Studying the QGP using Balance Functions from Au+Au Collisions at $\sqrt{s_{NN}}$ = 7.7 to 200 GeV

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For the STAR Collaboration

Balance Functions

- Balance functions are sensitive to charge formation mechanisms and relative diffusion.
- In heavy ion collisions, most of the detected charge is created during the evolution of the system.
- Charge creation can occur any time before chemical freeze-out.
- Balance functions can be used to study:
  - Delayed hadronization,
  - Time scales of charge production.
- We have measured balance functions from the RHIC Beam Energy Scan:
  - 7.7, 11.5, 19.6, 27, 39, 62.4, and 200 GeV Au+Au.

Observable – Balance Function

- The balance function is a conditional probability that a particle a in the bin p_1 will be accompanied by a particle b of opposite charge in the bin p_2:

$$B(p_2 \mid p_1) = \frac{1}{2}\left\{\rho(b, p_2 \mid a, p_1) - \rho(b, p_2 \mid b, p_1) + \rho(a, p_2 \mid b, p_1) - \rho(a, p_2 \mid a, p_1)\right\}$$

- It can be written as:

$$B(\Delta\eta) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta\eta) - N_{++}(\Delta\eta)}{N_+} + \frac{N_{-+}(\Delta\eta) - N_{--}(\Delta\eta)}{N_-}\right\}$$

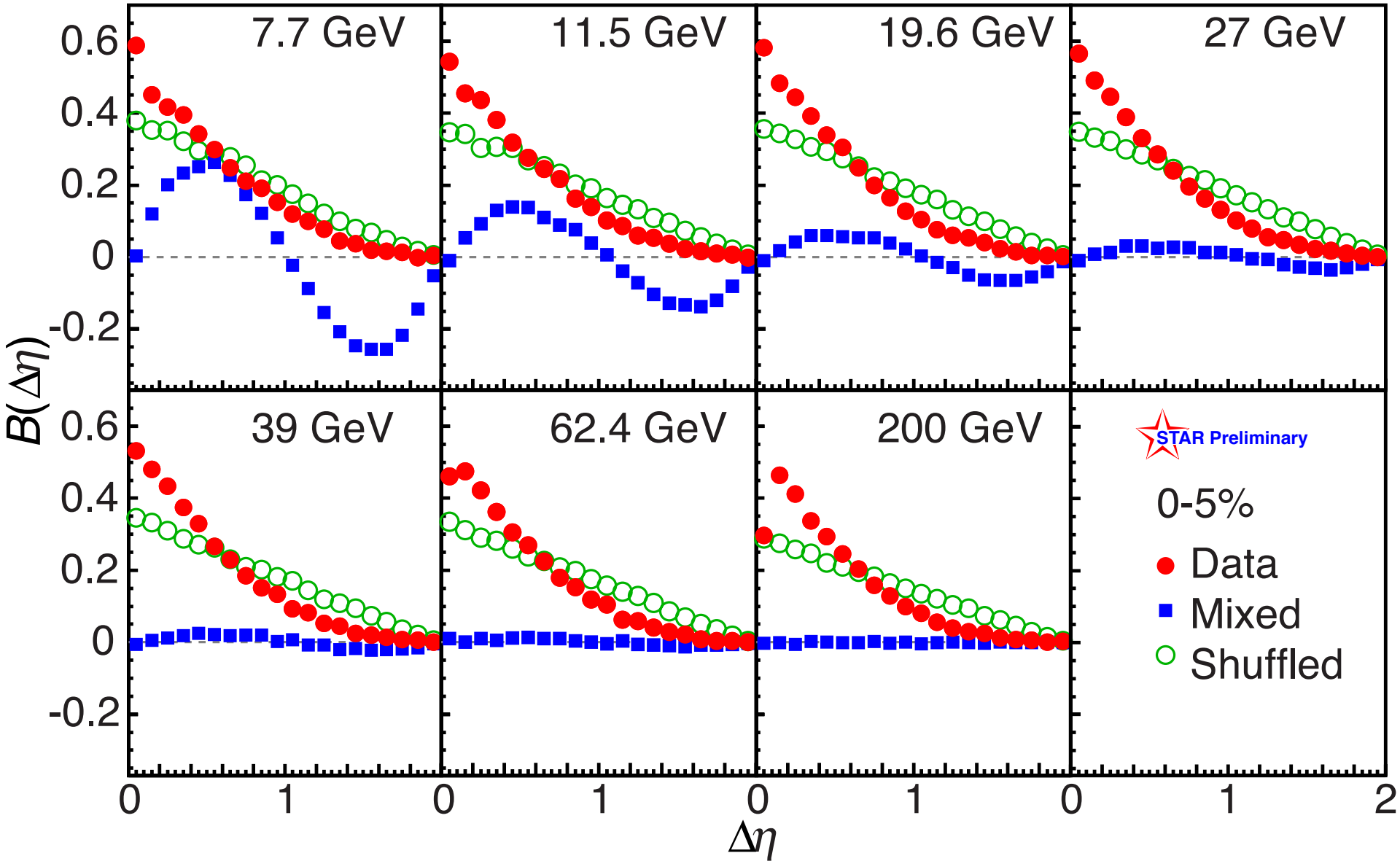
- The width of balance function is calculated via weighted average:

$$\langle \Delta\eta \rangle = \frac{\sum_{\Delta\eta \geq 0.1} B(\Delta\eta_i)\Delta\eta_i}{\sum_{\Delta\eta \geq 0.1} B(\Delta\eta_i)}$$

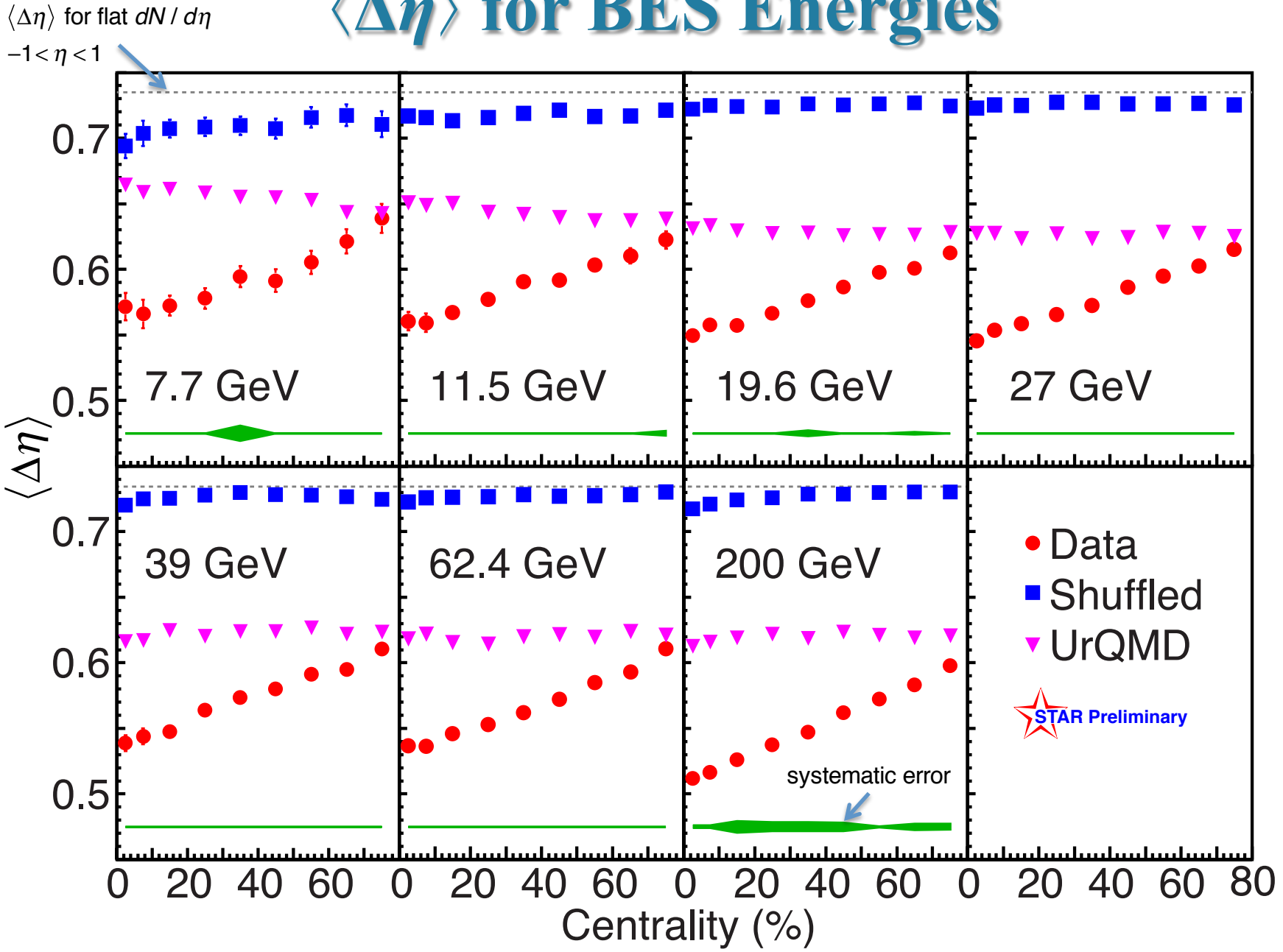
Balance Function

- STAR published a comprehensive paper on balance functions from 200 GeV Au+Au, *p*+*p*, and *d*+Au in 2010:
  - Phys. Rev. C **82**, 024905 (2010)
- STAR showed that the balance function for all charged particles $B(\Delta\eta)$ narrows in central collisions.
- Recently ALICE published a paper on balance functions from 2.76 TeV Pb+Pb claiming that the width of the balance functions from NA49, STAR, and ALICE were similar and that the interpretation of delayed hadronization was in question:
  - Phys. Lett. B **723**, 267 (2013)

