STAR ☆

RHIC & AGS
Annual Users' Meeting
Hosted By Brookhaven National Laboratory

# Study of off-diagonal cumulants of net-charge, net-proton and net-kaon multiplicity distributions in Au+Au collisions at STAR

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U.S. DEPARTMENT OF ENERGY | Office of Science

# Outline

✓ **Introduction**

  - Motivation
  - Observables

✓ **Analysis details**

✓ **Experimental results**

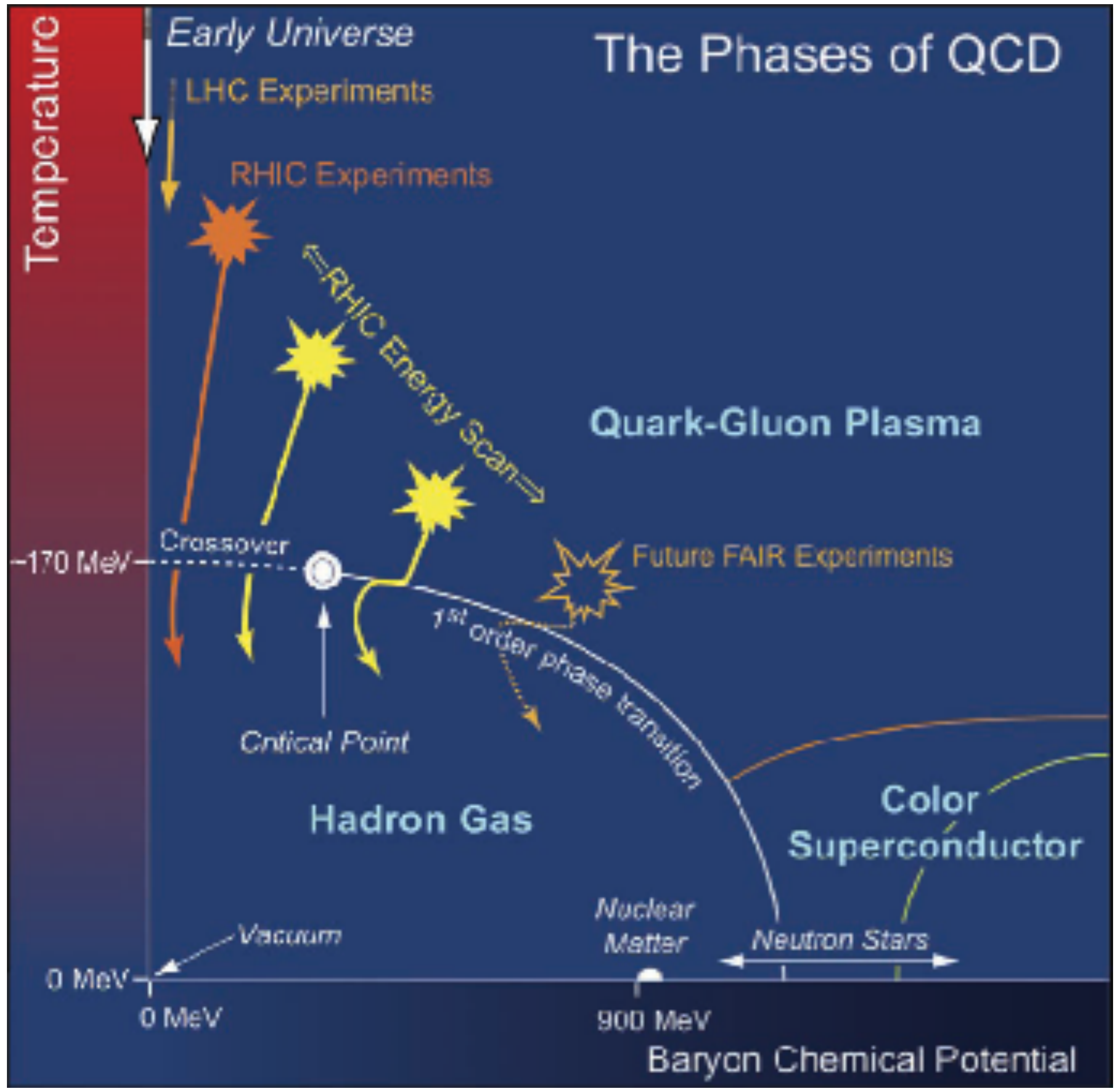
  - Centrality dependence
  - η dependence
  - Energy dependence

✓ **Summary**

# BES program - Mapping the QCD phase diagram

✓ Goal of Beam Energy Scan

- Explore the phase diagram



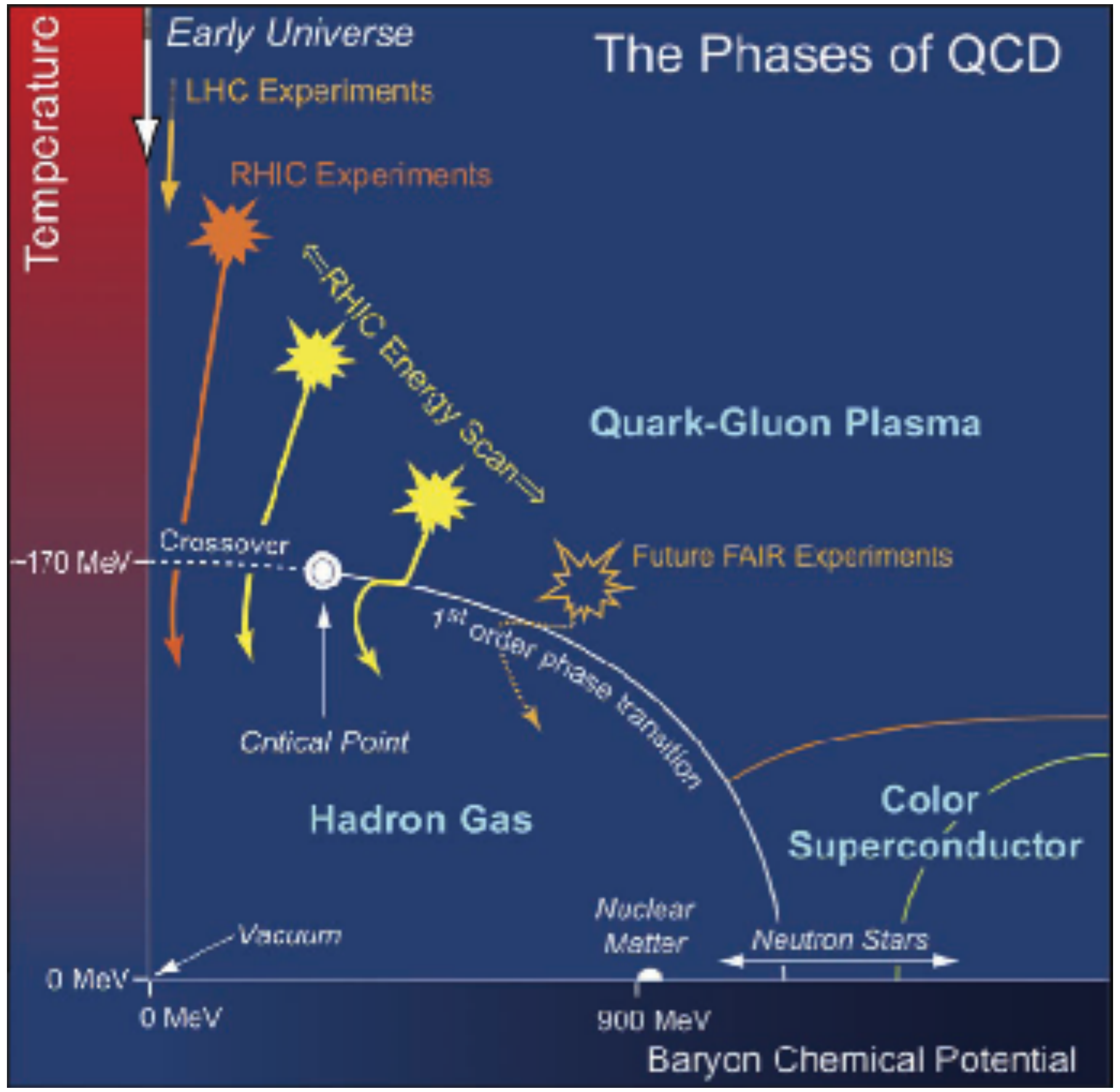
✓ Cumulants of net-particle distribution

- To extract the freeze-out parameters
- Higher order - locate the QCD critical point

# BES program - Mapping the QCD phase diagram

## ✓ Goal of Beam Energy Scan

- Explore the phase diagram



## ✓ Cumulants of net-particle distribution

- To extract the freeze-out parameters
- Higher order - locate the QCD critical point

## – Diagonal cumulants - “shape” of the distribution

- Probe of non-gaussian fluctuations
- net-proton, net-charge and net-kaon - published

[STAR collaboration PRL 105, 022302, PRL 113, 092301, arXiv:1709.00773]

## – Off-diagonal cumulants - First measurement

- Correlation between conserved charges is sensitive to the phase transition
- Better constrain of the freeze-out parameters

[V. Koch *et al.* PRL.95.182301 (2005), F. Karsch and K. Redlich, PLB 695 , 136142 (2011).]

