Measurement of event-plane correlations in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV with the ATLAS detector

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for the **ATLAS** Collaboration

- ATLAS event-Plane Correlation Note: http://cdsweb.cern.ch/record/1451882

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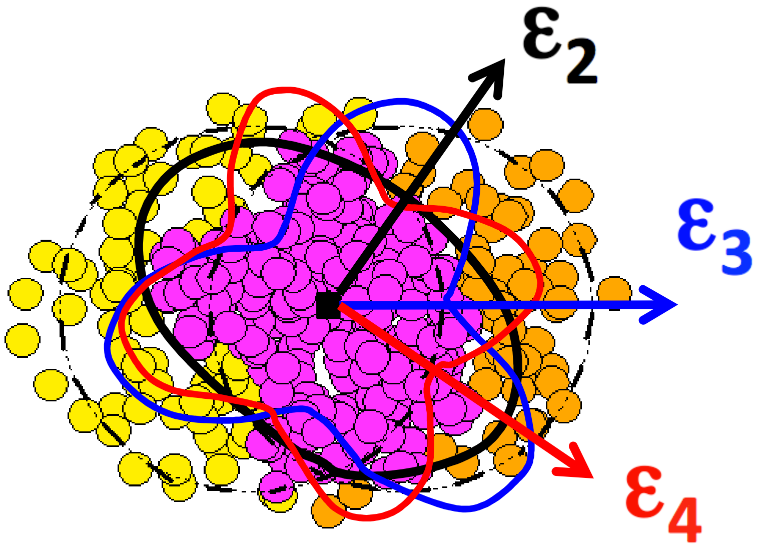
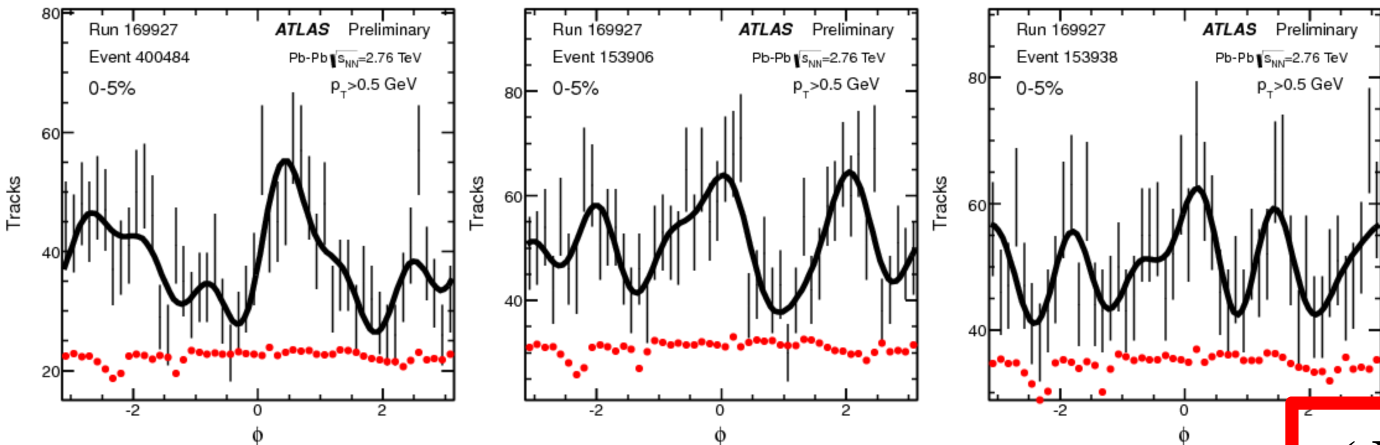
Introduction and motivation



Singles: $\dfrac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n} \cos n(\phi - \Phi_n)$



$\boxed{(\Phi_n - \Phi_m)\ correlations}$

- Studying the correlations between the Φ_n gives insight into the initial geometry and expansion mechanism of the fireball.

Quantifying the two-plane correlations

- The correlations are entirely described by the differential distribution:

$$\frac{dN_{events}}{d(k(\Phi_n - \Phi_m))} \quad : \quad k = LCM(m,n)$$

- The multiplication by the *Lowest common multiple, k* removes the *n*/*m*-fold ambiguity in Φ_m/Φ_n.

- The distribution can be expanded as a Fourier series.
  - The Fourier coefficients $V^j_{n,m}$ quantify the strength of the correlation.

$$\frac{dN_{events}}{d(k(\Phi_n - \Phi_m))} = 1 + 2\sum_{j=1}^{\infty} V^j_{n,m} \cos(j \times k(\Phi_n - \Phi_m))$$

$$V^j_{n,m} = \left\langle \cos(j \times k(\Phi_n - \Phi_m)) \right\rangle$$

Accounting for detector resolution

Measured planes : Ψ_n
True planes : Φ_n

Measure correlation between EP, followed by a simple resolution correction.

Desired correlator

Observed correlator

$$\left\langle \cos k\left(\Phi_n - \Phi_m\right)\right\rangle = \frac{\boxed{\left\langle \cos k\left(\Psi_n - \Psi_m\right)\right\rangle}}{\boxed{\mathrm{Res}\left\{k\Psi_n\right\}}\mathrm{Res}\left\{k\Psi_m\right\}}$$

arXiv: 1105.3928
PHENIX but no corrections for reso.

Resolution for individual planes

$$\boxed{\mathrm{Res}\left\{k\Psi_n\right\} = \left\langle \cos\left(k\Psi_n - k\Phi_n\right)\right\rangle}$$

All correlations of planes (2≤*n*,*m*≤6) where the resolution is good enough to make conclusive measurements are studied.

Two-plane correlators

- Sensitivity limit is set by the values of Res{}
- List of two-plane correlators:

$$\boxed{\begin{gathered}\langle\cos 4(\Phi_2-\Phi_4)\rangle\\ \langle\cos 8(\Phi_2-\Phi_4)\rangle\\ \langle\cos 12(\Phi_2-\Phi_4)\rangle\end{gathered}}$$

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

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

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

$$\langle\cos 12(\Phi_3-\Phi_4)\rangle$$

$$\langle\cos 10(\Phi_2-\Phi_5)\rangle$$

Two-plane correlators

- Sensitivity limit is set by the values of Res{}
- List of two-plane correlators:

$$\boxed{\begin{array}{c}\langle\cos 4(\Phi_2-\Phi_4)\rangle\\ \langle\cos 8(\Phi_2-\Phi_4)\rangle\\ \langle\cos 12(\Phi_2-\Phi_4)\rangle\end{array}}$$

$$\langle\cos 6(\Phi_2-\Phi_3)\rangle$$
$$\langle\cos 6(\Phi_2-\Phi_6)\rangle$$
$$\langle\cos 6(\Phi_3-\Phi_6)\rangle$$
$$\langle\cos 12(\Phi_3-\Phi_4)\rangle$$
$$\langle\cos 10(\Phi_2-\Phi_5)\rangle$$

- Can generalize into multi-plane correlations

Variable: $c_1\Phi_1 + 2c_2\Phi_2 ... + lc_l\Phi_l$ satisfying: $c_1 + 2c_2 ... + lc_l = 0$

arXiv:1104.4740, Bhalerao, Luzum, Ollitrault

$$\boxed{\begin{aligned}\langle\cos(c_1\Phi_1 + ... + lc_l\Phi_l)\rangle &= \frac{\langle\cos(c_1\Psi_1 + ... + lc_l\Psi_l)\rangle}{\mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}}\\ \mathrm{Res}\{c_n n\Psi_n\} &= \langle\cos c_n n(\Psi_n - \Phi_n)\rangle\end{aligned}}$$

arXiv:1203.5095
1205.3585

$$\mathrm{Res}\{(c_1\Psi_1 + ... + lc_l\Psi_l)\} = \mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}$$

Three-plane correlators

"2-3-5"

$$\boxed{\begin{array}{c}\langle\cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5)\rangle \\ \langle\cos(-8\Phi_2 + 3\Phi_3 + 5\Phi_5)\rangle\end{array}}$$

"2-4-6"

$$\boxed{\begin{array}{c}\langle\cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6)\rangle \\ \langle\cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6)\rangle\end{array}}$$

"2-3-4"

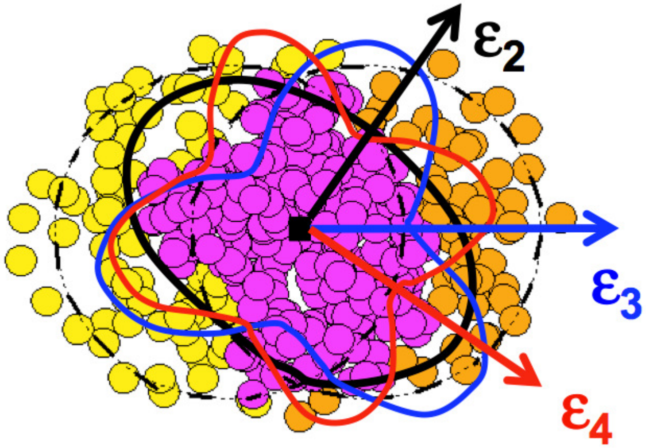
$$\boxed{\begin{array}{c}\langle\cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4)\rangle \\ \langle\cos(-10\Phi_2 + 6\Phi_3 + 4\Phi_4)\rangle\end{array}}$$

Constructed as linear combination of two-plane correlators, for example:

$$\begin{aligned} 2\Phi_2 + 4\Phi_4 - 6\Phi_6 &= 4(\Phi_4 - \Phi_2) - 6(\Phi_6 - \Phi_2) \\ -10\Phi_2 + 4\Phi_4 + 6\Phi_6 &= 4(\Phi_4 - \Phi_2) + 6(\Phi_6 - \Phi_2) \end{aligned}$$

Reflects correlation of two Φ_n relative to the third

Expectations from Glauber model

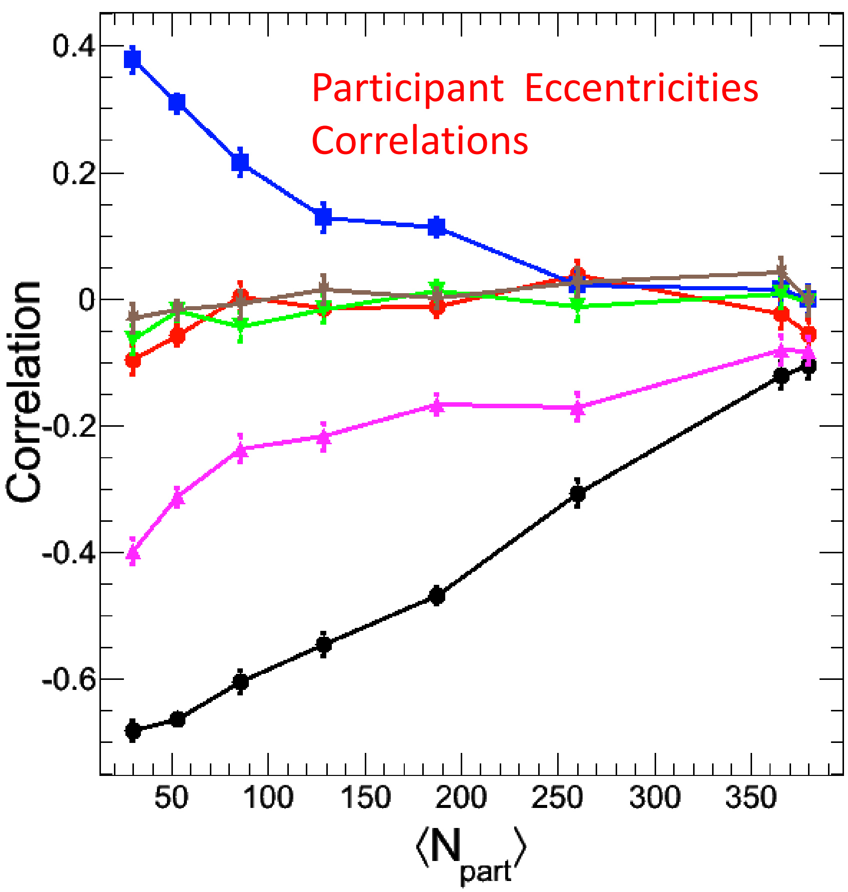


- Plane directions in configuration space

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

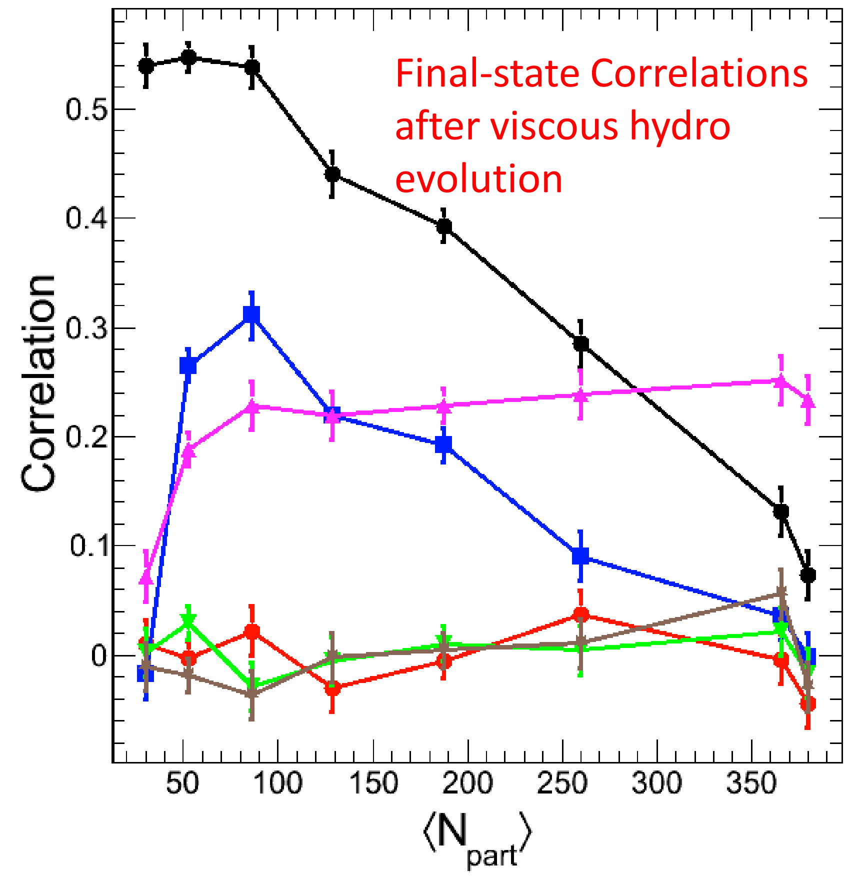
$$\Phi_n = \frac{\mathrm{atan}\left(\langle r^n \sin(n\phi)\rangle, \langle r^n \cos(n\phi)\rangle\right) + \pi}{n}$$

