Early stage of RHIC collisions and its equilibration: a story told by correlations

BNL Nuclear Physics Seminar

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The STAR Collaboration:

Argonne NL, U.Bern, U.Birmingham, Broohaven NL, Caltech, UC Berkeley, UC Davis, UCLA, Carnegie Mellon U., Creighton U., NPI AS Chech Republic, LHI JINR, PPL JINR, U. Frankfurt, IP Bhubaneswar, IIT Mumbai, Indiana U., IRS Strasbourg, U. Jammu, Kent State U., Lawrence Berkeley NL, MIT, Max-Plank-Instutut, MSU, MEPhI, City College of NY, NIKHEF, Ohio State U, Panjab U., Penn State U., IHEP Protvino, Purdue U., U. Rajasthan, Rice U., U. Sao Paolo, UST China, Shanghai IAP, SUBATECH, Texas A&M U., U. Texas, Tsinghua U., Valparaiso U., VECC Kolkata, Warsaw UT, U. Washington, Wayne State U, IPP CCNU (HZNU) Wuhan, Yale U., U. Zagreb

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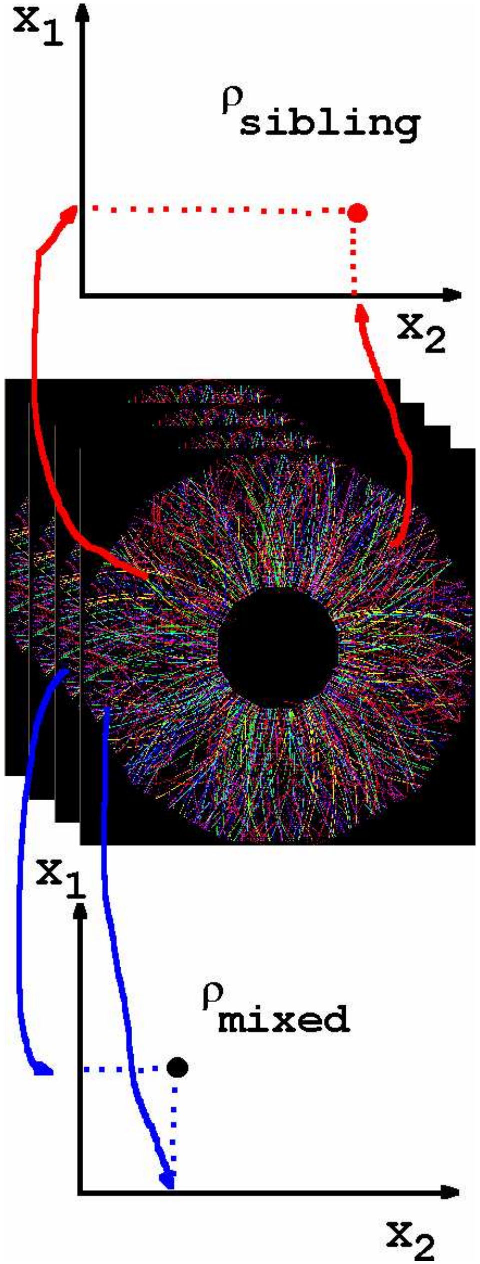

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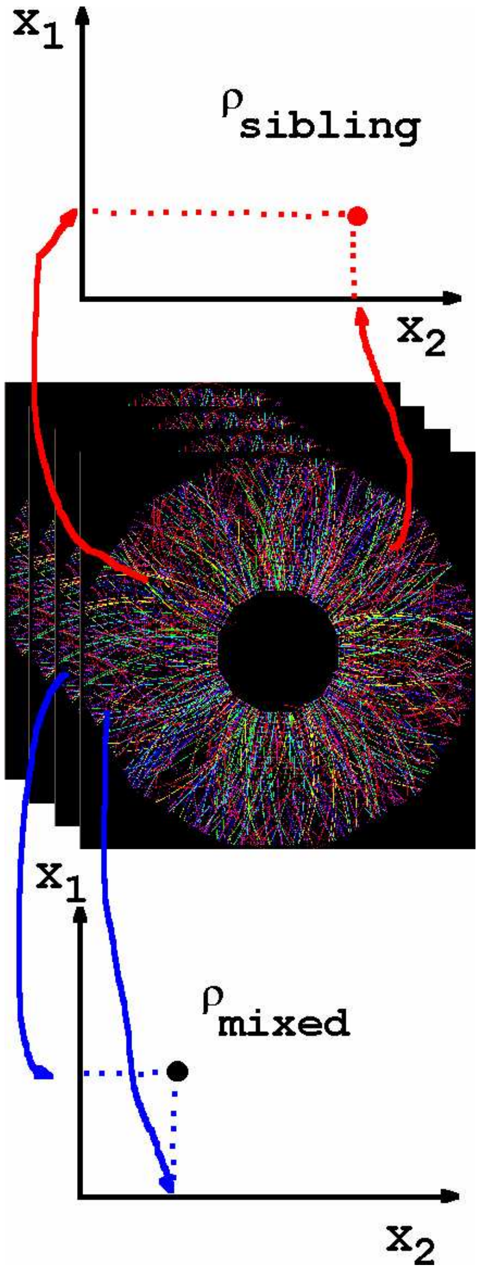
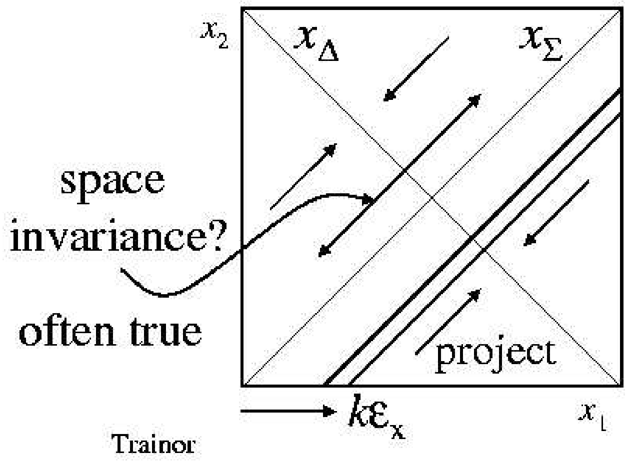


$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \rightarrow \begin{pmatrix} x_\Sigma \equiv x_1 + x_2 \\ x_\Delta \equiv x_1 - x_2 \end{pmatrix},$$

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.

$$\Delta R(x_1, x_2) = \frac{\rho_{sibling}(x_1, x_2)}{\rho_{mixed}(x_1, x_2)} - 1$$



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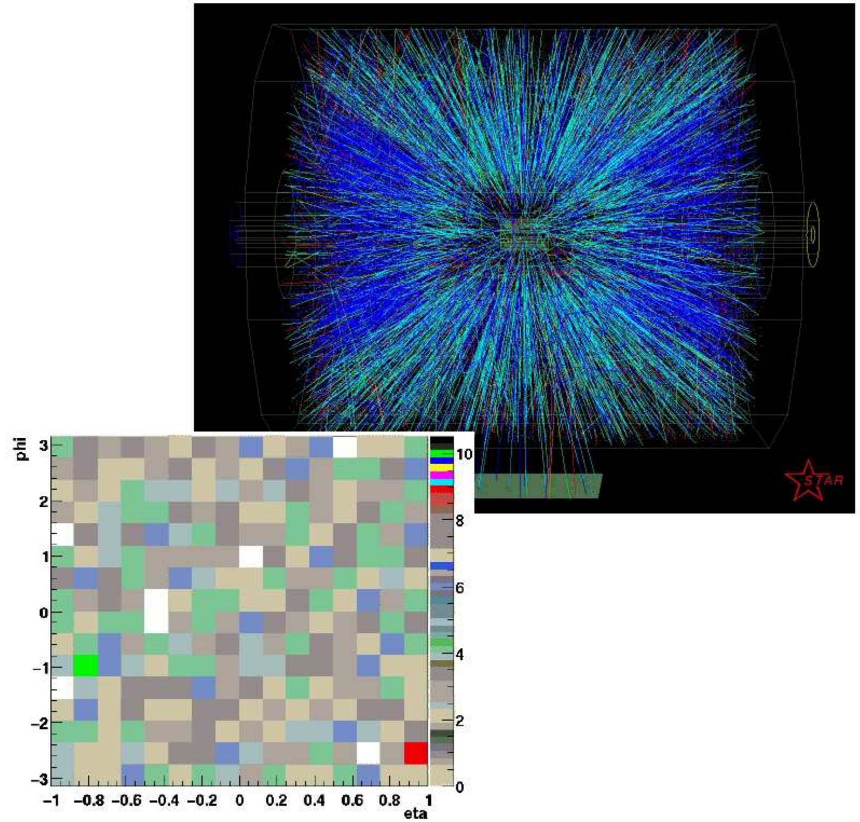

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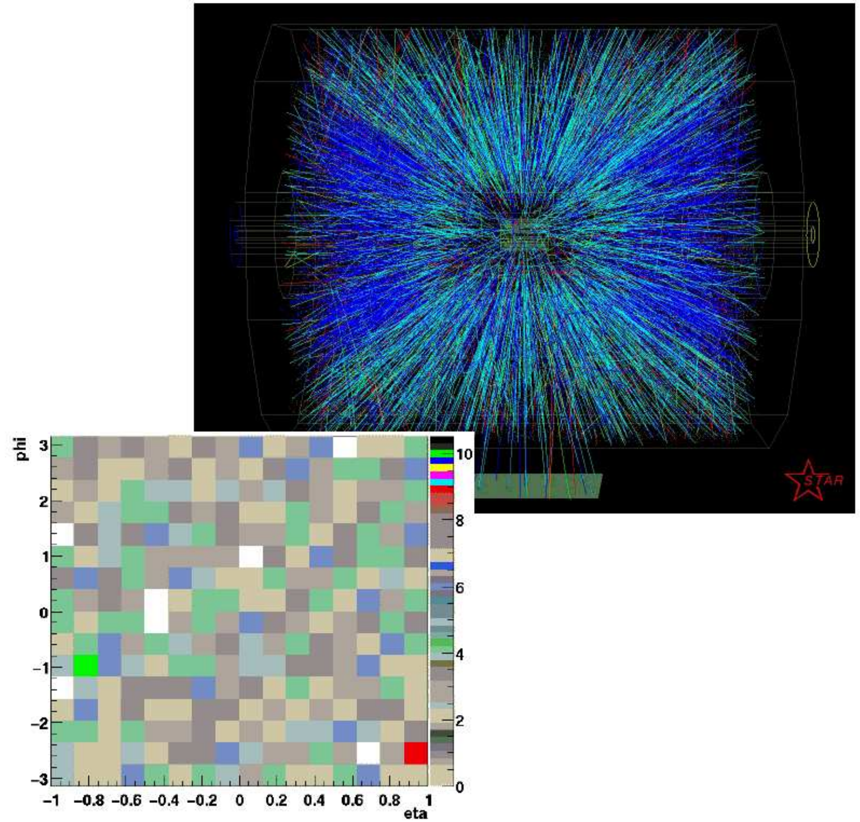

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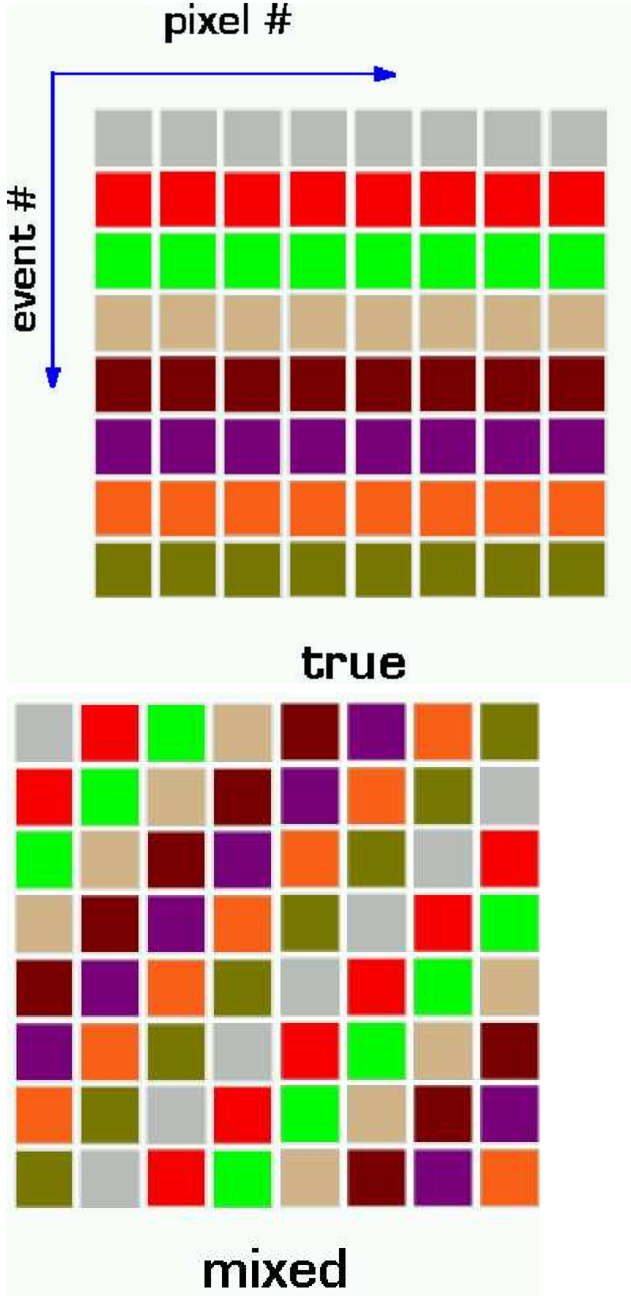

4 Discrete Wavelet Transform (DWT)

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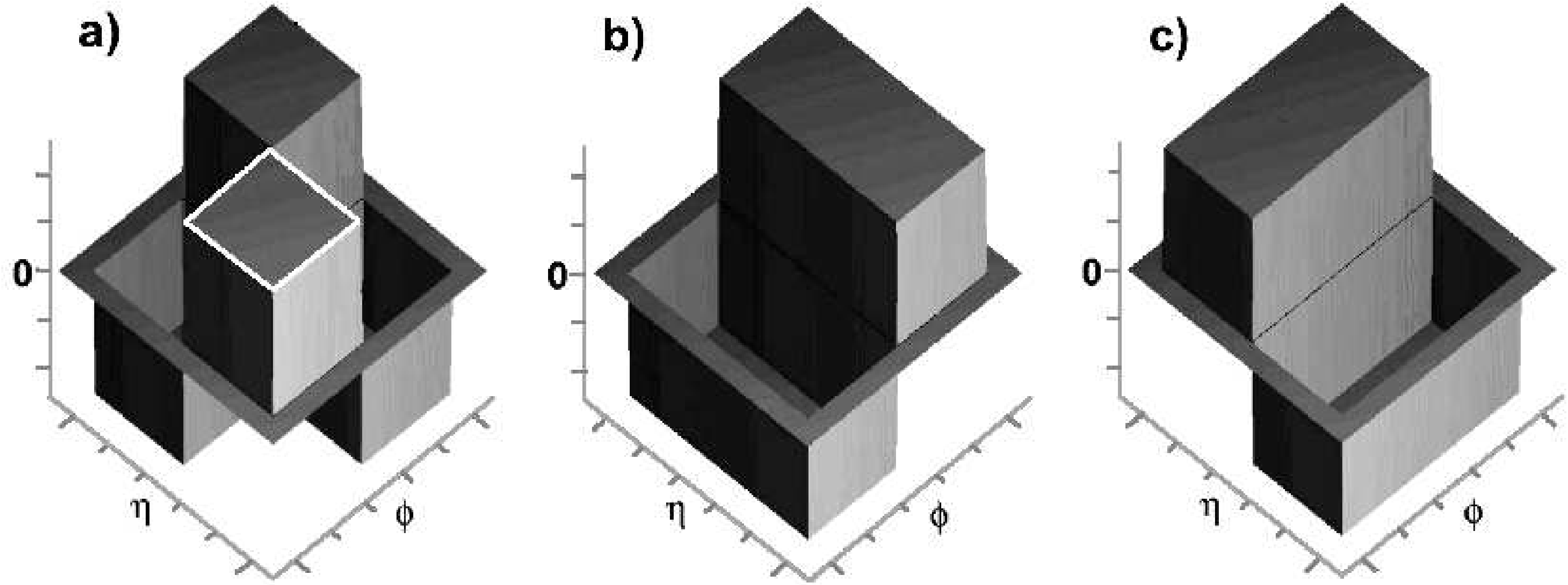

