Event by Event Flow in ATLAS and CMS

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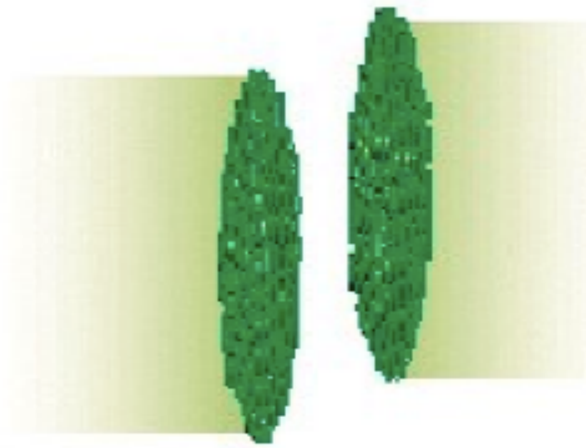
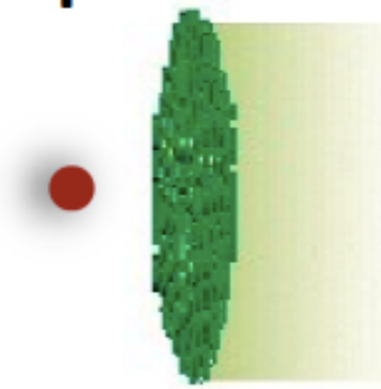
Some basic heavy-ion physics terminology

A + A



p + A

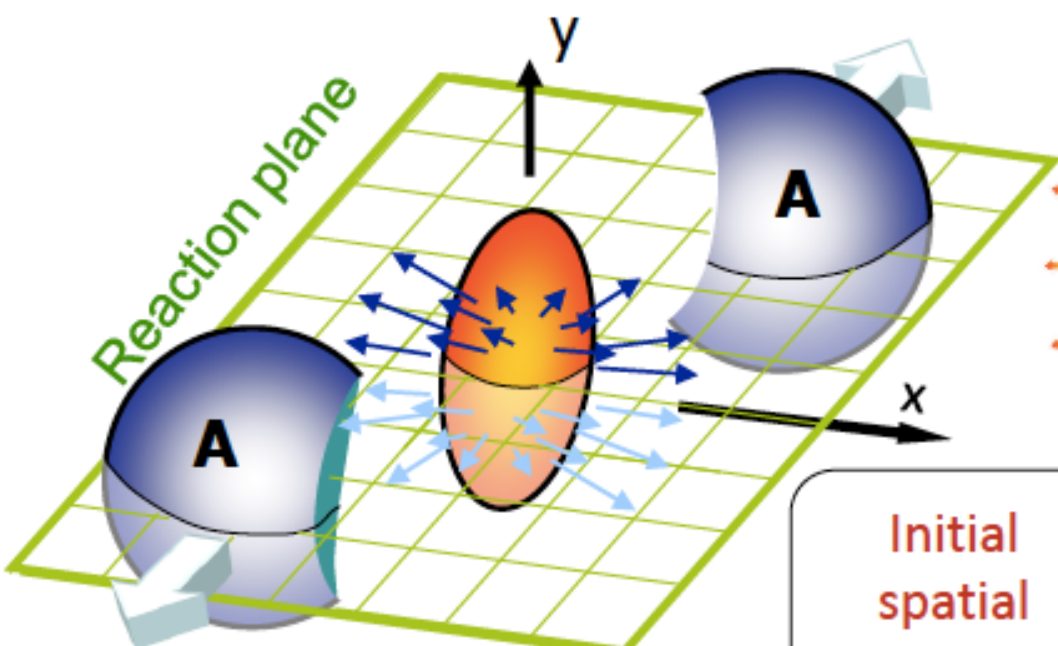


p + p

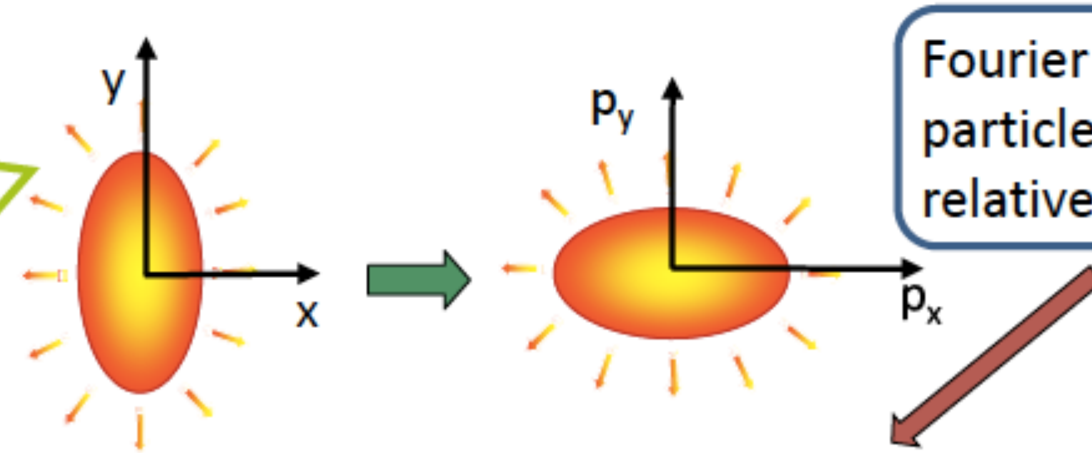
"hot/dense QCD matter"
final state effects
thermal and collective particle production (flow)

"cold nuclear matter"
initial state effects
shadowing and gluon saturation

"vacuum"
reference



J. Bielcikova (NPI ASCR)



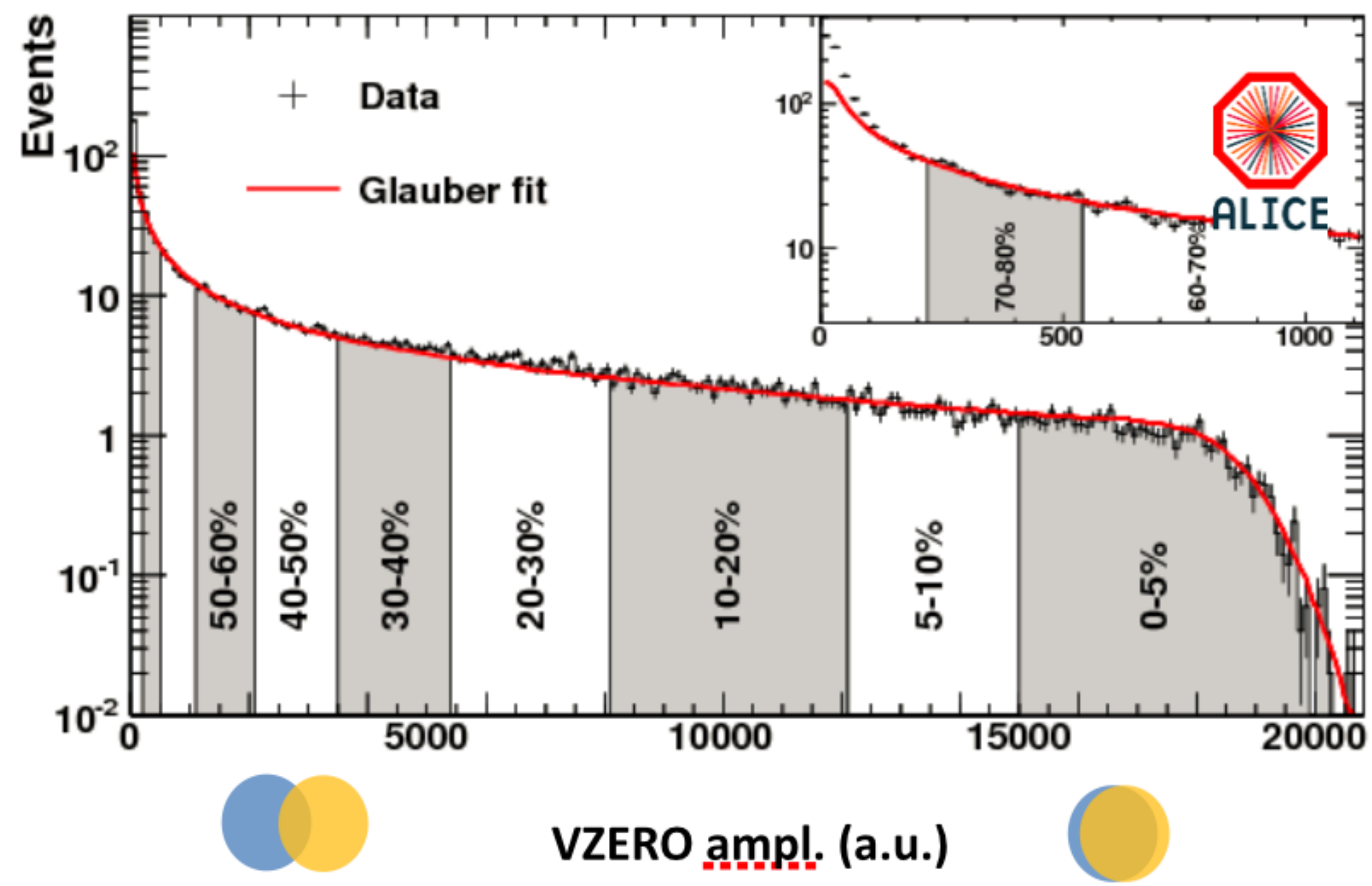
Fourier analysis of particle distribution relative to reaction plane

Initial spatial anisotropy → Strong pressure gradients → Elliptical (v_2) azimuthal anisotropy → Sensitivity to early expansion

Centrality in A+A:
impact parameter cannot be directly measured and has to be estimated from measurements of N_{ch}, E_T, ZDC, ..

Centrality is typically expressed as a % fraction of the total geometrical cross section: central is 0% centrality.

Glauber Model:
connects centrality to the number of binary collisions (N_{coll}) and nucleon participants (N_{part})



Modelling Primordial Fluctuations

MC-Glauber: Event-by-event fluctuations due to sampling of nucleon positions. Soft particle production proportional to the density of participating nucleons. Initial entropy is proportional to number of participating nucleons and number of binary collisions.

MC-KLN: Entropy production is determined by initial gluon production, calculated from structure function or participating nucleons.

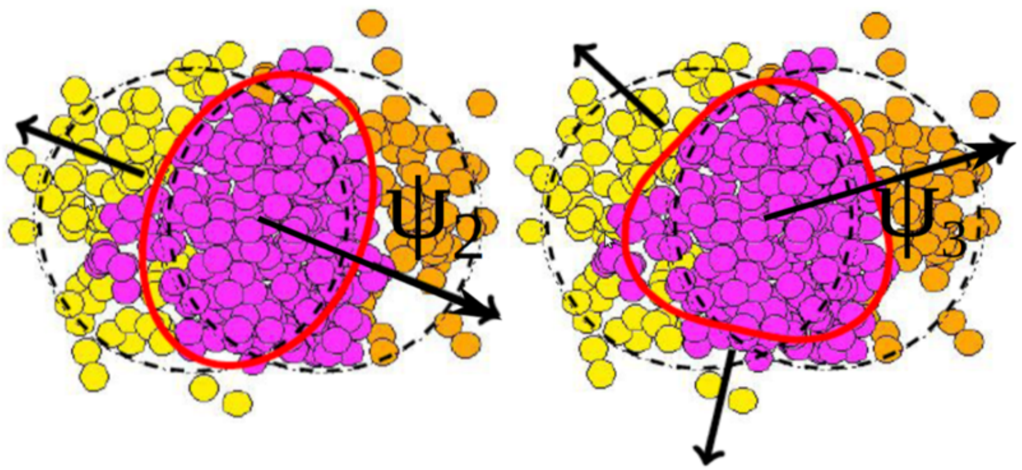
IP-Glasma: This model builds on the IP-Sat (impact parameter–dependent saturation) model to generate finite, deformed, fluctuating initial gluon field configurations in the transverse plane (longitudinal fluctuations are not yet included).

DIPSY: MC event generator, based on gluon radiation from colored dipoles (via dipole splitting), that uses BFKL evolution.

These initial fluctuations are then evolved through nonlinear viscous hydrodynamics into the final-state particle flow.

