

# Linear and non-linear flow modes of charged and identified particles in Pb–Pb collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV with ALICE

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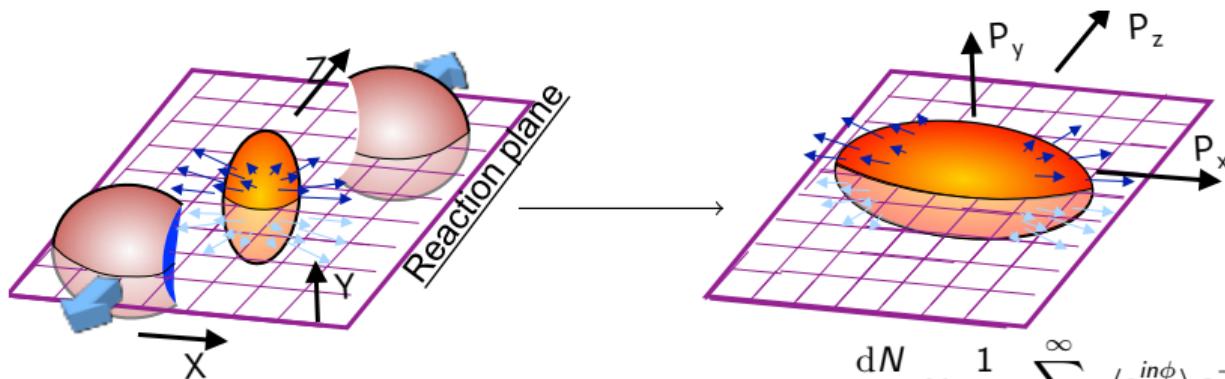


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# Anisotropic Flow

Initial geometry fluctuations → Transport  $\delta_\mu T^{\mu\nu} = 0$  → final-state particles



$$\varepsilon_n e^{in\Phi_n} \equiv -\frac{\langle r^n e^{in(\phi-\Phi_n)} \rangle}{\langle r^n \rangle}, \quad n \geq 2. \quad (1)$$

(theory only - initial state models)

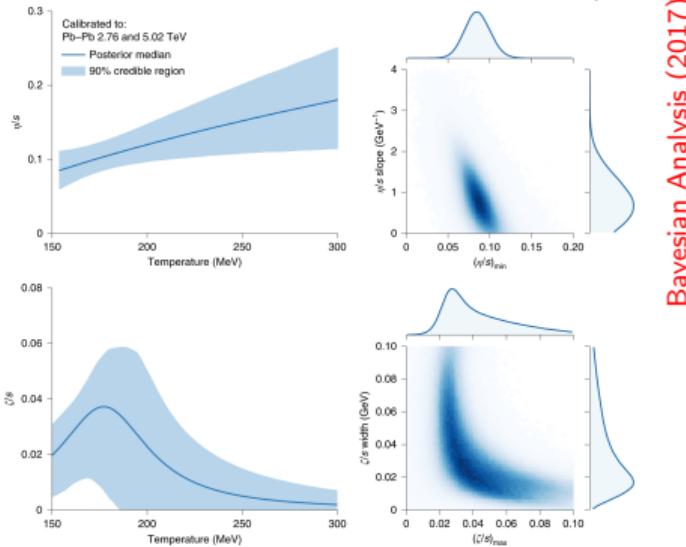
$$\frac{dN}{d\phi} \propto \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} \underbrace{\langle e^{in\phi} \rangle}_{V_n} e^{-in\phi}, \quad (2)$$

where  $V_n \equiv \langle e^{in\phi} \rangle = v_n e^{in\psi_n}$ . (experiments, theory - hydro+hadronization models with  $\eta/s(T)$ ,  $\zeta/s(T)$ )

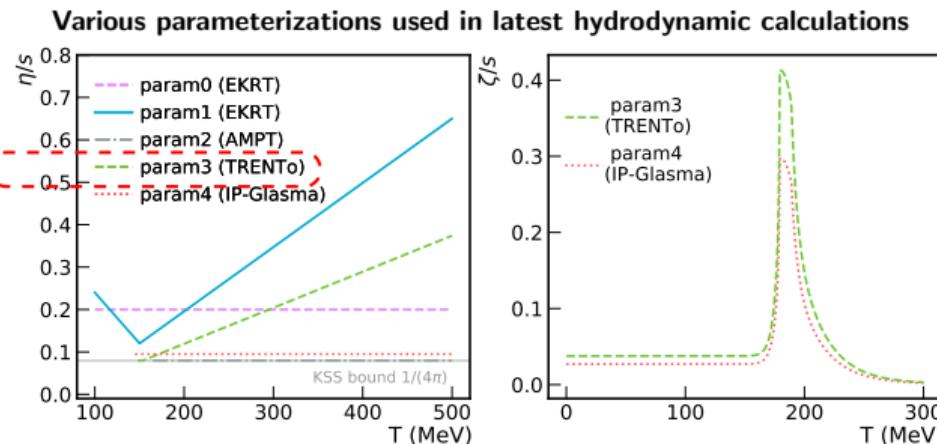
- Collectivity as a probe to the properties of the medium – transport properties such as  $\eta/s(T)$ ,  $\zeta/s(T)$

# Current understanding of the medium properties

Steffen A. Bass et. al, Nature Physics (2019)



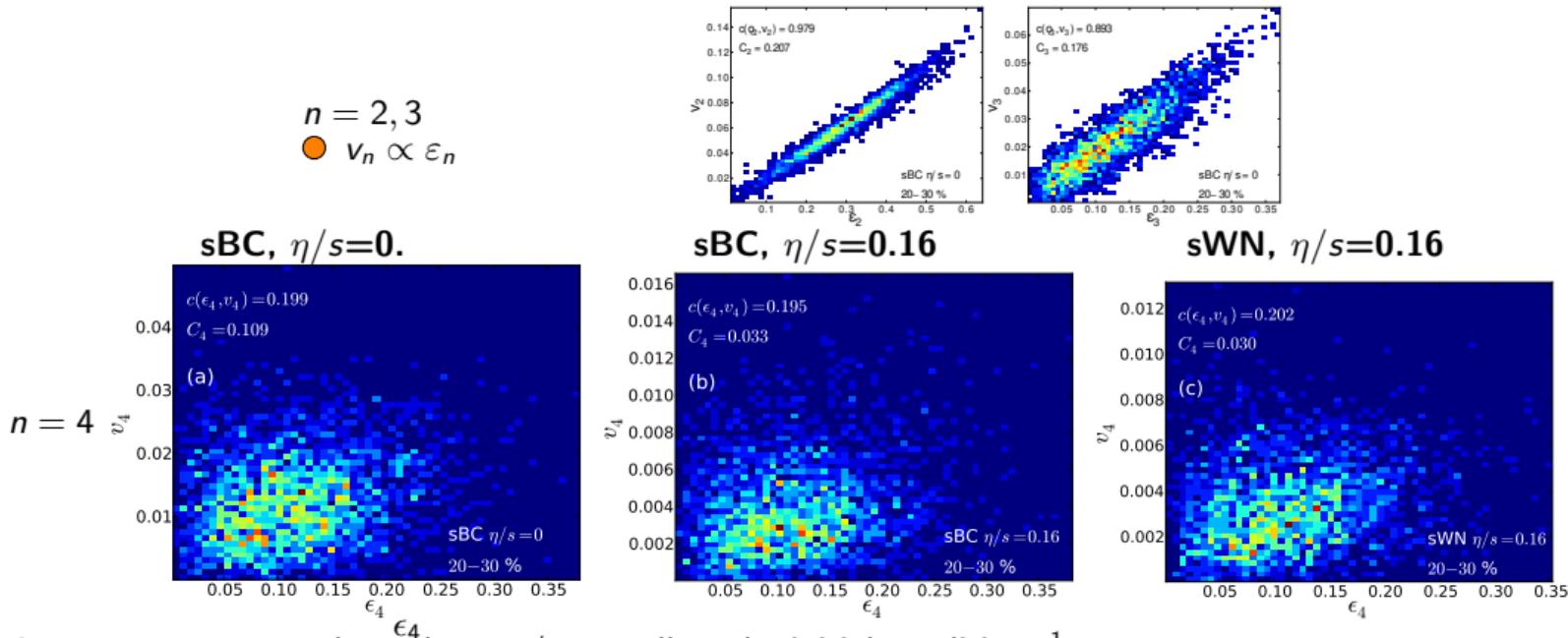
Bayesian Analysis (2017)



