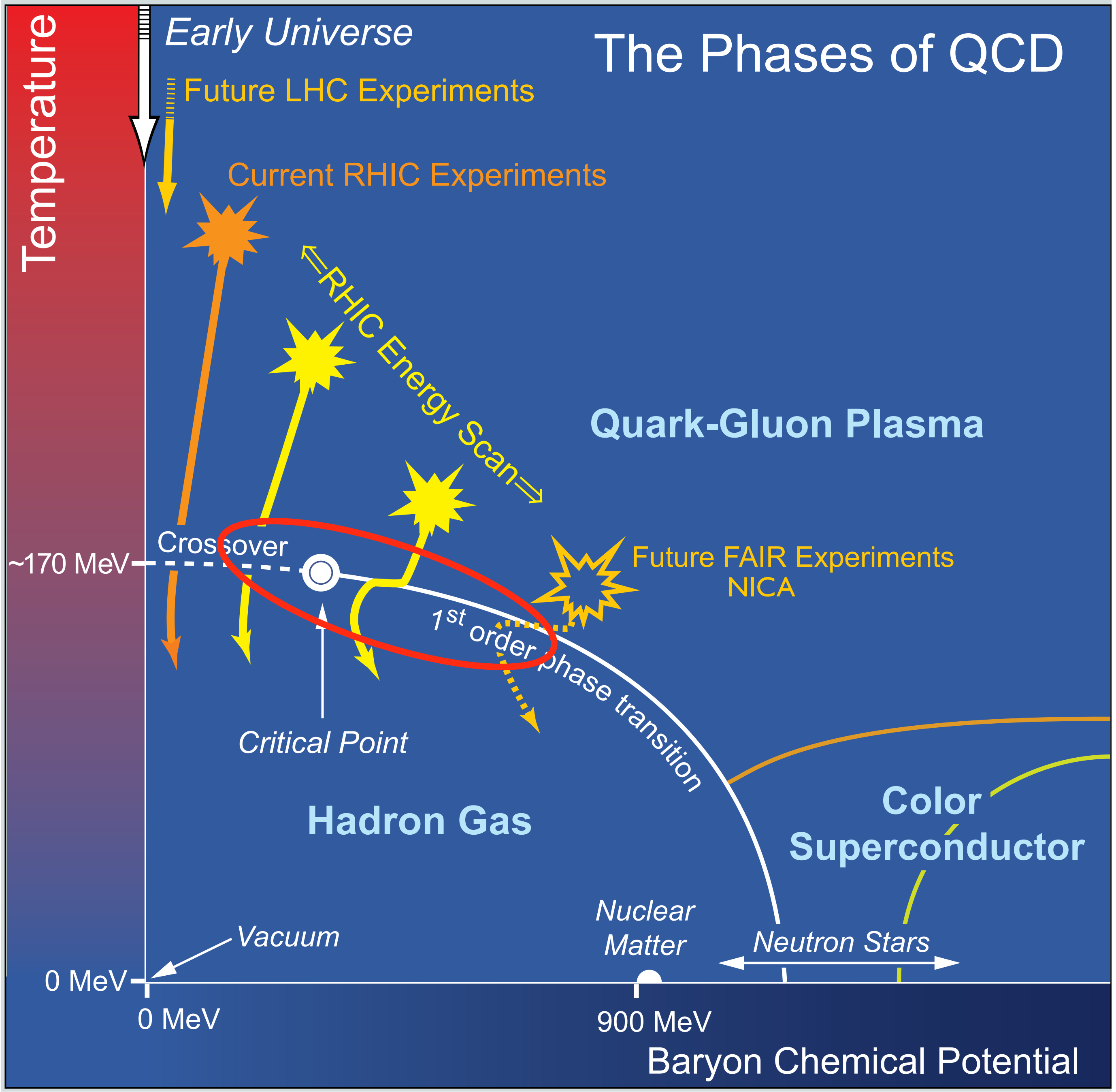
The STAR Beam Energy Scan (BES) Program

Michael K. Mitrovski
for the
STAR Collaboration

Outline

1. Introduction.
2. The STAR experiment.
3. Measurements used for an investigation into the onset of deconfinement and the nature of the phase transition
    a. Particle yields and spectra
    b. Azimuthal HBT and Anisotropic flow
    c. Event-by-Event fluctuations
4. Summary and Outlook.

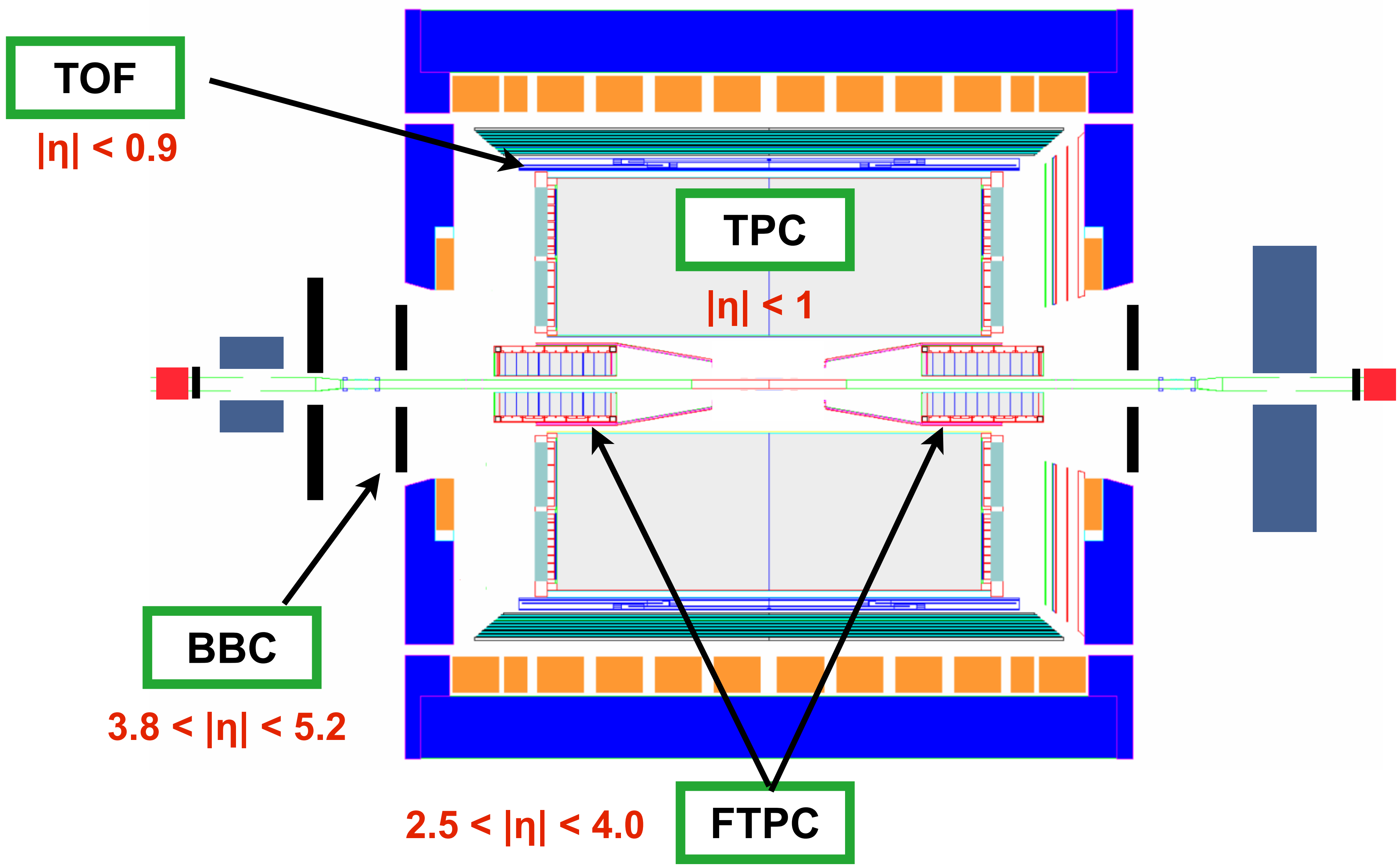
Phase Diagram of Strongly Interacting Matter



- The location for the onset of deconfinement and the critical point is theoretically not well constrained and in the BES program we are looking for signatures.
- Is a phase transition/critical point reflected in hadronic observables?
  - In order to search for the onset of deconfinement and the critical point RHIC started 2010 the „*Beam Energy Scan*“ (BES) program.
  - $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39 GeV
  - The BES program covers the region in the red circle

STAR Ref.: M. M. Aggarwal, arXiv: 1007.2613

The STAR Experiment



- TPC: Q, $\vec{x}$, $\vec{p}$, dE/dx
- TOF: time of flight

- $\pi^{\pm}$, $K^{\pm}$ and p : dE/dx in TPCs+TOF
- K^0_S, Λ, Ξ, Ω : decay topology + inv. mass. + dE/dx +TOF
- φ : inv. mass. + dE/dx + TOF

- Similar acceptance for all energies.

STAR Ref.: K. H. Ackermann et al.: NIM A 499 (2003) 624

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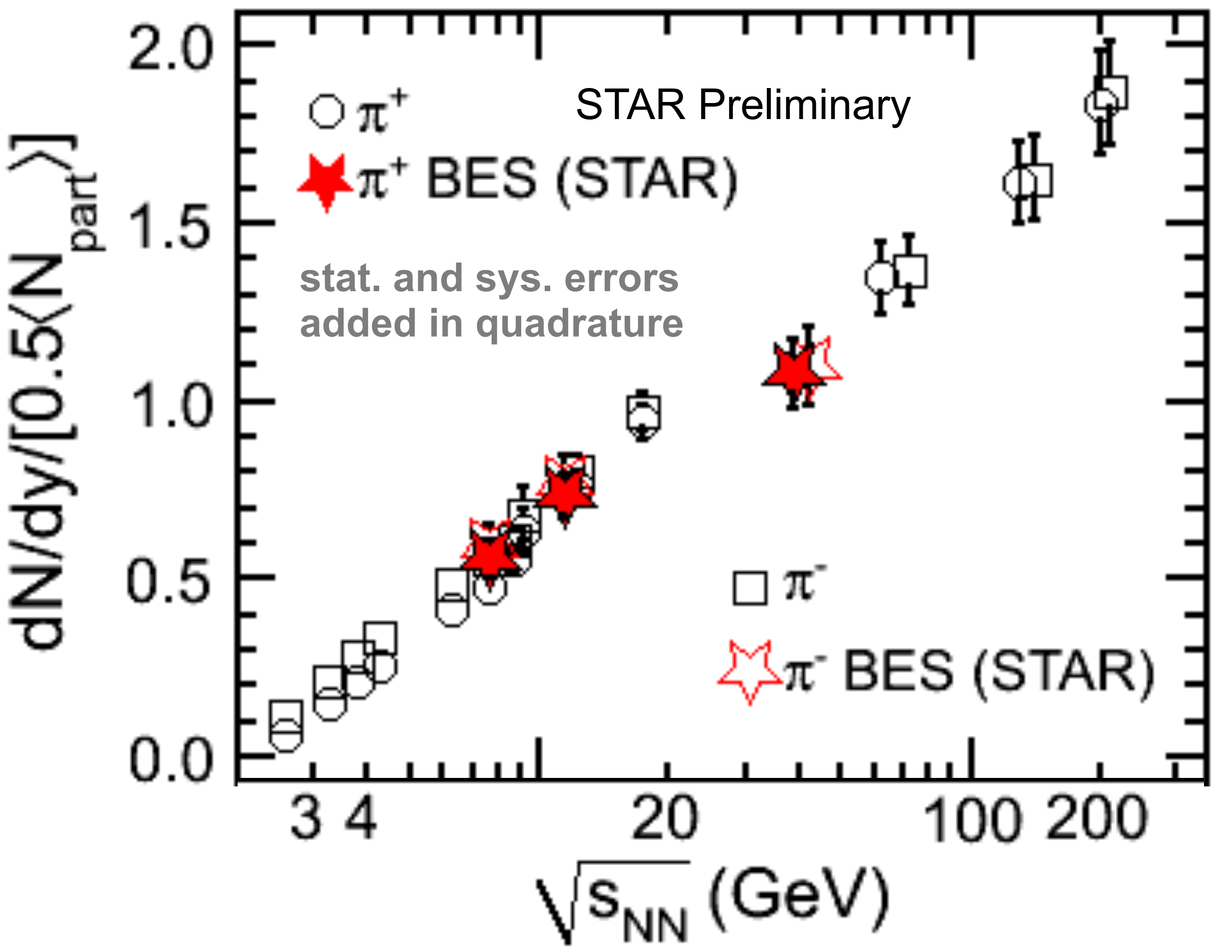
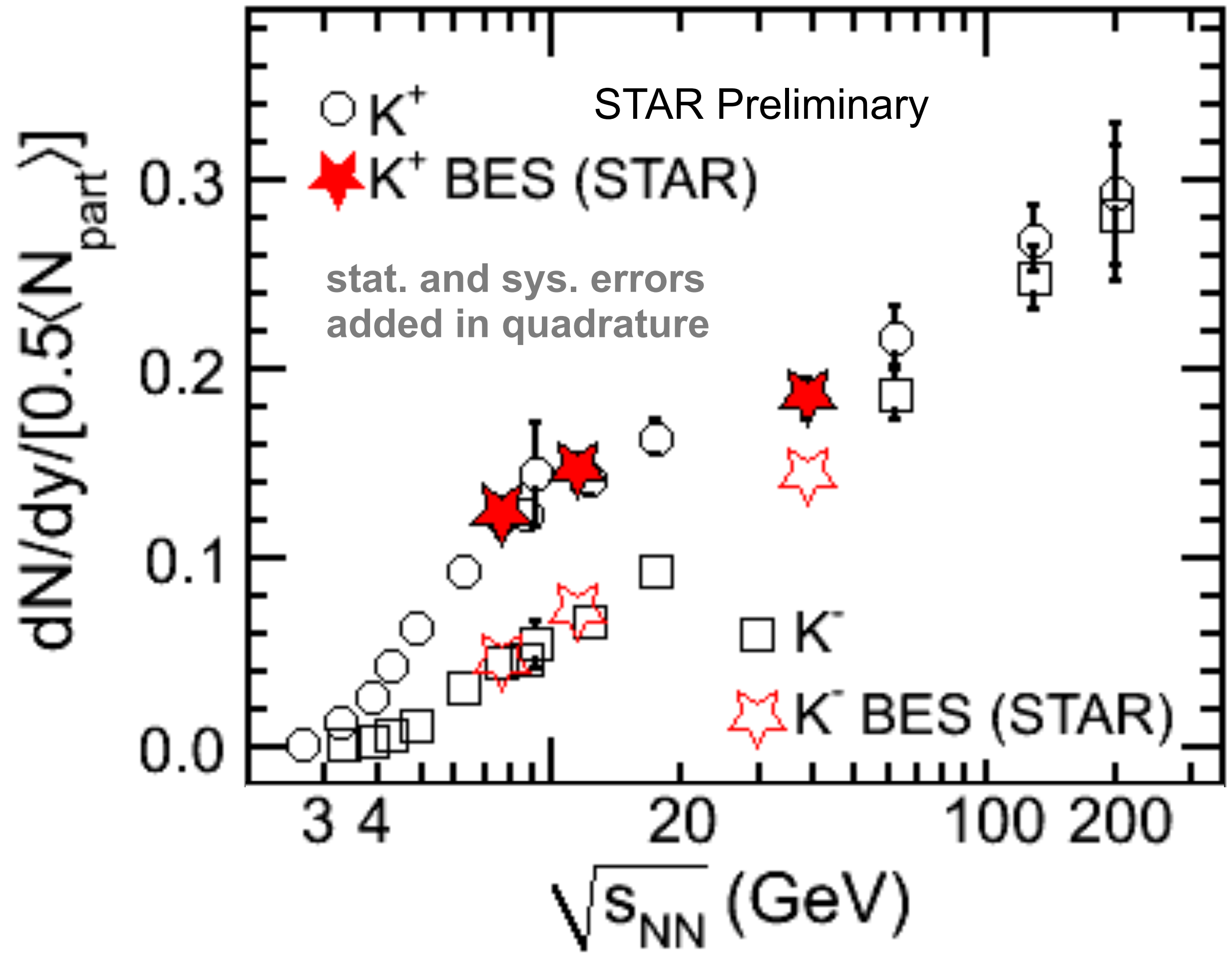
Midrapidity Yields vs. Energy

