Event shape fluctuations in nucleus-nucleus collisions: constrain the initial geometry

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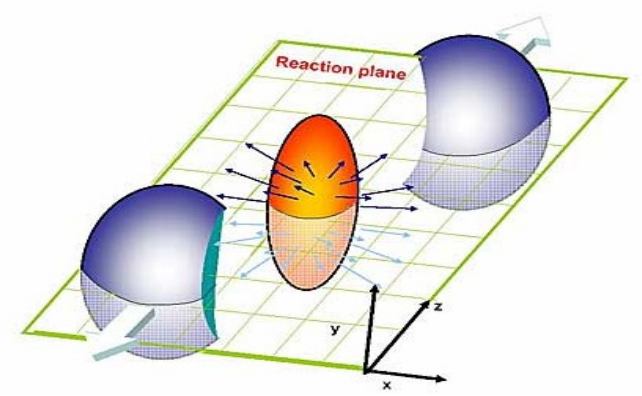
Incontro sulla fisica con ioni pesanti a LHC – Bologna 26-05-2015

Outline

- Motivation
- Event shape selection
- Correlations between flow harmonics
- p_T spectra and particle identification
- Summary and outlook

Event-by-event fluctuations



At first order, measurements can be described assuming nuclei as perfectly smooth spheres and the QGP as a perfect liquid.

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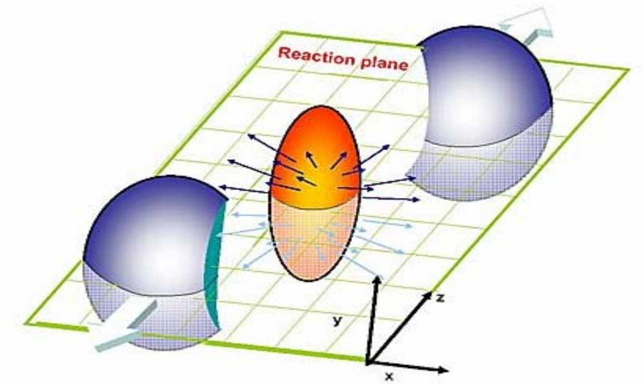

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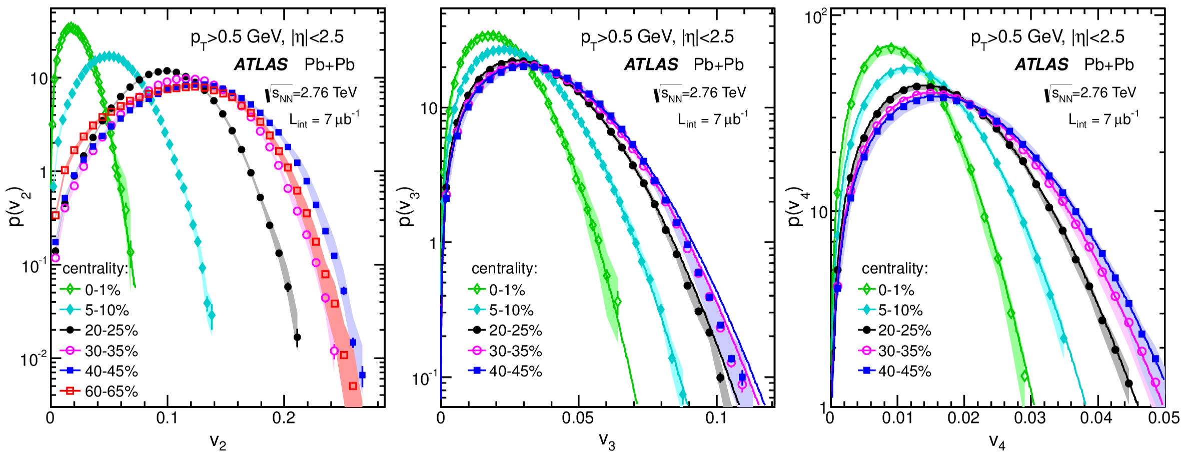


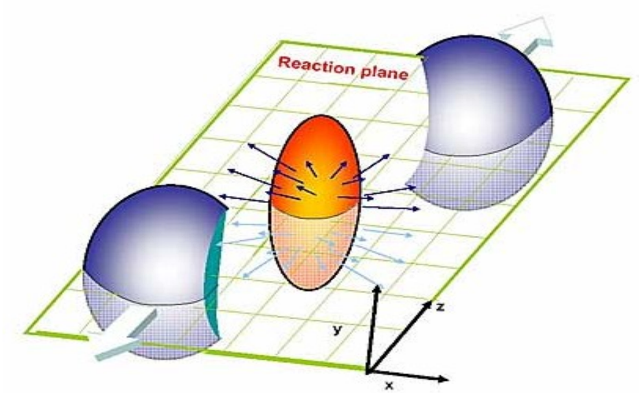
Initial shape is not smooth but a lumpy blob of energy density

Fluctuating shape affects details of final particle flow

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{i=0}^{\infty} v_n \cos[n(\phi - \psi_n)]$$

With fluctuations: odd harmonics are not zero.

Event-by-event fluctuations



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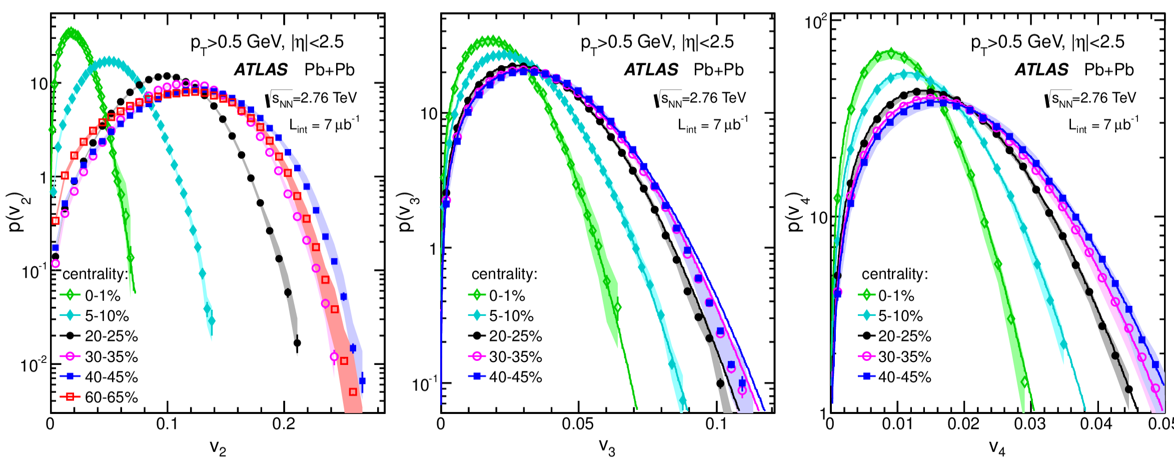

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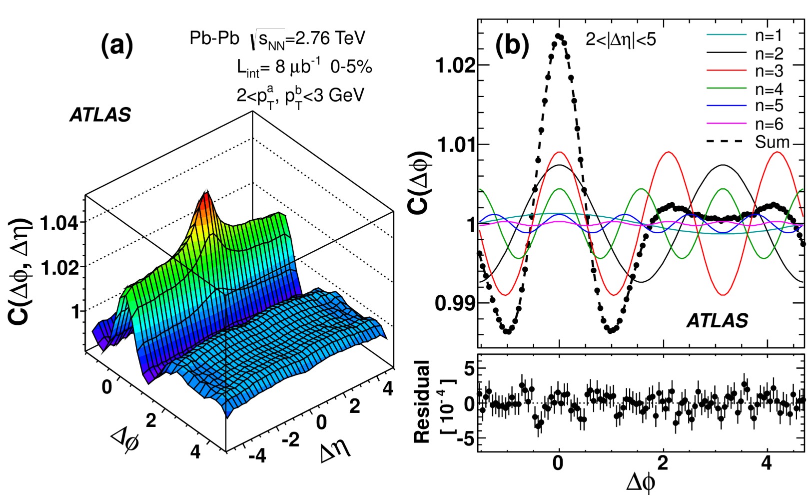


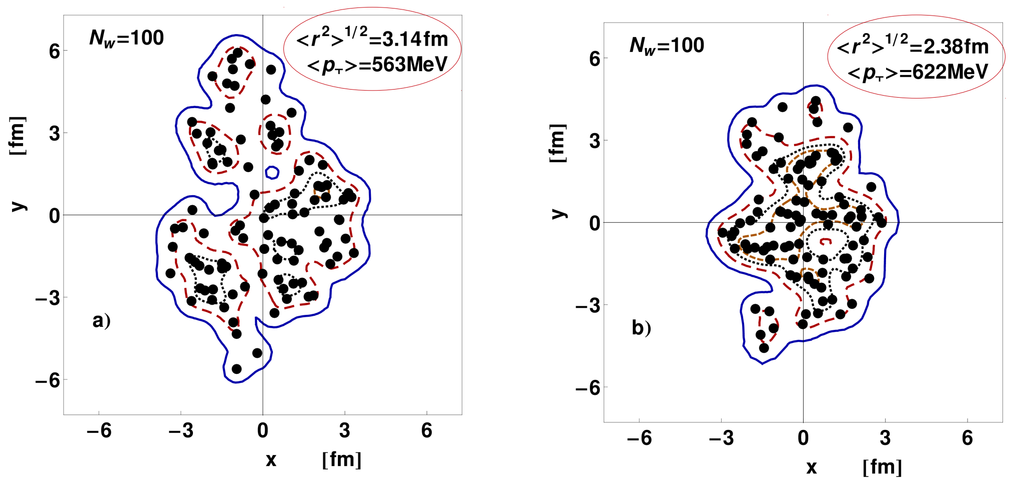
Fluctuations explain entire structure of two particle correlations

solid lines: v_1, v_2, v_3, v_4, v_5, v_6 term

dashed line: sum

points: correlation measurement

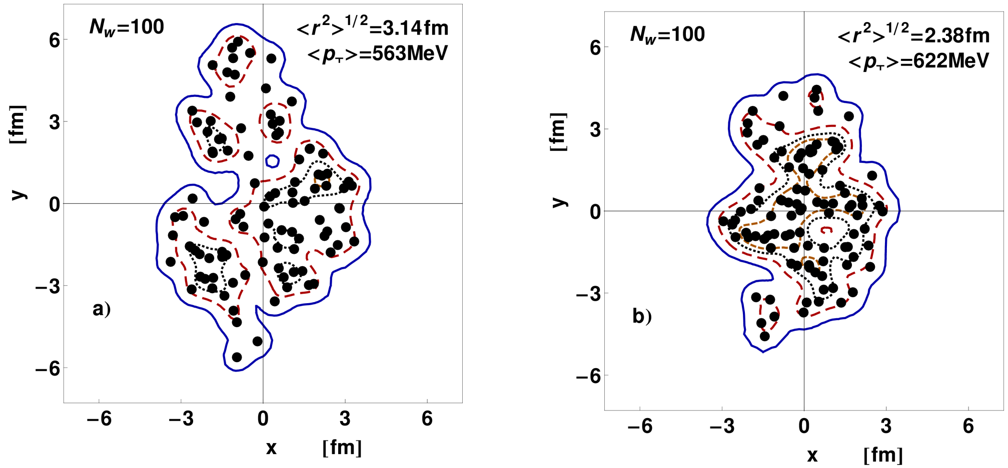
Event shape engineering



Each event has a different initial shape and density distribution, characterized by different set of harmonic eccentricity coefficients ε.

At fixed centrality: different initial shapes.

Event shape engineering



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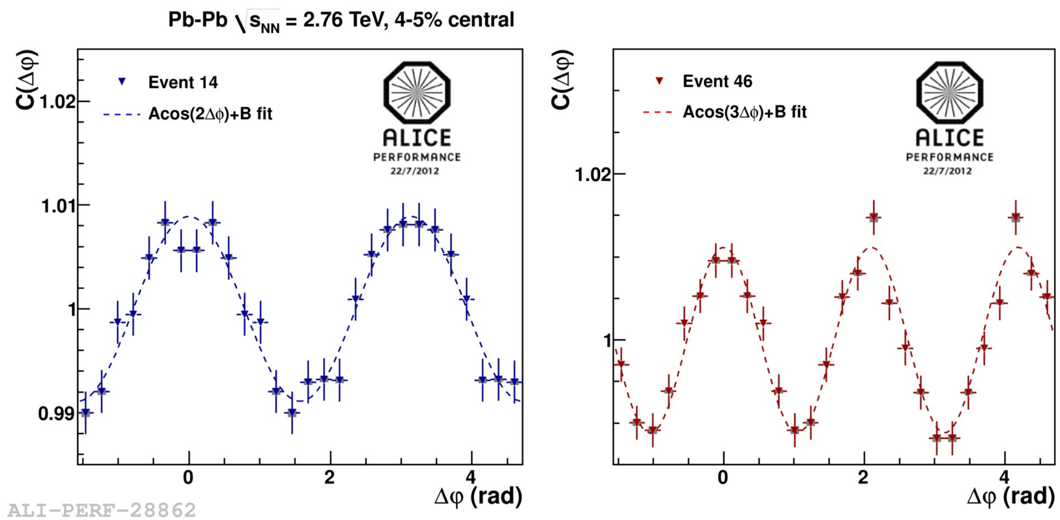


Each event develops its individual hydrodynamic flow, characterized by a set of harmonic flow coefficients v_n and flow angles ψ_n.

At fixed centrality, flow fluctuates → event selection based on flow

We can select events corresponding to nuclear collisions with different initial geometry configuration:

EVENT SHAPE ENGINEERING

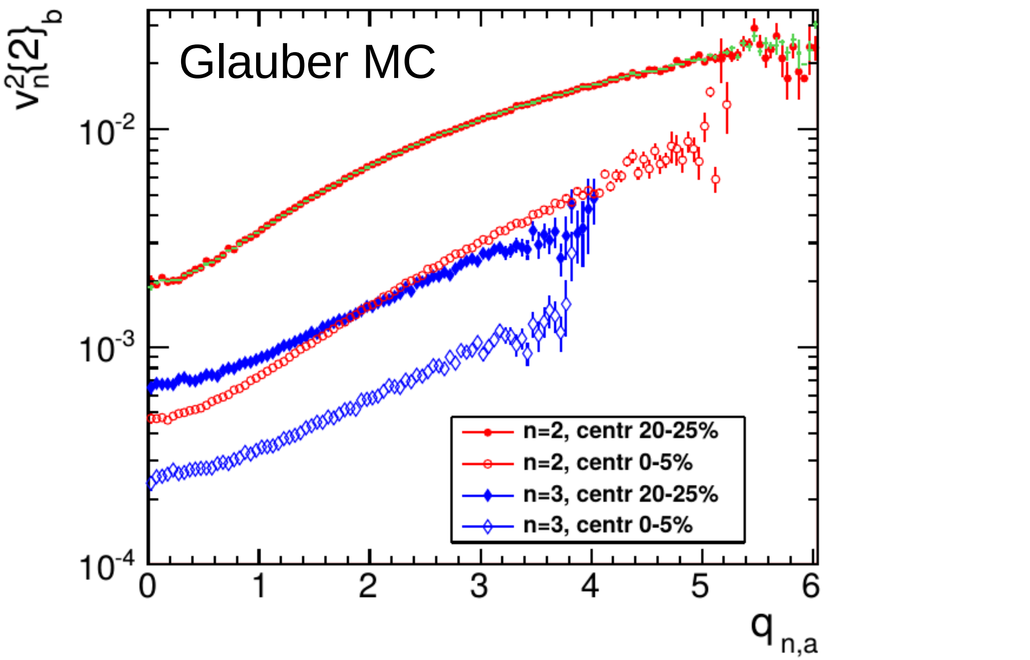
Schukraft et al, Phys.Lett. B719 (2013) 394-398

ESE in MC

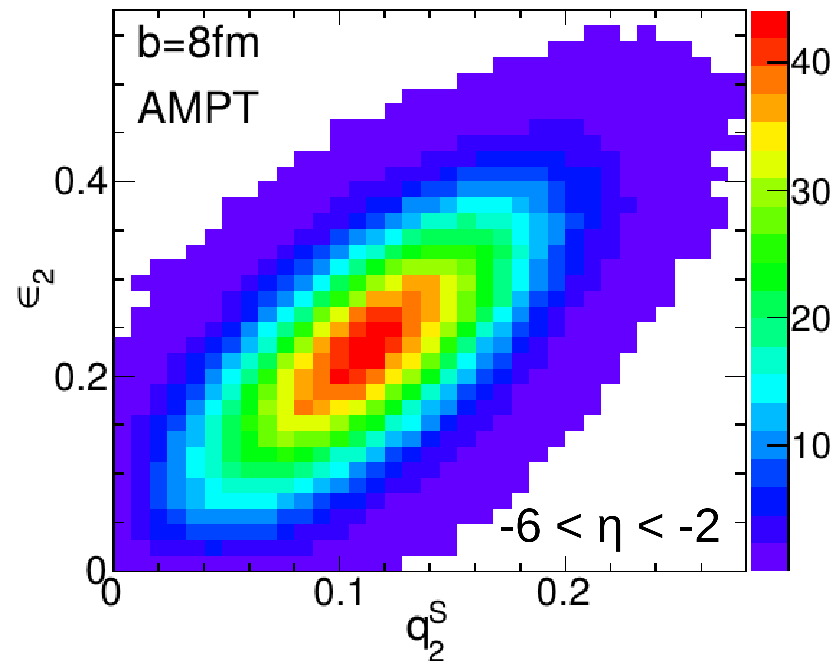
Event selection based on the magnitude of the **flow vector**

$$Q_{n,x} = \sum_i \cos(n\phi_i) \qquad \longrightarrow \qquad Q_n = \{Q_{n,x}, iQ_{n,y}\}$$
$$Q_{n,y} = \sum_i \sin(n\phi_i) \qquad\qquad q_n = |Q_n| / \sqrt{M}$$

Schukraft et al. Phys.Lett. B719 (2013) 394-398



Huo et al, Phys.Rev. C90 (2014) 024910



- q-vector and v_n^2 measured in different sub-events
- Large q_2 → larger v_2

- Strong positive correlation between eccentricity and q-vector
- $\langle\epsilon_2\rangle$ value is higher in 10% large q_2 sample

The shape of the initial geometry can be selected using the q-vector in the final state

