Particle Correlations from ALICE:

Latest Results

Andrew M. Adare

Yale University

for the

ALICE **collaboration**

What have we been up to since QM11?

Identified particle correlations...
Jet fragmentation vs. bulk physics

Near-side jet studies...
Shape & yield modification in Pb-Pb vs. pp

Single-event anisotropy...
Flow and fluctuations

3-particle correlations...
Can nonflow signals be extracted?

Transverse momentum correlations...
Harmonic analysis, flow comparisons

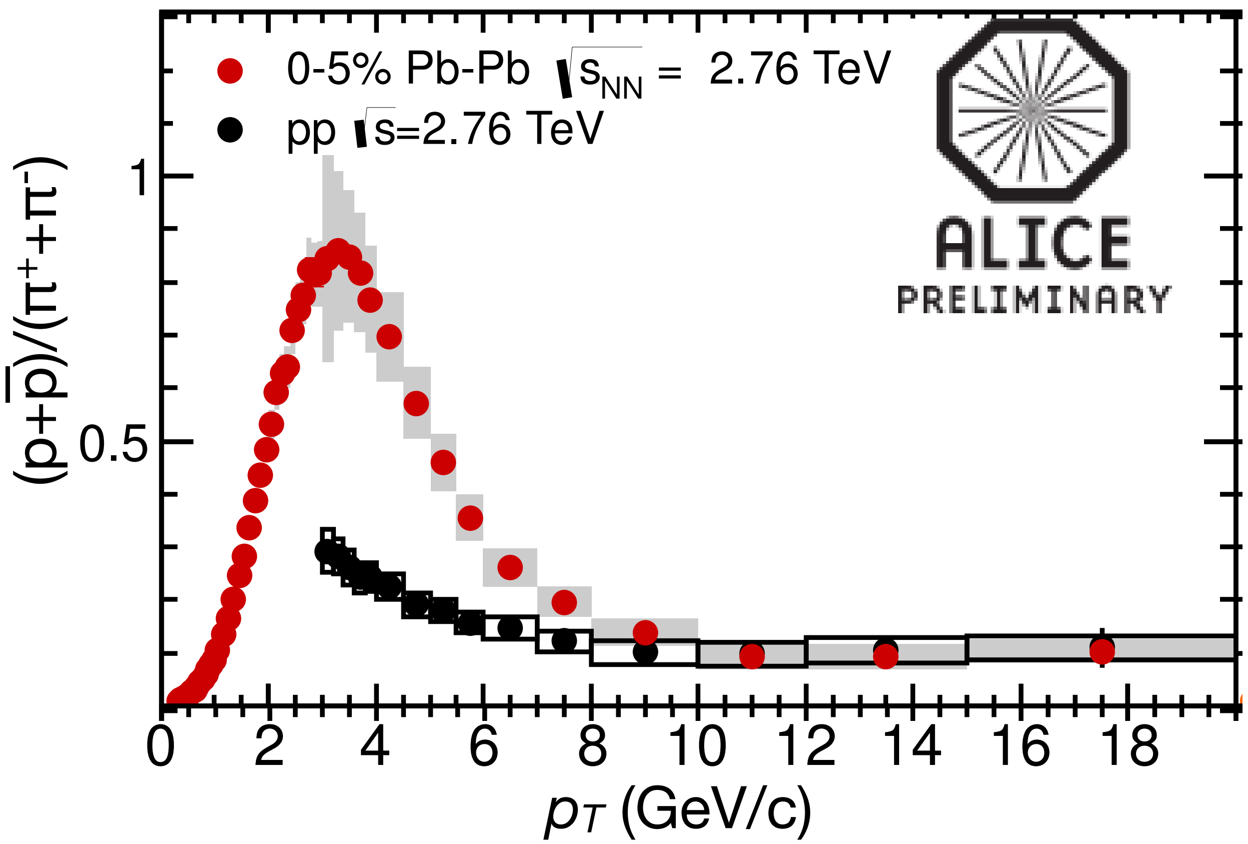
Charge balance studies...
Angular dependence of balance functions

Femtoscopy with identified particles...
Space-momentum and baryon-antibaryon ($B\bar{B}$) correlations

Identified particle correlations

Baryon enhancement, first observed at RHIC, also found at LHC.

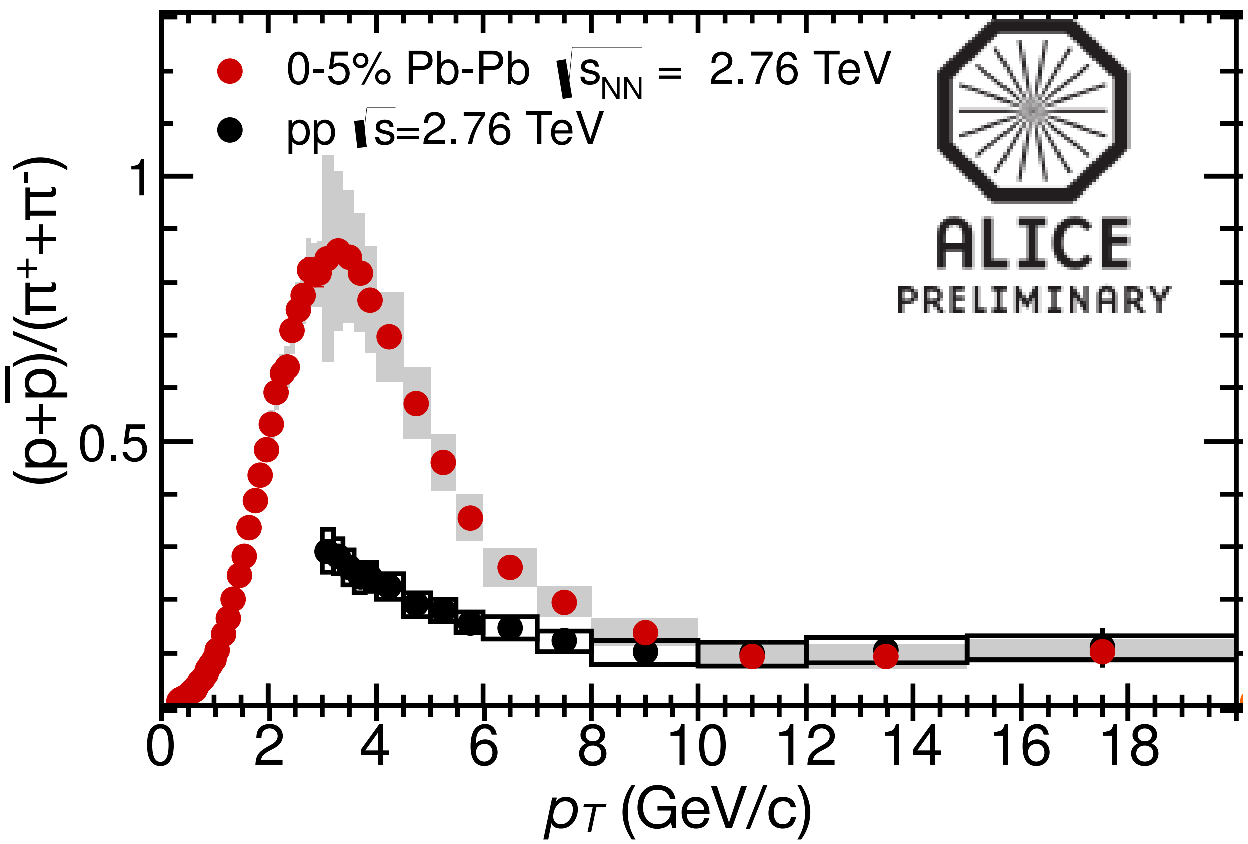
Is there a jet contribution?

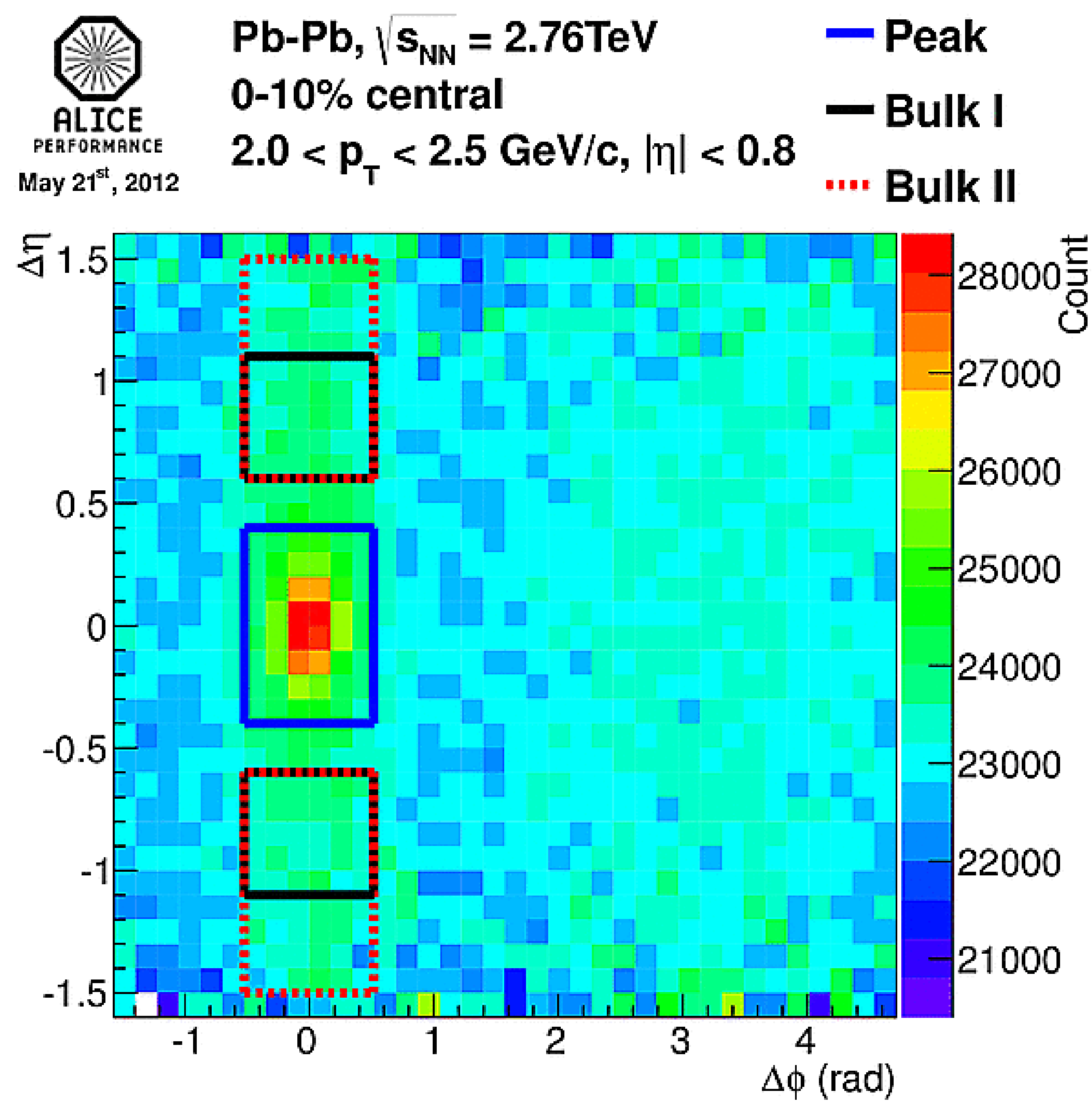


Identified particle correlations

Baryon enhancement, first observed at RHIC, also found at LHC.

Is there a jet contribution?





ALI-PERF-15359

Study in 2-particle Δφ-Δη correlations

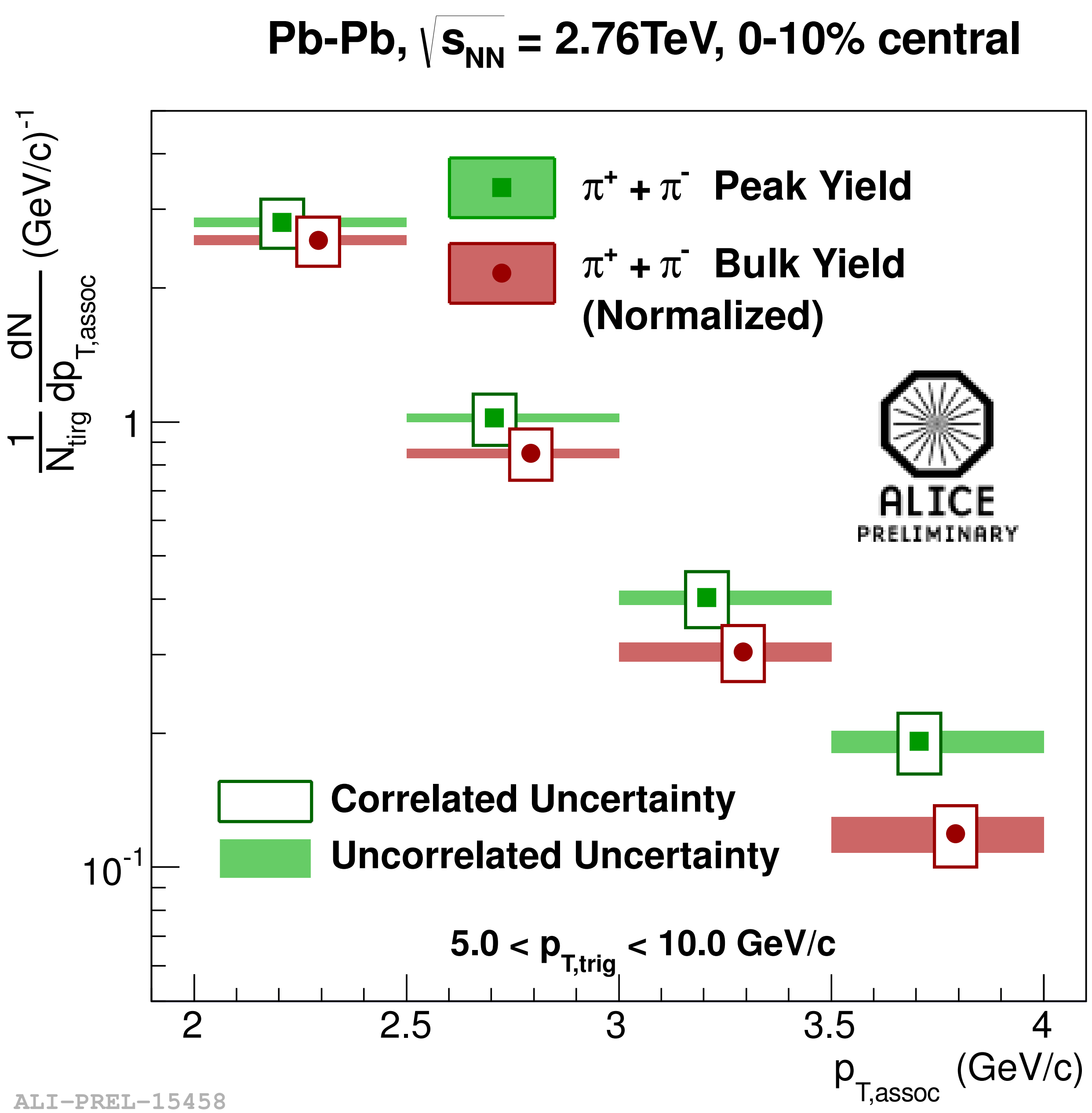
- Non-identified trigger particle (5-10 GeV/c)
- Identified associated π,K,p (1.5-4.5 GeV/c)

Measure conditional yields

- in "peak" region (Δφ,Δη near 0,0)
- in "bulk" regions (Δη > 0.6 on near side)

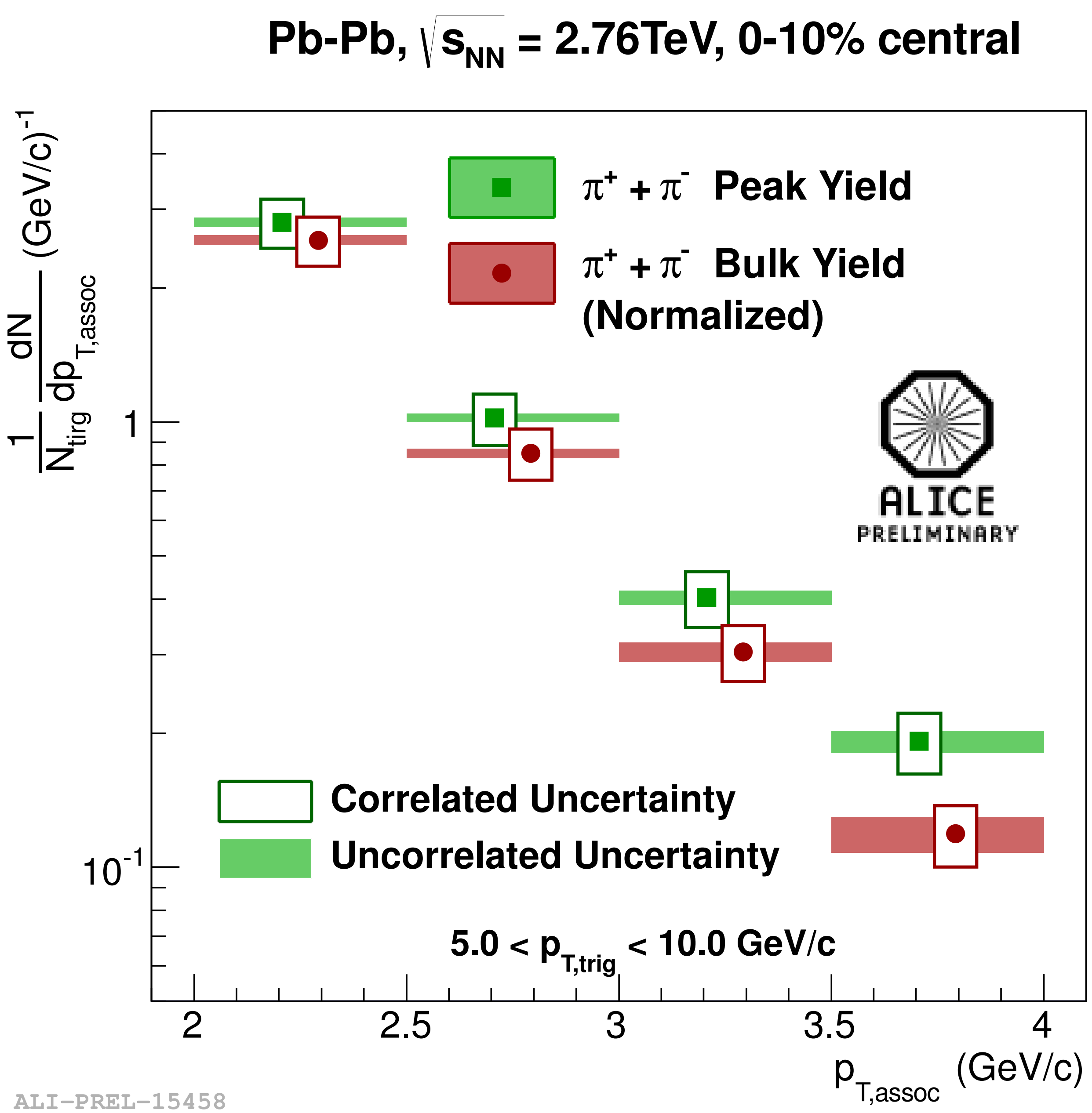
Conditional pion and proton spectra

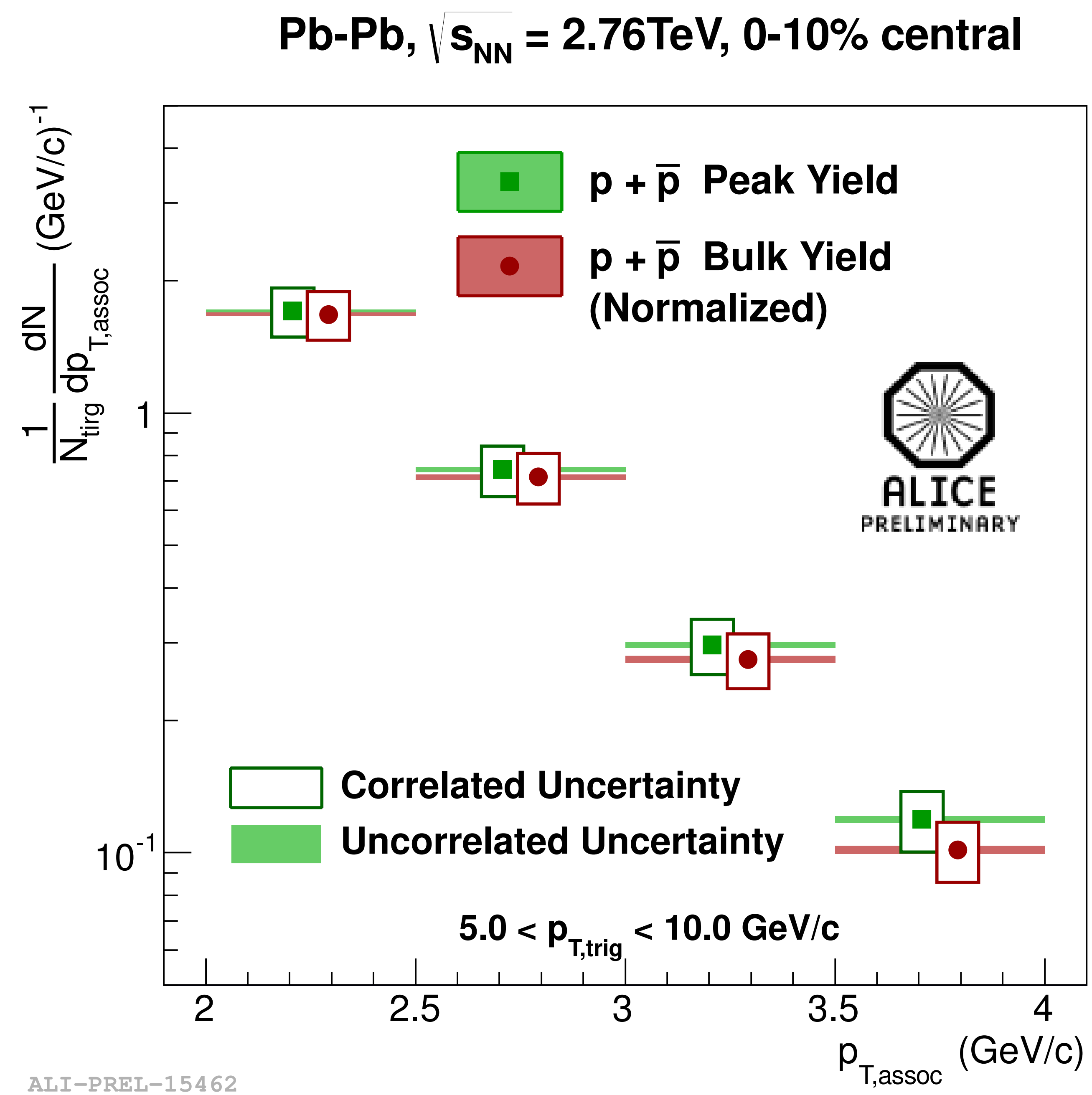
Associated pion yields enhanced in peak vs. bulk regions.



Conditional pion and proton spectra

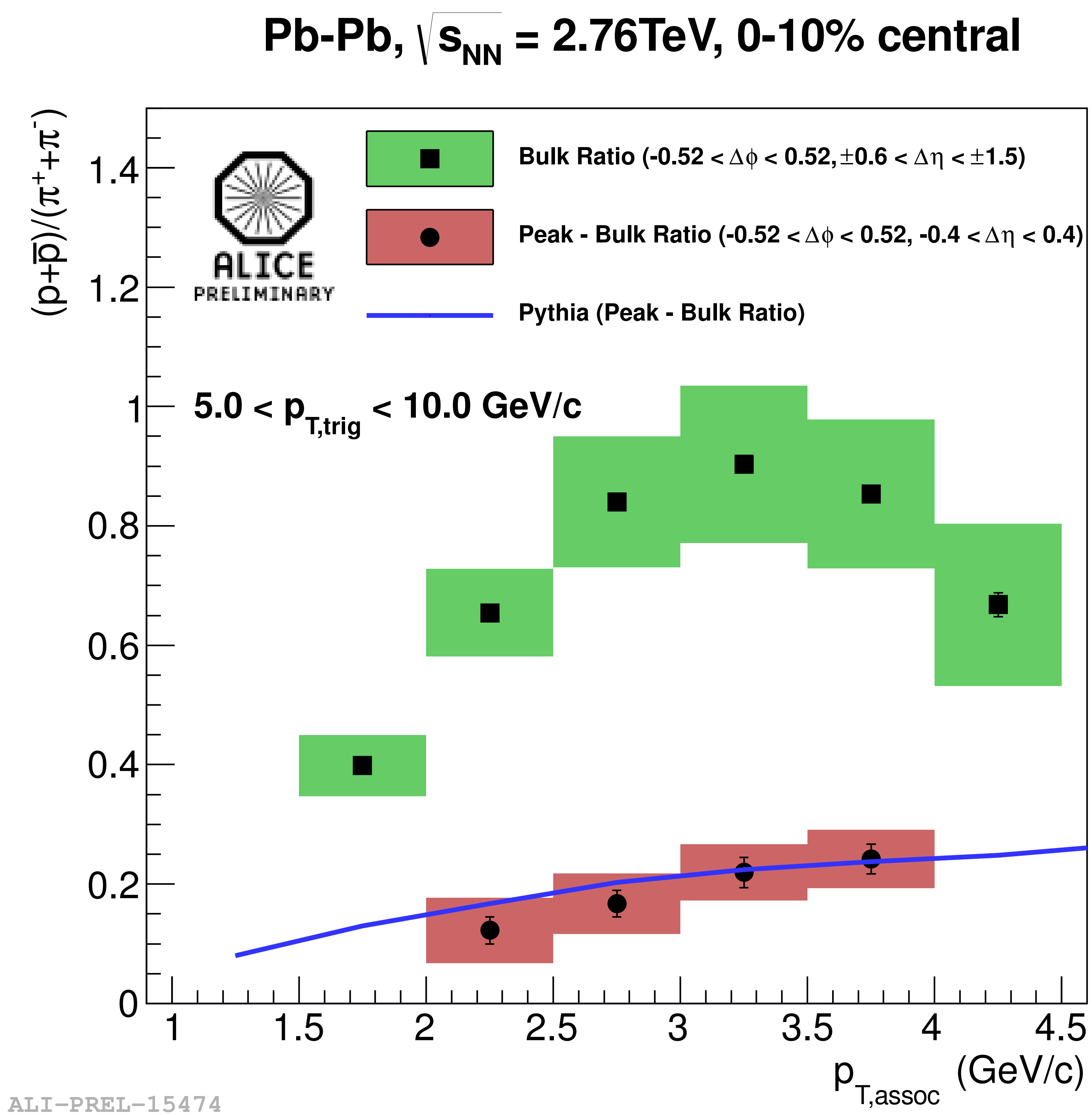
Associated pion yields enhanced in peak vs. bulk regions.
Similar effect for protons, but weaker.





What are the p/π ratios?

p/π ratio vs. associated p_T



Near-side peak:

- p/π ratio similar to pp (pythia).

In "bulk" region:

- p/π ratio strongly enhanced

Implications:

No medium-induced modification of jet particle ratios.

Baryon enhancement is from bulk, not jets.

Near-side peak shape analysis

Multiple observables suggest medium-induced energy loss (R_{AA}, I_{AA}, A_j)

Reconstructed-jet analyses: large-angle soft radiation, with weakly modified remnant jets.