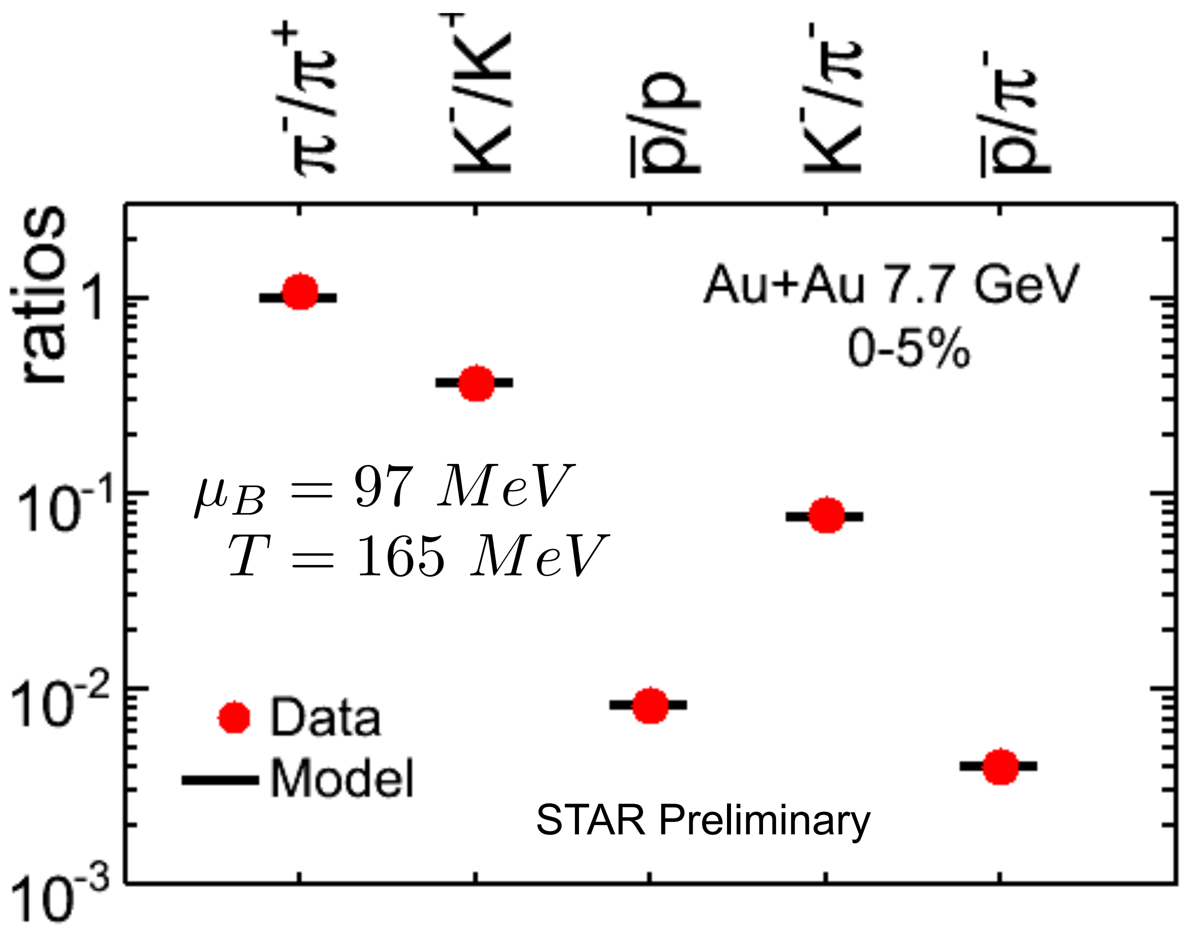


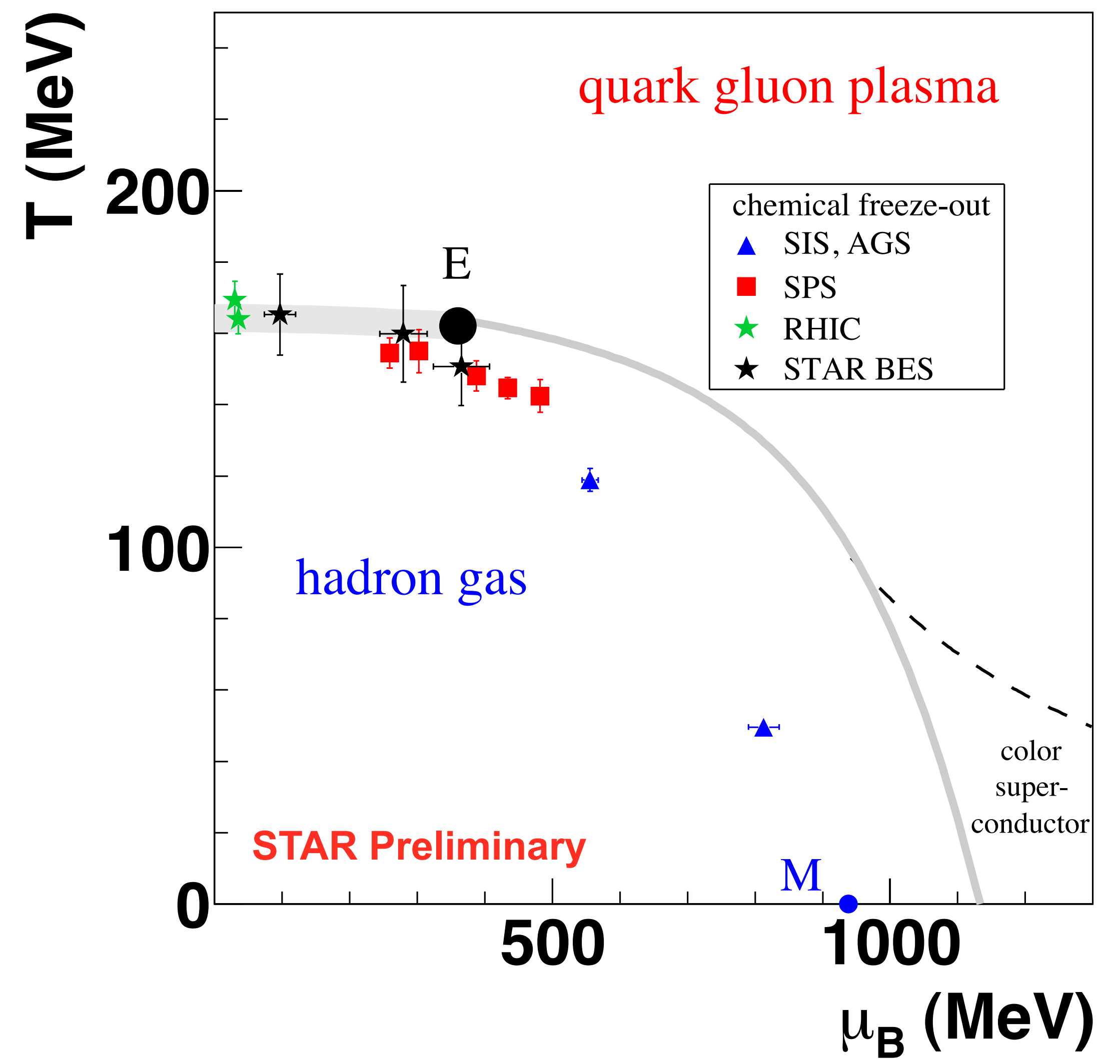


- **π yields consistent results with previous measurements from SPS (NA49).**
- **Monotonic energy dependence of π mid-rapidity yields with energy.**

- **K yields consistent results with previous measurements from SPS (NA49).**
- **Change of the energy dependence of K^+ yield between 7.7 and 11.5 GeV.**

Phase Diagram of Strongly Interacting Matter





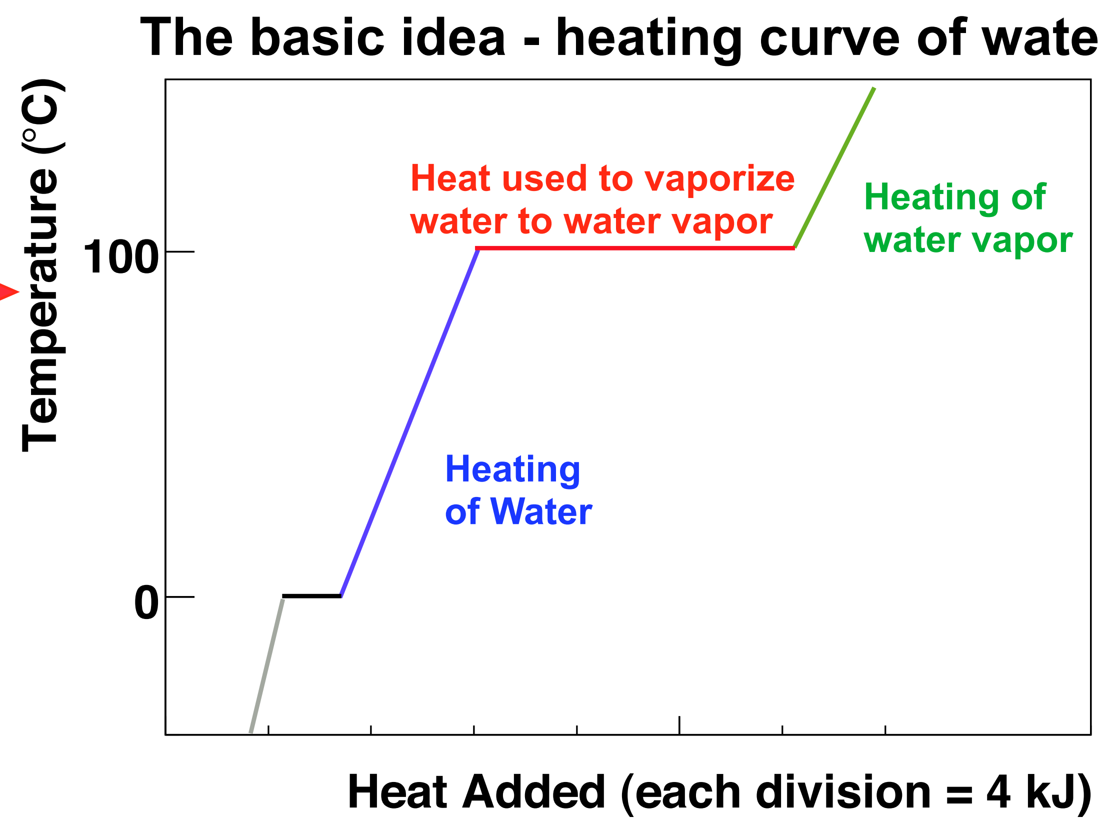
- **First results from the BES run using the statistical model.**
- **Extract chemical freeze-out parameters → phase diagram.**
  - **Note p and p̄ are not corrected for feed-down**
- **Chemical freeze-out points approach the predicted phase boundary at top SPS energies.**
- **Look for signatures for the onset of deconfinement and the critical point.**

STAR Ref.: B. I. Abelev et al., PRC79 (2009) 034909 and ref. therein

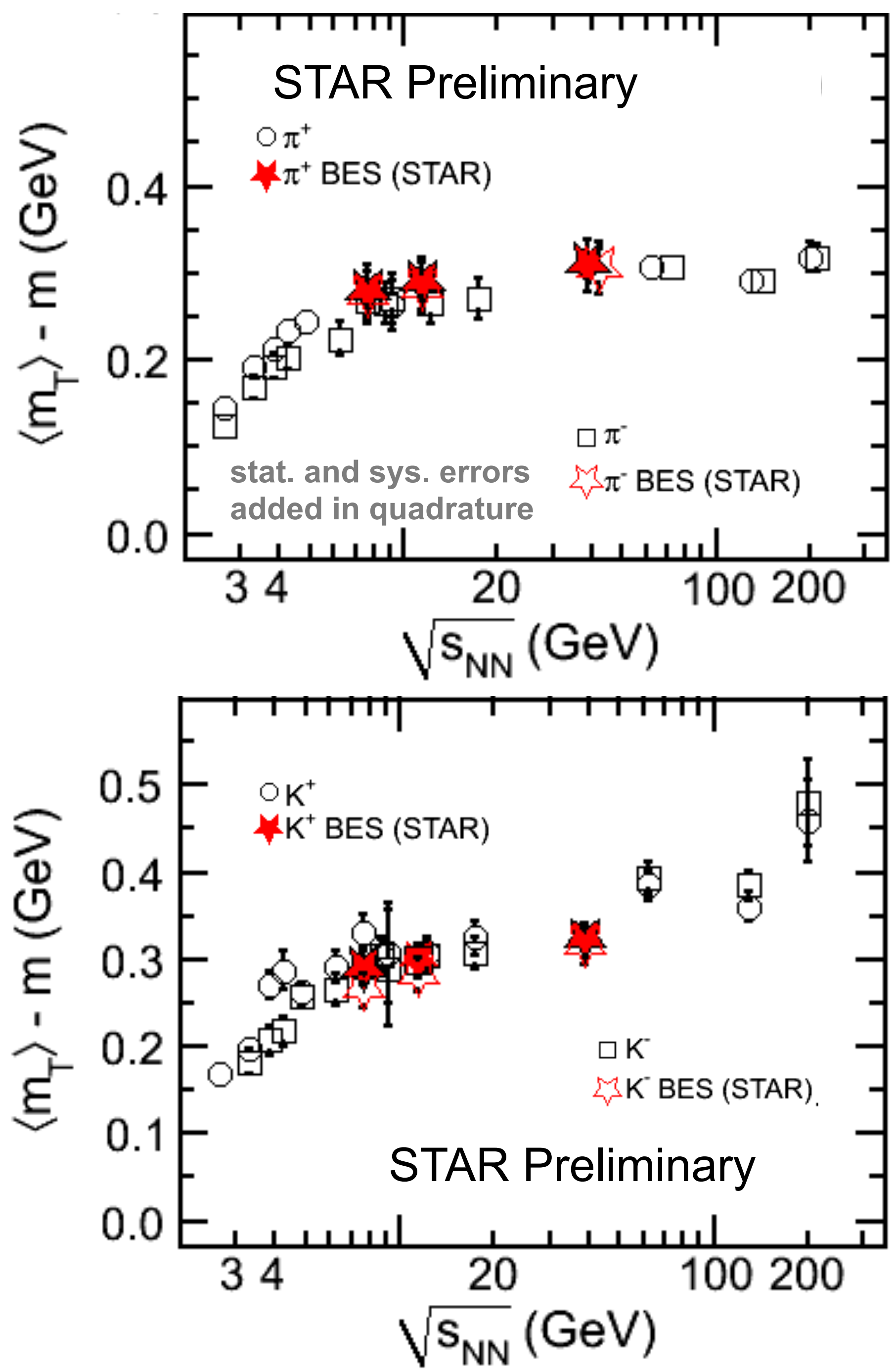
Becattini et al.:PRC73 (2006) 044905
R. Stock et al., arXiv:0911.5705
Critial Point and crossover from Lattice-QCD:
Fodor et al.:JHEP 0404 (2004) 050

$\langle m_t \rangle - m_0$

Hadronic observable



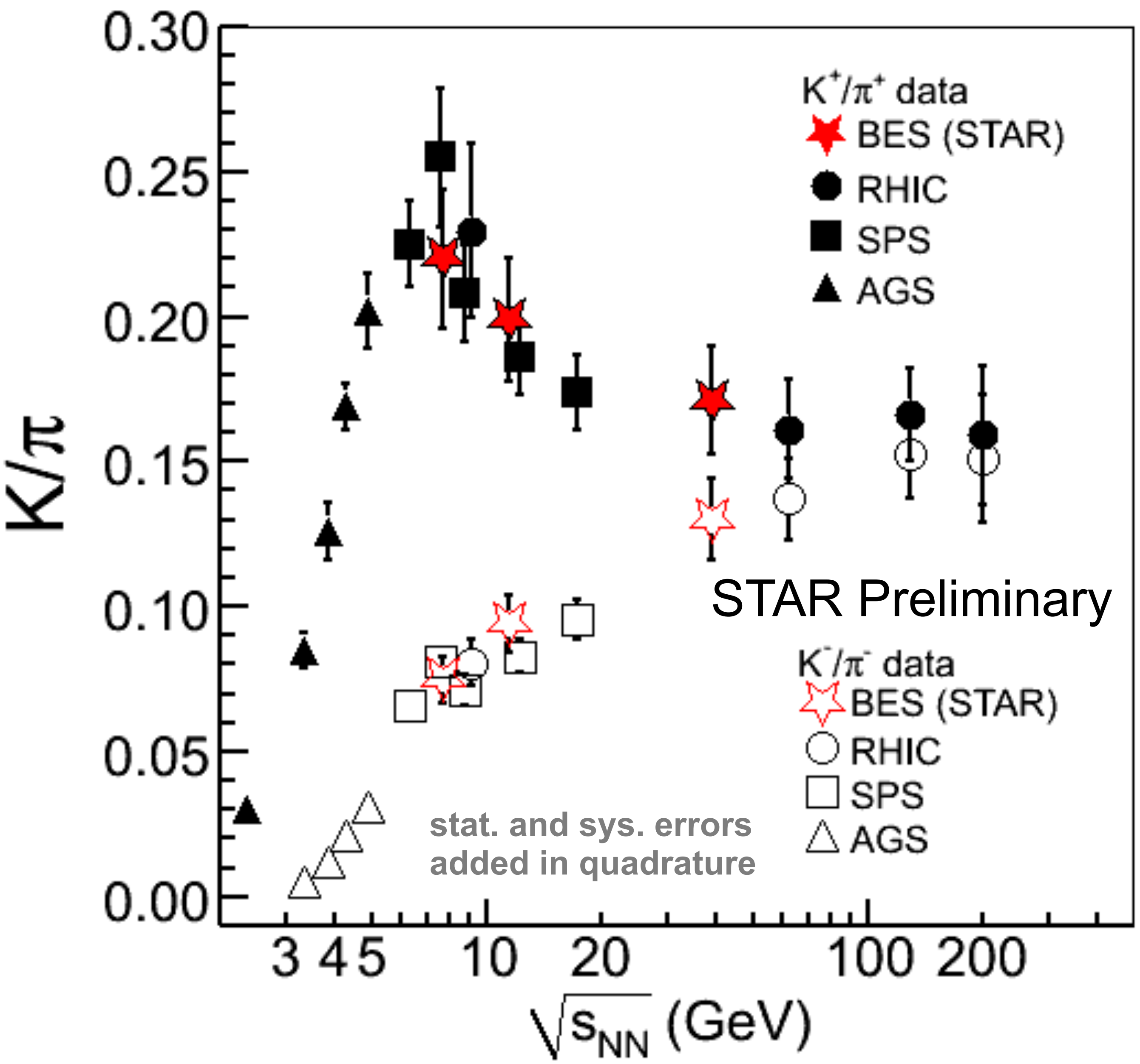
Collision energy



- Good agreement to previous measurements at SPS
- $\langle m_T \rangle$-m is constant for BES energies.

