Recent results from the PHENIX Beam Energy Scan

Twelfth Conference on the Intersections of Particle and Nuclear Physics - CIPANP 2015
Vail, Colorado
May 19-24, 2015

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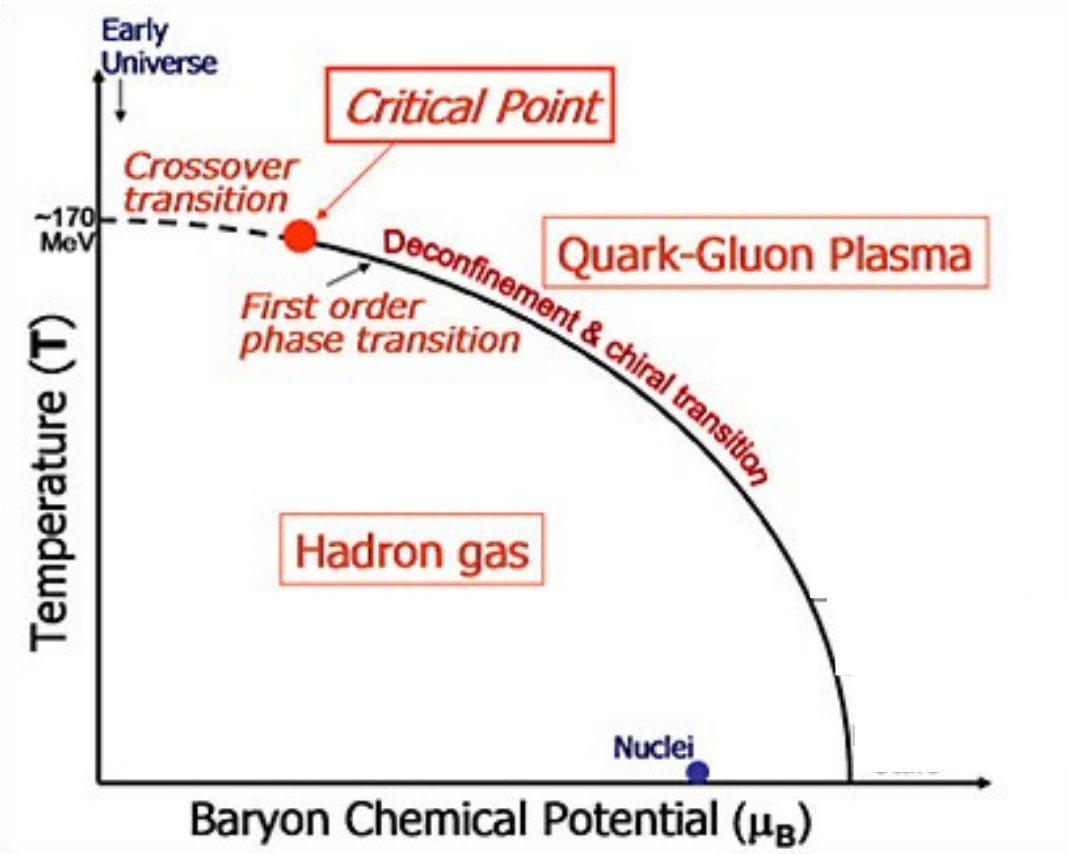
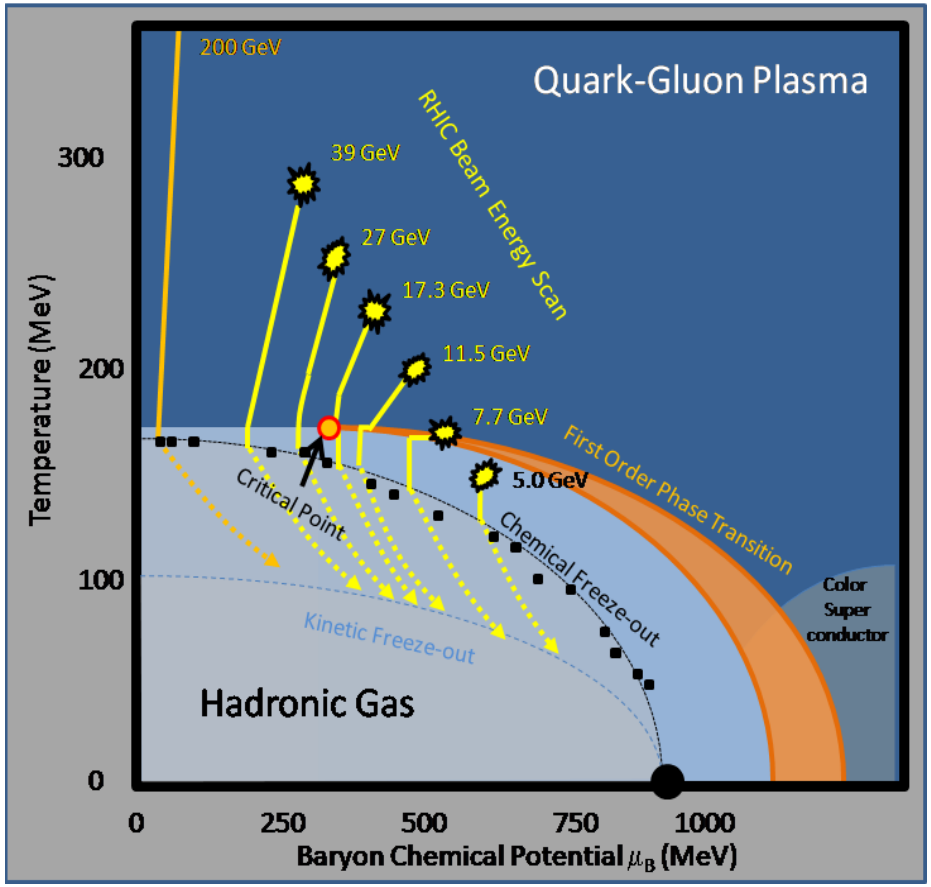
The QCD Phase Diagram

Conjectured phase diagram



- Low T and high μ_B: 1st order phase transition
- High T and low μ_B: Crossover transition
- ***This suggests the existence of a critical end point!***
- Location of 1st order phase boundary and Critical End Point (CEP) unknown
- ***Experiments at RHIC can help locate CEP and onset of deconfinement in T:μ_B***

Beam Energy Scan Program – Phase I (BES-I)



Strategy:

- Perform collisions across a range in μ_B
- Look for predicted signatures:
  - -Increased fluctuations in the vicinity of CEP
  - -Evidence of 1st order phase transition or softening of equation of state

This talk will focus on results of:

(1) charged particle multiplicity
(1) net charge fluctuations
(3) HBT measurements

performed at ***RHIC-PHENIX*** as part of the Beam Energy Scan.

