Towards Uli's Little-Bang Standard Model

Jiangyong Jia

Stony Brook University & Brookhaven National Laboratory

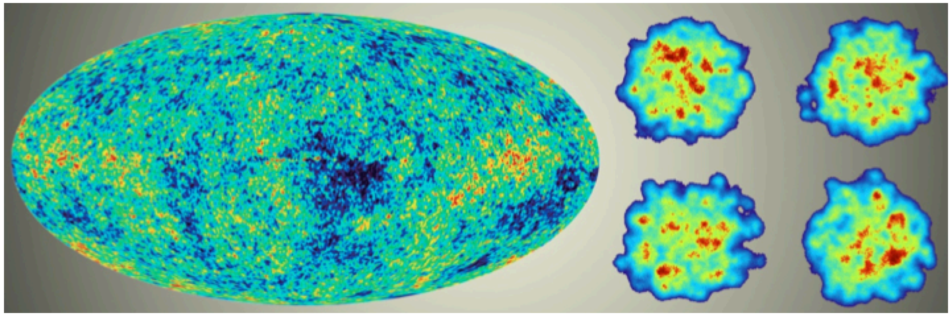
Towards the Little Bang Standard Model

Ulrich Heinz

Physics Department, The Ohio State University, Columbus, Ohio 43210, USA

E-mail: `heinz@mps.ohio-state.edu`

Abstract. I review recent progress in developing a complete dynamical model for the evolution of the Little Bang fireballs created in relativistic heavy-ion collisions, and using the model to extract the transport properties and initial density fluctuations of the liquid quark-gluon plasma state of matter of which makes up these Little Bangs during the first half of their lives.



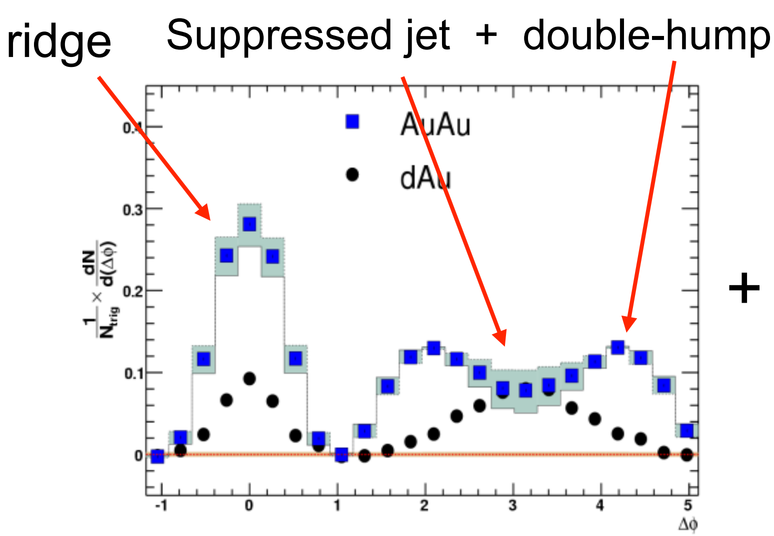
Before dawn era:

Workshop on Critical Examination of RHIC Paradigms

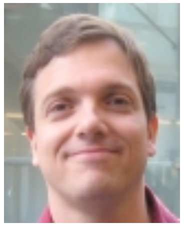
April 14-17, 2010, Austin

A) Hydodynamics vs Semi-Hard minijets
B) Recombination vs Fragmention
C) Semi-Hard mini-jets and pQCD

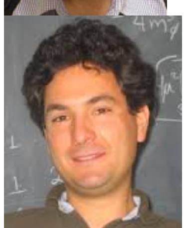
- There were lots of discussion on meaning of structures of 2PC
  - Jet-like, ridge-like, mach-cone, medium-response,…
  - Hydro-picture is also scrutinized as 2PC is used to extract v_2.



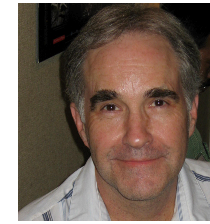
$+ 2v_2^t v_2^b \cos 2\Delta\phi = 2PC$





"Aren't you glad we had this meeting to resolve our conflict?"



PROCEEDINGS OF SCIENCE

http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=111

State-of-minds are captured by commentaries

Wednesday question and answer transcripts

Lanny Ray*
Department of Physics, The University of Texas at Austin, Austin, Texas 78712 USA
E-mail: ray@physics.utexas.edu

This is a transcript of the questions and answers following the Wednesday presentations. The audio recordings were generally transcribed as is but were in some cases edited for clarity, where every effort was made to be faithful to the speaker or participant's intended meaning. Additions inserted during the editing process to clarify the speaker's intent are enclosed in square brackets. Additional, contributed comments made after the workshop are identified as "Note added." Unintelligible audio portions are indicated by "[???]." Participants were: Rene Bellwied, Helen Caines, Yuri Dokshitzer, Rainer Fries, Ahmed Hamed, Uli Heinz, Rudy Hwa, Jiangyong Jia, David Kettler, Che-Ming Ko, Boris Kopeliovich, Christina Markert, Denes Molnar, Guy Moore, Lanny Ray, Thorsten Renk, Lijuan Ruan, Edward Shuryak, Raimond Snellings, Mike Tannenbaum, Derek Teaney, and Tom Trainor.

Friday question and answer transcripts

Thomas A. Trainor*
CENPA 354290, University of Washington, Seattle, WA 98195 USA
E-mail: trainor@hausdorf.npl.washington.edu

This is a transcript of the question-answer intervals following the Friday talk presentations. In some cases notes were added during participant review of the transcript (sources are specified). Participants were: Rene Belwied, Helen Caines, Yuri Dokshitzer, Ahmed Hamed, Ulrich Heinz, Jiangyong Jia, Boris Kopeliovich, Guy Moore, Jan Rak, Thorsten Renk, Lijuan Ruan, Anne Sickles, Mike Tannenbaum, Derek Teaney, Tom Trainor.

Thursday question and answer transcripts

Thomas A. Trainor*
CENPA 354290, University of Washington, Seattle, WA 98195 USA
E-mail: trainor@hausdorf.npl.washington.edu

This is a transcript of the question-answer intervals following the Thursday talk presentations. In some cases notes were added during participant review of the transcript (sources are specified). Participants were: Rene Belwied, Kevin Dusling, Ahmed Hamed, Ulrich Heinz, Rudy Hwa, Jiangyong Jia, David Kettler, Che-Ming Ko, Boris Kopeliovich, Christina Markert, Guy Moore, Duncan Prindle, Jan Rak, Lanny Ray, Thorsten Renk, Lijuan Ruan, Edward Shuryak, Raimond Snellings, Mike Tannenbaum, Derek Teaney, Tom Trainor.

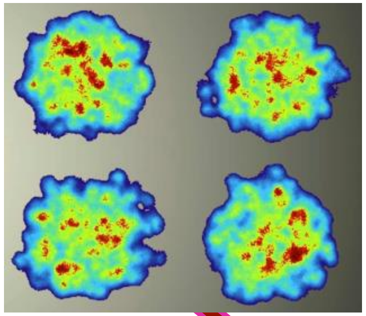
"Discussion on jet and spectrum structure vs. pQCD from high p_t down to the soft sector"

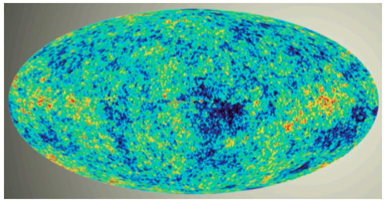
Ulrich Heinz*†
Department of Physics, The Ohio State University, Columbus, OH 43210, USA
E-mail: heinz@mps.ohio-state.edu

The following is a transscript of the discussion session on jet reconstruction and fragmentation that took place on April 16, 2010, during the workshop on *Critical Examination of RHIC Paradigms*. Participating in the discussion were Rene Bellwied, Helen Caines, Yuri Dokshitzer, Ahmed Hamed, Rudy Hwa, Jiangyong Jia, David Kettler, Boris Kopeliovich, Guy Moore, Jan Rak, Lanny Ray, Thorsten Renk, Lijuan Ruan, Anne Sickles, Raymond Snellings, Mike Tannenbaum, Derek Teaney, Tom Trainor, and one unidentified contributor. Their discussion contributions are identified below by their first names.

Paradigm shift with the realization of importance of initial state fluct, and consequently higher-order harmonic flow (Alver, Roland)

Towards the Little Bang Standard Model





Ulrich Heinz

Physics Department, The Ohio State University, Columbus, Ohio 43210, USA

E-mail: `heinz@mps.ohio-state.edu`

Abstract. I review recent progress in developing a complete dynamical model for the evolution of the Little Bang fireballs created in relativistic heavy-ion collisions, and using the model to extract the transport properties and initial density fluctuations of the liquid quark-gluon plasma state of matter of which makes up these Little Bangs during the first half of their lives.

- Large number of flow observables →

$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\text{evts}}} \frac{dN_{\text{evts}}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

$$\langle \cos(n_1\phi_1 + n_2\phi_2 ... + n_m\phi_m) \rangle =$$

$$\langle v_{n_1} v_{n_2} ... v_{n_m} \cos(n_1\Phi_{n_1} + n_2\Phi_{n_2} ... + n_m\Phi_{n_m}) \rangle \quad \Sigma n_i = 0$$

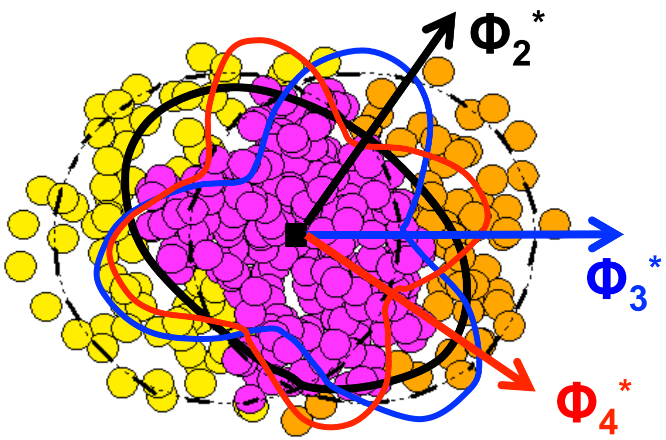
- Rich dynamics in longitudinal direction $v_n(\eta)$, $\Phi_n(\eta)$ →

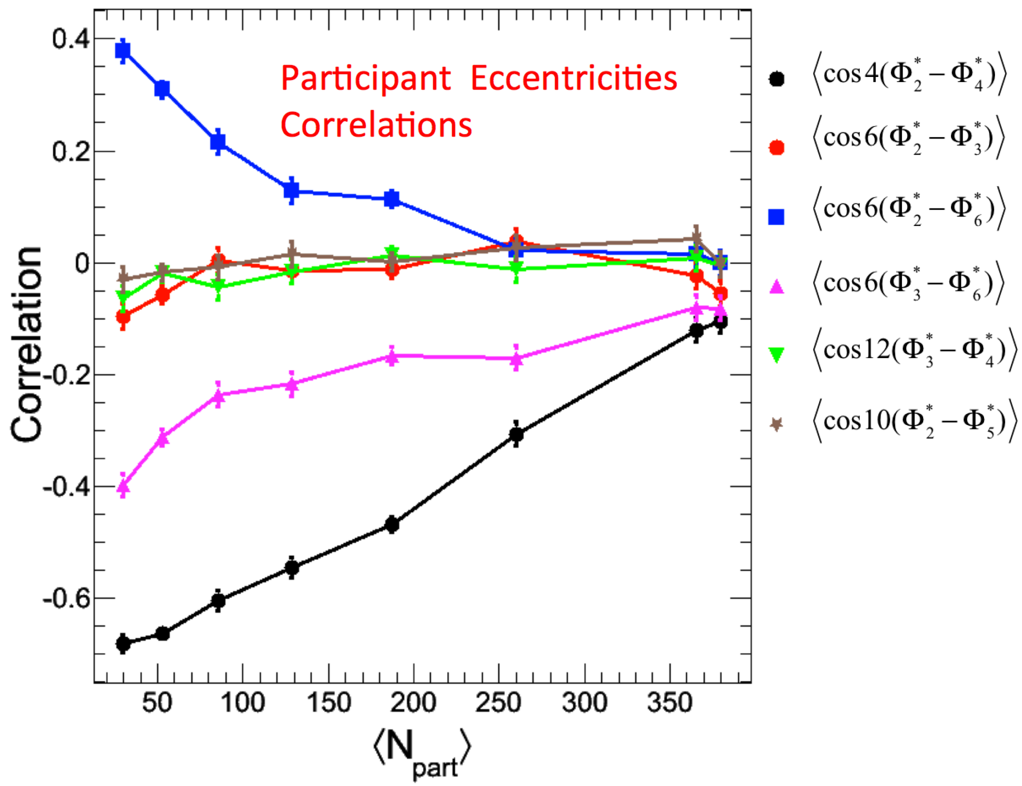
  factorization breaking/decorrelation, sub-leading flow,

- New analysis techniques: unfolding, shape engineering.

