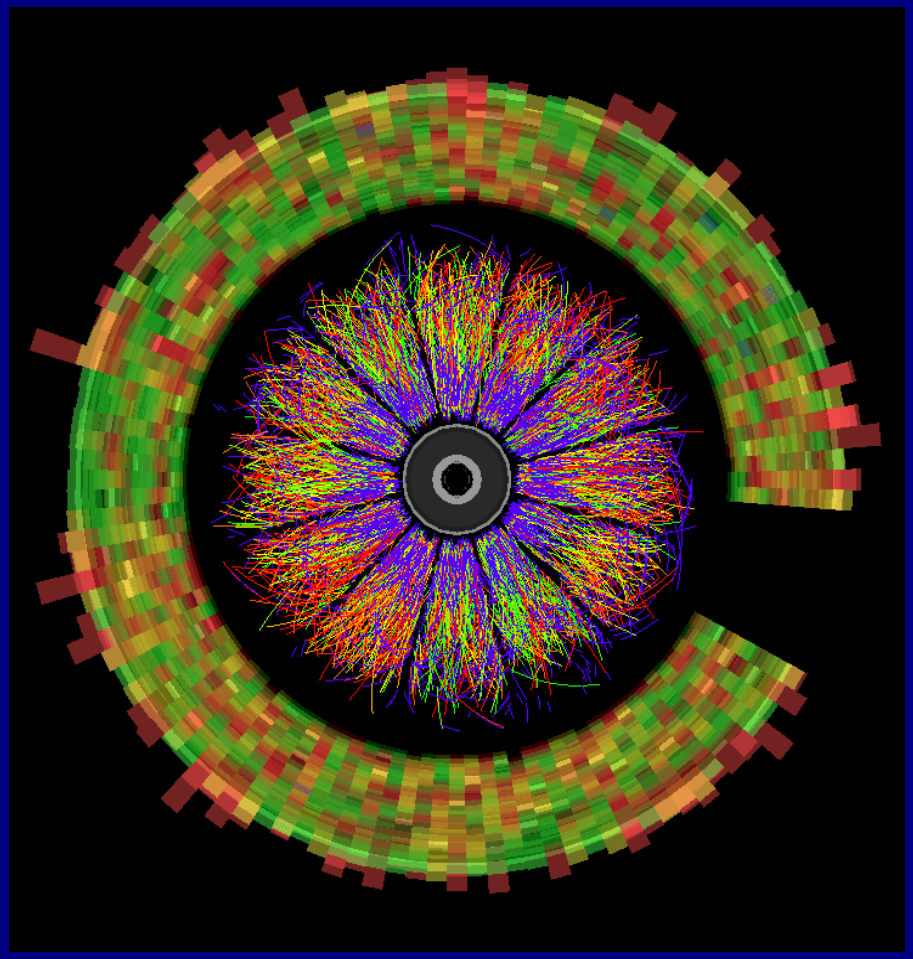
Two-particle correlations and rheometry of Quark Gluon Plasma in Au+Au collisions at 200 GeV



Monika Sharma for the STAR Collaboration

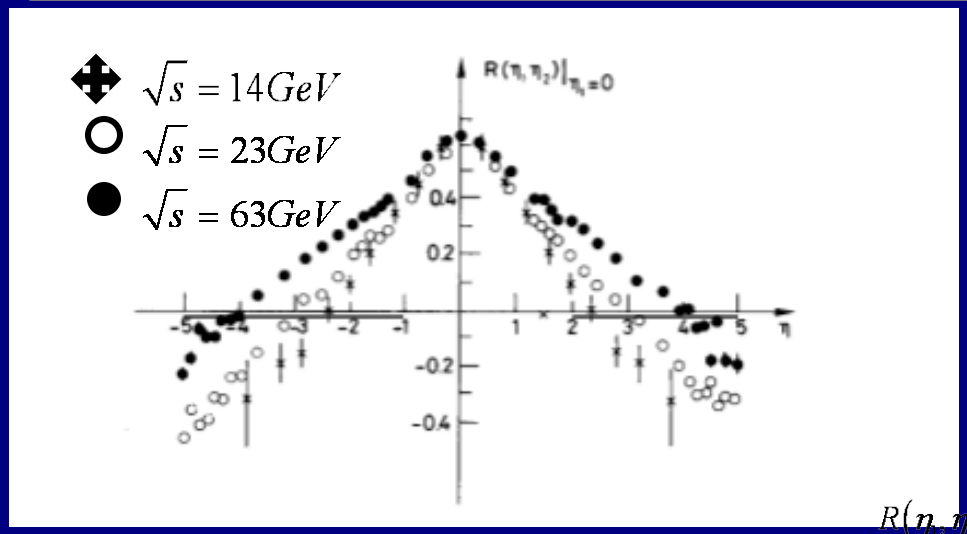
Wayne State University/Vanderbilt University

Aim: To understand underlying collision dynamics in heavy-ion scenario

Outline:

- ✓ Physics motivation
  - o The ridge
  - o Viscosity
  - o Delayed hadronization
  - o Fourier decomposition
- ✓ The ridge - R_2, C and $\rho_2^{\Delta p_{T_1} \Delta p_{T_2}}$
- ✓ Viscosity - hybrid observable: C
- ✓ Delayed hadronization - charge dependent result from
  - ✓ Number density: R_2 (R_2++, R_2--, R_2+-)
  - ✓ Hybrid observable: C (C_{++}, C_{--}, C_{+-})

Two-particle correlations



Two-particle correlations at ISR

L. Foa, Physics reports, 22 (1975) 1-56

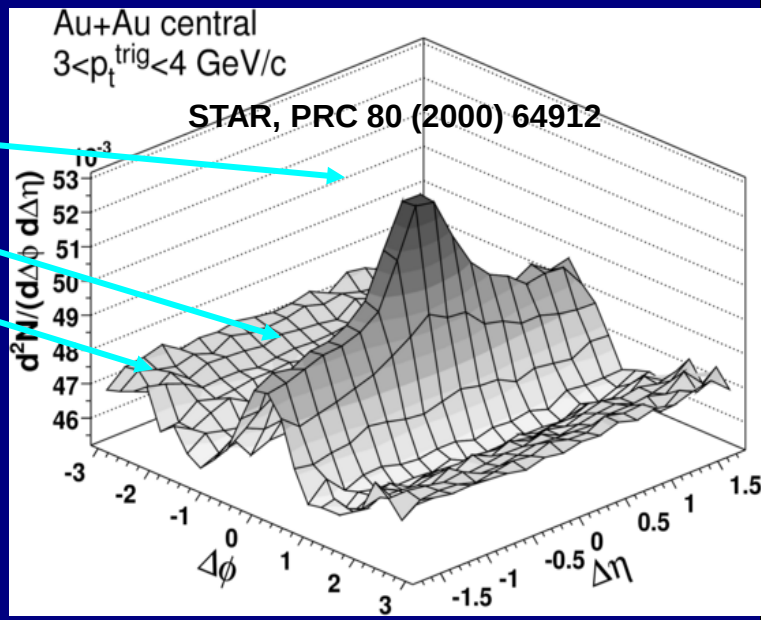
Fig: Correlation function $R(\eta_1, \eta_2)$ for $\eta_1 = 0$ at various energies.

Components:

a) Near-side jet peak

b) Near-side ridge

c) Away-side and elliptic flow (v_2)



Proposed explanations:

Glasma flux tubes: A. Dumitru et. al., hep-ph/0804.3858

Radial flow + trigger bias: S. Voloshin, nucl-th/0312065

E. Shuryak, nucl-th/0706.3531

S. Gavin et.al., nucl-th/0806.4718

Minijets: STAR, JPG32 (2006) L37

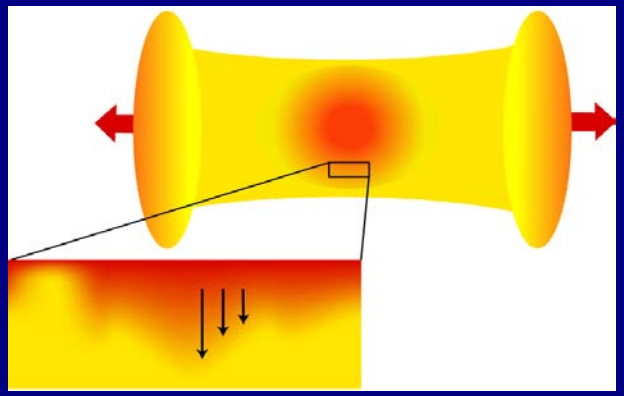
And many more……..

Measurement of viscosity based on p_T correlations

Gavin and Aziz, Phys. Rev. Lett. 97 (2006) 162302

- Viscous friction arises as fluid elements flow past each other, thereby reducing the relative velocity: damping of radial flow.
- T_{zr} changes the radial momentum current of the fluid, $T_{zr} = -\eta\, \partial v_r / \partial z$
- Diffusion equation for the momentum current

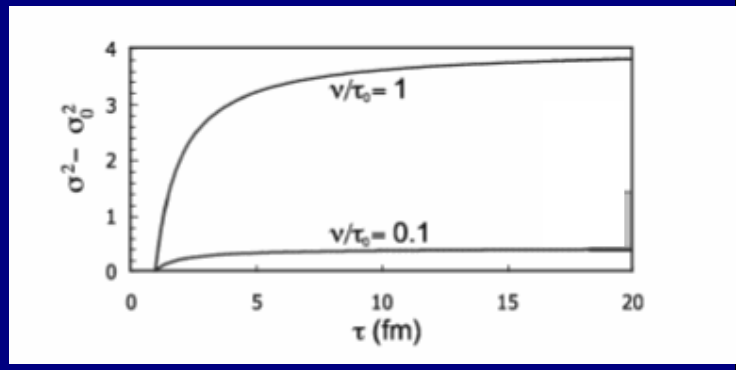
$$\left(\frac{\partial}{\partial t} - \nu \nabla^2\right) g_t = 0$$



- Viscosity reduces fluctuations, distributes excess momentum density over the collision volume: broadens the rapidity profile of fluctuations.
- Width of the correlation grows with diffusion time (system lifetime) relative to its original/initial width

$$\sigma^2 = \sigma_0^2 + 2\Delta V(\tau_f)$$

$$\Delta V(\tau) = \frac{2\nu}{\tau_0}\left(1 - \frac{\tau_0}{\tau}\right)$$



Rheometry of QGP….

