Estimation of QGP shear viscosity based on transverse momentum correlations

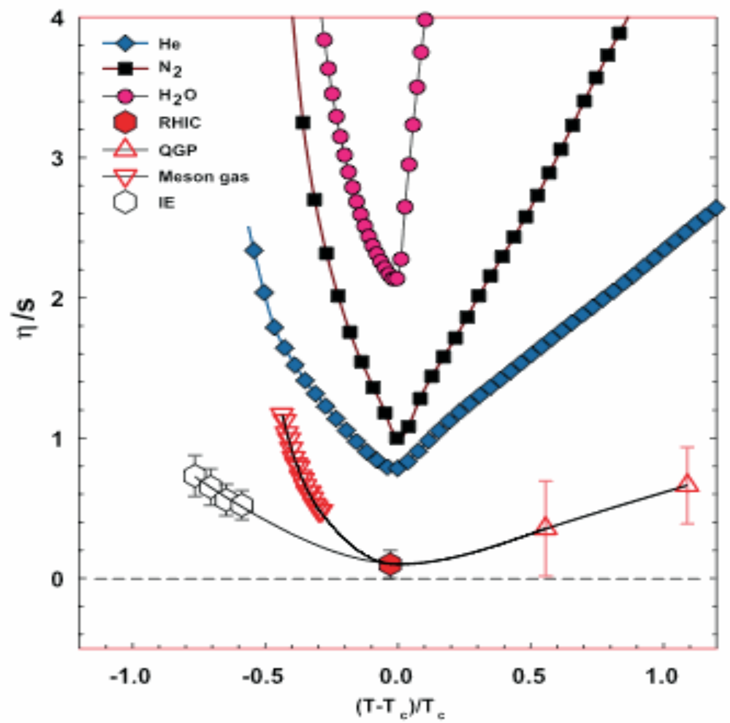
Monika Sharma for the STAR Collaboration
Wayne State University

Outline:
- ✓ Motivation
- ✓ Measurement method
- ✓ Observable definition
- ✓ Results discussion
- ✓ Summary

APS April Meeting 2010

Perfect Fluids …..

- Helium
- Ultra cold gasses



Plot taken from R.A. Lacey *et al* PRL 98 (2007) 092301

Fascinating observation!
- **Quark Gluon Plasma**
  T ~ 200 MeV ~ 10^{12}K
- **High temperature superliquid!**

Conjectured lower bound of Shear viscosity to entropy density $\frac{\eta}{s} \geq \frac{1}{4\pi}$

Supersymmetric Yang Mill Theory (Ads/CFT duality
Kovtun, Son & Starinets, PRL 94 (2005)

Transverse momentum correlation measurements can be used to extract information on kinematic viscosity: $\upsilon = \frac{\eta}{T_c s}$

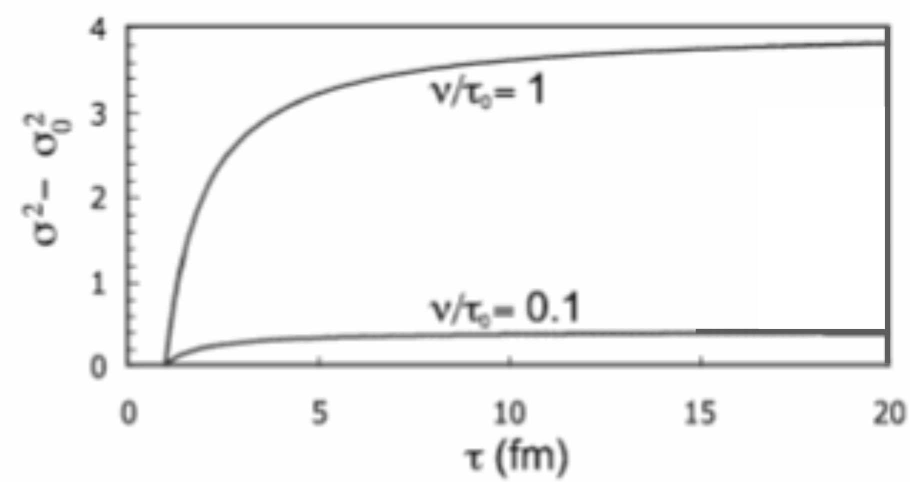
Sean Gavin, Phys. Rev Lett. 97 (2006) 162302

T_c : temperature
s : entropy density
η : shear viscosity

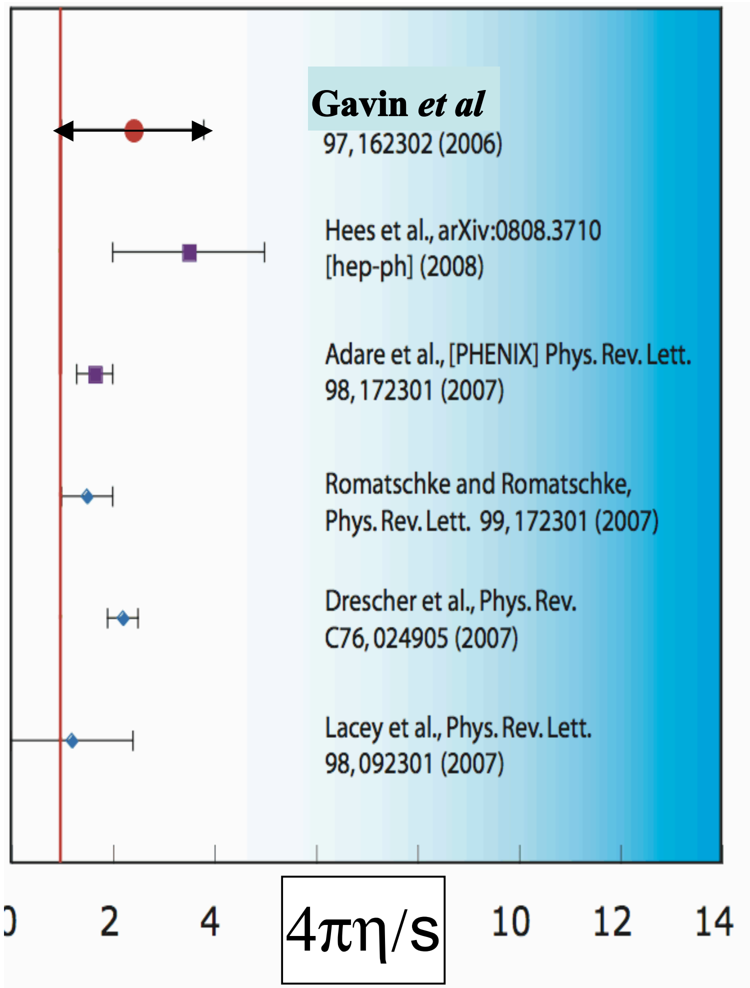
- υ estimated based on broadening of correlation function vs. pseudorapidity as a function of collision centrality

