Higher Moments of Net-Charge Multiplicity Distributions

Jochen Thäder
on behalf of the STAR Collaboration

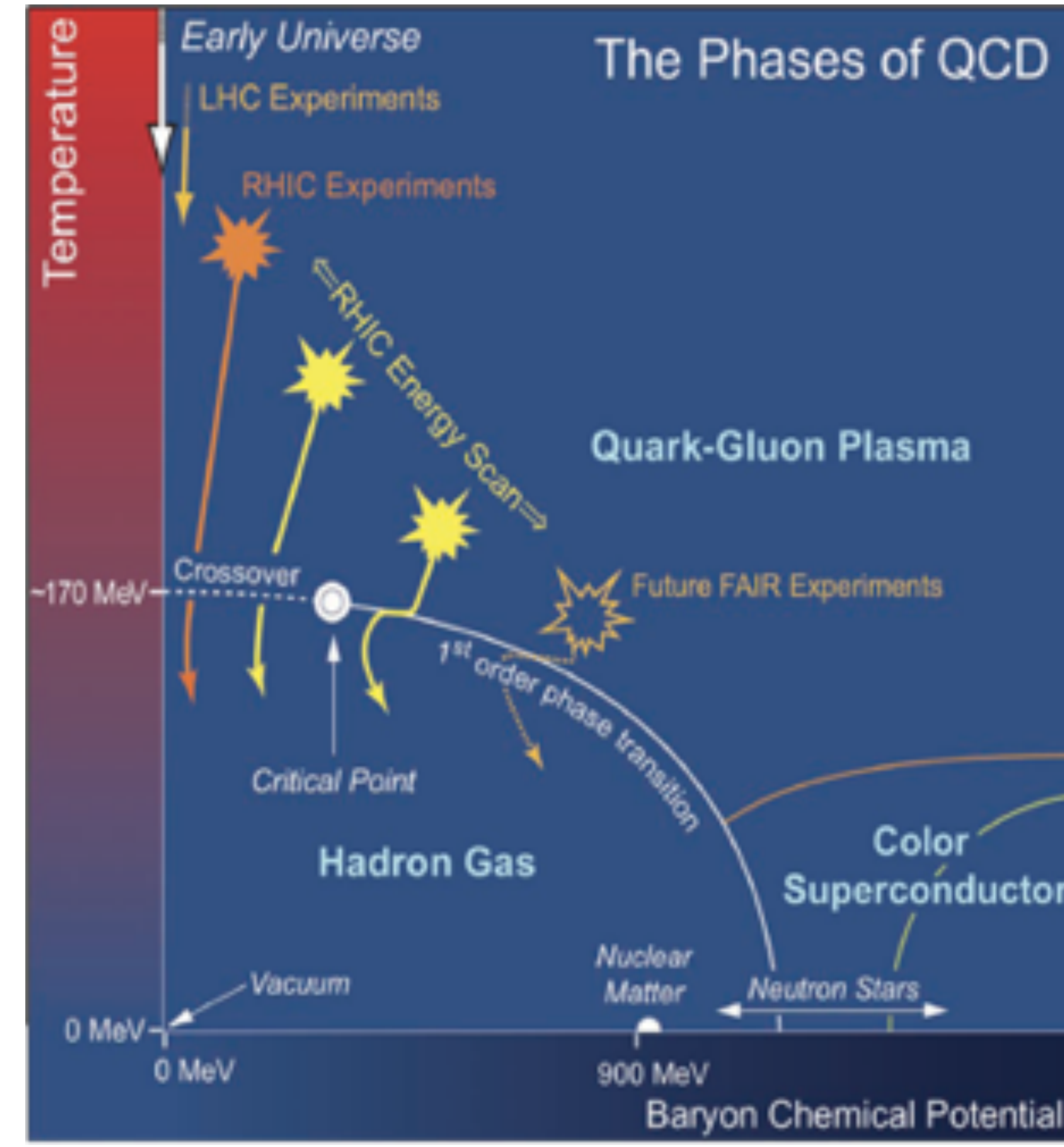
Lawrence Berkeley National Laboratory

GSI, Darmstadt

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 μ_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



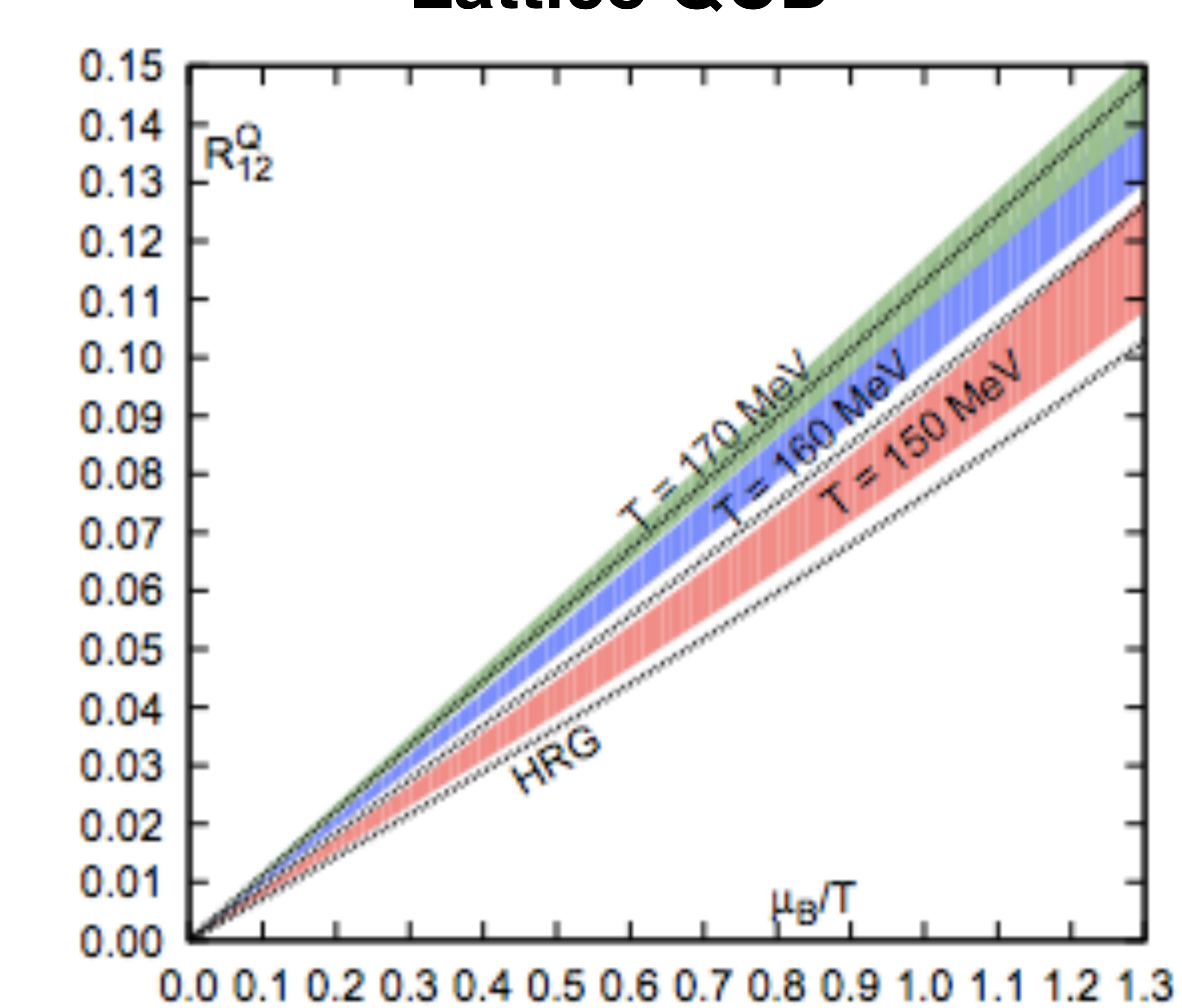
Connection to Theoretical Calculations

- 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 μ_B

Lattice QCD



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

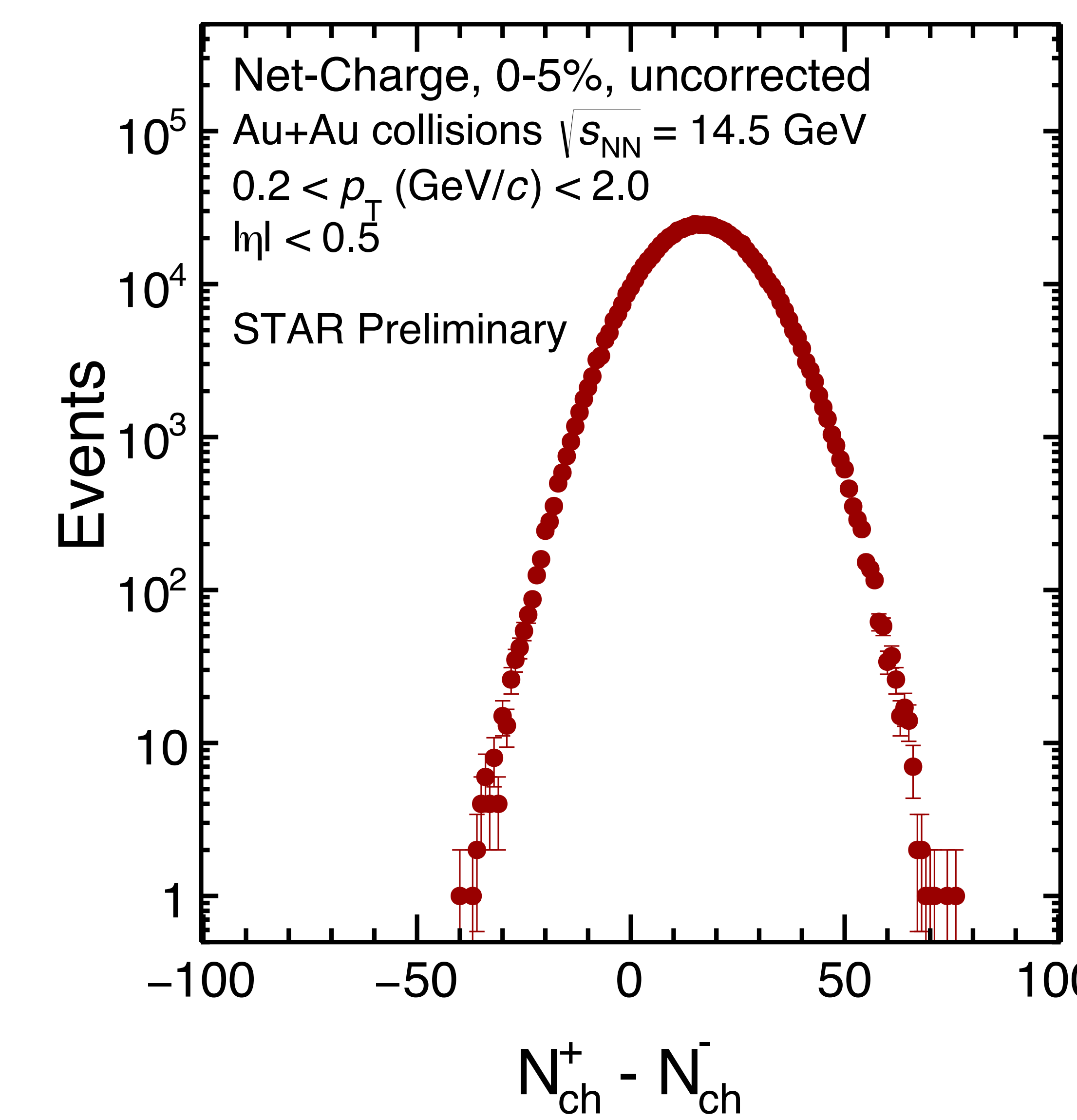
$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

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

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

$$i = B, Q, S$$

Experiment



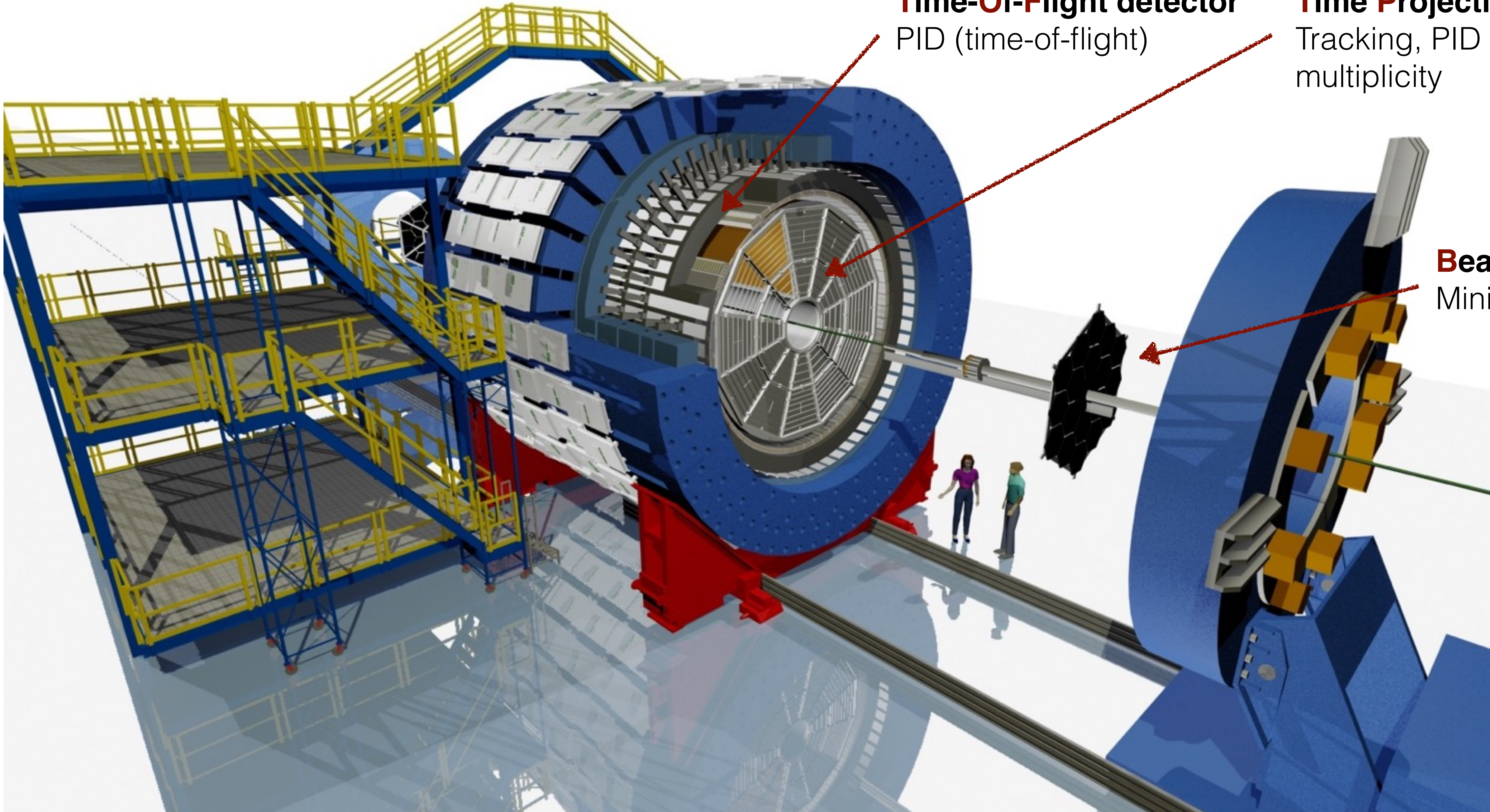
The STAR detector

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

Time-Of-Flight detector
PID (time-of-flight)

