Correlations at STAR: interferometry and event structure

ICPAQGP-2005, Kolkata, India.

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February 12, 2005

1 STAR fluctuation/correlation physics in this talk

Equilibration: Arguably the central issue of RHIC hadronic physics. Is it taking place ? What is the mechanism ? And what is equilibrating ?

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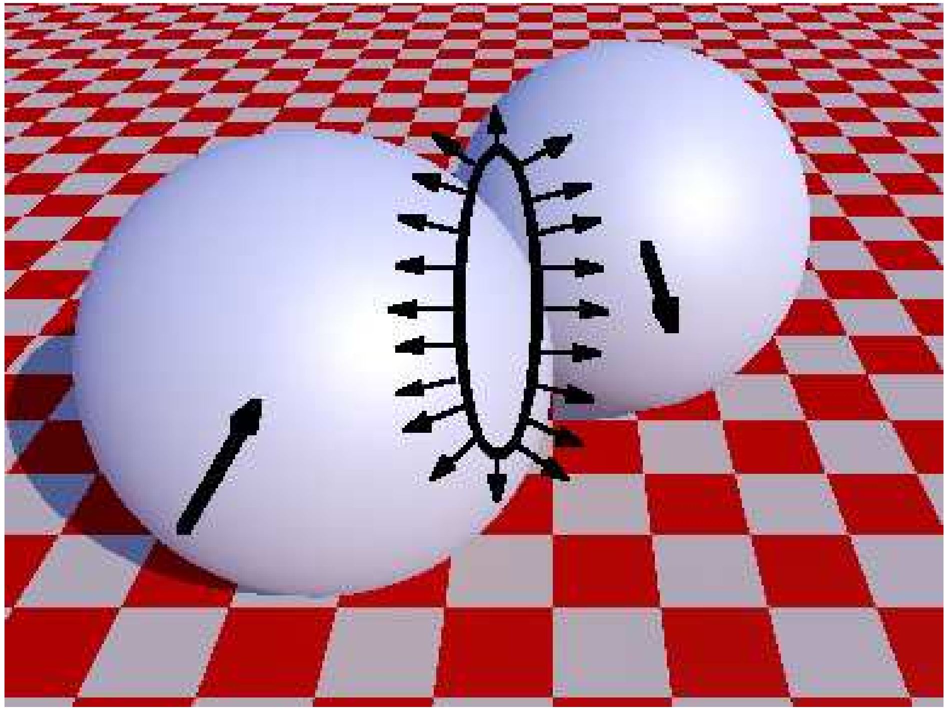
- Arguments for Blast Wave from HBT and p_t fluctuations
- Novel techniques throughout...

2 Flow – directed and elliptic



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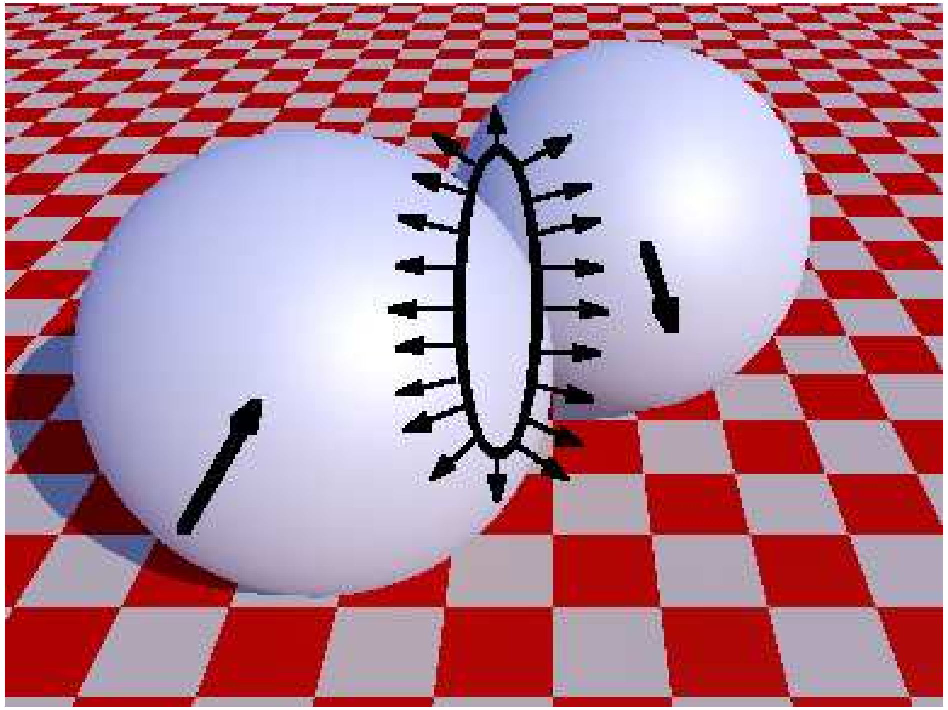

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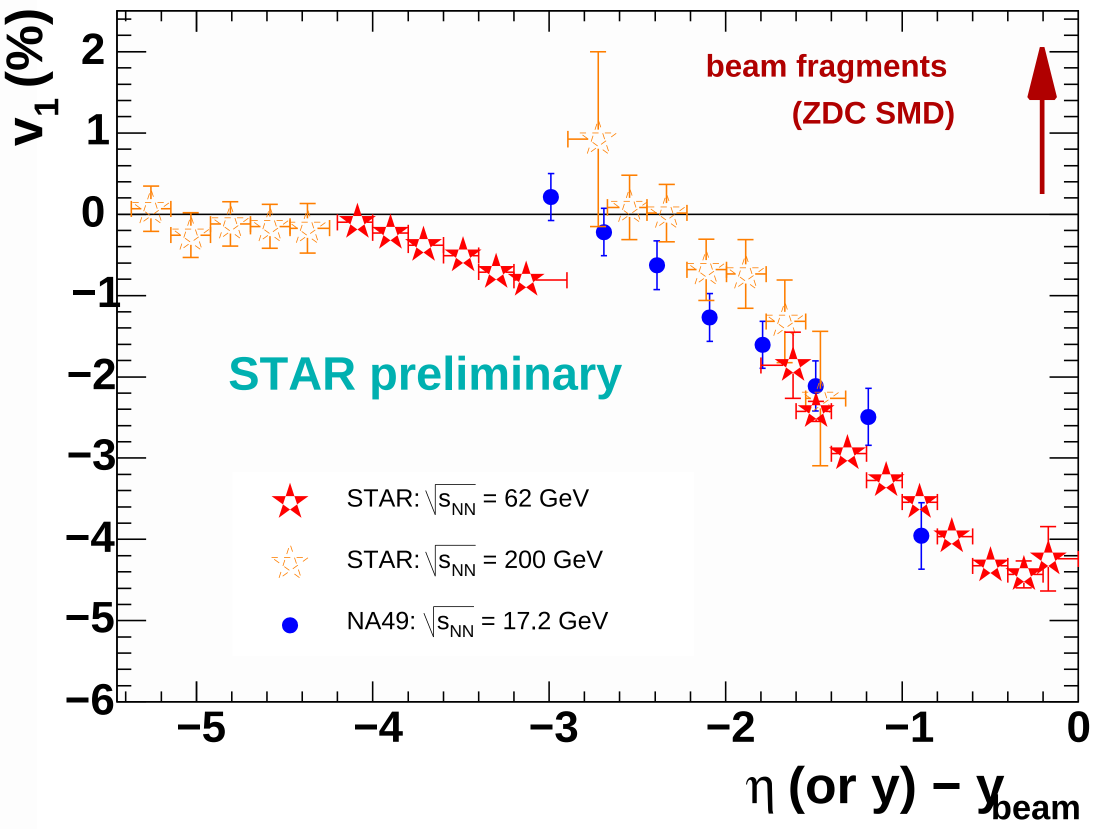
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\{1 + \sum_{m=1}^{\infty} 2v_m \cos[m(\phi - \Psi_r)]\} \tag{1}$$

- flow starts early – perhaps before hydro is applicable (stopping stage)
- testifies to equilibration
- sensitive to pressure and density gradients
- flow is a multiparticle effect; there is "non-flow"

Directed flow



Charged-particles v_1 from 3-particle cumulants in the projectile frame.

- monotonic around midrapidity
- Supports limiting fragmentation
- Antiflow !

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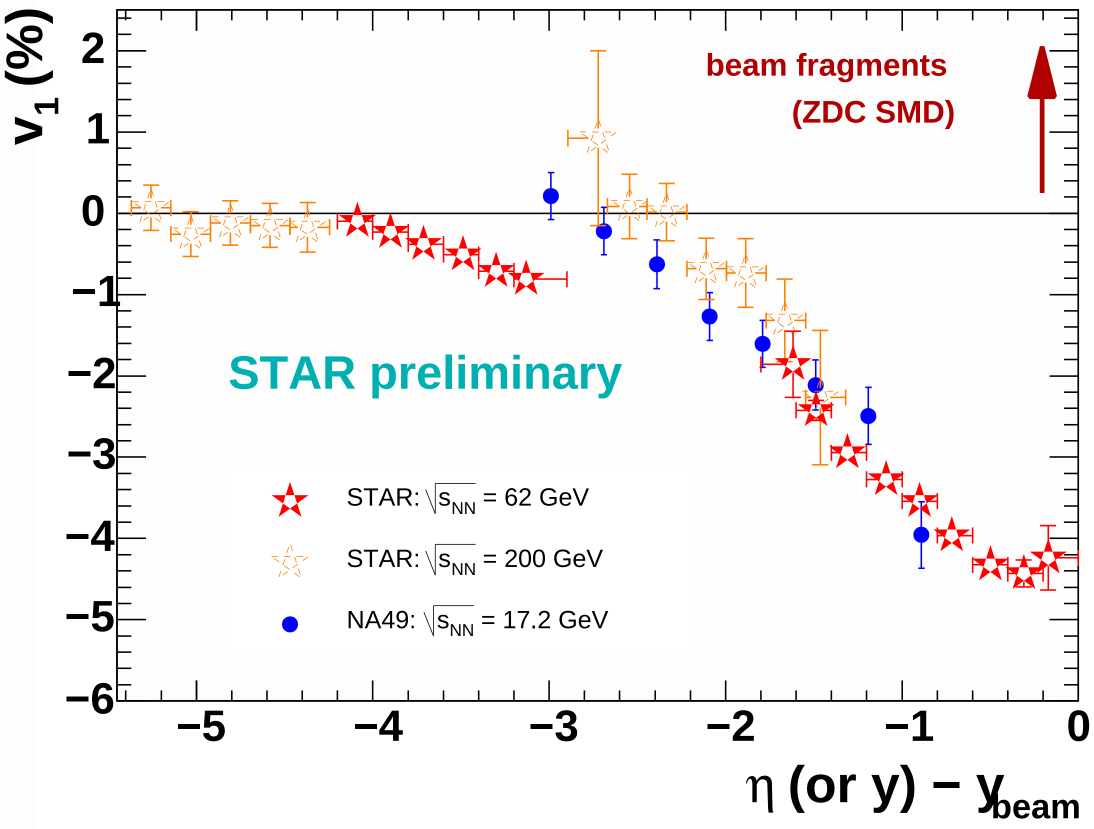

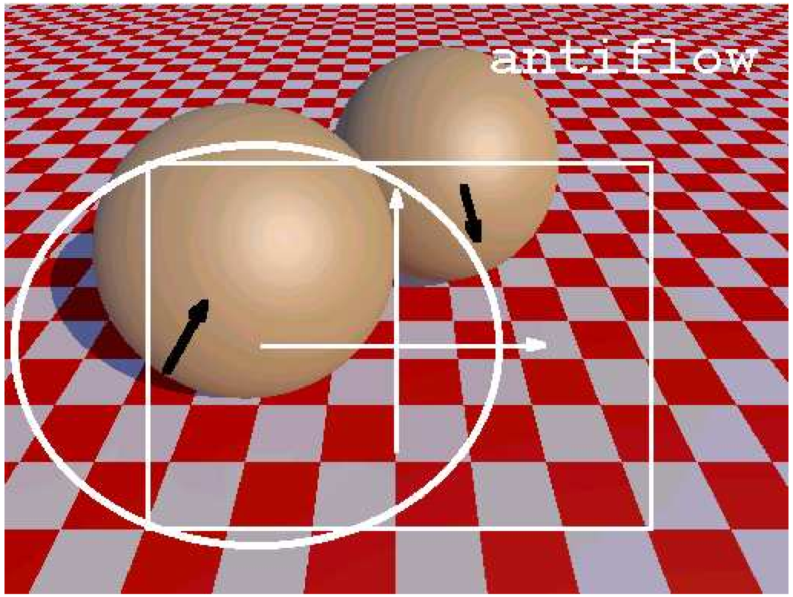

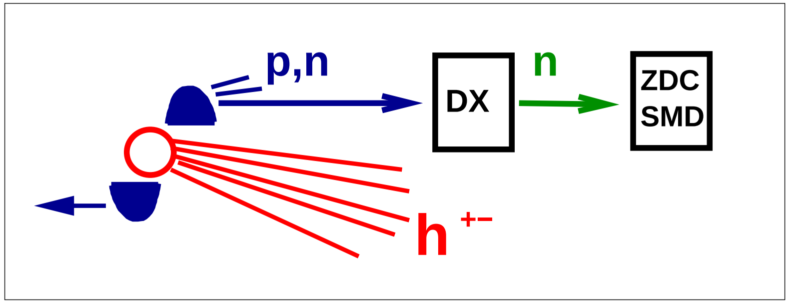

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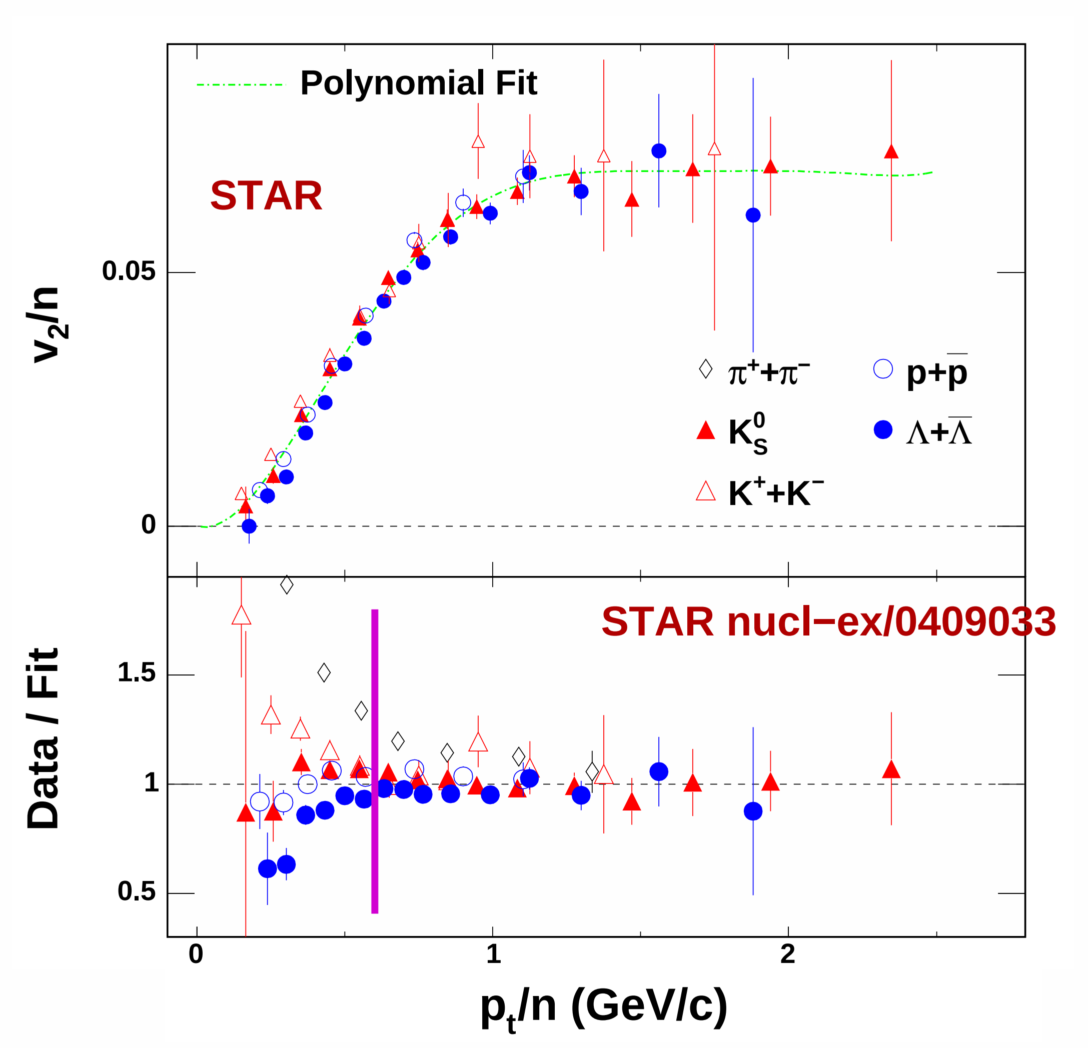
4 Elliptic flow and quark coalescence



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi) \qquad (2)$$

$$\frac{dN_{\mathrm{clscnc},n}}{d\phi}(p_t) \propto \left(\frac{dN(\frac{p_t}{n})}{d\phi} \right)^n \qquad (3)$$

$$(1 + 2v_2 \cos(2\phi))^n = \qquad (4)$$

$$1 + 2v_2 n \cos(2\phi) + \mathcal{O}(v_2^2)$$

STAR AuAu 200 GeV minbas; n is number of constituent quarks. Expect universality if quark coalescence dominates hadronization after the universal flow sets in. Valid at $p_t/n > 0.6$ GeV/c for K_S^0,$K^\pm$,p,$\bar{p}$,Λ,$\bar{\Lambda}$.