- Expected to be strongly modified by medium evolution in the final state (Qiu and Heinz, arXiv:1208.1200)

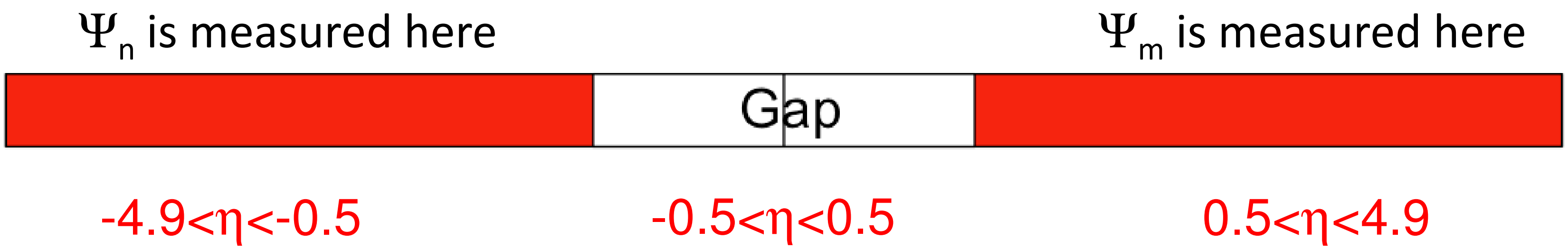


$\langle\cos(4(\Phi_2-\Phi_4))\rangle$
$\langle\cos(6(\Phi_2-\Phi_3))\rangle$
$\langle\cos(6(\Phi_2-\Phi_6))\rangle$
$\langle\cos(6(\Phi_3-\Phi_6))\rangle$
$\langle\cos(12(\Phi_3-\Phi_4))\rangle$
$\langle\cos(10(\Phi_2-\Phi_5))\rangle$

arXiv:1208.1200
1203.5095
1205.3585



Measuring the two-plane correlations



- Correlations are measured using EM+Forward calorimerers (-4.9<η<-4.9)
- If Ψ_n is measured in negative half (-4.9<η<-0.5), then Ψ_m is measured in positive half of calorimeters (and vice versa).
  - Thus same particles are not used in measuring both Ψ_n and Ψ_m.
  - Removes auto-correlation
- There is a Δη gap of 1 units between the two halves to remove any non-flow correlations

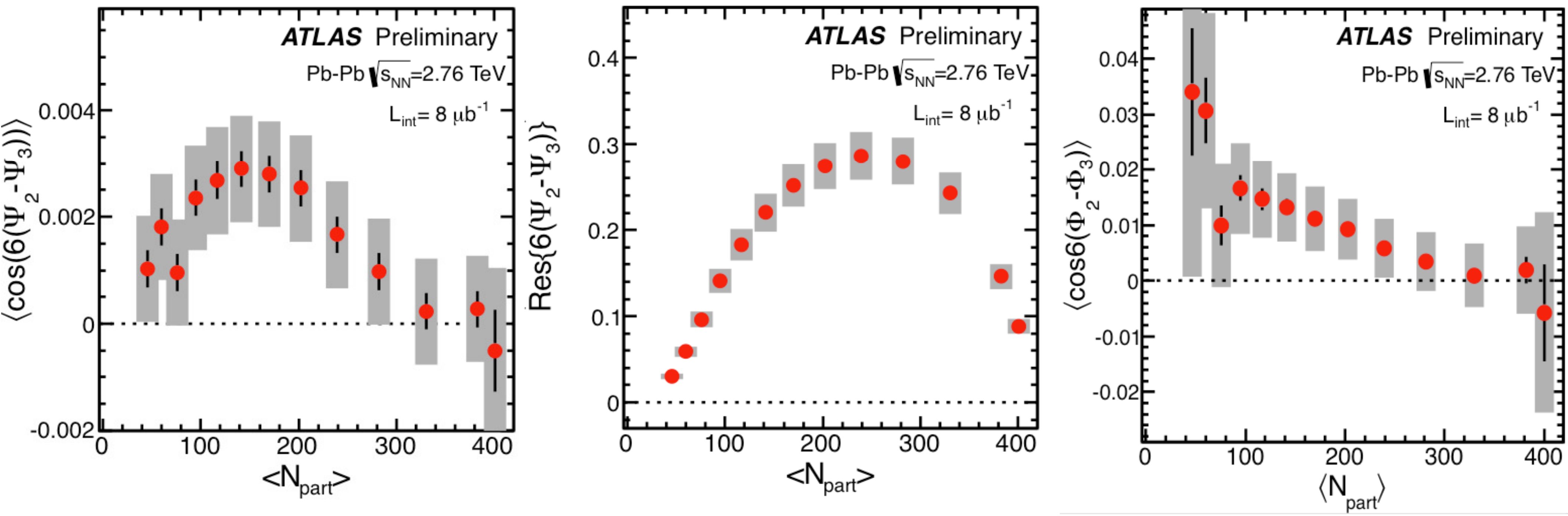
Correlation between Φ_2 and Φ_3

$$\frac{\langle \cos 6(\Psi_2 - \Psi_3) \rangle}{\mathrm{Res}\{6\Psi_2\}\mathrm{Res}\{6\Psi_3\}} = \langle \cos 6(\Phi_2 - \Phi_3) \rangle$$

Observed correlation

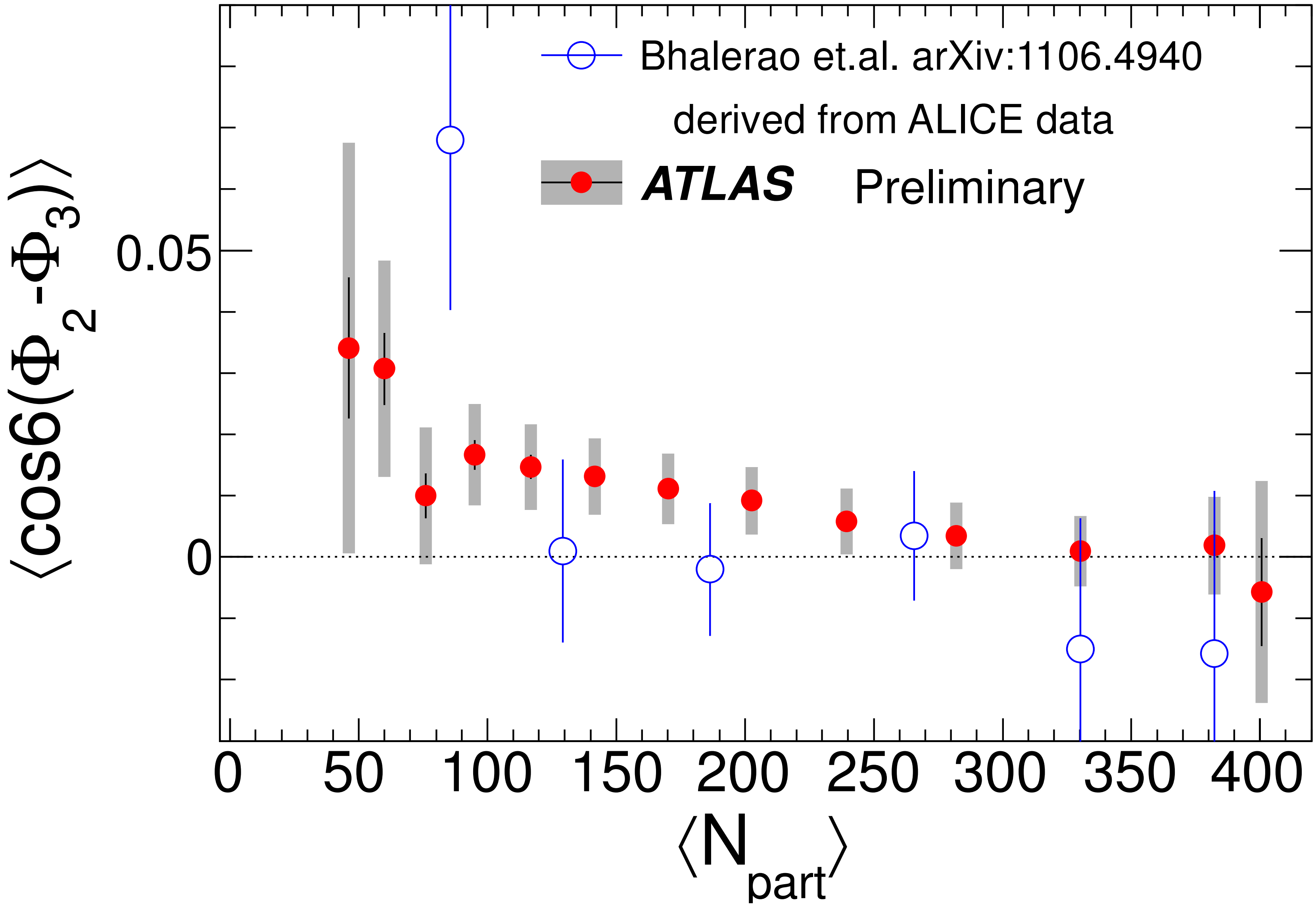
Combined Res

Corrected result



Small observed signal, good resolution → small corrected signal (<0.02)

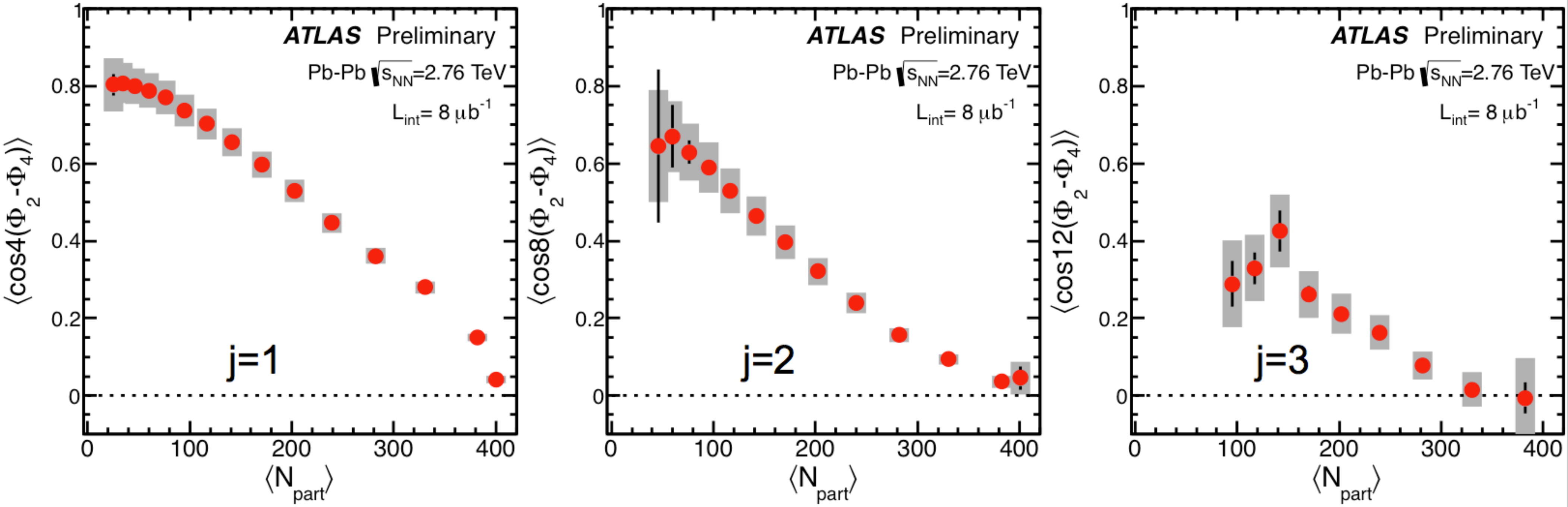
Comparison with ALICE



Overall magnitudes are similar, but our data shows slight increase towards peripheral collisions.

Correlation between Φ_2 and Φ_4

$\left\langle \cos 4(\Phi_2 - \Phi_4) \right\rangle$ $\left\langle \cos 8(\Phi_2 - \Phi_4) \right\rangle$ $\left\langle \cos 12(\Phi_2 - \Phi_4) \right\rangle$



$$\frac{dN_{\text{evts}}}{d\left(4(\Phi_2 - \Phi_4)\right)} \propto 1 + 2\sum_{j=1}^{\infty} V_{2,4}^{j} \cos 4j(\Phi_2 - \Phi_4) \qquad V_{2,4}^{j} = \langle \cos 4j(\Phi_2 - \Phi_4) \rangle$$

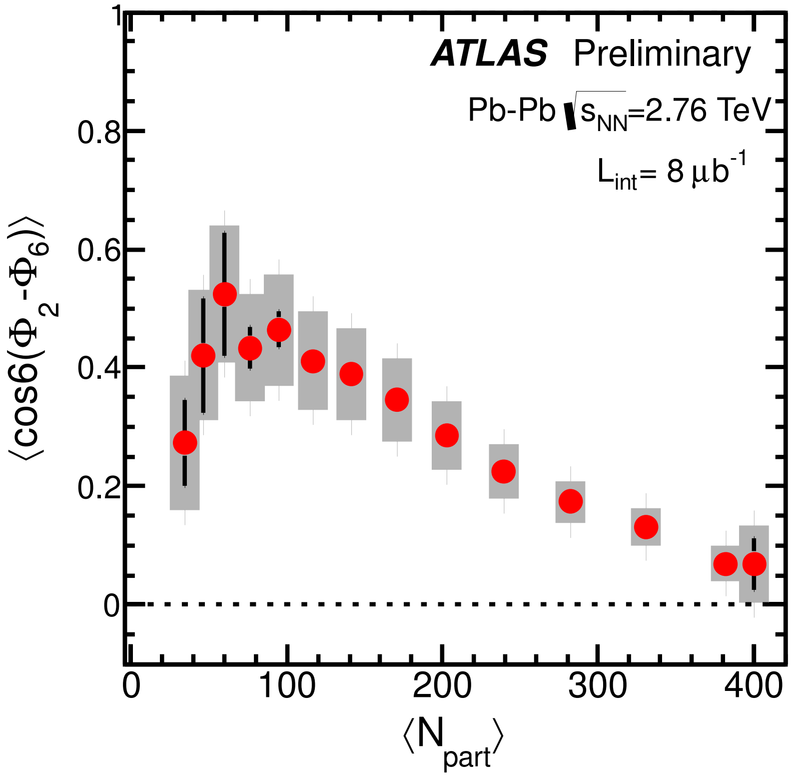
- Coefficients decrease slowly with *j*, imply a narrow correlation.
- Note: lowest-order coefficient is the projection of v_4 onto Φ_2 plane

$$\left\langle \cos 4(\Phi_2 - \Phi_4) \right\rangle = \frac{v_4\{\Phi_2\}}{v_4\{\Phi_4\}}$$