Correlation between phases: $p(\Phi_n,\Phi_m,\ldots)$

- Correlations exist in the initial geometry



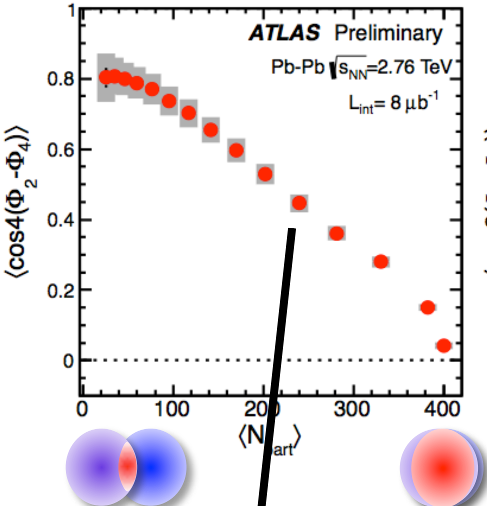


- Mostly generated during hydro evolution via non-linear mixing:

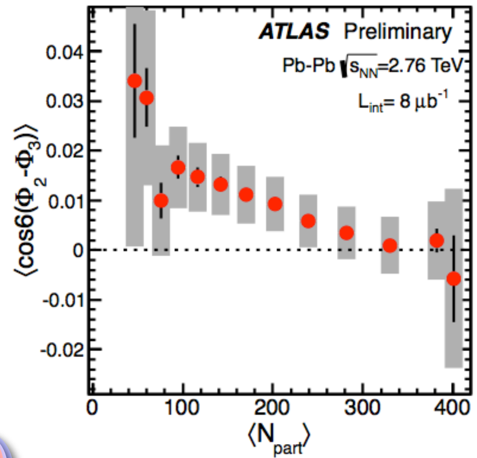
$$v_4 e^{i4\Phi_4} \propto \varepsilon_4 e^{i4\Phi^*_4} + c v_2^2 e^{i4\Phi_2} + \ldots$$

p(Φ$_n$, Φ$_m$) and p(Φ$_n$, Φ$_m$, Φ$_k$)

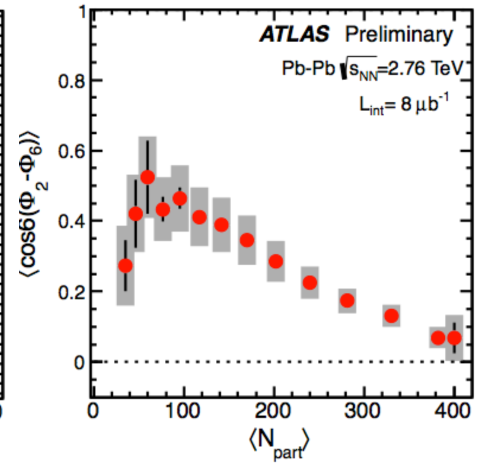
$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$



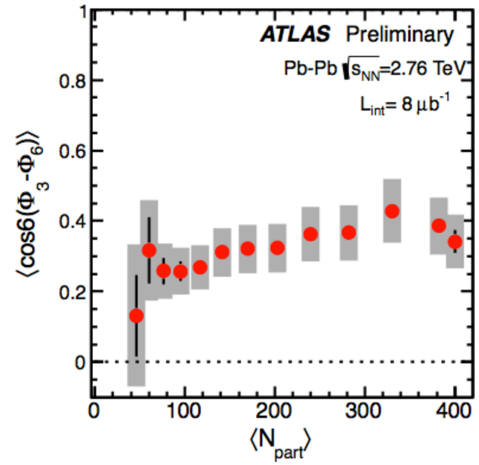
$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$



$\langle \cos 6(\Phi_2 - \Phi_6) \rangle$

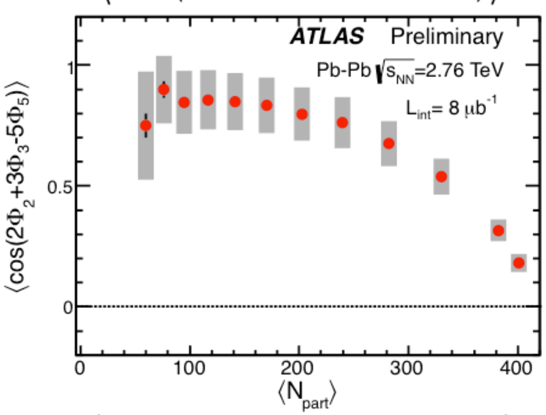


$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



$$v_4 e^{i4\Phi_4} \propto \varepsilon_4 e^{i4\Phi^*_4} + c v_2^{\,2} e^{i4\Phi_2} + \ldots$$

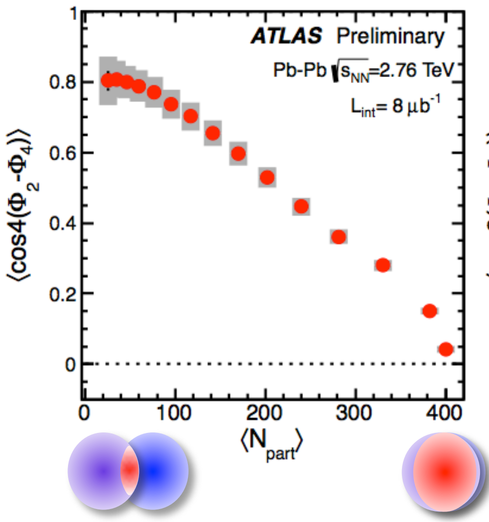
$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$



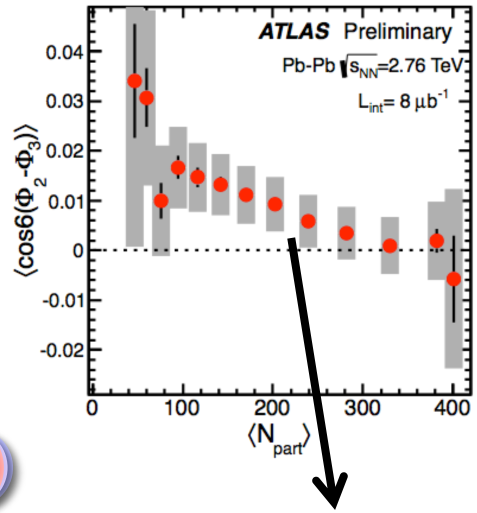
Teaney & Yan

$p(\Phi_n, \Phi_m)$ and $p(\Phi_n, \Phi_m, \Phi_k)$

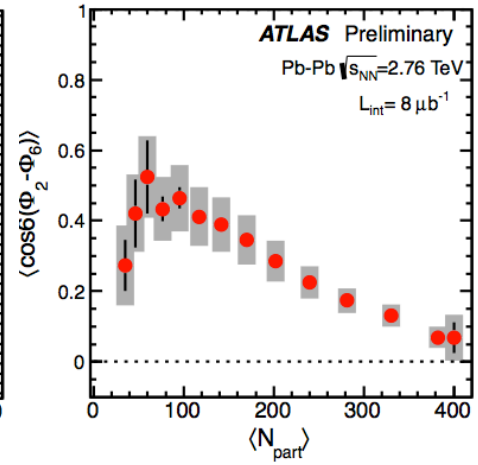
$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$



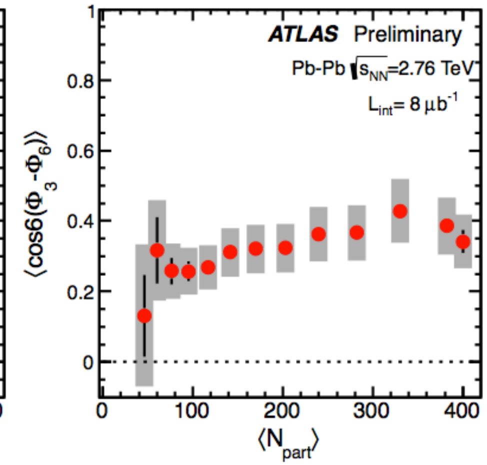
$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$



$\langle \cos 6(\Phi_2 - \Phi_6) \rangle$

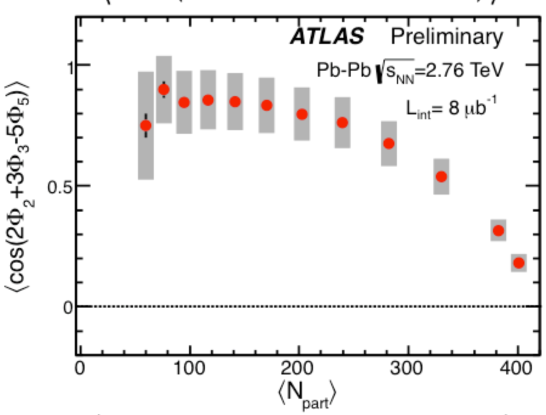


$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



Φ_2^* and Φ_3^* ~ uncorrelated

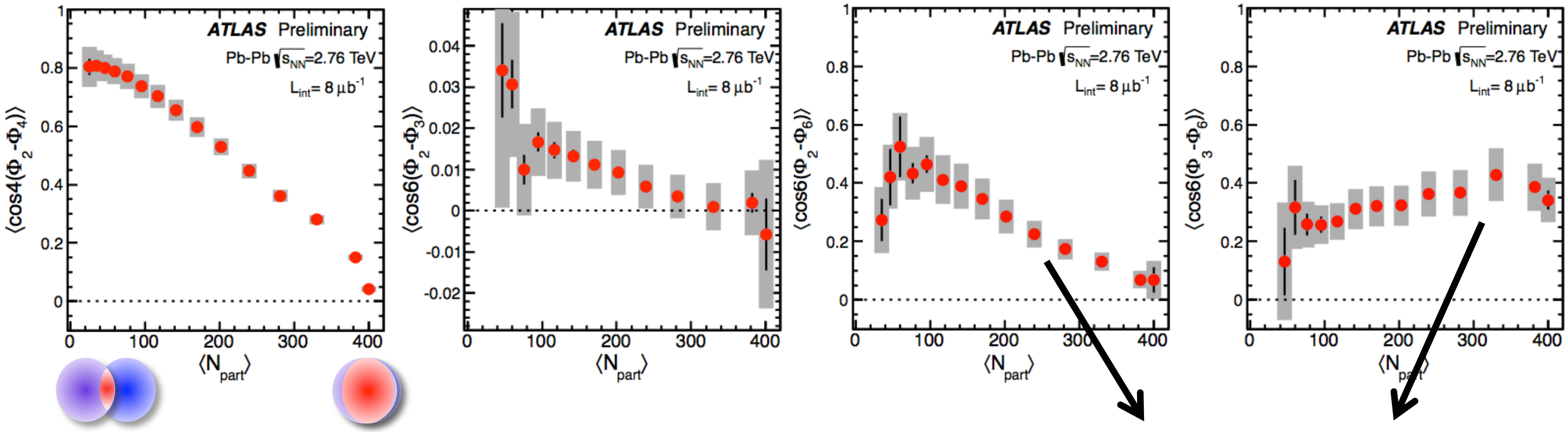
$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$



Teaney & Yan

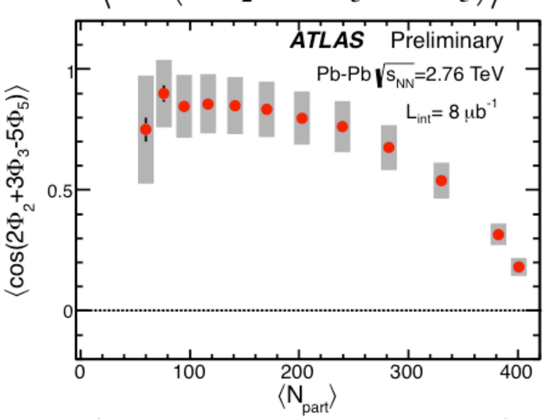
$p(\Phi_n, \Phi_m)$ and $p(\Phi_n, \Phi_m, \Phi_k)$

$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$ $\langle \cos 6(\Phi_2 - \Phi_3) \rangle$ $\langle \cos 6(\Phi_2 - \Phi_6) \rangle$ $\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



$$v_6 e^{i6\Phi_6} \propto \varepsilon_6 e^{i6\Phi_6^*} + c_1 v_2^3 e^{i6\Phi_2} + c_2 v_3^2 e^{i6\Phi_3} + \ldots$$

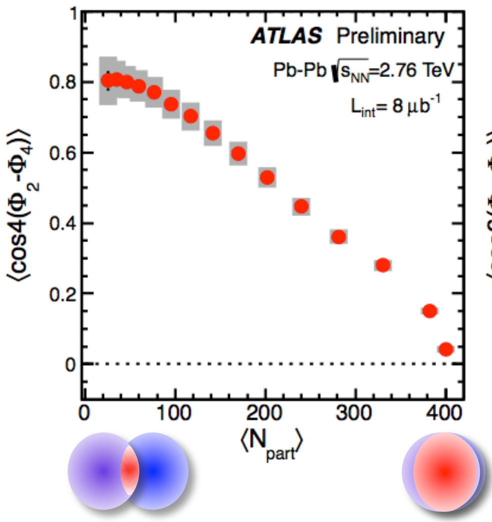
$$\left\langle \cos\left(2\Phi_2 + 3\Phi_3 - 5\Phi_5\right)\right\rangle$$



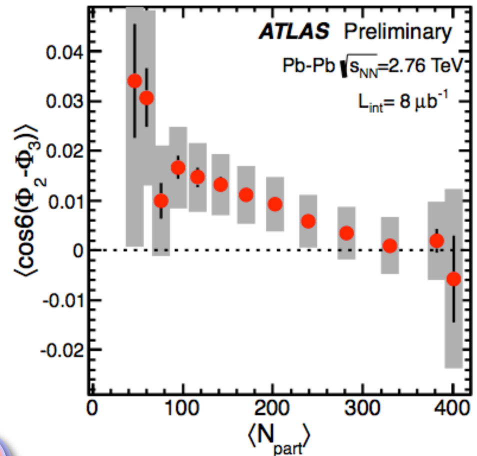
Teaney & Yan

$p(\Phi_n, \Phi_m)$ and $p(\Phi_n, \Phi_m, \Phi_k)$

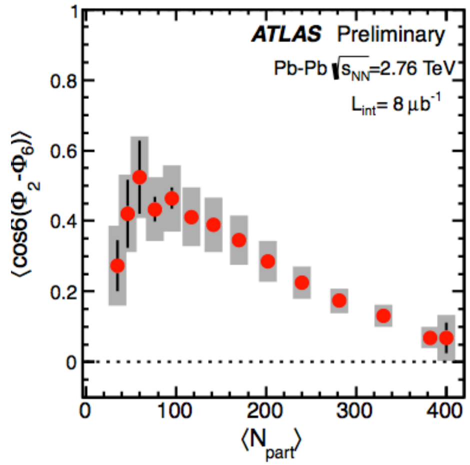
$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$



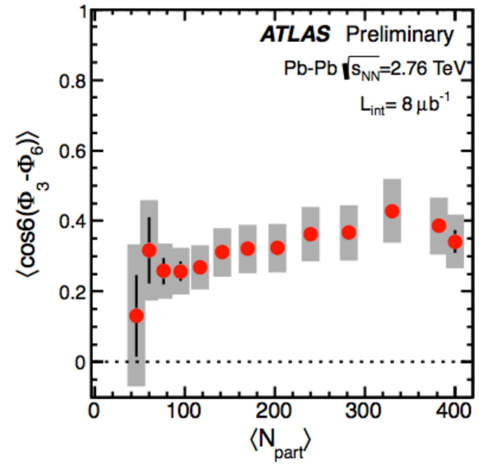
$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$