5 HBT definitions for bosons

$$C(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho(p_1)\rho(p_2)} \rightarrow C_{\rm exp}(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_{\rm mix}(p_1, p_2)} \tag{5}$$

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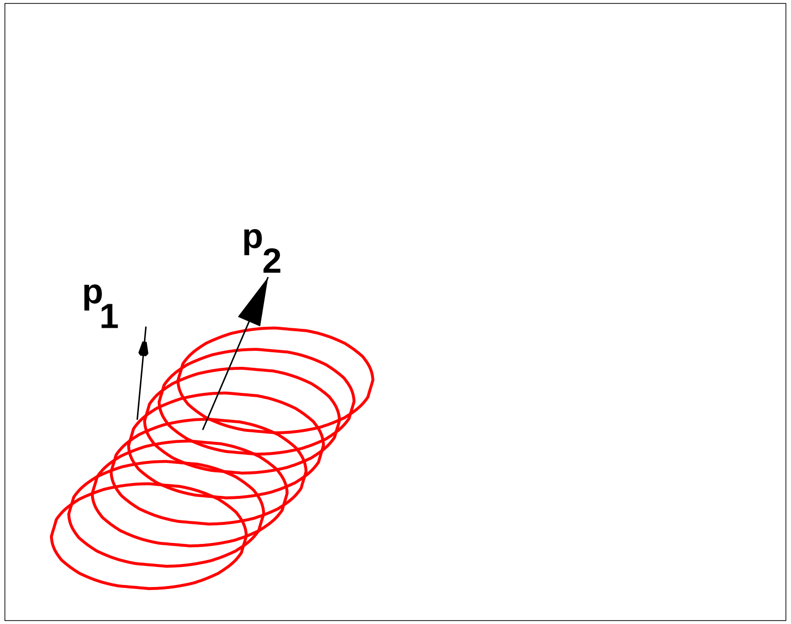

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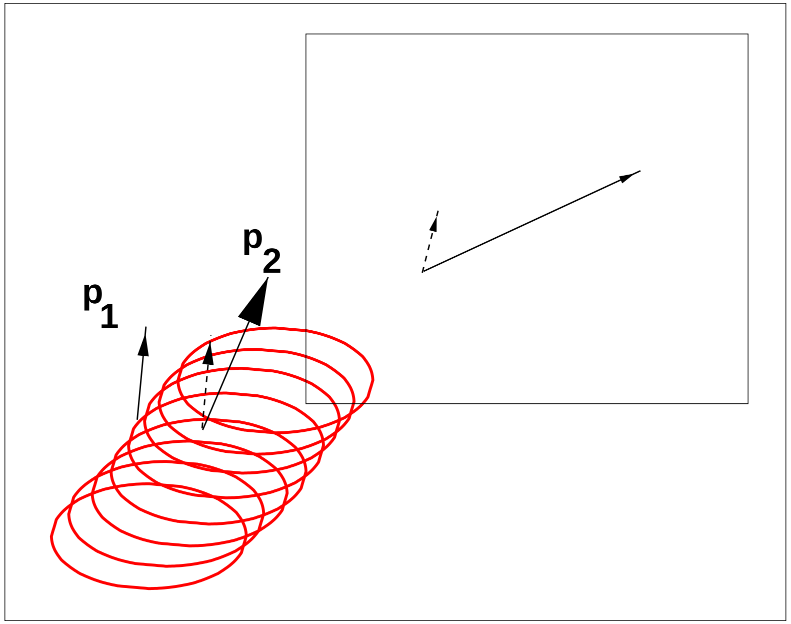

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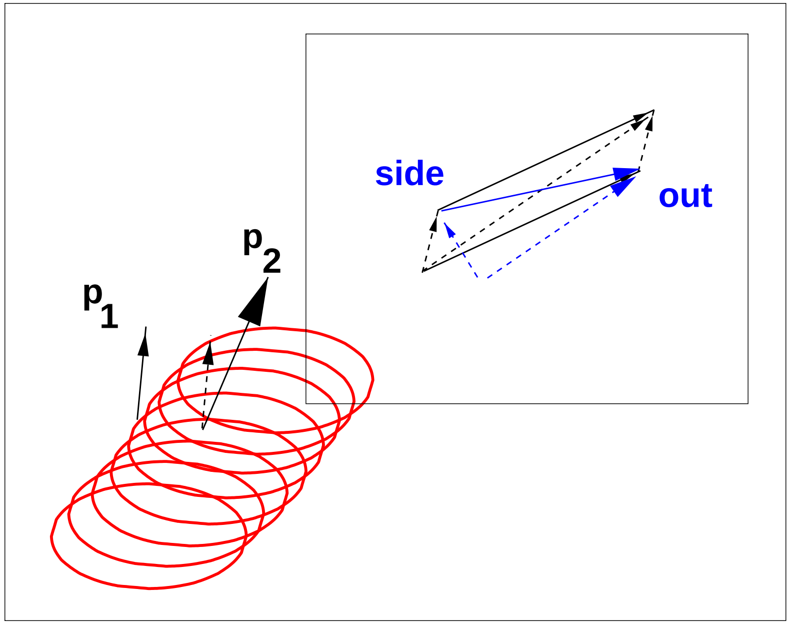

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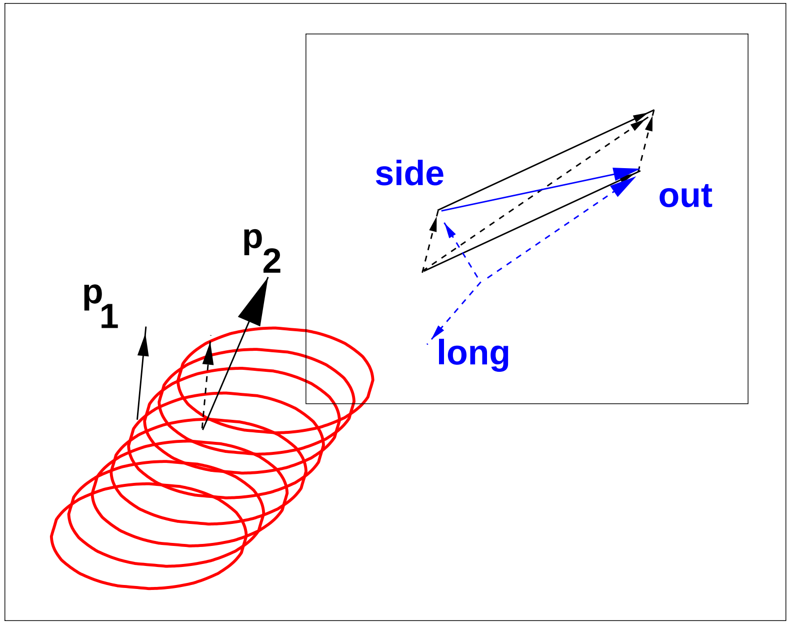

emission time $\rightarrow R_o^2$;
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longitudinal homogeneity $\rightarrow R_l^2$

Bertsch-Pratt parameterization: traditional

$$C_{\text{fit}}(\vec{q}) = 1 + \lambda \exp(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2 q_o q_s R_{os}^2) \tag{6}$$

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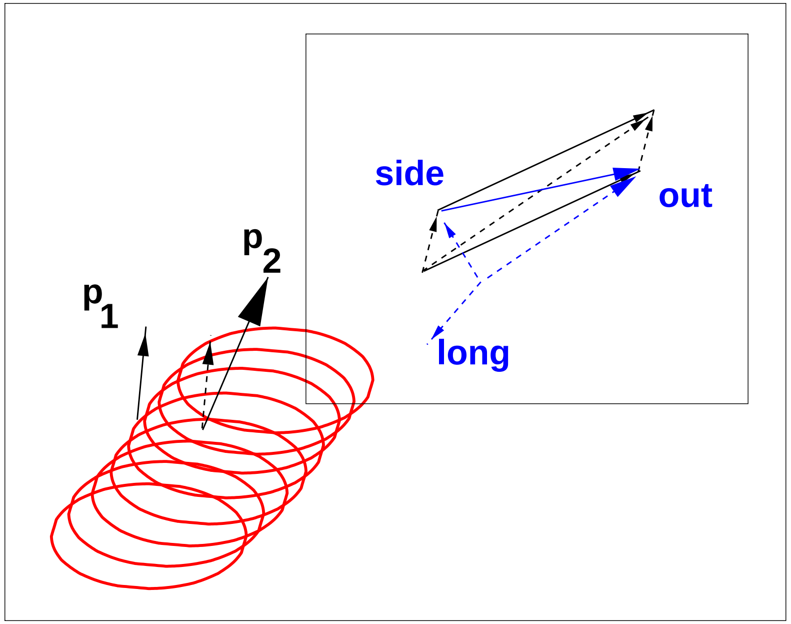

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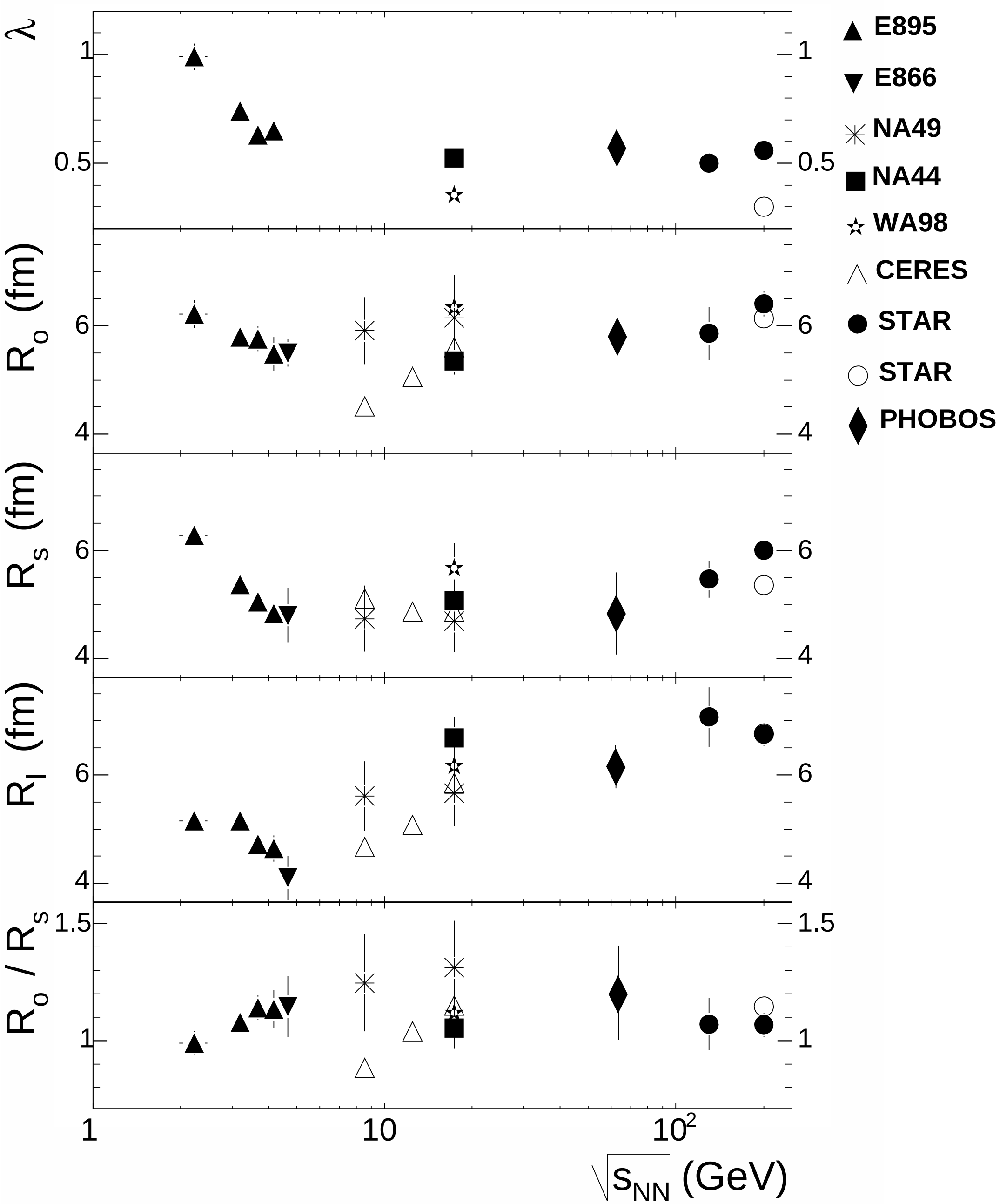
including Coulomb effect with Bowler-Sinyukov method (implies complete chaoticity)

$$C_{\rm fit}(\vec{q}) = (1 - \lambda) + \lambda K_{\rm Coulomb} \exp(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2 q_o q_s R_{os}^2) \quad (7)$$

6 The "HBT puzzle"



Open symbols:
Bowler-Sinyukov fits

- Causes of inhomogeneity ?
- $R_{\mathrm{out}} \approx R_{\mathrm{side}}$ – instantaneous emission ?
- R_{long} smaller than expected

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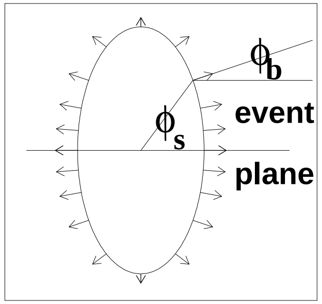
- 

x,y-dependent transverse blast (y_t of the source): [a] – ρ_0 and ρ_2:

$$\rho(r, \phi_s) = \left(\sqrt{\frac{x^2}{R_x^2} + \frac{y^2}{R_y^2}}\right)(\rho_0 + \rho_2 \cos(2\phi_b)) \qquad (8)$$

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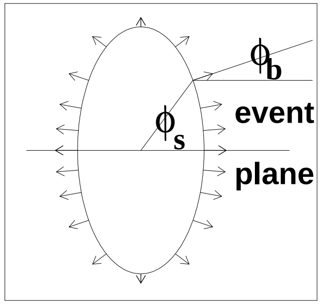
- 

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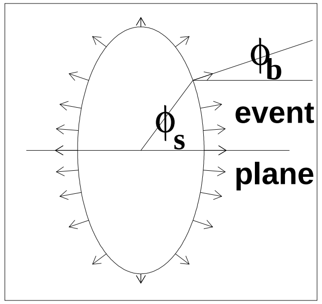
- 

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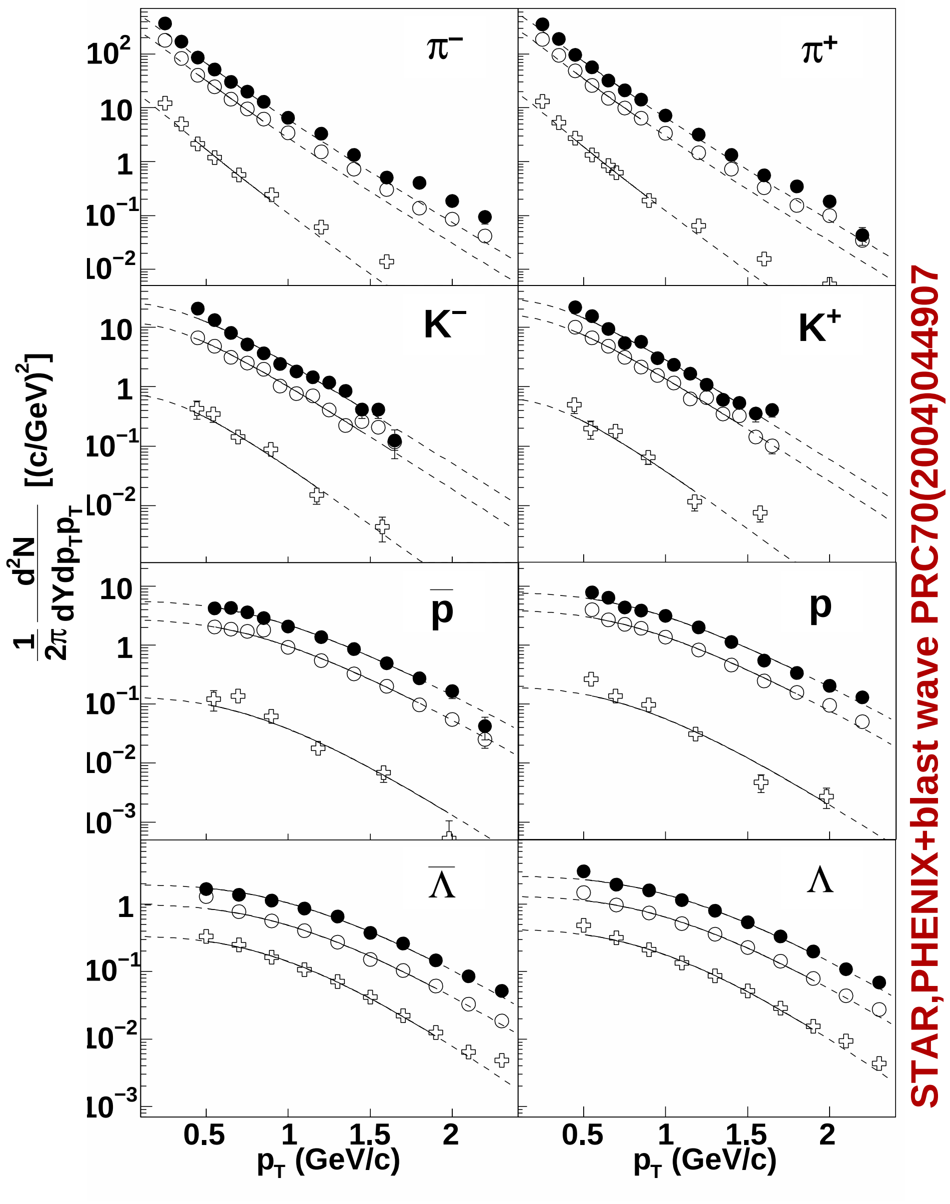
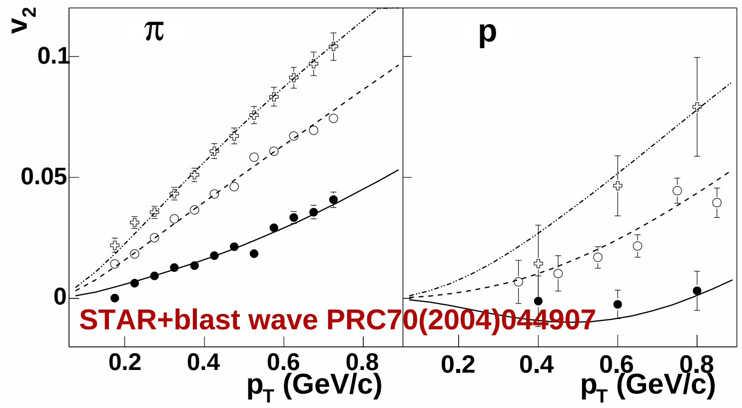
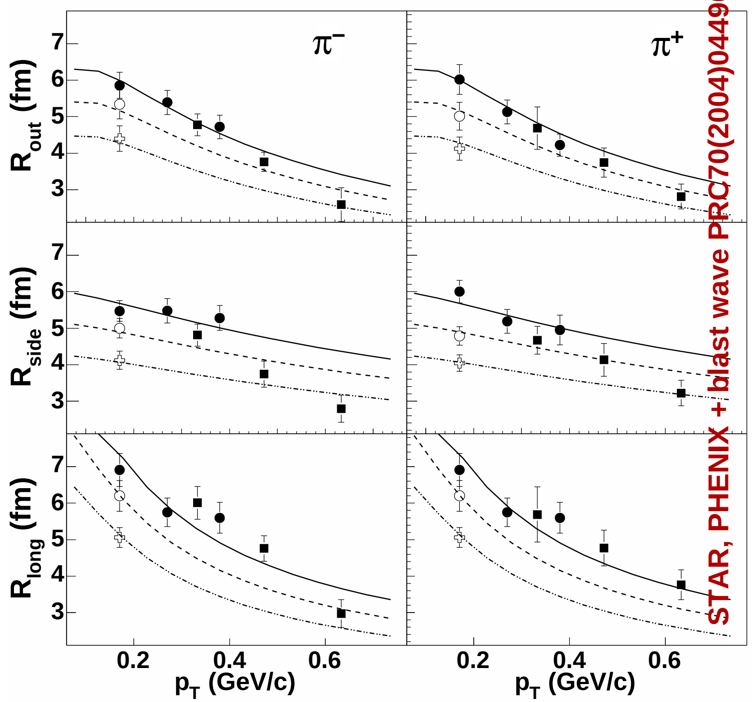
8 Combined fits with Blast Wave: spectra, v_2, HBT