Event shape selection

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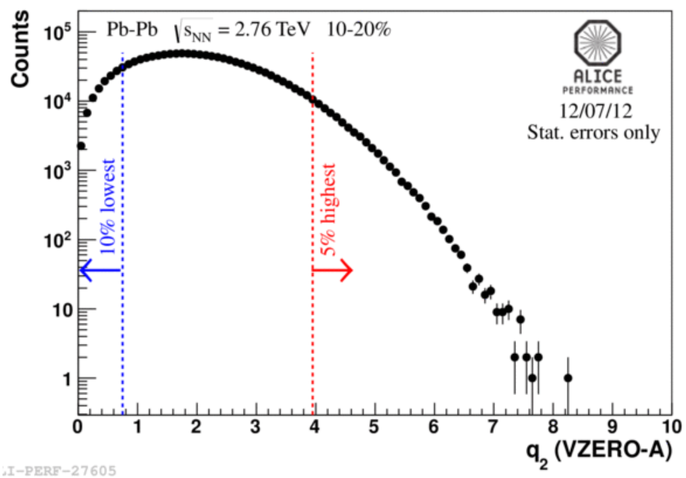
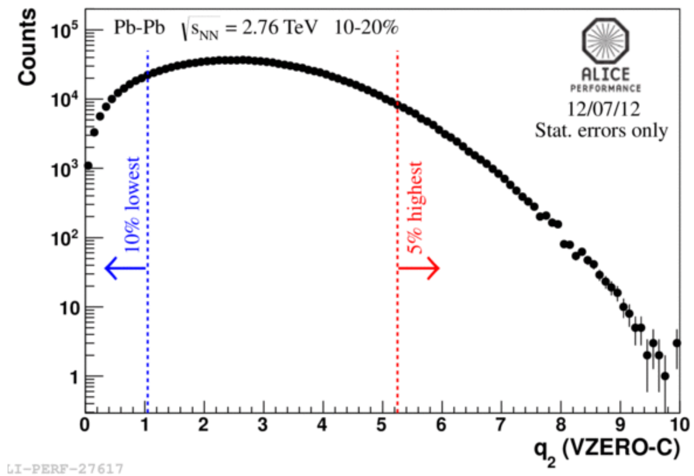
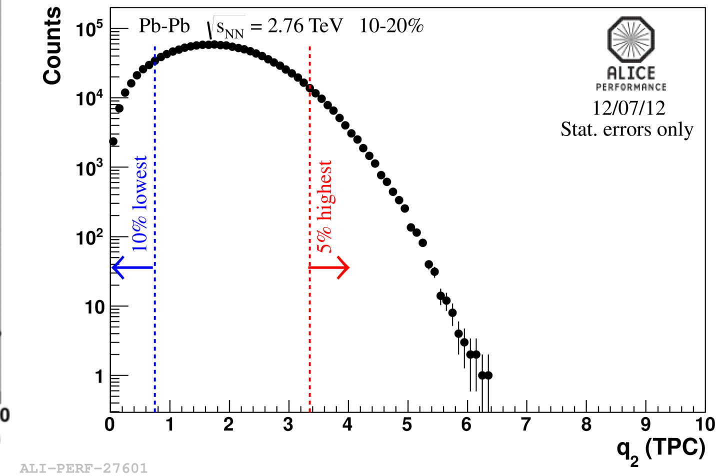
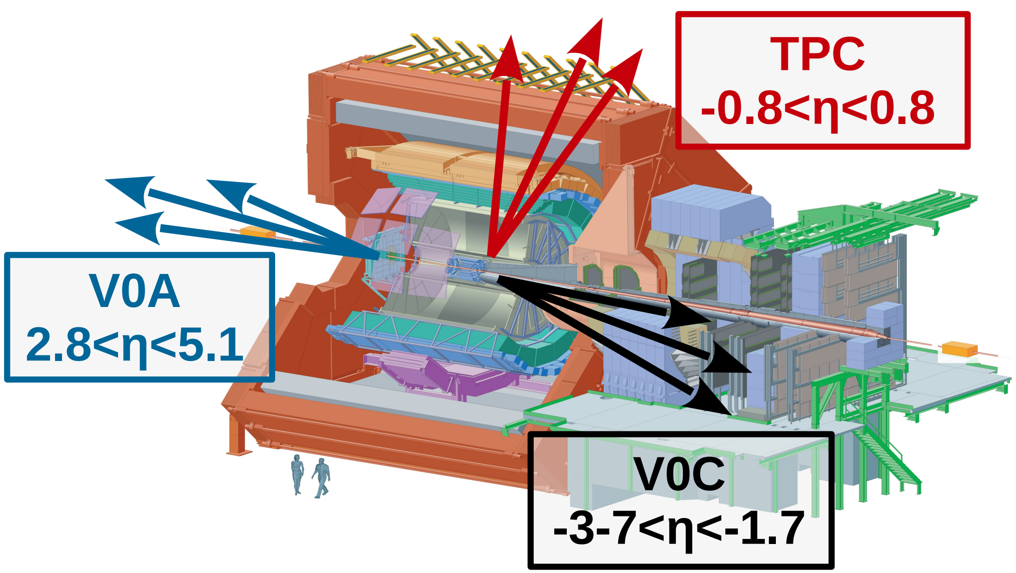








- V0A (2 .8<η<5.1)
- V0C (-3.7<η<-1.7)
- TPC (-0.8<η<0 or 0<η<0.8)

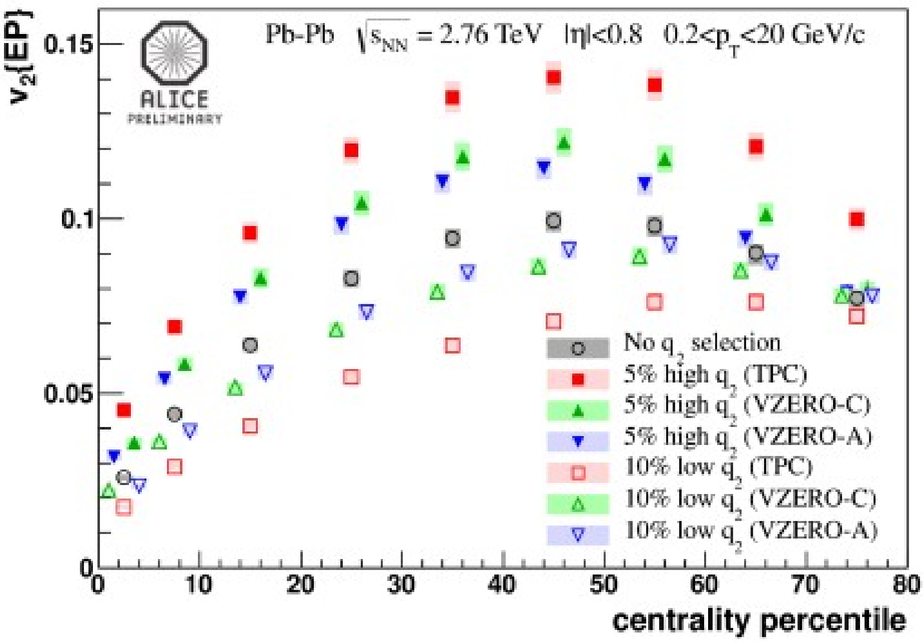
Different flow

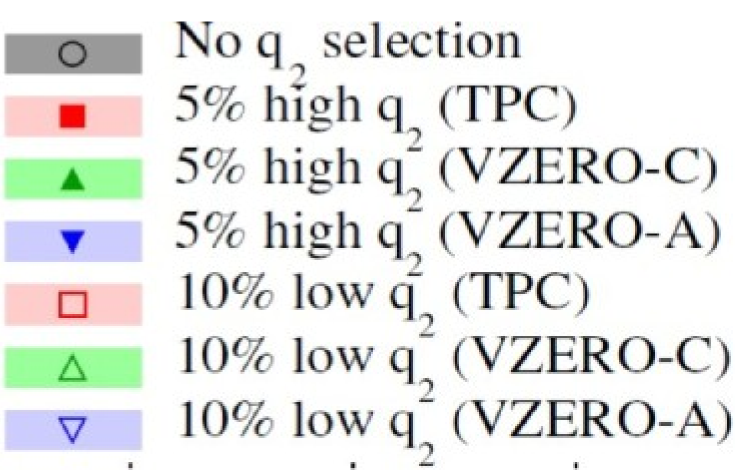
Different multiplicity

Different non-flow contribution

Elliptic flow

ALICE QM 2012





- Centrality dependence of the average v_2 variation in the large-q_2 and small−q_2 samples.

Elliptic flow

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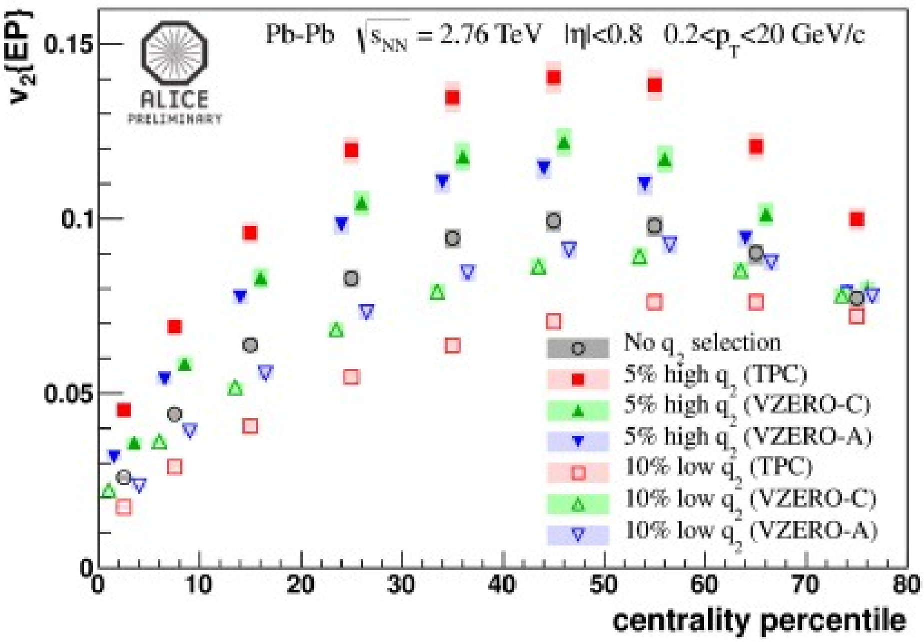
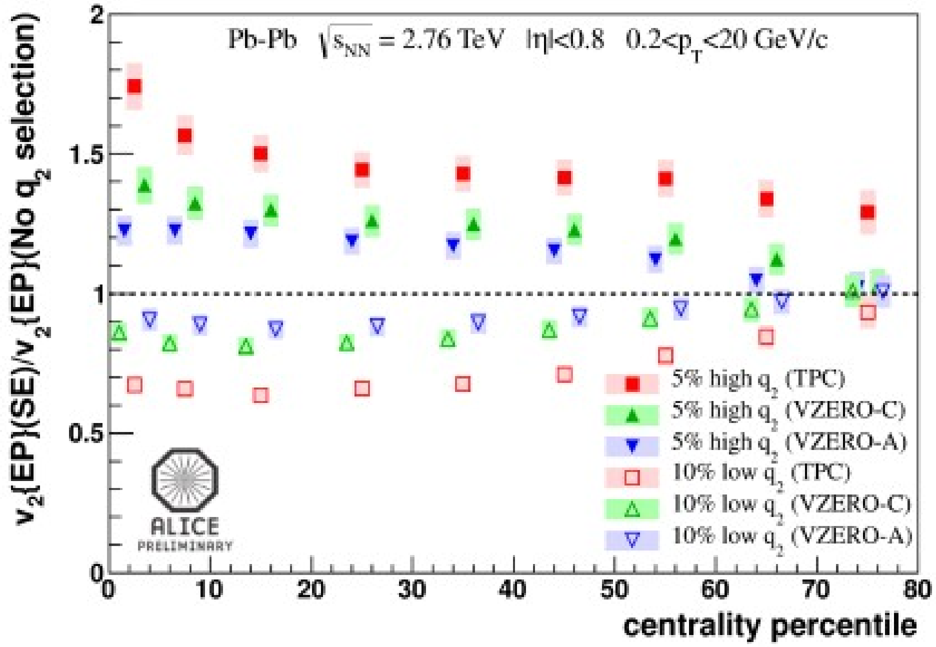
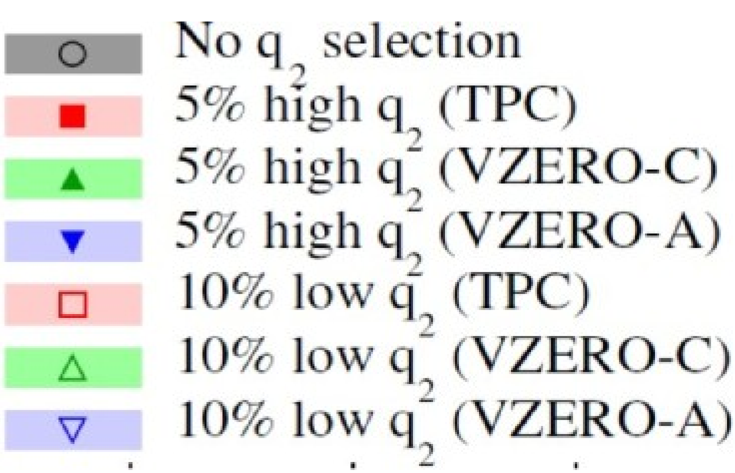
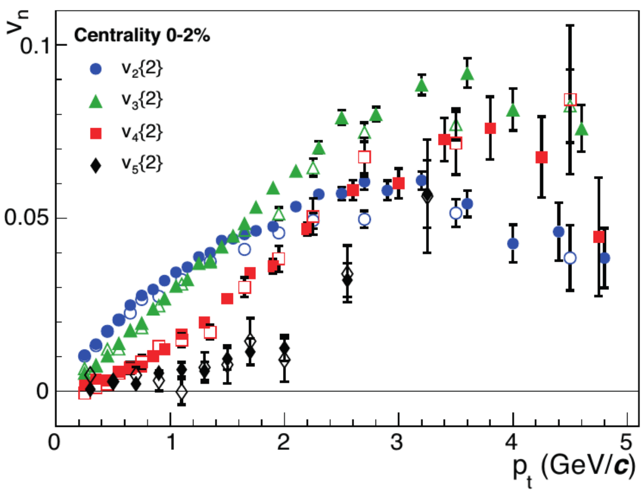


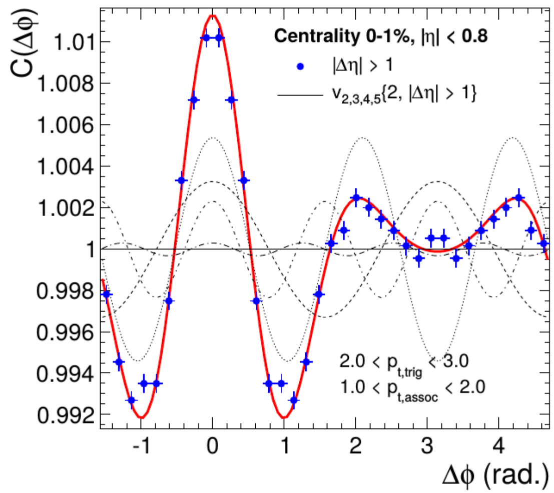




- Centrality dependence of the average v_2 variation in the large-q_2 and small−q_2 samples.
- q_2(TPC), q_2(V0A) with q_2(V0C) with different dynamic range.
- The TPC selection has a better selectivity than the V0C and V0A in all the centrality classes.
- Method sensitivity to the event shape deteriorates for peripheral collisions.

Anisotropic flow



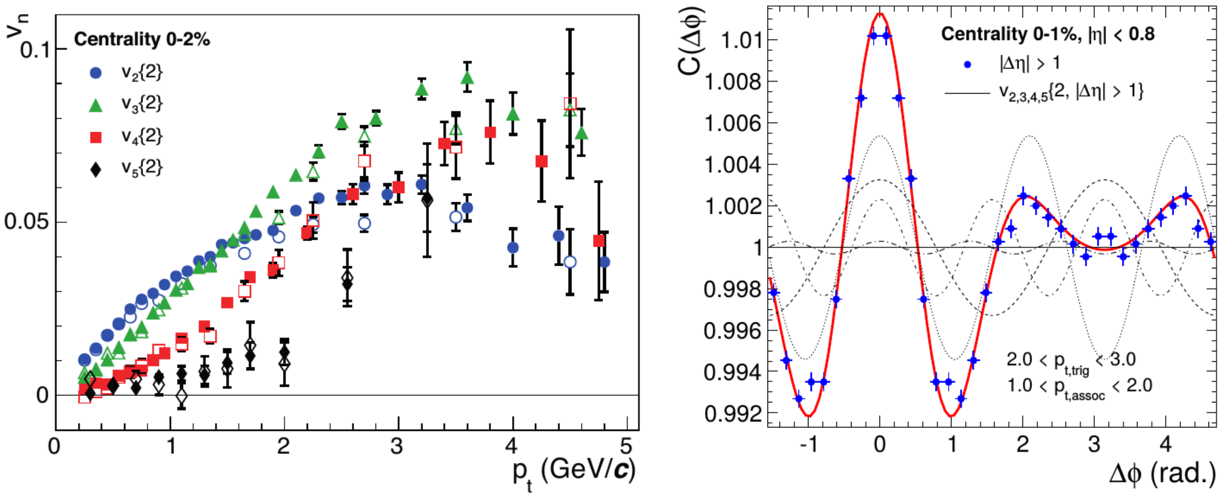


ALICE Collaboration PRL 107:032301, 2011

In the 1% most central collisions $v_3 > v_2$ → doubly-peaked correlation structure.

Event-by-event eccentricity fluctuations dominate the anisotropic flows in the most central collisions.

