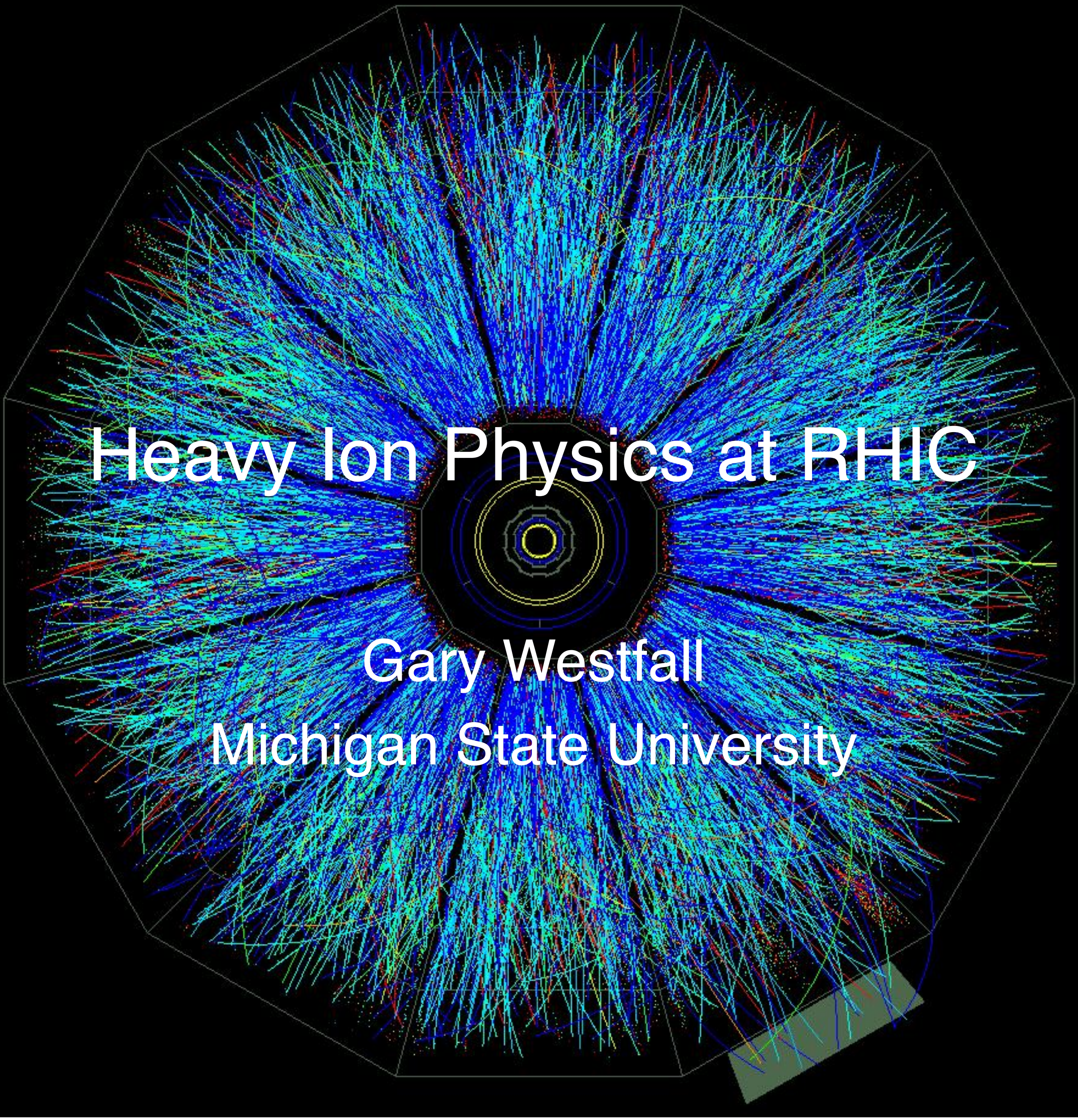


Heavy Ion Physics at RHIC

Gary Westfall

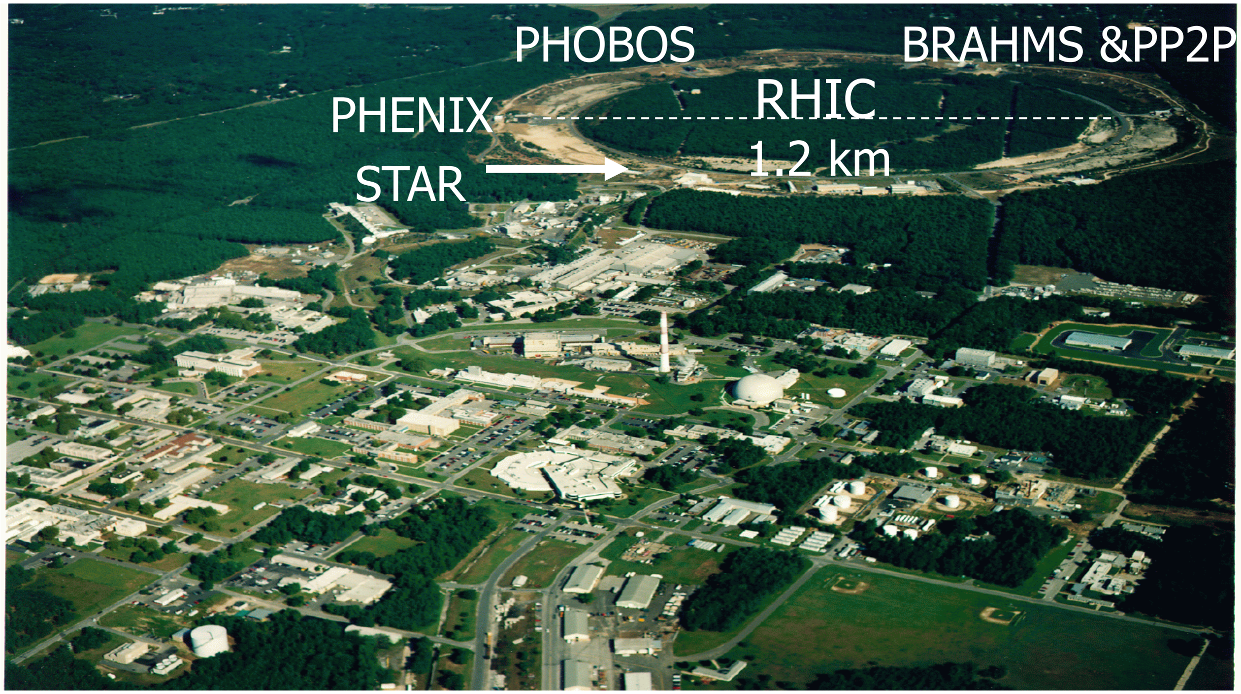
Michigan State University

Heavy Ion Physics at RHIC

- Huge amount of new results presented from PHENIX, STAR, ALICE, CMS, and ATLAS
- Find at
  - http://qm2011.in2p3.fr
- Impressions of heavy ion physics at RHIC from Quark Matter 2011
  - Things lost and things gained
- Dynamical Charge Correlations
  - The Role of Charge Conservation
- Beam Energy Scan
  - Search for the QGP Critical Point

Relativistic Heavy Ion Collider (RHIC)

- Flexibility
  - Polarized protons, 0.05 to 0.5 TeV
  - Nuclei from d to Au (Pb,U), 0.005 to 0.2 GeV
- Physics runs to date
  - Au+Au@7.7,11.5,19.6,39,62,130,200 GeV
  - Cu+Cu@22,62,200 GeV
  - Polarized p+p@200 & 500 GeV
  - d+Au@200 GeV



PHENIX Present + Upgrades

Charged Particle Tracking:

Drift Chamber
Pad Chamber
Time Expansion Chamber/TRD
Cathode Strip Chambers(Mu Tracking)
Forward Muon Trigger Detector
Si Vertex Tracking Detector- Barrel
Si Vertex Endcap (mini-strips)

Particle ID:

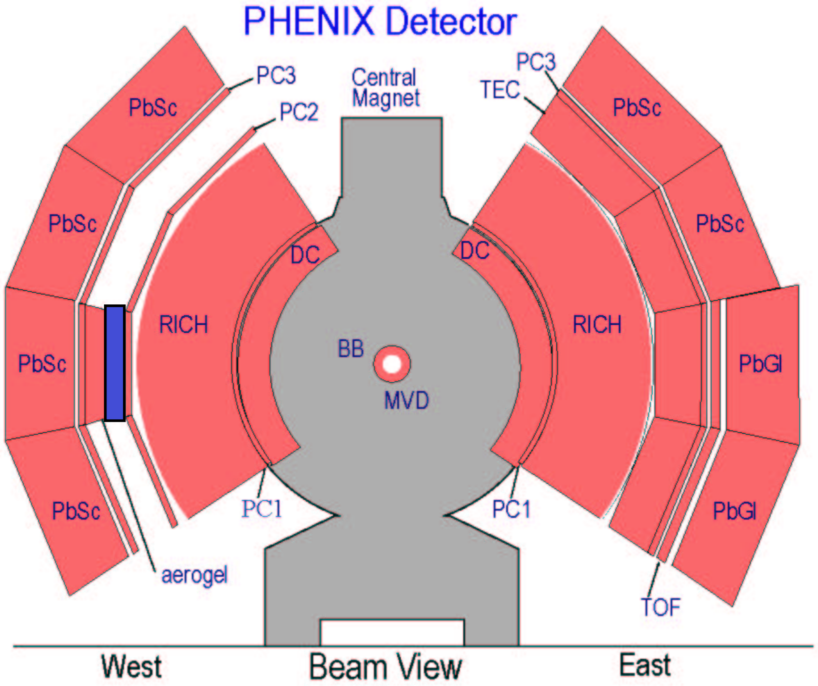
Time of Flight
Ring Imaging Cerenkov Counter
TEC/TRD
Muon ID (PDT’s)
Aerogel Cerenkov Counter
Multi-Gap Resistive Plate Chamber ToF
Hadron Blind Detector

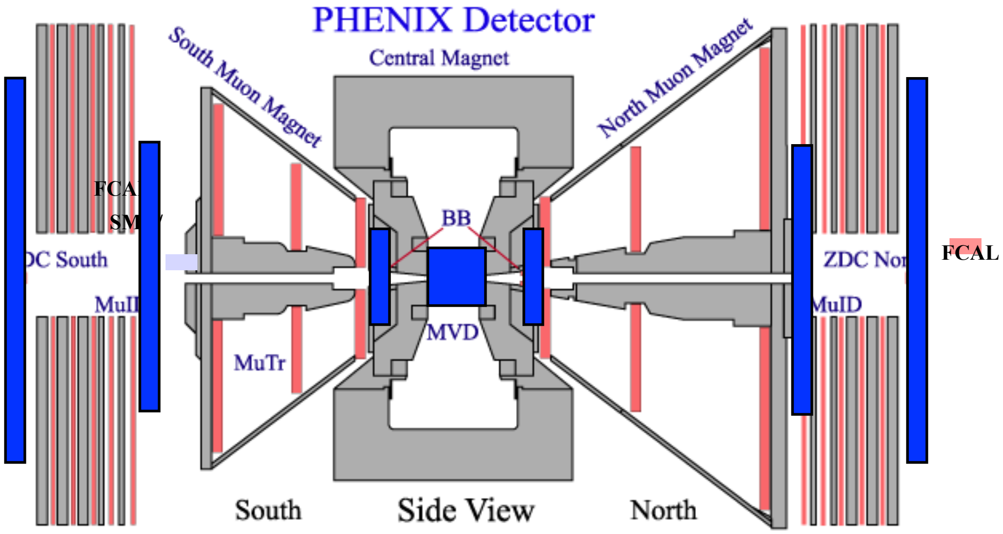
Calorimetry:

Pb Scintillator
Pb Glass
Nose Cone Calorimeter
Muon Piston Calorimeter

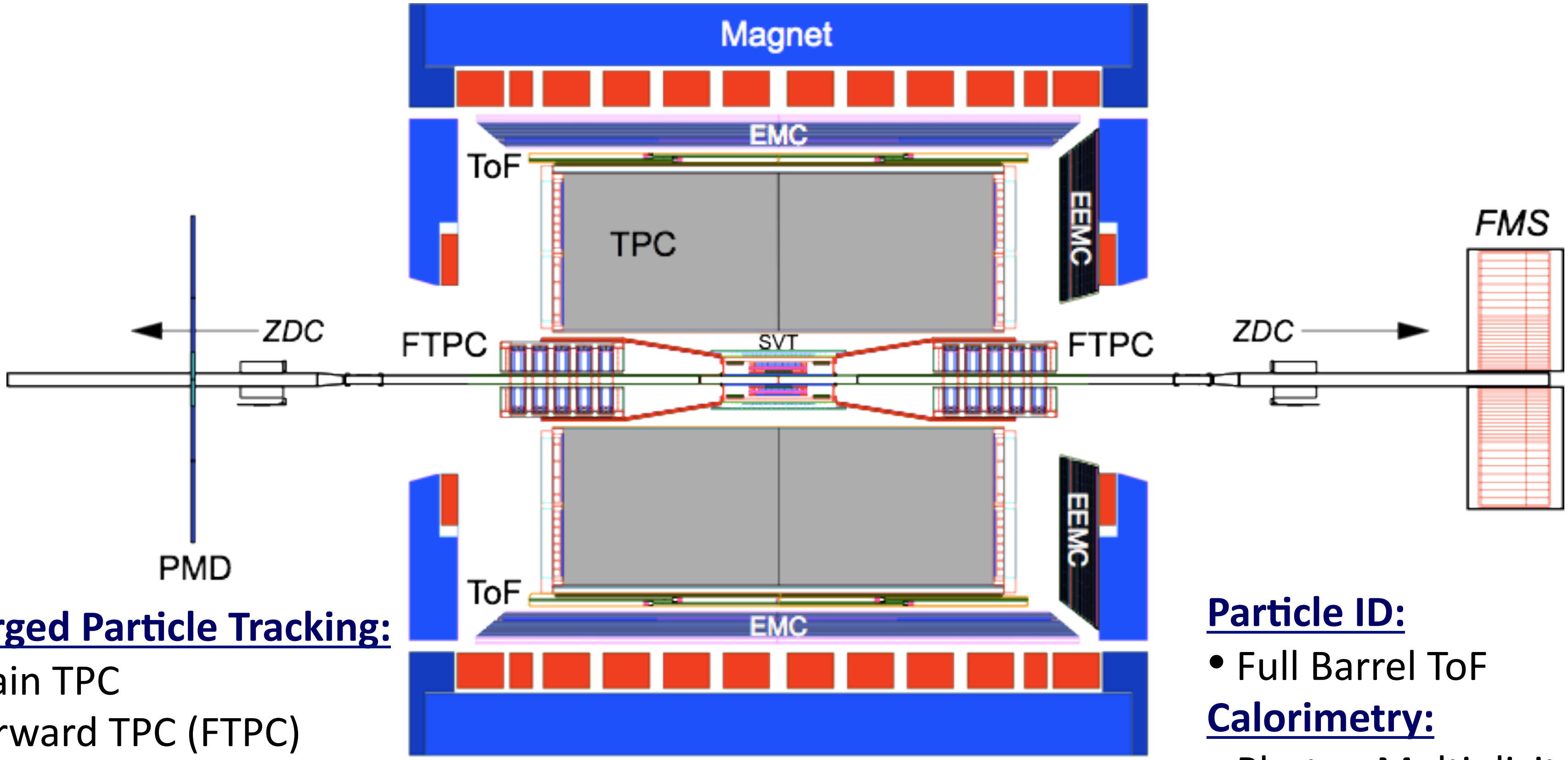
Event Characterization:

