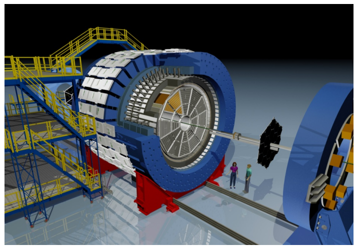
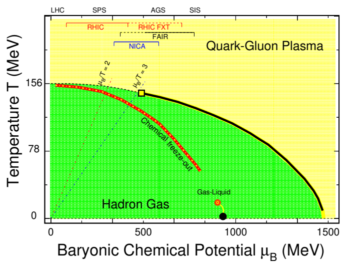
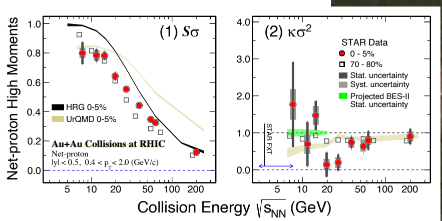
Net-proton number fluctuations and QCD critical point

Bedanga Mohanty, NISER

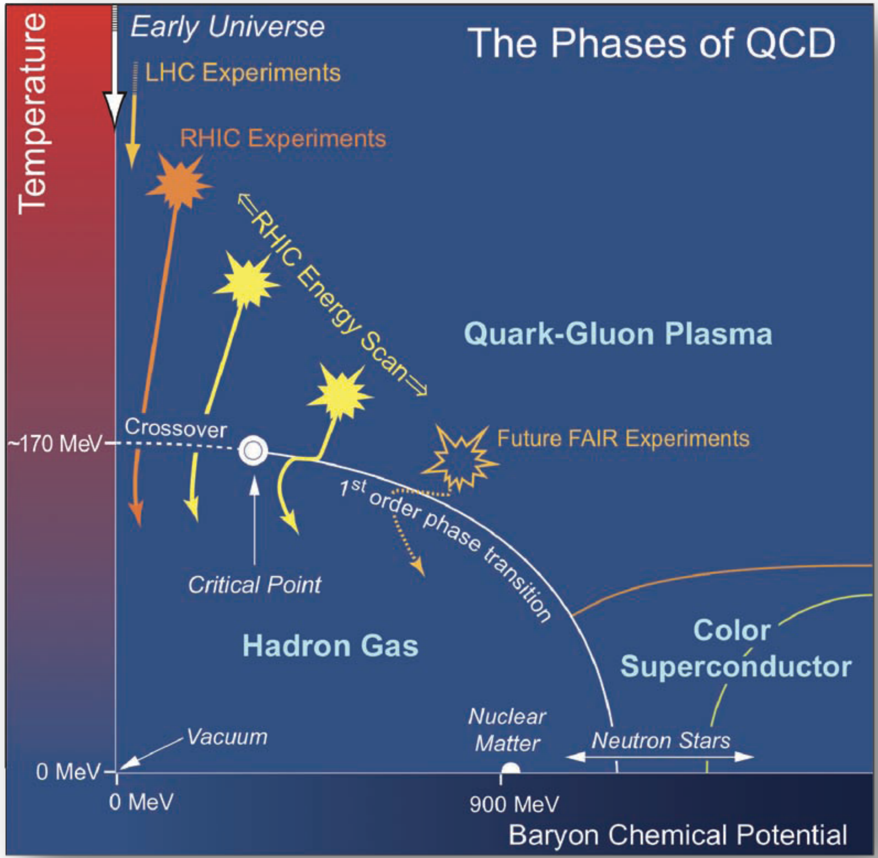
Outline:
1. Phase diagram and observable.
2. Theoretical status.
3. Experimental measurements at RHIC.
4. Future measurements.
5. Summary.







QCD phase diagram



US NP long range plan, 2015

Study the phase structure of QCD phase diagram.

Vary collision energy to change temperature and baryonic chemical potential.

Beam Energy Scan (BES) program at RHIC.

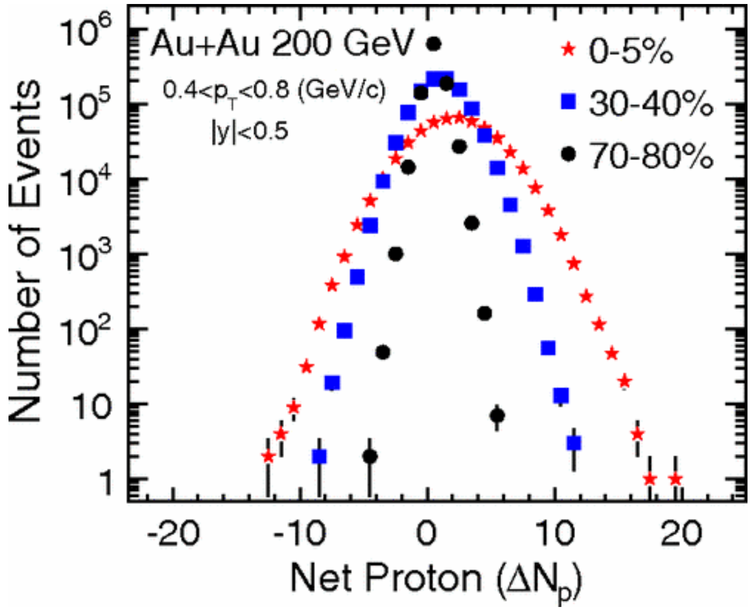
Starting point: 2009-2010

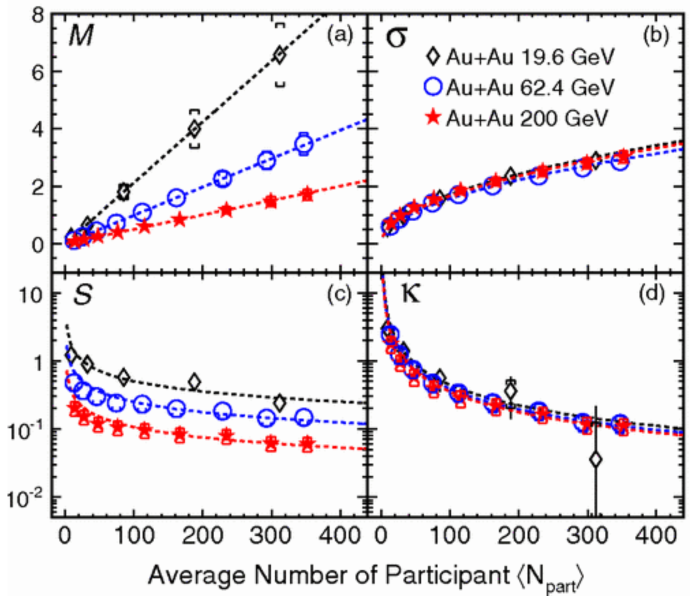
PHYSICAL REVIEW C **81**, 024911 (2010)

Identified particle production, azimuthal anisotropy, and interferometry measurements in Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV

We present the first measurements of identified hadron production, azimuthal anisotropy, and pion interferometry from Au + Au collisions below the nominal injection energy at the BNL Relativistic Heavy-Ion Collider (RHIC) facility. The data were collected using the large acceptance solenoidal tracker at RHIC (STAR) detector at $\sqrt{s_{NN}} = 9.2$ GeV from a test run of the collider in the year 2008. Midrapidity results on multiplicity density dN/dy in rapidity y, average transverse momentum $\langle p_T \rangle$, particle ratios, elliptic flow, and Hanbury-Brown–Twiss (HBT) radii are consistent with the corresponding results at similar $\sqrt{s_{NN}}$ from fixed-target experiments. Directed flow measurements are presented for both midrapidity and forward-rapidity regions. Furthermore the collision centrality dependence of identified particle dN/dy, $\langle p_T \rangle$, and particle ratios are discussed. These results also demonstrate that the capabilities of the STAR detector, although optimized for $\sqrt{s_{NN}} = 200$ GeV, are suitable for the proposed QCD critical-point search and exploration of the QCD phase diagram at RHIC.

Observables: higher moments





First measurements – 2009-2010

Developed at INT'2008

1) Higher moments of conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions.

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \quad \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

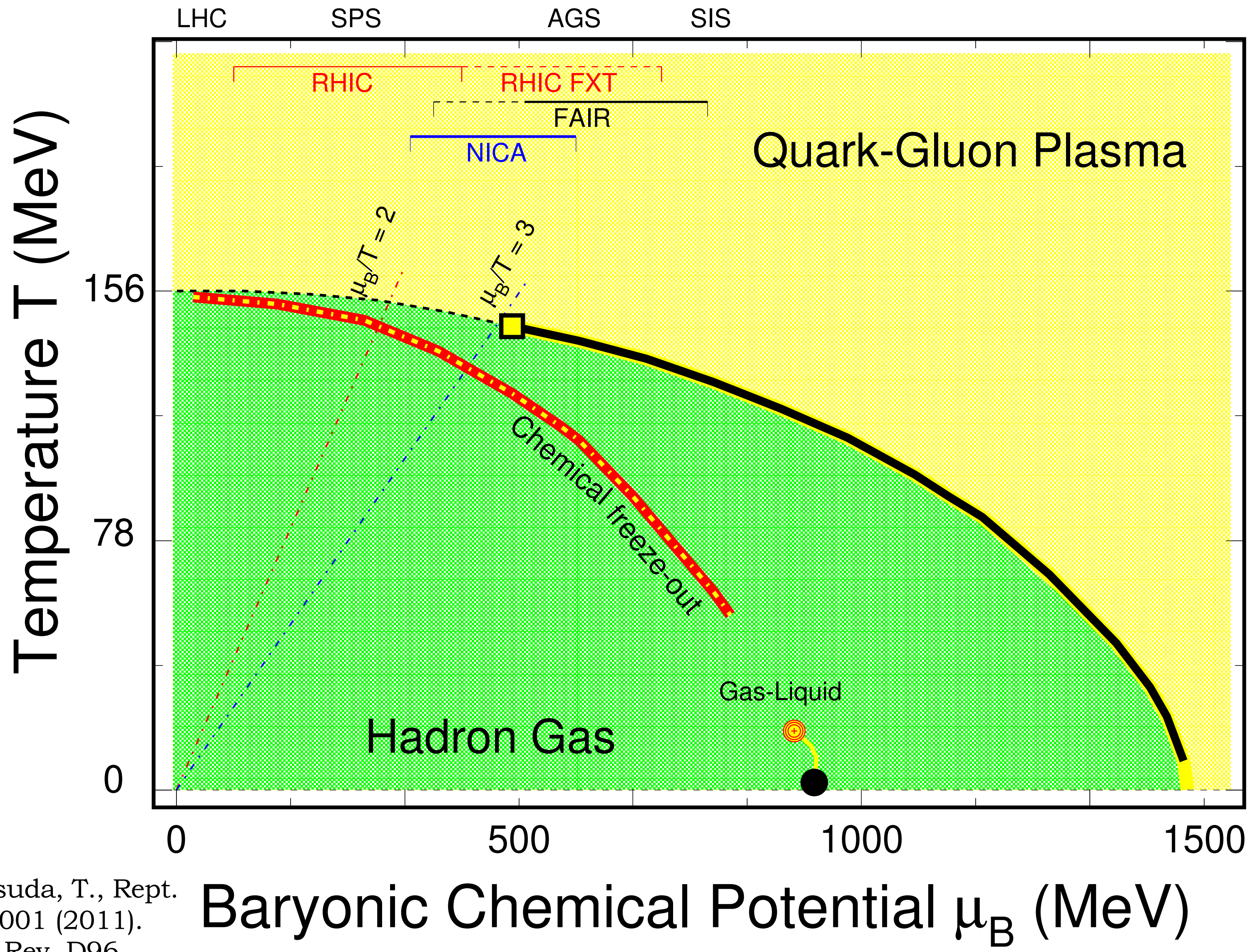
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) Extract susceptibilities and freeze-out temperature. An independent/important test of thermal equilibrium in heavy ion collisions.