→ Signature of change of EoS due to phase transition?

K/π Ratio



- Non-monotonic structure in K^+/π^+ ratio visible.
- K^-/π^- increases with energy.

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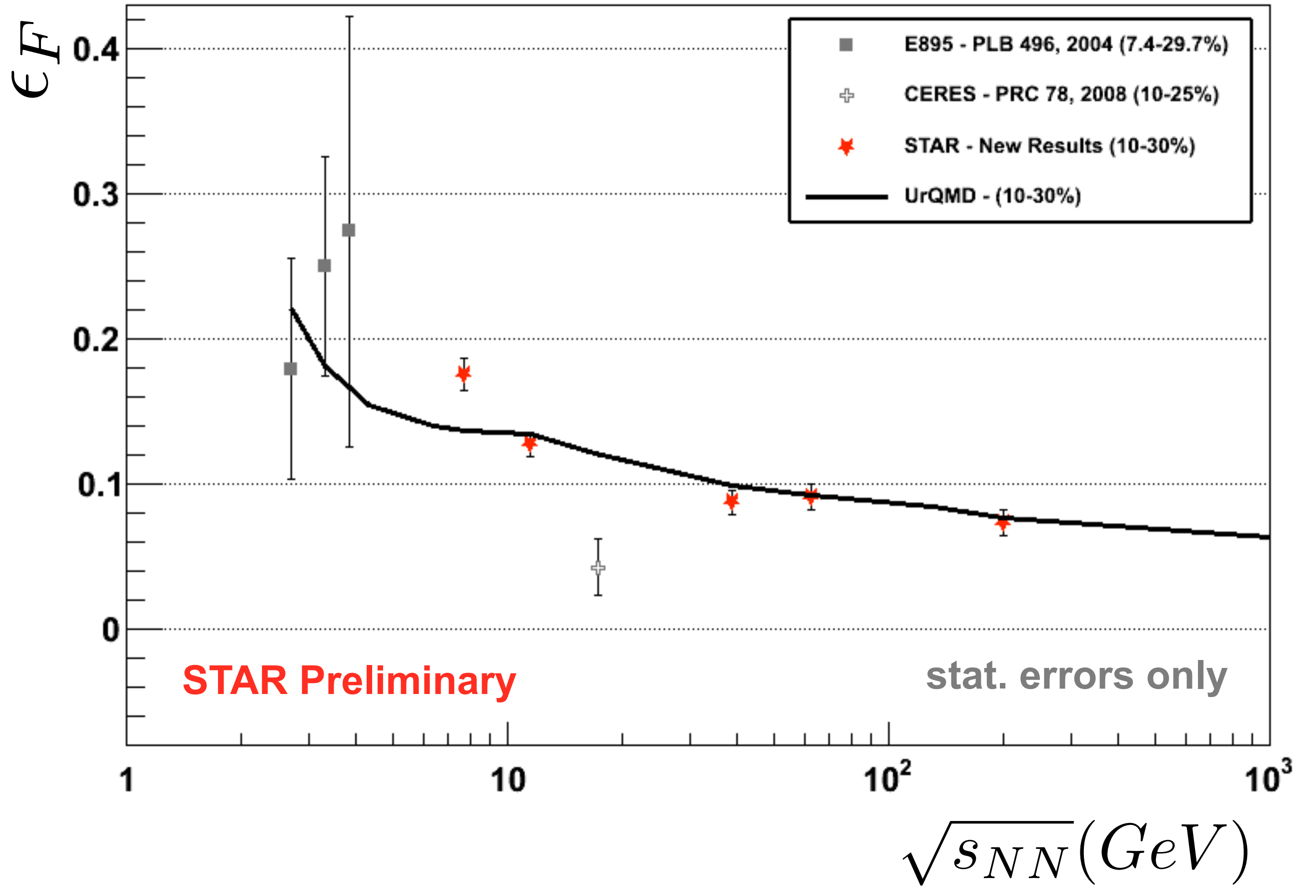
Softening of the EOS
Azimuthal HBT



- Initial out-of-plane eccentricity.
- Stronger in-plane pressure gradient drives preferential in-plane expansion.
- Longer lifetime or stronger pressure gradients (energy density) and c_s^2 cause more expansion and more spherical freeze-out shape.
- Measuring the eccentricity at freeze-out ε_F using azimuthal HBT:

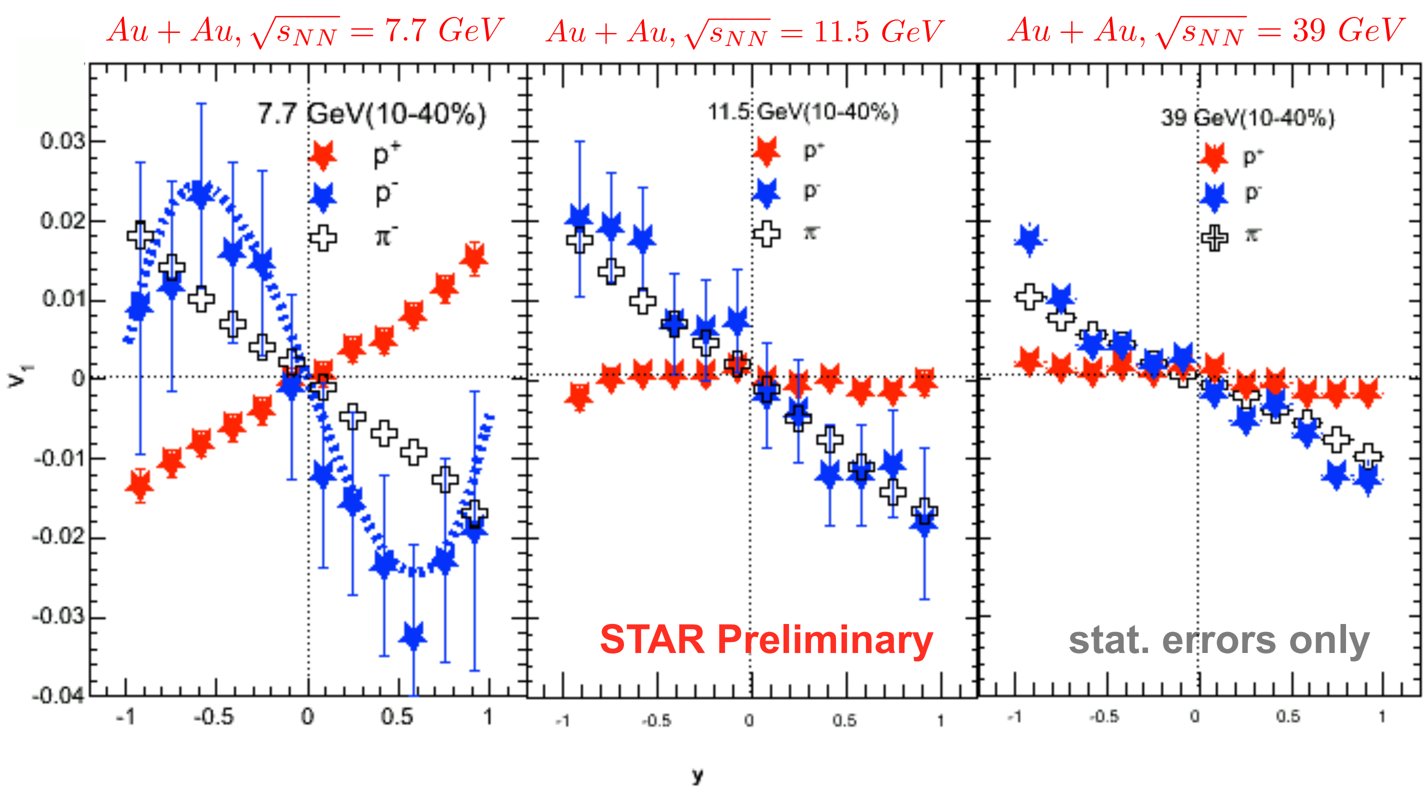
$$\epsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \approx 2\frac{R_{2,s}^2}{R_{0,s}^2}$$

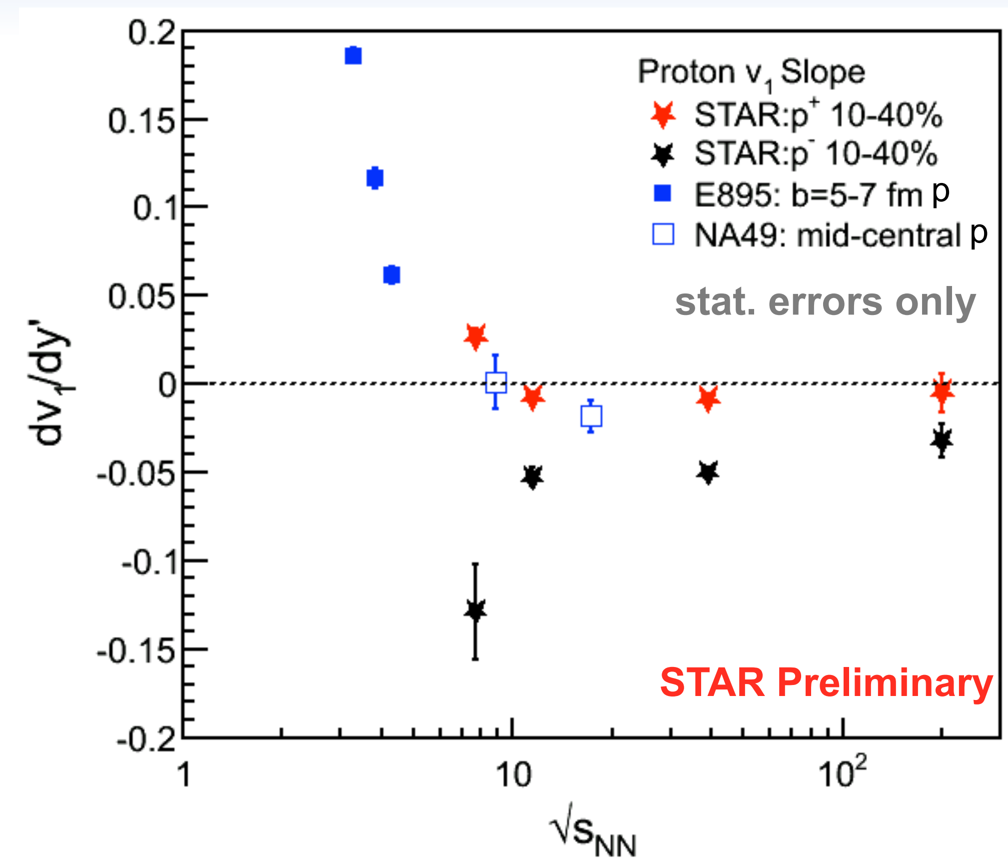
- STAR results alone are consistent with a monotonic decrease in the freeze-out eccentricity with increasing collision energy.
- STAR collected additional data at 19.6 and 27 GeV in Run11 to constrain the minimum between 11.5 and 39 GeV.
- UrQMD reproduce the general trend.
- Softening of the EOS?

E895 Ref.: M. A. Lisa et al., PLB496 (2000) 1
CERES Ref.: D. Adamova et al., PRC78 (2008) 064901
M. A. Lisa, E. Frodermann, G. Graef, M. Mitrovski, E. Mount, H. Petersen, M. Bleicher et al., NJP13 (2011) 065006

STAR Ref.: J. Adams et al., PRL93 (2004) 012301

Softening of the EOS
Directed flow v_1





- v_1 probes the early stage of the collision.
- Proton v_1 slope at midrapidity shows a change of sign.
- Difference between protons and anti-protons.

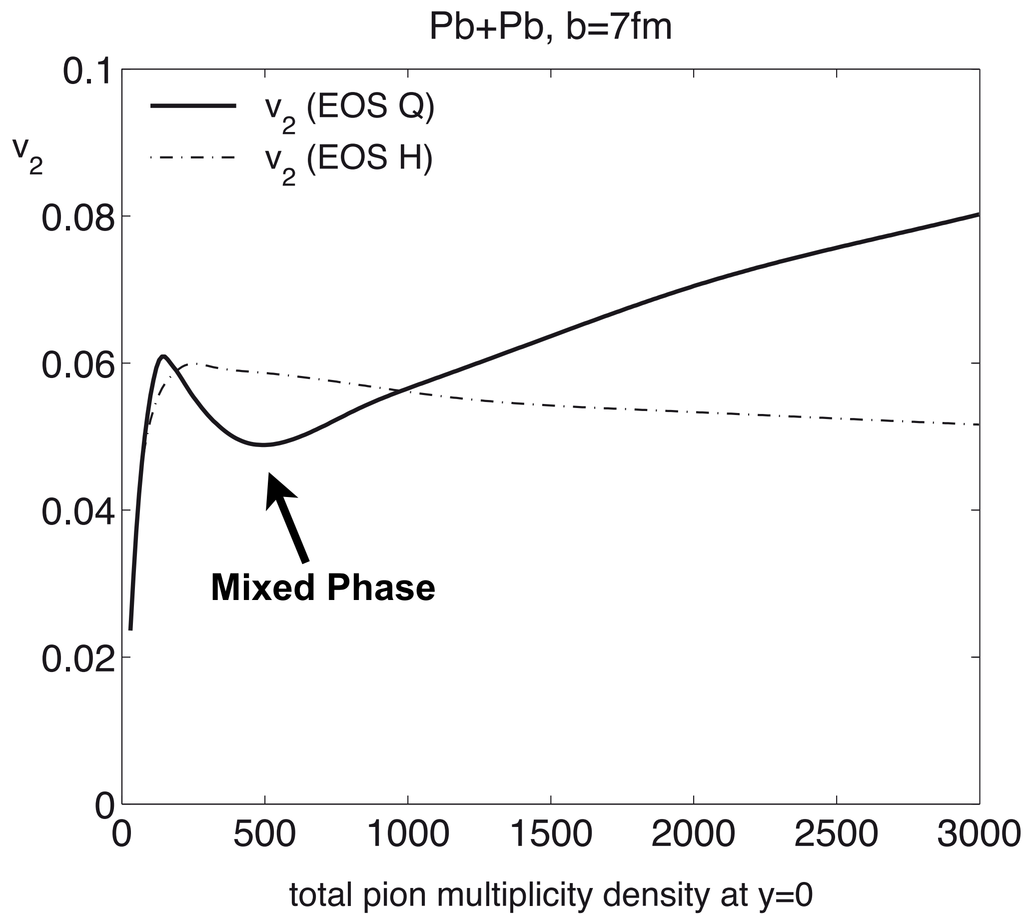
- STAR will constrain the minimum between 11.5 and 39 GeV with additional taken data at 19.6 and 27 GeV.

