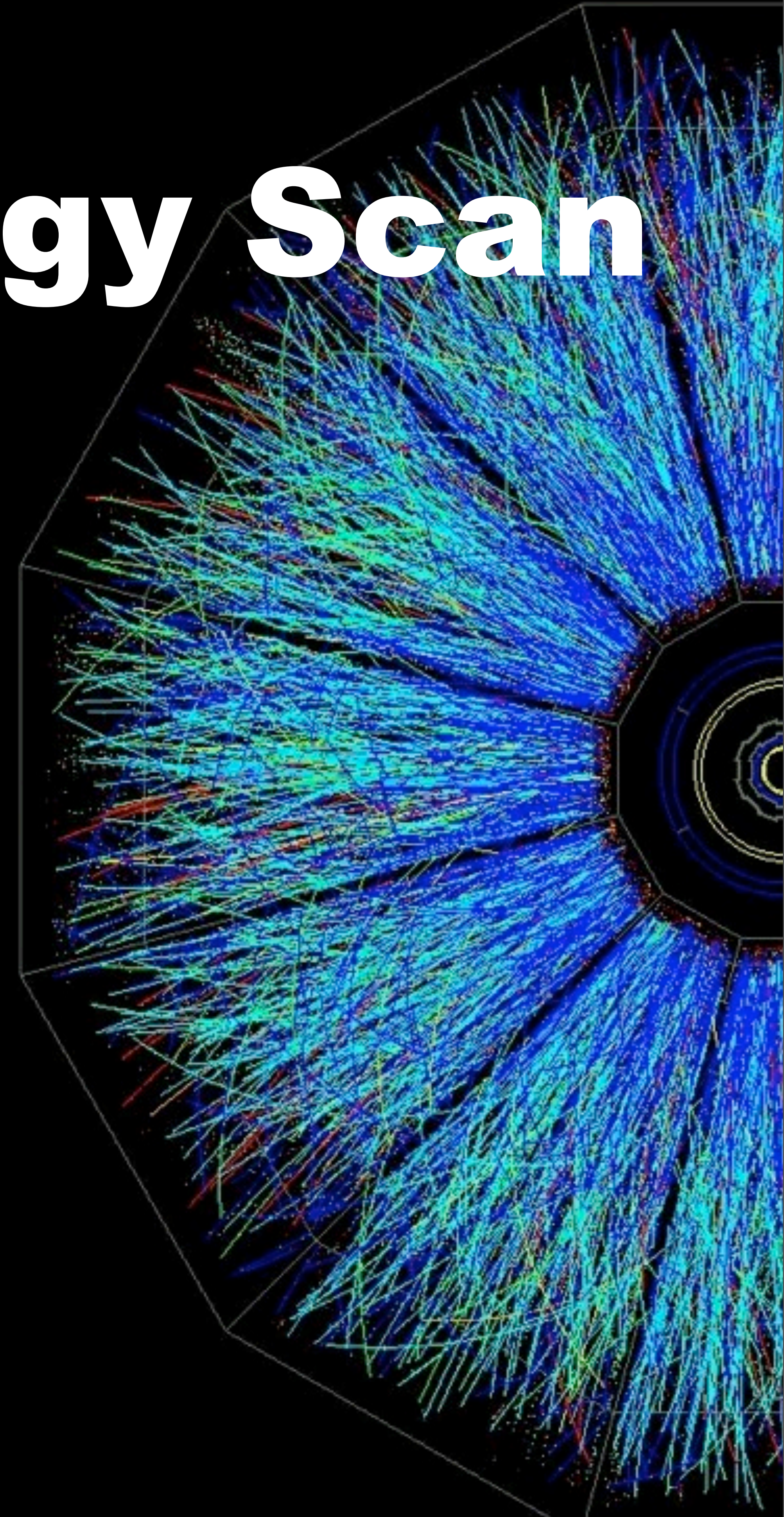
The Beam Energy Scan at RHIC-STAR



Hiroshi Masui
Lawrence Berkeley National Laboratory

Jan/23/2012,
Tsukuba University

BERKELEY LAB
Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY

STAR physics focus in heavy ion collisions

(a) QCD phase diagram - ***Critical point*** and ***phase boundary***

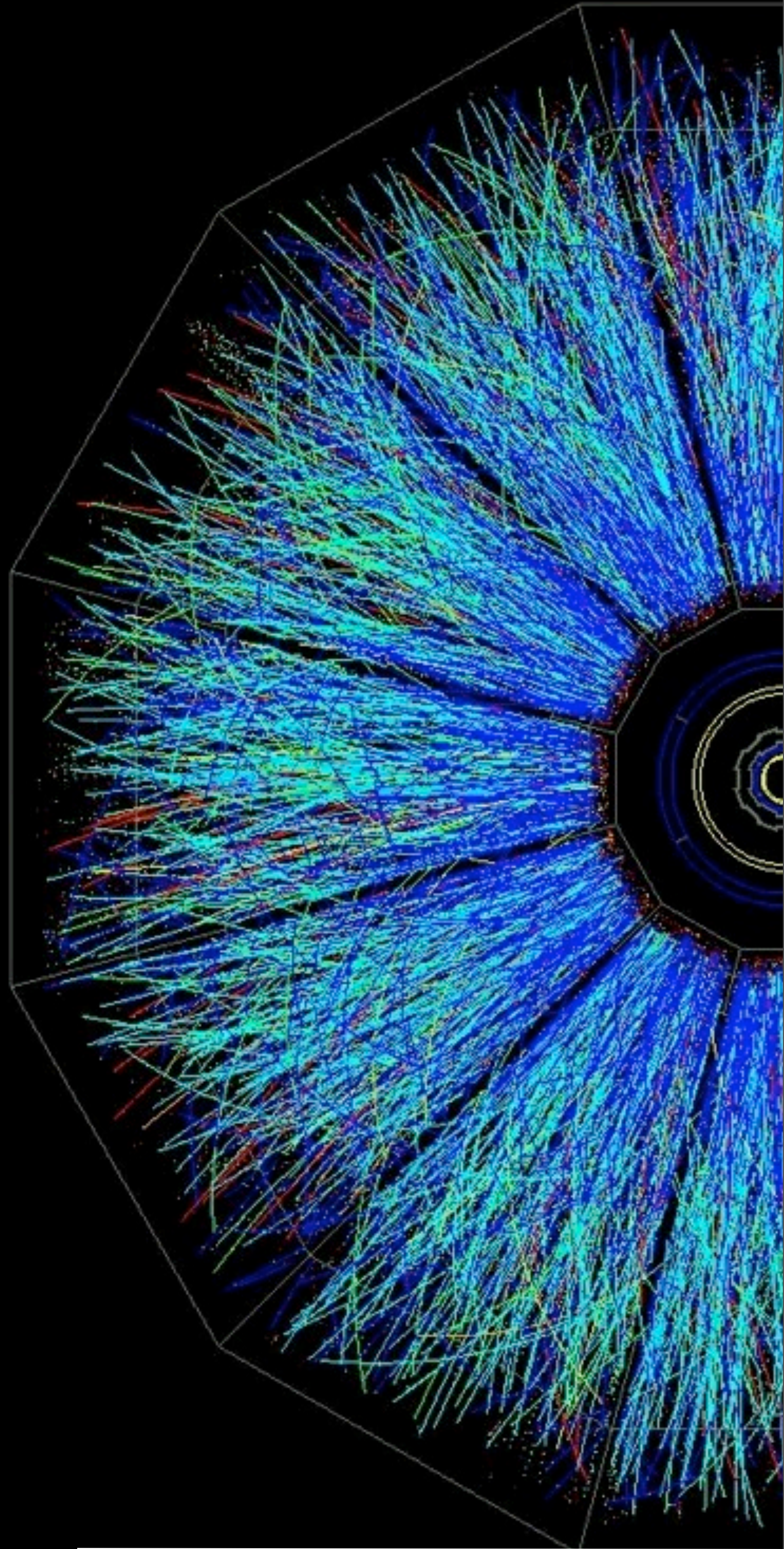
- RHIC Beam Energy Scan (***BES***) program

(b) Chiral symmetry restoration

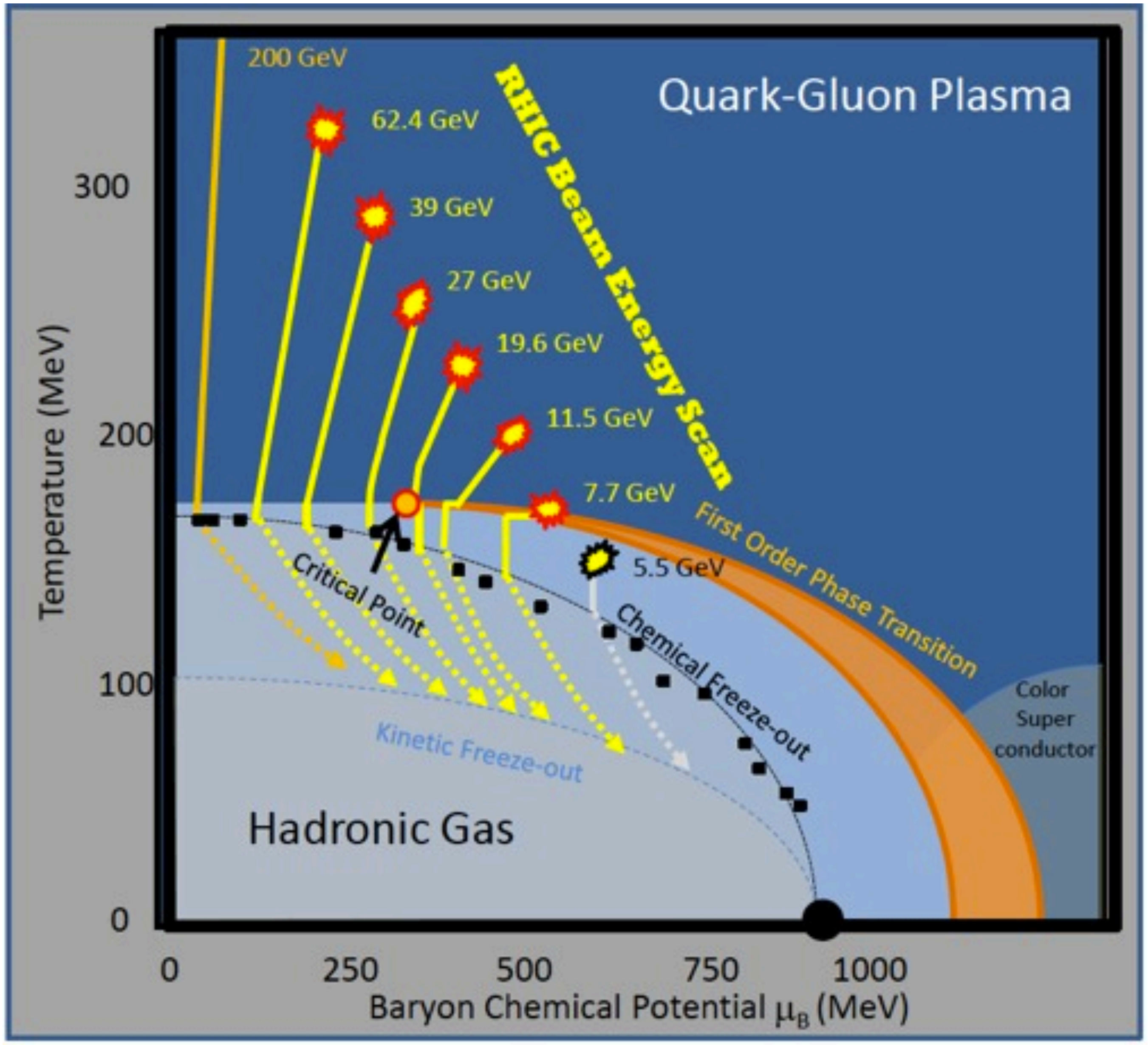
- di-lepton program

(c) QGP properties

- Heavy flavors, di-lepton



Beam Energy Scan (BES)



History & timeline

2007: STAR BES focus group formed
2008: Test run at $\sqrt{s_{NN}}$ = 9.2 GeV (*PRC***81***, 024901, 2010*)
2009: Proposal for BES Phase-I (*arXiv:1007.2613*)
2010: Data taking began (7.7, 11.5 and 39 GeV)
2011: Two further energies (19.6 and 27 GeV)
2012: Test run at 5 GeV

- Study the structure of QCD phase diagram
  ➡ Beam Energy Scan

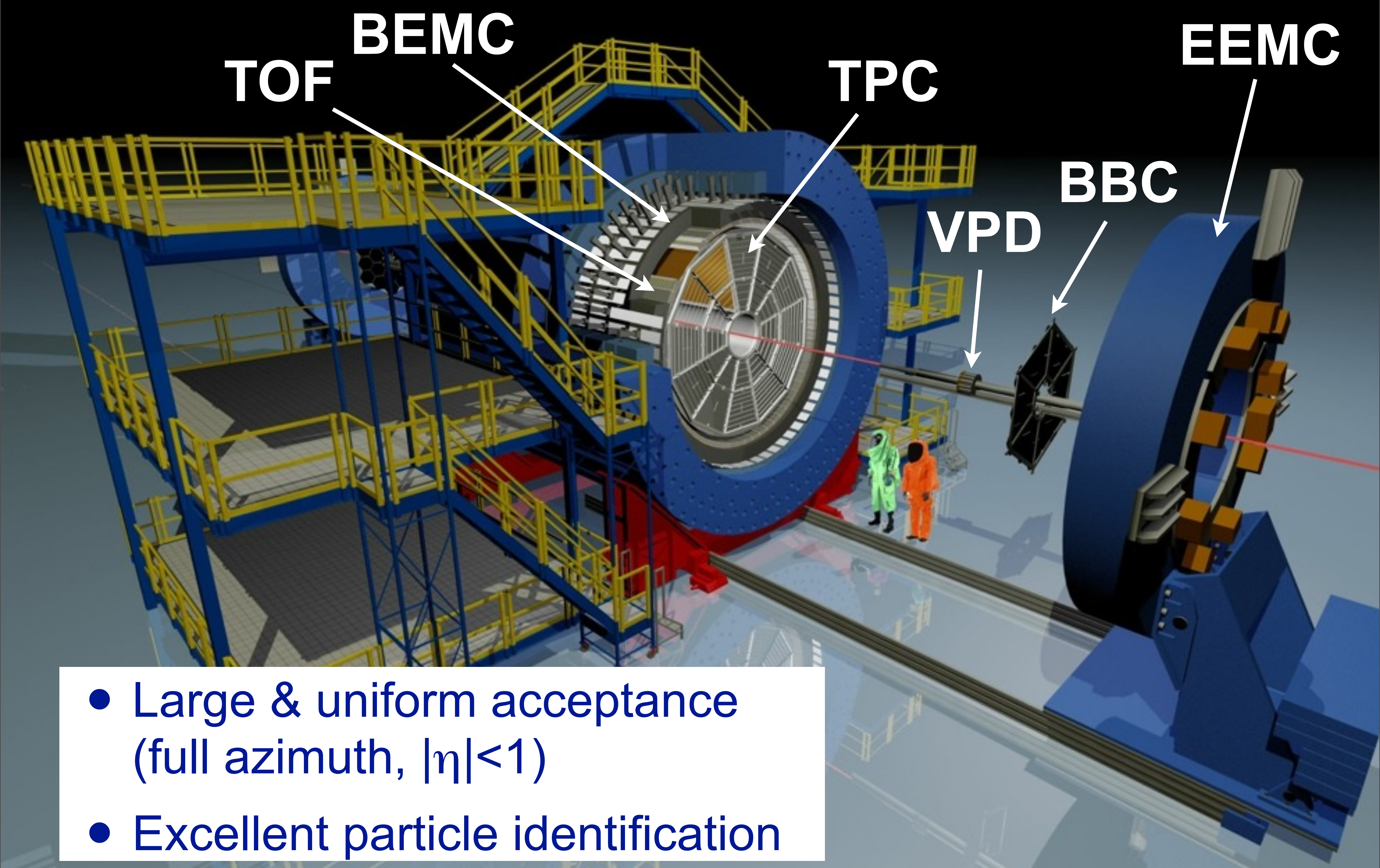
- Proposed signatures

1. ***Turn-off* QGP signals**
2. **Search for phase boundary (1st order phase transition)**
3. **Search for QCD critical point**