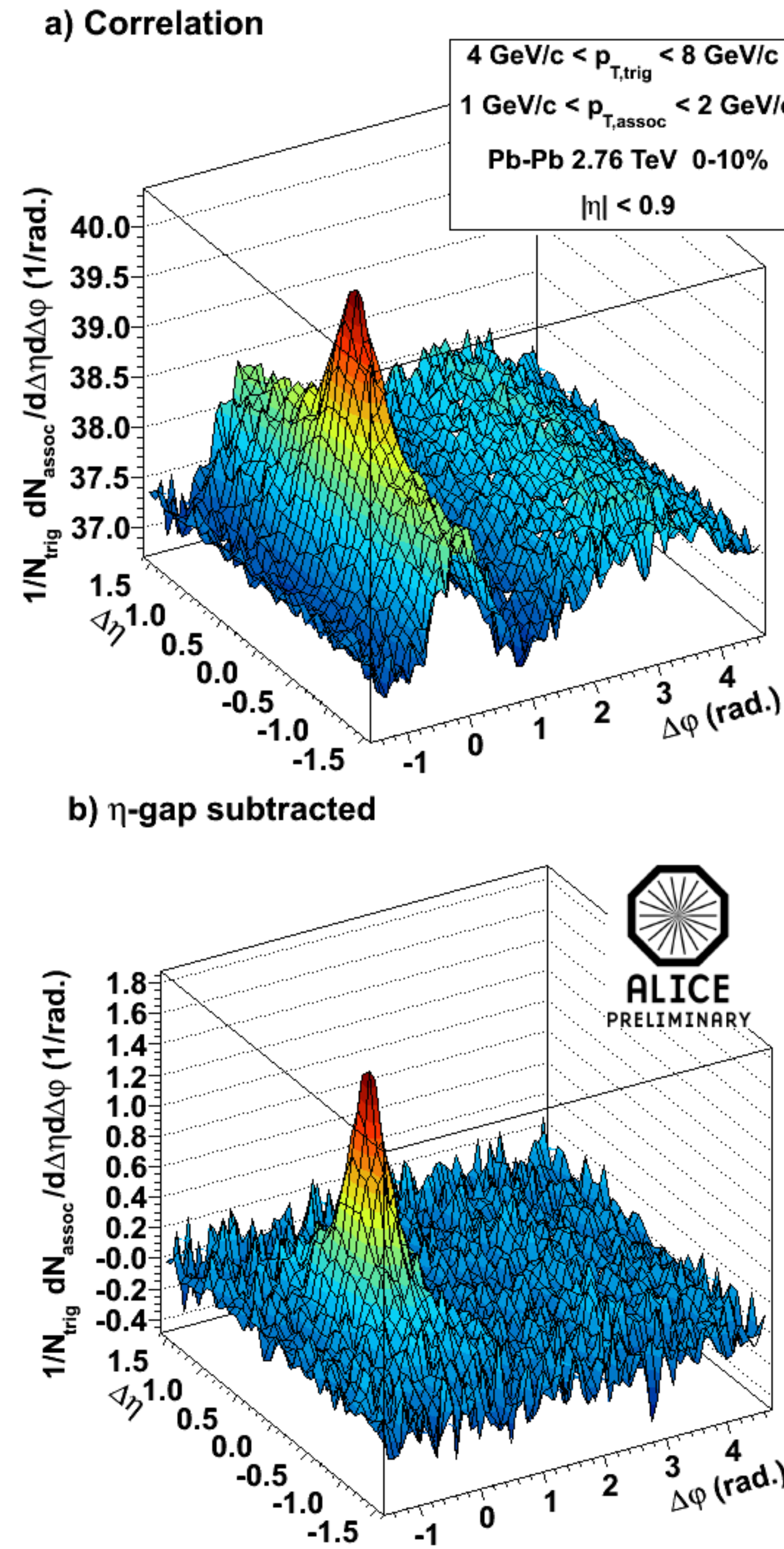
Check with dihadron correlations

Study modification in width & changes in eccentricity

Isolate near-side jet

Use long-range (i.e. in Δη) correlations as proxy for background

Away-side uniform in Δη, vanishes after subtraction

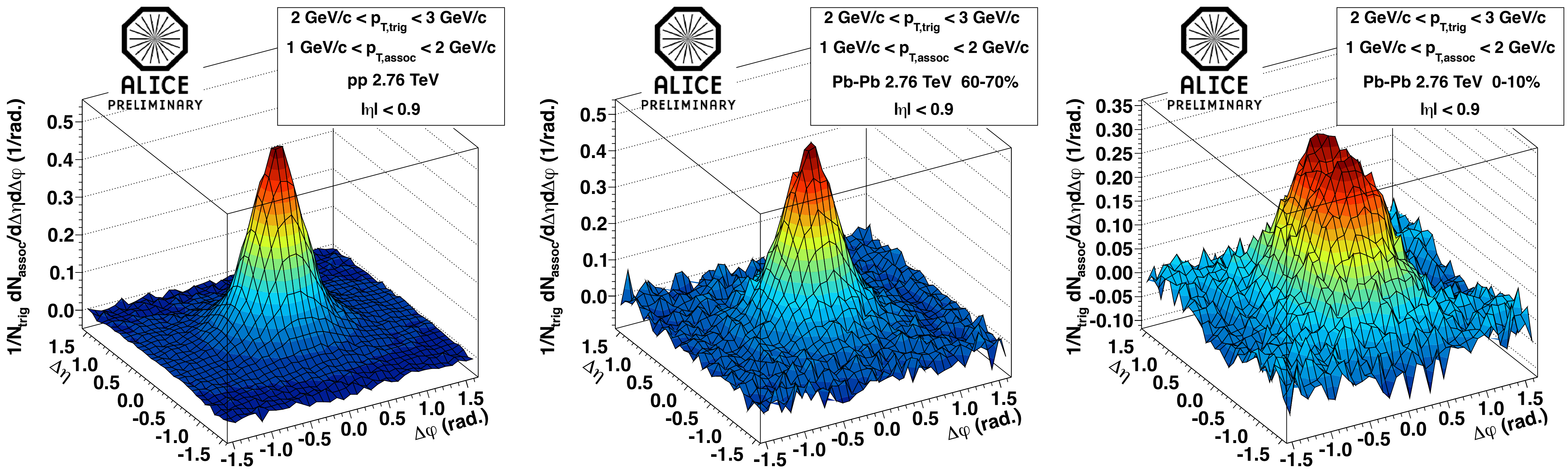


Near-side shape evolution

Distinct broadening with increasing centrality

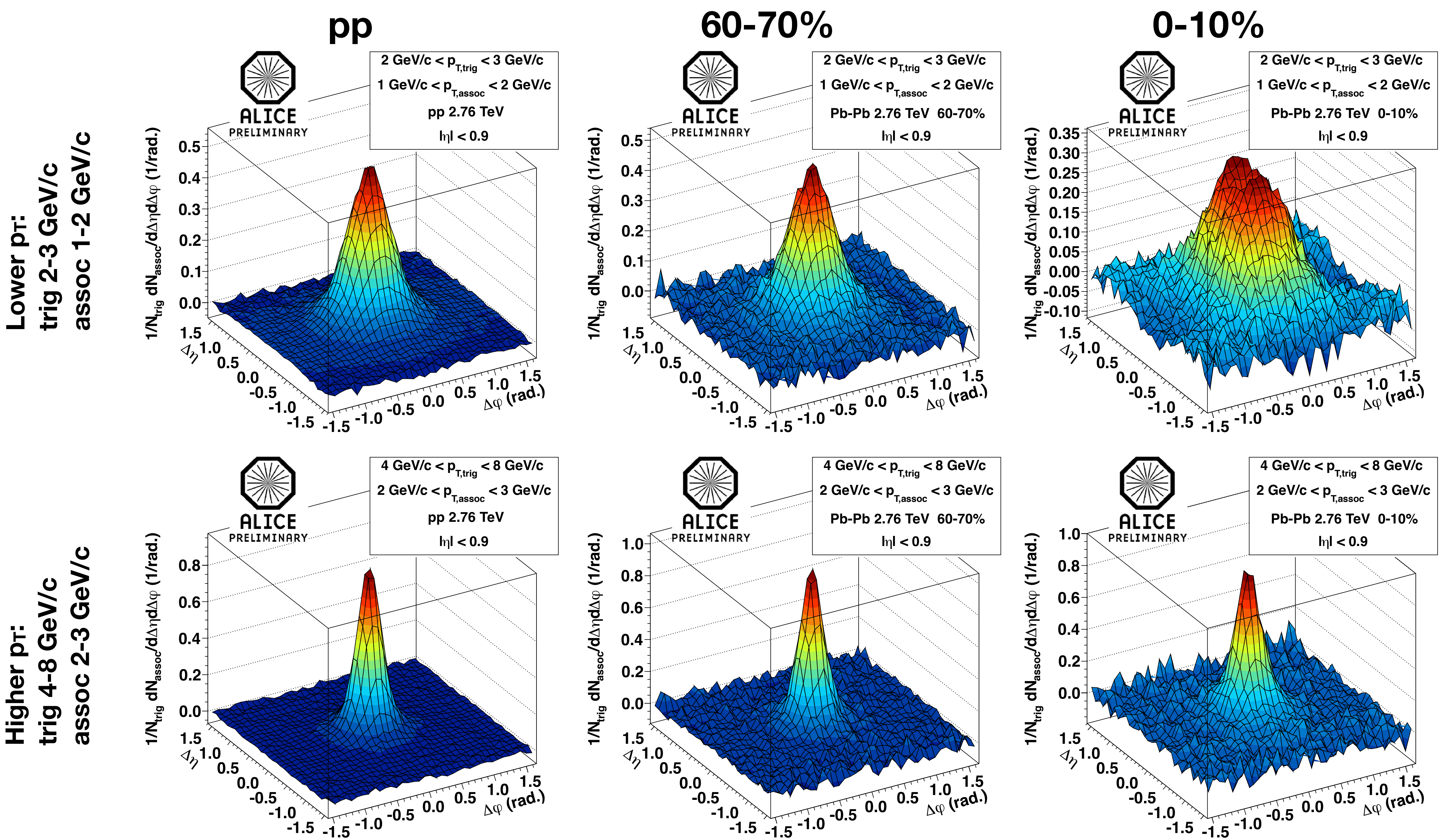
Lower pT:
trig 2-3 GeV/c
assoc 1-2 GeV/c

pp | 60-70% | 0-10%



Near-side shape evolution

Distinct broadening with increasing centrality



Near-side jet peak width in $\Delta\varphi$ and $\Delta\eta$

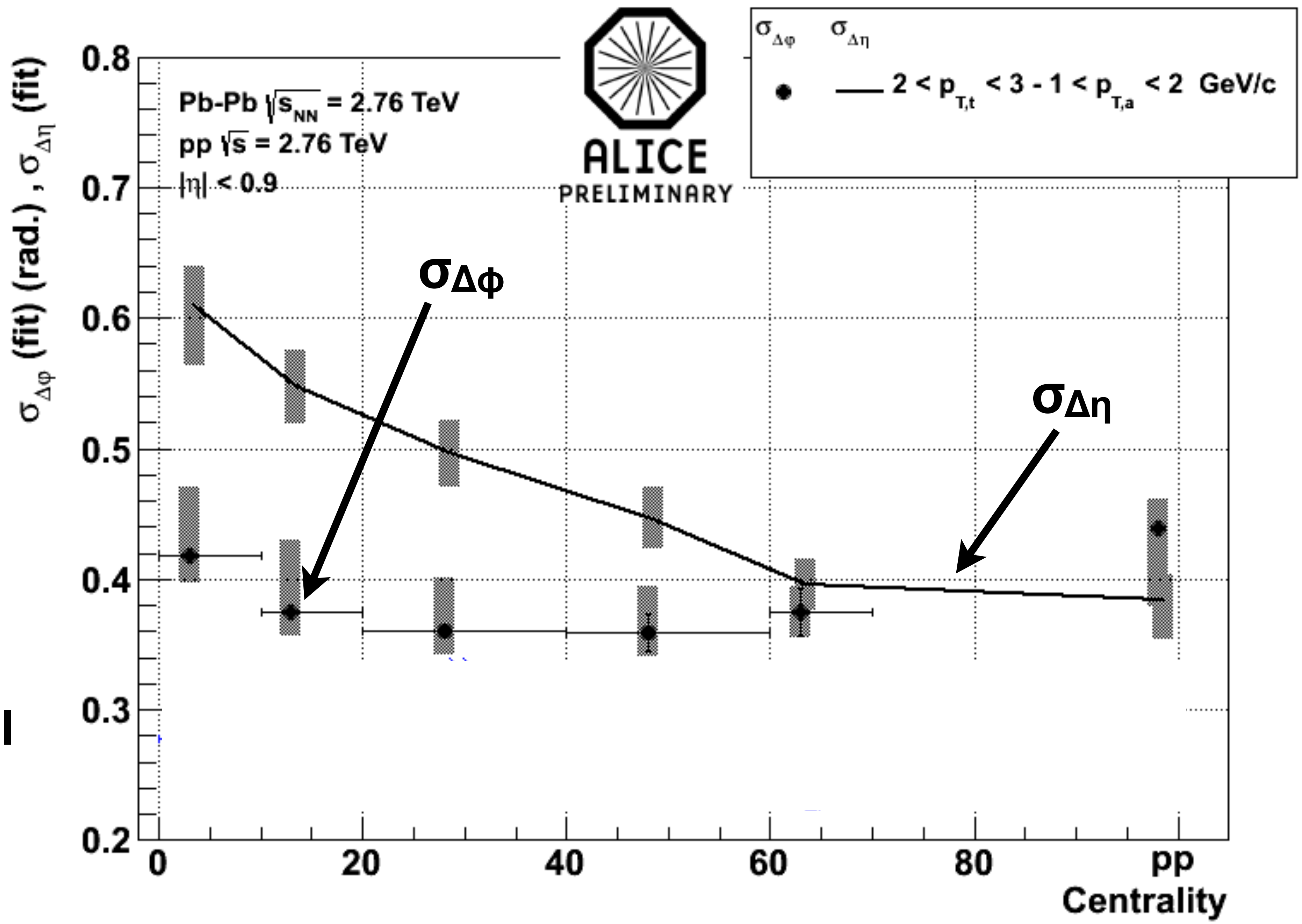
$\sigma_{\Delta\eta} > \sigma_{\Delta\varphi}$

In azimuthal direction

Width is only weakly dependent on centrality

In longitudinal direction

Jet peak becomes broader in more central collisions



Near-side jet peak width in Δφ and Δη

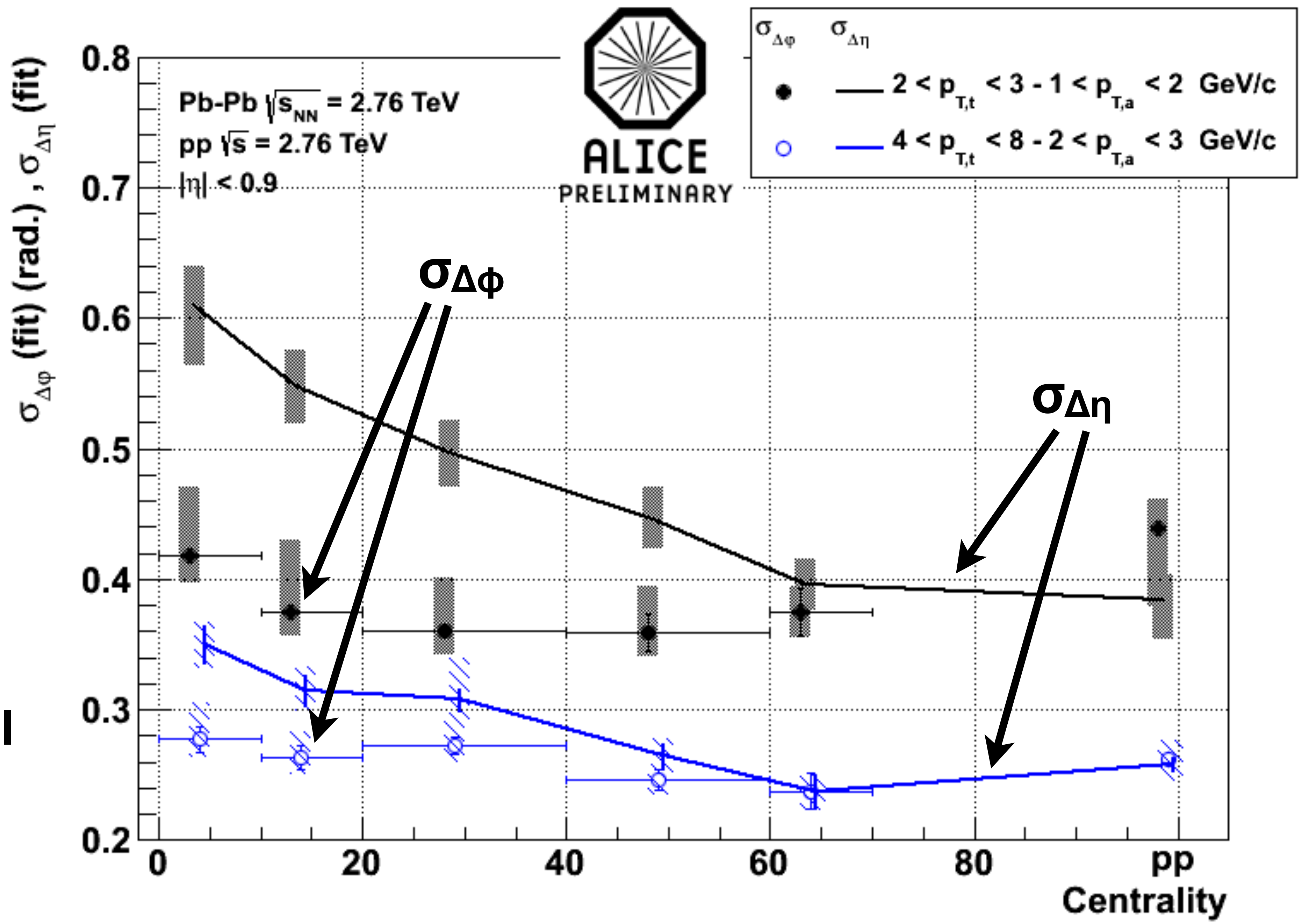
$\sigma_{\Delta\eta} > \sigma_{\Delta\varphi}$

In azimuthal direction

Width is only weakly dependent on centrality

In longitudinal direction

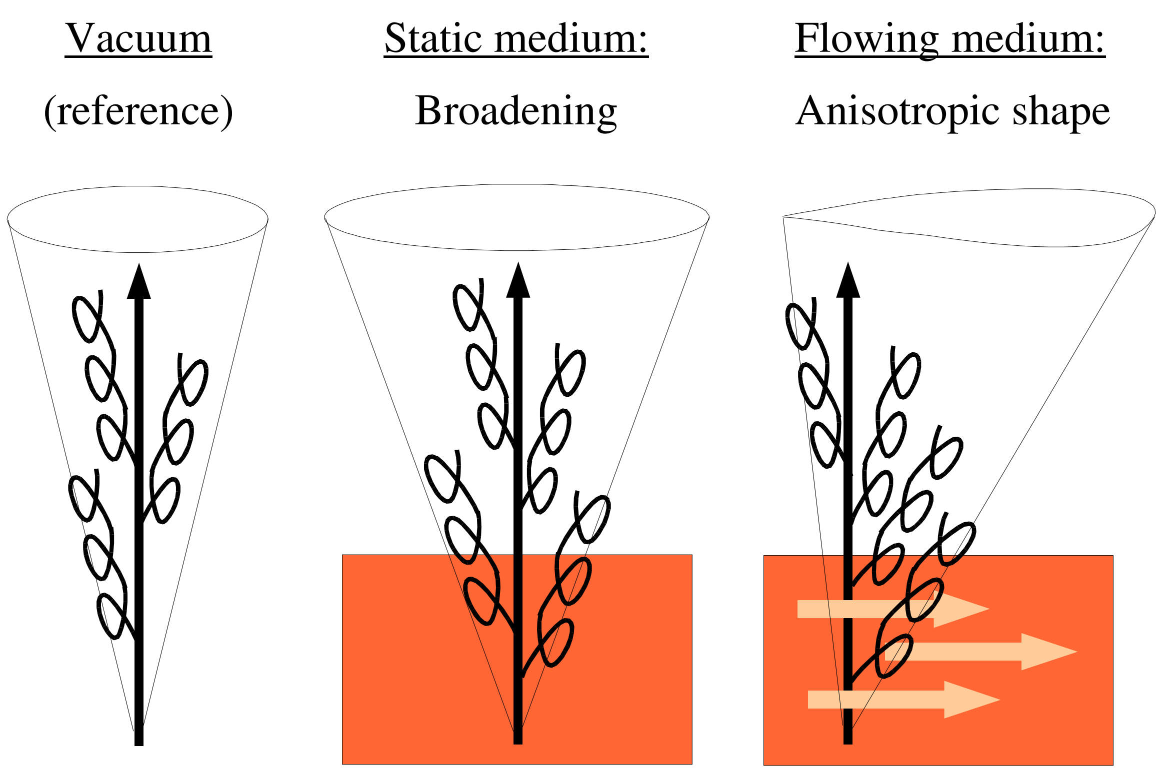
Jet peak becomes broader in more central collisions



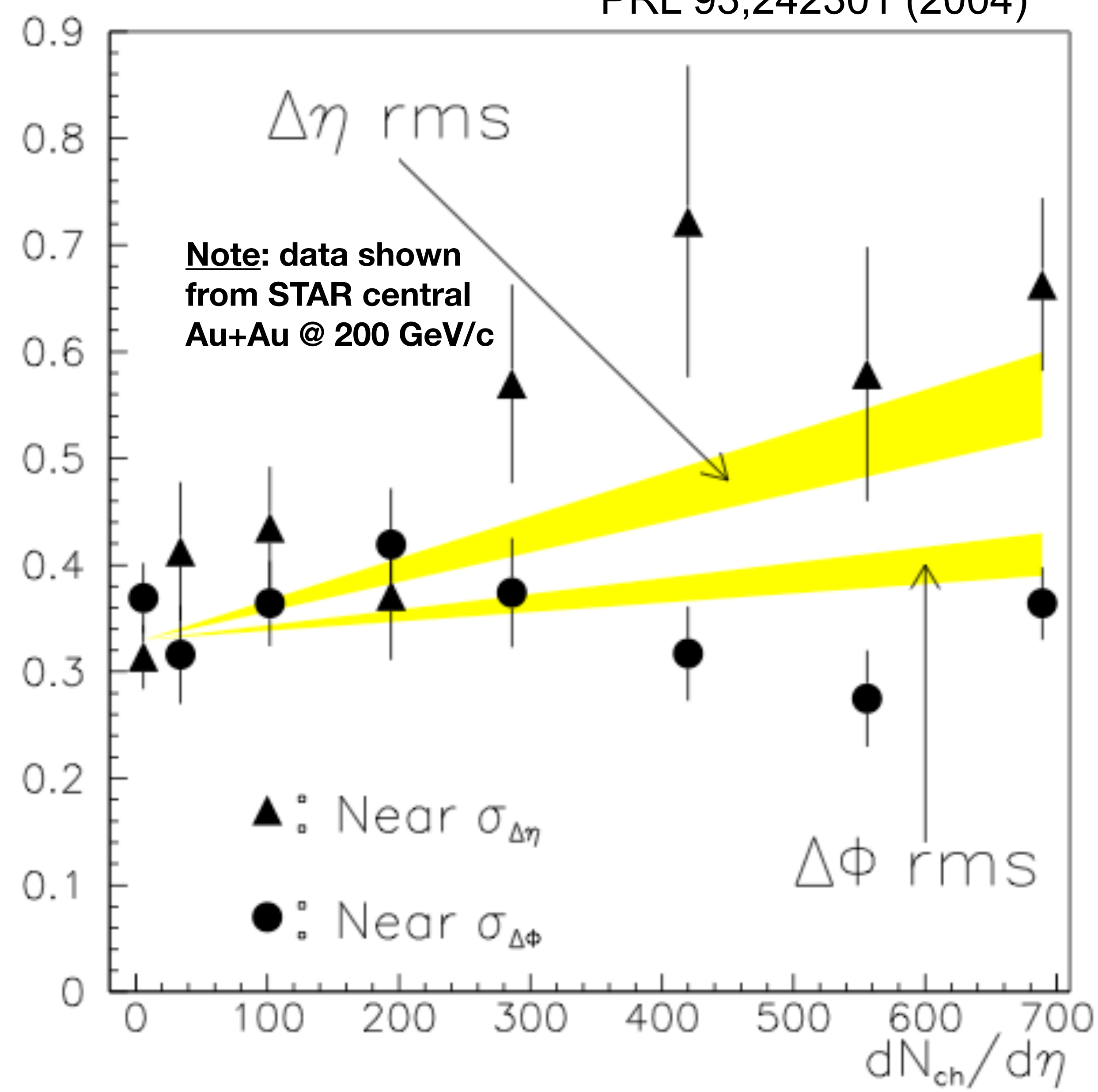
Longitudinal broadening

Armesto, Salgado, Wiedemann (2004)

Longitudinal flow deforms initially conical jet



PRL 93,242301 (2004)



Calculation (yellow band) in qualitative agreement with Pb-Pb trends

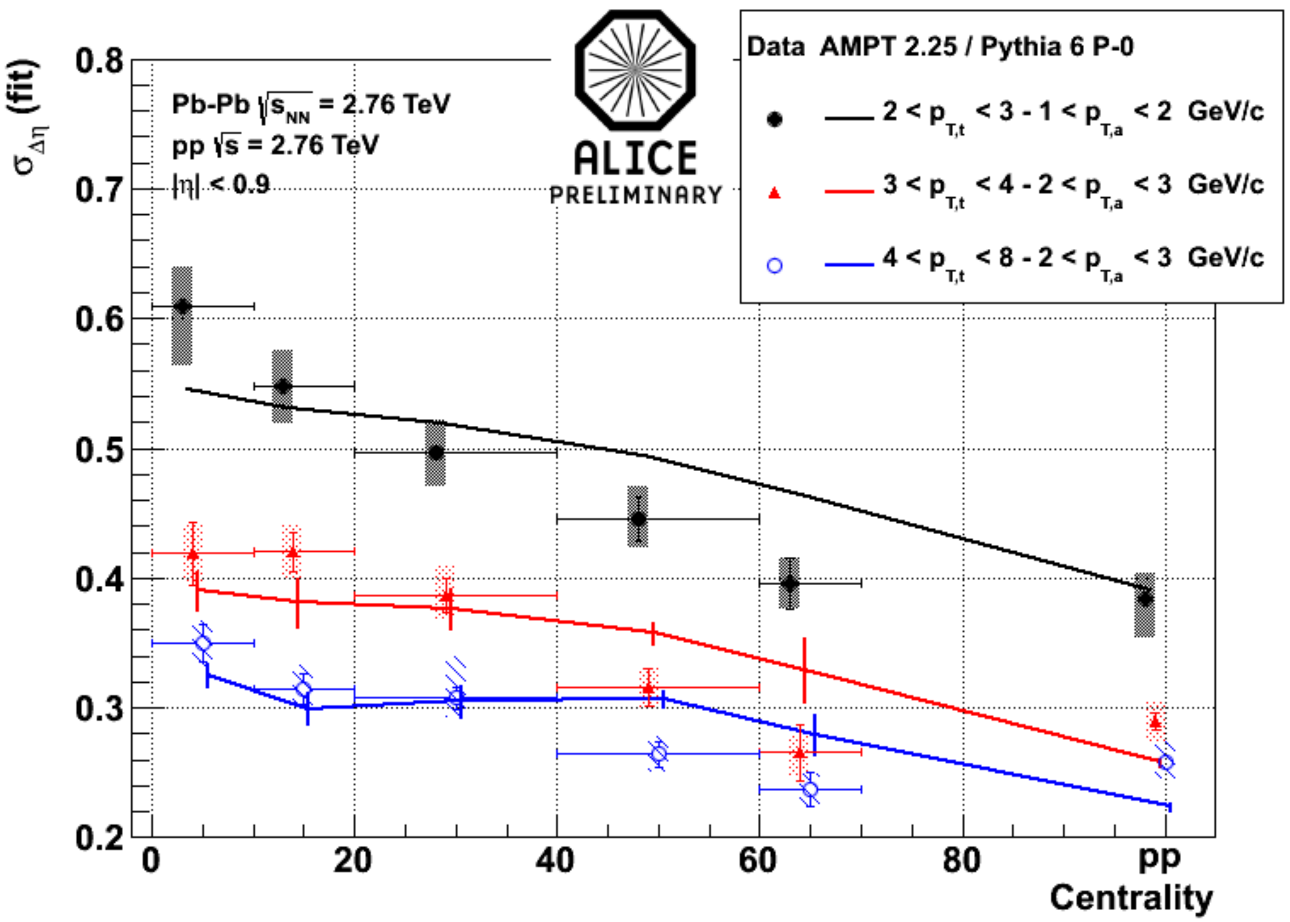
Supports jet-flow interaction picture

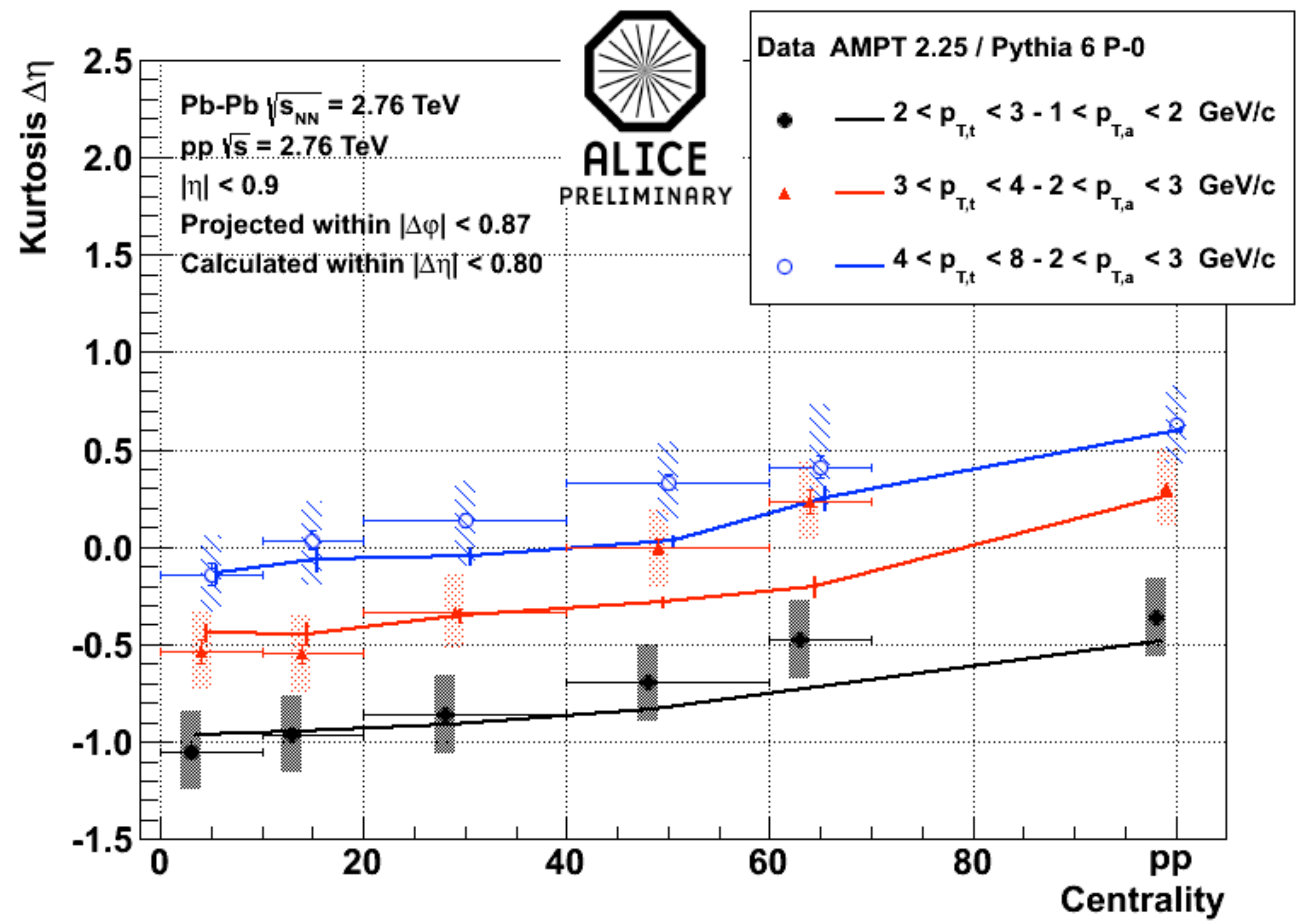
Comparison to AMPT

AMPT 2.25 includes jets (string melting) and flow

Approximately reproduces $\sigma_{\Delta\eta}$ (below) and $\sigma_{\Delta\varphi}$ (not shown)

"Peakedness" (i.e. excess kurtosis ≡ $\mu_4/\sigma^4 - 3$) also similar to data





Agreement supports jet-flow interaction interpretation.

How are near-side yields modified?