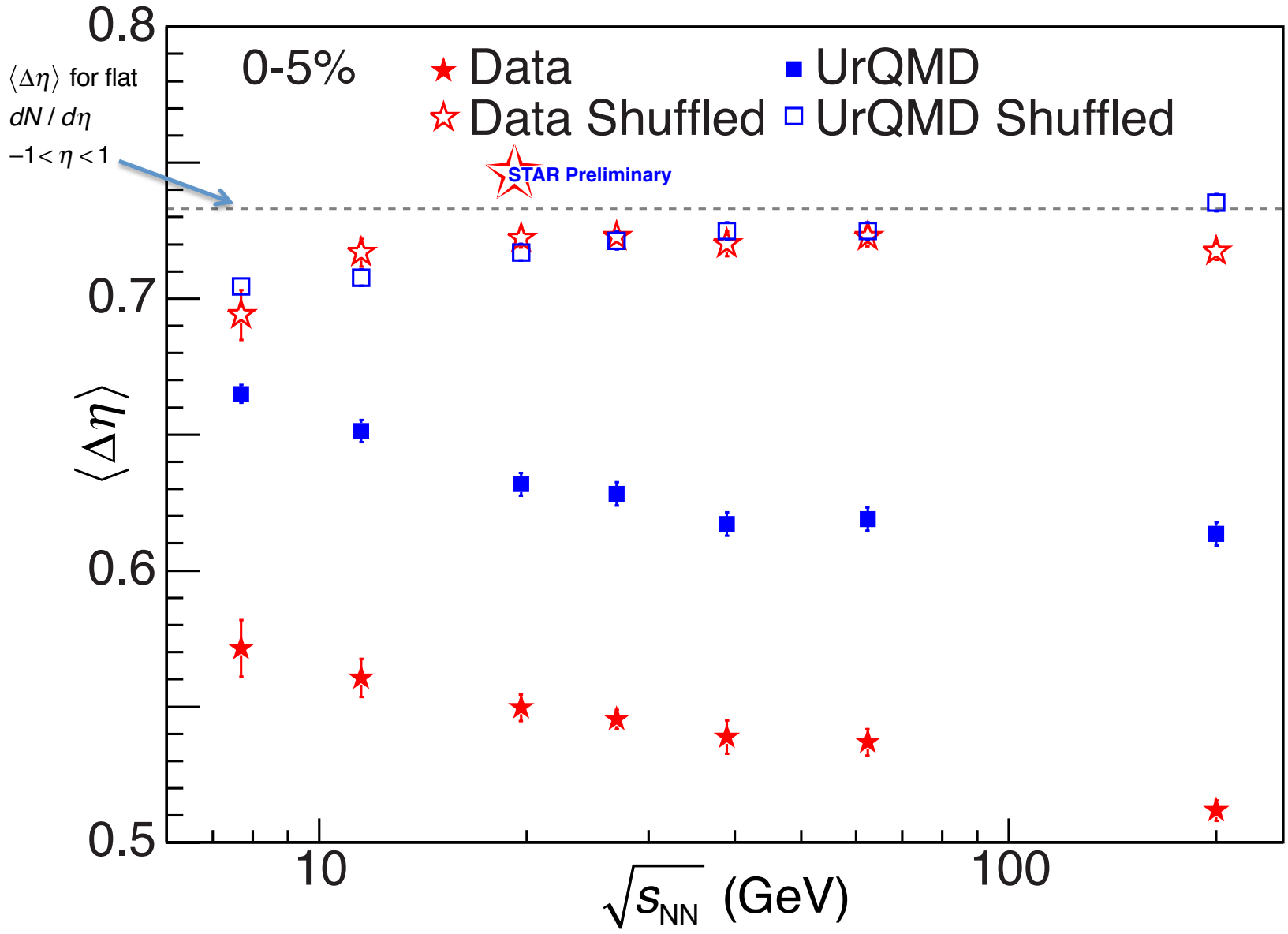
$B(\Delta\eta)$ for BES Energies 0-5%



⟨Δη⟩ for BES Energies



⟨Δη⟩ for BES Energies, 0-5%



Compare with ALICE

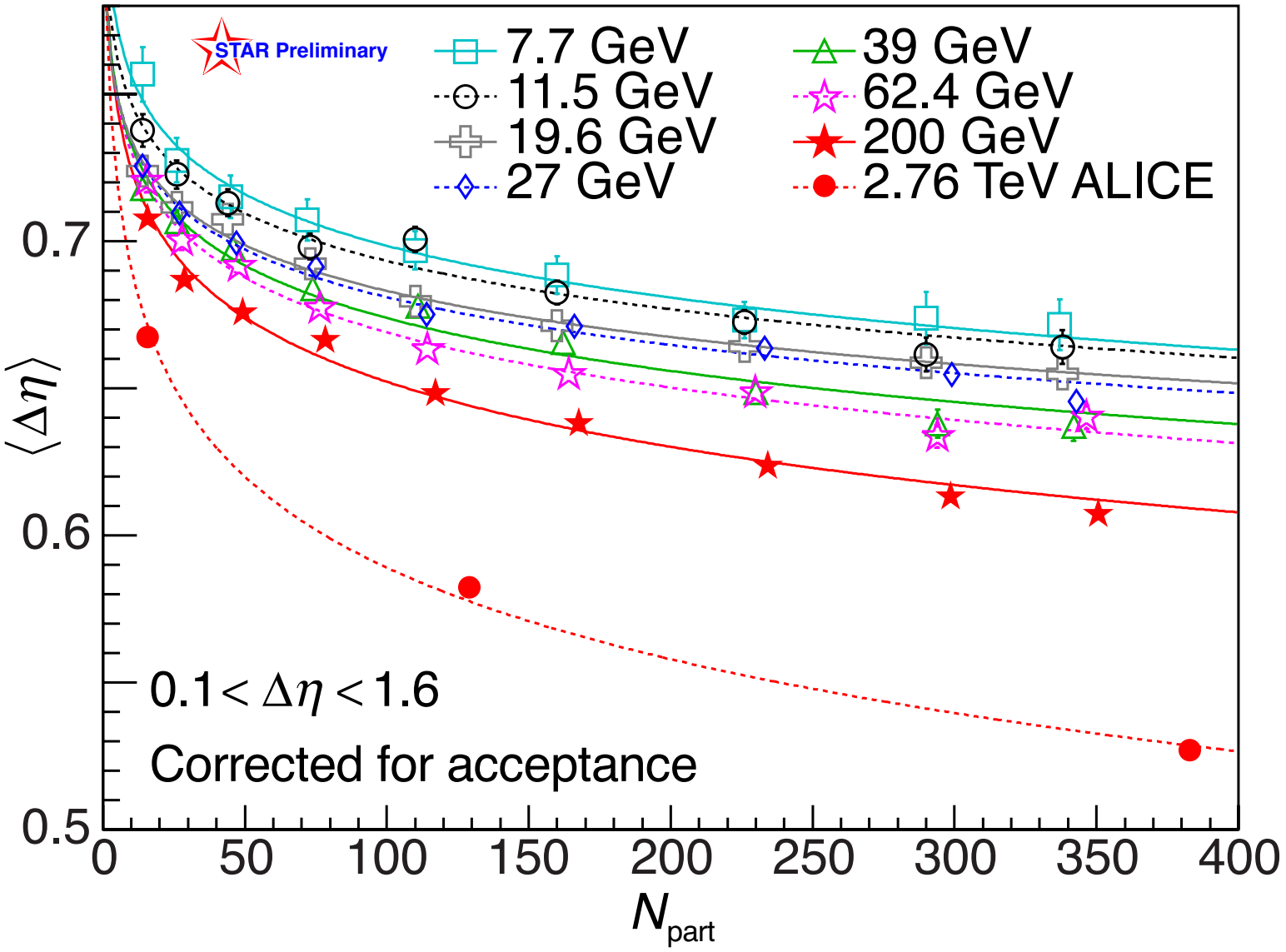
- To compare with ALICE, we corrected our BES balance function results using:

$$B(\Delta\eta) = B_{\infty}(\Delta\eta)\left(1 - \frac{\Delta\eta}{\Delta\eta_{\max}}\right) = B_{\infty}(\Delta\eta)\left(1 - \frac{\Delta\eta}{2}\right)$$