- ALICE data on multiplicity, spectra and flow are key inputs to estimate the properties of the QGP (including p–Pb data), i.e Global Bayesian Analysis and other theory groups.
- Best fit seems to indicate  $\eta/s \approx 0.12$  around  $T_c \approx 150$  MeV, very close to  $1/4\pi$  ( $\approx 0.08$ ) from string theory<sup>1</sup> (AdS/CFT correspondence).
- $\eta/s(T)$  and  $\zeta/s(T)$  should be constrained further (larger uncertainties) by separating the effects from the initial conditions.

<sup>1</sup>D. T. Son et. al. Phys. Rev. Lett. 94 (2005) 111601

Non-linearity of the higher order flow,  $\varepsilon_n \propto v_n$  holds only for  $n = 2, 3$



- $v_4$  response to  $\varepsilon_4$  depends on  $\eta/s$  as well as the initial conditions.<sup>1</sup>
- For a rather minimal value of  $\eta/s = 1/4\pi$ , larger contributions from non-linear corrections.<sup>2</sup>

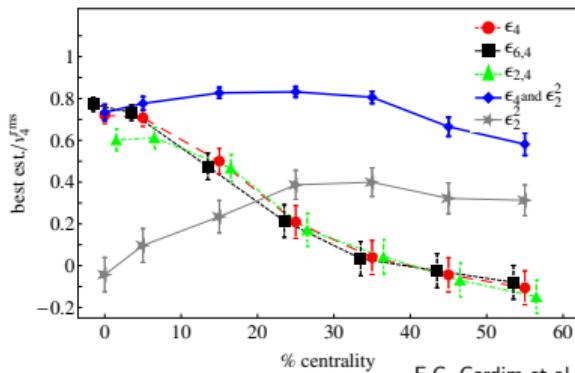
<sup>1</sup>H. Niemi et al., Phys. Rev. C 87, 054901 (2013)

<sup>2</sup>D.Teaney, L.Yan Phys.Rev. C86 (2012) 044908

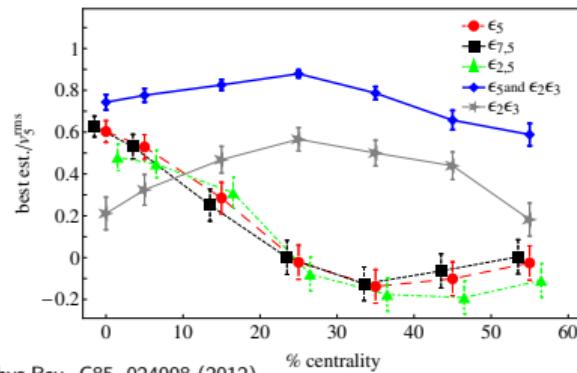
# Non-linearity of the higher order flow and cross-harmonic decomposition

- Decomposition into linear and non-linear contributions

$$v_4 e^{in\psi_4} = k \epsilon_4 e^{4i\Phi_4} + k' \epsilon_2^2 e^{4i\Phi_2}$$



$$v_5 e^{in\psi_5} = k \epsilon_5 e^{5i\Phi_5} + k' \epsilon_2 e^{2i\Phi_2} \epsilon_3 e^{3i\Phi_3}$$



The magnitude of the Non-linear contribution and non-linear flow mode coefficients:

$$\begin{aligned} v_{4,22} &= \frac{\Re \langle V_4 (V_2^*)^2 \rangle}{\sqrt{\langle |V_2|^4 \rangle}} \\ &\approx \langle v_4 \cos(4\psi_4 - 4\psi_2) \rangle, \quad (4) \\ \chi_{4,22} &= \frac{v_{4,22}}{\sqrt{\langle |V_2|^4 \rangle}}. \end{aligned}$$

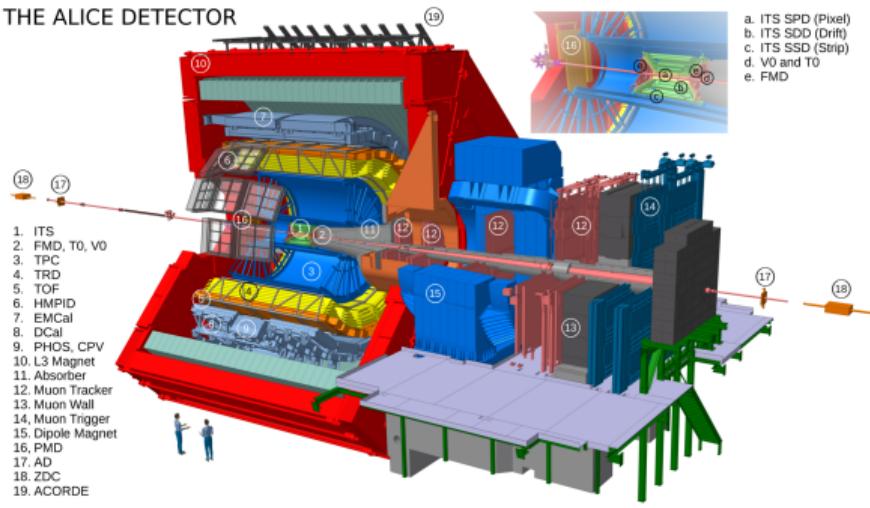
Linear part is extracted from the total and non-linear contributions:

$$\underbrace{\langle |V_{4L}|^2 \rangle^{\frac{1}{2}}}_{v_{4L}} = \underbrace{\langle |V_4|^2 \rangle}_{v_4^2} - \underbrace{\chi_{4,22}^2 \langle |V_2|^4 \rangle}_{v_{4,NL}^2} \quad (5)$$

$$\begin{aligned} V_4 &= V_{4L} + \chi_{4,22} V_2^2 \rightarrow v_{4,22} = \chi_{4,22} \langle |V_2|^4 \rangle^{\frac{1}{2}} \\ V_5 &= V_{5L} + \chi_{5,32} V_2 V_3 \rightarrow \dots \\ V_6 &= V_{6L} + \chi_{6,222} V_2^3 + \chi_{6,33} V_3^2 + \chi_{6,24} V_2 V_4 L \\ &\dots \end{aligned} \quad (3)$$

