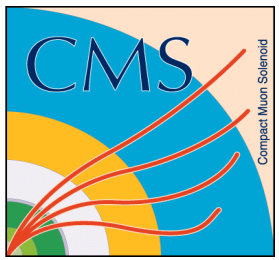
Leading and sub-leading flows at the LHC from the CMS

Damir Devetak
CMS Collaboration

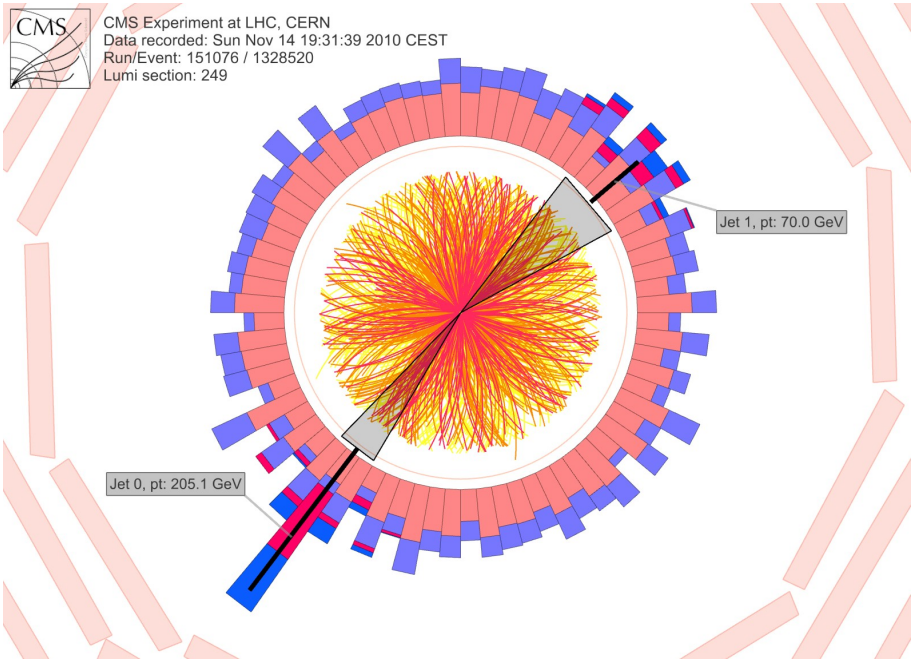
Excited QCD, Costa da Caparica 2016



UNIVERSITY OF BELGRADE,
VINCA INSTITUTE OF NUCLEAR SCIENCES

Studies of flow phenomena in CMS

- **Heavy ion collisions**



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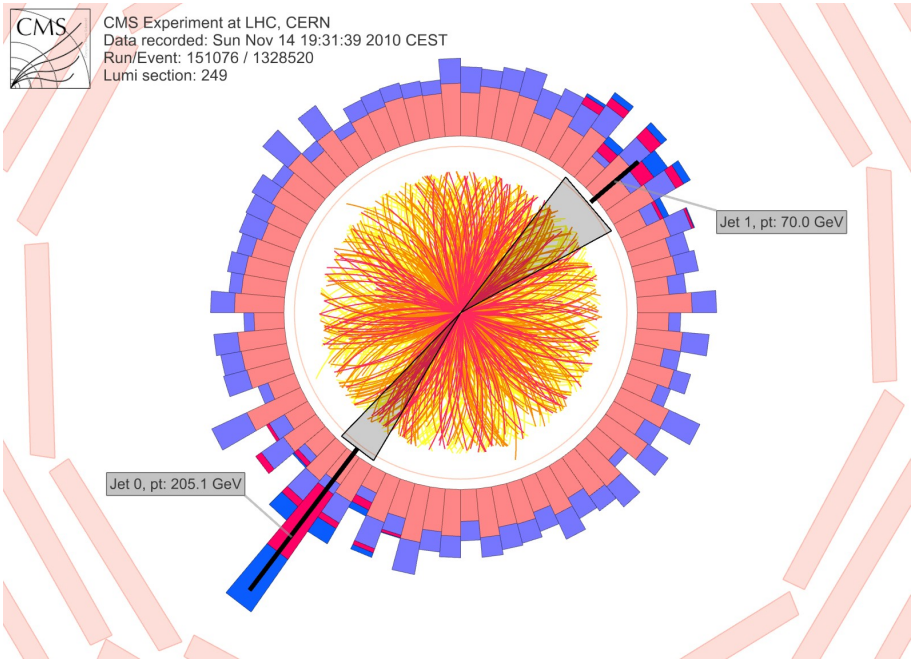

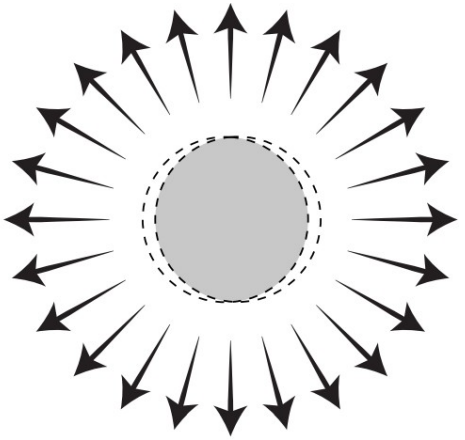

$$\frac{dN}{d\phi} \sim 1$$

Isotropic emission

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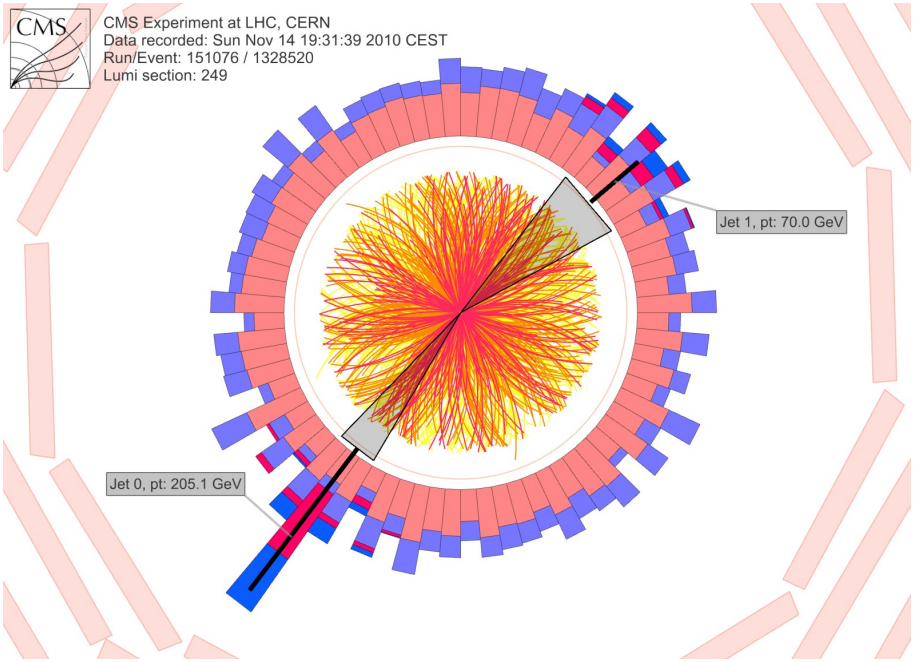

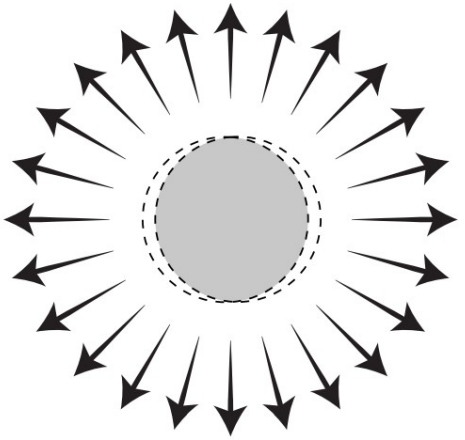

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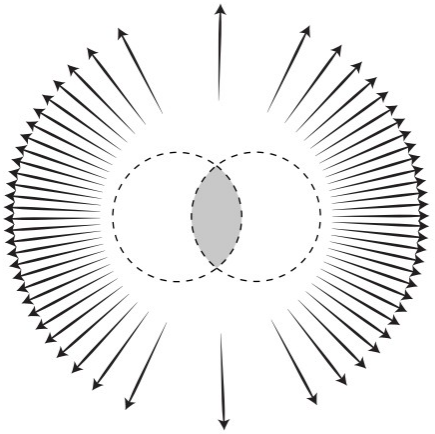

$$\frac{dN}{d\phi} \sim 1 + 2\sum_{n=1}^{N} v_n \cos n\left(\phi - \Psi_n\right)$$

Anisotropic emission

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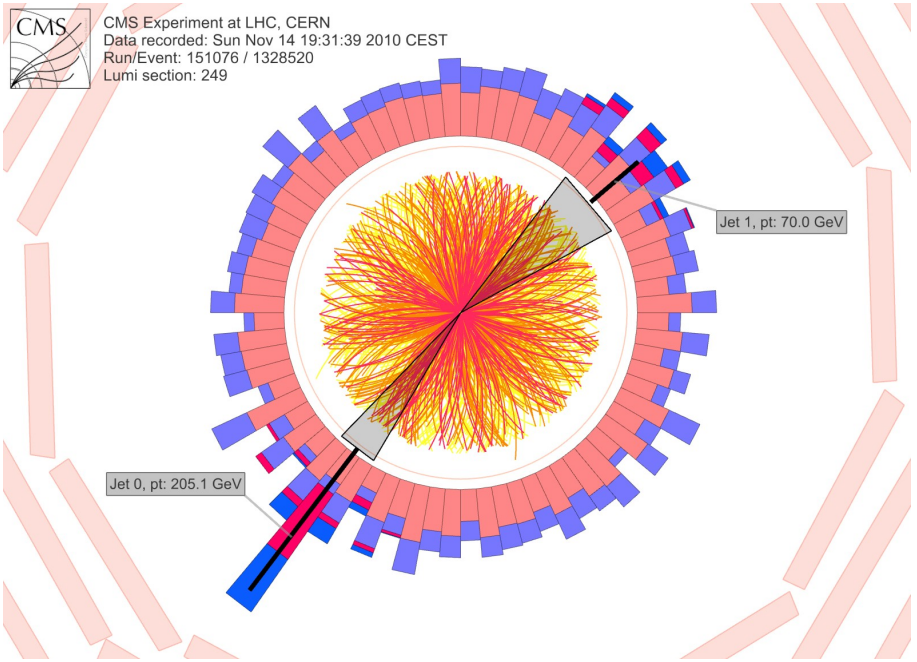

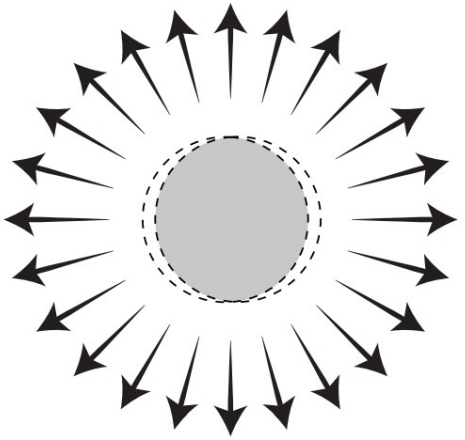

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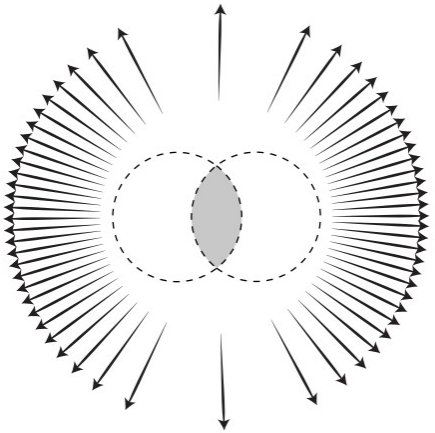

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Anisotropic emission

➔ **EVENT PLANE ANGLE METHOD**

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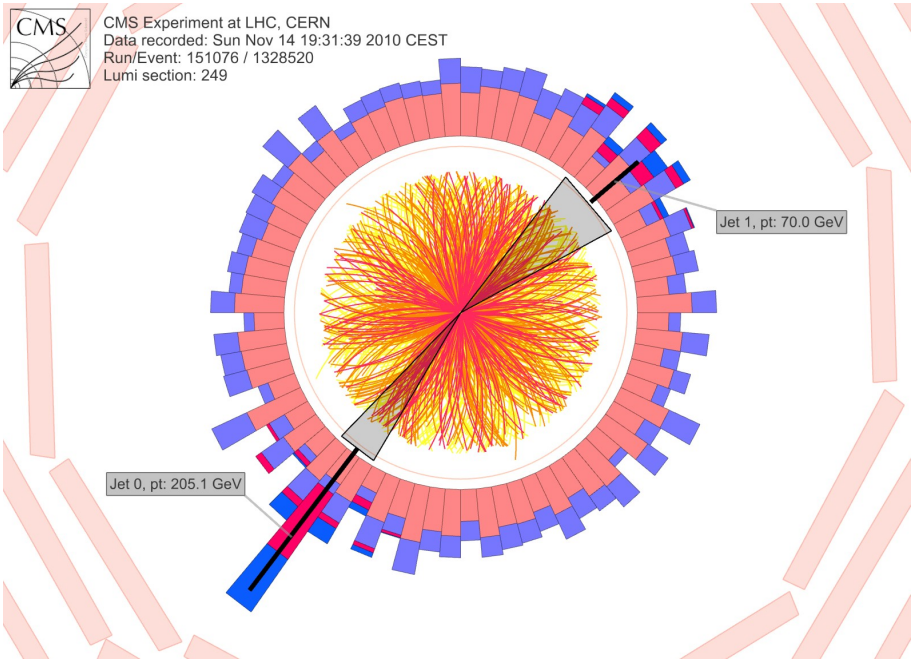

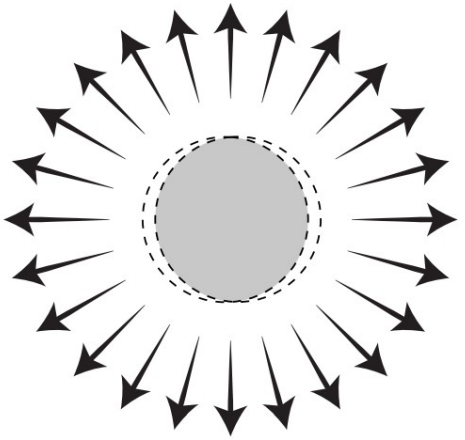

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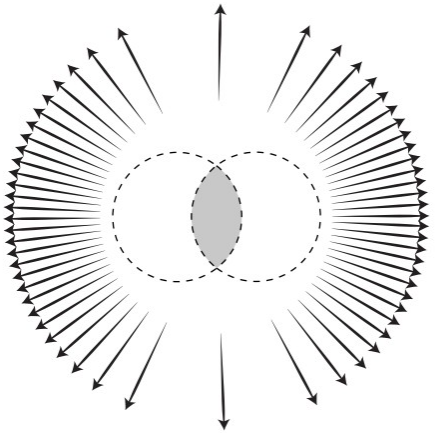

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Anisotropic emission

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- ➔ **TWO-PARTICLE CORRELATION METHOD**

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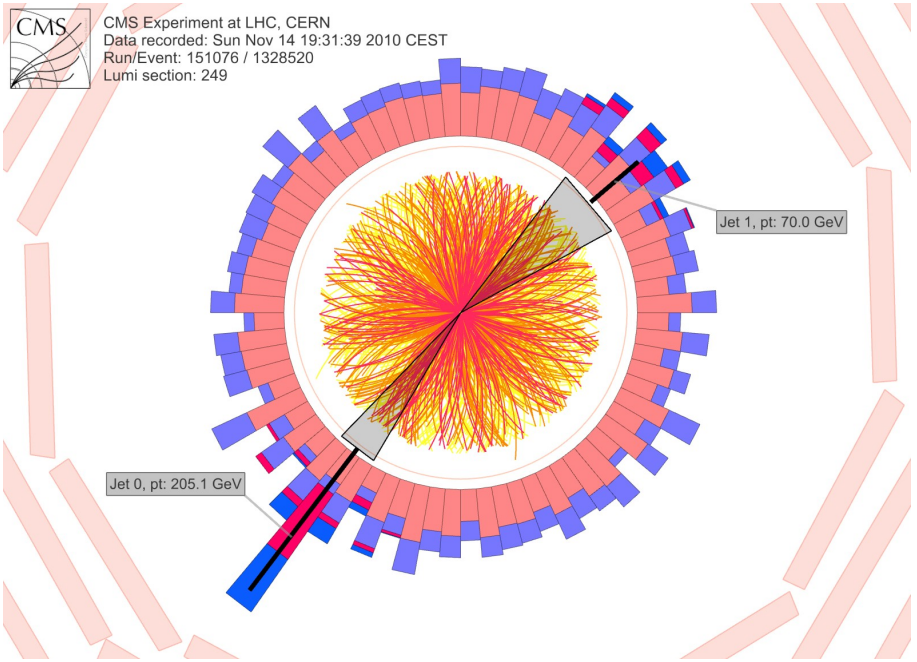

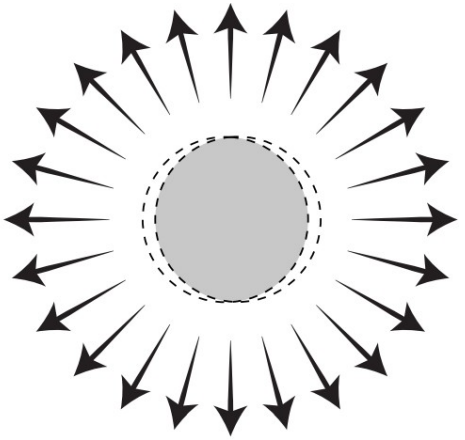

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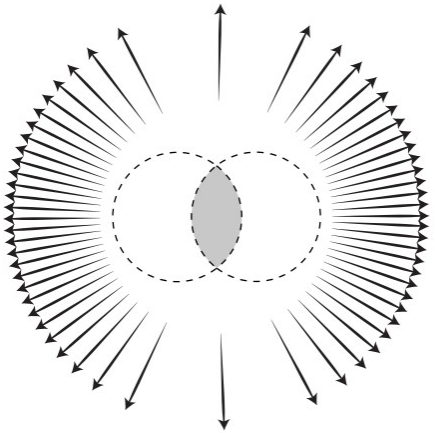

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Anisotropic emission

- ➔ **EVENT PLANE ANGLE METHOD**
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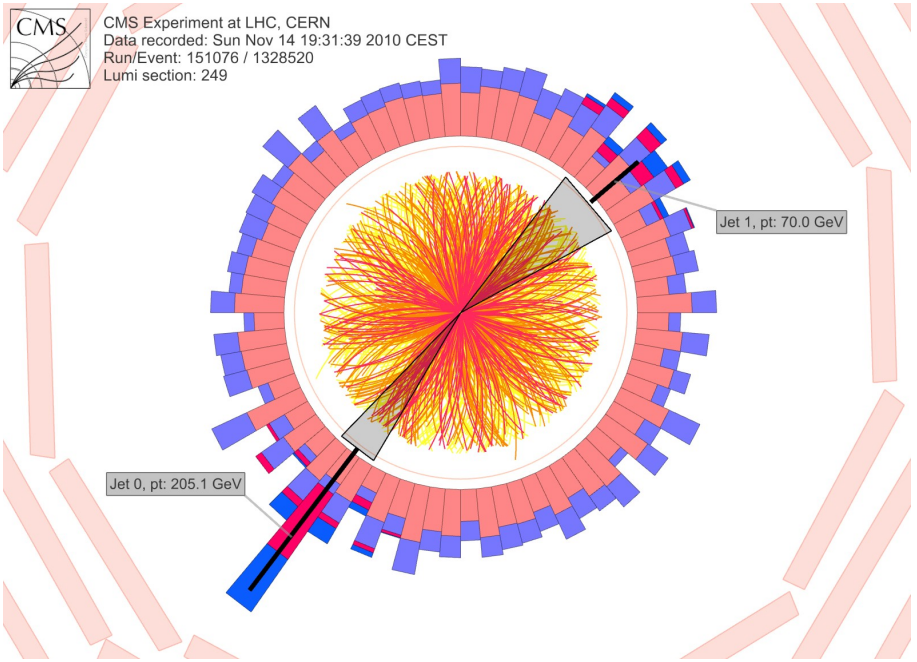

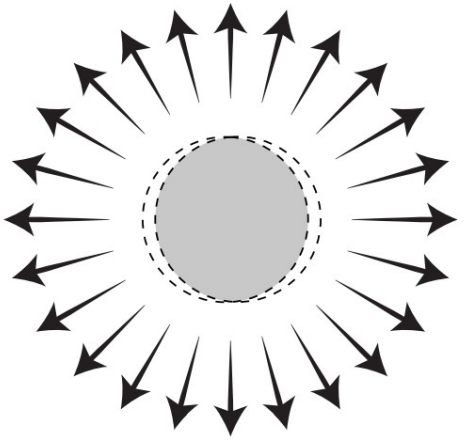

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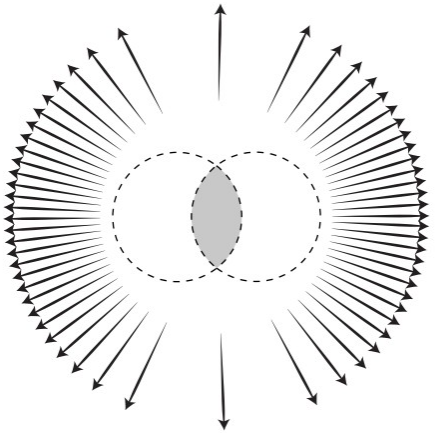

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Anisotropic emission

- ➔ **EVENT PLANE ANGLE METHOD**
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- ➔ **LEE-YANG ZERO (ALL-PARTICLE CORRELATION)**