- We then took the widths of the corrected balance function results using the ALICE acceptance of $\Delta\eta = 1.6$:

$$\langle \Delta\eta \rangle = \frac{\sum_{\Delta\eta=0.1}^{\Delta\eta=1.6} B(\Delta\eta)\Delta\eta}{\sum_{\Delta\eta=0.1}^{\Delta\eta=1.6} B(\Delta\eta)}$$

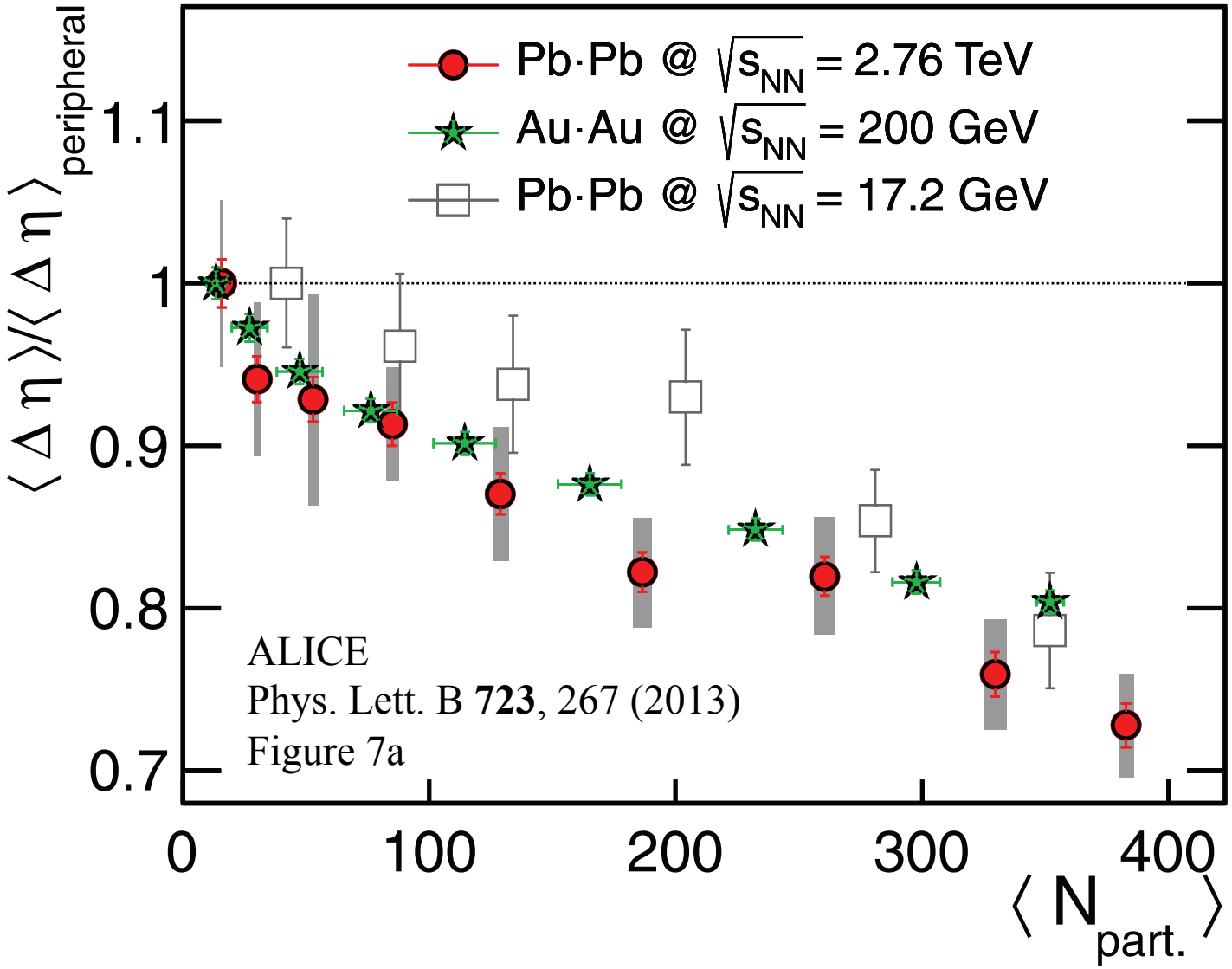
⟨Δη⟩ Compare with ALICE



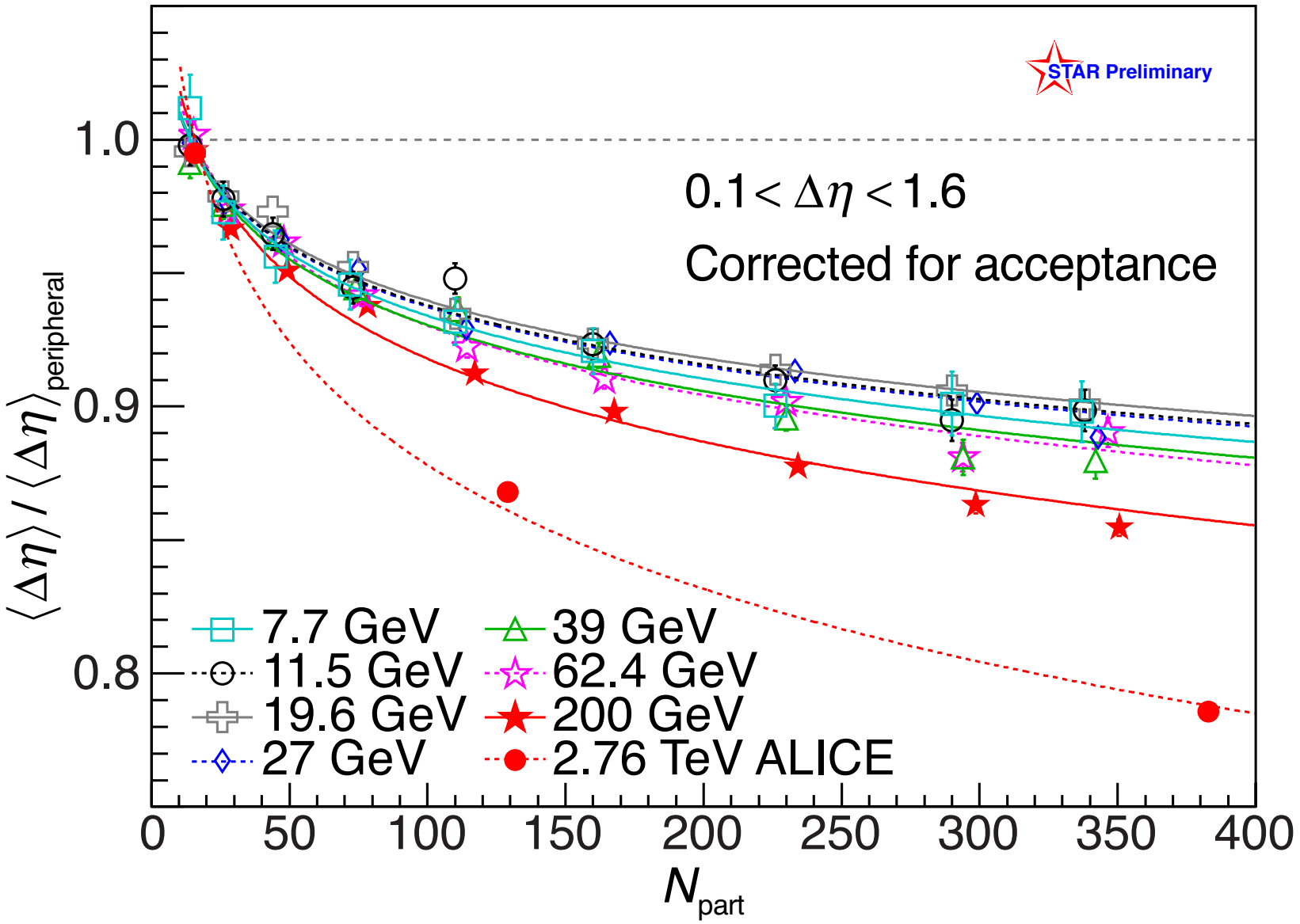
Relative Change in Width

- ALICE made the point in their paper that the relative change in the balance function widths did not change from 17.3 GeV to 200 GeV to 2.76 TeV.
- To show this point, they scaled by the width in the most peripheral bin.
- We will do the same thing for our BES balance functions except:
  - We use the range of $0.1 \leq \Delta\eta \leq 1.6$.
  - We use a fit to the measured widths to remove statistical fluctuations in the peripheral bins at low energies where the statistics are low.