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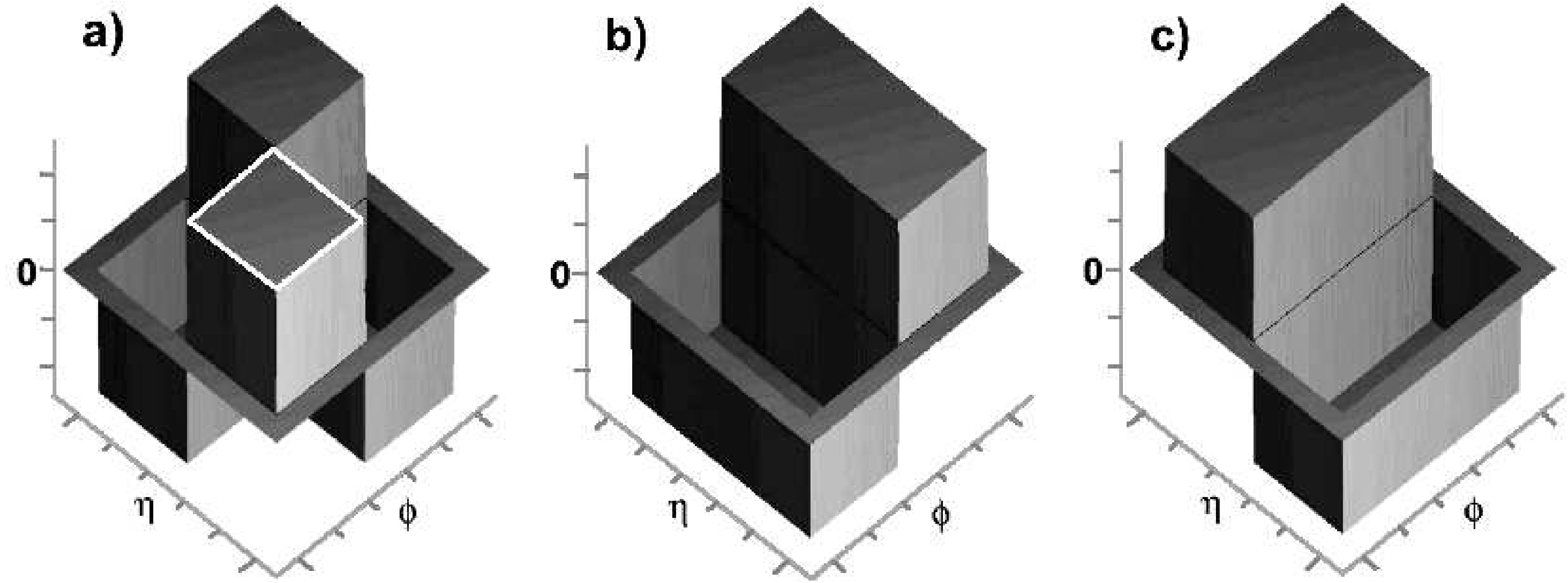

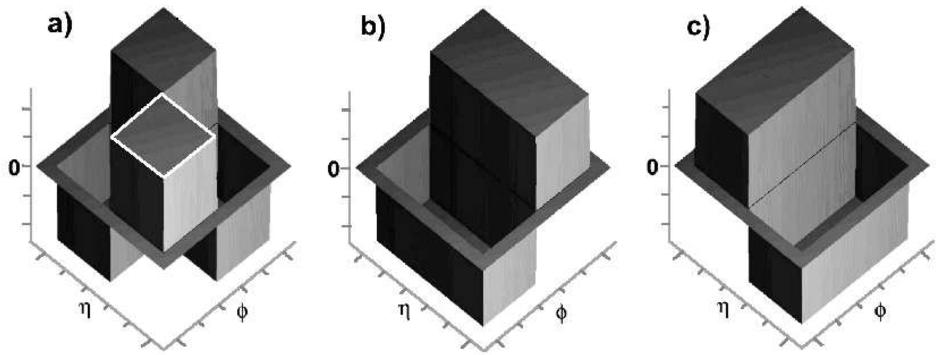

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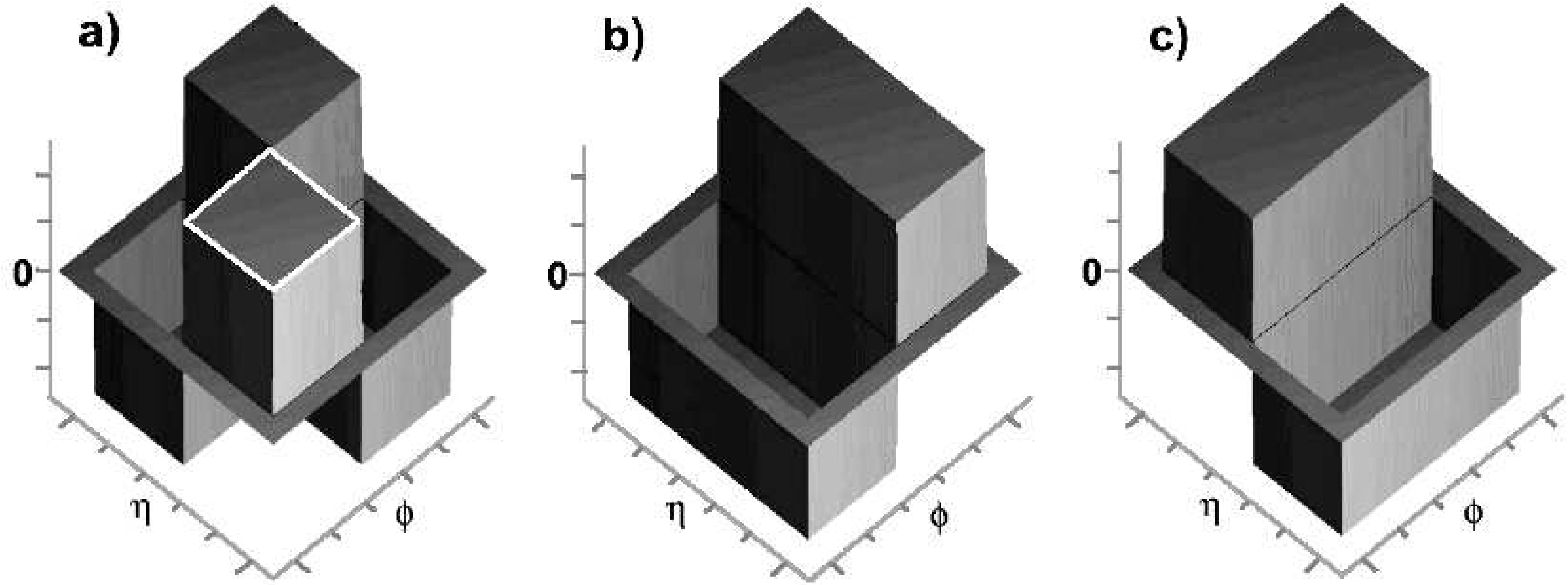

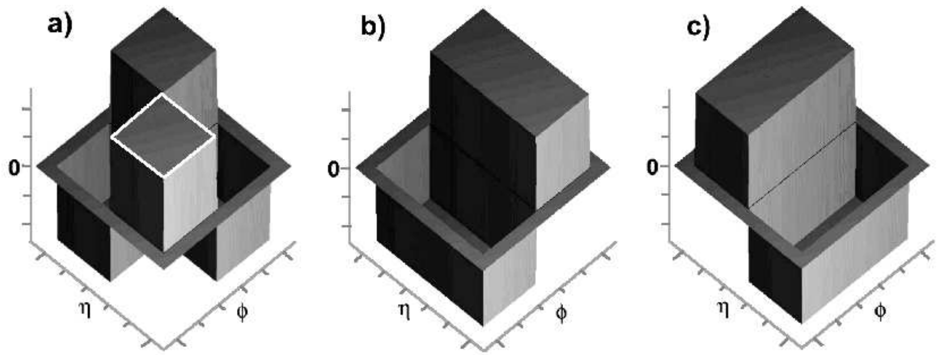

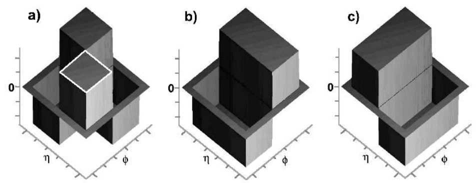

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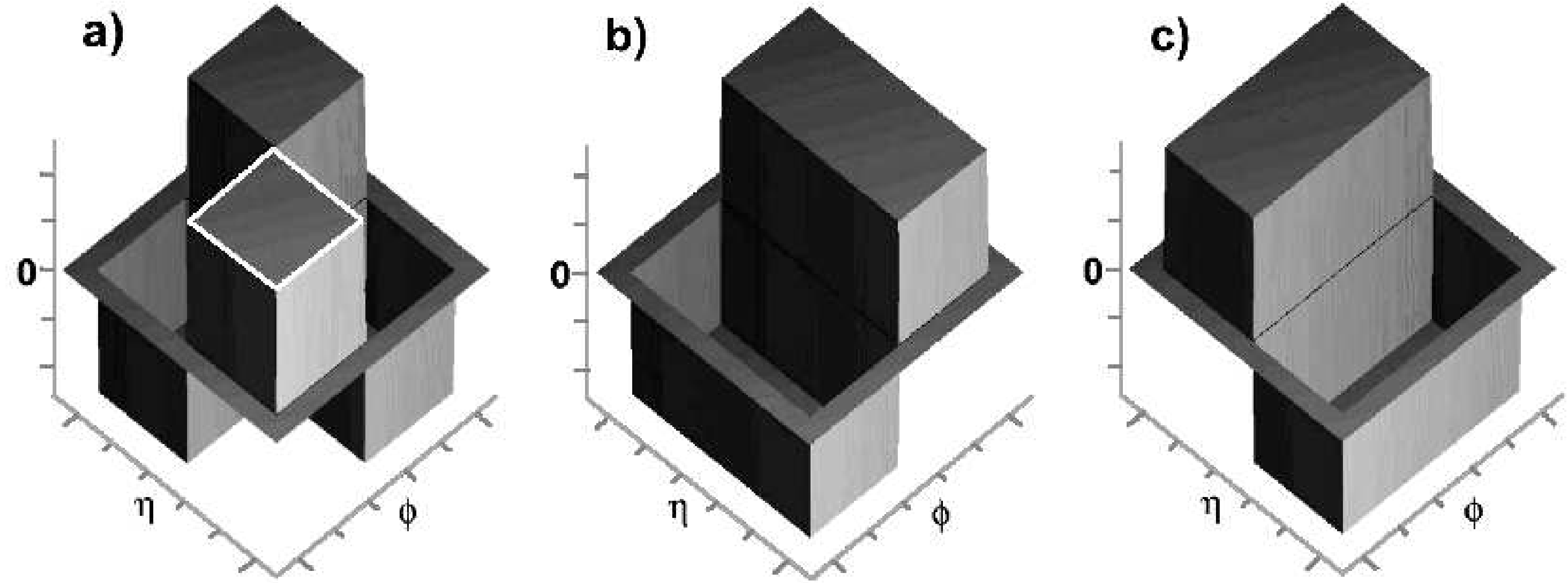

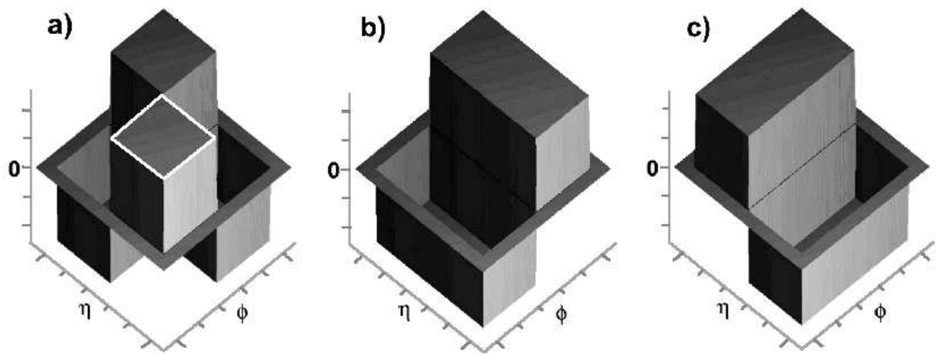

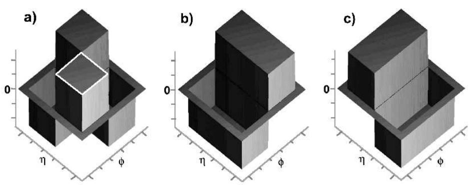

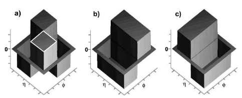

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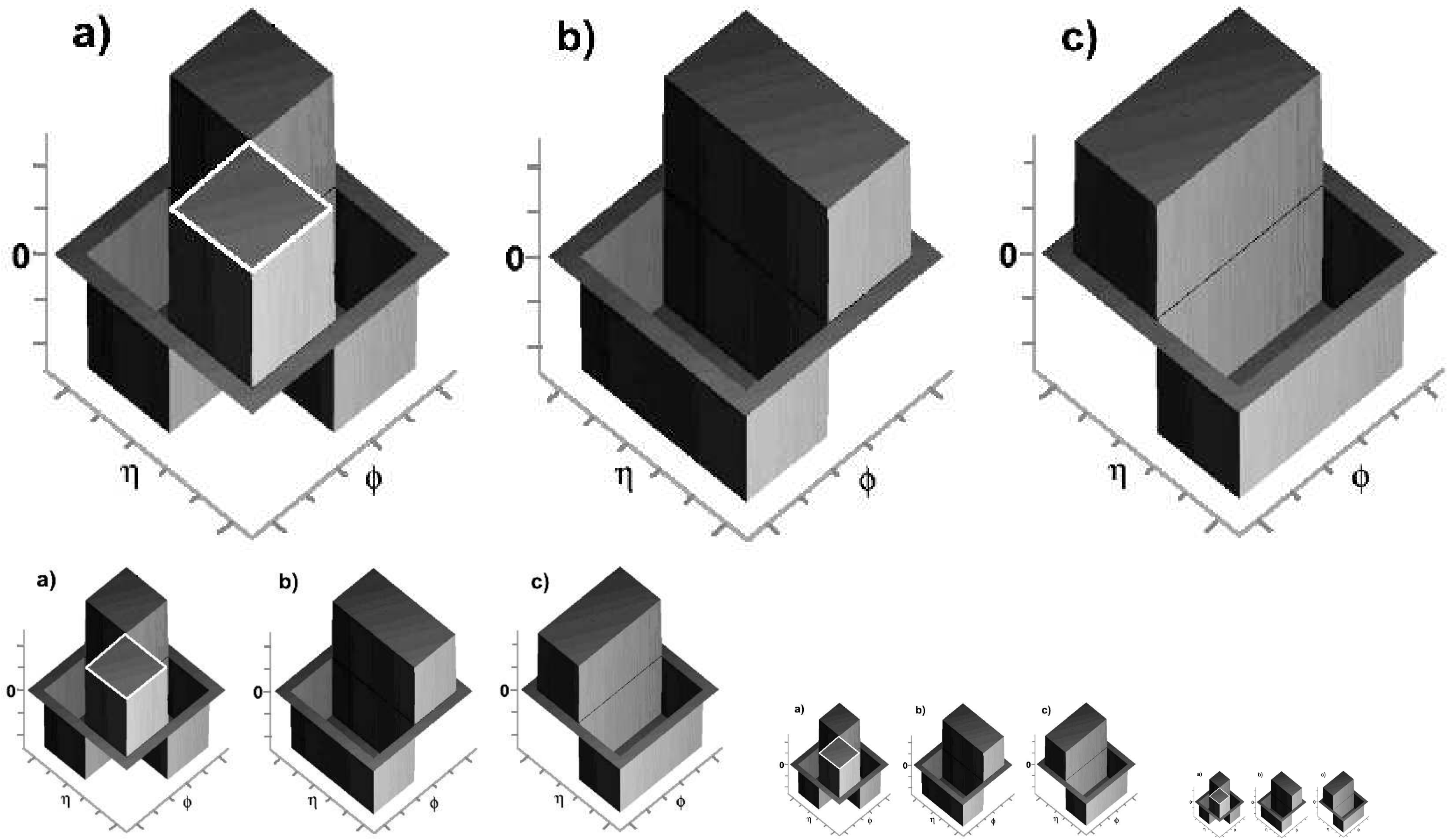

