Collective Flow in Large and Small Systems at the LHC

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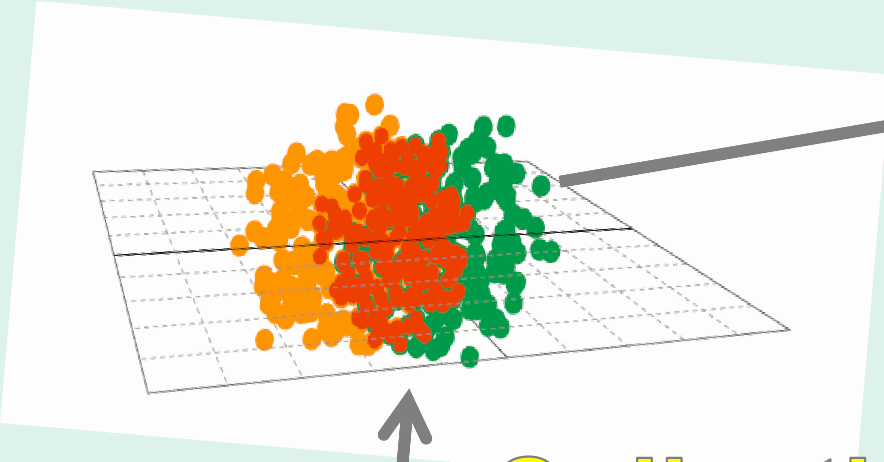
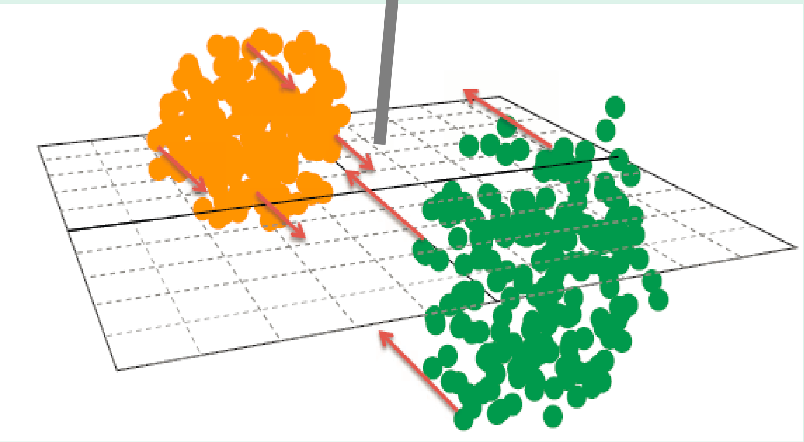
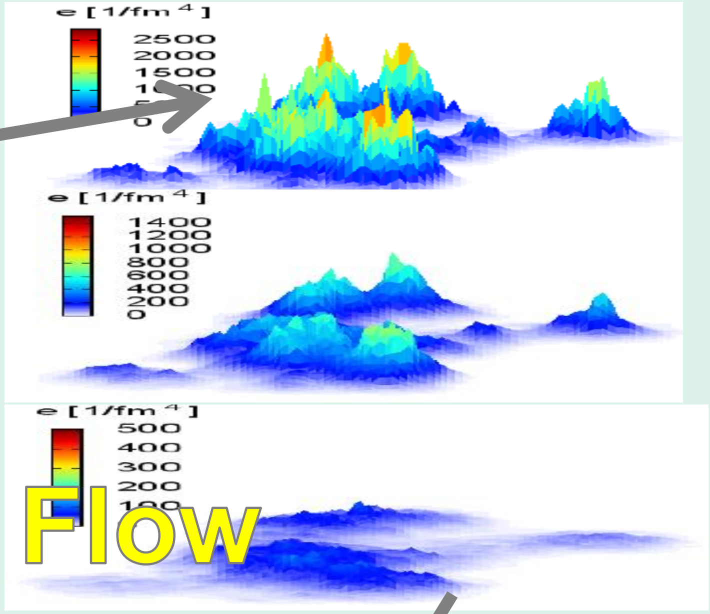
In collaboration with **Hao-Jie Xu**, Xiangrong Zhu, You Zhou … …

June. 30, 2016





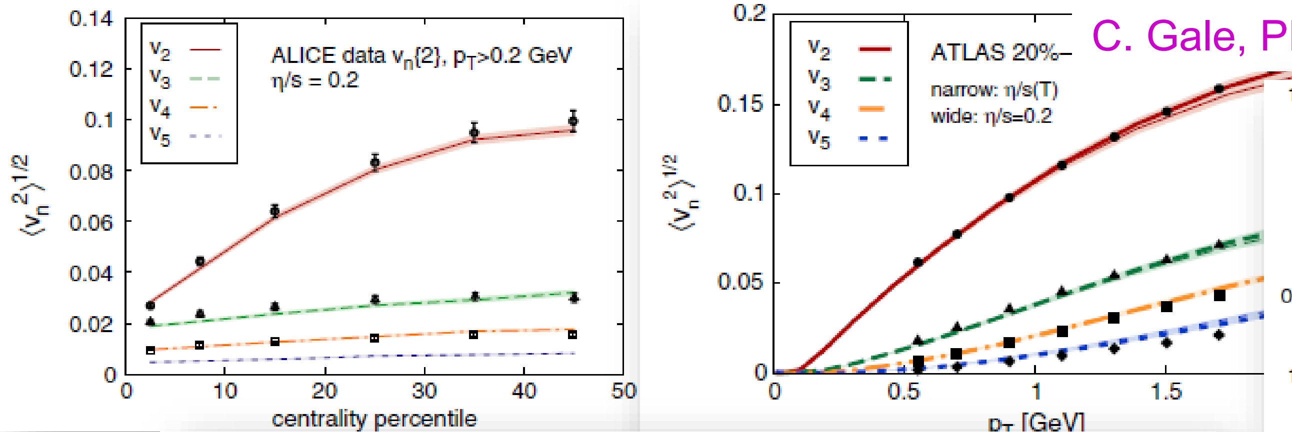
Collective Flow

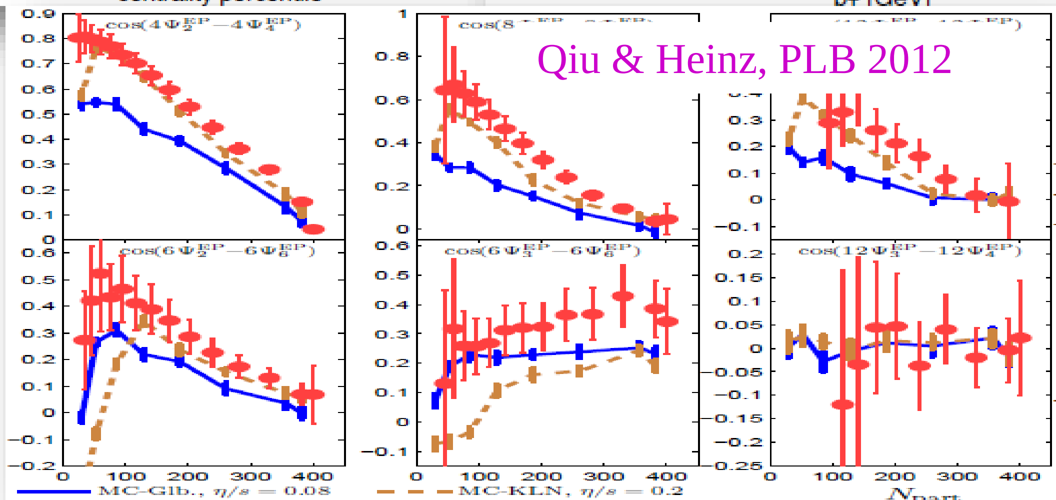


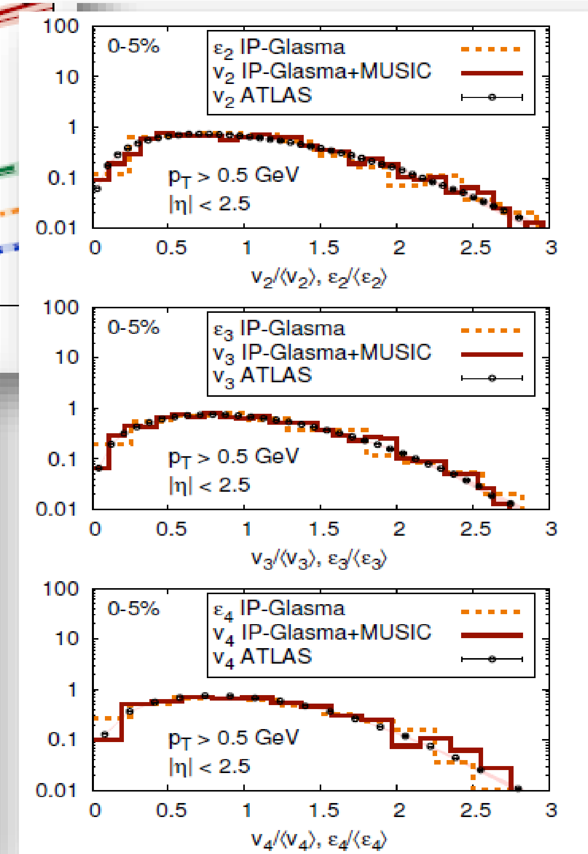
$$E\frac{dN}{d^3p}=\frac{dN}{dyp_Tdp_Td\varphi}$$

$$=\frac{1}{2\pi}\frac{dN}{dyp_Tdp_T}[1+2v_1(p_T,b)\cos(\varphi)+2v_2(p_T,b)\cos(2\varphi)$$

$$+2v_3(p_T,b)\cos(3\varphi)......]$$





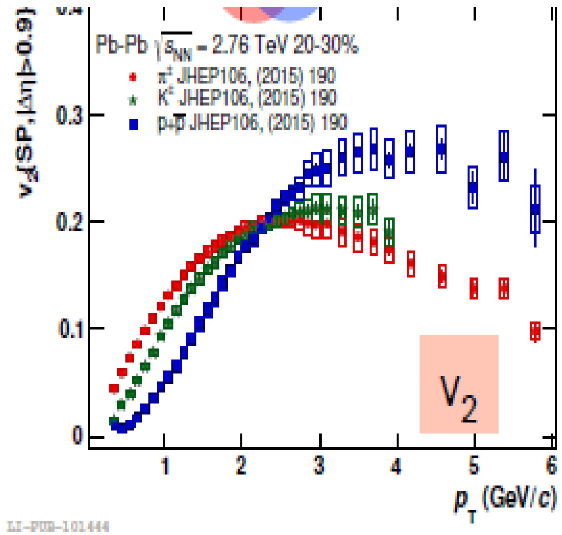


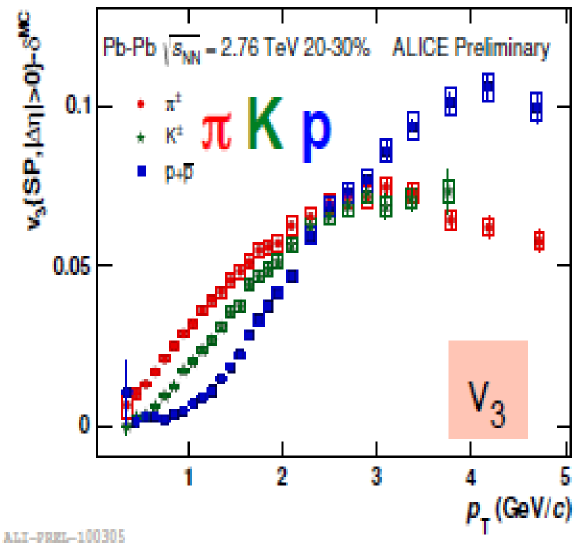
TODAY'S TOPIC: Collective Flow in Large and Small Systems

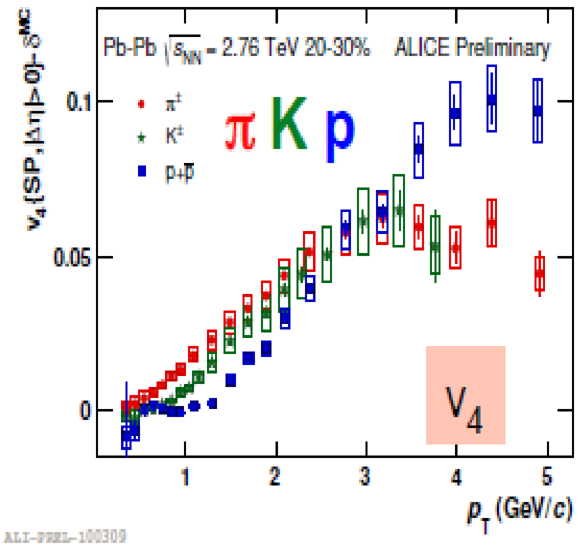
- -2.76 A TeV Pb+Pb collisions
  - -Higher-Order Flow Harmonics of Identified Hadrons (Xu, Li, Song PRC2016)
  - -Correlations of Flow Harmonics (Zhu, Xu, Zhou, Song, in preparation)
- -Collective flow in 7 & 13 TeV p+p collisions (Zhu, Xu, Deng, Zhou, Song, in preparation)

