# Higher Moments of Net-Particle Multiplicity Distributions


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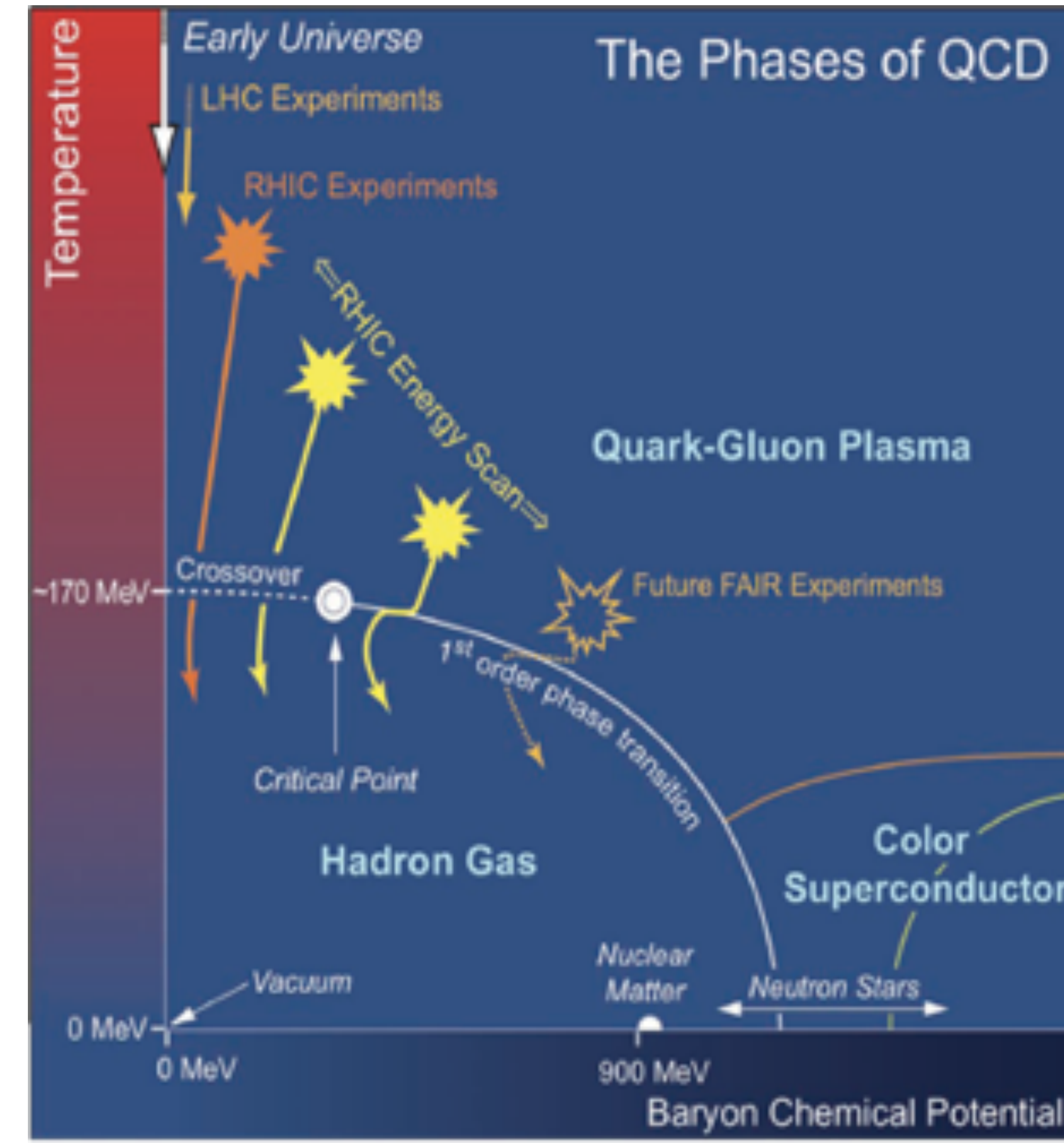
# Search for the QCD Critical Point

***Exploring the QCD Phase Diagram***

- Critical Point: Endpoint of the first order phase transition
- RHIC Beam Energy Scan Phase 1 (BES I) STAR Note 0598
  vary temperature $T$ and baryon chemical potential $\mu_B$
- Event-by-event fluctuations of conserved quantities to study of the phase transition
  - Charge **Q** / baryon number **B** / strangeness **S**
- Experimental observables:
  - Cumulants of event-by-event net-particle multiplicity distributions: **Net-charge** / **net-proton** (proxy for net-baryon) / **net-kaon** (proxy for net-strangeness)
  - Volume independent cumulant ratios



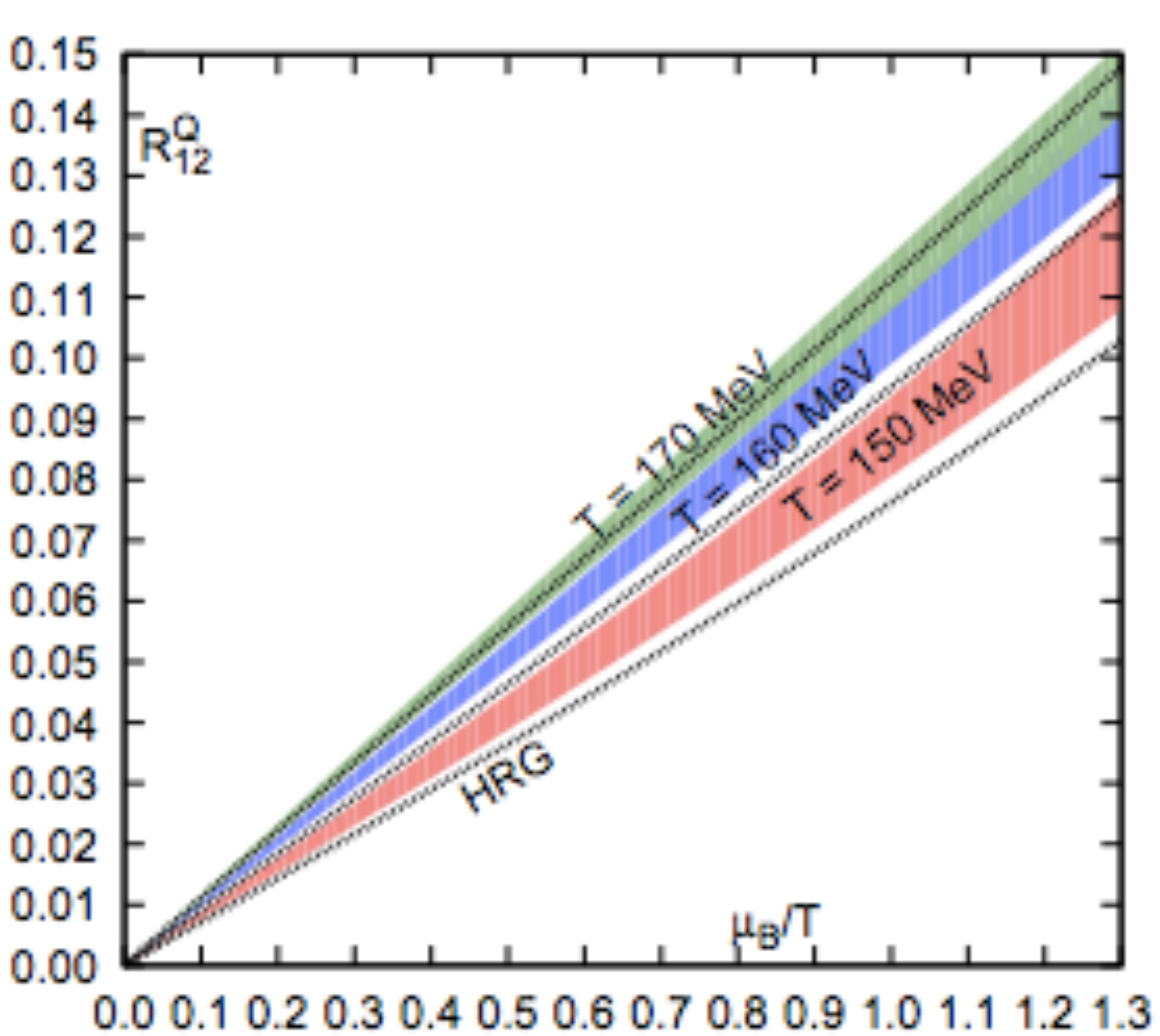
# Connection to Theoretical Calculations

- Susceptibility ratios of conserved quantities are assumed to be related to the moments of experimentally measurable multiplicity distributions

$$\chi_n^B = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

- Comparing first principal Lattice calculations with measured moments of conserved quantities, e.g. net-charge → extract the chemical freeze out parameters $T$ and $\mu_B$

**Lattice QCD**




HotQCD, PRL109, 192302 (2012)
WB Group, PRL111, 062005 (2013)