References:
- STAR: *PRL*105, 22303(10); *ibid*, 112, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06);
  M. Stephanov: *PRL*102, 032301(09) ; F. Karsch *et al., PLB695*, 136(11);
  R.V. Gavai and S. Gupta, *PLB696*, 459(11)
- A. Bazavov *et al.*, PRL109, 192302(12); V. Skokov *et al.*, PRC88, 034901(13);
  S. Borsanyi *et al.*, PRL111, 062005(13)
- PBM, A. Rustamov, J. Stachel, NPA960, 114(17)
- A. Bzdak, *et al.*, arXiv: 1906.00936, Physics Report, 853C, 1(2020)

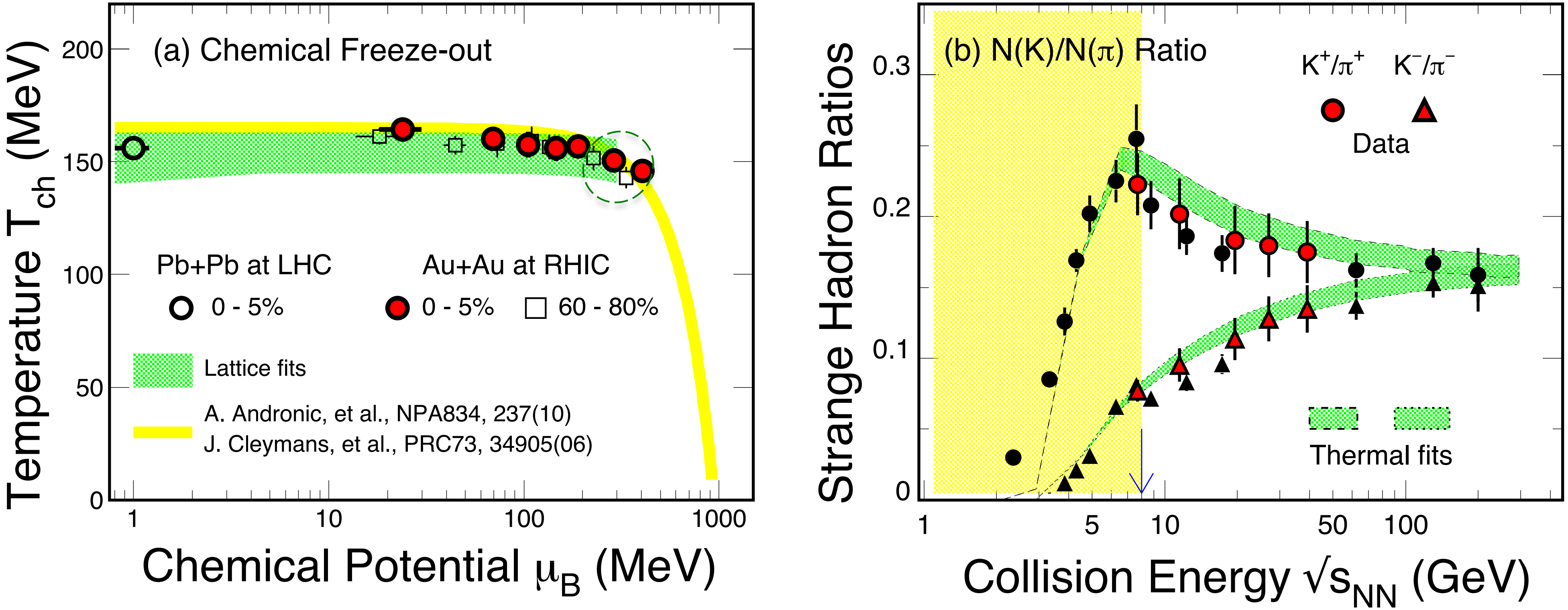
Theory: QCD phase structure

STAR: arXiv: 2001.02852



Fukushima, K. and Hatsuda, T., Rept. Prog. Phys. 74, 228 014001 (2011).
Bazavov, A. et al., Phys. Rev. D96, 074510 (2017); Phys. Rev. D95, 248 054504 (2017).

Freeze-out and high baryon density



Chemical Freeze-out: (GCE)

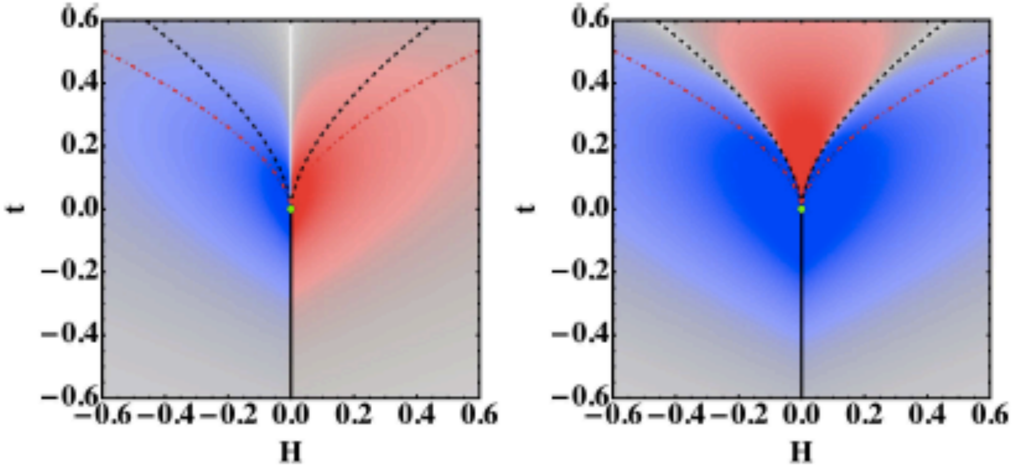
- Close to Lattice transition line.
- Weak dependence for temperature.
- Centrality dependence of μ_B.
- LGT: **CP if exits - $\mu_B \geq 300$ MeV?**

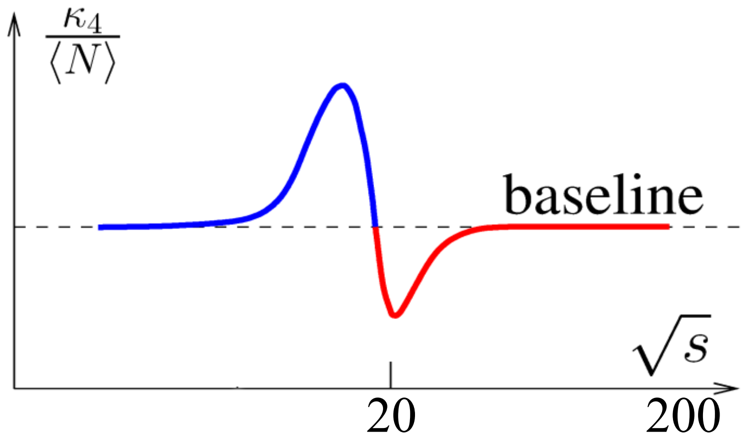
- The **K^+/π** ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV where model also predicted the peak of baryon density.
- **High Baryon Density Region**: ($\sqrt{s_{NN}} < 8$ GeV, $\mu_B \geq 420$ MeV)

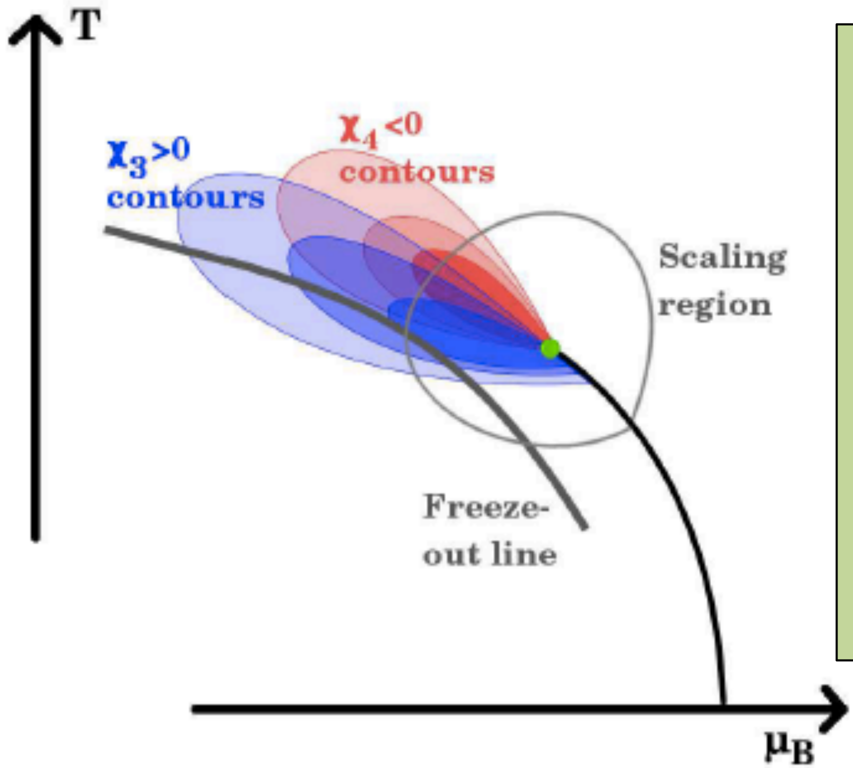
- ALICE: B.Abelev et al., PRL 109, 252301(12); PR C88, 044910(13).
- STAR: J. Adams, et al., NPA757, 102(05); PR C96, 044904(17); PRC96, 044904(17).
- J. Randrup and J. Cleymans, Phys. Rev. C74, 047901(06).

In discussion with N. Xu

CP expectation from model calculations





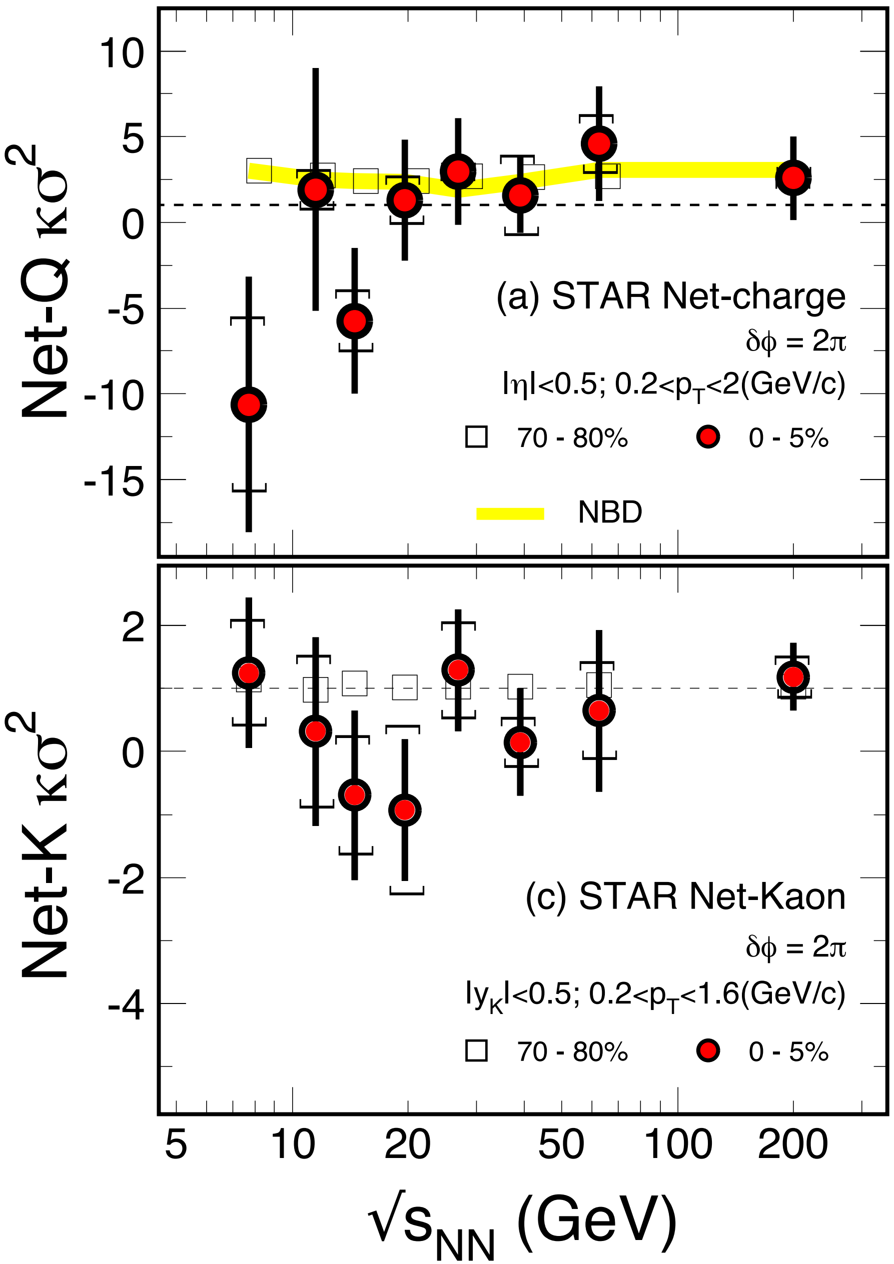


-Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP.*

- Critical region instead of a point.