Beam-Beam Counter
Zero Degree Calorimeter/Shower Max Detector
Forward Calorimeter
Reaction Plane Detector





STAR Present + Upgrades



Charged Particle Tracking:

- Main TPC
- Forward TPC (FTPC)
- SSD + Intermediate Tracker + Active Pixel Detector = HFT(was SSD +SVT)
- Forward GEM Tracker

Event Characterization & Trigger:

- Beam-Beam Counter (BBC)
- Zero Degree Calorimeter (ZDC)
- Forward Pion Detectors (FPD)

Particle ID:

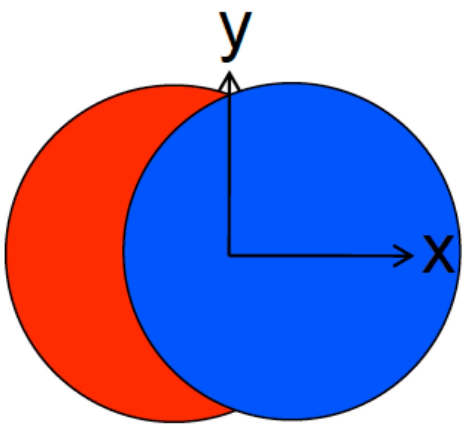
- Full Barrel ToF

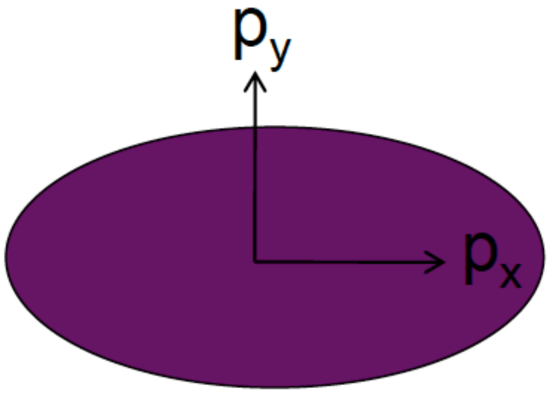
Calorimetry:

- Photon Multiplicity Detector (PMD)
- Barrel EMC
- Endcap EMC
- Forward Meson Spectrometer

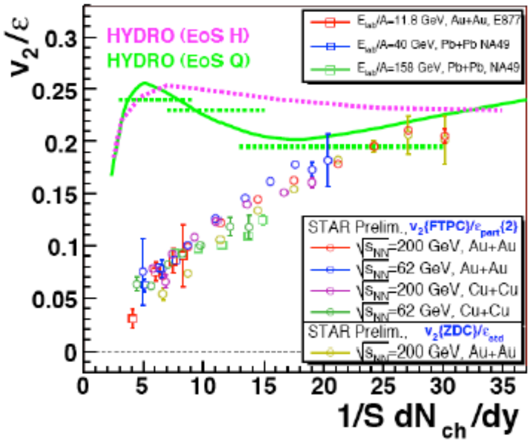
RHIC at QM '11

- Understanding of flow and related two particle correlations in terms of complete Fourier sum





Voloshin, Poskanzer, Snellings, arXiv:0809.2949

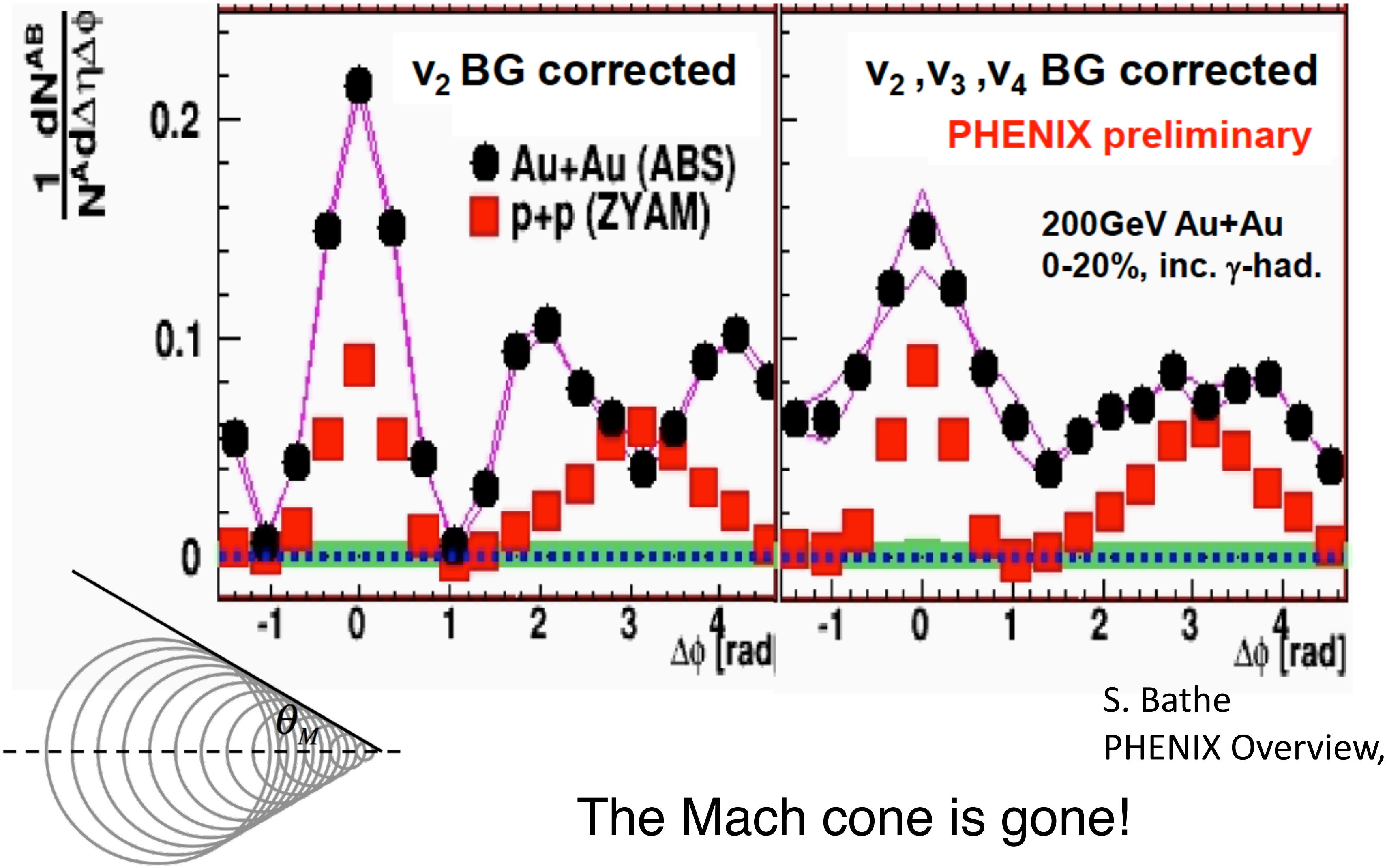


$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\phi + 2v_2^2 \cos 2\Delta\phi + 2v_3^2 \cos 3\Delta\phi + 2v_4^2 \cos 4\Delta\phi + \ldots$$

- v_1, v_2, v_3, v_4, v_5, v_6, ….
- Previously we had concentrated on v_2
  - Initial overlap geometry
  - Clear experimental signature
  - Relation to hydro, perfect liquid

P. Sorensen
QM11

Understanding the “Mach Cone”



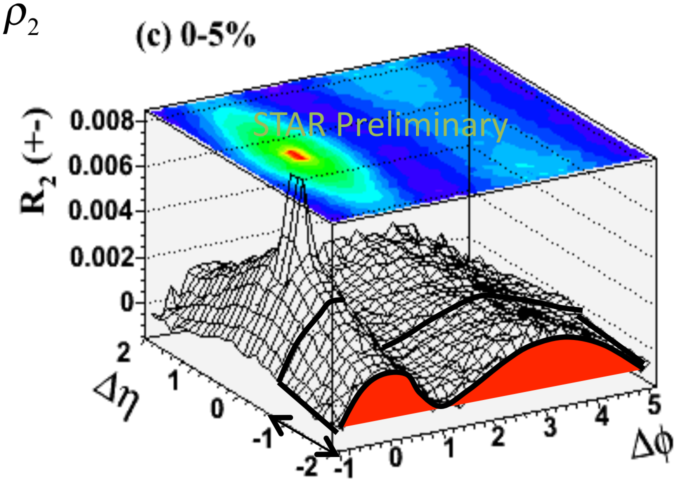
S. Bathe
PHENIX Overview, QM11

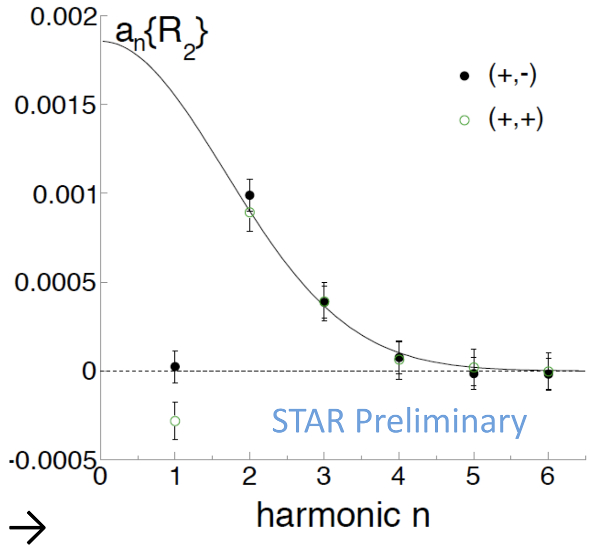
The Mach cone is gone!

Large Δη a_n Spectrum – The Ridge Explained

if flow dominates the correlations $a_n \approx v_n^2$

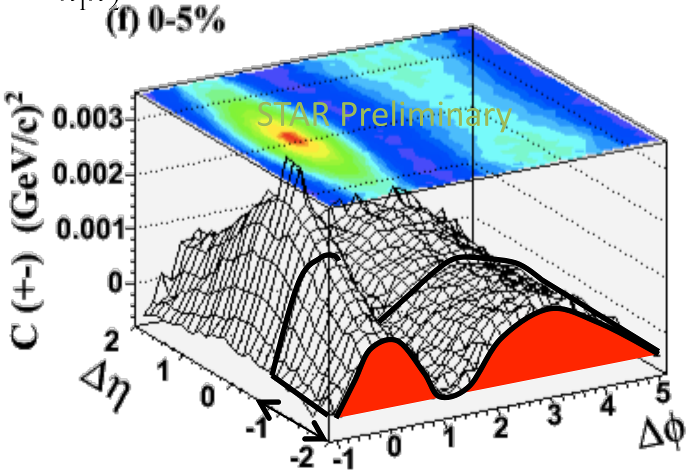
$$R_2 = \frac{\rho_{12}}{\rho_1 \rho_2} - 1$$

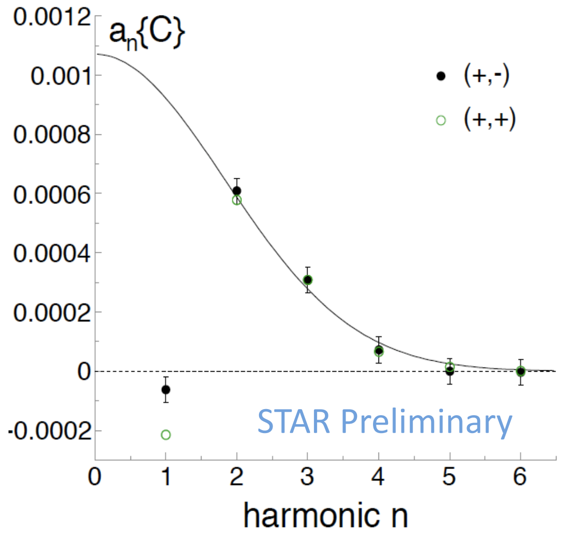




→ Fourier Tr. (0.7<Δη<2.0) →

$$C = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{j=1\neq i}^{n_2} p_{T,i} p_{T,j} \right\rangle}{\bar{n}_1 \bar{n}_2} - \bar{p}_{T,1} \bar{p}_{T,2}$$