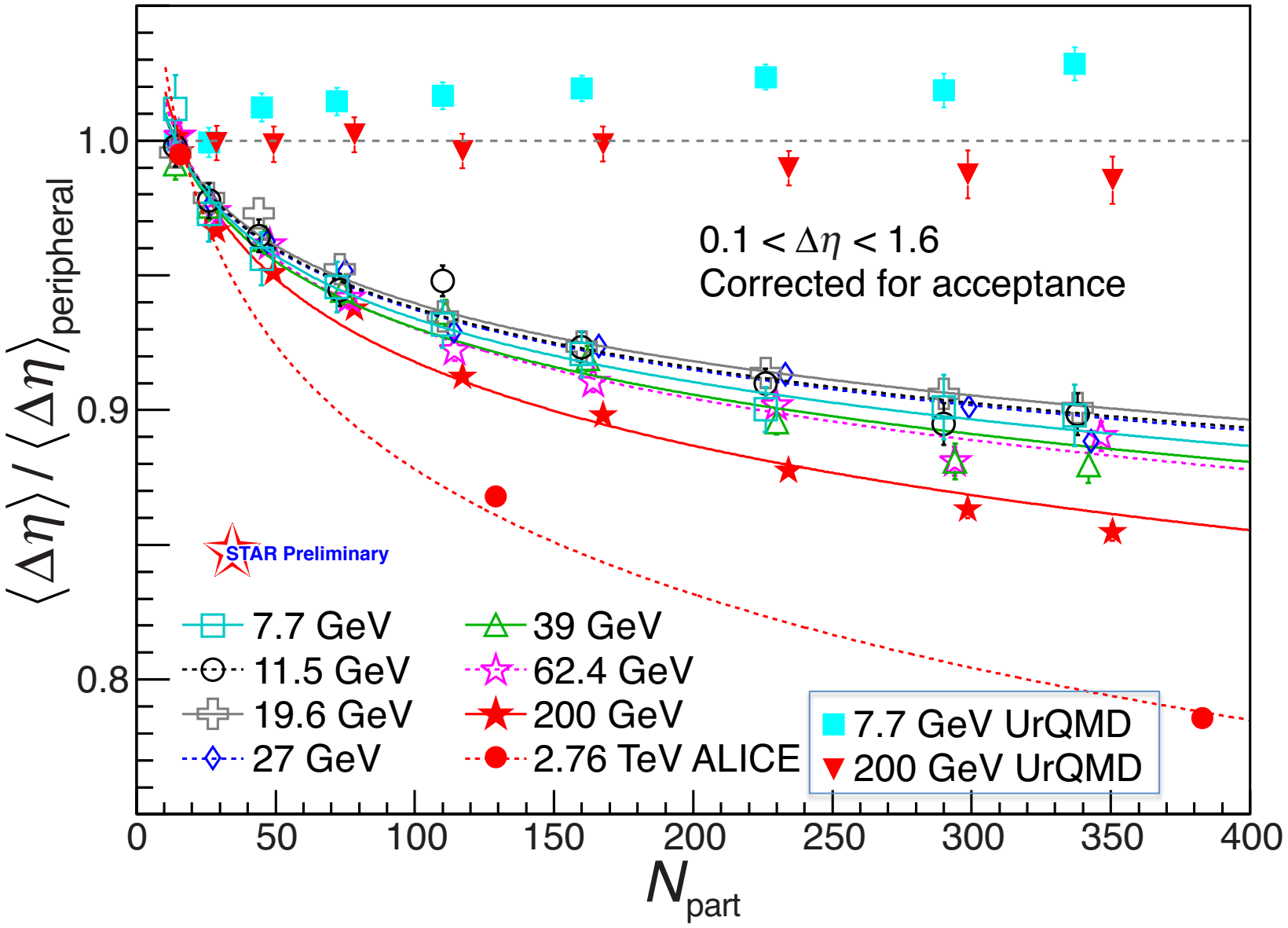
Relative Change in Width - ALICE



$\langle\Delta\eta\rangle/\langle\Delta\eta\rangle_{\text{peripheral}}$



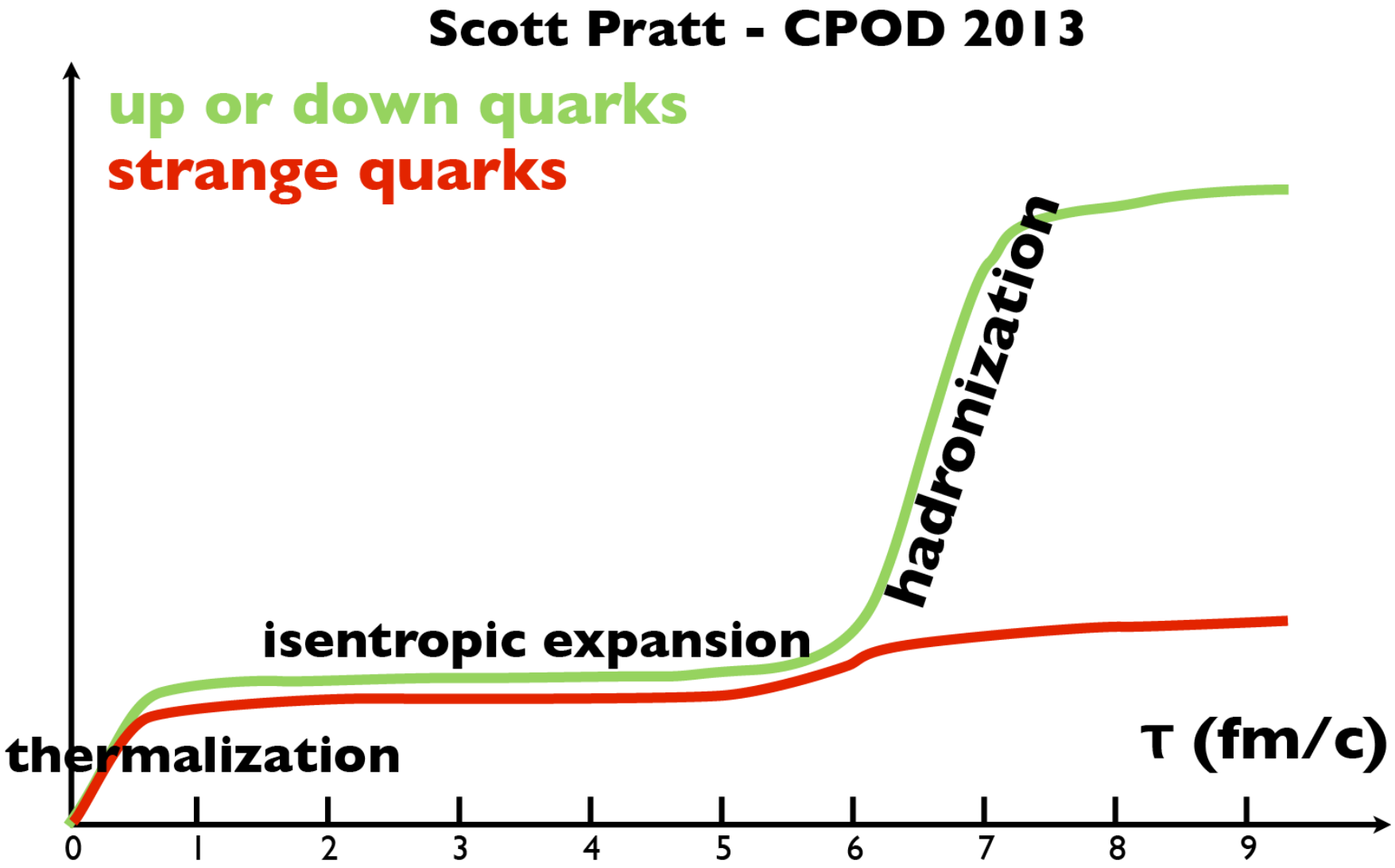
$\langle\Delta\eta\rangle/\langle\Delta\eta\rangle_{\text{peripheral}}$ Compared to URQMD



Generalized Balance Functions

- Scott Pratt predicts that two waves of charge creation can be observed using balance functions.
  - Scott Pratt, Phys. Rev. Lett. **108**, 212301 (2012).
- The first wave occurs ≈1 fm/c after the collision when the gluons thermalize into the QGP.
- The second wave occurs after an isentropic expansion when hadronization occurs around ≈5-10 fm/c.
  - The majority of charge production takes place in the second wave.
- These two waves of charge creation can be studied with balance functions of identified particles.
  - Pion pairs, kaon pairs, proton antiproton pairs, proton/K^- pairs.

