Correlations at STAR: interferometry and event structure

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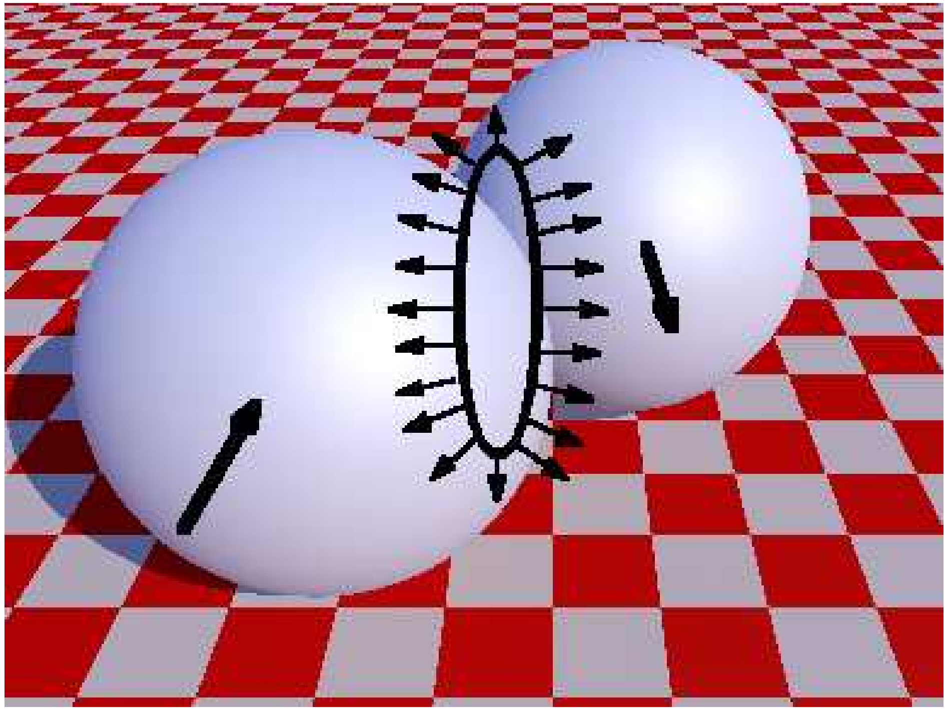
1 STAR fluctuation/correlation physics in this talk

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

- Elliptic flow: number and p_t correlation effects
- Medium modification of minijets
  (no trigger particle, $p_t < 2$ GeV/c)
- Hadronization: medium modification of charge-dependent correlations
- Azimuthal dependence in Bose-Einstein correlations
- Arguments for Blast Wave from HBT and p_t fluctuations
- Novel techniques throughout...

2 Flow – directed and elliptic

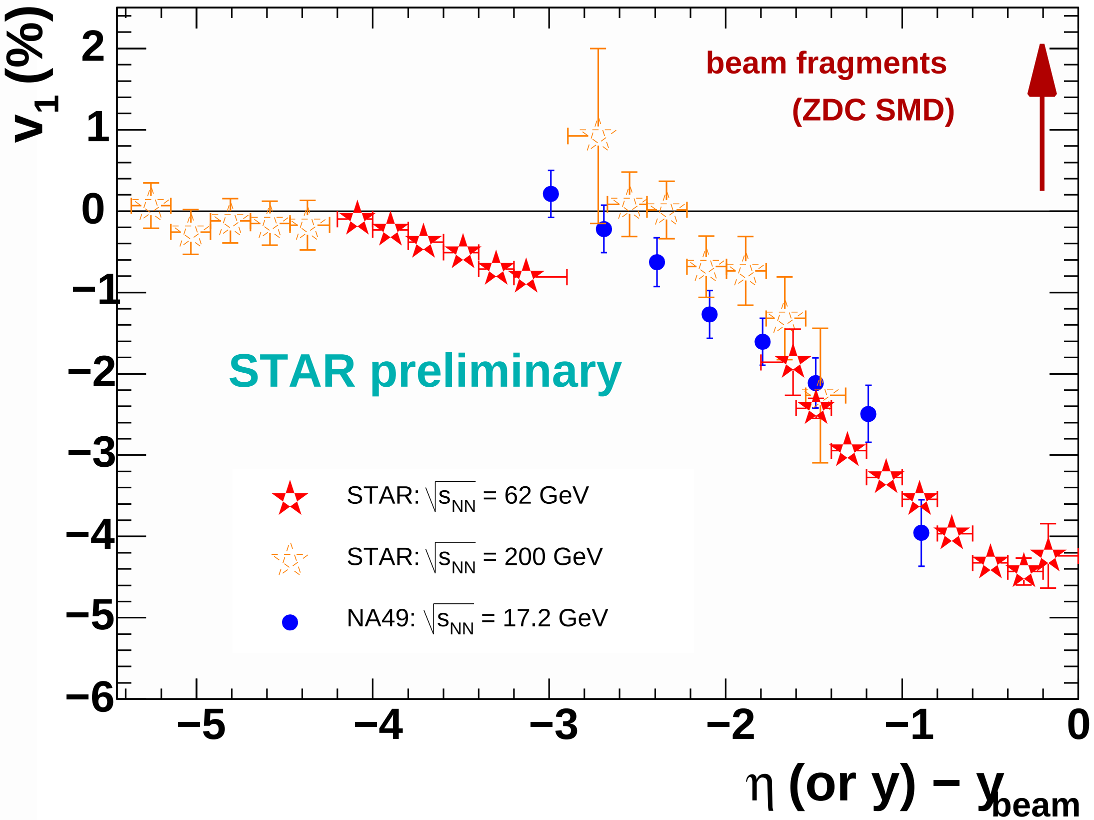


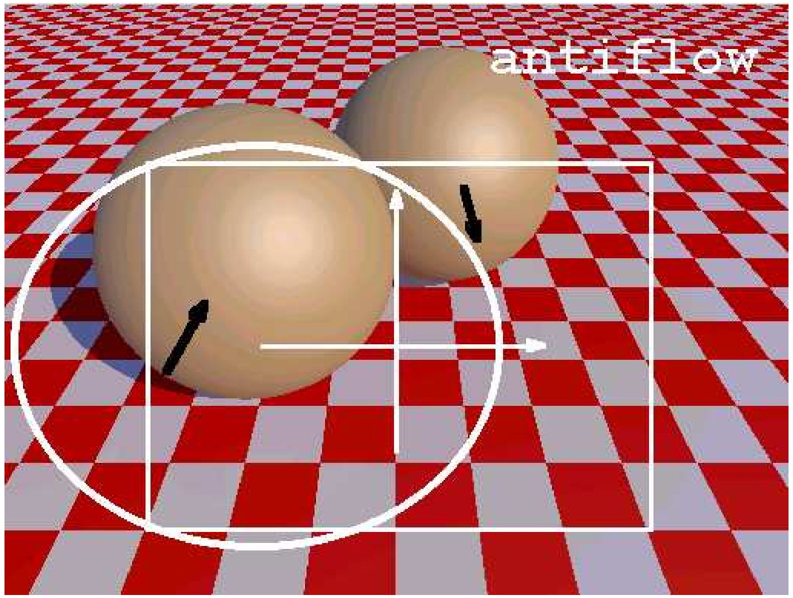
(x, y) anisotropy $\rightarrow$ rescattering $\rightarrow$ (p_x, p_y) anisotropy

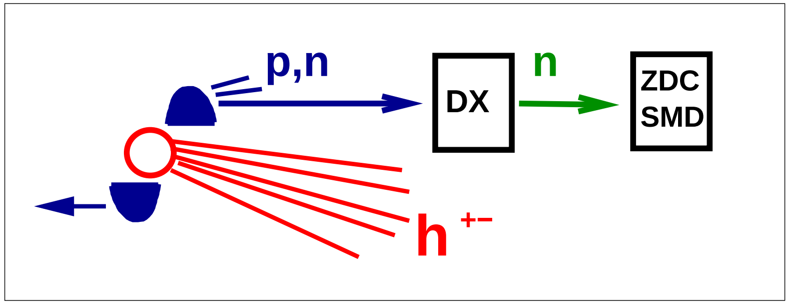
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\{1 + \sum_{m=1}^{\infty} 2v_m \cos[m(\phi - \Psi_r)]\} \tag{1}$$

