# Differential Transverse Momentum Correlations in p-Pb and Pb-Pb in ALICE

Sept. 21-28, Las Negras, Spain

Prabhat R. Pujahari,
for the ALICE Collaboration

WAYNE STATE UNIVERSITY

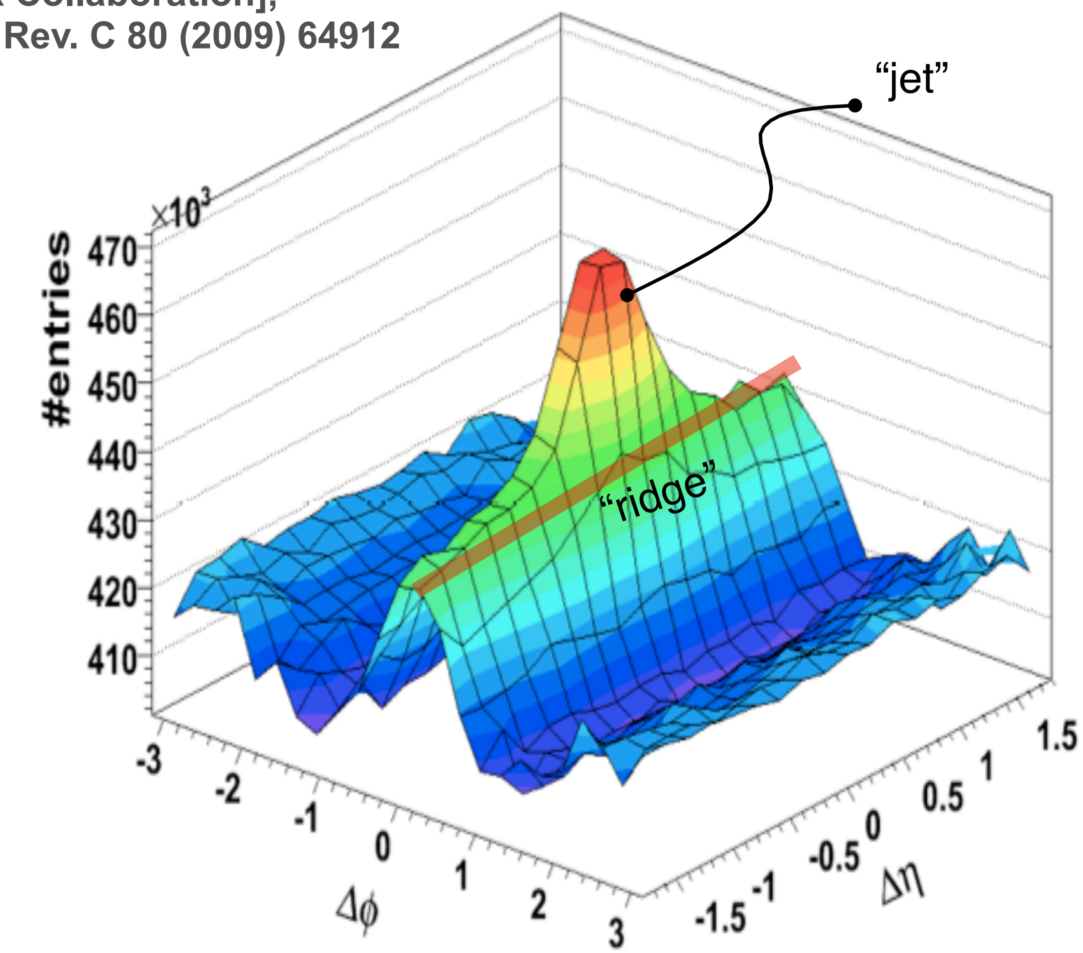
# Outline

- Introduction to 2-particle correlation features
  Near and away-side $(\Delta\eta, \Delta\varphi)$ correlation
- Observables
  Number ("old") and transverse momentum correlation ("new")
- Physics motivation
  Gain additional information on underlying particle production mechanisms
- Results (p-Pb vs. Pb-Pb systems)
  Correlation functions and Fourier decompositions
- Summary

# The "old" RHIC puzzle

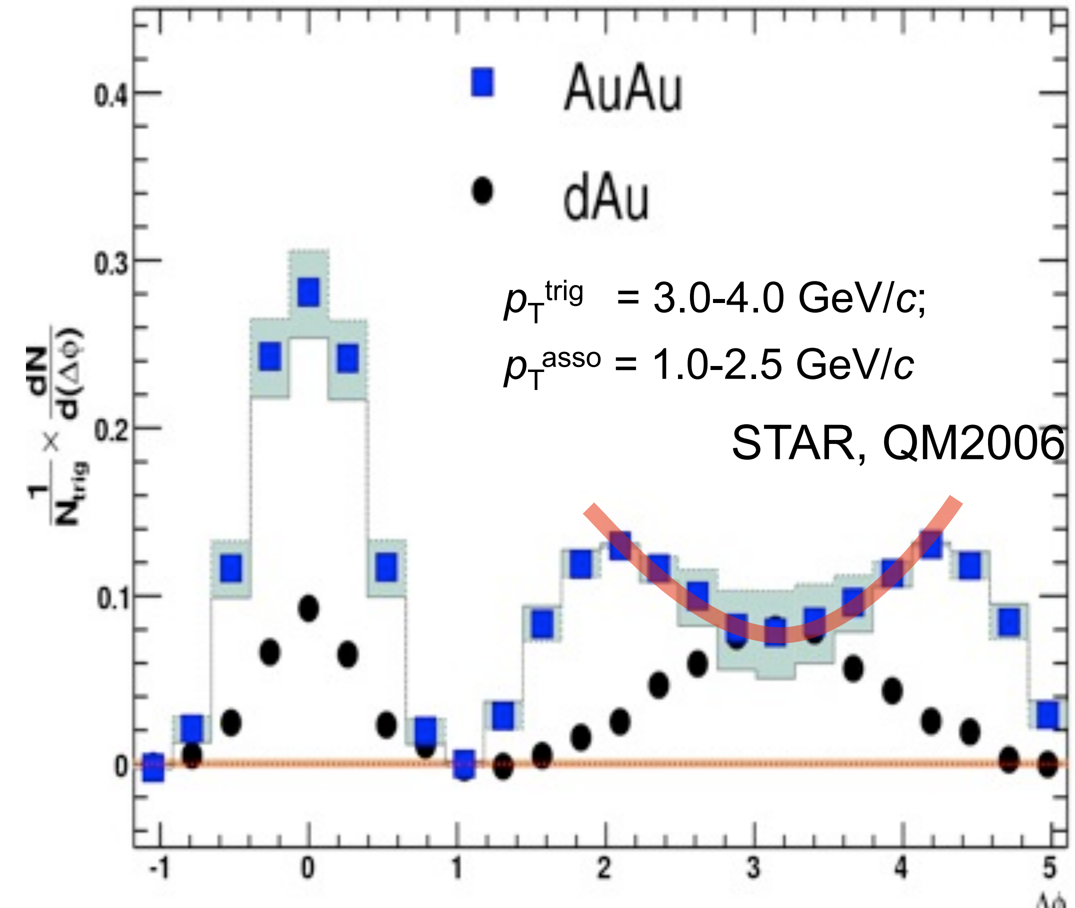
## "The Ridge"

[STAR Collaboration], Phys. Rev. C 80 (2009) 64912




## "The Valley"

Phys. Rev. Lett. 102, 052302




"With elliptic flow ($v_2$) only subtracted"

Au-Au collisions exhibits a long range rapidity correlation called the ridge - not seen in pp (at the same collision energy)

"The valley", double bump peak, observed in central Au-Au (2-particle correlation with background subtracted)

# Bigger and better at the LHC

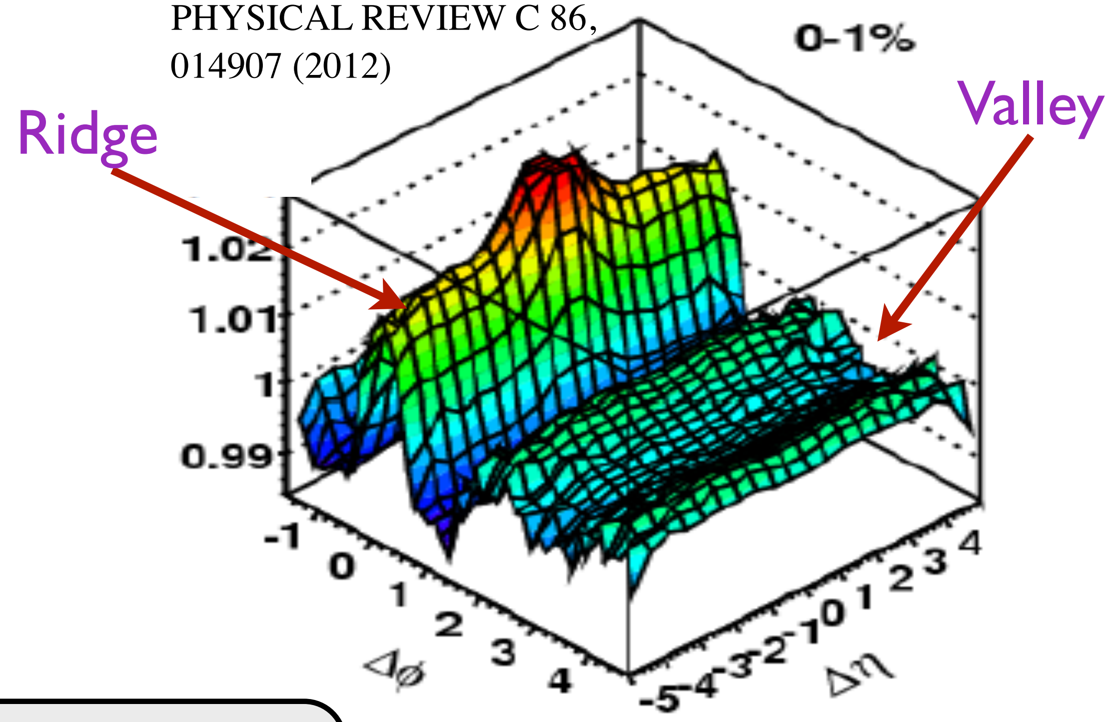
## Physics Processes:

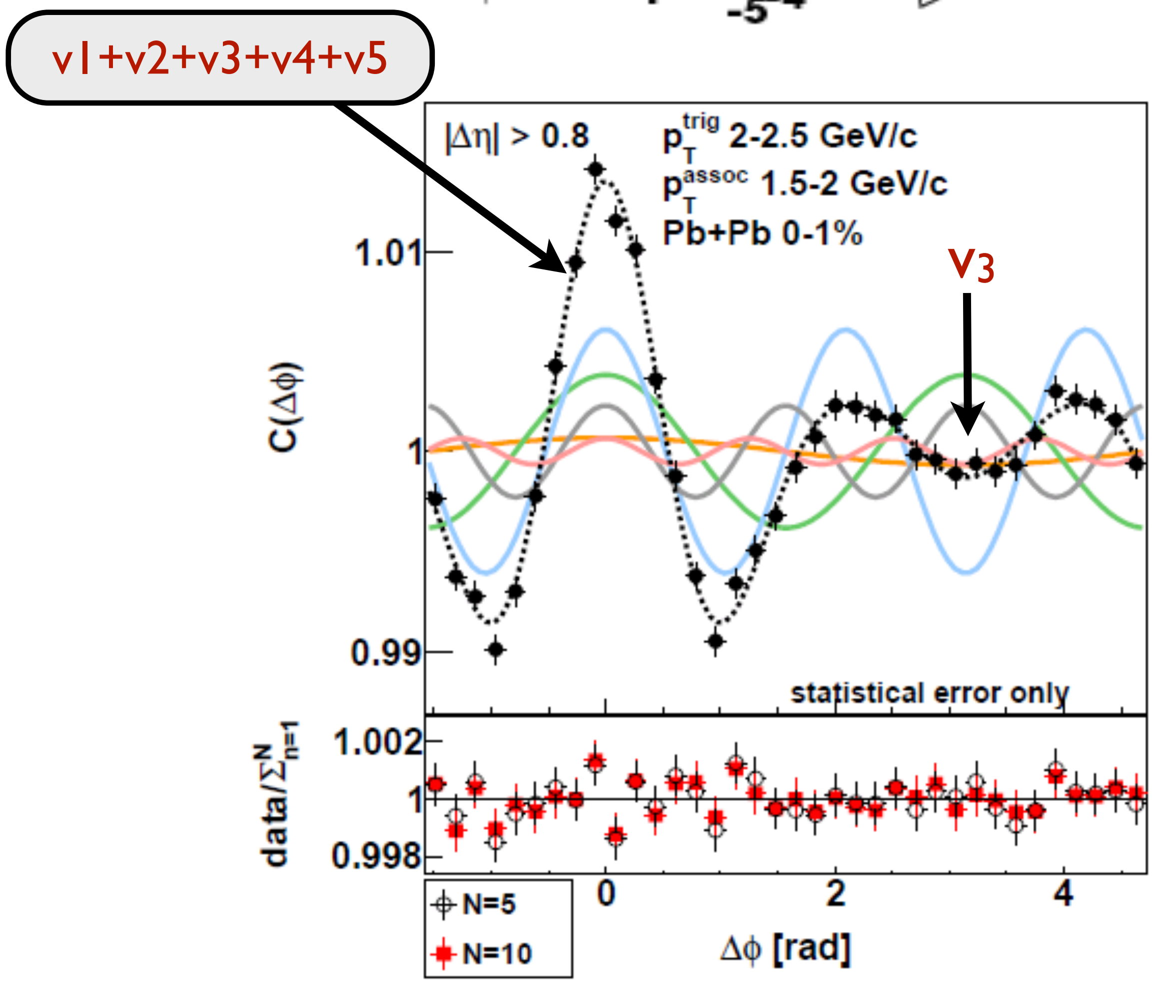
- Lumpy initial conditions also affect in long range rapidity correlations
  - Initial geometry fluctuation leads to even and odd harmonics in particle azimuthal distributions

- Hydrodynamic evolution
  *spatial anisotropy -> momentum anisotropy*

Two Particle Correlation (ATLAS)

PHYSICAL REVIEW C 86, 014907 (2012)



# And many open questions ...

- How large are the higher harmonics?
- Are all harmonics driven by initial geometry?
- Are the amplitudes of the harmonics correlated?
- At what $p_T$ do jets matter?
- Relative contributions of flow and "non-flow"?
- Is the mach cone (really) dead?
- etc, etc

Scope for new correlation observables ...