● central; ○ mid-central; ✣ peripheral



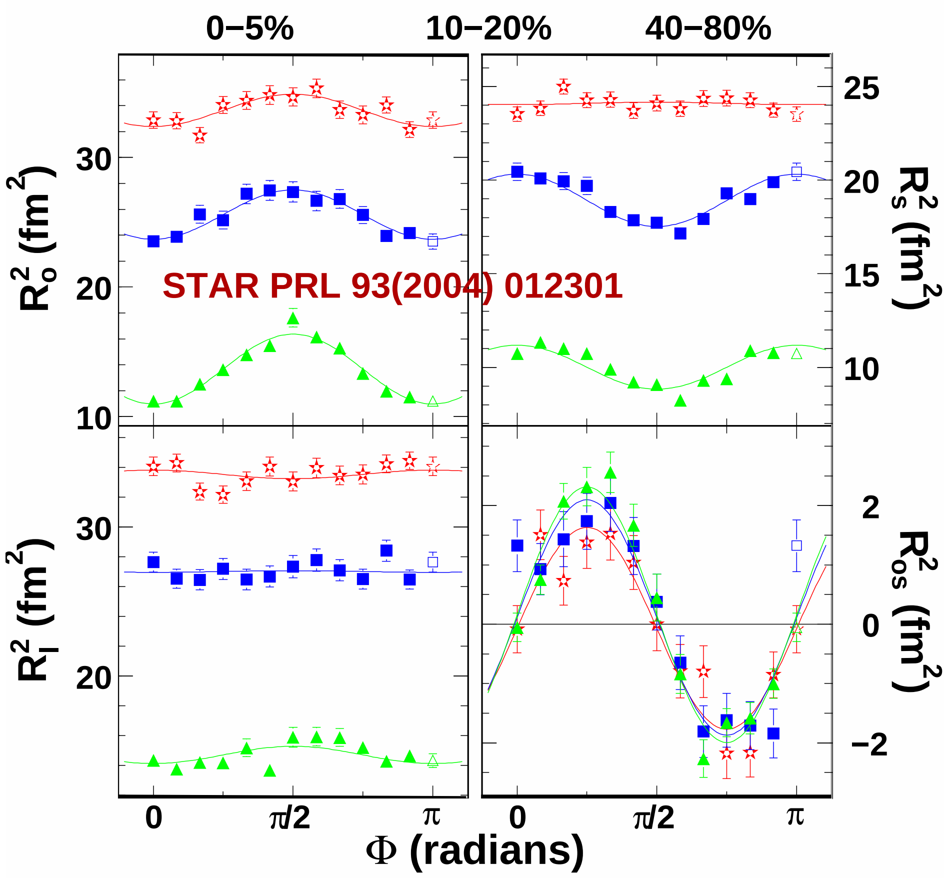
STAR ● central; ○ mid-central;
✣ peripheral; ■ PHENIX 30% central

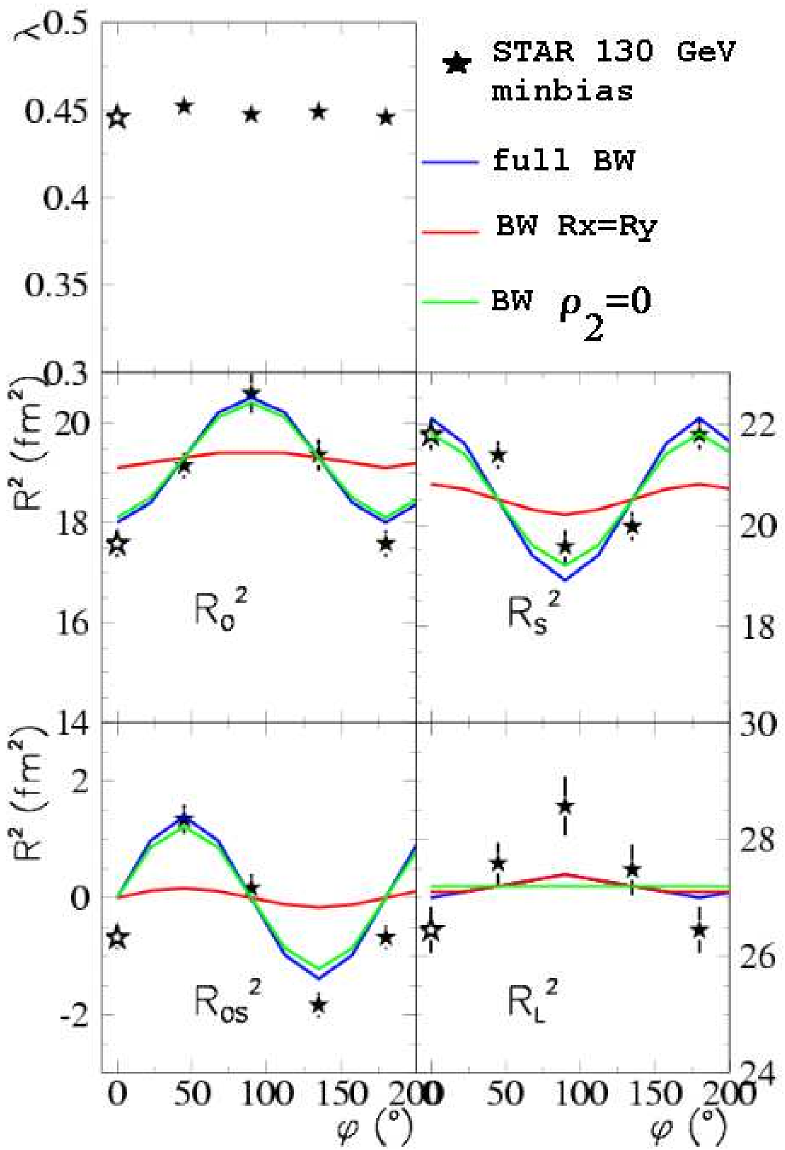
9 Blast Wave fit paramaters at RHIC

	centr	mid-c	periph
T(MeV)	106	107	100
ρ_0	0.89	0.85	0.79
ρ_2	$(6.0 \pm 0.8)10^{-2}$	$(5.8 \pm 0.5)10^{-2}$	$(5 \pm 1)10^{-2}$
R_x(fm)	13.2	10.4	8.0
R_y(fm)	13.0	11.8	10.1
τ(fm/c)	9.2	7.7	6.5
$\Delta\tau$ (fm/c)	0.003$\pm$1.3	0.06$\pm$1.3	0.6$\pm$1.8

Emission duration consistent with 0...

10 Blast Wave and the azimuthally-dependent HBT results





Left: STAR AuAu 200 GeV. Right: calculations for non-round source 10.8×11.4fm, τ=8.3fm/c, $\Delta\tau = 0$ compare with STAR AuAu 130 GeV data

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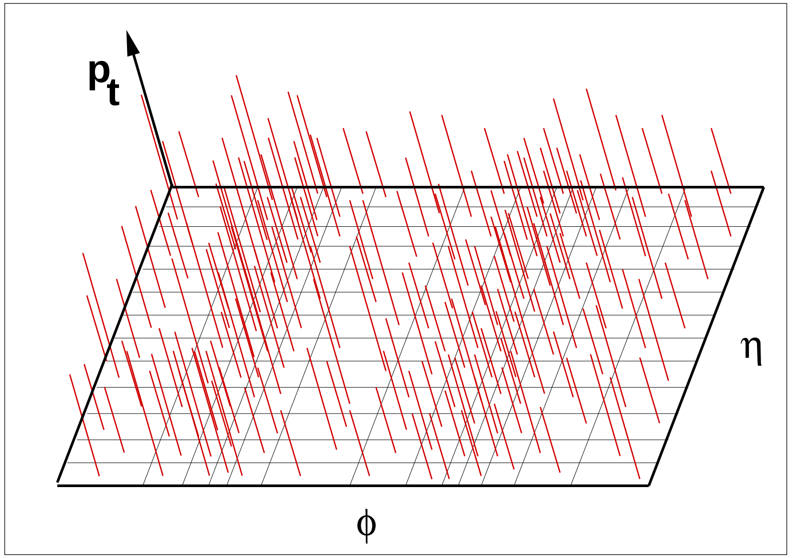

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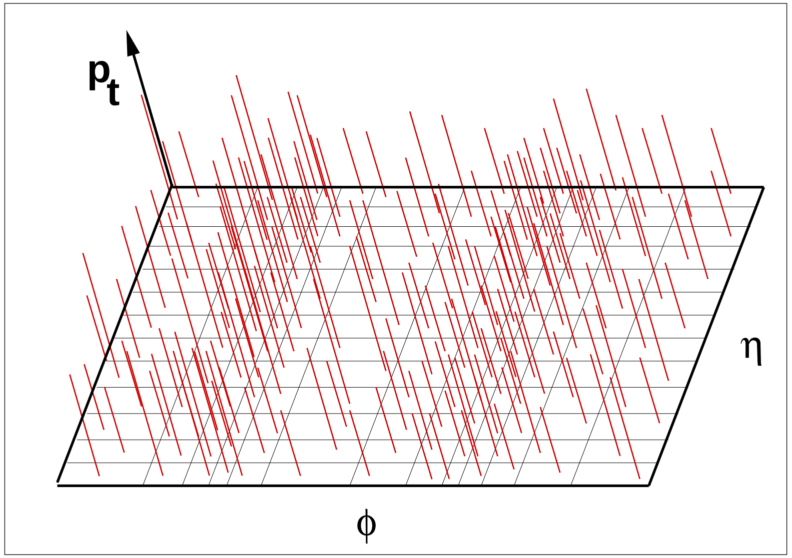

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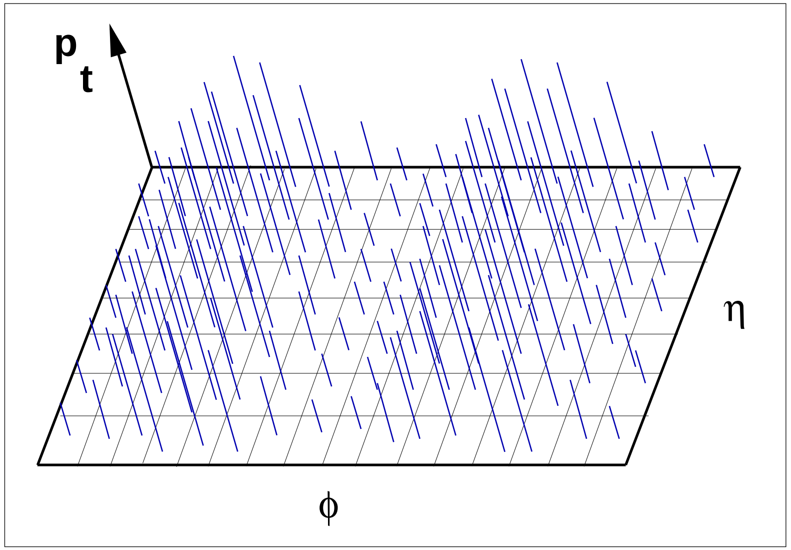

Also elliptic... flow (p_t effect) ! Pro: blast wave fits. Is there a **direct** measurement ?

12 Towards p_t correlation/fluctuation analysis

Problem: need to tell apart $p_{t,i}$ and number contributions to the $p_t \equiv \sum_{i \in (\eta,\phi)\mathrm{bin}} p_{t,i}$ $\Rightarrow$ can extract the p_t correlation alone.

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$$\mathrm{Var}[p_t] = \mathrm{Var}[\sum_i^n p_{t,i}] = \mathrm{Var}[\sum_i^n(\hat{p}_t + u_i)] = \hat{p_t}^2\mathrm{Var}[n] + \mathrm{Var}[u] + 2\hat{p}_t\mathrm{Cov}[n, u] \tag{10}$$

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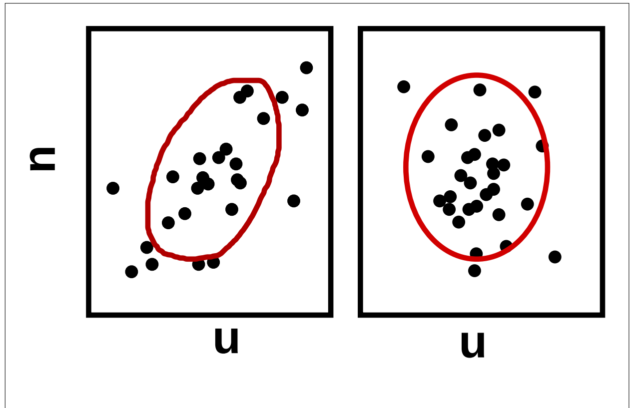

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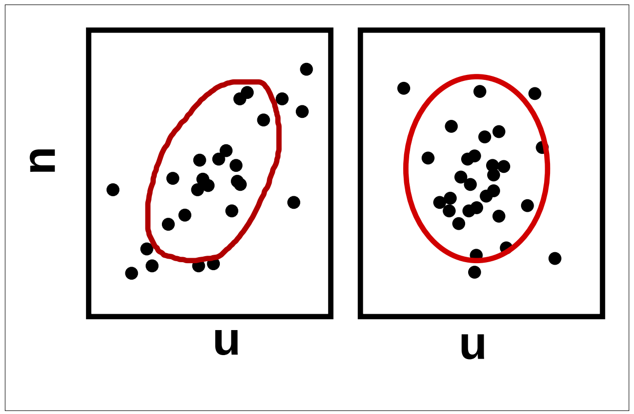

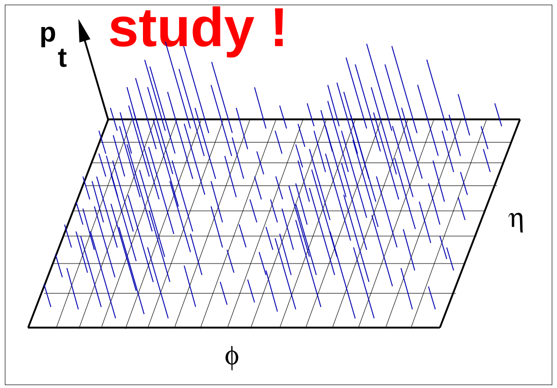

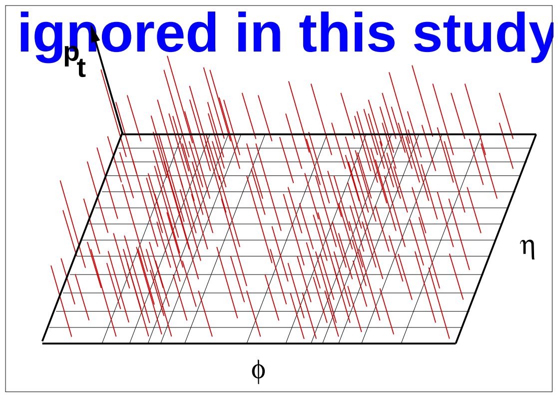

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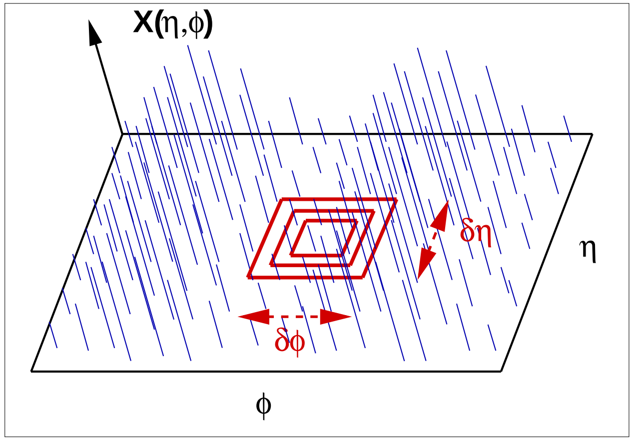

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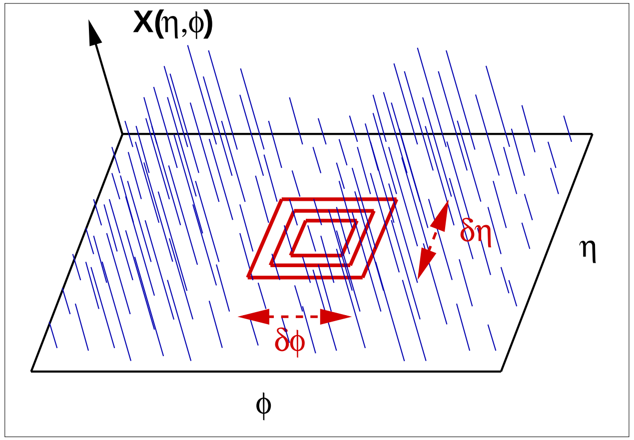

$$\mathrm{Var}[X;\delta\eta,\delta\phi] = \int_{-\delta\eta/2}^{\delta\eta/2} d\eta_1 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_1 \int_{-\delta\eta/2}^{\delta\eta/2} d\eta_2 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_2 \times[\overline{X(\eta_1,\phi_1)X(\eta_2,\phi_2)} - \overline{X(\eta_1,\phi_1)} \times \overline{X(\eta_2,\phi_2)}] \quad (12)$$

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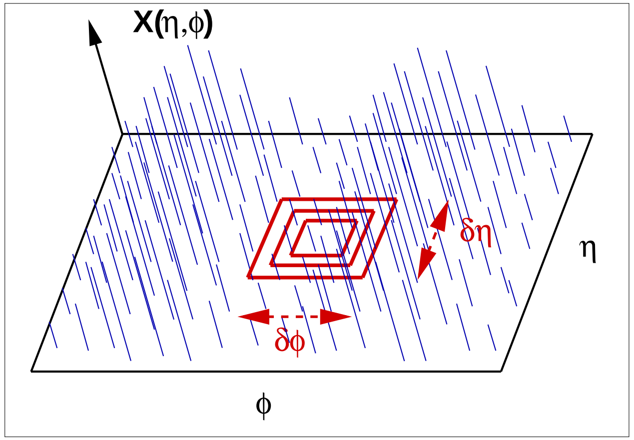