- M. Stephanov, *PRL107*, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, Phys. Rev. D93 (2016) 034037

STAR: Net-charge and net-kaon



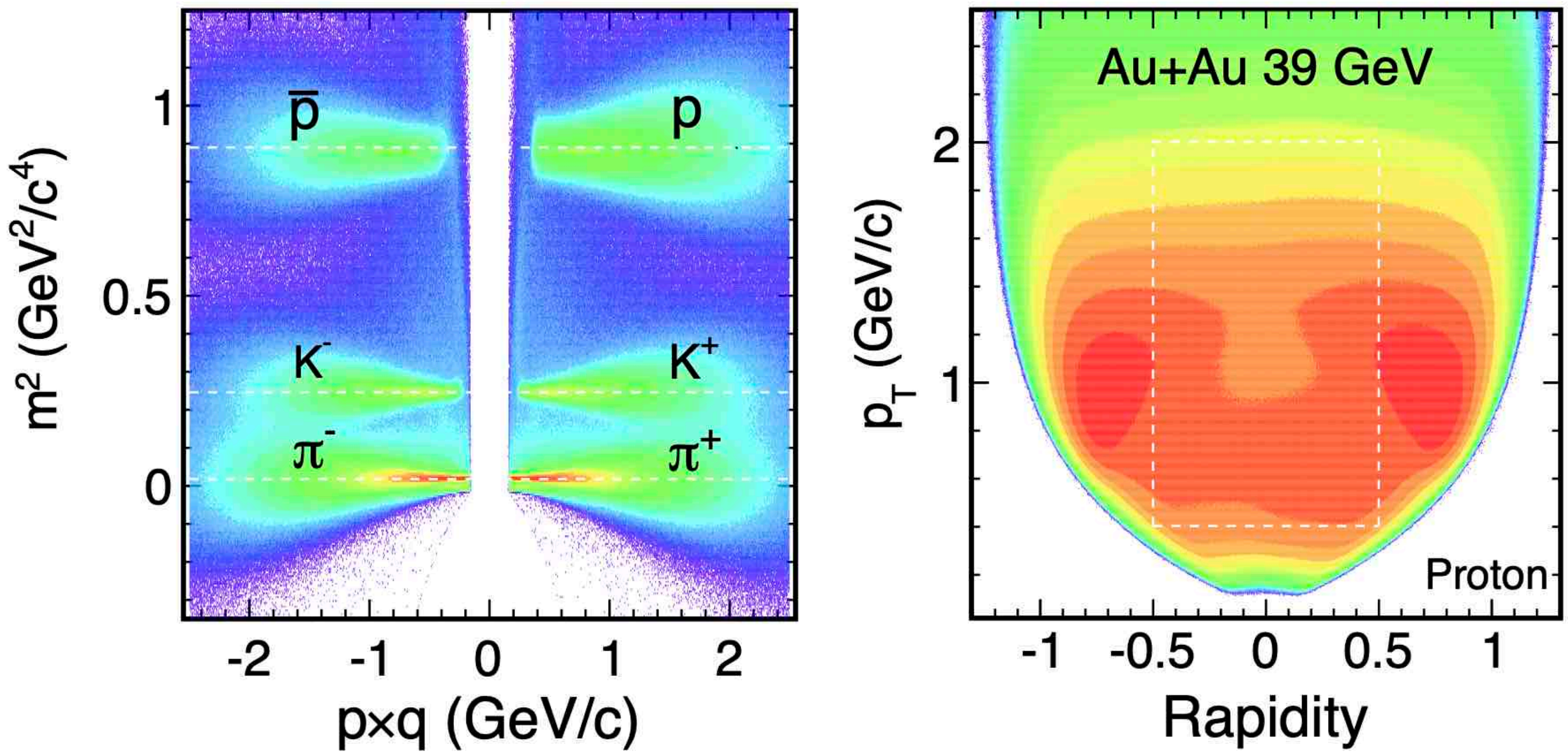
1) The results of net-charge and net-kaon show flat energy dependence.

2) The statistical uncertainty:

$$\sim \frac{\sigma^m}{\sqrt{N}\,\varepsilon^k}$$

STAR:
Phys. Rev. Lett. 113 (2014) 092301.
Phys. Lett. B 785 (2018) 551-560.

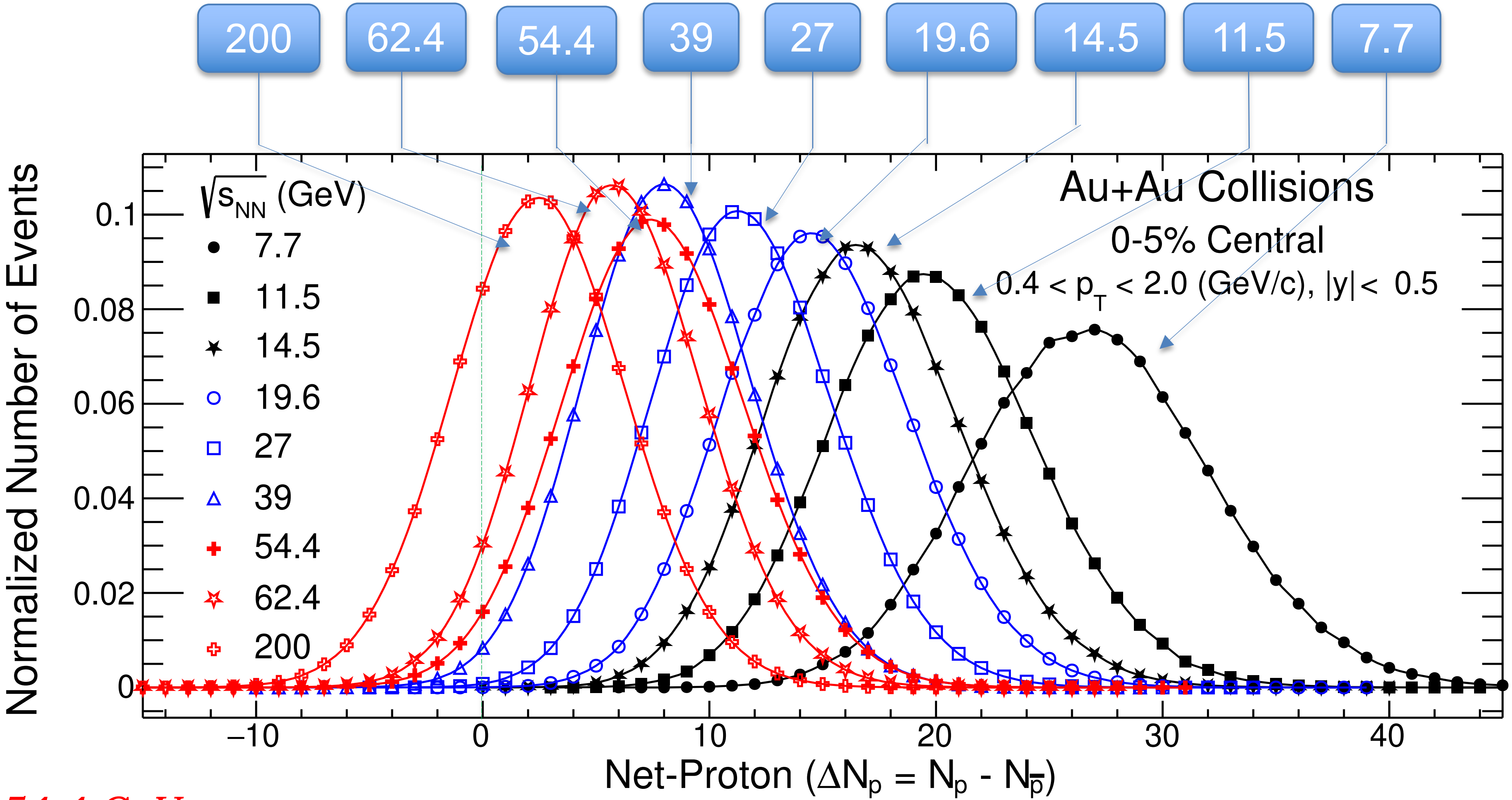
Proton identification



1) Purity of proton and anti-proton identification > 97% .
2) Uniform acceptance at midrapidity for all beam energies for collider experiment.