Relativistic Heavy Ion Collider

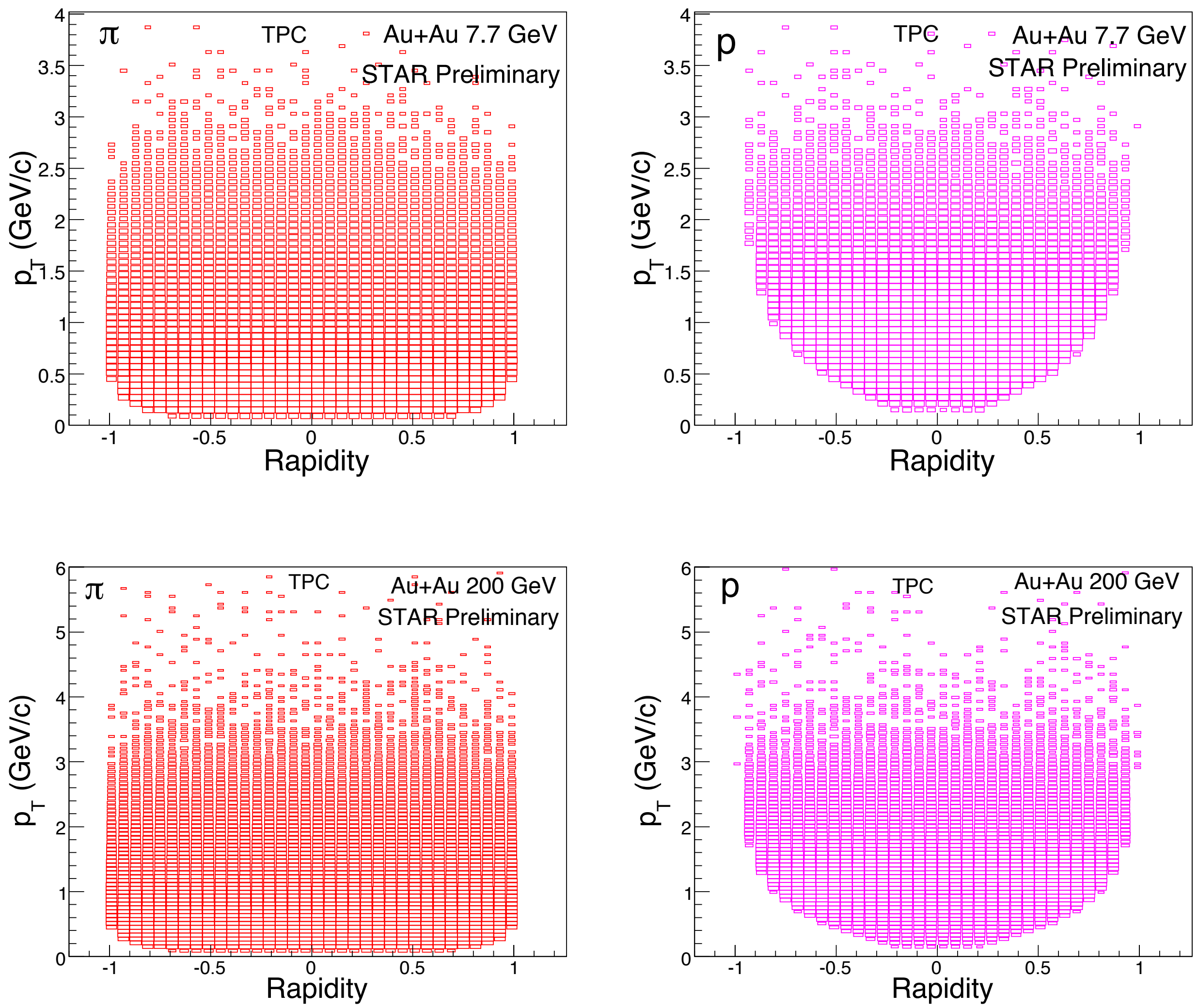
- ~4 km ring
- Maximum √s = 200 GeV (500 GeV) in Au+Au (p+p)
- 6 interaction points
  - 2 ongoing heavy ion experiments; ***PHENIX***, ***STAR***

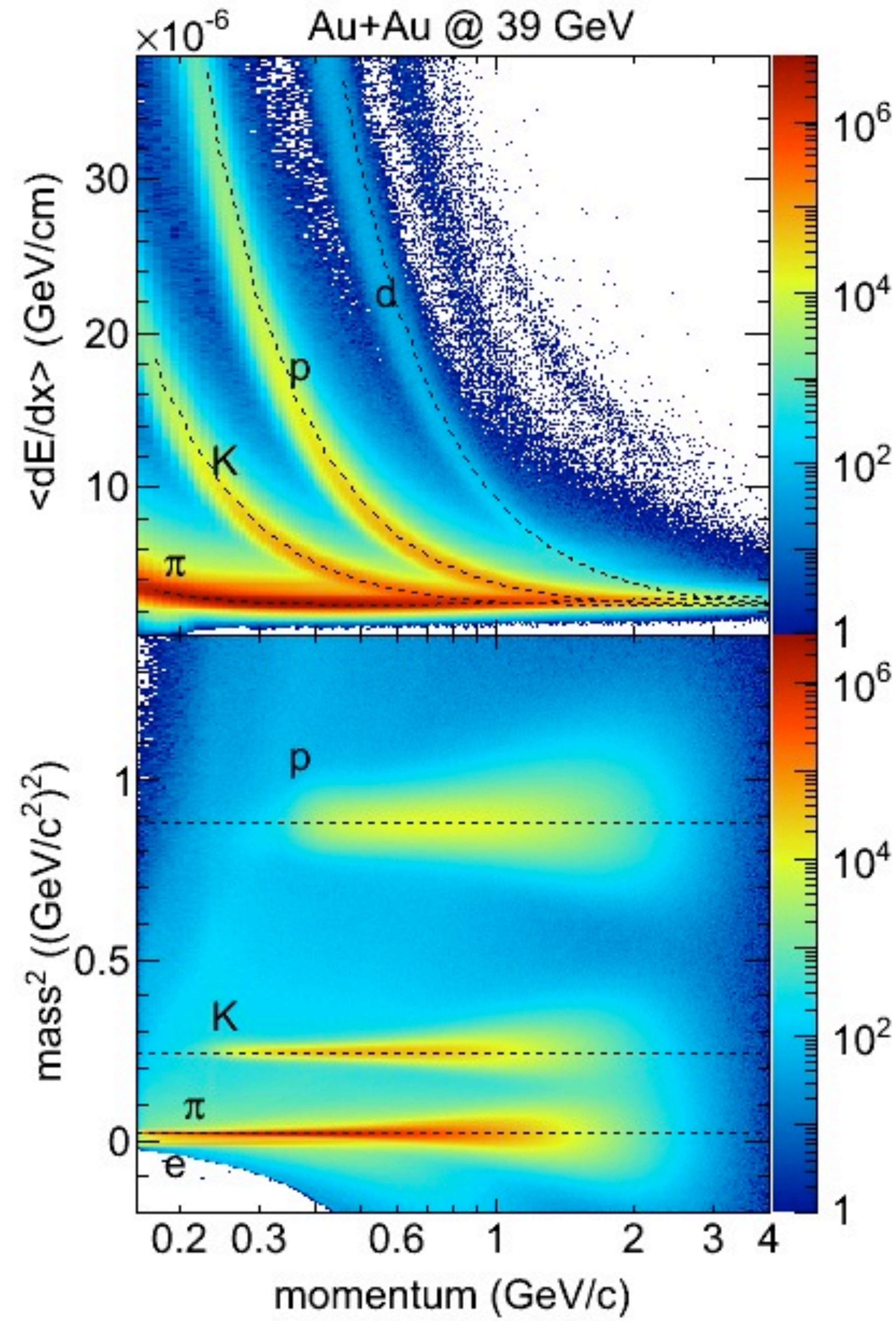
Solenoidal Tracker At RHIC



- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

Acceptance & particle identification



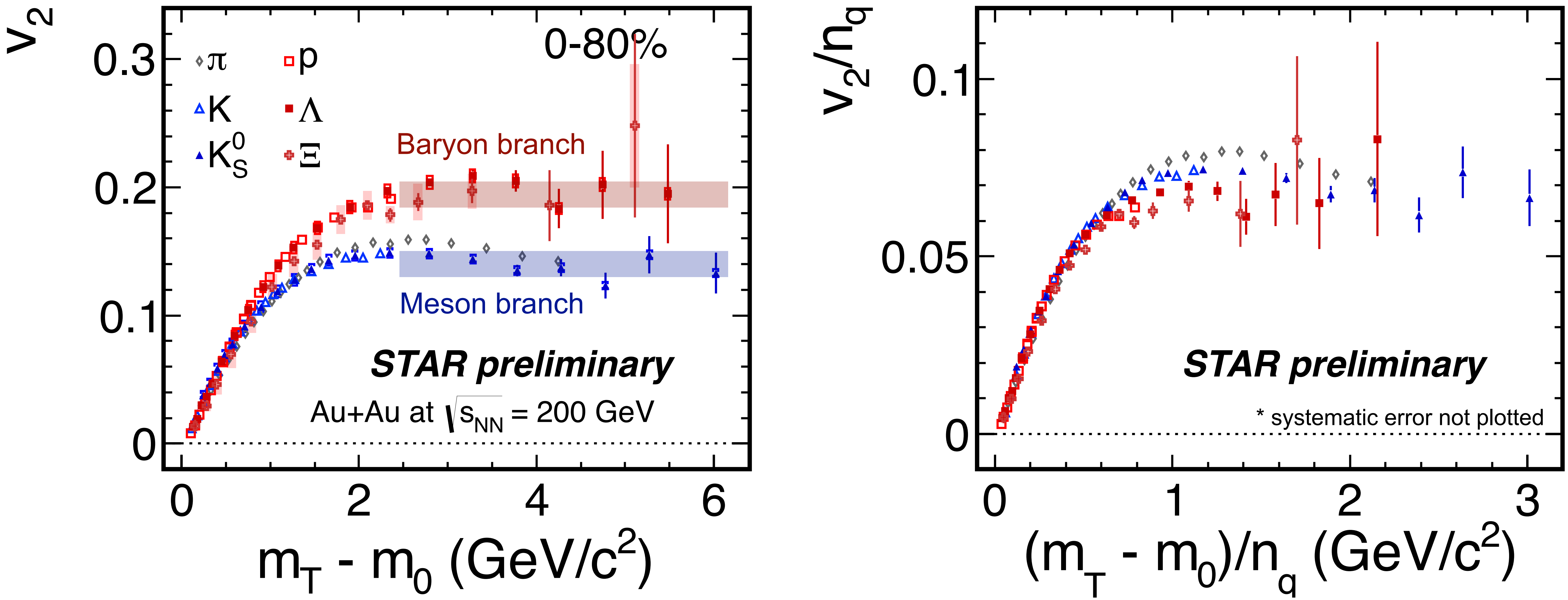


- Uniform acceptance
- dE/dx in TPC + m^2 in TOF
  - π/K separation p < 1.6 GeV/c
  - K/p separation p < 3 GeV/c

Turn-off QGP signals

- NCQ scaling of v_2
- High p_T suppression - R_{cp}
- Mixed harmonic correlation - signal for local parity violation

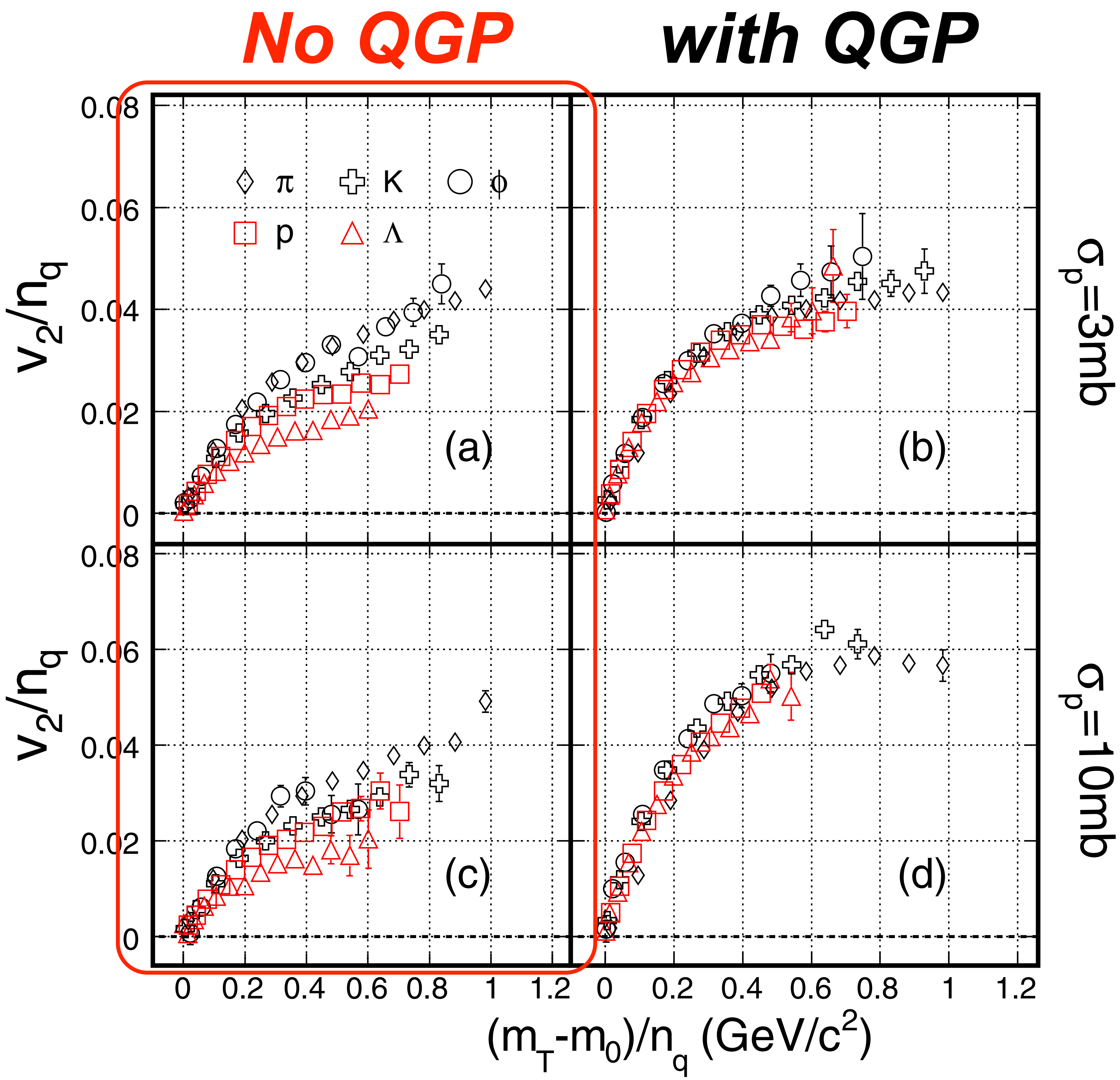
Partonic collectivity



- Clear meson & baryon branches
- Number of constituent quark (NCQ) scaling of v_2
  - within ~ ±10%

➡ Anisotropic flow develops at early partonic stage

Turn-off NCQ scaling ?