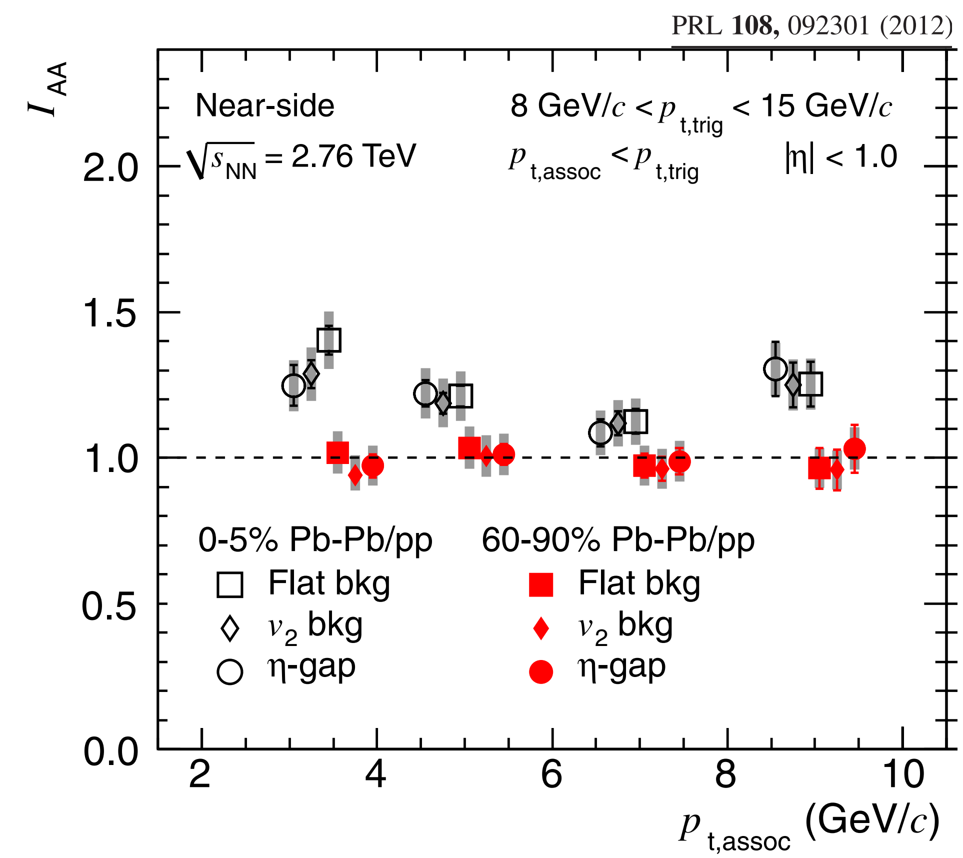
Extending I_{AA} to lower p_T^{assoc}

Initial near-side I_{AA} measurement

QM 2011, PRL 108, 092301 (2012):

First observation of near-side yield enhancement in central Pb-Pb

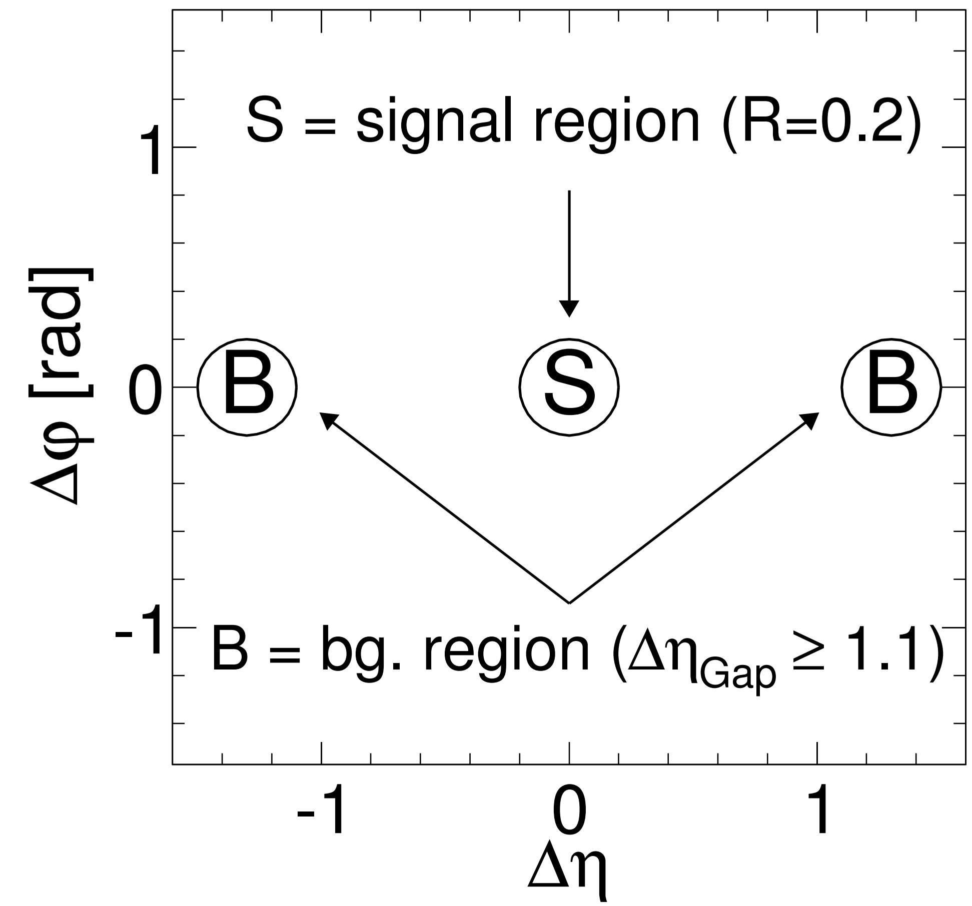
I_{AA} only for p_T^a > 3 GeV/c, where jet signal becomes dominant



Now: alternative subtraction approach

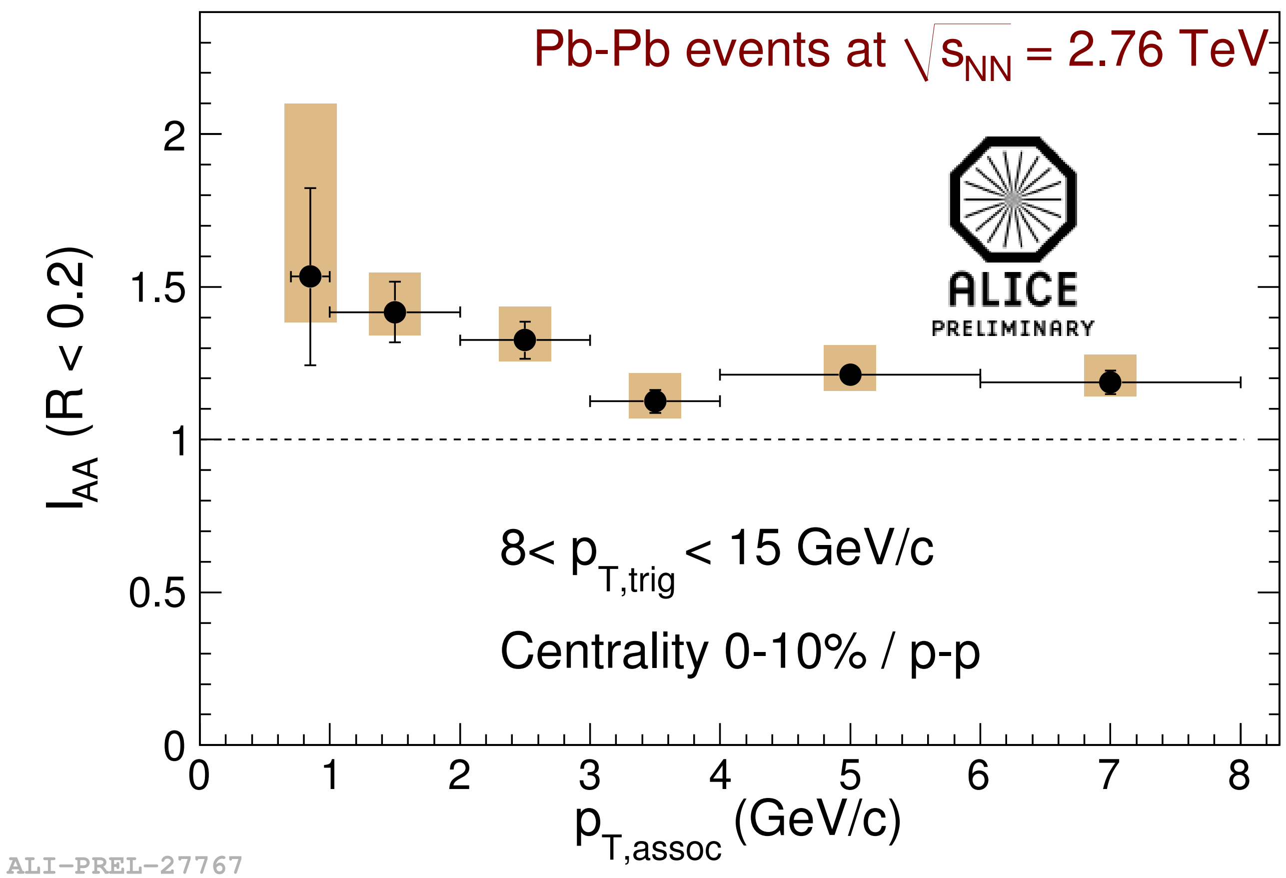
Subtract conditional yields in "B" from peak region "S"

Avoid flow modulation by using same Δφ range for both signal and background

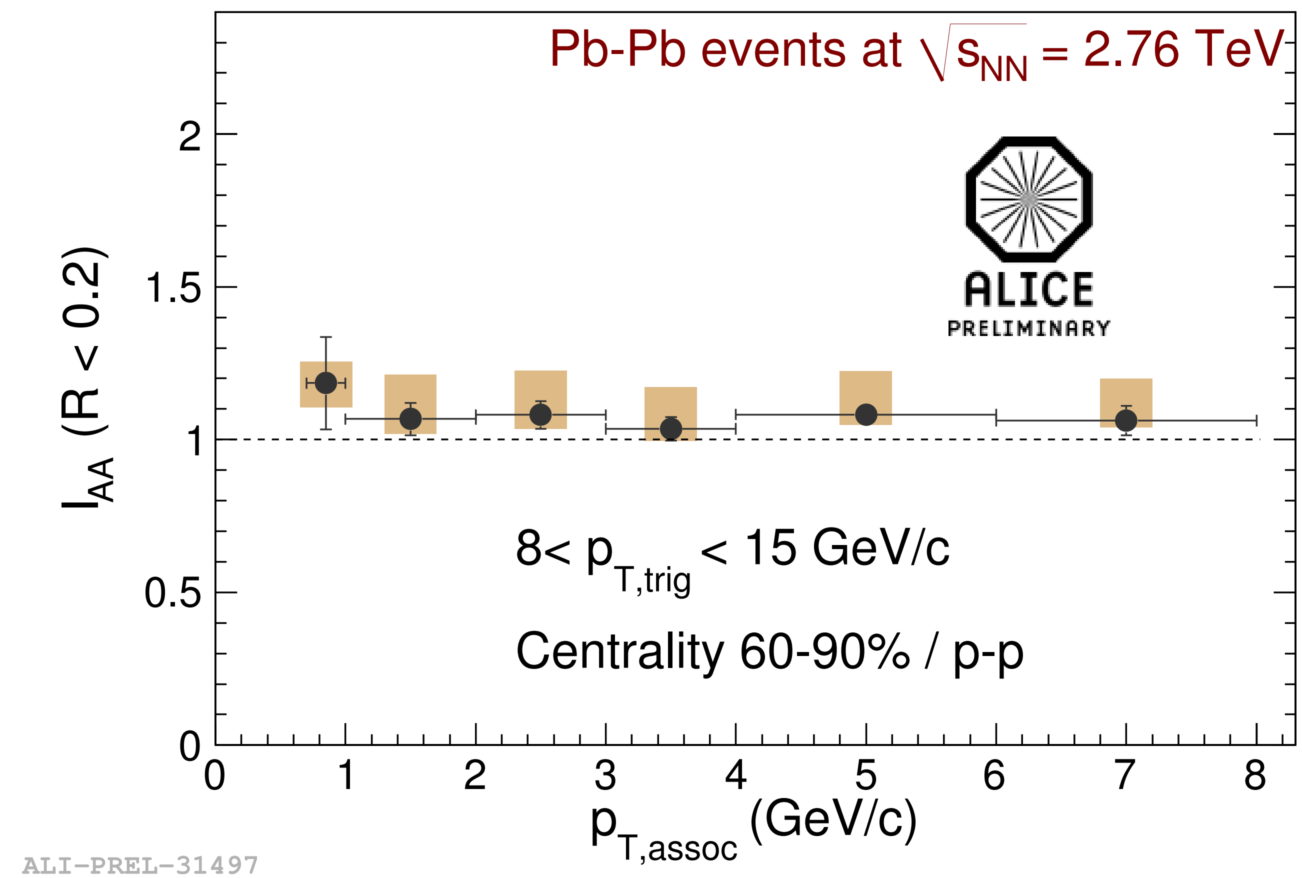


Near-side I_{AA}

20-50% enhancement in central Pb-Pb, compared to pp



central



peripheral

Filip Krizek (4B)

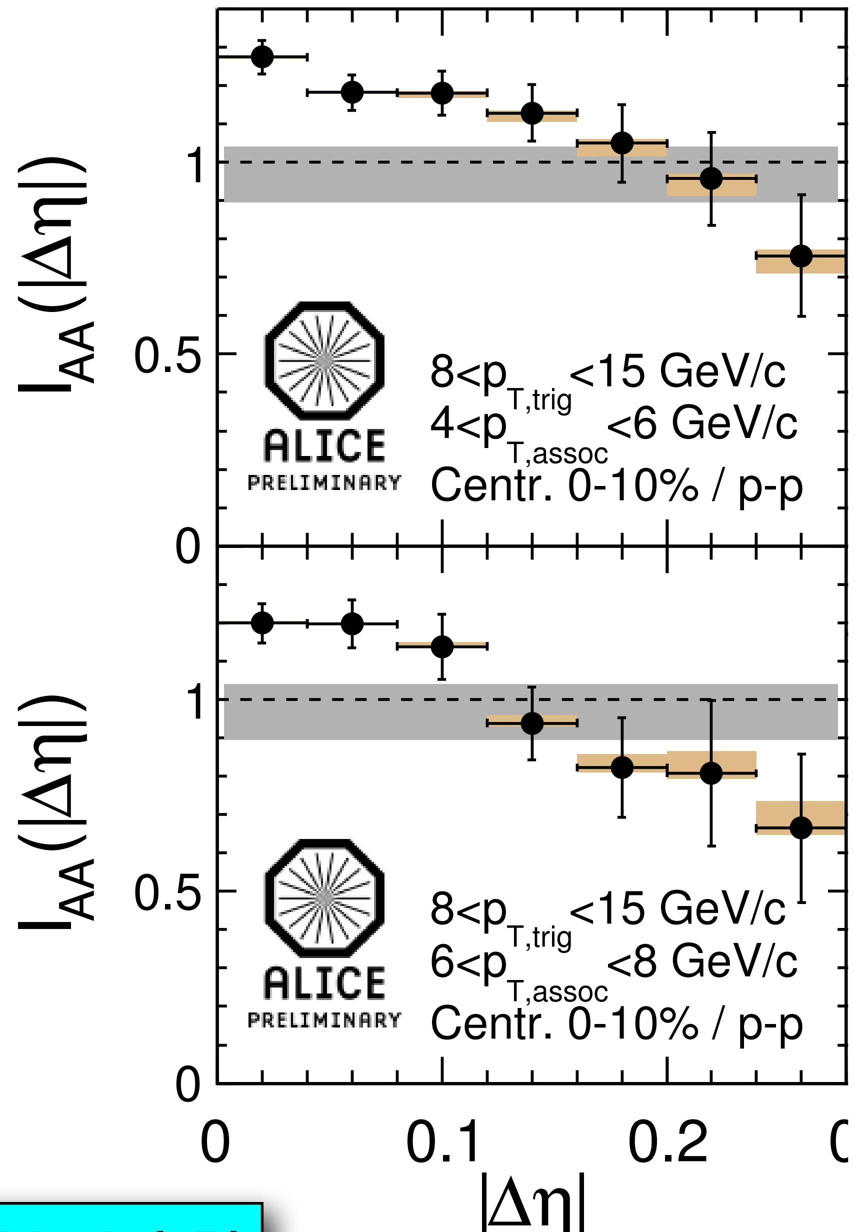
Near-side I_{AA} vs. $\Delta\eta$

I_{AA} decreases as the pair $\Delta\eta$ increases

Effect diminishes in more peripheral collisions

Consistent with near-side peak narrowing

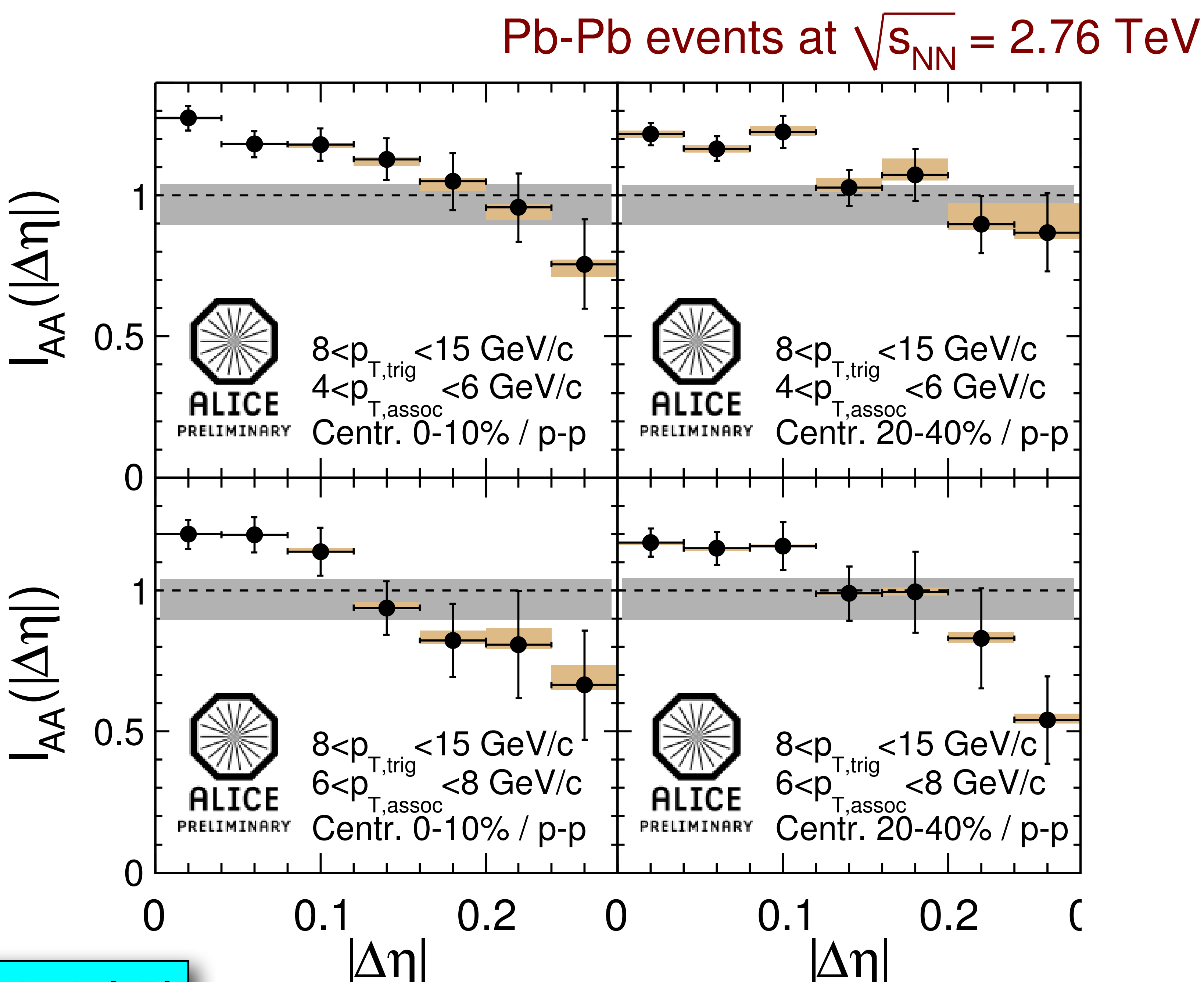
Pb-Pb events at $\sqrt{s_{NN}}$ = 2.76 TeV



Filip Krizek (4B)

Near-side I_{AA} vs. Δη

I_{AA} decreases as the pair Δη increases
Effect diminishes in more peripheral collisions
Consistent with near-side peak narrowing



Filip Krizek (4B)

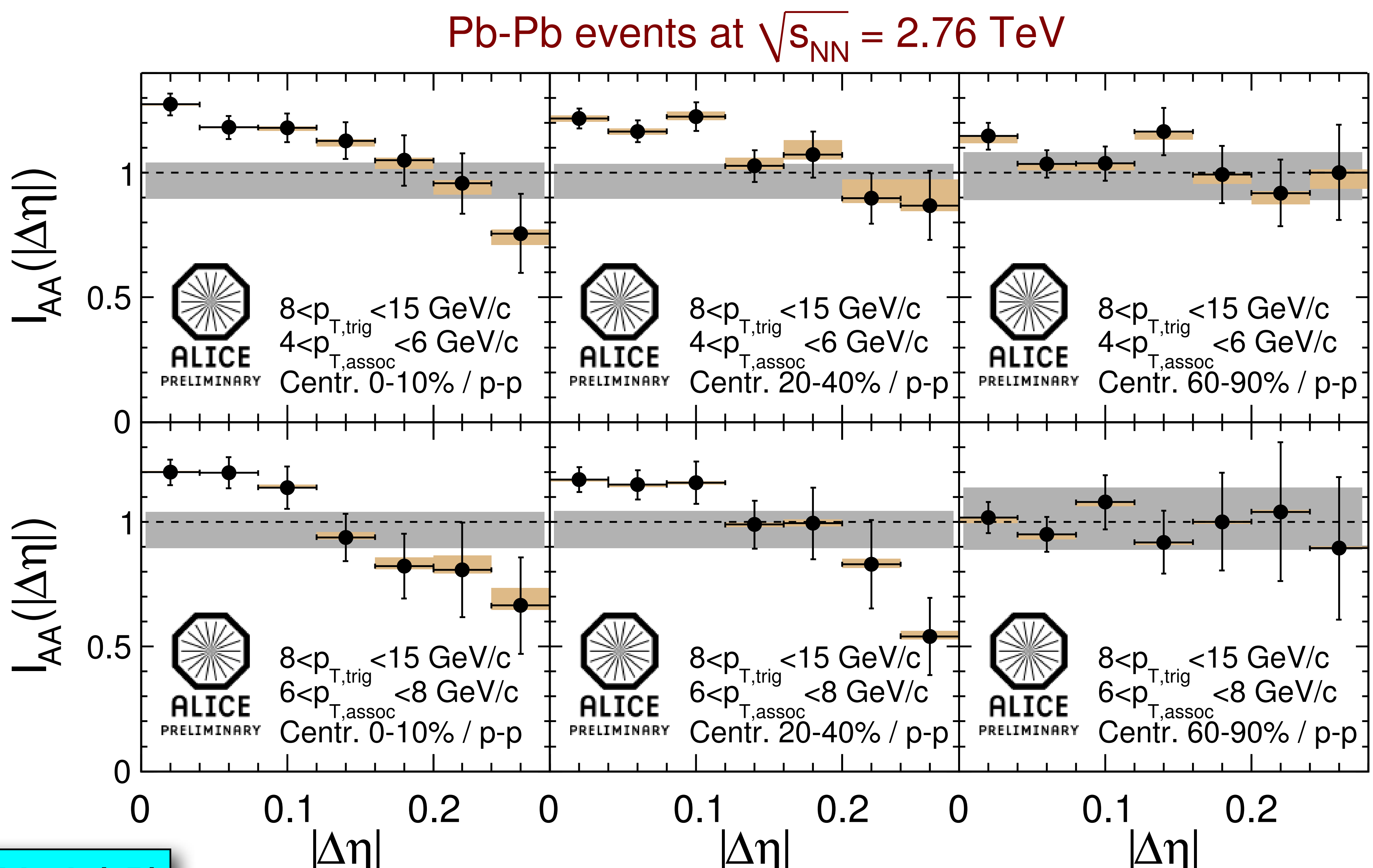
A. Adare (ALICE)

Near-side I_{AA} vs. Δη

I_{AA} decreases as the pair Δη increases

Effect diminishes in more peripheral collisions

Consistent with near-side peak narrowing



Filip Krizek (4B)

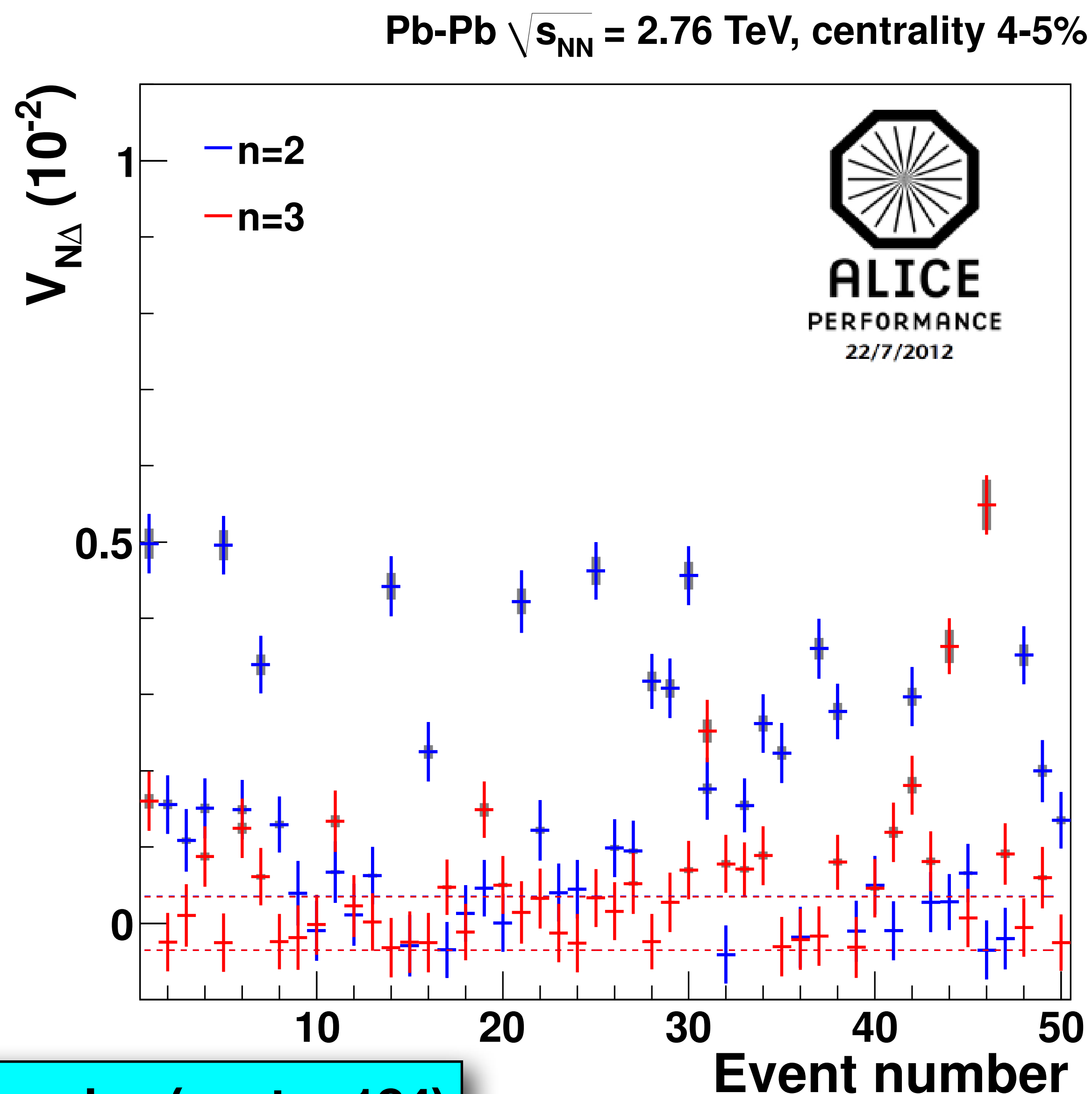
Event-by-event v_n fluctuations

$V_{2\Delta}$ and $V_{3\Delta}$ measured in single events

Large fluctuations observed even within a 1%-wide centrality bin

Dashed: Expectation from bkg. fluctuations

Excess anisotropy suggests flow fluctuations are large



A. Timmins (poster 184)

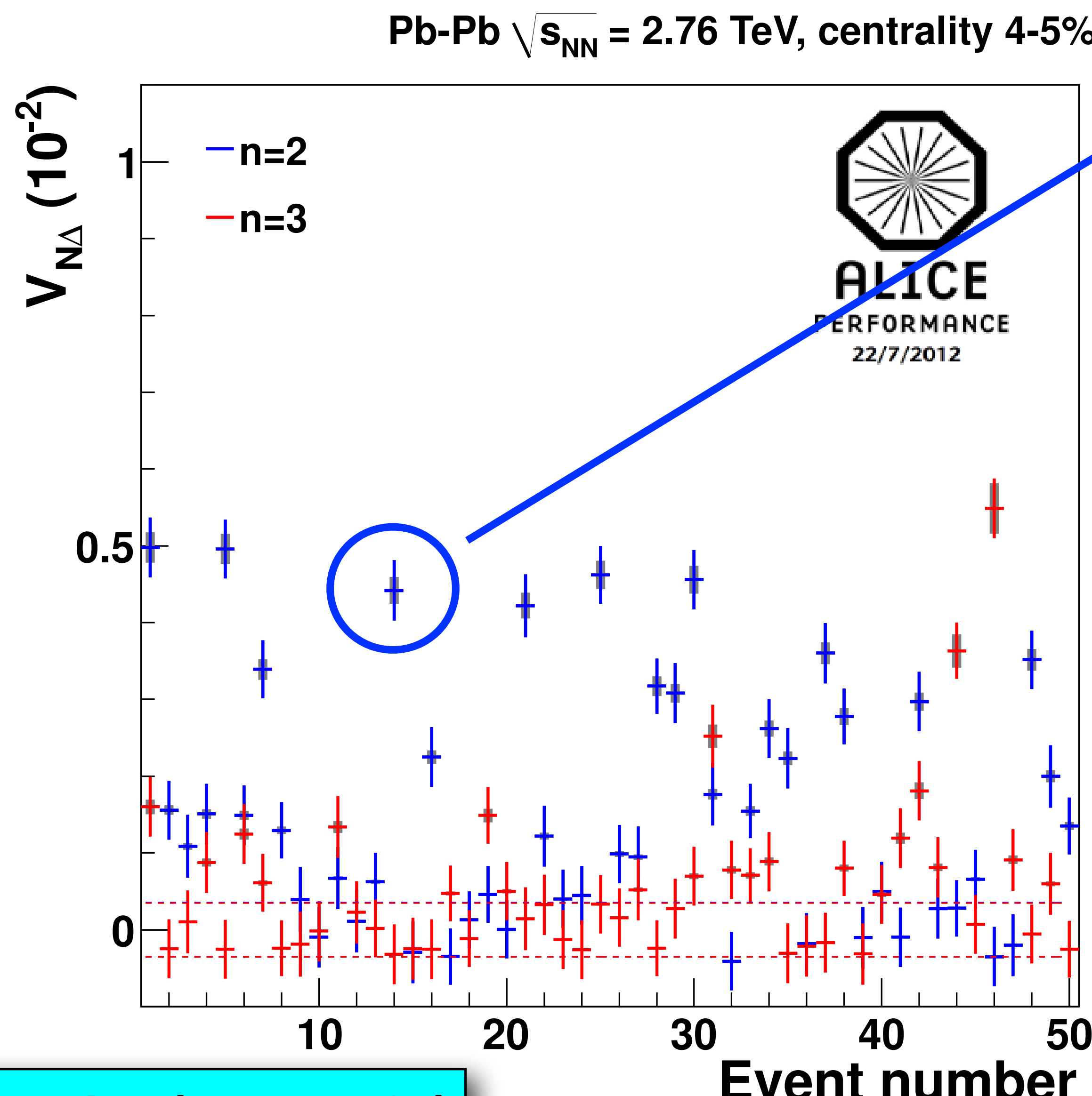
Event-by-event v_n fluctuations

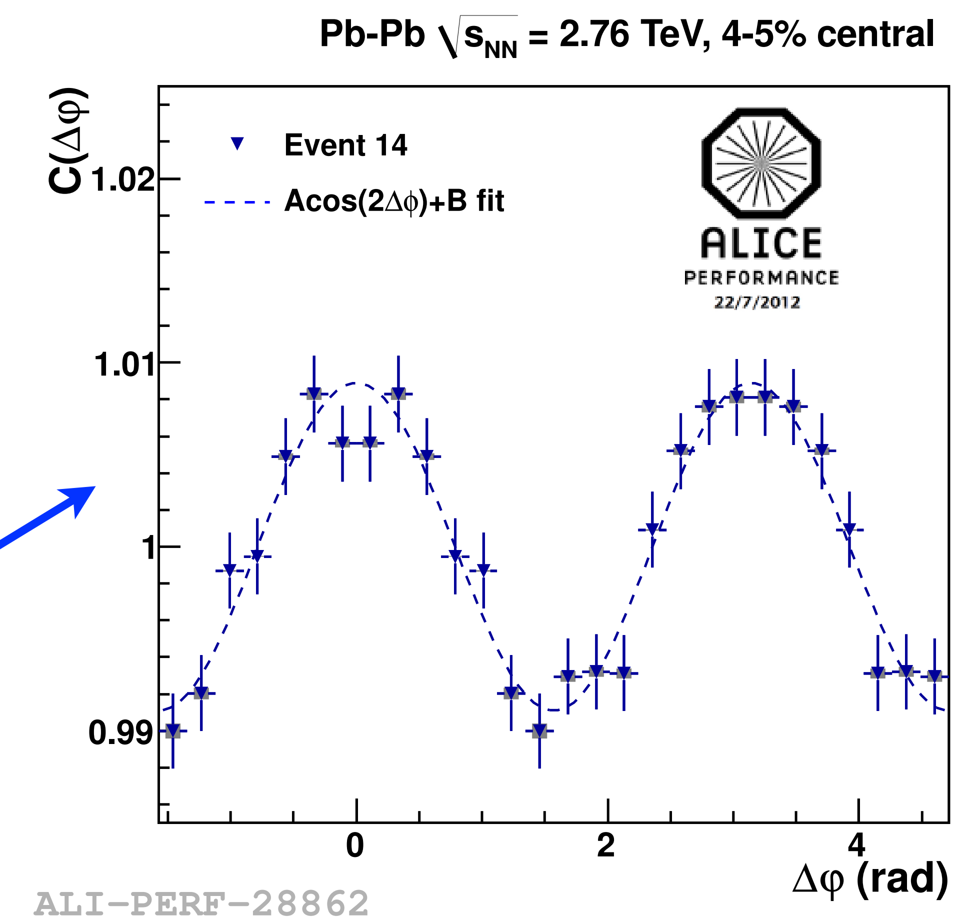
$V_{2\Delta}$ and $V_{3\Delta}$ measured in single events