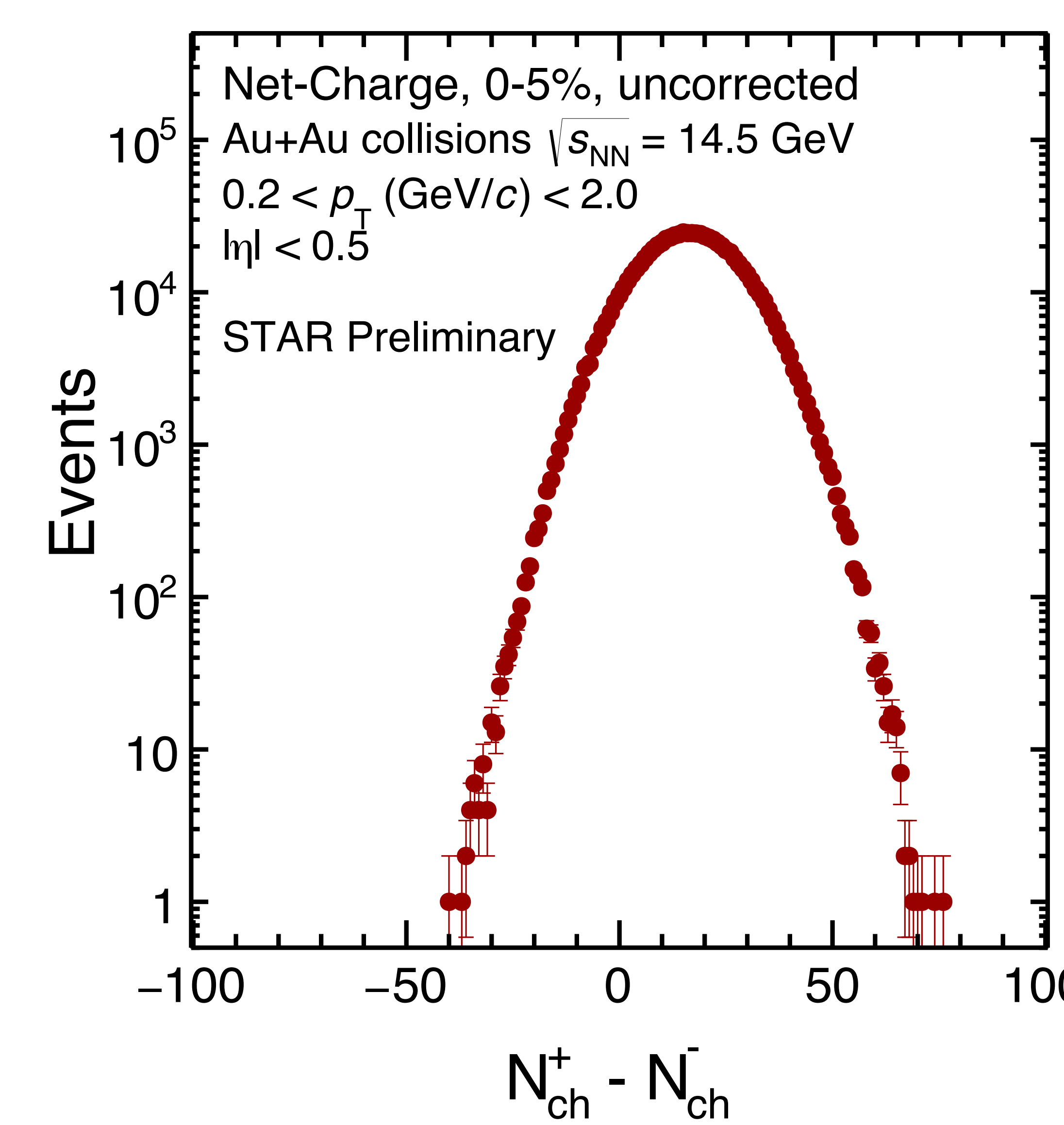
$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

$$\frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i}$$

$$\frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i}$$

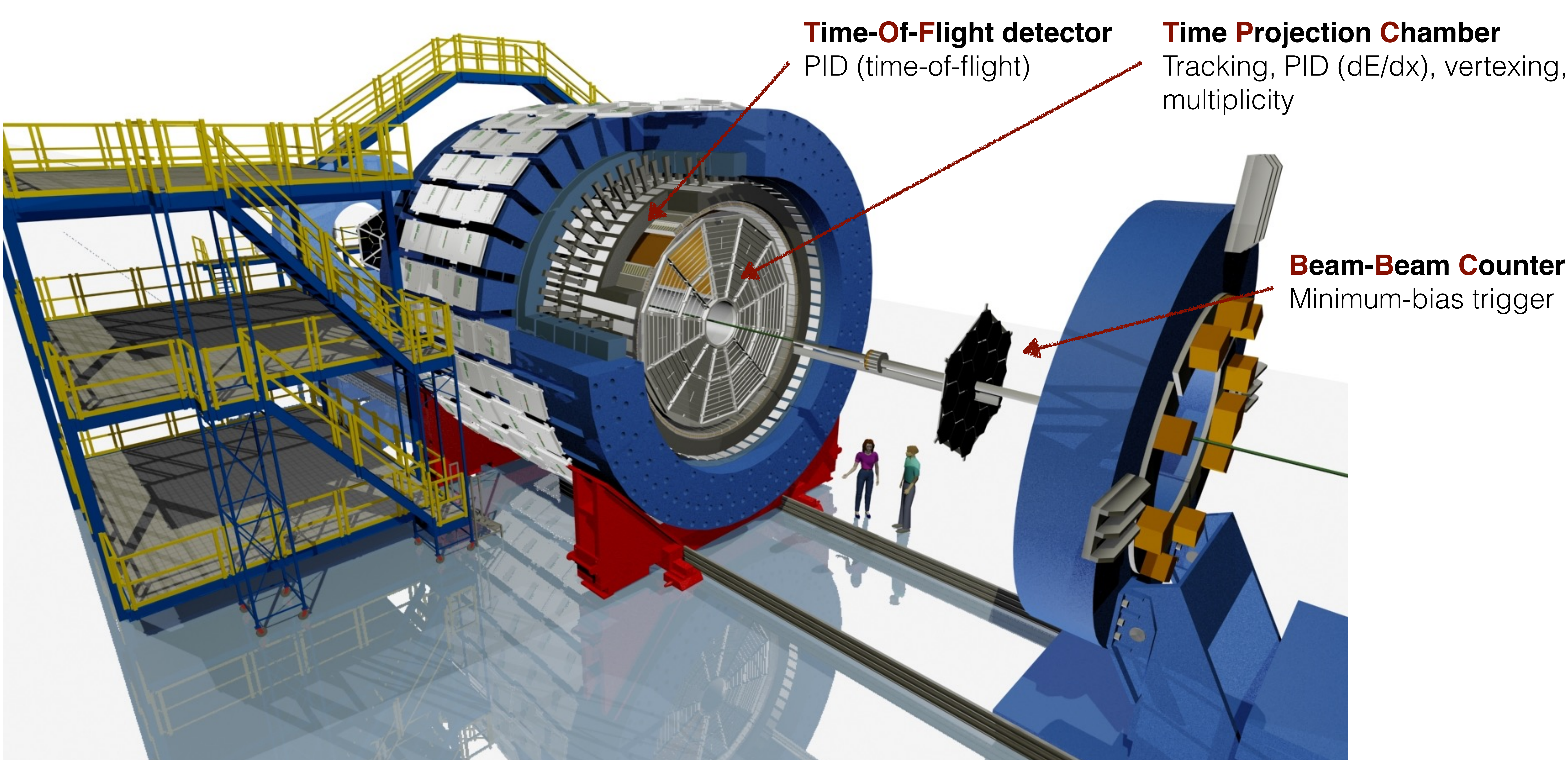
$$i = B, Q, S$$

**Experiment**



# The STAR detector

***Full azimuthal coverage, |η| < 1 → excellent PID, large uniform acceptance***



# Analysis Details

- RHIC Beam Energy Scan Phase I (BES I)
  - Au+Au $\sqrt{s_{NN}}$ : 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV
- Event Selection
  - Minimum bias trigger
  - Pile up removal with TOF
  - 0-80% Centrality
- Track selection
  - Good primary particles with sufficient length in the TPC DCA to primary vertex < 1 cm
- Kinematic cuts (next slide)
- Efficiency * acceptance corrections done

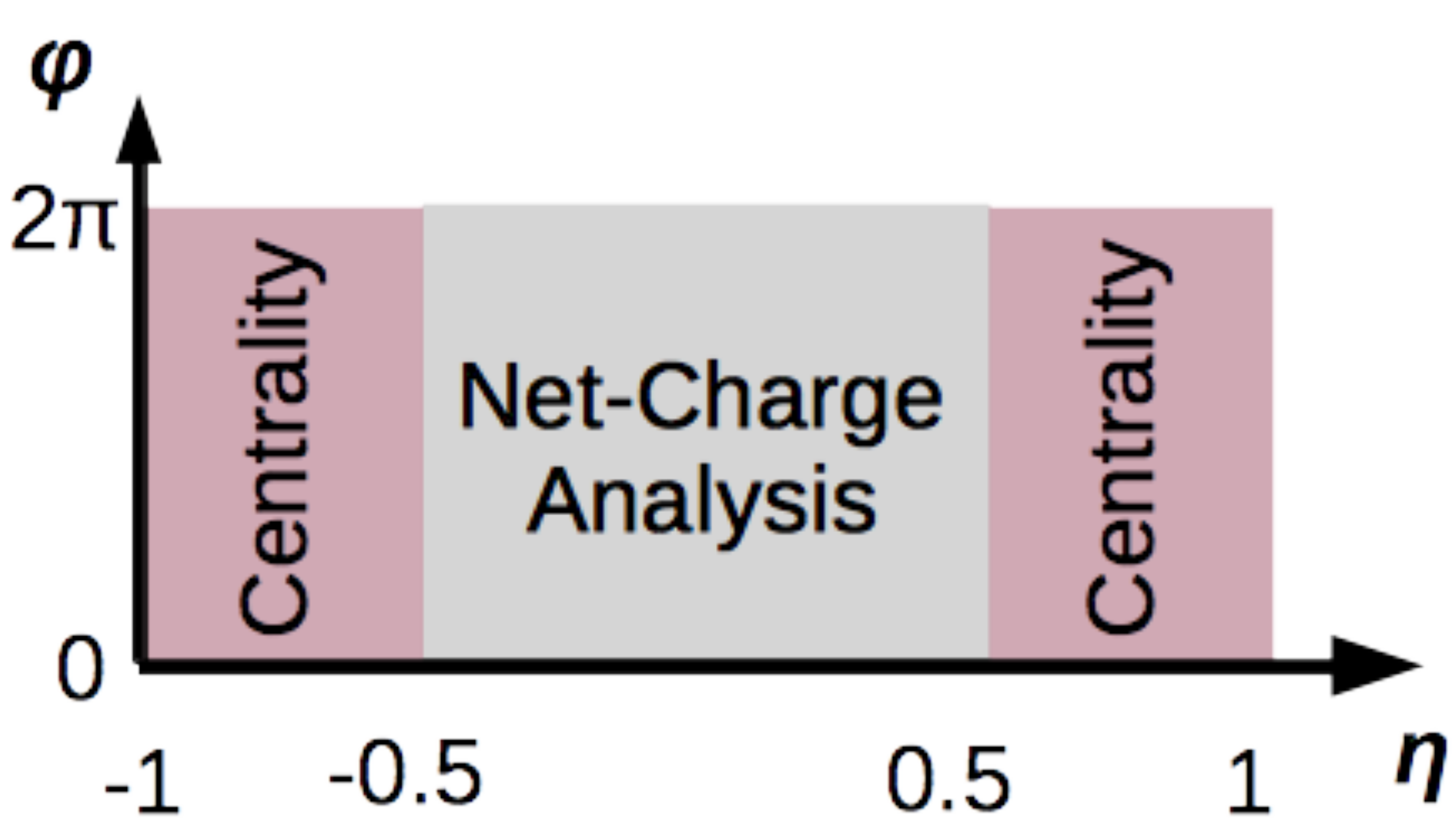
| $\sqrt{s_{NN}}$ (GeV) | Good events recorded (M events) | Year | $\mu_B$ (MeV) [0-5%] | T (MeV) [0-5%] |
|---|---|---|---|---|
| 7.7 | 4 | 2010 | 422 | 140 |
| 11.5 | 12 | 2010 | 316 | 152 |
| 14.5 | 20 | 2014 | 264 | 156 |
| 19.6 | 36 | 2011 | 206 | 160 |
| 27 | 70 | 2011 | 156 | 162 |
| 39 | 130 | 2010 | 112 | 164 |
| 62.4 | 67 | 2010 | 73 | 165 |
| 200 | 350 | 2010 | 24 | 166 |

