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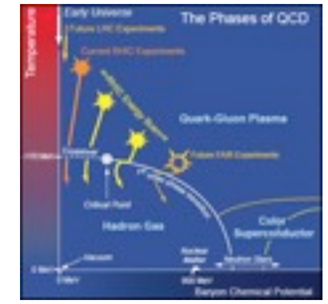
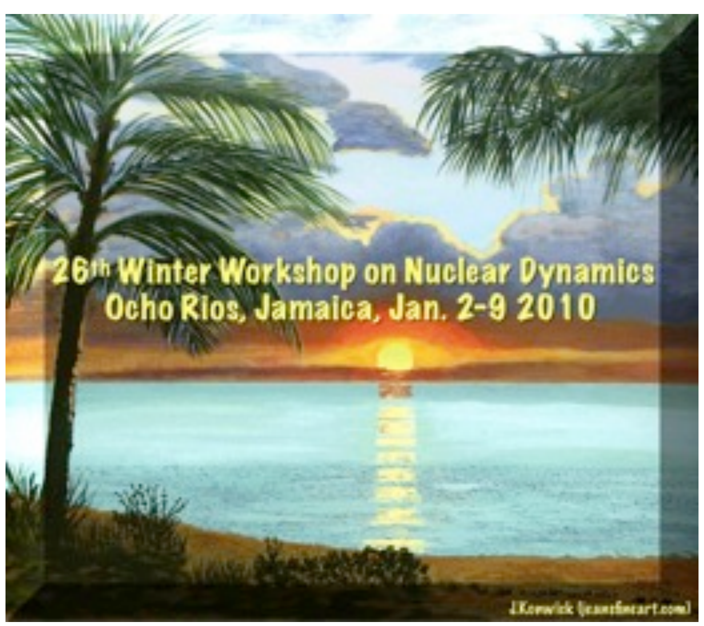


Rheology of the Quark Gluon Plasma

Measuring the shear viscosity with Pt Correlations

Claude A. Pruneau, for the STAR Collaboration

Wayne State University

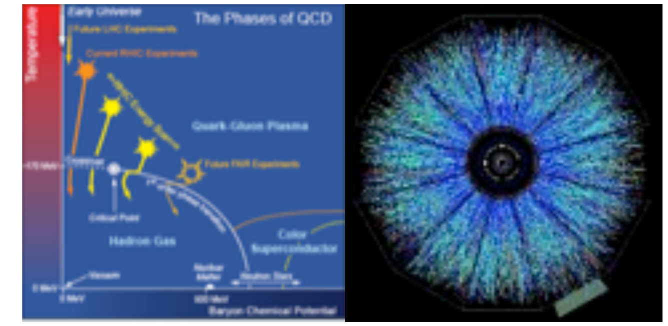


Acknowledgements

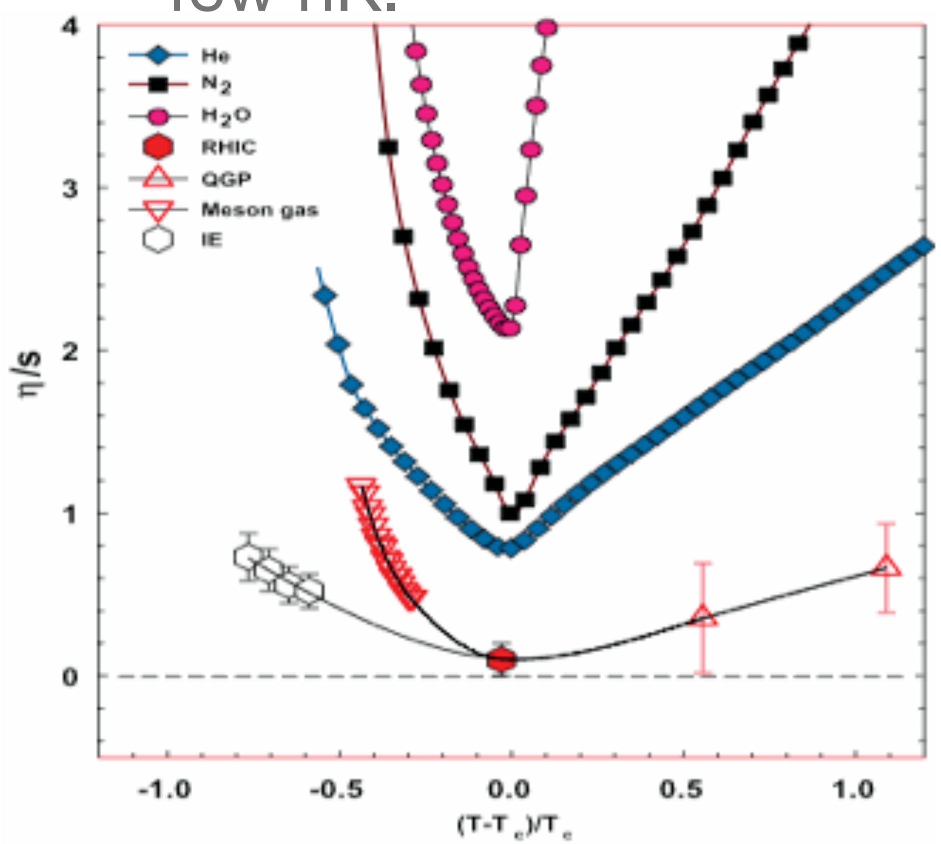
- **This talk based on a STAR Analysis carried out by Monika Sharma**
- **Thanks to S. Gavin for many discussions**

The perfect fluid!?!

Perfect Fluid?



- Superfluid Helium
- Ultra Cold Gasses
    - few nK.



Conjectured low bound of shear viscosity/entropy:

Supersymmetric Yang Mill Theory (Ads/CFT duality

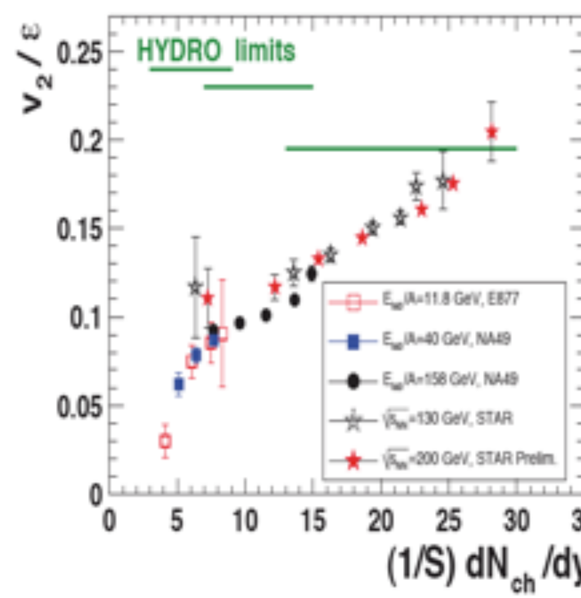
Kovtun, Son, & Starinets, PRL94(2005)

$$\frac{\eta}{\hbar s} \geq \frac{1}{4\pi}$$

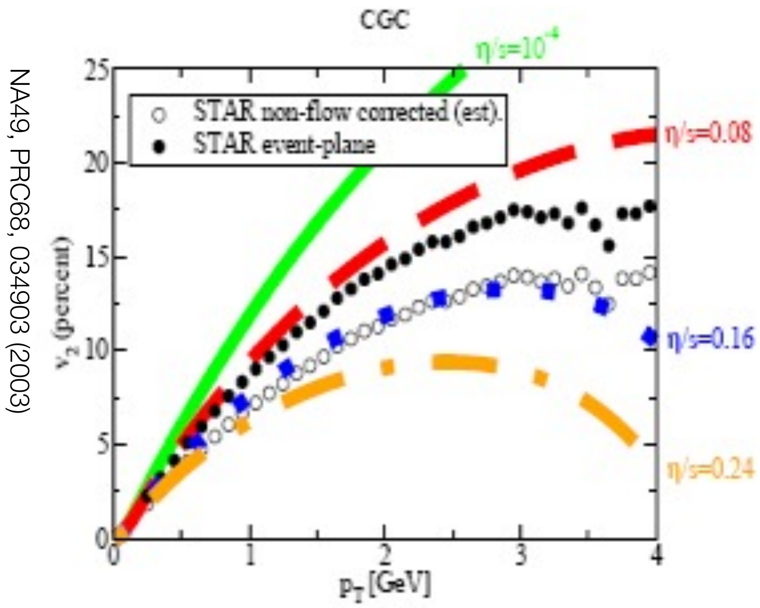
- Quark Gluon Plasma

T~200 MeV~10^{12} K

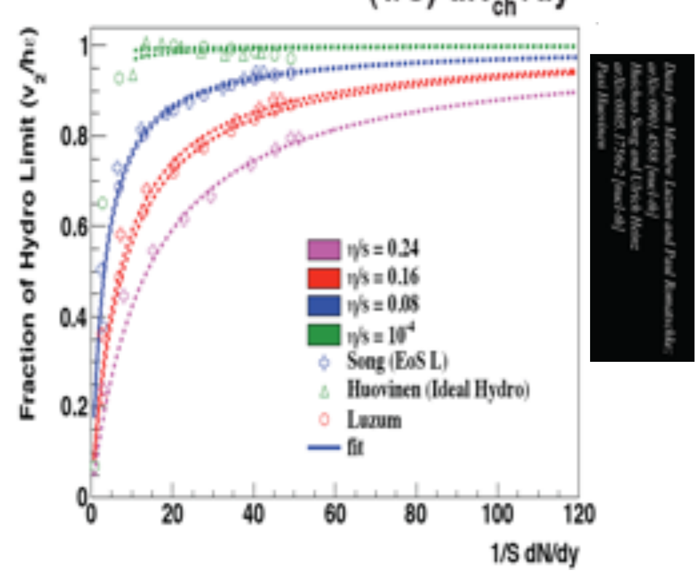
Temperature of early universe at ~1us



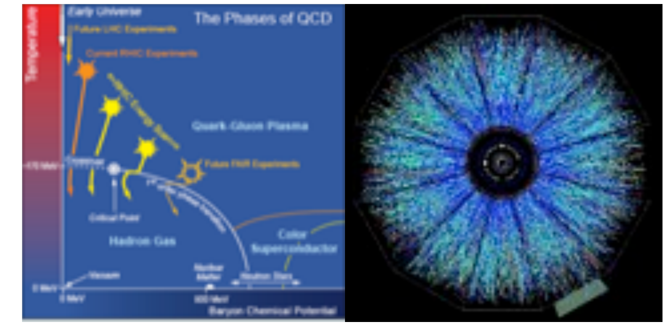
NA49, PRC68, 034903 (2003)
P.F. Kolb, J.Sollfrank, U.W.Heinz, PRC62, 054909(200)



M. Luzum & P. Romatschke, 0804.4015



Perfect Fluid?