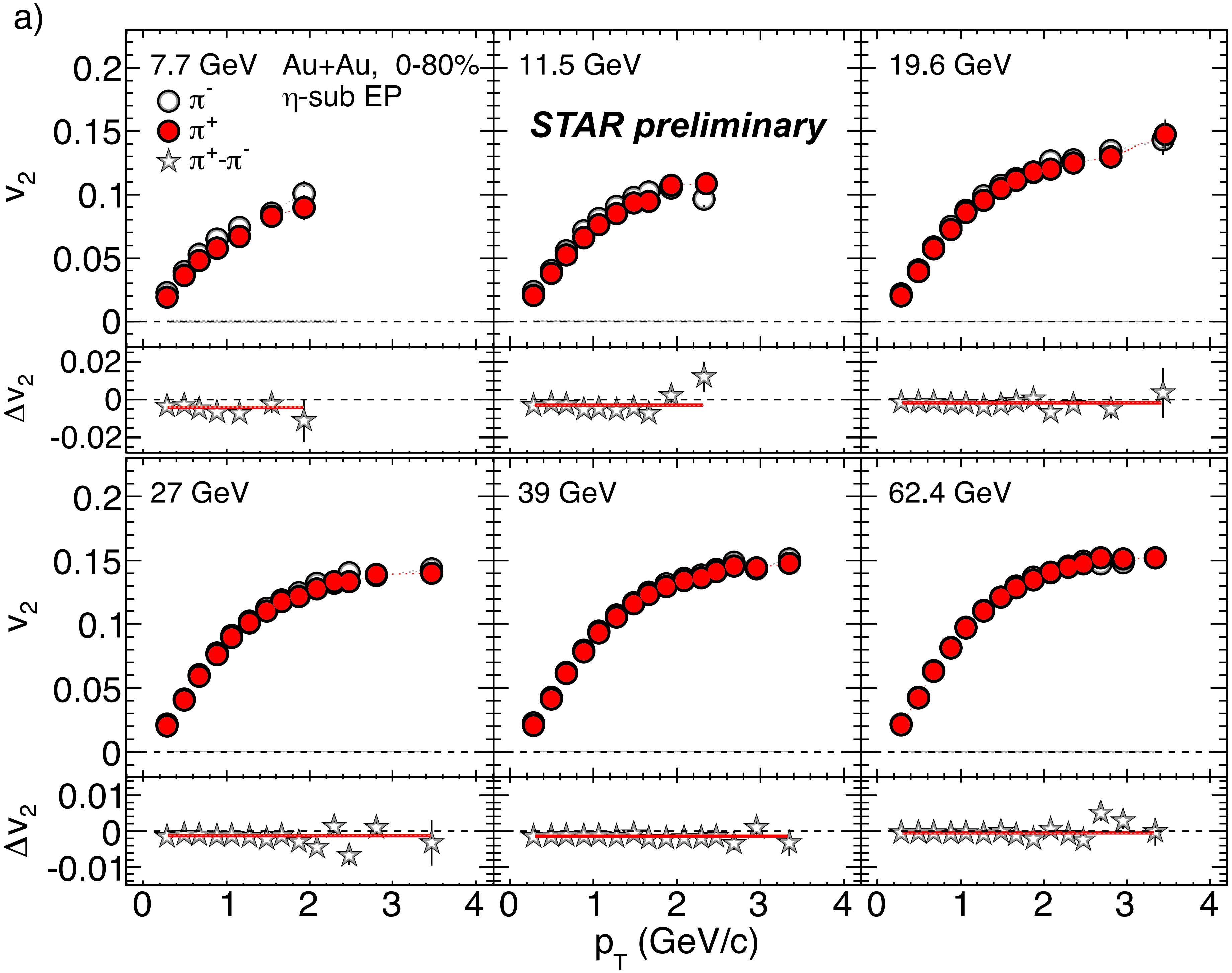


- AMPT model calculations show break down of NCQ scaling without QGP

➡ An important tool to search for possible phase boundary

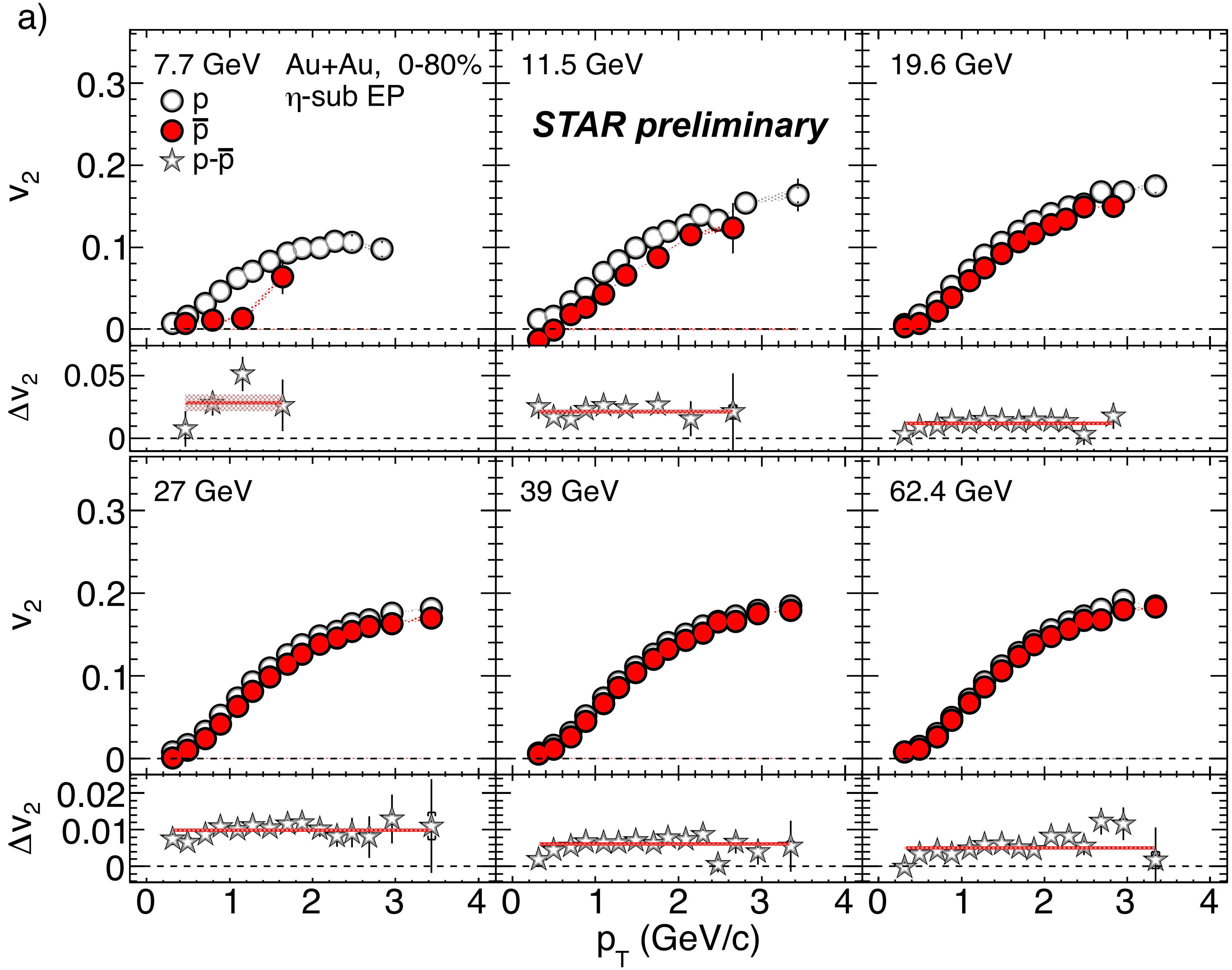
K. J. Wu, F. Liu and N. Xu,
J. Phys. G: Nucl. Part. Phys. 37 (2010) 094209

Energy dependence $v_2(p_T)$ - π



- Almost no difference at $\sqrt{s_{NN}}$ = 7.7-62.4 GeV

Energy dependence $v_2(p_T)$ - p, Λ



- Difference between baryons and anti-baryons increase as decreasing beam energy

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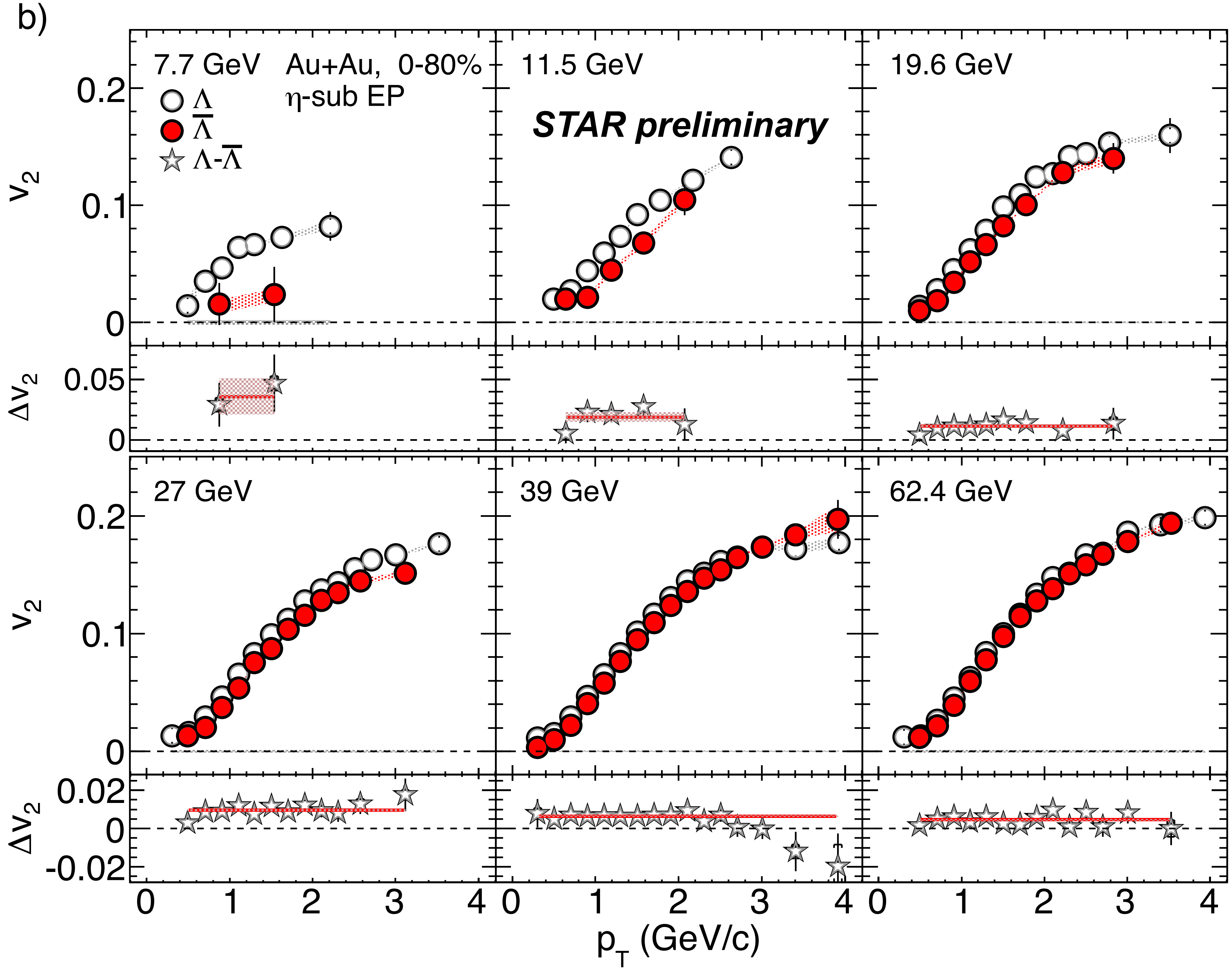