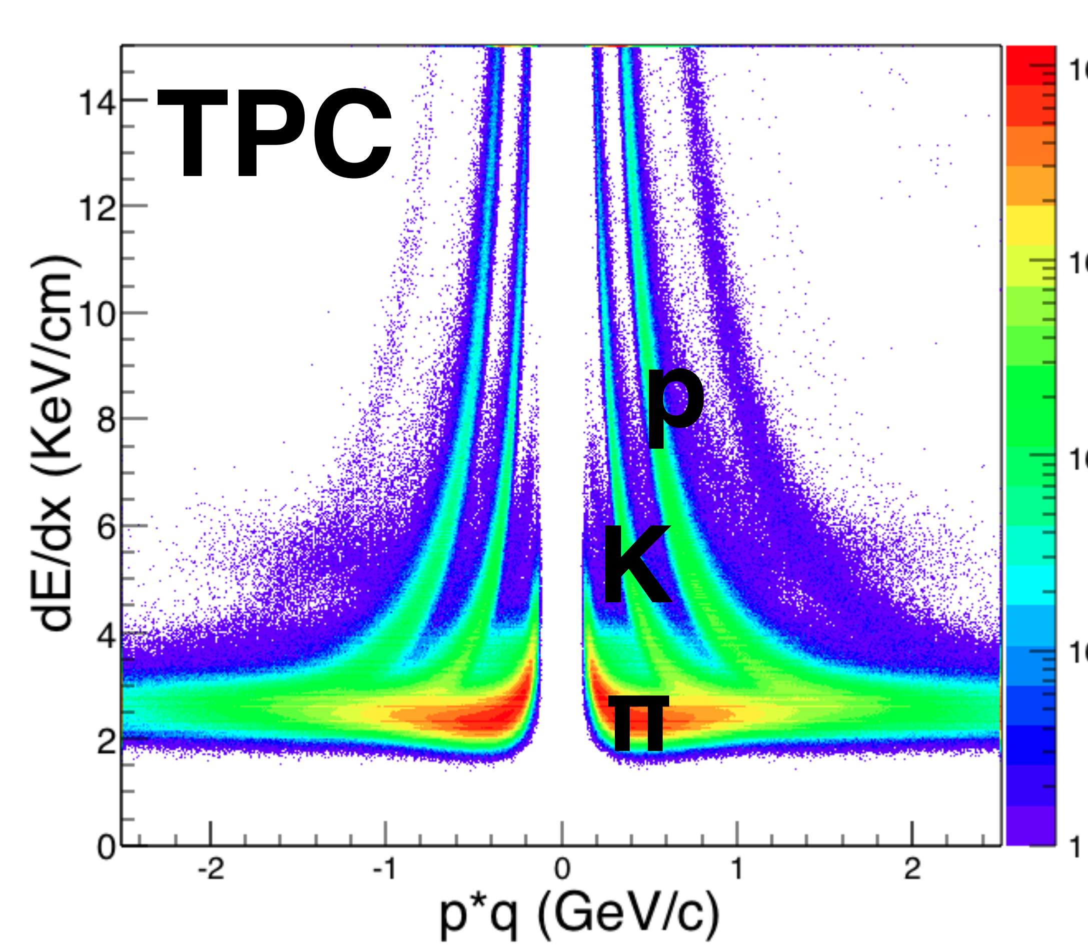
$\mu_B$, T : J. Cleymans et al., PRC 73, 034905 (2006)

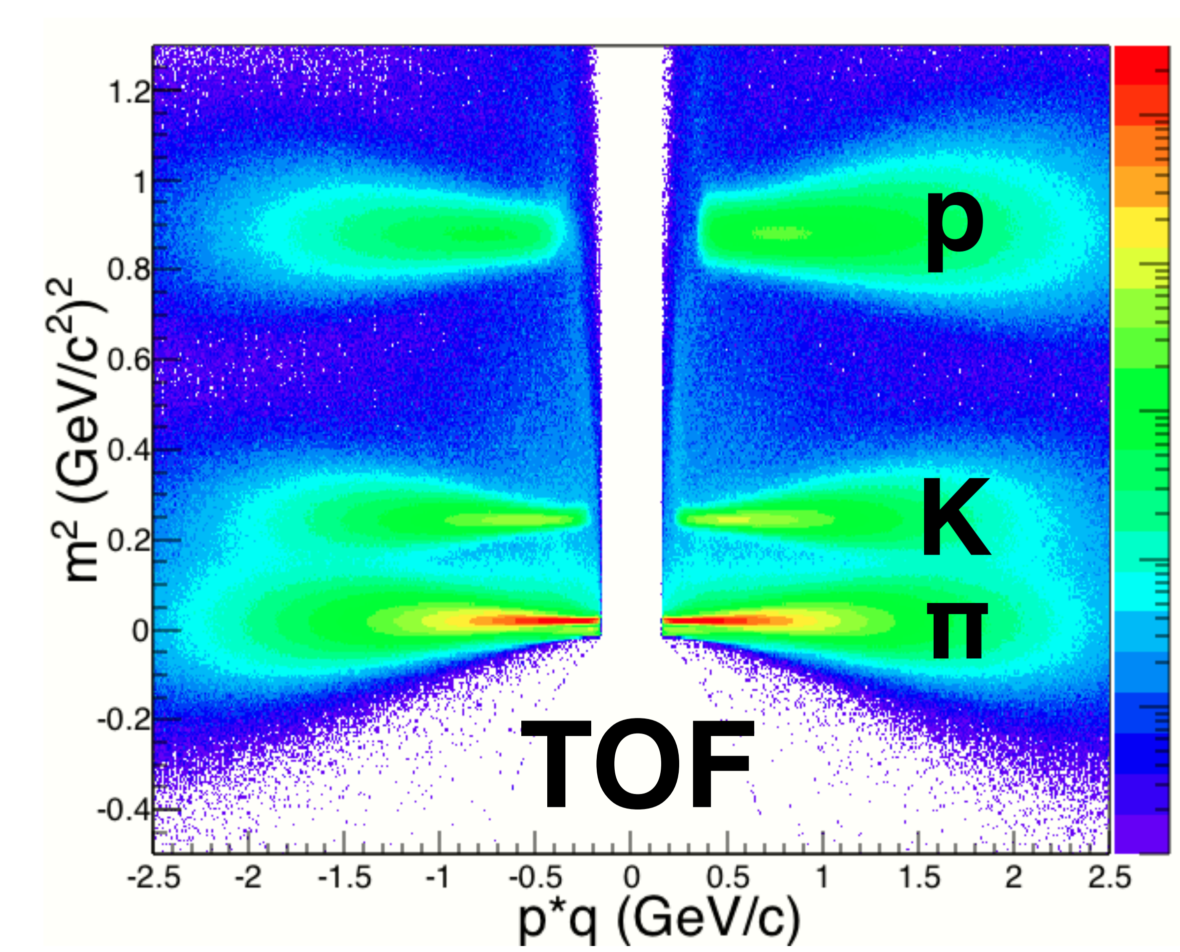
# Analysis Details

STAR, Phys. Rev. Lett. 112, 032302 (2014)
STAR, Phys. Rev. Lett. 113, 092301 (2014)

| | **Net-Charge** | **Net-Proton** | **Net-Kaon** |
| --- | --- | --- | --- |
| Kinematic cuts | $0.2 < p_T$ (GeV/$c$) $< 2.0$<br>$\|\eta\| < 0.5$ | $0.4 < p_T$ (GeV/$c$) $< 2.0$<br>$\|y\| < 0.5$ | $0.2 < p_T$ (GeV/$c$) $< 1.6$<br>$\|y\| < 0.5$ |
| Particle Identification | Reject protons form spallation for $p_T < 0.4$ GeV/$c$ | $0.4 < p_T$ (GeV/c) $< 0.8$ → TPC<br>$0.8 < p_T$ (GeV/c) $< 2.0$ → TPC+TOF | $0.2 < p_T$ (GeV/c) $< 0.4$ → TPC<br>$0.4 < p_T$ (GeV/c) $< 1.6$ → TPC+TOF |
| Centrality definition,<br>→ *to avoid auto-correlations* | Uncorrected charged primary particles multiplicity distribution | Uncorrected charged primary particles multiplicity distribution, without (anti-)protons | Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons |
| | $0.5 < \|\eta\| < 1.0$ | $\|\eta\| < 1.0$ | $\|\eta\| < 1.0$ |



