Measurement of Cumulants of Net-Charge Distributions in Au+Au Collisions at $\sqrt{s_{NN}} = 54.4$ GeV

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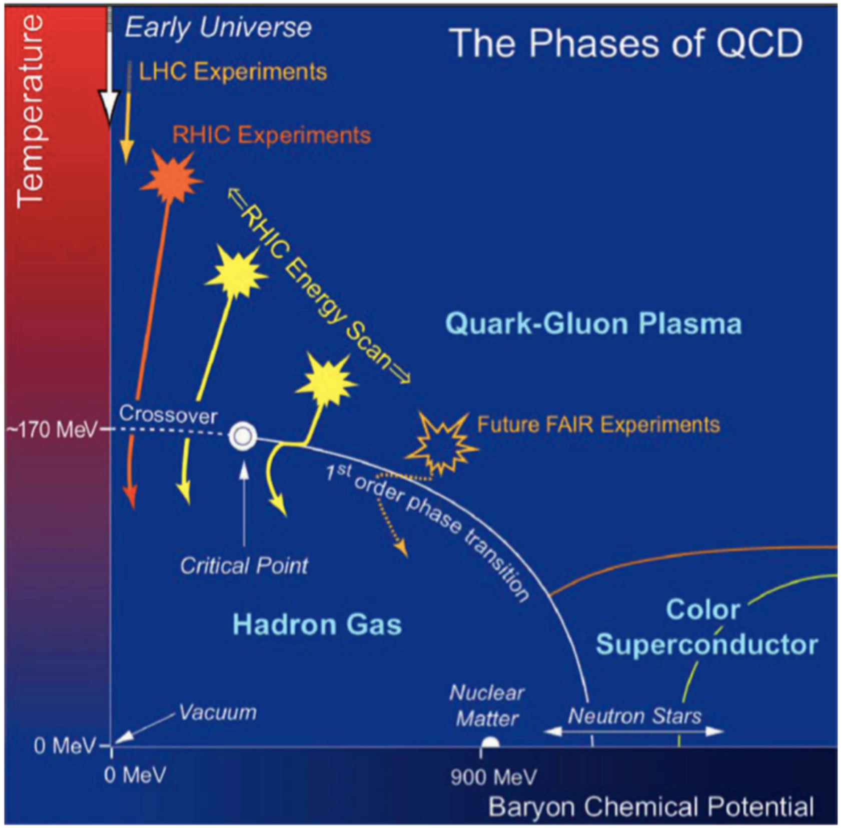
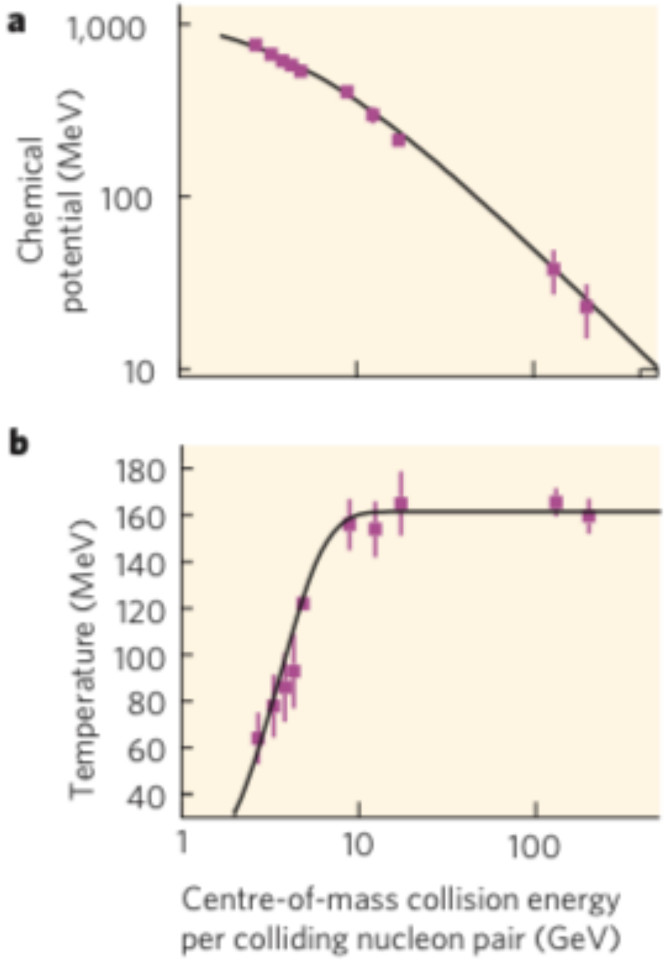
Motivation

Exploring the QCD Phase Diagram

✓ Study the properties of QGP medium.
✓ Search for the QCD critical point.





P. Braun-Munzinger & J. Stachel, Nature 448, 302-309 (2007)

STAR Internal Note on Studying the Phase Diagram of QCD Matter at RHIC - SN0598, (2014)

→ QCD phase diagram studied by varying the collision energy in heavy-ion collision experiments.

Observables

- ✓ Higher-order cumulants are sensitive to QCD phase transition.
- ✓ Connection to the susceptibility of the system (χ).

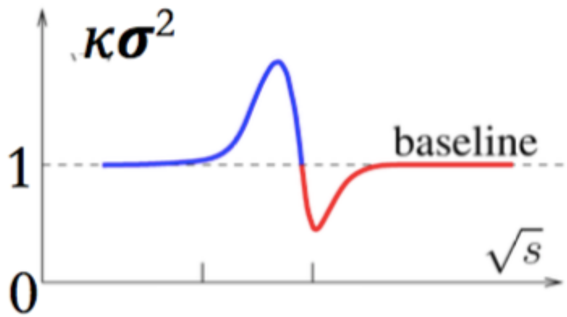
$$\frac{\sigma^2}{M} = \frac{C_{2,q}}{C_{1,q}} = \chi_q^{(2)}/\chi_q^{(1)}$$

$$S\sigma = \frac{C_{3,q}}{C_{2,q}} = \chi_q^{(3)}/\chi_q^{(2)} \qquad \text{for } q = B, Q, S$$

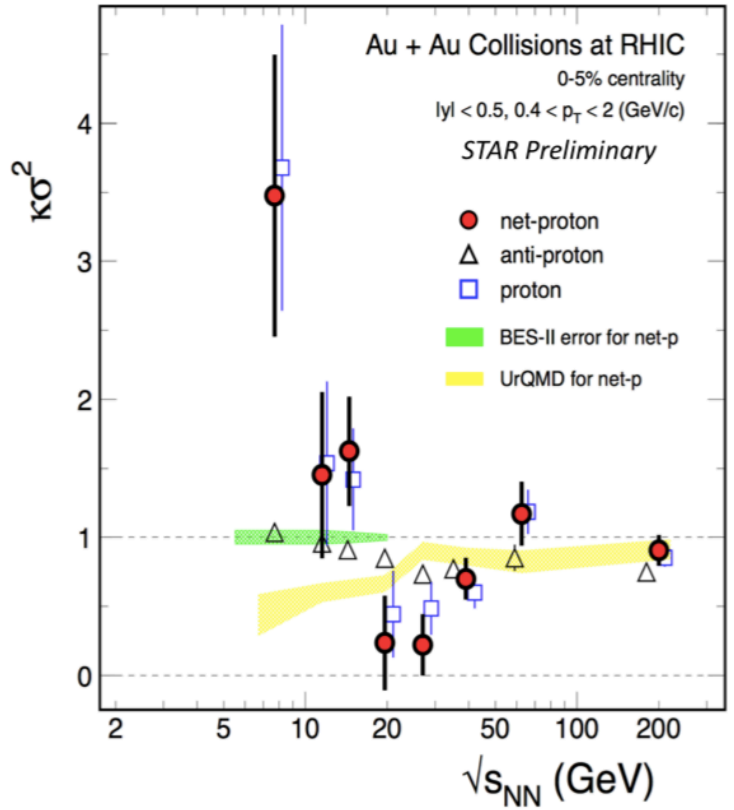
$$\kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} = \chi_q^{(4)}/\chi_q^{(2)}$$