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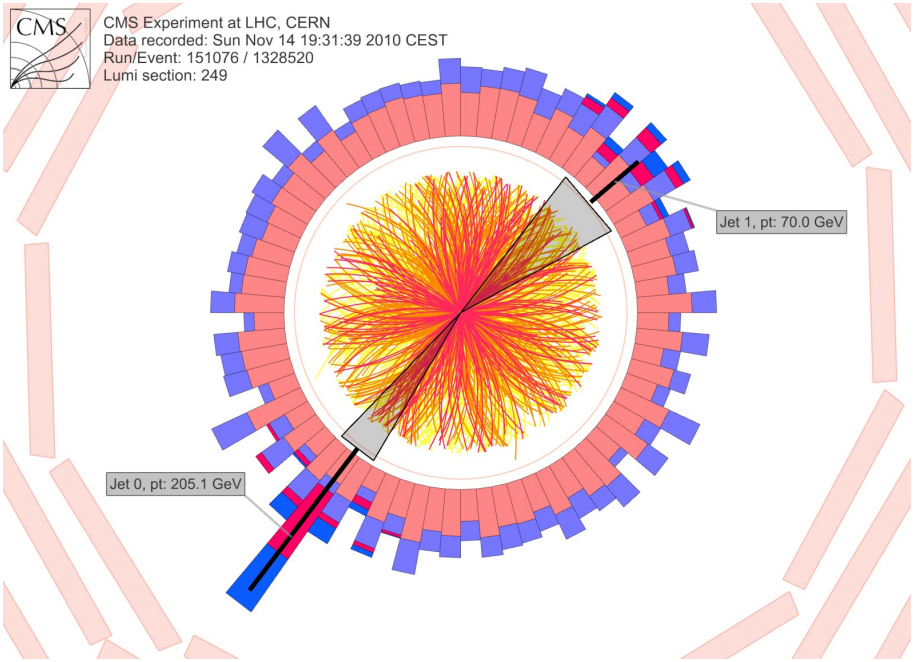

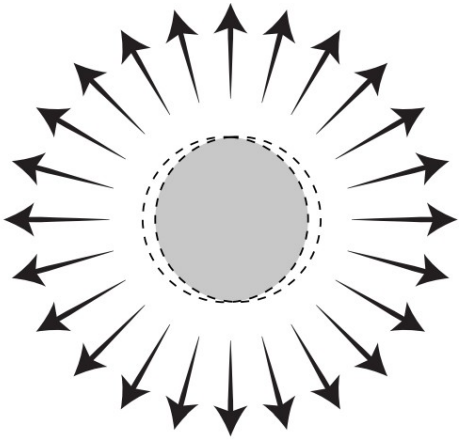

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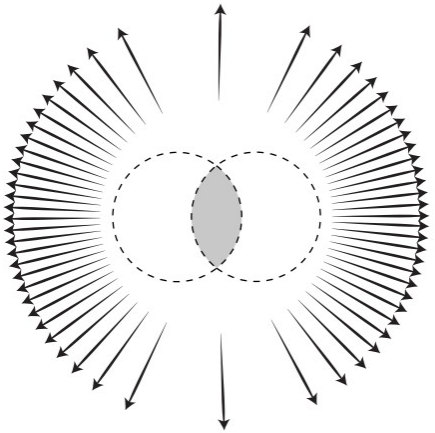

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Anisotropic emission

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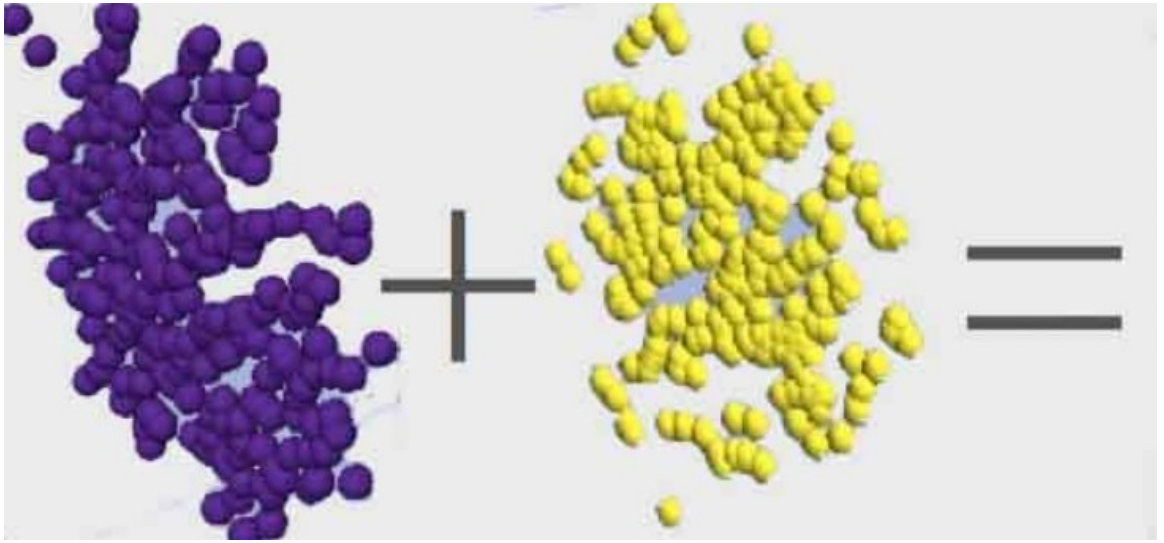
NEW METHOD:
PCA and two-particle correlations

INITIAL STATE FLUCTUATIONS



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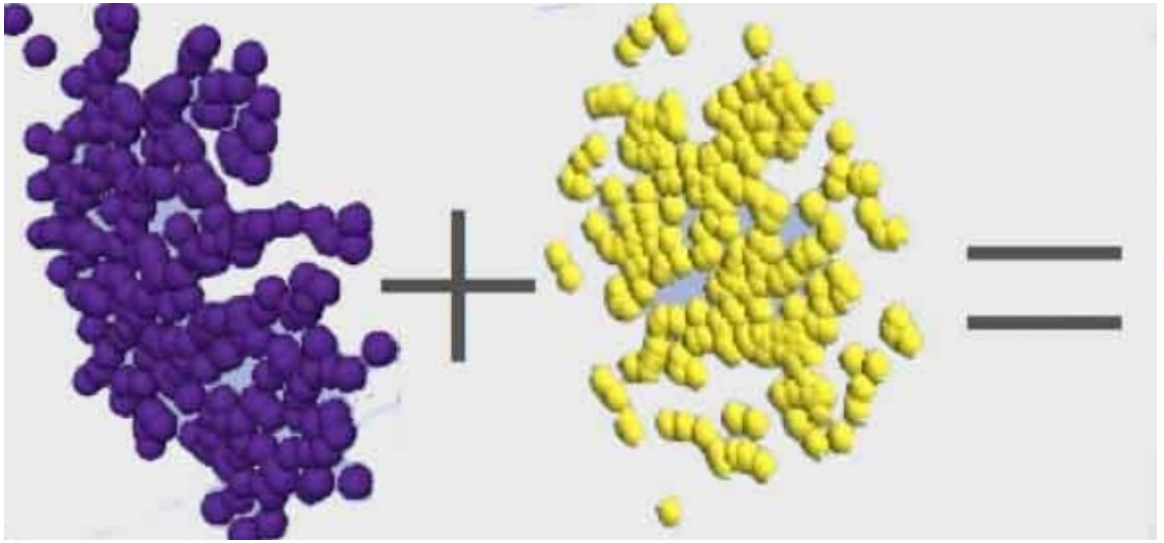

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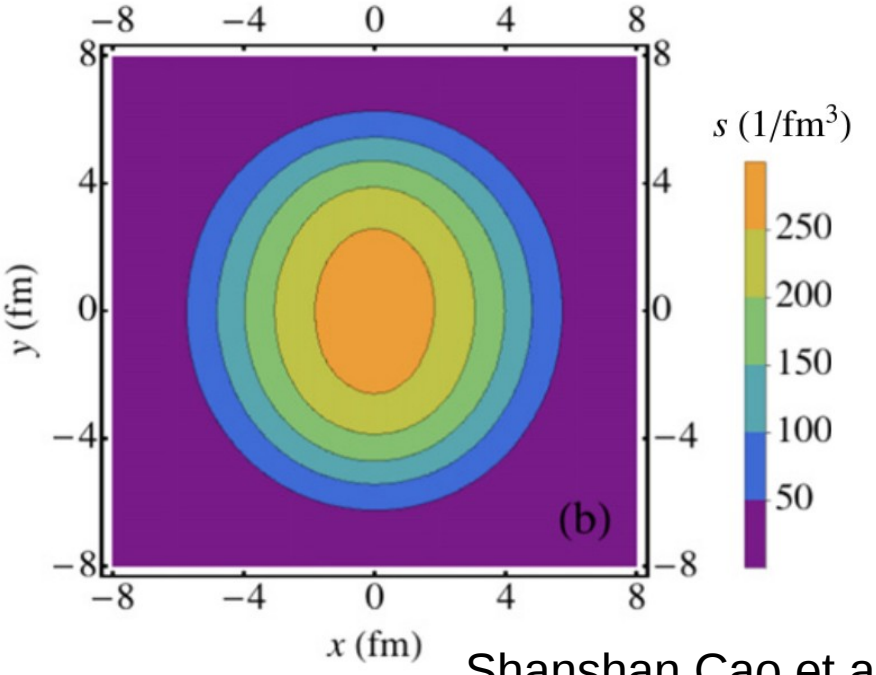
SMOOTH INITIAL ENTROPY DENSITY



Shanshan Cao et al, http://arxiv.org/abs/1404.3139

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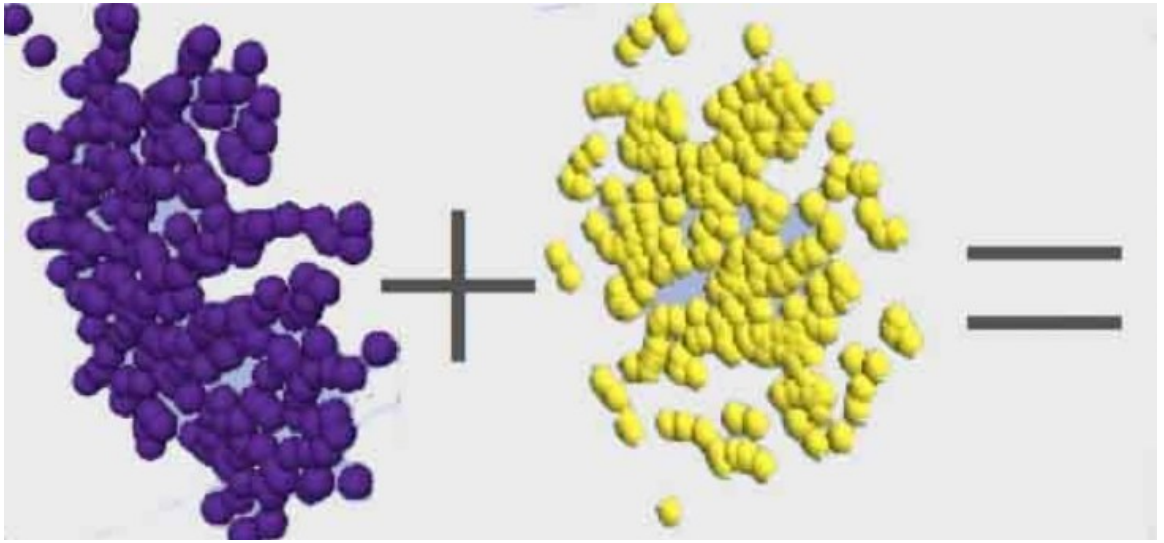

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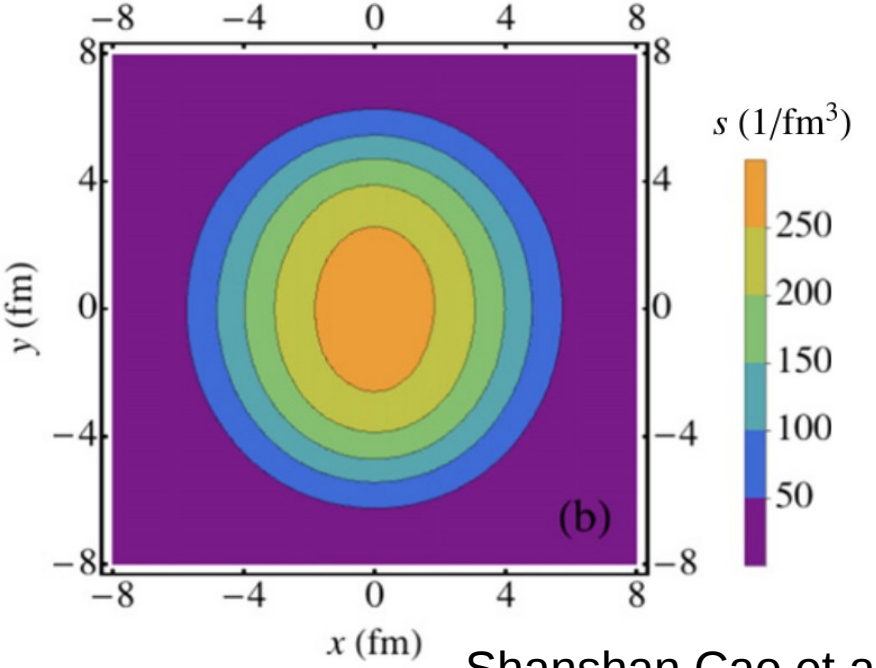
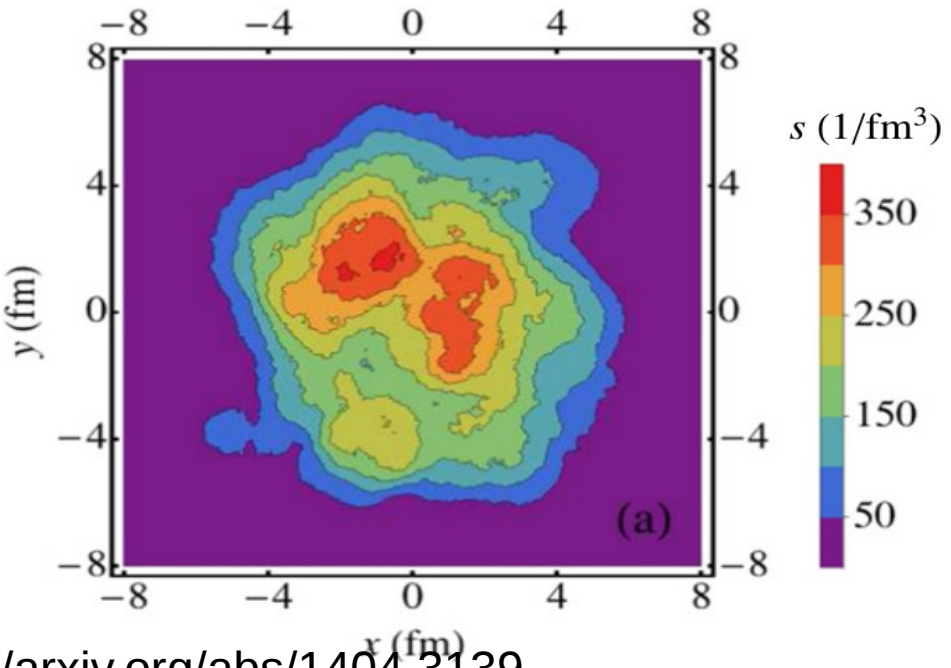


NON-SMOOTH INITIAL ENTROPY DENSITY



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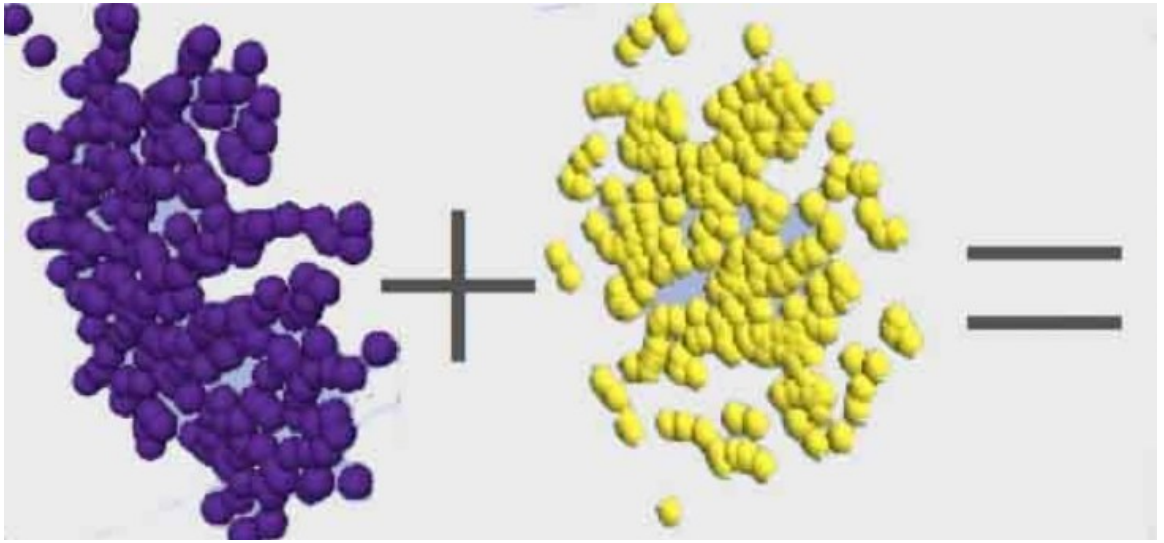
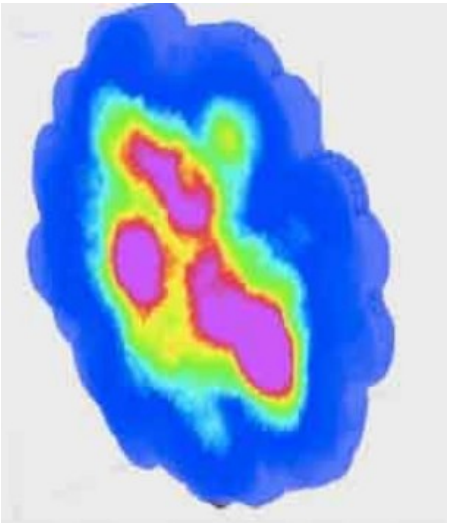
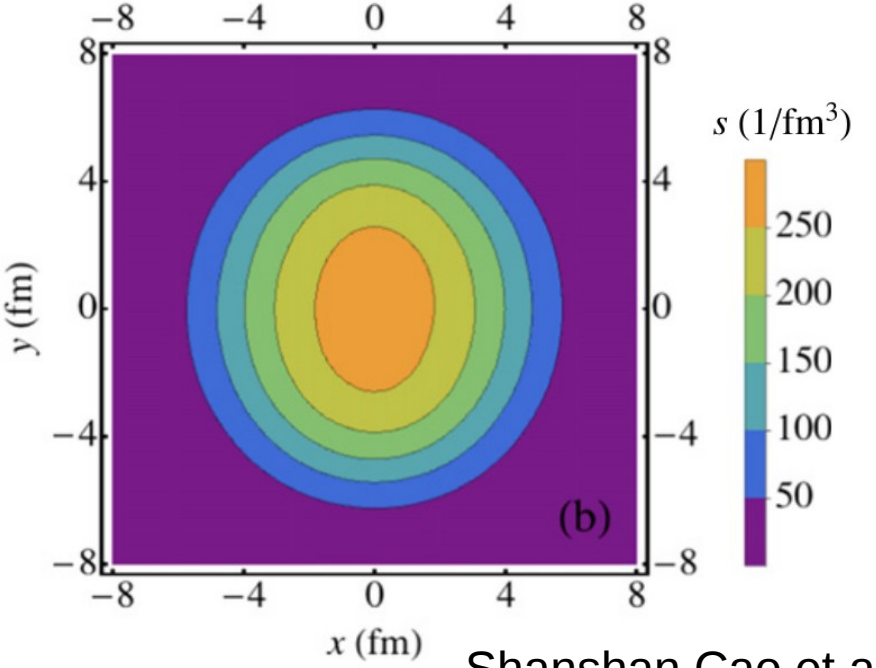




$\tau = 0.6 \frac{fm}{c}$

Image*

SMOOTH INITIAL ENTROPY DENSITY



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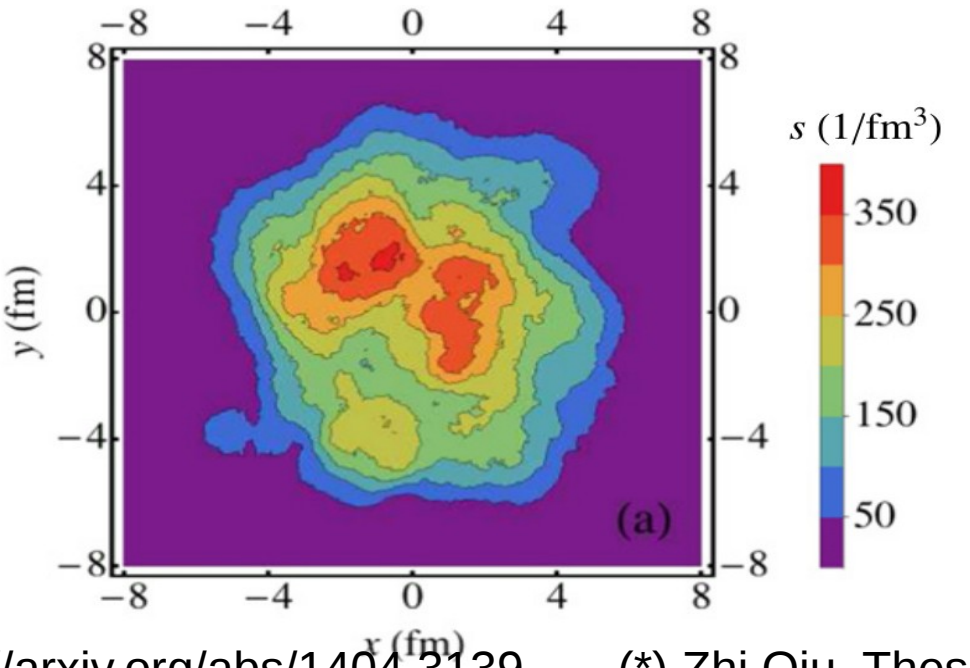