Time Projection Chamber
Tracking, PID (dE/dx), vertexing, multiplicity

Beam-Beam Counter
Minimum-bias trigger



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

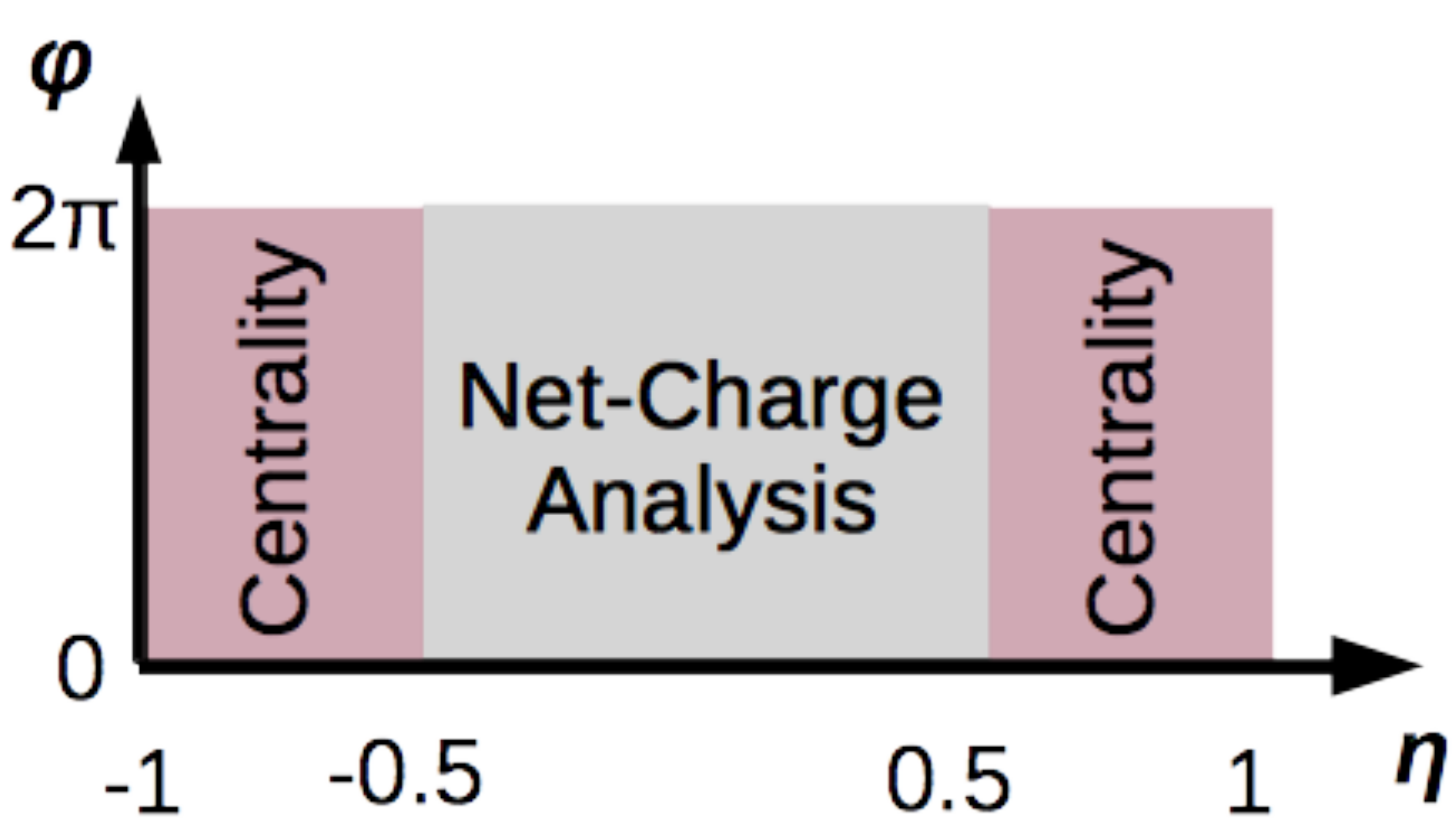
$\sqrt{s_{NN}}$ (GeV)	Good events recorded (M events)	Year	μ_B (MeV) [0-5%]	T (MeV) [0-5%]
7.7	4	2010	422	140
11.5	12	2010	316	152
14.5	20	2014	264	156
19.6	36	2011	206	160
27	70	2011	156	162
39	130	2010	112	164
62.4	67	2010	73	165
200	350	2010	24	166

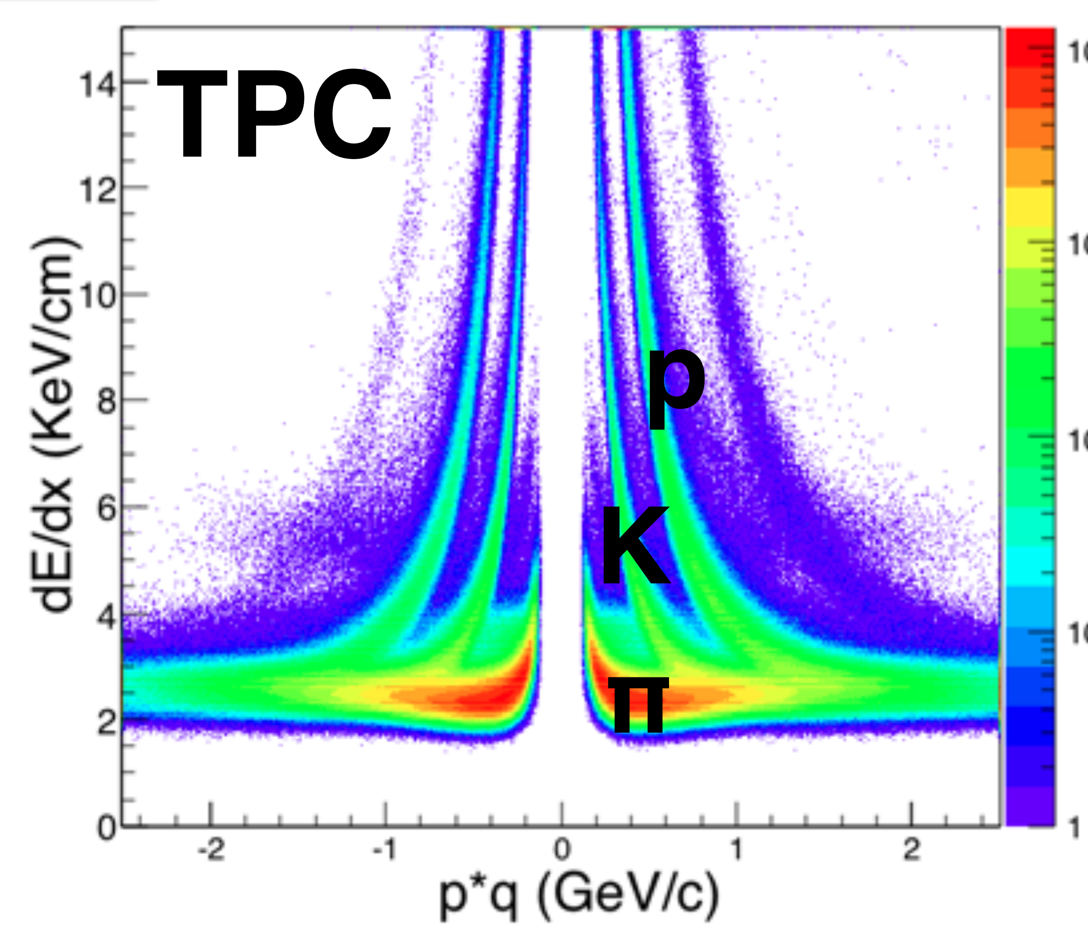
μ_B, T : J. Cleymans et al., PRC 73, 034905 (2006)

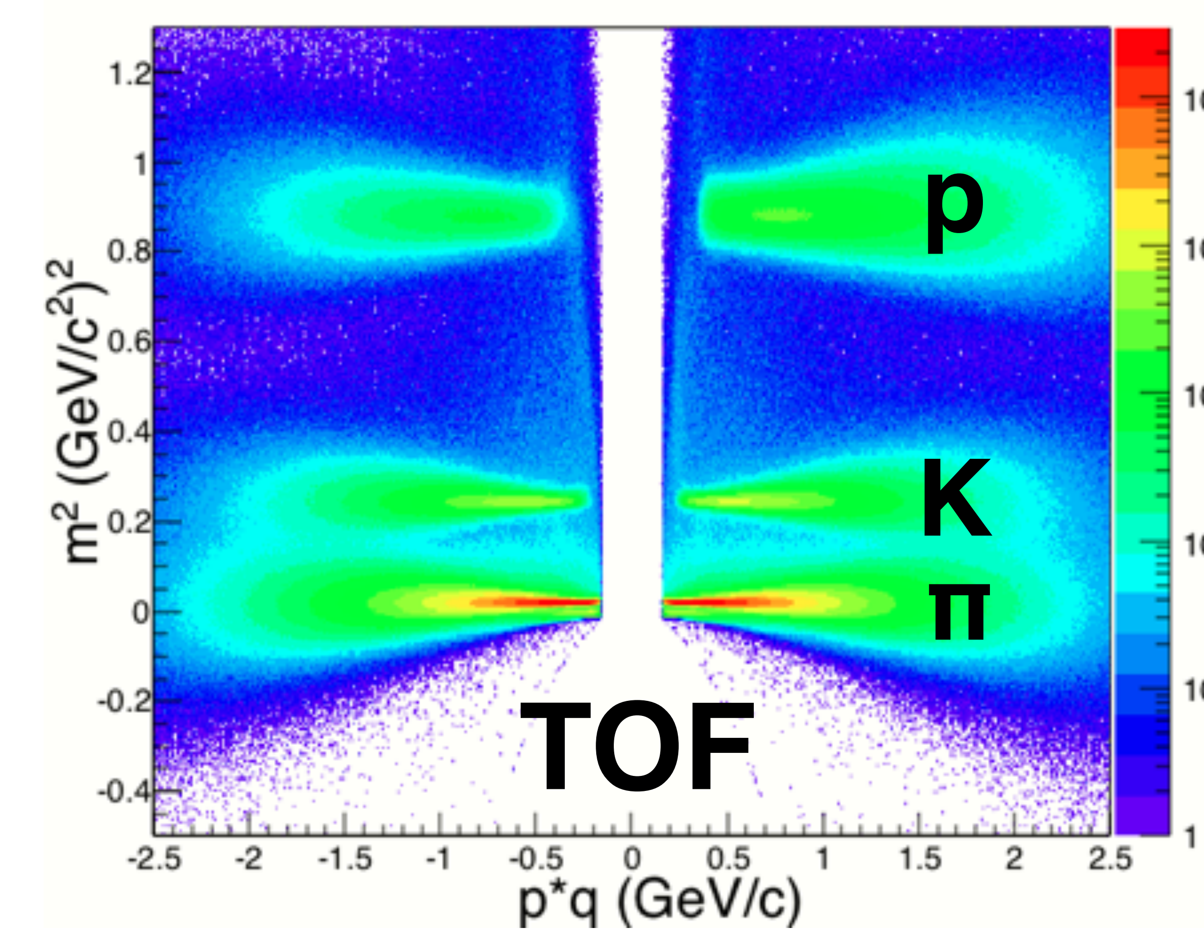
Analysis Details

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 $\|\eta\| < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\|y\| < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\|y\| < 0.5$
Particle Identification	Reject protons form spallation for $p_T < 0.4$ GeV/c	$0.4 < p_T$ (GeV/c) < 0.8 → TPC $0.8 < p_T$ (GeV/c) < 2.0 → TPC+TOF	$0.2 < p_T$ (GeV/c) < 0.4 → TPC $0.4 < p_T$ (GeV/c) < 1.6 → TPC+TOF
Centrality definition, → *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
	$0.5 < \|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.0$