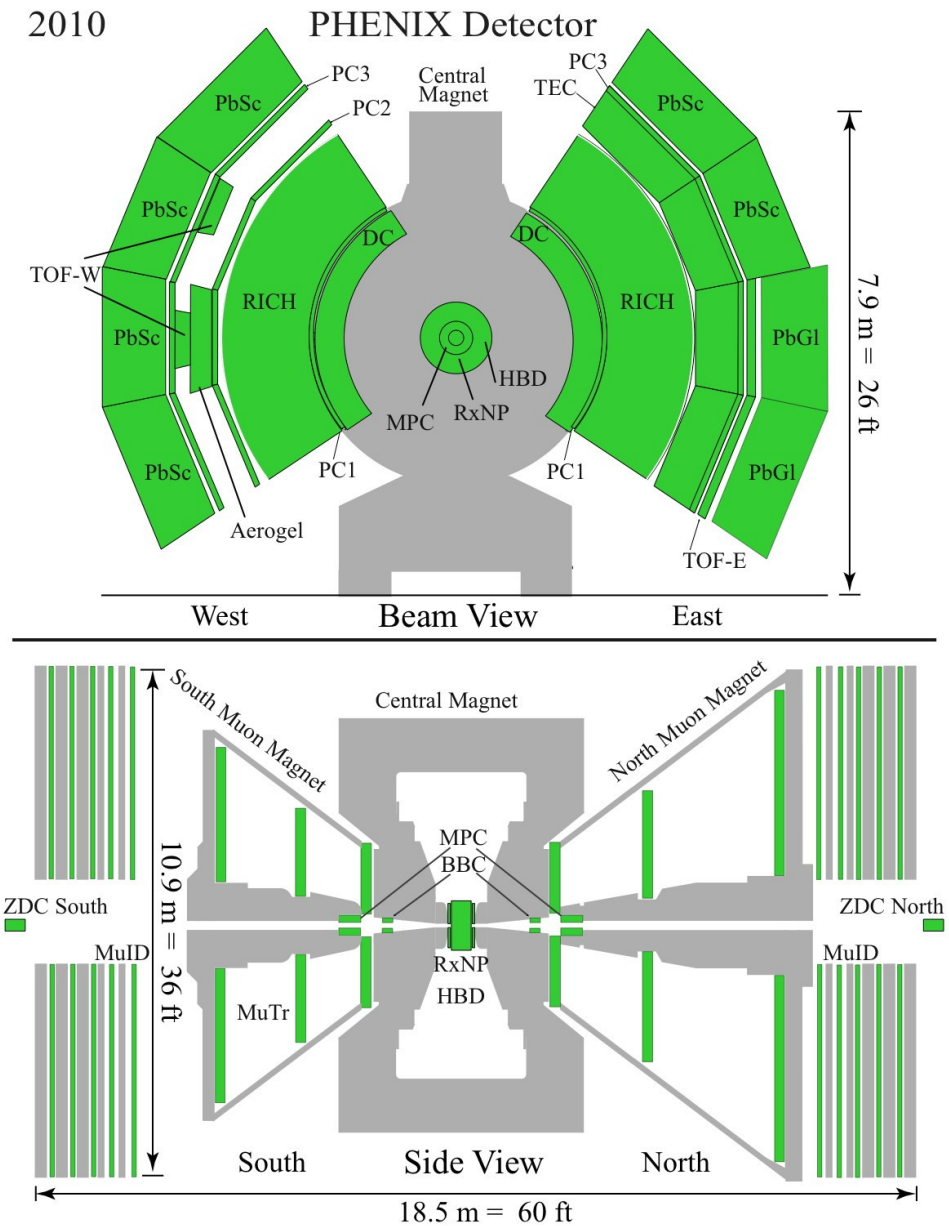
BES-I covered μ_B = 20 – 420 MeV!

Run summary from: http://www.rhichome.bnl.gov/RHIC/Runs/

Energy (GeV)	7.7	11.5 STAR only	14.5	19.6	27	39	62.4	200
μ_B(MeV)	420	315	260	205	155	115	70	20
Run-Year	2010	2010	2014	2011	2011	2010	2010	2010
Integrated Luminosity	1.75 μb^{-1}	7.82 μb^{-1}	72.3 nb^{-1}	15.7 μb^{-1}	32.7 μb^{-1}	107 μb^{-1}	281 μb^{-1}	5.01 nb^{-1}

The PHENIX Experiment

Beam View



Side View

Zero Degree Calorimeter (ZDC) & Beam Beam Counter (BBC)
Vertex and centrality determination

Drift Chamber (DC) & Pad Chamber (PC)
Tracking information

Electromagnetic Calorimeter (EMC) Lead Scintillator Sectors (Six Total)
and
Time-of-Flight Detector (TOF)
PID information: time-of-flight (t) and length of time-of-flight (L)

With their good timing resolution, the EMC and TOF detectors provide for very good PID capabilities

Results:

(1) Multiplicity

- Look for change in dynamics of particle production

(2) Net charge fluctuations

- Look for increase in fluctuations

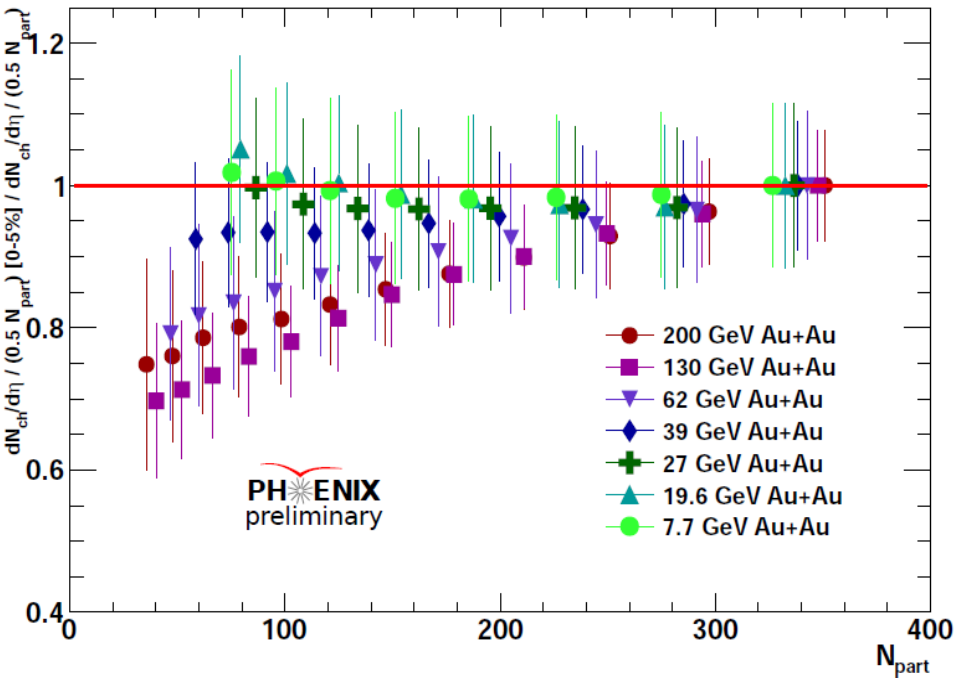
(3) HBT measurements

- Look for change in expansion dynamics

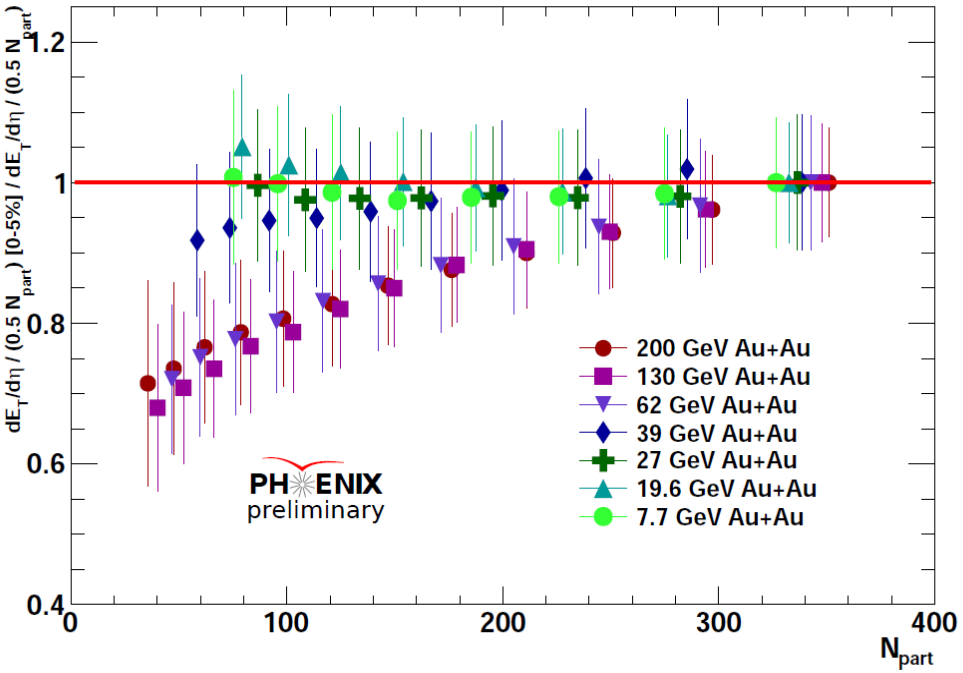
Multiplicity: Participant Nucleon Scaling

- A change in the particle production mechanism may have direct implications on fluctuation measurements.

Phys. Rev. C 89 (2014) 044905



Charged particle multiplicity dependence on N_{part} scaled to multiplicity at 0-5% for different beam energies in Au+Au



Transverse energy production dependence on N_{part} scaled to production at 0-5% for different beam energies in Au+Au

Participant nucleon scaling preferred below 39 GeV

Multiplicity: Participant Quark Scaling

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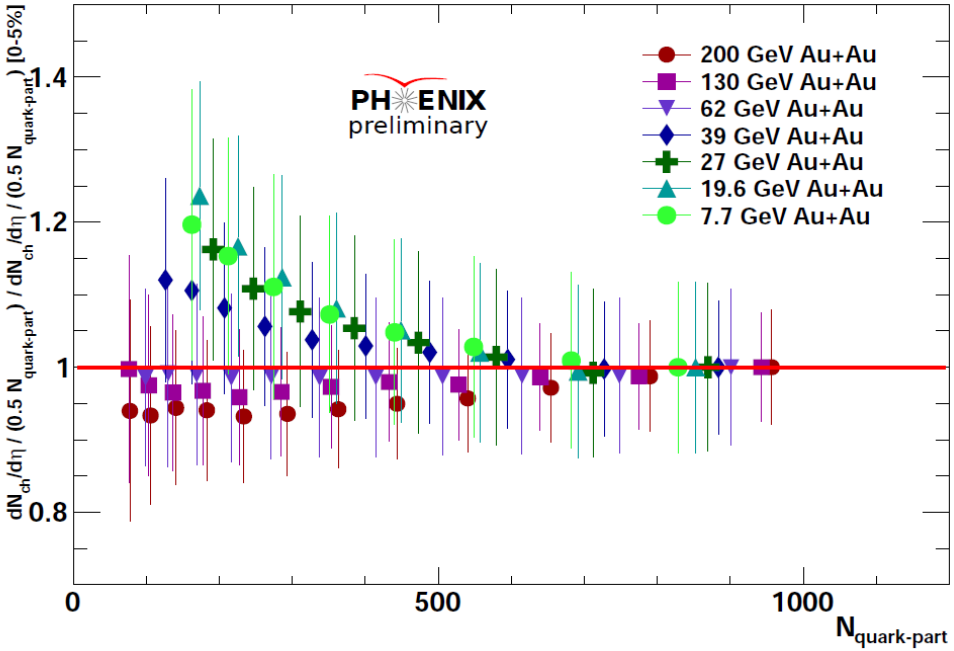
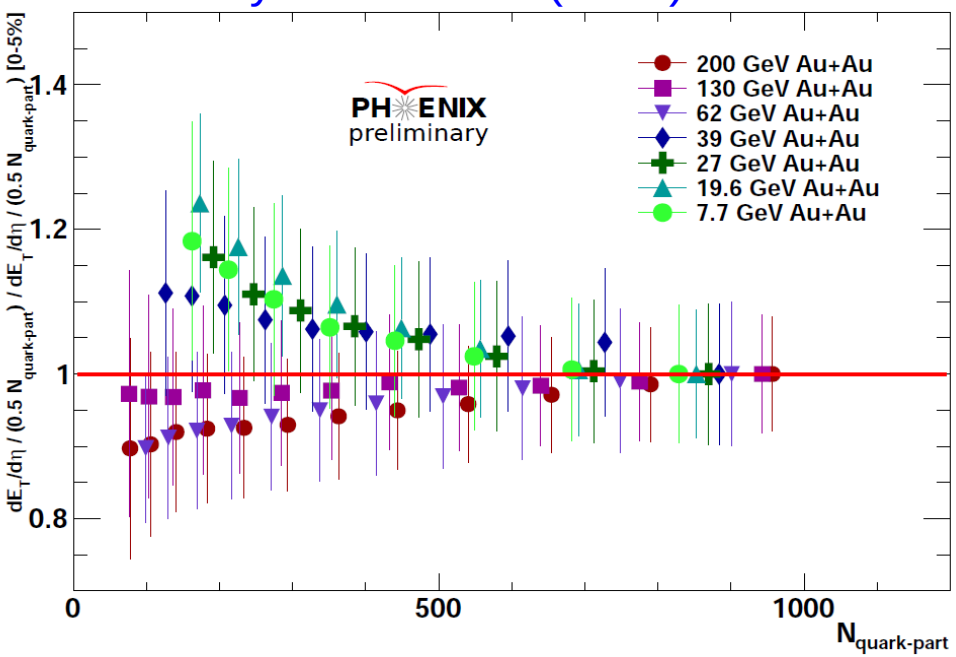


