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Correlations and fluctuations in large and small systems at the LHC energies

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In collaboration with:

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Outline

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- Correlations between flow harmonics in Pb+Pb collisions at $\sqrt{s_{\text{NN}}}=2.76 \text{ TeV}$
 - Experimental measurements of correlations on event-planes and flow harmonics
 - Correlations of flow harmonics from e-by-e VISH2+1 hydrodynamics
- Azimuthal correlations in p+Pb collisions at $\sqrt{s_{\text{NN}}}=5.02 \text{ TeV}$
 - Azimuthal correlations from hadronic cascade model, UrQMD
- Investigating anisotropic collectivity in pp collisions at the LHC energies
 - Initial conditions
 - Event-by-event hybrid approach iEBE-VISHNU in pp collisions at 7 and 13 TeV
- Summary

Correlations between flow harmonics in Pb+Pb collisions at $\sqrt{s_{\text{NN}}}=2.76 \text{ TeV}$



Introduction

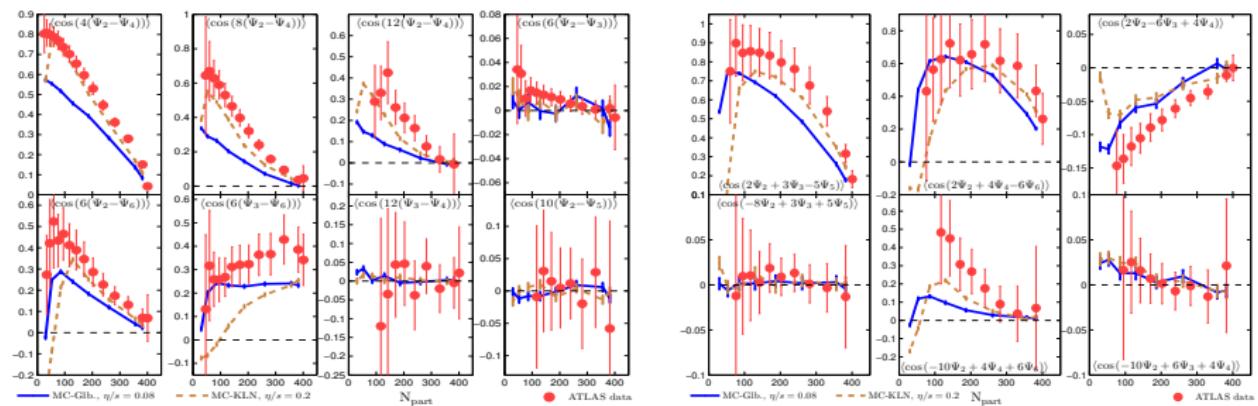
Anisotropic flow: initial anisotropic geometry and its fluctuations

Introduction

Anisotropic flow: initial anisotropic geometry and its fluctuations

- Correlations of event-plane angles

ATLAS, PRC 90 024905 (2014), Z. Qiu et al. PLB 717, 261 (2012)

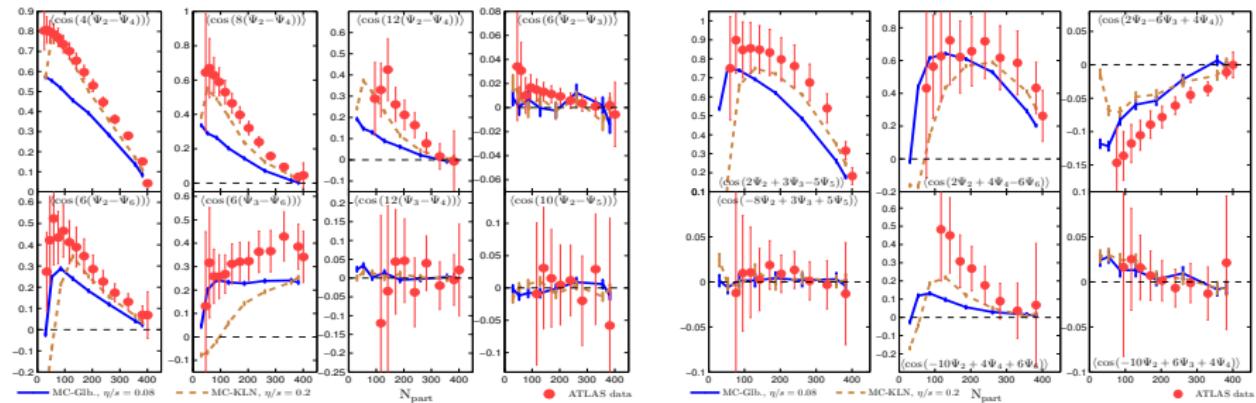


Introduction

Anisotropic flow: initial anisotropic geometry and its fluctuations

- Correlations of event-plane angles

ATLAS, PRC 90 024905 (2014), Z. Qiu et al. PLB 717, 261 (2012)



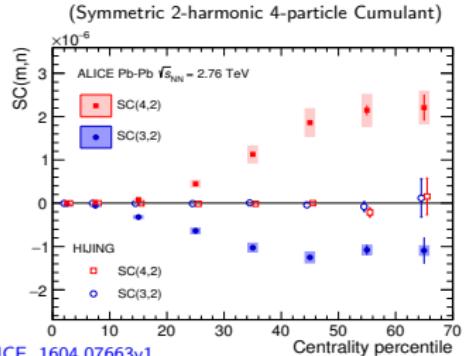
- Correlations of flow harmonics

$$SC(m, n) = \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle_c$$

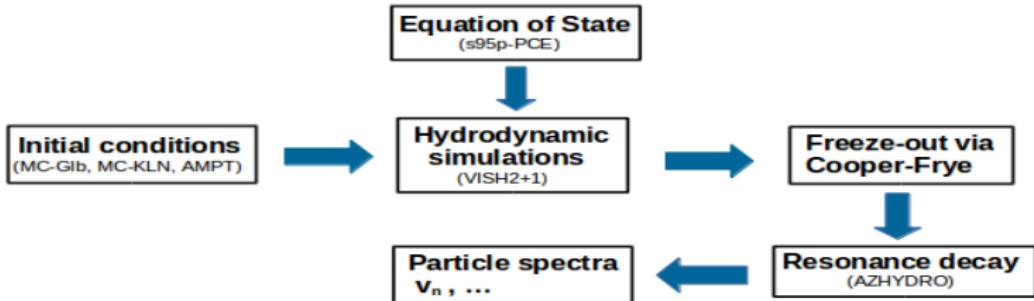
$$= \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

- correlation between v_2 and v_4
- anti-correlation between v_2 and v_3

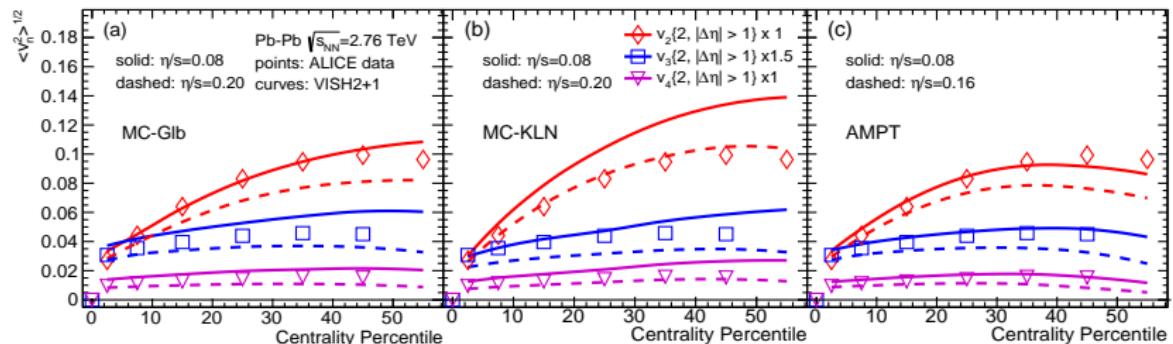
$SC(m, n)$ from HIJING are compatible with zero