- 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



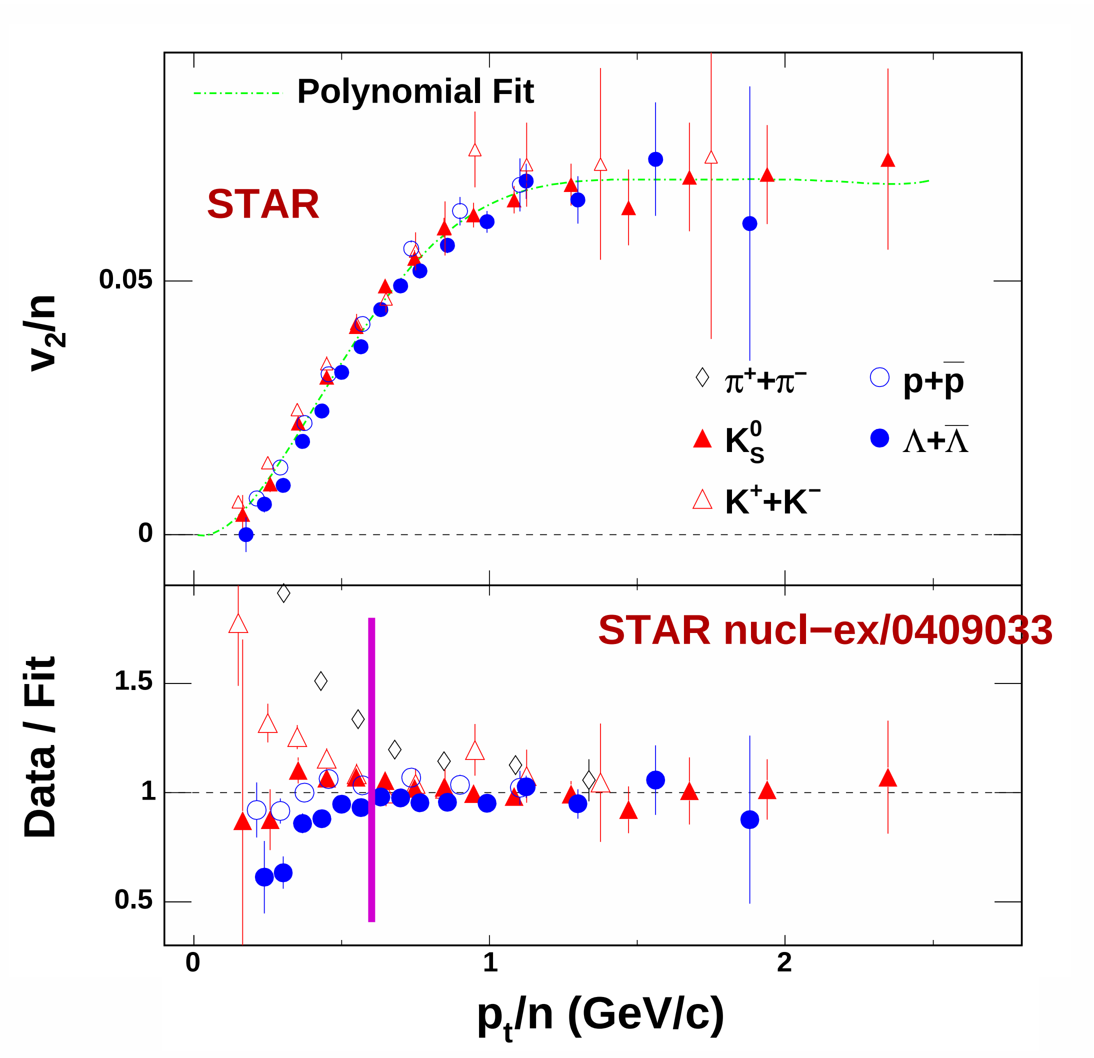




Charged-particles v_1 from 3-particle cumulants in the projectile frame.

- monotonic around midrapidity
- Supports limiting fragmentation
- Antiflow !

4 Elliptic flow and quark coalescence



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

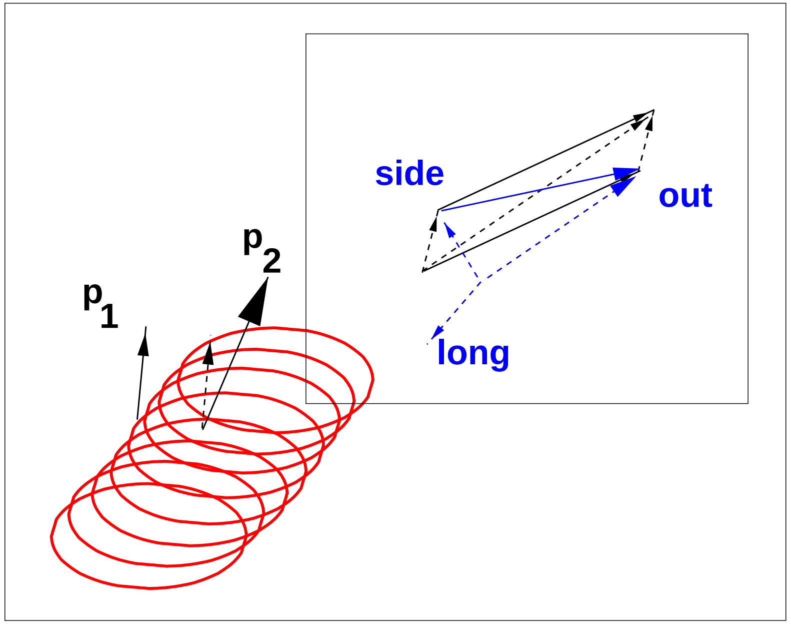
$$\frac{dN_{\mathrm{clscnc},n}}{d\phi}(p_t) \propto \left(\frac{dN(\frac{p_t}{n})}{d\phi}\right)^n \qquad (3)$$

$$(1 + 2v_2\cos(2\phi))^n = \qquad (4)$$
$$1 + 2v_2 n\cos(2\phi) + \mathcal{O}(v_2^2)$$

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

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



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

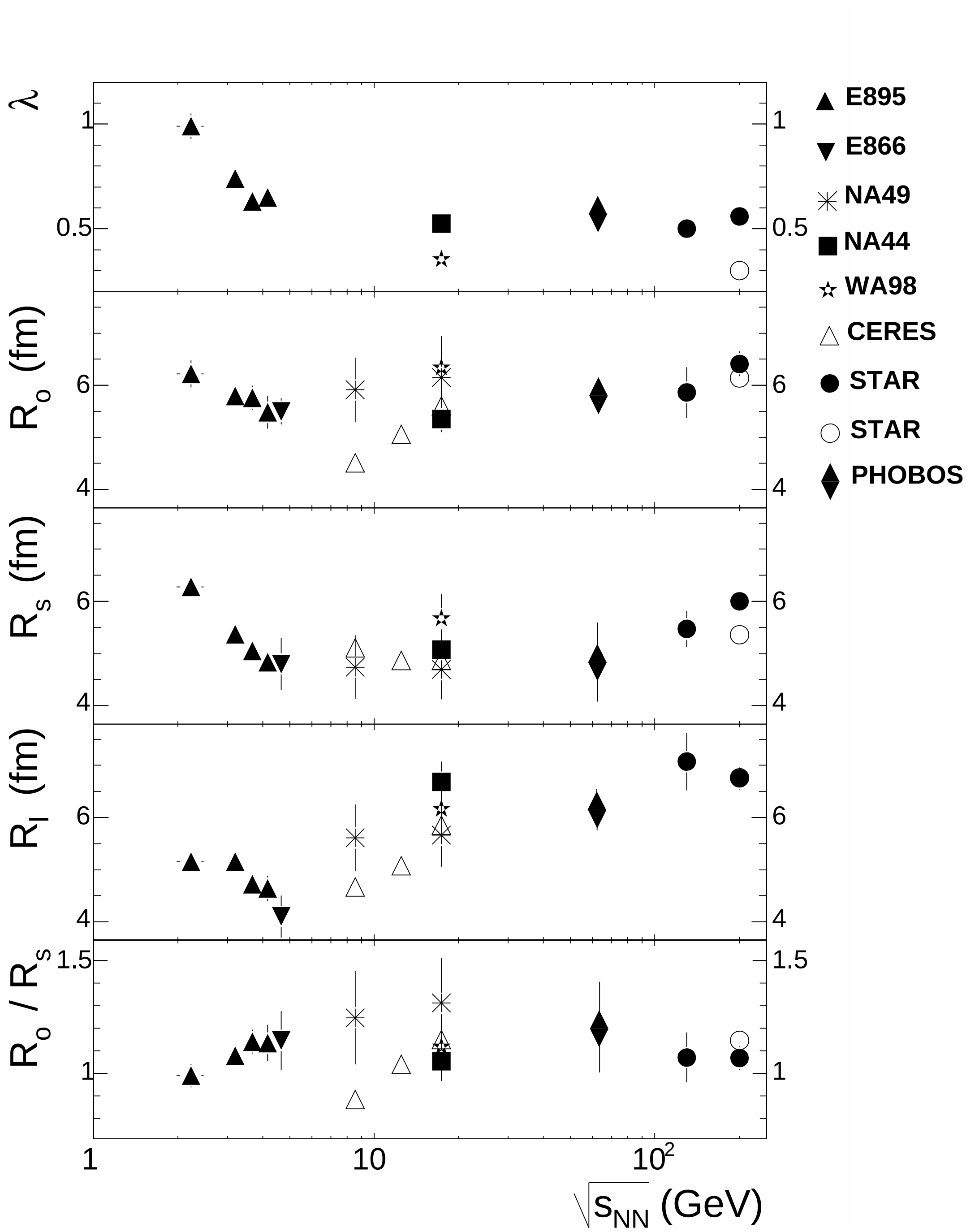
Bertsch-Pratt parameterization: traditional