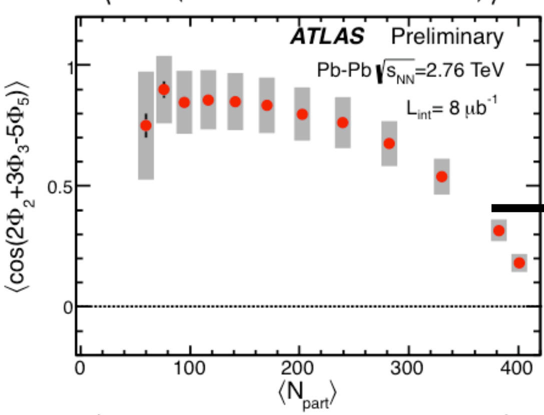
$\langle \cos 6(\Phi_2 - \Phi_6) \rangle$



$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



$\left\langle \cos\left(2\Phi_2 + 3\Phi_3 - 5\Phi_5\right) \right\rangle$



$$\longrightarrow \quad v_5 e^{i5\Phi_5} \propto \varepsilon_5 e^{i5\Phi_5^*} + c v_2 v_3 e^{i(2\Phi_2 + 3\Phi_3)} + \ldots$$

Teaney & Yan

On 5/31/12 5:28 PM, Ulrich Heinz wrote:

> Dear Jiangyong,
>
> I just got back from NN2012 and discussed with my student Zhi Qiu who, unbelievably, completed a first rough calculation of all the angular correlation signals shown in Figs. 6 and 7 of your paper, using e-by-e hydro with eta/s=1/4pi (MC-Glauber ICs). Statistics is still poor, and we don't have as many centrality bins as you guys do, but here is the status: We get all the correlators qualitatively right as far as their centrality dependence goes (i.e. we reproduce the general shape of the curves in your figures -- those that drop with Npart drop, those that rise in the data also rise in our calculations, and those that you find small we find unmeasurable with our present statistics). In the magnitudes we are off by a factor 2 in some of the correlations (with large error bars, though) -- generically our correlators are smaller than the measured ones. No idea what that means, at this point. I'll keep you posted. But this looks very encouraging!
>
> Ulrich
>
> On May 27, 2012, at 10:32 AM, JiangyongJia wrote:
>
>> Hi Ulrich,
>>
>> The slides are attached. I am still working on it, but mostly small tweaks.
>>
>> cheers,
>> Jiangyong
>>
>> On 5/27/12 3:18 PM, Ulrich Heinz wrote:
>>
>>> Can you send me the slides of your talk on this at HP2012?
>>>
>>> Ulrich Heinz
>>>
>>> Professor of Physics
>>> Ohio State University
>>> 191 West Woodruff Avenue
>>> Physics Research Building M2046
>>> Ph: 614-688-5363 (office)
>>> 614-876-8812 (home)
>>> heinz@mps.ohio-state.edu
>>>
>>> On May 27, 2012, at 7:24 AM, JiangyongJia wrote:
>>>
>>>> Dear friends,
>>>>
>>>> You may be interested in this new ATLAS results (to be presented in Hard Probes)
>>>> https://cdsweb.cern.ch/record/1451882
>>>>
>>>> Cheers,
>>>> Jiangyong

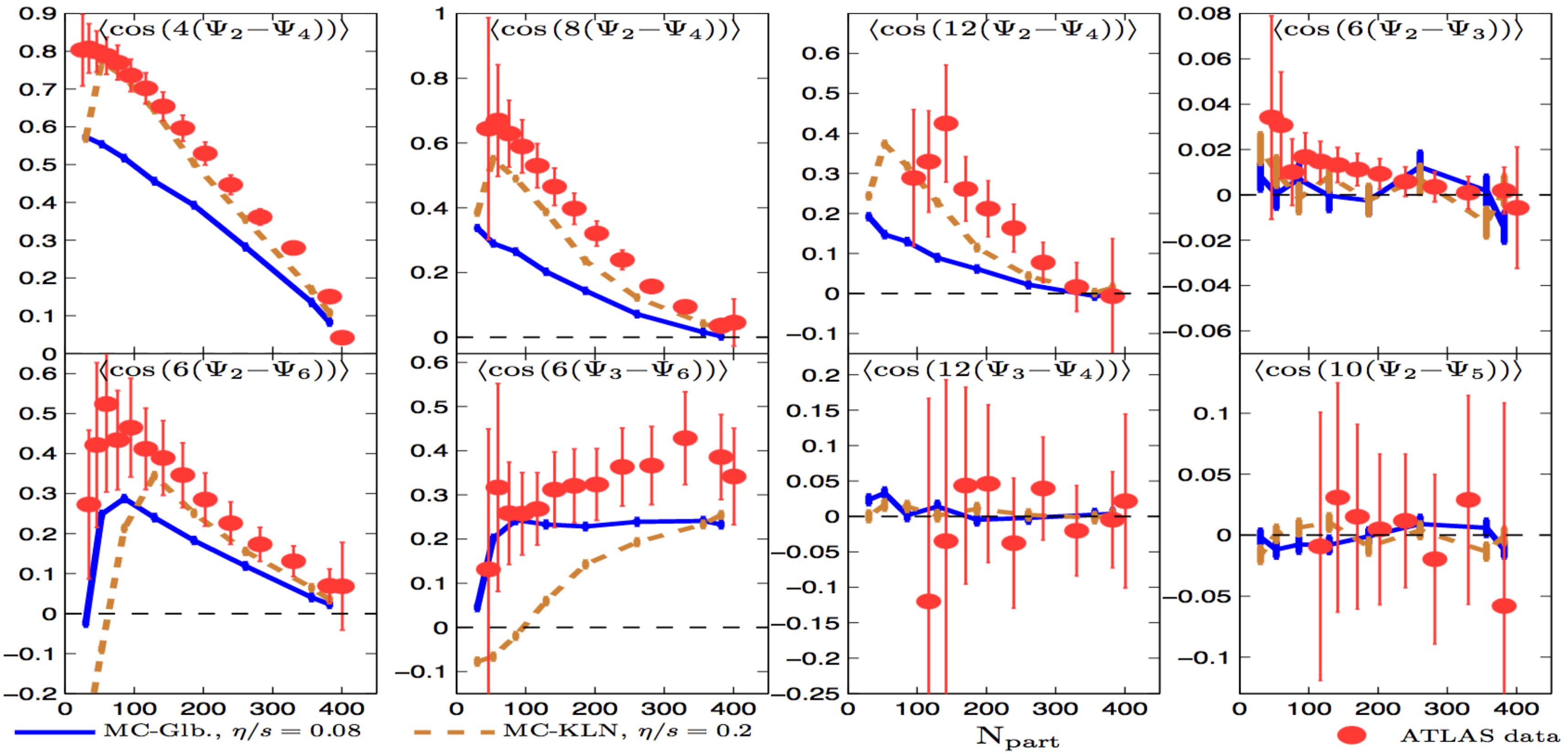
Compare to Uli's E-by-e hydro calculation

Hydrodynamic event-plane correlations in Pb+Pb collisions at sqrt(s)=2.76ATeV

Zhi Qiu, Ulrich W. Heinz

(Submitted on 6 Aug 2012 (v1), last revised 15 Sep 2012 (this version, v2))

The recently measured correlations between the flow angles associated with higher harmonics in the anisotropic flow generated in relativistic heavy-ion collisions are shown to be of hydrodynamic origin. The correlation strength is found to be sensitive to both the initial conditions and the shear viscosity of the expanding fireball medium.



- Reproduce correlations between two planes: Φ_n, Φ_m

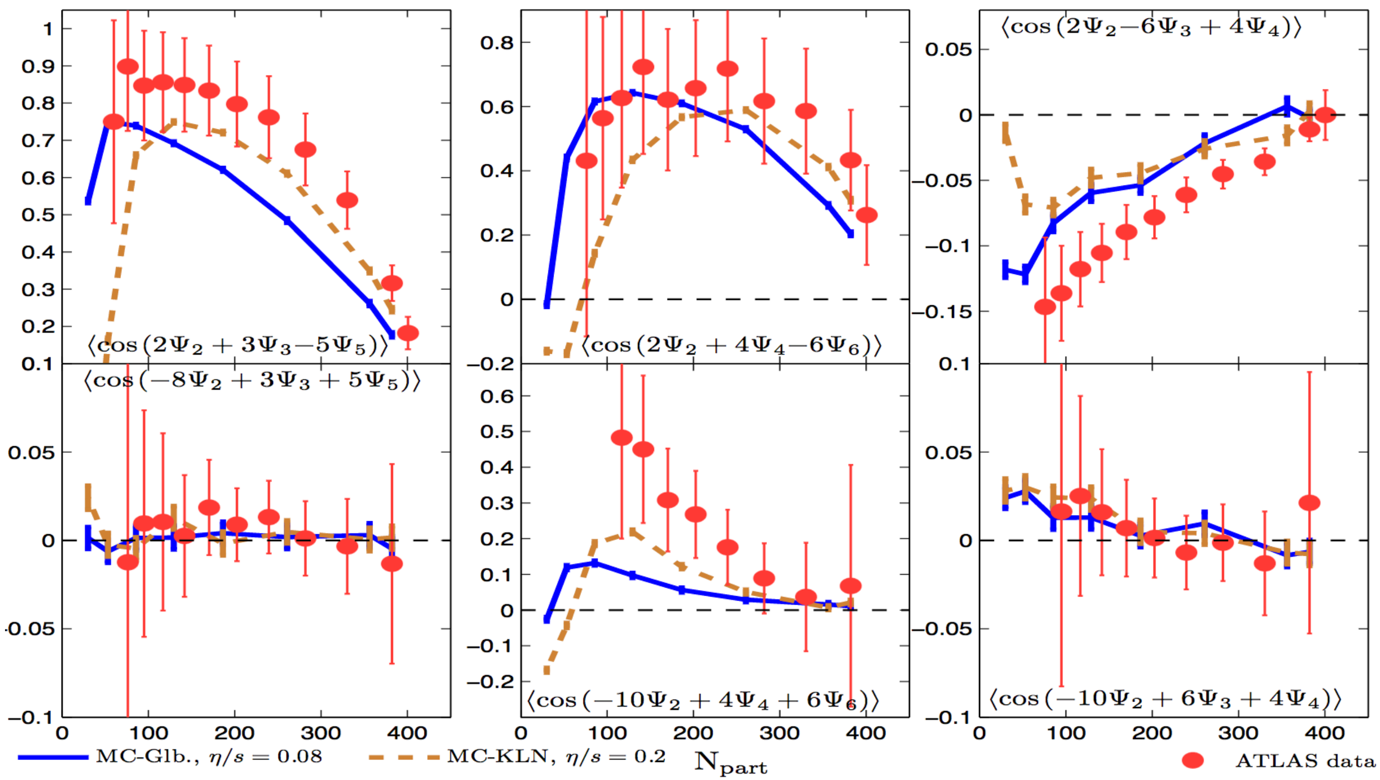
Compare to Uli's E-by-e hydro calculation

Hydrodynamic event-plane correlations in Pb+Pb collisions at sqrt(s)=2.76ATeV

Zhi Qiu, Ulrich W. Heinz

(Submitted on 6 Aug 2012 (v1), last revised 15 Sep 2012 (this version, v2))

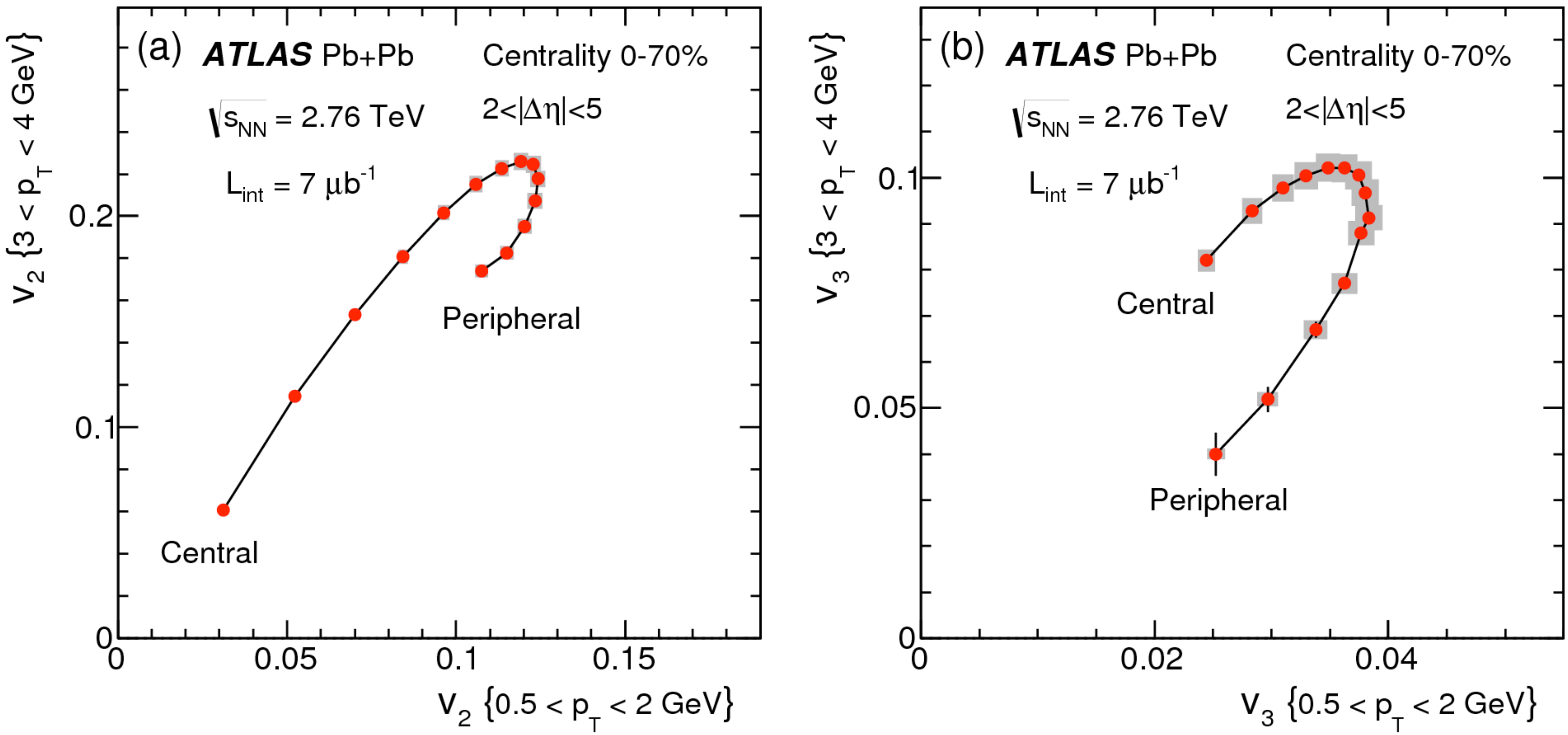
The recently measured correlations between the flow angles associated with higher harmonics in the anisotropic flow generated in relativistic heavy-ion collisions are shown to be of hydrodynamic origin. The correlation strength is found to be sensitive to both the initial conditions and the shear viscosity of the expanding fireball medium.