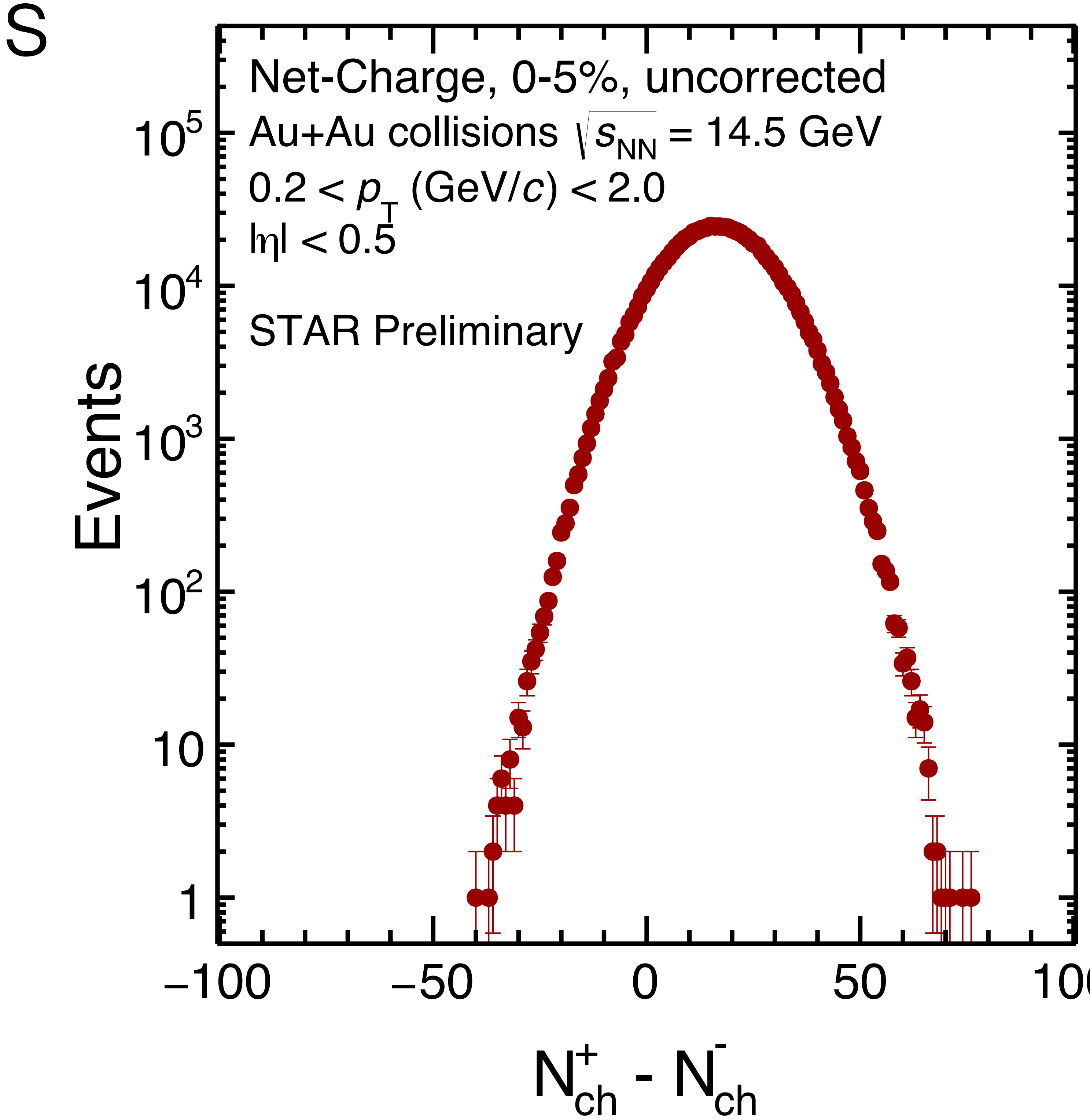



# Analysis Method

A. Bzdak and V. Koch, PRC86, 044904 (2012)
A. Bzdak and V. Koch, PRC91, 027901 (2015)
X. Luo, PRC91, 034907 (2015)

- Apply correction on raw net-particle distributions
  - **Finite Tracking / PID efficiency**
    → Factorial Moments
  - **Volume fluctuations**
  - **Remove auto-correlation effects**
- Net-Charge
  - Average efficiency for particle/anti-particles
- Net-Proton / Net-Kaon
  - $p_T$ dependent efficiency (2 $p_T$ efficiency bins)



# Analysis Method

***Error Estimation***

X. Luo, PRC91, 034907 (2015)

- Statistical Errors based on Delta Theorem

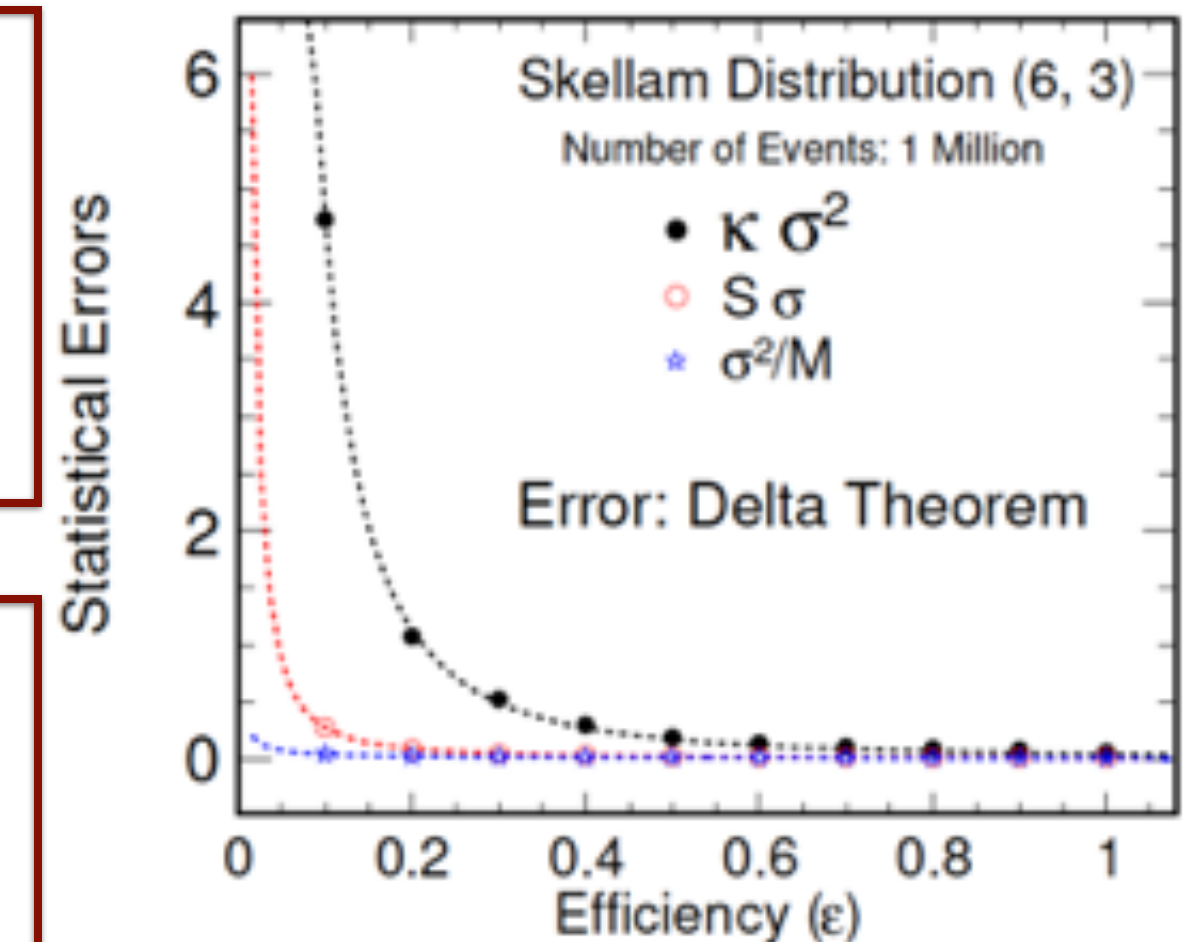
| Au+Au 14.5 GeV | **Net-Charge** | **Net-Proton** | **Net-Kaon** |
|---|---|---|---|
| Typical Width (σ) | 12.2 | 4.2 | 3.4 |
| Average efficiency (ε) | 65% | 75% | 38% |
| $\sigma^2 / \varepsilon^2$ | 355 | 32 | 82 |