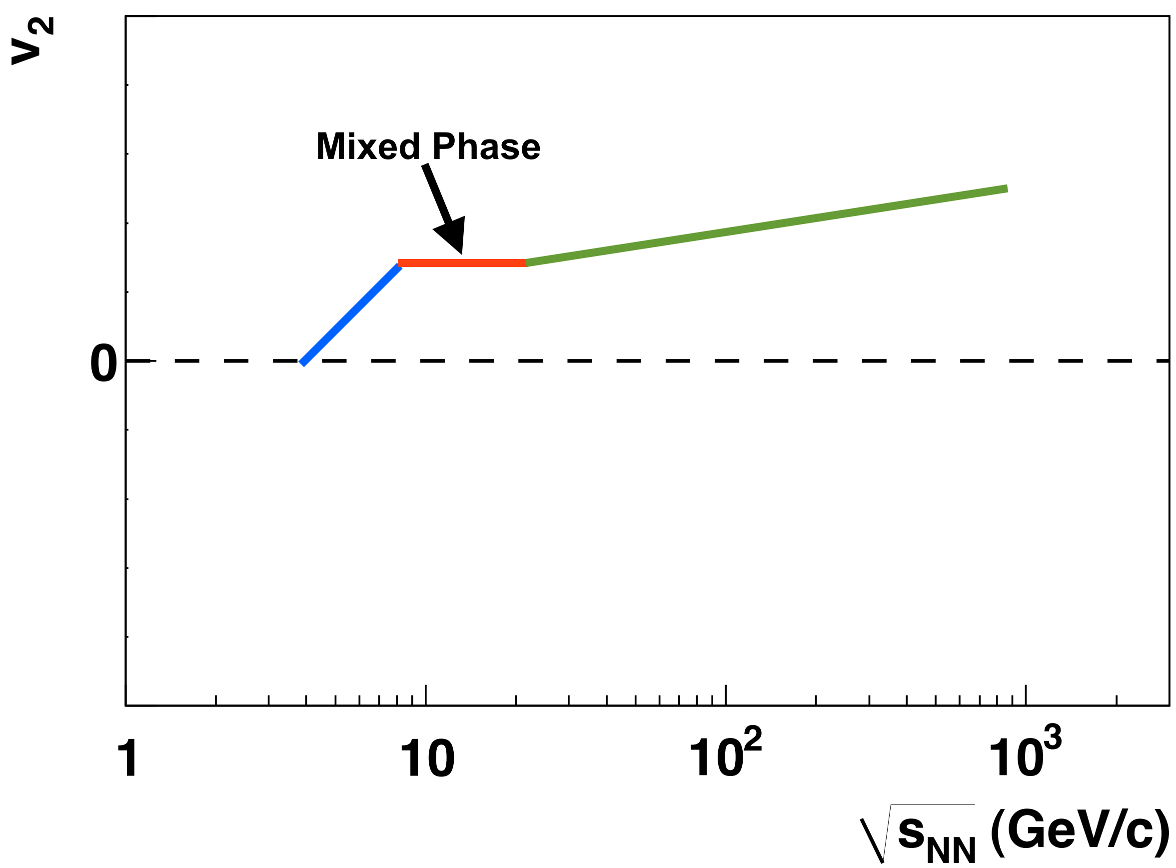
Possible scenarios:

- Sensitivity due to a 1st order phase transition?
  - Could lead to a event shape tilted w.r.t. beam axis (bounce off)
- Wiggle and negative slope results from positive space momentum correlations + baryon stopping.

E895 Ref.: H. Liu et al., PRL84 (2000) 5488
NA49 Ref.: C. Alt et al., PRC68 (2003) 034903
R. Snellings: PRL84 (2000) 2803
J. Cserna and D. Rohrich: PLB458 (1999) 454
J. Brachmann et al.: PRC61 (2000) 024909

Softening of the EOS
Elliptic flow v_2



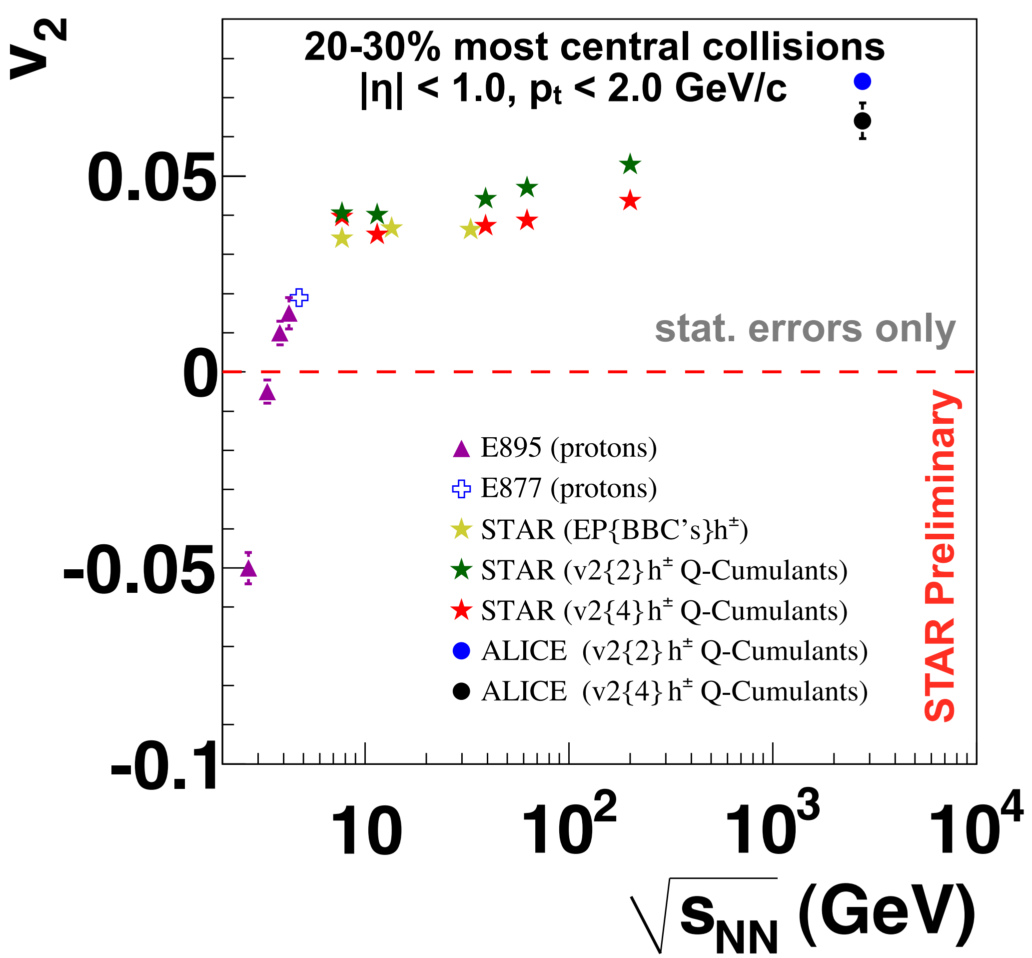


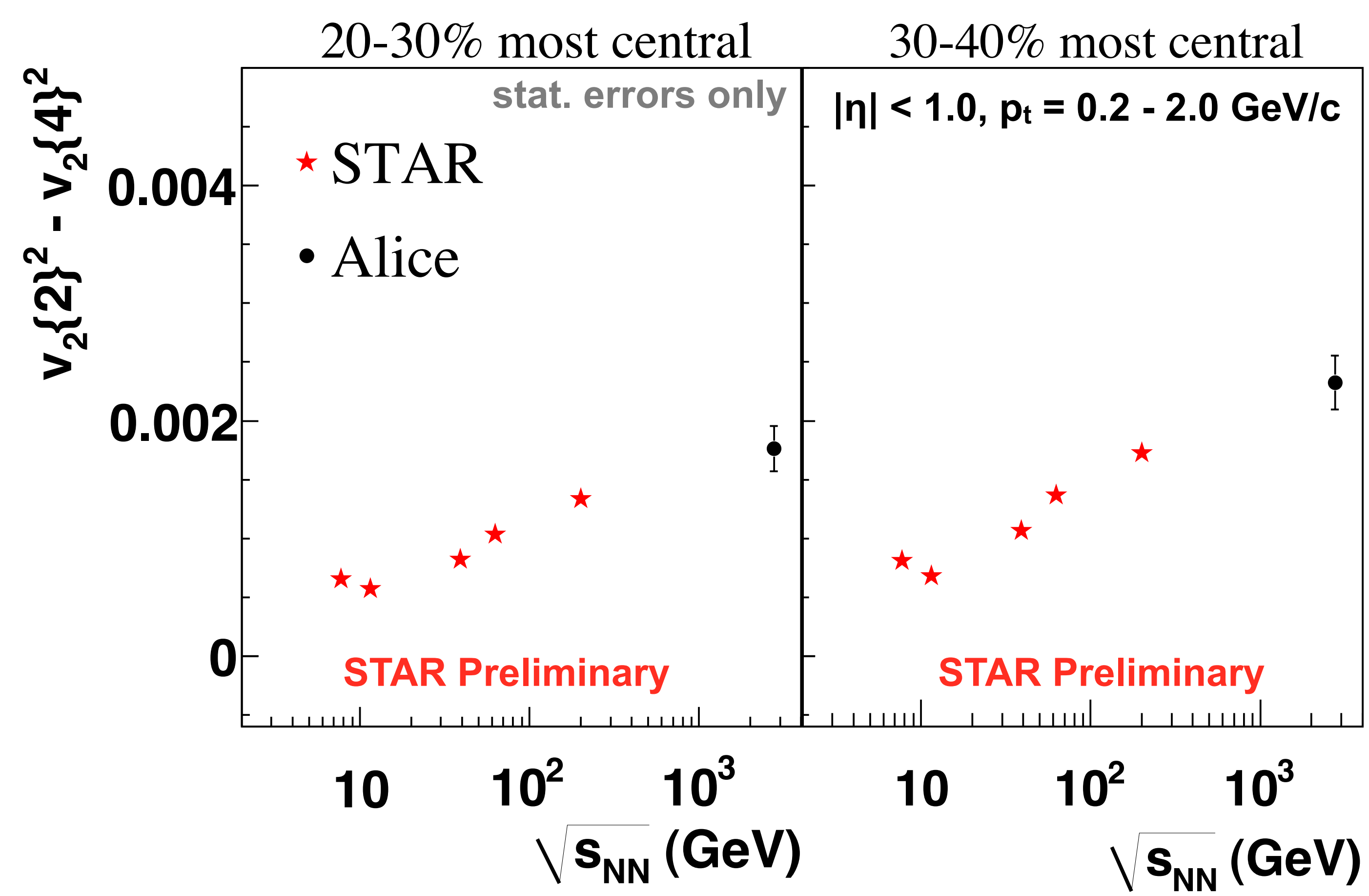
- **Hydro calculation shows a minimum for the elliptic flow when passing through a change of the EOS from hadronic matter to quark-gluon plasma.**

- **Another alternative is that a flattening is observed when we have a change of the EOS.**

Kolb et al.:PRC62 (2000) 054909

Softening of the EOS
Integrated elliptic flow v_2 and Non-Flow





- Additional data at 19.6 and 27 GeV will help to see a possible minimum or plateau for charged hadron v_2.

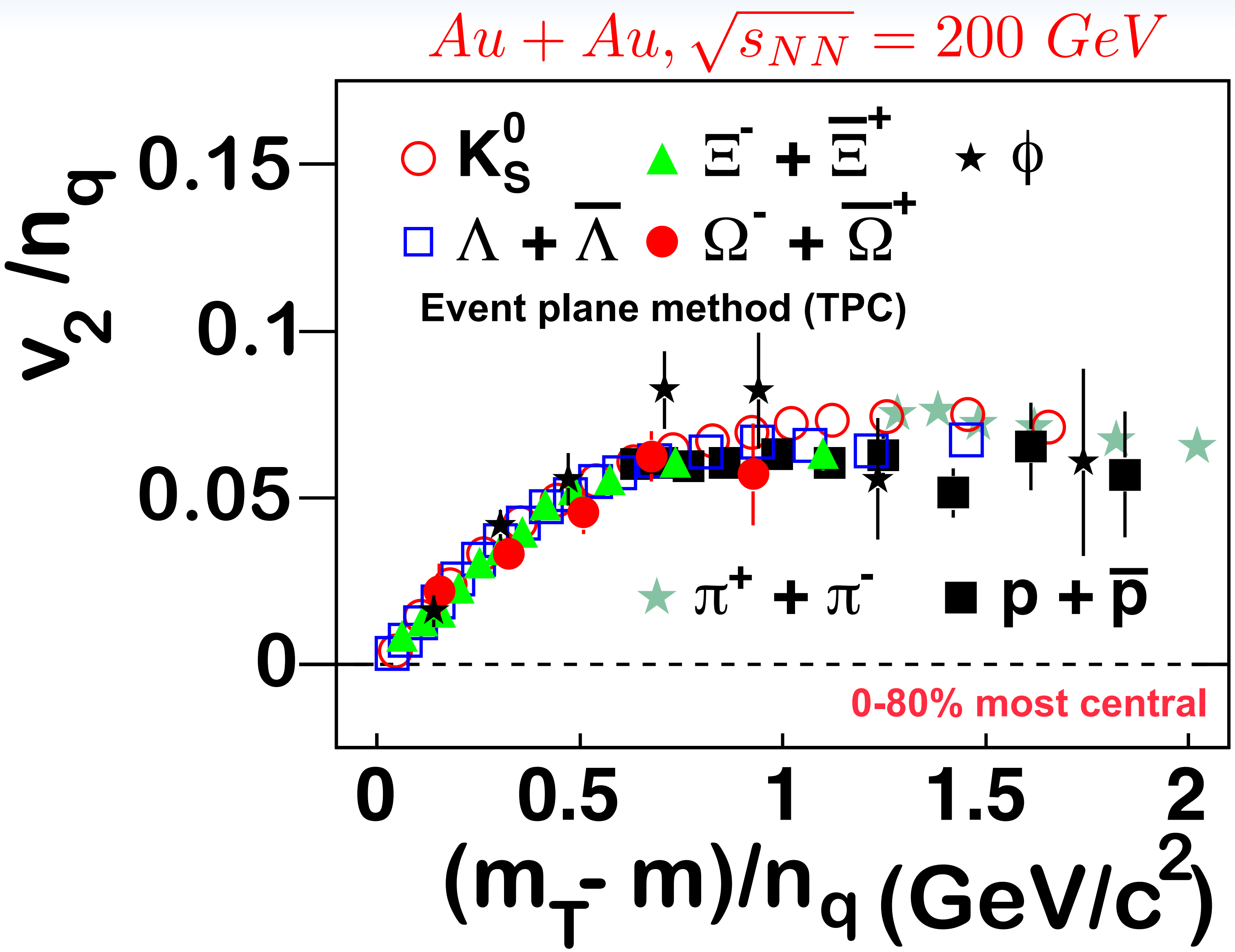
→ **Signature of change of EoS due to phase transition?**

- $v_2\{2\}^2 - v_2\{4\}^2 \approx \delta_2 + 2\sigma_{v2}^2$ shows also an interesting energy dependence
  - increase in conversion of initial anisotropy into momentum space?

S. A. Voloshin, A. M. Poskanzer, and R. Snellings, Landolt-Boernstein, Relativistic Heavy Ion Physics Vol. 1/23 (Springer-Verlag, Berlin, 2010), pp 5-54

J. Y. Ollitrault, A. M. Poskanzer and S. A. Voloshin, PRC80 (2009) 014904
P. Sorensen for the STAR Collaboration, JPG35 (2008) 104102
ALICE Ref.: K. Aamodt et al., PRL 105 (2010) 252302