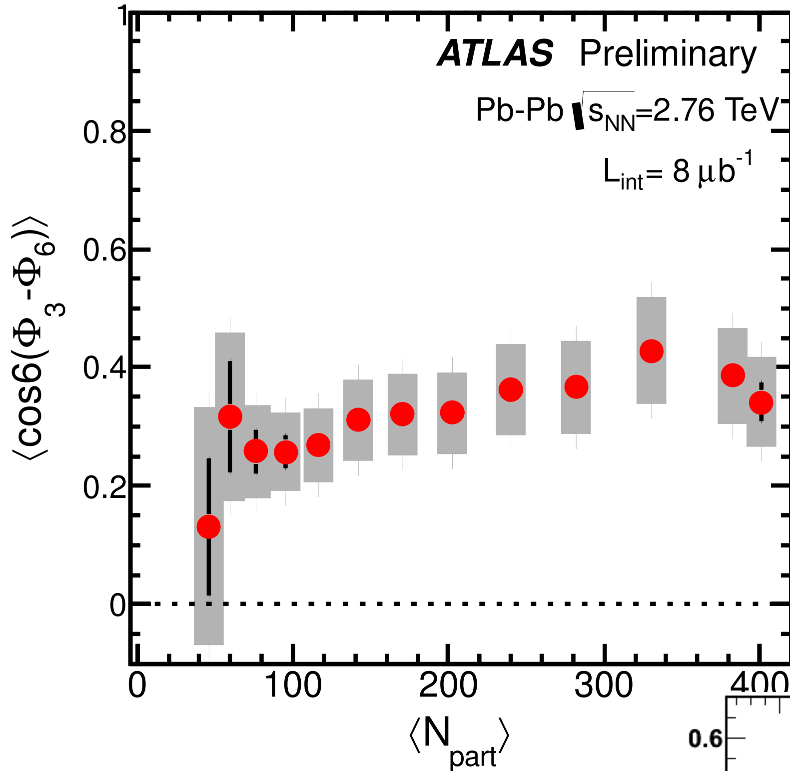
e.g. arXiv:1205.5761
ALICE Collaboration

Correlation of Φ_2 or Φ_3 with Φ_6

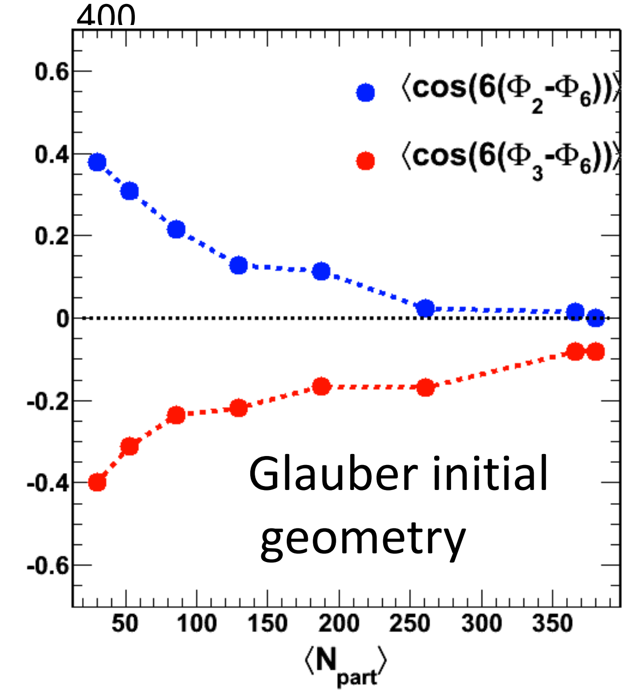
$\langle \cos 6(\Phi_2 - \Phi_6) \rangle$



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



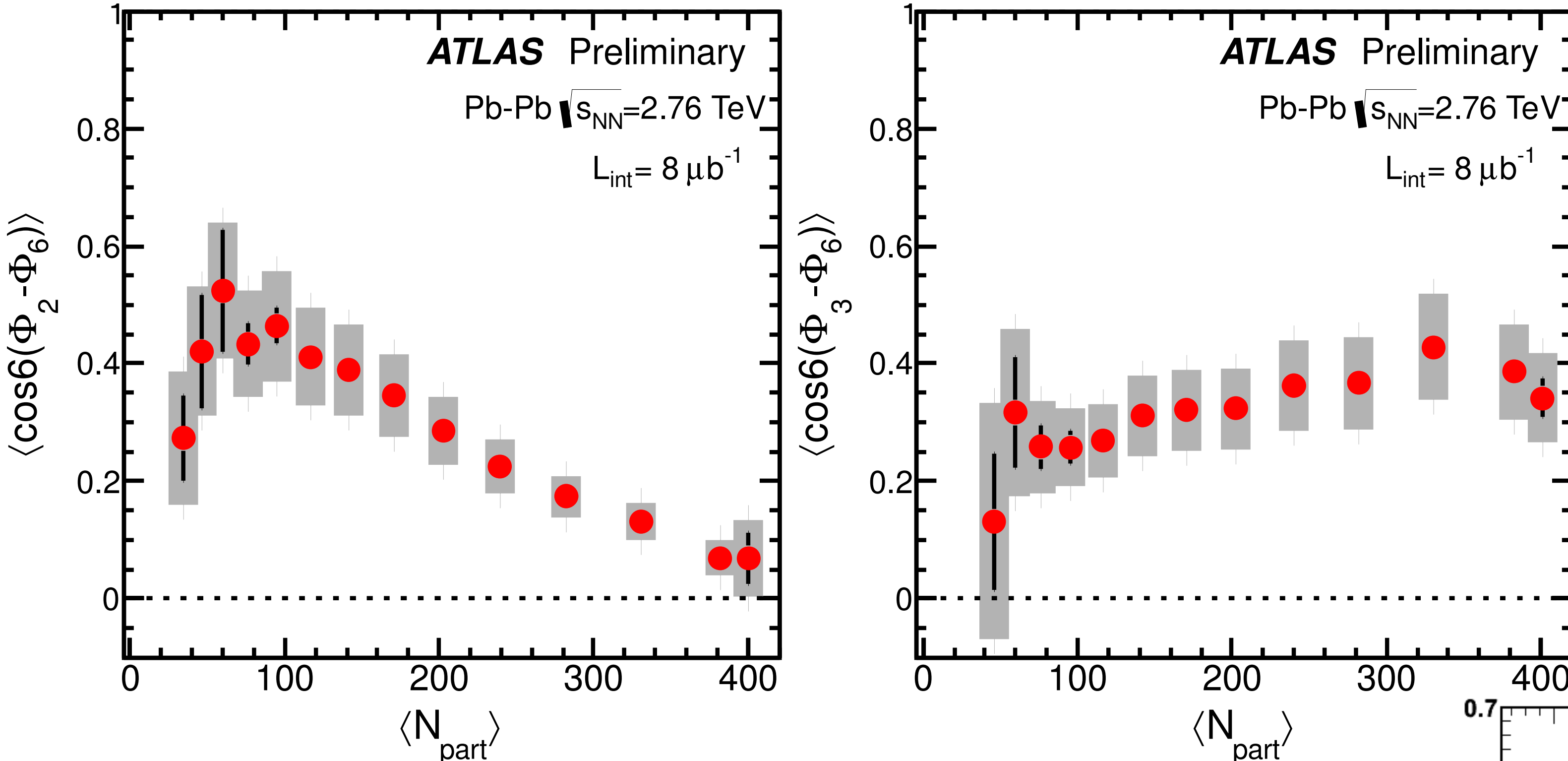
- Φ_2 and Φ_3 weakly correlated, but both strongly correlated with Φ_6.
- They show opposite centrality dependence
  - Φ_2-Φ_6 correlation may due to average geometry..
  - But Φ_3-Φ_6 correlation?
  - v_6 dominated by non-linear contribution: v_2^3, v_3^2 ?



Teaney and Yan

Correlation of Φ_2 or Φ_3 with Φ_6

$\left\langle \cos 6\left(\Phi_2 - \Phi_6\right)\right\rangle$ $\left\langle \cos 6\left(\Phi_3 - \Phi_6\right)\right\rangle$



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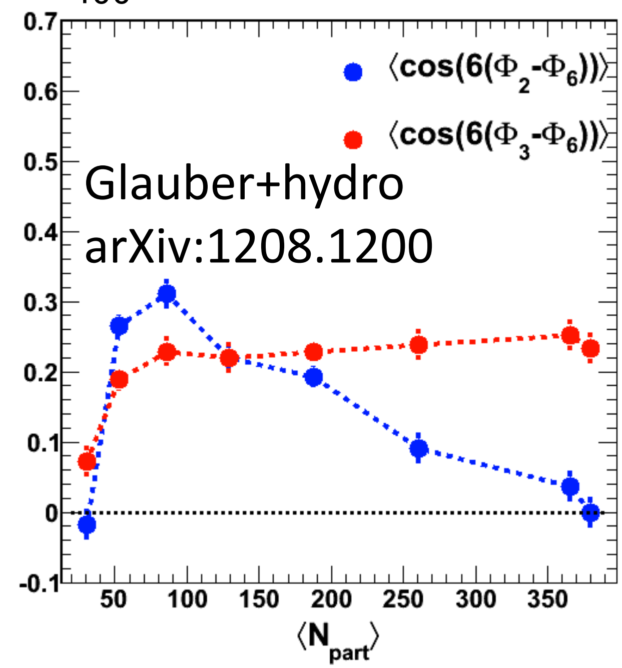
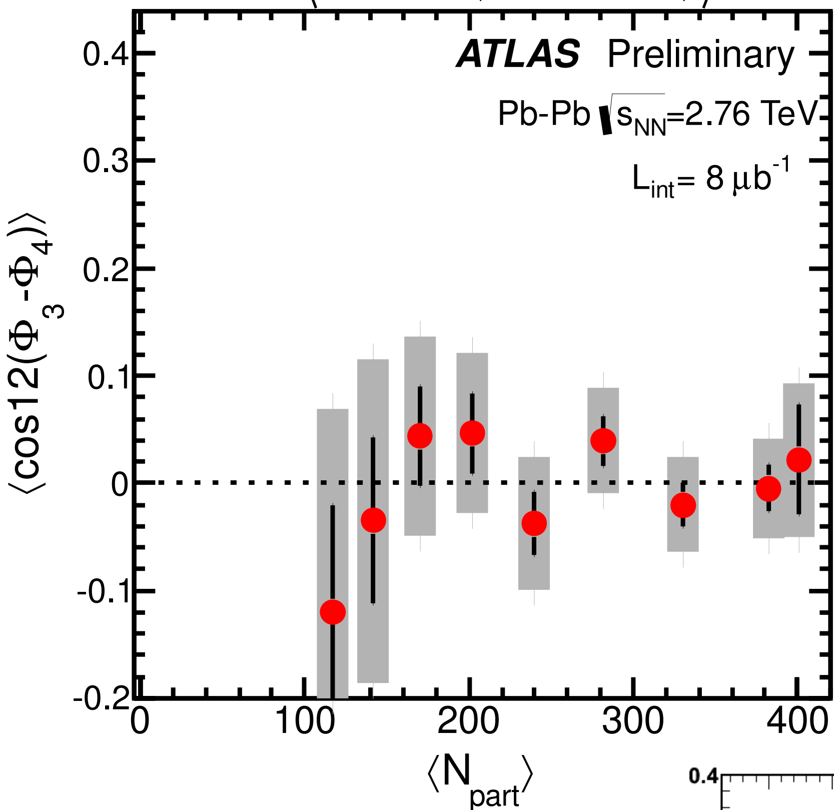


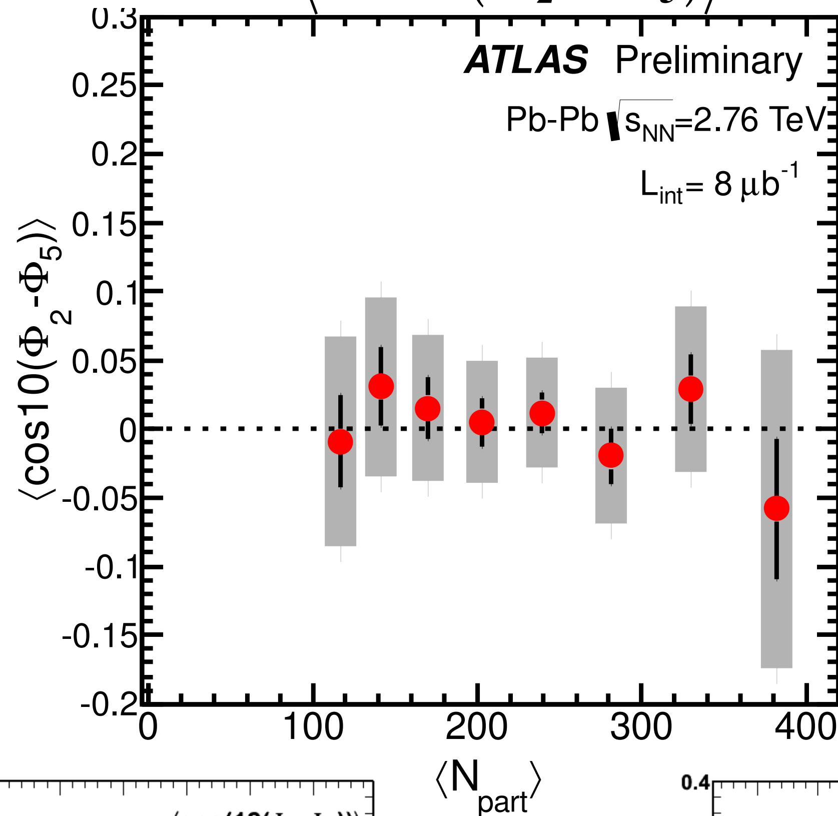
Teaney and Yan

Φ_3 vs Φ_4 and Φ_2 vs Φ_5

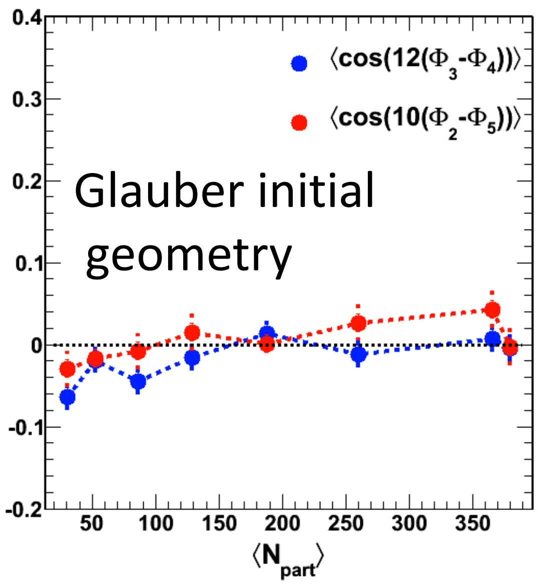
$\left\langle \cos 12\left(\Phi_3 - \Phi_4\right)\right\rangle$