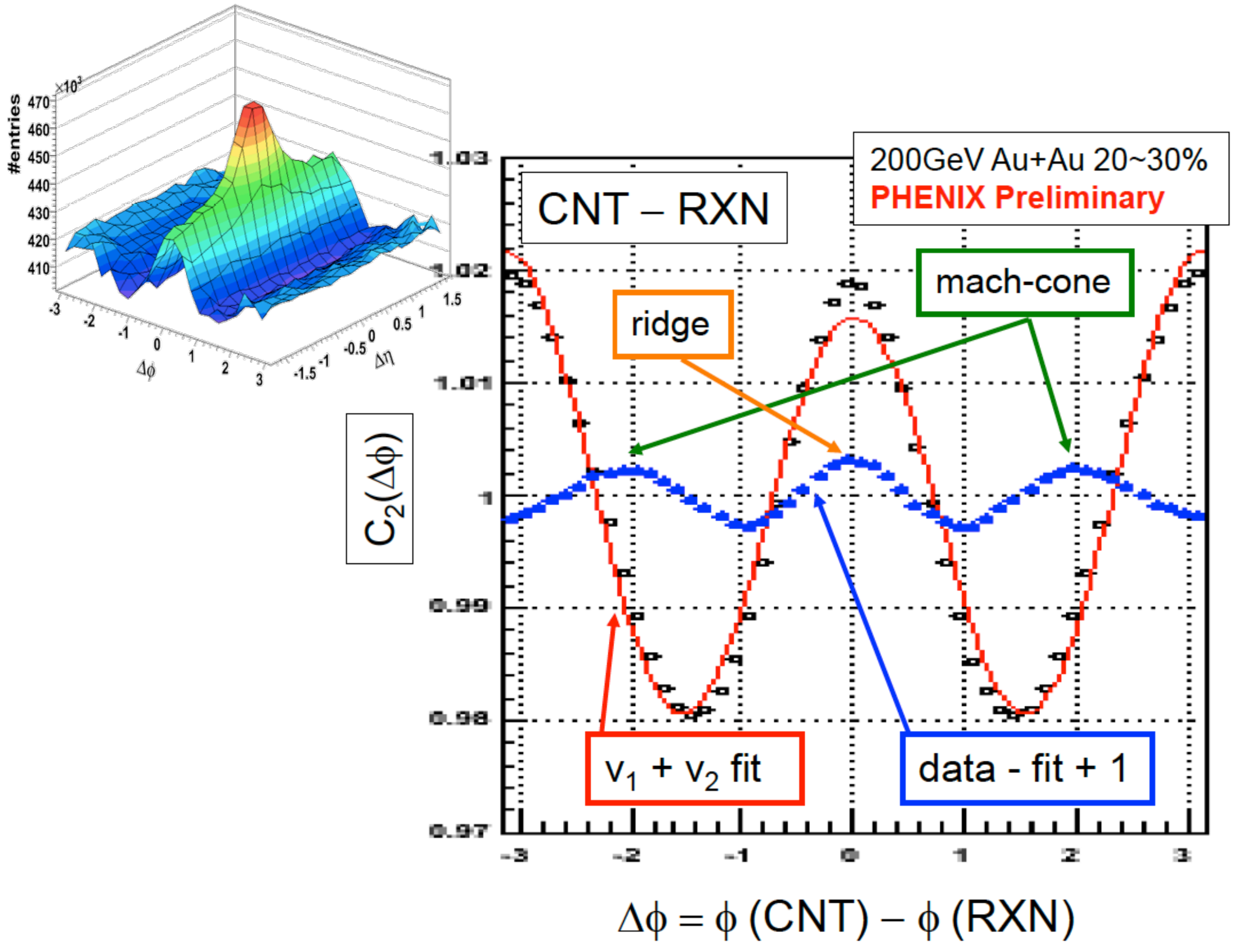




P. Sorensen
QM11

See also: A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]

Understanding the “Mach Cone” and the “Ridge”



RXN: $|\eta|=1.0\sim2.8$
CNT: $(|\eta|<0.35)$
charged hadrons
$p_T=2\sim4$(GeV/c)

clear 3rd order moment seen in long range $\Delta\phi$ correlation

another way of extracting the v_n parameters with forward anisotropy v_n without using Φ_n

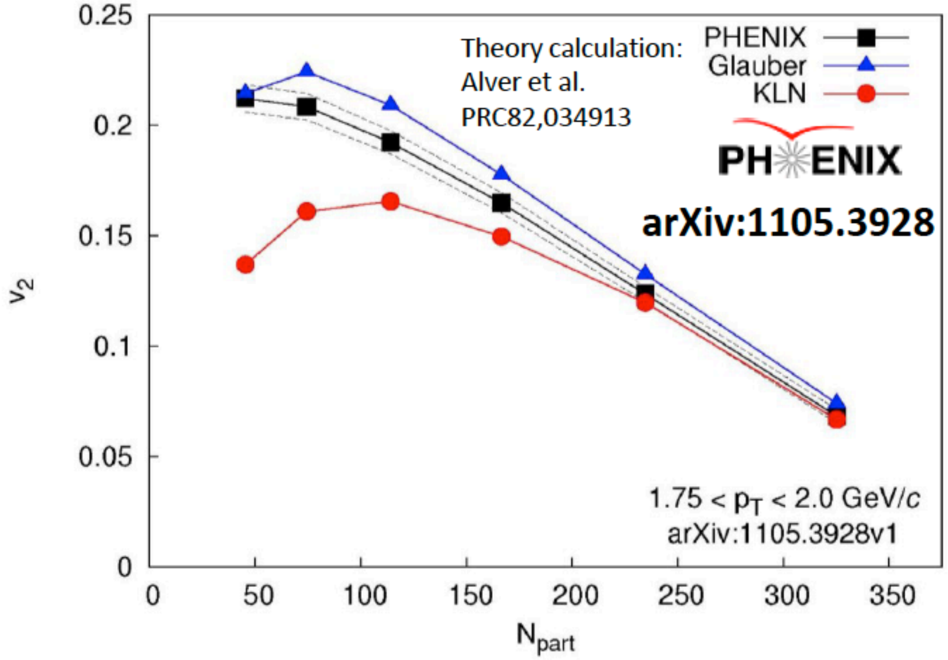
S. Esumi
QM11

Losses and Gains

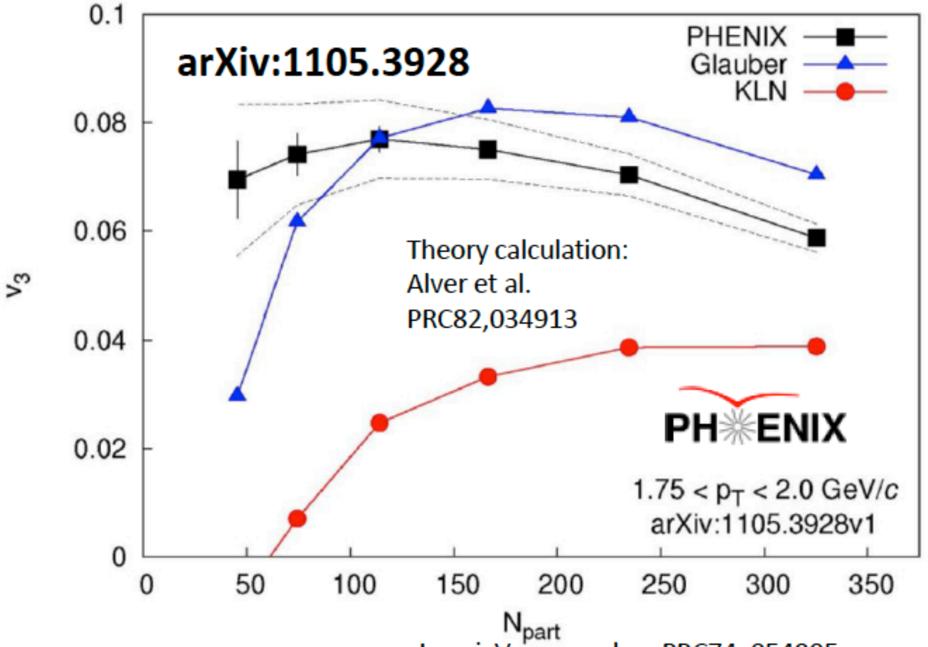
- The Mach cone seems to be gone
- The “ridge” is understood in terms of the sum of all moments of flow
- Many aspects of “non-flow” are no longer needed
- There were many gains in RHIC heavy ion physics also at QM 2011
- Following are several examples of gains

v_3 Untangles Initial State and η/s

v_2 described by Glauber and CGC



v_3 described only by Glauber



Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

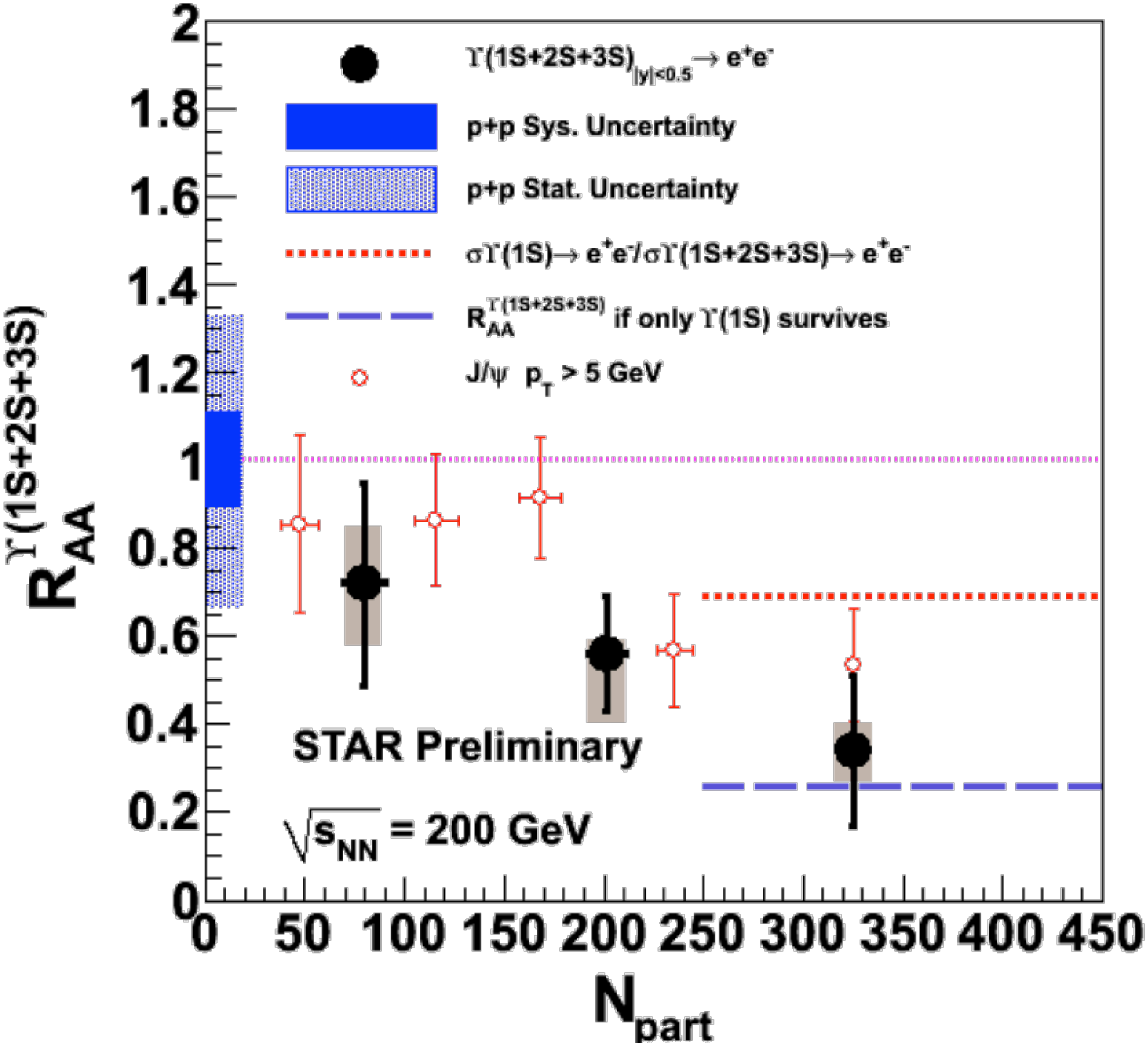
- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