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

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

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

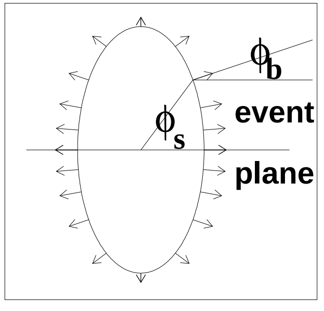
6 The "HBT puzzle"



Open symbols:
Bowler-Sinyukov fits

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

7 Modified Blast Wave model (Retiere,Lisa)

- elliptic source (R_x, R_y) with diffuse edge (α_S)
- thermal emission at temperature T, modulated by...
- 

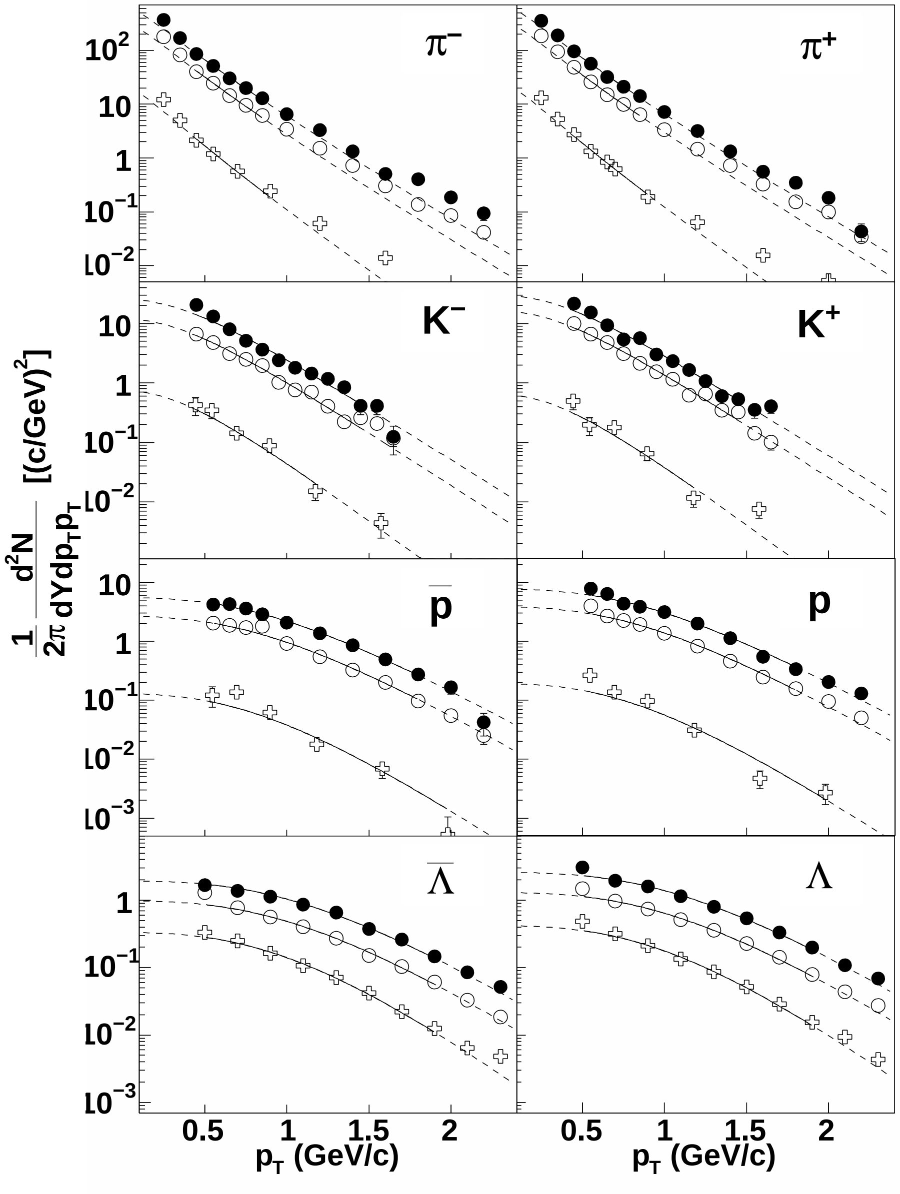
x,y-dependent transverse blast (y_t of the source): [a] – ρ_0 and ρ_2:

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

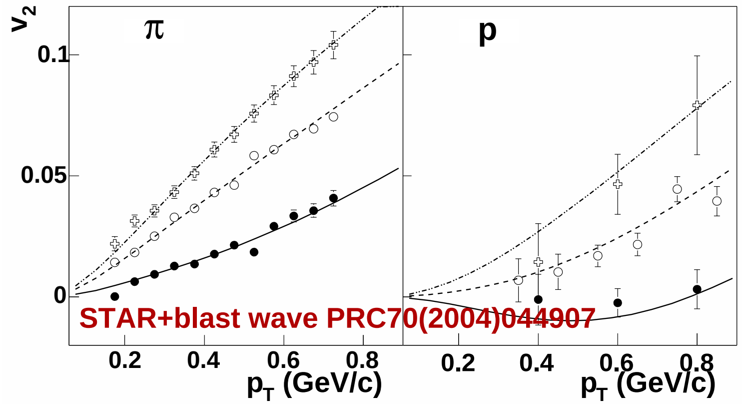
[a] Retiere,Lisa PRC70 (2004) 044907

- Gaussian freeze-out proper-time distribution (τ_0,$\Delta\tau$)

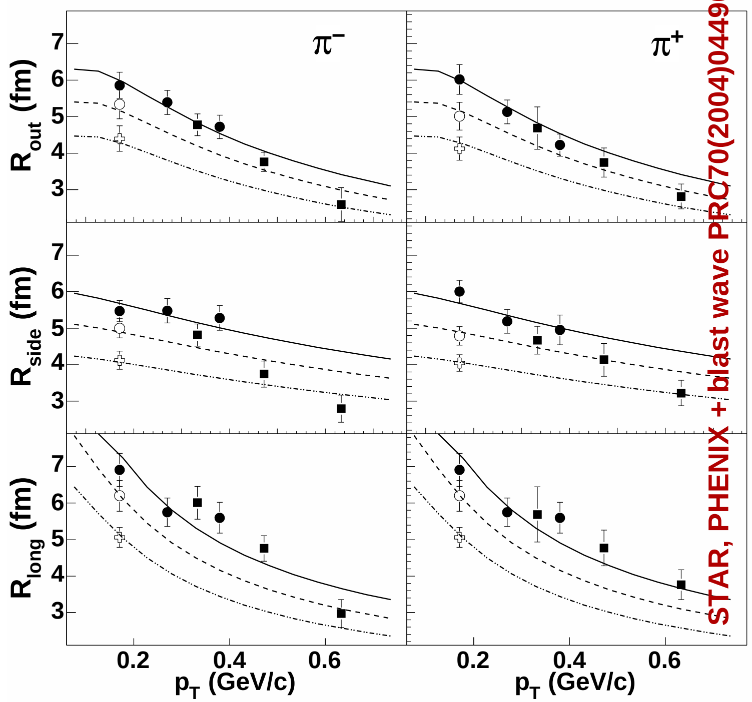
8 Combined fits with Blast Wave: spectra, v_2, HBT