# 2-particle correlation functions - definitions

Distribution of "correlated pairs"

$$C_2(x_1,x_2) = \rho_2(x_1,x_2) - \rho_1(x_1)\rho_2(x_2) \qquad x \equiv \{y, p_T\} \quad \rho(x) = \frac{1}{\sigma}\frac{d\sigma}{dx}$$

Number correlation function:

$$R_2(x_1,x_2) = \frac{C_2(x_1,x_2)}{\rho_1(x_1)\rho_1(x_2)}$$

$R_2$ is a robust observable;
single track efficiencies cancel out of this ratio

Transverse momentum correlation function:

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

measures deviation from the inclusive average momentum

$$\Delta p_T = p_{T,i} - \langle p_T \rangle$$

$$\langle p_{T,i} \rangle = \frac{\int \rho_1(\mathbf{p_i}) p_{T,i} \ dp_{T,i}}{\int \rho_1(\mathbf{p_i}) \ dp_{T,i}}$$

# Physics motivation I: features of $\Delta p_{\mathrm{T}} \Delta p_{\mathrm{T}}$ correlation

Why $\Delta p_{\mathrm{T}} \Delta p_{\mathrm{T}} (\Delta\eta, \Delta\varphi)$ is interesting ?

- Additional sensitivity to hardness of particles and their correlations (jet vs. non-jet)

- Positive correlation: both particles have $p_{\mathrm{T}}$ either higher or lower than the average $p_{\mathrm{T}}$

- Negative correlation: one particle has a higher $p_{\mathrm{T}}$ than average whereas the associated particle has $p_{\mathrm{T}}$ lower than average

- Integral part of this observable: sensitive to temperature fluctuation, average momentum fluctuation

- Flow factorization (see next slide...)

# Physics motivation II: factorization

- Factorization expected when correlations driven by geometry only

$$V_{n\Delta}(p_1, p_2) = v_n(p_1)v_n(p_2)$$

- Factorization expected to break down when jet and geometry have similar contributions

Geometrical flow model

Sharma and Pruneau, Phys Rev C, 79, 024905, 2009

Factorization for $\Delta p_{\rm T} \Delta p_{\rm T}$

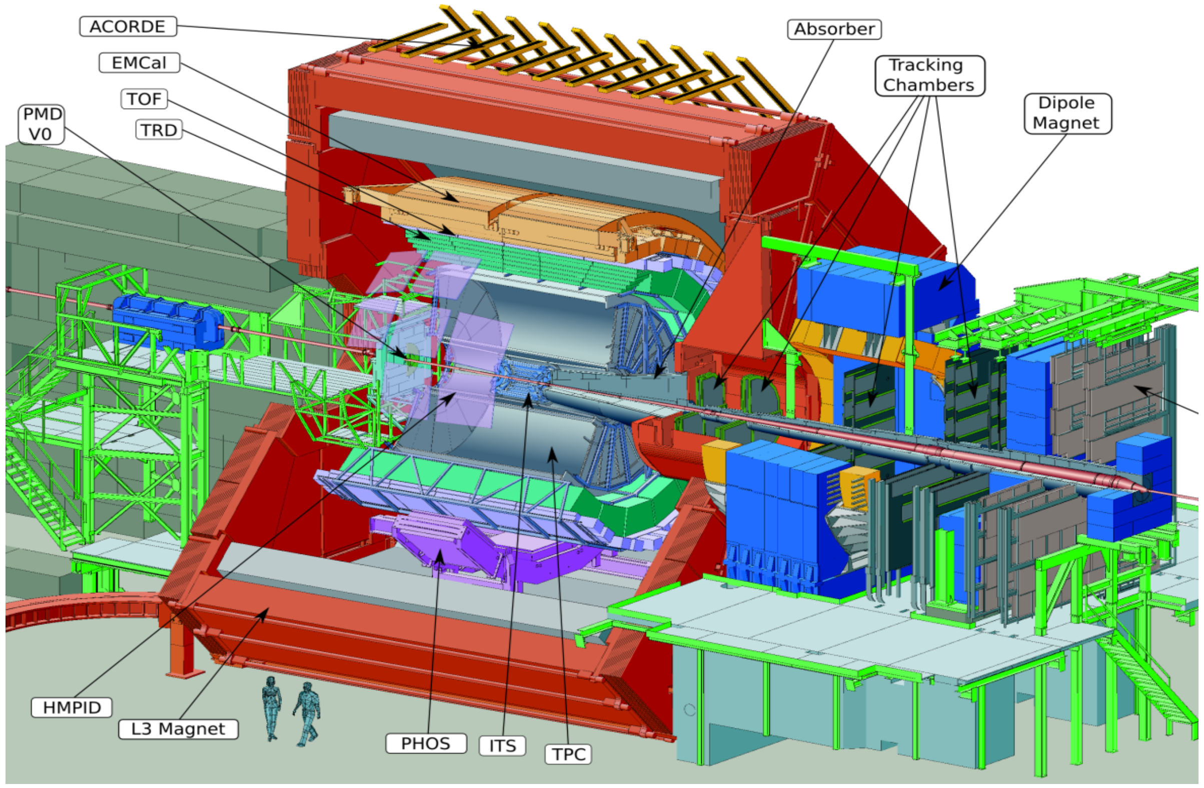
$$\Delta p_{\rm T} \Delta p_{\rm T}(\Delta\varphi) = \frac{2\sum_n \left(v_n^{p_1} - \langle p_{\rm T}\rangle v_n^1\right)\left(v_n^{p_2} - \langle p_{\rm T}\rangle v_n^2\right)}{1 + 2\sum_n v_n^1 v_n^2 cos(n\Delta\varphi)}$$

used later as: Eq. 2

Consequence:

FDC of $\Delta p_{\rm T} \Delta p_{\rm T}$ at large $\Delta\eta$ should scale with flow coefficients

# Experimental setup and methodology




TPC: gas drift detector
ITS: Silicon detector → *charged particles*

The centrality is selected using the magnitude of the VZERO (V0) signal (~ multiplicity)

- kinematic selection

$$|\eta| < 1.0, \ 0 < \varphi < 2\pi$$

$$0.2 < p_{\mathrm{T}} < 2.0 \ \mathrm{GeV}/c$$

- 4 different charge combinations: (+ -), (- +), (+ +), and (- -)
- Results for different charge combinations combined into charge independent (CI)