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Effects of ISF: Higher Harmonics

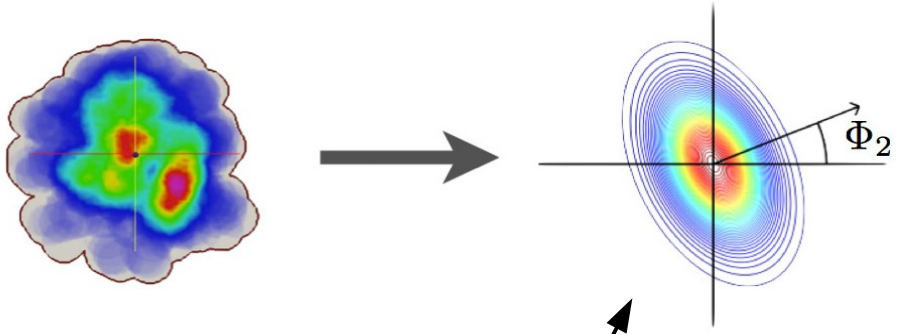
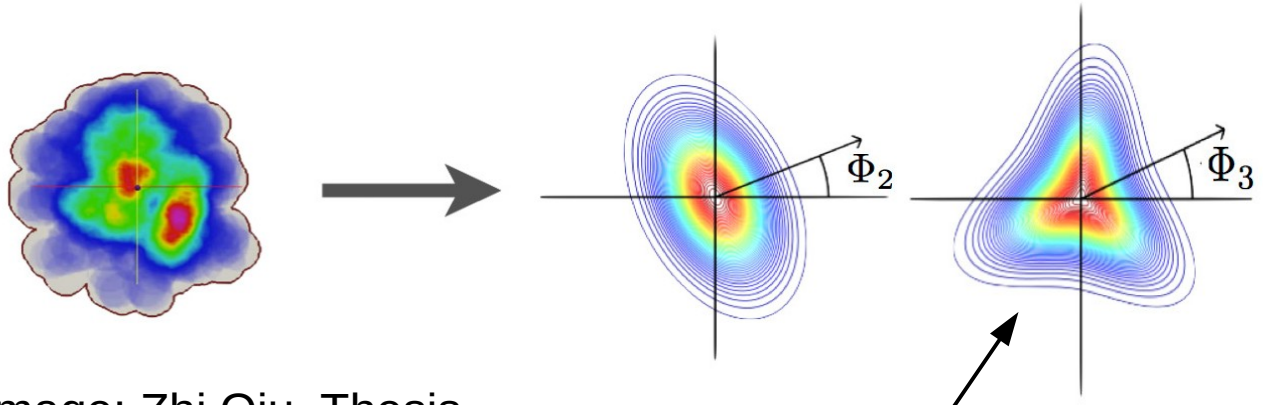


Image: Zhi Qiu, Thesis

$$\frac{dN}{d\phi} \sim 1 + 2\nu_2 \cos 2(\phi - \Phi_2)$$

ISF creates different geometrical shapes!

Effects of ISF: Higher Harmonics



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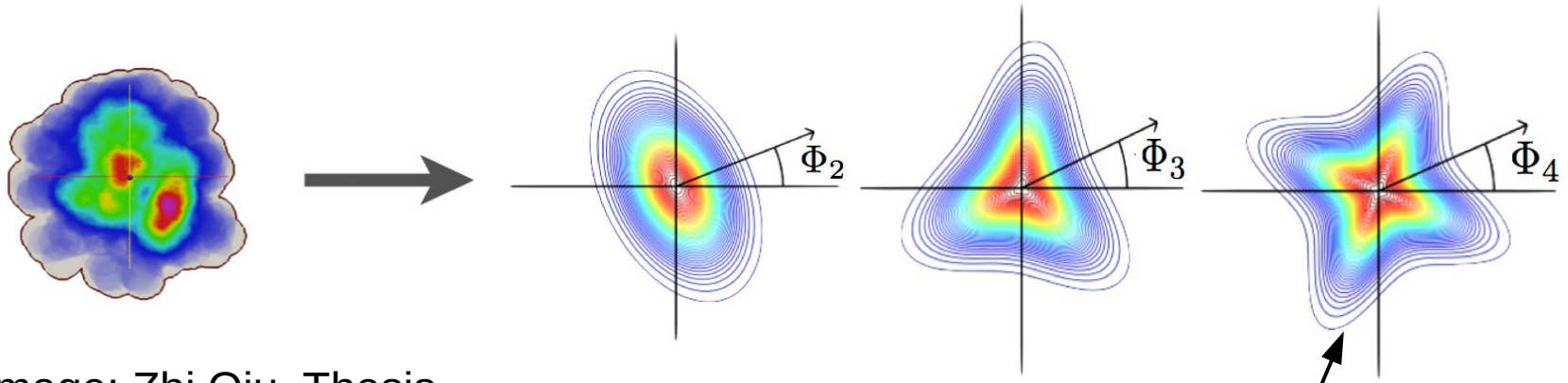

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$$\frac{dN}{d\phi} \sim 1 + 2\,\nu_2 \cos 2\left(\phi - \Phi_2\right) + 2\,\nu_3 \cos 3\left(\phi - \Phi_3\right) + 2\,\nu_4 \cos 4\left(\phi - \Phi_4\right)$$

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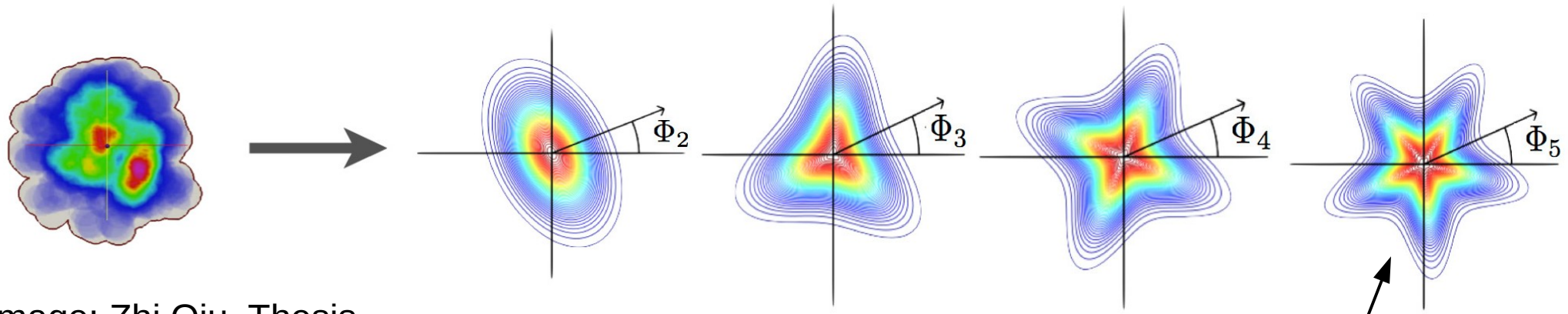
Effects of ISF: Higher Harmonics



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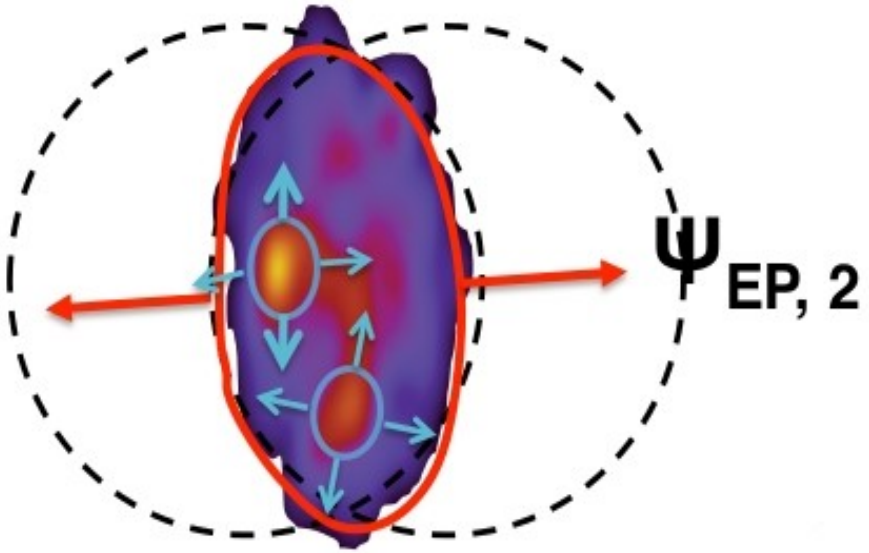
$$\frac{dN}{d\phi} \sim 1 + 2\,\nu_2 \cos 2\left(\phi - \Phi_2\right) + 2\,\nu_3 \cos 3\left(\phi - \Phi_3\right) + 2\,\nu_4 \cos 4\left(\phi - \Phi_4\right) + 2\,\nu_5 \cos 5\left(\phi - \Phi_5\right)$$

ISF creates different geometrical shapes!

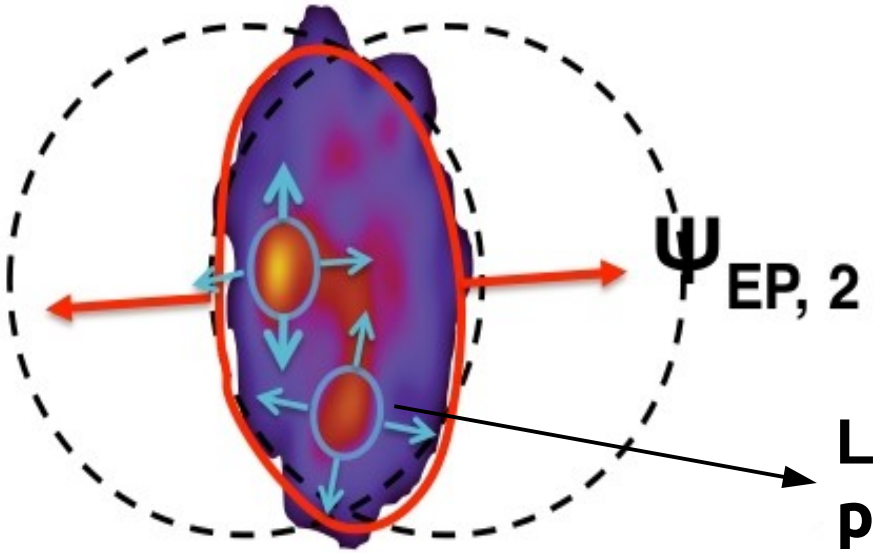
Effects of ISF: Factorization breaking



Ψ_2 is the direction of maximum particle density

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

Effects of ISF: Factorization breaking



Ψ_2 is the direction of maximum particle density

Local hotspots perturb the event plane of a smooth medium in a p_T

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

Event plane angle p_T and η dependent!

Effects of ISF: Factorization breaking

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

TWO-PARTICLE CORRELATIONS

Pearson like correlation coefficient

$$r_n = \frac{V_{\Delta n}\left(p_T^a, p_T^b\right)}{\sqrt{V_{\Delta n}\left(p_T^a, p_T^a\right) V_{\Delta n}\left(p_T^b, p_T^b\right)}} \sim \langle \cos\left(n\left(\Psi_n\left(p_T^a\right) - \Psi_n\left(p_T^b\right)\right)\right)\rangle$$

Effects of ISF: Factorization breaking

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$r_n = 1$ **factorization**

Effects of ISF: Factorization breaking

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

TWO-PARTICLE CORRELATIONS

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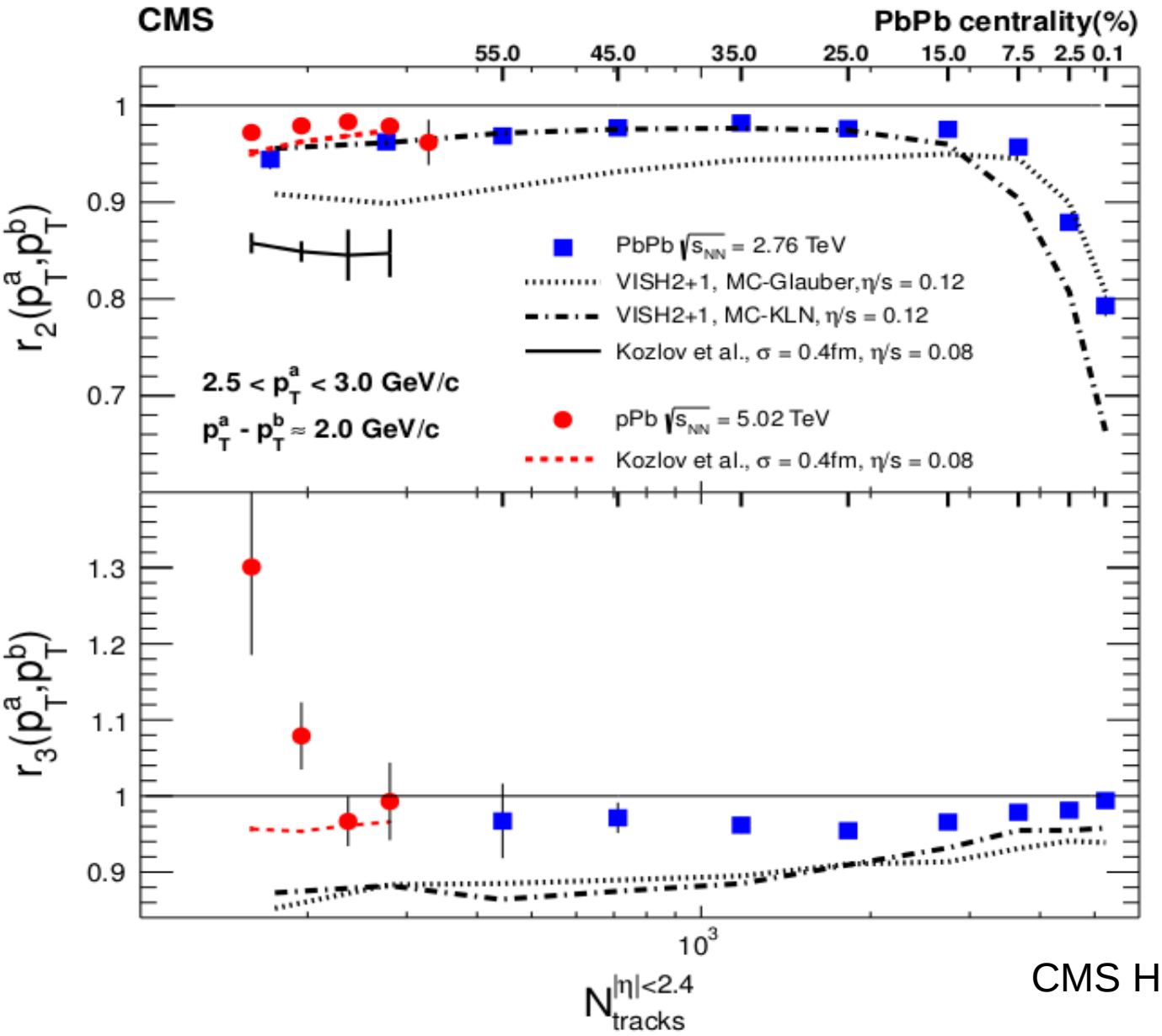
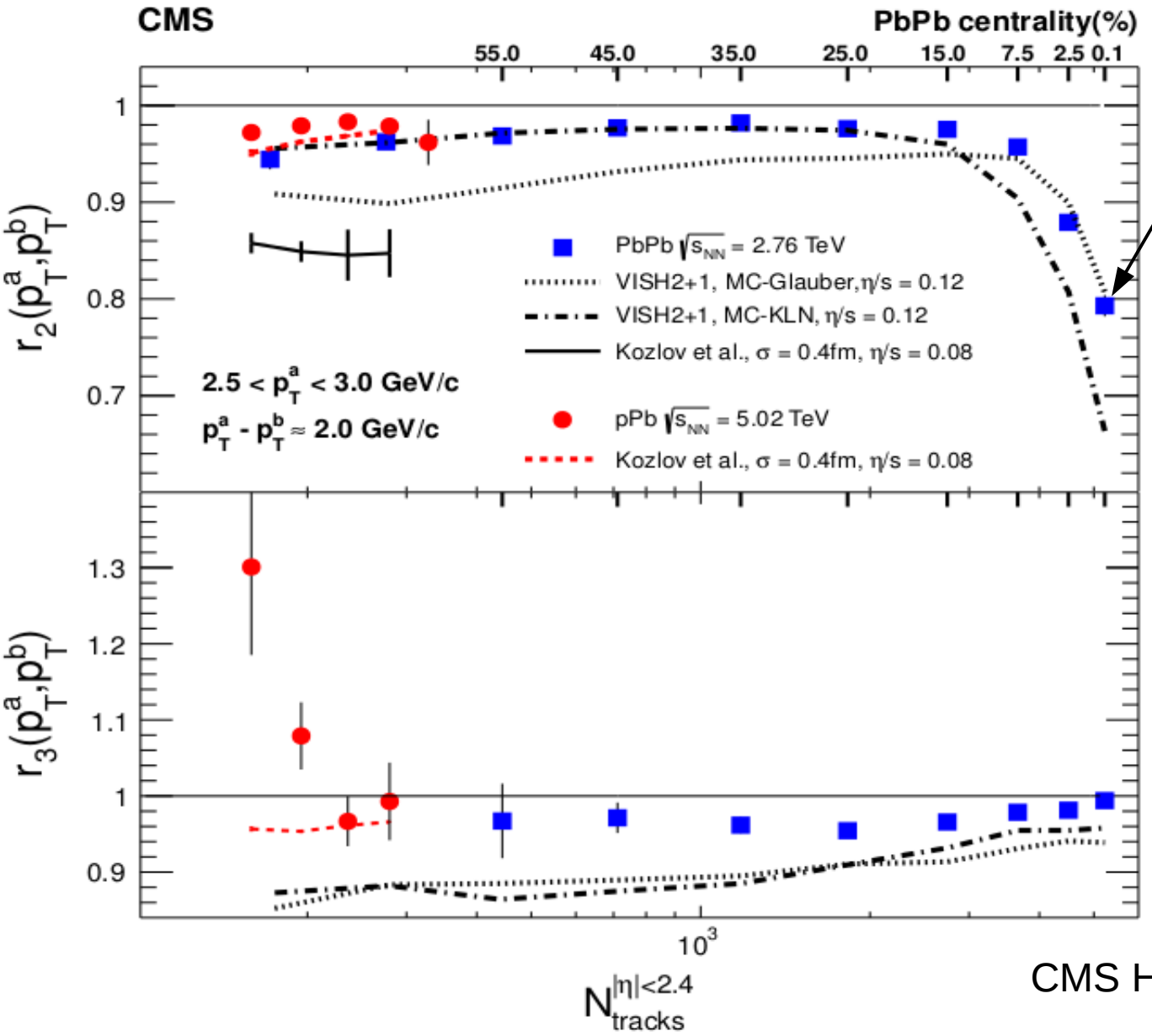
$r_n < 1$ **factorization breaking** p_T **dependence**

r_n vs. centrality



CMS HIN-14-012

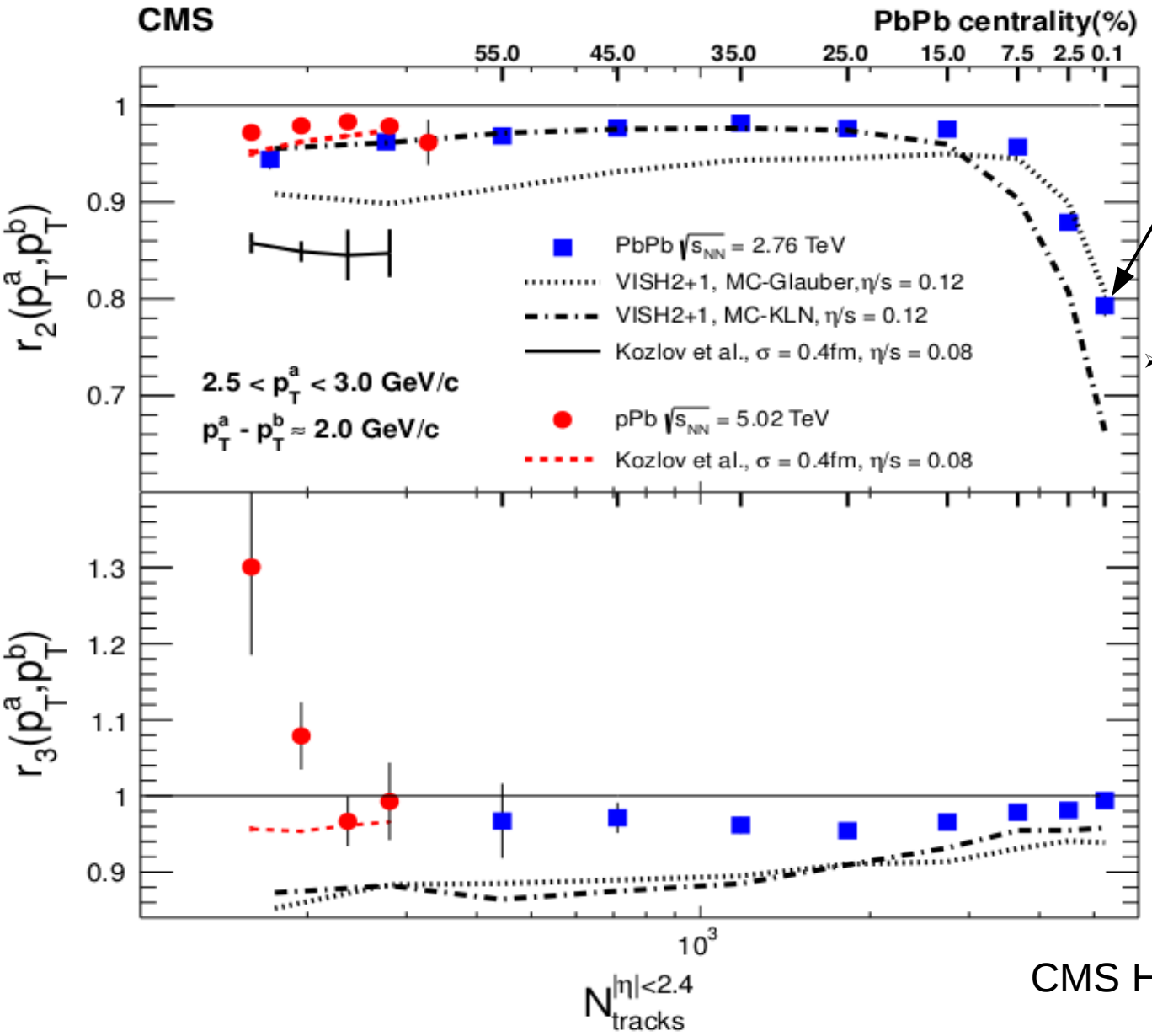
r_n vs. centrality



r_2 for UCC up to 20% !

