Stony Brook University | The State University of New York

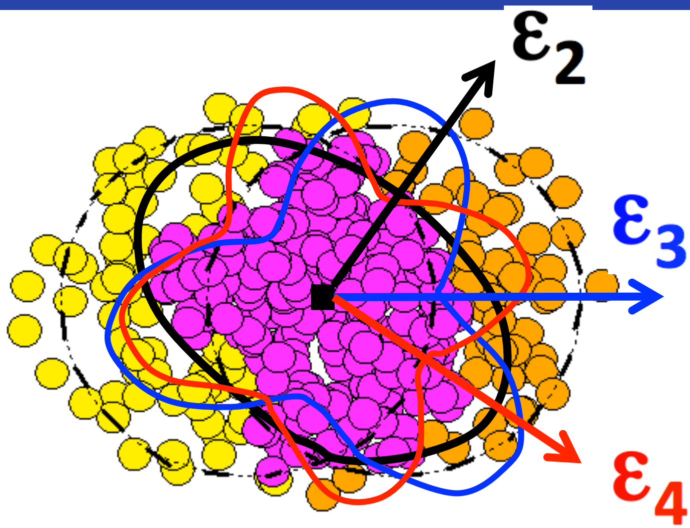
Selected flow results in Pb+Pb collisions from ATLAS

Jiangyong Jia on behalf of the ATLAS Collaboration

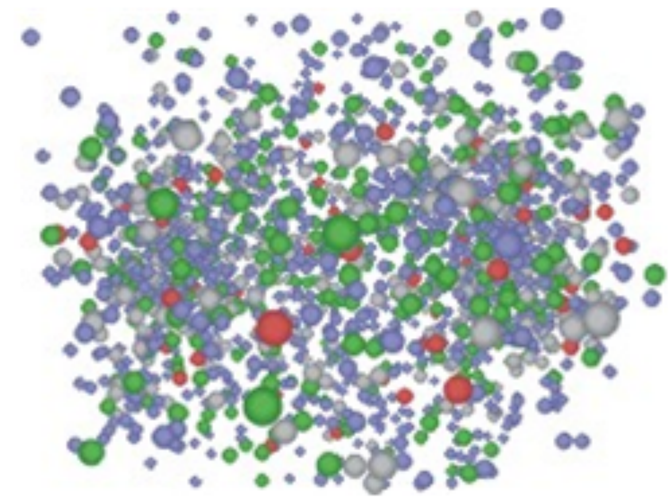
ISMD2013
XLIII International Symposium on Multiparticle Dynamics

Brookhaven National Laboratory
Office of Science | U.S. Department of Energy

Correlation/flow observables



Collective expansion

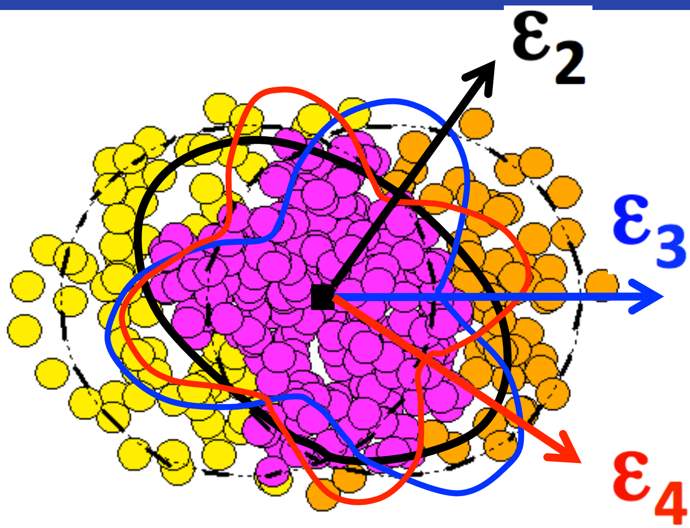


$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

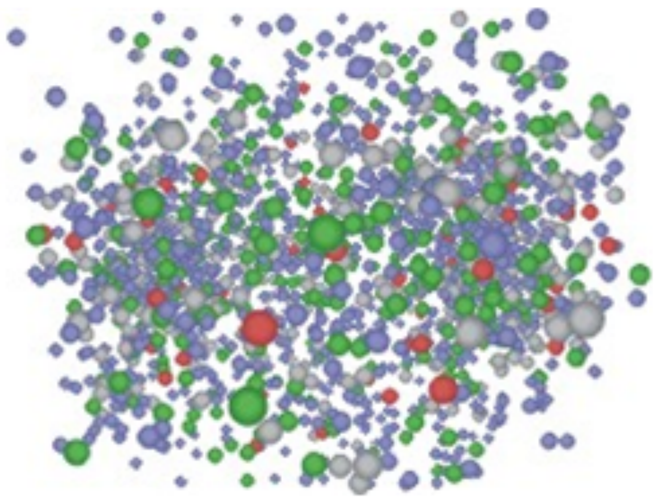
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n \mathrm{v}_n \cos n\left(\phi - \Phi_n\right)$$

$$\left\langle \mathrm{v}_n\left(p_T, \eta\right)\right\rangle$$

Correlation/flow observables



Collective expansion



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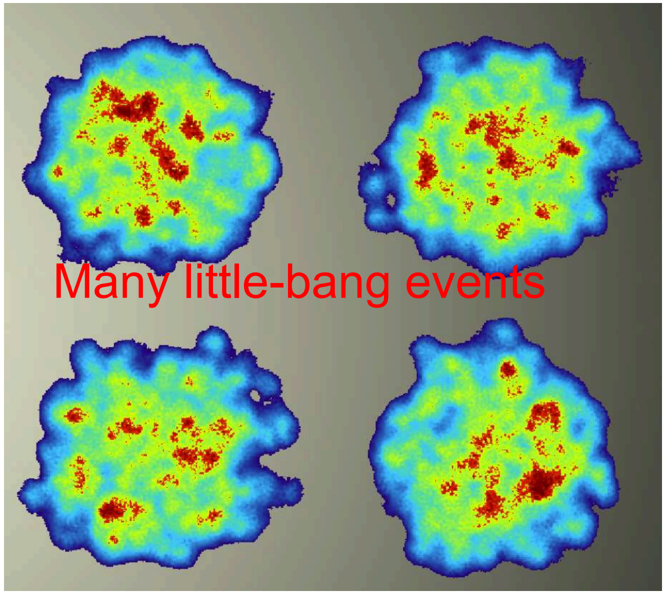


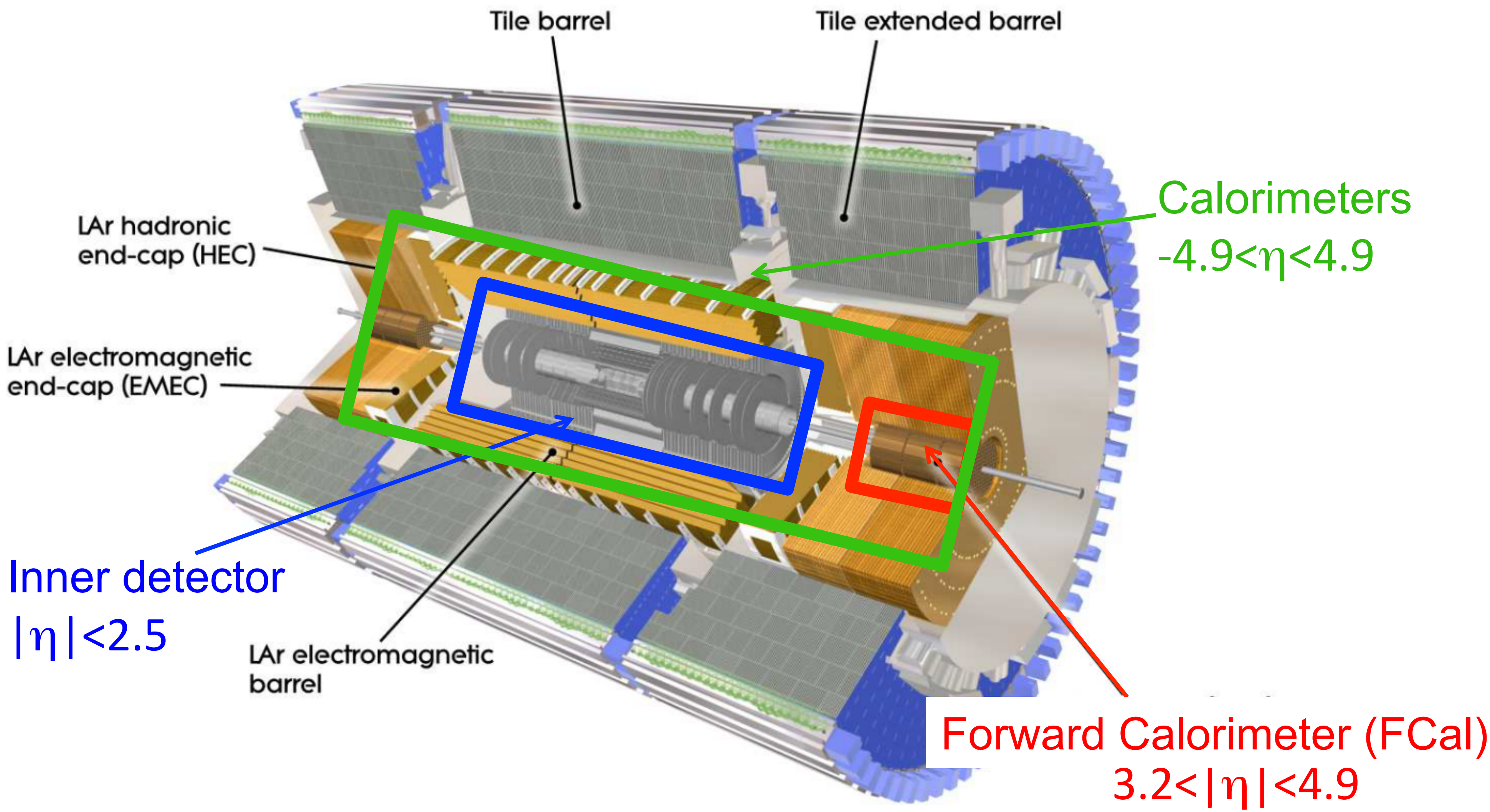
probability distributions:

$p(v_n, v_m, \ldots, \Phi_n, \Phi_m \ldots)$

- Event plane correlation: $p(\Phi_n, \Phi_m)$ and $p(\Phi_n, \Phi_m, \Phi_L)$
- EbyE v_n: $p(v_2)$, $p(v_3)$ and $p(v_4)$

Probes: initial geometry and transport properties of the QGP

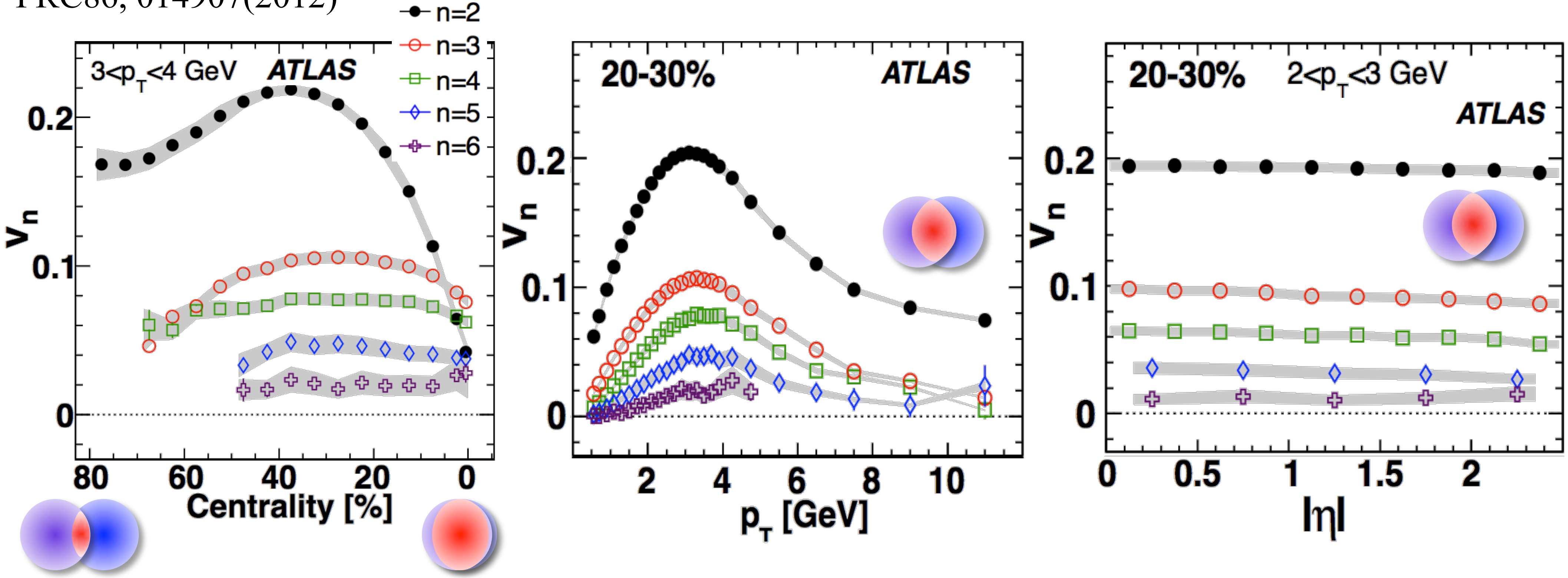
Observables at detector level



- E_T in forward calorimeter $3.2<|\eta|<4.9 \rightarrow$ centrality
- Tracks in inner detector $|\eta|<2.5$ $\rightarrow$ for v_n measurement
- E_T in calorimeter $-4.9<\eta<4.9 \rightarrow$ Event plane correlations

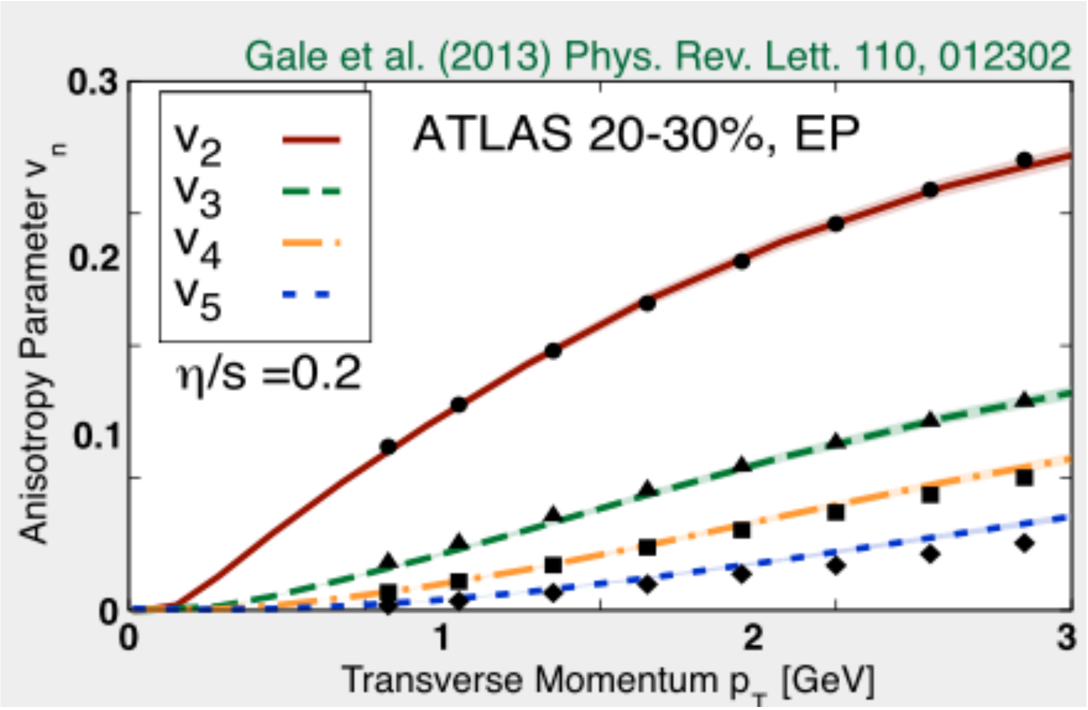
Summary of average flow $v_n(\text{cent}, p_T, \eta, n)$