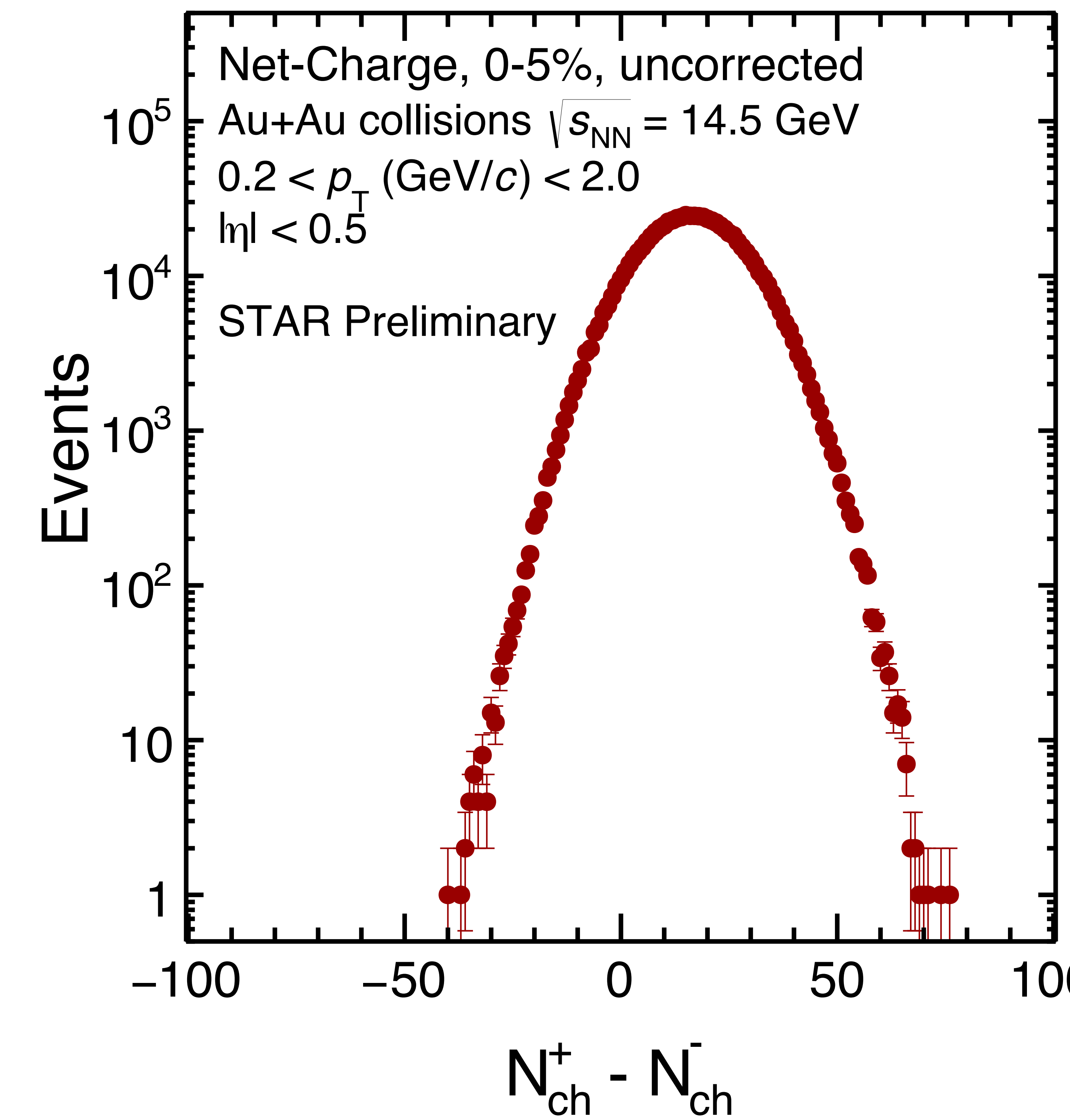




Analysis Method

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



Analysis Method

Error Estimation

X. Luo, PRC91, 034907 (2015)

- Statistical Errors based on Delta Theorem

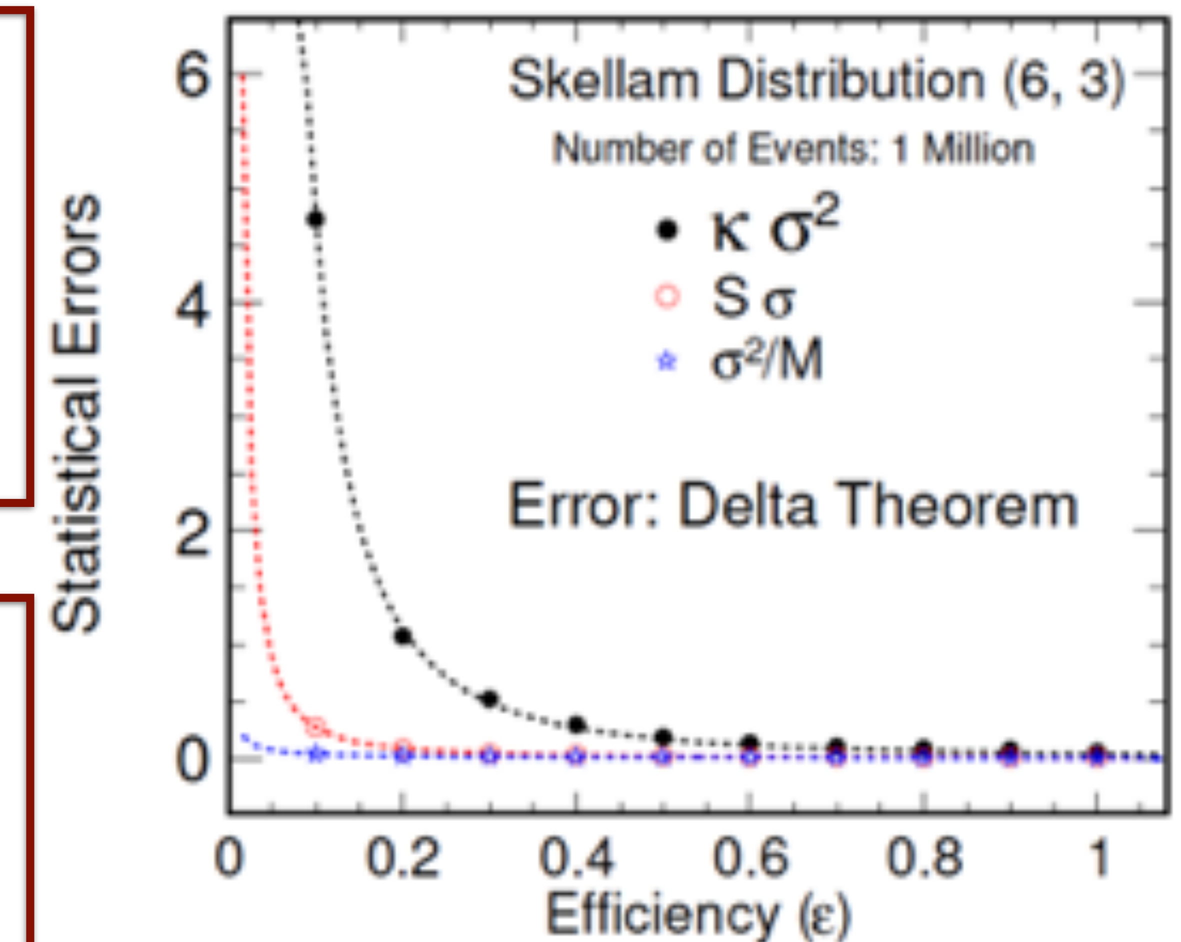
Au+Au 14.5 GeV	Net-Charge	Net-Proton	Net-Kaon
Typical Width (σ)	12.2	4.2	3.4
Average efficiency (ε)	65%	75%	38%
σ^2 / ε^2	355	32	82

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

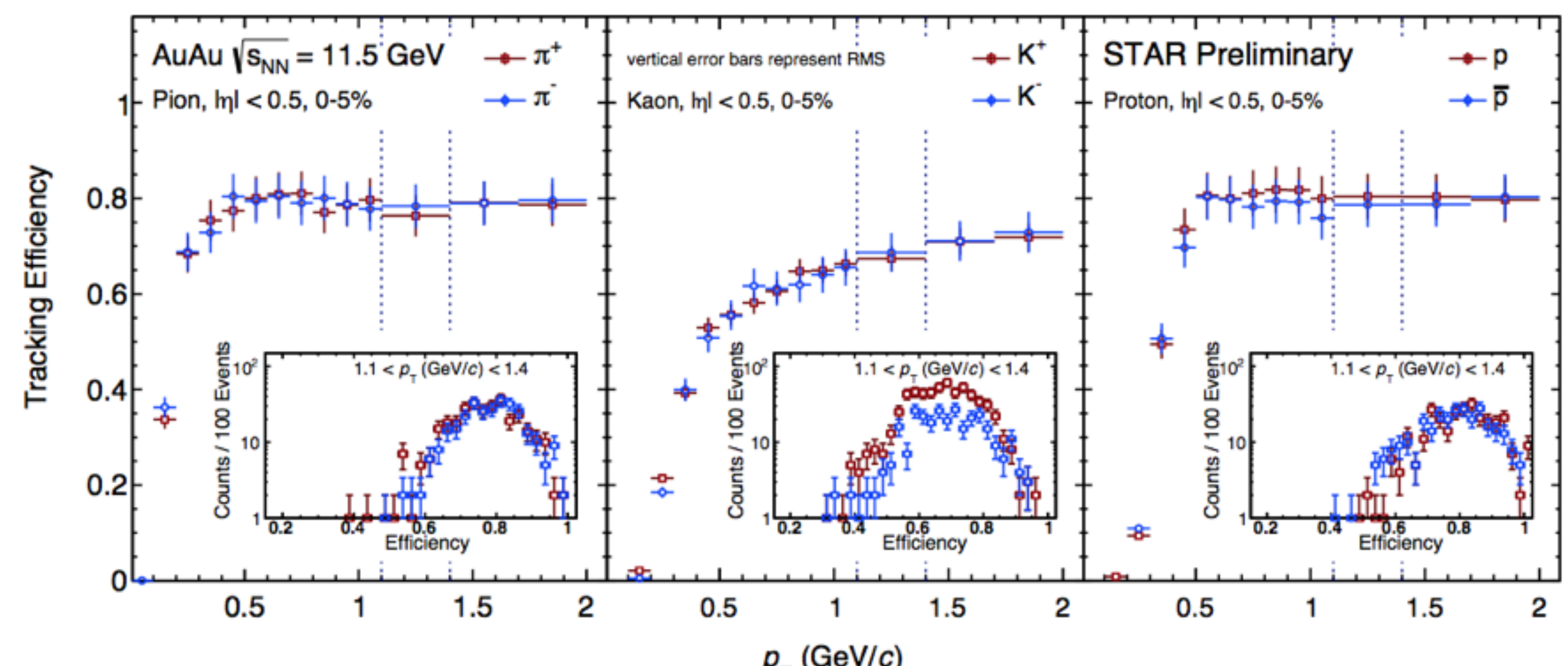
$$error\left(\frac{c_n}{c_2}\right) \propto \frac{\sigma^{n-2}}{\epsilon^{n/2}}, \; for\; n > 2$$

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

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



- 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



Efficiency Studies

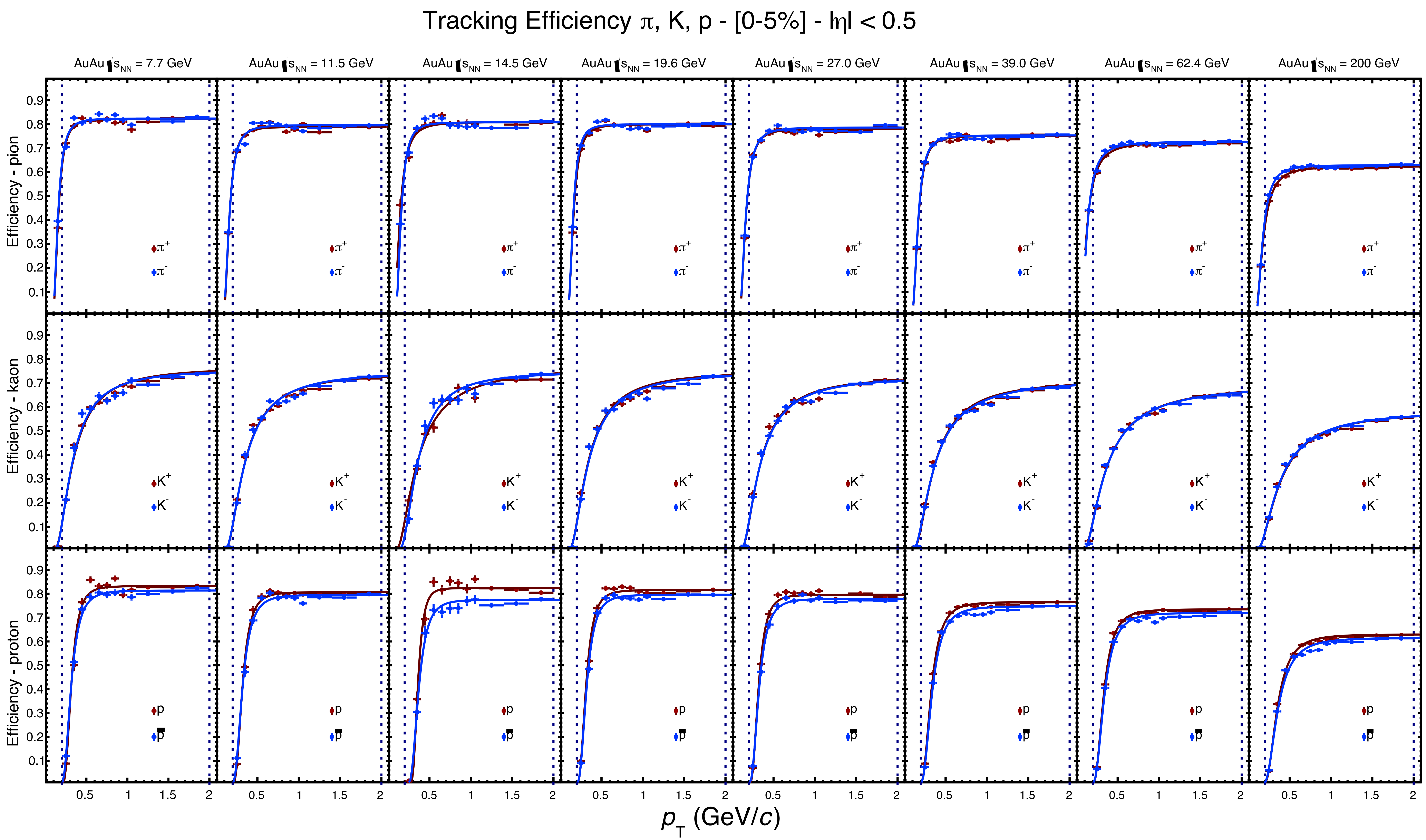
Efficiency Studies

Overview

- Construct efficiencies for charged particles
  - π, K, p tracking efficiencies extracted from embedding
  - Use relative fractions for π, K, p to get charged efficiencies
- For efficiencies study
  - Extract efficiency per 100 events of different p_T bins
  - Use the width as systematic uncertainty

