Correlation structure of STAR events

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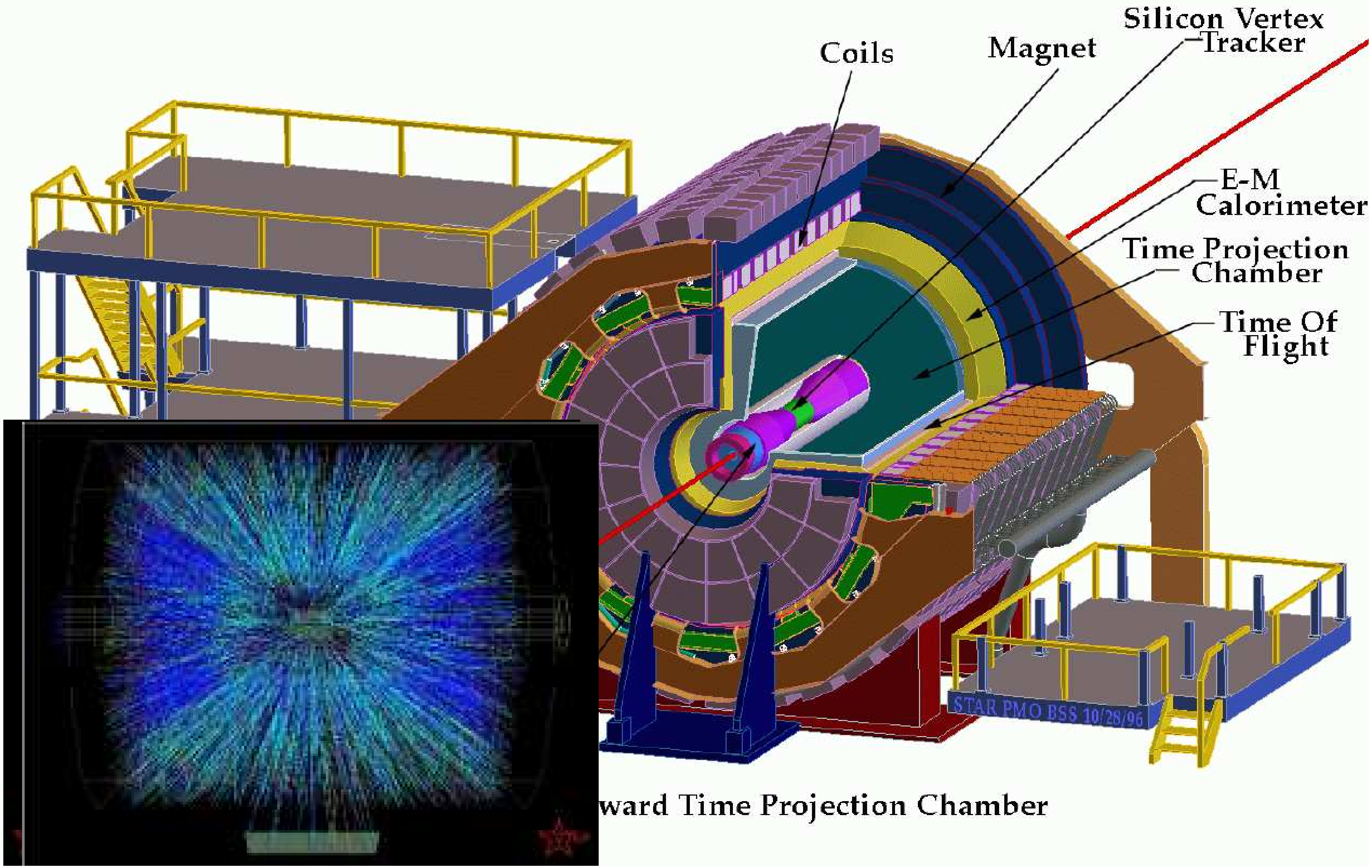
STAR Detector



1 Content of the talk

- Equilibration

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

- Methods

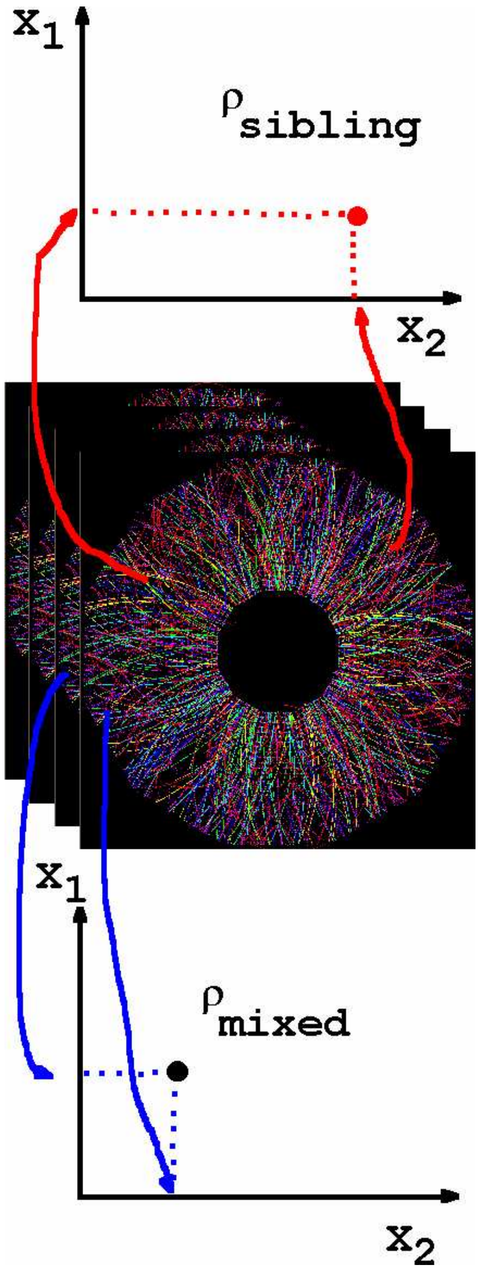
  Initial state: a "calibrated" source of correlations. Watch their evolution into final state in time = system size.

  - Direct construction of a correlation function.
  - Inversion of scale-dependent variance
  - Discrete Wavelet Transform

- Observations

- Conclusions

2 Autocorrelation

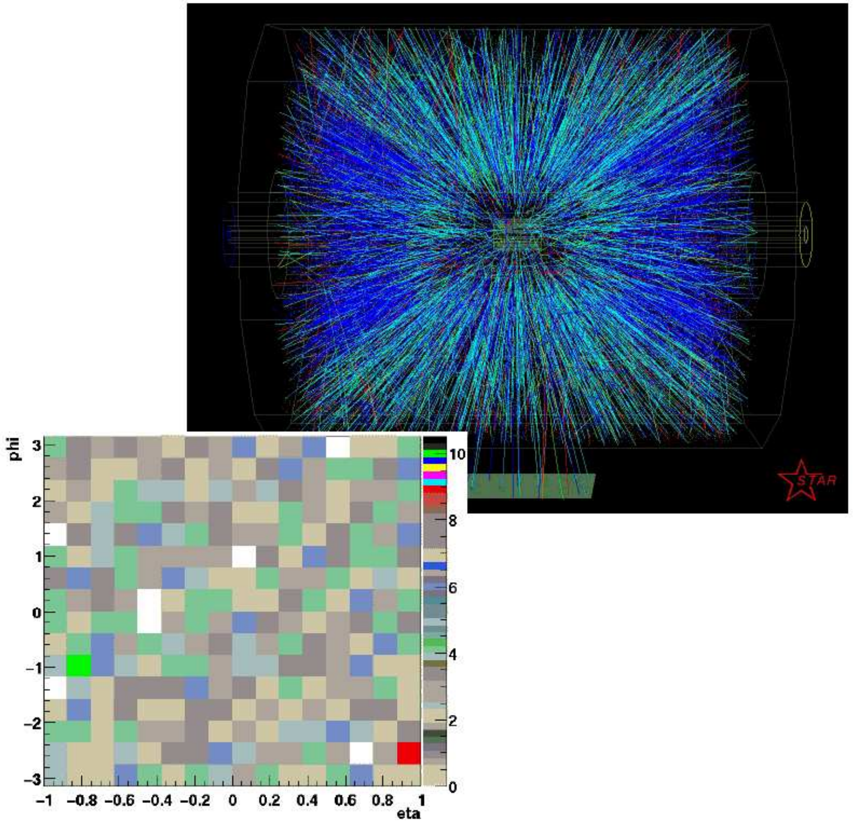


$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \to \begin{pmatrix} x_\Sigma \equiv x_1 + x_2 \\ x_\Delta \equiv x_1 - x_2 \end{pmatrix},$$

