Beam Energy Scan Results

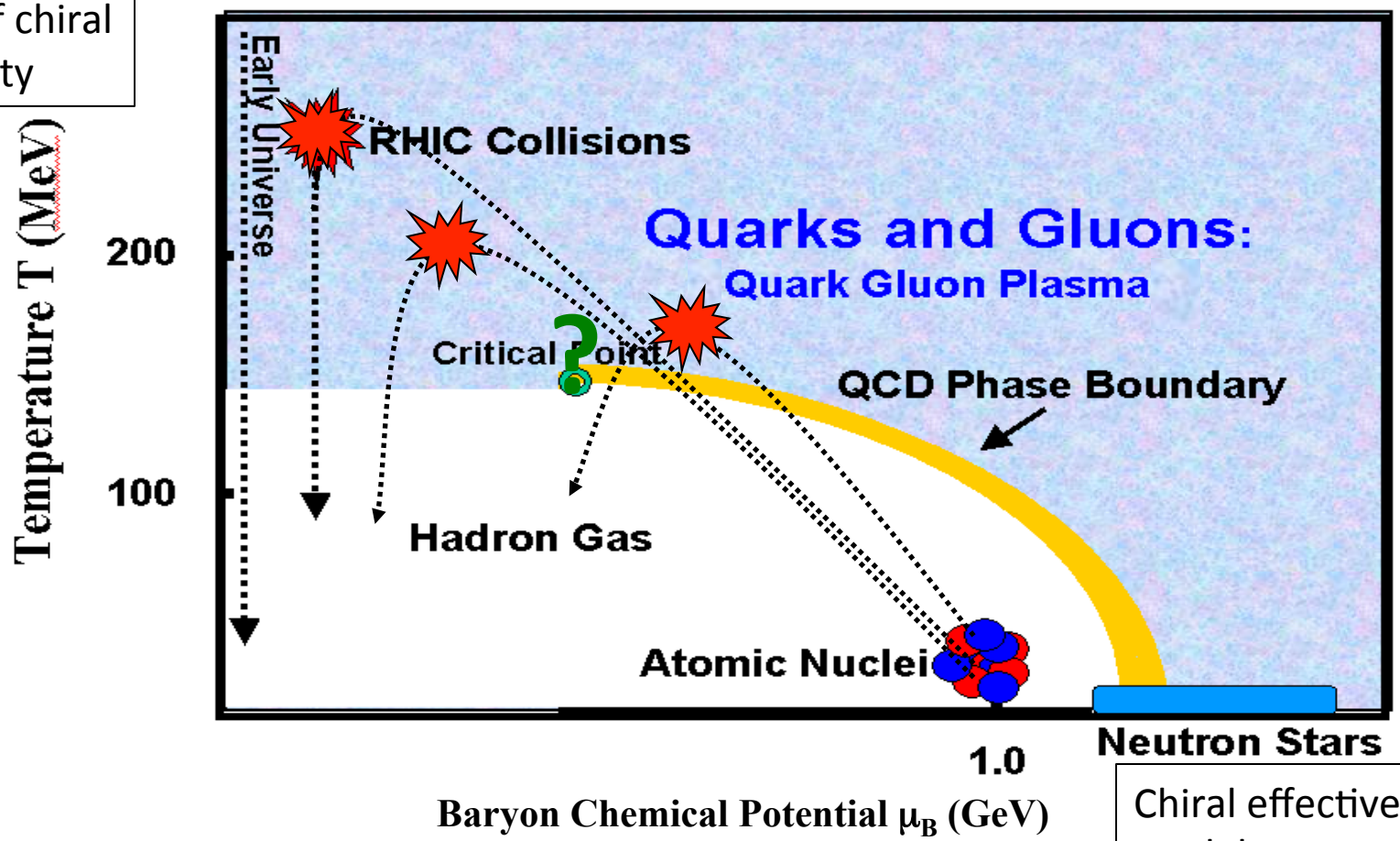
Ron Soltz for PHENIX

Lawrence Livermore National Laboratory

With help from Jeff Mitchell, Mike T., Alex Mwai, Roy Lacy, & Ajit

BES Motivation = CEP

LQCD EoS and behavior of chiral susceptibility



Chiral effective models

μ_B>0 calculations difficult, data needed

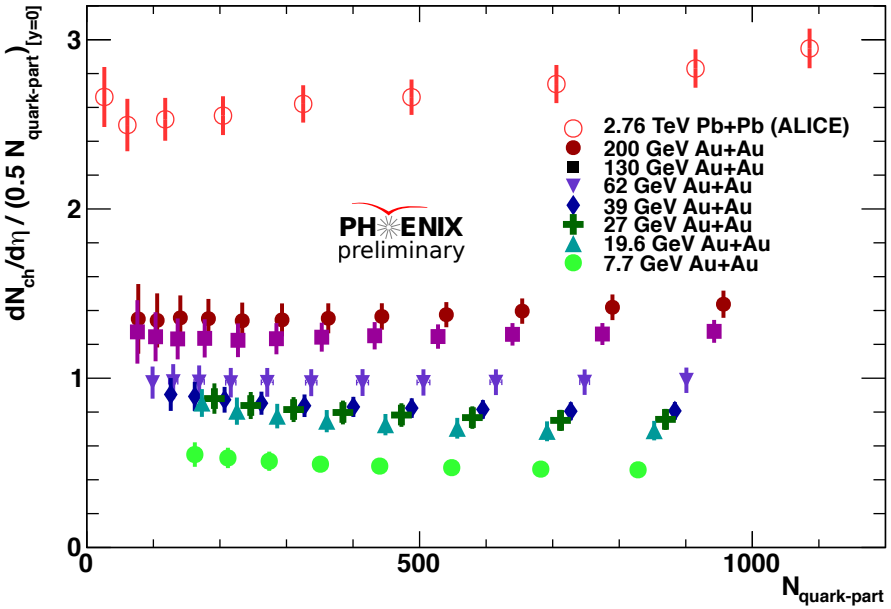
PHENIX Data and Measurements

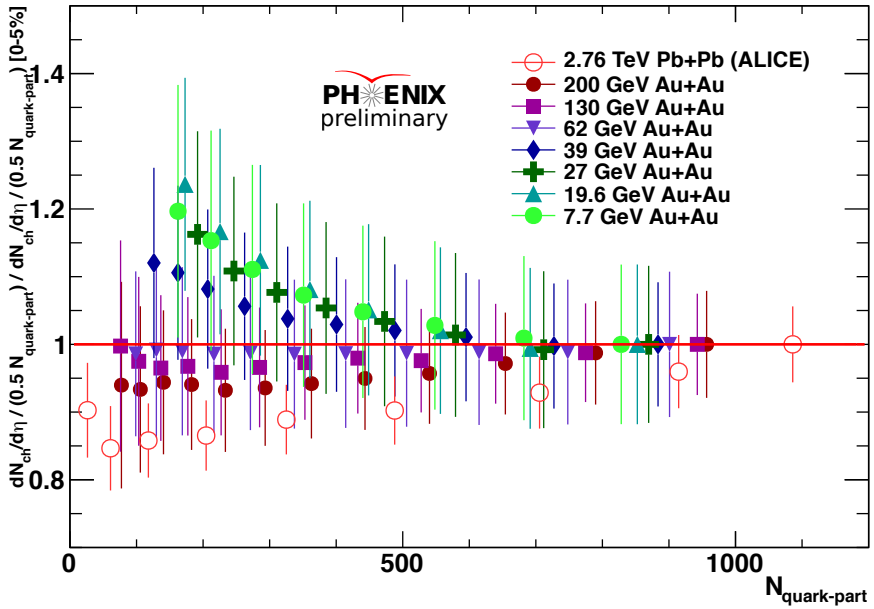
- Published
  - π^0 suppression
    - PRL.109.152301
  - J/psi
    - PRC.86.064901
- This talk
  - Multiplicity
  - HBT Radii
  - Fluctuations

RHIC Run	Year	Species	Energy	Ldt
Run-1	2000	Au+Au	130 GeV	1 μb-1
Run-2	2001-2	Au+Au	200 GeV	24 μb-1
Run-2		Au+Au	19 GeV	0.4 μb-1
		p+p	200 Gev	150 nb-1
Run-3	2002/3	d+Au	200 GeV	2.74 nb-1
		p+p	200 GeV	0.35 nb-1
Run-4	2003/4	Au+Au	200 GeV	241 μb-1
		Au+Au	62.4 GeV	9 μb-1
Run-5	2005	Cu+Cu	200 GeV	3 nb-1
		Cu+Cu	62.4 GeV	0.19 nb-1
		Cu+Cu	22.4 GeV	2.7 μb-1
Run-6	2006	p+p	200 GeV	10.7 pb-1
		p+p	62.4 GeV	100 nb-1
Run-7	2007	Au+Au	200 GeV	813 μb-1
Run-8	2007/2008	d+Au	200 GeV	80 nb-1
		p+p	200 GeV	5.2 pb-1
		Au+Au	9.2 GeV	
Run-9	2009	p+p	200 GeV	16 pb-1
		p+p	500 GeV	14 pb-1
Run-10	2010	Au+Au	200 GeV	1.3 nb-1
		Au+Au	62.4 GeV	100 μb-1
		Au+Au	39 GeV	40 μb-1
		Au+Au	7.7 GeV	260 mb-1
Run-11	2011	p+p	500 GeV	27 pb-1
		Au+Au	200 GeV	915 μb-1
		Au+Au	27 GeV	5.2 μb-1
		Au+Au	19.6 GeV	13.7 M events
Run-12	2012	p+p	200 GeV	9.2 pb-1
		p+p	510 GeV	30 pb-1
		U+U	193 GeV	171 μb-1
		Cu+Au	200 GeV	4.96 nb-1
Run-13	2013	p+p	510 GeV	156 pb-1
Run-14	2014	Au+Au	15 GeV	44.2 μb-1
		Au+Au	200 GeV	>1.5 nb-1