- ✓ Sensitive to correlation length:

$$C_{2,q} \propto \xi^2, \quad C_{3,q} \propto \xi^{4.5}, \quad C_{4,q} \propto \xi^7$$



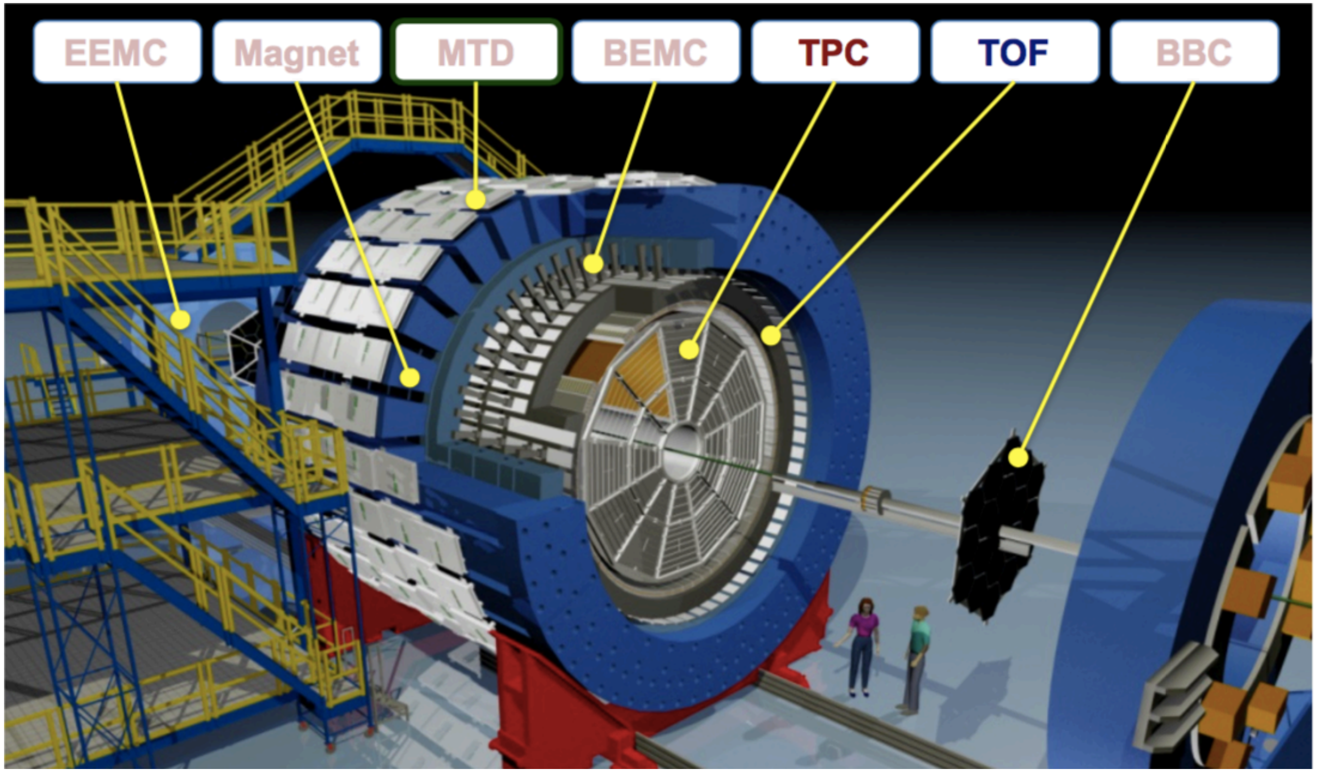
$\kappa\sigma^2$ as a function of collision energy



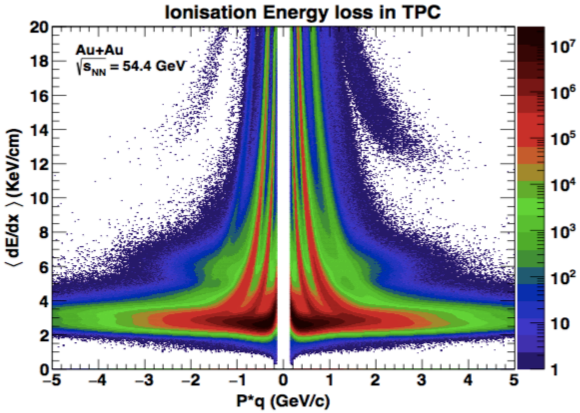
X. Luo [STAR Collaboration], PoS CPOD 2014, 019 (2015)

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
R. V. Gavai and S. Gupta, Phys. Lett. B 696, 459 (2011)
S. Gupta, X. Luo, B. Mohanty, H. G. Ritter, and N. Xu, Science 332,1525 (2011).
J. Phys. G: Nucl. Part. Phys. 38 (2011) 124147