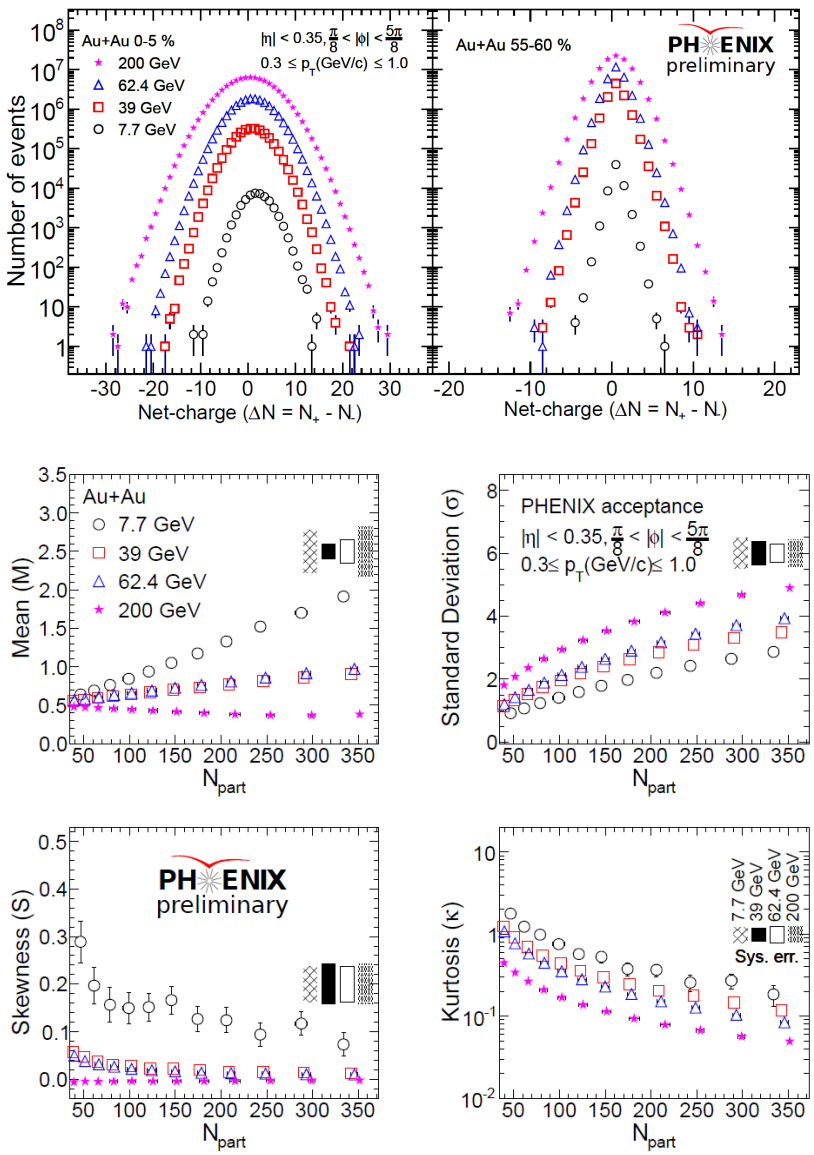


Charged particle multiplicity dependence on number of quark participants ($N_{quark\text{-}part}$) scaled to multiplicity at 0-5% for different beam energies in Au+Au

Transverse energy production dependence on $N_{quark\text{-}part}$ scaled to production at 0-5% for different beam energies in Au+Au

- Participant quark scaling works above 39 GeV
- **Might be showing a change in the dynamics of particle production. This has to be taken into consideration when studying charge fluctuations—a key signature of CEP**

