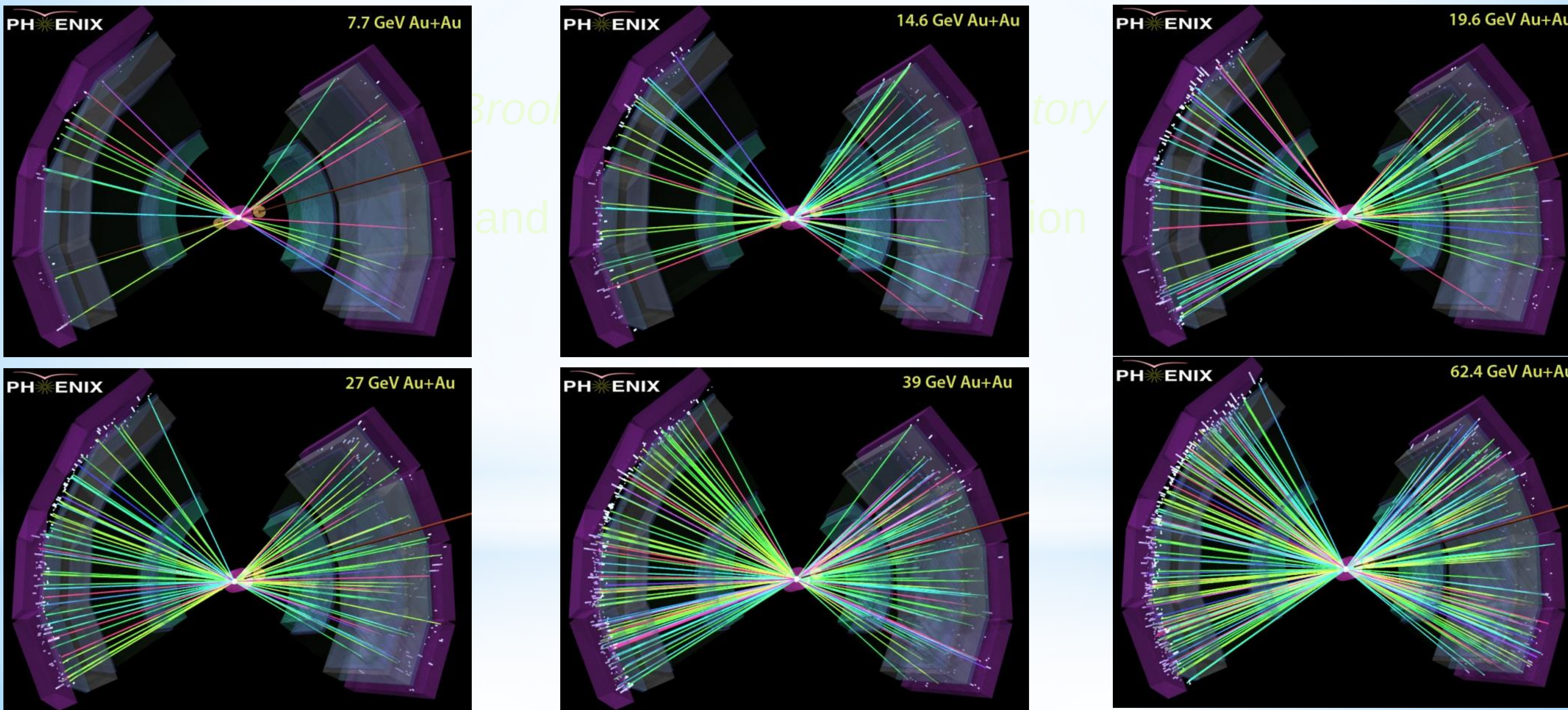
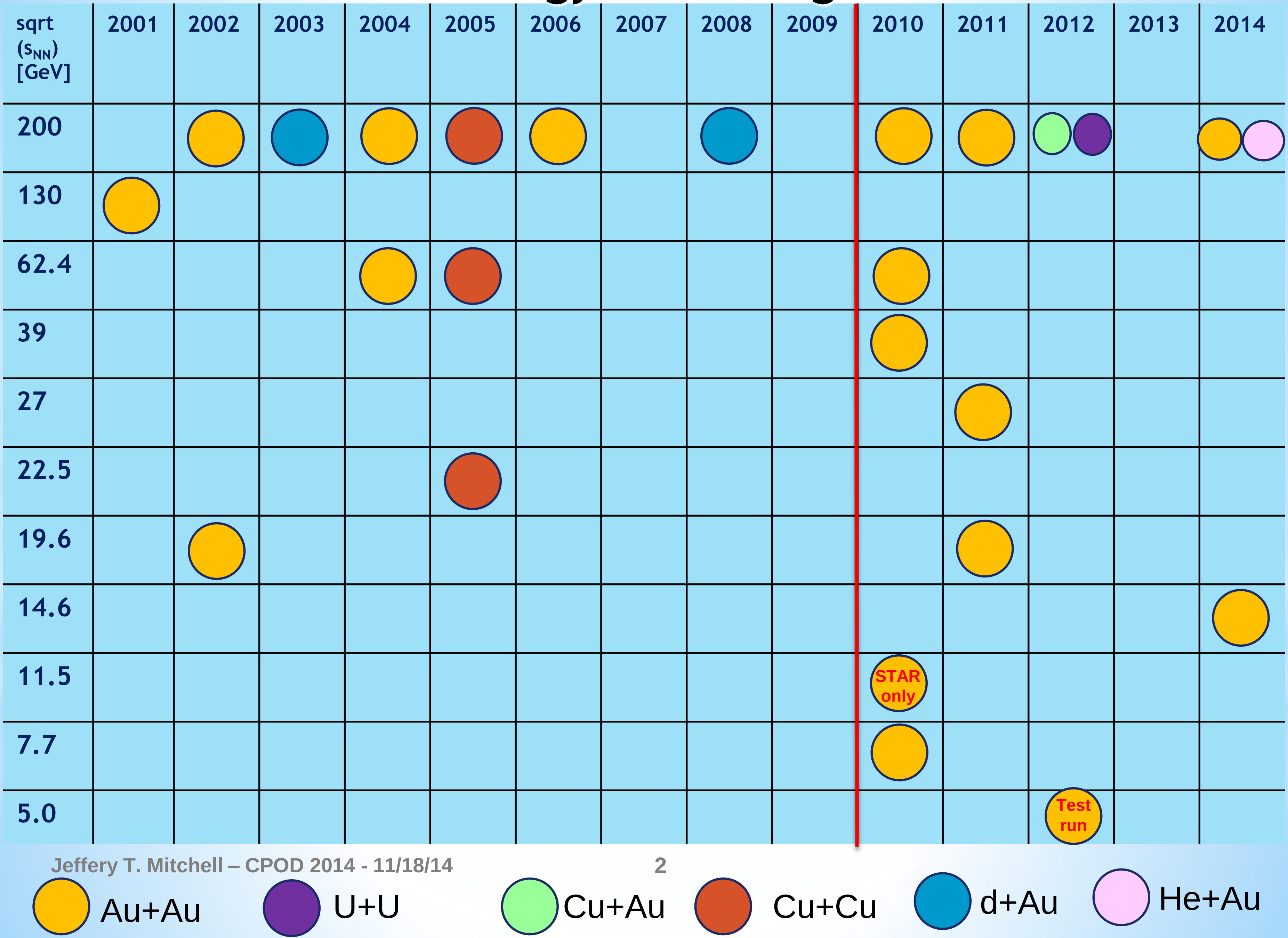
PHENIX Global Variables and Fluctuations from the RHIC Beam Energy Scan

Jeffery T. Mitchell for the PHENIX Collaboration



The RHIC Beam Energy Scan Program: Overview



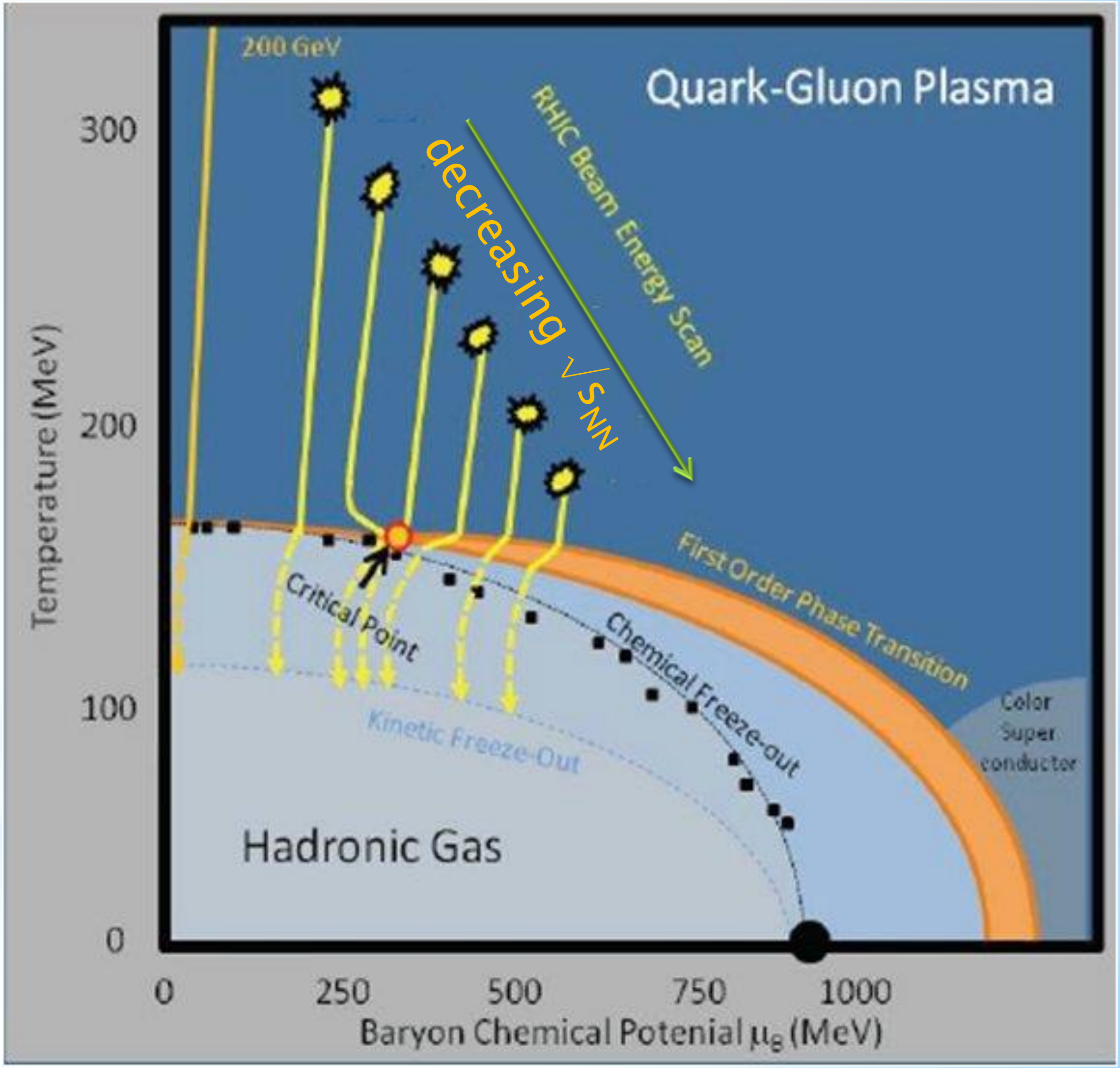
The RHIC Beam Energy Scan Program: Probing the Nuclear Matter Phase Diagram

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:

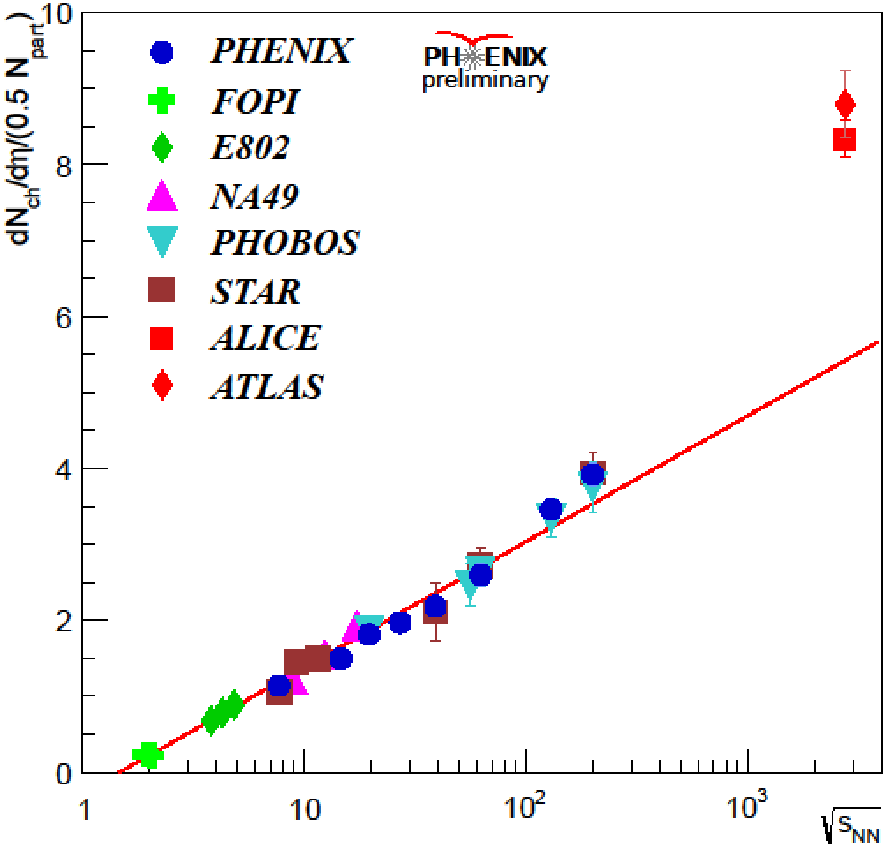
- Global Variables
- Participant Nucleon Scaling
- Participant Quark Scaling
- Fluctuations
- BES-II plans

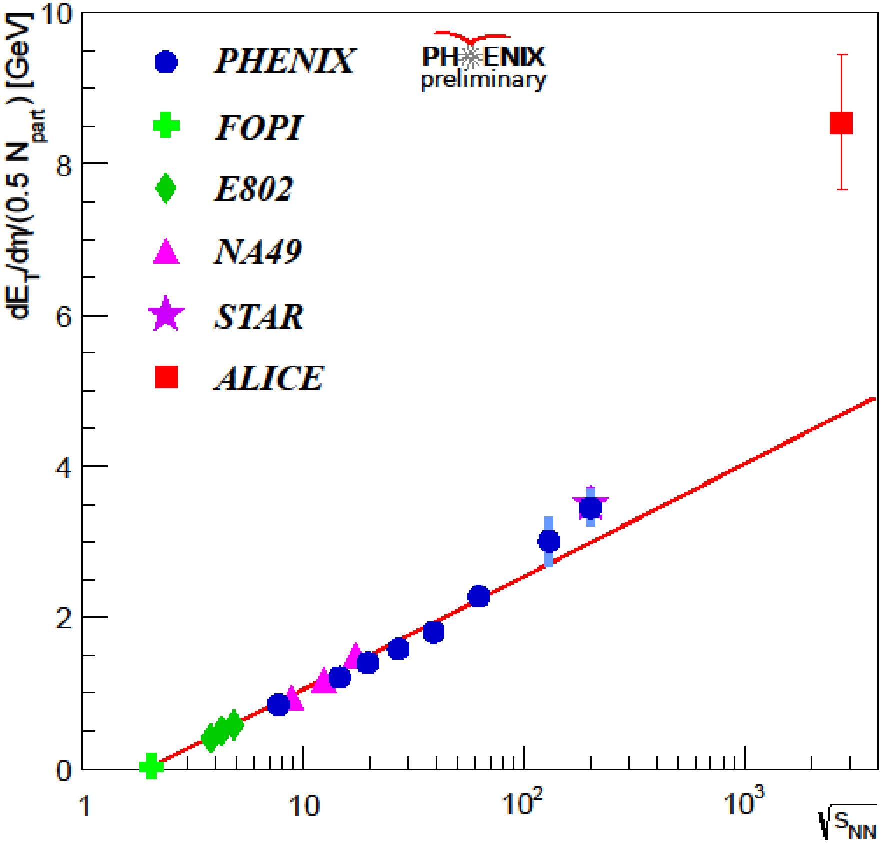


The development of multiplicity and transverse energy production

Mid-rapidity

Central collisions

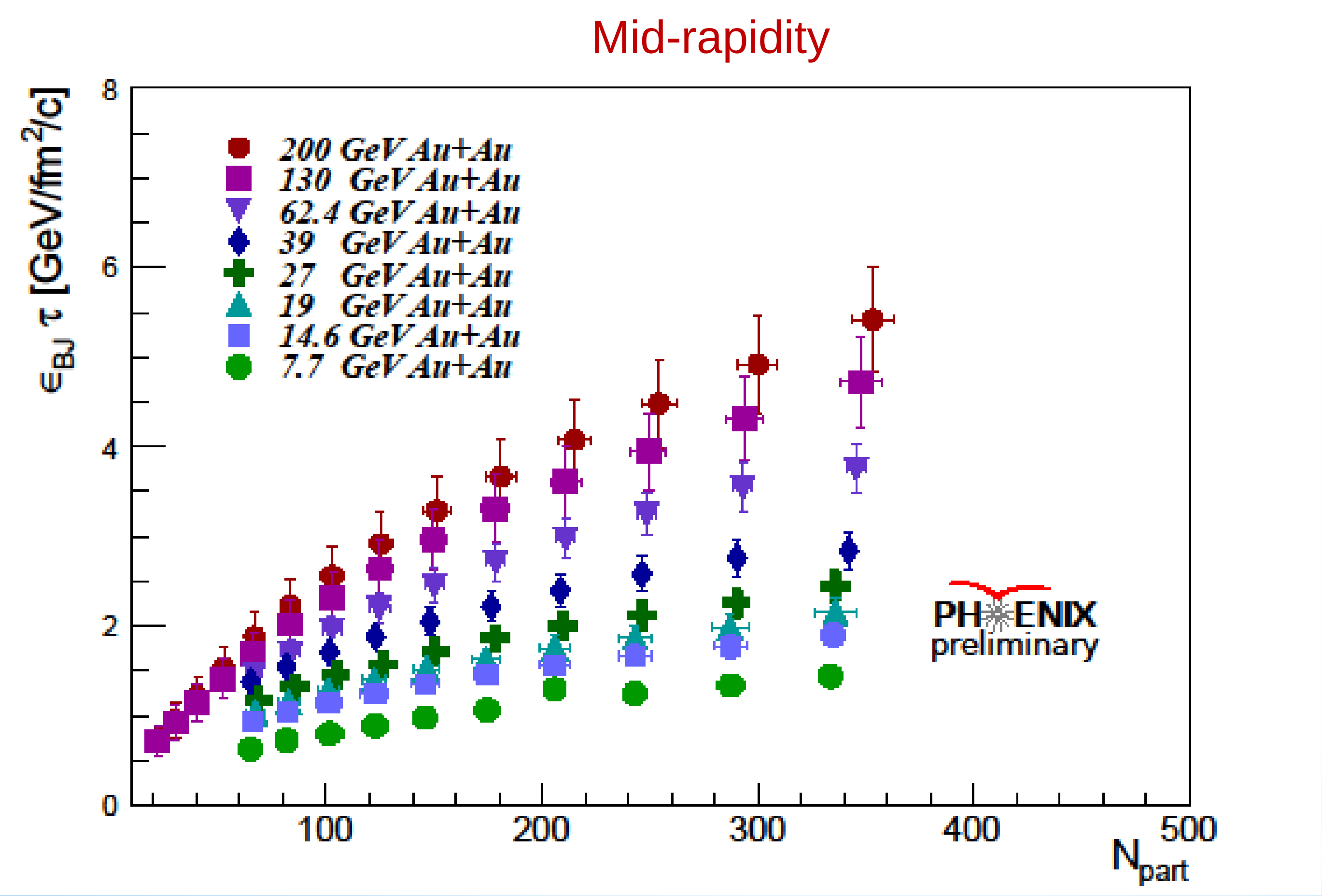




Note the new data points at 15 GeV.

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

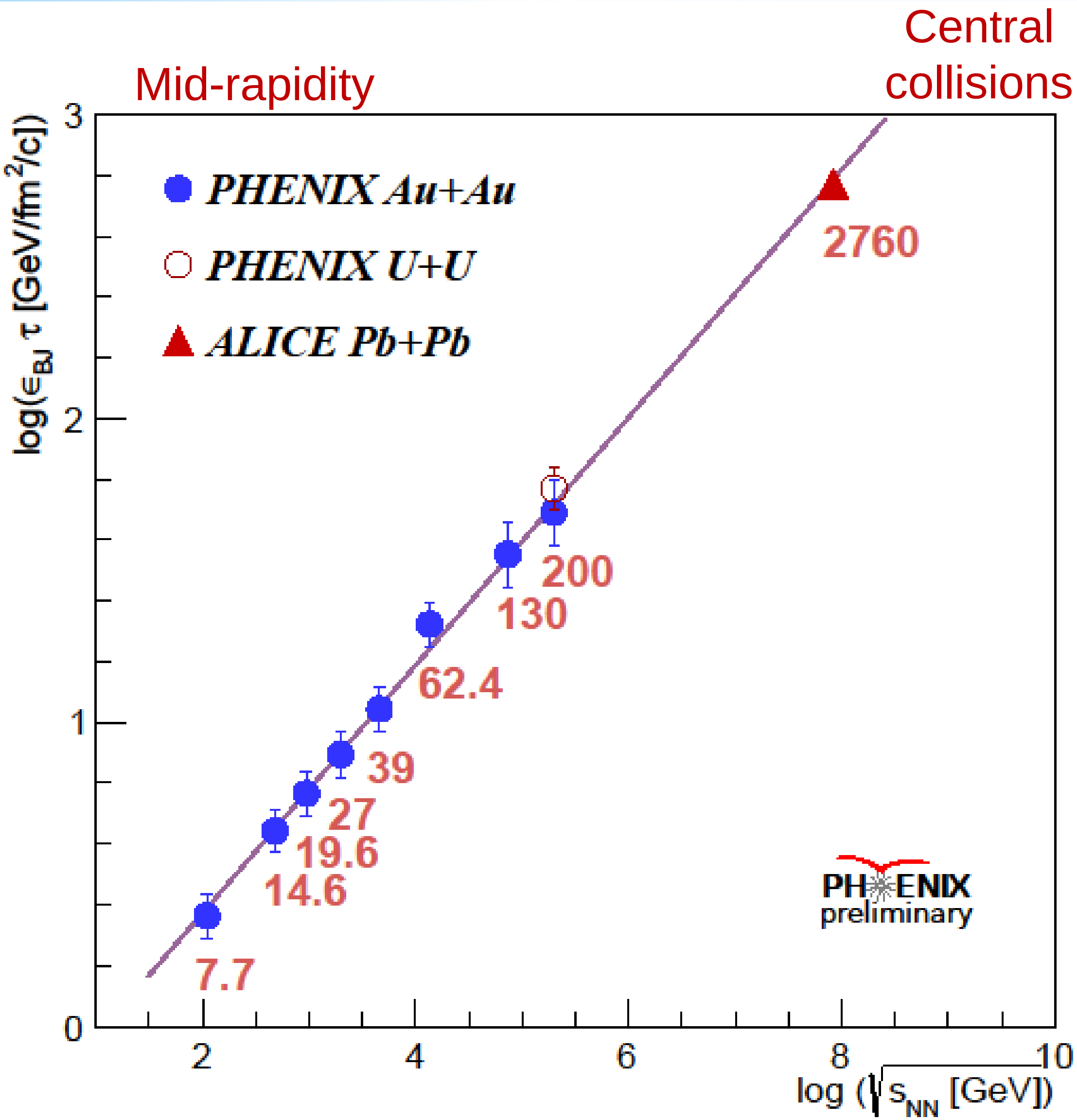
Bjorken Energy Density: Centrality Dependence