Anisotropic Flow

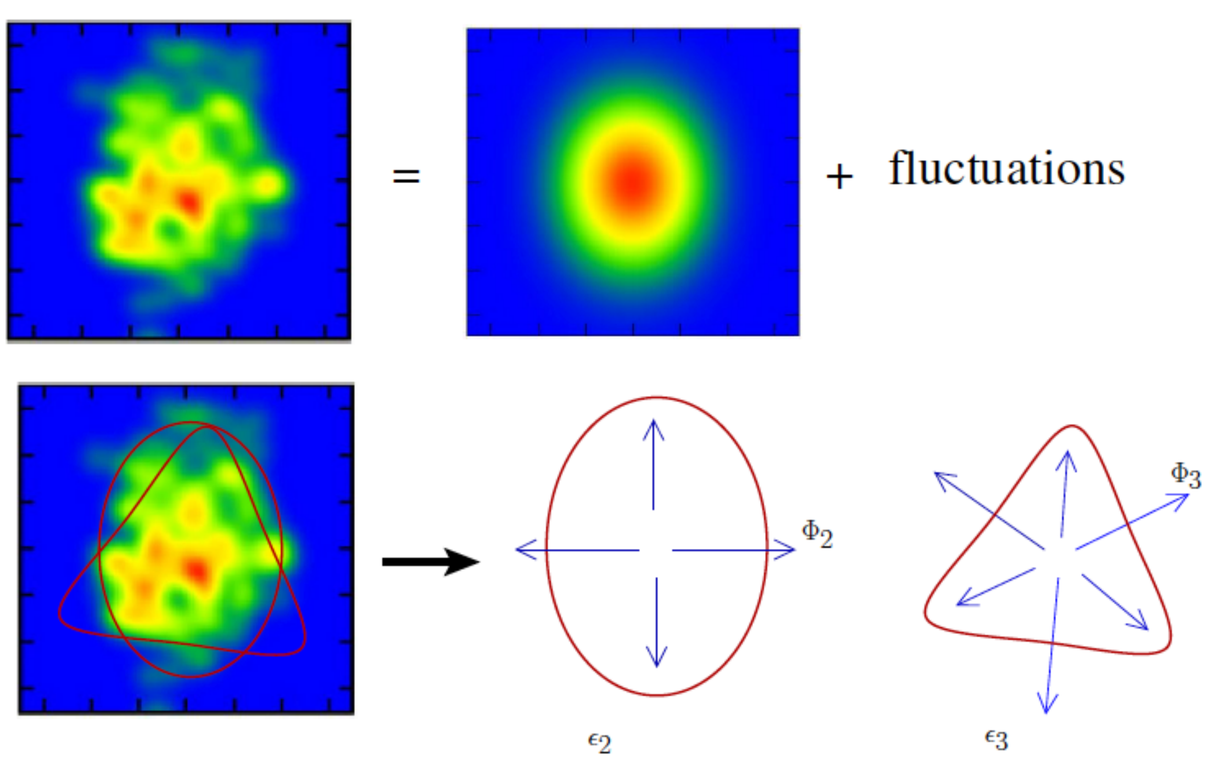
$$\frac{dN}{d\phi} \sim 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$$



B. Alver and G. Roland , Phys. Rev. C **81** (2010) 054905

Fourier transform of azimuthal angle distribution Φ.
Fourier coefficients v_n
Event plane angles Ψ_n

Event plane angles Ψ_n characterize the direction of maximum particle density in the event.



v_2 elliptic flow
- due to initial asymmetry

v_3 and higher orders
- due to initial fluctuations

General Prob. distribution $$p(\nu_n, \nu_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{evts}} \frac{dN_{evts}}{d\nu_n, d\nu_m, ..., d\Phi_n, d\Phi_m, ...}$$

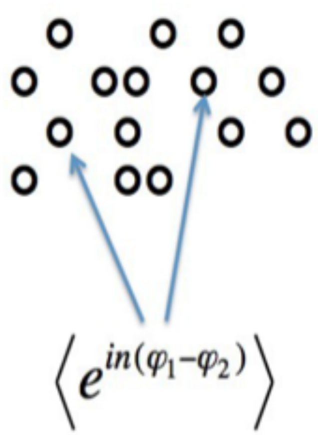
One measures projections of this general prob-distribution:

Event plane method,
Scalar product method:

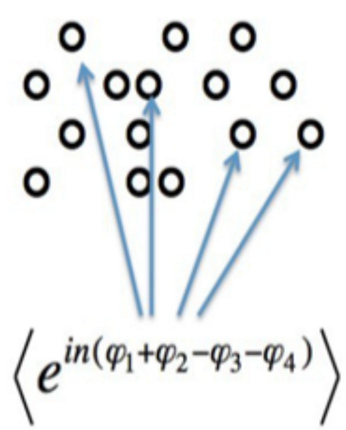
$$\frac{dN}{d\phi} \sim 1 + 2\sum_n v_n \cos[n(\phi - \Psi_{EP,n})]$$

Multi-particle correlations:

2-PC



4-PC



Lee-Yang Zero
(All-Particle Correlation)

e.g. 2 PC $$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2\sum_n V_{n\Delta} \cos(n\Delta\phi)$$

Flow methods

Correlations of 2k particles:

$$\langle\langle 2k\rangle\rangle = \langle corr_n\{2k\}\rangle = \langle\langle e^{in(\phi_1+\ldots+\phi_k-\phi_{k+1}-\ldots-\phi_{\{2k\}})}\rangle\rangle = \langle v_n\{2k\}^{2k}\rangle$$

Cumulant method:

The idea of using 2k-particle cumulants is to suppress the non-flow contribution by eliminating the correlations which act between fewer than 2k particles.

$$c_n\{2\} = \langle\langle 2\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3$$

$$\longrightarrow$$

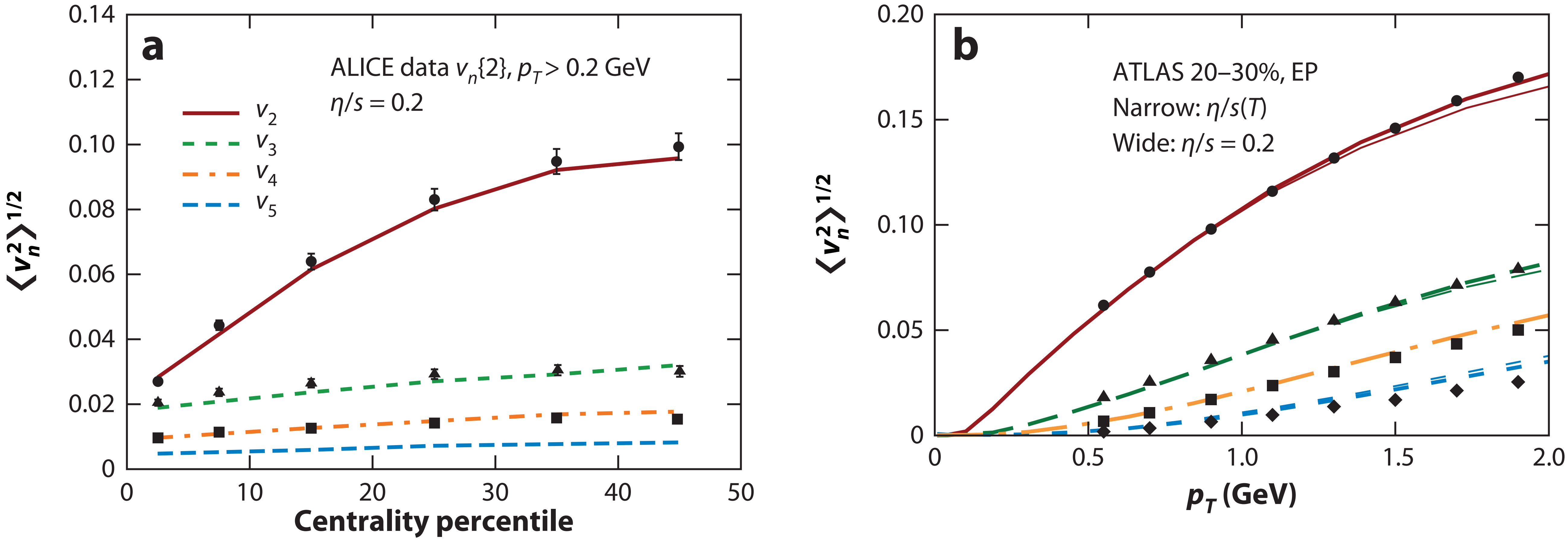
$$v_n\{2\} = \sqrt{c_n\{2\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$

Observables

J. Jia 2014 *J. Phys. G: Nucl. Part. Phys.* **41** 124003

	pdfs	cumulants
Flow-amplitudes	$p(v_n)$	$v_n\{2k\},\ k = 1,2,...$
	$p(v_n, v_m)$	$\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle,\ n \neq m$ ...
	$p(v_n, v_m, v_l)$	$\langle v_n^2 v_m^2 v_l^2\rangle + 2\langle v_n^2\rangle\langle v_m^2\rangle\langle v_l^2\rangle -$ $\langle v_n^2 v_m^2\rangle\langle v_l^2\rangle - \langle v_m^2 v_l^2\rangle\langle v_n^2\rangle - \langle v_l^2 v_n^2\rangle\langle v_m^2\rangle$ $n \neq m \neq l$ ...
	...	Obtained recursively as above
EP-correlation	$p(\Phi_n, \Phi_m, ...)$	$\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k k c_k = 0$
Mixed-correlation	$p(v_l, \Phi_n, \Phi_m, ...)$	$\langle v_l^2 v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle -$ $\langle v_l^2\rangle\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k k c_k = 0,\ n \neq m \neq l ...$

Single flow harmonics v_n

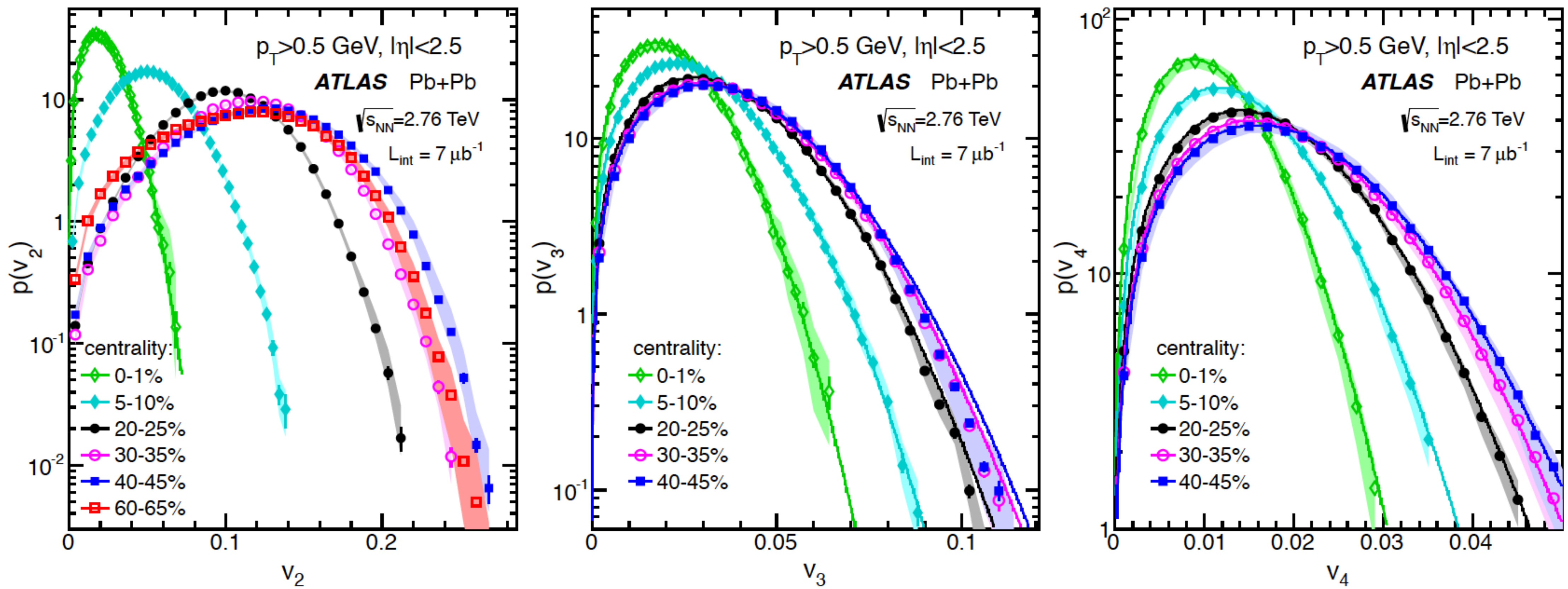


Heinz, Snelling, Ann.Rev.Nucl.Part.Sci. 63 (2013) 123-151

Good agreement is found between data and model calculations based on viscous hydrodynamical calculations (IP-Glasma), which include gluon fluctuations and gluon saturation.

