Wayne State University
College of Liberal Arts & Sciences
Department of Physics and Astronomy

New Evidence for the Dominance of Collective Flow in Pb-Pb Collisions

6th International Conference on New Frontiers in Physics (ICNFP 2017)
August 2017, Kolymbari, Crete, Grece

Claude A. Pruneau
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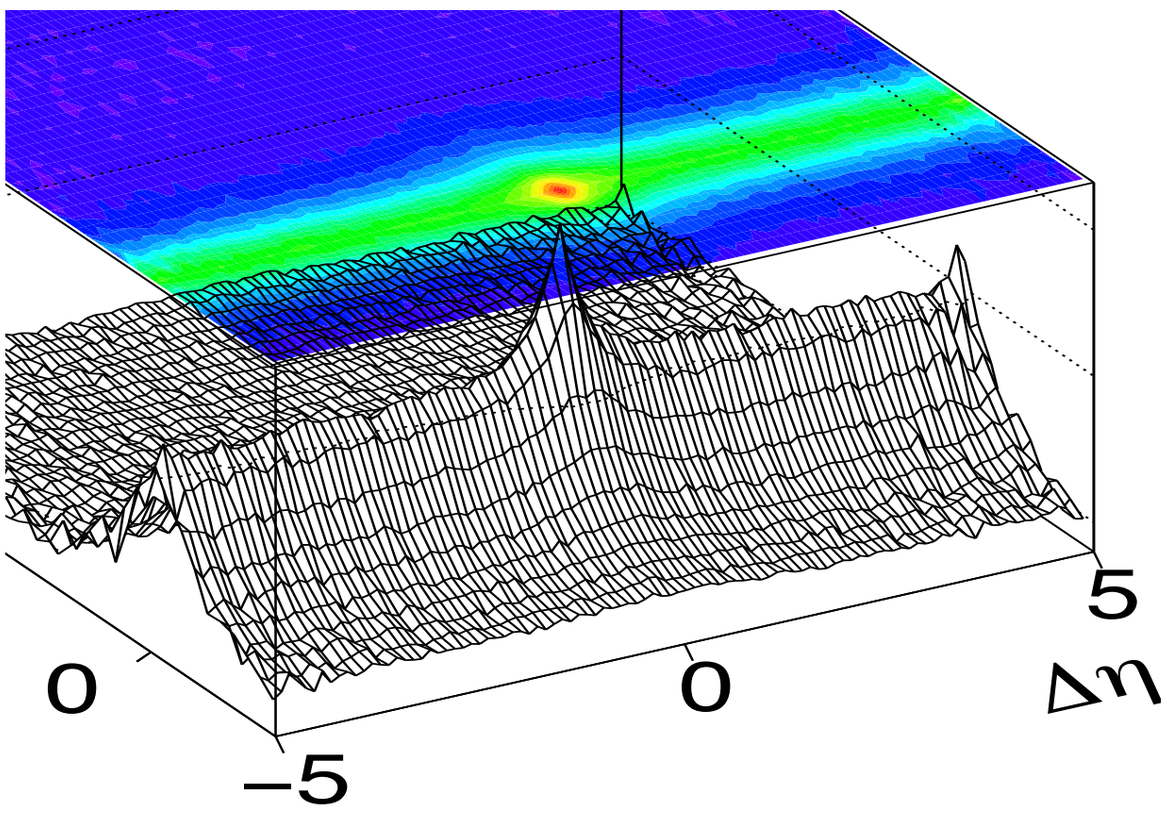
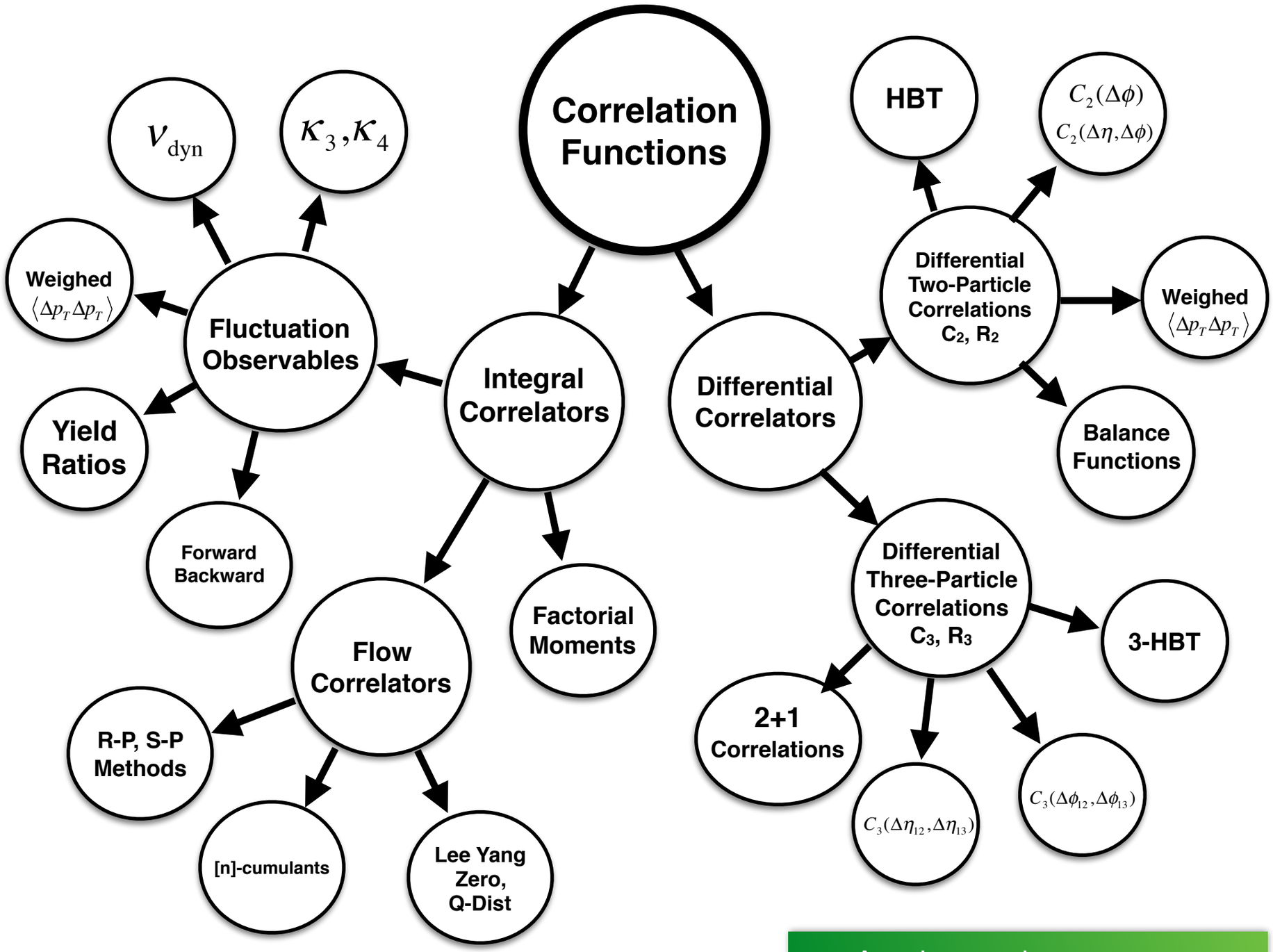
for the ALICE Collaboration



The Multiple Facets of Correlation Functions



- Majority of papers published in Heavy-Ion physics involve some form of **correlation measurement**.
  - Flow
  - HBT: System size/geometry
  - Jet Modification
  - QGP Properties
- What else can we learn from correlation measurements?

And much more …

Figure from Data Analysis Techniques for Physical Scientists, C.P., Cambridge University Press, to appear in print Fall 2017.

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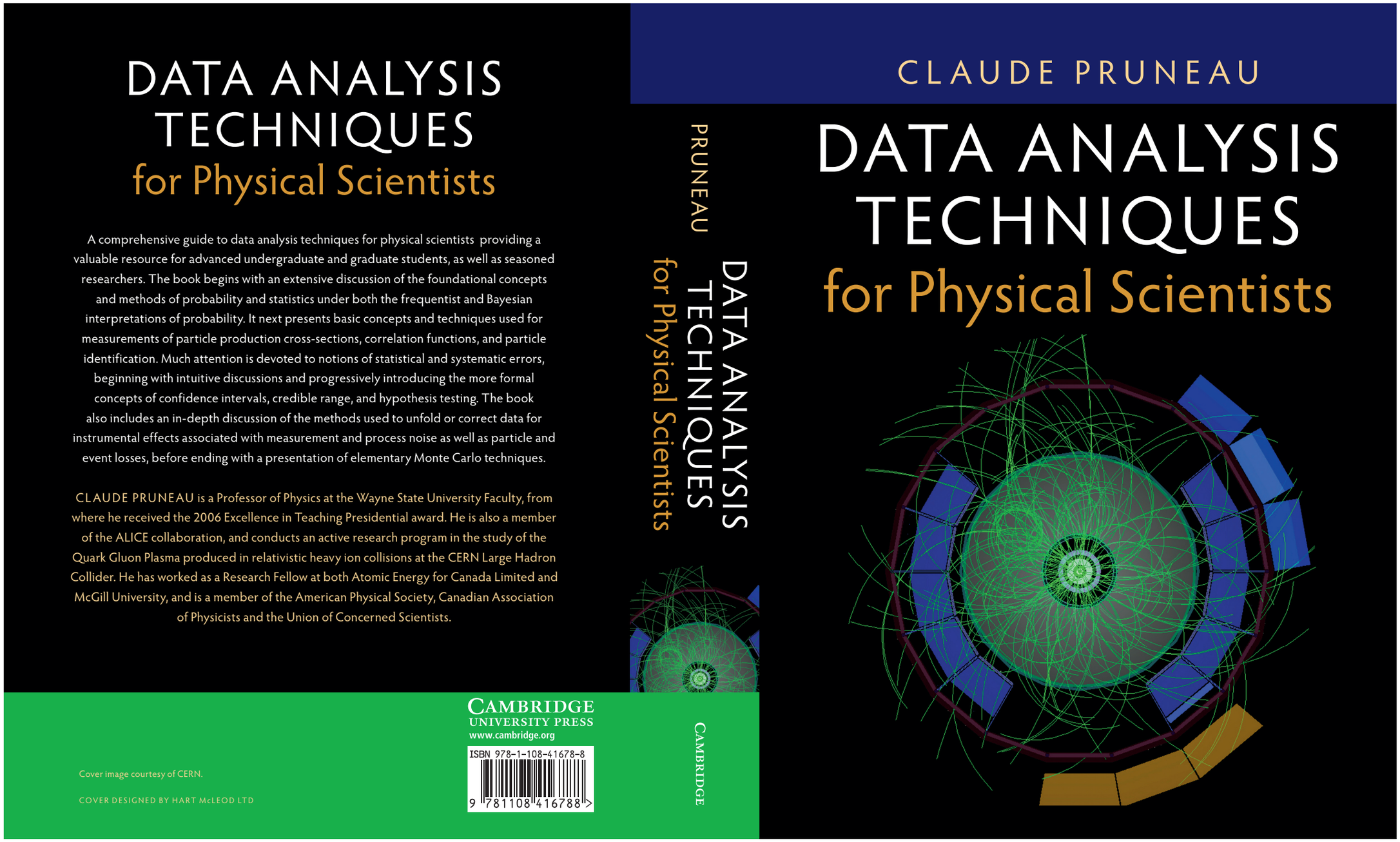
Coming soon to a bookstore near you....



Expected print release: October 2017

Correlation Function Measurements

- **Correlation functions** are based on **n-cumulants**
- Cumulants are calculated starting w/ **n-particle densities**

- n-Particle densities can be
  - **fully differential**

$$\rho_1(\vec{p}_1) \equiv \rho_1(\phi_1, \eta_1, p_{T,1})$$
$$\rho_2(\vec{p}_1, \vec{p}_2) \equiv \rho_2(\phi_1, \eta_1, p_{T,1}, \phi_2, \eta_2, p_{T,2})$$
$$\cdots$$
$$\rho_n(\vec{p}_1, \ldots, \vec{p}_n) \equiv \rho_n(\phi_1, \eta_1, p_{T,1}, \ldots, \phi_n, \eta_n, p_{T,n})$$

  - **partially integrated (some coordinates marginalized)**
    - **Examples:**

$$\rho_1(\phi_1) \equiv \int_{\Omega_1} \rho_1(\phi_1, \eta_1, p_{T,1})\, d\eta_1\, dp_{T,1}$$

$$\rho_2(\eta_1, \eta_2) \equiv \iint_{\Omega_1, \Omega_2} \rho_2(\phi_1, \eta_1, p_{T,1}, \phi_2, \eta_2, p_{T,2})\, d\phi_1 dp_{T,1} d\phi_2 dp_{T,2}$$

Very many ways to marginalize the densities to bring focus on specific aspects of correlations.

