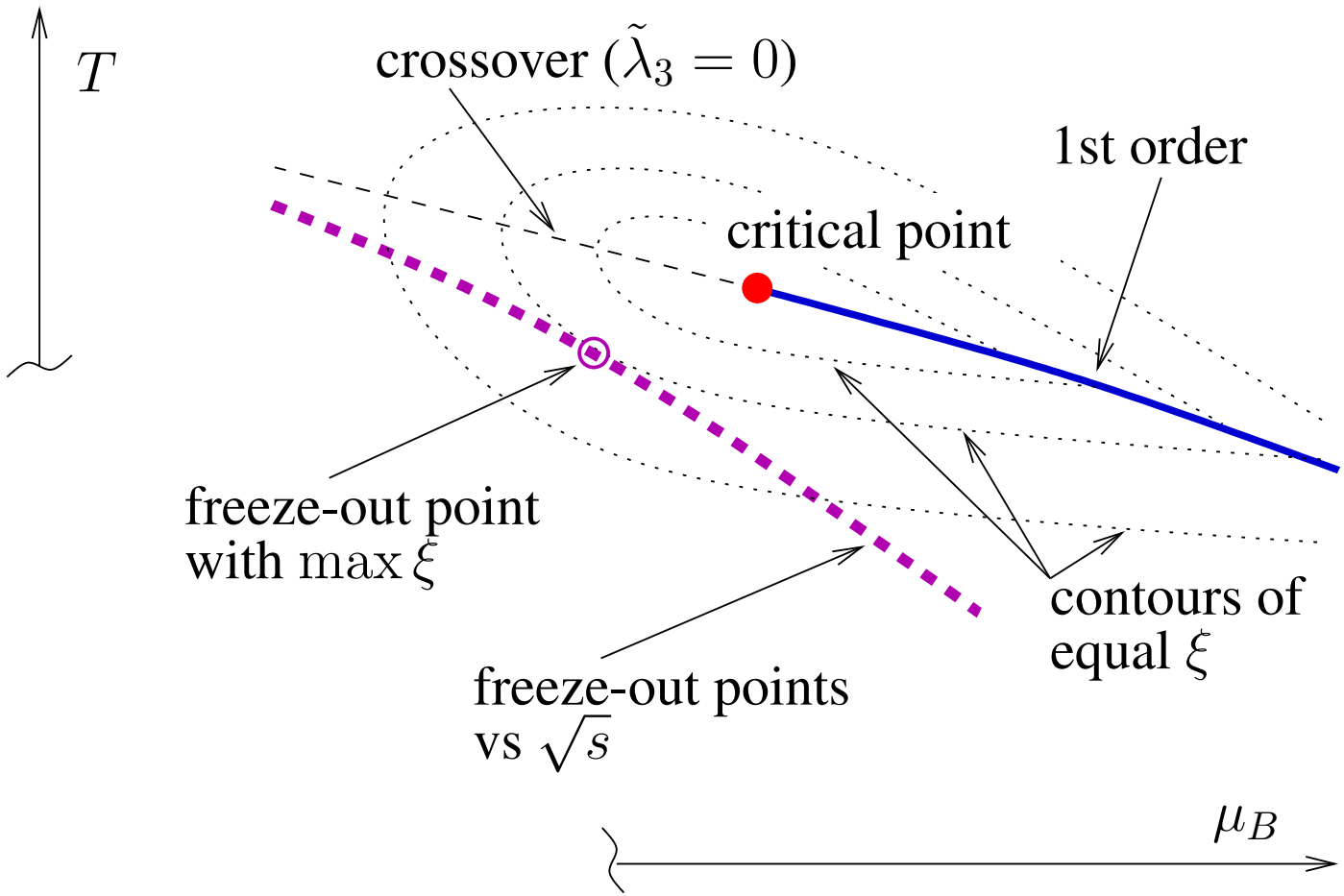
QCD critical point searches at STAR

Matthias Heinz

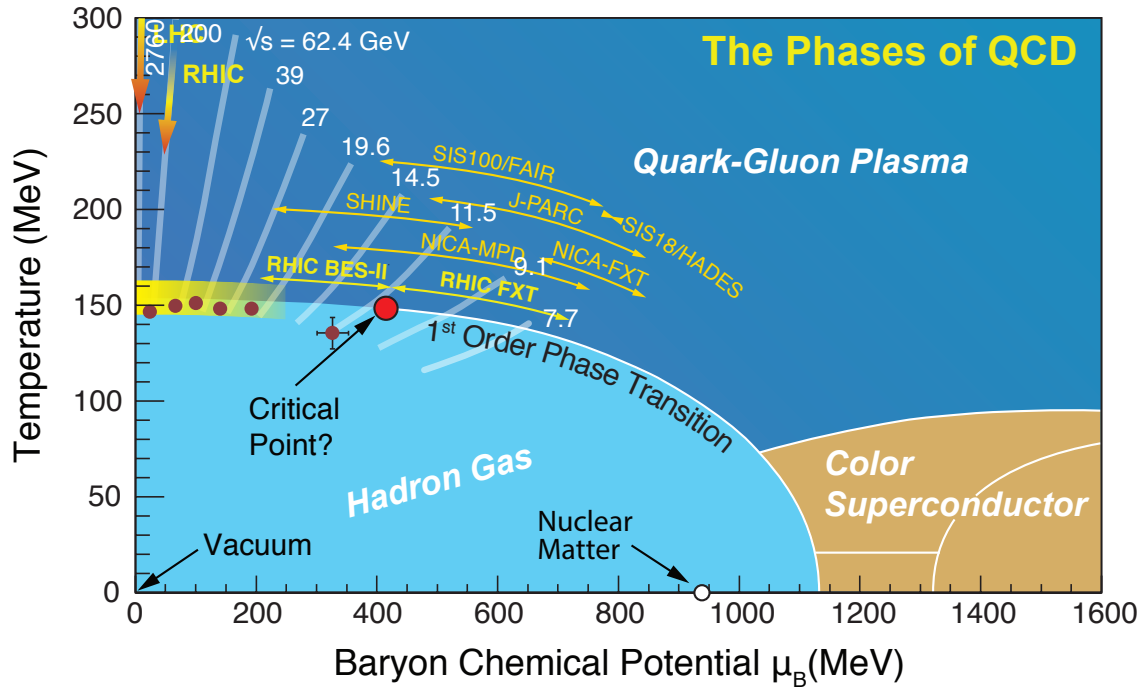
TECHNISCHE UNIVERSITÄT DARMSTADT



The RHIC beam energy scan

TECHNISCHE UNIVERSITÄT DARMSTADT

- Quark-gluon plasma
- Hadron gas
- First-order phase transition and critical point



Caines 2017

Critical point physics

Stephanov, Rajagopal

TECHNISCHE UNIVERSITÄT DARMSTADT

- Critical mode σ which develops infinite correlation length ξ near critical point
- Treat σ as a classical field
- Note that for the zero momentum mode $\sigma_0 = \int d^3x \sigma(x)/V$, there are cumulants:

