The RHIC Beam Energy Scan Program: Results from the PHENIX Experiment

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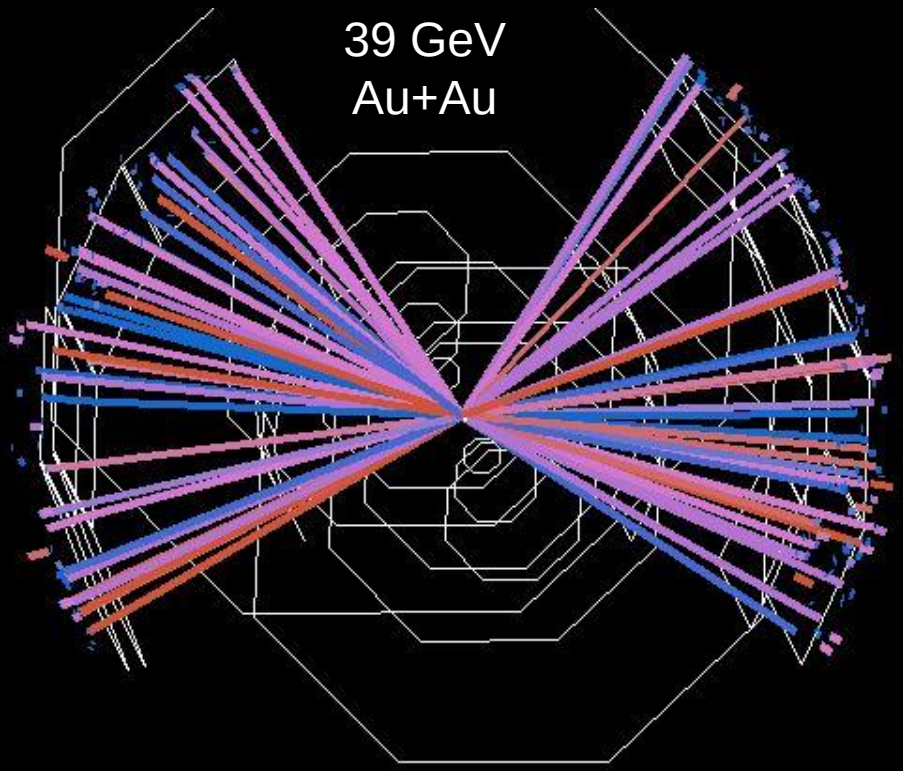
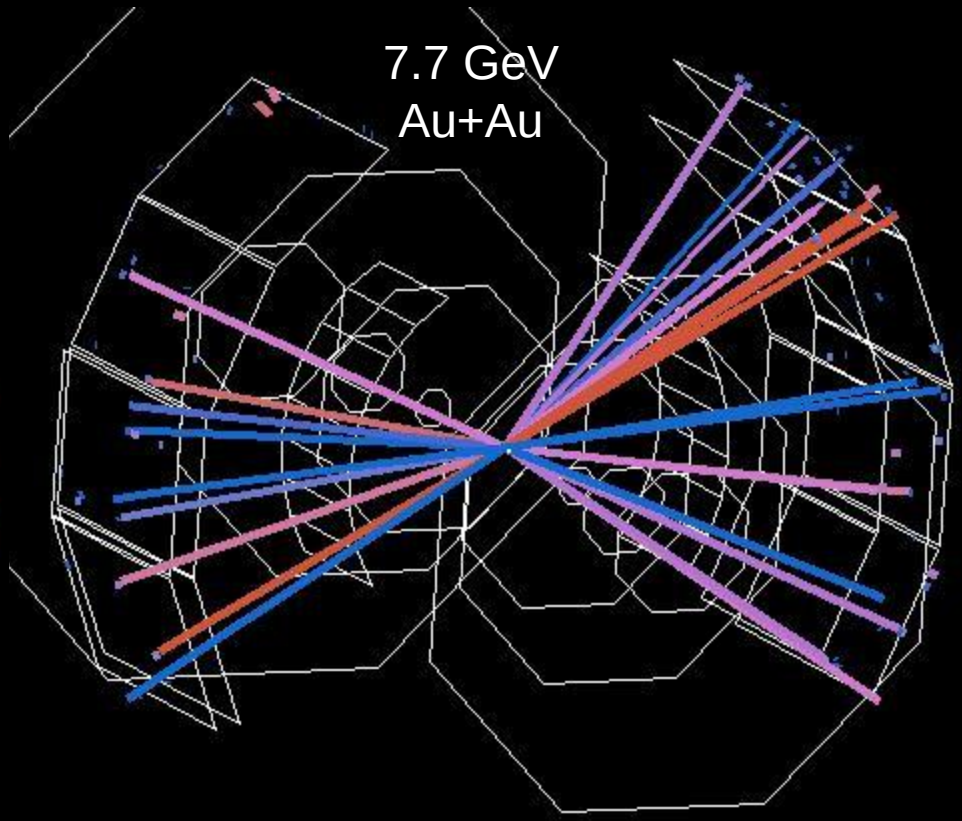
and the PHENIX Collaboration





The RHIC Beam Energy Scan Program: Overview

sqrt (s_{NN}) [GeV]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
200		Au+Au	d+Au	Au+Au	Cu+Cu		Au+Au	d+Au		Au+Au	Au+Au	Cu+Au, U+U
130	Au+Au											
62.4				Au+Au	Cu+Cu					Au+Au		
39										Au+Au		
27											Au+Au	
22.5					Cu+Cu							
19.6		Au+Au									Au+Au	
11.5										STAR only		
7.7										Au+Au		
5.0												Test run

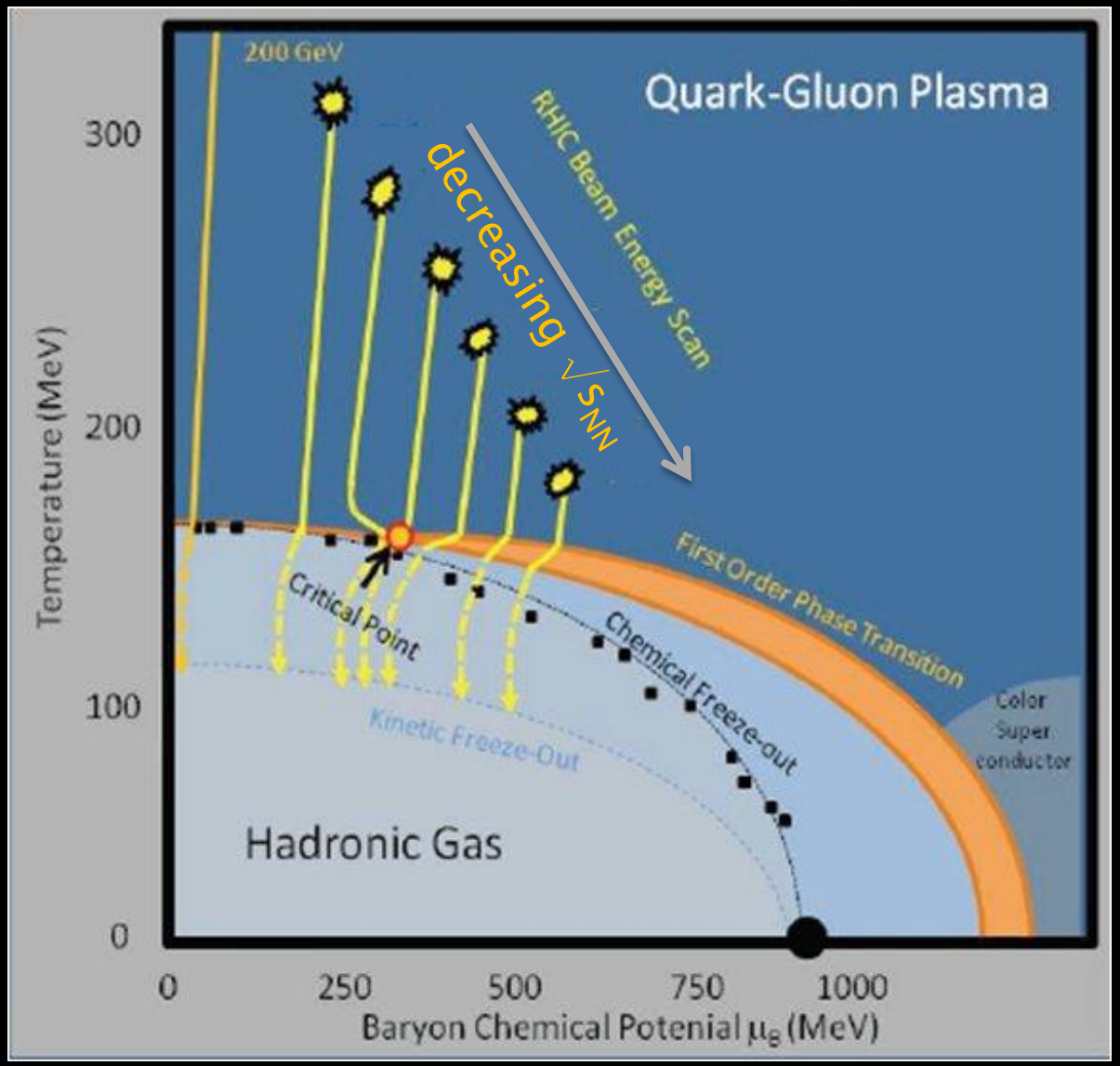
Au+Au U+U Cu+Au Cu+Cu d+Au

The RHIC Beam Energy Scan Program: Probing the Nuclear Matter Phase Diagram

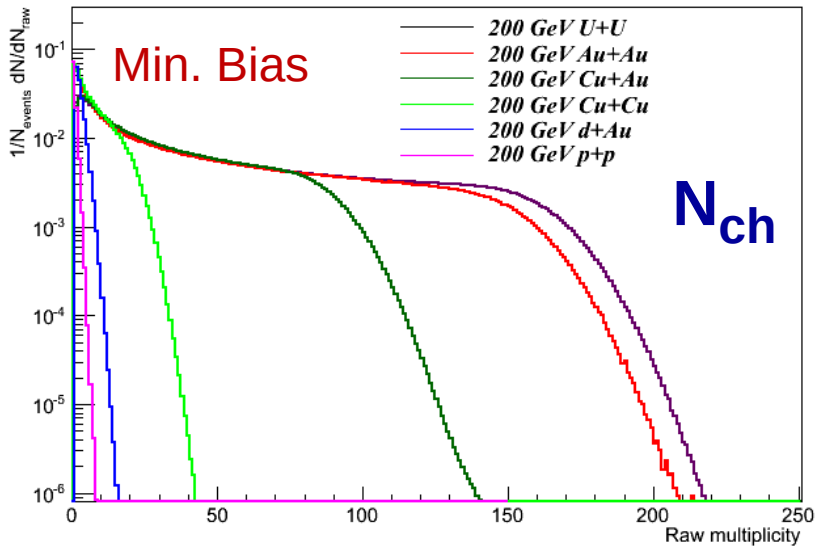
By systematically varying the RHIC beam energy, heavy ion collisions will be able to probe different regions of the QCD phase diagram.

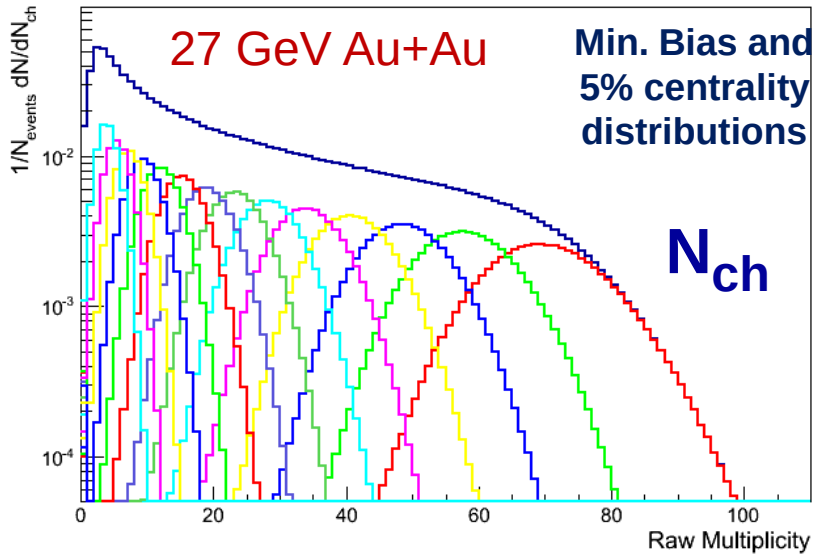
PHENIX is searching for signatures of the onset of deconfinement and searching for signatures of the critical point.

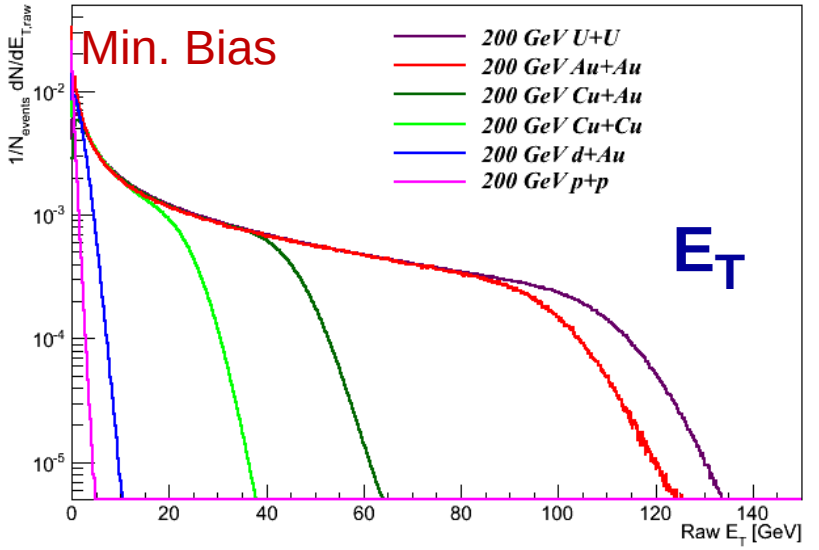
Outline:
- Charged Particle Multiplicity
- Transverse Energy
- Multiplicity Fluctuations
- Net Charge Fluctuations
- Pion HBT
- Flow
- R_{AA}

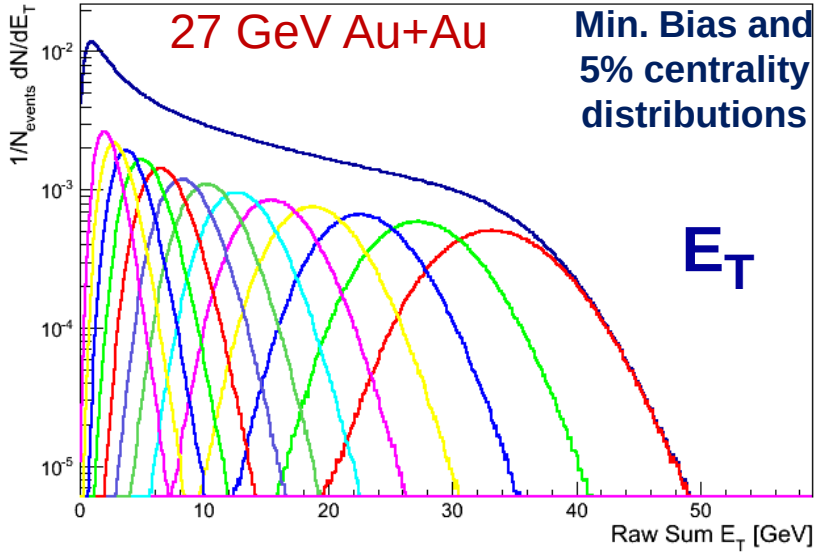


Global Observables: Charged Particle Multiplicity and Transverse Energy Production