Anisotropic flow



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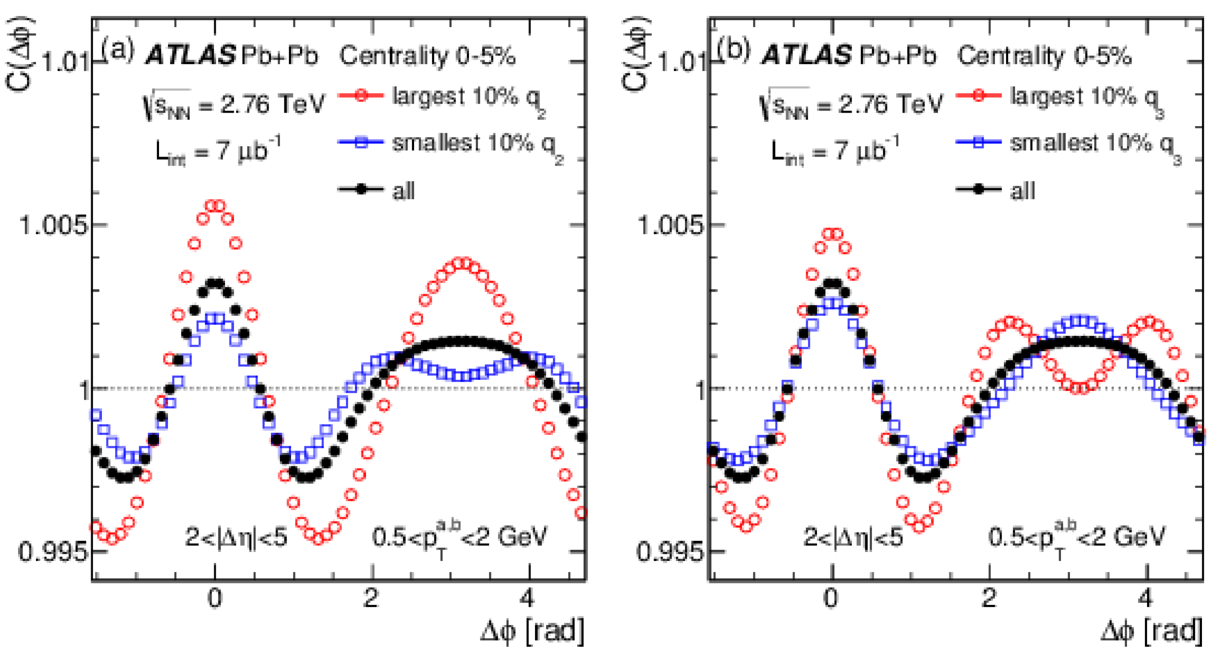

ATLAS Collaboration arXiv:1504.01289v1 [hep-ex]

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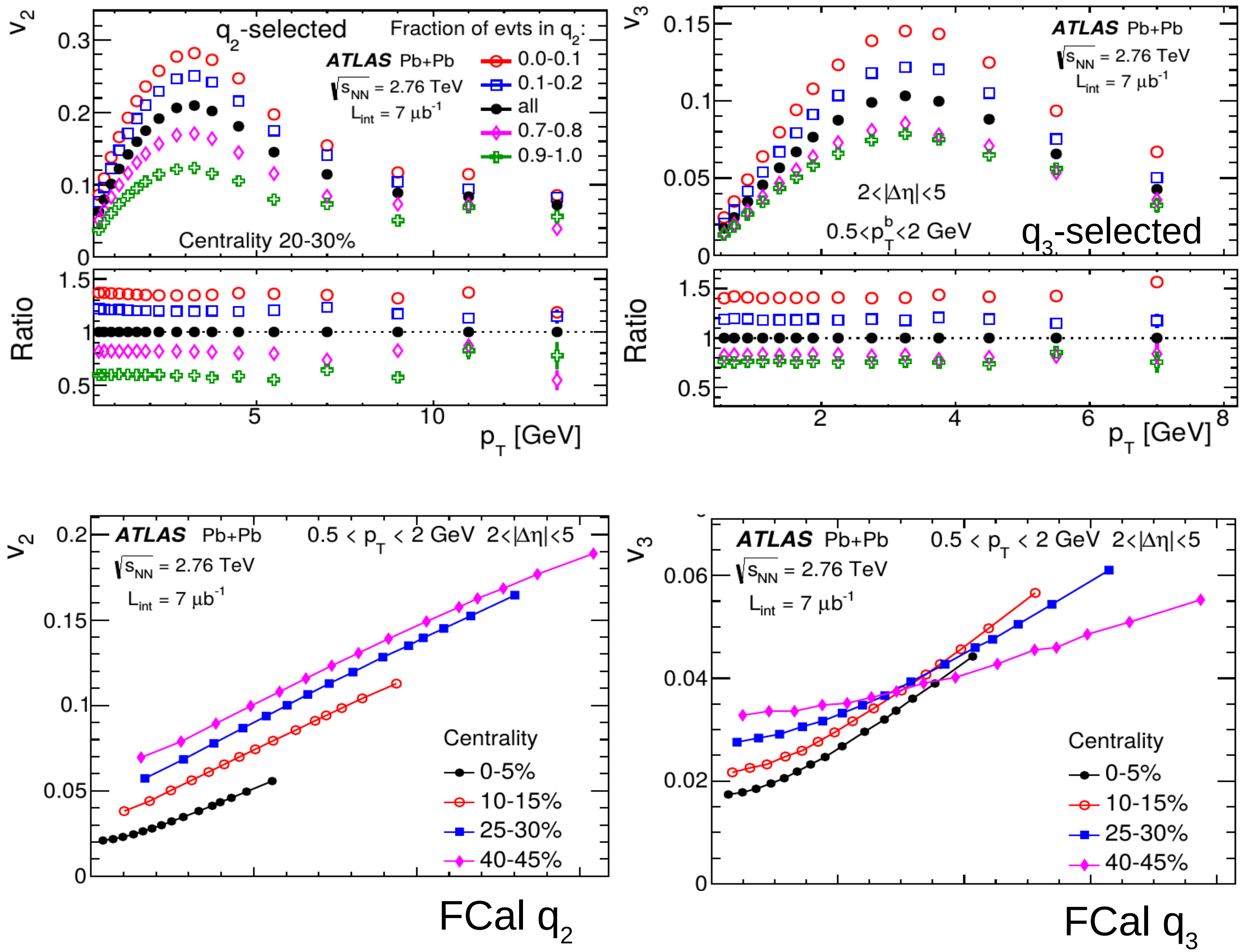
Event-by-event eccentricity fluctuations dominate the anisotropic flows in the most central collisions.

Events selected with the largest and smallest q_2 or q_3 values.

Double-peack structure for Small-q_2 or large-q_3: dominant contribution of the triangular flow under these q_m selections.

The magnitude of the modulation strongly correlated with the q_m value → the global ellipticity or triangularity can be selected by q_2 or q_3.

Anisotropic flow



- Ratios constant up to p_T = 10 Gev/c → similar flow fluctuations
- Event-Shape selection (3.2<|η|<4.9), v_n (|η|<2.5)

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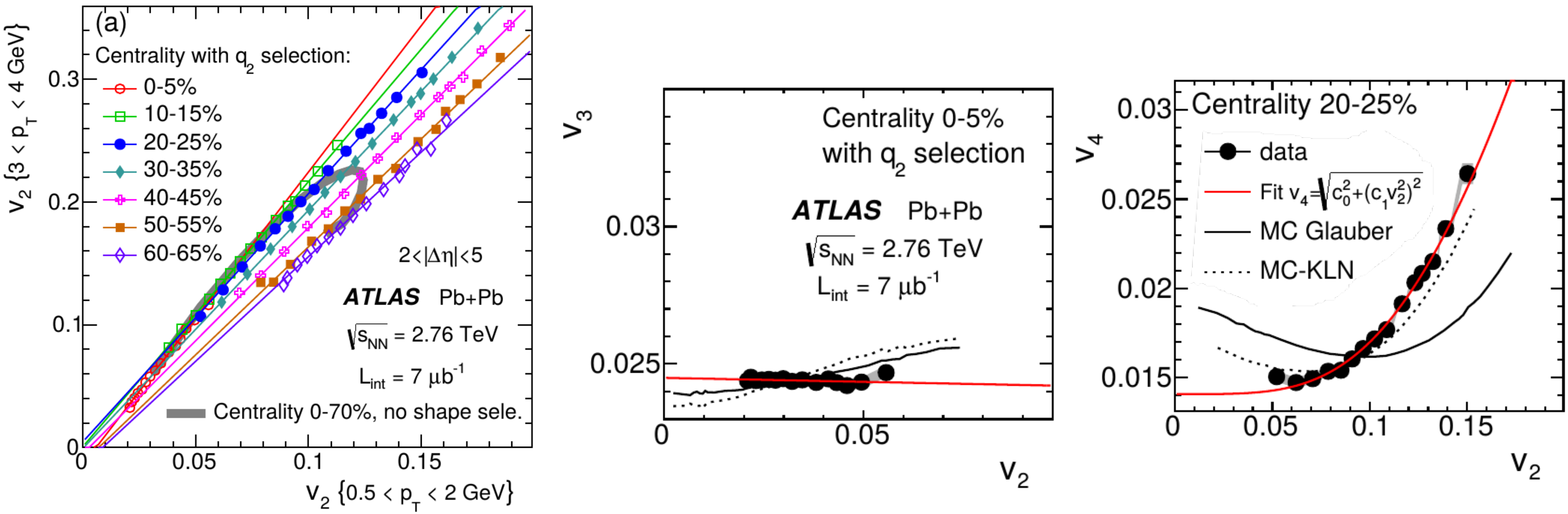
Anisotropic flow



Compare (v_n, v_m) correlations to (ε_n, ε_m) correlations calculated in Glauber & CGC models.

- (v_2, v_2) - Non-trivial dependence with centrality (boomerang like) → different centrality dependence of v_n. Within one centrality the dependence is linear → Indicates that viscous correction mostly controlled by system size, not shape!
- (v_3, v_2) - Good agreement in several centralities, some deviation in (0-5)% central events.
- (v_4, v_2) - Initial geometry models not reproduce data. Non-linear dynamical mode mixing produces these correlations.

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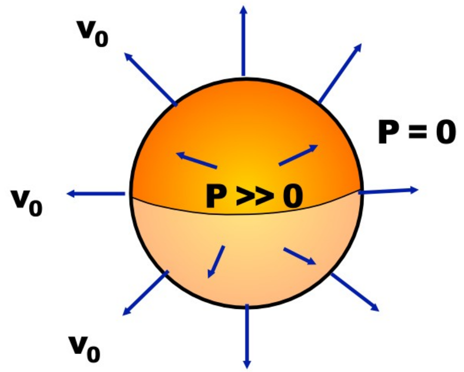
Spectra with ESE

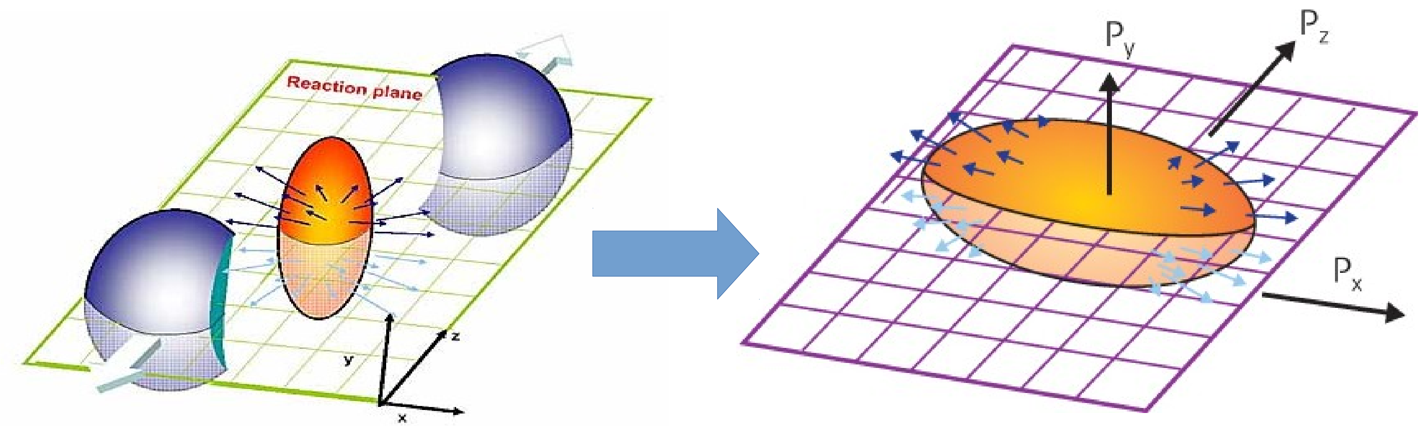
- Physics observables affected by the combined effect of either radial and anisotropic flow, the individual contribution can't be easily disentangled.
- Understand connection between initial condition and hydro response
- Constrain initial conditions:
  - Fix the centrality of the collision
  - Fix the shape of the collision (ESE)

Analysis of transverse momentum spectra in these events



Radial flow:

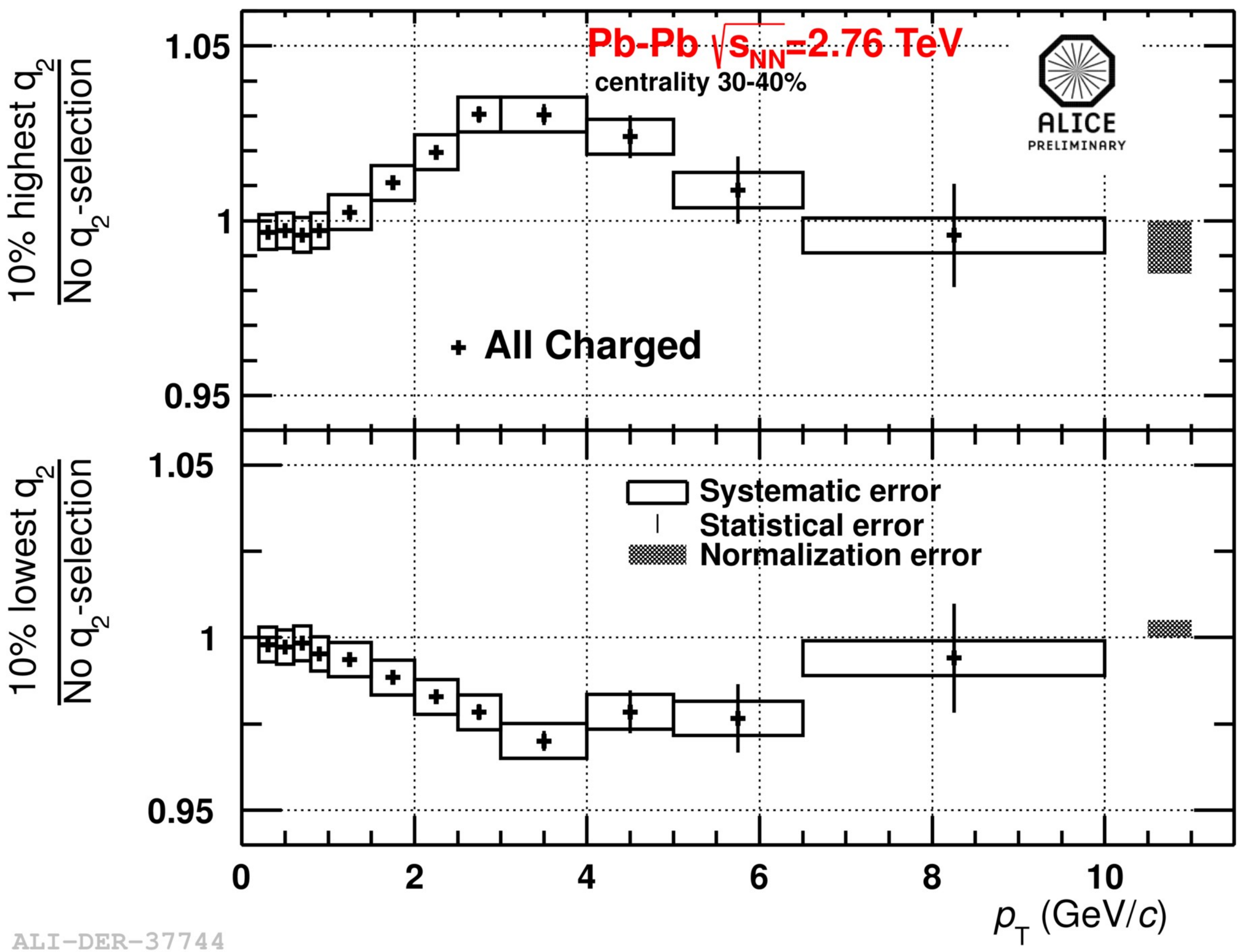
- Isotropic expansion
- Physics observable: p_T spectra
- Flat p_T spectrum for heavier particles → Mass ordering



Anisotropic flow:

- Anisotropic expansion

Spectra with ESE



- Raw spectra used for the ratios: efficiency does not depend on q_2 selection
- Modification of the p_T-spectrum: large q_2 harder spectrum, opposite for small q_2

ALICE QM 2012

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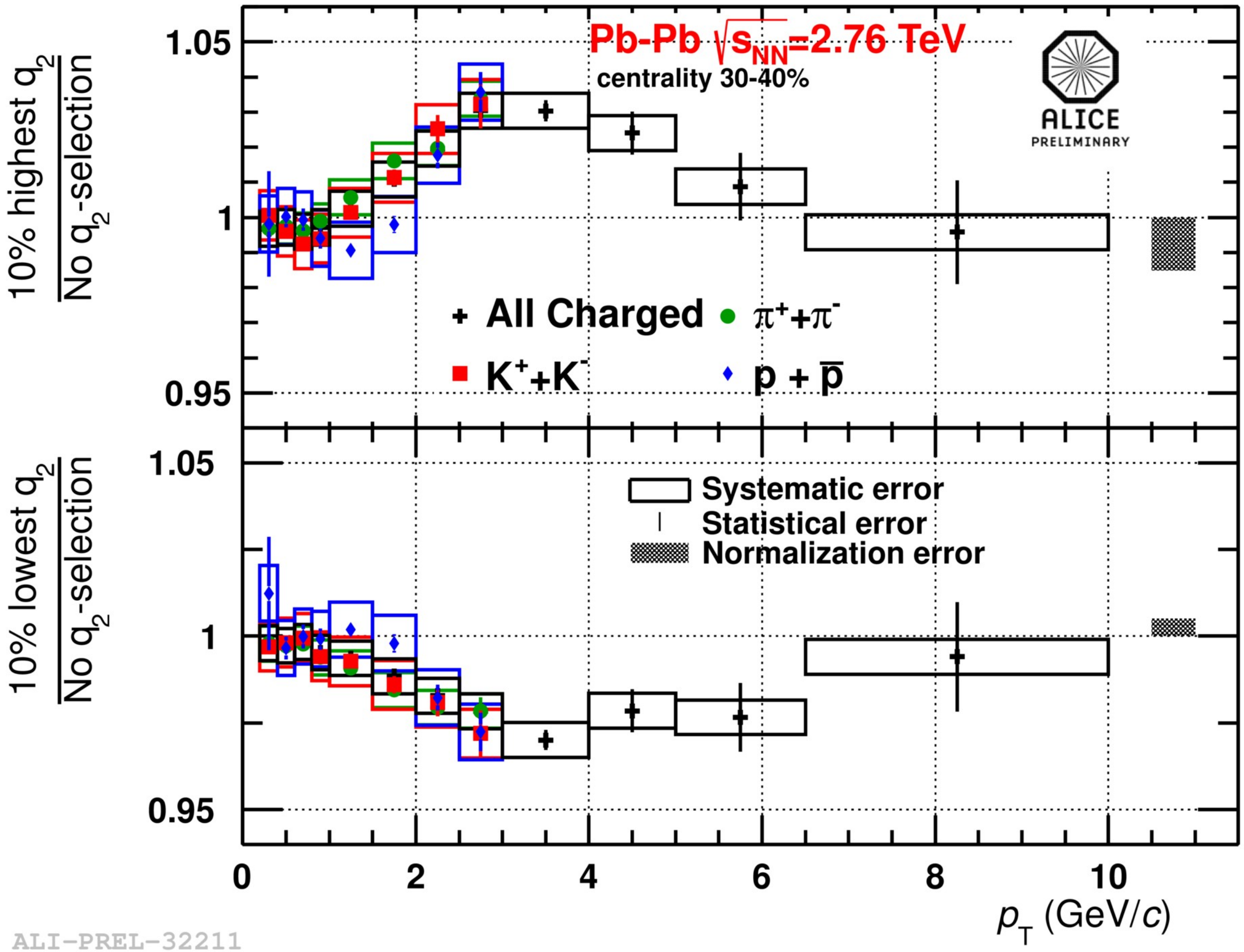

- Raw spectra used for the ratios: efficiency does not depend on q_2 selection
- Modification of the p_T-spectrum: large q_2 harder spectrum, opposite for small q_2
- same effect for all the particles
- hint of mass ordering?

Shape Fluctuation → Pressure Fluctuations (radial flow)?