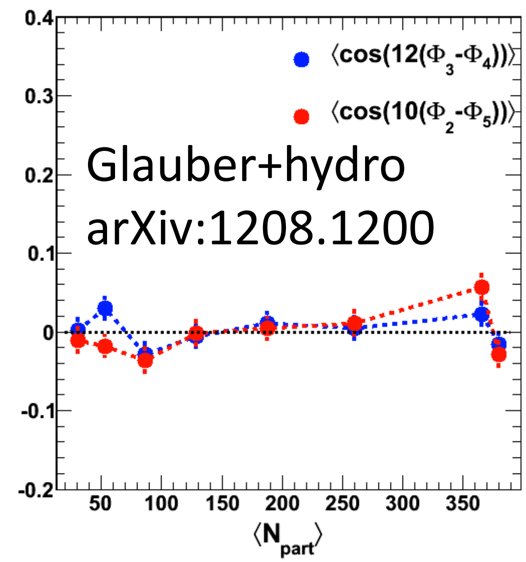


$\left\langle \cos 10\left(\Phi_2 - \Phi_5\right)\right\rangle$

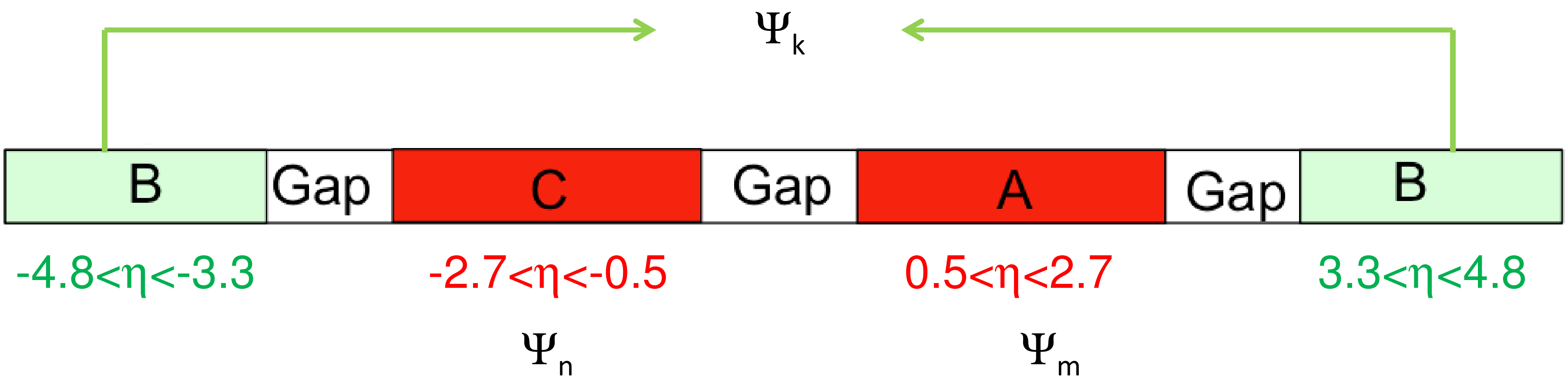


correlations are weak (< few %)





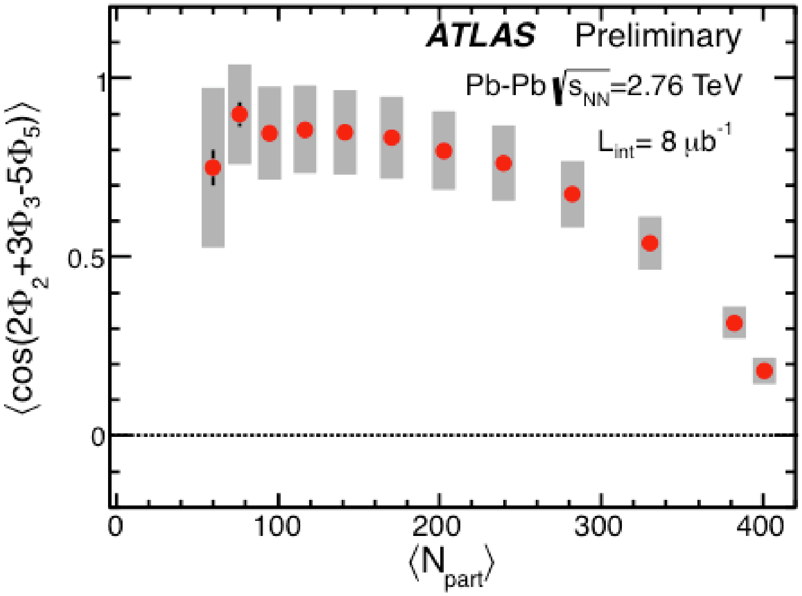
Measuring the three-plane correlations



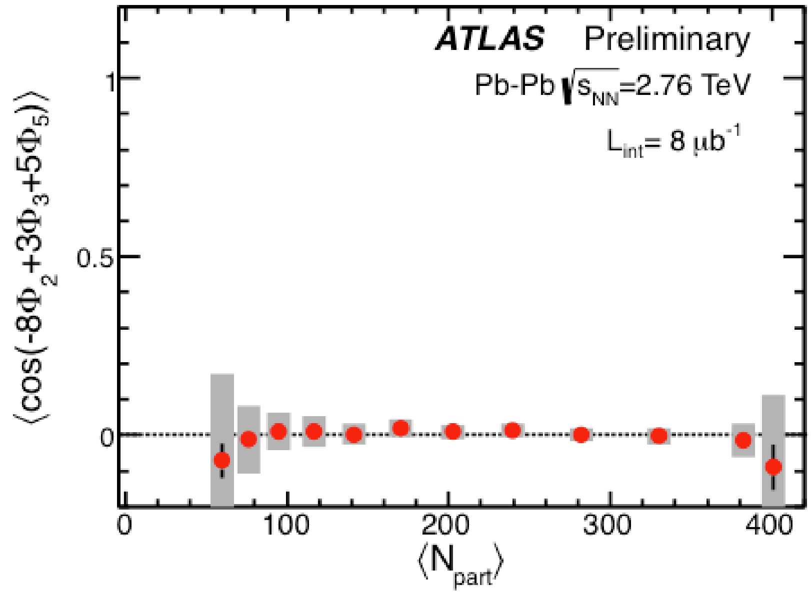
- Ψ_n ,Ψ_m and Ψ_k are measured in different parts of the calorimeter.
  - Thus same particles are not used in measuring any of the Ψ's.
  - Thus there is no auto-correlation
- There is a $\Delta\eta$ gap between any two of the detectors
- Event mixing is used to remove detector effects

Three-plane : "2-3-5" correlation

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



$$\left\langle \cos\left(-8\Phi_2 + 3\Phi_3 + 5\Phi_5\right)\right\rangle$$



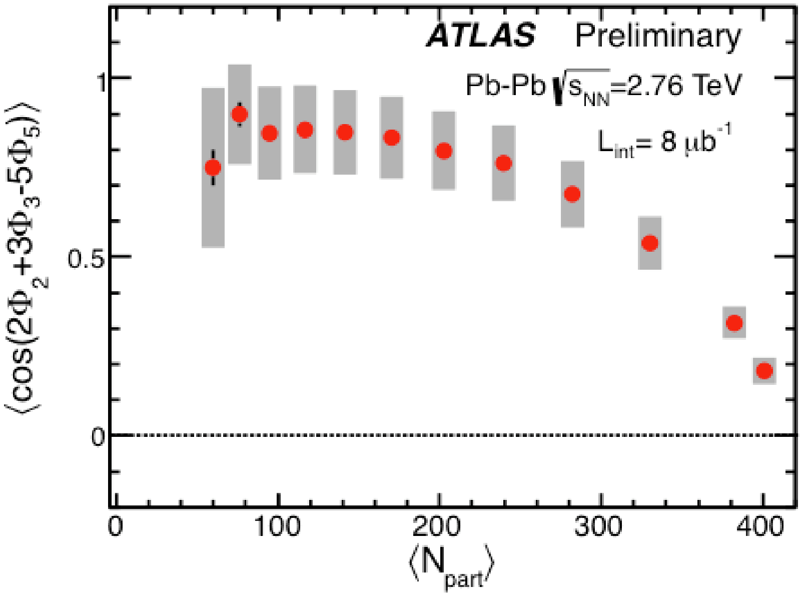
$$(2\Phi_2 + 3\Phi_3 - 5\Phi_5) = 3(\Phi_3 - \Phi_2) - 5(\Phi_5 - \Phi_2)$$

$$(-8\Phi_2 + 3\Phi_3 + 5\Phi_5) = 3(\Phi_3 - \Phi_2) + 5(\Phi_5 - \Phi_2)$$

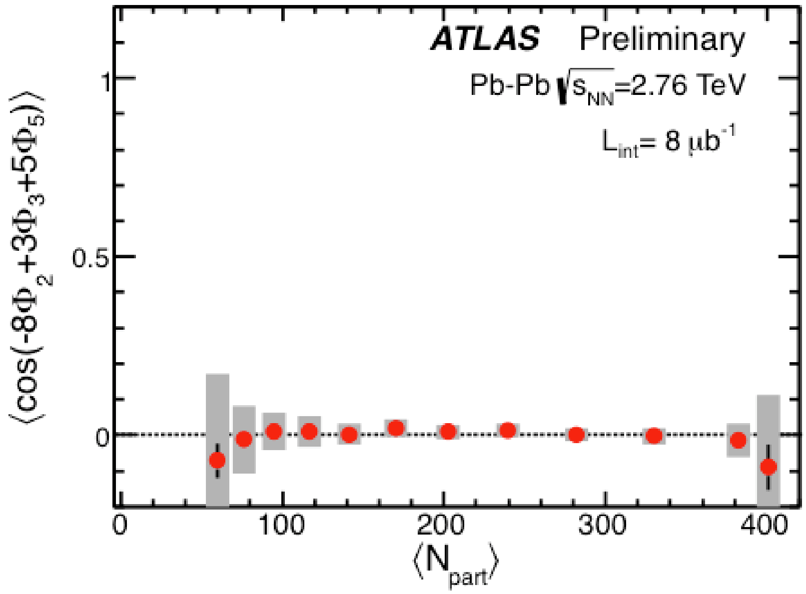
- Φ_5 and Φ_3 are individually weakly correlated with Φ_2
- But $(2\Phi_2 + 3\Phi_3 - 5\Phi_5)$ correlation in non-zero

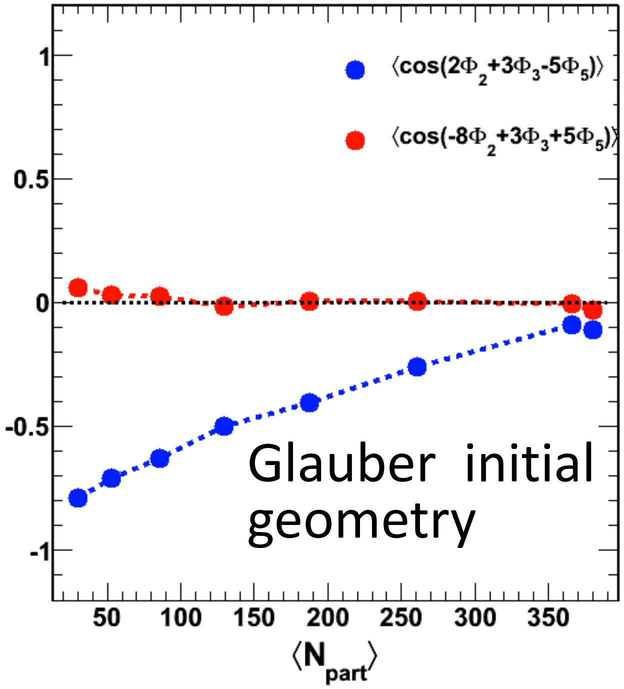
Three-plane : "2-3-5" correlation

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



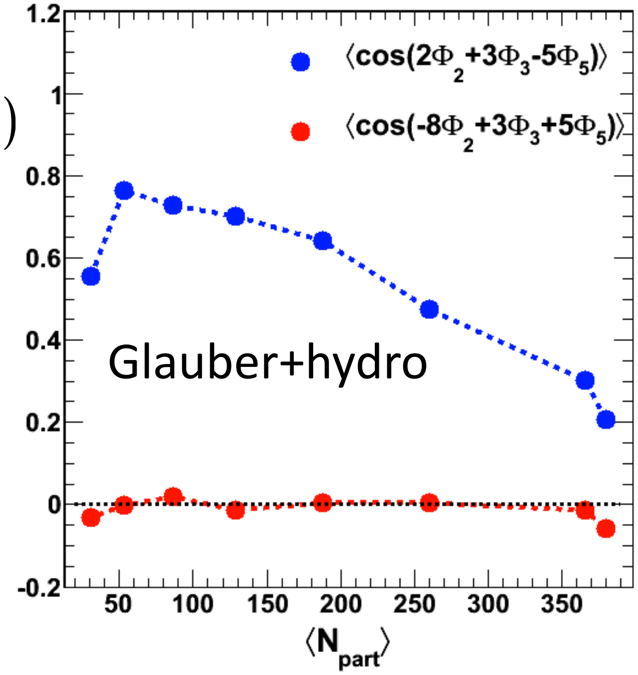
$$\left\langle \cos\left(-8\Phi_2 + 3\Phi_3 + 5\Phi_5\right)\right\rangle$$