Higher-Order Flow Harmonics of Identified Hadrons in 2.76 A TeV Pb+Pb collisions

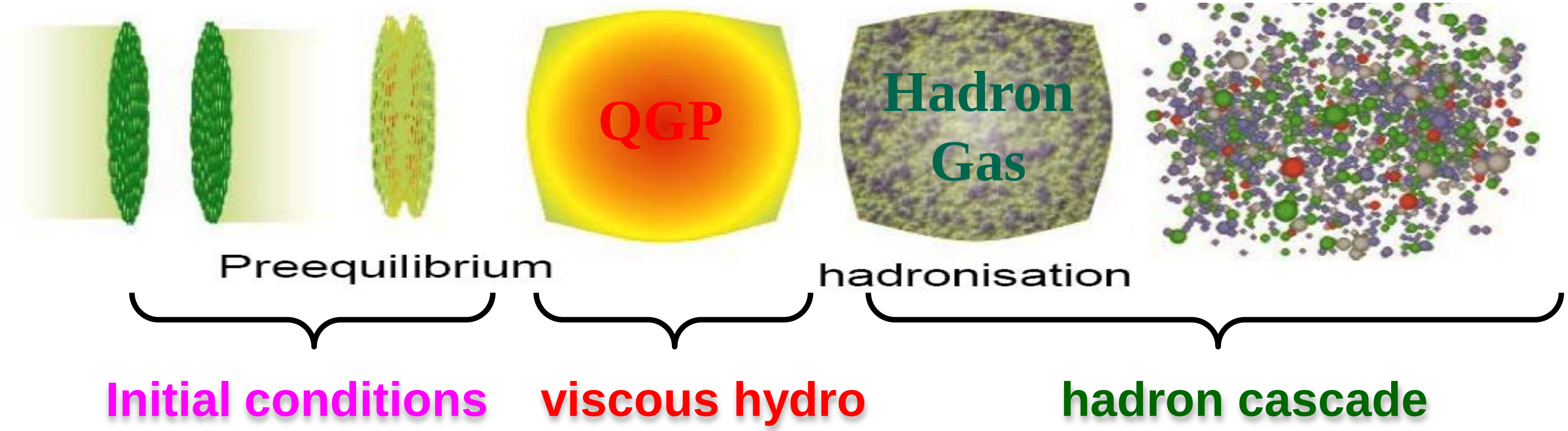
ALICE: 1606.06507







iEBE-VISHNU



Initial conditions

- MC-Glauber or MC-KLN **(… Song et al PRL 2011, PRC 2011 … …)**

-fluctuations of nucleon positions

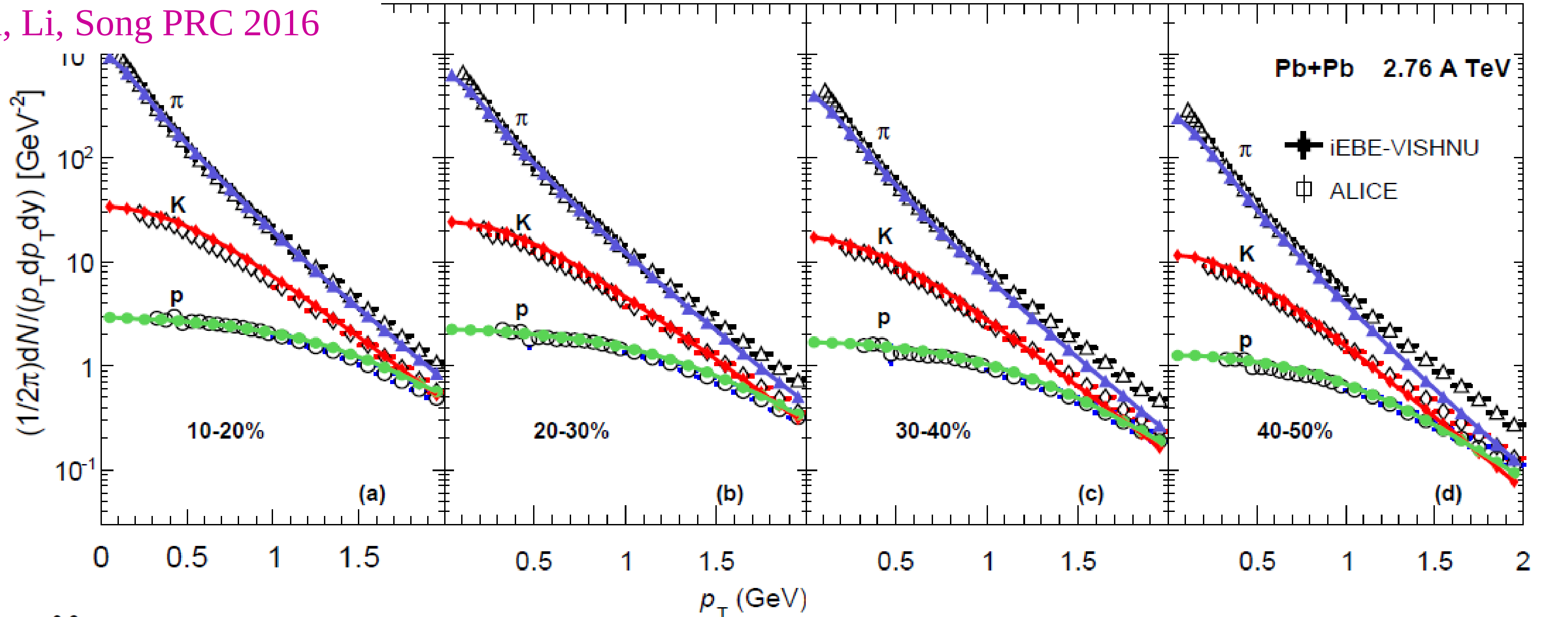
- AMPT initial conditions **(Xu, Li & Song PRC2016)**

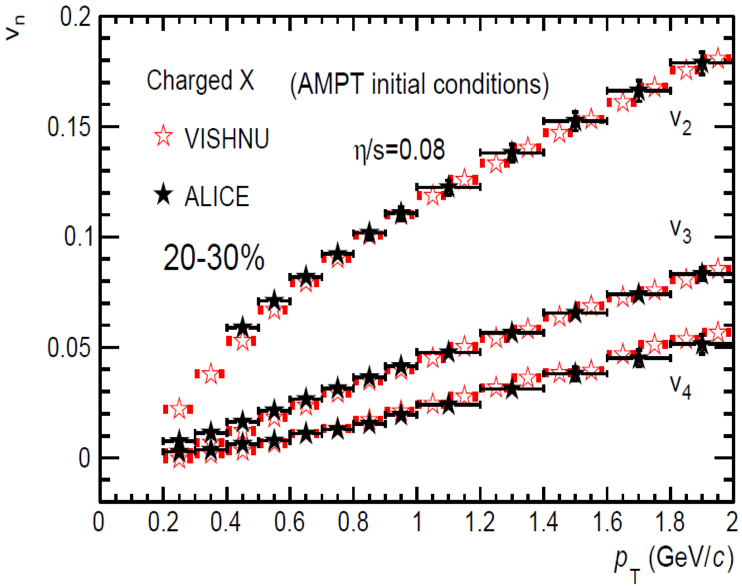
-fluctuations of partons in momentum & position space

$$\epsilon(x,y) = K \sum_i \frac{p_i \cdot U_0}{2\pi\sigma^2\tau_0\Delta\eta_s} \exp\left(-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma^2}\right),$$

P_T spectra & V_n

Xu, Li, Song PRC 2016



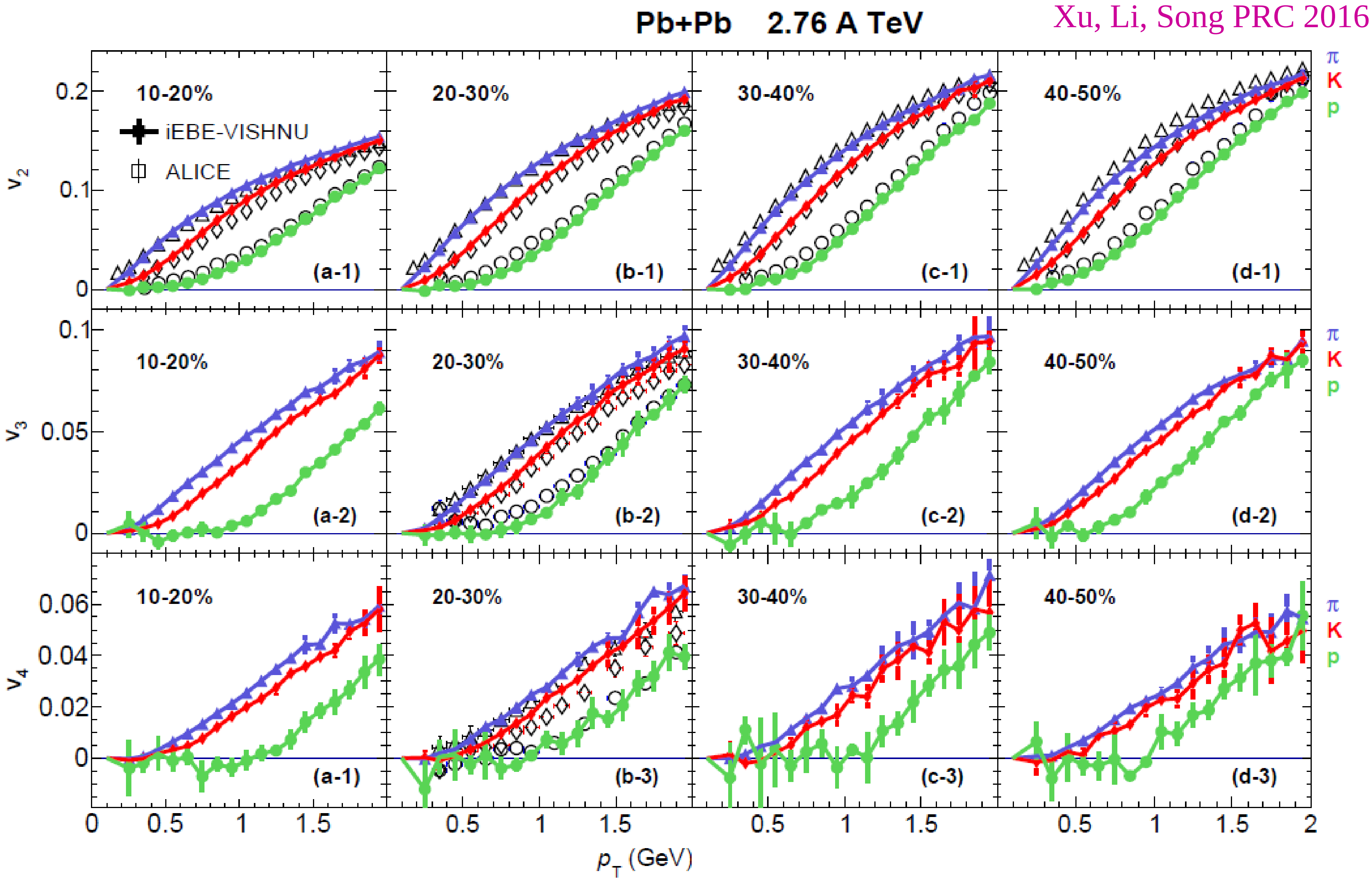


iEBE-VISHNU (AMPT initial conditions)

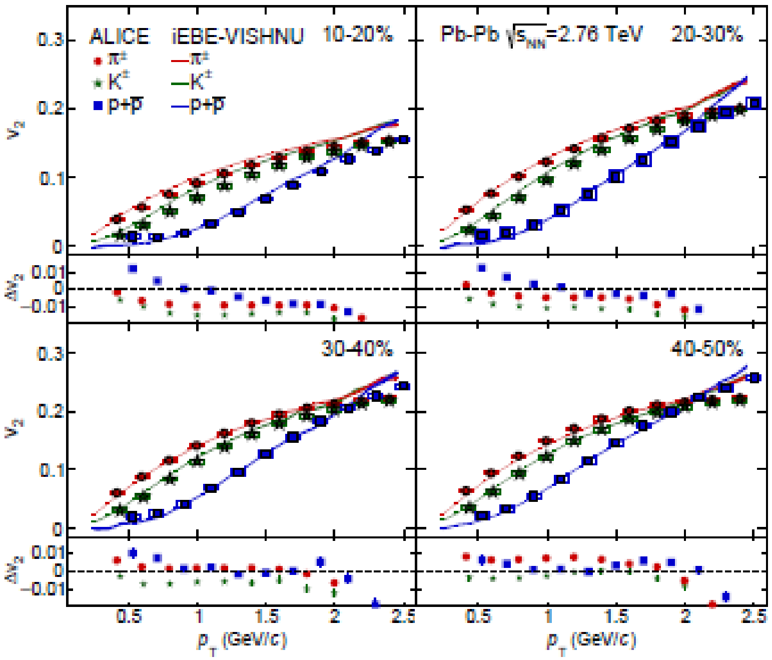
- Free parameters: (τ_0, S_0, η/s , σ)
- Fine tune free parameters to nicely fit the pT spectra (PID) and V_n of all charged hadrons