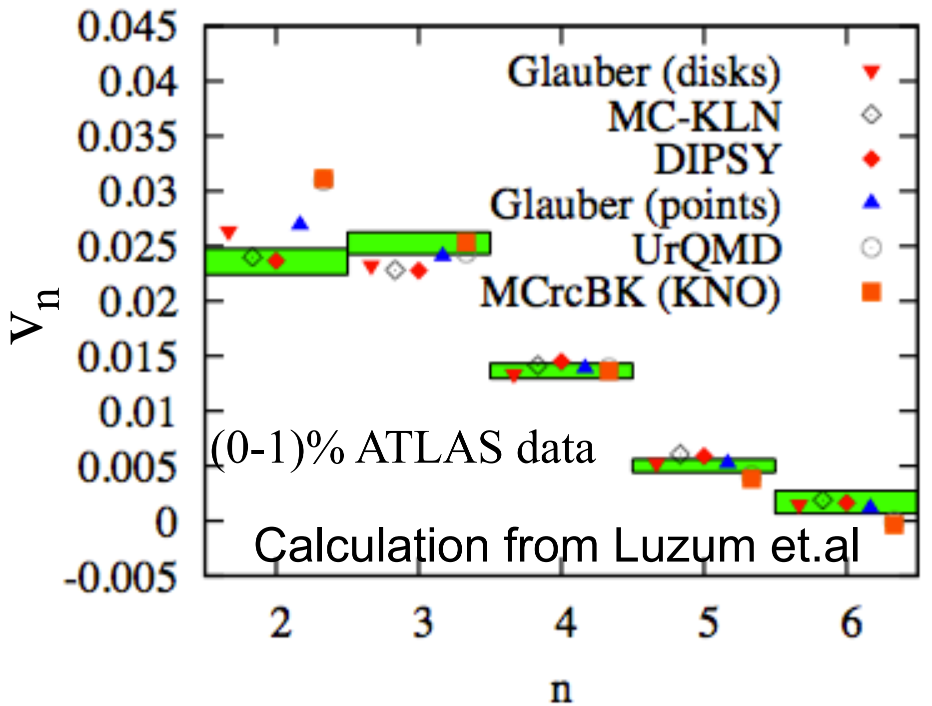
PRC86, 014907(2012)



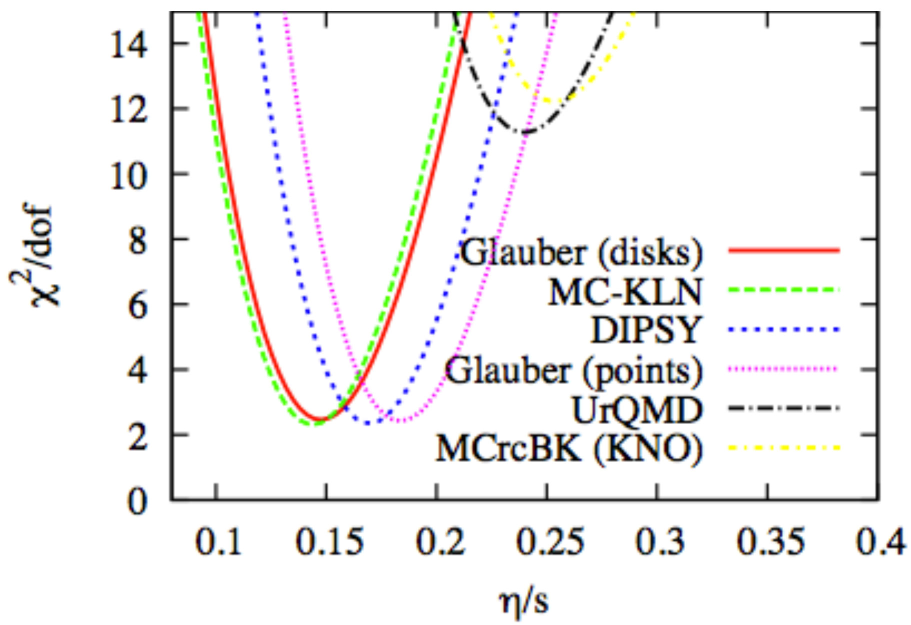
- **Features of Fourier coefficients**
  - **v_n coefficients rise and fall with centrality→ collision geometry**
  - **v_n coefficients rise and fall with p_T. → hydrodynamic response**
  - **v_n coefficients are ~boost invariant. → global event shape**

Comparison of v_n results with hydro models



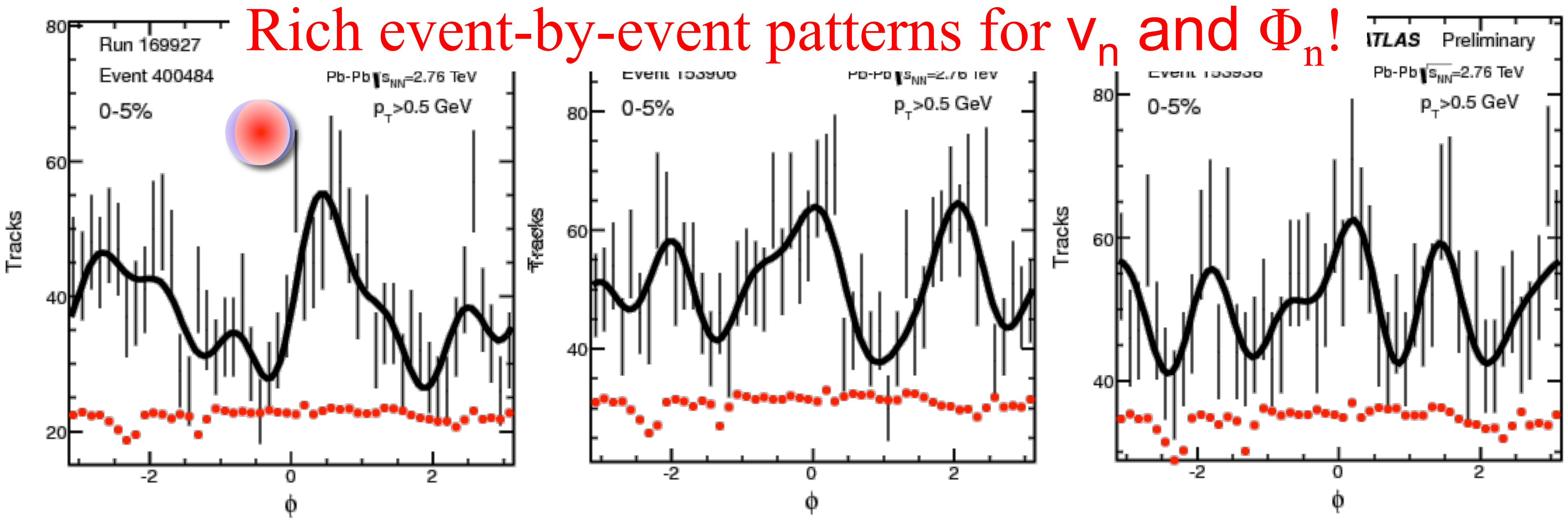


Constrain η/s & initial geometry



ATLAS data PRC86, 014907(2012)

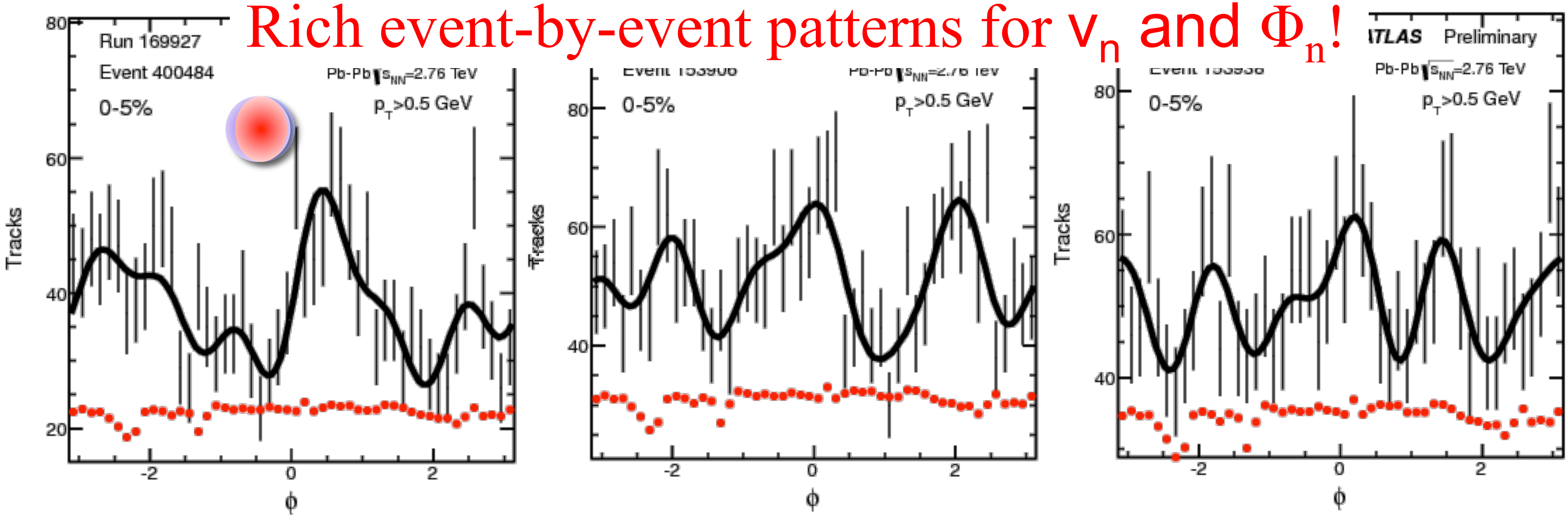
Event-by-event fluctuation seen in data



$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n^{obs} \cos n\left(\phi - \Phi_n^{obs}\right)$$

Event-by-event fluctuation seen in data

Rich event-by-event patterns for v_n and Φ_n!



$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n^{obs} \cos n\left(\phi - \Phi_n^{obs}\right)$$

Obtain $p(v_n)$ from $p(v_n^{obs})$

response function: $p(v_n^{obs}|v_n)$

ATLAS arXiv: 1305.2942

Obtain $p(\Phi_n,\Phi_m)$ from $p(\Phi_n^{obs},\Phi_m^{obs})$

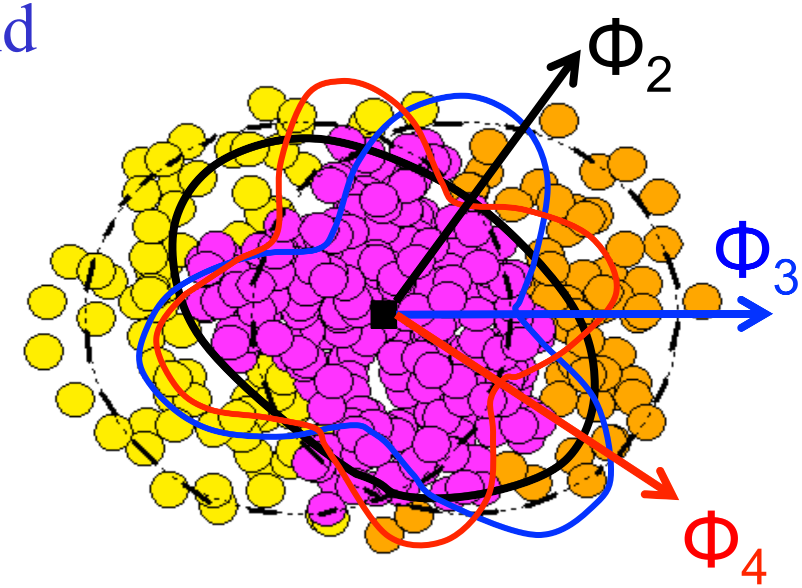
Determine resolution corrections

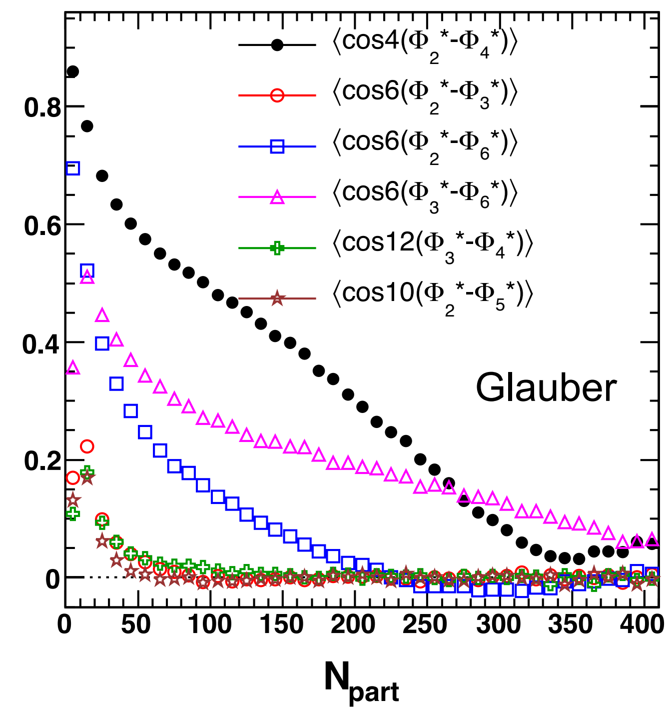
ATLAS-CONF-2012-49

Event plane correlations: p(Φ_n,Φ_m.....)