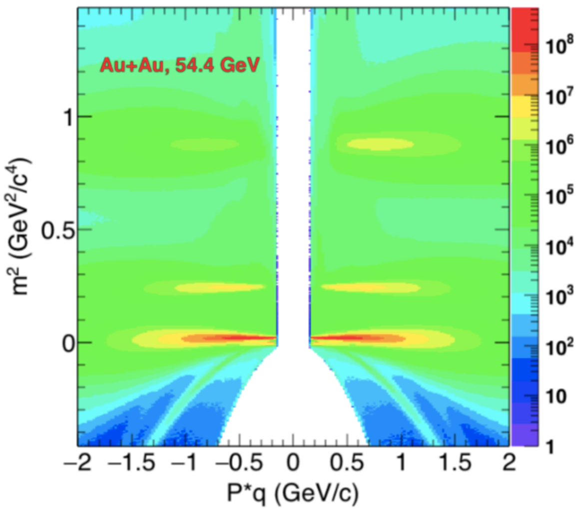
The STAR Detector



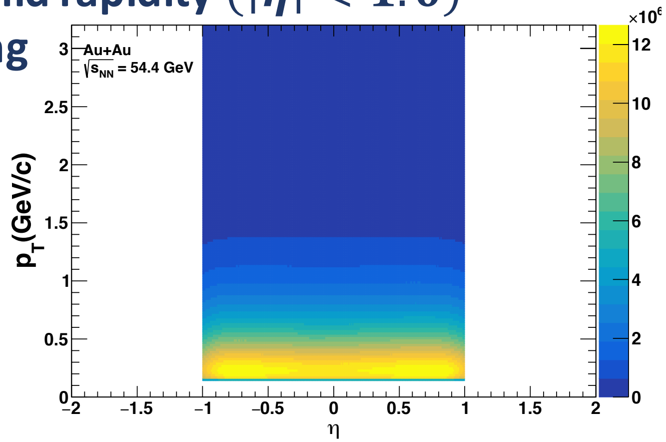
TPC



TOF

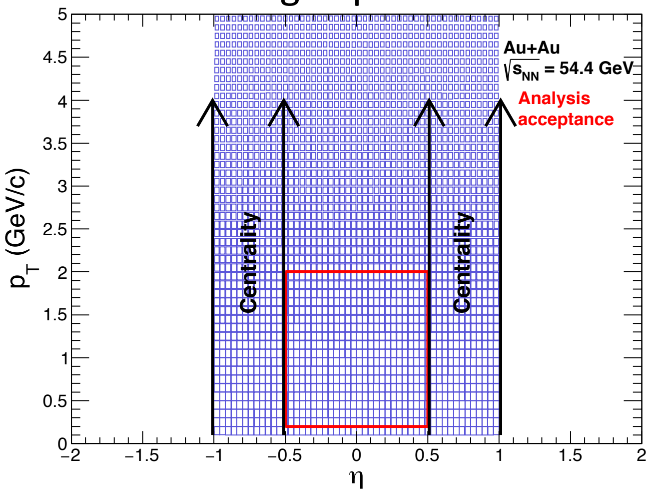


- Uniform acceptance at mid rapidity $(|\eta| < 1.0)$
- Excellent PID and tracking

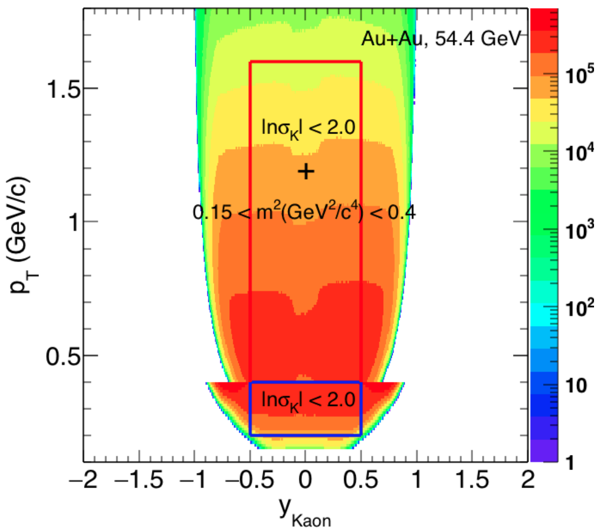


Particle Identification and Phase Space

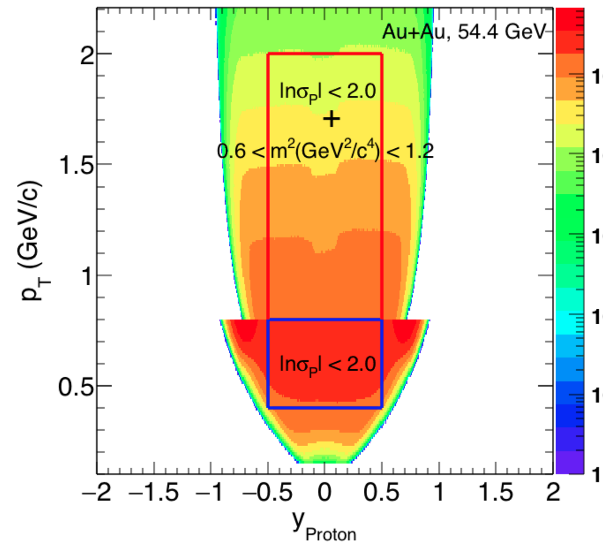
Charged particles



K^+ and K^-



Protons and antiprotons

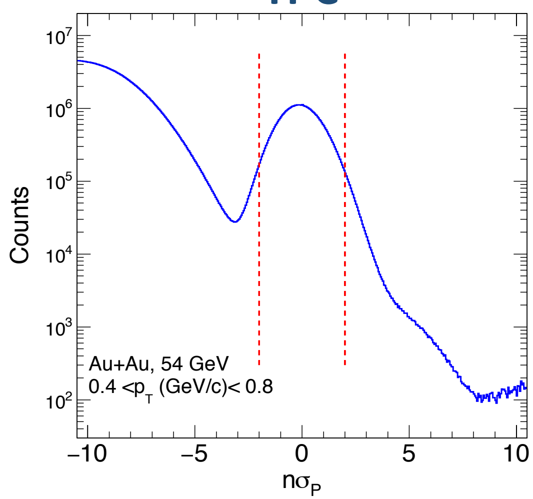


➢ PID

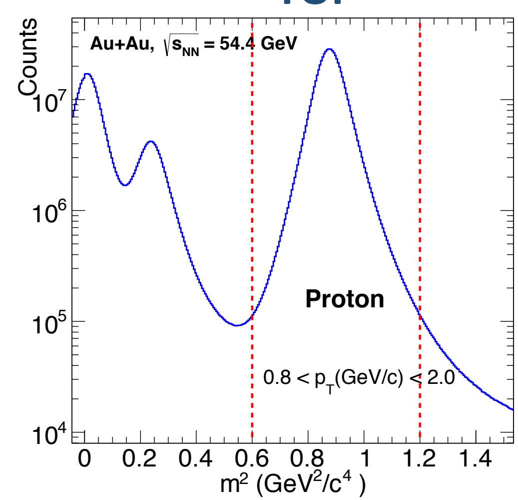
TPC → Time Projection Chamber
dE/dx ionization energy loss (low p_T)

TOF → Time-of-Flight
Track time of flight and m^2 (high p_T)

TPC

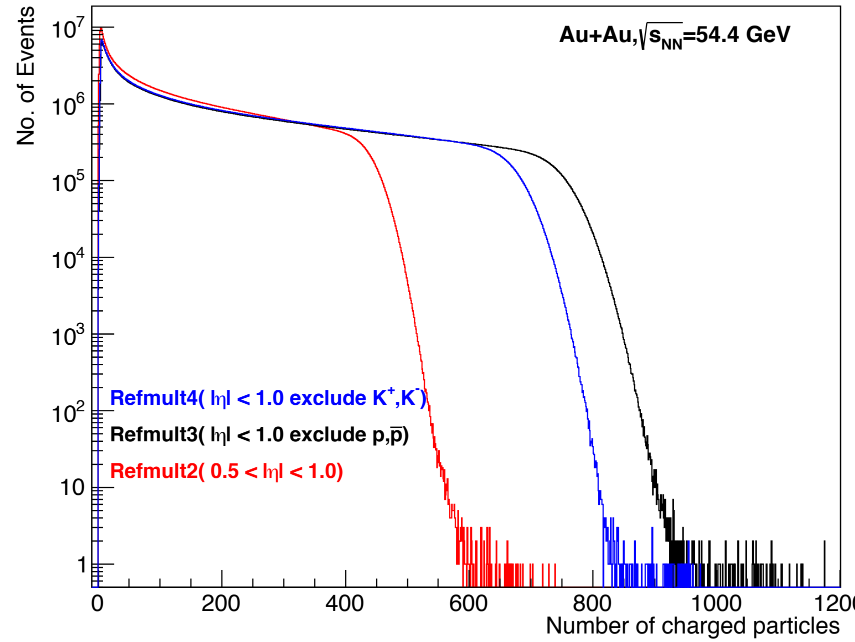


TOF



Centrality Determination

- Centrality is determined from charged particle multiplicity excluding particles of interest.