Partonic Collectivity

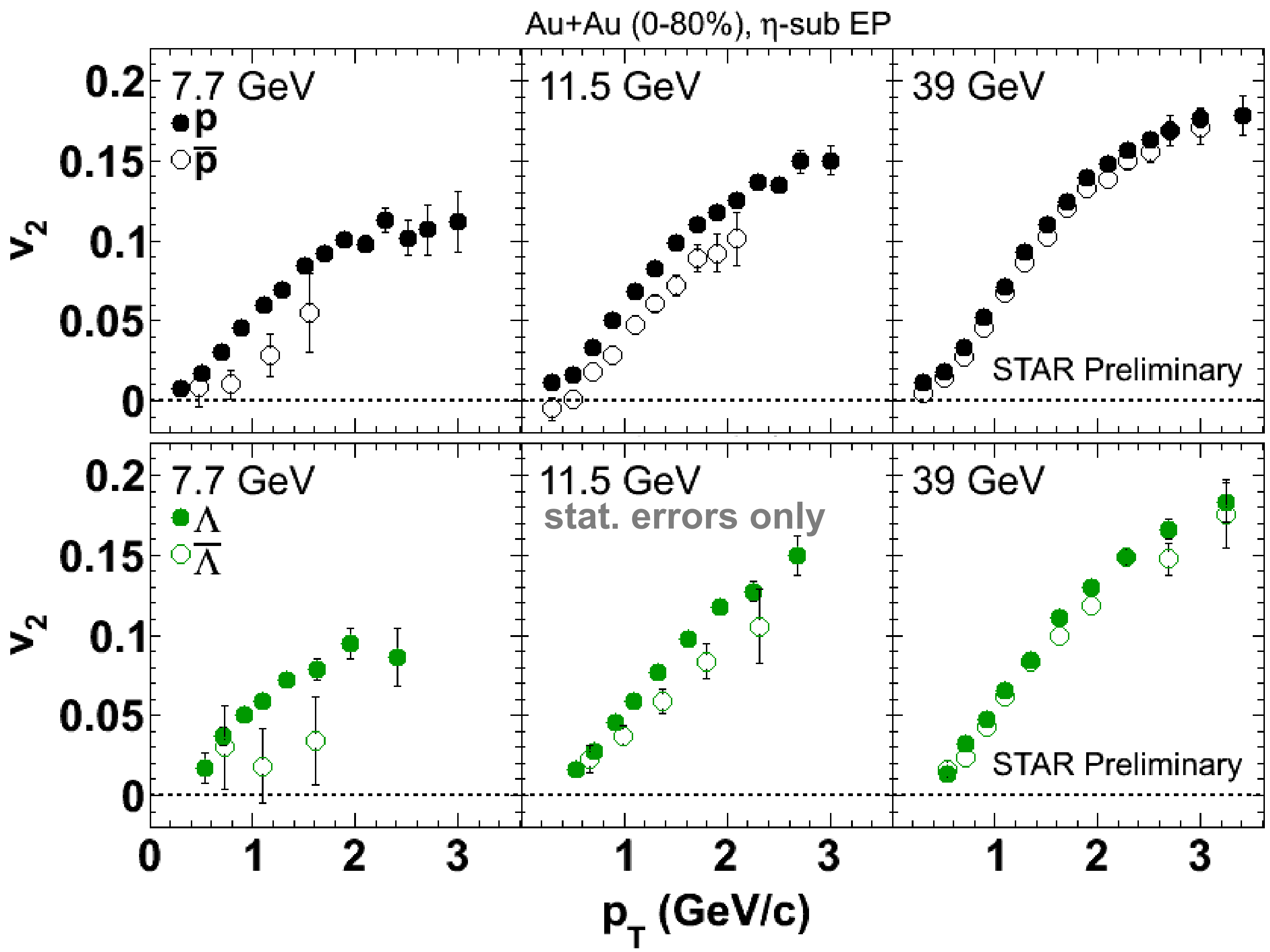


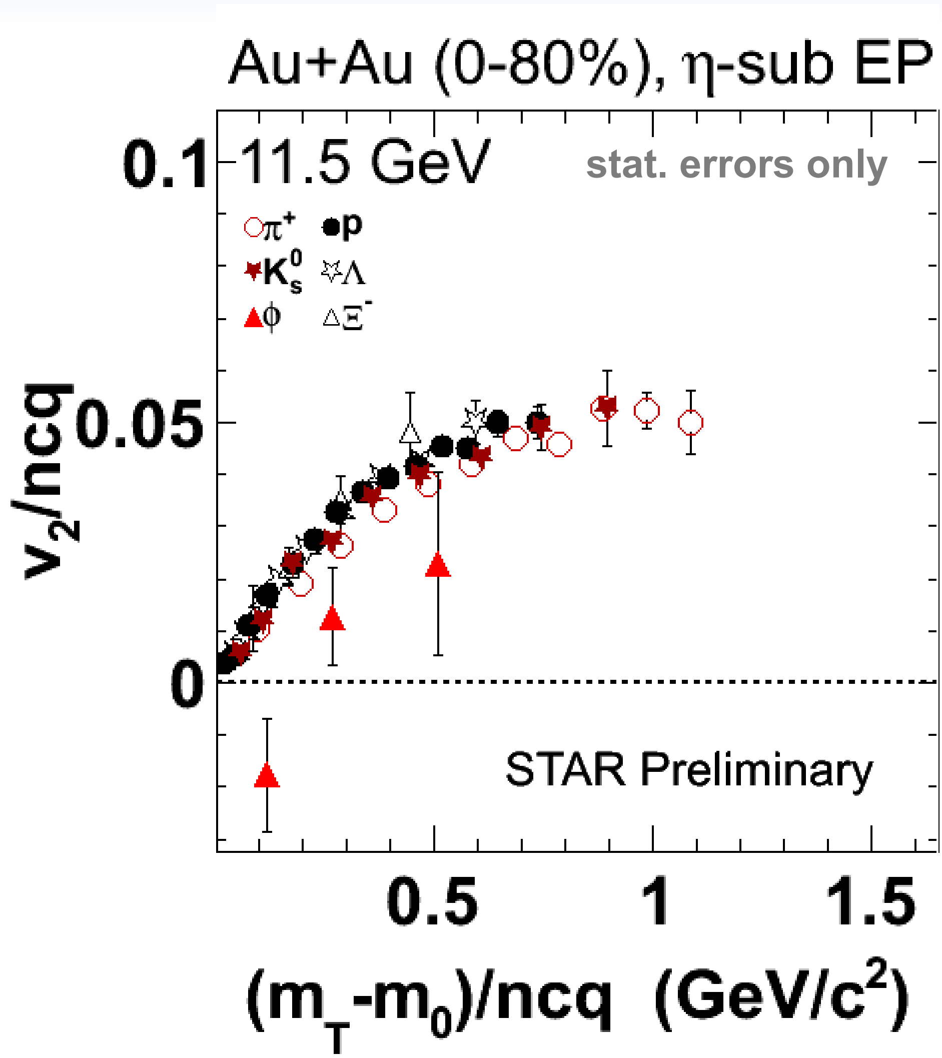
- v_2 of light and multi-strange hadrons are scaling by the number of constituent quarks.

  ⇒ also visible for Φ and Ω which indicates that the collectivity develops at the partonic level

STAR Ref.: B. I. Abelev et al.: PRC 77 (2008) 054901

Partonic Collectivity





- Difference between particle and anti-particle v_2 gets larger when decreasing collision energies.
- NCQ scaling seems to be broken between particles and anti-particles at lower energies.
- Difference between baryon and anti-baryon due to
  - Baryon transport to midrapidity?
  - Absorption in hadronic medium?

- Φ-Meson does not follow the trend of other mesons with a mean deviation of 2.6 σ and measurements at intermediate p_t is needed to draw an overall conclusion.

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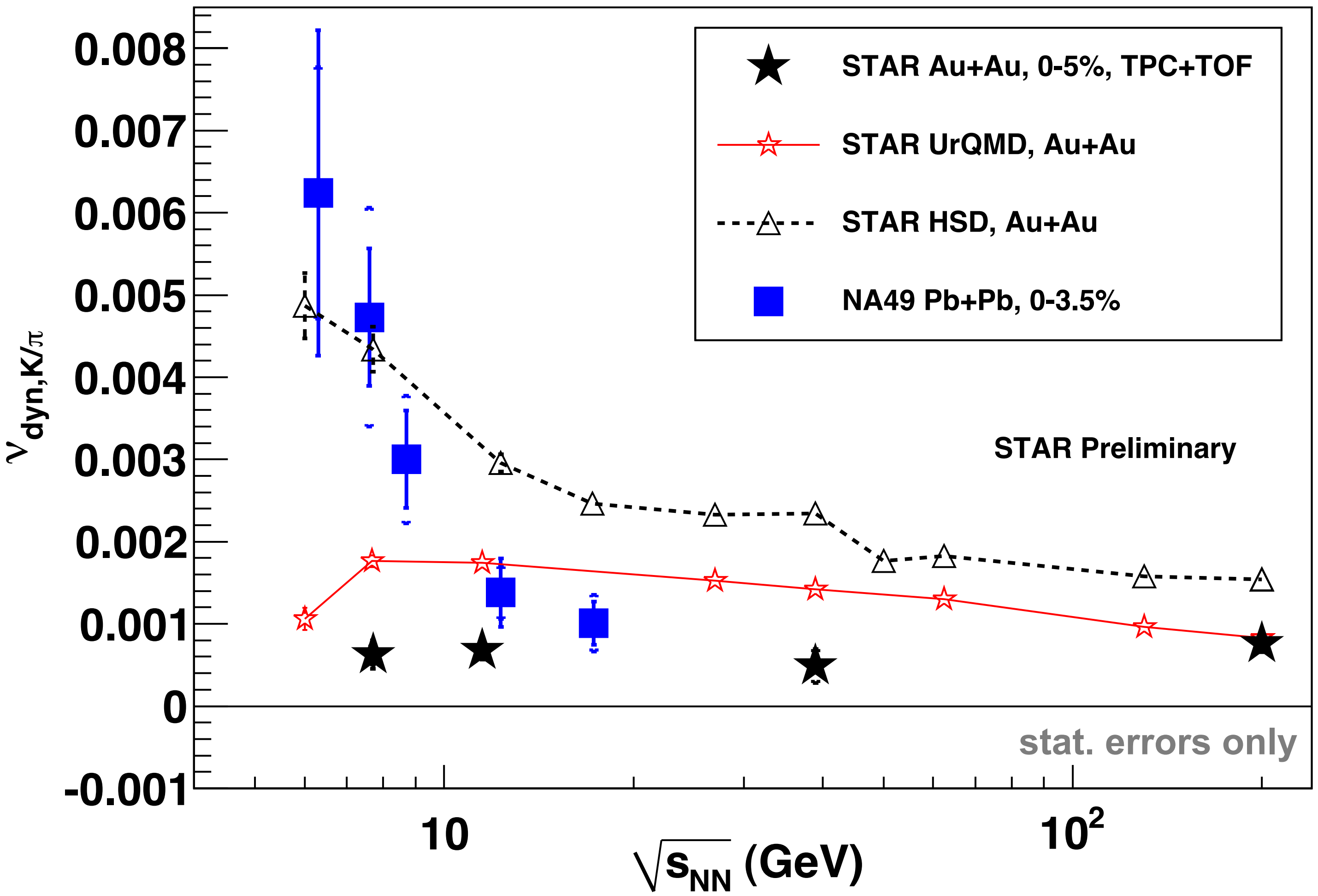


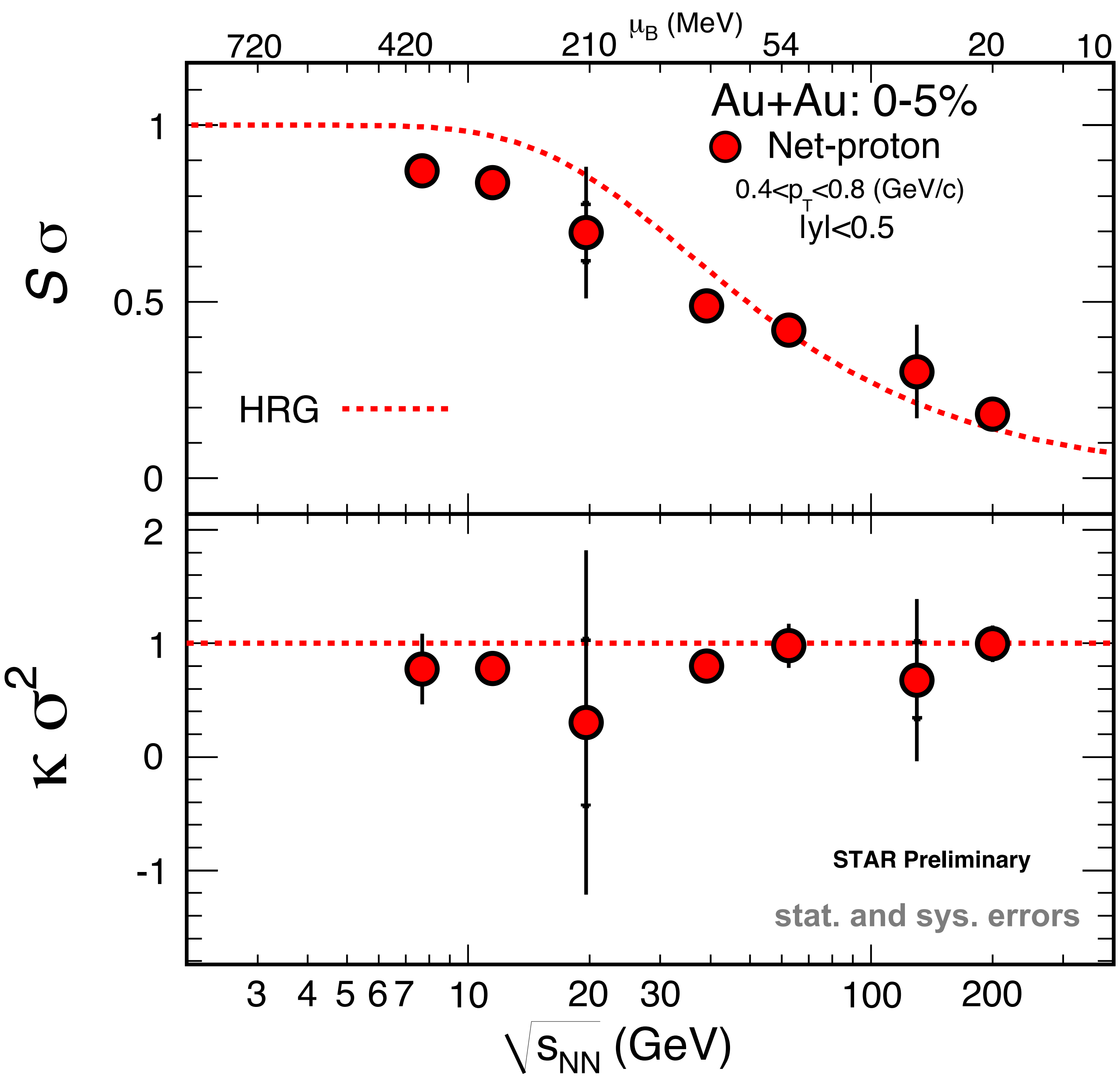
- No variation from 7.7 GeV to top RHIC energies.
- Deviation between NA49 and STAR at 7.7 GeV.
- Difference between NA49 and STAR could have different reasons, e.g.: different PID selection and/or acceptance (Physics maybe changes with acceptance) (still under discussion).
- UrQMD overpredicts the STAR measurements at all energies except 200 GeV, but under-predicts the measurements from NA49 at low energies.
- HSD overpredicts the measurements from STAR but catches the trend from NA49.

NA49 Ref.: C. Alt et al., PRC79 (2009) 044910

NA49: $\sigma_{dyn} = sign\left(\sigma^2_{data} - \sigma^2_{mix}\right)\sqrt{\left|\sigma^2_{data} - \sigma^2_{mix}\right|}$, relative width σ = *RMS* / *Mean* x 100 [%]

STAR: $\nu_{dyn,P_1/P_2} = \frac{\langle N_{P_1}(N_{P_1}-1)\rangle}{\langle N_{P_1}\rangle^2} + \frac{\langle N_{P_2}(N_{P_2}-1)\rangle}{\langle N_{P_2}\rangle^2} - \frac{\langle N_{P_1}N_{P_2}\rangle}{\langle N_{P_1}\rangle\langle N_{P_2}\rangle}$, $\sigma^2_{dyn} \approx \nu_{dyn}$

Higher Moments: Net-Proton Kurtosis



- **Critical point effect**
  - **Higher moments are more sensitive to diverging sigma field:**

    $\langle N^2 \rangle \approx \xi^2, \ \langle N^4 \rangle \approx \xi^7$

  - **Divergence should be reflected in net-baryon and net-proton kurtosis**
  - **Kurtosis*Variance = 1 for Poisson distribution, if not close to the critical point**
- **Phase transition effect**
  - **net-proton kurtosis as proxy for net-baryon**
- **7.7, 11.5 and 39 GeV deviates from HRG expectations for Sσ.**
- **11.5 and 39 GeV deviates from HRG expectations for κσ².**

STAR Ref.: M. M. Aggarwal et al.: PRL105 (2010) 022302

Karsch and Redlich: PLB695 (2011) 136

Summary

• Successful RHIC BES program from collider/accelerator and experimental side!

a) Particle yields and spectra

b) Azimuthal HBT and Anisotropic flow

c) Event-by-Event fluctuations

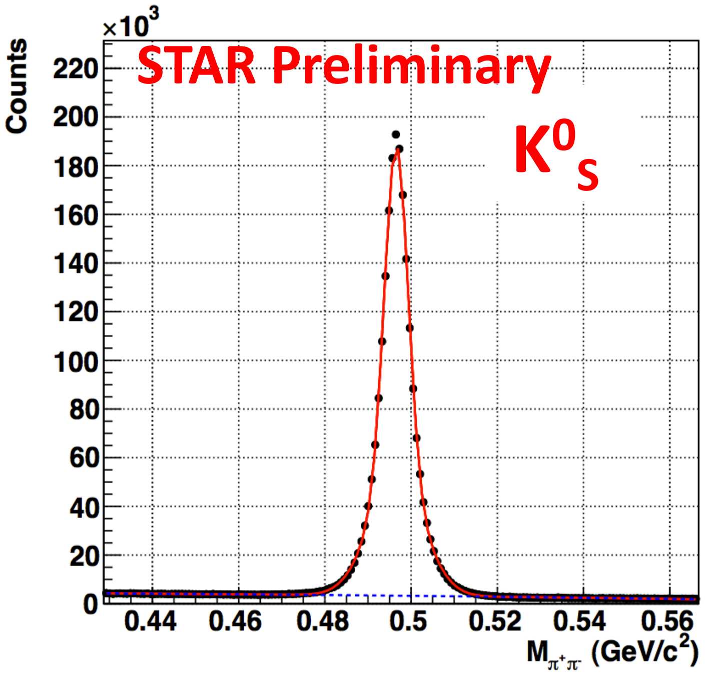
• Interesting observations were made with high quality data at 7.7, 11.5 and 39 GeV Au+Au collisions, part of the BES program in STAR at RHIC.