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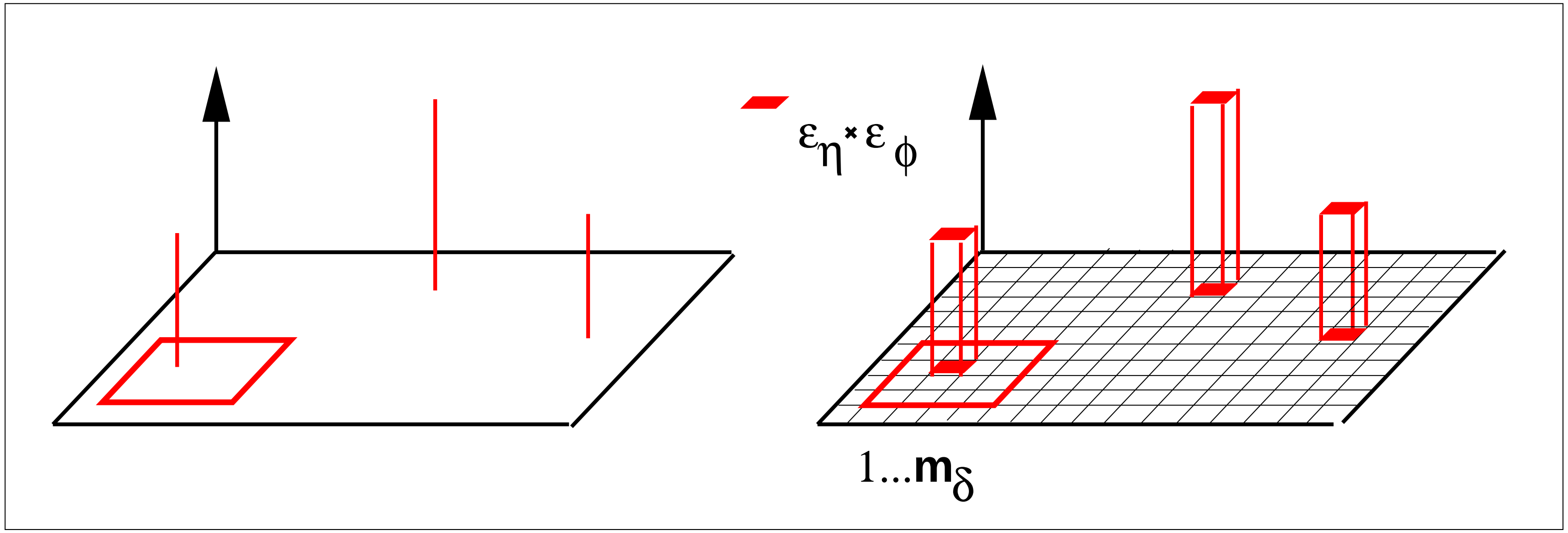
Compare with uncorrelated reference; recognize autocorrelation $\rho(X,t_\Delta) \equiv \overline{X(t)X(t+t_\Delta)}$ (t-average).

$$\Delta\sigma^2(X,\delta\eta,\delta\phi) = \quad (13)$$

$$\int_{-\delta\eta/2}^{\delta\eta/2} d\eta_1 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_1 \int_{-\delta\eta/2}^{\delta\eta/2} d\eta_2 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_2 \Delta\rho(X,\eta_1-\eta_2,\phi_1-\phi_2) \quad (14)$$

$$= 2\int_0^{\delta\eta} d\eta_\Delta 2\int_0^{\delta\phi} d\phi_\Delta(\delta\eta-\eta_\Delta)(\delta\phi-\phi_\Delta)\Delta\rho(X,\eta_\Delta,\phi_\Delta) \quad (15)$$

14 The actual analysis is discrete: $\int \rightarrow \sum$



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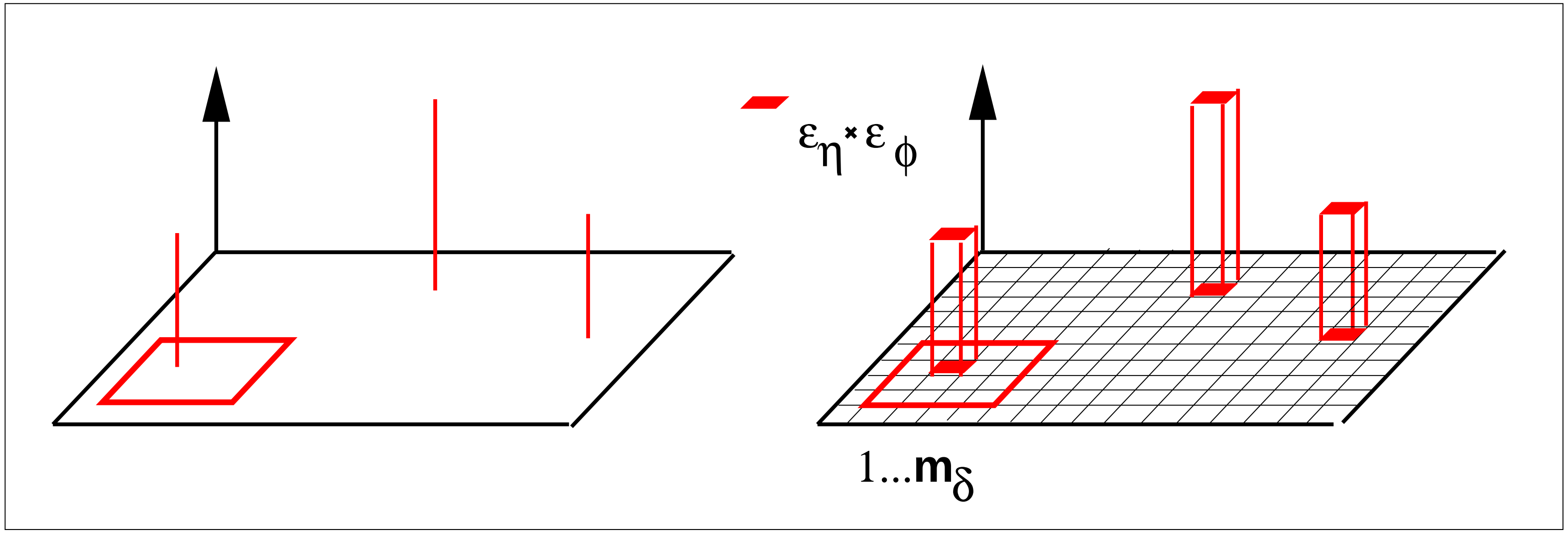

kernel K:

$$(\delta\eta - \eta_\Delta)(\delta\phi - \phi_\Delta) \to \varepsilon_\eta \varepsilon_\phi K_{m_\delta n_\delta : kl} \equiv \varepsilon_\eta \varepsilon_\phi (m_\delta - k + \frac{1}{2})(n_\delta - l + \frac{1}{2}) \qquad (16)$$

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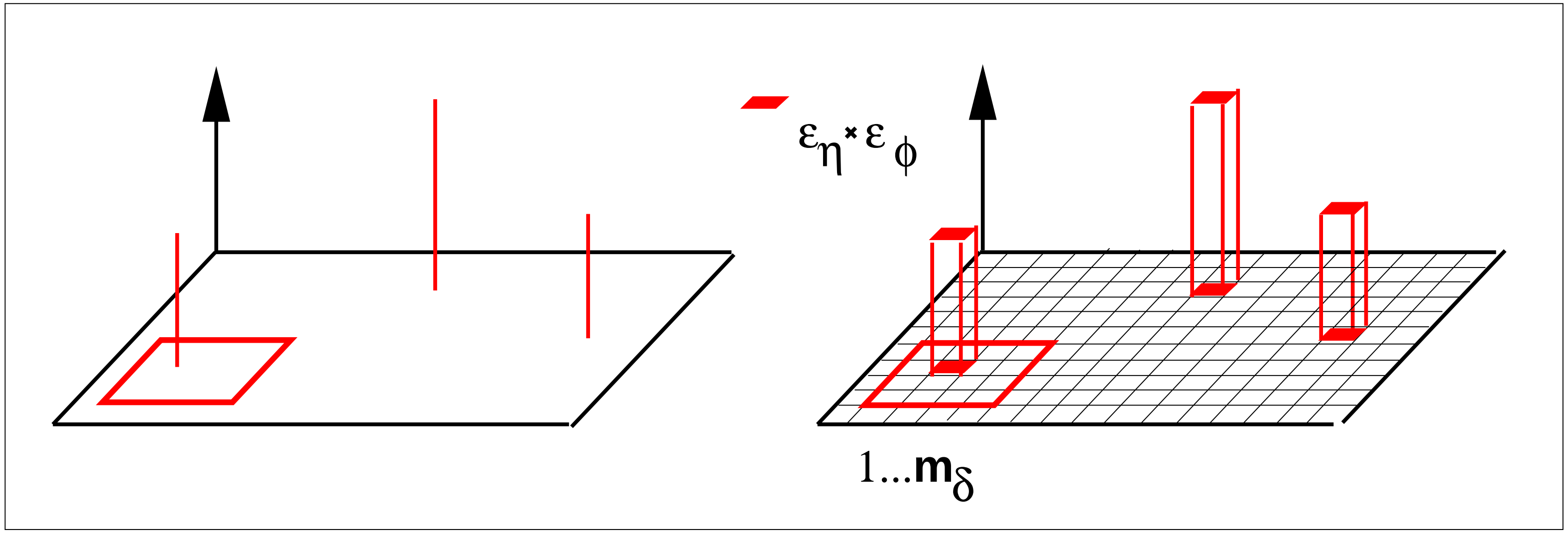

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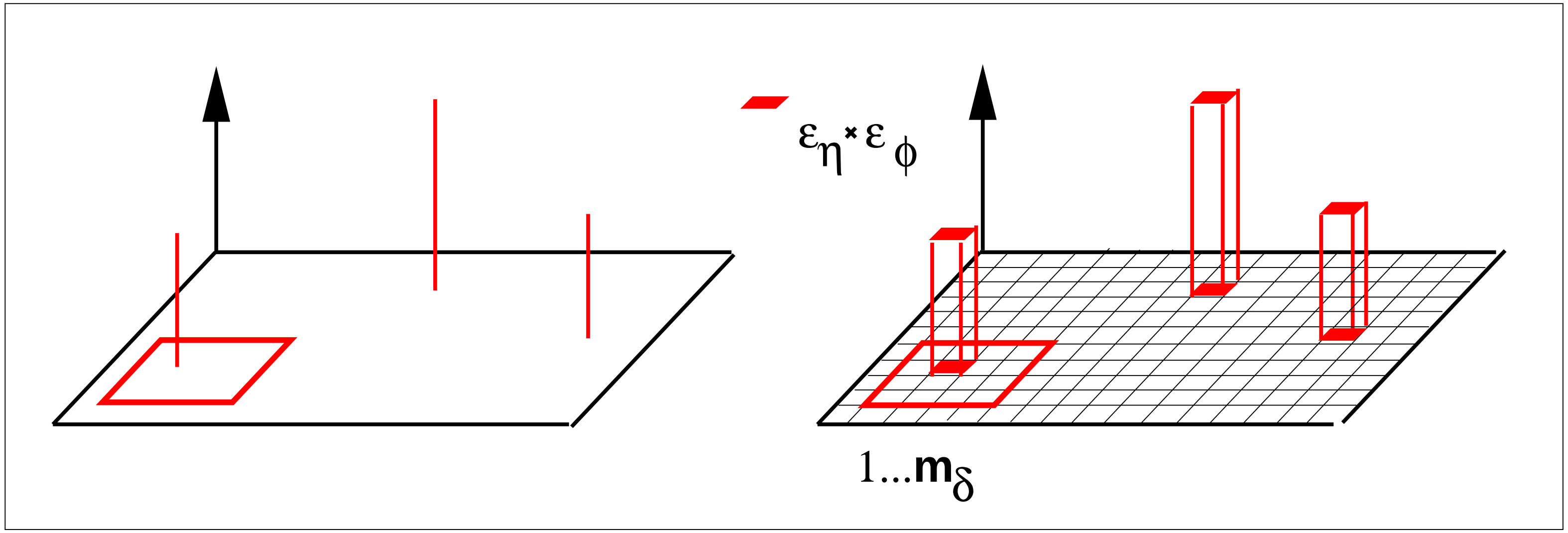

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$$\Delta\sigma^2_{p_t:n}(m_\delta \varepsilon_\eta, n_\delta \varepsilon_\phi) = 4 \sum_{k,l=1}^{m_\delta, n_\delta} \varepsilon_\eta \varepsilon_\phi K_{m_\delta n_\delta : kl} \frac{\Delta\rho(p_t : n; k\varepsilon_\eta, l\varepsilon_\phi)}{\sqrt{\rho_{\rm ref}(n; k\varepsilon_\eta, l\varepsilon_\phi)}} \quad (18)$$

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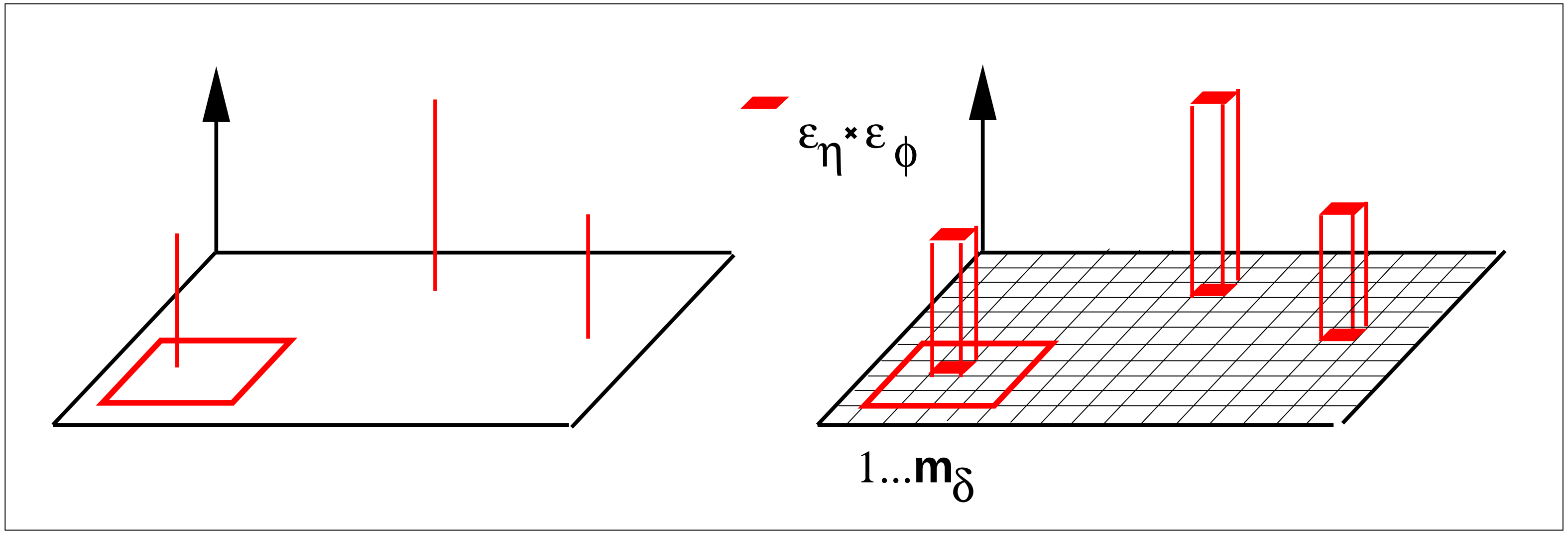

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Inverse problem: knowing $\Delta\sigma^2$, solve for $\Delta\rho/\sqrt{\rho_{\mathrm{ref}}}$ $\Rightarrow$ save $O(N)$ in CPU time !

15 p_t correlations from the inversion

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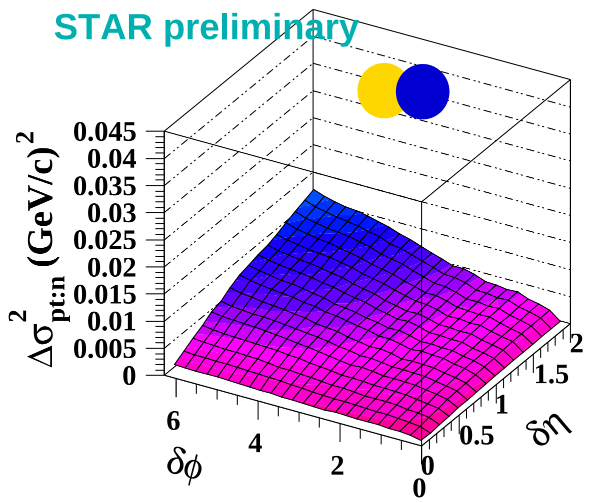

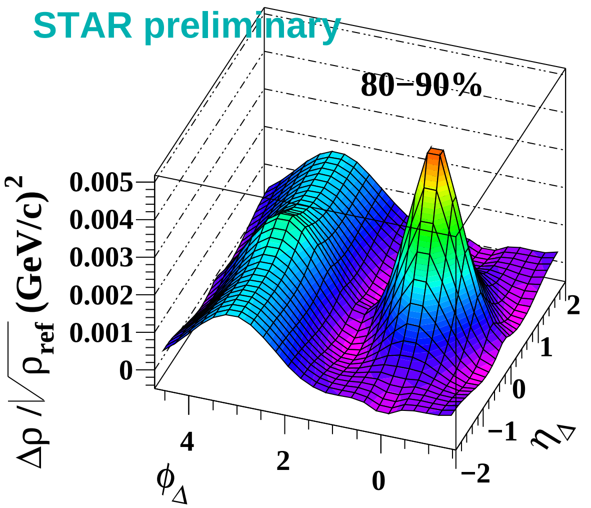

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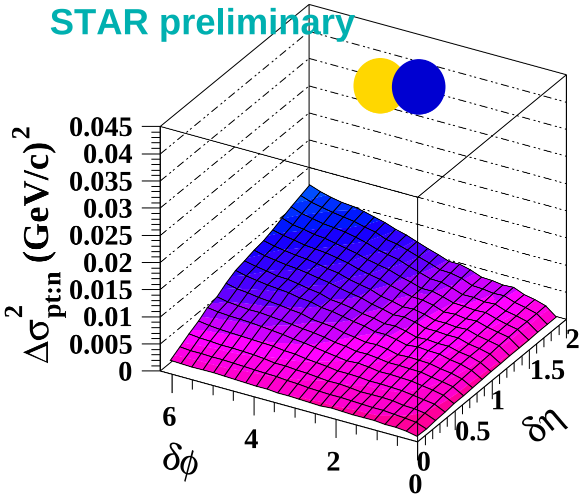

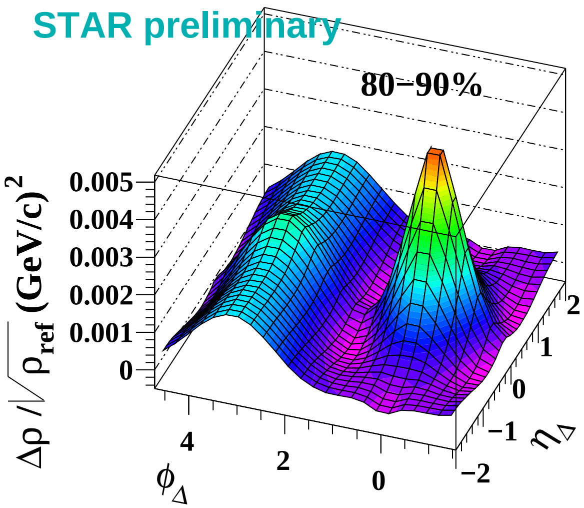

Top: AuAu 200 GeV, scale dependence of the "pure" p_t variance.