- Reproduce correlations between three planes: Φ_n, Φ_m, Φ_k

Flow magnitude correlation: $p(v_n,v_m)$

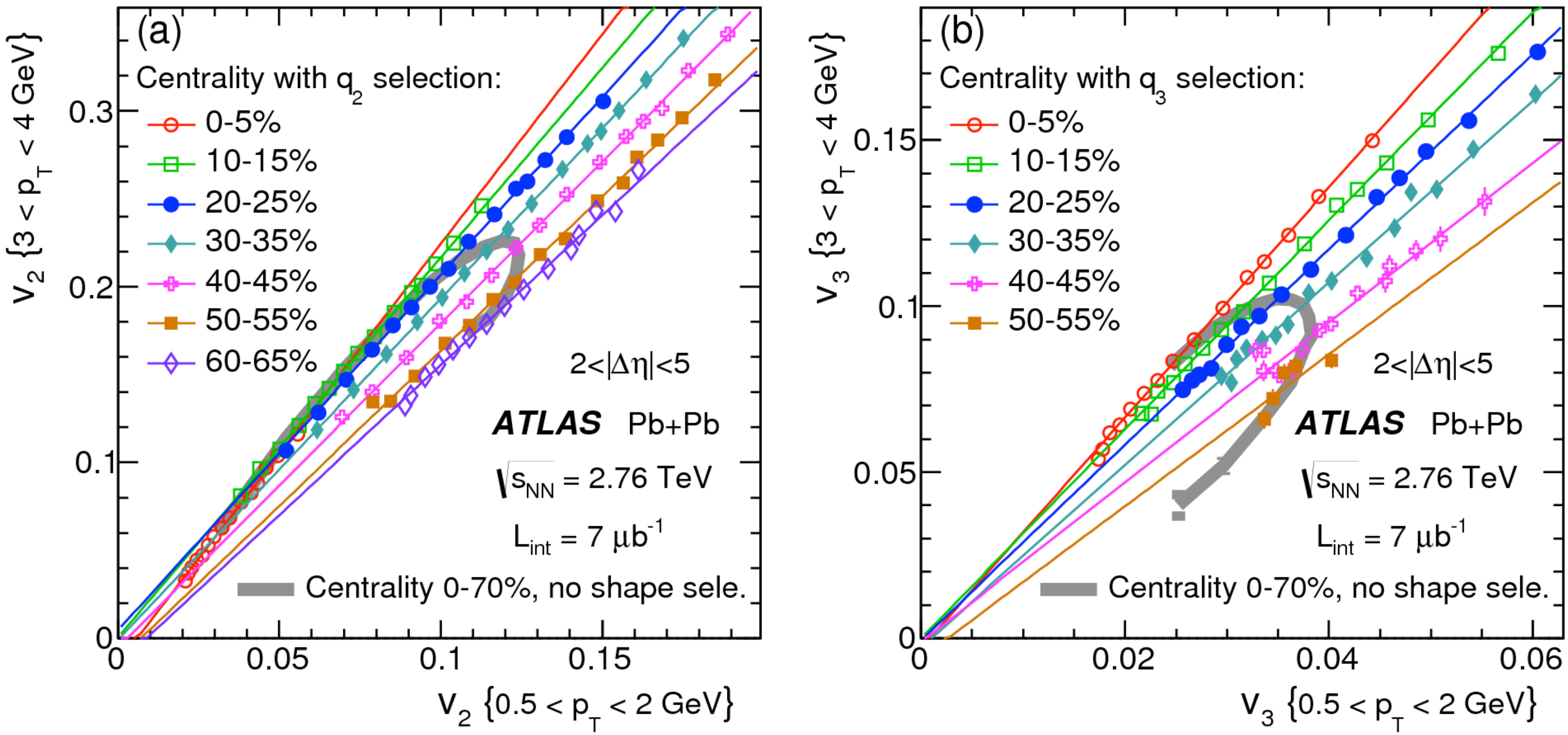
- Correlating low-p_T v_n with high-p_T v_n
  - boomerang consistent with stronger viscous damping at higher p_T.



Flow magnitude correlation: $p(v_n,v_m)$

- Correlating low-p_T v_n with high-p_T v_n
  - boomerang consistent with stronger viscous damping at higher p_T.
- Correlating low-p_T v_n with high-p_T v_n for fixed centrality
  - Linear response between v_n and ε_n.

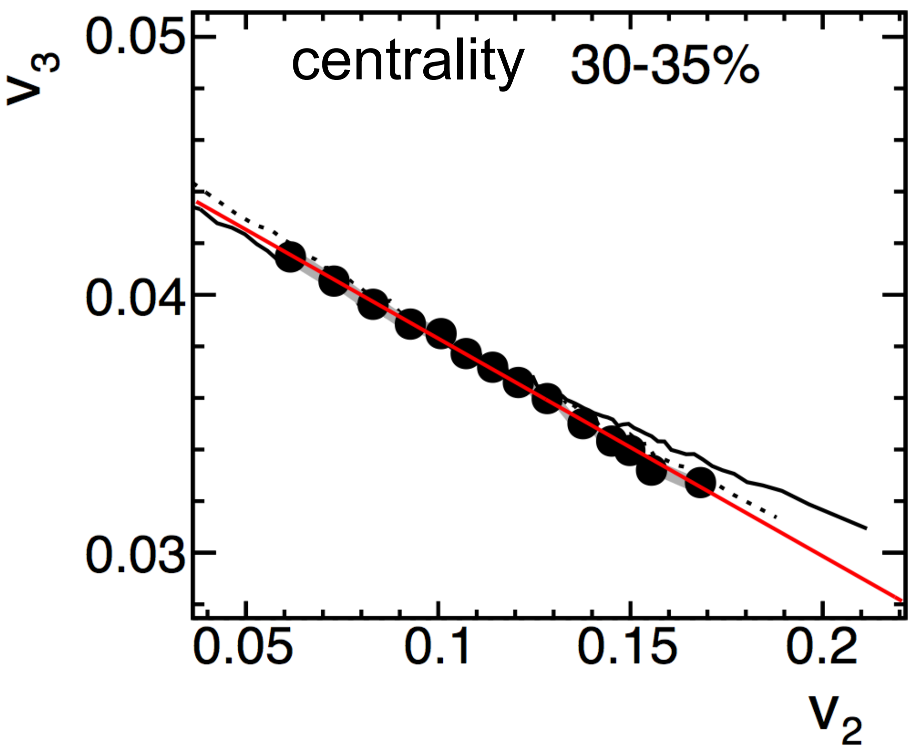
Fix size and change shape

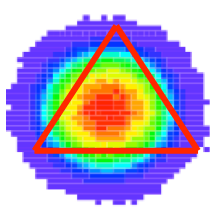


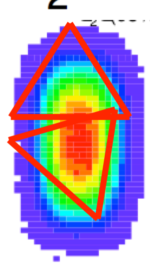
$p(v_n,v_m)$ within fixed centrality/system-size

Anti-correlation between v_2 and v_3

Large ε_2 reduce ε_3 → seen in Glauber model

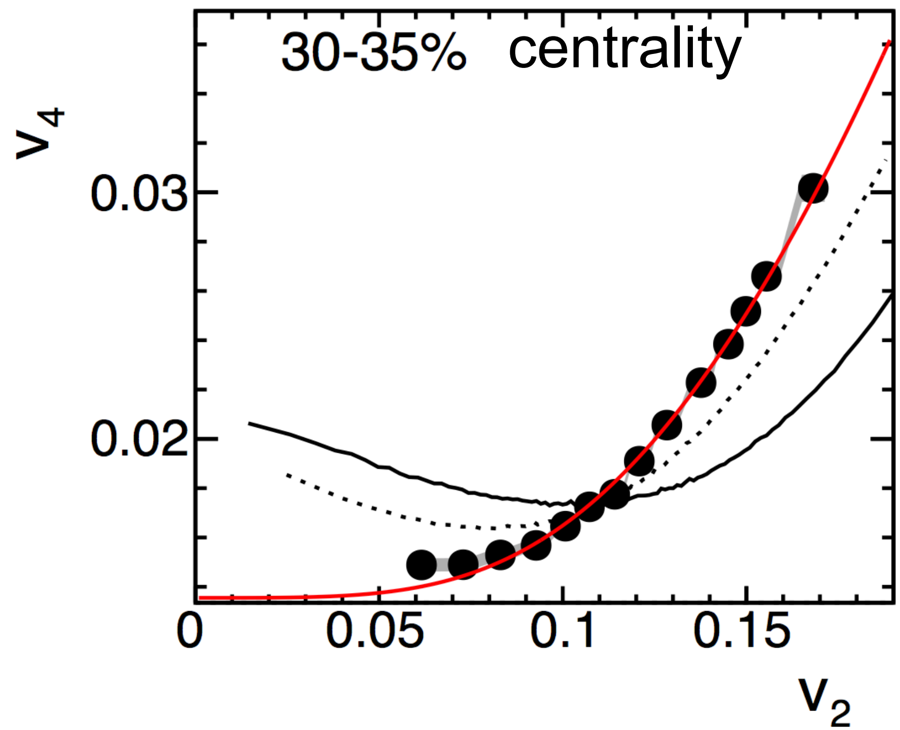






Quadratic correlation between v_2 and v_4

- Non-linear mode mixing



$$v_4 e^{i4\Phi_4} \propto \varepsilon_4 e^{i4\Phi^*_4} + c v_2^{\,2} e^{i4\Phi_2} + \ldots$$

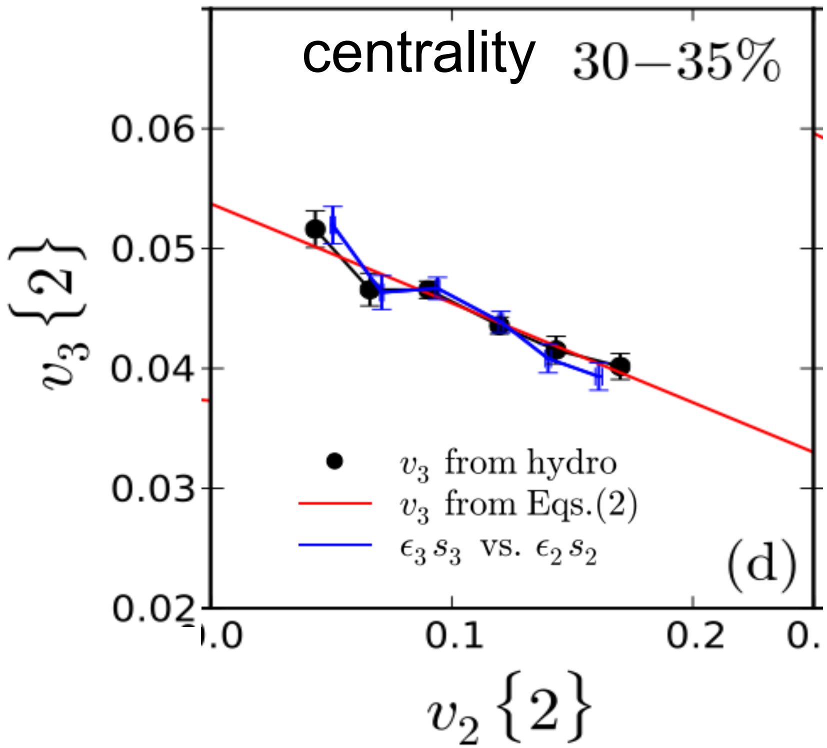
Hydrodynamic flow amplitude correlations in event-by-event fluctuating heavy-ion collisions

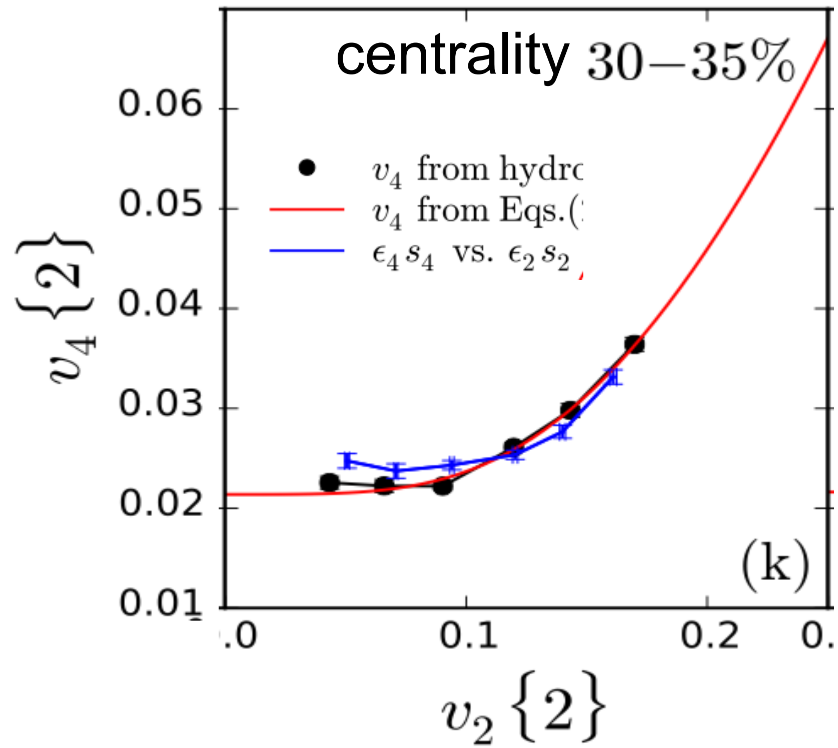
Jing Qian, Ulrich Heinz

(Submitted on 6 Jul 2016 (v1), last revised 11 Jul 2016 (this version, v2))

1607.01732

The effects of event-by-event fluctuations in the initial geometry of the colliding nuclei are important in the analysis of final flow observables in relativistic heavy-ion collisions. We use hydrodynamic simulations to study the amplitude correlations between different orders of event-by-event fluctuating anisotropic flow harmonics. While the general trends seen in the experimental data are qualitatively reproduced by the model, deviations in detail, in particular for peripheral collisions, point to the need for more elaborate future calculations with a hybrid approach that describes the late hadronic stage of the evolution microscopically. It is demonstrated explicitly that the observed anti-correlation between v_2 and v_3 is the consequence of approximately linear hydrodynamic response to a similar anti-correlation of the corresponding initial eccentricities ϵ_2 and ϵ_3. For $n > 3$, the hydrodynamic correlations between $v_{2,3}$ and v_n deviate from the rescaled correlations among the corresponding initial eccentricities, demonstrating nonlinear mode coupling effect in higher order flows.