- Correlations exist in the initial geometry and are also generated during hydro evolution: non-linear mixing, e.g.

$$v_4 e^{-i4\Phi_4} = k\varepsilon_4 + v_2 v_2 e^{-i4\Phi_2} + \ldots$$





Event plane correlations: $p(\Phi_n,\Phi_m.....)$

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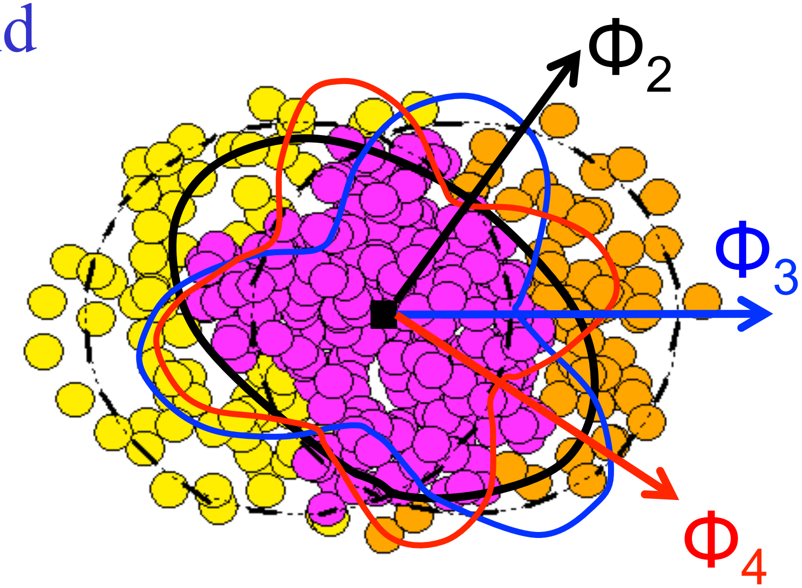


- The correlation quantified via correlators

$$\frac{dN_{events}}{d(4(\Phi_2-\Phi_4))} = 1 + 2\sum_{j=1}^{\infty} V^j \cos(4j(\Phi_2-\Phi_4))$$

$$V^j = \langle \cos(4j(\Phi_2-\Phi_4)) \rangle$$

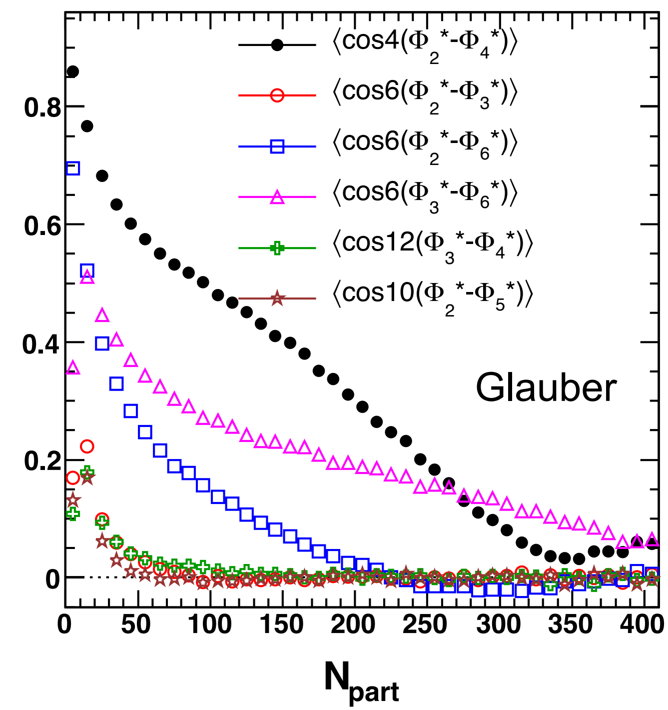
Jia, Soumya, Teany, arXiv:1205.3585 arXiv:1203.5095

- Generalize to three-plane correlations

$$2\Phi_2 + 4\Phi_4 - 6\Phi_6 \;=\; 4(\Phi_4-\Phi_2) - 6(\Phi_6-\Phi_2)$$

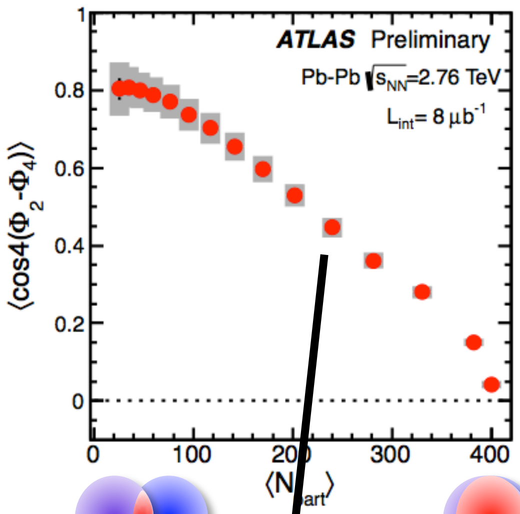
Measured correlators:

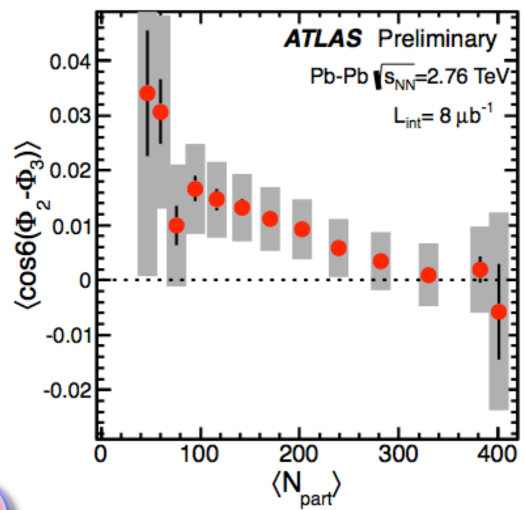
$\langle\cos 4(\Phi_2-\Phi_4)\rangle$	$\langle\cos(2\Phi_2+3\Phi_3-5\Phi_5)\rangle$
$\langle\cos 8(\Phi_2-\Phi_4)\rangle$	$\langle\cos(-8\Phi_2+3\Phi_3+5\Phi_5)\rangle$
$\langle\cos 12(\Phi_2-\Phi_4)\rangle$	$\langle\cos(2\Phi_2+4\Phi_4-6\Phi_6)\rangle$
$\langle\cos 6(\Phi_2-\Phi_3)\rangle$	$\langle\cos(-10\Phi_2+4\Phi_4+6\Phi_6)\rangle$
$\langle\cos 6(\Phi_2-\Phi_6)\rangle$	$\langle\cos(2\Phi_2-6\Phi_3+4\Phi_4)\rangle$
$\langle\cos 6(\Phi_3-\Phi_6)\rangle$	$\langle\cos(-10\Phi_2+6\Phi_3+4\Phi_4)\rangle$

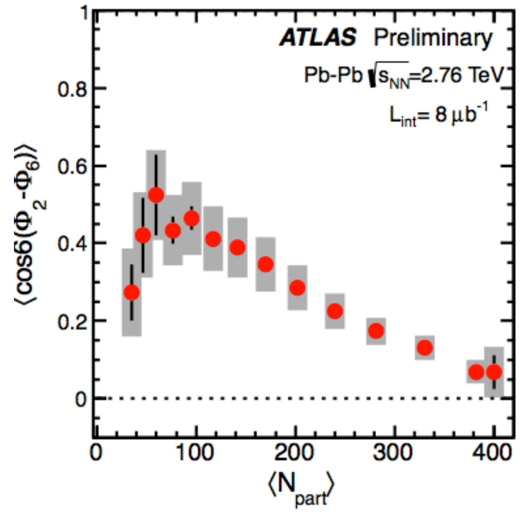


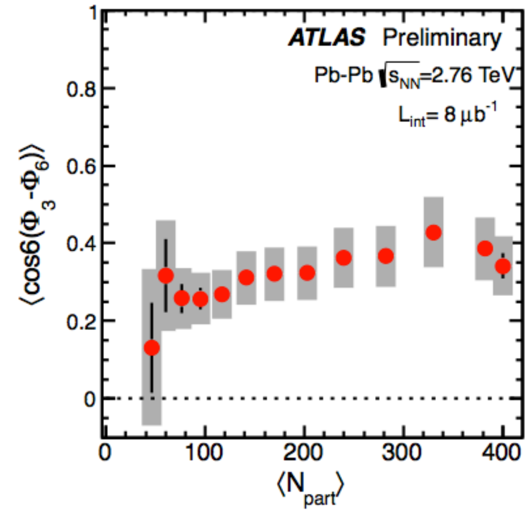
Event plane correlation results

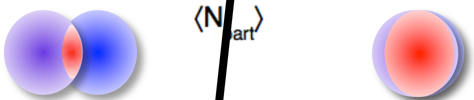
$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$ $\langle \cos 6(\Phi_2 - \Phi_3) \rangle$ $\langle \cos 6(\Phi_2 - \Phi_6) \rangle$ $\langle \cos 6(\Phi_3 - \Phi_6) \rangle$





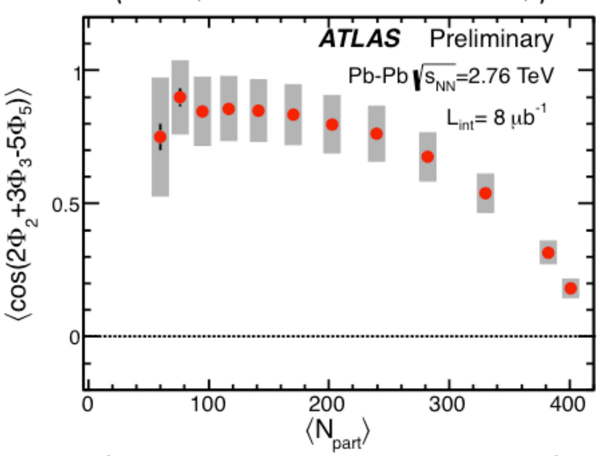






$$v_4 e^{-i4\Psi_4} = k\varepsilon_4 + v_2 v_2 e^{-i4\Psi_2} + \ldots$$

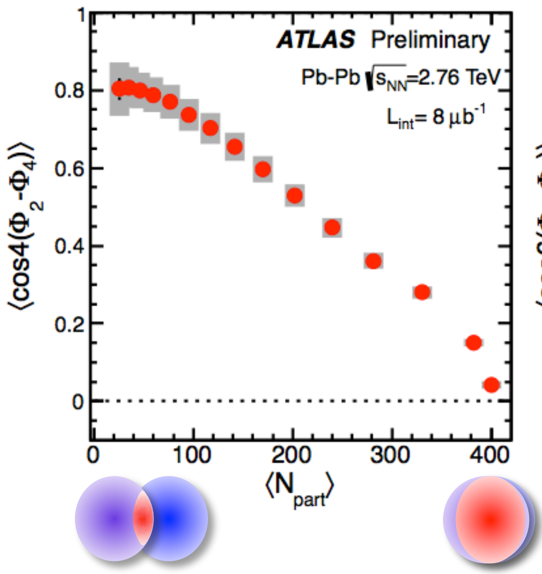
$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$



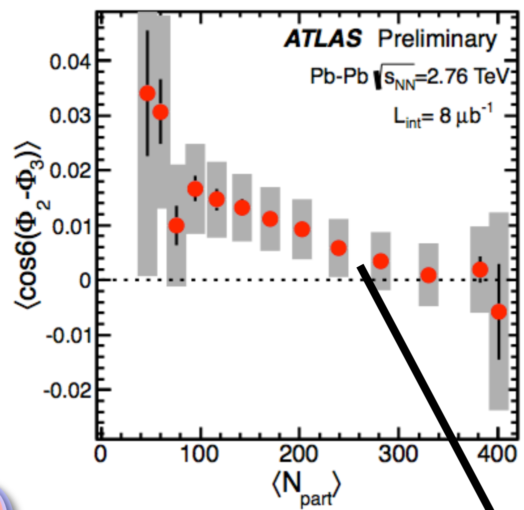
Teaney & Yan

Event plane correlation results

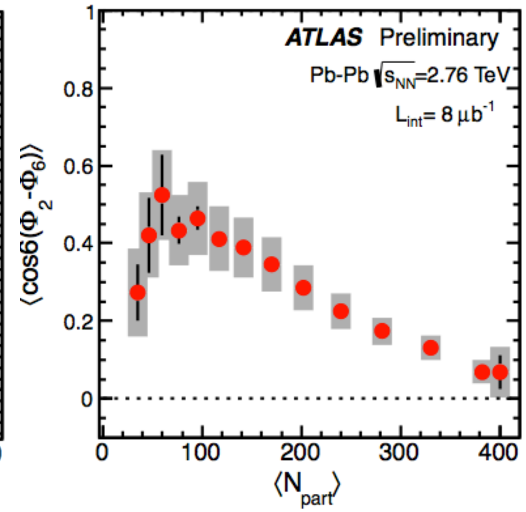
$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$



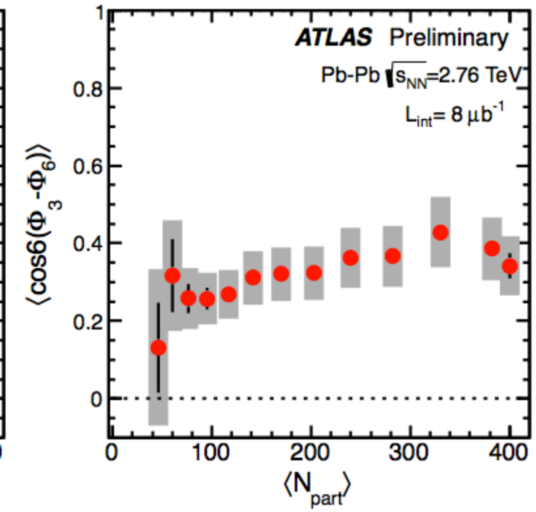
$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$



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

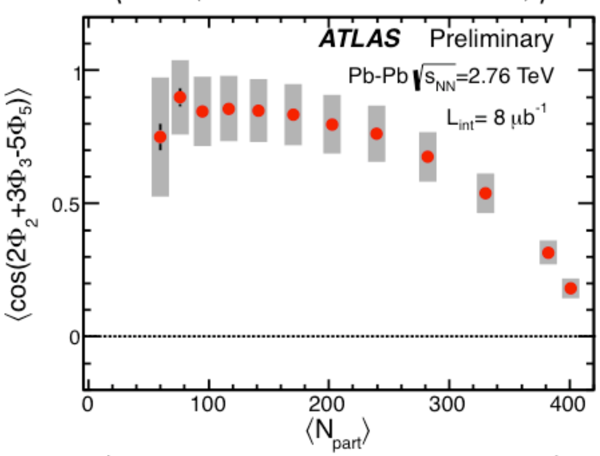


$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



$$v_2 e^{-i2\Psi_2} = k\varepsilon_2 + v_1 v_1 e^{-i2\Psi_1} + \ldots$$
$$v_3 e^{-i3\Psi_3} = k\varepsilon_3 + v_1 v_2 e^{-i(\Psi_1 + 2\Psi_2)} + \ldots$$

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



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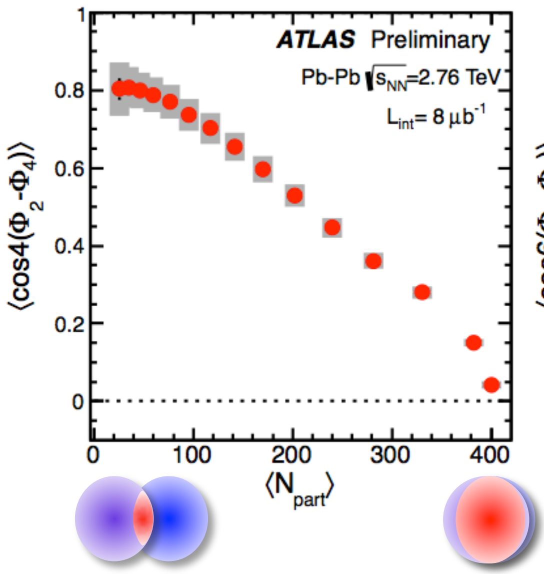
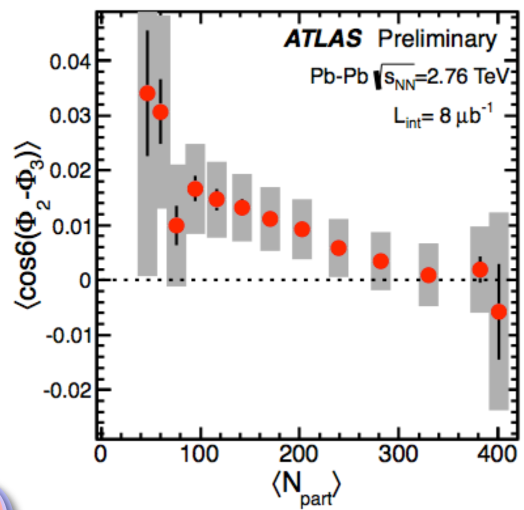
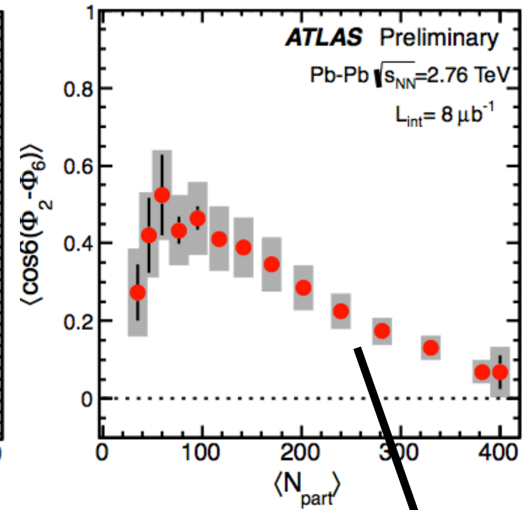