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

- Viscous friction arises as the fluid elements flow past each other thereby reducing the relative velocity: damping of radial flow.
- Viscosity reduces fluctuations, distributing excess momentum density over the collision volume: broadens the rapidity profile of fluctuations.
- Width of the correlation grows with system lifetime relative to its initial width



Estimate from two particle correlations



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

Based on:

p_T correlations, $\eta / s \approx 0.08$
STAR, J. Phys. G32. L37, 2006 (AuAu 200 GeV)

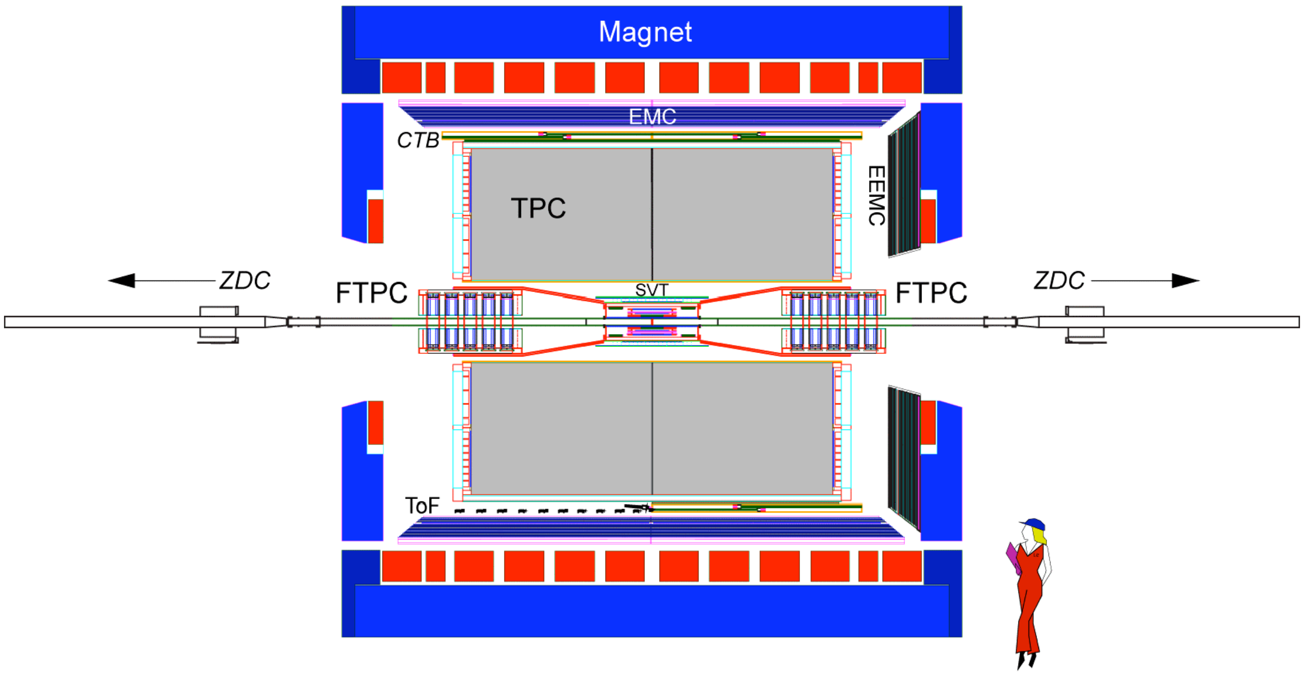
Number density correlations, $\eta / s \approx 0.3$
STAR, PRC 73, 064907, 2006 (AuAu 130 GeV)

But, ……
Proper estimation of viscosity to entropy density ratio requires a study of transverse momentum flow which includes both…..

$$C = \frac{\left\langle \sum_{i \neq j} p_{T_i} p_{T_j} \right\rangle (\eta_1, \phi_1, \eta_2, \phi_2)}{\langle n_1 \rangle (\eta_1, \phi_1) \langle n_2 \rangle (\eta_2, \phi_2)} - \langle p_T \rangle (\eta_1, \phi_1) \langle p_T \rangle (\eta_2, \phi_2)$$