$$CI = \frac{1}{2}\{LS + US\}$$

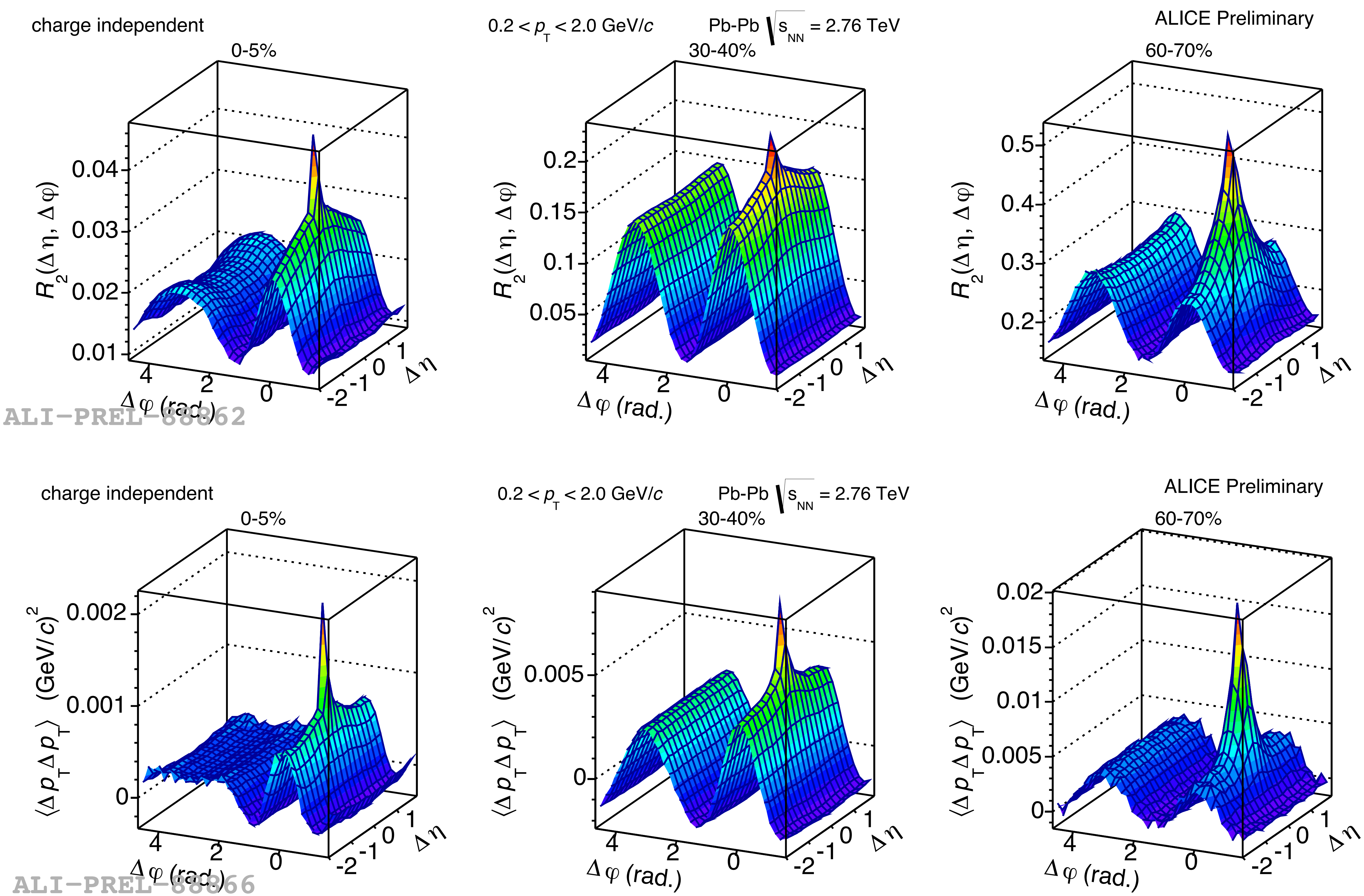
$$LS = \frac{1}{2}\{(++) + (--)\}$$

$$US = \frac{1}{2}\{(+-) + (-+)\}$$

# Correlation functions in Pb-Pb

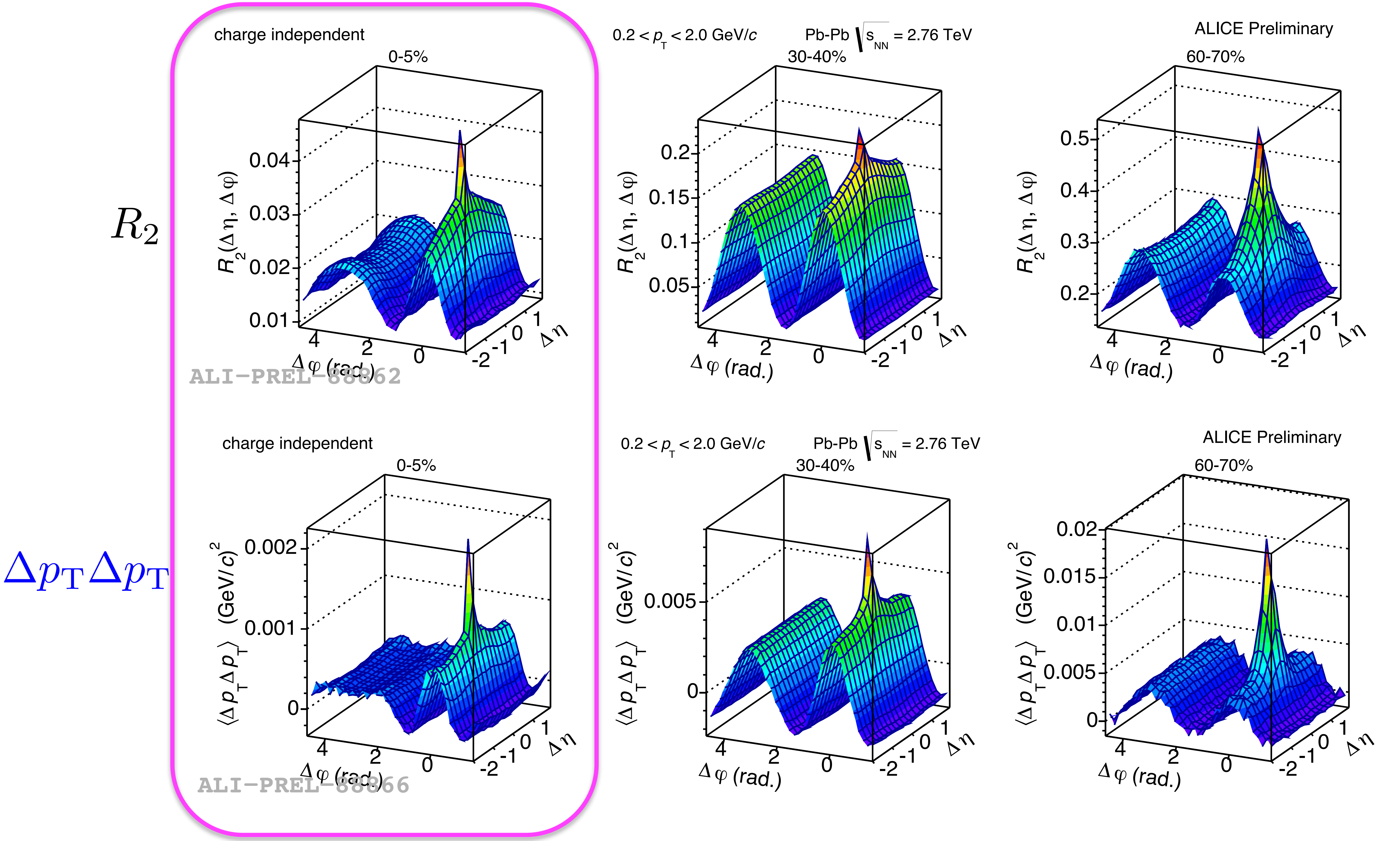
$R_2$

$\Delta p_T \Delta p_T$




- Away-side ‘double bump’ in most central collision for $\Delta p_T \Delta p_T$

# Correlation functions in Pb-Pb

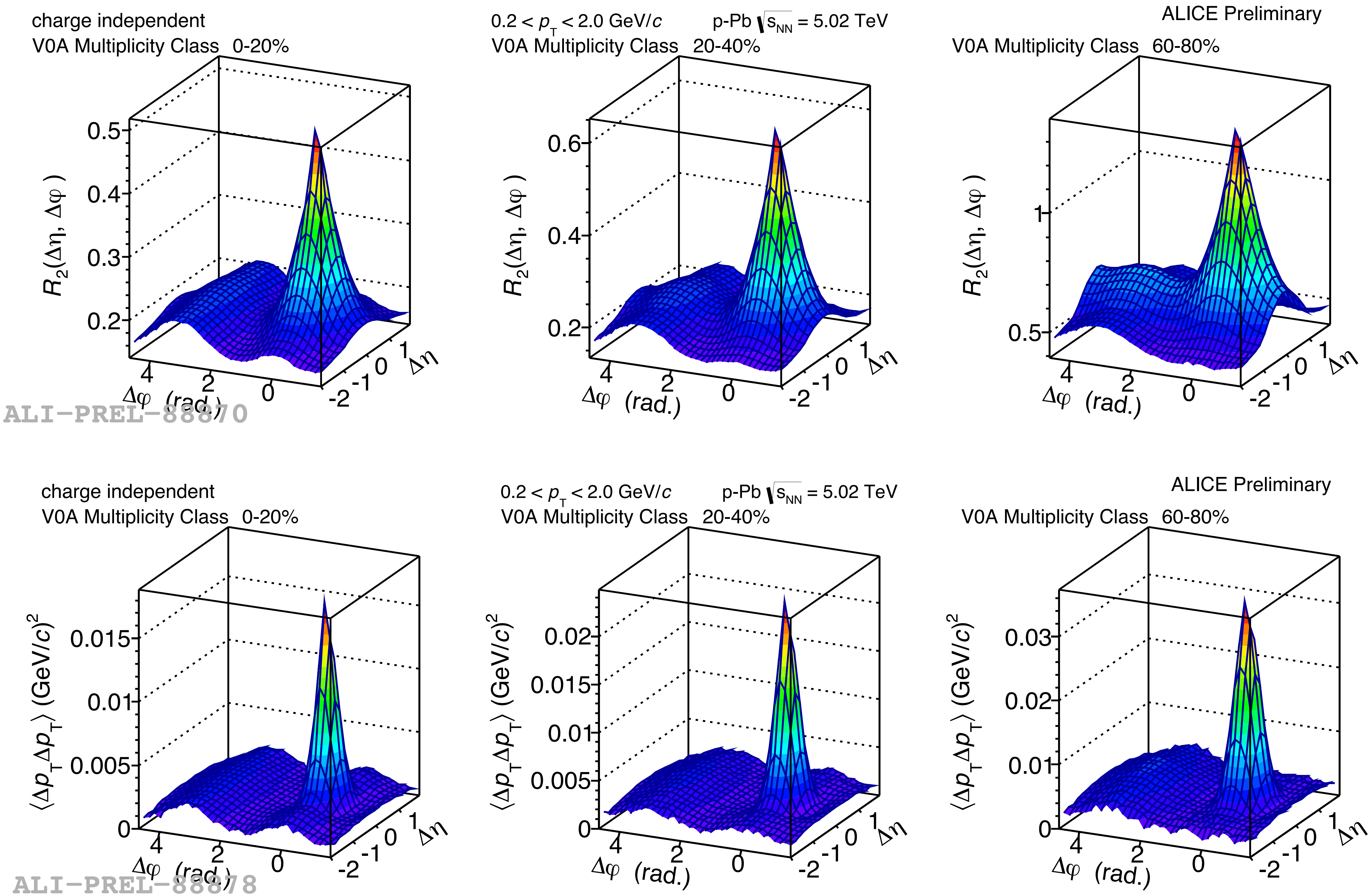



- Away-side 'double bump' in most central collision for $\Delta p_T \Delta p_T$

# correlation functions in p-Pb

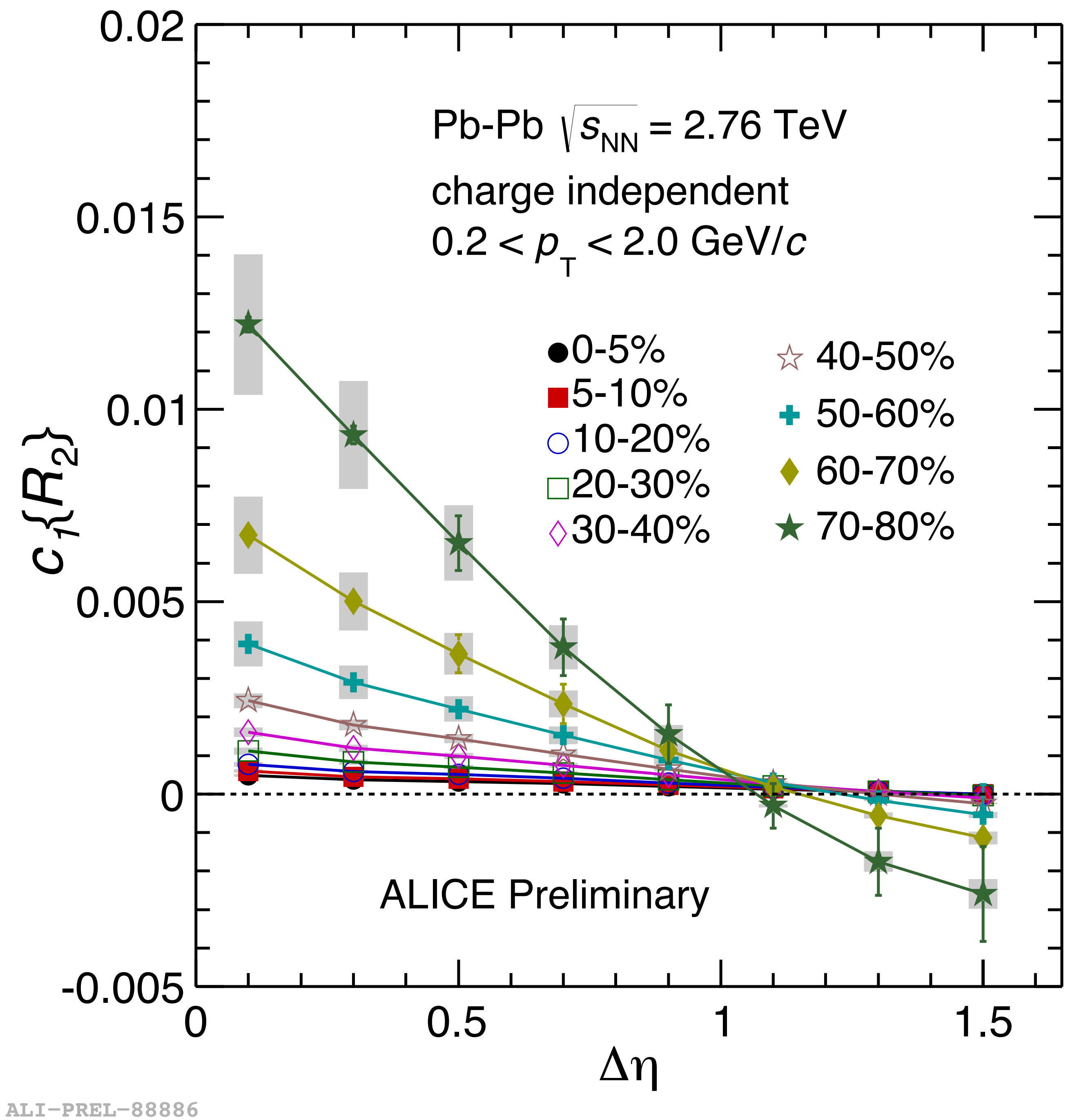
$R_2$

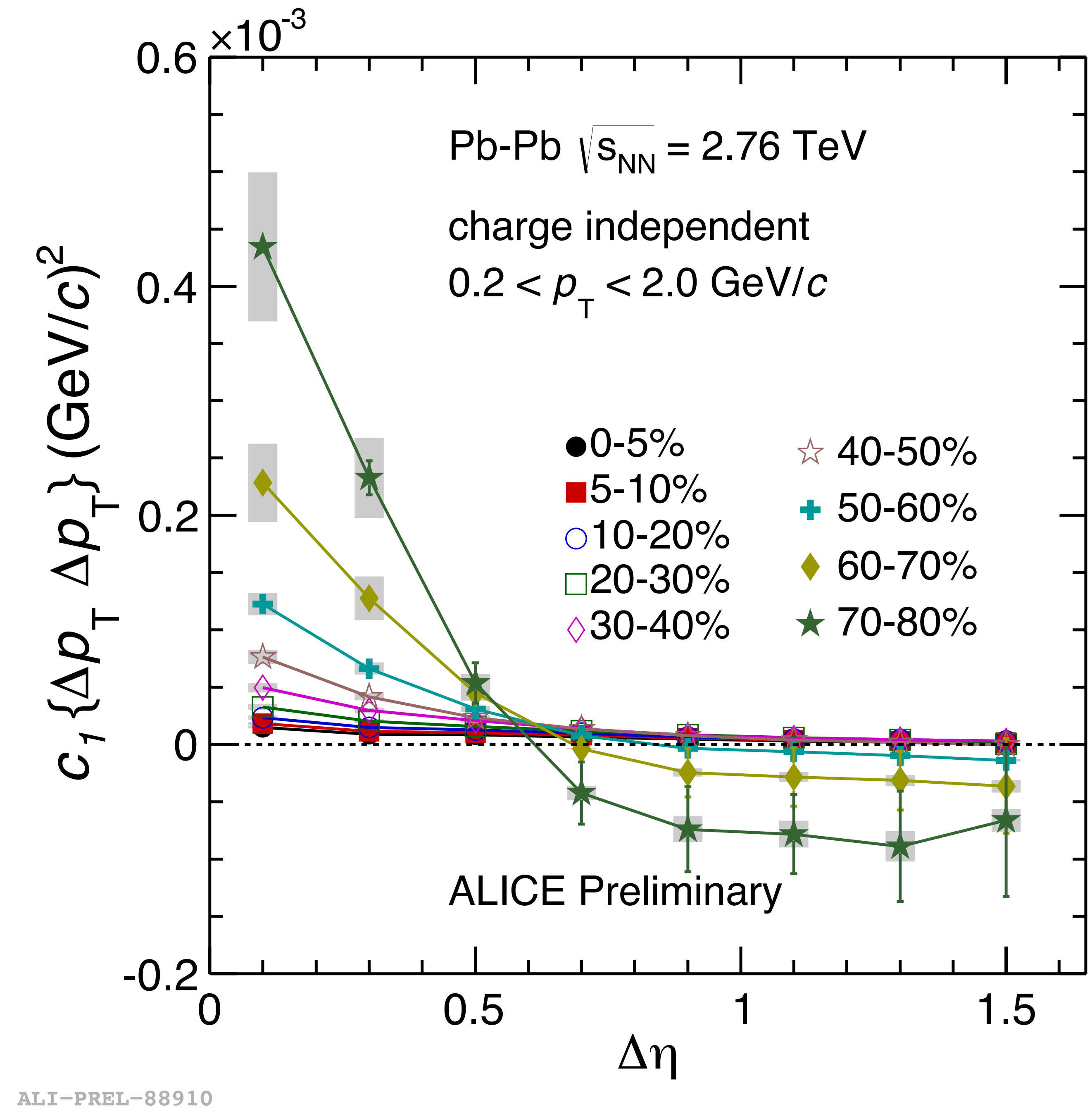
$\Delta p_T \Delta p_T$




- Diminishing $cos(\Delta\varphi)$ modulations
- Narrower near side peak in $\Delta p_T \Delta p_T$