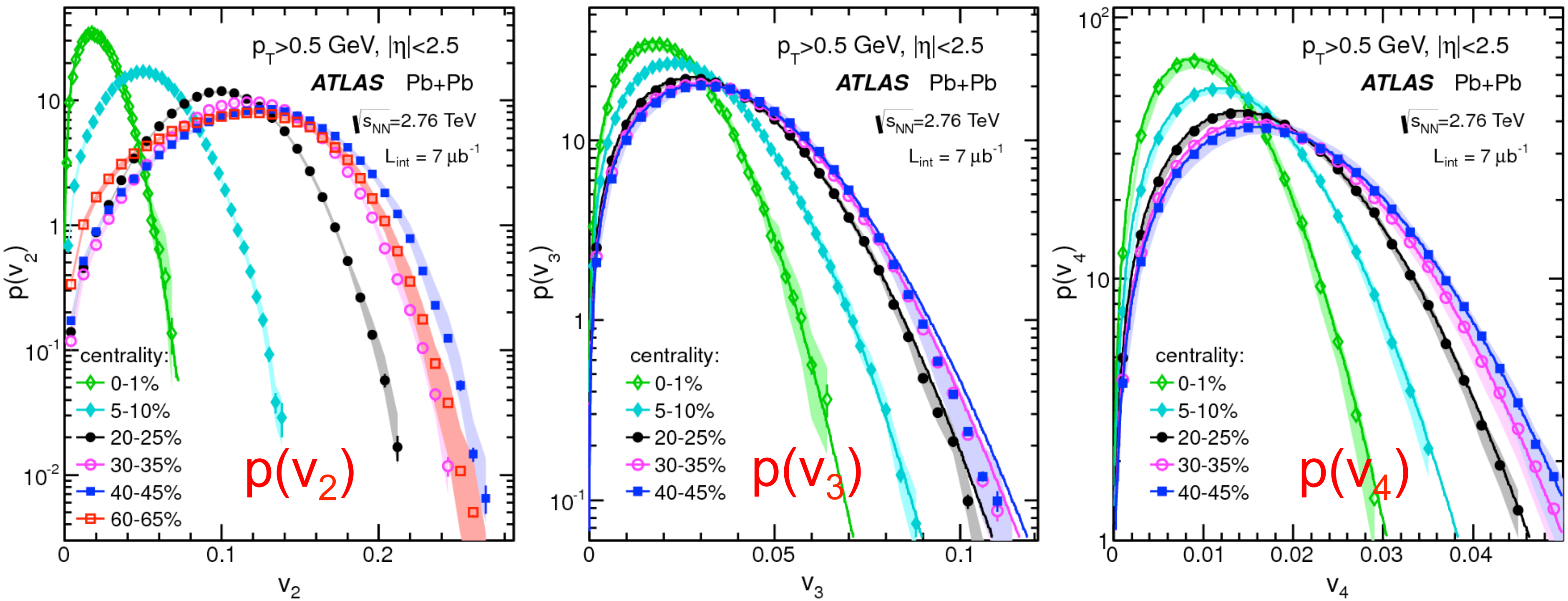




- Qualitatively reproduced by the EbyE hydro.

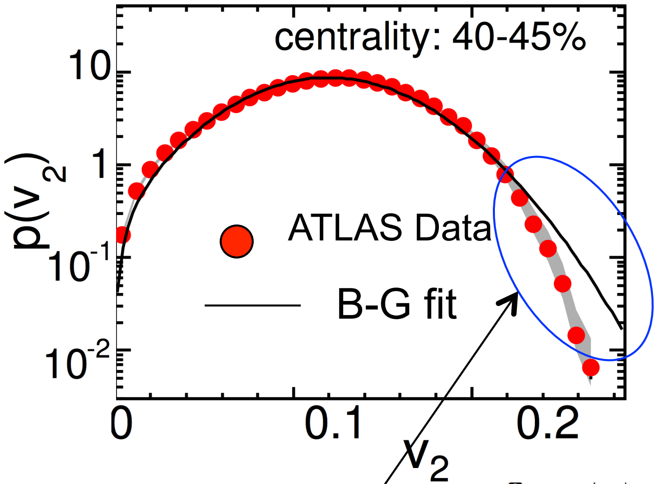
$p(v_n)$ distribution in fixed centrality

JHEP11(2013)183



- Directly probes the initial condition.

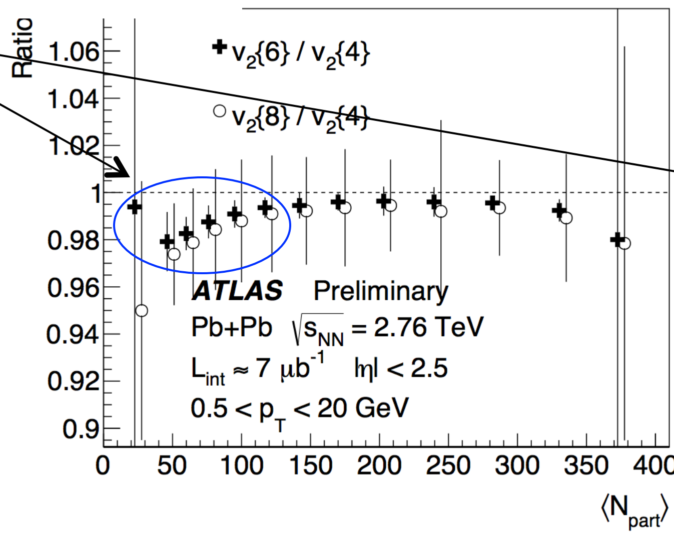
Non-Gaussianity in the $p(v_2)$ distribution

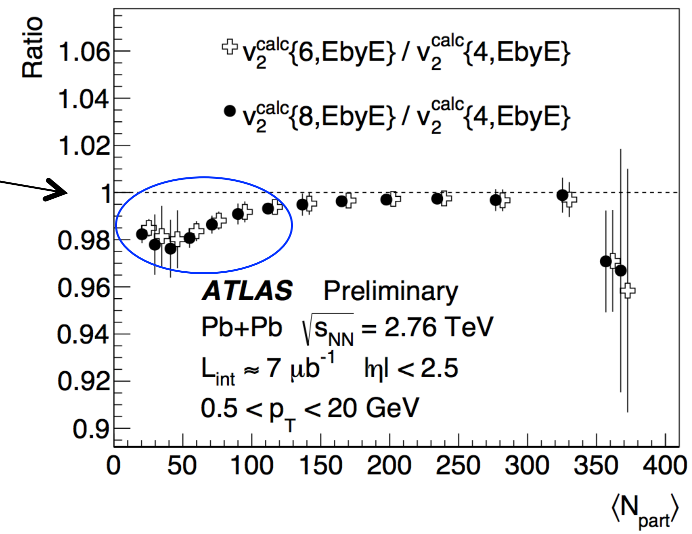


$\langle v_2\rangle \approx k \langle \varepsilon_2 \rangle$

- Reflected by a 1-2% change beyond 4th order cumulants

Non-Bessel Gaussian behavior

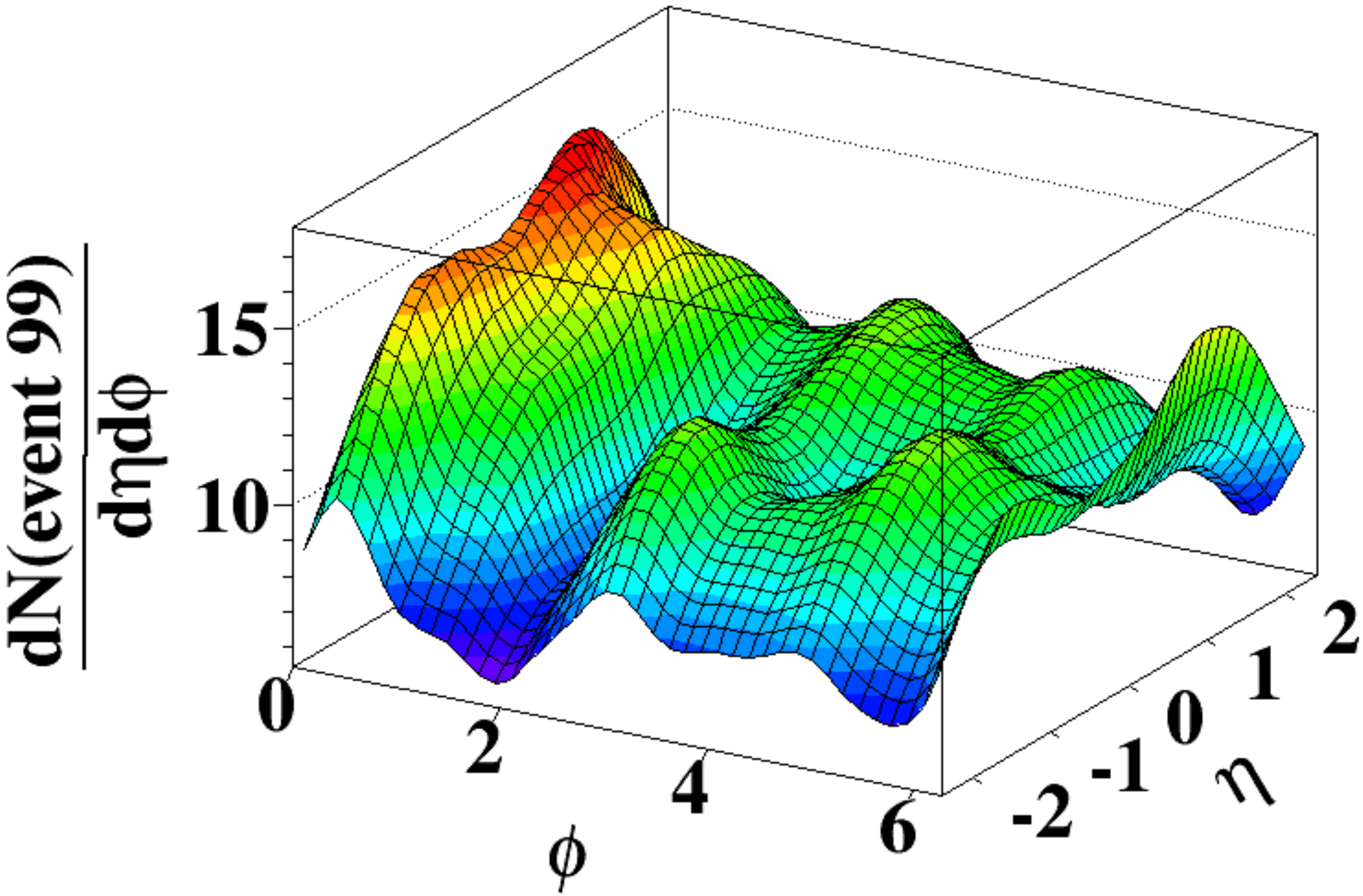




Jean-Yves et.al 1511.03896

- Linear+cubic response between v_2 & ε_2?.
- unclear whether this exhausts all the feature of $p(v_2)$?
- Clearly more important in smaller system

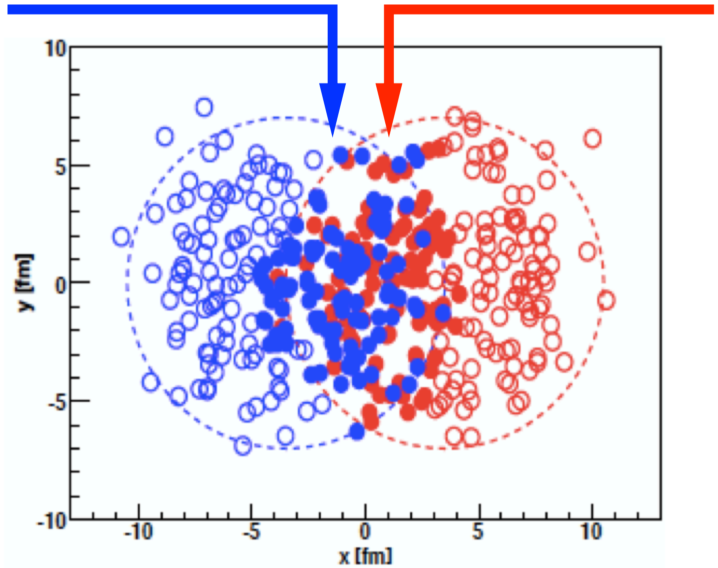
Longitudinal flow dynamics



Curtsey of L.Pang and X.N Wang, EbyE 3D hydro+AMPT condition

Three types of longitudinal correlations

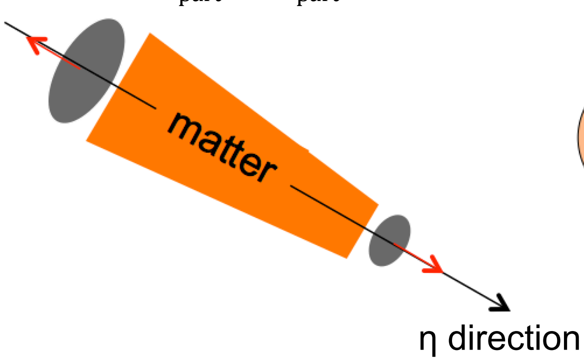
$N^{\mathrm{F}}_{\mathrm{part}}$ $\varepsilon^{\mathrm{F}}_{n} e^{in\Psi^{F}_{n}}$



$N^{\mathrm{B}}_{\mathrm{part}}$ $\varepsilon^{\mathrm{B}}_{n} e^{in\Psi^{B}_{n}}$