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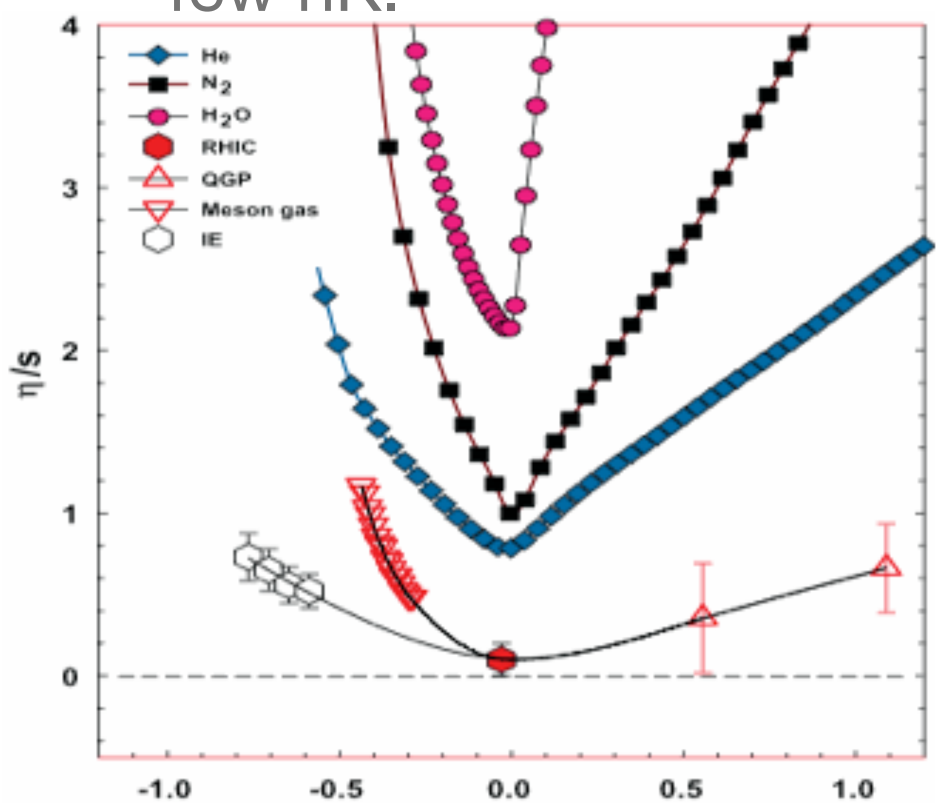

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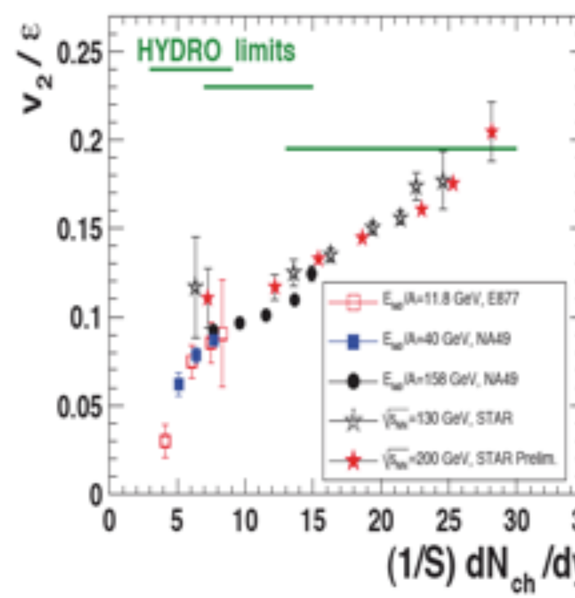

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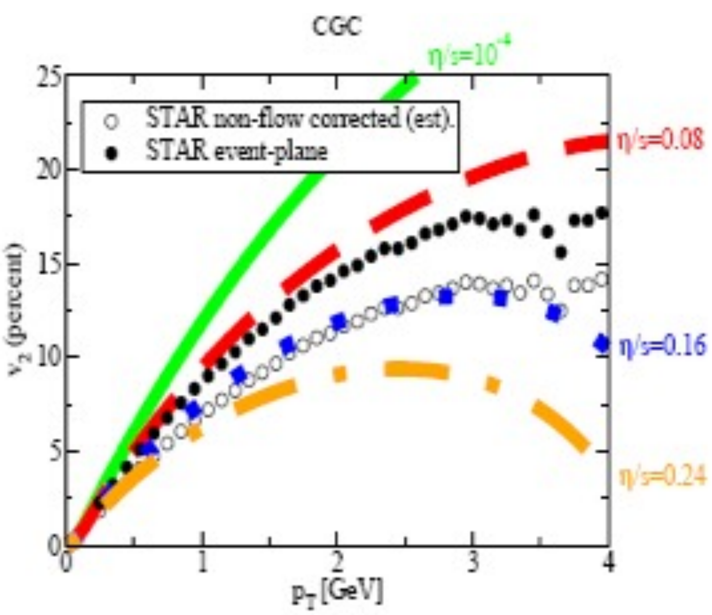

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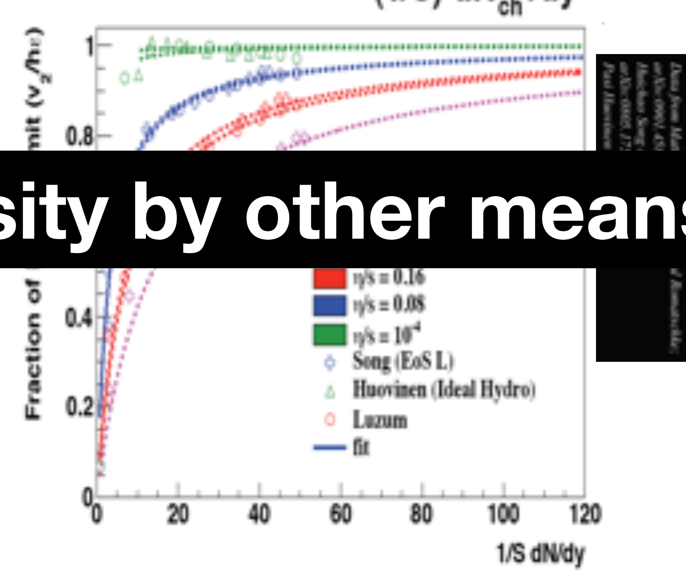


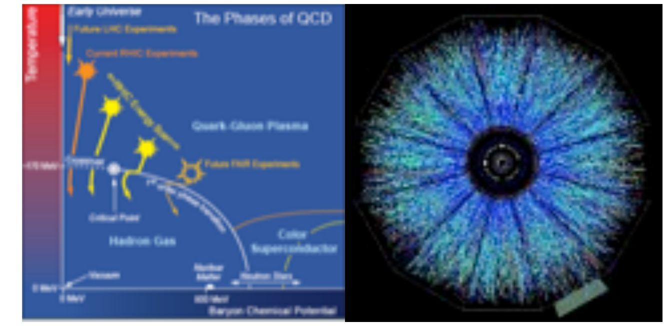
Can we measure the viscosity by other means at RHIC?

viscosity/entropy:

Supersymmetric Yang Mill Theory (Ads/CFT duality
Kovtun, Son, & Starinets, PRL94(2005)

$$\frac{\eta}{\hbar s} \geq \frac{1}{4\pi}$$

Perfect Fluid?



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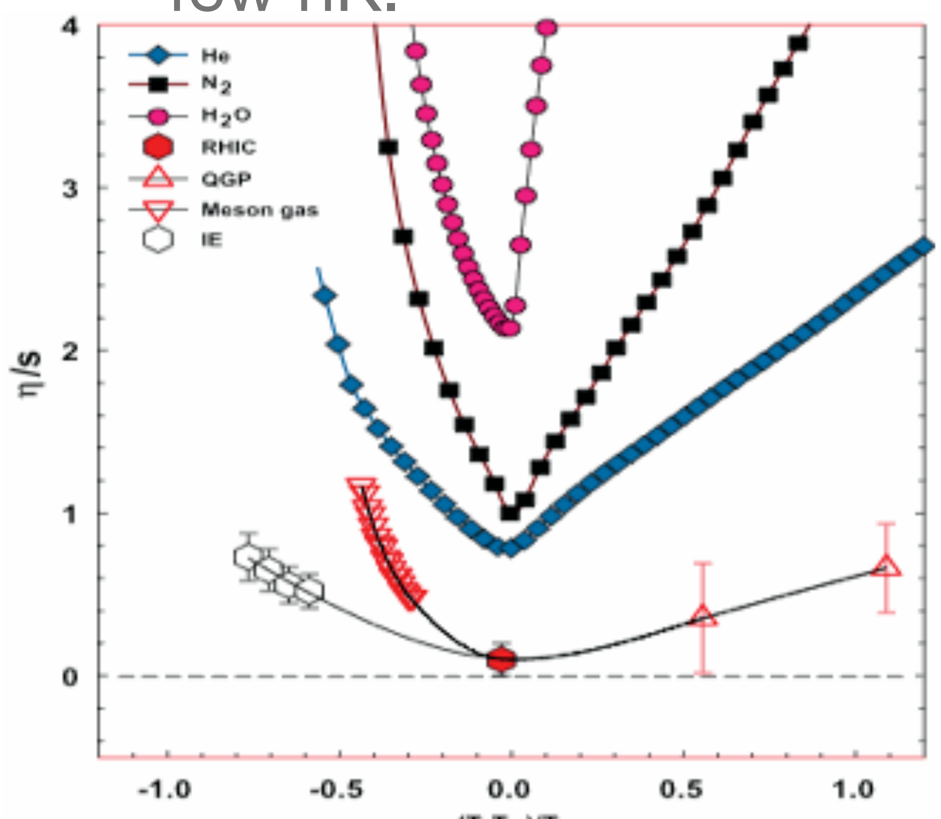

- Quark Gluon Plasma
  T~200 MeV~10^{12} K
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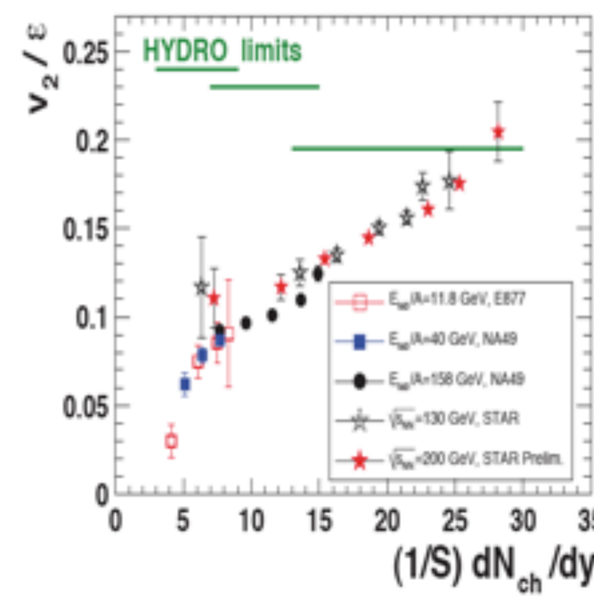