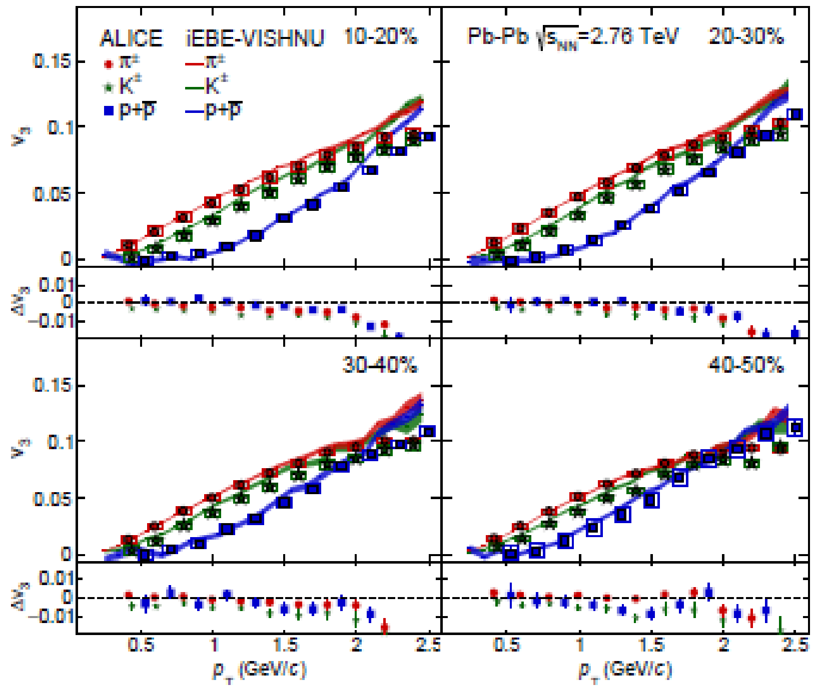
V_2, V_3, V_4 of identified hadrons

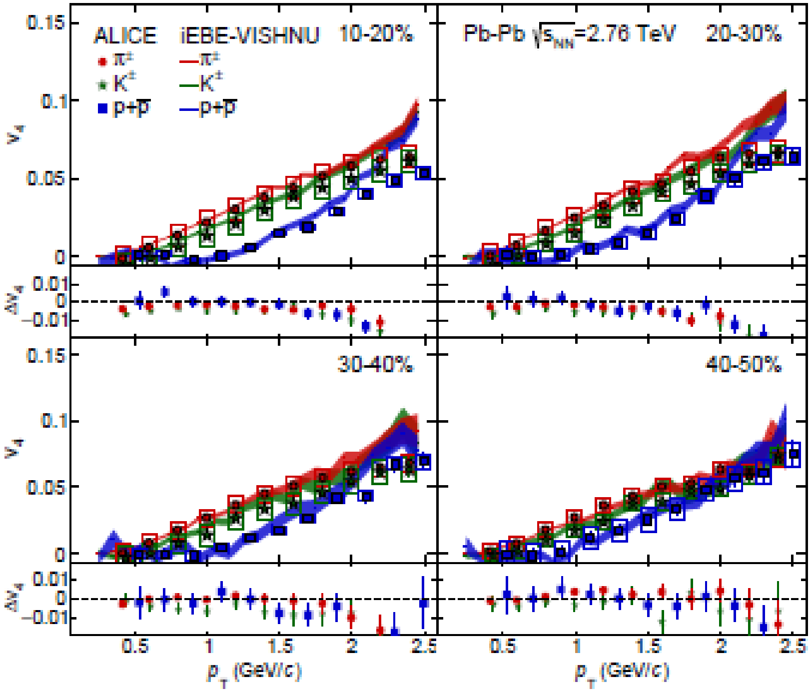
Xu, Li, Song PRC 2016



-V_3 & V_4 shows similar mass orderings as V_2 for various centrality



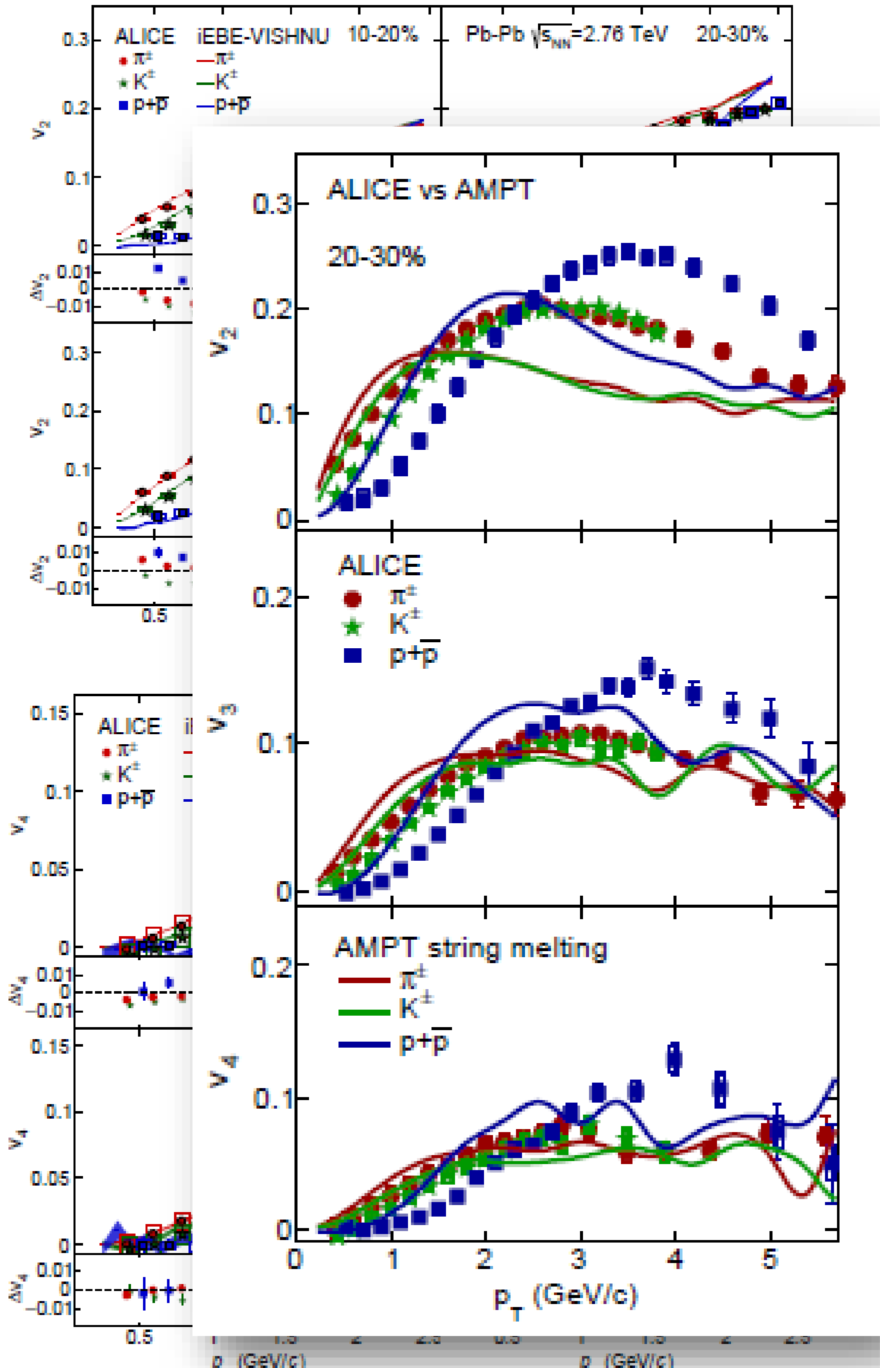


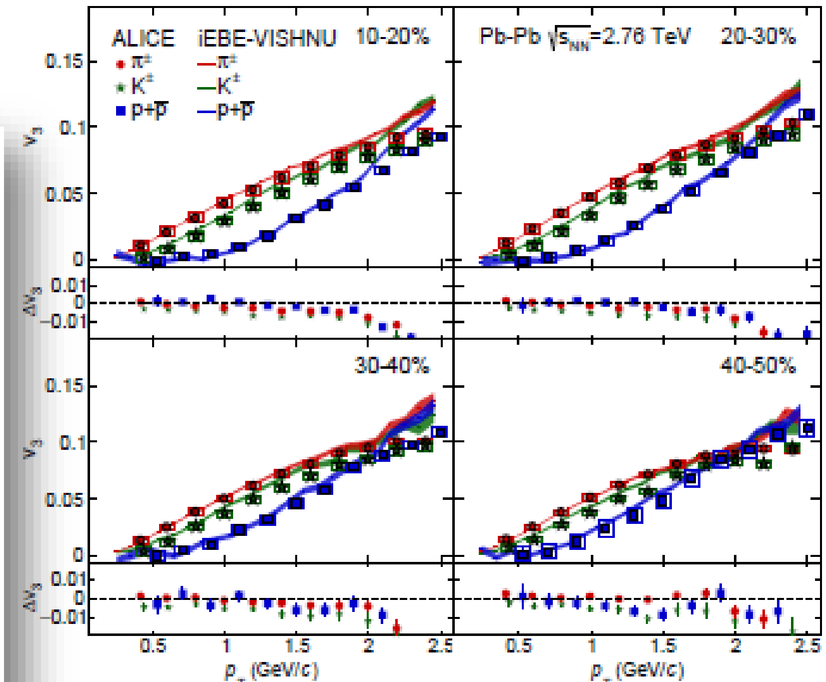


-iEBE-VISHNU (AMPT initial conditions) nicely describe the ALICE V_n of pions,kaons and protons at various centralities

ALICE: 1606.06507

iEBE- VISHNU: Xu, Li, Song PRC 2016





-iEBE-VISHNU (AMPT initial conditions) nicely describe the ALICE V_n of pions,kaons and protons at various centralities

-AMPT can only capture the V_n mass-ordering, but not quantitatively describe the data

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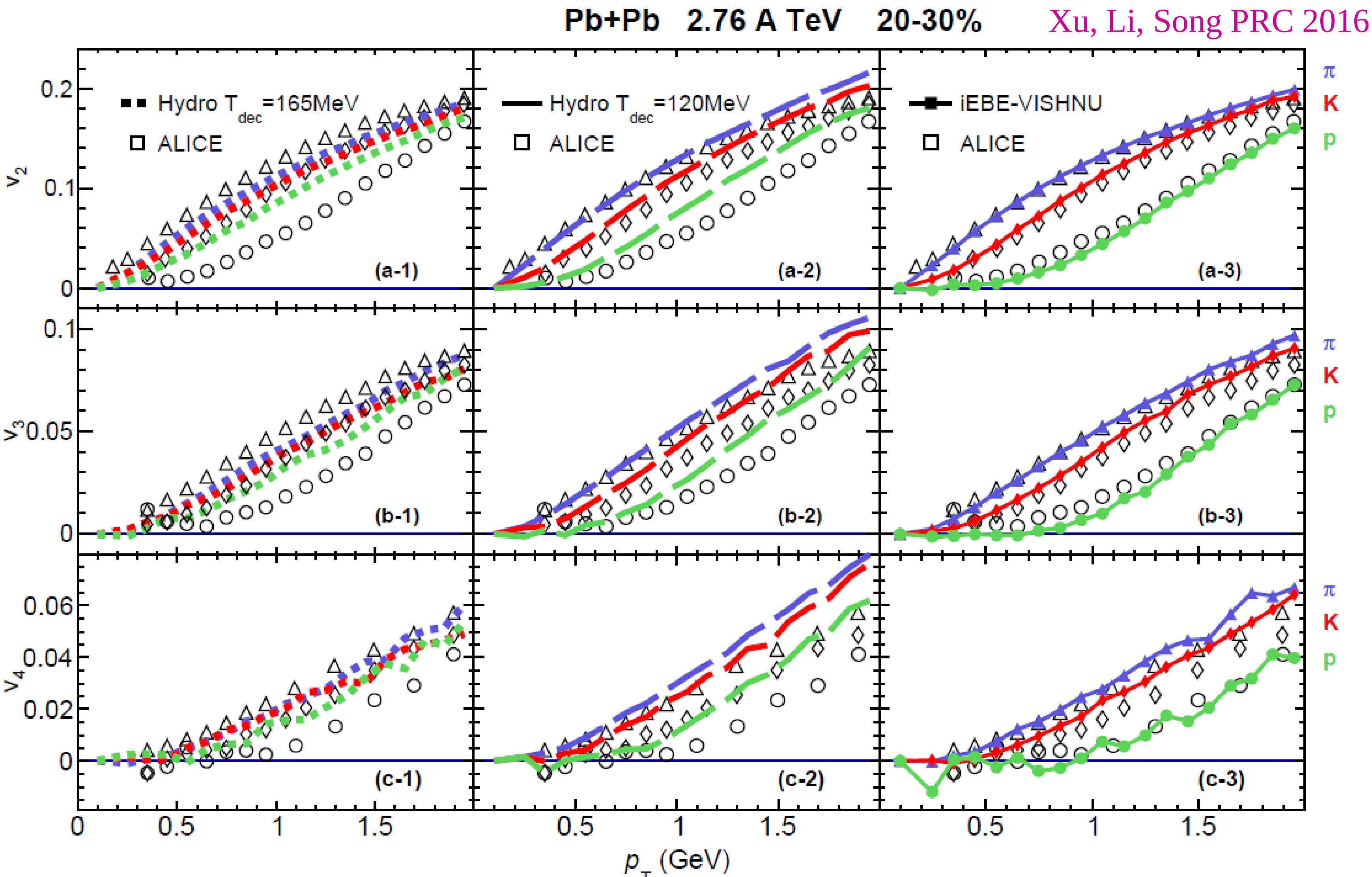
iEBE- VISHNU: Xu, Li, Song PRC 2016

Mass splitting of V_n



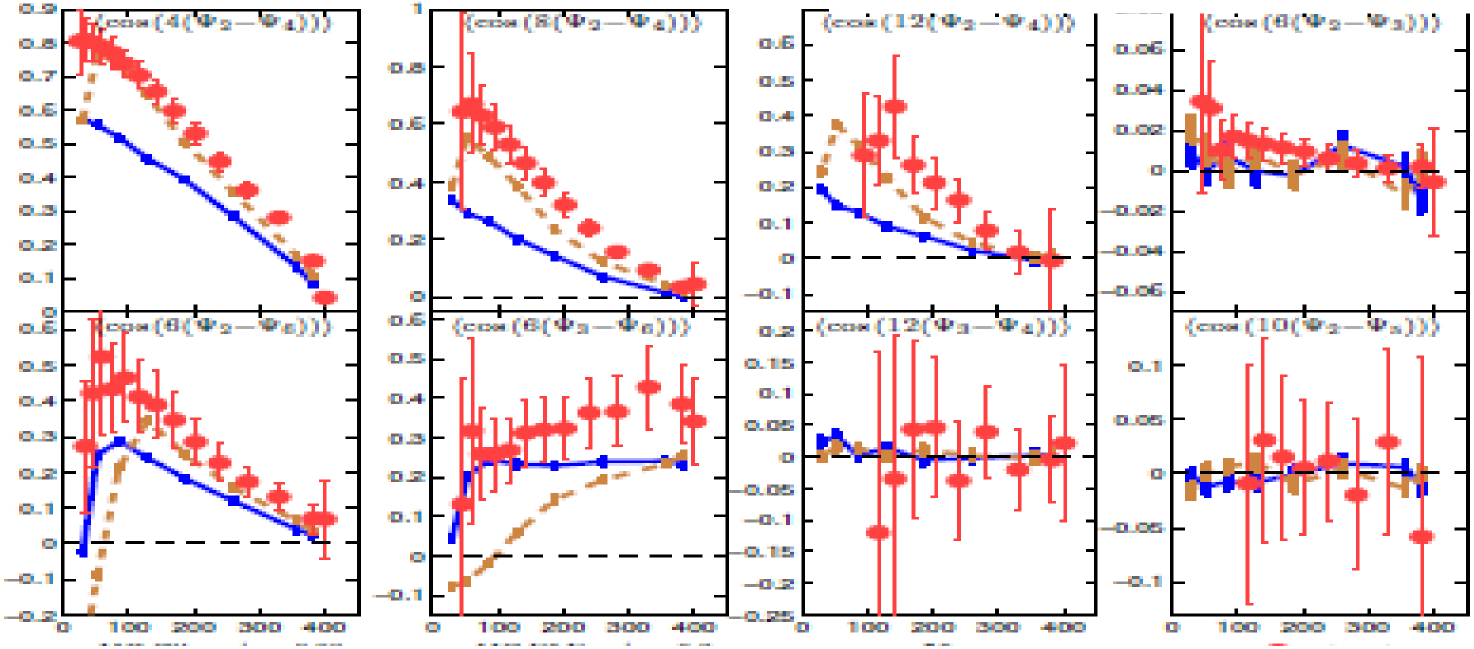
-Hadronic interactions rebalance the generations of radial and anisotropic flow, leading to a nice description of v_n of identified hadrons

Correlations of Flow Harmonics in 2.76 A TeV Pb+Pb collisions

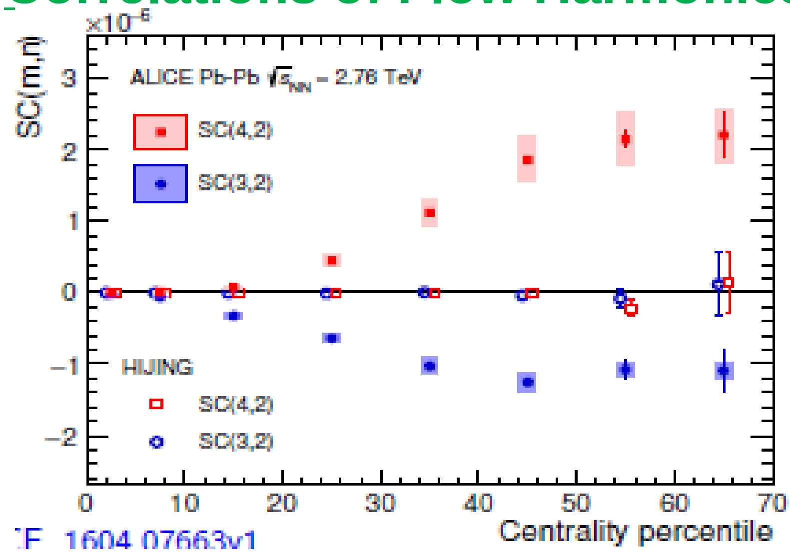
Zhu, Xu, Zhou, Song, in preparation

Correlations of Event Plane Angles

Qiu & Heinz, PLB 2012, ATLAS, PRC 2014



Correlations of Flow Harmonics

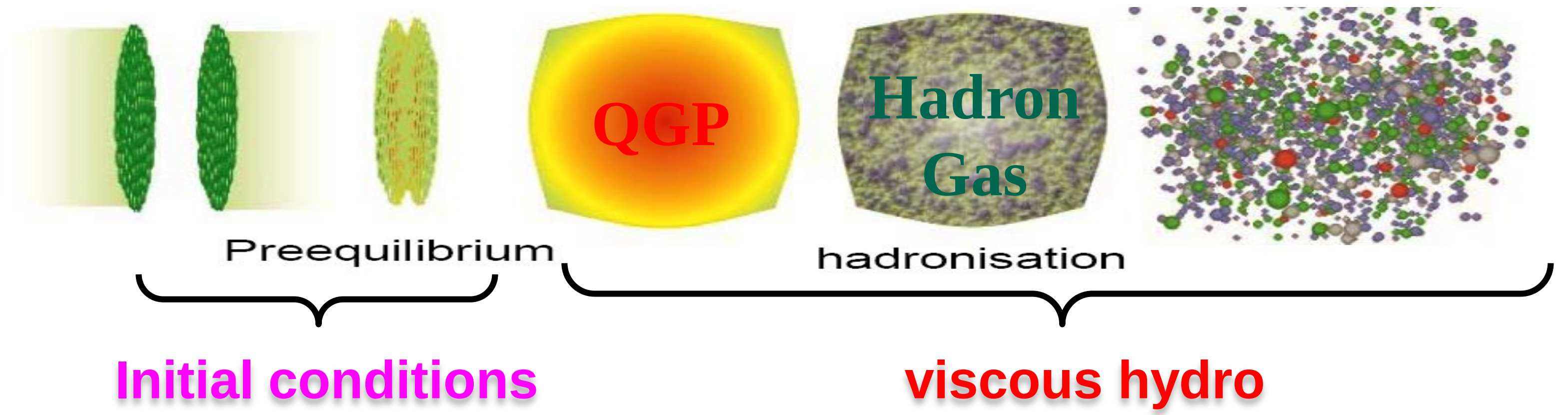


ALICE, 1604.07663

$$SC^v(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

- V_2 and V_4 are correlated
- V_3 and V_4 are anti-correlated
- SC(m,n) from HIJING are compatible to zero