# Analysis details

## THE ALICE DETECTOR



- Min. bias Pb–Pb data at 5.02 TeV recorded in 2015
- TPC+ITS tracking
- V0 centrality determination
- TOF information for pileup removal

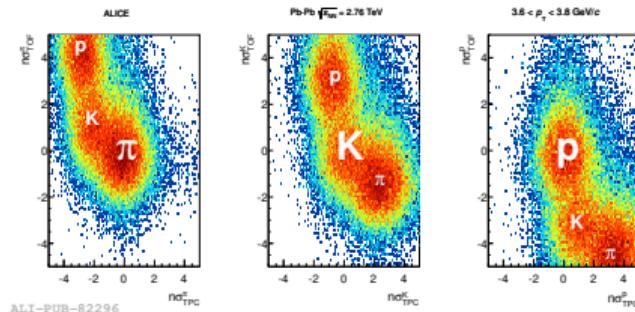
## Unidentified flow ( $p_T$ -integrated):

- TPC+ITS tracking (hybrid)
- 42M Pb–Pb events in 0-60%
- $0.4 < |\eta| < 0.8$
- $0.2 < p_T < 5.0 \text{ GeV}/c$

Comparison to 2.76 TeV results  
from Phys.Lett.B773 (2017) 68

## Identified flow ( $p_T$ -differential):

- 45M Pb–Pb events in 0-50%
- $0.0 < |\eta| < 0.8$
- Identification:**
- $\pi^\pm$ : purity > 90%,  
 $0.4 < p_T < 6.0 \text{ GeV}/c$
- $K^\pm$ : purity > 80%,  
 $0.4 < p_T < 4.0 \text{ GeV}/c$
- $p + \bar{p}$ : purity > 80%,  
 $0.4 < p_T < 6.0 \text{ GeV}/c$
- $K_s^0, \Lambda + \bar{\Lambda}_s^0, \phi$ : purity >  
80% (reconstruction via decay products)



# Analysis method

Flow reconstruction by multiparticle correlations, with 2 sub-events around  $|\Delta\eta| < 0.8$  to suppress the non-flow.

- Integrated flow (for charged unidentified):

$$v_{n,mk}^2 = \frac{(\langle 3 \rangle_{n|-m,-k})^2}{\langle 4 \rangle_{m,k|-m,-k}} \quad (6)$$

- $p_T$ -differential flow (for  $\pi^\pm, K^\pm, p + \bar{p}$ ):

$$v_{n,mk}(p_T) = \frac{(\langle 3 \rangle'_{n|-m,-k}(p_T))^2}{\langle 4 \rangle_{m,k|-m,-k}} \quad (7)$$

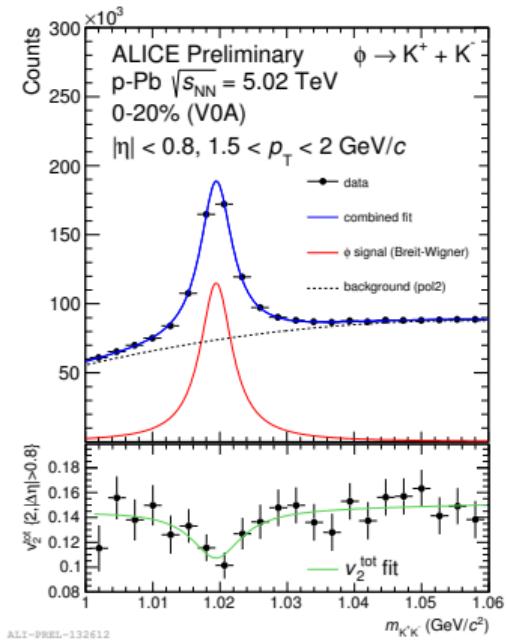
for which RFPs (reference particles): charged particles in  $0.2 < p_T < 5.0 \text{ GeV}/c$

- For decaying particles,  $m_{\text{inv}}$  method is used ( $K_s^0, \Lambda + \bar{\Lambda}, \phi$ ):

$$v_{n,mk}(p_T, m_{\text{inv}}) = \frac{(\langle 3 \rangle'_{n|-m,-k}(p_T, m_{\text{inv}}))^2}{\langle 4 \rangle_{m,k|-m,-k}}, \quad (8)$$

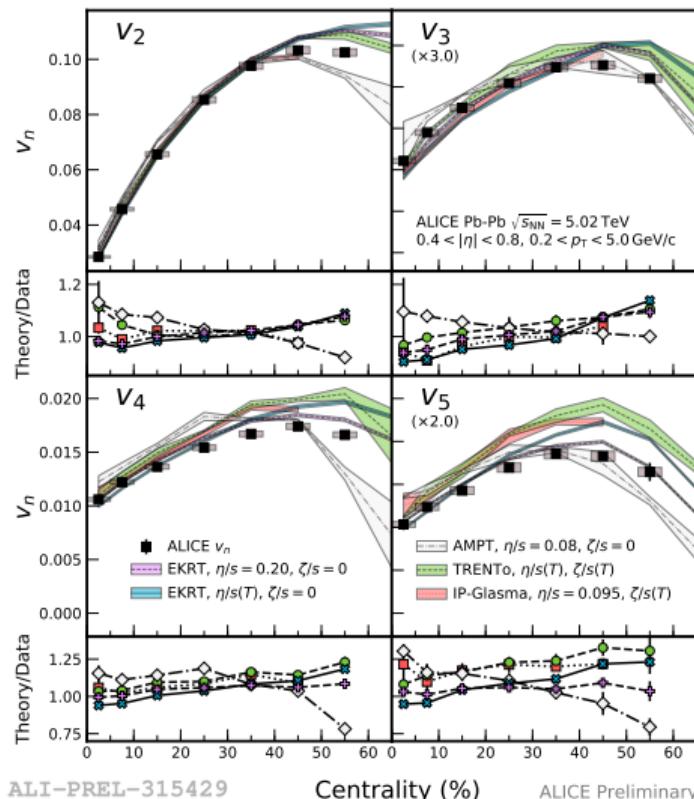
where

$$\langle 3 \rangle'_{n|-m,-k}(m_{\text{inv}}) = \frac{N^{\text{sig}}}{N^{\text{tot}}}(m_{\text{inv}})\langle 3 \rangle'^{\text{sig}}_{n|-m,-k}(m_{\text{inv}}) + \frac{N^{\text{bkg}}}{N^{\text{tot}}}(m_{\text{inv}})\langle 3 \rangle'^{\text{bkg}}_{n|-m,-k}(m_{\text{inv}}) \quad (9)$$