STAR,PHENIX+blast wave PRC70(2004)044907



● central; ○ mid-central; ✚ peripheral



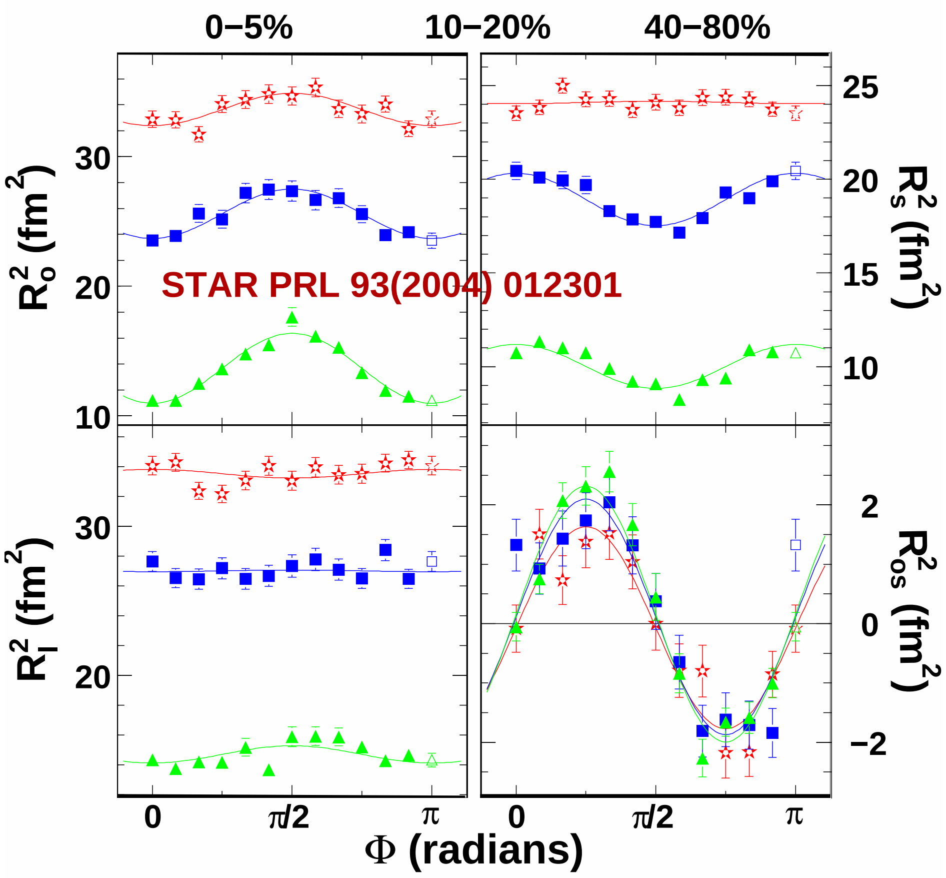
STAR ● central; ○ mid-central;
✚ peripheral; ■ PHENIX 30% central

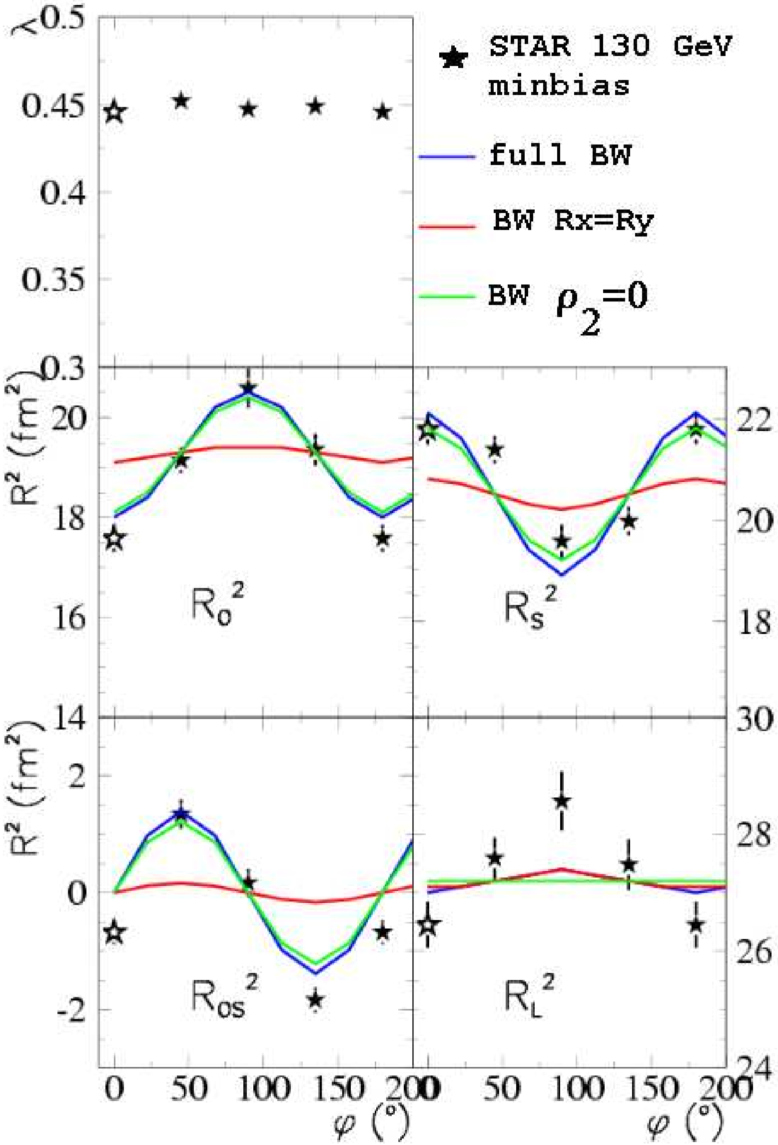
9 Blast Wave fit paramaters at RHIC

	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± 1.3	0.06± 1.3	0.6± 1.8

Emission duration consistent with 0...

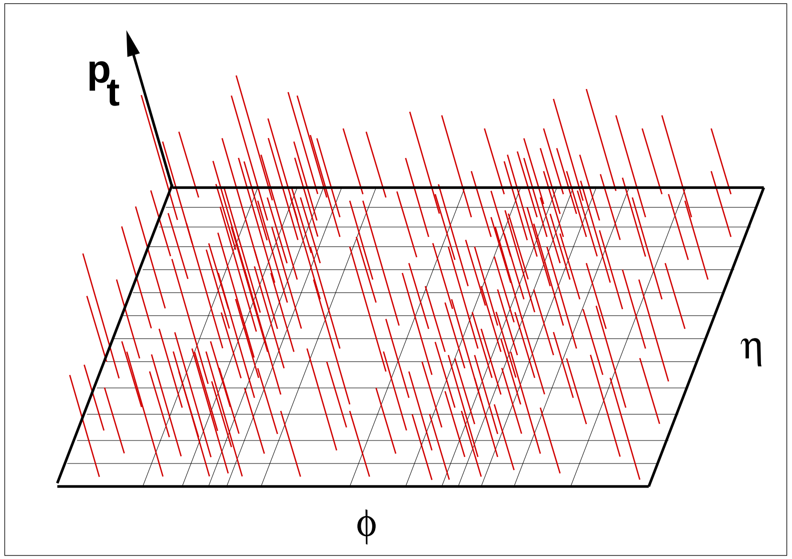
10 Blast Wave and the azimuthally-dependent HBT results



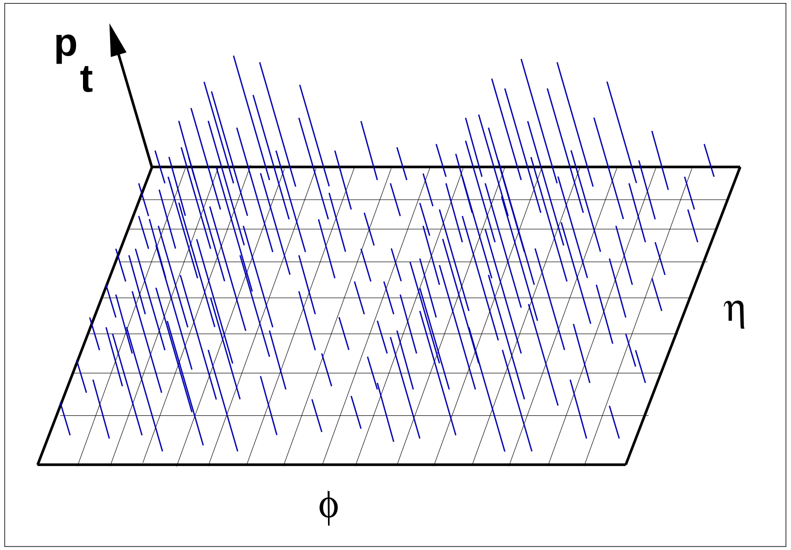


Left: STAR AuAu 200 GeV. Right: calculations for non-round source 10.8×11.4fm, τ=8.3fm/c, $\Delta\tau = 0$ compare with STAR AuAu 130 GeV data

11 Flow: do we see a blast wave ?



This p_t field may have elliptic flow (number effect). Abounds at RHIC.