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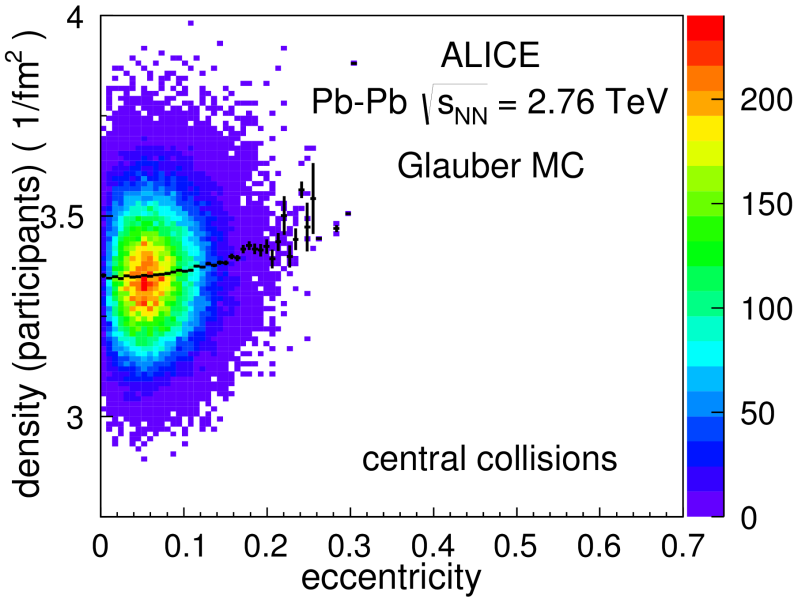
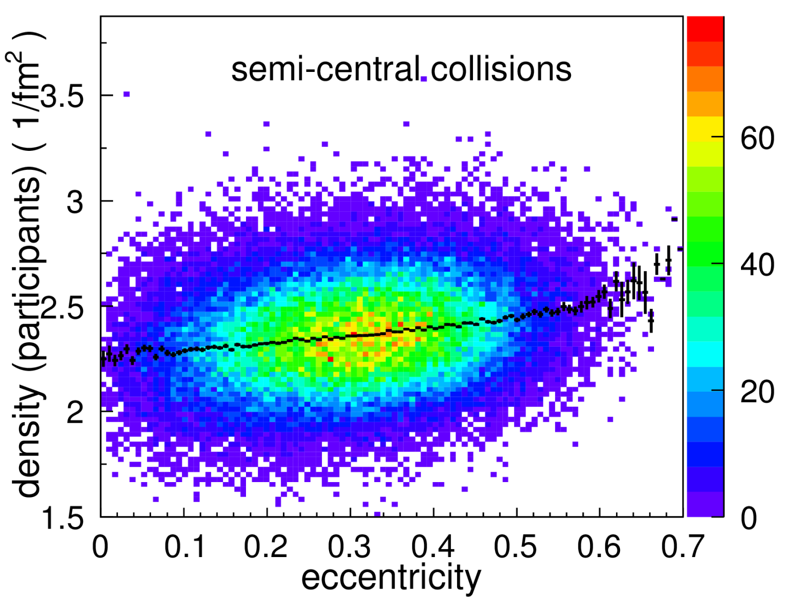
Spectra ESE: Glauber MC



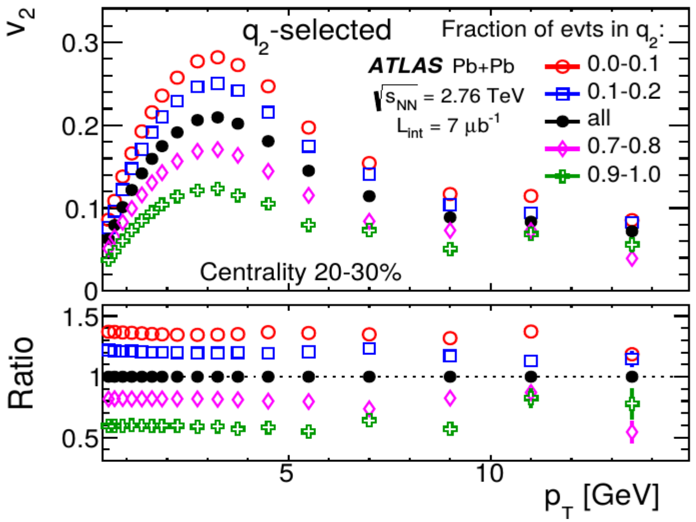


- The participant density N_{part}/area used as a proxy for the magnitude of the pressure gradients (responsible for the radial flow).
- The observed correlation between the density and eccentricity is similar the correlation between radial flow and event shape.
- Central collisions: weaker correlation between area and eccentricity.

- Glasma e CGC predictions? Can these measurements contrain initial condition models?
- Full hydro simulation needed.

Summary and outlook

- Event shape selection is sensitive to the detector selectivity
- v_2-v_2 correlations indicate viscous effects controlled by system size and not system shape.
- small anti-correlation between v_2 and v_3 → Initial geometry effect (described by CGC & Glauber).
- strong correlation between v_4-v_2 and v_5-v_2 → Indicate non-linear response to initial geometry (not described by initial geometry models)



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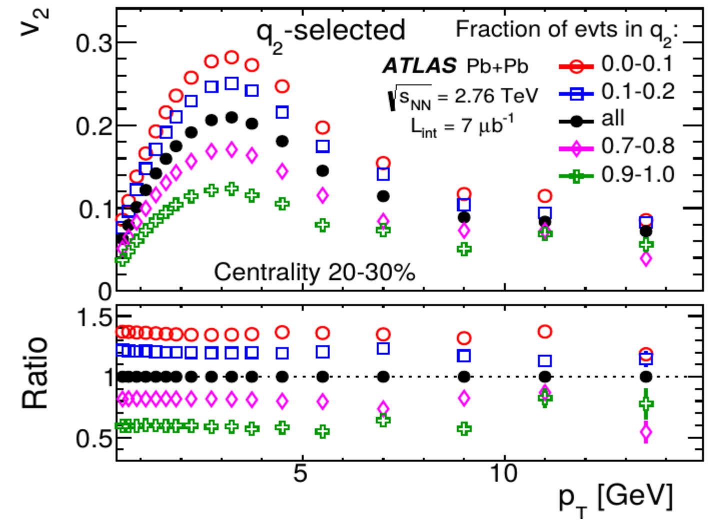
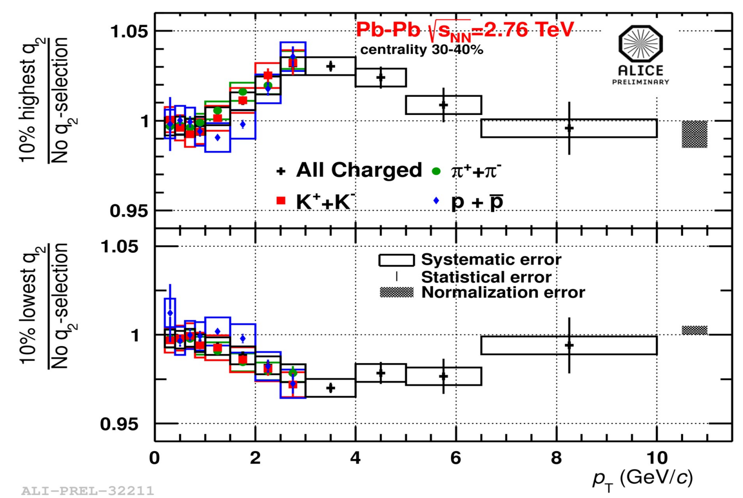


- Modification of the p_T spectrum in semi-central (30-40%) in the intermediate p_T region (from ~1 up to ~5 GeV/c) is observed.
- Hint of mass ordering in the region between ~1 up to ~3 GeV/c.



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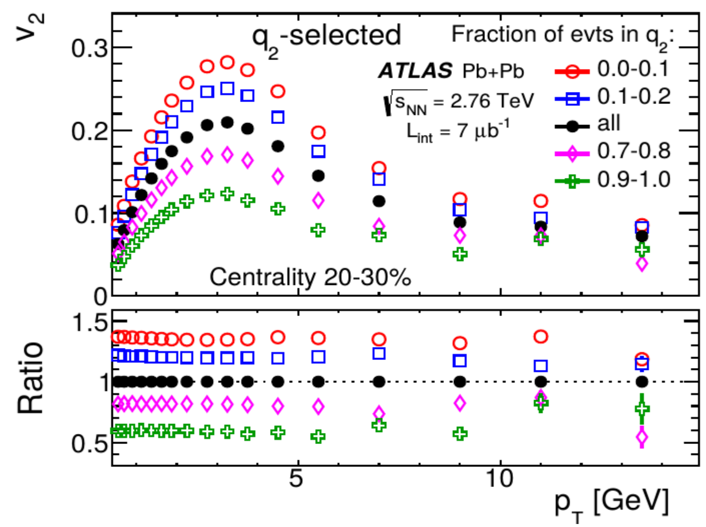

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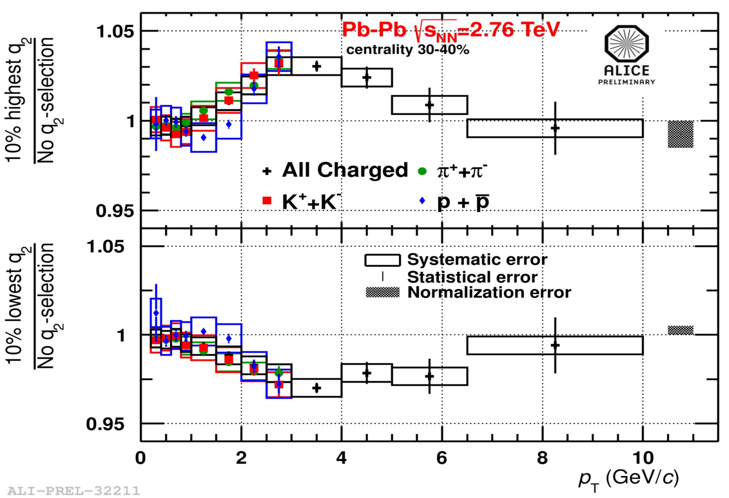
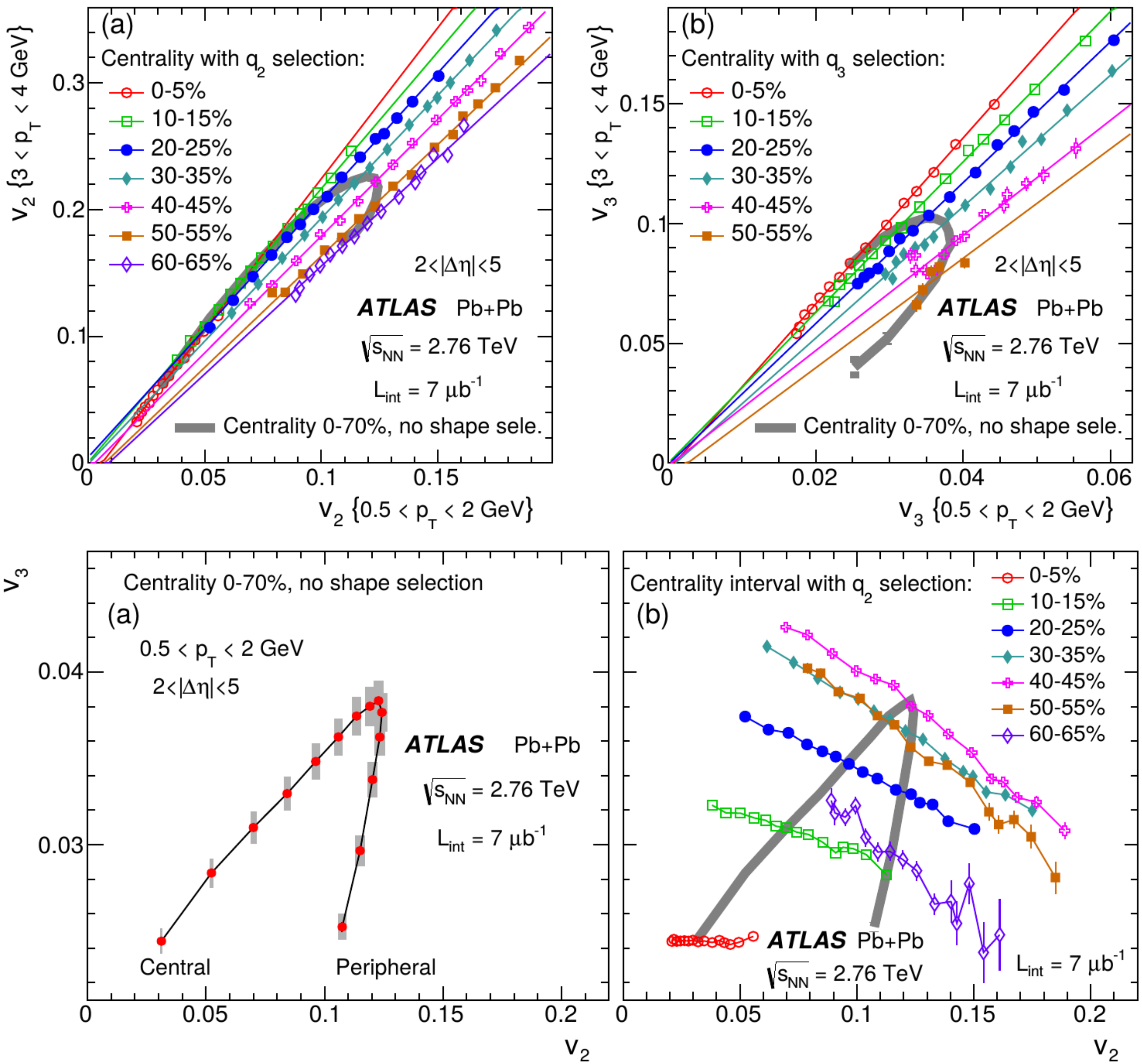


To which extent the differential ESE measurements can constrain quantitatively the transport coefficients of the medium and the fluctuations patterns in the initial conditions?

Backup

Anisotropic flow



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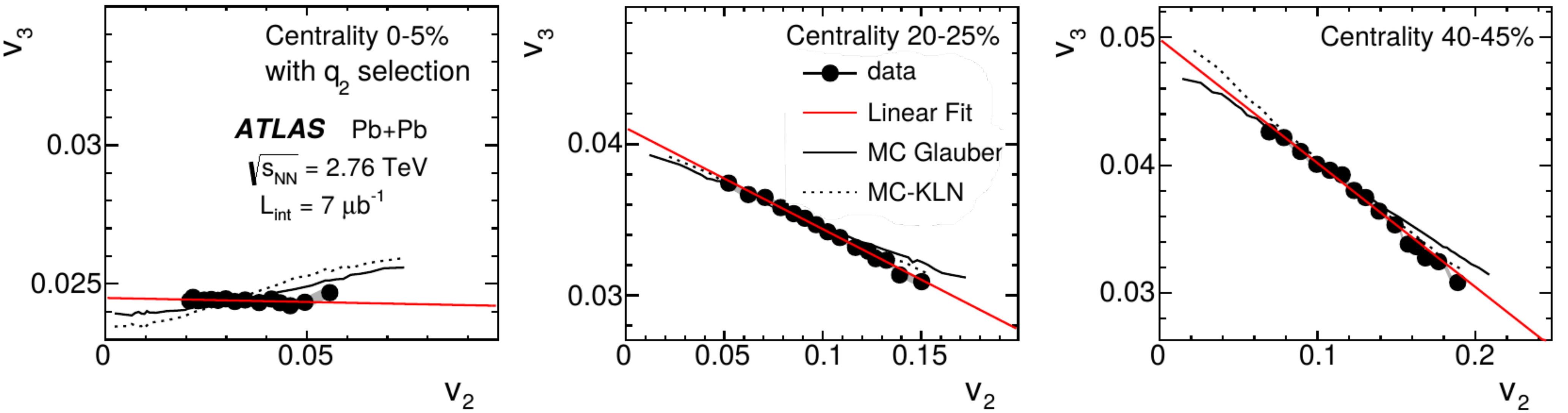
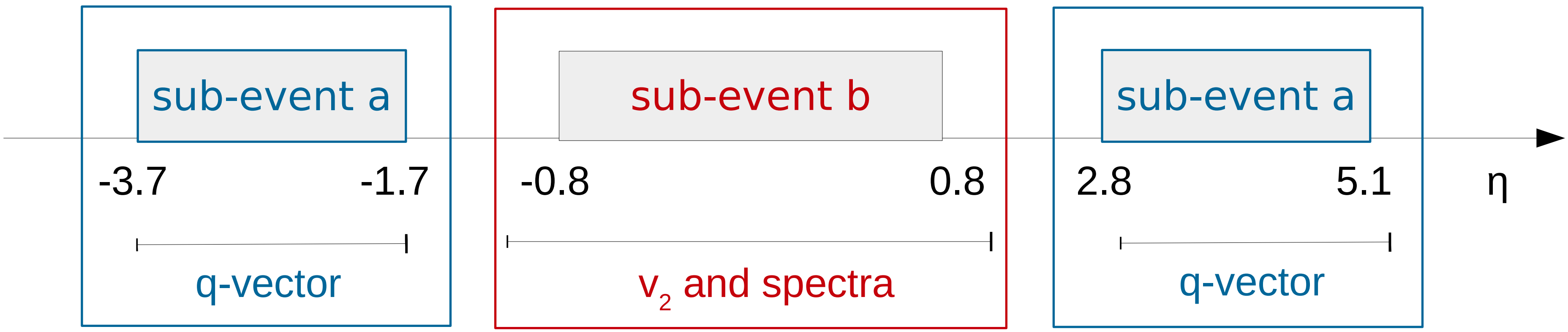


Event shape engineering

Event selection based on the magnitude of the **flow vector**

$$Q_{n,x} = \sum_i \cos(n\phi_i) \qquad Q_{n,y} = \sum_i \sin(n\phi_i)$$

$$\rightarrow \quad Q_n = \{Q_{n,x}, iQ_{n,y}\} \qquad q_n = |Q_n| / \sqrt{M}$$



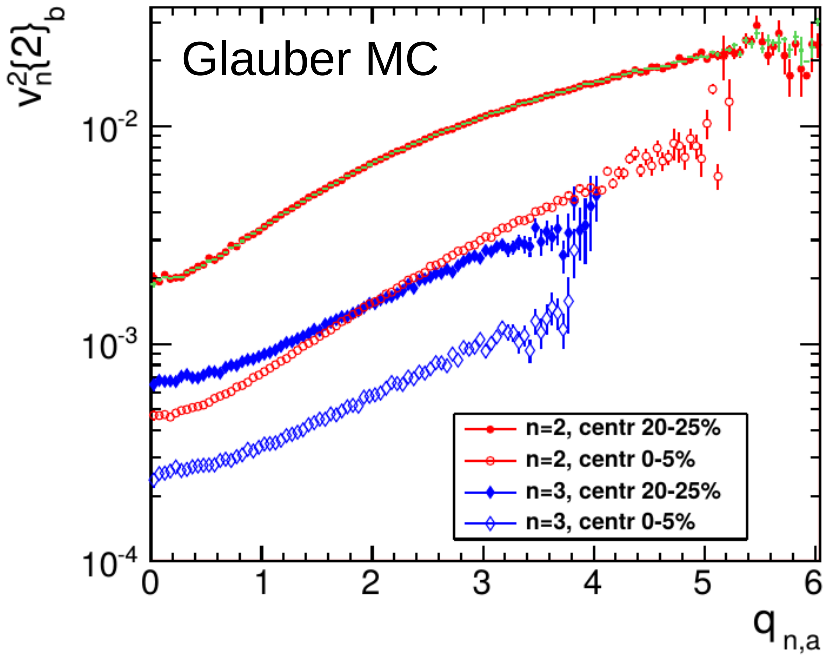
Need to avoid biases from non-flow: **sub-events with large pseudo-rapidity separation**

Measure q_2 in one independent sub-event for the event selection (sub-event a)

Study observables of interest in another pseudo-rapidity window (sub-event b)