$$\epsilon_{Bj} = \frac{1}{A_\perp \tau} \frac{dE_T}{dy}$$

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

Bjorken Energy Density Excitation Function

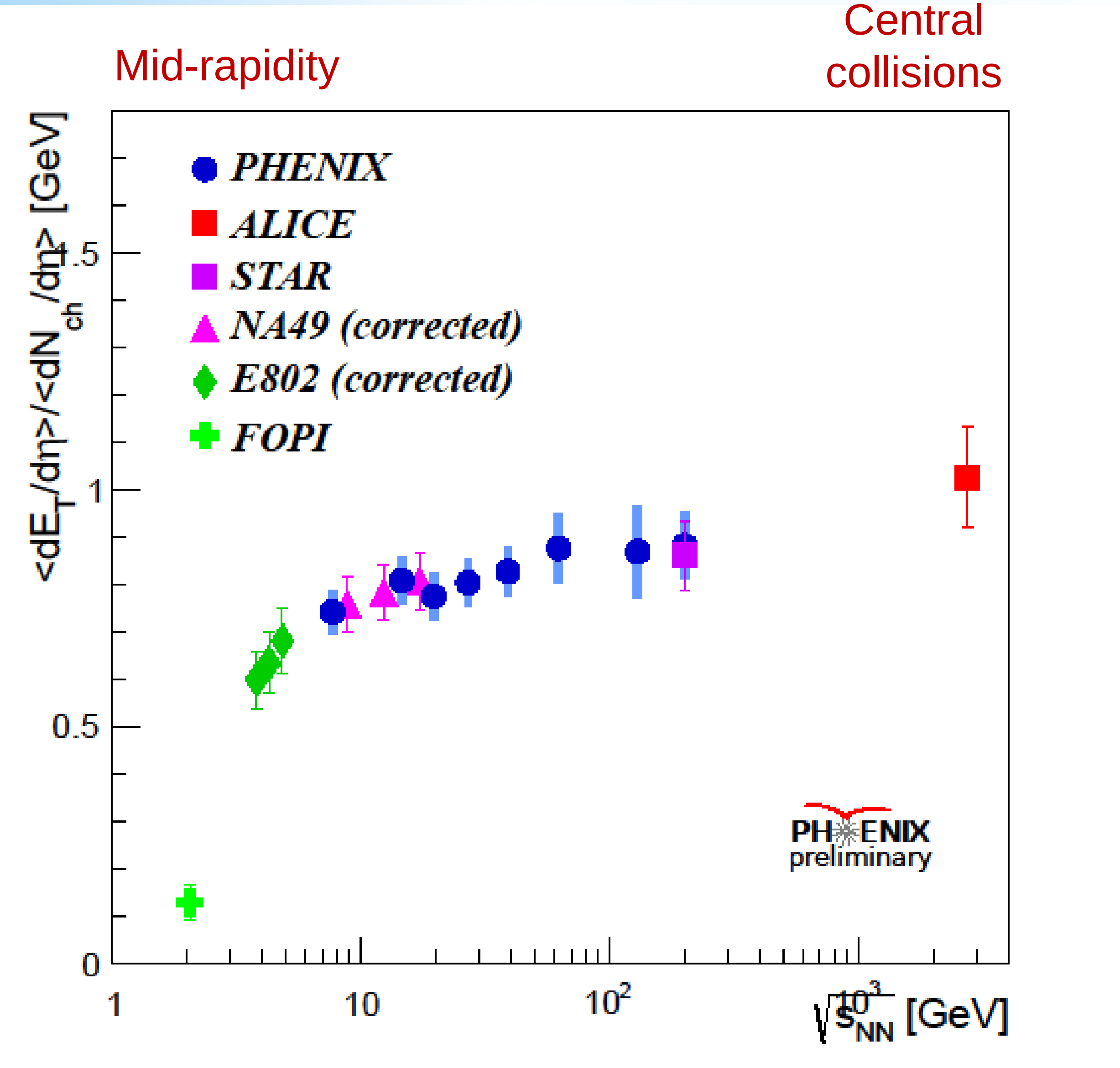


$$\epsilon_{Bj} = \frac{1}{A_{\perp}\tau}\frac{dE_T}{dy}$$

Over this collision energy range, the Bjorken energy density scales exponentially. The line is a power law fit to all of the points. The power is 0.41.

The ALICE data point is from C.~Loizides et al., arXiv:1106.6324 (2011).

Energy Per Charged Particle

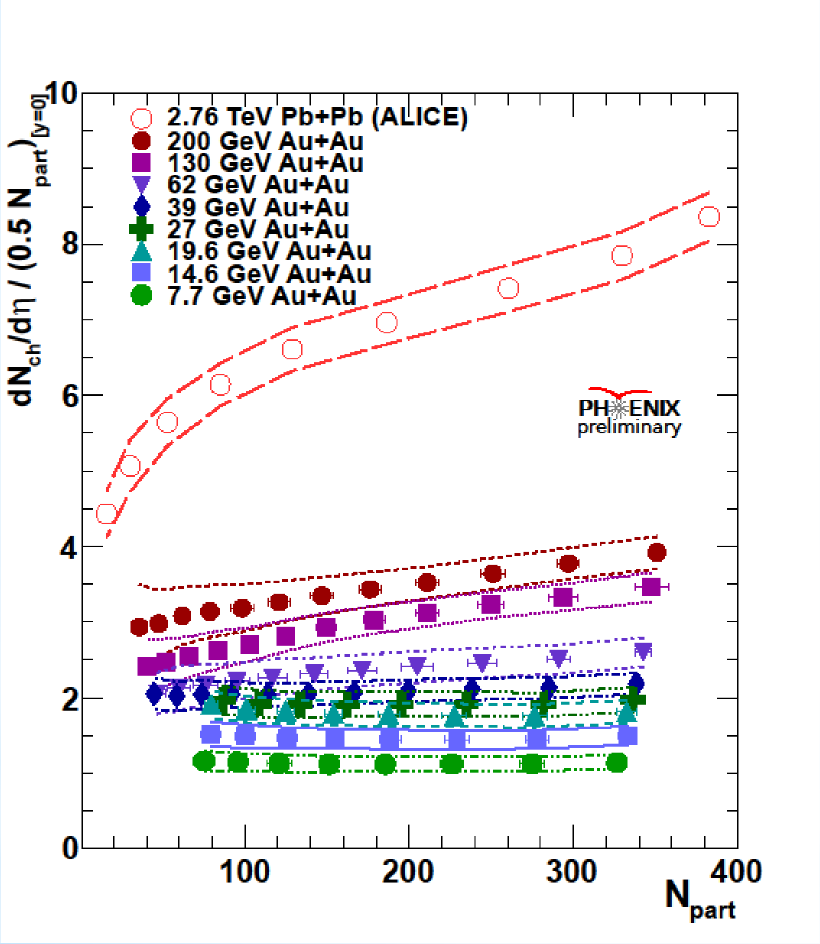


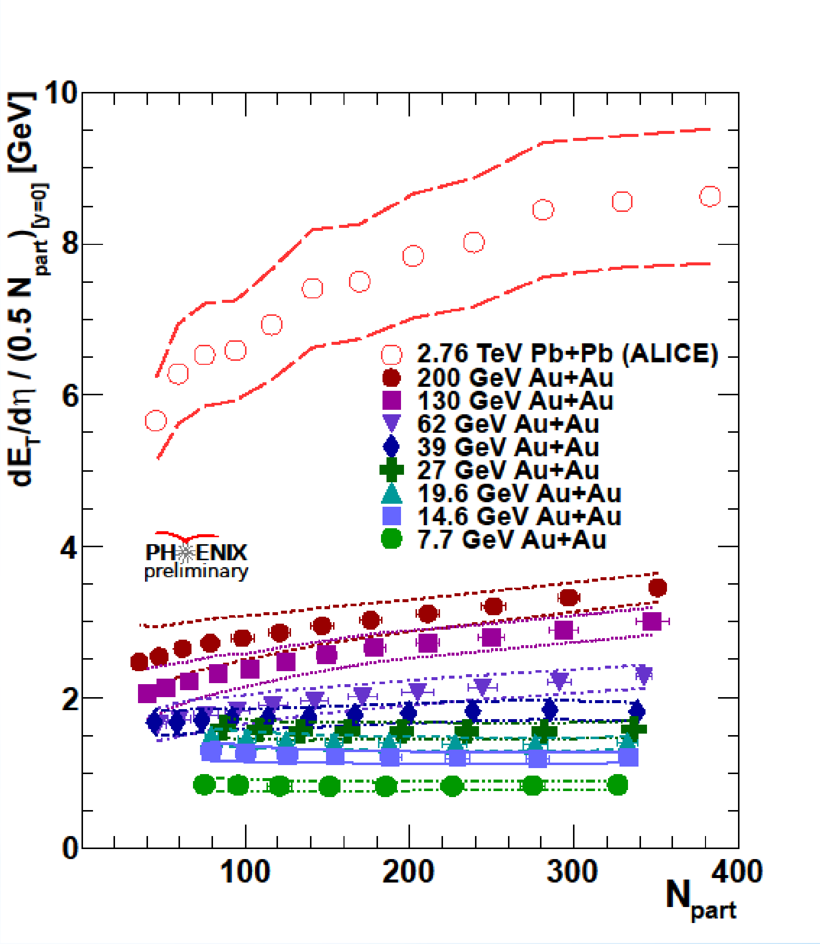
There is very little change in the transverse energy per charged particle from 7.7 GeV to 200 GeV.

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

Participant Nucleon Scaling

The PHENIX 200 GeV Au+Au analysis is published in Phys. Rev. C71 (2005) 034908.
The PHENIX 62.4 GeV Au+Au analysis is published in Phys. Rev. C89 (2014) 044905.