$$error(c_n) \propto \frac{\sigma^n}{\epsilon^n}$$

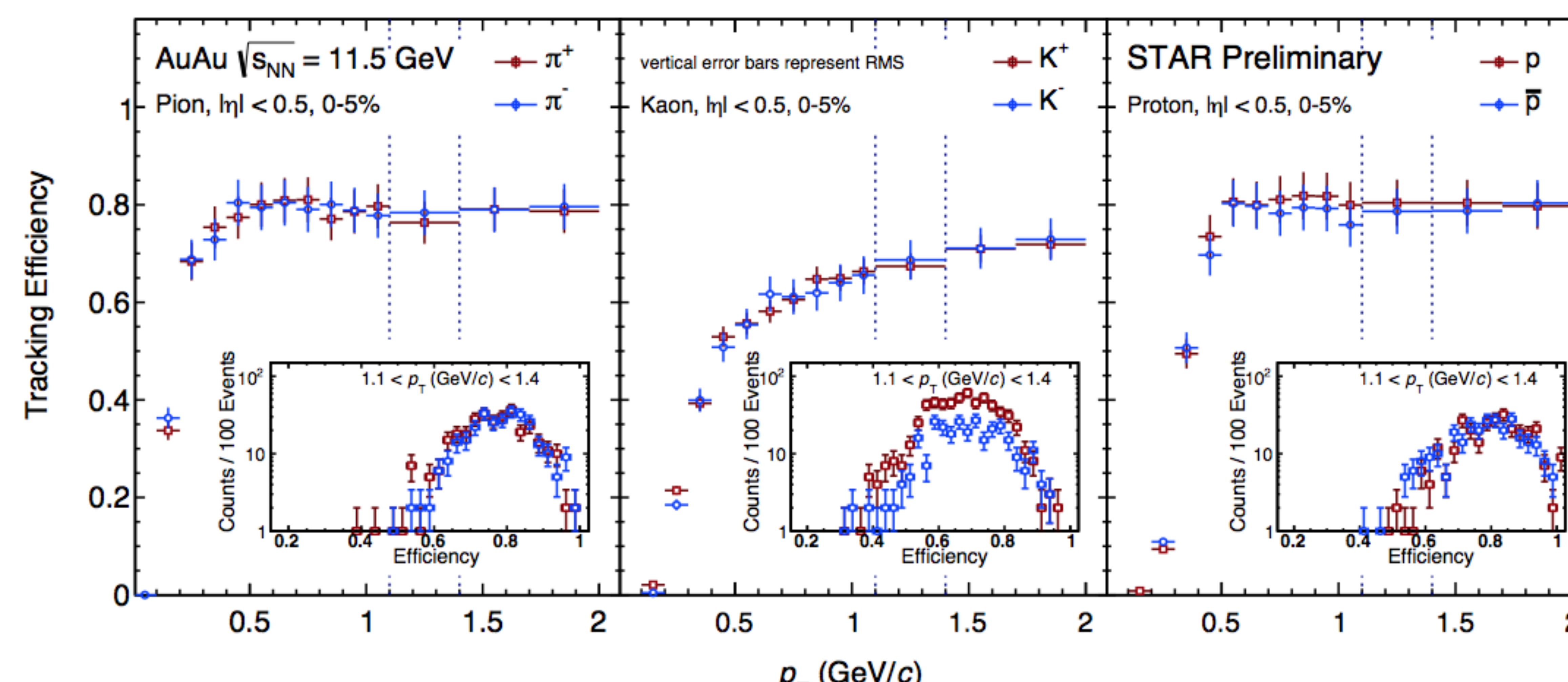
$$error\left(\frac{c_n}{c_2}\right) \propto \frac{\sigma^{n-2}}{\epsilon^{n/2}},\ for\ n>2$$

$$error(S\sigma) \propto \frac{\sigma}{\epsilon^{3/2}}$$

$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\epsilon^2}$$

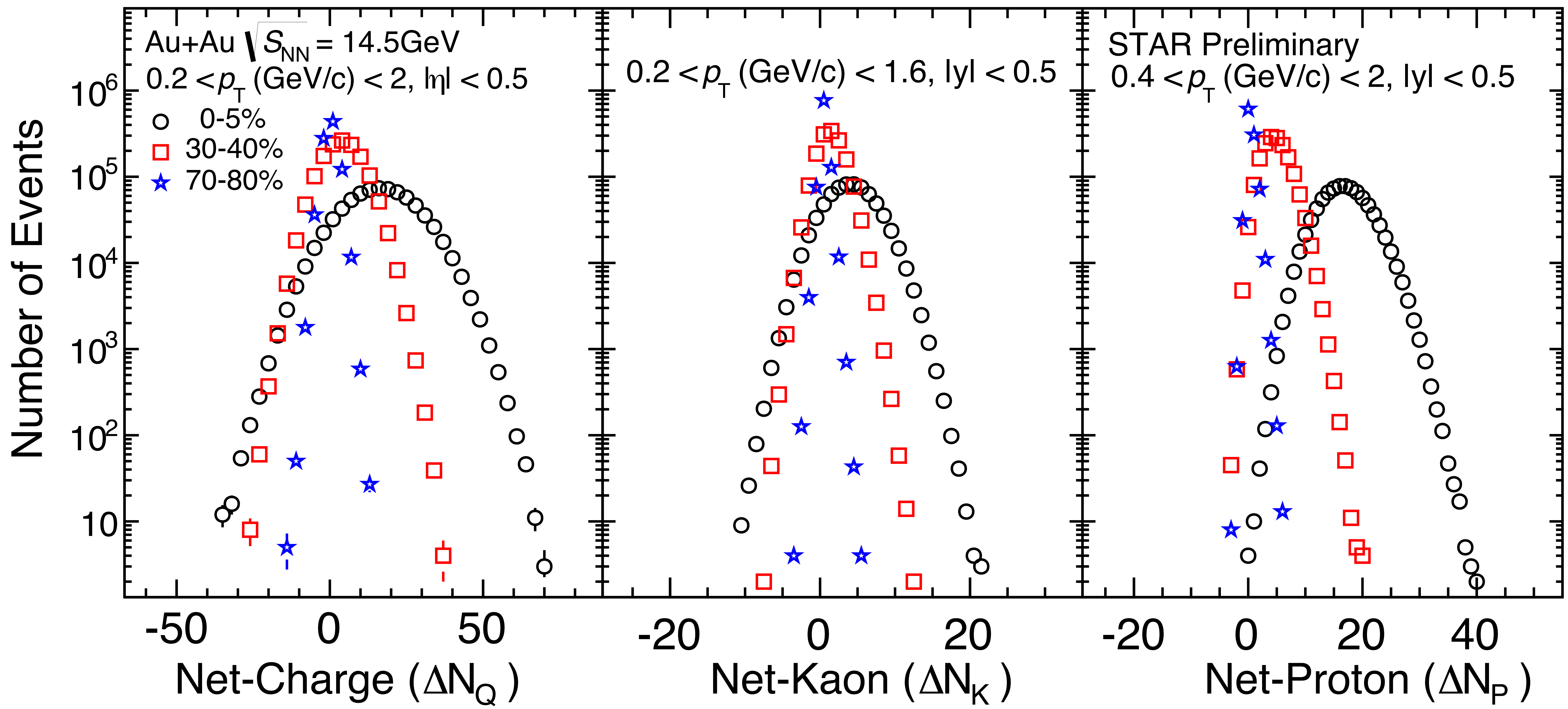



- With same N events:
  - error(net-charge) > error(net-kaon) > error(net-proton)
  - **Protons are the favored probe**
- Systematic error estimation
  - Includes uncertainties on efficiency and efficiency fluctuations
  - PID and track cuts



# Event-By-Event Net-Particle Multiplicity Distribution

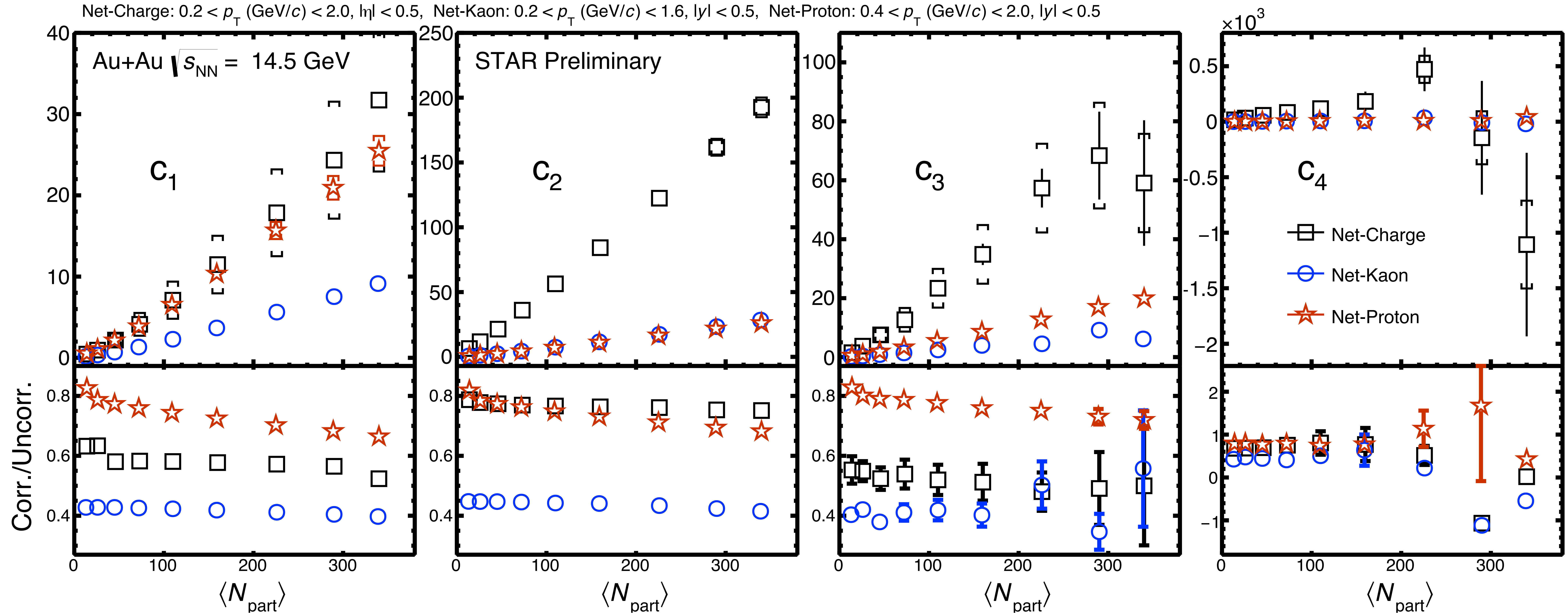
***Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV***