$F^{\lambda}_{m,i,j}(\phi,\eta)$–Haar wavelet **orthonormal basis** in (ϕ,η): scale fineness (m), directional modes of sensitivity (λ), track density $\rho(\eta,\phi,p_T)$, locations in 2D (i,j). **DWT is an expansion in this basis.**

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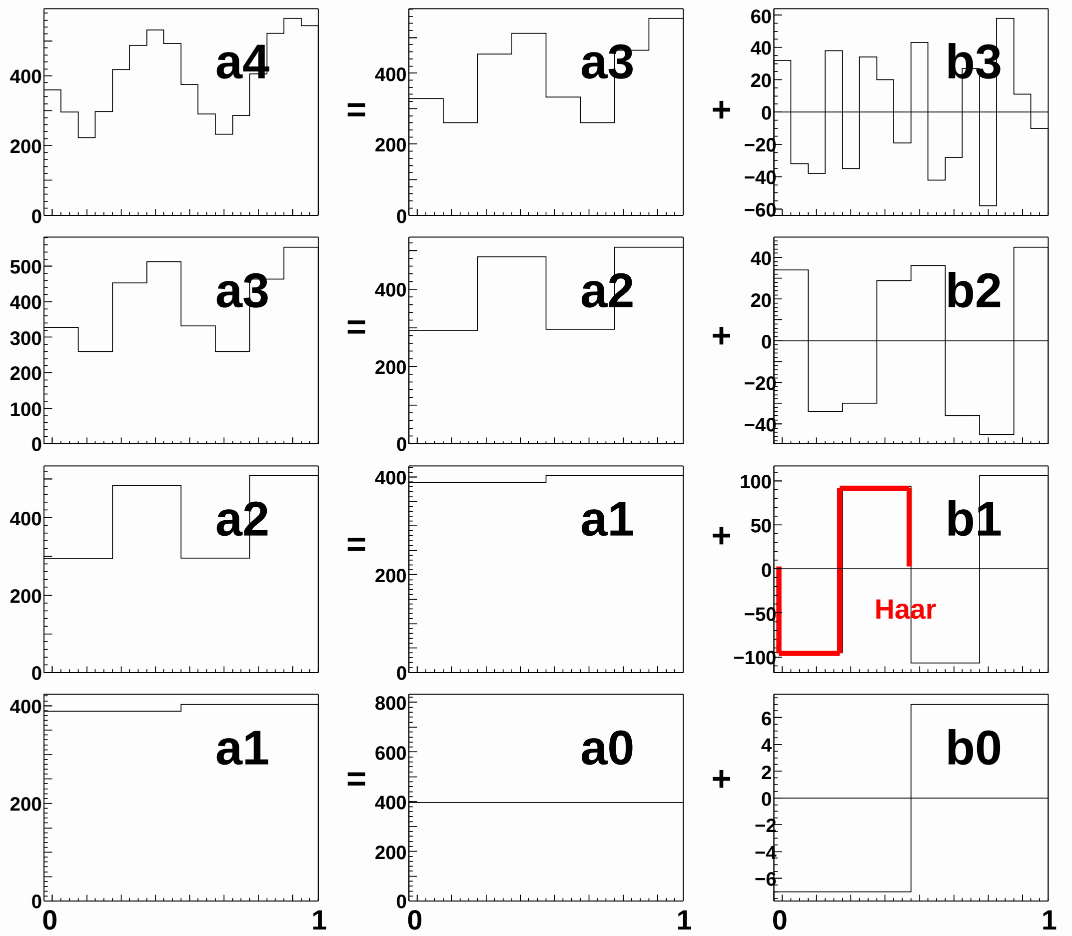

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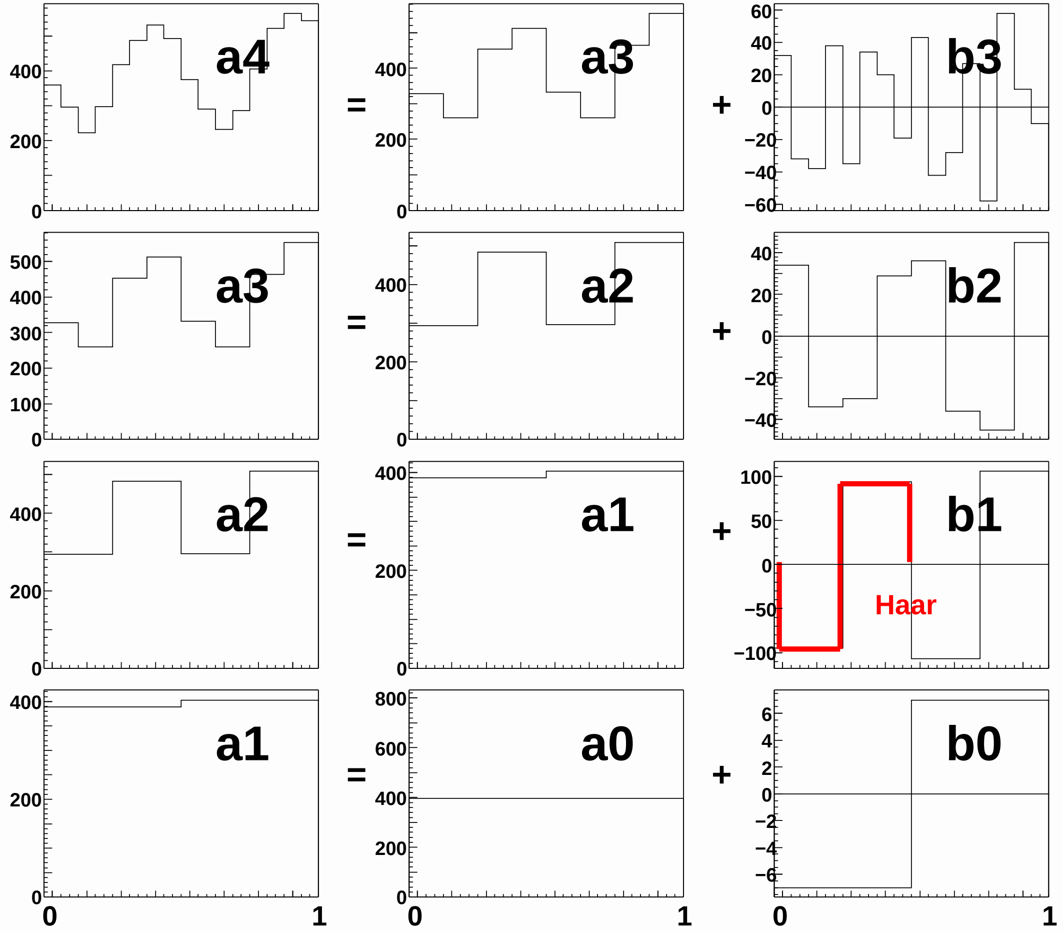
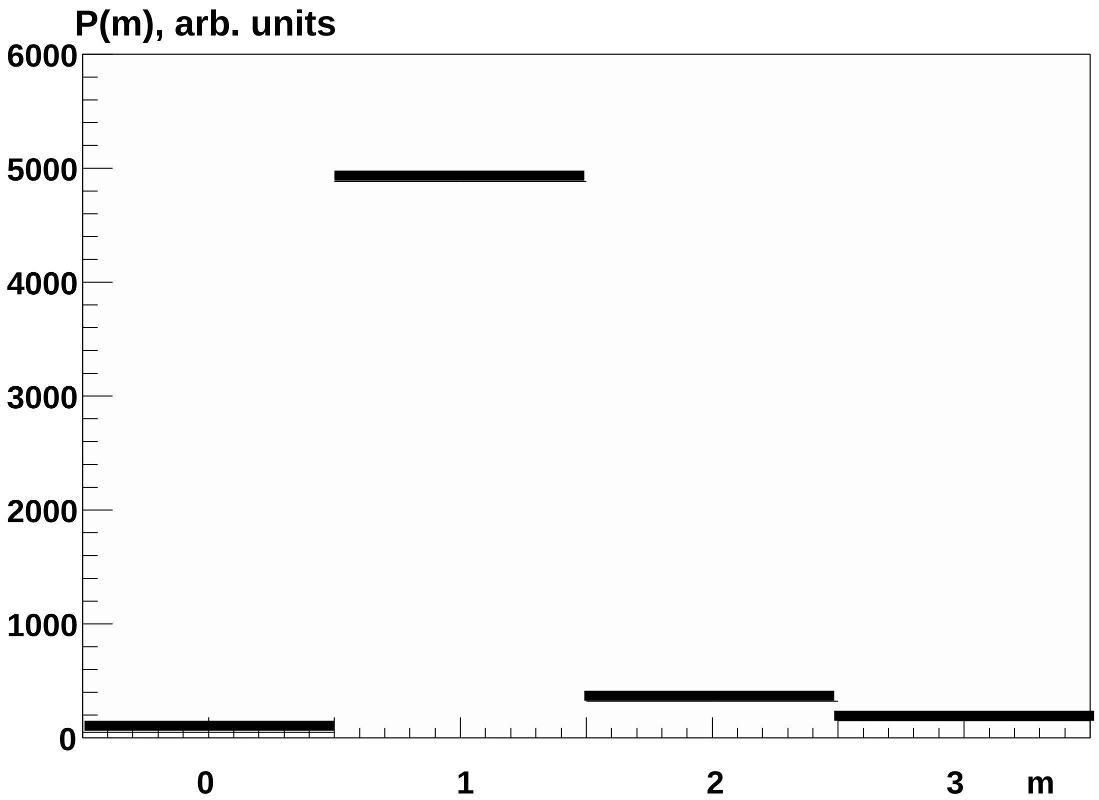


Elliptic flow-inspired example: x axis – an angle in "natural units" $(2\pi = 1)$, y axis – multiplicity. The multiresolution theorem: **a4 = a0+b0+b1+b2+b3**, can have better fineness.



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 $O(N)$!

6 DWT Power Spectra and the Hilbert Space

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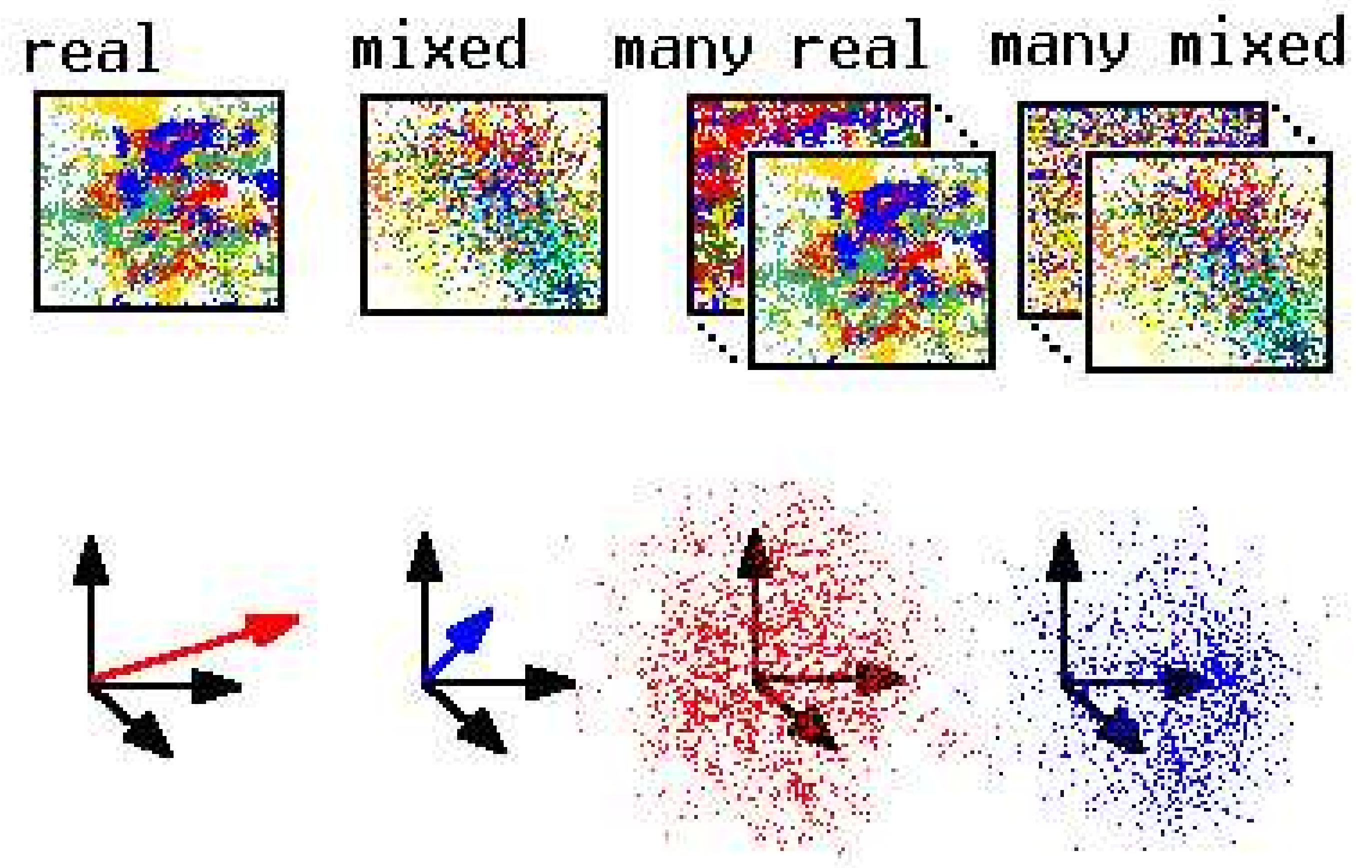