ESE in MC

Schukraft et al, Phys.Lett. B719 (2013) 394-398



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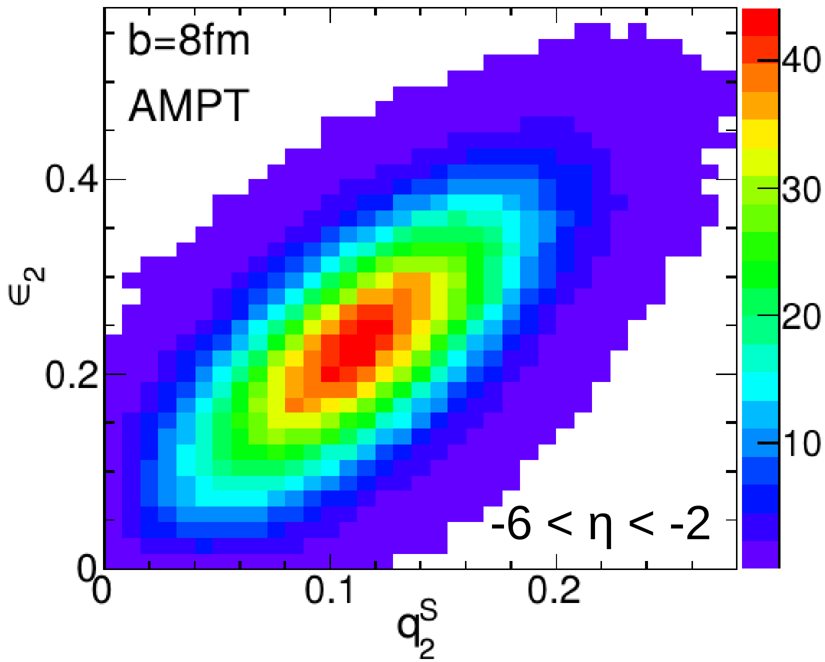


- q-vector evaluated in sub-event a, v_n^2 measured in sub-event b
- Large q_2 → larger v_2

- Strong positive correlation between eccentricity and q-vector
- $\langle\varepsilon_2\rangle$ value is higher in 10% large q_2 sample

The shape of the initial geometry can be selected using the q-vector in the final state

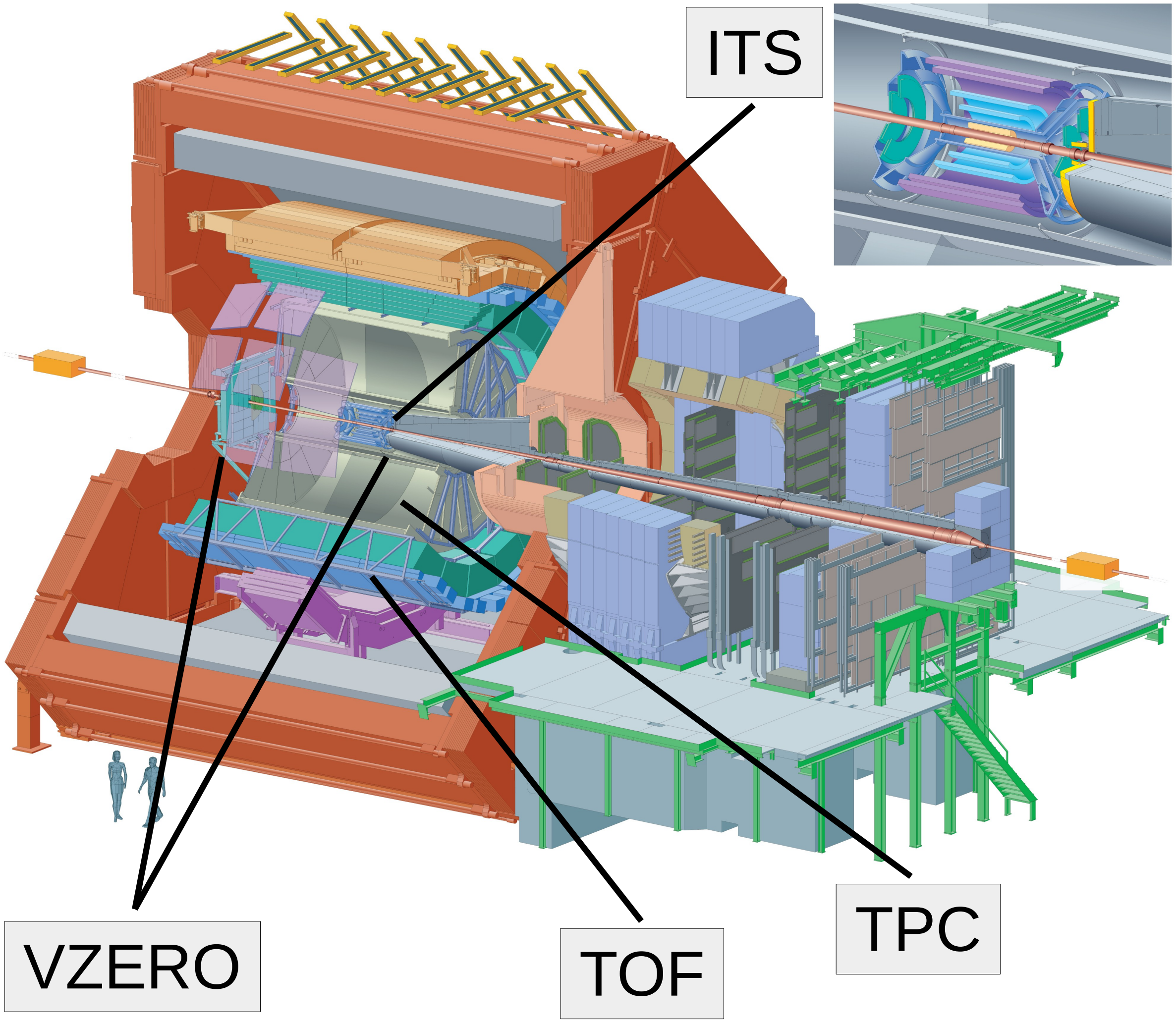
The ALICE detector

Inner Tracking System (ITS)
- Primary vertex reconstruction
- Combined ITS-TPC tracking

Time Projection Chamber (TPC)
- Main tracking system
- PID from energy loss in the gas

Time Of Flight (TOF)
- Tracks extrapolated from ITS-TPC
- PID from time of flight measurement

VZERO
- VZEROA ($2.8<\eta<5.1$)
- VZEROC ($-3.7<\eta<-1.7$)
- Trigger, centrality selection, event plane calculation



~10M minimum bias Pb-Pb events at $\sqrt{s_{NN}}$ = 2.76 TeV (2010 run) used for this analyisis.

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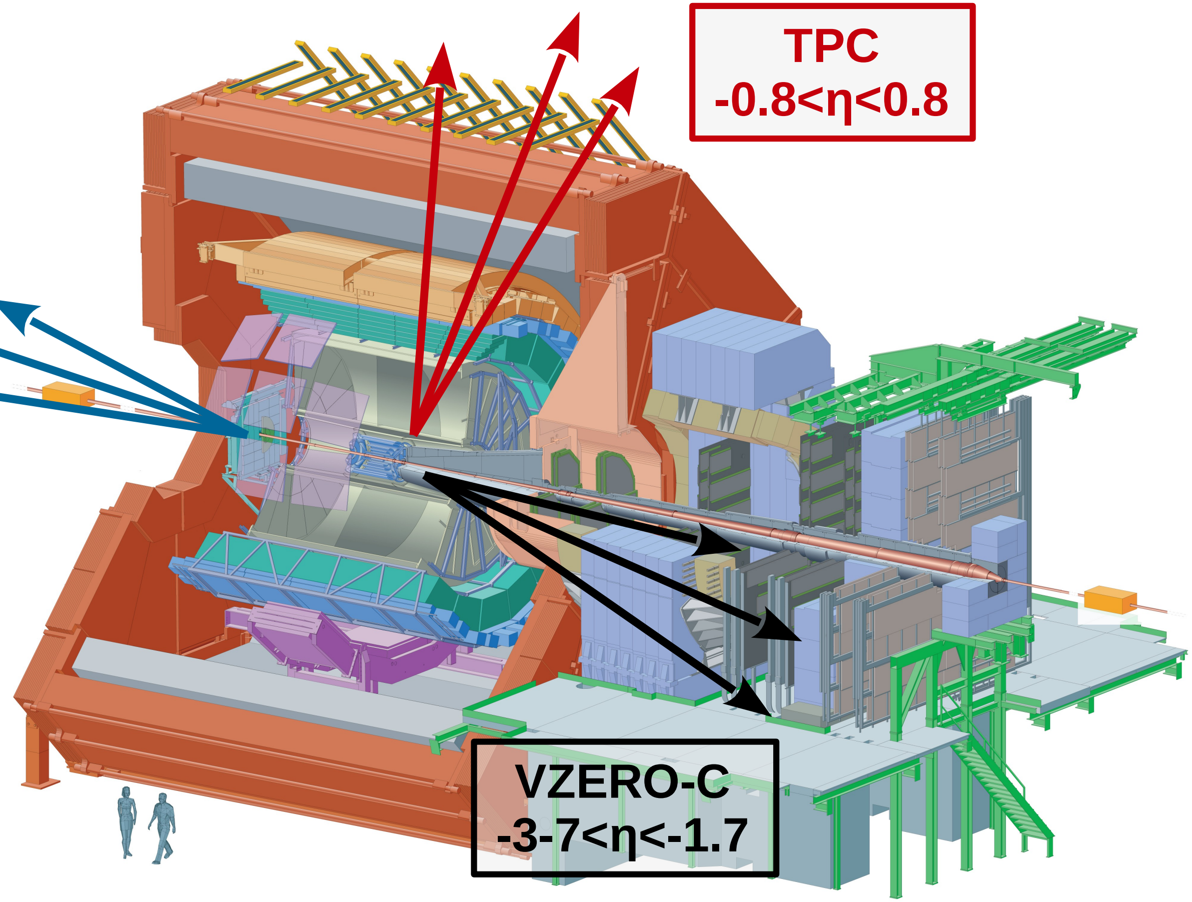

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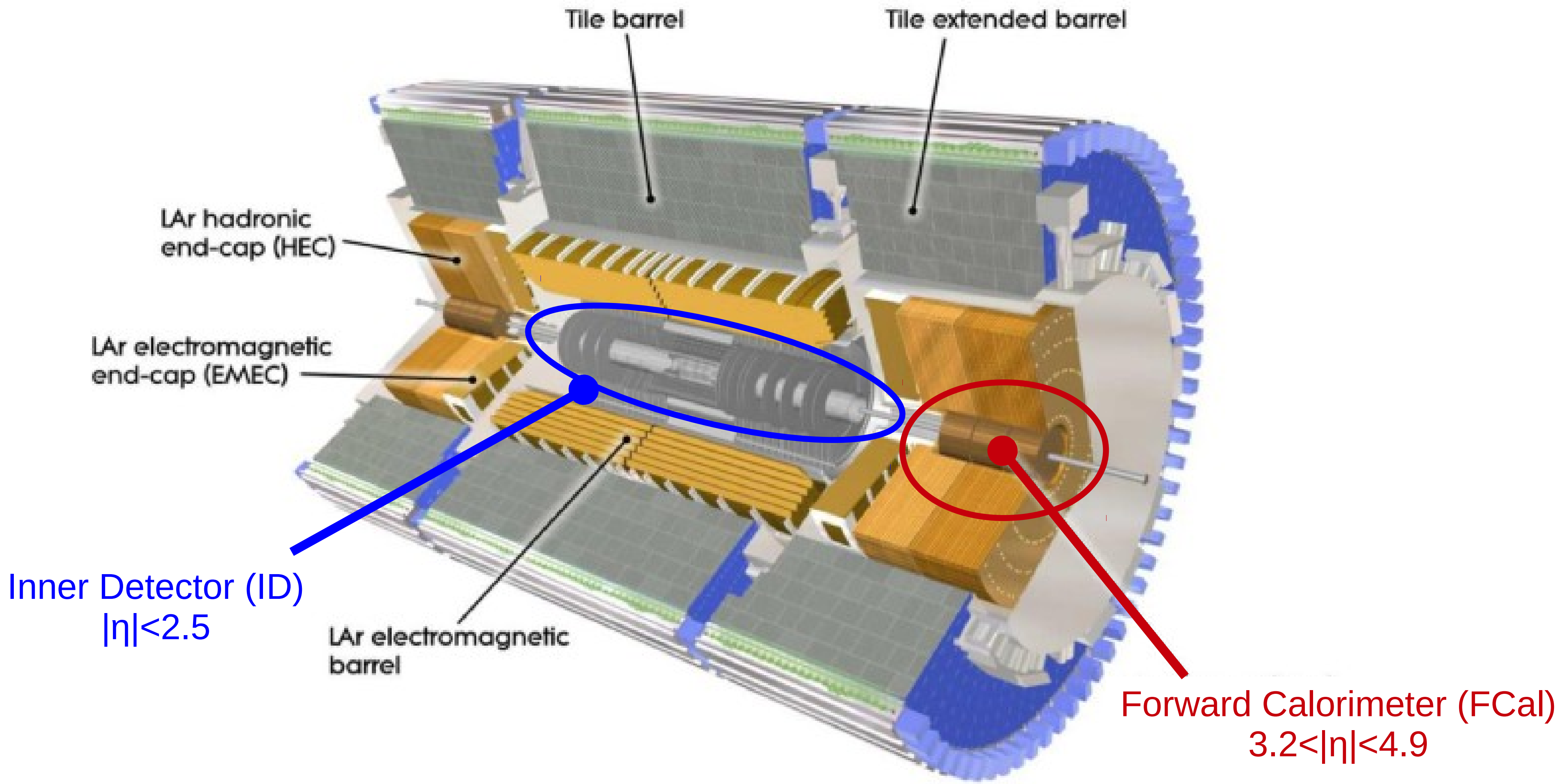


- FCal coverage : 3.2<|η|<4.9 (determine Centrality, Event-Shape selection)
- Tracking coverage : |η|<2.5 (Track reconstruction, vn measurement)

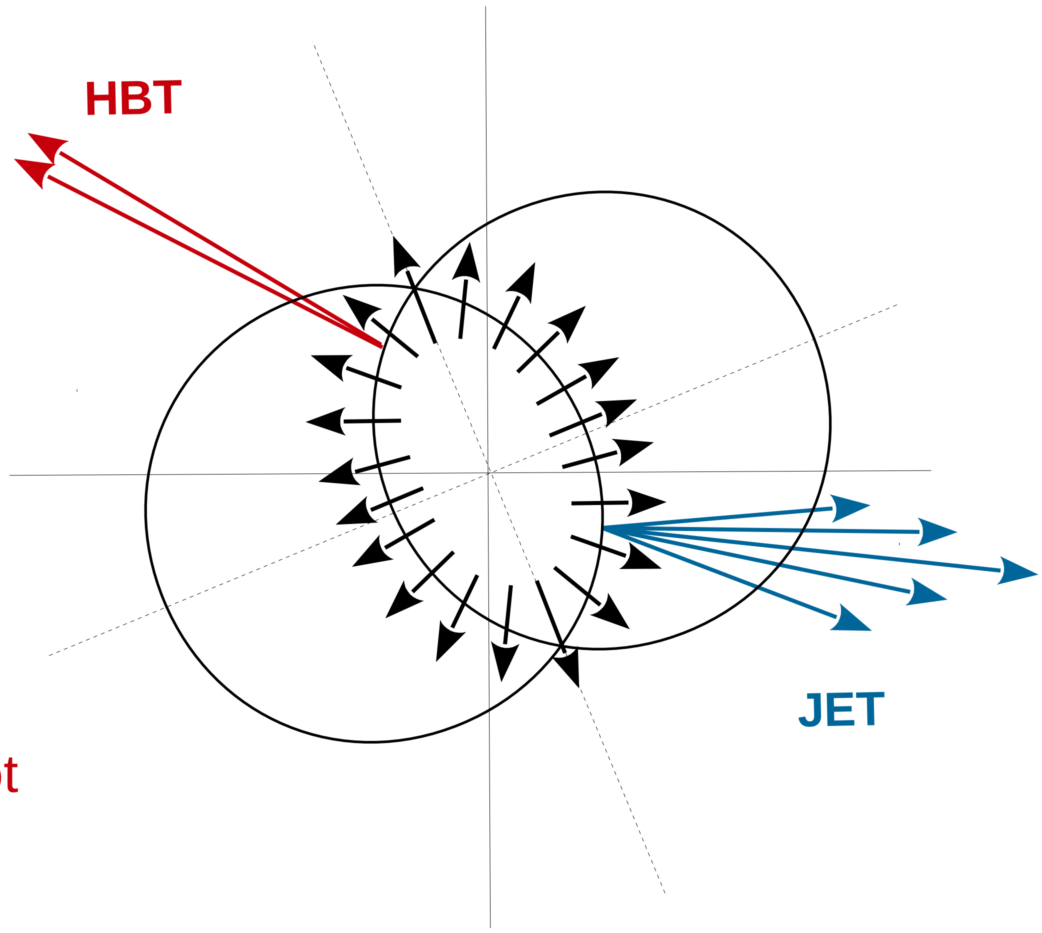
Non-flow contribution

Non-flow definition

contribution to v_n from azimuthal correlations between particles not due to their correlation with the reaction plane

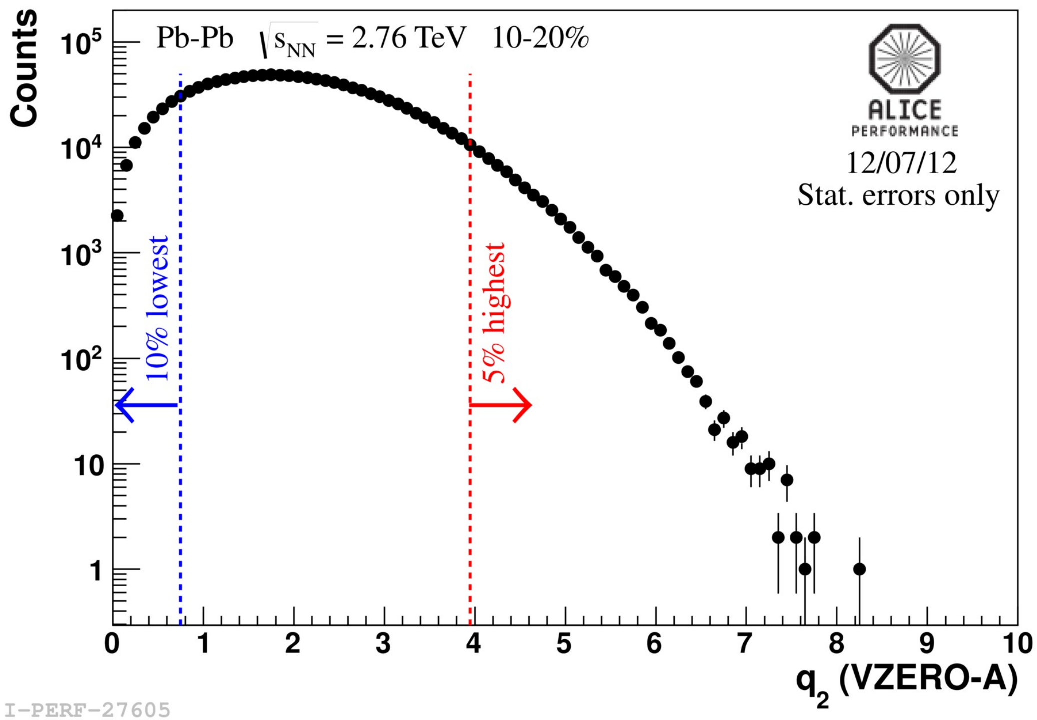
Examples

- HBT
- Resonances
- Jets
- …

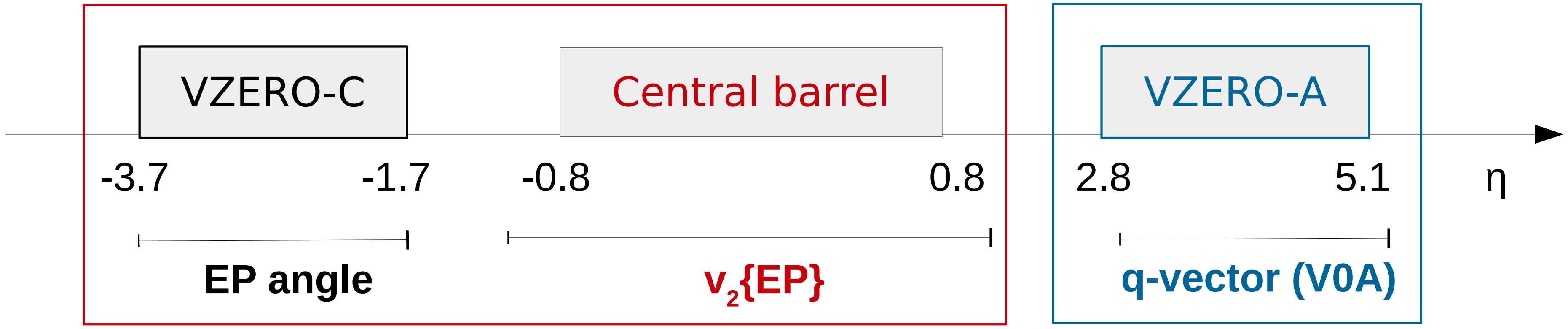


Large gap in pseudo-rapidity between sub-events suppresses correlations not related to the azimuthal asymmetry in the initial geometry