Net Charge Fluctuations



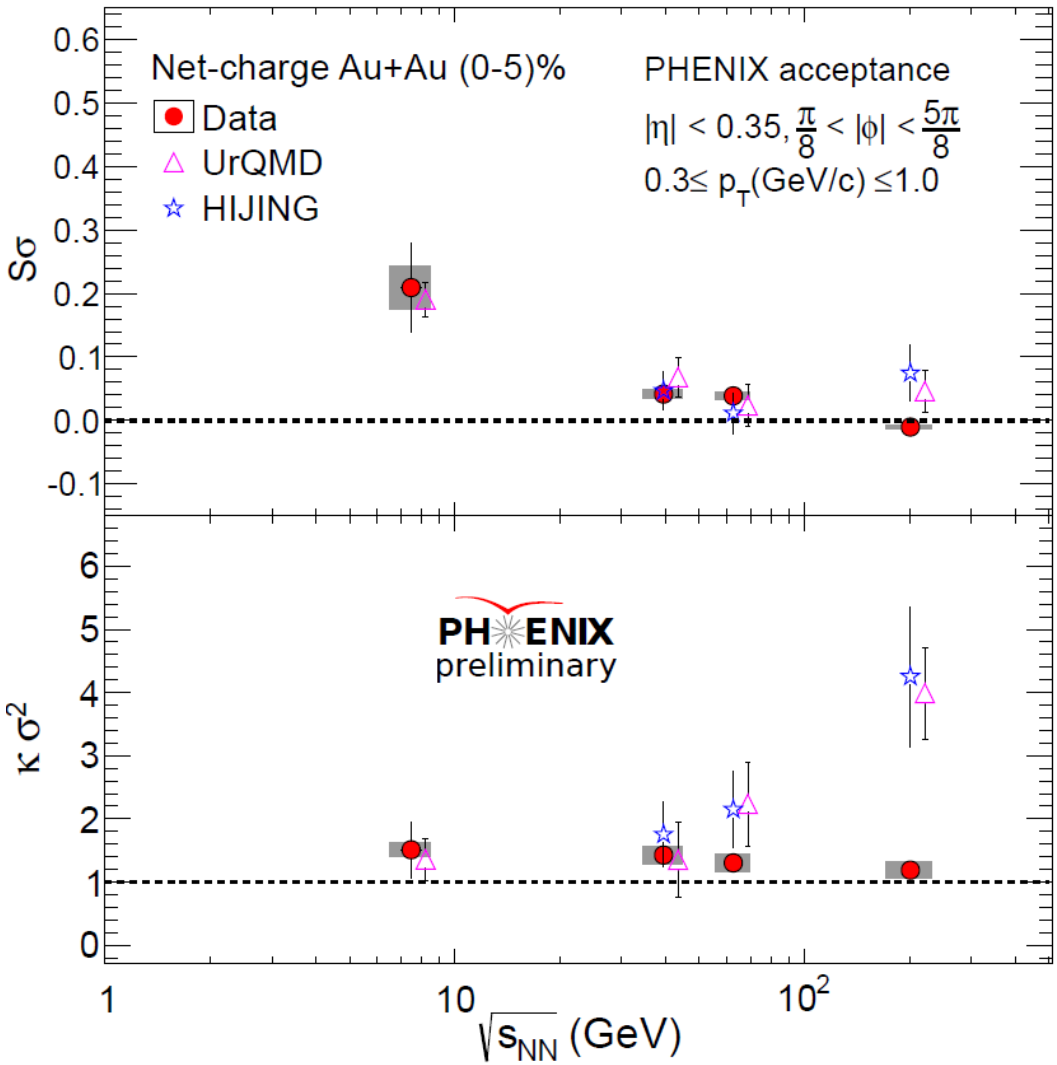
Panels (a) and (b) show net charge distributions

Panels (c), (d), (e), (f) shows moments dependence on $\langle N_{part} \rangle$

- Fluctuations of conserved quantities (e.g. charge) sensitive to coherence length (ξ) which diverges at CEP
  - *Net charge easily measurable in experiment - panels (a) and (b)*
- Finite size effects lead to smearing of critical phenomena
- Moments of conserved quantities more sensitive. Related to ξ and higher-order susceptibilities
- For multiplicity (N), mean (M), and where $\delta N = N - \mu$
  - Variance $\sigma^2 = \langle(\delta N)^2\rangle \sim \xi^2$
  - *Skewness* $S = \langle(\delta N)^3\rangle/\sigma^3 \sim \xi^{4.5}$
  - *Kurtosis* $\kappa = \langle(\delta N)^4\rangle/\sigma^4 - 3 \sim \xi^7$

- For fixed beam energy
  - M and σ increase with $\langle N_{part} \rangle$
  - S and κ decrease with $\langle N_{part} \rangle$
- For fixed $\langle N_{part} \rangle$
  - S, κ and M decrease with energy
  - σ increase with energy

Excitation Functions of Moments of Net Charge Fluctuations



- Moments related to susceptibilities:
  - $S\sigma \sim \chi^{(3)} / \chi^{(2)}$
  - $\kappa\sigma^2 \sim \chi^{(4)} / \chi(^{(2)}$

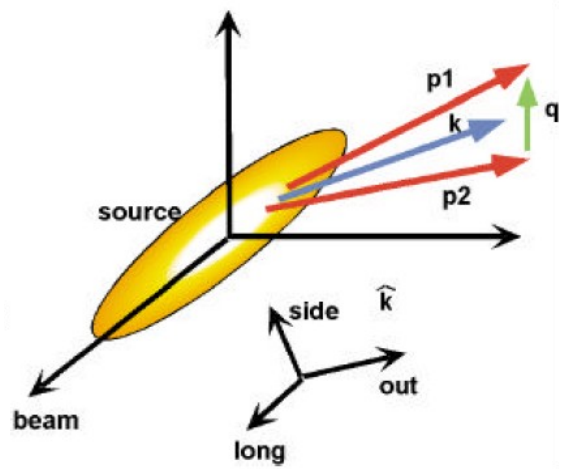
- Taking ratios removes volume dependence
  -allows comparison across energies and collision systems

Results compared with UrQMD and HIJING model predictions within PHENIX acceptance

- $S\sigma$ decreases with increasing energy
- $\kappa\sigma^2$ does not show a strong energy dependence

- Data does not show an excess above the model predictions

Changes in Expansion Dynamics of System: HBT



Based on quantum interference of identical particles whose position-momentum correlation can be expressed as:

$$C_2(q,k)-1=\int (d^3 r S_k(r)[|(\psi(k,r))|^2-1])$$

$$q=p_1-p_2 \quad k=(p_1+p_2)/2$$

Space-time information extracted by fitting $C_2(q_i)$ with:

$$C_2(q_{side},q_{out},q_{long})=1+\lambda\exp(-R_{side}^2 q_{side}^2-R_{out}^2 q_{out}^2-R_{long}^2 q_{long}^2-2R_{os}^2 q_{out}^2 q_{side}^2)$$