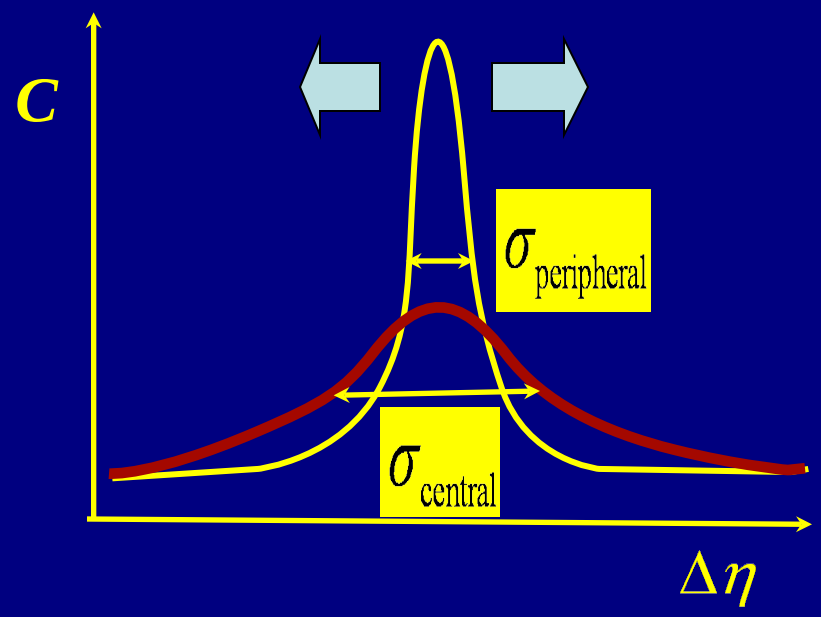
- ***Integral*** **correlation function (Gavin & Aziz, Phys. Rev. Lett. 97 (2006) 162302)**

$$C = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{i \neq j=1}^{n_2} p_{T_i} p_{T_j} \right\rangle}{\langle n \rangle_1 \langle n \rangle_2} - \langle p_T \rangle_1 \langle p_T \rangle_2$$

$$\sigma_c^2 - \sigma_0^2 = 4\upsilon\left(\tau_0^{-1} - \tau_f^{-1}\right)$$

$$\upsilon = \frac{\eta}{T_c s}$$

η = shear viscosity
T_c = critical temperature
S = entropy density
τ_0 = formation time
τ_f = freeze-out time



Broadening:

$$\sigma_c^2 \approx \sigma_{Diffusion}^2 + \sigma_0^2$$

Delayed hadronization

- **Clocking Hadronization**
  - ✓ Is hadronization delayed beyond 1 fm/c timescale?
  - ✓ What is pre-hadronic state? QGP?

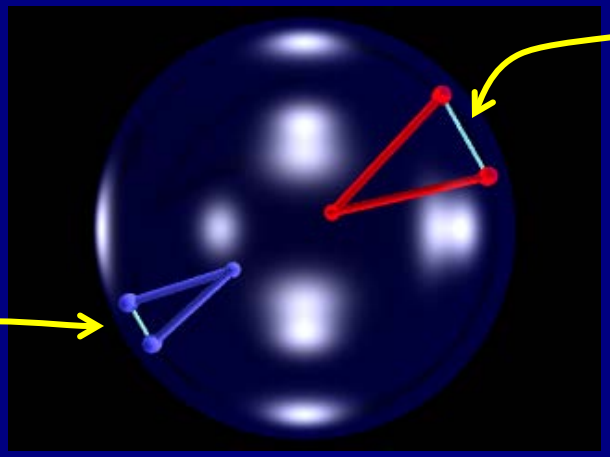
- Based upon the fact that charge is conserved locally, and produced pairs are initially correlated in coordinate space.

- Balance function (BF) quantifies the degree of this separation and relates it with the time of hadronization.

$$B(\Delta y) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_+} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_-}\right\}$$

Bass-Danielewicz-Pratt, PRL 85, 2000

Early hadronization scenario: Pairs separate in rapidity due to expansion and rescattering.



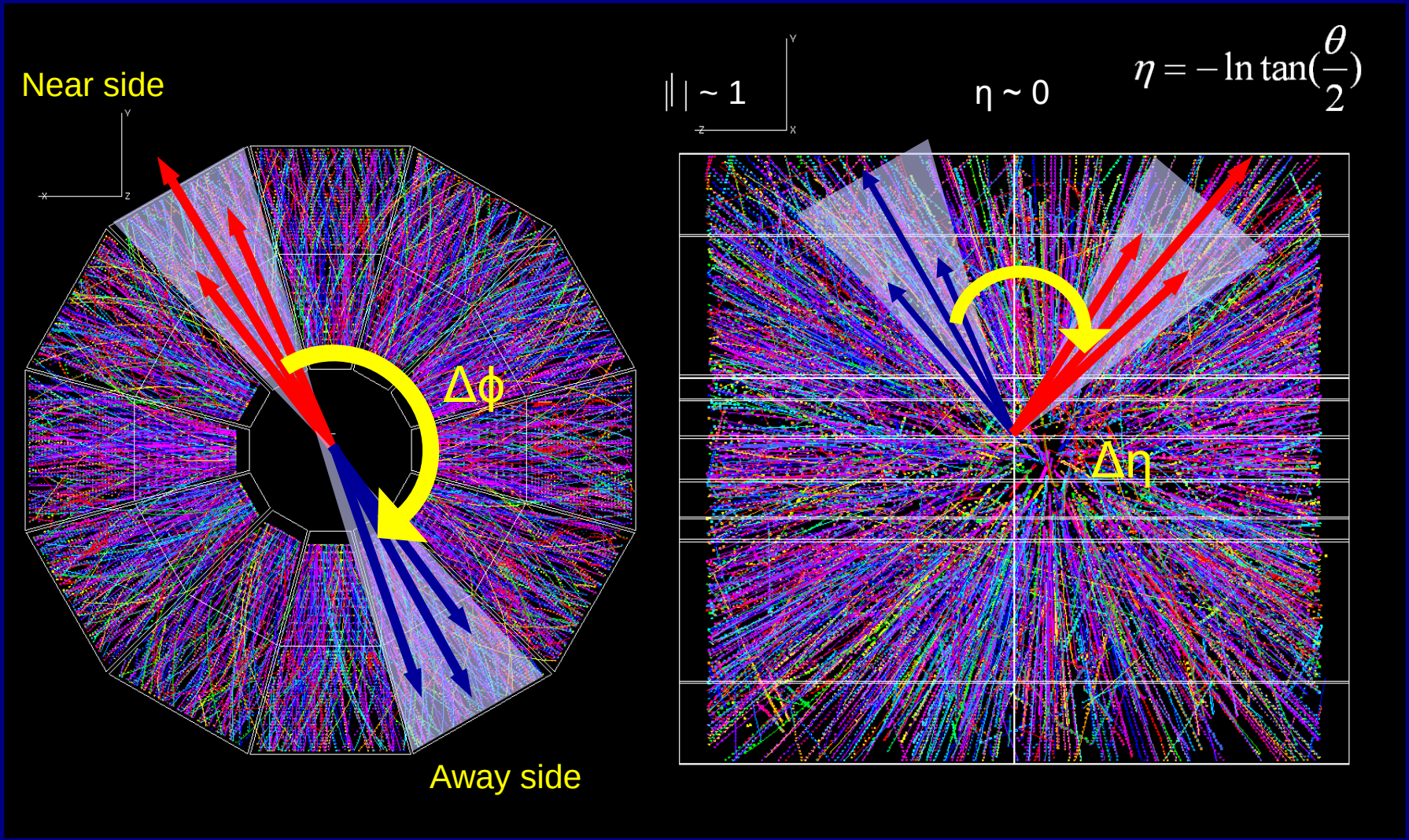
Delayed hadronization scenario: Pairs are more strongly correlated in rapidity.

$$O_{CD} = O_{+-} - \frac{1}{2}\left(O_{++} + O_{--}\right)$$

O = observable

Can O_{CD} be compared to BF?

2-D (Δη,Δϕ) correlations



Definitions:

- **Number density correlation measure:**

$$R_2 = \frac{\rho_2(\Delta\eta, \Delta\phi)}{\rho_1 \rho_1(\Delta\eta, \Delta\phi)} - 1$$

where

$$\rho_1 = \frac{d^3 N_1}{d\eta d\phi dp_T}$$

$$\rho_2 = \frac{d^6 N_2}{d\eta_1 d\phi_1 dp_{T_1} d\eta_2 d\phi_2 dp_{T_2}}$$

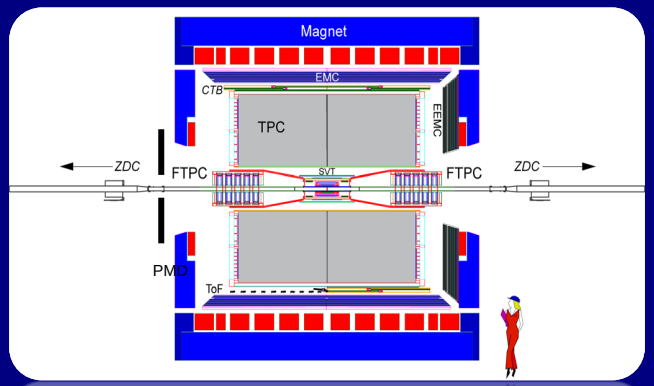
- **Transverse momentum correlation measure:**

$$\rho_2^{\Delta p_{T_1} \Delta p_{T_2}} = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{i \neq j=1}^{n_2} \left(p_{T_i} - \langle p_T \rangle_1 \right) \left(p_{T_j} - \langle p_T \rangle_2 \right) \right\rangle}{\langle n_1 n_2 \rangle}$$

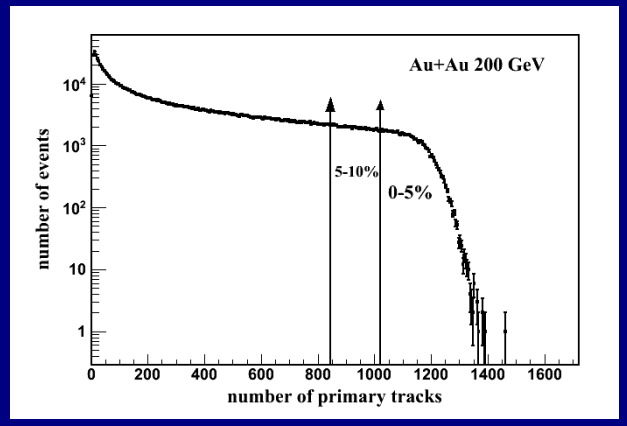
- **Hybrid correlation measure,**

$$C = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{i \neq j=1}^{n_2} p_{T_i} p_{T_j} \right\rangle}{\langle n \rangle_1 \langle n \rangle_2} - \langle p_T \rangle_1 \langle p_T \rangle_2$$

STAR Analysis



- Data from STAR TPC, 2ϕ coverage
- Dataset: RHIC run IV: AuAu 200 GeV
- Events analyzed: 8 Million
- Minimum bias trigger
- Track kinematic cuts
  - Goal: measure medium properties i.e., **Bulk Correlations**
  - $|\eta|<1.0$
  - $0.2< p_T < 2.0$ GeV/c, **No trigger and associated particle**
- Analysis done vs. collision centrality measured based on multiplicity in $|\eta|<1.0$



Modeling nuclear collisions in ideal hydrodynamics is limited to low $p_T\,(< 2GeV/c)$