Charge Production Timeline



Generalized Balance Functions

- Here we present generalized balance functions from central Au+Au collisions (0-5%) at 200 GeV:
  - TPC+TOF particle identification,
  - Pions and kaons: $p_T > 0.2$ GeV/c, $p < 1.6$ GeV/c,
  - Protons: $p_T > 0.4$ GeV/c, $p < 3.0$ GeV/c,
  - $\phi \longrightarrow K^+ + K^-$ is suppressed for the kaon balance function.
- The generalized balance function is written as:

$$B_{\alpha\beta}\left(p_1 \mid p_2\right) \equiv \frac{\left\langle \left[n_\alpha\left(p_1\right) - n_{\bar{\alpha}}\left(p_1\right) \right] \left[n_\beta\left(p_2\right) - n_{\bar{\beta}}\left(p_2\right) \right] \right\rangle}{\left\langle n_\beta\left(p_2\right) + n_{\bar{\beta}}\left(p_2\right) \right\rangle}$$

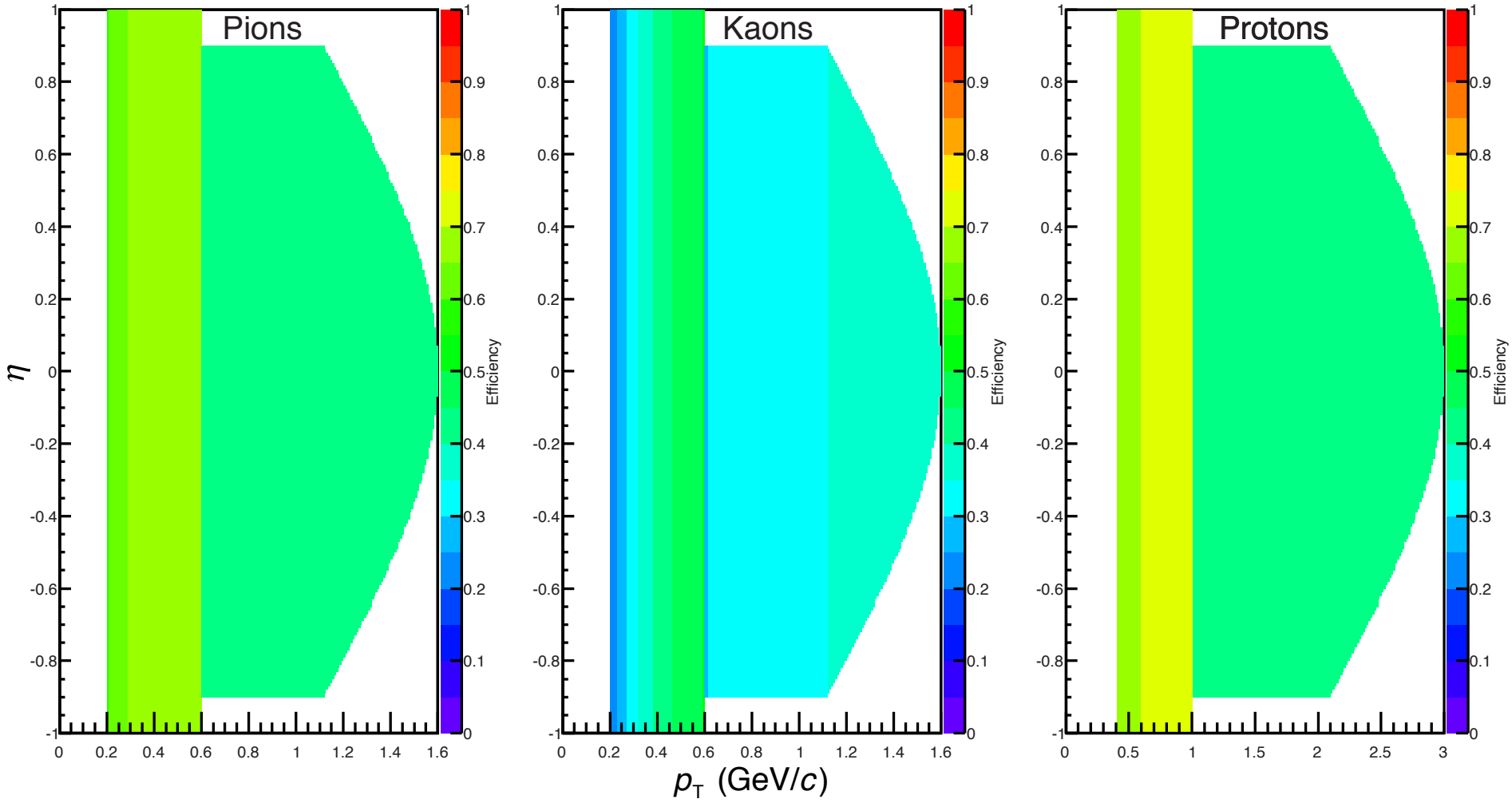
- 4 parameter fit was done to $B(\Delta y)$ for pion pairs, kaon pairs, proton pairs, and pK^- pairs.
  - A STAR acceptance and efficiency code was used for the model comparisons.

STAR Acceptance and Efficiency

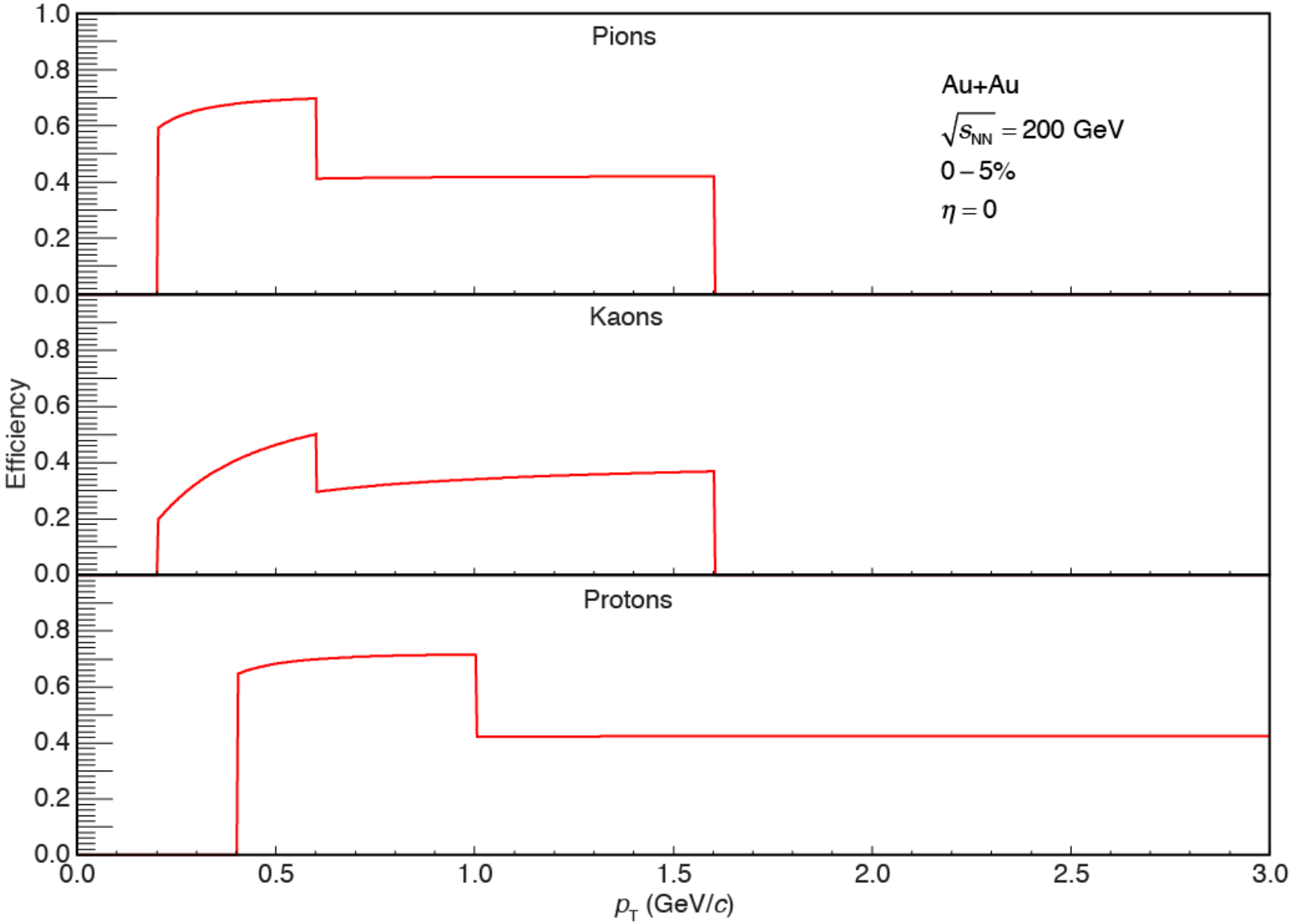
- A STAR acceptance and efficiency code for pions, kaons, and protons was used to filter the model calculations.
- The code was used for 0-5% Au+Au collisions at 200 GeV only.
- The code was based on the functional forms from the paper published by STAR, Phys. Rev. C **79**, 034909 (2009).
- The functional forms were fit to embedding data from Run 10 Au+Au 200 GeV.
- A constant TOF matching efficiency, taken from the data, was used for:
  - Pions and kaons, $p_T > 0.6$ GeV/c and $p < 1.6$ GeV/c.
  - Protons, $p_T > 1.0$ GeV/c and $p < 3.0$ GeV/c.