Similar for Pb-Pb non-linear flow modes

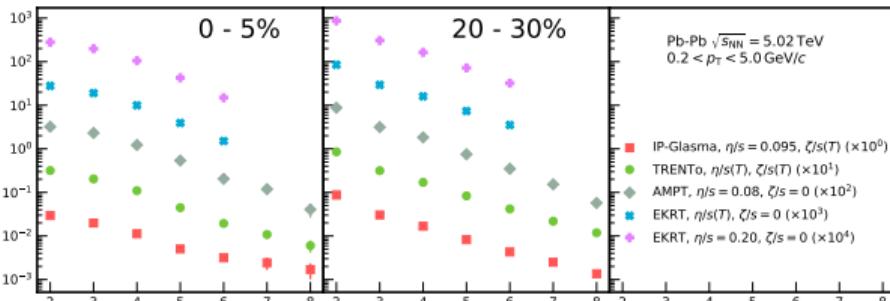
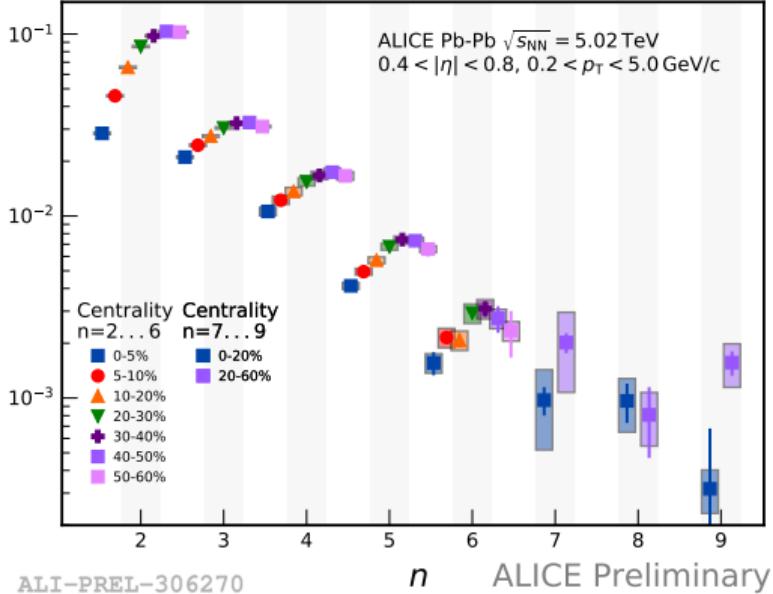
# Anisotropic flow up to $v_5$ (unidentified hadrons)



- Hydrodynamic calculations agree well with the data up to  $v_3$ .
- AMPT ( $\eta/s = 0.08$ ) describes the data best in mid-peripheral collisions, but fails to describe the central collisions for  $n = 4, 5$
- IP-Glasma, TRENTo: good description for  $n = 2, 3$ , overestimations at  $n \geq 4$
- EKRT ( $\eta/s = 0.20$ ): best agreement among all model configurations at  $n \geq 4$
- EKRT ( $\eta/s(T)$ ): comparable up to mid-central collisions, but overestimate the data for peripheral collisions for  $n = 4, 5$
- As  $n$  increases, the sensitivity to model parameterizations gets larger

Centrality dependence measured up to  $v_9$  (backup).

# Anisotropic flow (unidentified hadrons)

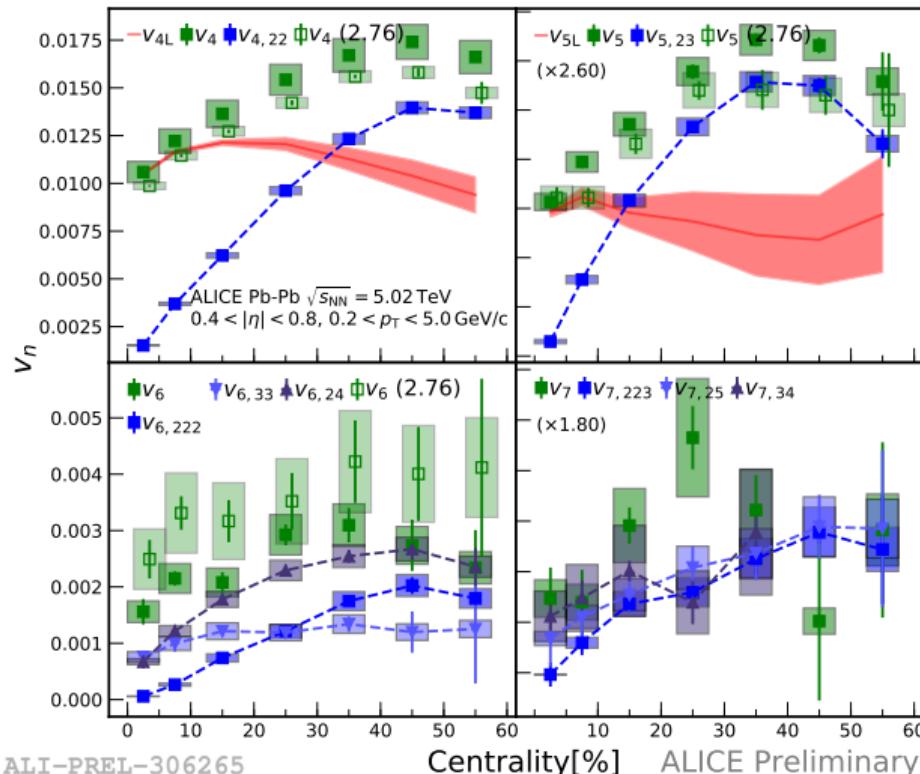


- Power spectra is measured up to  $v_9$  in various centrality bins.
- Clear decrease in magnitude  $v_n \propto e^{-k' n^2}$  (viscous damping<sup>1</sup>) is observed as  $n$  increases
  - Clear damping also observed in hydrodynamical calculations
  - Slope of the calculations is dependent on the model parameterizations
- Interesting feature predicted in acoustic model<sup>2</sup> for  $n \geq 7$  can be further investigated with 2018 data