NA49, PRC68, 034903 (2003)
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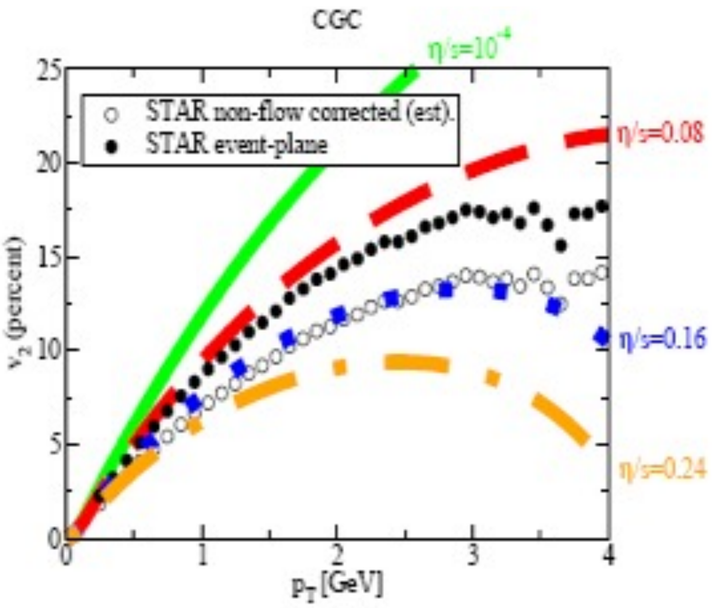
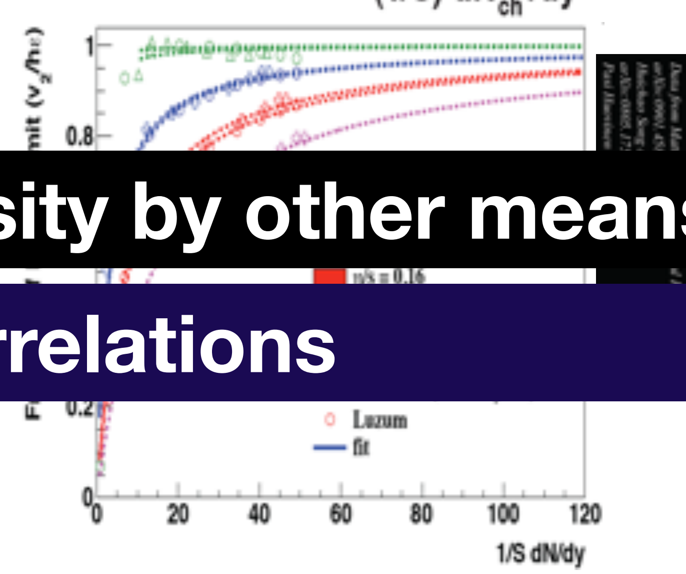


M. Luzum & P. Romatschke, 0804.4015



Can we measure the viscosity by other means at RHIC?

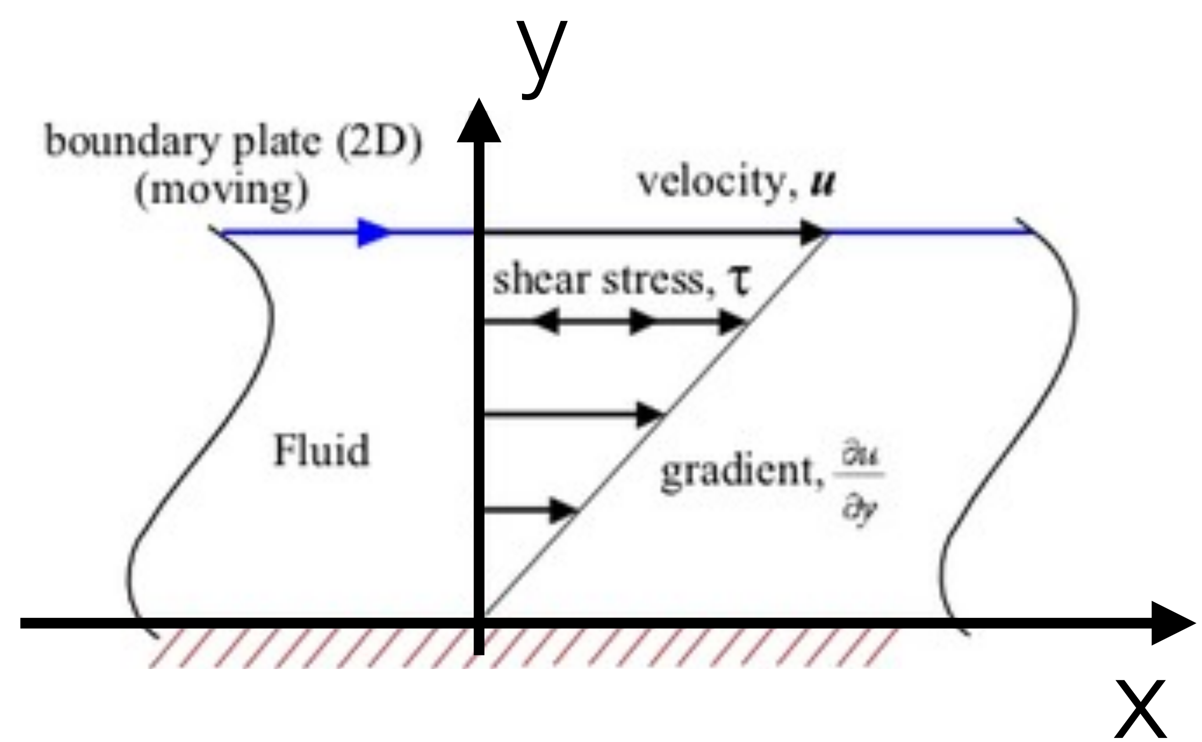
Yes: Use ptpt 2-particle correlations

Kovtun, Son, & Starinets, PRL94(2005)

$$\frac{\eta}{\hbar s} \geq \frac{1}{4\pi}$$

Rheometry: Measurement of Shear Viscosity

- Stress vs Deformation $\tau = \eta \frac{du}{dy}$
  - Velocity Gradient (m/s): du/dy
  - Shear Stress (Pa): τ
  - Dynamic viscosity (Pa s): η
- Kinematic Viscosity (m^2/s): $\nu = \frac{\eta}{\rho}$
  - Density (kg/m^3): ρ
- Relation to the Mean Free Path (m), λ: $\nu = \frac{1}{2}\bar{u}\lambda$
- In terms of the stress energy tensor: $T_{yx} = -\eta \frac{dv_x}{dy}$



Reynolds number, Re

- Definition

$$Re = \frac{\rho V L}{\mu} = \frac{\rho V L}{\nu}$$

where:

- V is the mean fluid velocity (SI units: m/s)
- L is a characteristic length, (traveled length of fluid) (m)
- μ is the dynamic viscosity of the fluid (Pa·s or N·s/m² or kg/m·s)
- ν is the kinematic viscosity (ν = μ / ρ) (m²/s)
- rho is the density of the fluid (kg/m³)

- In the context of HI collisions:
  An effective Reynolds number

$$Re = \frac{3}{4}\frac{\tau_o T s}{\eta}$$

where:

- T is the system temperature
- s the entropy of the system
- η shear viscosity
- τ_o formation time

Small Re implies laminar flow
Large value implies turbulent flow

Prediction/Estimate by S. Gavin, Nucl. Phys. A435 (1985) 826.

$$Re \sim 5$$

Measurement of viscosity based on p_t p_t Correlations

Gavin and Abdel-Aziz, nucl-th/0606061 (2006)

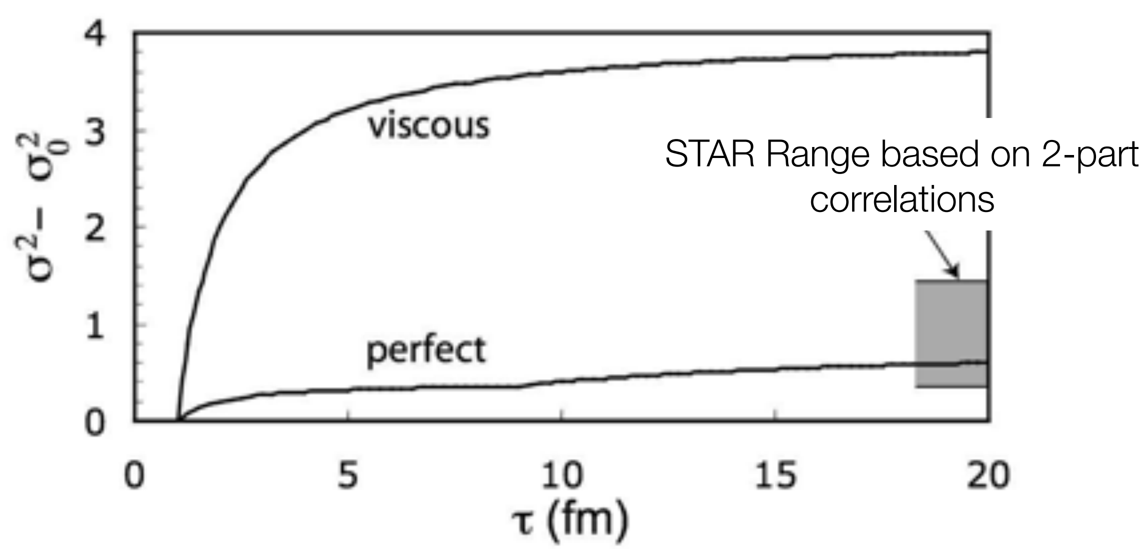
- Viscous friction arises as fluid elements flow past each other thereby reducing the relative velocity: damping of radial flow.
- T_{zr} changes the radial momentum current of the fluid $T_{0r} = \gamma^2 (\varepsilon + p) v_r$
- Diffusion equation for the momentum current $\left(\frac{\partial}{\partial t} - \nu \nabla^2\right) g_t = 0$
- 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 $r_g = \langle g_t(x_1) g_t(x_2)\rangle - \langle g_t(x_1)\rangle\langle g_t(x_2)\rangle$

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

$$\Delta V(\tau) \equiv \left\langle (\eta - \langle \eta \rangle)^2 \right\rangle = \frac{2\nu}{\tau_o}\left(1 - \frac{\tau_o}{\tau}\right)$$