Event-by-event hydrodynamics VISH2+1

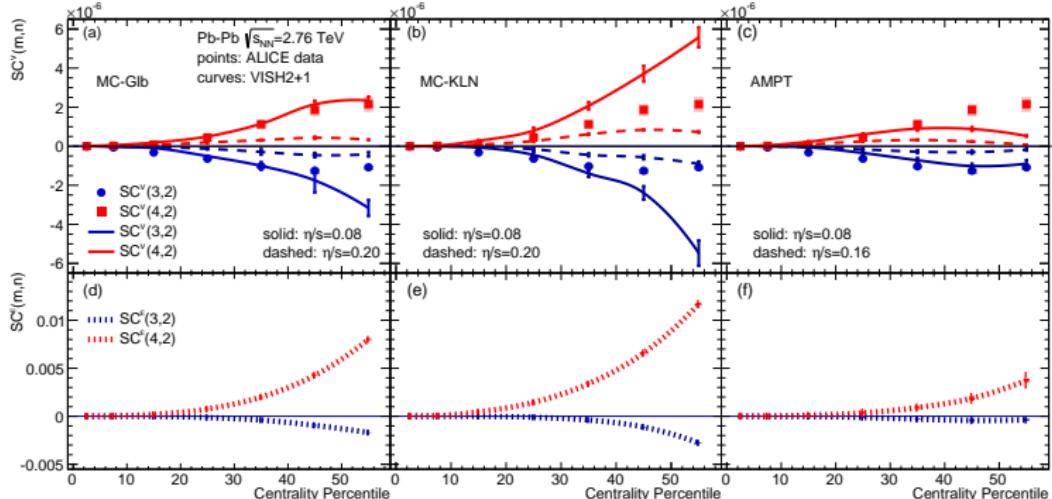


To investigate the initial conditions dependence of correlations of flow harmonics, **MC-Glauber**, **MC-KLN** and **AMPT** initial conditions are used.



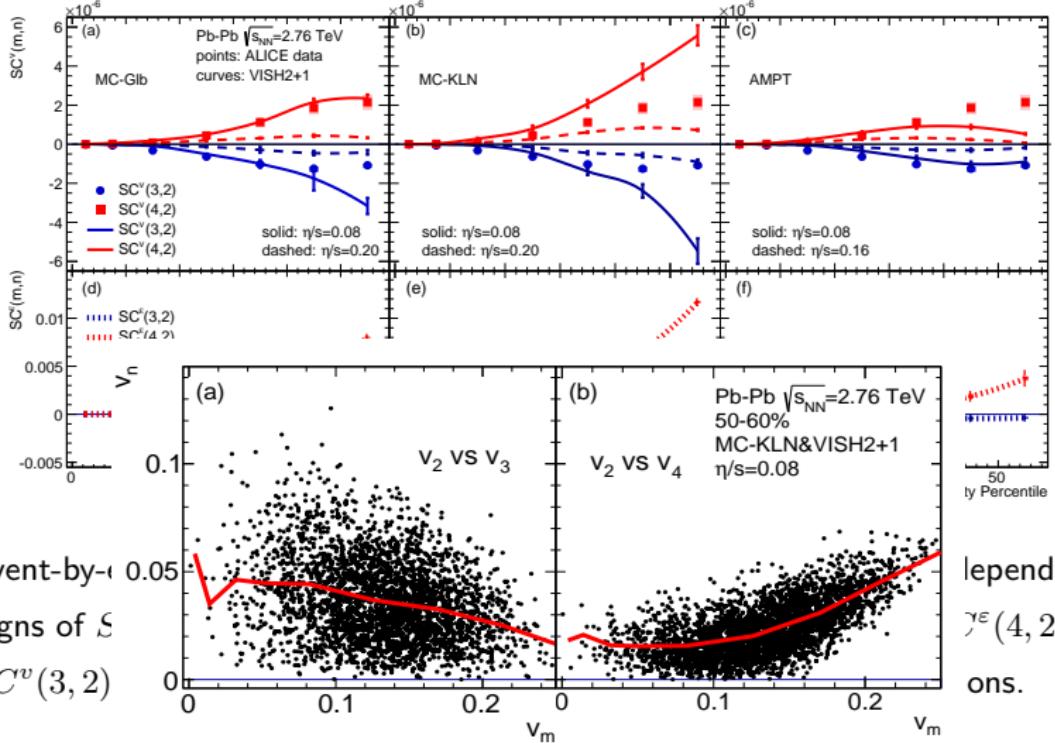
v_n from hydrodynamics with AMPT initial conditions and $\eta/s=0.08$ are compatible with data.

Centrality dependence of $SC(m, n)$



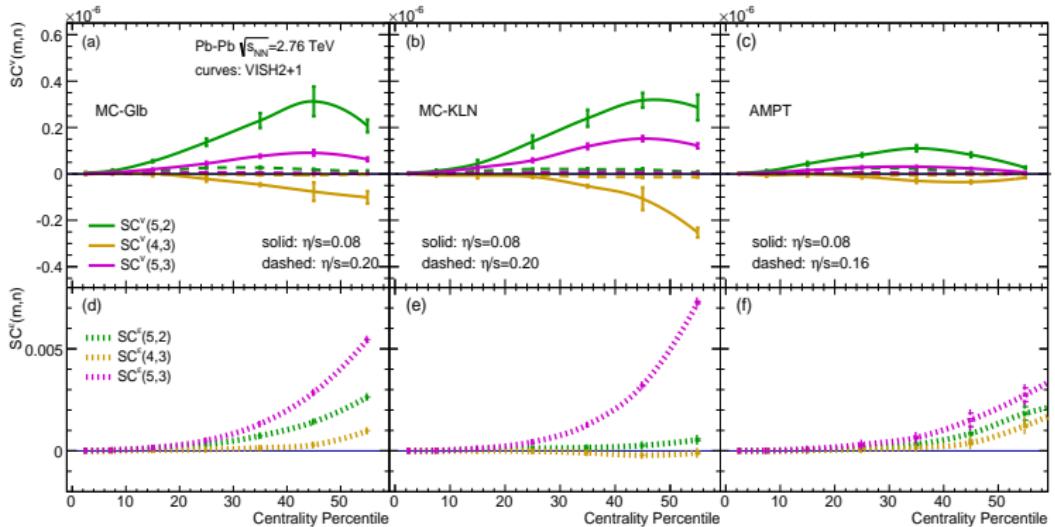
- Event-by-event hydrodynamics qualitatively describes the centrality dependence.
- Signs of $SC^v(3, 2)$ and $SC^v(4, 2)$ are same as the $SC^e(3, 2)$ and $SC^e(4, 2)$.
- $SC^v(3, 2)$ and $SC^v(4, 2)$ are sensitive to both η/s and initial conditions.

Centrality dependence of $SC(m, n)$



- Event-by-event v_n dependence.
- Signs of S dependence.
- $SC^v(3, 2)$ dependence.
- $SC^v(4, 2)$.