# Mapping the QCD phase diagram

$$\begin{pmatrix} \sigma_Q^2 & \sigma_{Q,p}^{1,1} & \sigma_{Q,k}^{1,1} \\ \sigma_{p,Q}^{1,1} & \sigma_p^2 & \sigma_{p,k}^{1,1} \\ \sigma_{k,Q}^{1,1} & \sigma_{k,p}^{1,1} & \sigma_k^2 \end{pmatrix}$$

✓ Connection to theory and experiment [V. Koch arXiv:0810.2520]

**Theory:**
**susceptibility**

$$\chi^{\mathbf{ijk}}_{\mathbf{BQS}} = \frac{\partial^{\mathbf{i+j+k}}(\mathbf{P}/\mathbf{T^4})}{\partial^{\mathbf{i}}(\mu_{\mathbf{B}}/\mathbf{T})\partial^{\mathbf{j}}(\mu_{\mathbf{Q}}/\mathbf{T})\partial^{\mathbf{i}}(\mu_{\mathbf{S}}/\mathbf{T})}$$

$$\chi^{\mathbf{ijk}}_{\mathbf{BQS}} = \frac{\mathbf{1}}{\mathbf{VT^3}}\mathbf{M}^{\mathbf{ijk}}_{\mathbf{BQS}}$$

for i+j+k < 3

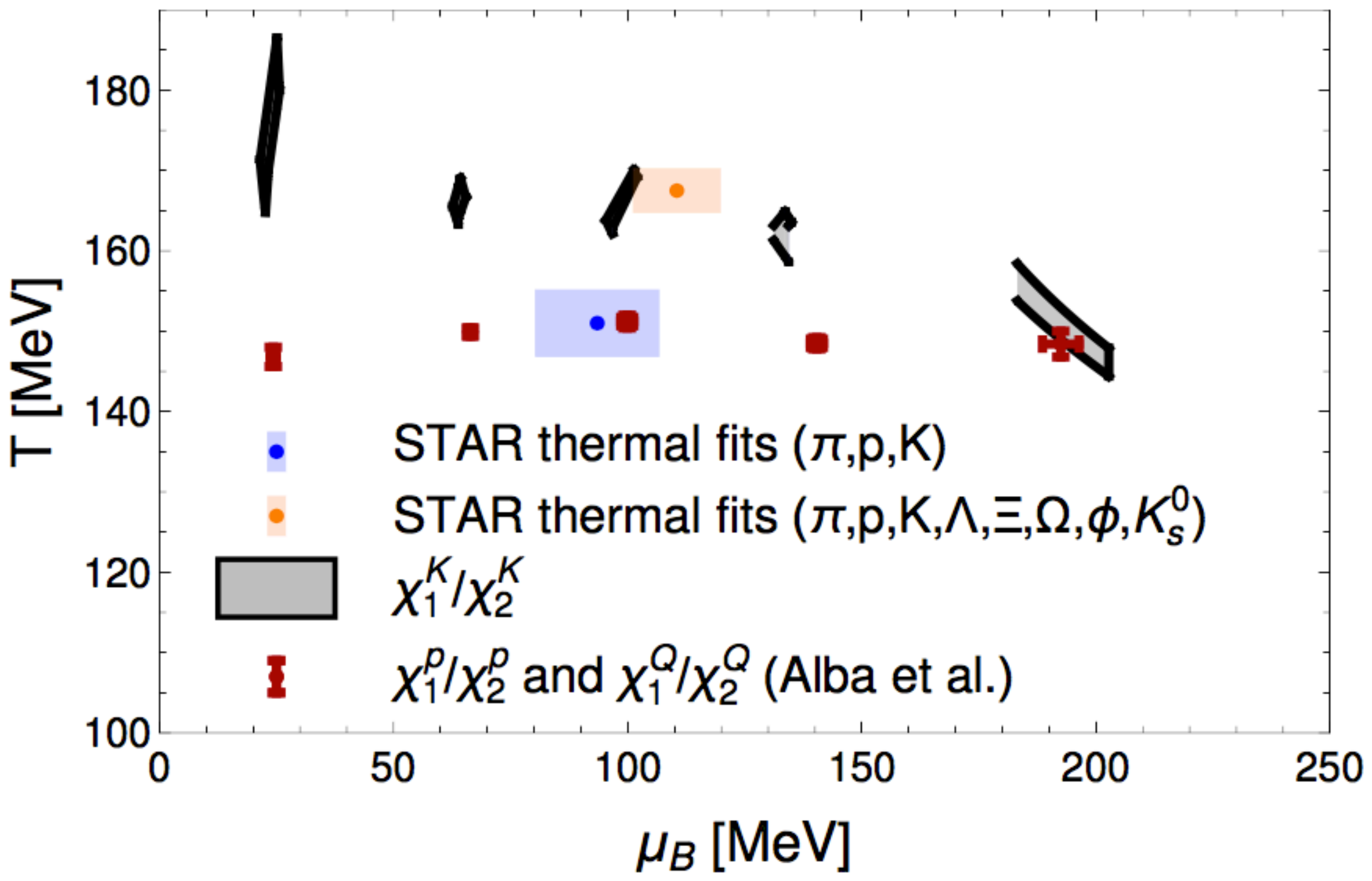
$$\longleftrightarrow$$

**Experiment:**
**net-particle cumulants**

$$\mathbf{M^{ijk}} = \langle(\mathbf{B} - \langle\mathbf{B}\rangle)^{\mathbf{i}}(\mathbf{Q} - \langle\mathbf{Q}\rangle)^{\mathbf{j}}(\mathbf{S} - \langle\mathbf{S}\rangle)^{\mathbf{k}}\rangle$$

# Mapping the QCD phase diagram

$$\begin{pmatrix} \sigma^2_Q & \sigma^{1,1}_{Q,p} & \sigma^{1,1}_{Q,k} \\ \sigma^{1,1}_{p,Q} & \sigma^2_p & \sigma^{1,1}_{p,k} \\ \sigma^{1,1}_{k,Q} & \sigma^{1,1}_{k,p} & \sigma^2_k \end{pmatrix}$$



[R. Bellwied et al. arXiv:1805.00088]