Here, q is decomposed in the longitudinal co-moving system (LCMS): q_{side}, q_{out}, q_{long}

q_{side} - is perpendicular to the beam direction. Gives R_{side}

q_{out} - is parallel to the average transverse momentum of pair or k_T. Gives R_{out}

q_{long} - is along beam direction. Gives R_{long}

Linking HBT radii to source parameters

- HBT radii = initial size + size due to expansion + effects of position-momentum correlations
- We need to be able to disentangle the individual components
- Relate HBT radii to actual physical observables

$$R_{side}^2 = \frac{R_{geom}^2}{1+\frac{m_T}{T}\upsilon^2}$$

$$R_{out}^2 = \frac{R_{geom}^2}{1+\frac{m_T}{T}\upsilon^2} + \frac{1}{2}\left(\frac{T}{m_T}\right)^2 \beta_T^2 \tau_0^2$$

$$R_{long}^2 = \tau^2 \frac{T}{m_T} \frac{K_2(m_T/T)}{K_1(m_T/T)}$$

R_{geom} is the geometrical transverse size, T is the temperature, β_T is the transverse flow and τ_0 is the emission duration

τ is the system lifetime, K_1 and K_2 are modified Bessel functions and m_T is the transverse mass defined as:

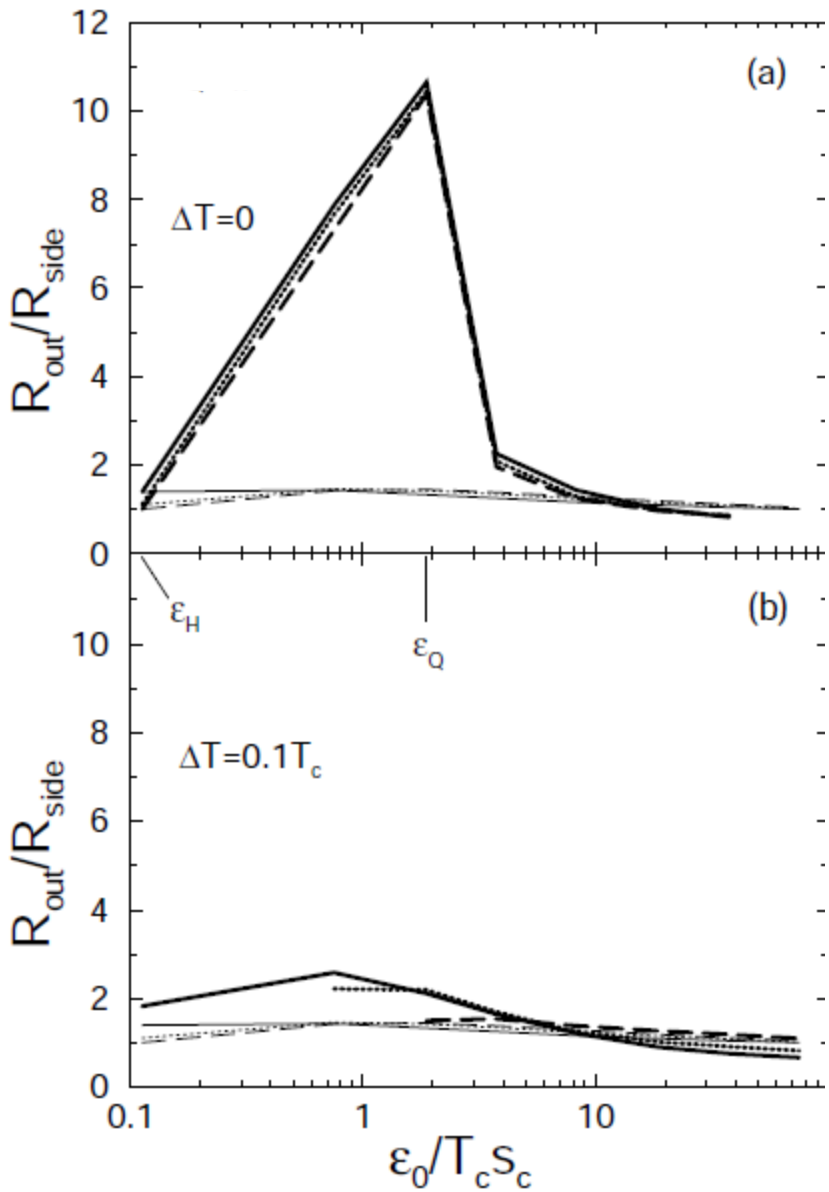
$$m_T = \sqrt{k_T^2 + m^2}$$

Where m is the pion rest mass

$$R_{out}^2 - R_{side}^2 \propto \Delta\tau \qquad \frac{R_{out}}{R_{side}} \propto \Delta\tau$$

Since R_{out} encodes information about the transverse size as well as the emission duration while R_{side} only has information about the transverse size