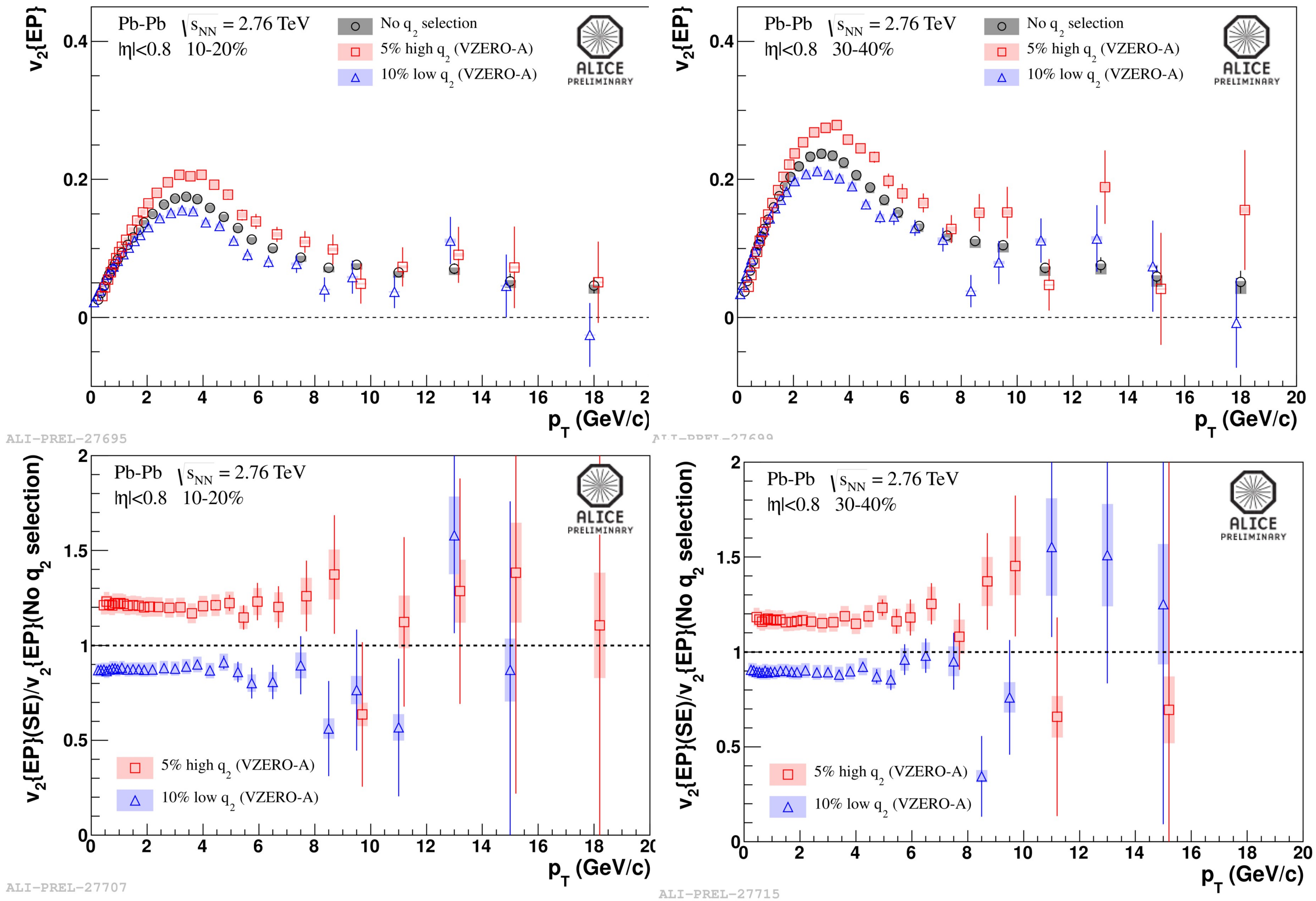
Elliptic flow with ESE: selection



- q-vector from VZERO-A (2.8<η<5.1)
- v_2 evaluated using tracks from TPC (-0.8<η<0.8) and event-plane from VZERO-C (-3.7<η<-1.7)
- Large Δη separation between the three detectors → non-flow suppression



Elliptic flow with ESE



5% high q_2

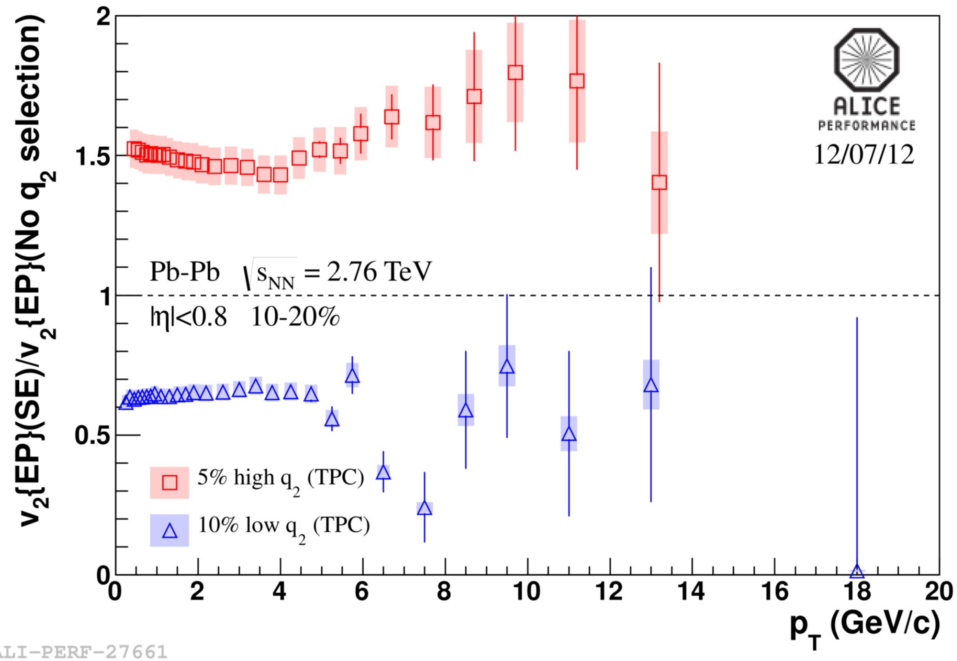
10% low q_2

No q_2 selection

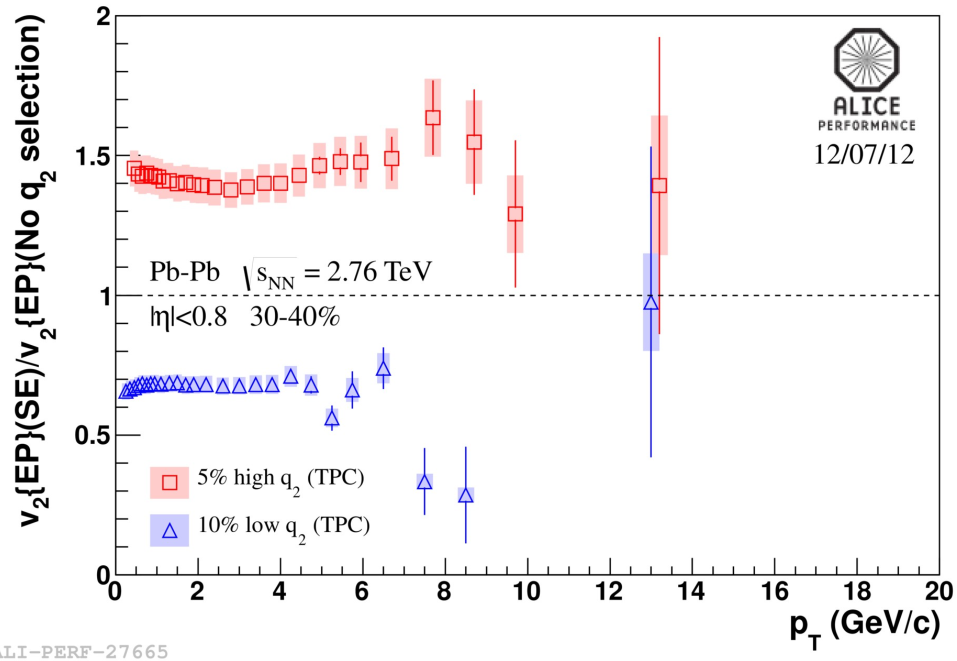
- q-vector from V0A ($2.8<\eta<5.1$)
- v_2 from TPC ($-0.8<\eta<0.8$)
- Event-plane from V0C ($-3.7<\eta<-1.7$)

- Event plane method used to evaluate v_2 (see backup)
- Ratios constant up to p_T = 6 Gev/c → similar flow fluctuations
- Smaller flow fluctuations effect for p_T > 6 Gev/c

Elliptic flow with ESE



ALI-PERF-27661



ALI-PERF-27665

- q_2 from half TPC: $-0.8<\eta<0$ or $0<\eta<0.8$
- v_2 evaluated using tracks from the other half of TPC ($-0.8<\eta<0.8$) and event-plane from VZERO
- Non flat ratios may be due to non-flow contributions

Spectra with ESE

Elliptic flow is related with the eccentricity of the collision: $v_2 \propto \epsilon_2$

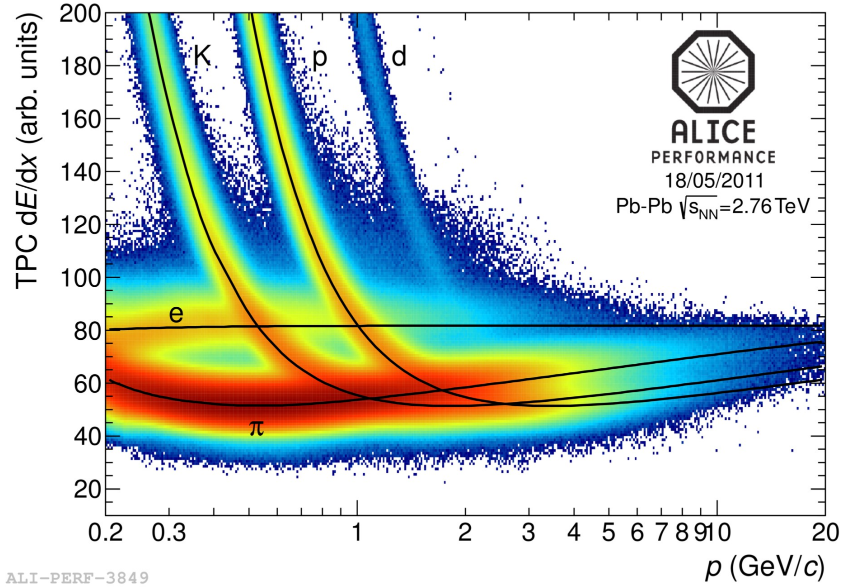
Understand connection between initial condition and hydro response

Event-shape selection: constraint initial condition (size and geometry of the collision fixed)

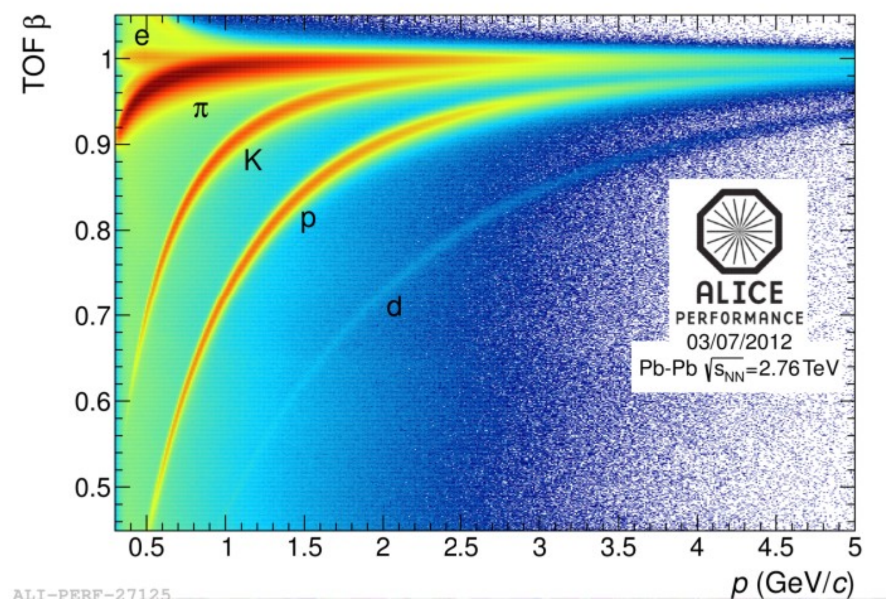
Analysis of transverse momentum spectra in event shaped event: correlation between radial and anisotropic flow?

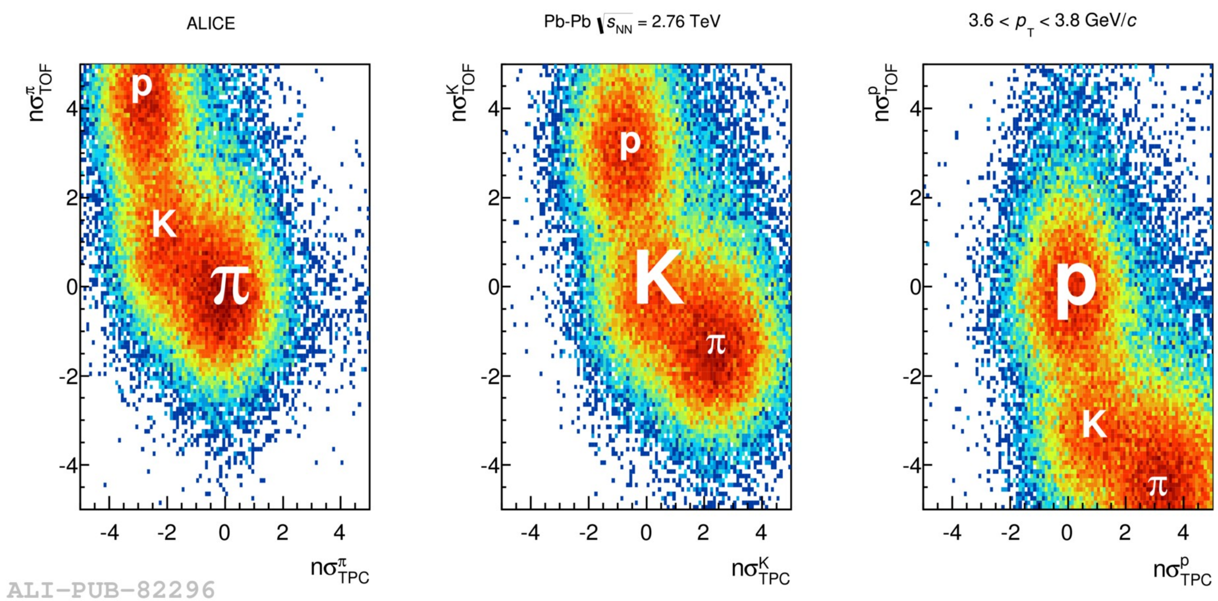
ALICE Particle IDentification

Time Projection Chamber



Time Of Flight





$$N^2_{\sigma,PID} = N^2_{\sigma,TPC} + N^2_{\sigma,TOF}$$

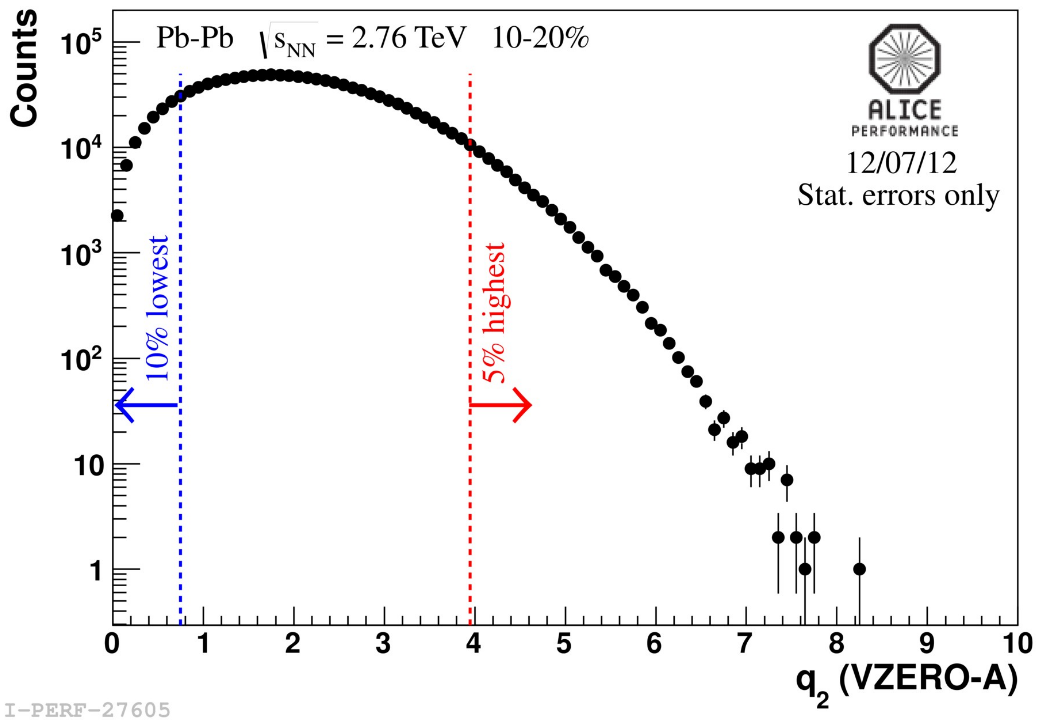
$$N^2_{\sigma,PID} < 3$$

$$N^2_{\sigma,PID} = N^2_{\sigma,TPC} \rightarrow p_T < 0.6\ \mathrm{GeV}/c$$

Event plane method

- Flow vectors calculation: $Q_{n,x}=\sum_i w_i \cos(n\phi_i)$ $Q_{n,y}=\sum_i w_i \sin(n\phi_i)$
- Event plane angle calculation: $\psi_n=\left(\tan^{-1}\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right)/n$
- Flow coefficients: $v_n^{obs}=\langle\cos[n(\phi_i-\psi_n)]\rangle$
- Event plane resolution correction: $v_n=v_n^{obs}/R_n$ $R_n=\langle\cos(n(\psi_n-\Psi_n))\rangle$