EBE-VISH2+1



Initial conditions

- **MC-Glauber or MC-KLN** (… … Song et al PRL 2011, PRC 2011 … …)
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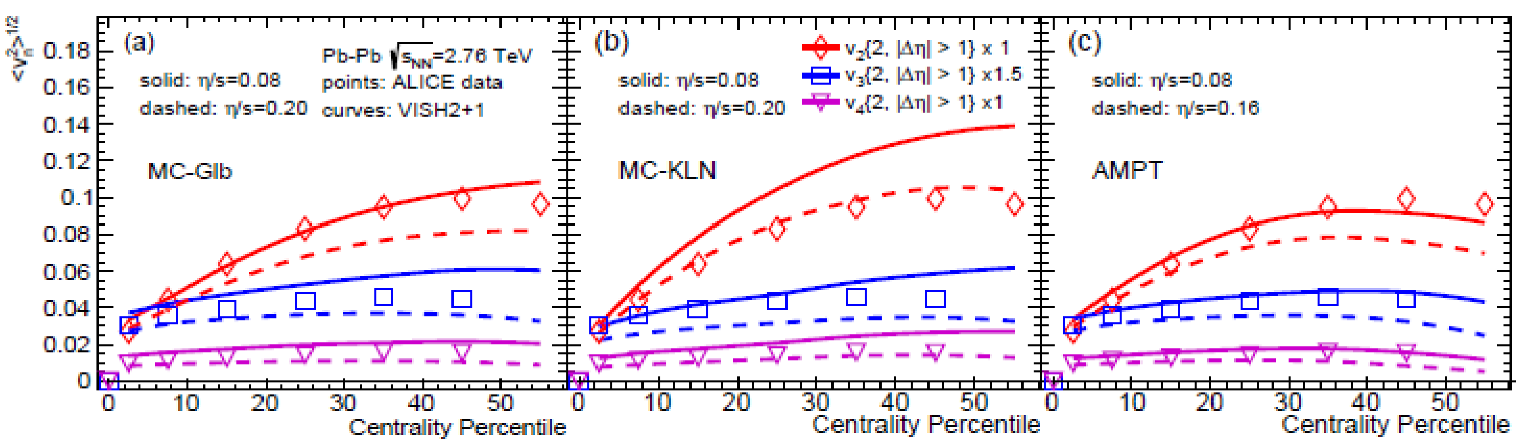
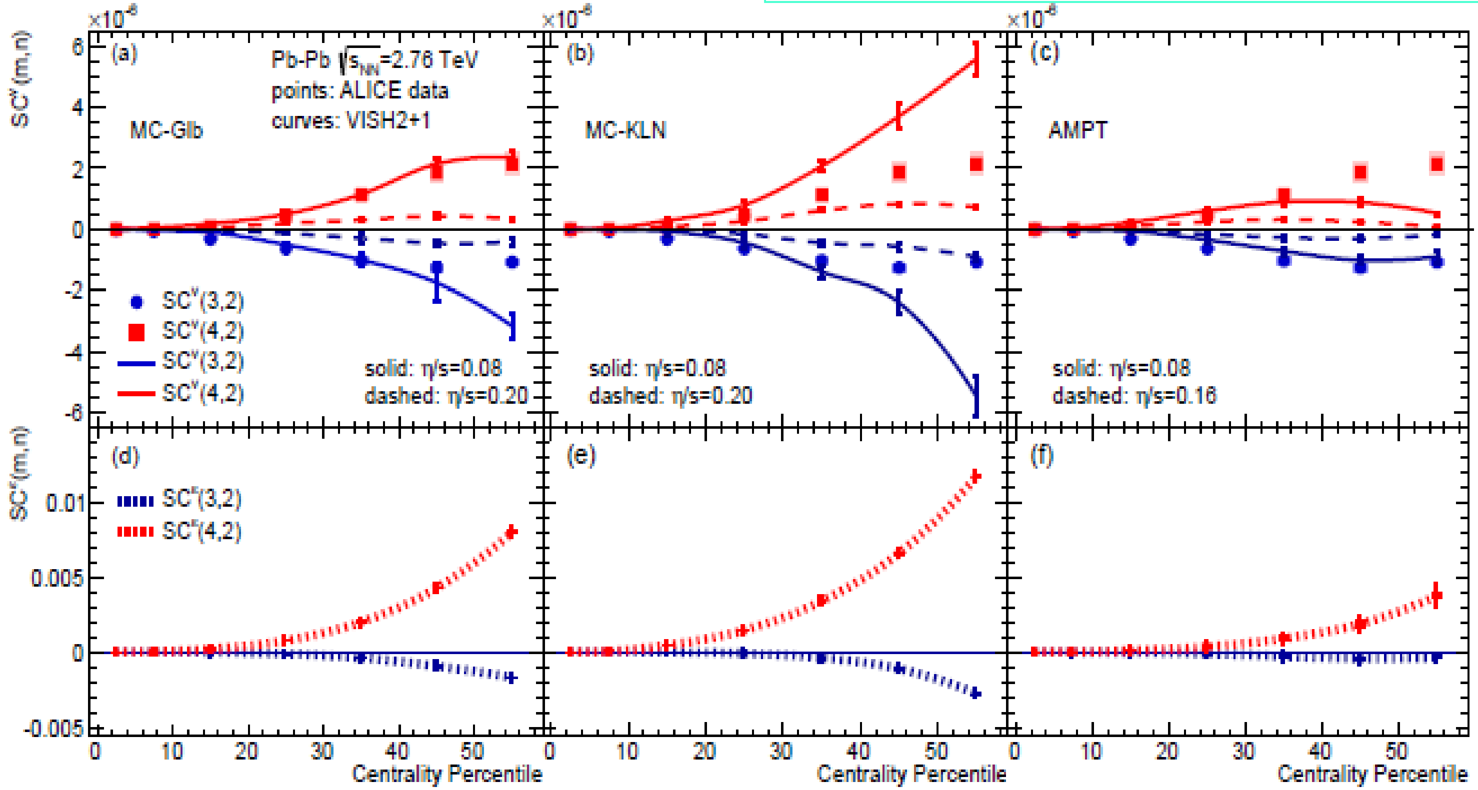
  - -fluctuations of partons in momentum & position space



$SC^v(3,2)$ & $SC^v(4,2)$

$$SC^{v}(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

$$SC^{\varepsilon}(m,n) = \langle \varepsilon_m^2 \varepsilon_n^2 \rangle - \langle \varepsilon_m^2 \rangle \langle \varepsilon_n^2 \rangle$$



Zhu, Xu, Zhou, Song, in preparation

-$SC^v(3,2)$ and $SC^v(4,2)$ are sensitive to both initial conditions and η/s

-hydrodynamic simulations correctly capture the sign of $SC^v(3,2)$ and $SC^v(4,2)$

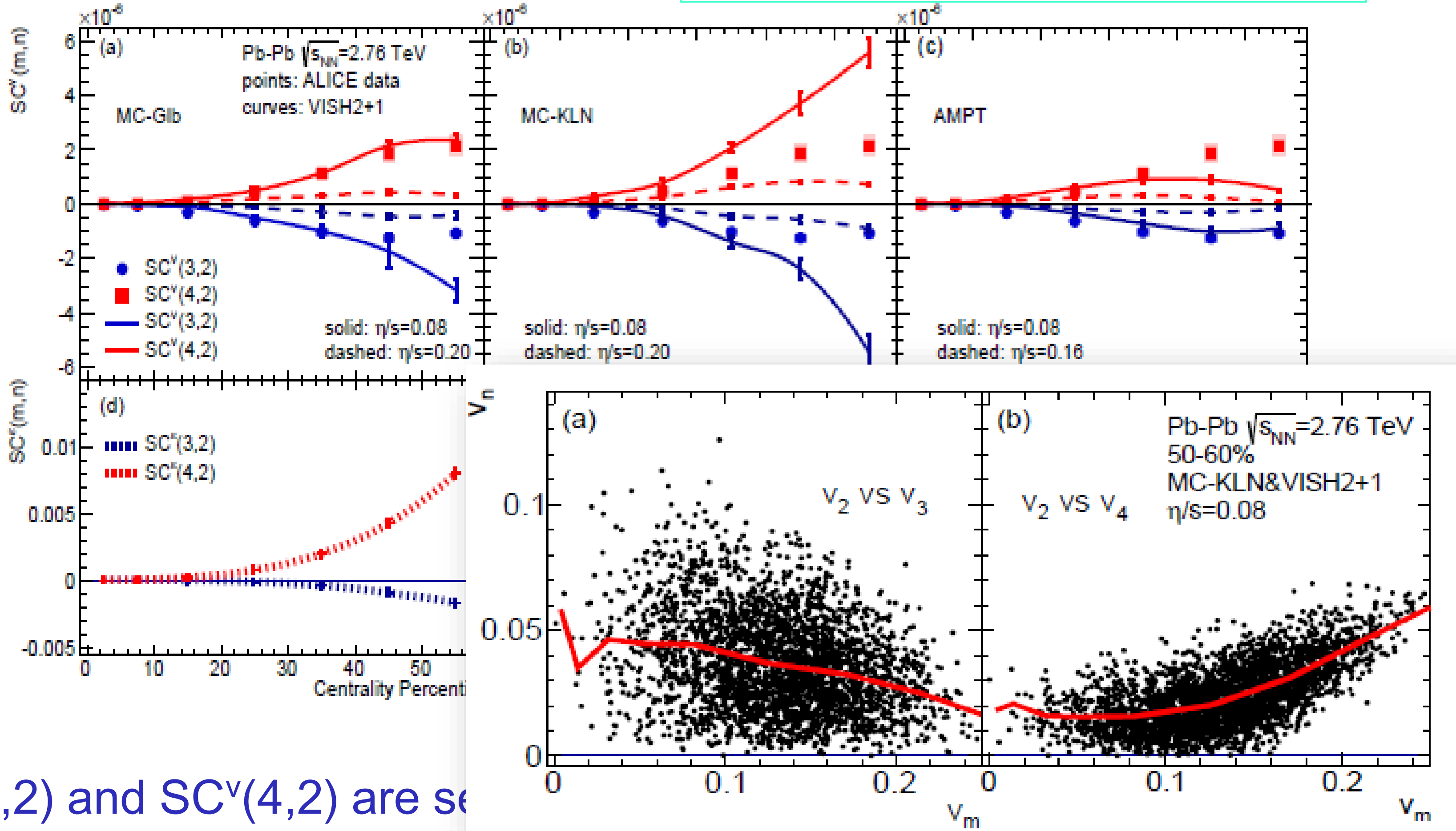
-V_2 and V_4 are correlated, V_2 and V_3 are anti-correlated

-$SC^v(3,2)$ and $SC^v(4,2)$ follow the sign of $SC^{\varepsilon}(3,2)$ and $SC^{\varepsilon}(4,2)$

$SC^v(3,2)$ & $SC^v(4,2)$

$$SC^v(m,n) = \langle v_m^2 \, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

$$SC^\varepsilon(m,n) = \langle \varepsilon_m^2 \varepsilon_n^2 \rangle - \langle \varepsilon_m^2 \rangle \langle \varepsilon_n^2 \rangle$$



on

-$SC^v(3,2)$ and $SC^v(4,2)$ are se

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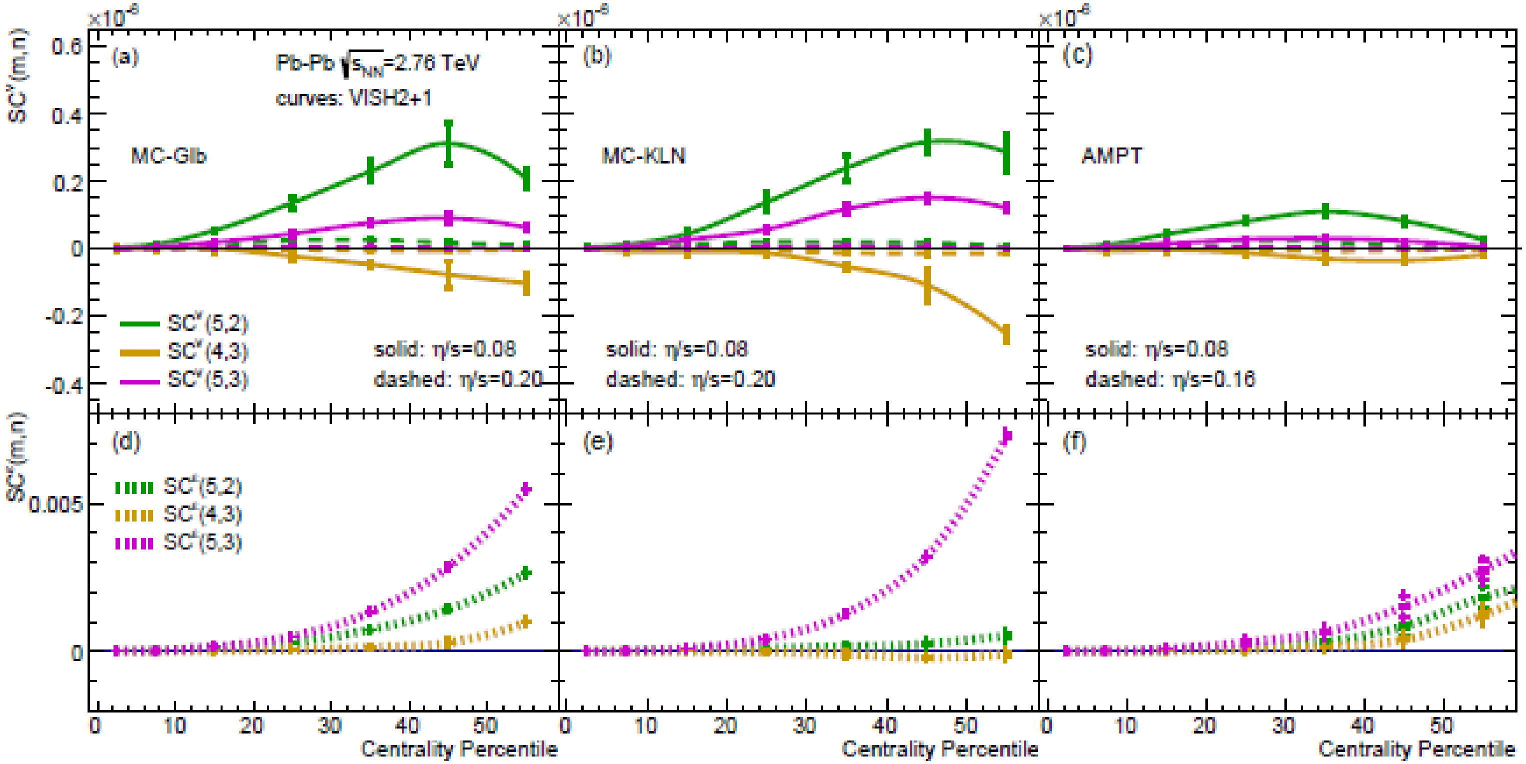
-$SC^v(3,2)$ and $SC^v(4,2)$ follow the sign of $SC^\varepsilon(3,2)$ and $SC^\varepsilon(4,2)$

$SC^v(5,2)$, $SC^v(4,3)$ & $SC^v(5,3)$

$$SC^v(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

$$SC^\varepsilon(m,n) = \langle \varepsilon_m^2 \varepsilon_n^2 \rangle - \langle \varepsilon_m^2 \rangle \langle \varepsilon_n^2 \rangle$$



