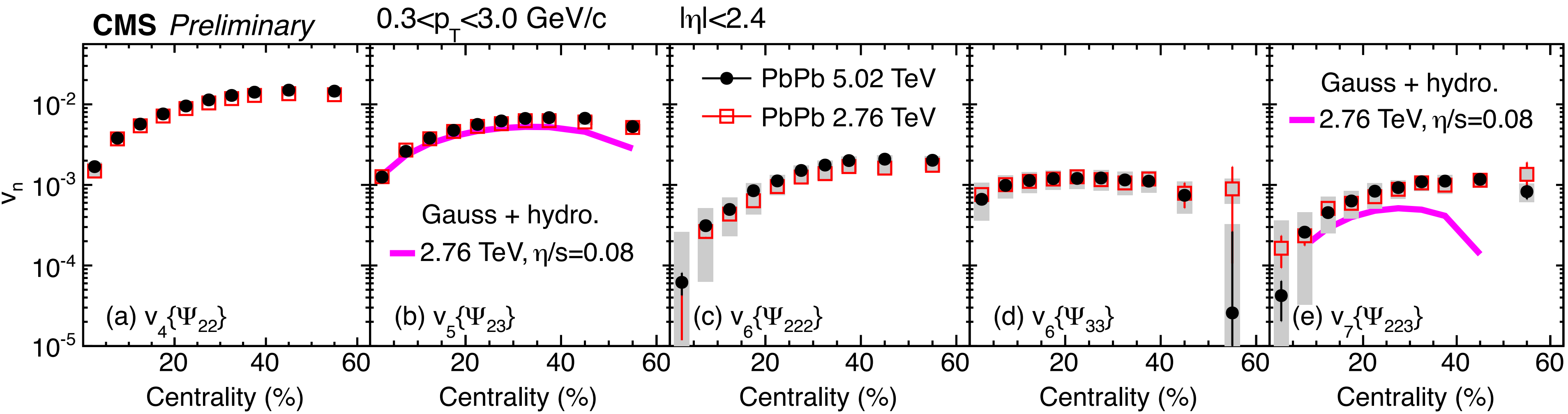
- Larger contribution of non-linear part for odd v_5 and v_7 in 20-60% centrality bin
- For all v_n the difference is stronger for central (0-20%) wrt semi-central (20-60%)
- Smaller statistical uncertainties from mixed harmonics