Tracking Efficiencies for Identified Hadrons

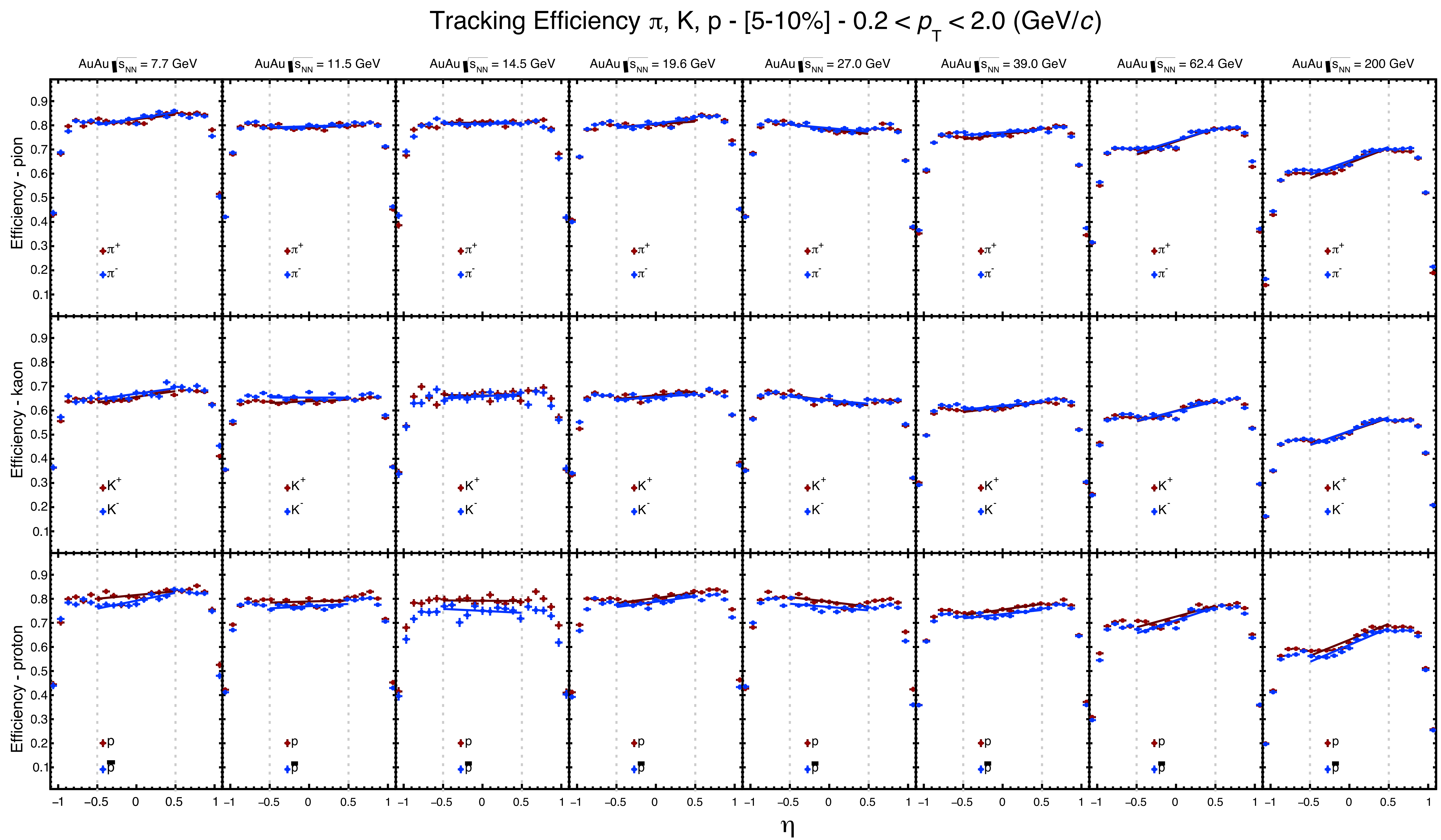
$\sqrt{s_{NN}}$ = 7.7 GeV - 200 GeV, 0 .2 < p_T < 2.0 GeV/c, $|\eta|$ < 0.5, 0-5% central



2015-09-13 16:38:50

Tracking Efficiencies for Identified Hadrons

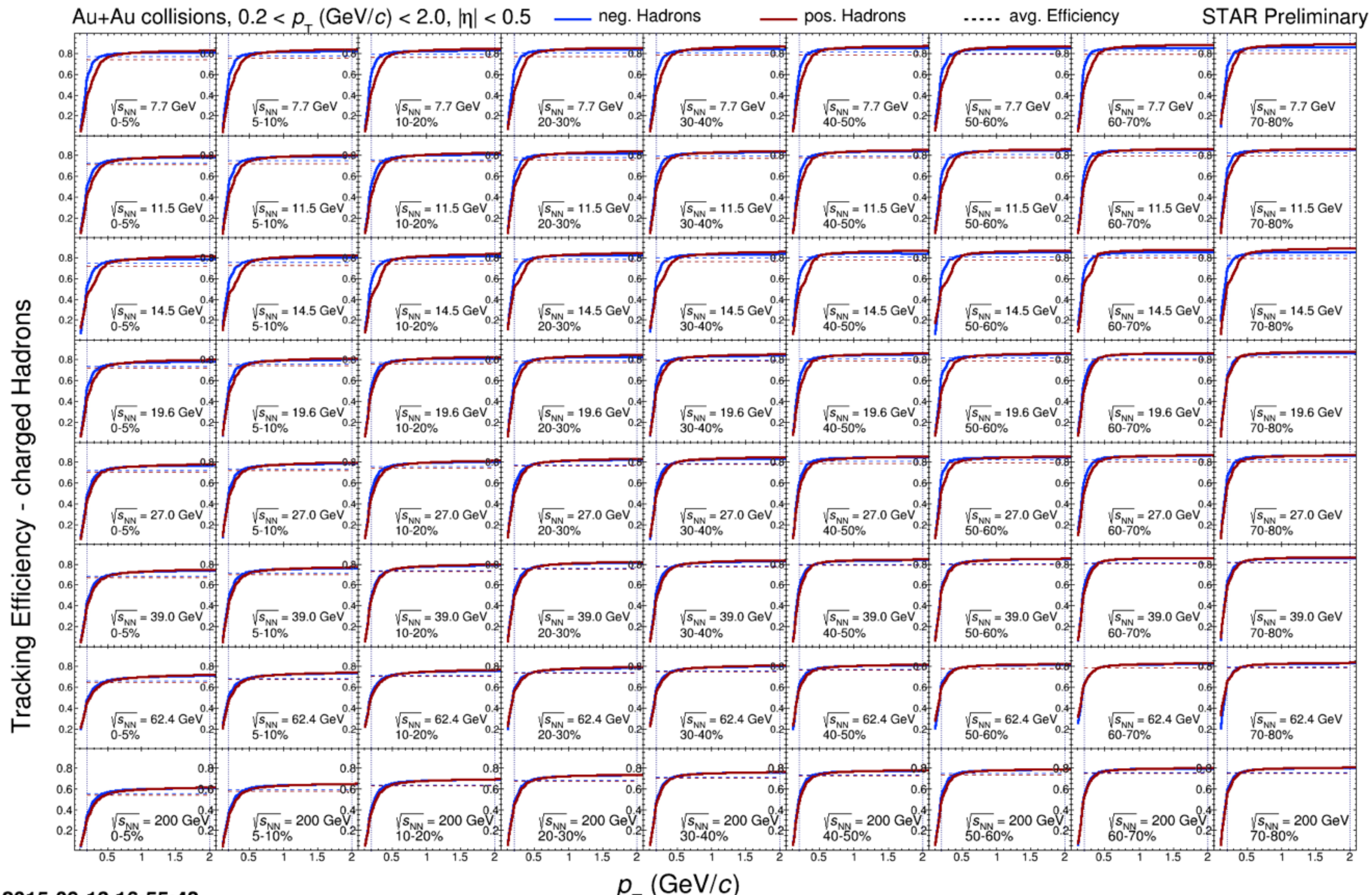
$\sqrt{s_{NN}}$ = 7.7 GeV - 200 GeV, 0 .2 < p_T < 2.0 GeV/c, |η| < 0.5, 0-5% central



2015-09-13 16:39:23

Tracking Efficiencies for Charged Hadrons

$\sqrt{s_{NN}}$ = 7.7 GeV - 200 GeV, 0 .2 < p_T < 2.0 GeV/c, $|\eta|$ < 0.5, 0-80% central

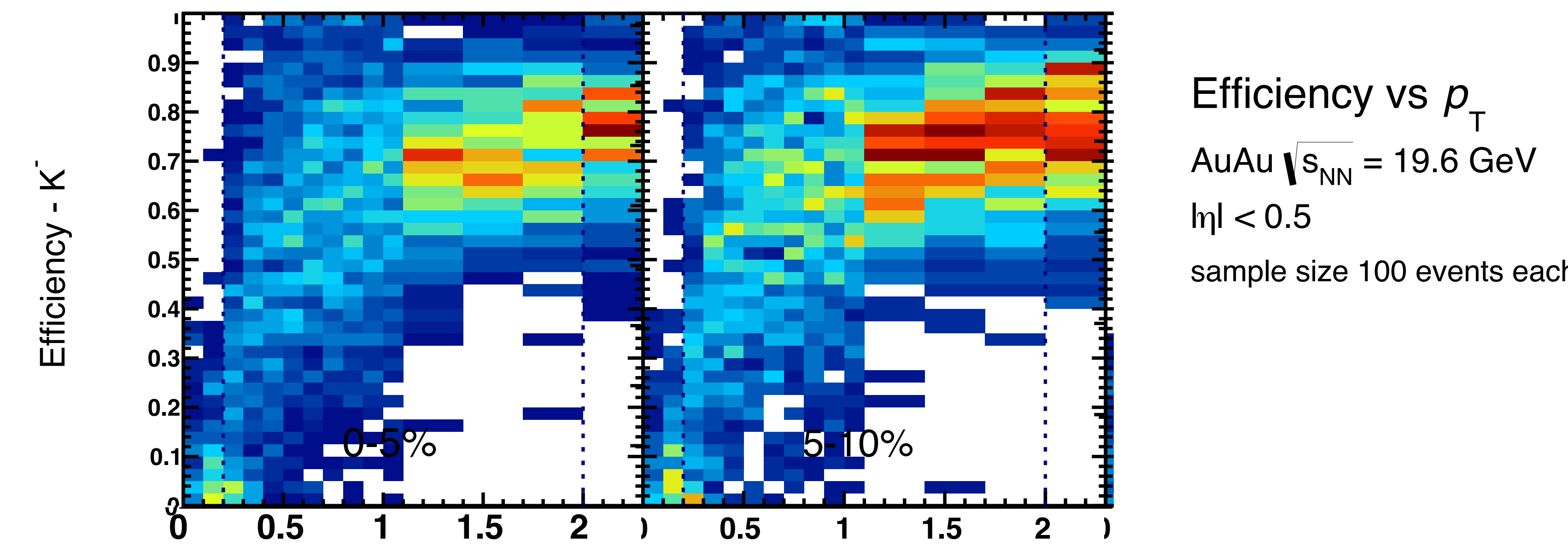


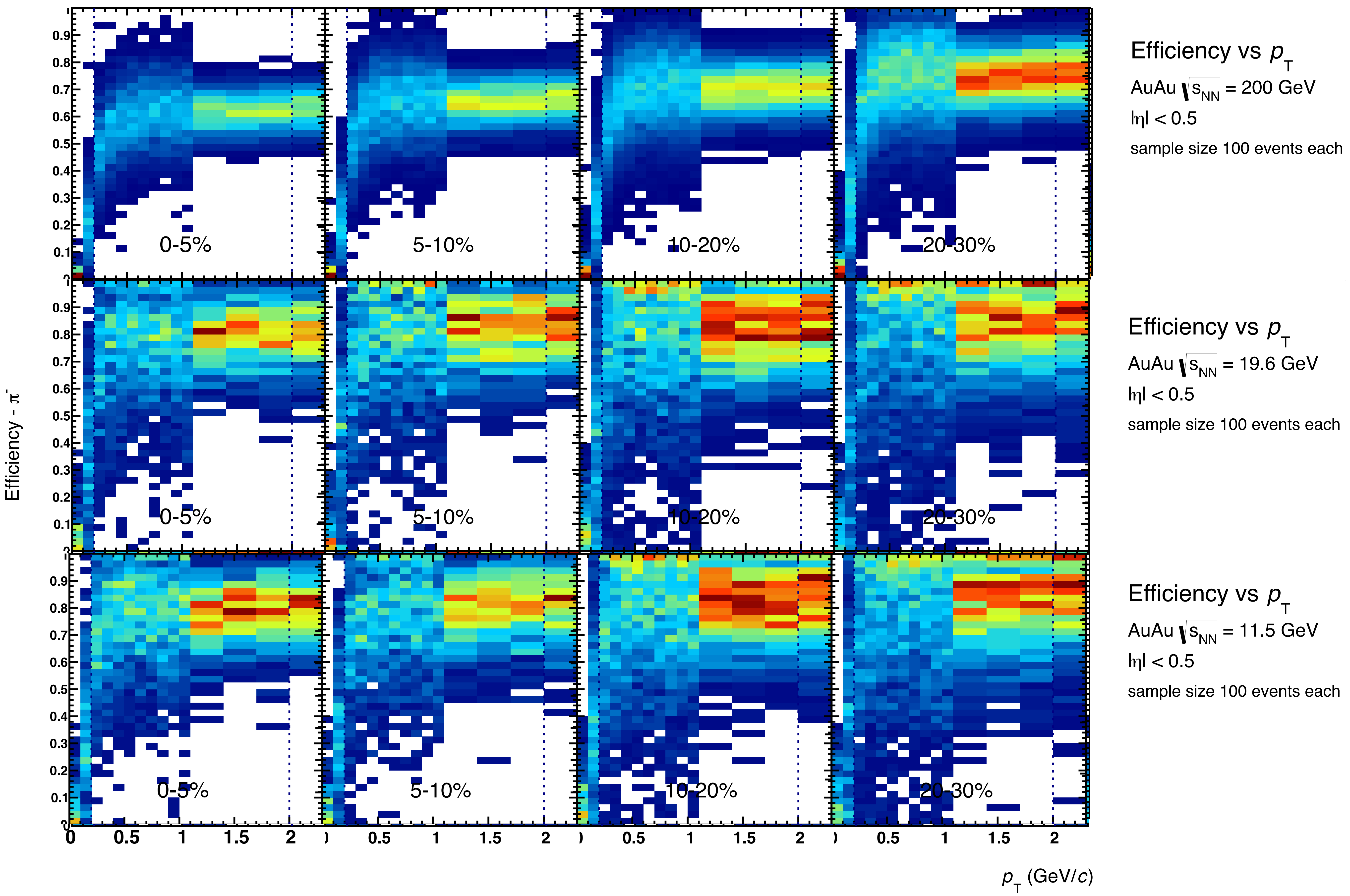
2015-09-13 16:55:43

Efficiency Studies

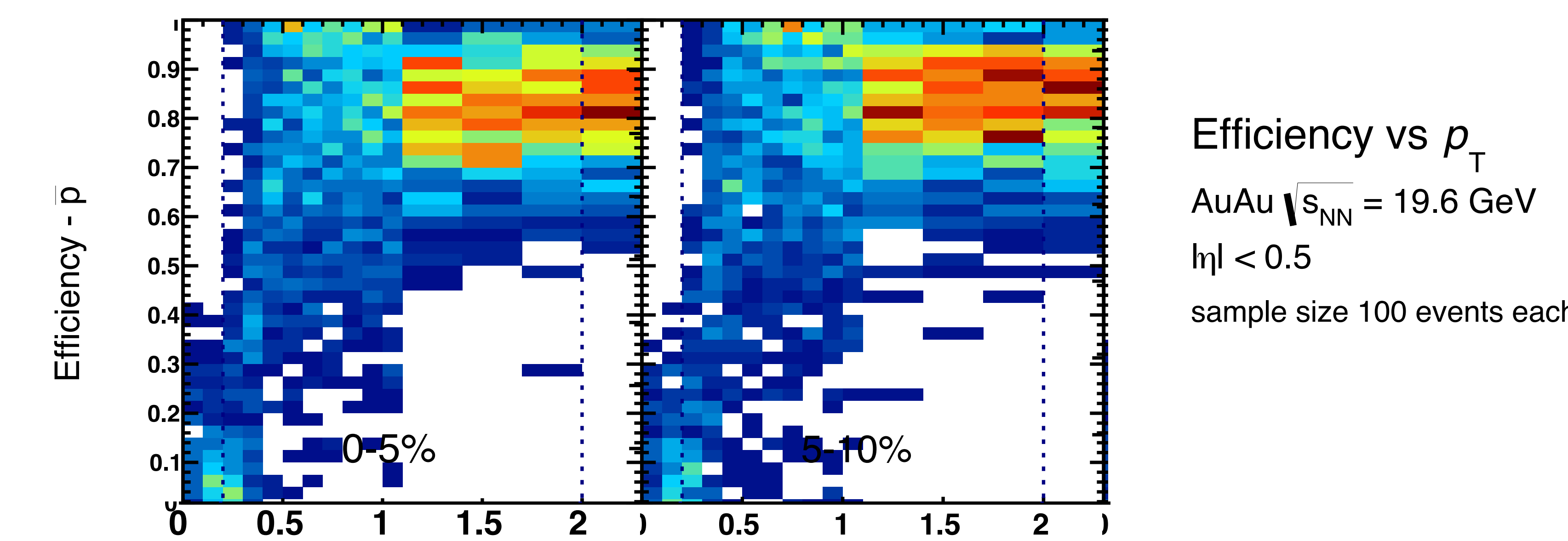
Efficiency Distribution vs p_T (100 events per entry)