CMS HIN-14-012

r_n vs. centrality

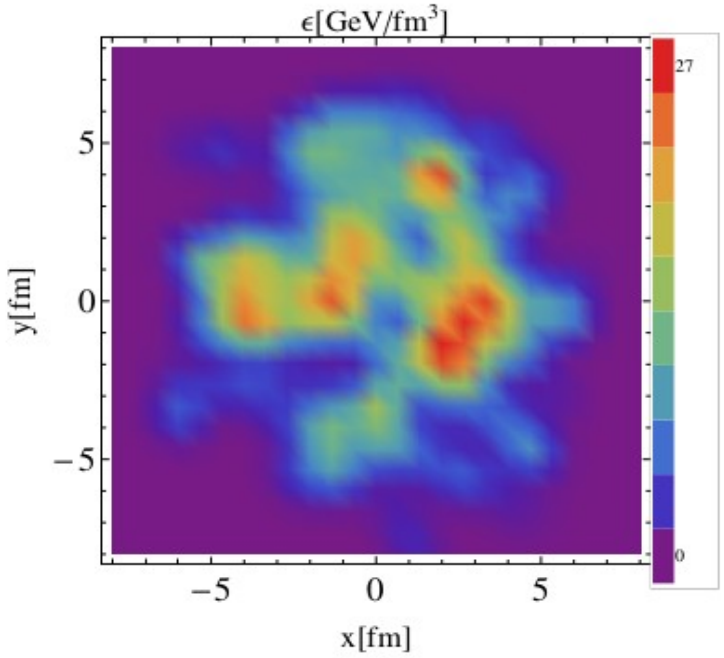


r_2 for UCC up to 20% !

- Hydro models describe quantitatively well the r_n values

CMS HIN-14-012

flow angle dependence

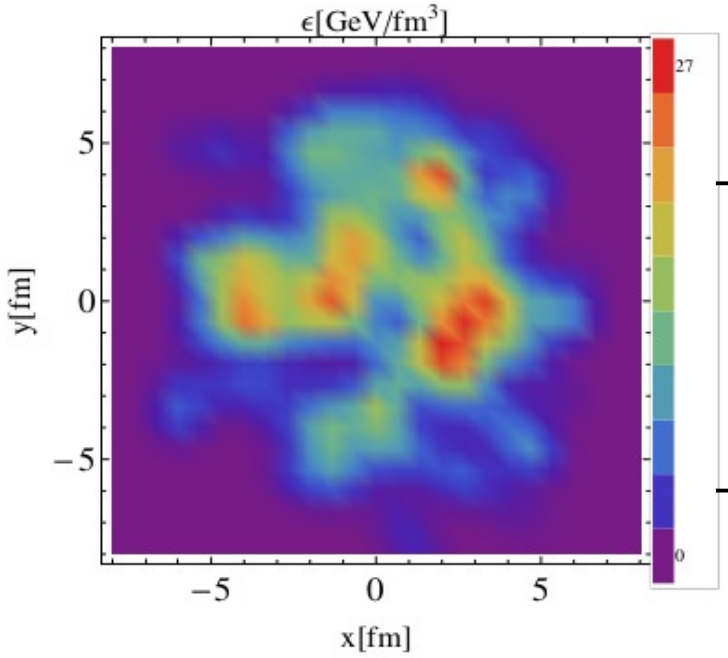


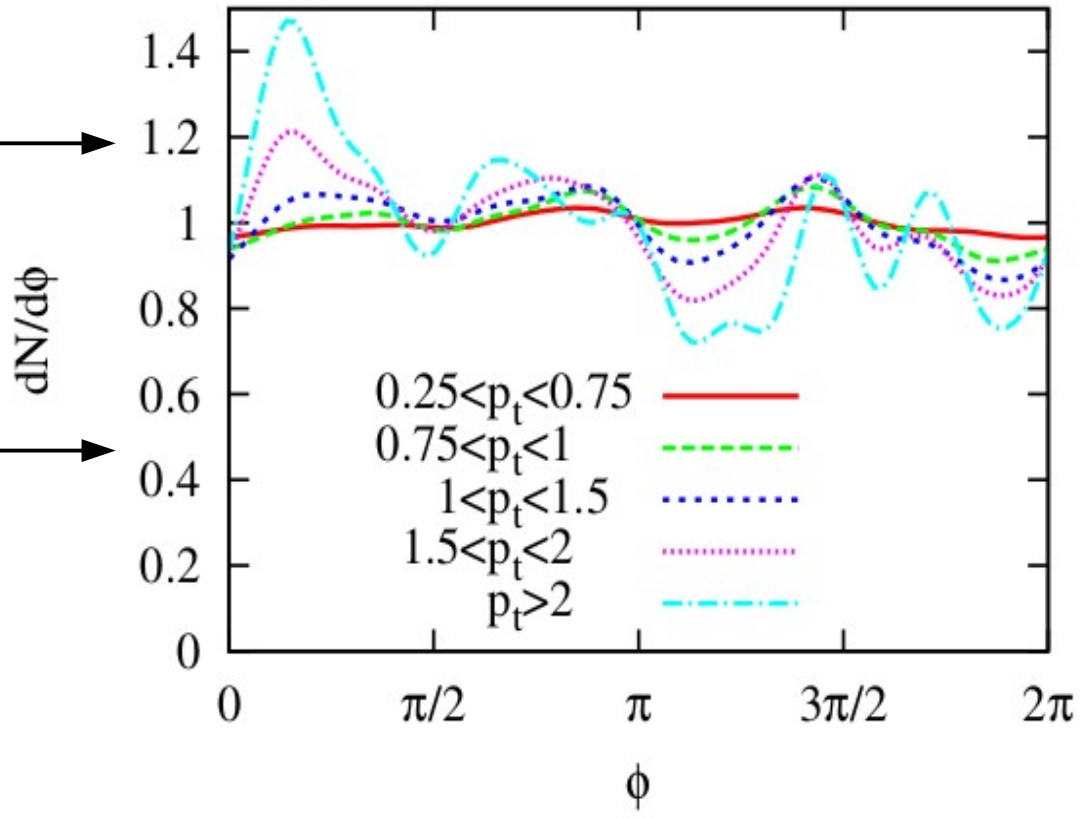
random central (b = 0) Pb-Pb at 2.76 TeV

flow angle dependence

Hydro evolution

Ollitrault, Gardim: Hydro overview





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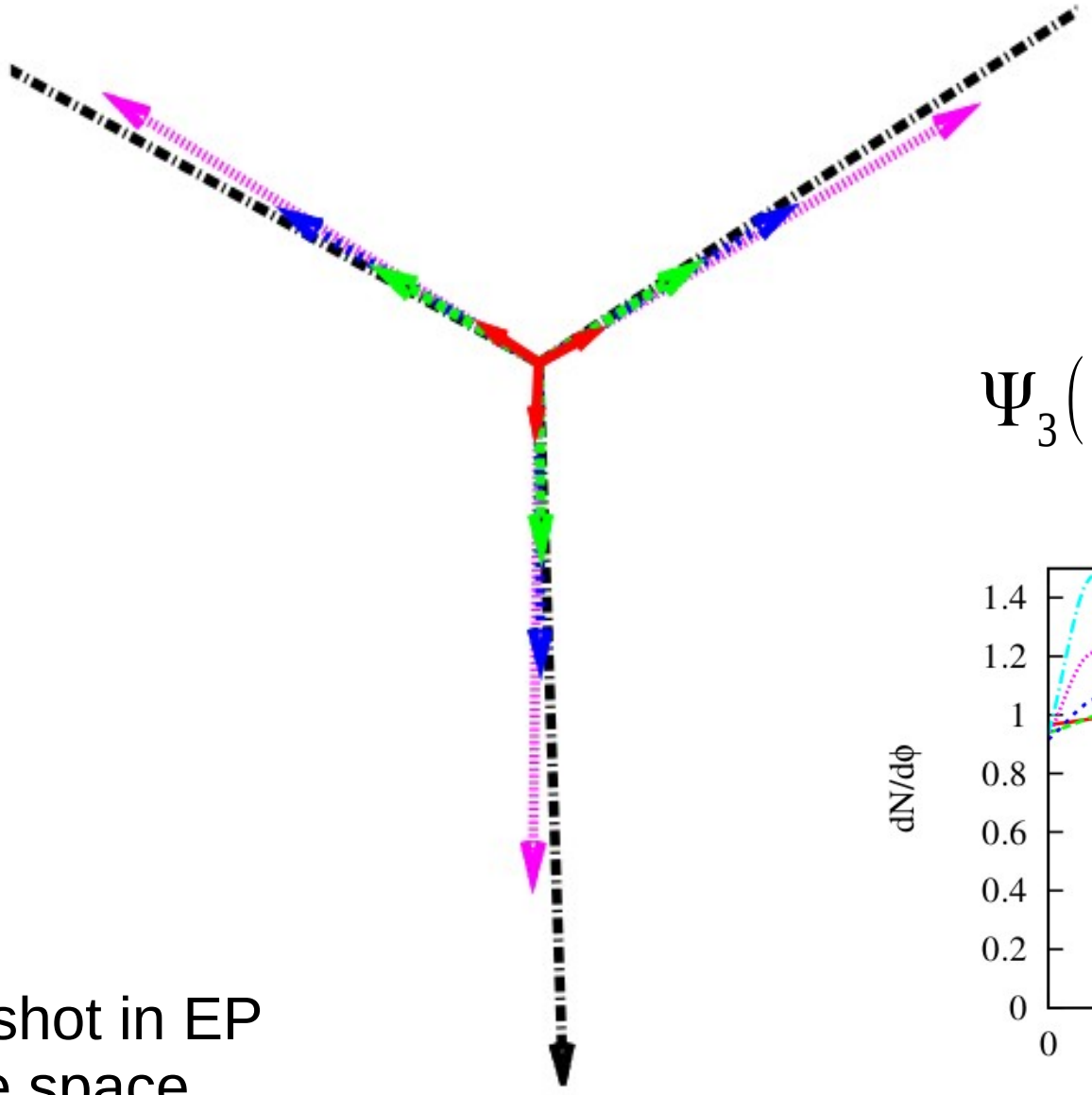
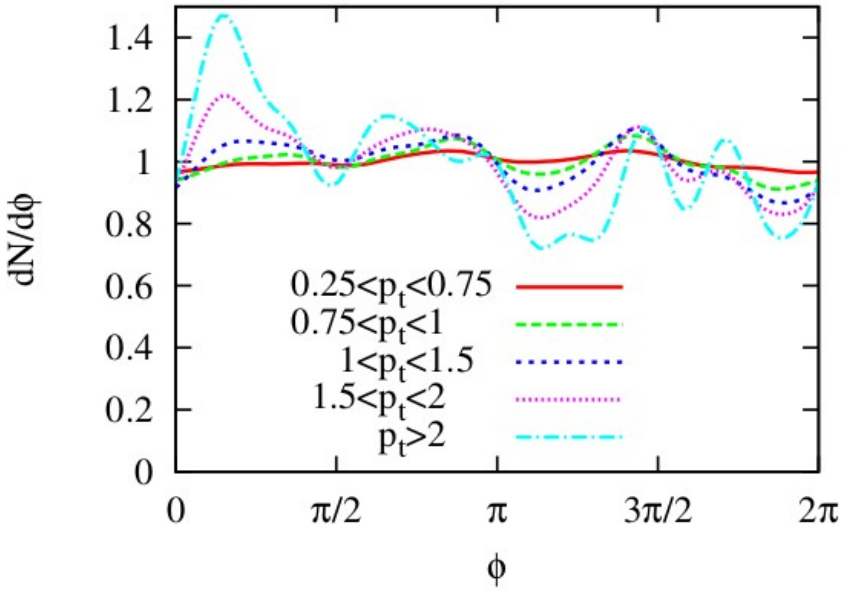
azimuthal distribution of outgoing particles

flow angle dependence



Snapshot in EP phase space

$$\Psi_3(high\ p_T) \neq \Psi_3(low\ p_T)$$



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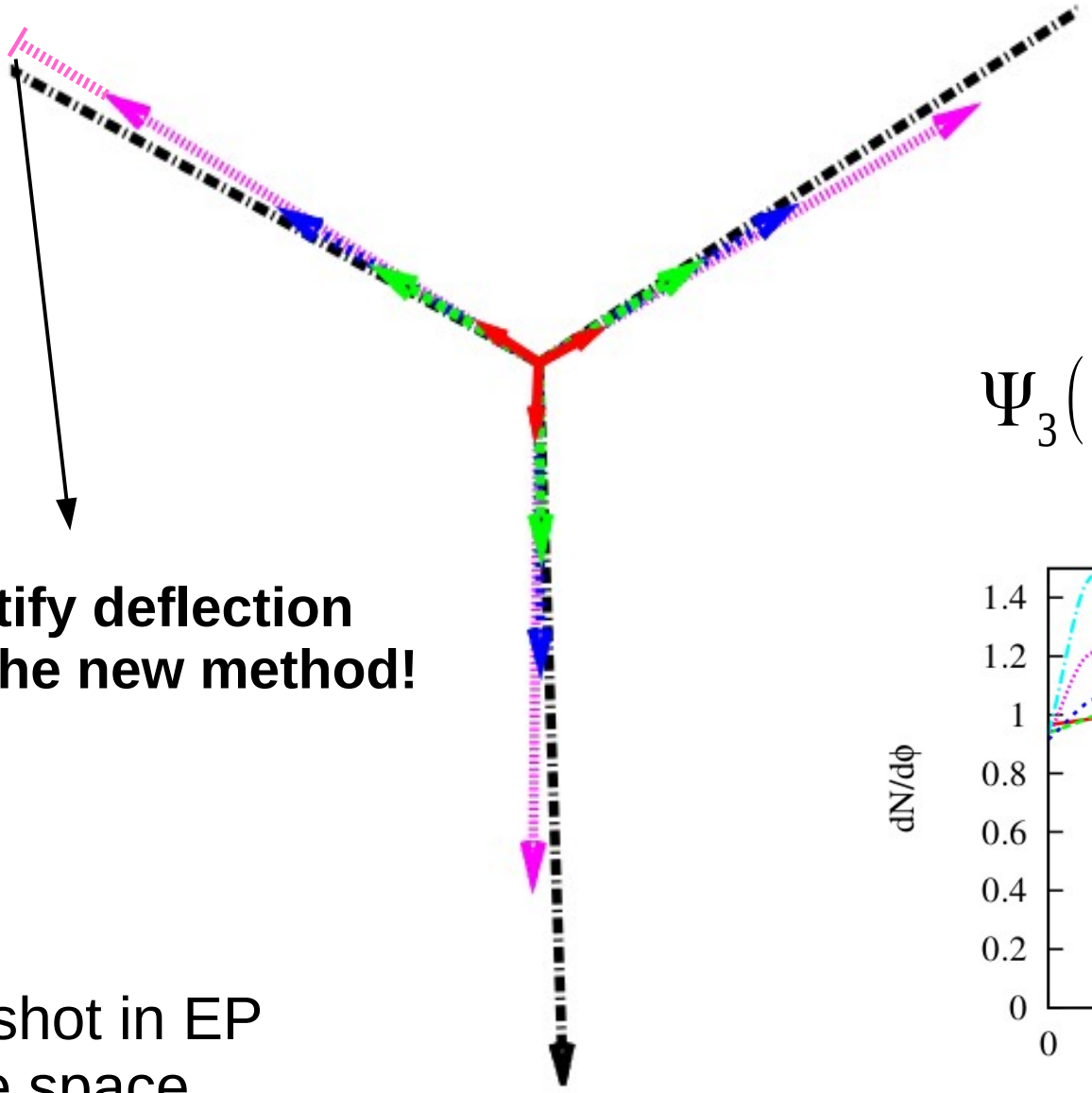

Quantify deflection with the new method!

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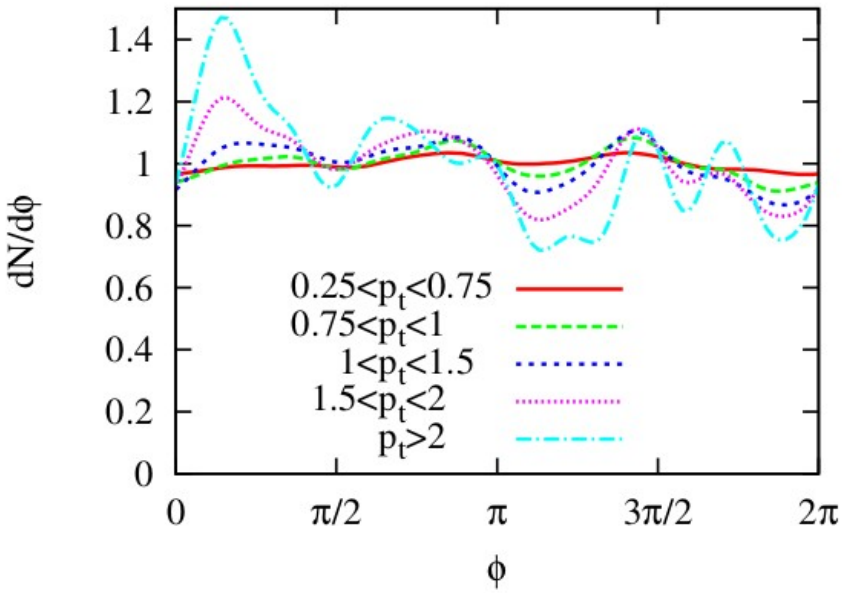

Snapshot in EP phase space

The Method

Paper: Principal component analysis of event-by-event fluctuations, Rajeev S. Bhalerao, Jean-Yves Ollitrault, Subrata Pal, and Derek Teaney, Phys. Rev. Lett. 114, 152301;

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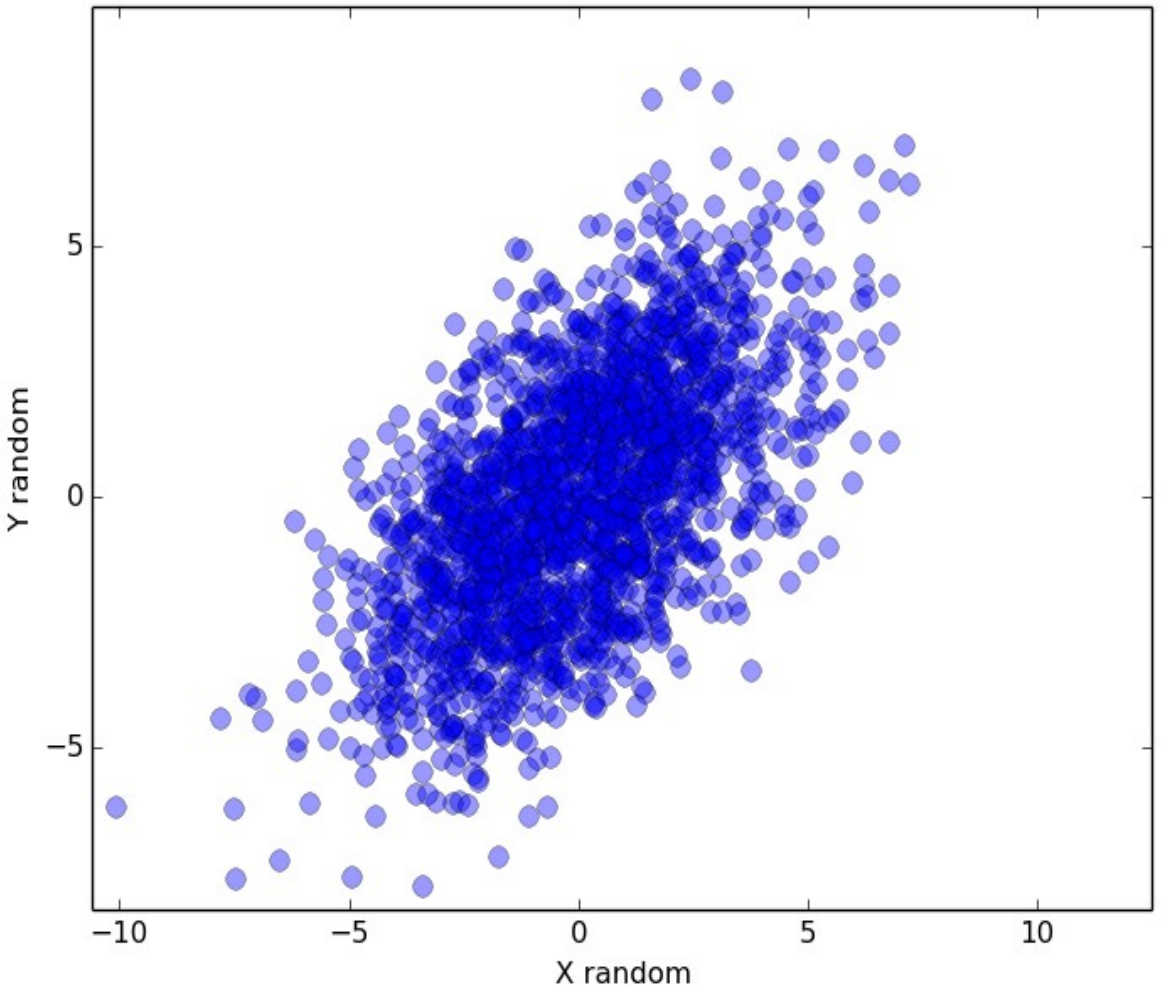
PCA is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components..(Wikipedia).