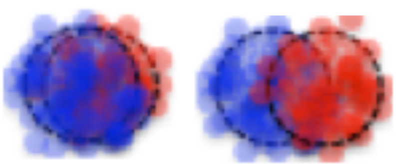
Non-linear response *vs* p_T



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

Mixed harmonics *vs* centrality and hydro predictions



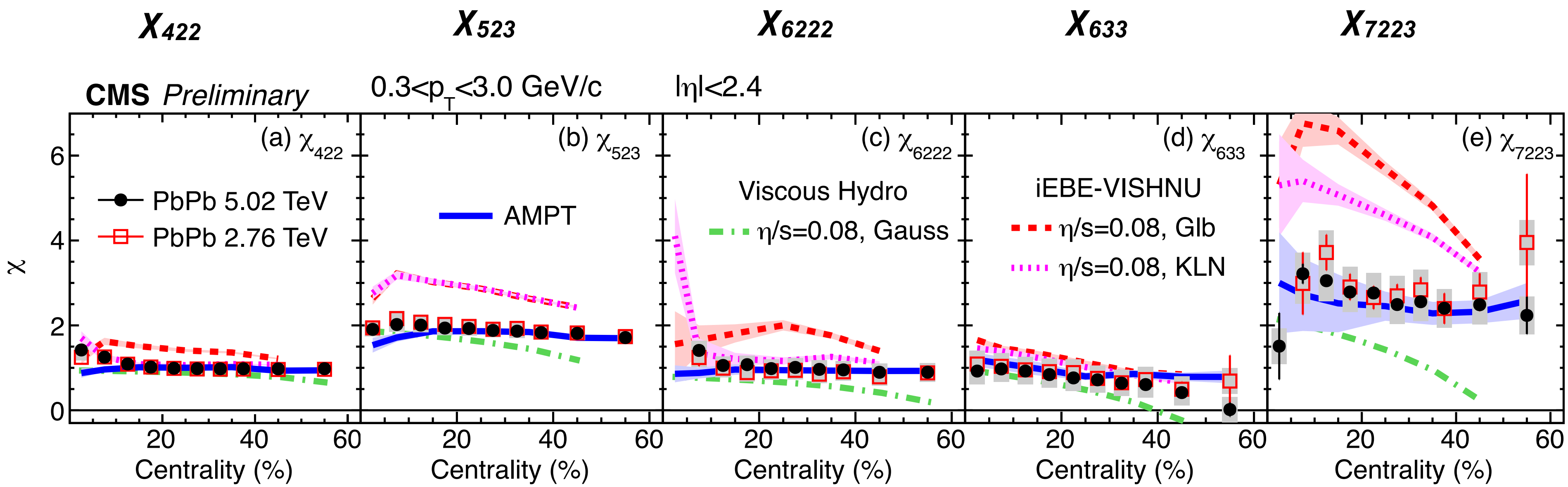


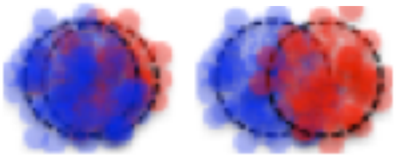
CMS PAS HIN-16-018

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 *η/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





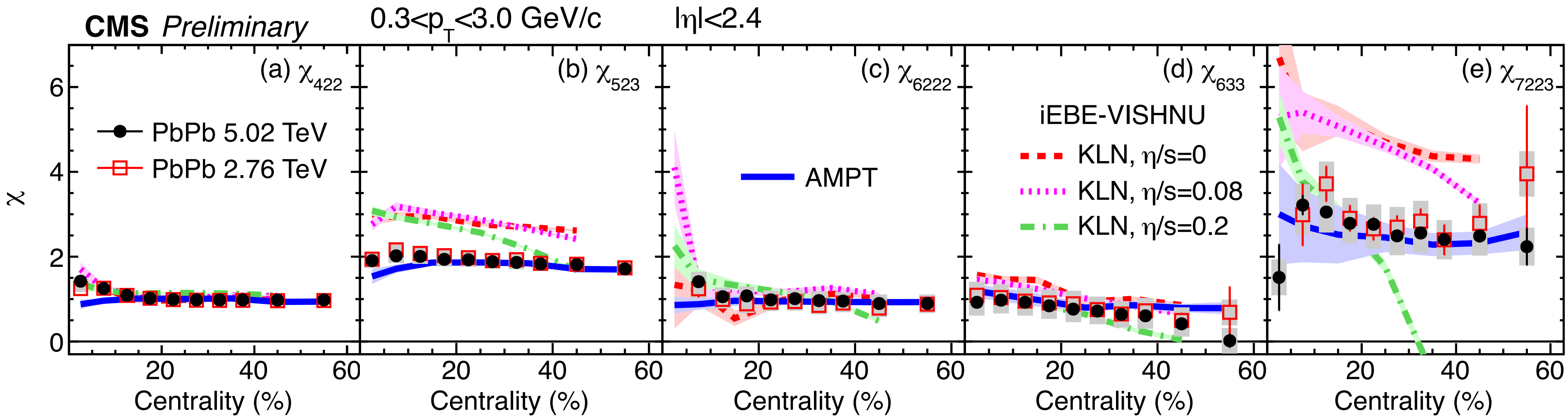
PLB **744** (2015) 82
PRC **93** (2016) 064901