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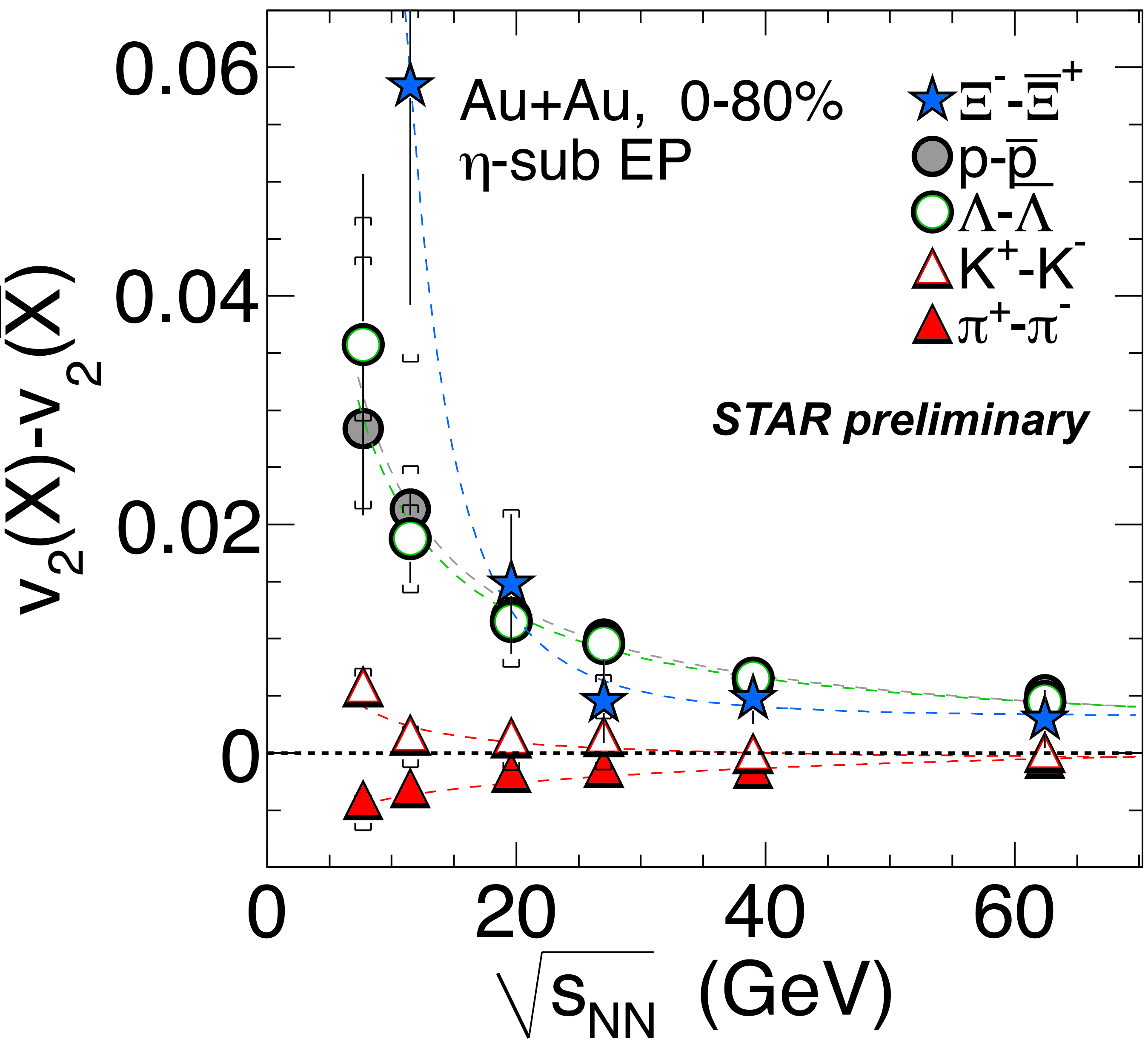
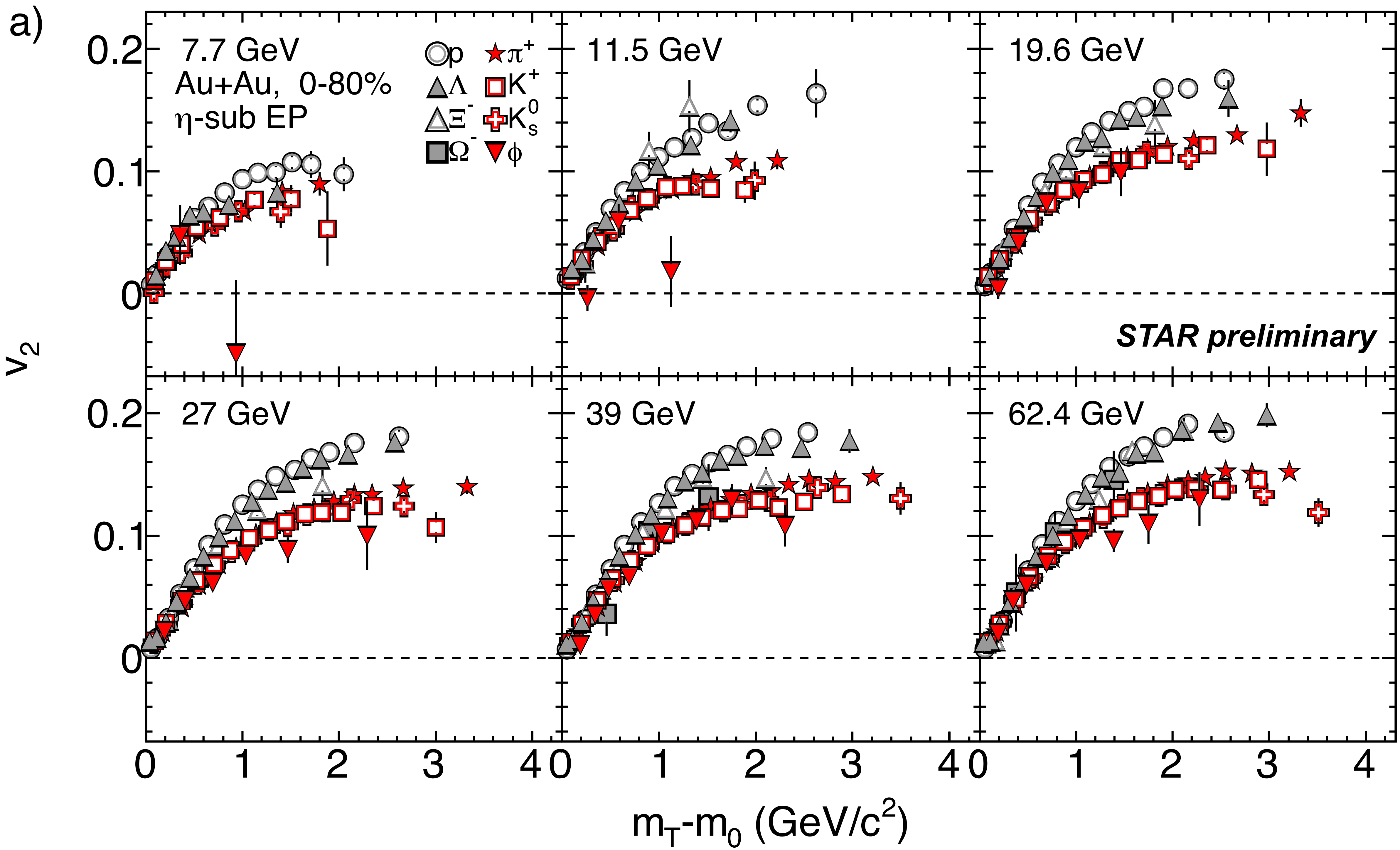
Difference of v_2



- Significant difference of v_2 between baryons and anti-baryons
- Small difference for mesons

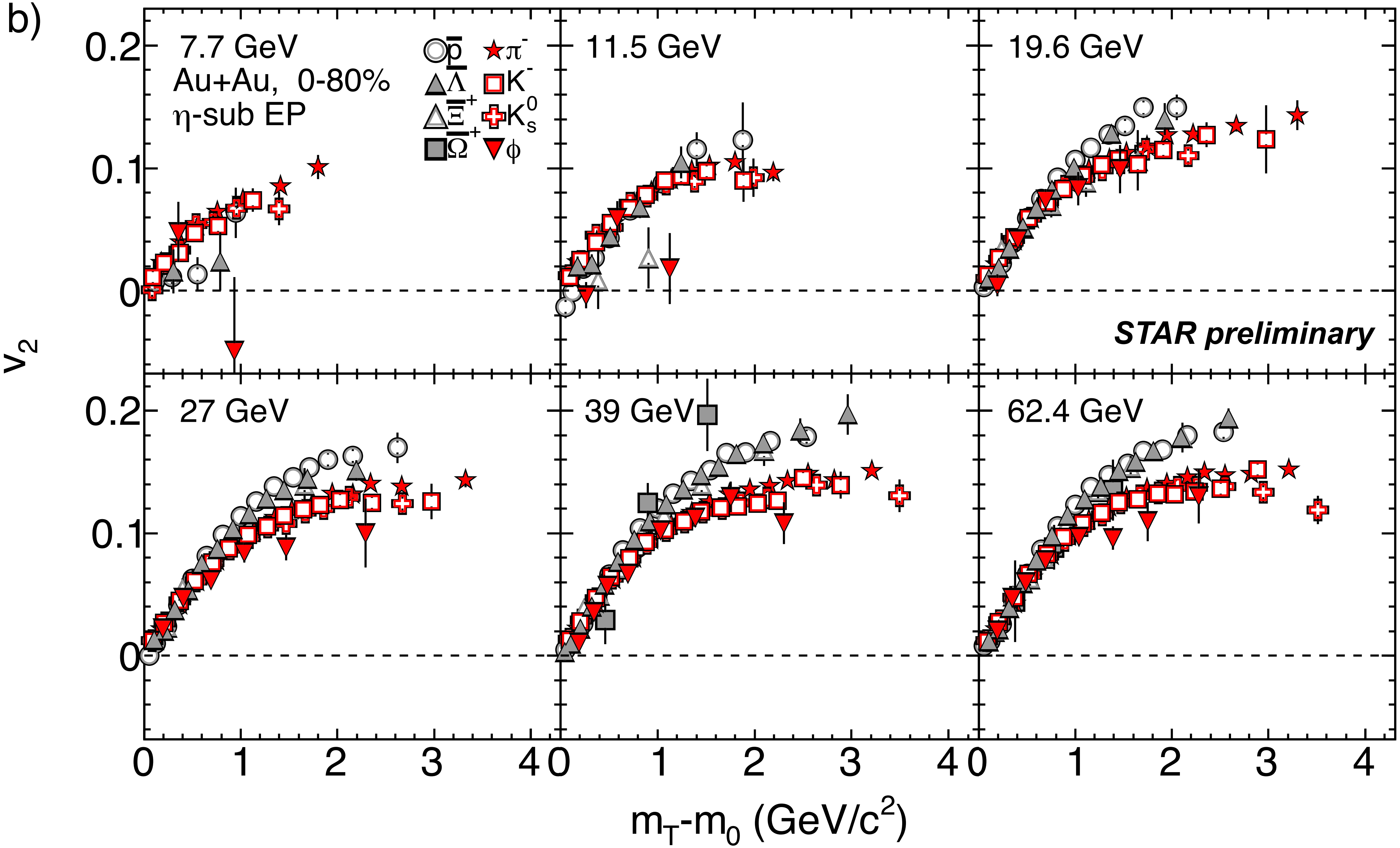
➡ NCQ scaling breaks down between particles and anti-particles

Test NCQ scaling



- Splitting decreases with decreasing energy, and disappears at 11.5 GeV for anti-particles

Test NCQ scaling



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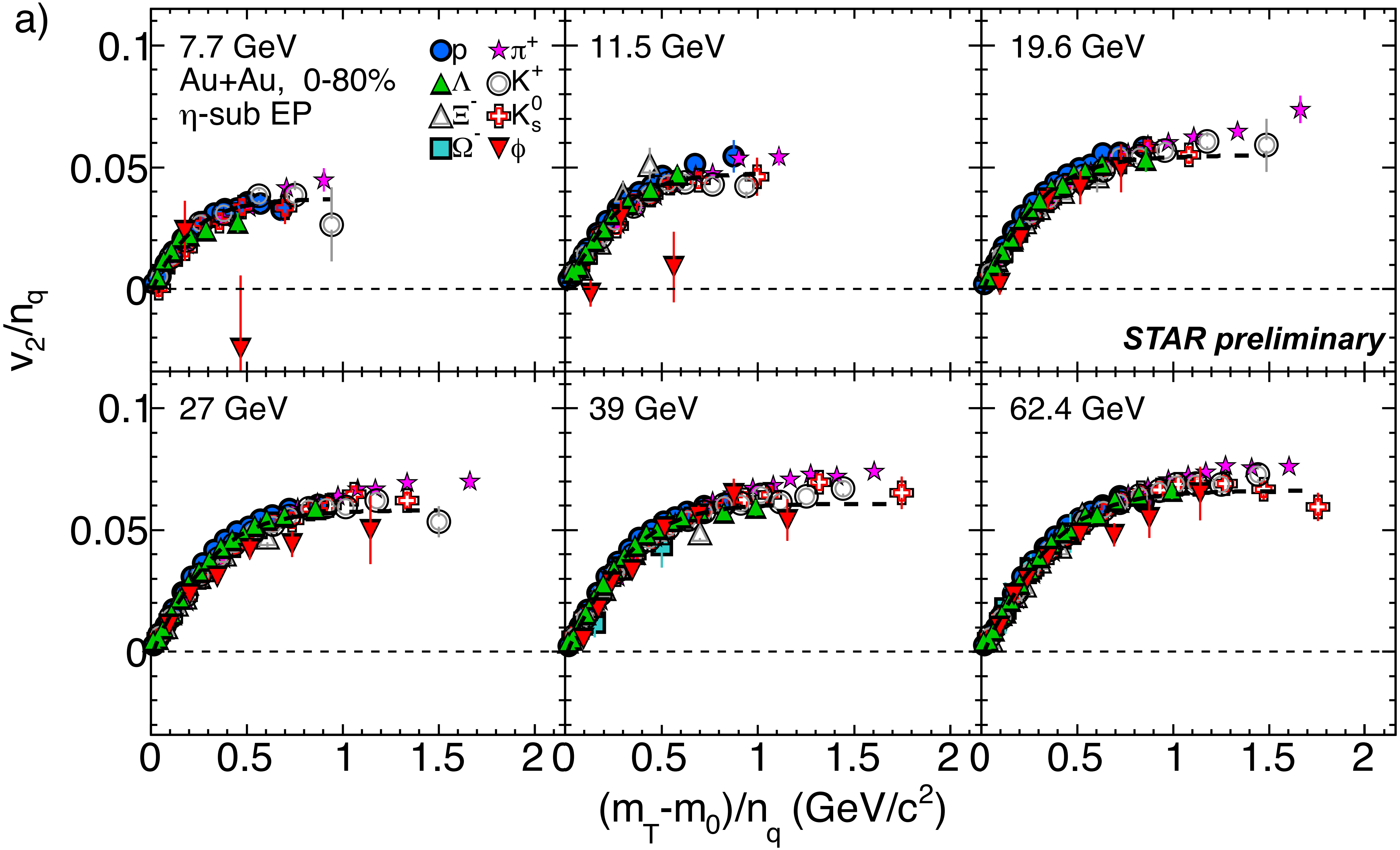
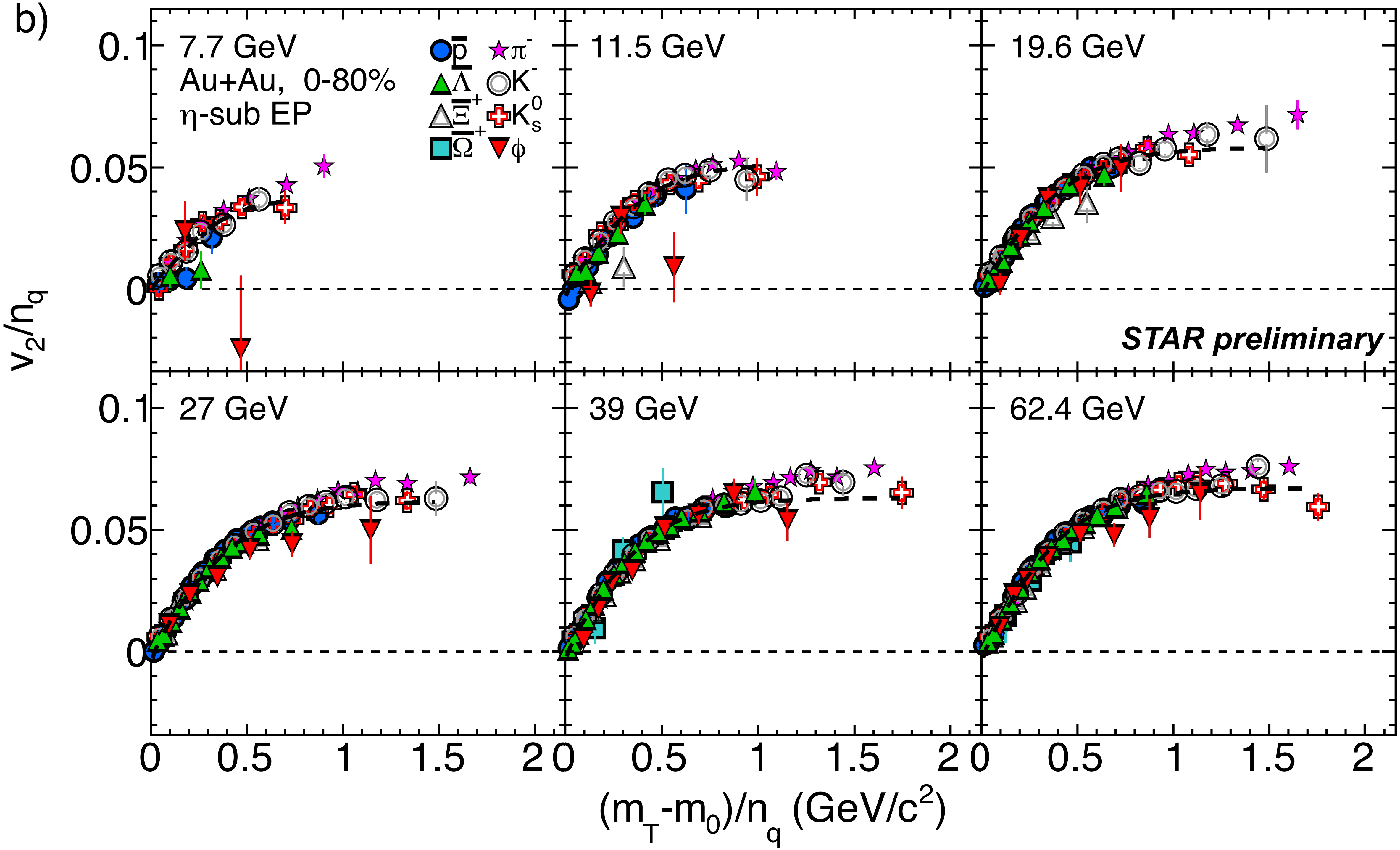