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 $p_t \equiv \sum_{i\in(\eta,\phi)\text{bin}} p_{t,i} \Rightarrow$ can extract the p_t correlation alone.

Solution: $p_t - n\hat{p}_t$ can be free of n-contribution into $\mathrm{Var}[p_t - n\hat{p}_t]$

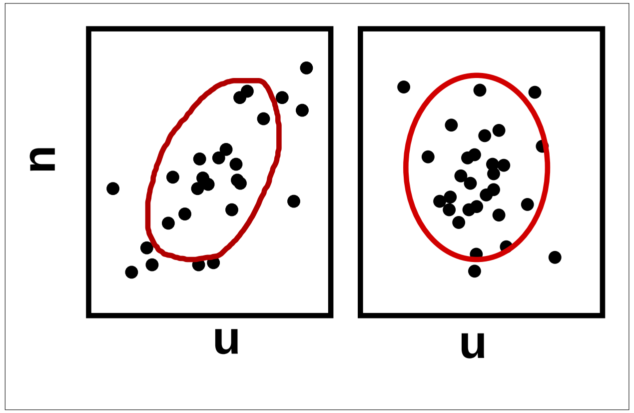
Q:Under what conditions ?

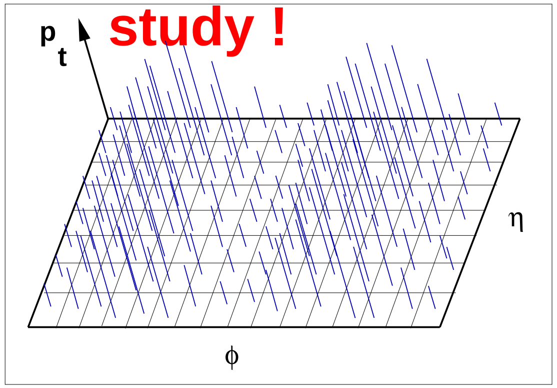
$$\sigma^2(p_t : n) \equiv \mathrm{Var}[p_t - n\hat{p}_t] = \mathrm{Var}[p_t] + \hat{p}_t{}^2\mathrm{Var}[n] - 2\hat{p}_t\mathrm{Cov}[n, p_t] \tag{9}$$

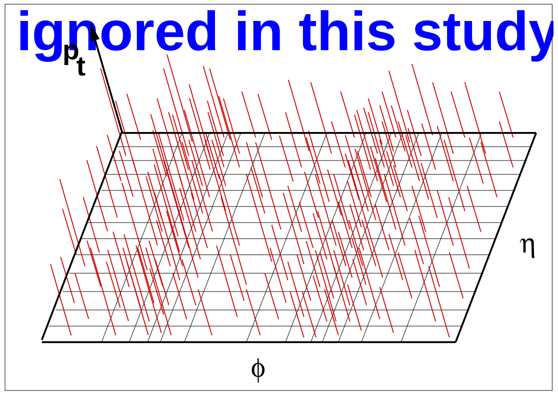
$$\mathrm{Var}[p_t] = \mathrm{Var}[\sum_i^n p_{t,i}] = \mathrm{Var}[\sum_i^n (\hat{p}_t + u_i)] = \hat{p}_t{}^2\mathrm{Var}[n] + \mathrm{Var}[u] + 2\hat{p}_t\mathrm{Cov}[n, u] \tag{10}$$

$$\mathrm{Cov}[n, p_t] = \overline{np_t} - \bar{n}\bar{p}_t = \hat{p}_t\mathrm{Var}[n] \tag{11}$$

A:Independent p_t and n production, when $\mathrm{Cov}[n, u] \equiv \overline{nu} = 0$, where $u \equiv \sum_i^n u_i$, $u_i = p_{t,i} - \hat{p}_t$.

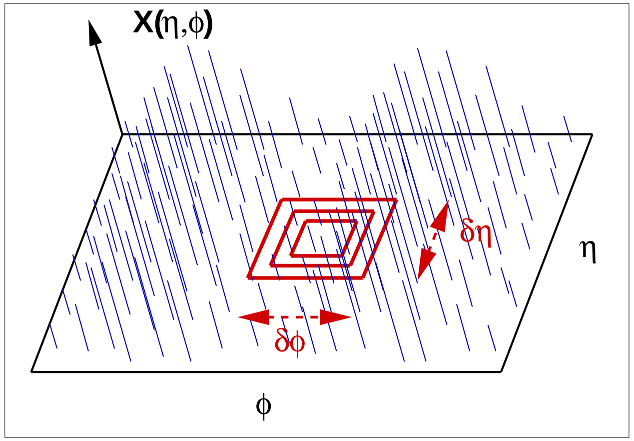






13 Get correlations from fluctuations

Extract correlation structure of random field X from the scale dependence of variance (van Marcke "Random Fields" MIT 1983; Trainor,Porter,Prindle hep-ph/0410180)



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

$$\times[\overline{X(\eta_1,\phi_1)X(\eta_2,\phi_2)} - \overline{X(\eta_1,\phi_1)} \times \overline{X(\eta_2,\phi_2)}]$$

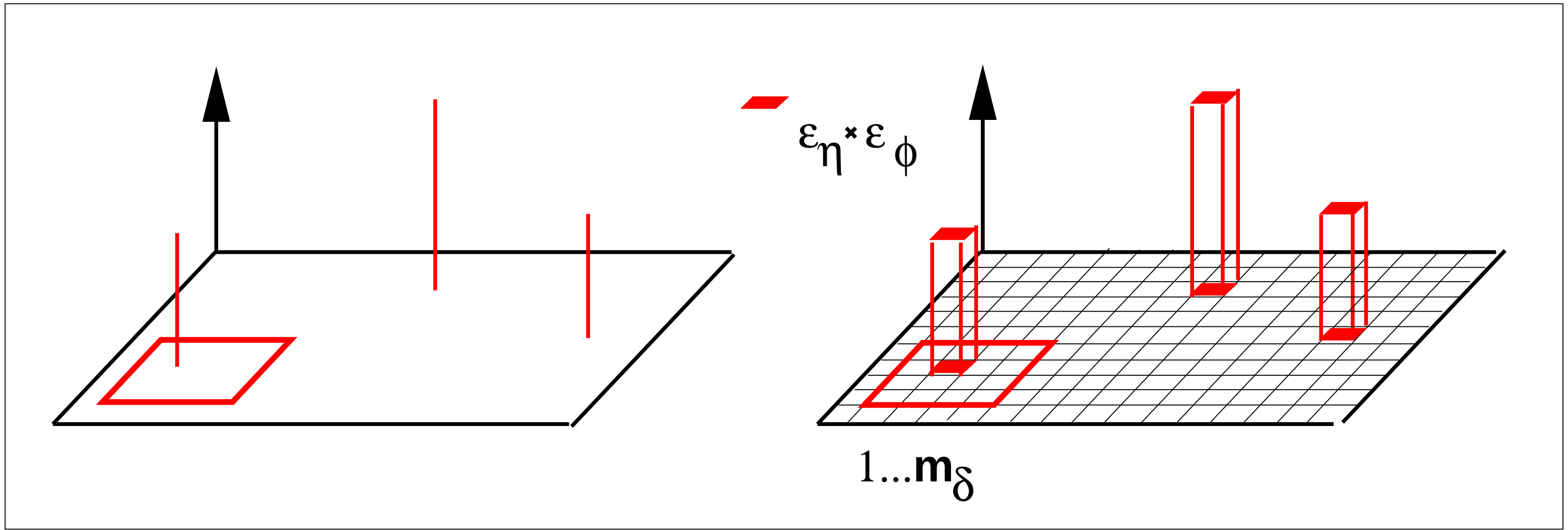
Compare with uncorrelated reference; recognize autocorrelation $\rho(X,t_\Delta) \equiv \overline{X(t)X(t+t_\Delta)}$ (t-average).

$$\Delta\sigma^2(X,\delta\eta,\delta\phi) = \tag{13}$$

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

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

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



kernel K:

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

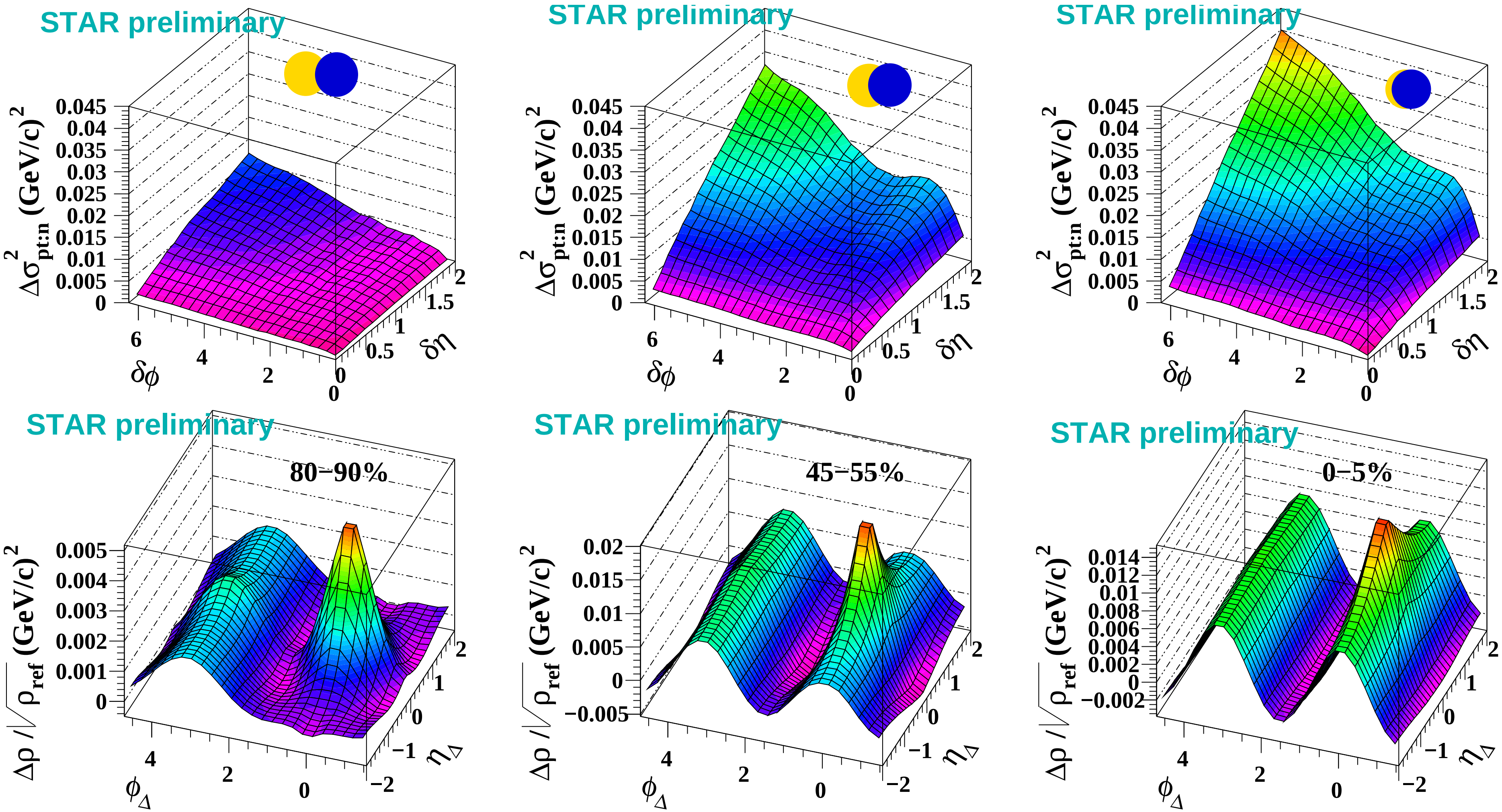
reference density $\rho_{\rm ref}$ makes a per-particle measure:

$$\rho_{\rm ref} \propto \bar{n}^2 \Rightarrow \frac{1}{\sqrt{\rho_{\rm ref}}} \propto \frac{1}{\bar{n}} \tag{17}$$