  - **fully integrated — all coordinates marginalized.**

$$\langle N \rangle = \int_{\Omega_1} \rho_1(\phi_1, \eta_1, p_{T,1})\, d\eta_1\, dp_{T,1}\, d\phi_1$$

$$\langle N_1 N_2 \rangle \equiv \iint_{\Omega_1, \Omega_2} \rho_2(\phi_1, \eta_1, p_{T,1}, \phi_2, \eta_2, p_{T,2})\, d\phi_1 d\eta_1 dp_{T,1} d\phi_2 d\eta_2 dp_{T,2} \quad \text{if} \quad \Omega_1 \neq \Omega_2$$

$$\langle N(N-1) \rangle \equiv \iint_{\Omega_1, \Omega_2} \rho_2(\phi_1, \eta_1, p_{T,1}, \phi_2, \eta_2, p_{T,2})\, d\phi_1 d\eta_1 dp_{T,1} d\phi_2 d\eta_2 dp_{T,2} \quad \text{if} \quad \Omega_1 = \Omega_2$$

$$\langle N(N-1)\cdots(N-n+1) \rangle \equiv \iint_{\Omega} \rho_n(\phi_1, \eta_1, p_{T,1}, \ldots, \phi_n, \eta_n, p_{T,n})\, d\phi_1 d\eta_1 dp_{T,1} \cdots d\phi_n d\eta_n dp_{T,n} \quad \text{if} \quad \Omega_1 = \Omega_2 = \cdots = \Omega_n$$

Correlation Function Measurements (2)

- n-Cumulants

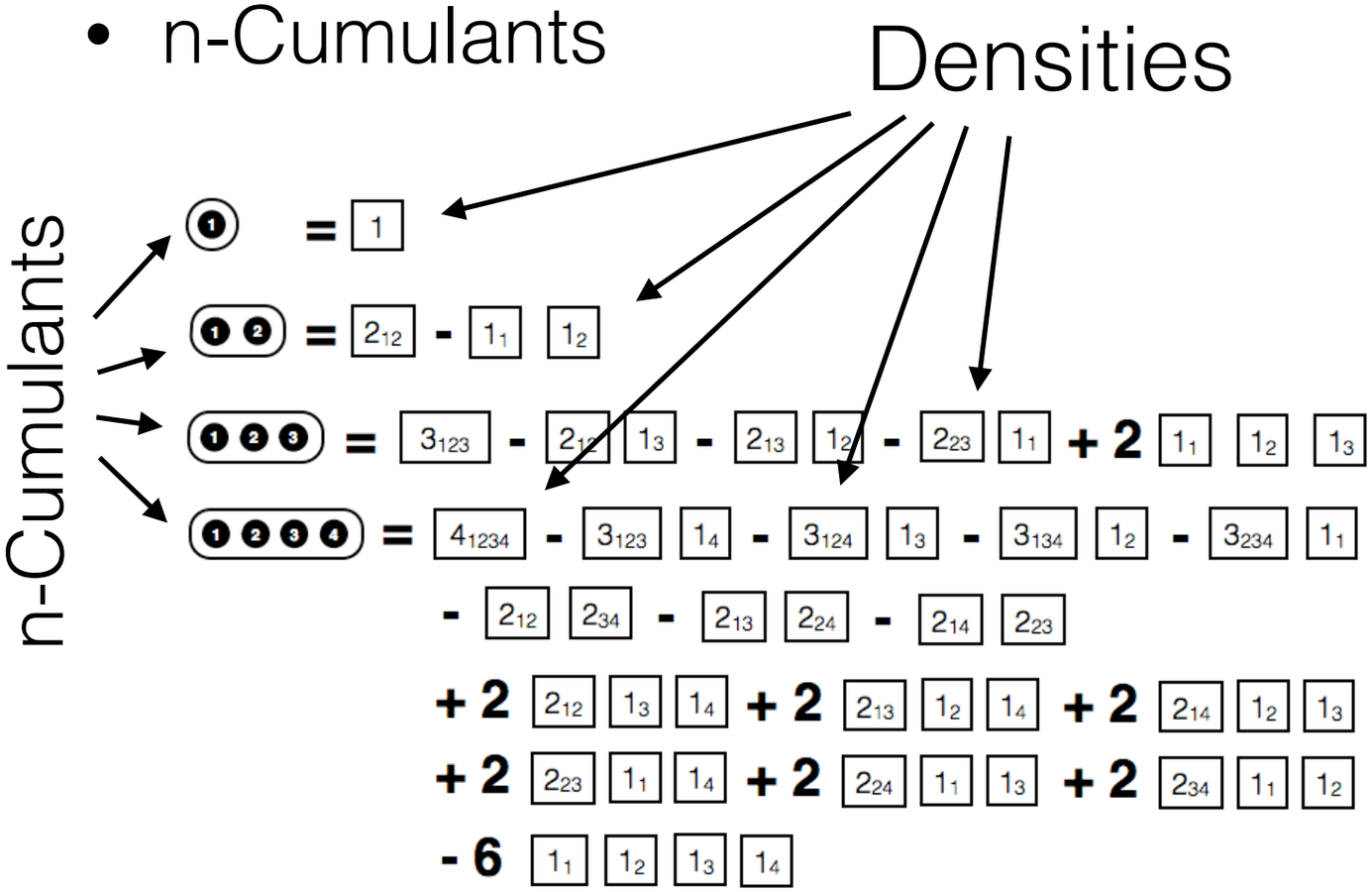


Figure from Data Analysis Techniques for Physical Scientists, C.P., Cambridge University Press, to appear in print Fall 2017.

2-particle correlations

Densities

$$\rho_1(\eta_1) = \int_{\Omega_1} d\phi_1\, dp_{T,1}\, \rho_1(\phi_1, \eta_1, p_{T,1})$$

$$\rho_2(\eta_1, \eta_2) = \int_{\Omega_1} d\phi_1\, dp_{T,1} \int_{\Omega_2} d\phi_2\, dp_{T,2}\, \rho_2(\phi_1, \eta_1, p_{T,1}, \phi_2, \eta_2, p_{T,2})$$

Cumulants

$$C_2(\eta_1, \eta_2) \equiv \rho_2(\eta_1, \eta_2) - \rho_1(\eta_1)\rho_1(\eta_2)$$

Normalized Cumulants

$$R_2(\eta_1, \eta_2) \equiv \frac{\rho_2(\eta_1, \eta_2) - \rho_1(\eta_1)\rho_1(\eta_2)}{\rho_1(\eta_1)\rho_1(\eta_2)}$$

This talk's focus : 2-Particle Correlations

Densities:

$$\rho_1(\vec{p}_1) \equiv \rho_1(\phi_1, \eta_1, p_{T,1})$$

$$\rho_2(\vec{p}_1, \vec{p}_2) \equiv \rho_2(\phi_1, \eta_1, p_{T,1}, \phi_2, \eta_2, p_{T,2})$$

2-Cumulant:

$$C_2(\eta_1, \eta_2) \equiv \rho_2(\eta_1, \eta_2) - \rho_1(\eta_1)\rho_1(\eta_2)$$

Normalized 2-Cumulants:

$$R_2(\eta_1, \eta_2) \equiv \frac{\rho_2(\eta_1, \eta_2) - \rho_1(\eta_1)\rho_1(\eta_2)}{\rho_1(\eta_1)\rho_1(\eta_2)}$$

Transverse Momentum Correlator:

$$\langle \Delta p_T \Delta p_T \rangle_I = \frac{\int_{\text{accept}} \rho_2 \Delta p_{T,i} \Delta p_{T,j} d\eta_1 d\phi_1 dp_{T,1} d\eta_2 d\phi_2 dp_{T,2}}{\int_{\text{accept}} \rho_2 d\eta_1 d\phi_1 dp_{T,1} d\eta_2 d\phi_2 dp_{T,2}}$$

Weighted Cumulants

M. Sharma & C.P., PRC 79, 024905 (2009)

- Transverse Momentum Correlator (Definition)

$$\langle \Delta p_T \Delta p_T \rangle_I = \frac{\int_{\text{accept}} \rho_2 \Delta p_{T,i} \Delta p_{T,j} d\eta_1 d\phi_1 dp_{T,1} d\eta_2 d\phi_2 dp_{T,2}}{\int_{\text{accept}} \rho_2 d\eta_1 d\phi_1 dp_{T,1} d\eta_2 d\phi_2 dp_{T,2}}$$

- Measured according to:

$$\langle \Delta p_T \Delta p_T \rangle_I = \frac{\sum_{\alpha=1}^{N_{\text{ev}}} S'^{\Delta p_T \Delta p_T}_{\alpha}}{\sum_{\alpha=1}^{N_{\text{ev}}} N_\alpha (N_\alpha - 1)} = \frac{\langle S'^{\Delta p_T \Delta p_T} \rangle}{\langle N(N-1) \rangle}$$

- where $S_\alpha^{\Delta p_T \Delta p_T} = \sum_{i,j=1}^{N_\alpha} \Delta p_{T,i} \Delta p_{T,j}$ $\qquad \Delta p_T = p_{T,i} - \langle p_T \rangle$

- Dimensionless pT Correlator:

$$P_2 = \frac{\langle \Delta p_T \Delta p_T \rangle}{\langle p_T \rangle^2}$$

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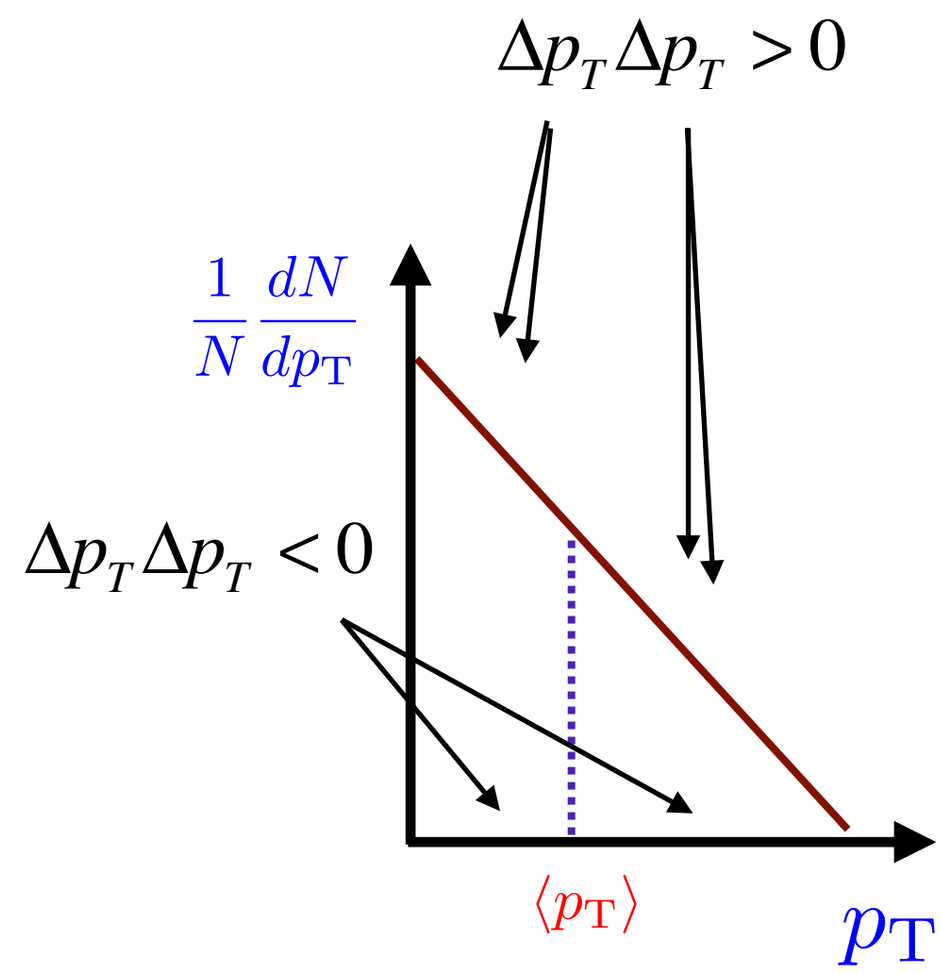
Differential pT correlations