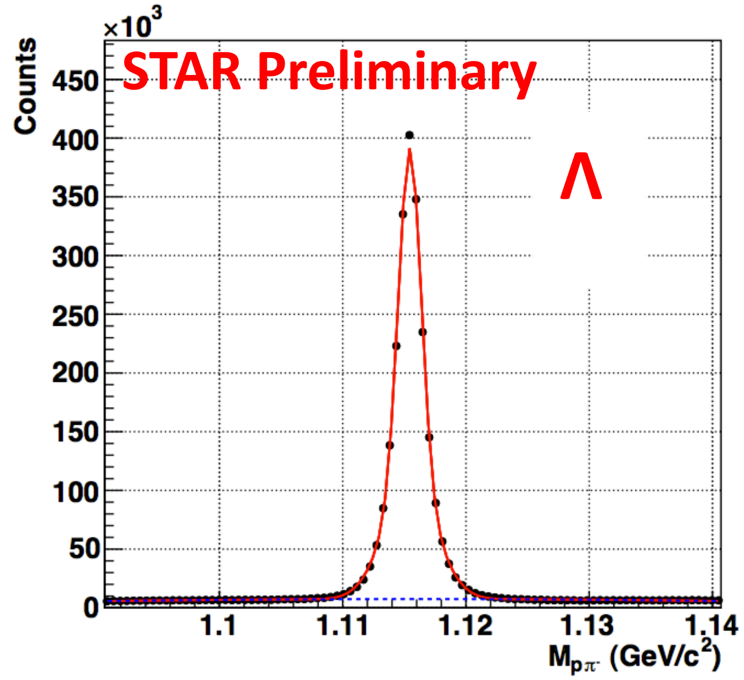
• Additional data at 19.6 and 27 GeV will allow us to perform a systematical study of the QCD phase structure and search for the possible QCD critical point.

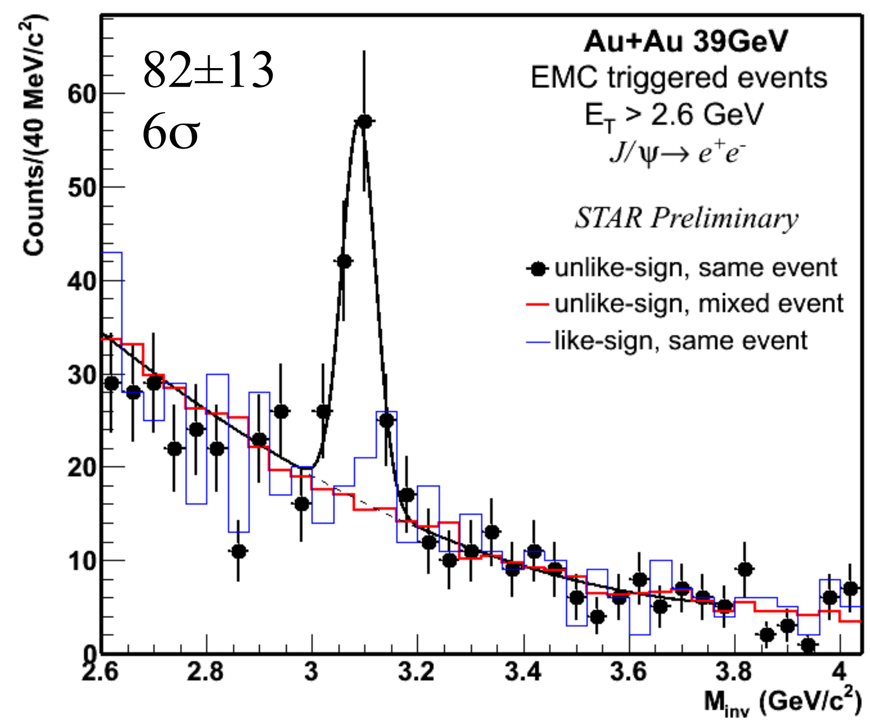
Outlook

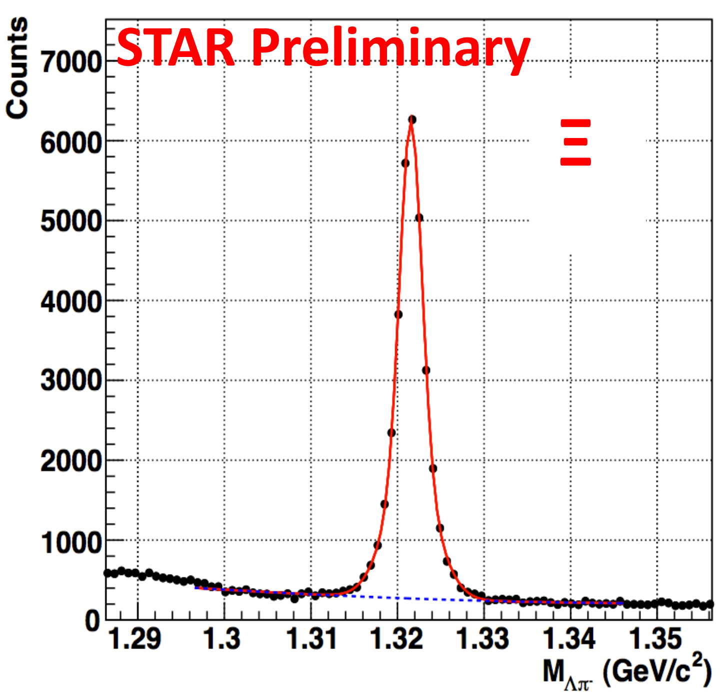
$Au + Au, \sqrt{s_{NN}} = 7.7\ GeV$

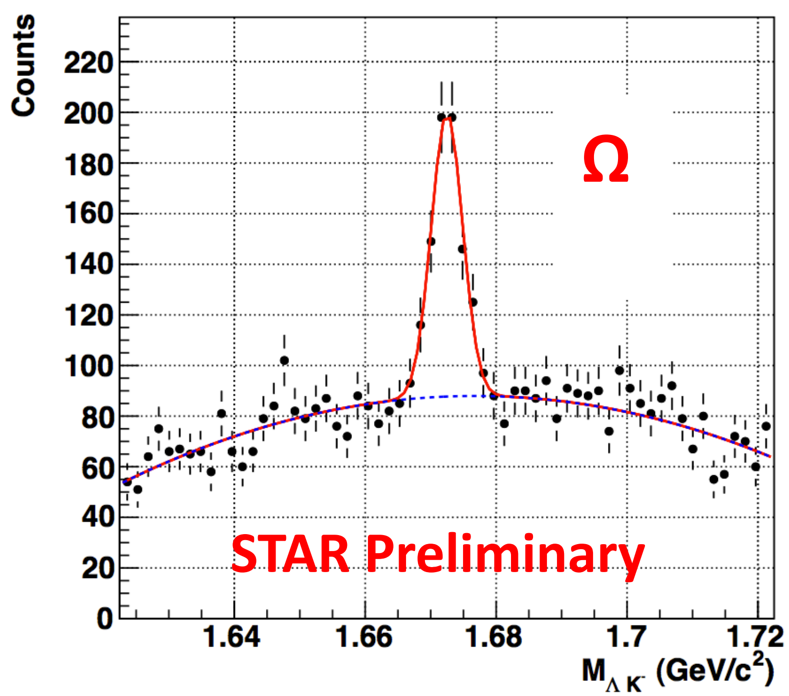
$Au + Au, \sqrt{s_{NN}} = 39\ GeV$

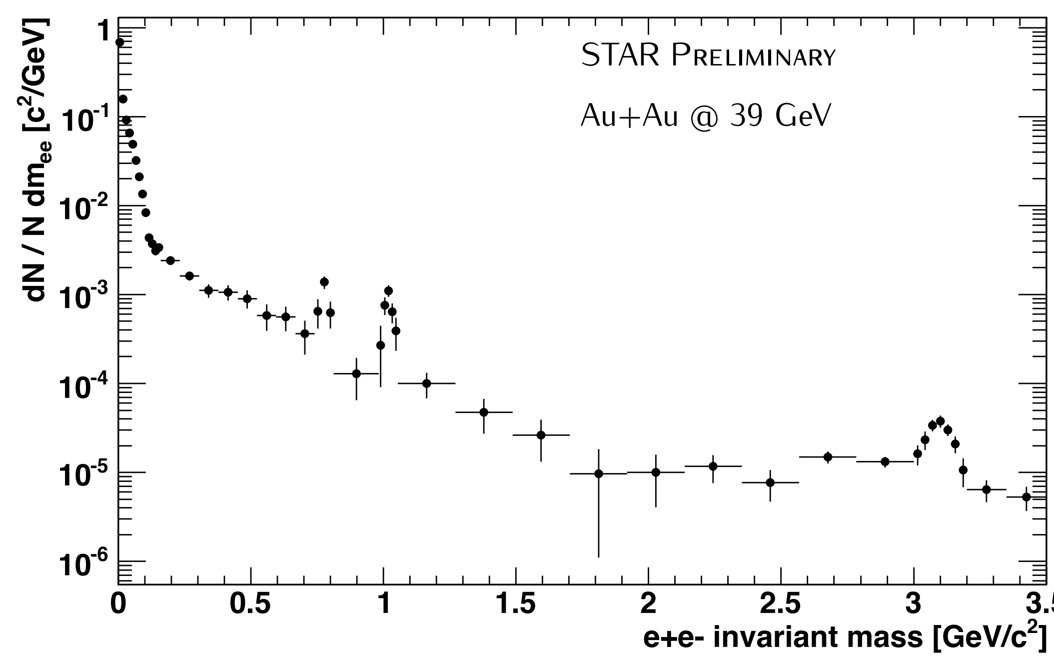












The End and Thanks for Your Attention

Yield, <mt>-m, K/π

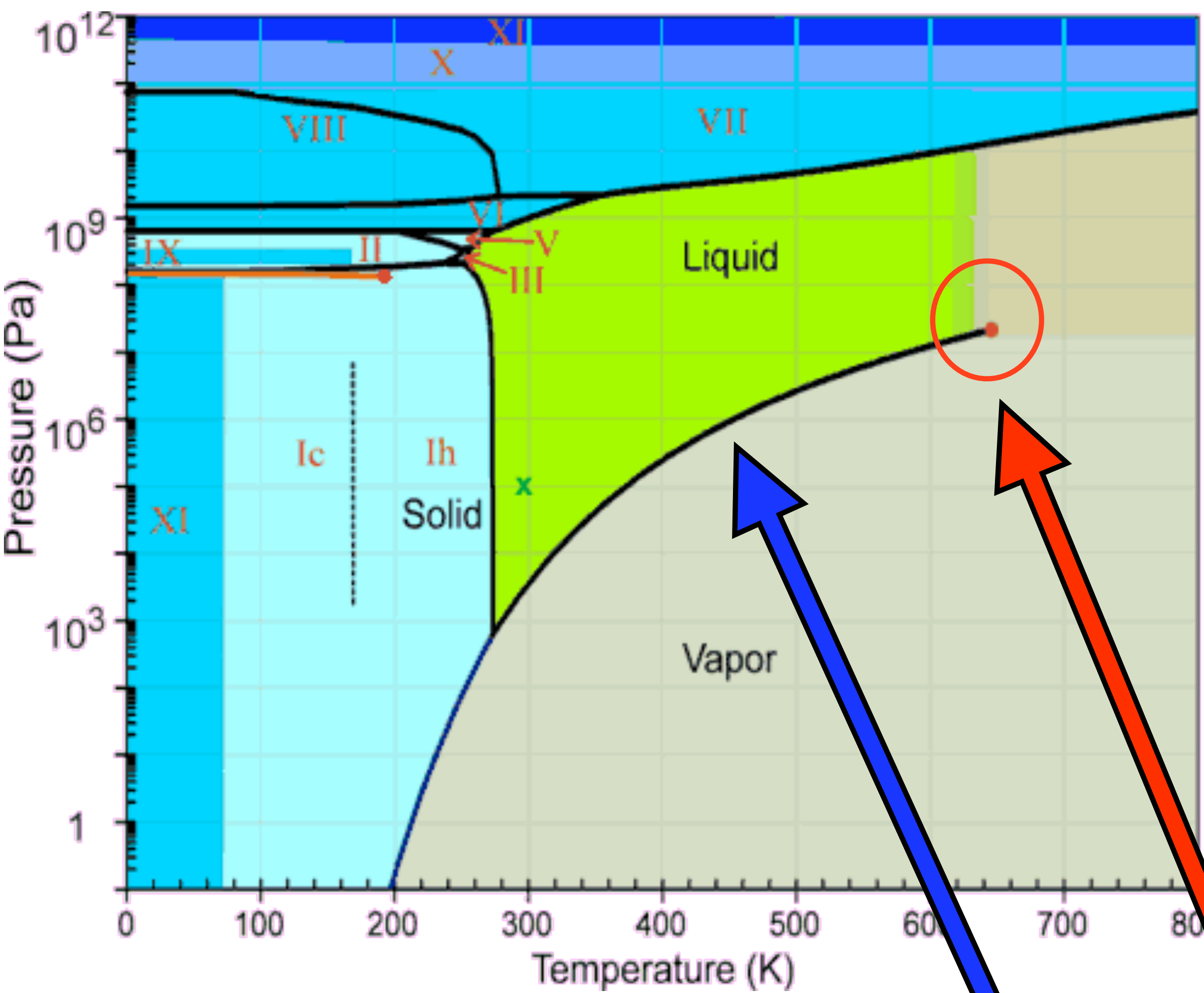
E802 Ref.: L. Ahle et al., PRC58 (1998) 3523
L. Ahle et al., PRC80 (1999) 044904
E895 Ref.: J. L. Klay et al., PRC68 (2003) 054905
E877 Ref.: J. Barrette et al., PRC62 (2000) 024901

NA49 Ref.: S. V. Afanasiev et al., PRC66 (2002) 054902
C. Alt et al., PRC77 (2008) 024903

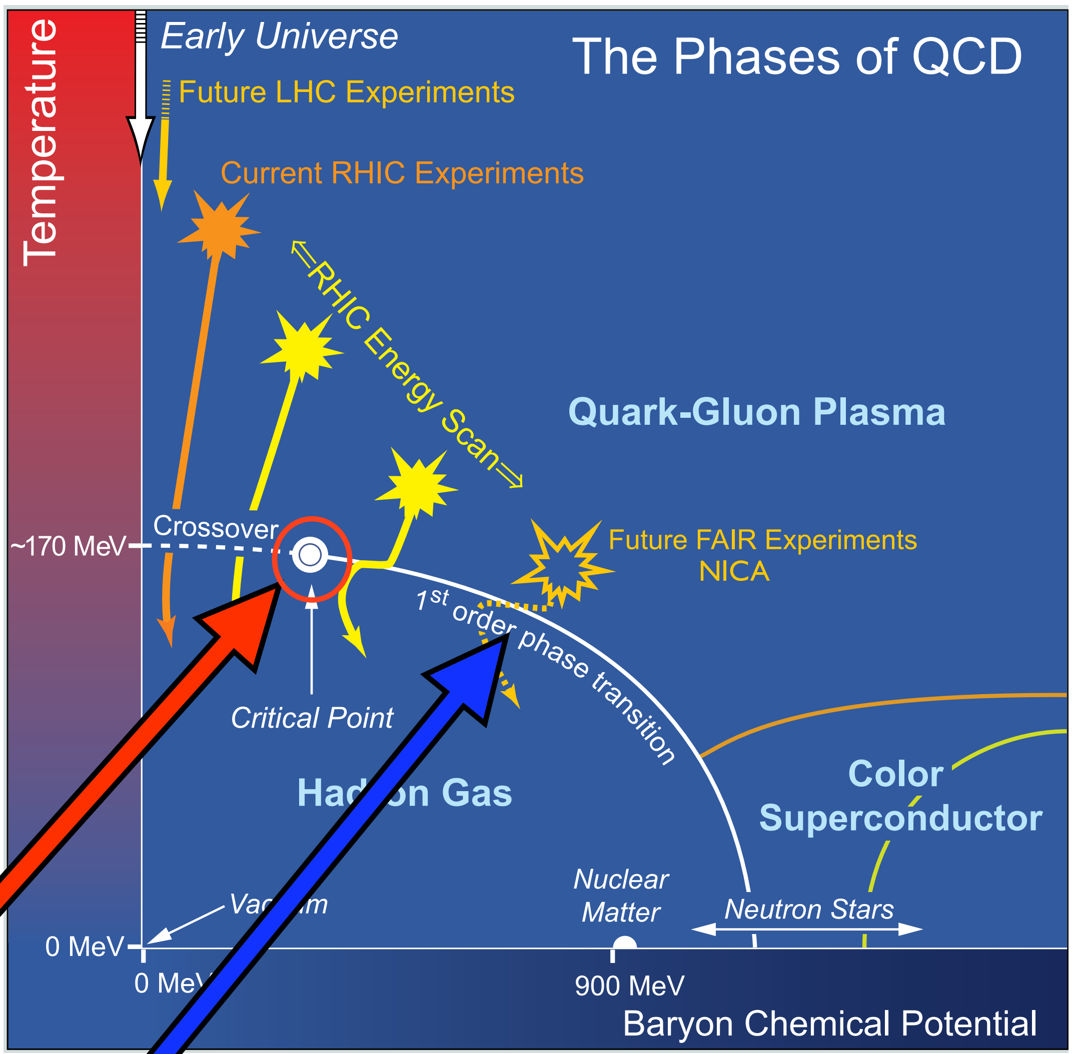
STAR Ref.: B. I. Abelev et al., PRC79 (2009) 034909
B. I. Abelev et al., PRC81 (2010) 024911