Flow Distribution $p(v_n)$

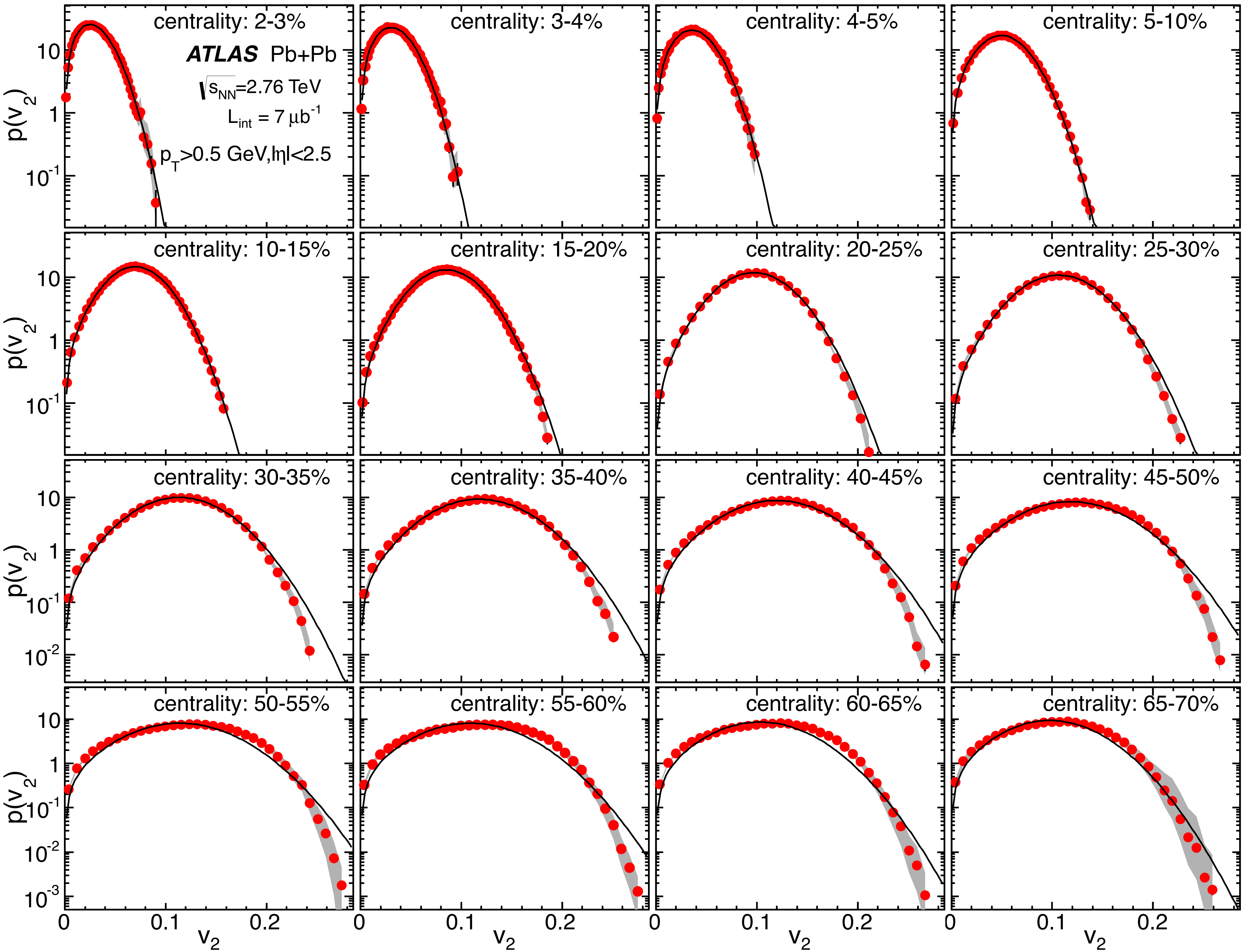
ATLAS, JHEP 11 (2013) 183



Probability distribution of EbyE v_n for several centrality bins. The shaded bands indicate the uncertainty on the v_n-shape.

Solid lines: Bessel-Gaussian function based on measurement of $\langle v_n \rangle$ for the fluctuation-only scenario.

Flow Distribution $p(v_n)$

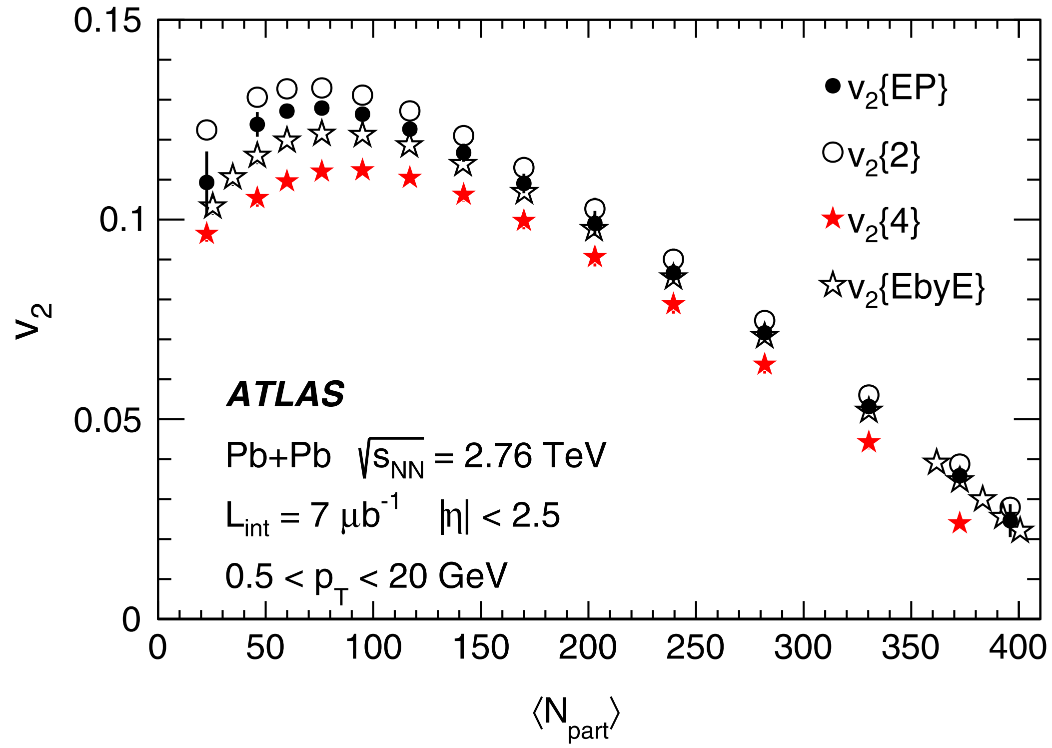


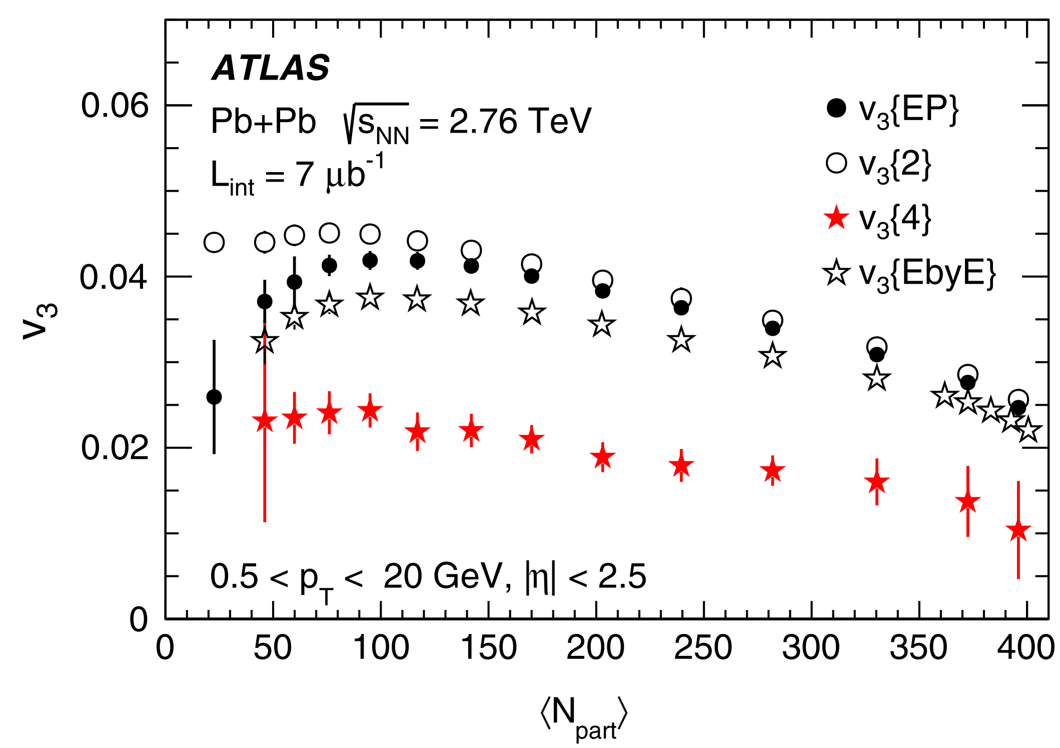
Deviations for v_2 from Bessel-Gaussian function at mid-central and peripheral collisions

