Harmonious Harmonics?
After the Common Origin of Correlations and Flow

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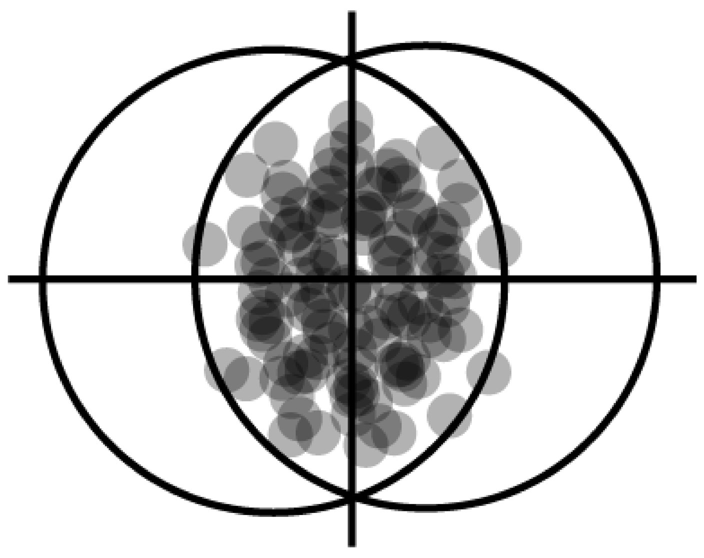
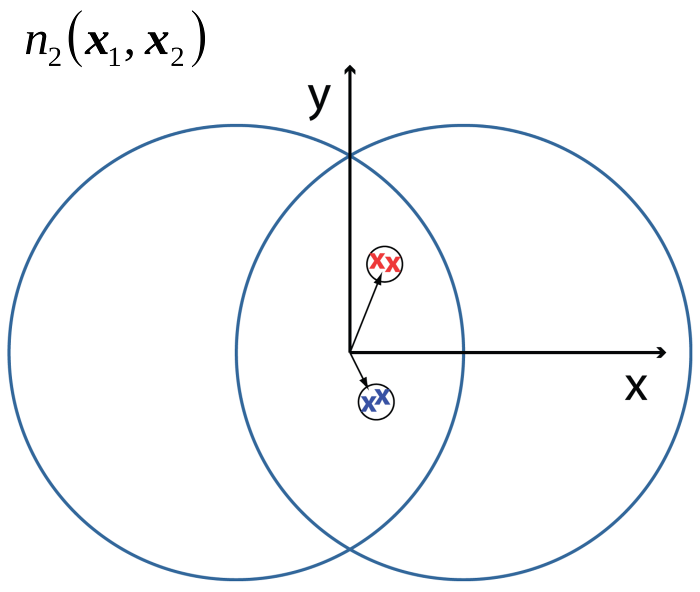
Abstract: We show that initial state fluctuations in concert with later-stage hydrodynamic flow describes a range of observables including both even and odd flow harmonics, the ridge, and multiplicity, momentum and flow fluctuations. This is the first comparison between multiplicity and transverse momentum fluctuations and flow fluctuations in the same framework. The simultaneous investigation of these observables allows us to study the interplay of correlations induced by collision geometry and common points of production. We employ a framework of initial state Glasma flux tubes followed by later stage hydrodynamic flow modeled in a blast wave. Our approach has the advantage that we can test our calculations over a broad range of collision systems and energies and provide useful benchmarks for more rigorous event-by-event hydrodynamic simulations. Our survey over these observables reveals a common energy and centrality dependence that we attribute to the production mechanism. Glasma calculations are consistent with this dependence.

What is the influence of lumpy initial conditions?