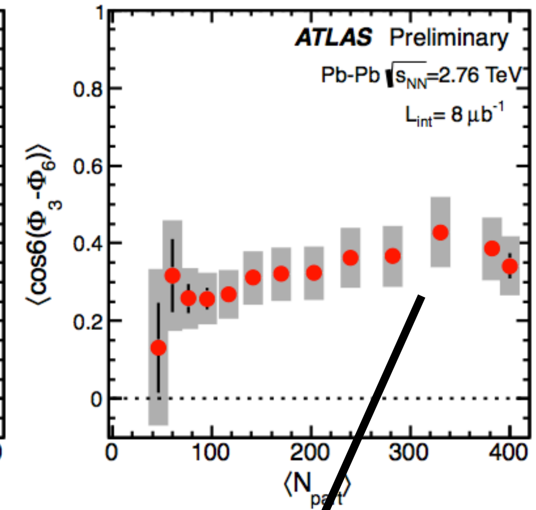
$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$



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

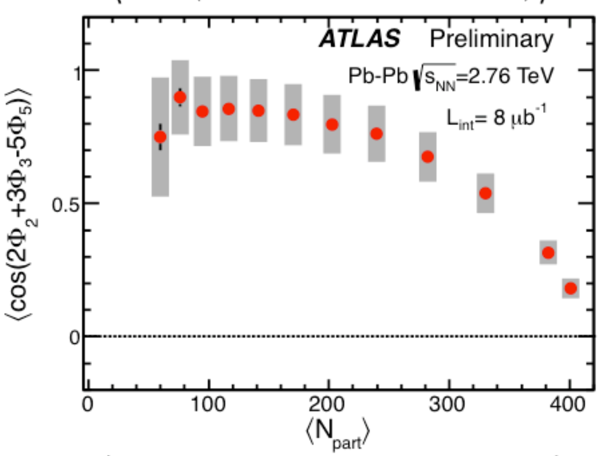


$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



$$v_6 e^{-i6\Psi_6} = k\varepsilon_6 + v_2 v_2 v_2 e^{-i6\Psi_2} + v_3 v_3 e^{-i6\Psi_3} + \ldots$$

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



Teaney & Yan

Event plane correlation results

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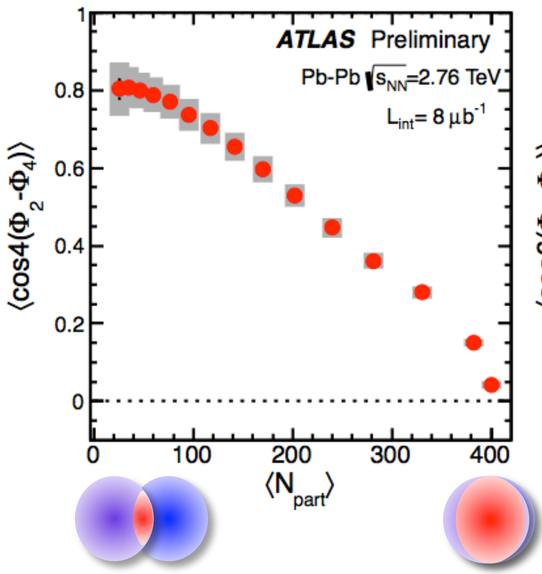
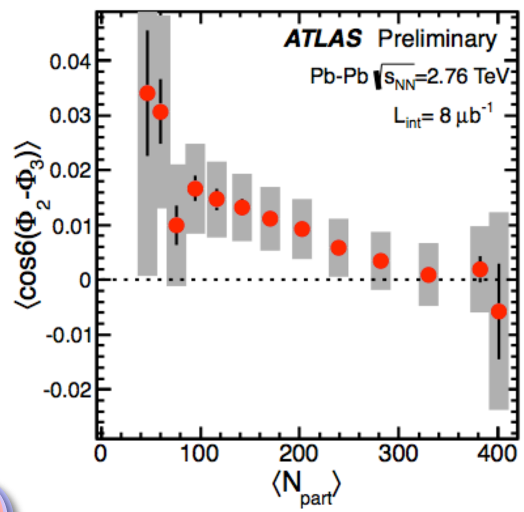


$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$



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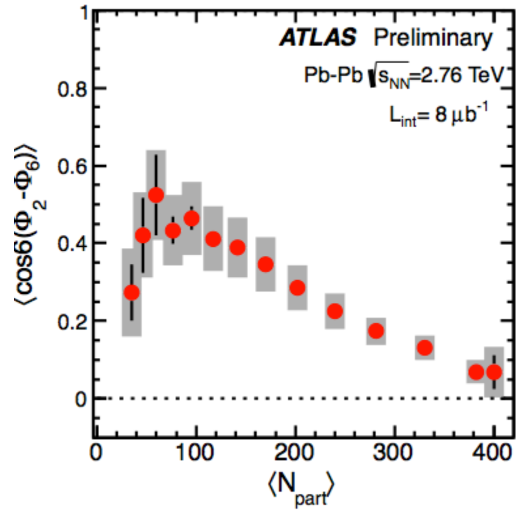
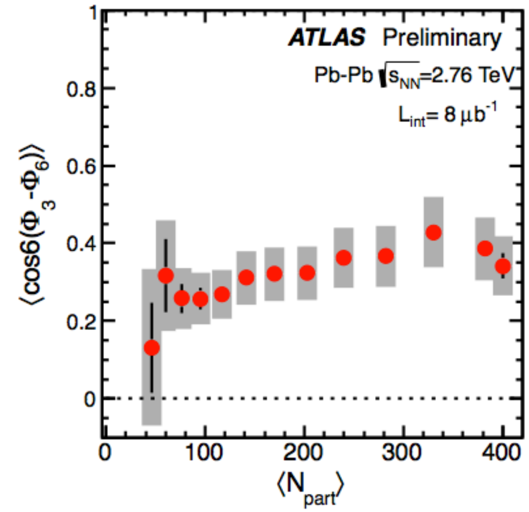
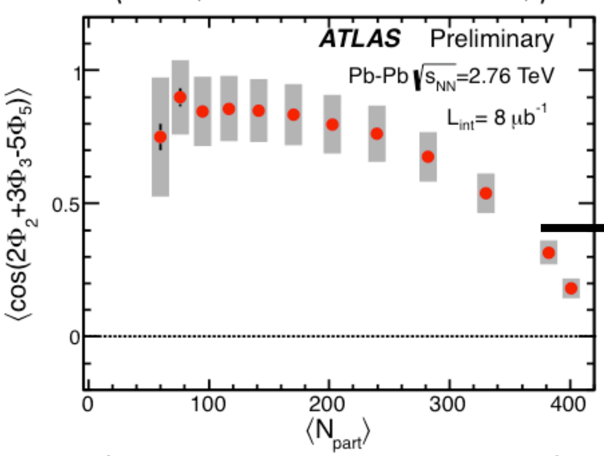


$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$



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

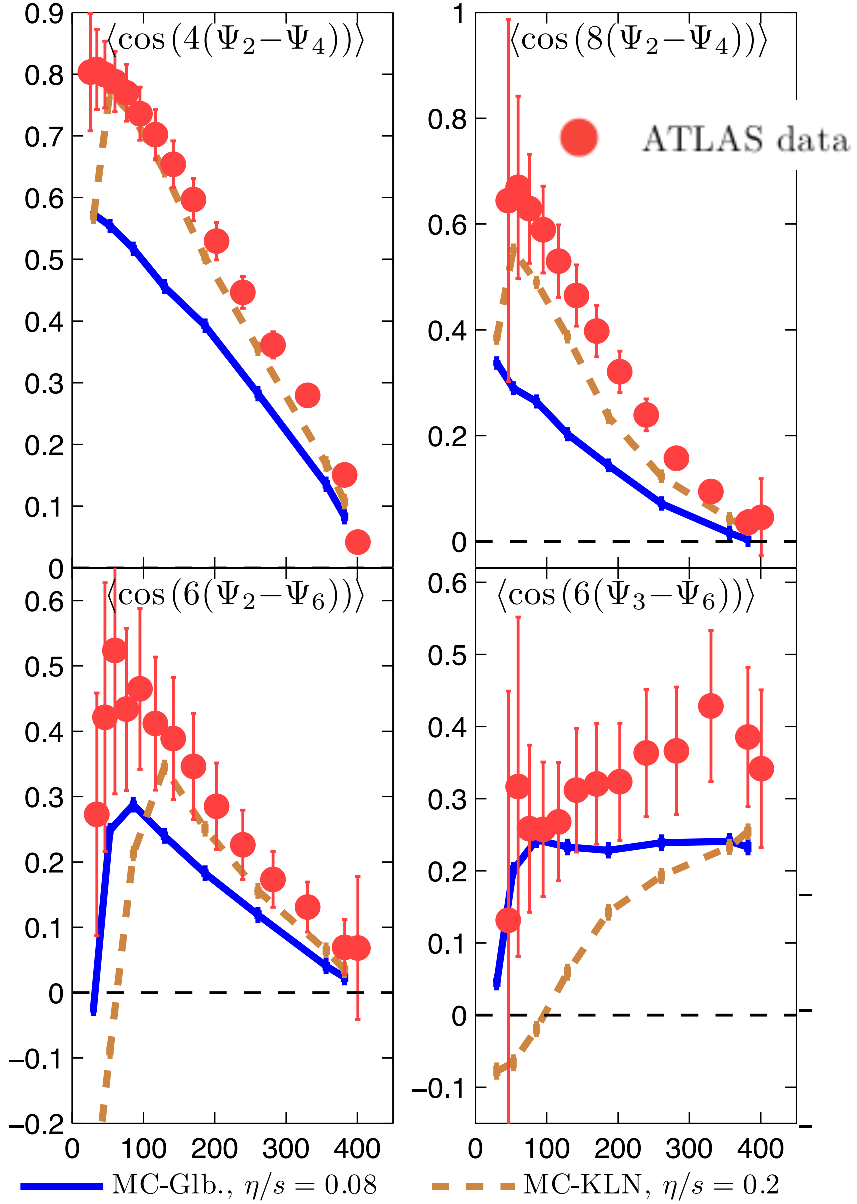


$$v_5 e^{-i5\Psi_5} = k\varepsilon_5 + v_2 v_3 e^{-i(2\Psi_2+3\Psi_3)} + \ldots$$