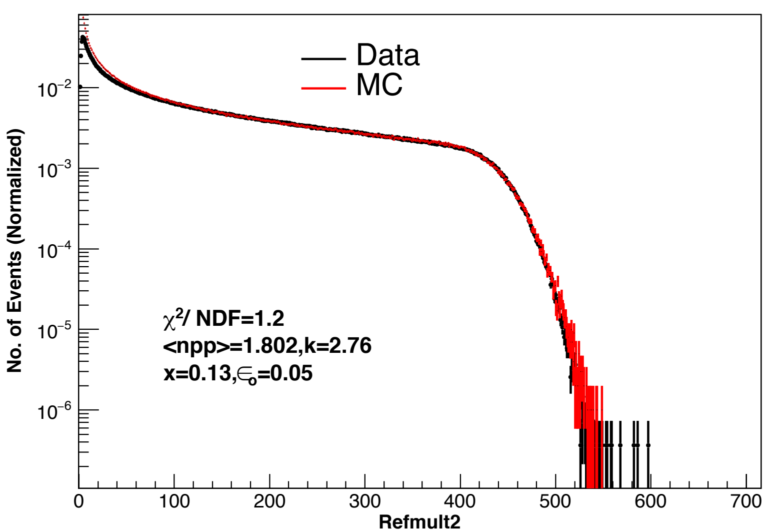
- The multiplicity distributions are corrected for longitudinal position of the collision vertex (V_z) and luminosity dependence.

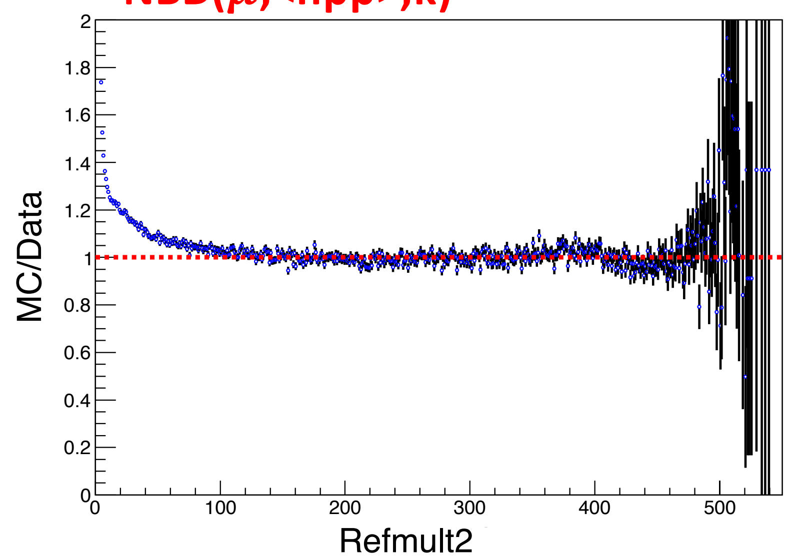
Refmult2 and MC Glauber Model comparison

Glauber + two component model

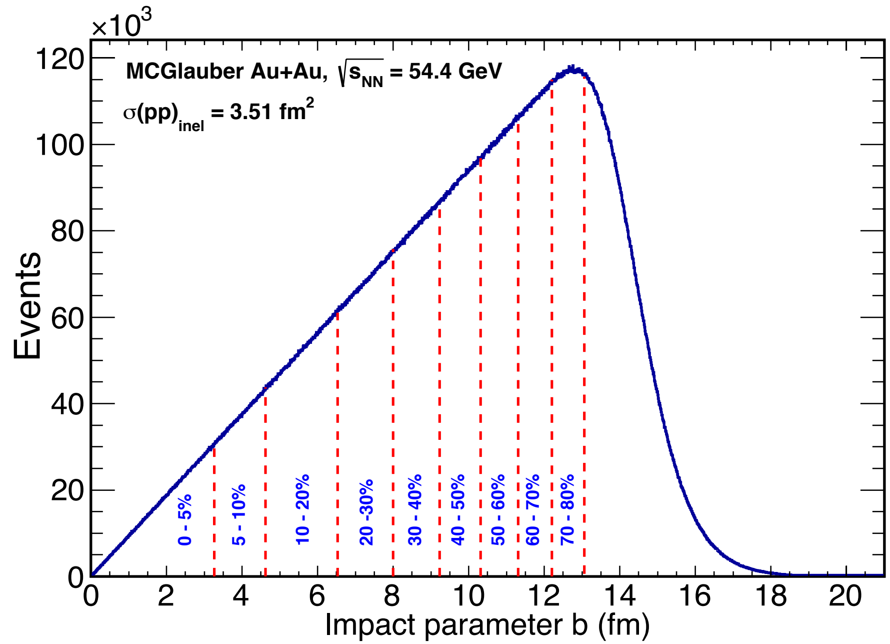
- **Simulate $\frac{dN_{ch}}{d\eta}$ using the two component model** $$\frac{dN_{ch}}{d\eta} = \mu\left(x * N_{coll} + (1-x) * \frac{N_{part}}{2}\right)$$

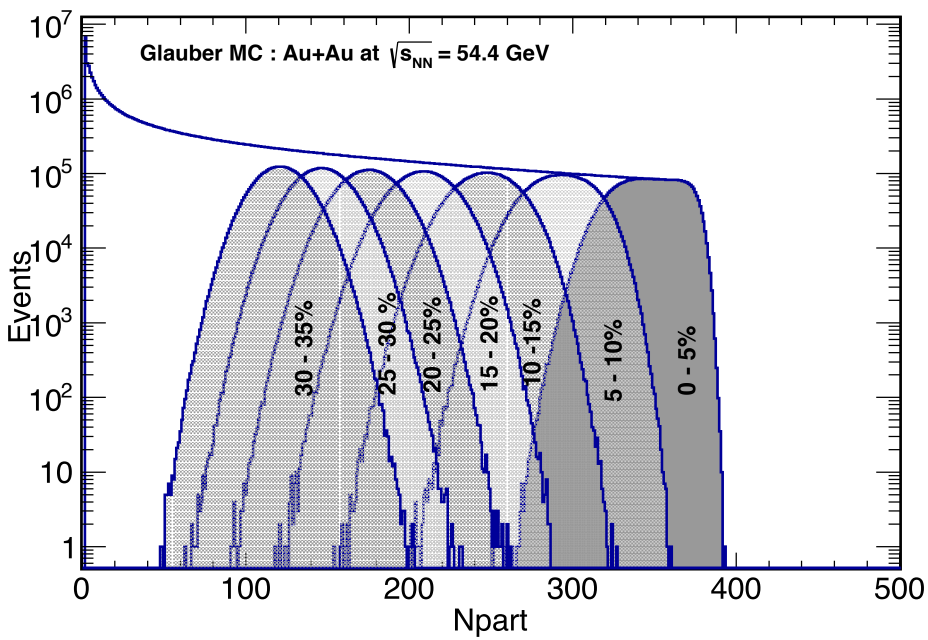
NBD(μ;<npp>,k)





Number of Participants (N_{part}) and Impact Parameter (b)