$$\kappa_2 = \left\langle \sigma_0^2 \right\rangle = \frac{T}{V}\xi^2$$

$$\kappa_3 = \left\langle \sigma_0^3 \right\rangle \sim \frac{T}{V}\xi^6$$

$$\kappa_4 = \left\langle \sigma_0^4 \right\rangle_c \sim \frac{T}{V}\xi^8$$

- Higher-order cumulants are especially sensitive to the increase in the correlation length

Critical point observables

TECHNISCHE UNIVERSITÄT DARMSTADT

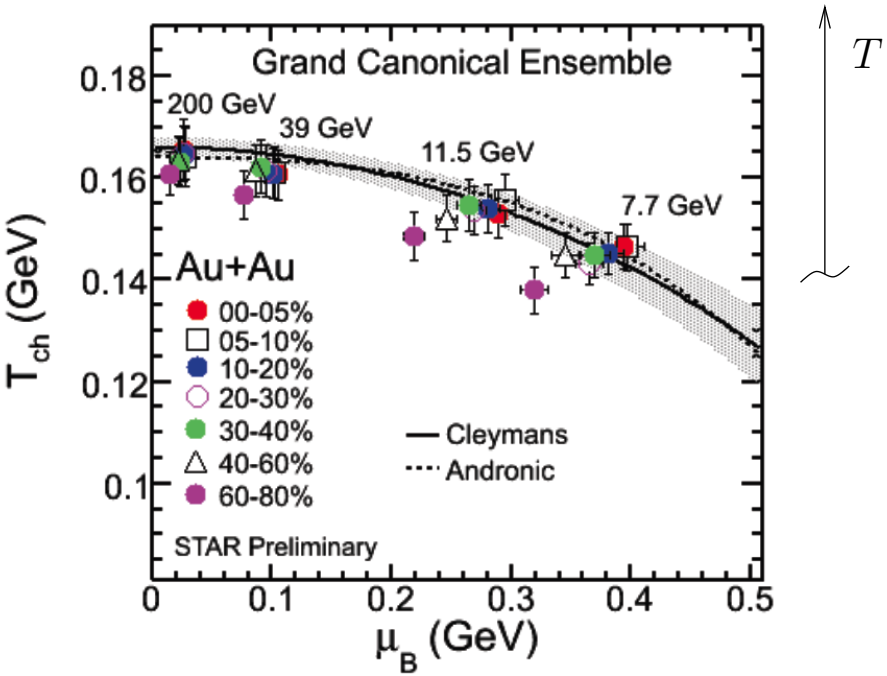
- Can adopt similar approach to distributions of conserved quantities in experiment
  - Net baryon number B
  - Net charge Q
  - Net strangeness S
- Connect to theory via susceptibility χ