Teaney & Yan

Compare with EbE hydro calculation

Initial geometry + hydrodynamic Zhe & Heinz 1208.1200



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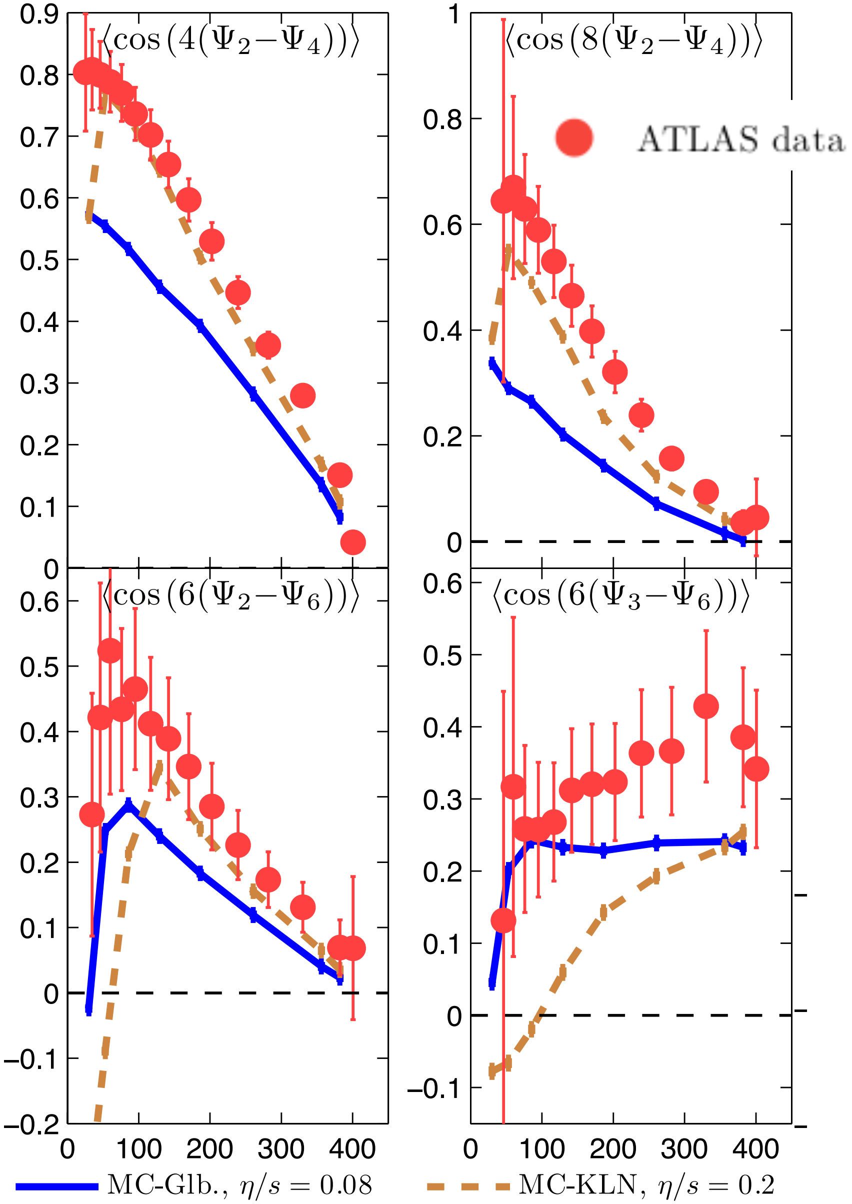
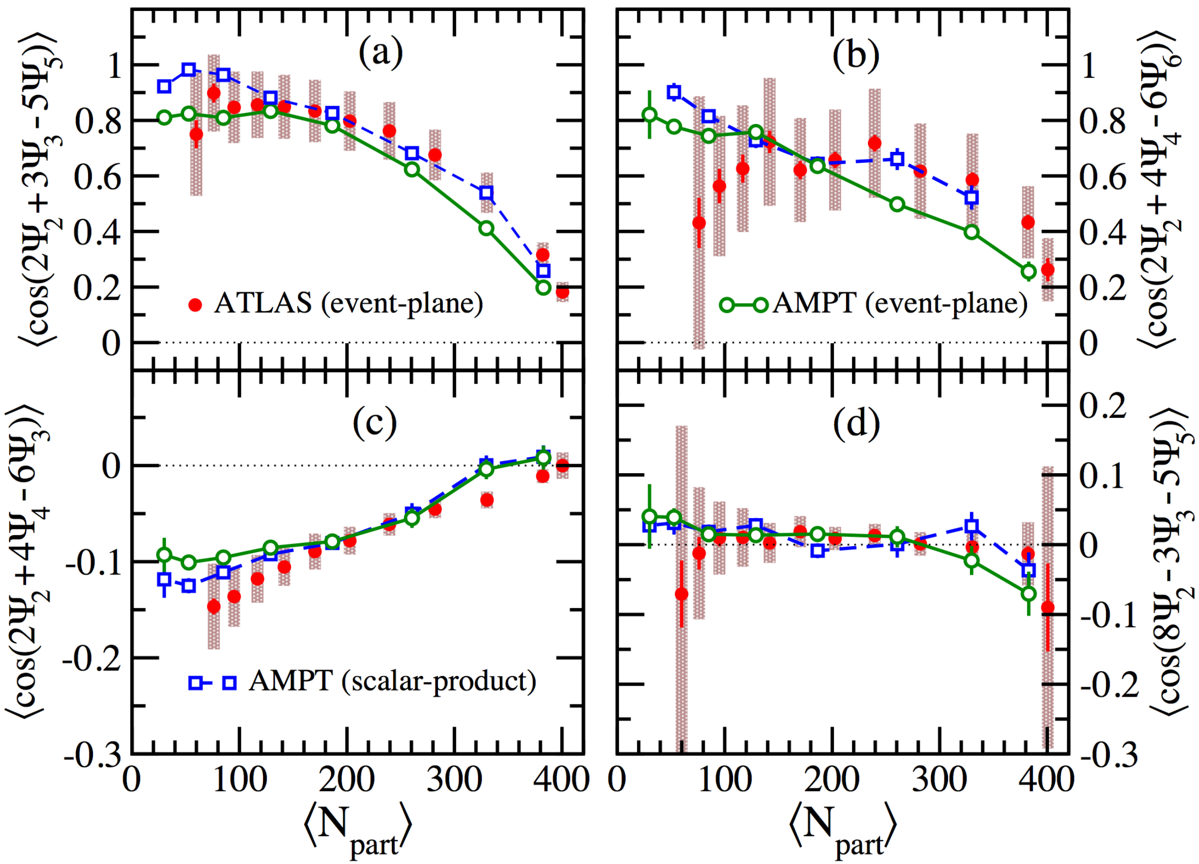
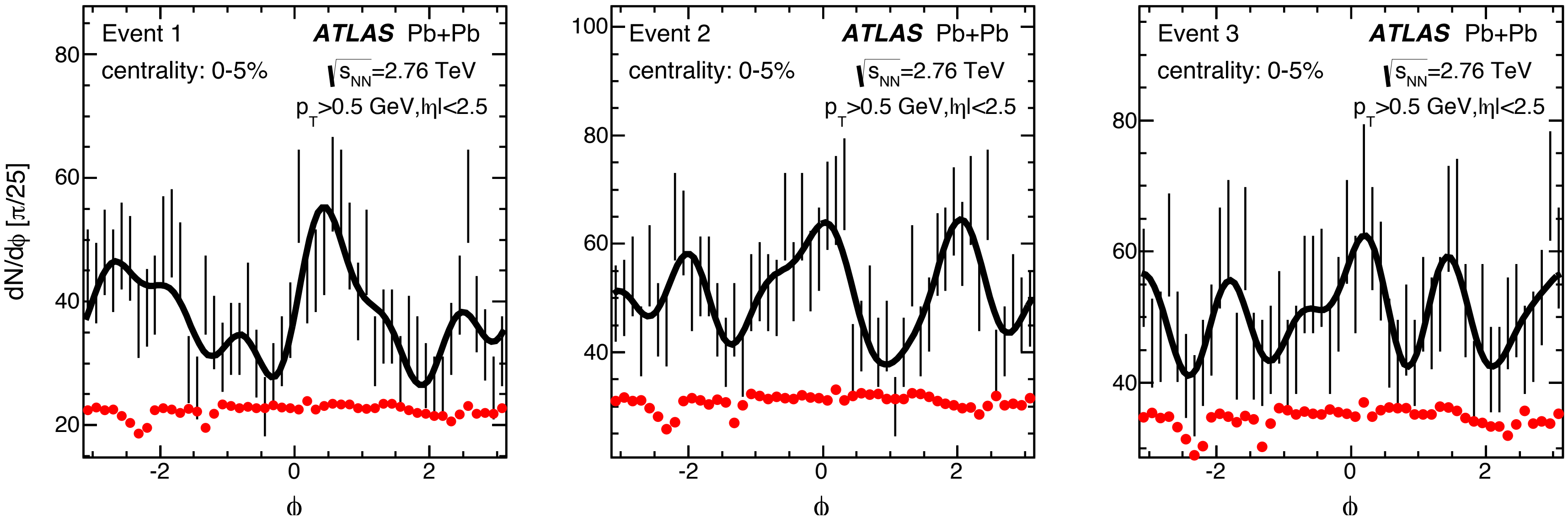


Initial geometry + transport 1307.0980 Bhalerao,et.al.



EbyE hydro and transport models reproduce features in the data

Measuring the p(v_n) distributions

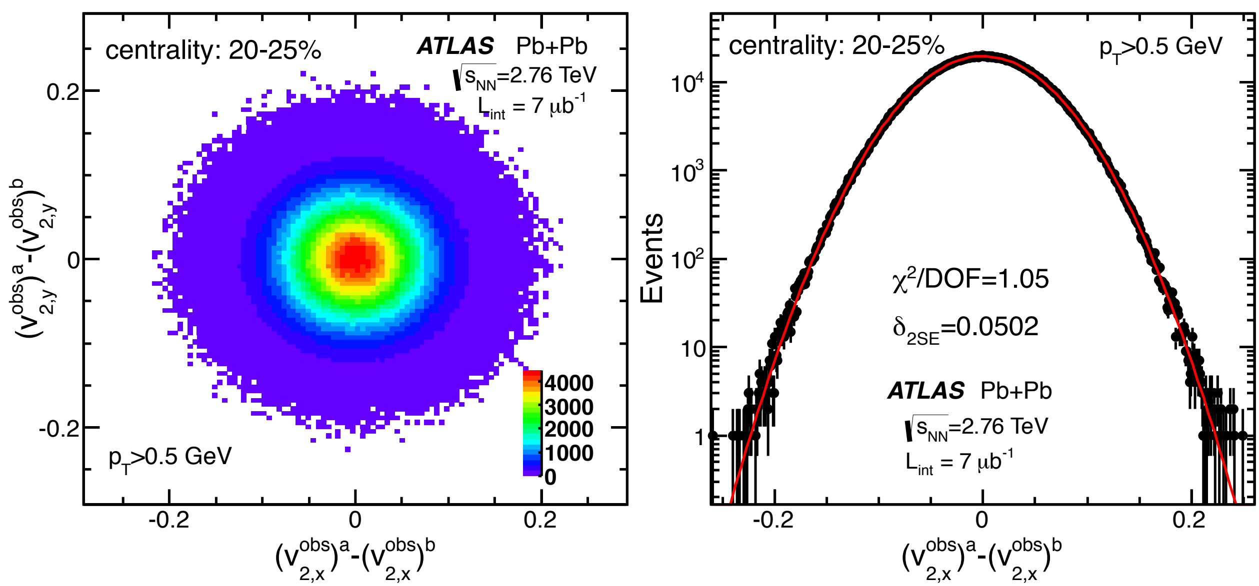


ATLAS
1305.2942

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n^{obs} \cos n\left(\phi - \Phi_n^{obs}\right)$$

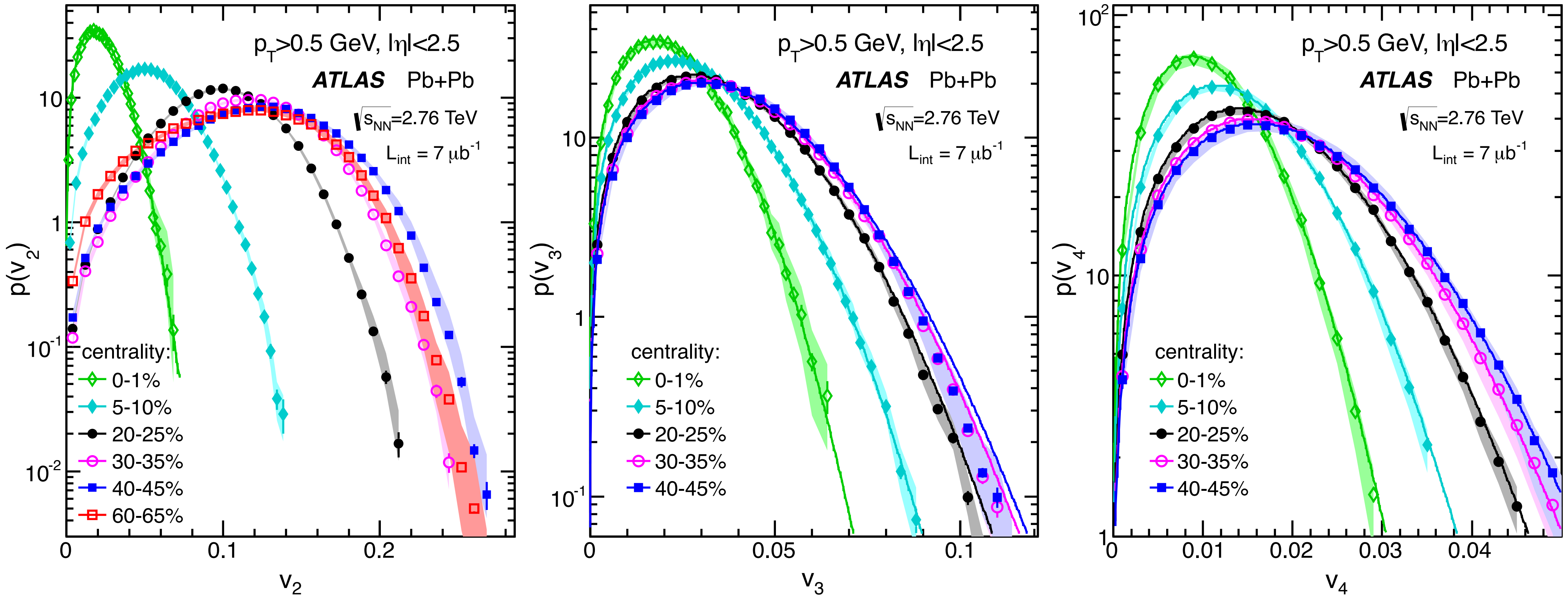
Decompose the φ distributions in each event

Finite number & nonflow effects require unfolding (e.g. Bayesian) to recover original distribution



Confirmed in simulation studies arxiv:1304.1471, J.Jia and S. Mohapatra

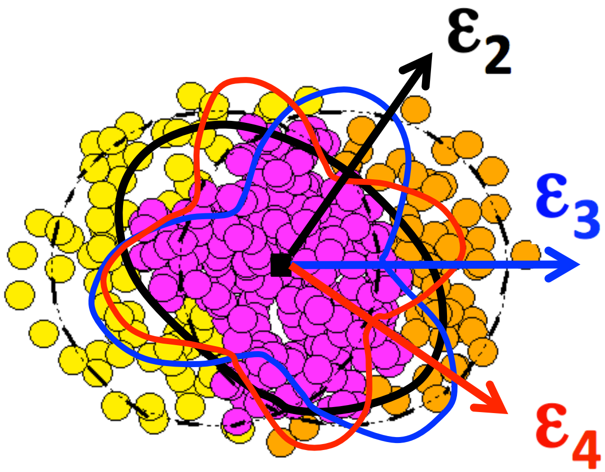
$p(v_n)$ distributions



Probability distribution for v_2, v_3 and v_4 in many centrality ranges

ATLAS 1305.2942 Submitted to JHEP

Expectation for v_n fluctuations



$$\vec{\varepsilon}_n = \left(\frac{\left\langle r^n \cos(n\phi) \right\rangle}{\left\langle r^n \right\rangle}, \frac{\left\langle r^n \sin(n\phi) \right\rangle}{\left\langle r^n \right\rangle} \right)$$

arXiV: 0708.0800, 0809.2949

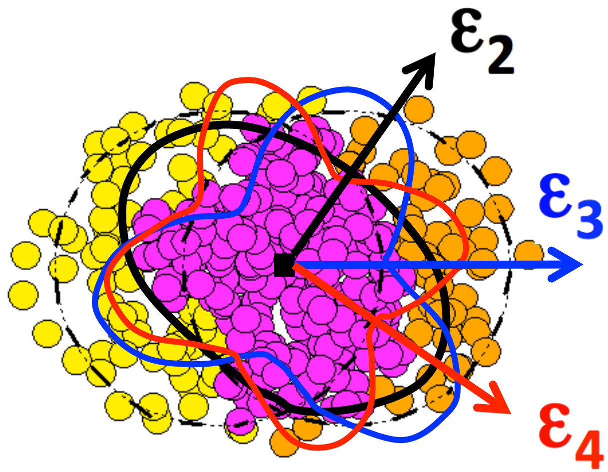
$$\vec{\varepsilon}_n = \vec{\varepsilon}_n^{\,RP} + \vec{\Delta}_n^{\,fluc}$$

$$p(\vec{\varepsilon}_n) \propto \exp\left(\frac{-(\vec{\varepsilon}_n - \vec{\varepsilon}_n^{\,RP})^2}{2\delta_{\varepsilon_n}^2} \right)$$

$$\vec{\varepsilon}_n^{\,RP} \rightarrow Mean\,Geometry$$

$$\delta_{\varepsilon_n} \rightarrow Fluctuations$$

Expectation for v_n fluctuations



$$\vec{\varepsilon}_n = \left(\frac{\langle r^n \cos(n\phi) \rangle}{\langle r^n \rangle}, \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \rangle} \right)$$

arXiV: 0708.0800, 0809.2949

$$\vec{v}_n = (v_n \cos n\Phi_n, v_n \sin n\Phi_n)$$

$$\vec{\varepsilon}_n = \vec{\varepsilon}_n^{RP} + \vec{\Delta}_n^{fluc}$$

$$\vec{v}_n = \vec{v}_n^{RP} + \vec{p}_n^{fluc}$$

$$p(\vec{\varepsilon}_n) \propto \exp\left(\frac{-(\vec{\varepsilon}_n - \vec{\varepsilon}_n^{RP})^2}{2\delta_{\varepsilon_n}^2} \right)$$

$$\vec{v}_n \propto \vec{\varepsilon}_n$$

$$p(\vec{v}_n) \propto \exp\left(\frac{-(\vec{v}_n - \vec{v}_n^{RP})^2}{2\delta_n^2} \right)$$