Participant-quark scaling

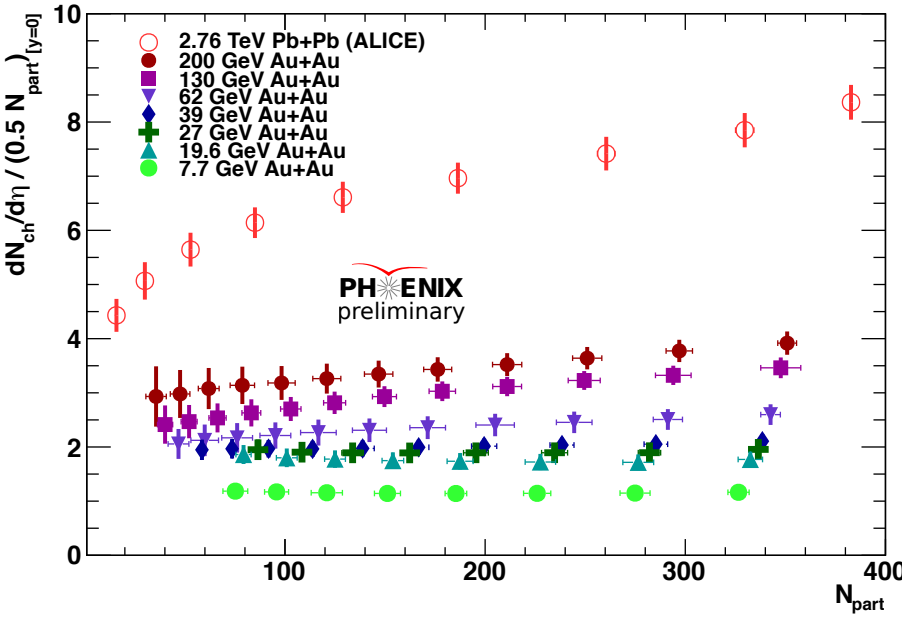
10.1103/PhysRevC.89.044905

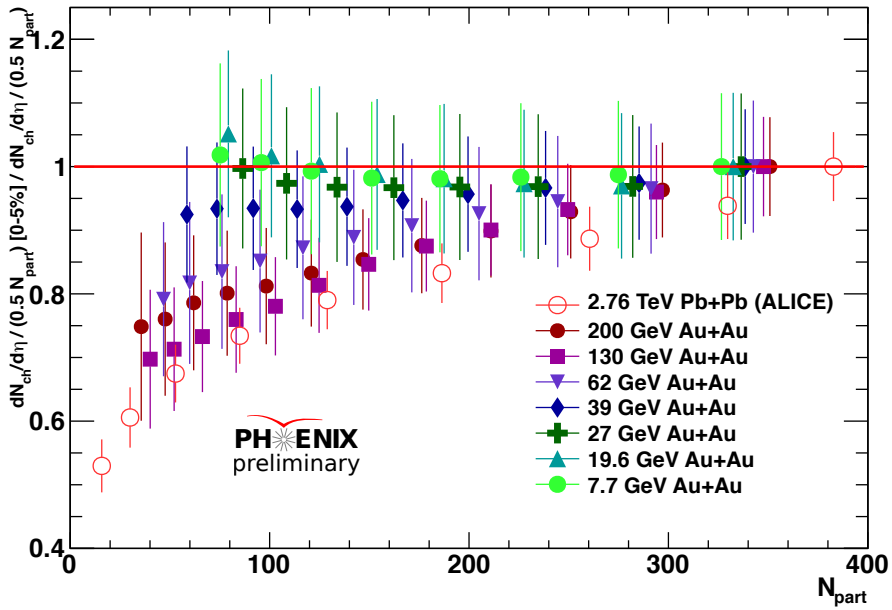




Participant quark scaling works well $\sqrt{s_{NN}}$= 62-200 GeV

Nucleon Scaling





Participant nucleon scaling works well $\sqrt{s_{NN}}$ <= 27 GeV

Scaling observations

- Change in production dynamics may have implications for CEP signatures
- Smooth change from nucleon to quark scaling and beyond ... ?

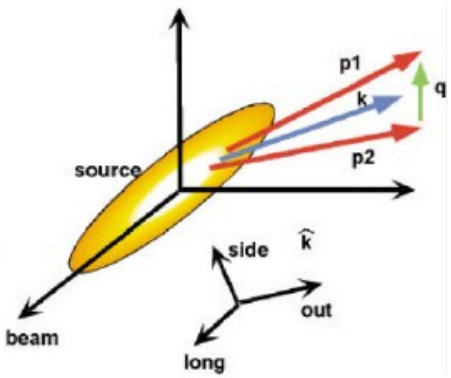
We have two very different pictures of protons, in the lab frame (quark model) and the infinite momentum frame (parton model).

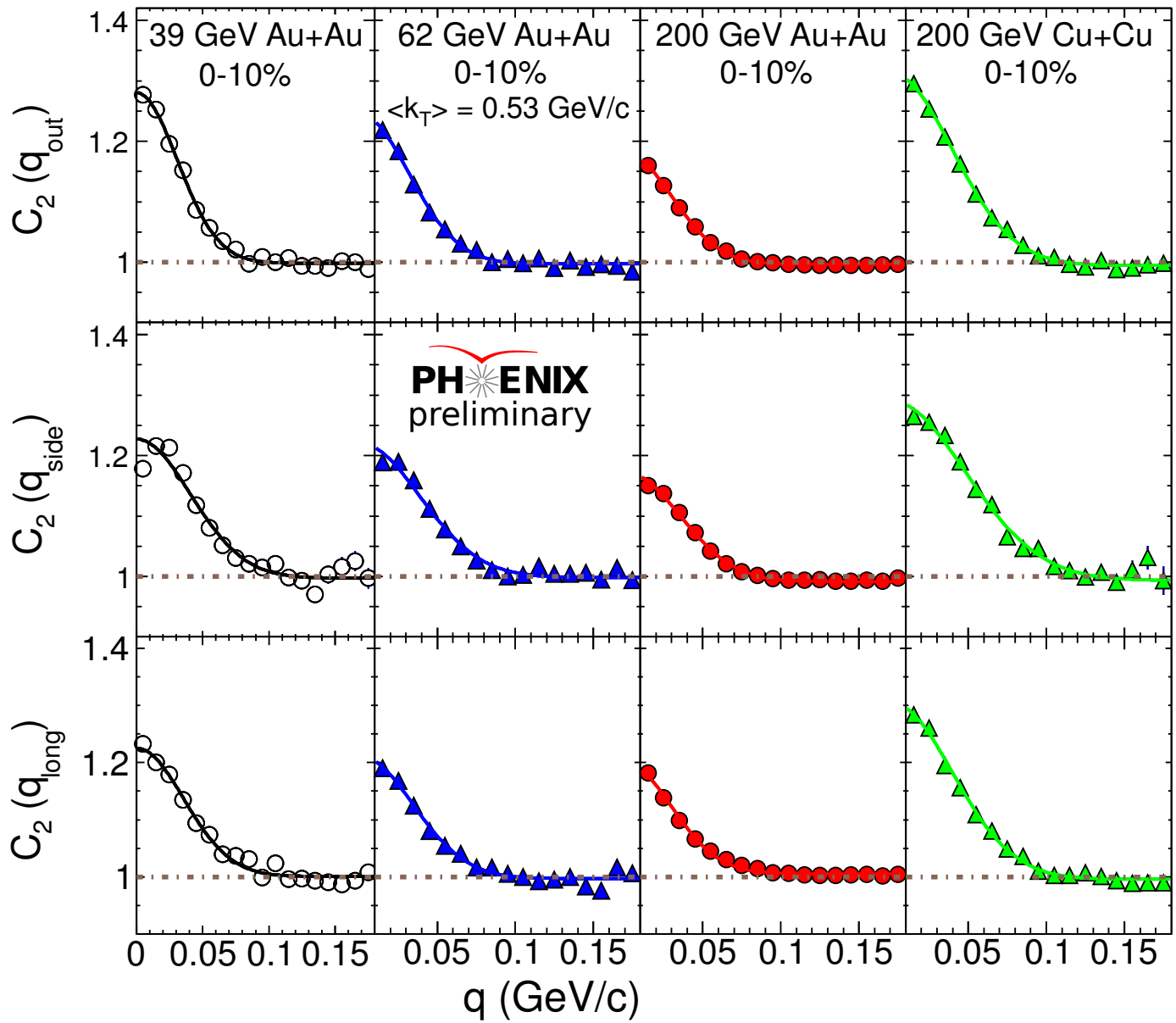
- *How does one proton manage to become the other?*
- *Are there intermediate pictures?*

F. Wilczek, QM 2014

HBT BES Results

- 3D Gaussian fits
- Bertsch-Pratt coord.
- LCMS ($p_{1z}+p_{2z}=0$)
- Coulomb Corrected





Ye Olde HBT formulae

- Formerly used to understand dynamics

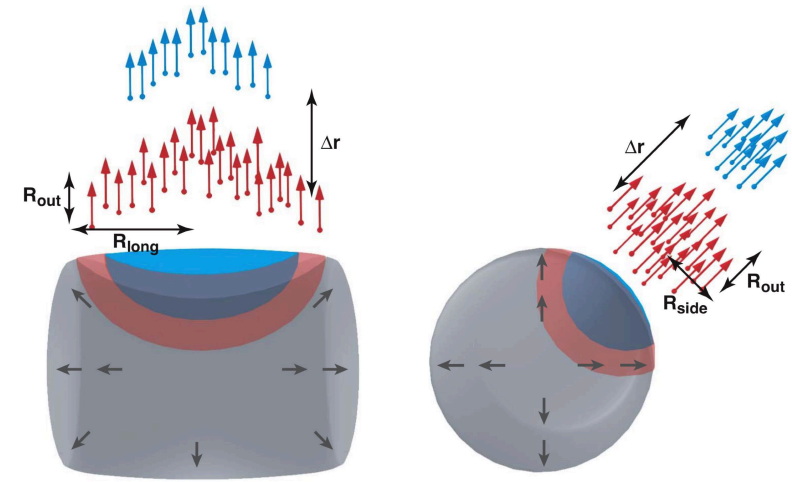
  before era of multi-stage models, assumptions too restrictive

Chapman, Scotto, Heinz, PRL.74.4400 (95)

$$R_{side}^2 = \frac{R_{geo}^2}{1+\frac{m_T}{T}\beta_T^2}$$

$$R_{out}^2 = \frac{R_{geo}^2}{1+\frac{m_T}{T}\beta_T^2} + \underline{\beta_T^2(\Delta\tau)^2}$$