- Uncorrected raw event-by-event net-particle multiplicity distribution for Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV

# Corrected Cumulants

## *Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV*

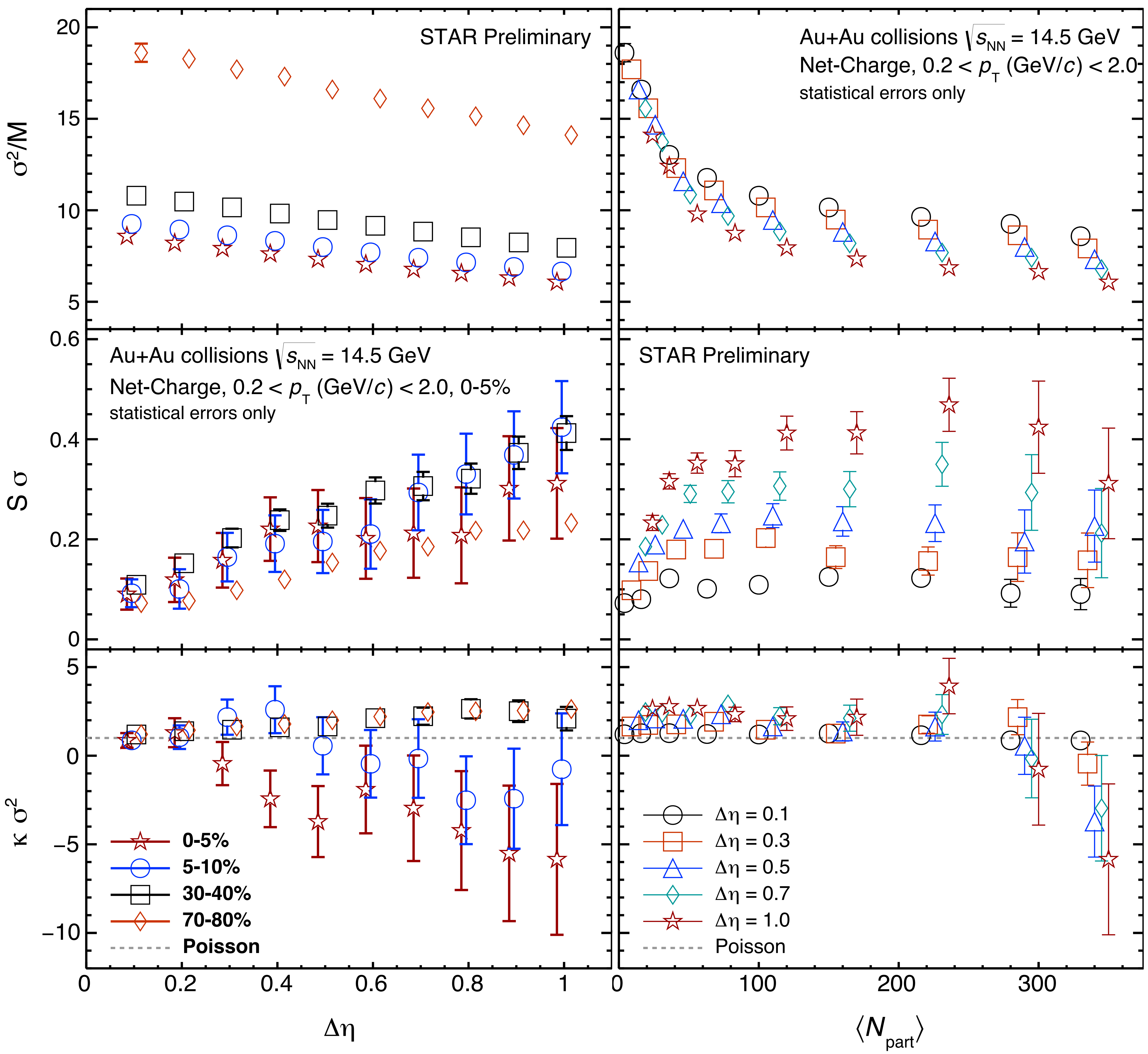



- Correction smallest for net-protons for all cumulants
- Corrections approximately flat with <$N_{part}$>

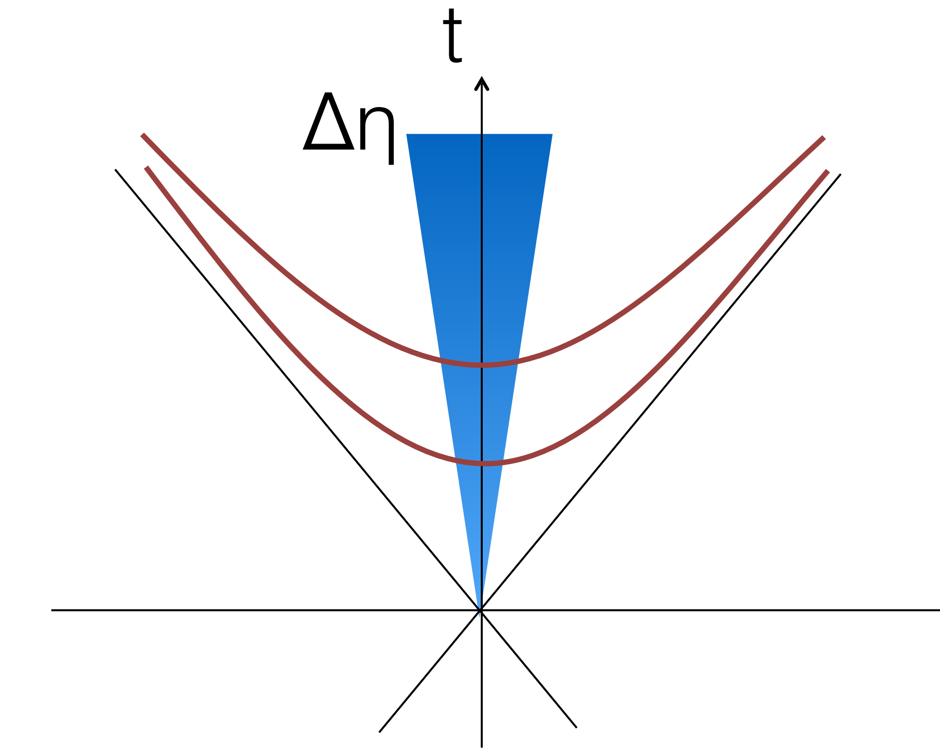
# Net-Charge – Δη Dependence

## *Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV*


S. Jeon, V. Koch, arXiv:hep-ph/0304012
V. Koch, arXiv:0810.2520
M. Kitazawa, Nucl. Phys. A942 (2015) 65-96
M. Sakaida et al, PRC90 (2014) 6, 064911