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

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

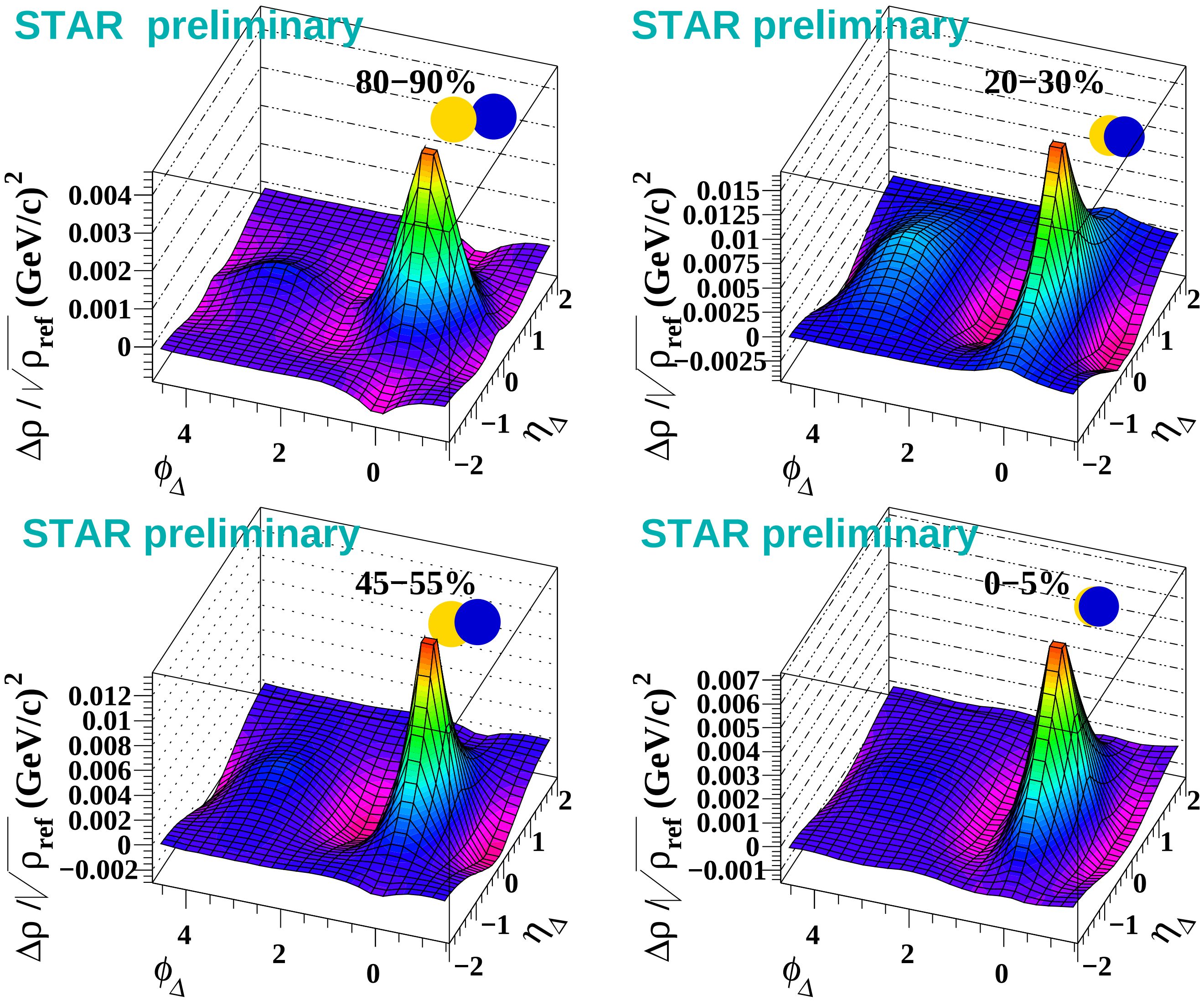
15 p_t correlations from the inversion



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

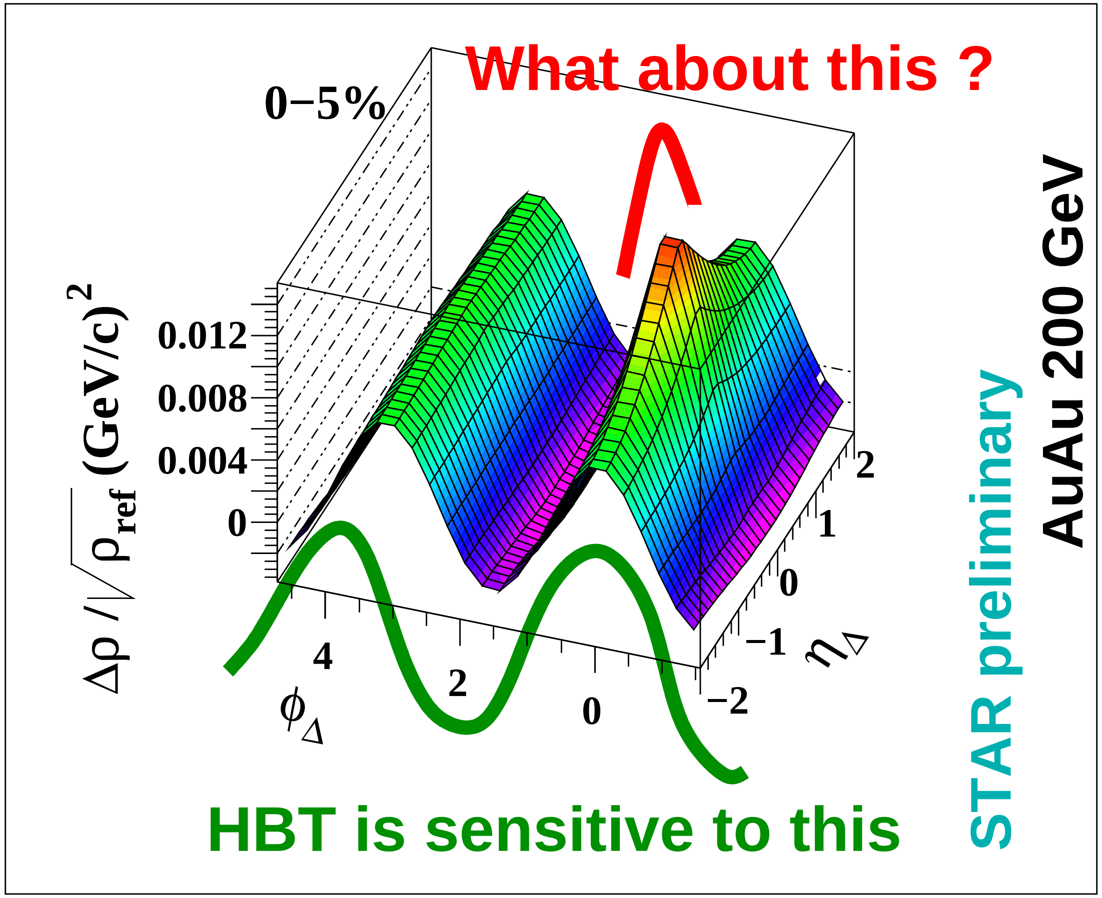
First direct evidence of elliptic flow as a velocity phenomenon at RHIC. Next, subtract the flow contribution to look at minijets.

16 Localized p_t correlations: minijets



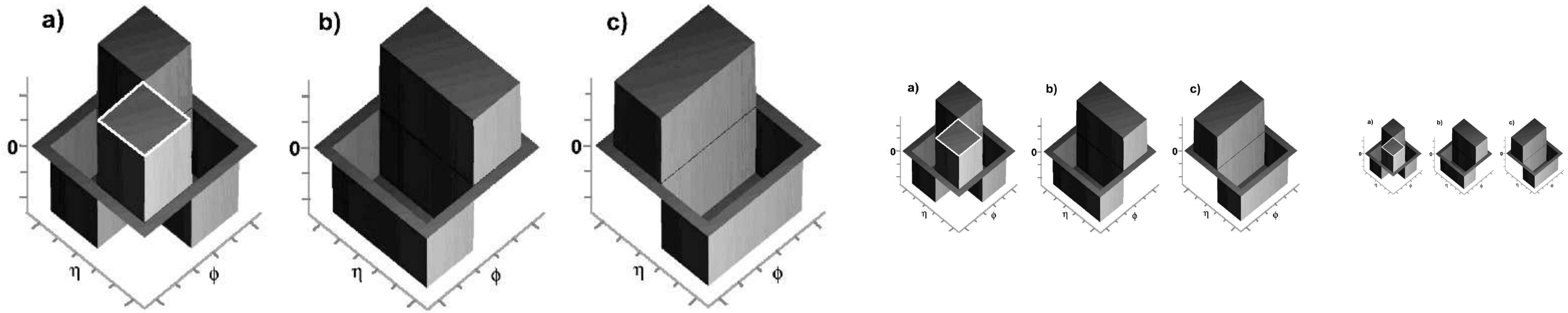
AuAu 200 GeV. In η, correlation broadens with centrality; in ϕ the trend is opposite. The surrounding background seems to recoil.

17 Minijet implications for HBT



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)



$F^{\lambda}_{m,l,k}(\phi,\eta)$–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.**
Power of local fluctuations, mode λ:

$$P^{\lambda}(m) = 2^{-2m}\sum_{l,k}\langle\rho, F^{\lambda}_{m,l,k}\rangle^2 \tag{19}$$

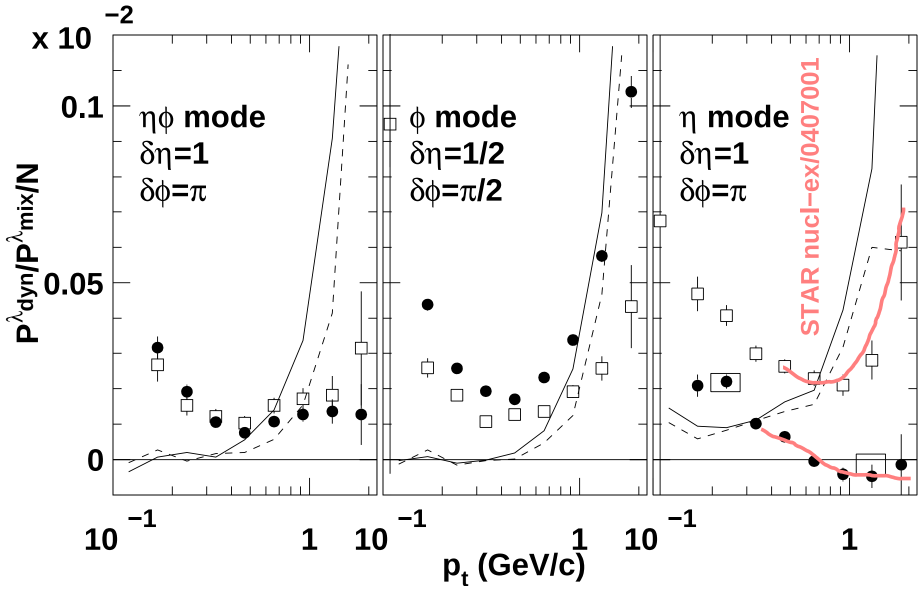
"dynamic texture":

$$P^{\lambda}_{\rm dyn}(m) \equiv P^{\lambda}_{\rm true}(m) - P^{\lambda}_{\rm mix}(m) \tag{20}$$

Normalized:

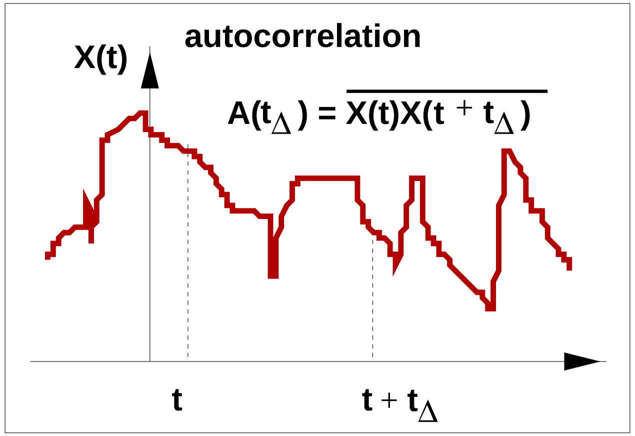
$$P^{\lambda}_{\rm dyn}(m)/P^{\lambda}_{\rm mix}(m)/n(p_t) \tag{21}$$

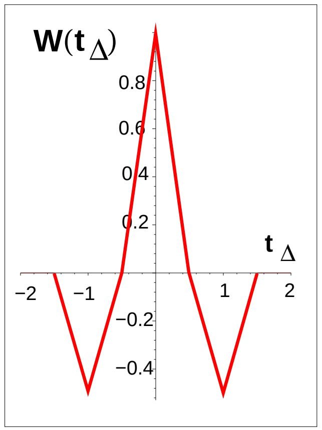
19 Longitudinal minijet broadening



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.