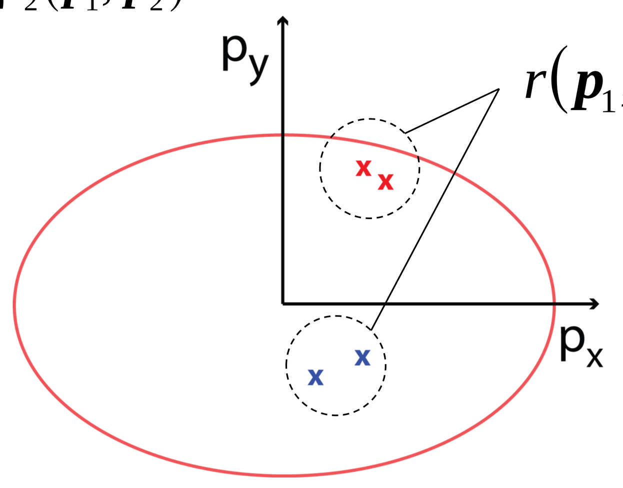
Initial State Configuration

$n_2(x_1, x_2)$



Final State Momentum

$\rho_2(p_1, p_2)$



correlations = pairs - singles²

Borghini, Dinh, Ollitrault ,Phys.Rev. C63 (2001) 054906

$$r(\mathbf{p}_1,\mathbf{p}_2)=\rho_2(\mathbf{p}_1,\mathbf{p}_2)-\rho_1(\mathbf{p}_1)\,\rho_1(\mathbf{p}_2)$$

Model:

Momentum Correlation Function: $$r(p_1,p_2)=\iint_{\text{freeze-out surface}} c(x_1,x_2)f(x_1,p_1)f(x_2,p_2)$$

Spatial Correlation Function: $$c(x_1,x_2)=\langle n_2(x_1,x_2)\rangle-\langle n_1(x_1)\rangle\langle n_1(x_2)\rangle$$

From Flux Tubes: $$c(x_1,x_2)\approx\mathcal{R}\langle N\rangle^2\delta(\mathbf{r}_t)\rho_{FT}(\mathbf{R}_t)$$

$\delta(\vec{r}_t)$ Correlated partons from same flux tube

$\mathbf{r}_t=\mathbf{r}_{t1}-\mathbf{r}_{t2}$

$\mathbf{R}_t=(\mathbf{r}_{t1}+\mathbf{r}_{t2})/2$

$$\rho_{FT}(\vec{R}_t)\approx\frac{2}{Area}\left(1-\frac{R_t^2}{R_A^2}\right)$$ Average all flux tube probability distributions

In CGC-Glasma

Correlation Strength: $$\mathcal{R}=\frac{\sigma^2-\mu}{\mu^2}\frac{1}{\langle K\rangle}+\frac{\langle K^2\rangle-\langle K\rangle^2}{\langle K\rangle^2}\approx\frac{1}{\langle K\rangle}$$

K tubes with parton means μ and variances σ^2

Gluon Density: $$\frac{dN}{dy}=\frac{gluons}{tube}\times\langle K\rangle\propto\langle K\rangle\alpha_s^{-1}(Q_s^2)$$

Saturation scale Q_s^2

Kharzeev, Nardi, Phys.Lett. B507 (2001) 121-128

Glasma Correlation Scale: $$\mathcal{R}\frac{dN}{dy}\propto\alpha_s^{-1}(Q_s^2)$$

Multiplicity Fluctuations:

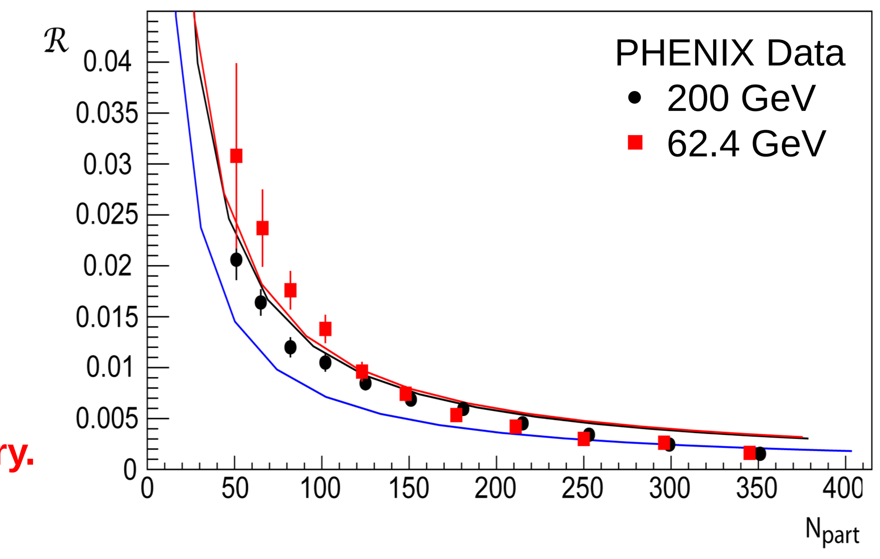
Influence of "lumps": $r\,(\mathbf{p}_1,\mathbf{p}_2)\neq 0$

$$\iint r(\mathbf{p}_1,\mathbf{p}_2)d\mathbf{p}_1 d\mathbf{p}_2=Var(N)-\langle N\rangle$$

Non-zero values indicate non-Poissonian behavior

$$\mathcal{R}=\frac{Var(N)-\langle N\rangle}{\langle N\rangle^2}\propto\frac{1}{\langle N_{sources}\rangle}$$

Independent of geometry. Independent of flow.