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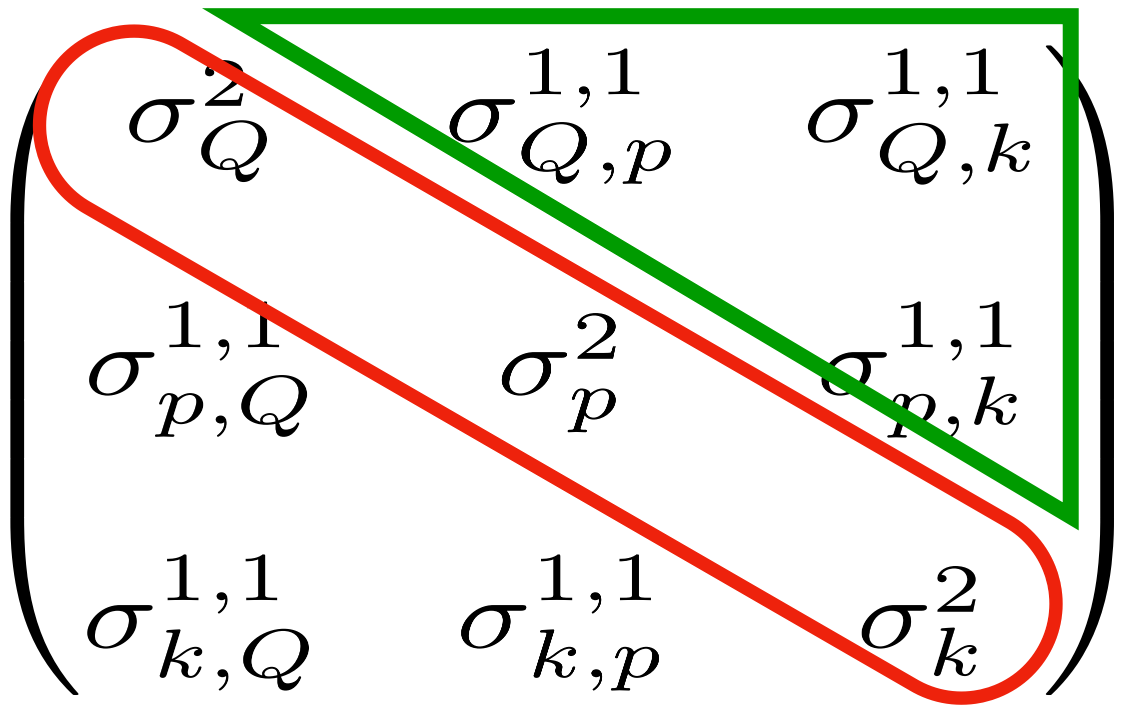
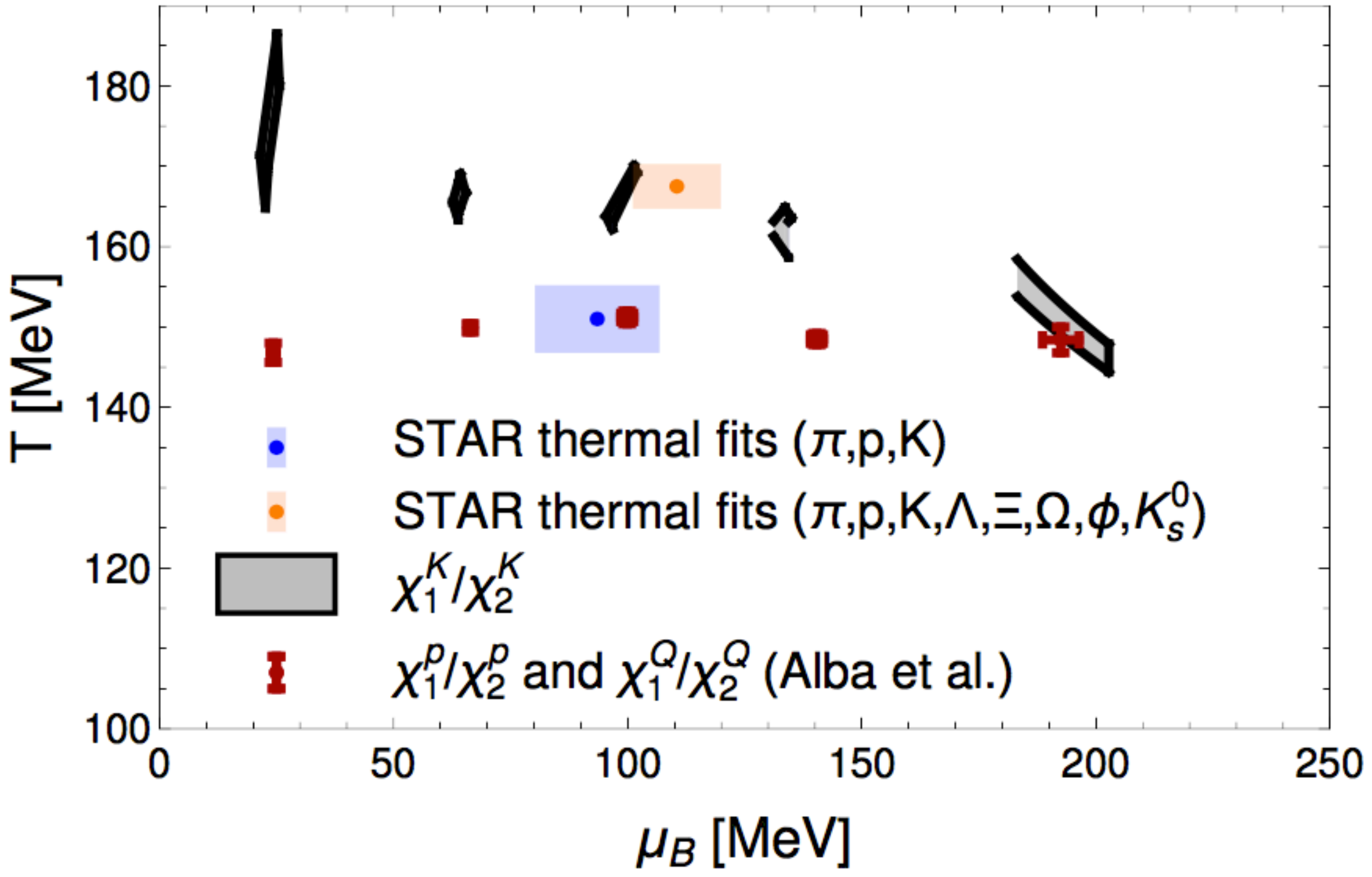
✓ From the published net-proton (p), net-charge (Q) and net-kaon (k) cumulants - freeze-out parameters (T, μB) have been extracted with large uncertainties

# Mapping the QCD phase diagram



$$\begin{pmatrix} \sigma^2_Q & \sigma^{1,1}_{Q,p} & \sigma^{1,1}_{Q,k} \\ \sigma^{1,1}_{p,Q} & \sigma^2_p & \sigma^{1,1}_{p,k} \\ \sigma^{1,1}_{k,Q} & \sigma^{1,1}_{k,p} & \sigma^2_k \end{pmatrix}$$



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**Theory:**
**susceptibility**

$$\chi^{ijk}_{BQS} = \frac{\partial^{i+j+k}(P/T^4)}{\partial^i(\mu_B/T)\partial^j(\mu_Q/T)\partial^i(\mu_S/T)}$$

$$\chi^{ijk}_{BQS} = \frac{1}{VT^3}M^{ijk}_{BQS}$$

for i+j+k < 3

**Experiment:**
**net-particle cumulants**

$$M^{ijk} = \langle (B-\langle B\rangle)^i (Q-\langle Q\rangle)^j (S-\langle S\rangle)^k \rangle$$

✓ From the published net-proton (p), net-charge (Q) and net-kaon (k) cumulants - freeze-out parameters (T, μB) have been extracted with large uncertainties

✓ The 2nd-order cumulant matrices of all combinations of p, Q and k cumulants can provide better understanding of freeze-out and constrain different model parameters

[V. Koch *et al.* PRL.95.182301 (2005), A. Majumder and B. Muller, PRC. 74 (2006)
A. Bazavov et al. PRD. (2012) 034509, F. Karsch and K. Redlich, PLB 695 , 136142 (2011).]

# Observables

- ✓ “Variance” — Self correlation

$$\boxed{c_2 = \sigma^2 = \langle(\delta X)^2\rangle}$$

- ✓ “Covariance” — Cross correlation

$$\boxed{c_{1,1} = \sigma^{1,1} = \langle(\delta X)(\delta Y)\rangle}$$

$$\begin{pmatrix} \sigma^2_Q & \sigma^{1,1}_{Q,p} & \sigma^{1,1}_{Q,k} \\ \sigma^{1,1}_{p,Q} & \sigma^2_p & \sigma^{1,1}_{p,k} \\ \sigma^{1,1}_{k,Q} & \sigma^{1,1}_{k,p} & \sigma^2_k \end{pmatrix}$$

- ✓ “Ratio” — Excess correlation compare to self correlation

$$\boxed{C_{X,Y} = \sigma^{1,1}/\sigma^2}$$

Volume independent

# Observables

✓ "Variance" — Self correlation

$$\boxed{c_2 = \sigma^2 = \langle(\delta X)^2\rangle}$$

✓ "Covariance" — Cross correlation

$$\boxed{c_{1,1} = \sigma^{1,1} = \langle(\delta X)(\delta Y)\rangle}$$

Where

$$\delta X = X - \langle X \rangle$$

X and Y can be:
Net charge: $Q = N_{Q^+} - N_{Q^-}$
Net proton: $p = N_{p^+} - N_{p^-}$,
Net kaon: $k = N_{k^+} - N_{k^-}$