τ_o Formation Time

τ_f Freeze-out Time

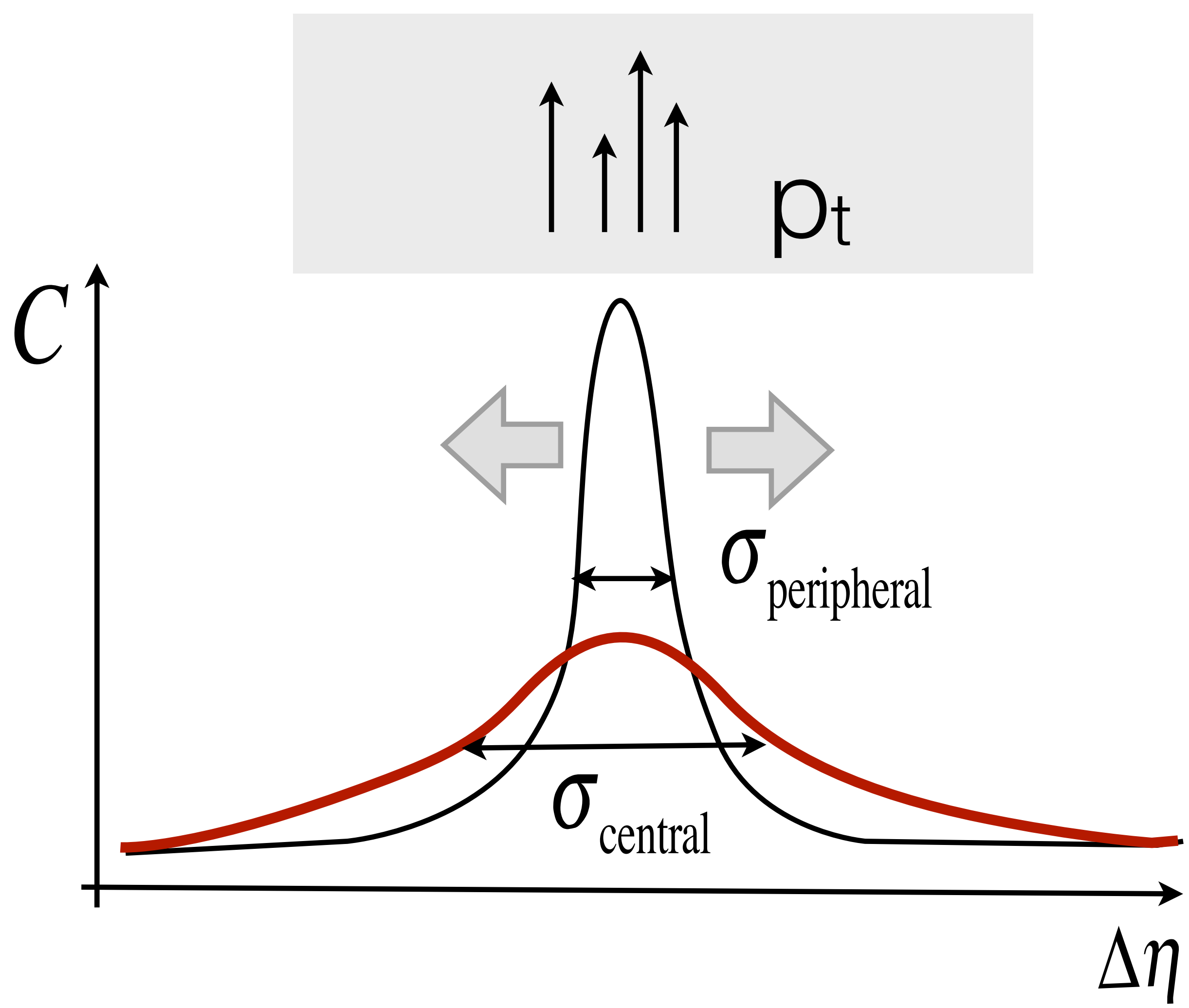


Reometry of the QGP with p_t-p_t Correlations

- ***Integral*** **Correlation Function (S. Gavin, M. Abdel-Aziz, nucl-th/060606)**

$$C(\Delta\eta) = \langle p_{\perp,1} p_{\perp,2} \rangle - \langle p_\perp \rangle^2$$

$$\langle p_{t1} p_{t2} \rangle \equiv \frac{1}{\langle N \rangle^2} \left\langle \sum_{\text{pairs } i \neq j} p_{ti} p_{tj} \right\rangle \qquad \langle p_t \rangle \equiv \frac{1}{\langle N \rangle} \left\langle \sum p_{ti} \right\rangle$$



$$\sigma_c^2 - \sigma_p^2 = 4\nu\left(\tau_{f,p}^{-1} - \tau_{f,c}^{-1}\right)$$

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

$\tau_{f,p}$ $\tau_{f,c}$ Freeze out Times

Estimate by Gavin, PRL 97, 162302 (2006)
(Integral) Transverse Momentum Correlations

$$0.08 < \eta/s < 0.3$$

based on

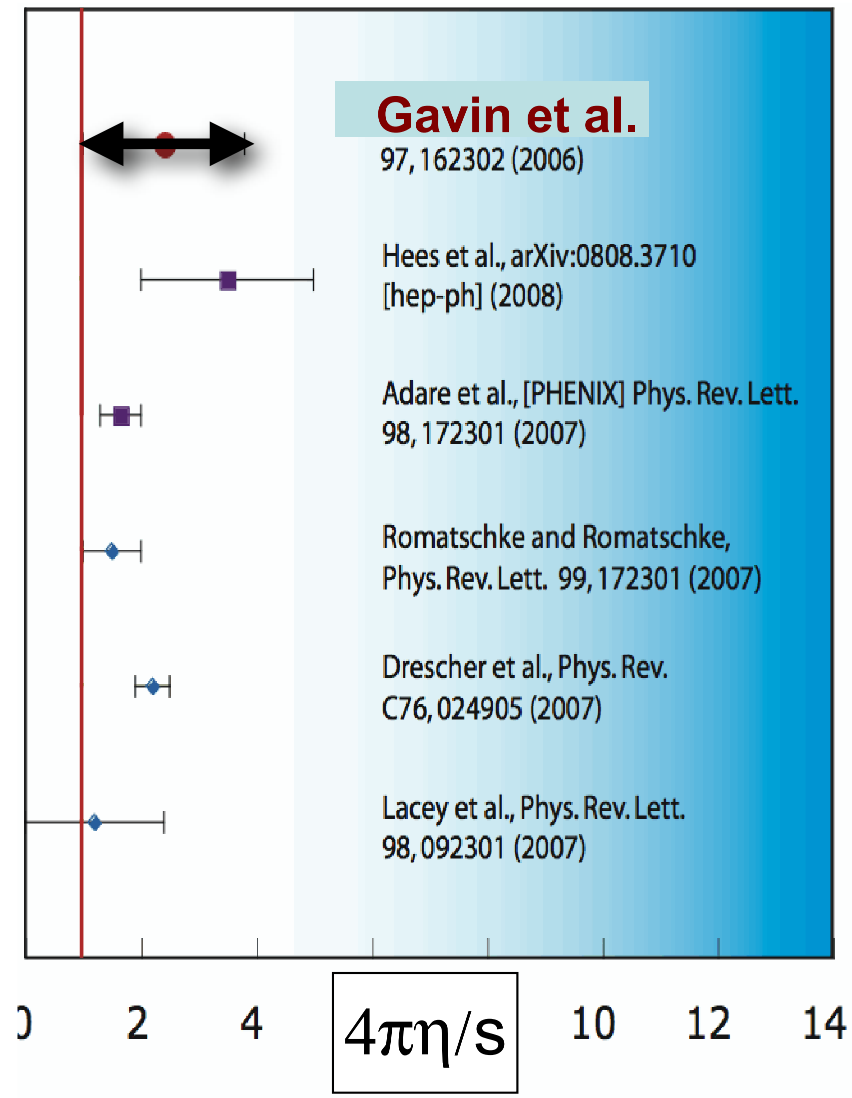
p_T correlations
STAR, J. Phys. G32, L37, 2006 (AuAu 200 GeV)

$$\eta/s \approx 0.08$$

Number density correlations
STAR, PRC 73, 064907, 2006 (AuAu 130 GeV)

$$\eta/s \approx 0.3$$

But, ...
Proper estimation of η/s requires an observable with contributions from number density & pT correlations

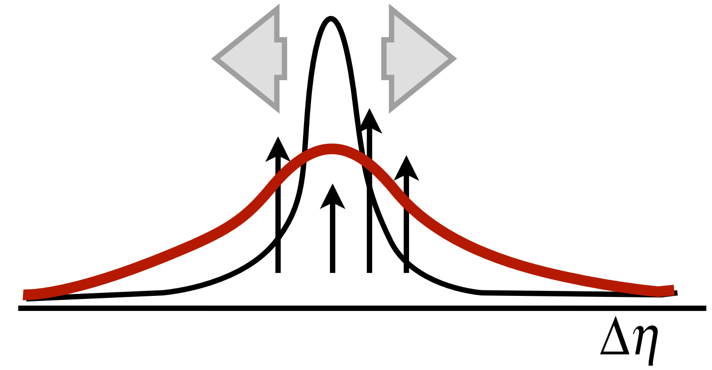


$$C = \langle p_{t1} p_{t2} \rangle - \langle p_t \rangle^2$$

$$\langle p_{t1} p_{t2} \rangle \equiv \frac{1}{\langle N \rangle^2} \left\langle \sum_{\text{pairs } i \neq j} p_{ti} p_{tj} \right\rangle$$

$$\langle p_t \rangle \equiv \frac{1}{\langle N \rangle} \left\langle \sum p_{ti} \right\rangle$$

This work: Differential p_t p_t Correlations



$$C(\Delta\eta,\Delta\varphi)=\frac{\left\langle \sum_{i=1}^{n_1}\sum_{j\neq i=1}^{n_2} p_i p_j \right\rangle}{\langle n_1\rangle\langle n_2\rangle}-\langle p_{t,1}\rangle\langle p_{t,2}\rangle$$

$$\Delta\eta=\eta_1-\eta_2$$

$$\Delta\varphi=\varphi_1-\varphi_2$$

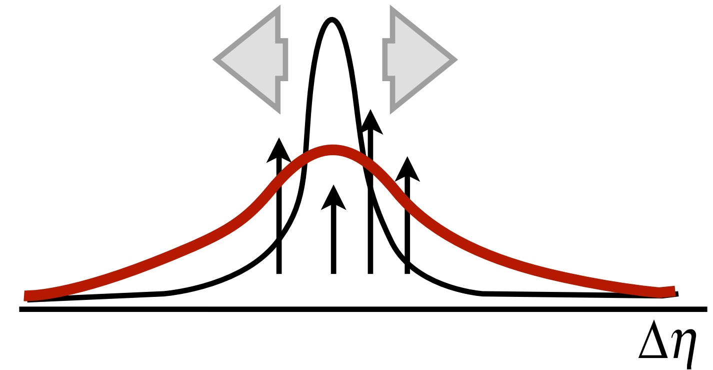
Inclusive average p_t: $\langle p_{t,i}\rangle(\eta_i,\varphi_i)=\frac{\left\langle \sum_{k=1}^{n_1} p_{t,k}\right\rangle}{\langle n_i\rangle}$