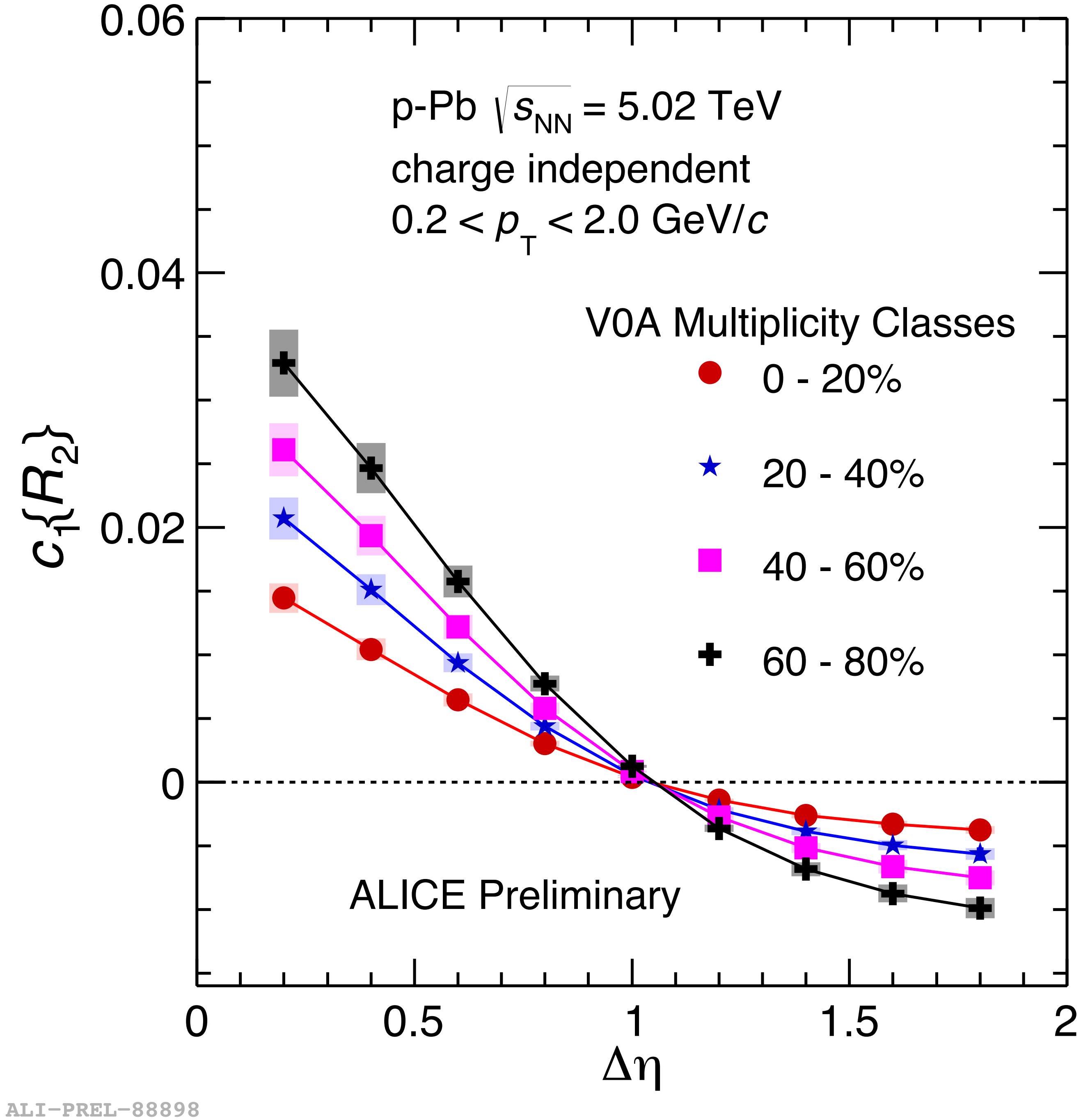
# Harmonic coefficient ( $c_1$ ) in Pb-Pb

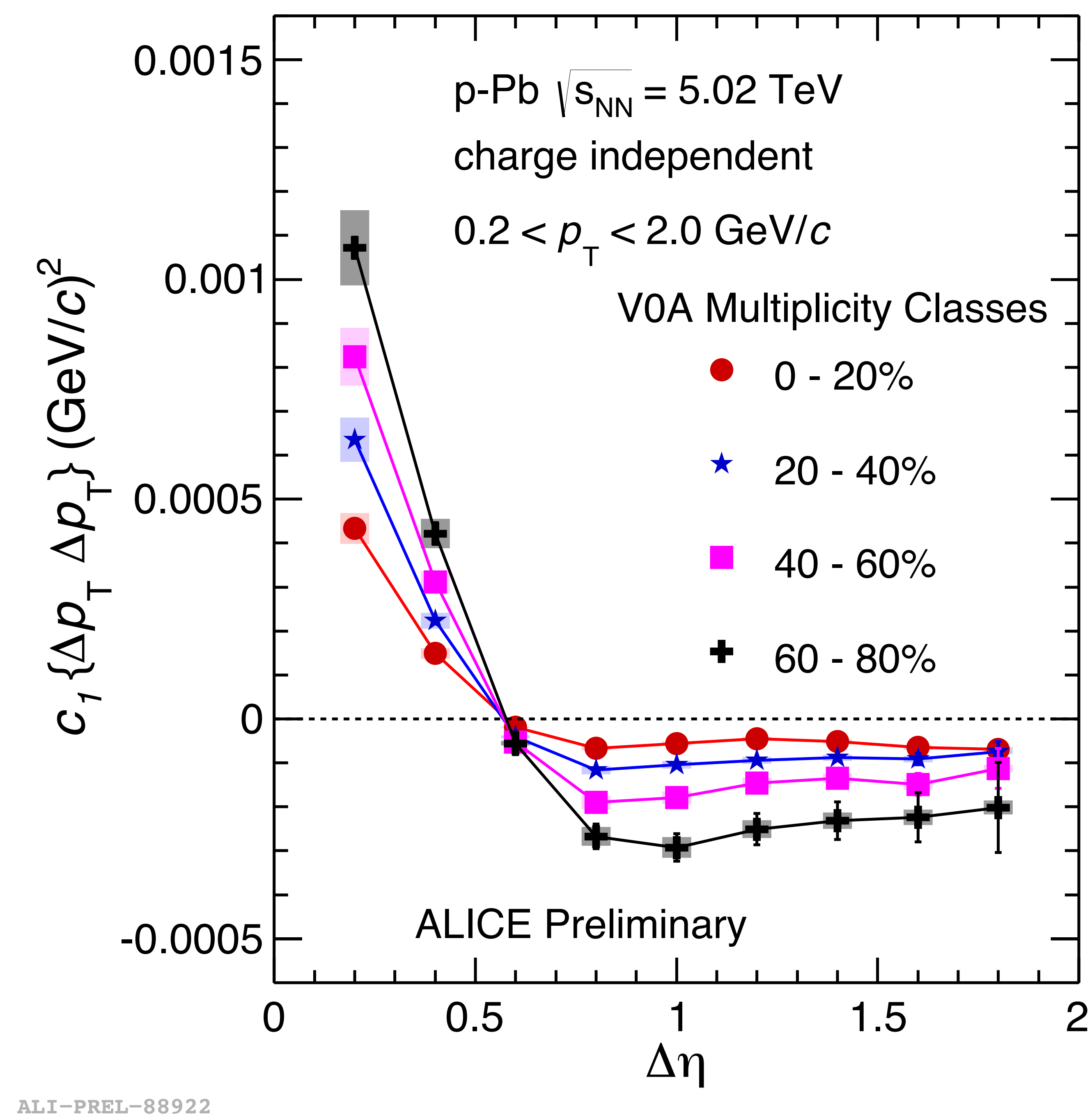



- $\Delta p_T \Delta p_T$ changes sign at lower $\Delta\eta$ than $R_2$

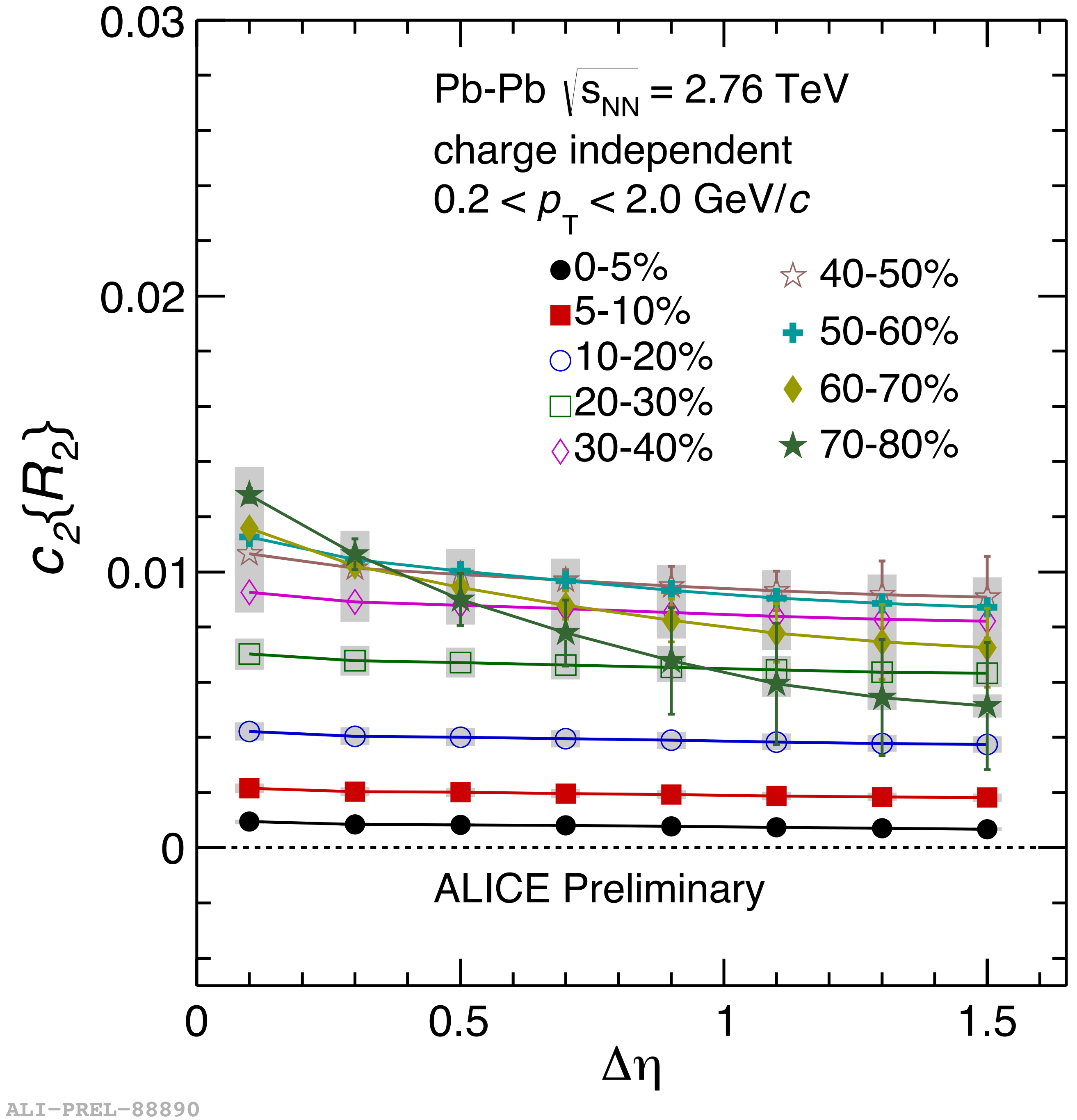
# Harmonic coefficient ( $c_1$ ) in p-Pb

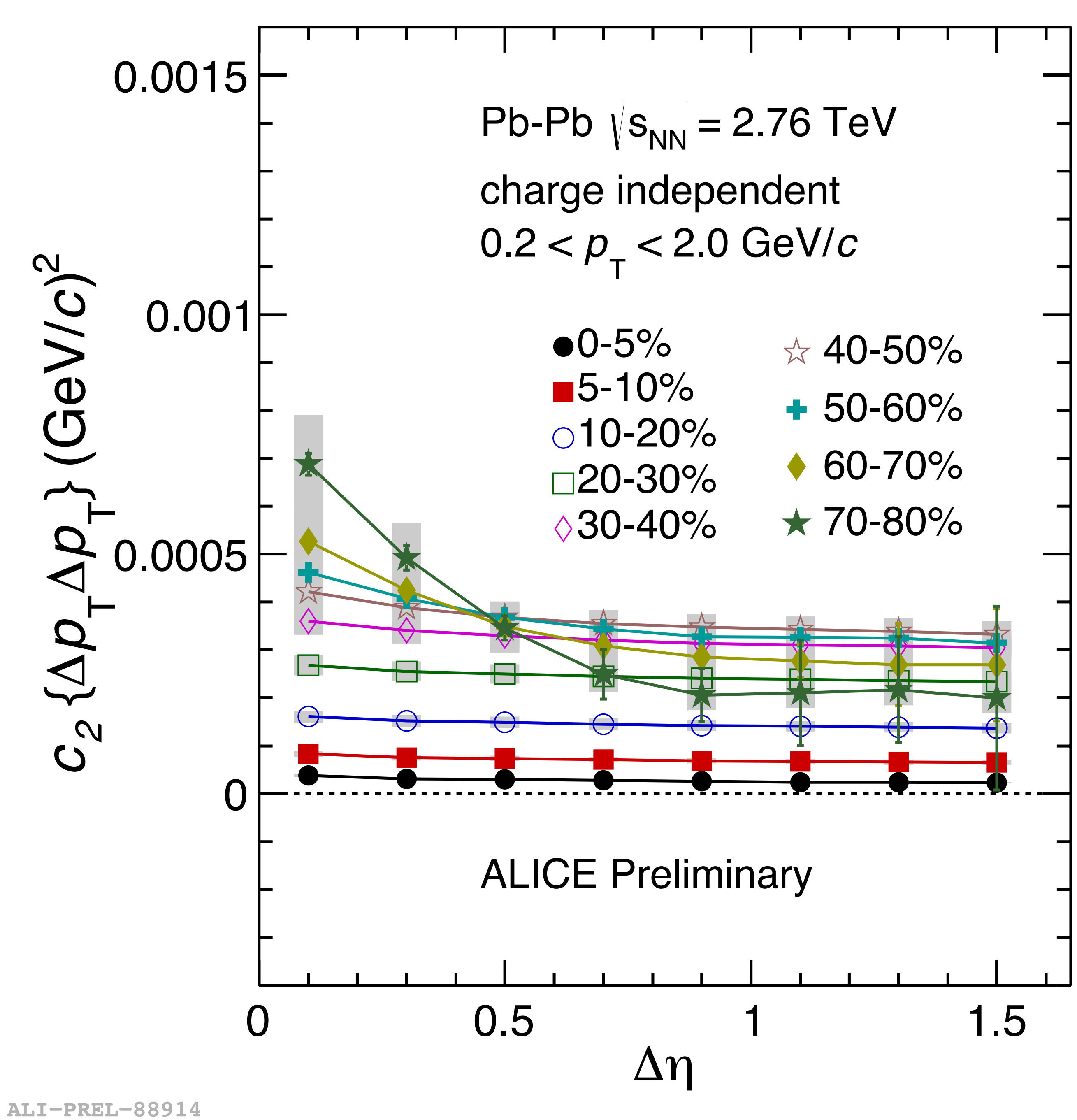



$R_2$ :'longer' range correlation
$\Delta p_T \Delta p_T$ :'shorter' range correlation