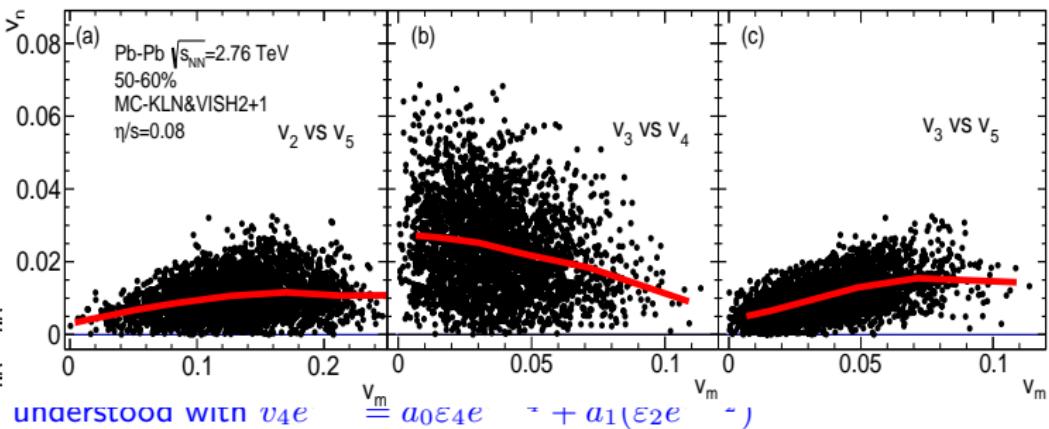
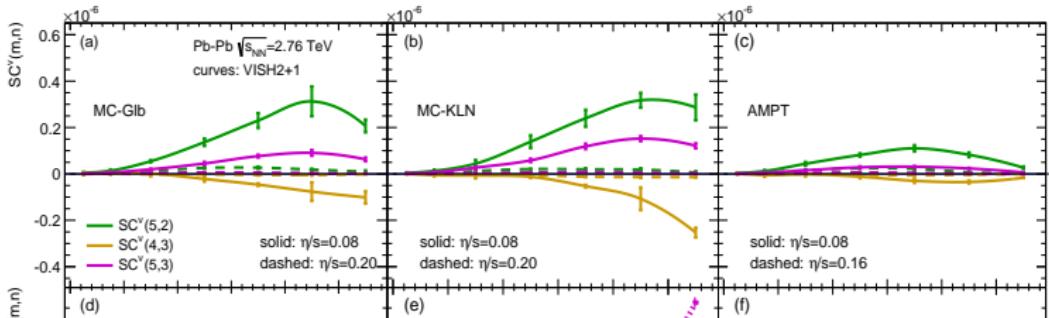
Centrality dependence of $SC(m, n)$



- v_5 and v_2 , v_5 and v_3 are correlated, and v_4 and v_3 are anti-correlated
- Signs of $SC^v(5, 2)$ and $SC^v(5, 3)$ are same as the $SC^e(5, 2)$ and $SC^e(5, 3)$
- Signs of $SC^v(4, 3)$ are opposite from $SC^e(4, 3)$
 \Leftarrow understood with $v_4 e^{i4\Psi} = a_0 \varepsilon_4 e^{i4\Phi_4} + a_1 (\varepsilon_2 e^{i2\Phi_2})^2$

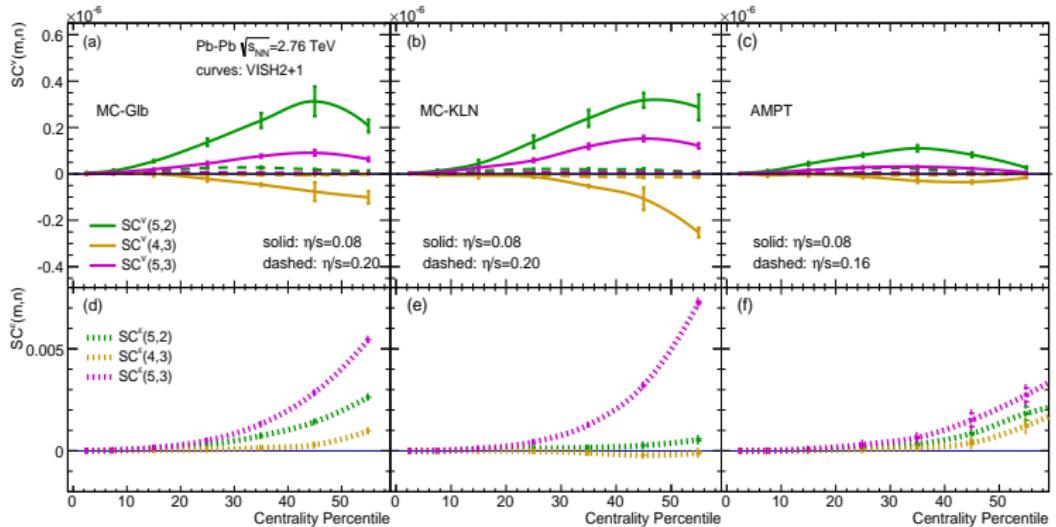
Gardim et al., Phys. Rev. C 85, 024908 (2012)
 Teaney et al., Phys. Rev. C 86, 044908 (2012)
 Teaney et al., Phys. Rev. C 90, 024902 (2014)

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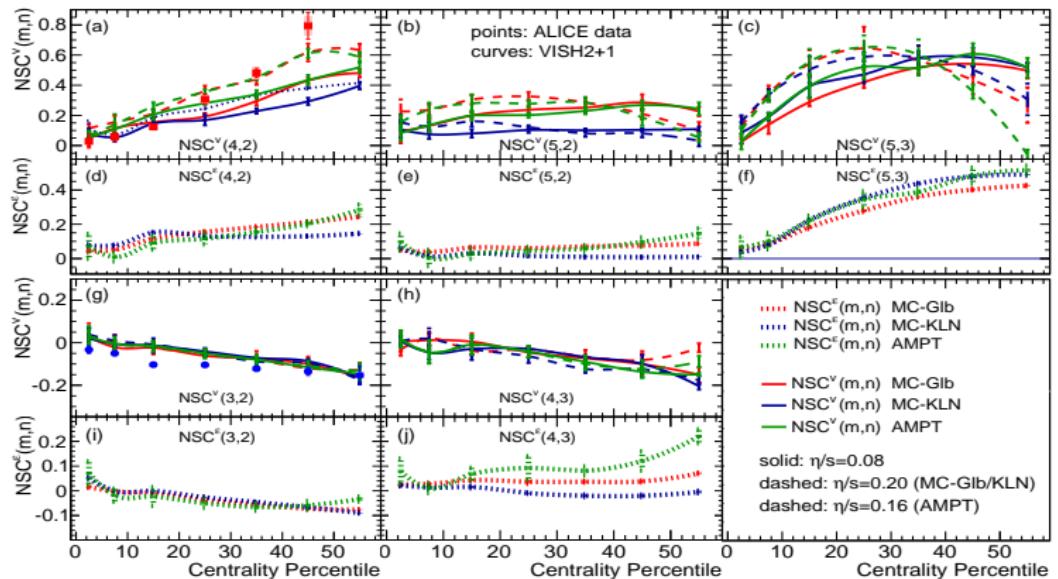
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Gardim et al., Phys. Rev. C 85, 024908 (2012)
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 Teaney et al., Phys. Rev. C 90, 024902 (2014)

