QCD critical point searches at STAR

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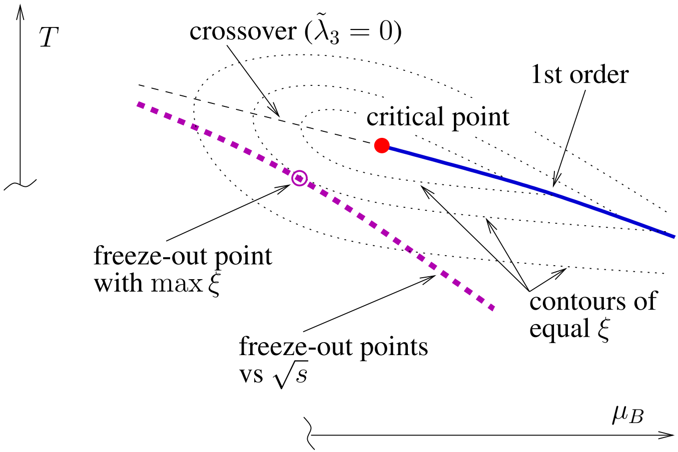
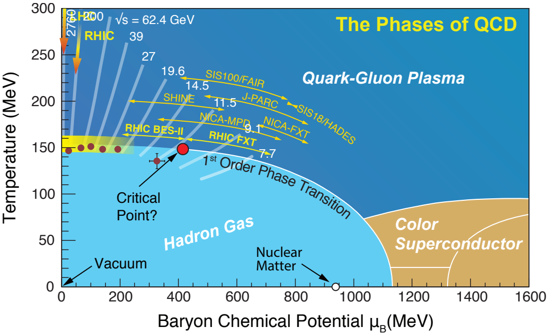


Stephanov 2009

The RHIC beam energy scan

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



Caines 2017

Critical point physics

Stephanov, Rajagopal

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- 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

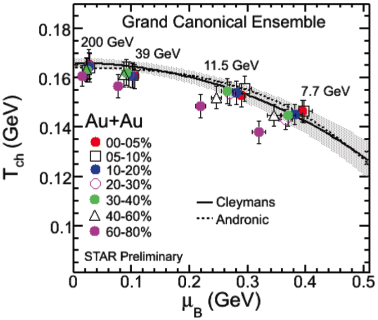
- Can adopt similar approach to distributions of conserved quantities in experiment
  - Net baryon number B
  - Net charge Q
  - Net strangeness S
- Connect to theory via susceptibility χ

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

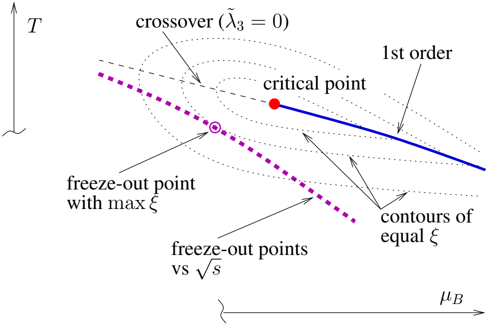
- Measurements of event-by-event fluctuations of conserved quantities allow us to observe critical point

Overall approach

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

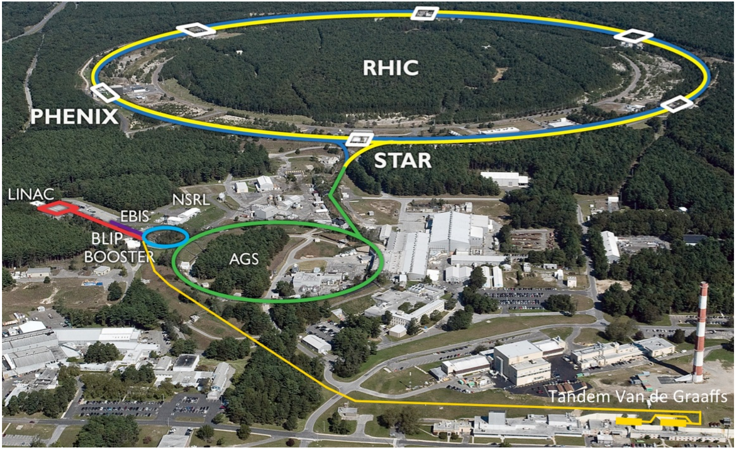


STAR (Schmah et al.) 2013



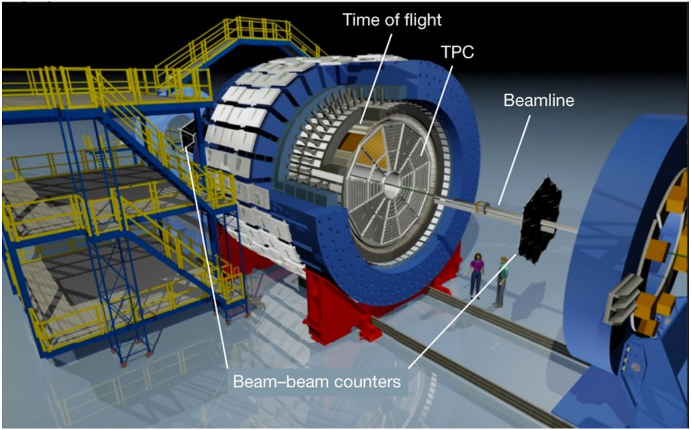
Stephanov 2009

The STAR detector



BNL 2019

The STAR detector



STAR (Adamcyzk et al.) 2017

Net proton number measurements

- 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

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- 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