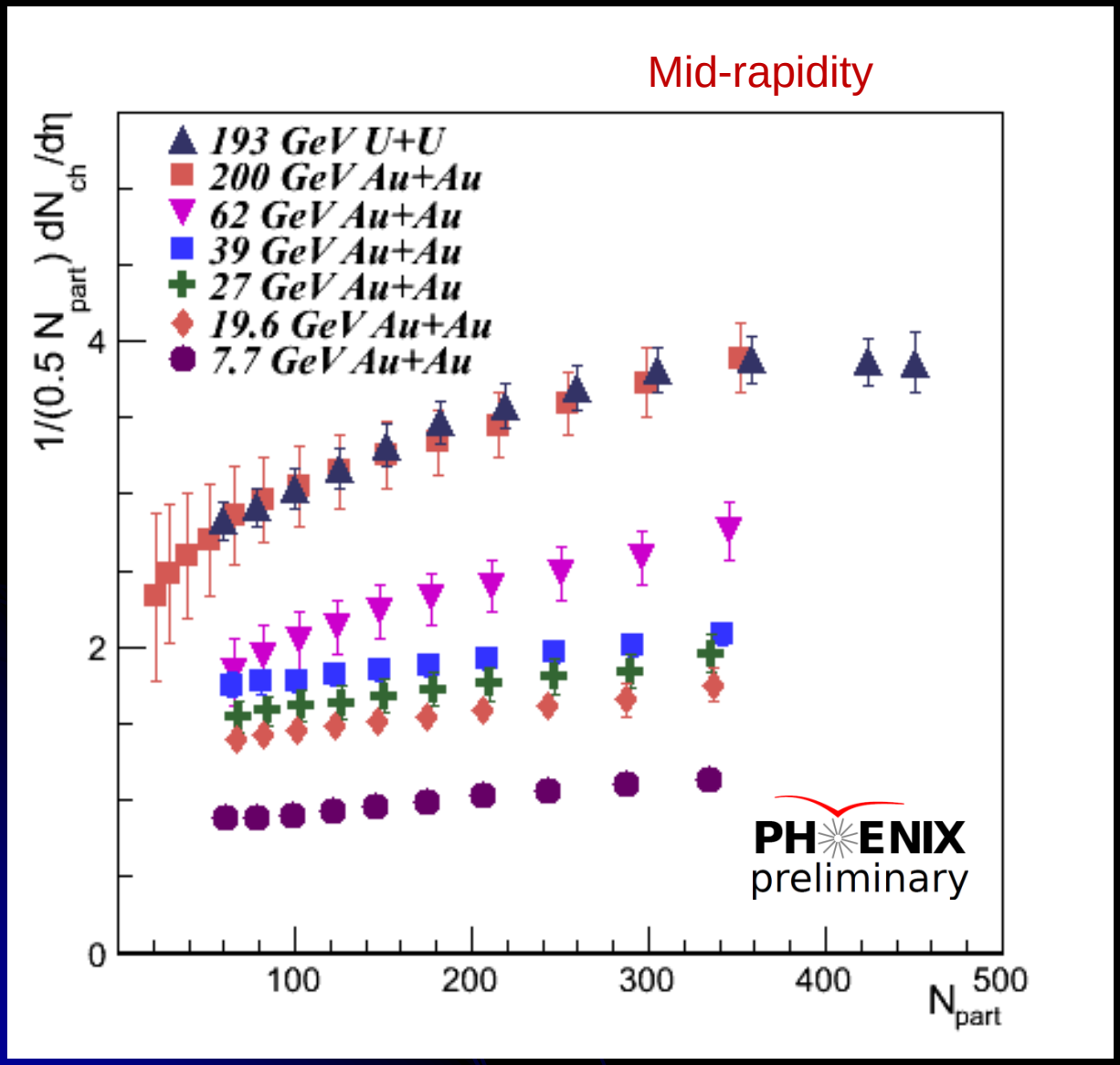






Charged Particle Multiplicity

The 200 GeV Au+Au analysis is described in Phys. Rev. C71 (2005) 034908

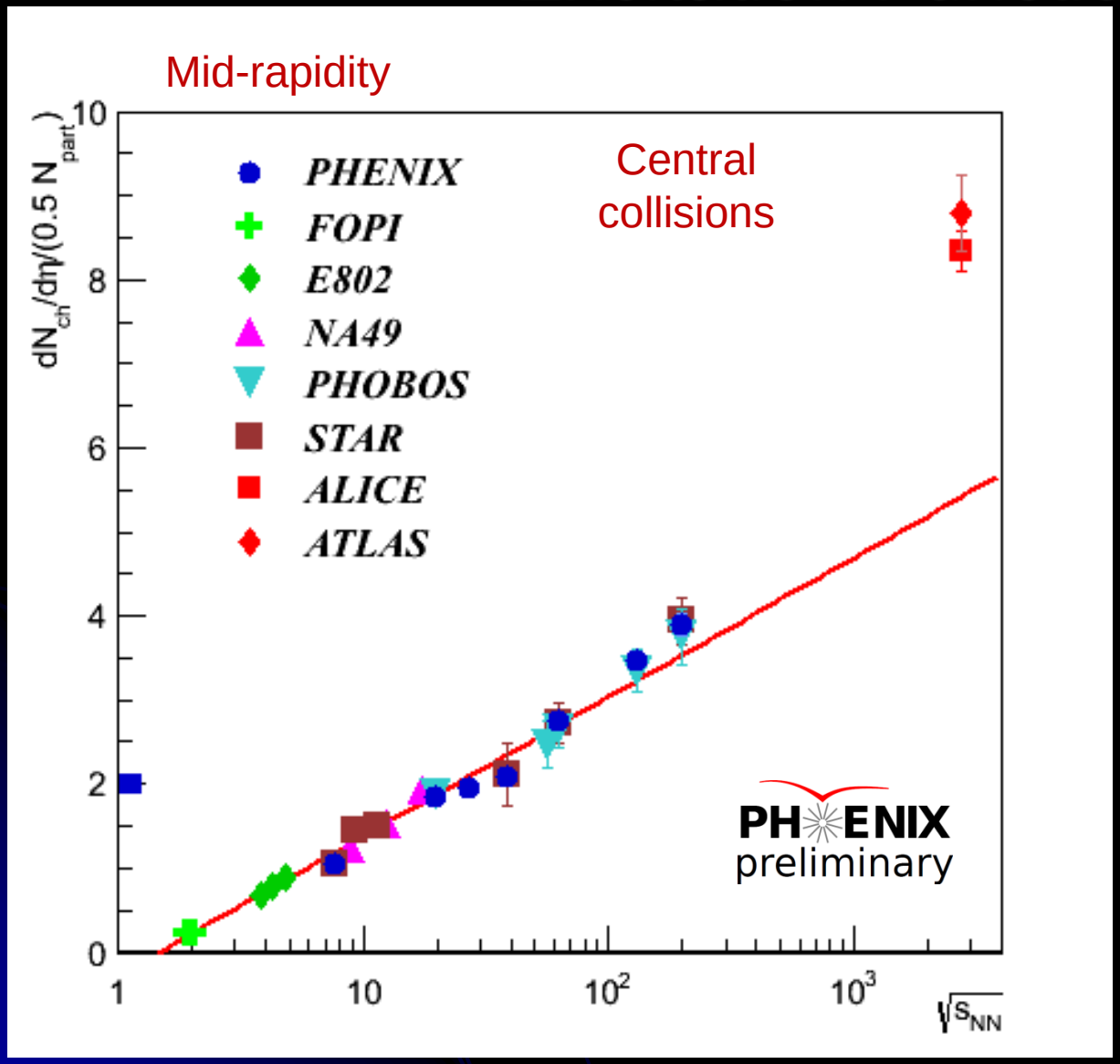


The particle density increases with increasing collision energy.

There is an increase in particle density for more central collisions at all collision energies.

The Au+Au and U+U particle densities are similar.

Charged Particle Multiplicity: Excitation Function

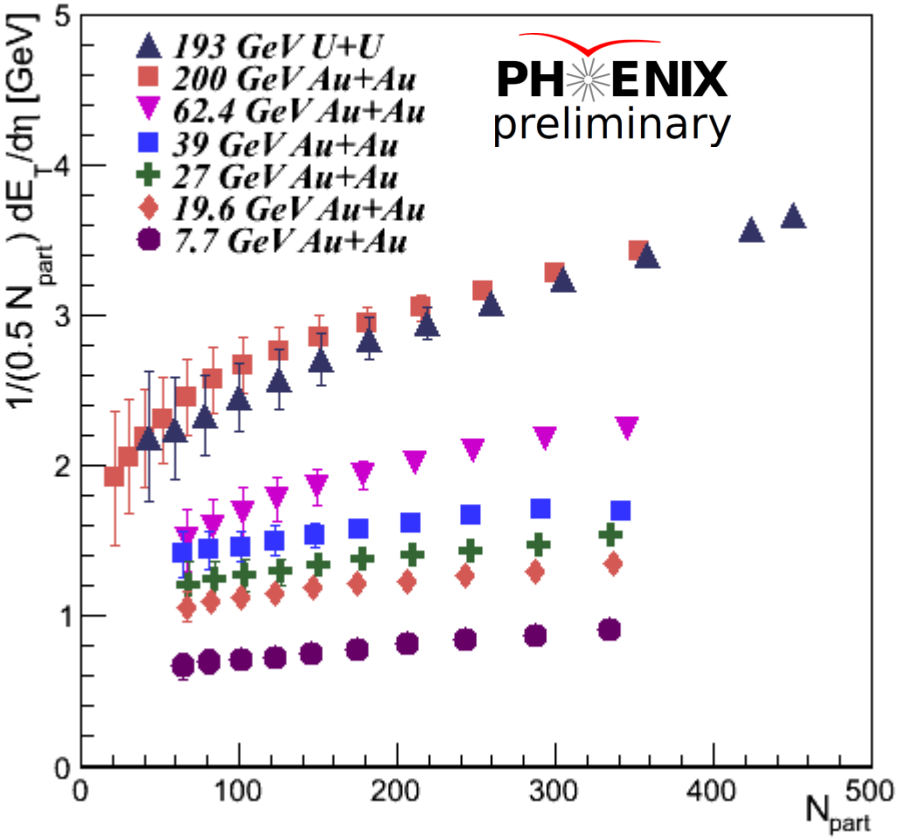


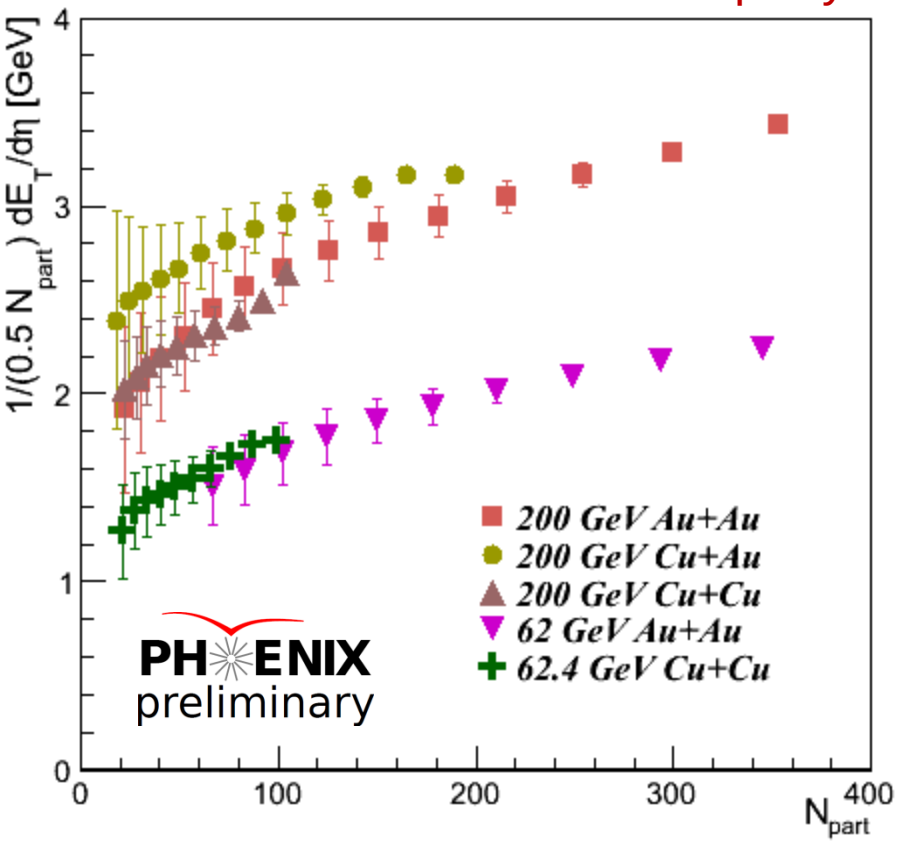
The red line is a logarithmic fit to all data points excluding the LHC points.

At or below RHIC energies, the multiplicity per participant pair increases linearly with log(sqrt(s_{NN})).

Transverse Energy Production

Mid-rapidity

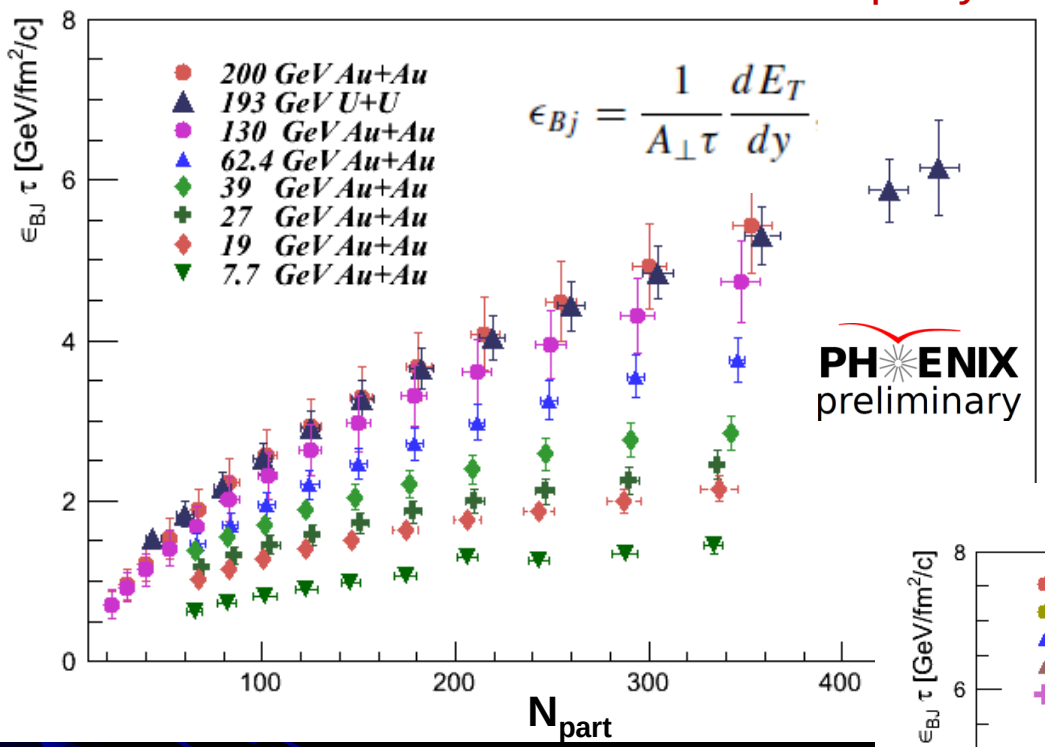




- Transverse energy production increases with increasing collision energy.
- There is an increase in transverse energy production for more central collisions at all collision energies.
- Transverse energy production in Cu+Cu at the same N_{part} is similar to that in Au+Au at the same collision energy.