Theoretical caveats

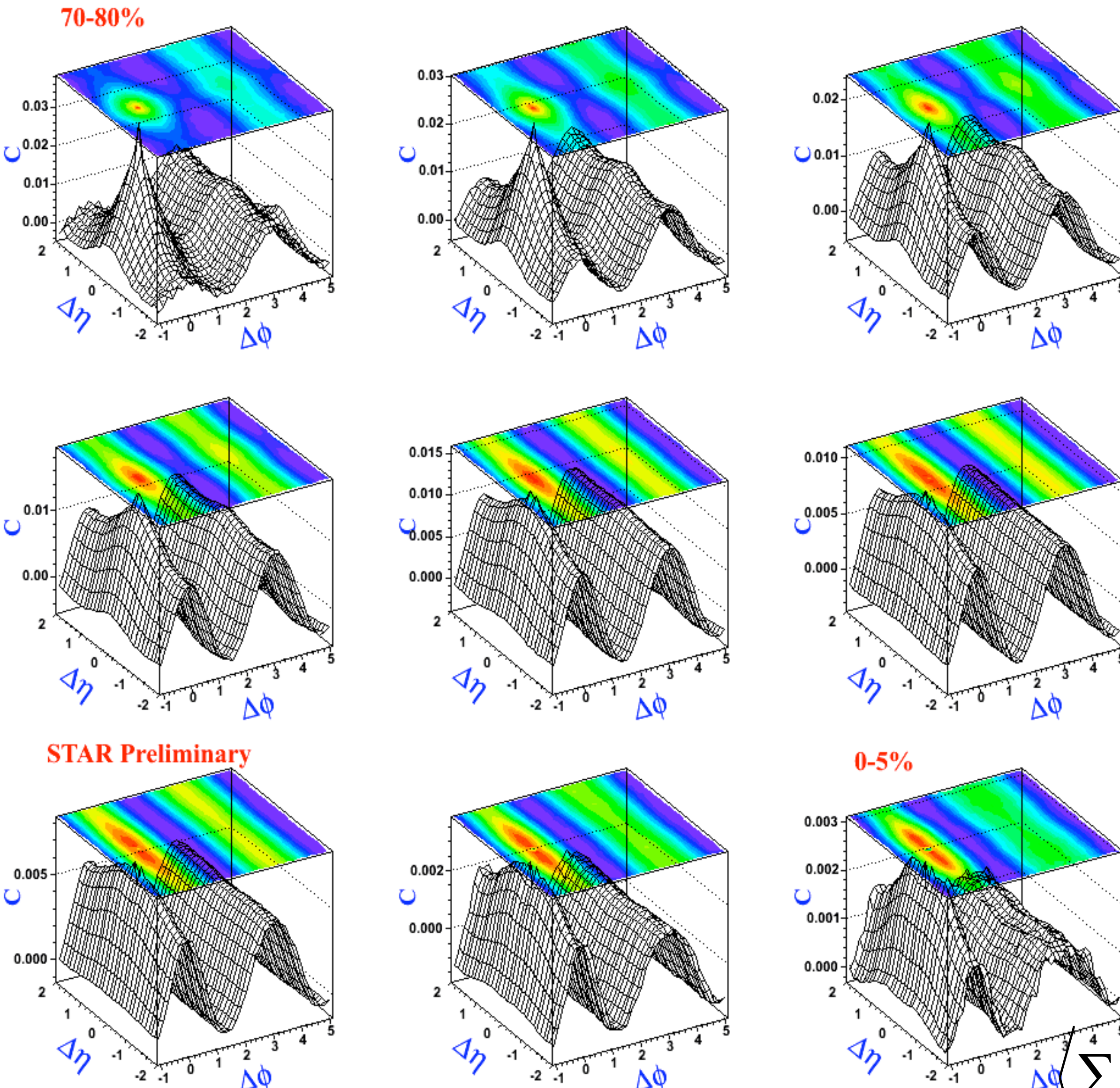
- **The system temperature and viscosity vary through the lifetime of the collision system.**
  - **Our measurement will yield a time averaged number.**
- **Change in freeze out times (peripheral collisions) reflect changes in the ratio,** η / s
- **Other effects may contribute to the longitudinal broadening of the correlation function**
  - **Decays, jets, radial flow etc…**
  - **Diffusion is expected to dominate**



- Analyzed data from TPC, has 2π coverage
- Dataset: Run IV AuAu 200 GeV
- Events analyzed: 8 Million
- Minimum bias trigger

- Cuts applied:
  - $|\eta| < 1.0$
  - $0.2 < p_T < 2.0$ GeV/c
  - Analysis done vs. collision centrality
  - Centrality slices: 0-5%, 5-10%, 10-20%…….

Results

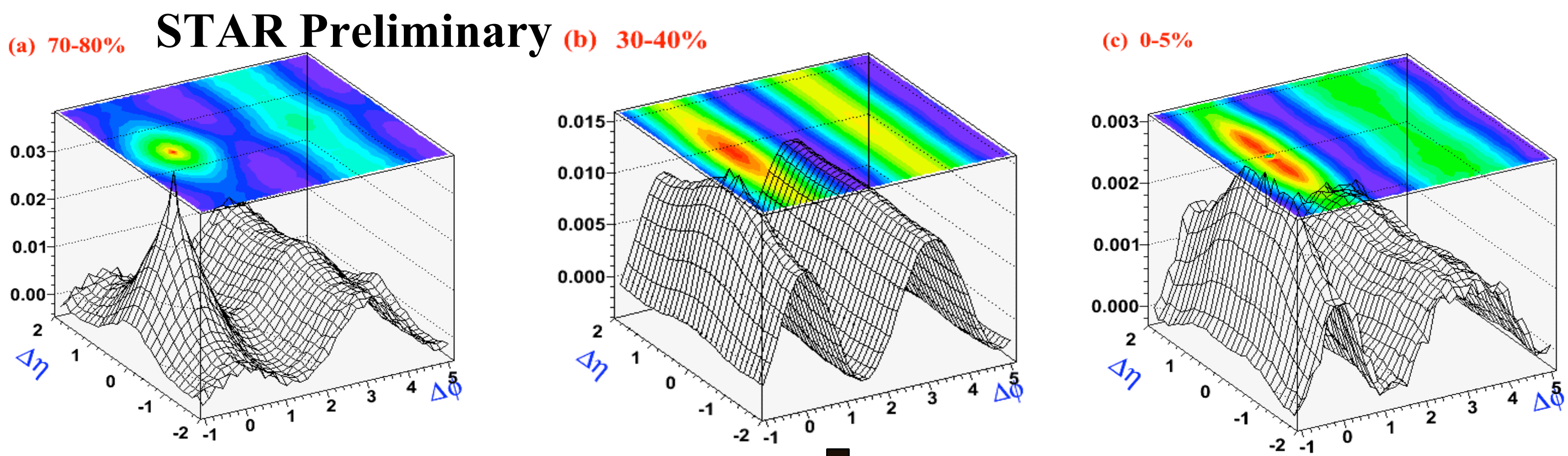


- Prominent near side peak in peripheral collisions
- Ridge-like structure on the away-side (momentum conservation) in peripheral collisions.