← Two models →

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

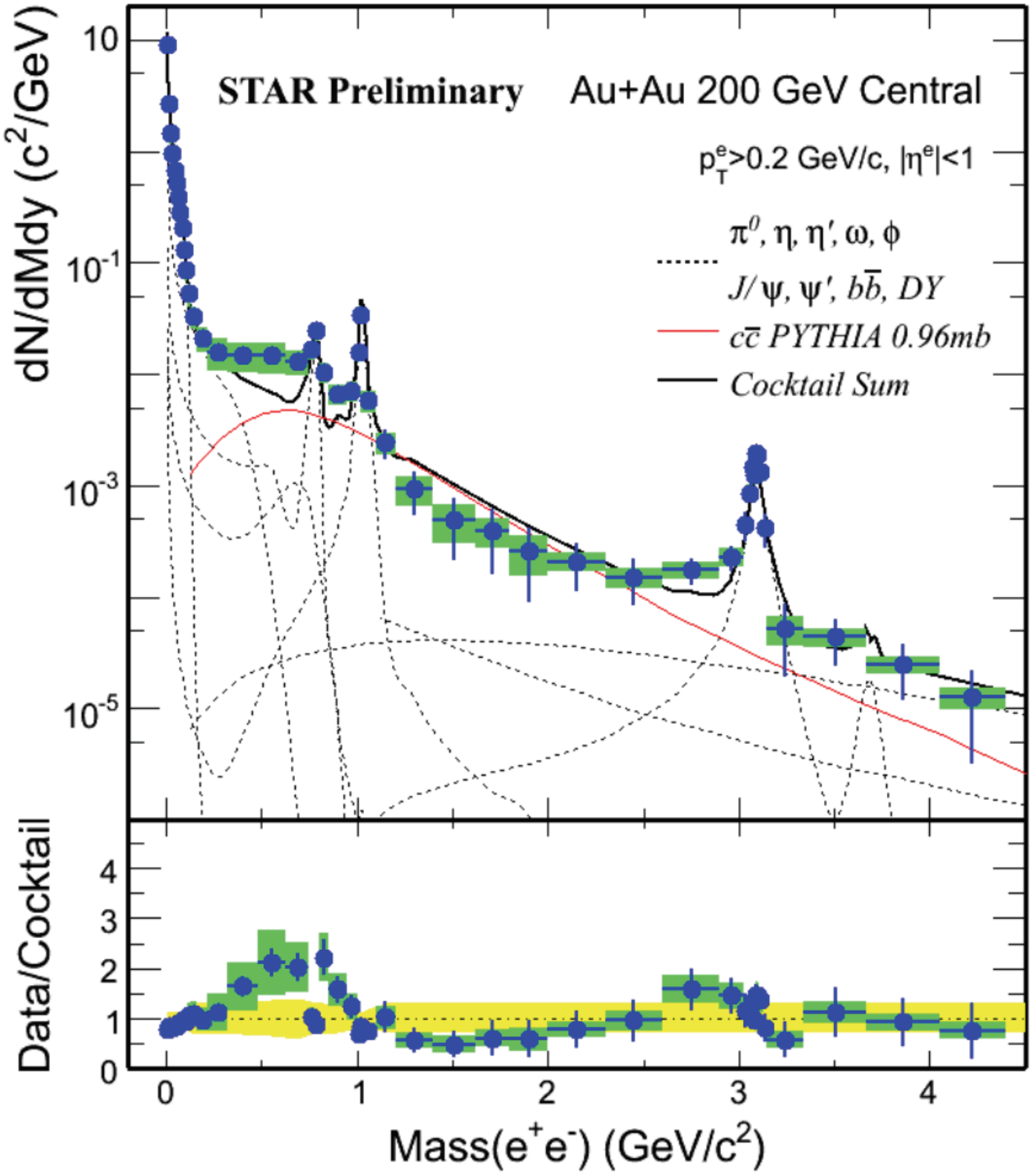
S. Bathe
PHENIX Overview, QM11

Observation of *Y* Suppression



R. Reed
QM11

Electromagnetic Probes in STAR

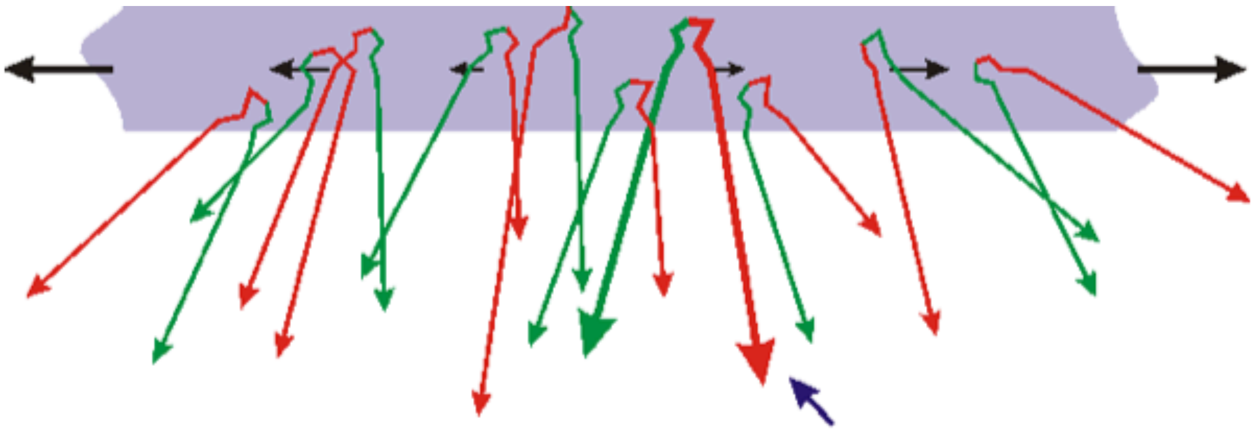


J. Zhao
QM11

Dynamical Charge Correlations

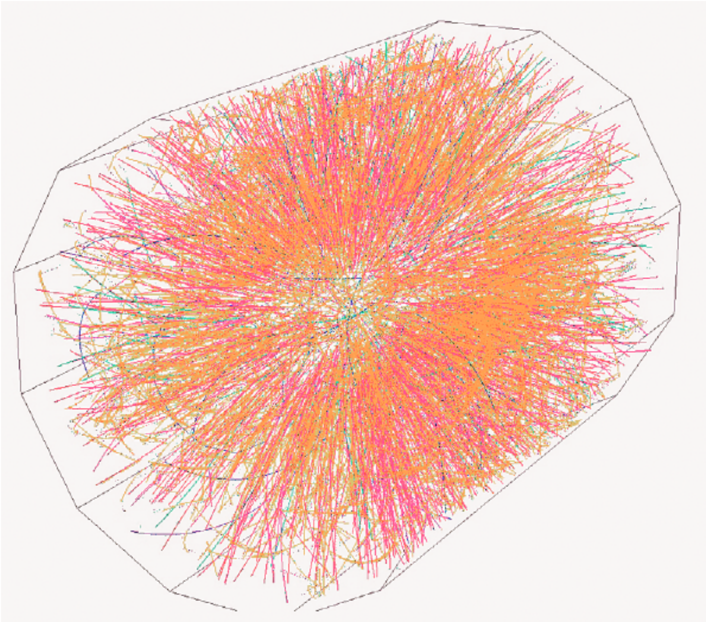
- Observed charge is created during the evolution of the system
- QGP will strongly affect charge formation and relative diffusion
- Various correlators have been proposed to study dynamical charge correlations
- Three particle correlator
  - Voloshin, PRC 70, 057901 (2004)
  - STAR, PRL 103, 251601 (2009)
  - Related three particle correlator to local parity violation
- Balance function
  - Schlichting and Pratt, PRC 83, 014913 (2011)

Charge Conservation



For every +*q*, there is a balancing -*q*

Who is his partner?



Charge Balance Function

- Charge balance function in terms of $\Delta\eta$
  - Bass, Danielewicz, and Pratt, PRL **85**, 2689 (2000)

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

    - Normalizes to unity for perfect acceptance
    - Narrows for delayed hadronization
    - Broadens for diffusion
    - Narrows for cooling
- Charge balance function in terms of $\Delta\phi$

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

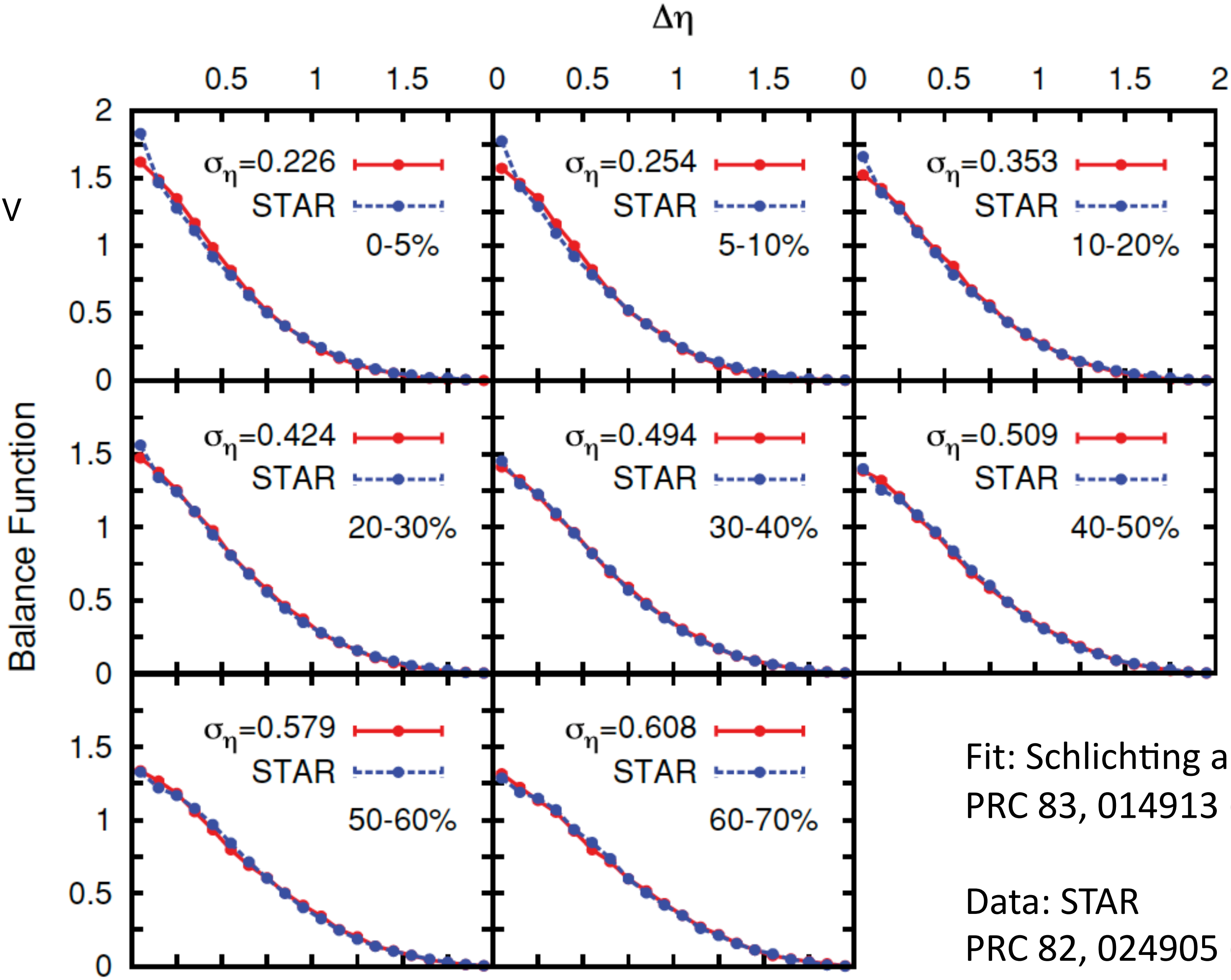
    - Normalizes to unity for perfect acceptance
    - Narrows for radial flow

Blast Wave

- Thermal blast wave model
- Based on STAR parameterization of STAR spectra and v_2
  - T – kinetic freeze-out temperature
  - β_x, β_y – in-plane and out-of-plane transverse collective velocities
  - R_x, R_y – in-plane and out-of-plane dimensions of freeze-out surfaces
  - σ_η, σ_ϕ – relative spread of emission points of balancing charges
- Canonical methods are used to enforce local charge conservation along the emitting surface

Width in η

Au+Au
200 GeV

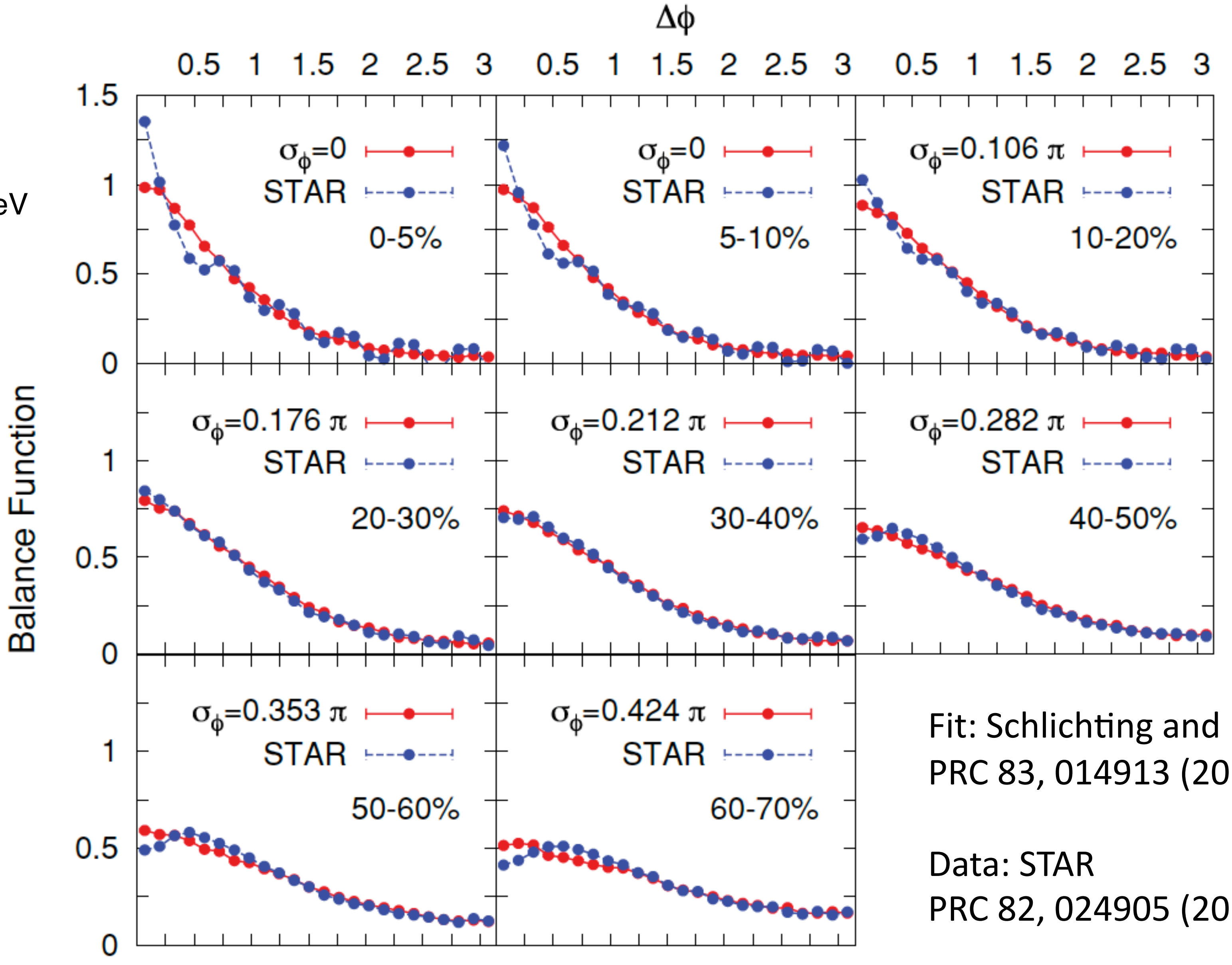


Fit: Schlichting and Pratt
PRC 83, 014913 (2011)

Data: STAR
PRC 82, 024905 (2010)