Normalized Symmetric Cumulants $NSC(m, n)$



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



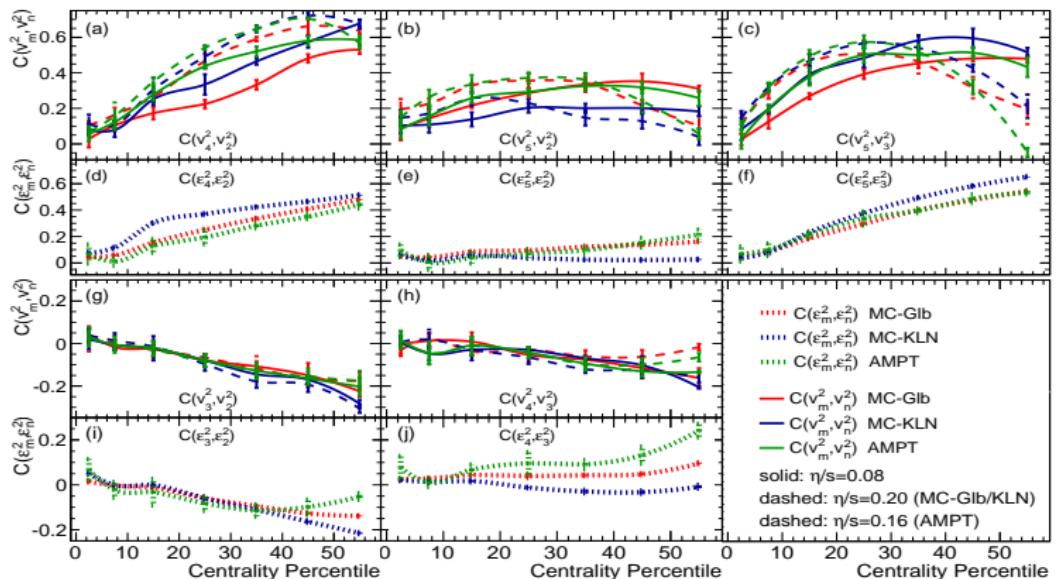
- $NSC^v(3, 2)$ are insensitive to η/s and initial conditions, and also roughly fit the measurements from ALICE.
- $NSC^v(4, 2)$, $NSC^v(5, 2)$, $NSC^v(5, 3)$ are sensitive to η/s and initial conditions.

Pearson correlation coefficients

$C(v_m, v_n)$ was first proposed by H. Niemi in [PRC 87, 054901 \(2013\)](#)

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

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



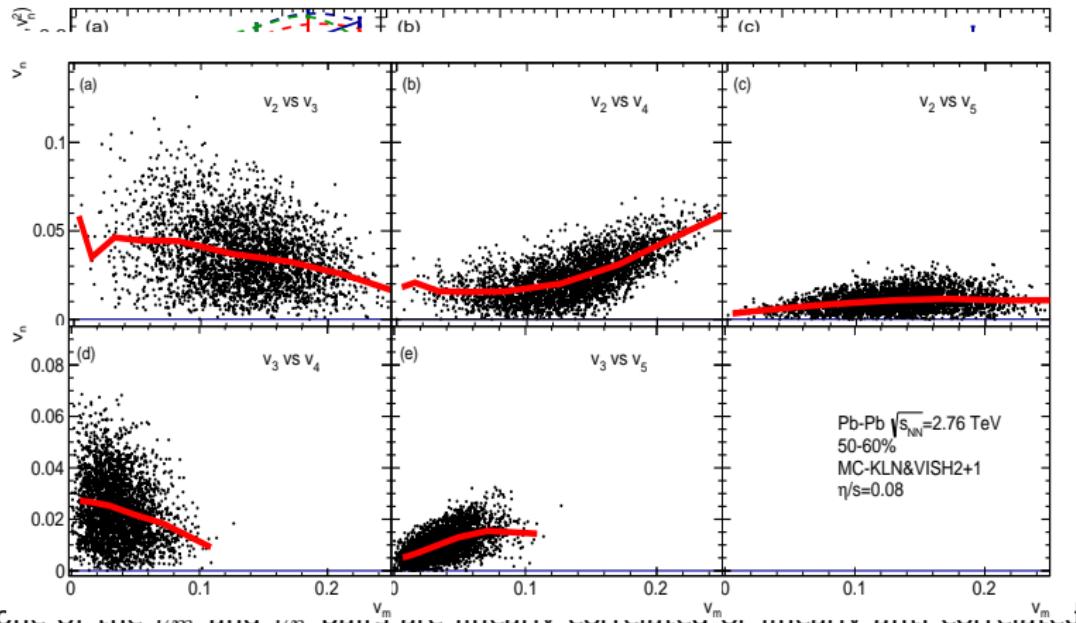
- None of the v_m and v_n pairs are linearly correlated or linearly anti-correlated

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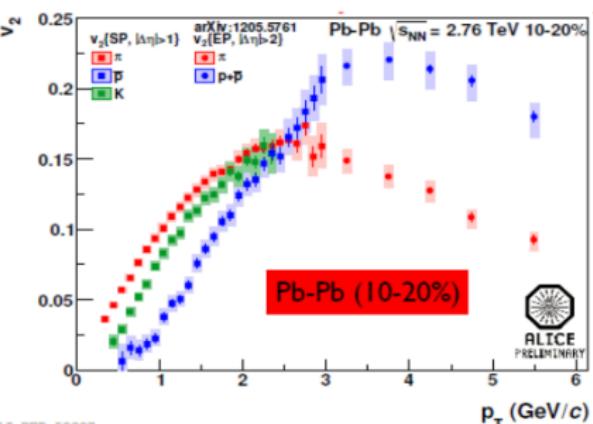
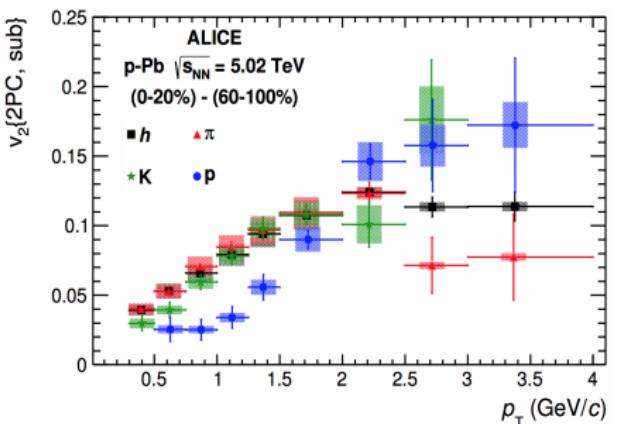
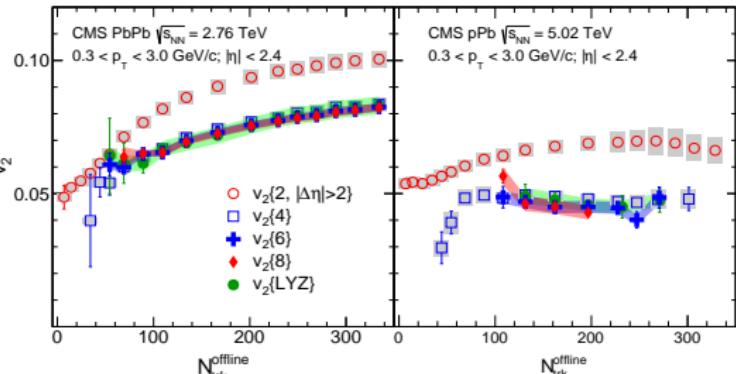
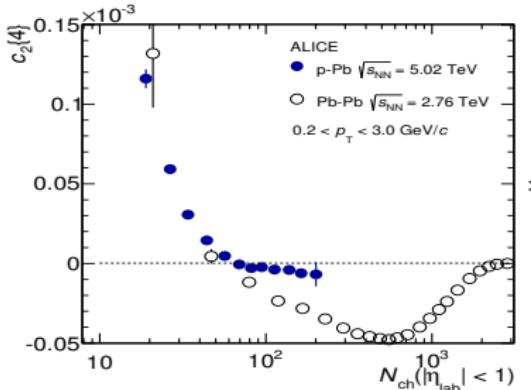
$$C(v_m^2, v_n^2) = \frac{\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\sqrt{\langle v_m^4 \rangle - \langle v_m^2 \rangle^2} \sqrt{\langle v_n^4 \rangle - \langle v_n^2 \rangle^2}}$$