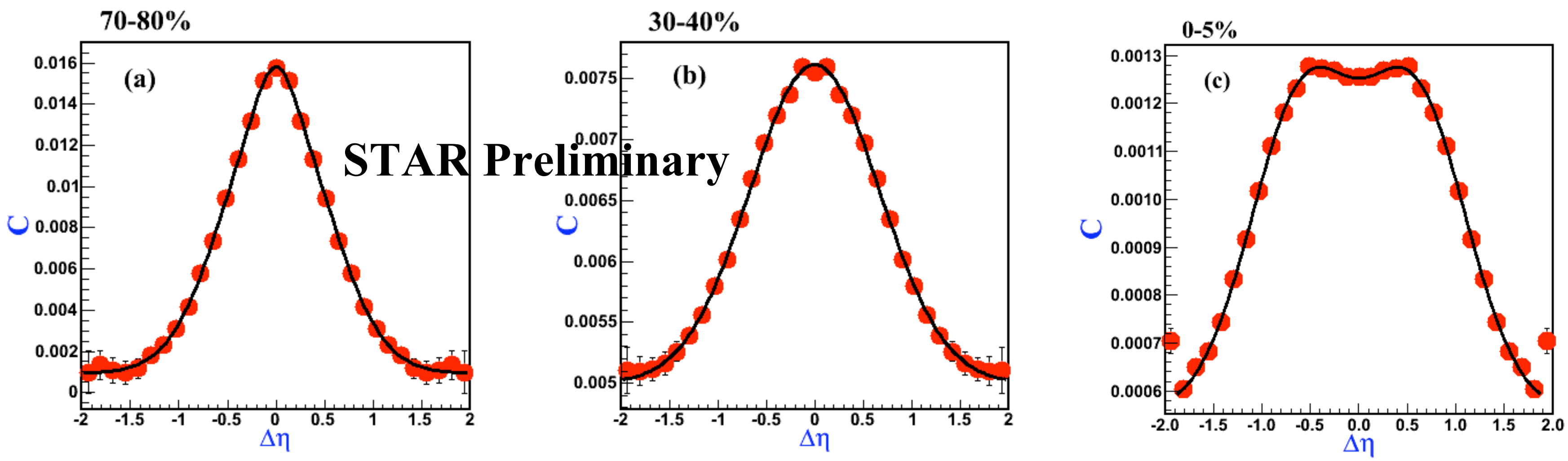
- Monotonic reduction of the correlation amplitude with increasing N_{part}.
- Evidence of elliptic flow component in mid-central central collisions.

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

$$C = \frac{\left\langle \sum_{i \neq j} p_{T_i} p_{T_j} \right\rangle (\eta_1, \phi_1, \eta_2, \phi_2)}{\langle n_1 \rangle (\eta_1, \phi_1) \langle n_2 \rangle (\eta_2, \phi_2)} - \langle p_T \rangle (\eta_1, \phi_1) \langle p_T \rangle (\eta_2, \phi_2)$$

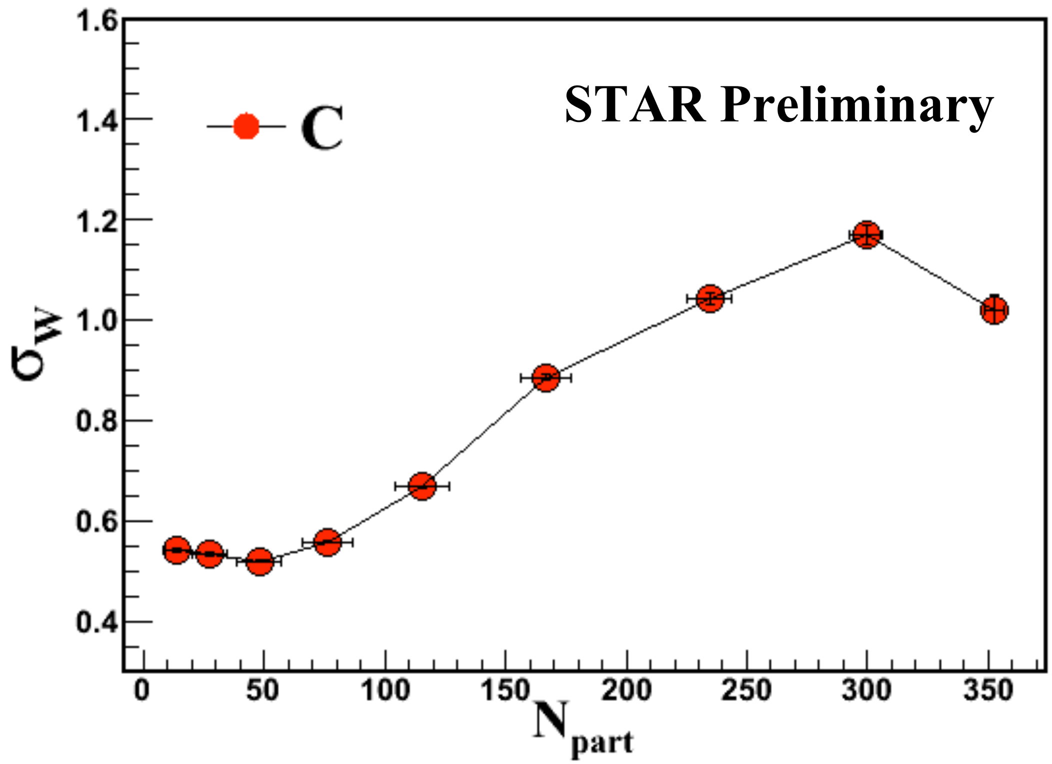


Near-side projection



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

Correlation width vs. collision centrality



- Width approximately constant in most peripheral bins.
  - Incomplete thermalization?
  - Radial flow effects?
  - Event centrality selection technique?
- Linear increase for N_{part} > ~100
- Decrease in most central collisions

Estimation of shear viscosity

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

$$\sigma_{w,70-80\%} = 0.542 \pm 0.003 \quad \tau_f = 1 \ \textbf{fm/c}$$

$$\sigma_{w,0-5\%} = 1.021 \pm 0.029 \quad \tau_c = 20 \ \textbf{fm/c}$$

✓ **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

$$\Rightarrow \quad \frac{\eta}{s} = 0.17 \pm 0.02(stats.) + 0.34^{theory}(sys.)$$