✓ "Ratio" — Excess correlation compare to self correlation

$$\boxed{C_{X,Y} = \sigma^{1,1}/\sigma^2}$$

Volume independent

✦ Acceptance window |η| dependence

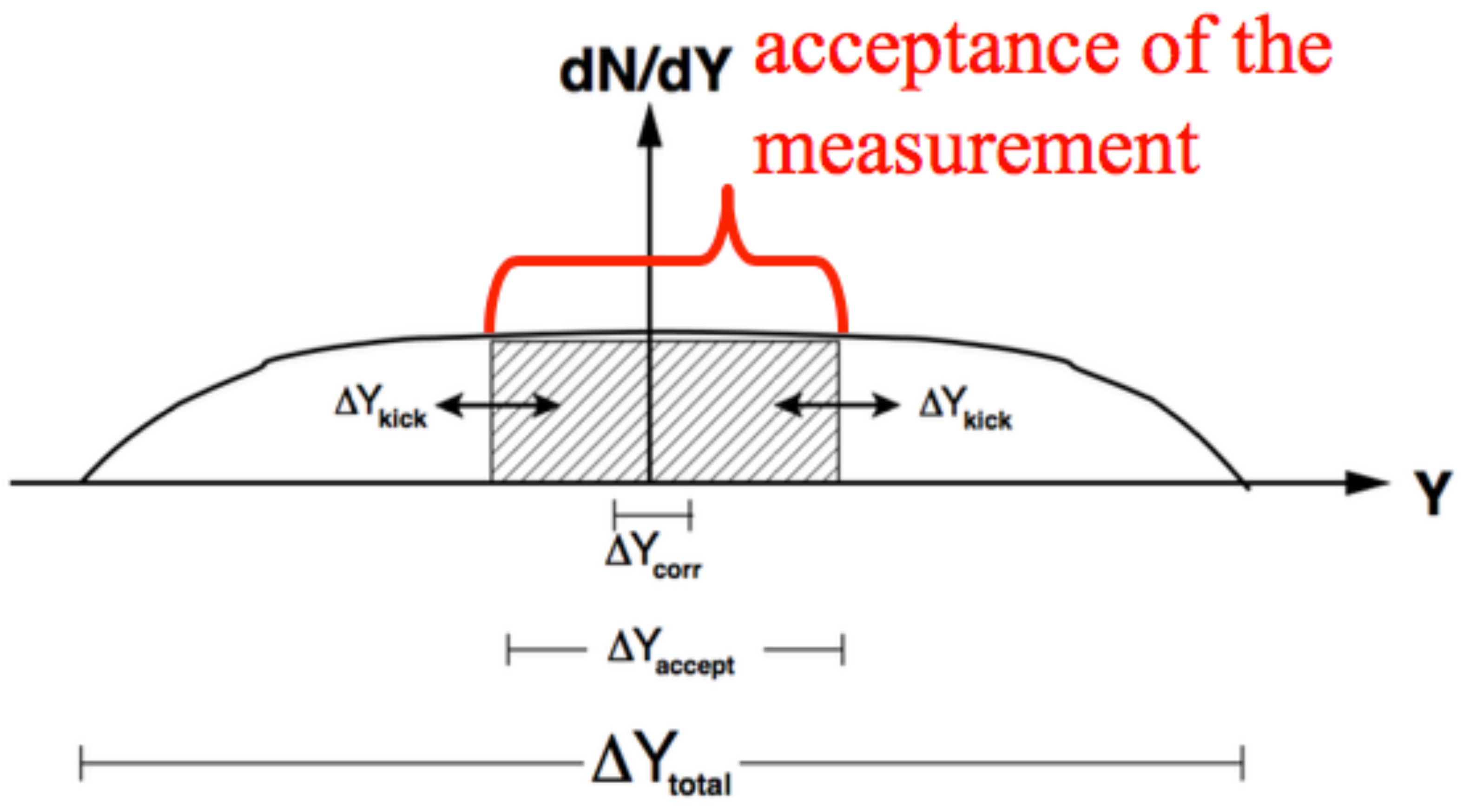
No signal
0 %
Δη=0

η acceptance

No signal
100 %
$\Delta\eta = \Delta Y_{total}$

Poisson fluctuation
ratio ~ 1

fluctuation = 0 baryon/charge/
strangeness # conservation



Brewer, Mukherjee, Rajagopal, Yin, arXiv:1804.10215

- Optimum Δη window to capture the signals?

# Analysis details

- ✓ Particle identification : Using TPC and TOF detector $|\eta| < 0.5$ & $0.4 < p_T < 1.6$ GeV/c
- ✓ Centrality selection : Using uncorrected charge particle multiplicity excluding analysis region $0.5 < |\eta| < 1.0$
- ✓ Centrality bin-width correction (CBWC) :

  To eliminate/minimize the impact parameter (or volume) variations due to the finite centrality bin.

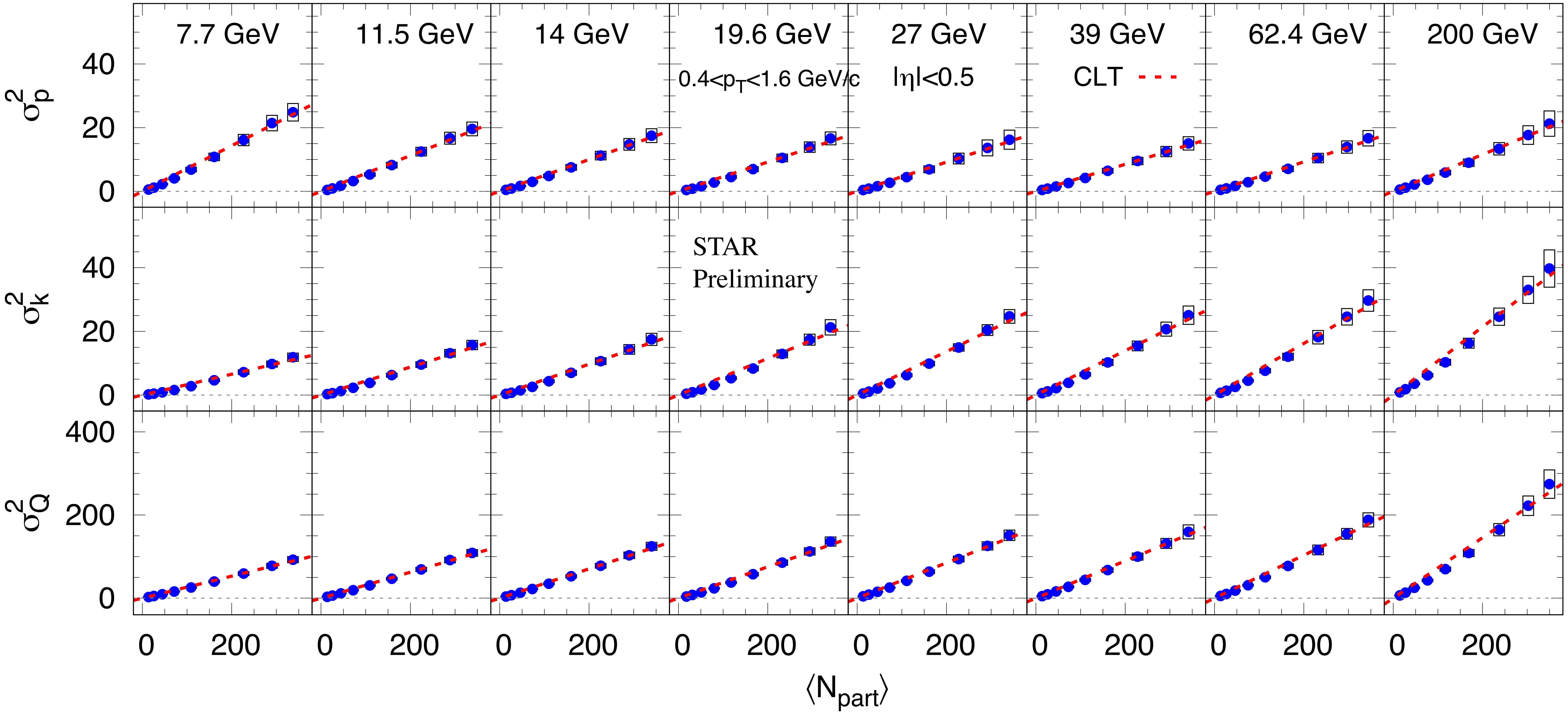
  [X. Luo et al J. Phys. G 40, 105104 (2013)]

  $$X = \frac{\sum_i n_i X_i}{\sum_i n_i},$$ i runs for each multiplicity bins

- ✓ Efficiency correction and statistical uncertainty estimation:
  - Efficiency correction is done using Binomial efficiency response assumptions with positive and negative charged particle separate efficiencies
  - statistical uncertainty estimation — using analytical methods of error propagation

[A. Bzdak and V. Koch: PRC.86.044904 , PRC.91.027901,
X. Luo : PRC.91.034907, A Chatterjee *et al*. JPG: Nucl. Part. Phys. 43 125103 (2016).]

# 2nd-order diagonal cumulants



→ Net proton (p)