- None of the v_m and v_n pairs are linearly correlated or anti-correlated

Azimuthal correlations in p+Pb collisions at $\sqrt{s_{\text{NN}}}=5.02 \text{ TeV}$

Collective flow in p+Pb? – Experimental Observations



ALICE Collaboration, PRC (2014), PLB (2013); CMS Collaboration PRL (2015)

ALT-PER-52227

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

- **Initial State?**

- K. Dusling and R. Venugopalan, Phys. Rev. D87 no. 5, (2013) 051502, Phys. Rev. D87 no. 5, (2013) 054014, Phys. Rev. D87 no. 9, (2013) 094034;
Y. V. Kovchegov and D. E. Wertepny, Nucl.Phys. A906 (2013) 5083;
L. McLerran, et al., Nucl.Phys. A916 (2013) 210;
T. Lappi, et al., JHEP 1601 (2016) 061

- **QGP?**

- P. Bozek, Phys. Rev. C85 (2012) 014911, Phys. Rev. C88 (2013) 014903;
A. Bzdak, et al., Phys. Rev. C87 no. 6, (2013) 064906;
E. Shuryak and I. Zahed, Phys. Rev. C88 (2013) 044915;
P. Bozek and W. Broniowski, Phys. Rev. C88 no. 1, (2013) 014903, Phys. Lett. B720 (2013) 250;
G. Y. Qin and B. Muller, Phys. Rev. C89 (2014) 044902;

K. Werner et al., Phys.Rev.Lett. 112 (2014) no.23, 232301.

- **Hadronic matter?**

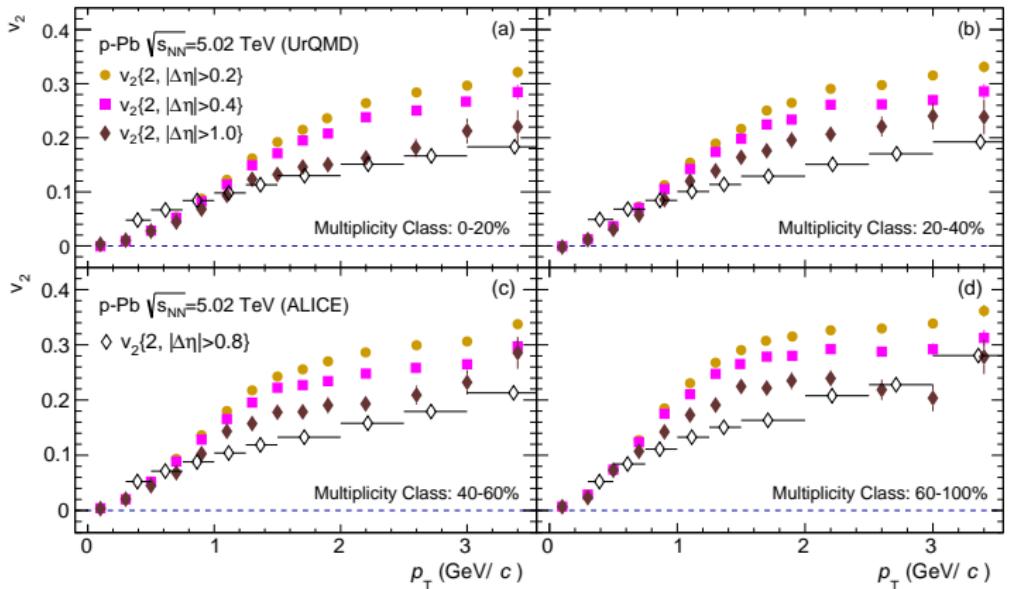
UrQMD Baseline Calculations

Y. Zhou, X. Zhu, P. Li and H. Song, Phys. Rev. C **91**, 064908 (2015).

Assumption:

p+Pb collisions only produce hadronic systems without reach the threshold of the QGP formation

$v_2(p_T)$ in p+Pb collisions at 5.02 TeV



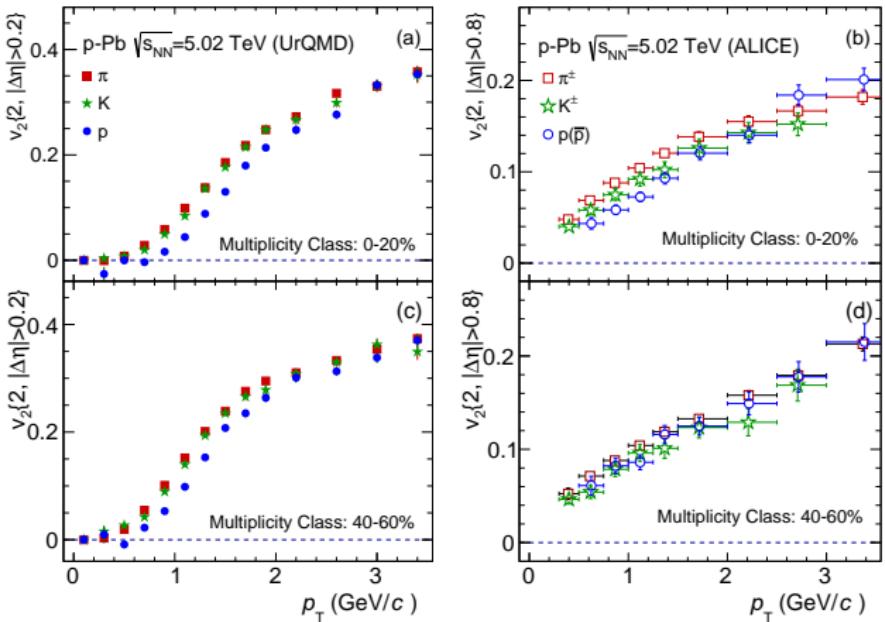
Y. Zhou *et al*, PRC 91, 064908 (2015)

- Sizeable values of $v_2\{2\}$ with different pseudorapidity gap.
- With large pseudo-rapidity gap, $v_2\{2\}$ from UrQMD is comparable with the experimental data

v_2 mass ordering in p+Pb collisions at 5.02 TeV

UrQMD

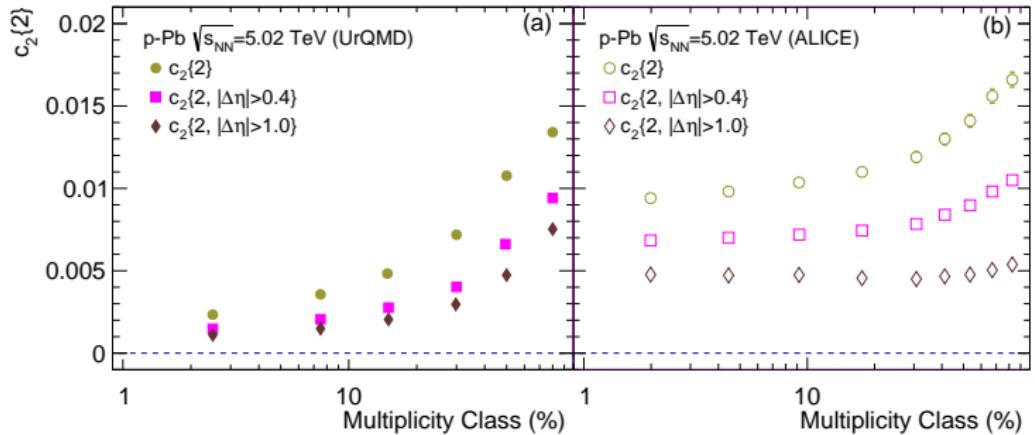
ALICE



Y. Zhou et al, PRC 91, 064908 (2015)

- Remarkable mass ordering is produced by UrQMD like ALICE data.