- Scaling seems to hold in this representation
- ϕ meson does not follow the trend at highest p_T

Test NCQ scaling



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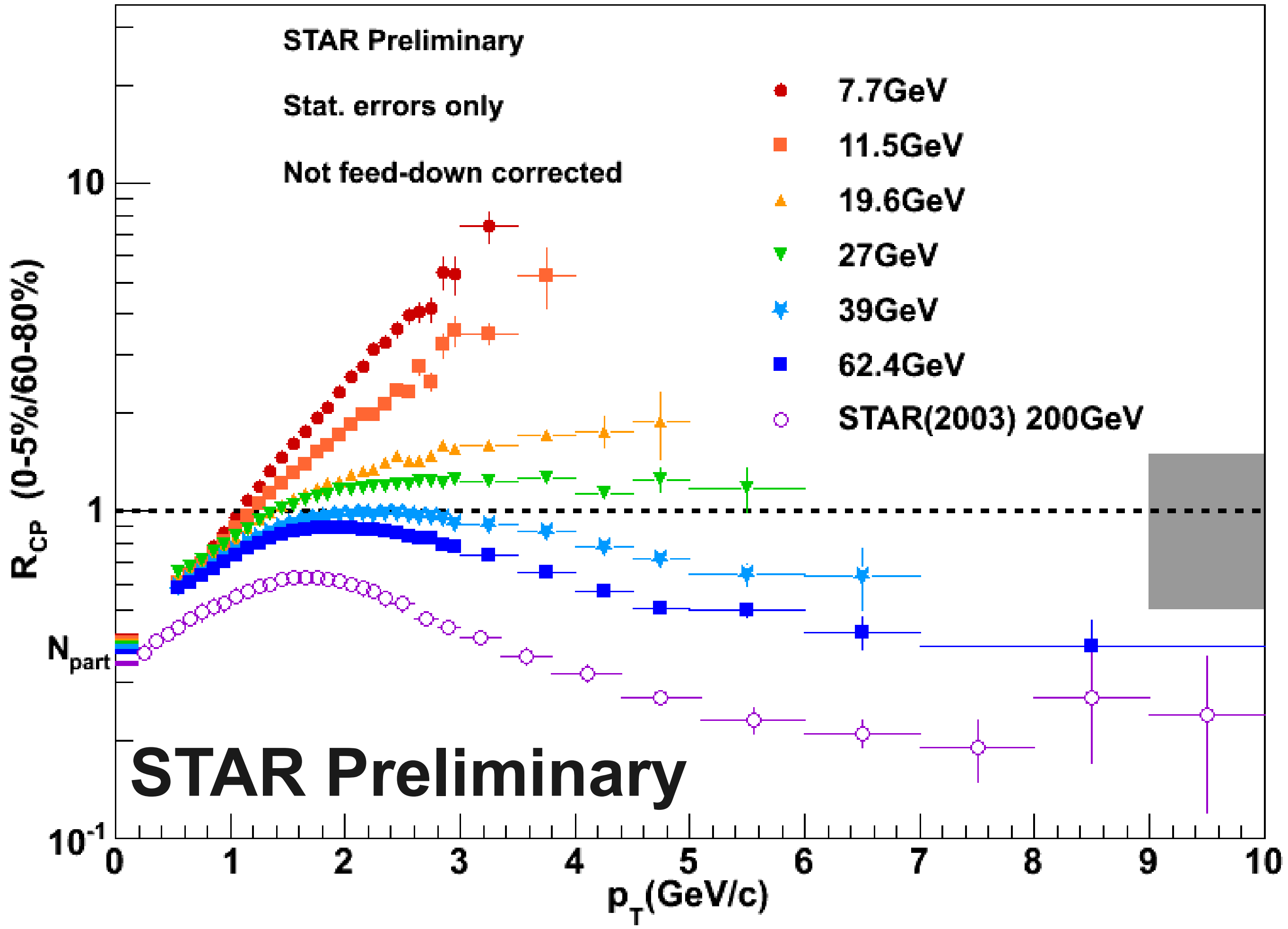
- φ meson does not follow the trend at highest p_T

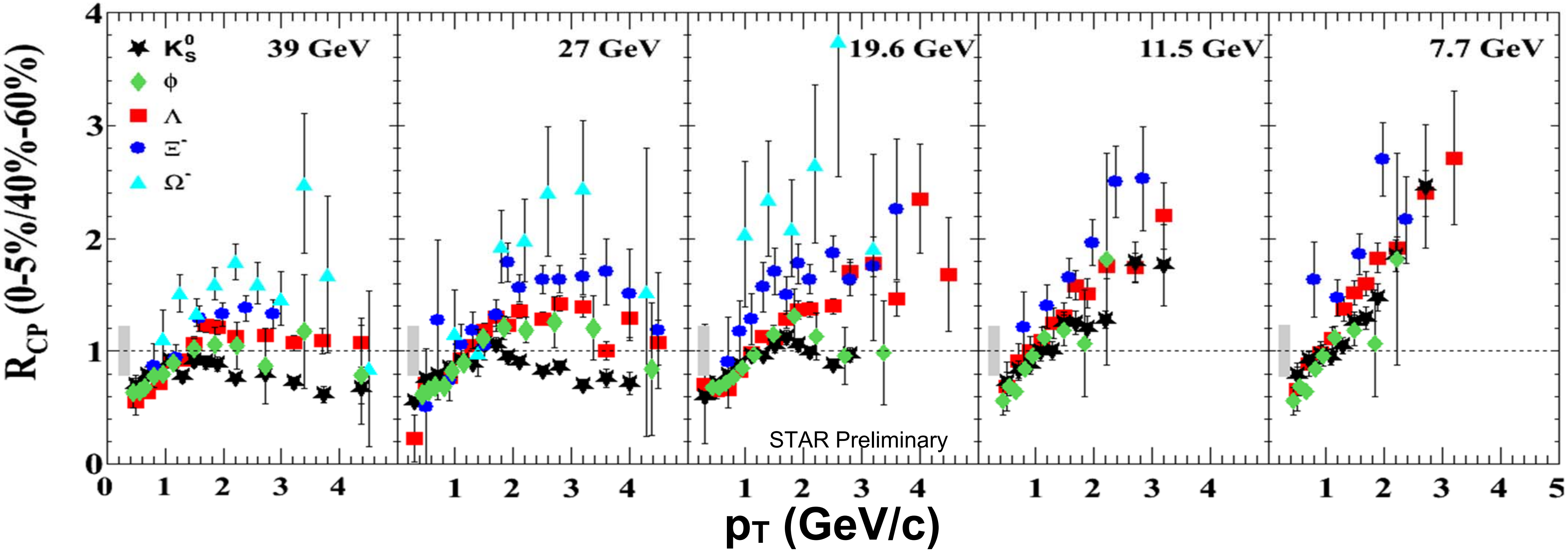
R_{cp} for charged hadrons



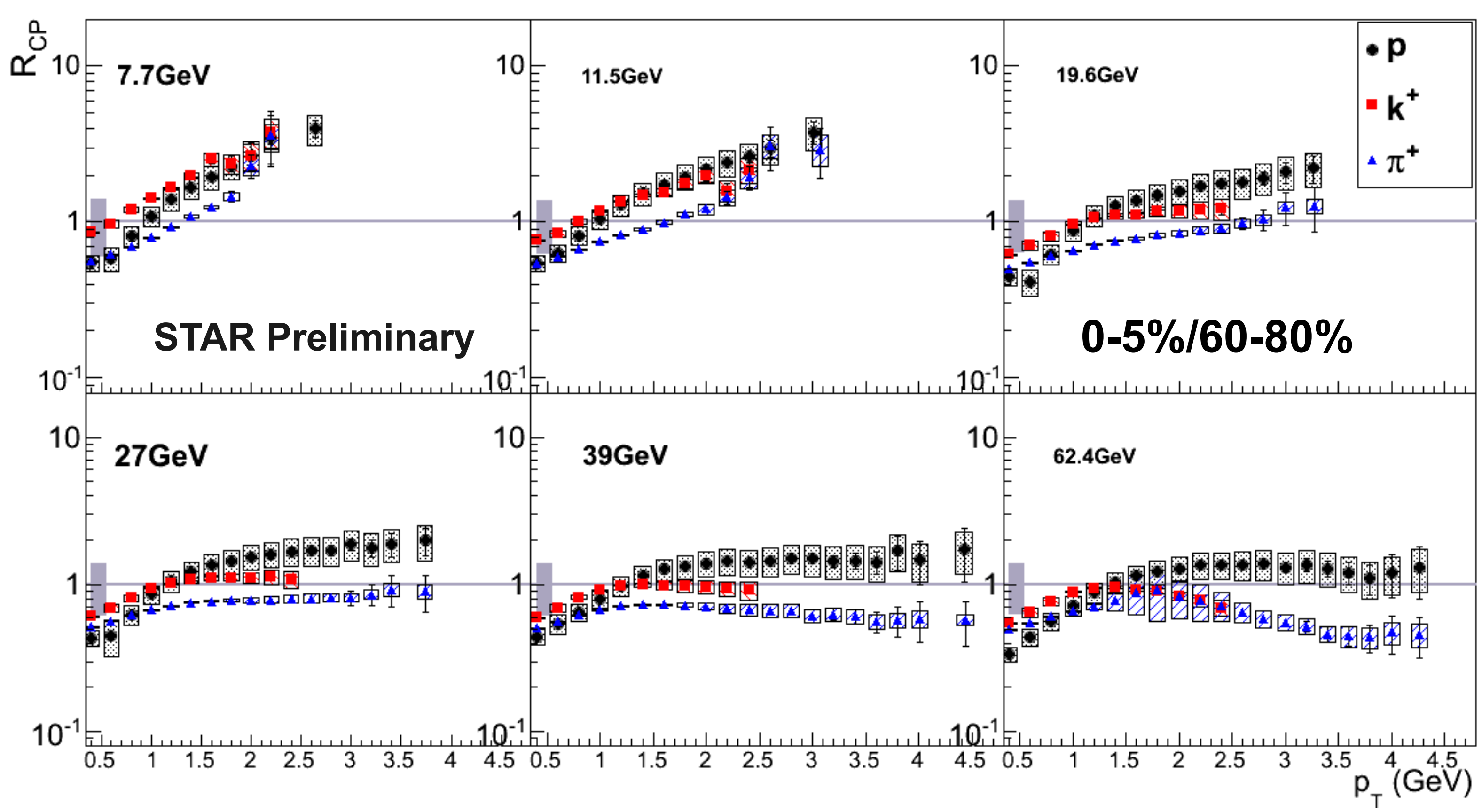
$$R_{cp}(p_T) = \frac{\left(\frac{d^2N^{A+A}}{\langle N_{coll}\rangle\, dp_T dy}\right)_{central}}{\left(\frac{d^2N^{A+A}}{\langle N_{coll}\rangle\, dp_T dy}\right)_{peripheral}}$$

- R_{cp} is statistically below unity for 39, 62.4, 200 GeV
- Smooth monotonic increase with decreasing energy
- High p_T suppression turns off at lower collisions energies