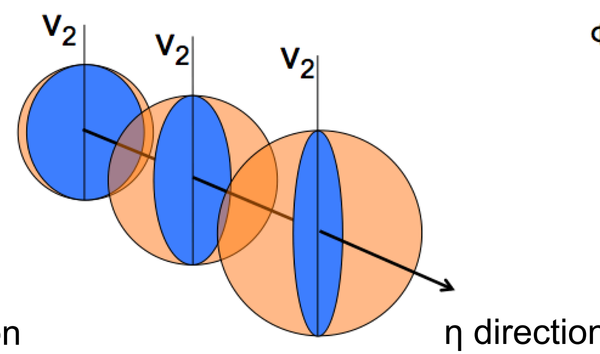
Consequences:

(a) $N^{\mathrm{F}}_{\mathrm{part}} \neq N^{\mathrm{B}}_{\mathrm{part}}$



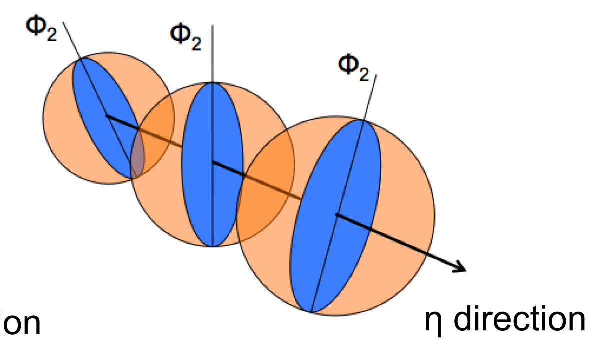
Asymmetry in multiplicity

(b) $\varepsilon^{\mathrm{F}}_{2} \neq \varepsilon^{\mathrm{B}}_{2}$



Asymmetry in flow magnitude

(c) $\Psi^{\mathrm{F}}_{2} \neq \Psi^{\mathrm{B}}_{2}$



Torque/twist of flow plane

Two-particle correlation observables

Most general form in angular space: $C(\eta_1, \eta_2, \Delta\phi)$

$$C(\eta_1,\eta_2,\Delta\phi) = \underline{C_N(\eta_1,\eta_2)}\left[1+2\sum_n \underline{V_{n\Delta}(\eta_1,\eta_2)}\cos n\Delta\phi\right]$$

FB Multiplicity fluctuation

FB flow fluctuation

$$C_N(\eta_1,\eta_2) = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle}$$

ATLAS observable

$$V_{n\Delta}(\eta_1,\eta_2) = \langle \mathrm{v}_n(\eta_1)\mathrm{v}_n(\eta_2)\cos n[\Phi_n(\eta_1)-\Phi_n(\eta_2)]\rangle$$

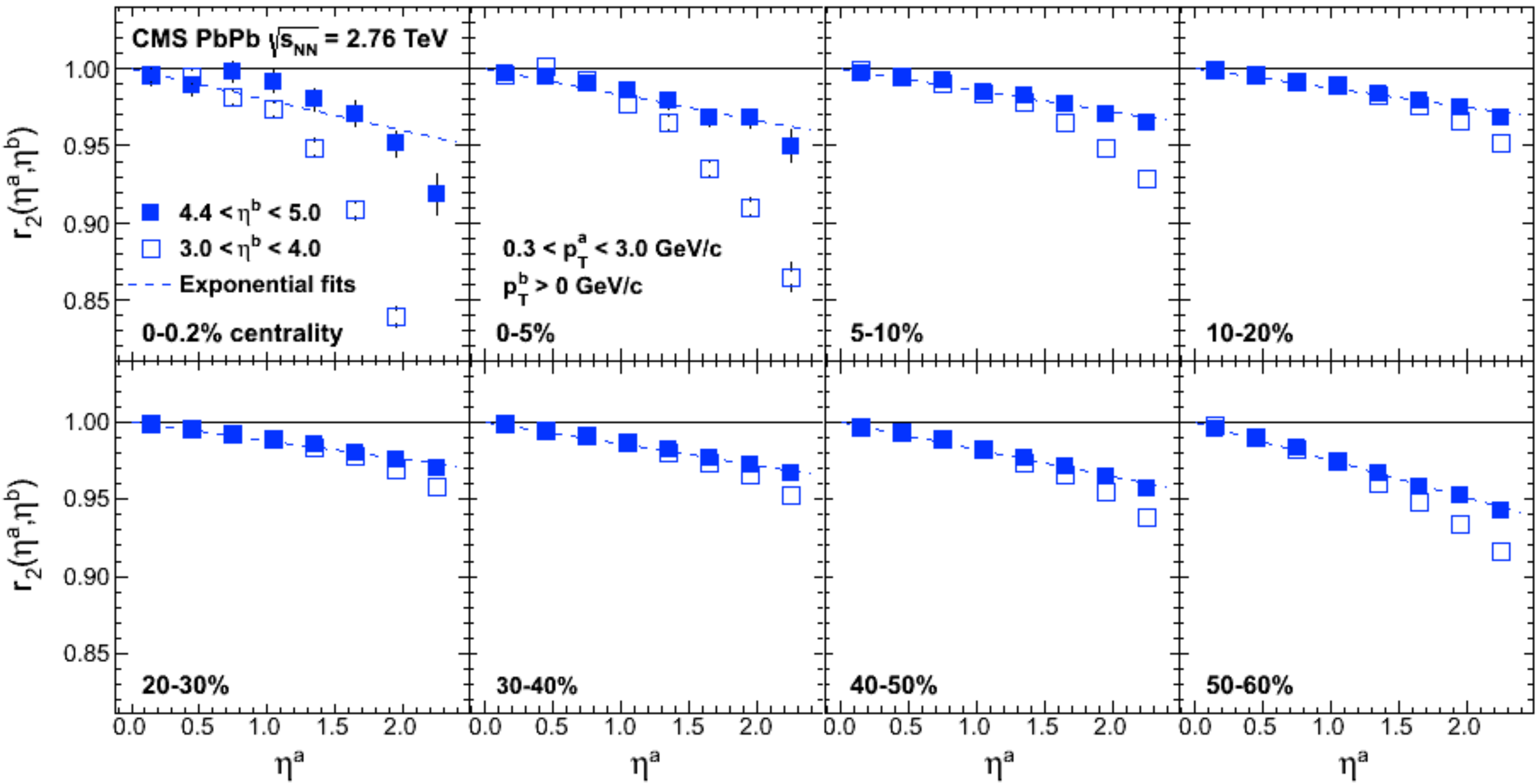
CMS observable: $r(\eta,\eta_{ref}) = \dfrac{V_{n\Delta}(-\eta,\eta_{ref})}{V_{n\Delta}(\eta,\eta_{ref})}$

Driven by N_{part} asymmetry

Driven by twist & asymmetry of ε_n

2^{nd}-order flow in PbPb

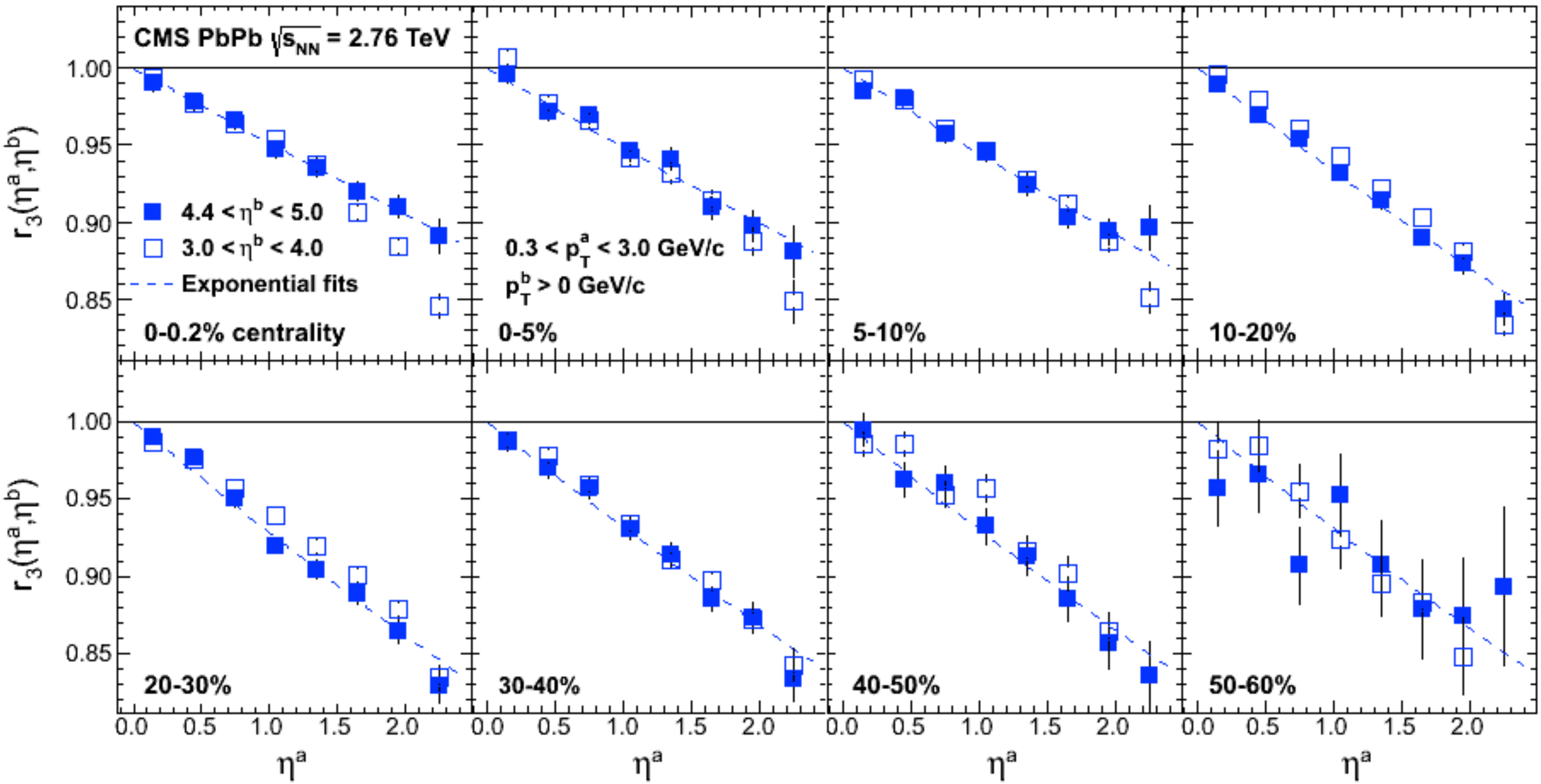
$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$



- Linear function except in most central collisions
- Slope decreases then increases from central to peripheral

3^{rd}-order flow in PbPb

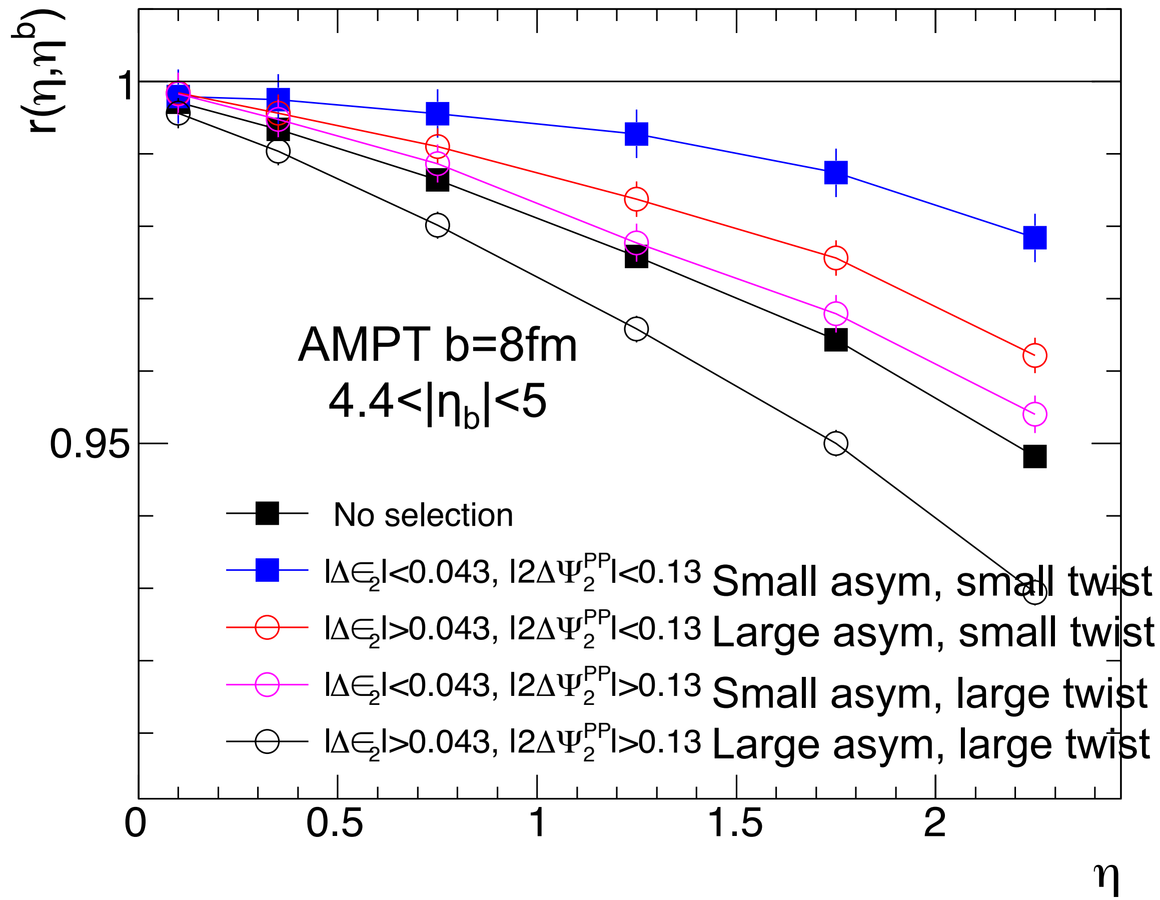
$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$



- De-correlation independent of centrality

Separate asymmetry and twist contributions

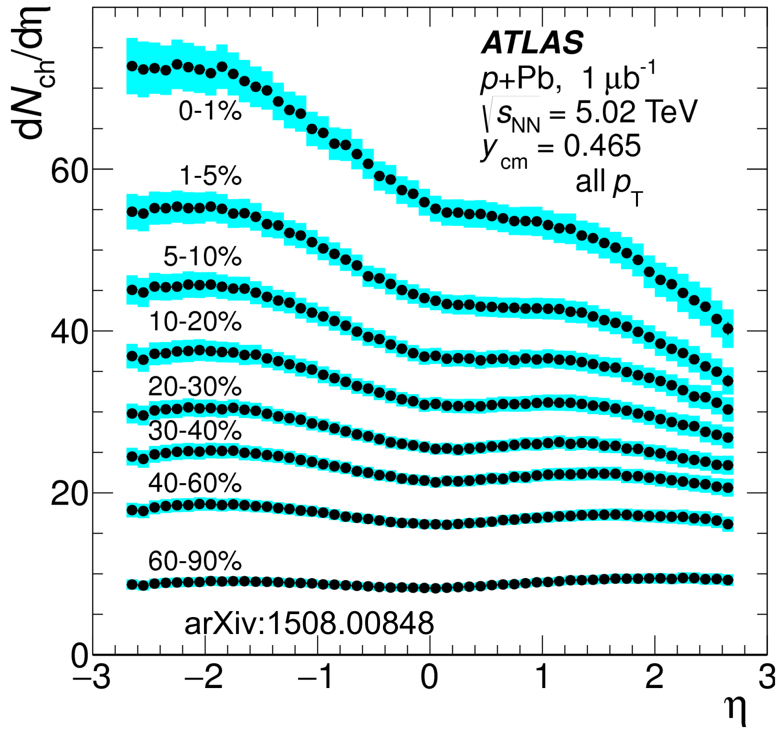
- Select asymmetry and twist based on eccentricity vector in AMPT
  - Cut on asymmetry : $\Delta\varepsilon_2 = \varepsilon_2^F - \varepsilon_2^B$, cut on twist: $\Delta\Psi_2 = \Psi_2^F - \Psi_2^B$



asymmetry contribution > 50% of the twist contribution.