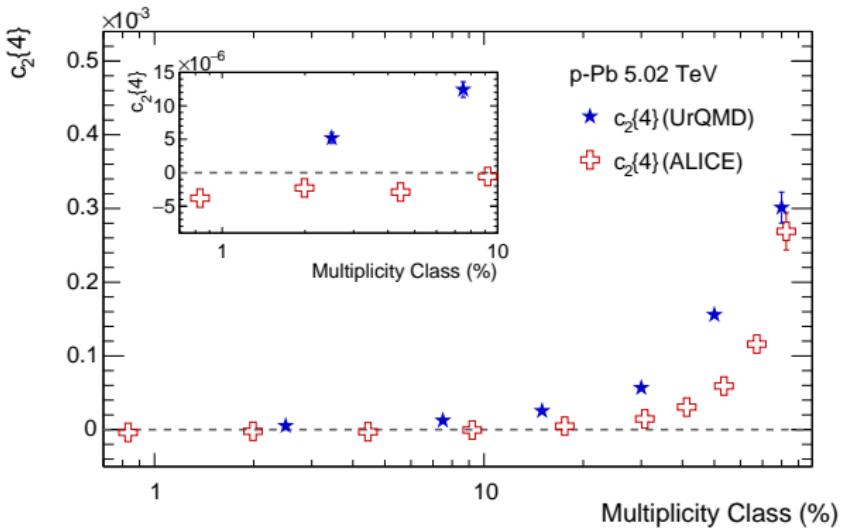
Multi-particle cumulants of v_2 from UrQMD



Y. Zhou et al, PRC 91, 064908 (2015)

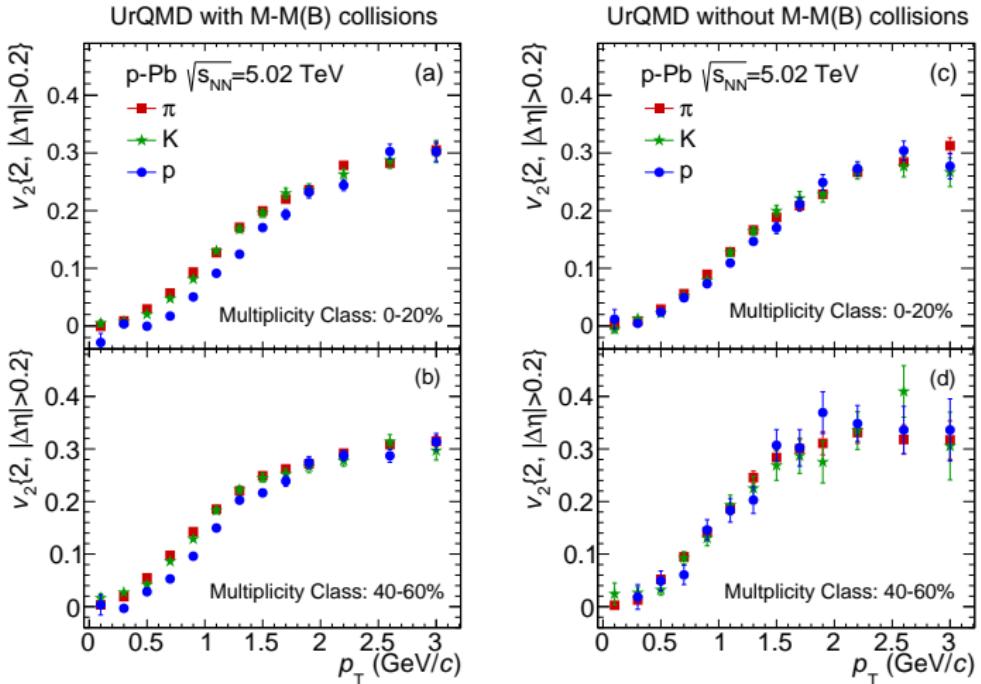
- 2-particle correlations of v_2 : $c_2\{2\} = \langle\langle 2 \rangle\rangle = \langle\langle e^{i2(\phi_1 - \phi_2)} \rangle\rangle = \langle v_2^2 + \delta_2^2 \rangle$
- The UrQMD systems are largely influenced by non-flow effects
- Non-flow effects: $\delta \sim 1/M$, M multiplicity in one event
- $c_2\{2\}$ is **positive**.

Multi-particle cumulants of v_2 from UrQMD



- ALICE results of $c_2\{4\}$ becomes negative when centrality $< 10\%$.
- But, $c_2\{4\}$ from UrQMD keeps **positive** at all centrality bins.
- UrQMD simulations for p+Pb collisions are non-flow dominant.
- In p+Pb collisions, effects from initial state and/or QGP are needed to generate collectivity.

Where is the mass ordering from?

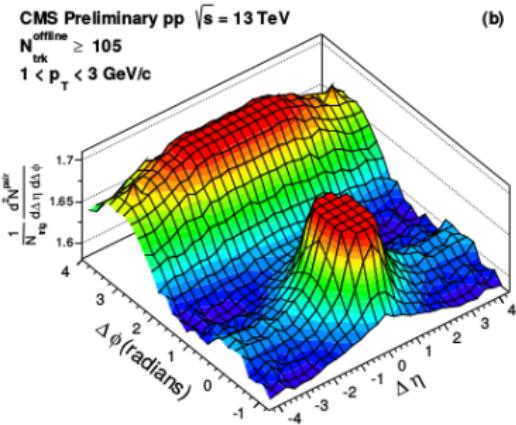
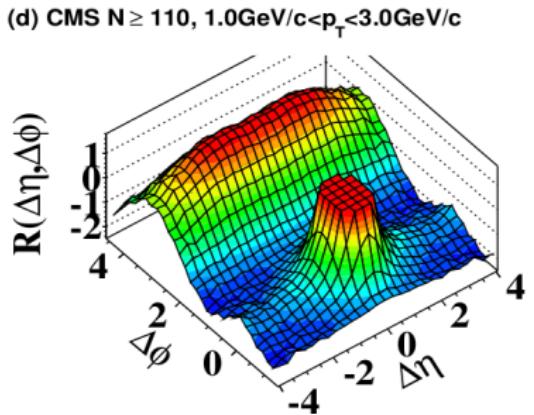


- Hadronic interactions can generate a mass ordering of $v_2(p_T)$ of identified particles.
- v_2 mass-ordering is not necessarily associated with strong fluid-like expansions