Principal Component Analysis



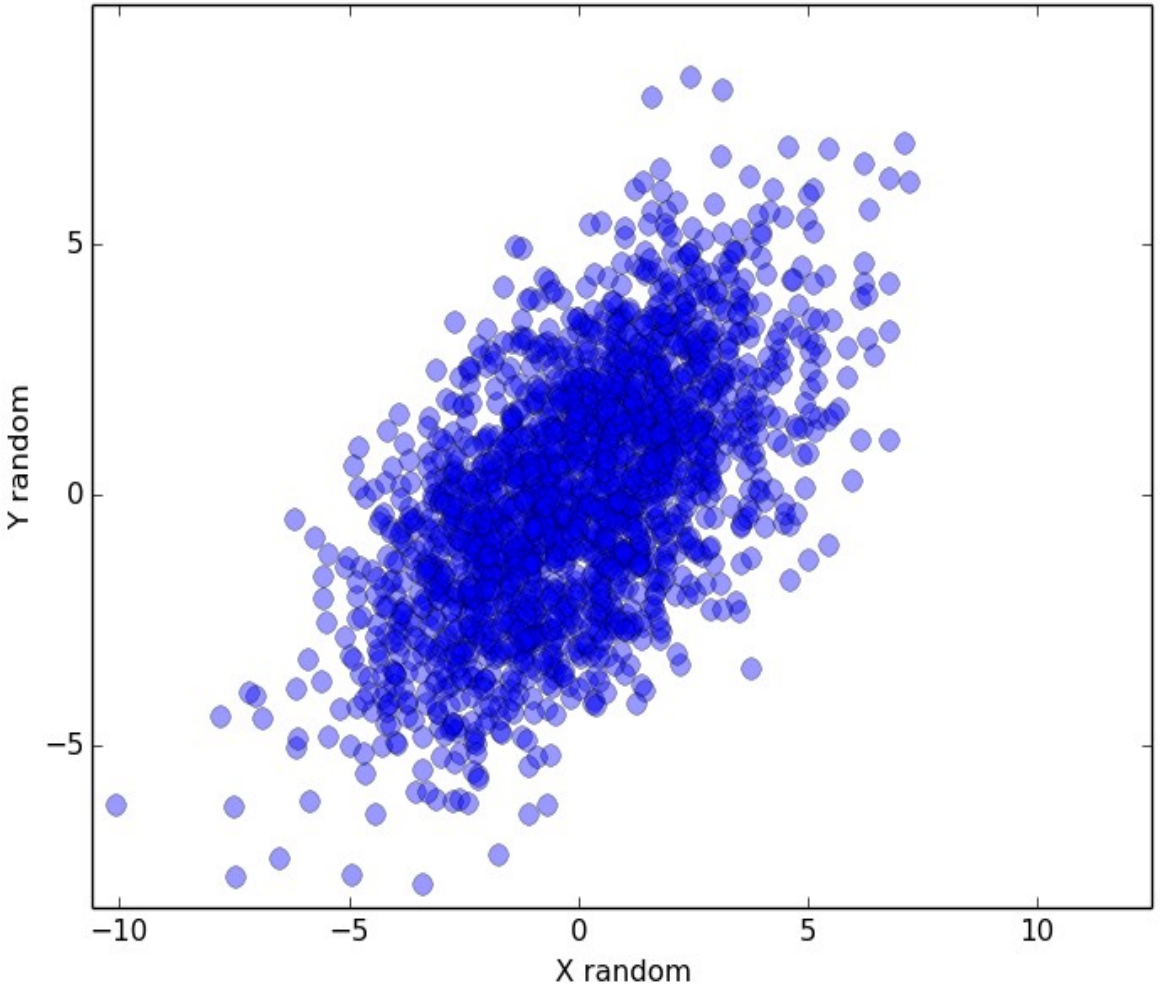
Random data generated by multivariate distribution (2D-Gaus)

$X_n = (x_1 , x_2 , ..., x_n)$

$Y_n = (y_1 , y_2 , ..., y_n)$

Principal Component Analysis

2D-Gaus data cloud



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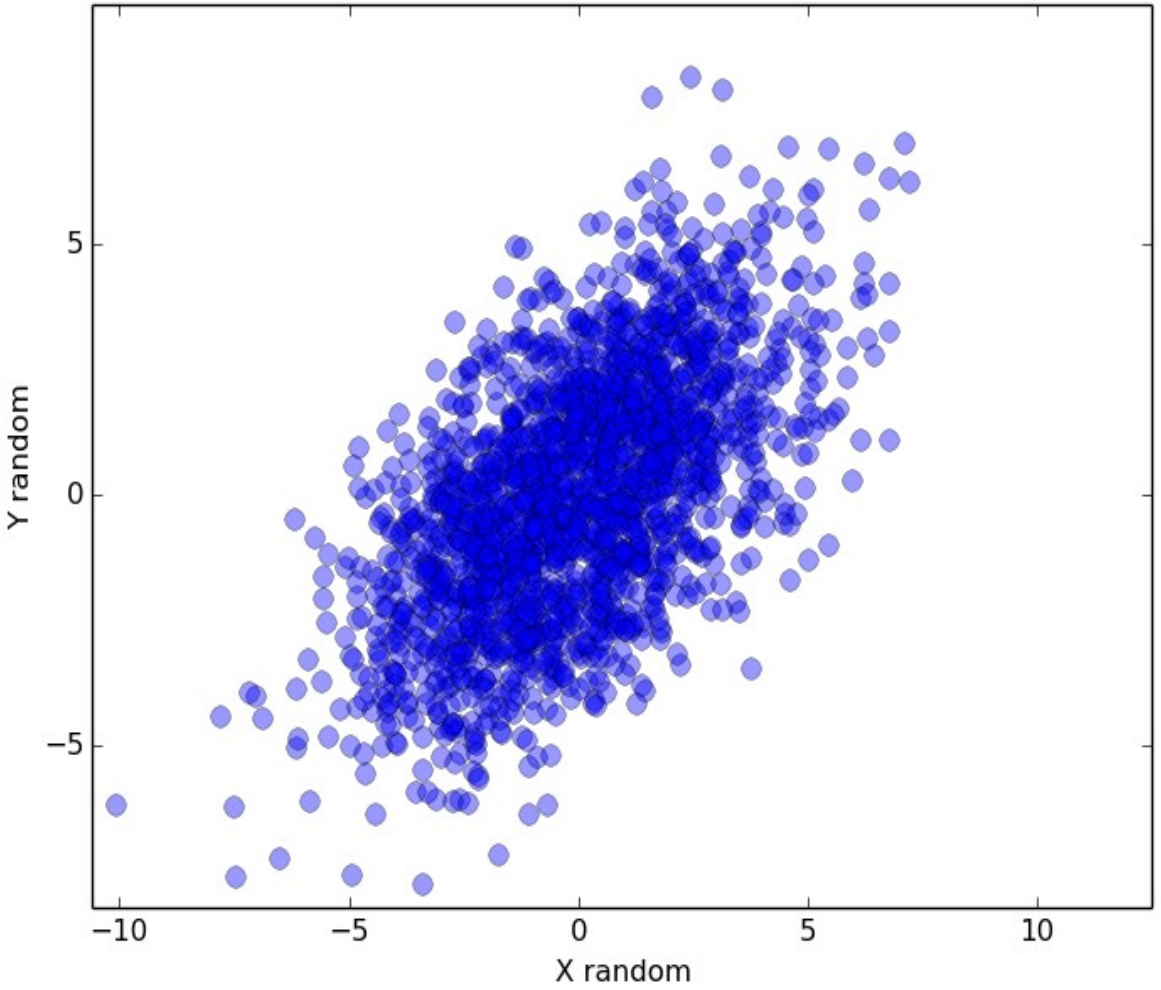

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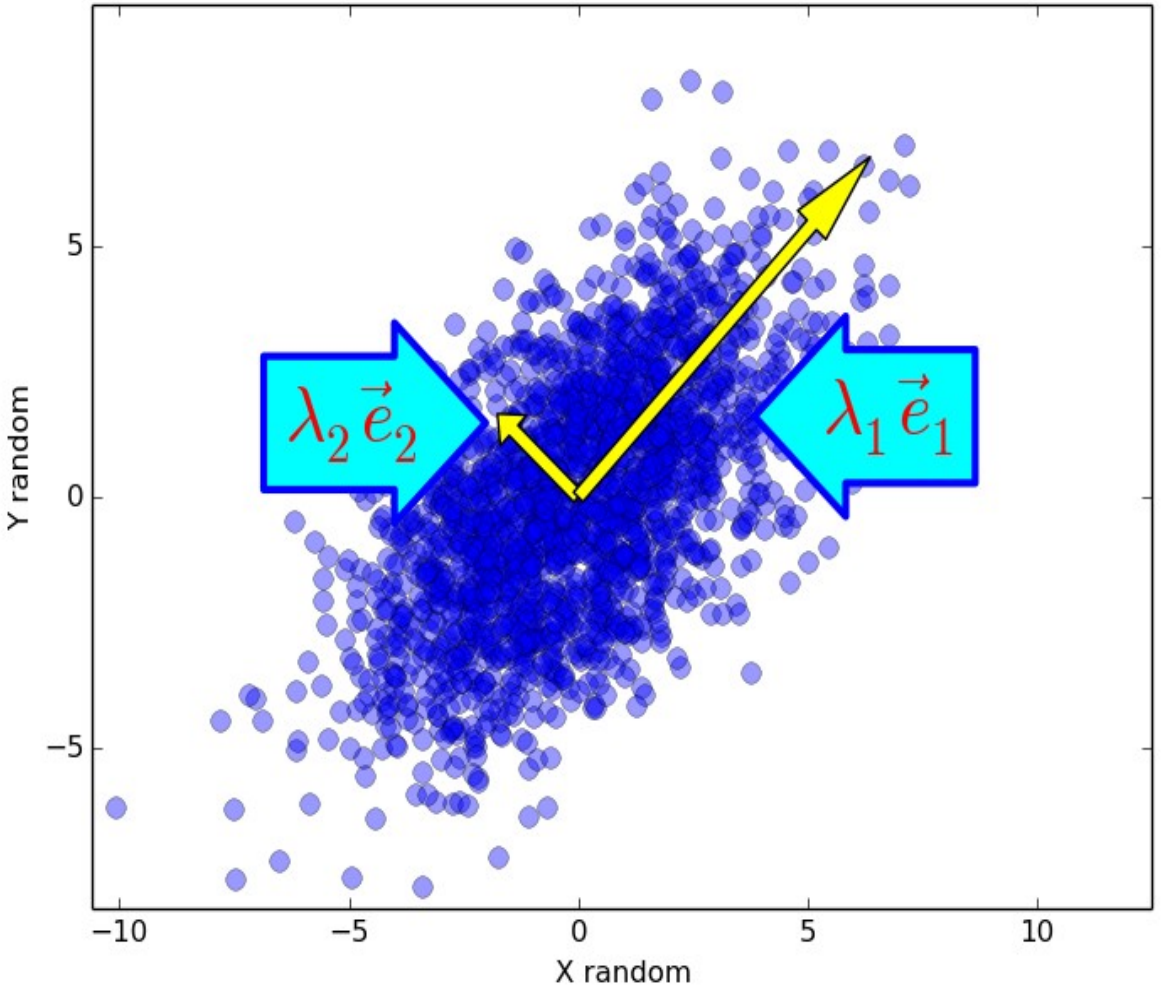
Solving the eigenvalue problem gives what?

Principal Component Analysis

2D-Gaus data cloud



PCA: Optimization method that fits any n-dimensional elipse with eigenvalues and eigenvectors.

Principal Component Analysis

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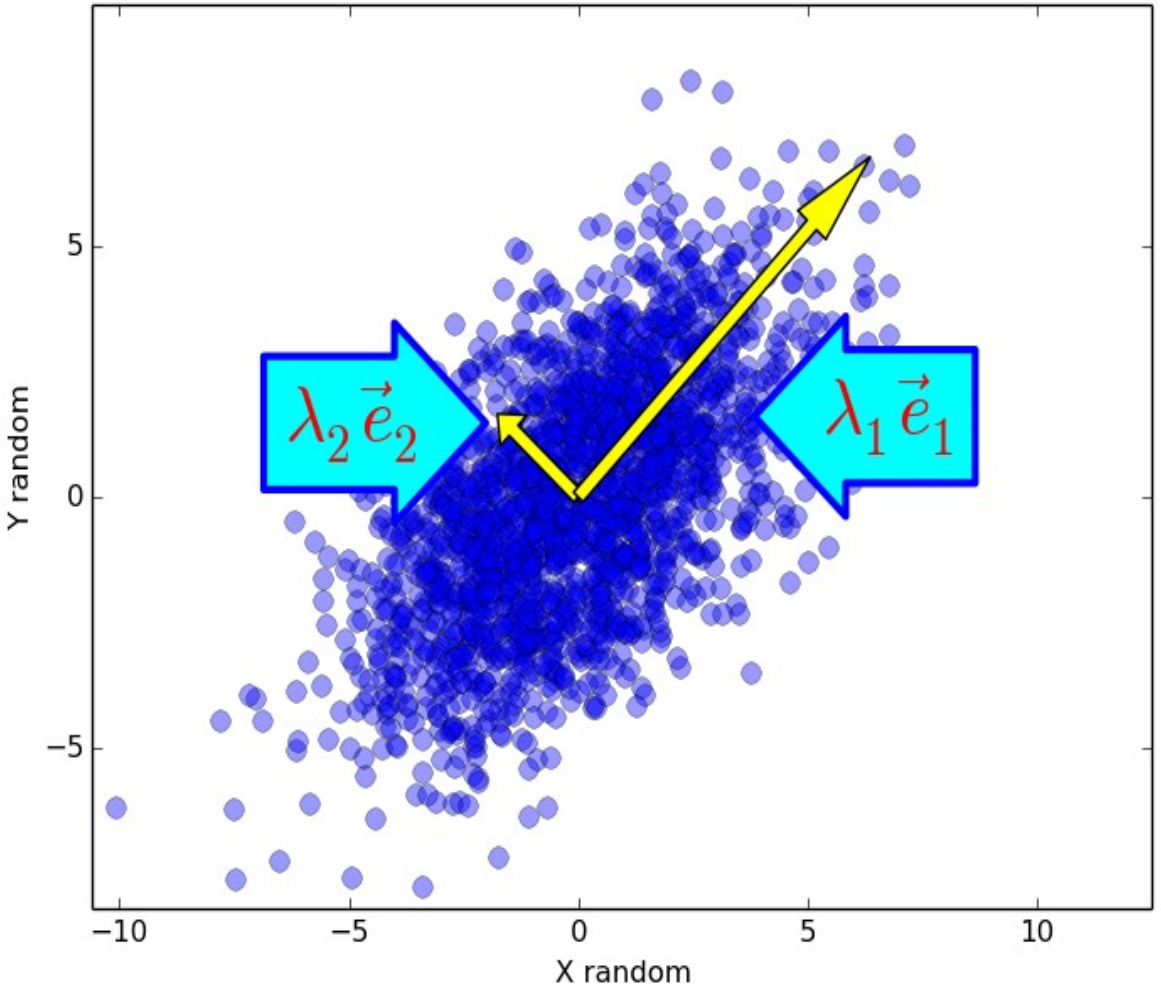

PCA: Optimization method that fits any n-dimensional elipse with eigenvalues and eigenvectors.

First principal component:
e$_1$ pointing in the direction of max. var. od data cloud

Second principal component:
e$_2$ pointing in the direction of max. var. od data cloud

Calculation

Defining the covariance matrix element with **two-particle** harmonics

$$V_{n\Delta}(p_T^1, p_T^2) = f(S)\langle cosn\,\Delta\phi\rangle_S - f(B)\langle cosn\,\Delta\phi\rangle_B,$$

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Non flow cut

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Non flow cut

With N_b differential bins (p^1_T , p^2_T) form covariance matrix $\Sigma_{N_b\,x\,N_b}$

Calculation

$$V_n^{(\alpha)}(p_T^i) = \sqrt{\lambda^i}\, e_i^{(\alpha)}$$

MODES A FUNCTION OF λ, e

$$\lambda_1 > \lambda_{2.....} > \lambda_n$$

Calculation

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Decomposition of the harmonic with the modes:

$$V_{n\Delta}(p_T^1, p_T^2) = \sum_{\alpha=1}^{N_b} V_n^{(\alpha)}(p_T^1)\, V_n^{(\alpha)*}(p_T^2)$$, full reconstruction

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$$V_{n\Delta}(p_T^1, p_T^2) \approx \sum_{\alpha=1}^{k<N_b} V_n^{(\alpha)}(p_T^1)\, V_n^{(\alpha)*}(p_T^2)$$, expected

Physical meaning of modes

Need to divide the modes with multiplicity

$$v_n^{(\alpha)}(p_T) = \frac{V_n^{(\alpha)}(p_T)}{M(p_T)}$$

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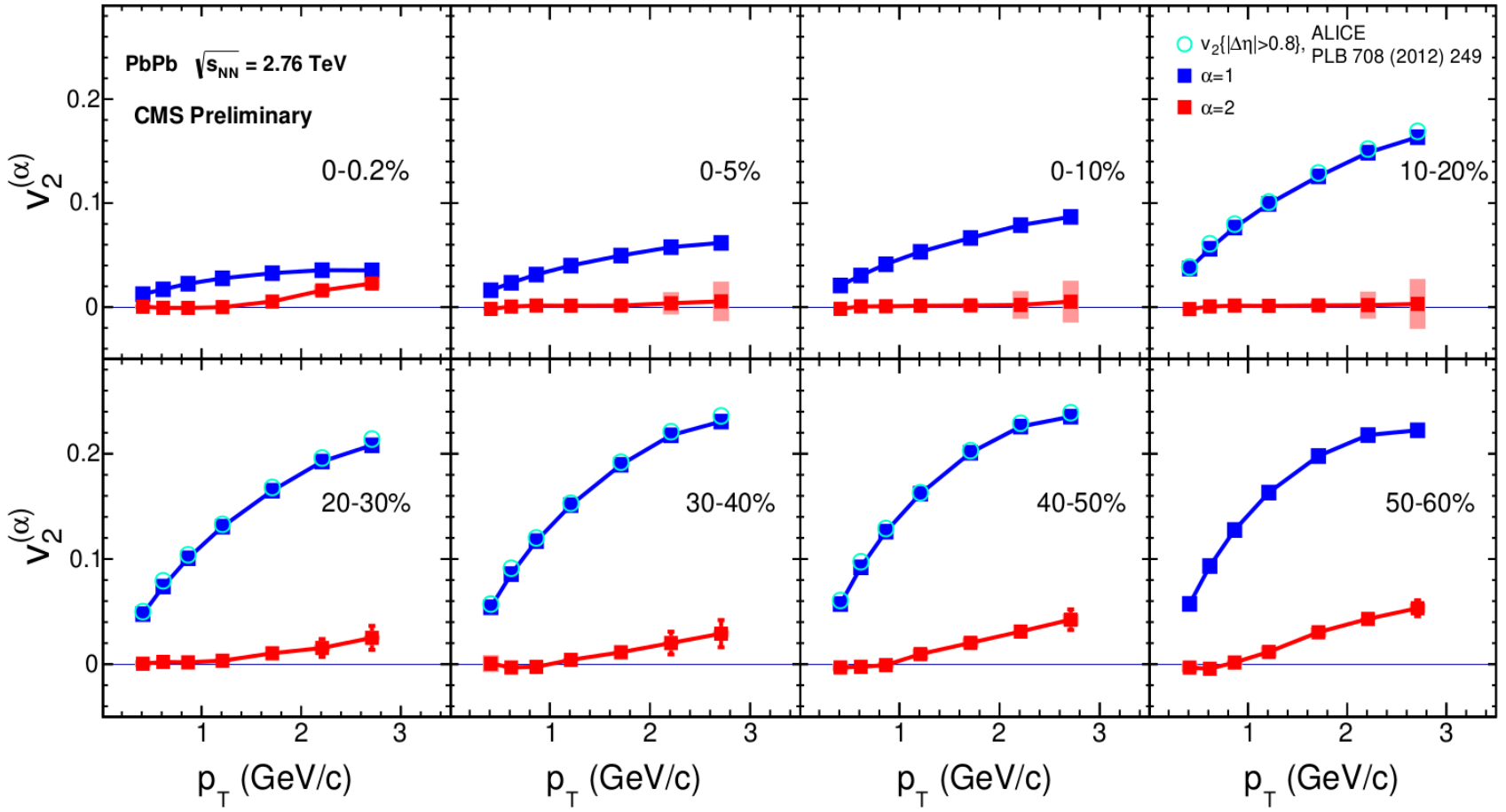
Leading flow α = 1 corresponding to standard single particle anisotropy