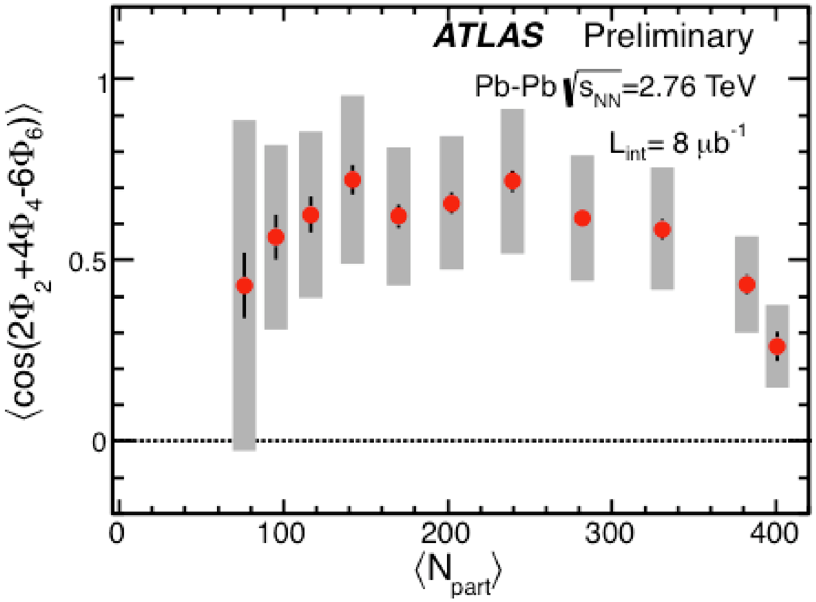
Glauber geometry does not match the $\cos\left(2\Phi_2 + 3\Phi_3 - 5\Phi5\right)\rangle$ correlation

Hydro evolution qualitatively reproduces the centrality dependence

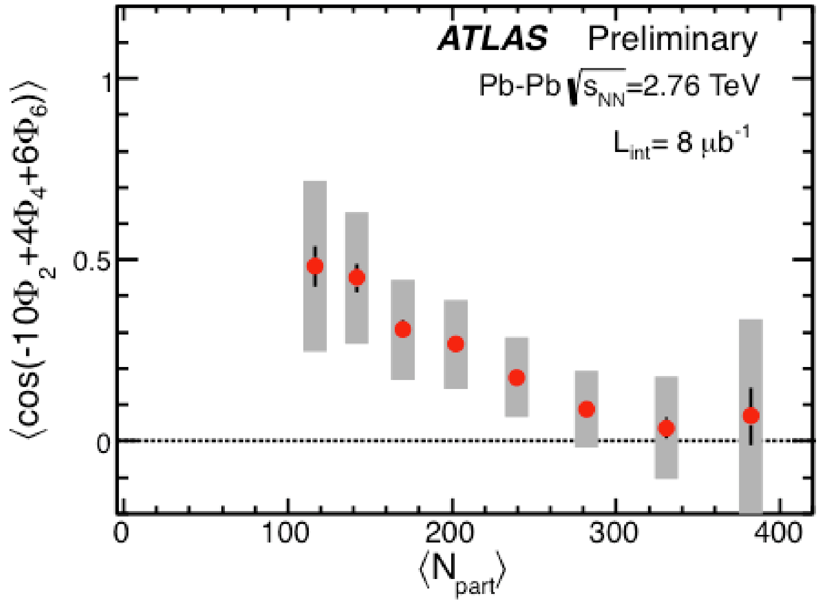


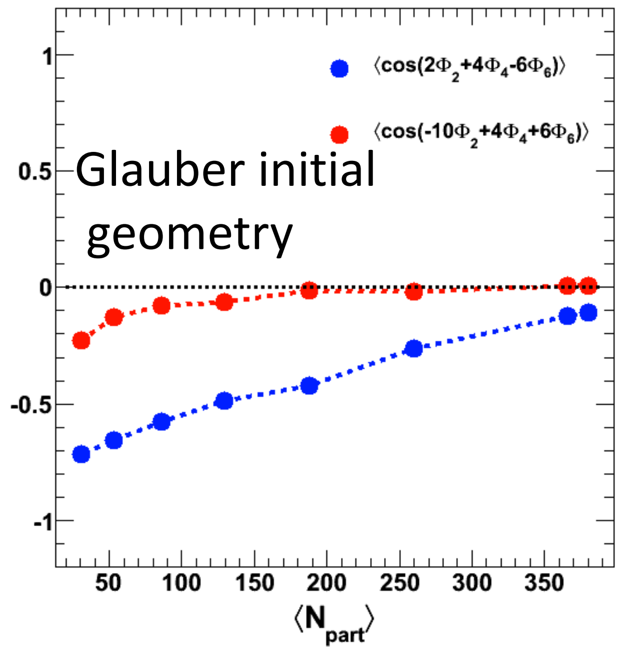
Three-plane : "2-4-6" correlation

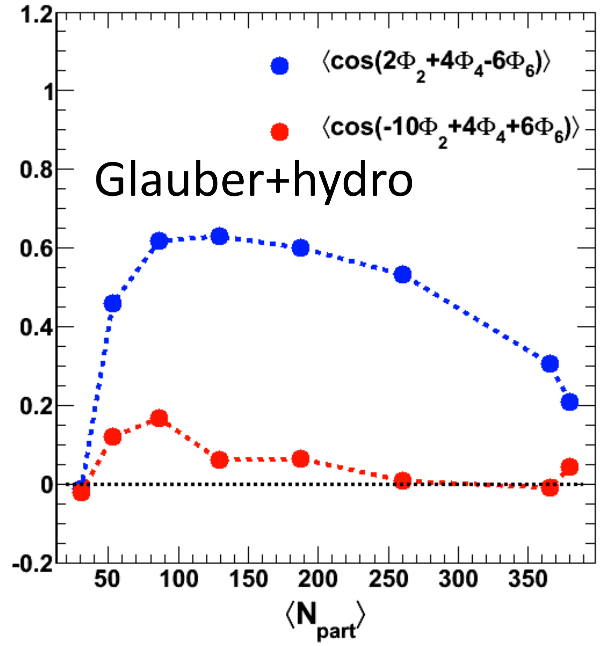
$$\left\langle \cos\left(2\Phi_2 + 4\Phi_4 - 6\Phi_6\right)\right\rangle$$



$$\left\langle \cos\left(-10\Phi_2 + 4\Phi_4 + 6\Phi_6\right)\right\rangle$$

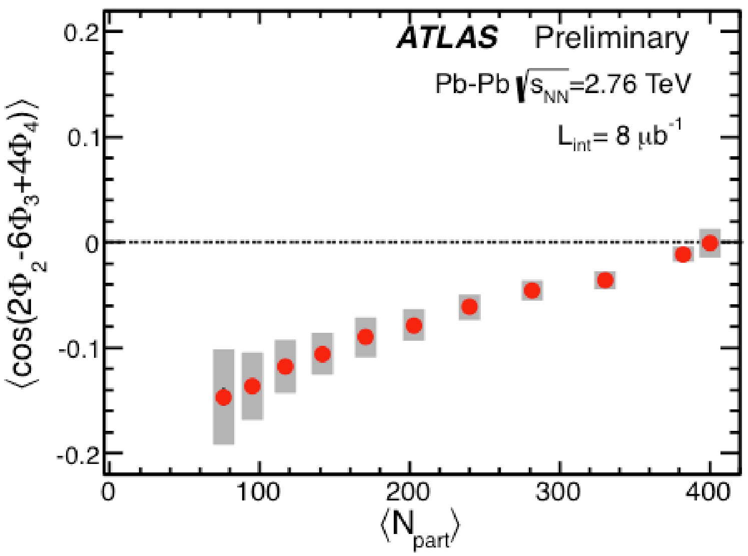




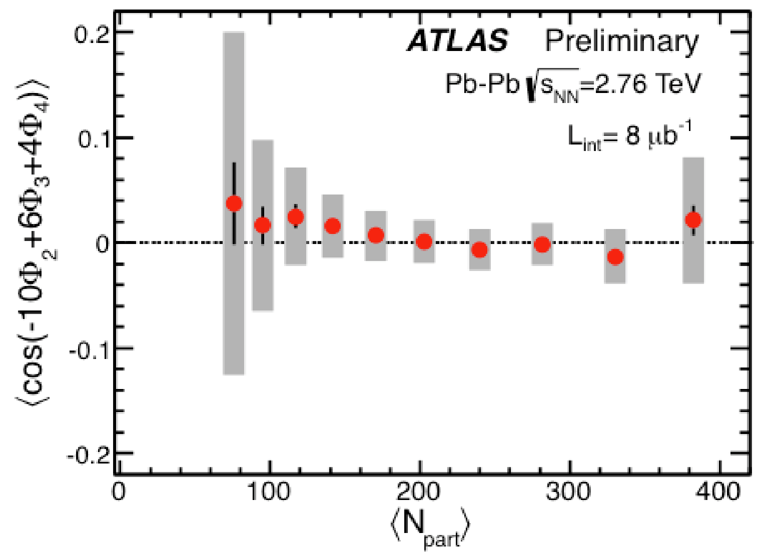


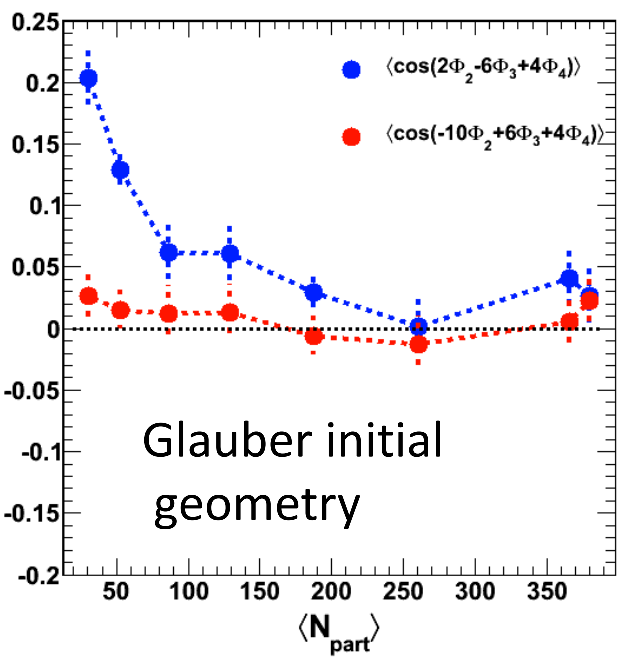
Three-plane : "2-3-4" correlation

$$\left\langle \cos\left(2\Phi_2 - 6\Phi_3 + 4\Phi_4\right)\right\rangle$$



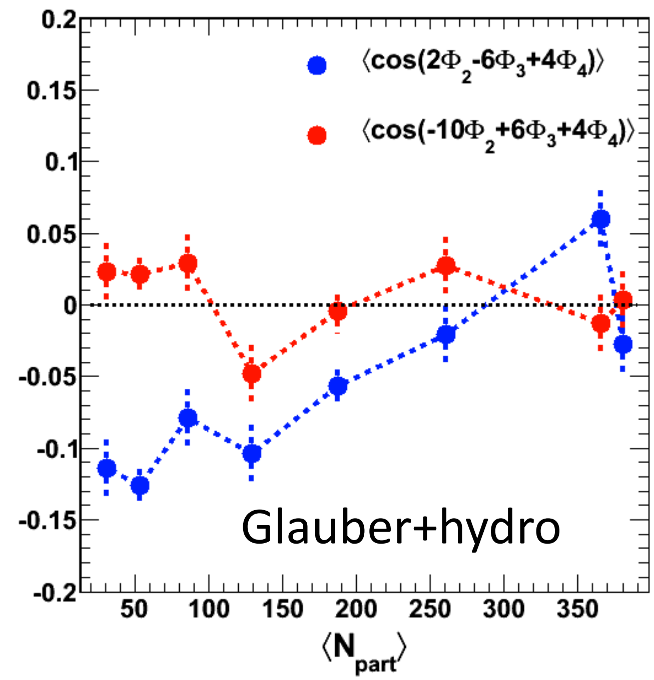
$$\left\langle \cos\left(-10\Phi_2 + 6\Phi_3 + 4\Phi_4\right)\right\rangle$$



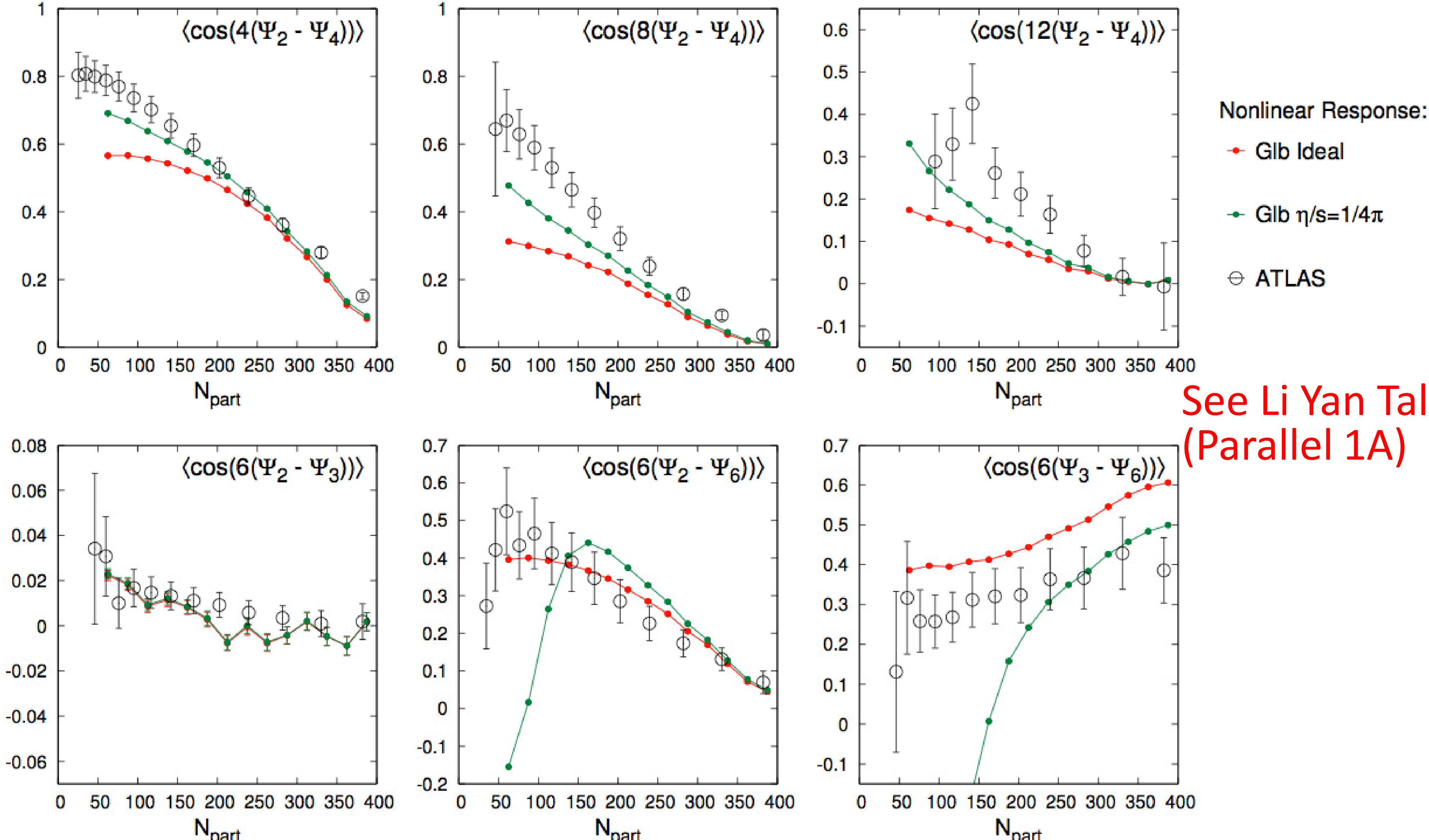


The first correlator is negative and its magnitude increases linearly with decreasing N_{part}.