Investigating anisotropic collectivity in pp collisions at the LHC energies

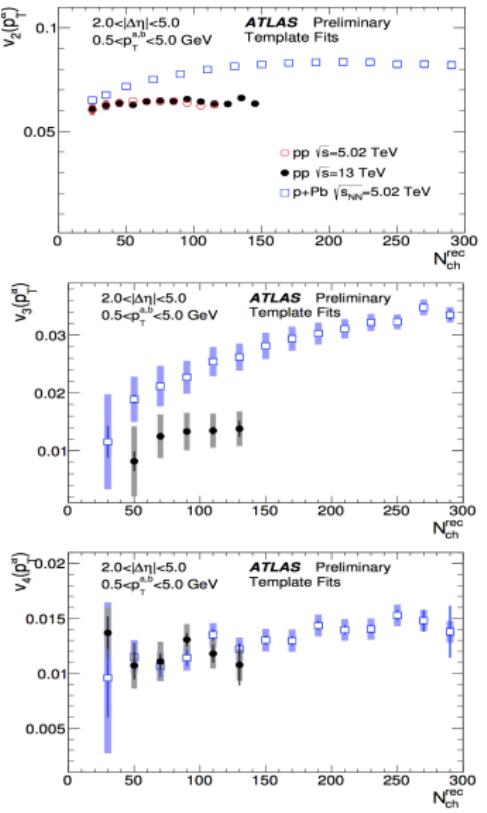
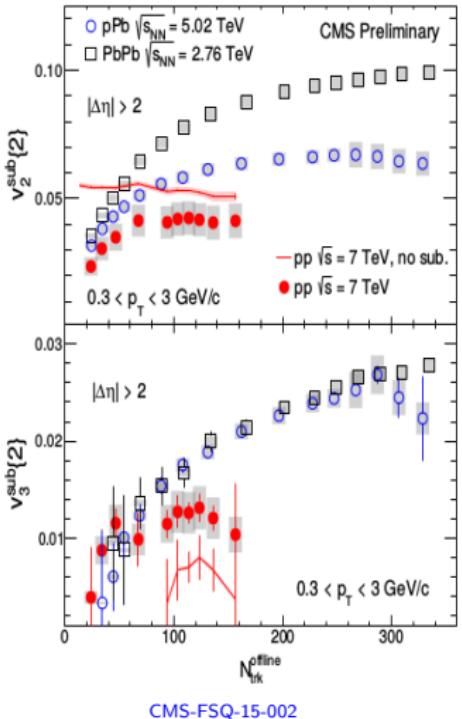
Introduction

“Ridge” -like structure in high multiplicity pp collisions at the LHC



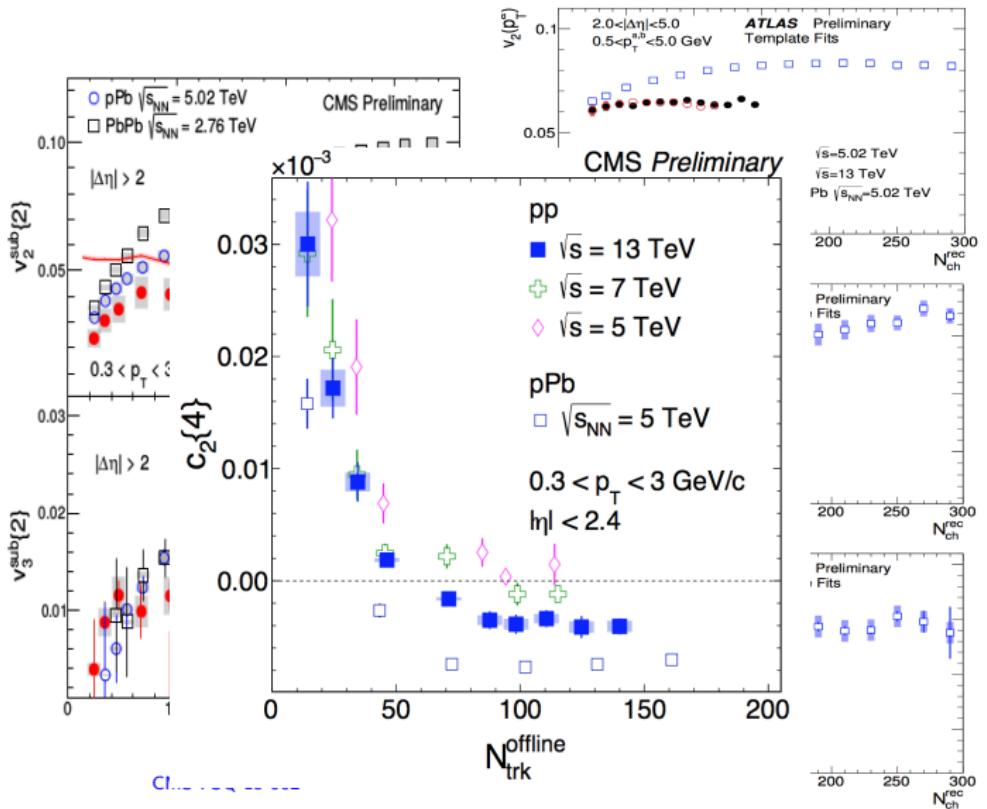
CMS, JHEP 1009 (2010) 091, CMS-FSQ-15-002

Anisotropy harmonics from pp collisions



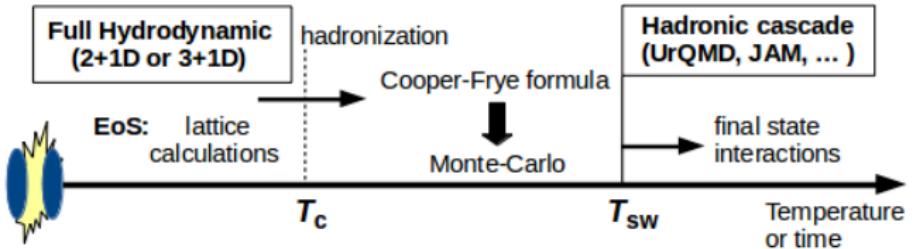
ATLAS, report in Initial Stages 2016

Anisotropy harmonics from pp collisions



ATLAS, report in Initial Stages 2016

Event-by-event hybrid approach iEBE-VISHNU



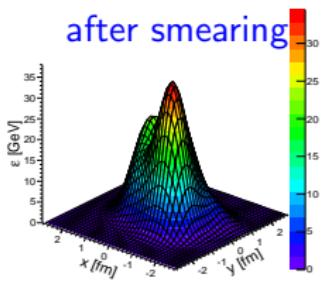
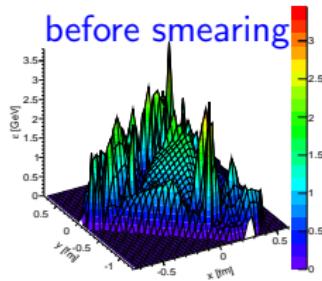
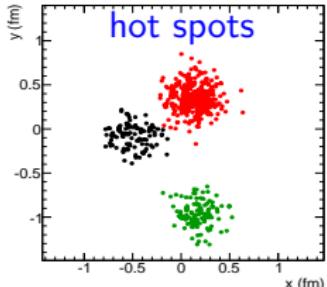
iEBE-VISHNU **hybrid approach:** VISH2+1+UrQMD

- Initial condicaitons: HIJING 2.0 [Phys. Lett. B 711 \(2012\) 301](#)

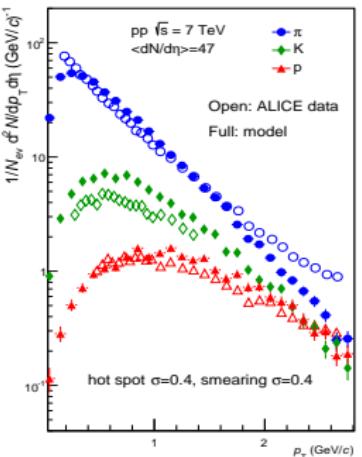
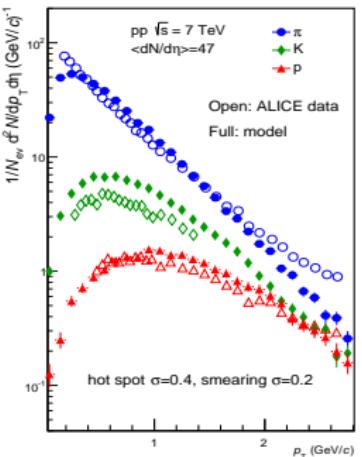
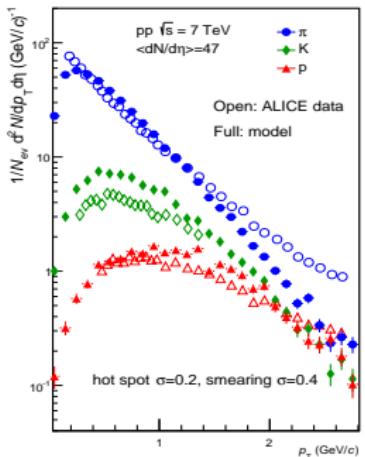
hard parton jets and the soft interaction between nucleon remnants
 → treated as independent strings ⇒ hot spots