$$R_{long}^2 \approx \tau^2 \frac{T}{m_T}\frac{K_2}{K_1}$$



$$R_i = a + \frac{b}{\sqrt{m_T}}$$

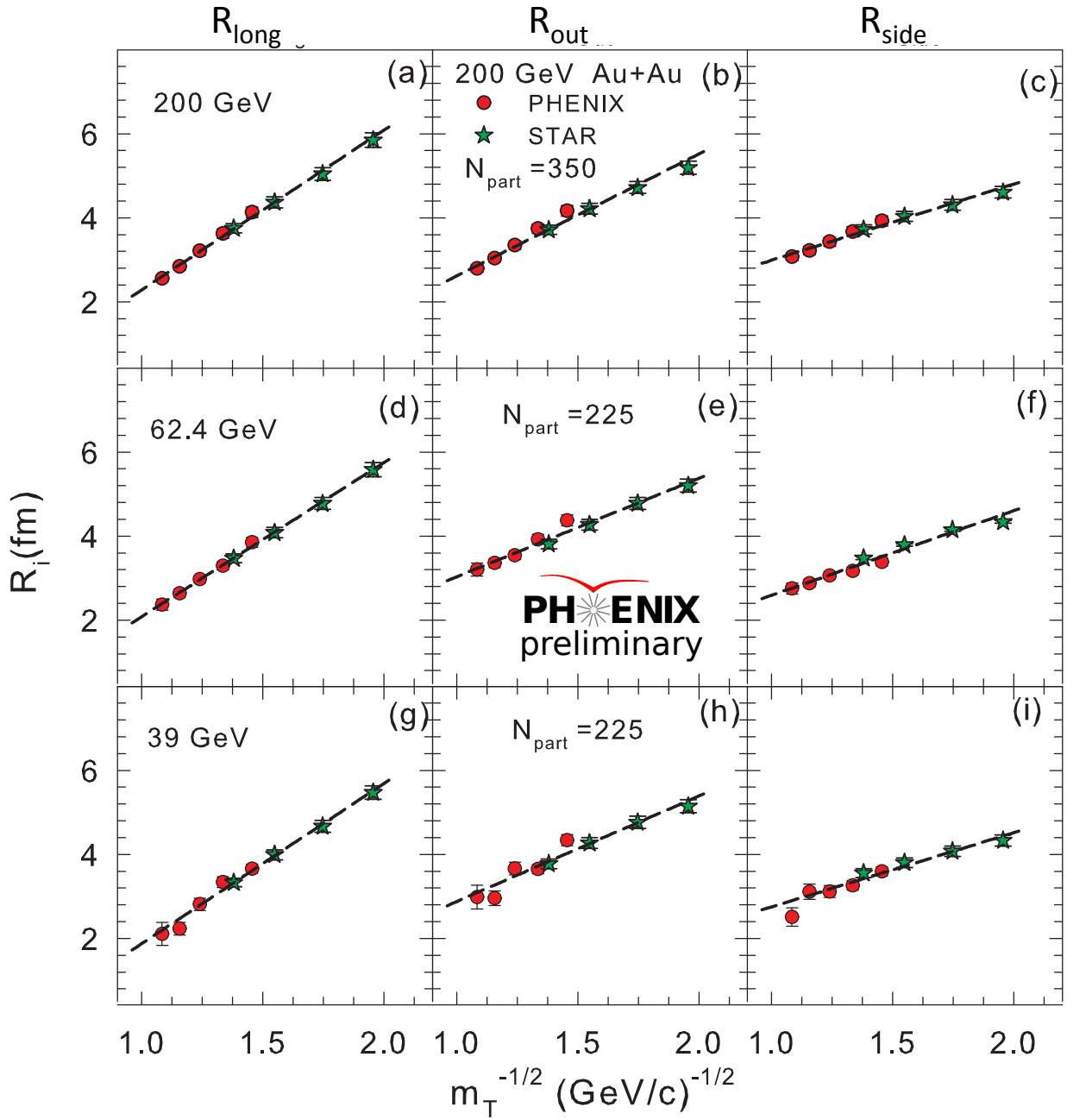
empirical fit just as effective

Makhlin, Sinyukov, ZPC.39.69 (88) (R^2_{out}-R^2_{side}) sensitive to emission duration

Anticipate extended emission duration with 1st order transition

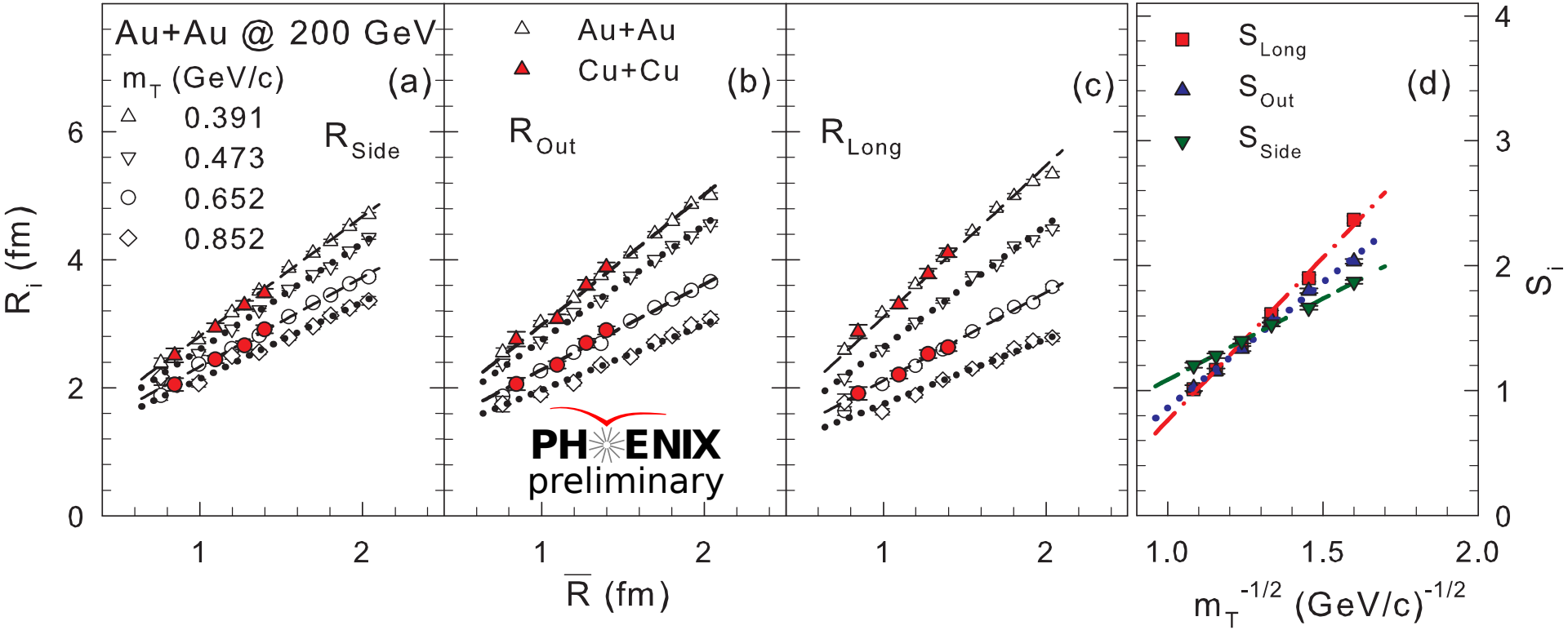
m_T scaling

- PHENIX and STAR consistent arxiv:1403.4972
- all radii linear
  - $R_i = a + b/\sqrt{m_T}$
- Used to interpolate to common m_T



Geometric Scaling

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

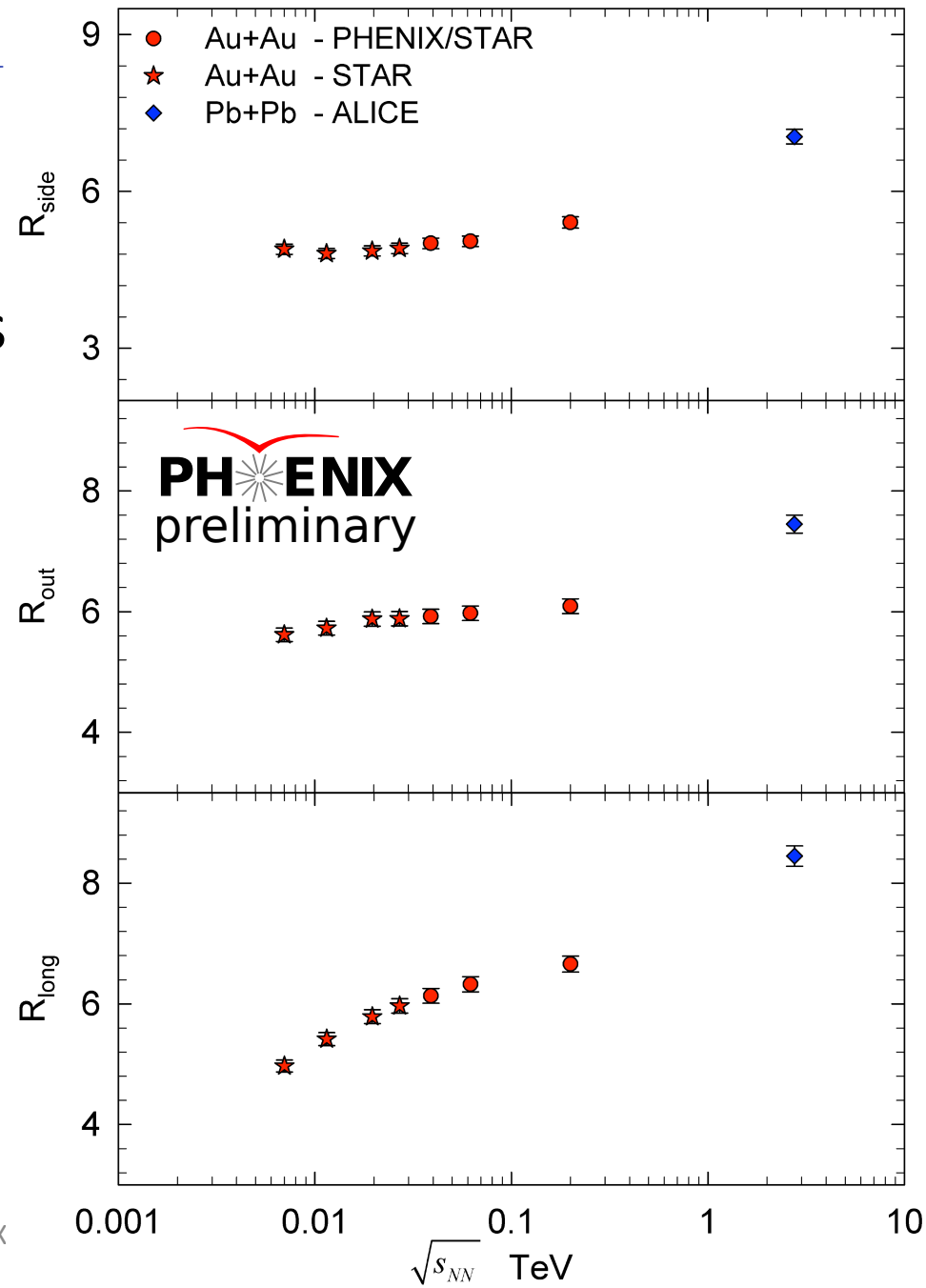


All radii linear in $\overline{R}$, all slopes linear in $1/\sqrt{m_T}$

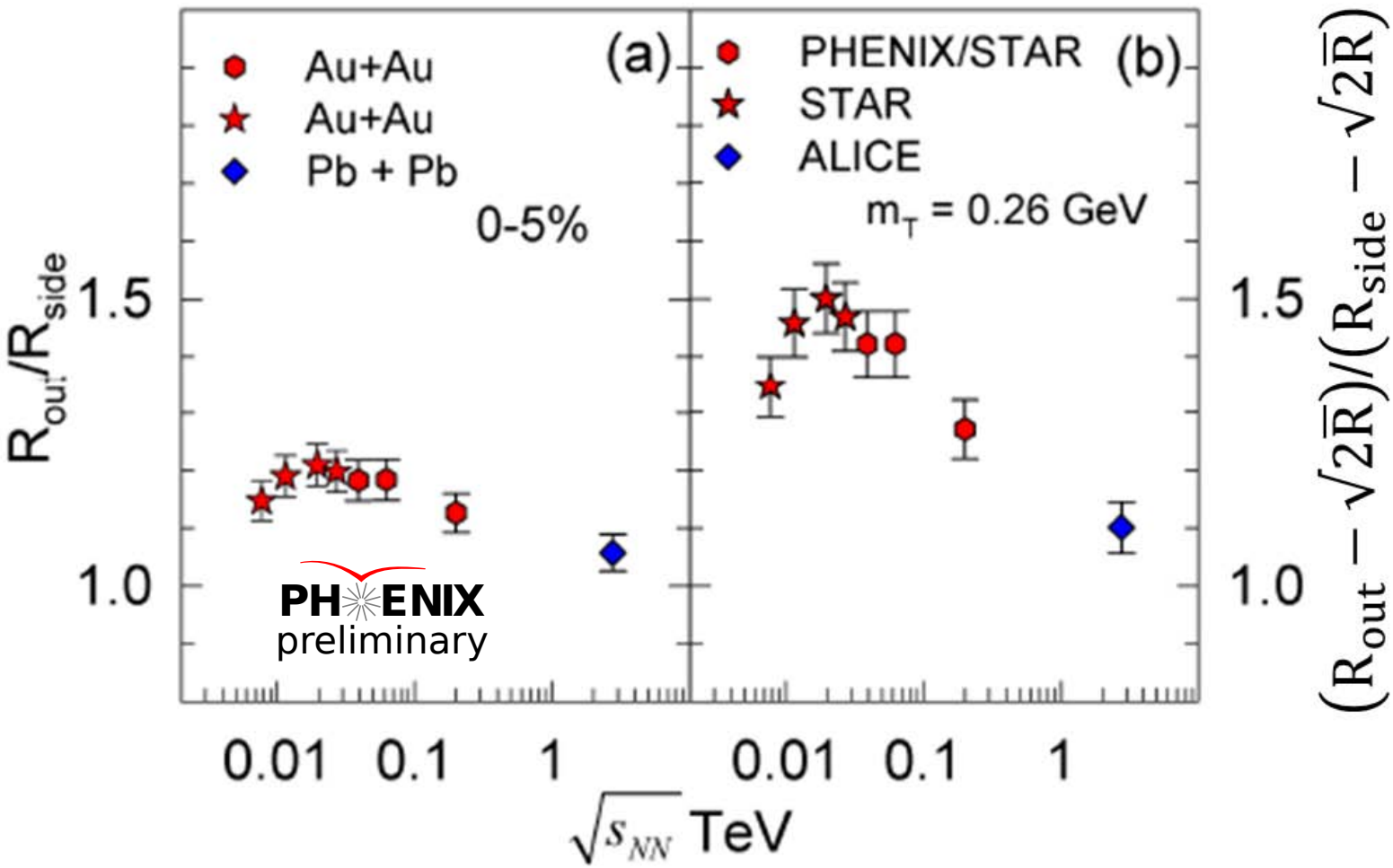
For 0-5% central $\overline{R} = \sigma_x/\sqrt{2} = \sigma_y/\sqrt{2}$