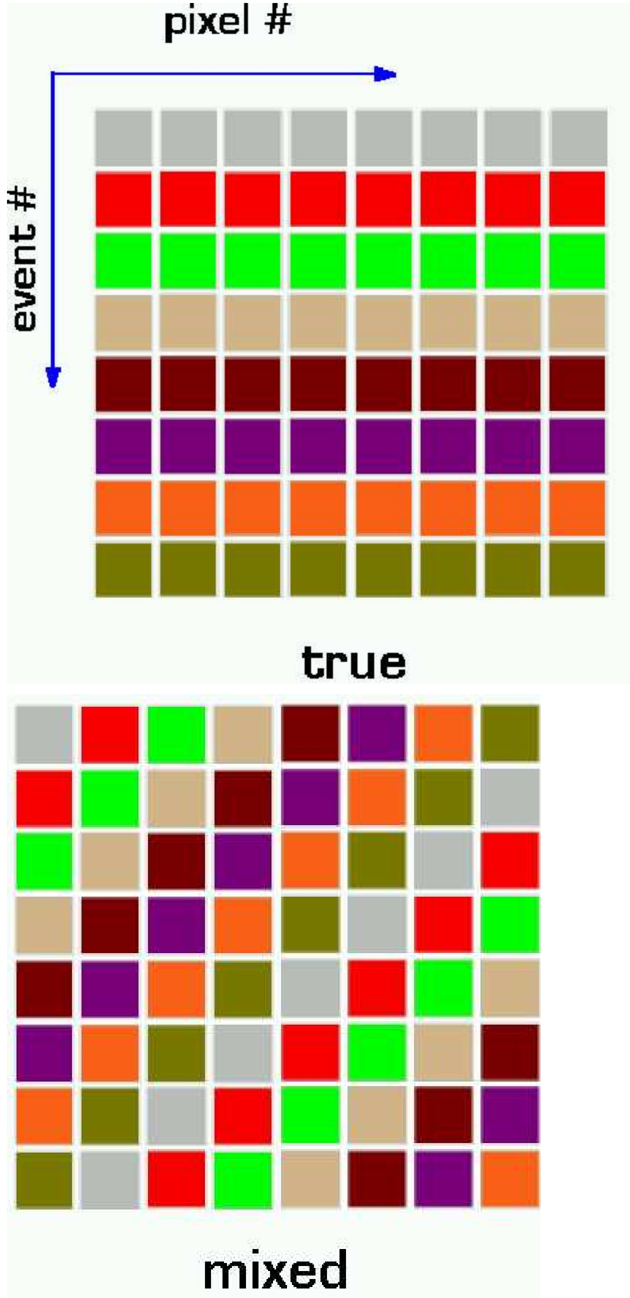
always a lossless transformation of data. **Autocorrelation** A is a projection of a two-point distribution onto difference variable(s) x_Δ, lossless for x_Σ-invariant (homogenous, stationary) problems.

$$\Delta R(x_1, x_2) = \frac{\rho(x_1, x_2)}{\rho_{\text{ref}}(x_1, x_2)} - 1$$

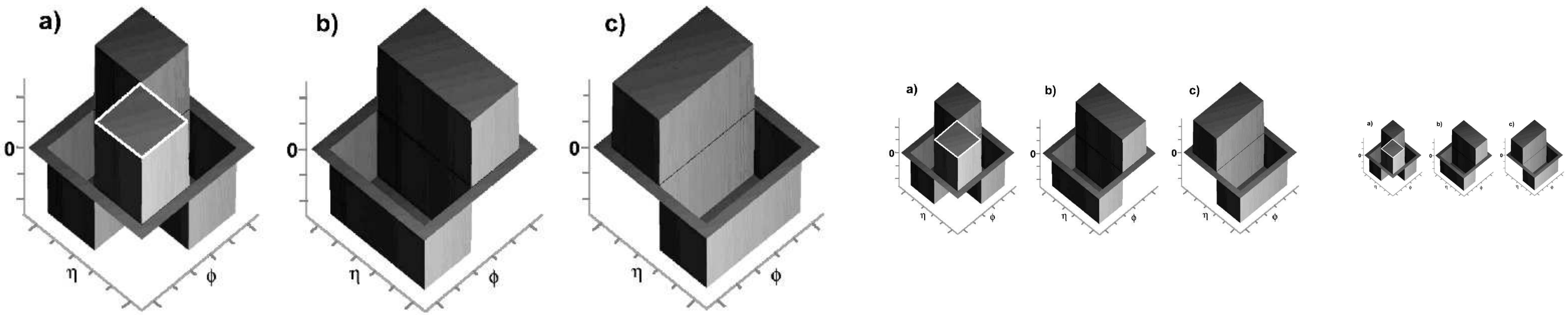
3 Uncorrelated event reference for DWT



mixed events: no pixel used twice; ≤ 1 pixel from any event in the same mixed event; no mixing of events with largely different multiplicity and vertex.



4 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:

$$P^{\lambda}(m) = 2^{-2m} \sum_{l,k} \langle \rho, F^{\lambda}_{m,l,k} \rangle^2 \tag{1}$$

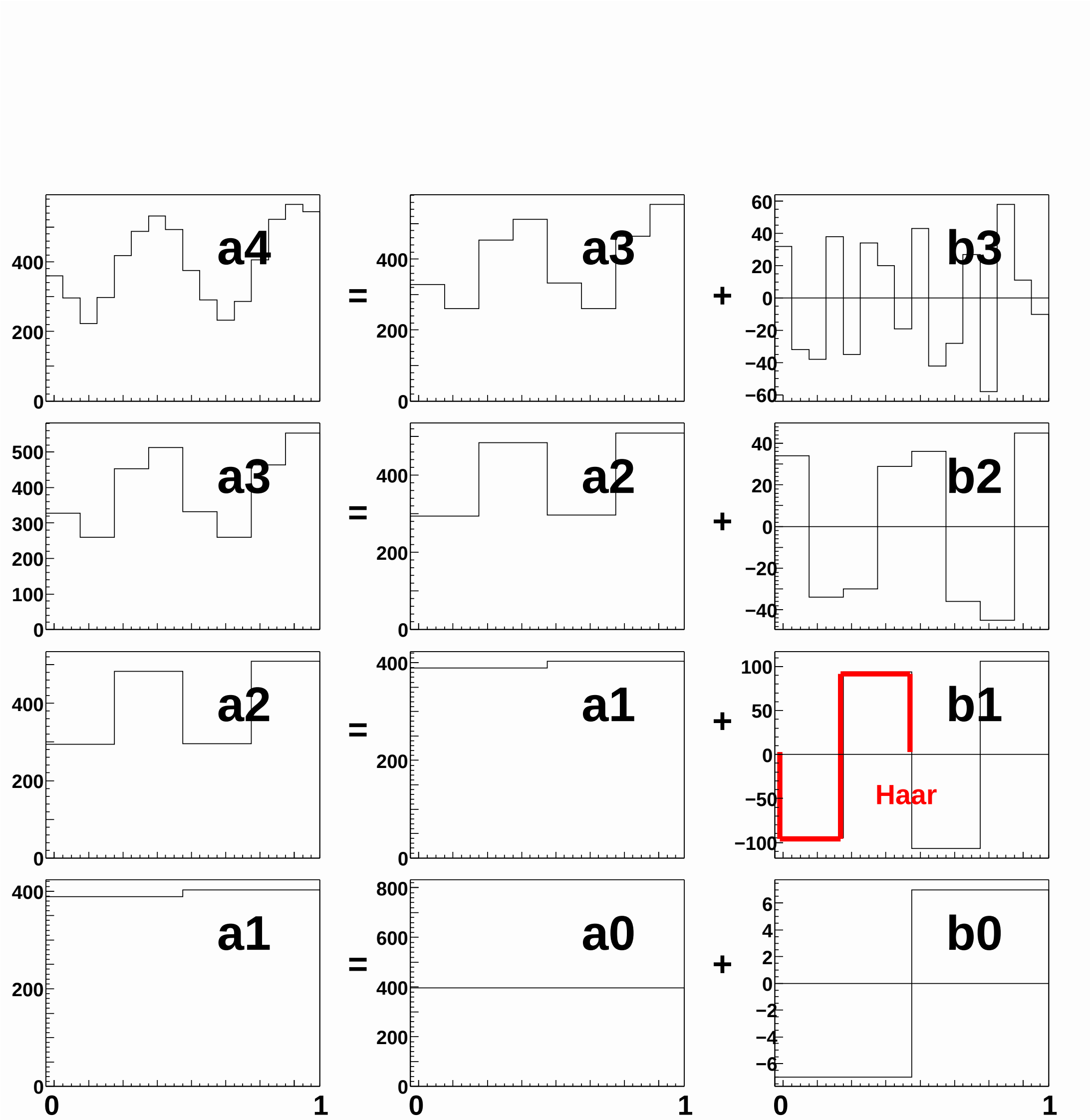
“dynamic texture”:

$$P^{\lambda}_{\rm dyn}(m) \equiv P^{\lambda}_{\rm true}(m) - P^{\lambda}_{\rm mix}(m) \tag{2}$$

Normalized:

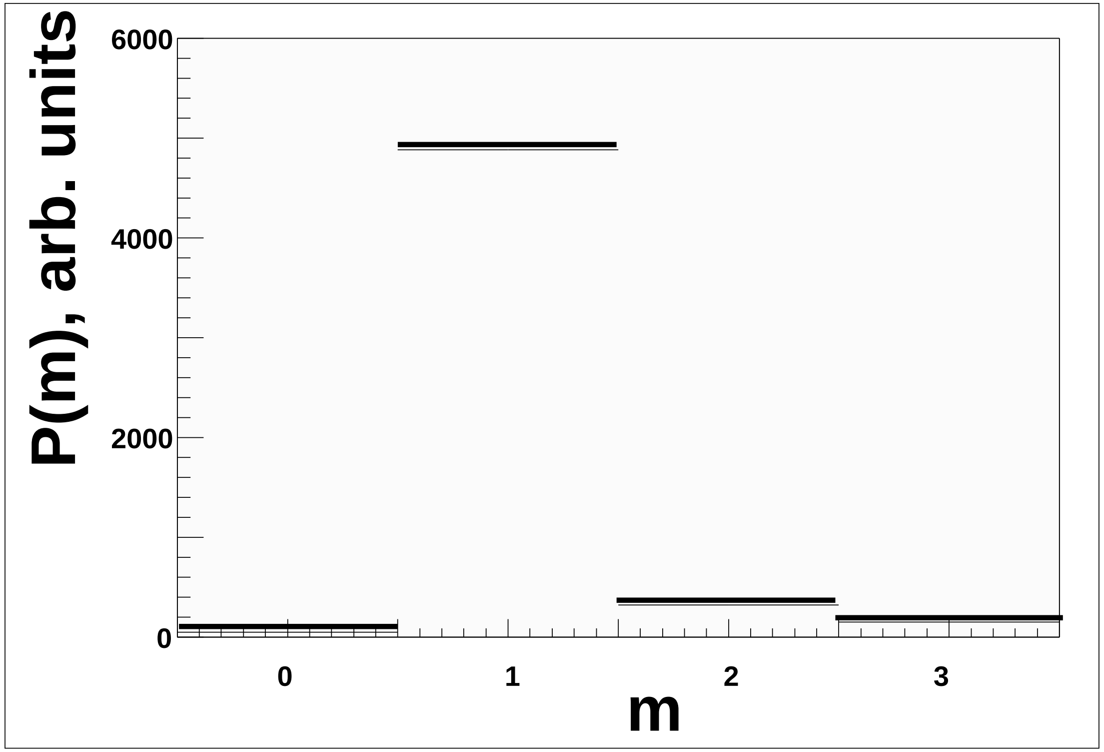
$$P^{\lambda}_{\rm dyn}(m)/P^{\lambda}_{\rm mix}(m)/n(p_t) \tag{3}$$

5 A flow-like example



Elliptic flow-inspired example: x axis – an angle in "natural units" $(2\pi = 1)$, y axis – multiplicity. The multiresolution theorem: **a4 = a0+b0+b1+b2+b3**, can have better fineness.