STAR Acceptance and Efficiency

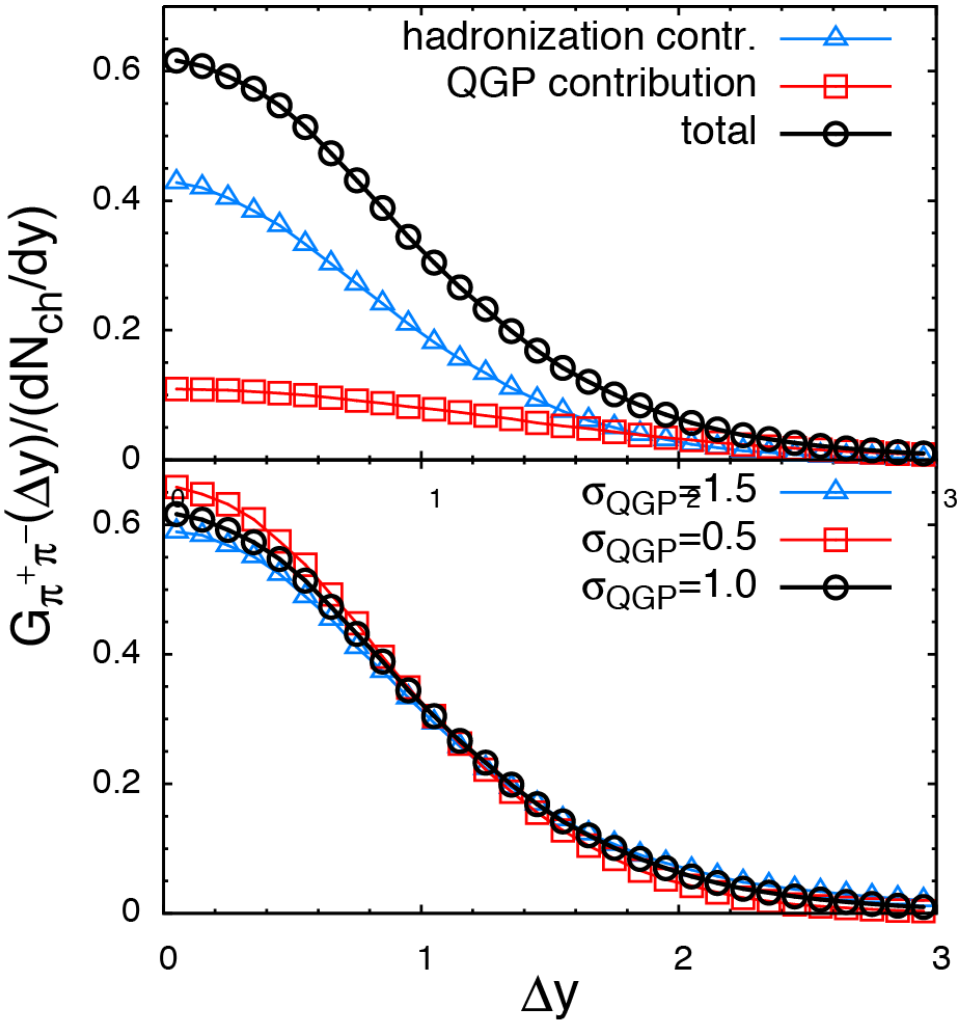
200 GeV Au+Au 0-5%



STAR Acceptance and Efficiency at $\eta = 0$



Generalized Pion Balance Function



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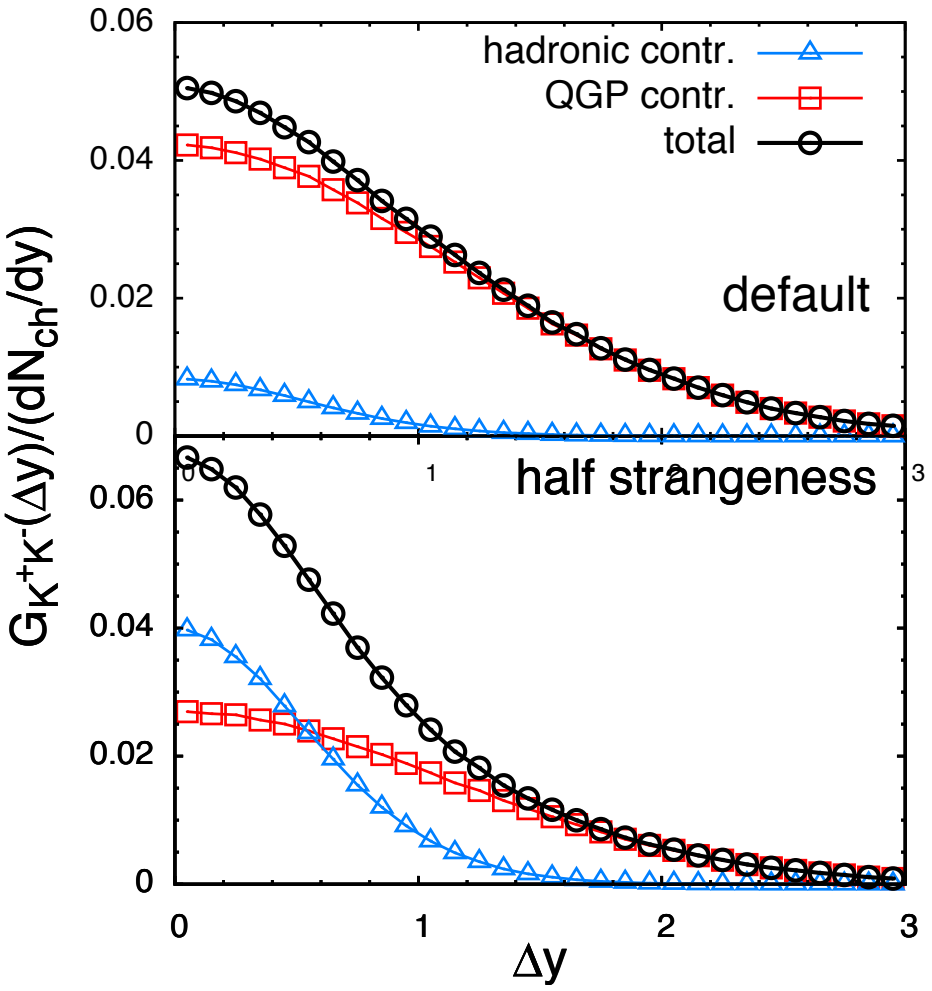
- The hadronization part is narrower.
- We can't separate components due to thermal smearing.
- The pion balance function narrows with centrality.

Generalized Kaon Balance Function



- There is little hadronic contribution.
- The kaon balance function can test whether the QGP is rich in strangeness.