Transverse momentum of particles in bin *i*: $p_{t,i}$

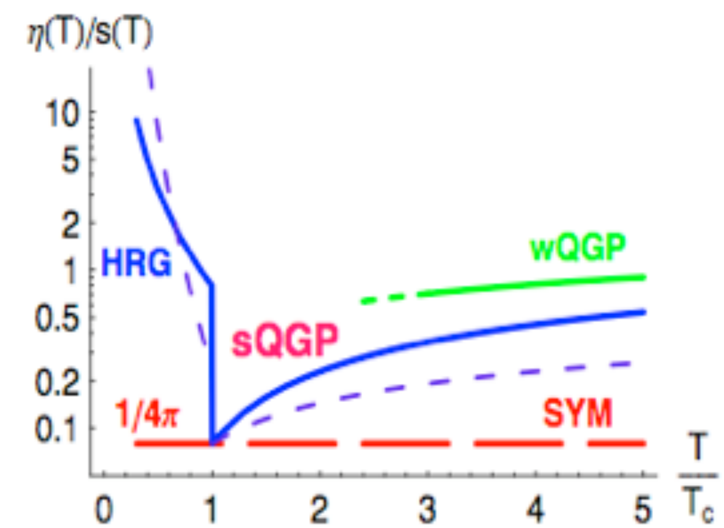
Number of particles in bin *i* $n_i \equiv n_i(\eta_i,\varphi_i),\quad i=1,2$

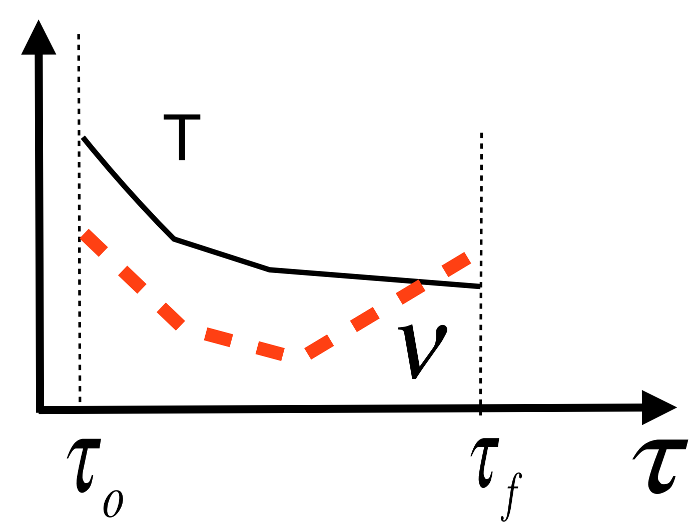
Broadening $\sigma_c^2 \approx \sigma_{Diffusion}^2 + \sigma_0^2$

Theoretical/Physics Caveats



- The system temperature, viscosity, and Reynolds# vary through the lifetime of the collision system.
  - Our measurement will yield ***time averaged quantities***
- Freeze out times must be inferred from other data + model
- Other effects may contribute to the longitudinal shape of the correlation function
  - Decays, thermal broadening, jets, radial flow, CGC, etc
  - Jet expected to have minor impact in the momentum range considered in this analysis.
  - **Diffusion expected to dominate the broadening (see next few slides)**
- A detailed interpretation of the measurements requires collision models that provide comprehensive understanding of HI data.





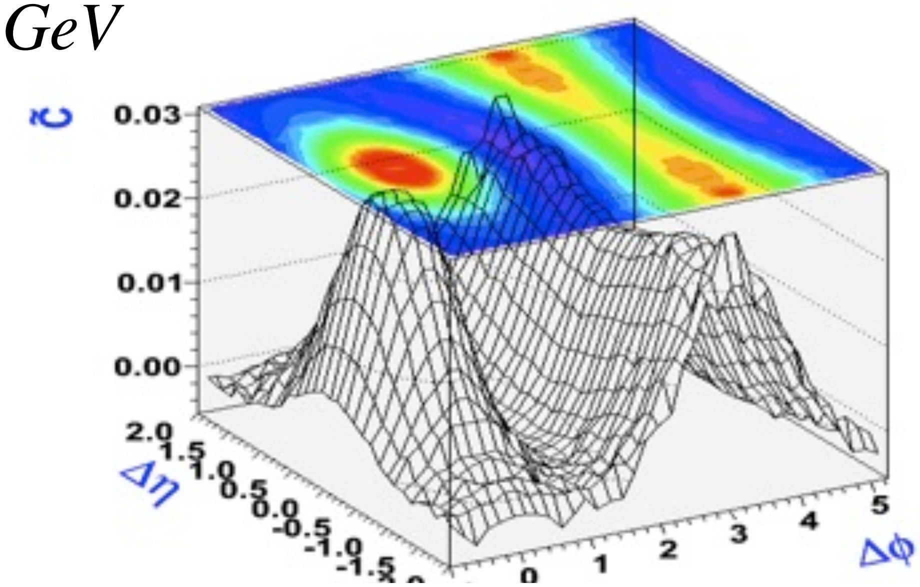
Dynamical Effects (1): Radial Flow

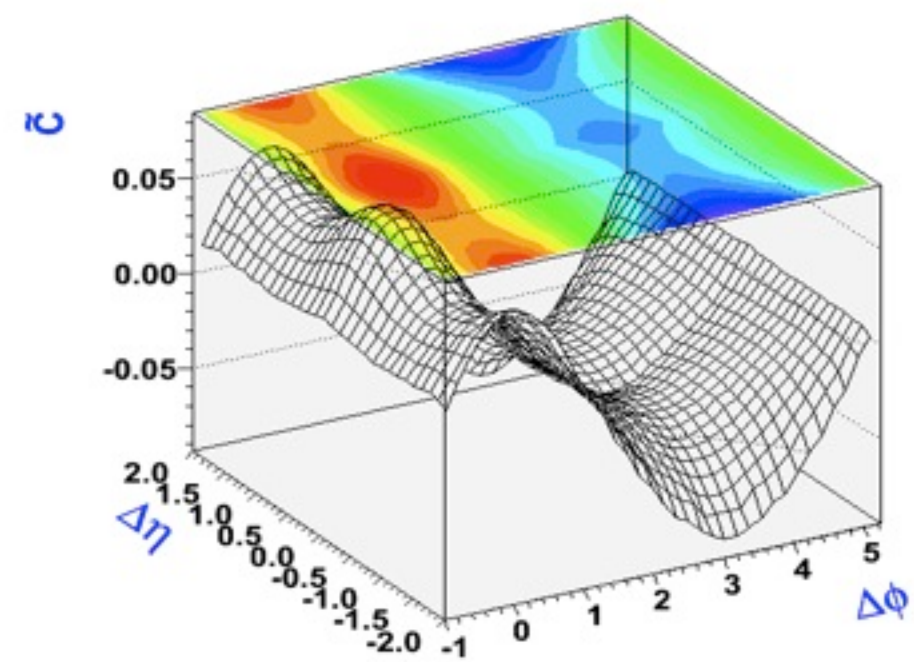
- Based on PYTHIA p+p collisions at $\sqrt{s} = 200 \;\; GeV$

$$0.2 < p_T < 2.0 \text{ GeV/c}$$

$$|\eta| < 1$$

- PYTHIA Simulation including radial flow (transverse boost) with v/c=0.3





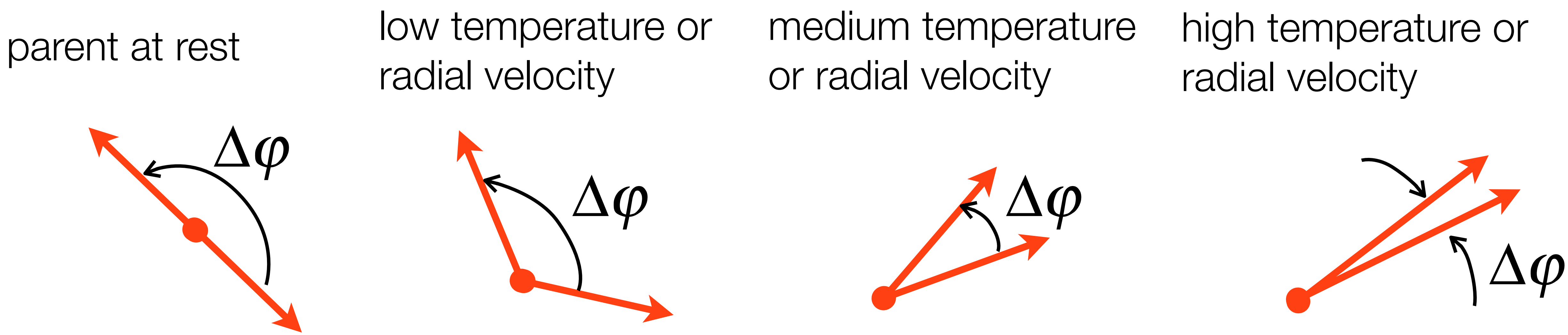
- Near-side kinematic focusing, formation of ridge-like structure,
- Different shapes
- Narrowing of near side

S. A. Voloshin, arXiv:nucl-th/0312065
C. Pruneau, et al., Nuclear. Phys. A802, 107 (2008)

See M. Sharma & C. A. Pruneau, Phys. Rev. C 79 (2009) 024905 for more details.

Dynamical Effects (2): Resonance Decays

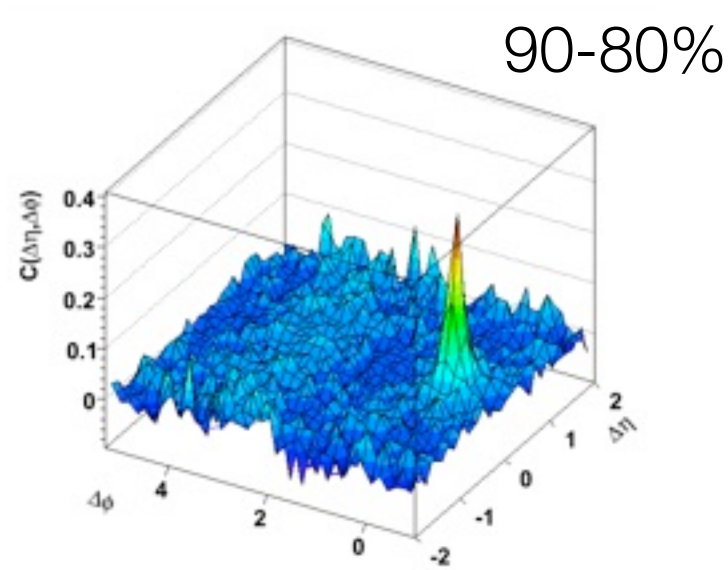
- An increase in system temperature and/or radial flow implies kinematical focusing of the decay products: ***narrowing of the correlation function***.