STAR: arXiv: 2001.02852

Energy dependence of net-proton

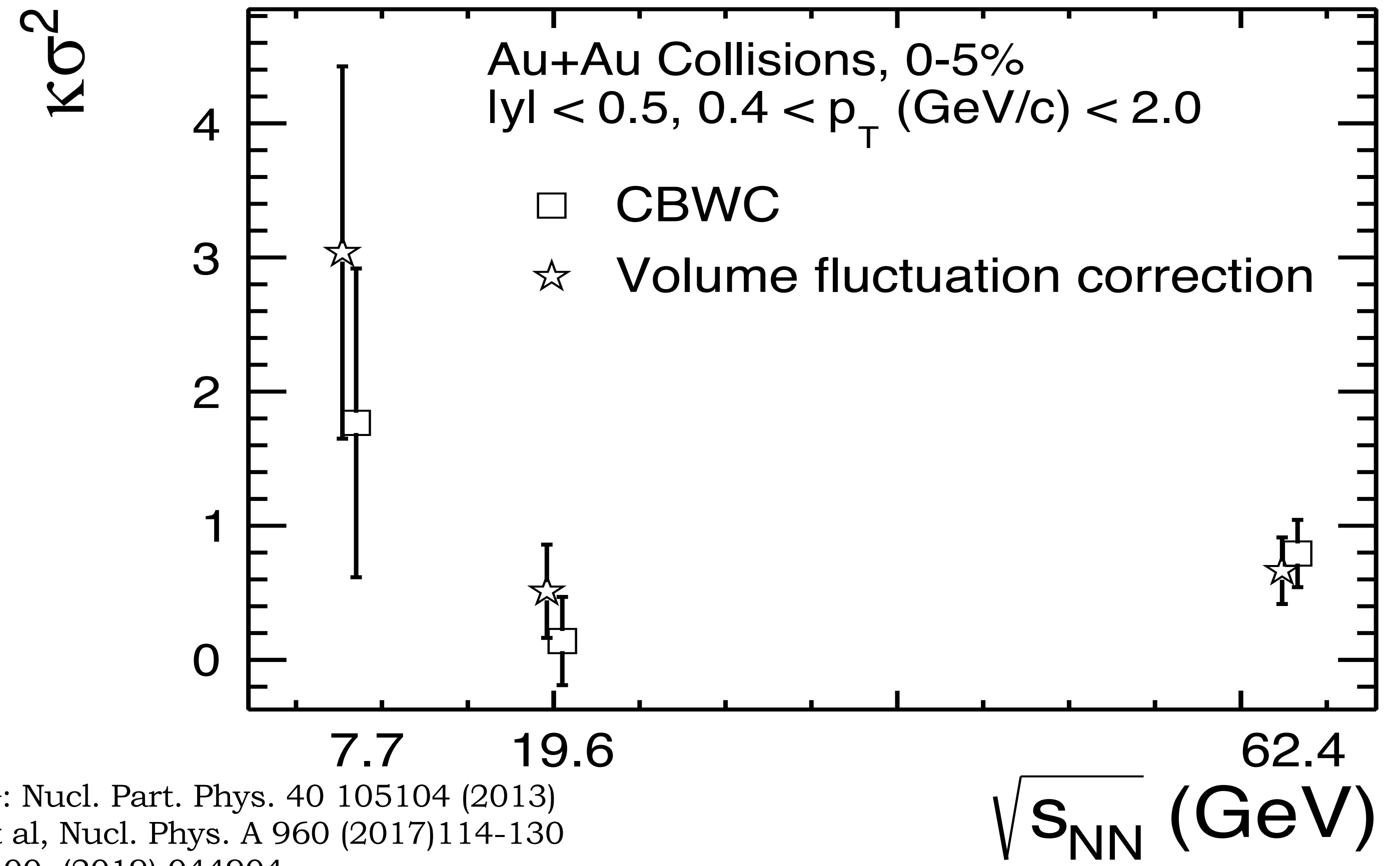


54.4 GeV new

1) Net-proton distributions, top 5% central collisions, efficiency uncorrected.
2) Value of mean and the width increase as energy decreases, effect of baryon stopping.

STAR: arXiv: 2001.02852

Volume fluctuations



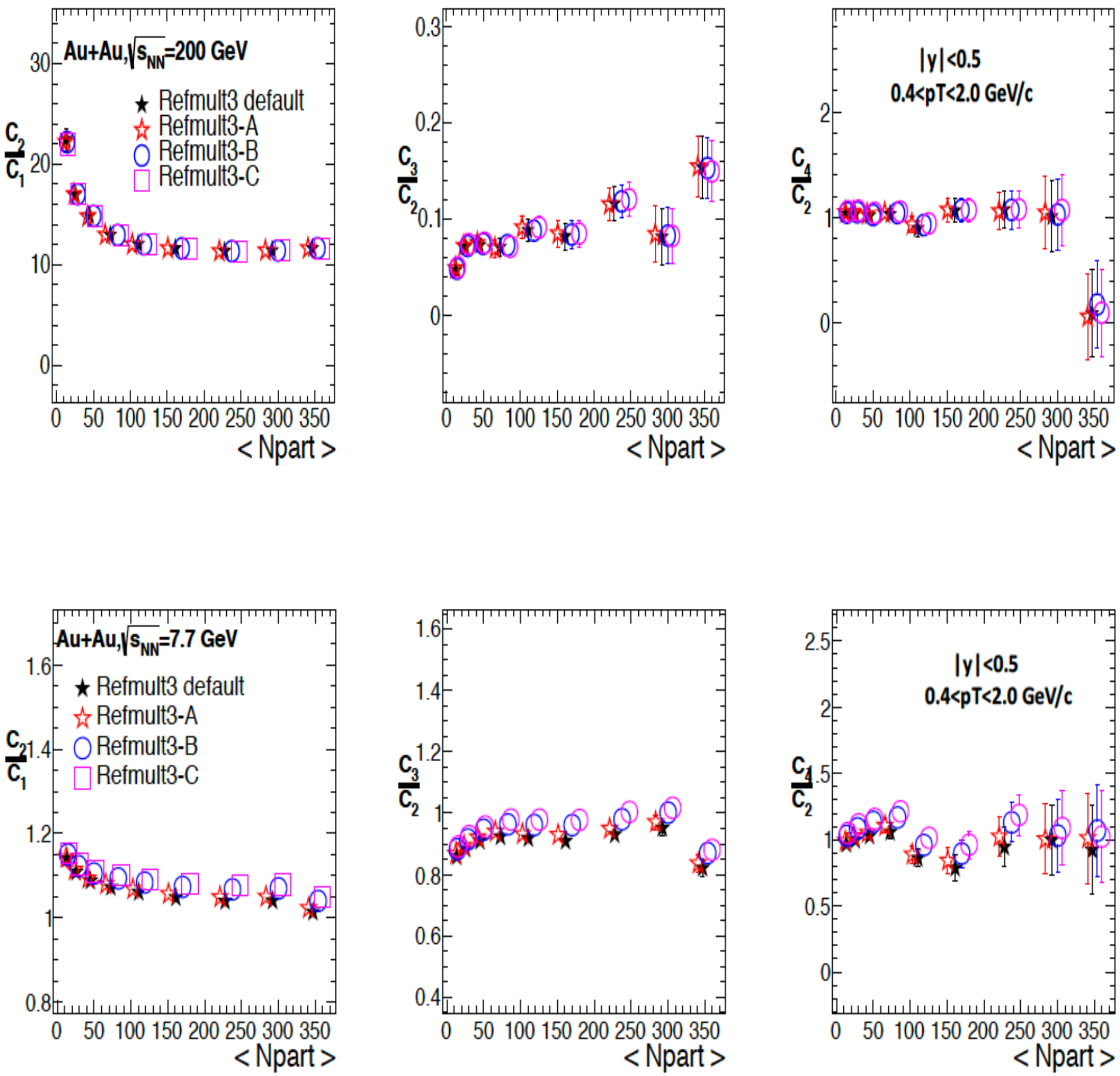
Luo et al, J. Phys. G: Nucl. Part. Phys. 40 105104 (2013)
Braun-Munzinger et al, Nucl. Phys. A 960 (2017)114-130
Sugiura et al, PRC 100, (2019) 044904
Skokov et al., Phys. Rev. C88 (2013) 034911)

1) Centrality Bin Width Correction – Data driven approach.
2) Volume fluctuation correction – Model dependent.
3) Results from both methods are consistent.

STAR: arXiv: 2001.02852
T. Nonaka, PhD Thesis, 2018

Centrality and self-correlations

HIJING Model based

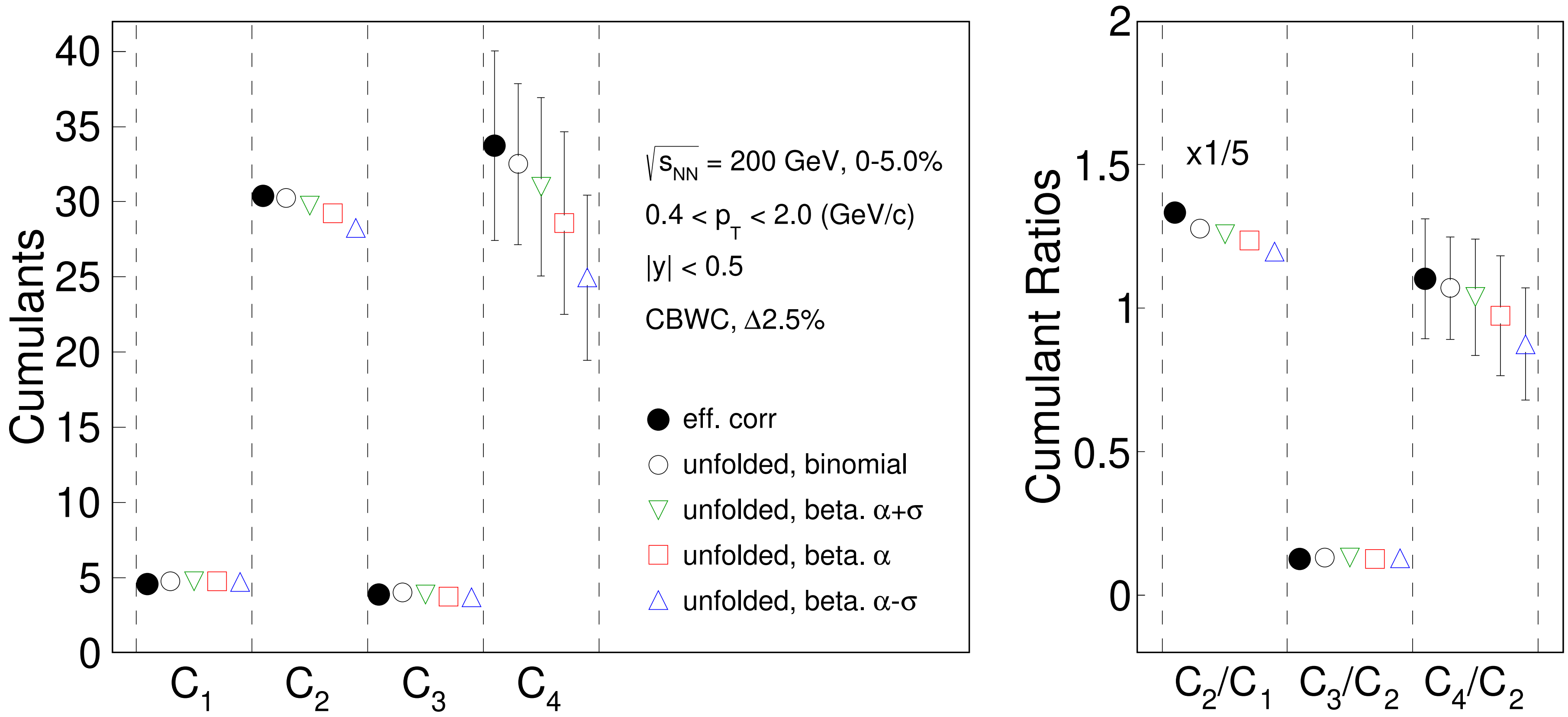


Refmult3 (default)	Charged tracks within $\lvert\eta\rvert < 1.0$ and $p_T > 0.1$ GeV/c. NO proton & antiproton.
Refmult3-A	Refmult3 (default) + no contributions from lambda decay
Refmult3-B	Refmult3 (default) + no contributions from decay of delta baryon
Refmult3-C	Refmult3 (default) + no contributions from Lambda and Delta baryons decay

Model based study: self correlation effects due to choice of centrality absent.