<sup>1</sup>E. Shuryak, PRC84,044912 (2011), R. Lacey et. al. arXiv:1301.0165

<sup>2</sup>E. Shuryak, PRC84,044912 (2011), Universe 3 (2017) no.4, 75

# Linear and non-linear decomposition up to 7<sup>th</sup> order



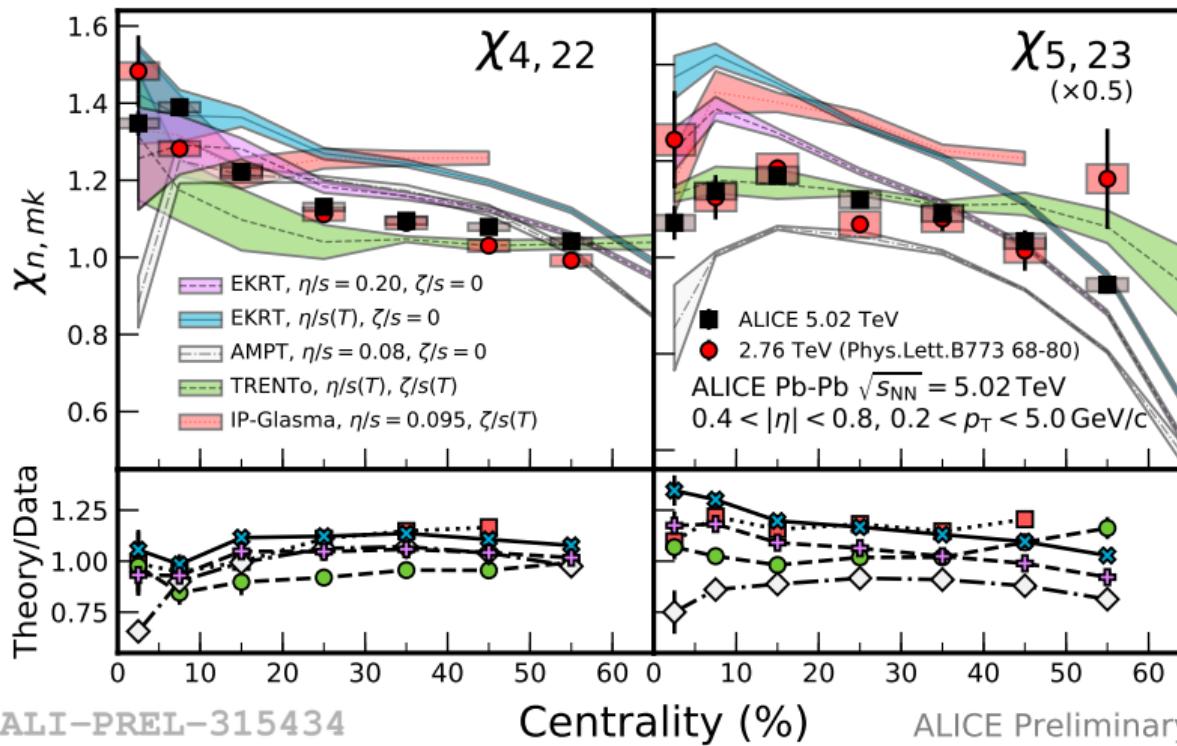
- **Linear** component dominant in central collisions
- **Non-linear** component increasingly dominant in mid-central to peripheral collisions
- Strength of the non-linear flow mode depends on the harmonic order.

Measured quantities  $v_n$  and  $v_{n,m}$ , from which the **linear** component is derived.

# Non-linear flow mode coefficients (unidentified hadrons), hydrodynamic predictions

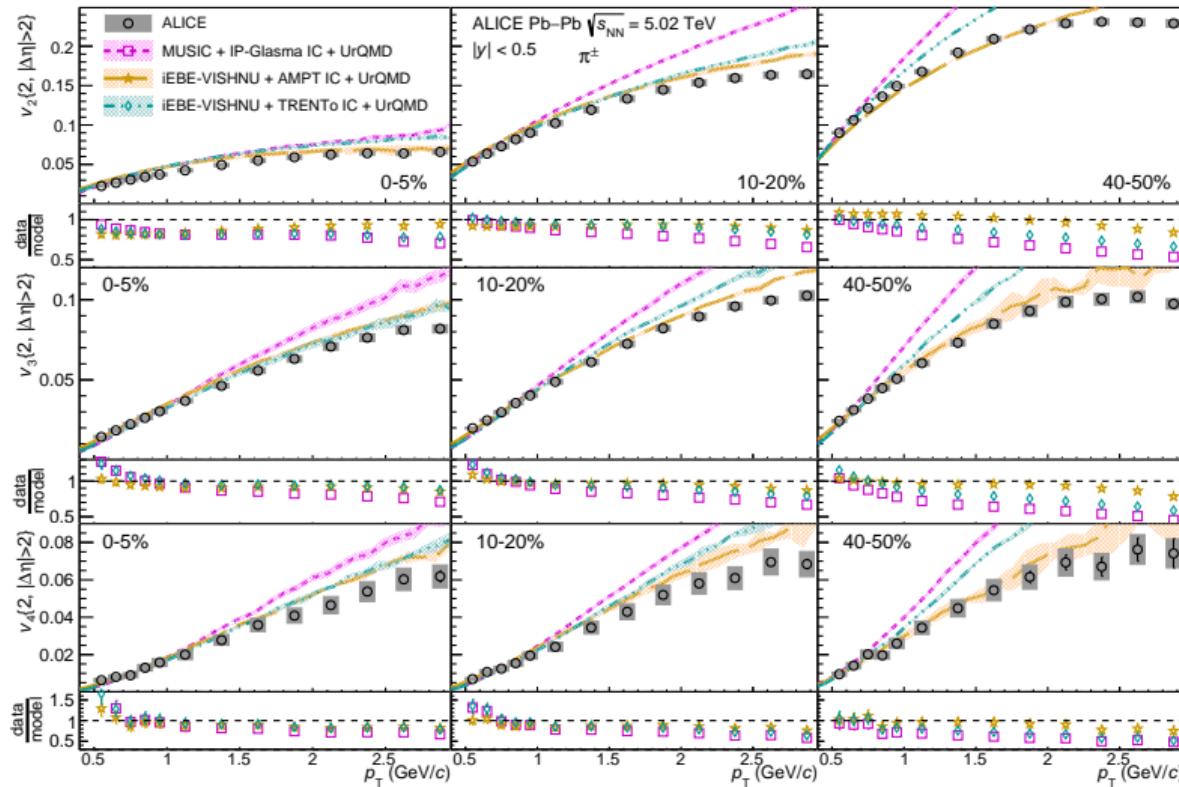
$$V_4 = V_4^L + \chi_{4,22}(V_2)^2$$

$$V_5 = V_5^L + \chi_{5,32} V_2 V_3$$



- Clear centrality dependence for  $n = 4, 5$
- Non-linear response at  $n = 5$  larger than for  $n = 4$
- Large disagreements between the data and the models for  $\chi_{5,23}$ .
- Model parameterizations need further tuning to capture the magnitude and the centrality dependence.

# $v_n(p_T)$ of identified hadrons, hydrodynamic predictions

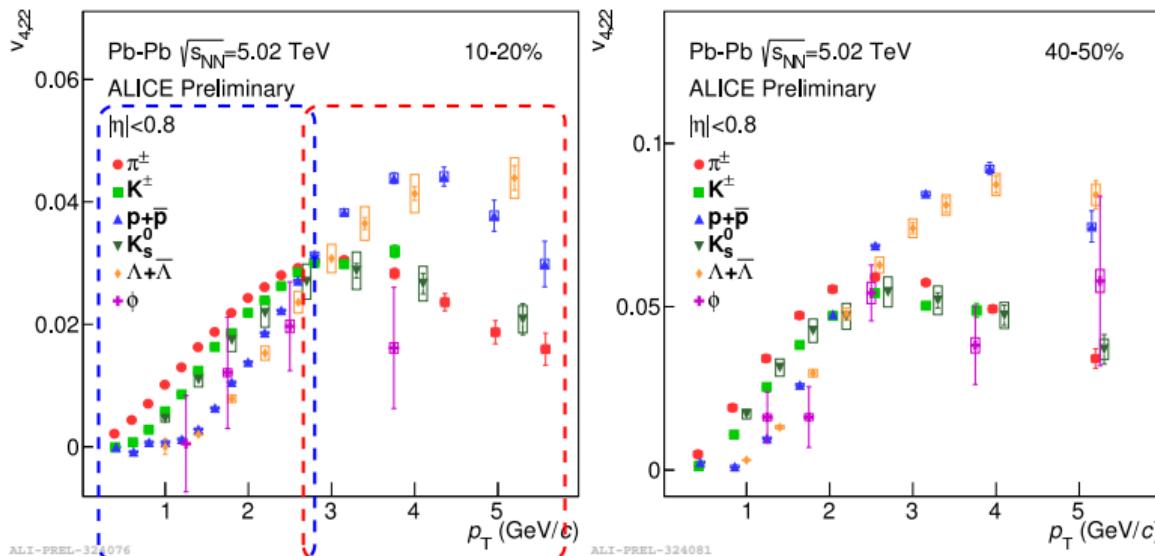


$\pi^\pm$  identified flow (ALICE, JHEP09(2018)006)