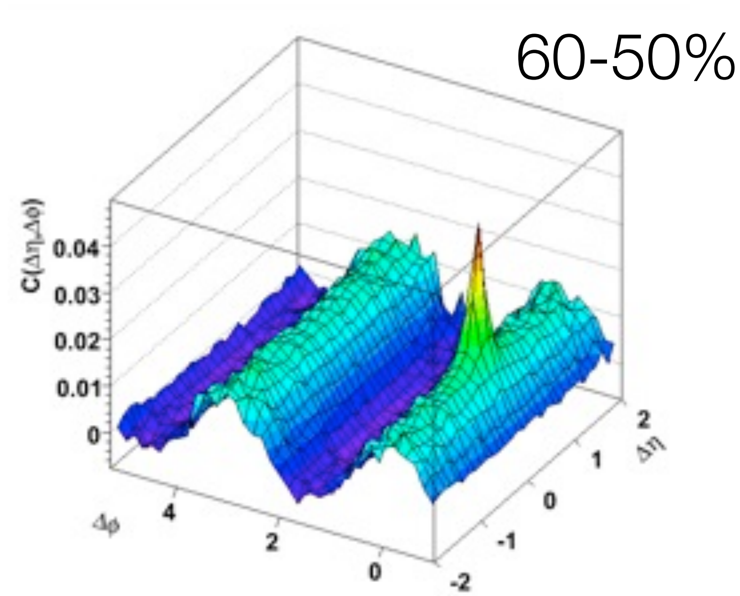


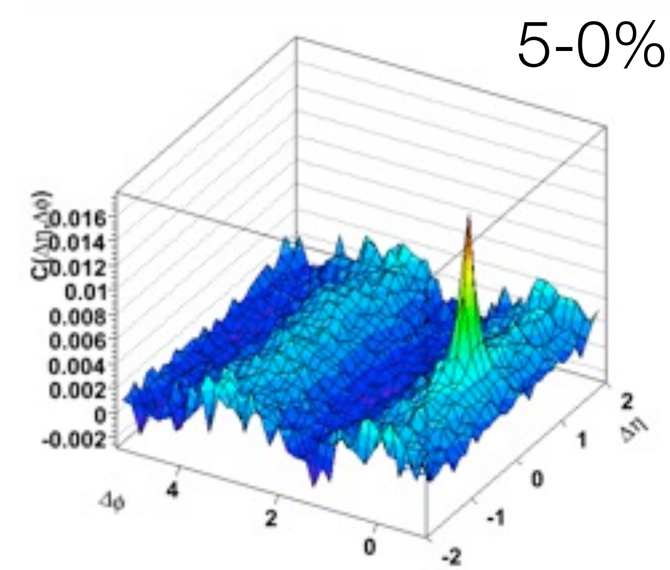
- Note however that re-scattering after decay implies causes ***thermal diffusion***, and ***correlation broadening***. --- needs modeling to properly assess its impact...

Dynamical Effects (3): Core vs Corona

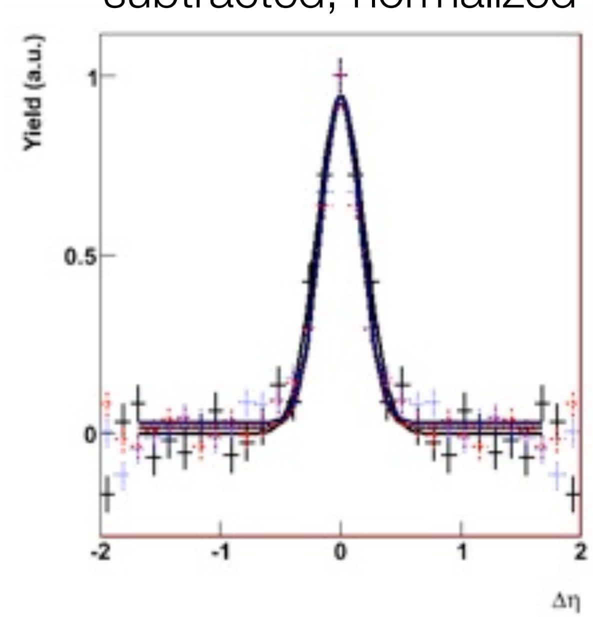
- Simulation of Au Au @ sqrt(s)=200 GeV based on the **EPOS-1 Not HYDRO** (courtesy of K. Werner)





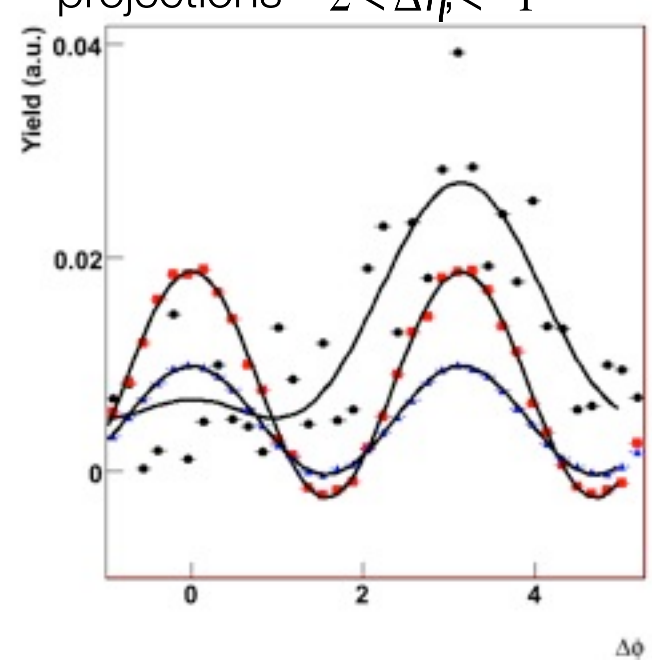


projections within $|\Delta\varphi|<1$, offset subtracted, normalized

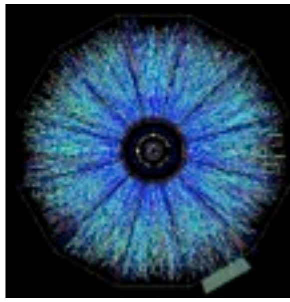


No broadening
No ridge

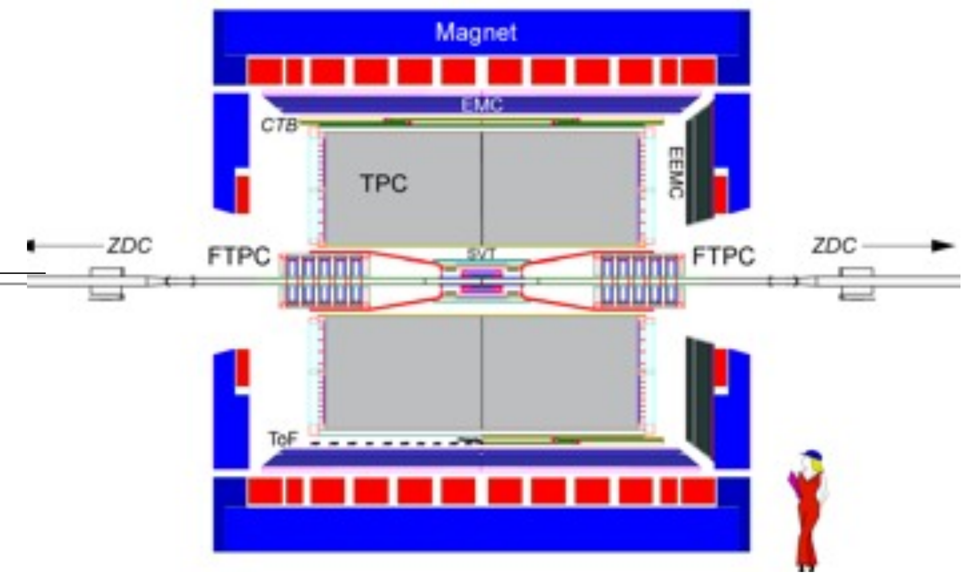
projections $-2<\Delta\eta<-1$



Momentum conservation and elliptic flow



STAR Analysis



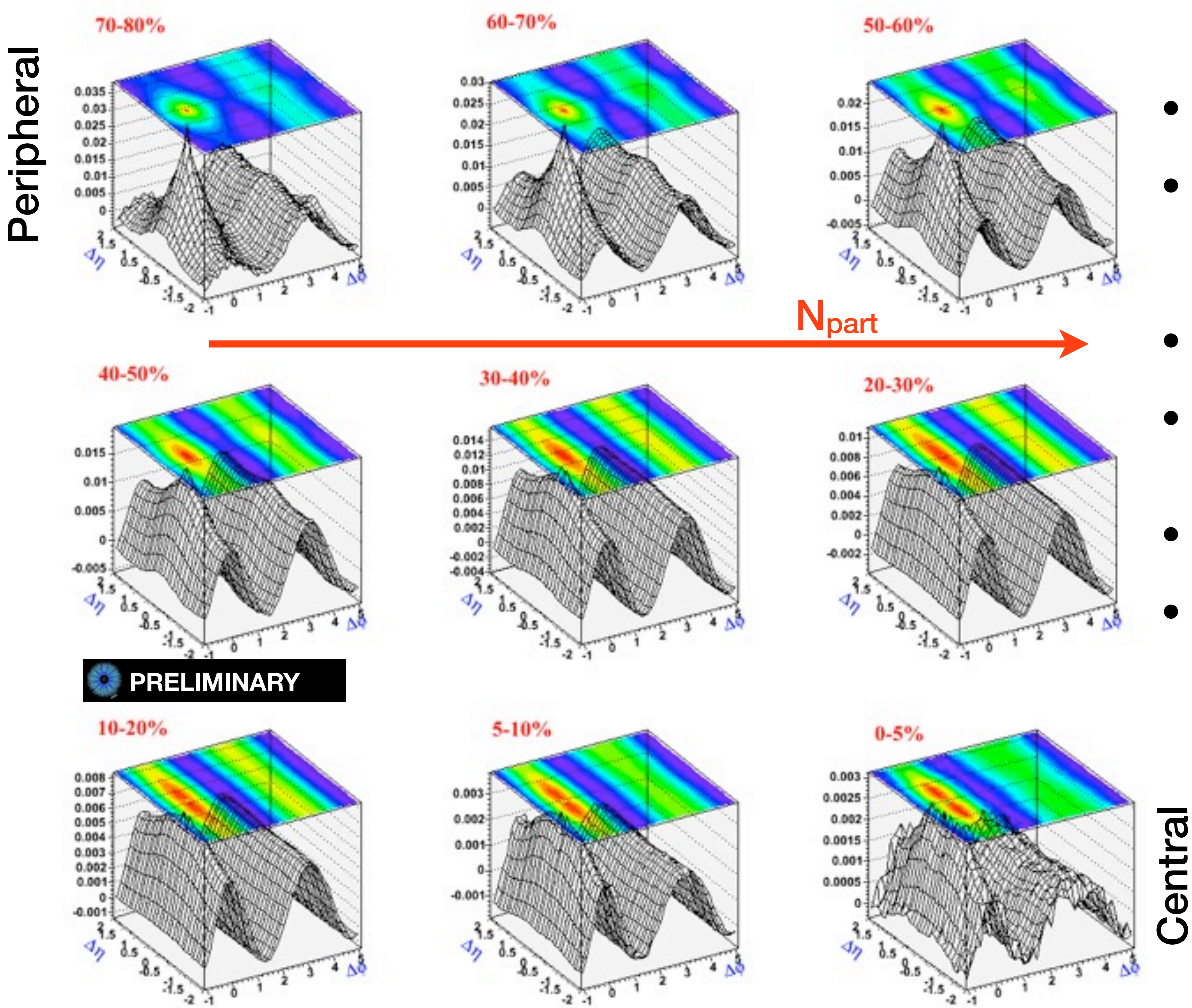
- Data from STAR TPC, 2π coverage
- Dataset: RHIC Run IV: AuAu 200 GeV
- Events analyzed: 10 Million
- Minimum bias trigger
- Track Kinematic Cuts
  - Goal: Measure medium properties i.e. Bulk Correlation
  - $|\eta| < 1.0$
  - $0.2 < p_T < 2.0$ GeV/c

Note: Using STAR usual track and event quality cuts

- Analysis done vs. collision centrality measured based on multiplicity in $|\eta| < 1.0$
  - Centrality bins: 0-5%, 5-10%, 10-20%.......