Large fluctuations observed even within a 1%-wide centrality bin

Dashed: Expectation from bkg. fluctuations

Excess anisotropy suggests flow fluctuations are large





A. Timmins (poster 184)

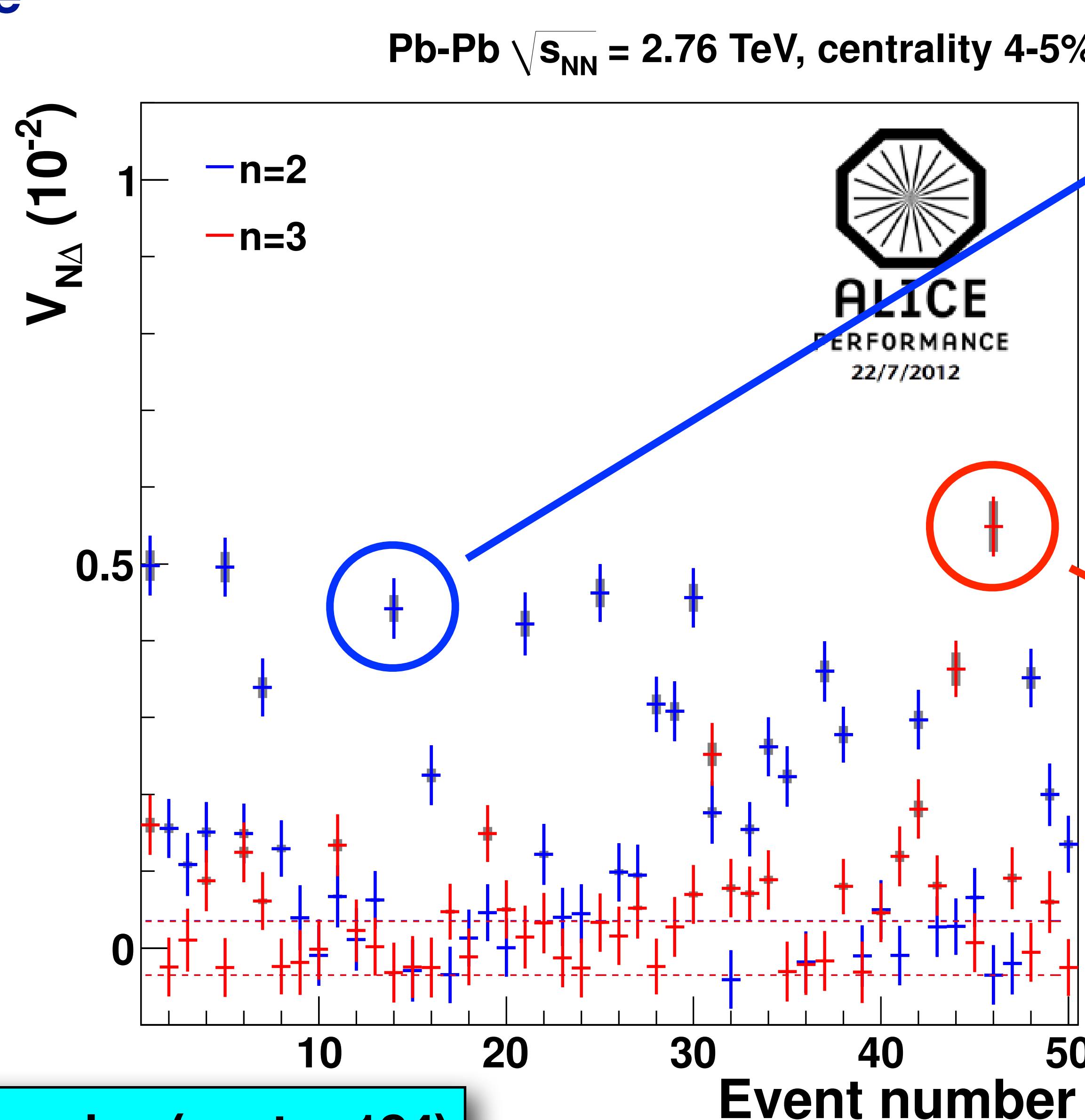
Event-by-event v_n fluctuations

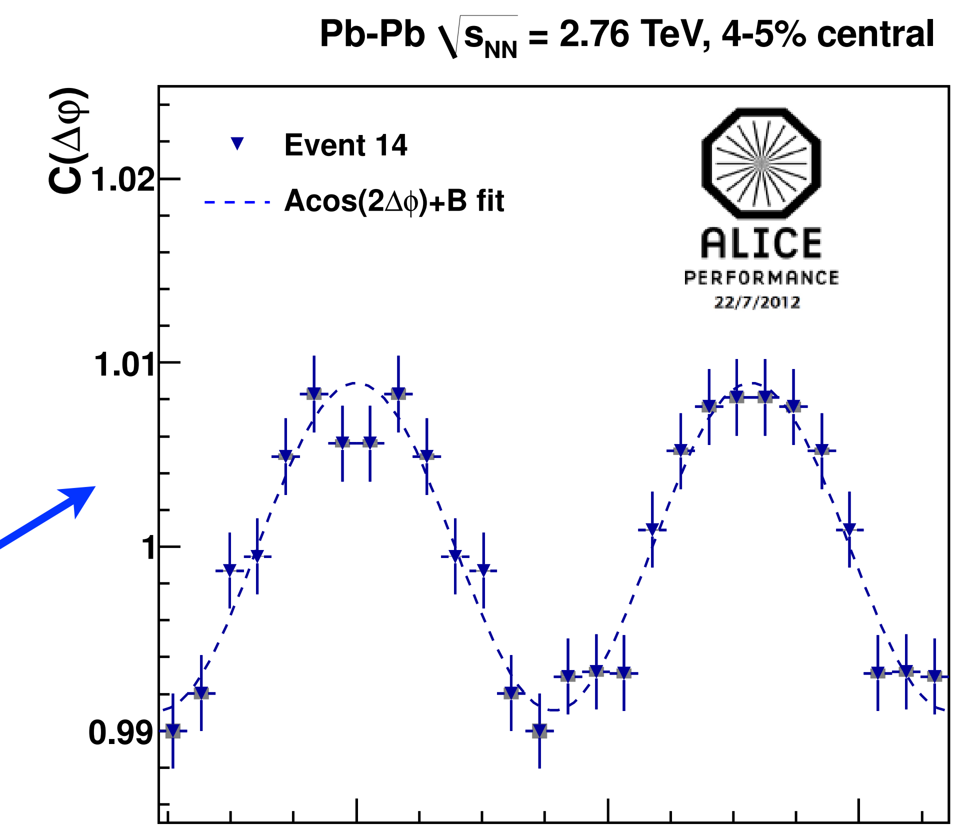
$V_{2\Delta}$ and $V_{3\Delta}$ measured in single events

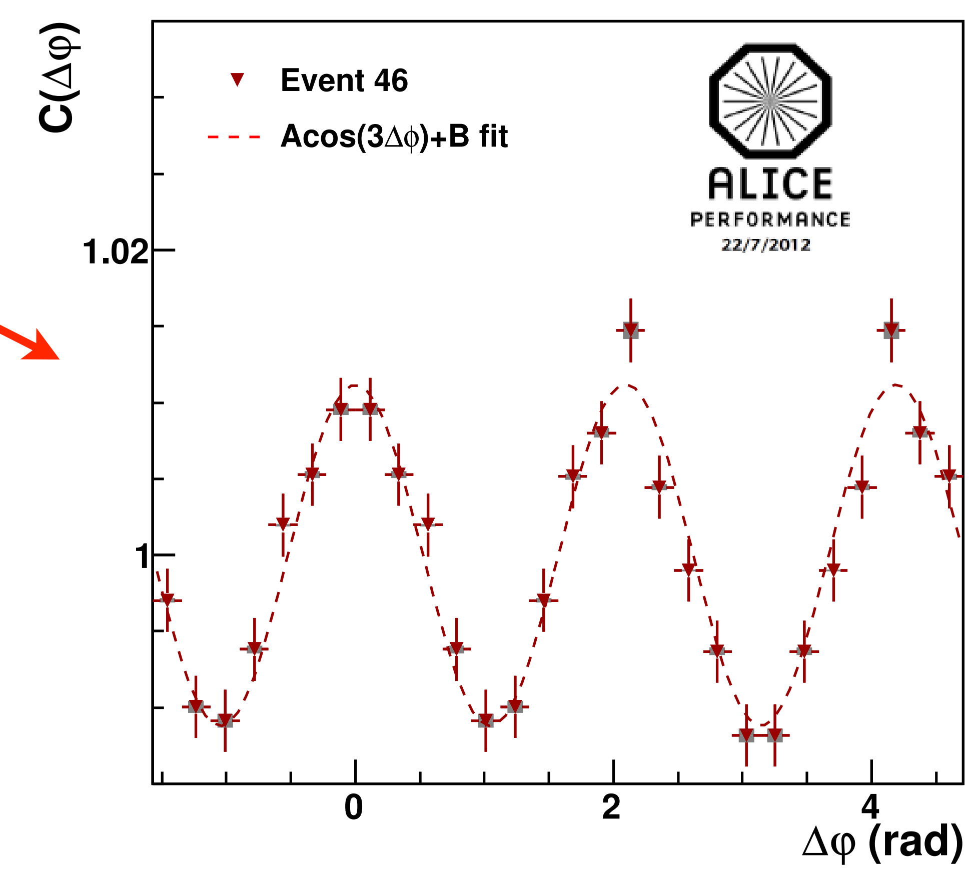
Large fluctuations observed even within a 1%-wide centrality bin

Dashed: Expectation from bkg. fluctuations

Excess anisotropy suggests flow fluctuations are large







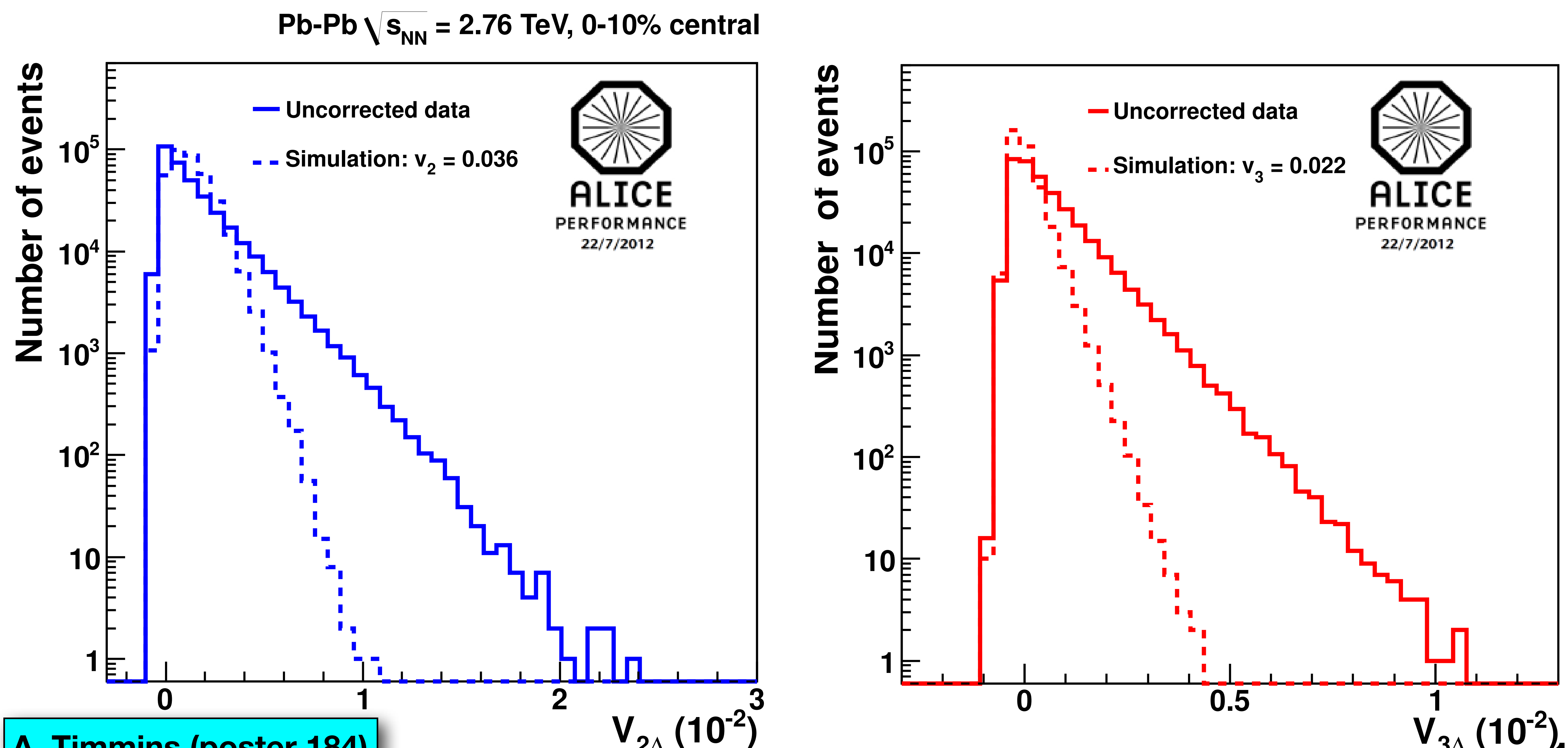
A. Timmins (poster 184)

$V_{2\Delta}$ and $V_{3\Delta}$ distributions

Measures the Q-vector distribution dN_{evt}/dQ_n^2

$$Q_n^2 = M + M(M-1)\langle\cos[n(\phi_i - \phi_j)]\rangle$$

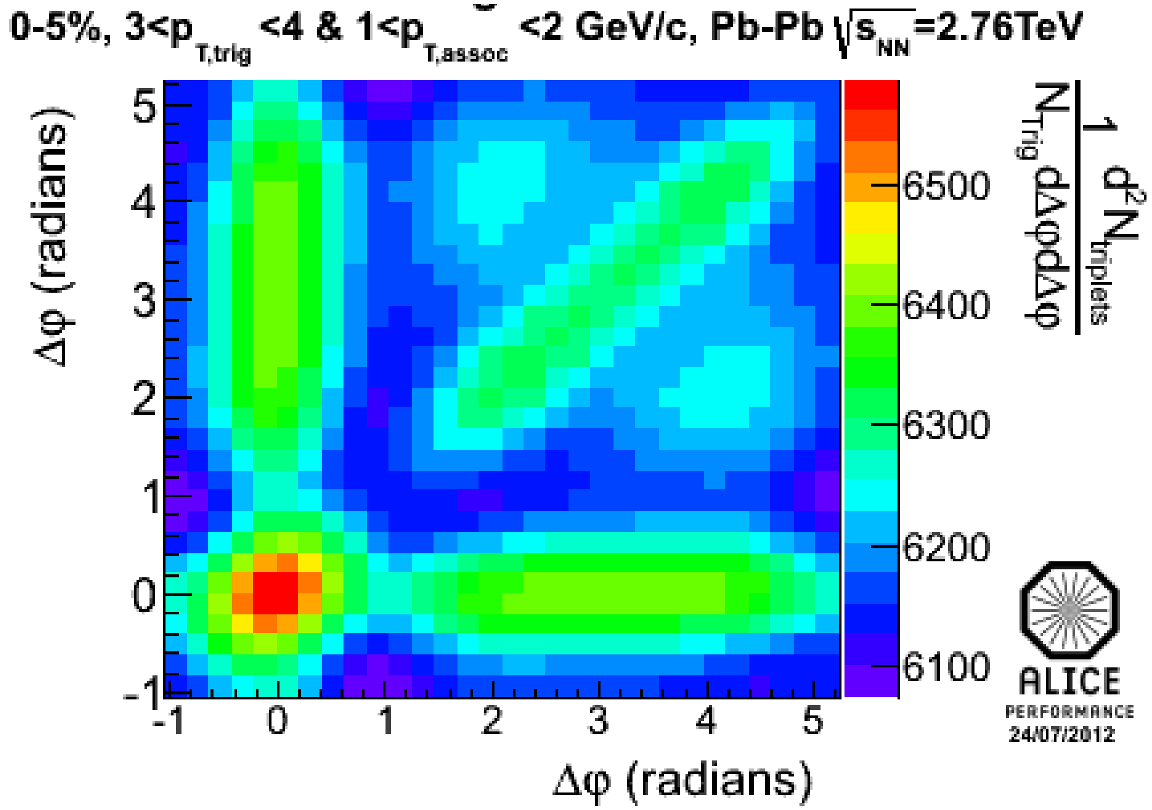
- Distribution broadened by flow fluctuations and nonflow
- Functional fit to Bessel-Gaussian can provide flow measurement



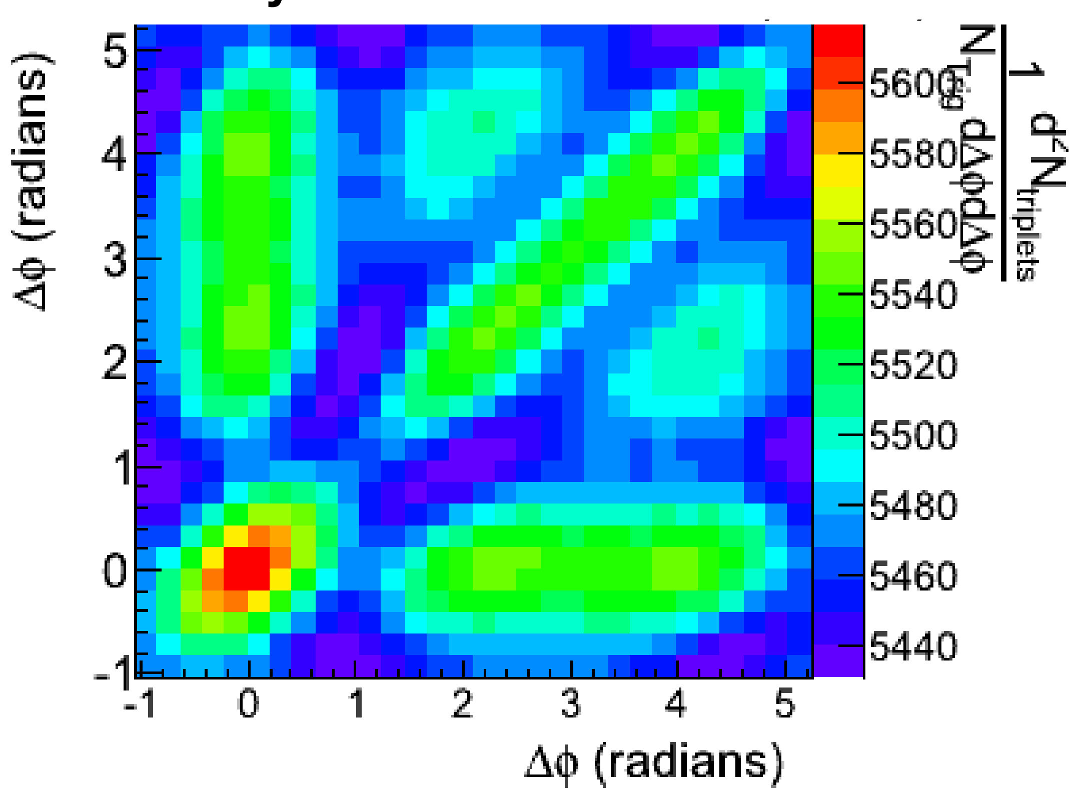
A. Timmins (poster 184)

3-particle correlations

0-5% Pb-Pb (no bkg. subtraction)



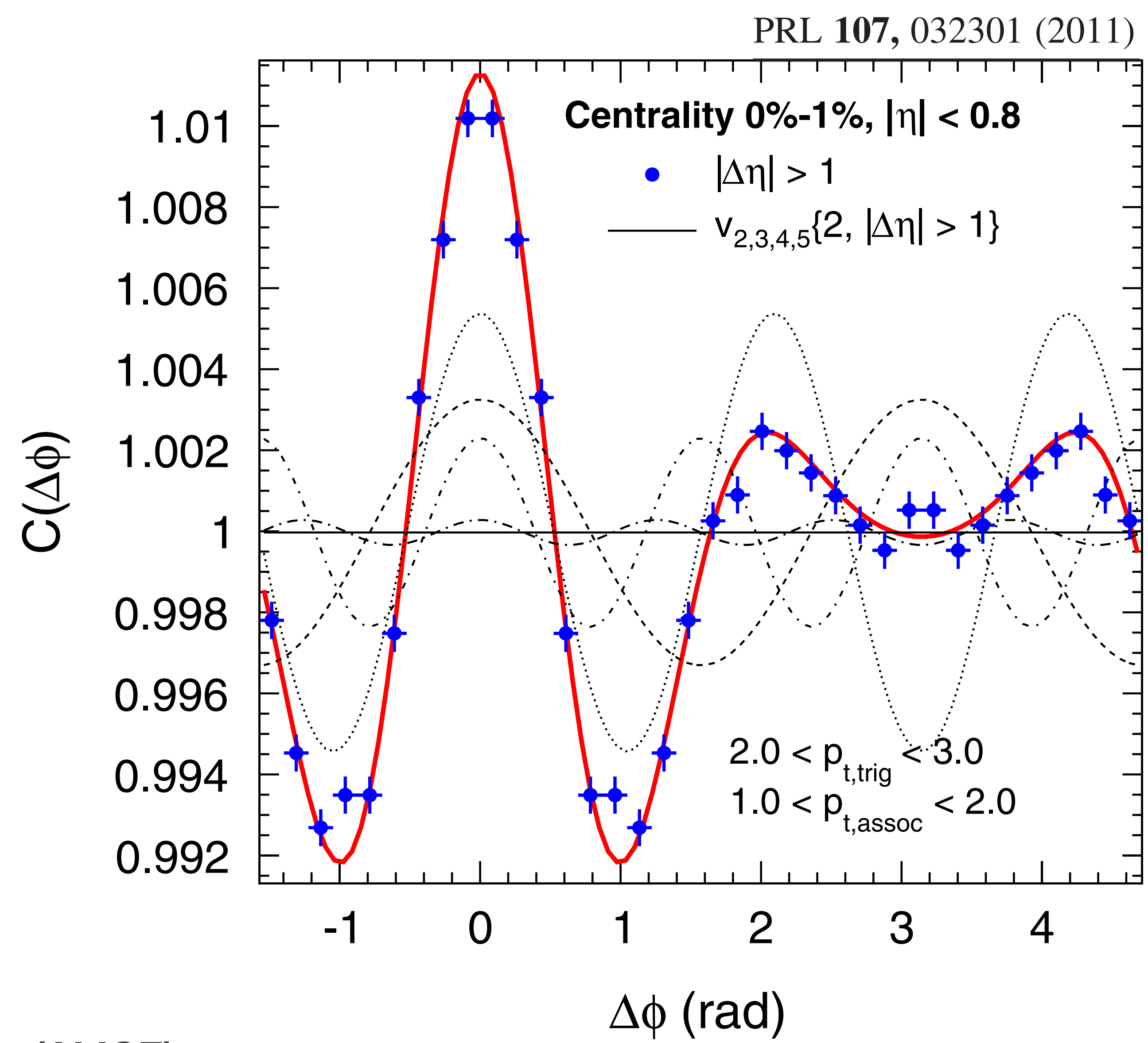
Flow-only simulation



Flow dominates at low - intermediate p_T

Two-particle correlations suggest flow dominance at low - intermediate p_T

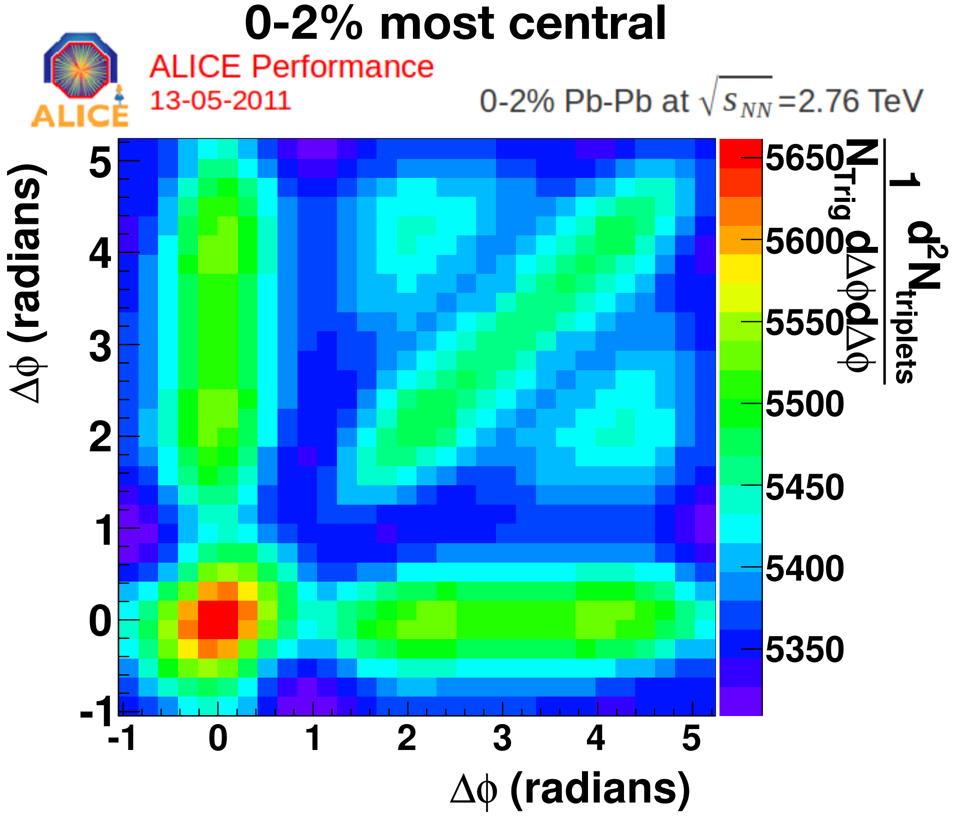
Any non-flow signal must be small



Three-particle angular distributions

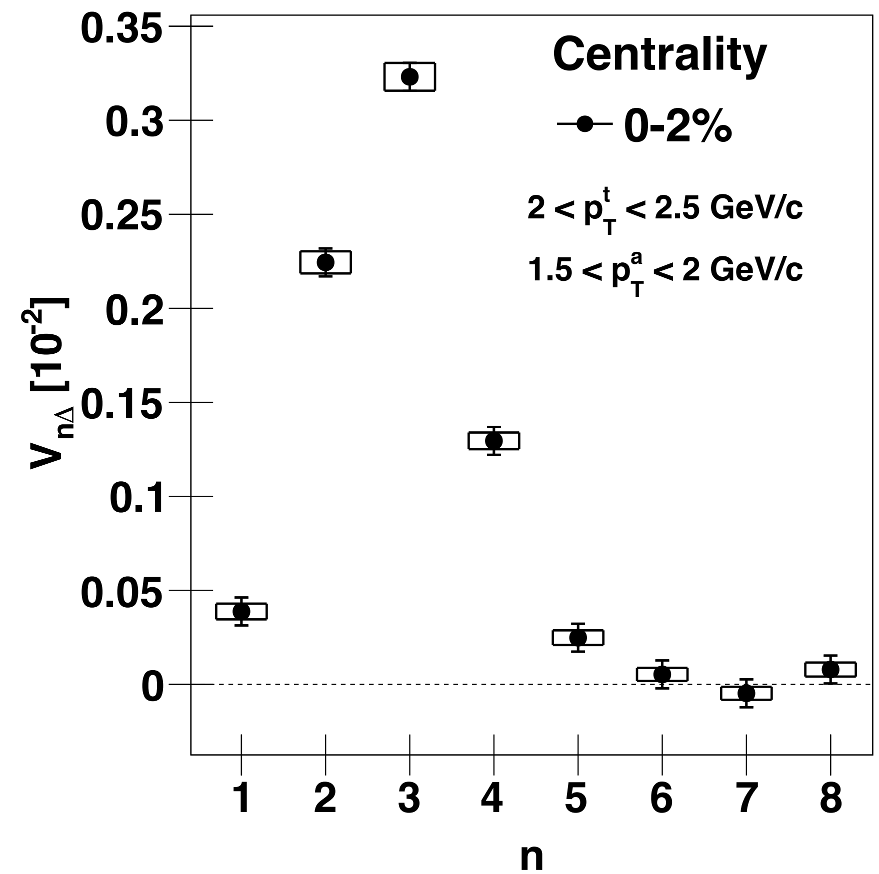
Full correlation (no background subtraction)