Slices: 0-5%, 5-10%……. 70-80%

Results

$$\rho_1 = \frac{d^3 N_1}{d\eta d\phi d}$$

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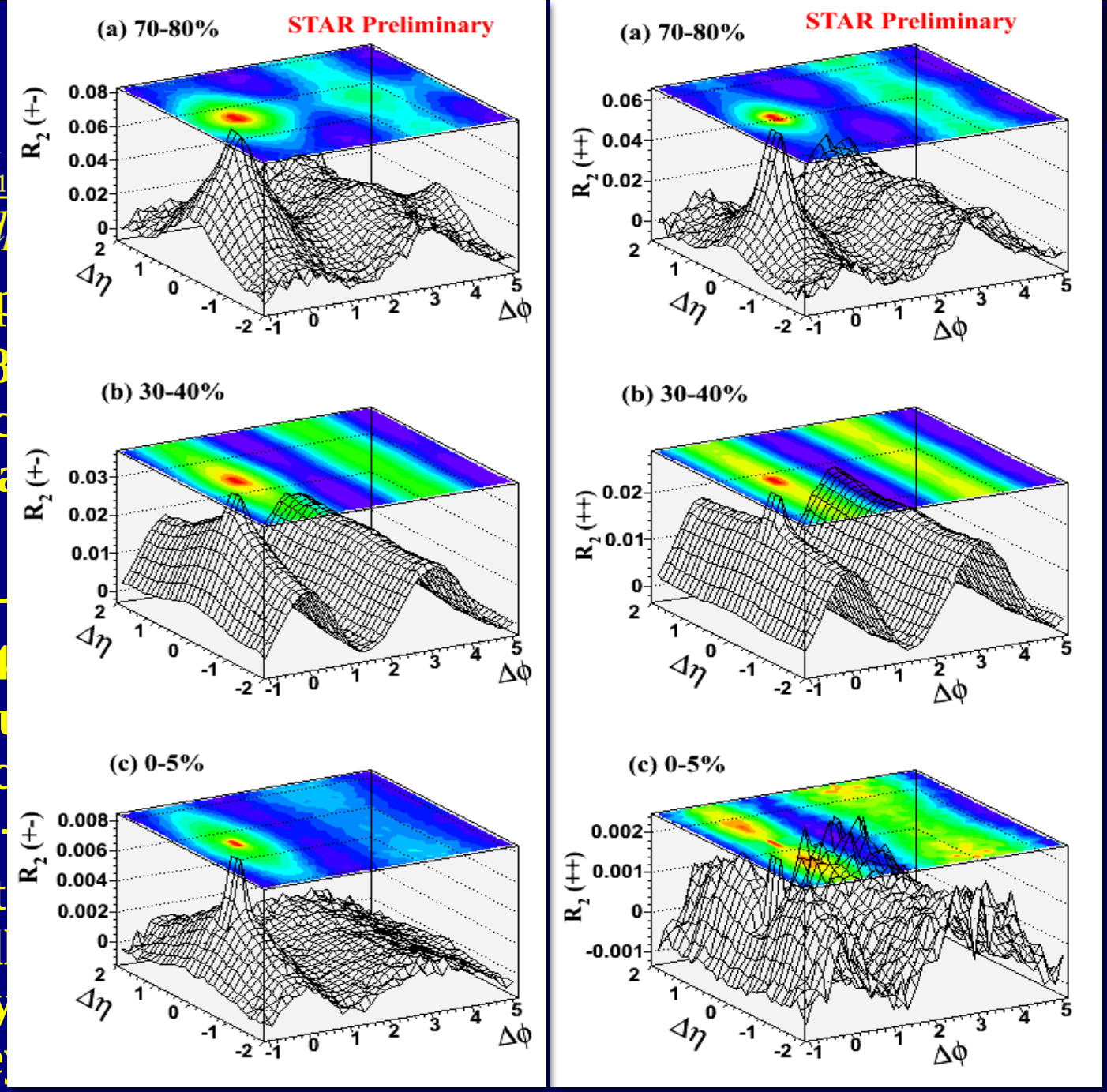
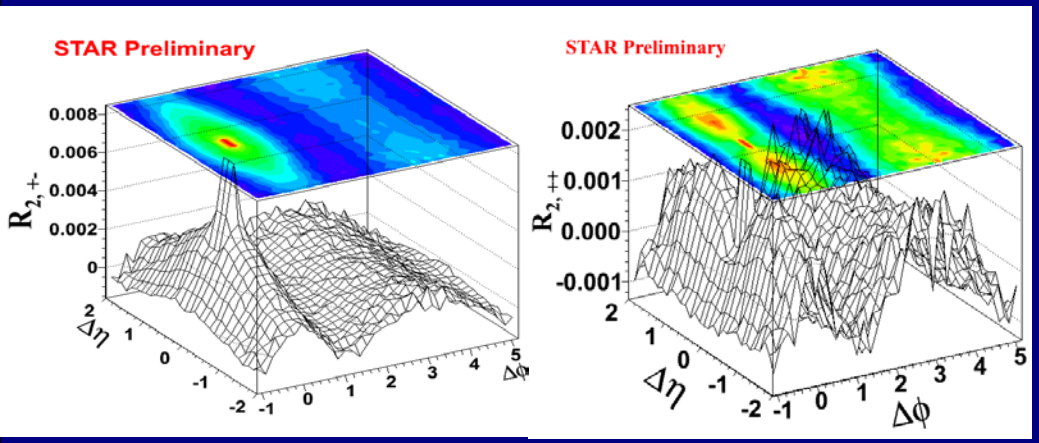
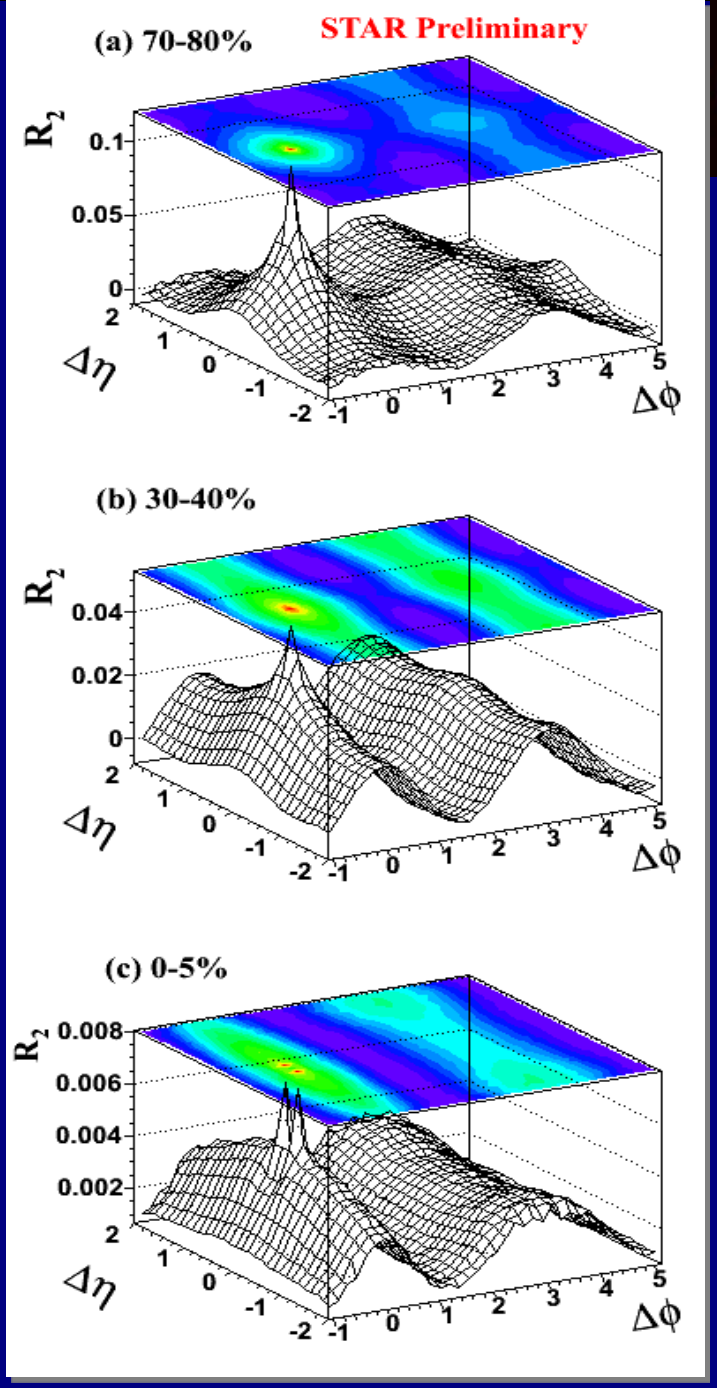


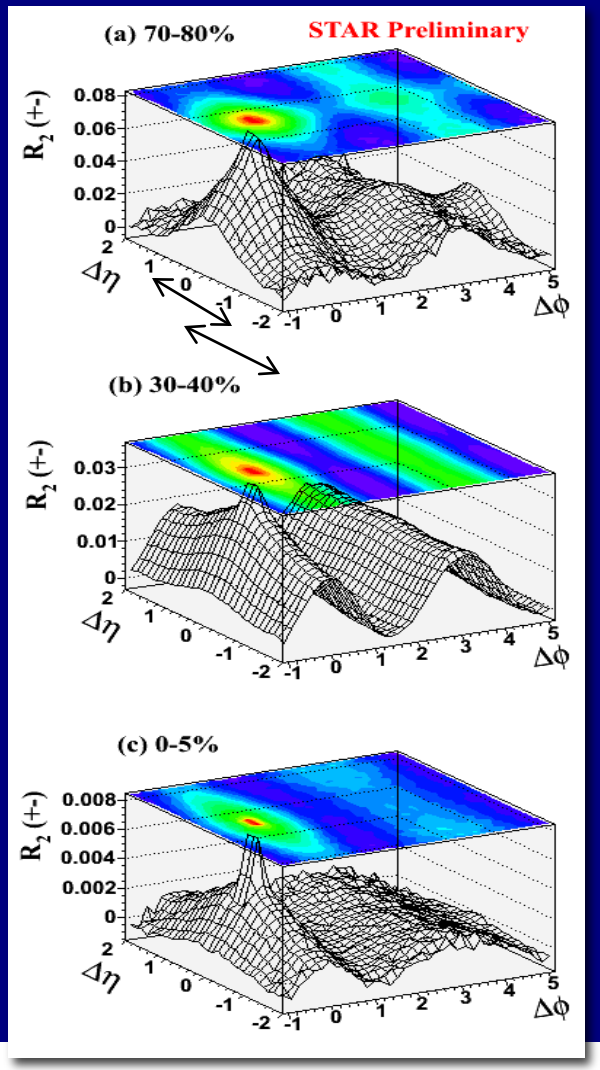
The Ridge

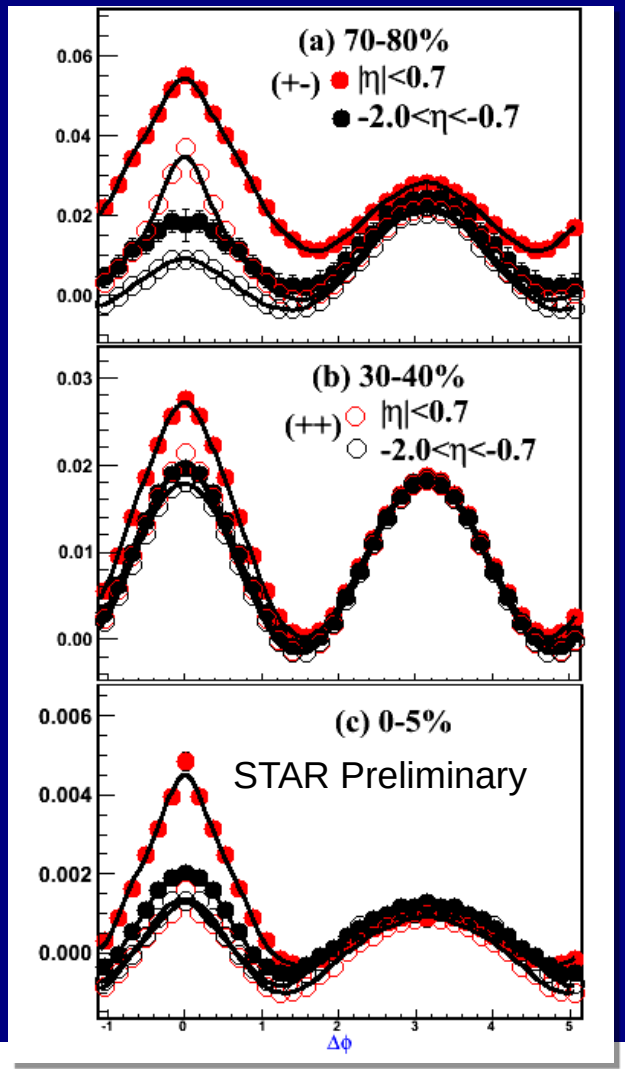
- R_2 inclusive
- Magnitude of unlike sign ($R_2(+-)$) charge combination dominate compared to like sign ($R_2(++)$) on the near-side.