Bottom: corresponding autocorrelation

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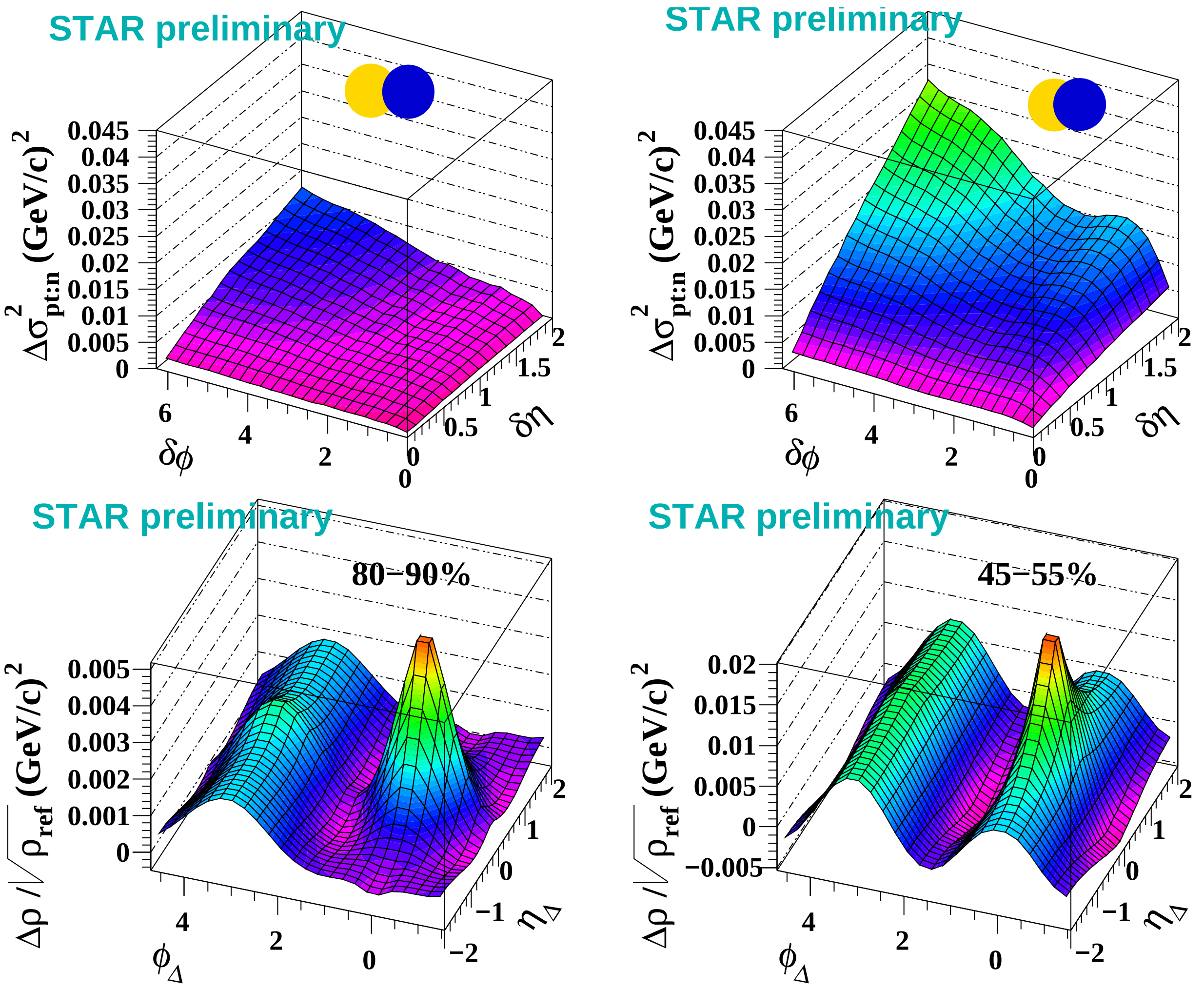

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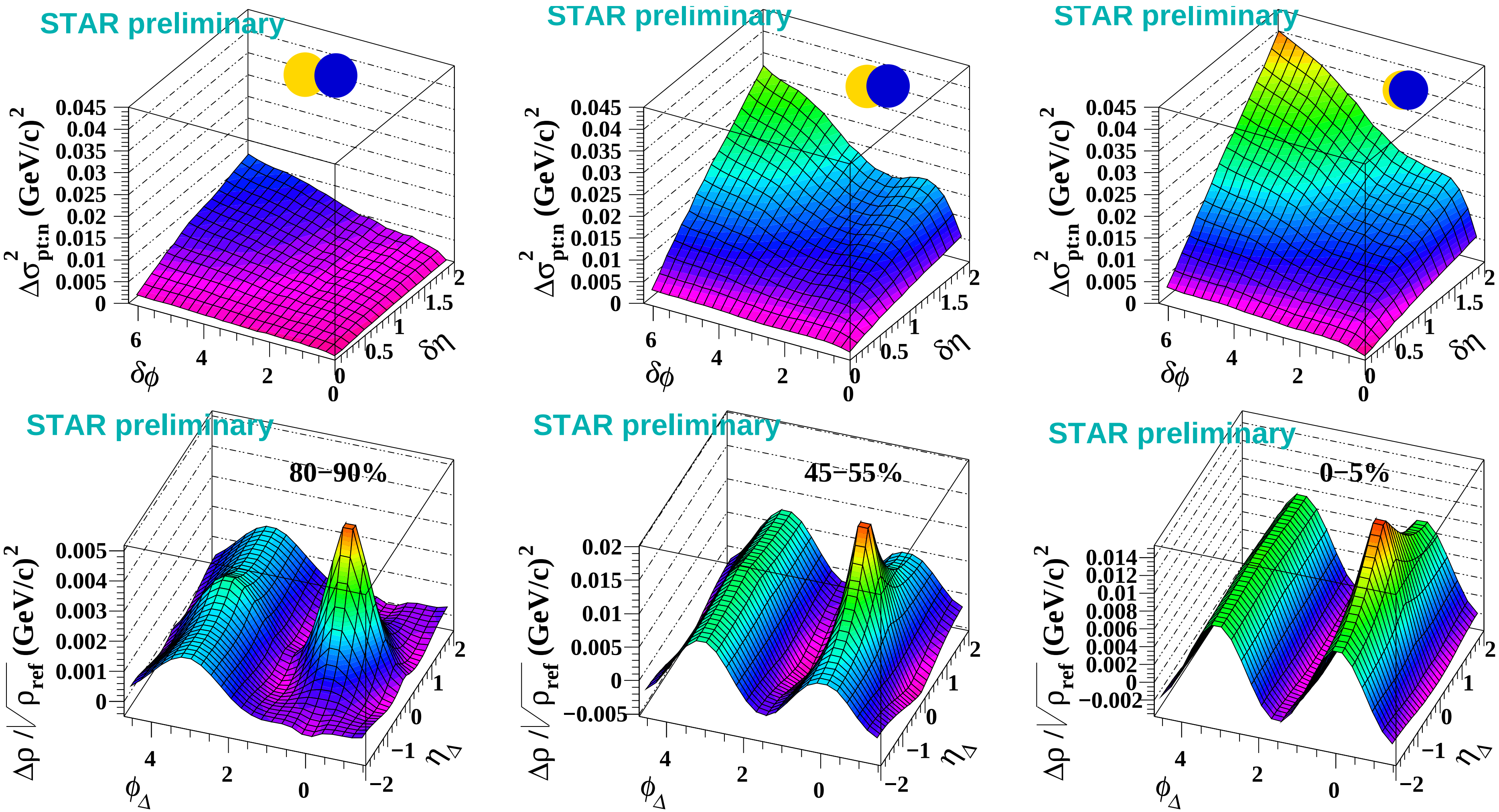

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First direct evidence of elliptic flow as a velocity phenomenon at RHIC. Next, subtract the flow contribution to look at minijets.

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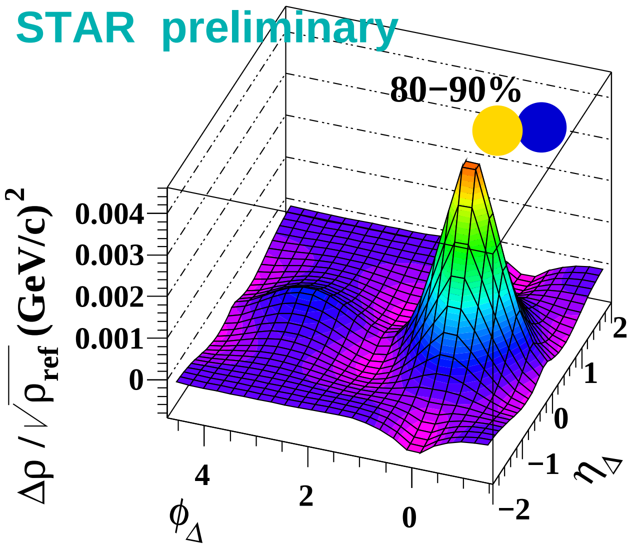

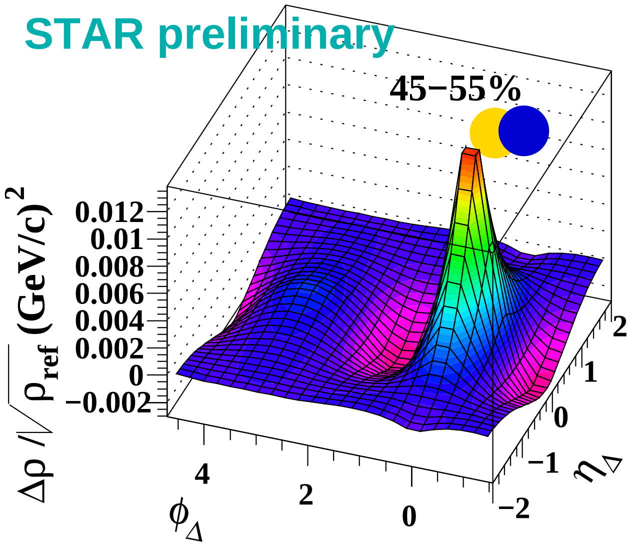

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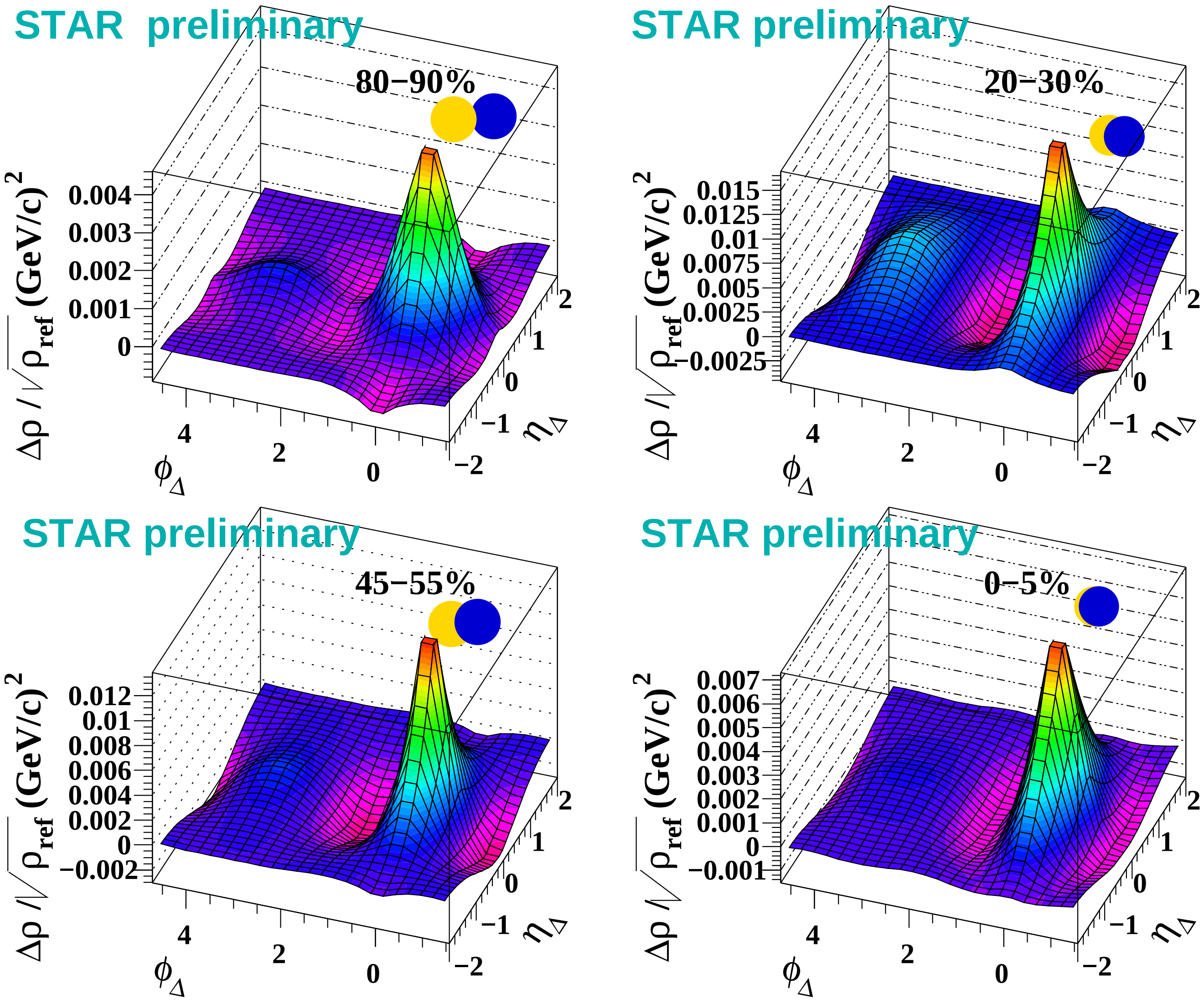

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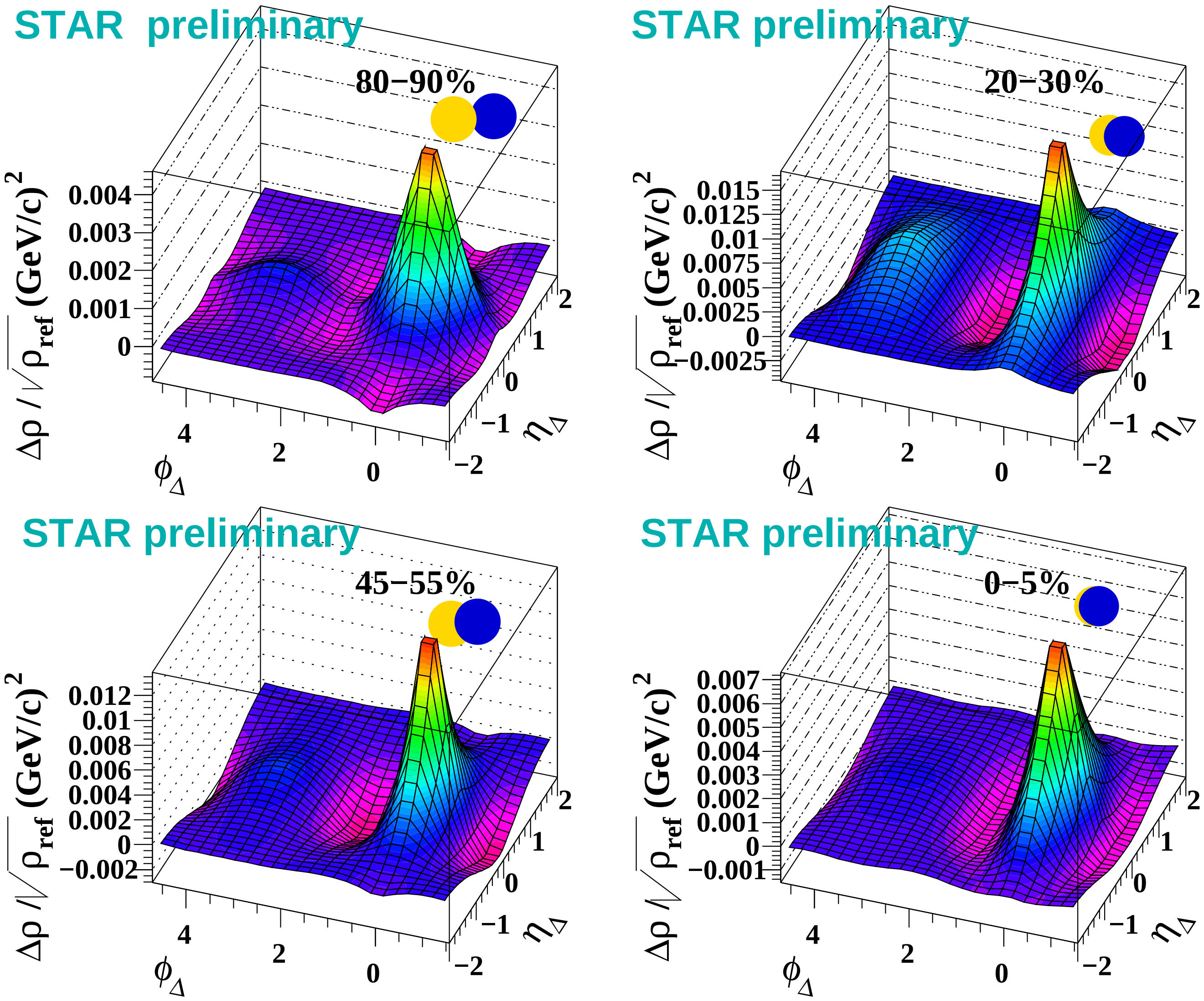

STAR AuAu 200 GeV. In η, correlation broadens with centrality; in ϕ the trend is opposite. The surrounding background seems to recoil.