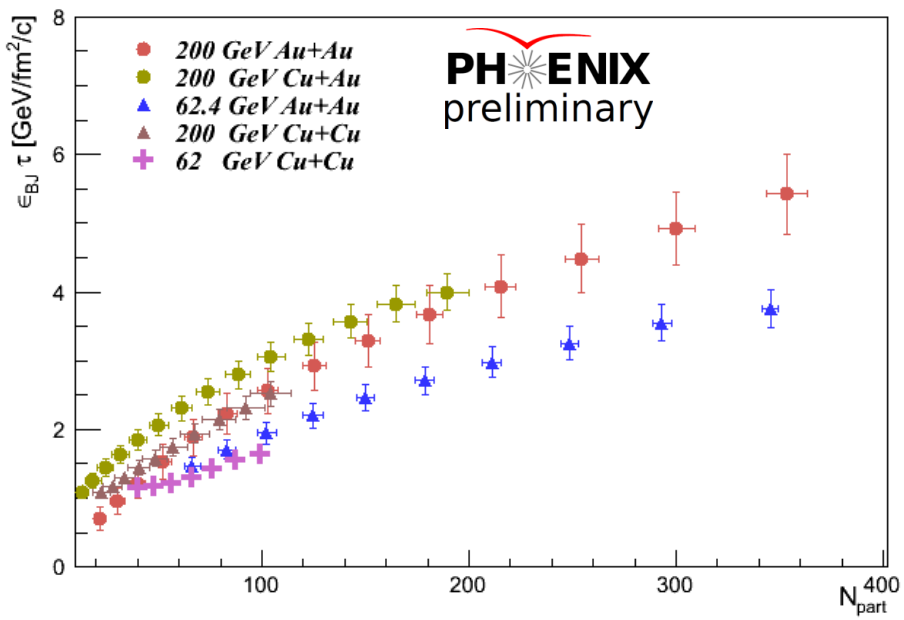
Bjorken Energy Density

Mid-rapidity



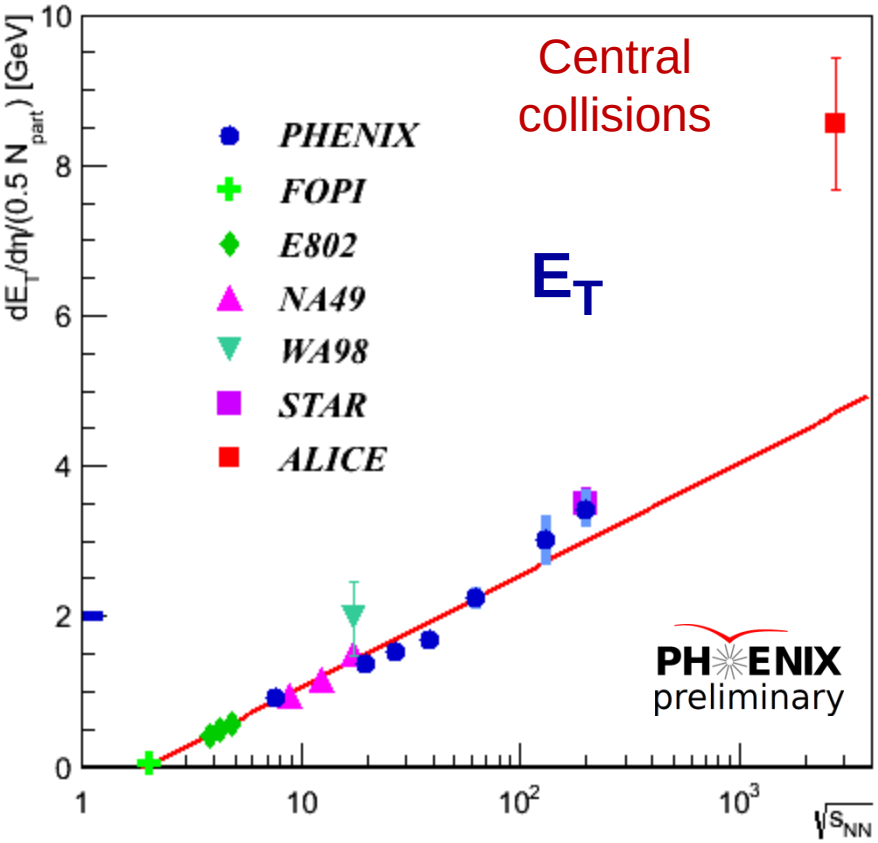
New RHIC energy density record in U+U collisions = 6.15 GeV/fm^2/c. The upper U+U point is for the upper 1% centrality bin. All other points are 5% centrality bins.

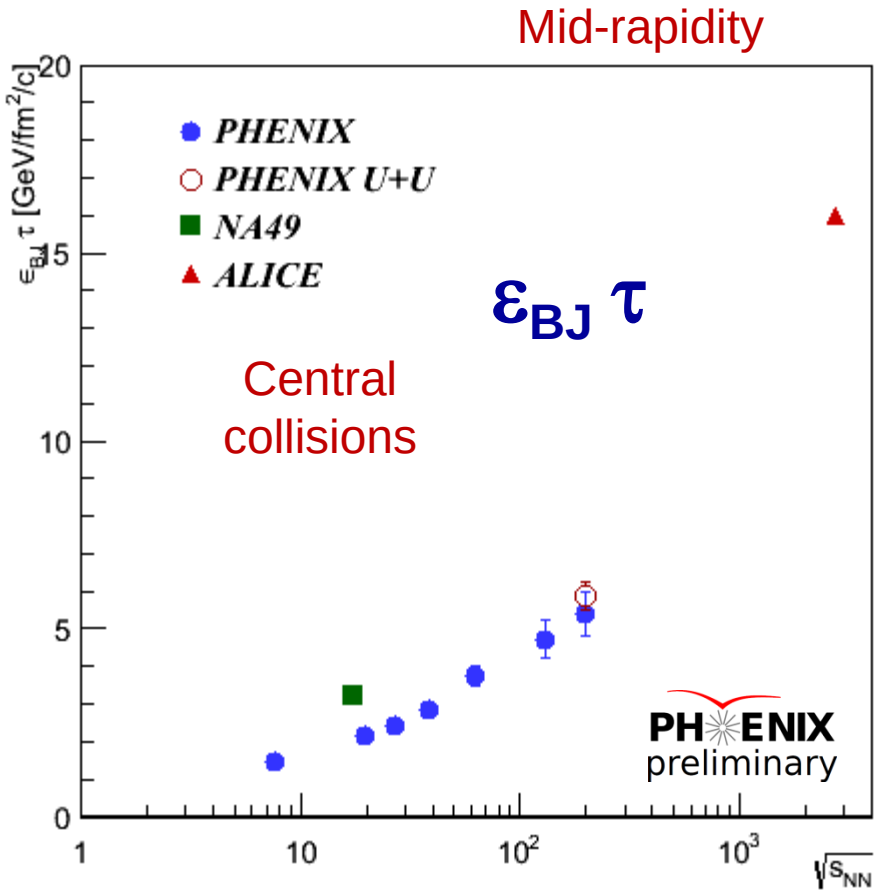
Mid-rapidity



ε_{BJ} increases by a factor of 3.8 when going from 7.7 to 200 GeV.

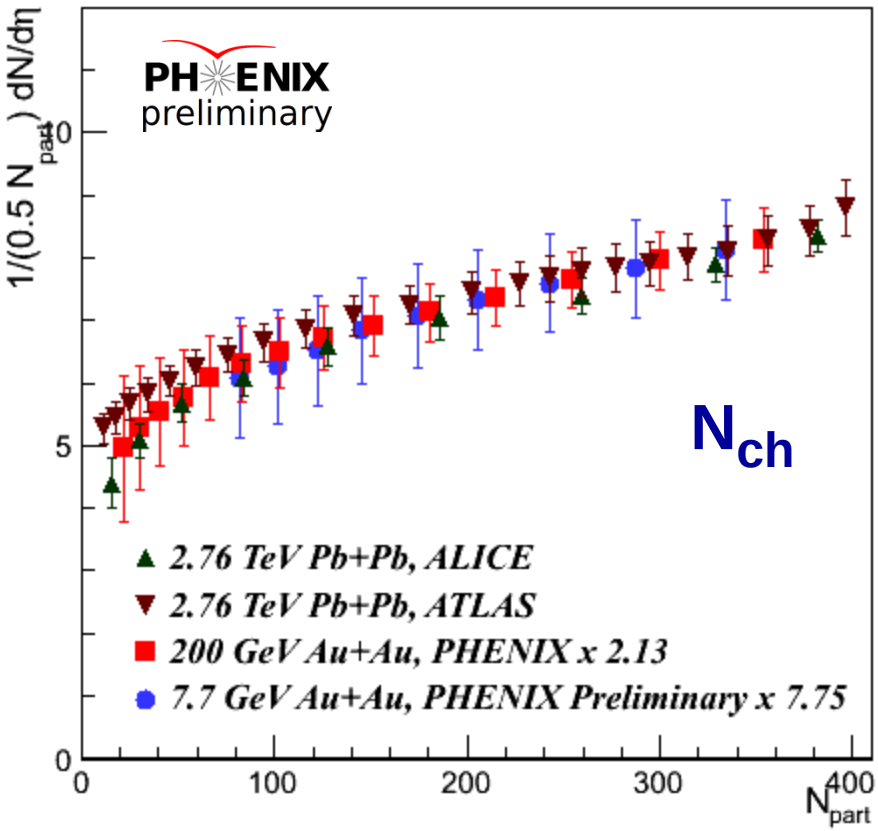
Transverse Energy Production: Excitation Function

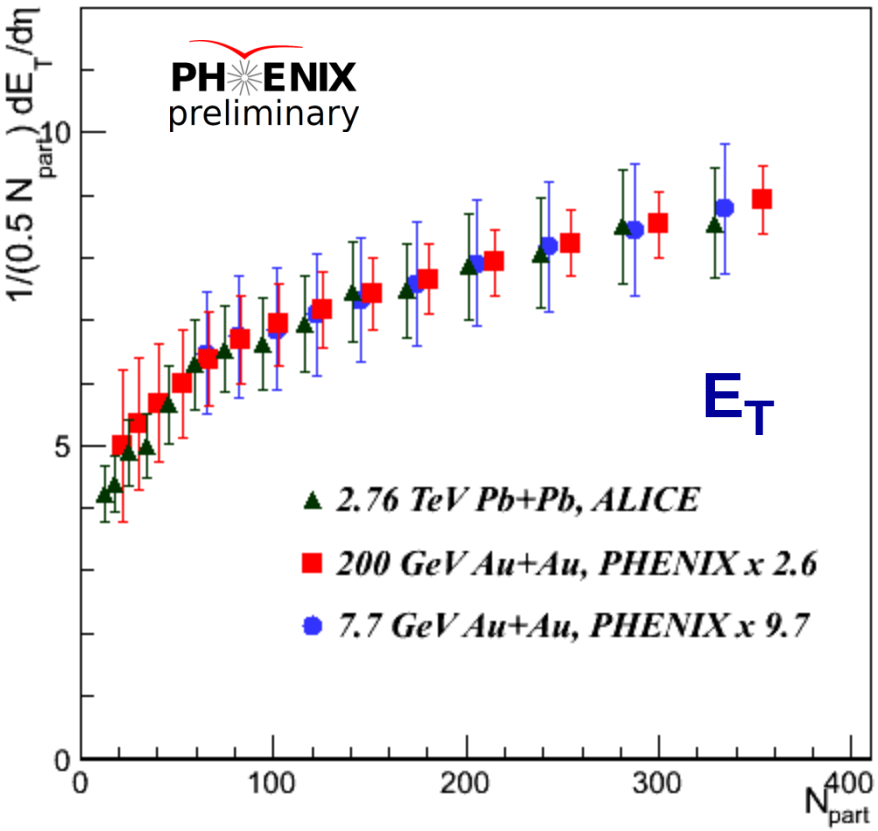




Monotonic behavior is observed in E_T production in 0-5% central Au+Au collisions. The red line is a logarithmic fit to all points excluding the ALICE point. ε_{BJ} increases by a factor of 11.1 when going from 7.7 GeV to 2.76 TeV.