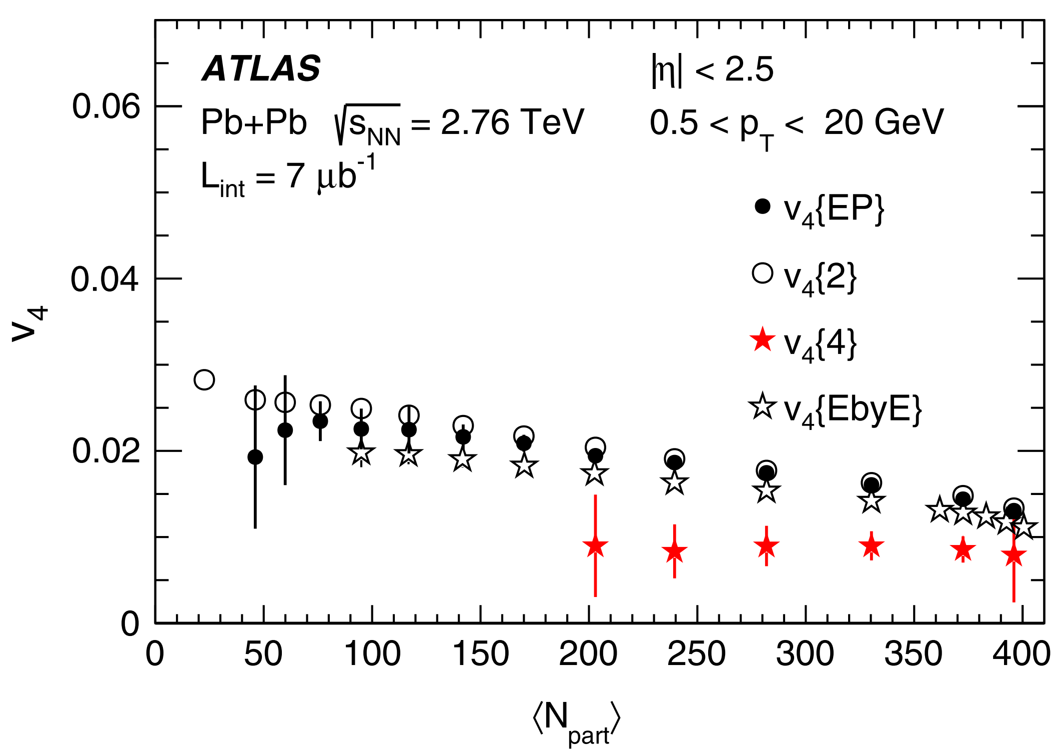
ATLAS JHEP 11(2013) 183

Comparison of different v_n measurements

ATLAS, Eur. Phys. J. C (2014) 74:3157





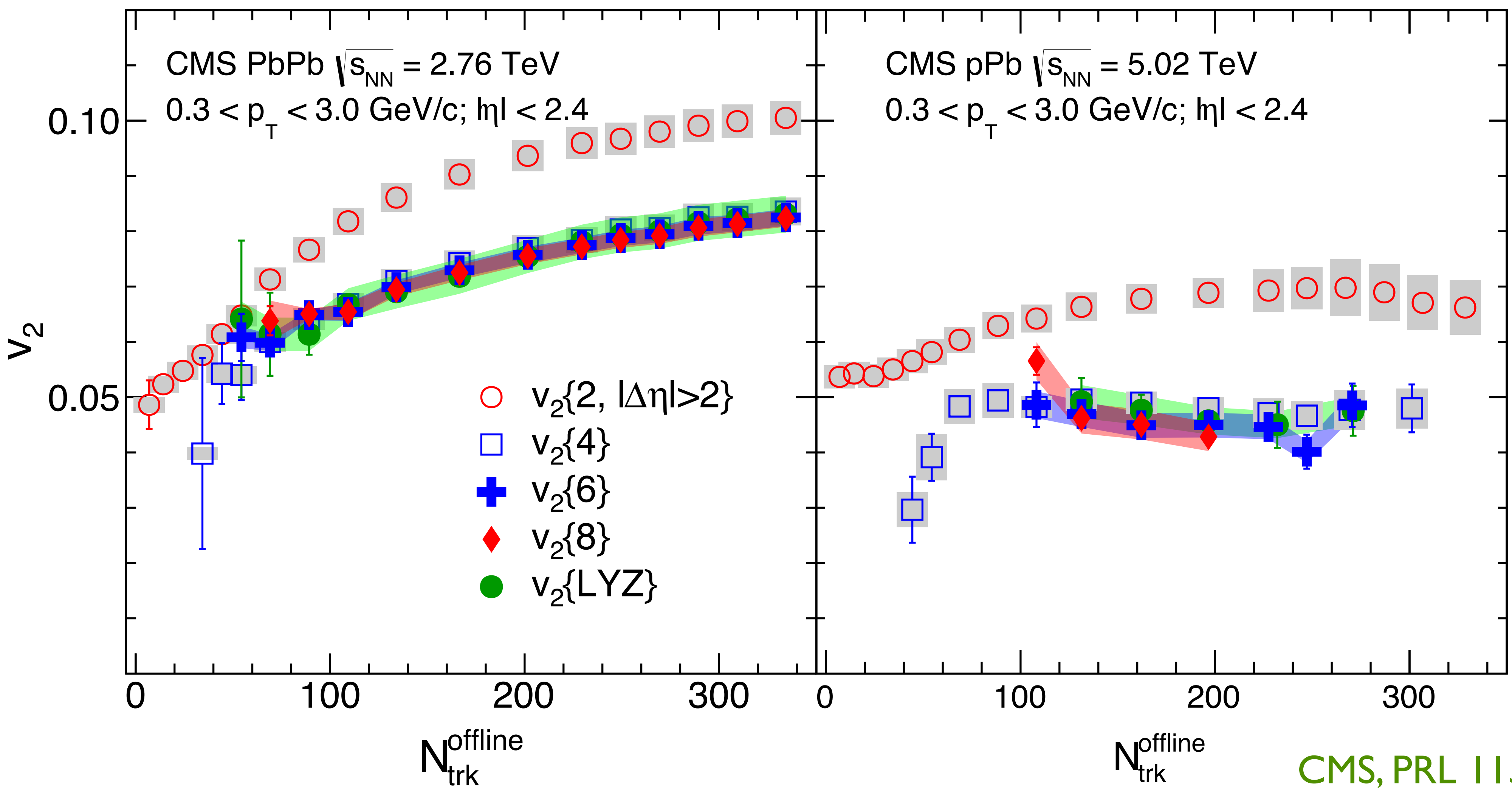


Comparisons of v_n measurements using different methods.

Tendency:
$v_n\{2\} > v_n\{EP\} > v_n\{EbyE\} > v_n\{4\}$

Comparison PbPb and pPb

CMS uses multi-particle correlation techniques to measure flow and event-by-event fluctuations.



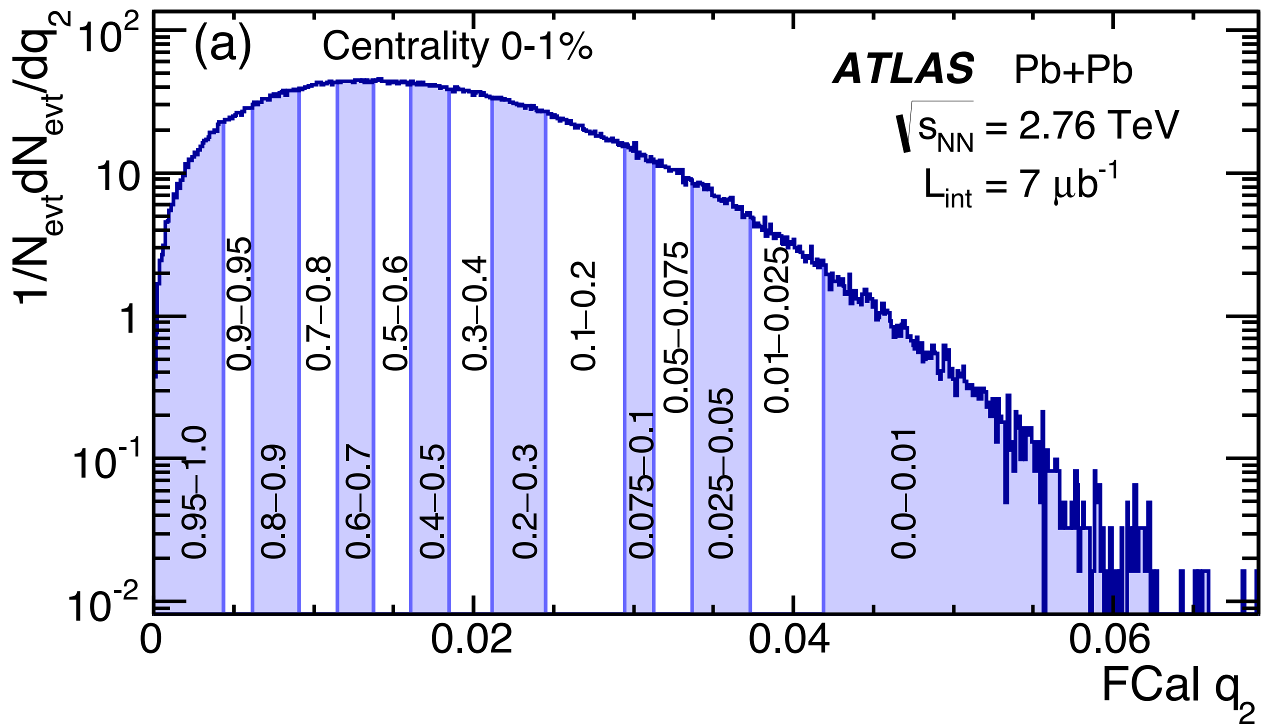
CMS, PRL 115 (2015) 012301

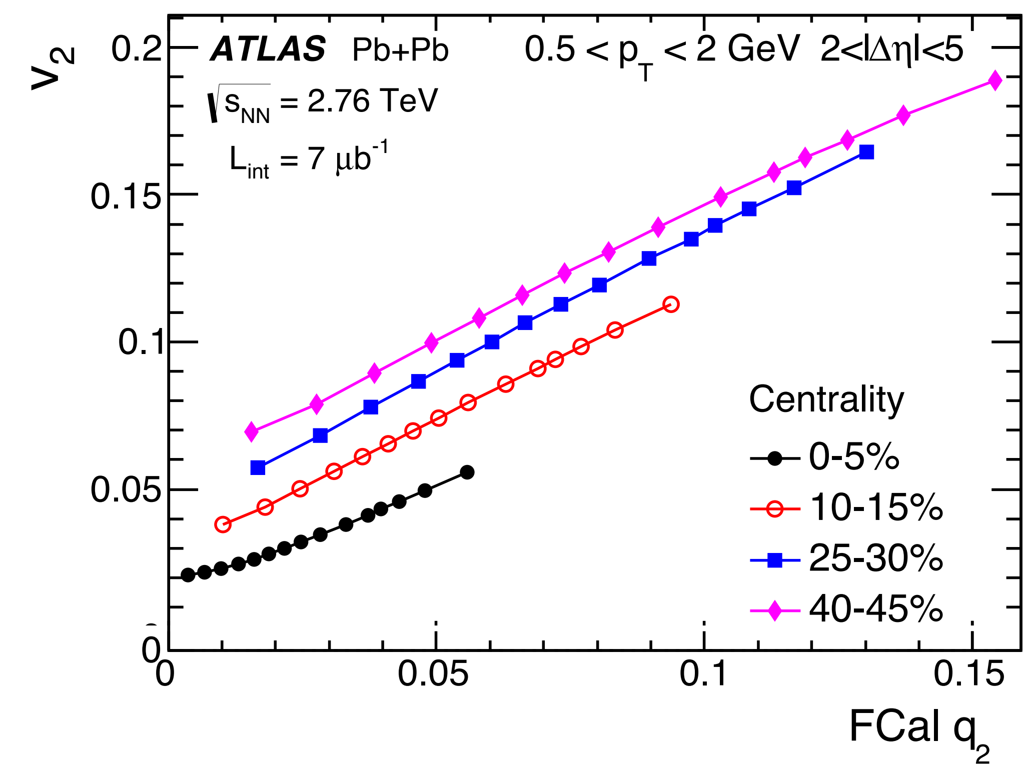
v_2 signal also in pPb:

$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ\}$ ± 2% (PbPb) ± 10% (pPb)

Flow amplitude correlations p(v_n, v_m)

ATLAS, arxiv 1504.01289





Measurement of flow vector $\mathbf{q_2}$ (shape parameter) in the forward calorimeter for the 1% most-central collisions.

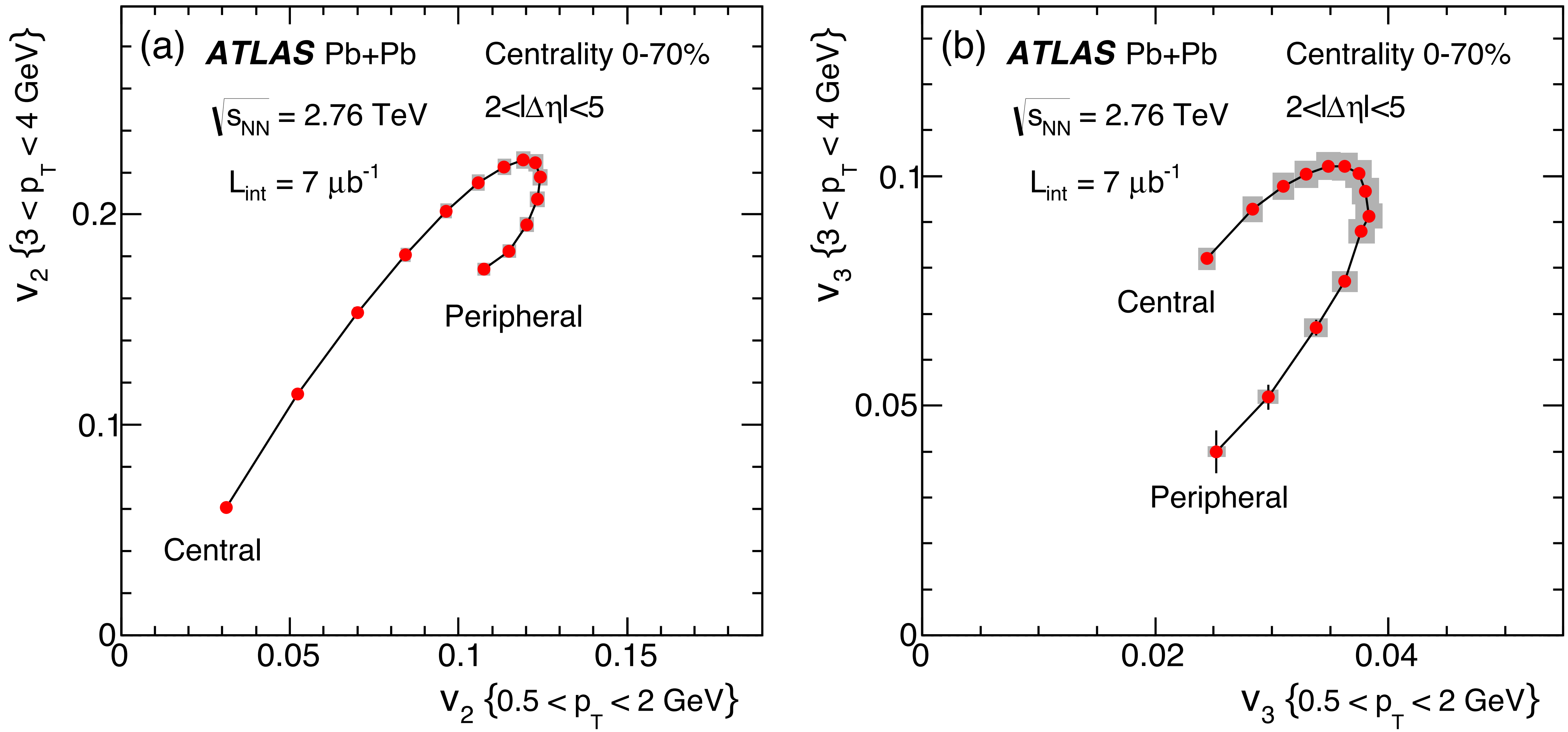
Correlation between q_2 and v_2 in four centrality bins.

$$\boldsymbol{q}_m = q_m e^{im\Psi_m^{\rm obs}} = \frac{\Sigma w_j e^{-im\phi_j}}{\Sigma w_j} - \langle \boldsymbol{q}_m \rangle_{\rm evts}, \; m = 2 \text{ or } 3$$

where w_j is the E_T of the j^{th} tower at azimuthal angle φ_j in the FCAL.