Kaon





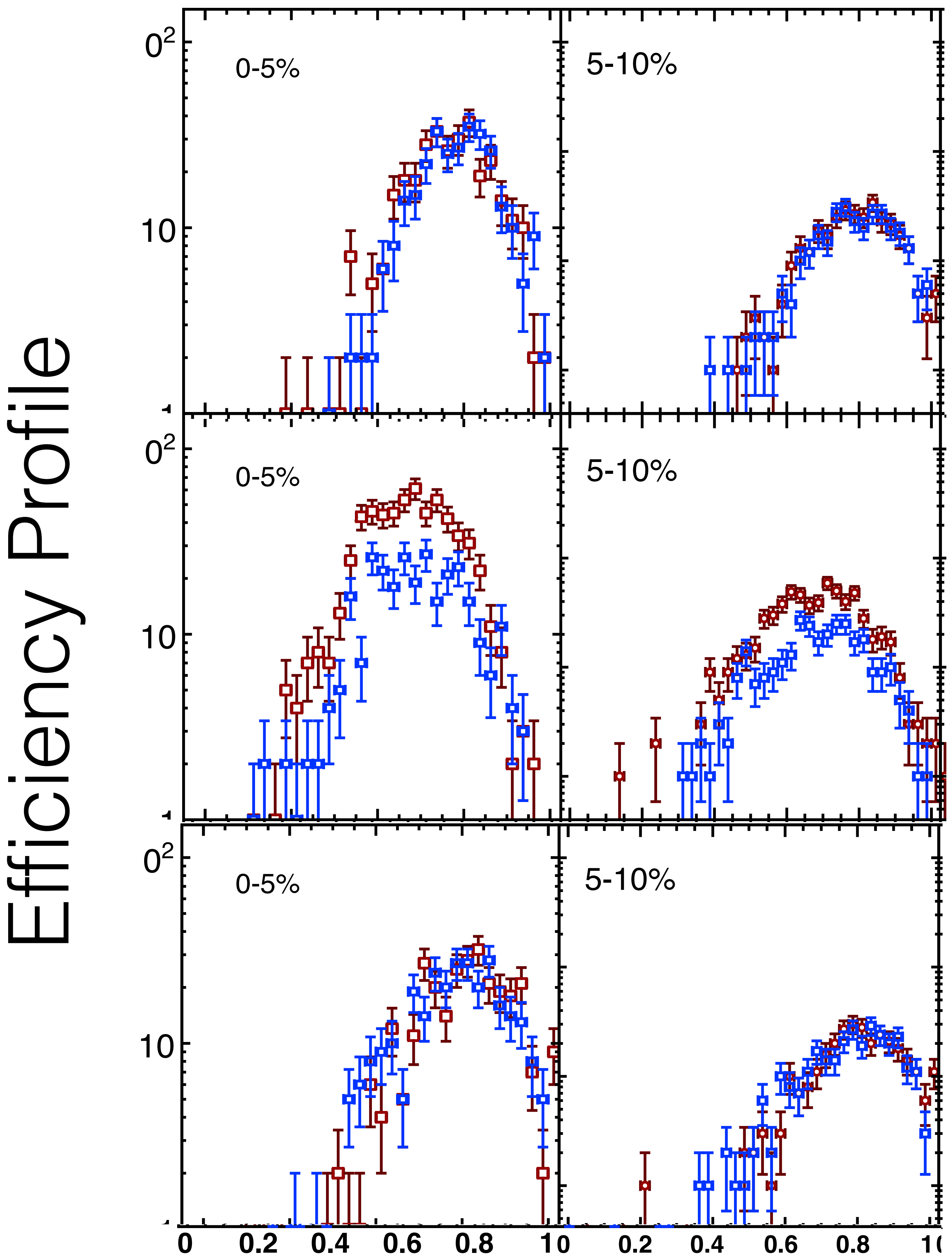
Pion



Proton

Efficiency Studies

Efficiency Distribution Profile - $1.1 < p_T < 1.4$ (GeV/c)



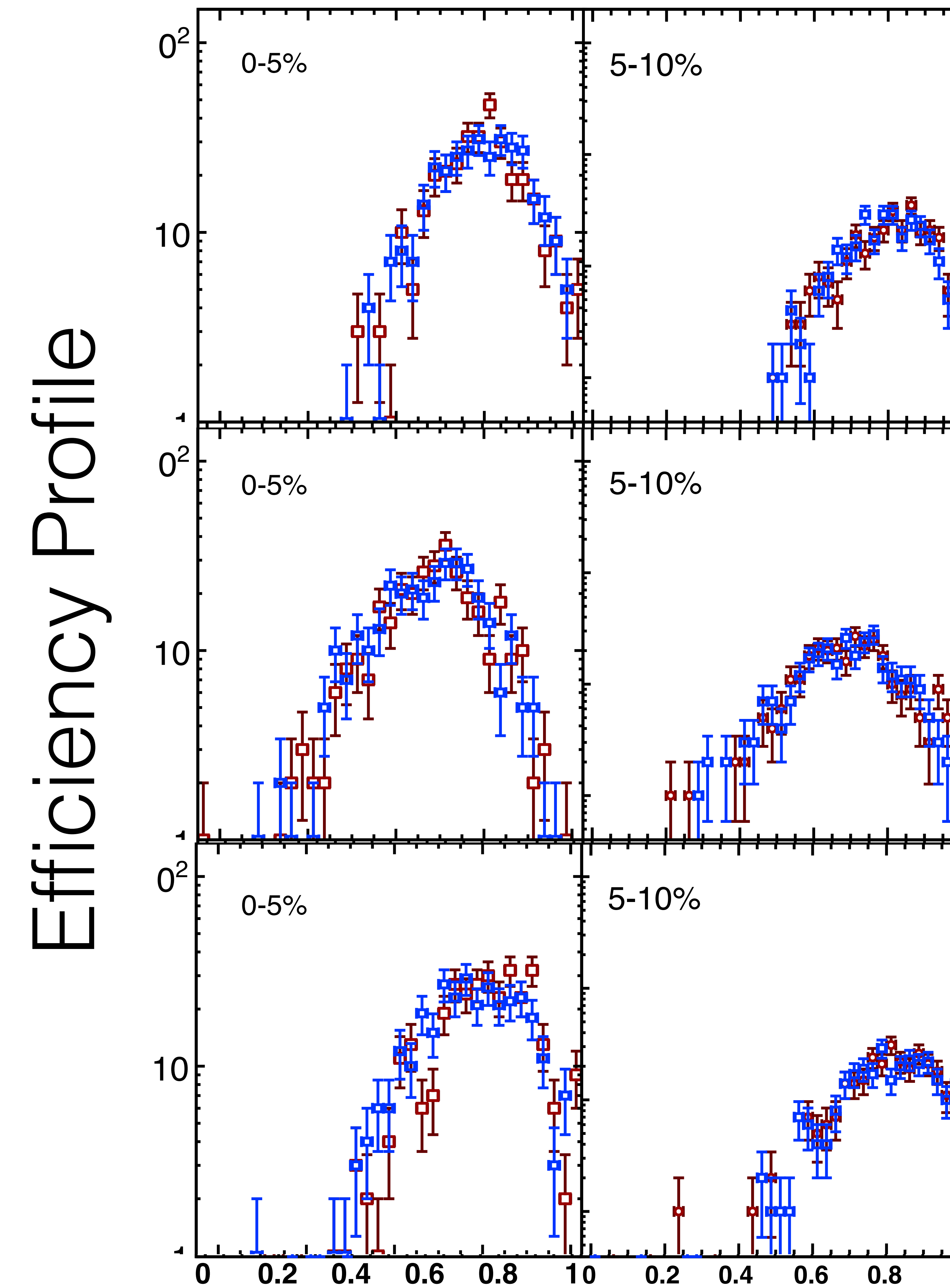
Efficiency Width
AuAu $\sqrt{s_{NN}}$ = 11.5 GeV
$|\eta| < 0.5$
$1.1 < p_T < 1.4$ (GeV/c)
sample size 100 events each

Efficiency Width
AuAu $\sqrt{s_{NN}}$ = 19.6 GeV
$|\eta| < 0.5$
$1.1 < p_T < 1.4$ (GeV/c)
sample size 100 events each