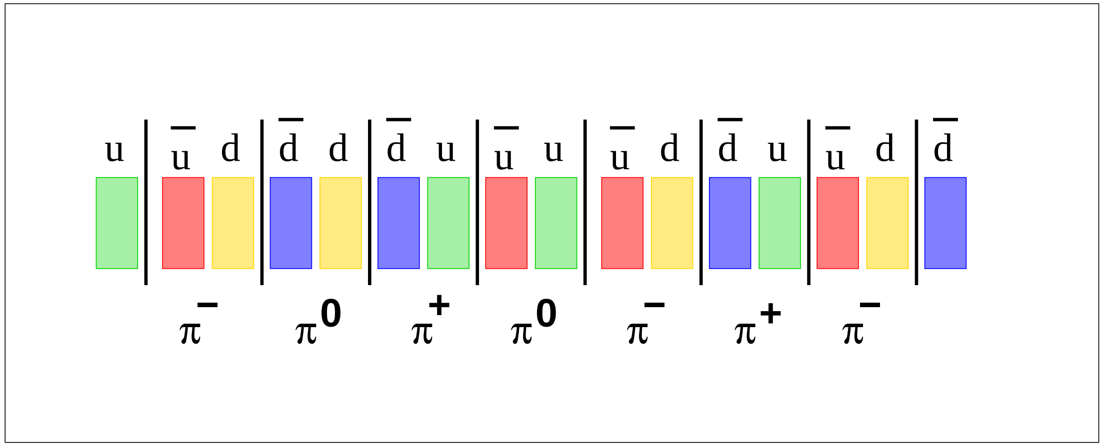


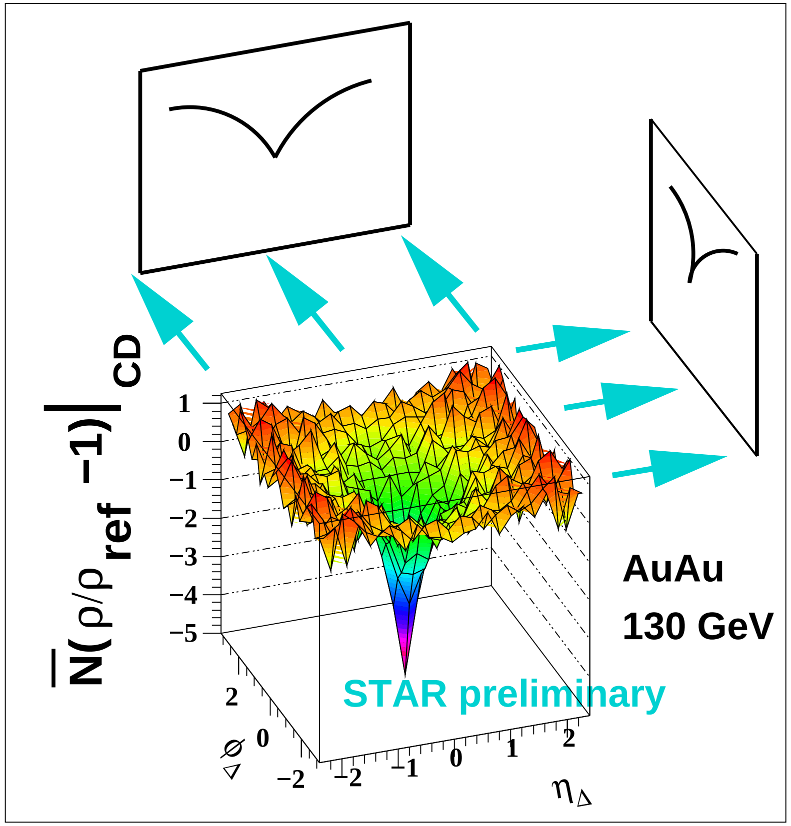


$P(m)$ differentiates correlation on scale m. Minijet elongation $\Rightarrow$ correlation broadening $\Leftrightarrow$ reduced correlation gradient $\Leftrightarrow$ reduced "texture"

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

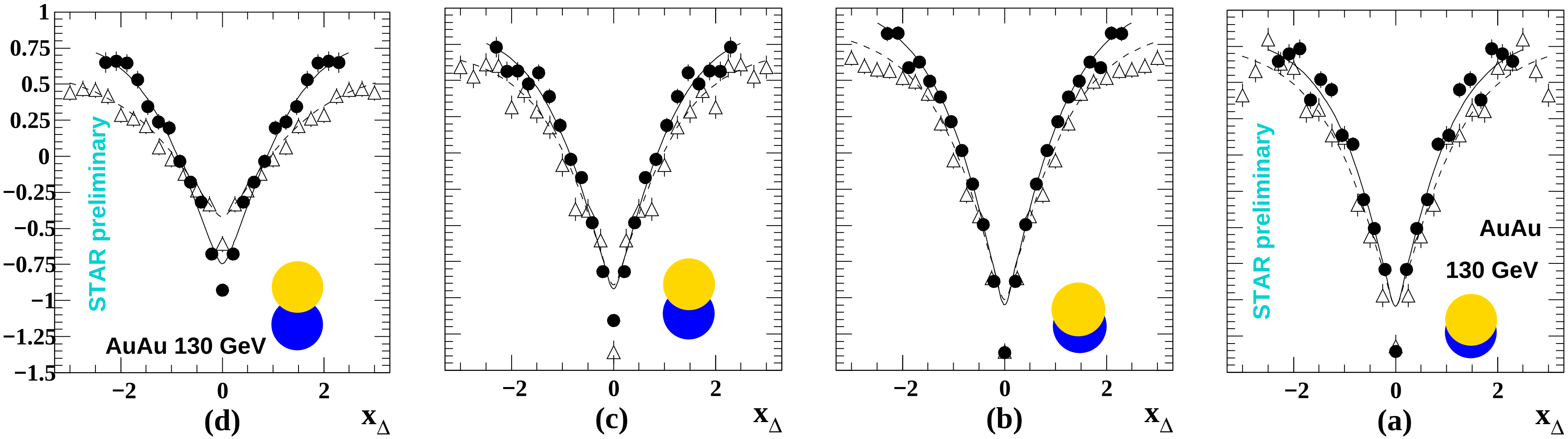
20 Charge-dependent correlations = Like sign - Unlike sign



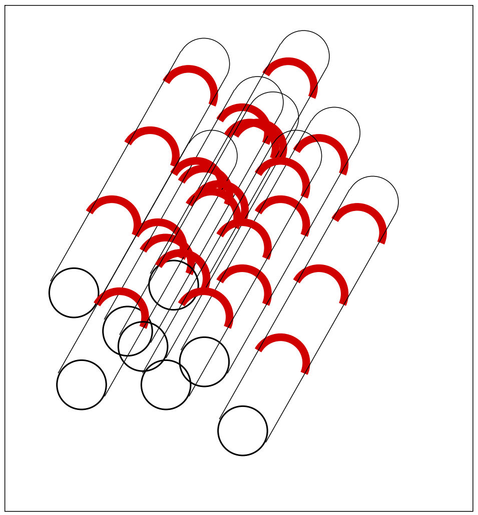


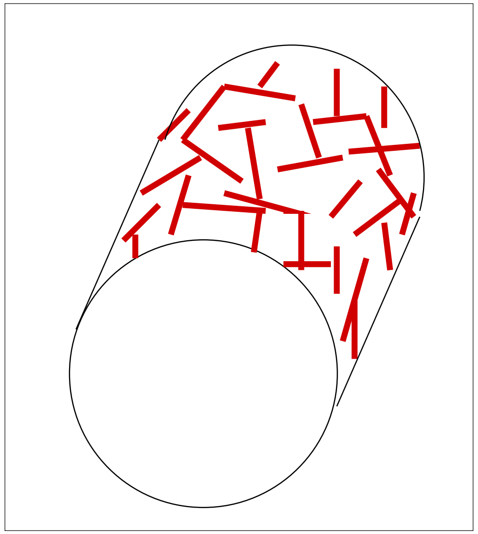
The driving physics: charge conservation in hadronization. Suppress short range correlations – BEC and conversion e^+e^- – by a kinematic pair cut. The $\bar{N}\times$ is good when number of correlation sources $\propto N$.

21 Modified hadronization geometry ?



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.





22 Conclusion: correlation measurements quantify equilibration in various aspects

- Blast Wave success suggests dynamical effects as the likely root of the "HBT puzzle".
- First direct measurements of p_t correlation structure reveal azimuthal anisotropy of p_t field $\Rightarrow$ elliptic flow is a velocity phenomenon
- Semi-hard scattering leaves a trace in the soft p_t domain – new at RHIC ! Is HBT (homogeneity length/current correlator length) unscathed ?
- The mini-jet correlation structure in central events is modified; consistent with dissipation of momentum. How exactly does the coupling between longitudinal flow and mini-jets work ? What do we learn about the expanding fluid ?
- 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