R_{cp} for identified hadrons

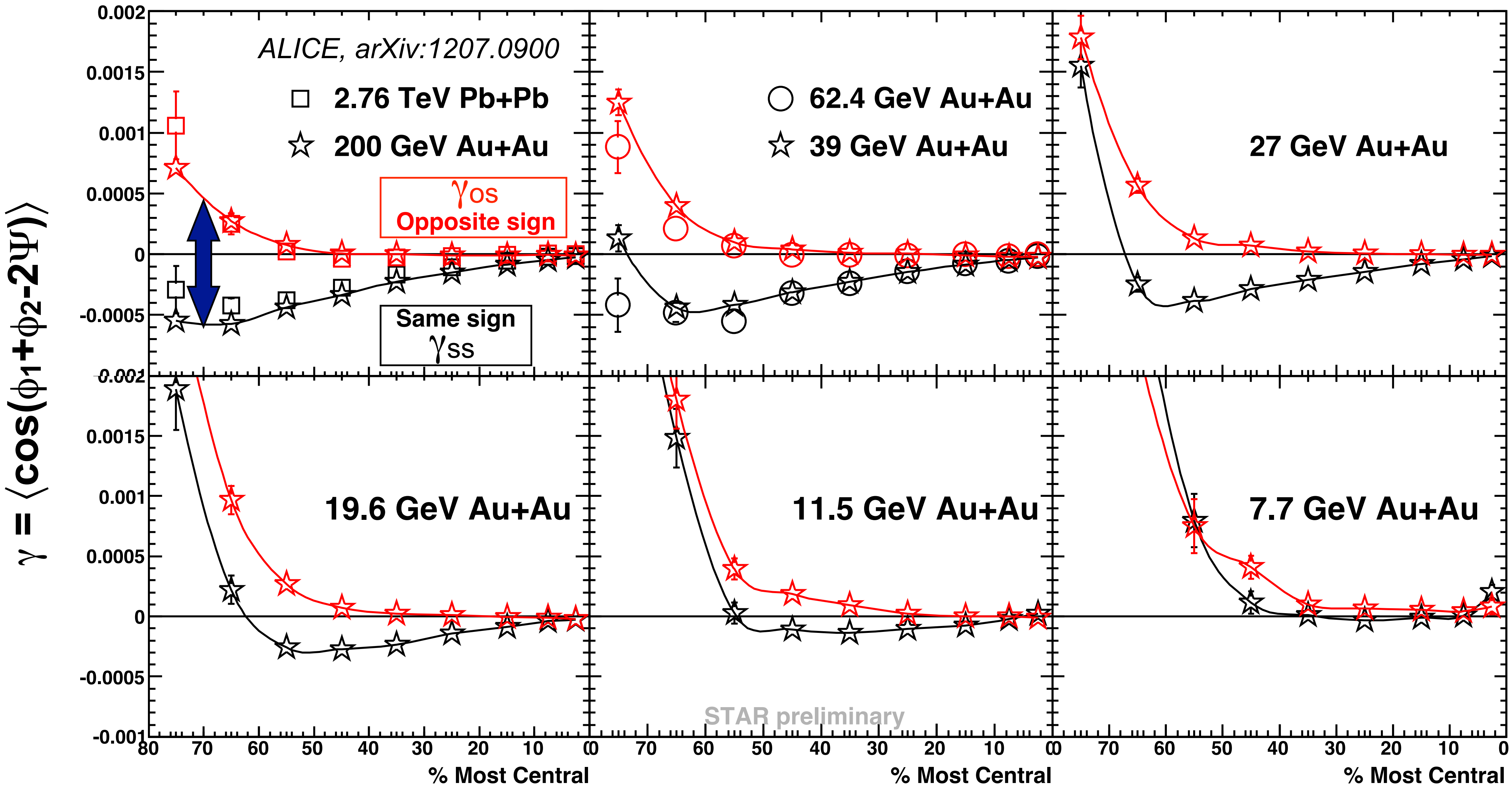


φ meson R_{cp}
0-10%/40-60%



- No K^0_S suppression at 7.7 and 11.5 GeV
- Particle type dependence becomes smaller at 7.7 and 11.5 GeV

Mixed harmonic correlation



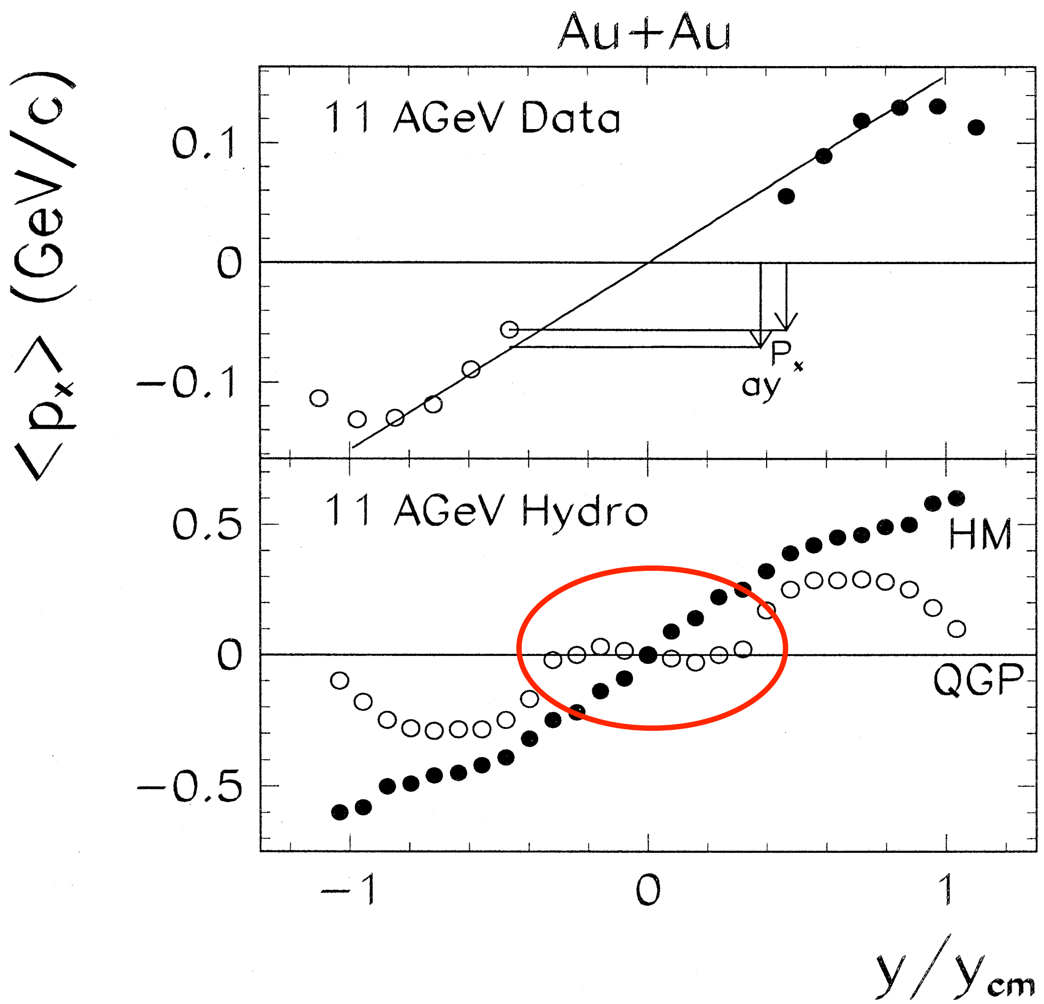
- Charge separation (γ_{OS}-γ_{SS}) decreases with decreasing energy, disappears in s_{NN} 11.5 GeV