M. Sharma & C.P., PRC 79, 024905 (2009)

$$\langle \Delta p_T \Delta p_T \rangle \propto \int_{accept} \rho_2(\vec{p}_1, \vec{p}_2) \Delta p_T \Delta p_T \, dp_{T,1} \, dp_{T,2}$$

- Not positive definite
- Sensitivity to …
  - pT hardness of particles & correlations (e.g. HBT, jet, non-jet)
  - e-by-e temperature & average momentum fluctuations,
  - collective flow



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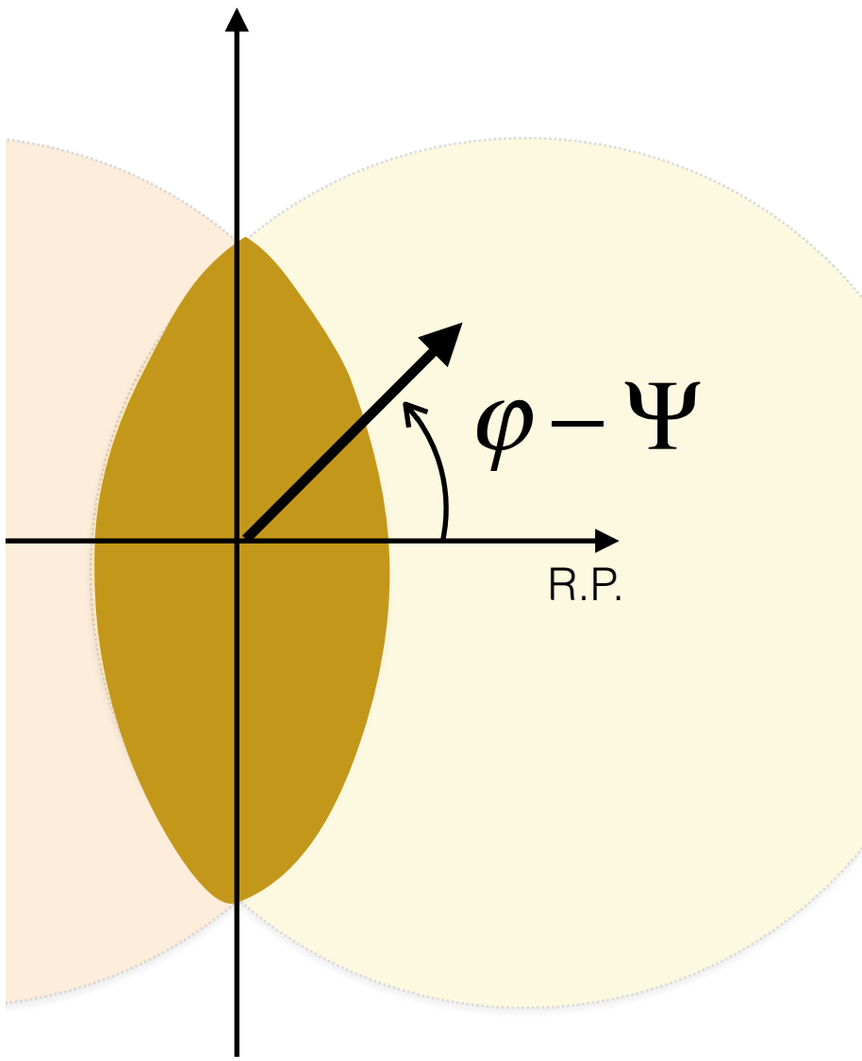
A Flow Ansatz

M. Sharma & C.P., PRC 79, 024905 (2009)

- Assume particle correlations only determined by their emission relative to the reaction plane (RP).
- Probability of Emission of one particle:

$$P_1(\eta, \varphi, p|\Psi) = P_1(\eta, p)\left\{1 + 2\sum_n v_n(\eta, p)\cos\left(n\left(\varphi - \Psi\right)\right)\right\}$$



- Joint Probability of Emission of two particles:

$$P_2(\eta_1, \varphi_1, p_1, \eta_2, \varphi_2, p_2) = P_1(\eta_1, p_1)P_1(\eta_2, p_2) \times \left\{1 + 2\sum_n v_n(\eta_1, p_1)v_n(\eta_2, p_2)\cos\left(n\left(\varphi_1 - \varphi_2\right)\right)\right\}$$

A Flow Ansatz (2)

Sharma & Pruneau, PRC 79, 024905 (2009)

- The pTpT correlator determined by:

$$\langle \Delta p_T \Delta p_T \rangle(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{2\sum_n \left[v_n^{p_T}(\eta_1) - \langle p_T \rangle(\eta_1) v_n(\eta_1)\right]\left[v_n^{p_T}(\eta_2) - \langle p_T \rangle(\eta_2) v_n(\eta_2)\right]\cos\left[n(\varphi_1-\varphi_2)\right]}{1+2\sum_n v_n(\eta_1) v_n(\eta_2)\cos\left[n(\varphi_1-\varphi_2)\right]}$$

$$\simeq 2\sum_n \left[v_n^{p_T}(\eta_1) - \langle p_T \rangle(\eta_1) v_n(\eta_1)\right]\left[v_n^{p_T}(\eta_2) - \langle p_T \rangle(\eta_2) v_n(\eta_2)\right]\cos\left[n(\varphi_1-\varphi_2)\right]$$

$$= 2\sum_n v_n^{\Delta p_T \Delta p_T}(\eta_1) v_n^{\Delta p_T \Delta p_T}(\eta_2)\cos\left[n(\varphi_1-\varphi_2)\right]$$

- with

$$v_n(\eta) = \frac{1}{P_n(\eta)}\int P_n(\eta,p_T) v_n(\eta,p_T)\, dp_T$$

$$v_n^{p_T}(\eta) = \frac{1}{P_n(\eta)}\int P_n(\eta,p_T) v_n(\eta,p_T) p_T\, dp_T$$

$$\langle p_T \rangle = \frac{1}{P_n(\eta)}\int P_n(\eta,p_T) p_T\, dp_T$$

Test of Flow Dominance:
Measure Fourier coefficients of pTpT momentum correlator & compare to this ansatz with flow coefficients obtained by "standard methods"

Dimensionless pT Correlator

- Express correlator in terms of dimensionless quantity:

$$P_2(\Delta\eta,\Delta\phi) = \frac{\langle \Delta p_T \Delta p_T \rangle}{\langle p_T \rangle^2}$$

$$v_n[P_2] = \frac{v_n^{pT}}{\langle p_T \rangle} - v_n$$

"Regular" Flow Coefficient

$$v_n^{pT} = \int \rho_1 v_n(p_T) p_T \, dp_T$$

"pT Weighted" Flow Coefficient

2-Particle Correlation Functions

- Experimental Program: Measure Correlation vs. …
  - Collision system size, centrality, pT range, particle species, etc.
- For specific charged particle pair combinations
  - LS : Like-sign pairs $O^{(LS)} = \frac{1}{2}\left(O^{(++)} + O^{(--)}\right)$
  - US : Unlike-sign pairs $O^{(US)} = \frac{1}{2}\left(O^{(+-)} + O^{(-+)}\right)$
  - CI : Charge Independent $O^{(CI)} = \frac{1}{2}\left(O^{(LS)} + O^{(US)}\right)$
  - CD: Charge Dependent $O^{(CD)} = \frac{1}{2}\left(O^{(US)} - O^{(LS)}\right)$

R_2 & P_2 Measurements by ALICE

- **Pb - Pb collisions at** $\sqrt{s_{NN}} = 2.76\ \mathrm{TeV}$
- **Charged particle tracks & Pairs (ITS+TPC):**

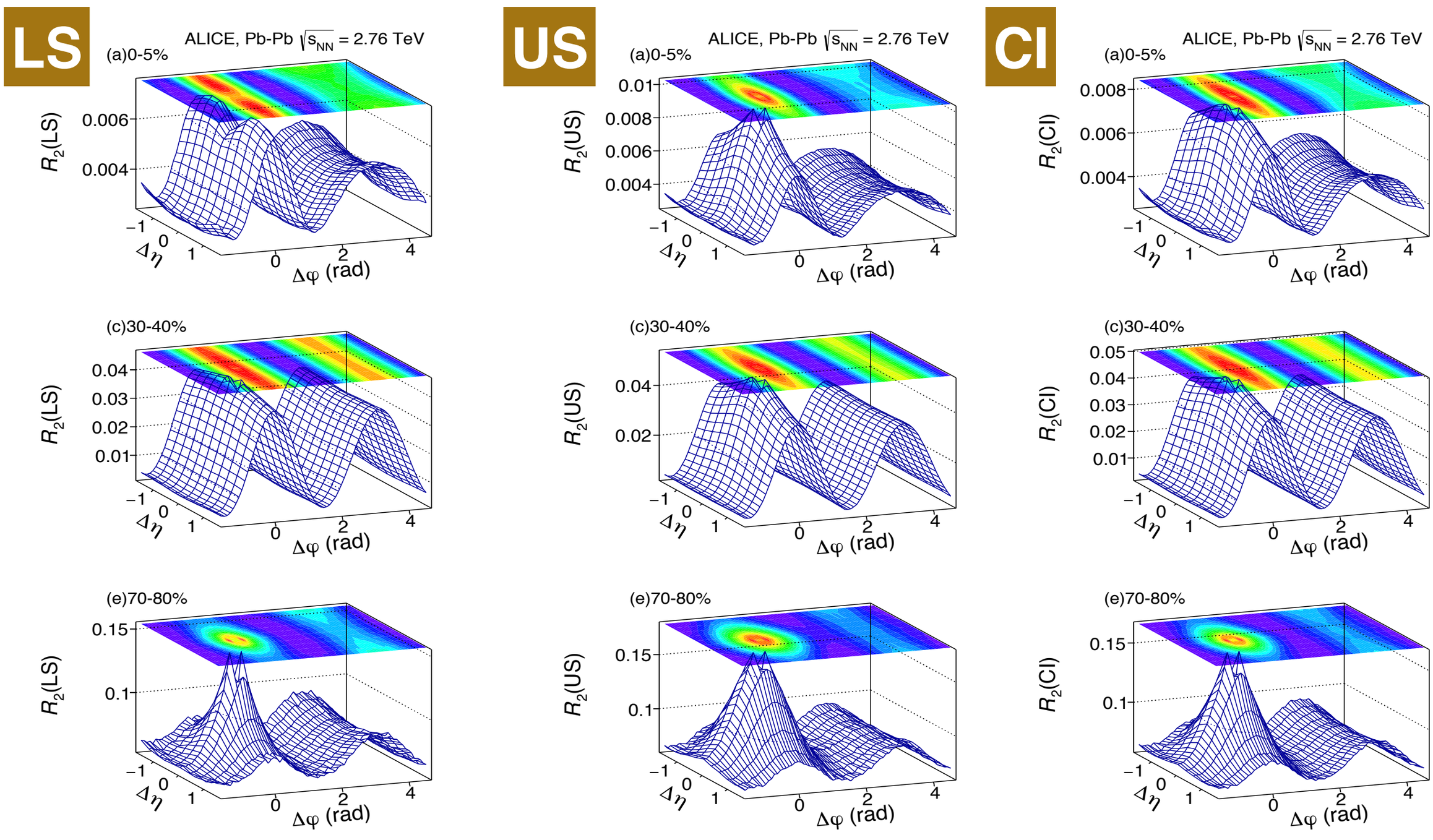
$$0.2 \le p_T \le 2.0; \quad |\eta| \le 1.0; \quad |\Delta\eta| \le 2.0$$

- **Centrality Determination w/ V0 Detectors**
- **Track Quality Criteria:**
  - **DCA_z<3.2 cm, DCA_{xy}<2.4 cm;**
  - **>70 hits/track;**
- **Suppression of electrons with TPC track dE/dx**