Some theory predictions for HBT



A sharp, 1st order transition

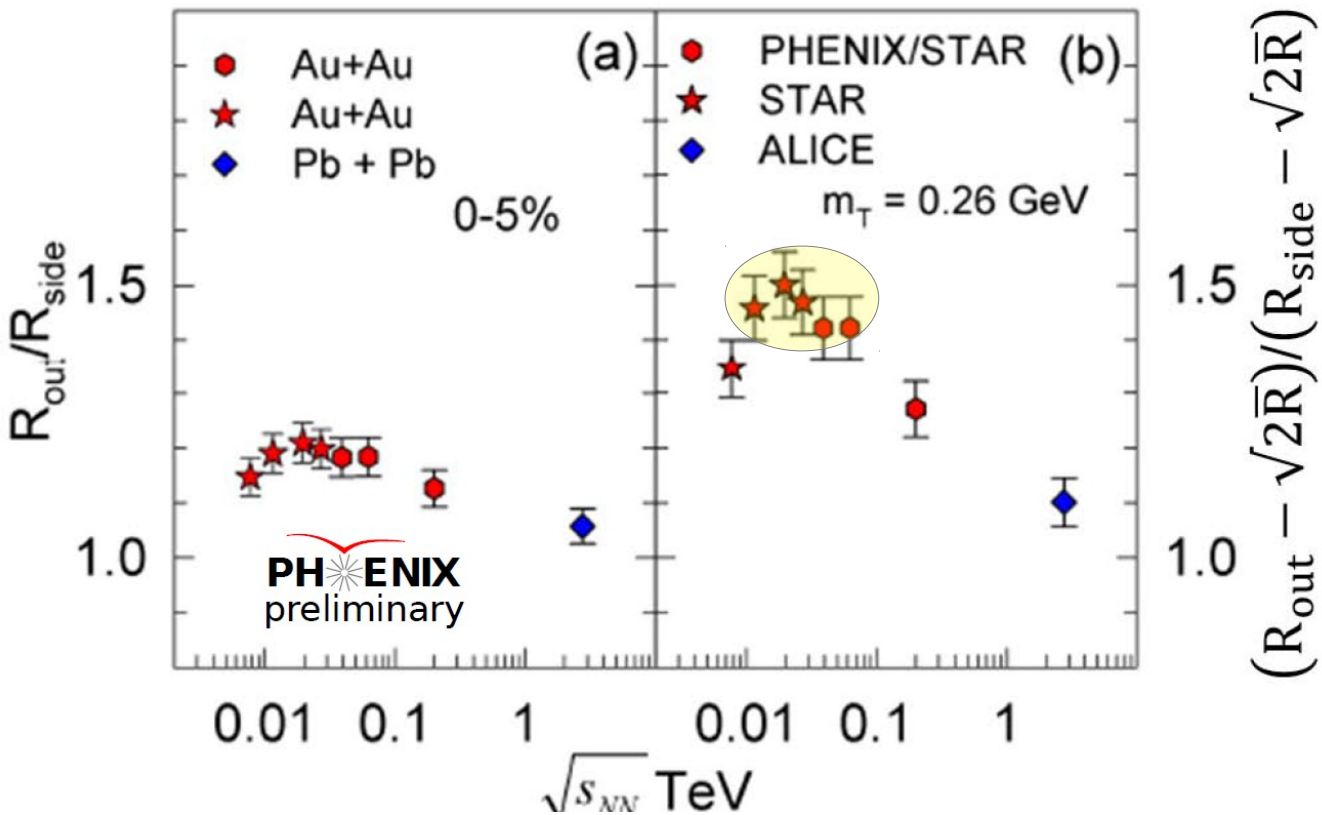
Broader transition width

Figure obtained from: Nucl.Phys.A608:479-512,1996

Hydro, for example, predicts that the R_{out}/R_{side} ratio will show a dramatic increase in the vicinity of the critical point due to increased emission duration

Expansion dynamics in HBT: R_{out}/R_{side} and $(R_{out} - 2\bar{R})/(R_{side} - 2\bar{R})$

$$R_{out}^2 = \frac{R_{geom}^2}{1+\frac{m_T}{T}\upsilon^2} + \frac{1}{2}\left(\frac{T}{m_T}\right)^2 \beta_T^2 \tau_0^2 \qquad R_{side}^2 = \frac{R_{geom}^2}{1+\frac{m_T}{T}\upsilon^2} \qquad \frac{R_{out}}{R_{side}} \propto \Delta\tau$$



- $\bar{R}$ is the initial transverse size defined as:

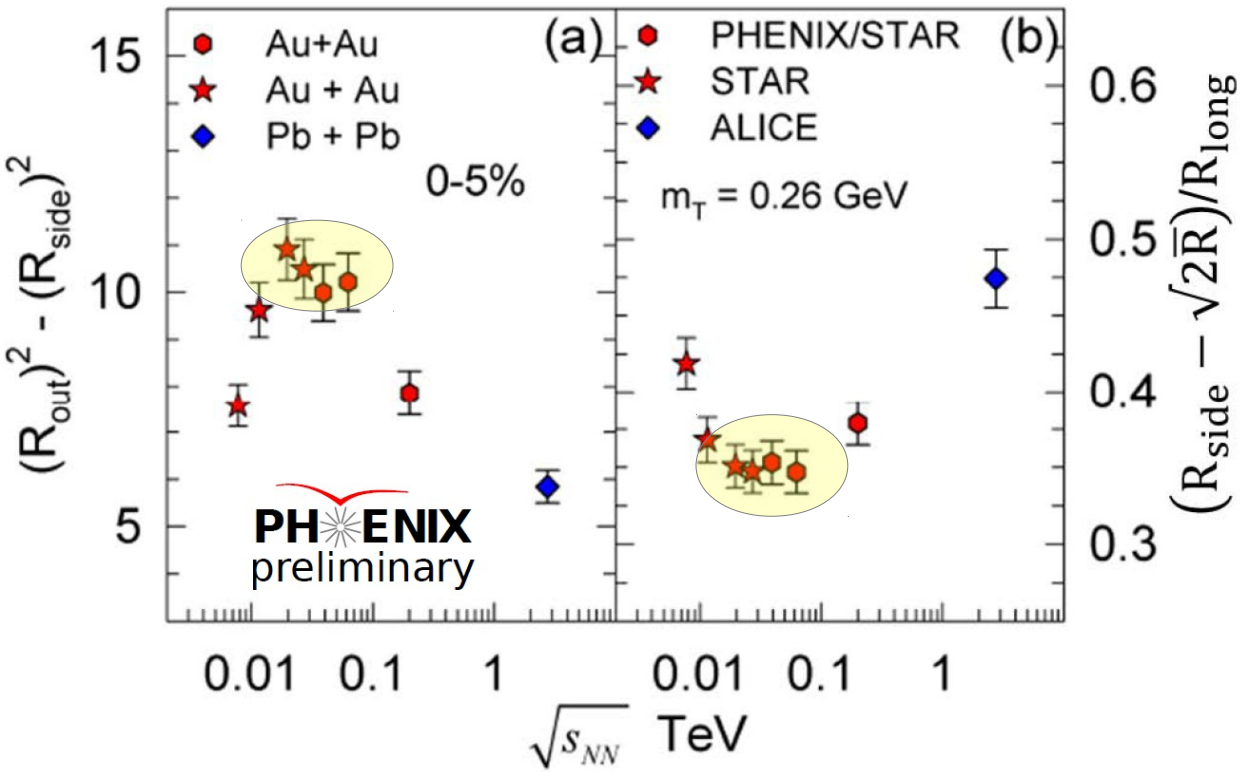
$$\frac{1}{\bar{R}} = \sqrt{\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}}$$

Where: σ_x, σ_y are the RMS widths of the density distributions

- A maximum is observed in $(R_{out} - \sqrt{2}\bar{R})/(R_{side} - \sqrt{2}\bar{R})$ dependence on beam energy over a narrow range
- This demonstrates importance of accounting for the contribution of initial size

Expansion dynamics in HBT: $R^2_{out} - R^2_{side}$ and $(R_{side} - 2\bar{R})/R_{long}$