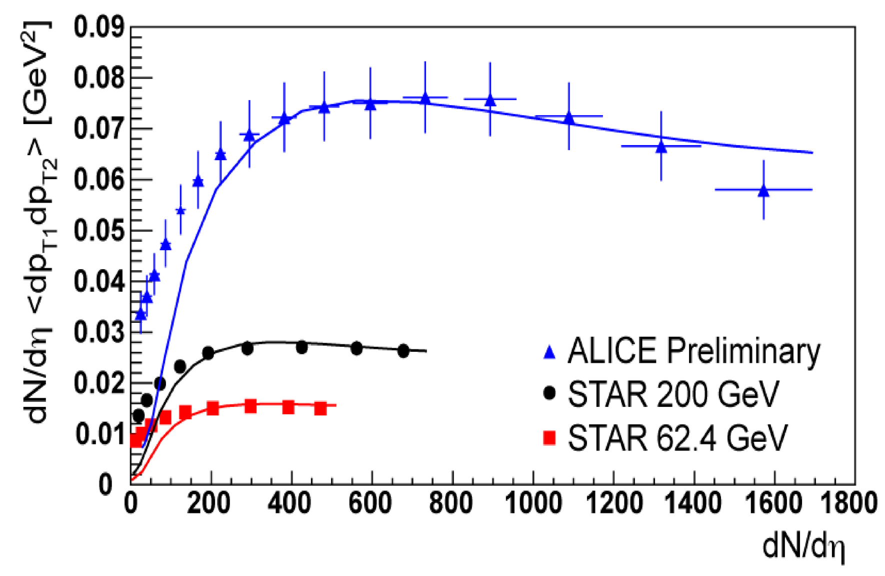
p_T Covariance:

Influence of "lumps": Correlations, $r\,(\mathbf{p}_1,\mathbf{p}_2)$, are modified by transverse expansion based on origin.

$$\langle\delta p_{t1}\delta p_{t2}\rangle\equiv\iint\delta p_{t1}\delta p_{t2}\frac{r(\mathbf{p}_1,\mathbf{p}_2)}{\langle N(N-1)\rangle}d\mathbf{p}_1 d\mathbf{p}_2$$

$$\delta p_t\equiv p_t-\langle p_t\rangle$$

Independent of geometry and anisotropic flow, but not average expansion.



Fourier Coefficients

Influence of "lumps": fluctuating event geometry + correlation modifications from flow

$\mathcal{F}$ { pairs = singles² + correlations }

$$v_n\{2\}^2\approx\langle v_n\rangle^2+2\sigma_n^2$$

Borghini, Dinh, Ollitrault; Voloshin, Poskanzer, Tang, Wang

***v_n* factorization is a signature of flow if $\sigma_n = 0$**

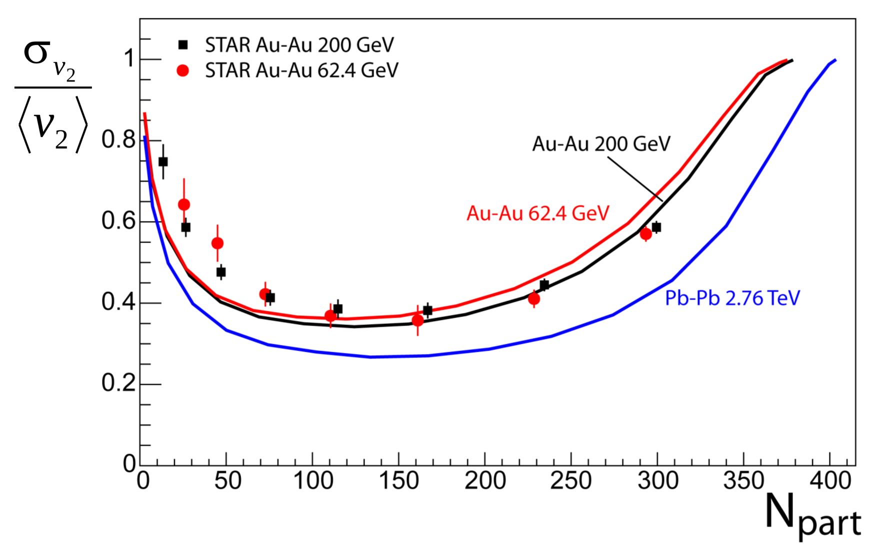
- $\langle v_n\rangle^2$ = reaction plane correlations.
- Take $v_n\{4\}\approx\langle v_n\rangle$ from blast wave (dasheed lines in v_n graphs)
- Calculate $v_n\{2\}$ using σ_n^2 and $\langle v_n\rangle^2$