Sub-leading flow α = 2,3.. direct response to initial state fluctuations

RESULTS

V_2 PbPb at 2.76TeV



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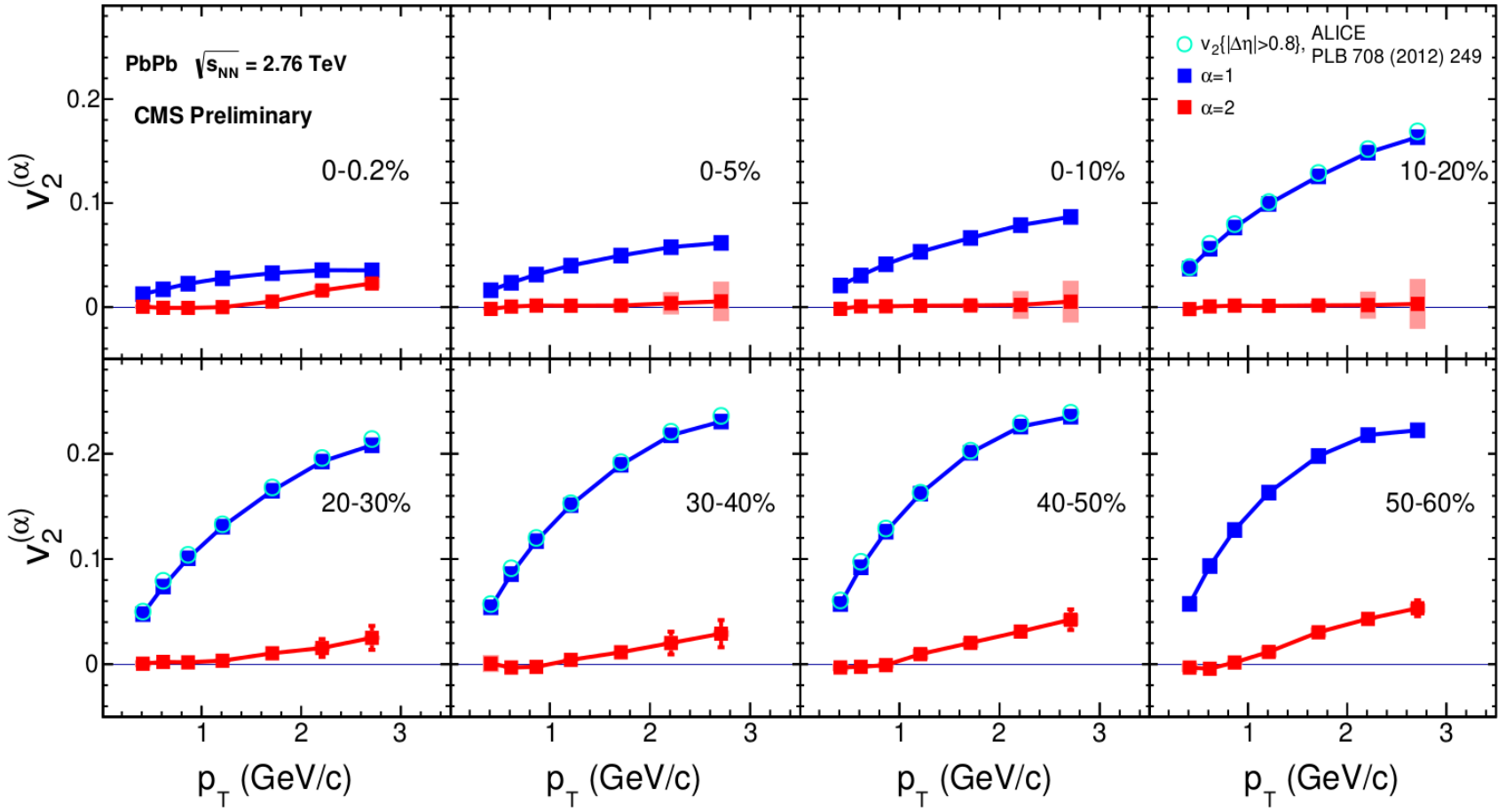

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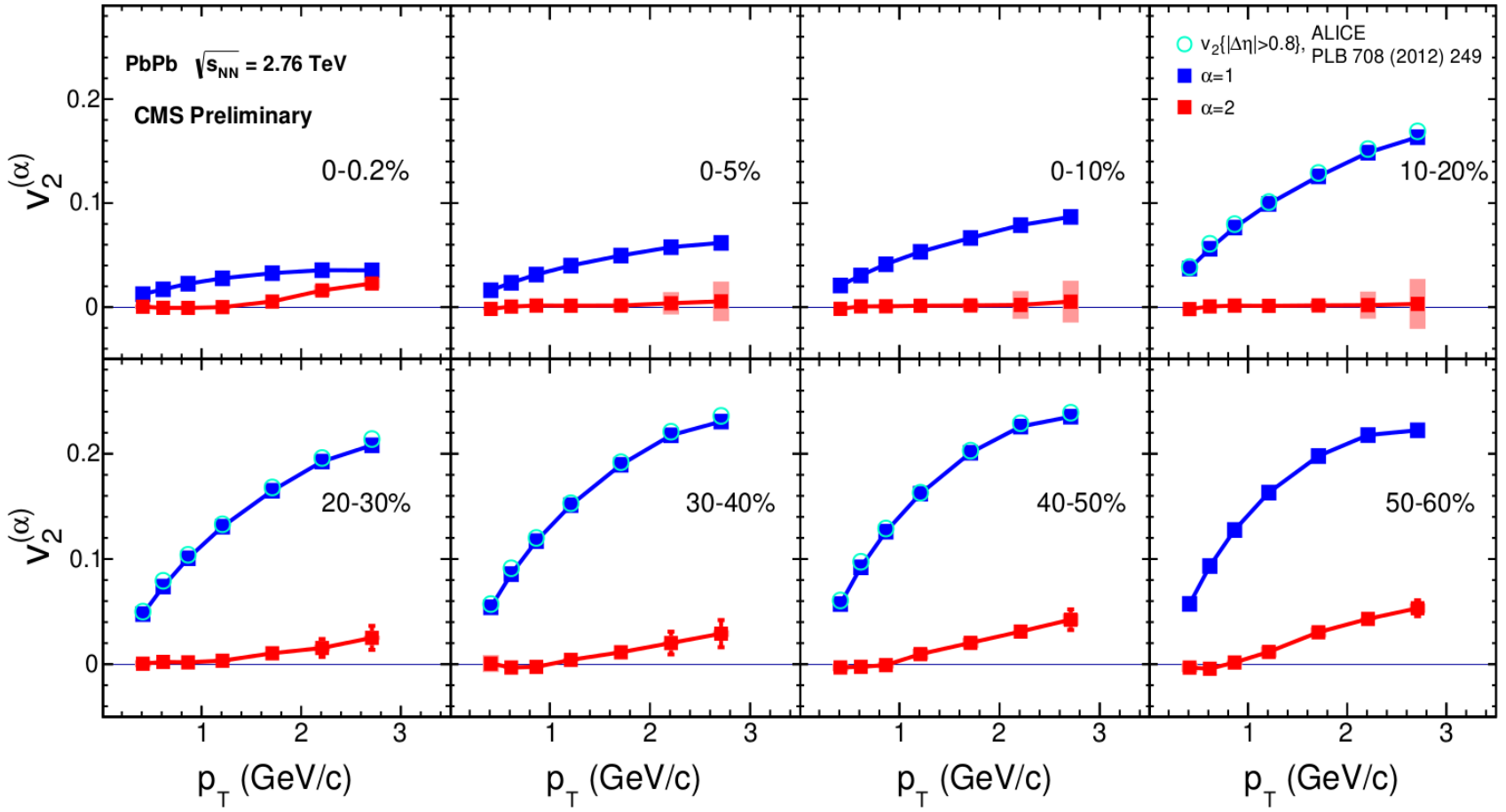

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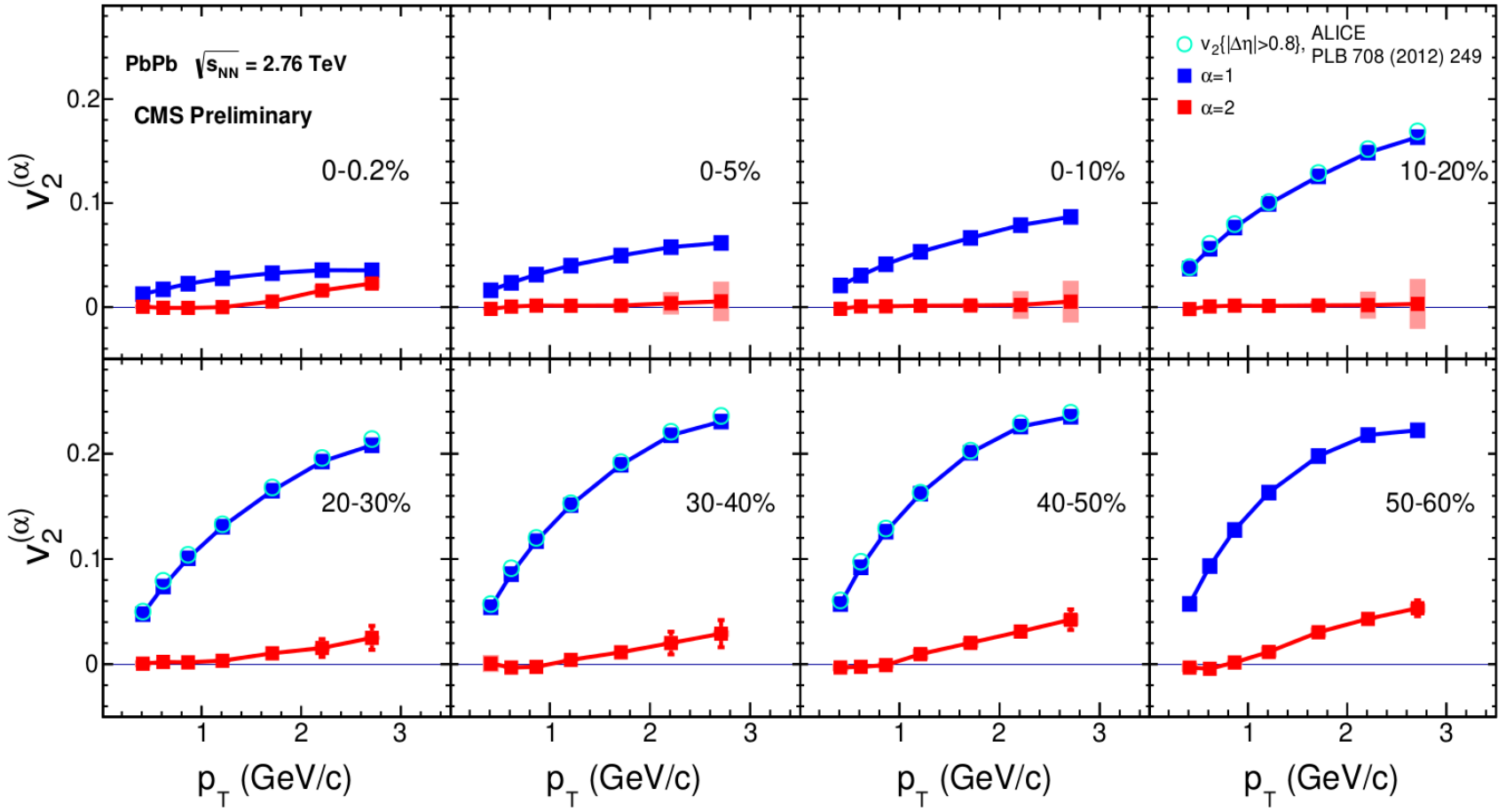

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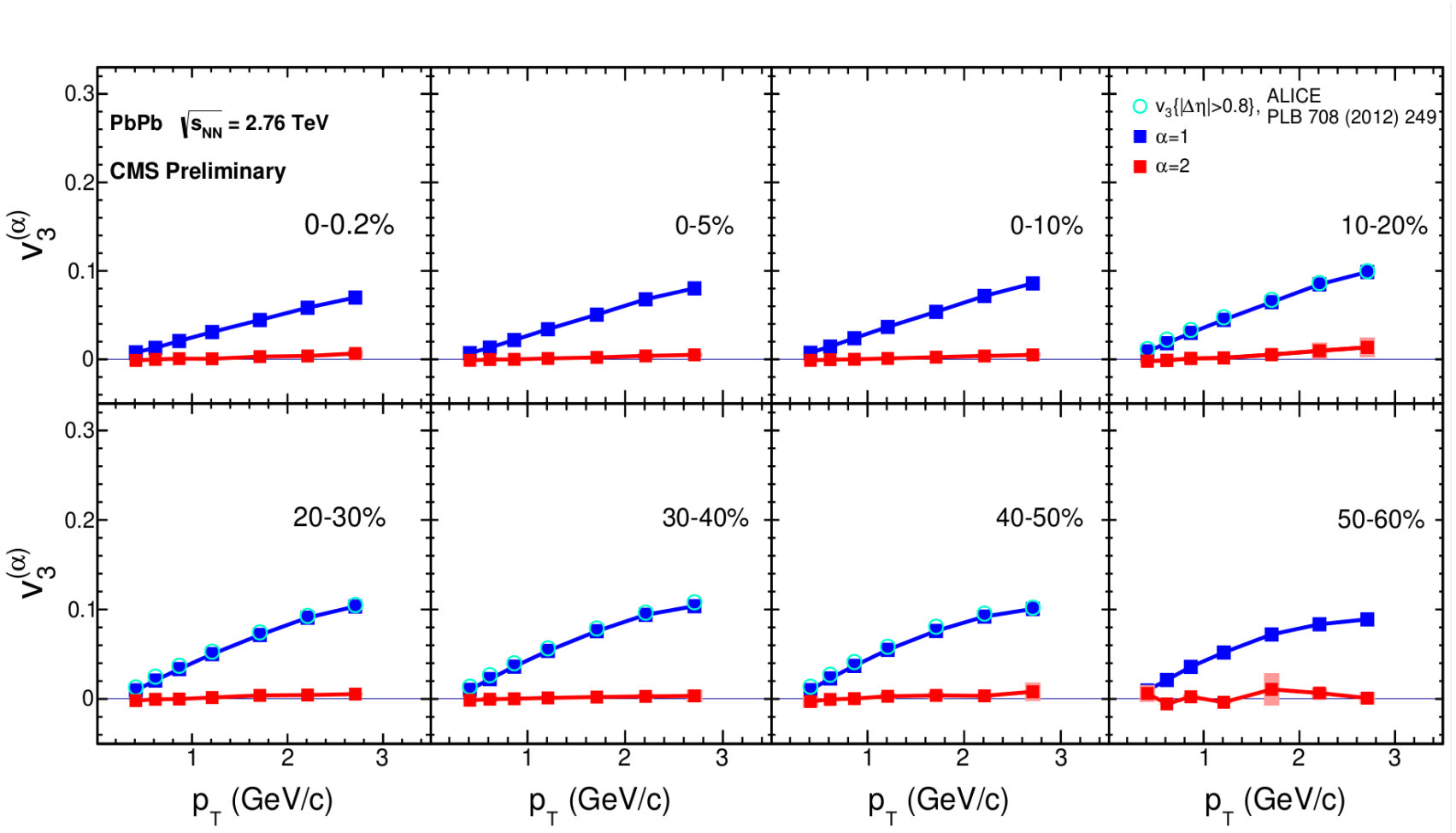
- Increase of subflow with p_T and centrality

V_3 PbPb at 2.76TeV



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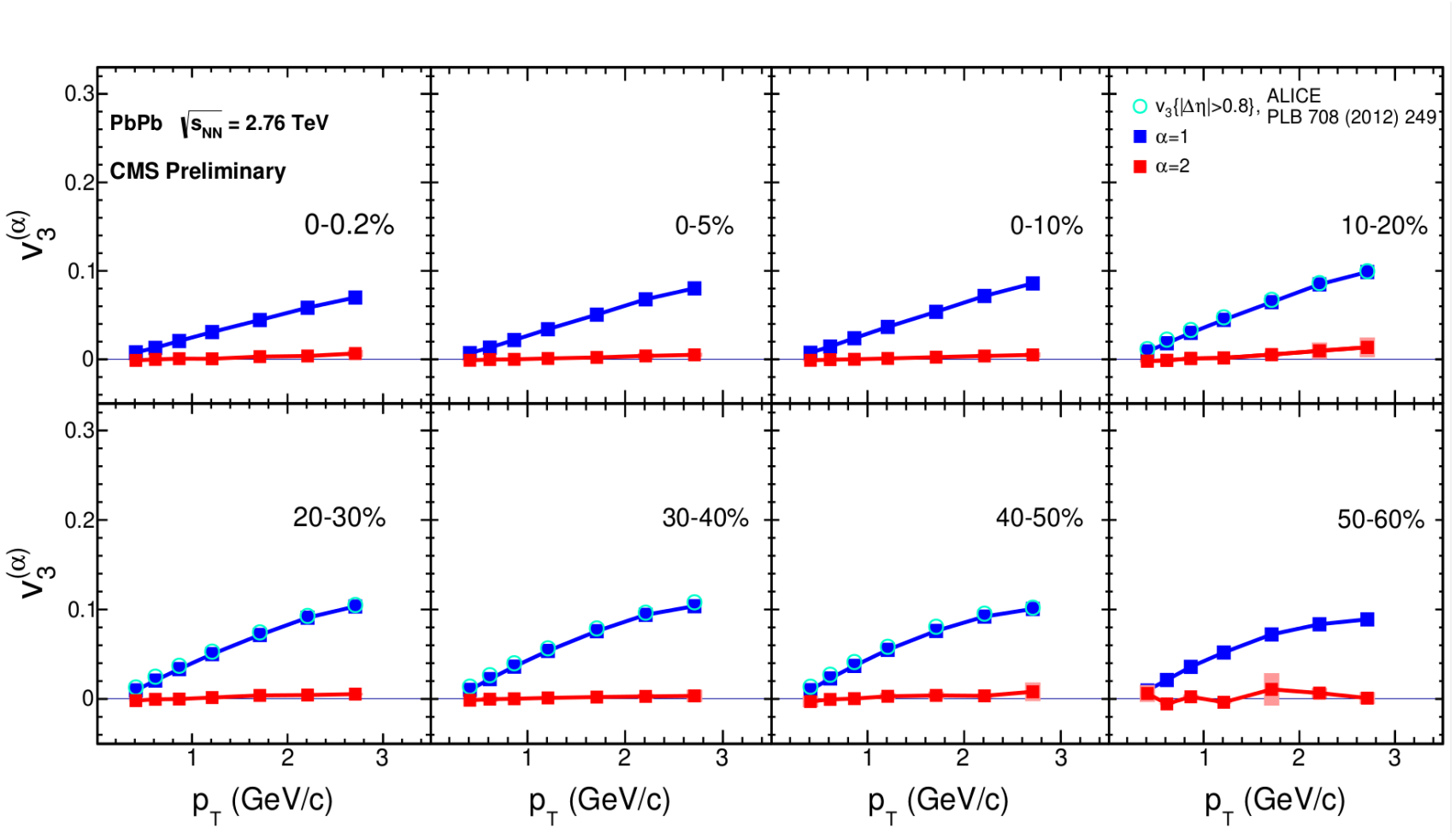

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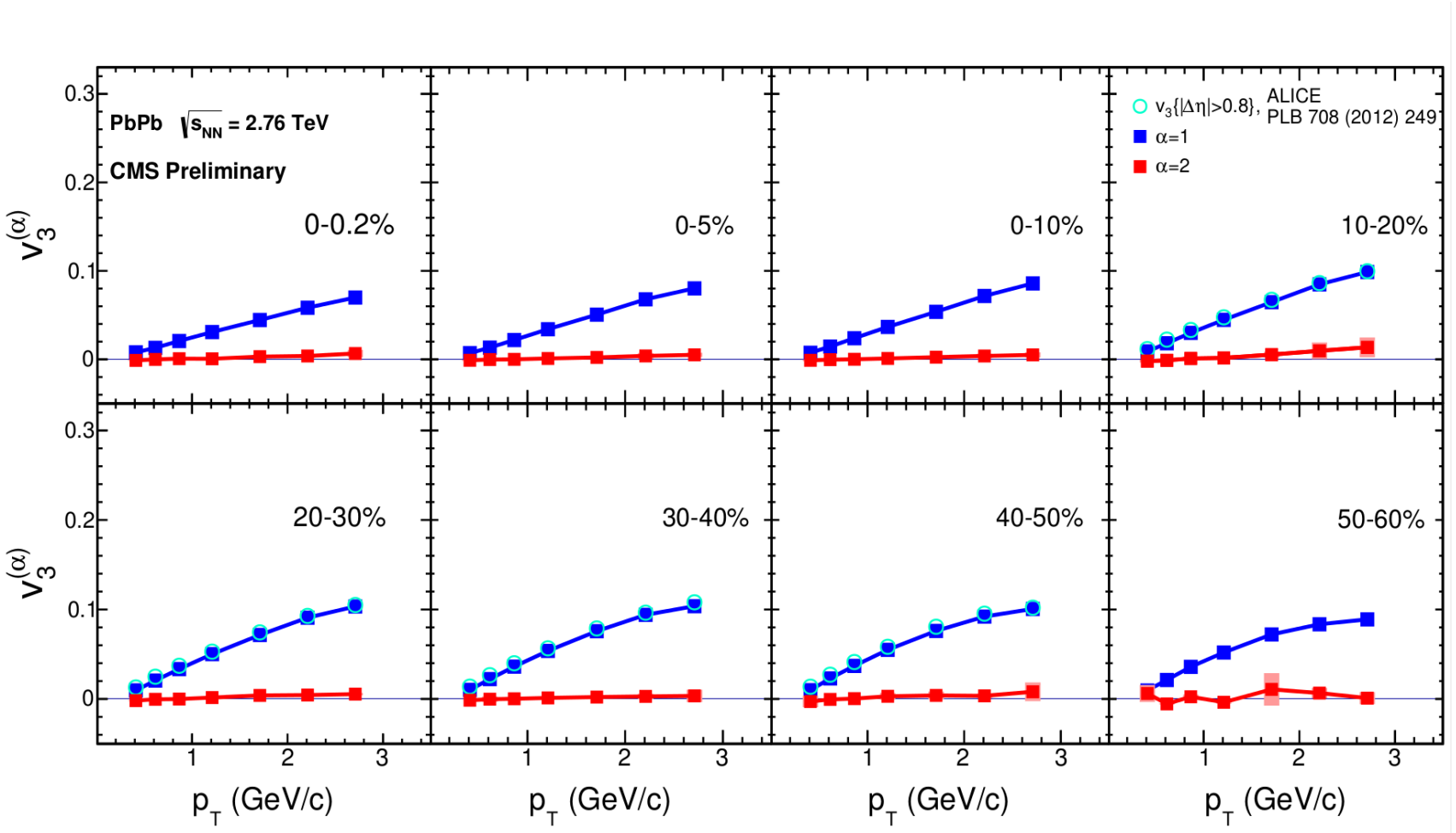