$$\chi_B^{(n)} = \frac{1}{VT^3} C_{n,B}$$

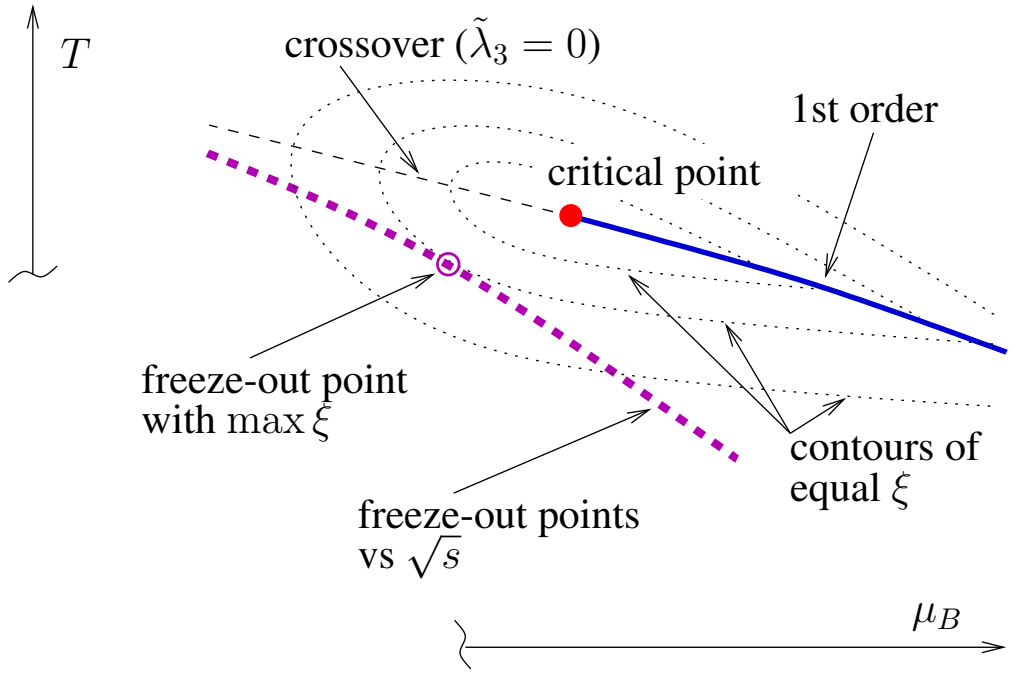
- Measurments of event-by-event fluctuations of conserved quantities allow us to observe critical point

Overall approach

- Lower $\sqrt{s_{NN}}$ probes larger μ_B
- At beam energy scan energies, collision centrality affects μ_B as well