6 Example of a DWT power spectrum

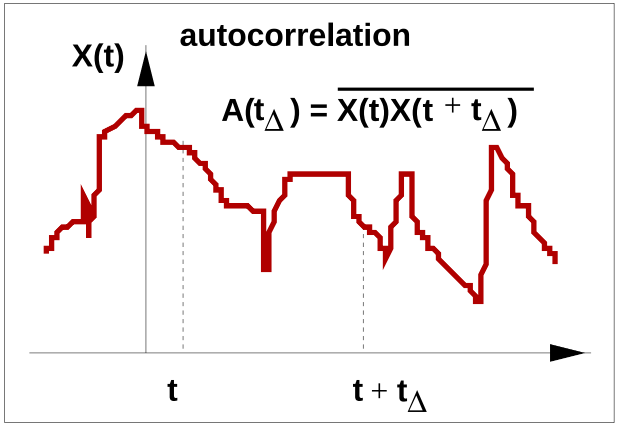


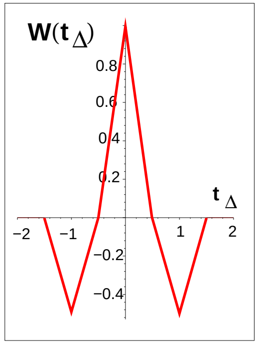
Power spectrum of that flow event as a function of "fineness" m. The dominant contrubution is $m = 1$ (the "v_2" harmonic, **b1**). Statistical fluctuations also contribute.

$P(m) = 2^{-m} \sum_i \langle \rho, F_{m,i} \rangle^2$.

Computational complexity $O(N)$!

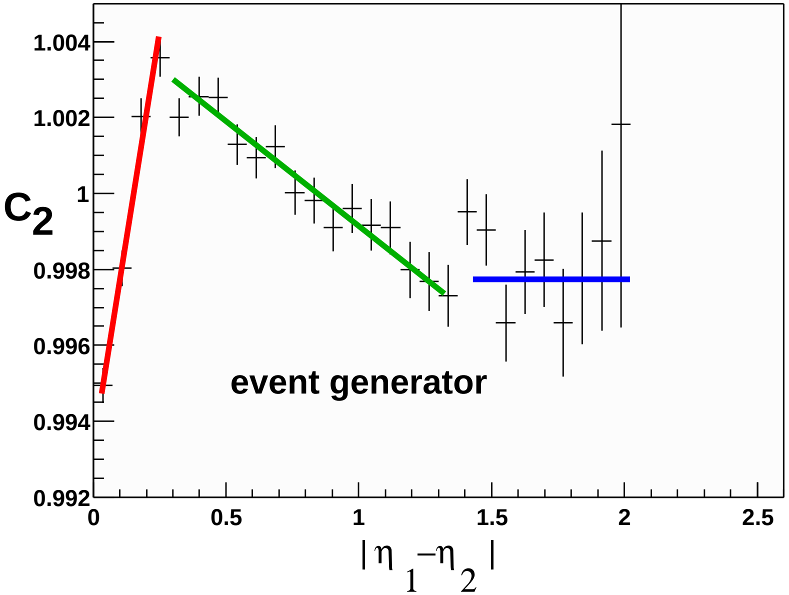
7 "Dynamic texture" as a nonparametric measure of the correlation shape

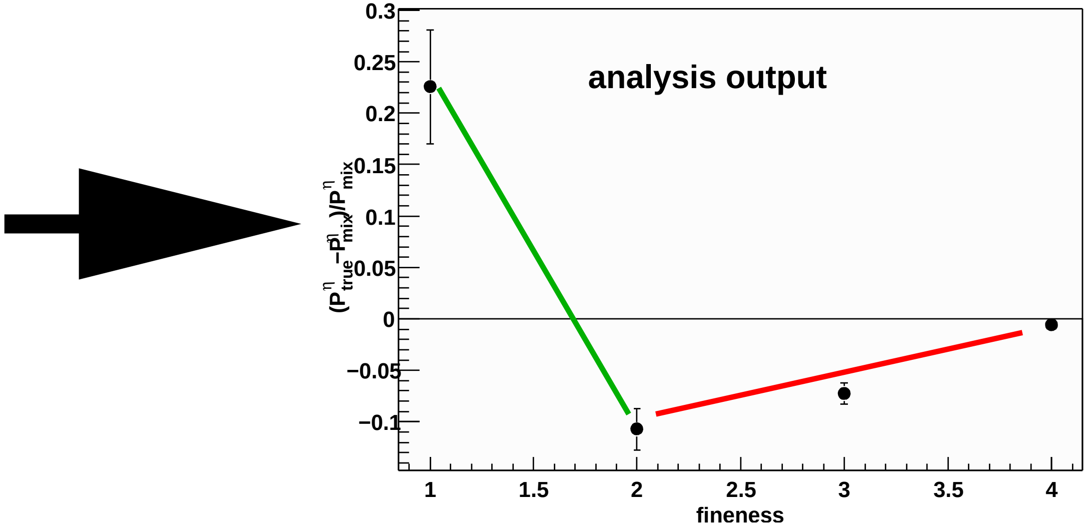




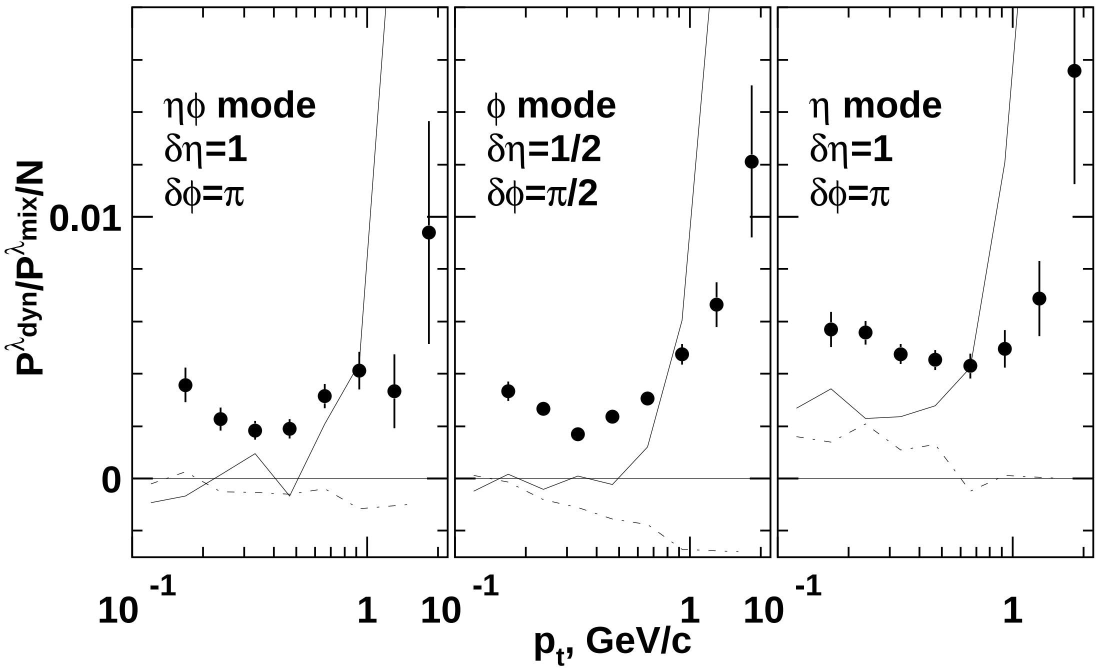
$$P(m) = \overline{\int_{-\infty}^{\infty} X(\tau/2)X(-\tau/2)W(\tau,m)\,d\tau},$$

where W is the weight function for the Haar wavelet. $P(m)$ reflects differential structure on scale m. See example:





8 “Dynamic texture” p_t dependence: peripheral events, $\sqrt{s_{NN}} = 200$ GeV

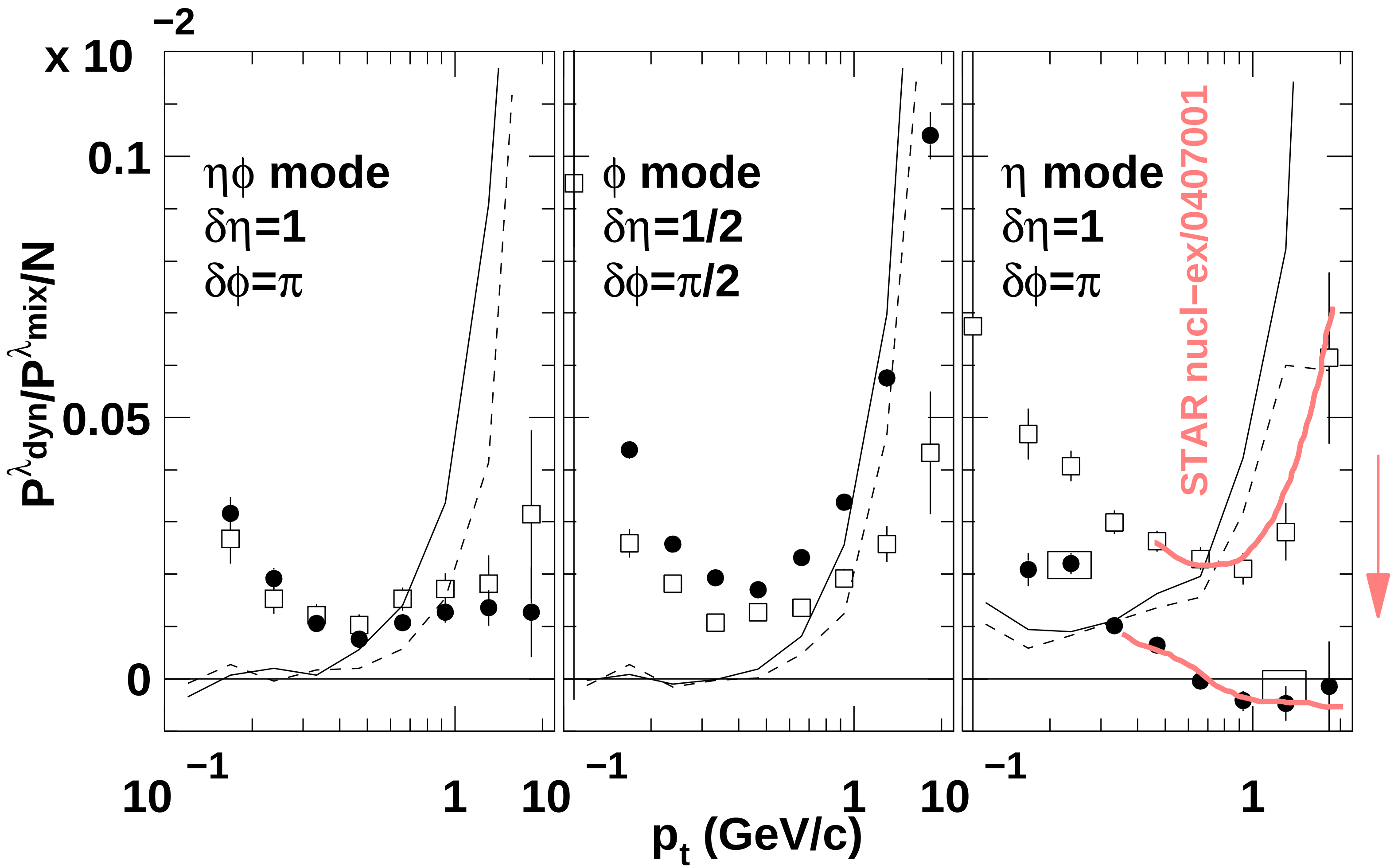


Peripheral (60-84%) events: normalized dynamic texture for fineness scales $m = 0, 1, 0$ from left to right panels, respectively, as a function of p_t. • – STAR data; solid line – standard HIJING, dash-dotted line – HIJING without jets.

Qualitative trends in peripheral data are as expected. What signal to expect in the central data, if correlation does not change ?

$$\left(\frac{P_{\rm true}}{P_{\rm mix}} - 1\right)\frac{1}{N}\bigg|_{\rm centr} = \left(\frac{P_{\rm true}}{P_{\rm mix}} - 1\right)\bigg|_{\rm periph}\frac{1}{N_{\rm centr}} \qquad (4)$$

9 Longitudinal minijet broadening: DWT data

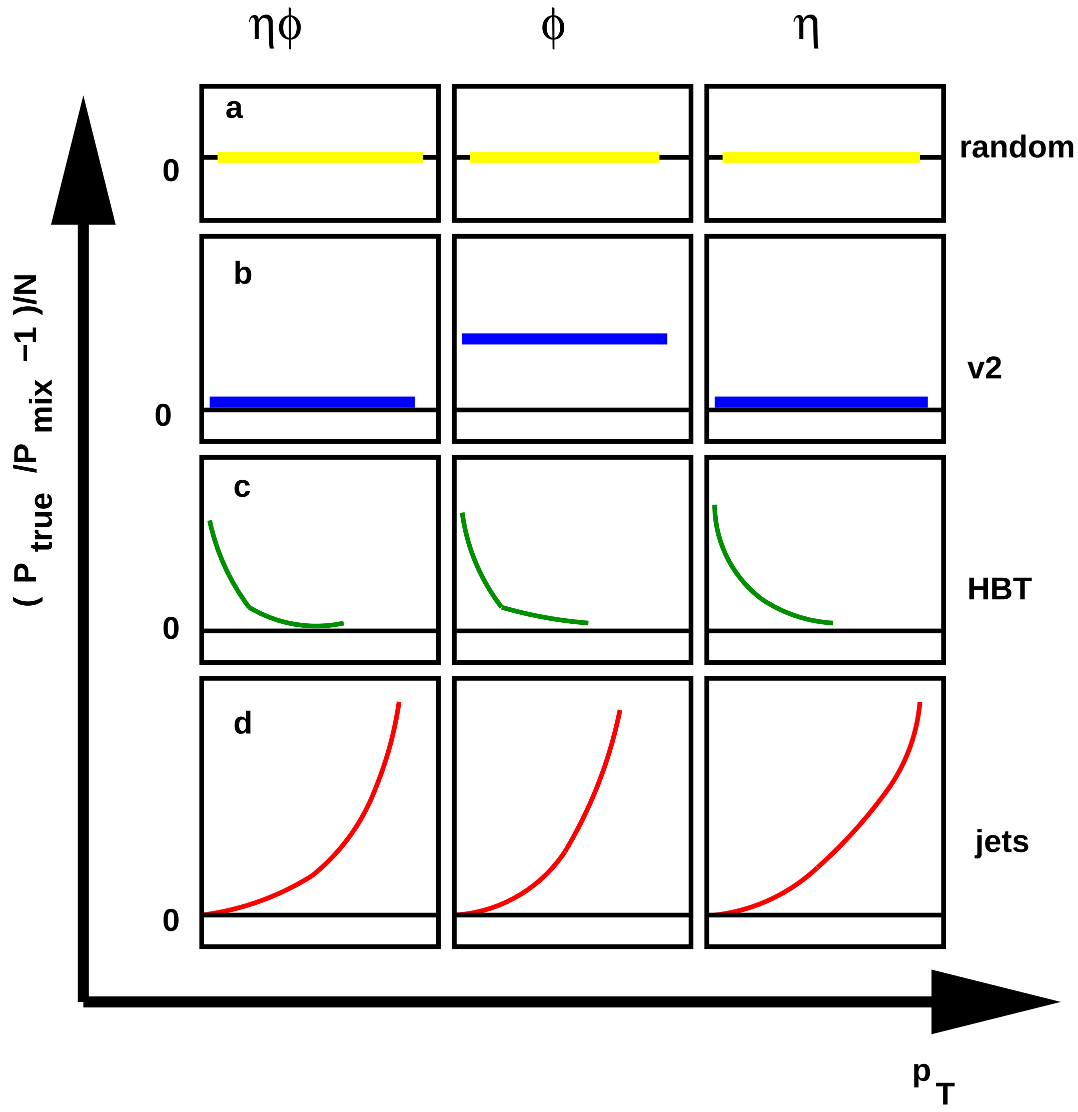


Central (top 4%) events: normalized dynamic texture for fineness scales $m = 0, 1, 0$ from left to right panels, respectively, as a function of p_t.

● STAR data; solid line – Hijing without jet quenching; dashed line – Hijing with quenching; □ peripheral STAR data renormalized to compare.

Minijet elongation ⇒ correlation broadening ⇔ reduced correlation gradient ⇔ reduced “texture”

10 "Dynamic texture" response



Dynamic texture response in various idealized situations (showing only one scale):

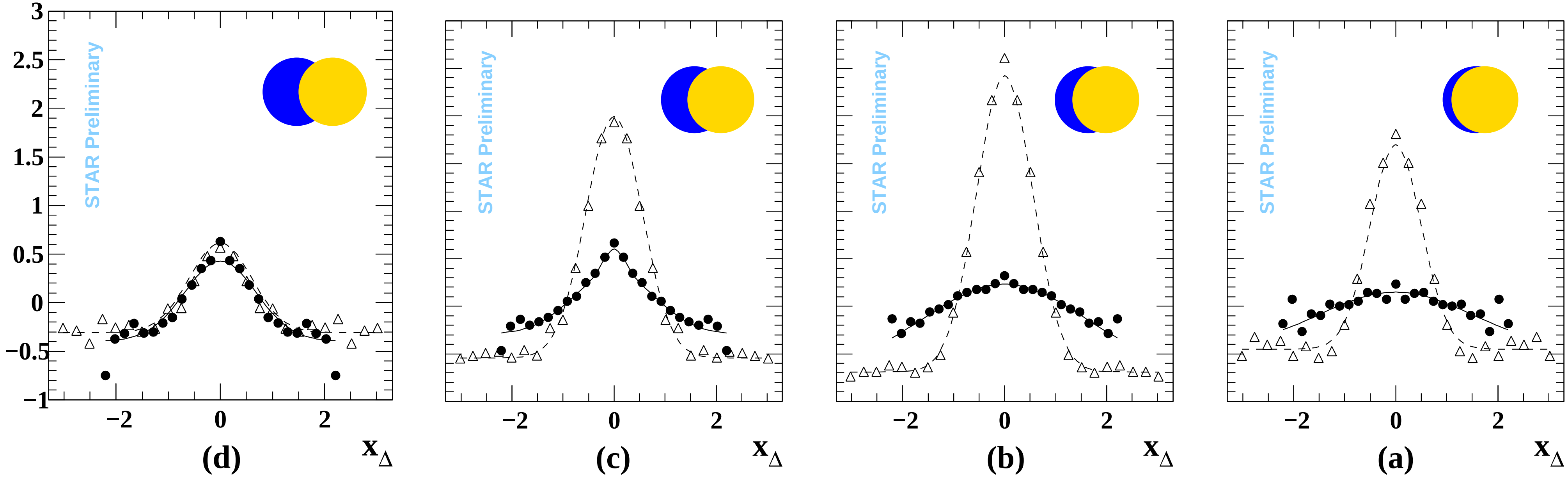
(a) events of random (uncorrelated) particles