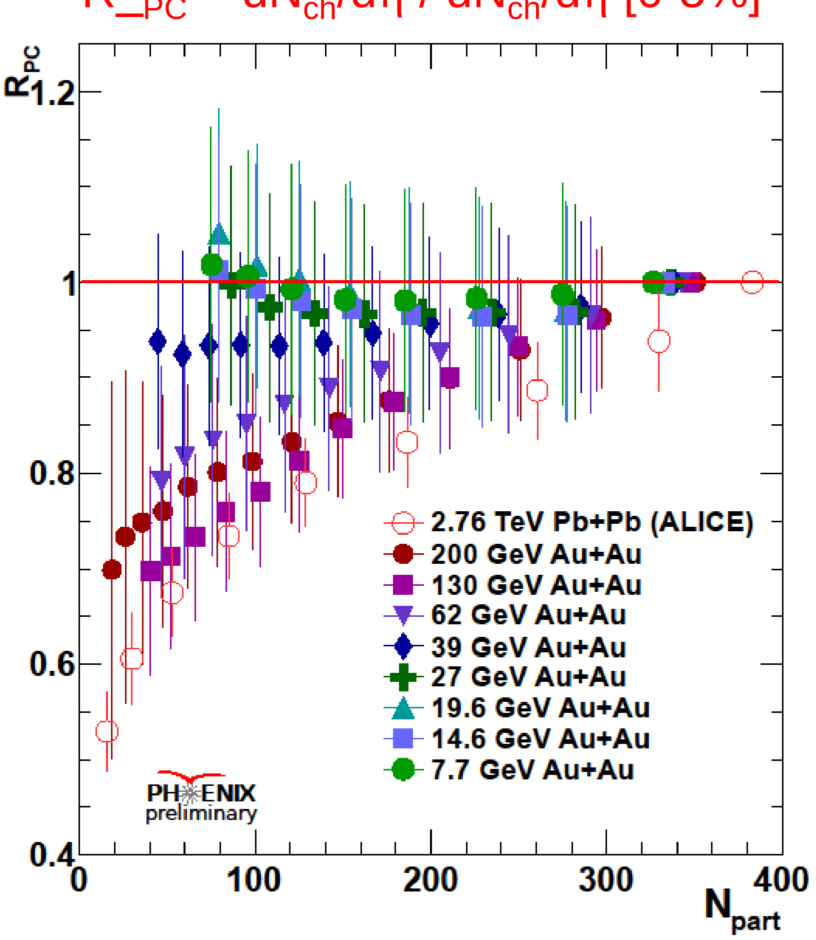




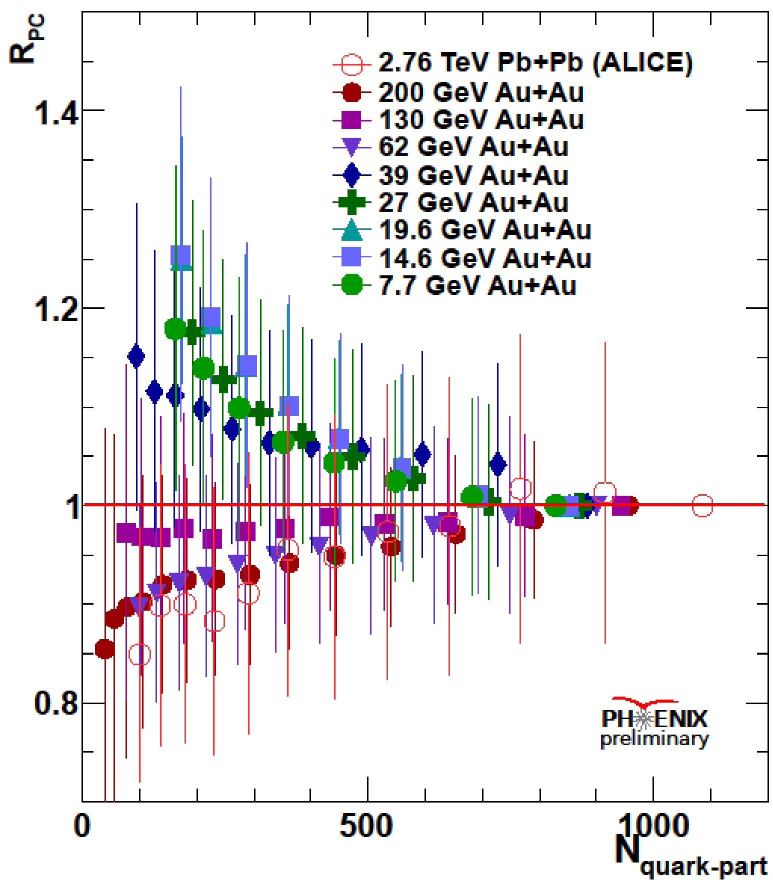
Below 39 GeV, participant nucleon scaling describes the data well.

Participant Nucleon Scaling

$R\_{PC} = dN_{ch}/d\eta \ / \ dN_{ch}/d\eta$ [0-5%]



$R\_{PC} = dE_T/d\eta \ / \ dE_T/d\eta$ [0-5%]



The error bars represent correlated systematic errors.

Participant nucleon scaling describes the data best below 39 GeV.

Estimating the number of quark participants

sqrt(s_{NN}) [GeV]	$\sigma_{inelastic}$ [mb]	σ_{qq} [mb]
2760	64.0	18.4
200	42.3	9.36
130	39.6	8.60
62.4	36.0	7.08
39	34.3	6.73
27	33.2	6.35
19.6	32.5	6.12
14.6	32.0	6.00
11.5	31.7	5.93
7.7	31.2	5.79

The number of quark participants is estimated using a modified Glauber model using the procedure described in M.L. Miller et al., Ann. Rev. Nucl. Part. Sci. 57, 205 (2007).

Here, nucleons are replaced by 3 constituent quarks with a radial distribution sampled from the proton form factor:

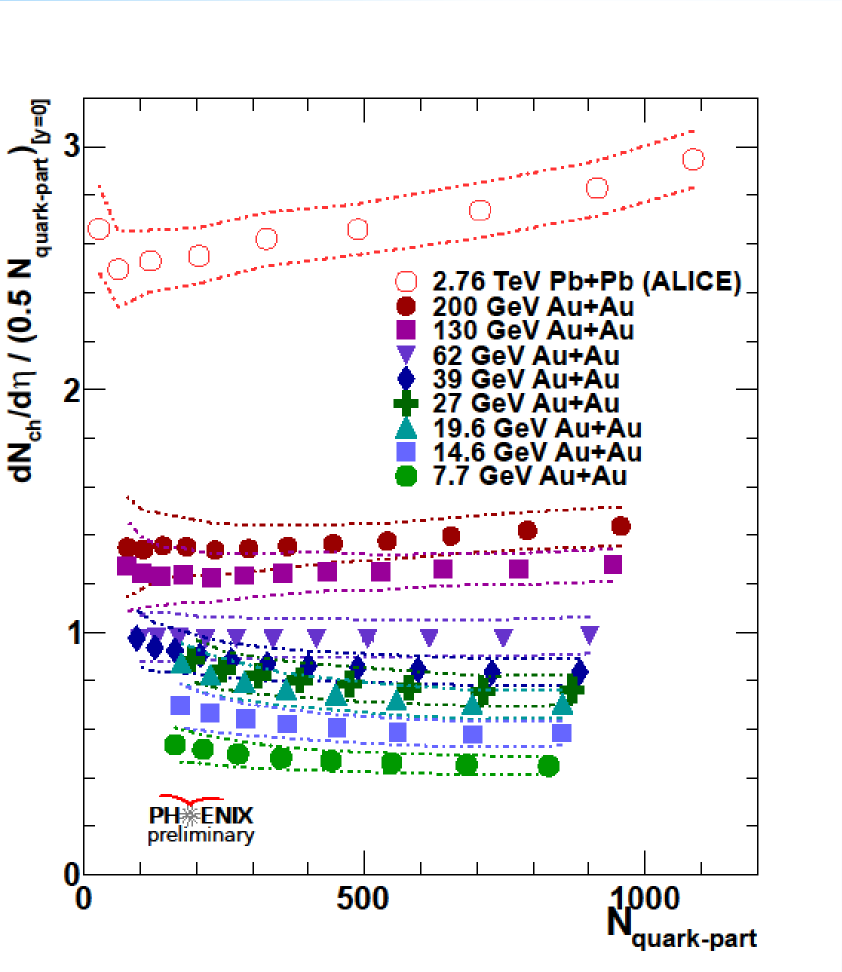
$$\rho^{proton}(r) = \rho_0^{proton} \times \exp(-ar)$$

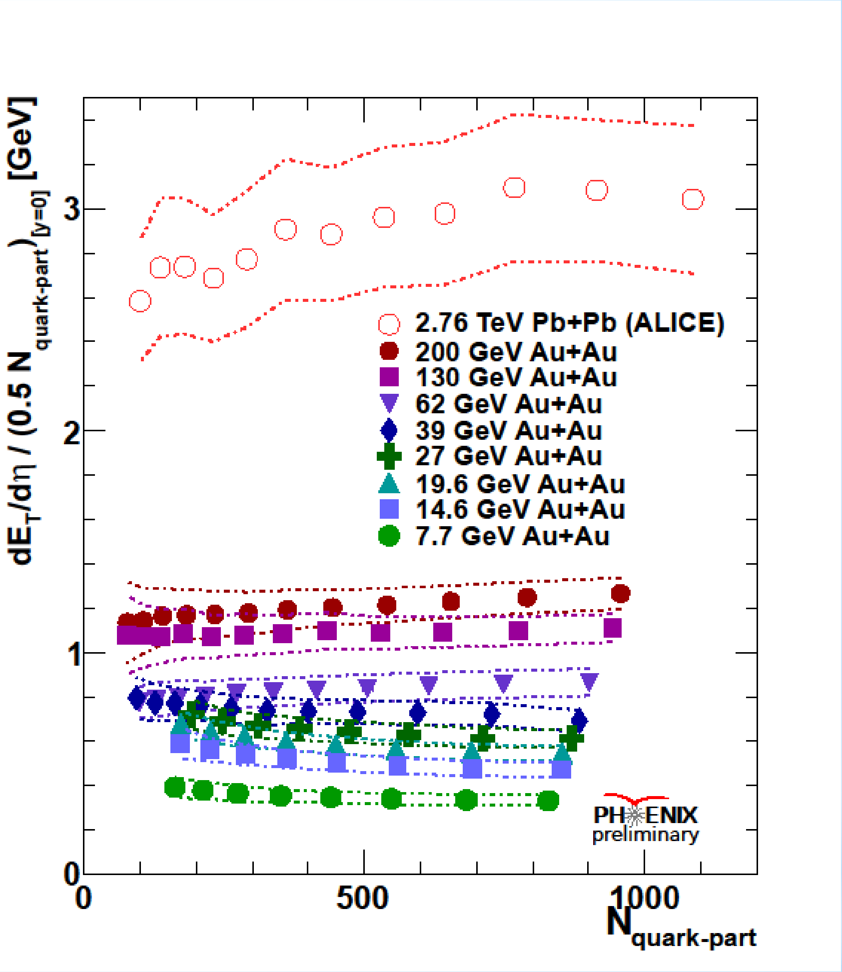
The q-q inelastic cross section is estimated by matching the n-n inelastic cross section in p+p collisions.

Interactions occur if the following condition is met:

$$d < \sqrt{\frac{\sigma_{qq}^{inel}}{\pi}}$$

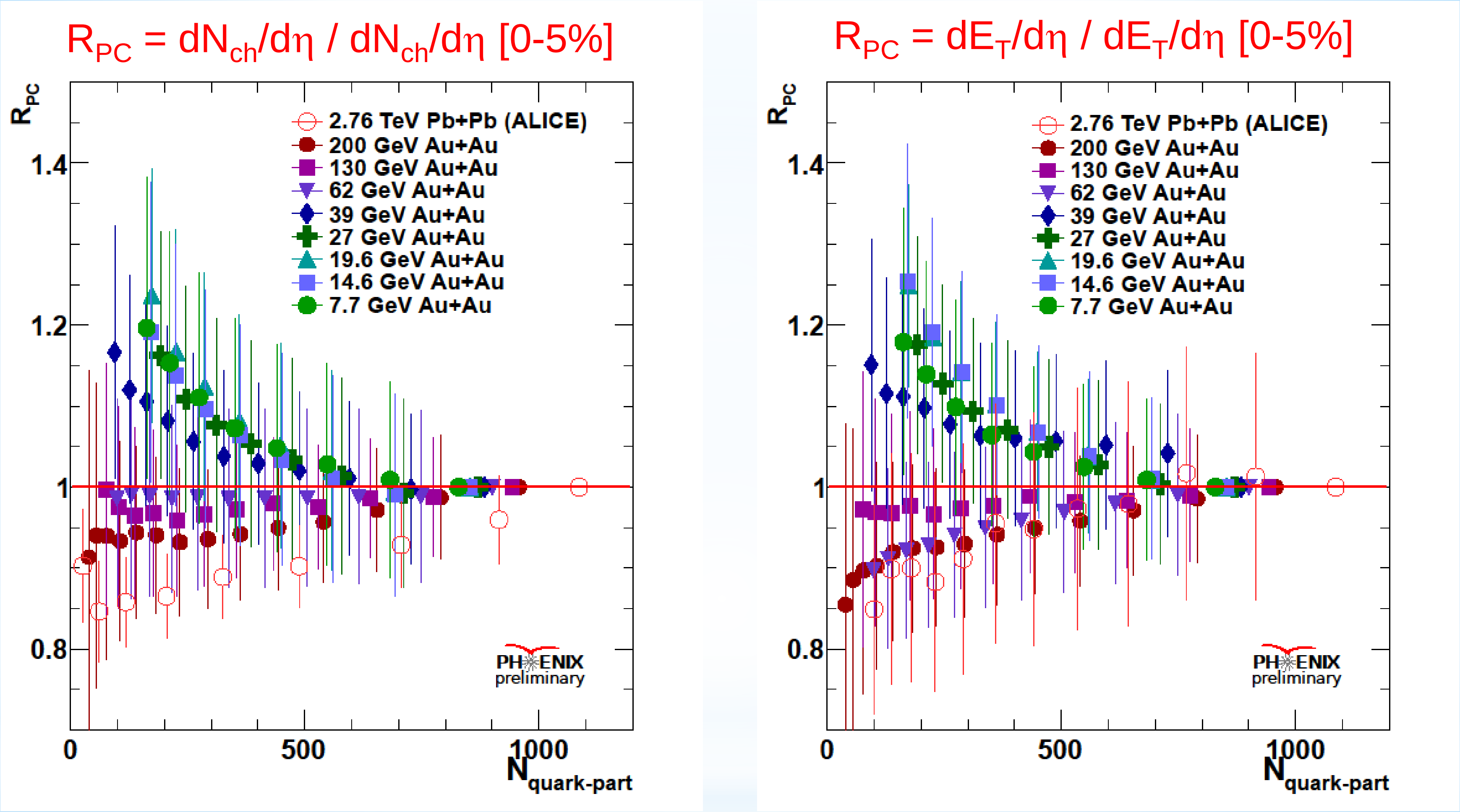
Participant Quark Scaling





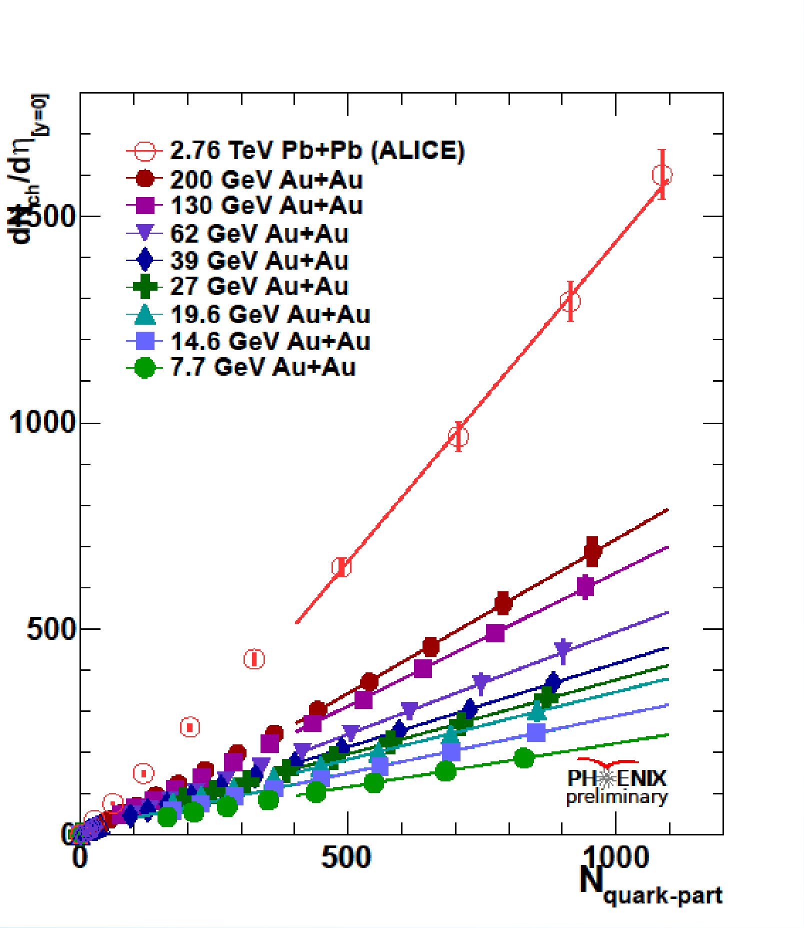
Above 39 GeV, participant nucleon scaling describes the data well.

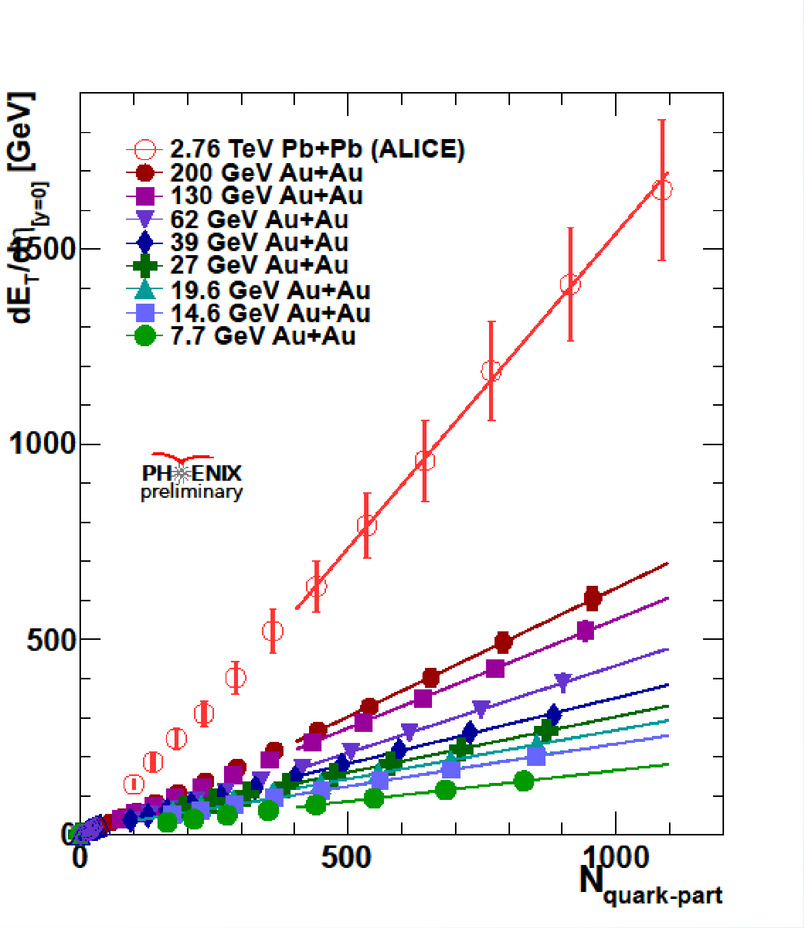
Participant Quark Scaling



The error bars represent correlated systematic errors.
Participant quark scaling describes the data best above 39 GeV.

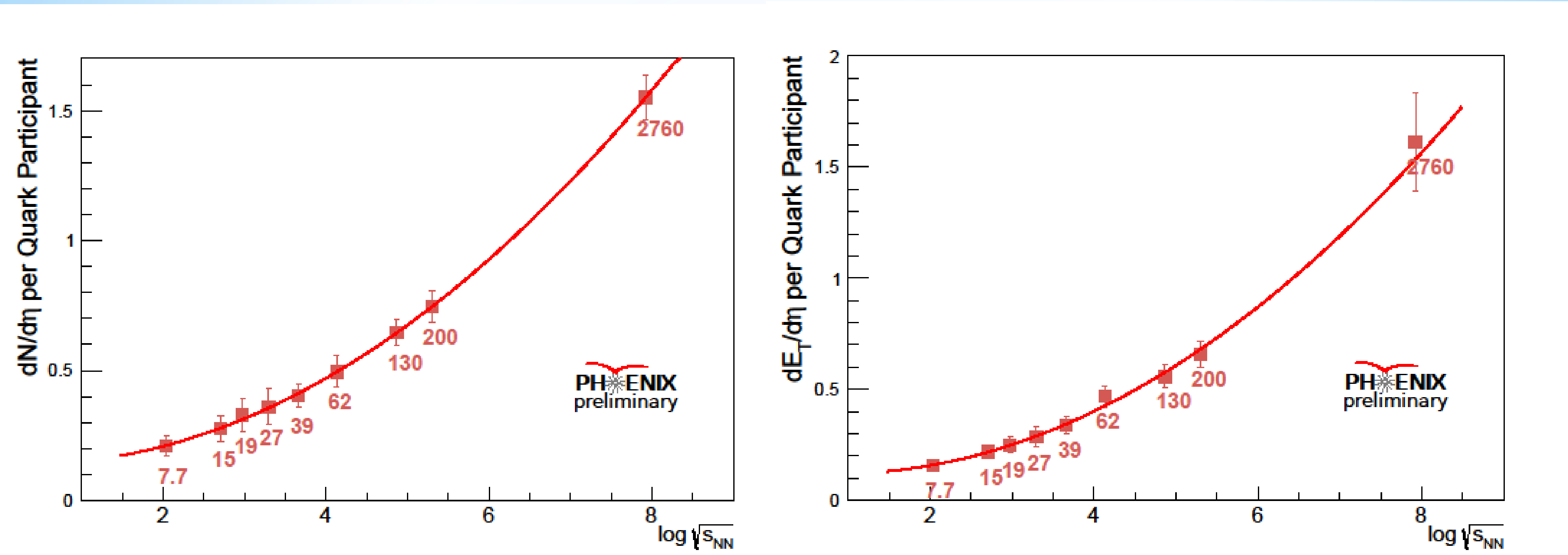
Estimating dN/dη and dE_T/dη per Quark Participant





$dN_{ch}/d\eta$ and $dE_T/d\eta$ as a function of $N_{quark-part}$ are fit to straight lines over a region where there is a good fit for all energies, $N_{quark-part}$>400. The slopes are then extracted and plotted as a function of sqrt(s_{NN}).

dN/dη and dE_T/dη per Quark Participant



The slopes increase as the collision energy increases.

The red line is a 2nd-order polynomial fit to all of the data points.