R_2 Correlations in Pb - Pb

P. Pujahari, C. Pruneau, et al, ALICE Collaboration, To be submitted to PRC

0.2 < pT < 2.0 GeV/c



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P_2 Correlations in Pb - Pb

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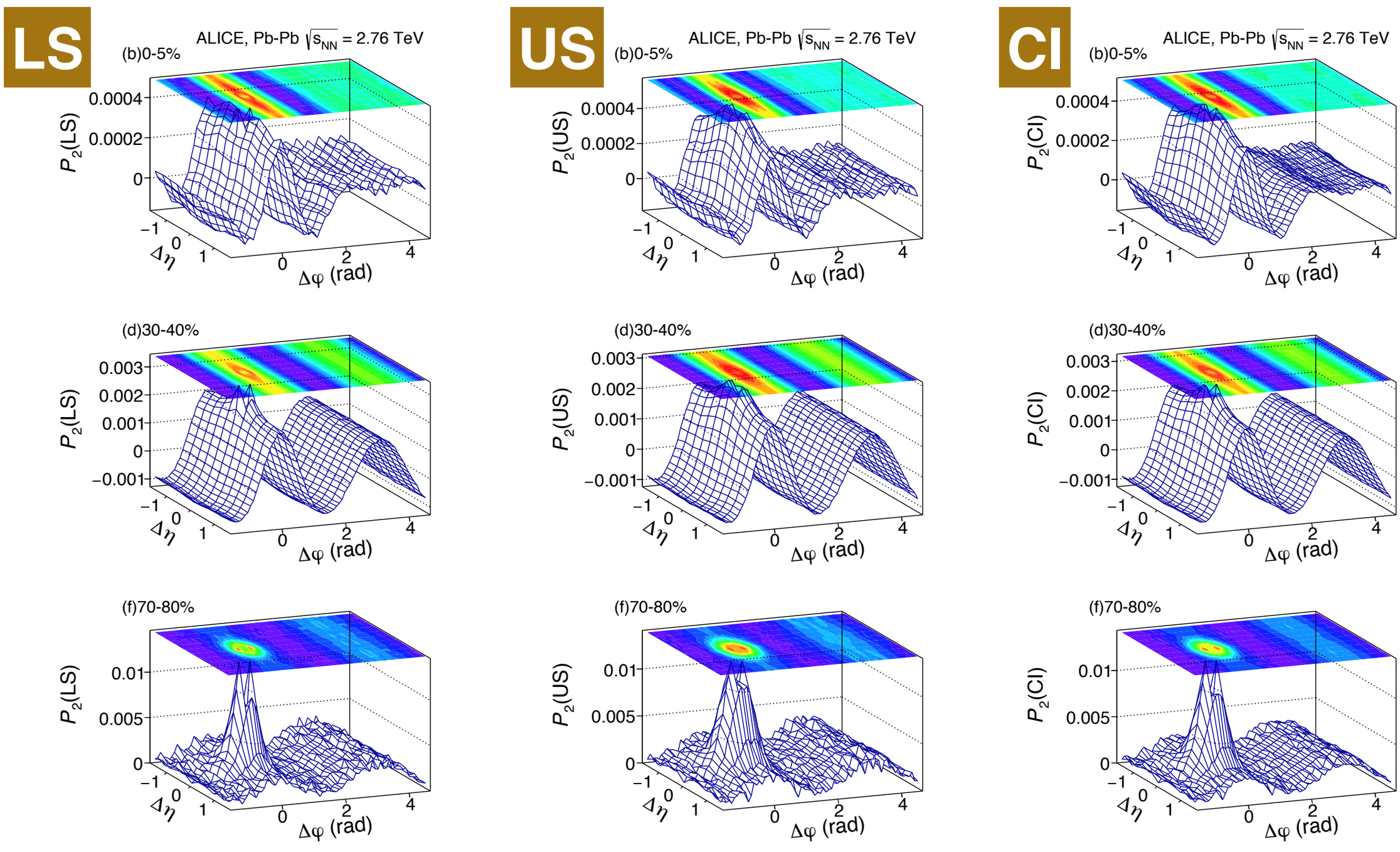

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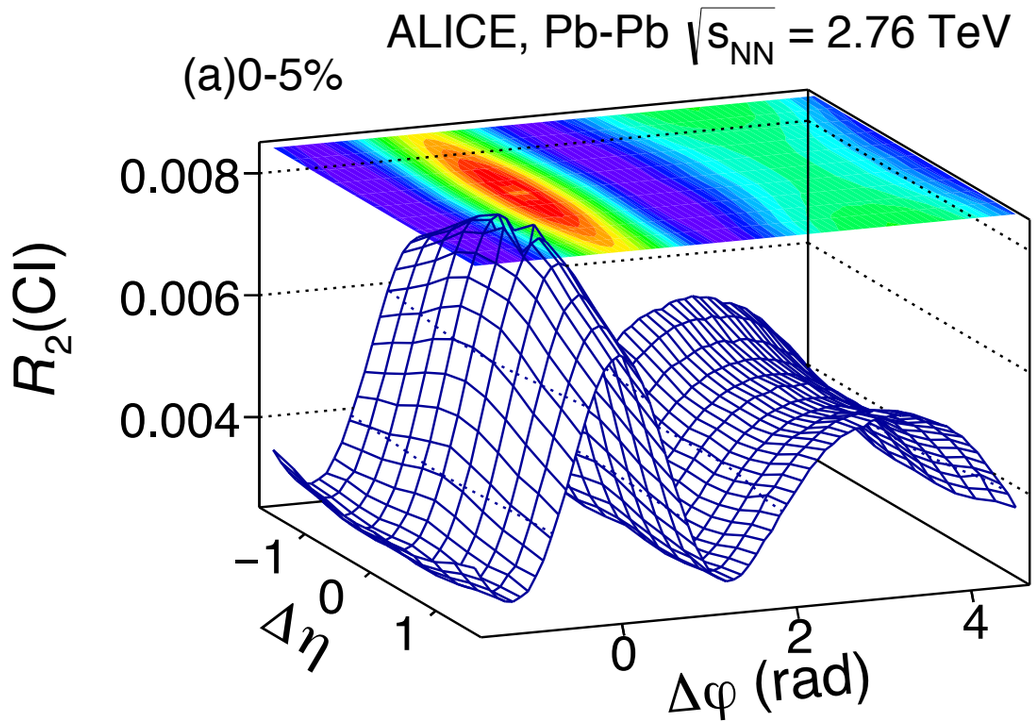
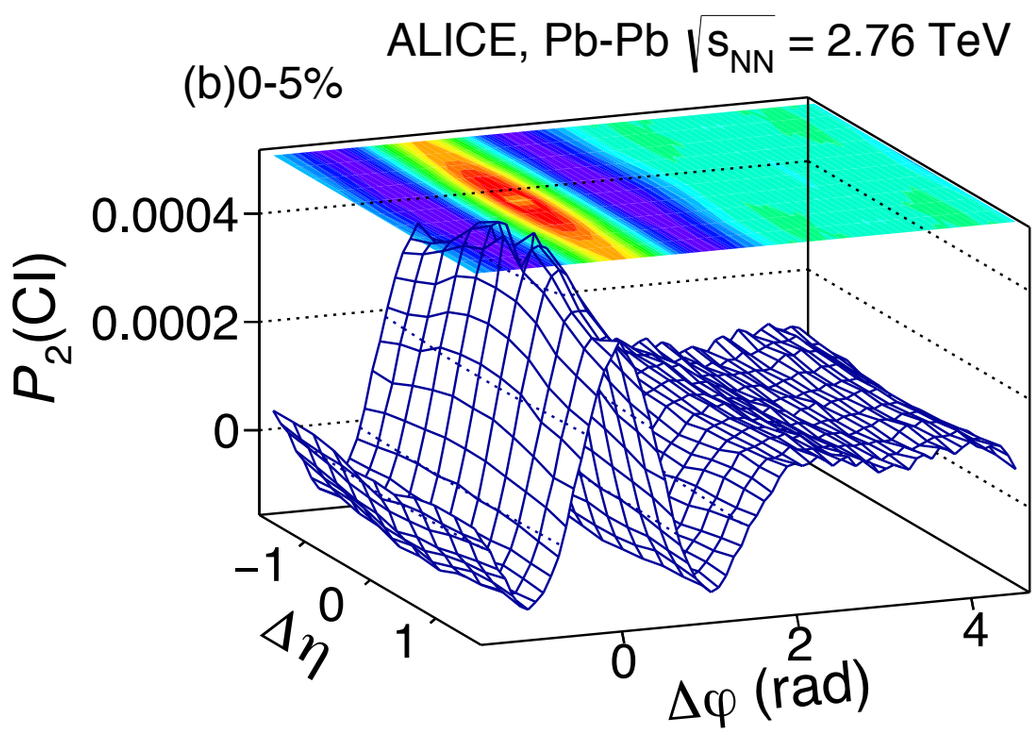
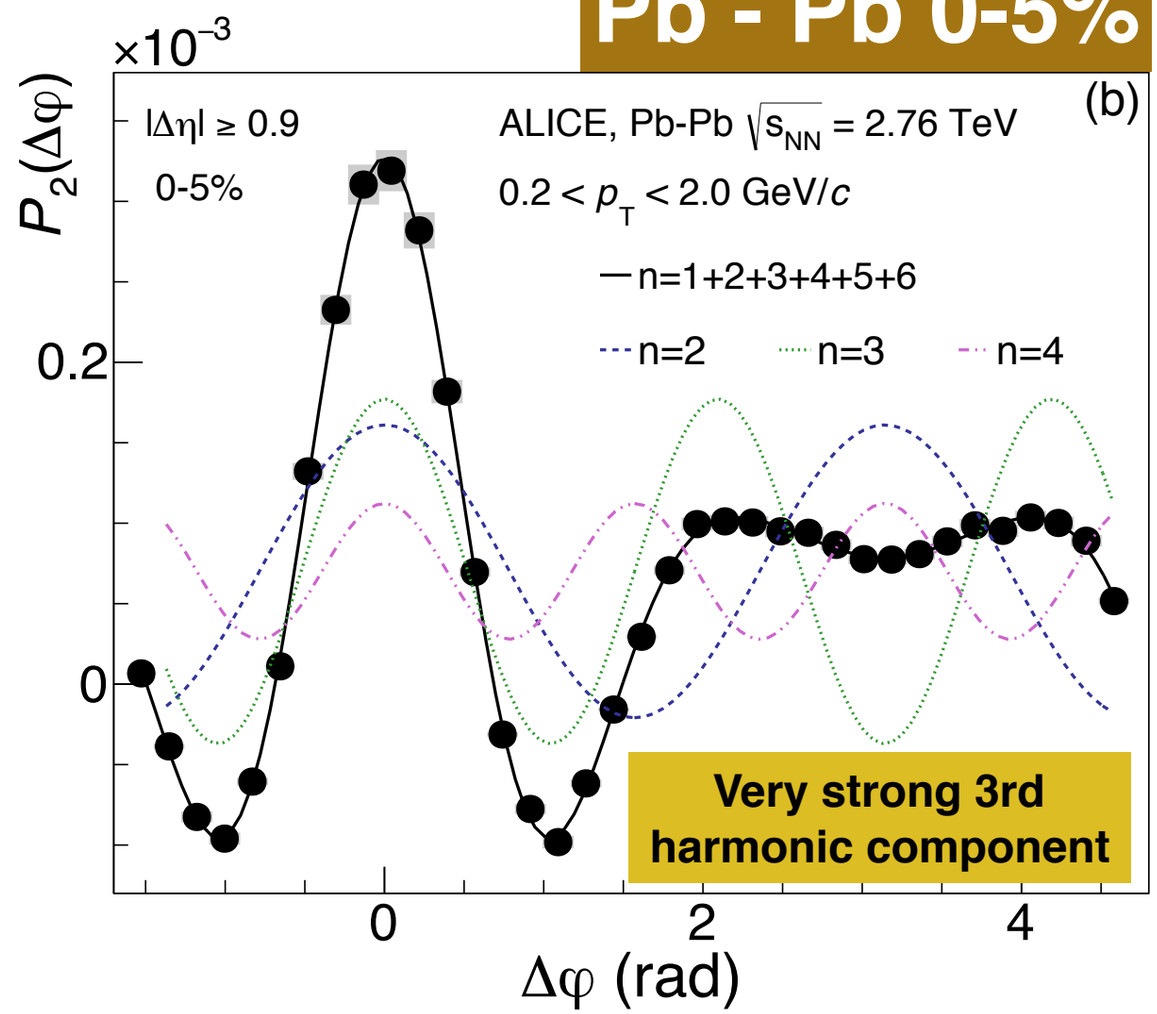
P_2 vs R_2 Comparison

J. Adam *et al.* (ALICE) Phys. Rev. Lett. **118**, 162302 (2017)





Pb - Pb 0-5%



Looks Familiar?