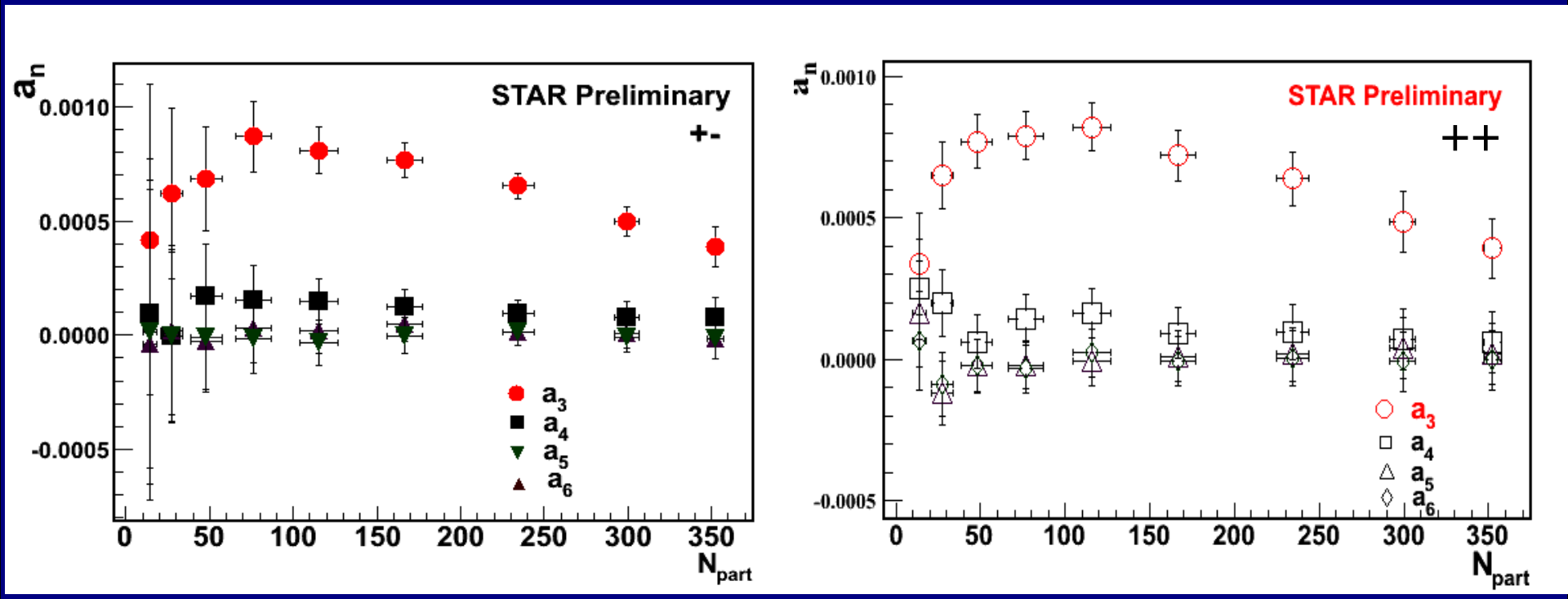
Fourier decomposition





$$F(\Delta\phi) = a_0 + a_1\cos(\Delta\phi) + a_2\cos(2\Delta\phi) + a_3\cos(3\Delta\phi) + a_4\cos(4\Delta\phi) + a_5\cos(5\Delta\phi) + a_6\cos(6\Delta\phi)$$
$$+a_7\cos(7\Delta\phi) + a_8\cos(8\Delta\phi) + a_9\cos(9\Delta\phi)$$

Co-efficients of Fourier decomposition



Similar values of Fourier co-efficients for unlike (+-) and like (--) sign.

Hybrid co

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- Mid-cen (30-40% modulat emerges
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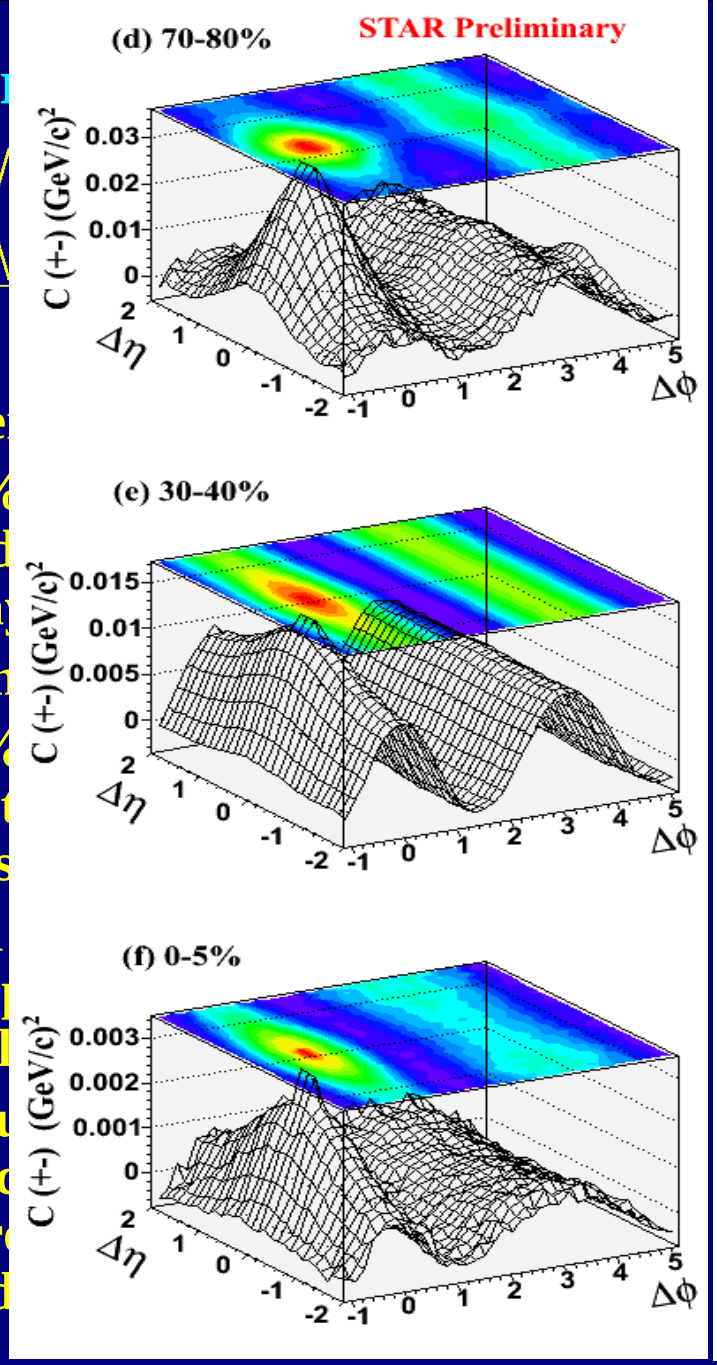
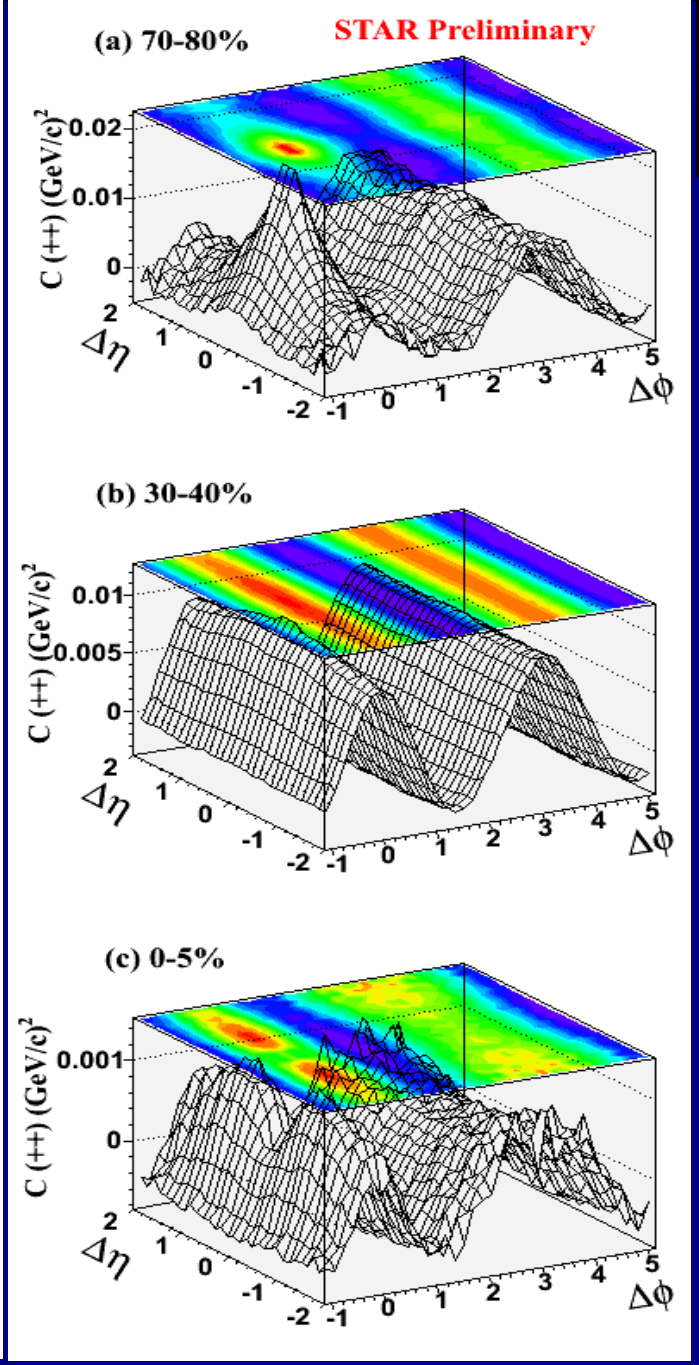
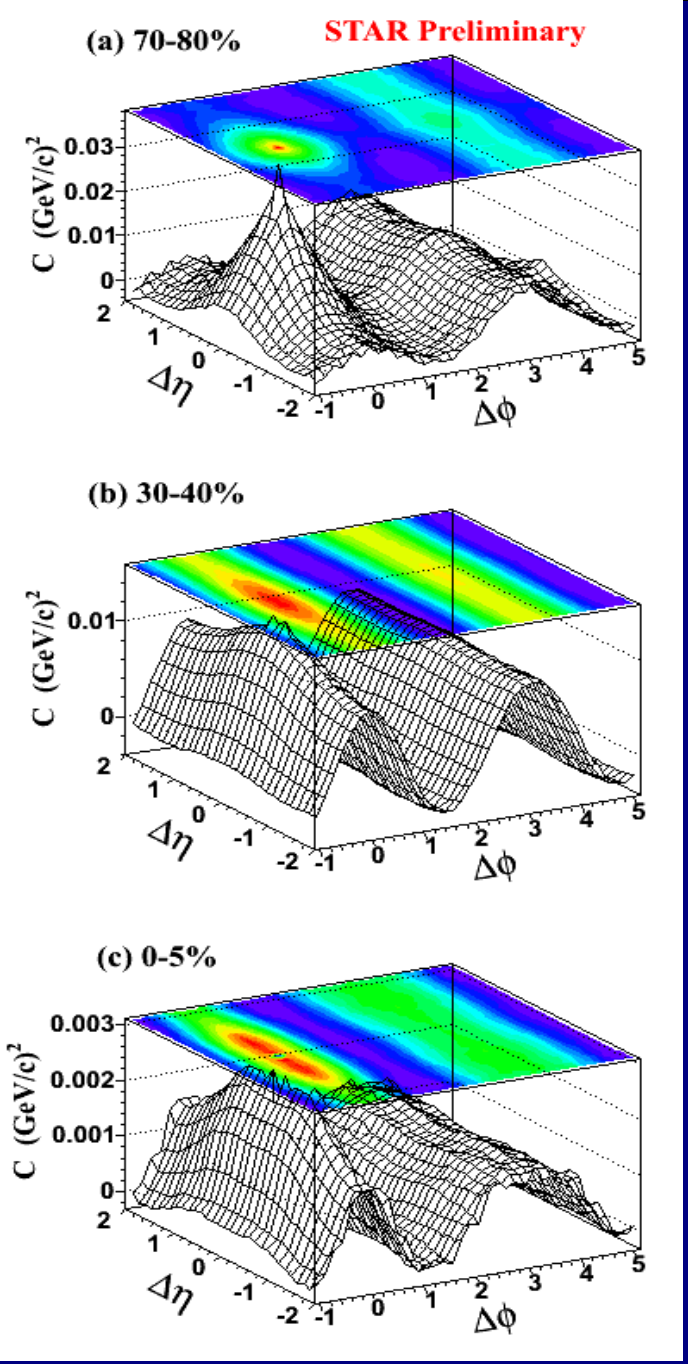