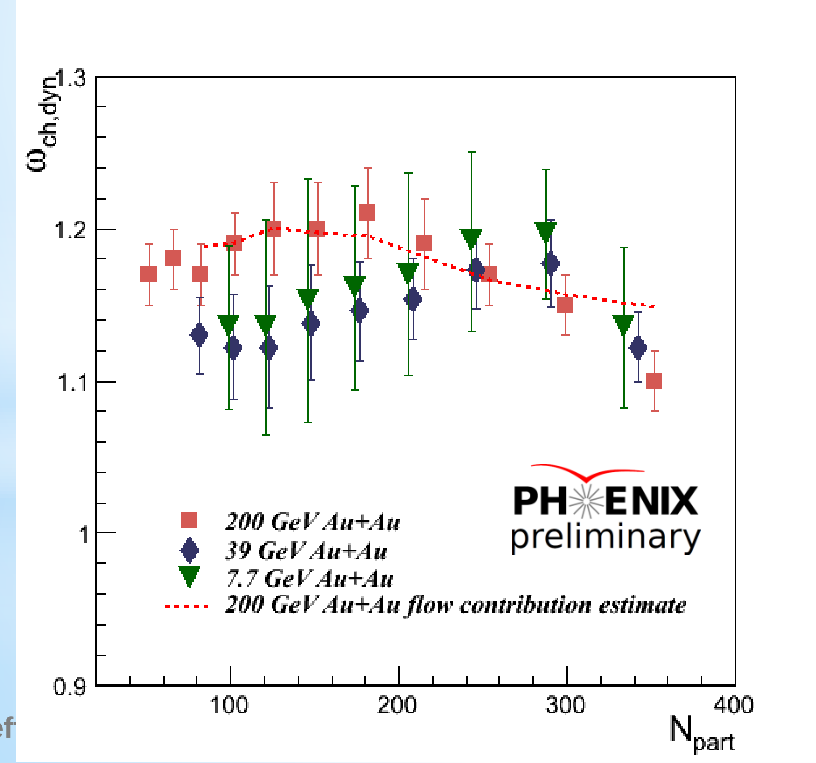
Multiplicity Fluctuations

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

Grand Canonical Ensemble

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

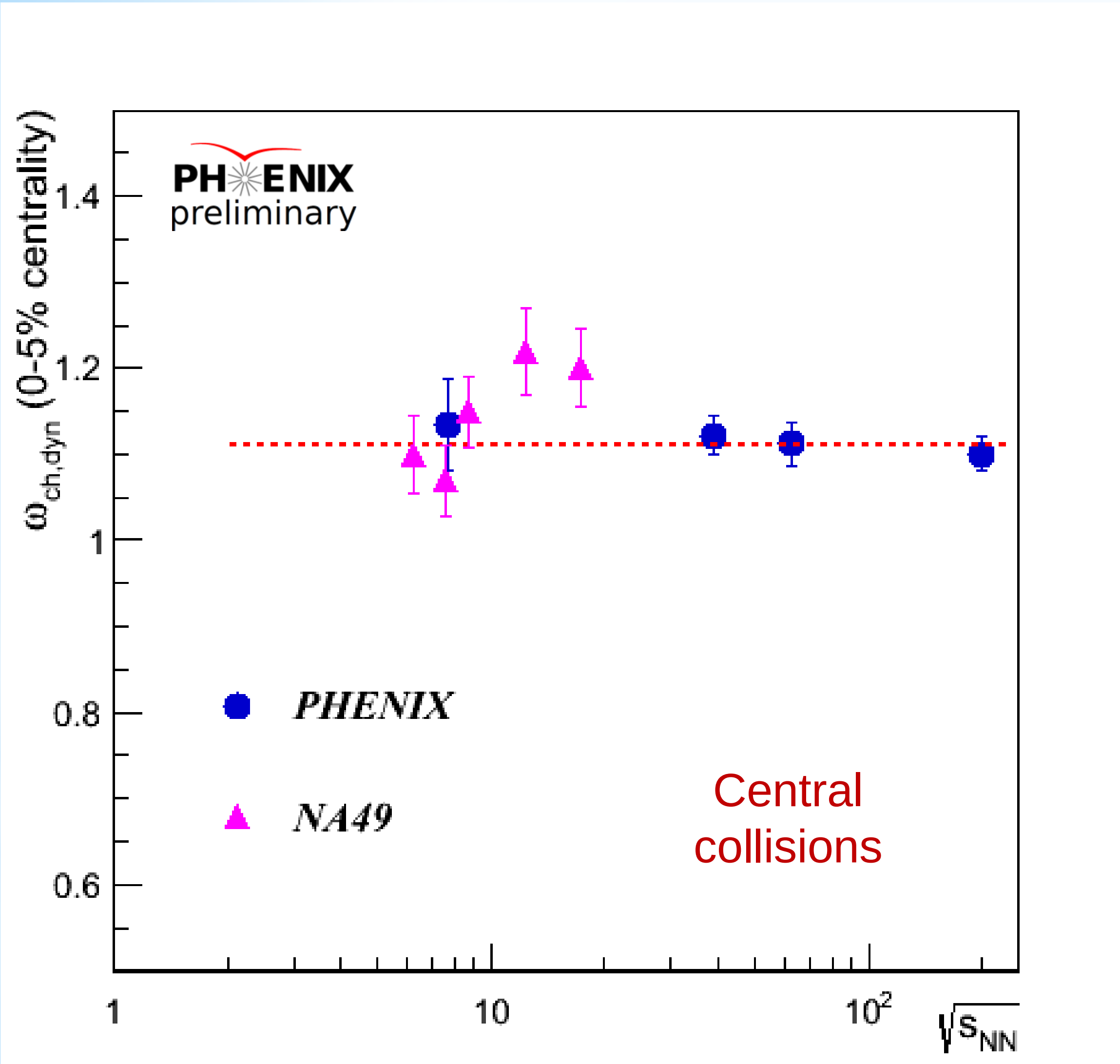
ω_N → "Scaled Variance"



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 yet been observed.

Stay tuned for new results at 14.6, 19.6 and 27 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: $\kappa = \langle (N-\langle N\rangle)^4\rangle/\sigma^4-3 \sim \xi^7$

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

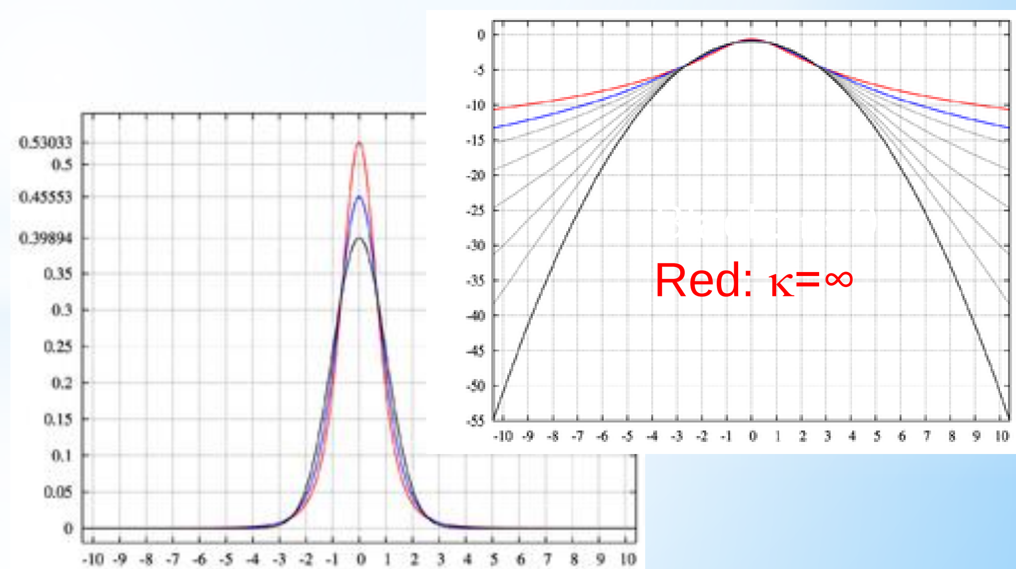
$$S\sigma=\frac{T\chi_B^{(3)}}{\chi_B^{(2)}}$$

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

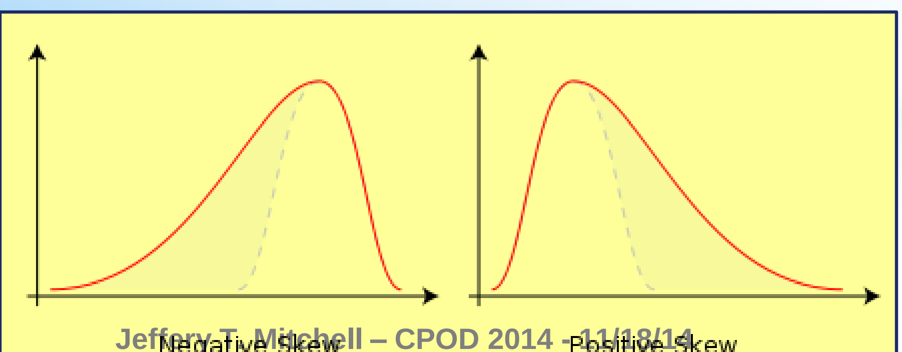
The quantities $S\sigma$ and $\kappa\sigma^2$ are related to the quark number susceptibilities (χ):
$S\sigma \sim \chi^{(3)}/\chi^{(2)}$ and $\kappa\sigma^2 \sim \chi^{(4)}/\chi^{(2)}$.

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.

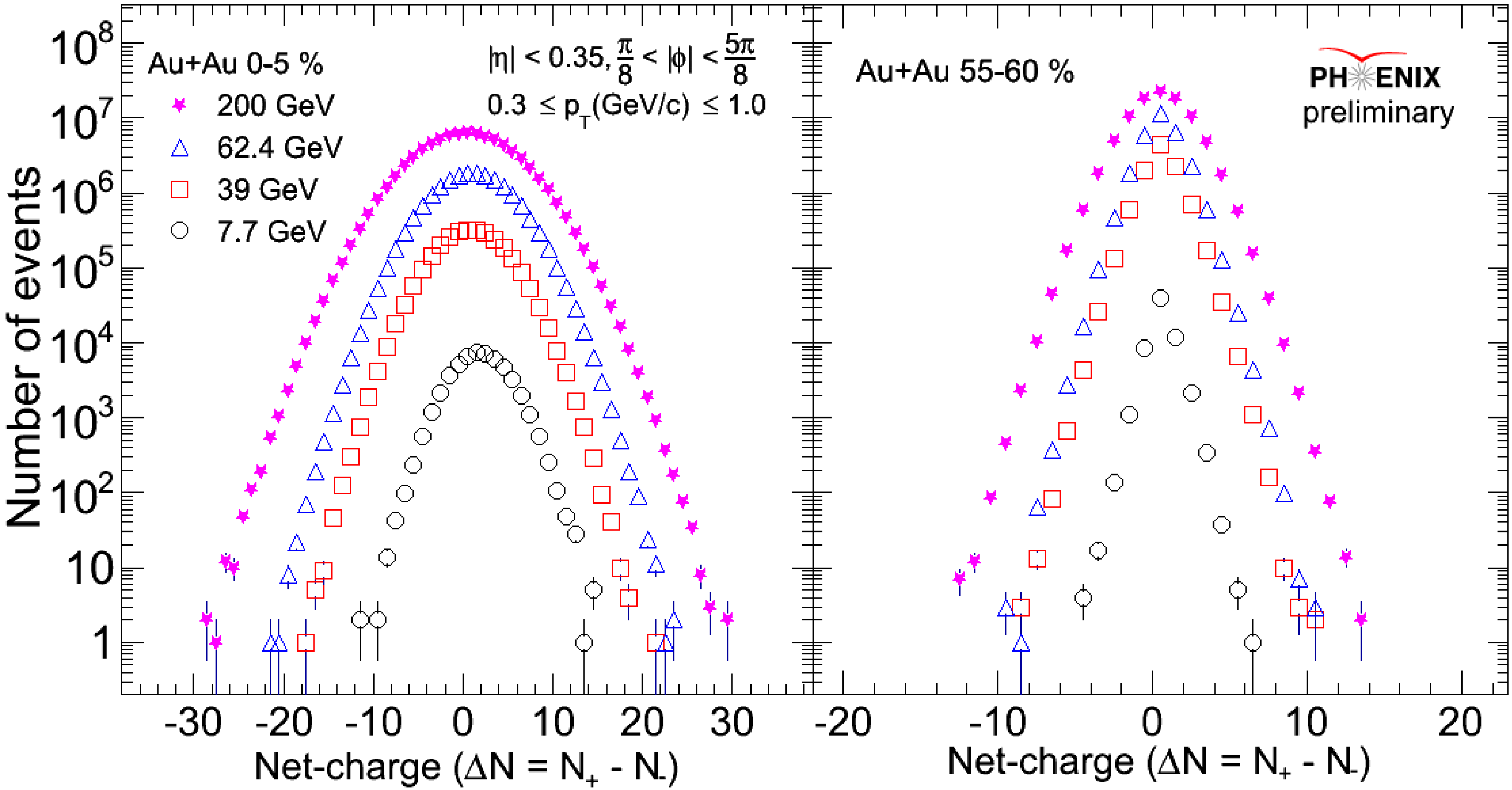
Kurtosis → "bulging"



Skewness

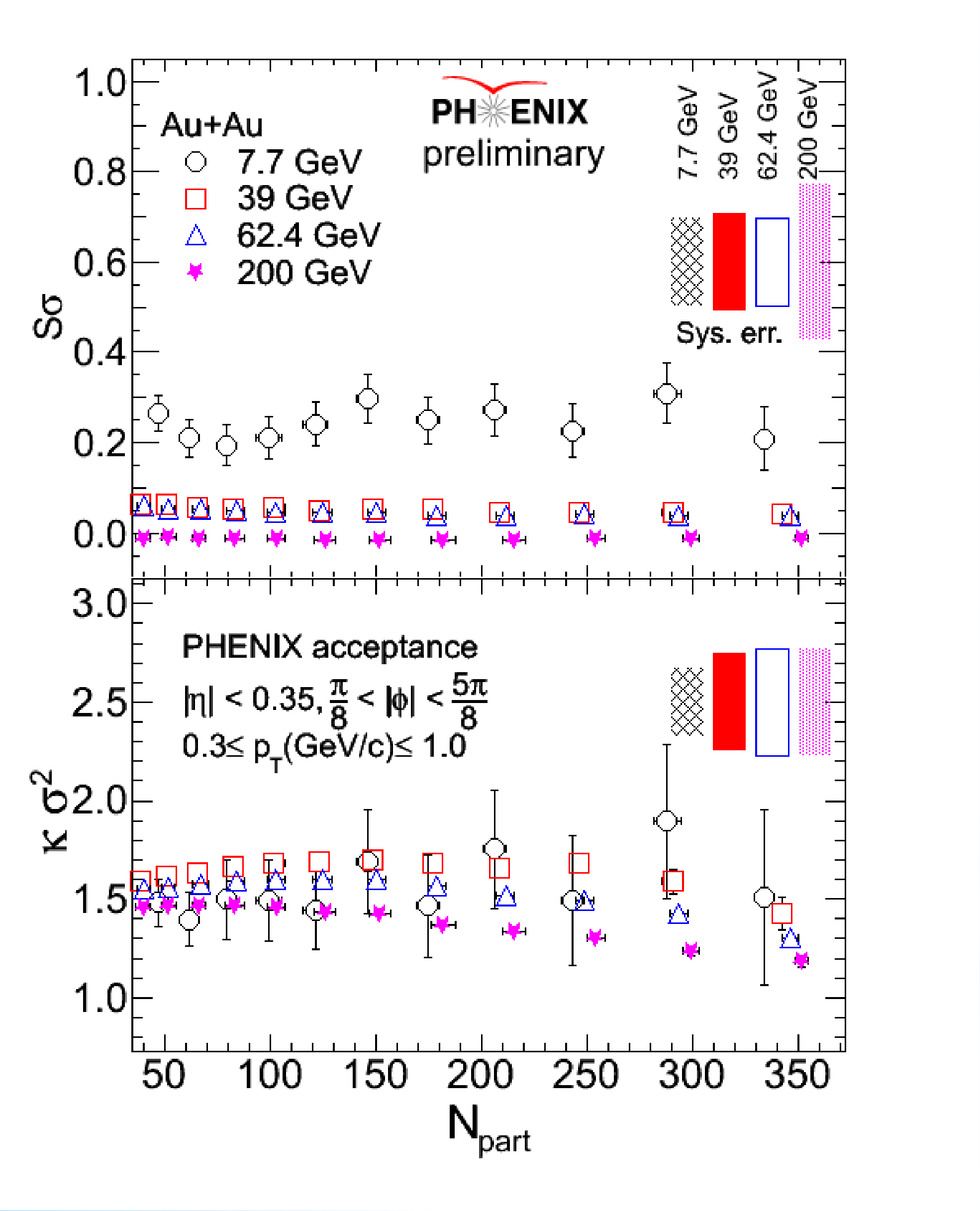


Higher Moments of Net Charge Distributions



All datasets cover several orders of magnitude.