Search for 1st order phase transition

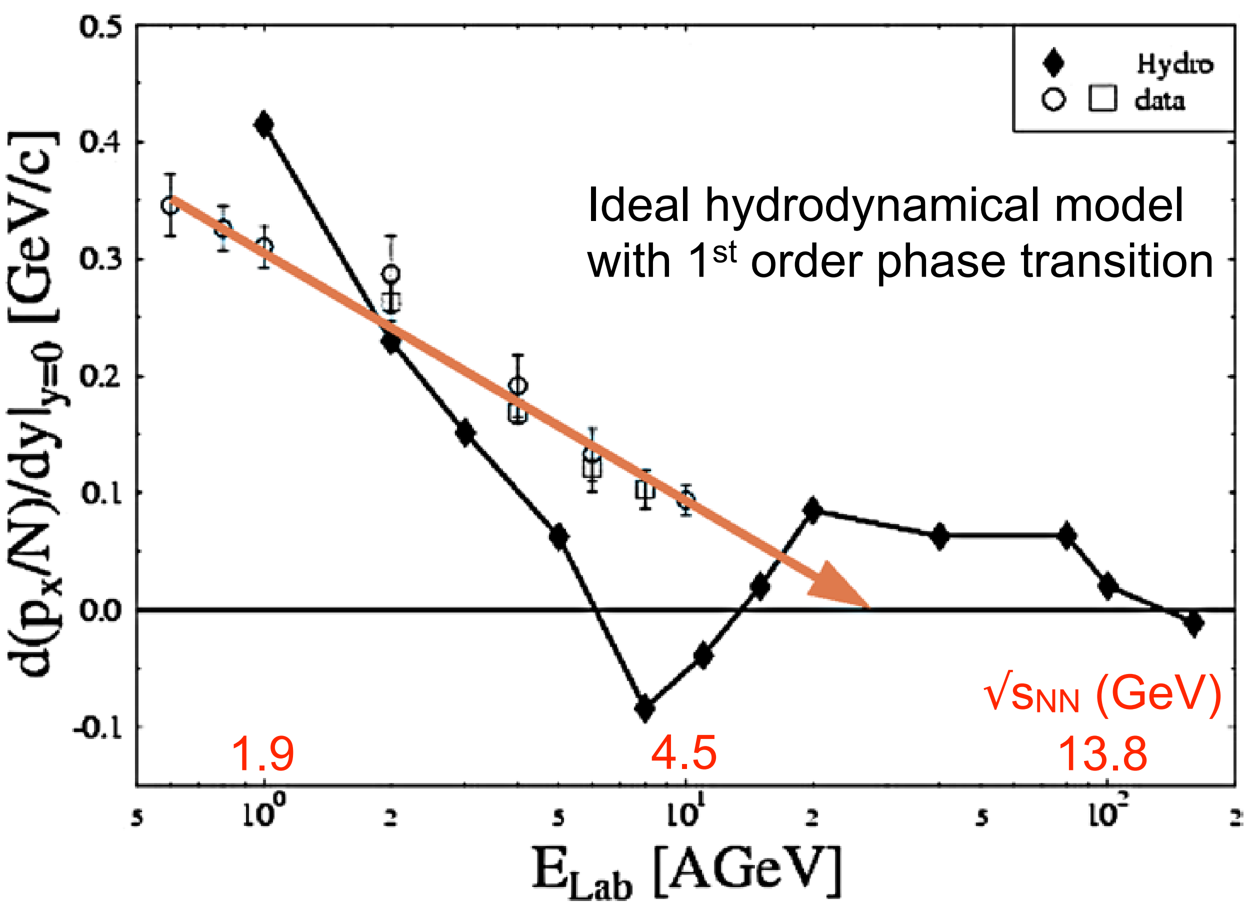
- Directed flow v_1
- azimuthal HBT

Directed flow v_1 - early predictions

*L. P. Csernai, D. Rohrich, PLB**458**, 454 (1999)*

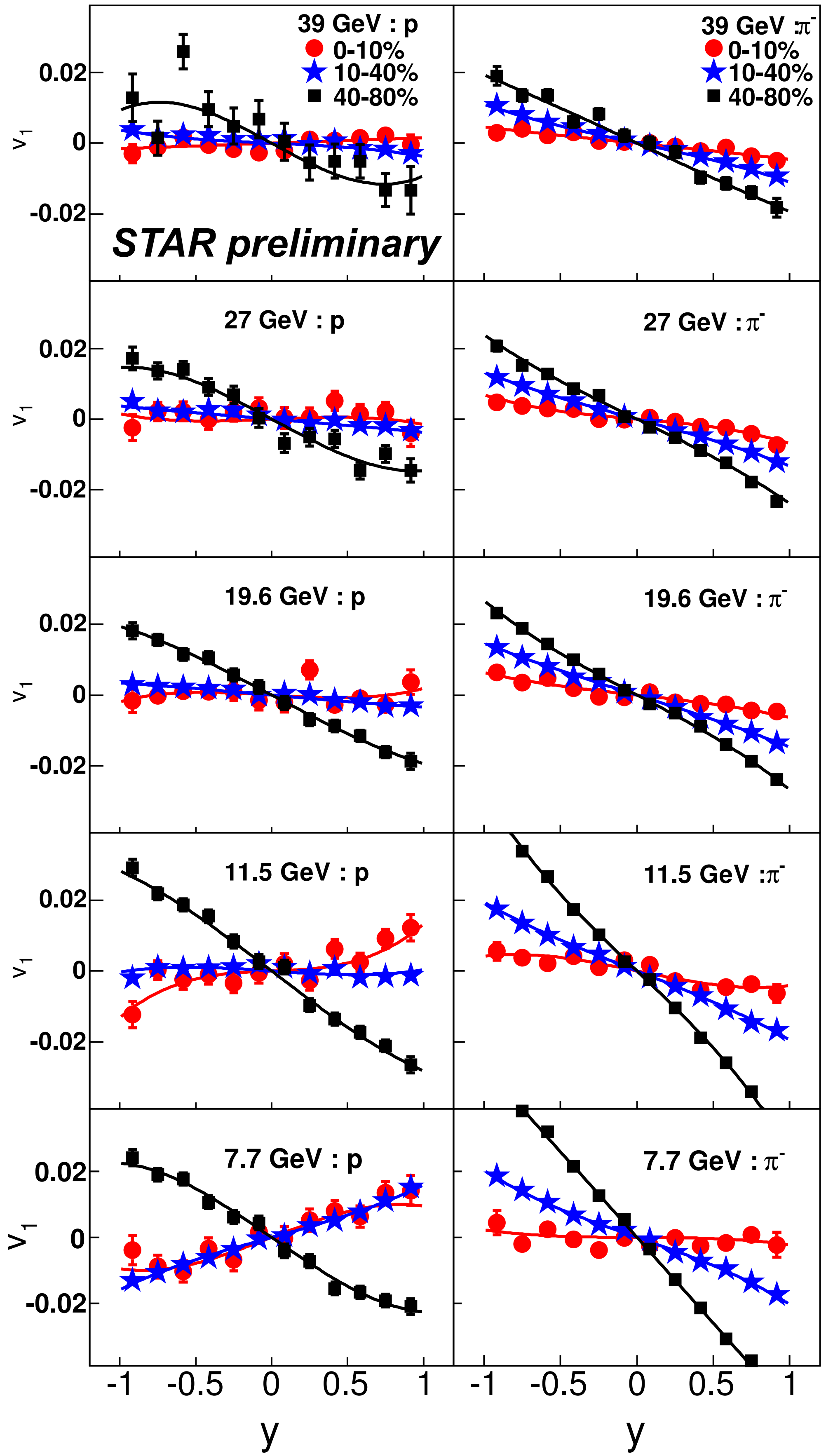


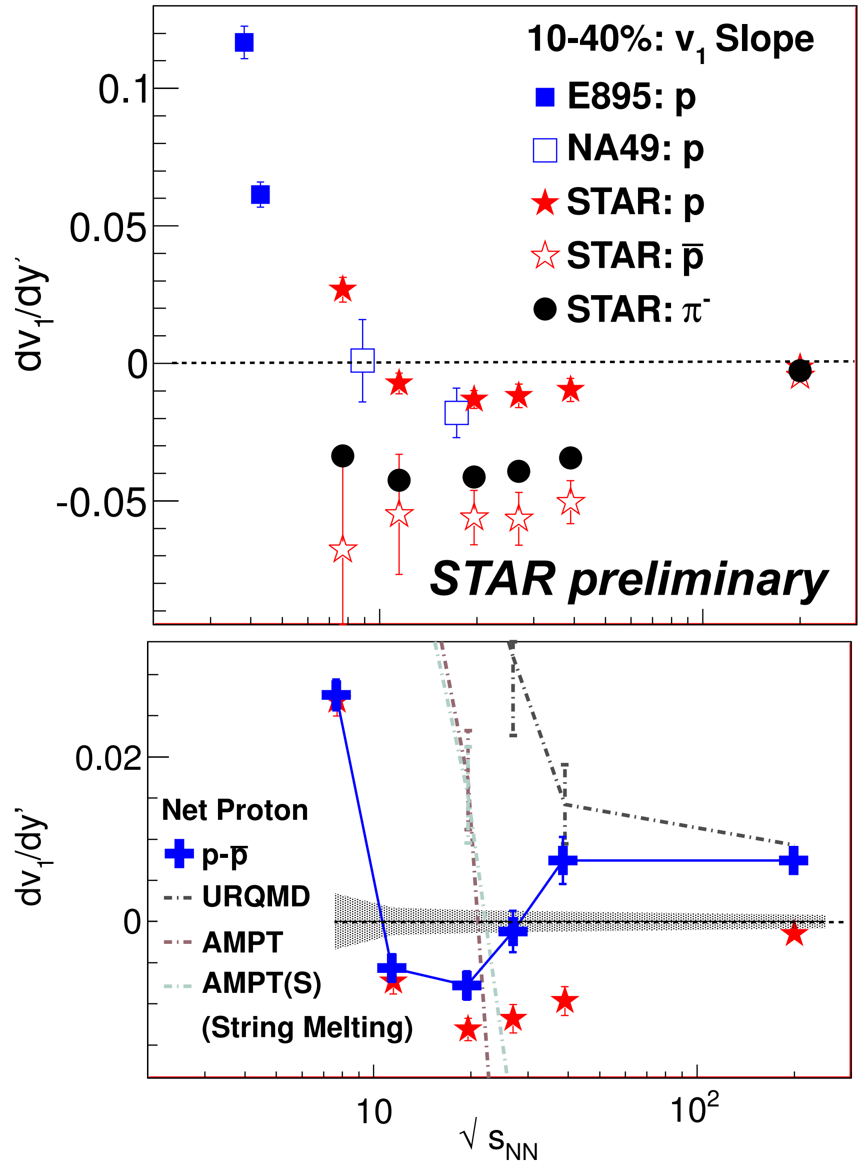
*H. Stocker, NPA**750**, 121 (2005)*



- Linear rapidity dependence without QGP at low energy
  - "Bounce-off" of spectators
- v_1 slope becomes flat with 1st order phase transition
  - Early predictions show minimum around $\sqrt{s_{NN}}$ ~5 GeV

Excitation function of v_1 & dv_1/dy

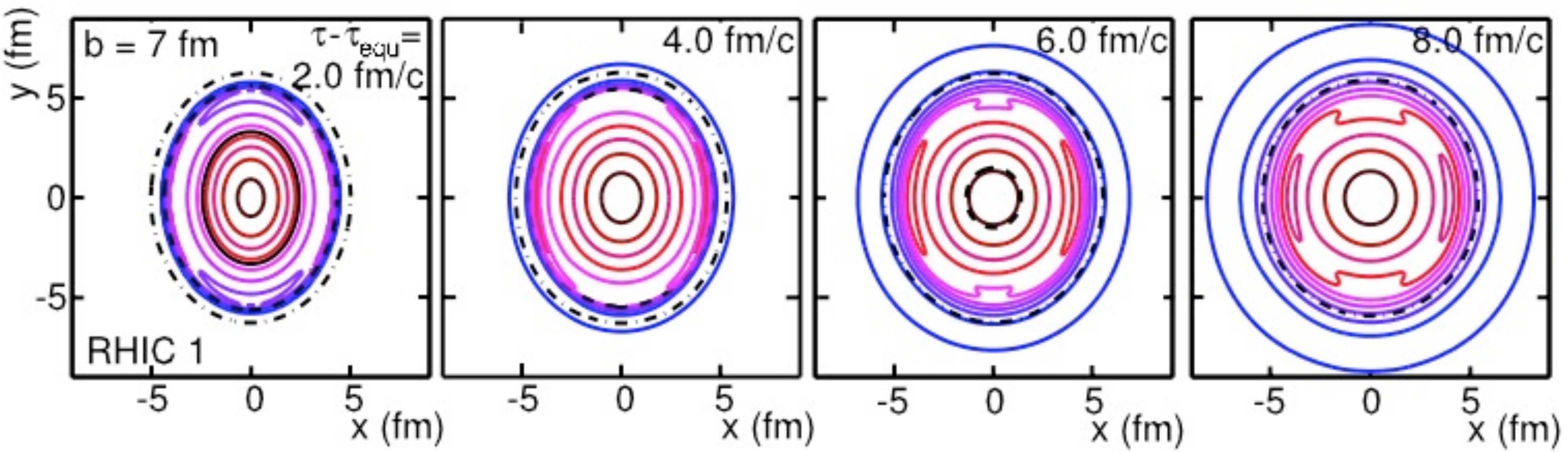


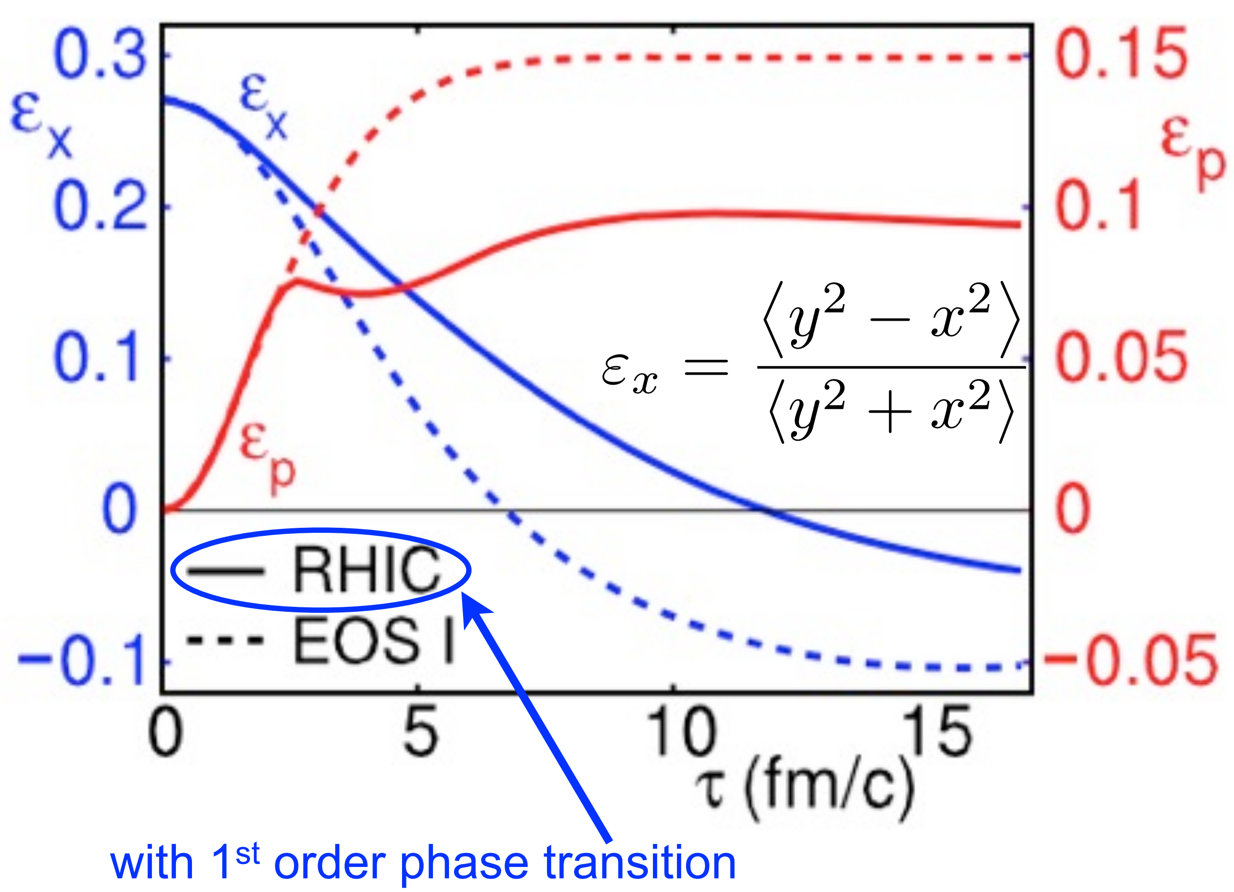


- Non-monotonic behavior for net-proton v_1 slope
- Cascade models (UrQMD, AMPT) can't describe the data

Evolution of initial spatial anisotropy

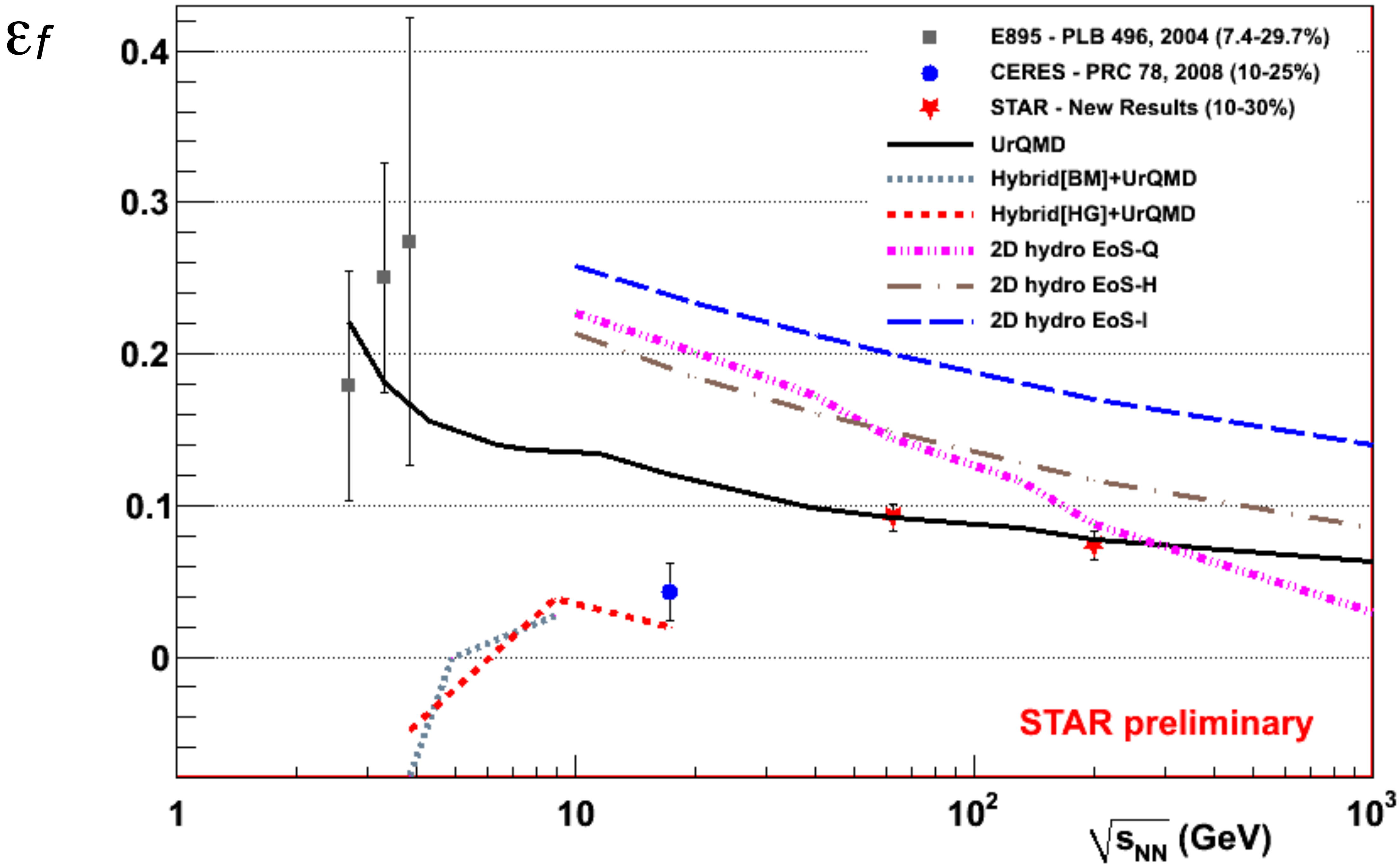
*P. F. Kolb et al, PRC**62**, 054909 (2000)*