(b) p_t-independent elliptic flow

(c) Correlations at low $Q_{\rm inv}$ (Bose-Einstein correlations and Coulomb effect)

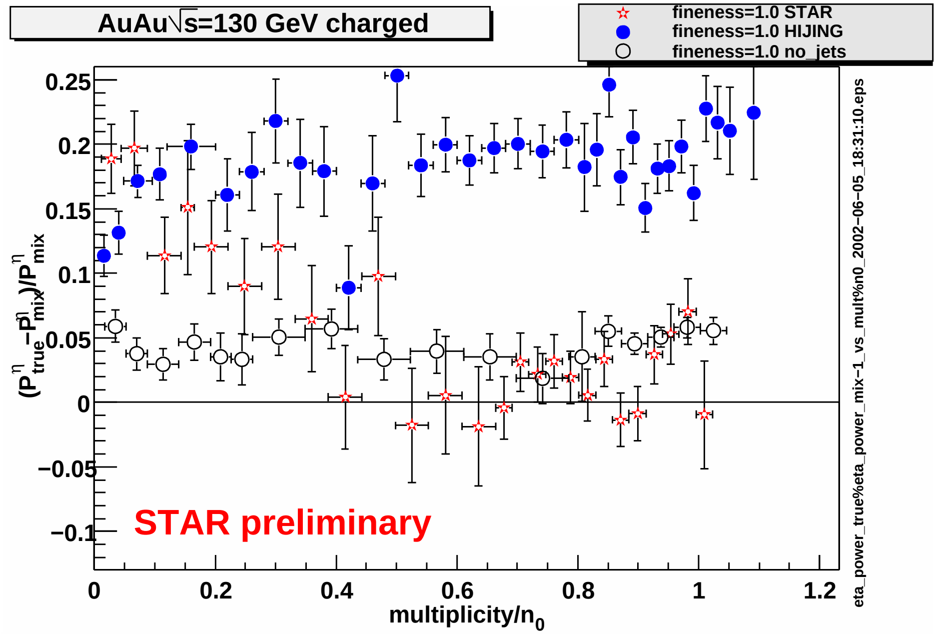
(d) HIJING jets

11 Longitudinal minijet broadening: correlation data

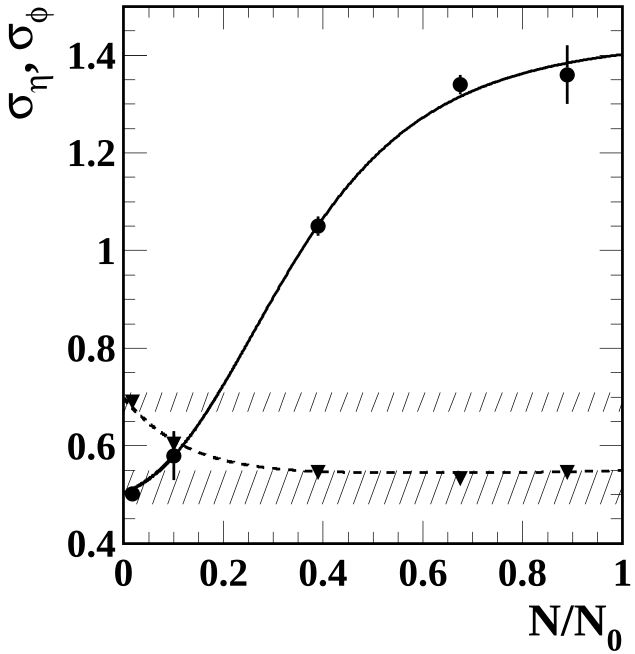


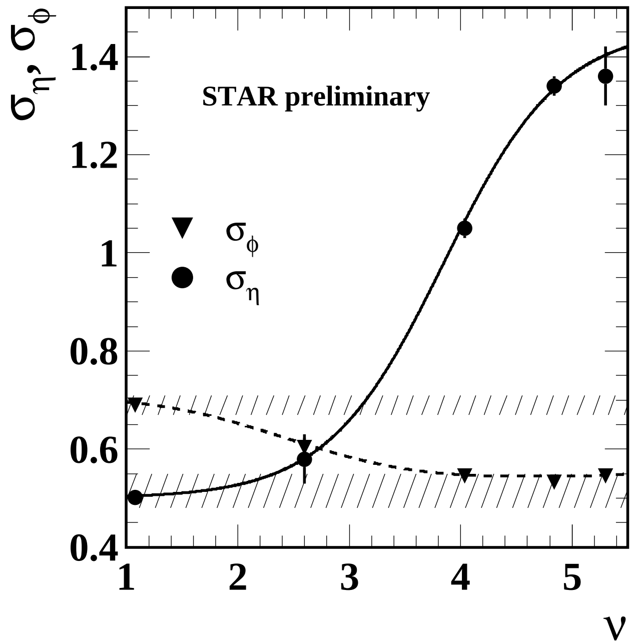
Projections of $\bar{N}[\rho(\eta_\Delta, \phi_\Delta)/\rho(\eta_\Delta, \phi_\Delta)_{\rm ref} - 1]|_{CI}$ on x_Δ which is ϕ_Δ (Δ) or η_Δ (●). v_1 and v_2 are subtracted.

12 Longitudinal minijet broadening: centrality dependence



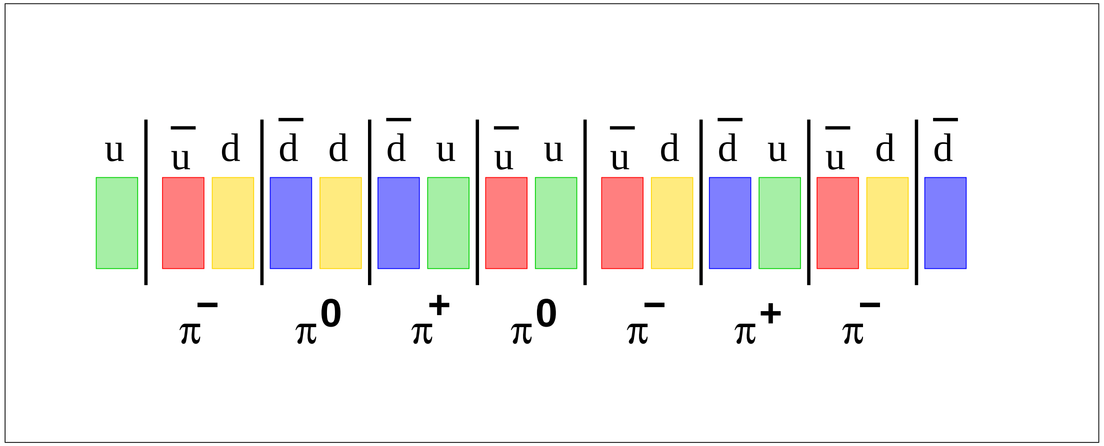
nucl-ex/0211015. STAR DWT analysis of charge-independent correlations, AuAu, $\sqrt{s_{NN}} = 130$ GeV

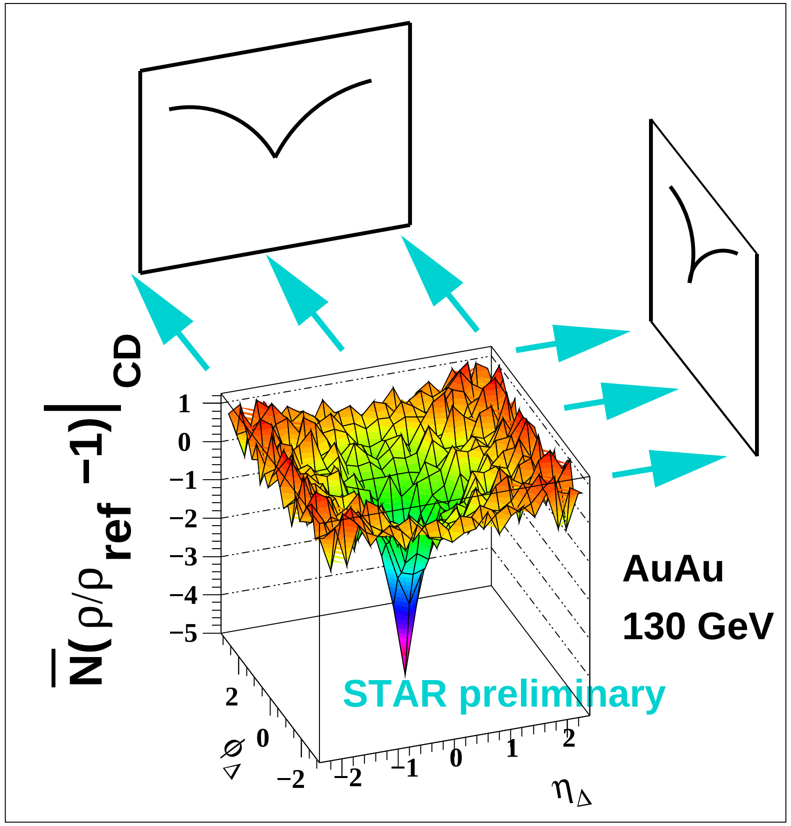




nucl-ex/0411003. STAR two-particle correlation analysis. The step-like character of the centrality dependence is elucidated using $\nu = (N_{\rm part}/2)^{\frac{1}{3}}$