17 Minijet implications for HBT

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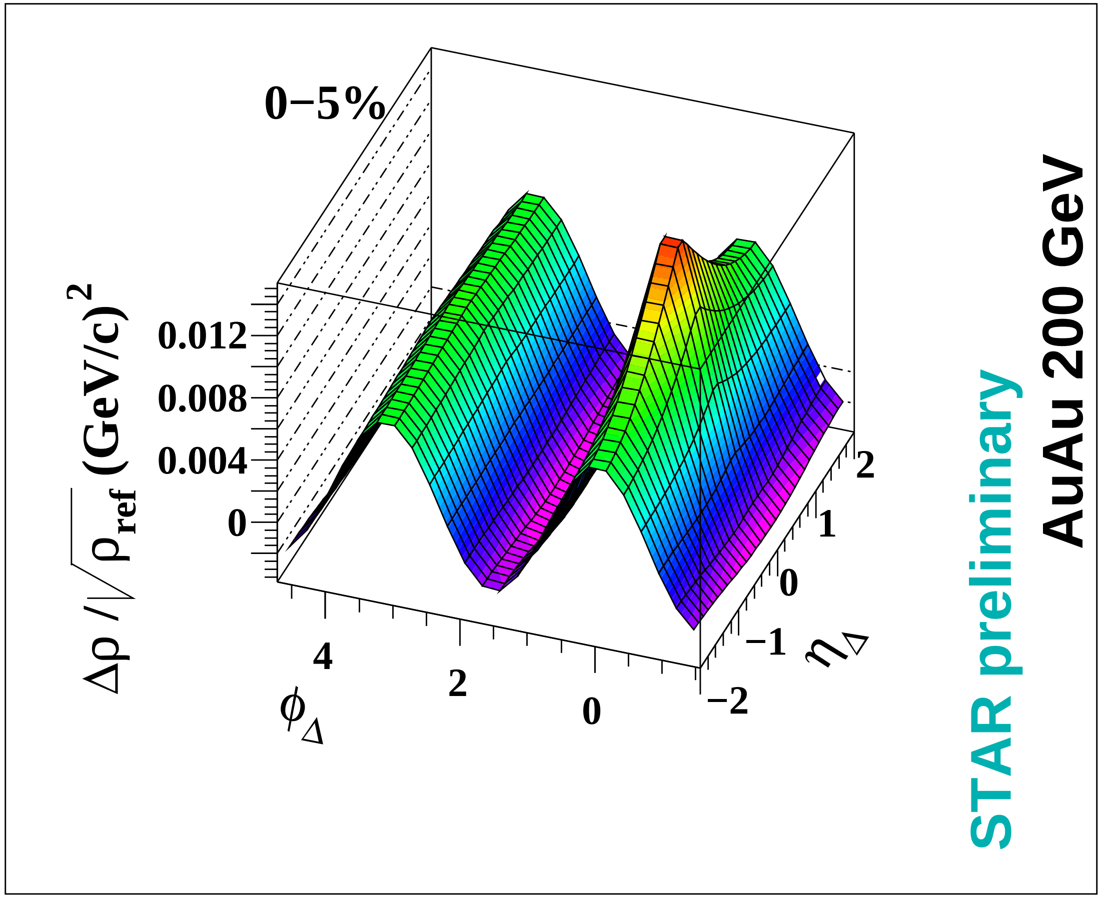

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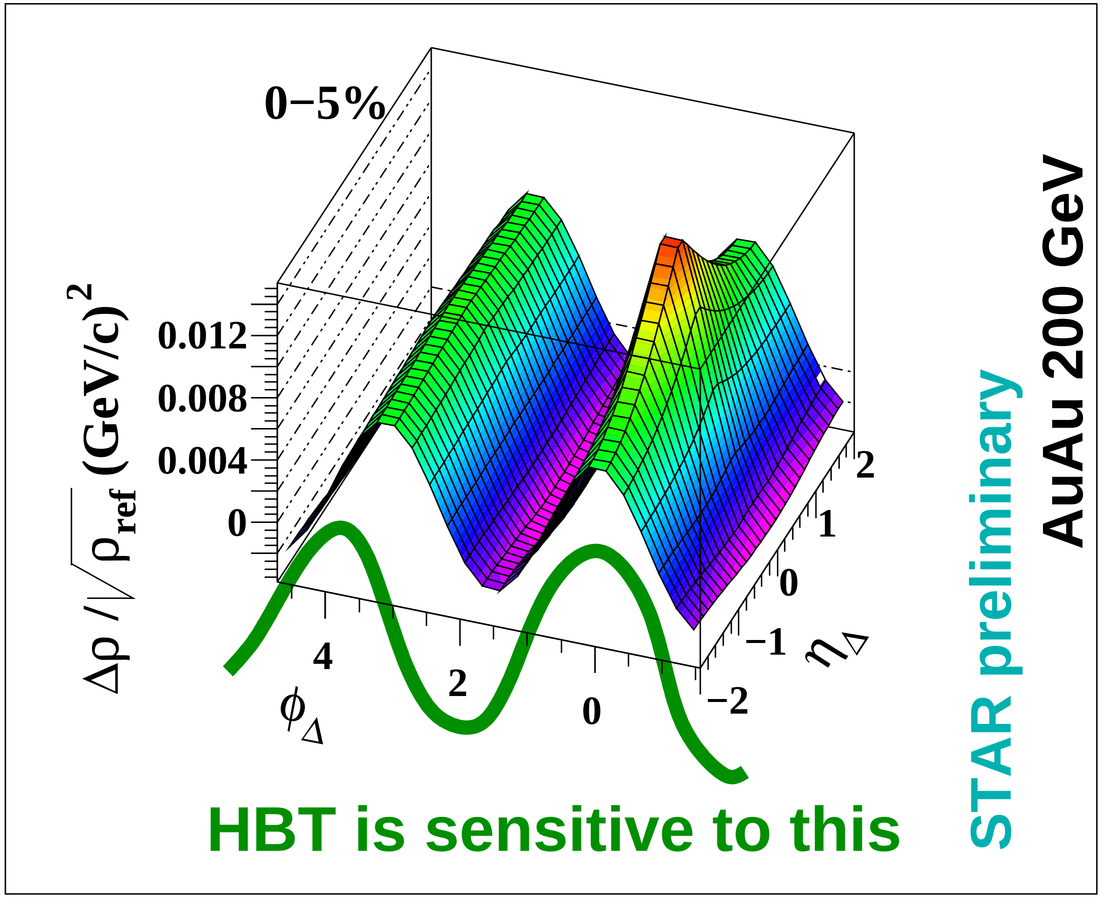

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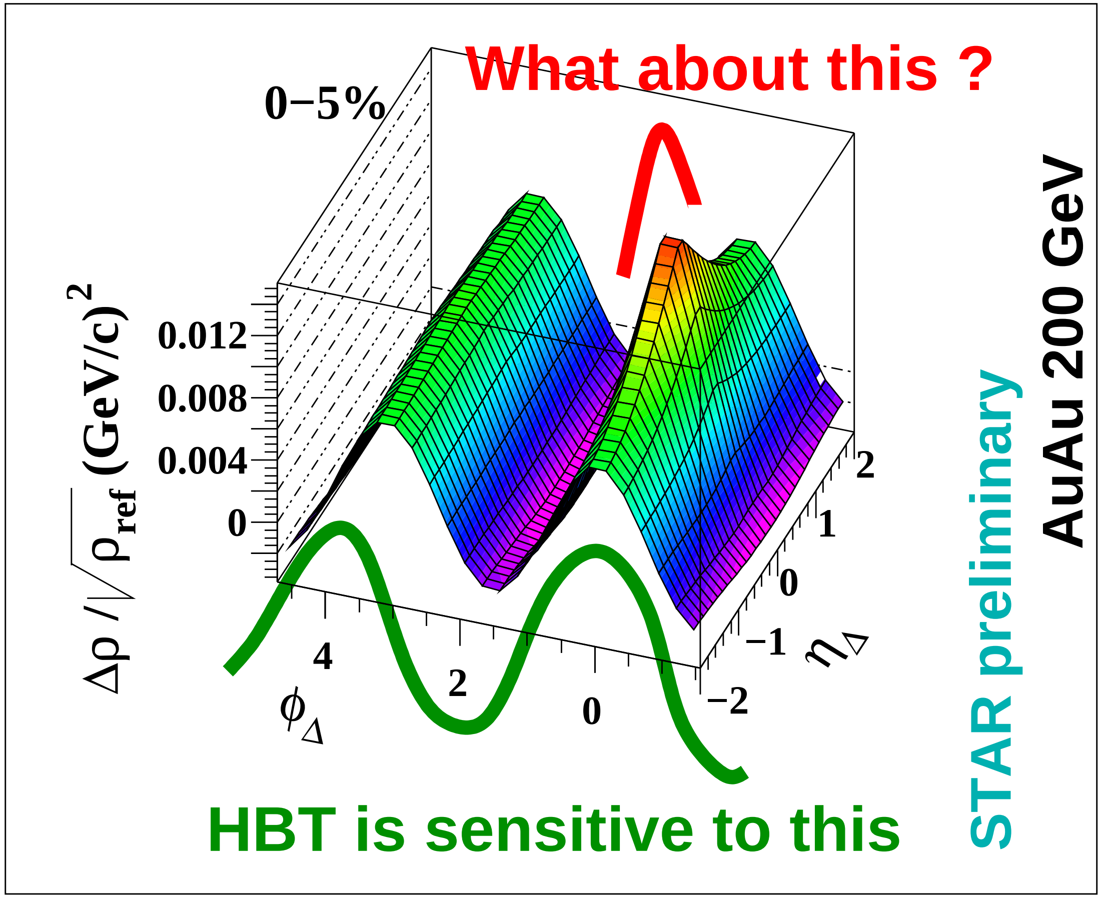

Minijet contribution at soft p_t has been hithereto ignored in the HBT studies. It is likely to contribute to the HBT puzzle by reducing homogeneity lengths/two current correlation length, as compared to the fully equilibrated case. Source of space-momentum correlation.

18 Local hadron density fluctuations and Discrete Wavelet Transform (DWT)

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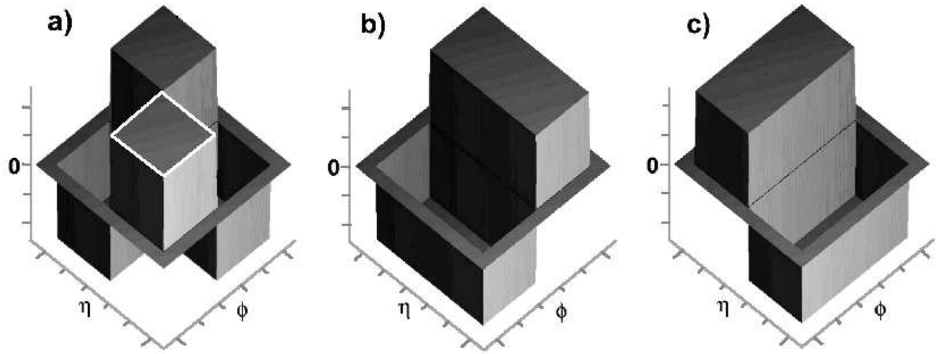

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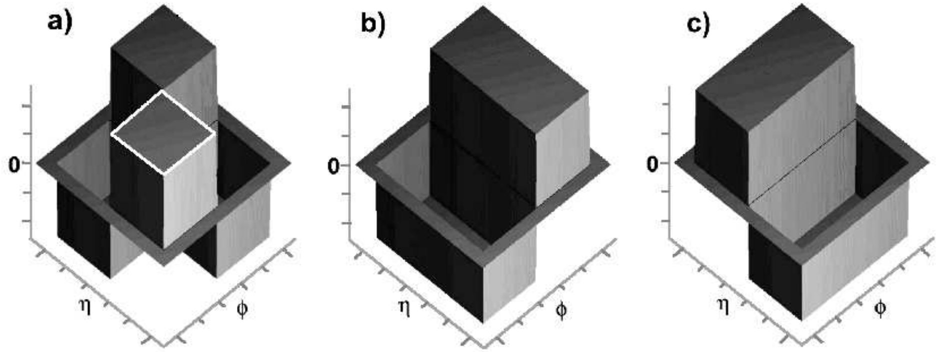

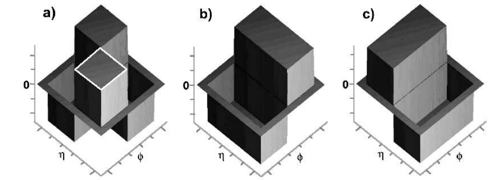

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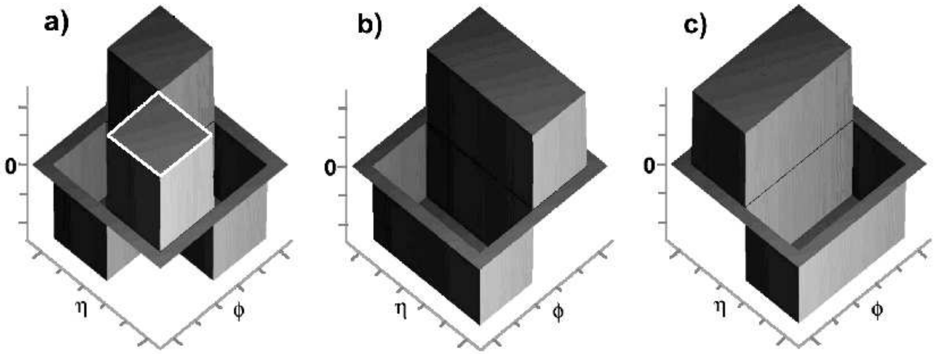

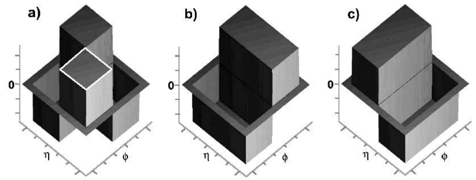

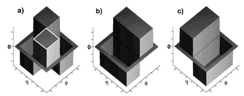

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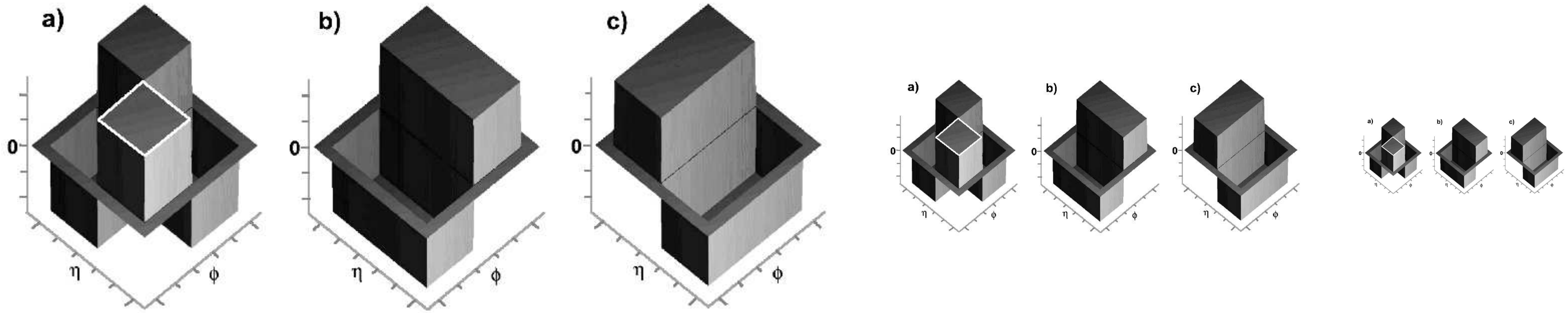

$F^{\lambda}_{m,l,k}(\phi,\eta)$–Haar wavelet **orthonormal basis** in (ϕ,η). scale fineness (m), directional modes of sensitivity (λ), track density $\rho(\eta,\phi,p_t)$, locations in 2D (l,k). **DWT is an expansion in this basis.**

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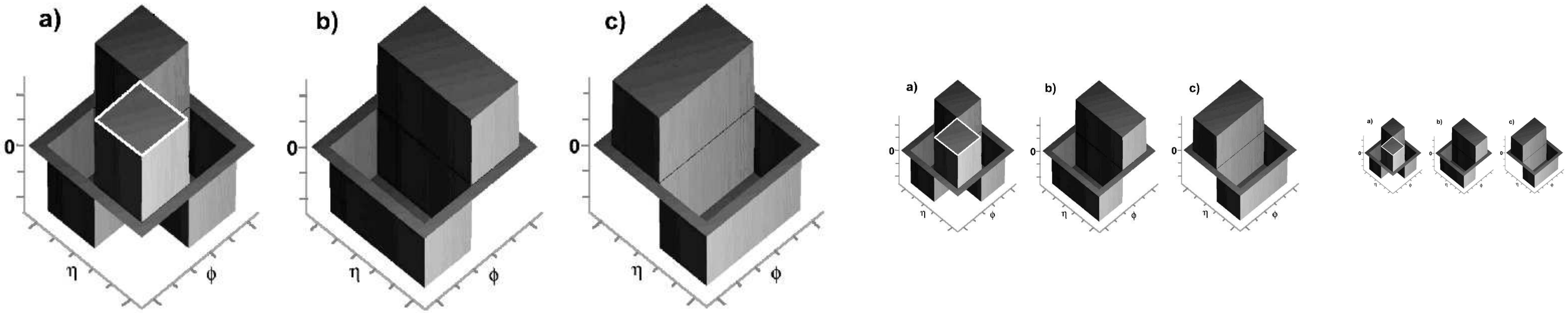

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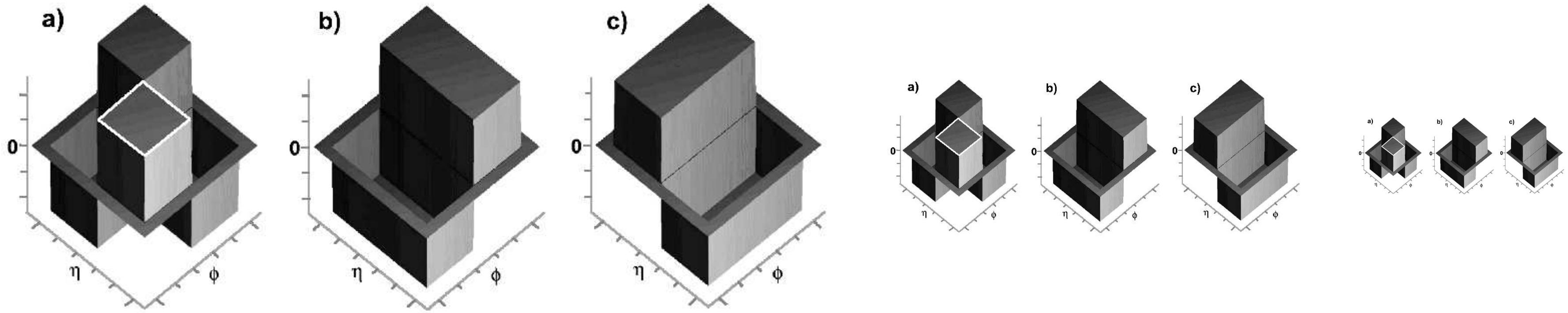