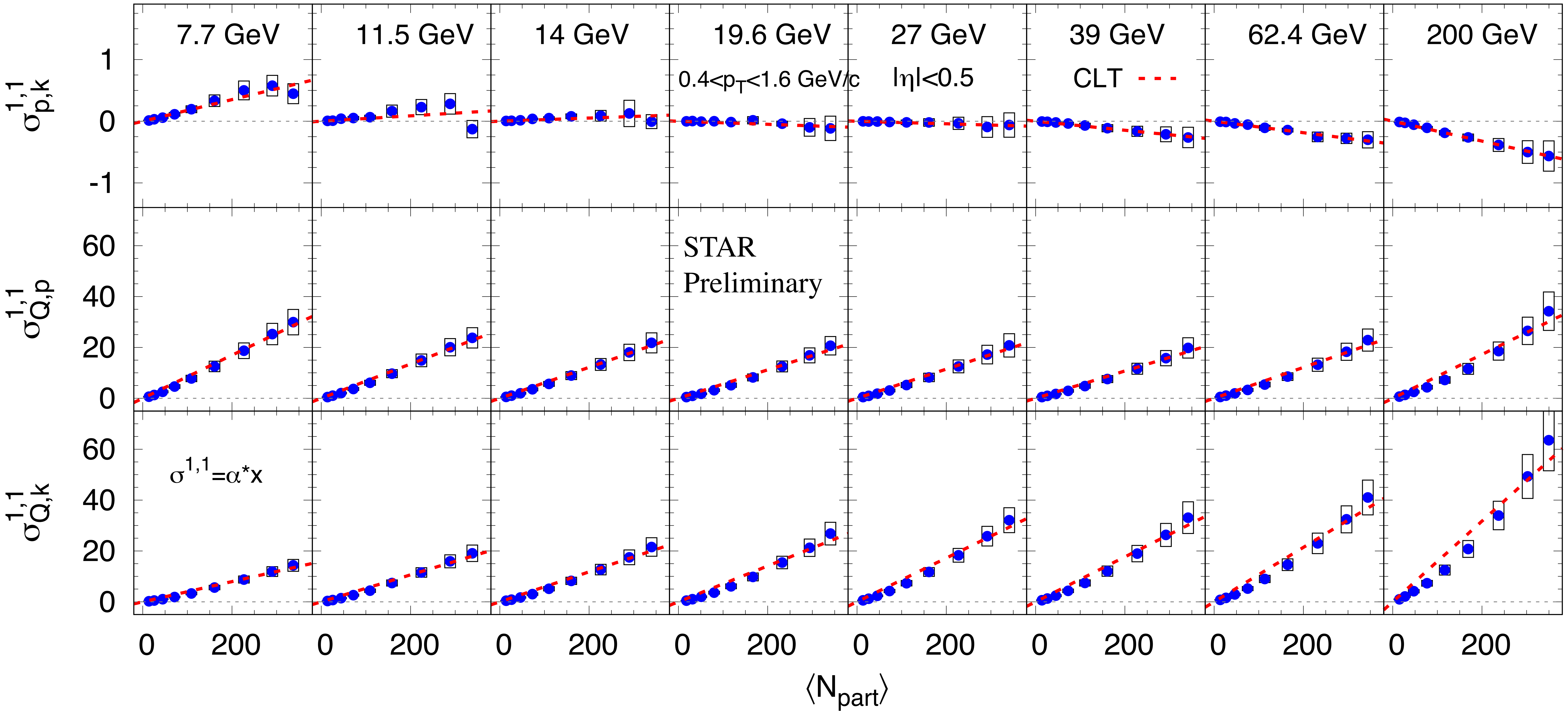
→ Net kaon (k)

→ Net charge (Q)

✓ Variance increases with number of colliding nucleons and consistent with CLT expectation.

Central Limit Theorem (CLT) : $\sigma^2 \propto \langle N_{part} \rangle$

# 2nd-order off-diagonal cumulants



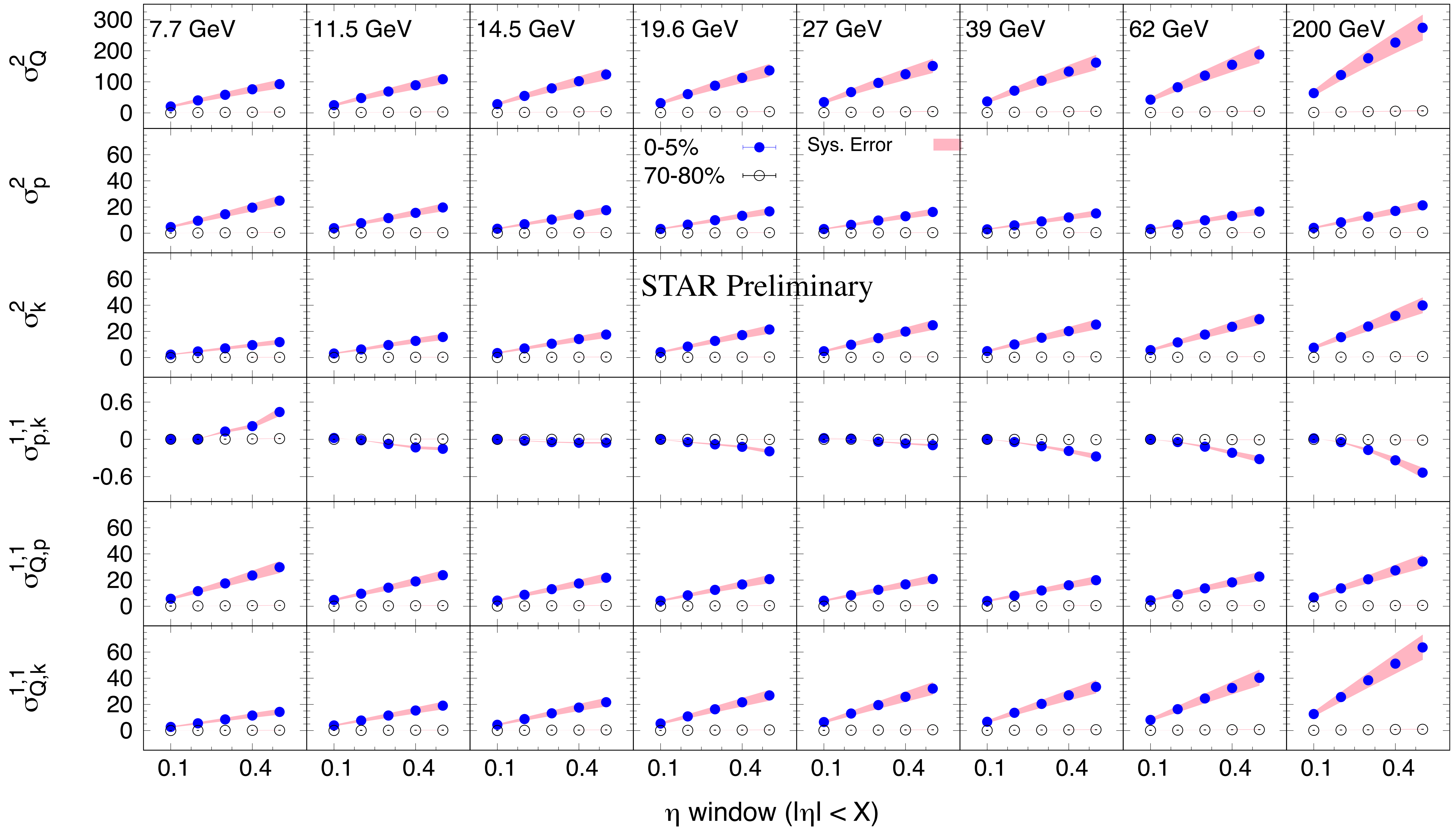
net proton & net kaon

net charge & net proton

net charge & net kaon

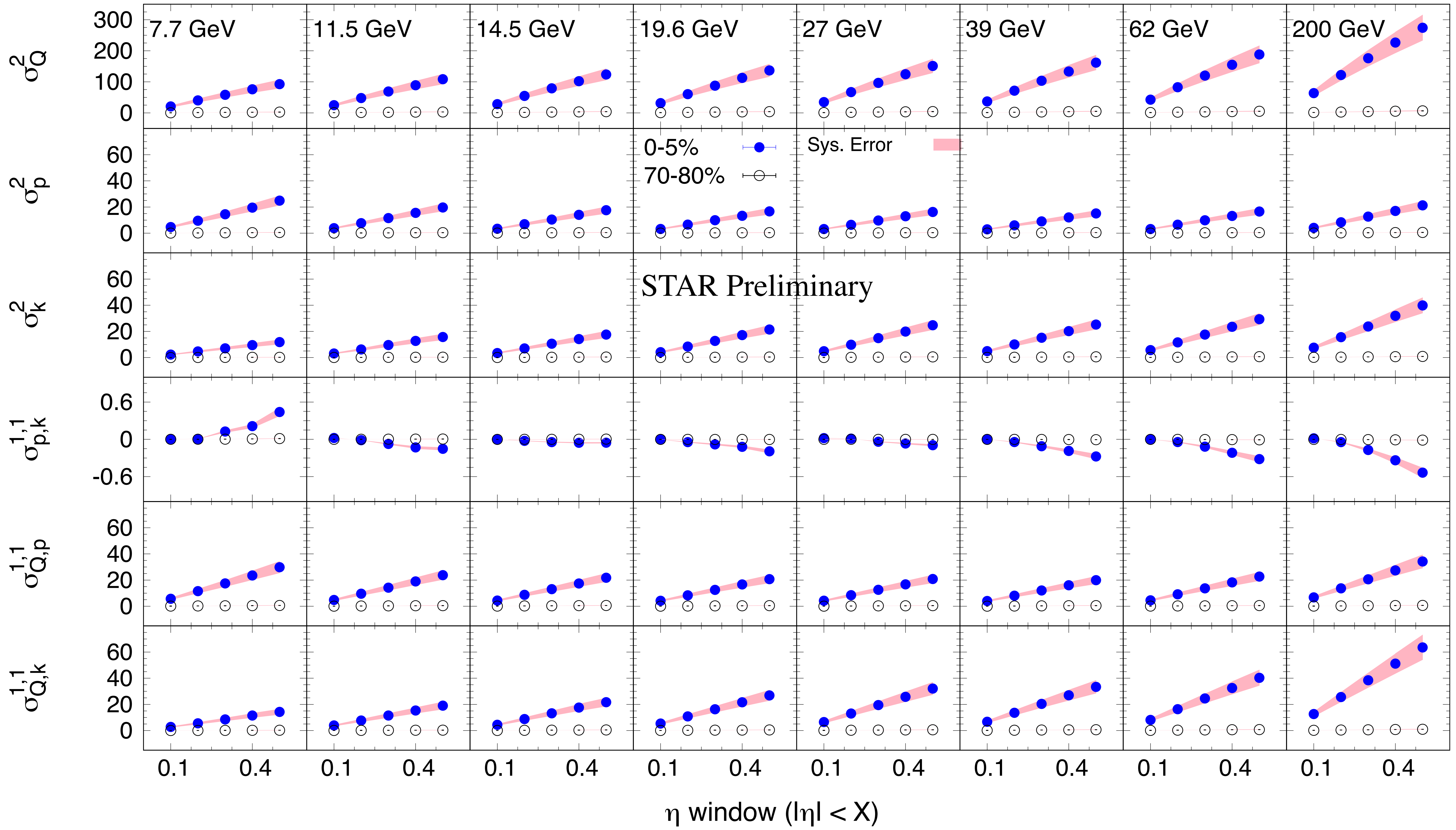
- ✓ Covariance shows linear dependence with respect to centrality.
- ✓ The covariance between net proton and net kaon is positive at low energy and negative at higher energy — Indicating p and k are anti-correlated at high energy.
- ✓ Covariance follows the CLT-like variance : $\sigma^{11} \propto \langle N_{part} \rangle$