Zhu, Xu, Zhou, Song, in preparation

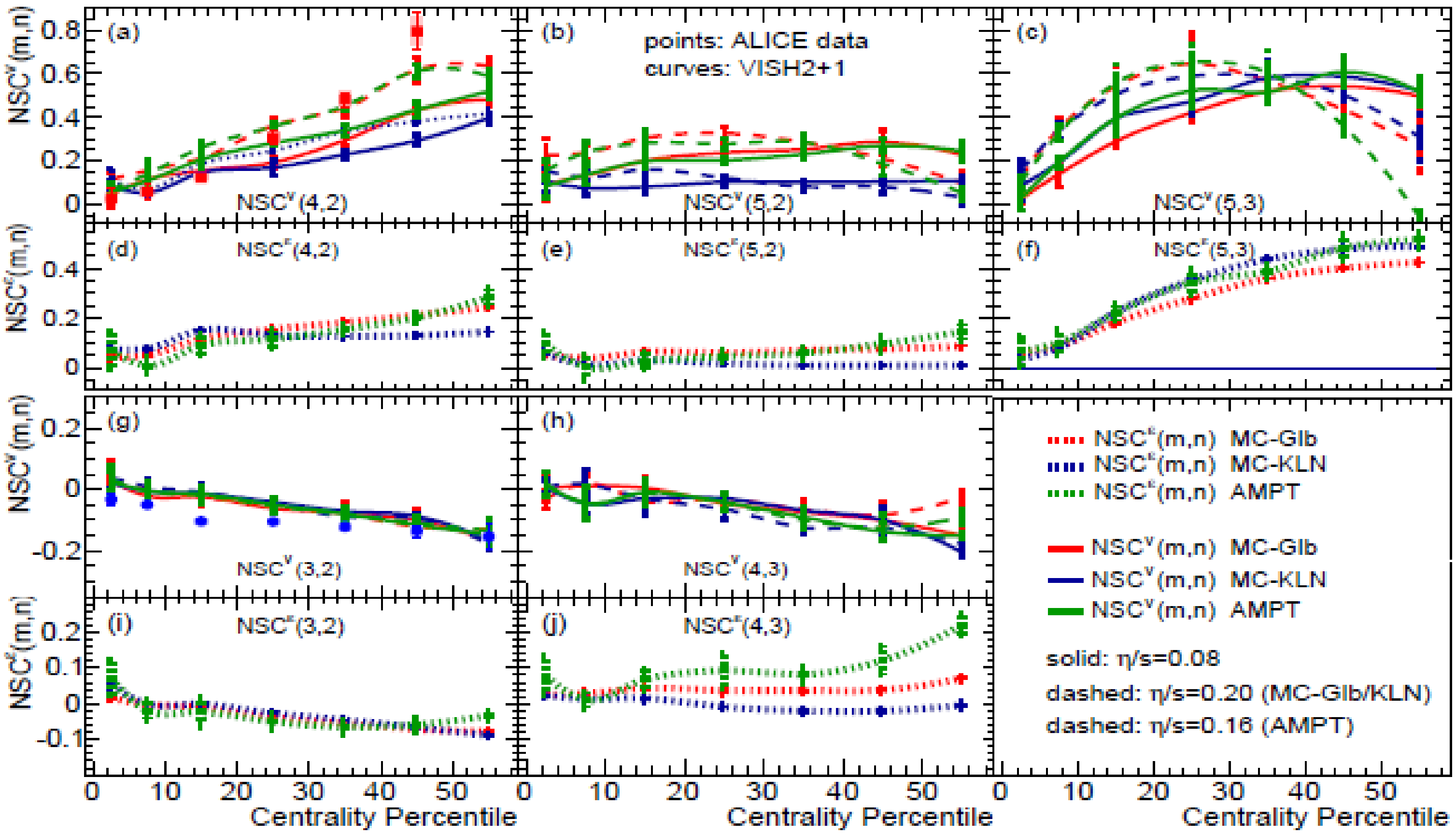
- V_2 and V_5 ; V_3 and V_5 are correlated, V_3 and V_4 are anti-correlated
- $SC^v(5,2)$ and $SC^v(5,3)$ respectively follow the sign of $SC^\varepsilon(5,2)$ and $SC^\varepsilon(5,3)$
- $SC^v(4,3)$ & $SC^\varepsilon(4,3)$ show opposite signs

$$v_4 e^{i4\Psi} = a_0 \varepsilon_4 e^{i4\Phi_4} + a_1 (\varepsilon_2 e^{i2\Phi_2})^2$$

Normalized Symmetric Cumulants NSC^v(m,n)

$$NSC^v(m,n) = \frac{SC^v(m,n)}{\langle v_m^2\rangle\langle v_n^2\rangle} = \frac{\langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle}{\langle v_m^2\rangle\langle v_n^2\rangle}$$

$$NSC^\varepsilon(m,n) = \frac{SC^\varepsilon(m,n)}{\langle \varepsilon_m^2\rangle\langle \varepsilon_n^2\rangle} = \frac{\langle \varepsilon_m^2 \varepsilon_n^2\rangle - \langle \varepsilon_m^2\rangle\langle \varepsilon_n^2\rangle}{\langle \varepsilon_m^2\rangle\langle \varepsilon_n^2\rangle}$$



Zhu, Xu, Zhou, Song, in preparation

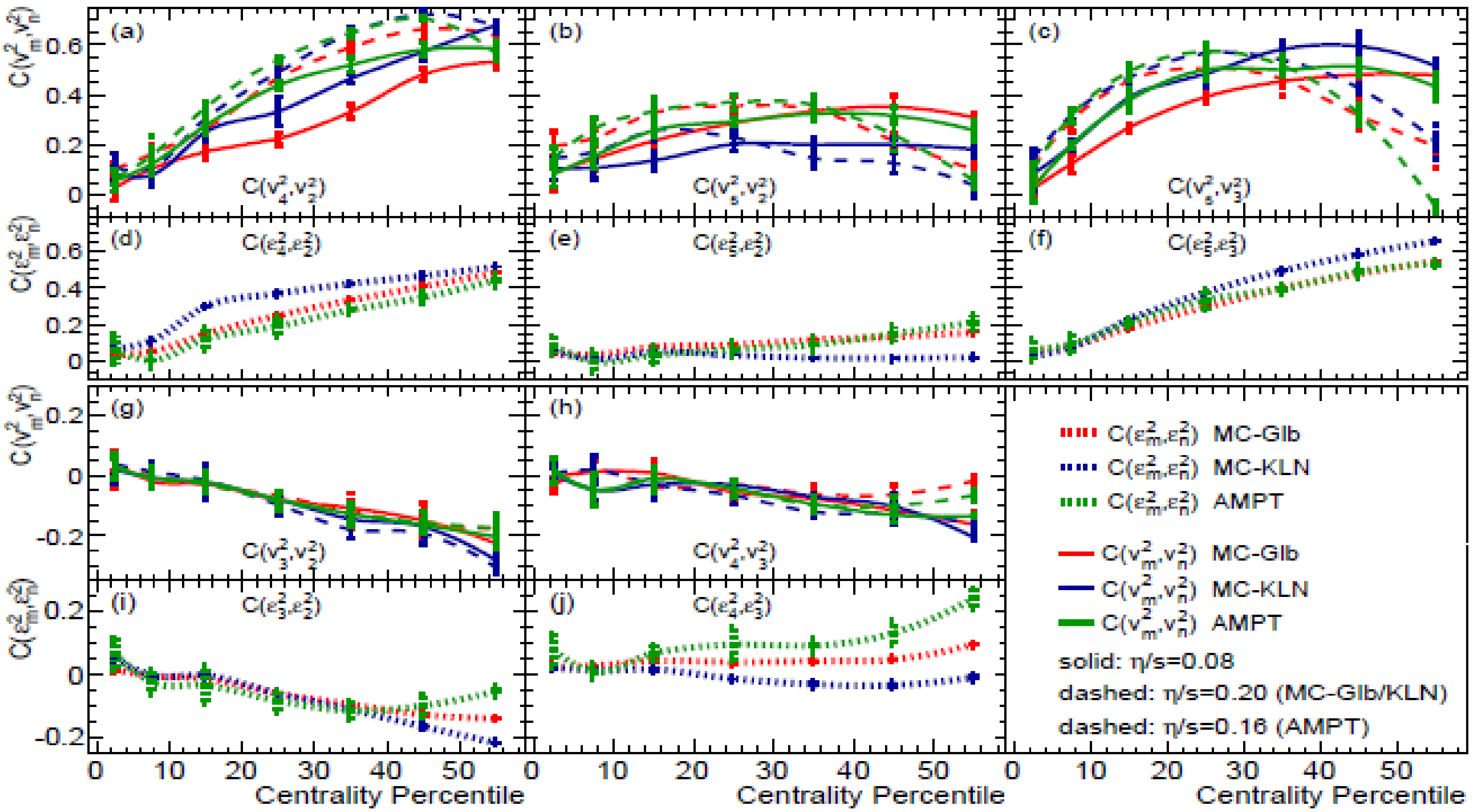
- -NSC^v (3,2): insensitive to η/s and initial conditions, roughly fit the ALICE data
- -NSC^v (4,2), NSC^v (5,2) & NSC^v (5,3): sensitive to η/s and initial conditions

Pearson correlation coefficients

$$C(v_m^2, v_n^2) = \frac{\langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle}{\sqrt{\langle v_m^4\rangle - \langle v_m^2\rangle^2}\sqrt{\langle v_n^4\rangle - \langle v_n^2\rangle^2}}$$

$$C(\varepsilon_m^2, \varepsilon_n^2) = \frac{\langle \varepsilon_m^2 \varepsilon_n^2\rangle - \langle \varepsilon_m^2\rangle\langle \varepsilon_n^2\rangle}{\sqrt{\langle \varepsilon_m^4\rangle - \langle \varepsilon_m^2\rangle^2}\sqrt{\langle \varepsilon_n^4\rangle - \langle \varepsilon_n^2\rangle^2}}$$

C=1 or -1: v_m and v_n is linearly correlated or anti-correlated, and C=0: uncorrelated



Zhu, Xu, Zhou, Song, in preparation

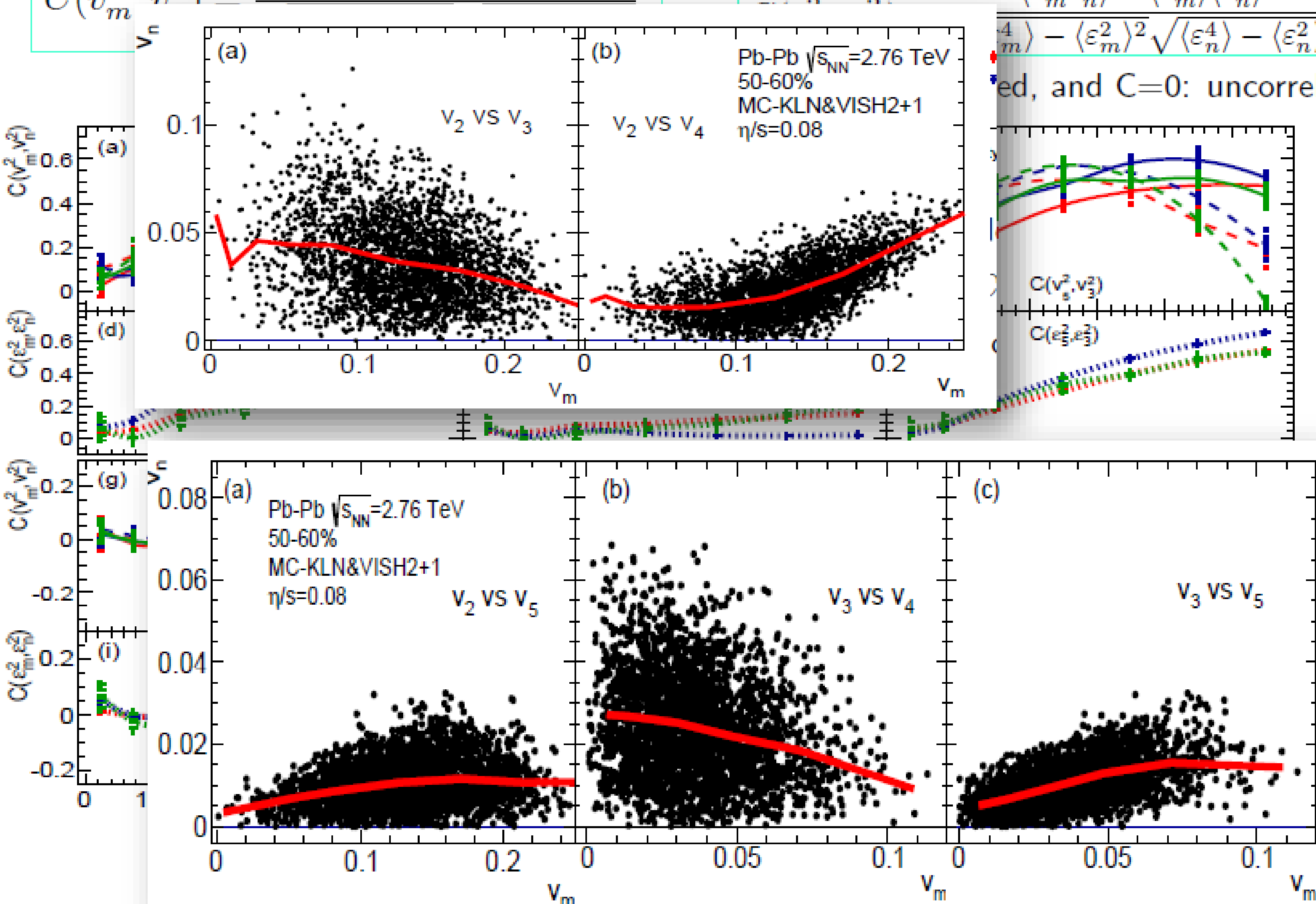
-None of the Vn and Vm pairs are linearly correlated or linearly anti-correlated

Pearson correlation coefficients

$$C(v_m^2, v_n^2) = \frac{\langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle}{\ldots}$$

$$\ldots = \frac{\langle \varepsilon_m^2 \varepsilon_n^2\rangle - \langle \varepsilon_m^2\rangle\langle \varepsilon_n^2\rangle}{\ldots\rangle - \langle \varepsilon_m^2\rangle^2 \sqrt{\langle \varepsilon_n^4\rangle - \langle \varepsilon_n^2\rangle^2}}$$