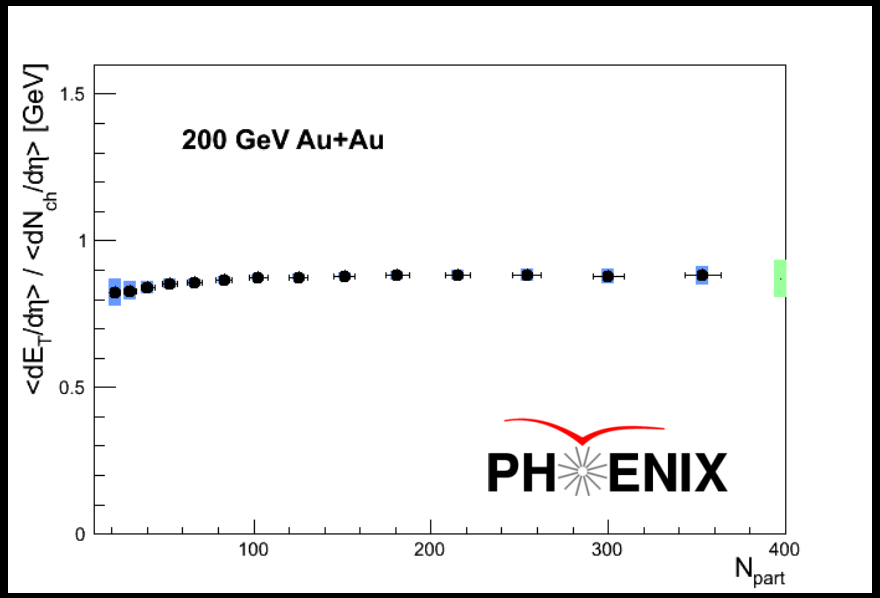
RHIC and LHC Comparisons

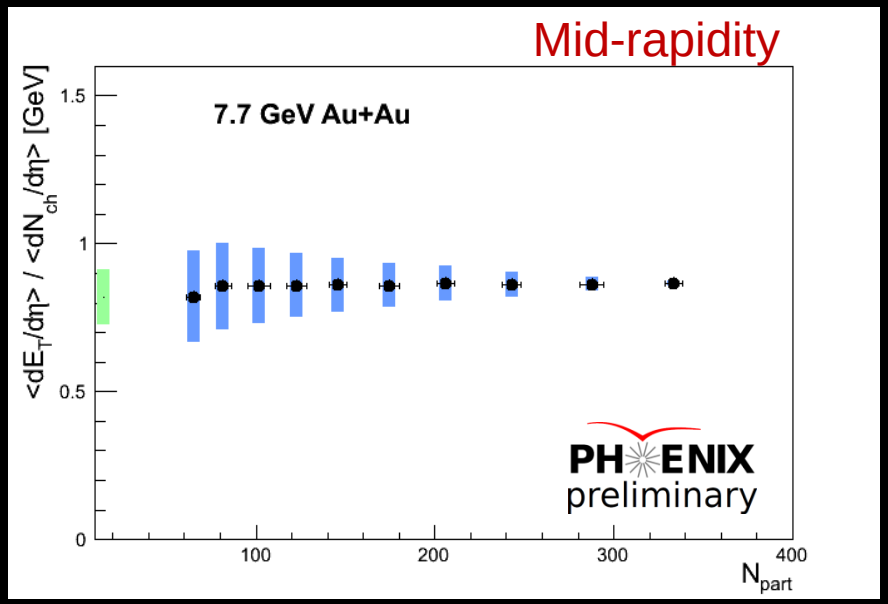


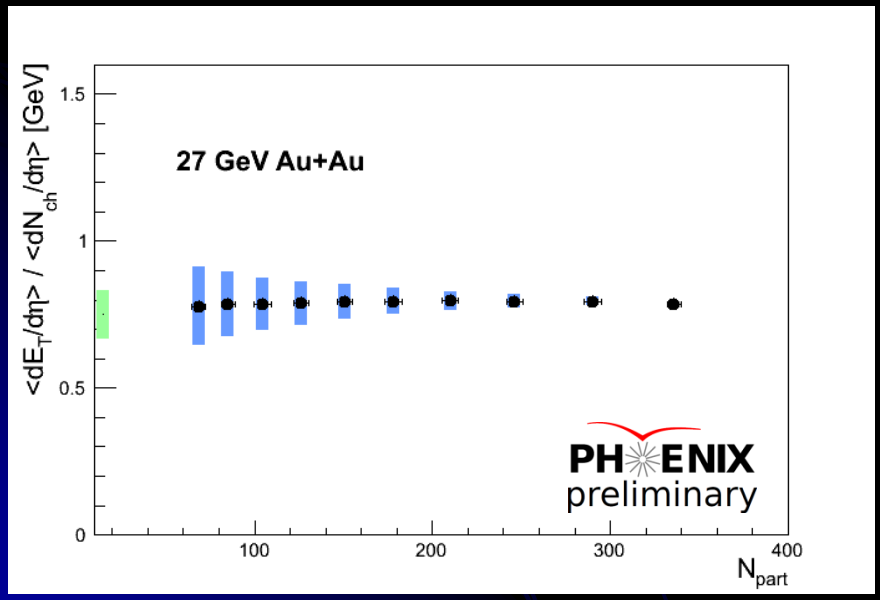


- There is no significant change in the shape of the centrality-dependence of the particle density or transverse energy from 7.7 GeV Au+Au collisions up to 2.76 TeV Pb+Pb collisions.
- It appears that the collision geometry is driving the centrality dependence.

Transverse Energy per Charged Particle

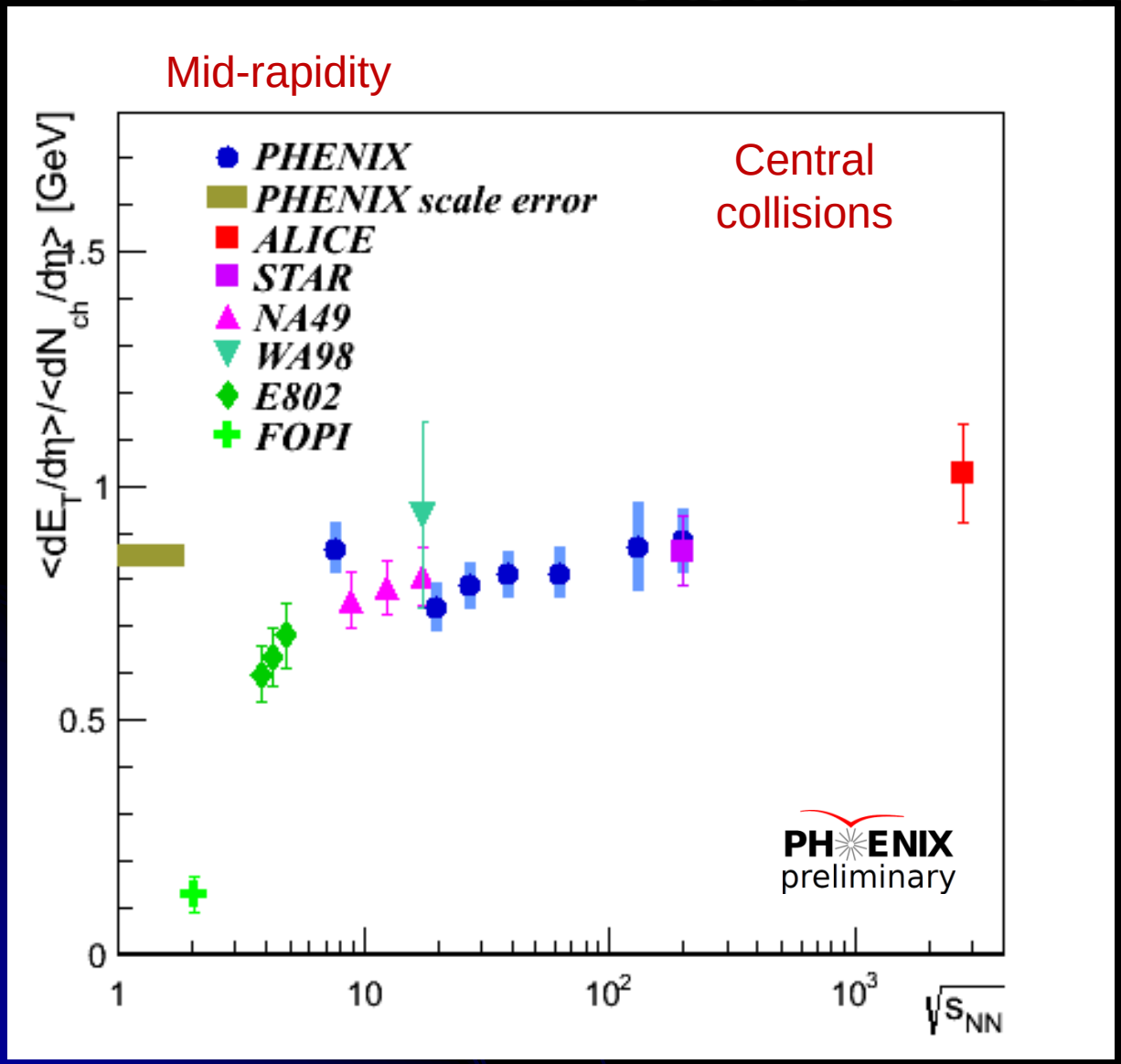






The transverse energy per charged particle is flat as a function of centrality for all collision energies from 7.7 GeV to 200 GeV.

Transverse Energy per Charged Particle: Excitation Function



There is very little change in the transverse energy per charged particle from 7.7 GeV to 200 GeV.

There is only a slight increase at LHC energies (16%).

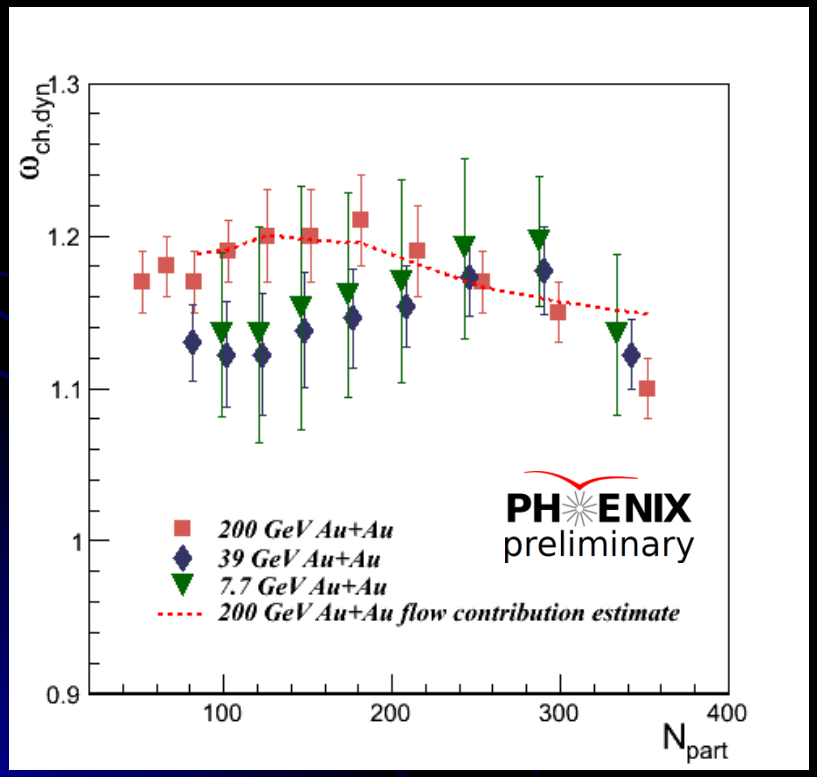
Multiplicity Fluctuations

- Multiplicity fluctuations may be sensitive to divergences in the compressibility of the system near the critical point.

Grand Canonical Ensemble

$$\left(\sigma^2 / \langle N \rangle\right) = \omega_{ch} = \langle N \rangle / k_{NBD} + 1 = k_B T \left(\frac{\langle N \rangle}{V}\right) k_T$$

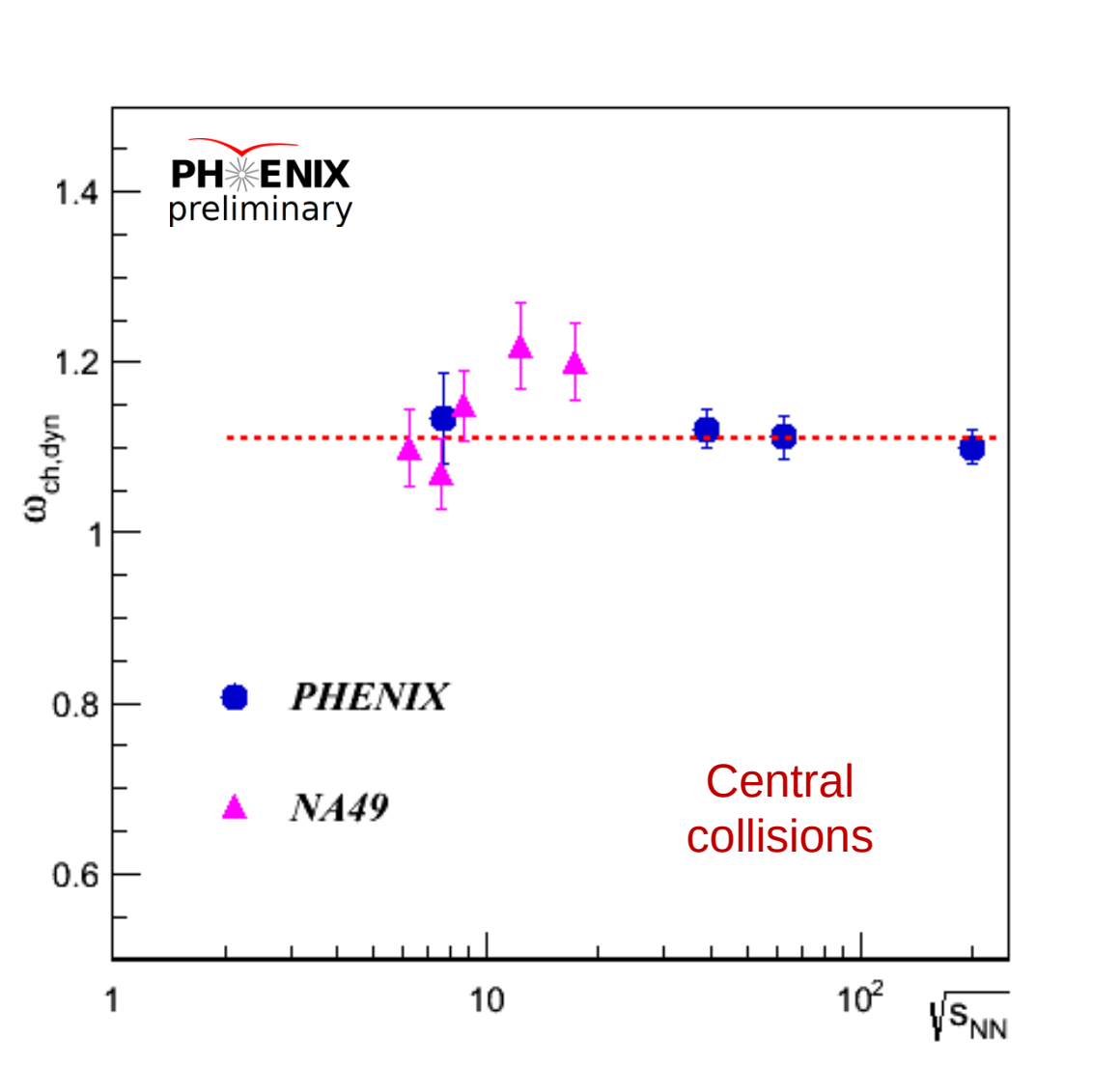
ω_N → "Scaled Variance"



The scaled variance is quoted within the PHENIX acceptance and has been corrected for contributions from impact parameter fluctuations ($\omega_{ch,dyn}$).

The centrality-dependent shape of the fluctuations is primarily driven by contributions from flow.

Multiplicity Fluctuations: Excitation Function



The NA49 data is from C. Alt et al., Phys. Rev. C78, 034914 (2008).

The dashed red line is a constant fit to the PHENIX data only.

No significant increase in multiplicity fluctuations have been observed.

Stay tuned for new results at 19.6 and 27 GeV. It would be interesting to add a point at 15 GeV.