STAR: arXiv: 2001.02852

Efficiency correction procedures

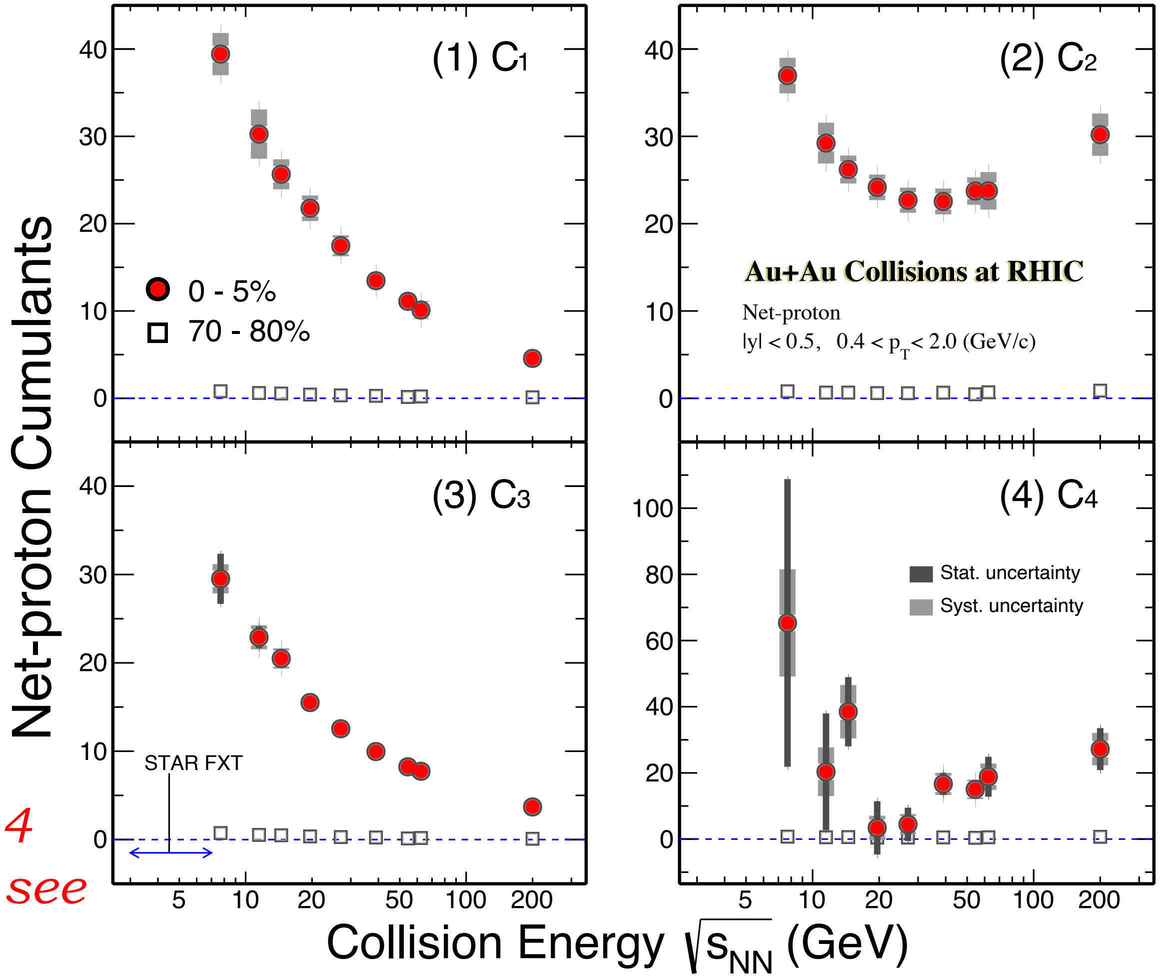


STAR: Phys. Rev. Lett. 112, 032302 (2014)
Luo, Phys. Rev. C91, 034907 (2015)
Esumi et al, arXiv:2002.11253
Nonaka et al., Nucl. Instrum. Meths A906 (2018) 10

1) Consistent between binomial method and unfolding method.
2) Additionally checked the momentum expansion method and results are consistent.

STAR: arXiv: 2001.02852

Energy dependence of net-proton

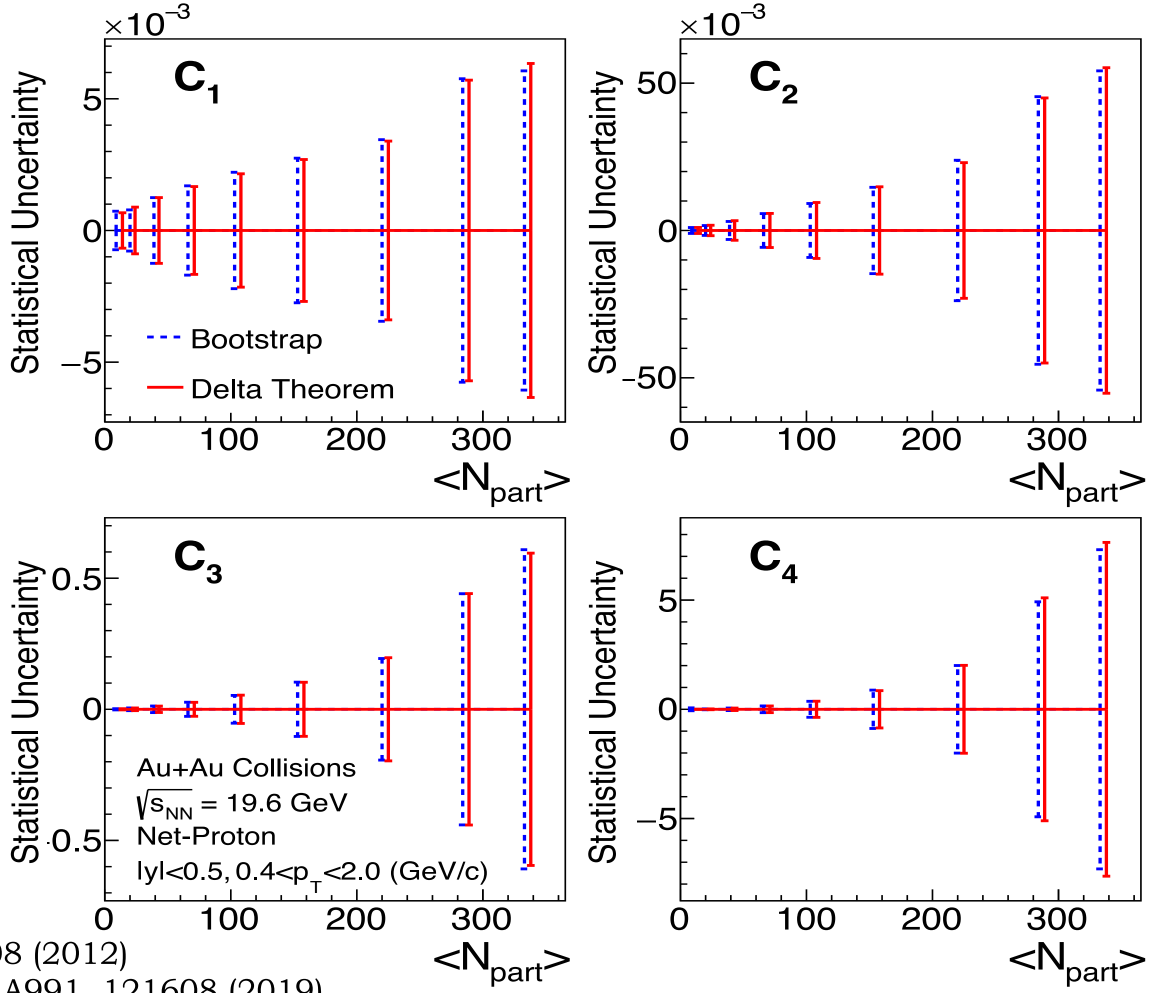


New: 54.4, 62.4 and 7.7 GeV – see talk by Nu Xu

1) Cumulants of net-proton distributions, central and peripheral collisions. Efficiency and acceptance correction applied.
2) Value of mean increase as energy decreases, effect of baryon stopping.

STAR: arXiv: 2001.02852

Robustness of statistical errors

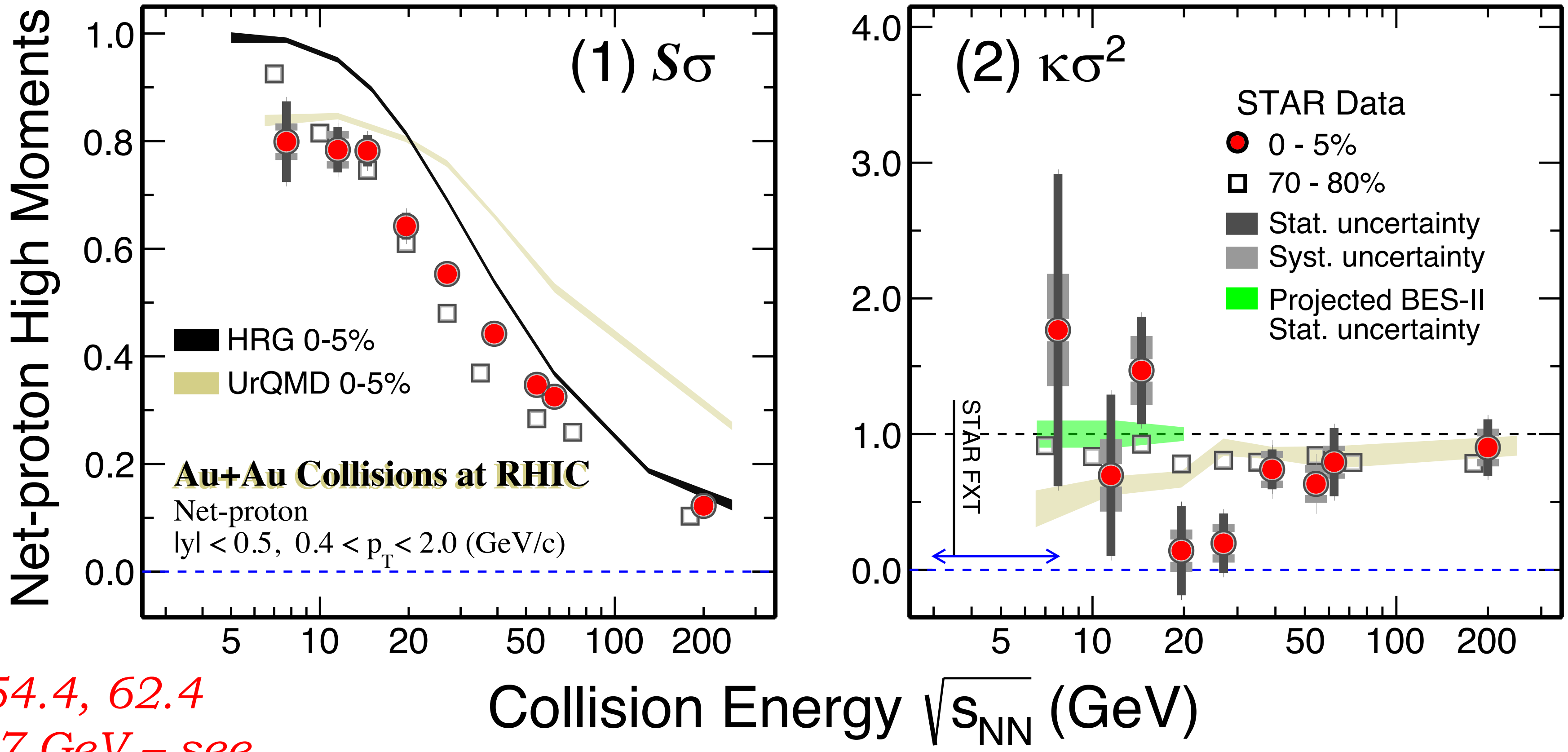


Luo, J. Phys. G39, 025008 (2012)
Pandav et al, Nucl. Phys. A991, 121608 (2019)

1) Boot strap method.
2) Delta theorem method.
3) Results from both methods are consistent.

STAR: arXiv: 2001.02852

Energy dependence of Net-proton



New: 54.4, 62.4 and 7.7 GeV – see talk by Nu Xu

1) Ratios of the net-proton cumulants, top 5% central and 70-80% peripheral collisions.
2) Net-proton: **non-monotonic energy dependence** in the most central Au+Au collisions starting at $\sqrt{s_{NN}}$ < 39 GeV.