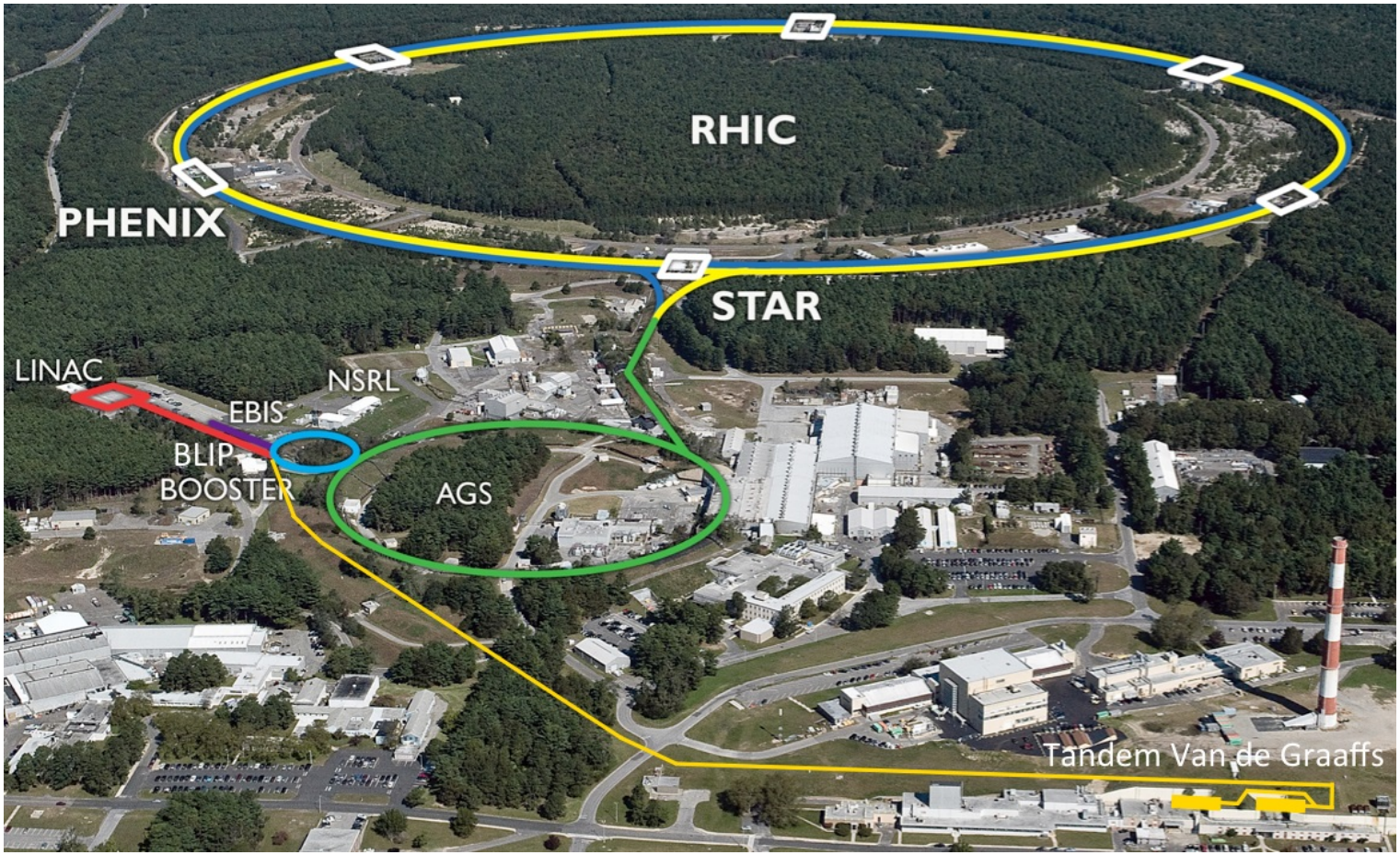
STAR (Schmah et al.) 2013



Stephanov 2009

The STAR detector

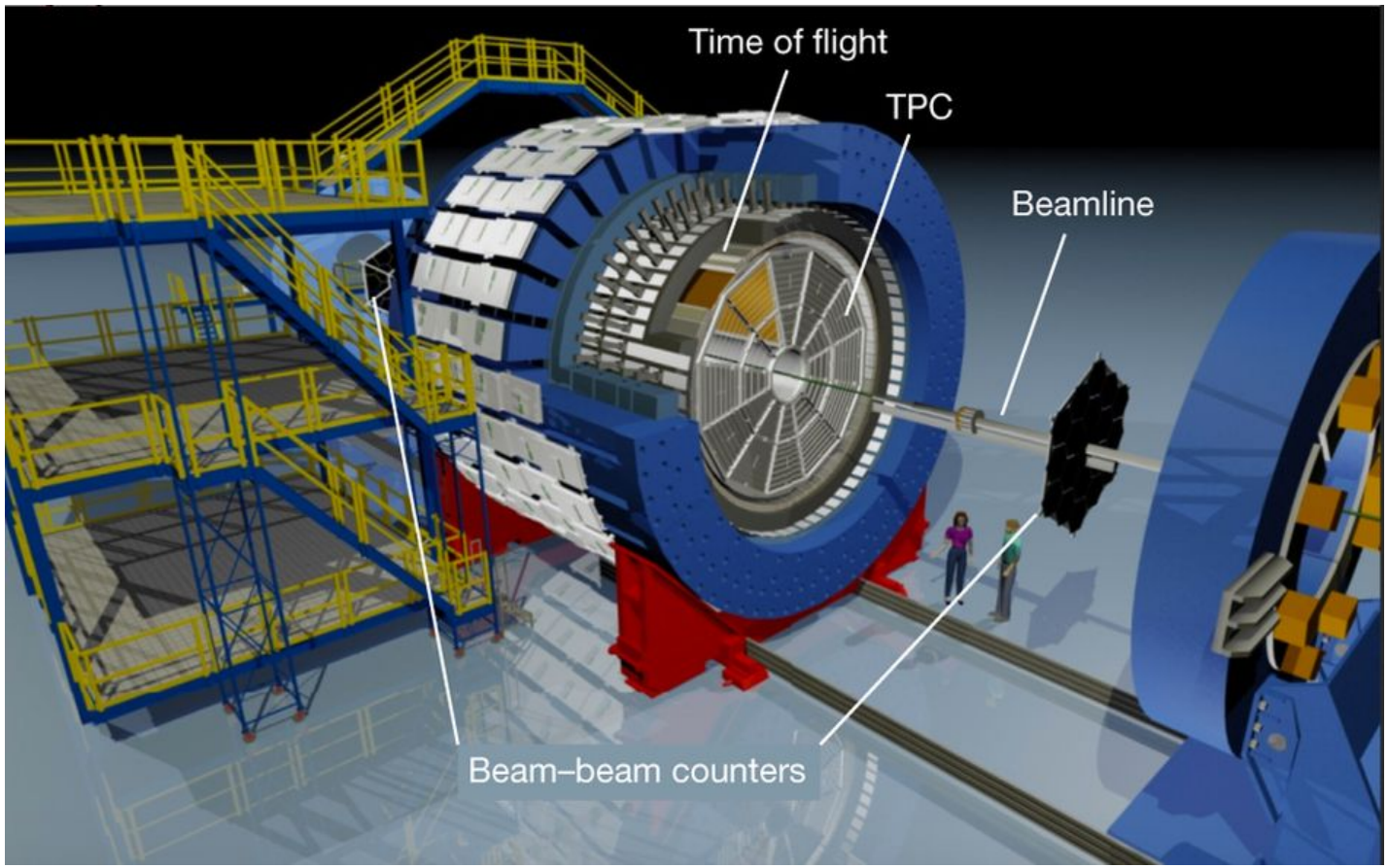
TECHNISCHE UNIVERSITÄT DARMSTADT



BNL 2019

The STAR detector

TECHNISCHE UNIVERSITÄT DARMSTADT



STAR (Adamcyzk et al.) 2017

Net proton number measurements

TECHNISCHE UNIVERSITÄT DARMSTADT

- Consider net proton number ΔN_p as proxy for net baryon number
- Can also consider as proxy for net charge number

$$\Delta N_p = N_p - N_{\bar{p}}$$

- Au+Au collisions
- Center-of-mass energies: 7.7, 11.5, 19.6, 27, 39, 62.4, and 200 GeV
- Transverse momentum range: $0.4 < p_T < 2$ GeV/c
- Pseudorapidity acceptance: $|\eta| < 1.0$

Centrality bin width correction

TECHNISCHE UNIVERSITÄT DARMSTADT

- Minimum centrality bin size is single value for particle multiplicity
- Typically work in terms of ranges, like 0-5%
- Need to correctly assemble cumulant value within a larger centrality bin

$$C_n = \frac{\sum_{r=N_1}^{N_2} n_r C_n^r}{\sum_{r=N_1}^{N_2} n_r} = \sum_{r=N_1}^{N_2} \omega_r C_n^r$$

- Corrected cumulants can be used to compute cumulant ratios
- Propagation of statistical errors is straightforward
- Question: Why not apply the same treatment to cumulant ratios?