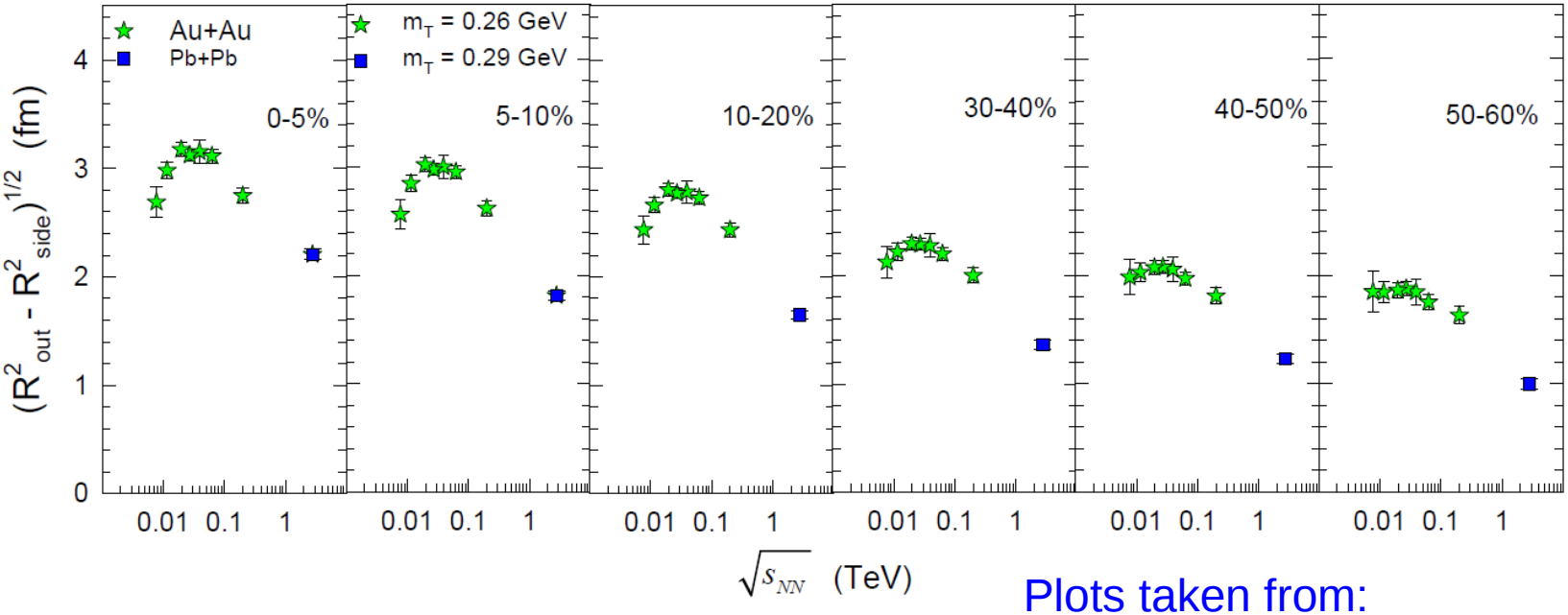
$$R^2_{out} = \frac{R^2_{geom}}{1+\frac{m_T}{T}\upsilon^2} + \frac{1}{2}\left(\frac{T}{m_T}\right)^2 \beta^2_T \tau^2_0 \qquad R^2_{side} = \frac{R^2_{geom}}{1+\frac{m_T}{T}\upsilon^2} \qquad R^2_{long} = \tau^2 \frac{T}{m_T}\frac{K_2(m_T/T)}{K_1(m_T/T)}$$

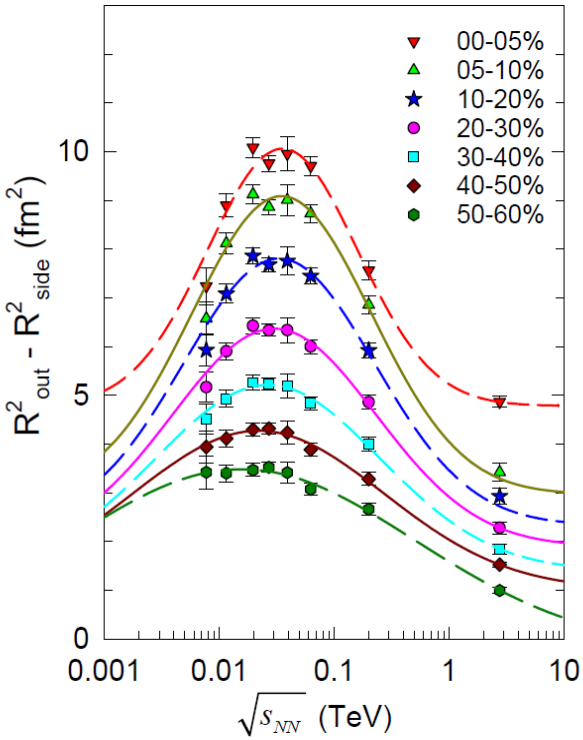


arXiv:1410.2559

- A maximum is observed in (a) $R^2_{out} - R^2_{side}$ dependence on beam energy ($\sqrt{s_{NN}}$) with complimentary minimum in (b) $(R_{side} - \sqrt{2}\bar{R})/R_{long}$ dependence on $\sqrt{s_{NN}}$
- Nonmonotonic behavior over small range in $\sqrt{s_{NN}}$ may point to a change in the reaction dynamics over this range
- Additional energy scans over the range of interest (BES II) needed

Expansion dynamics in HBT: R^2_{out} - R^2_{side} centrality dependence





Plots taken from:

Phys. Rev. Lett. 114, 142301 (2015)

- $R^2_{out} – R^2_{side}$ signal decreases with increasing centrality
- Peak shifted to lower energy with increase in centrality
- Width of distribution increase with centrality
- Attributed to finite size effects at the onset of deconfinement

Summary

- Participant nucleon scaling evident below 39 GeV; participant quark scaling above 39 GeV
  - -Implications with regard to fluctuation studies

- Excitation functions of ratios of moments of net charge do not show a marked excess from model predictions

- Nonmonotonic behavior observed in HBT measurements proportional to system emission duration and expansion speed over narrow energy range (~27-50 GeV)
  - -Could be indicative of softening of equation of state/onset of deconfinement

- Beam Energy Scan Program II will provide further insight