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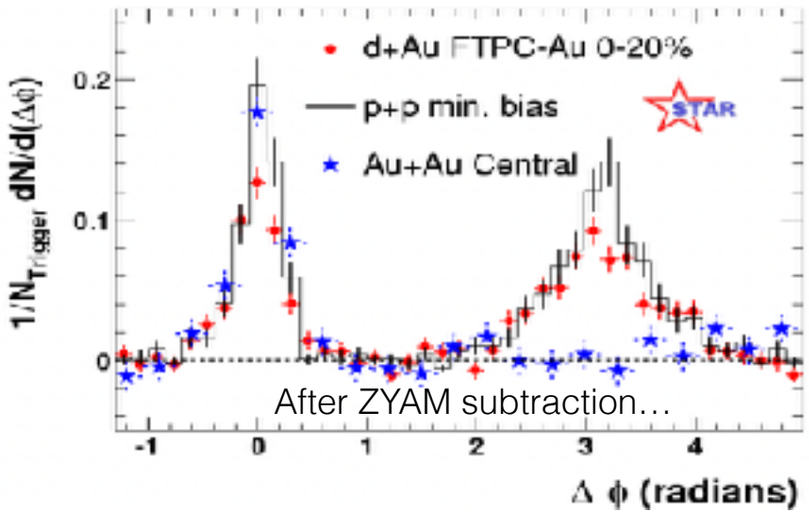
Historical Context & Short Digression…

Adams *et al.*, STAR Collaboration,
PRL **91** (2003) 072304

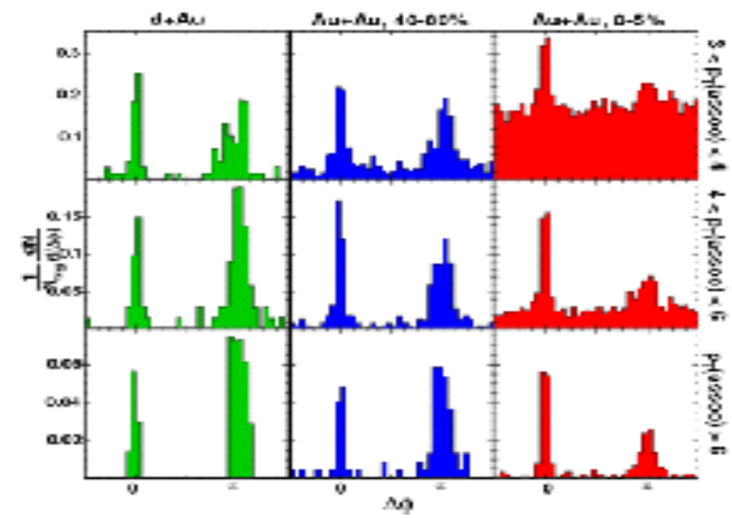


After ZYAM subtraction…

Disappearance of the away-side jet!

Adams et al, STAR Collaboration

PRL 97 (2006) 162301



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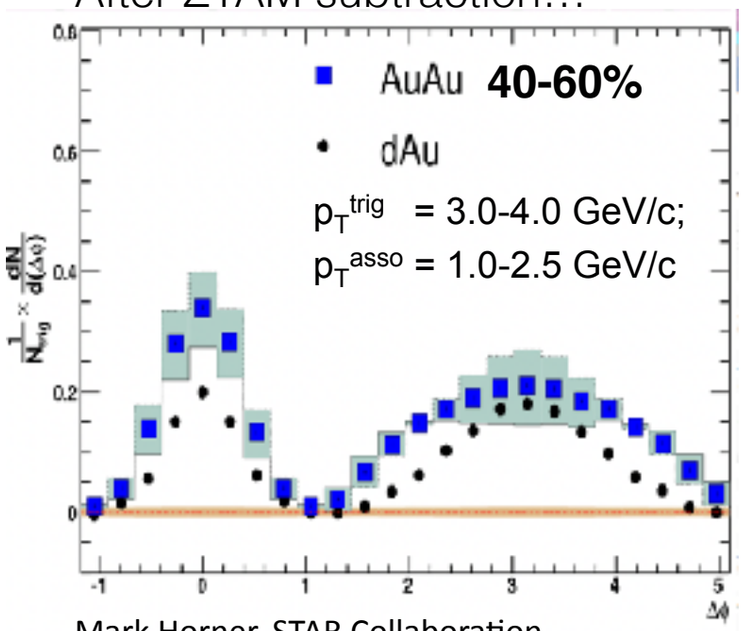
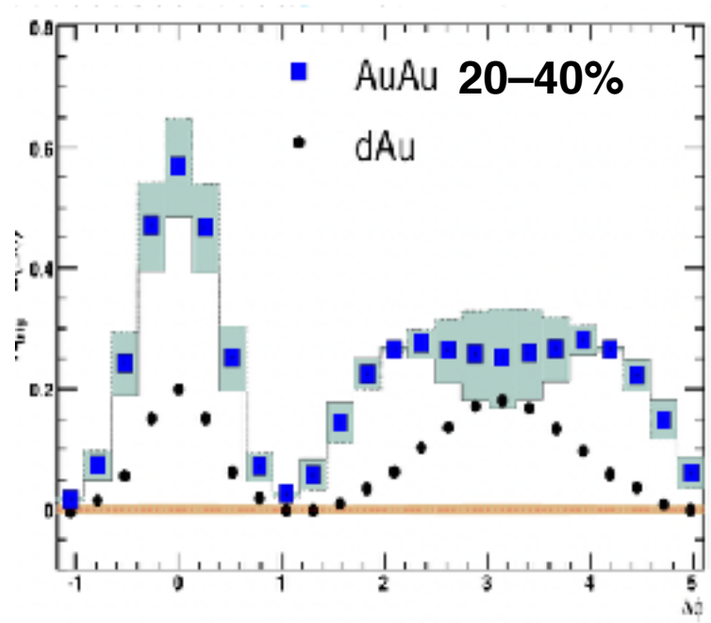
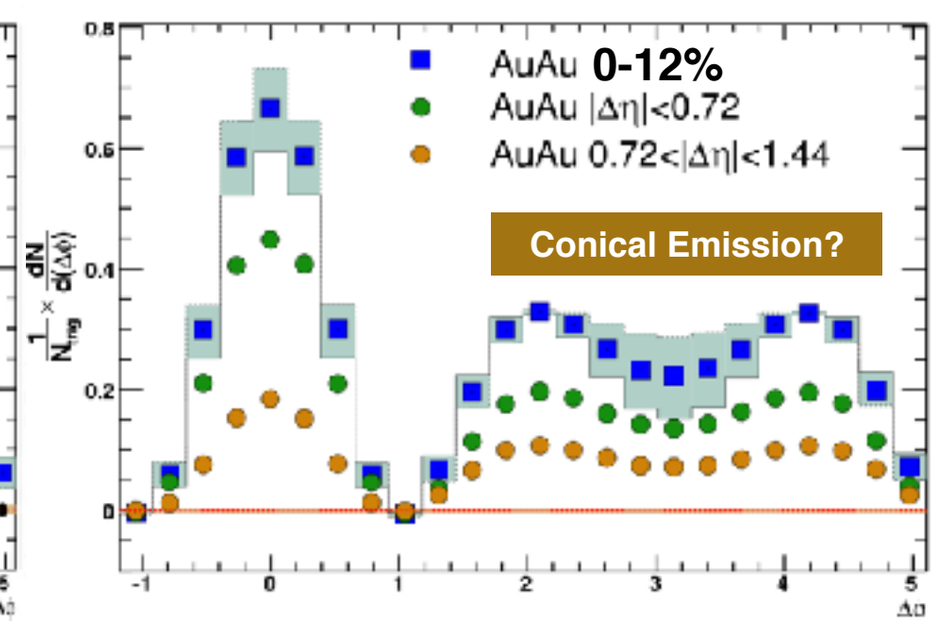


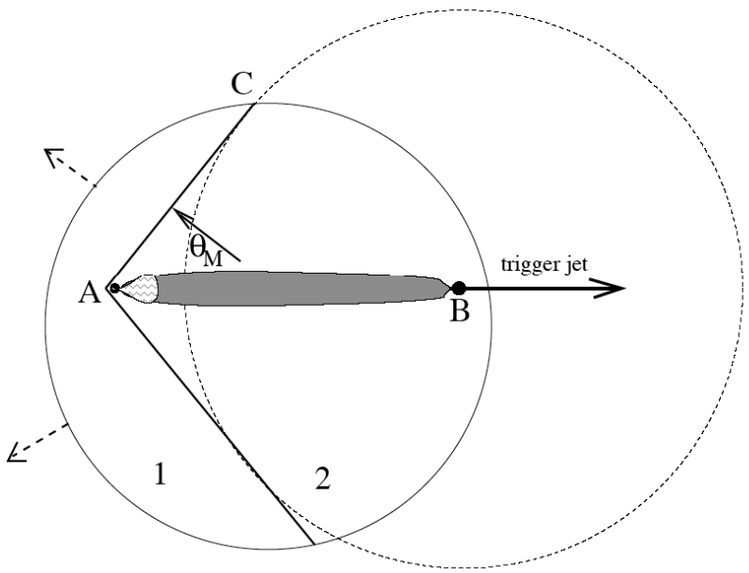


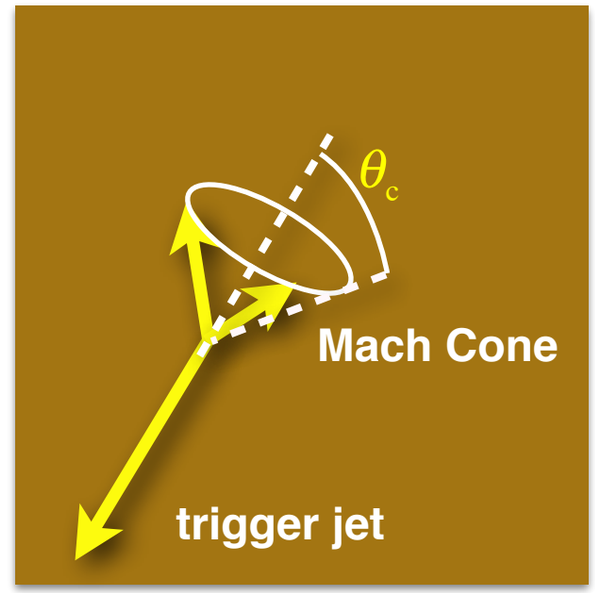


Mark Horner, STAR Collaboration
J. Phys. G: Nucl. Part. Phys. 34 (2007) S995

Conical Emission Maybe?

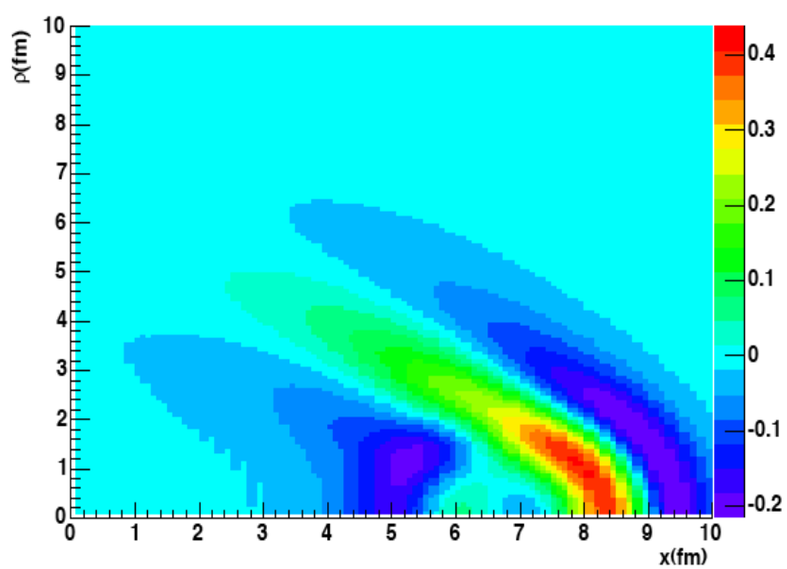
E. Shuryak, B. Muller, H. Stocker + many others

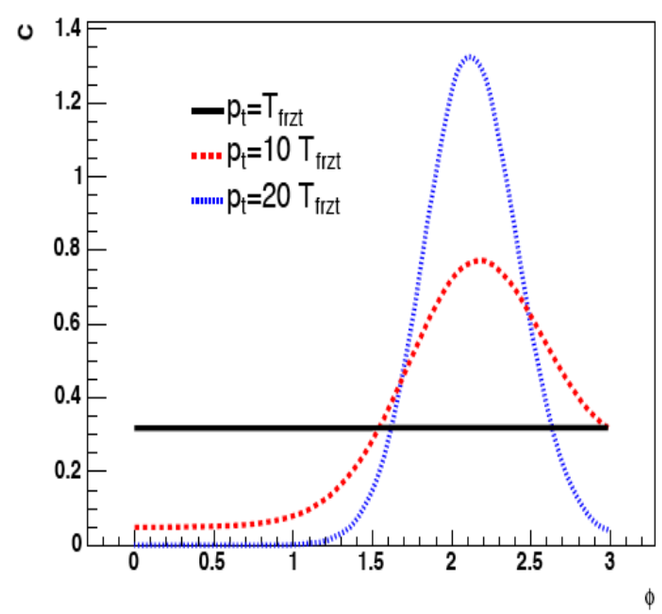




Potential sensitivity to speed of sound in medium!!