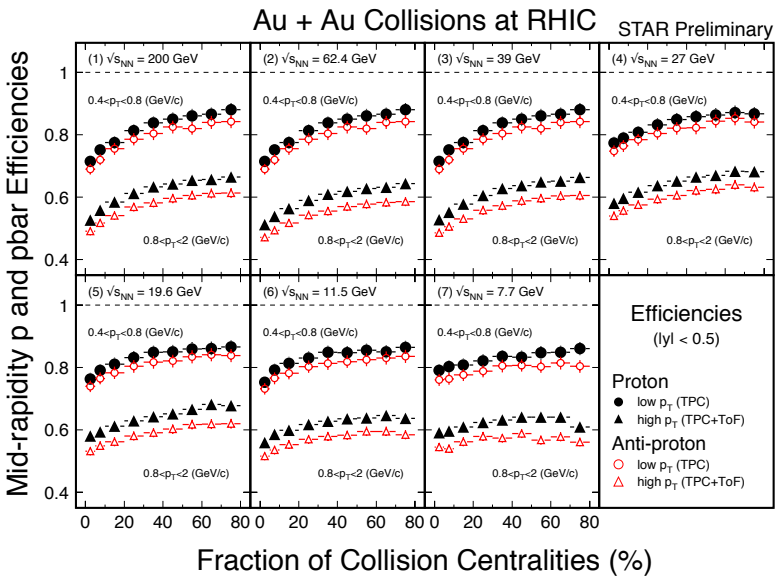
$$\frac{\sum_{r=N_1}^{N_2} \omega_r C_n^r}{\sum_{r=N_1}^{N_2} \omega_r C_m^r} \neq \sum_{r=N_1}^{N_2} \omega_r \frac{C_n^r}{C_m^r}$$

Determining centrality

TECHNISCHE UNIVERSITÄT DARMSTADT

- Care needs to be taken when determining centrality
- In general, more particles used in centrality allows for better resolution
- However, we need to avoid autocorrelation effects by determining centrality with the same particles used later in the analysis
- Introduce new centrality definition:
  - For net-proton analyses, determine centrality with charged kaon and pion multiplicities in $|\eta| < 1$
  - For net-charge analyses (not discussed here), use particles in $0.5 < |\eta| < 1$ and do analysis with particles in $|\eta| < 0.5$