STAR Analysis
PRELIMINARY

Results: C vs Collision Centrality



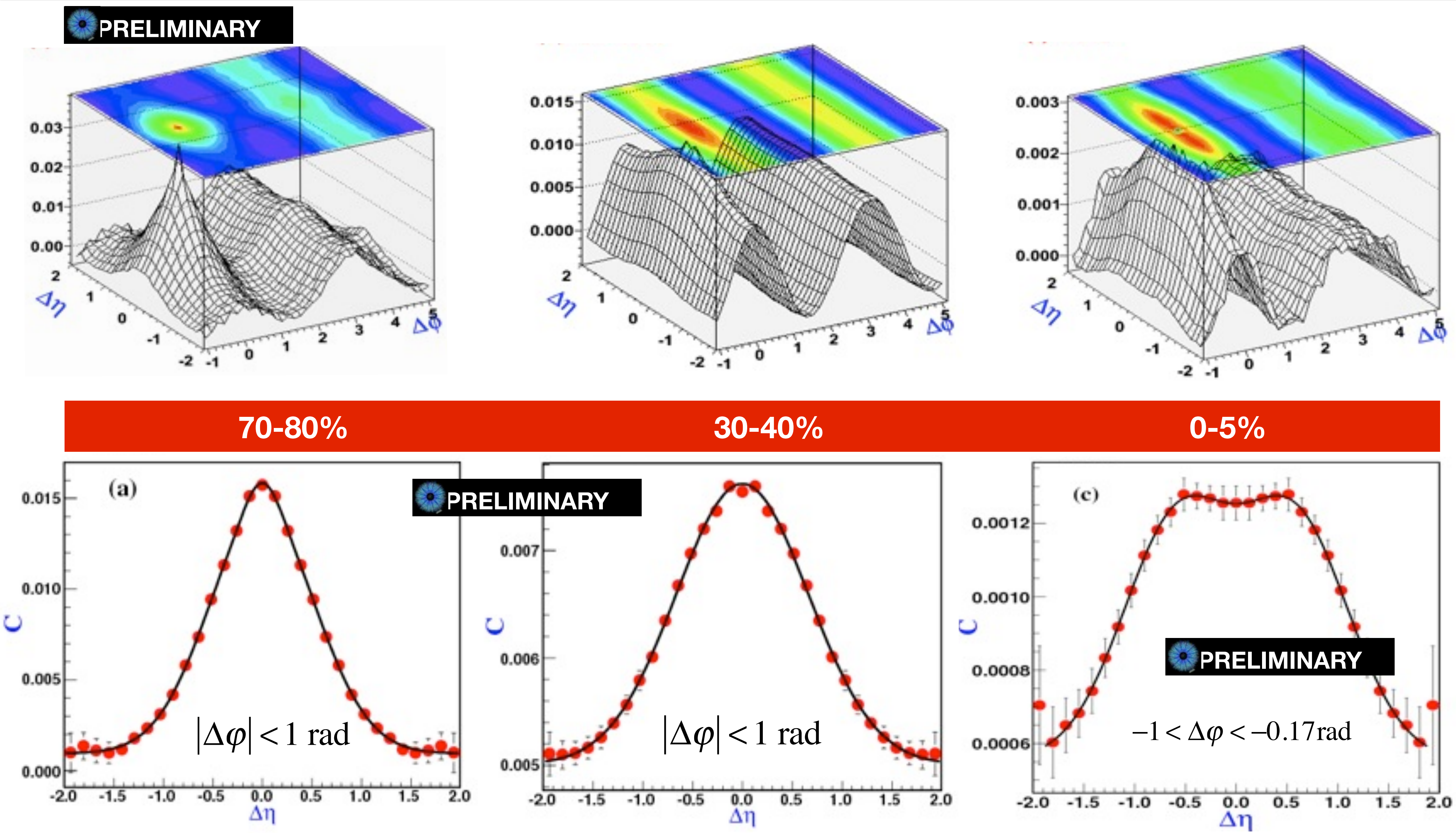
- Prominent near side peak in peripheral collisions
- Ridge-like structure on the away-side (momentum conservation) in peripheral collisions

- Monotonic reduction of the correlation amplitude with increasing N_{part}.
- Evidence of elliptic flow component in mid-central collisions.

- Emergence of a near side ridge with increasing N_{part}.
- Monotonic elongation in $\Delta\eta$ of the near side peak with increasing N_{part}.

STAR Analysis PRELIMINARY

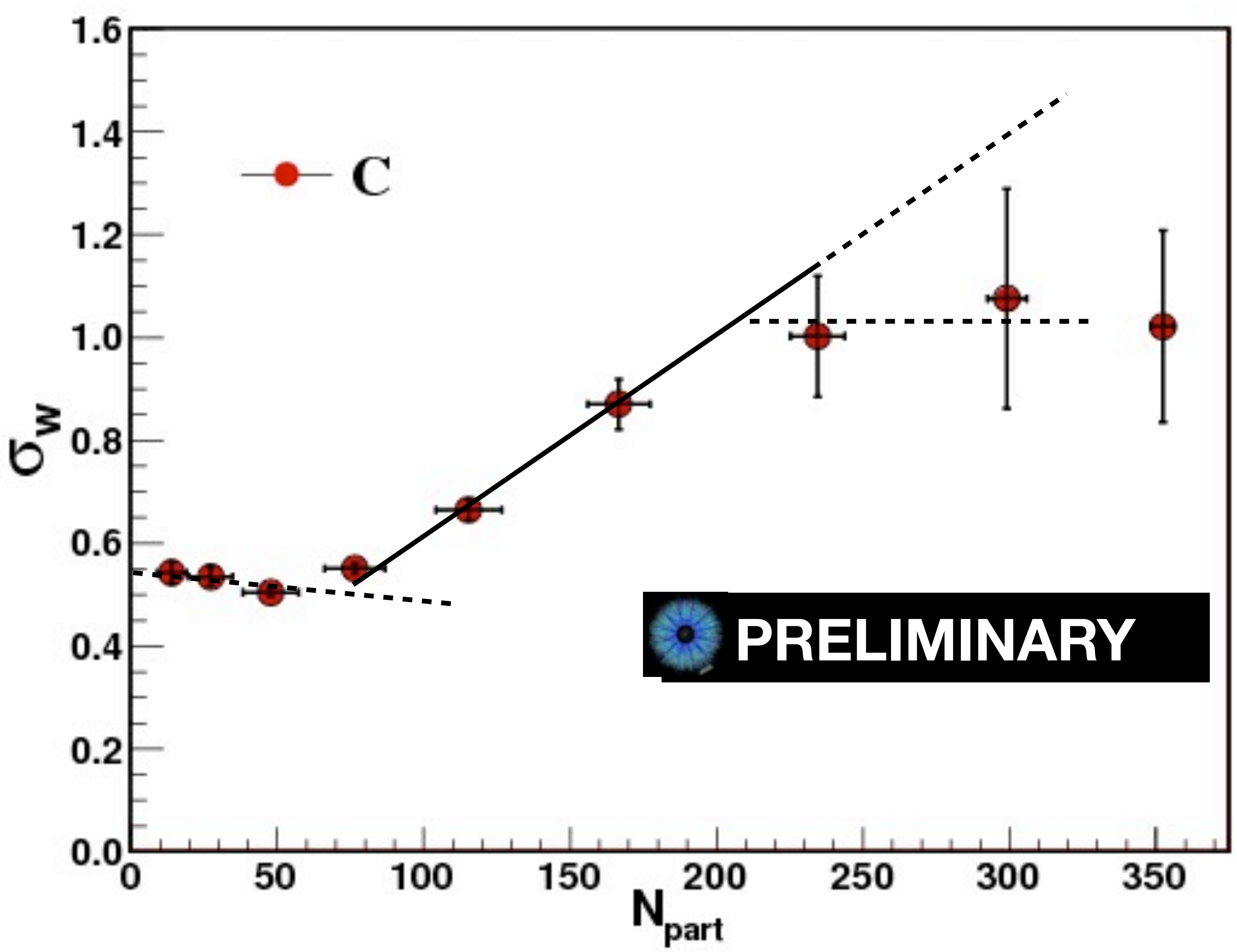
C --- Near Side Projection



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

Correlation Width vs. Collision Centrality

STAR Analysis PRELIMINARY



- Width approximately constant (decreasing actually) in most peripheral bins
  - Incomplete thermalization ?
  - Radial flow effect?
  - Corona dominated
  - Event centrality selection technique?
- Linear increase with N_{part} > ~100
- Saturation for most central collisions?
- Freeze-out expected to increase with N_{part}. Observed width does not change much, what does that mean? Require theoretical model improvements!

STAR Analysis PRELIMINARY

Estimation of the shear viscosity

From S. Gavin: $\sigma_c^2 - \sigma_p^2 = 4\vartheta\left(\tau_p^{-1} - \tau_c^{-1}\right)$

$$\sigma_{p+p} \simeq \sigma_{70-80\%} = 0.54 \pm 0.02^{*} \qquad \tau_{p+p} \approx 1 \text{ fm/c}$$

$$\sigma_{w,0-5\%} = 1.0 \pm 0.2 \qquad \tau_c = 20 \text{ fm/c}$$

Width approx. constant for N_{part}<50; These collisions do not feature significant thermalization. Extrapolate to N_{part} = 2. i.e. equivalent to p+p, thus use time ~ 1 fm/c;
Bjorken PRD27(1983), Teany Nucl.Phys.62(2009), Dusley *et al.* arXiv:0911.2720

→ $$\frac{\eta}{s} = 0.17 \pm 0.08$$ PRELIMINARY

Use 20 fm/c for central collisions as per Gavin's analysis,
if using value of ~10 fm/c derived from STAR blast-wave fit would yield approx. same value

$$\frac{\eta}{s} = 0.5 \pm 0.2$$

If assuming thermalization at 70-80%, negligible radial flow effects, and time ~ 3 fm/c (as per STAR Blastwave fit). But why is the width constant for Npart<50? Why not use 60-70%, or 50-60% ? More theoretical work to be done to understand this issue: viscosity function of system size, or lifetime?