Very Cool Concept!



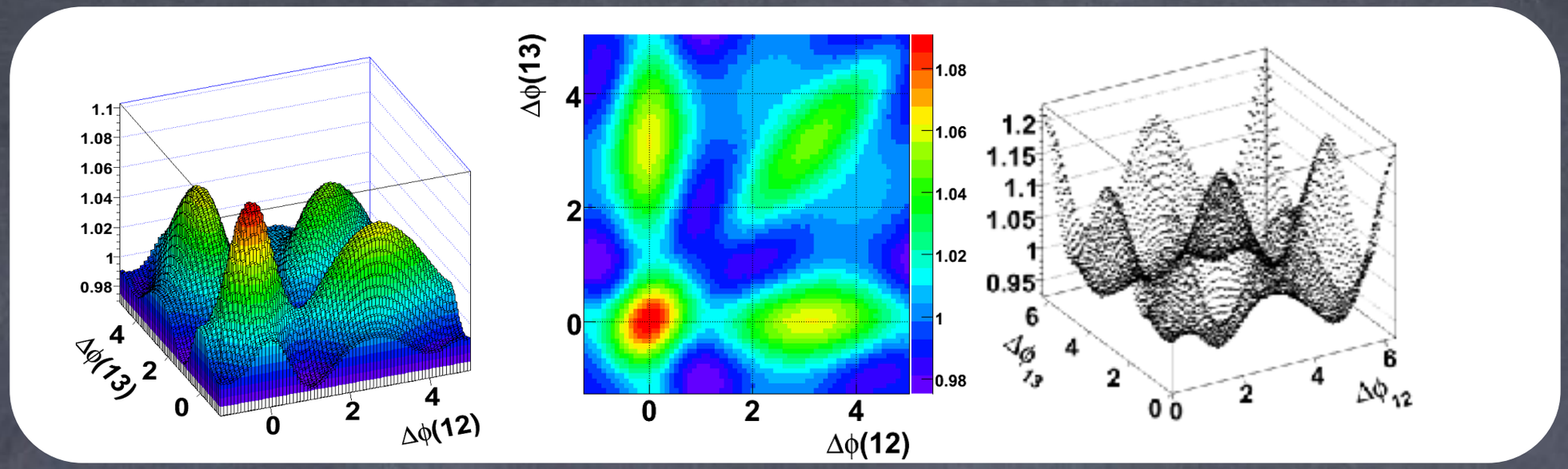


Alternative Interpretation Cherenkov radiation: V. Koch, A. Majumder

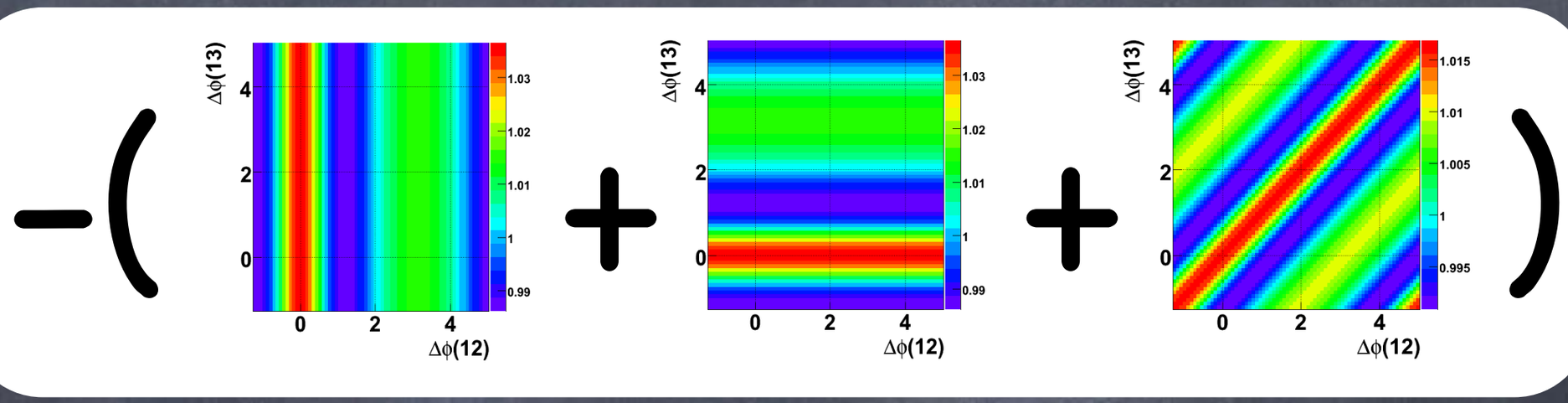
What about flow? How could we miss this?

We did not!

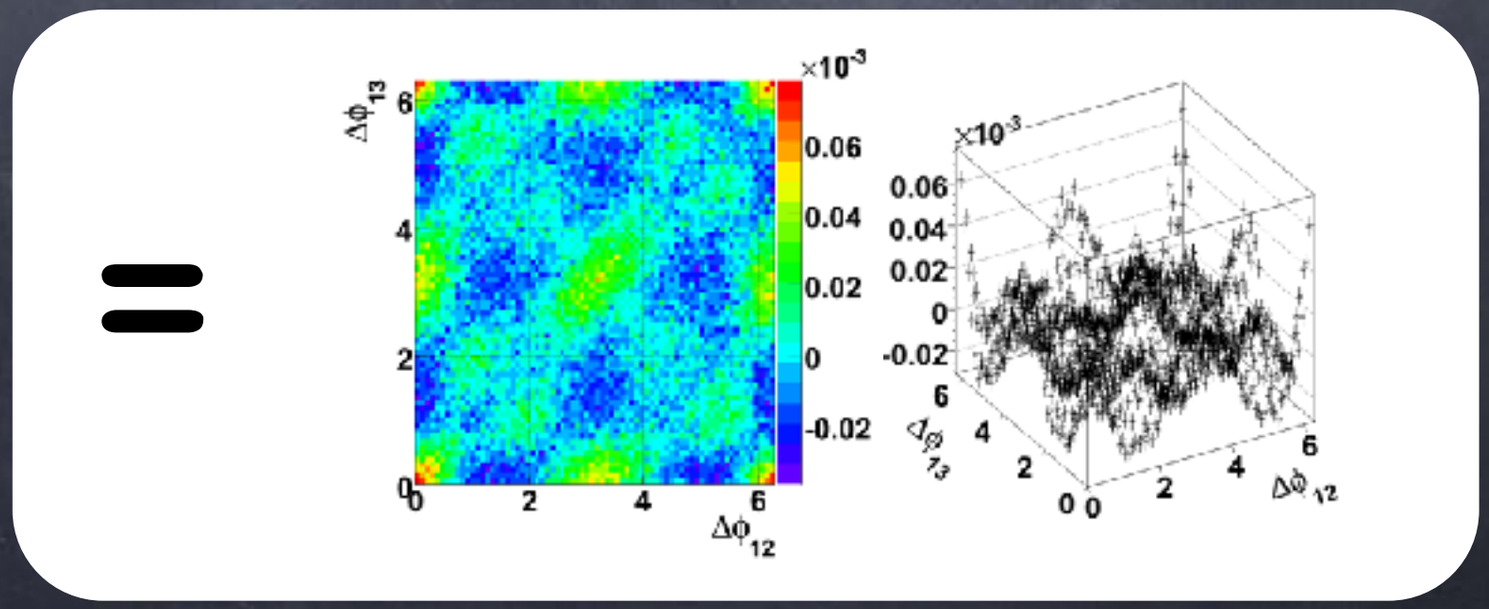
3-Particle Density
(3 views)



Combinatorial
Terms



3-Cumulant
(2 views)



STAR Preliminary

Anisotropic Flow

C.P., arXiv:0810.1461

$$P_F(\varphi_i \mid \psi) = 1 + 2\sum_m v_m(i)\cos\big(m(\varphi_i - \psi)\big)$$

$$C_{2,Flow}(\Delta\varphi_{ij}) = (2\pi)^{-2}\langle N_i N_j\rangle\Big(1 - d_{ij} + 2\sum_m v_m(i)v_m(j)\cos\big(m$$

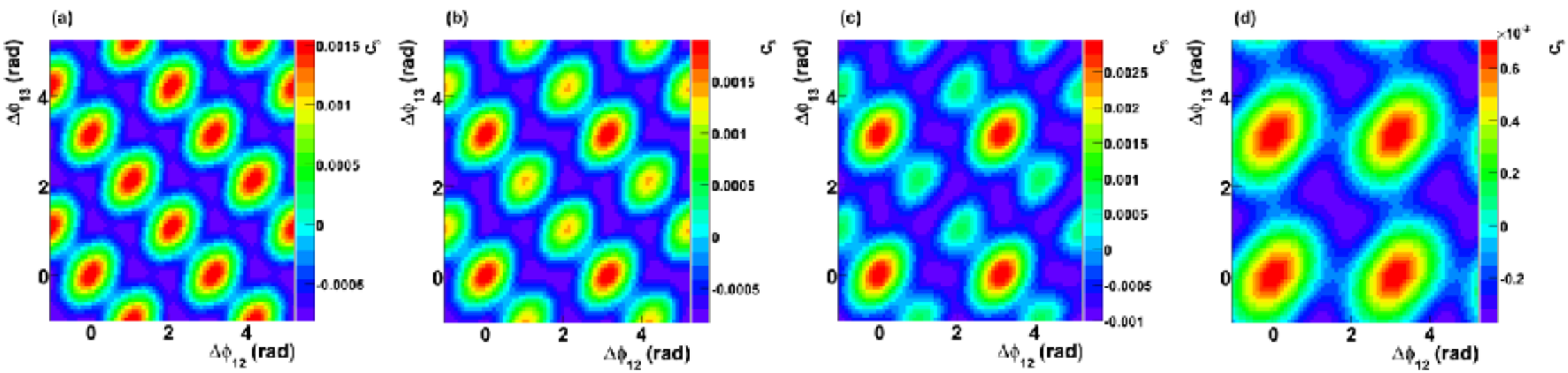
$$C_{3,Flow}(\Delta\varphi_{ij},\Delta\varphi_{ik}) = (2\pi)^{-3}\langle N_i N_j N_k\rangle\begin{cases}\Phi_3(\Delta\varphi_{ij},\Delta\varphi_{ik}) \\ +(1-f_{ijk})\Phi_2(\Delta\varphi_{ij}) + (1-f \\ +1 - f_{ijk} - f_{ikj} - f_{jki} + 2g_{ijk}\end{cases}$$

$$\Phi_2(\Delta\varphi_{ij}) = 2\sum_m v_p(i)v_m(j)\cos\big(p\varphi_i - m\varphi_j - n\varphi_k\big)$$

$$\Phi_3(\Delta\varphi_{ij},\Delta\varphi_{ik}) = 2\sum_{p,m,n} v_p(i)v_m(j)v_n(k)\begin{bmatrix}\delta_{p,m+n}\cos\big(p\varphi_i - m\varphi_j - n\varphi_k\big) \\ +\delta_{m,p+n}\cos\big(-p\varphi_i + m\varphi_j - n\varphi_k\big) \\ +\delta_{n,m+k}\cos\big(-p\varphi_i - m\varphi_j + n\varphi_k\big)\end{bmatrix}$$

$$d_{ij} = \frac{\langle N_i\rangle\langle N_j\rangle}{\langle N_i N_j\rangle};\quad f_{ij} = \frac{\langle N_i N_j\rangle\langle N_k\rangle}{\langle N_i N_j N_k\rangle};\quad g_{ij} = \frac{\langle N_i\rangle\langle N_j\rangle\langle N_k\rangle}{\langle N_i N_j N_k\rangle}$$