Width in ϕ

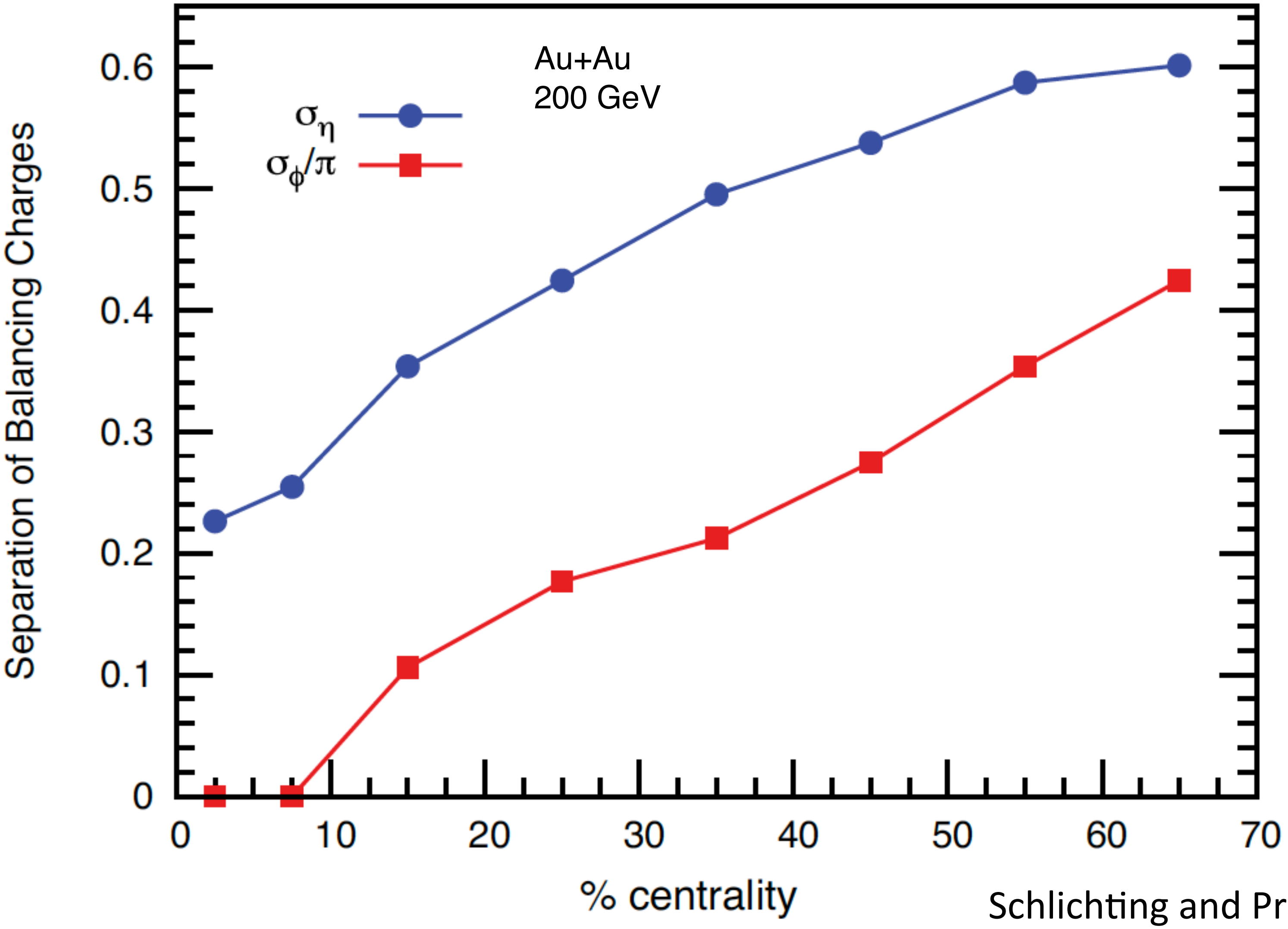
Au+Au
200 GeV



Fit: Schlichting and Pratt
PRC 83, 014913 (2011)

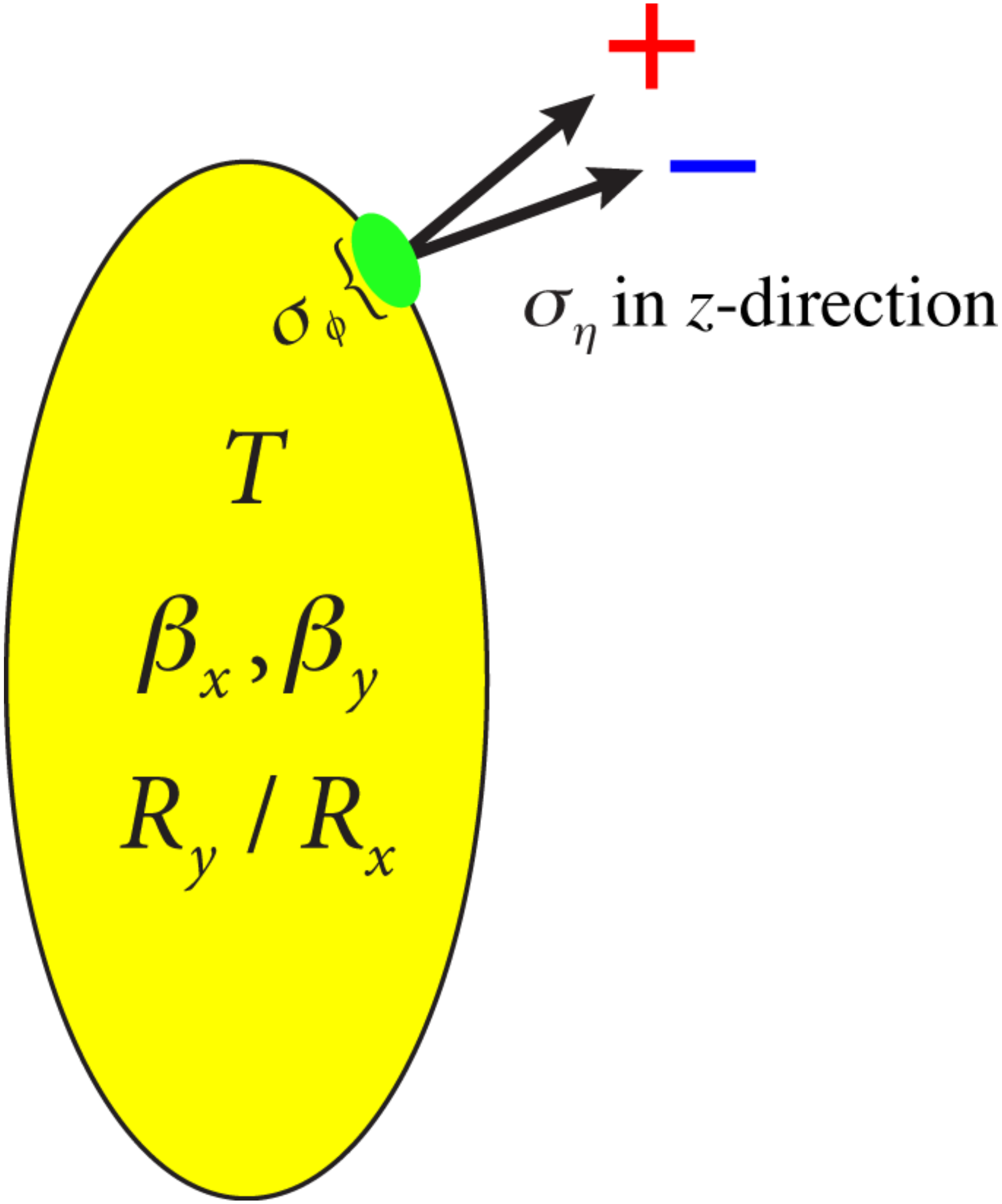
Data: STAR
PRC 82, 024905 (2010)

Widths



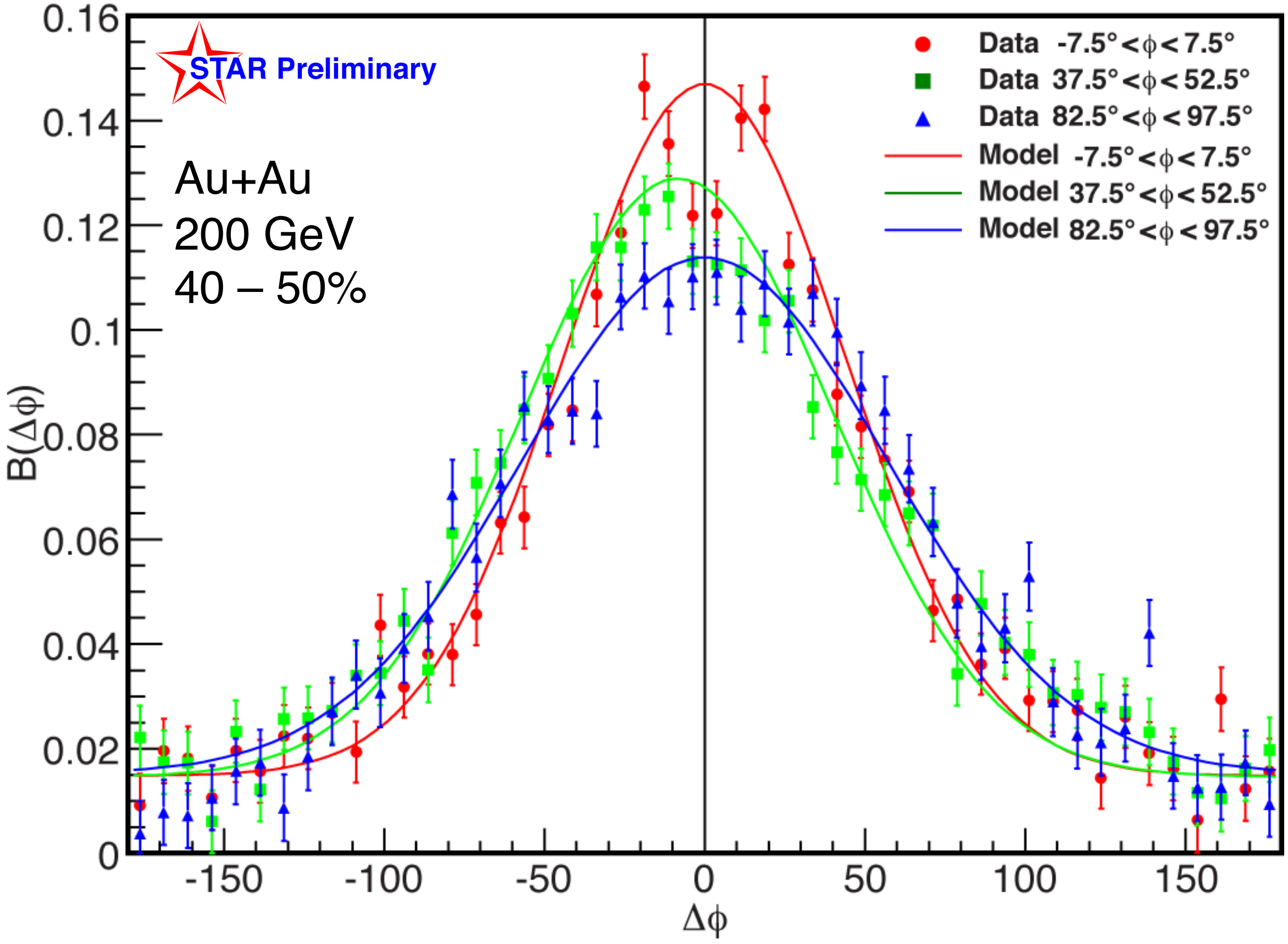
Schlichting and Pratt
PRC 83, 014913 (2011)

Blast Wave Illustration



Event-Plane Dependent Balance Function

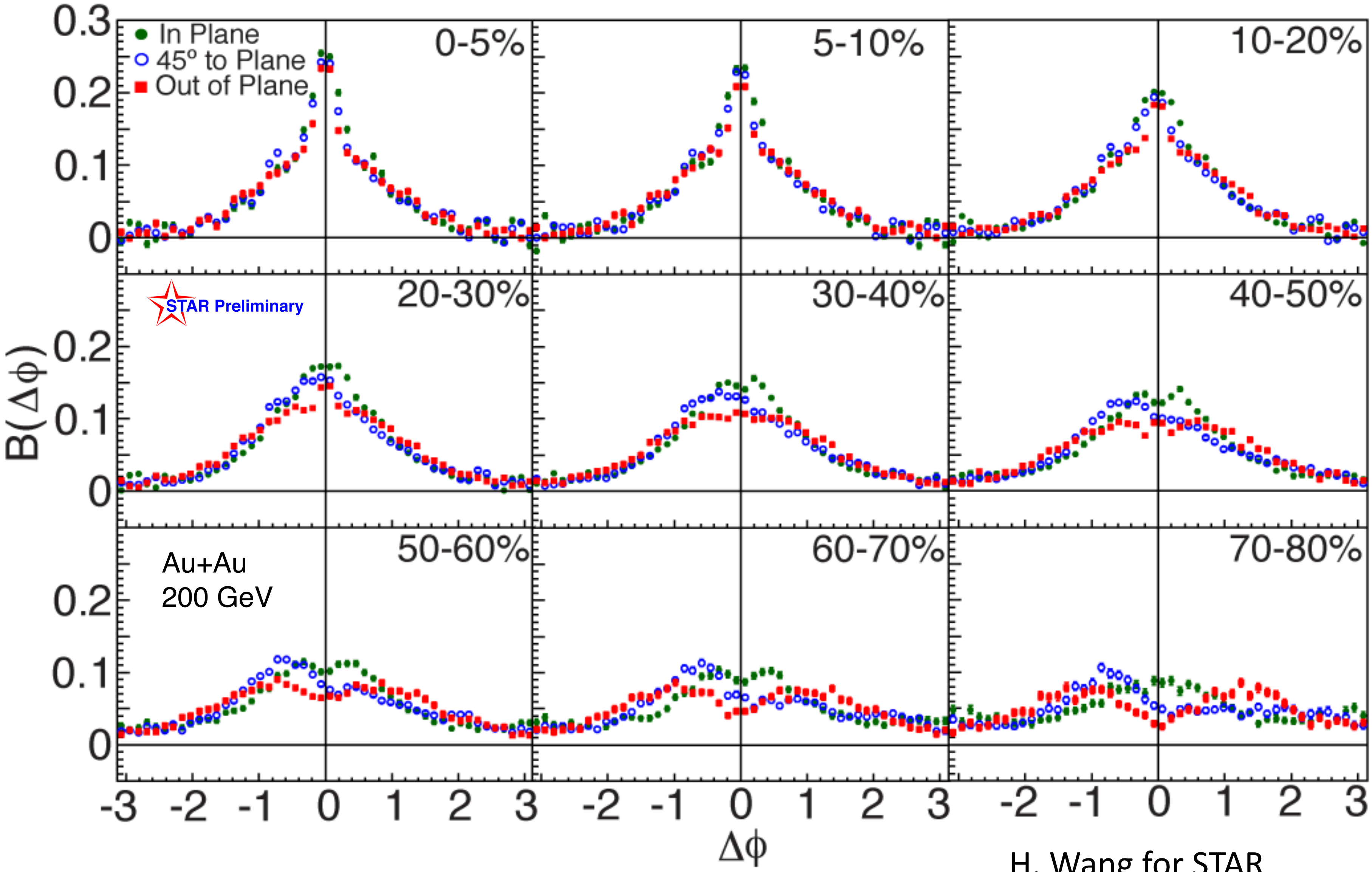
$$B(\phi,\Delta\phi) = \frac{1}{2}\left\{ \frac{N_{+-}(\phi,\Delta\phi) - N_{++}(\phi,\Delta\phi)}{N_{+}} + \frac{N_{-+}(\phi,\Delta\phi) - N_{--}(\phi,\Delta\phi)}{N_{-}} \right\}$$



Data
Hui Wang for STAR
Poster, QM2011

Model
Schlichting and Pratt
PRC 83, 014913
(2011)