Hybrid correlation measure C (CI)

$$C = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{i \neq j=1}^{n_2} p_{T_i} p_{T_j} \right\rangle}{\langle n \rangle_1 \langle n \rangle_2} - \langle p_T \rangle_1 \langle p_T \rangle_2$$

- Advocated to be an experimental probe of viscosity that is independent of elliptic flow.
- Diffusion due to viscous effects broadens the rapidity profile of transverse momentum correlations.
- Not another model for an explanation of near-side ridge!

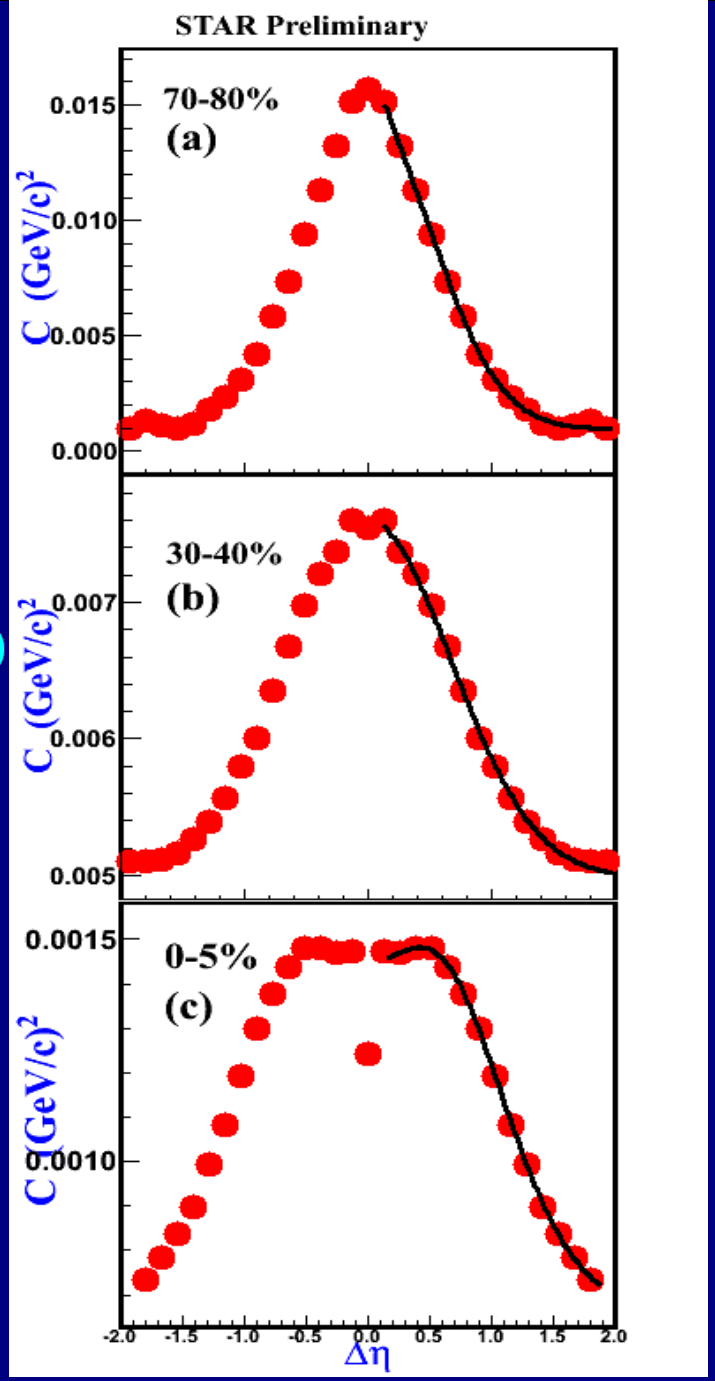


Quantification of near-side broadening

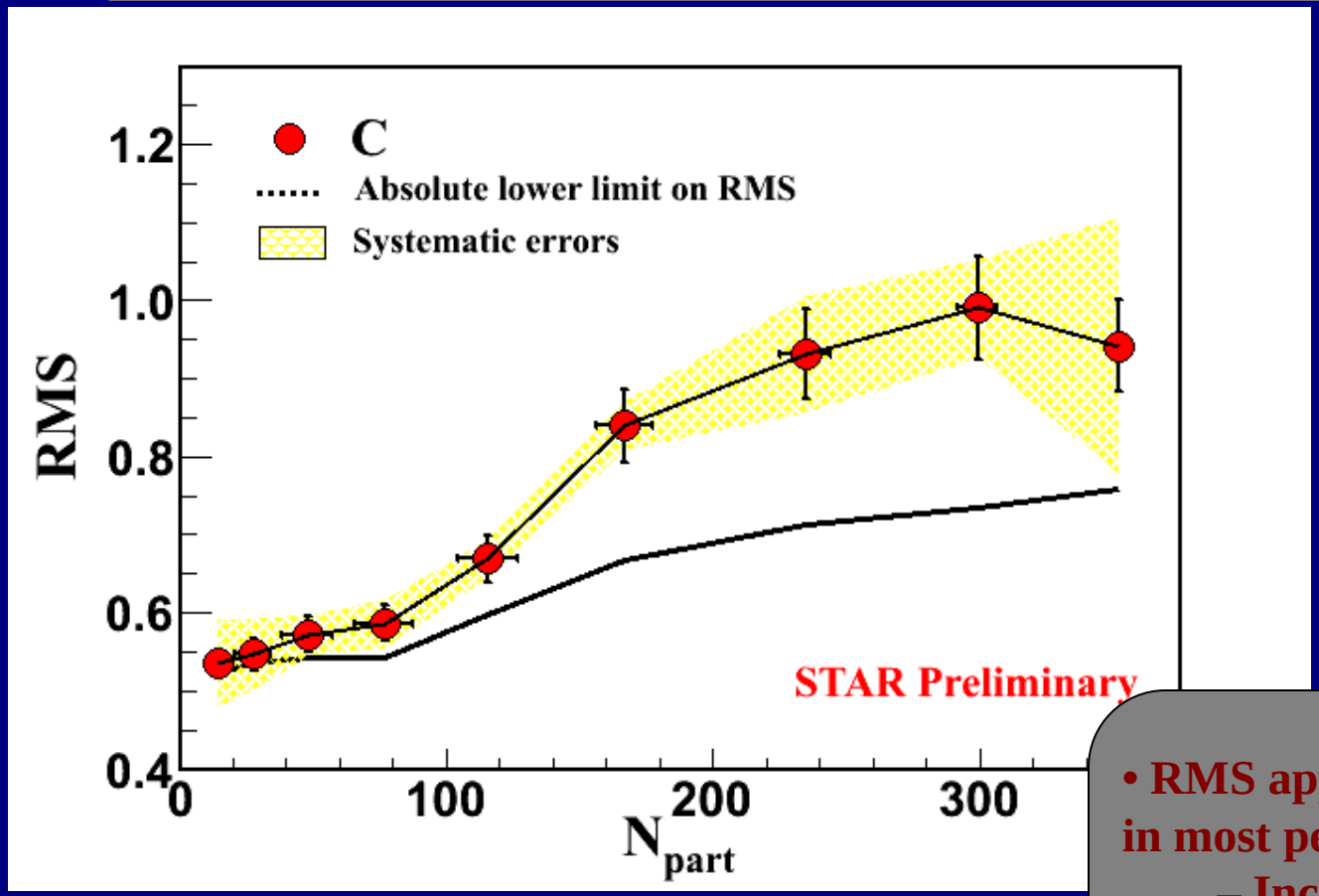
- Projection of the near-side, $|\Delta\phi| < 1.0$
- Fit parametrization:

$$C(b, a_w, \sigma_w, a_n, \sigma_n) = b + a_w \exp(-\Delta\eta^2 / 2\sigma_w^2) + a_n \exp(-\Delta\eta^2 / 2\sigma_n^2)$$

Baseline subtracted to estimate the RMS.



RMS vs. collision centrality



- RMS approximately constant in most peripheral bins.
  - Incomplete thermalization?
  - Radial flow effects?
  - Event centrality selection technique?

Estimation of shear viscosity

$$\sigma_c^2 - \sigma_0^2 = 4\upsilon\left(\tau_0^{-1} - \tau_{c,f}^{-1}\right)$$

$$\sigma_0 = 0.536 \pm 0.056 \qquad \tau_0 = 1 \text{ fm/c}$$

$$\sigma_c = 0.942 \pm 0.166 \qquad \tau_f = 20 \text{ fm/c}$$

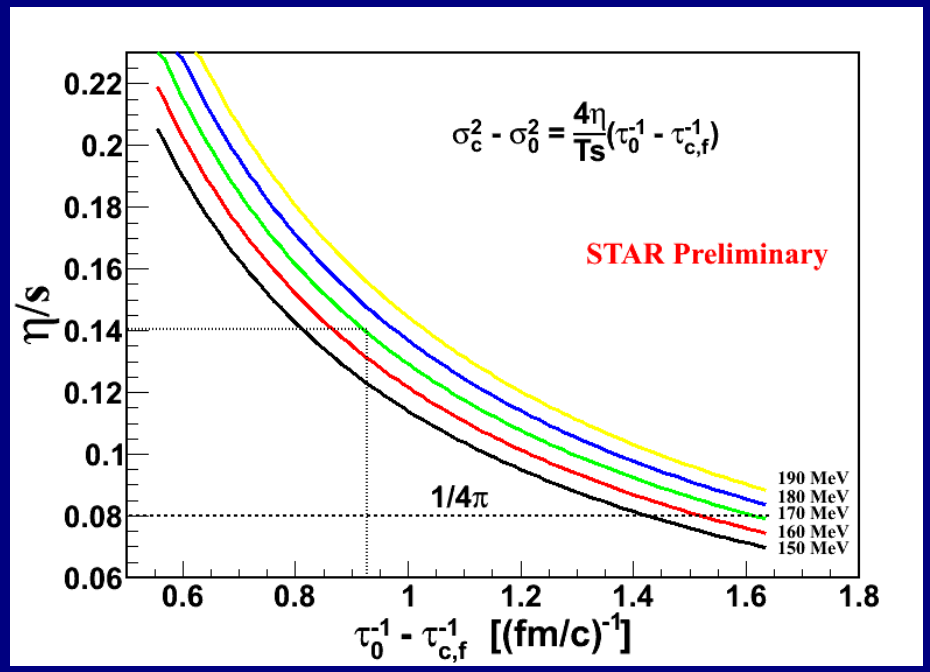
$$\frac{\eta}{s} = 0.13 \pm 0.03(stats.)$$

(Model dependent)

STAR paper to be submitted to PLB very soon.