HBT radii vs. $\sqrt{s_{NN}}$

- PHENIX,STAR,ALICE data
- m_T=0.26 GeV interpolations
- R_{long} decreasing with $\sqrt{s_{NN}}$
- R_{out},R_{long} curvature differ from R_{side}
- construct ratios and differences



Measures of emission duration

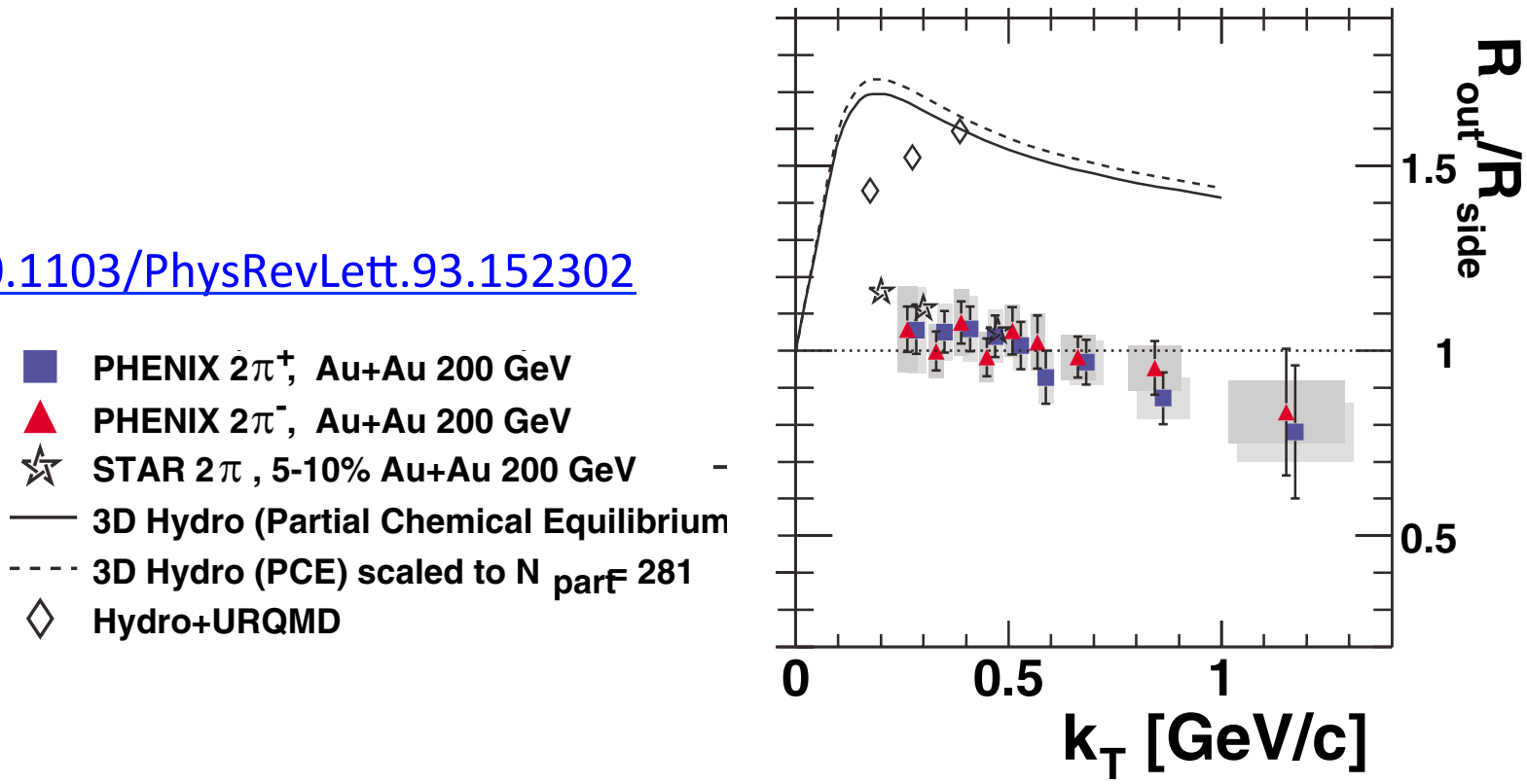


- Non-monotonicity in R_{out}/R_{side}
- Subtract $\sqrt{2}\bar{R}$ to (over) estimate expansion

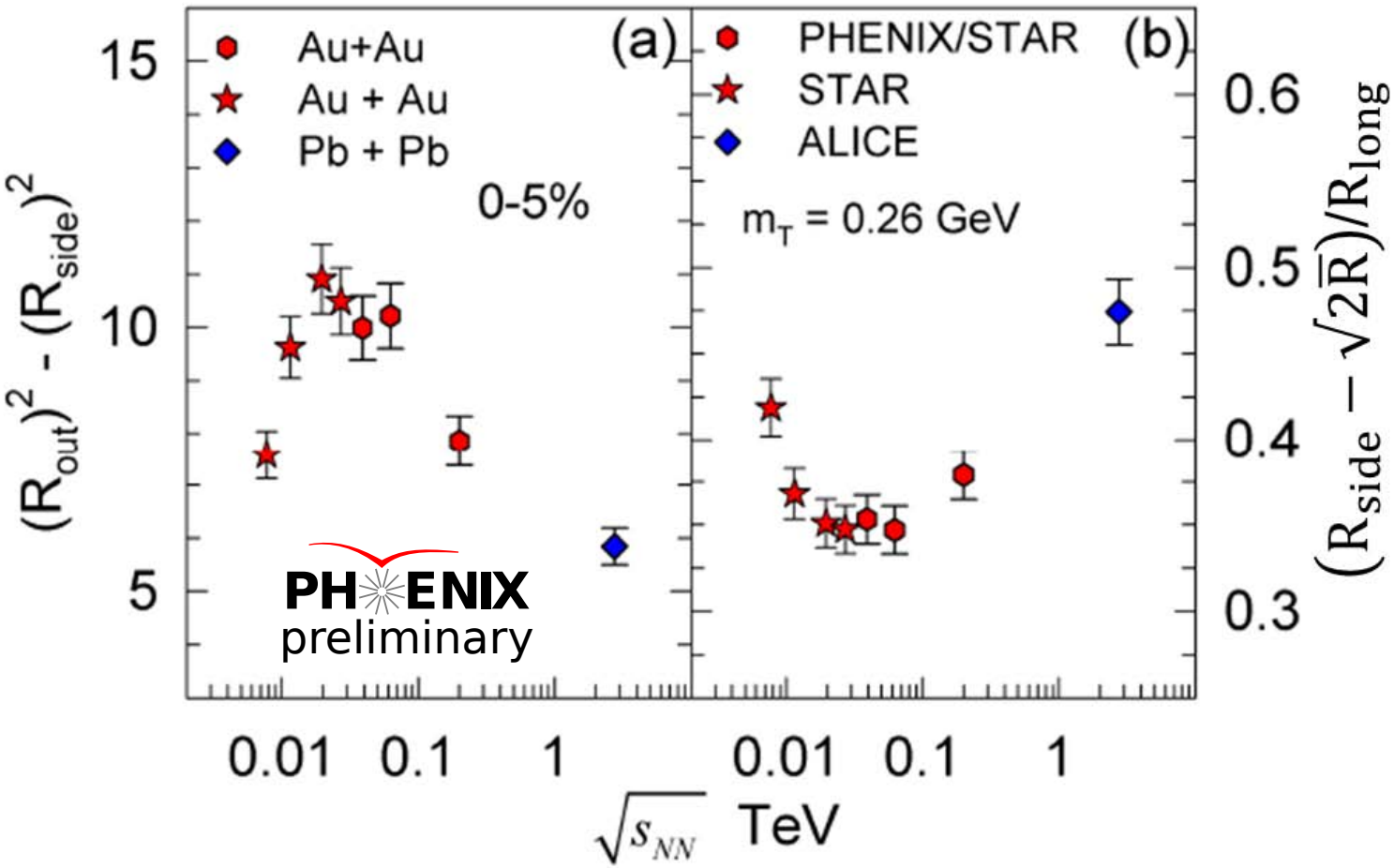
The R_{out}- R_{side} story

- R_{out}/R_{side} ratio suggested Rischke and Gyulassy (96)
- adopted by RHIC/SPS experiments partly to avoid negative R^2_{out}-R^2_{side} for k_T>0.5 GeV/c