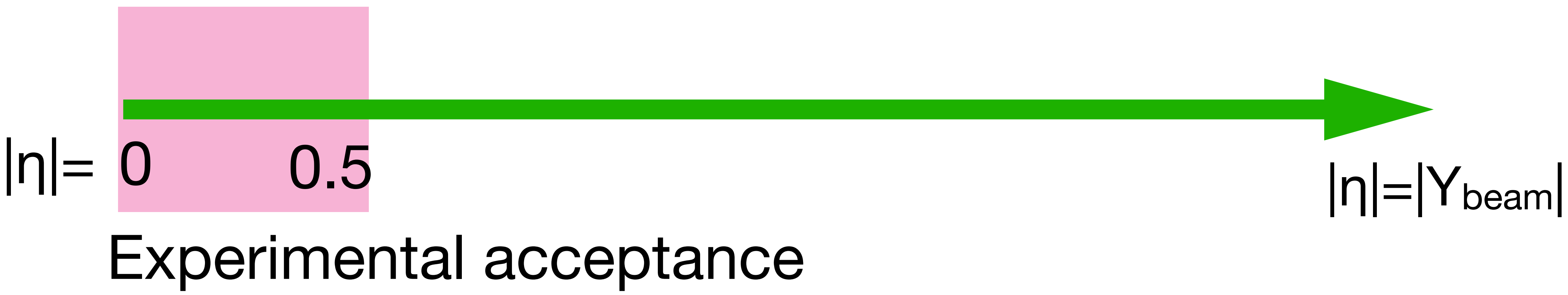
# Acceptance dependence



- ✓ All diagonal and off-diagonal cumulant cumulants of Q, p and k show linear dependence on |η| acceptance window within our analysis region compared peripheral collisions
- ✓ No non-monotonic variation as a function of acceptance is observed.

# Acceptance dependence




$|\eta|=$ 0 0.5

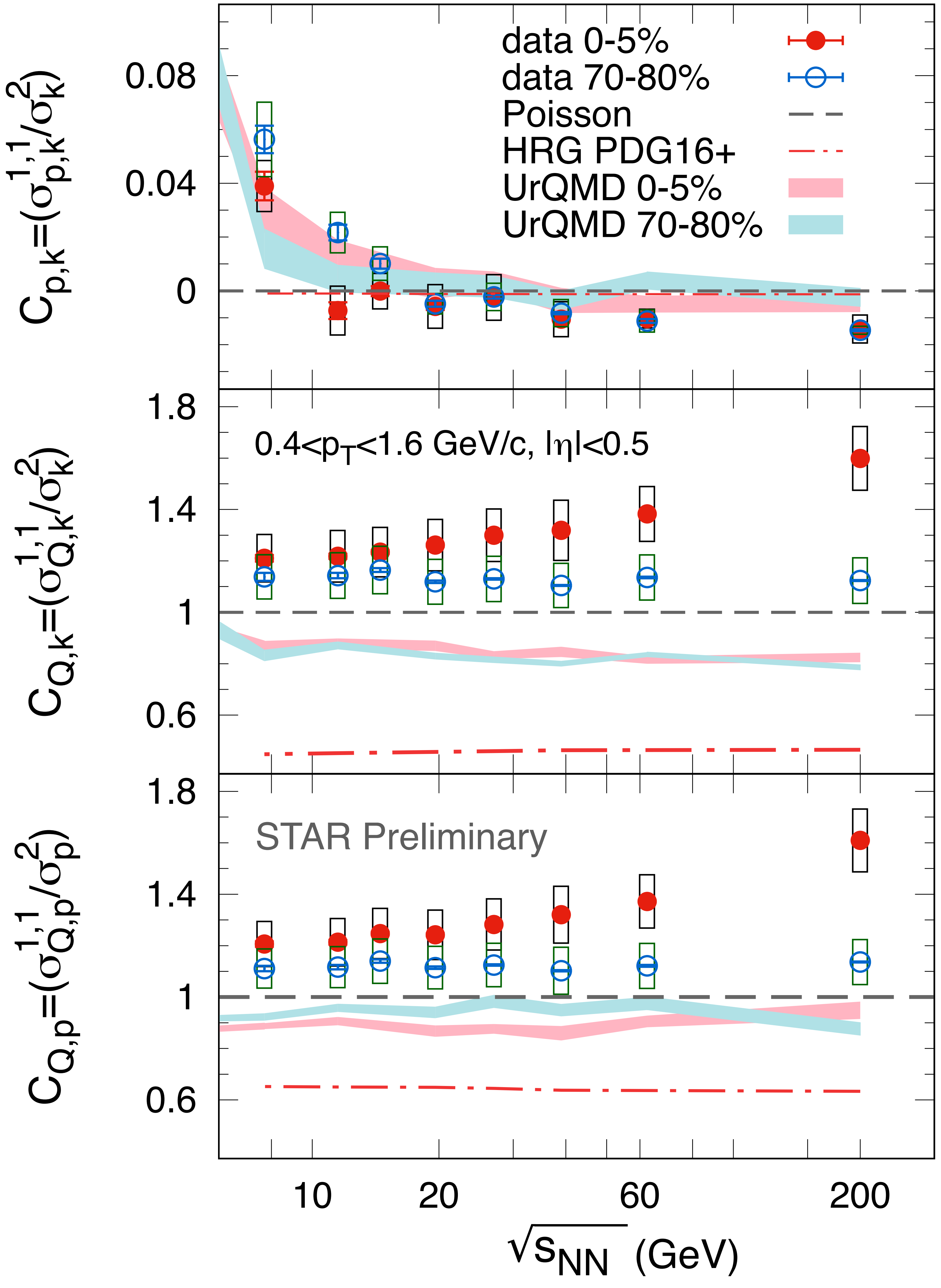
$|\eta|=|Y_{beam}|$

Experimental acceptance

- ✓ All diagonal and off-diagonal cumulant cumulants of Q, p and k show linear dependence on |η| acceptance window within our analysis region compared peripheral collisions
- ✓ No non-monotonic variation as a function of acceptance is observed.