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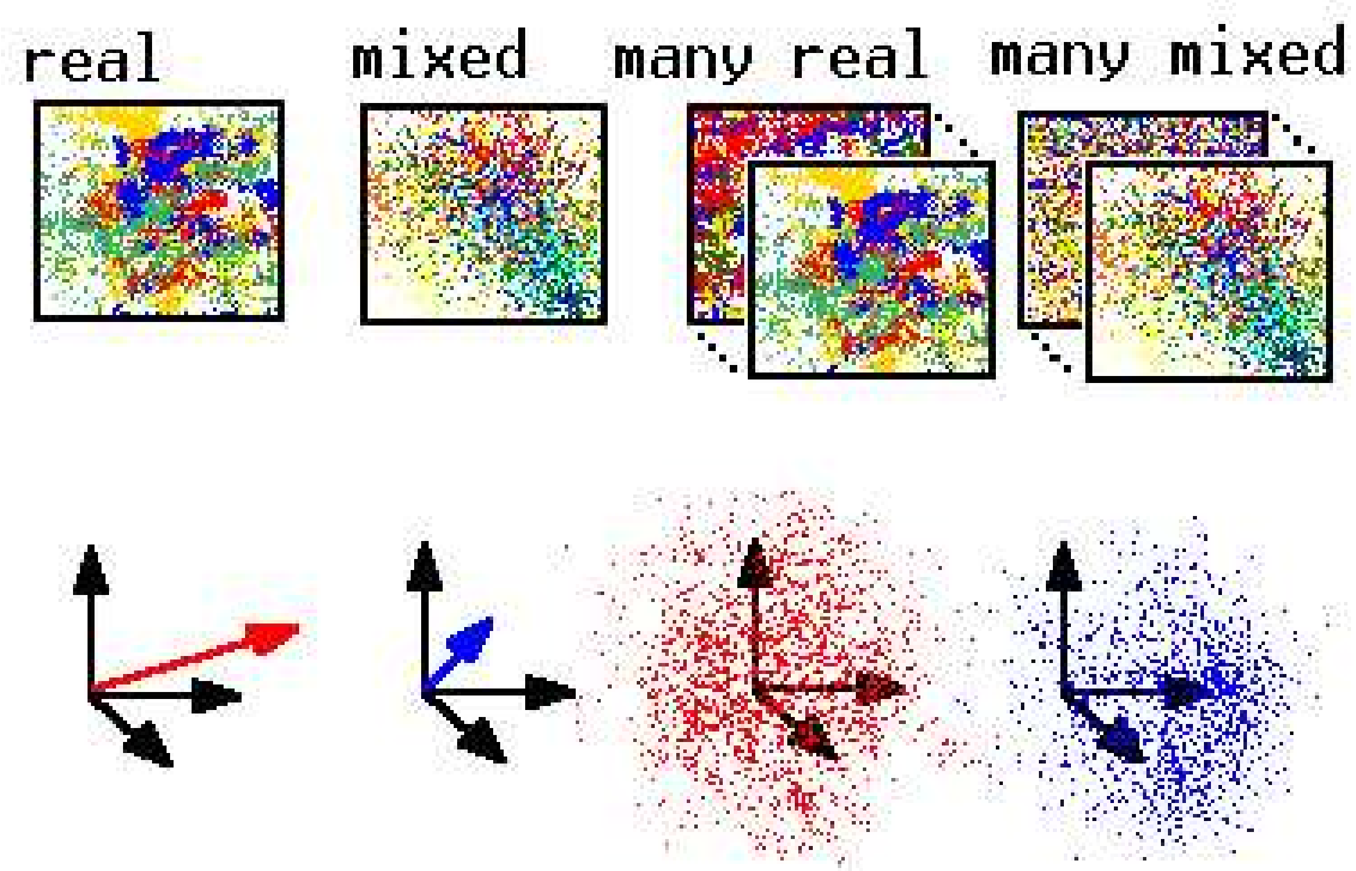

Power of local fluctuations, mode λ: $P^{\lambda}(m) = 2^{-2m} \sum_{i,j} \langle \rho, F^{\lambda}_{m,i,j} \rangle^2 \propto$ norm^2 in the DWT subspace. "Dynamic texture" $P^{\lambda}_{dyn}(m) \equiv P^{\lambda}_{true}(m) - P^{\lambda}_{mix}(m)$.

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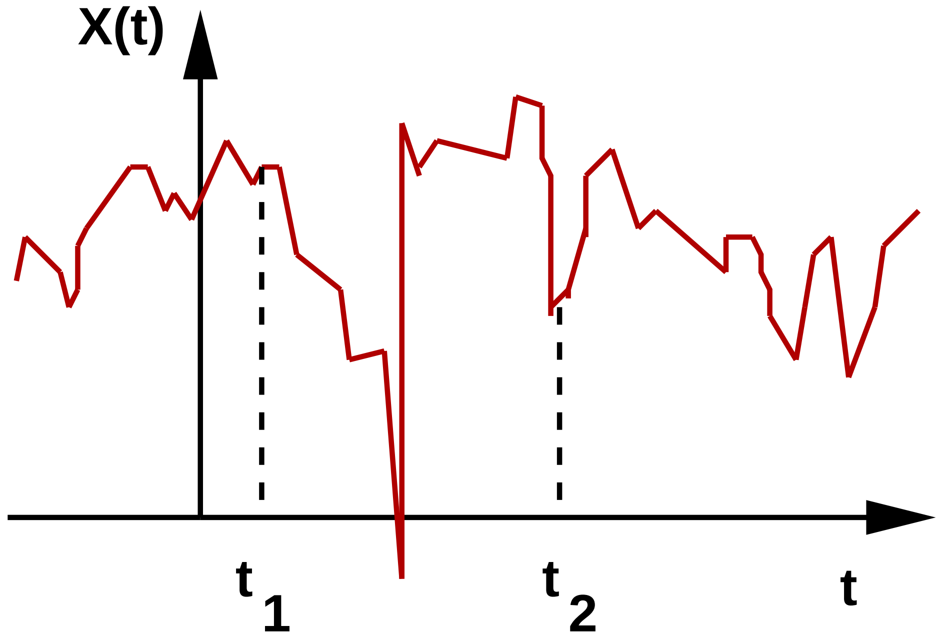

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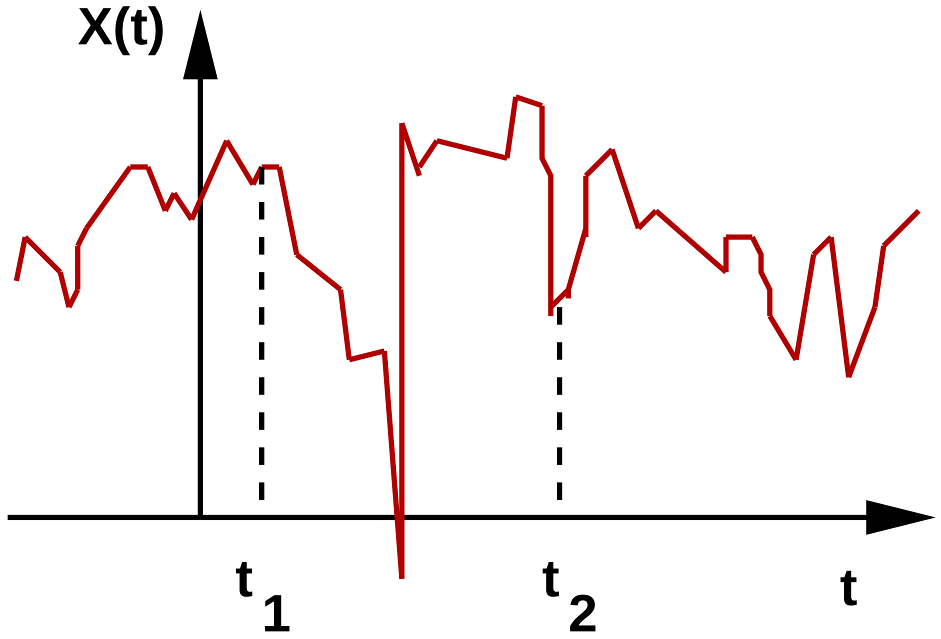

Autocorrelation

$$A(\tau) = \int_{-\infty}^{\infty} X(t)X(t+\tau)\,dt \tag{1}$$

where $\tau = t_2 - t_1$, and $X(t)$ is "homogeneous random field".

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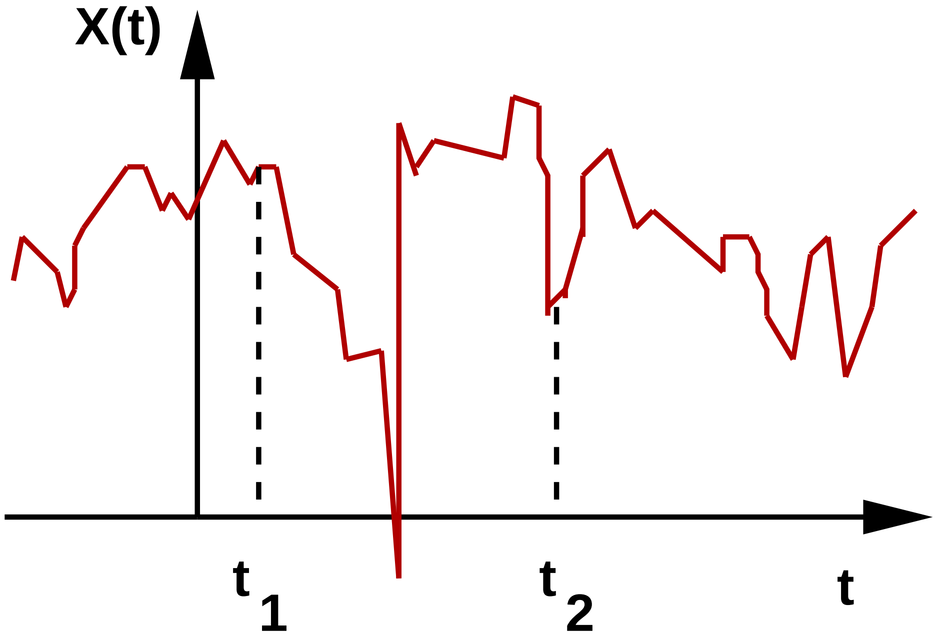

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where $\tau = t_2 - t_1$, and $X(t)$ is "homogeneous random field".

Wiener-Khinchin theorem relates $A(\tau)$ with the local fluctuation power spectrum $P(\omega)$ via Fourier transform $\mathcal{F}$.

$$\mathcal{F}_{\omega\to\tau}(P(\omega)) = A(\tau) \quad (2)$$

$$P(\omega) = \mathcal{F}_{\tau\to\omega}(A(\tau)) \quad (3)$$

$$O(N) \to O(N^2) \quad (4)$$

Prefer $O(N)$ for initial data processing for CPU reasons.

In the **Haar discrete wavelet** basis, the integral equation 3 looks different:

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

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

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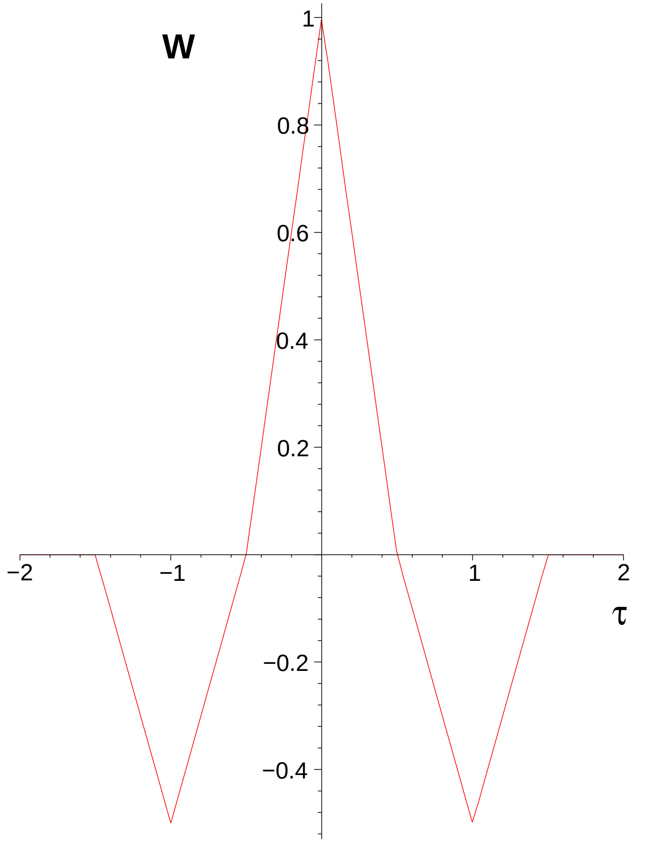

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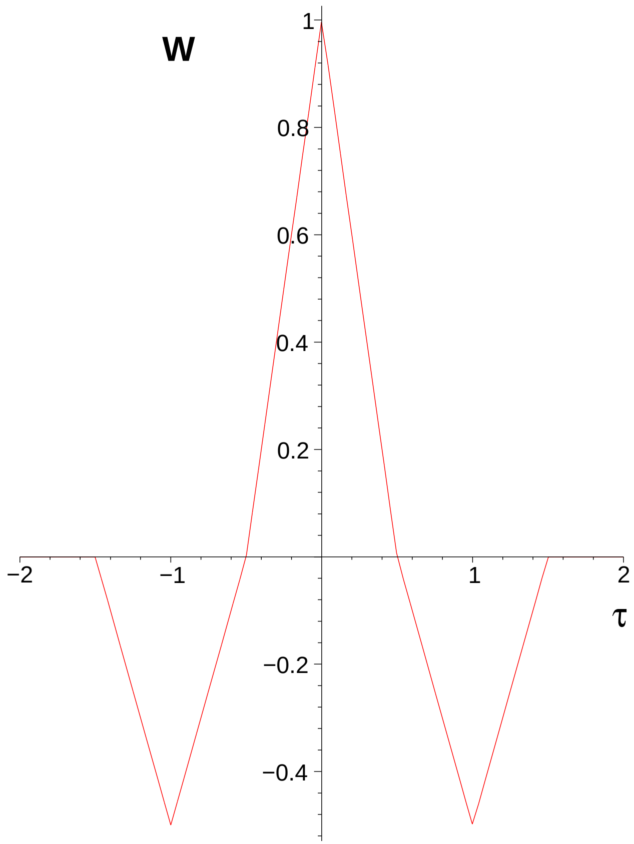

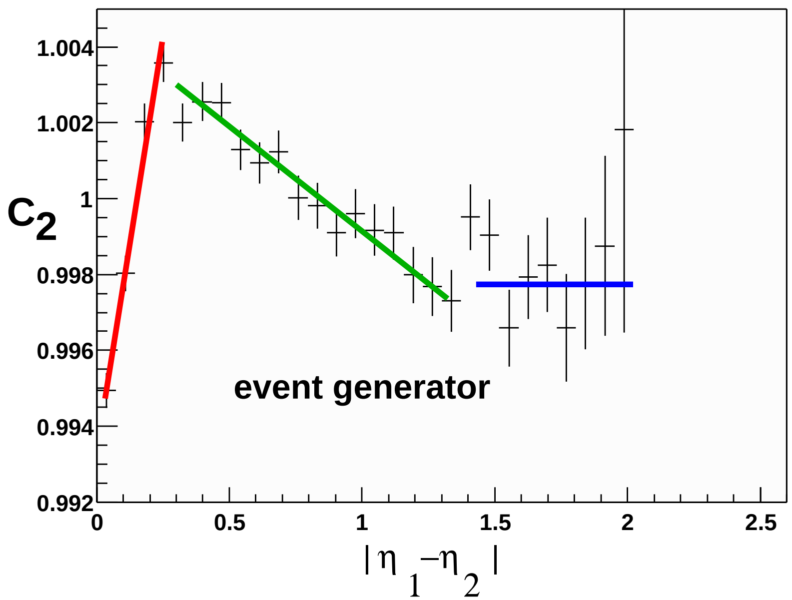

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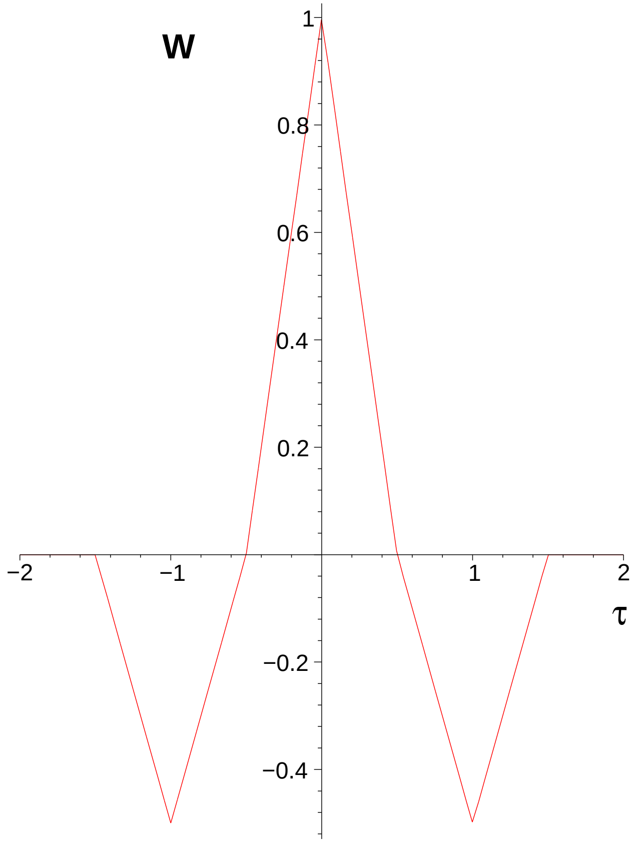