Event-Plane Dependent Balance Function

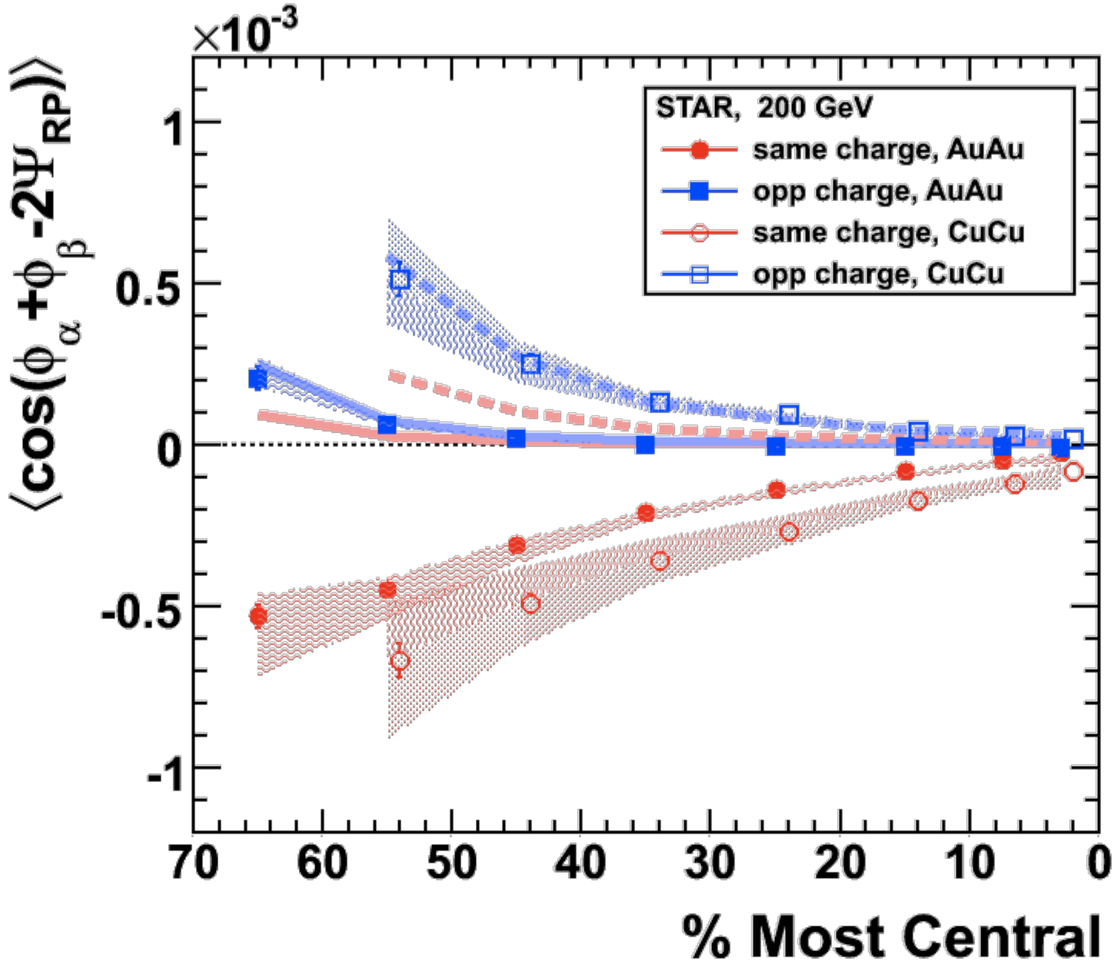


H. Wang for STAR
QM2011

Relation to Three Particle Correlator

- The three particle correlator proposed by Voloshin and measured by STAR is

$$\gamma_{\alpha\beta} = < \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) >$$



STAR
PRL 103, 251601 (2009)

Relation to Three Particle Correlator

- This can related to the event-plane dependent balance function through

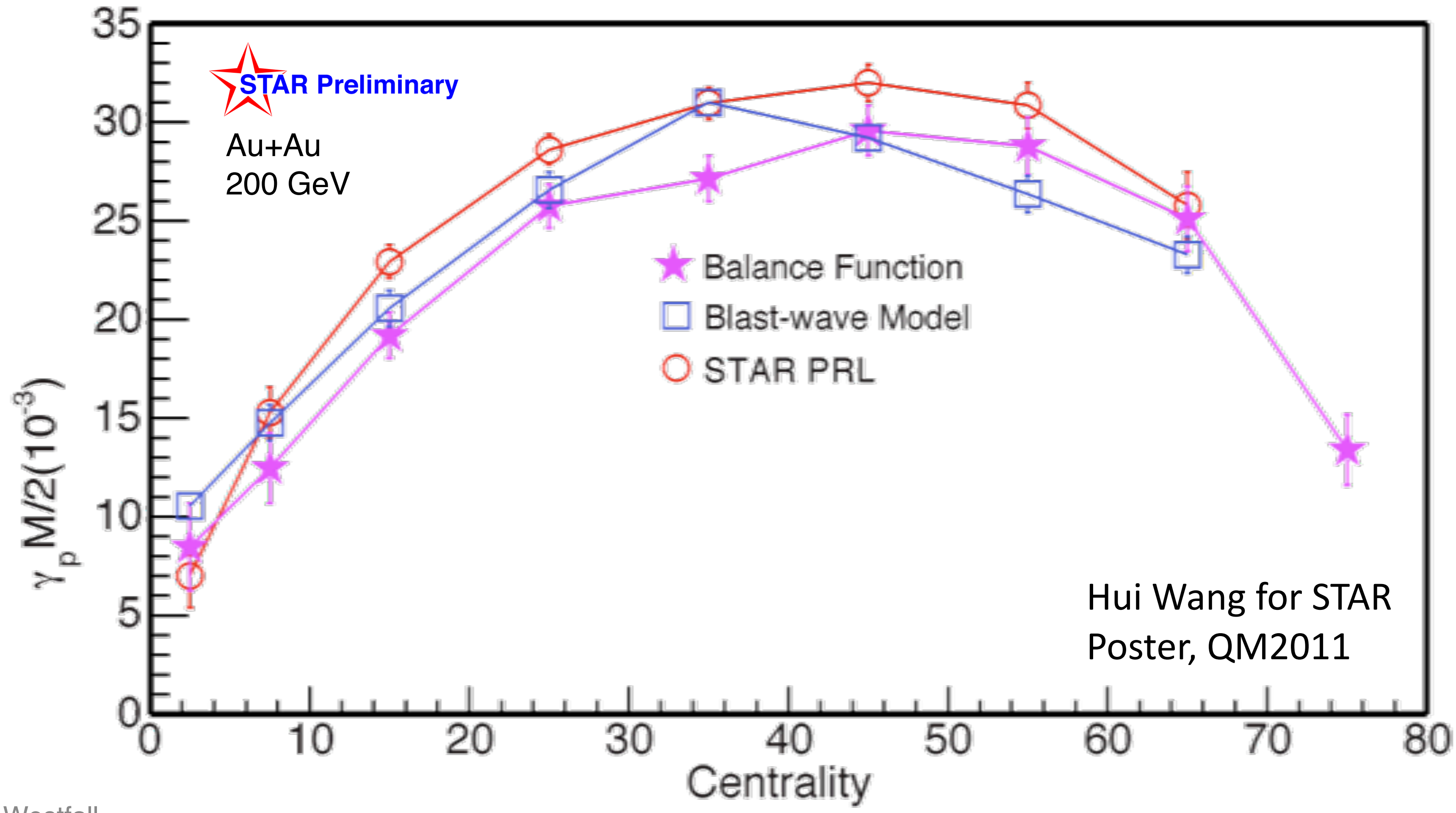
$$\gamma_p = \left(2\gamma_{+-} - \gamma_{++} - \gamma_{--}\right)$$

$$\gamma_p = \frac{2}{M^2}\int d\phi d\left(\Delta\phi\right)\frac{dM}{d\phi}B\left(\phi,\Delta\phi\right)\left[\cos 2\phi \cos\Delta\phi - \sin 2\phi \sin\Delta\phi\right]$$

- The event-plane dependent balance function can be related to the different in the same-sign and opposite sign three particle correlator

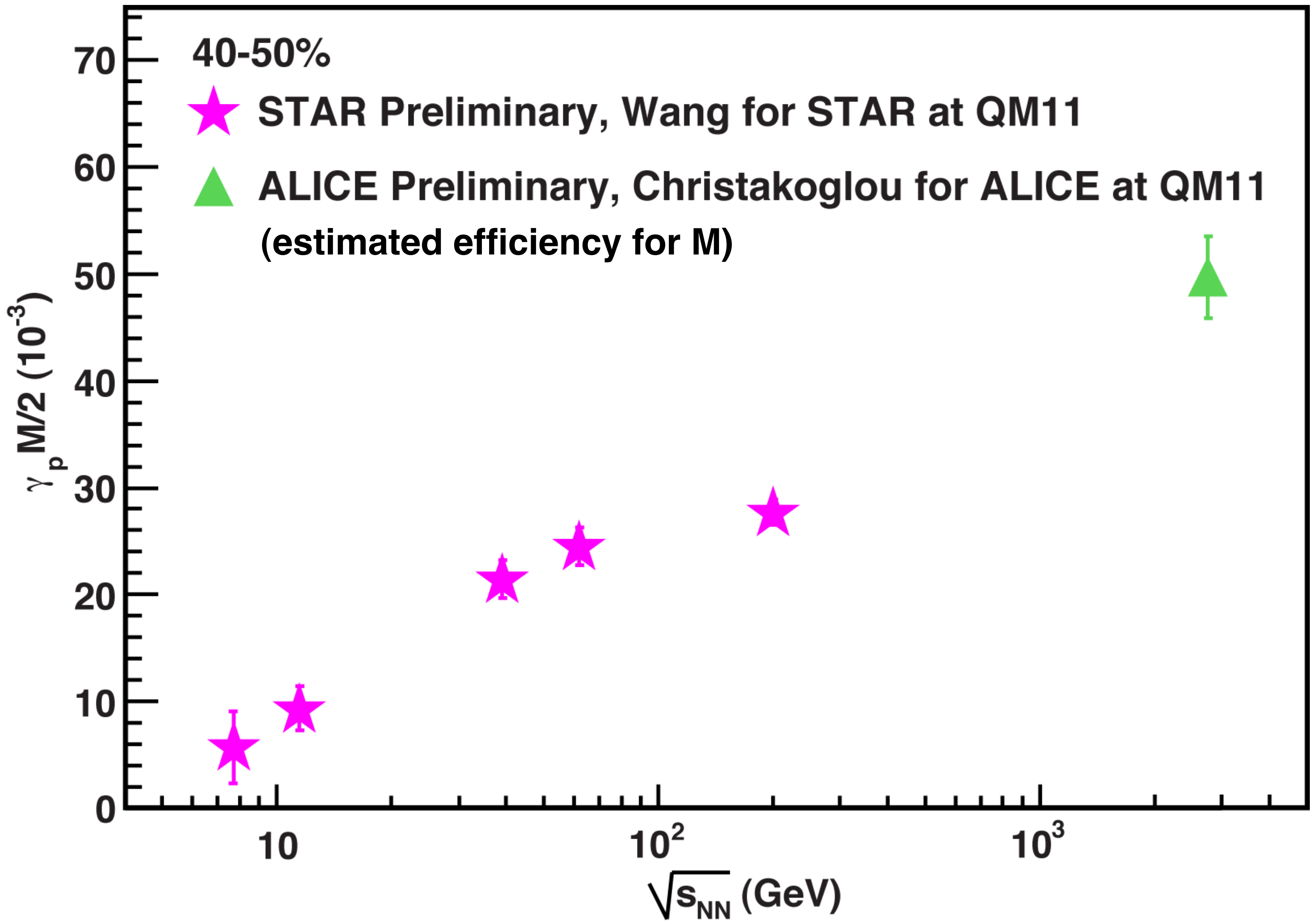
Compare

- The difference between same-sign and opposite sign three particle correlators can be explained in terms of local charge conservation and flow



Hui Wang for STAR
Poster, QM2011

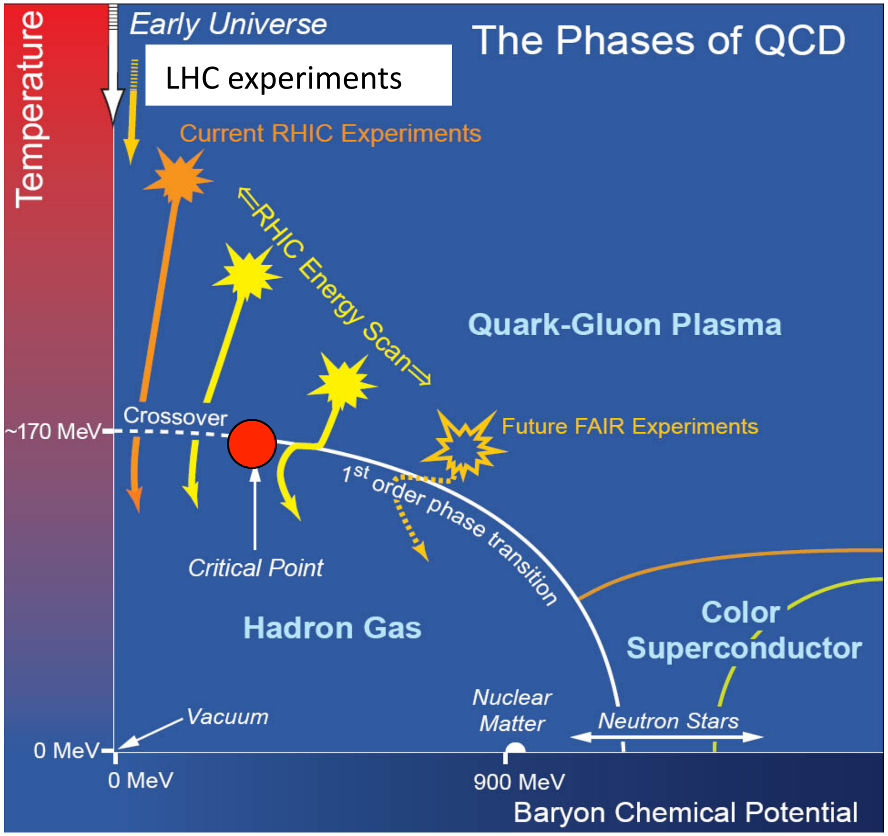
Extend to LHC Energies



Beam Energy Scan at RHIC

QCD Phase Diagram (Hadrons -- Partons)

Theory and Experimental approaches



Motivation:

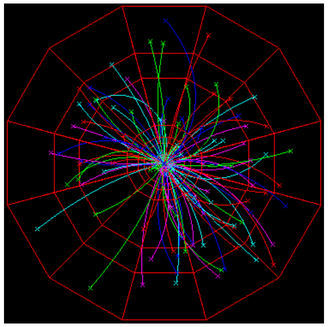
Search for signals of phase boundary
Search for signals for critical point