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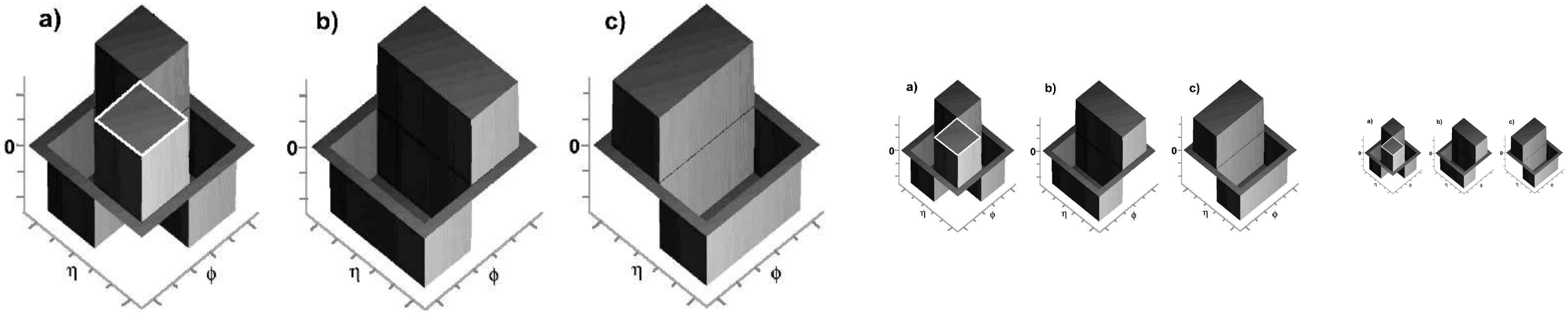

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Normalized:

$$P^{\lambda}_{\text{dyn}}(m)/P^{\lambda}_{\text{mix}}(m)/n(p_t) \tag{21}$$

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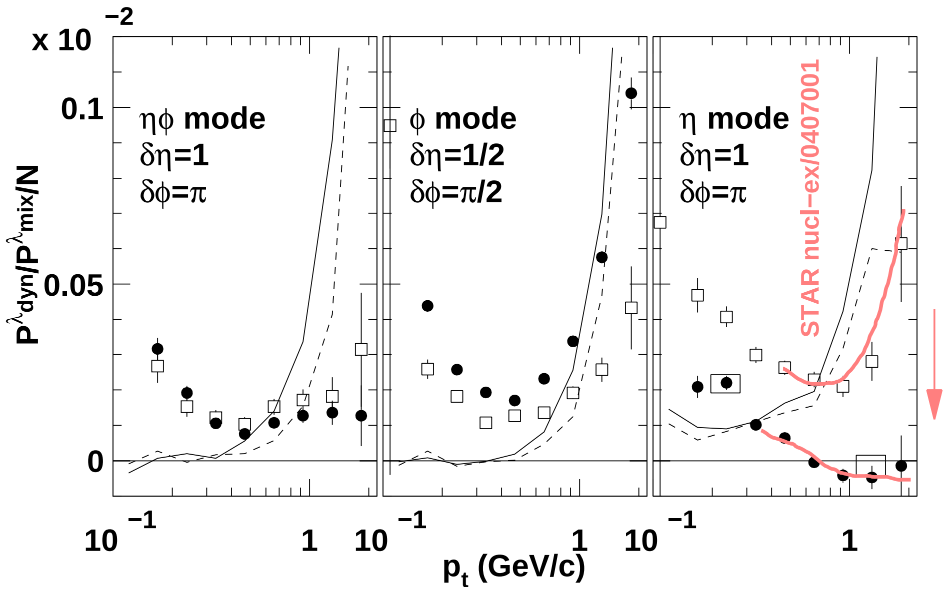

Central events: normalized dynamic texture for fineness scales $m = 0, 1, 0$ from left to right panels, respectively, as a function of p_t.
● STAR data; solid line – Hijing without jet quenching; dashed line – Hijing with quenching; □ peripheral STAR data renormalized to compare.

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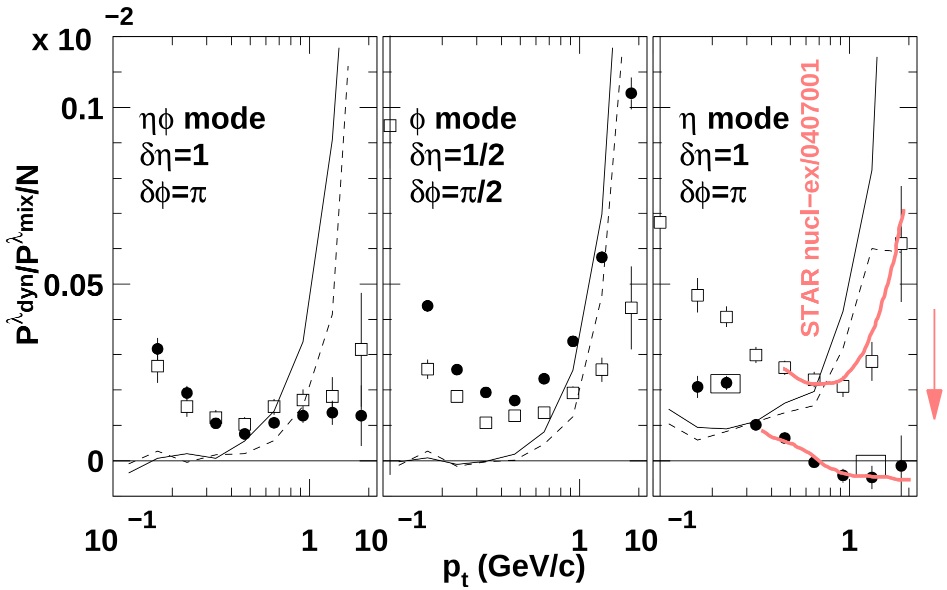

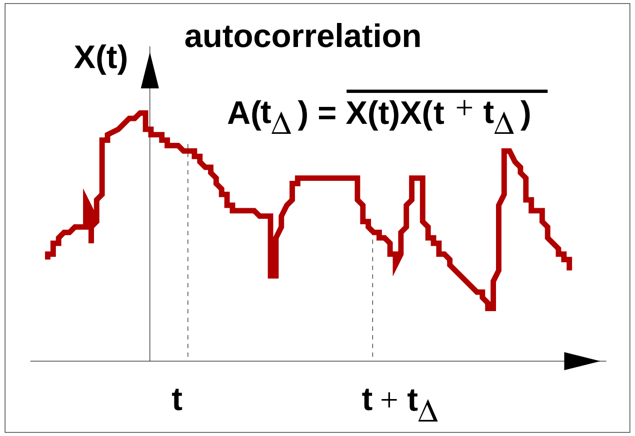

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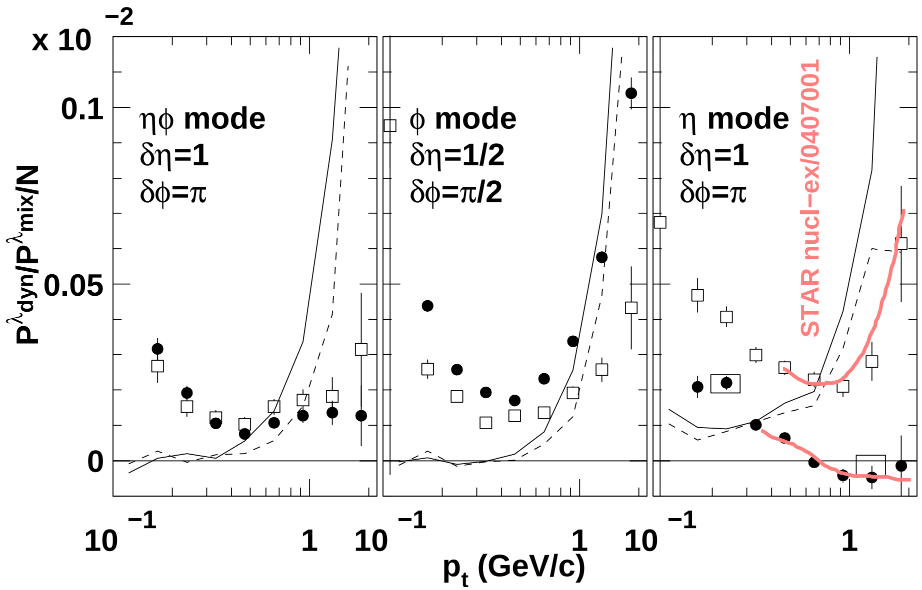

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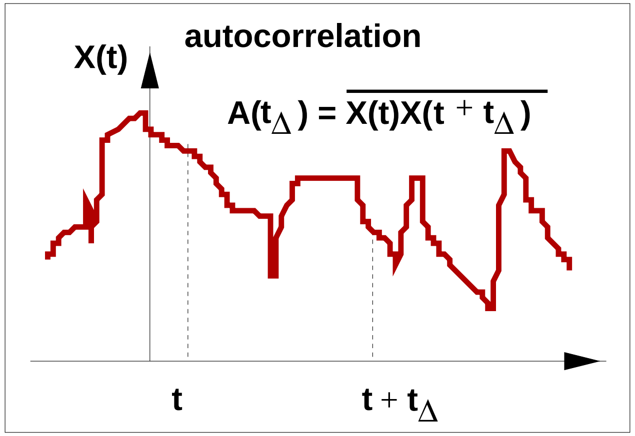

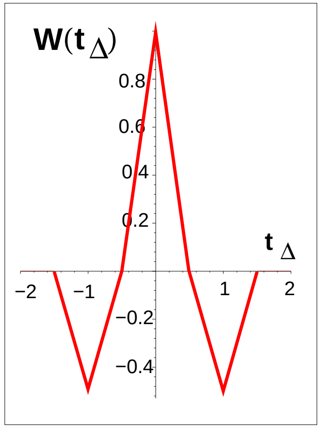

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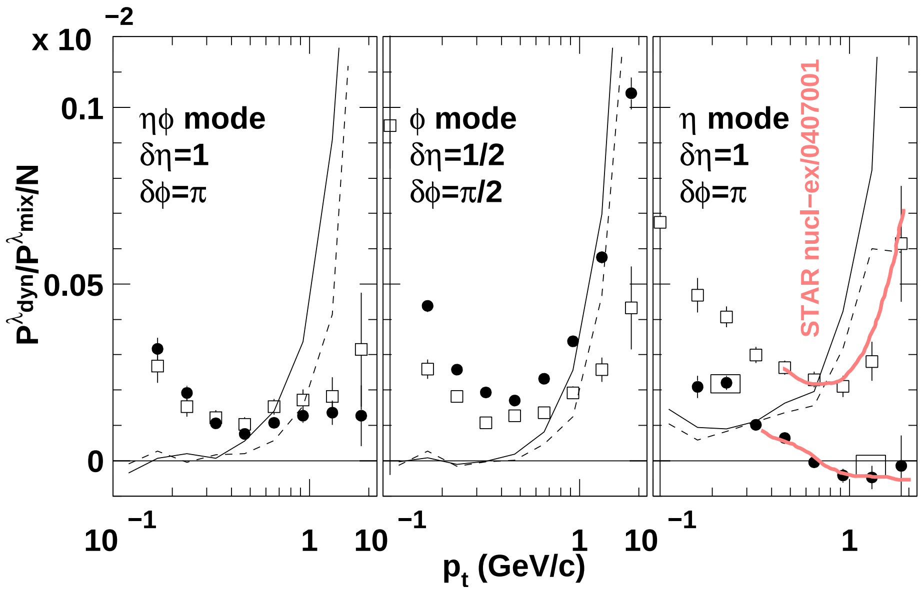

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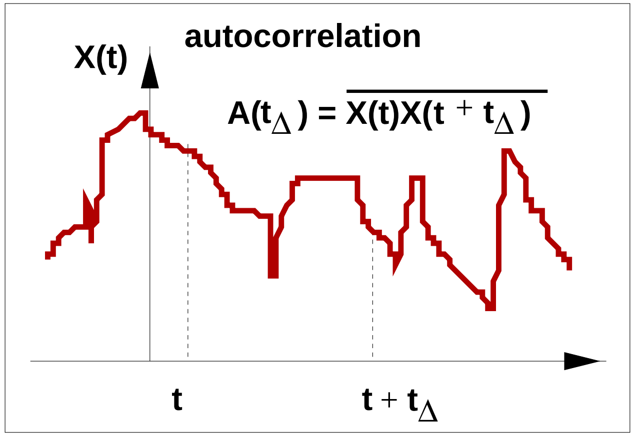

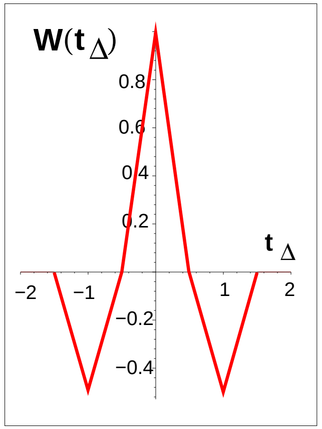

$$P(m) = \overline{\int_{-\infty}^{\infty} X(t_\Delta/2)X(-t_\Delta/2)W(t_\Delta, m)\, dt_\Delta}, \tag{22}$$

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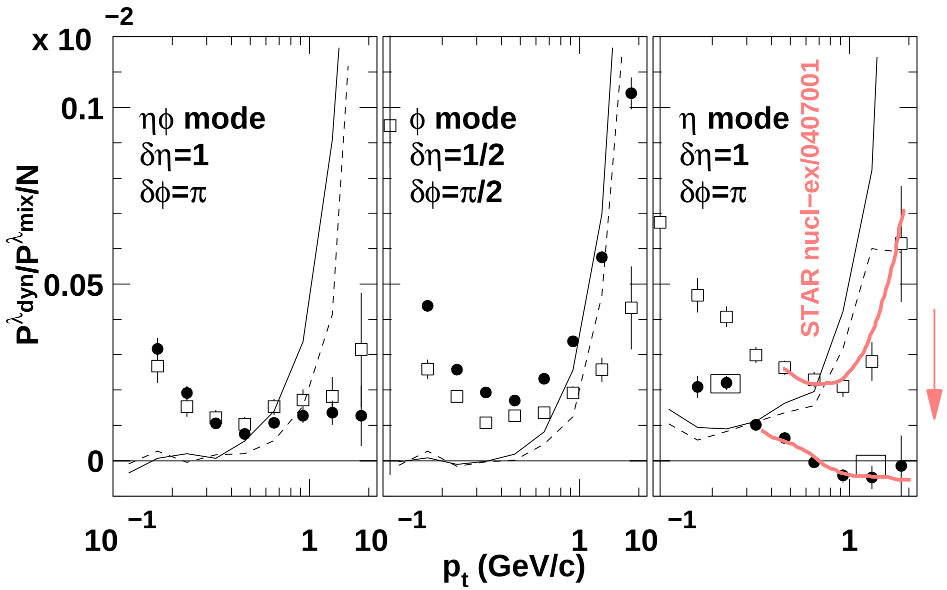

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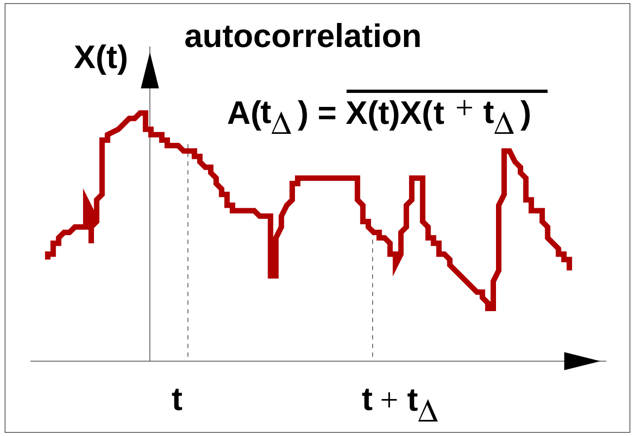

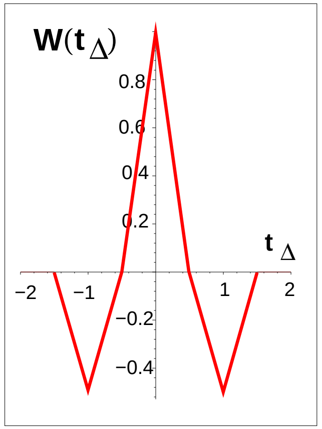

$P(m)$ differentiates correlation on scale m. Minijet elongation ⇒ correlation broadening ⇔ reduced correlation gradient ⇔ reduced "texture"

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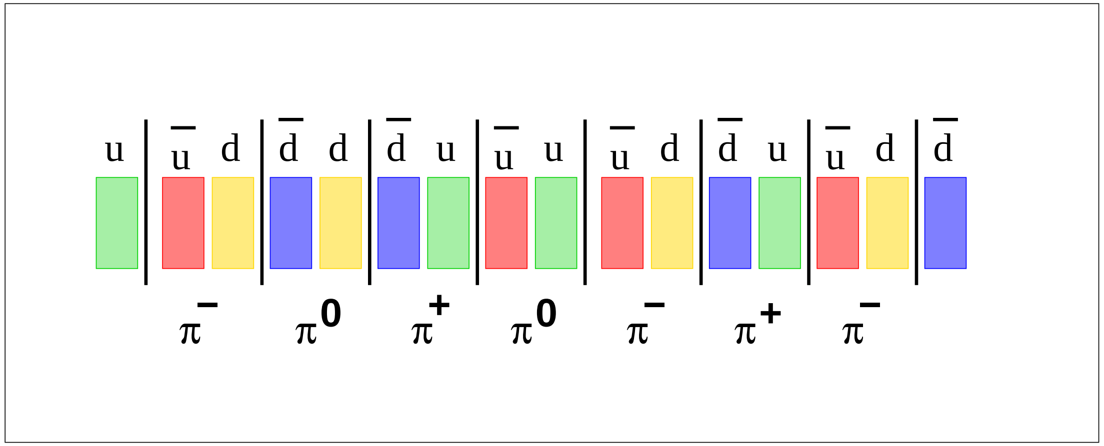

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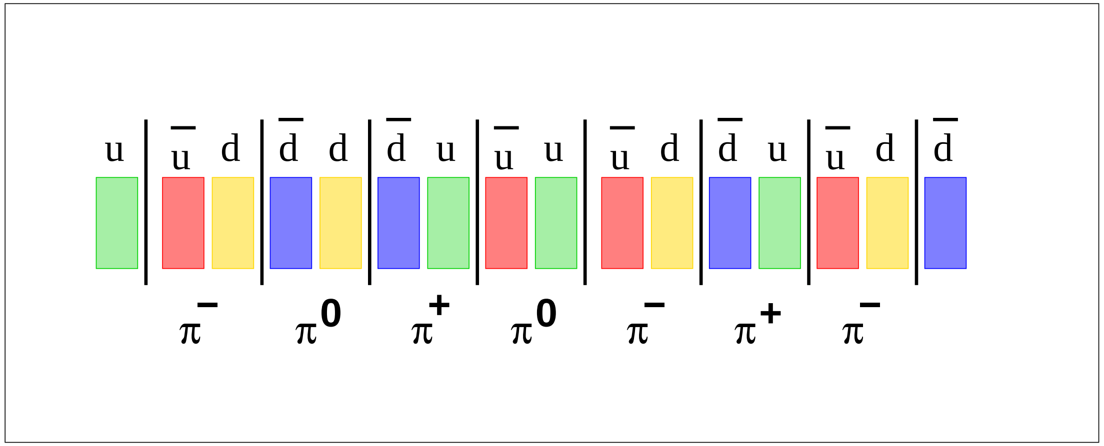

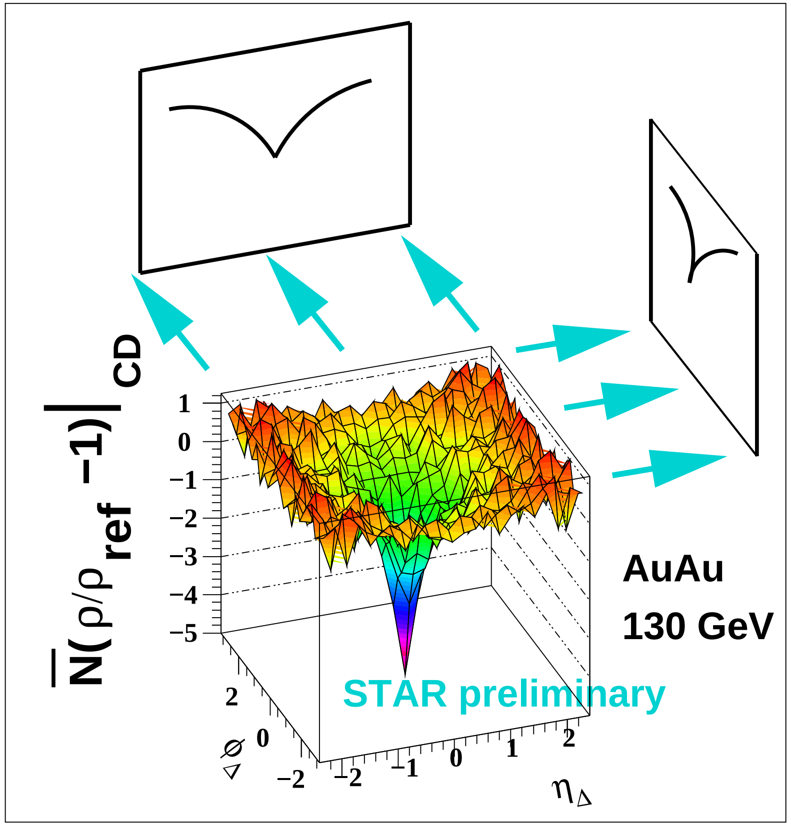

The driving physics: charge conservation in hadronization. Suppress short range correlations – BEC and conversion e^+e^- – by a kinematic pair cut. The $\bar{N}\times$ is good when number of correlation sources $\propto N$.