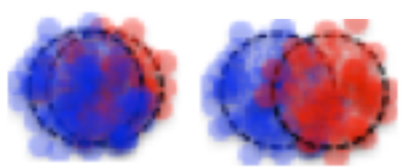
CMS PAS HIN-16-018
NPA **956** (2016) 340

- 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

χ_{422} χ_{523} χ_{6222} χ_{633} χ_{7223}



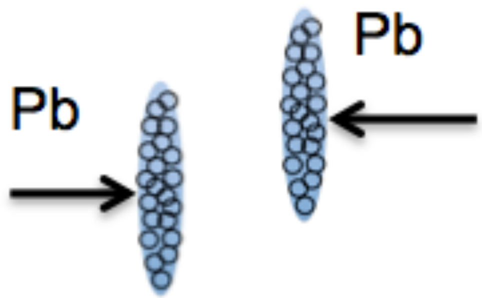


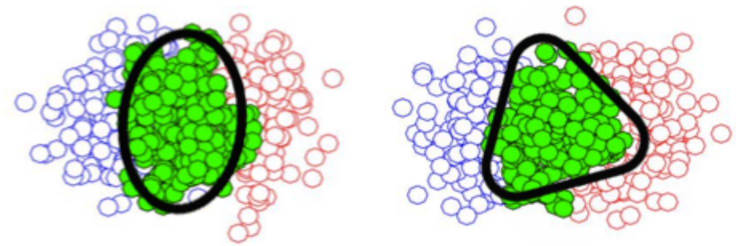
PLB **744** (2015) 82
PRC **93** (2016) 064901

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

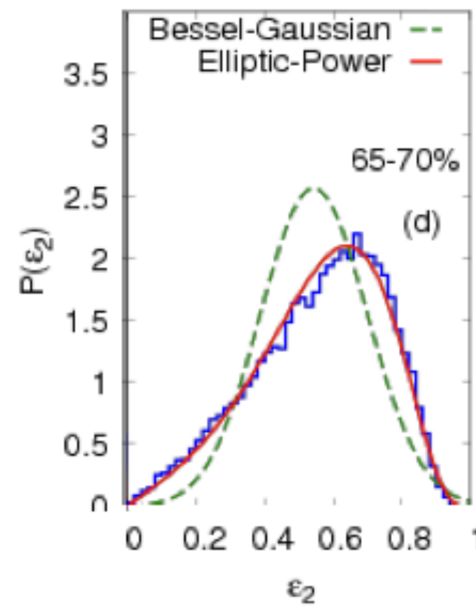
- No strong centrality and energy dependence
- Data for all harmonics are described well with AMPT predictions
- Strong sensitivity to the initial-state conditions
- Sensitivity to η/s