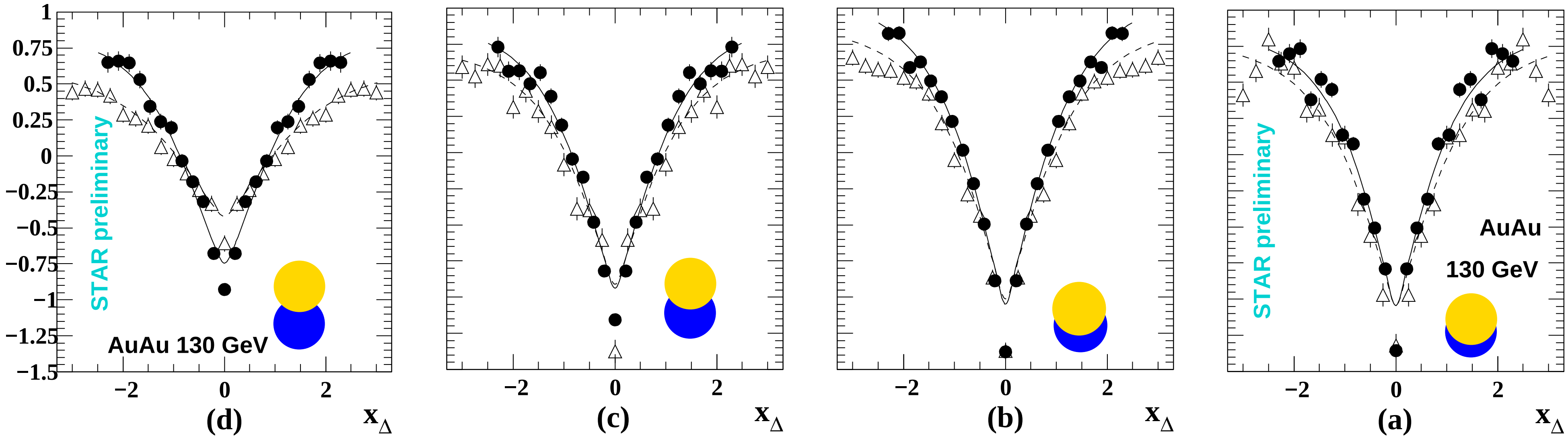
13 Charge-dependent correlations = Like sign - Unlike sign



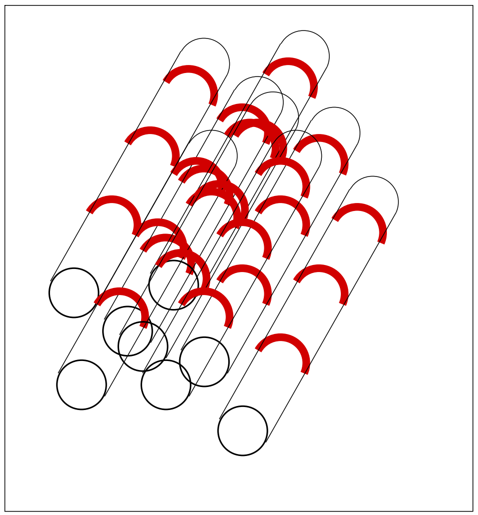


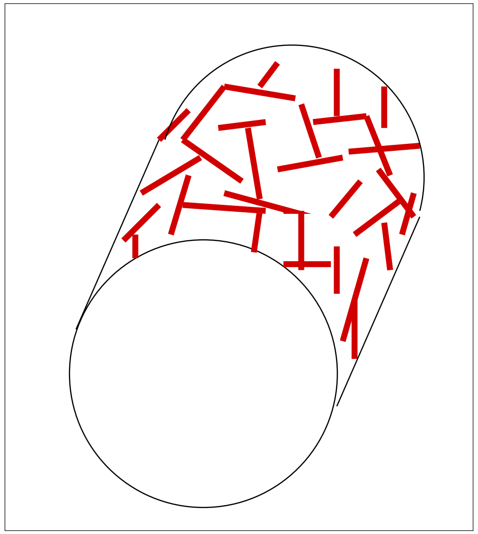
The driving physics: charge conservation in hadronization. Suppress short range correlations – BEC and conversion e^+e^- – by a kinematic pair cut. The $\bar{N}\times$ is good when number of correlation sources $\propto N$.

14 Modified hadronization geometry ?

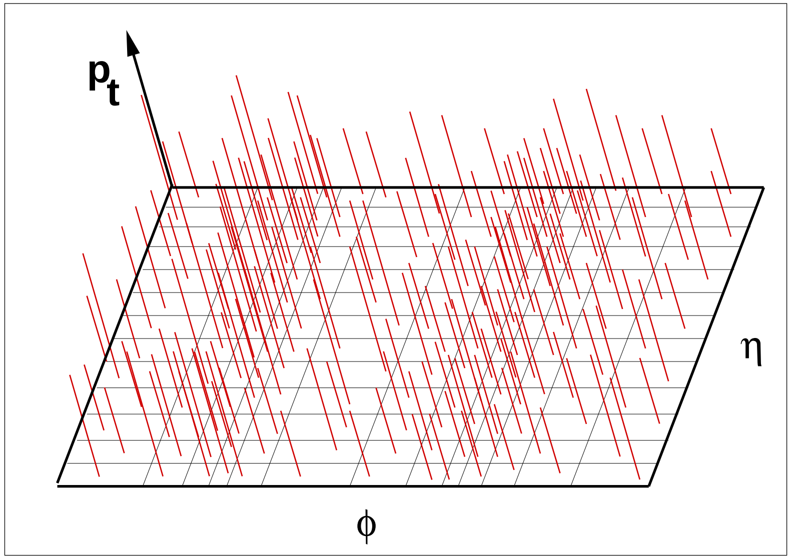


Projections of $\bar{N}(\rho(\eta_\Delta,\phi_\Delta)/\rho(\eta_\Delta,\phi_\Delta)_{\text{ref}}-1)|_{CD}$ on x_Δ which is ϕ_Δ (Δ) or η_Δ (●). $\eta-\phi$ width disparity (d, peripheral) is gone in (a) $\Rightarrow$ transition from (string) 1D to bulk (>2D) fragmentation symmetrizes η and ϕ.

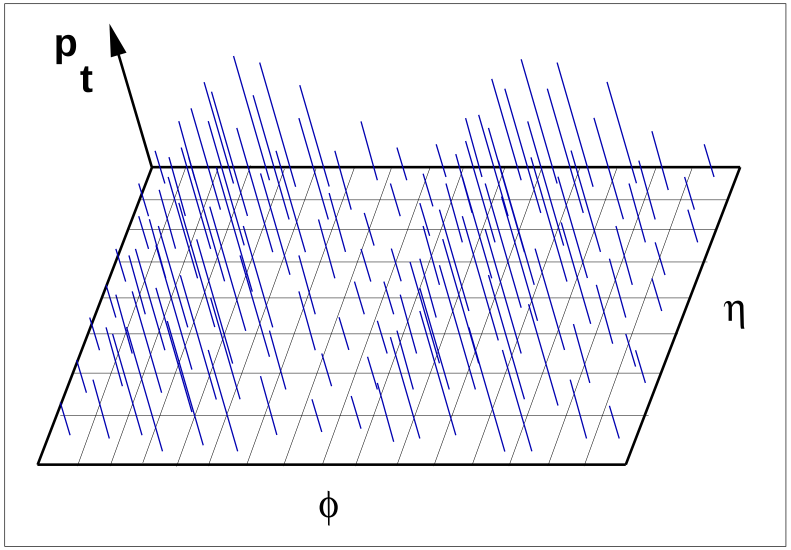




15 Number and p_t correlations



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 ?

16 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.

Solution: use $p_t - n\hat{p}_t$

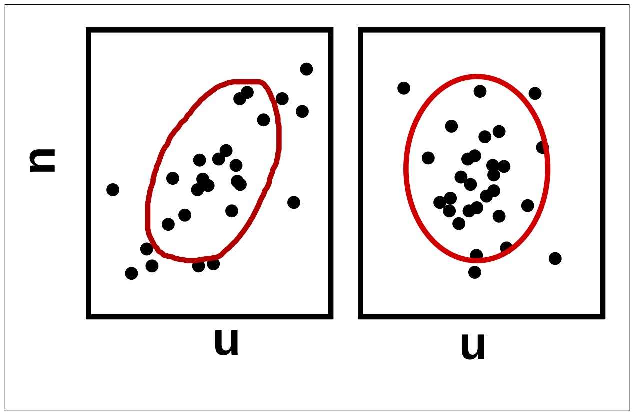
Q:When is the n-contribution into $\mathrm{Var}[p_t - n\hat{p}_t]$ canceled ?

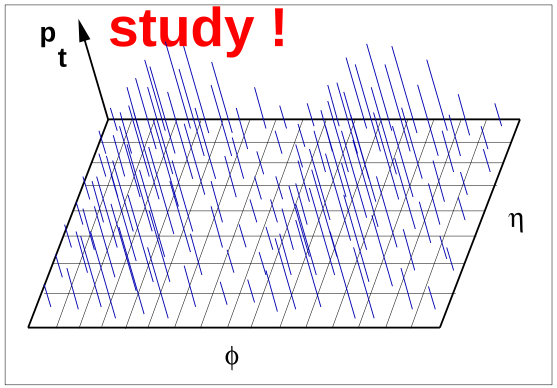
$$\sigma^2(p_t : n) \equiv \mathrm{Var}[p_t - n\hat{p}_t] = \mathrm{Var}[p_t] + \hat{p}_t{}^2\mathrm{Var}[n] - 2\hat{p}_t\mathrm{Cov}[n, p_t] \tag{5}$$

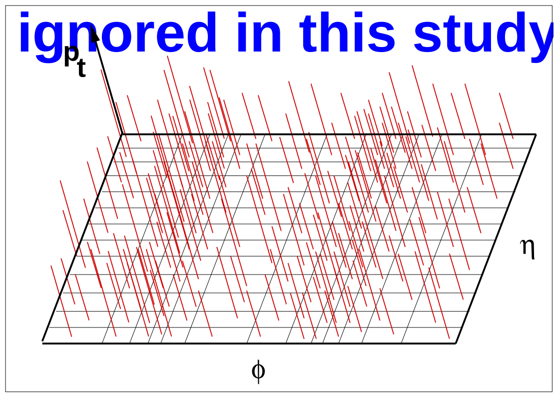
$$\mathrm{Var}[p_t] = \mathrm{Var}[\sum_i^n p_{t,i}] = \mathrm{Var}[\sum_i^n (\hat{p}_t + u_i)] = \hat{p}_t{}^2\mathrm{Var}[n] + \mathrm{Var}[u] + 2\hat{p}_t\mathrm{Cov}[n, u] \tag{6}$$

$$\mathrm{Cov}[n, p_t] = \overline{np_t} - \bar{n}\bar{p_t} = \hat{p}_t\mathrm{Var}[n] \tag{7}$$