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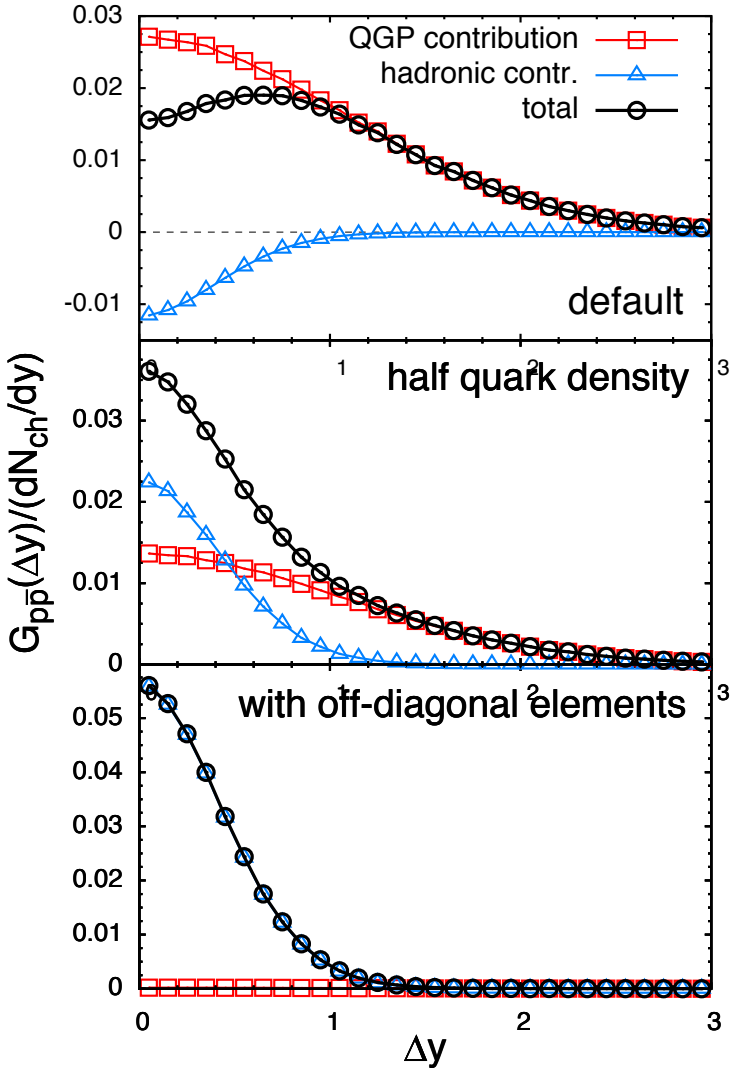
Generalized Proton Balance Function



- The hadron contribution is negative.
- The proton balance function tests the two-wave hypothesis.
- There is no narrowing with centrality.
- The proton balance function is sensitive to the quark density of the QGP.

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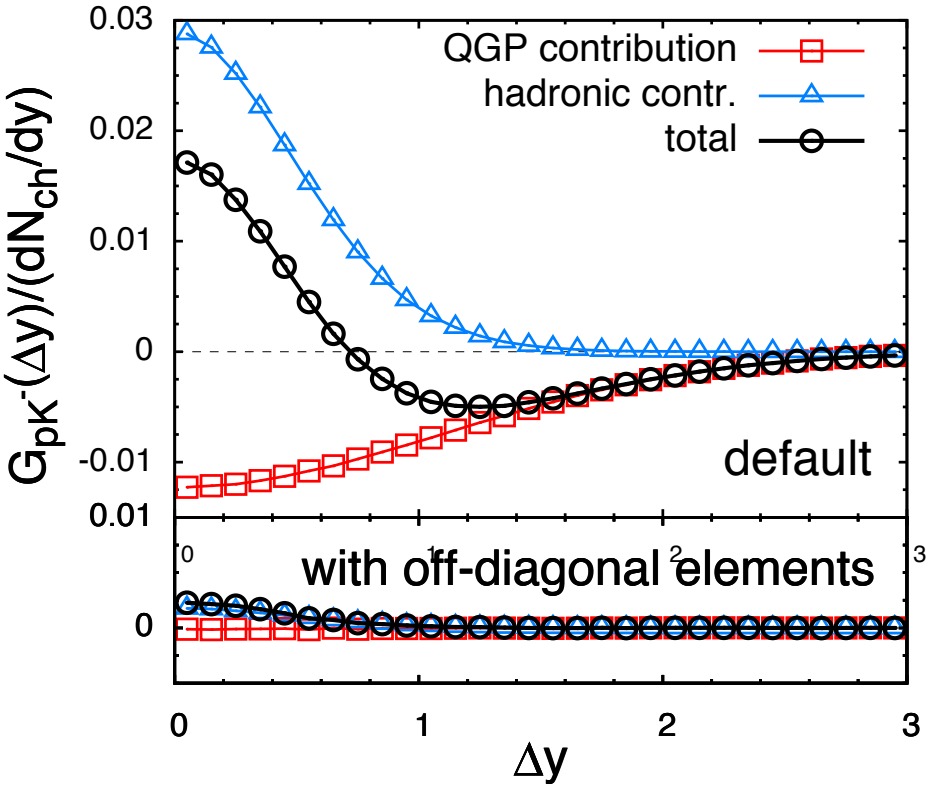
Generalized Proton-Kaon Balance Function



- The QGP contribution is negative.
- The proton-K^- balance function dips below zero.
- The proton-K^- balance function is too narrow for one source.

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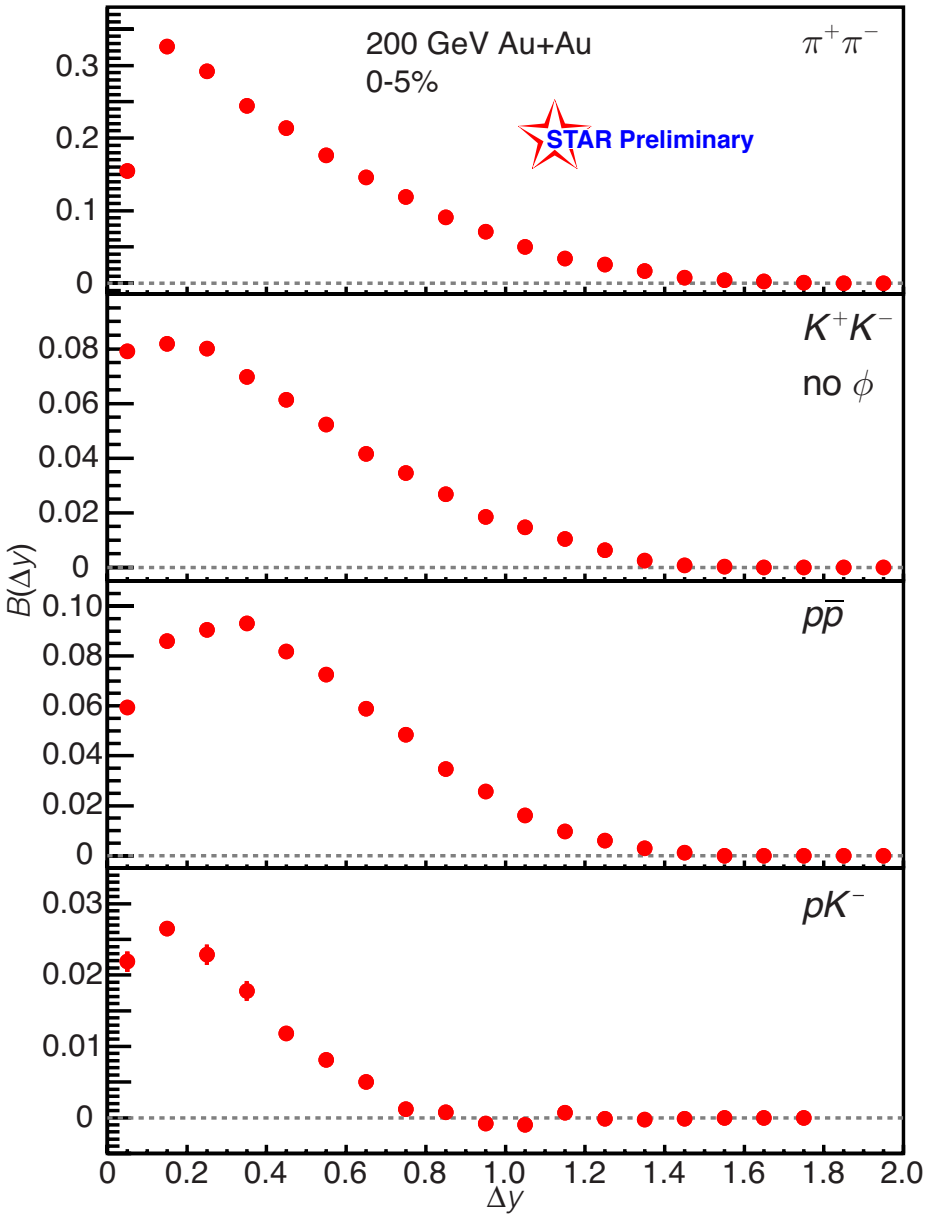
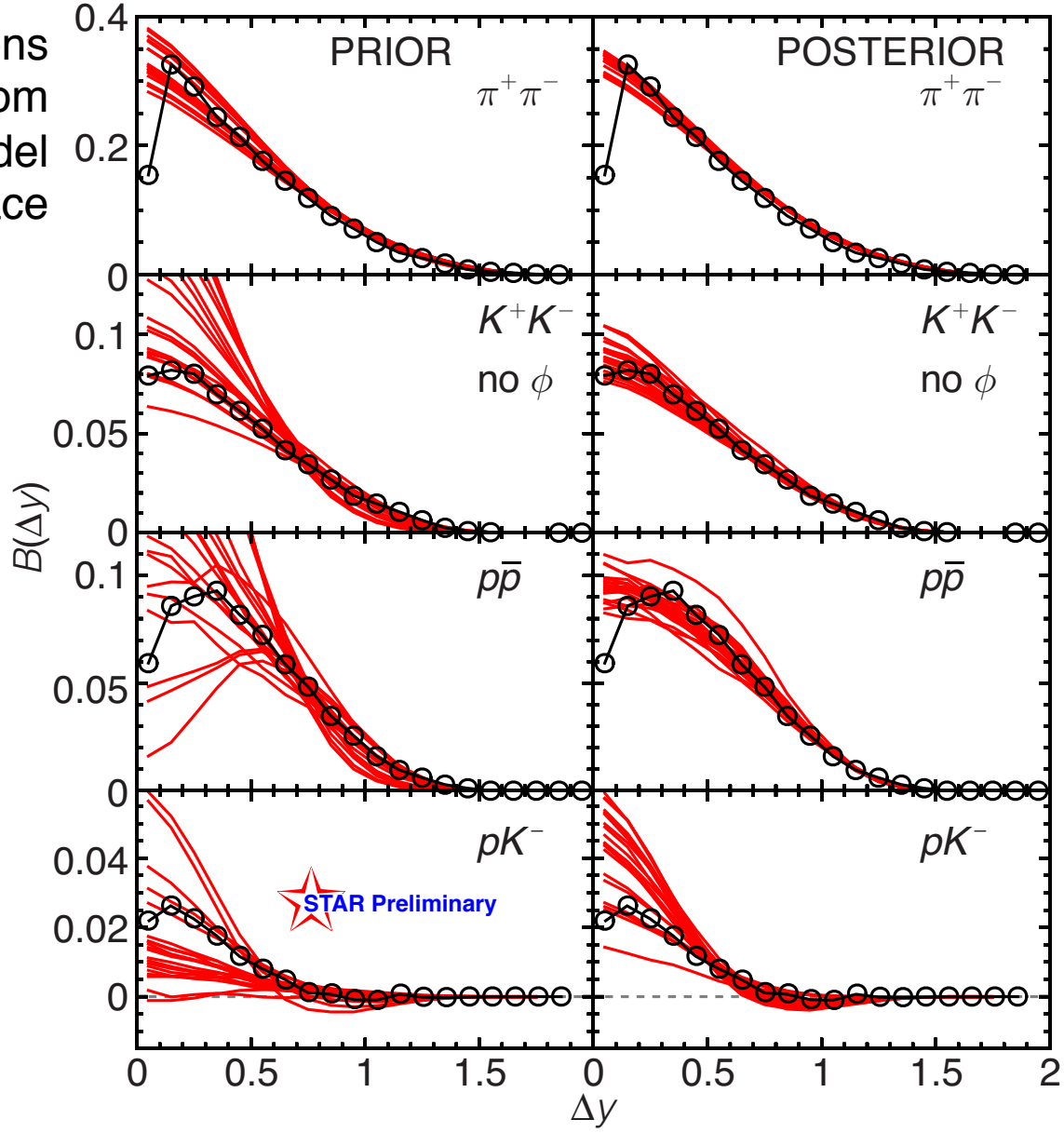
$B(\Delta y)$ 0-5%