$\vec{\varepsilon}_n^{RP} \rightarrow Mean\,Geometry$

$\delta_{\varepsilon_n} \rightarrow Fluctuations$

$\vec{v}_n^{RP} \rightarrow Mean\,Geometry$

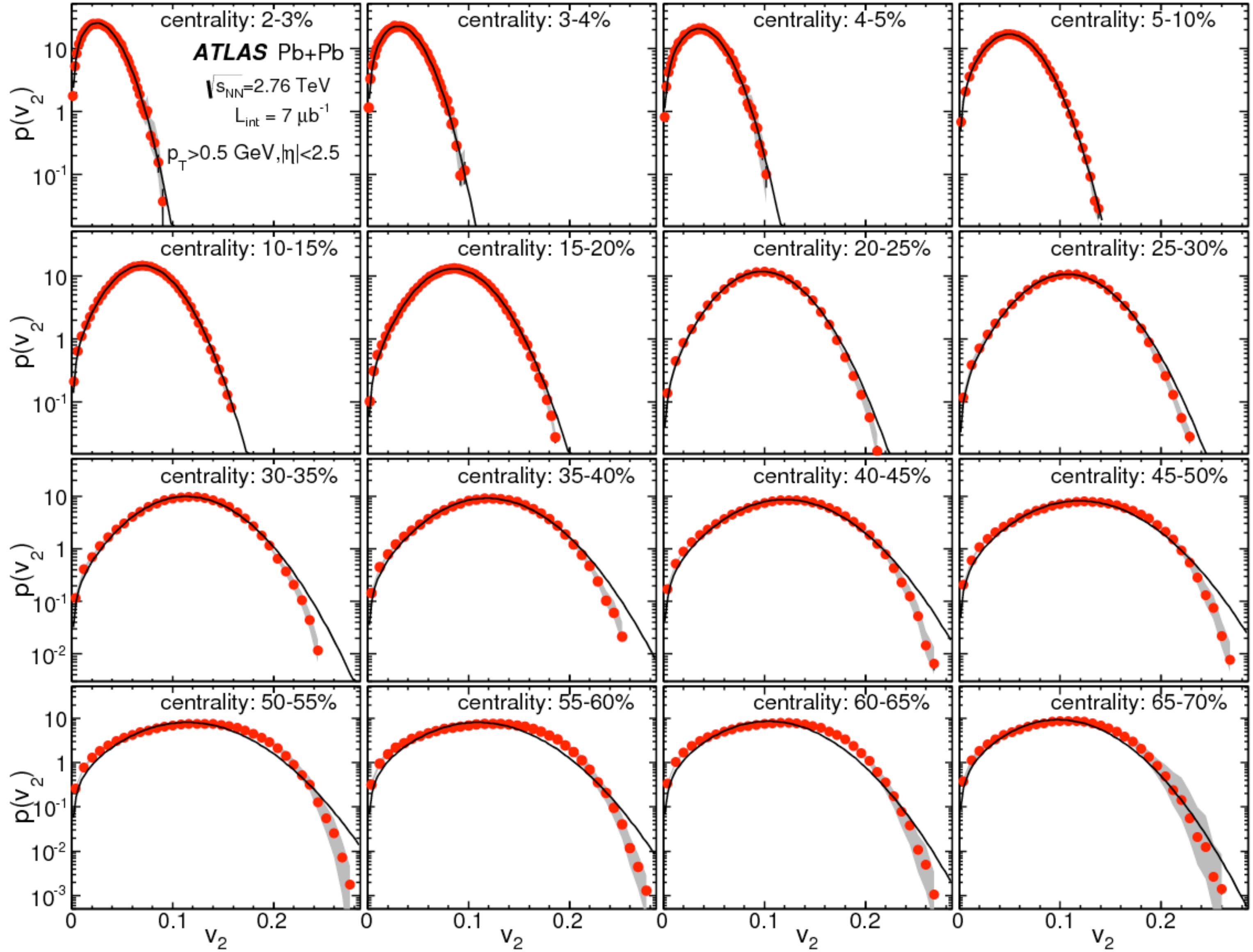
$\delta_n \rightarrow Fluctuations$

$$p(v_n) \propto v_n \exp\left(\frac{-(v_n^2 + (v_n^{RP})^2}{2\delta_n^2} \right) I_0\left(\frac{v_n v_n^{RP}}{\delta_n^2}\right)$$

Are flow fluctuations Gaussian?

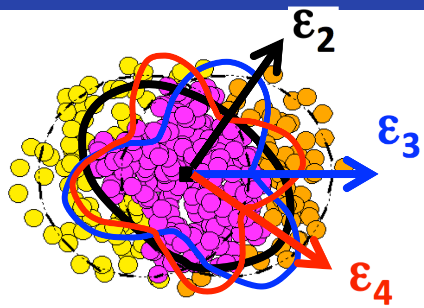
$$p(\vec{v}_2) \propto \exp\left(\frac{-(\vec{v}_2 - \vec{v}_2^{RP})^2}{2\delta^2}\right) \longrightarrow p(v_2) \propto v_2 \exp\left(\frac{-(v_2^2 + (v_2^{RP})^2}{2\delta^2}\right) I_0\left(\frac{v_2 v_2^{RP}}{\delta^2}\right)$$

First indication of non-Gaussian behavior



ATLAS 1305.2942

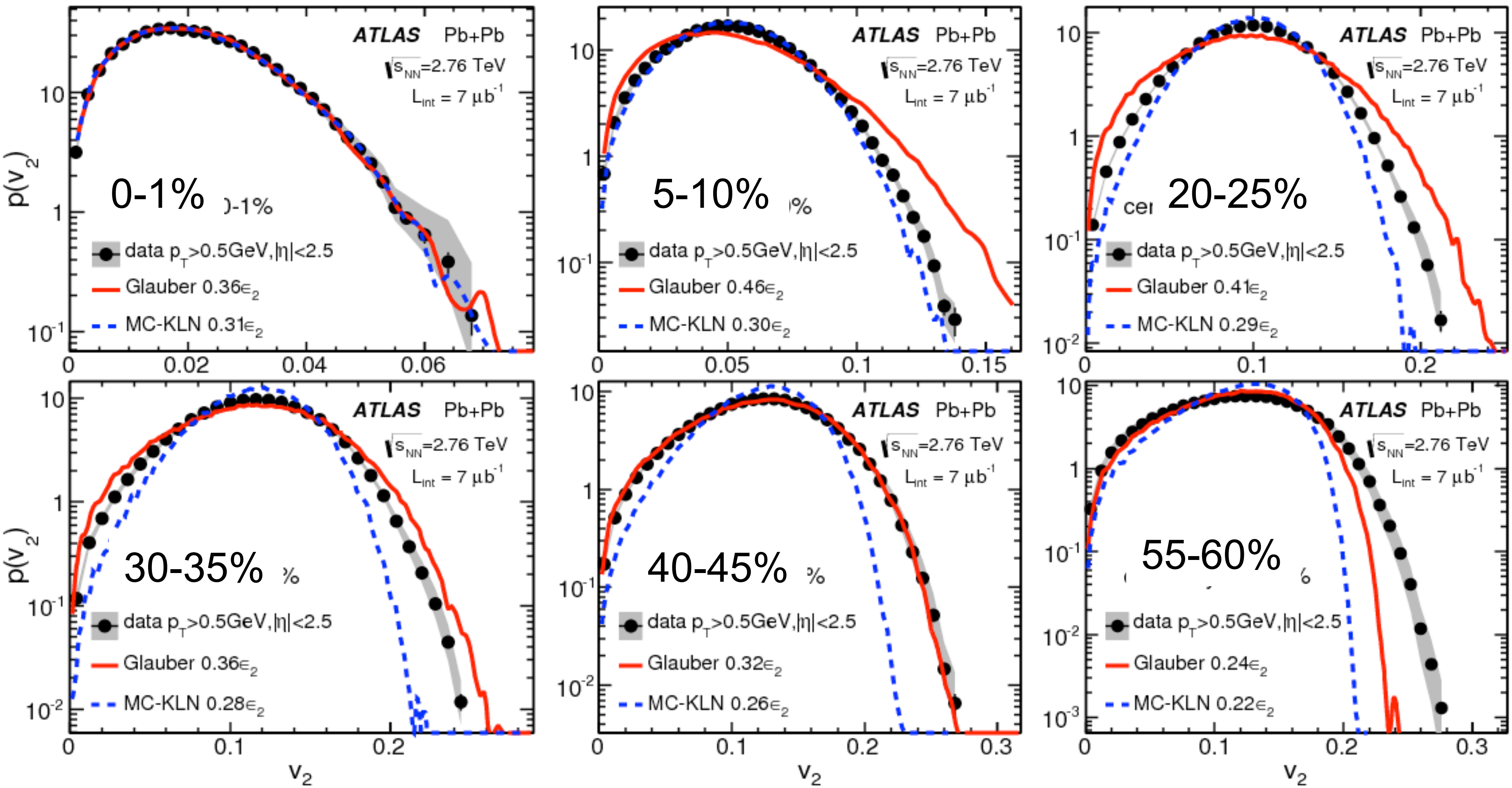
Measuring the hydrodynamic response



$$v_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi\rangle^2 + \langle r^n \sin n\phi\rangle^2}}{\langle r^n\rangle}$$

Glauber and CGC mc-kln

ε_2 distribution is rescaled so $<\varepsilon_2> = <v_2>$



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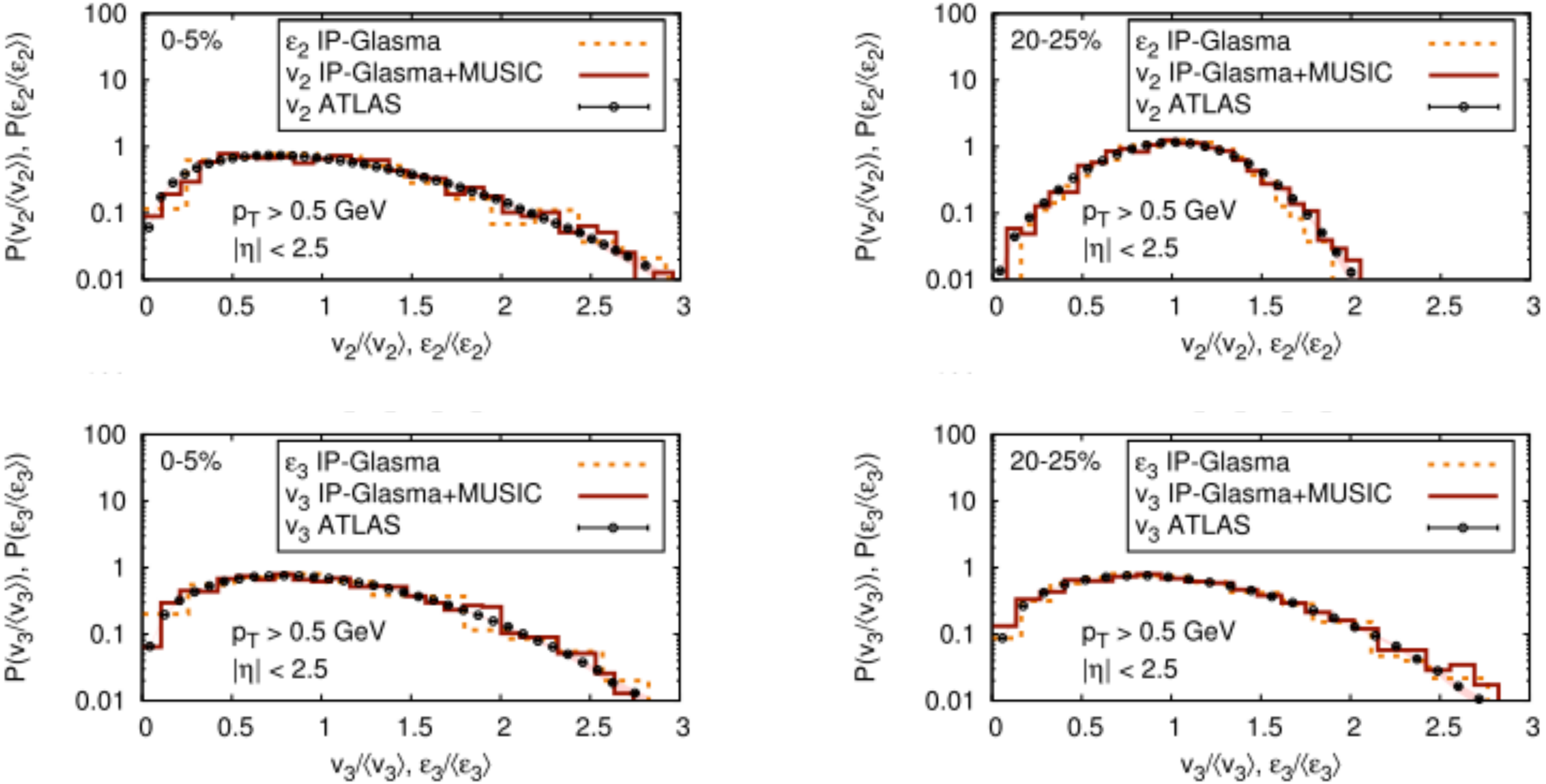
Models need to map p(ε_2) to p(v_2)

Comparison to IP-Glasma model

arXiv:1301.5893 B. Schenke et.al.

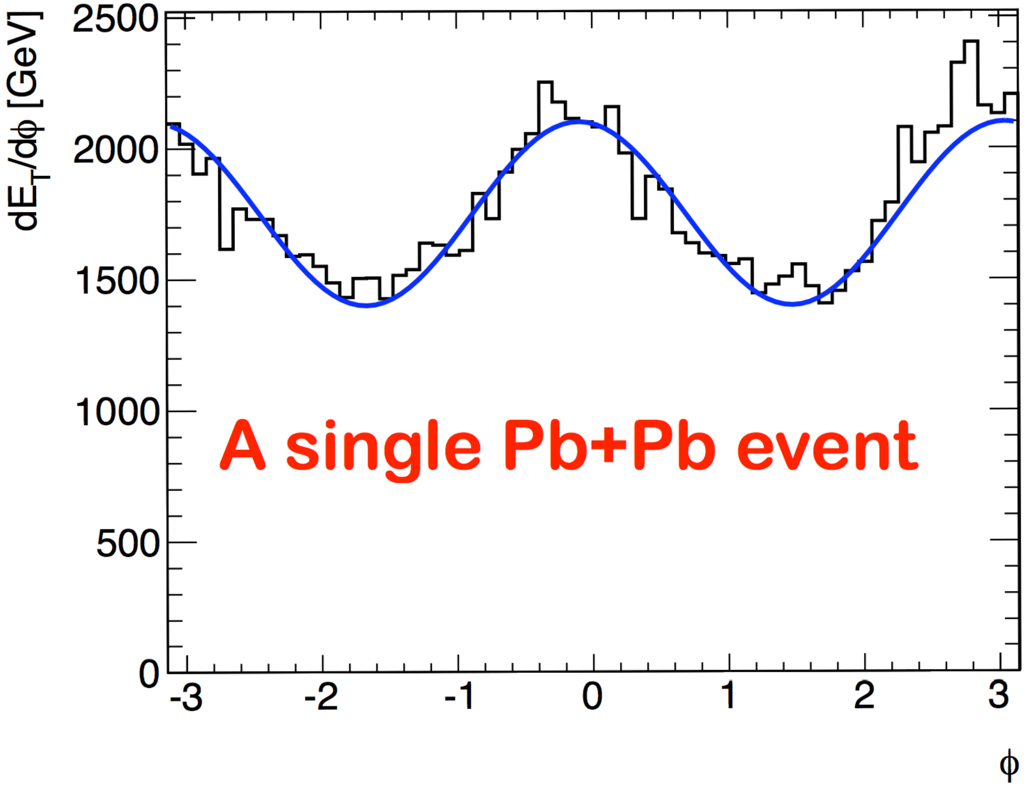


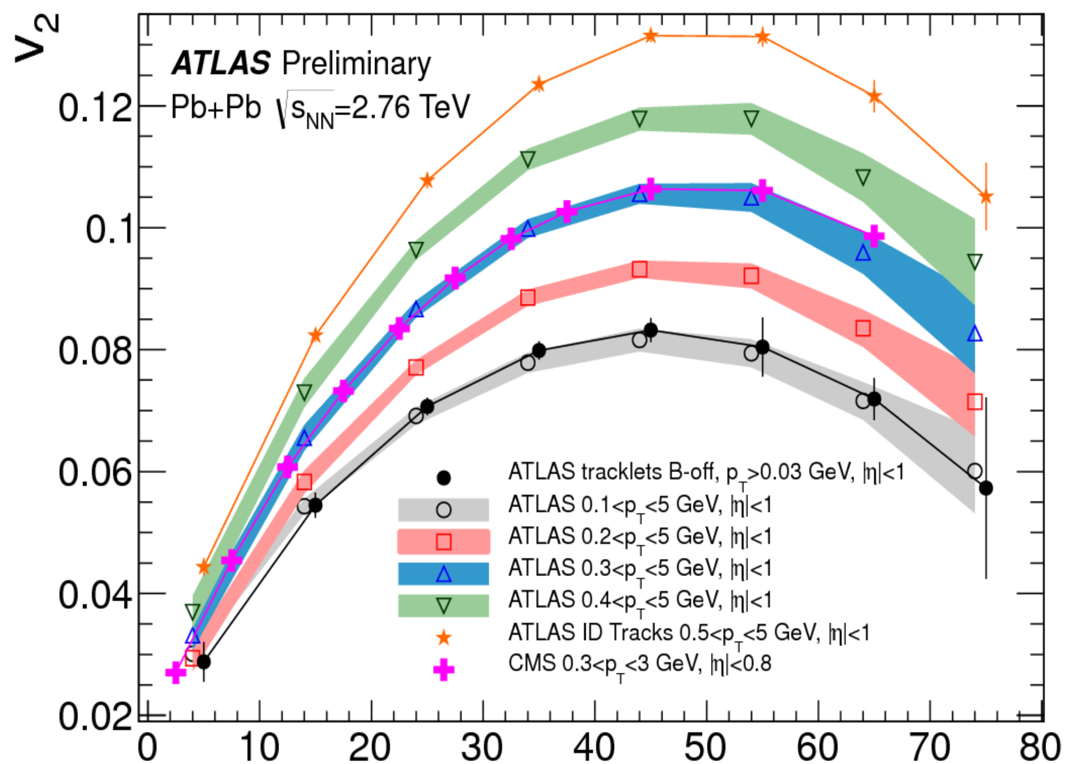
- Model calculation shows good consistency
- But more statistics in theory calculation are needed