History: Proposal in 2008

(A) Demonstrate RHIC/Experiment can operate below injection energy

Test run 2008/2009 -

STAR:PRC 81 (2010) 024911

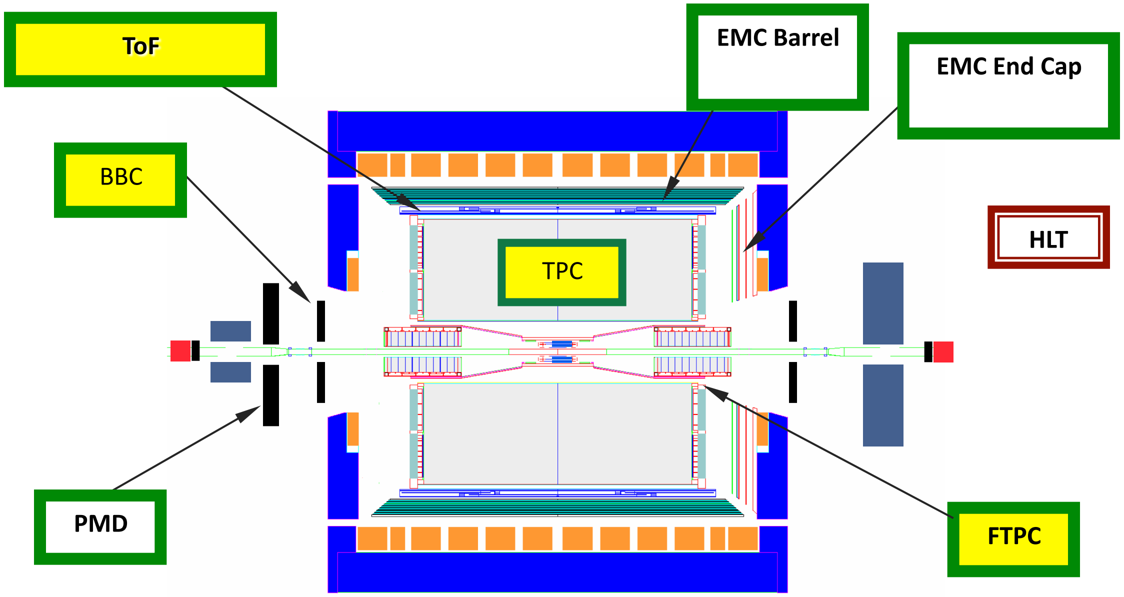


(B) Establish observables

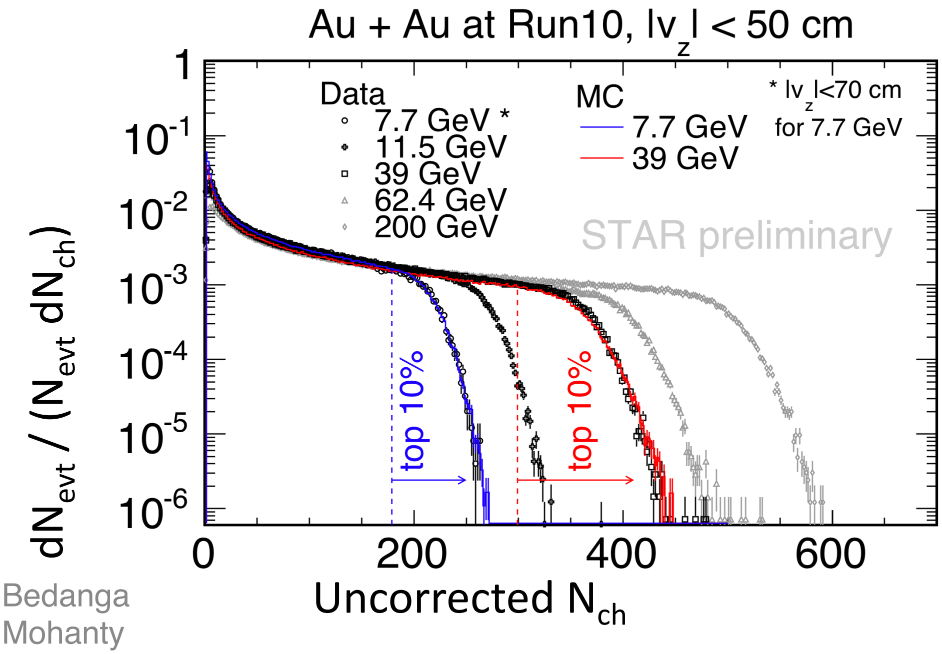
NCQ scaling of v_2	Partonic vs. hadronic degrees of freedom
Dynamical charge correlations	Partonic vs. hadronic degrees of freedom
Azimuthally sensitive HBT	1^{st} order phase transition
v_1 vs. rapidity	1^{st} order phase transition
Fluctuations	Critical point

http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
arXiv:1007.2613

RHIC BES 2010-2011



Particle identification over 2π in azimuthal angle and two units in pseudorapidity

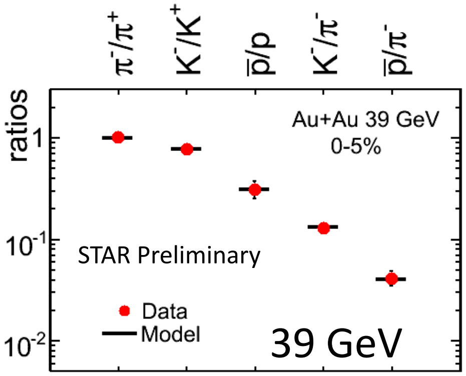

Au + Au at Run10, $|v_z| < 50$ cm

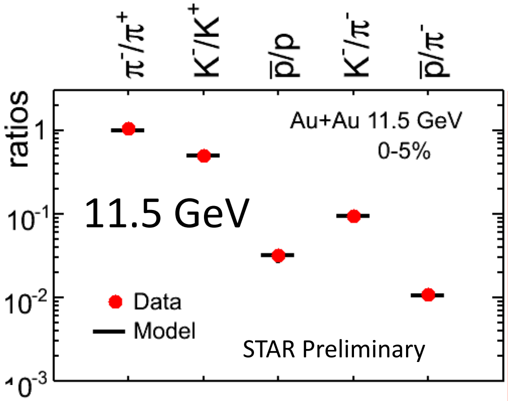
$\sqrt{s_{NN}}$ (GeV)	Good events in milions of events
5.0	
7.7	~ 5
11.5	~ 11
19.6	~ 17
27	Expected ~ 150
39	~ 170

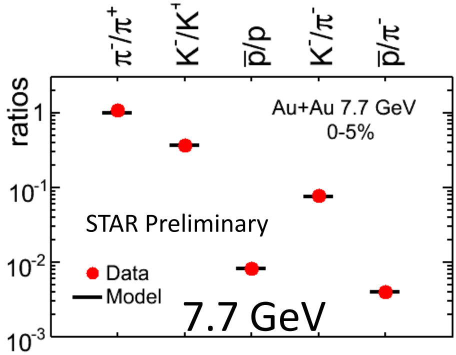
Bedanga Mohanty

Freeze-out Conditions

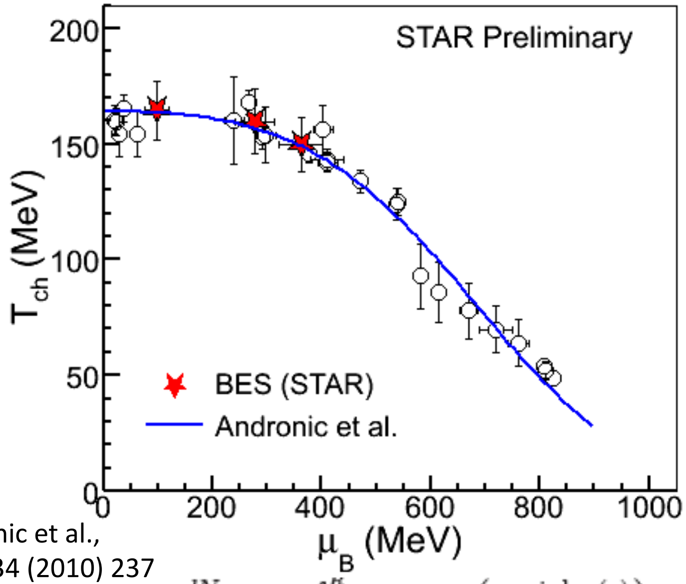
$$\frac{N_i}{N_j} \sim \exp\left(\frac{\mu_{i,\mathrm{ch.}} - \mu_{j,\mathrm{ch.}}}{T_{\mathrm{ch.}}} - \frac{m_i - m_j}{T_{\mathrm{ch.}}}\right)$$





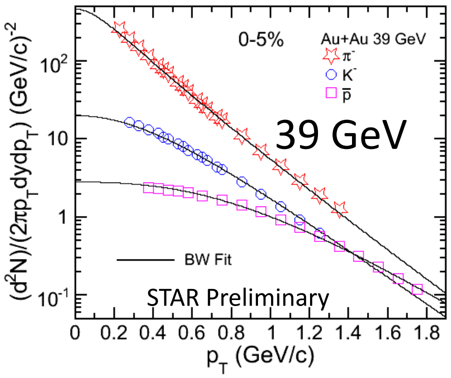


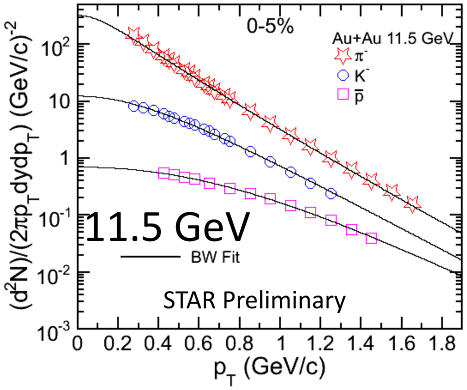
Chemical freeze-out:
Particle ratios

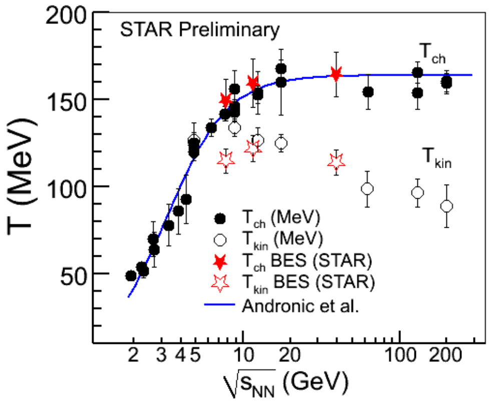


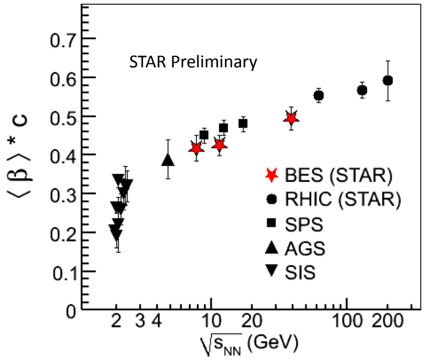
Andronic et al.,
NPA 834 (2010) 237

$$\frac{dN}{p_T\,dp_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{\mathrm{kin}}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{\mathrm{kin}}}\right),$$







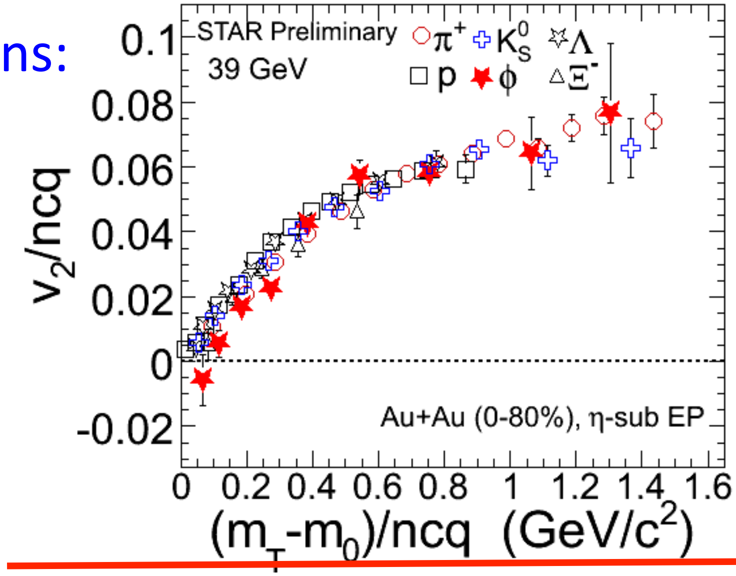


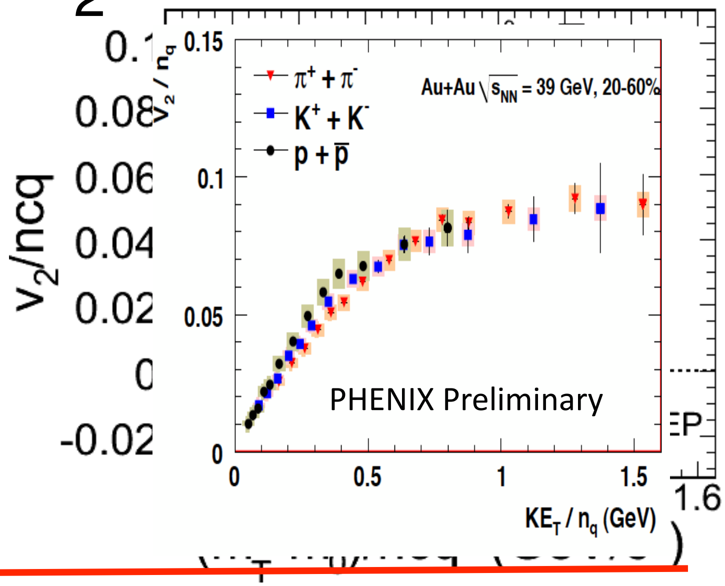
Kinetic freeze-out : Momentum distributions