Elliptic flow with ESE: selection



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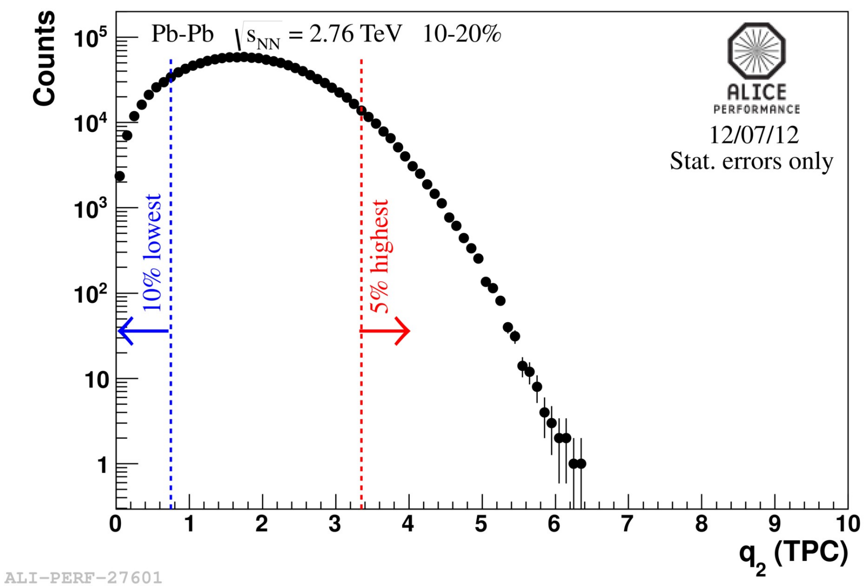
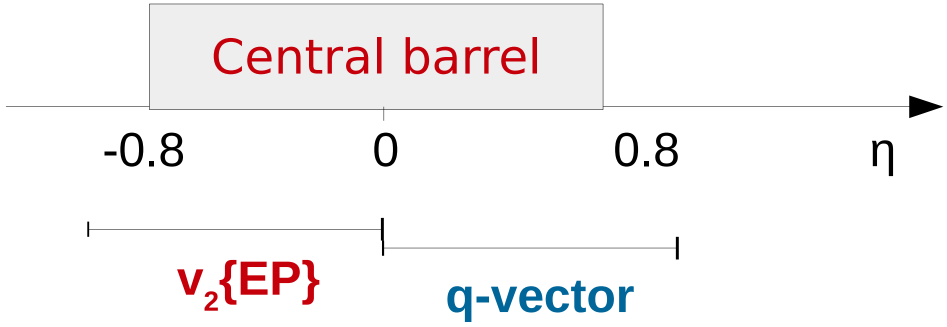
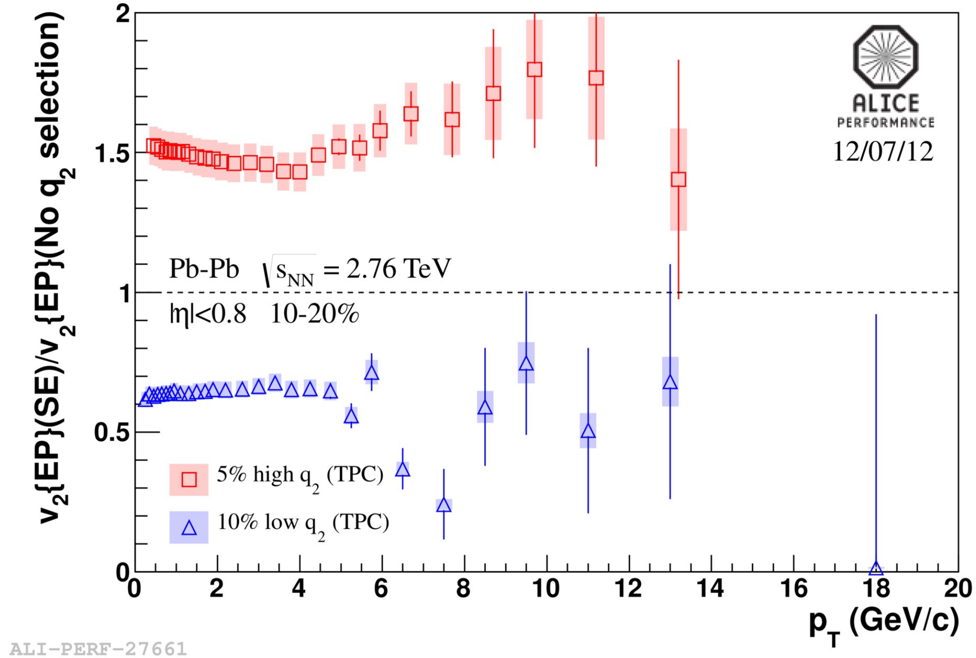
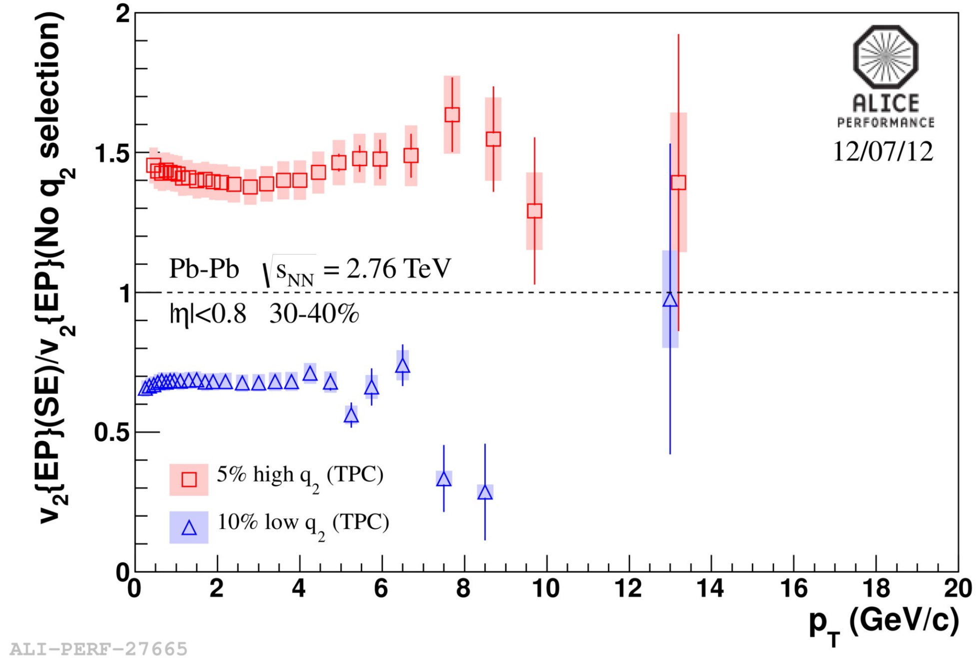


- q-vector from TPC (-0.8<η<0 or 0<η<0.8) and v_2 from the other TPC η window



Elliptic flow with ESE





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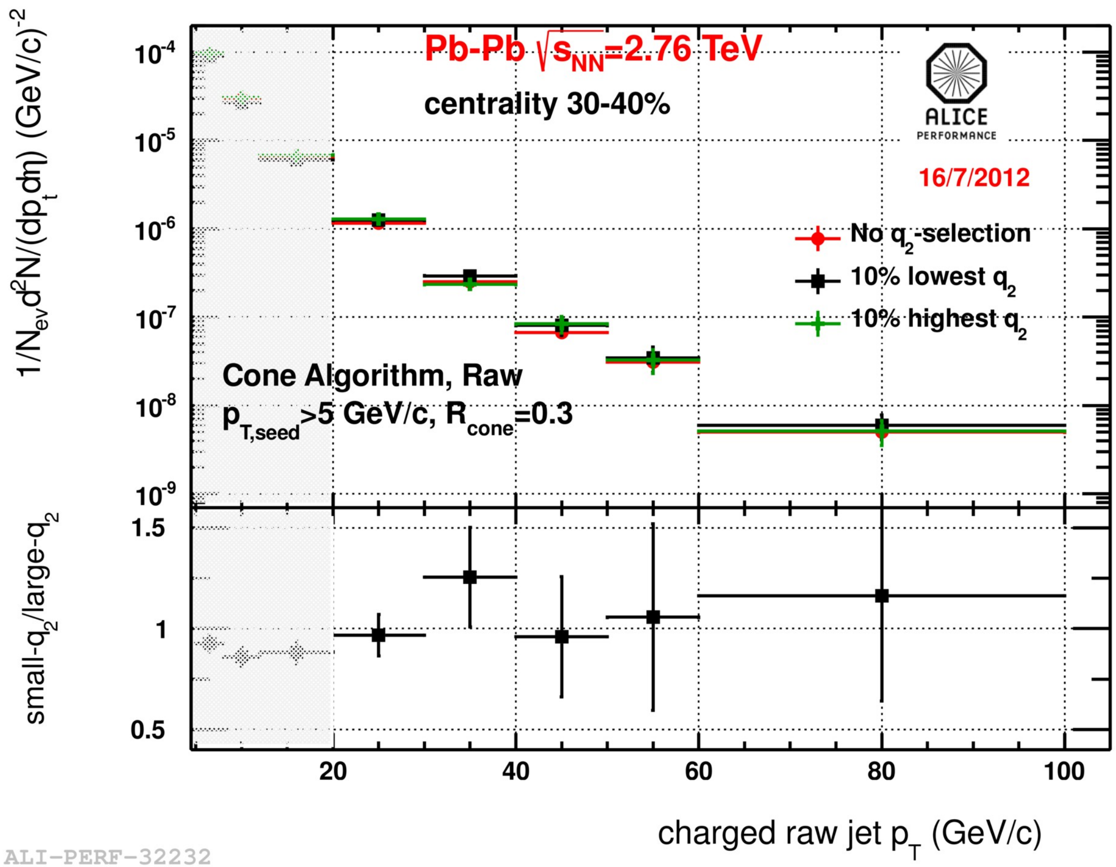
- Non flat ratios may be due to non-flow contributions

Spectra with ESE



Jet contamination

Background

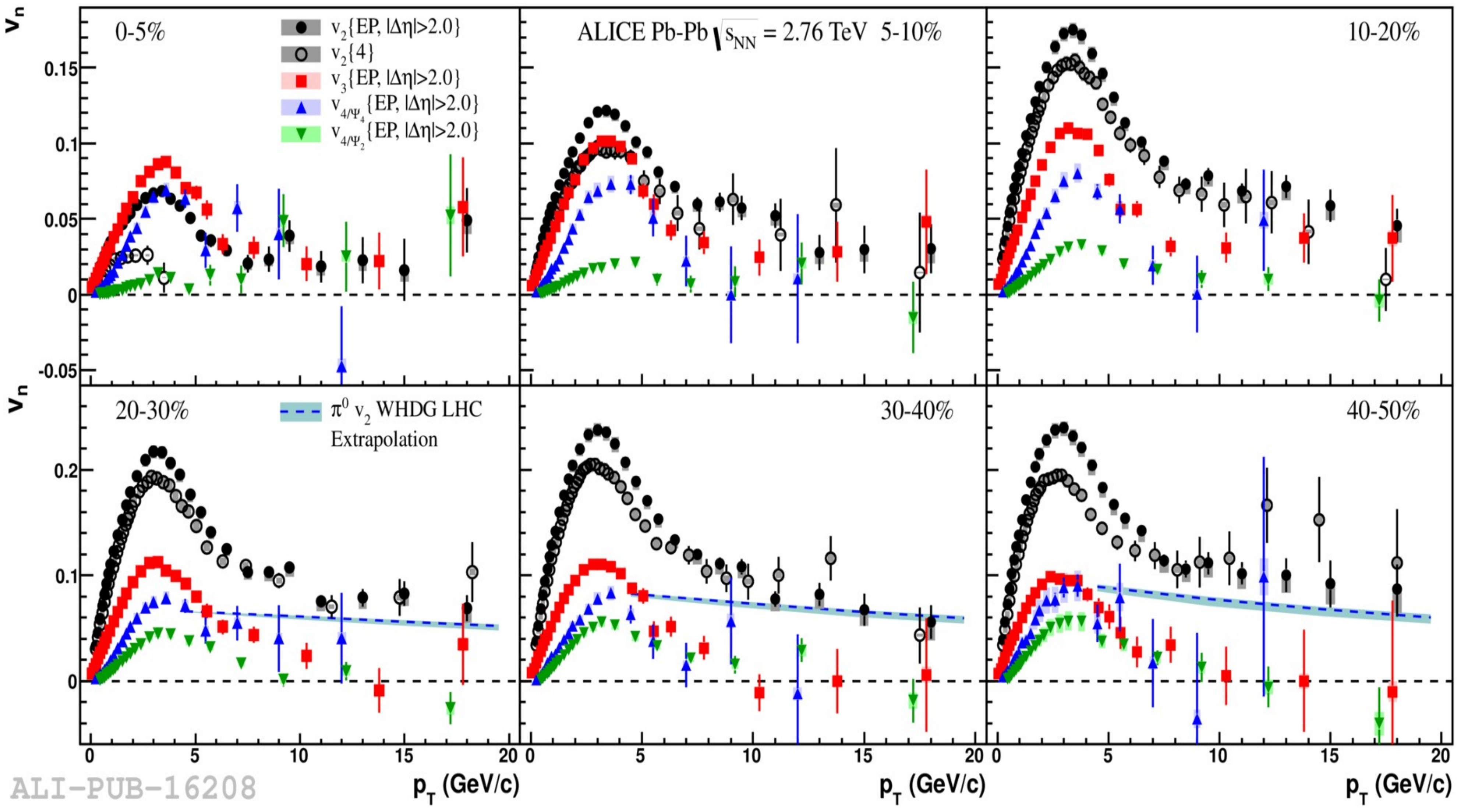
- $P_{T,tot}$ = total pT in the event
- density = $p_{T,tot}$ / acceptance

Energy in a cone

- seed particle: (p_T>5GeV/c)
- $p_{T,sum}$ = sum of p_T in R<0.3
- area=$\pi \cdot R^2$
- $p_{T,jet}$= $p_{T,sum}$ - (density · area)

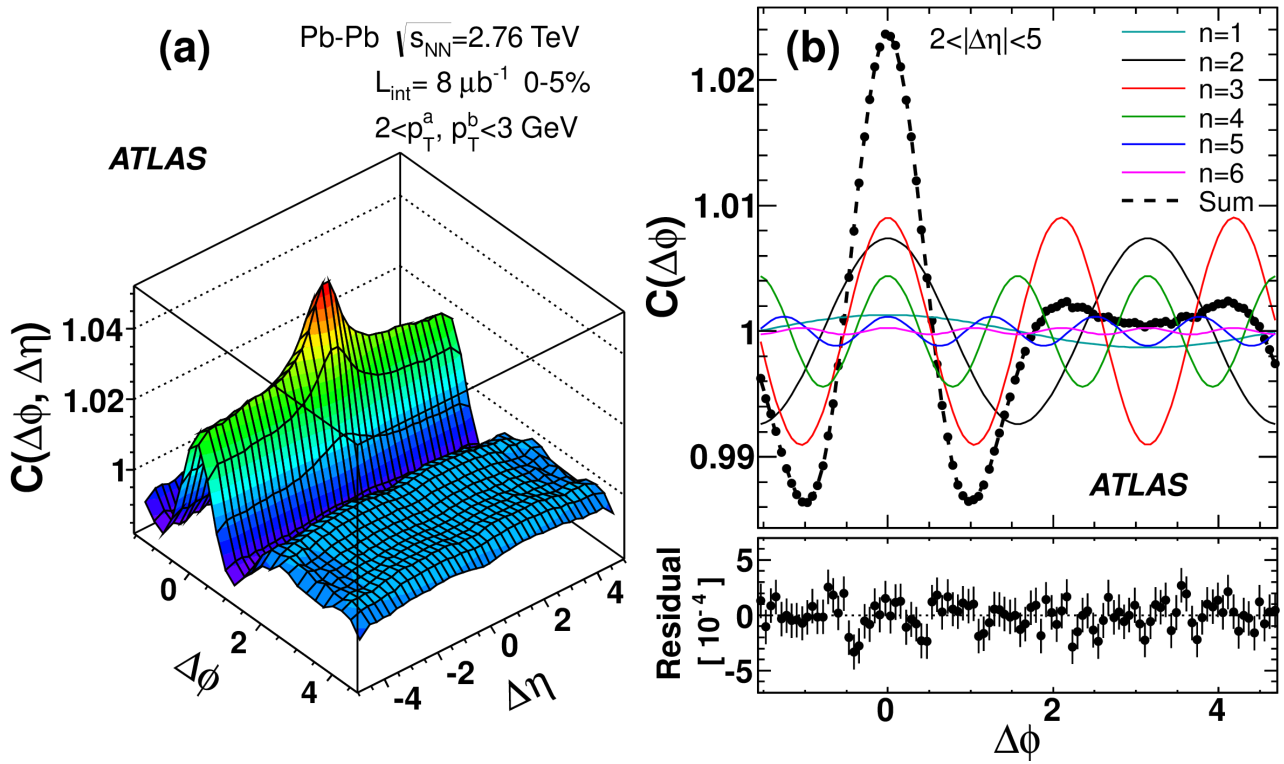
- method reliable only above ~20 GeV/c
- ratio is flat, “jet” contribution similar

ESE



v_n
0-5%
$v_2\{EP, |\Delta\eta|>2.0\}$
$v_2\{4\}$
$v_3\{EP, |\Delta\eta|>2.0\}$
$v_{4/\Psi_4}\{EP, |\Delta\eta|>2.0\}$
$v_{4/\Psi_2}\{EP, |\Delta\eta|>2.0\}$
ALICE Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV 5-10%
10-20%
20-30%
π^0 v_2 WHDG LHC Extrapolation
30-40%
40-50%
p_T (GeV/c)
ALI-PUB-16208