Efficiency correction and statistical error estimation

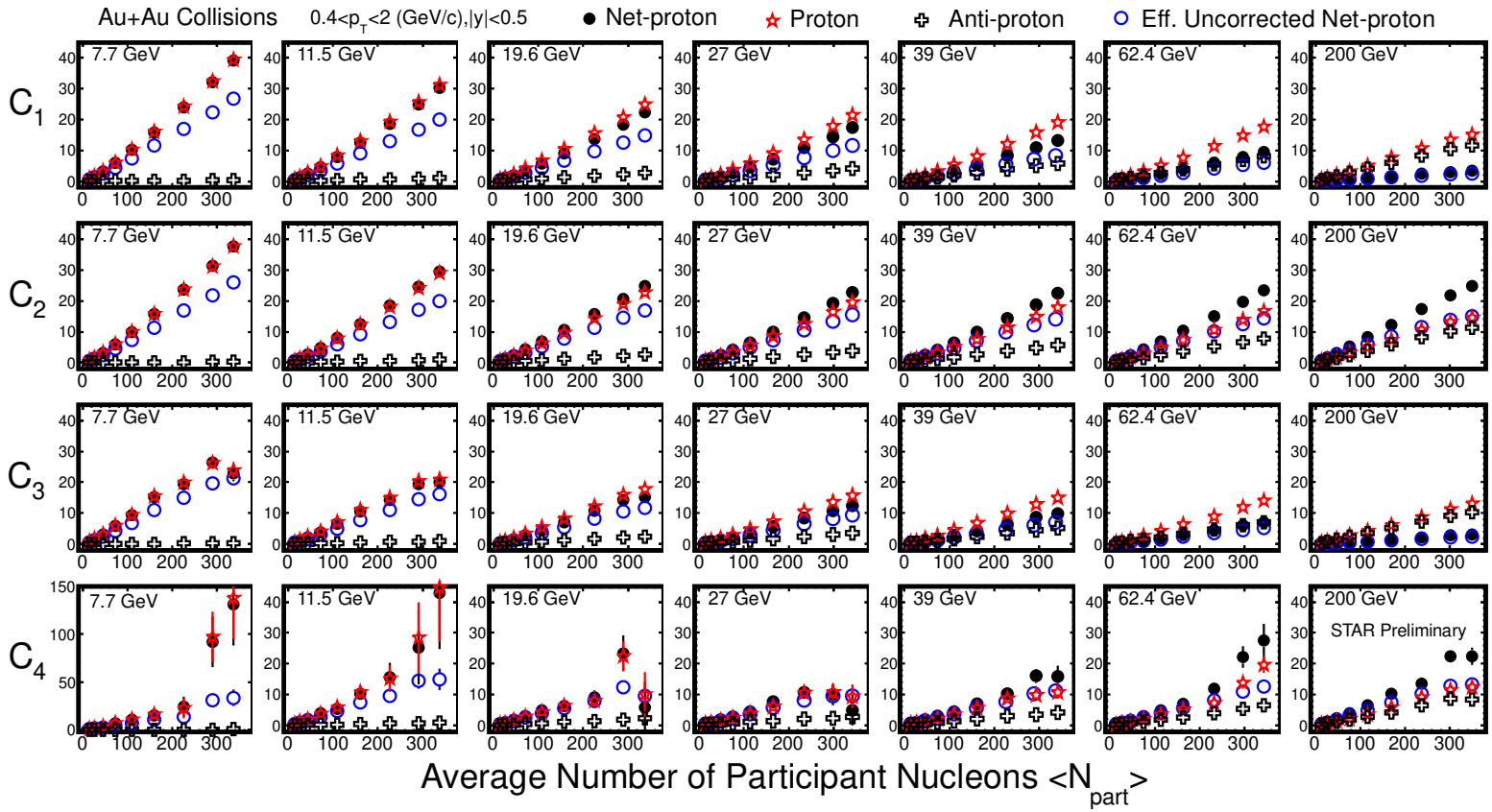


STAR (Luo et al.) 2015

- Need to account for detector efficiency
- Particle identification is handled differently for low and high p_T
  - For $0.4 < p_T < 0.8$ GeV/c, only the TPC is used
  - For $0.8 < p_T < 2.0$ GeV/c, both TOF and TPC are used
- Estimate statistical error along with efficiency correction (Delta theorem)
- Should take place just before doing centrality bin width correction