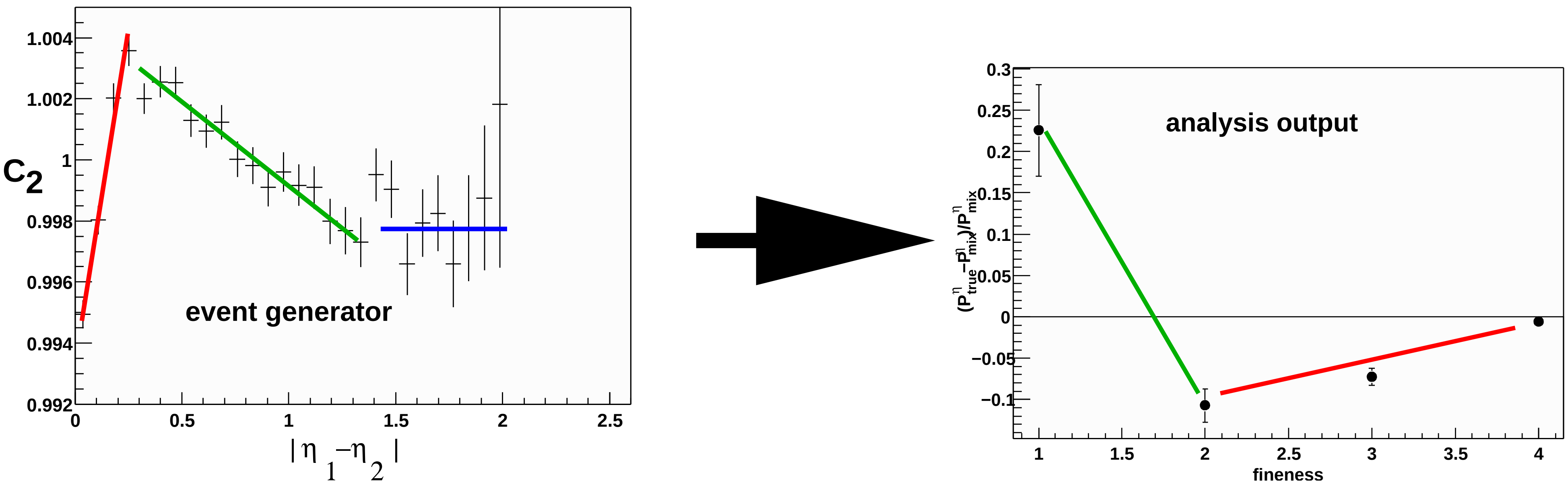

8 Centrality dependence

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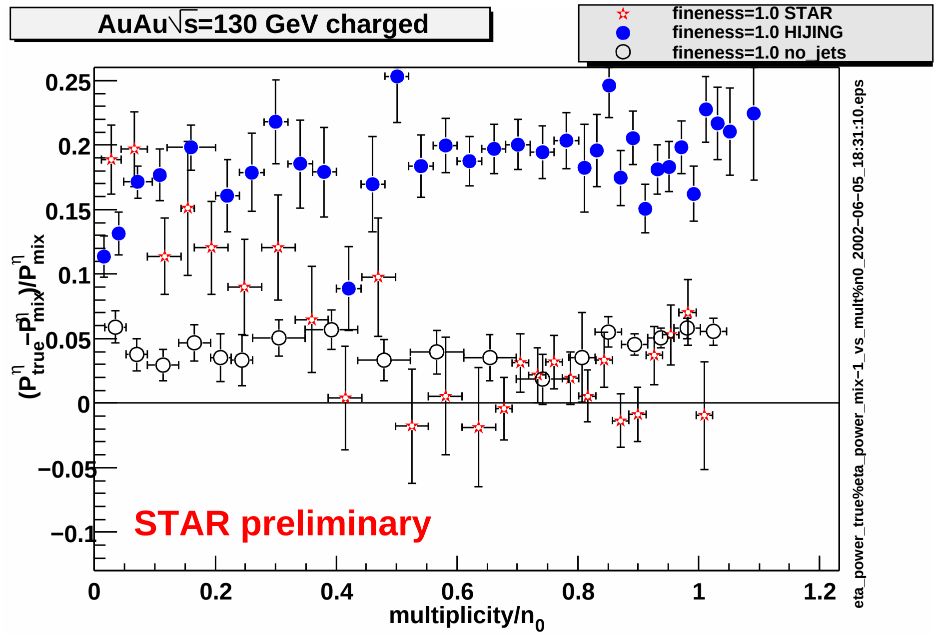
Istron Bay, Greece, June 2002, nucl-ex/0211015. STAR DWT analysis of charge-independent correlations, AuAu, $\sqrt{s_{NN}} = 130$ GeV



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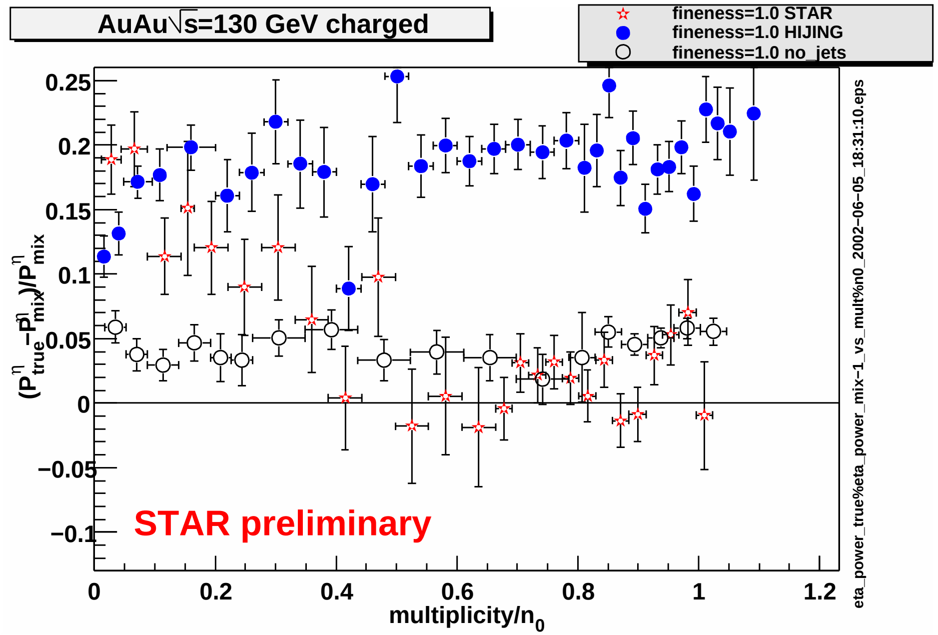

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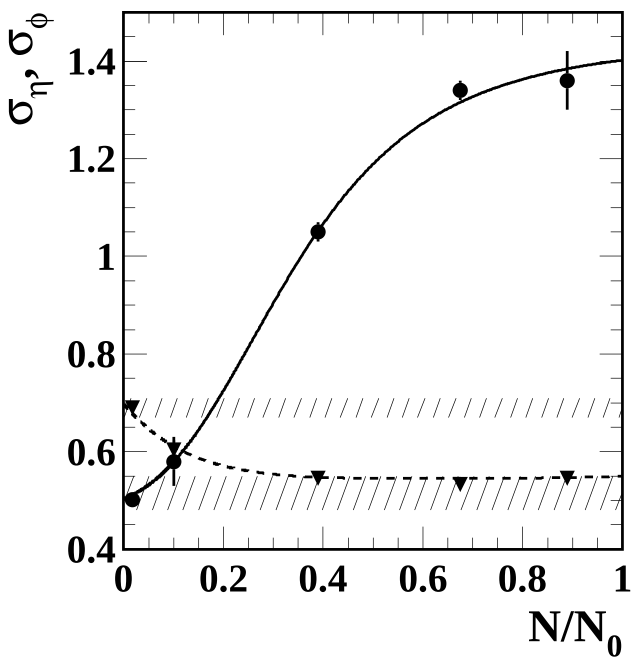
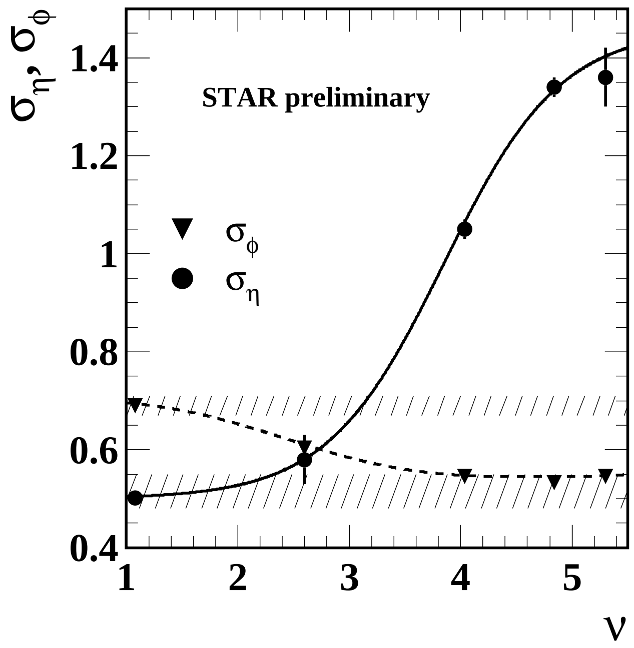
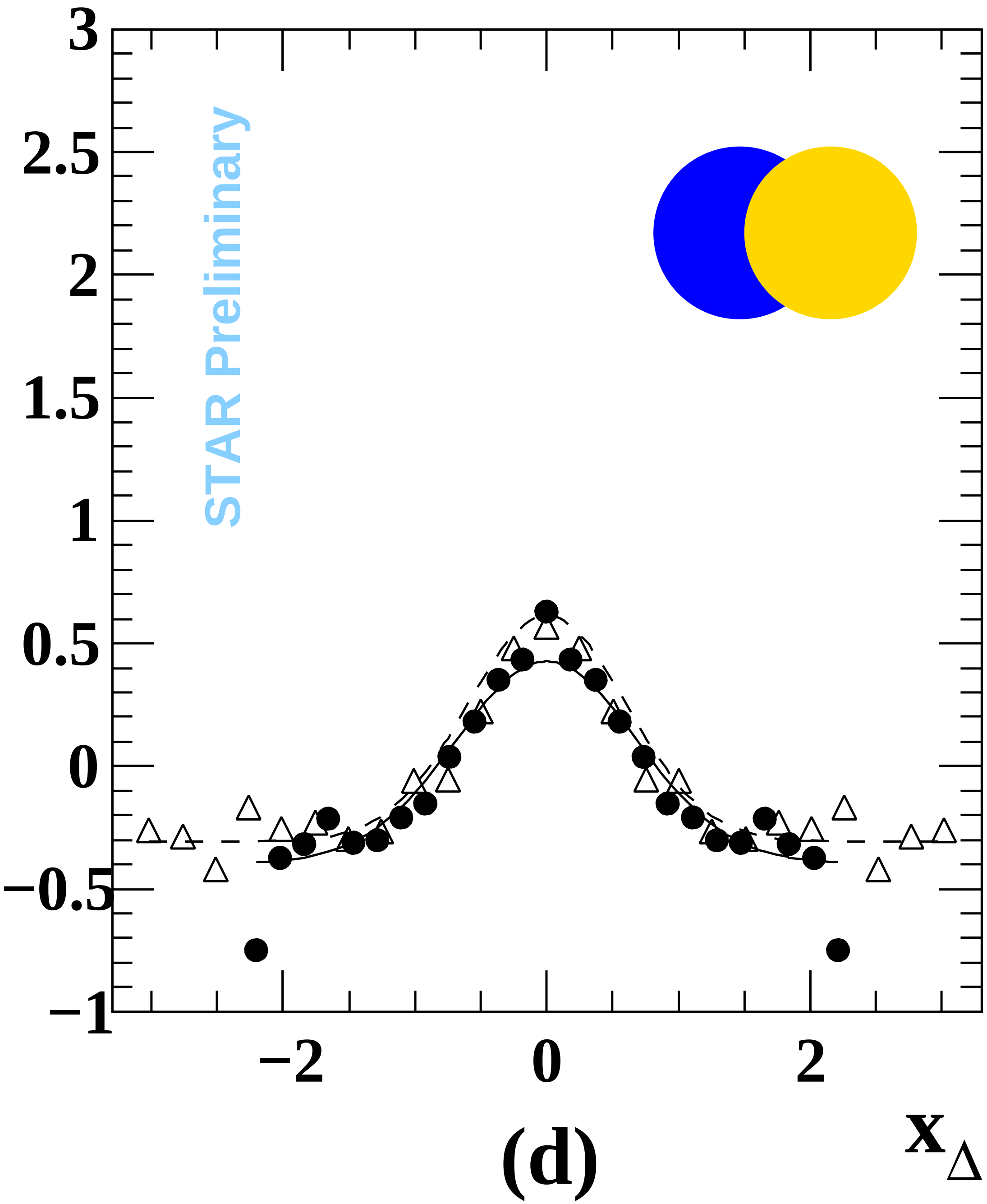
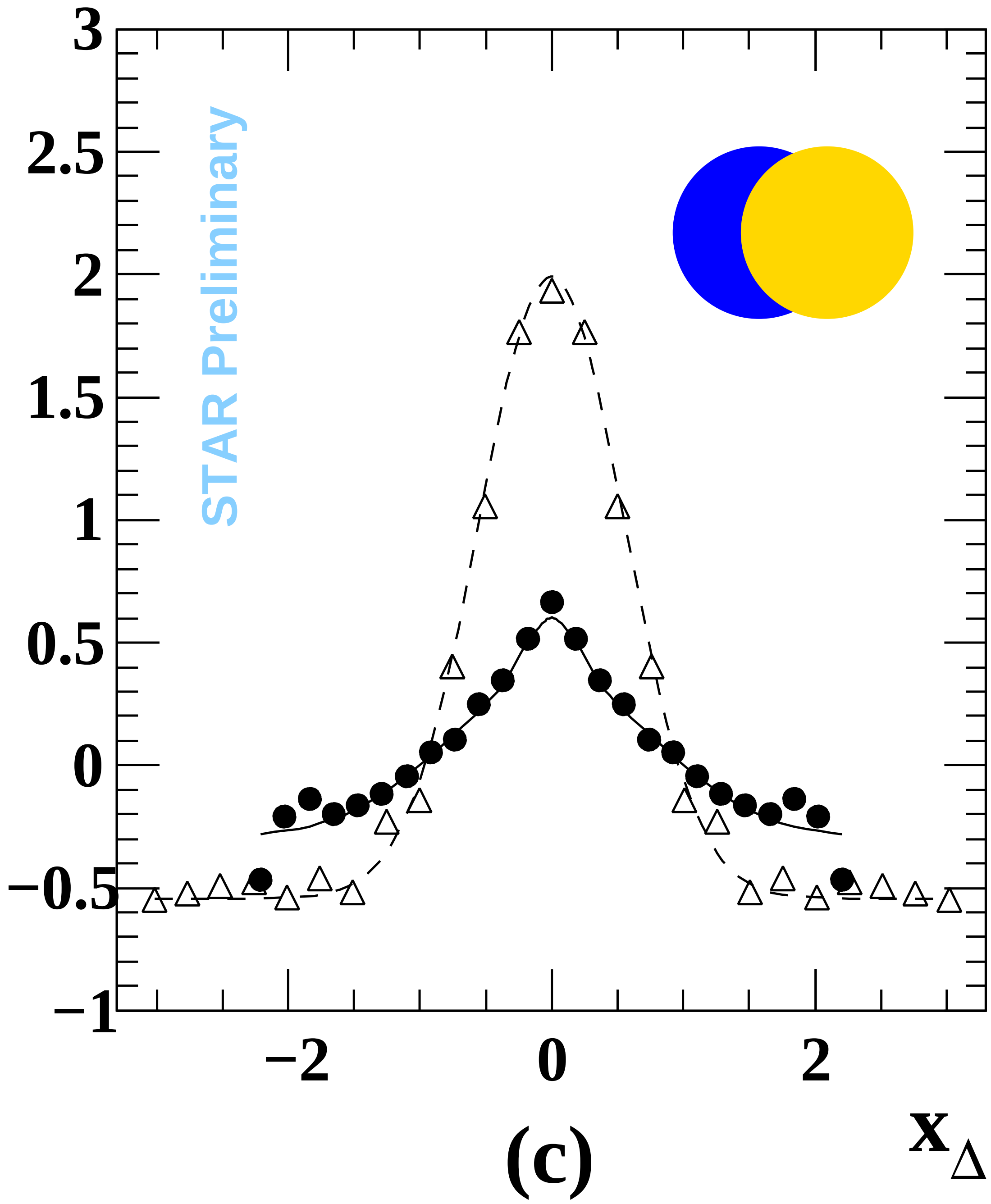




[STAR two-particle correlation analysis, to be submitted to PRL] The step-like character of the centrality dependence is elucidated using $\nu = (N_{part}/2)^{\frac{1}{3}}$



Per-particle-normalized charge-independent autocorrelations $N\Delta R$ in difference variables η_Δ (solid dots) and ϕ_Δ (open triangles). v_1 and v_2 are subtracted.