10.1103/PhysRevLett.93.152302



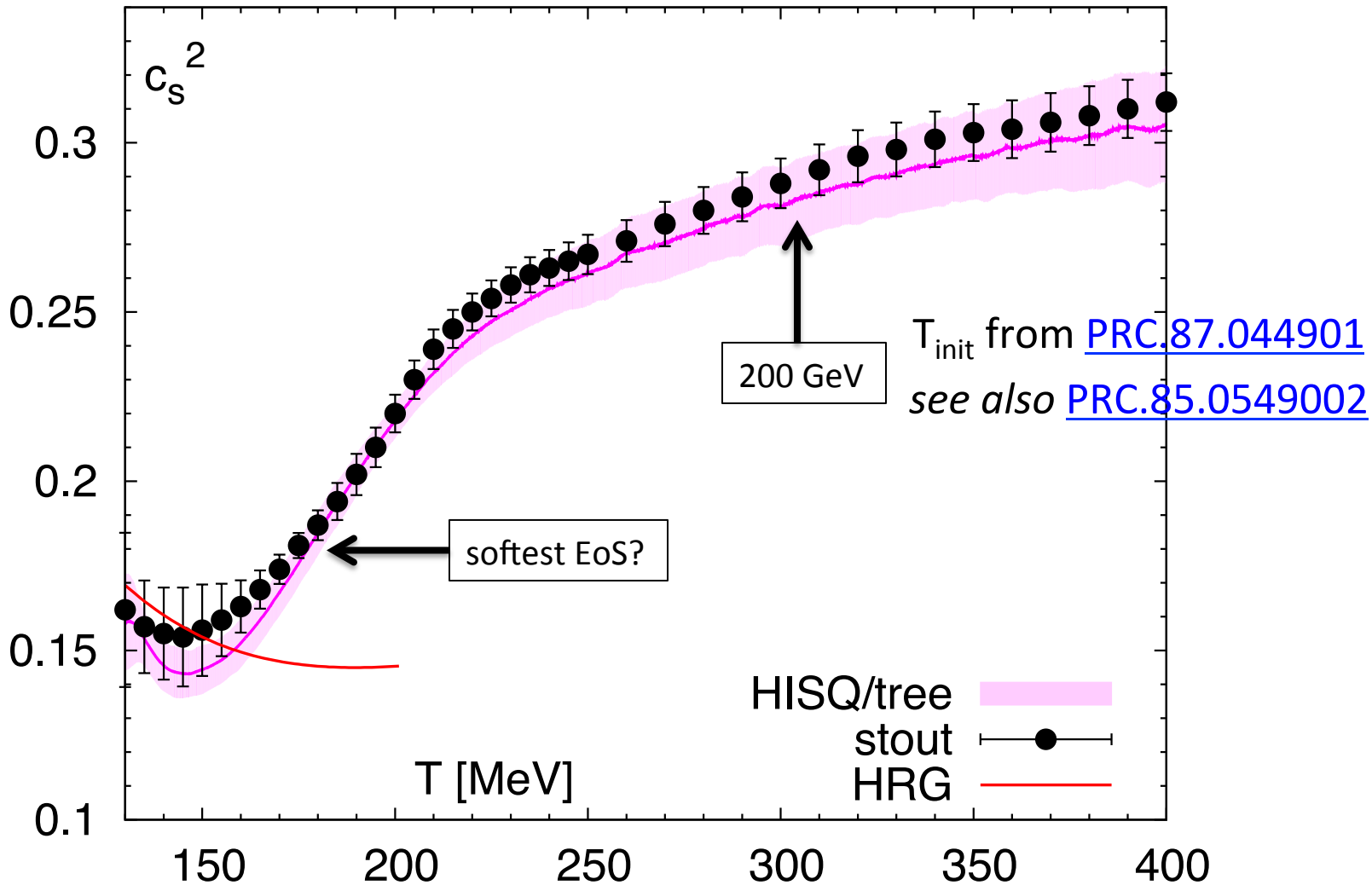
Emission duration and expansion/lifetime



- Non-monotonicity magnified with $(R_{out})^2 - (R_{side})^2$
- R_{side}/R_{long} indicative of expansion/lifetime

The EoS, the softest point, and $T_{initial}$

A. Bazavov, Quark Matter 2014



T_{init} from PRC.87.044901

see also PRC.85.0549002

Fluctuations in (s)PHENIX

- Sensitive to correlation length, ξ [LQCD]

Variance : $\sigma^2 = \langle(\Delta\mathcal{N})^2\rangle \sim \xi^2$ $[\chi^{(2)}/\chi^{(1)}]$

Skewness: $S\sigma = \langle(\Delta\mathcal{N})^3\rangle/\sigma^2 \sim \xi^{2.5}$ $[\chi^{(3)}/\chi^{(2)}]$

Kurtosis: $K\sigma^2 = \langle(\Delta\mathcal{N})^4\rangle/\sigma^2 - 3\sigma^2 \sim \xi^5$ $[\chi^{(4)}/\chi^{(2)}]$

- Quark susc., χ, LQCD calculate directly (μ=0)
  - for μ>0, higher order terms needed
- sPHENIX in 2019 (timing is of the essence)

  strong interest in BES-2 physics

  large acceptance detectors: VTX, Si, TPC

Statistics and Error Scaling

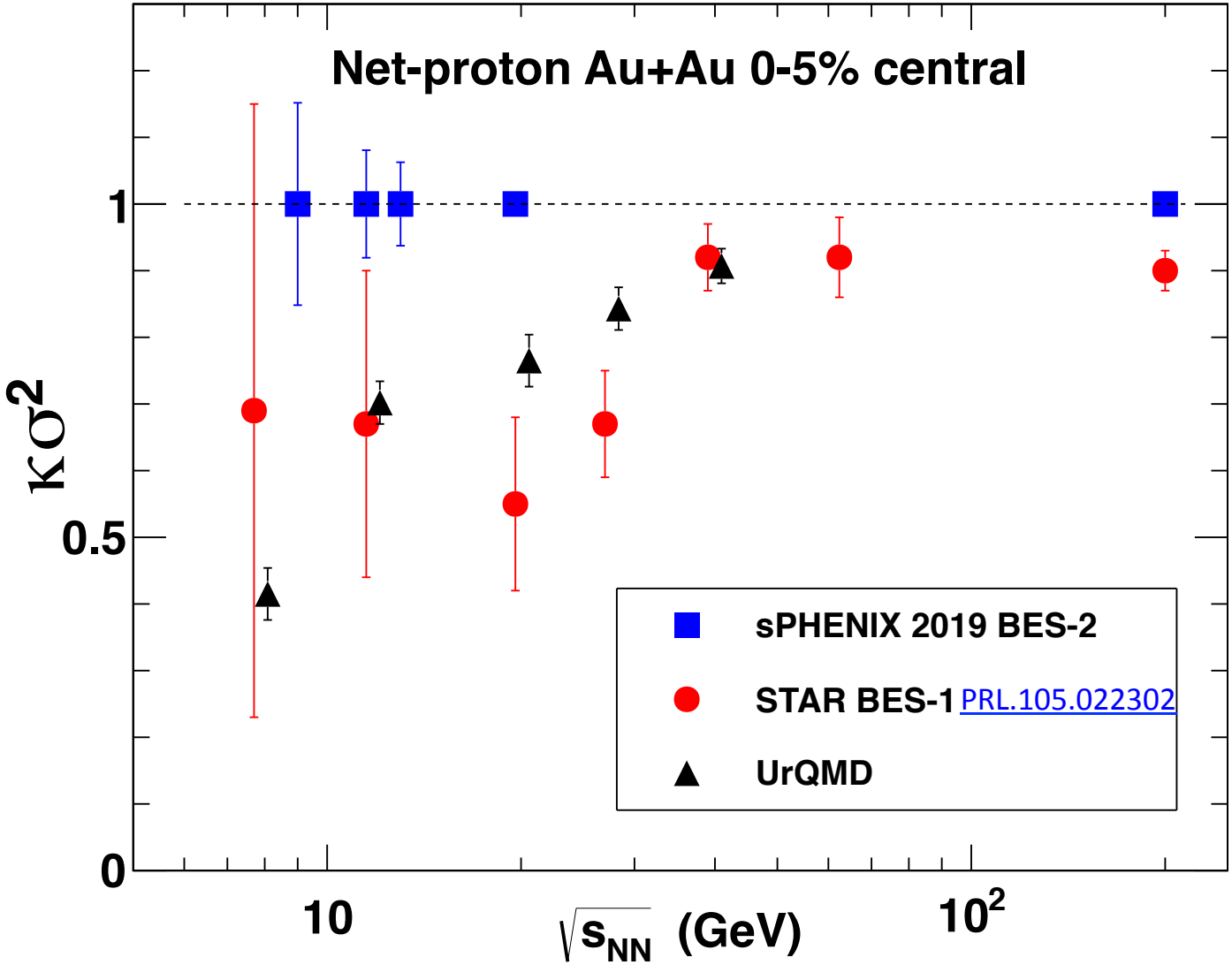
From Table 4.2 PHENIX BES-2 Whitepaper: http://www.phenix.bnl.gov/plans.html

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
	11.5	315	45	15	45	112.5
	13.0	281	23	17	50	125
Au+Au	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	1.2 pb^{-1}	3.6 pb^{-1}	9 pb^{-1}

Net-proton kurtosis errors follow formulae in Luo (12) JPG.39.025008

BES2 sPHENIX (wishful) projections

http://www.phenix.bnl.gov/plans.html - BES2 Whitepaper



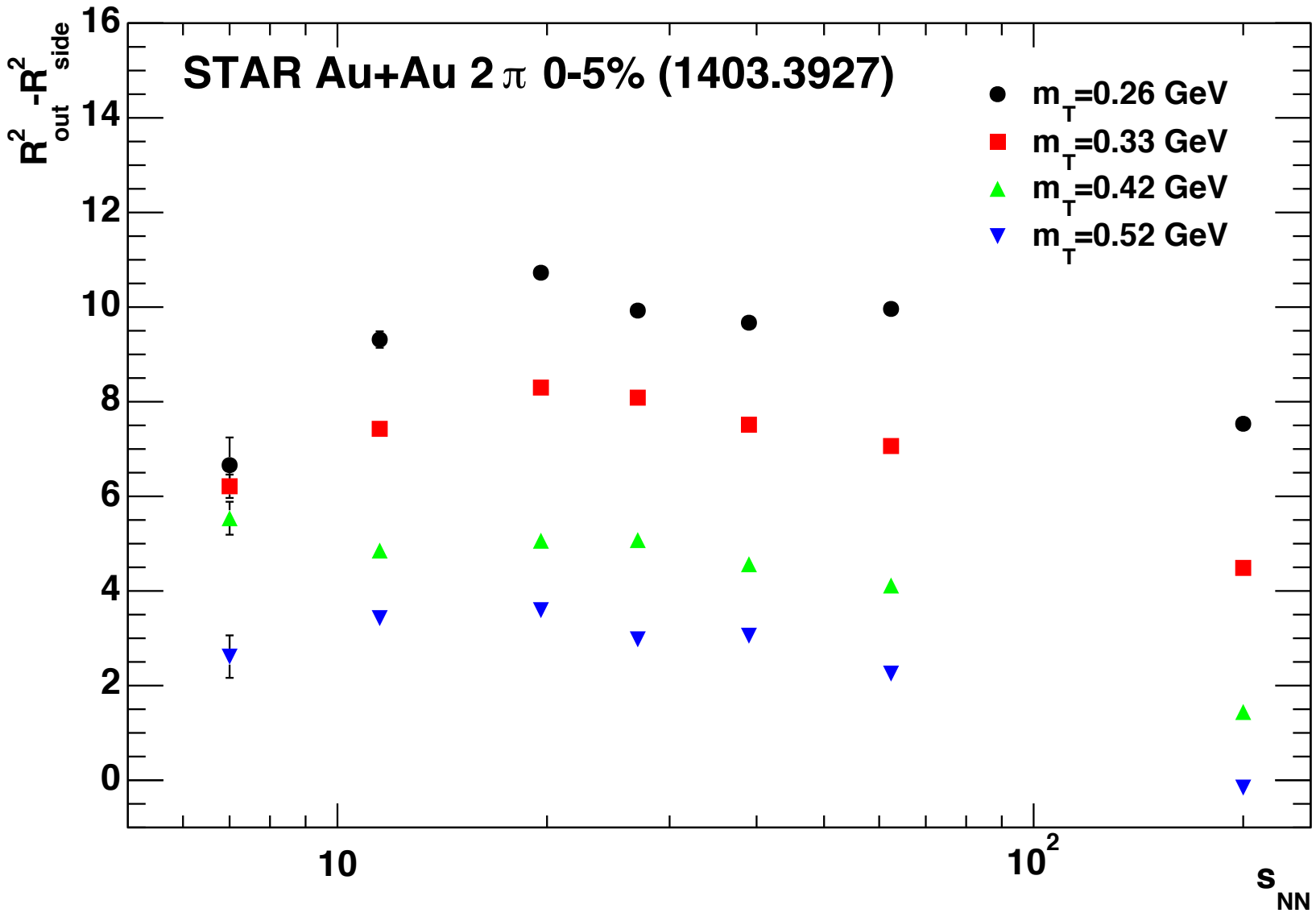
Summary Conclusions

- Nucleon Scaling below 27 GeV
  - implications for CEP signatures
  - onset for parton dynamics
- Non-monotonic behavior in R_{out}:R_{side} ratios and differences, R_{side}:R_{long} (expansion/lifetime)
  - if location at softest EoS, peak height is key to CEP
  - also consider nucleon dominated freeze-out
  - multi-stage modeling needed for HBT
- sPHENIX interest in BES-2 physics