Fine splitting of harmonics and skewness





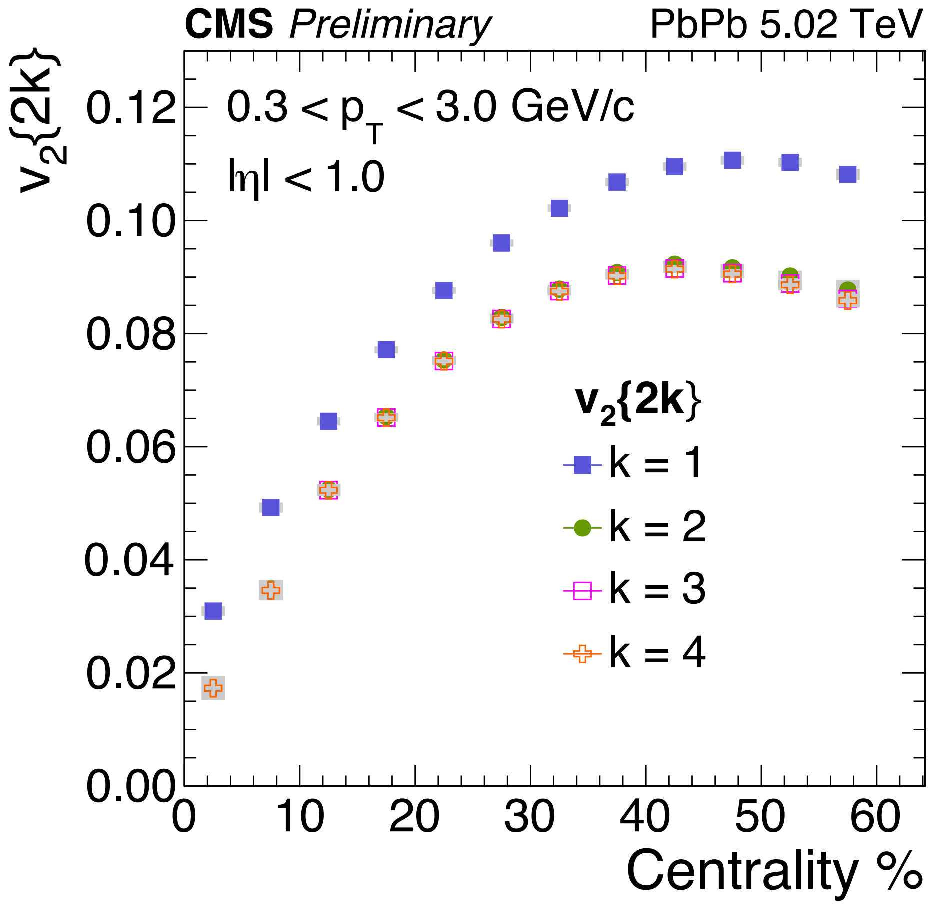
PRC **81** (2010) 054905



PRC **90** (2014) 024903

- ✧ Participant eccentricity fluctuates
- ✧ Probed by multi-particle cumulants
- ✧ Fine splitting is observed between *$v_2\{4\}$* and *$v_2\{6\}$*
- ✧ *$p\{\varepsilon_2\}$* is skewed
- ✧ Skewness can help in constraining the initial conditions

Different order cumulants *vs* centrality

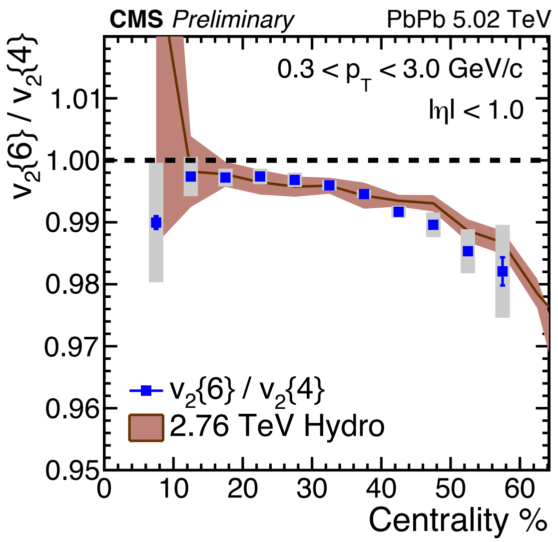


CMS PAS HIN-16-019

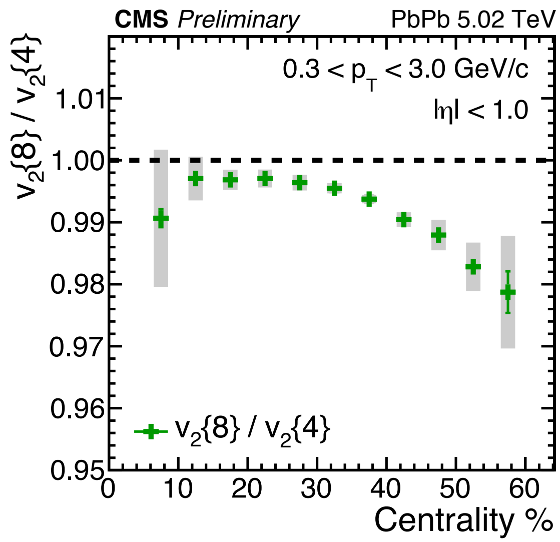
- Rough ordering of $v_2\{2k\}$ cumulants show an expected behavior: $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Weakly visible splitting of the higher-order cumulants is more pronounced in peripheral collisions