STAR Preliminary

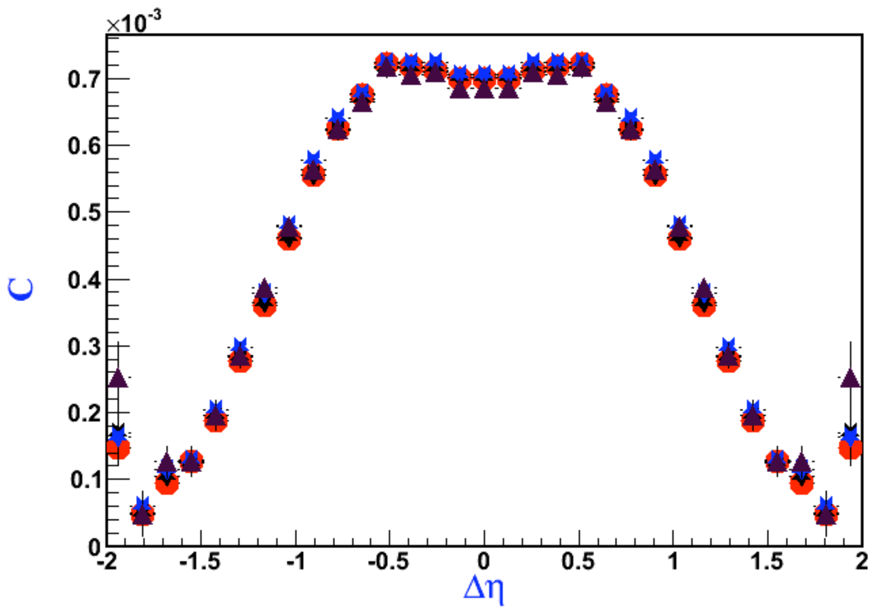
Non Gaussian shape observed in central collisions suggests broadening could have contributions from other phenomena as well.

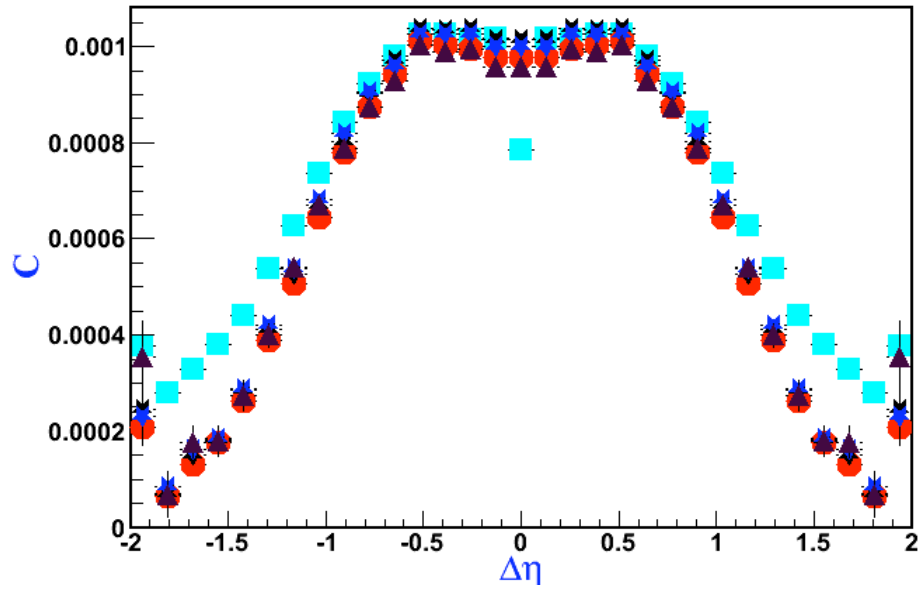
The above value is thus an upper limit of the time averaged viscosity if $\tau_f = 1 fm/c$

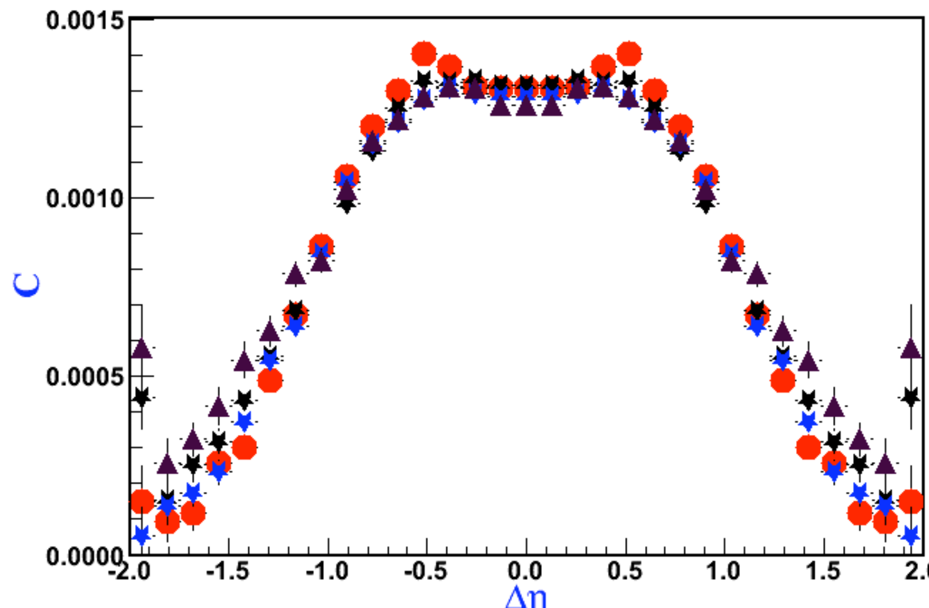
Conclusions:

- Presented first measurements of viscosity based on transverse momentum correlations using C at RHIC.
- C exhibits near-side ridge-like structure in the momentum space for the most central collisions.
- The over-all shape of the correlation function evolves significantly from peripheral to the most-central collisions.
- We use a near-side projection (i.e., $|\Delta\phi| < 1.0$) of C to determine the evolution of momentum correlations with centrality.
- Based on the formula given by Gavin *et al* and common estimates of freeze-out times, we estimate an upper bound on the viscosity of the matter produced in Au+Au collisions.