Higher Moments of Net Charge Distributions

The correlation length (ξ) is related to various moments of conserved quantities:

Variance: $\sigma^2 = \langle(N-\langle N\rangle)^2\rangle \sim \xi^2$

Skewness: $S = \langle(N-\langle N\rangle)^3\rangle/\sigma^3 \sim \xi^{4.5}$

Kurtosis: $\kappa = \langle(N-\langle N\rangle)^4\rangle/\sigma^4 - 3 \sim \xi^7$

$$\chi_B^{(n)}\left(\frac{T}{T_c},\frac{\mu_B}{T}\right) = \frac{1}{T^n}\frac{\partial^n}{\partial(\mu_B/T)^n}P\left(\frac{T}{T_c},\frac{\mu_B}{T}\right)\Bigg|_{T/T_c}$$

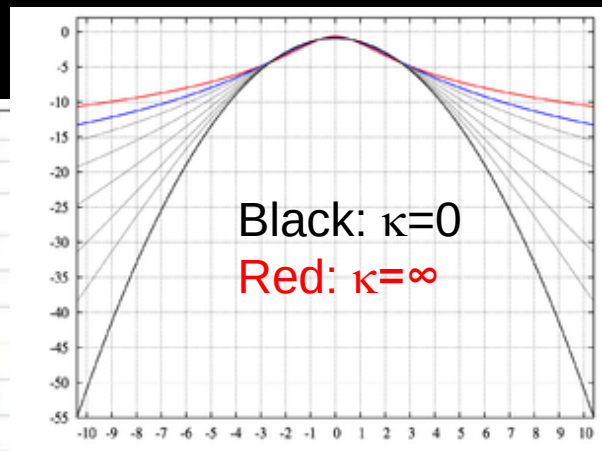
$$S\sigma = \frac{T\chi_B^{(3)}}{\chi_B^{(2)}}$$

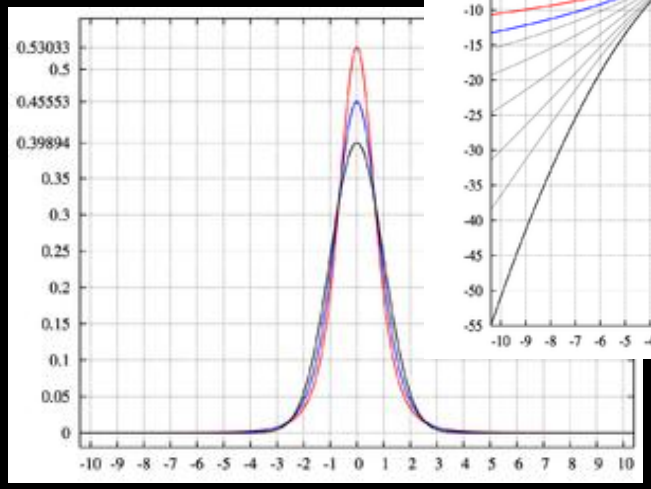
$$\kappa\sigma^2 = \frac{T^2\chi_B^{(4)}}{\chi_B^{(2)}}$$

The quantities $S\sigma$ and $\kappa\sigma^2$ are related to the quark number susceptibilities (χ):
$S\sigma \sim \chi^{(3)}/\chi^{(2)}$ and $\kappa\sigma^2 \sim \chi^{(4)}/\chi^{(2)}$.

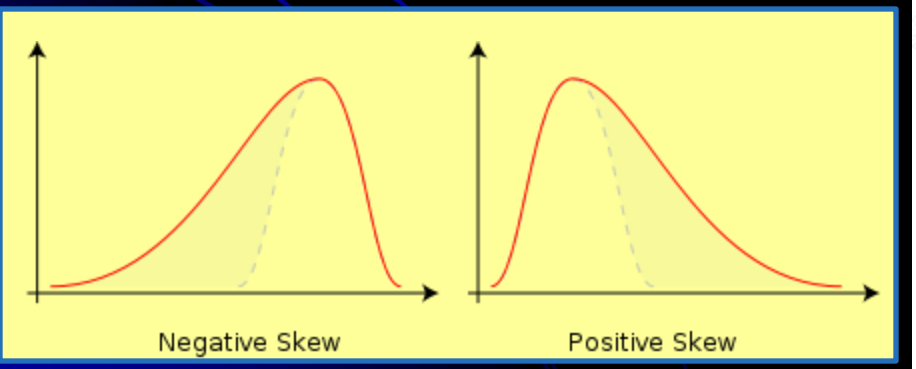
Since the correlation length is expected to diverge at the critical point, it is expected that the quantities $S\sigma$ and $\kappa\sigma^2$ will be large there.

Kurtosis → "bulging"

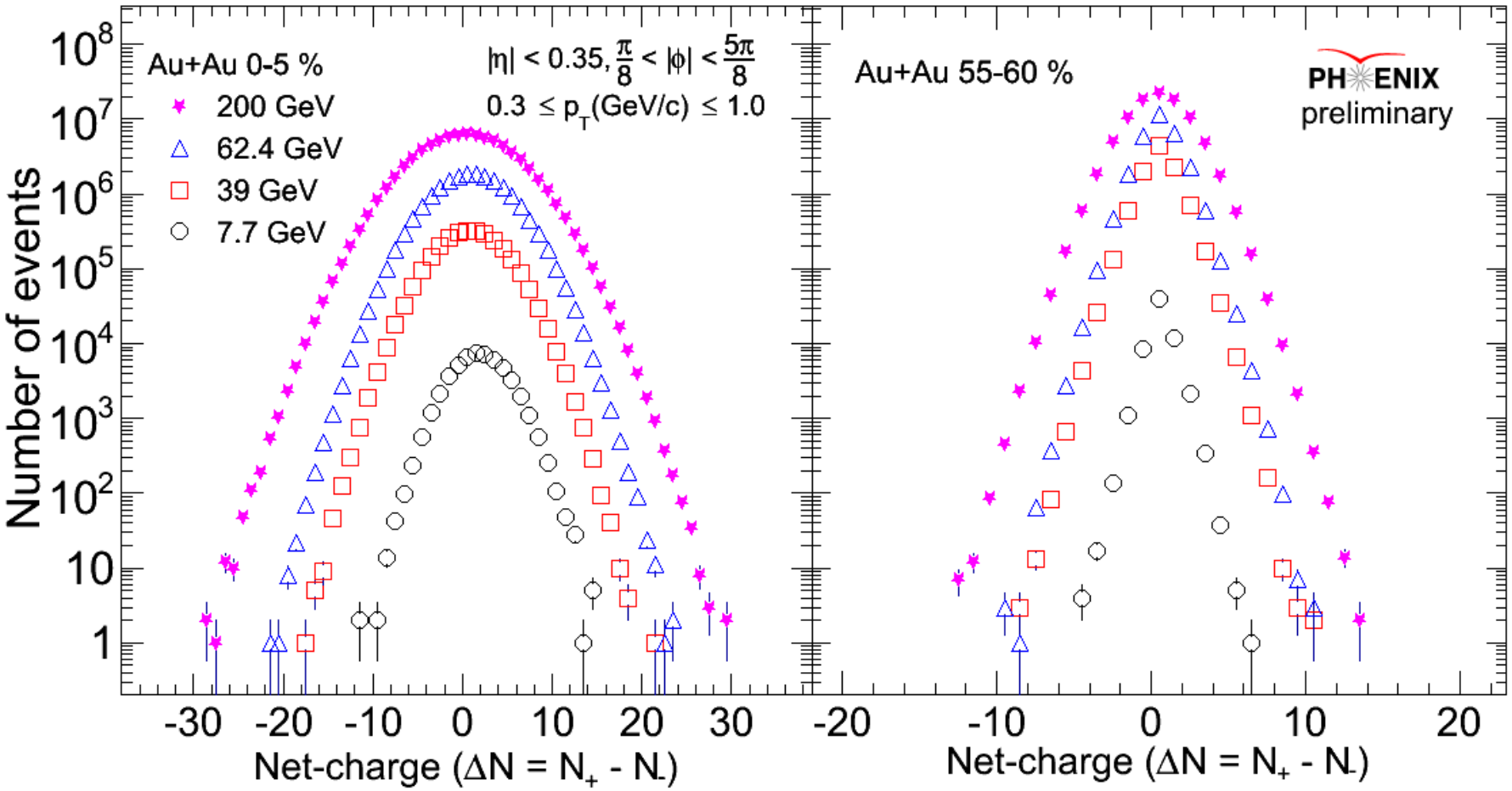




Skewness

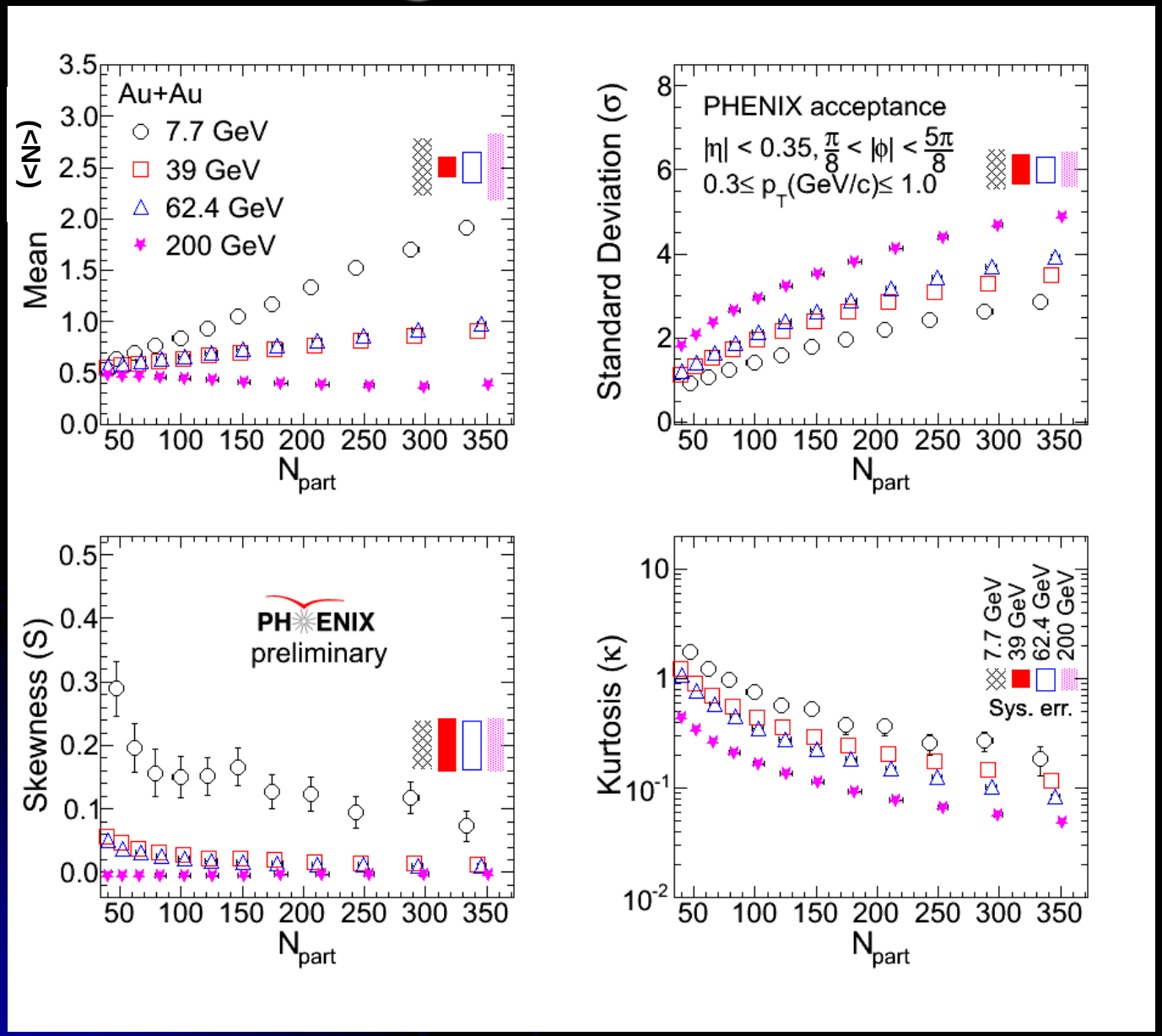


Higher Moments of Net Charge Distributions



All datasets cover several orders of magnitude.

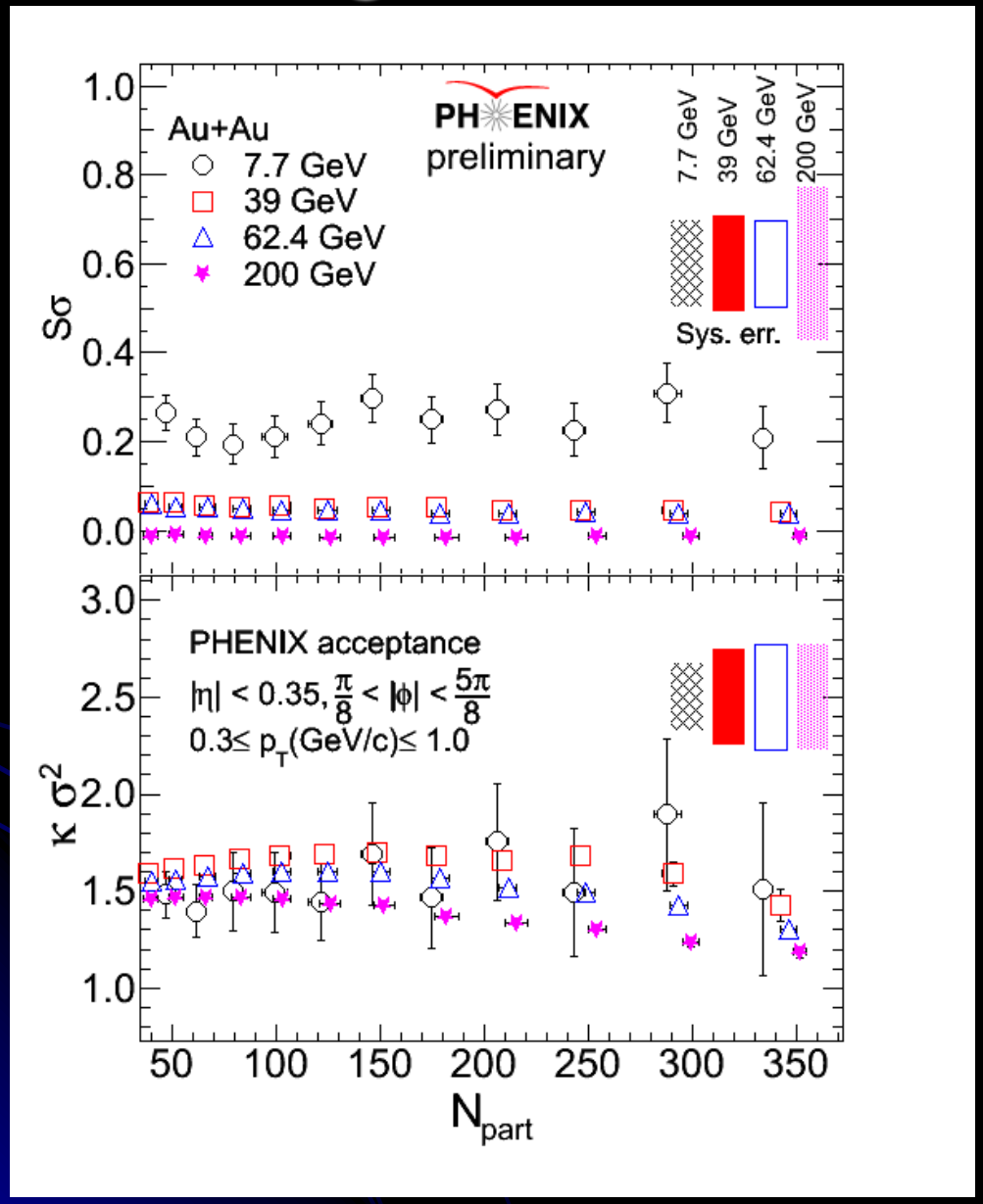
Net Charge Moments vs. Centrality



The skewness and kurtosis tends to increase with decreasing beam energy.