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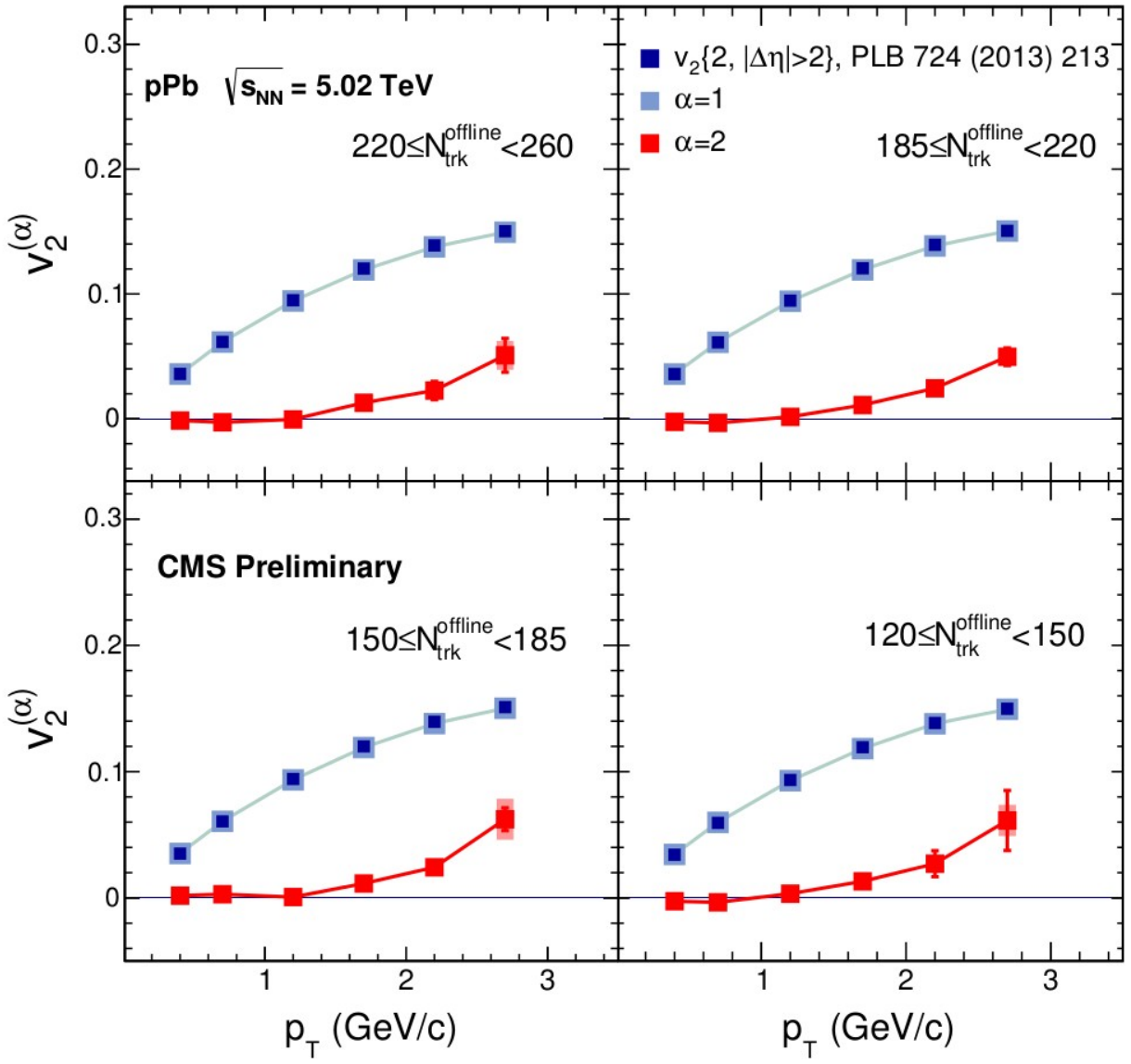

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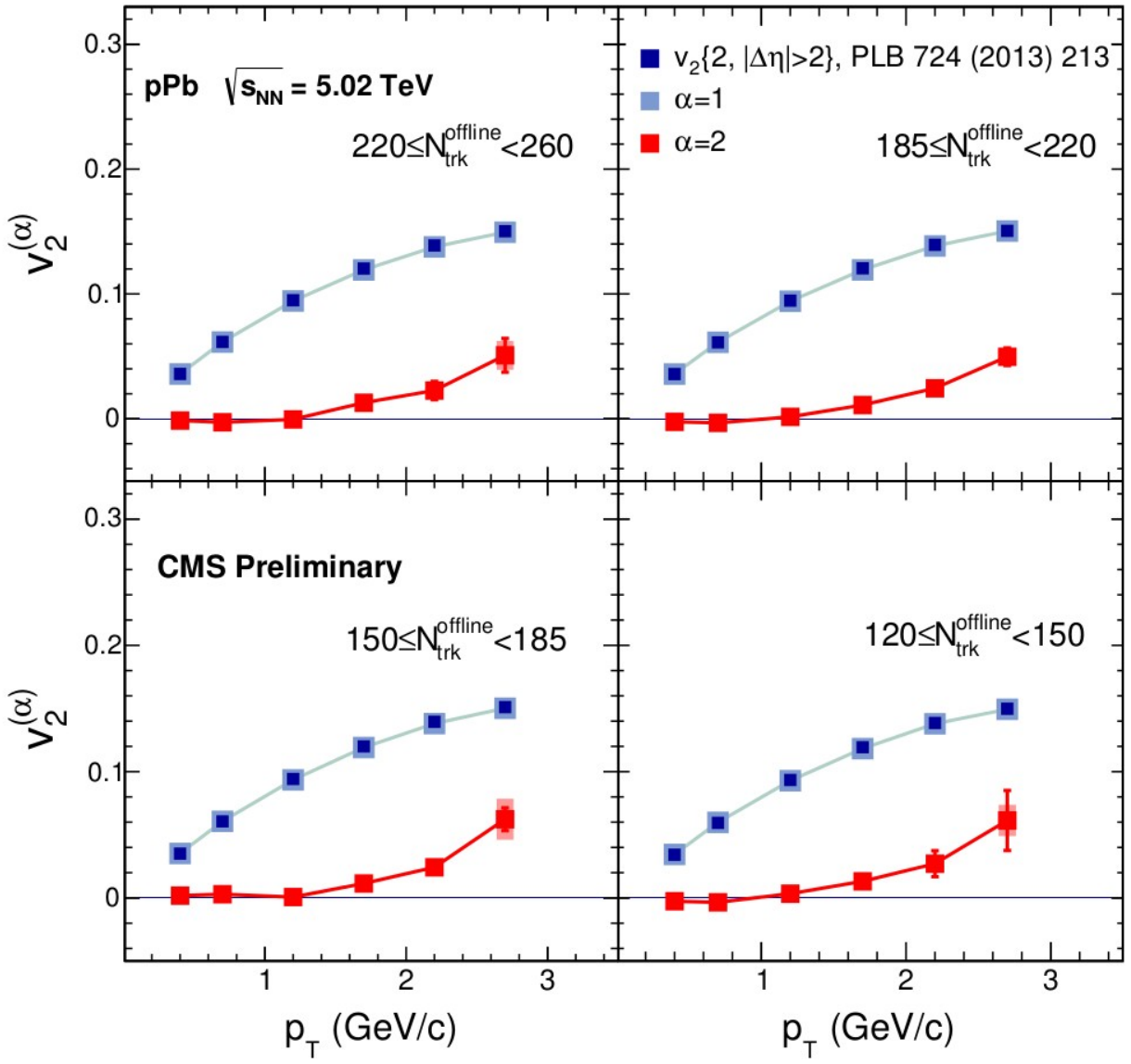

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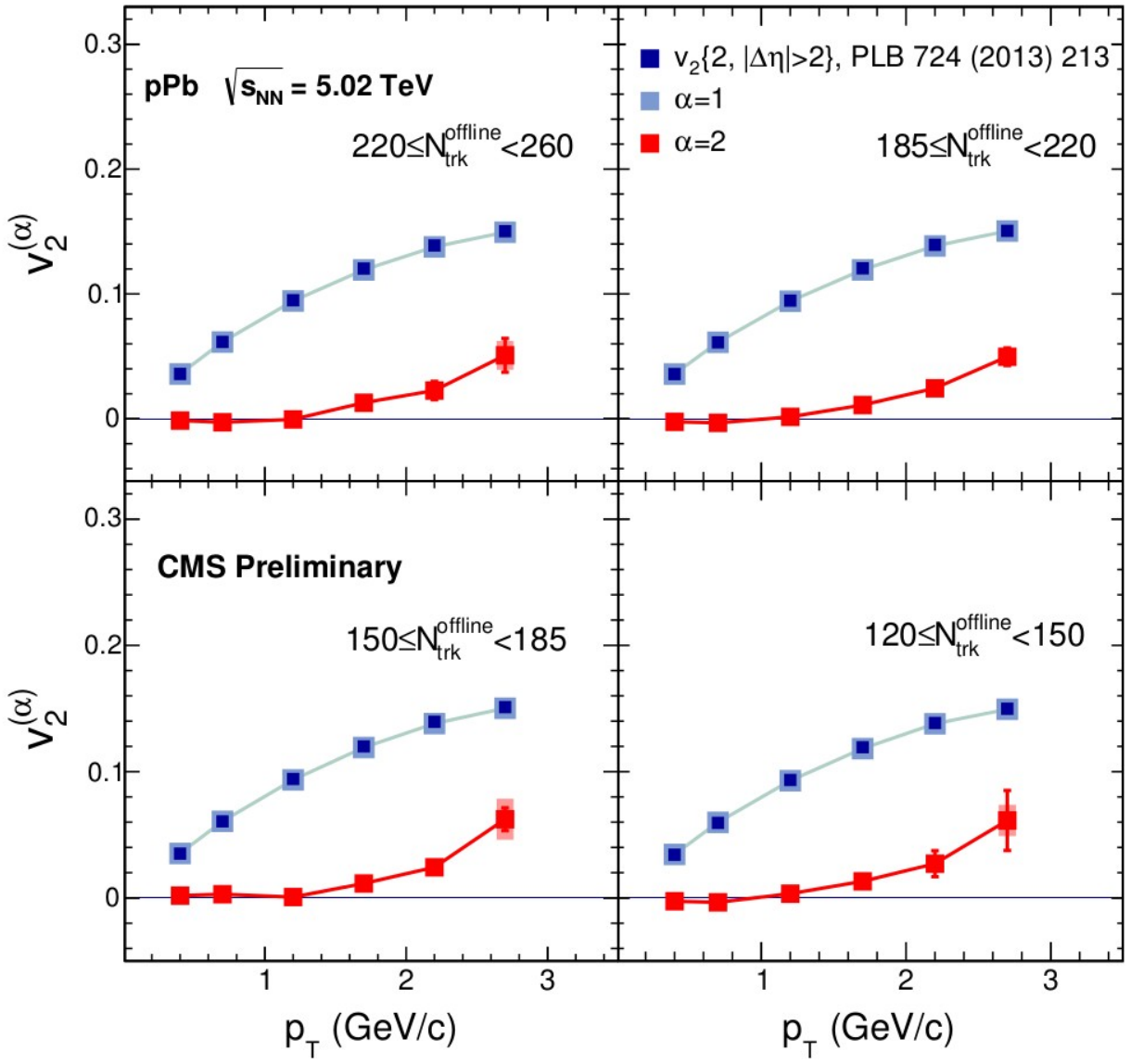

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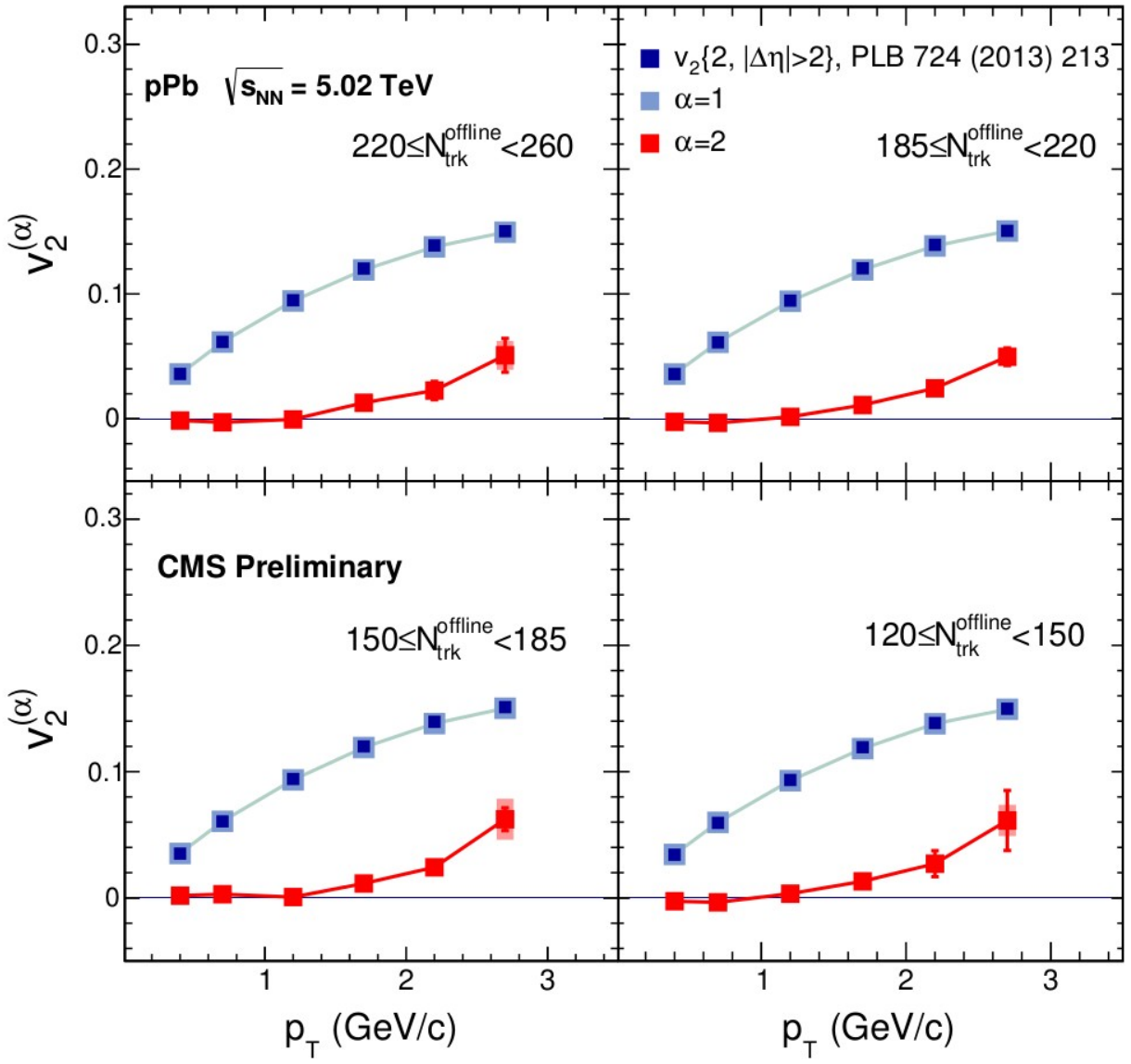

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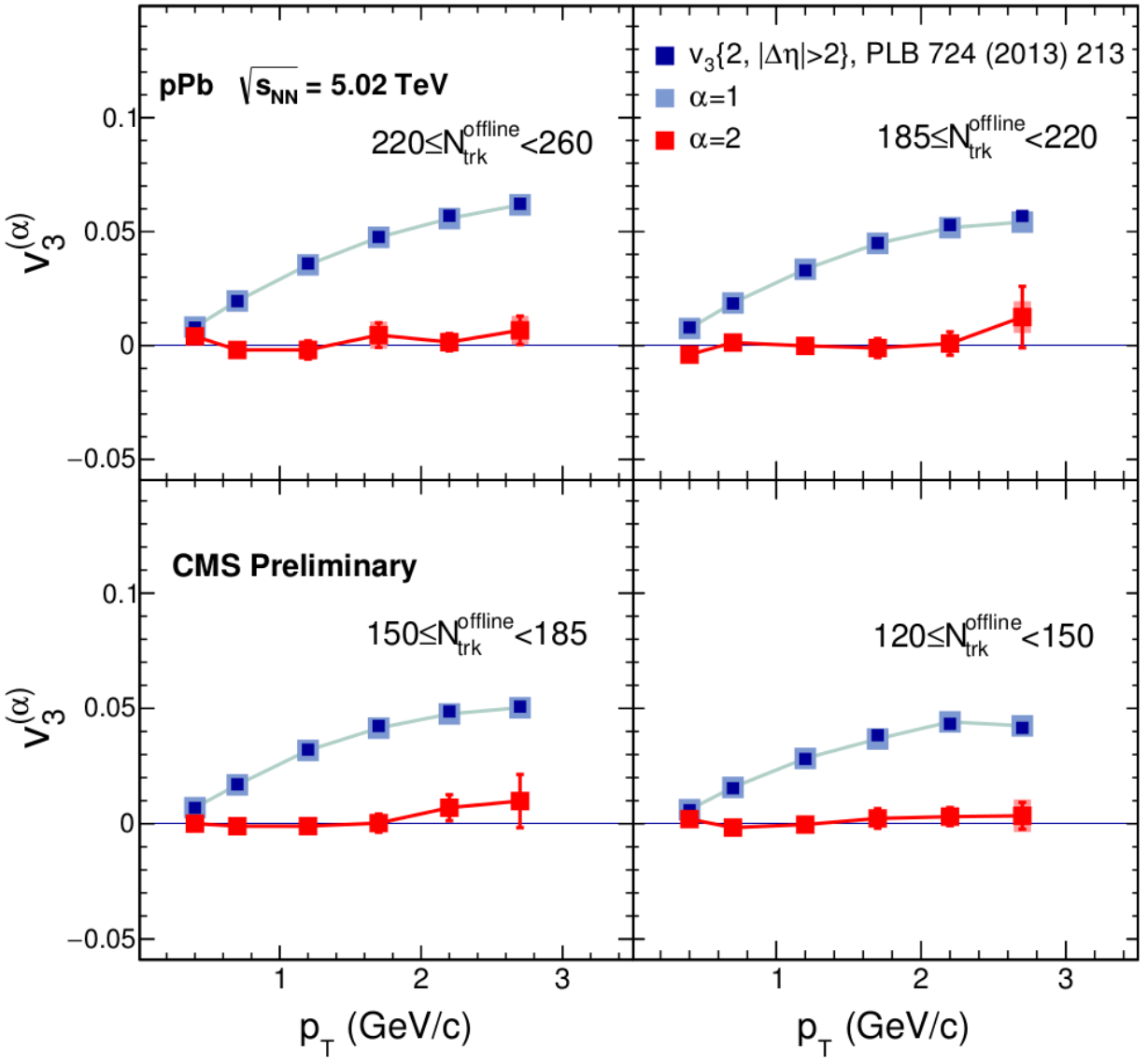

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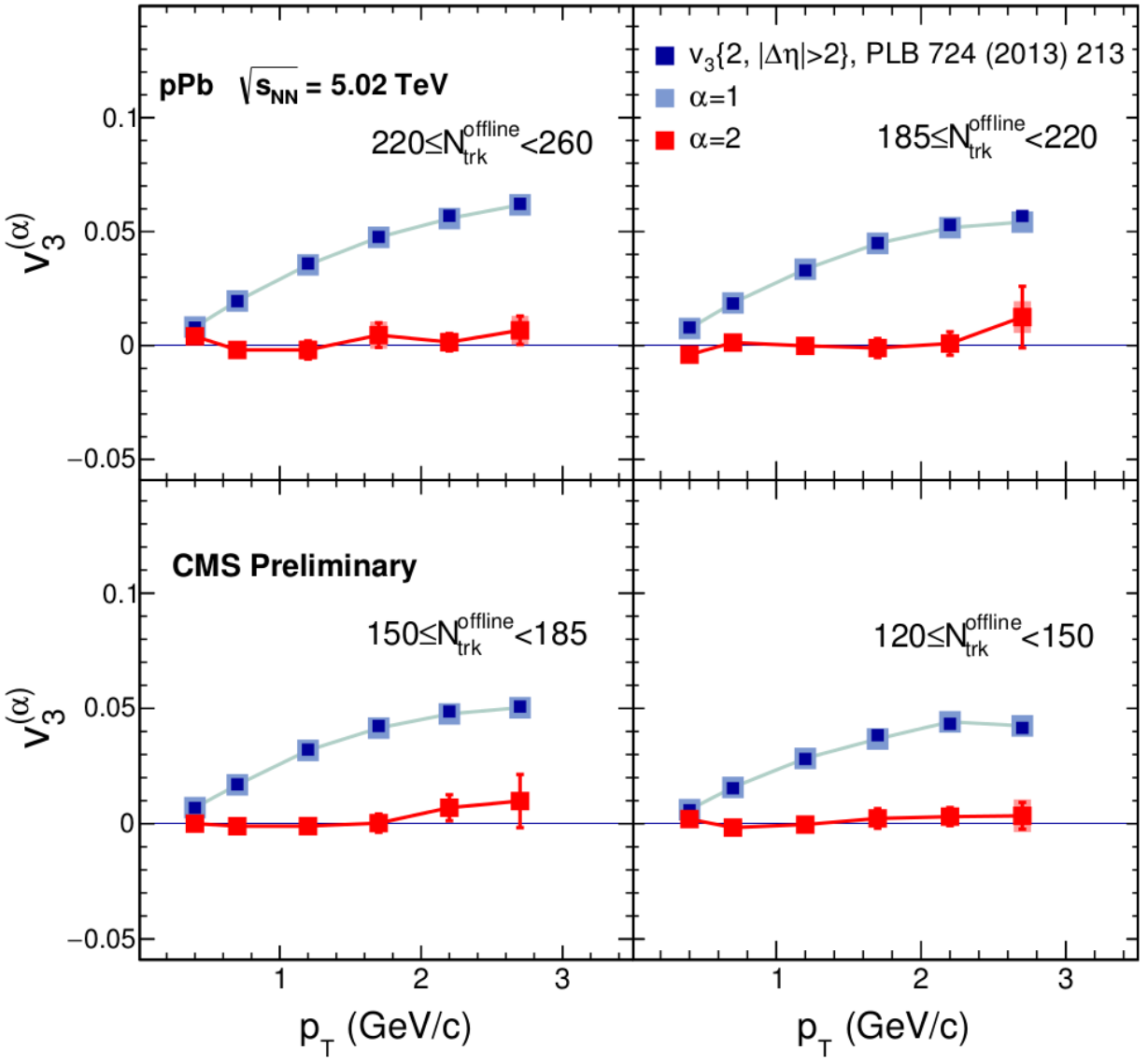