Back up

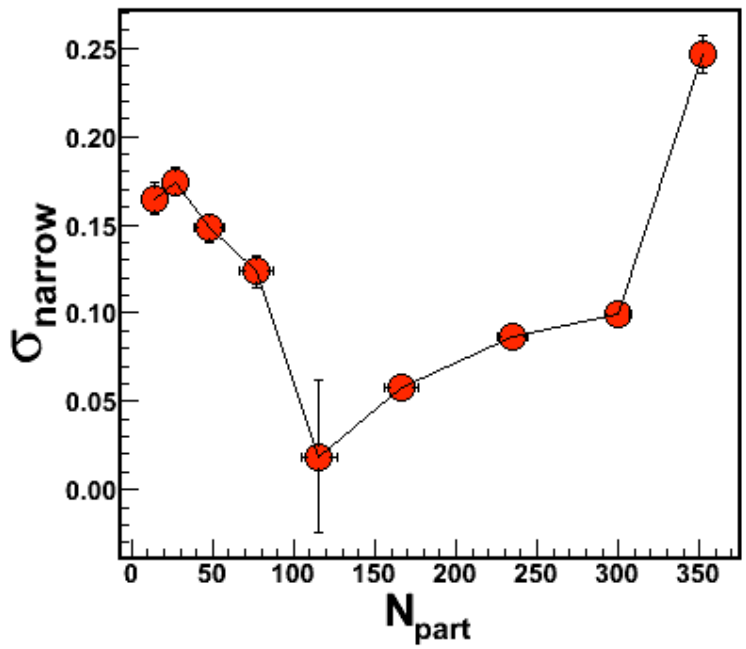

×10^-3
C
Δη


C
Δη

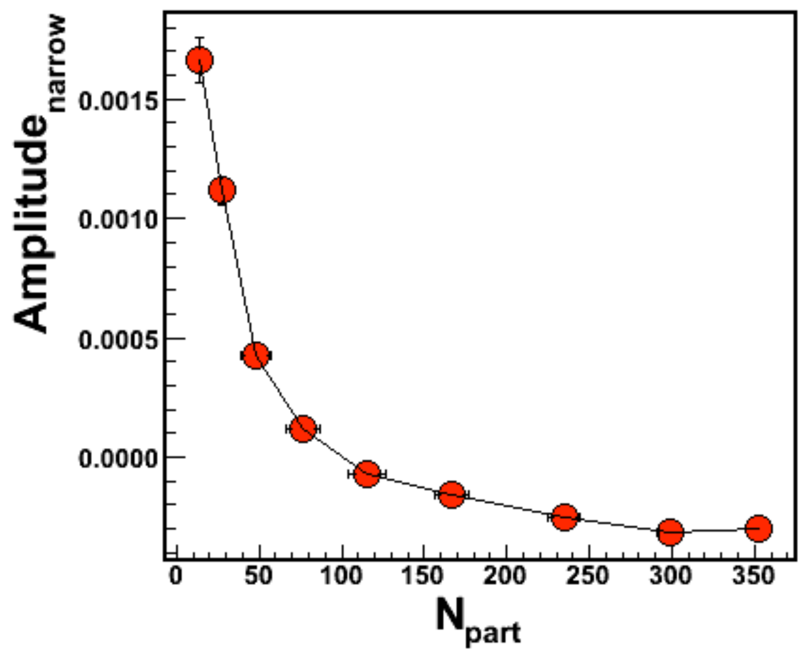

C
Δη

Sigma/RMS as a function of centrality

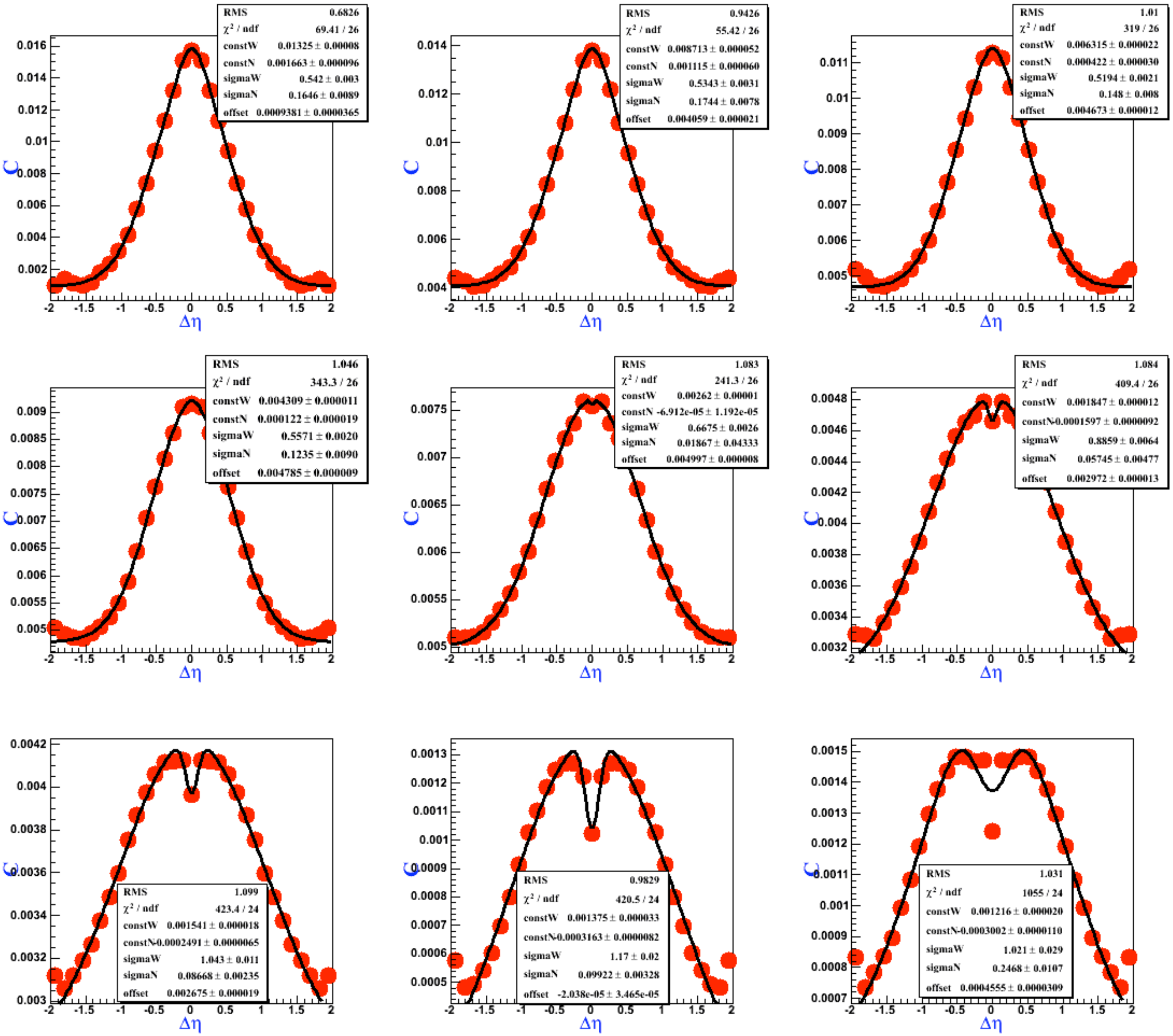
Centrality	Standard statistical errors	$E = \sqrt{\frac{\sum_{i=1}^{N} w_i R_i^2}{N\sum_{i=1}^{N} w_i}}$	$E = \sqrt{\frac{\sum_{i=1}^{N} w_i R_i^2}{\sum_{i=1}^{N} w_i}}$	RMS $\lvert\Delta\phi\rvert<1.0$ radians	RMS $-1.0<\Delta\phi<0.17$ radians
70-80%	0.542+0.021	0.542+0.003	0.542+0.02	0.5406	0.5449
60-70%	0.534+0.018	0.501+0.002	0.501+0.009	0.5505	0.5505
50-60%	0.504+0.088	0.519+0.002	0.519+0.012	0.5764	0.5753
40-50%	0.550+0.010	0.557+0.002	0.557+0.011	0.5941	0.5992
30-40%	0.664+0.019	0.667+0.003	0.667+0.016	0.6722	0.6230
20-30%	0.8641+0.051	0.886+0.006	0.891+0.036	0.8452	0.7315
10-20%	1.003+0.117	1.043+0.011	1.043+0.064	0.9267	0.8480
5-10%	1.075+0.211	1.17+0.02	1.17+0.13	0.987	0.8899
0-5%	1.108+0.255	1.021+0.029	1.021+0.186	0.9449	0.8229