Higher-order cumulants ratios

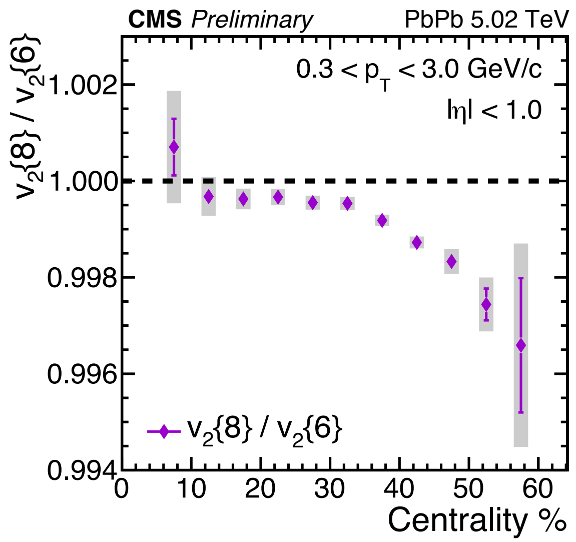
$v_2\{6\}/v_2\{4\}$



$v_2\{8\}/v_2\{4\}$



$v_2\{8\}/v_2\{6\}$

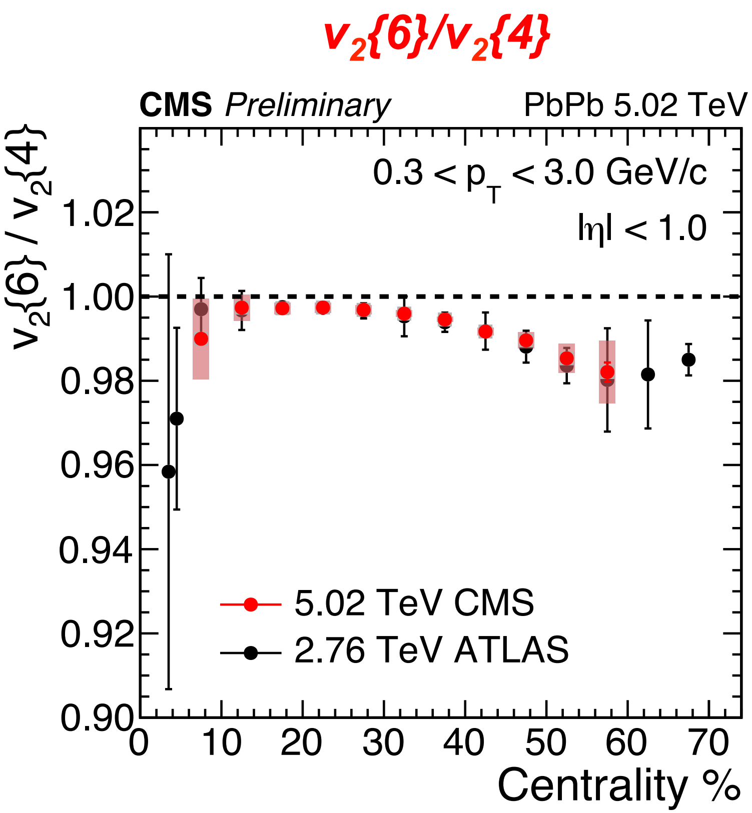


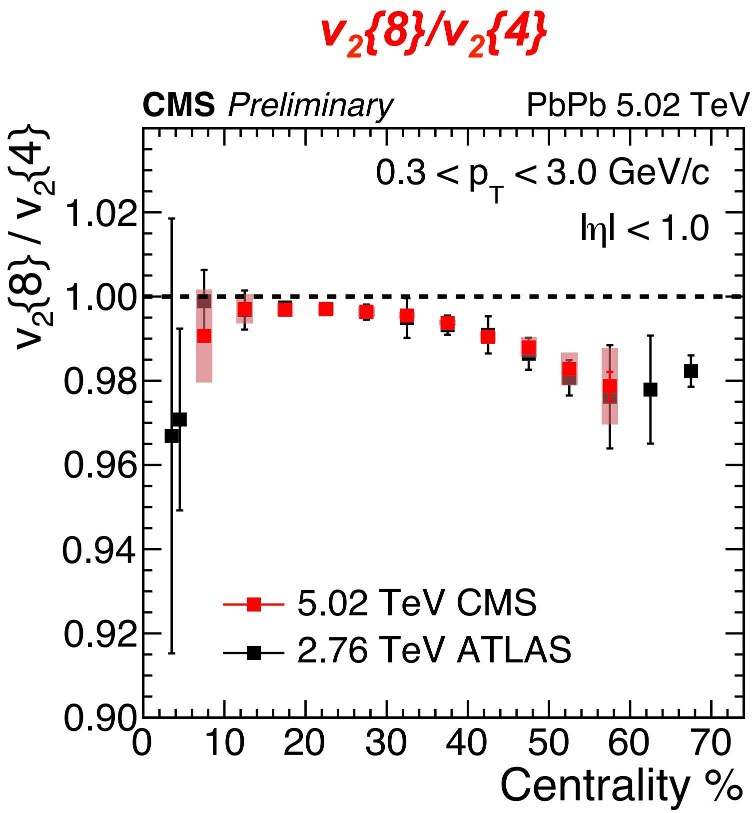
CMS PAS HIN-16-019

Hydro: PRC 95 (2017) 014903

- Earlier observation $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ is consistent with the Gaussian model fluctuation of flow harmonics
- But, there is a fine splitting between higher-order cumulants which orders them as: $v_2\{4\} > v_2\{6\} > v_2\{8\}$
- The effect is on the percent level
- Hydrodynamic predictions for 2.76 TeV consistent with measurement at 5.02 TeV