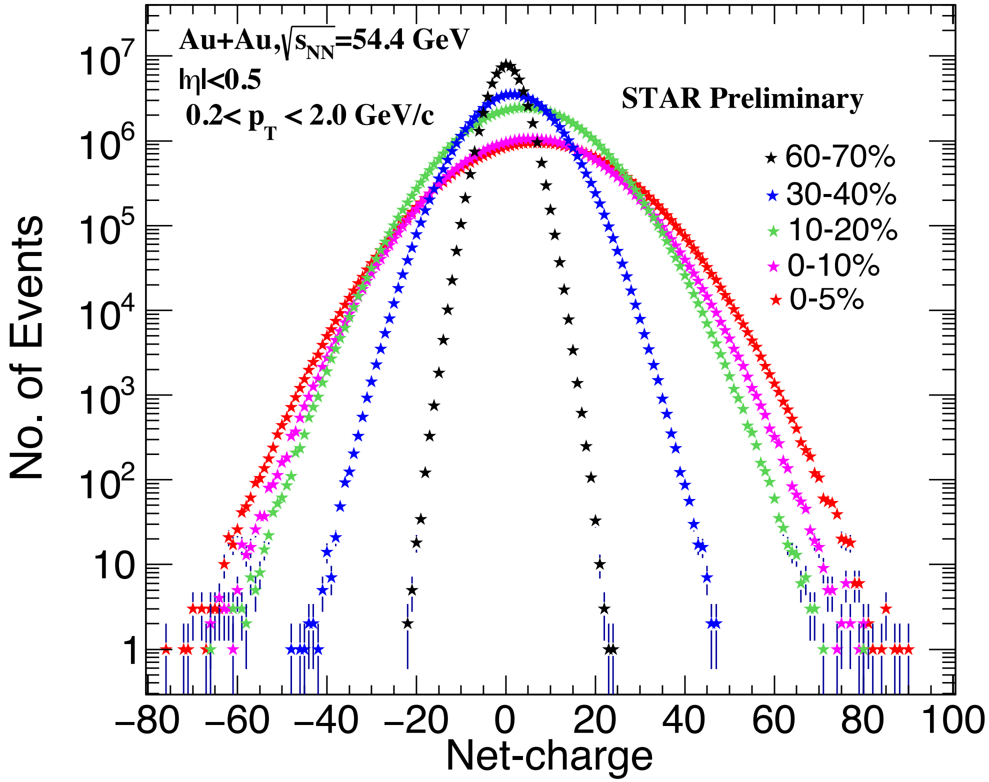




- Events with small impact parameter are less probable.
- N_{part} which corresponds to initial volume of the system decreases from central to peripheral collisions.

Centrality (%)	$<N_{coll}>$	$<N_{part}>$
0 – 5	903.5	346.9
5 – 10	714.5	292.2
10 – 20	508.6	227.7
20 – 30	318.4	160.9
30 – 40	189.8	110.5
40 – 50	106.7	72.7
50 – 60	56.12	44.8
60 – 70	26.68	25.5
70 – 80	11.88	13.2

Event-by-event Net charge Distributions



- ✓ Mean ($\boldsymbol{M}$) and variance ($\boldsymbol{\sigma}$) of distributions decrease from central to peripheral collisions.
- ✓ $\boldsymbol{Error(C_n) \propto \sigma^n/\sqrt{N}}$ → large statistical uncertainties on cumulants of net charge.
- ✓ Volume fluctuation → Centrality bin width correction (CBWC)

  X.Luo, B.Mohanty, J. Phys. G: Nucl. Part. Phys. 40 105104

$$\boldsymbol{C_m = \sum_r w_r \; C_{m,r}}$$

- ✓ Finite detector efficiency → Efficiency correction of cumulants assuming binomial detector response.

  A.Bzdak and V.Koch .PRC 86, 044904 (2012)

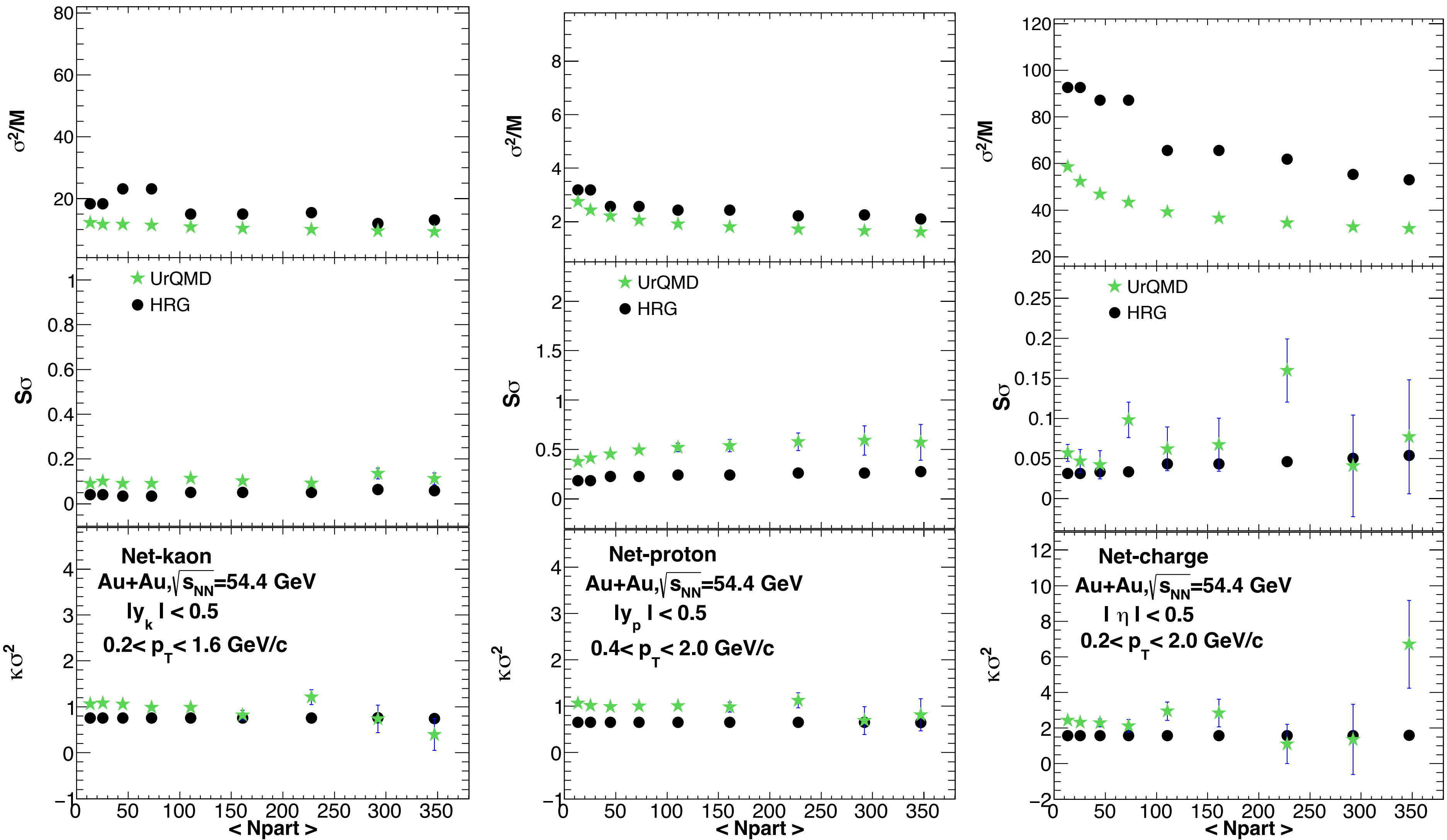
Moment Products of Net-particle Multiplicity Distributions

→The UrQMD and HRG model expectations for moment products are shown.

→Uncertainties are statistical only, obtained using Delta Theorem.