0-2% most central



Two-particle harmonics

Phys Lett B 708 (2012) 249–264



0-2% most central Pb-Pb: 3rd harmonic dominates

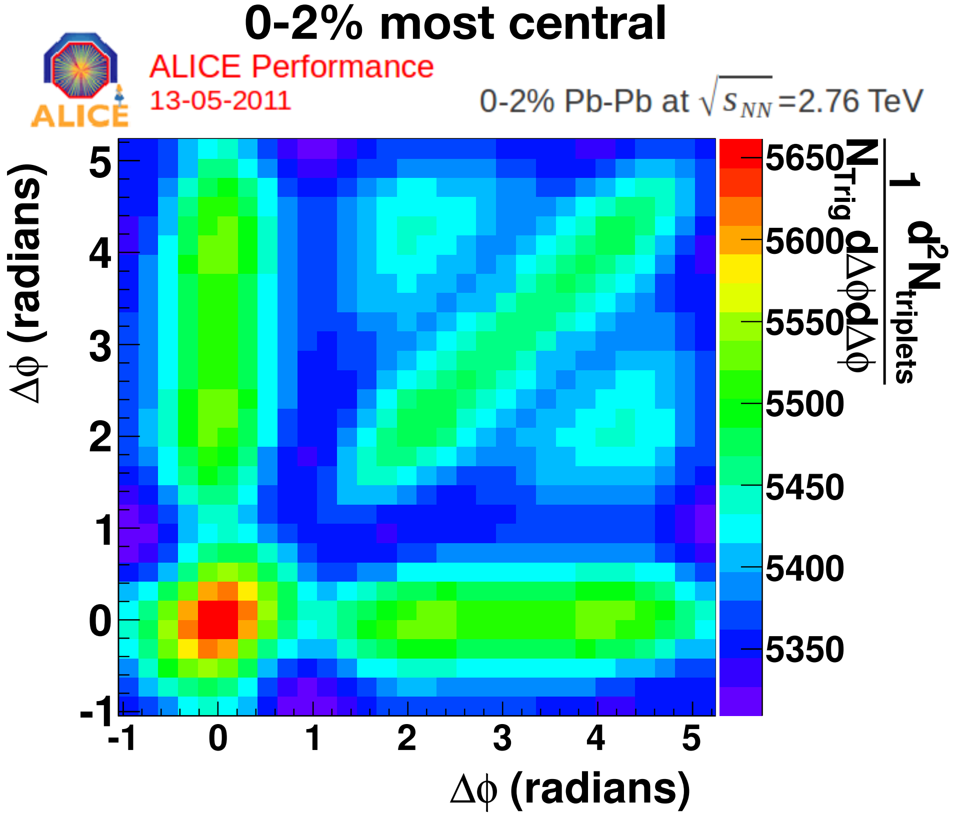
Distinct off-diagonal peaks

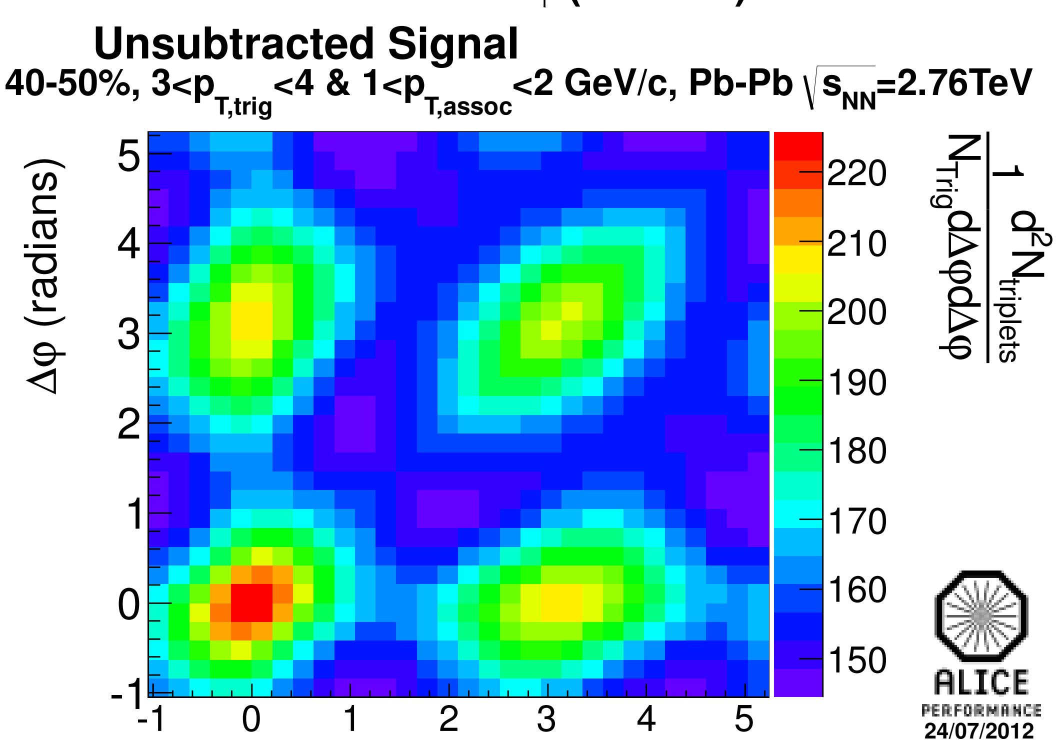
J. Ulery (4B, poster 175)

Three-particle angular distributions

Full correlation (no background subtraction)

0-2% most central

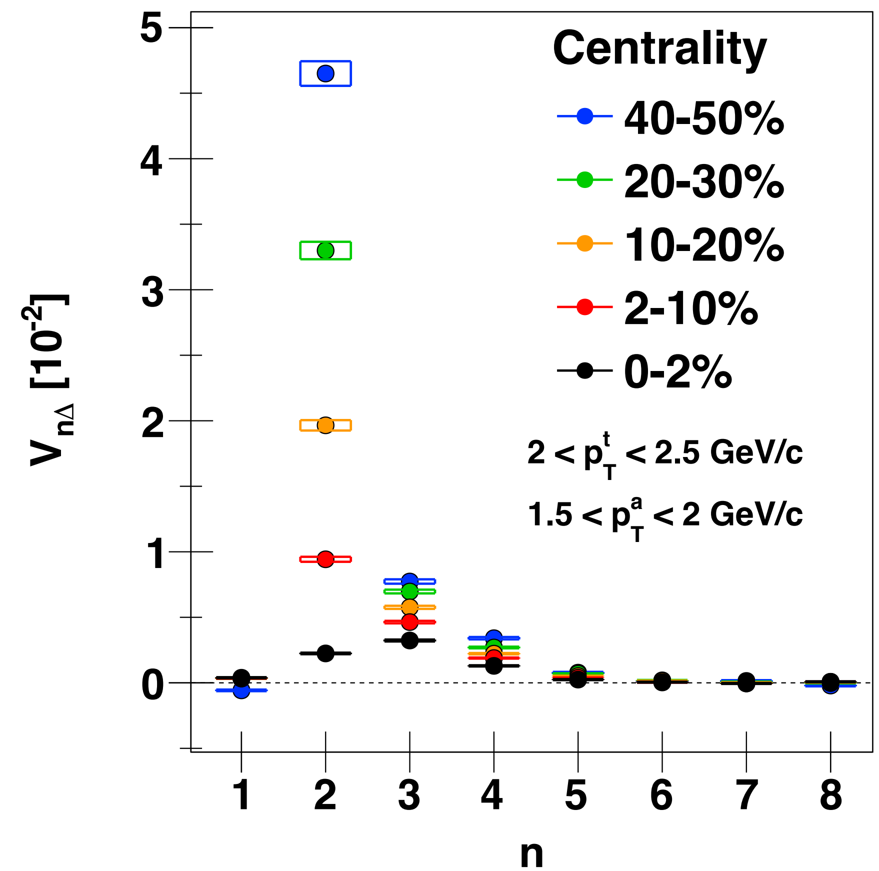




40-50% most central

Two-particle harmonics

Phys Lett B 708 (2012) 249–264



0-2% most central Pb-Pb: 3rd harmonic dominates

Distinct off-diagonal peaks

40-50% mid-central Pb-Pb: 2nd harmonic dominates

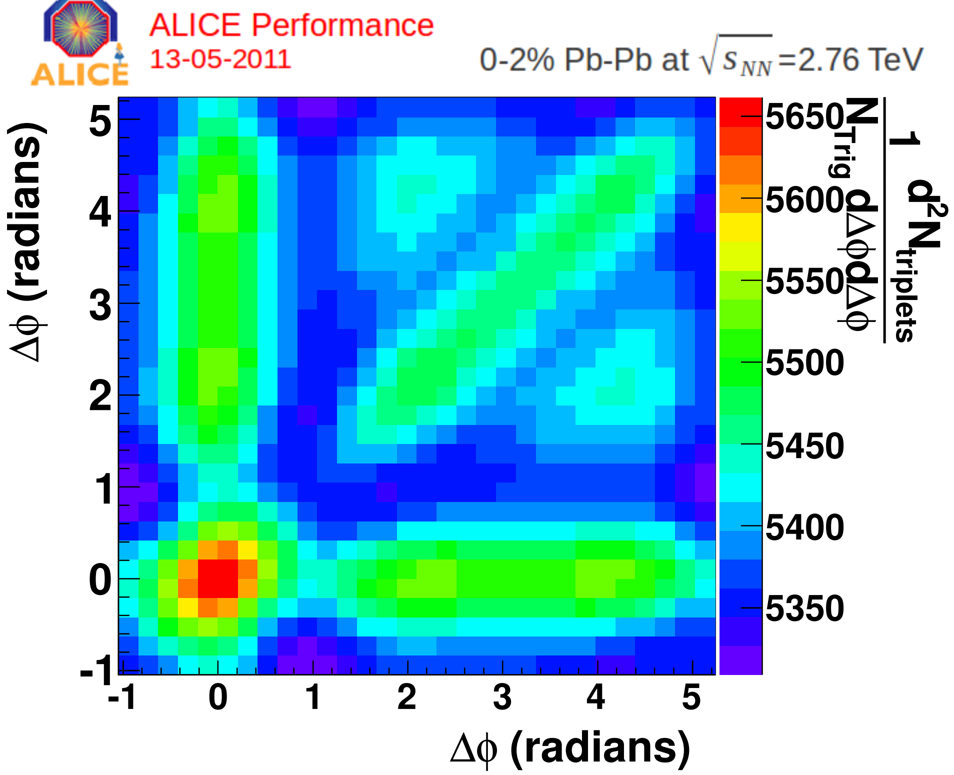
4-peak structure

J. Ulery (4B, poster 175)

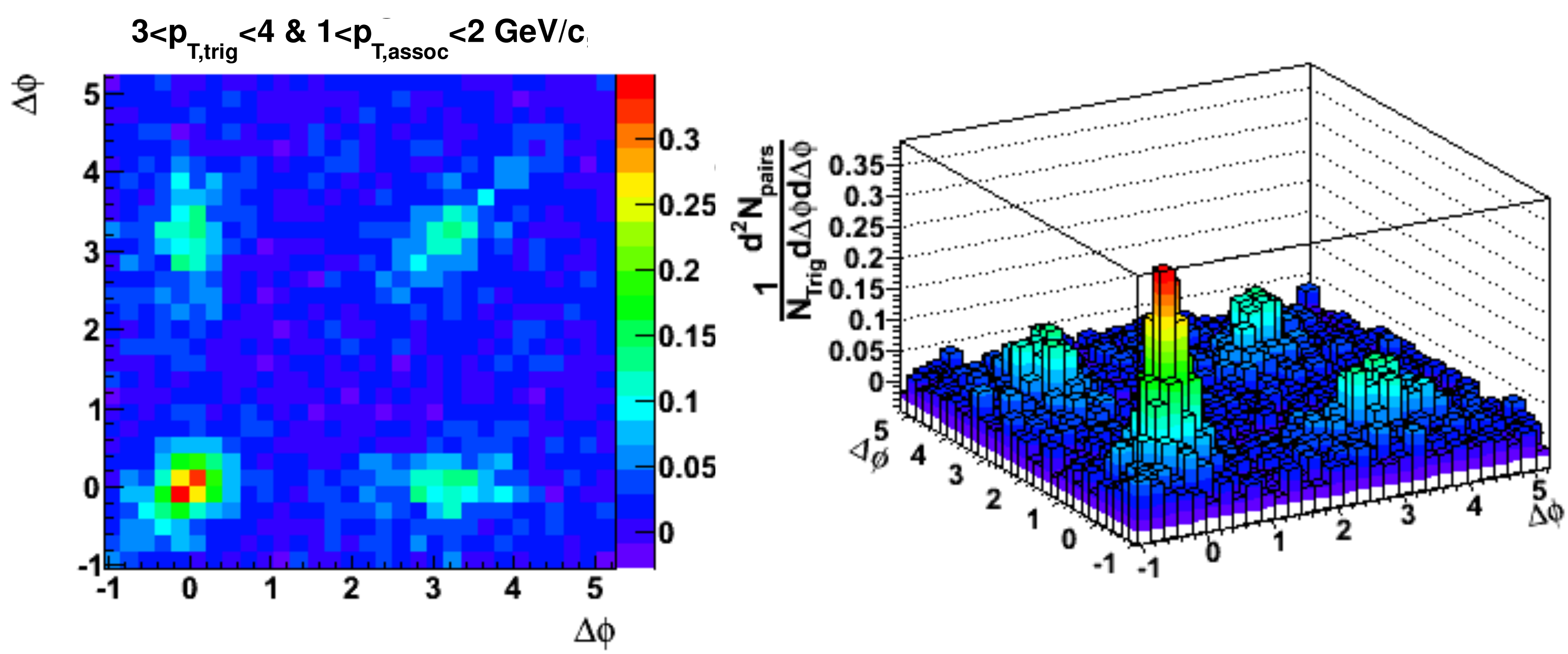
Three-particle angular distributions

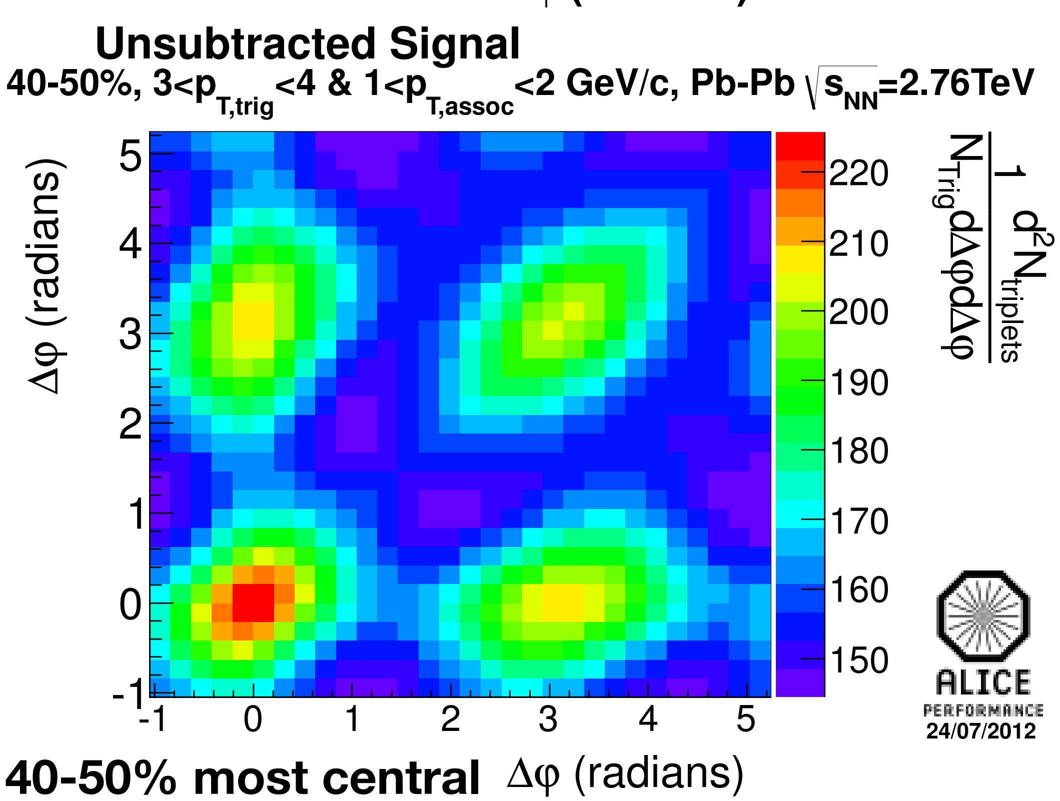
Full correlation (no background subtraction)

0-2% most central



pp @ 900 GeV





40-50% most central

0-2% most central Pb-Pb: 3rd harmonic dominates

Distinct off-diagonal peaks

40-50% mid-central Pb-Pb: 2nd harmonic dominates

4-peak structure

pp (900 GeV): di-jet signal dominates

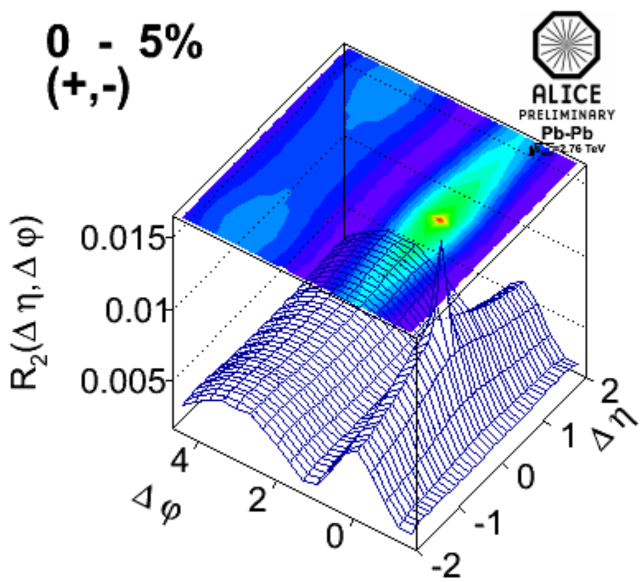
k_T broadening on away side

J. Ulery (4B, poster 175)

Charge-dependent correlations

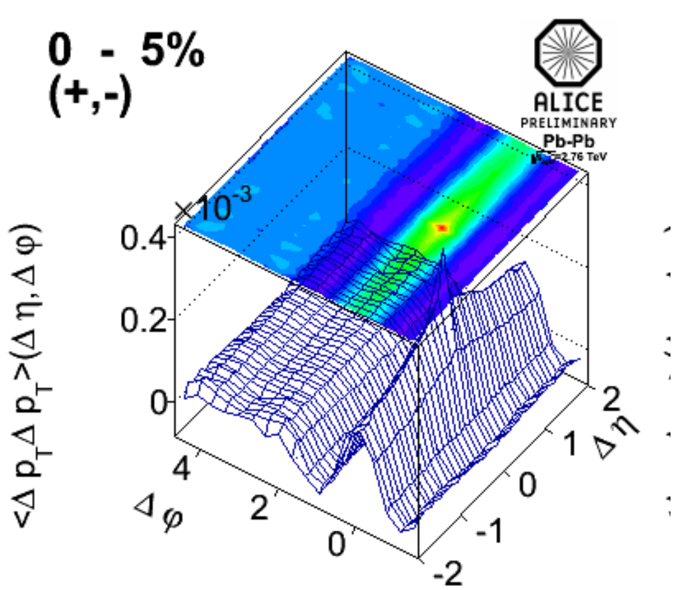
Number density correlations

$$R_2(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\rho_1(\eta_1,\varphi_1)\rho_1(\eta_2,\varphi_2)} - 1$$



Δp_T-Δp_T correlations

$$\langle \Delta p_{t,1} \Delta p_{t,2} \rangle = \frac{\int \rho_2 \, \Delta p_{t,1} \Delta p_{t,2} \, dp_{t,1} dp_{t,2}}{\int \rho_2 \, dp_{t,1} dp_{t,2}}$$

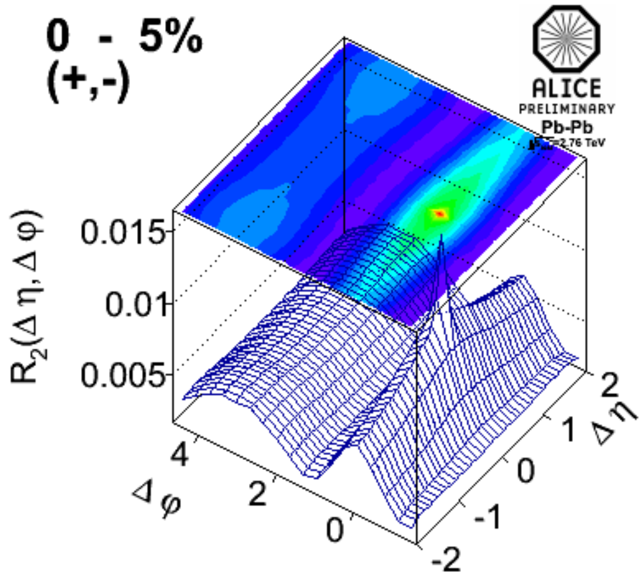


C. Pruneau (poster 418)

Charge-dependent correlations

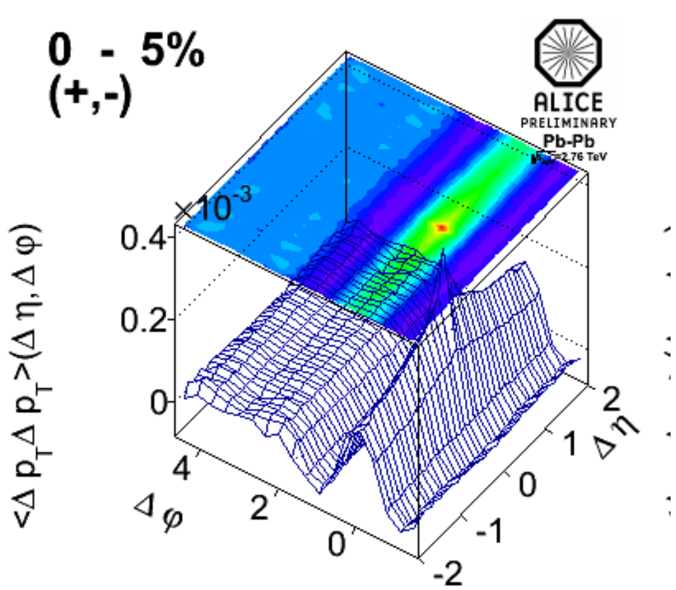
Number density correlations

$$R_2(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\rho_1(\eta_1,\varphi_1)\rho_1(\eta_2,\varphi_2)} - 1$$



ΔpT-ΔpT correlations

$$\langle \Delta p_{t,1} \Delta p_{t,2} \rangle = \frac{\int \rho_2 \, \Delta p_{t,1} \Delta p_{t,2} \, dp_{t,1} dp_{t,2}}{\int \rho_2 \, dp_{t,1} dp_{t,2}}$$



Extract Fourier coefficients a_n from fits

For a particular projection to Δη,

$$F(\Delta\phi) = a_0 + \sum_{n=1}^{6} a_n \cos(n\Delta\phi)$$

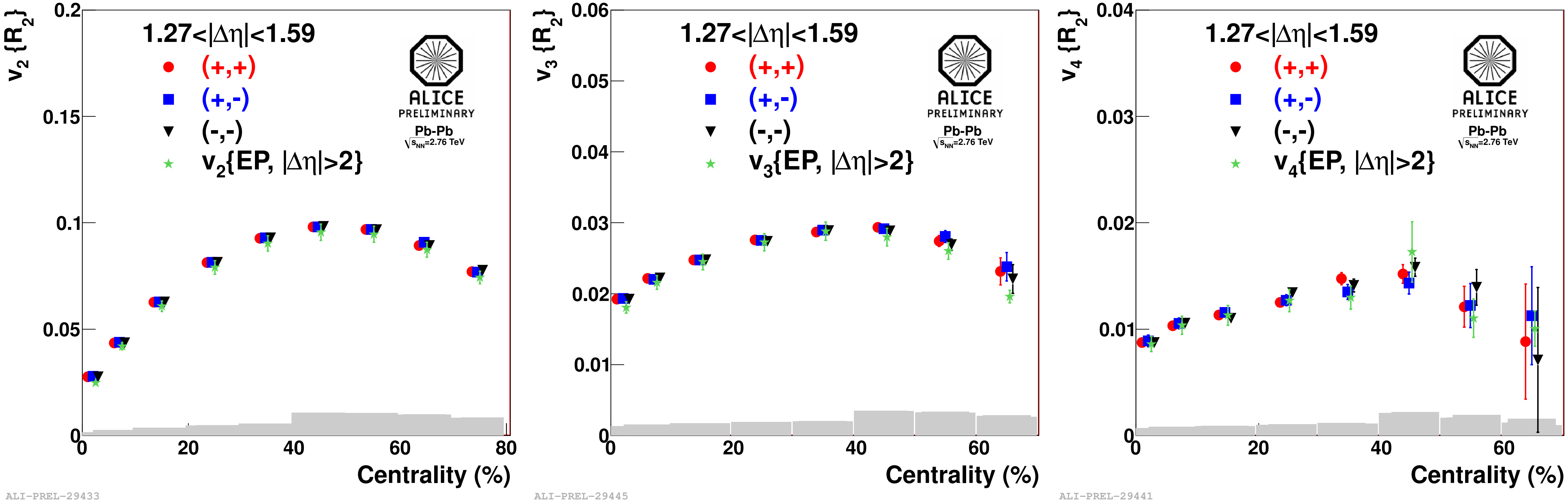
From a_n, compute single-particle v_n values:

$$v_n\{R_2 \text{ or } \Delta p_T \Delta p_T\} = \text{sign}(a_n)\sqrt{\frac{|a_n|}{2}}$$

C. Pruneau (poster 418)

Other harmonics: v_1-v_4

Centrality dependence



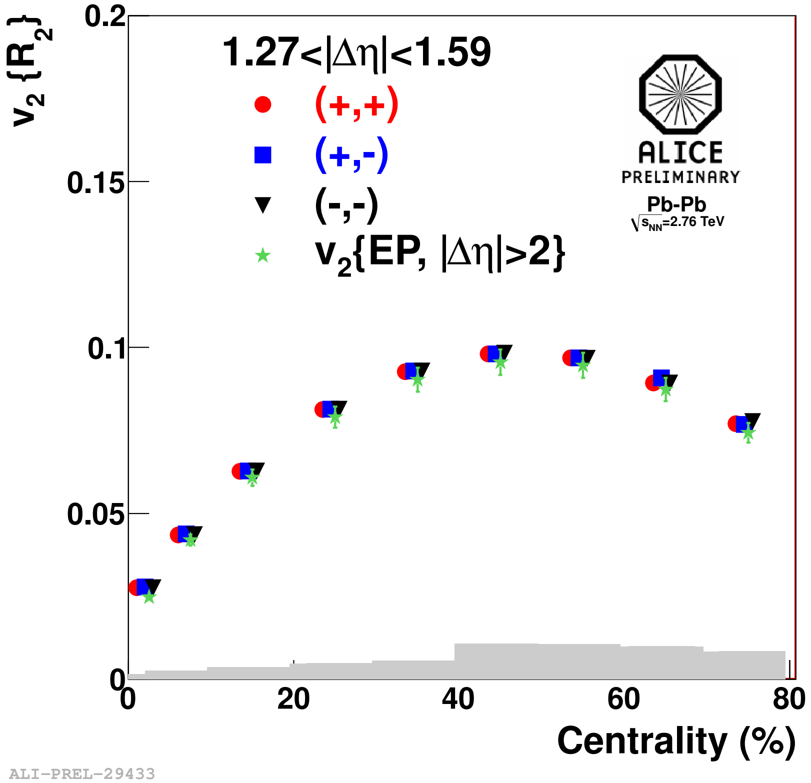
v_2-v_4 have similar features:

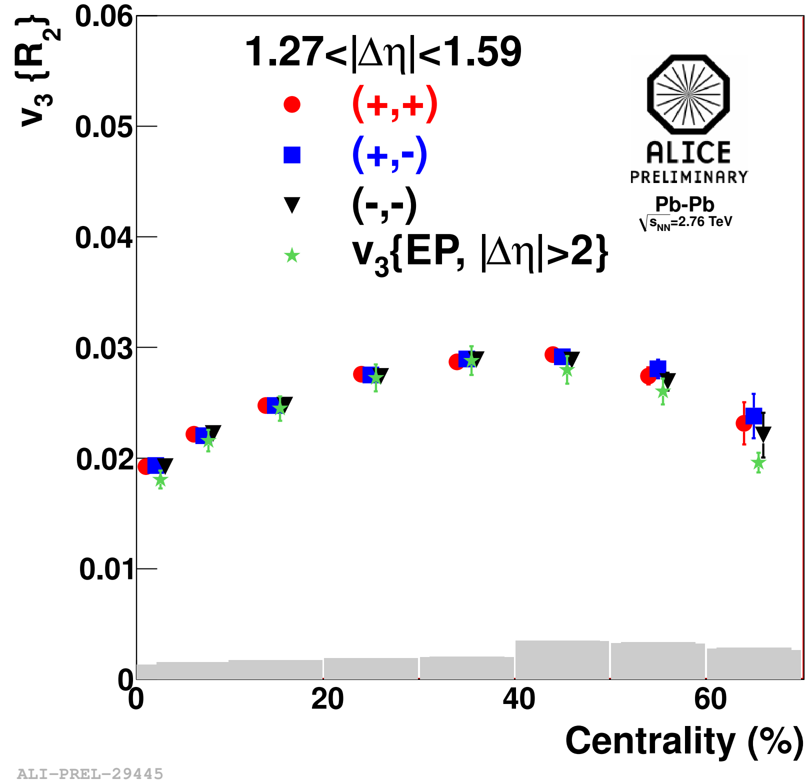
- independent of charge
- independent of Δη
- Agree with EP method: harmonics factorize

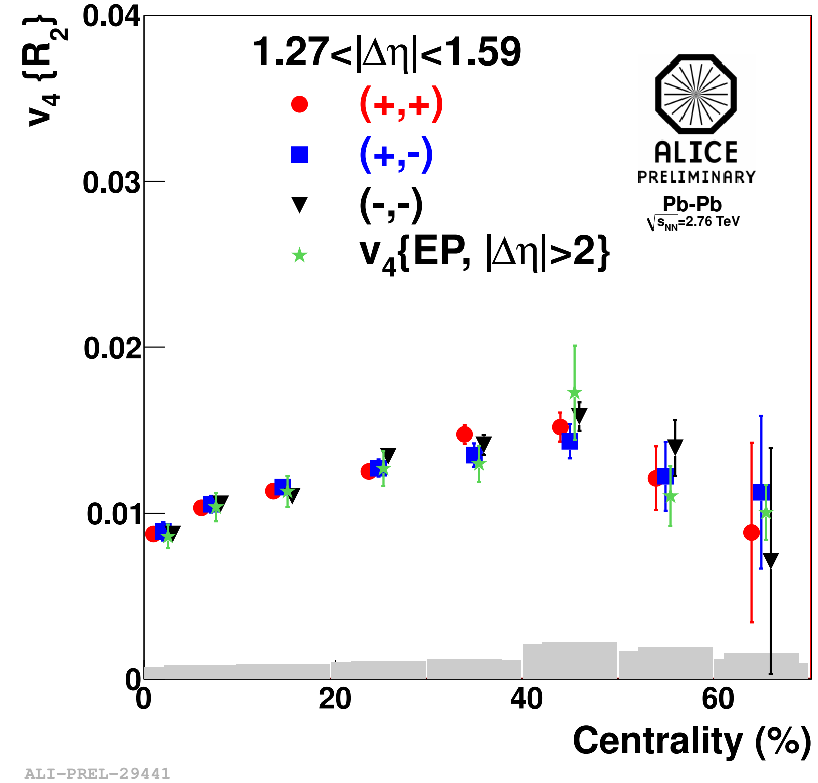
C. Pruneau (poster 418)