Phase Diagram of Strongly Interacting Matter

The phase diagram of water



The phase diagram of strongly interacting matter is under study



critical point

1st order phase transition

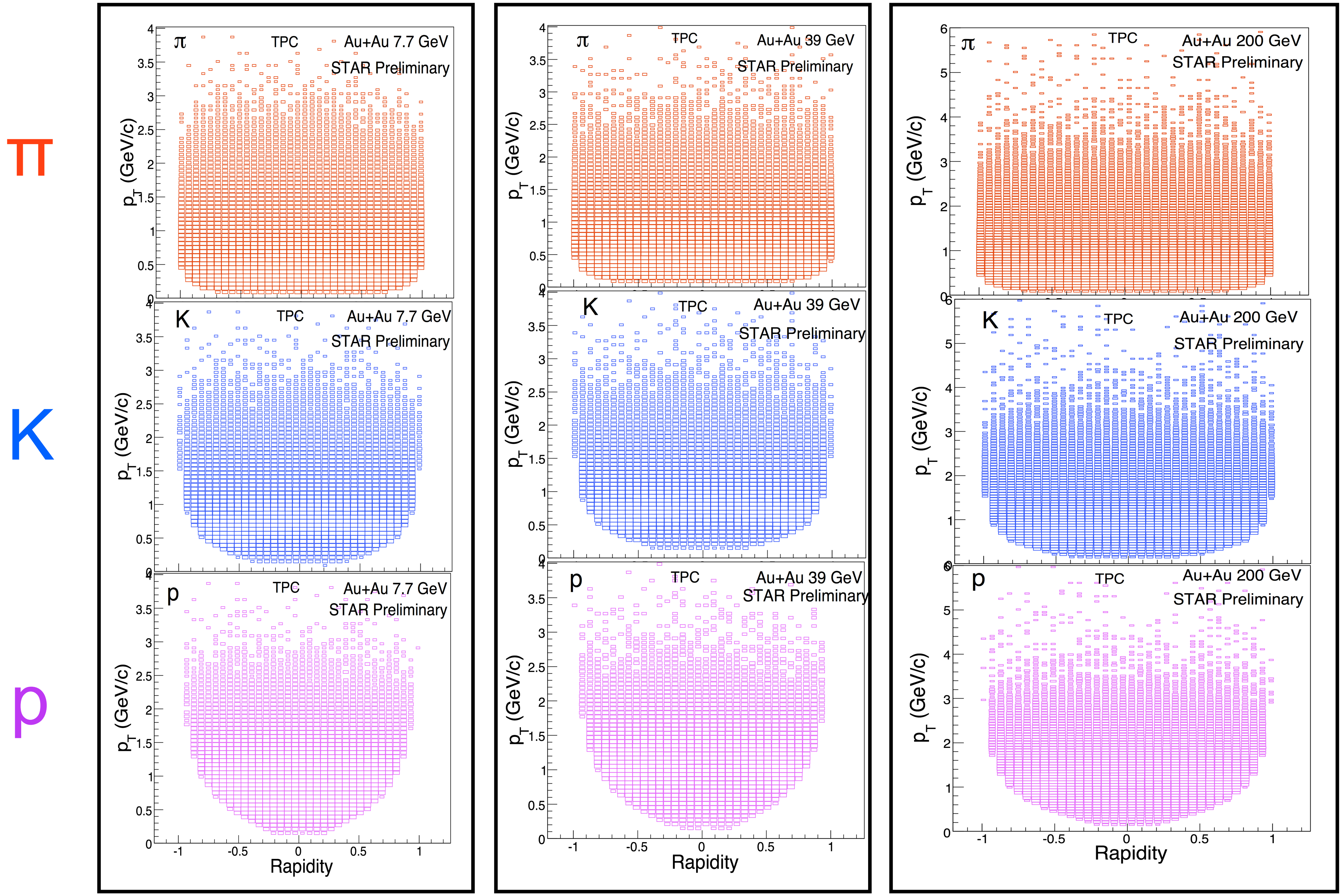
USA-NSAC 2007 Long-range plan

The BNL Accelerator Complex

- Beam species from p to $^{197}Au^{79+}$ (2012 with Electron Beam Ion Source (EBIS) up to U).
- Beam energy from $\sqrt{s_{NN}}$ = 7.7 - 200 GeV at RHIC.

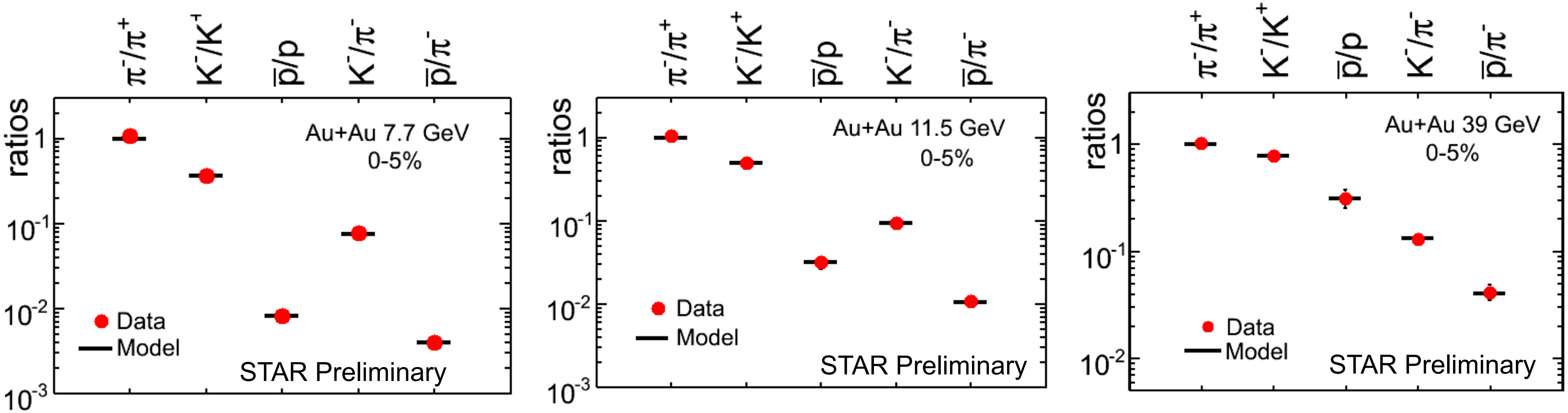
The STAR Acceptance

$Au + Au, \sqrt{s_{NN}} = 7.7\ GeV$ $Au + Au, \sqrt{s_{NN}} = 39\ GeV$ $Au + Au, \sqrt{s_{NN}} = 200\ GeV$



- **Similar acceptance for all energies.**

Statistical Model



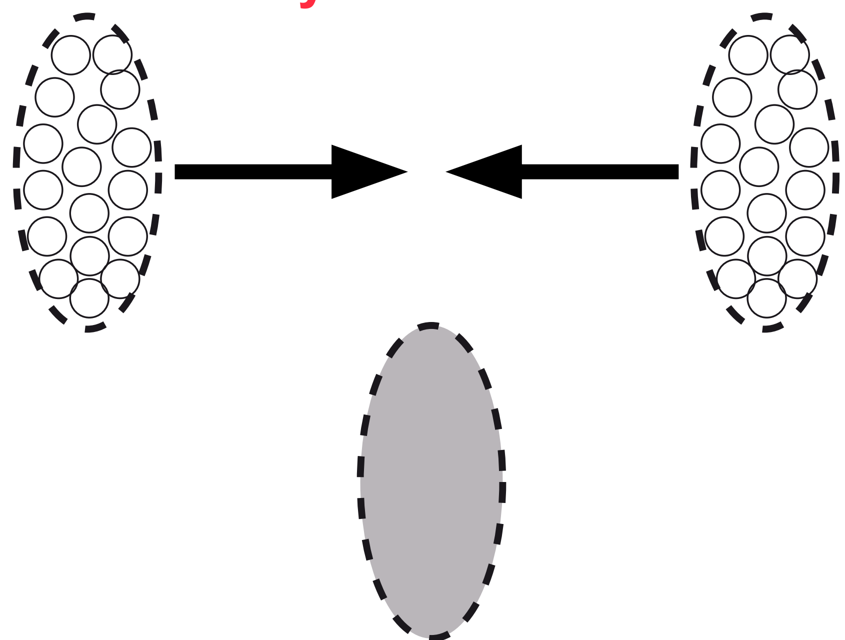
- Assumption of chemical equilibrium at freeze-out.
- Particle production can be described with a few parameters: V, T, μ_B, γ_s.
- Extract chemical freeze-out parameters → phase diagram.
  - Note p and $\bar{p}$ are not corrected for feed-down

STAR Ref.: B. I. Abelev et al., PRC79 (2009) 034909 and ref. therein

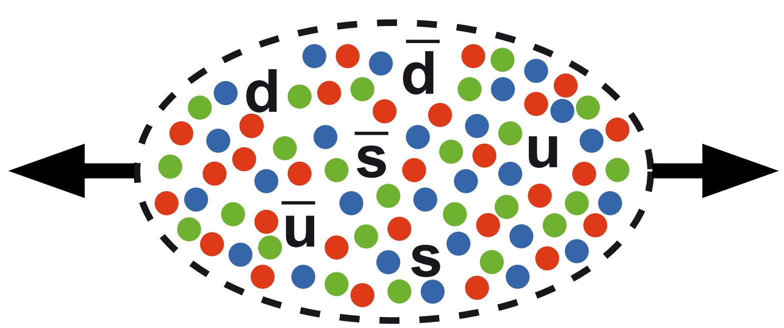
$$\langle n_i \rangle = \frac{(2J_i+1)\,V}{(2\pi)^3} \int d^3p \, \frac{1}{\gamma_s^{-S_i} exp[(E_i - (\mu_B + \mu_S + \mu_Q))/T] \pm 1}$$

Partonic Collectivity

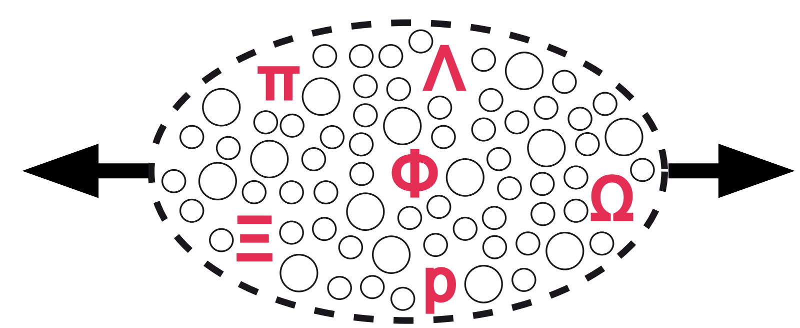
Heavy Ion collision



Partonic collectivity



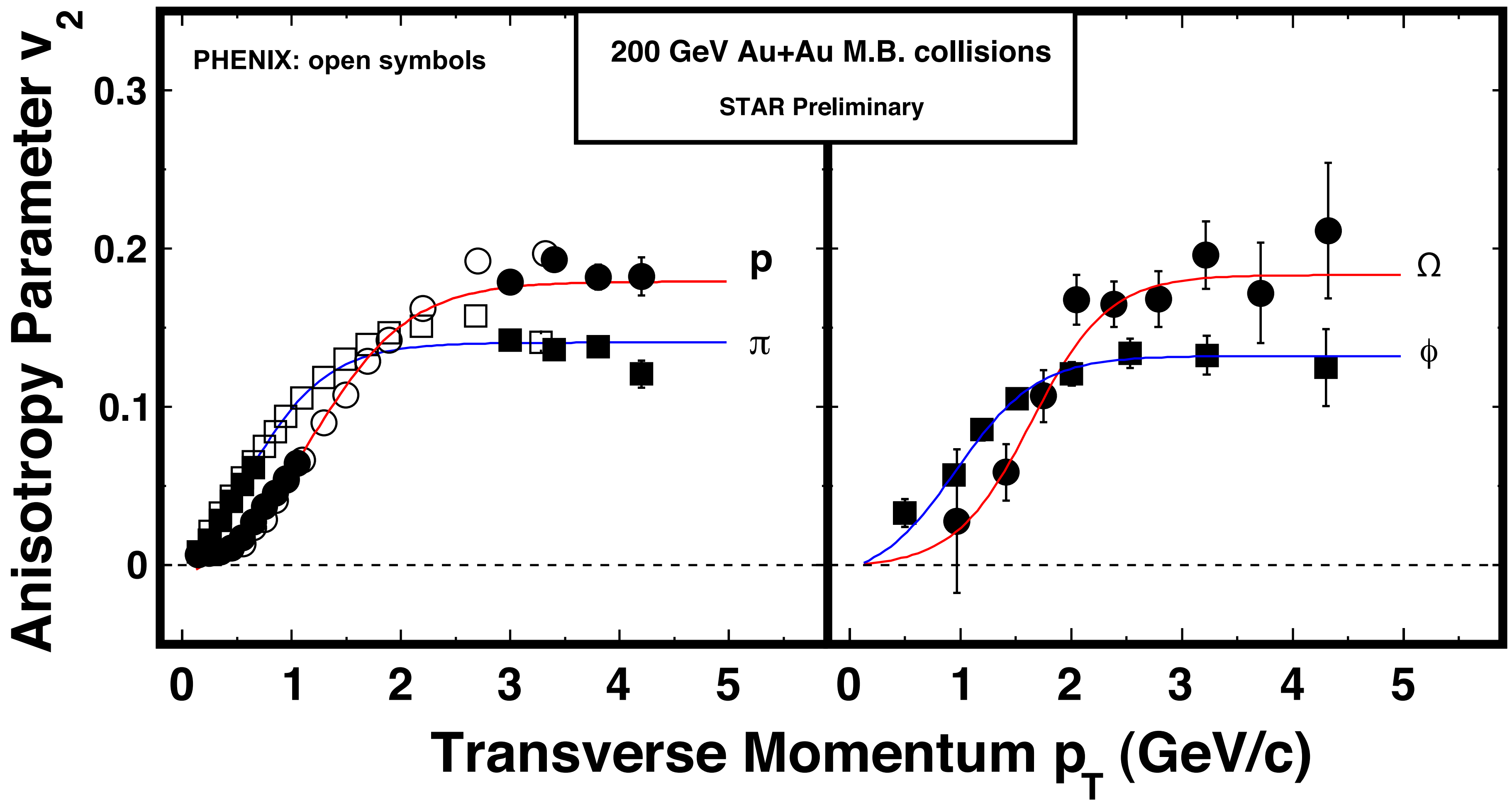
Hadronic collectivity



- **Collectivity develops on the quark level and persists after hadronization.**

- **Collectivity develops on the hadronic level and will be different for every hadron species due to differing cross-section.**

Partonic Collectivity



- At low p_t (≤ 2 GeV/c) hadronic mass ordering effect is visible.
- At high p_t (> 2 GeV/c) number of quarks ordering.