X.Luo, J. Phys. G: Nucl. Part. Phys. 39, 025008 (2012)

→ For both UrQMD and HRG σ^2/M, $S\sigma$ and $\kappa\sigma^2$ show weak dependence on centrality.

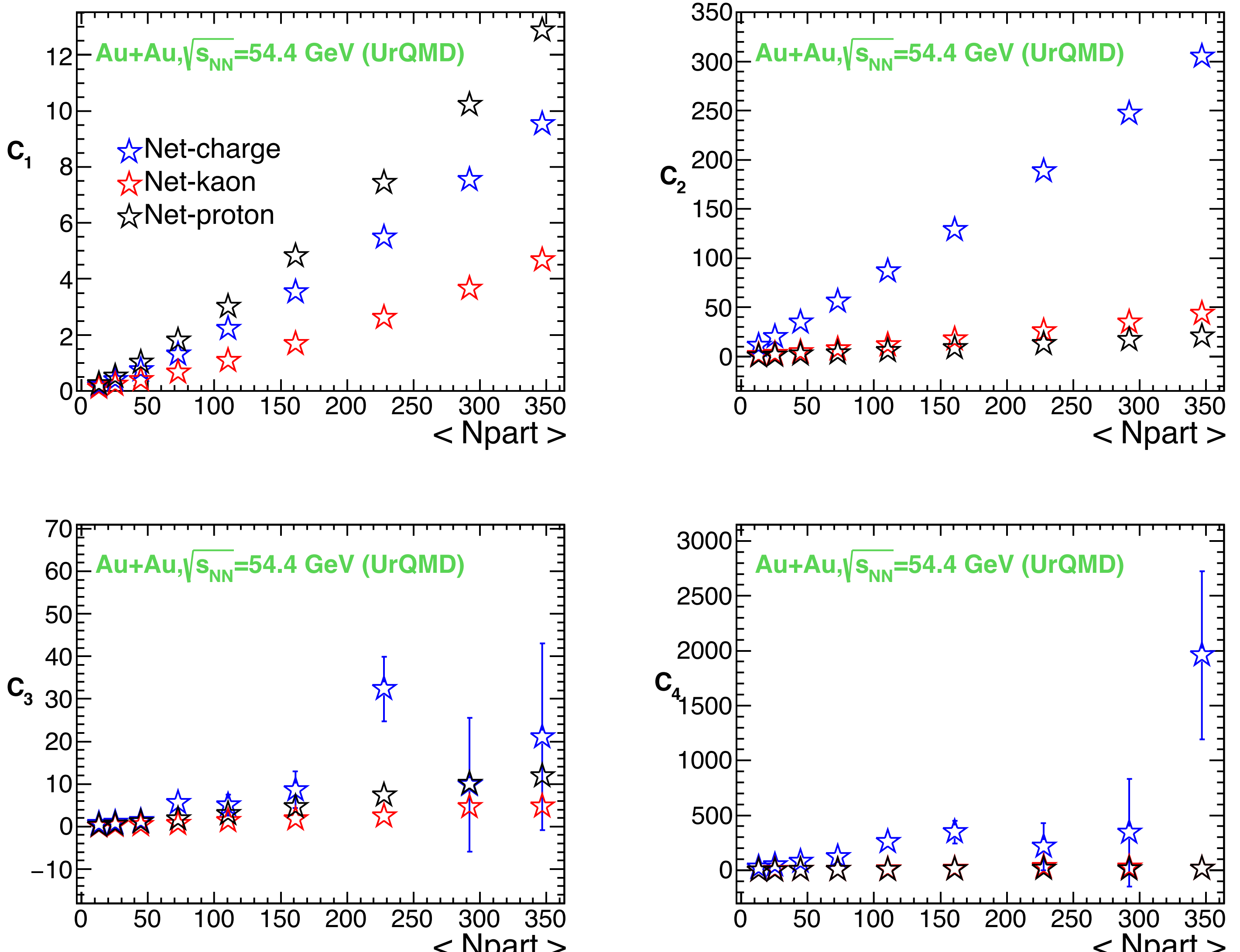


Centrality Dependence of Cumulants

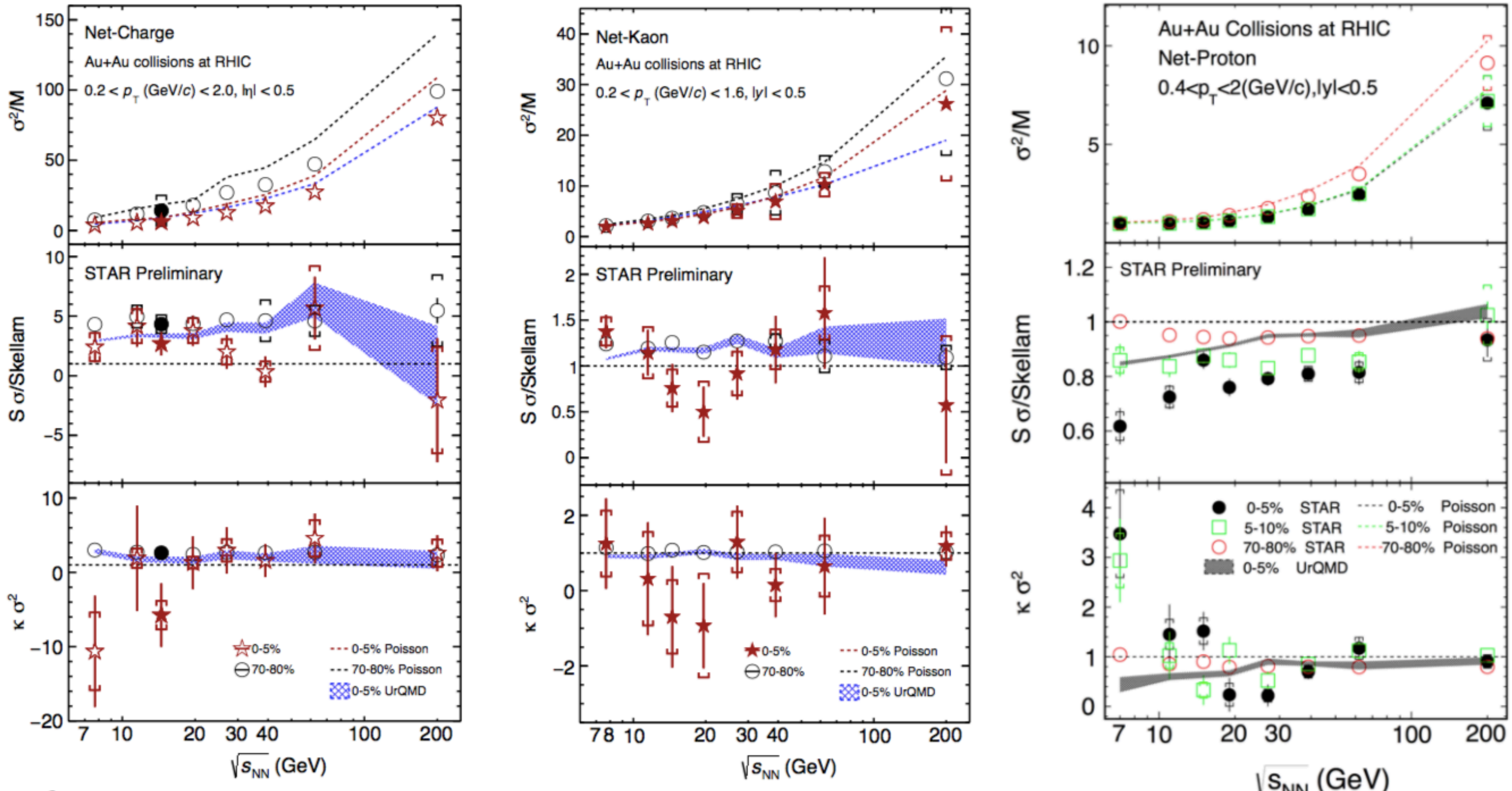
→ C_1, C_2: smooth increase from peripheral to central collisions.