Other harmonics: v_1-v_4

Centrality dependence





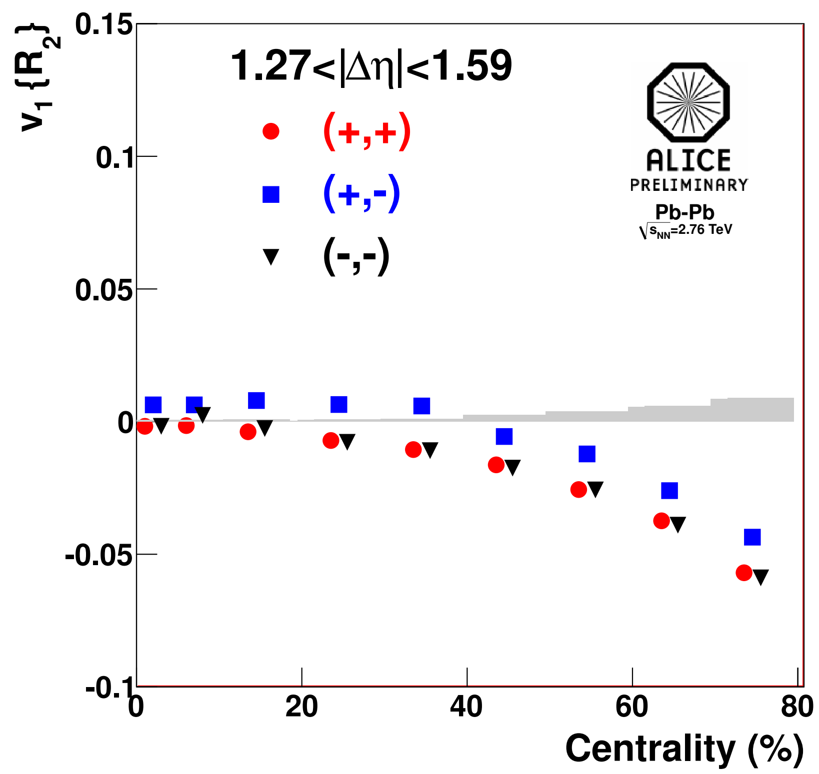


v_2-v_4 have similar features:

- independent of charge
- independent of Δη
- Agree with EP method: harmonics factorize

v_1:

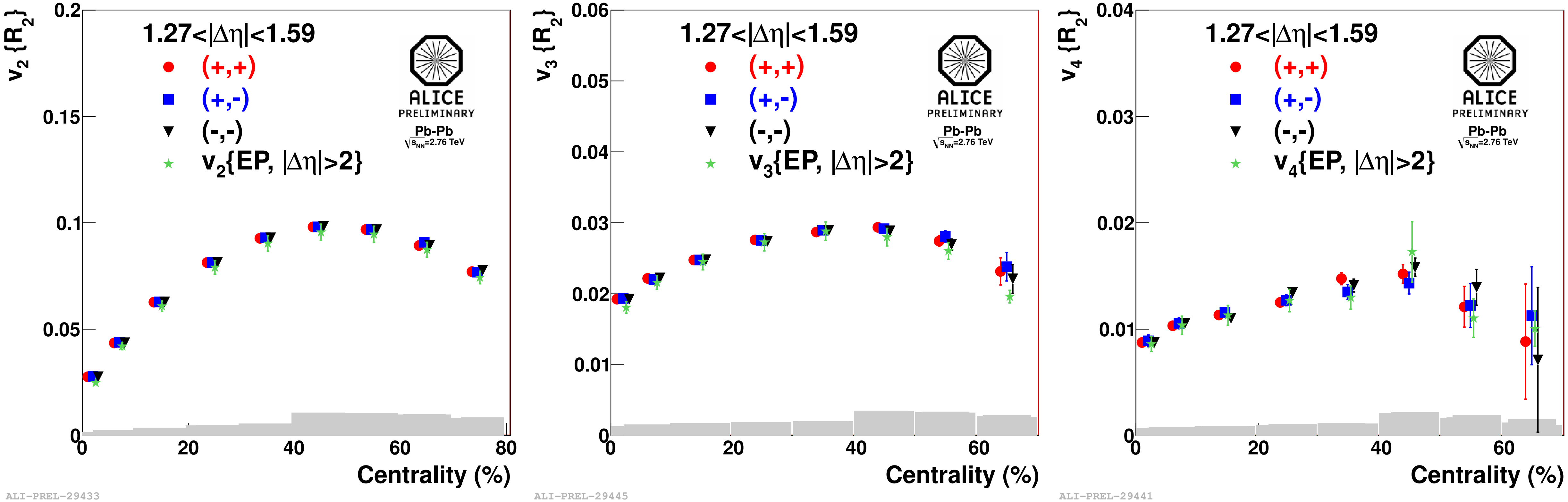
- charge-dependent for R_2
- charge-independent for Δp_T-Δp_T



C. Pruneau (poster 418)

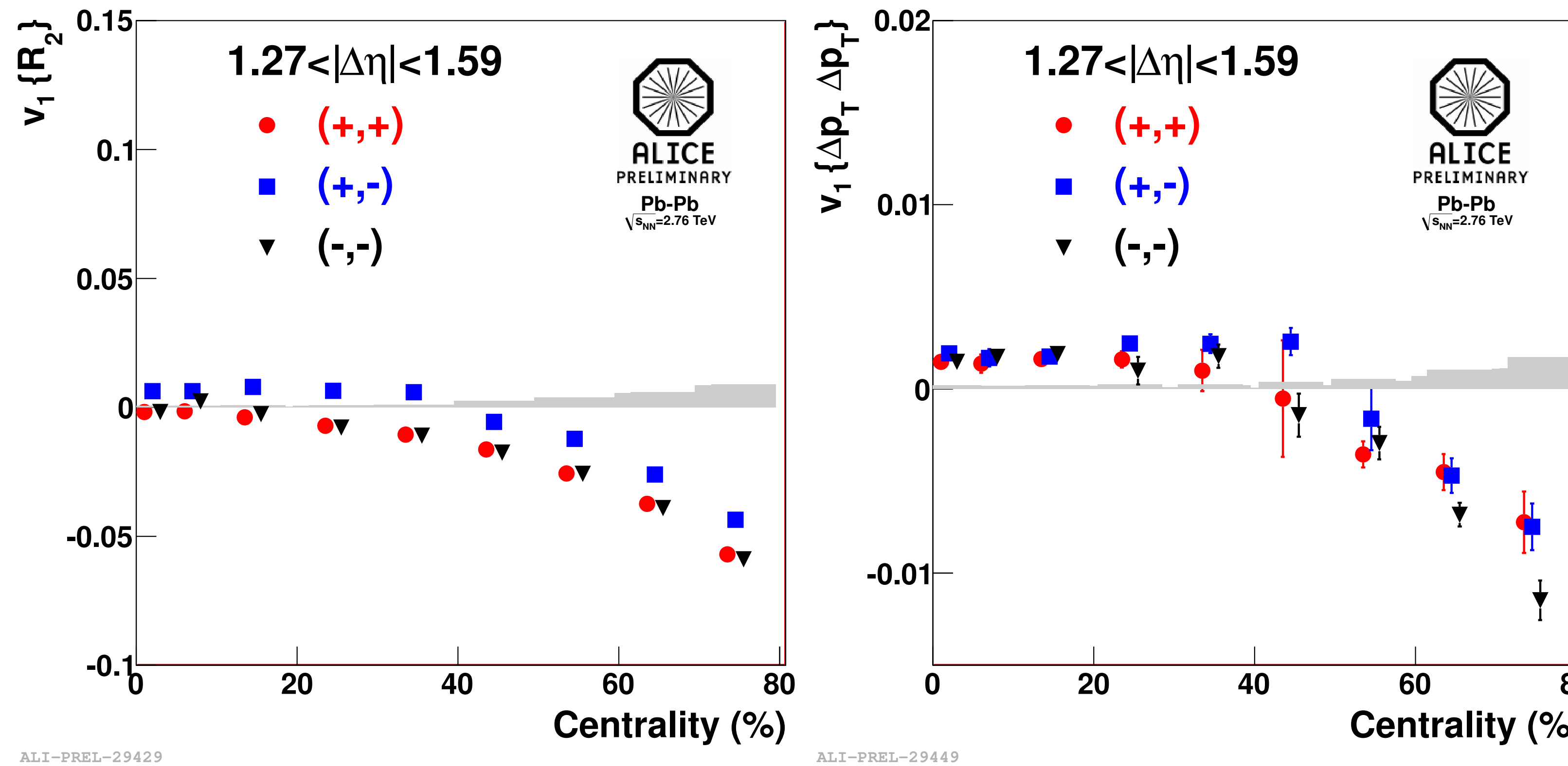
Other harmonics: v_1-v_4

Centrality dependence



v_2-v_4 have similar features:
- independent of charge
- independent of Δη
- Agree with EP method: harmonics factorize

v_1:
- charge-dependent for R_2
- charge-independent for Δp_T-Δp_T



C. Pruneau (poster 418)

Correlation of balancing charges

Charge balance function in Δη (or Δφ)

$$B(\Delta\eta) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta\eta) - N_{++}(\Delta\eta)}{N_+} + \frac{N_{-+}(\Delta\eta) - N_{--}(\Delta\eta)}{N_-}\right\}$$

Bass, Danielewicz, Pratt, PRL 85, 2689 (2000).

Sensitive to

Collective motion

Charge separation at freeze-out

Hadronization time

Reference data

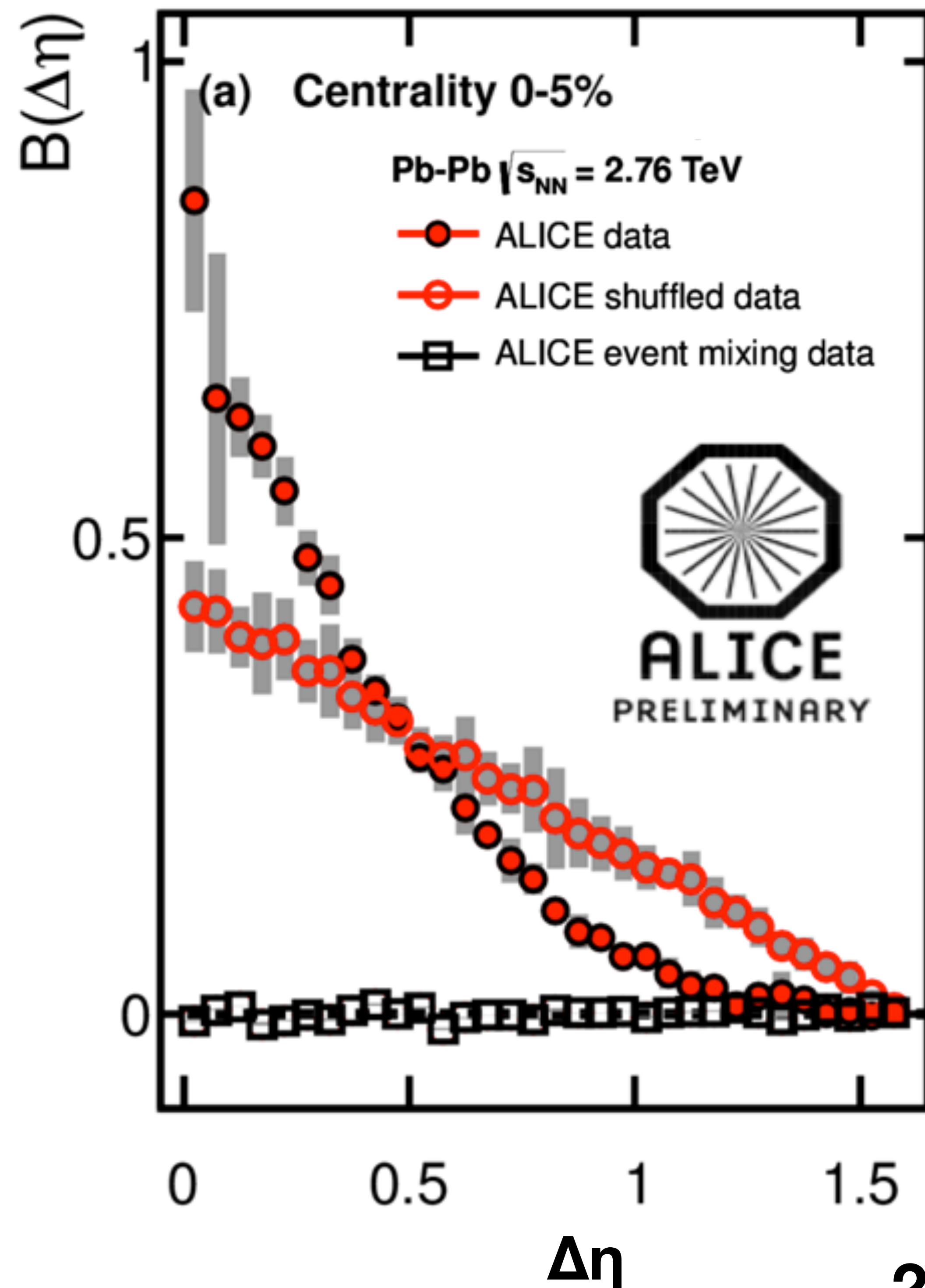
Shuffled events:

No charge-momentum correlations

Mixed events:

No momentum correlations

Subtracted from data as acceptance correction



M. Weber (2C)

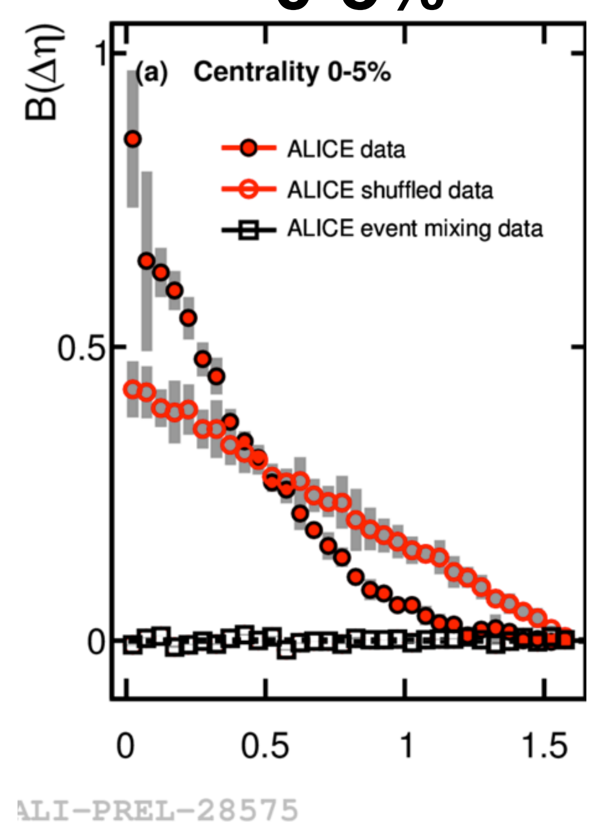
B(Δη) and B(Δφ)

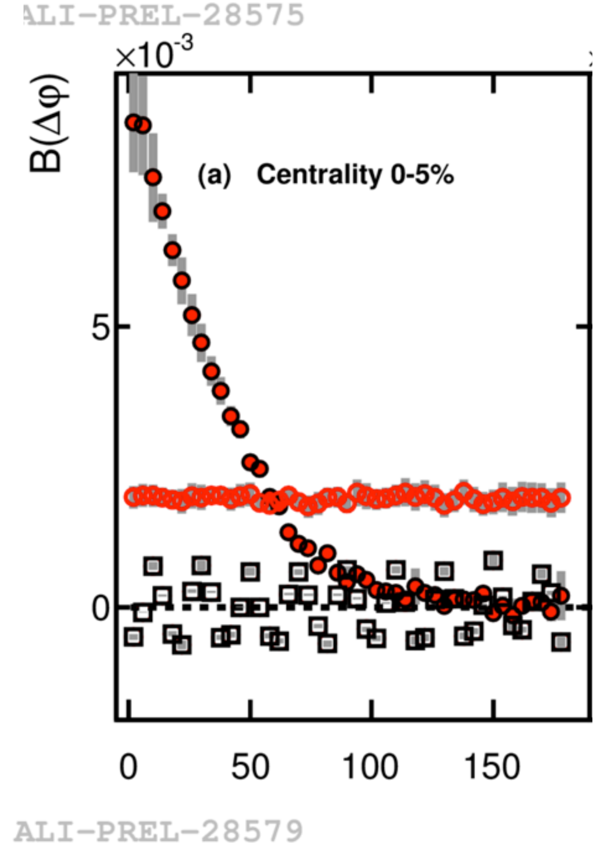
Trends:

B falls to zero with increasing pair separation

B becomes narrower in more central data

0-5%





"Focusing" observed in central data

Consistent with

- Large radial flow

- Long QGP lifetime, delayed creation of charges

M. Weber (2C)

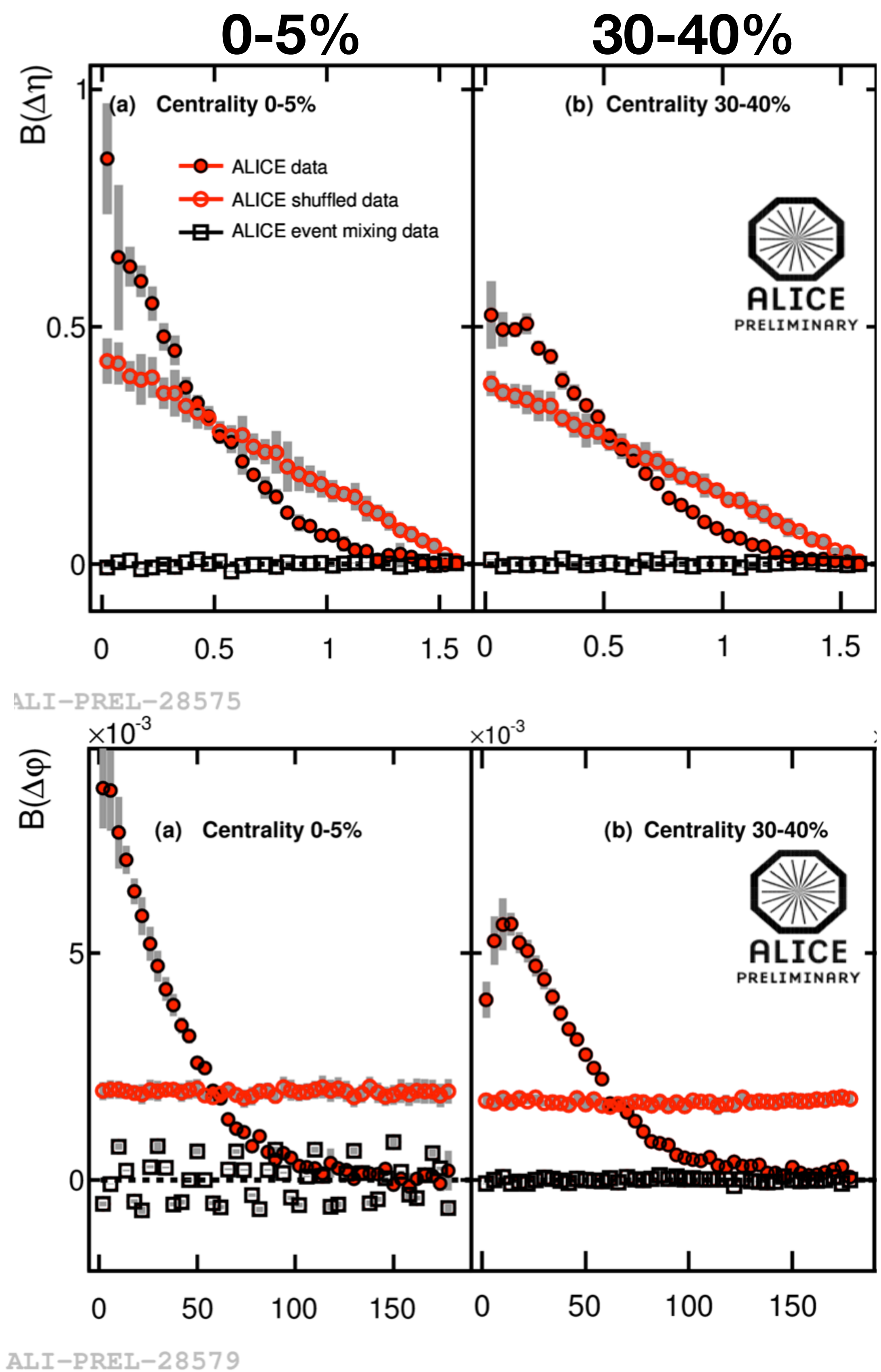
A. Adare (ALICE)

B(Δη) and B(Δφ)

Trends:

B falls to zero with increasing pair separation

B becomes narrower in more central data



"Focusing" observed in central data

Consistent with
- Large radial flow
- Long QGP lifetime, delayed creation of charges

M. Weber (2C)

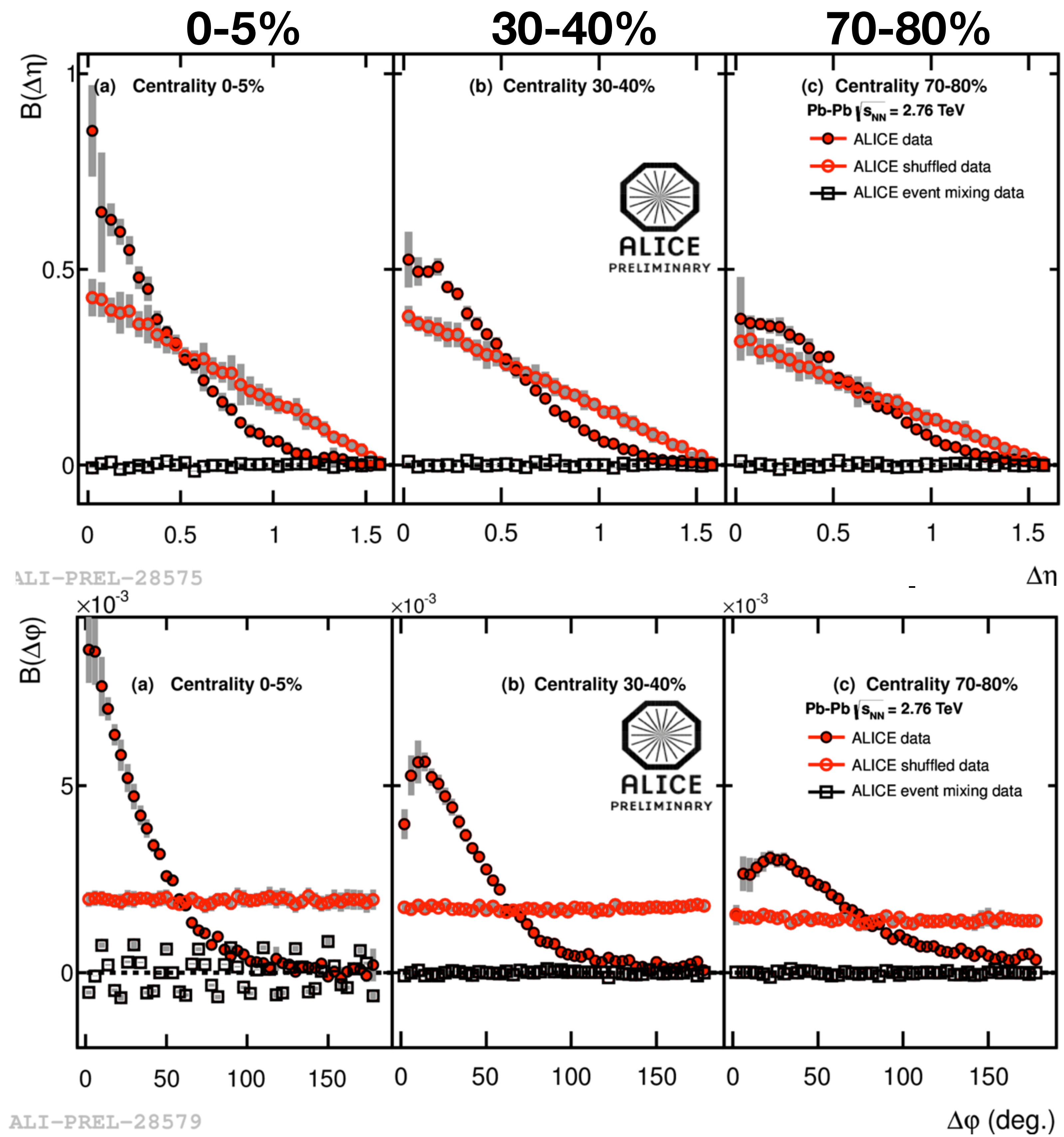
A. Adare (ALICE)

B(Δη) and B(Δφ)

Trends:

B falls to zero with increasing pair separation

B becomes narrower in more central data



"Focusing" observed in central data

Consistent with

- Large radial flow

- Long QGP lifetime, delayed creation of charges

M. Weber (2C)

A. Adare (ALICE)

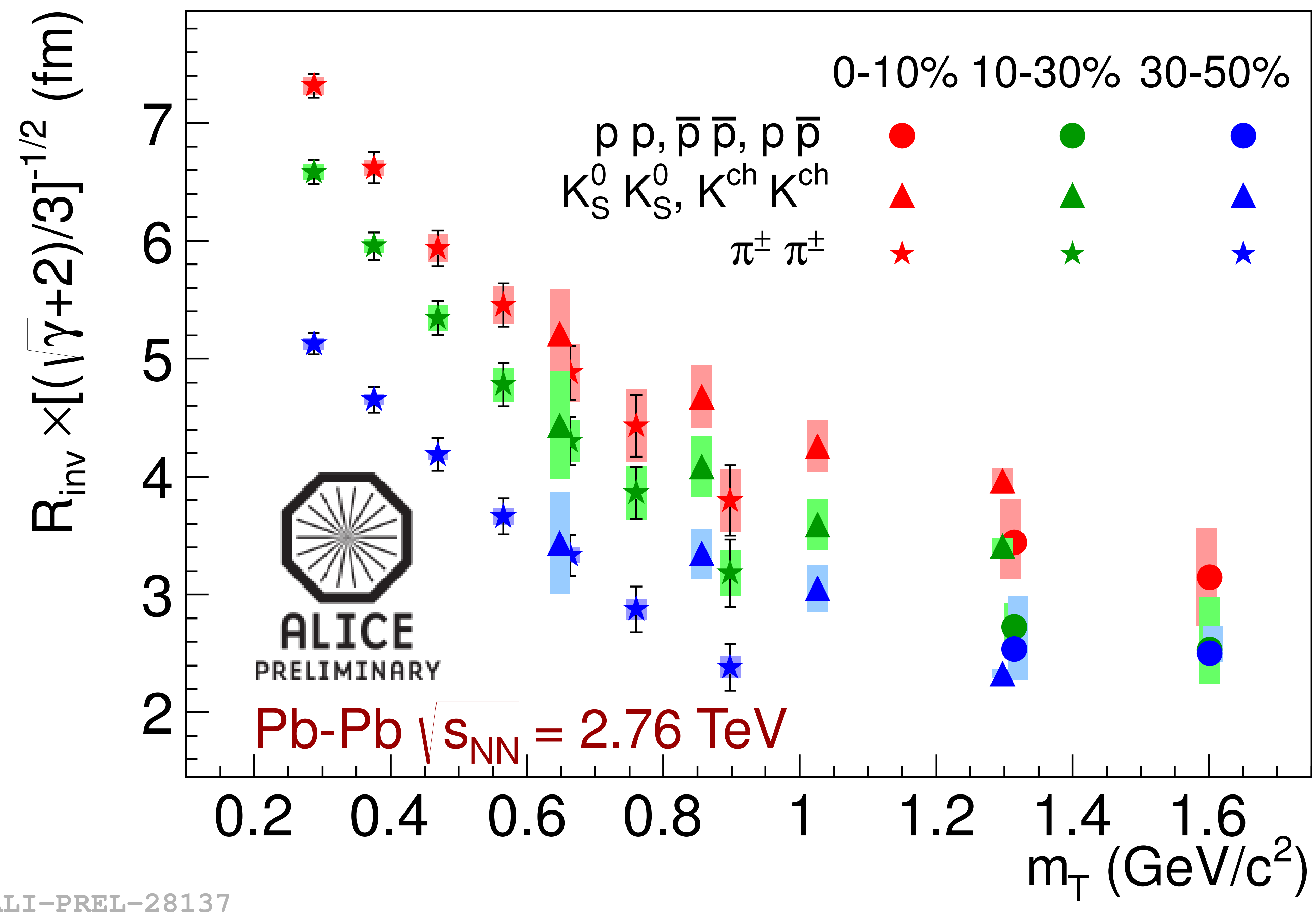
Space-momentum correlations

Collective flow induces strong x-p correlations.

For flow-induced correlations, a common approximate m_T scaling of femtoscopic radii expected for particles of different mass.