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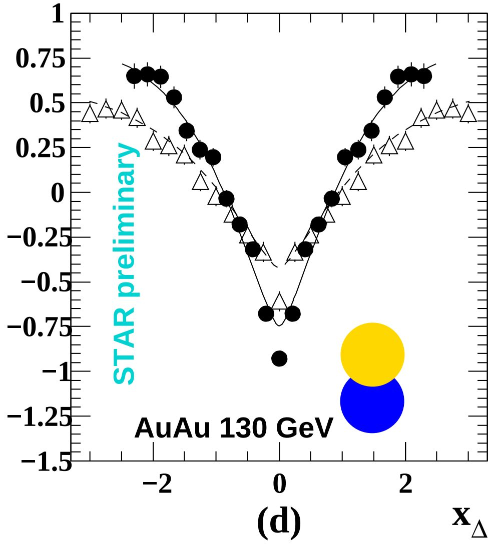

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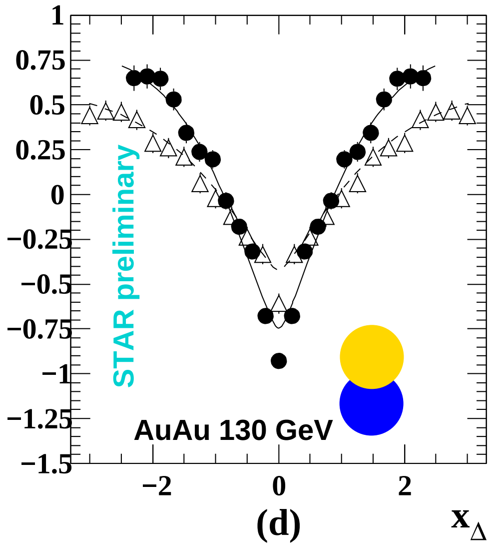

Projections of $\bar{N}[\rho(\eta_\Delta, \phi_\Delta)/\rho(\eta_\Delta, \phi_\Delta)_{\rm ref} - 1]|_{CD}$ on x_Δ which is ϕ_Δ (Δ) or η_Δ (●). $\eta - \phi$ width disparity (d, peripheral) is gone in (a) $\Rightarrow$ transition from (string) 1D to bulk (>2D) fragmentation symmetrizes η and ϕ.

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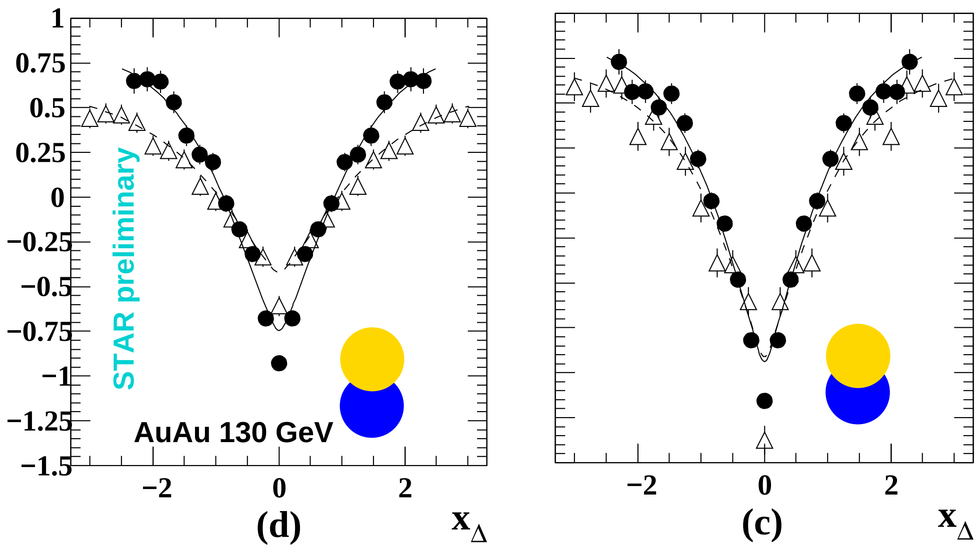

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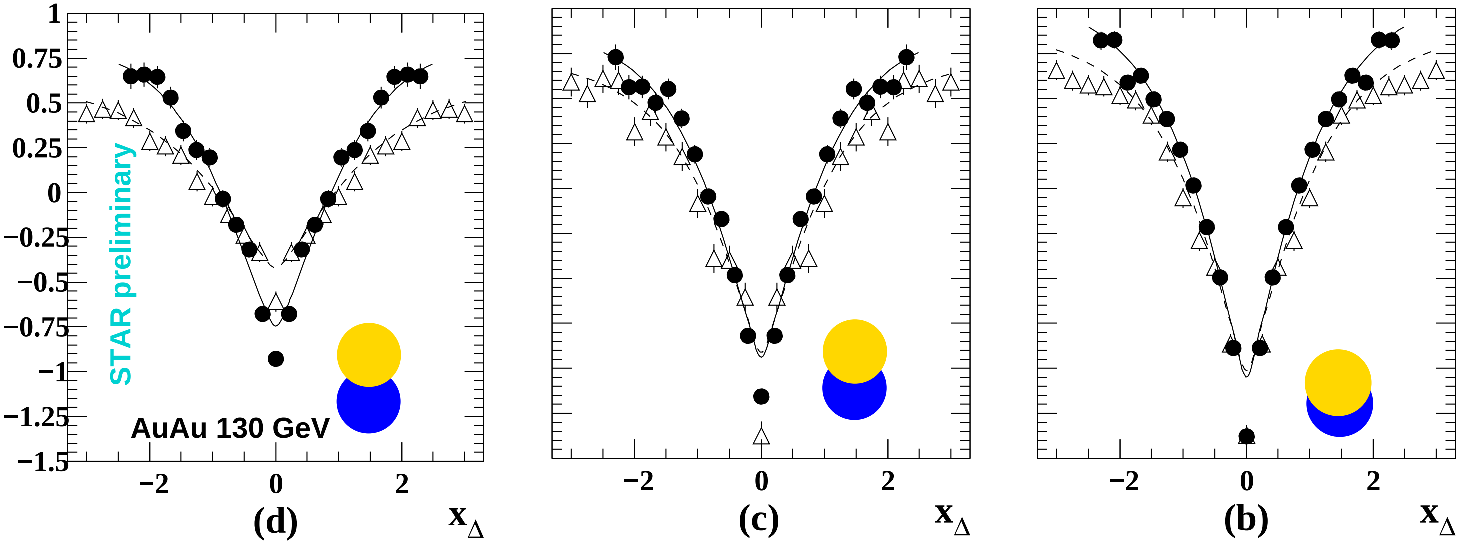

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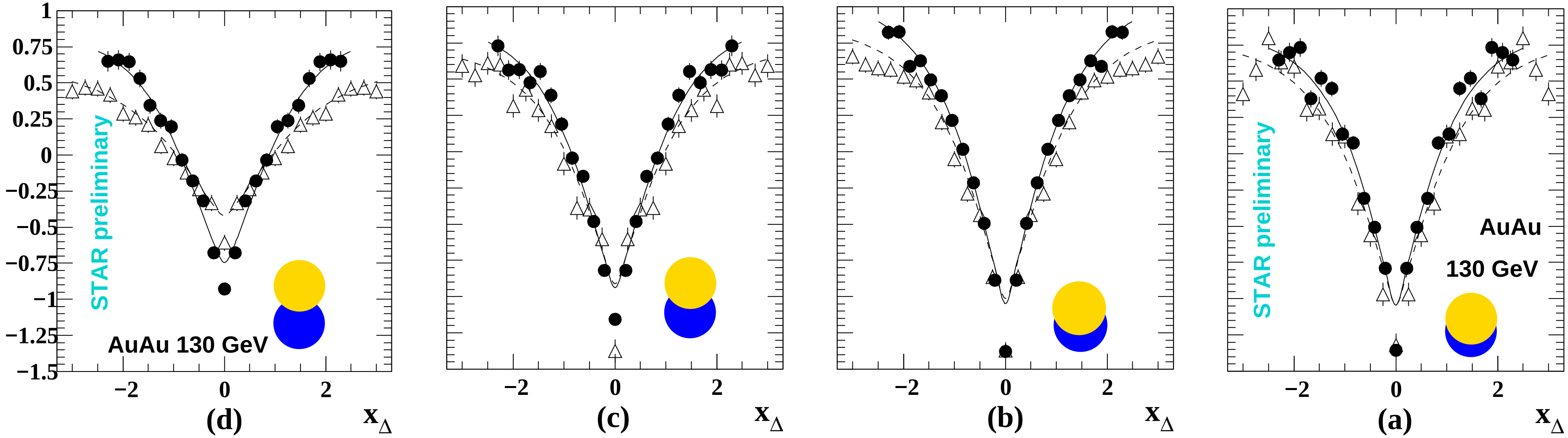

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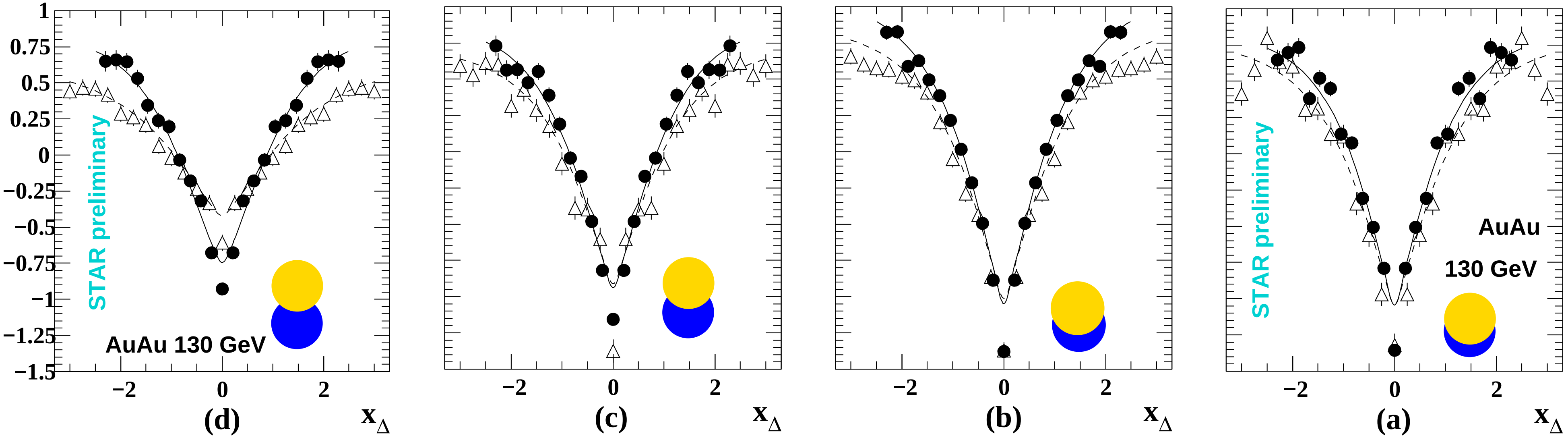

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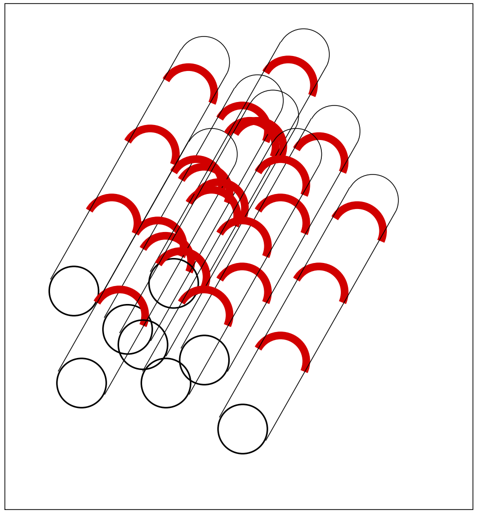

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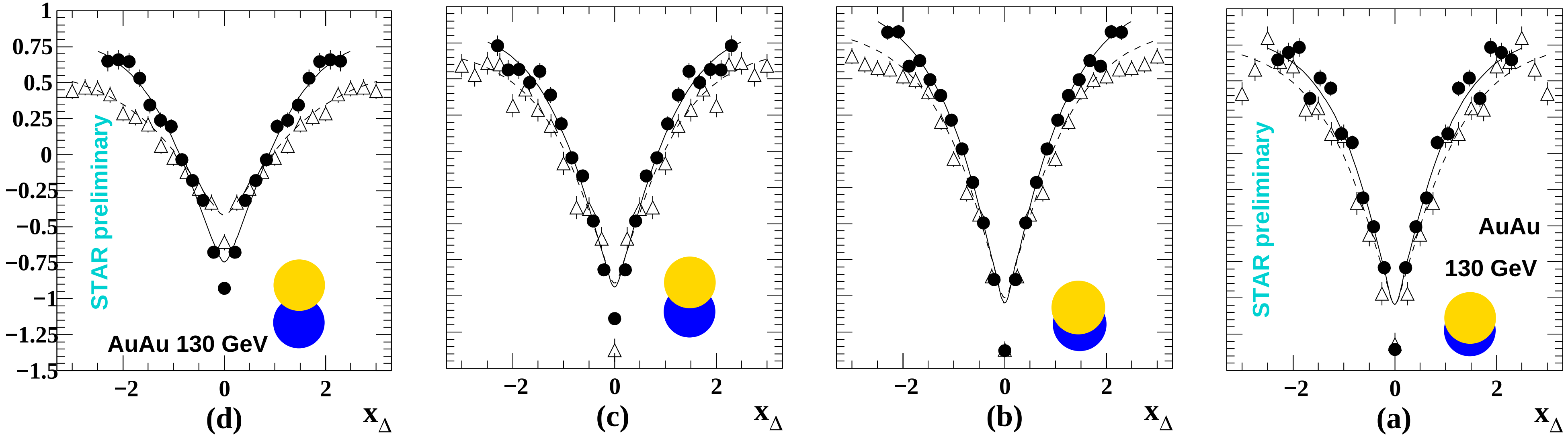

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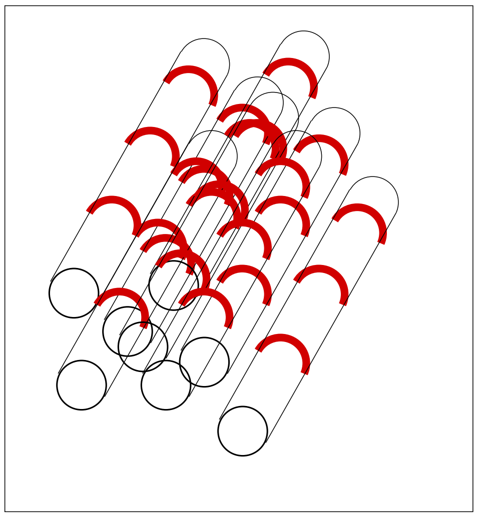

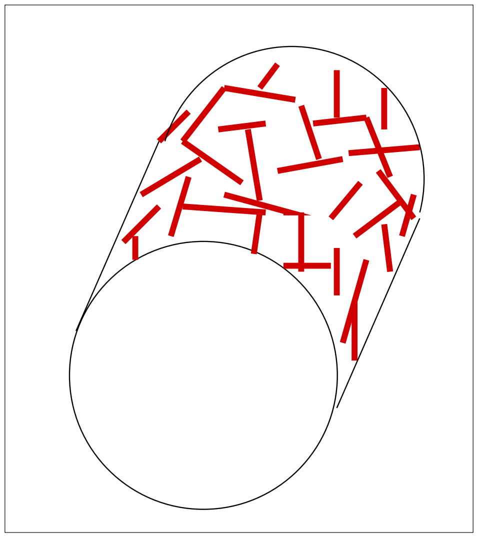

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- Increased symmetry of the charge-dependent correlation on (η,ϕ) in the central collisions may point to a change in the hadronization geometry in the medium

23 Extra slides

24 Notation and glossary

- HBT – Hanbury-Brown and Twiss technique (intensity interferometry)
- i – particle index
- N – total number of particles in an event
- n, $n(p_t)$ – number of particles within a kinematic cut (bin)
- $\overline{(\ldots)}$ – average over events
- $\hat{p}_t$ – inclusive mean p_t per particle
- $x_\triangle$ (variants: $t_\triangle$, $\eta_\triangle$, $\phi_\triangle$ ...) – difference variable $= x_i - x_{i'}$.
- δx – scale (range of local integration; e.g. see Fig.13)
- Δx – the upper limit on δx

25 Directed flow and antiflow