Completely different than Glauber expectations



Comparison with Teaney and Yan



See Li Yan Talk (Parallel 1A)

The correlations are well reproduced using Teaney and Yan's cumulant method (see Li Yan talk in Parallel 1A).

Their method includes linear+non-linear response to initial geometry

Event plane correlations: Summary

- We measured correlations between two and three event planes
  - Significant correlations are observed for $\langle\cos(4(\Phi_2-\Phi_4))\rangle$, $\langle\cos(8(\Phi_2-\Phi_4))\rangle$, $\langle\cos(12(\Phi_2-\Phi_4))\rangle$, $\langle\cos(6(\Phi_2-\Phi_6))\rangle$, $\langle\cos(6(\Phi_3-\Phi_6))\rangle$ $\langle\cos(2\Phi_2+3\Phi_3-5\Phi5))\rangle$, $\langle\cos(2\Phi_2+4\Phi_4-6\Phi_6))\rangle$ and $\langle\cos(-10\Phi_2+4\Phi_4+6\Phi6))\rangle$
  - Correlation is very small but nonzero for $\langle\cos(6(\Phi_2-\Phi_3))\rangle$
  - Correlation is negative for $\langle\cos(2\Phi_2-6\Phi_3+4\Phi_4))\rangle$

- Some correlations qualitatively similar to Glauber model, others are not
  - Correlations can be generated dynamically via hydrodynamic evolution.

Qiu and Heinz, arXiv:1208.1200
Teaney and Yan, arXiv:1206.1905

- This measurement provides new constraints for models.
  - Do Glauber initial conditions describe these correlations well or some other models (CGC/KLN)?
  - Given a set of initial conditions, what kind of medium response would produce these correlations (linear/non-linear or ideal/viscous hydro)?

BACKUP SLIDES

BACKUP SLIDES

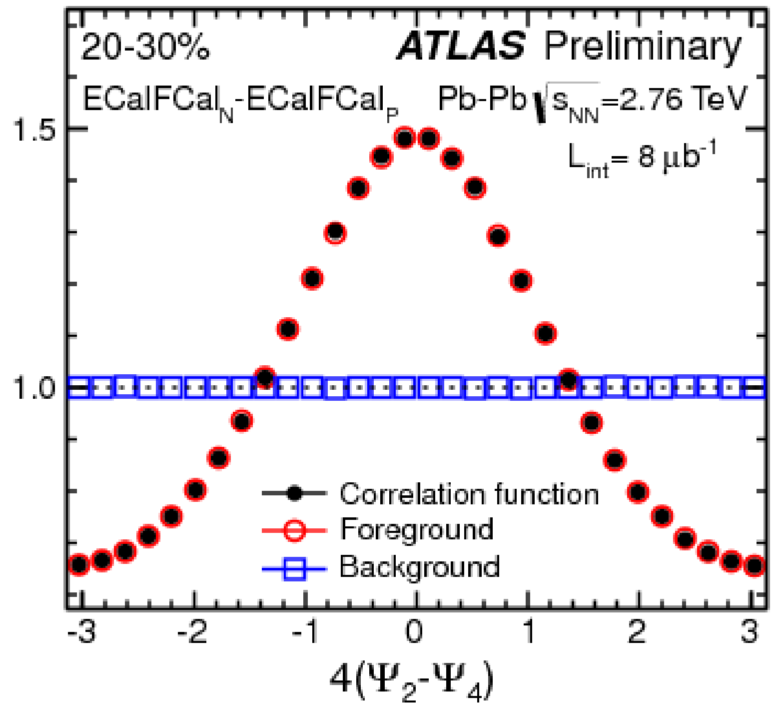
Event-plane correlations

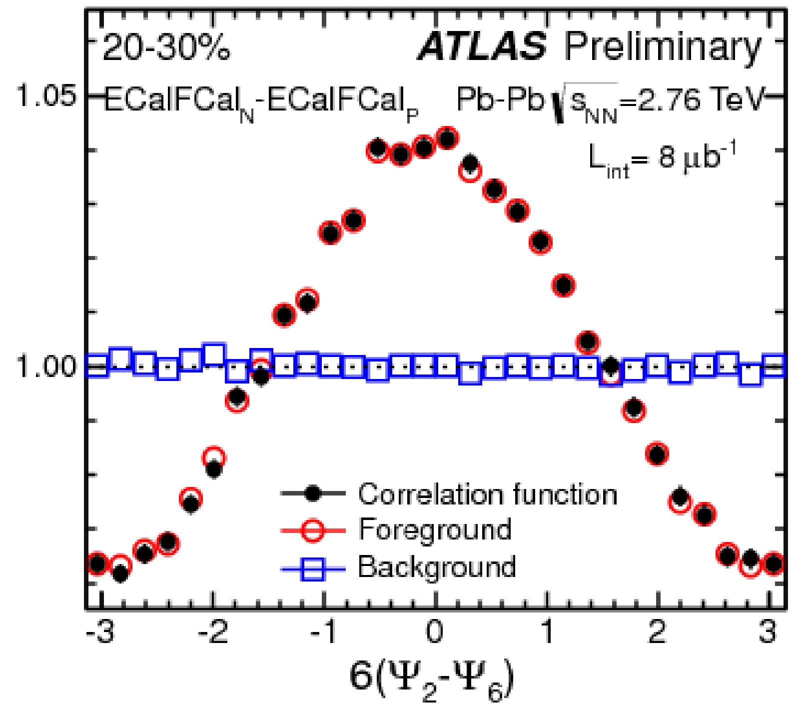
Event mixing technique is used to remove detector effects Ψ_n:

$$\frac{dN_{events}}{d(k(\Psi_n - \Psi_m))} \propto \frac{S(k(\Psi_n - \Psi_m))}{B(k(\Psi_n - \Psi_m))}$$

S: Ψ_n and Ψ_m from same event

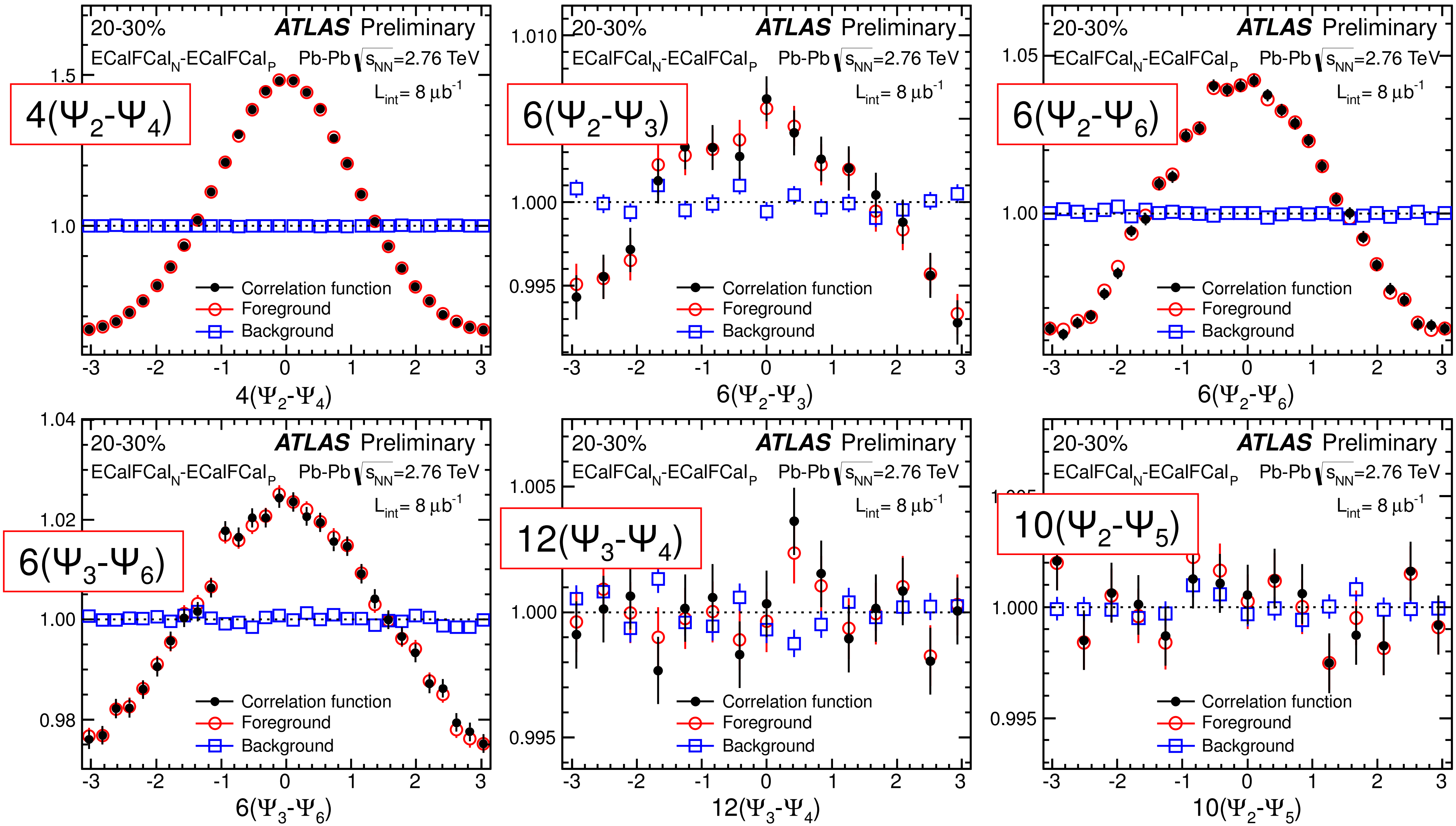
B: Ψ_n and Ψ_m from different event





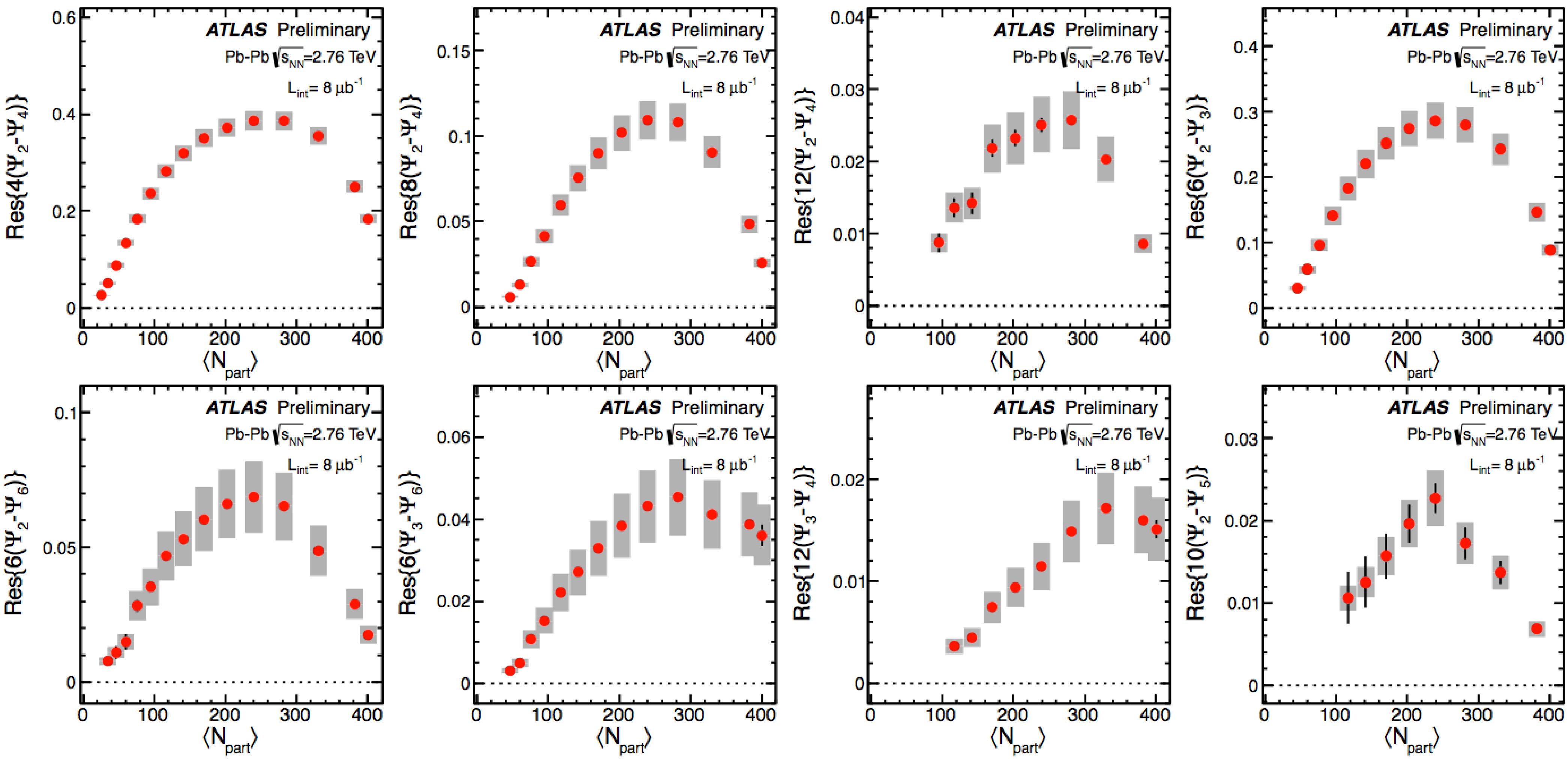
Observed two-plane signal

$$\frac{dN_{\mathrm{evts}}}{d\left(k(\Psi_n-\Psi_m)\right)} \propto C(k(\Psi_n-\Psi_m)) = \frac{S(k(\Psi_n-\Psi_m))}{B(k(\Psi_n-\Psi_m))}$$