# Harmonic coefficient ( $c_2$ ) in Pb-Pb

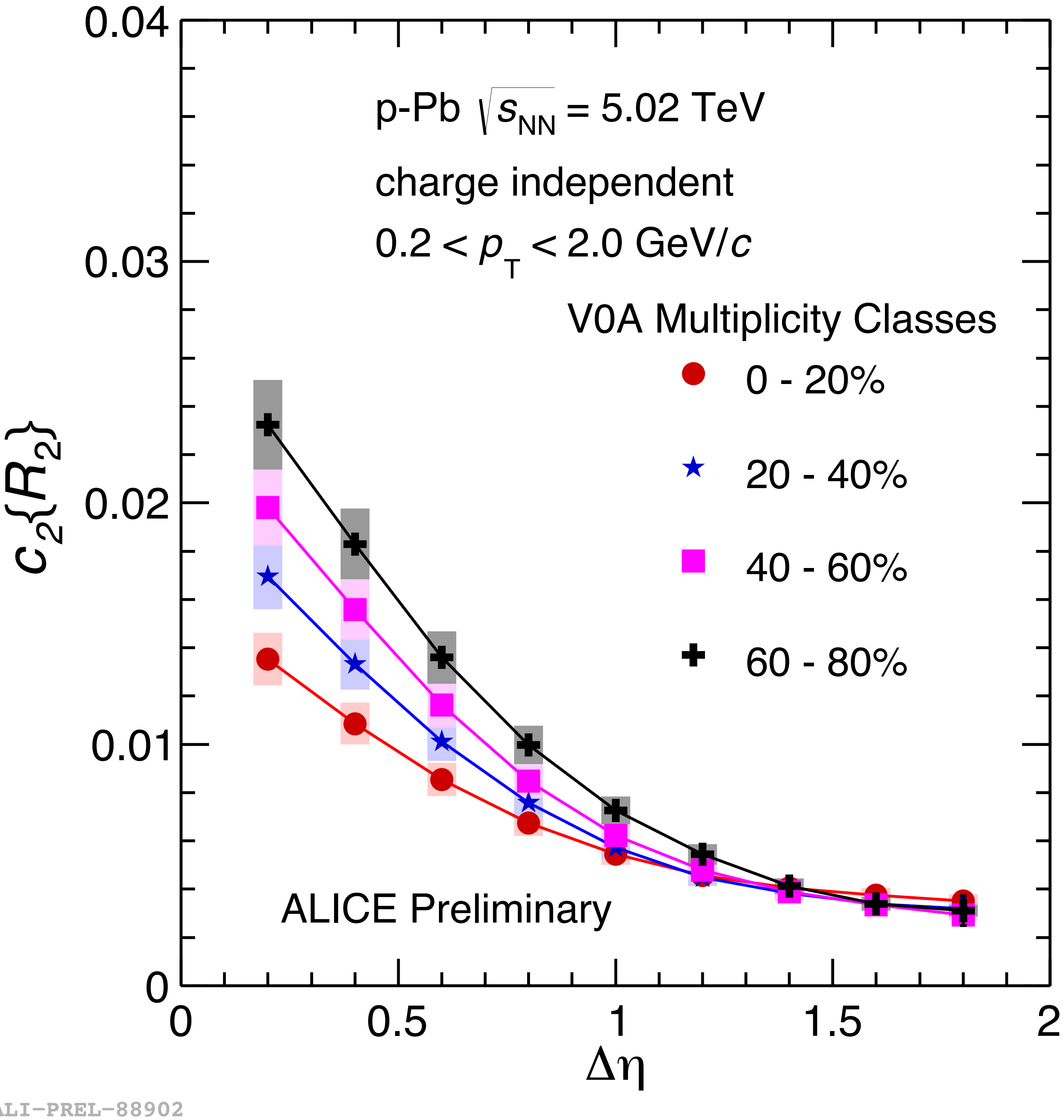


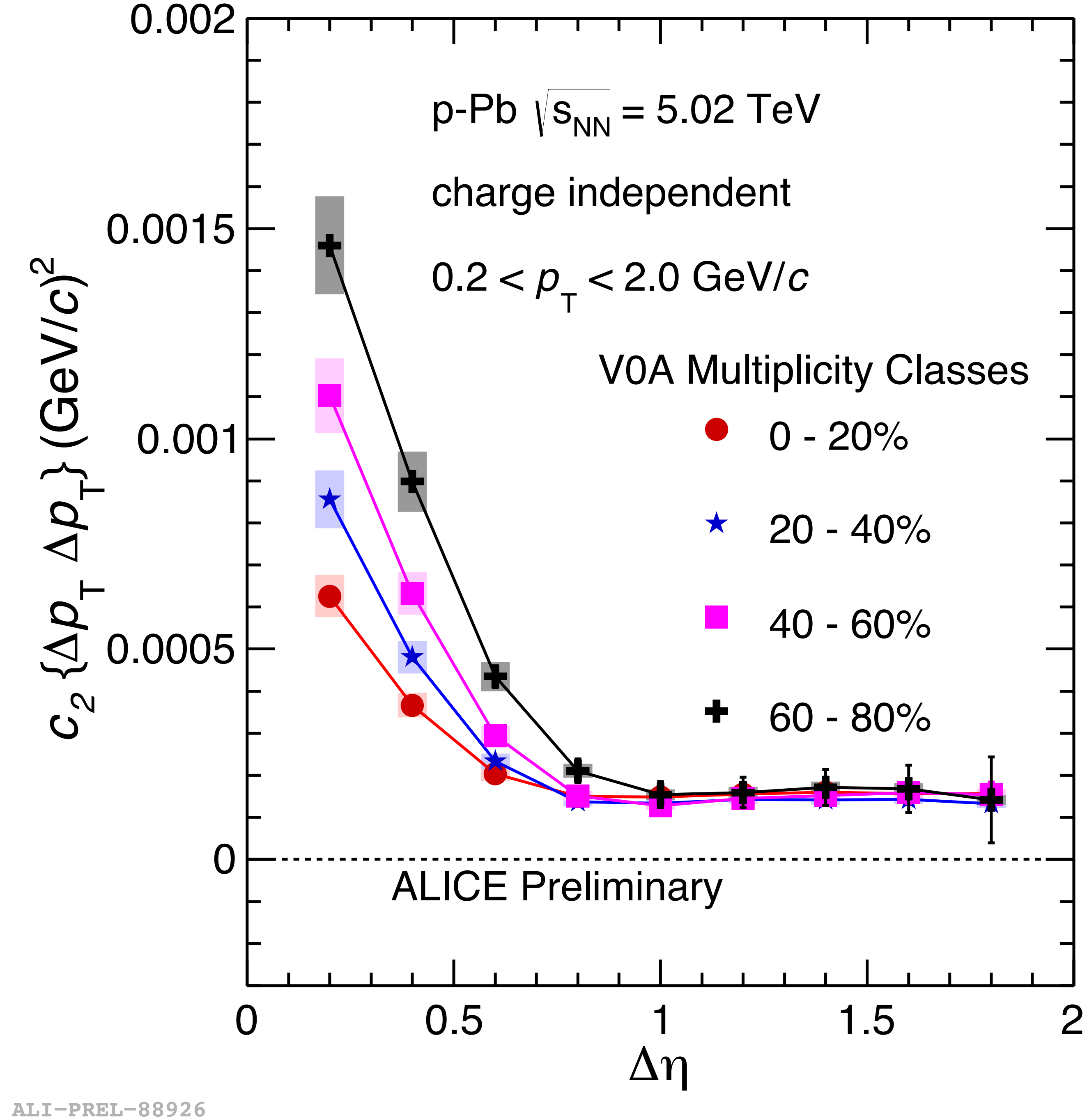




- Independent of $\Delta\eta$ for 0-60% centrality for $R_2$ and $\Delta p_T \Delta p_T$
- Centrality dependent of $c_2$

(increases with decreasing centrality for 0-60%)