→ Higher value of C_2 for net charge as compared to net proton and net kaon.

(Wider distribution and large statistical errors)



Results from Beam Energy Scan I



X. Luo and N. Xu, [arXiv:1701.02105 [nucl-ex]]

→ σ^2/M increases as a function of collision energy.

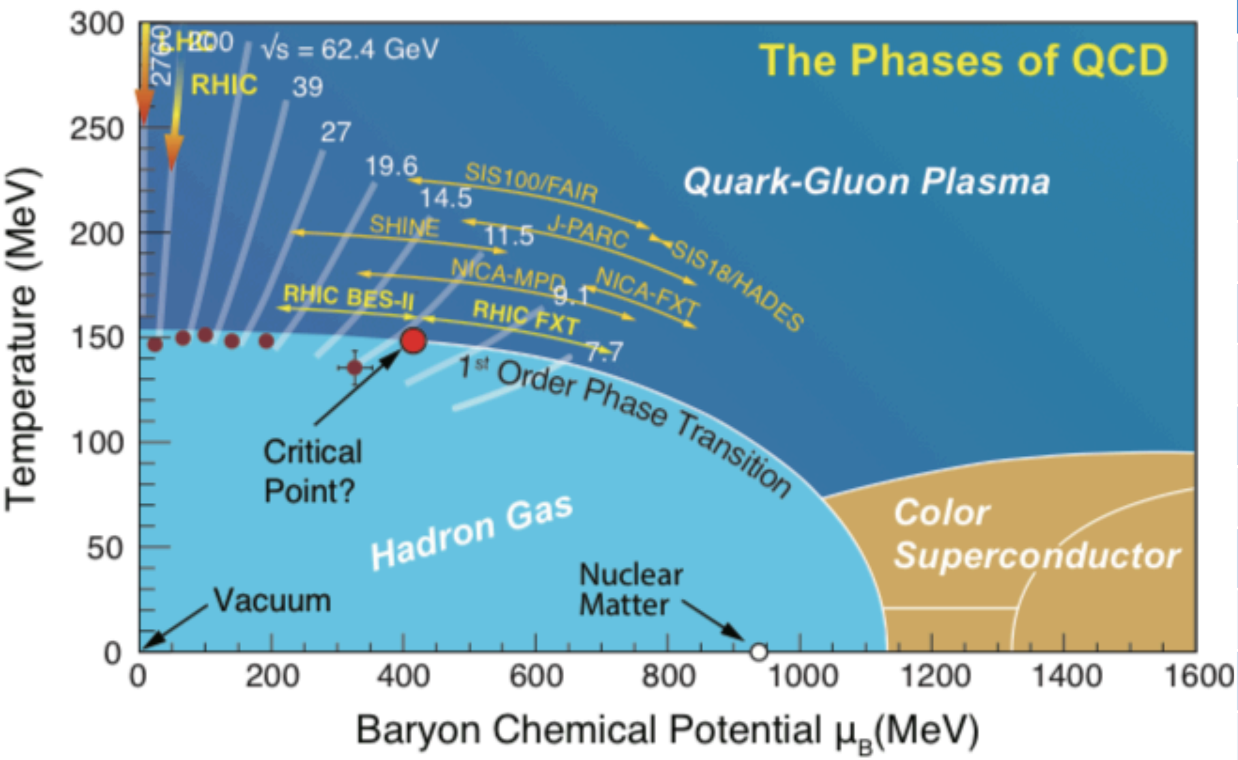
→ $S\sigma$/Skellam expectation shows a weak dependency on center of mass energy.

→ $S\sigma$, $\kappa\sigma^2$ of net charge and net kaon → Consistent with the UrQMD predictions.

→ $\kappa\sigma^2$: large statistical uncertainties→ Need for precision measurement.

Beam Energy Scan II (BES-II) at RHIC

Detailed study of the phase diagram → Higher event statistics and detector upgrades.



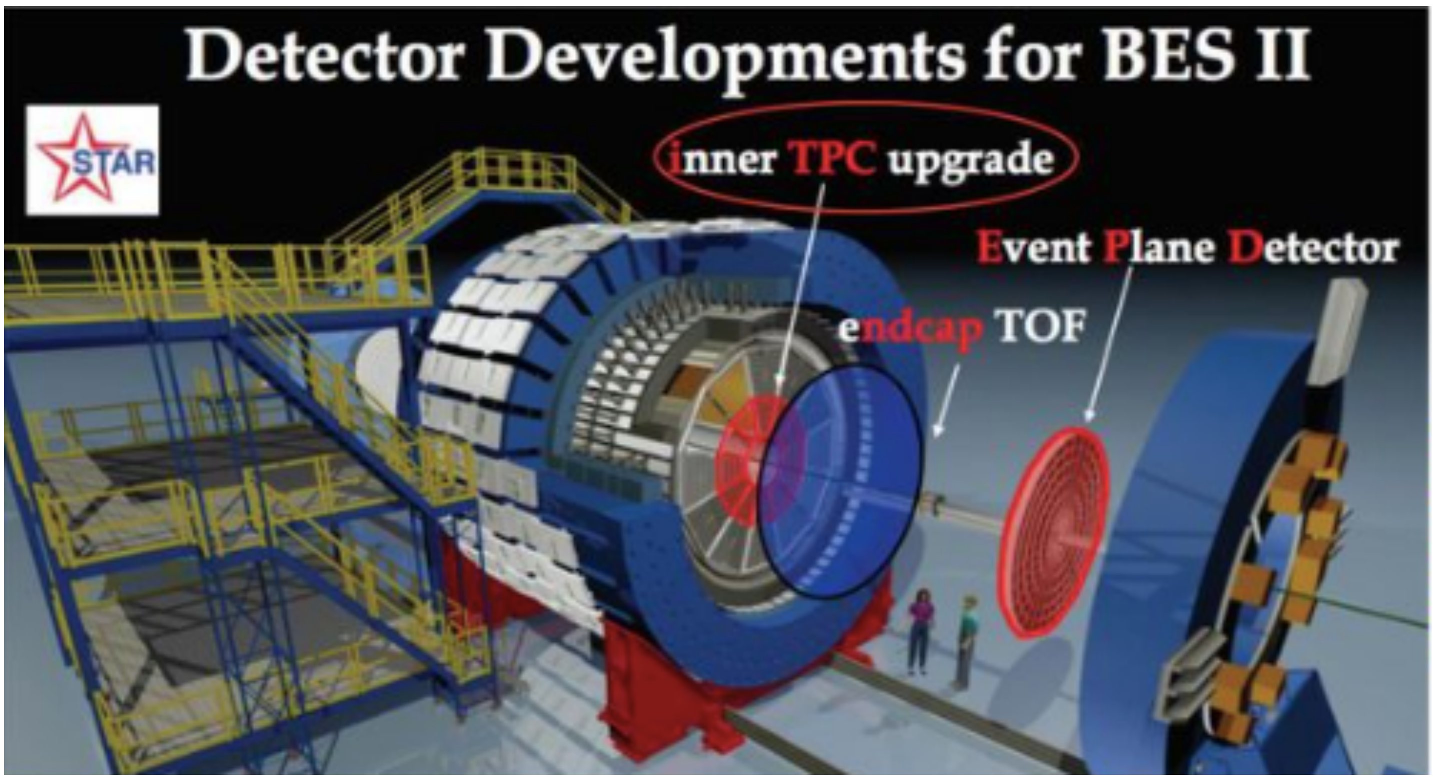
H. Caines, The Search for a Behavior (and Other Features of the QCD Phase Diagram) Status and Future, QM 2017.