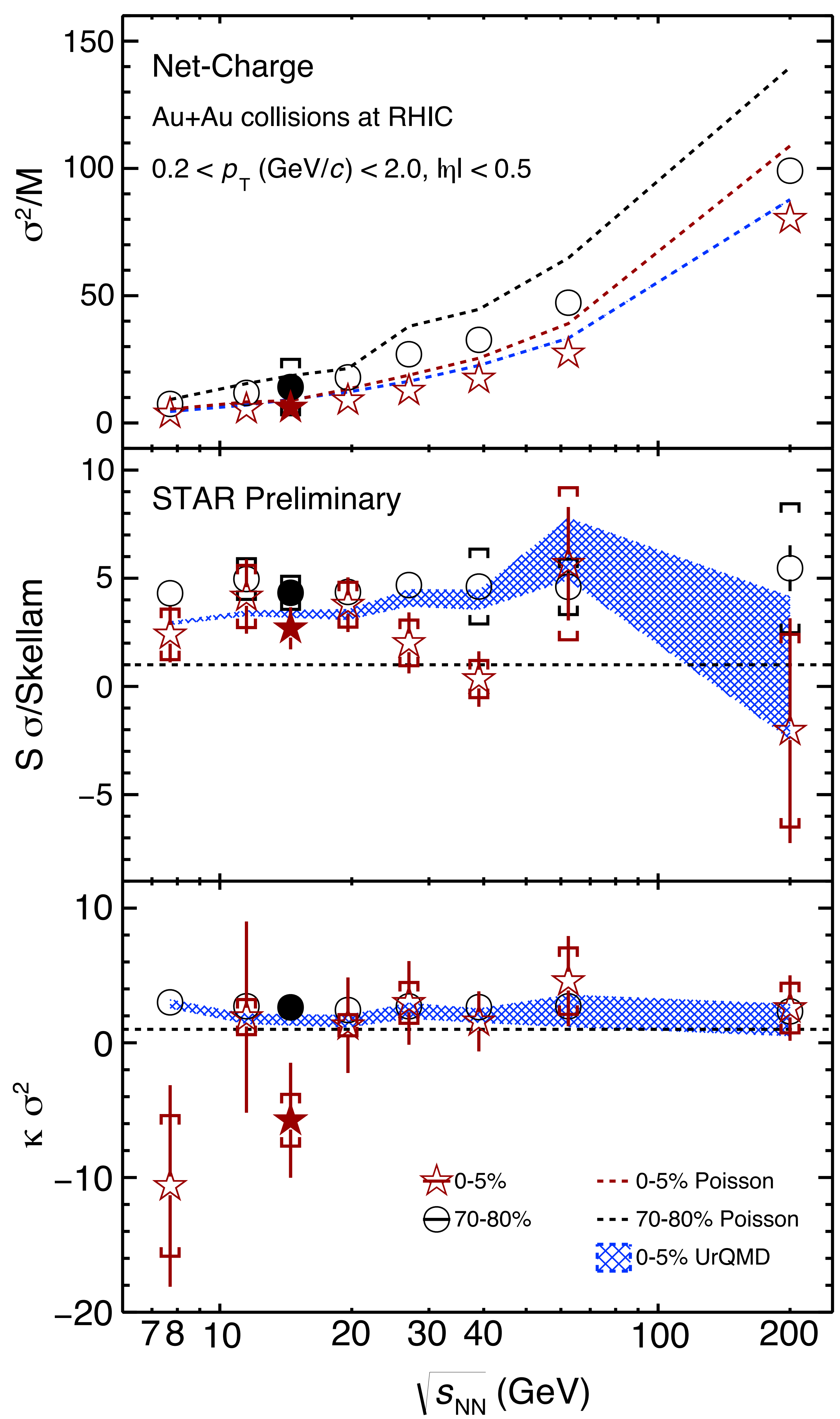

- Δη dependence of fluctuation observables encode history of the hot medium




- Smooth trend for $\sigma^2$/M, Sσ and κ$\sigma^2$ with increasing Δη
  - Different trend of κ$\sigma^2$ for central and peripheral collisions vs Δη
- The smaller the Δη window, the closer to poisson expectation
- Ordering in Δη vs <$N_{part}$> for $\sigma^2$/M, Sσ and κ$\sigma^2$ observed

# Corrected Cumulant Ratio of Net-Charge

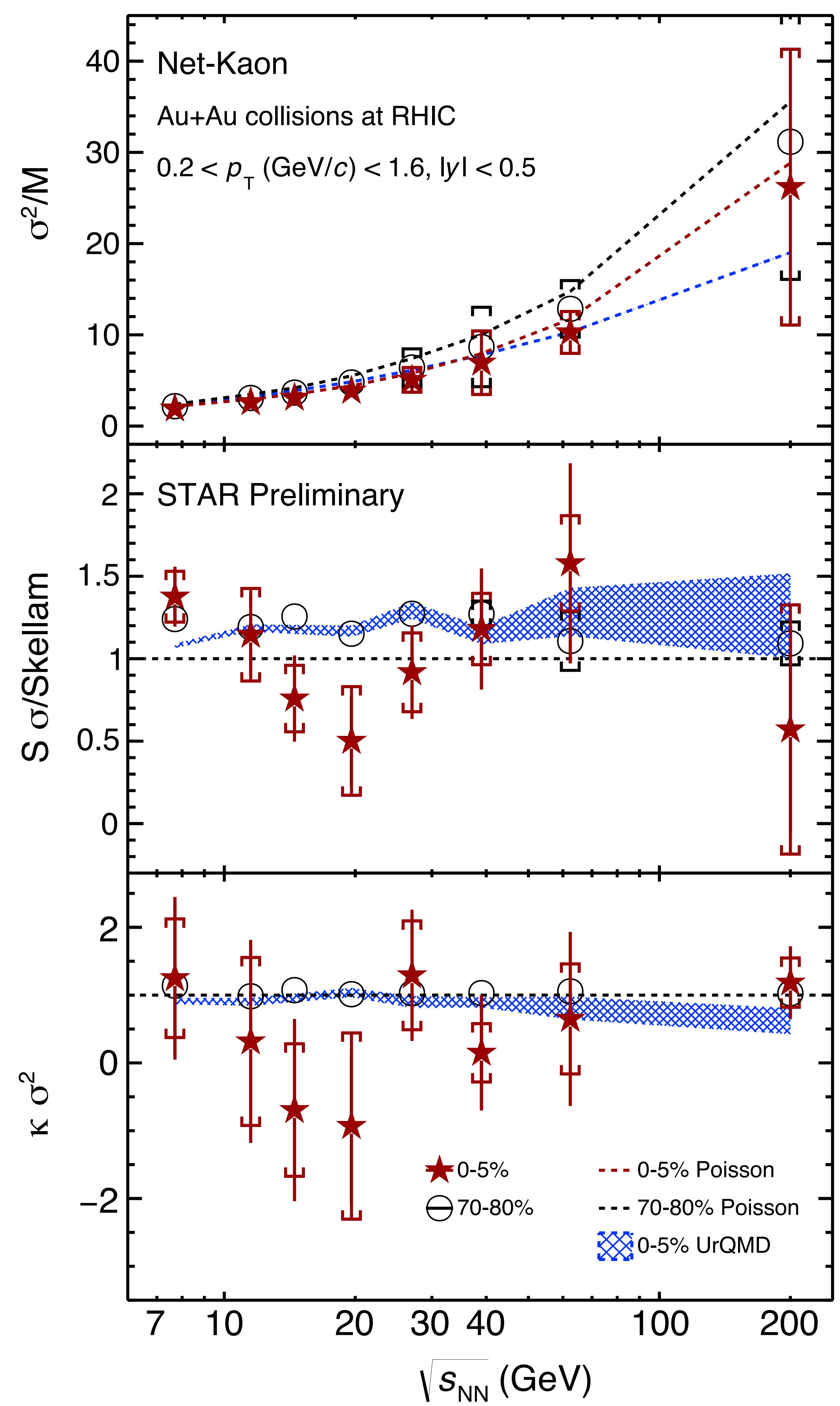
***Collision Energy Dependence***




- 14.5 GeV data-point added to published *Phys. Rev. Lett. 113, 092301 (2014)*
  - Fits well into trends
- $\sigma^2/M$ increases with increasing collision energy
- For most central collisions (0-5%), $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with unity
- UrQMD (no Critical Point), shows no energy dependence

# Corrected Cumulant Ratio of Net-Kaon

***Collision Energy Dependence***

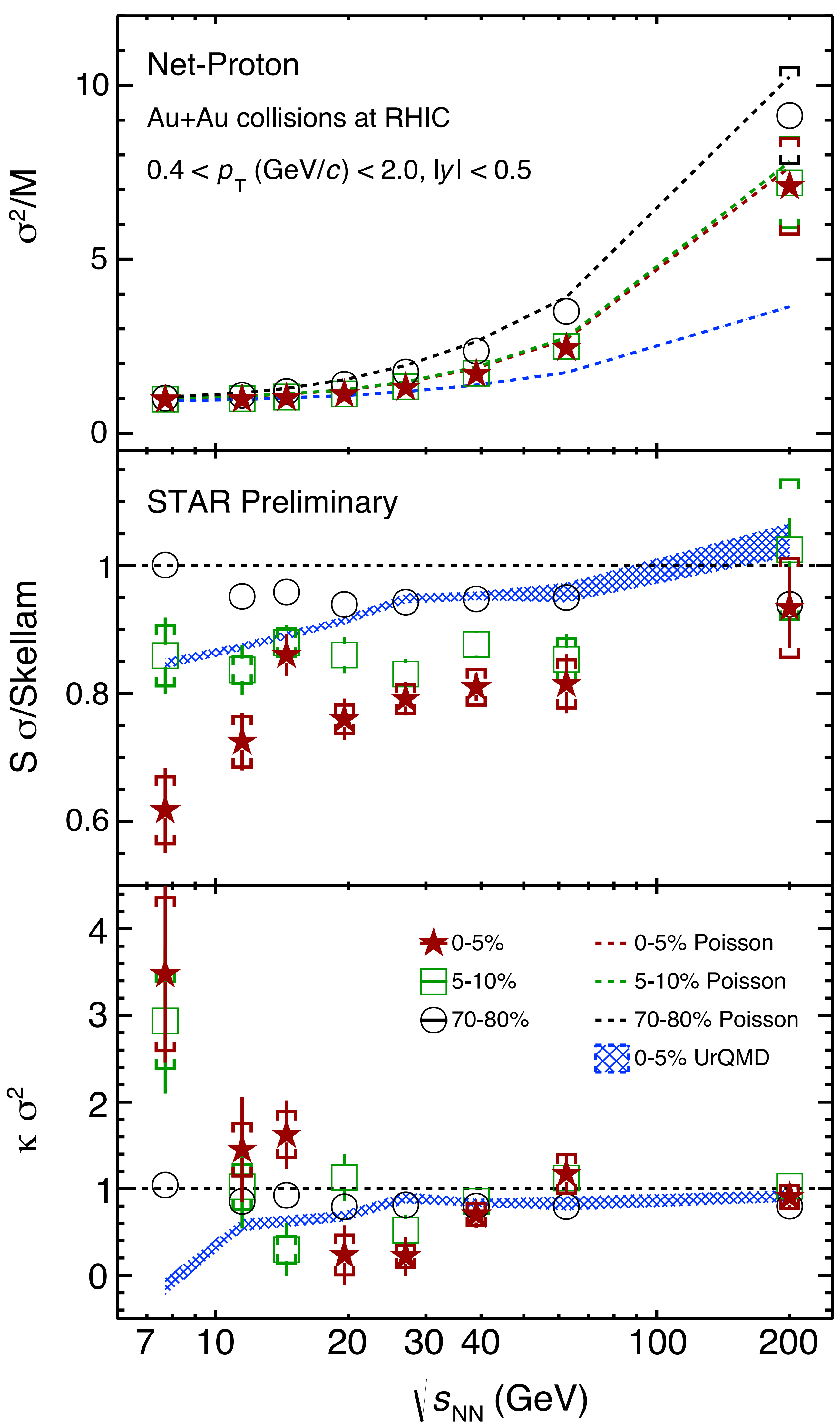



- $\sigma^2$/M increases with energy
- $\sigma^2$/M and Sσ/Skellam are consistent with the Poisson expectation for most central collisions
- For most central collisions (0-5%), $\kappa\sigma^2$ is consistent with unity (= Poisson expectation)
  - More statistics needed
- UrQMD (no Critical Point), shows no energy dependence