…ed, and C=0: uncorrelated



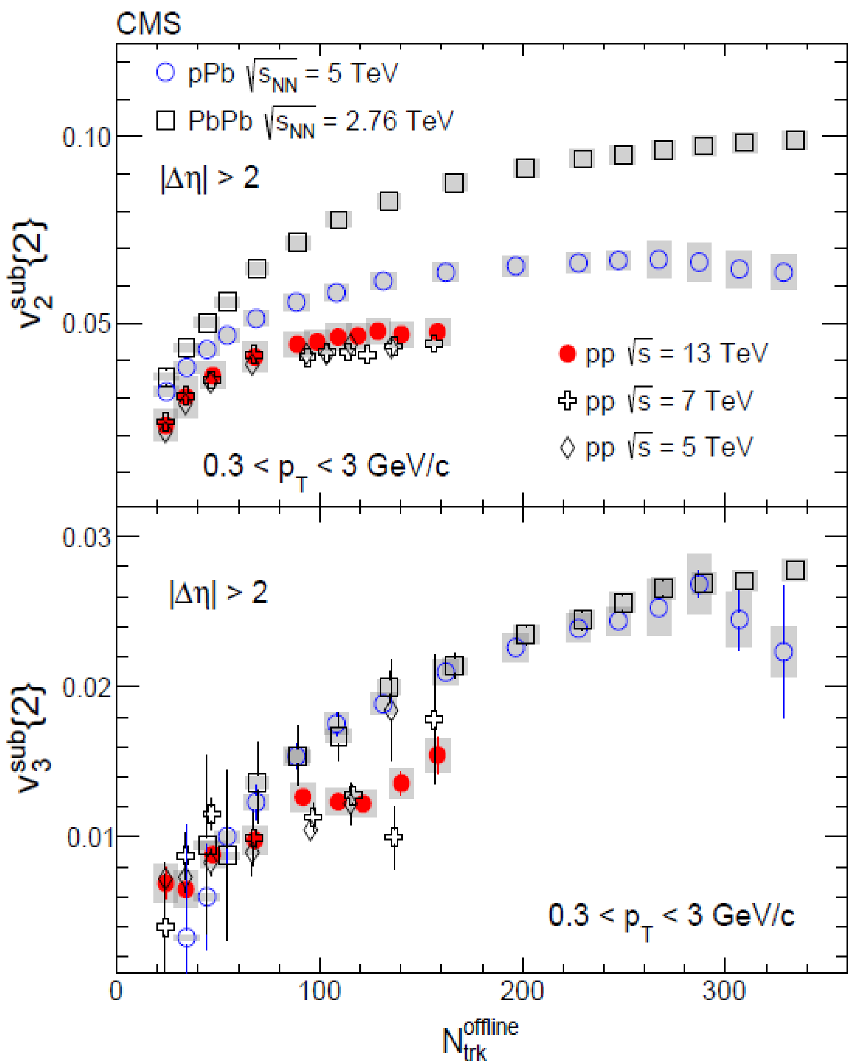
…paration

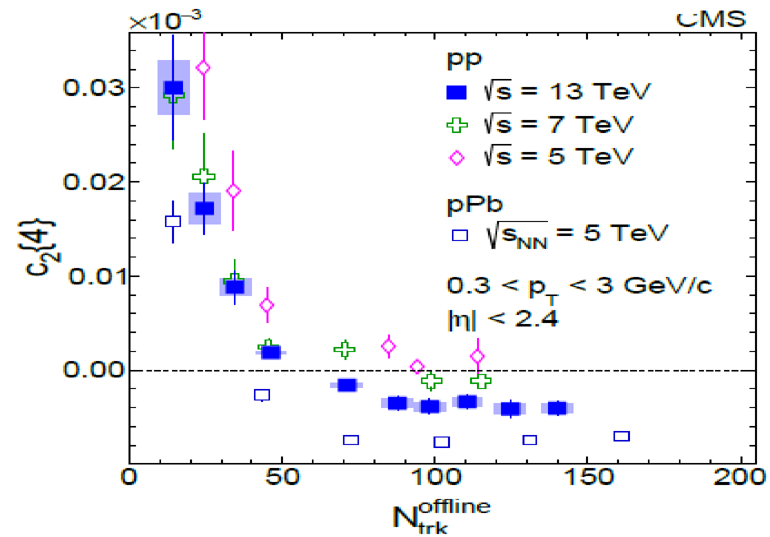
-None of the Vn and Vm pairs are linearly correlated or linearly anti-correlated

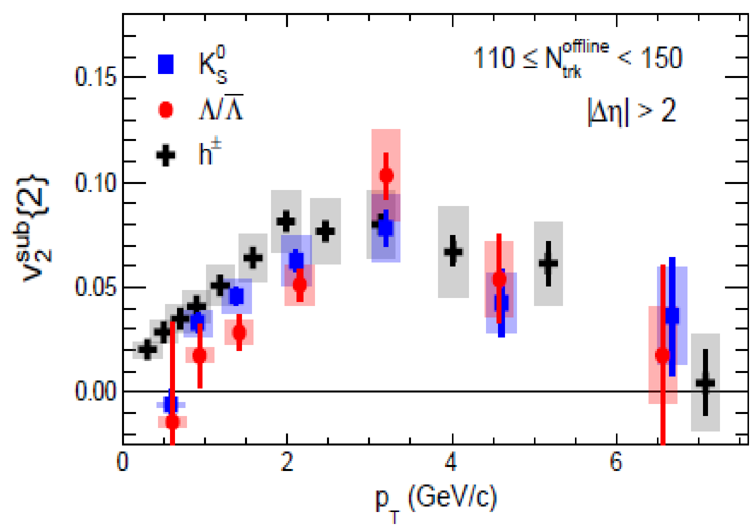
Collective flow in smaller systems

-p+p collisions at 7 & 13 TeV

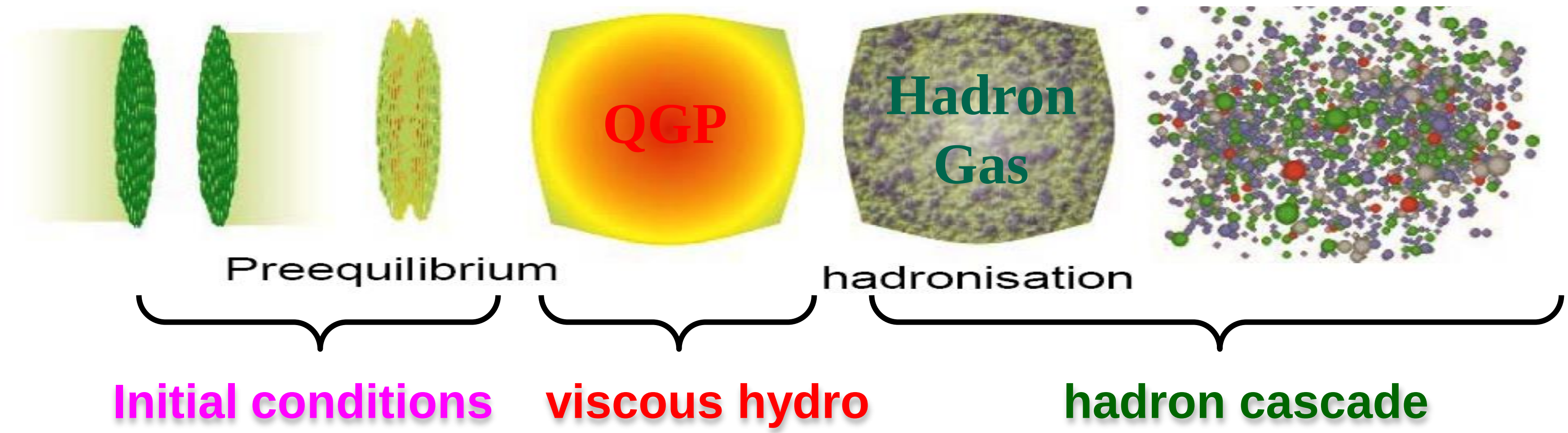
CMS 1606.06198





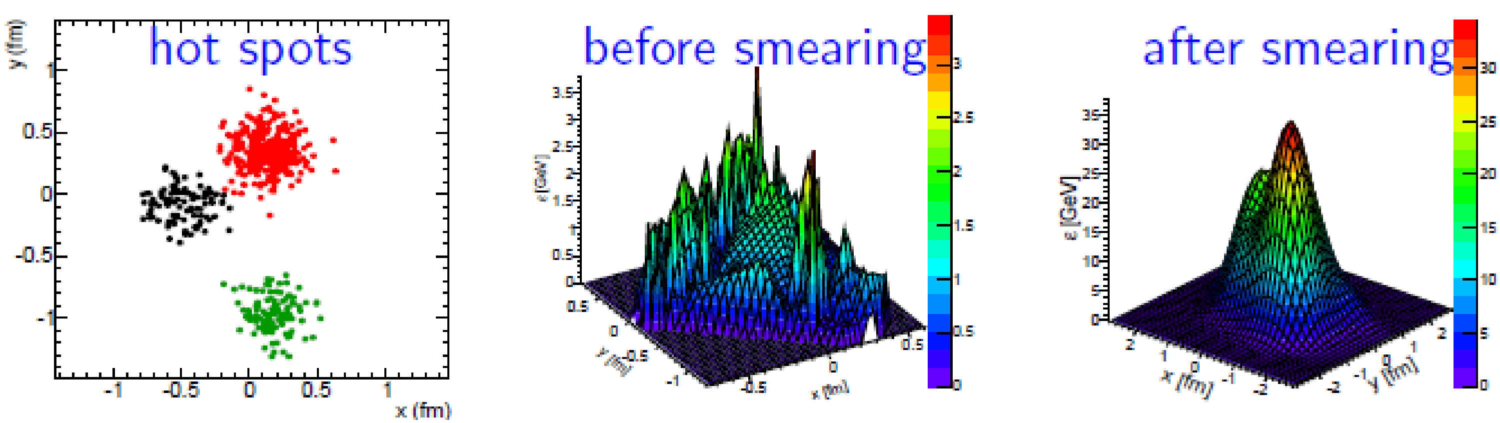


iEBE-VISHNU



Initial conditions

- HIJING initial conditions (depose energy by strings)



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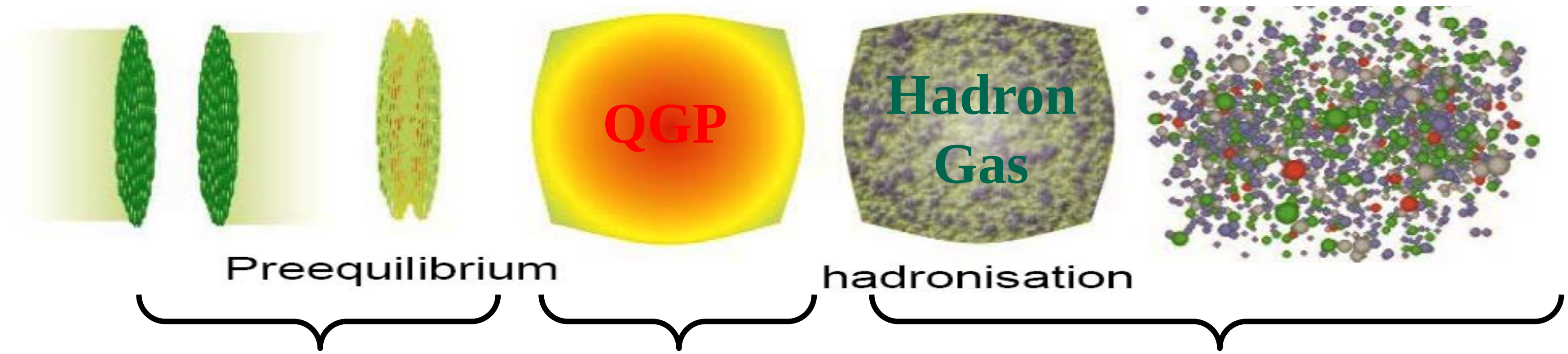
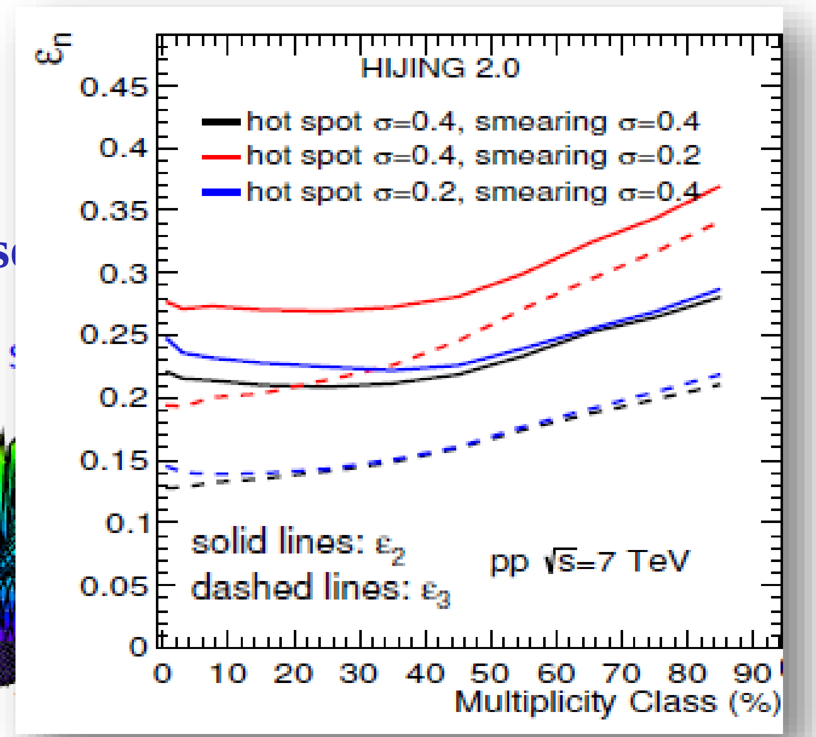
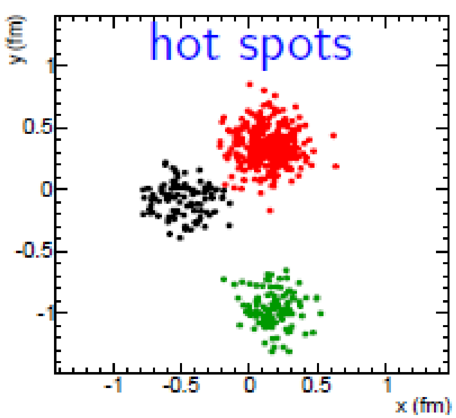


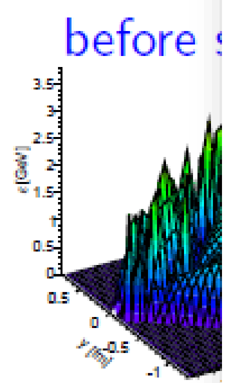
Initial conditions **viscous hydro** **hadron cascade**