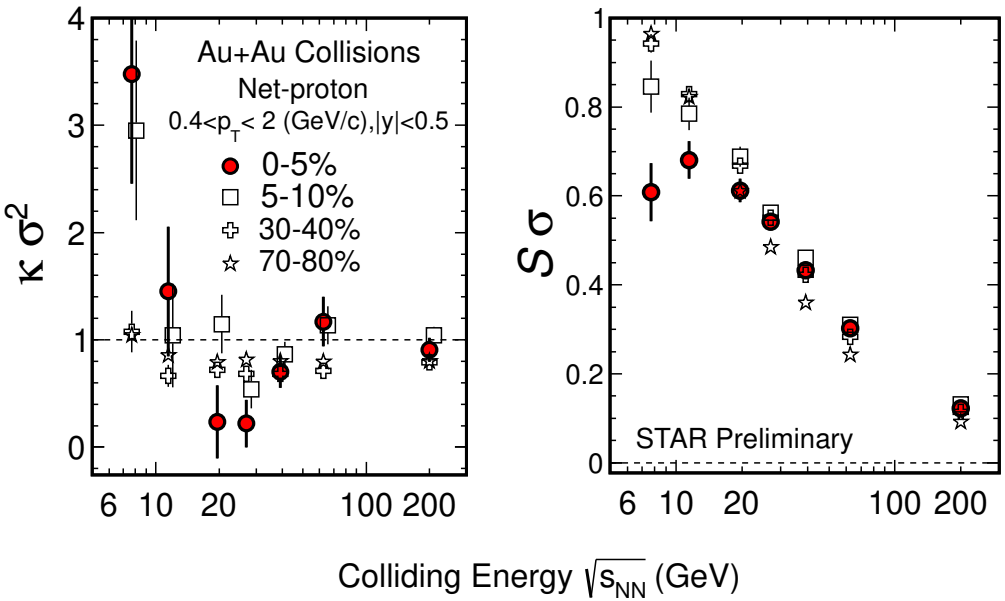
Observed cumulants up to fourth order

TECHNISCHE UNIVERSITÄT DARMSTADT



STAR (Luo et al.) 2015

Cumulant ratios



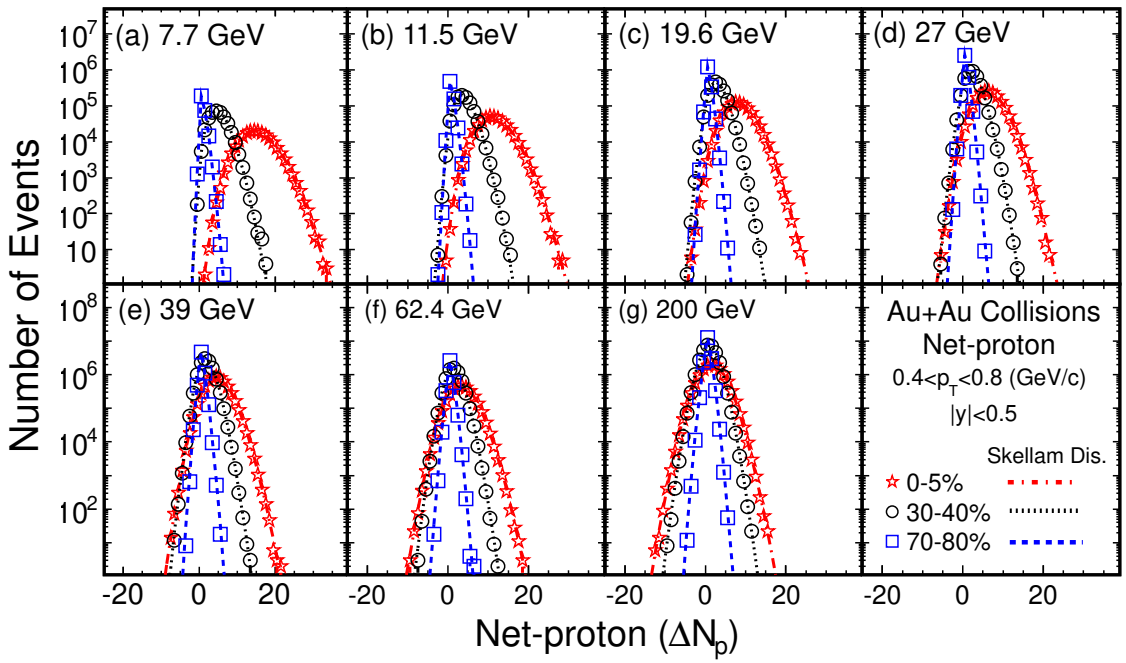
STAR (Luo et al.) 2015

$$\kappa\sigma^2 = C_4/C_2$$

$$S\sigma = C_3/C_2$$

- Form ratios of cumulants to cancel volume and temperature dependence
- S is skewness
- κ is kurtosis

Skellam distributions

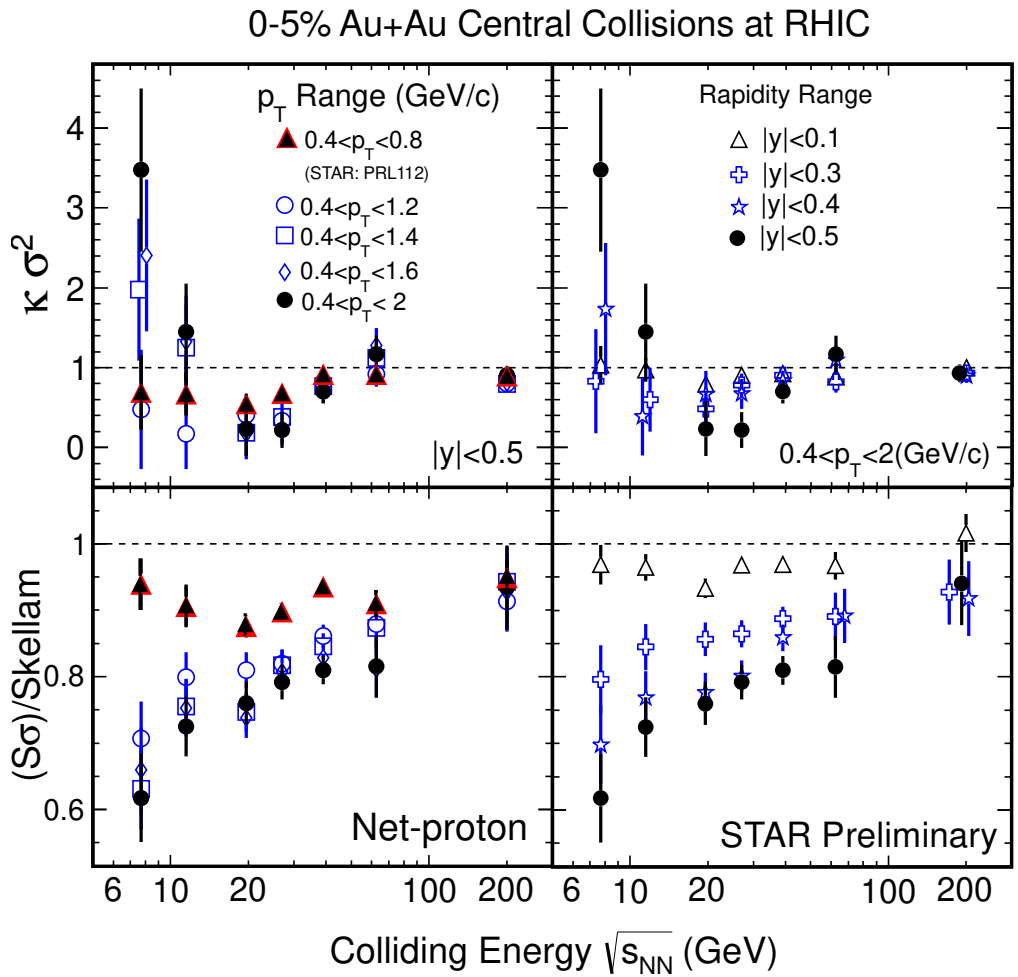


STAR (Adamcyzk et al.) 2014

- Assume protons and anti-protons are distributed as if sampled from independent Poisson distributions
- Represents thermal statistical fluctuations of net-proton number