0^{th}-order: FB multiplicity asymmetry

- dN/dη shape reflects asymmetry in num. of F-B sources

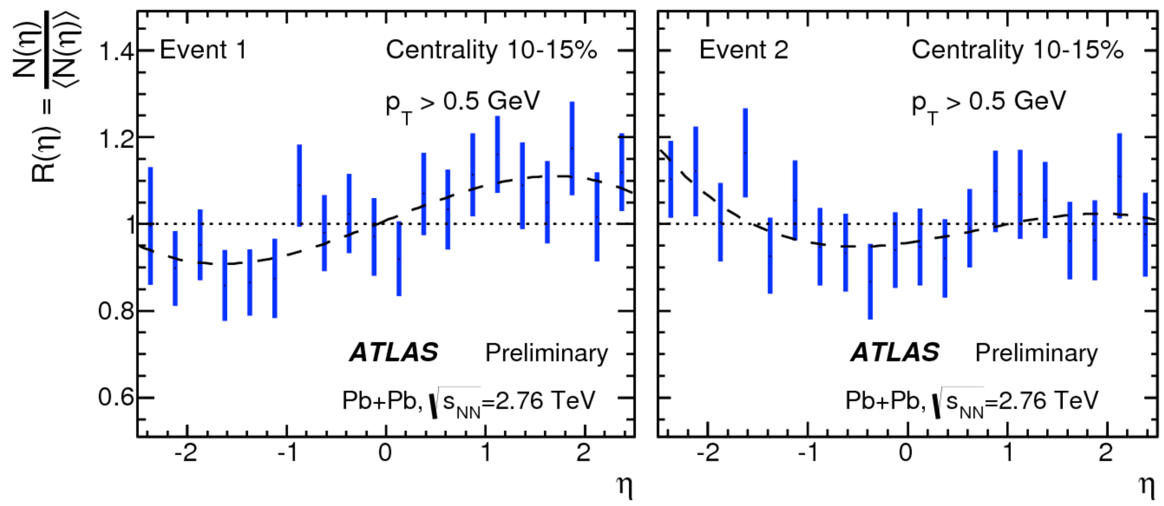


Measure FB asymmetry fluctuation event-by-event?

Pseudorapidity correlation function

Single particle distribution

$$R_S(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle}$$



$$C = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} = \langle R_S(\eta_1) R_S(\eta_2) \rangle_{events}$$

Mixed events

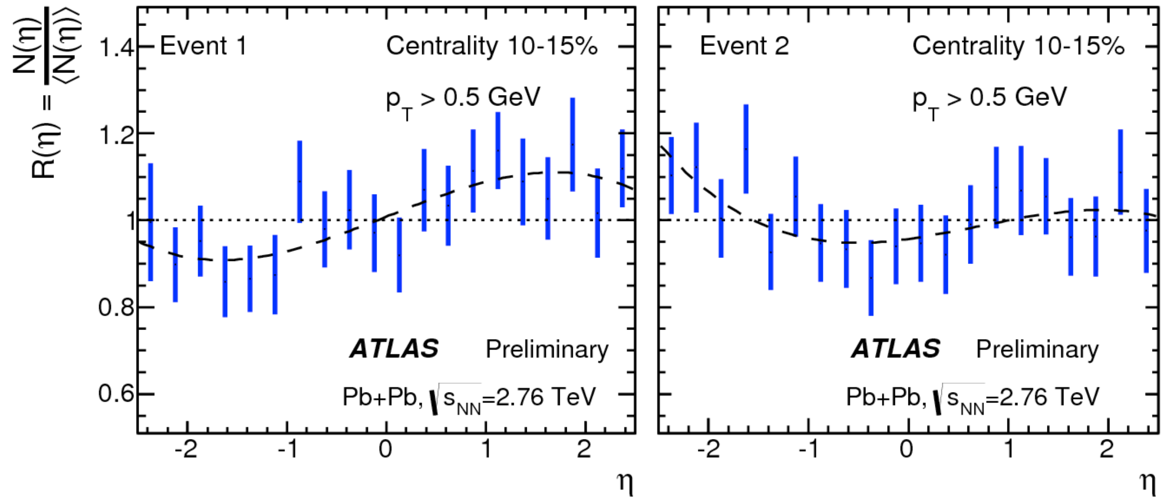
Disentangles statistical fluctuation from dynamical fluctuation

Can also do multi-particle correlations: Bzdak, Bozek, Broniowski 1509.02967, 1509.04124

Leading-order contribution

Single particle distribution

$$R_S(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle} \approx 1 + a_1\eta$$

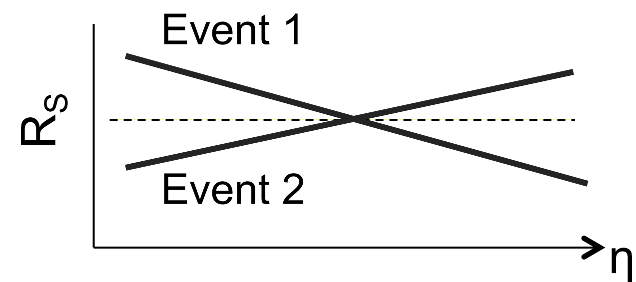


$$C = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} = \langle R_S(\eta_1)R_S(\eta_2)\rangle_{events}$$

$$\approx 1 + \langle a_1\eta_1 a_1\eta_2\rangle$$

$$= 1 + \langle a_1^2\rangle \eta_1\eta_2$$

Mixed events



Disentangles statistical fluctuation from dynamical fluctuation

Can also do multi-particle correlations: Bzdak, Bozek, Broniowski 1509.02967, 1509.04124

Properties of multiplicity correlation

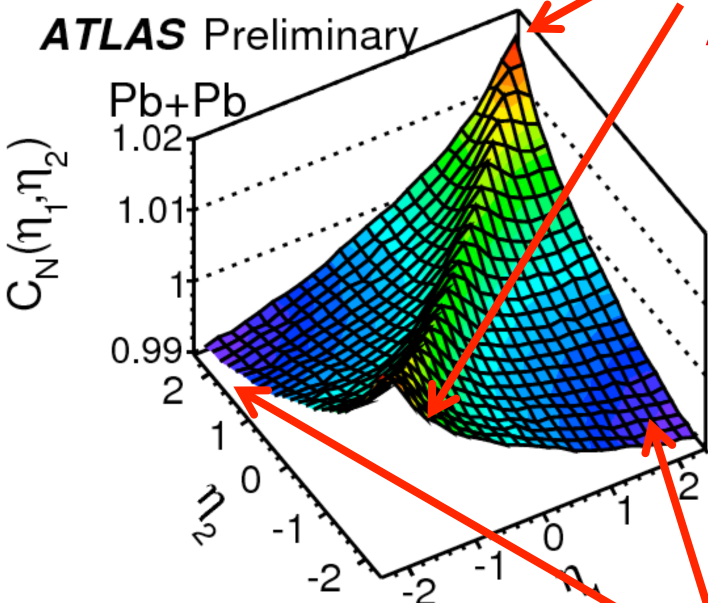
$$C_N = 1 + \delta_{SRC} + \delta_{LRC}$$

$p_T > 0.2$ GeV

$100 \le N_{ch}^{rec} < 120$

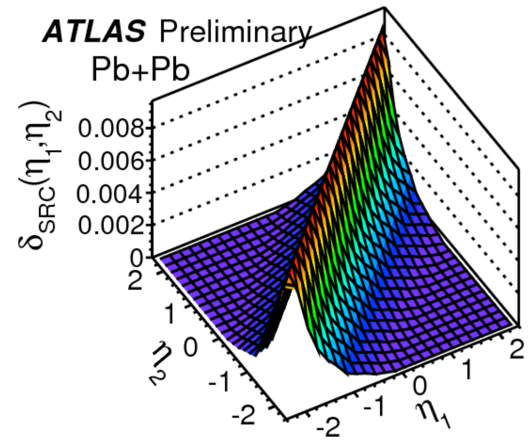
Short-range correlation δ_{SRC}

$\Delta\eta = \eta_1 - \eta_2 \sim 0$



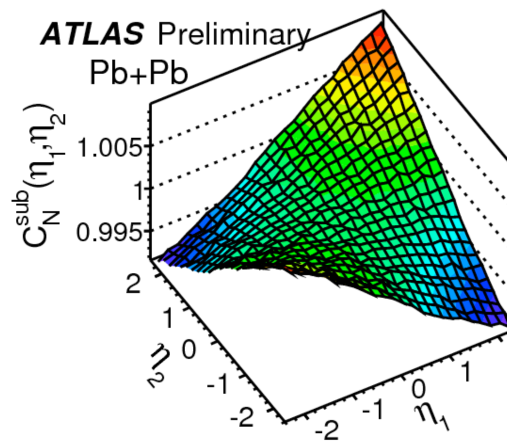
Long range correlation δ_{LRC}

=



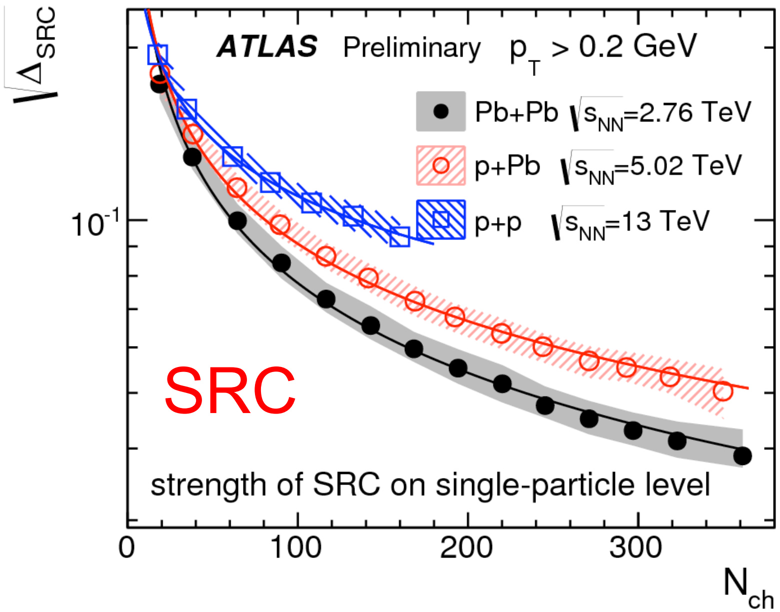
$$\Delta_{SRC} = \frac{\int \delta_{SRC}(\eta_1,\eta_2) d\eta_1 d\eta_2}{4Y^2}$$

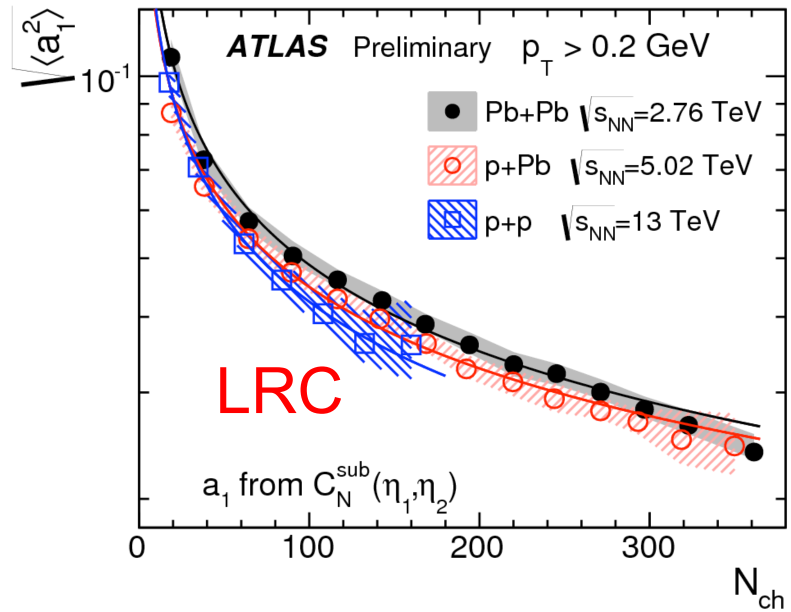
=



Consistent with $\approx 1 + \langle a_1^2 \rangle \eta_1 \eta_2$

Dependence on N_{ch} and collision systems





SRC controlled by num. of sources

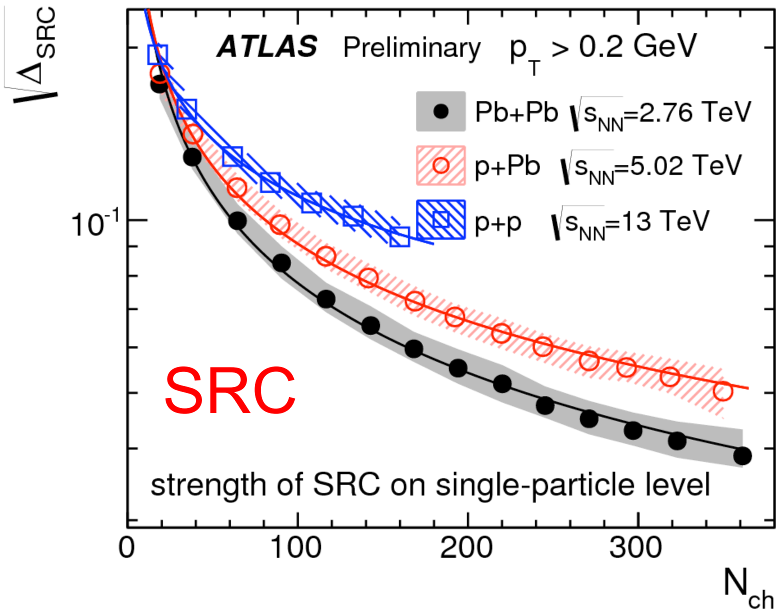
$$\boxed{n = n_f + n_b \propto N_{ch}}$$