hot spot: Gaussian distribution with σ

initial energy density: Gaussian smearing with σ to all partons in hot spots



p_T -spectra of π , K and p

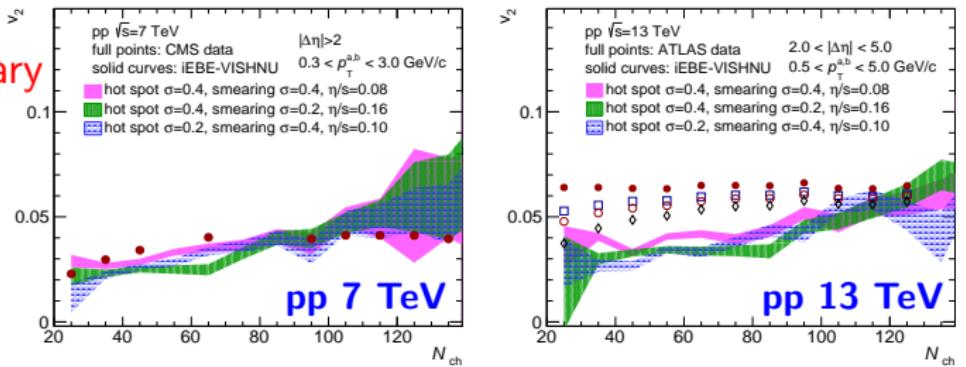
 $\eta/s = 0.10$
 $\eta/s = 0.16$
 $\eta/s = 0.08$


C. Andrei, Nucl.Phys. A 931 (2014) 888

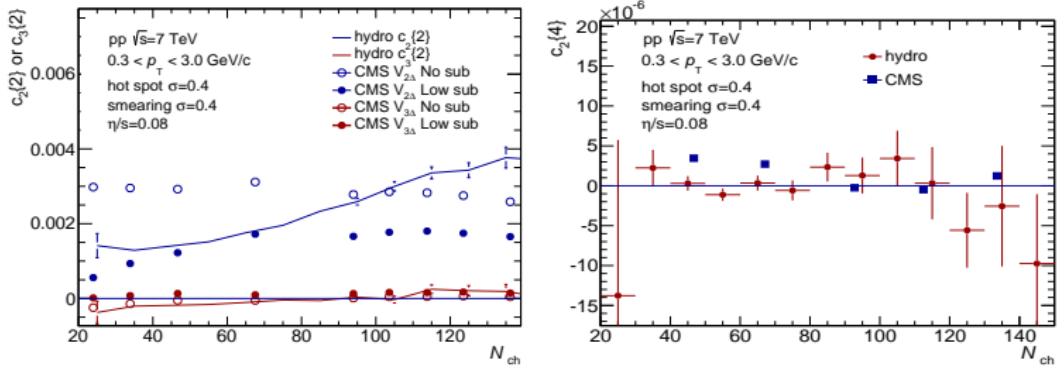
- Different τ_0 are used to fit well the p_T -spectra.
- Roughly reproduce the p_T -spectra slopes for all three hadron species.
- iEBE-VISHNU gives reasonable radial flow in high multiplicity pp collisions.

Anisotropic momentum vs multiplicity in pp collisions

Preliminary



Our calculations roughly reproduce the measurements from CMS at $N_{ch}[20, 120]$



Positive $c_2\{2\}$ at full N_{ch} , but negative $c_3\{2\}$ at $N_{ch} < 100$ like CMS data.
Negative $c_2\{4\}$ at $N_{ch} > 100$. More statistics is needed.



Summary

- **Correlations between flow harmonics in Pb+Pb collisions at the LHC**

- Symmetric Cumulants $SC(m, n)$, normalized SC $NSC(m, n)$, and Pearson correlation coefficients $C(v_m^2, v_n^2)$ with $m(n) = 2 \sim 5$ are studied.
- $SC(m, n)$ are sensitive to both η/s and initial conditions.
- Hydrodynamic $SC(3, 2)$ and $SC(4, 2)$ qualitatively describe the data.
- $NSC(3, 2)$ and $C(v_3^2, v_2^2)$ are mainly determined by corresponding correlations in the initial state.

- **Correlations in p+Pb collisions**

- UrQMD simulations shows hadronic interactions can not produce flow data measured in experiments; effects from initial state and /or QGP are needed.
- v_2 mass-ordering is observed in UrQMD, which is the consequence of hadronic interactions.
- Mass-ordering is not necessarily associated with strong fluid-like expansions.

- **Investigating collective flow in pp collisions**

- Initial conditions from HIJING 2.0 + Event-by-Event hybrid approach iEBE-VISHNU is used to studied pp collisions.
- Our calculations roughly reproduce the measurements at 7 TeV from the CMS.
- Positive $c_2\{2\}$ and negative $c_2\{4\}$ are also observed from our calculations.
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Thanks for your attention!

Backup

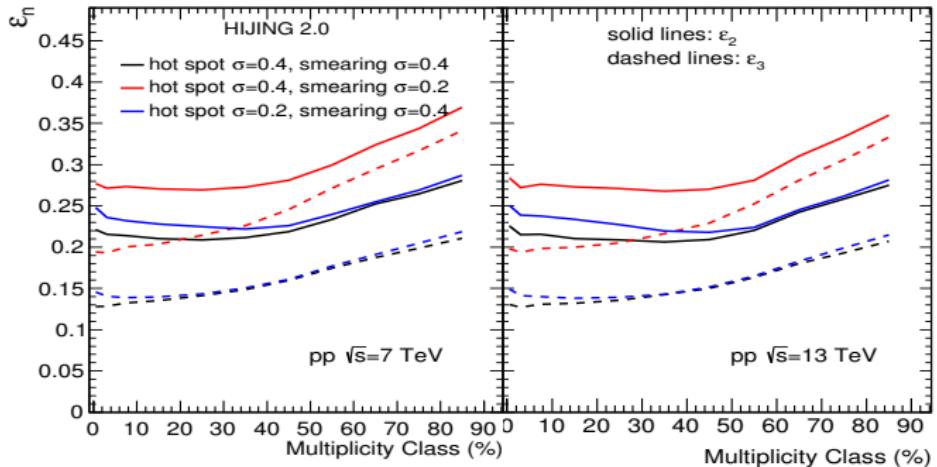


Initial conditions from HIJING 2.0

HIJING: hard parton jets and the soft interaction between nucleon remnants
→treated as independent strings

- Partons from each string build a hot spot
 - The center of the hot spots:
 $n_p(r) = \frac{n_0}{1+e^{(r-R_0)/d}}$, $n_0 = 0.17/fm^3$, $R_0=0.56$ fm, and $d=0.112$ fm
 - The spatial parton distribution in each hot spot:
 $f(r) = e^{-r/r_0}$, r_0 gives the size of the hot spots
- Initial energy density profiles: a Gaussian smearing of partons within $|\eta_s| < 1$
 $\varepsilon(x, y) = K \sum_i \frac{E^*}{2\pi\sigma^2 r_0 \Delta\eta_s} \exp\left(-\frac{(x-x_i)^2 + (y-y_i)^2}{2\sigma^2}\right)$
 K : normalization factor, σ : Gaussian smearing factor, E^* : Lorentz invariant energy of partons

Eccentricity ε_2 and ε_3 of the initial conditions



- sizeable ε_2 and ε_3
- hot spot size and smearing factor dependence
- collision energy independent