# Harmonic coefficient ($c_2$) in p-Pb

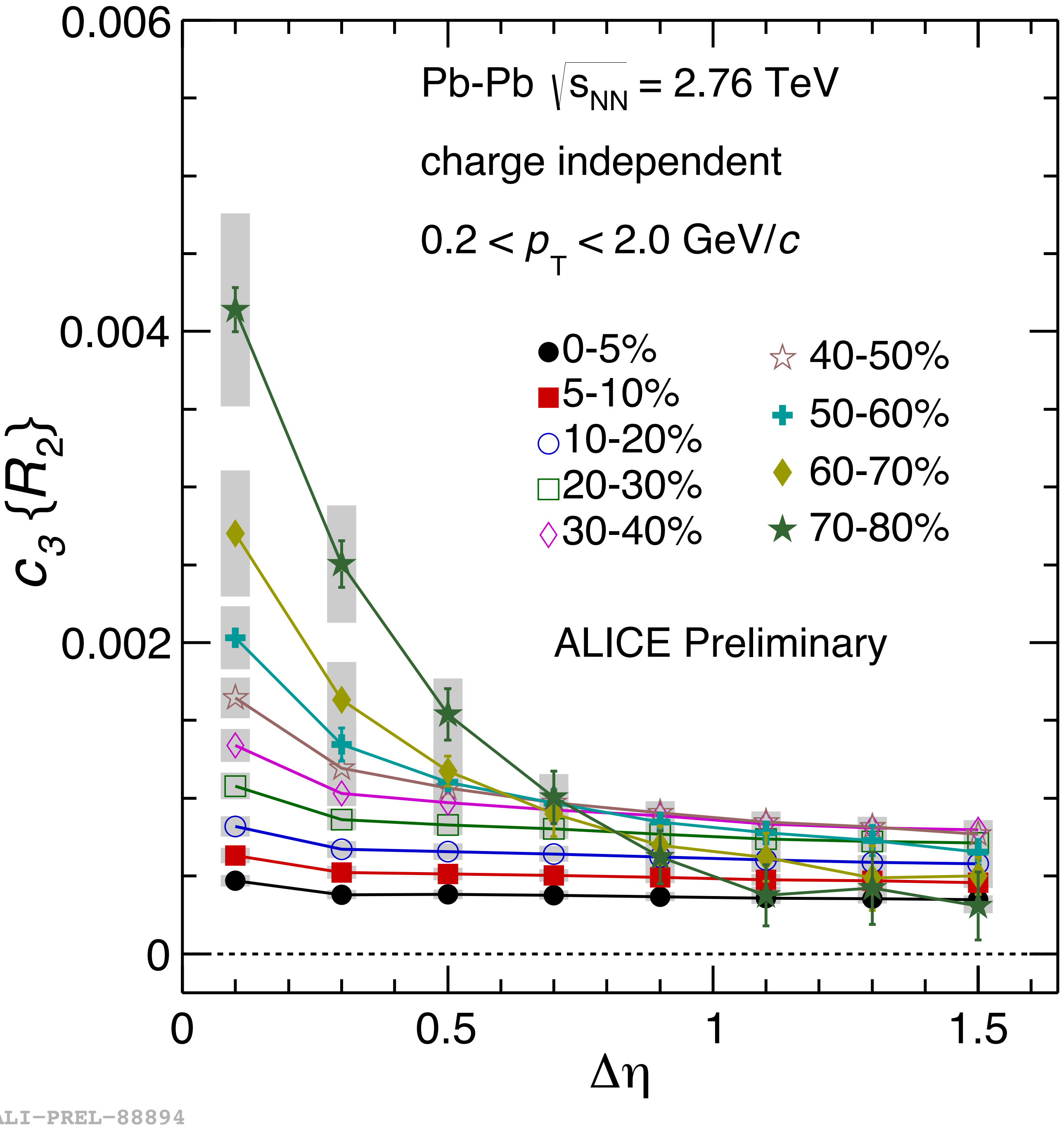


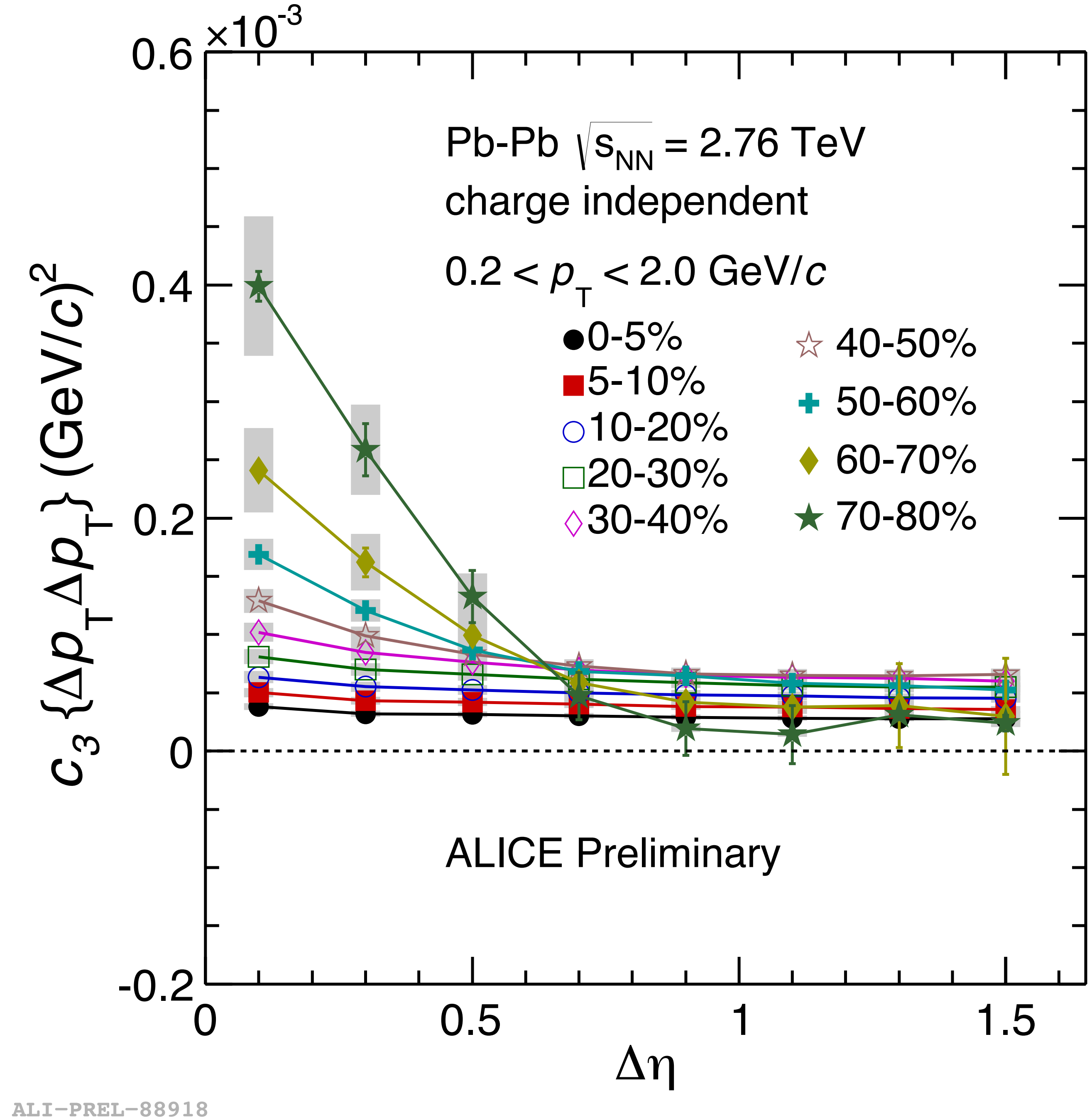




$c_2\{\Delta p_\mathrm{T} \Delta p_\mathrm{T}\}$ saturates at smaller $\Delta\eta$ than $c_2\{R_2\}$

For $c_2\{\Delta p_\mathrm{T} \Delta p_\mathrm{T}\}$ all 4 centralities merge at $\Delta\eta \geq 1.0$

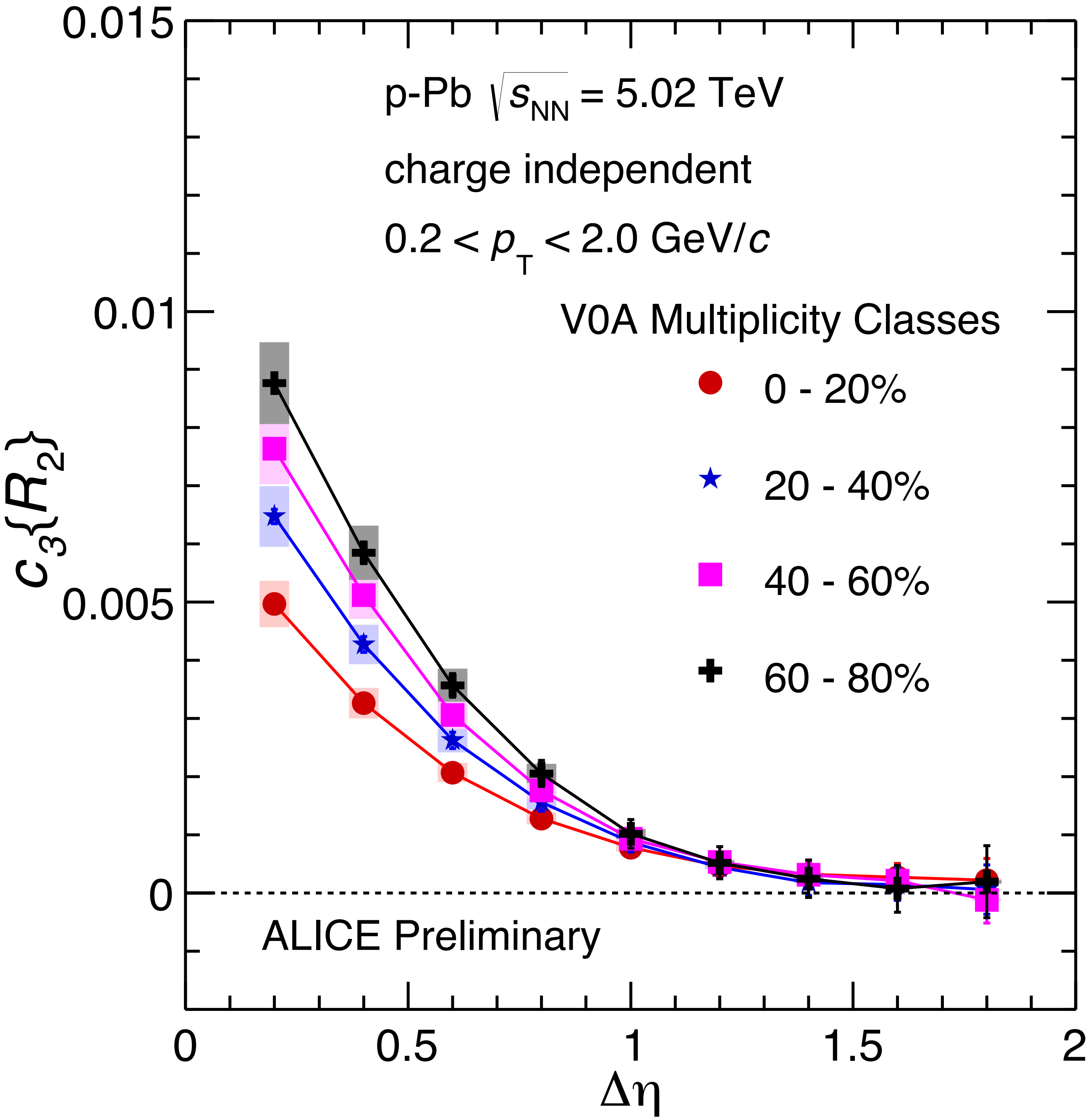
# Harmonic coefficient ( $c_3$ ) in Pb-Pb