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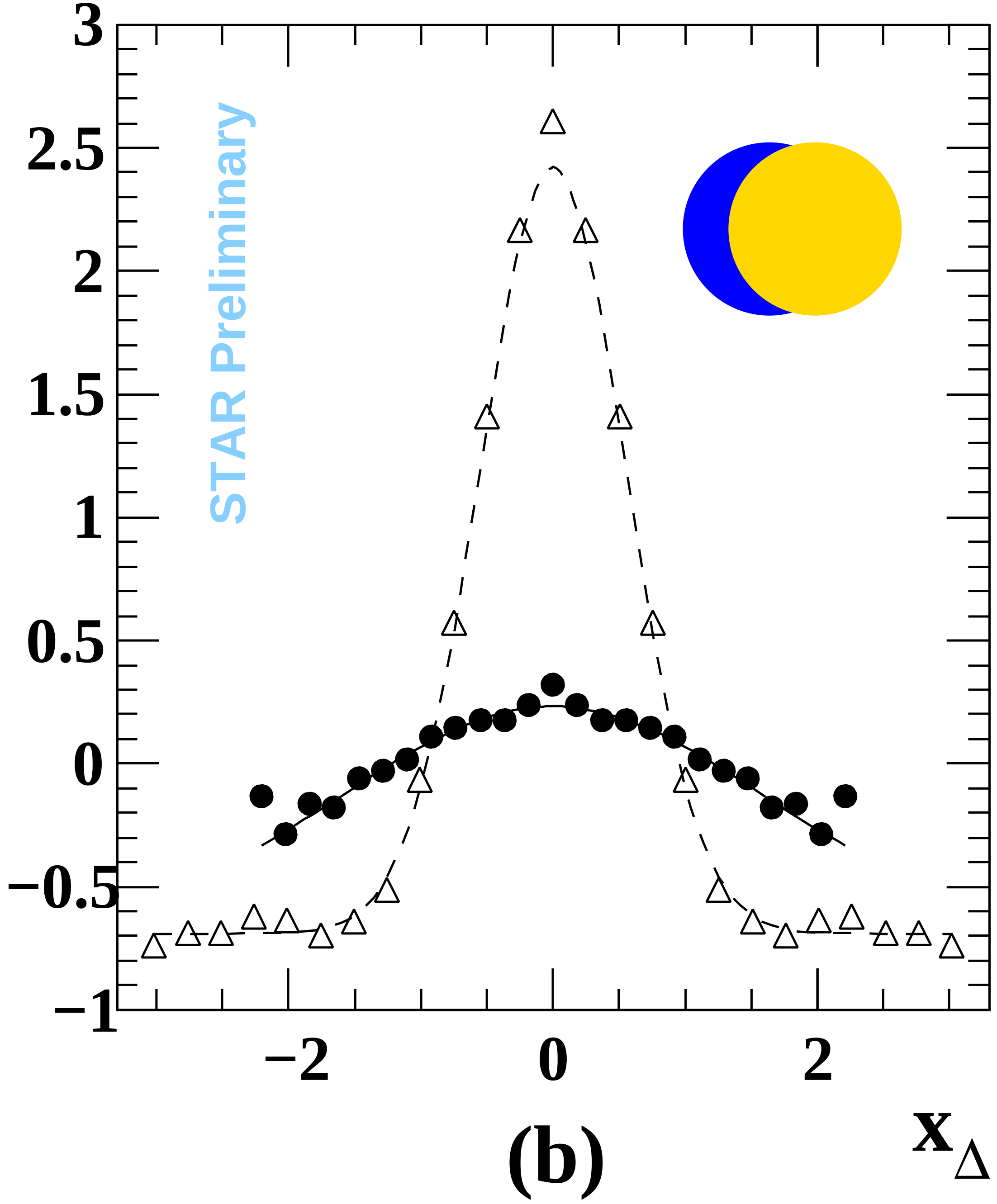

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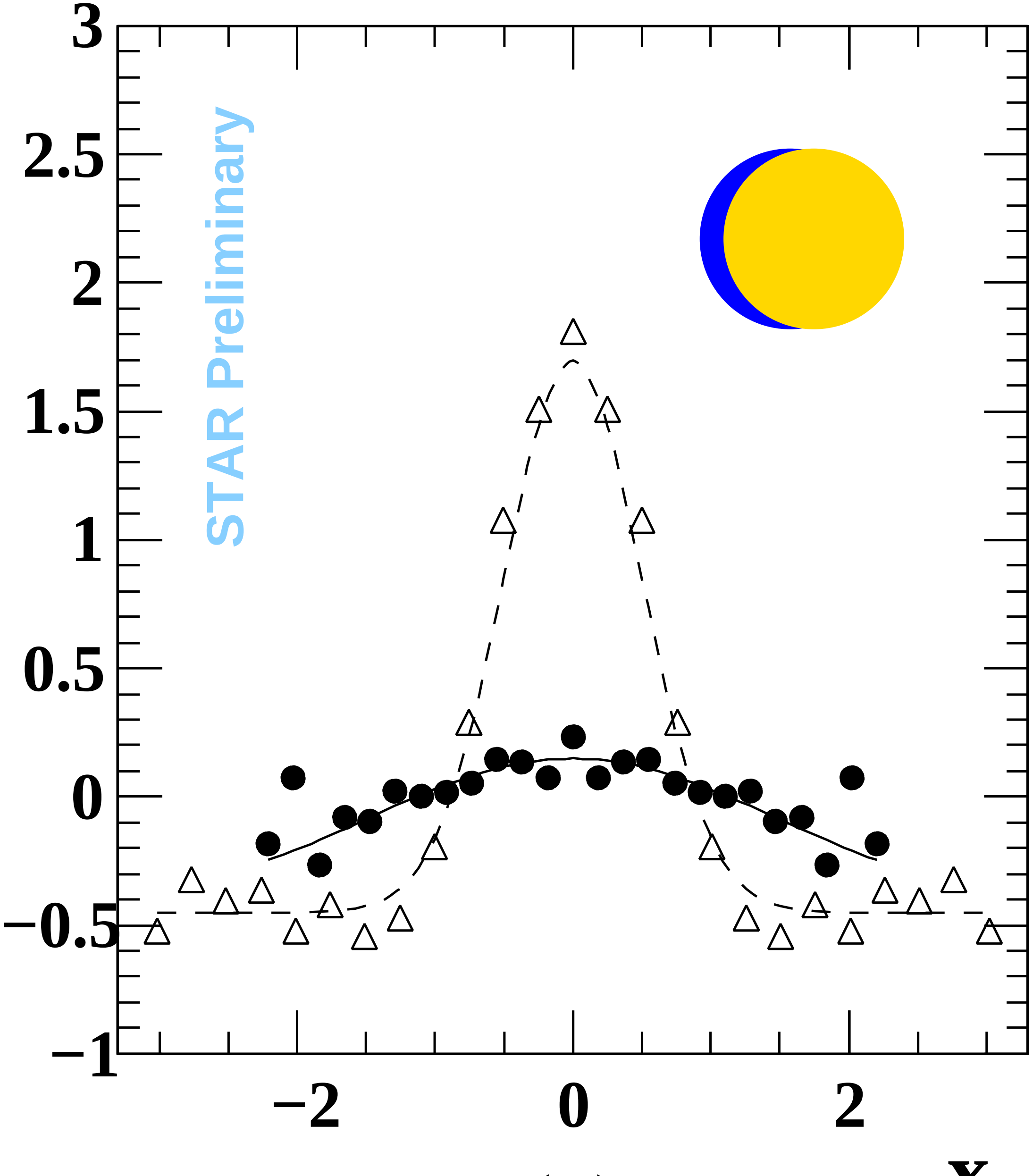

(a)

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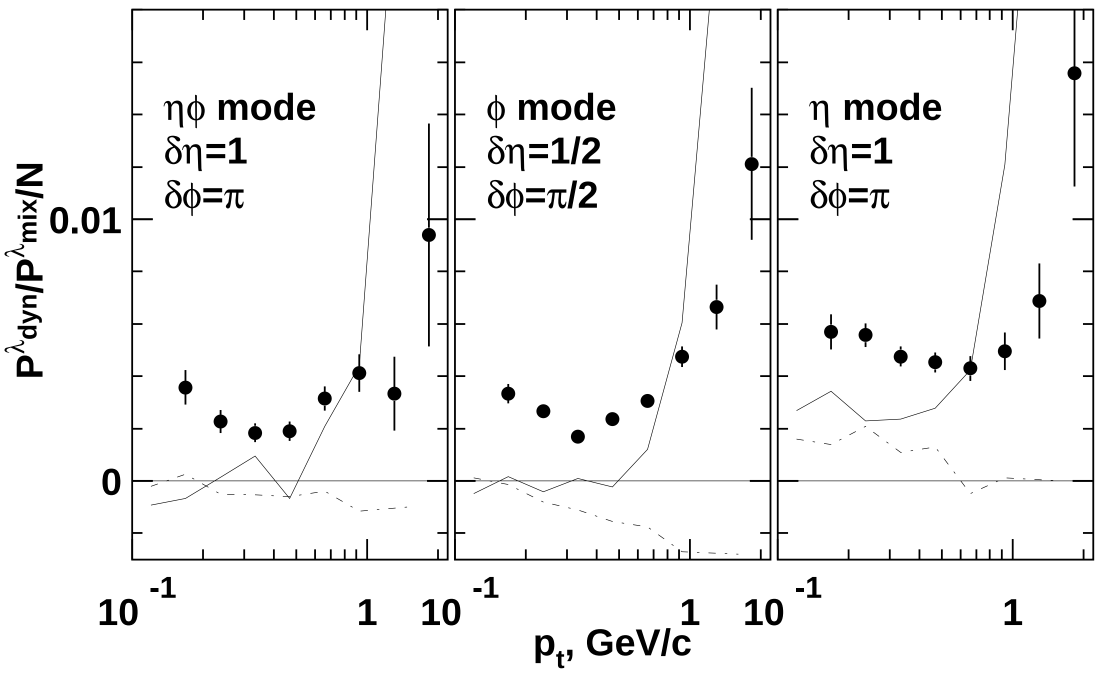
9 p_t dependence: peripheral events, $\sqrt{s_{NN}} = 200$ GeV



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

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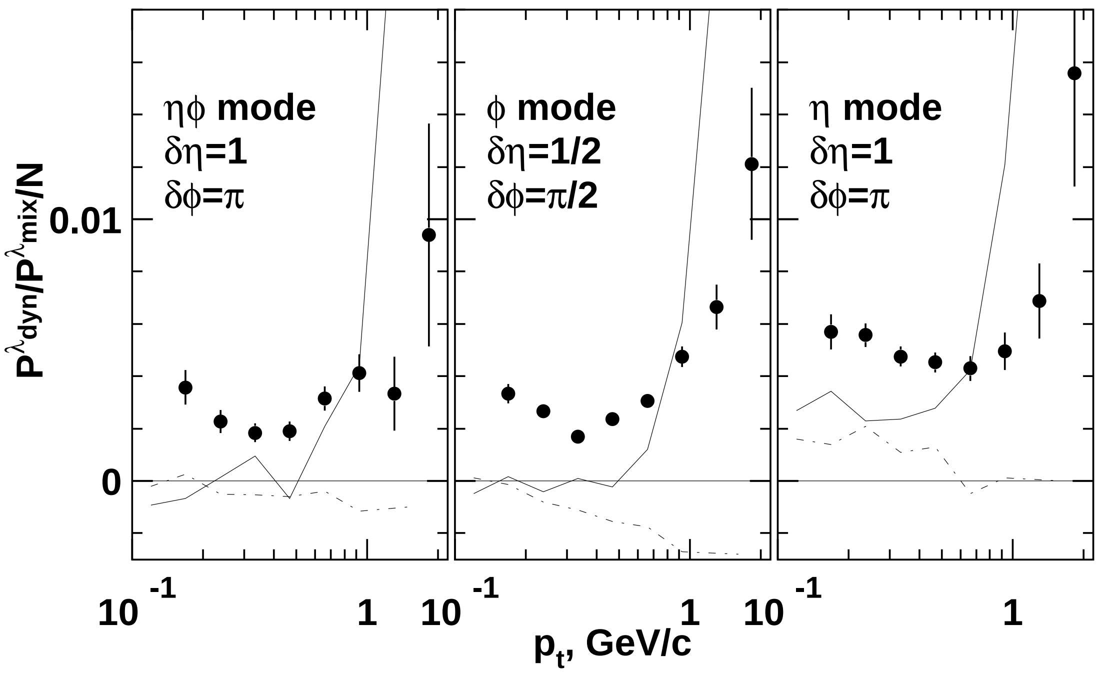

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Qualitative trends in peripheral data are as expected. What signal to expect in the central data, if correlation does not change ?

$$\left(\frac{P_{true}}{P_{mix}} - 1\right)\frac{1}{N}\bigg|_{central} = \left(\frac{P_{true}}{P_{mix}} - 1\right)\bigg|_{peripheral}\frac{1}{N_{central}} \tag{5}$$

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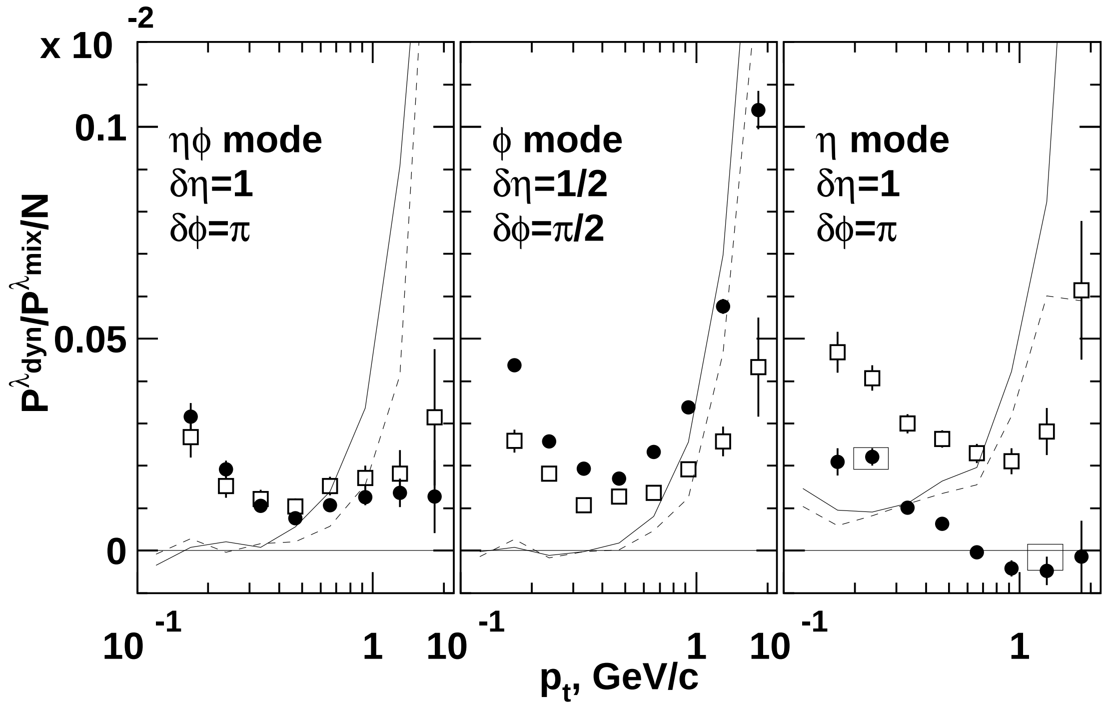

Central (top 4%) events: normalized dynamic texture for fineness scales $m = 0, 1, 0$ from left to right panels, respectively, as a function of p_t. ● – STAR data; solid line – standard HIJING; dashed line – HIJING with jet quenching; boxes – peripheral STAR data just shown, renormalized as just described.