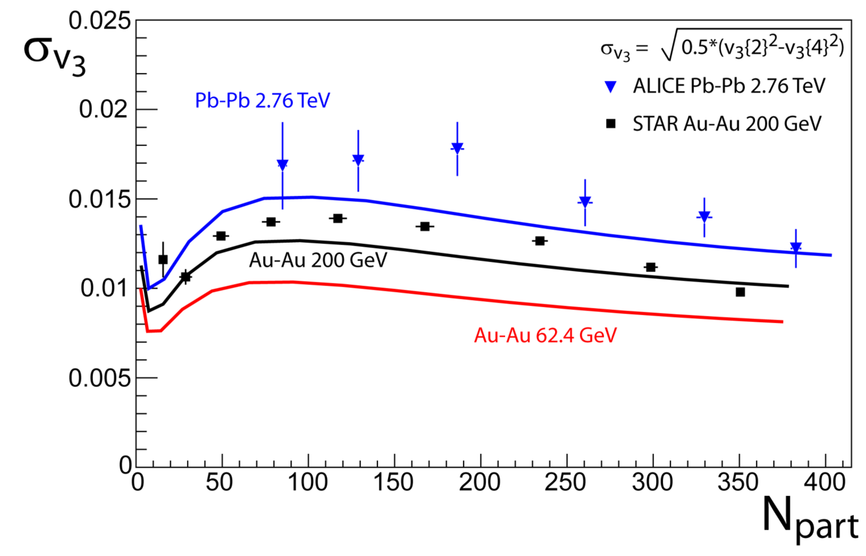
Correlated Part:

$$\sigma_n^2=\left(v_n\{2\}^2-v_n\{4\}^2\right)/2\qquad\Delta\phi=\phi_1-\phi_2$$

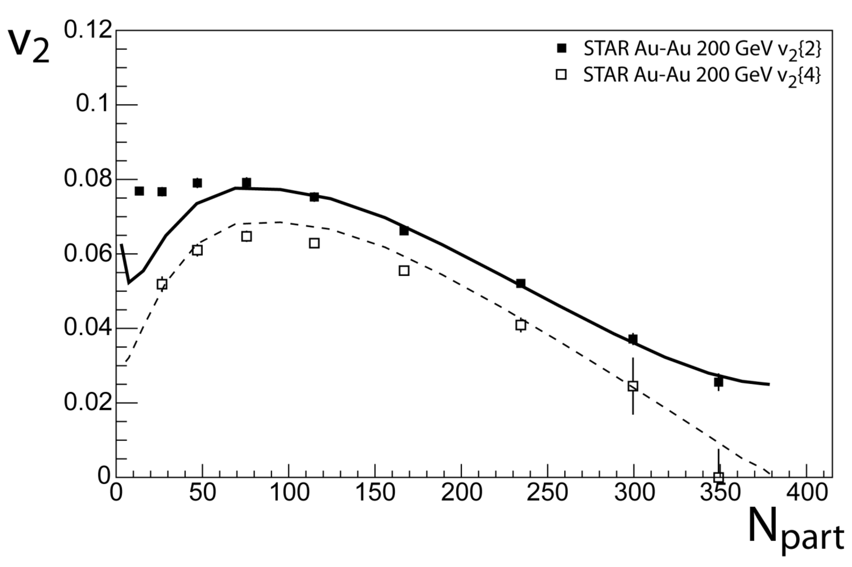
$$\sigma_n^2=\iint\frac{r(\mathbf{p}_1,\mathbf{p}_2)}{2\langle N(N-1)\rangle}\cos(n\Delta\phi)\,d\mathbf{p}_1 d\mathbf{p}_2$$