- Larger discrepancies in higher centrality classes
- TRENTo overestimates the data in mid-peripheral collisions at high  $p_T$
- AMPT agrees better than TRENTo –  $v_2$  to  $v_4$  reproduced qualitatively

$v_{4,22}(p_T)$  (identified hadrons)

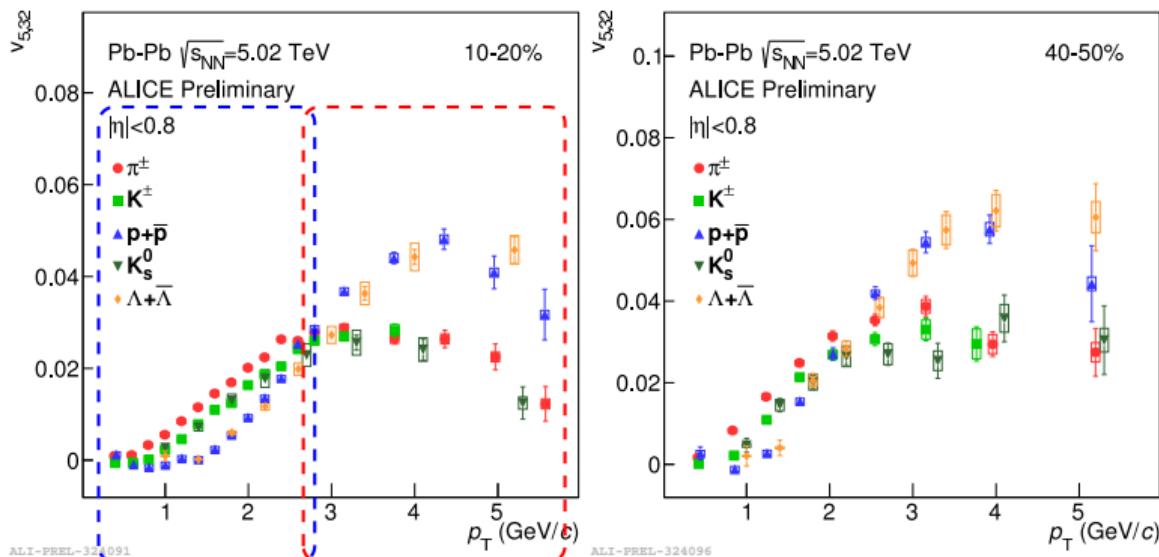
$$V_4 = V_4^L + \chi_{4,22}(V_2)^2 \rightarrow v_{4,22} = \chi_{4,22} \langle |V_2|^4 \rangle^{\frac{1}{2}}$$



- **Mass ordering** in low  $p_T$  region:  $v(\pi^\pm) > v(K) > v(p), v(\Lambda), v(\phi)$
- **Particle type grouping** in  $p_T > 2.5 \text{ GeV}/c$ : quark coalescence as primary particle production mechanism, as  $v(\Lambda), v(p) > v(\pi^\pm), v(K), v(\phi)$
- Clear centrality dependence, larger for peripheral collisions.

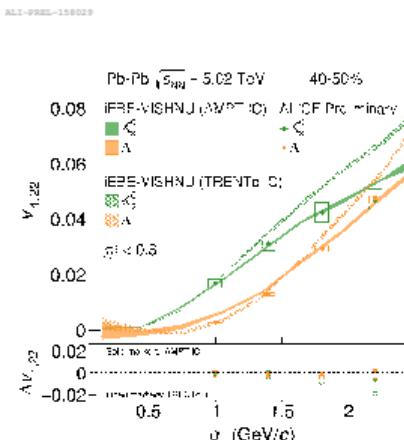
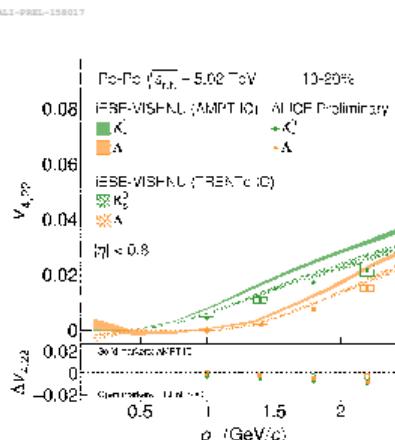
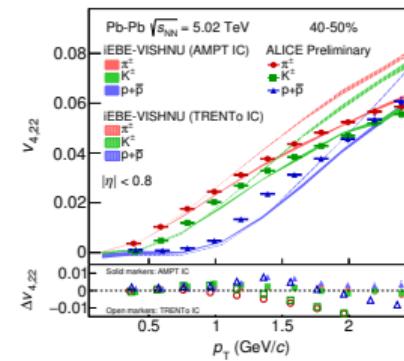
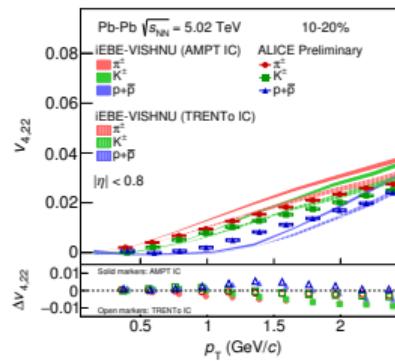
$v_{5,23}(p_T)$  (identified hadrons)

$$V_5 = V_5^L + \chi_{5,32} V_2 V_3 \rightarrow v_{5,23} = \chi_{5,32} \langle |V_2|^2 |V_3|^2 \rangle^{\frac{1}{2}}$$



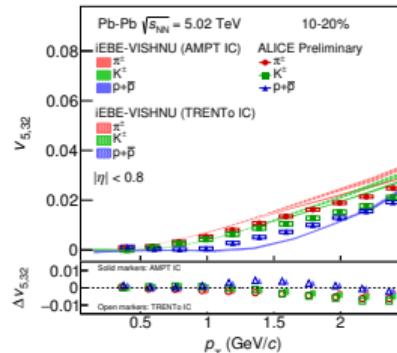
- Mass ordering in low  $p_T$  region:  
 $v(\pi^\pm) > v(K) > v(p), v(\Lambda)$
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 $v(\Lambda), v(p) > v(\pi^\pm), v(K)$
- Clear centrality dependence, small value in central collisions

# $v_{4,22}(p_T)$ (identified hadrons), hydrodynamic predictions

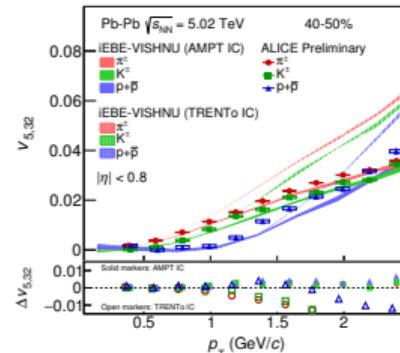


- AMPT: minor overestimation in central collisions, very good agreement in mid-peripheral collisions
- AMPT reproduces  $v_n(p_T)$  and  $v_{4,22}(p_T)$  simultaneously
- TRENTo overestimates higher  $p_T$  in mid-peripheral collisions.
- AMPT vs TRENTo: AMPT has a better overall agreement, especially in mid-peripheral collisions. In central collisions, TRENTo estimates the data slightly better.
- Mass ordering reproduced by both models.