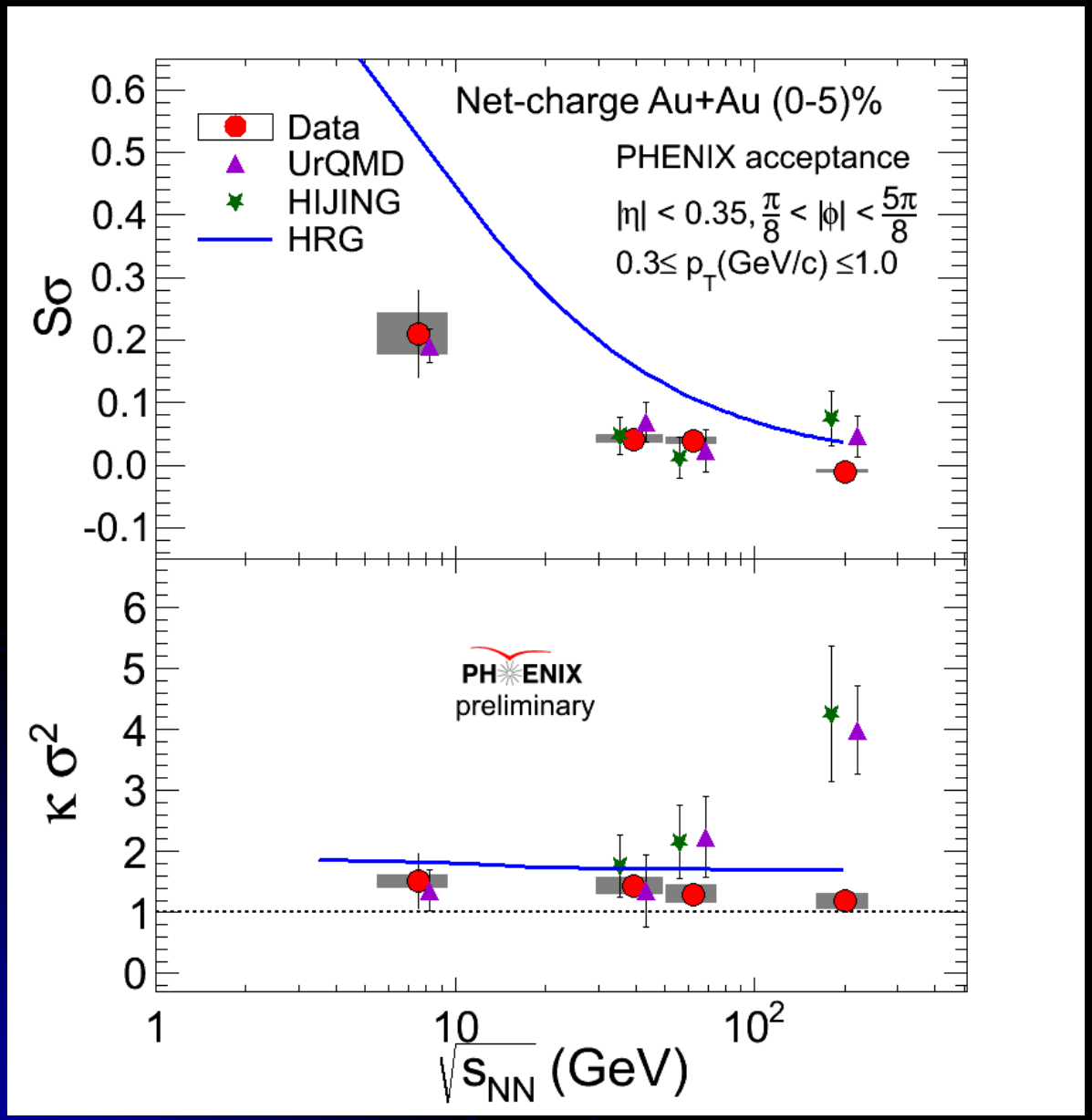
The skewness and kurtosis tends to decrease in more central collisions.

Net Charge Sσ and κσ² vs. Centrality



The products of the moments are relatively flat as a function of centrality.

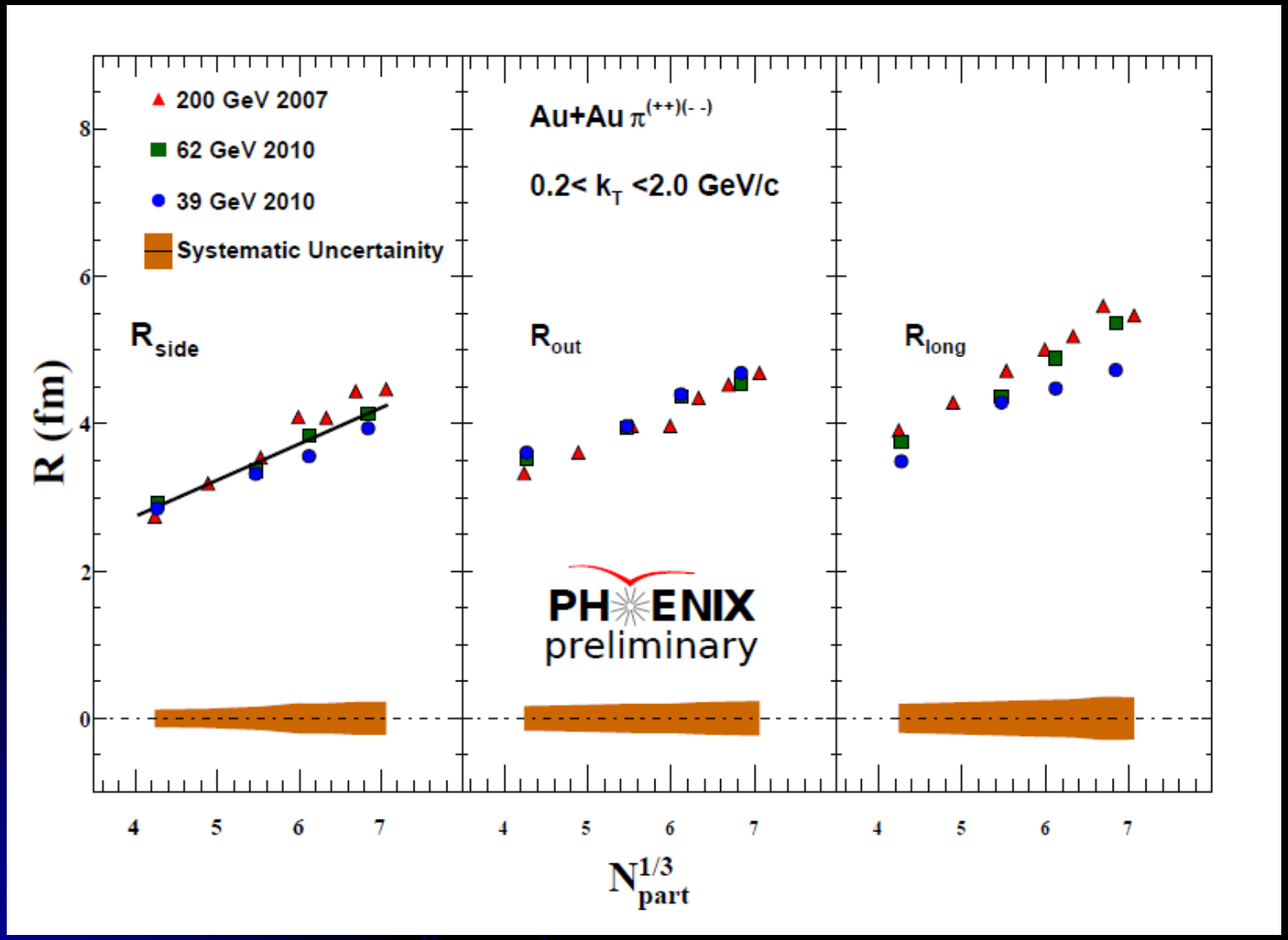
Net Charge Sσ and κσ² Excitation Function



The products of the net charge moments show no significant increase above URQMD, HIJING, or Hadron Resonance Gas predictions.

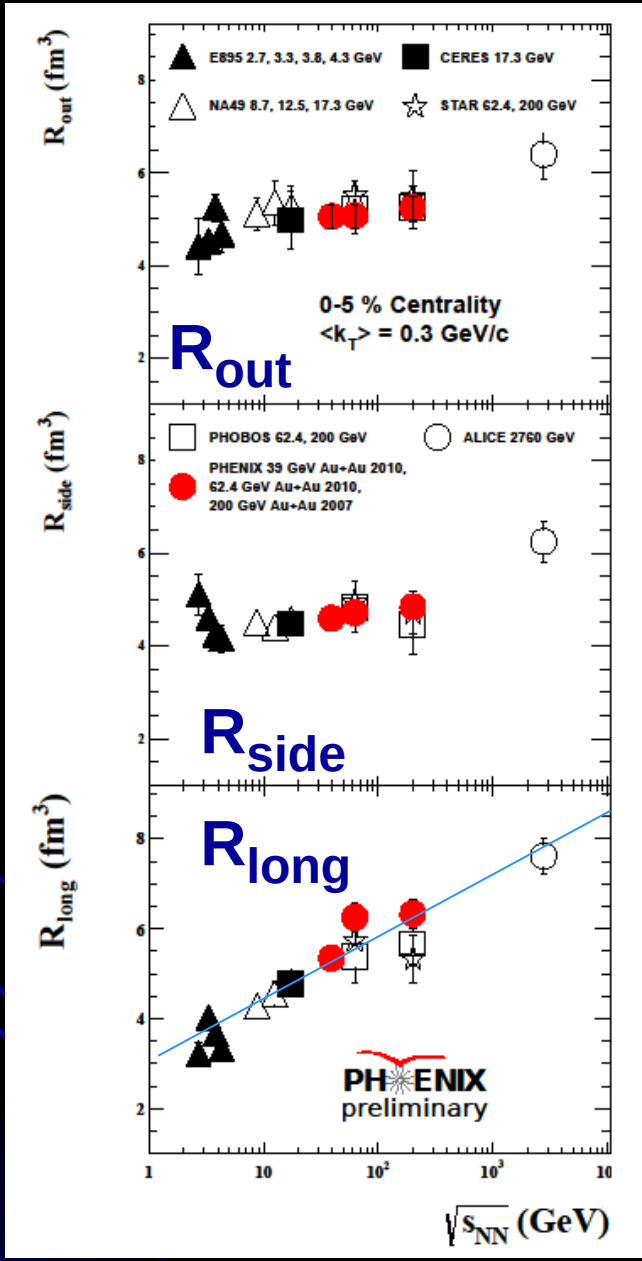
Stay tuned for new results at 19.6 and 27 GeV.

HBT Radii vs. Centrality



R_{out}, R_{side}, and R_{long} all increase with increasing centrality.

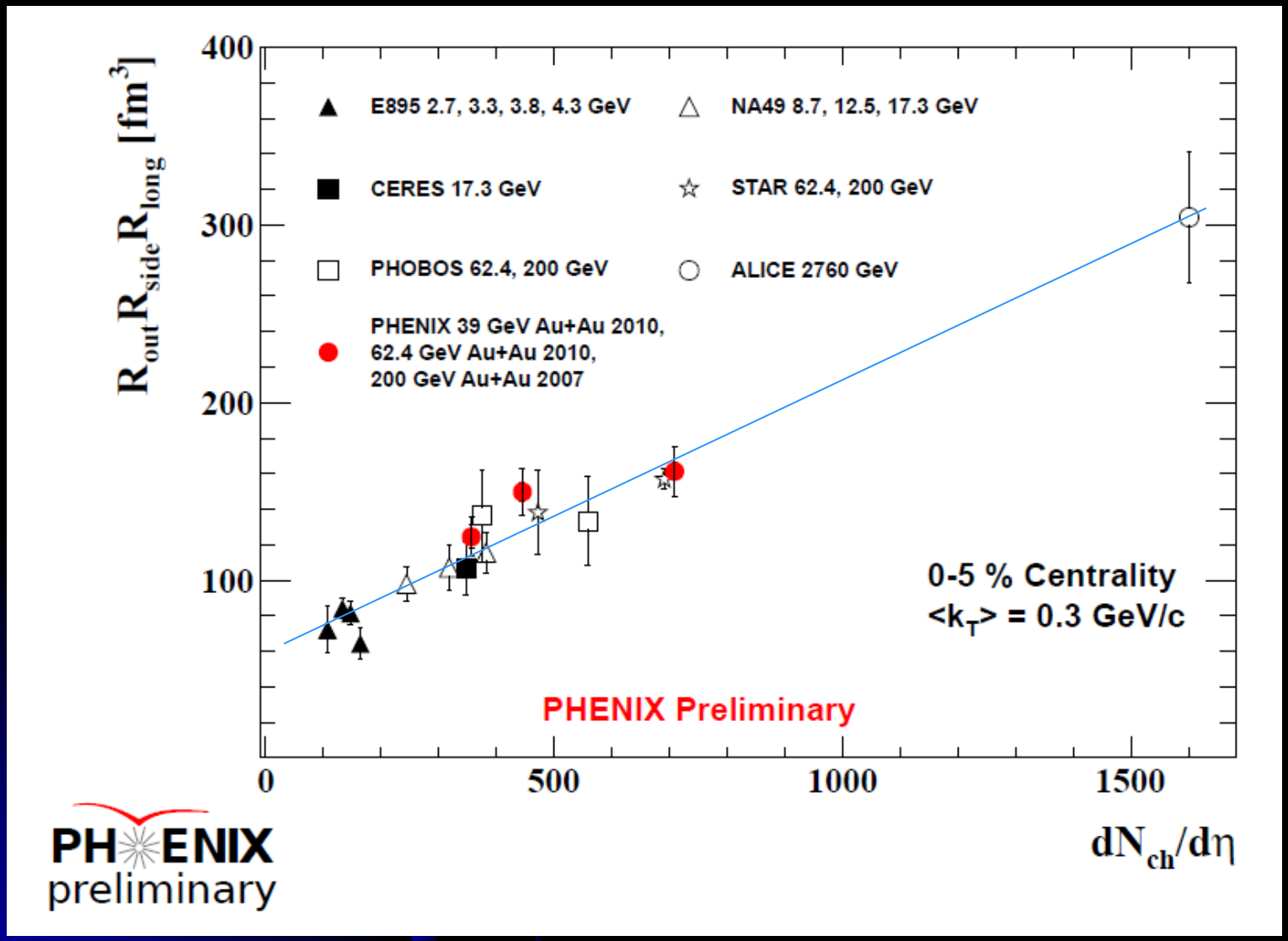
HBT Radii: Excitation Function



There is no significant change in R_{out} and R_{side} vs. sqrt(s_{NN}) from 39 to 200 GeV.

R_{long} increases with sqrt(s_{NN}).