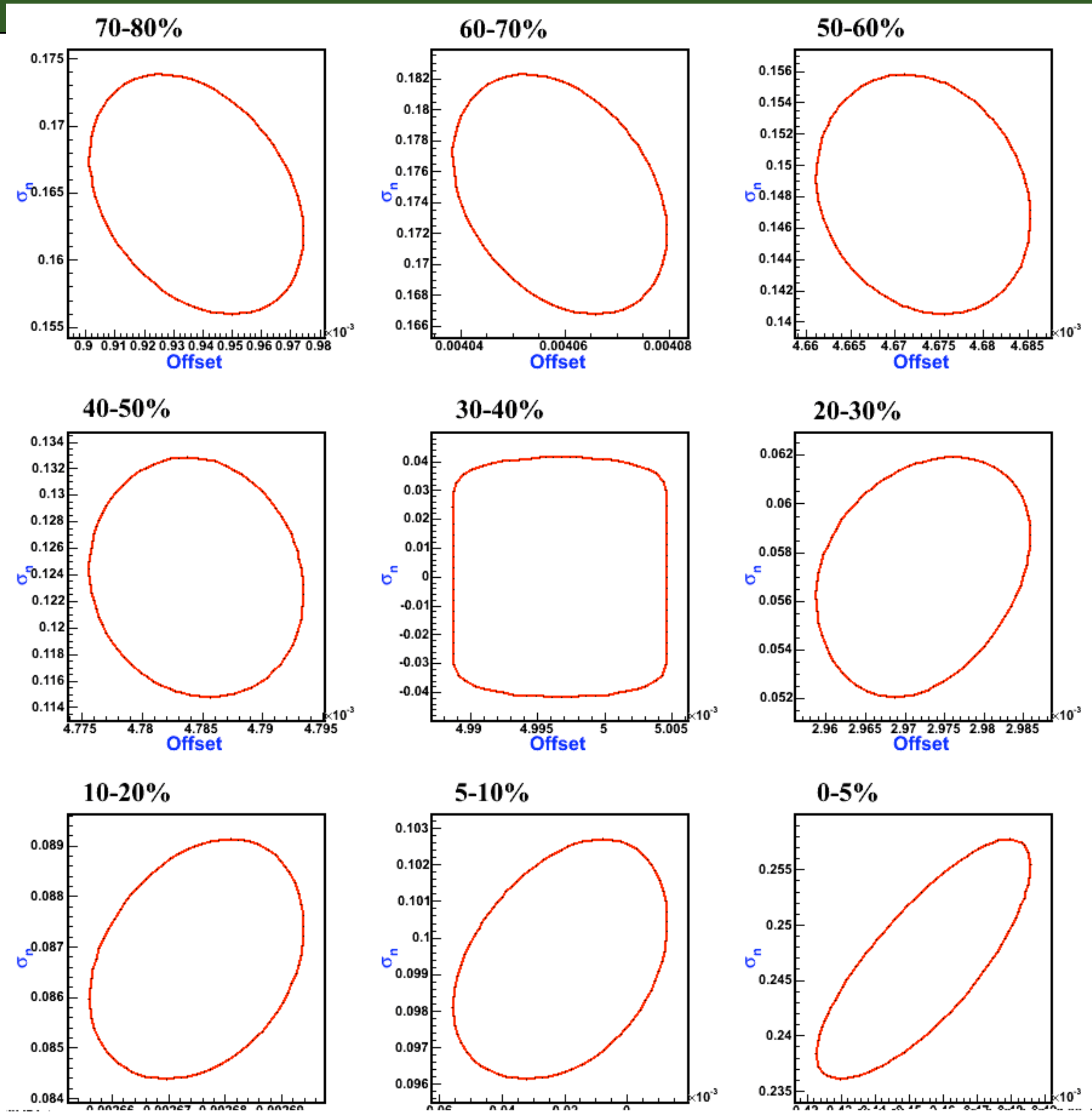


σnarrow
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
Npart

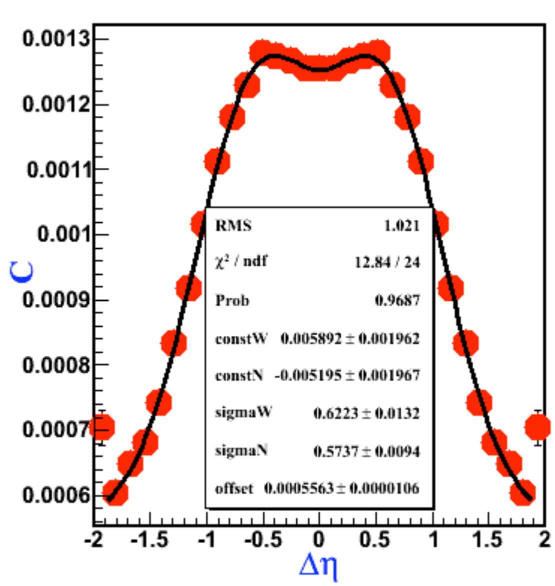


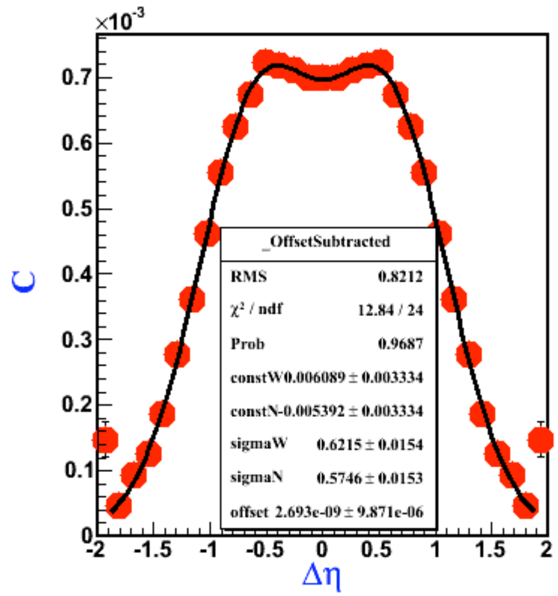
Amplitudenarrow
0.0015
0.0010
0.0005
0.0000
0
50
100
150
200
250
300
350
Npart

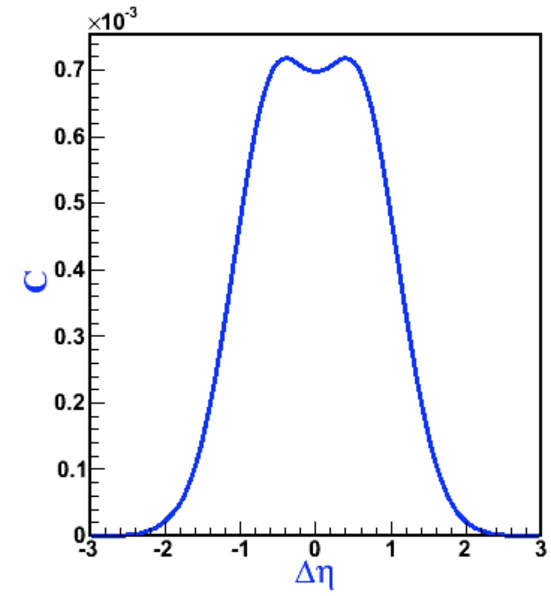

RMS 0.6826
χ² / ndf 69.41 / 26
constW 0.01325 ± 0.00008
constN 0.001663 ± 0.000096
sigmaW 0.542 ± 0.003
sigmaN 0.1646 ± 0.0089
offset 0.0009381 ± 0.0000365
RMS 0.9426
χ² / ndf 55.42 / 26
constW 0.008713 ± 0.000052
constN 0.001115 ± 0.000060
sigmaW 0.5343 ± 0.0031
sigmaN 0.1744 ± 0.0078
offset 0.004059 ± 0.000021
RMS 1.01
χ² / ndf 319 / 26
constW 0.006315 ± 0.000022
constN 0.000422 ± 0.000030
sigmaW 0.5194 ± 0.0021
sigmaN 0.148 ± 0.008
offset 0.004673 ± 0.000012
RMS 1.046
χ² / ndf 343.3 / 26
constW 0.004309 ± 0.000011
constN 0.000122 ± 0.000019
sigmaW 0.5571 ± 0.0020
sigmaN 0.1235 ± 0.0090
offset 0.004785 ± 0.000009
RMS 1.083
χ² / ndf 241.3 / 26
constW 0.00262 ± 0.00001
constN -6.912e-05 ± 1.192e-05
sigmaW 0.6675 ± 0.0026
sigmaN 0.01867 ± 0.04333
offset 0.004997 ± 0.000008
RMS 1.084