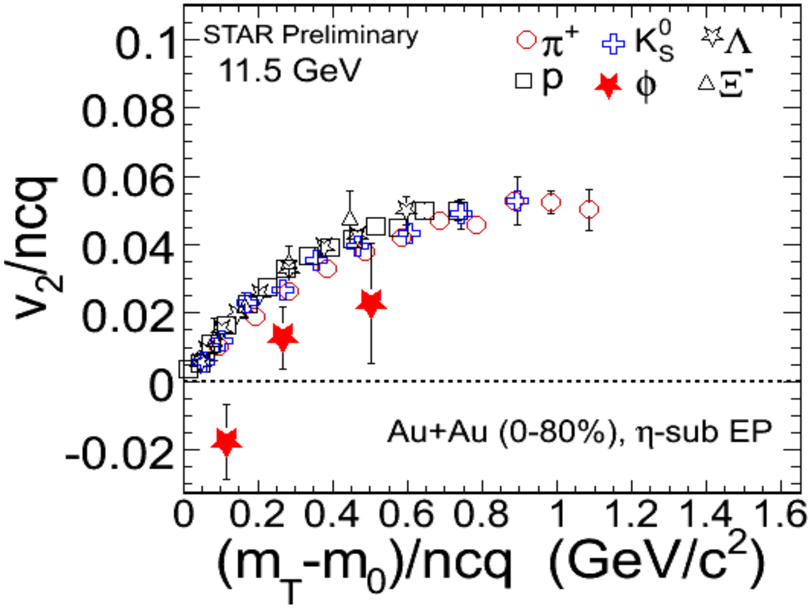
Bedanga
Mohanty

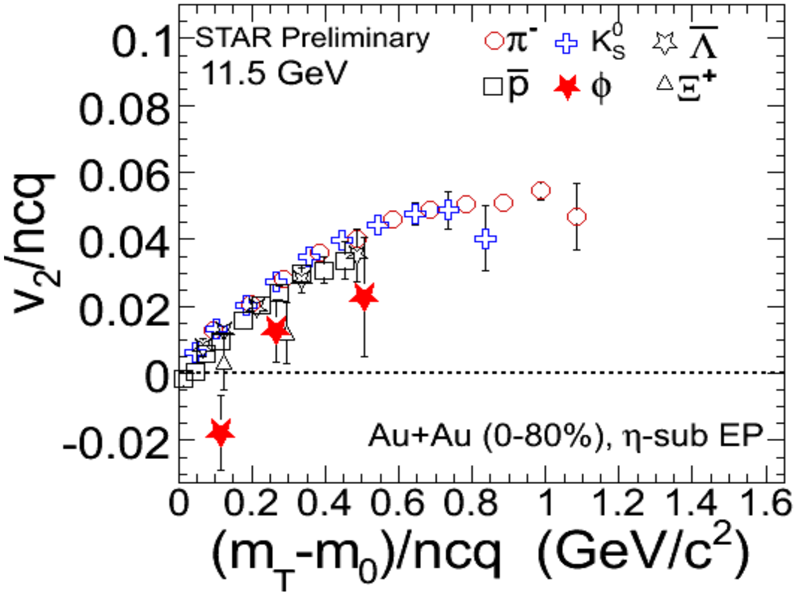
NCQ scaling of v_2

Observations:









ϕ meson v_2 falls off the trend from other hadrons at 11.5 GeV

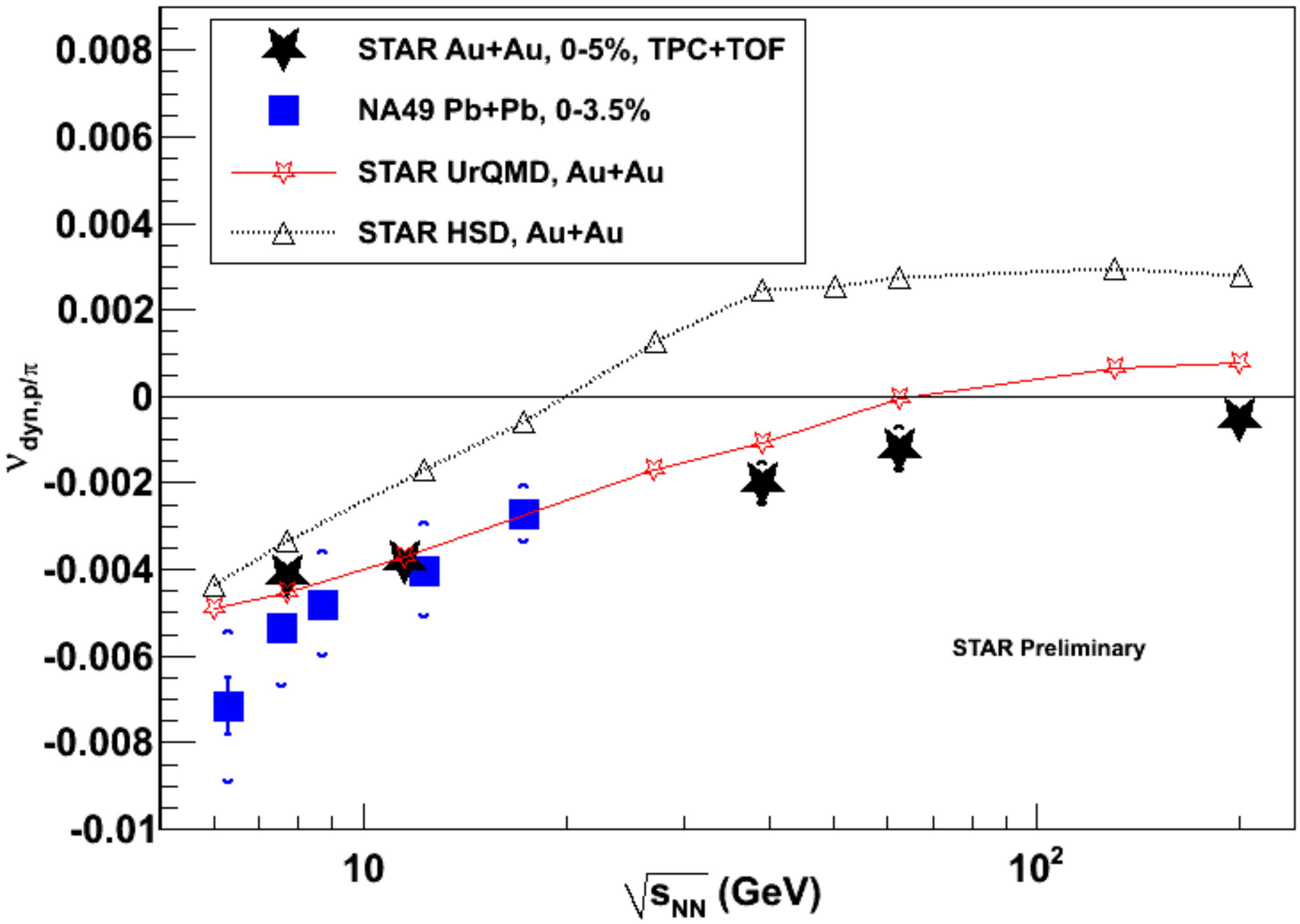
Particle Ratio Fluctuations

- Particle ratio fluctuations can be affected by charge conservation
- Particle ratio fluctuation may be sensitive to phase transitions
- Look at fluctuations using v_{dyn}

$$v_{\text{dyn},K\pi} = \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2\frac{\langle N_K N_\pi \rangle}{\langle N_K \rangle \langle N_\pi \rangle}$$

- Measures deviation from Poisson behavior
- Study $v_{\text{dyn},K\pi}$, $v_{\text{dyn},p\pi}$, $v_{\text{dyn},Kp}$

$\nu_{\mathrm{dyn},p/\pi}$



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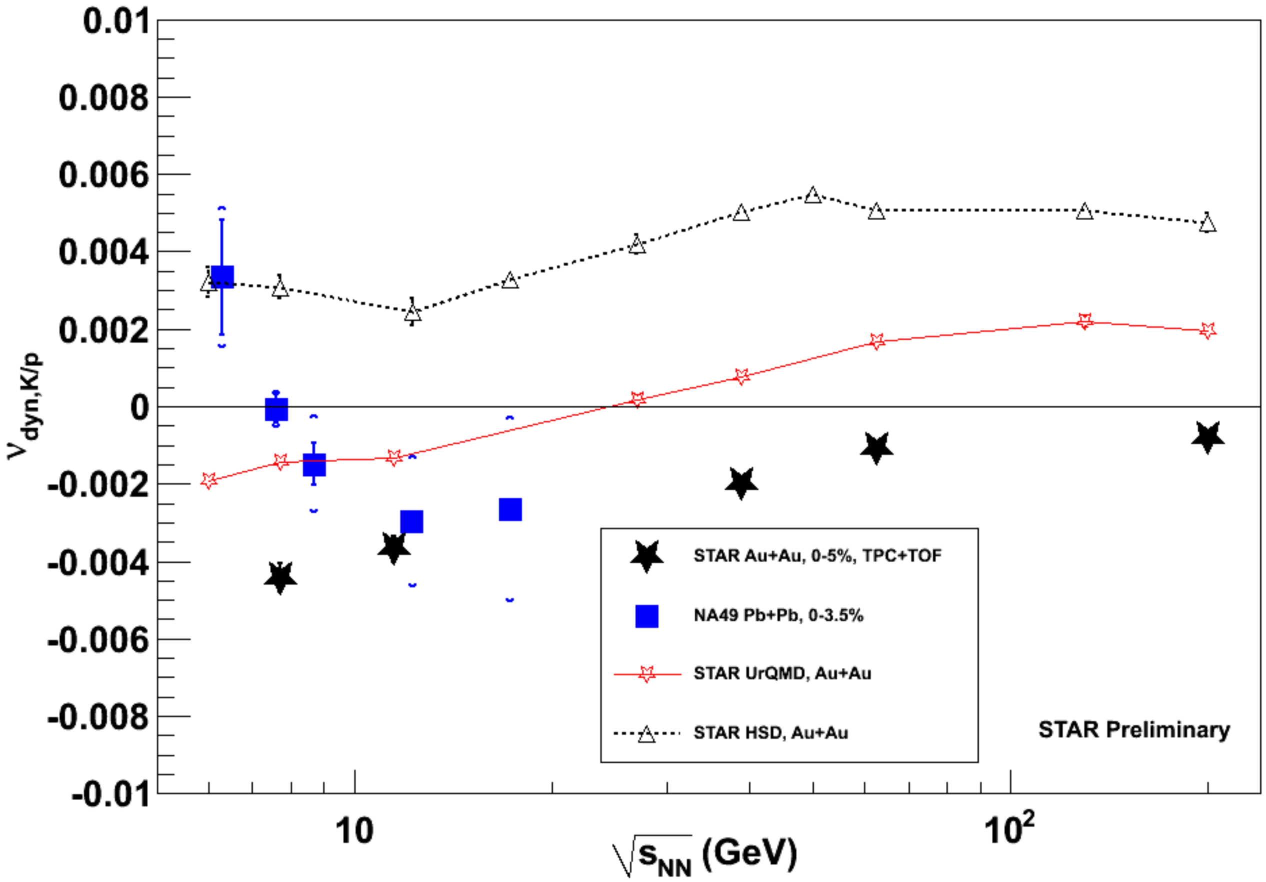
$\nu_{\mathrm{dyn},K/p}$



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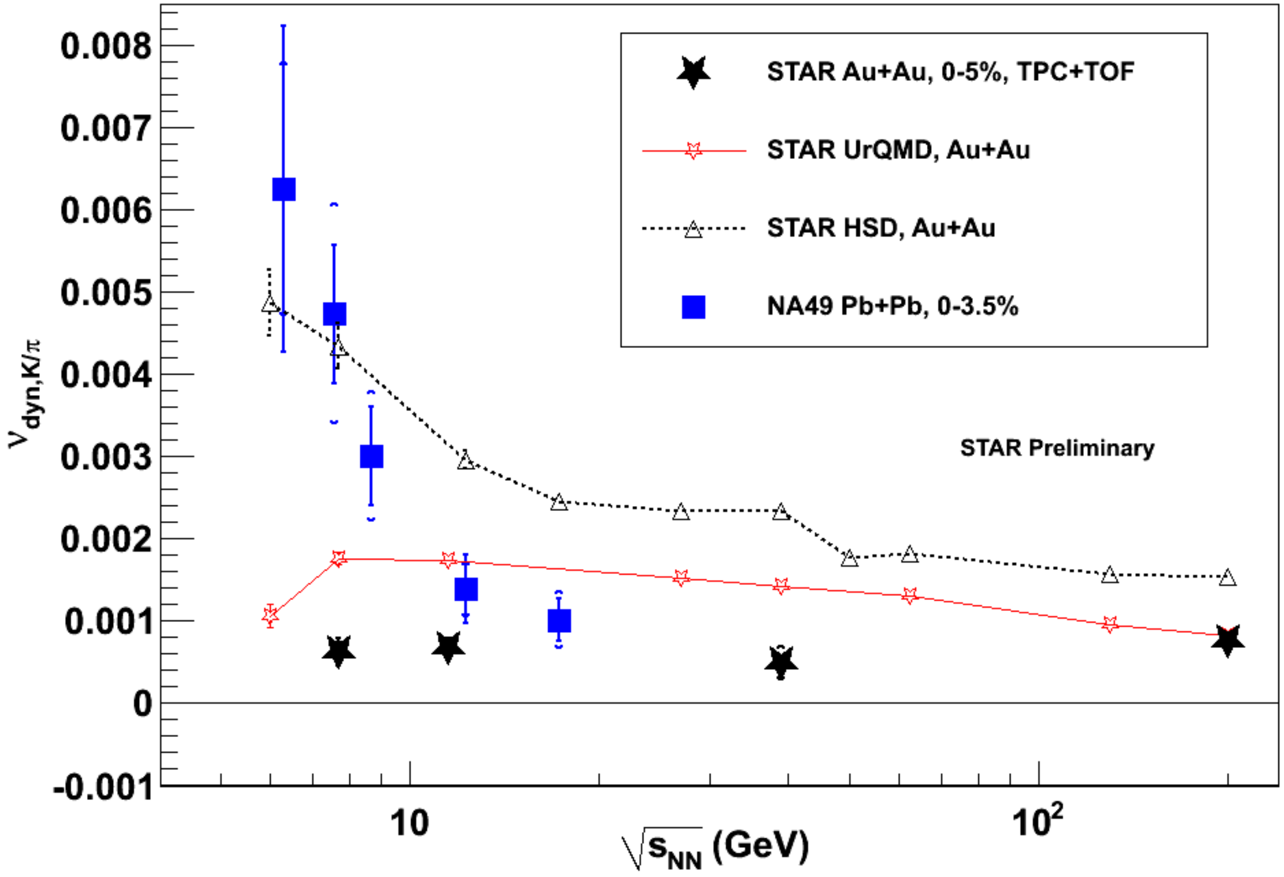
$\nu_{\mathrm{dyn},K/\pi}$



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Summary

- RHIC has a vibrant heavy ion physics program that is complementary to the heavy ion physics program at the LHC
- New capabilities of PHENIX and STAR expand the coverage of all aspects of heavy ion physics at RHIC energies
  - Electromagnetic probes
  - Heavy flavor physics
- The beam energy scan at RHIC has the promise of exploring the QCD phase diagram
  - Search for the QCD critical point