$\kappa\sigma^2$ and $S\sigma$/Skellam

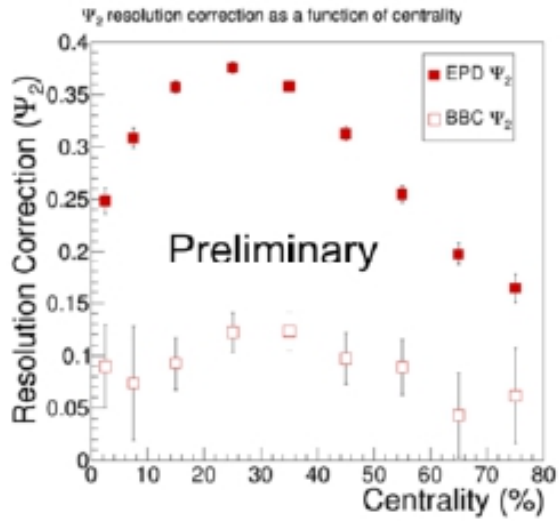
TECHNISCHE UNIVERSITÄT DARMSTADT



Beam energy scan II

TECHNISCHE UNIVERSITÄT DARMSTADT

- Run at $\sqrt{s_N N}$ = 9.1 GeV in addition to BES-I energies
- Energies below 7.7 GeV via fixed-target program
- Detector upgrades:
  - iTPC: inner time projection chamber with wider acceptance $|\eta| < 1.5$ and higher resolution
  - EPD: event plane detector to better determine event plane and offer improved centrality determination

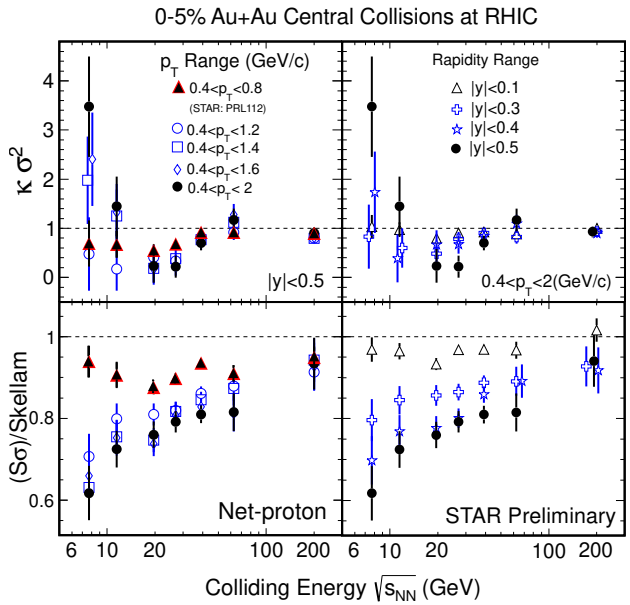


STAR (Yang et al.) 2019

Summary

TECHNISCHE UNIVERSITÄT DARMSTADT

- Key ideas:
  - Look to higher cumulants of distribtions of conserved quantities
  - Use ratios to cancel dependence on quantities other than ξ
  - Look for non-monotonic behavior in ratios
- Results seem suggestive, but not conclusive
- Would like theoretical predictions for susceptibility ratios
- Need better statistics $\rightarrow$ BES-II



STAR (Luo et al.) 2015

References I

Adamczyk, L. et al. (2014).
Energy Dependence of Moments of Net-proton Multiplicity Distributions at RHIC.
Phys. Rev. Lett., 112:032302.

Adamczyk, L. et al. (2017).
Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid.
Nature, 548:62–65.

References II

TECHNISCHE UNIVERSITÄT DARMSTADT


Agakishiev, H. et al. (2011).
Observation of the antimatter helium-4 nucleus.
Nature, 473:353.
[Erratum: Nature475,412(2011)].


Athanasiou, C., Rajagopal, K., and Stephanov, M. (2010).
Using Higher Moments of Fluctuations and their Ratios in the Search for the QCD Critical Point.
Phys. Rev., D82:074008.


BNL (2019).
https://www.bnl.gov/cad/accelerator/.

References III

TECHNISCHE UNIVERSITÄT DARMSTADT

Caines, H. (2017).
The Search for Critical Behavior and Other Features of the QCD Phase Diagram – Current Status and Future Prospects.
Nucl. Phys., A967:121–128.

Esha, R. (2018).
Measurement of the cumulants of net-proton multiplicity distributions by STAR.

PoS, CPOD2017:003.

References IV

Luo, X. (2015).
Energy Dependence of Moments of Net-Proton and Net-Charge Multiplicity Distributions at STAR.
PoS, CPOD2014:019.

Schmah, A. (2013).
The beam energy scan at RHIC: Recent results from STAR.
J. Phys. Conf. Ser., 426:012007.

Stephanov, M. A. (2009).
Non-Gaussian fluctuations near the QCD critical point.
Phys. Rev. Lett., 102:032301.

References V

TECHNISCHE UNIVERSITÄT DARMSTADT

Yang, Q. (2019).
The STAR BES-II and Forward Rapidity Physics and Upgrades.
Nucl. Phys., A982:951–954.