Pion

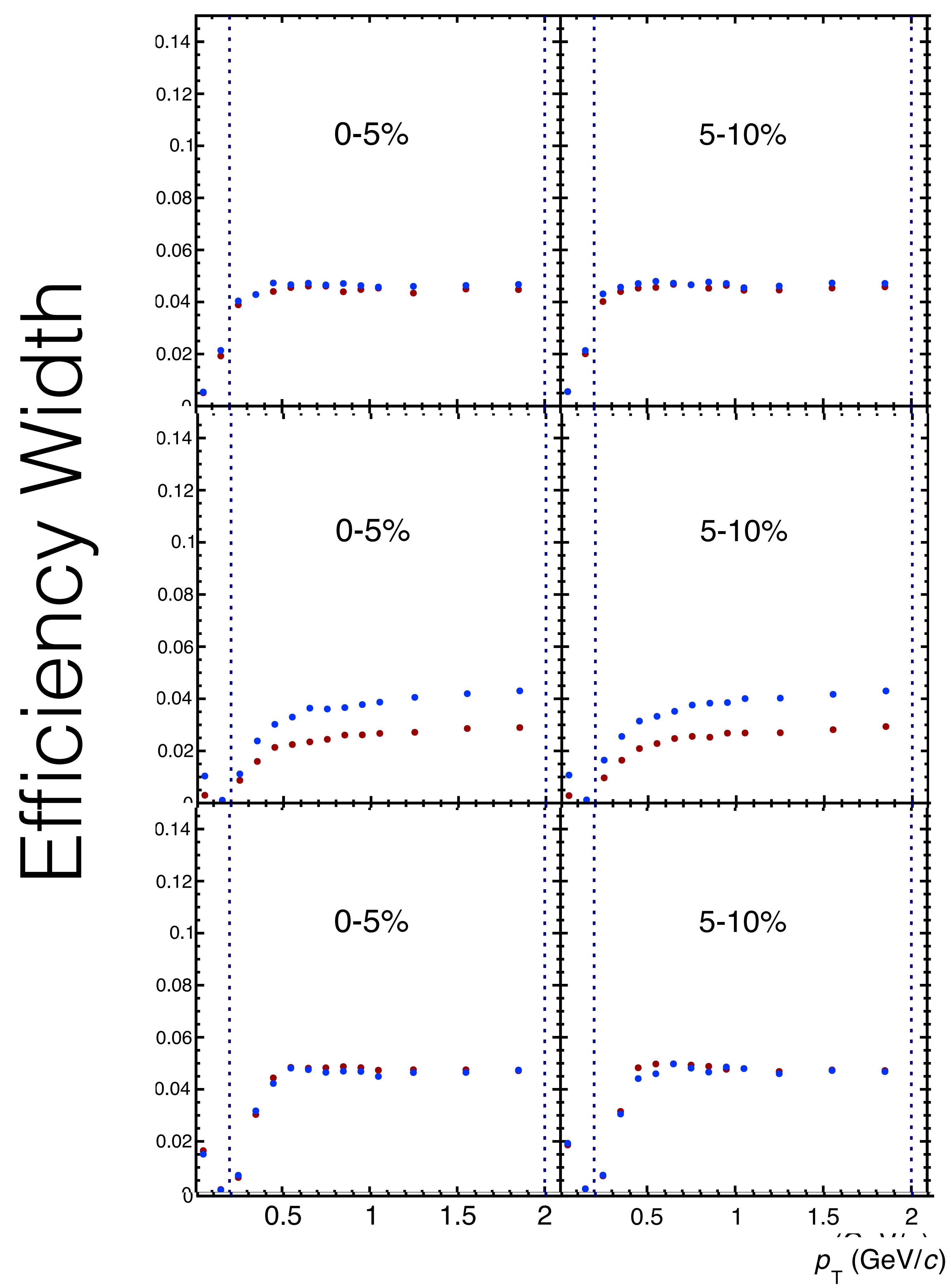
Kaon

Proton



Efficiency Studies

Efficiency Distribution Width -



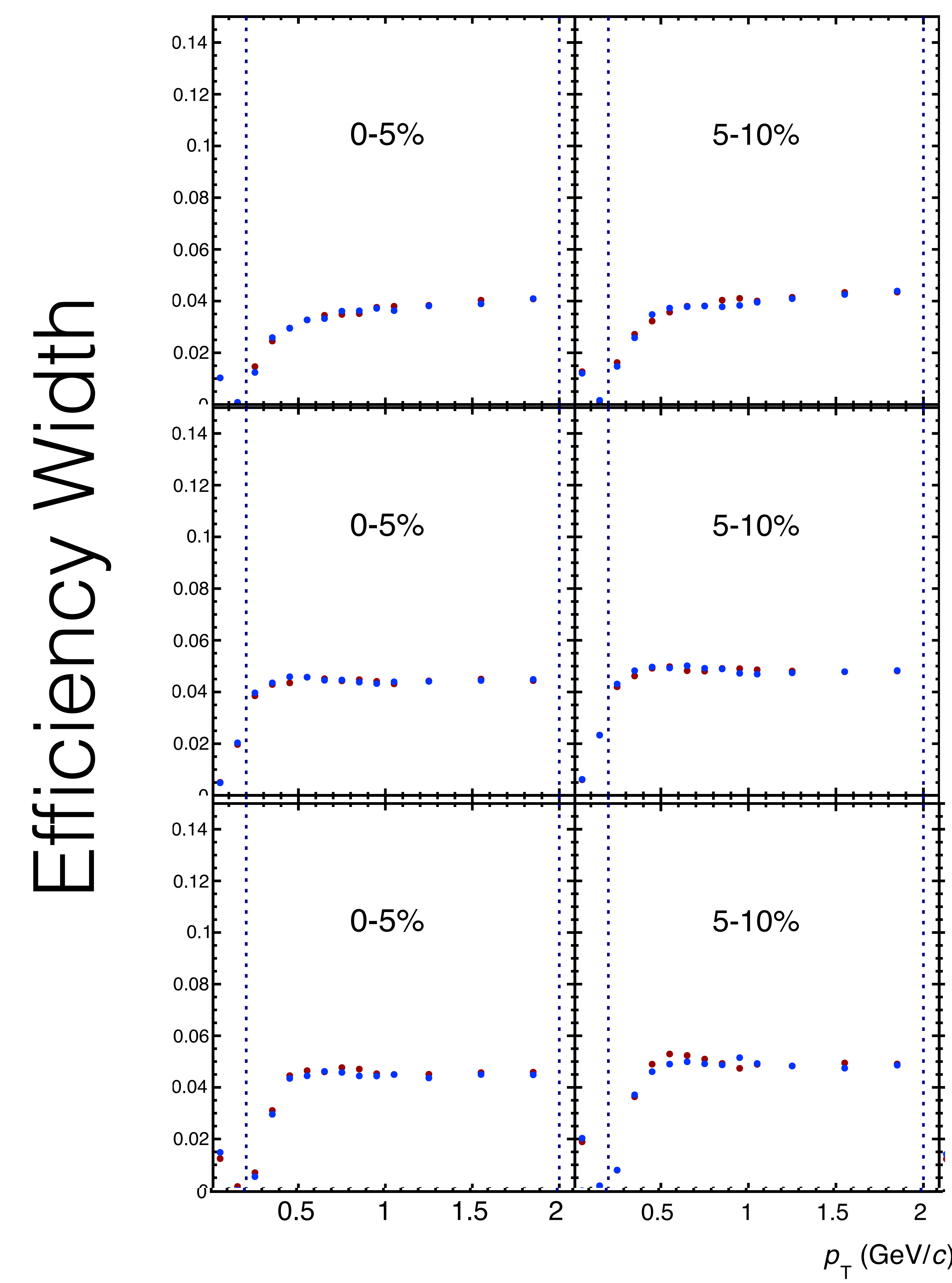
Efficiency Width
AuAu $\sqrt{s_{NN}}$ = 11.5 GeV
|η| < 0.5
sample size 100 events each

Efficiency Width
AuAu $\sqrt{s_{NN}}$ = 19.6 GeV
|η| < 0.5
sample size 100 events each

Pion

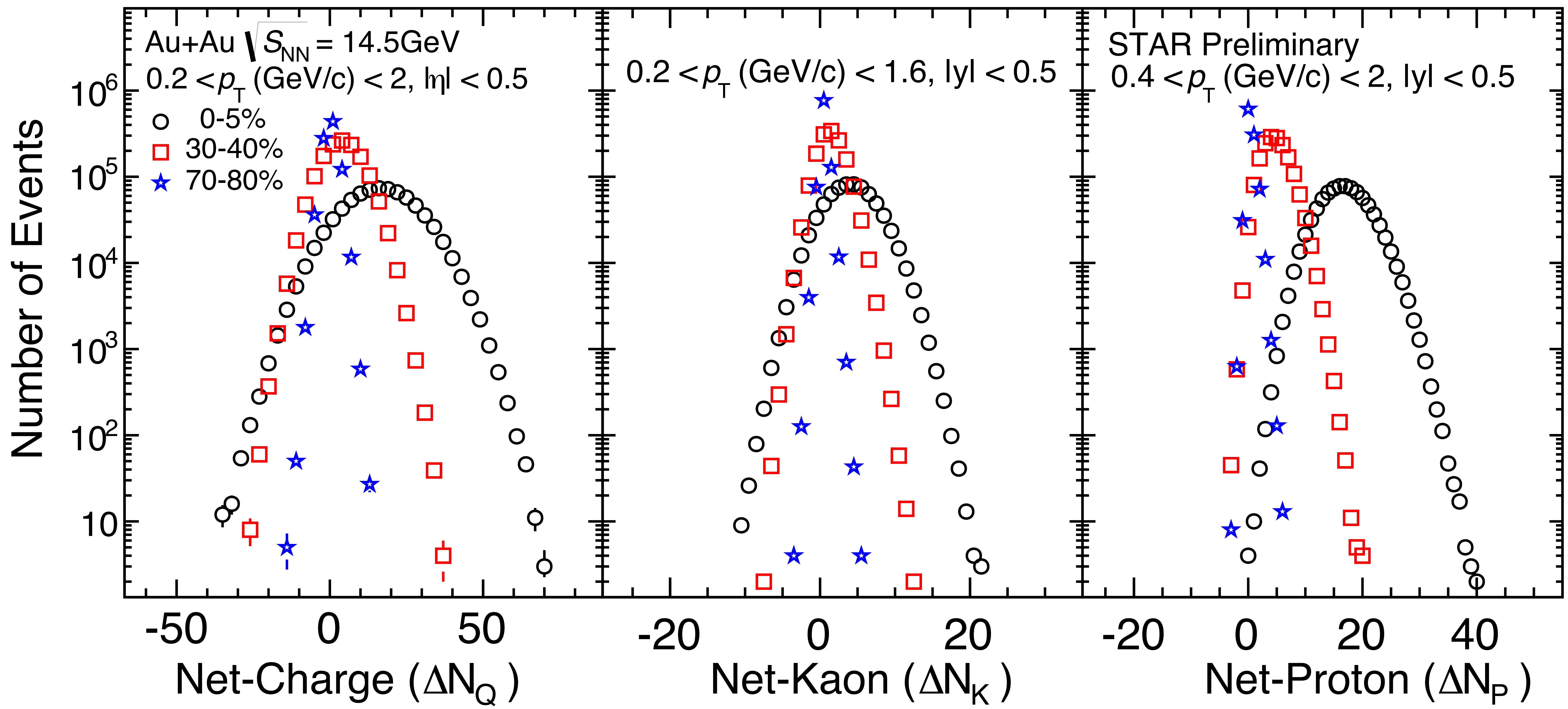
Kaon

Proton



Event-By-Event Net-Particle Multiplicity Distribution

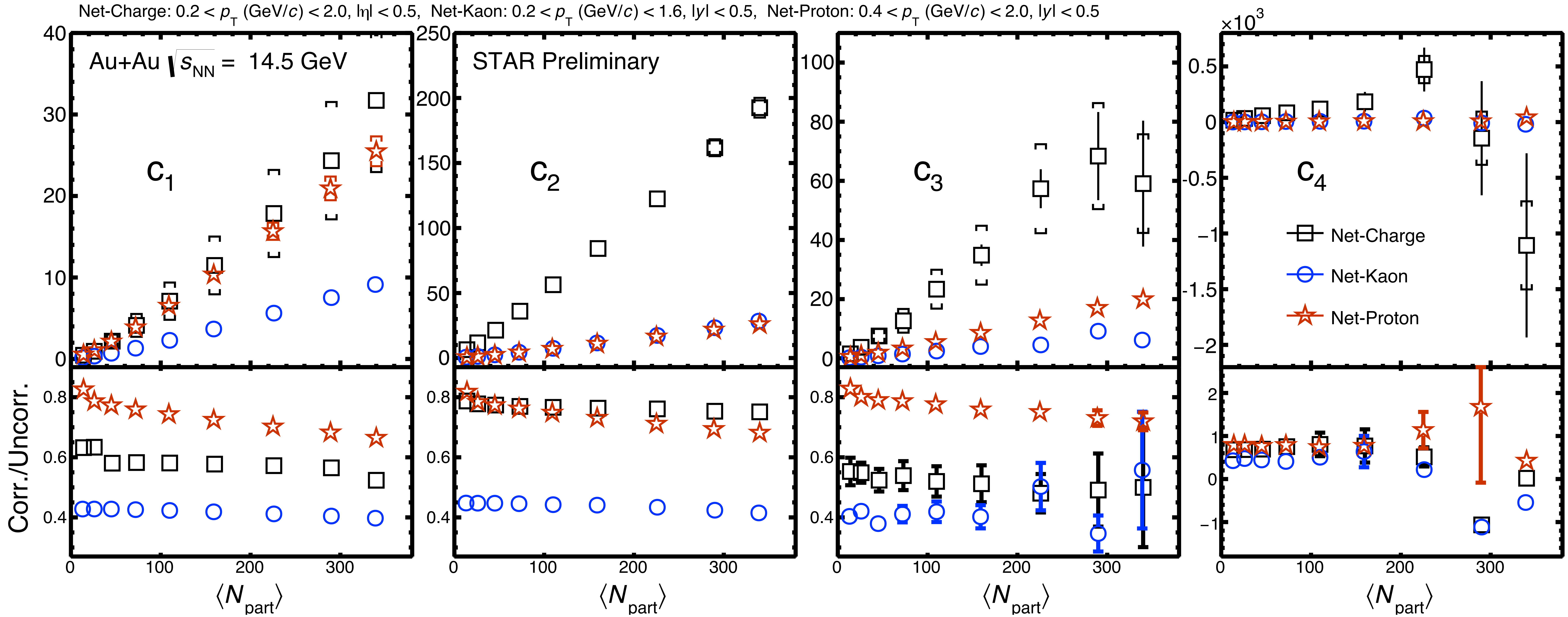
Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV



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

Corrected Cumulants

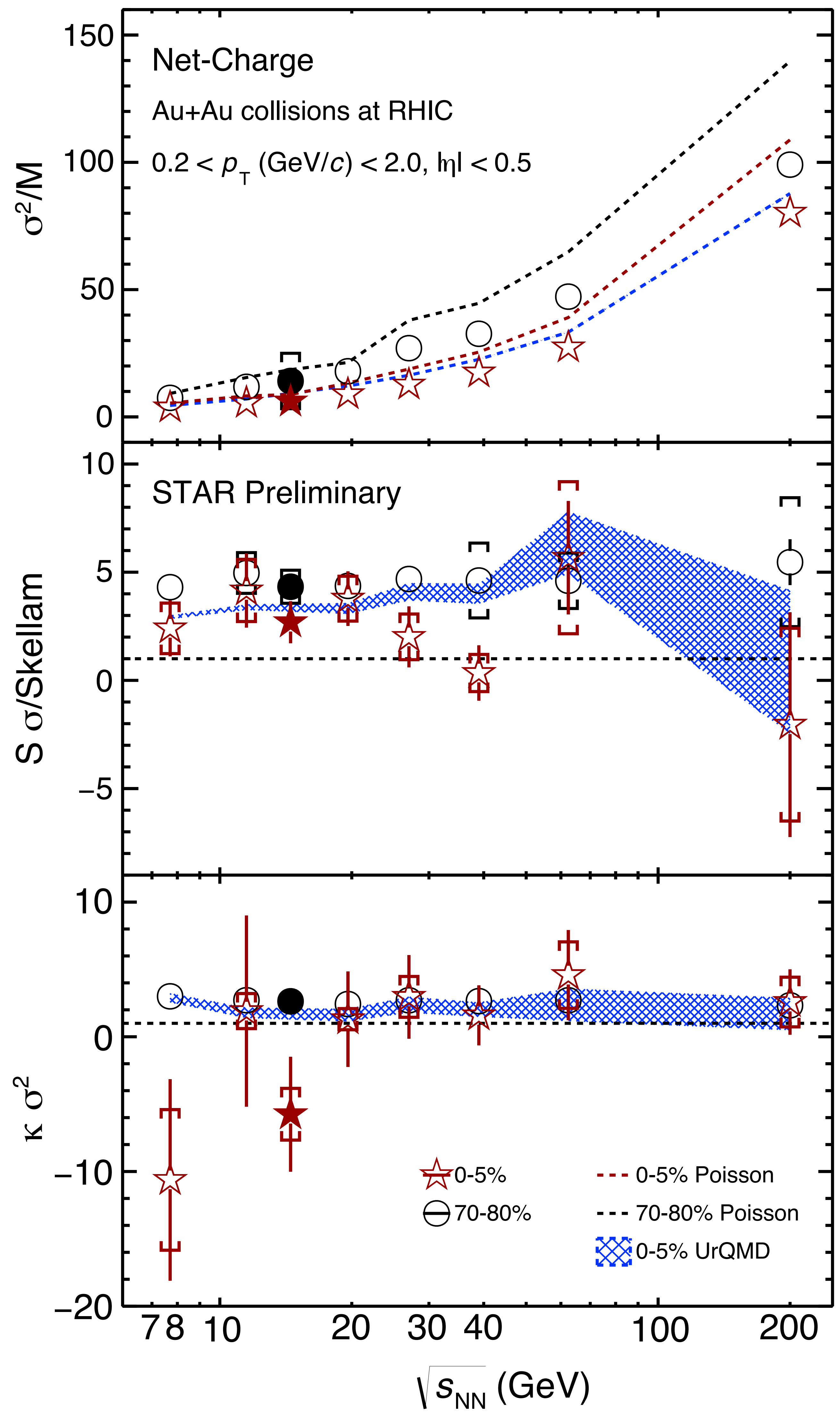
Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV



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

Corrected Cumulant Ratio of Net-Charge

Collision Energy Dependence

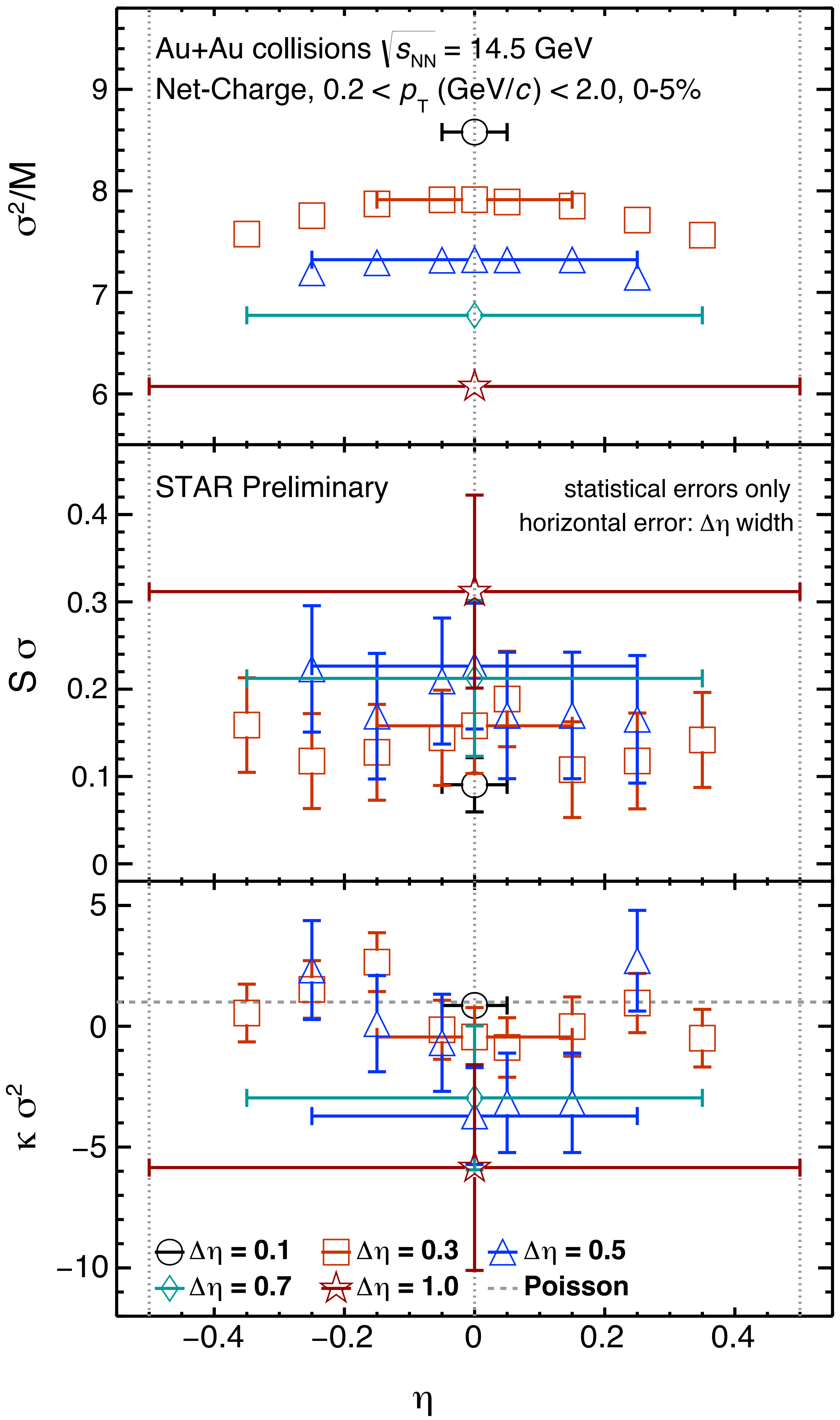


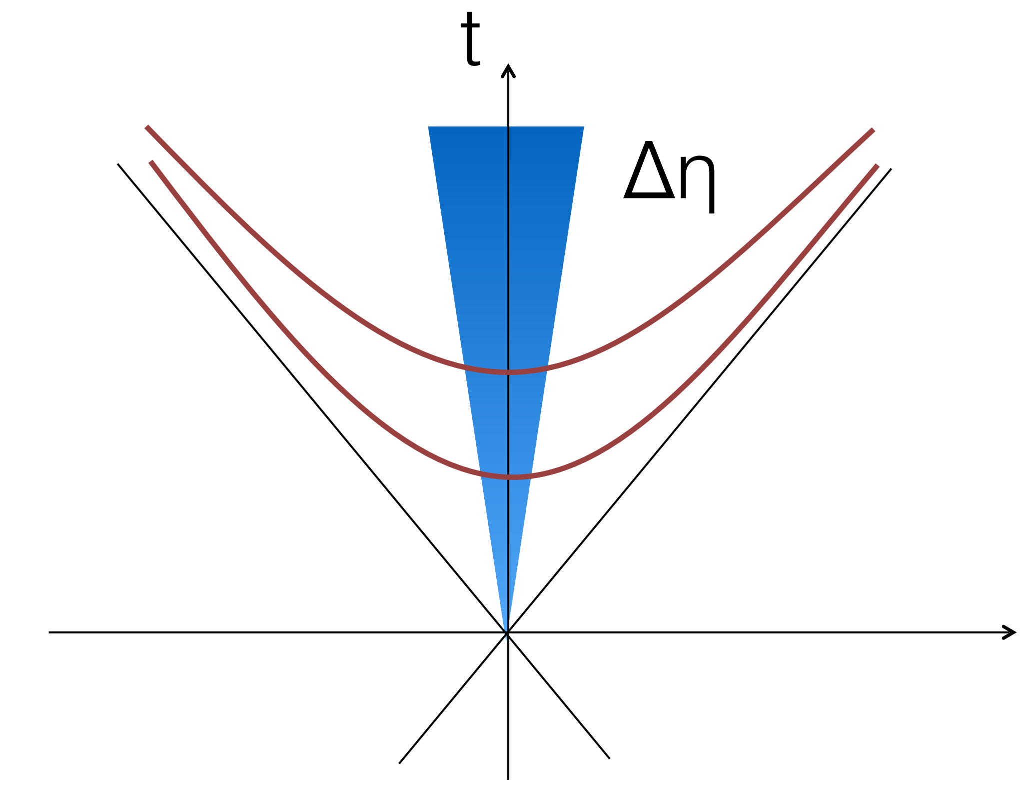
- 14.5 GeV data-point added to published *Phys. Rev. Lett. 113, 092301 (2014)*
  - Fits well into trends
- σ^2/M increases with increasing collision energy
- For most central collisions (0-5%), $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with unity
- UrQMD (no Critical Point), shows no energy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

η, $\Delta\eta$ Dependence Studies

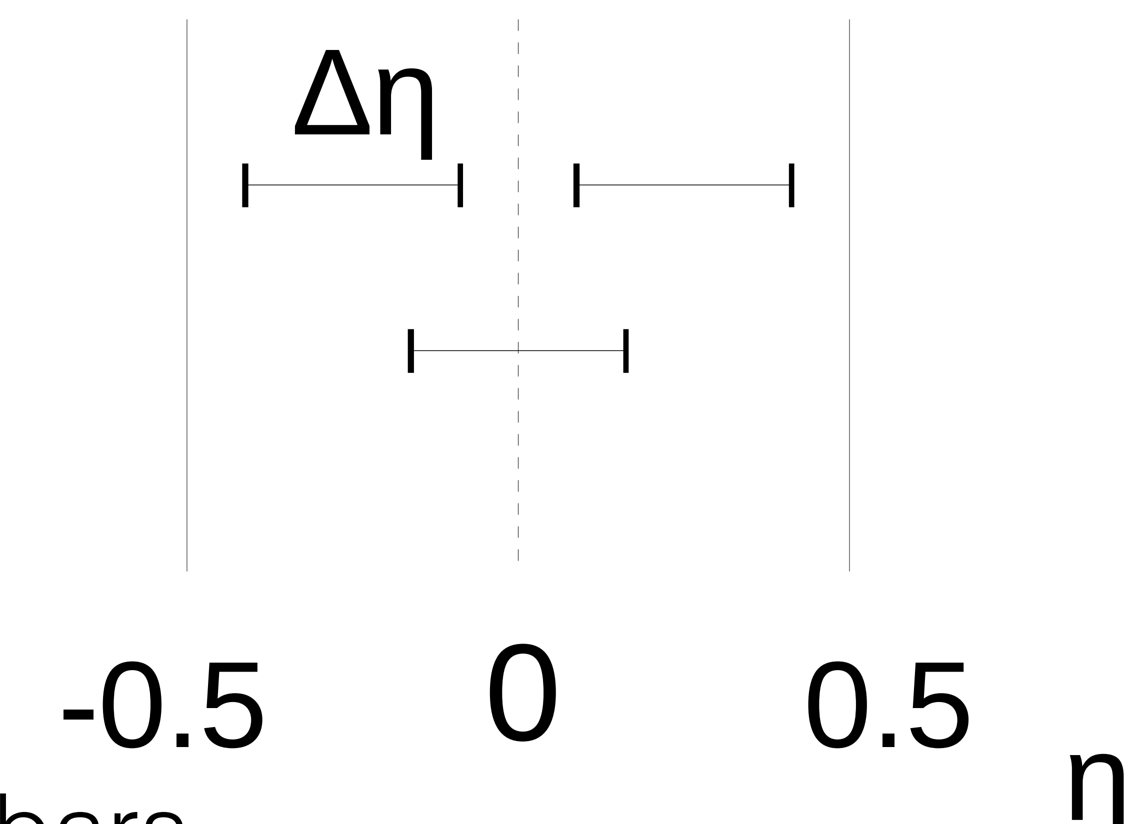
Net-Charge – η, Δη Dependence

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





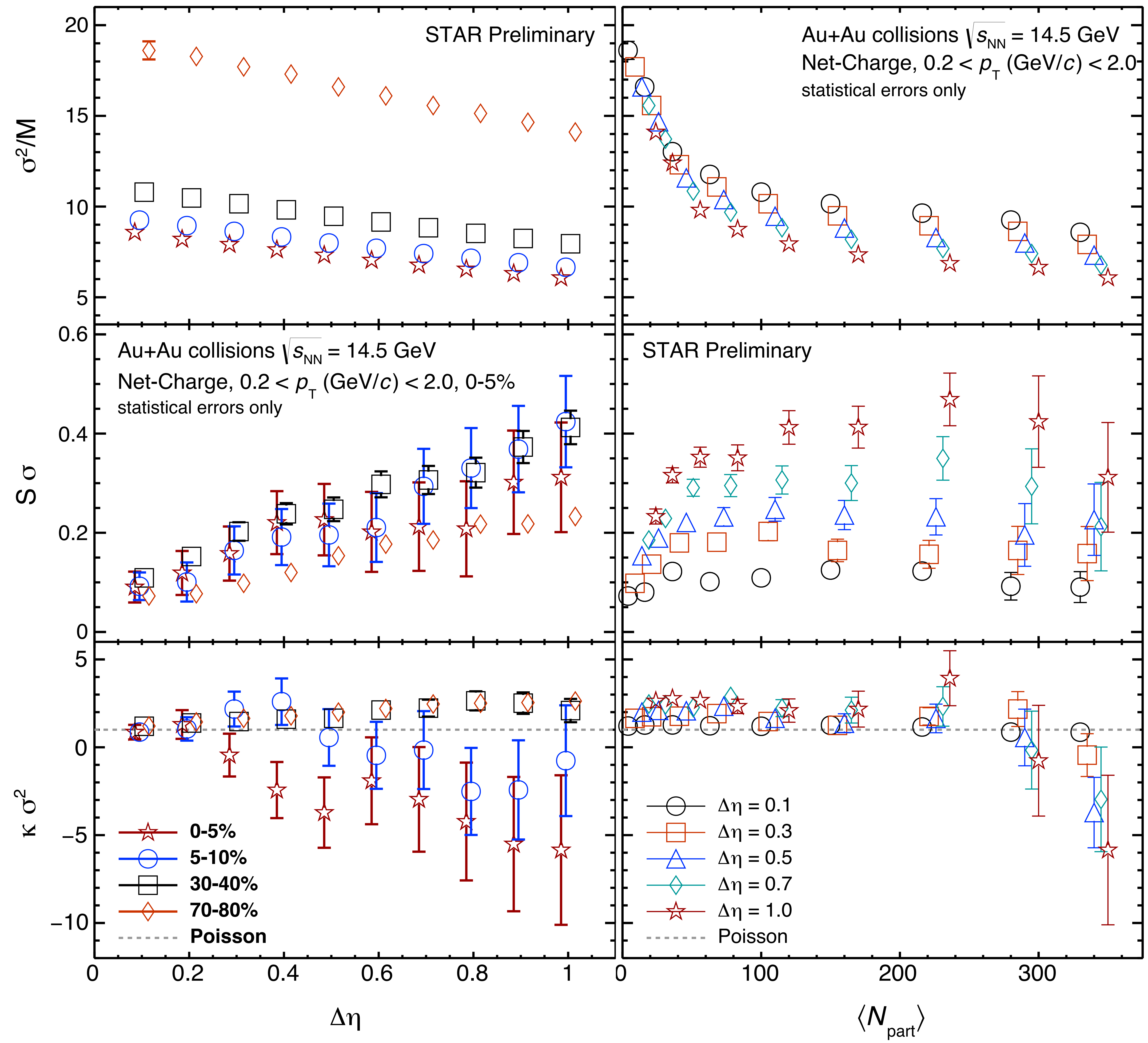
- Δη dependence of fluctuation observables encode history of the hot medium
- Constant p_T range: $0.2 < p_T < 2.0$ GeV/c
- Varied width of pseudo rapidity interval Δη :
  - 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
- Varied midpoint of interval
  - But always within |η| < 0.5



- For data points at η = 0:
  - Δη window indicated by horizontal error bars
- Data points are at middle of Δη window