STAR: arXiv: 2001.02852

QCD inspired fit – Data driven approach

LQCD: HotQCD, PRD 96 (2017) 074510

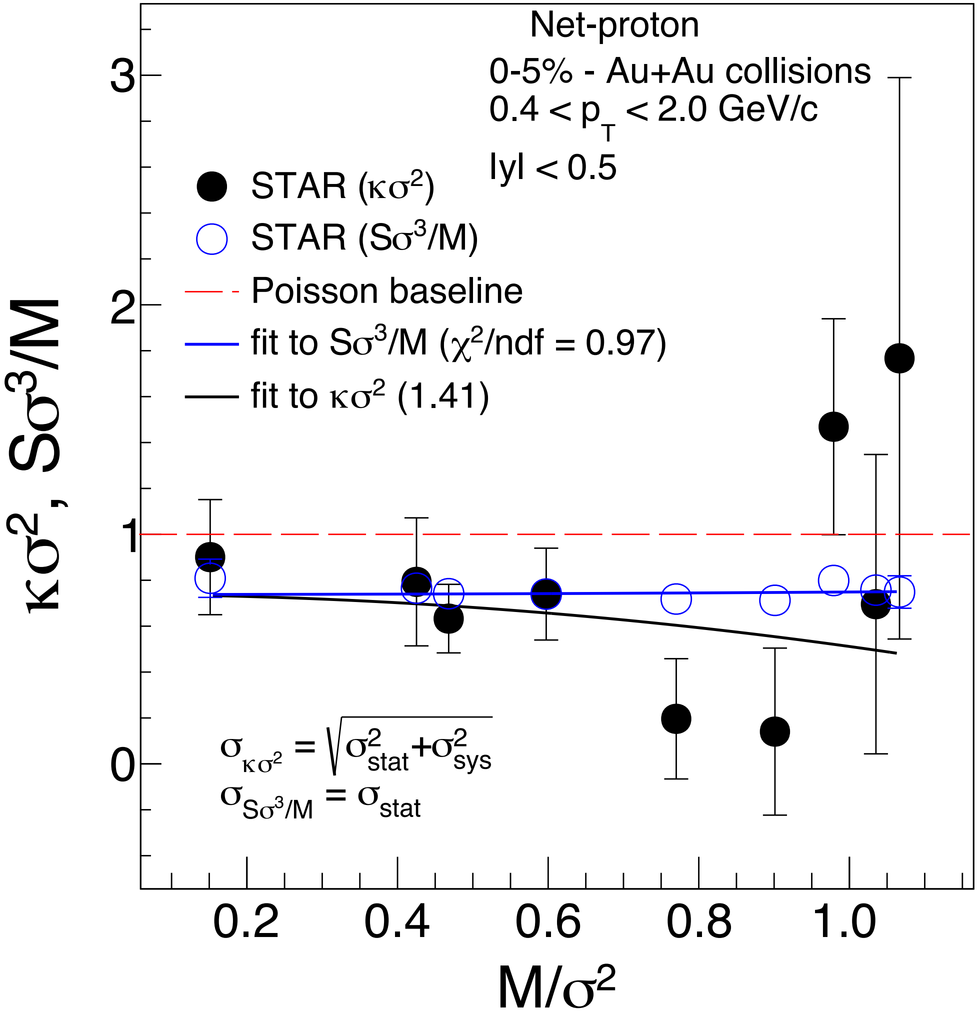
Data STAR: arXiv: 2001.02852*

1. $\frac{S\sigma^3}{M} = p_{0eq1} + p_{1eq1} \times \left(\frac{M}{\sigma^2}\right)^2$
2. $\kappa\sigma^2 = p_{0eq2} + p_{1eq2} \times \left(\frac{M}{\sigma^2}\right)^2$
3. $S\sigma = p_{0eq3} \times \left(\frac{M}{\sigma^2}\right)^1 + p_{1eq3} \times \left(\frac{M}{\sigma^2}\right)^3$

LQCD: Fix parameters for (3) by fitting to (1) and (2) to experimental data (see figure on right)

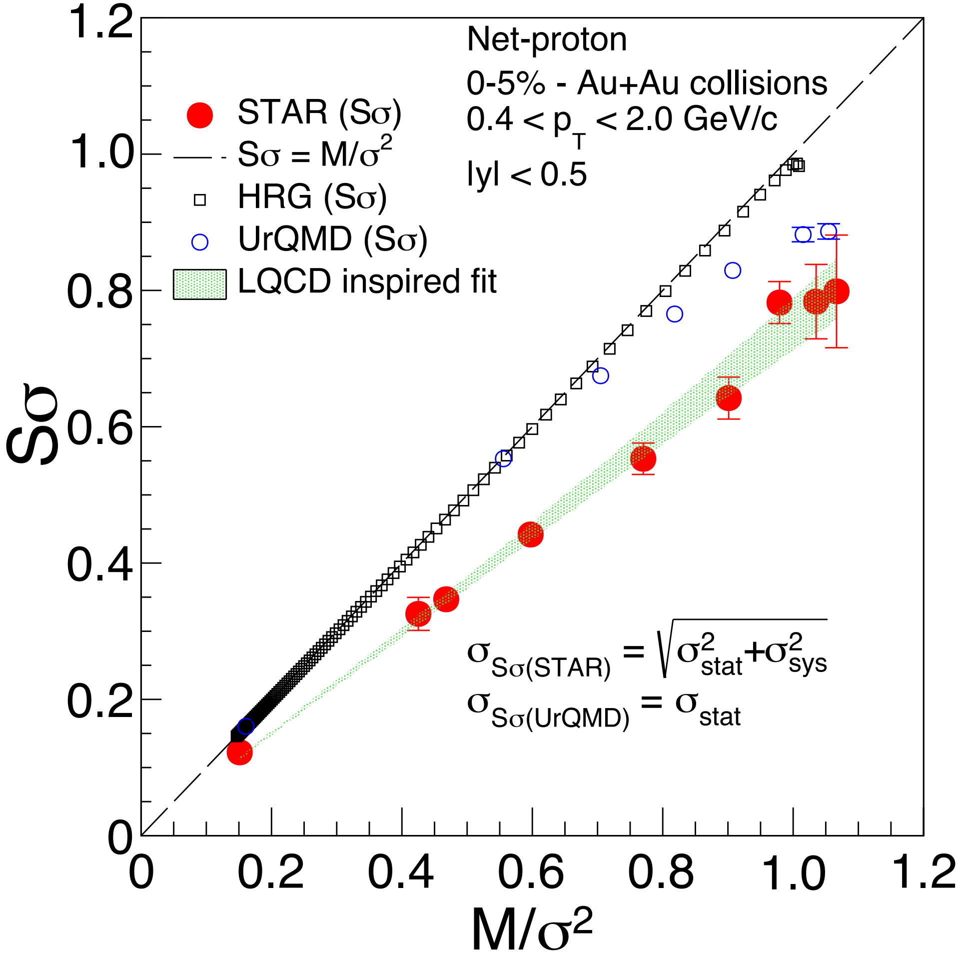
$p_{0eq1} = p_{0eq3}$ and $p_{1eq1} = p_{1eq3}$

$\frac{S\sigma^3}{M}$ **vs** $\frac{M}{\sigma^2}$ **fit**		$\kappa\sigma^2$ **vs** $\frac{M}{\sigma^2}$ **fit**	
p_{0eq1}	0.737923± 0.0123468	p_{0eq2}	0.738311± 0.146083
p_{1eq1}	0.0108781 ± 0.0262533	p_{1eq2}	−0.226858± 0.340679
χ^2/ndf	0.97	1.41	



In discussion with F. Karsch, N. Xu and A. Pandav

Net-proton higher moments: data and theory

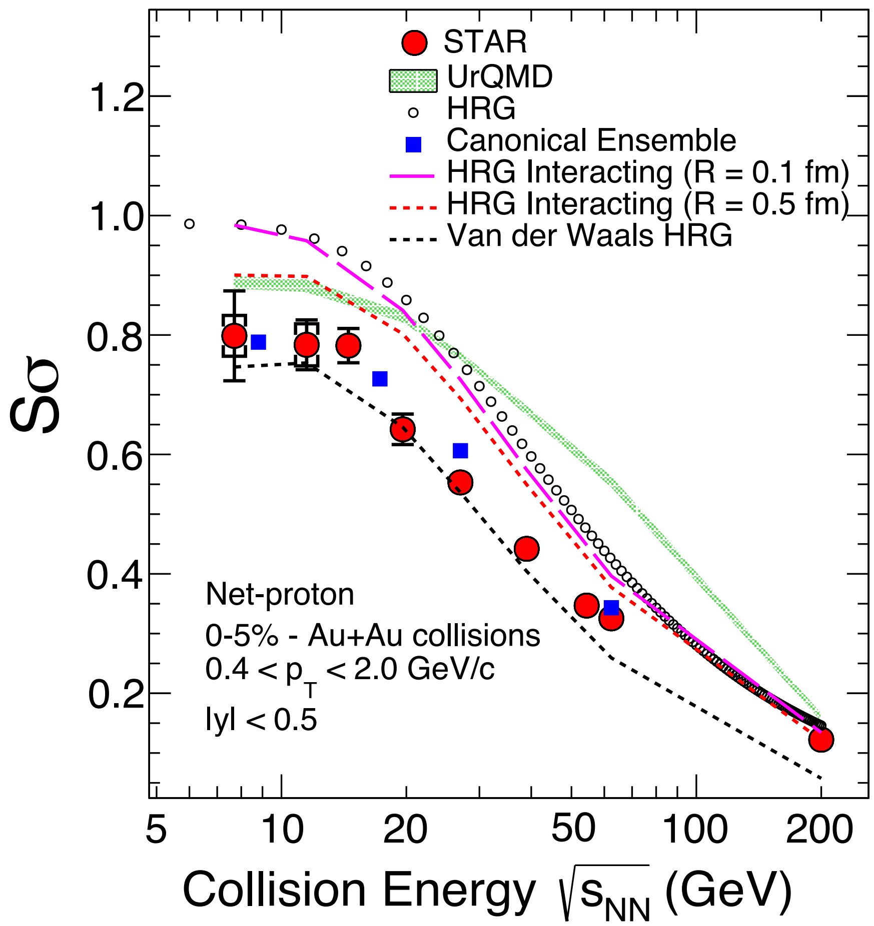


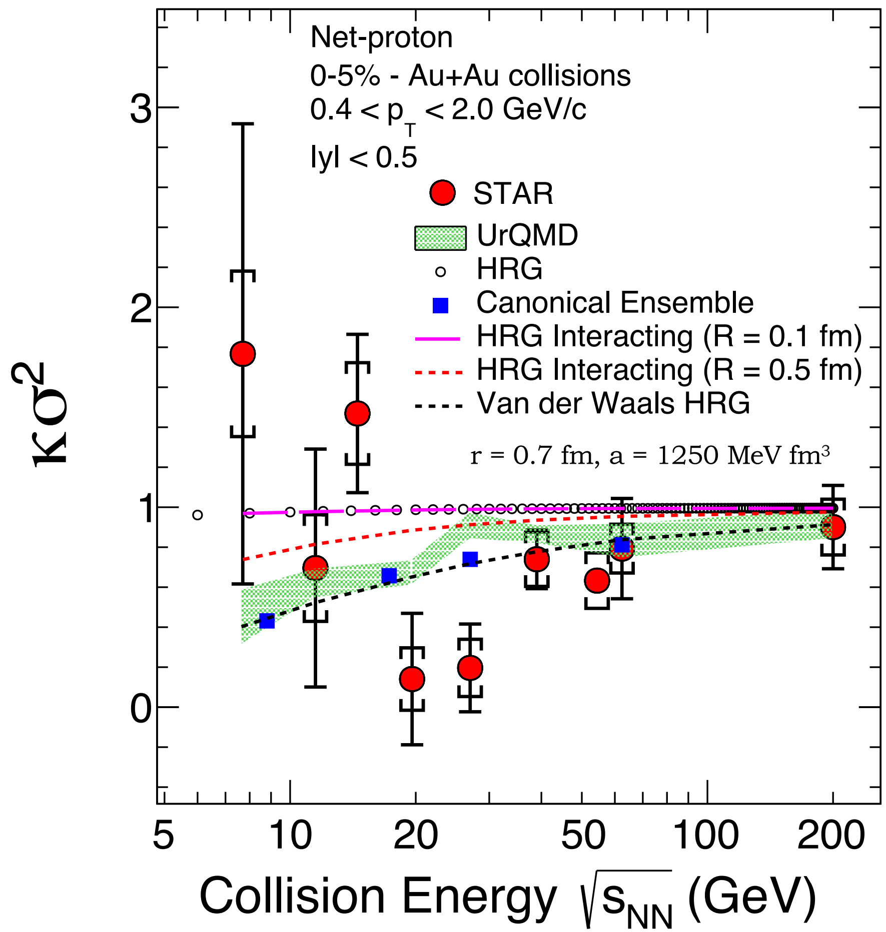
In discussion with F. Karsch, N. Xu and A. Pandav

Data STAR: arXiv: 2001.02852*

✓ Higher collision energy data and LQCD (inspired) features similar.
✓ Measurements deviate from HRG and UrQMD calculations.
→ Strongly interacting QCD matter.