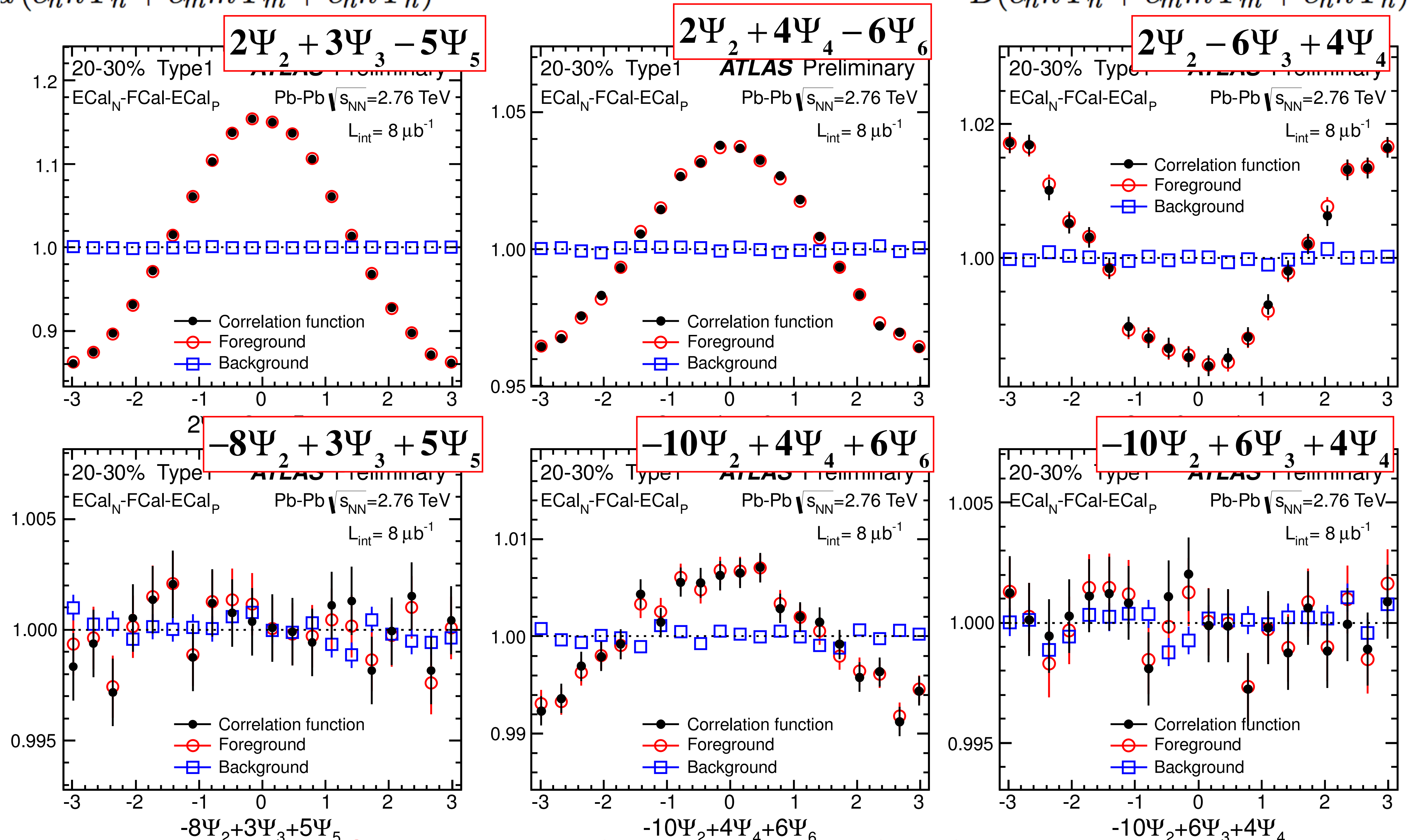
Significant correlations beyond detector systematics

Two-plane resolutions



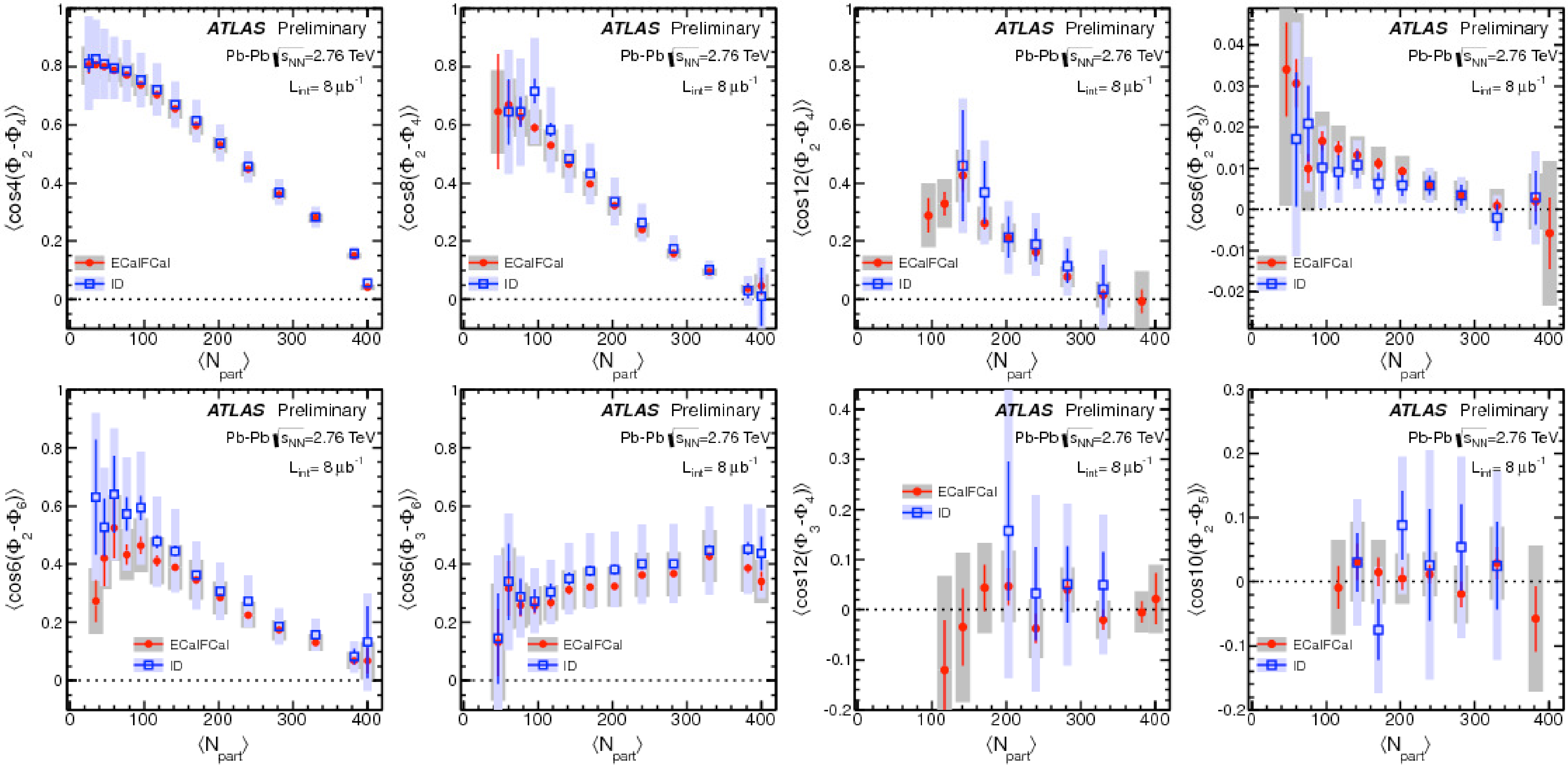
Observed three-plane signal

$$\frac{dN_{\mathrm{evts}}}{d\left(c_n n\Psi_n + c_m m\Psi_m + c_h h\Psi_h\right)} \propto C(c_n n\Psi_n + c_m m\Psi_m + c_h h\Psi_h) = \frac{S(c_n n\Psi_n + c_m m\Psi_m + c_h h\Psi_h)}{B(c_n n\Psi_n + c_m m\Psi_m + c_h h\Psi_h)}$$

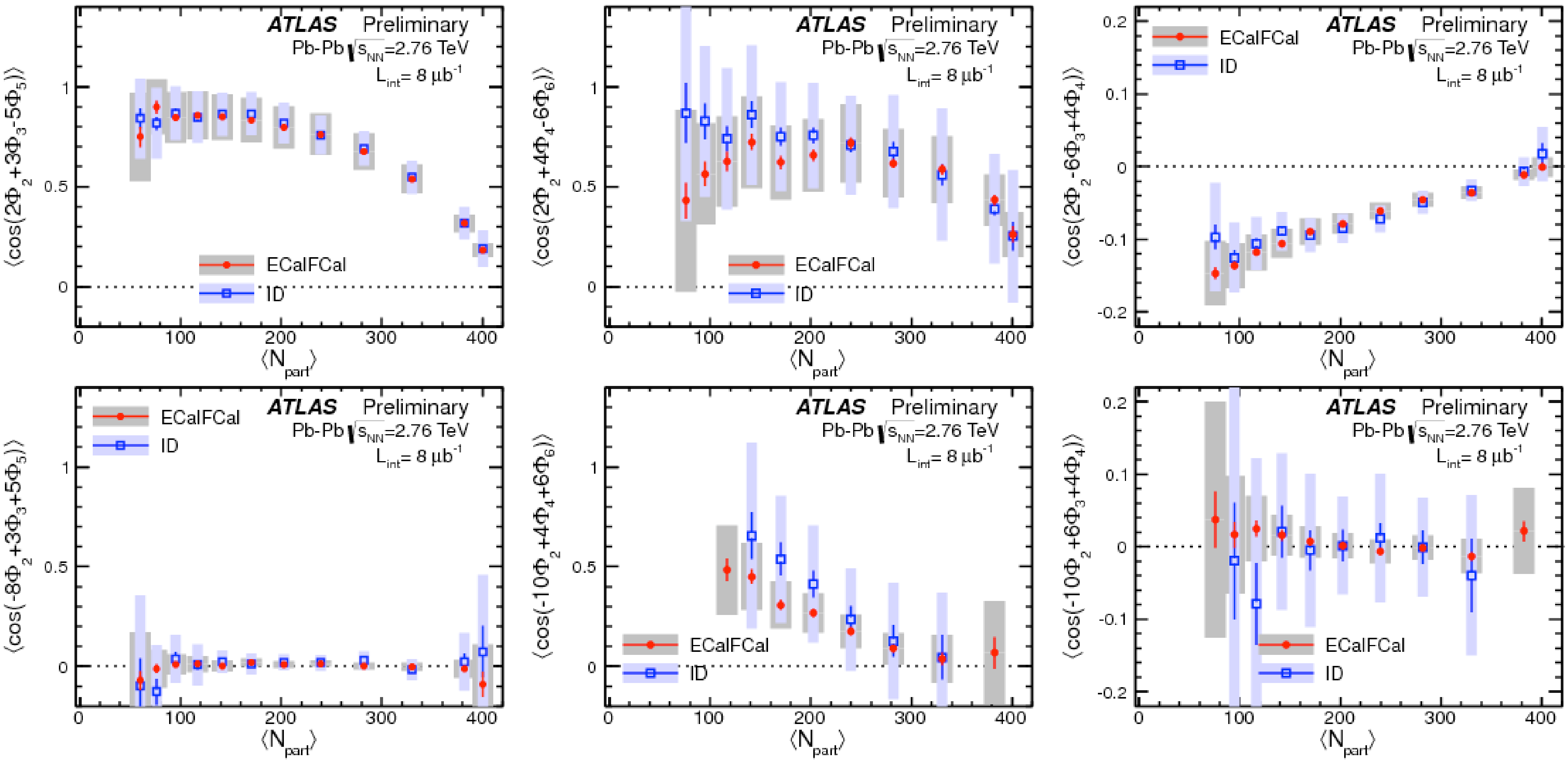


Significant correlations signals observed

Two-plane correlations : ID

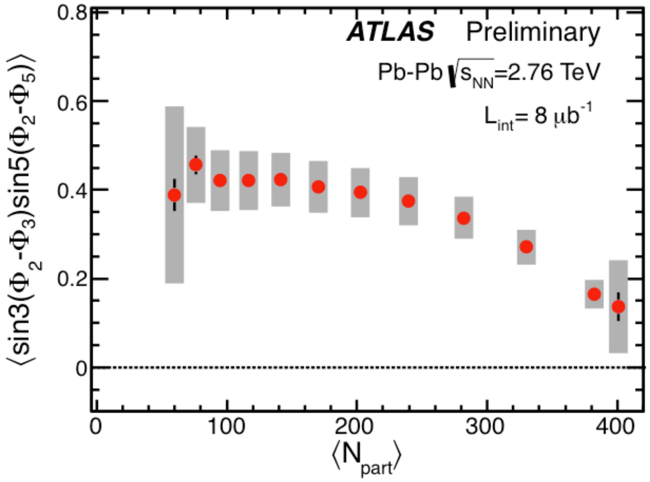


Three-plane correlations : ID

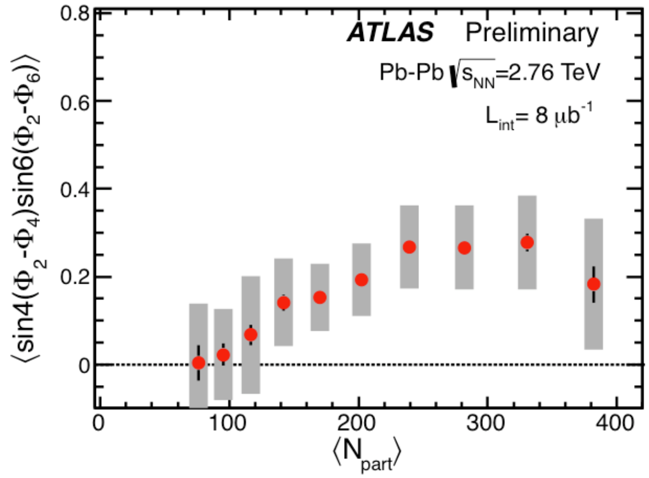


Deriving the sine and cosine product

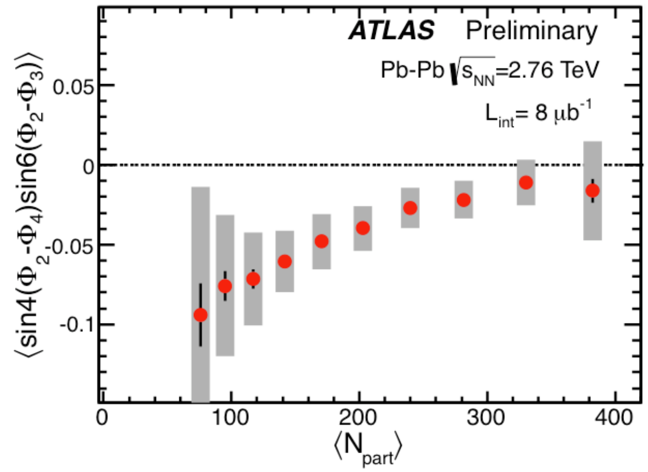
$\langle \sin 3(\Phi_2 - \Phi_3) \sin 5(\Phi_2 - \Phi_5) \rangle$