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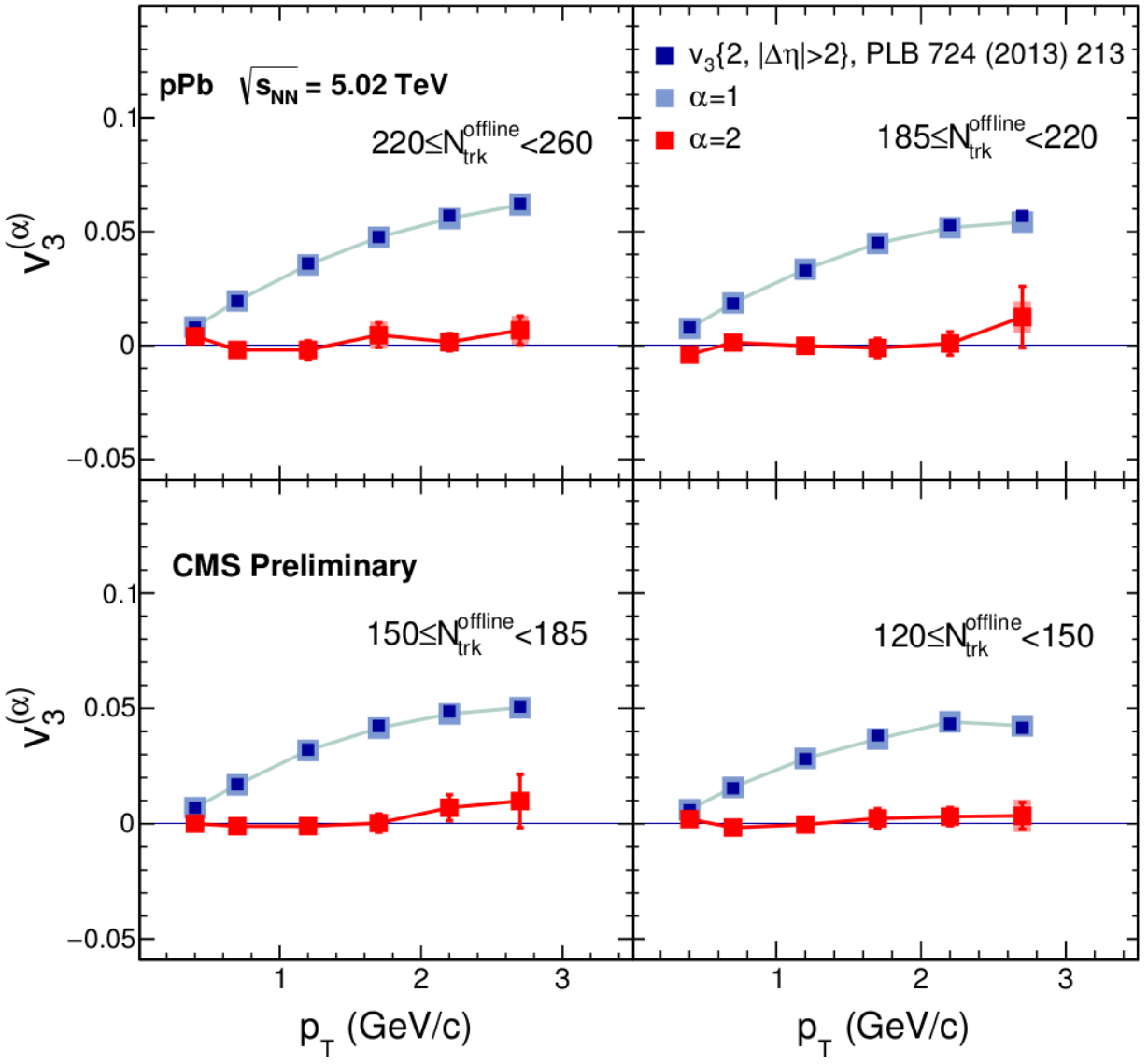

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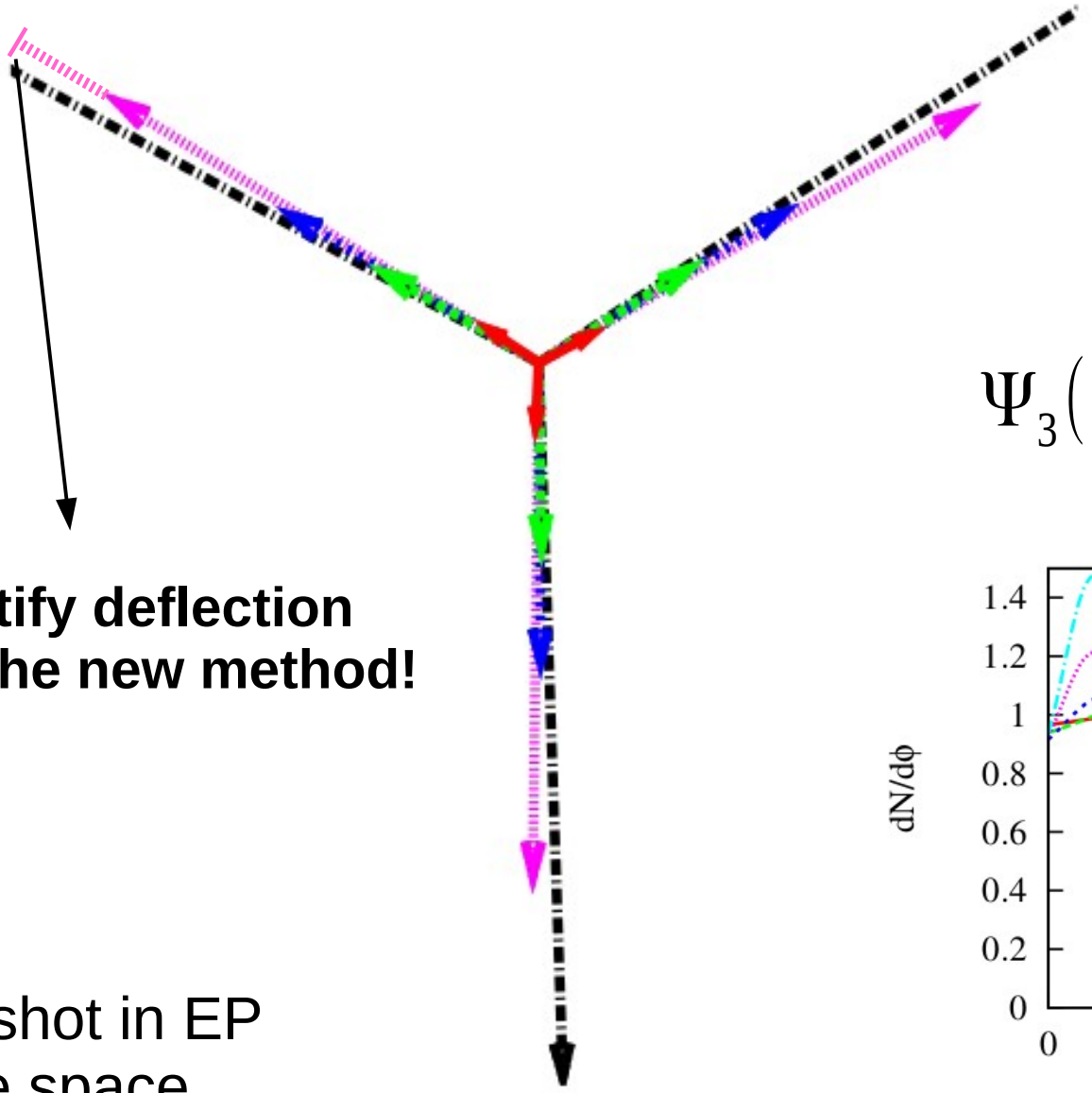
Closer look: subflow



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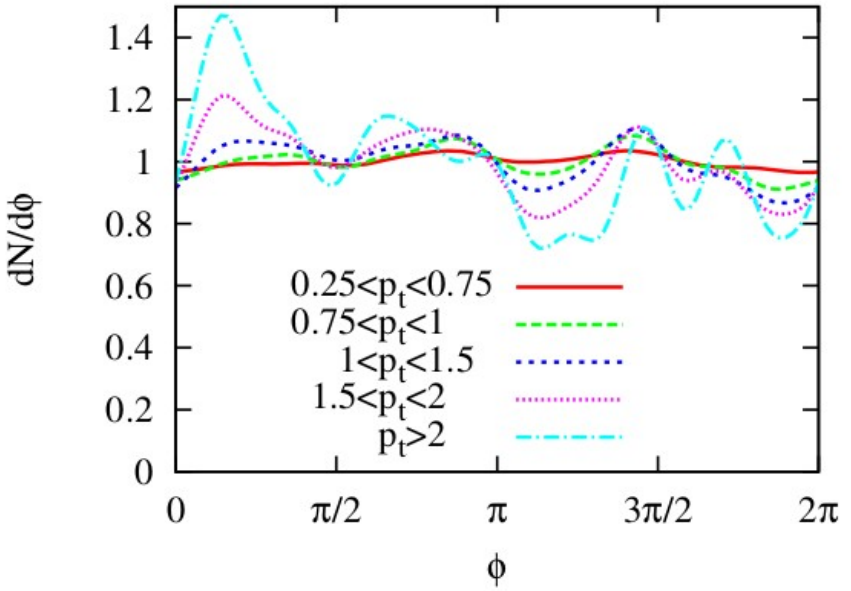

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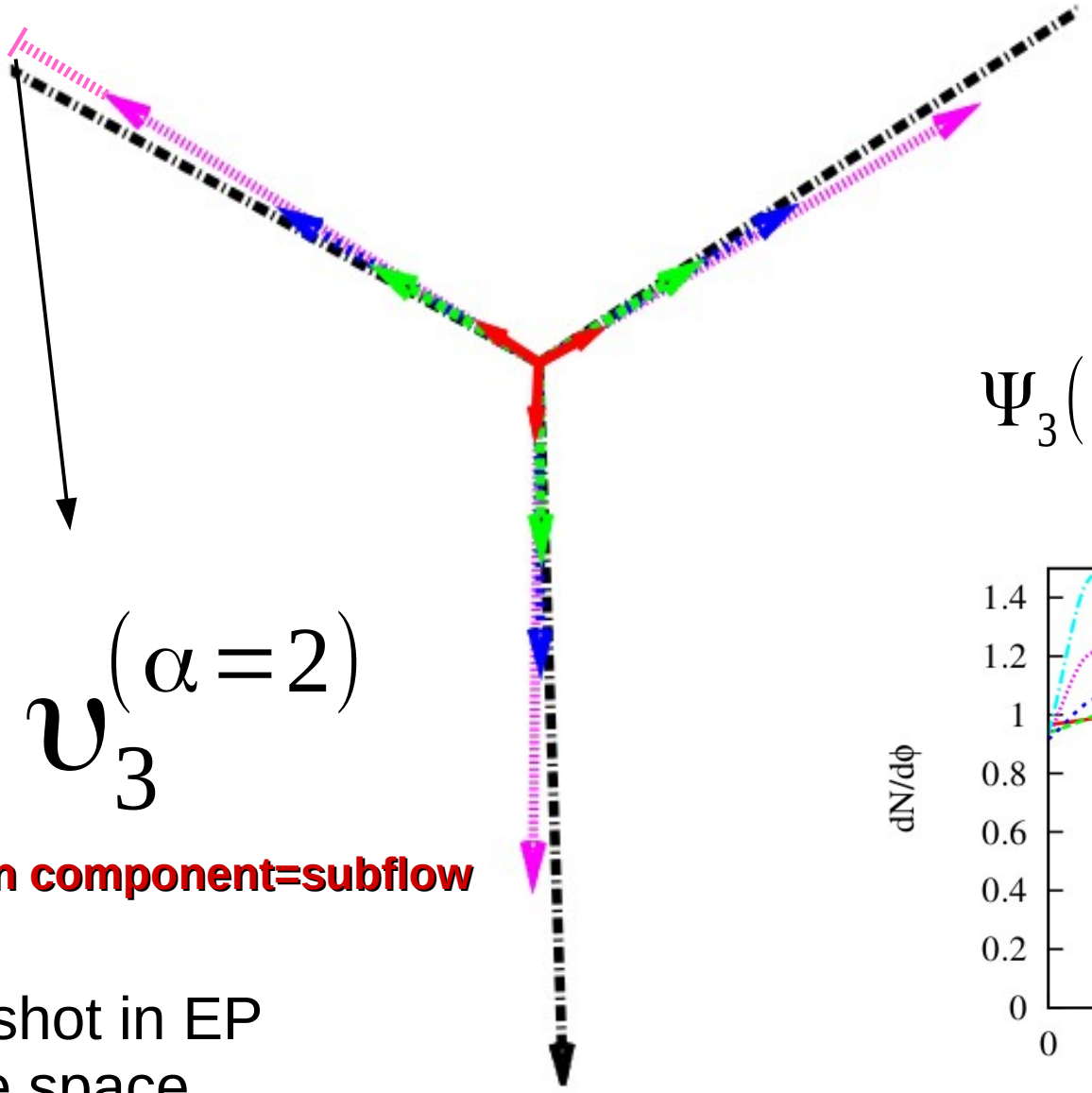

$$\upsilon_3^{(\alpha=2)}$$

Deflection component=subflow

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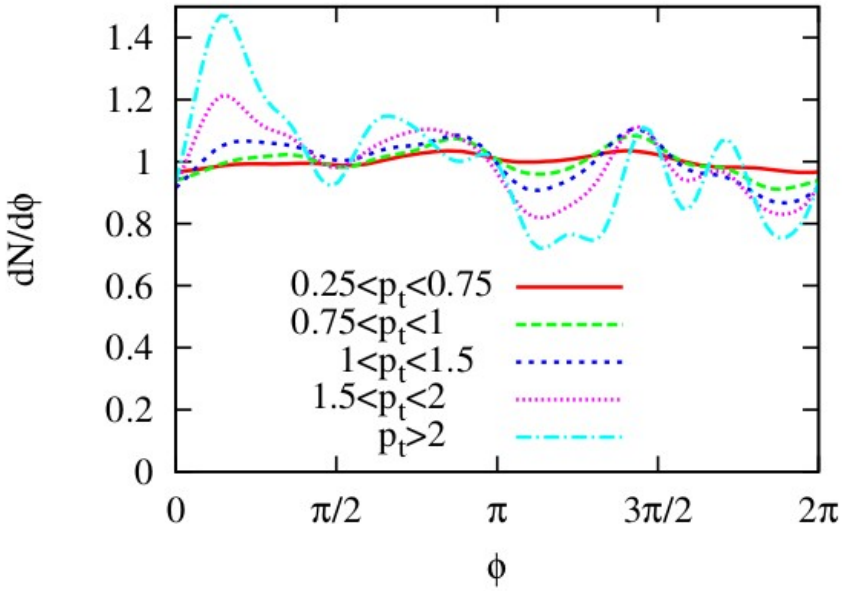

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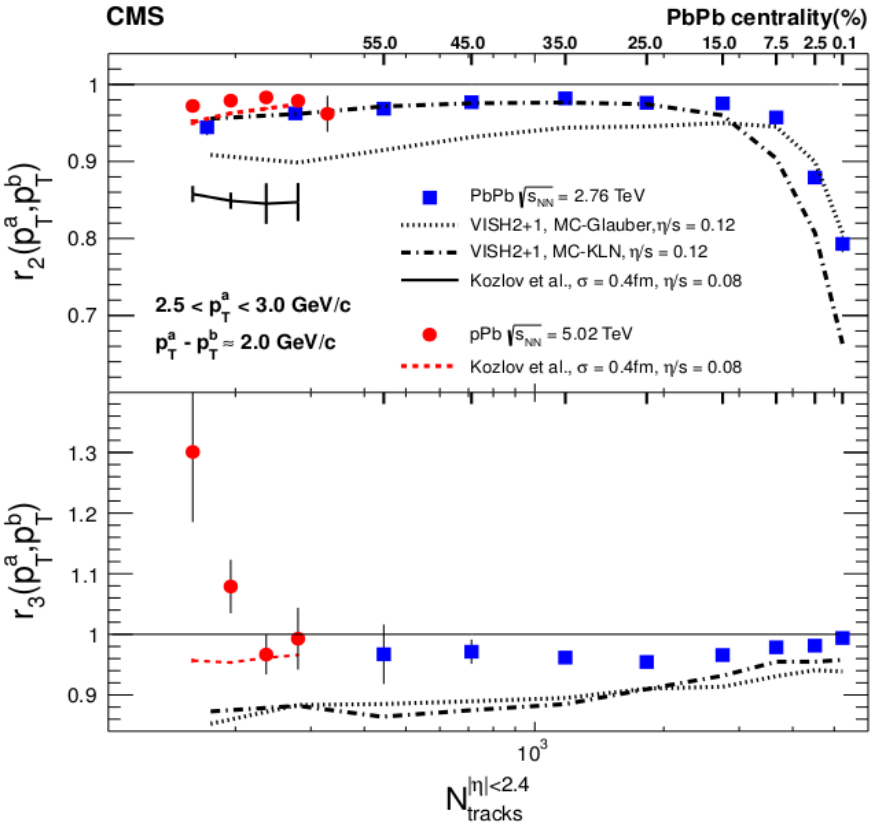
$$r_n = \frac{V_{\Delta n}(p_T^a, p_T^b)}{\sqrt{V_{\Delta n}(p_T^a, p_T^a) V_{\Delta n}(p_T^b, p_T^b)}}$$



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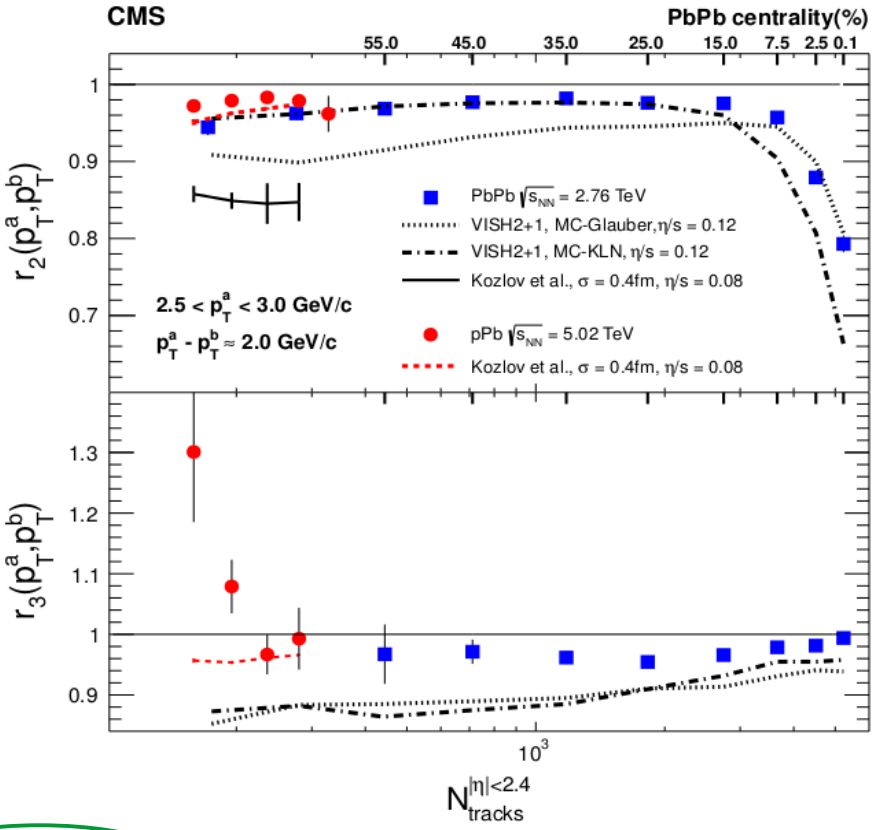
$$r_n \approx 1 - \frac{1}{2}\left[\frac{V_n^{(2)}(p_T^a)}{V_n^{(1)}(p_T^a)} - \frac{V_n^{(2)}(p_T^b)}{V_n^{(1)}(p_T^b)}\right]^2$$



subflow

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- Exposes a completely new variable, **the subflow**, which implies effects like factorization breaking
- The method can also be applied to **multiplicity** fluctuations and **rapidity** fluctuations of the expanding medium
- Exciting results to follow

THANK YOU