χ² / ndf 409.4 / 26
constW 0.001847 ± 0.000012
constN-0.0001597 ± 0.0000092
sigmaW 0.8859 ± 0.0064
sigmaN 0.05745 ± 0.00477
offset 0.002972 ± 0.000013
RMS 1.099
χ² / ndf 423.4 / 24
constW 0.001541 ± 0.000018
constN-0.0002491 ± 0.0000065
sigmaW 1.043 ± 0.011
sigmaN 0.08668 ± 0.00235
offset 0.002675 ± 0.000019
RMS 0.9829
χ² / ndf 420.5 / 24
constW 0.001375 ± 0.000033
constN-0.0003163 ± 0.0000082
sigmaW 1.17 ± 0.02
sigmaN 0.09922 ± 0.00328
offset -2.038e-05 ± 3.465e-05
RMS 1.031
χ² / ndf 1055 / 24
constW 0.001216 ± 0.000020
constN-0.0003002 ± 0.0000110
sigmaW 1.021 ± 0.029
sigmaN 0.2468 ± 0.0107
offset 0.0004555 ± 0.0000309
C
Δη



70-80%
60-70%
50-60%
40-50%
30-40%
20-30%
10-20%
5-10%
0-5%
σ_n
Offset
$\times 10^{-3}$


RMS 1.021
χ^2 / ndf 12.84 / 24
Prob 0.9687
constW 0.005892 ± 0.001962
constN -0.005195 ± 0.001967
sigmaW 0.6223 ± 0.0132
sigmaN 0.5737 ± 0.0094
offset 0.0005563 ± 0.0000106
C
Δη


×10^-3
_OffsetSubtracted
RMS 0.8212
χ^2 / ndf 12.84 / 24
Prob 0.9687
constW0.006089 ± 0.003334
constN-0.005392 ± 0.003334
sigmaW 0.6215 ± 0.0154
sigmaN 0.5746 ± 0.0153
offset 2.693e-09 ± 9.871e-06
C
Δη


×10^-3
C
Δη