Summary

- Detailed differential measurement of $v_n(p_T,\eta,\text{centrality})$ for n=2-6
  - Detailed constraints on geometry models and η/s
- Event-by-event fluctuation of the QGP and its evolution can be accessed via $p(v_n,v_m,\ldots,\Phi_n,\Phi_m\ldots)$
  - First measurements of 2- and 3- event plane correlations: $p(\Phi_n,\Phi_m)$ and $p(\Phi_n,\Phi_m,\Phi_L)$.
  - First measurements of the $p(v_2)$, $p(v_3)$ and $p(v_4)$.
  - Strong non-linear effects in the hydrodynamic response to initial geometry fluctuations.

Event anisotropy is large



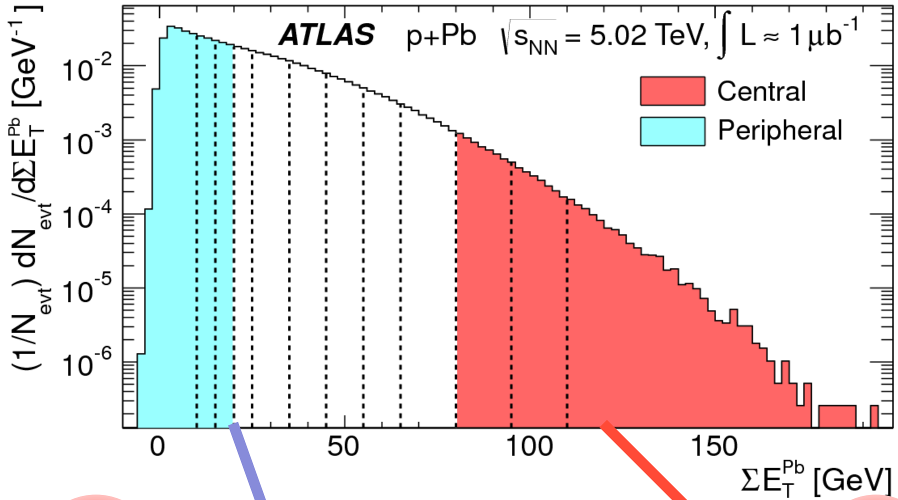


$$\frac{dN}{d\phi} = N_0\left[1+2\sum_n \mathrm{v}_\mathrm{n} \cos n\left(\phi-\Phi_n\right)\right]$$

- Large energy modulation, N_0v_2, on the order of hundreds of GeV.

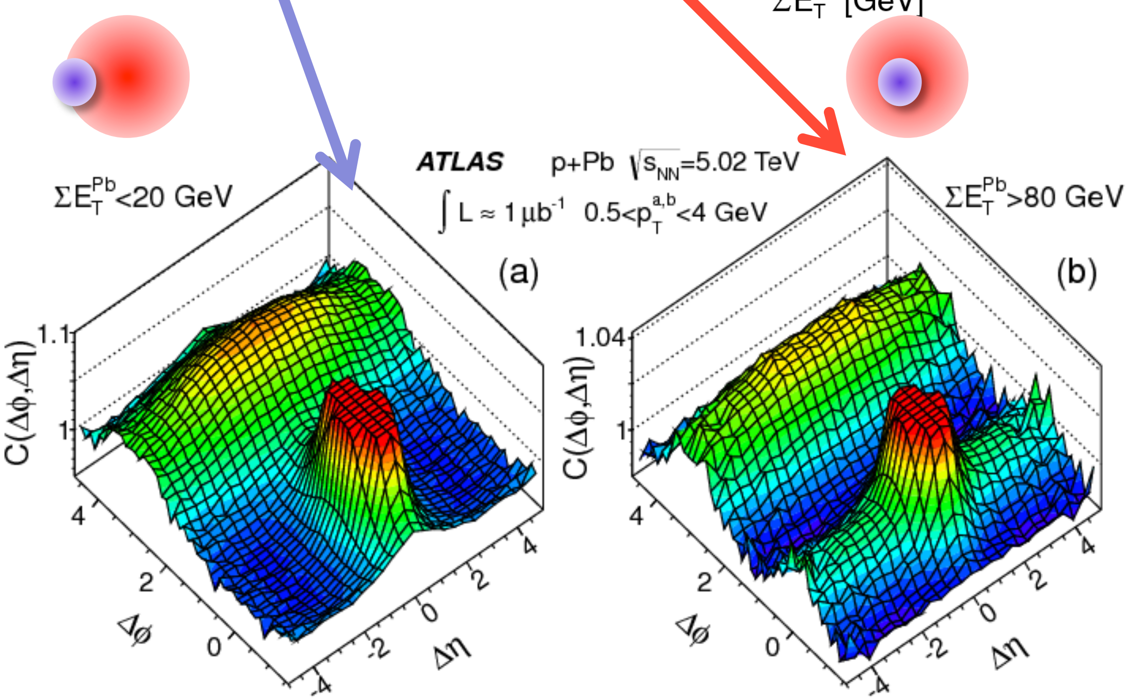
  $N_0v_2 \gg \sqrt{N_0}$ statistical fluctuations or $v_2 \gg 1/\sqrt{N_0}$
- The concept of collective flow and global event direction Φ_n, are valid.

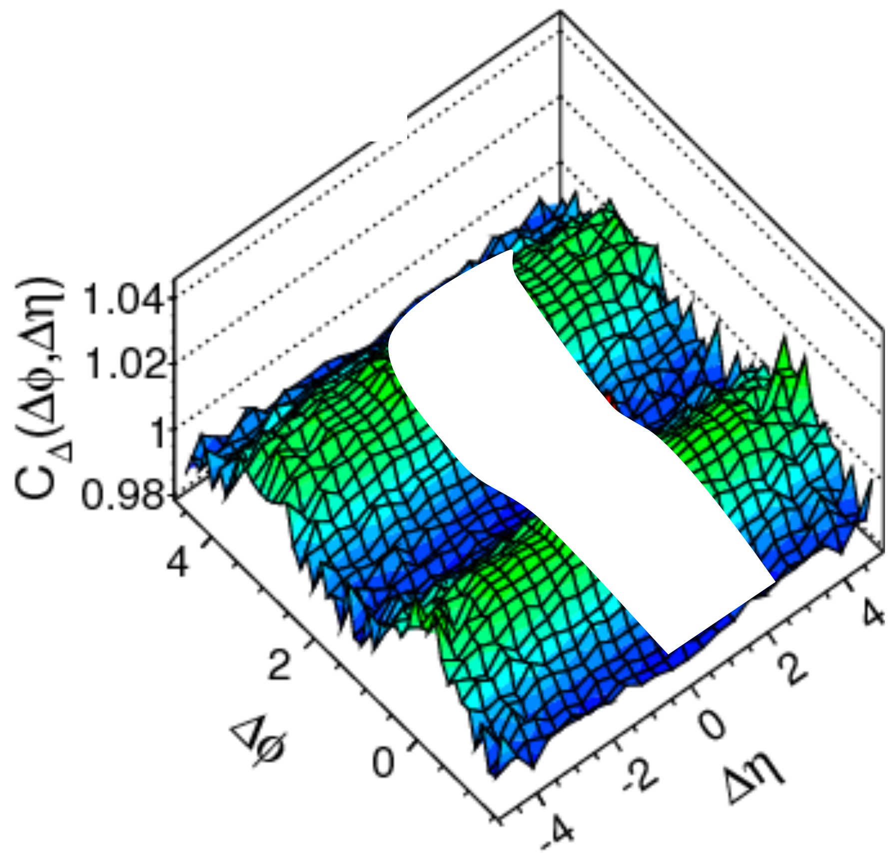
Double ridge in p+Pb collisions



Influence of away-side jet estimated from low multiplicity events

Discovery of the double-ridge in high multiplicity p+Pb

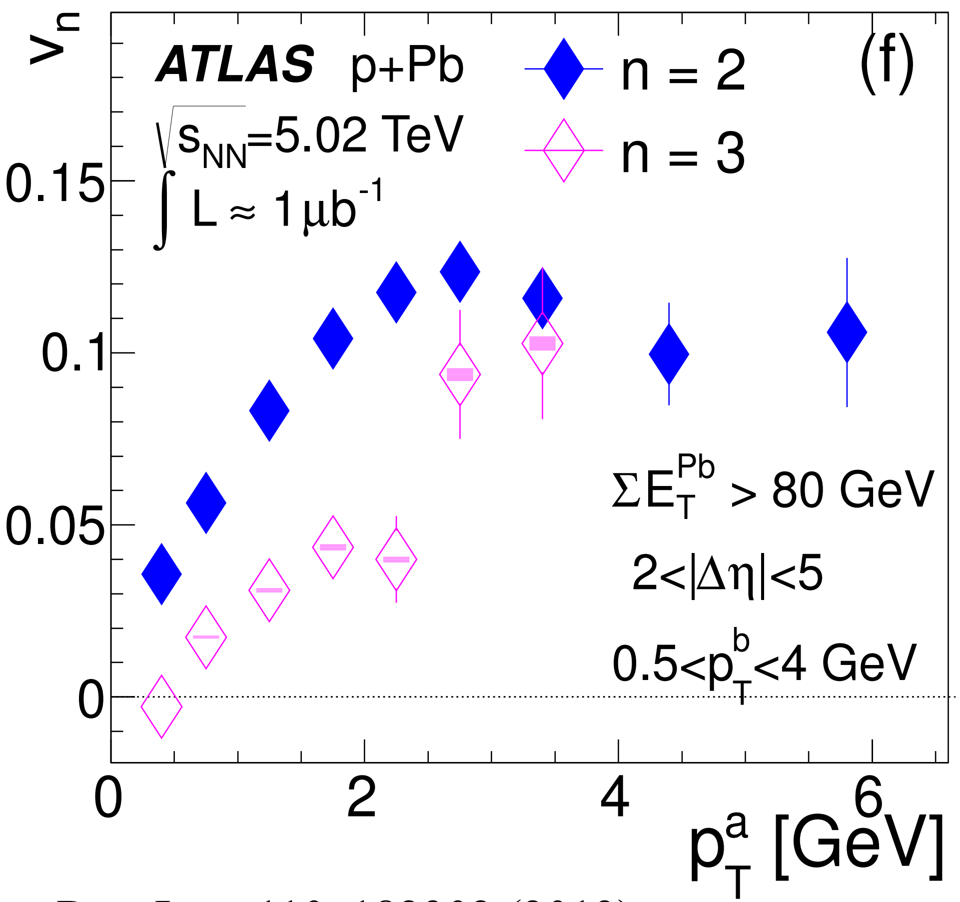




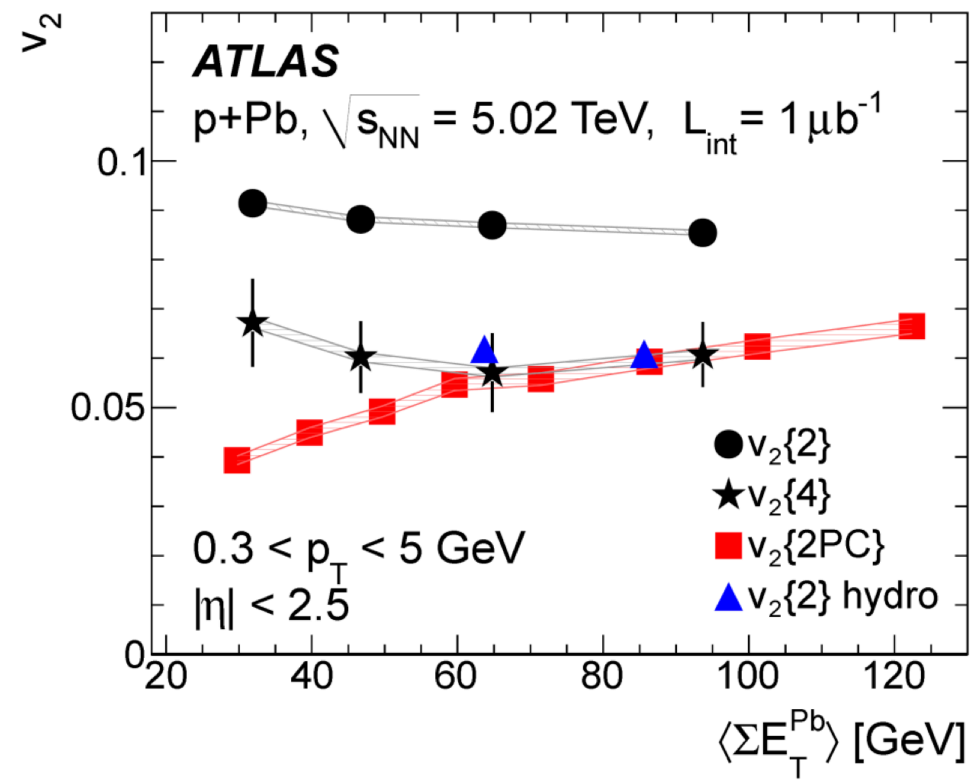
Phys. Rev. Lett. 110, 182302 (2013)

v_2 and v_3 from p+Pb

- Significant v_2 and v_3, comparable to Pb+Pb collisions.
- Significant $v_2\{4\} \approx 0.06$ suggest large collective motion.
- v_2 values compatible with hydrodynamics (also CGC)
  - But v_3 , $v_2\{4\}$, and PID v_2 (ALICE) challenging for CGC.