200 GeV Au+Au
0-5%
STAR Preliminary
$\pi^+\pi^-$
K^+K^-
no ϕ
$p\bar{p}$
pK^-
$B(\Delta y)$
Δy

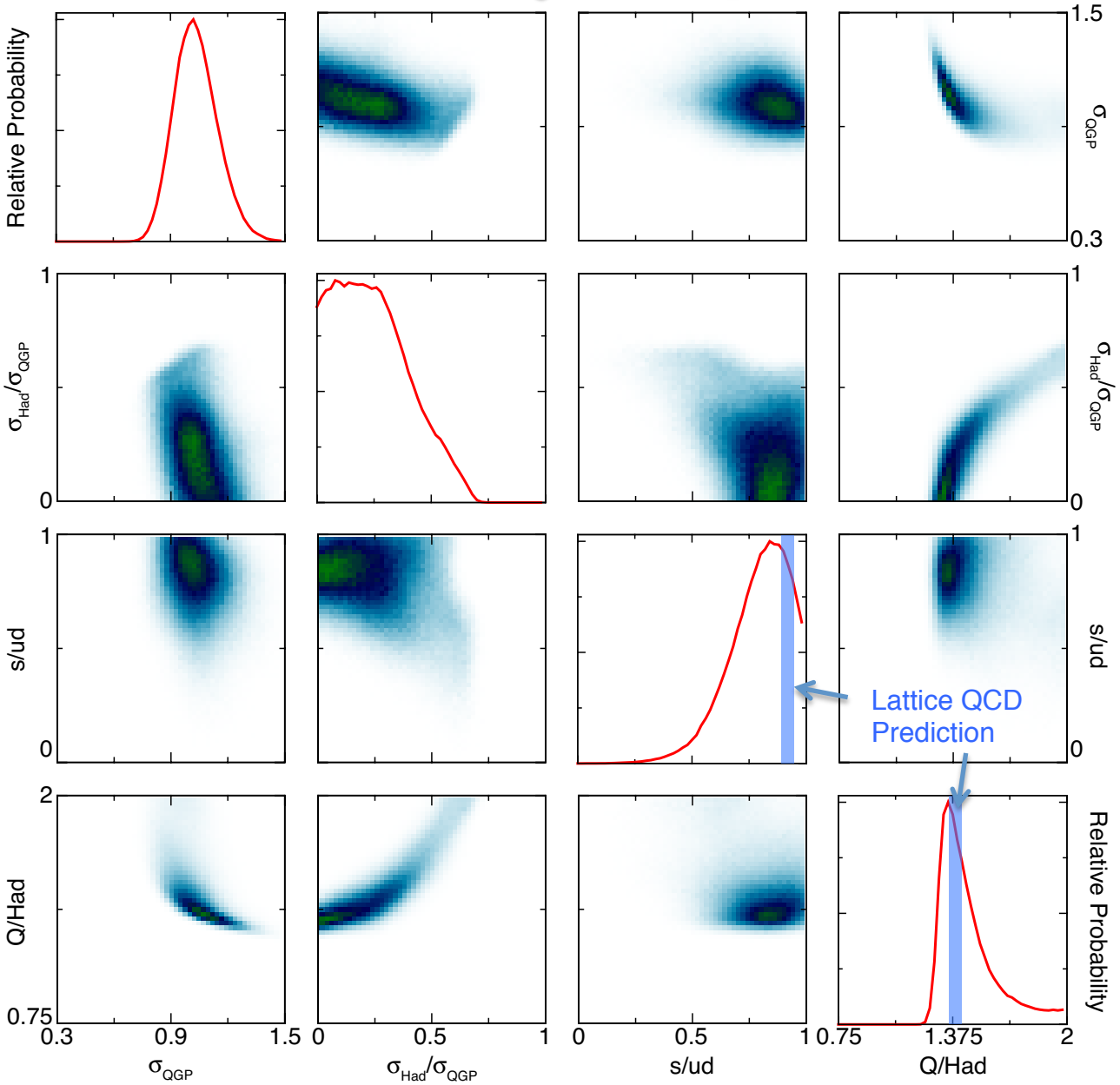
$B(\Delta y)$ Prior and Posterior

Model calculations sampled from complete model space



Model calculations after global minimization

Chemistry of QGP



Conclusions

- Balance functions in terms of $\Delta\eta$ narrow in central collisions and at high energies.
  - This is consistent with delayed hadronization.
- Comparison of Pratt's model [Scott Pratt, PoS(CPOD 2013) 023] to STAR data for balance functions for 0-5% Au+Au collisions at 200 GeV gives the results:
  - The ratio of strange quarks to up and down quarks $s/u = s/d = 0.75$,
  - Expected from LQCD: 0.9 – 0.95,
  - The ratio of the number of quarks in QGP to the number of final state hadrons Q/Had = 1.35,
  - Expected from LQCD: 1.4.
- This is the first time that the chemistry of the quark gluon plasma has been directly measured.