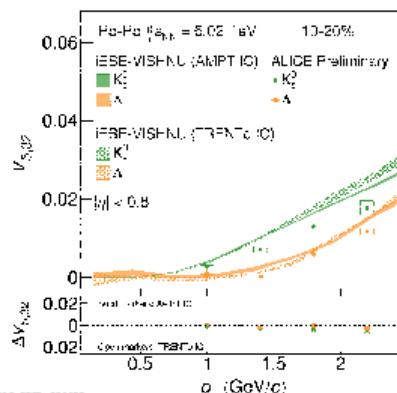
# $v_{5,23}(p_T)$ (identified hadrons), hydrodynamic predictions



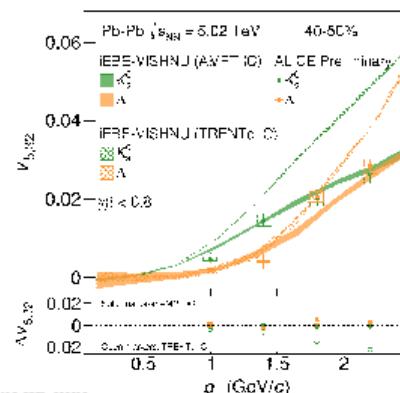
ALICE-PREL-158033



ALICE-PREL-157993



ALICE-PREL-334422



ALICE-PREL-333318

- AMPT: minor overestimation in central collisions, very good agreement in mid-peripheral collisions
- AMPT reproduces  $v_n(p_T)$  and  $v_{5,23}(p_T)$  simultaneously
- TRENTo overestimates higher  $p_T$  in mid-peripheral collisions.
- AMPT vs TRENTo: AMPT has a better overall agreement, especially in mid-peripheral collisions. In central collisions, TRENTo estimates the data slightly better.
- Mass ordering reproduced by both models.

# Summary

General:

- The flow coefficients, flow modes and non-linear flow mode coefficients of the charged and identified hadrons are measured up to the 9<sup>th</sup> and 7<sup>th</sup> harmonic, respectively.
- Cross harmonic decomposition: higher order harmonic non-linear flow mode is more sensitive  $\eta/s$ ,  $\zeta/s$  parameterizations.
- Better constraints on initial conditions and  $\eta/s(T)$ ,  $\zeta/s(T)$  with improved precision and extended harmonic orders.
- Additional constraint from the mass dependence of non-linear flow mode for identified particles ( $\pi^\pm$ ,  $K^\pm$ ,  $p + \bar{p}$ ,  $K_s^0$ ,  $\Lambda + \bar{\Lambda}_s^0$ ,  $\phi$ )

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Hydrodynamic models:

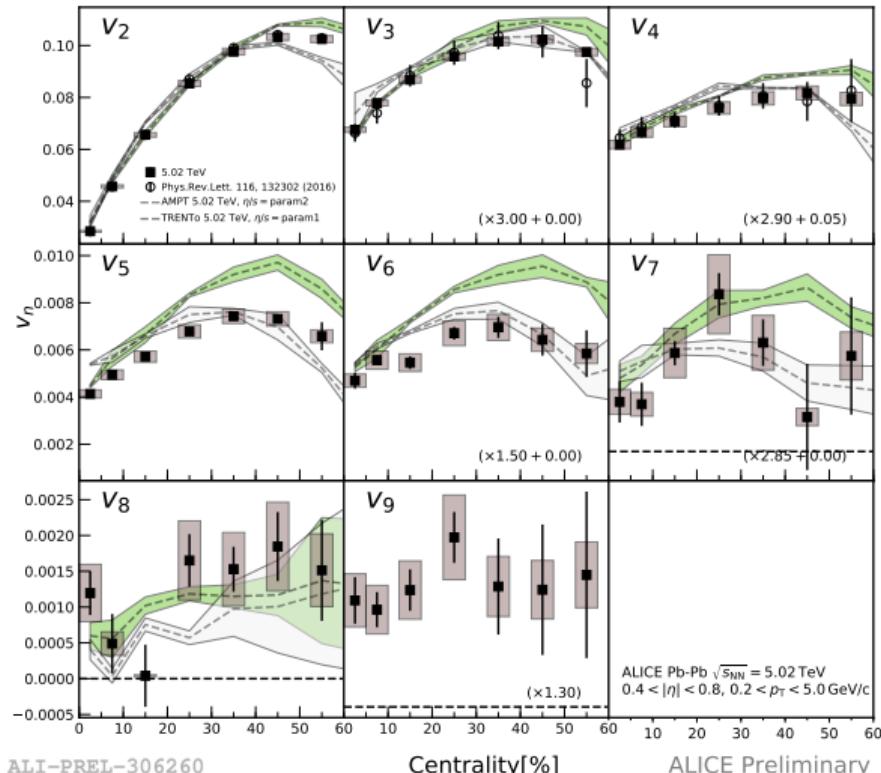
- Good agreement for low order harmonic  $v_n$ . However, higher orders and higher  $p_T$   $v_n$  are not well reproduced.
- Good simultaneous description of  $v_n(p_T)$  and  $v_{n,mk}(p_T)$  for identified particles with AMPT initial conditions.
- Mass ordering reproduced for identified particles. Discrepancies observed for intermediate  $p_T$ -region.

Our data can help to further constrain  $\eta/s$  and  $\zeta/s$  in model calculations.