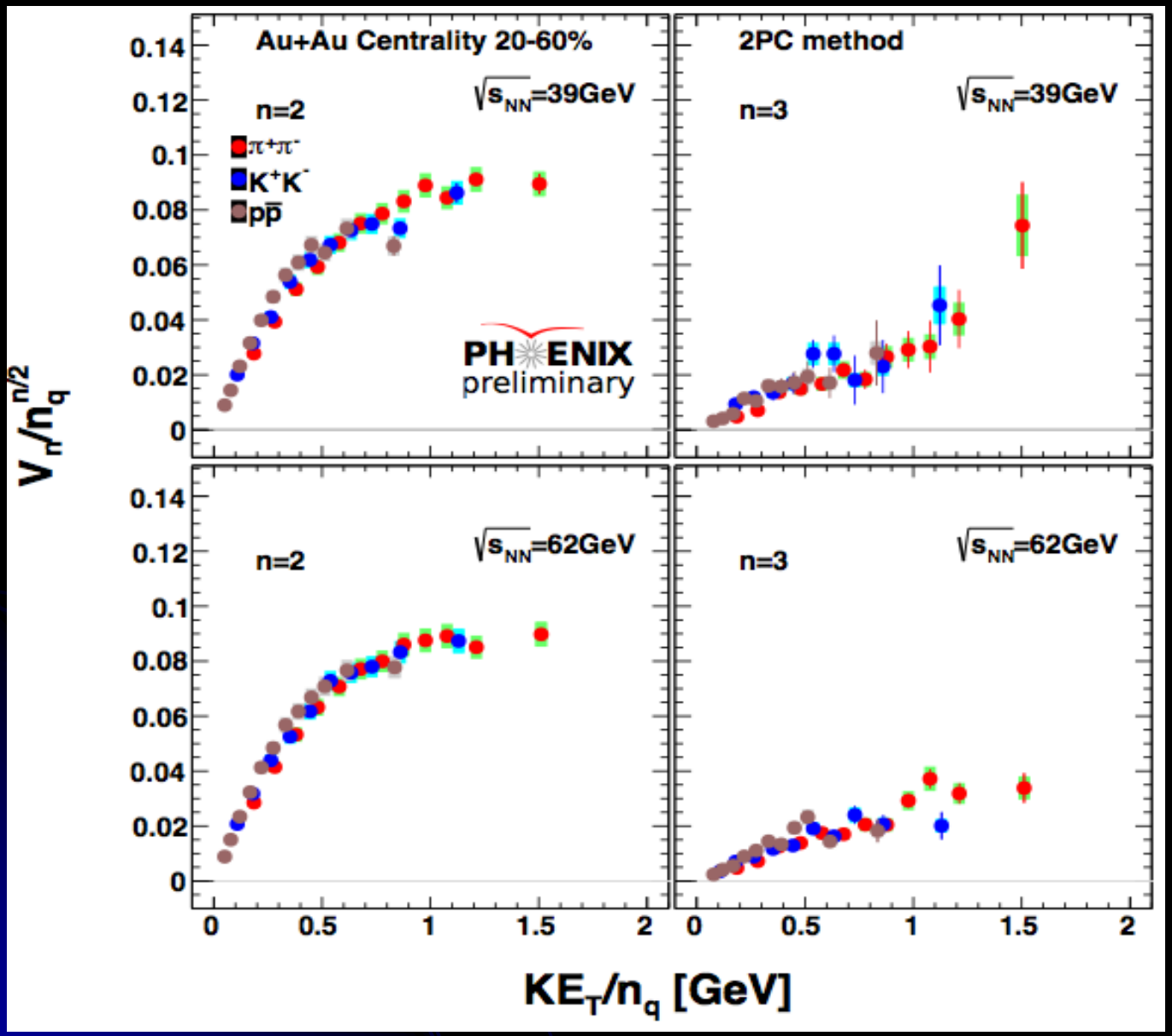
Pion freeze-out Volume: Excitation Function



The quantity $R_{out}*R_{side}*R_{long}$ estimates the pion freeze-out volume, V_f.

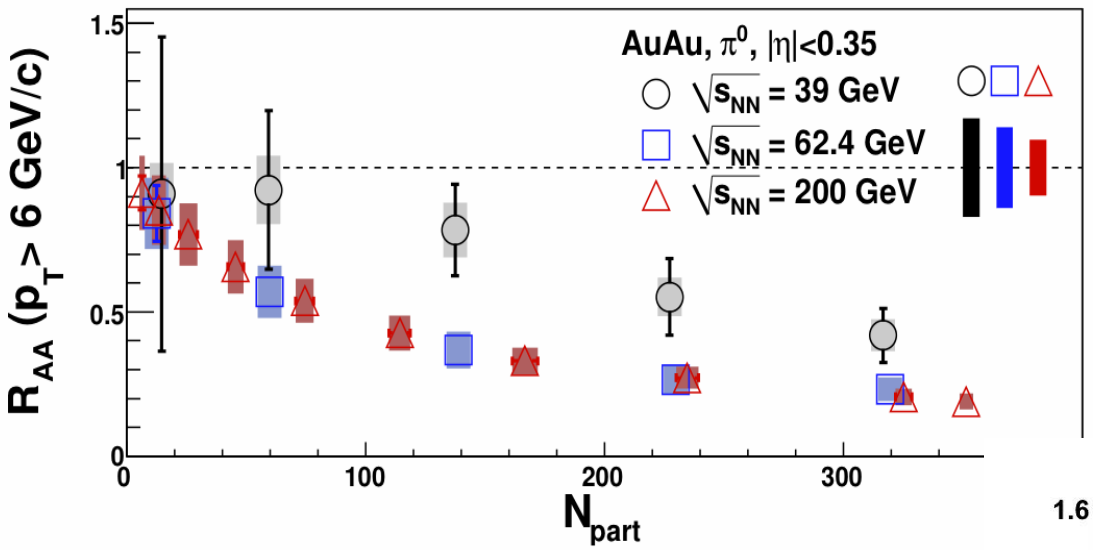
The PHENIX data are consistent with the trend displayed by previous results.

Identified Particle Flow



Scaling of v_2 and v_3 by the number of constituent quarks is preserved at 62 GeV and 39 GeV.

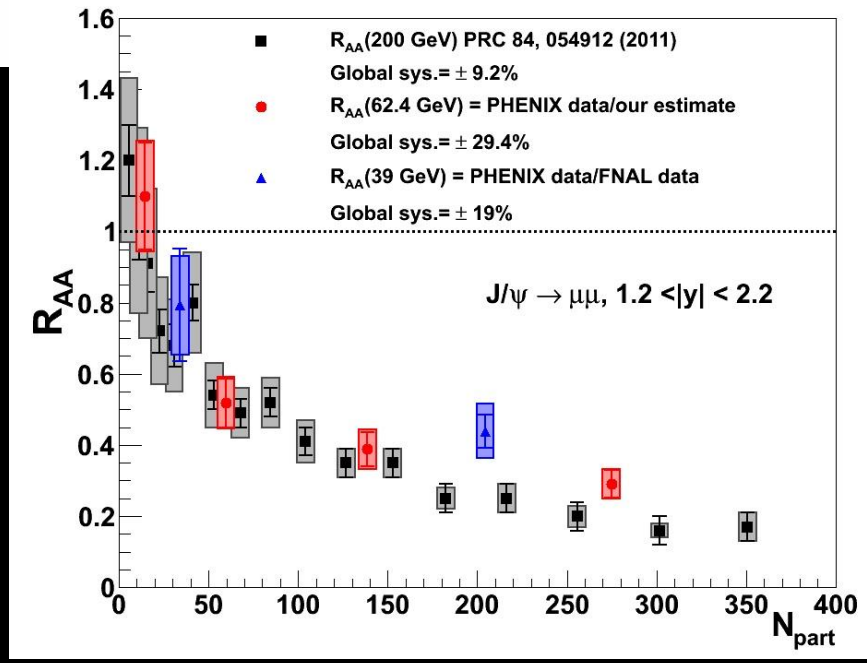
Energy Loss Measurements



arXiv:1204.1526v1

R_{AA} at 62 GeV is similar to that at 200 GeV.

Strong suppression is still observed at 39 GeV, but it is less than at higher energies. π^0 R_{AA} results at 27 GeV are coming soon.



Summary

New results from 39, 27, 19.6, and 7.7 GeV Au+Au collisions are shown.

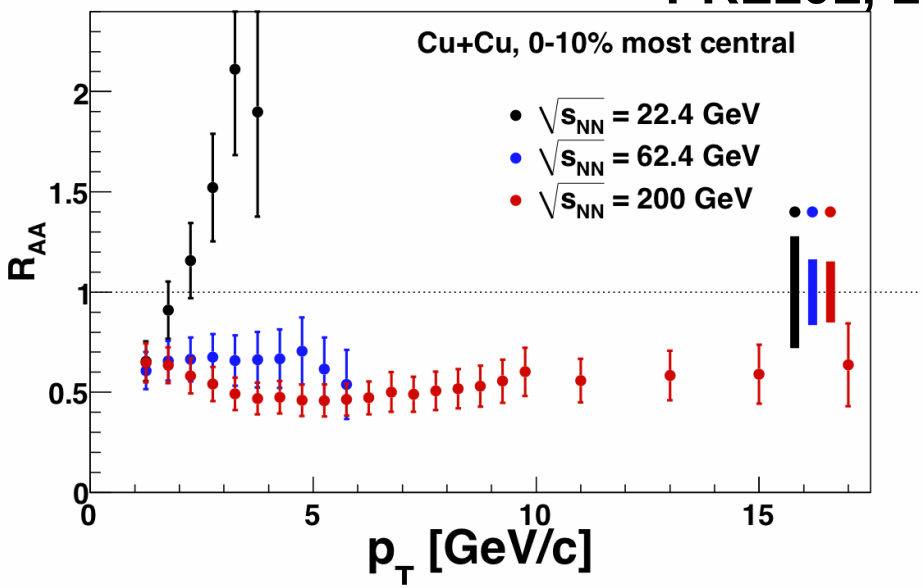
• Charged particle multiplicity and transverse energy production tend to scale logarithmically with sqrt(s_{NN}) up to the top RHIC energy.
• The centrality-dependent shape of multiplicity and transverse energy production shows little change from 7.7 GeV to 2.76 TeV.
• No increases in charged particle multiplicity fluctuations are observed at 7.7 or 39 GeV.
• No significant excess in the moments of net charge are observed above URQMD, HIJING, or Hadron Resonance Gas predictions at 7.7 or 39 GeV.
• The pion freeze-out volume at 62.4 and 39 GeV is consistent with trends established in previous measurements.
• Constituent quark scaling of v_2 holds at 62.4 and 39 GeV.
• Strong suppression is observed at 62.4 and 39 GeV, although less suppression is seen at 39 GeV.

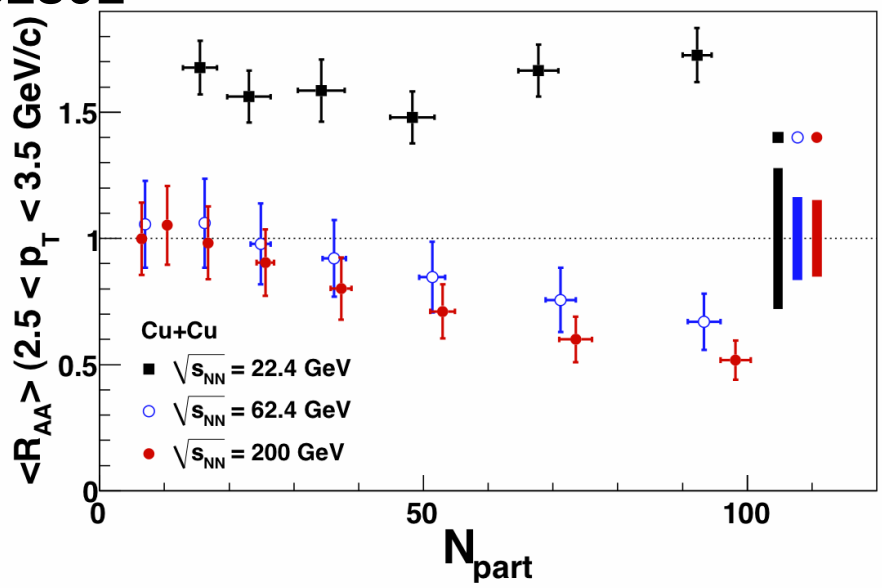
• So far, PHENIX observes no signs of the critical point. Stay tuned for much more soon.

Auxiliary Slides

PHENIX π^0 Energy Loss Measurements in Cu+Cu Collisions

PRL101, 162301

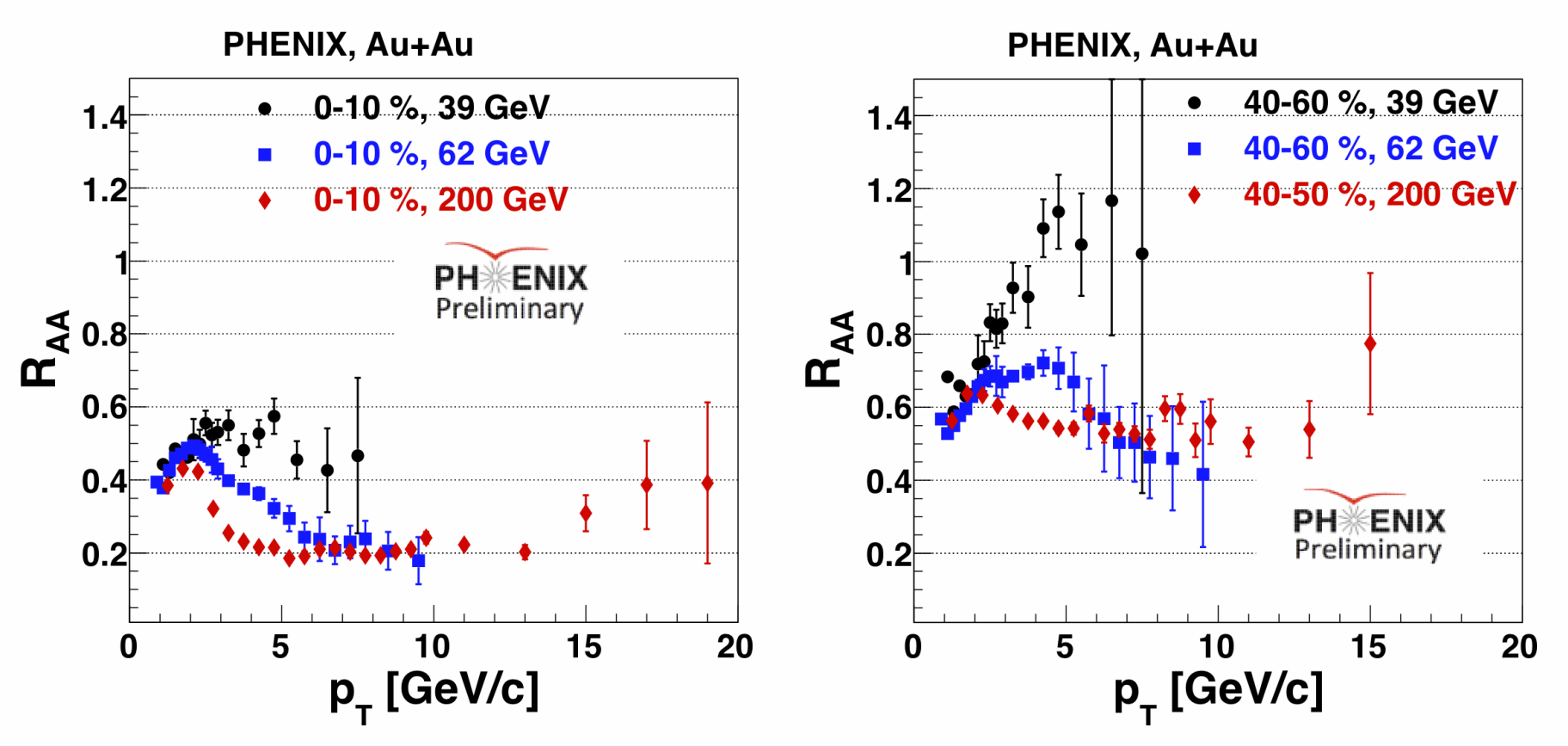




From the Cu+Cu energy scan:

- **Significant suppression** at $\sqrt{s_{NN}}$ = 200 and 62.4 GeV
- **Moderate enhancement** at $\sqrt{s_{NN}}$ = 22.4 GeV

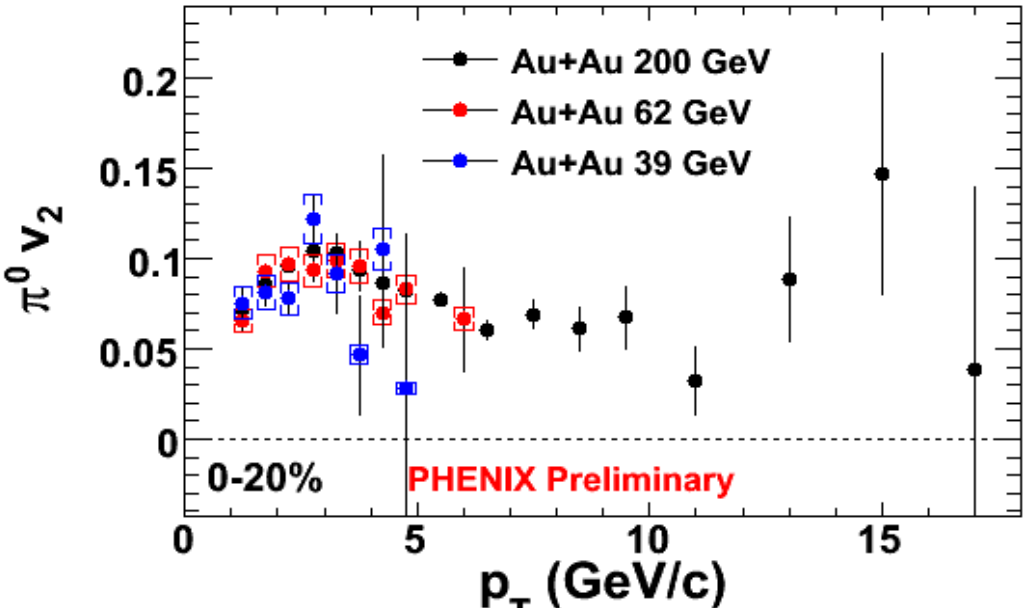
π^0 R_{AA} in Au+Au at 39 and 62 GeV

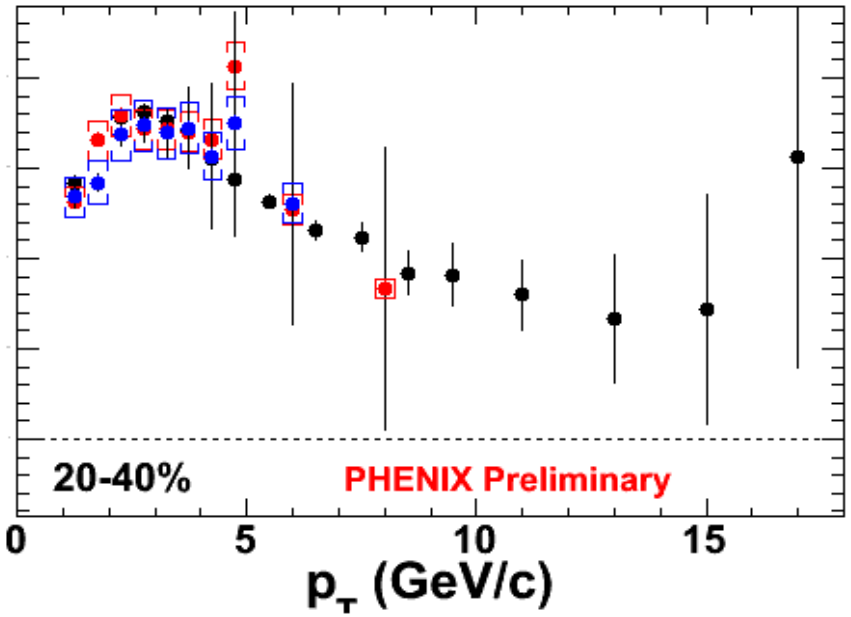


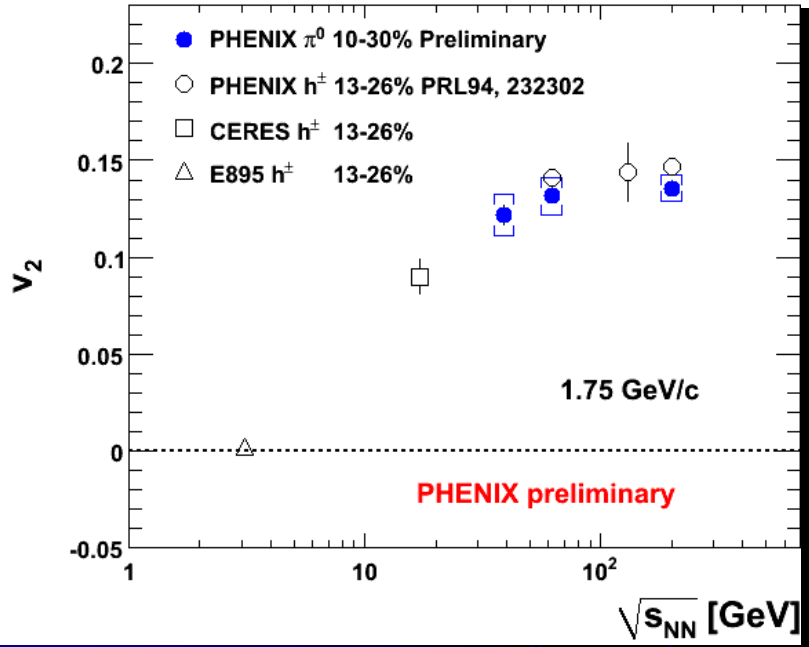
π^0 R_{AA} as a function of p_T in PHENIX at $\sqrt{s_{NN}}$ = **39, 62** and **200** GeV.

- Still observe a strong suppression (factor of 2) in the most central $\sqrt{s_{NN}}$ = 39 GeV collisions.
- R_{AA} from $\sqrt{s_{NN}}$ = 62 GeV data is comparable with the R_{AA} from $\sqrt{s_{NN}}$ = 200 GeV for p_T 6 >GeV/c.
- Peripheral $\sqrt{s_{NN}}$ = 62 and 200 GeV data show suppression, but the $\sqrt{s_{NN}}$ = 39 GeV does not.

Elliptic Flow at 62 and 39 GeV: π^0

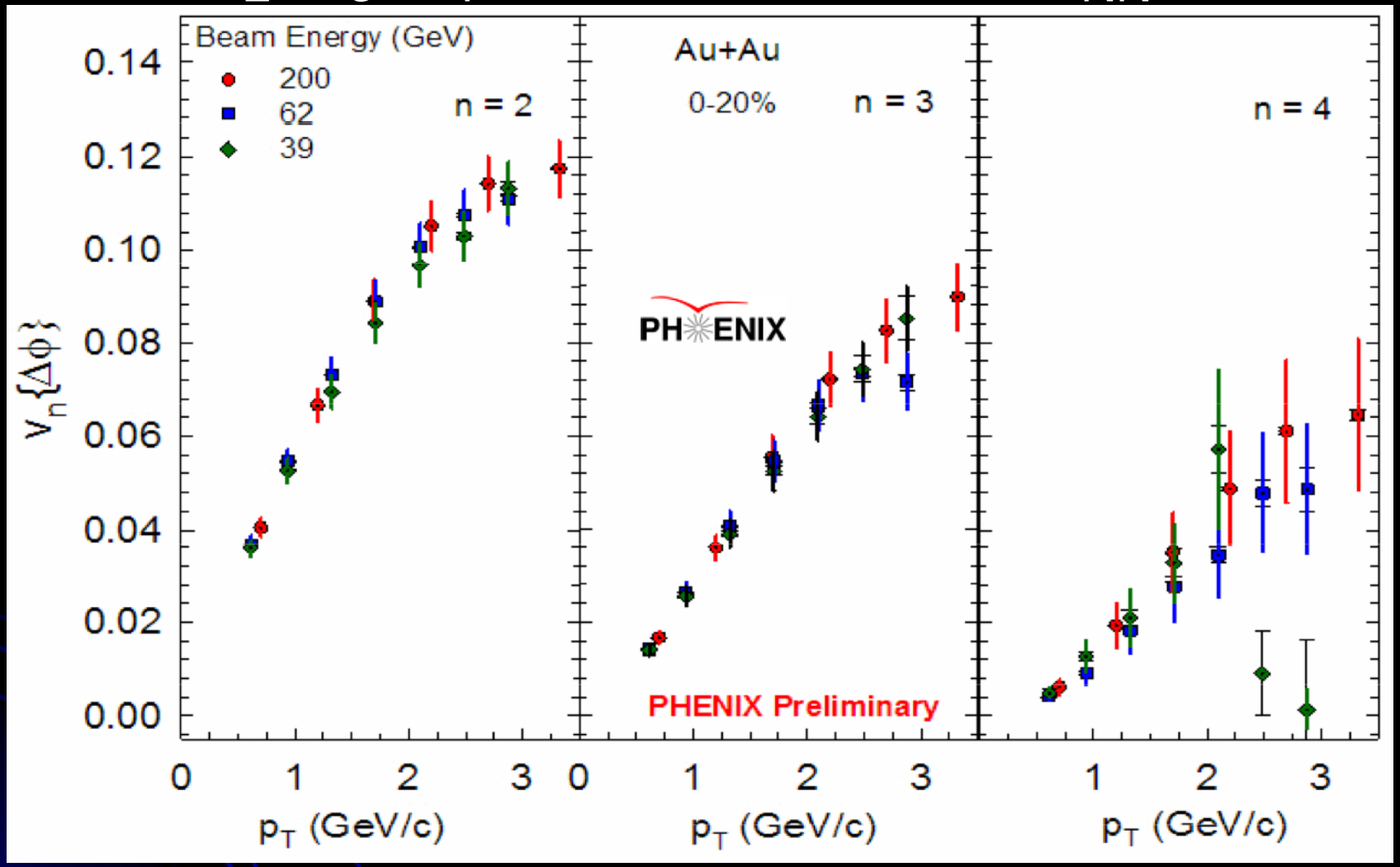




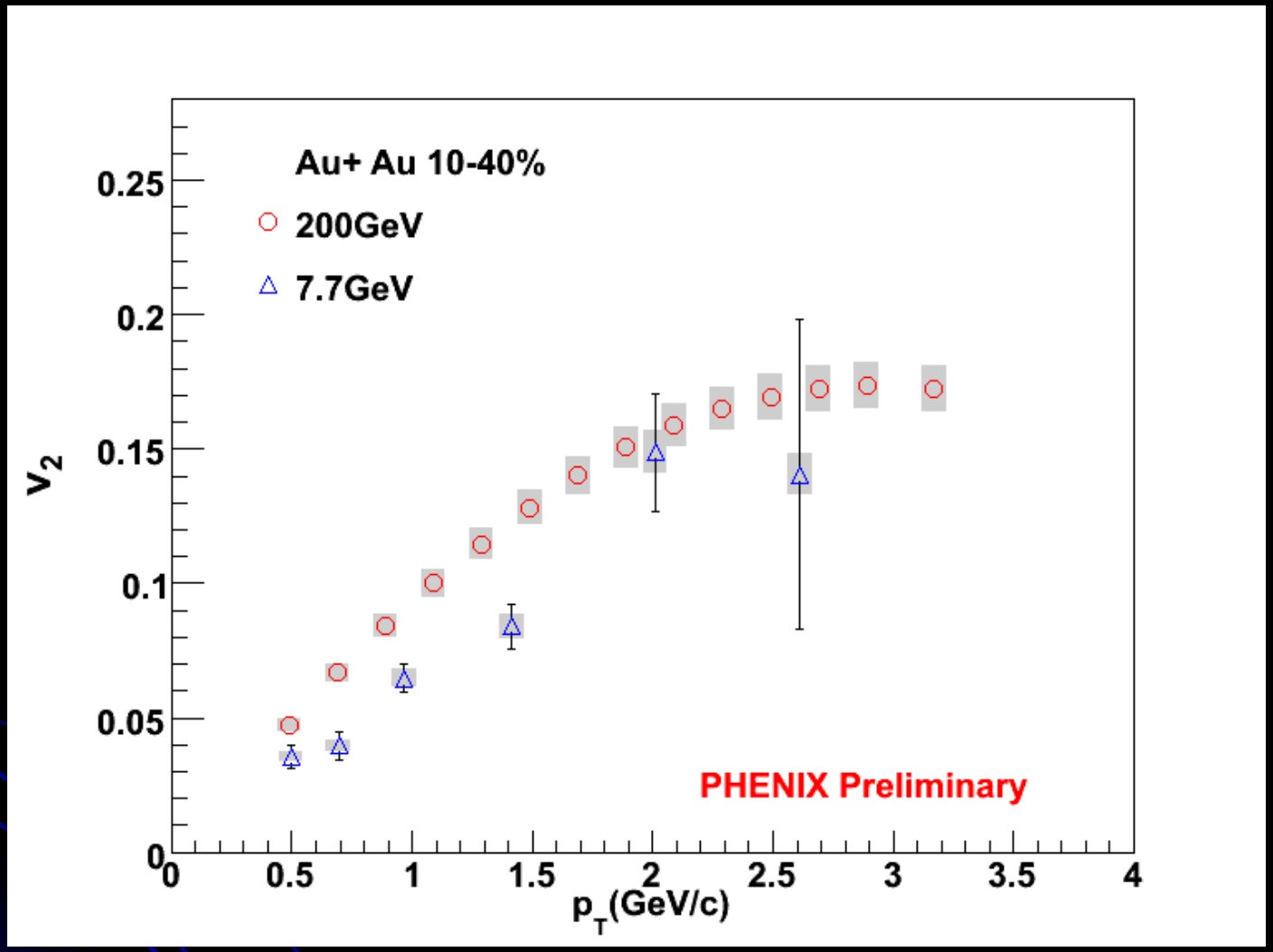


There is little change in the magnitude of v_2 from 39 GeV to 200 GeV.

v_2, v_3, v_4 as a function of $\sqrt{s_{NN}}$



v_2 in 7.7 GeV Au+Au Collisions



The magnitude of v_2 at 7.7 GeV is significantly lower than the magnitudes at 39, 62 and 200 GeV