3-Cumulant



$d_{ij} = f_{ij} = g_{ij} = 1$

$v_4 > 0$

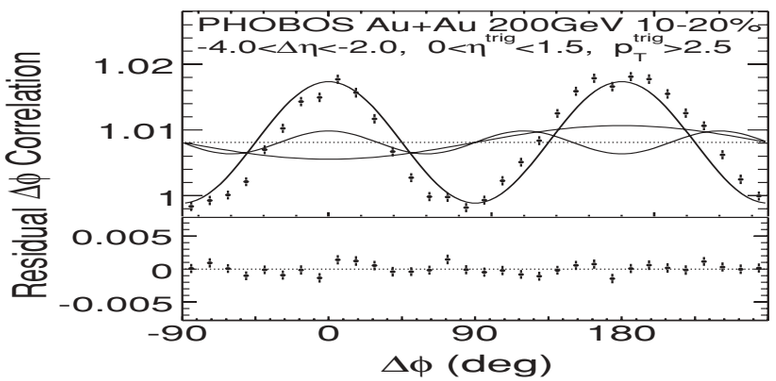
$$\frac{v_2 v_2 v_4}{(1-f_{ij})v_2 v_2} = 0.5$$

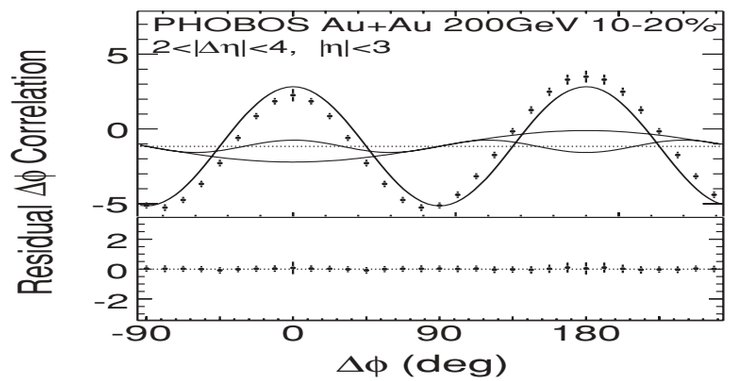
$$\frac{v_2 v_2 v_4}{(1-f_{ij})v_2 v_2} = 2$$

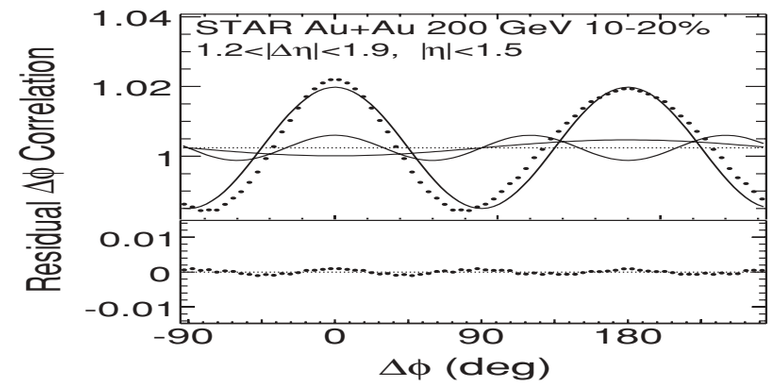
$f_{ij} < 1$

$v_4 = 0$

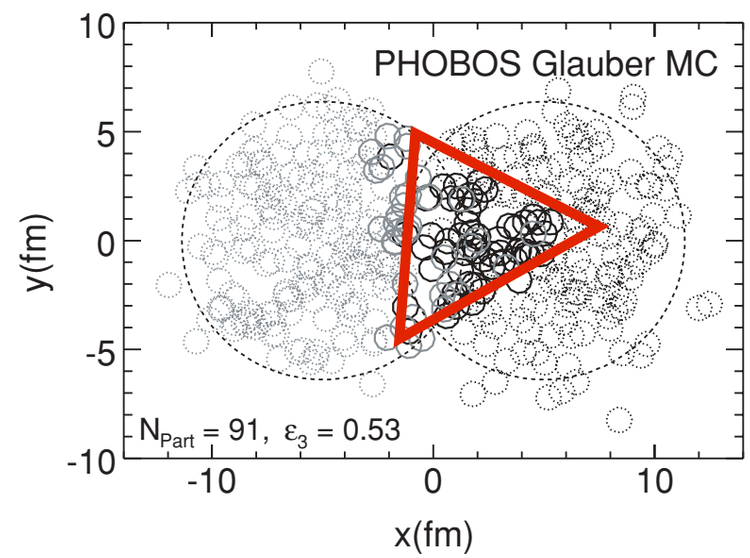
Paradigm Shift



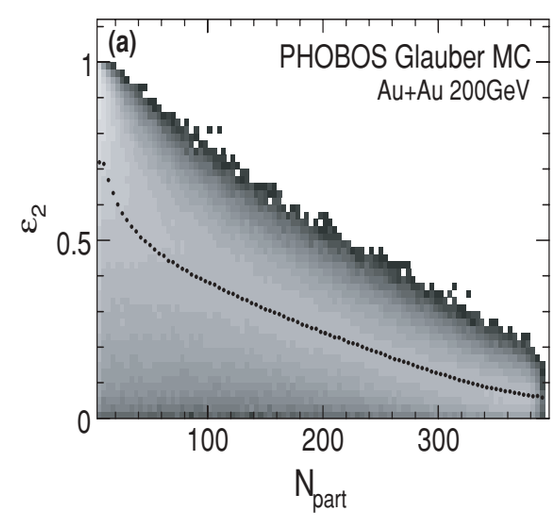


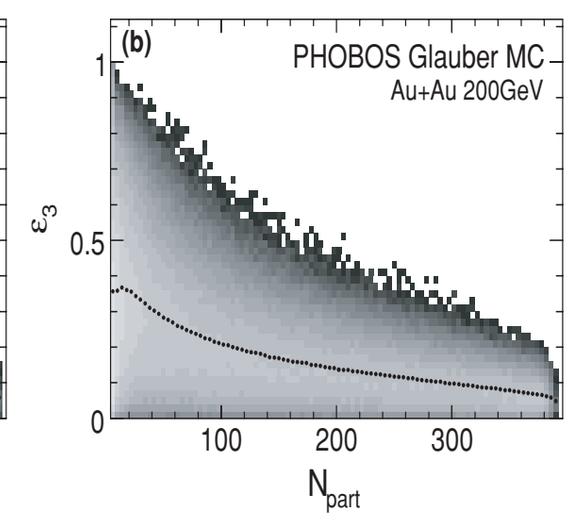


- B. Alver & G. Roland, PRC 81, 054905 (2010) Collision-geometry fluctuations and triangular flow in heavy-ion collisions
- Underlying Assumptions
  - Initial Collisions Produce Long Range Correlations
  - Fast Thermalization >>> Medium
  - Hydrodynamic Evolution
    - ***Spatial Anisotropy >>> Momentum Anisotropy***
  - Finite System Has Non-zero Odd Spatial Eccentricities
- **Consequence:**
  - **Initial Geometry Fluctuations Produce Odd Harmonics**



AuAu

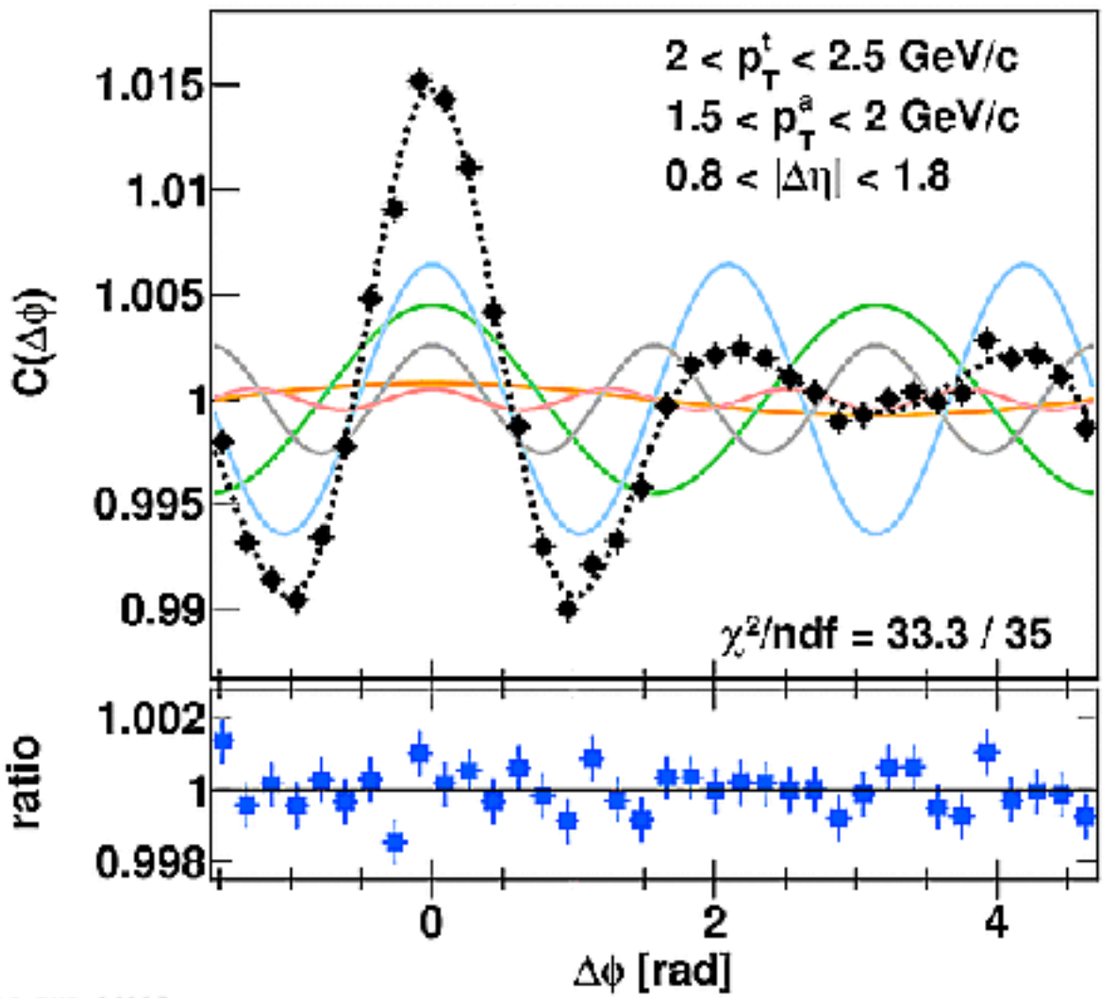




The “ridge” and the “valley”