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

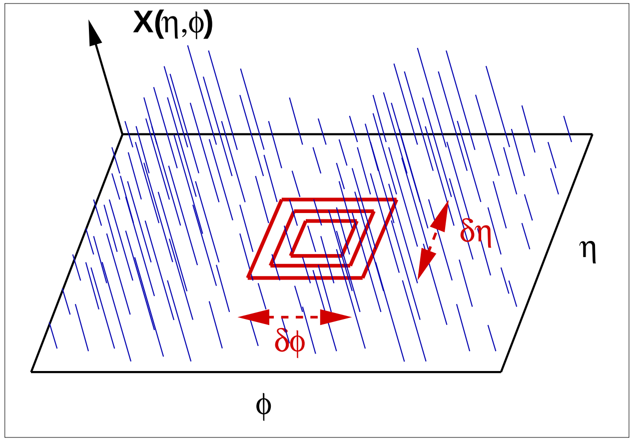






17 Get correlations from fluctuations

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)



$$\mathrm{Var}[X;\delta\eta,\delta\phi] = \int_{-\delta\eta/2}^{\delta\eta/2} d\eta_1 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_1 \int_{-\delta\eta/2}^{\delta\eta/2} d\eta_2 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_2 \qquad (8)$$

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

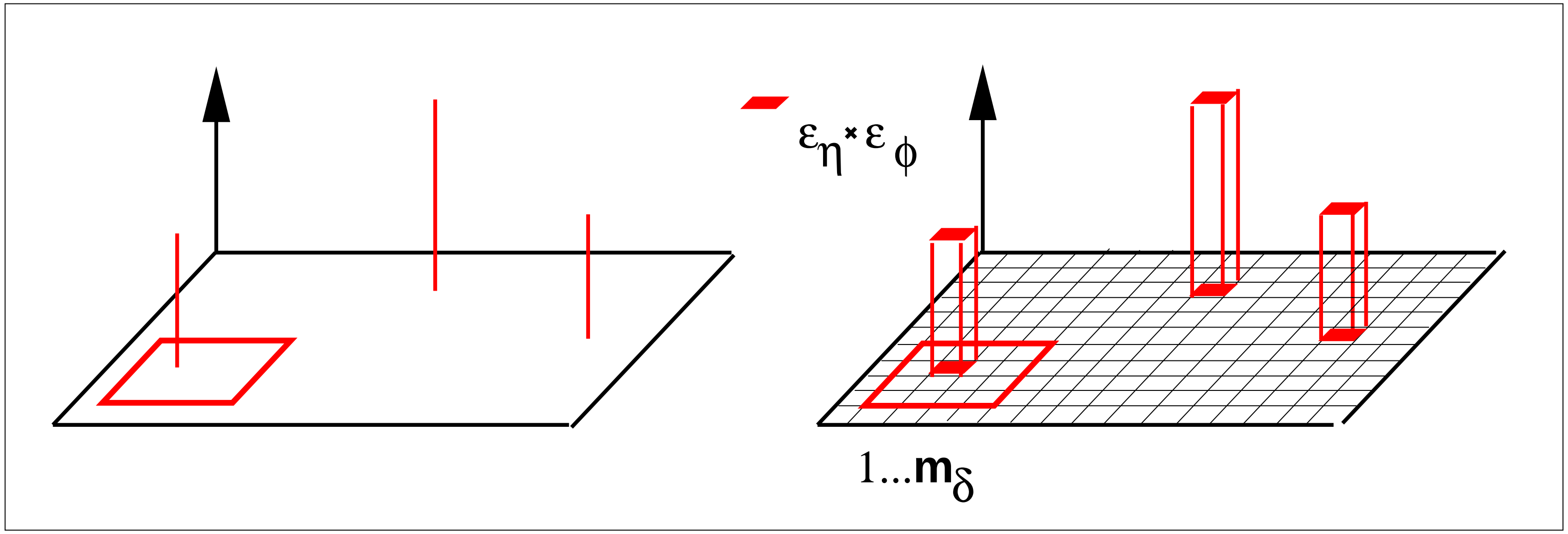
Compare with uncorrelated reference; recognize autocorrelation $\rho(X,t_\Delta) \equiv \overline{X(t)X(t+t_\Delta)}$ (t-average).

$$\Delta\sigma^2(X,\delta\eta,\delta\phi) = \qquad (9)$$

$$\int_{-\delta\eta/2}^{\delta\eta/2} d\eta_1 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_1 \int_{-\delta\eta/2}^{\delta\eta/2} d\eta_2 \int_{-\delta\phi/2}^{\delta\phi/2} d\phi_2 \Delta\rho(X,\eta_1-\eta_2,\phi_1-\phi_2) \qquad (10)$$

$$= 2\int_0^{\delta\eta} d\eta_\Delta 2\int_0^{\delta\phi} d\phi_\Delta(\delta\eta-\eta_\Delta)(\delta\phi-\phi_\Delta)\Delta\rho(X,\eta_\Delta,\phi_\Delta) \qquad (11)$$

18 The actual analysis is discrete: $\int \to \sum$



kernel K:

$$(\delta\eta - \eta_\Delta)(\delta\phi - \phi_\Delta) \to \varepsilon_\eta\varepsilon_\phi K_{m_\delta n_\delta : kl} \equiv \varepsilon_\eta\varepsilon_\phi(m_\delta - k + \frac{1}{2})(n_\delta - l + \frac{1}{2}) \qquad (12)$$

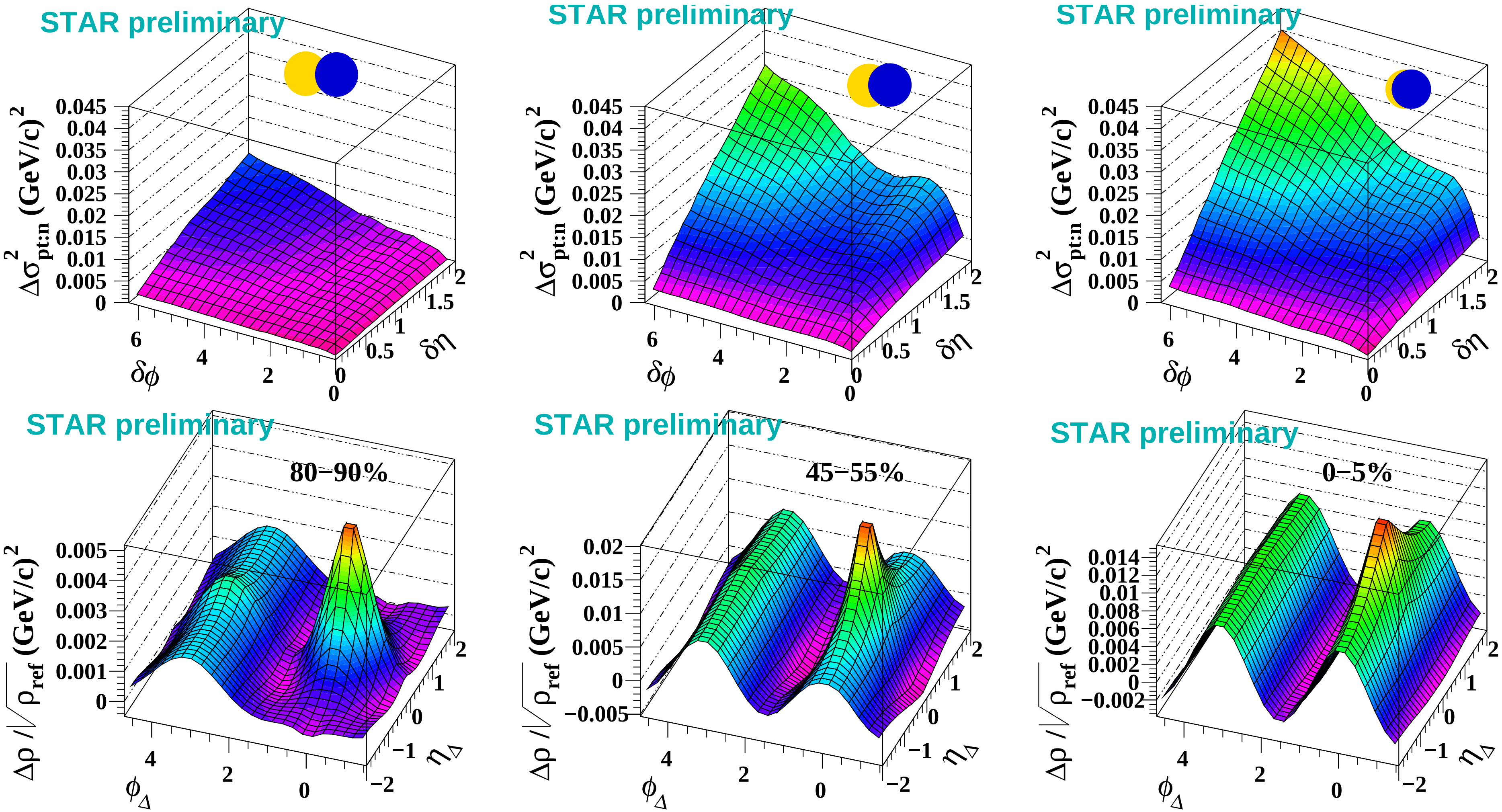
reference density ρ_{ref} makes a per-particle measure:

$$\rho_{\text{ref}} \propto \bar{n}^2 \Rightarrow \frac{1}{\sqrt{\rho_{\text{ref}}}} \propto \frac{1}{\bar{n}} \qquad (13)$$

$$\Delta\sigma^2_{p_t:n}(m_\delta\varepsilon_\eta, n_\delta\varepsilon_\phi) = 4\sum_{k,l=1}^{m_\delta, n_\delta} \varepsilon_\eta\varepsilon_\phi K_{m_\delta n_\delta : kl} \frac{\Delta\rho(p_t : n; k\varepsilon_\eta, l\varepsilon_\phi)}{\sqrt{\rho_{\text{ref}}(n; k\varepsilon_\eta, l\varepsilon_\phi)}} \qquad (14)$$