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- 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

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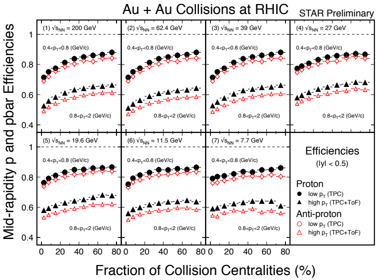

STAR (Luo et al.) 2015

- 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

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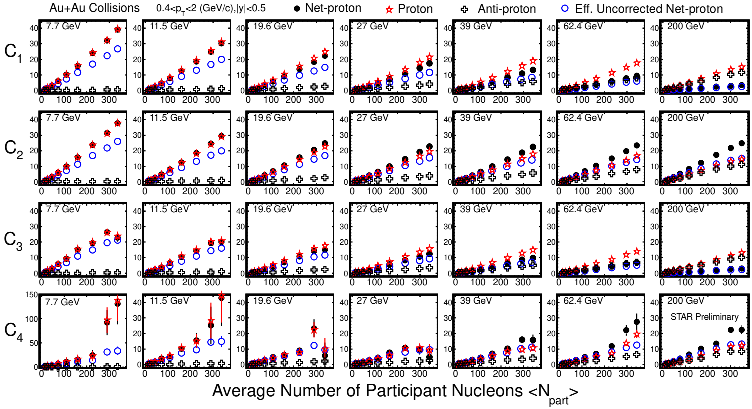
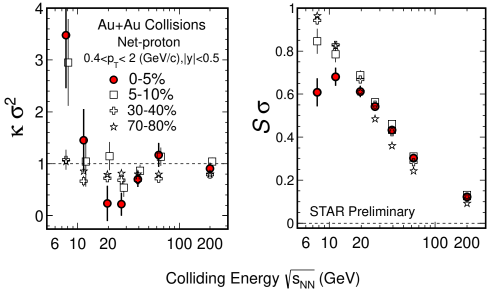


STAR (Luo et al.) 2015

Cumulant ratios



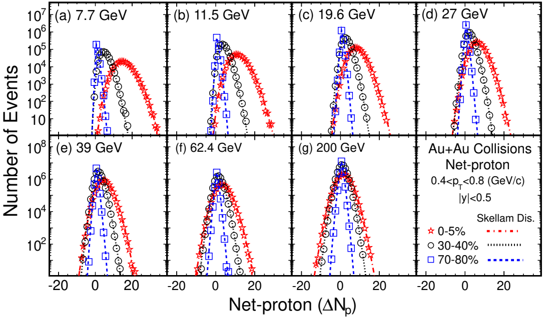
STAR (Luo et al.) 2015

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

$$S\sigma = C_3/C_2$$

- 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

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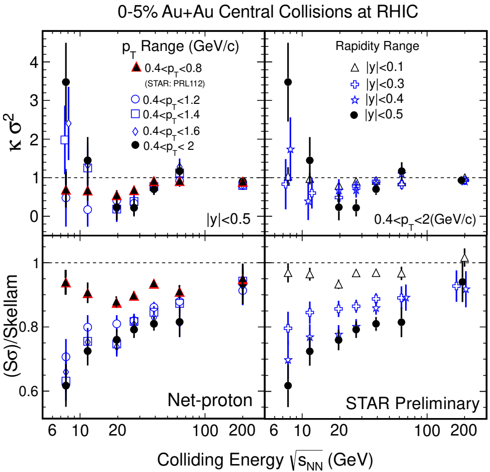
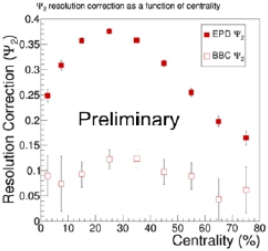


STAR (Luo et al.) 2015

Beam energy scan II

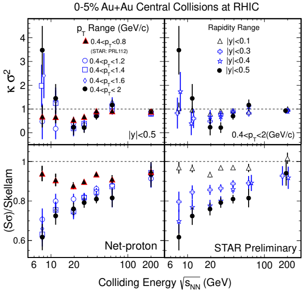
- Run at $\sqrt{s_{NN}}$ = 9.1 GeV in addition to BES-I energies
- Energies below 7.7 GeV via fixed-target program
- Detector upgrades:
  - iTPC: inner time projection chamber with wider acceptance $|\eta| < 1.5$ and higher resolution
  - EPD: event plane detector to better determine event plane and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



STAR (Yang et al.) 2019

Summary

- Key ideas:
  - Look to higher cumulants of distributions 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 → BES-II



STAR (Luo et al.) 2015

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