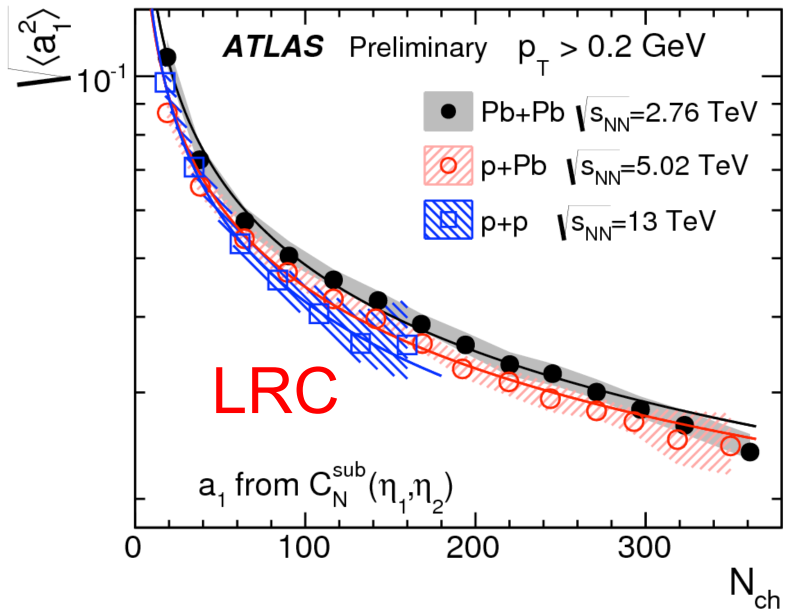
LRC controlled by FB asymmetry of sources

$$\boxed{A_n = \frac{n_f - n_b}{n_f + n_b}} \qquad \langle a_1^2 \rangle \propto \langle A_n^2 \rangle$$

Expect 1/√N for independent-source emission

Dependence on N_{ch} and collision systems





SRC controlled by num. of sources

$$\boxed{n = n_f + n_b \propto N_{\rm ch}}$$

LRC controlled by FB asymmetry of sources

$$\boxed{A_n = \frac{n_f - n_b}{n_f + n_b}} \qquad \langle a_1^2 \rangle \propto \langle A_n^2 \rangle$$

Expect 1/√N for independent-source emission

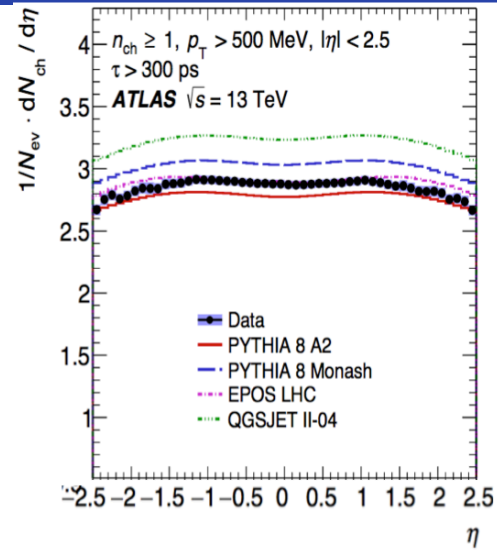
- Fit with $c/N_{\rm ch}^{\alpha}$

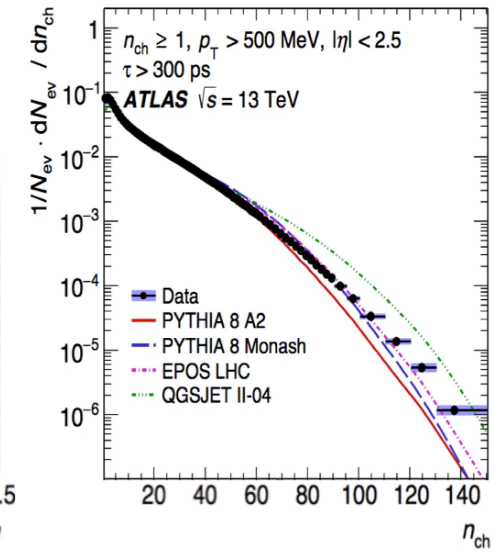
	Pb+Pb	*p*+Pb	*pp*
α for $\sqrt{\Delta_{\rm SRC}}$	0.505 ± 0.011	0.450 ± 0.010	0.365 ± 0.014
α for $\sqrt{\langle a_1^2 \rangle}$	0.454 ± 0.011	0.433 ± 0.014	0.465 ± 0.018

- SRC: more pair/source for smaller system
- LRC: 1/√N behavior independent of collision system

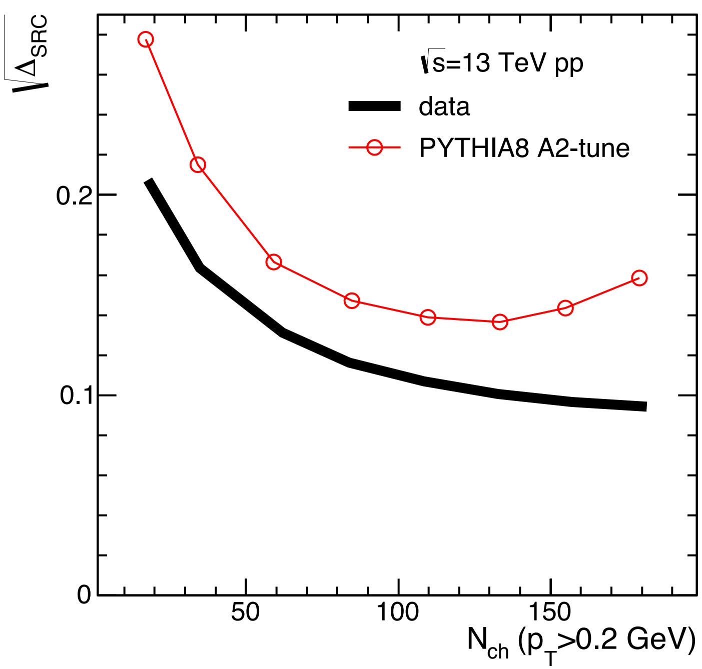
Compare with PYTHIA8 and EPOS-LHC

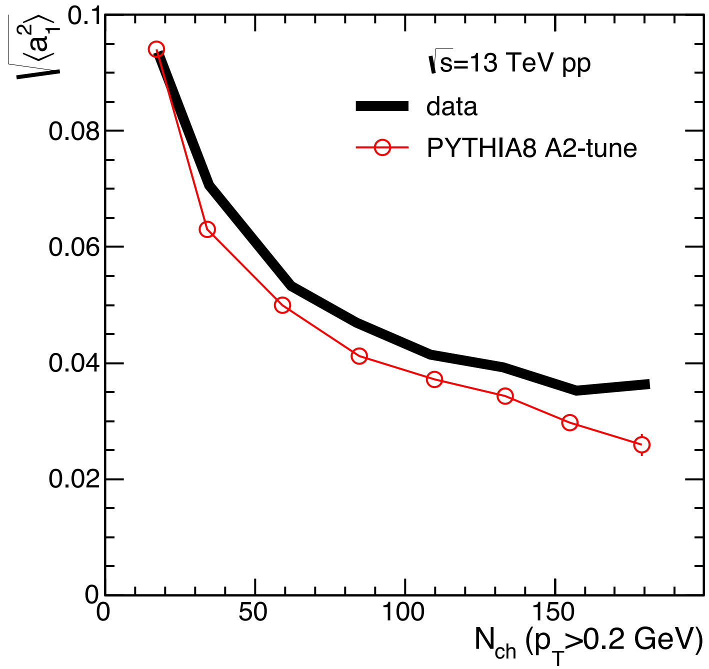
- Tuned to dN/dη and N_{ch} distribution via MPI





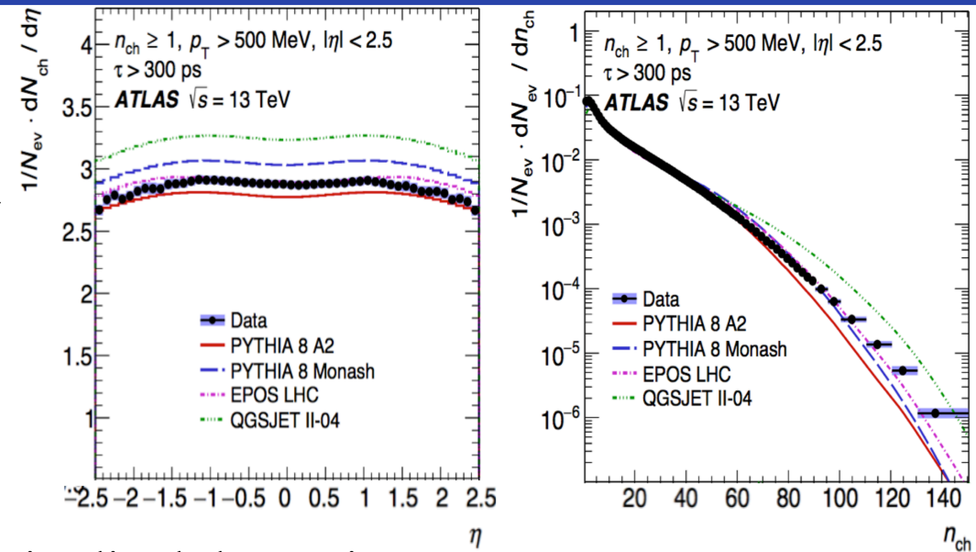
- Models:
  - Over-estimate the SRC
  - Under-estimate the LRC



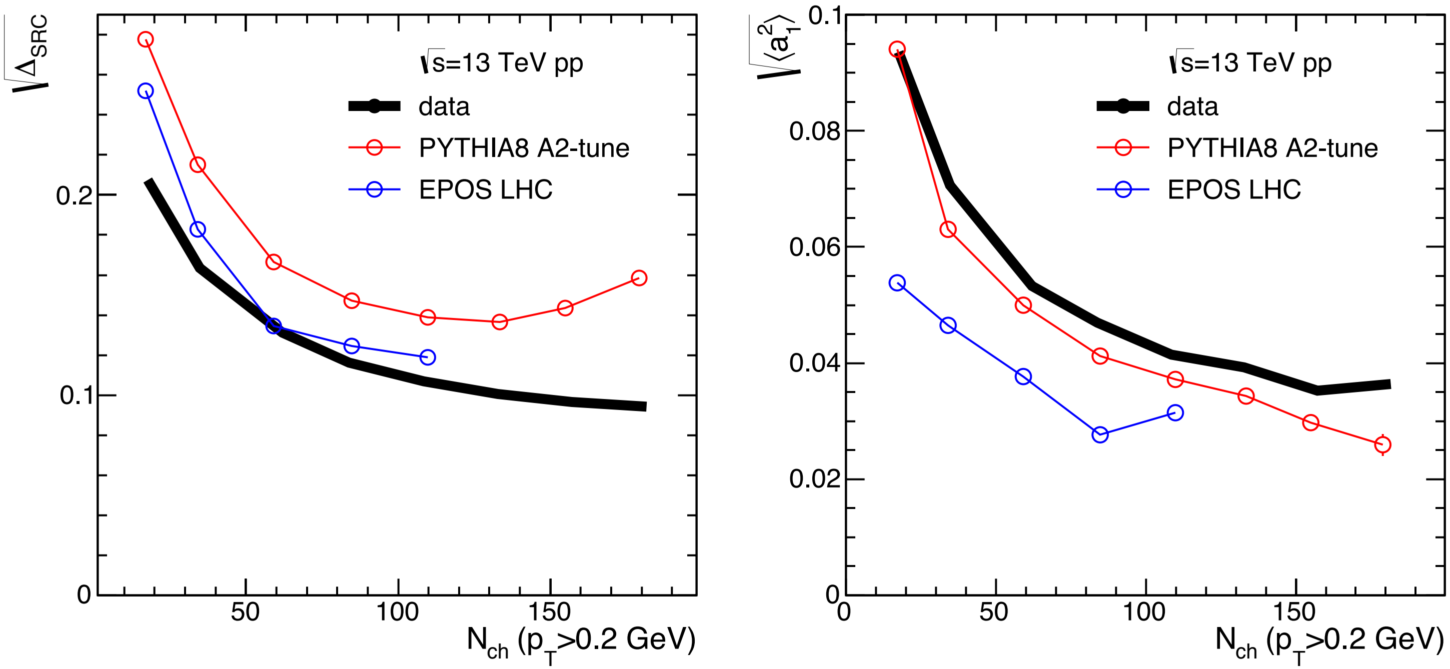


Compare with PYTHIA8 and EPOS-LHC

- Tuned to dN/dη and N_{ch} distribution via MPI



- Models:
  - Over-estimate the SRC
  - Under-estimate the LRC
  - LRC in EPOS is very small, no longitudinal dynamics



Summary

- Toward Uli's Little Bang standard model
  - Transverse correlations via EbyE observables provide detailed info on the space-time picture and properties of the medium
  - Longitudinal correlations directly probe rapidity structure of initial condition & mechanism for rapidity transports.
  - 3+1D boost-variant EbyE viscous hydro to take advantage of the rich information.
- Are we there yet?

VISH2+1D → EbyE VISH2+1D → EbyE VISH3+1D

2007 2011 ?