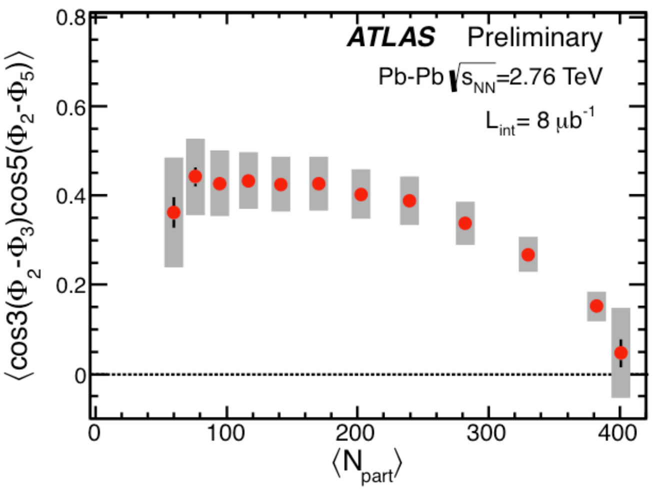
$\langle \sin 4(\Phi_2 - \Phi_4) \sin 6(\Phi_2 - \Phi_6) \rangle$



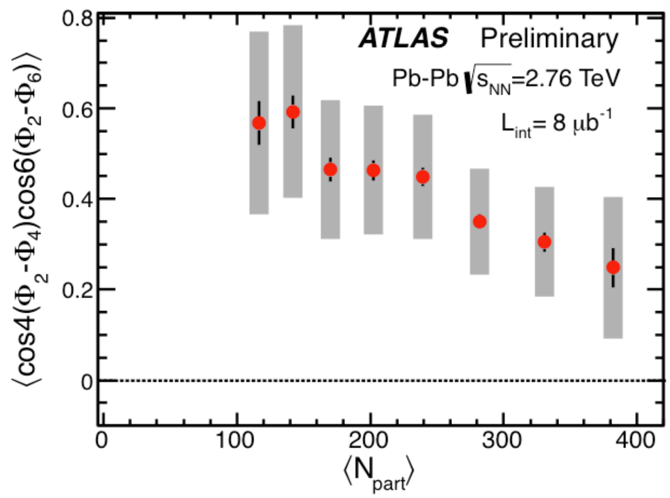
$\langle \sin 6(\Phi_2 - \Phi_3) \sin 4(\Phi_2 - \Phi_4) \rangle$



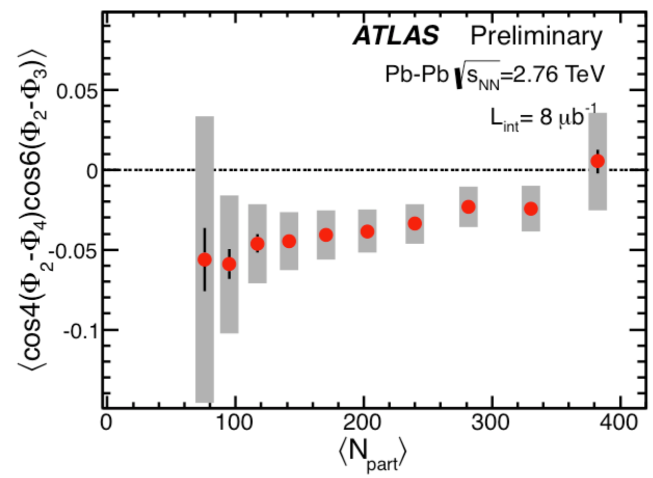
$\langle \cos 3(\Phi_2 - \Phi_3) \cos 5(\Phi_2 - \Phi_5) \rangle$



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

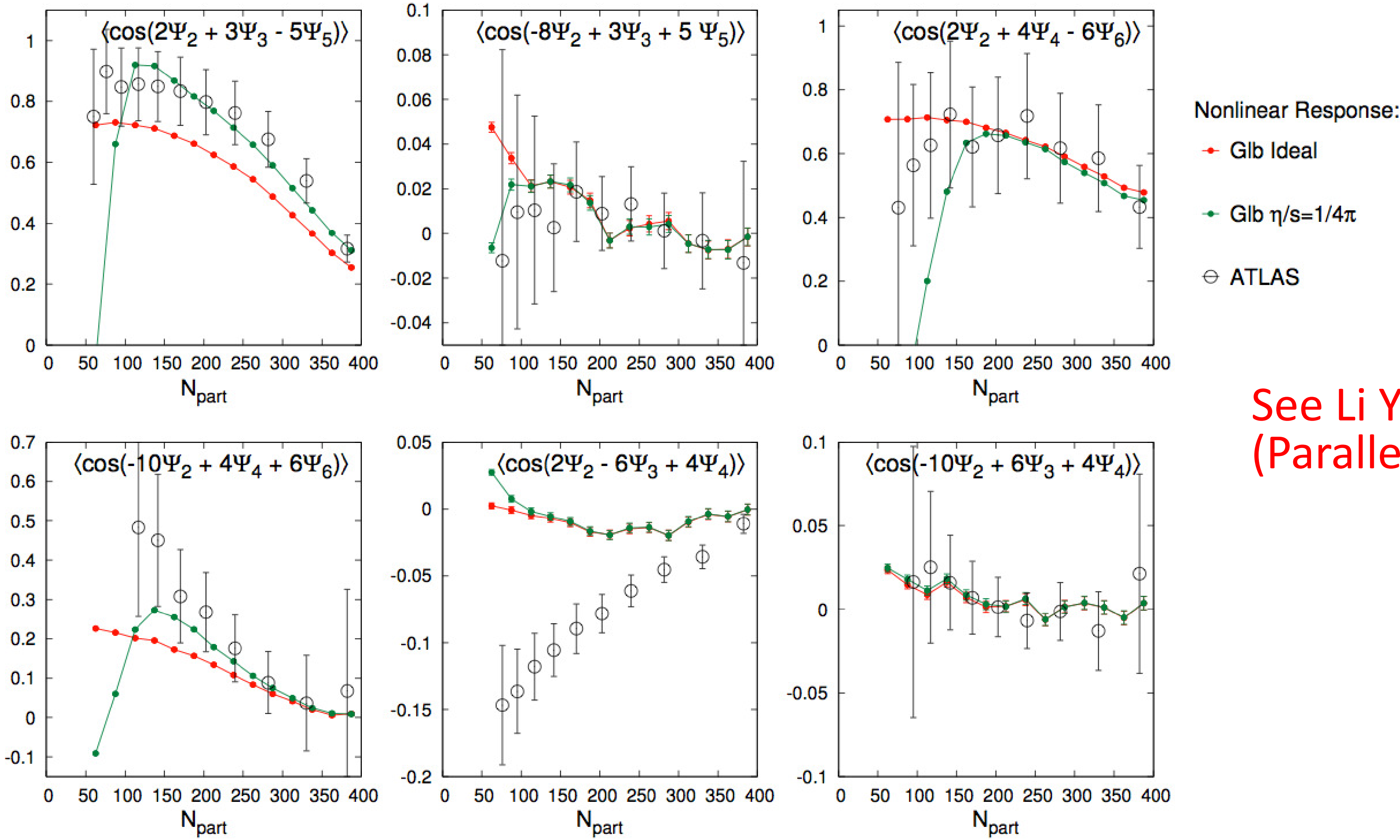


$\langle \cos 6(\Phi_2 - \Phi_3) \cos 4(\Phi_2 - \Phi_4) \rangle$



$$\begin{aligned}
2\Phi_2 + 4\Phi_4 - 6\Phi_6 &= 4(\Phi_4 - \Phi_2) - 6(\Phi_6 - \Phi_2) \\
-10\Phi_2 + 4\Phi_4 + 6\Phi_6 &= 4(\Phi_4 - \Phi_2) + 6(\Phi_6 - \Phi_2) \\
\langle \sin 4(\Phi_2 - \Phi_4) \sin 6(\Phi_2 - \Phi_6) \rangle &= \frac{1}{2}\left(\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6) \rangle - \langle \cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6) \rangle\right) \\
\langle \cos 4(\Phi_2 - \Phi_4) \cos 6(\Phi_2 - \Phi_6) \rangle &= \frac{1}{2}\left(\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6) \rangle + \langle \cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6) \rangle\right)
\end{aligned}$$

Comparison with Teaney and Yan

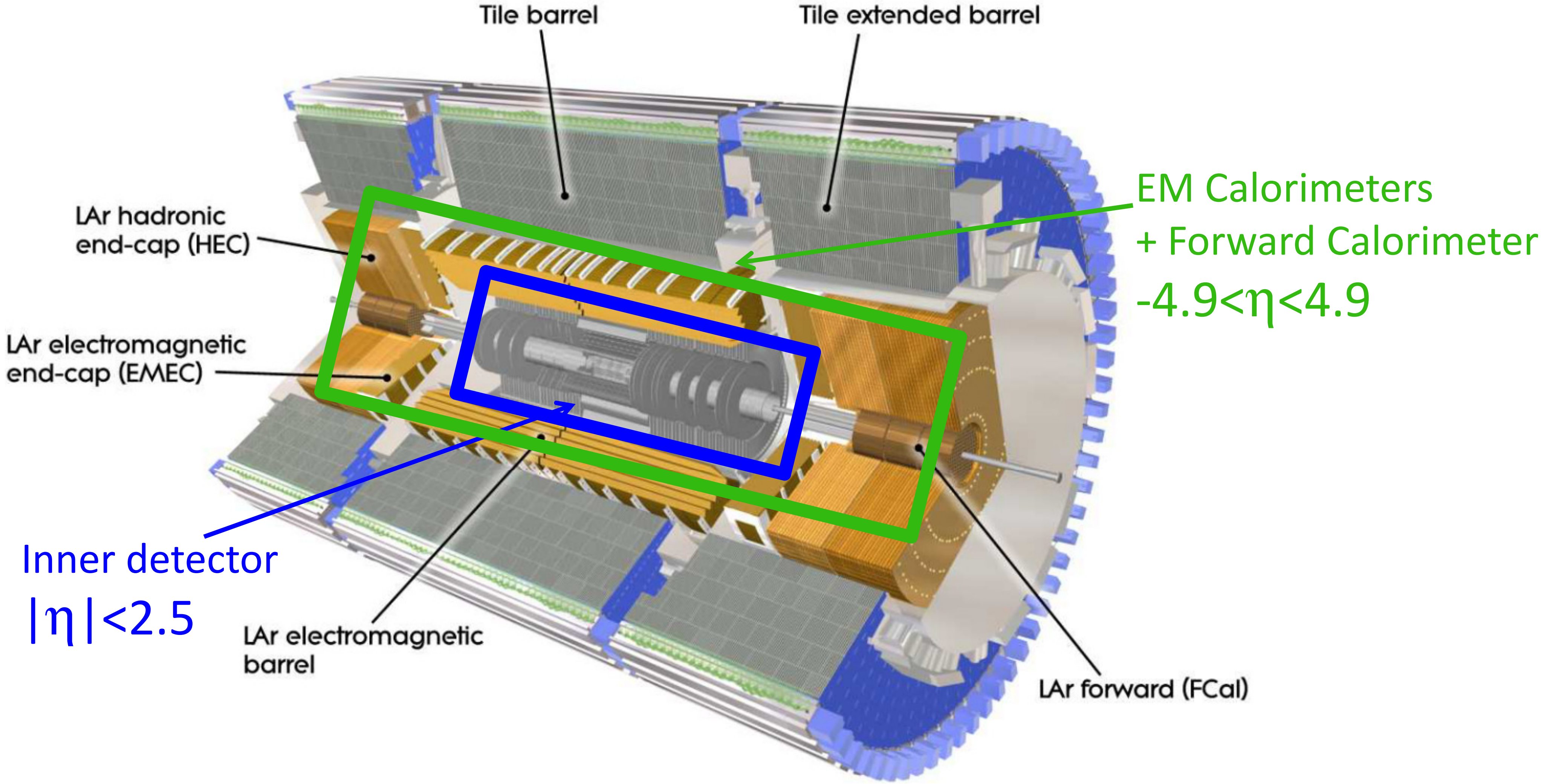


See Li Yan Talk (Parallel 1A)

The correlations are well reproduced using Teaney and Yan's cumulant method (see Li Yan talk in Parallel 1A).

Their method includes linear+non-linear response to initial geometry

ATLAS Detector



- EM Cal + FCal coverage : $-4.9 < \eta < 4.9$
- Tracking coverage : $|\eta| < 2.5$