**See Poster Ji Xu**
**Board ID 0127, Ex4**

# Corrected Cumulant Ratio of Net-Proton

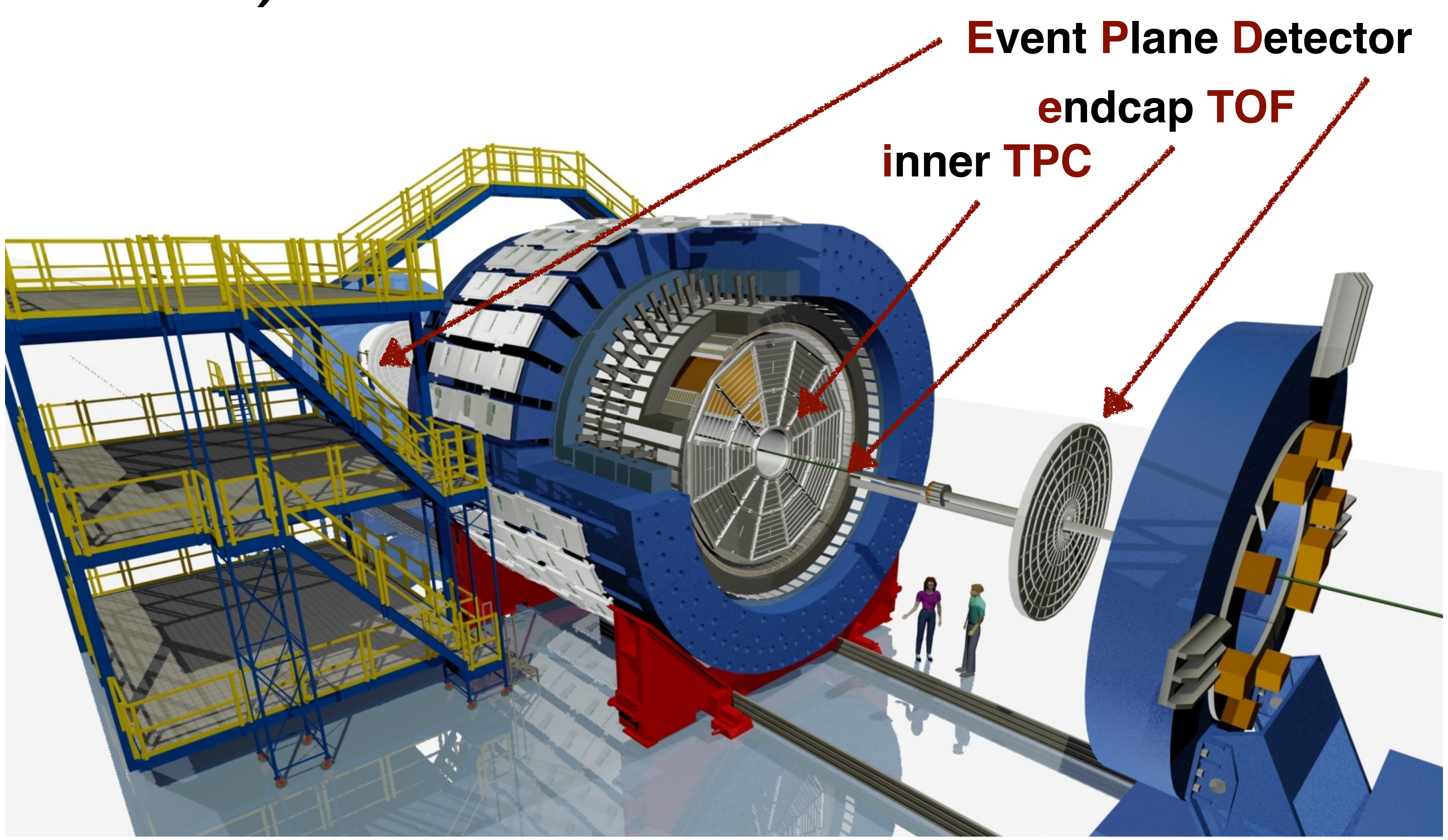
## *Collision Energy Dependence*

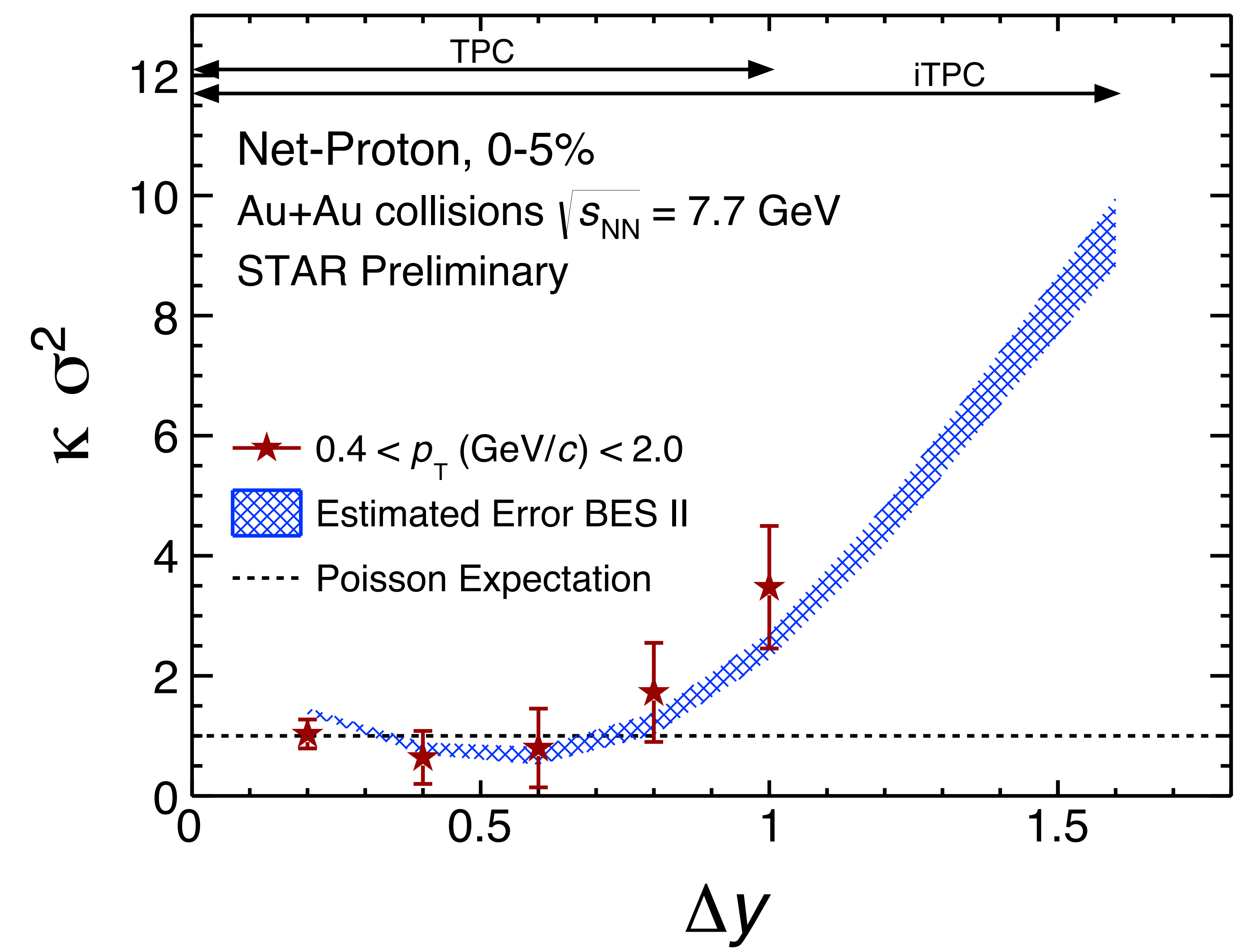



- $\sigma^2$/M increases with increasing energy, consistent with Poisson expectation
- Sσ/Skellam increases with increasing energy
- Non-monotonic behavior of net-proton $\kappa\sigma^2$ seen in top 5% central collisions
  - 5-10% central collisions in between
  - → however: smooth trend in centrality
  - Peripheral collisions show smooth trend
  - Detailed extensive studies have been carried out and are still in progress
- UrQMD (no Critical Point), shows suppression at lower energies - due to baryon number conservation

# Plans for Beam Energy Scan Phase II

***(2019-2020)***




Larger rapidity acceptance crucial for further critical point search with net-protons

**iTPC Upgrade**
Replace aging wires
Full pad coverage
→ better dE/dx
$-1.5 < \eta < 1.5$
$p_T > 60$ MeV/c

**EPD Upgrade**
Replaces aging BBC
Event centrality
→ Suppress auto-correlation
Better trigger & b/g reduction
$-4.5 < \eta < -1.8$ , $1.8 < \eta < 4.5$

**eTOF**
Larger rapidity coverage
Extends PID in forward direction
$1.05 < \eta < 1.5$

# Summary and Outlook

- **New results for $\sqrt{s_{NN}}$ = 14.5 GeV** Au+Au collisions for net-charge, net-kaon, and net-proton
- **New results** of energy and centrality dependence of **net-kaon**
- Study of **pseudo-rapidity dependence** shows that acceptance is **crucial** for the **critical point search**
- **Non-monotonic behavior** seen in **net-proton** $\kappa\sigma^2$
- **RHIC Beam Energy Scan II** will bring larger event sample and wider phase-space to **boost** the **critical point search**


Thank you !!