Theoretical uncertainties:

- ✓ **References for freeze out time estimates in peripheral collisions**
  - **Bjorken PRD 27 (1983)**
  - **Teaney, Nucl. Phys. 62 (2009)**
  - **Dusling et al. arXiv:0911.2720**
  - **M. Luzum & P. Romatschke arXiv:0901.4588**



Courtesy T. Ullrich

Delayed hadronization

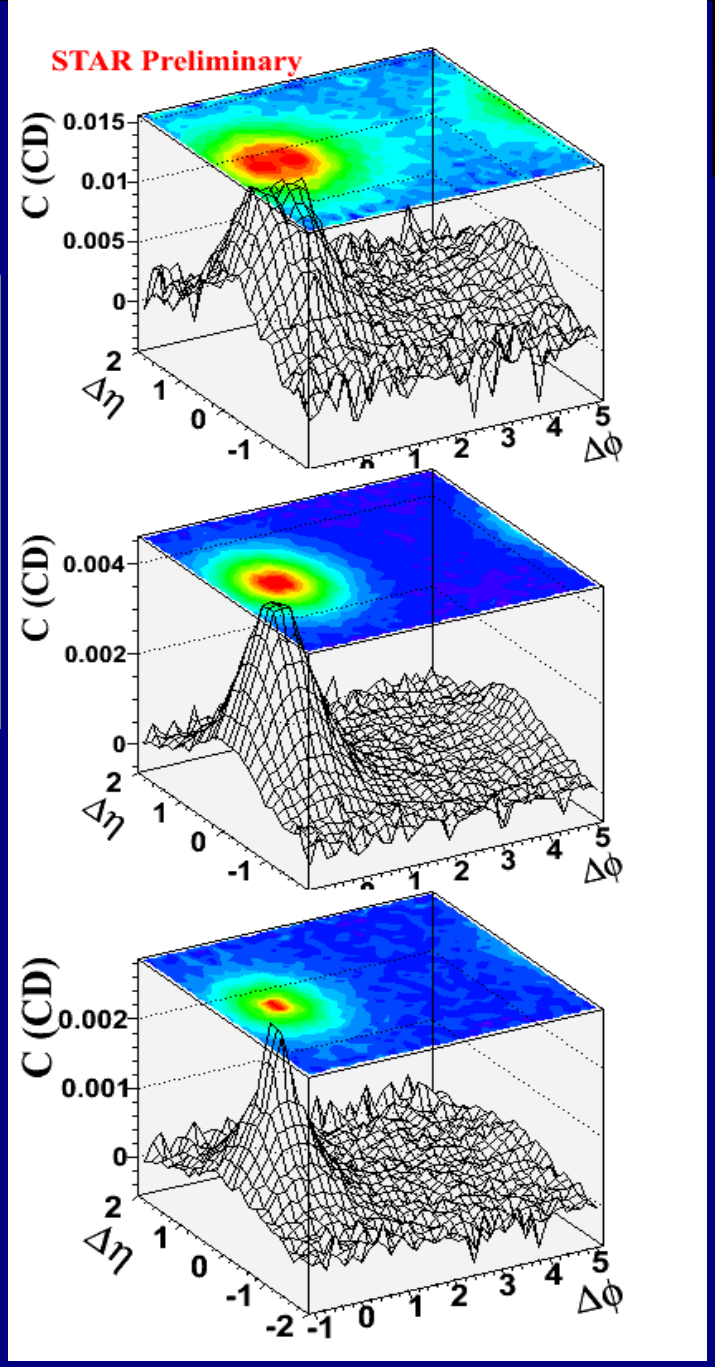
- Narrowing of charge dependent correlation function in azimuth and pseudorapidity.

$$O_{CD} = O_{+-} - \frac{1}{2}\left(O_{++} + O_{--}\right)$$

O = observable

$$R_2(CD) = R_{2,+-} - \frac{1}{2}\left(R_{2,++} + R_{2,--}\right)$$

$$C(CD) = C_{+-} - \frac{1}{2}\left(C_{++} + C_{--}\right)$$



Transvers
measure

$$\rho_2^{\Delta p_{T_1}\Delta p_{T_2}} =$$

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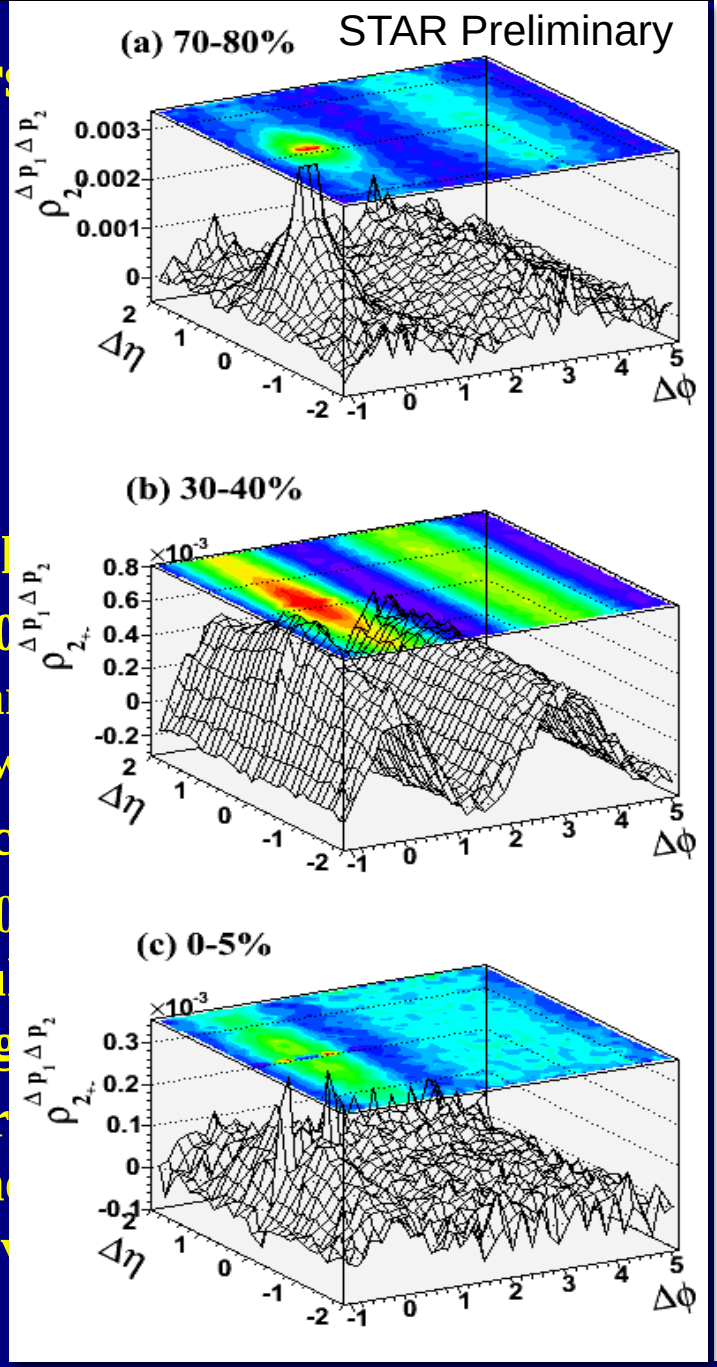
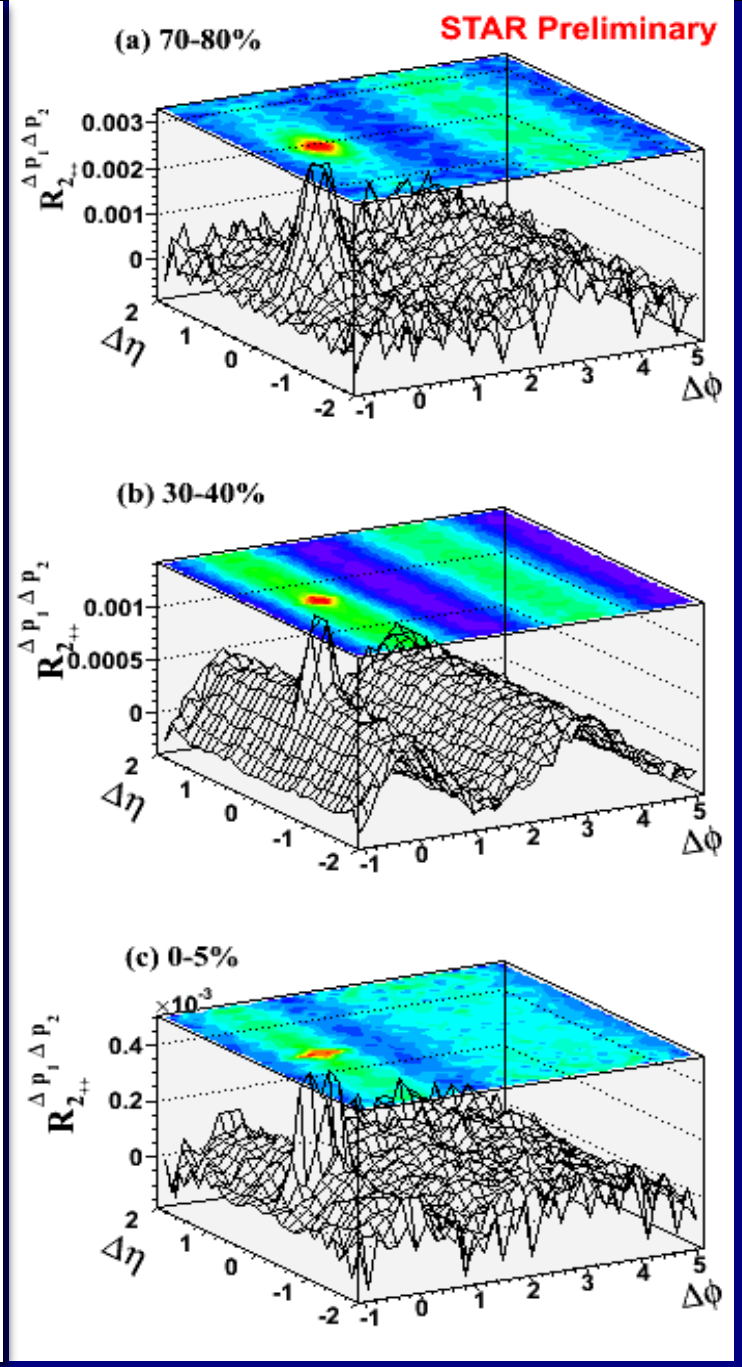