$\sqrt{s_{NN}}$ (GeV)	Events (in millions)	μ_B (MeV)
COLLIDER MODE		
7.7	100	420
9.1	160	370
11.5	230	315
14.5	300	260
19.6	400	205
FIXED TARGET MODE		
7.7	100	420
6.2	100	487
5.2	100	541
4.5	100	589
3.9	100	633
3.5	100	666
3.2	100	699
3.0	100	721

Key Measurements in BES-II

- Search for the QCD critical point → **Kurtosis of net proton**
- Search for the first-order phase transition → **Directed flow of protons and net-protons**
- Study of the chiral symmetry restoration in QGP medium → **Dielectron Invariant Mass Spectra**

Detector Upgrades:

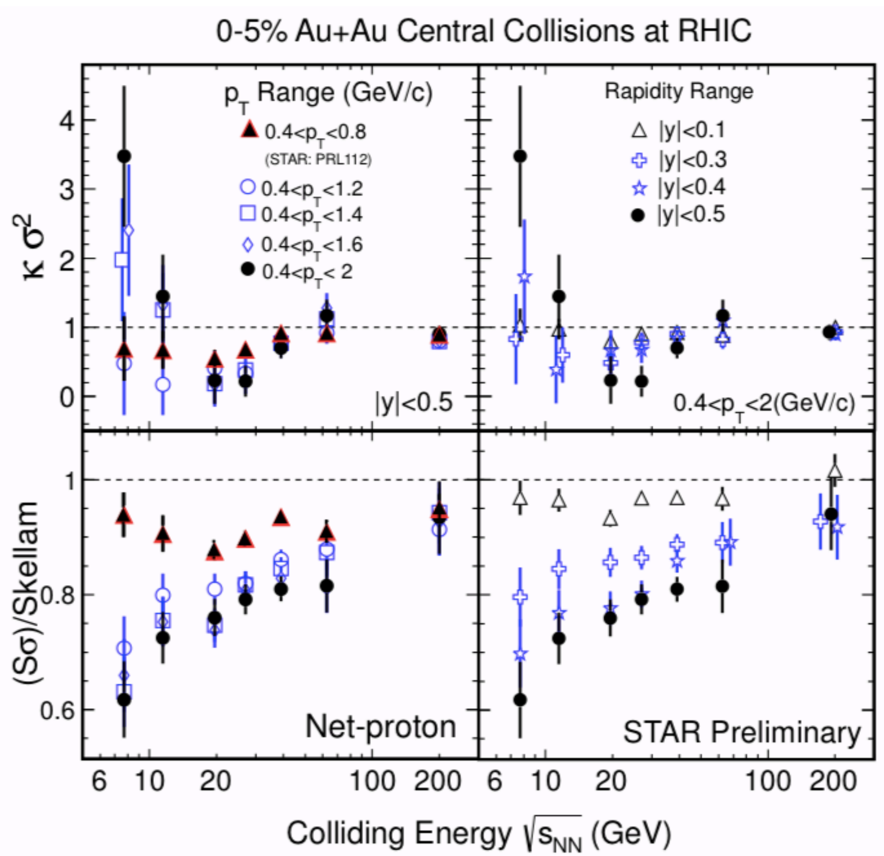


- ✓ Increased η coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$
- ✓ p_T > 60 MeV/c.
- ✓ Improved dE/dx and momentum resolution
- ✓ Better event plane and centrality resolution.

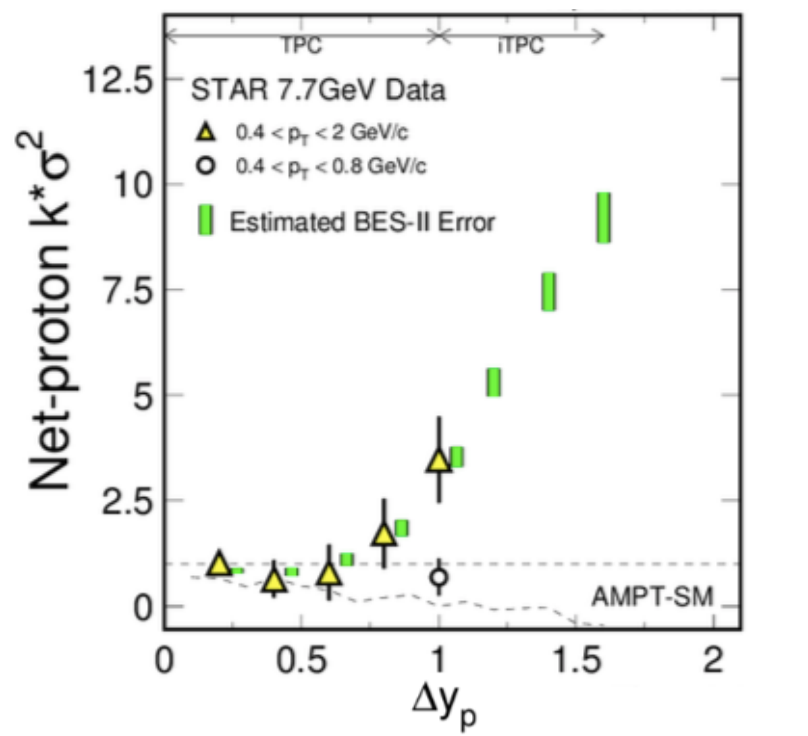
Measurement of Kurtosis of net proton

- ✓ Increased rapidity coverage → $\Delta y_p < 1.6$ (previously $\Delta y_p < 1.0$)
- ✓ $\kappa \propto (\Delta y)^4$ for $\Delta y \leq 2.0$

B. Ling and M. Stephanov, Phys.Rev. C93 (2016) 034915
M.A. Stephanov [Int. J. Mod. Phys. A 20,4387 (2005)] [hep - ph/0402115]



L. Adamczyk et al . (STAR collaboration), Phys. Rev. Lett. 112 , 032302 (2014).



STAR Internal Note Technical Design Report for the iTPC Upgrade- SN0644, (2015)

BES-II → Smaller statistical uncertainties and improved kurtosis signal are expected.

Conclusions

- The cumulants and moment products calculated using the UrQMD and HRG models have been studied as a function of centrality for Au+Au at $\sqrt{s_{NN}} = 54.4$ GeV .
- Centrality determination have been performed using the Glauber model.
- With BES-II STAR will be able to provide a larger rapidity and momentum coverage on a par with the improved PID. This will be helpful for many key measurements aimed to study the QCD phase diagram.

Outlook

- Efficiency correction of cumulants for Au+Au at $\sqrt{s_{NN}} = 54.4$ GeV at RHIC.
- Statistical baseline study for cumulants and moment products.
- Estimation of systematic uncertainties.
- Fluctuation measurements at BES-II.