Net-Charge – Δη Dependence

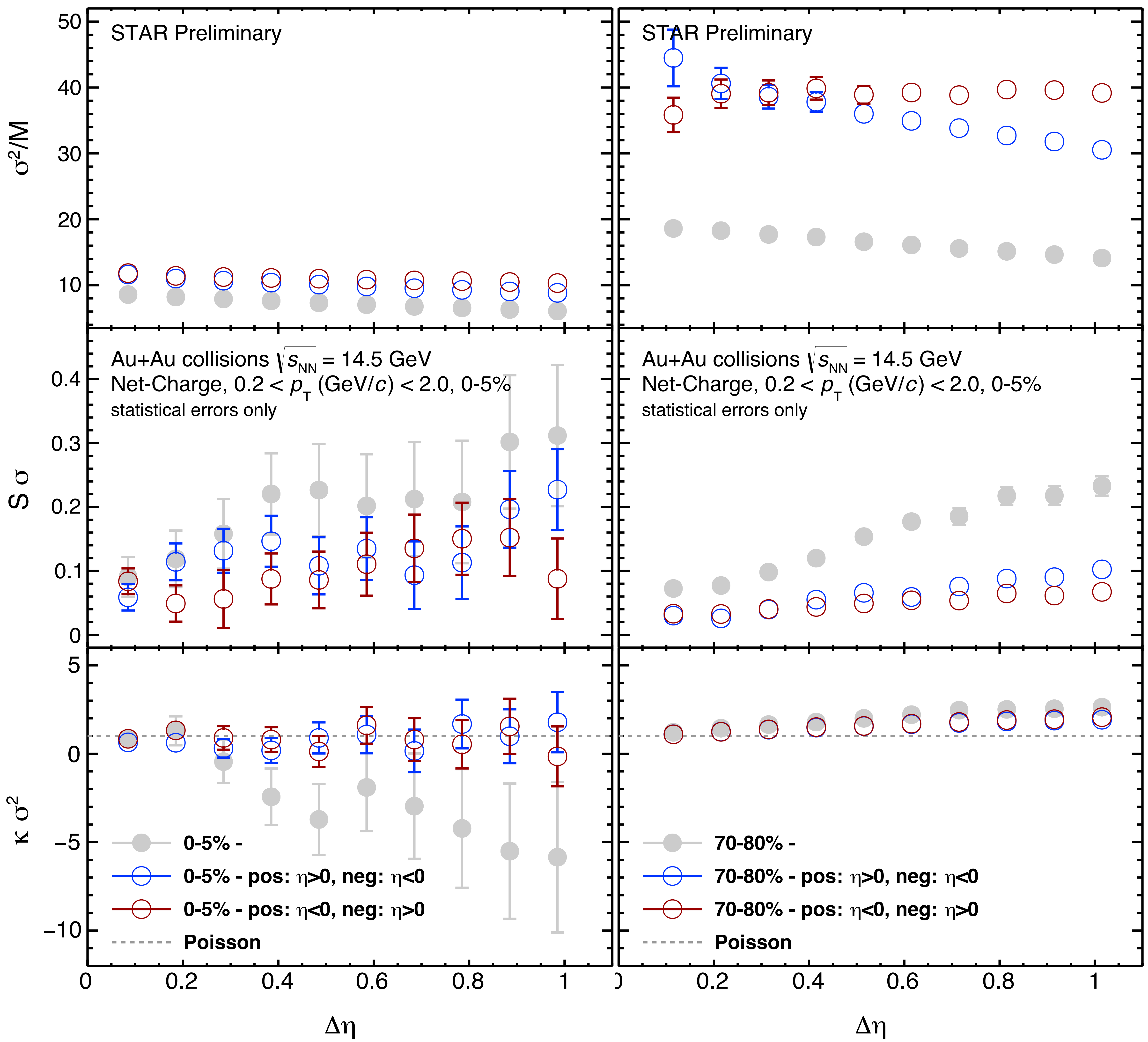
Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV



- Smooth trend for σ^2/M, Sσ and κσ^2 with increasing Δη
  - Different trend of κσ^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 σ^2/M, Sσ and κσ^2 observed

Net-Charge – Δη Dependence

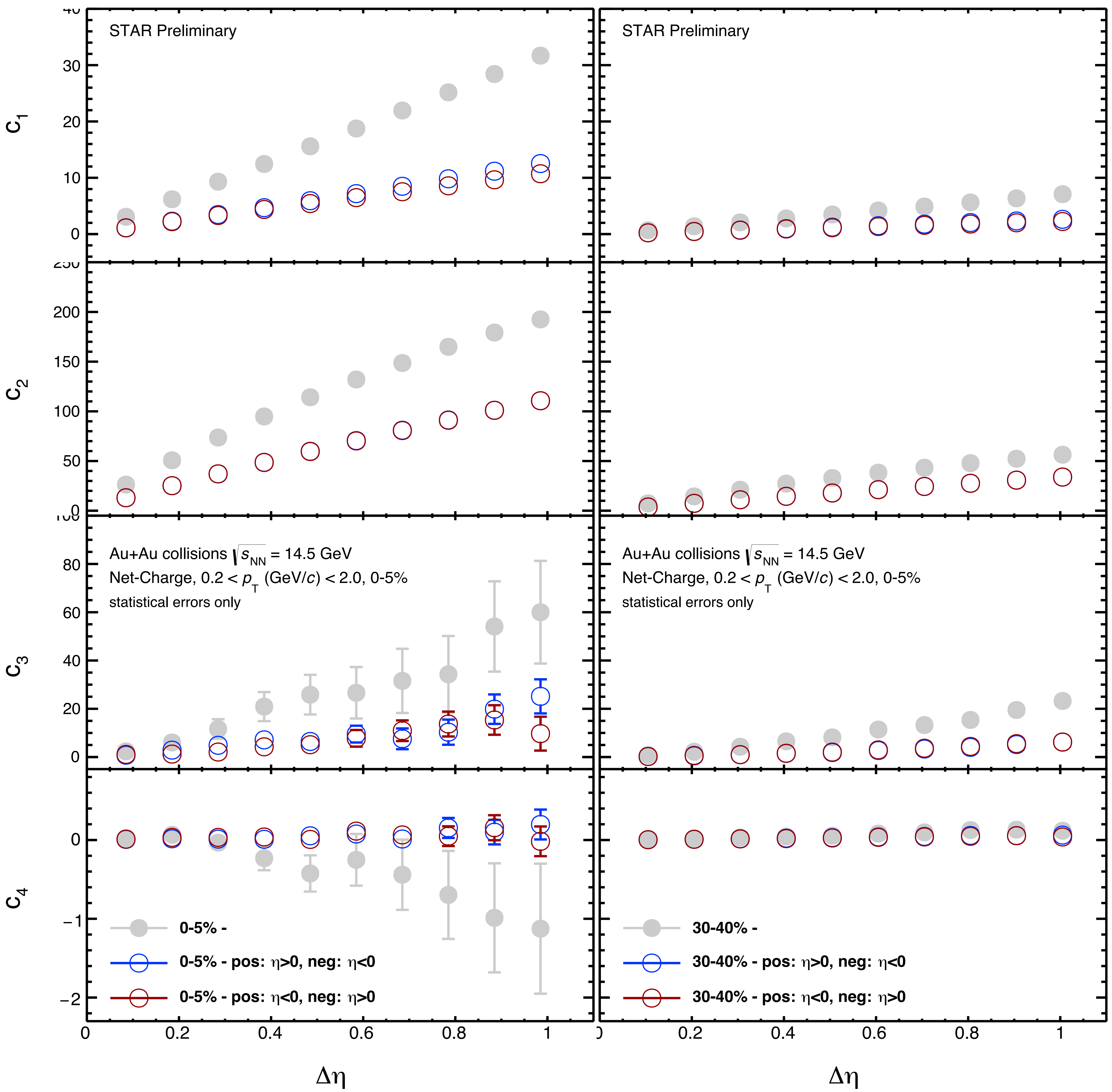
Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV



- De-correlate charges in different regions
  - Separate charges in positive and negative pseudo rapidity regions
    - positive particles: η > 0 negative particles: η < 0
    - positive particles: η < 0 negative particles: η > 0
- -> Closer to poisson expectation

Net-Charge – Δη Dependence

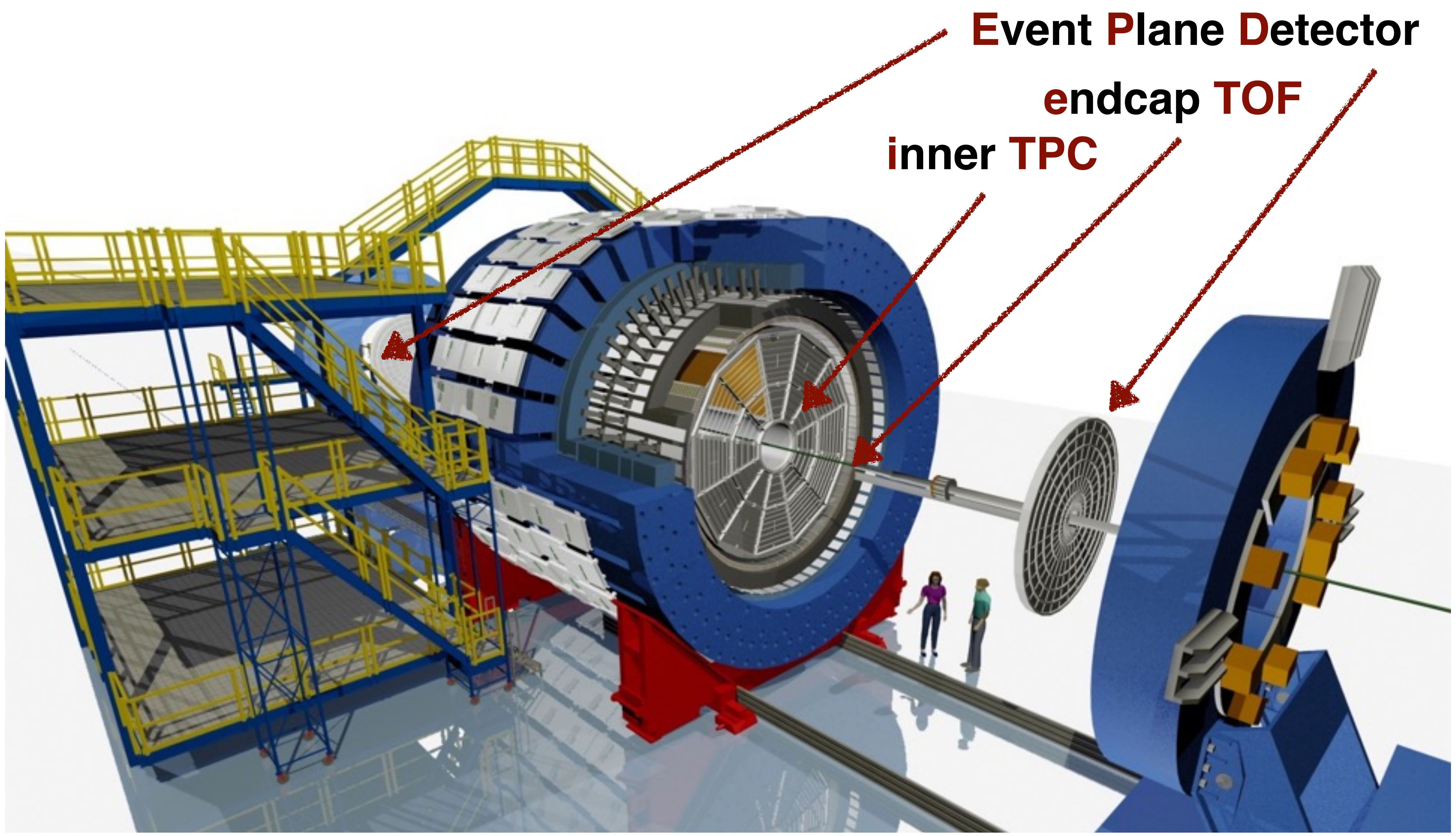
Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV

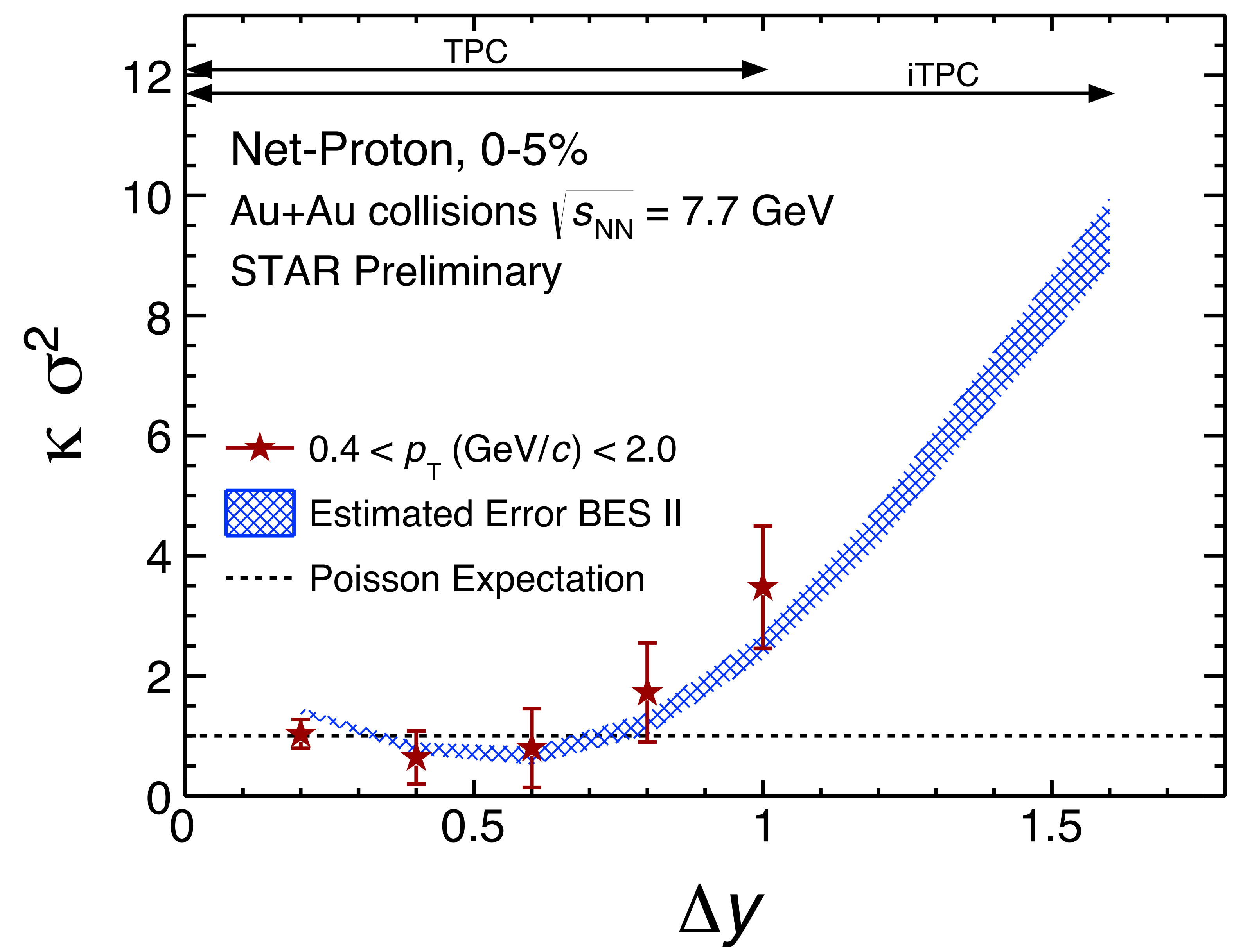


- De-correlate charges in different regions
  - Separate charges in positive and negative pseudo rapidity regions
    - positive particles: η > 0
      negative particles: η < 0
    - positive particles: η < 0
      negative particles: η > 0
- -> Closer to poisson expectation

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

- Not a lot of news since QM :)
- **New results for $\sqrt{s_{NN}}$ = 14.5 GeV** Au+Au collisions for net-charge
- Study of **pseudo-rapidity dependence** shows that acceptance is **crucial** for the **critical point search**
- **RHIC Beam Energy Scan II** will bring larger event sample and wider phase-space to **boost** the **critical point search**
- **Immediate next steps: study pseudo-rapidity dependence also for other energies**


Thank you !!