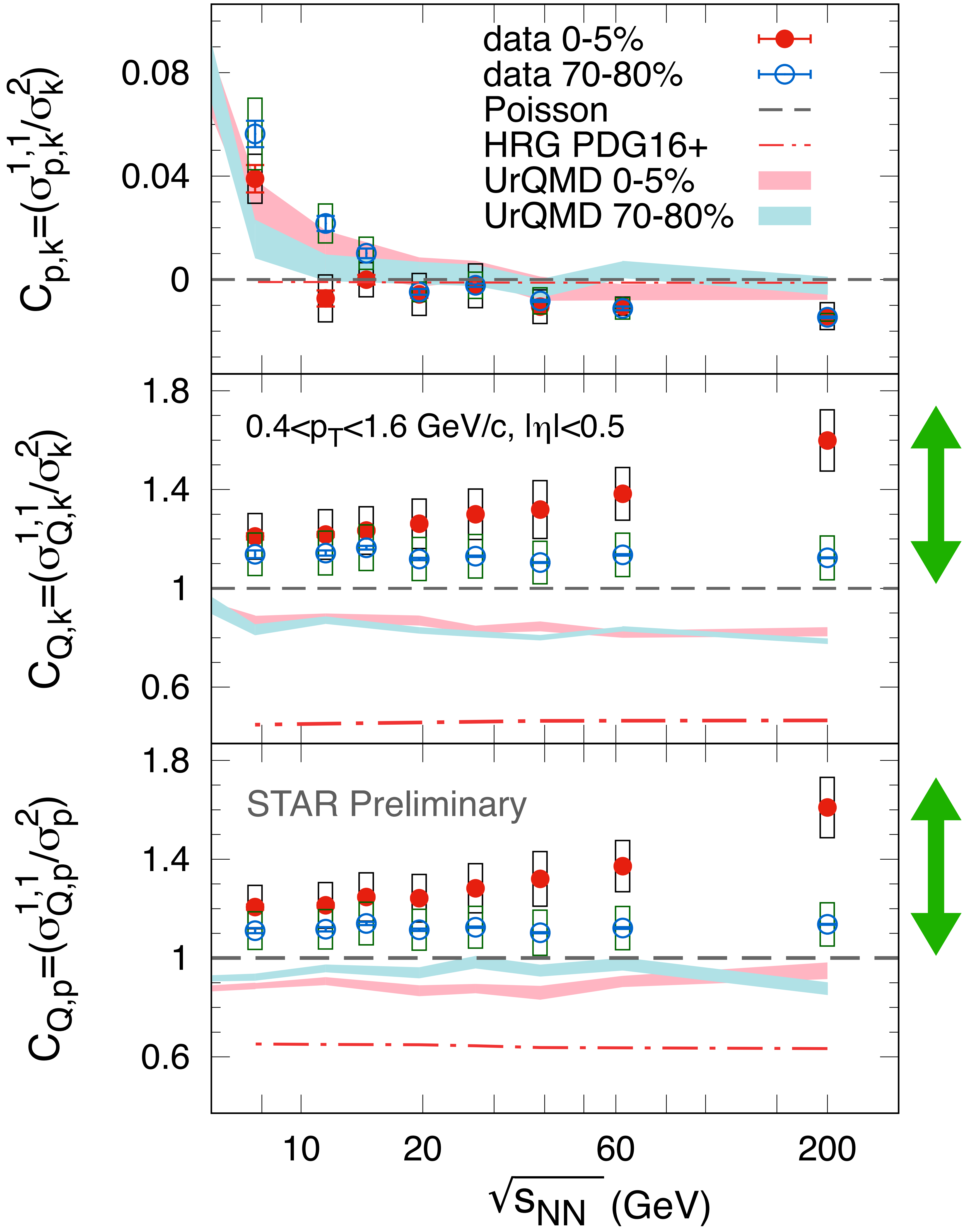
- ‣ With the current acceptance we can only explore a small portion of acceptance.
- ‣ BES-II may give better insight in η-acceptance dependence.

# Beam-energy dependence of cumulant ratio



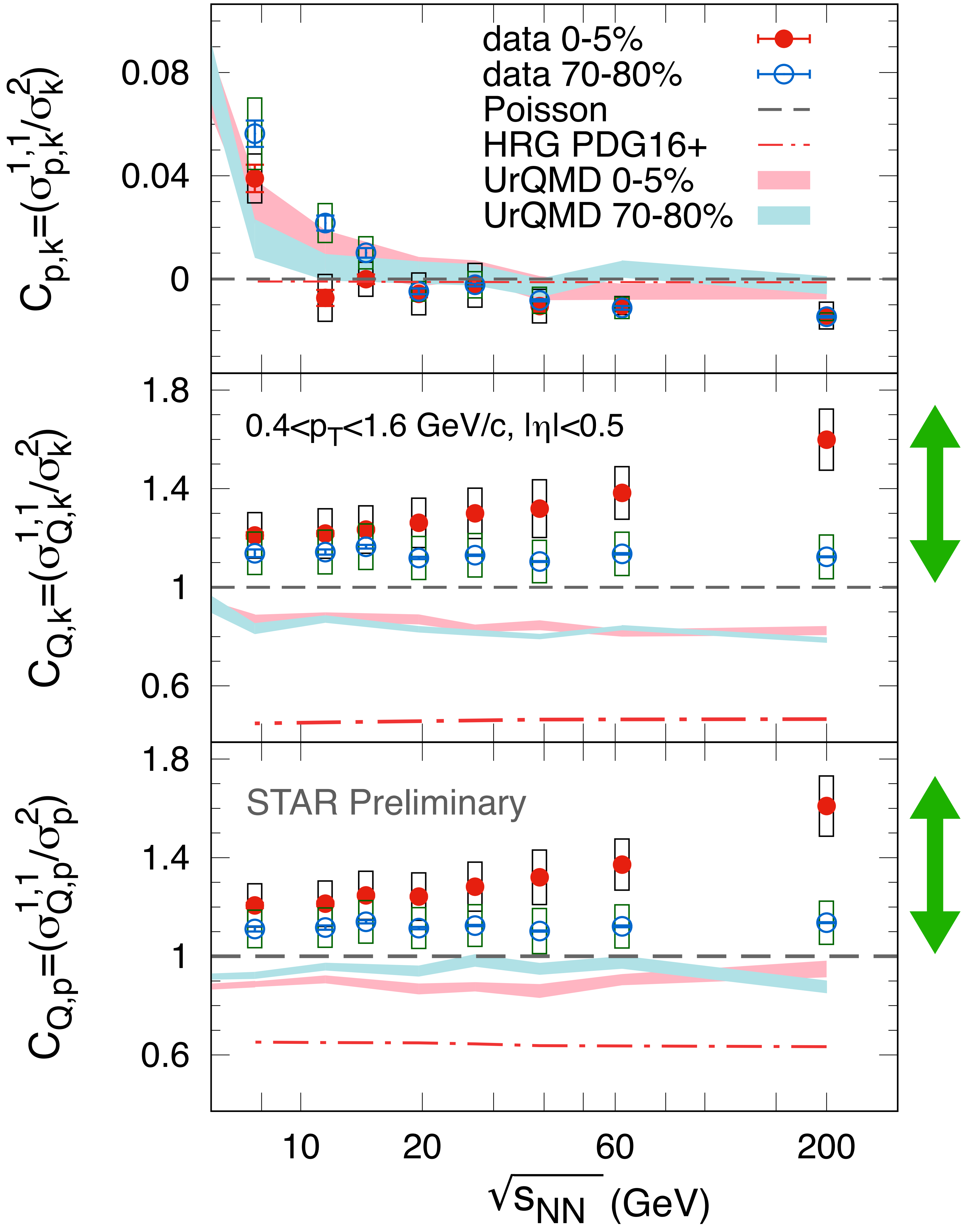
- ✓ Volume-independent normalized correlations between net proton and net kaon are positive at low energies and negative at high energies.

# Beam-energy dependence of cumulant ratio



- ✓ Volume-independent normalized correlations between net proton and net kaon are positive at low energies and negative at high energies.
- ✓ An excess correlation between net charge and net kaon, and same in net charge and net proton is observed with respect to peripheral collisions. These excess correlation increase with beam energy.
  - What is the source of the excess correlation?

# Beam-energy dependence of cumulant ratio



- ✓ Volume-independent normalized correlations between net proton and net kaon are positive at low energies and negative at high energies.
- ✓ An excess correlation between net charge and net kaon, and same in net charge and net proton is observed with respect to peripheral collisions. These excess correlation increase with beam energy.
  - ▸ What is the source of the excess correlation?
- ✓ This correlation cannot be explained from the thermal (HRG) and non-thermal (UrQMD) hadronic model calculations.