Flow amplitude correlations $p(v_n, v_m)$

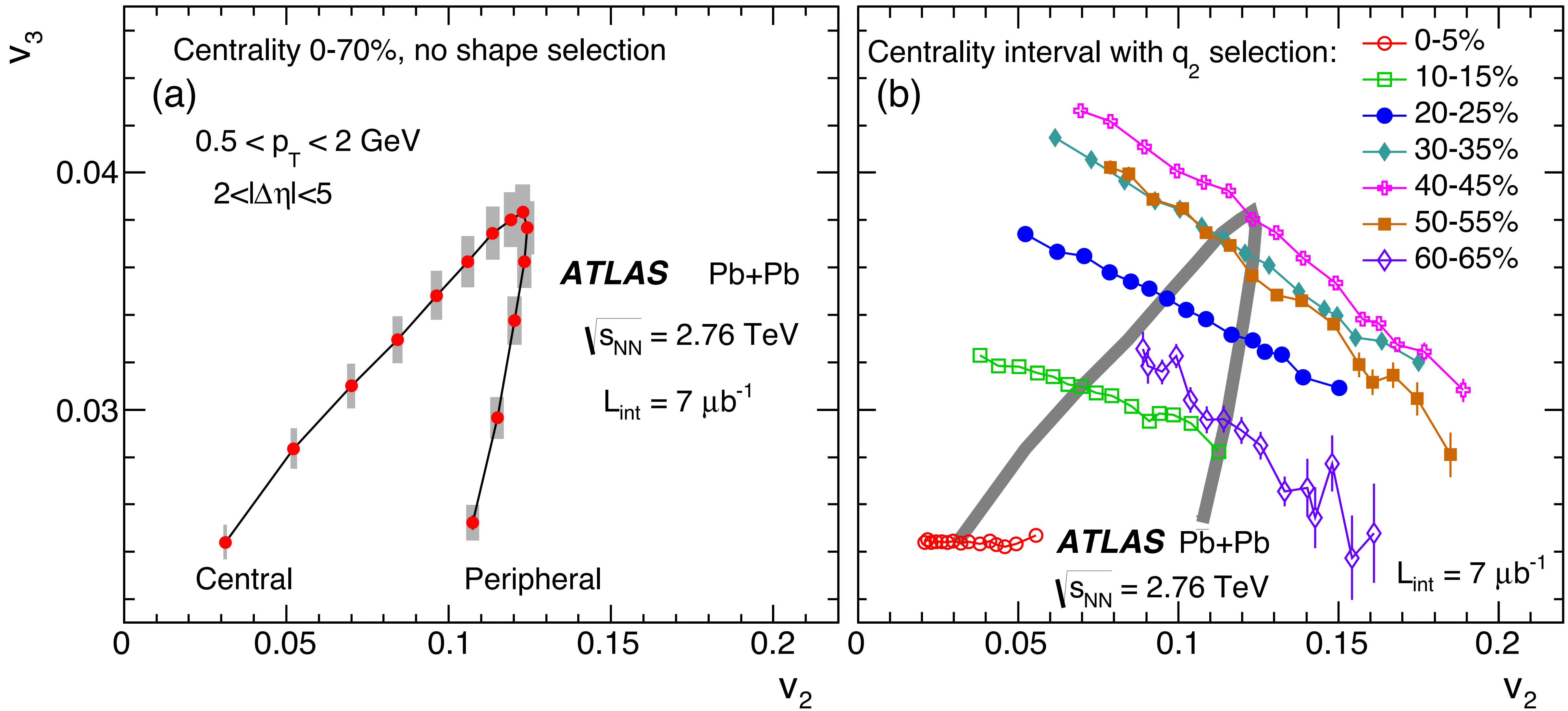
ATLAS, arxiv 1504.01289



Correlation of v_2 and v_3 for two p_T bins.
Values are calculated in fourteen 5% centrality bins in the range 0-70%.

Flow amplitude correlations $p(v_n, v_m)$

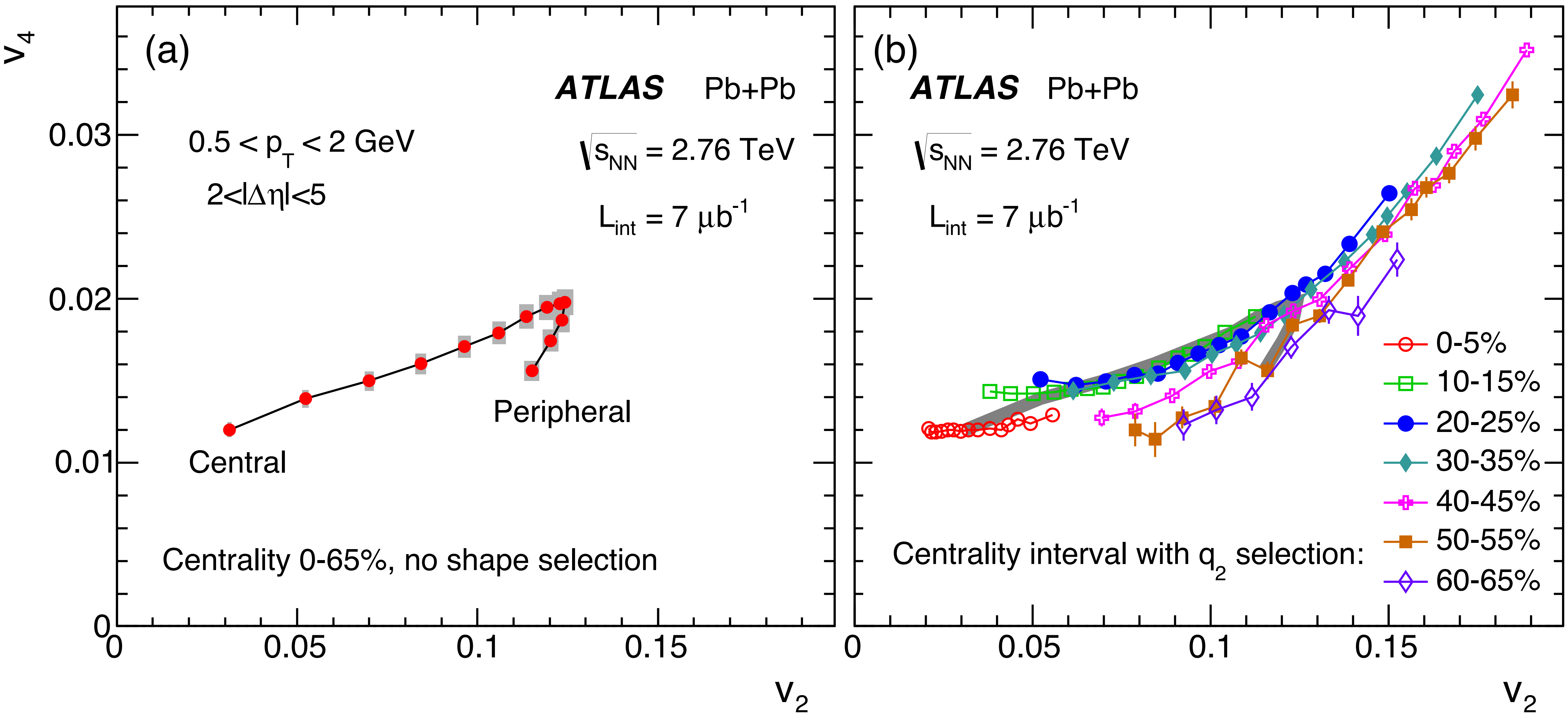
ATLAS, arxiv 1504.01289



Fourteen 5% centrality bins.
No shape selection.

Fifteen q_2 intervals in seven centrality ranges

Flow amplitude correlations $p(v_n, v_m)$

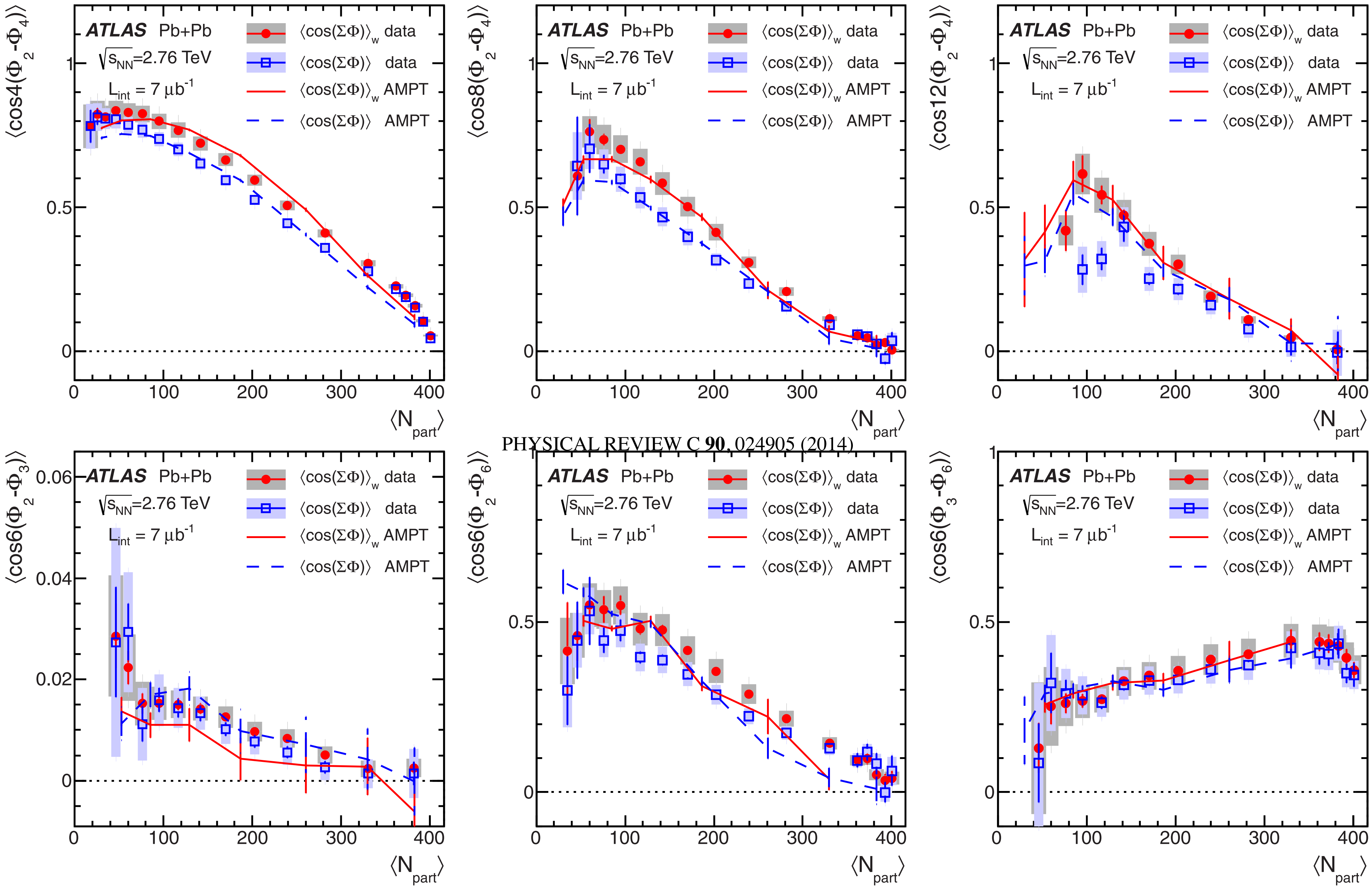


Thirteen 5% centrality bins.
No shape selection.

Fifteen q_2 intervals in seven centrality ranges

Event plane correlations p(Φn, Φm, ...)

ATLAS, Phys. Rev. C **90**, 024905 (2014)



Solid line: scalar product method
Dashed line: event plane method

Factorization breaking in correlations

CMS uses multi-particle correlations to study factorization breaking effects which are due to initial state fluctuations. These measurements provide information about event-plane fluctuations.

$$\frac{dN}{d\phi} \sim 1 + 2\sum_{n=1}^{N} v_n(p_T,\eta)\cos n(\phi - \Psi_n(p_T,\eta))$$

$$\frac{dN^{pairs}}{d\Delta\phi} \sim 1 + 2\sum_{n=1}^{N} V_{n\Delta}(p_T^a, p_T^b)\cos n(\Delta\phi)$$

$$V_{\Delta n}(p_T^a, p_T^b) = \upsilon_n(p_T^a)\,\upsilon_n(p_T^b)\cos n(\Psi_n(p_T^a) - \Psi_n(p_T^b))$$

$$V_{\Delta n}(p_T^a, p_T^b) \stackrel{?}{=} \upsilon_n(p_T^a)\,\upsilon_n(p_T^b)$$