Net Charge $S\sigma$ and $\kappa\sigma^2$ vs. Centrality



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

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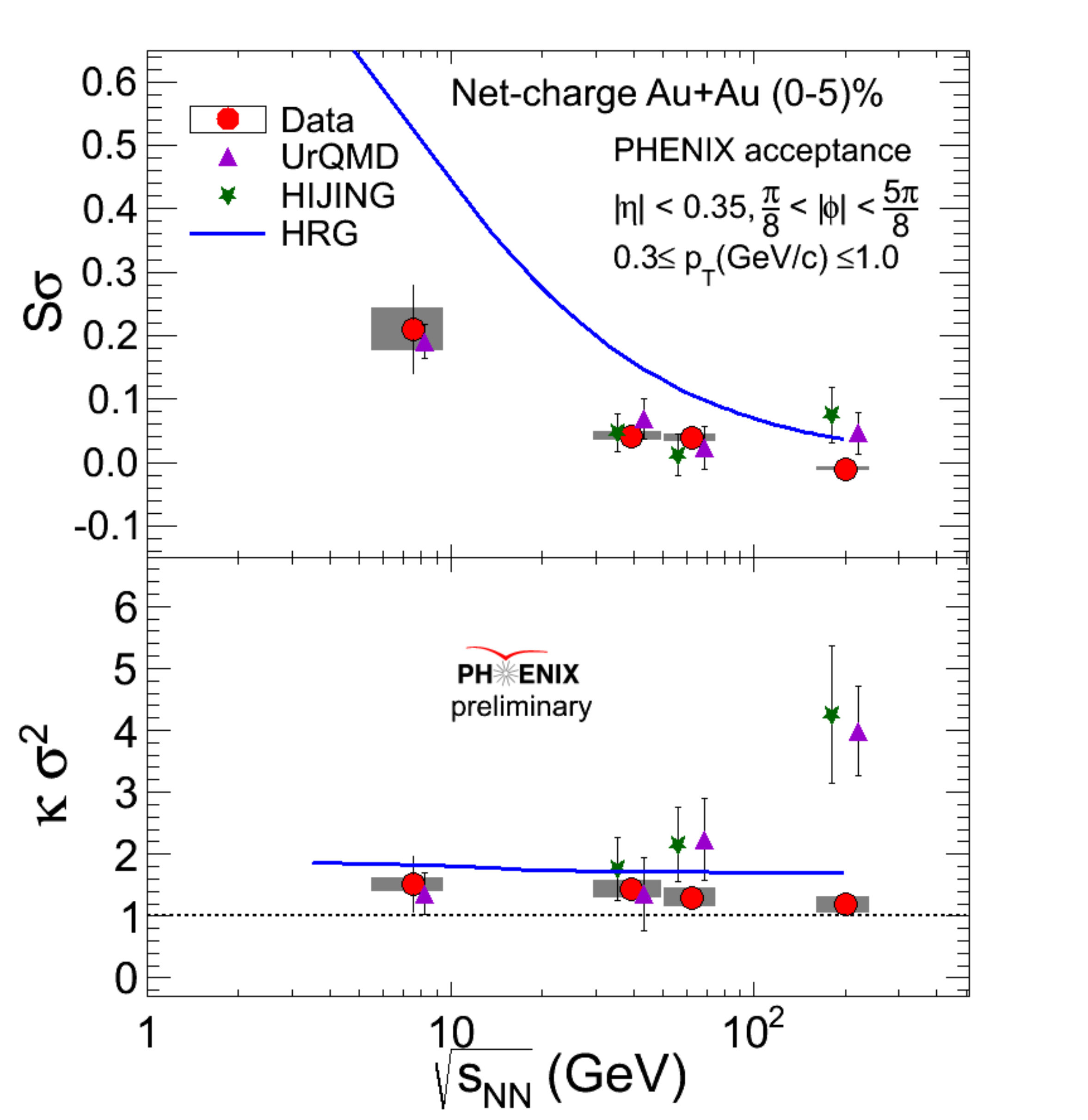
Net Charge Sσ and κσ² Excitation Function



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 14.6, 19.6, and 27 GeV.

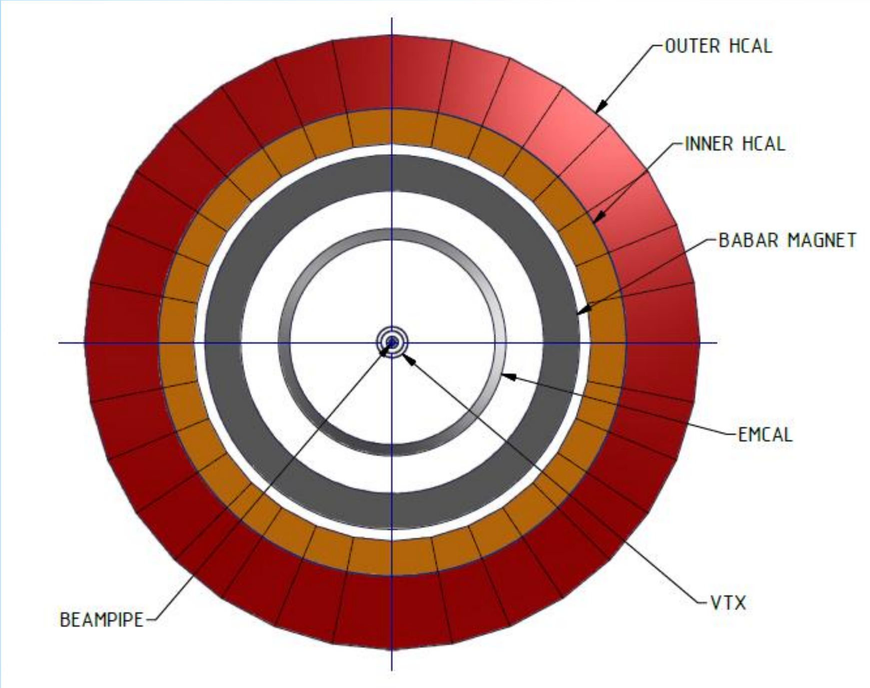
PHENIX and the BES-II Program

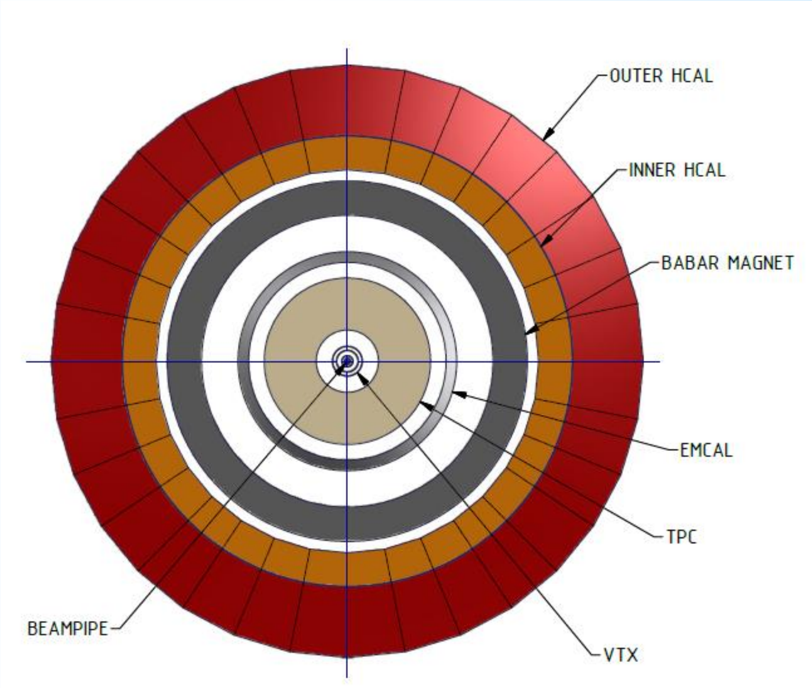
See the PHENIX BES-II white paper at http://www.phenix.bnl.gov/plans.html

The RHIC Beam Energy Scan II program is currently planned to span 2 years of RHIC running from 2018 to 2019. This will utilize the bunched beam electron cooling upgrade of RHIC.

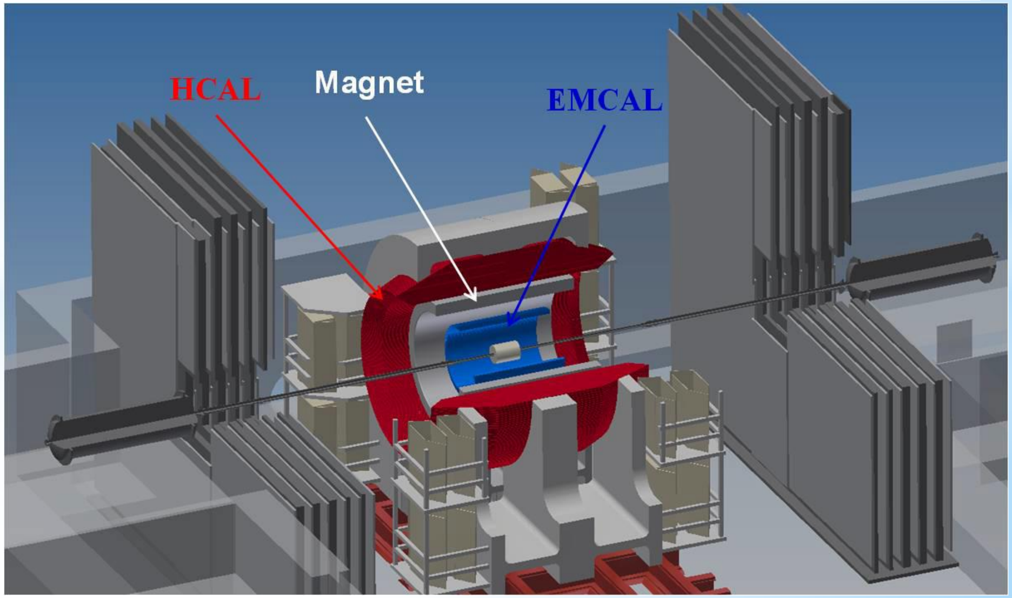
PHENIX plans to complete the program of its current detector after the 2016 run.
After that, PHENIX will be disassembled and sPHENIX will be installed.
This cannot be accomplished during the planned 18-20 month gap between the 2016 run and the BES-II program.
So, PHENIX will not be able to participate in BES-II in 2018.
PHENIX does plan to participate in the BES-II in 2019 with the sPHENIX detector.

PHENIX and the BES-II Program





The sPHENIX detector for 2019 will consist of the HCAL, any available portion of the EMCAL, and either a reconfigured VTX detector (above left) or a micro-TPC (above right).



PHENIX: Initial BES-II Run Request

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time (Days)	Events(M) $\lvert z_{vtx}\rvert < 10$cm	Events(M) $\lvert z_{vtx}\rvert < 30$cm	Events(M) $\lvert z_{vtx}\rvert < 1$ m
Au+Au 11.5	315	45	15	45	112.5
13.0	281	23	17	50	125
9.0	376	41	6	17	42.5
19.6	205	4	33	100	2500
200	20	10	1200	3600	9000
p+p 200		10	3.6 pb^{-1}	1.2 pb^{-1}	9 pb^{-1}

These tables are shown in the PHENIX BES-II white paper at http://www.phenix.bnl.gov/plans.html.