# Summary

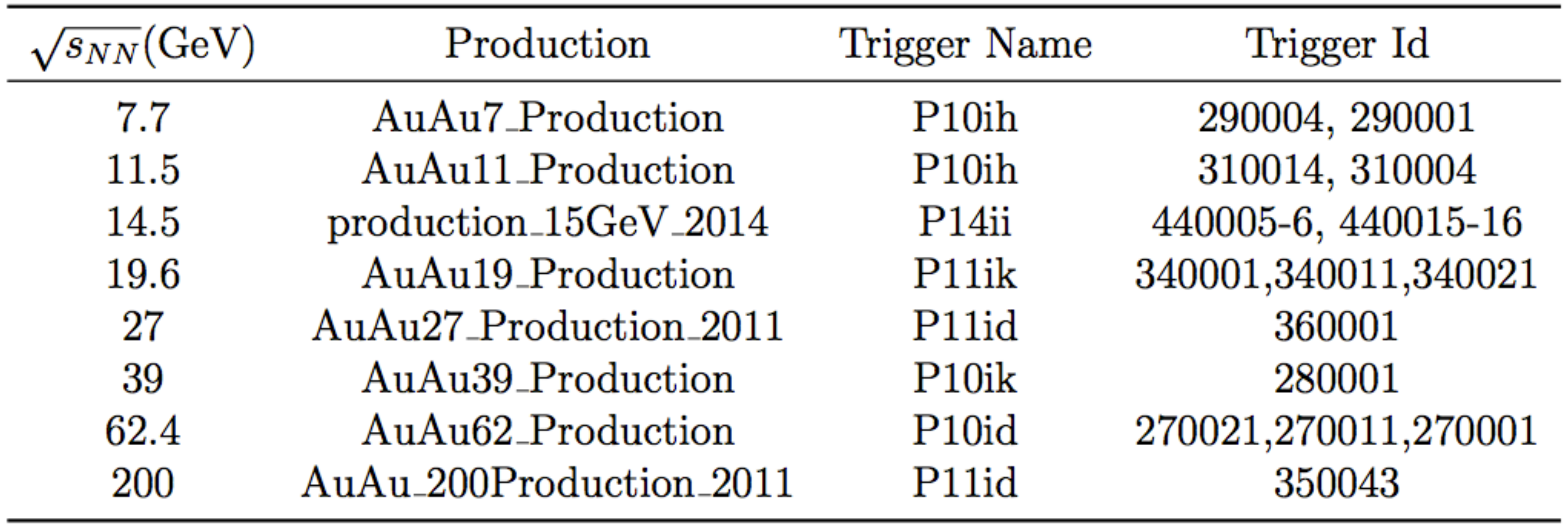
- ✓ First measurement of all 2nd-order cumulant ($\sigma_{(X,Y=p,Q,k)}$) matrix elements as a function of collision centrality for Au+Au collisions at $\sqrt{s_{NN}}$= 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV are presented. Detailed results are shown for the kinematic range of $|\eta| < 0.5$ and $0.4 < p_T < 1.6$ GeV/c as well as different $|\eta|$ windows.
- ✓ An excess correlations between net-charge and net kaon, and net charge, and net proton are observed for central collisions with respect to the peripheral ones. The correlations increase with the increase of beam energy. This increase is much larger compared to the Poisson baseline and has not been observed for the UrQMD event generator.
- ✓ Net proton and net kaon shows anti-correlations for central collisions and for $\sqrt{s_{NN}} > 27$ GeV.
- ✓ Both diagonal and off-diagonal cumulants of net charge, net kaon and net proton show linear dependence with the $\Delta\eta$ acceptance window.
- ✓ These cumulant matrix elements provide important step to map QCD phase diagram.

*Thank you*

# Backup

# Backup

## Data set



| $\sqrt{s_{NN}}$(GeV) | Production | Trigger Name | Trigger Id |
|---|---|---|---|
| 7.7 | AuAu7_Production | P10ih | 290004, 290001 |
| 11.5 | AuAu11_Production | P10ih | 310014, 310004 |
| 14.5 | production_15GeV_2014 | P14ii | 440005-6, 440015-16 |
| 19.6 | AuAu19_Production | P11ik | 340001,340011,340021 |
| 27 | AuAu27_Production_2011 | P11id | 360001 |
| 39 | AuAu39_Production | P10ik | 280001 |
| 62.4 | AuAu62_Production | P10id | 270021,270011,270001 |
| 200 | AuAu_200Production_2011 | P11id | 350043 |

## PID

| | Proton | Kaon | Charge |
|---|---|---|---|
| pT (TPC only) | 0.4 - 0.8 GeV/c | — | 0.4 - 1.6 GeV/c |
| pT (TPC+TOF) | 0.8 - 1.6 GeV/c | 0.4 - 1.6 GeV/c | — |
| $\lvert\eta\rvert$ | $< 0.5$ | | |
| Centrality | Refmult2 ( $-1.0<\eta<-0.5$ && $0.5<\eta<1.0$ ) | | |
| DCA | < 1 cm | | |
| nHitsdedx | > 5 | | |
| nFitPoints | > 20 | | |
| PID (TPC) | nSigmaProton < 2 | nSigmaKaon < 2 &&<br>nSigmaPion > 2 | all charge |
| PID (TOF) | $0.6 < m^2 < 1.2$ | $0.15 < m^2 < 0.4$ | — |

# Efficiency estimation

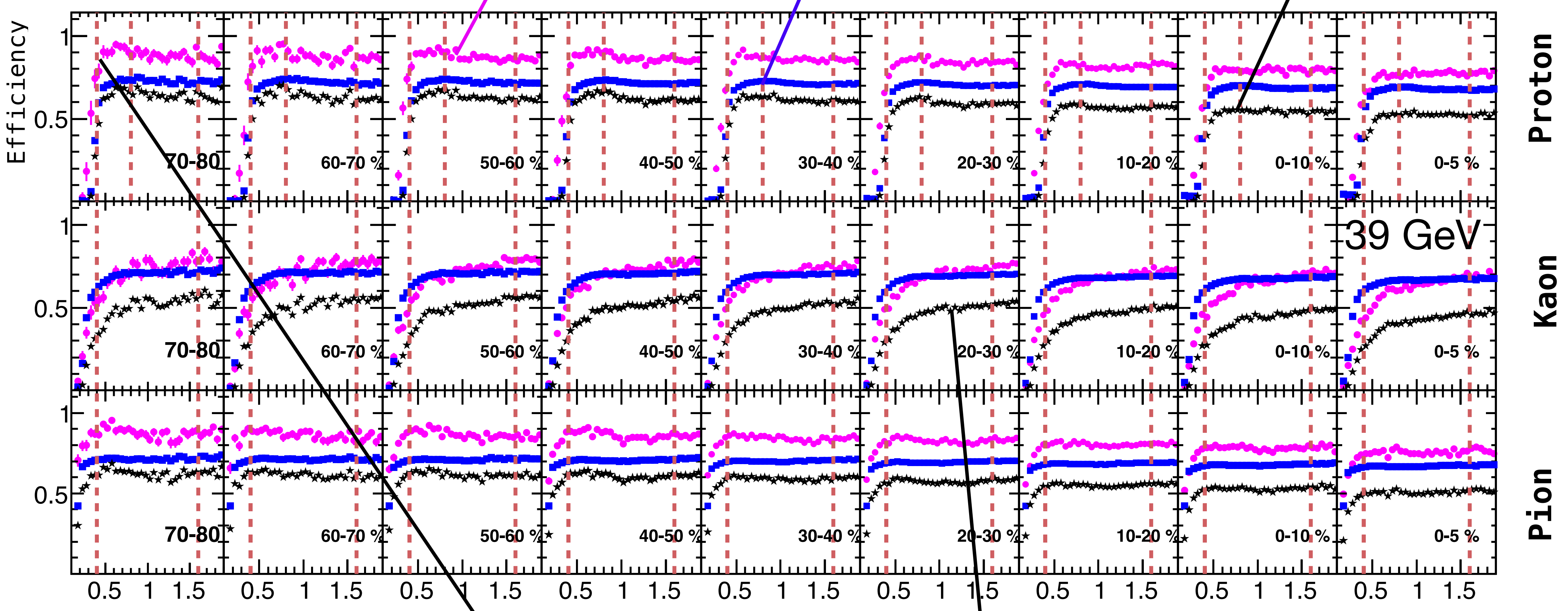
## ✱TPC efficiency

$$\varepsilon_{TPC} = \frac{\text{Reconstructed tracks having associated MC tracks}}{\text{MC tracks } (\pi^{\pm}, K^{\pm}, p, \bar{p})}$$

TCP efficiency

TOF match efficiency

TPC*TOF efficiency



**bin-I**
TPC-MC efficiency

**bin-II**
TPC+TOF efficiency

## ✱TOF matching efficiency

$$\varepsilon_{TOF} = \frac{\text{track quality cut } \&\& \ |n\sigma_{particle}| < 2 \ \&\& \ \text{TOF matched} > 0}{\text{track quality cut } \&\& \ |n\sigma_{particle}| < 2}$$

| Quantity | Efficiency bins | |
|---|---|---|
| | **TPC efficiency** | **(TPC*TOF) efficiency** |
| **p, pbar** | $0.4 < p_T < 0.8$ (GeV/c) | $0.8 < p_T < 1.6$ (GeV/c) |
| **k+,k-** | ———— | $0.4 < p_T < 1.6$ (GeV/c) |
| **Q+,Q-** | $0.4 < p_T < 1.6$ (GeV/c) | ———— |

**$p_T$-integrated efficiency :**

$$\langle \varepsilon_{bin-I} \rangle = \frac{\int_a^b \varepsilon_{TPC}(p_T) f(p_T) p_T dp_T}{\int_a^b f(p_T) p_T dp_T}$$

$$\langle \varepsilon_{bin-II} \rangle = \frac{\int_a^b \varepsilon_{TPC}(p_T) \varepsilon_{TOF}(p_T) f(p_T) p_T dp_T}{\int_a^b f(p_T) p_T dp_T}$$