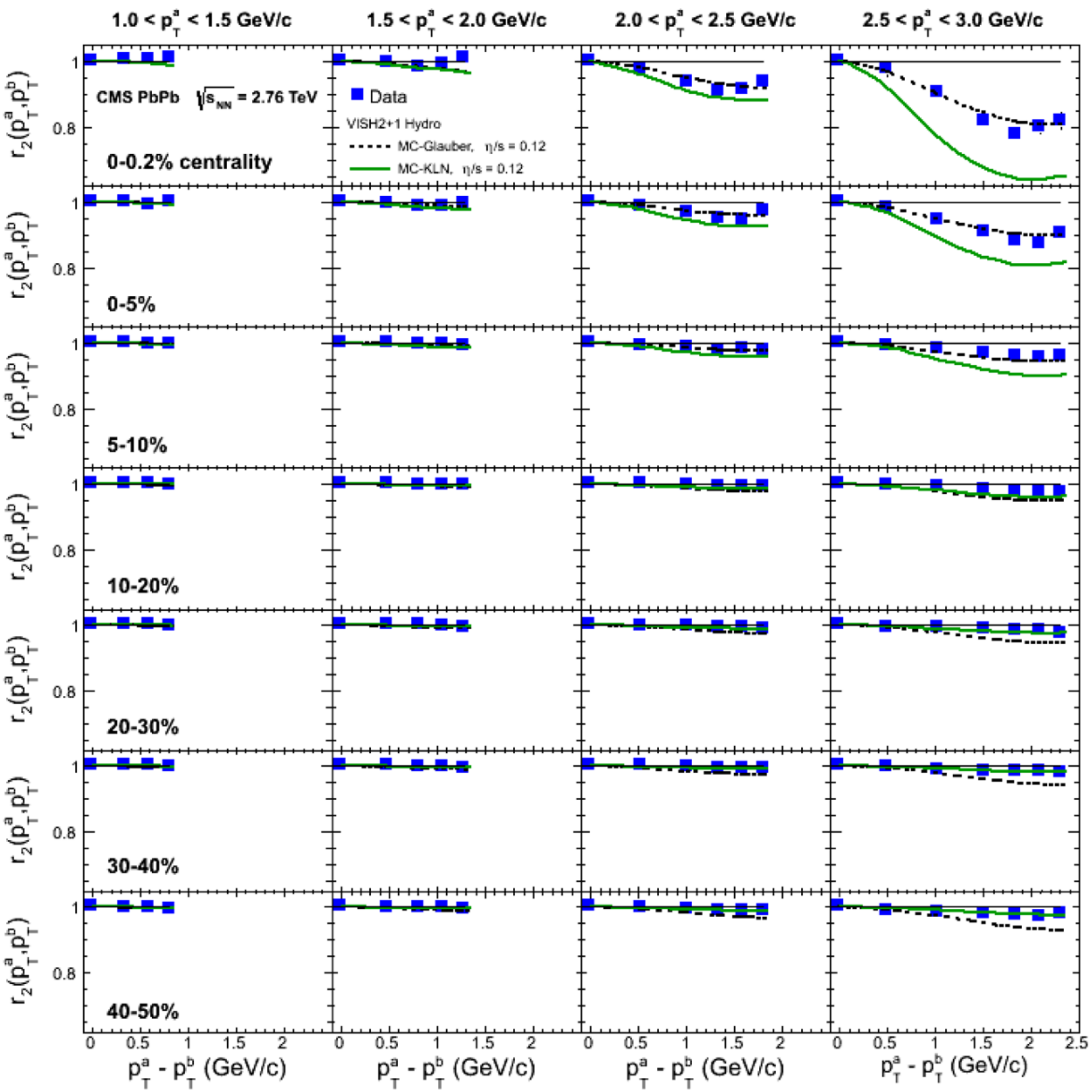
=1 or ≠1

$$r_n = \frac{V_{\Delta n}(p_T^a, p_T^b)}{\sqrt{V_{\Delta n}(p_T^a, p_T^a)\,V_{\Delta n}(p_T^b, p_T^b)}}$$

=1 FACTORIZATION

r_2 in PbPb

CMS, arXiv:1503.01692



p_T dependent factorization ratio as function of p_T^a-p_T^b

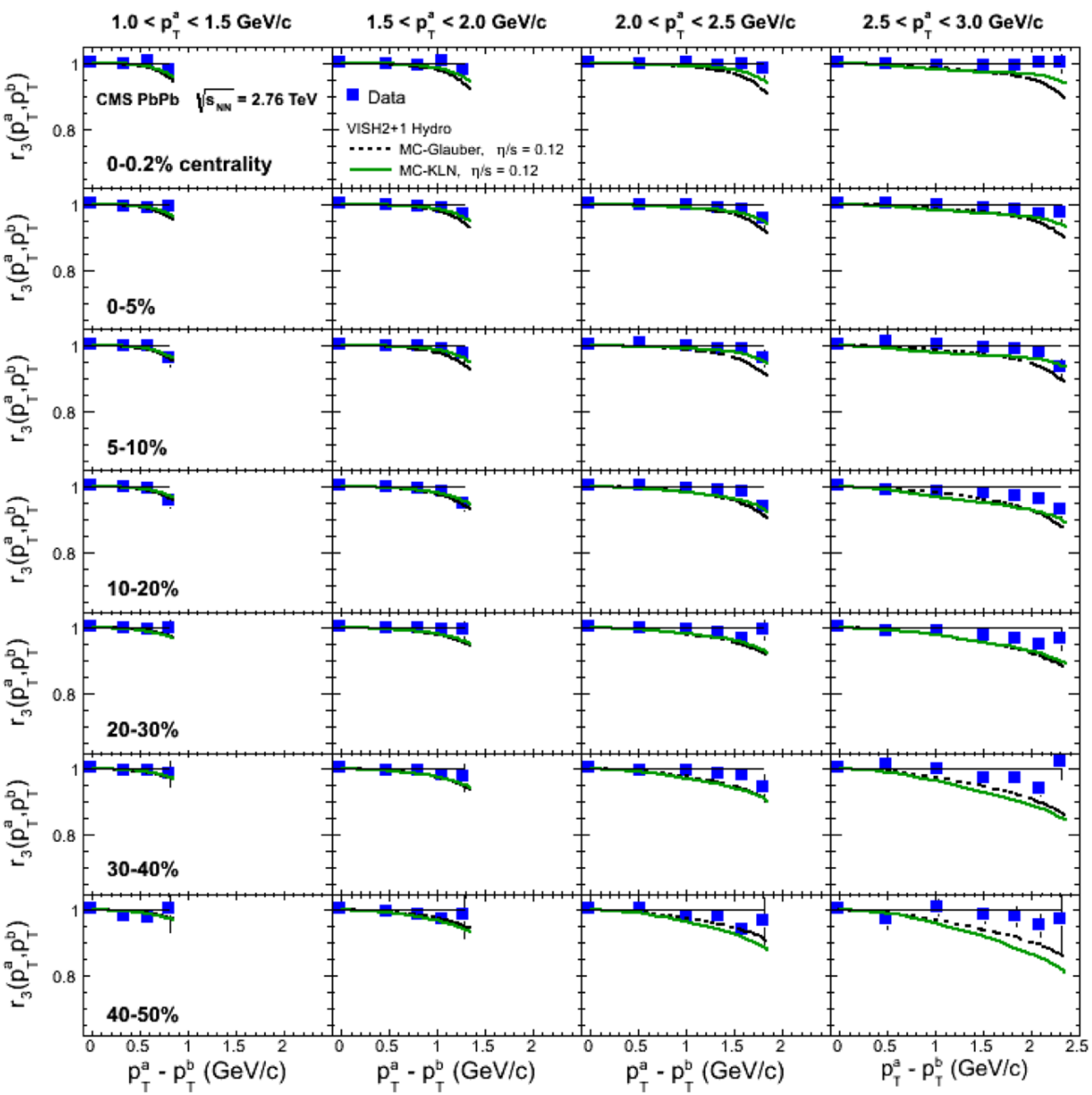
in bins of p_T^a for different centrality ranges in PbPb.

Comparison with
MC-Glauber : dashed line
MC-KLN: solid green line

Factorization breaking at high p_T^a and high p_T^a-p_T^b

r_3 in PbPb

CMS, arXiv:1503.01692



p_T dependent factorization ratio as function of p_T^a-p_T^b

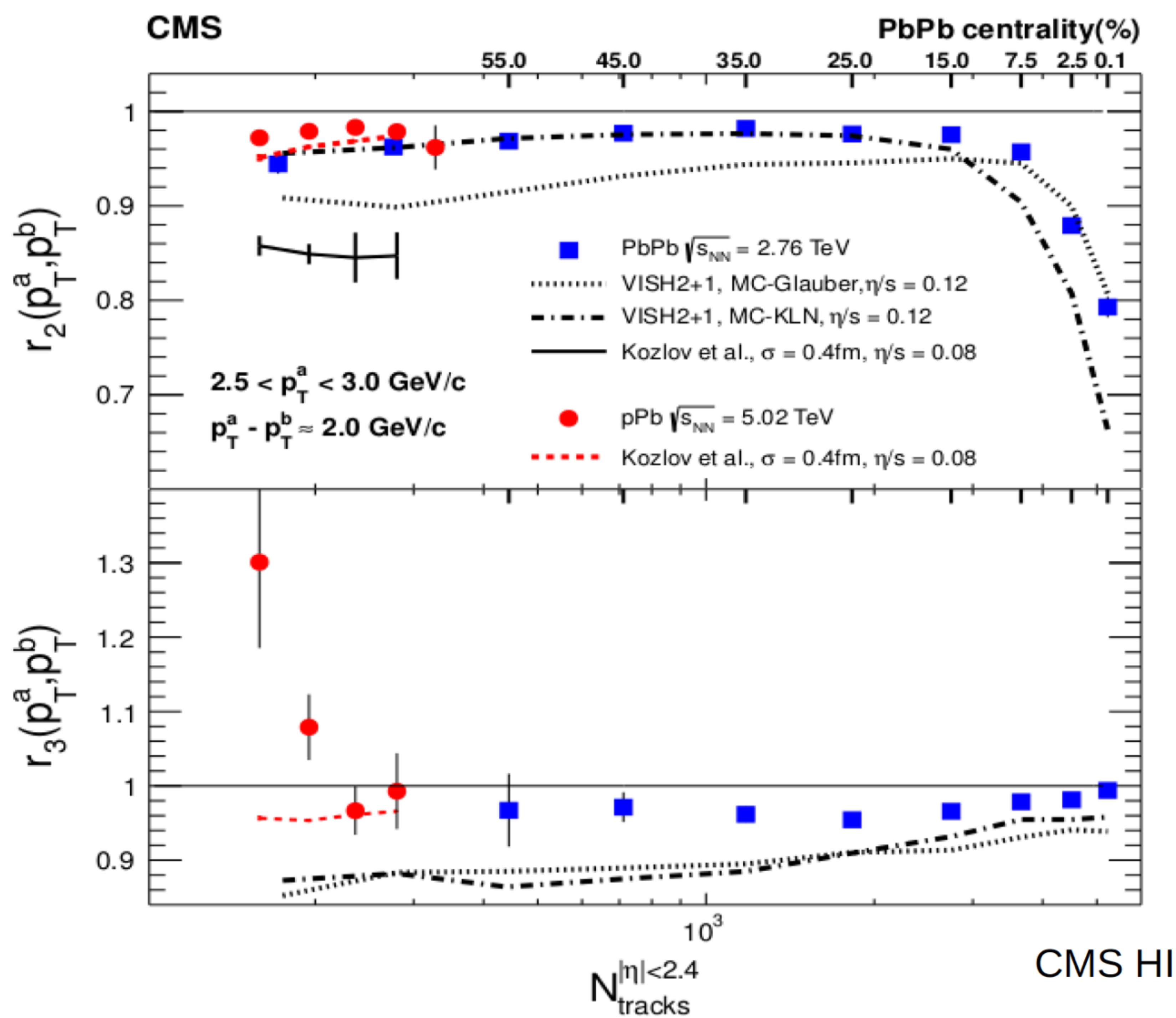
in bins of p_T^a for different centrality ranges in PbPb.

Comparison with
MC-Glauber : dashed line
MC-KLN: solid green line

Factorization breaking at high p_T^a and high p_T^a-p_T^b

r_n vs. centrality

CMS, arXiv:1503.01692



The p_T-dependenct factorization ratios as function of event multiplicity.

Breakdown of factorization observed in r_2 for centrality < 5%.