Comparison to other measurements



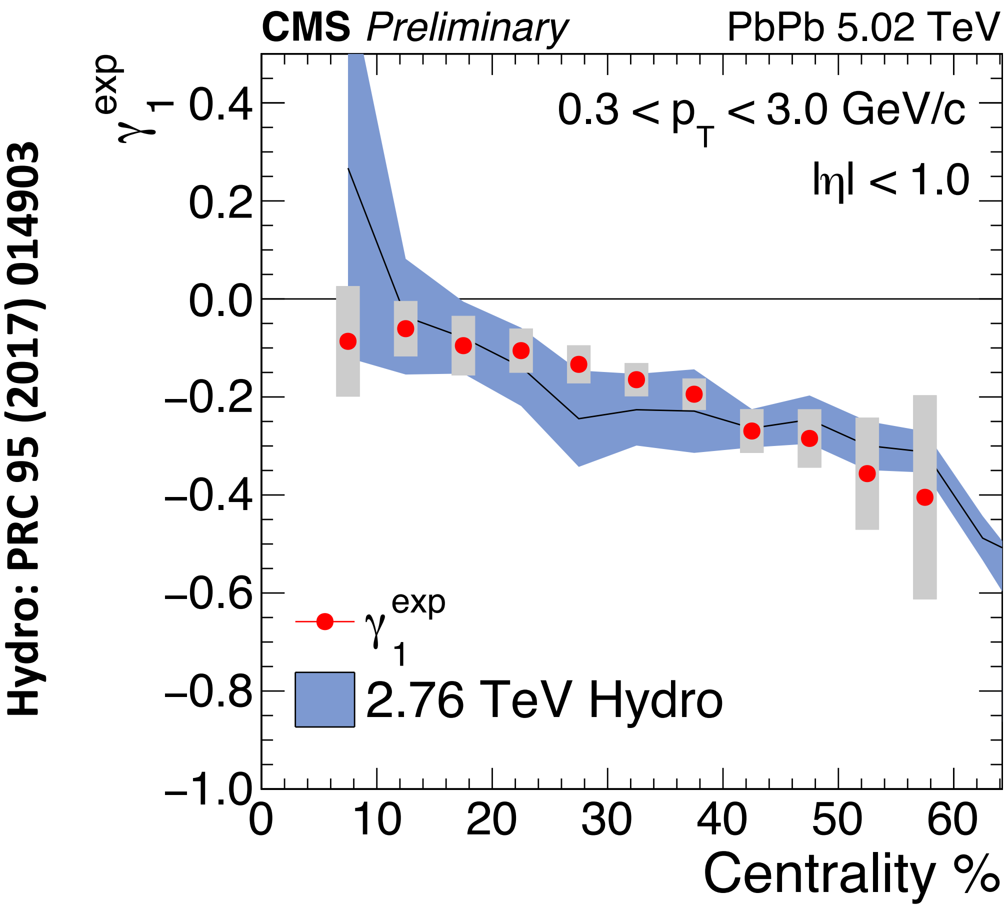


CMS PAS HIN-16-019

ATLAS: Eur.Phys.J. C 74 (2014)3157

- Due to a weak energy dependence between 2.76 and 5.02 TeV, higher-order cumulant ratios consistent between these two measurements
- CMS achieved better precision in these measurements

Skewness γ_1^{exp}



- Experimental definition:

$$\gamma_1^{exp} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{\left(v_2\{2\}^2 - v_2\{4\}^2\right)^{3/2}}$$

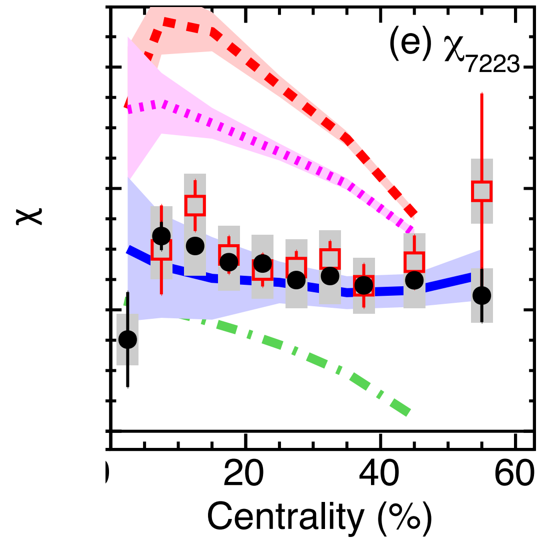
$$\approx \frac{\left\langle \left(v_2^{RP} - \left\langle v_2^{RP} \right\rangle\right)^3 \right\rangle}{\left(\sqrt{\left\langle \left(v_2^{RP}\right)^2 \right\rangle - \left\langle v_2^{RP} \right\rangle^2}\right)^3}$$

CMS PAS HIN-16-019

- If flow harmonic fluctuation is Gaussian, then skewness should be zero
- Non-Gaussian fluctuations makes splitting between $v_2\{4\}$ and $v_2\{6\}$ cumulants and lead to a negative γ_1^{exp}
- Hydrodynamic predictions for 2.76 TeV consistent with 5.02 TeV measurement

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 χ_{422}, χ_{523}, χ_{6222}, χ_{633} and χ_{7223} are measured in 5.02 TeV PbPb collisions
- These results are sensitive to initial conditions and η/s at freeze-out, providing constraints on the theoretical description of heavy ion collisions



- Higher-order cumulants are splitted and ordered as: $v_2\{4\} > v_2\{6\} > v_2\{8\}$
- A negative skewness is observed