Event-by-event fluctuations



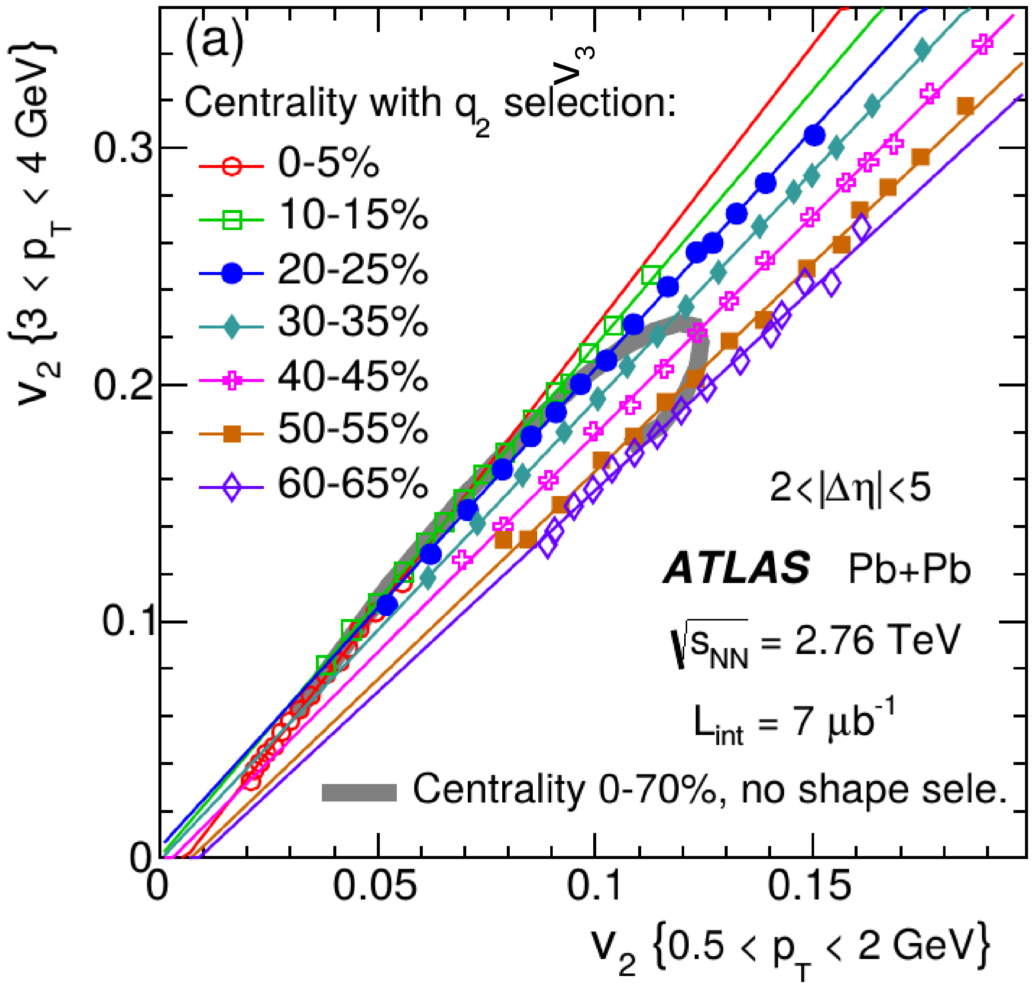
Fluctuations explain entire structure of two particle correlations

solid lines: v_1, v_2, v_3, v_4, v_5, v_6 term

dashed line: sum

points: correlation measurement

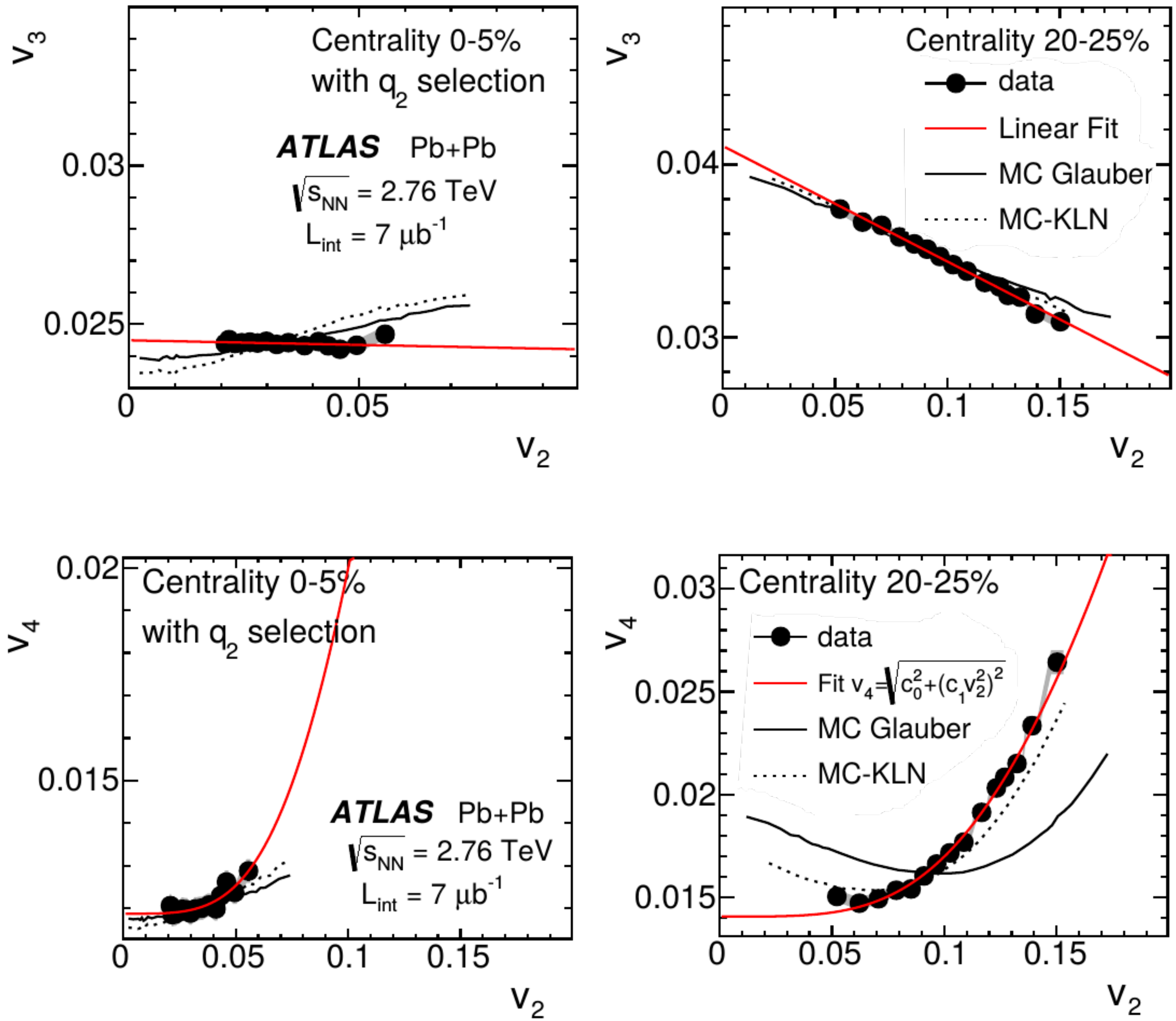
Anisotropic flow



Saw non-trivial dependence with centrality (boomerang like) → different centrality dependence of v_n.

within one centrality the dependence is linear → Indicates that viscous correction mostly controlled by system size, not shape!

Anisotropic flow



Compare (v_3, v_2) correlations to (ε_3, ε_2) correlations calculated in Glauber & CGC models.

Good agreement in several centralities, some deviation in (0-5)% central events.

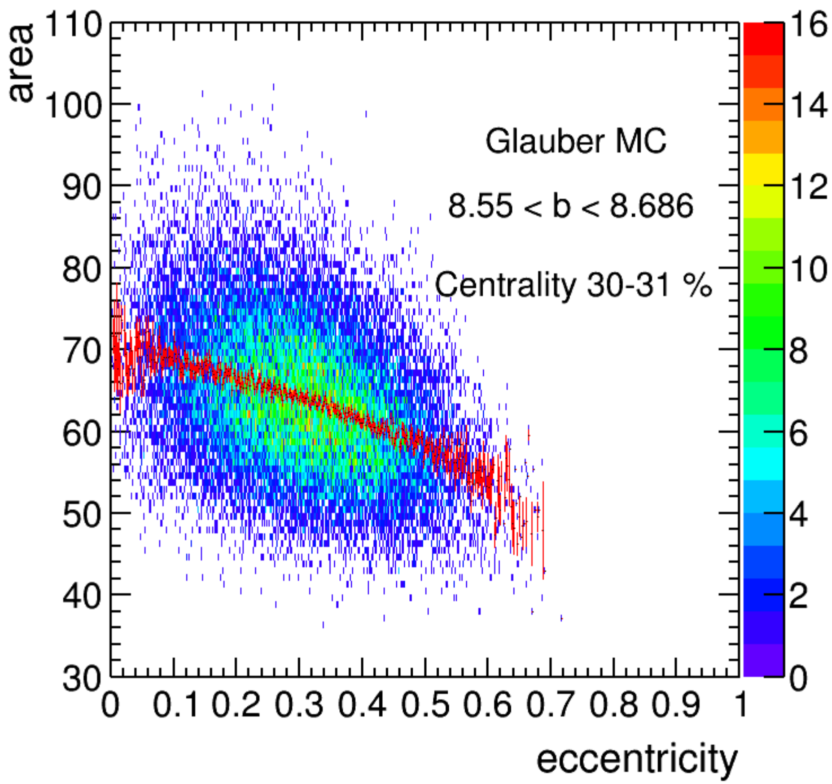
Fit un-correlated + correlated components:

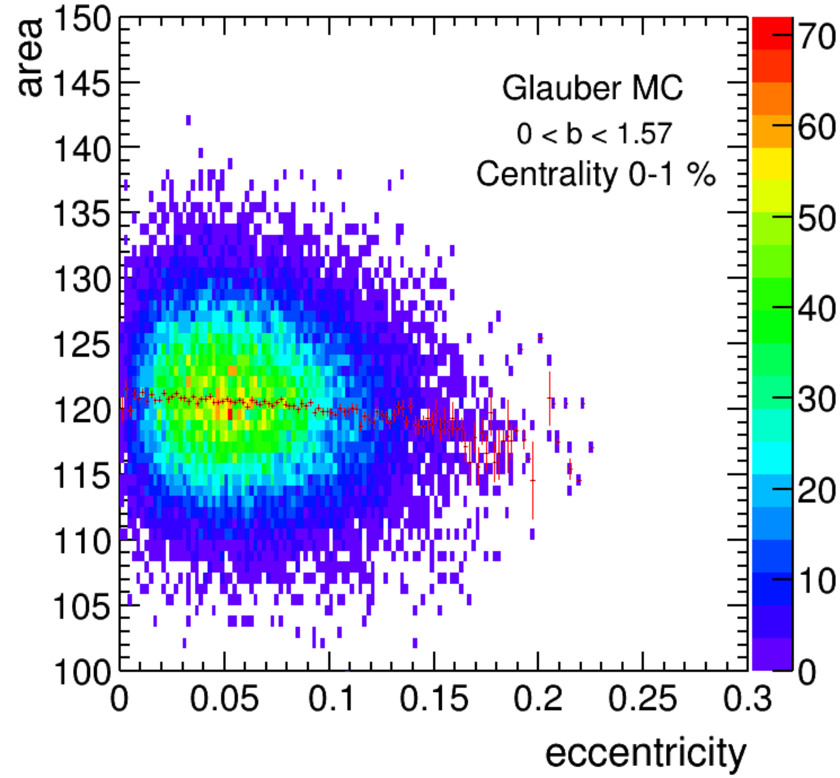
$$v_4=\sqrt{c_0^2+c_1^2 v_2^4}$$

Initial geometry models not reproduce data. Non-linear dynamical mode mixing produces these correlations

Measurements can constrain initial geometry models

Spectra ESE: Glauber MC

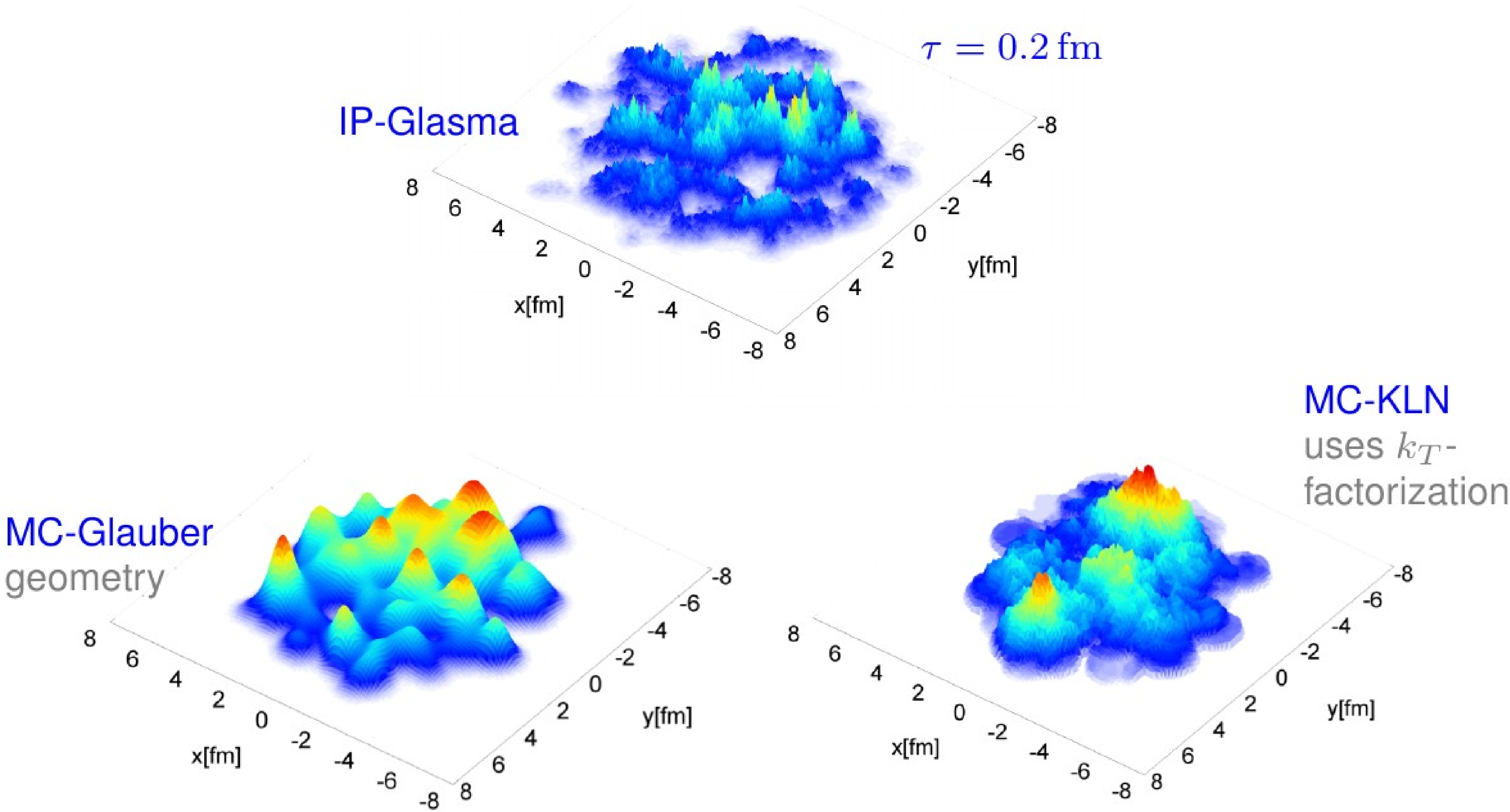




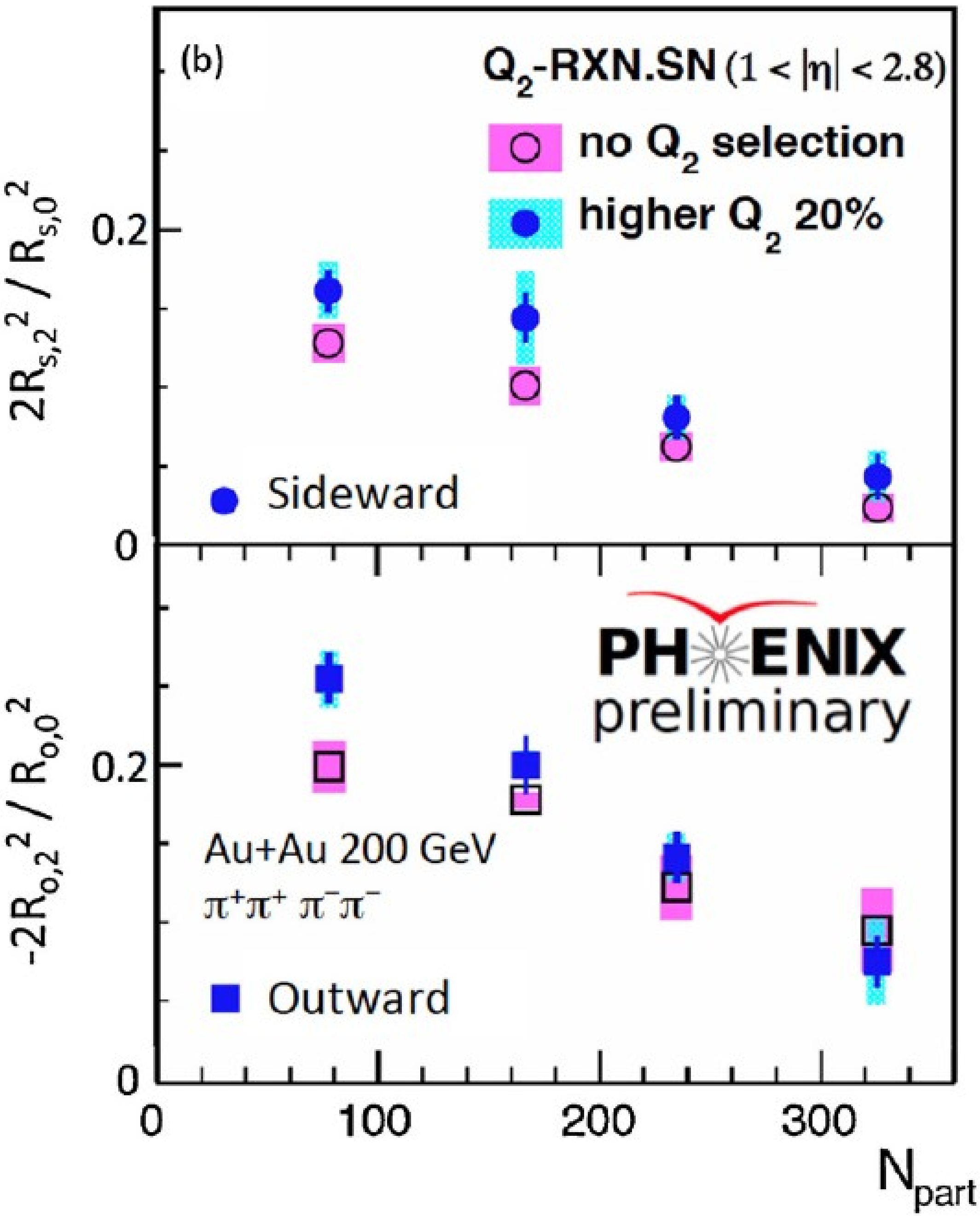
- Area and eccentricity are anti-correlated at fixed b_{imp} (centrality)
- Area inversely related to transverse density (N_{part}/A): positive correlation between eccentricity and density.

- Centrality 0-1 %: weaker correlation between area and eccentricity.
- Glasma e CGC predictions? Can these measurements contrain initial condition models?
- Full hydro simulation needed

Initial energy density



HBT with ESE



The measured azimuthal dependences of radius parameters are fitted with a function:

$$R_{\mu}^{2} = R_{\mu,0}^{2} + 2R_{\mu,2}^{2}\cos(2\,\Delta\varphi)$$

the extracted final eccentricity:

$$\varepsilon_{final} = |2R_{\mu,2}^{2} / R_{\mu,0}^{2}|$$