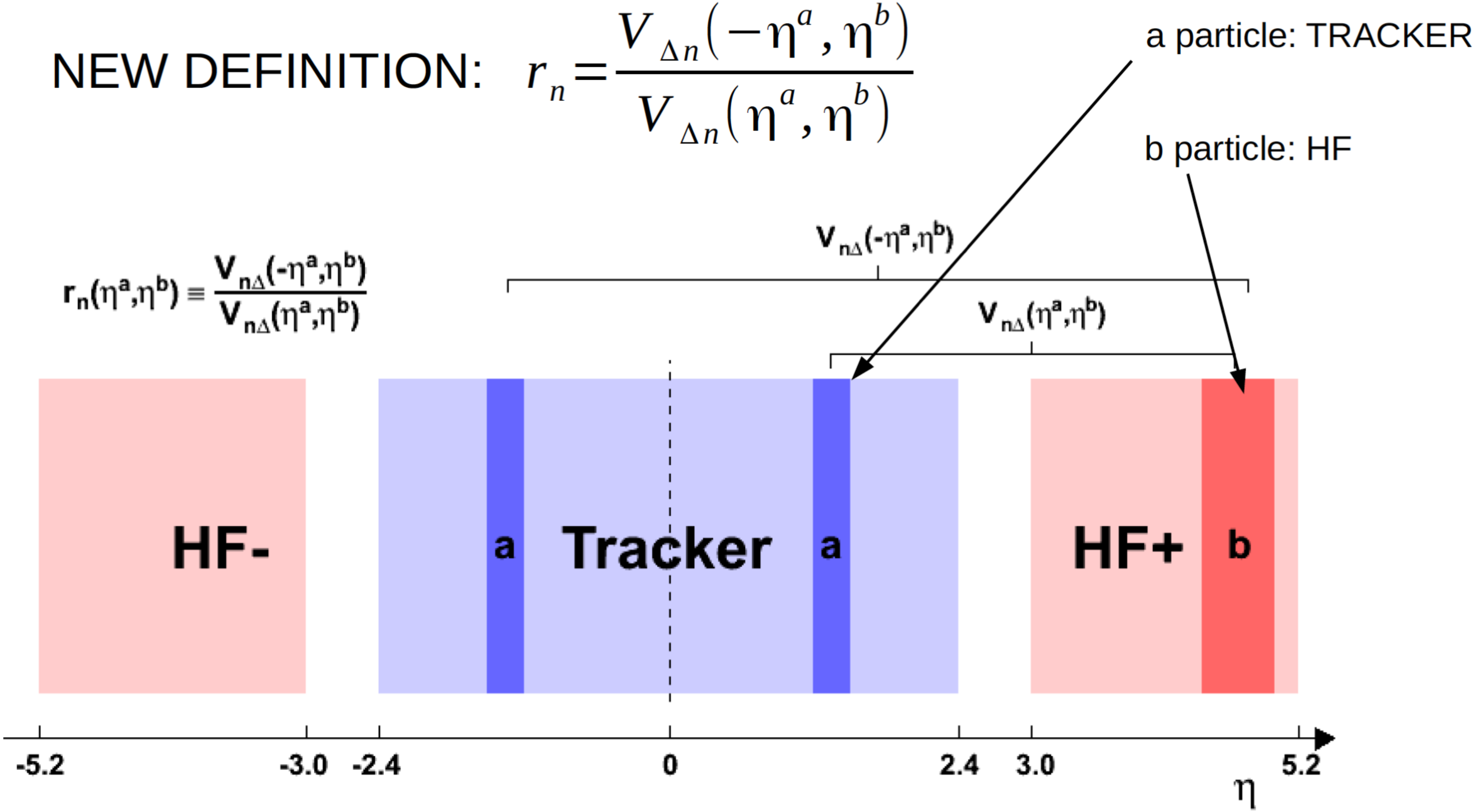
For r_3 factorization holds at the 2-3% level.

No MC calculation can describe data over full centrality range.

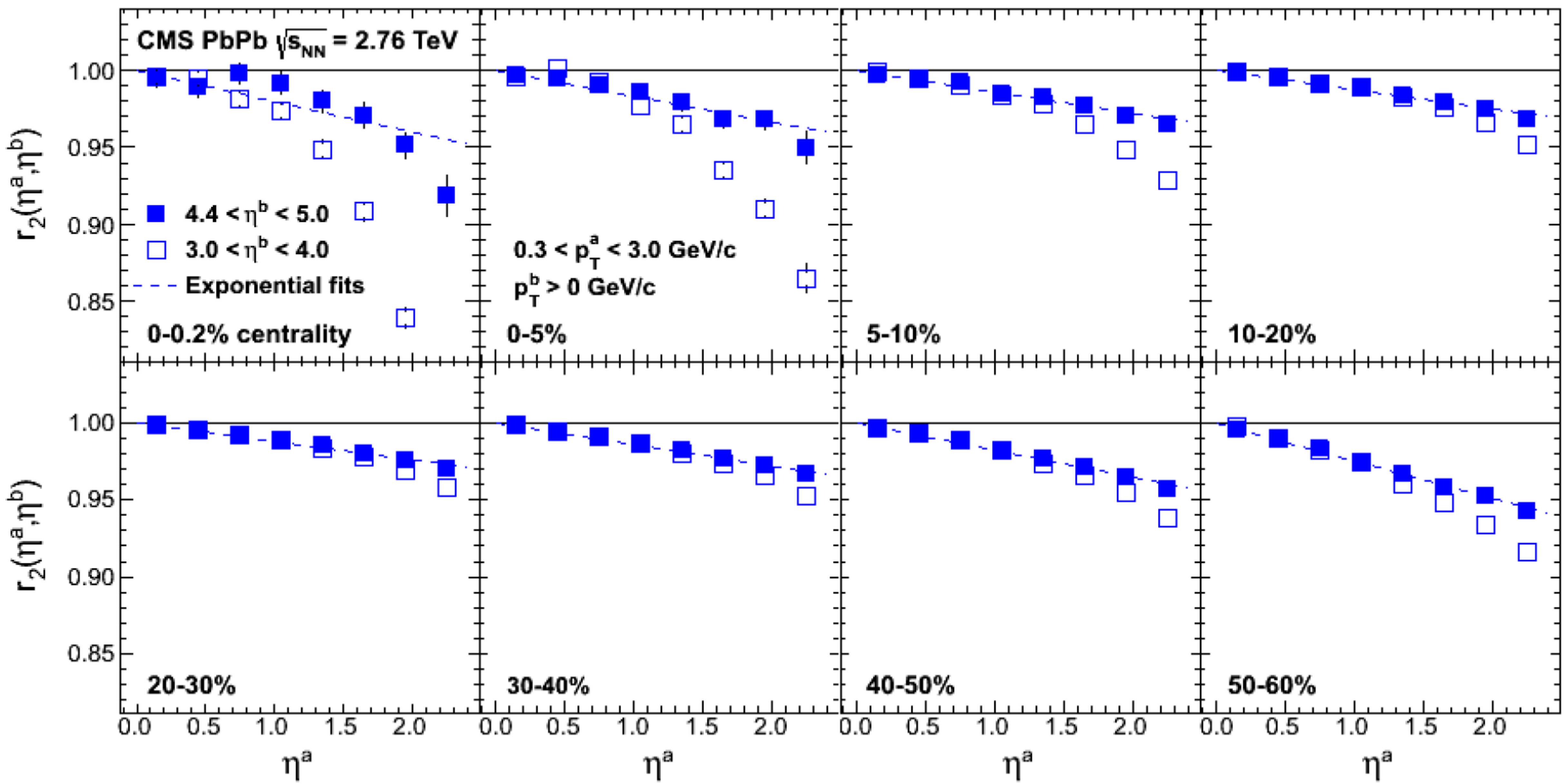
CMS: Pseudo-Rapidity Factorization Breakdown

Study of longitudinal fluctuations

NEW DEFINITION: $$r_n = \frac{V_{\Delta n}(-\eta^a, \eta^b)}{V_{\Delta n}(\eta^a, \eta^b)}$$