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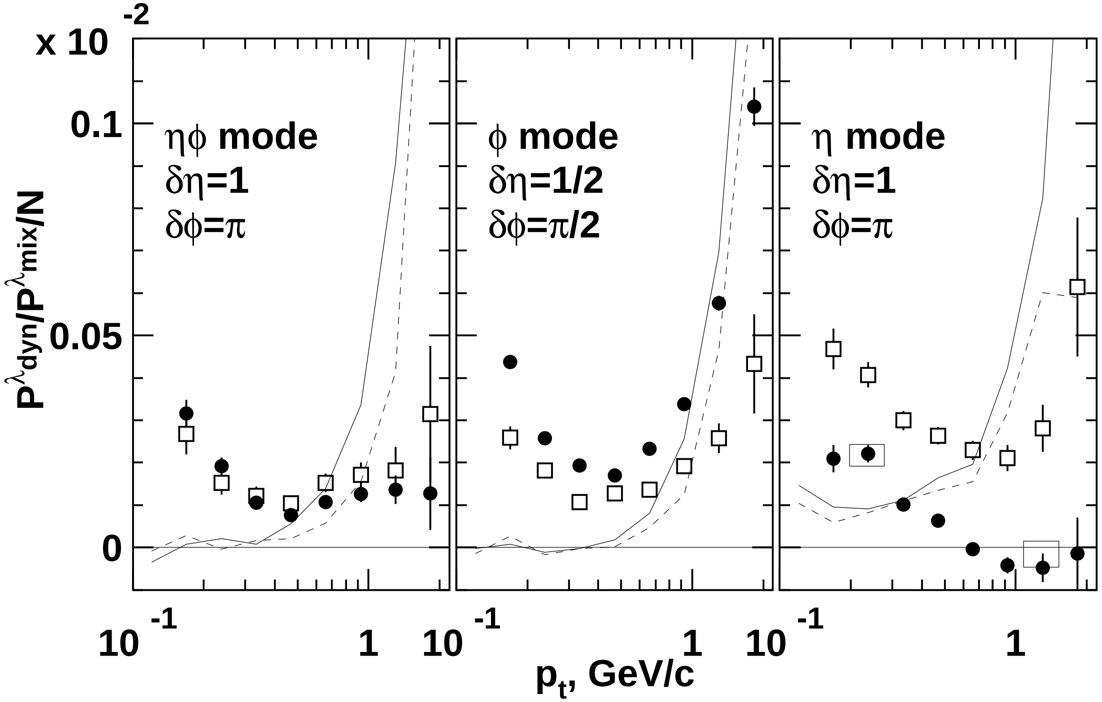

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We are observing a modification of the minijet structure predominantly in the longitudinal, η direction. Longitudinal expansion of the hot and dense medium formed early in the collision makes this direction special and is likely to be part of the modification mechanism.

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via rejection/acceptance algorithm, according to a multiparticle probability density distribution. In general, for N particles denoted $1, 2, ..., N$ the differential probability density

$$P(1, 2, ..., N) = P(1)P(2|1)P(3|1, 2)...P(N|1, 2, ..., N-1),$$

where $P(2|1)$ and subsequent terms are conditional single particle probabilities.

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$$C(1, 2) = \frac{P(1, 2)}{P(1)P(2)} = \frac{P(2|1)}{P(2)}.$$

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A two-particle approximation: continue by induction

$$P(3|1, 2) = P((3|1)|2) = P(3|1)C(2, (3|1)) \approx P(3)C(3, 1)C(2, 3),$$

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where $P(2|1)$ and subsequent terms are conditional single particle probabilities.

Two-particle correlation

$$C(1,2) = \frac{P(1,2)}{P(1)P(2)} = \frac{P(2|1)}{P(2)}.$$

Add particle 2 to particle 1:

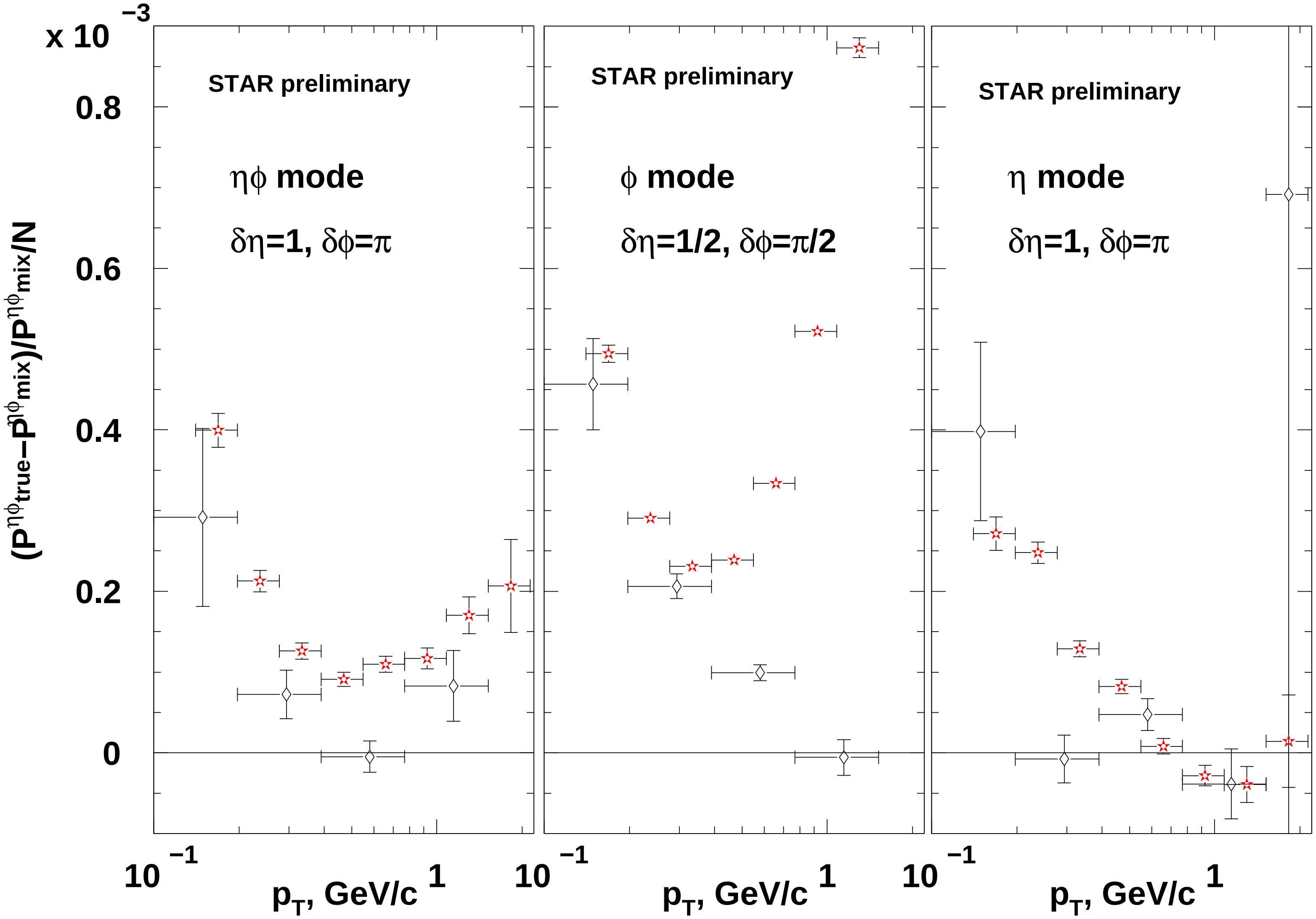
$$P(2|1) = P(2)C(1,2)$$

A two-particle approximation: continue by induction

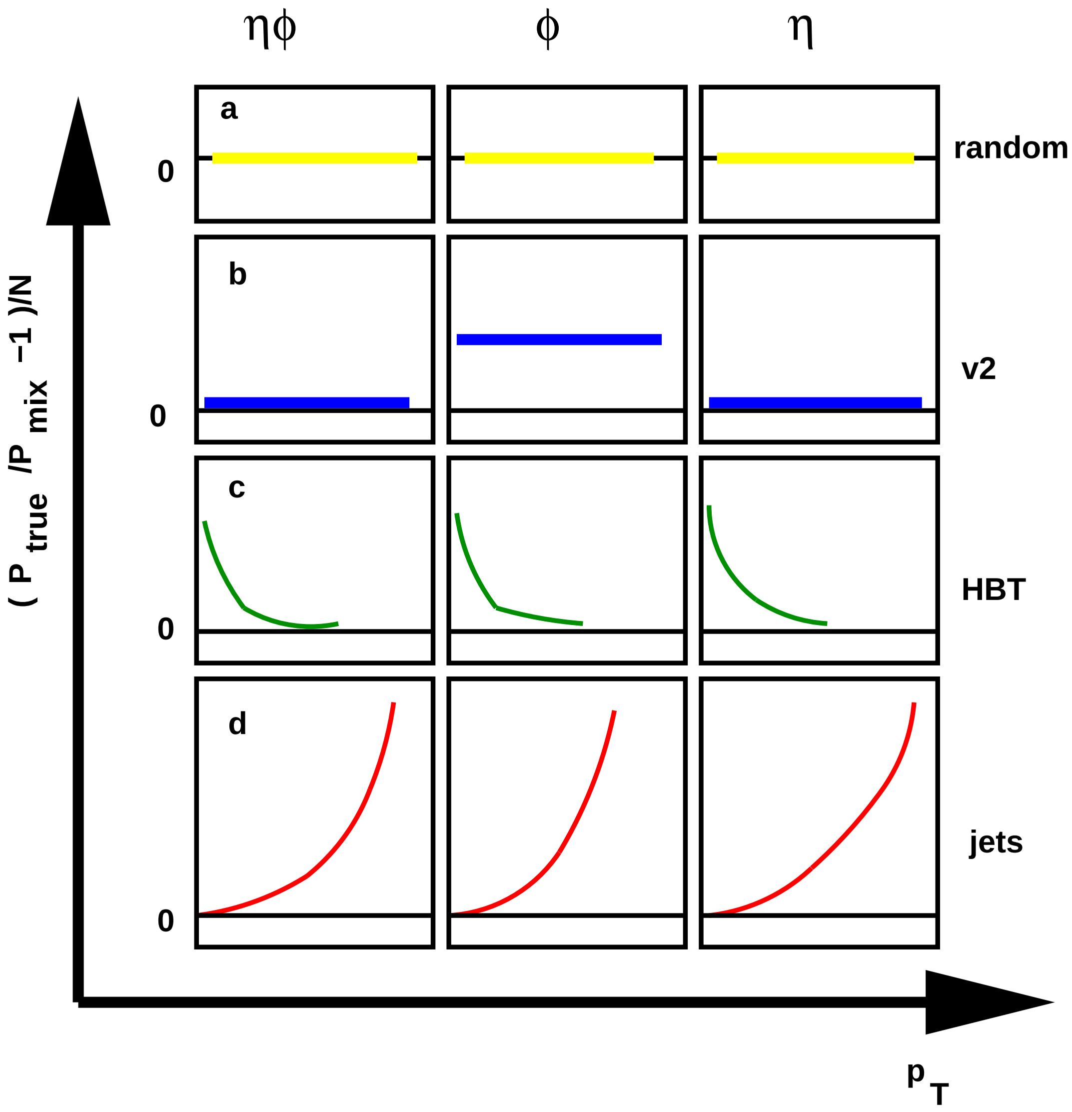
$$P(3|1,2) = P((3|1)|2) = P(3|1)C(2,(3|1)) \approx P(3)C(3,1)C(2,3),$$

$$P(N|1,2,...,N-1) \approx P(N)\Pi_{i=1}^{i=N-1}C(i,N)$$

12 Understanding low p_t



An event generator tuned to reproduce like- and unlike-sign correlations in Q_{inv}, reproduces the low p_t trends in the data. HBT, Coulomb and string fragmentation physics contribute at low p_t.