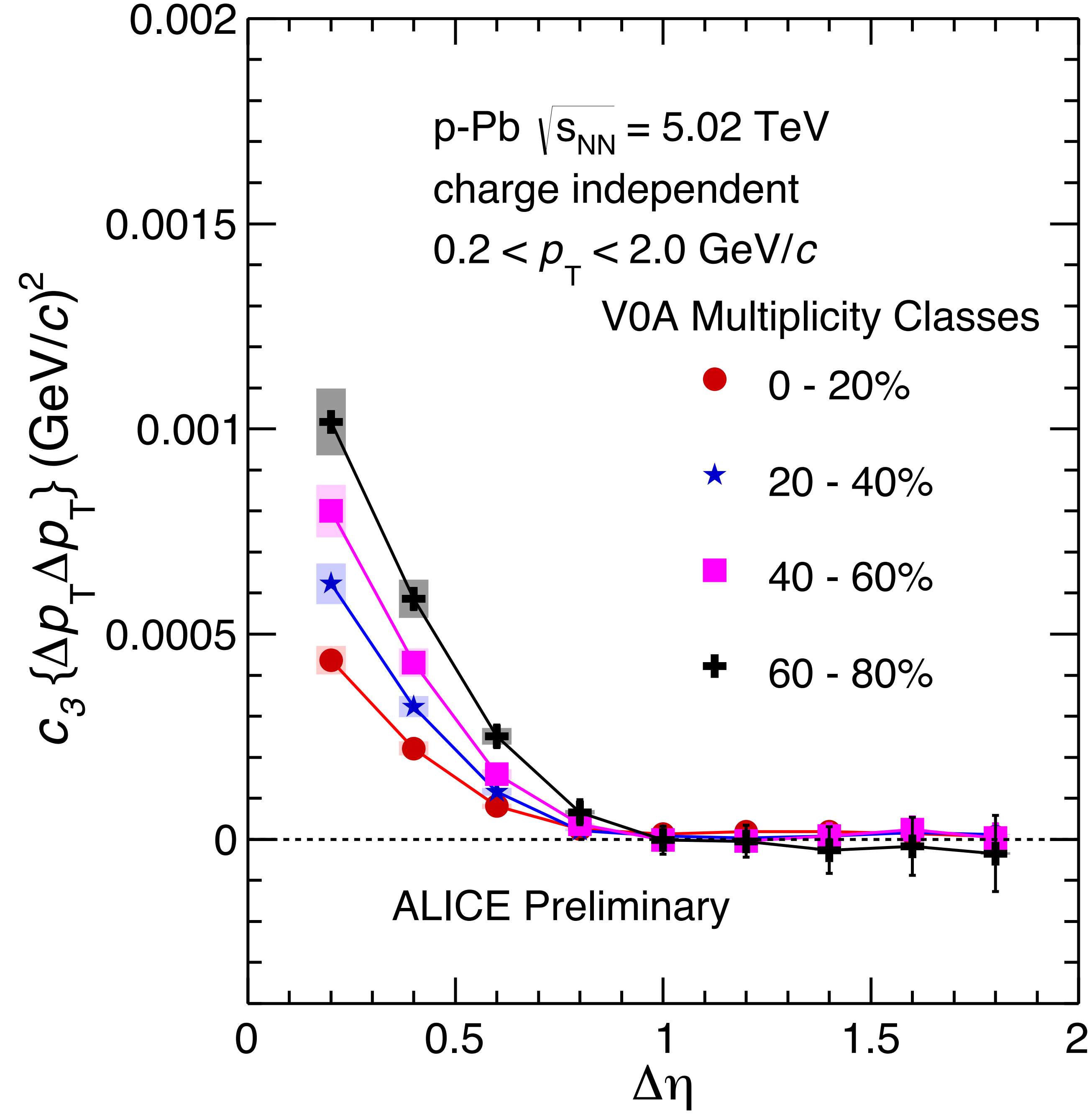



- Independent of $\Delta\eta$ for 0-60% centrality at $\Delta\eta > 0.5$

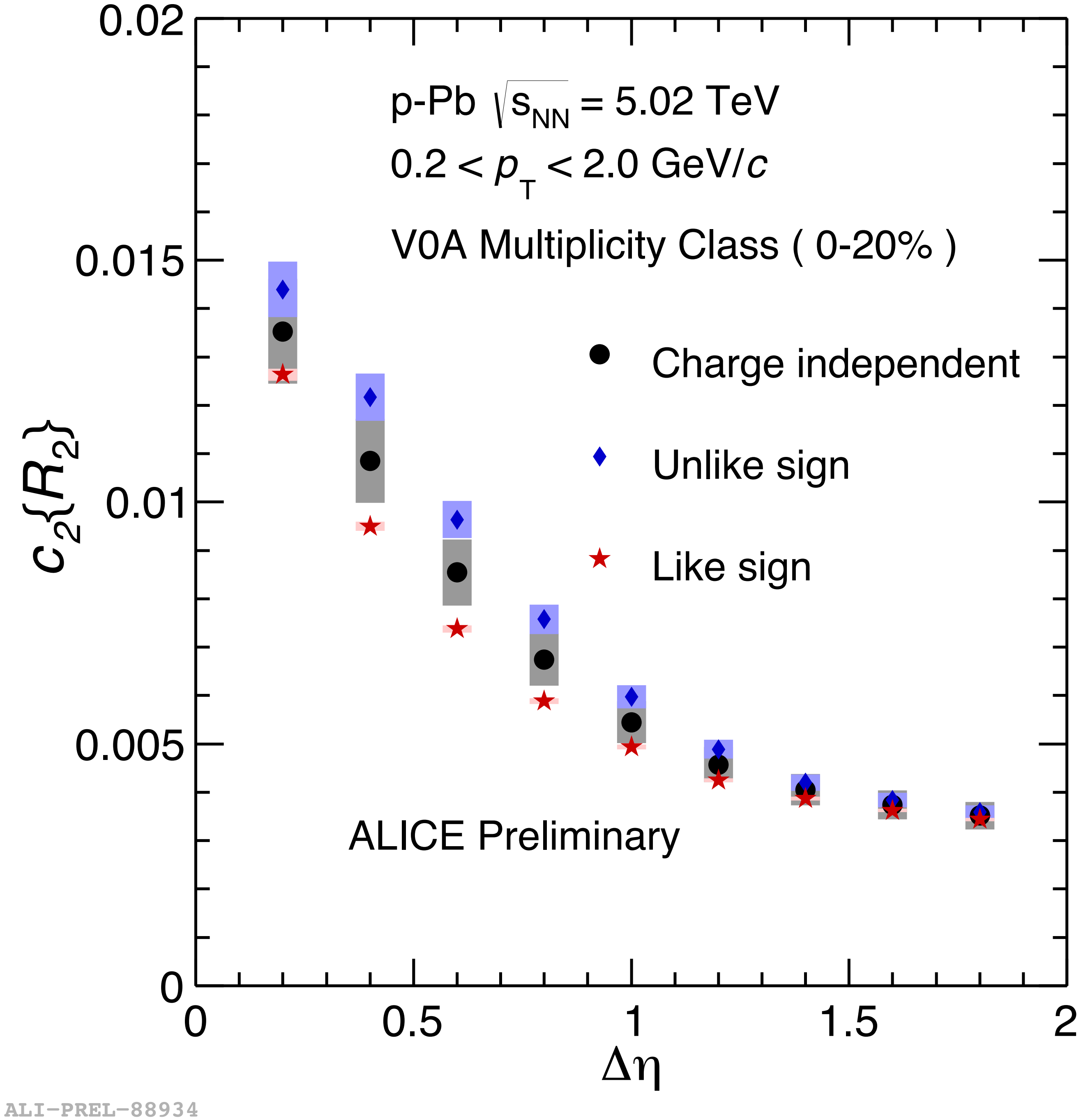
# Harmonic coefficient ($c_3$ ) in p-Pb

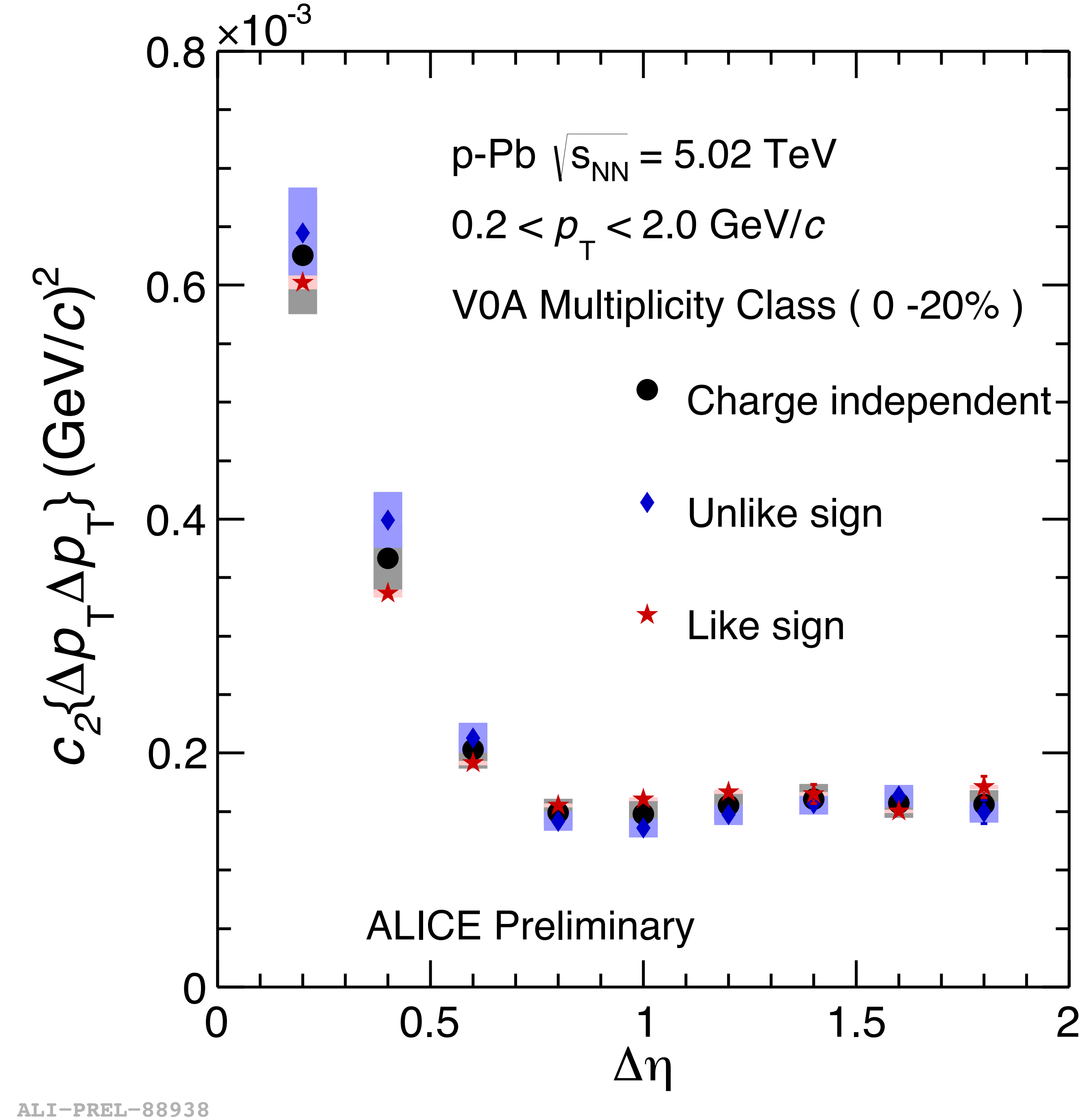



- $c_3\{\Delta p_\mathrm{T} \Delta p_\mathrm{T}\}$ saturates and consistent with 'zero' at $\Delta\eta \geq 1.0$

# Like sign vs. unlike sign ($c_2$) in p-Pb




- US > LS at low $\Delta\eta$
  - Contributions from charge conservation and resonances
- US and LS merge at large $\Delta\eta$
  - Earlier in $c_2\{\Delta p_T \Delta p_T\}$

# What do we lean from the new observable $\Delta p_{\mathrm{T}} \Delta p_{\mathrm{T}}$ ?

**Two component model**

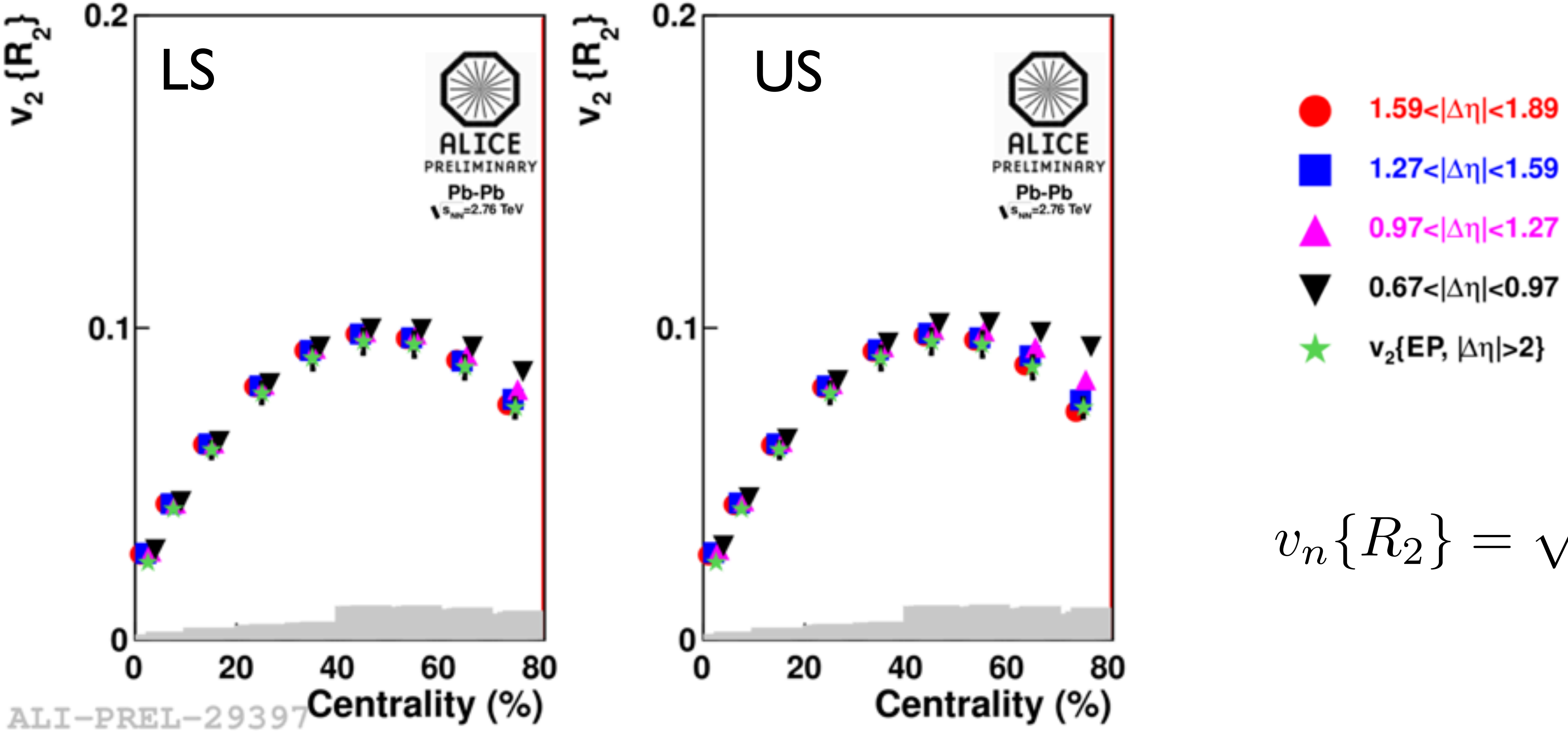
Assuming correlation can be split into two sources

Short range

Long range

- The saturation of $\Delta p_{\mathrm{T}} \Delta p_{\mathrm{T}}$ at smaller $\Delta\eta$ than $R_2$ might be an indication that this observable has a "shorter" range correlation
- Is $\Delta p_{\mathrm{T}} \Delta p_{\mathrm{T}}$ =0 for long range correlation ?

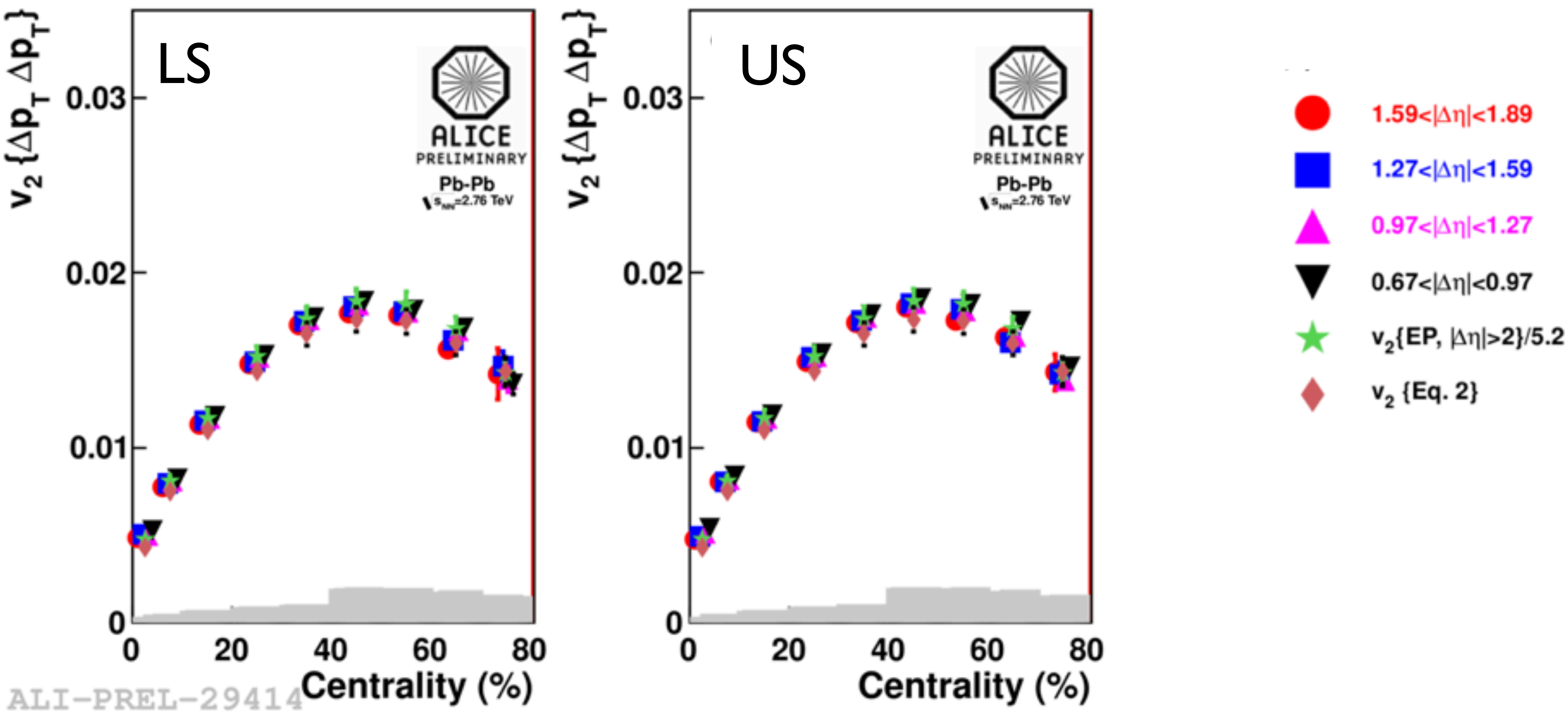
# $v_2\{R_2\}$ vs. centrality in Pb-Pb




$$v_n\{R_2\} = \sqrt{b_n}$$

- Measurements compared to $v_2\{EP\}$ by ALICE
  - Good agreement for large eta ranges $\Delta\eta > 1.0$