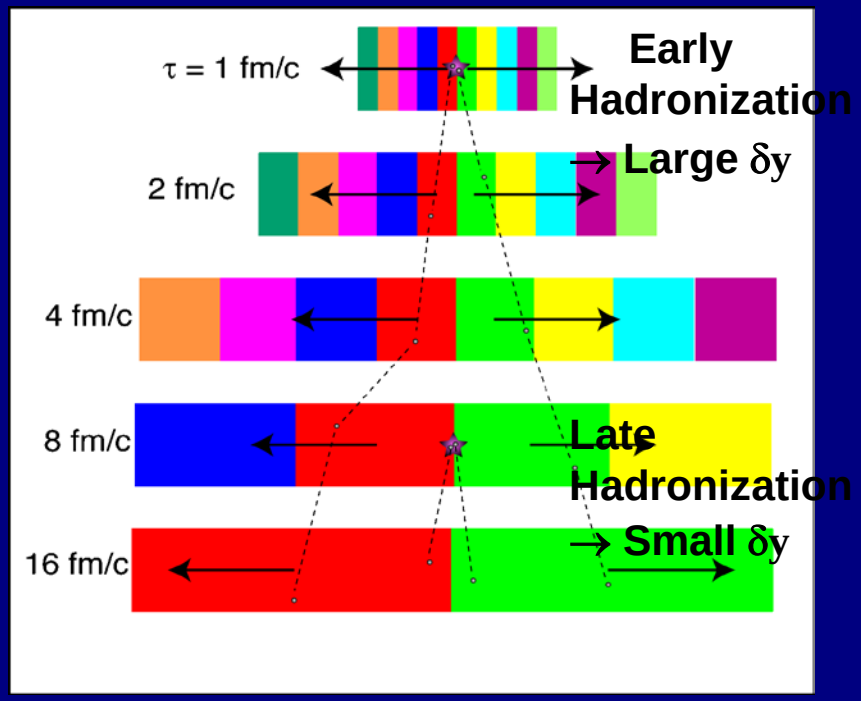


Summary

- Results shown for three different correlation functions, R_2, C and $\rho_2^{\Delta p_{T1}\,\Delta p_{T2}}$.
- Response of each of these correlation functions is different to the collision dynamics.
- C interpreted to be sensitive to viscous effects.
- Charge dependent results of R_2 and C sensitive to delayed hadronization, radial flow.
- Striking similarities such as ridge and away-side saddle shape is observed for same-sign (++, --) and unlike-sign (+-) charged combinations for R_2, C.
- Near-side valley type structure observed for like-sign charge combinations of C in most central collisions while no such structures are seen in $\rho_2^{\Delta p_{T1}\,\Delta p_{T2}}$.
- Co-efficients of Fourier decomposition of unlike and like signs are presented for R_2. Finite a_3 observed in both cases.