The strategy is to use the shortened time to take data at energies for which PHENIX has no data in order to fill in the gaps in μ_B.

Physics Analysis	N_{evt} ($\times 10^6$)	Required Detectors
Charged Particle Multiplicity	5	VTX and/or TPC
Multiplicity Fluctuations	5	VTX and/or TPC
Charged Particle p_T Spectra	10	VTX and/or TPC
p_T Fluctuations	10	VTX and/or TPC
Moments of Net Charge	10	VTX and/or TPC
Charged Particle Flow	10	VTX and/or TPC
Charged Particle R_{CP}	30	VTX and/or TPC
Di-hadron Correlations	50	VTX and/or TPC
Chiral Magnetic Effect	10	VTX and/or TPC
Transverse Energy	5	EMCal
Neutral Pion Spectra	10	EMCal
Neutral Pion R_{CP}	100	EMCal
Identified Particle Spectra	10	TPC
Identified Particle Ratios	10	TPC
Identified Particle Flow	30	TPC
Identified Particle HBT	50	TPC
Moments of Net Protons	100	TPC
Particle Ratio Fluctuations (K/π,$\overline{p}/p$)	100	TPC

sPHENIX BES-II $\kappa\sigma^2$ Error Estimates

Species	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time (Days)	Events(M) $\lvert z_{vtx}\rvert < 10$cm	Events(M) $\lvert z_{vtx}\rvert < 30$cm	Events(M) $\lvert z_{vtx}\rvert < 1$ m
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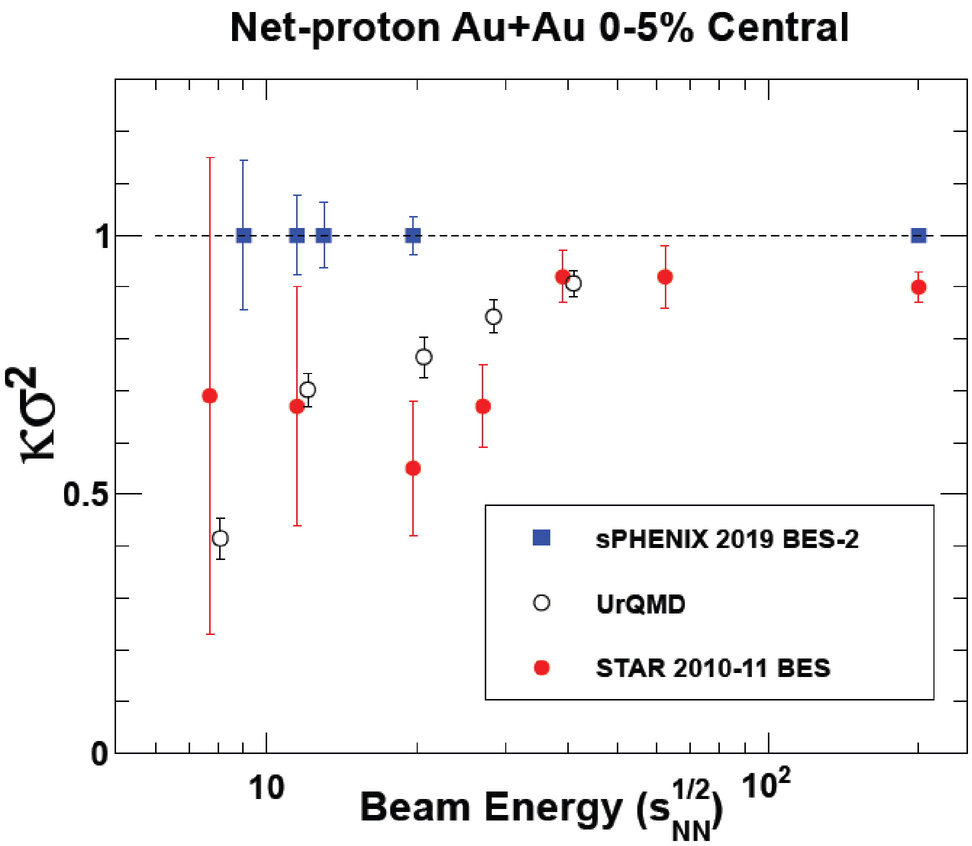
p+p	200		10	1.2 pb^{-1}	3.6 pb^{-1}	9 pb^{-1}



The net proton kurtosis errors follow the formulae in Luo, J. Phys. G39, 025008.

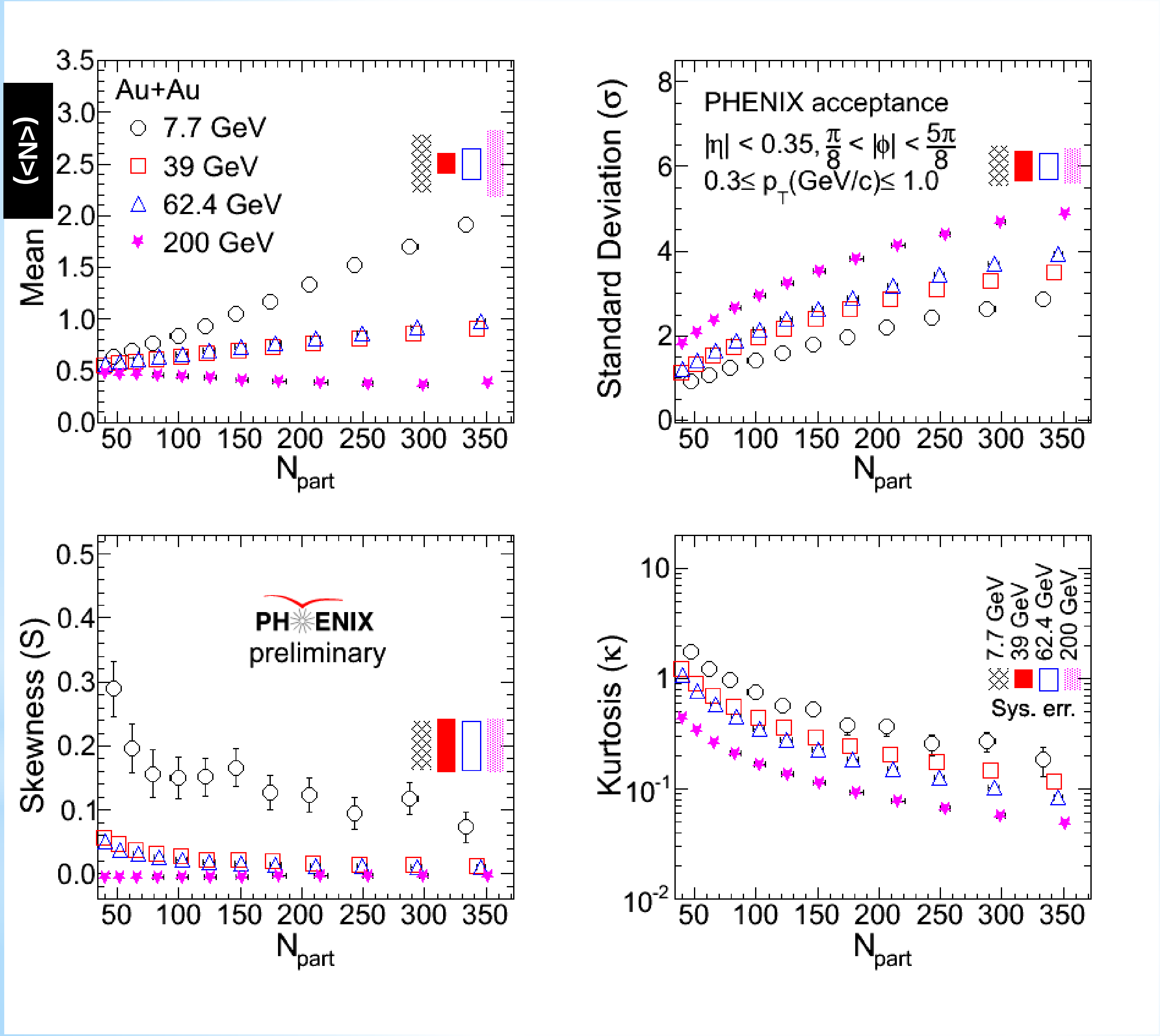
sPHENIX should be able to significantly improve on the STAR BES-I errors for this measurement.

Summary

- The first results from the 14.6 GeV Au+Au dataset are shown.
- Bjorken energy density scales exponentially from 7.7 GeV to 2.76 TeV.
- The multiplicity and transverse energy data can best be described by participant nucleon scaling below 39 GeV.
- The multiplicity and transverse energy data can best be described by participant quark scaling above 39 GeV.
- No significant excess in multiplicity fluctuations or in moments of the net charge have been seen, but data at more energies will be available soon.
- PHENIX plans to participate in the second half of the BES-II program using the sPHENIX detector.

*Auxiliary Slides

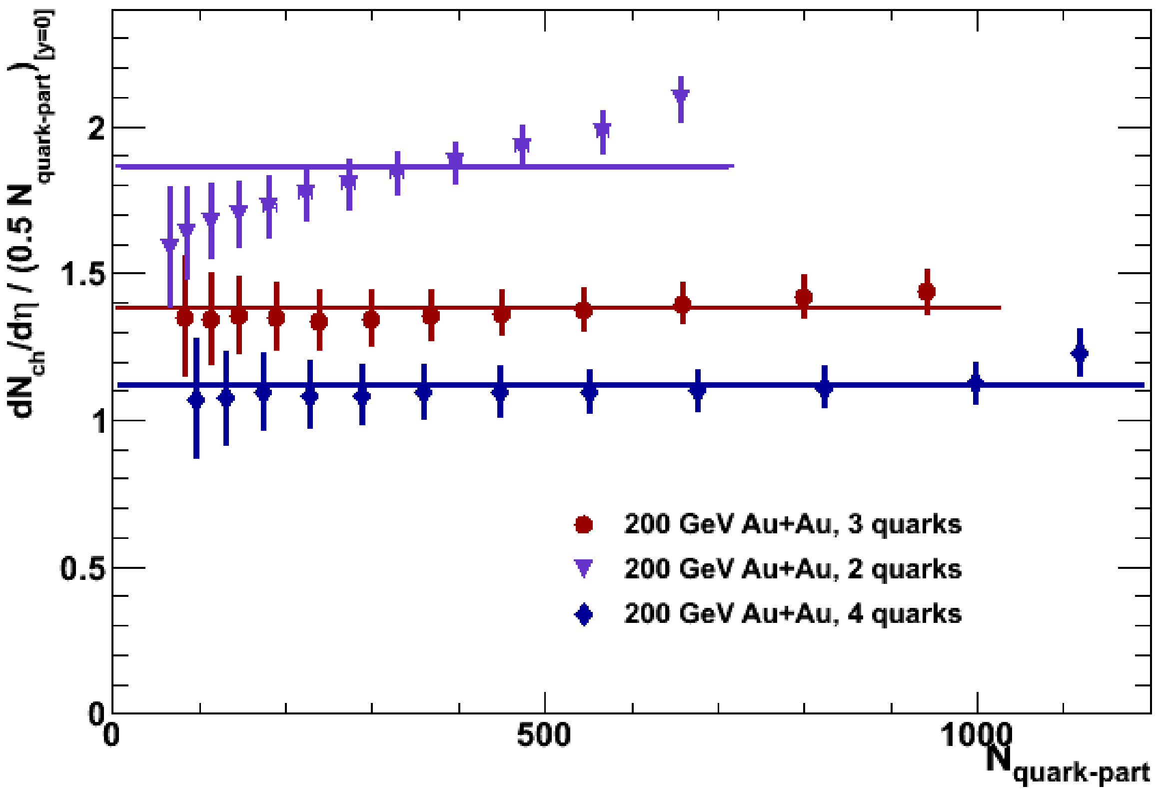
Net Charge Moments vs. Centrality



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

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

Participant Quark Scaling: Varying the degrees of freedom



Calculated N_{qp} by distributing 2, 3, and 4 quarks in the modified Glauber model.

For each case, the quark-quark inelastic cross section was adjusted to reproduce the nucleon-nucleon cross section.

The scaling breaks down for the 2 quark case. However the 4 quark case scales well with the exception of the most central point.