Net-proton higher moments and HRG





Data compared to various variants of HRG Model (1) Grand canonical ensemble, (2) Canonical ensemble, (3) Excluded volume & (4) Van der Waals.

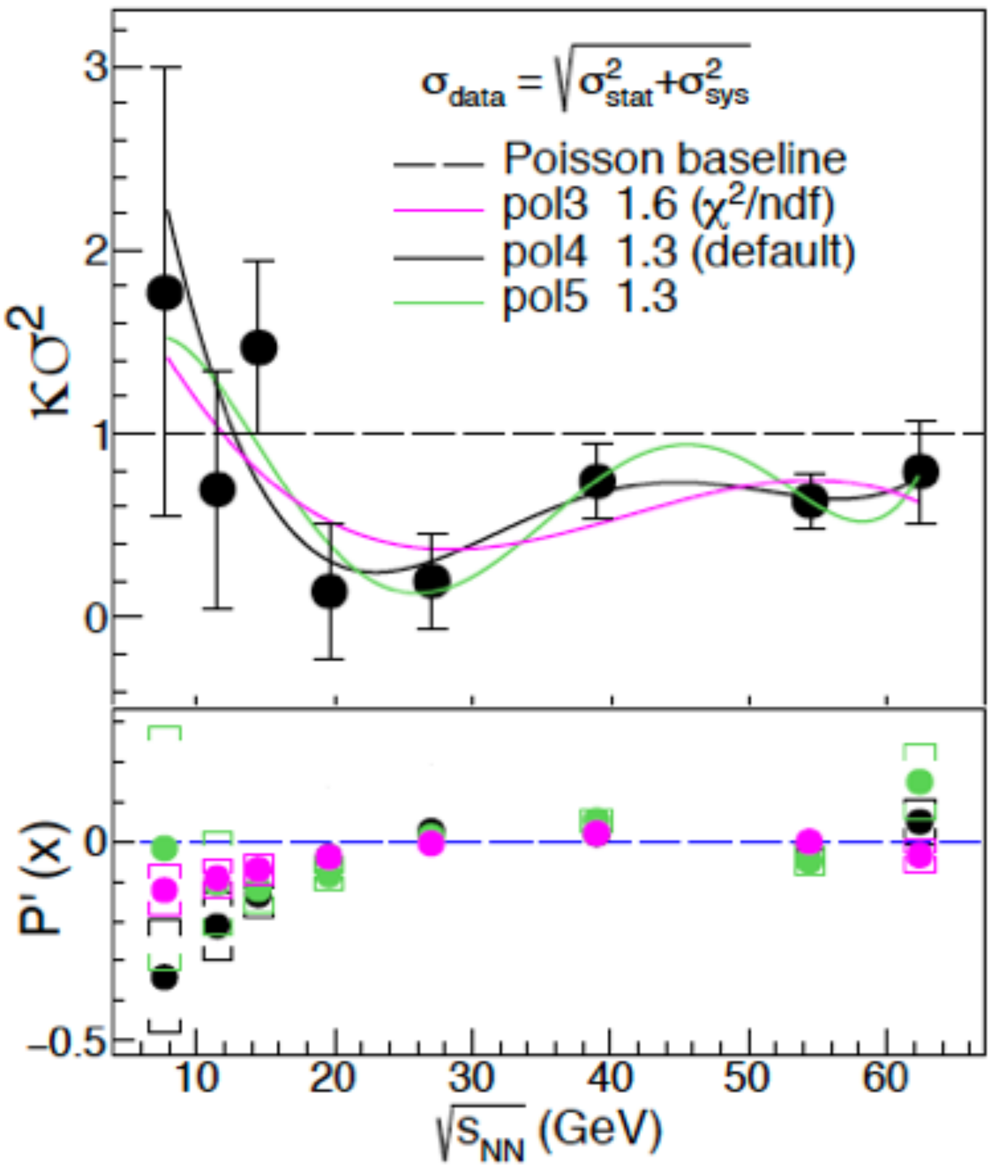
P. Garg et al, *Phys.Lett.B* 726 (2013) 691-696
S. Samanta, BM, e-Print: 1905.09311
A.Bhattcharyya et al., Phys.Rev.C 90 (2014) 3, 034909
PBM et al., e-Print: 2007.02463 [nucl-th]

In discussion with N. Xu, S. Samanta and A. Pandav

Non-monotonic variation

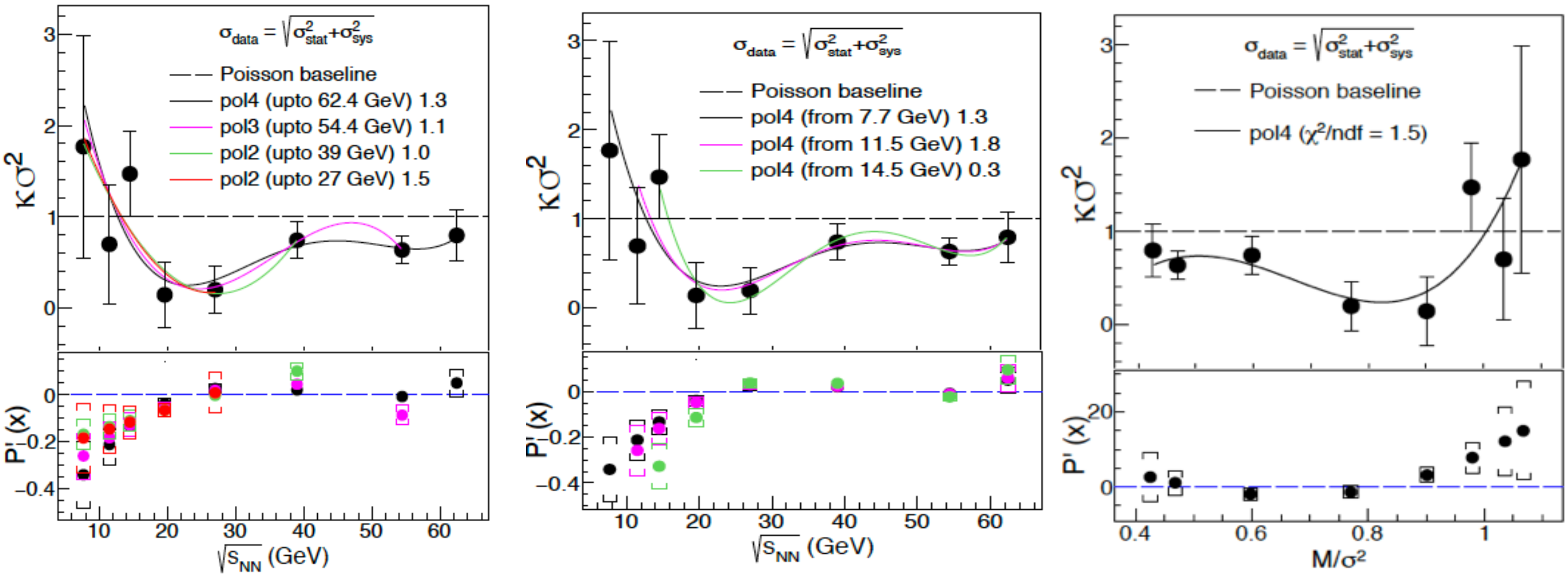
1. Fit the data to polynomial function.
2. Take the best fit function.
3. Obtain derivative of the function.
4. If sign changes, then dependence is non-monotonic.

1. Randomly vary each data point within its uncertainties.
2. Do this 1 million times.
3. Each time fit to the polynomial function and obtain derivatives at each energy.
4. Find out the number of times all the derivatives have same sign.
5. Probability at least one derivative value is of different sign = 0.998857.
6. Significance = 3.05.



In discussion with A. Pandav

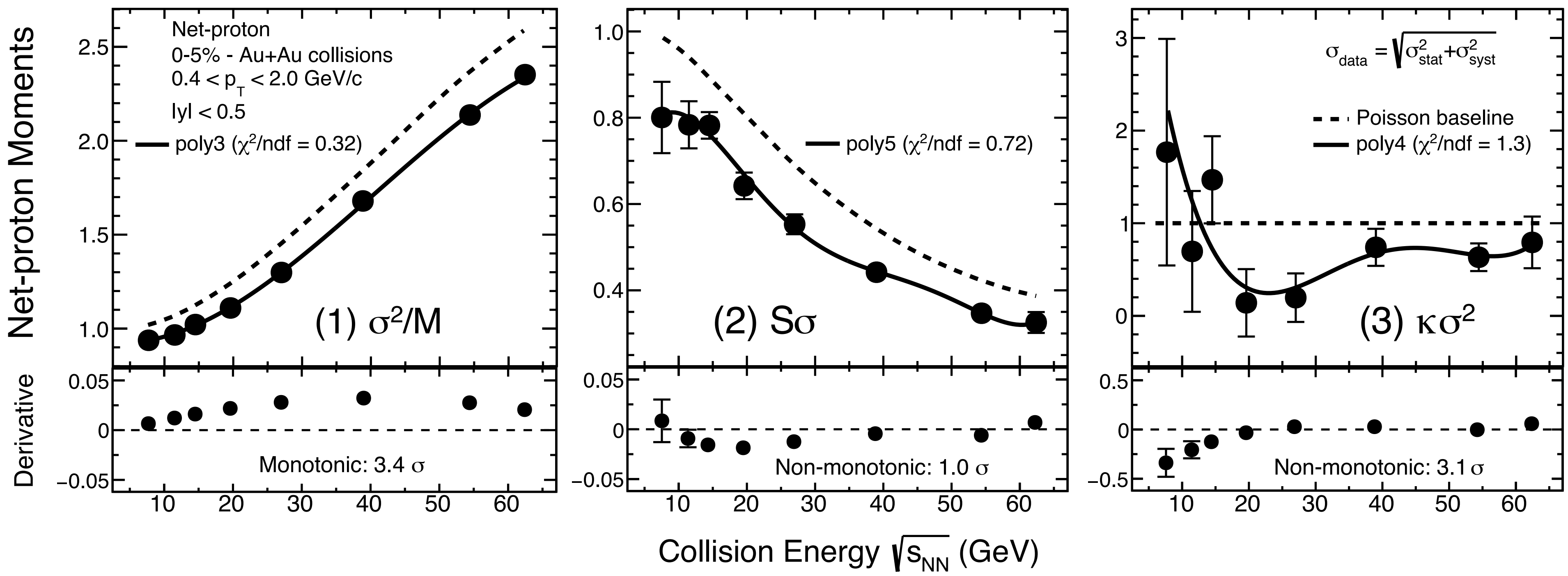
Non-monotonic variation



1) The results are robust to variation of fit range with energy.
2) Similar significance when studied $\kappa\sigma^2$ versus M/σ^2.