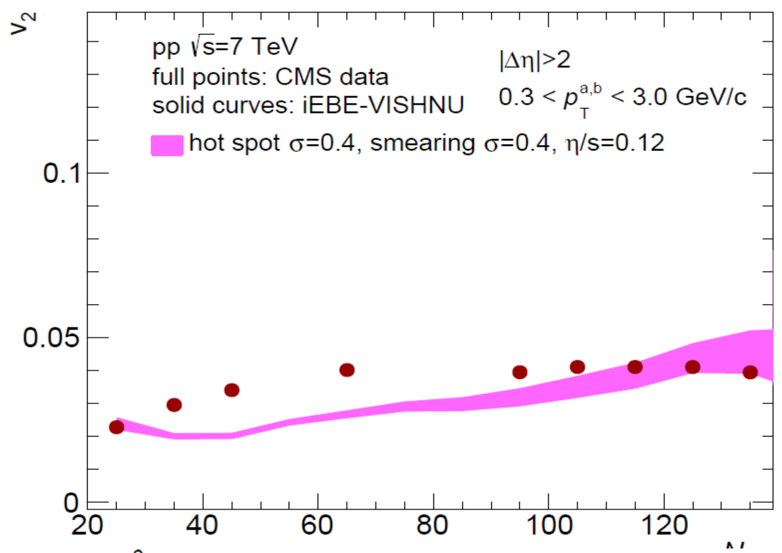
Initial conditions

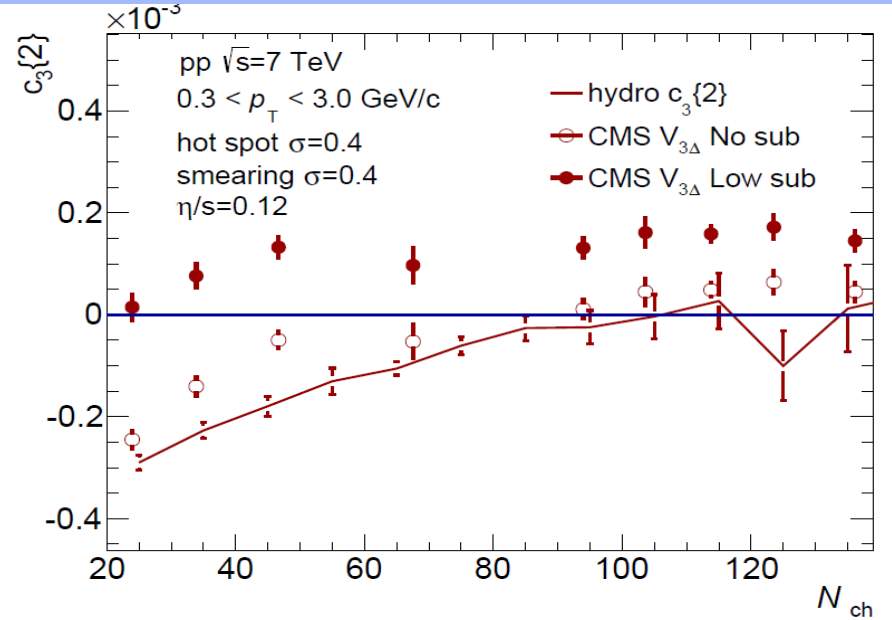
- **HIJING initial conditions (depos**

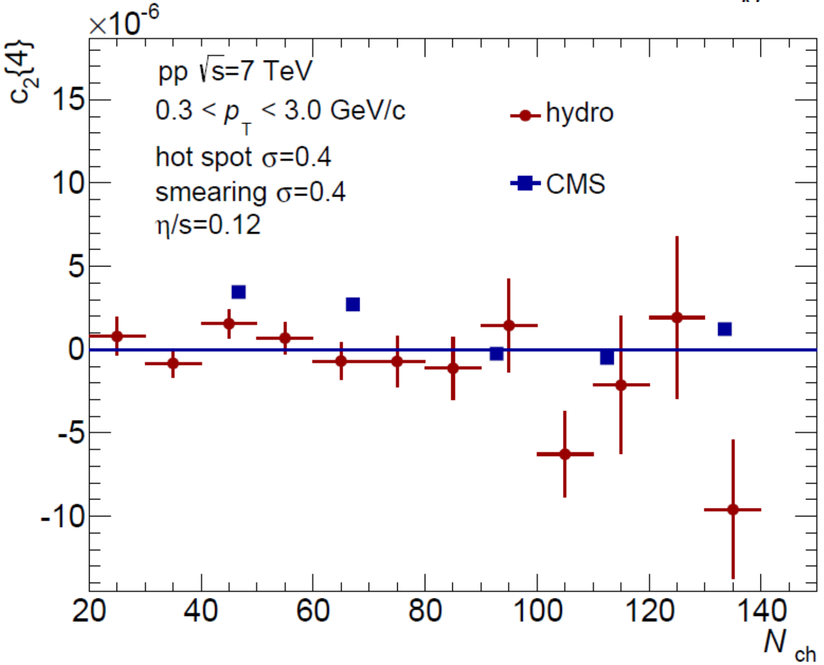




Collective flow in p+p -- Hydro Simulations







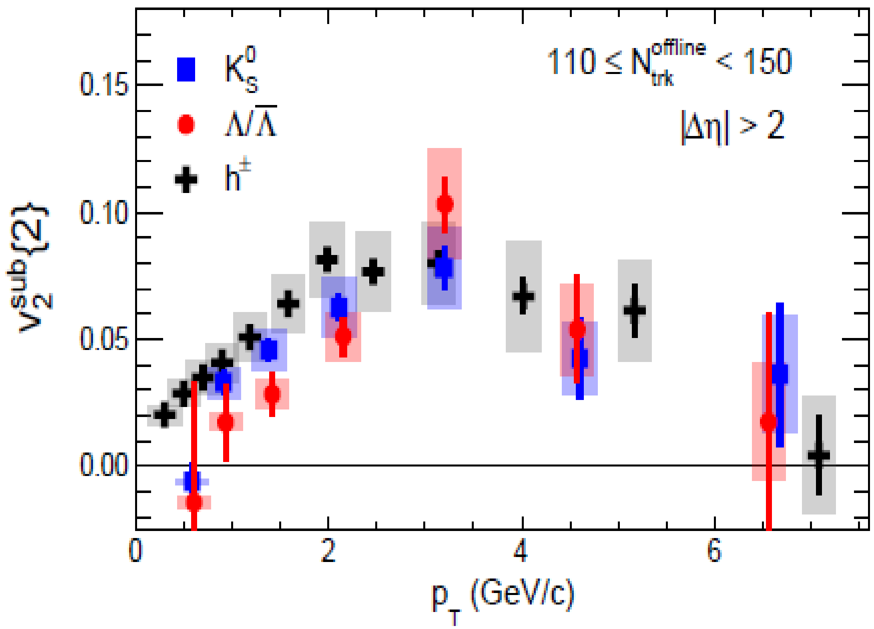
iEBE-VISHNU (HIJING (hot spots))

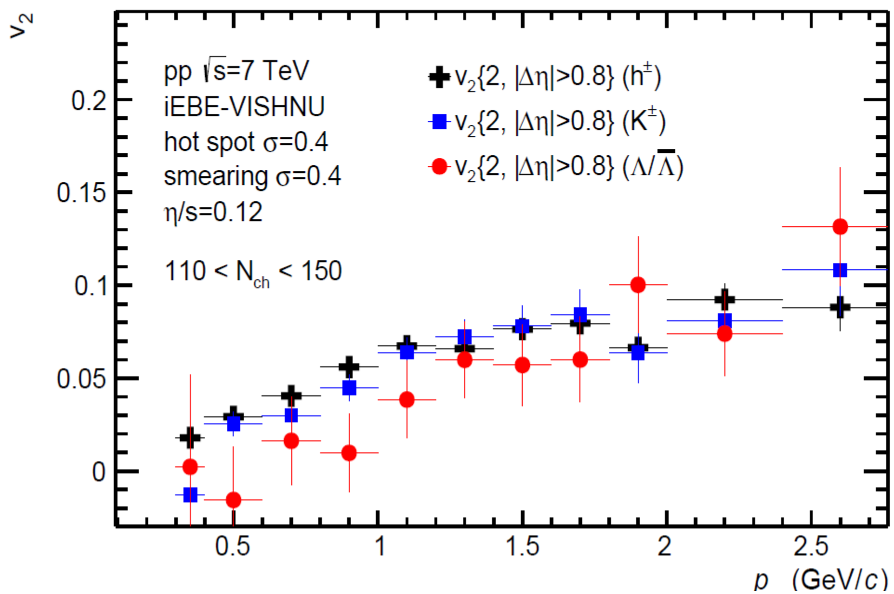
-Multiplicity dependent V_2

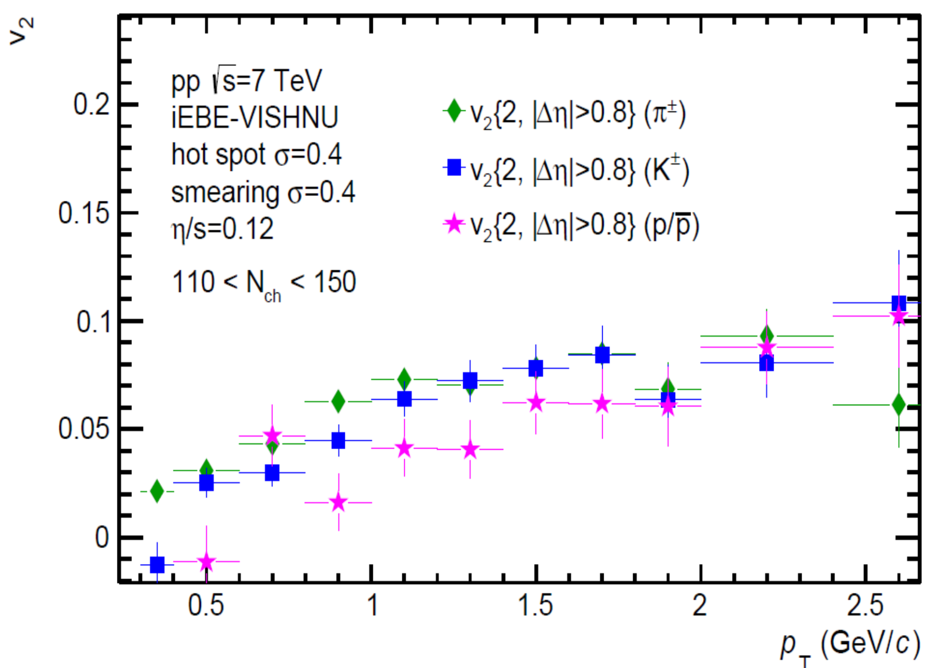
-development of triangular flow at high multiplicity events

-The trend of changing sign of $C_2\{4\}$ (high statistical run is still needed)

Collective flow in p+p -- Hydro Simulations







iEBE-VISHNU
(HIJING (hot spots))

-Similar mass-ordering of h K and Λ as observed in exp.

-also shows mass-ordering of π K p.

Summary

Higher-Order Flow Harmonics of Identified Hadrons in 2.76 A TeV Pb+Pb collisions

-iEBE-VISHNU nicely describe the V_n data from ALICE

-Hadronic interactions rebalance the generations of radial and anisotropic flow, leading to a nice description of v_n of identified hadrons

Correlations of flow harmonics in 2.76 A TeV Pb+Pb collisions

-iEBE-VISH2+1 qualitatively describe SC(3,2), SC(4,2); V_2 and V_4 are correlated, V_2 and V_3 are anti-correlated ;

-Predictions of SC(5,2), SC(5,3) and SC(4,3) shows V_2 and V_5, V_3 and V_5 are correlated, V_3 and V_4 are anti-correlated ;

-Normalized symmetric cumulants NSC(3,2) are insensitive to both initial conditions and η/s

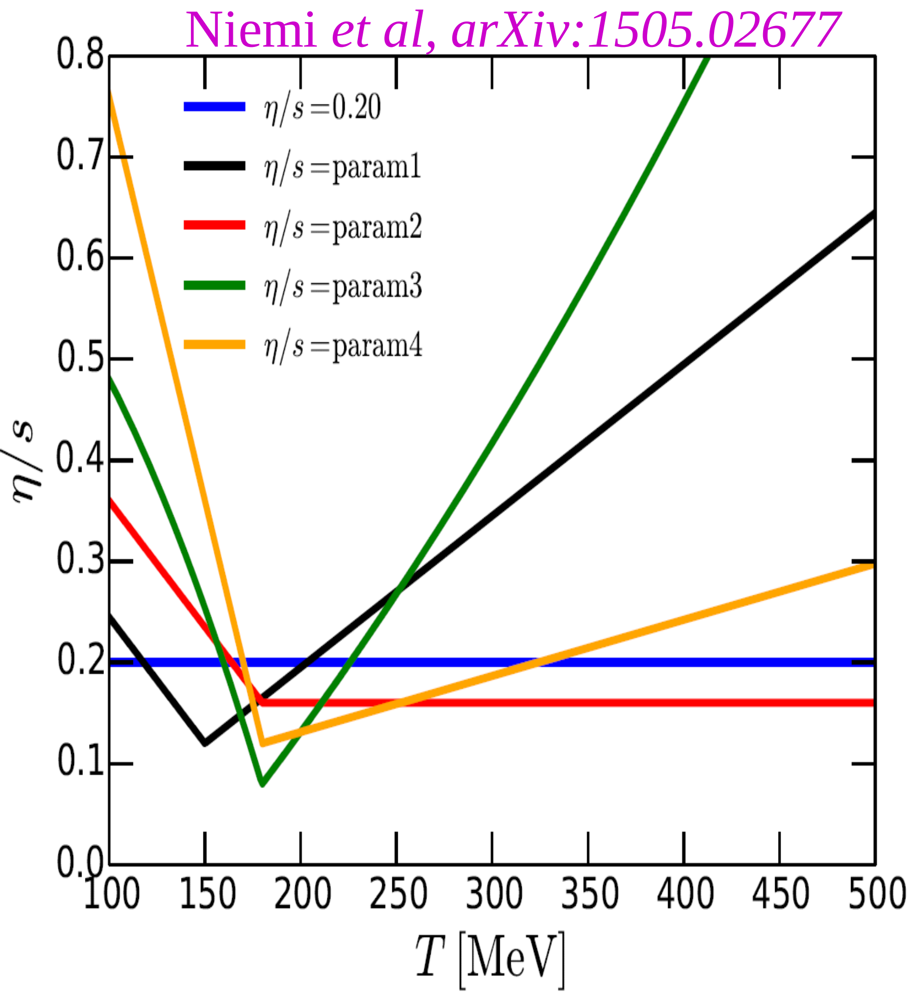
Collective flow in p+p collisions

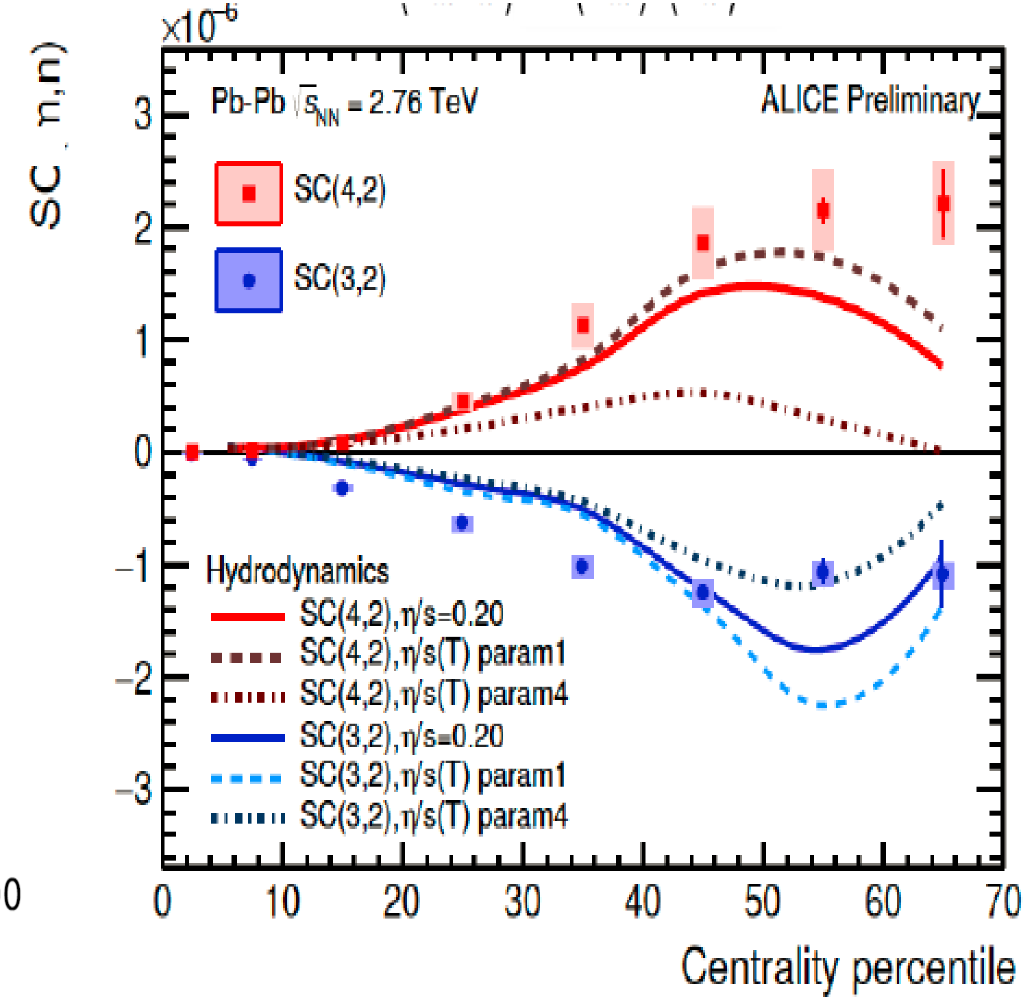
-hydrodynamics can naturally describes v2 v3, C2{4} and the v2 mass-ordering in the high multiplicity events

Thank You

$SC^v(3,2)$ & $SC^v(4,2)$ –hydrodynamic simulations with η/s(T)

Niemi *et al, arXiv:1505.02677*





-hydrodynamic simulations with η/s(T) correctly capture the sign of SC(3,2) and SC(4,2), but can not quantitatively describe the data

Fluctuations and Correlations in smaller systems

-p+Pb collisions at 5 TeV

Where dose the correlations (collective flow) in 5.02 TeV p-Pb collisions come from?