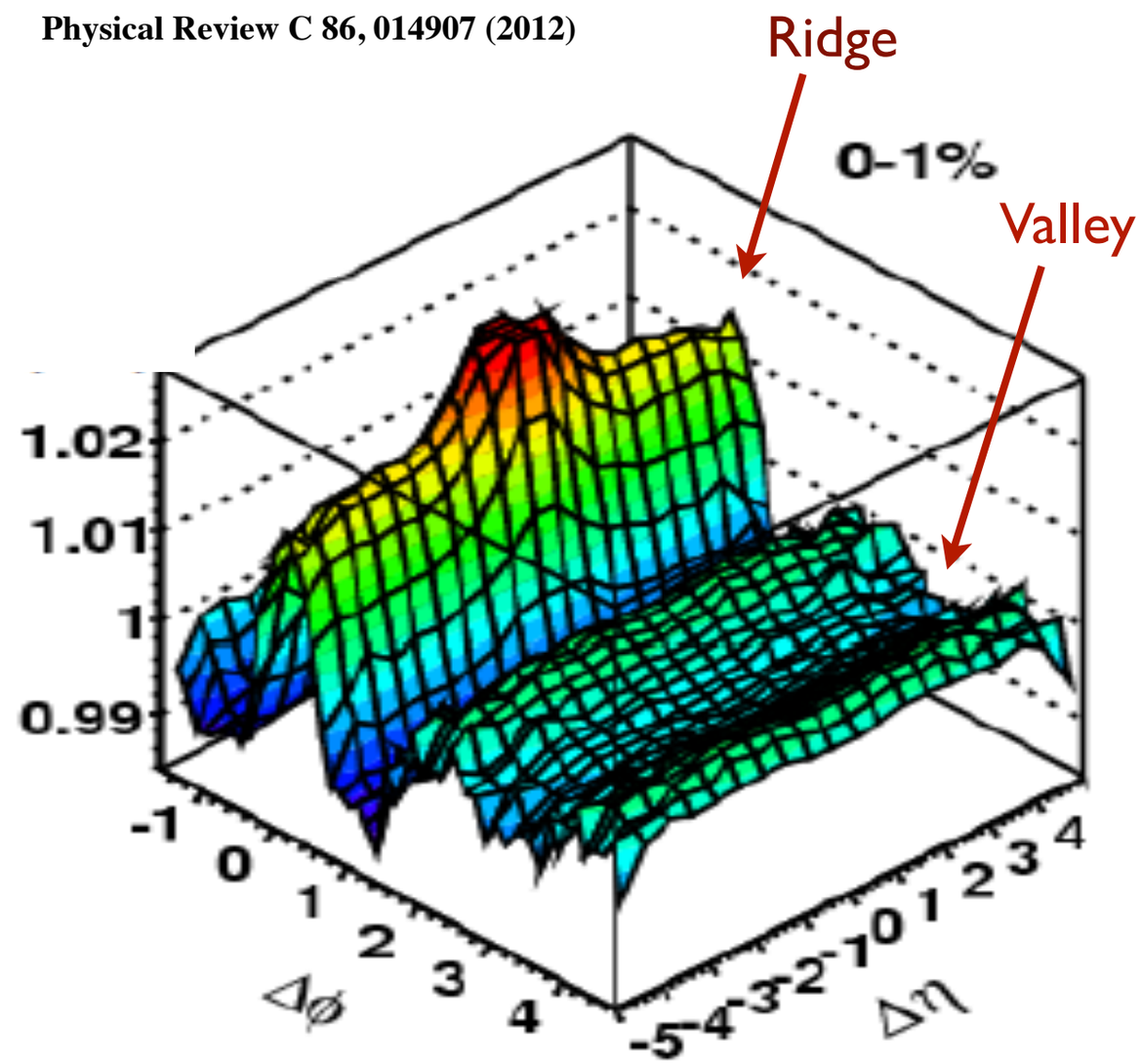
ALICE Collaboration
PLB 708 (2012) 249–264

0-2% 2.76 TeV Pb-Pb Collisions



ALI-PUB-11115

ATLAS Collaboration
Physical Review C 86, 014907 (2012)



Fourier Decomposition of R_2 & P_2

- Examine Fourier decomposition of P_2 vs. $\Delta\eta$

$$O_2 = \left(b_0 + 2\sum_{n=1}^{6} b_n \cos\left[n\left(\varphi_1 - \varphi_2\right)\right]\right)$$ in slices of $\Delta\eta$

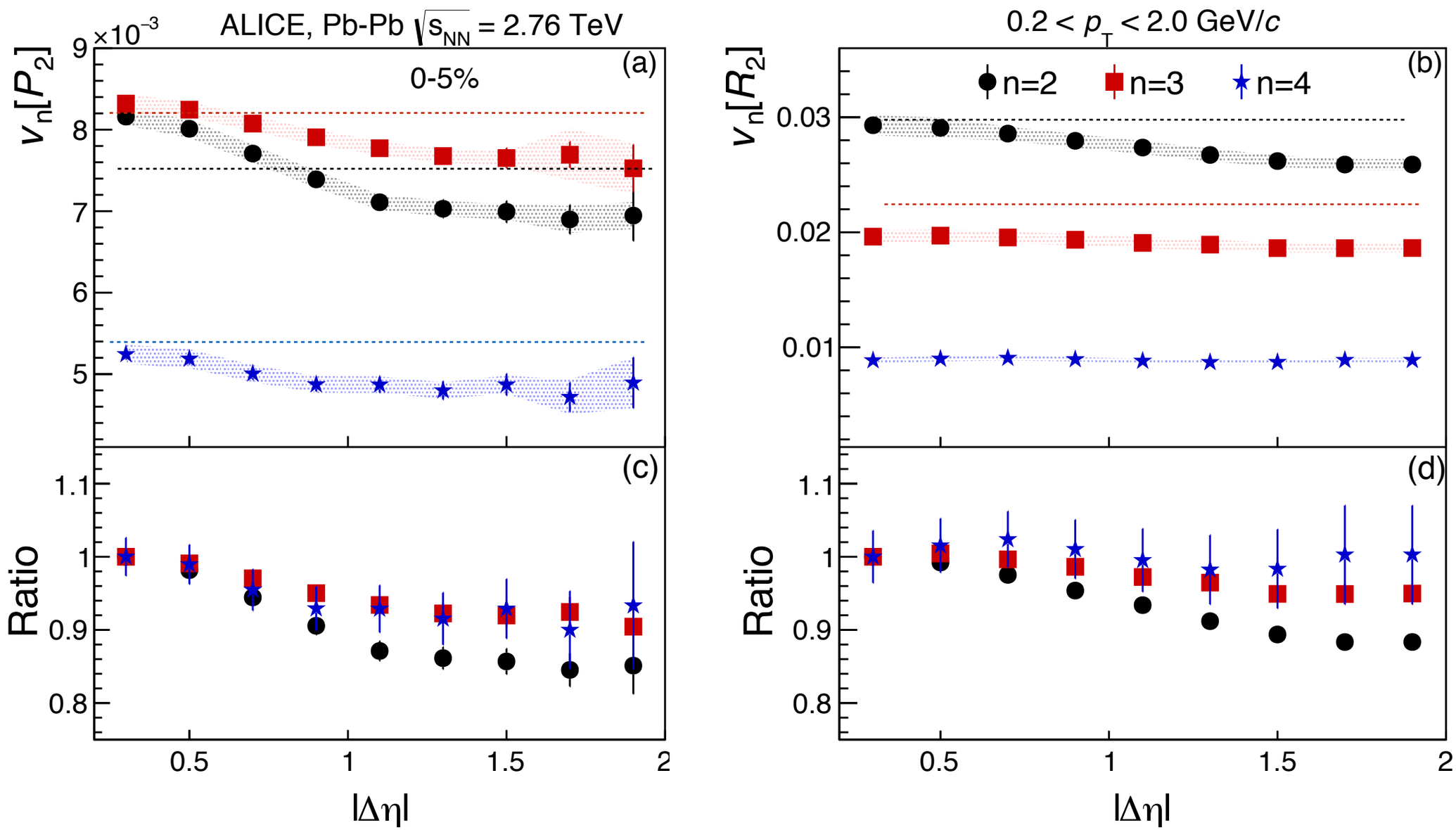
$$P_2(\Delta\eta,\Delta\phi) = \frac{\left\langle \Delta p_T \Delta p_T \right\rangle}{\left\langle p_T \right\rangle^2}$$

$$v_n[P_2] = \frac{v_n^{pT}}{\left\langle p_T \right\rangle} - v_n^{pT}$$

Flow coefficients from Scalar Product Method

$V_n[P_2]$, $V_n[R_2]$ vs Pair Separation

P. Pujahari, C.P., ALICE Collaboration, PRL 118, 162302 (2017).



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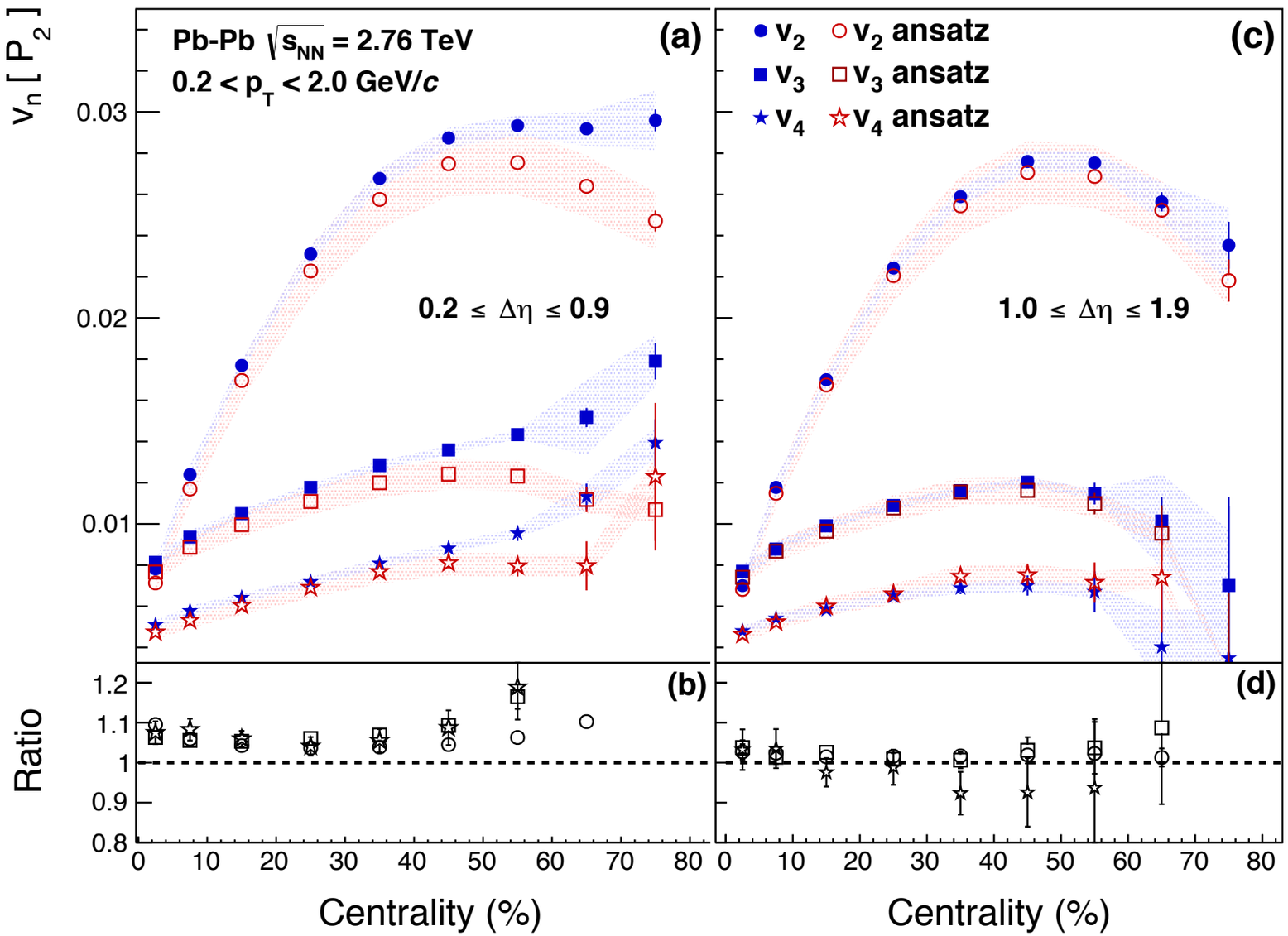
$V_n[P_2]$ vs. Collision Centrality

P. Pujahari, C.P., ALICE Collaboration, PRL 118, 162302 (2017).



Very good agreement between P_2 Fourier coefficients and flow ansatz in $1 < \Delta\eta < 1.9$.

Further evidence for the dominance (and existence) of flow in A+A collisions.

Summary/Conclusions

- P_2 correlation functions exhibit dip in 0-5% Pb - Pb collisions.
  - P_2 more sensitive than R_2 to third harmonic
- Fourier coefficients of P_2 …
  - “plateau earlier” than those of R_2.
  - factorize
  - have a magnitude in excellent agreement w/ expectation from flow ansatz.
- This work provides an additional test (and confirmation) of the strong dominance of flow in 2-particle correlations observed in Pb - Pb collisions (for pair separation in excess of 0.9 units of rapidity).

Yes: Flow is real!

But: How large does the system have to be?

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