Non Gaussian shape observed in most central collisions suggests broadening could have contributions from other phenomena as well diffusion (viscosity).
The above value is thus an upper limit of the time averaged viscosity.

* statistical errors only at this stage, systematic errors under study.

STAR Analysis PRELIMINARY

Estimation of the Reynolds Number

- Neglect central collision freeze out time contribution, and approximate the peripheral freeze out time as the formation time.

S. Gavin, Nucl. Phys. A435 (1985) 826.

$$\mathrm{Re} = \frac{3}{4}\frac{\tau_o T s}{\eta} \Rightarrow \sigma_c^2 - \sigma_p^2 = 4\frac{\nu}{\tau_p}\left(1 - \frac{\tau_p}{\tau_c}\right) \simeq 3\mathrm{Re}^{-1} \quad \text{for} \quad \tau_o \approx \tau_{f,p} \ll \tau_{f,c}$$

$$\sigma_p = 0.54 \pm 0.02$$

$$\sigma_c = 1.0 \pm 0.2$$

Estimate $\Rightarrow$

$$\mathrm{Re} \approx \left(\frac{\sigma_c^2 - \sigma_p^2}{3}\right)^{-1} = 5 \pm 2$$

(Very) PRELIMINARY

What does it mean?

* statistical errors only at this stage, systematic errors under study.

STAR Analysis PRELIMINARY

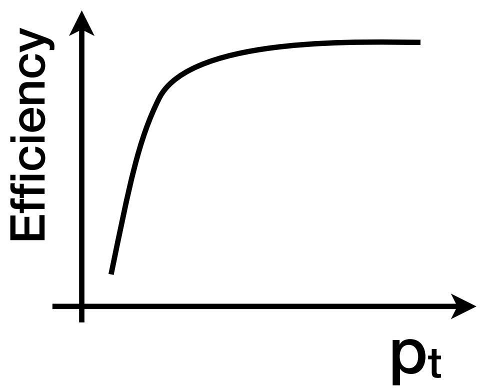
Summary

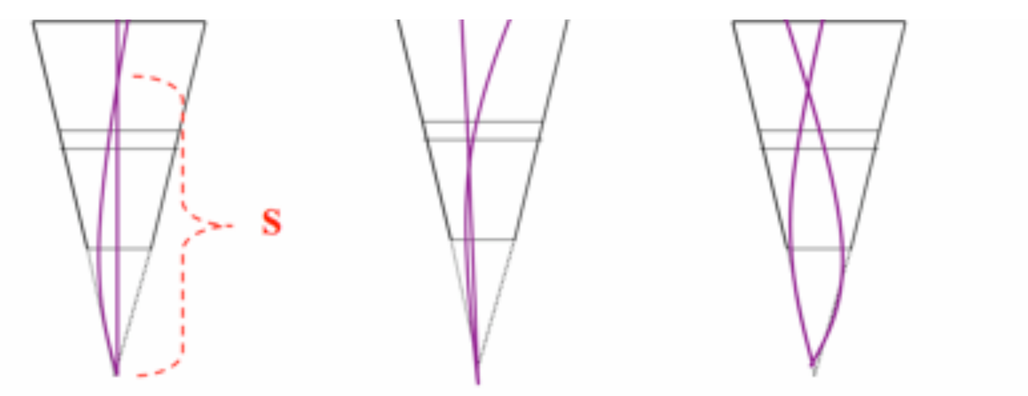
- First measurement of the differential observable C advocated by Gavin *et al.* for measurements of shear viscosity in Au + Au collisions at $\sqrt{s_{NN}} = 200GeV$
- C behave as expected with collision centrality
  - "Strong" flow component in mid-central collisions
  - Emergence of a ridge on the near side for large N_{part}.
  - Longitudinal broadening of the near side correlation peak
- Estimate of the Reynolds number $\mathrm{Re} = 5 \pm 2$ PRELIMINARY
- Estimate of the shear viscosity (Upper limit?) $\frac{\eta}{s} \leq 0.17 \pm 0.08$ PRELIMINARY

Additional Material

Analysis: Technical Details

- In order to mitigate efficiency dependencies on the z-vertex position, field polarity, and detector occupancy, ...
- Reported correlation functions are a weighted average of values measured for
  - specific z-vertex bins of 2.5 cm in the range |z| < 25 cm.
  - forward (F) and reverse (R) full field data
- Offset correction: Average correlation offsets differences vs z-bin and F/R field are set to zero: dispersion provides estimate of systematic error assoc. w/ pt dependence of efficiency.
- Statistical errors based on the variance of the measurements in different z bins and field polarity, after offset correction.
- Include track merging correction



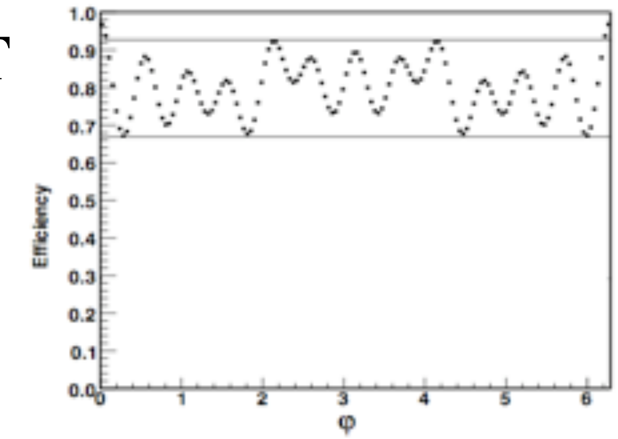


"S", shows up in azimuth as a point where tracks have merged.

Experimental Caveat: Observable Robustness(?)

Study with PYTHIA, p+p collisions at $\sqrt{s} = 200$ GeV

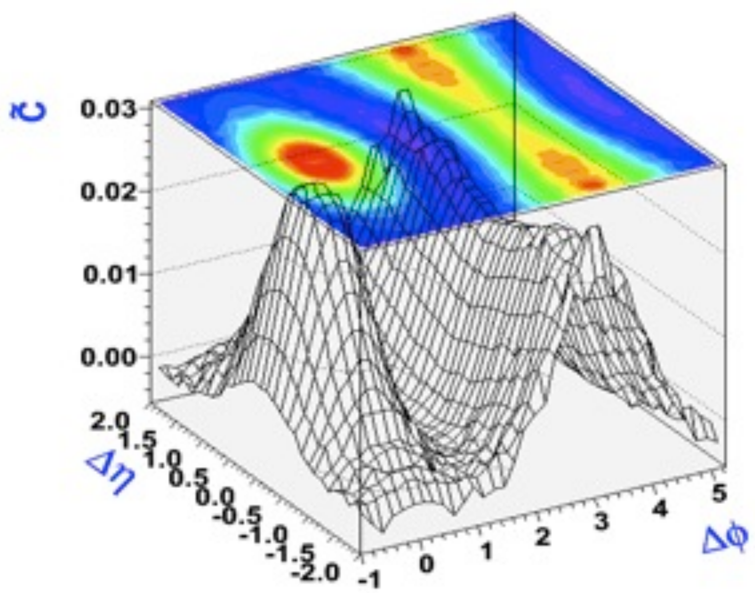
Twelve fold angular efficiency dependence, and linear dependence on pT



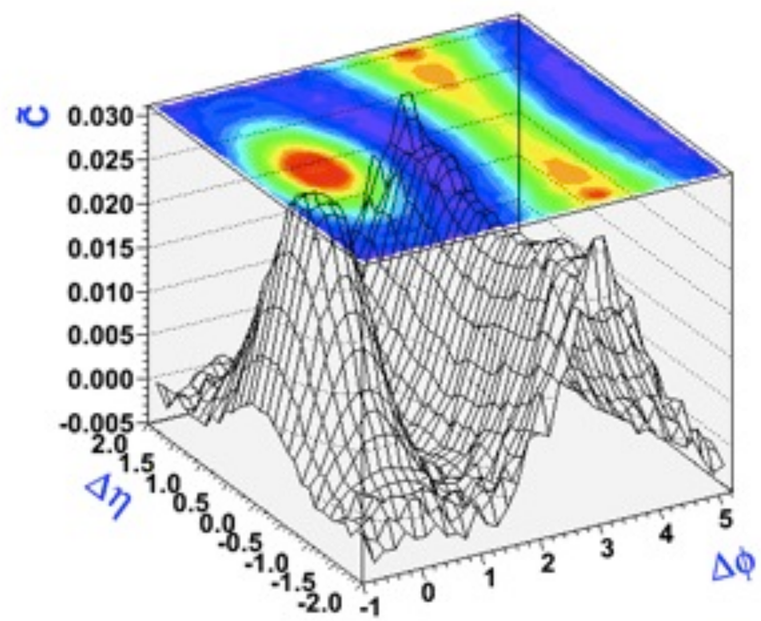
$$\varepsilon(\varphi, p_\perp) = \varepsilon_0 (1 - a p_\perp)\left[1 + \sum_{n=1}^{12} \varepsilon_i \cos(n\varphi)\right]$$

ε_o=0.8, a =0.05

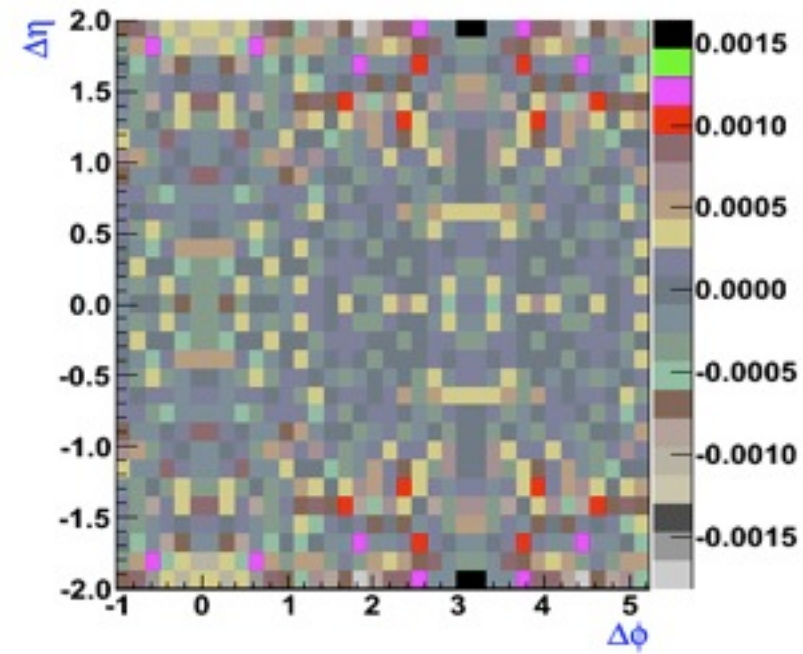
Efficiency = 100%



Efficiency = 80%



Difference



Statistical error = 0.001, difference = 0.0005 => Robust Observable if efficiency has small dependence on pt.

In practice, a measurement 'near' detection threshold in p_t, implies the observable is not perfectly robust (Simulation in progress)