Backup

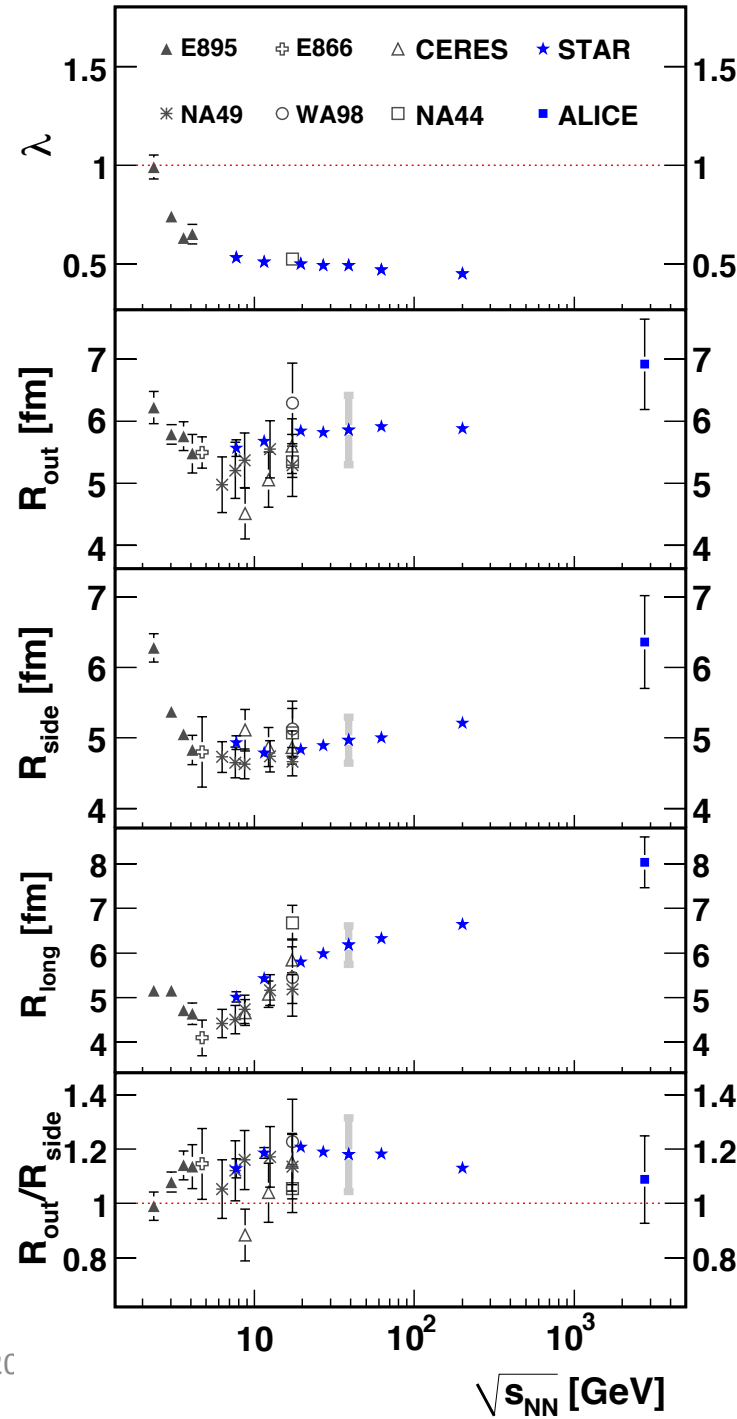
- Starts here.

STAR Results

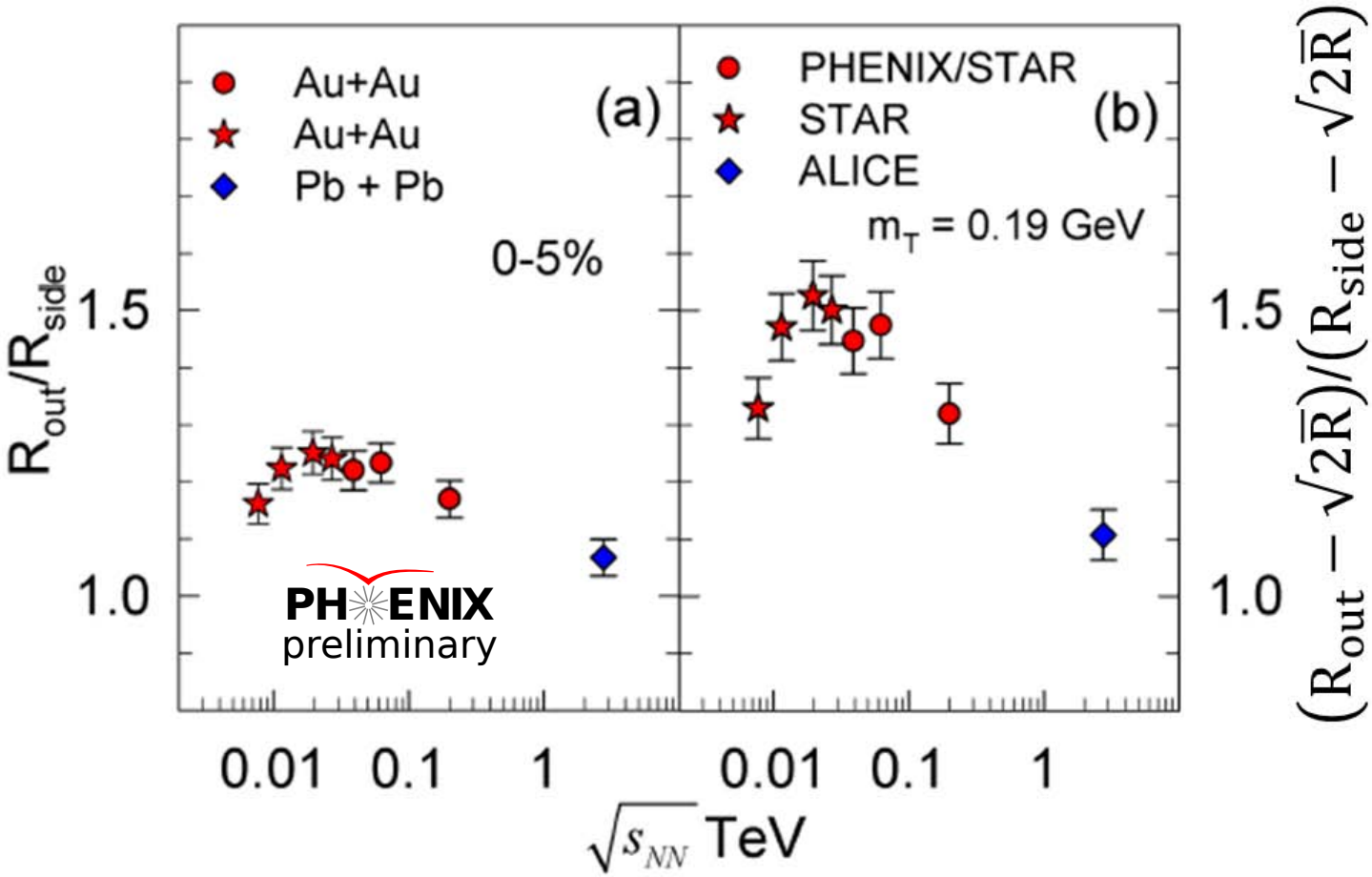


HBT radii vs. $\sqrt{s_{NN}}$

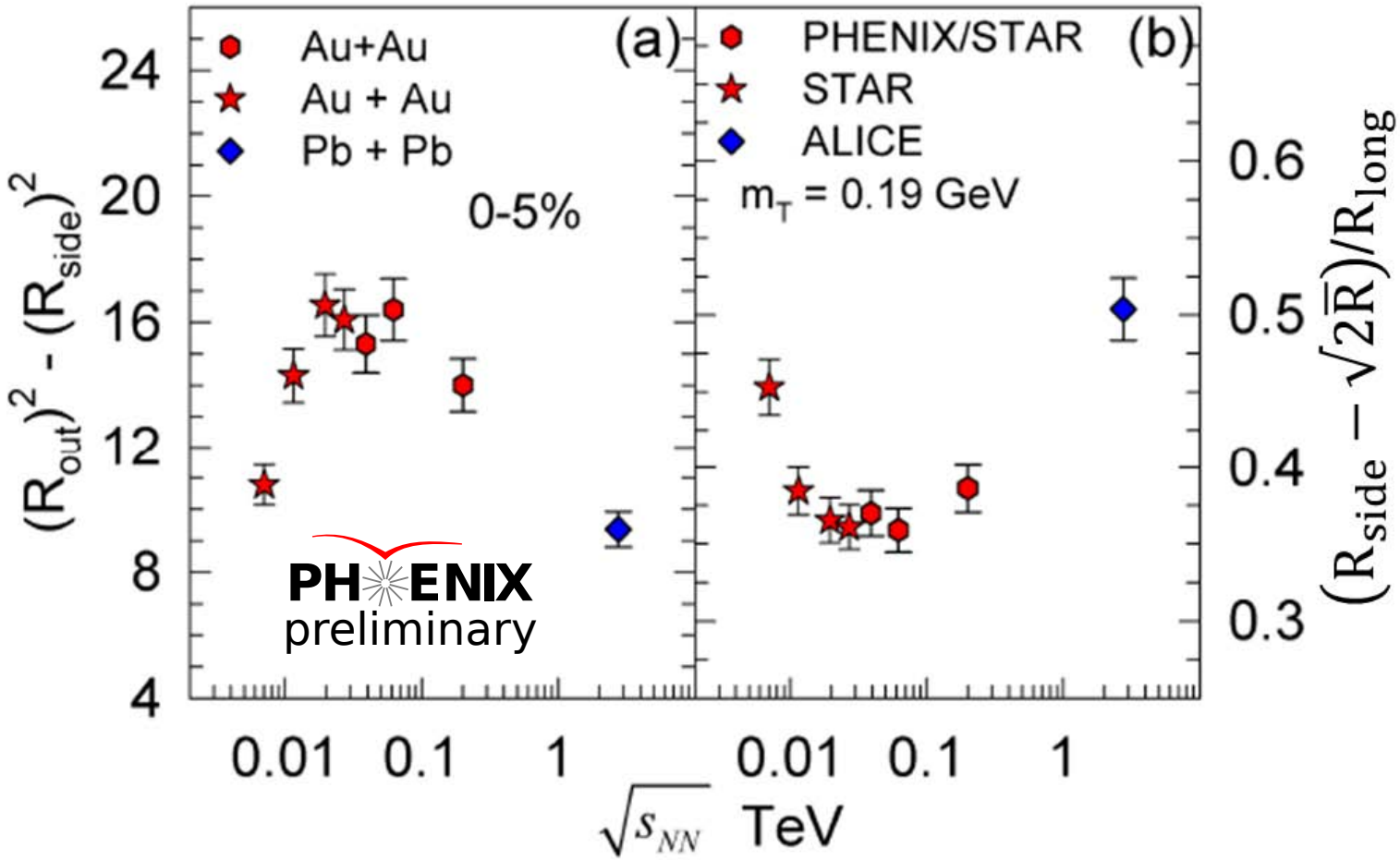
- STAR arxiv:1403.4972
- evidence for 1st order behavior not readily apparent
- construct ratios and differences
- interpolate to common m_T