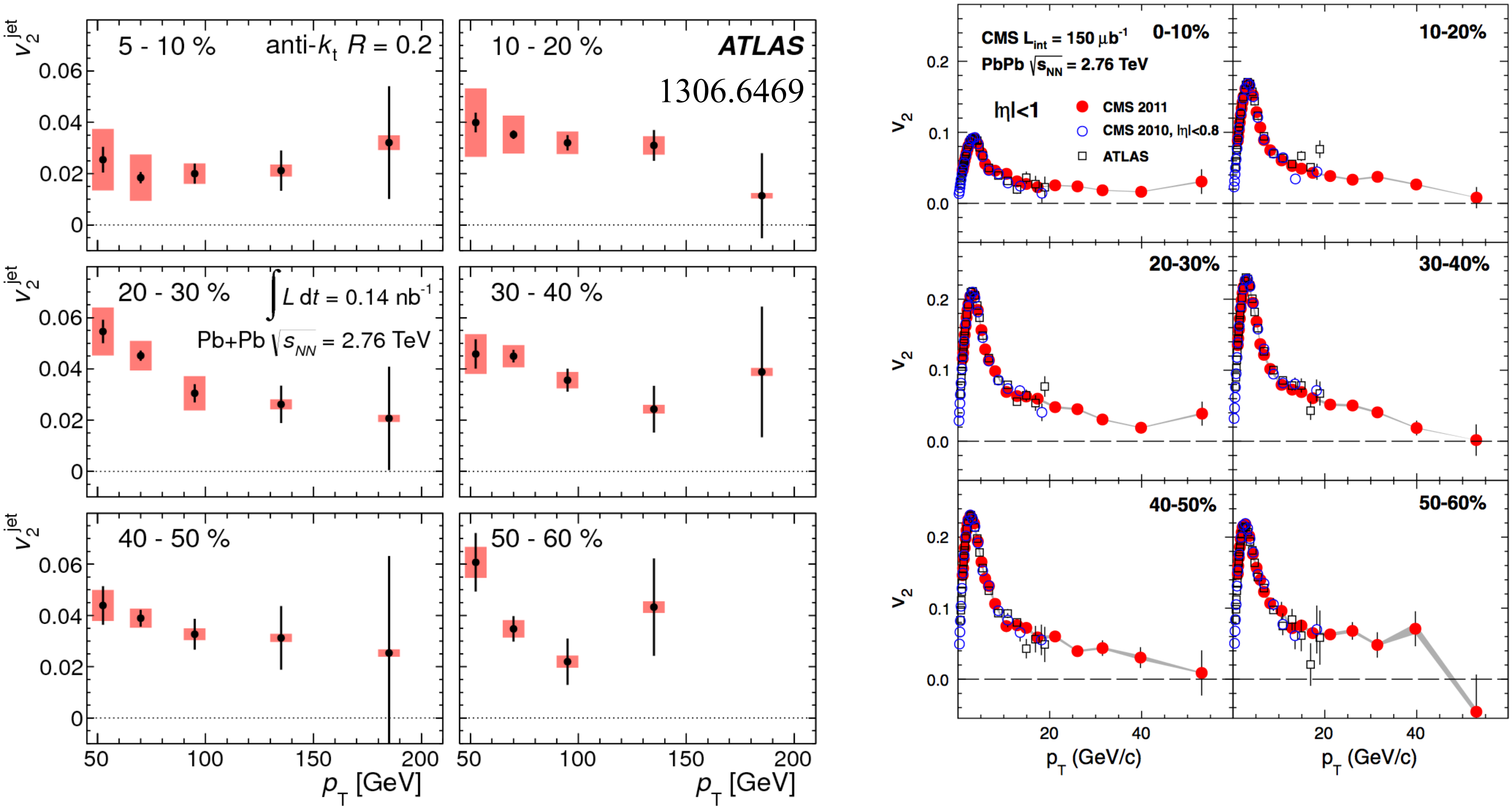
Phys. Rev. Lett. 110, 182302 (2013)



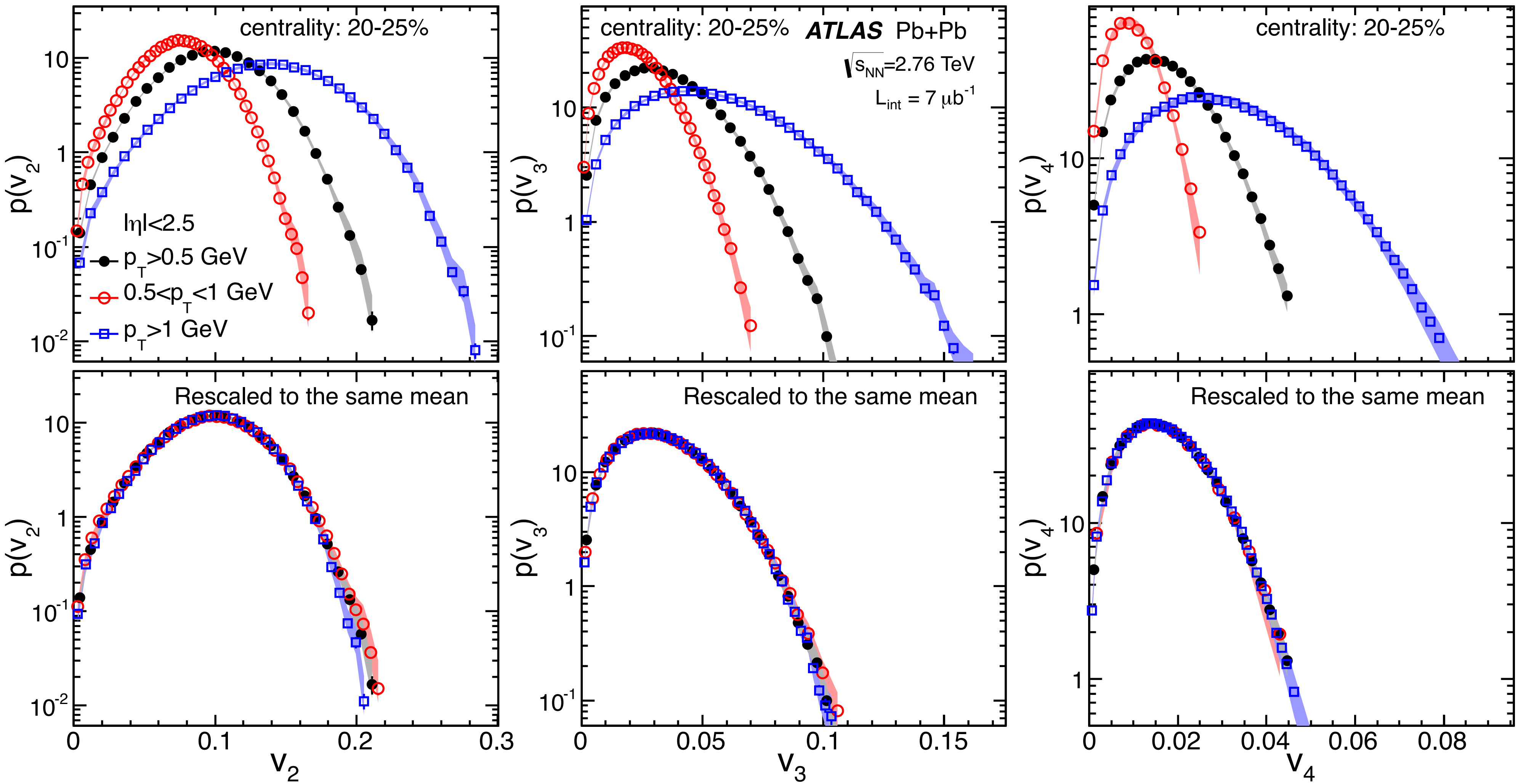
Phys. Lett. B725, 60 (2013)

Jet tomography

- Significant jet v_2 over 50-200 GeV, clearly sensitive to Path length
  - Comparable to charged hadron v_2 at high p_T
- Better constraint on $\Delta E(L)$?



All p_T respond: same shape



Low and high p_T appear different, but coincide when rescaled to same $\langle v_n \rangle$

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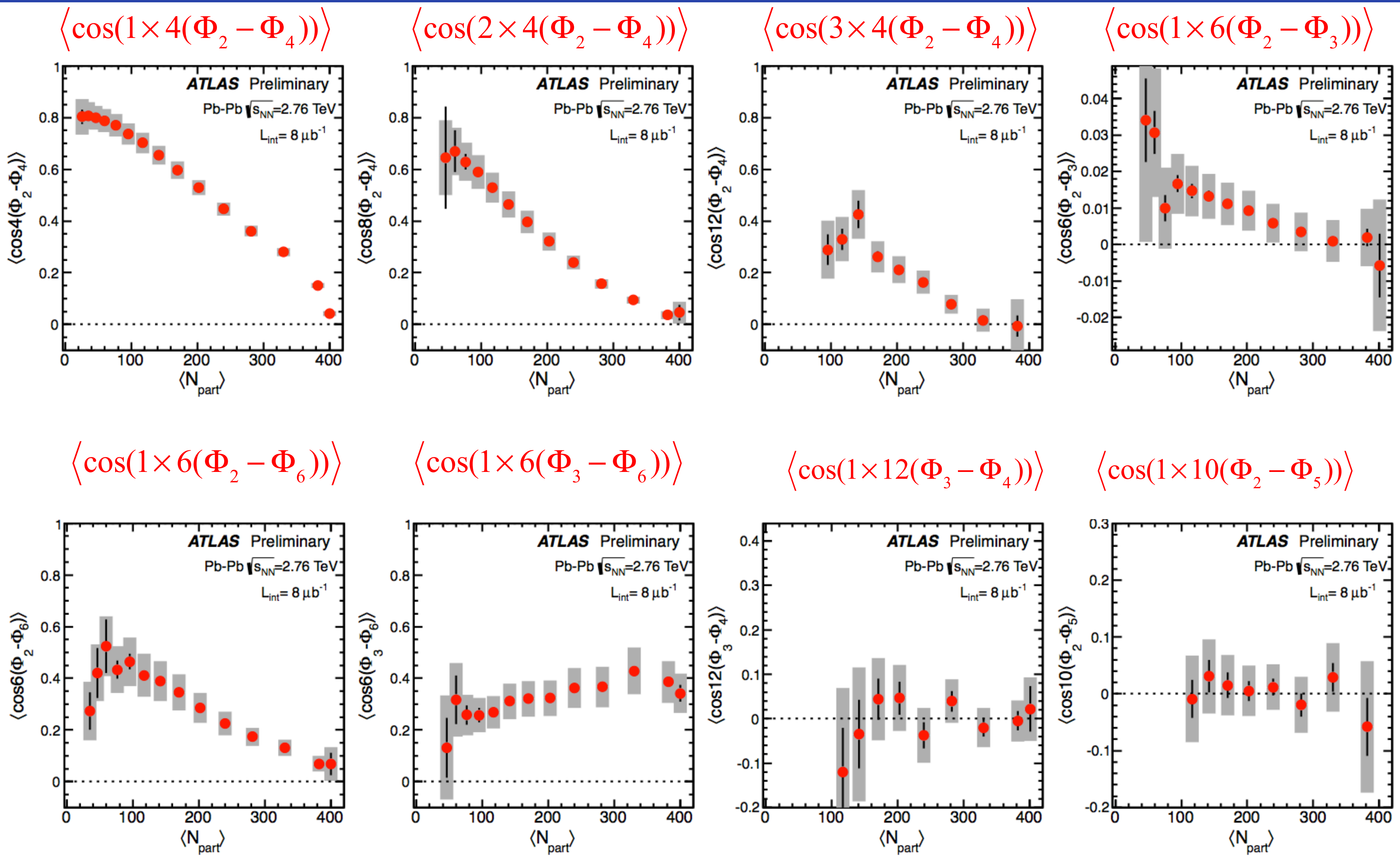
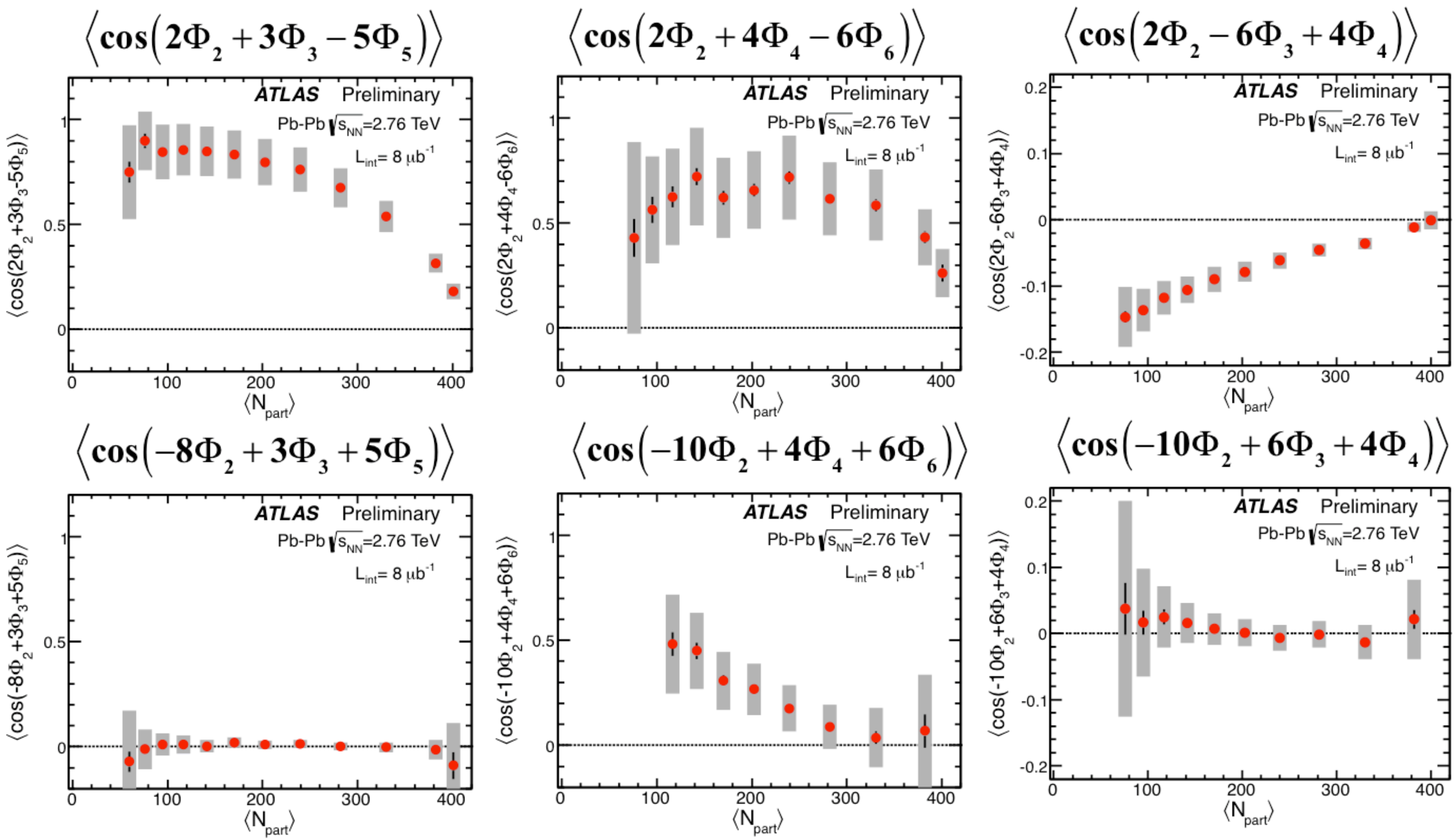
Two-plane correlations



Rich patterns for the centrality dependence

Three-plane correlations



Rich patterns for the centrality dependence