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_{inv} (Bose-Einstein correlations and Coulomb effect)

(d) HIJING jets

13 Scale dependence

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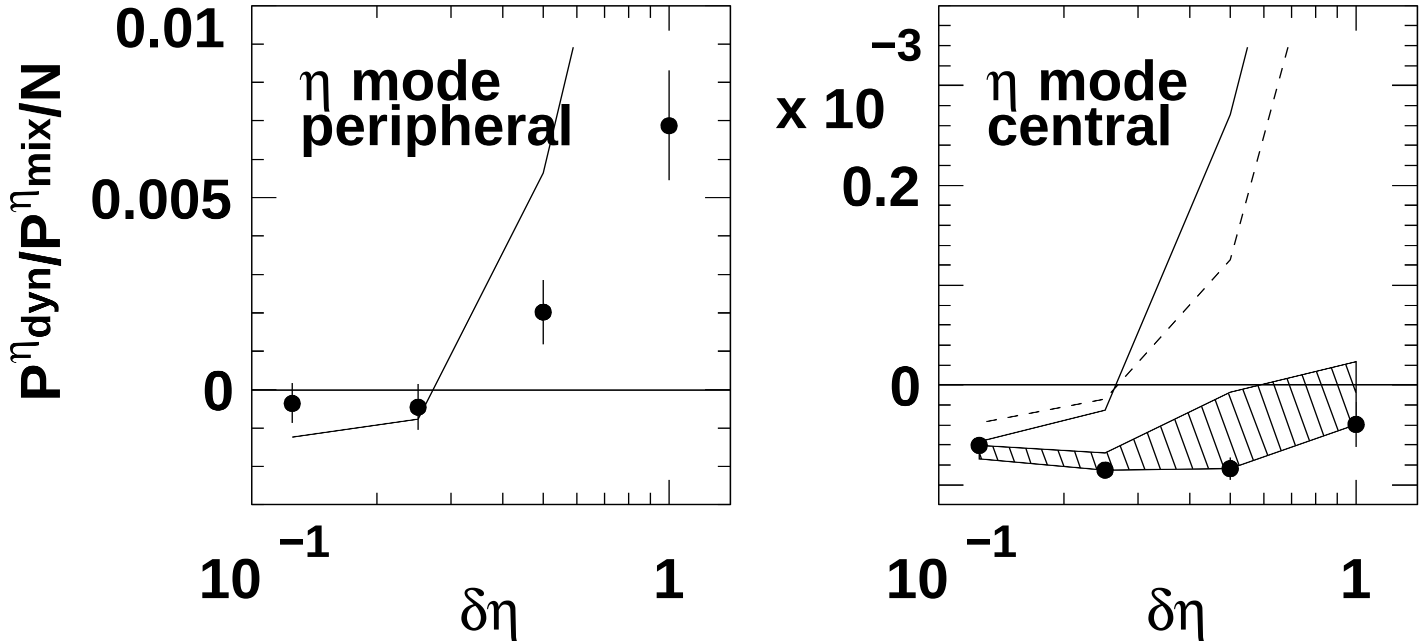

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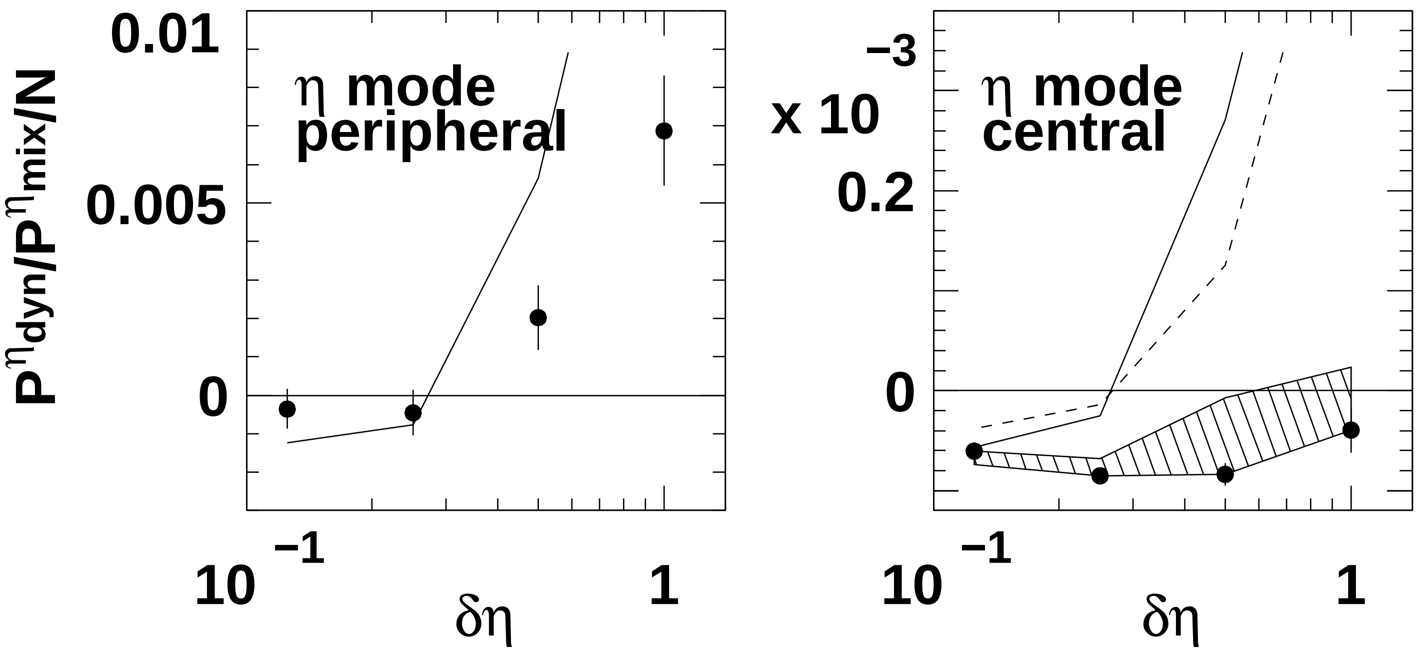

Scale dependence of the dynamic texture measure in peripheral and central events for $1.1 < p_t < 1.5$ GeV/c. •– STAR data; solid line – standard HIJING; dashed line – HIJING with jet quenching. An estimate of systematic error, mainly due to track merging, is shown as a hatched area.

14 Rapidity scale and collision history

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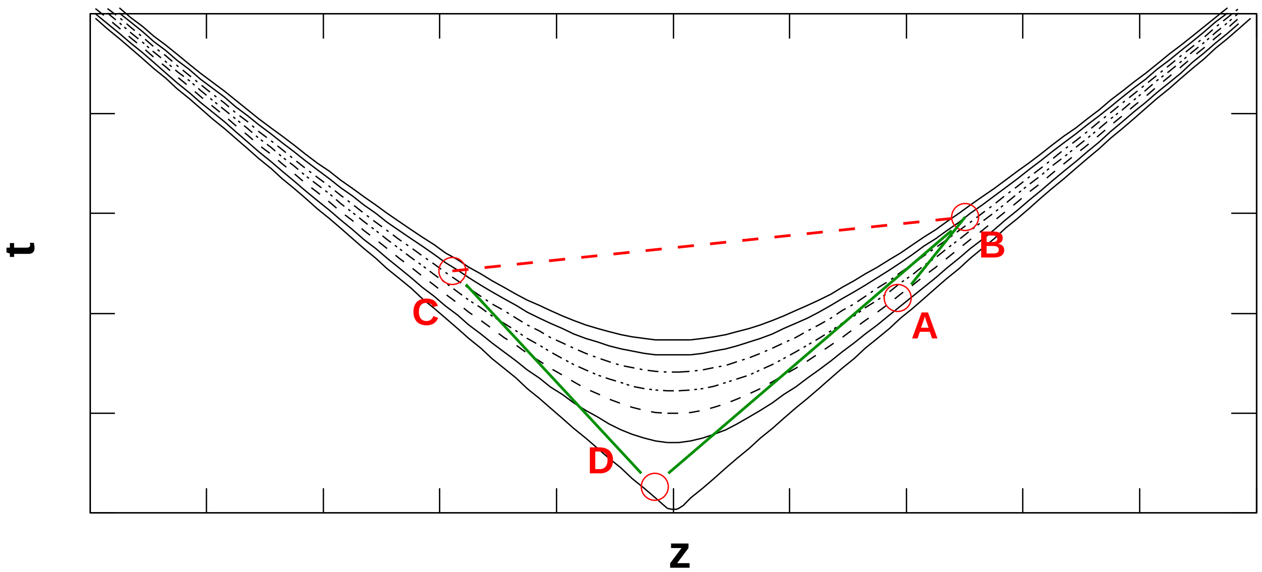

Bjorken expansion: $t = (z^2 + \tau^2)^{1/2}$, CB is space-like; DC, DA, DB, AB contacts possible.

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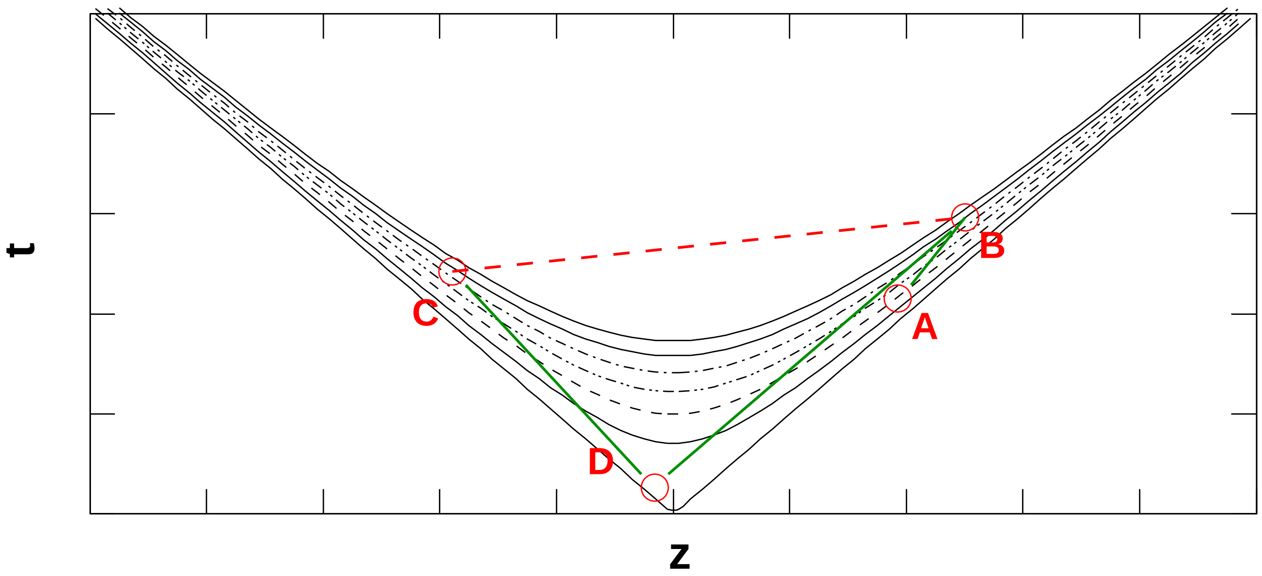

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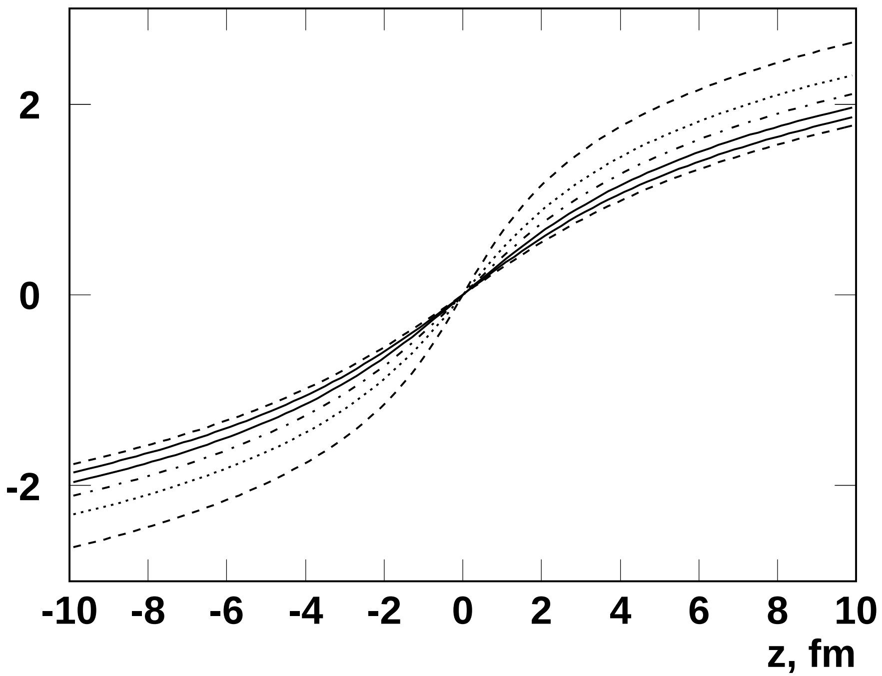

$y = \frac{1}{2} \ln \frac{t+z}{t-z}$ Rapidity and causality: large $\delta y \Longleftrightarrow$ large δz. Large δy correlations reflect early state, otherwise acausal.

15 Summary

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- More info: nucl-ex/0407001

16 Extra slides

17 What is scale ?

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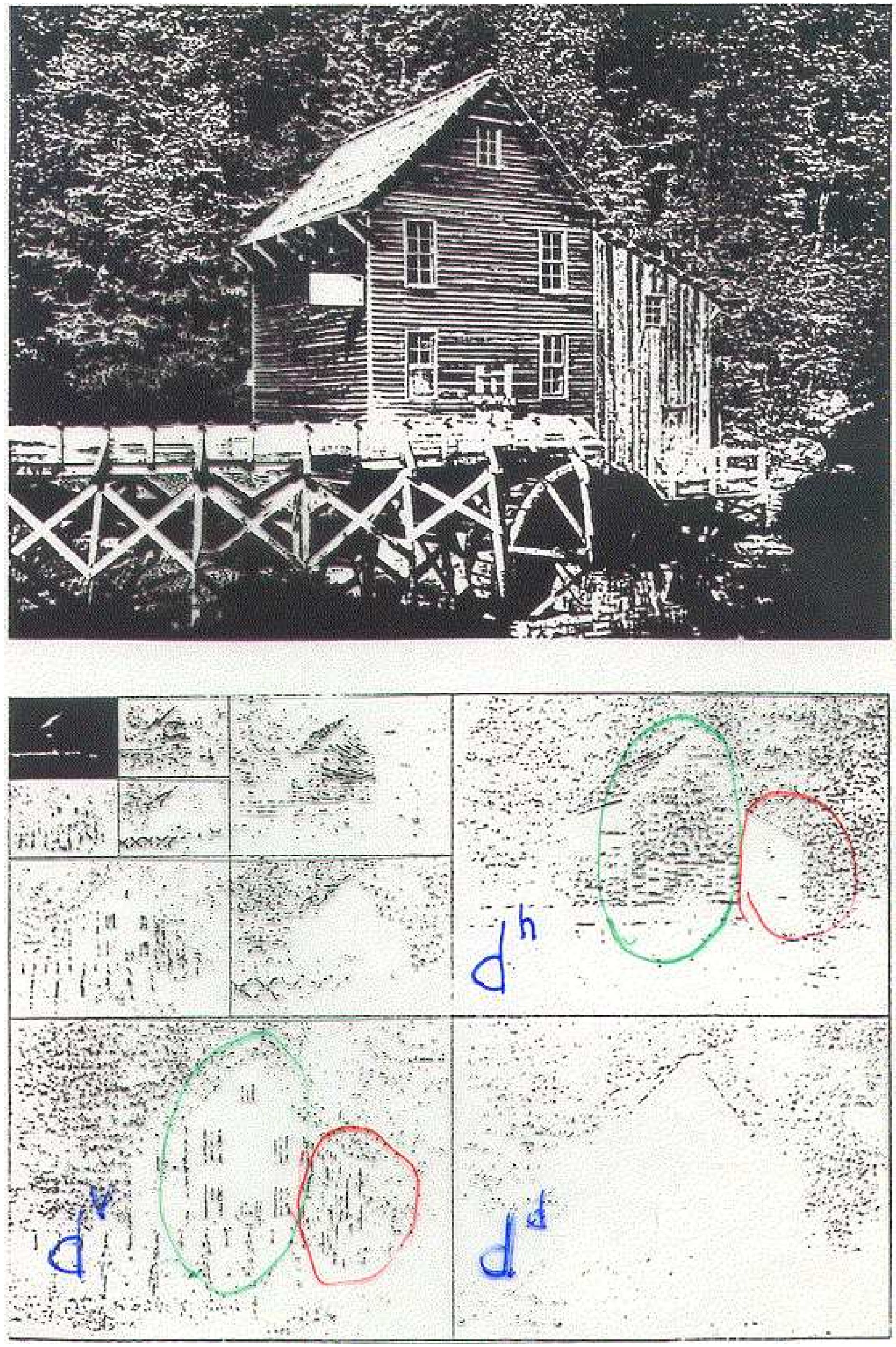
"Fifty Abstract Paintings Which as Seen from Two Yards Change into Three Lenins Masquerading as Chinese and as Seen from Six Yards Appear as the Head of a Royal Bengal Tiger", S.Dali, 1963.

18 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.