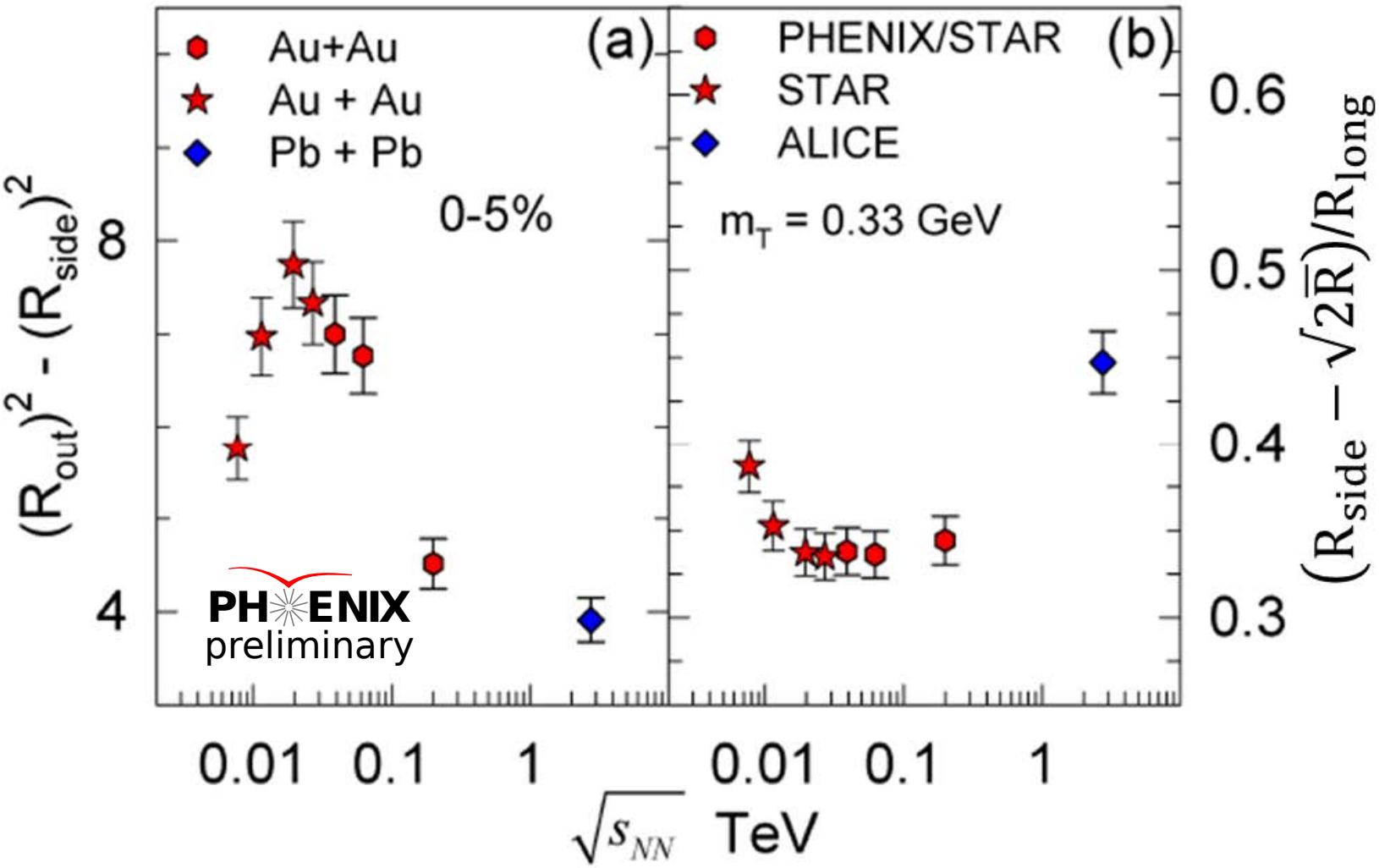
$m_T = 0.19$ GeV


Au+Au
Au+Au
Pb + Pb
(a)
0-5%
PHENIX
preliminary
PHENIX/STAR
STAR
ALICE
(b)
m_T = 0.19 GeV
R_{out}/R_{side}
$(R_{out} - \sqrt{2}\bar{R})/(R_{side} - \sqrt{2}\bar{R})$
1.5
1.0
0.01
0.1
1
$\sqrt{s_{NN}}$ TeV

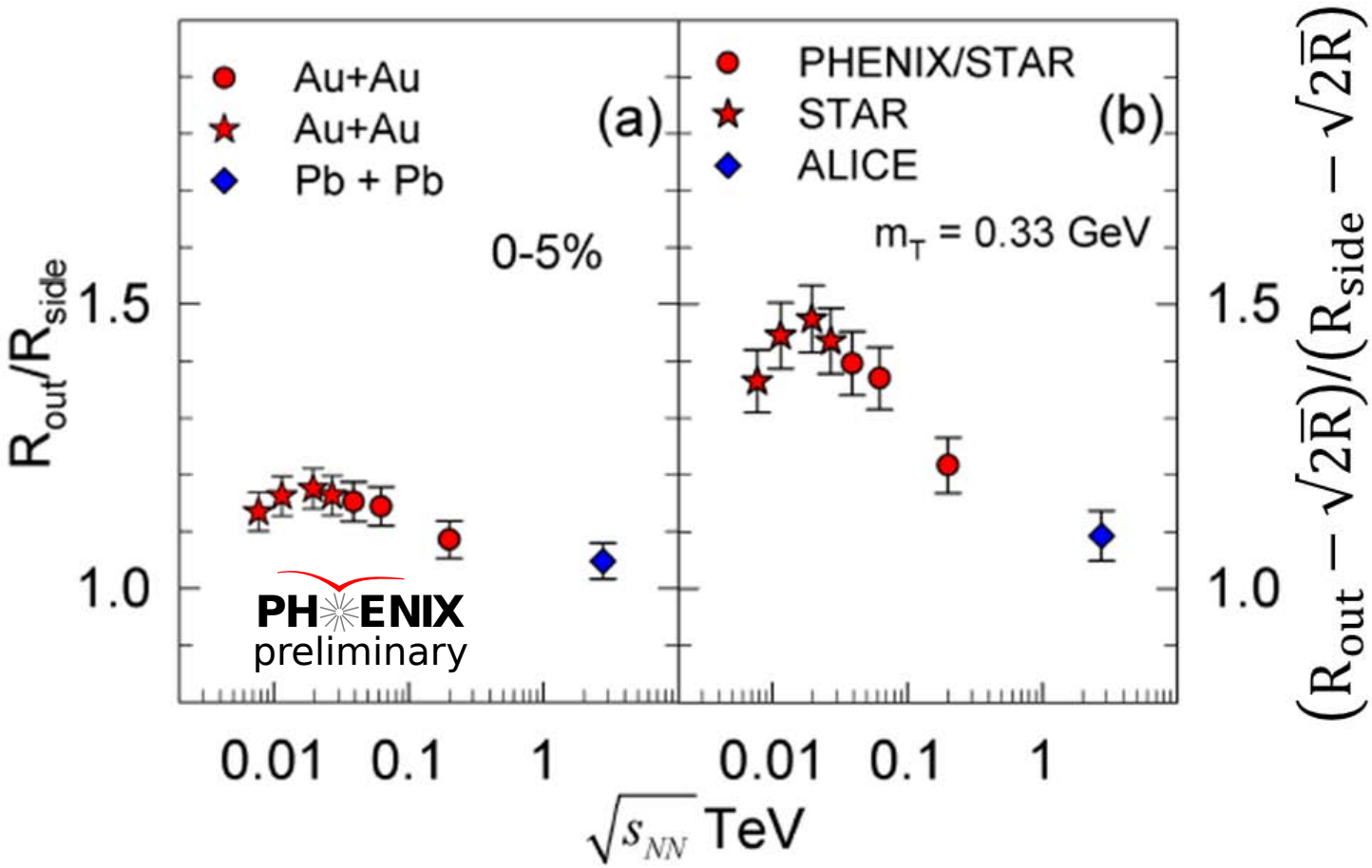
$m_T = 0.19$ GeV


Au+Au
Au + Au
Pb + Pb
(a)
0-5%
PHENIX/STAR
STAR
ALICE
(b)
m_T = 0.19 GeV
PHENIX
preliminary
$(R_{out})^2 - (R_{side})^2$
$(R_{side} - \sqrt{2}\bar{R})/R_{long}$
$\sqrt{s_{NN}}$ TeV
24
20
16
12
8
4
0.6
0.5
0.4
0.3
0.01
0.1
1