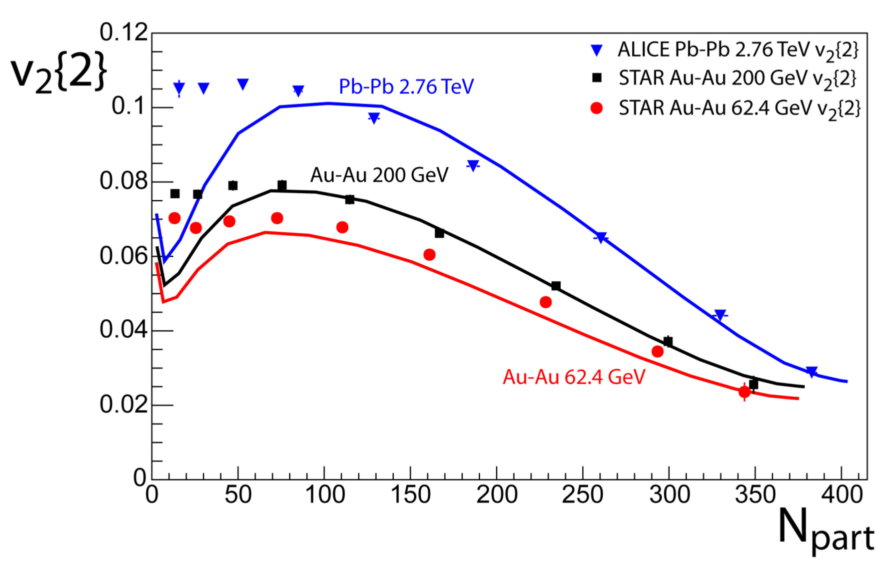
Geometry induces "reaction plane" correlations. Geometry influences the modification of same source correlations, but the existence of the correlations are not unique to any given geometry. i.e. if $v_n\{4\}=0$ (no reaction plane correlations) $v_n\{2\}^2=2\sigma_n^2$