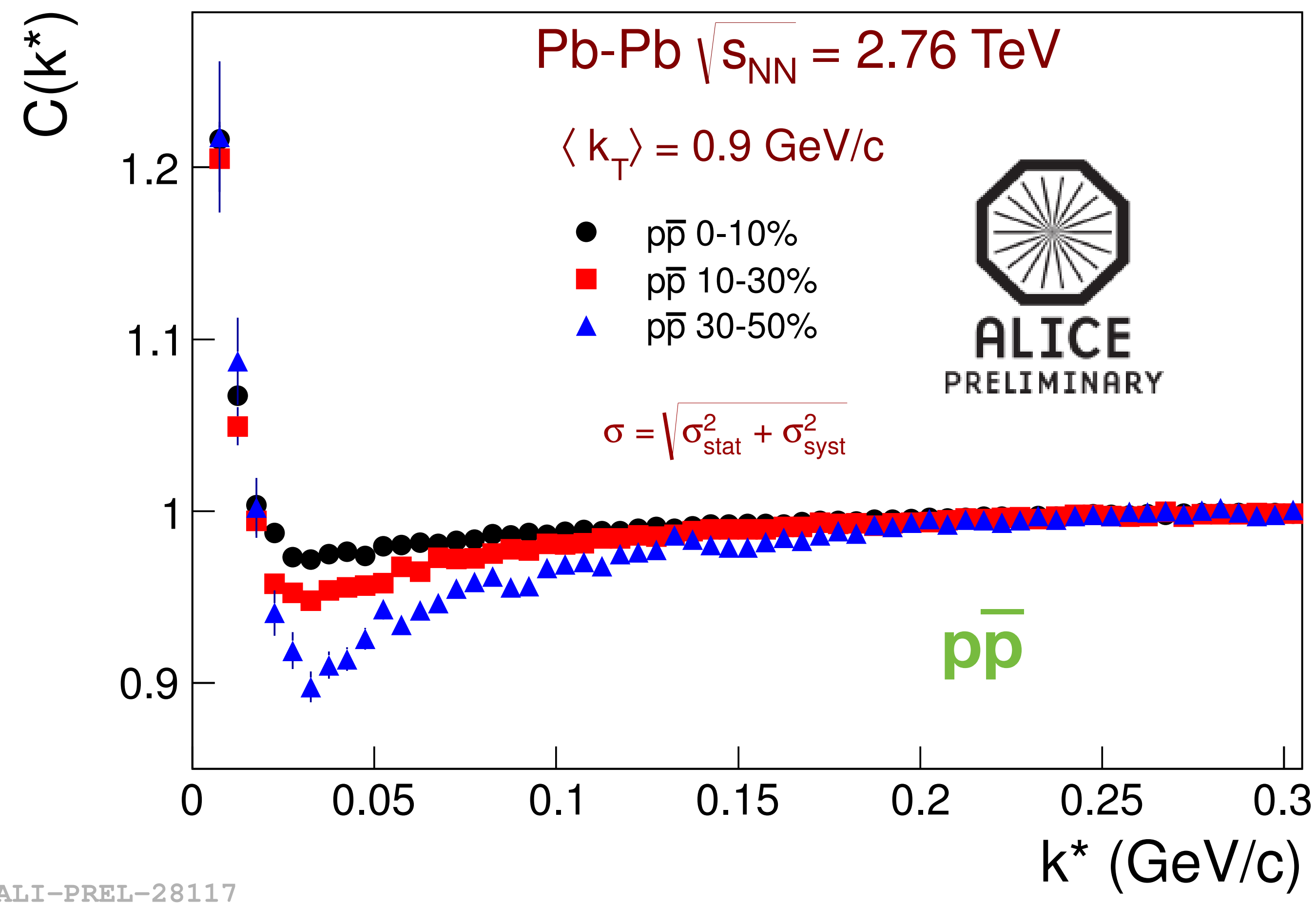
ALICE measured radii for π, K, p vs. m_T and centrality

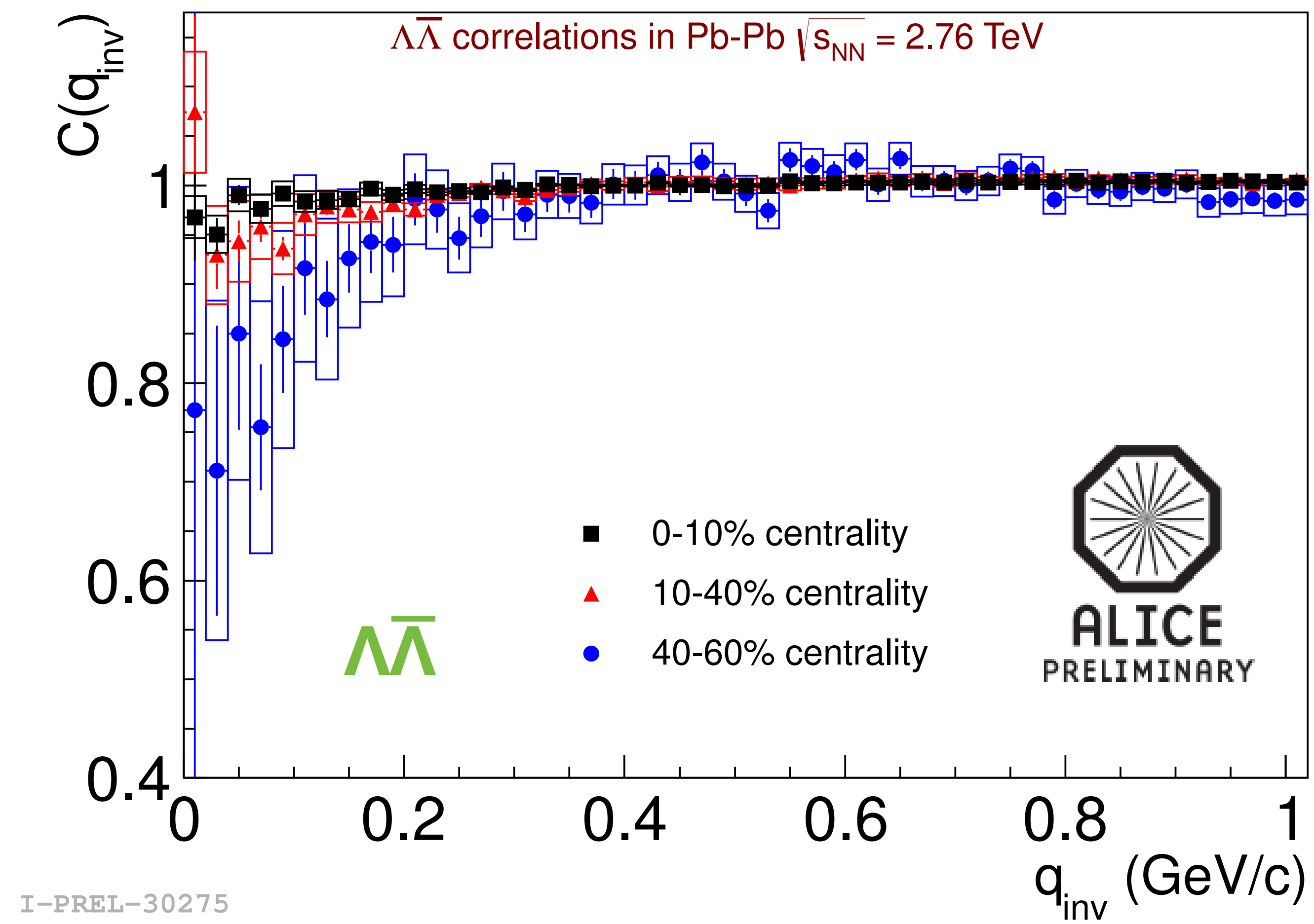
Approximate scaling observed for 1D R_{inv} radius scaled by kinematic factor



M. Szymanski (1C)

Annihilation seen in $B\bar{B}$ correlations





Final state rescattering proposed as explanation for low p yield

If true, should be reflected in $B\bar{B}$ femtoscopic correlations

ALICE observes significant annihilation in various $B\bar{B}$ channels

Beginnings of precise interaction cross-section measurements for many rare $B\bar{B}$ pair types

M. Szymanski (1C)

Summary

Identified particles

- p/π enhancement comes from bulk, not jet fragmentation.
- $B\bar{B}$ femtoscopic correlations indicate $p\bar{p}$ annihilation in final state

Flow dominance at low to intermediate p_T

- 3-particle correlations: Inclusive distributions consistent with flow-only simulations
  - Remaining signal small, but possibly nonzero
- Transverse momentum and number density correlations:
  - Agree with v_n obtained by event-plane methods
  - Fourier analysis supports long-range factorization for v_2-v_4

Broadening & enhanced yield of near-side jet peak

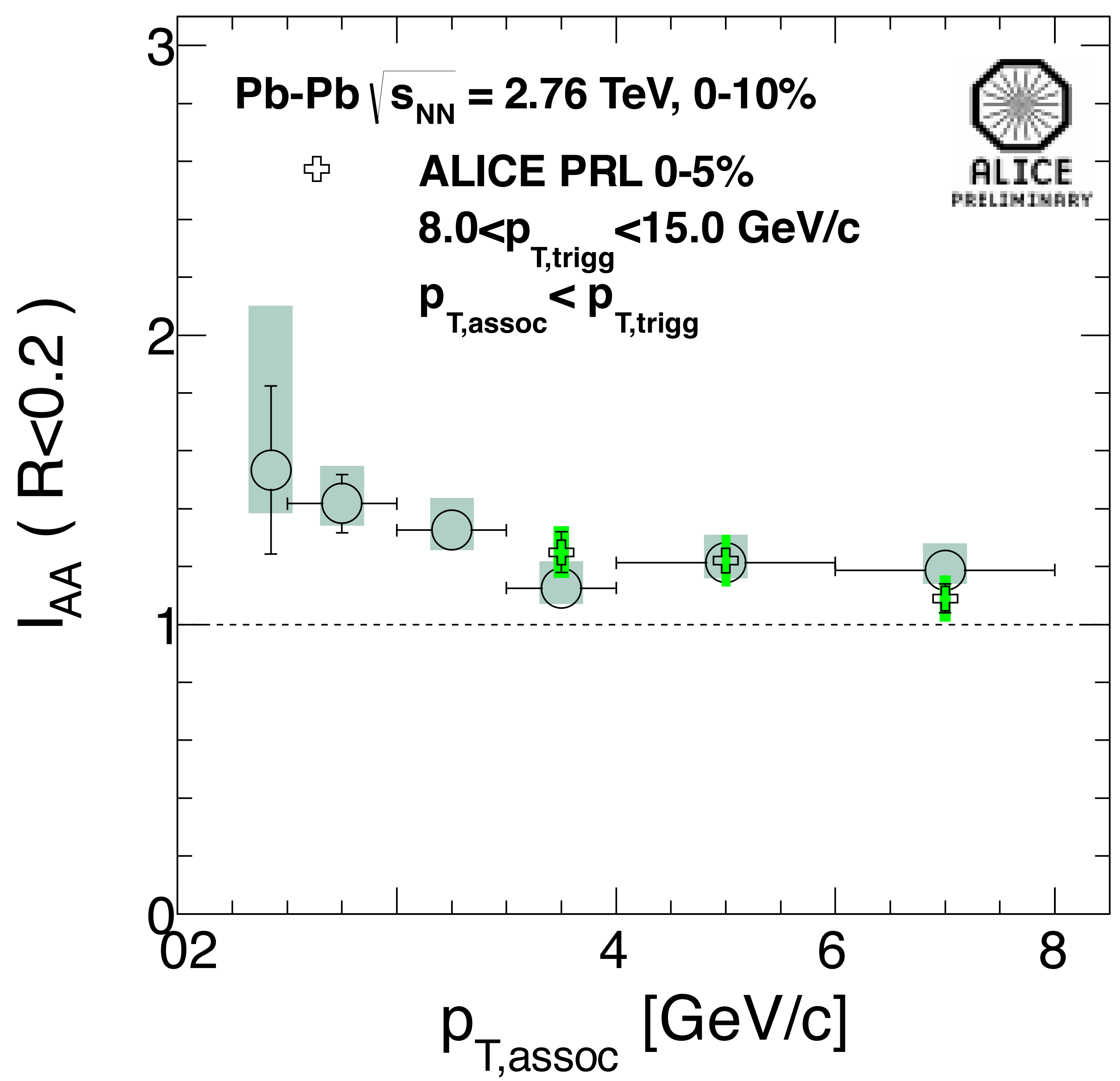
- Significant longitudinal broadening in more central collisions, compared to pp
- Yield enhanced at all associated p_T, compared to pp

Charge dependence

- Charge balance function "focused" in $\Delta\eta$ by strong radial flow + long QGP lifetime
- Fourier harmonics: v_1 sensitive to charge combination and $\Delta\eta$; v2 and higher are not

Backups

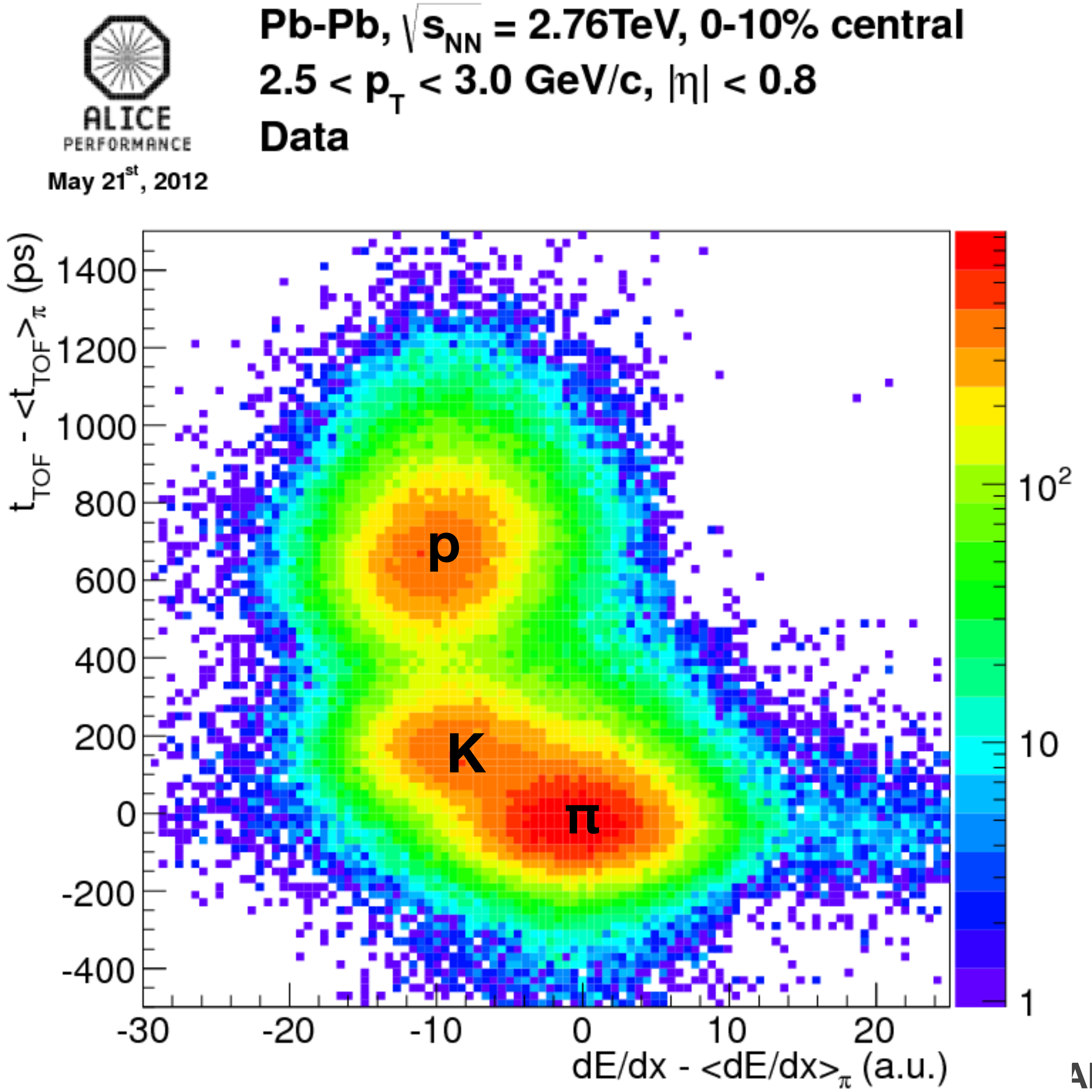
Comparison to published IAA

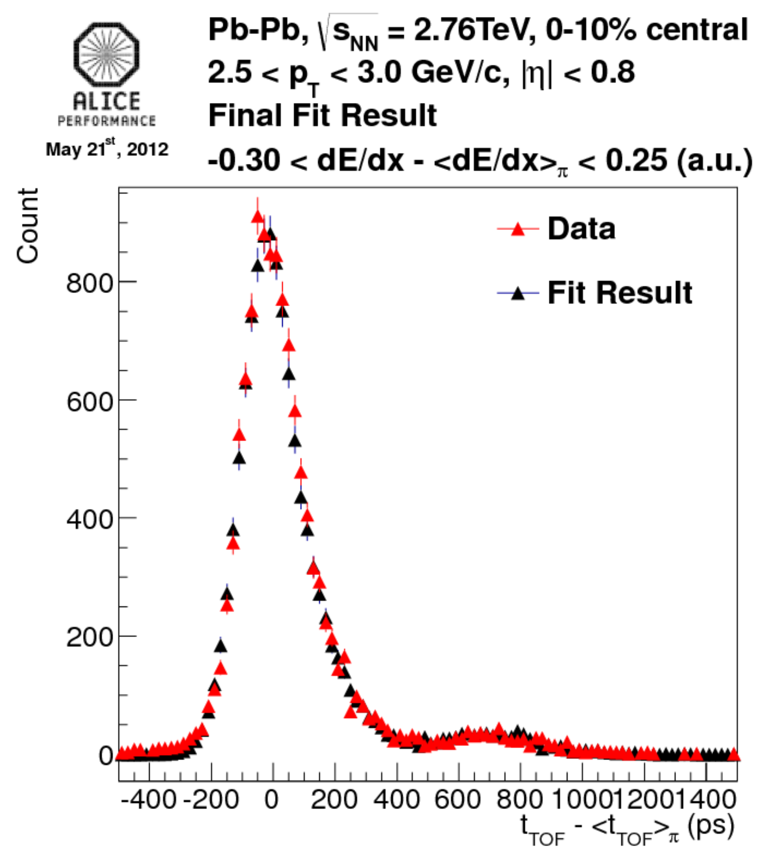


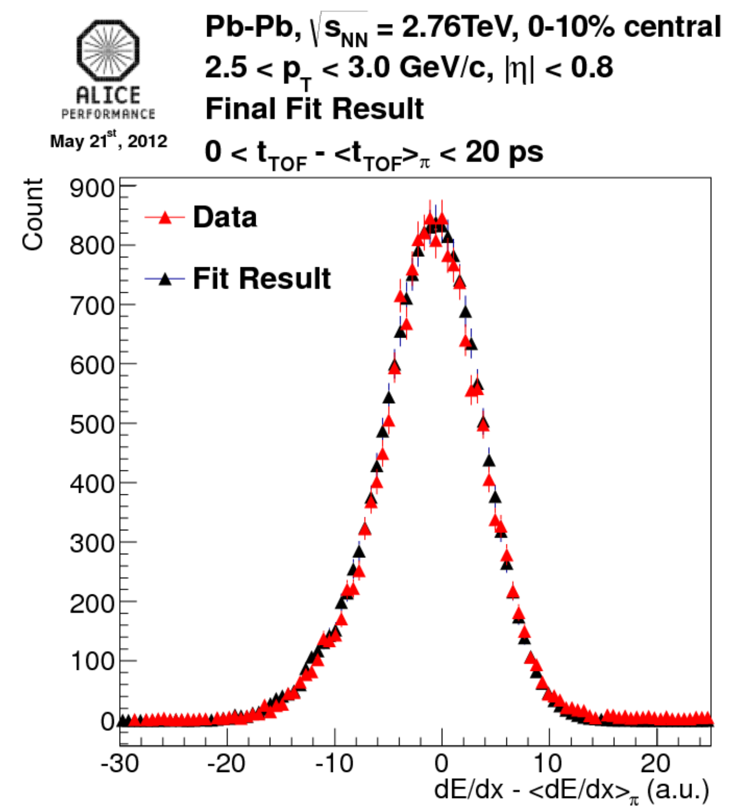
PID method

Correlate dE/dx from TPC and flight time from TOF detector.

Quantities relative to pion assumption







ALICE)

v_2 from R_2 and Δp_T-Δp_T correlations

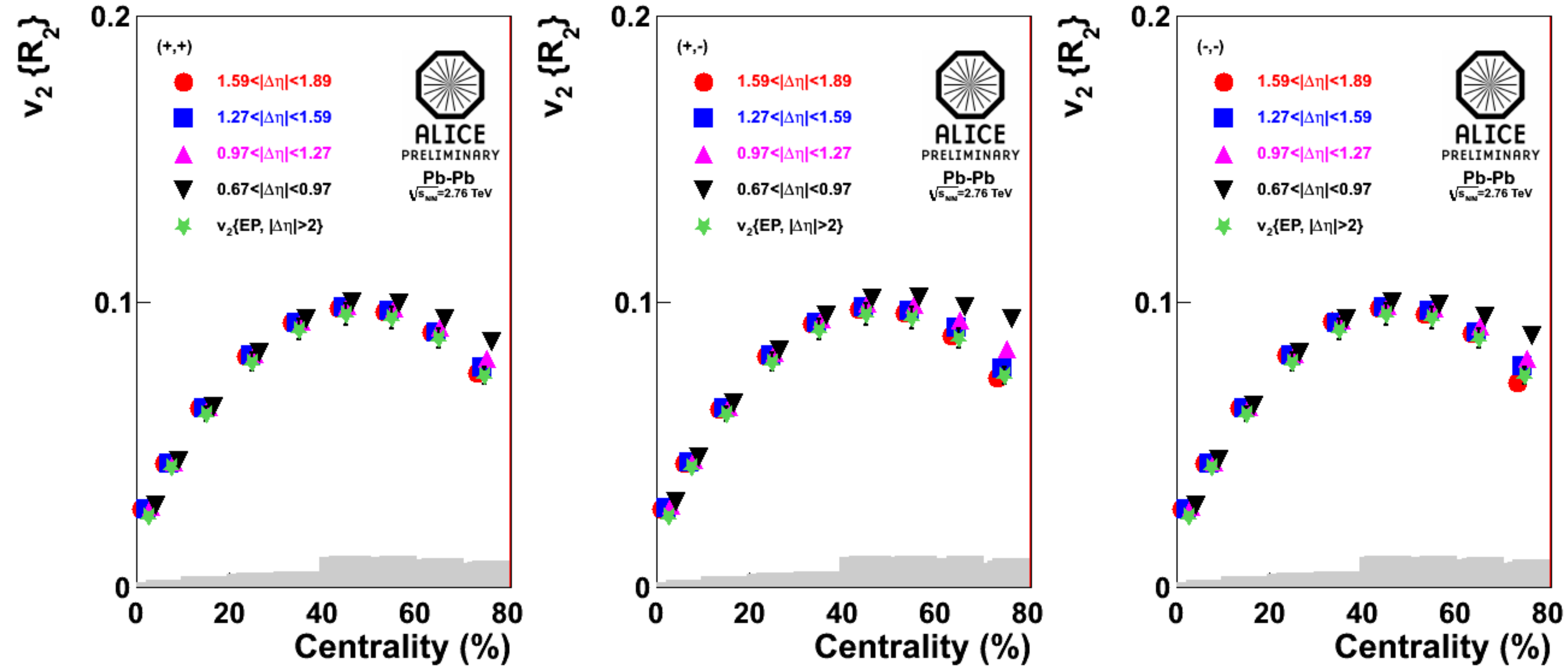
v_2 from number density correlations

- colors: $\Delta\eta$ ranges

v_2 decreases with $\Delta\eta$ in peripheral collisions

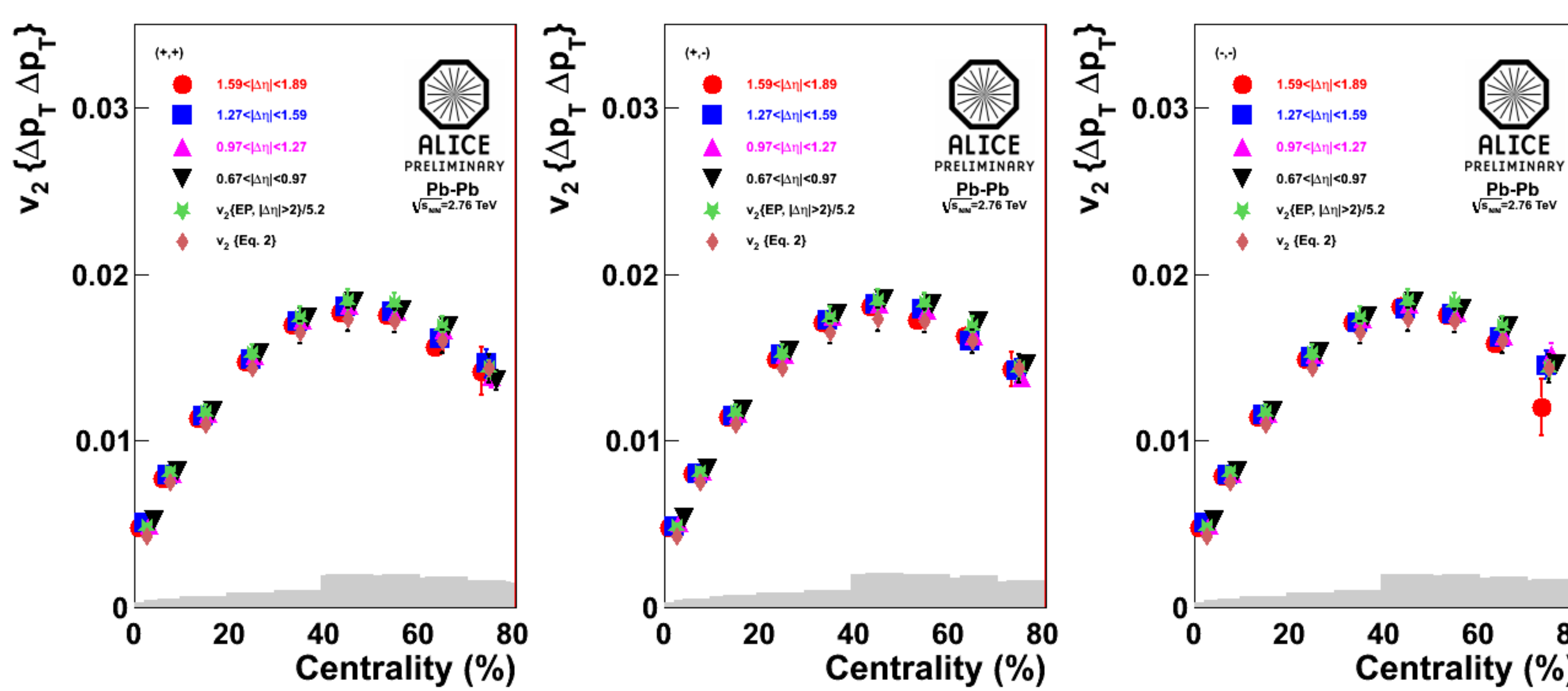
- panels: charge comb.

v_2 indep of charge



v_2 from Δp_T-Δp_T correlations

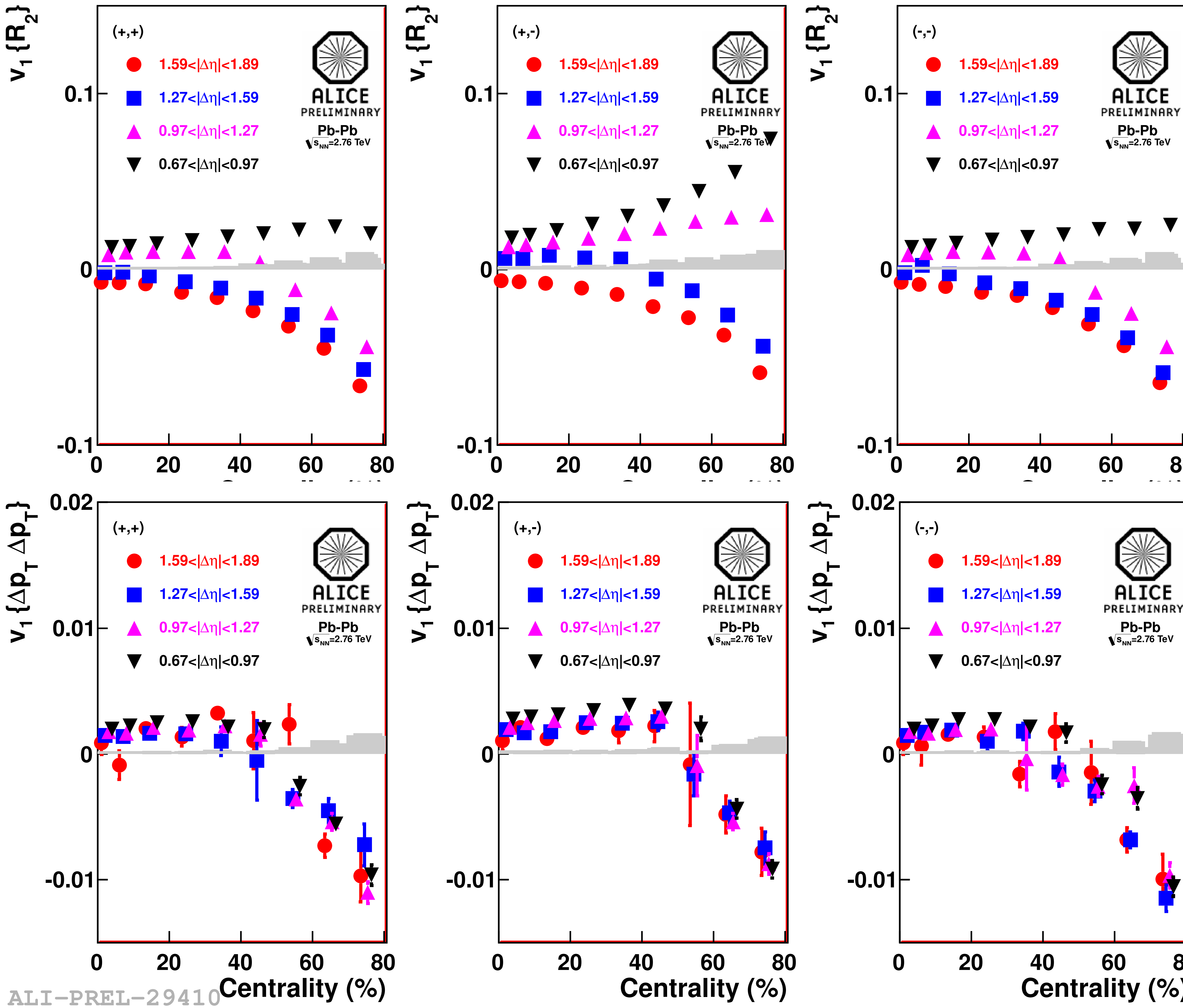
- v_2 indep. of $\Delta\eta$ at all centralities
- As for R_2, no charge dependence



Both techniques consistent with v_2\{EP\}

Flow dominates

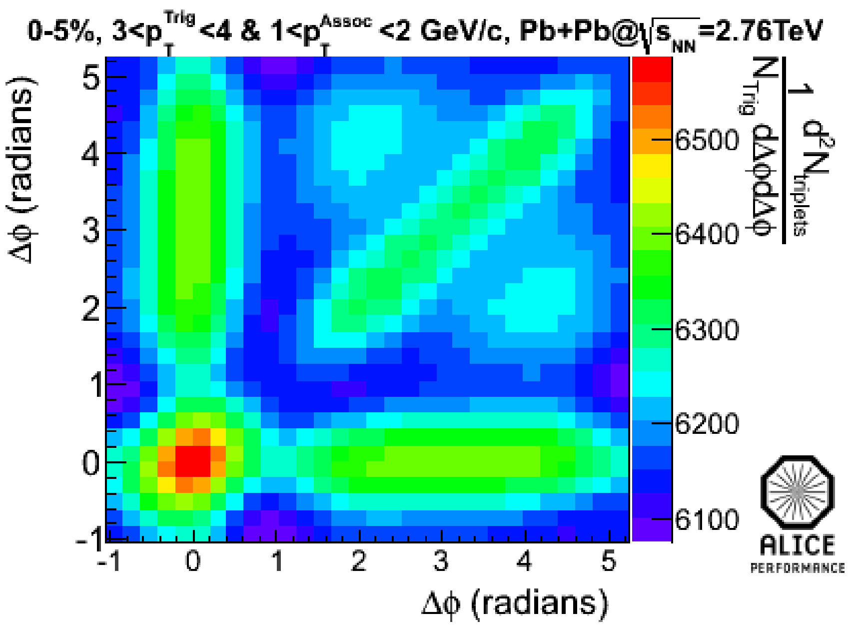
The first harmonic



Three-particle angular distributions

Full correlation (no background subtraction) - centrality evolution:

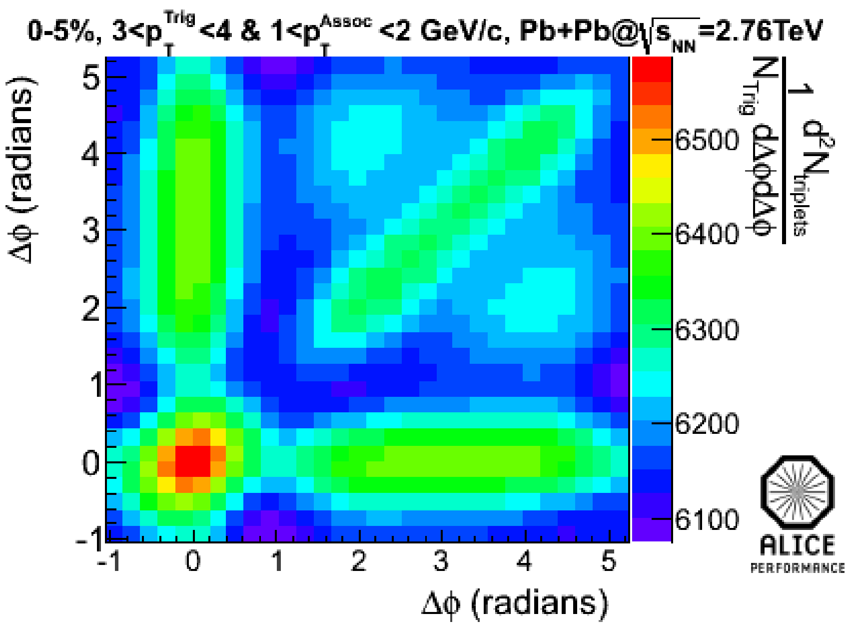
0-5% most central

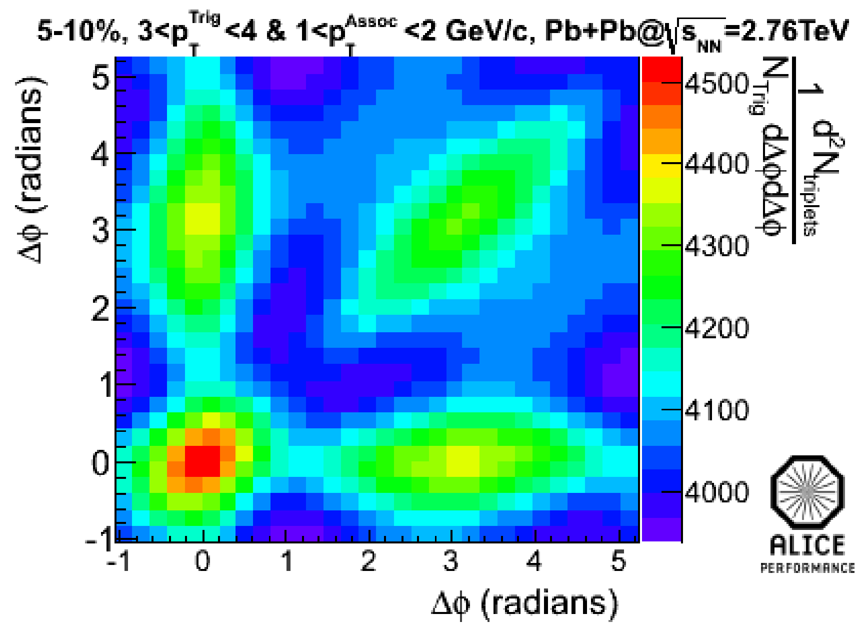


Three-particle angular distributions

Full correlation (no background subtraction) - centrality evolution:

0-5% most central

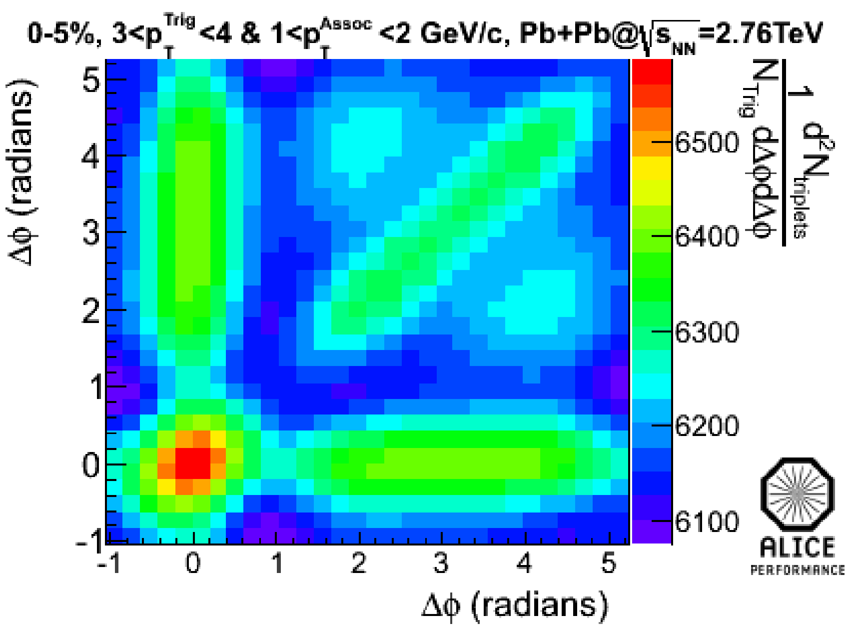


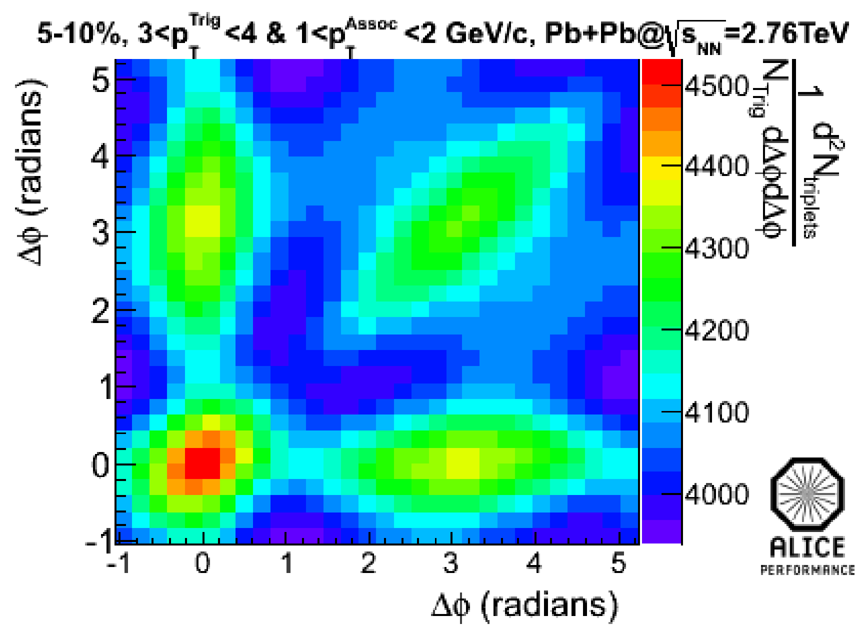


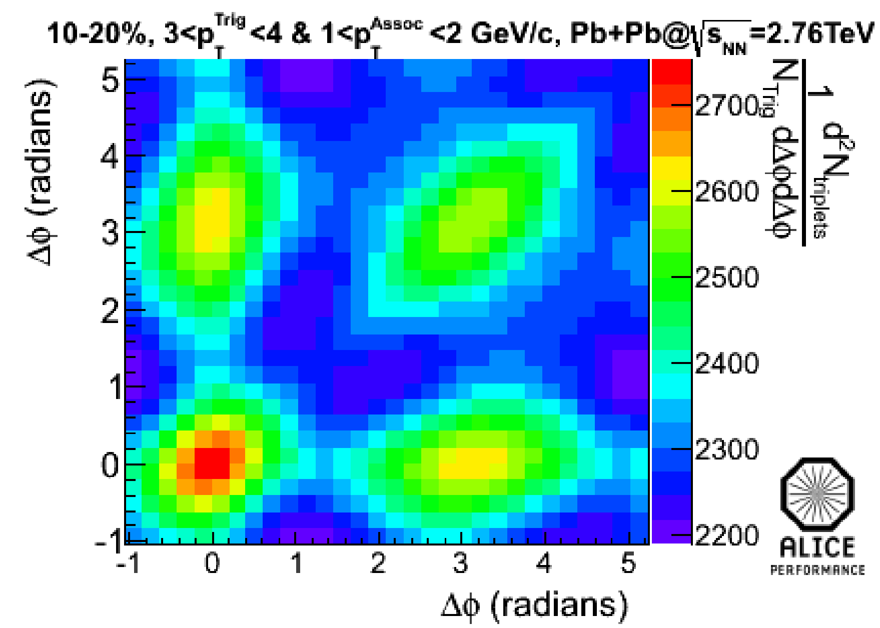
Three-particle angular distributions

Full correlation (no background subtraction) - centrality evolution:

0-5% most central



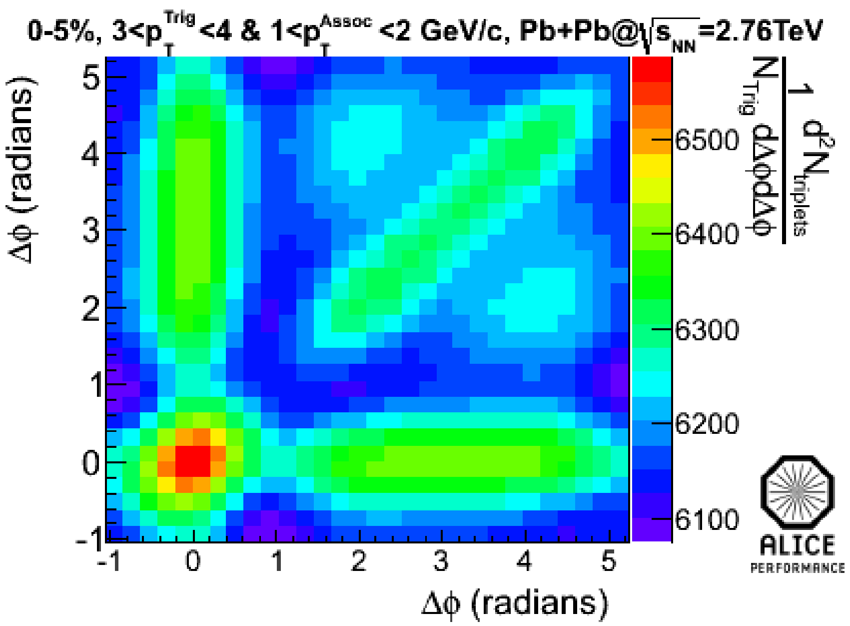


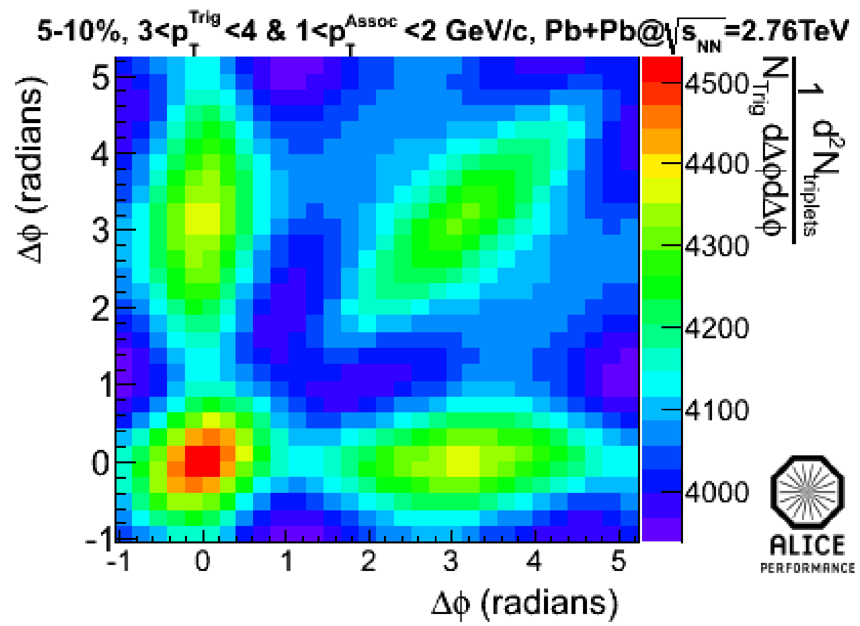


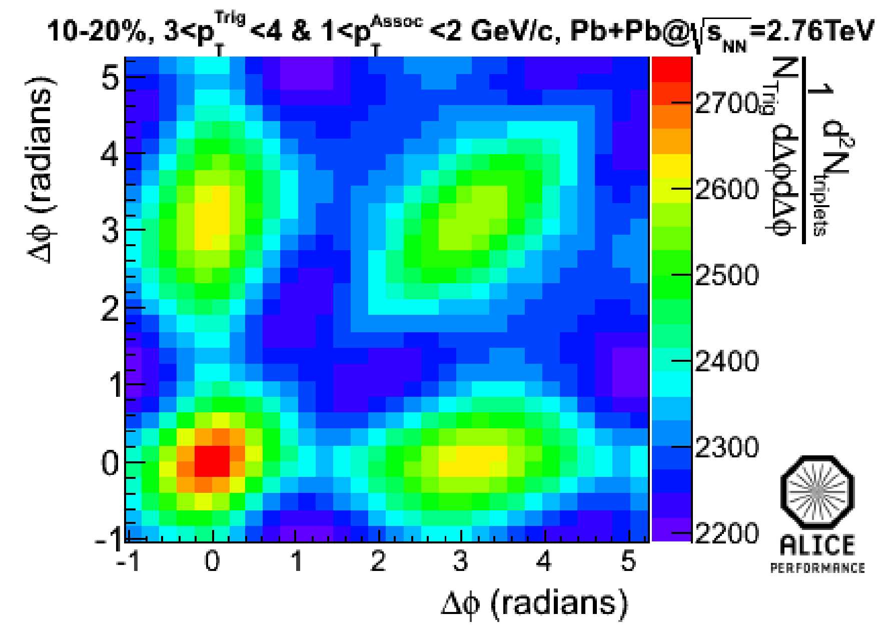
Three-particle angular distributions

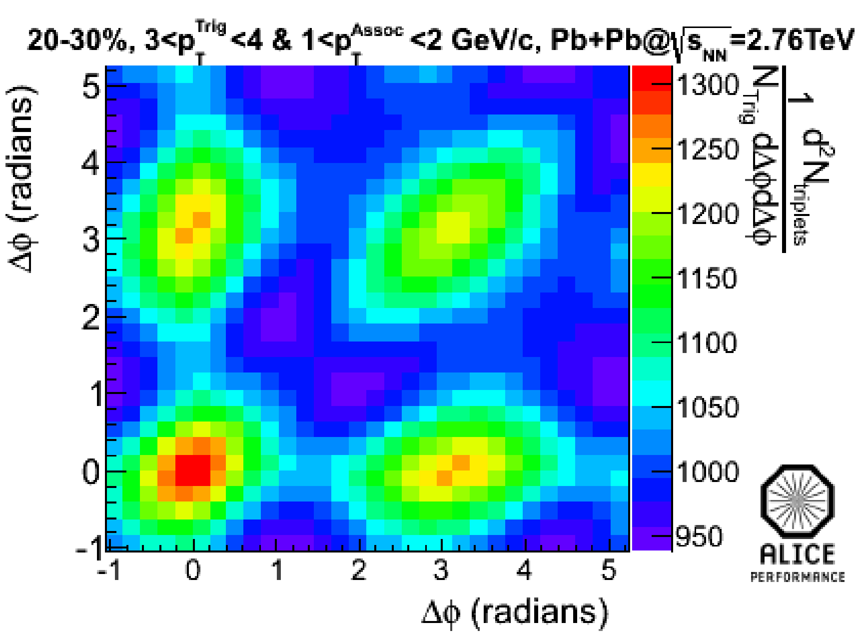
Full correlation (no background subtraction) - centrality evolution:

0-5% most central





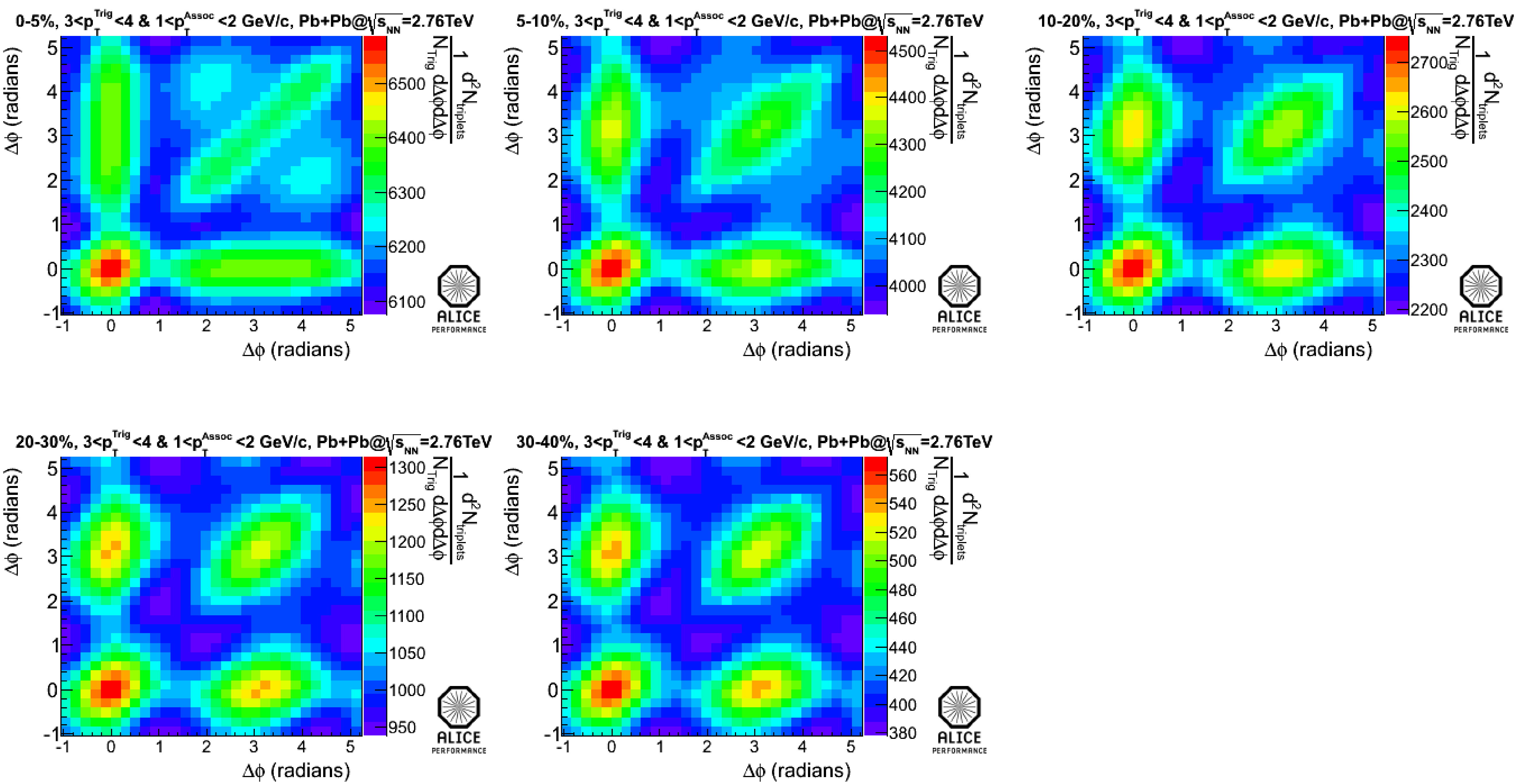




Three-particle angular distributions

Full correlation (no background subtraction) - centrality evolution:

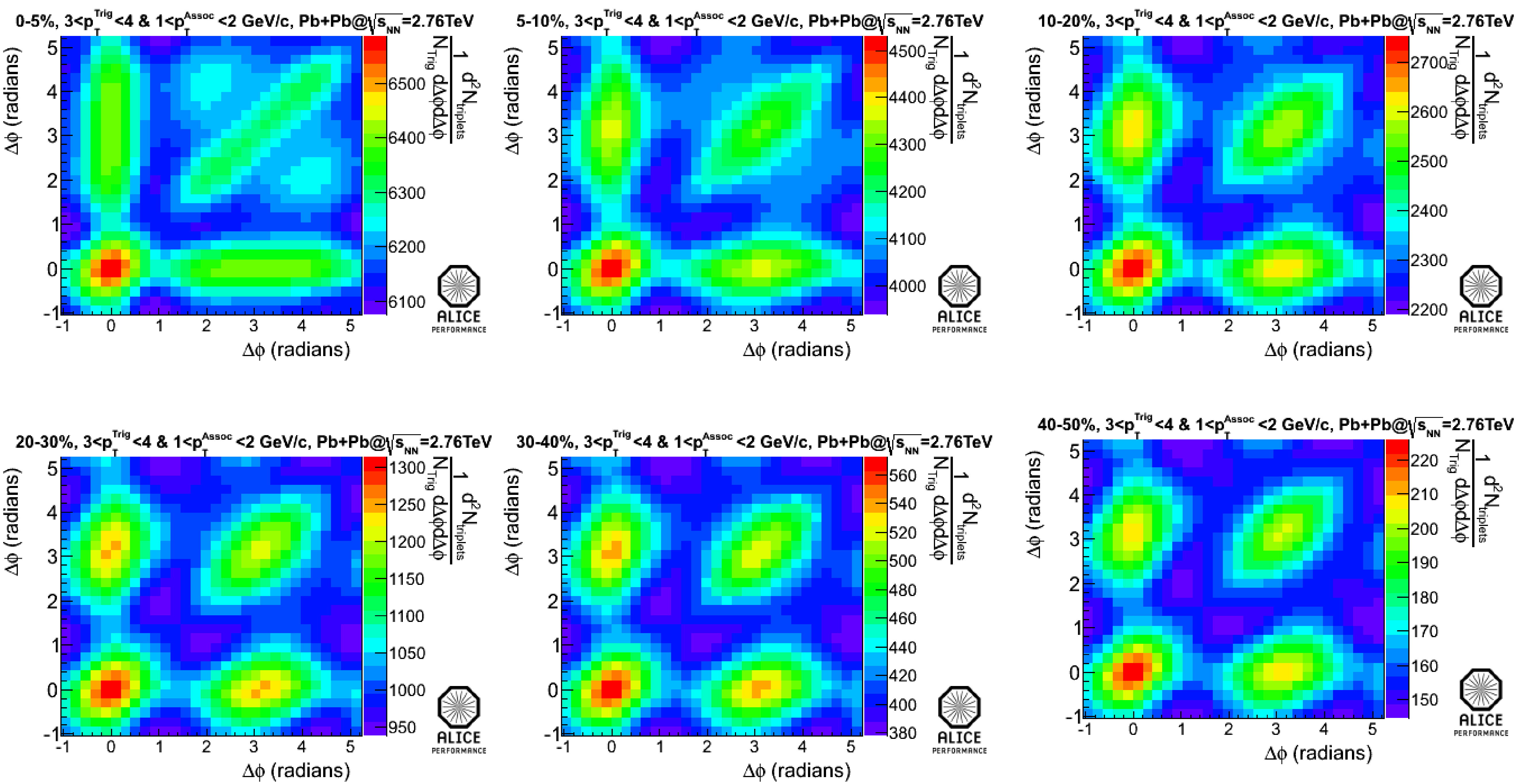
0-5% most central



Three-particle angular distributions

Full correlation (no background subtraction) - centrality evolution:

0-5% most central



40-50% most central

3-particle correlations - flow simulation

Details:

Event by event v2,v3,v4,v5,psi2,psi3,psi4, and psi5 from Glauber model.
Using 3x the v2,v3,v4, and v5 as these are low-pt flow values.
Generate a Poisson number of triggers and associated particles with the flow correlations wrt the corresponding reaction plane. This gives realistic flow fluctuations and correlations between the reaction planes.

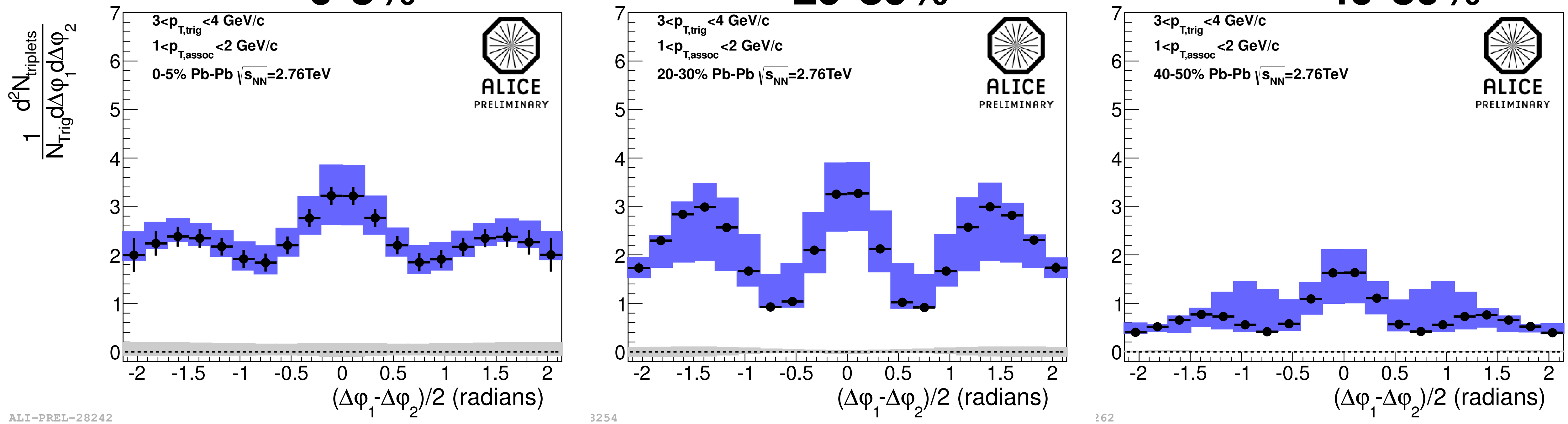
Isolating non-flow signals?

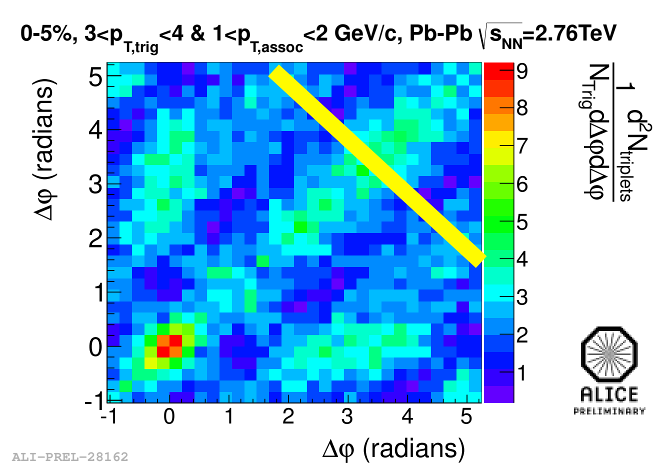
Under the (strong) assumptions:

- Flow and non-flow sources combine additively & are independent
- Nonflow signal is positive definite (zero yield at minimum)
- 3-particle background fully described by combinations of v_2, v_3, and v_4

A nonzero structure remains:

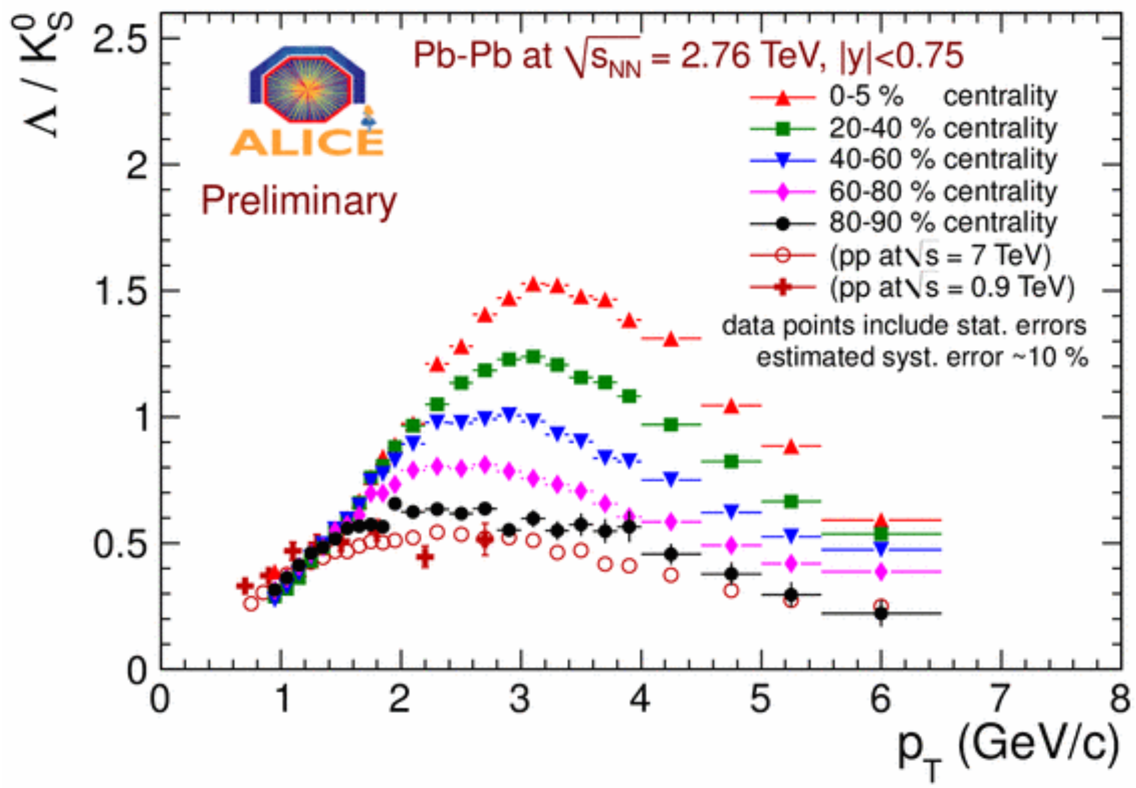
0-5% 20-30% 40-50%





A. Adare (ALICE)

J. Ulery (4B, poster 175)



Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, |y|<0.75
ALICE
Preliminary
0-5 % centrality
20-40 % centrality
40-60 % centrality
60-80 % centrality
80-90 % centrality
(pp at $\sqrt{s}$ = 7 TeV)
(pp at $\sqrt{s}$ = 0.9 TeV)
data points include stat. errors
estimated syst. error ~10 %
Λ / K^0_S
p_T (GeV/c)