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

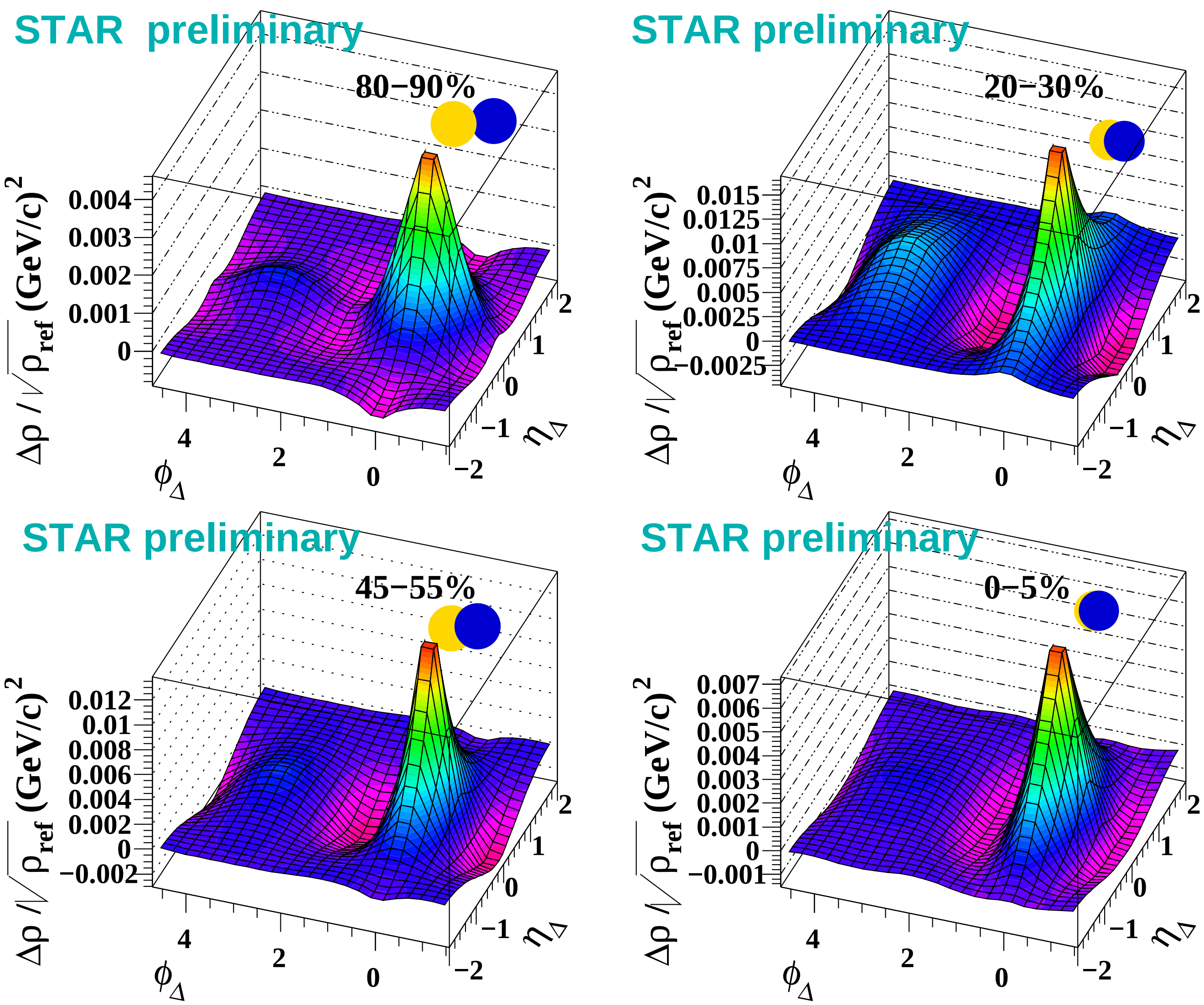
19 p_t correlations from the inversion



Top:
scale dependence of the "pure" p_t variance.
Bottom:
corresponding autocorrelation

First direct evidence of elliptic flow as a p_t blast. Next, subtract the flow contribution to look at minijets.

20 Localized p_t correlations: minijets



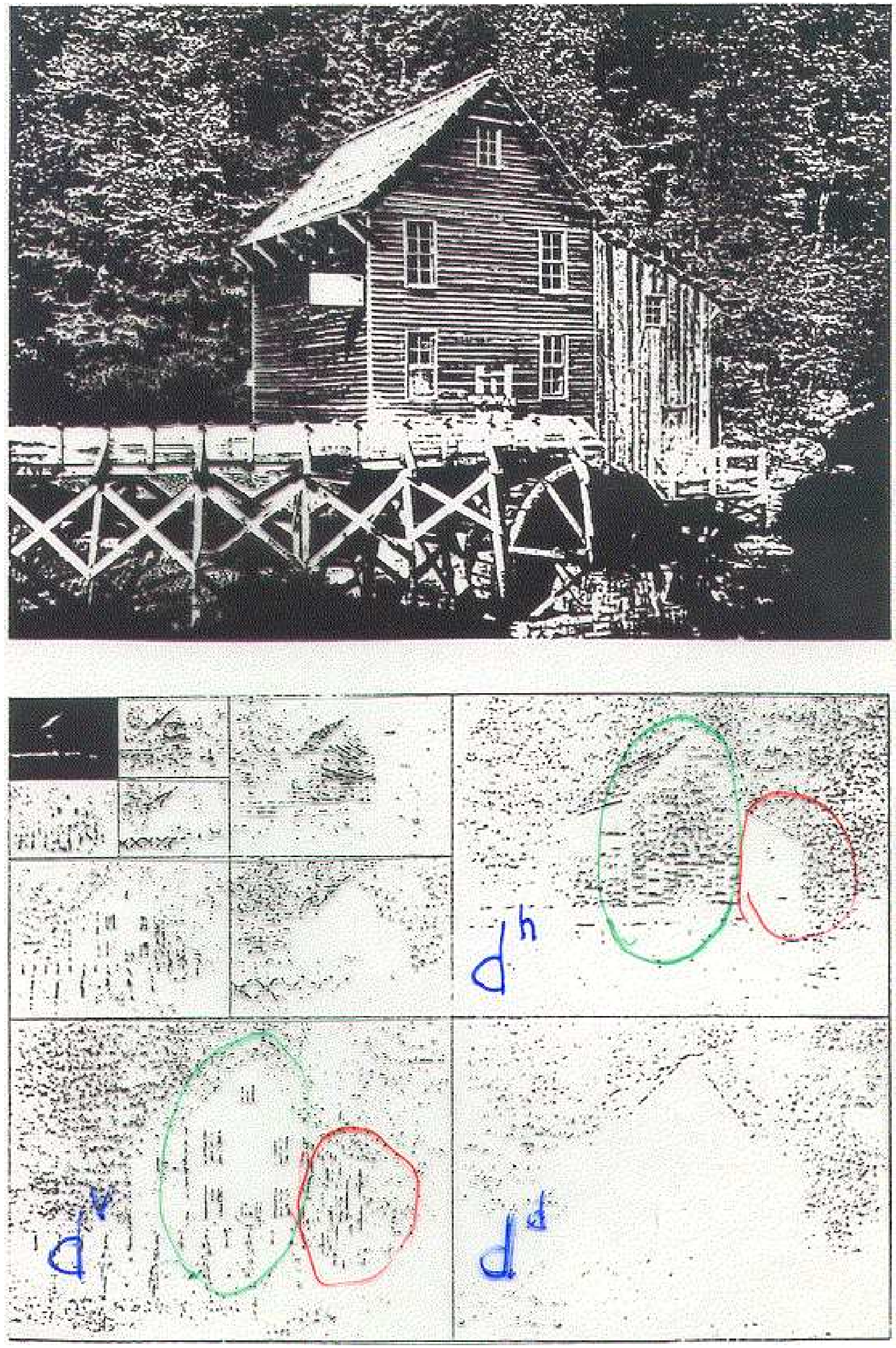
AuAu 200 GeV. In η, correlation broadens with centrality; in ϕ the trend is opposite. The surrounding background seems to recoil.

21 Conclusions

- Semi-hard scattering leaves a trace in the soft p_t domain – new at RHIC !
- First direct measurements of p_t correlation structure reveal azimuthal anisotropy of p_t field $\Rightarrow$ elliptic flow is a velocity phenomenon
- The minijet correlation structure is modified with centrality; the effect appears to "turn on" around $\nu = (N_{\text{part}}/2)^{1/3} \approx 3$. Broadening of the correlation in η and weakening of P^{η}_{dyn} on the coarse scale are consistent descriptions of the effect. 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

22 Extra slides

23 DWT of a photographic image



Reproduced from textbook: I.Daubechies, "Ten lectures on wavelets". The original caption: "A real image, and its wavelet decomposition into three multiresolution layers. On the wavelet components one clearly sees that the $d^{j,v}$,$d^{j,h}$,$d^{j,d}$ emphasize, respectively, vertical, horizontal, and diagonal edges. In this figure, the bottom picture has been overexposed to make details in the $d^{j,\lambda}$ more apparent. I would like to thank M.Barlaud for providing this figure." The colored marks are mine.