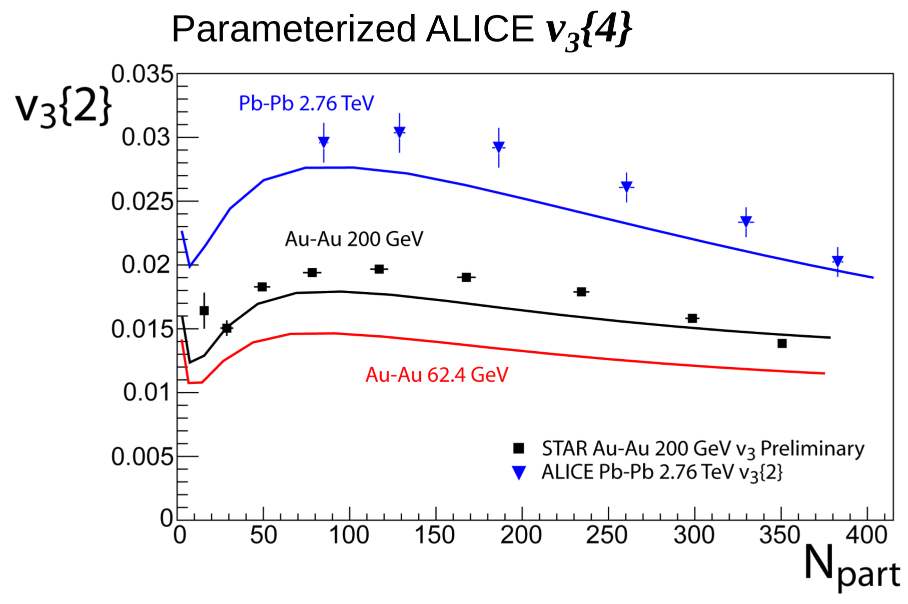


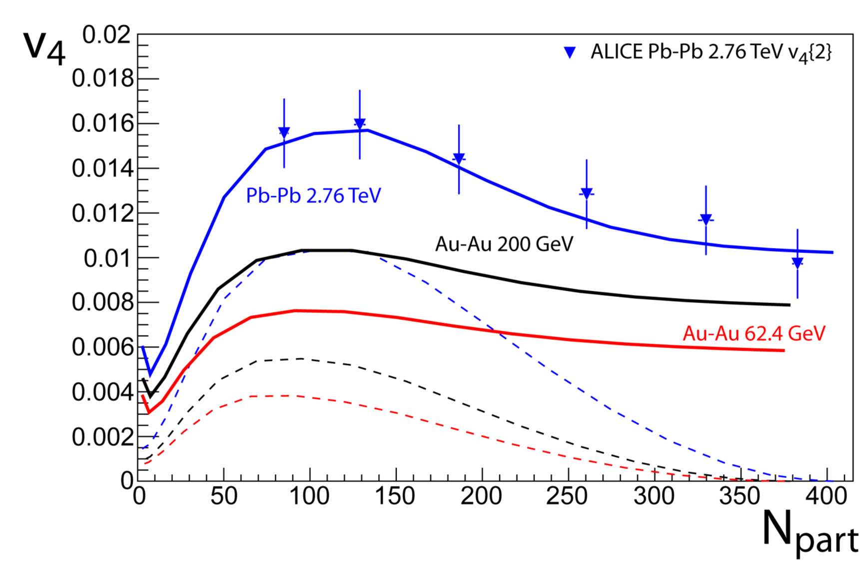


Blast Wave $v_3\{4\}=0$
STAR $v_3\{4\}=0$ consistent with zero
Parameterized ALICE $v_3\{4\}$









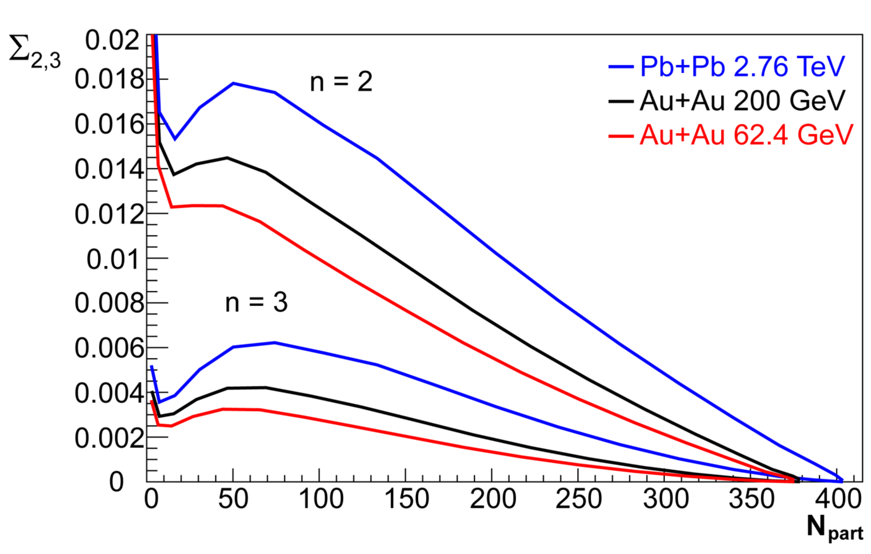
$v_n\{4\}$ Corrections

$$v_n\{4\}^4=\langle v_n\rangle^4-\langle v_n\rangle^2\cdot 2\,\mathrm{Re}\{\Sigma_n^2\}-|\Sigma_n^2|^2$$

$$\Sigma_n^2=\iint\frac{r(\mathbf{p}_1,\mathbf{p}_2)}{\langle N(N-1)\rangle}\cos 2n(\Phi-\psi_{RP})\,d\mathbf{p}_1 d\mathbf{p}_2$$

$$\Phi=(\phi_1+\phi_2)/2$$

These corrections should also contribute to Chiral Magnetic Effect measurements.



The Soft Ridge

$$\frac{\Delta\rho(\Delta\phi)}{\sqrt{\rho_{ref}}}=\frac{2}{2\pi}\frac{dN}{dy}\sum_{n=1}\langle v_n\rangle^2\cos n\Delta\phi+\frac{1}{2\pi}\frac{dN}{dy}\frac{r(\Delta\phi)}{\rho_{ref}}$$

ρ_{ref} = mixed event pairs

Flow subtracted ridge:

$$2\frac{dN}{dy}\sigma_n^2\approx\int\frac{\Delta\rho(\Delta\phi)}{\sqrt{\rho_{ref}}}\cos n\Delta\phi$$

Ridge correlations come from flow fluctuations.