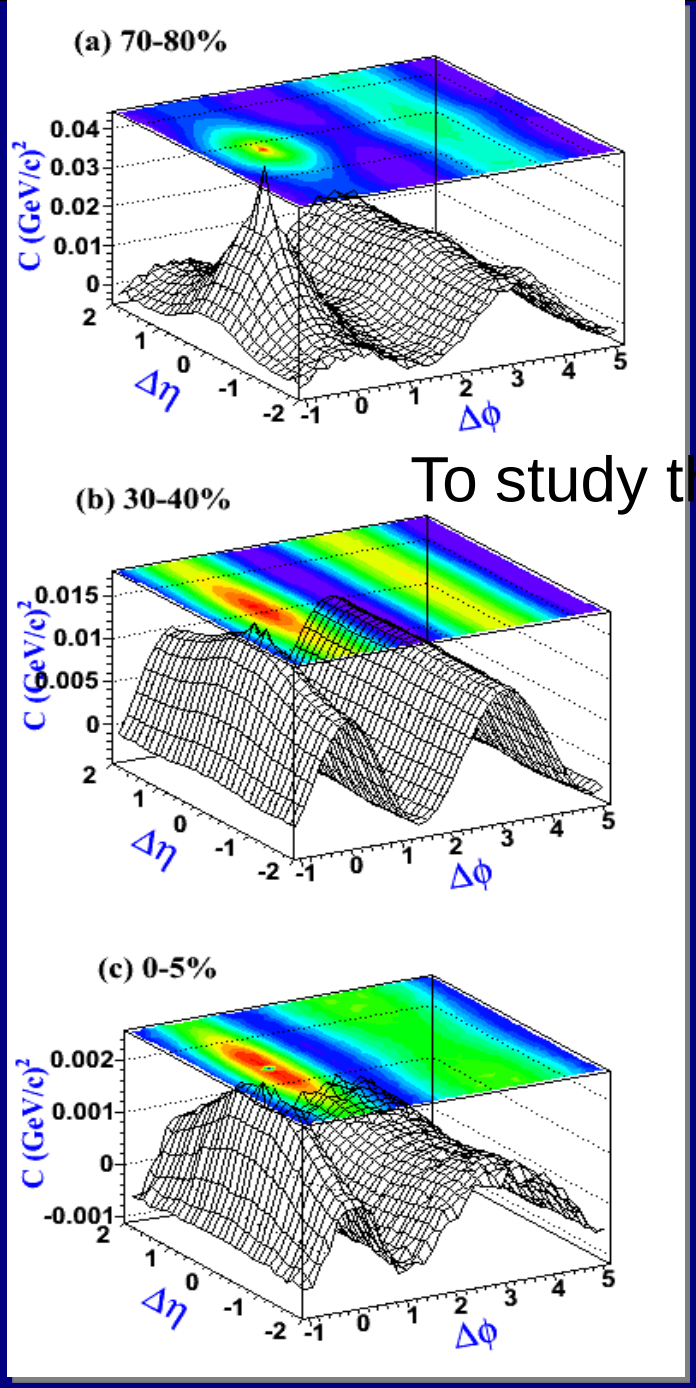
Back-up

- Delayed Hadronization

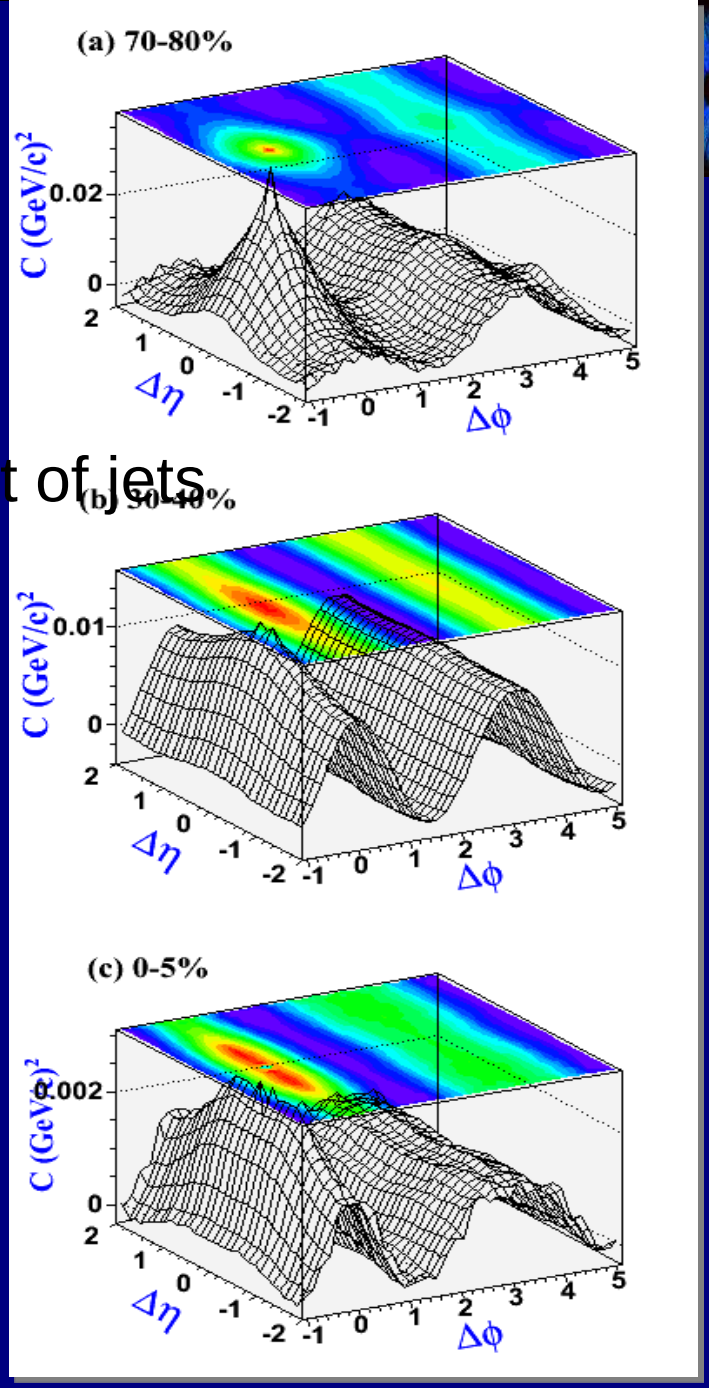


To study the effect of jets

$0.2<p_T<20.0$ GeV/c

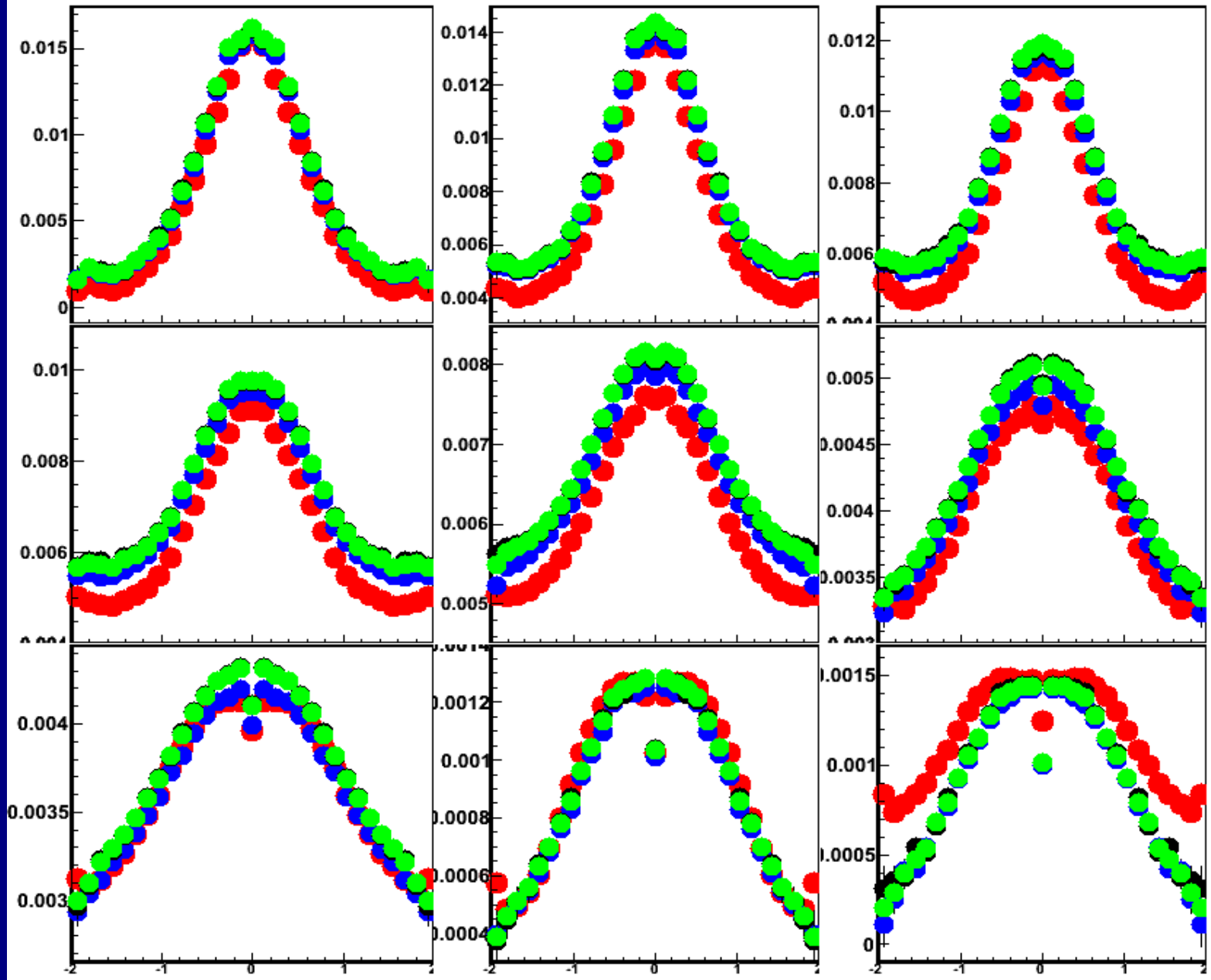


$0.2<p_T<2.0$ GeV/c



Near side ($|\Delta\phi| < 1.0$ radians) comparison

- $0.2<p_T<20.0$ GeV/c (RFF)
- $0.2<p_T<20.0$ GeV/c (FF)
- $0.2<p_T<2.0$ GeV/c

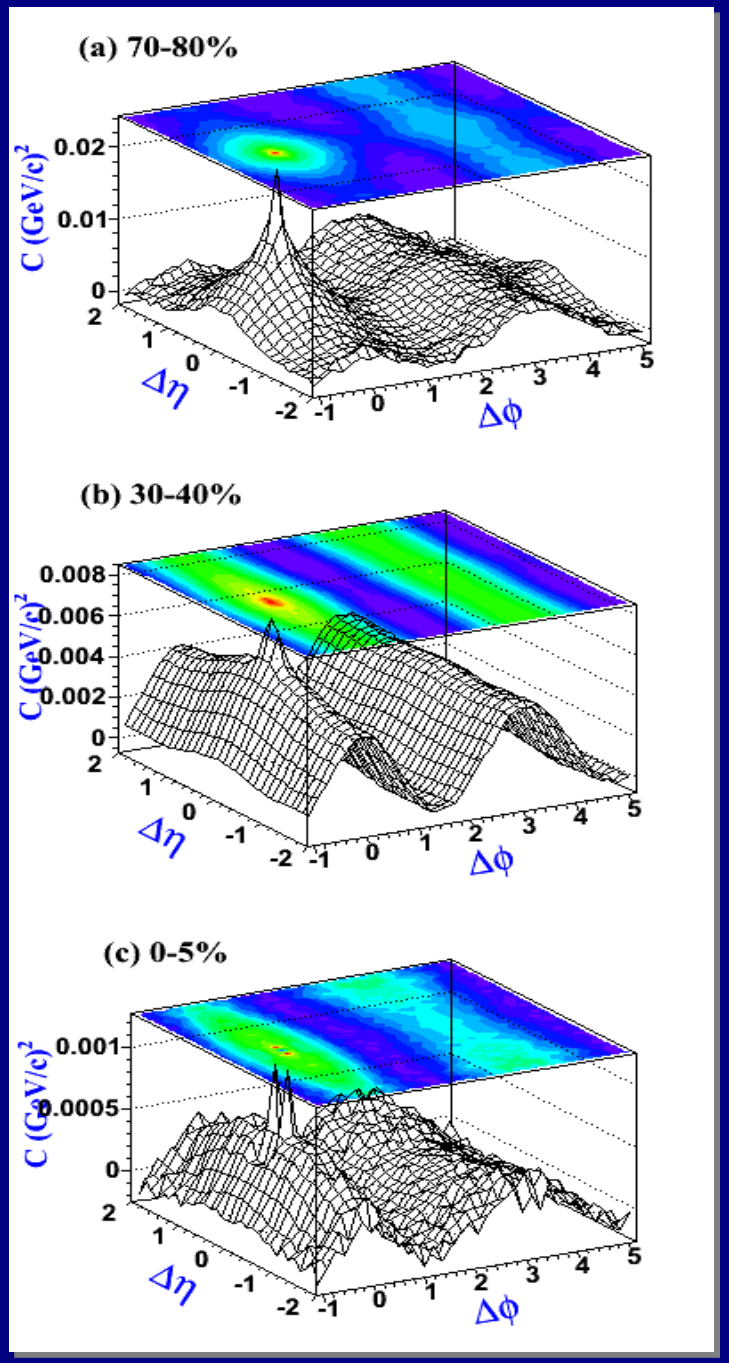


Monika Sharma

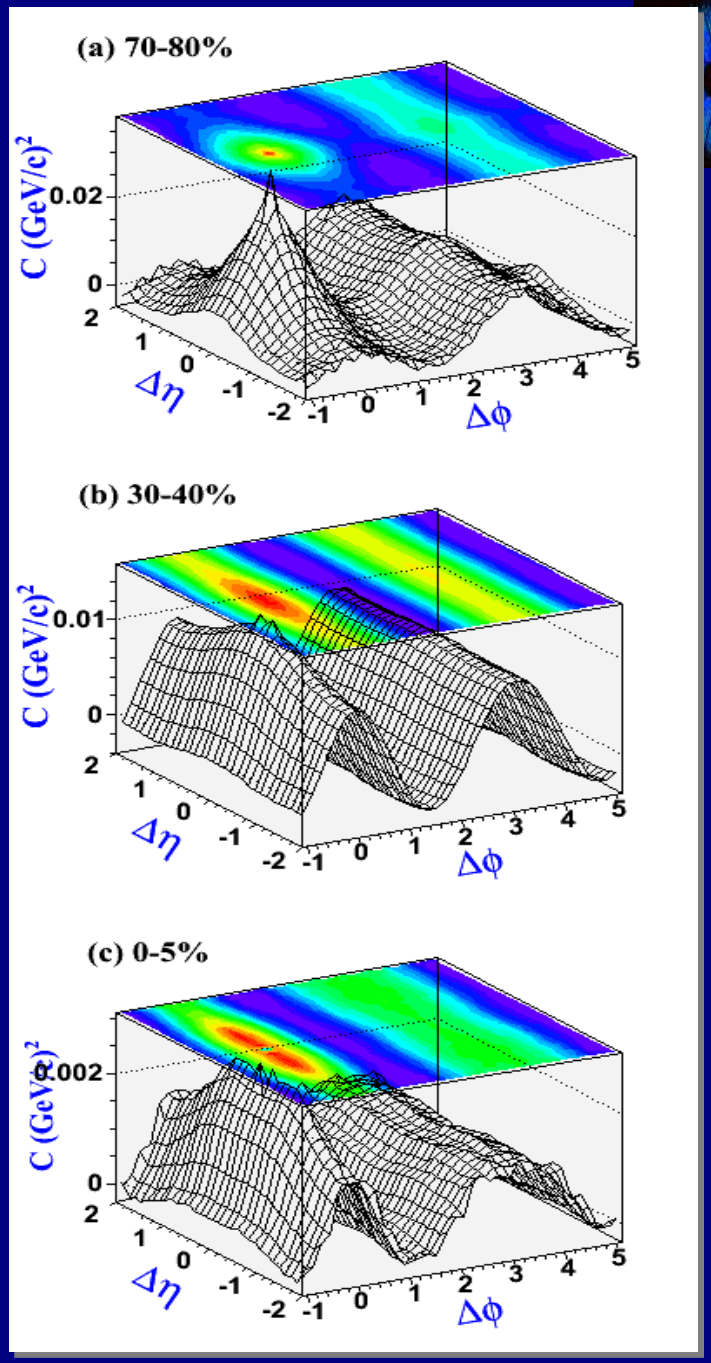
RMS comparison (0-5%)

- **RMS ($0.2 < p_T < 2.0$ GeV/c) = 0.942**
- **RMS ($0.2 < p_T < 20.0$ GeV/c) (FF) = 0.875**
- **RMS ($0.2 < p_T < 20.0$ GeV/c) (RFF) = 0.908**
- **RMS ($0.2 < p_T < 20.0$ GeV/c) (RFF + FF) = 0.88**
- **Fractional change = 6.6%**

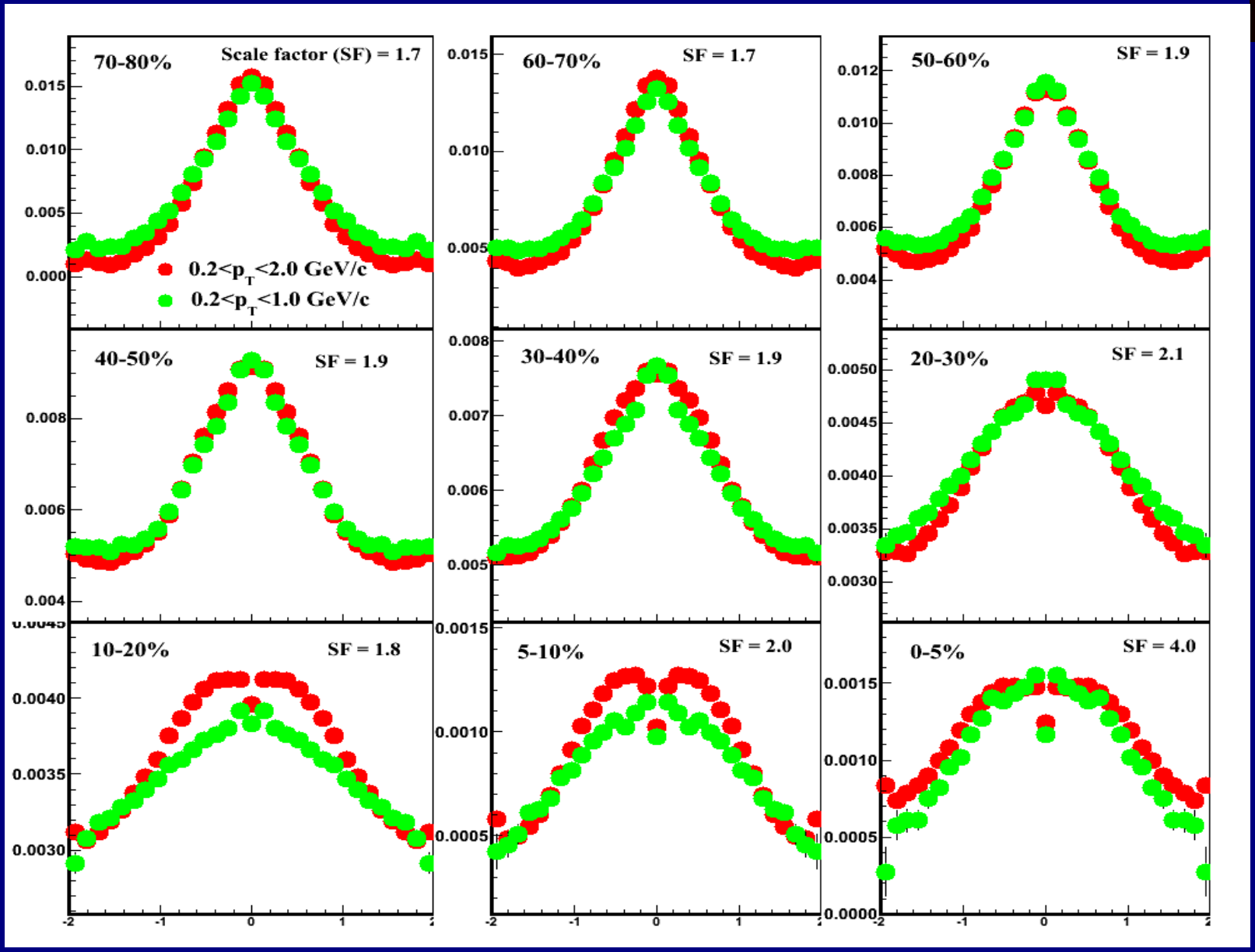
$0.2<p_T<1.0$ GeV/c



$0.2<p_T<2.0$ GeV/c



Near side ($|\Delta\phi| < 1.0$ radians) comparison



RMS comparison (0-5%)

- **RMS ($0.2 < p_T < 2.0$ GeV/c) = 0.942**
- **RMS ($0.2 < p_T < 1.0$ GeV/c) = 0.95**