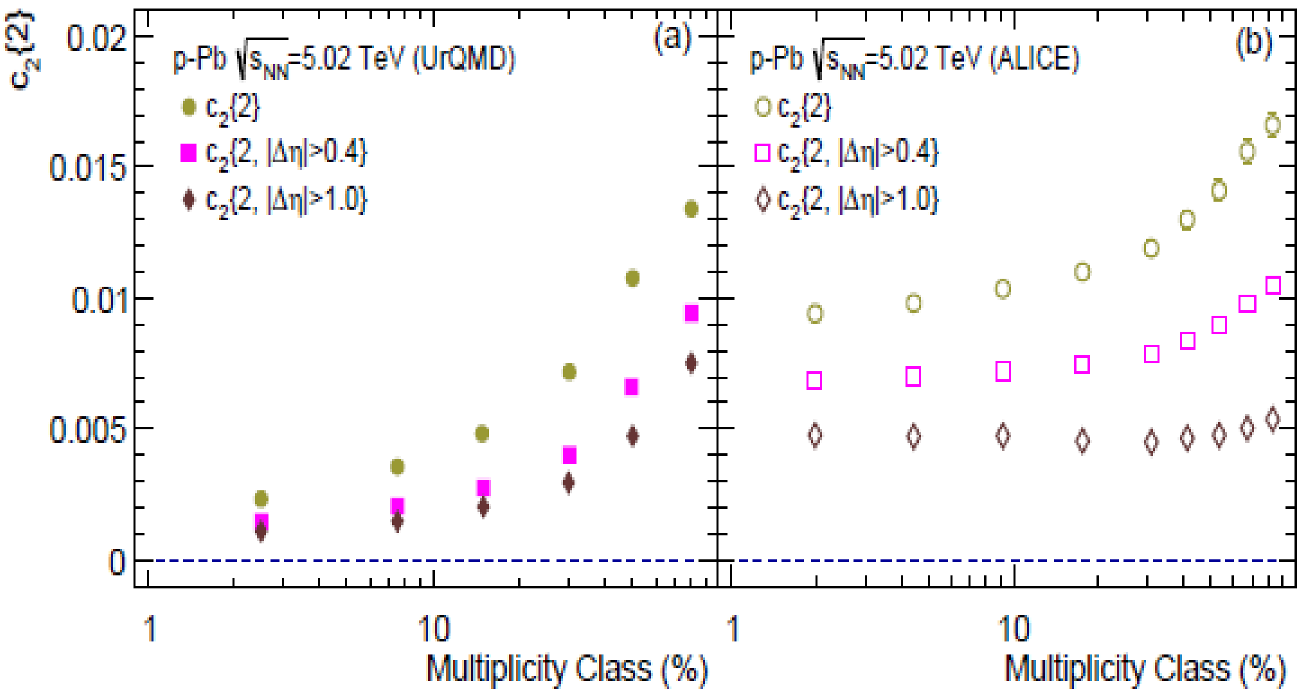
-Initial State?
-QGP ?

UrQMD Baseline Calculations

Zhou, Zhu, Li, Song, PRC 2015

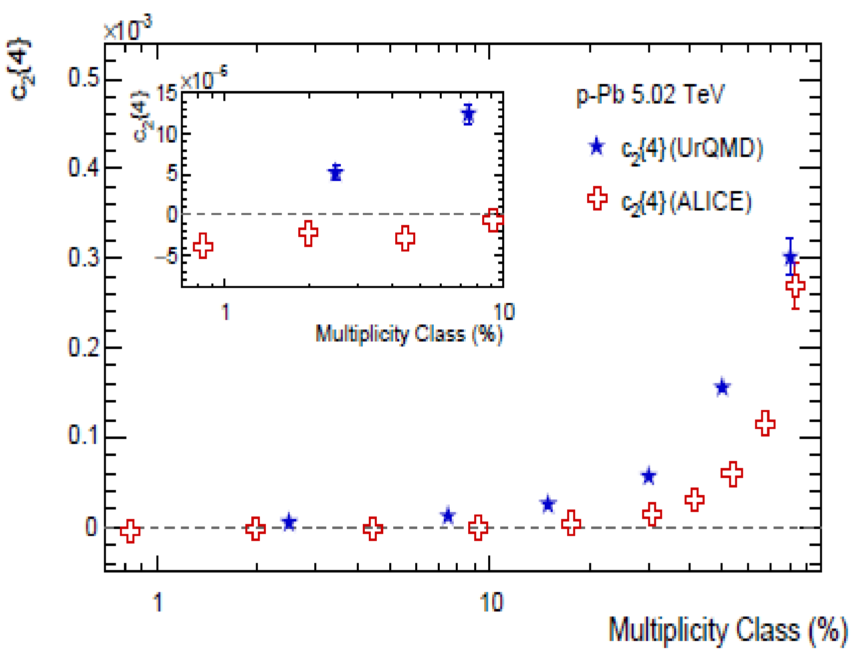
Assumption: p-Pb collisions only produce hadronic systems without reach the thresh hold of the QGP formation

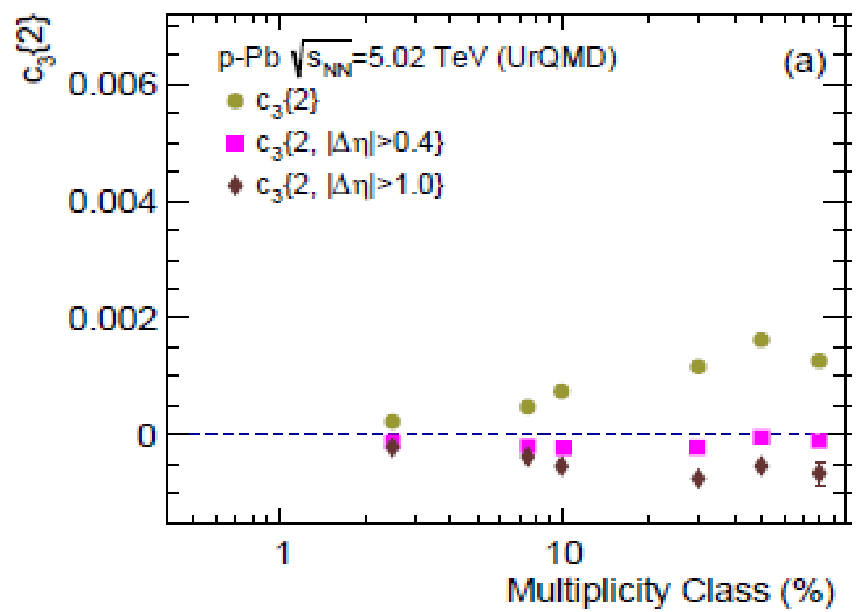
Zhou, Zhu, Li, Song, PRC2015



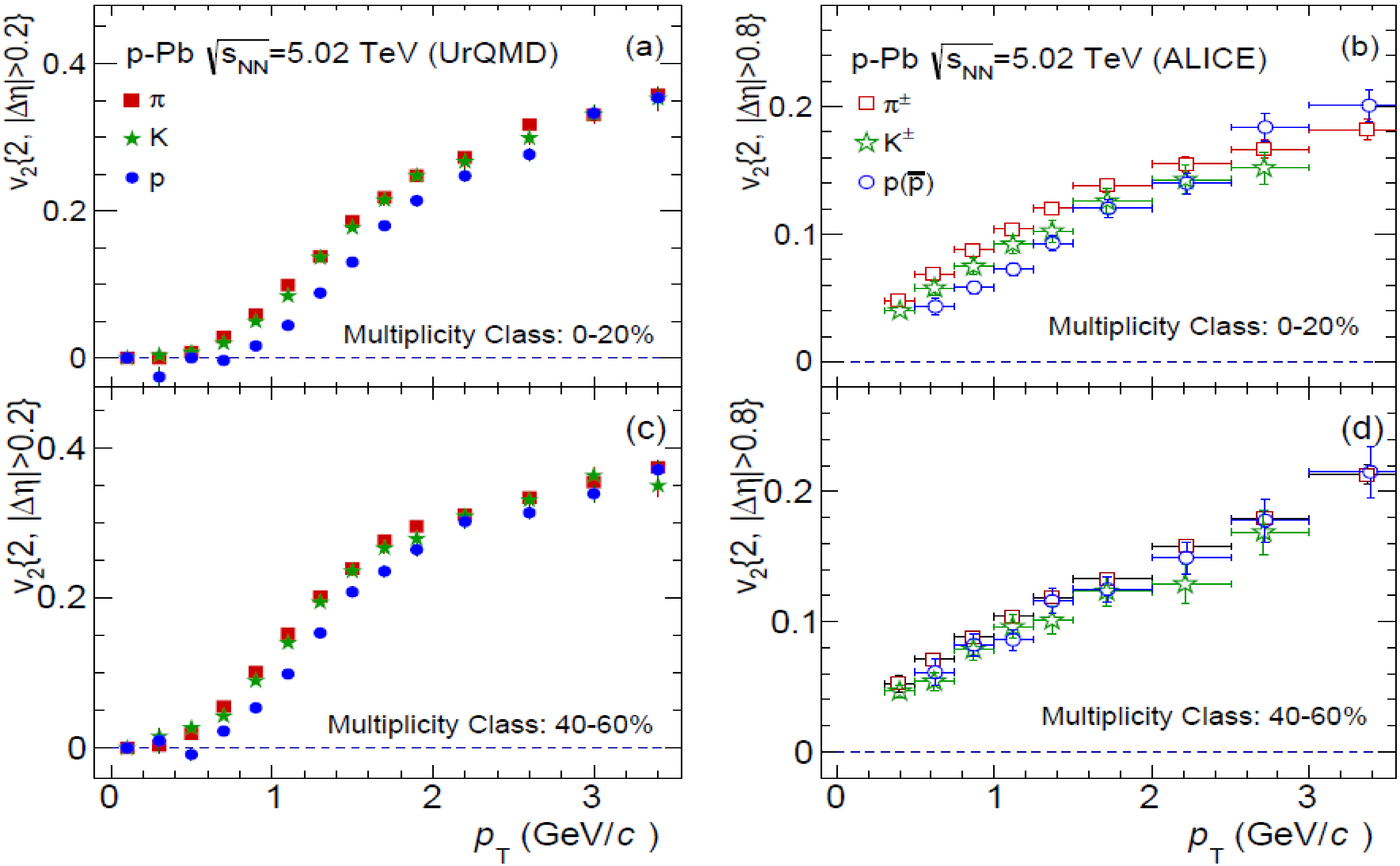
- -The UrQMD systems are largely influenced by non-flow effects

- -To reproduce the flow data, effects from initial state and/or QGP are needed





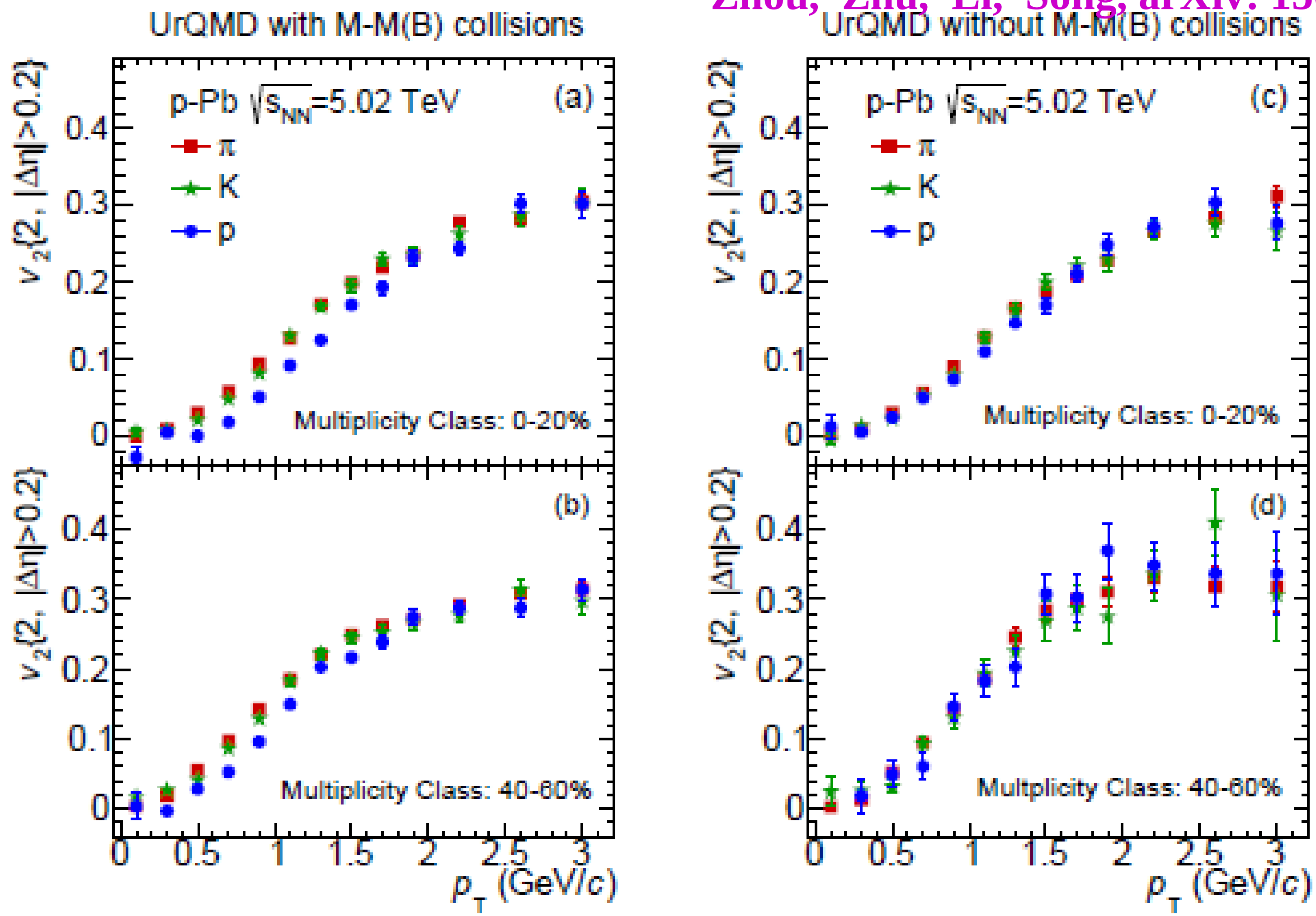
V_2 mass ordering in p+Pb collisions at 5.02 TeV



V_2 mass ordering is produced by UrQMD, similar to the ALICE data

Hadronic interactions & v2 mass ordering

Zhou, Zhu, Li, Song, arXiv: 1503.06986



-Hadronic interaction can generate a mass ordering for 2- particle correlations

-Additive quark model: different M-M M-B cross-sections