# $v_2\{\Delta p_T \Delta p_T\}$ vs. centrality in Pb-Pb

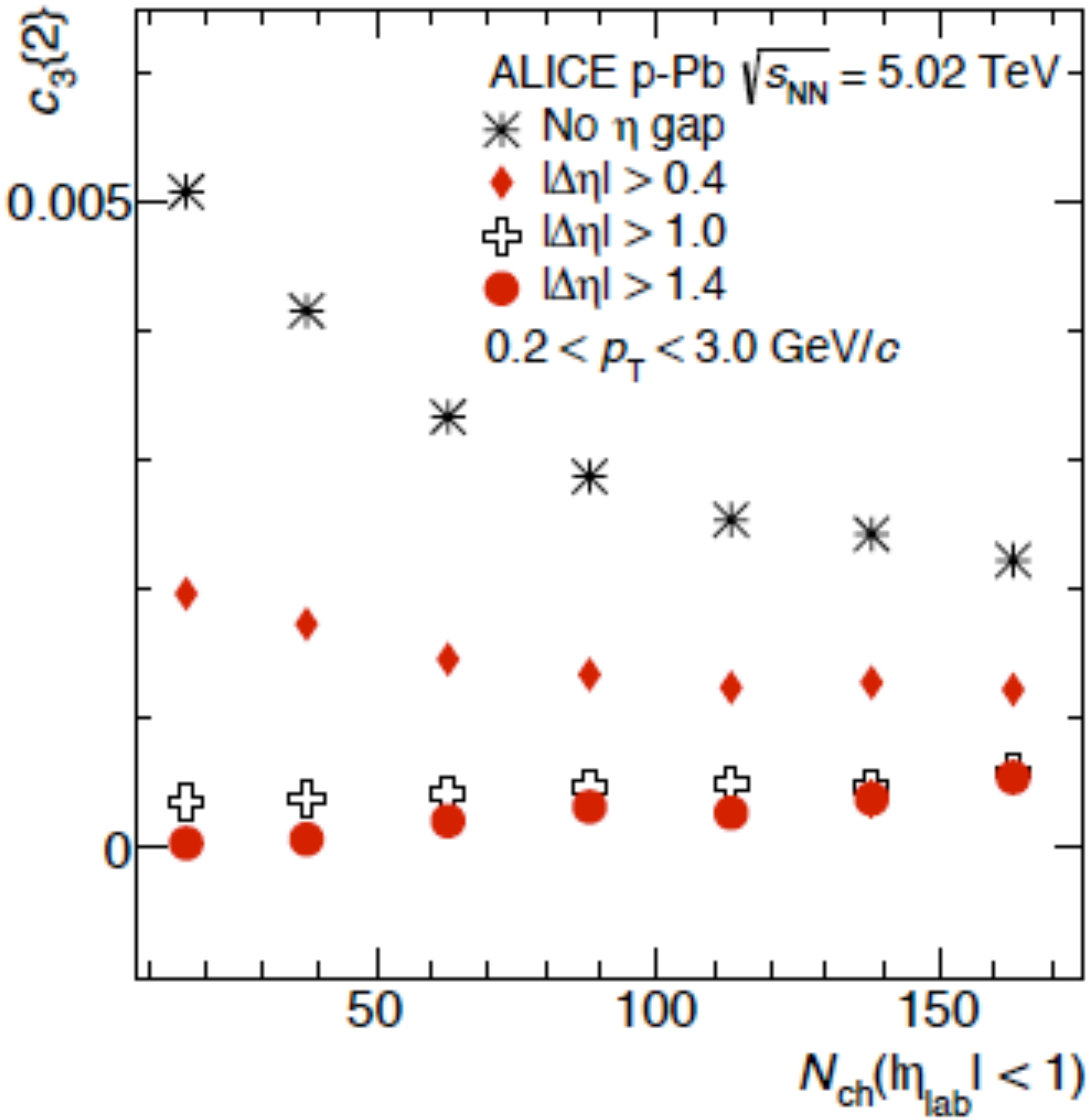



- Centrality dependence in excellent agreement w/scaled $v_2$ {EP} coefficients
- Excellent agreement w/coefficients "predicted" based on geometric flow model (Eq. 2) coefficients

# Summary

- First measurement of the differential observable $\Delta p_{\mathrm{T}}\Delta p_{\mathrm{T}}$
- $\Delta p_{\mathrm{T}}\Delta p_{\mathrm{T}}$ shows an away-side double bump in most central (0-5%) Pb-Pb
    - Not seen in $R_2$ (0-5% central) correlation function
- Harmonic coefficient $c_1\{\Delta p_{\mathrm{T}}\Delta p_{\mathrm{T}}\}$ changes sign at lower $\Delta\eta$ than $c_1\{R_2\}$
- Harmonic coefficient $c_2$ for $\Delta p_{\mathrm{T}}\Delta p_{\mathrm{T}}$ saturates earlier than $R_2$
    - $\Delta p_{\mathrm{T}}\Delta p_{\mathrm{T}}$ behaves more like a "shorter" range correlation
- Fourier coefficient of $\Delta p_{\mathrm{T}}\Delta p_{\mathrm{T}}$ scale according to geometrical model --- Yet another form of "factorization" !
    - Additional support for models describing correlations based on initial geometry and fluctuations in initial conditions

Back up Slides …




arXiv:1406.2474

## Two particle Number correlations and Flow Factorization

- Two-Particle Correlation -- Fourier Decomposition

$$\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} V_{n\Delta}(p_1, p_2)\cos\left(n(\phi_1 - \phi_2)\right)$$

- Flow Factorization

$$V_{n\Delta}(p_1, p_2) = \left\langle\left\langle e^{in\left(\phi_1 - \phi_2\right)}\right\rangle\right\rangle = \left\langle\left\langle e^{in\left(\phi_1 - \Psi_n\right)}\right\rangle\left\langle e^{in\left(\phi_1 - \Psi_n\right)}\right\rangle\right\rangle = \left\langle v_n\{2\}(p_1) v_n\{2\}(p_2)\right\rangle$$

- Factorization Expected When Correlations Driven by ...
  - Geometry Only
  - Jet Only(?)
- Factorization Expected to Break Down
  - When Jet & Geometry have 'similar' contributions

# Transverse momentum correlation

$$\langle \Delta p_{t,1} \Delta p_{t,2} \rangle (\eta_1, \phi_1, \eta_2, \phi_2) = \frac{\int \rho_2(\eta_1, \phi_1, p_{t1}, \eta_2, \phi_2, p_{t2}) \Delta p_{t1} \Delta p_{t2} dp_{t1} dp_{t2}}{\int \rho_2(\eta_1, \phi_1, p_{t1}, \eta_2, \phi_2, p_{t2}) dp_{t1} dp_{t2}}$$

$$\langle \Delta p_t \Delta p_t \rangle (\Delta\eta, \Delta\varphi) = \frac{\sum_{events} \sum_{accept} \Delta p_{t,1} \Delta p_{t,2}}{\sum_{events} n_{pairs}(\Delta\eta, \delta\varphi)}$$

$$\text{where, } \Delta p_t = p_{t,i} - \langle p_t \rangle$$

$$\langle p_{t,i} \rangle = \frac{\int \rho_1(\mathbf{p_i}) p_{t,i} \; dp_{t,i}}{\int \rho_1(\mathbf{p_i}) \; dp_{t,i}}$$

## $\Delta\eta$ Slices - Fourier Decomposition Fits

$$F(\Delta\varphi) = b_0 + 2\sum_{n=1}^{6} b_n(n\Delta\varphi)$$

Fourier harmonics:

$$c_n\{R_2\} = \frac{b_n}{b_0 + 1}$$

$$c_n\{\Delta p_{\mathrm{T}}\Delta p_{\mathrm{T}}\} = b_n$$

# Can we test factorization for $\Delta p_T \Delta p_T$ ?

Hypothesis: the correlations in particles production are only due to flow

$$P(\eta,\phi,p_\perp \mid \{\Psi_n\}) = P(\eta,p_\perp)\left(1+2\sum_n v_n(\eta,p_\perp)\cos\left(n\left(\phi-\Psi_n\right)\right)\right)$$

Sharma and Pruneau, Phys Rev C, 79, 024905, 2009, arXiv:0810.0716

Prediction for $\langle \Delta p_{t,1} \Delta p_{t,2} \rangle$

$$\langle \Delta p_t \Delta p_t \rangle(\eta_1,\eta_2,\Delta\phi) = \frac{2\sum_n \left(v_n^p(\eta_1) - \langle p_t \rangle(\eta_1) v_n(\eta_1)\right)\left(v_n^p(\eta_2) - \langle p_t \rangle(\eta_2) v_n(\eta_1)\right)\cos(n\Delta\phi)}{1+2\sum_n v_n(\eta_1)v_n(\eta_1)\cos(n\Delta\phi)}$$

$$v_n(\eta) = \frac{1}{P(\eta)}\int P(\eta,p_t)v_n(\eta)\,dp_t$$ Regular Flow Coefficients

$$v_n^{p_t}(\eta) = \frac{1}{P(\eta)}\int P(\eta,p_t)v_n(\eta)\,p_t\,dp_t$$ pT weighted Flow Coefficients

Consequence: FDC of $\langle \Delta p_{t,1} \Delta p_{t,2} \rangle$ at large $\Delta\eta$ should scale with flow coefficients

# Factorization

- 2-particle correlation -- Fourier decomposition (FDC)

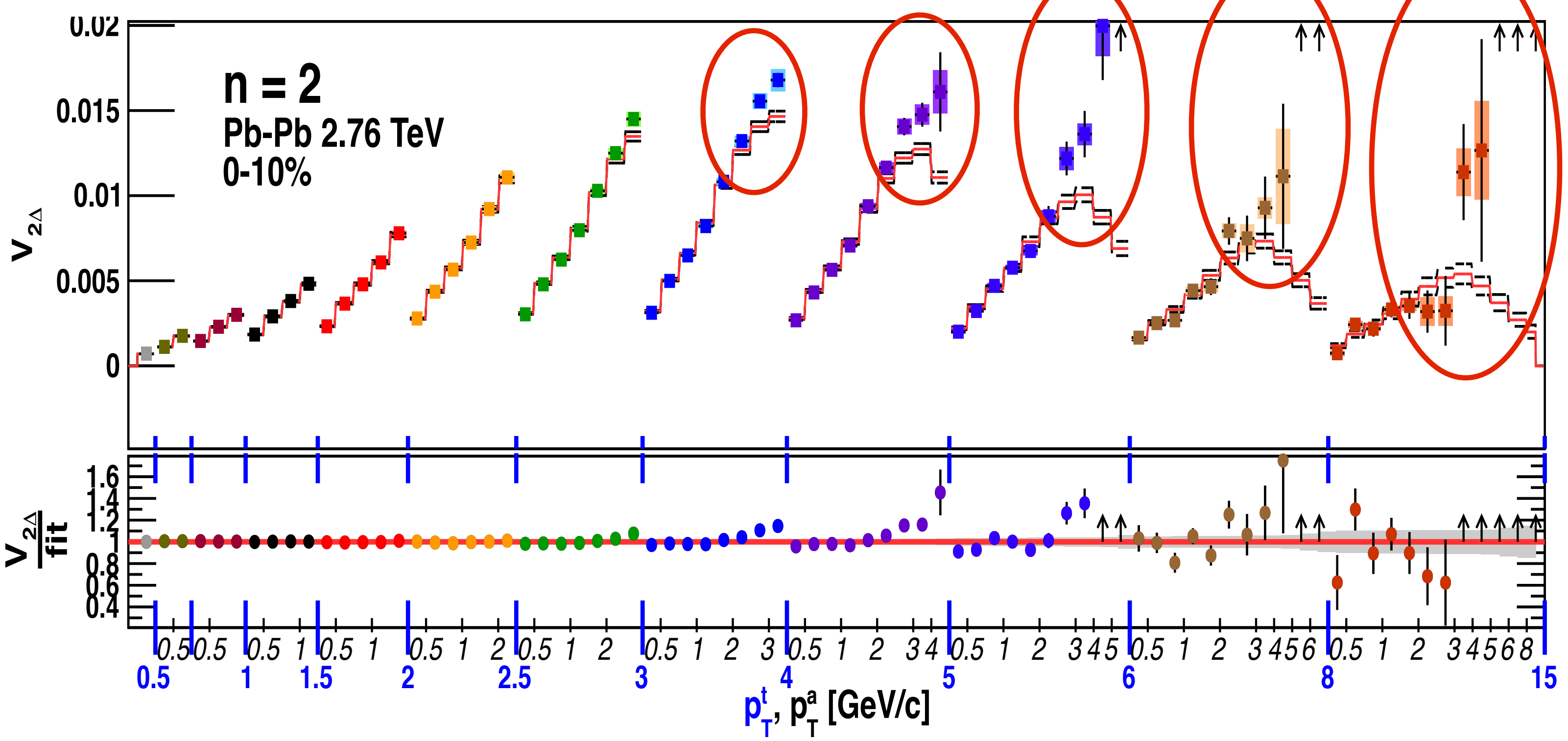
$$\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} V_{n\Delta}(p_1, p_2)\cos\left(n(\phi_1 - \phi_2)\right)$$

ALICE $v_n\{2\}$
PRL 107 032301 (2011)

- Factorization expected when correlations driven by geometry only

$$V_{n\Delta} = v_n(p_1)\ v_n(p_2)$$

- Factorization expected to break down when jet and geometry have similar contributions




Physics Letters B 708 (2012) 249–264

- Fit supports factorization at low $p_T^a$ ⇒ suggests flow correlations.

- Fit deviates in jet-dominated high $p_T^a$ region ⇒ collective description less appropriate

'Geometrical flow model'

Sharma and Pruneau, Phys Rev C, 79, 024905, 2009, arXiv: 0810.0716

Can we test factorization for $\Delta p_T \Delta p_T$?

Consequence: FDC of $\langle \Delta p_{t,1} \Delta p_{t,2} \rangle$ at large $\Delta\eta$ should scale with flow coefficients