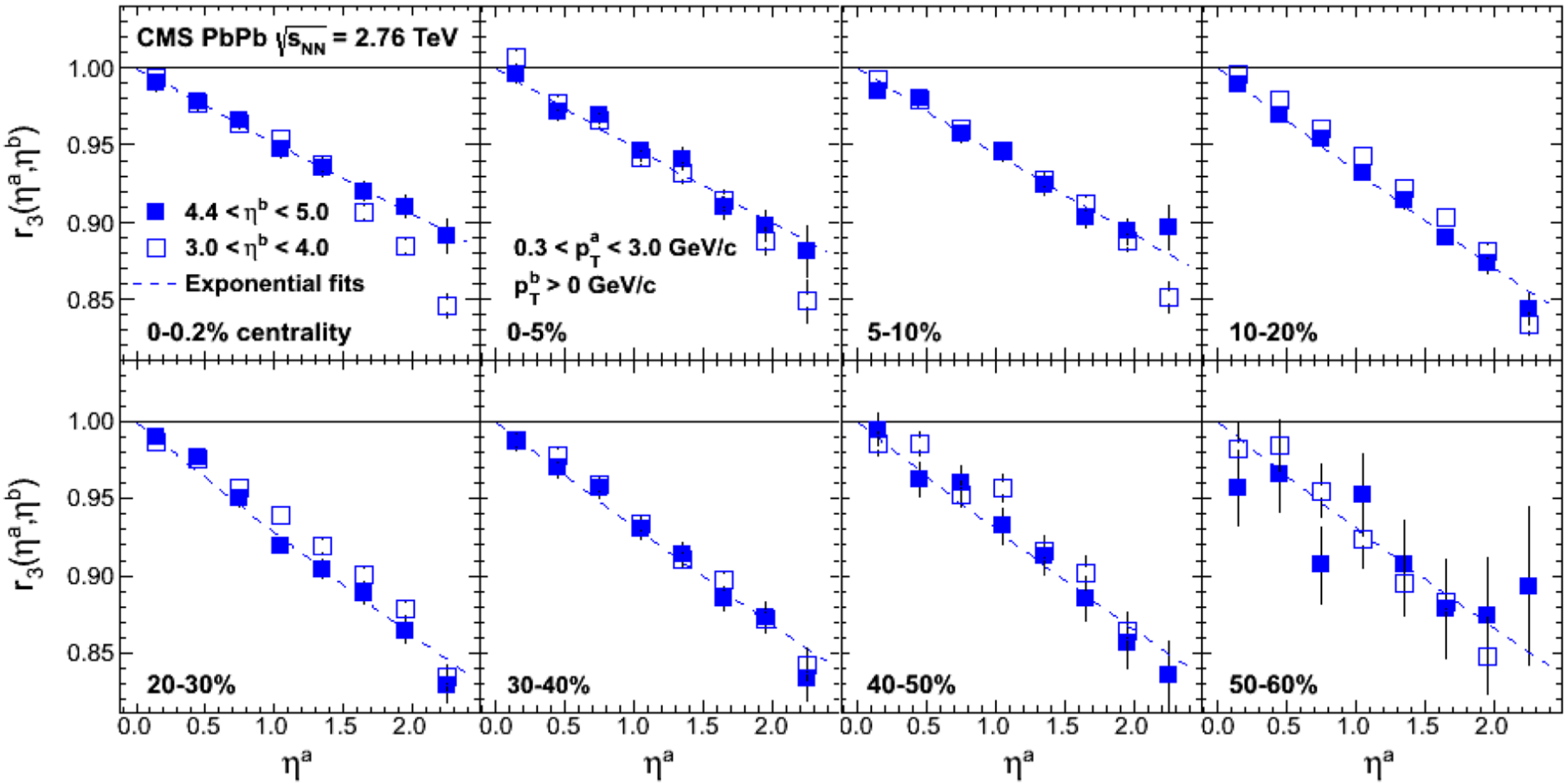


CMS: $r_2(\eta^a, \eta^b)$ in PbPb



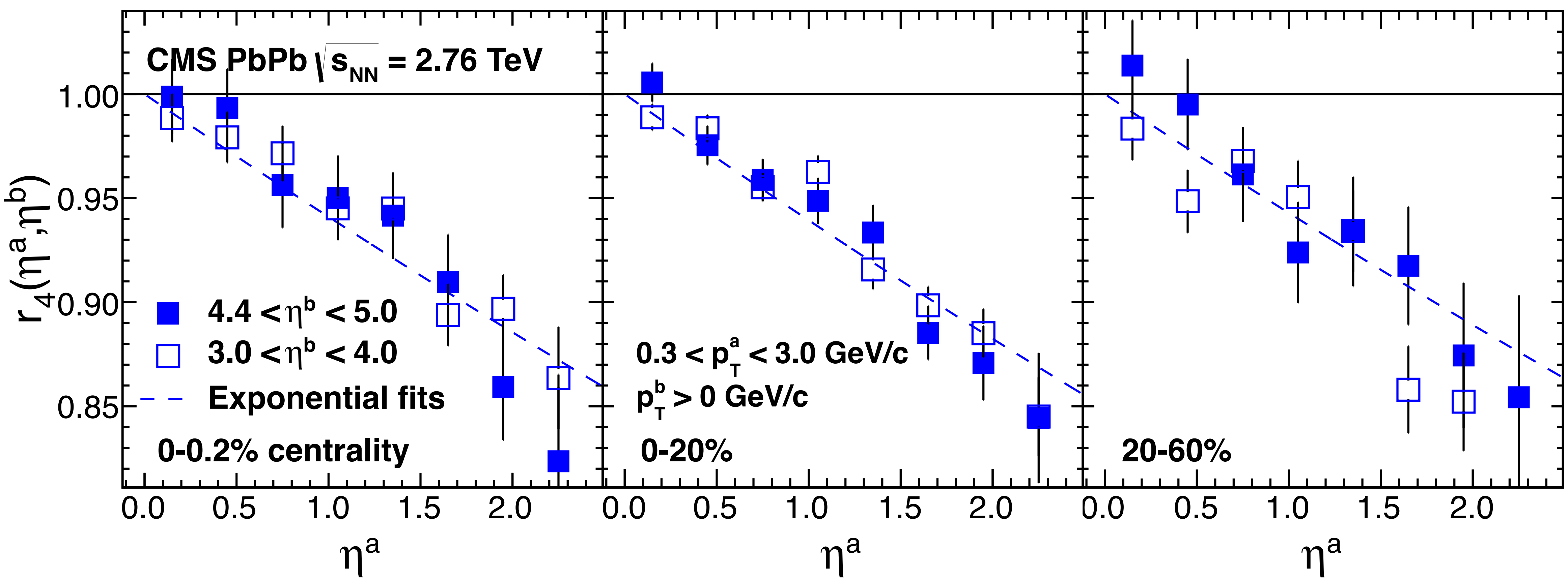
Factorization breaking effects below 5%

CMS: $r_3(\eta^a, \eta^b)$ in PbPb



r_3 is more sensitive to longitudinal fluctuations than r_2

CMS: $r_4(\eta^a, \eta^b)$ in PbPb



r_4 also is more sensitive to longitudinal fluctuations than r_2

Conclusions

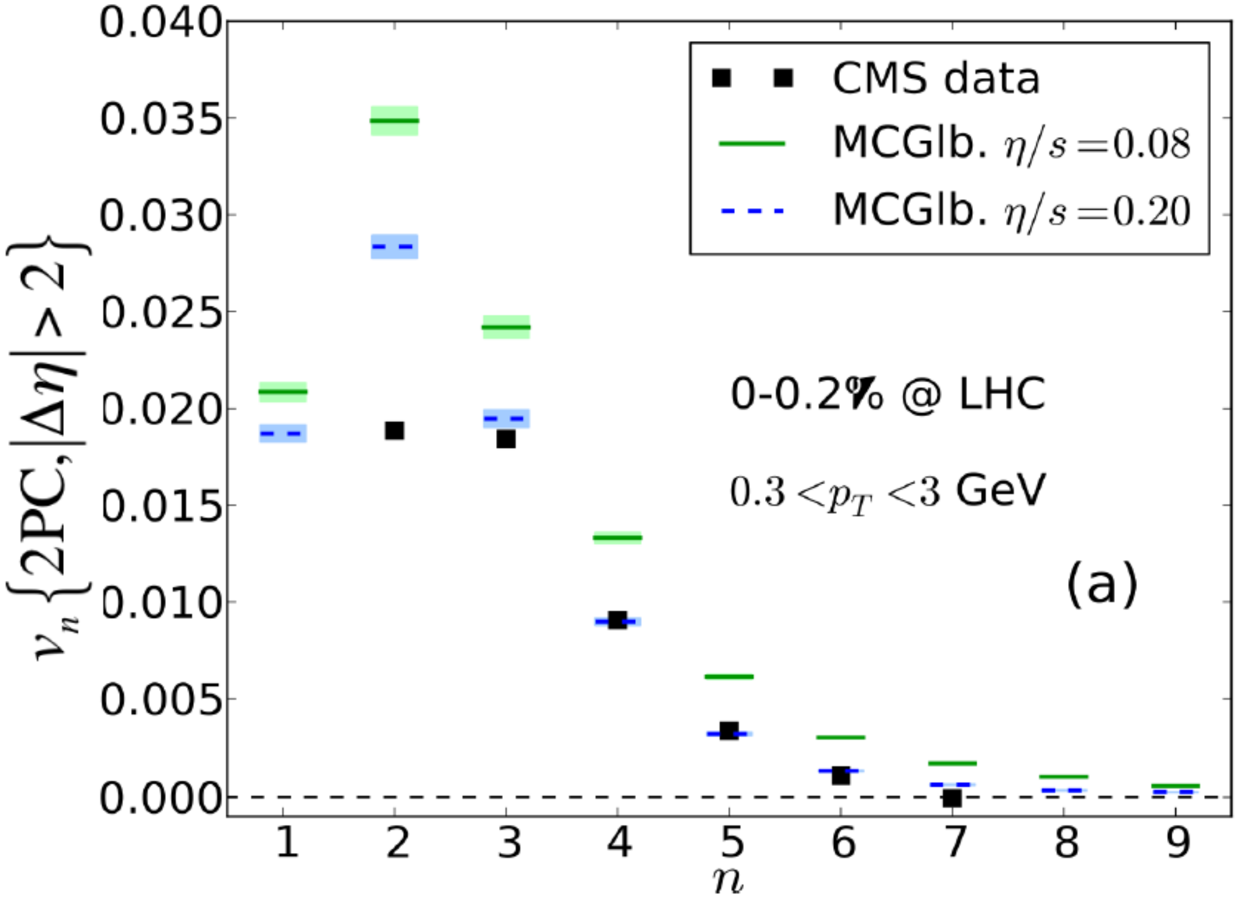
- High precision measurements on azimuthal anisotropy in PbPb and pPb by ATLAS and CMS.
- Large variety of (new) methods, e.g. v_n-v_m, EP correlations, show promising potential for further insight in HI collisions. ATLAS and CMS results on event-plane fluctuations
- Collective flow also established in pPb collisions
- Good description of data by viscous hydrodynamic models with fluctuating initial-state conditions.

Backup Slides

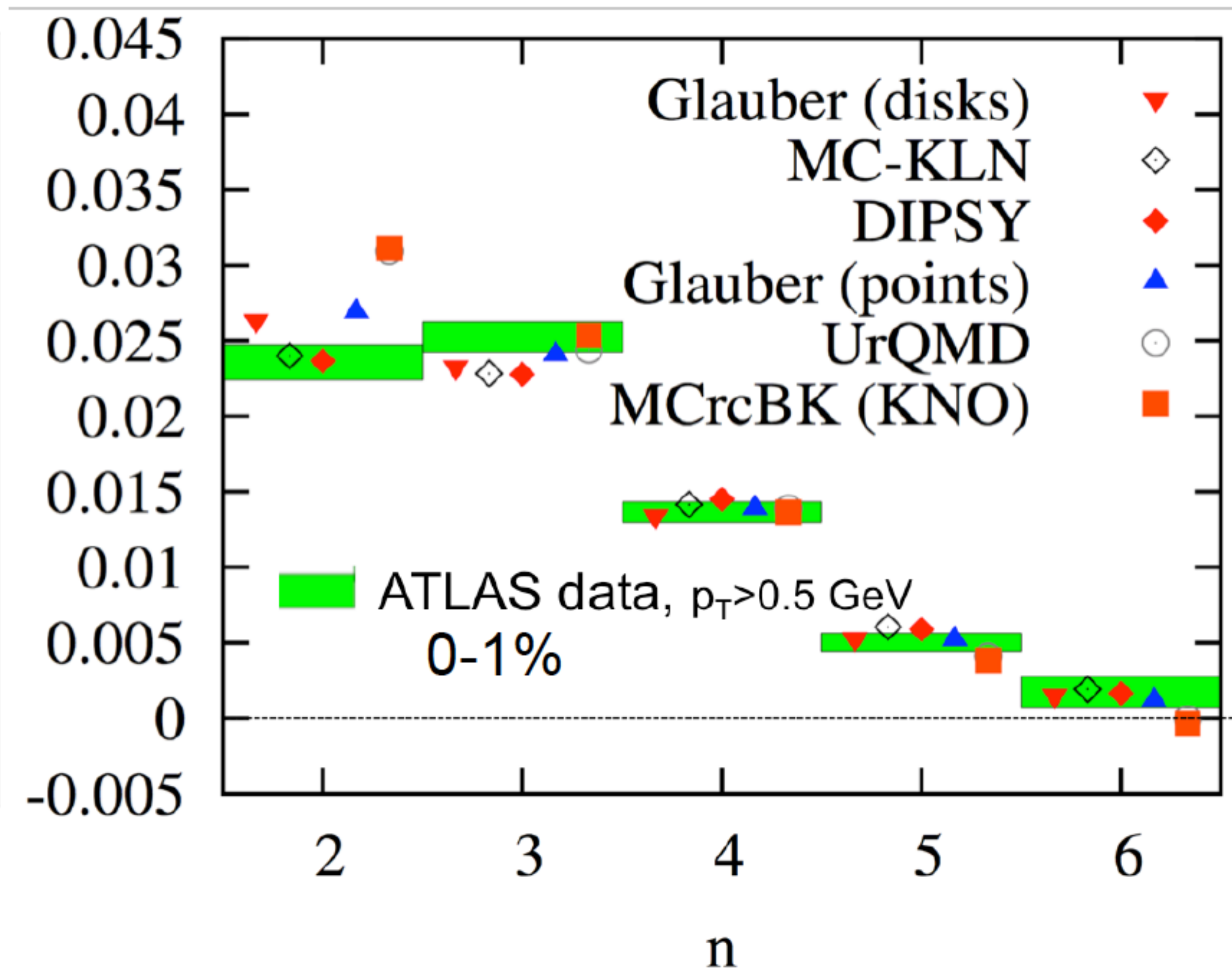
Single flow harmonics v_n: ultra-central collisions

Ultra-central Pb+Pb collisions are sensitive to EbyE fluctuations

J. Jia, J. Phys. G: Nucl. Part. Phys. 41 (2014) 124003
CMS, JHEP02(2014)088



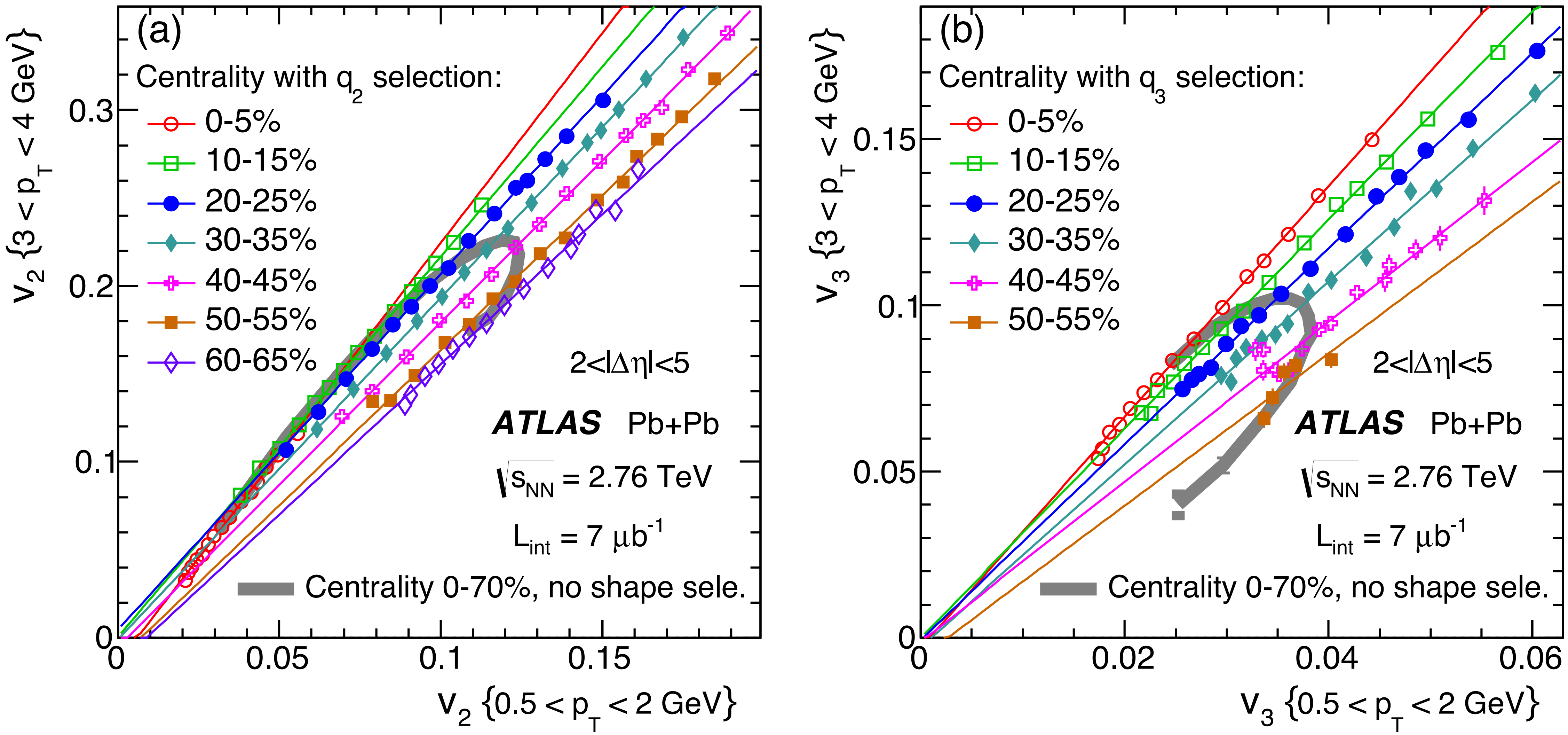
Luzum, Ollitrault, Nuclear Physics A 904-905 (2013)



Comparison with hydrodynamic calculation at various initial conditions show discrepancies, mainly in the relative strength of v_2 and v_3.

Flow amplitude correlations $p(v_n, v_m)$

ATLAS, arxiv 1504.01289



Correlation of v_2 and v_3 for two p_T intervals for various centrality bins. Data points are calculated in each centrality bin for several intervals in the shape parameter q_m.
They increase monotonically with q_m.

Flow amplitude correlations p(vn, vm)