# Backup

# Backup

# Anisotropic flow @ $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ (the total contribution of all flow modes)



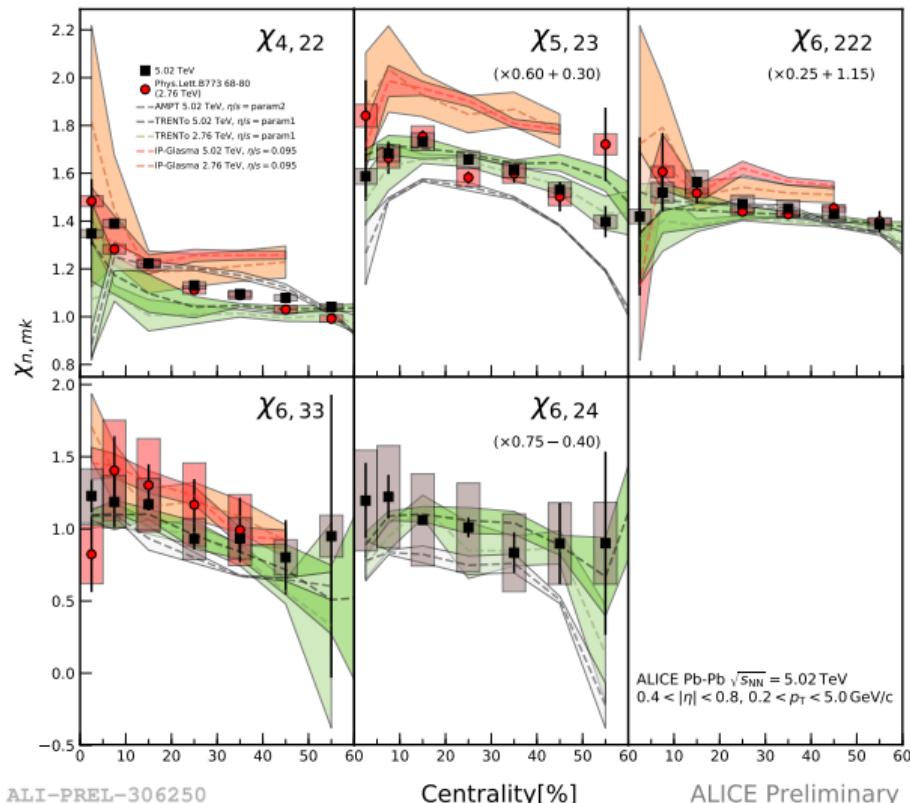
- TRENTo – overestimating  $v_5$  and  $v_6$
- AMPT – good agreement in every case.

ALI-PREL-306260

Centrality[%]

ALICE Preliminary

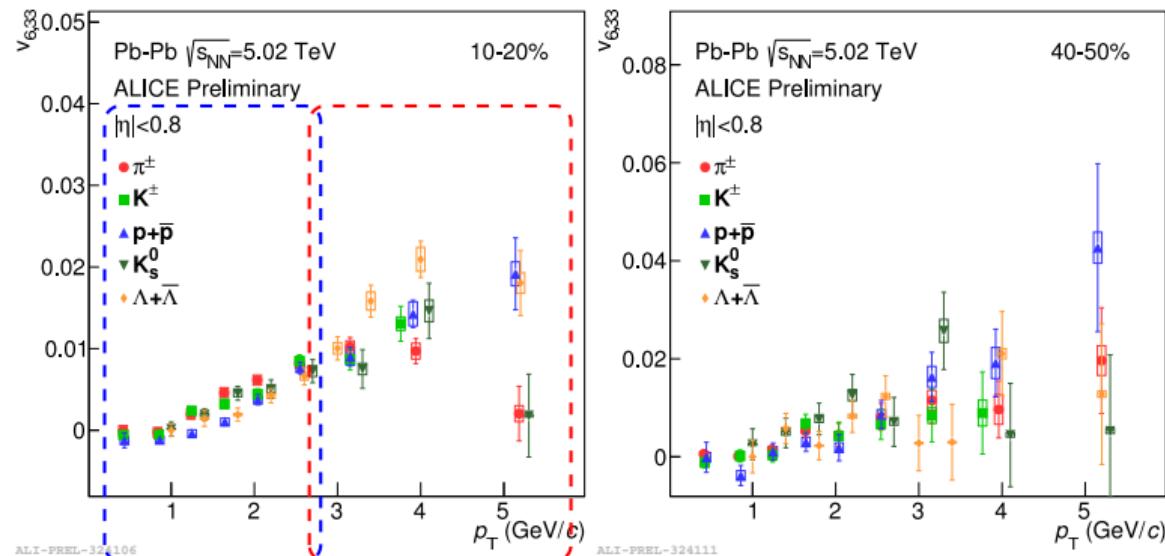
## Non-linear flow mode coefficients



- No energy dependence between measurements or model calculations
  - TRENTO: overall good agreement with the data
  - AMPT: same, except for underestimation of  $\chi_{5,23}$
  - IP-Glasma: overestimation in mid-peripheral collisions

# $v_{6,33}(p_T)$ (identified hadrons)

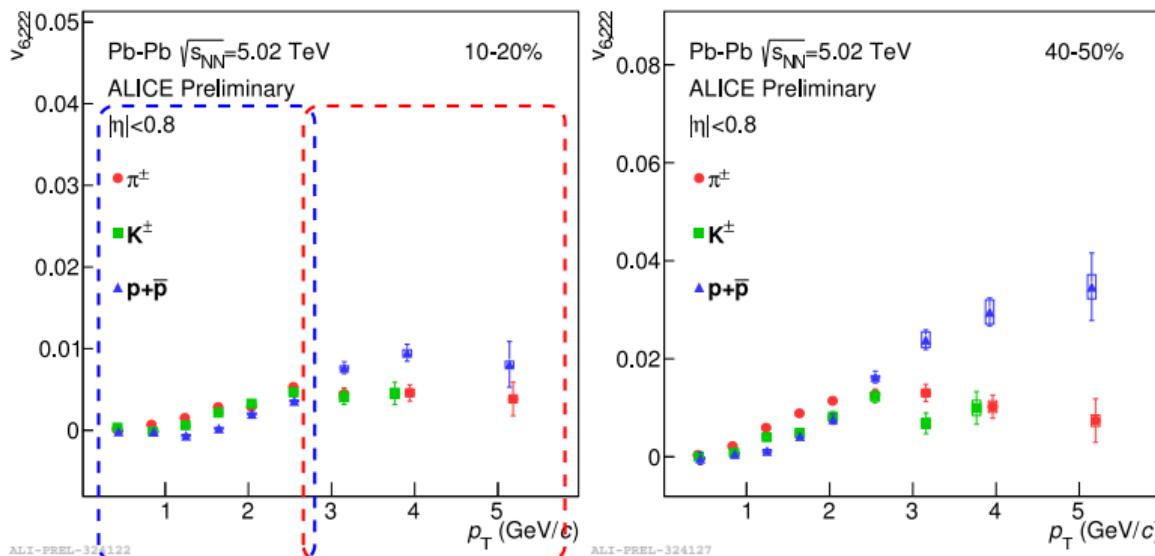
$$V_6 = V_6^L + \chi_{6,222}(V_2)^3 + \chi_{6,33}(V_3)^2 \rightarrow v_{6,33} = \chi_{6,33} \langle |V_3|^4 \rangle^{\frac{1}{2}}$$



- Mass ordering in low  $p_T$  region:  
 $v(\pi^\pm) > v(K) > v(p), v(\Lambda)$
- Particle type grouping in  $p_T > 2.5$  GeV/c: quark coalescence as primary particle production mechanism, as  
 $v(\Lambda), v(p) > v(\pi^\pm), v(K)$

## $v_{6,222}(p_T)$ (identified hadrons)

$$V_6 = V_6^L + \chi_{6,222}(V_2)^3 + \chi_{6,33}(V_3)^2 \rightarrow v_{6,33} = \chi_{6,222} \langle |V_2|^6 \rangle^{\frac{1}{2}}$$



- Mass ordering in low  $p_T$  region:  
 $v(\pi^\pm) > v(K) > v(p), v(\Lambda)$
- Particle type grouping in  $p_T > 2.5$  GeV/c: quark coalescence as primary particle production mechanism, as  
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- Clear centrality dependence, small value in central collisions