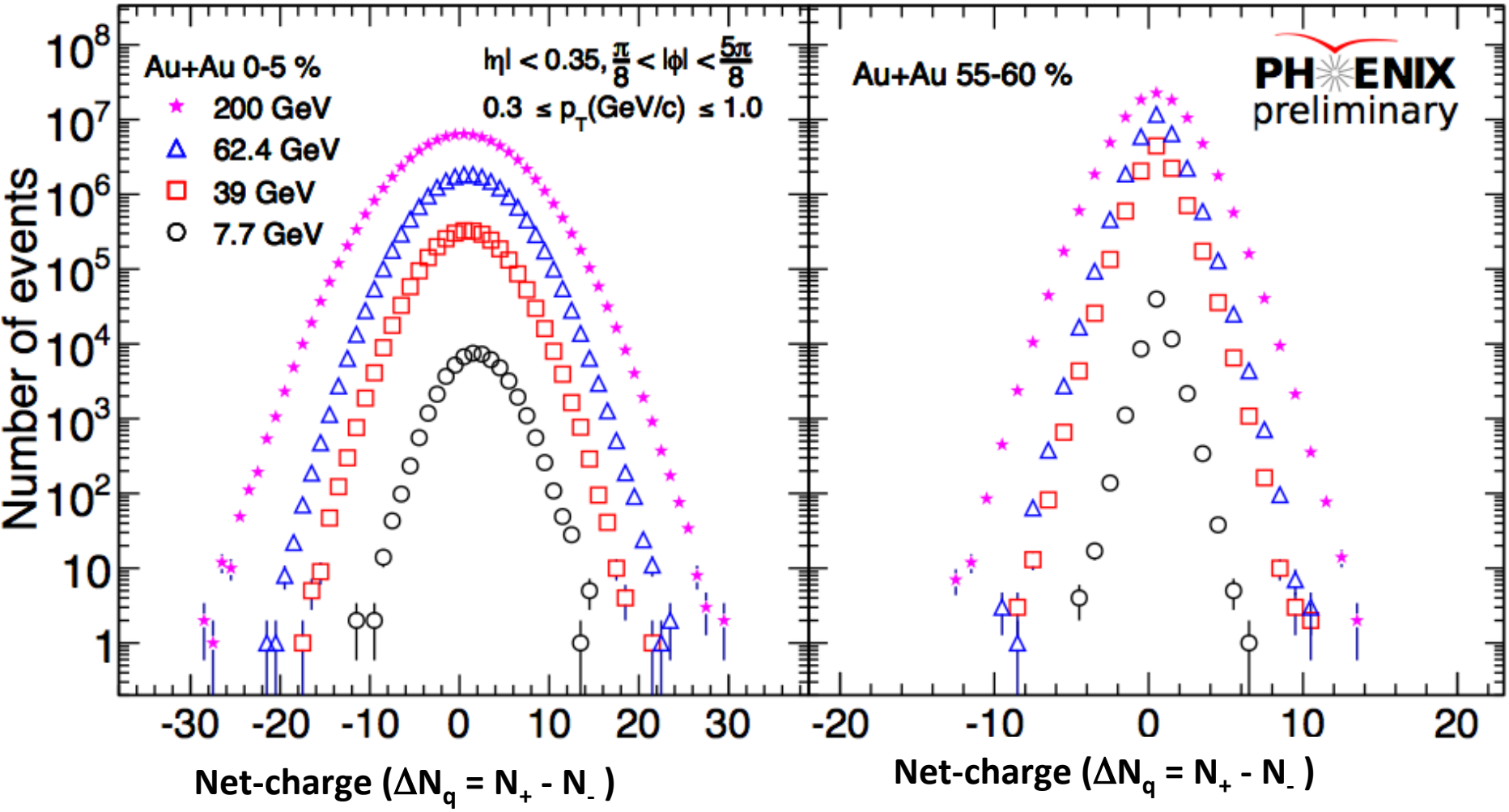
$m_T = 0.33$ GeV


Au+Au
Au + Au
Pb + Pb
(a)
0-5%
PHENIX
preliminary
PHENIX/STAR
STAR
ALICE
(b)
m_T = 0.33 GeV
$(R_{out})^2 - (R_{side})^2$
$(R_{side} - \sqrt{2}\bar{R})/R_{long}$
8
4
0.6
0.5
0.4
0.3
0.01
0.1
1
$\sqrt{s_{NN}}$ TeV

$m_T = 0.33$ GeV


Au+Au
Au+Au
Pb + Pb
(a)
0-5%
PHENIX
preliminary
PHENIX/STAR
STAR
ALICE
(b)
m_T = 0.33 GeV
R_{out}/R_{side}
$(R_{out} - \sqrt{2}\bar{R})/(R_{side} - \sqrt{2}\bar{R})$
1.5
1.0
0.01
0.1
1
$\sqrt{s_{NN}}$ TeV

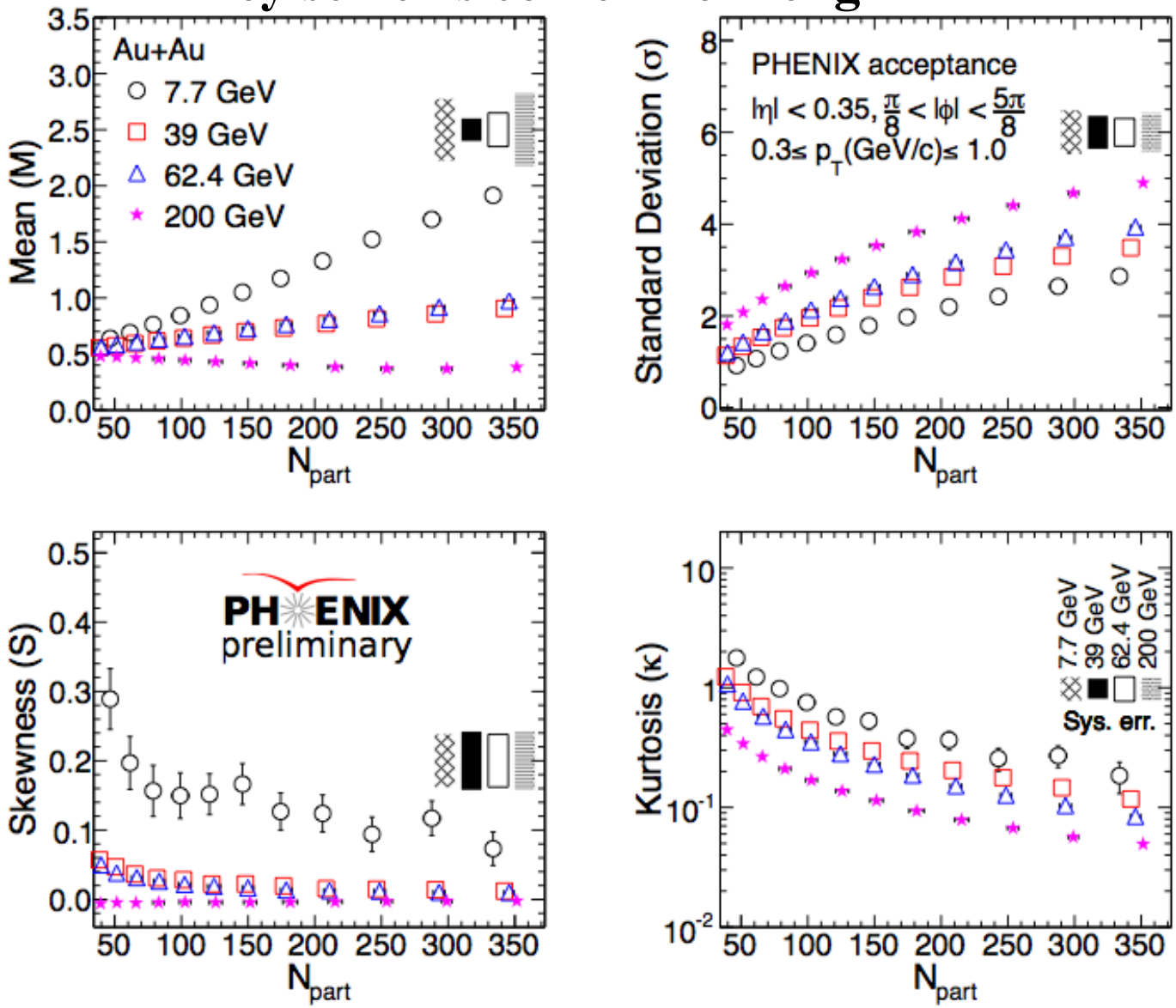
Net Charge Distributions



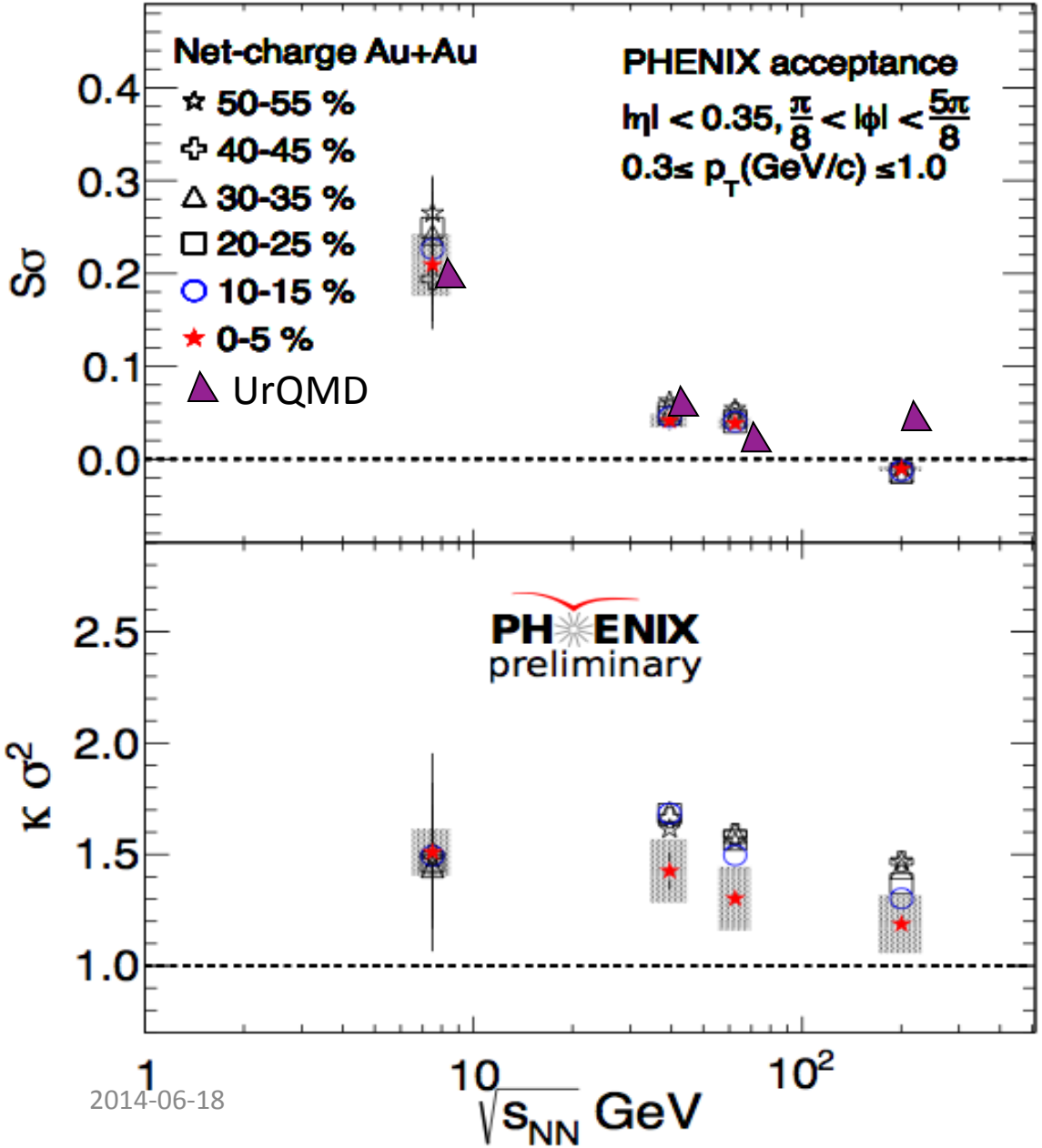
- Correlation length related to moments of conserved quantities including net charge
- Correlation length should diverge at the critical point in the phase diagram

Net Charge Moments

They scale as correlation length



$\sqrt{s_{NN}}$ Dependence of Net Charge Fluctuations



- Neither $\mathcal{K}$ nor S vary with centrality at 7.7, 39, 62.4 and 200 GeV
- Kurtosis vs energy is flat within errors
- Skewness tracks UrQMD prediction
- Analysis of data sets from $\sqrt{s}$ = 19.6, 27 GeV still to be completed