  ⇒ **Collectivity develops at the partonic stage**

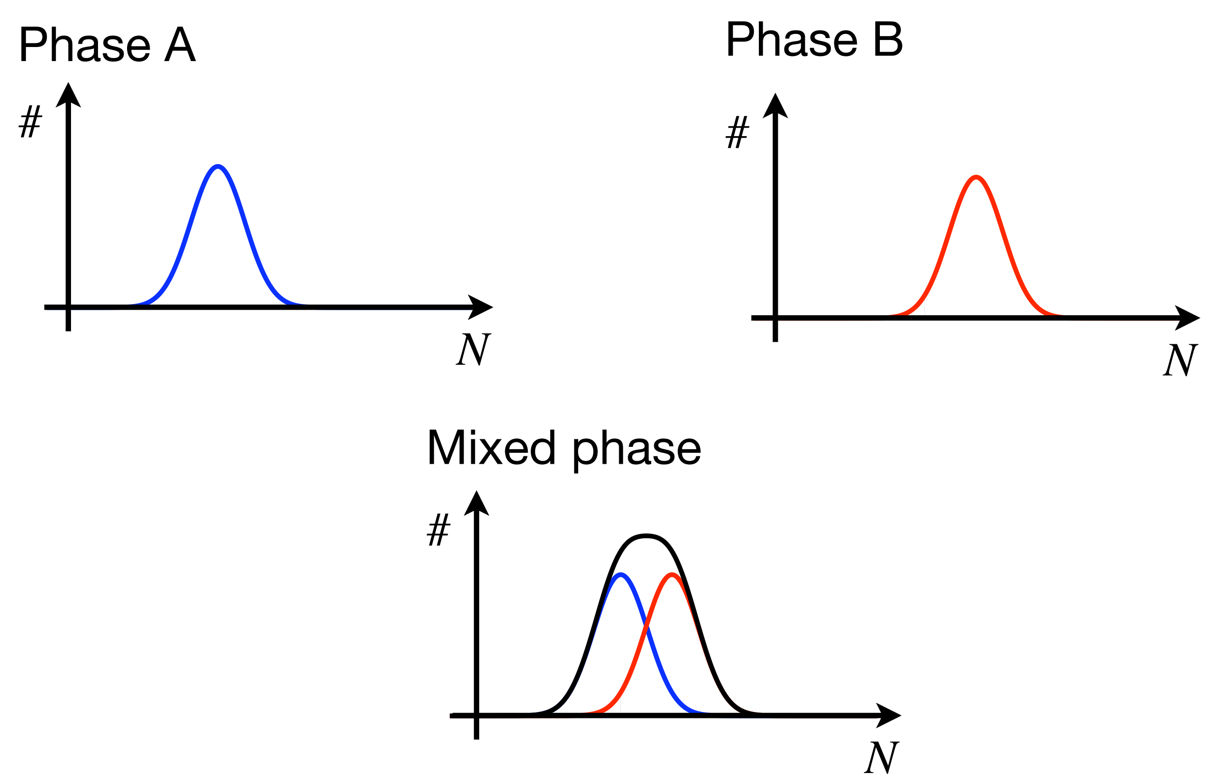
STAR Ref.: S. Shi for the STAR Collaboration: NPA 830 (2009) 187

PHENIX: Issah and Tarenko, nucl-ex/0604011

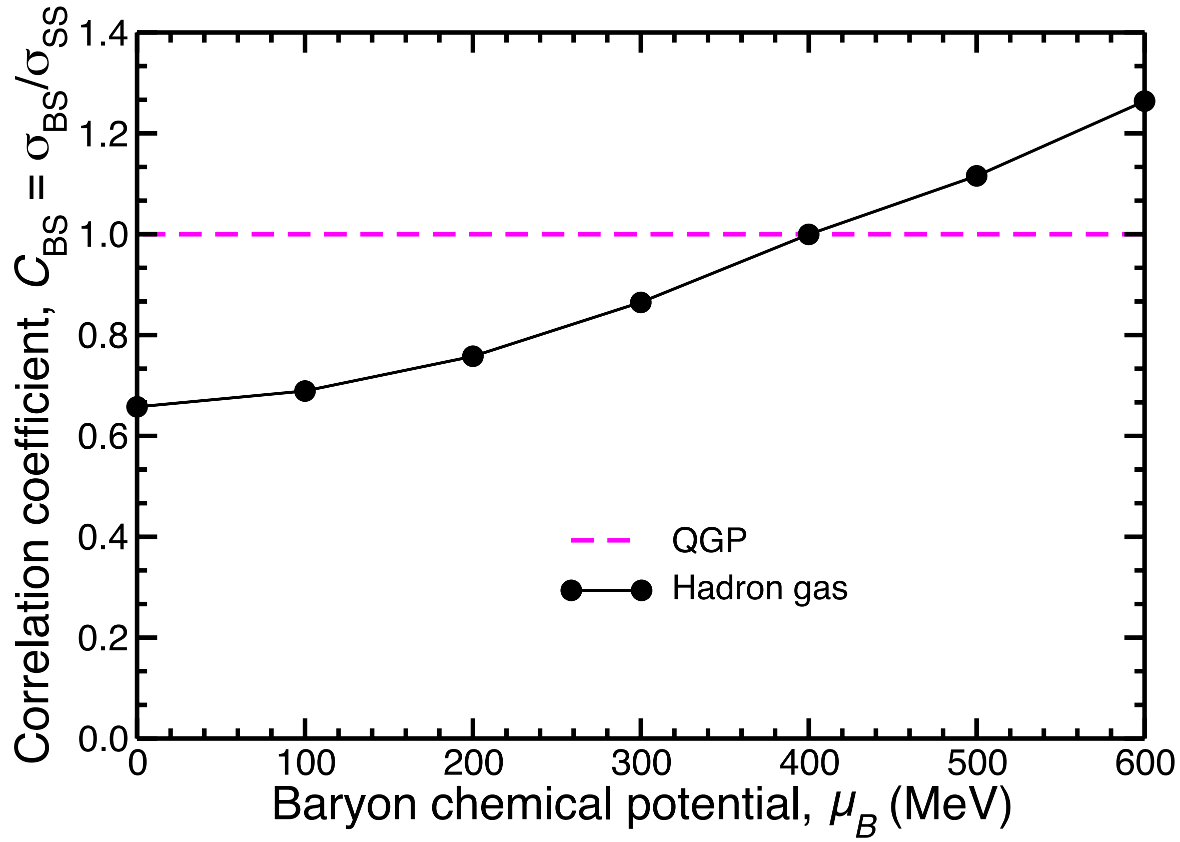
NQ inspired fit: Dong et al., PLB 597 (2004) 328

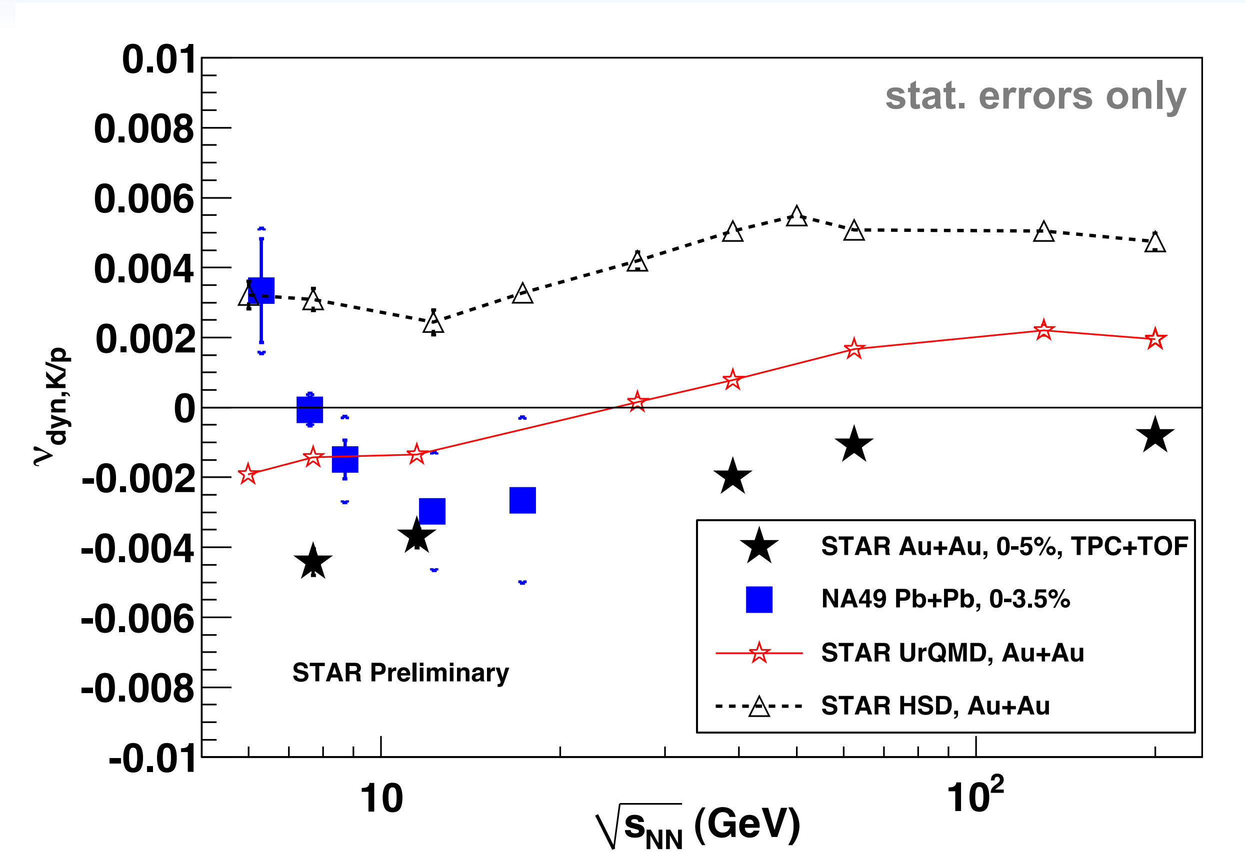
Introduction in Ratio Fluctuations

- **Hadron ratios...**
  - **... are an intensive quantity**
  - **... characterize the chemical composition of the fireball**
  - **... are not affected by hadronic re-interaction when looking at conserved quantities (baryon number, strangeness)**
- **Change of particle (e.g. strangeness) production properties at the phase transition**
  - **Two event classes**
  - **Larger fluctuations in the mixed phase**



K/p Ratio Fluctuations





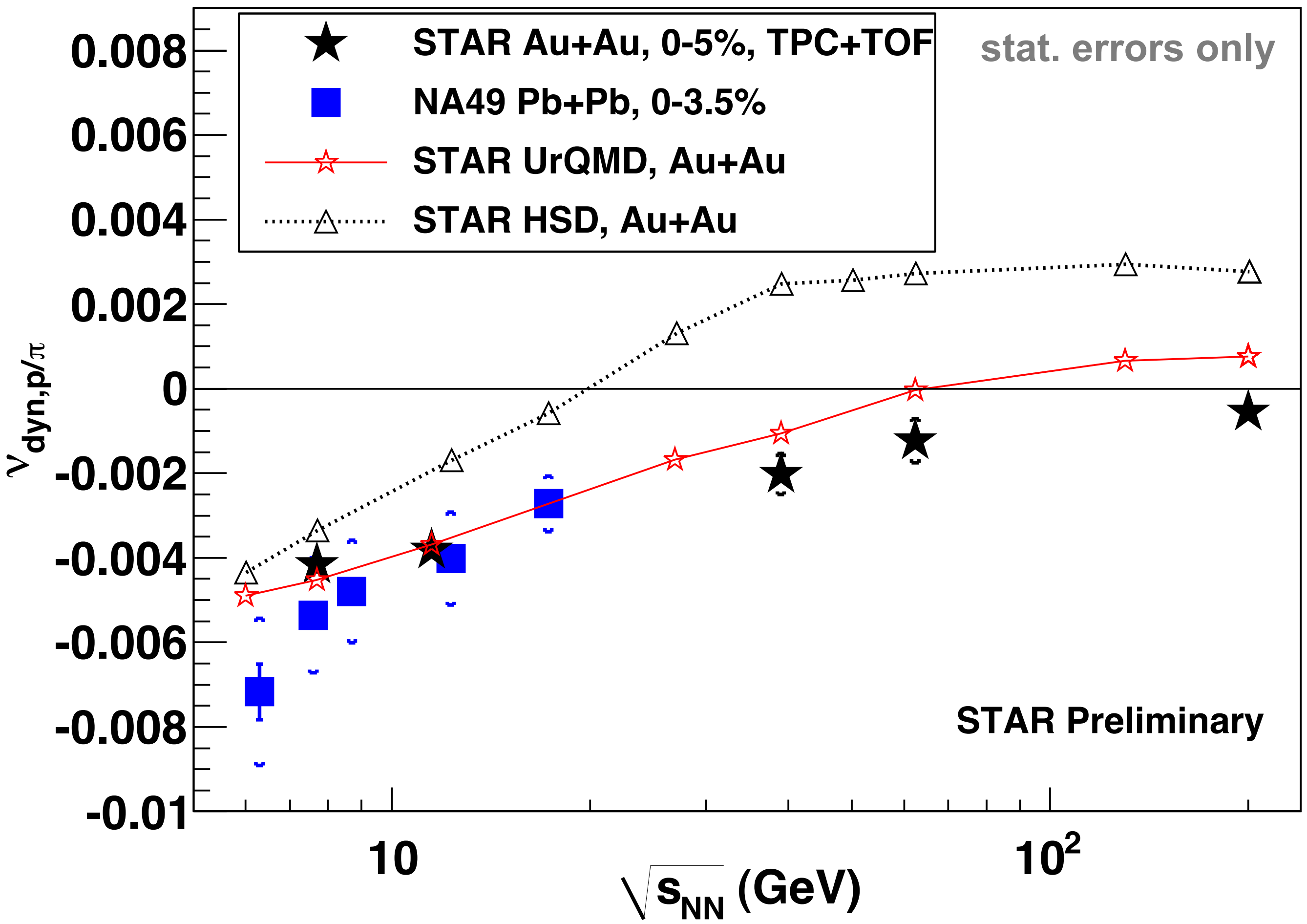
- **QGP: strangeness is carried by strange quarks, baryon number and strangeness is correlated.**
- **HG: strangeness is carried by K and Λ, baryon-strangeness correlation changes with μ_B.**

- **K/p is an approximation for C_{BS}?**
- **Deviation between NA49 and STAR at 7.7 GeV.**
- **Difference between NA49 and STAR could have different reasons, e.g.: different PID selection and/or acceptance (Physics maybe changes with acceptance) (still under discussion).**
- **UrQMD and HSD fails to describe the measurements.**

Koch et. al.:PRL 95 (2005) 182301

NA49 Ref.: T. Anticic et al.: arXiv:1101.3250

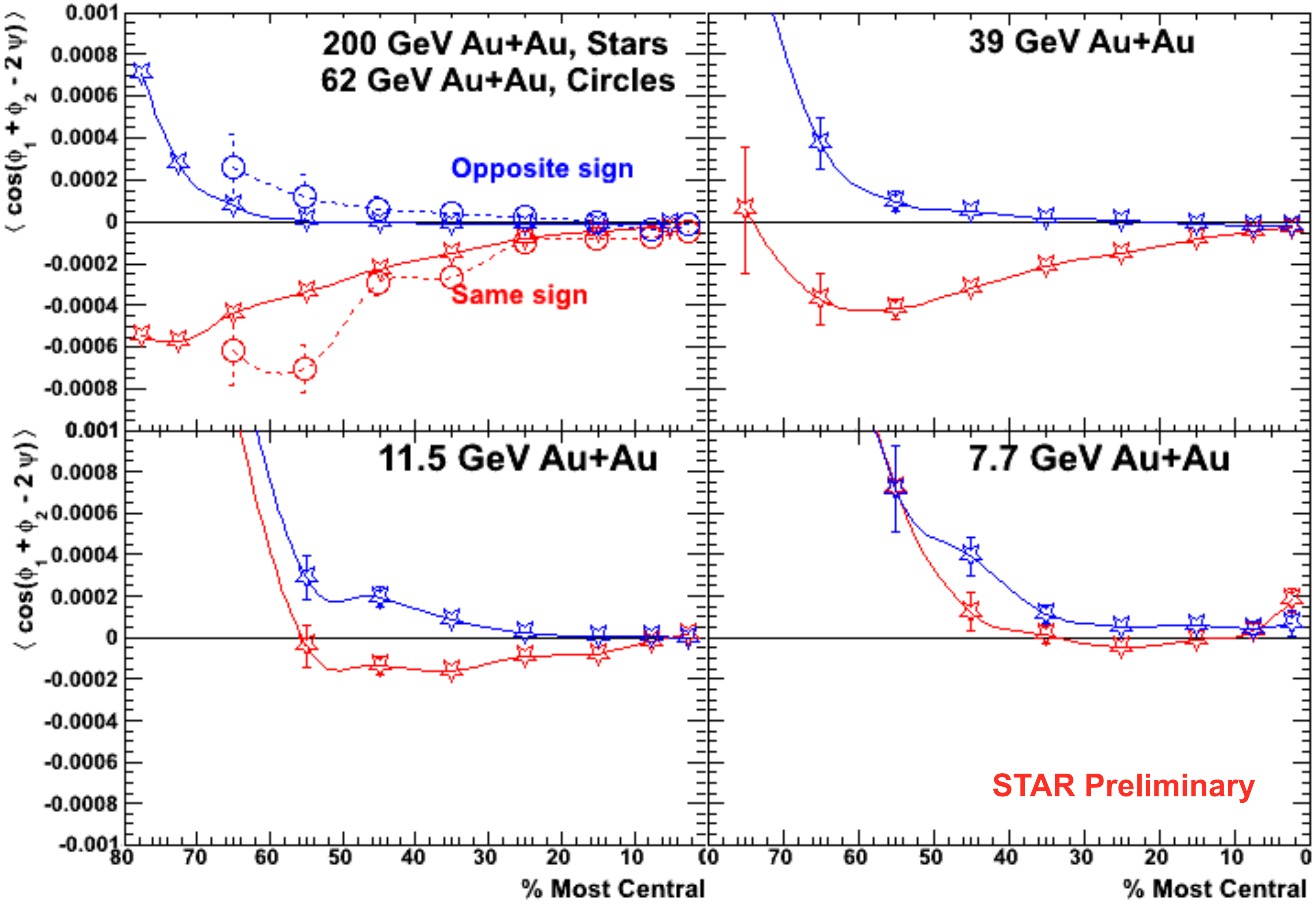
p/π Ratio Fluctuations



- $\nu_{dyn,\,p/\pi}$ increases with energy.
- Good agreement between NA49 and STAR measurements.
- UrQMD and HSD catches the trend but cannot fully describe the data.

NA49 Ref.: C. Alt et al., PRC79 (2009) 044910

Energy Dependence of Charge Separation



- Difference between same and opposite charge correlations is decreasing with decreasing energy.
- The B field decreases but last longer.
- Chiral symmetry may cease to be restored.

Kharzeev, Pisarski, Tytgat: PRL81 (1998) 512
Voloshin: PRC70 (2004) 057901

STAR Ref.:B. I. Abelev et al., PRL103 (2009) 251601