STAR: arXiv: 2001.02852

Collision energy dependence



STAR: arXiv: 2001.02852

Data	Monotonic	~ Non-Monotonic	Non-Monotonic
Theory	$\langle(\delta N)^2\rangle \approx \xi^2$	$\langle(\delta N)^3\rangle \approx \xi^{4.5}$	$\langle(\delta N)^4\rangle \approx \xi^7$

M. Stephanov: *PRL*102, 032301(09)

Higher moments/cumulants are sensitive observables.

In discussion with A. Pandav and N. Xu

Upcoming results

- BES-II.
- Fixed Target.
- 5^{th}, 6^{th} , 7th and 8th Order Correlations.

Possibility of STAR running in 2023-2025 with Au+Au at 200 GeV to collect ~ 15-20 Billion events will help higher order correlation measurements.

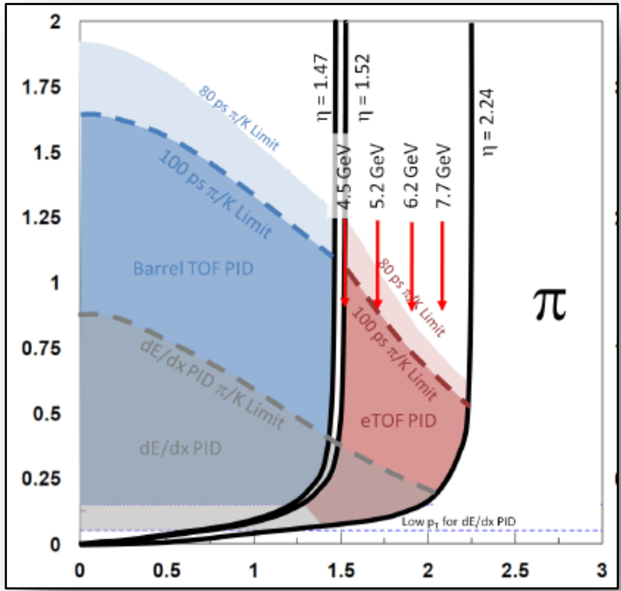
2019 - 2021: BES-II at RHIC

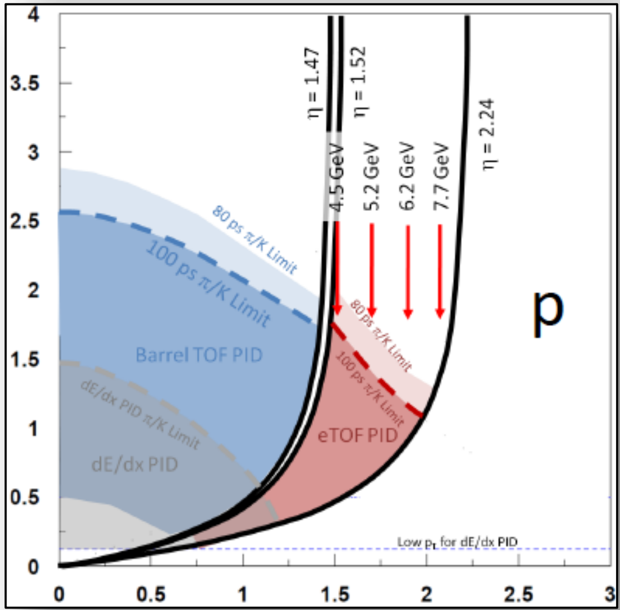
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	1200	2017		90	
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-21** / 2011	**3**	206	160
14.5	**300** / 20	**2019-21** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-21** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-21** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-21** / 2010	**14**	420	140

Precision measurements: map the QCD phase diagram **$200 < \mu_B < 420$ MeV**.

RHIC – Fixed Target Program

Collider Energy	Fixed-Target Energy	Single beam AGeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721
5.0	2.5	1.6	0.82	774



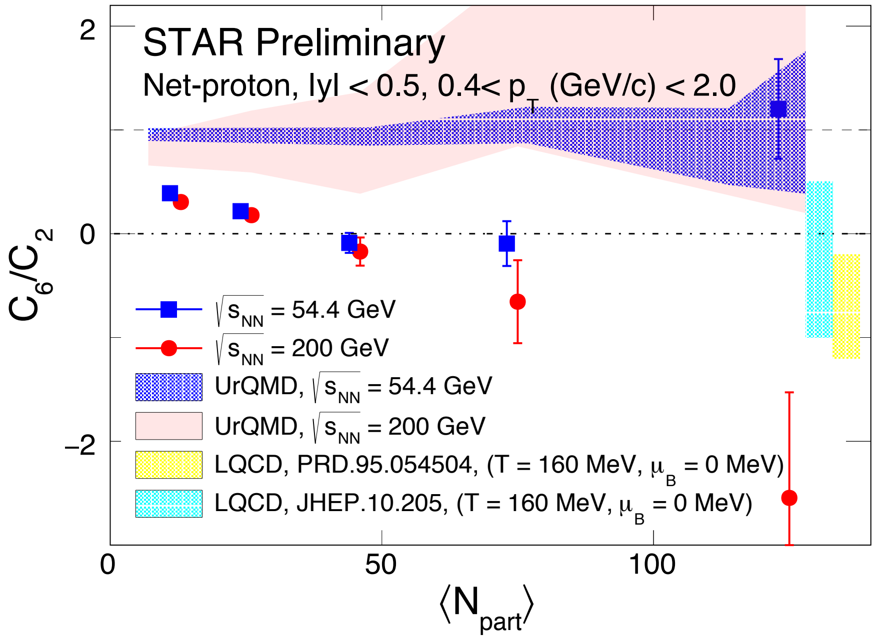


D. Cebra: INT Program INT-16-3: Exploring the QCD Phase Diagram through Energy Scans. **Extend scan to 750 MeV in μ_B.**

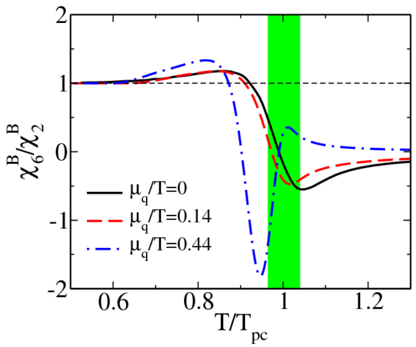
Sixth order correlations

Goal: Identification of O(4) chiral criticality on the phase boundary.

Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~2	~10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~0.5	<0	~1	<0



B. Friman et al, Eur.Phys.J. C71 (2011) 1694



The C_6 of baryon number and electric charge fluctuations remain negative at the chiral transition temperature.

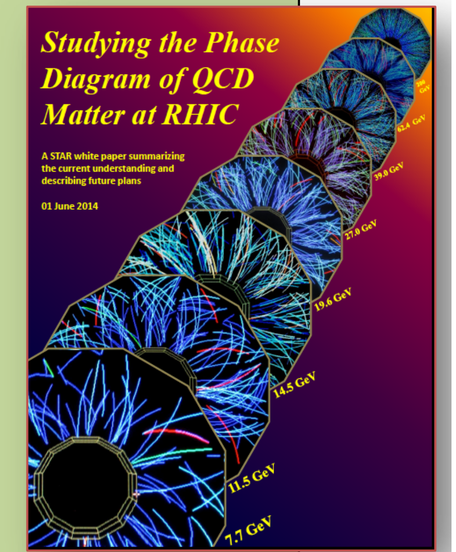
For most central collisions (0-40%)
$C_6/C_2 < 0$ at 200 GeV
$C_6/C_2 > 0$ at 54.4 GeV

STAR: A. Pandav and T. Nonaka

Observed a **negative sign** of C_6/C_2 of net-proton distribution for most central collisions at 200 GeV.

Summary

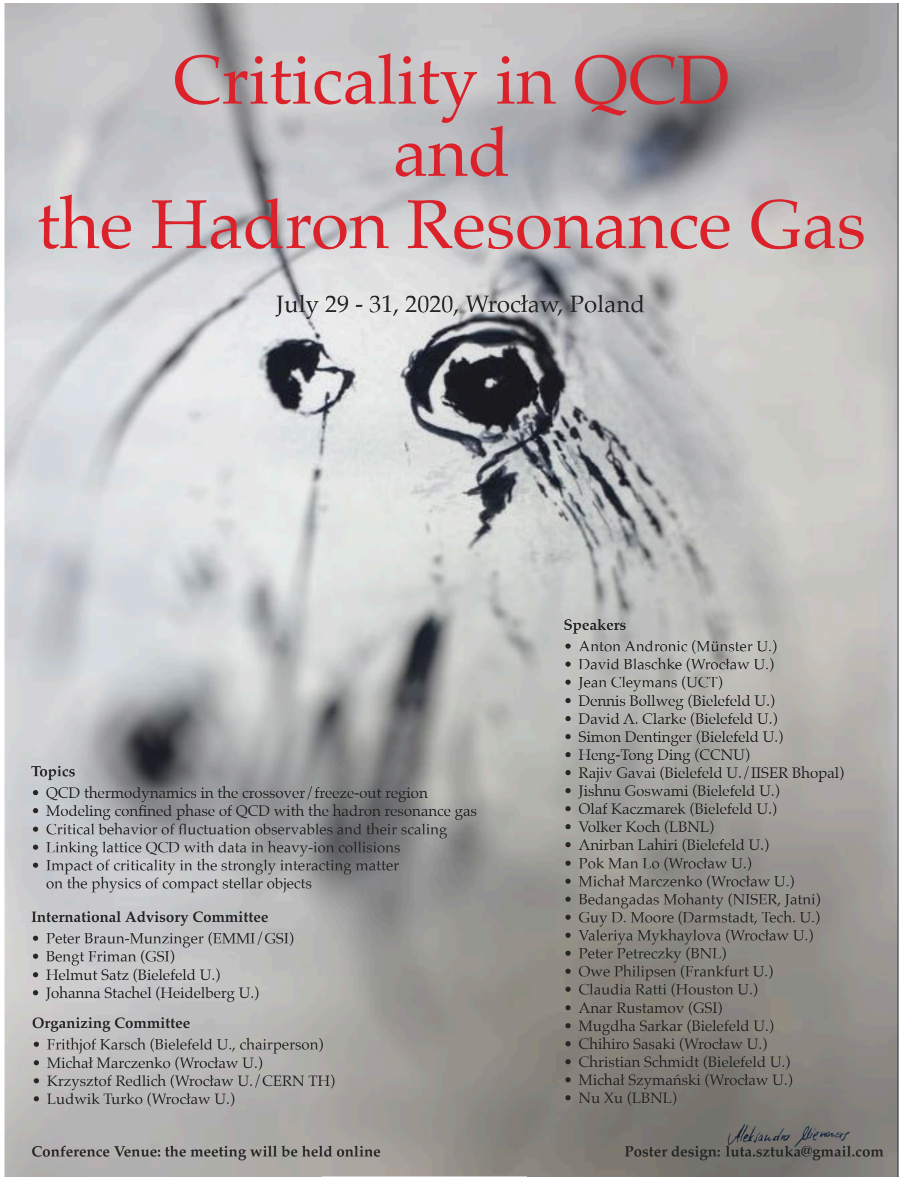
1) **STAR BES-I** was successfully completed. **Non-monotonic variation** of $\kappa\sigma^2$ with collision energy observed with **3 sigma significance.**
2) **BES-II** is underway. The focus is in the region of **7.7 – 19.6 GeV** in collider mode.
3) **FXT mode** will extend the energy down to 3 GeV ($\mu_B \sim 750 MeV$).
4) **Higher Order** correlation results – related to cross-over and 1st order transitions will get **available soon**.



Acknowledgements

All members of the STAR Collaboration, F. Karsch and S. Gupta.

Thanks to the organizers for the invitation.



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