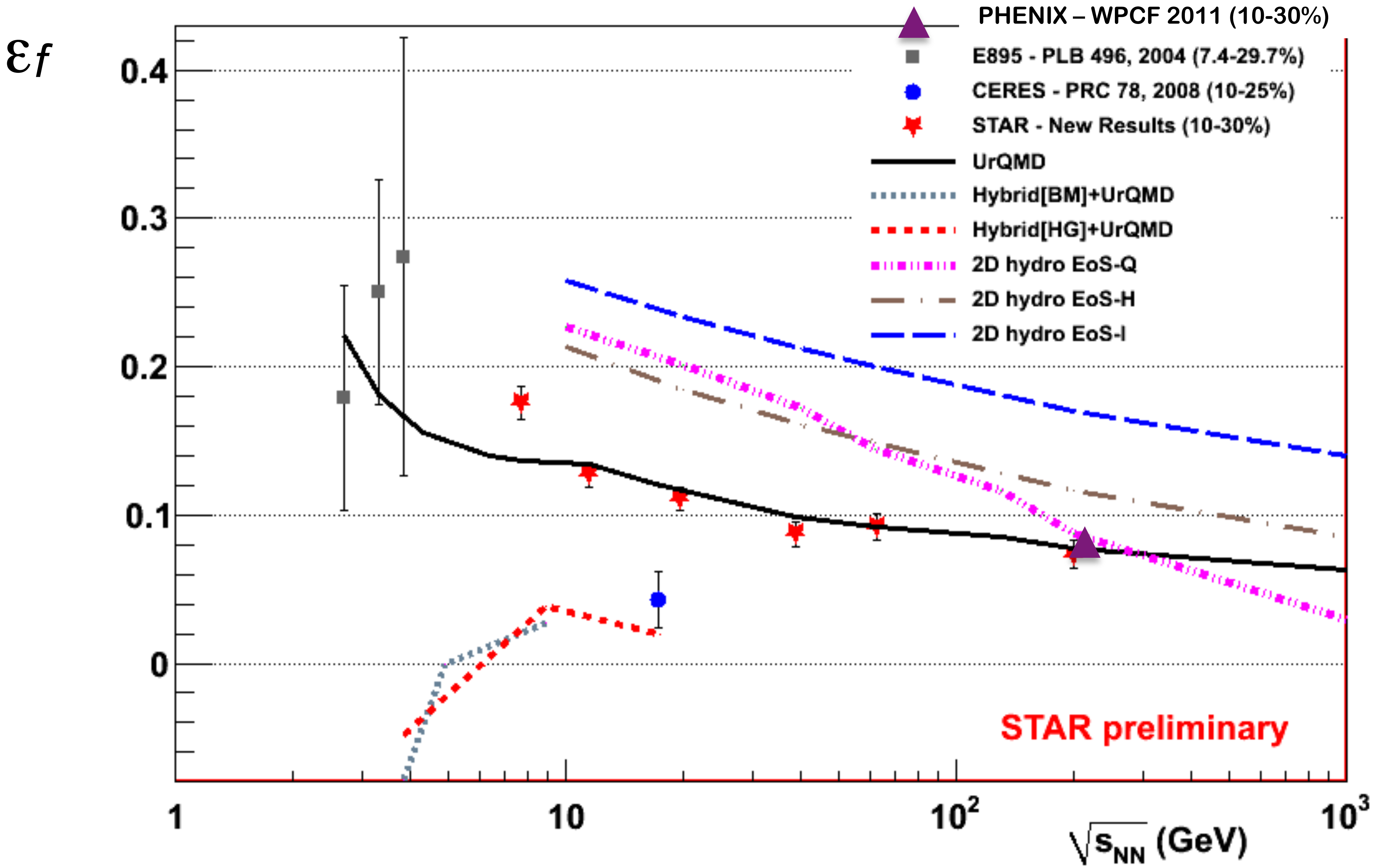
- Spatial anisotropy (eccentricity) is sensitive to EOS
- Non-monotonic behavior could indicate the softest point of EOS

Freeze-out eccentricity (-2010)



- Minimum around 20 GeV ??

Freeze-out eccentricity from BES, STAR

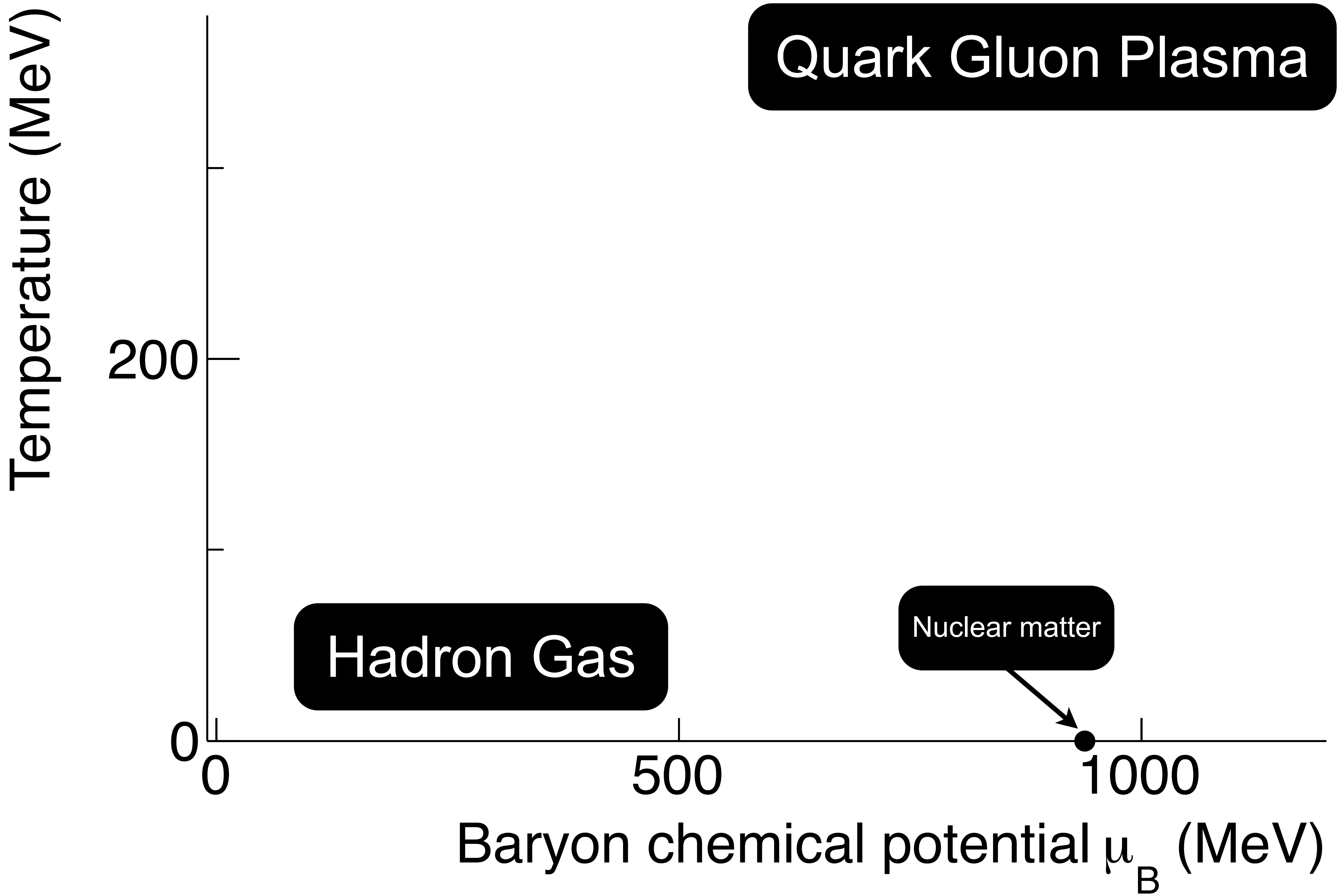


- Monotonic decrease from 7.7 to 200 GeV from STAR
  - No minimum around 20 GeV

Search for QCD critical point

- Moment of multiplicity distribution for conserved quantities

Critical point search



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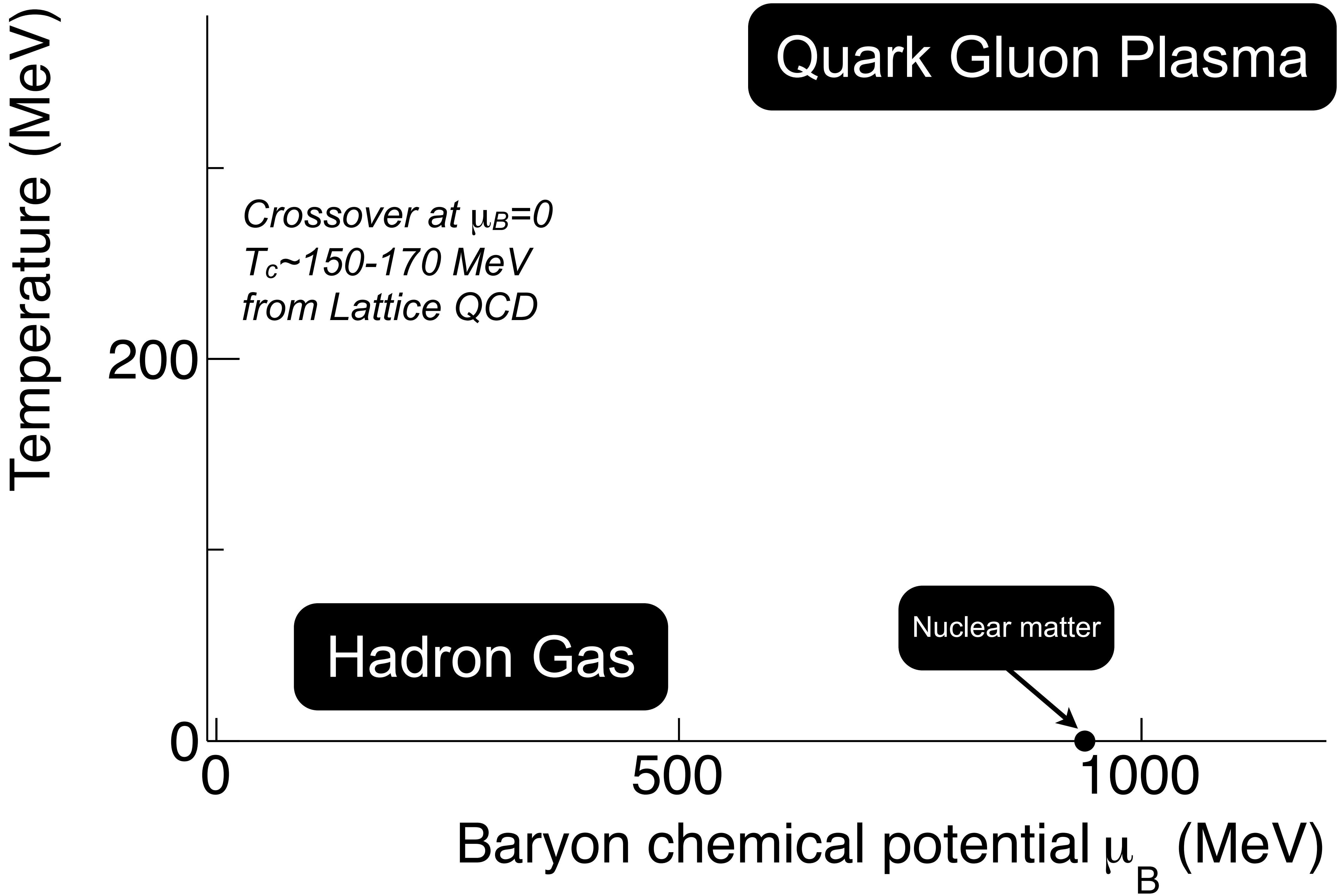

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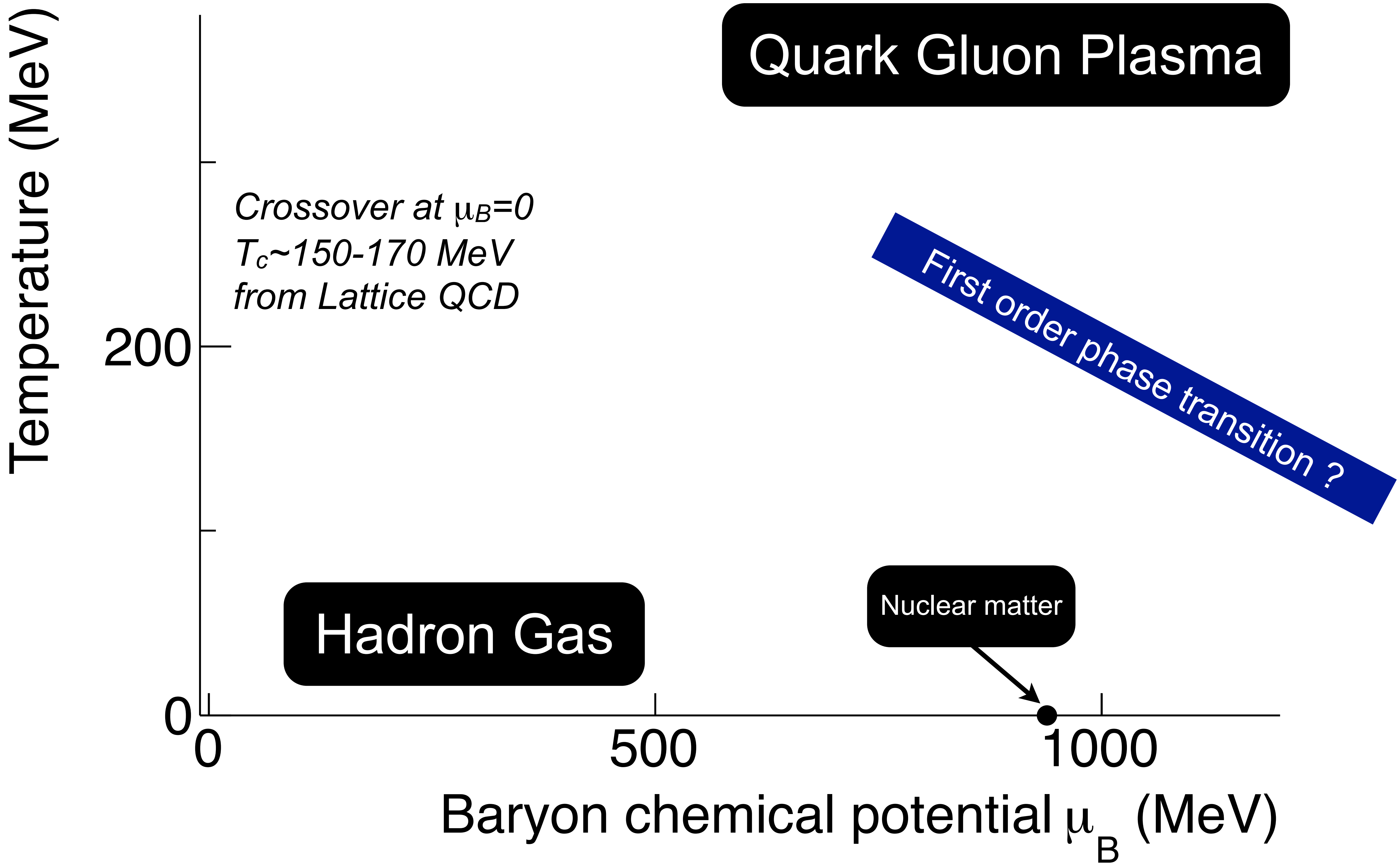

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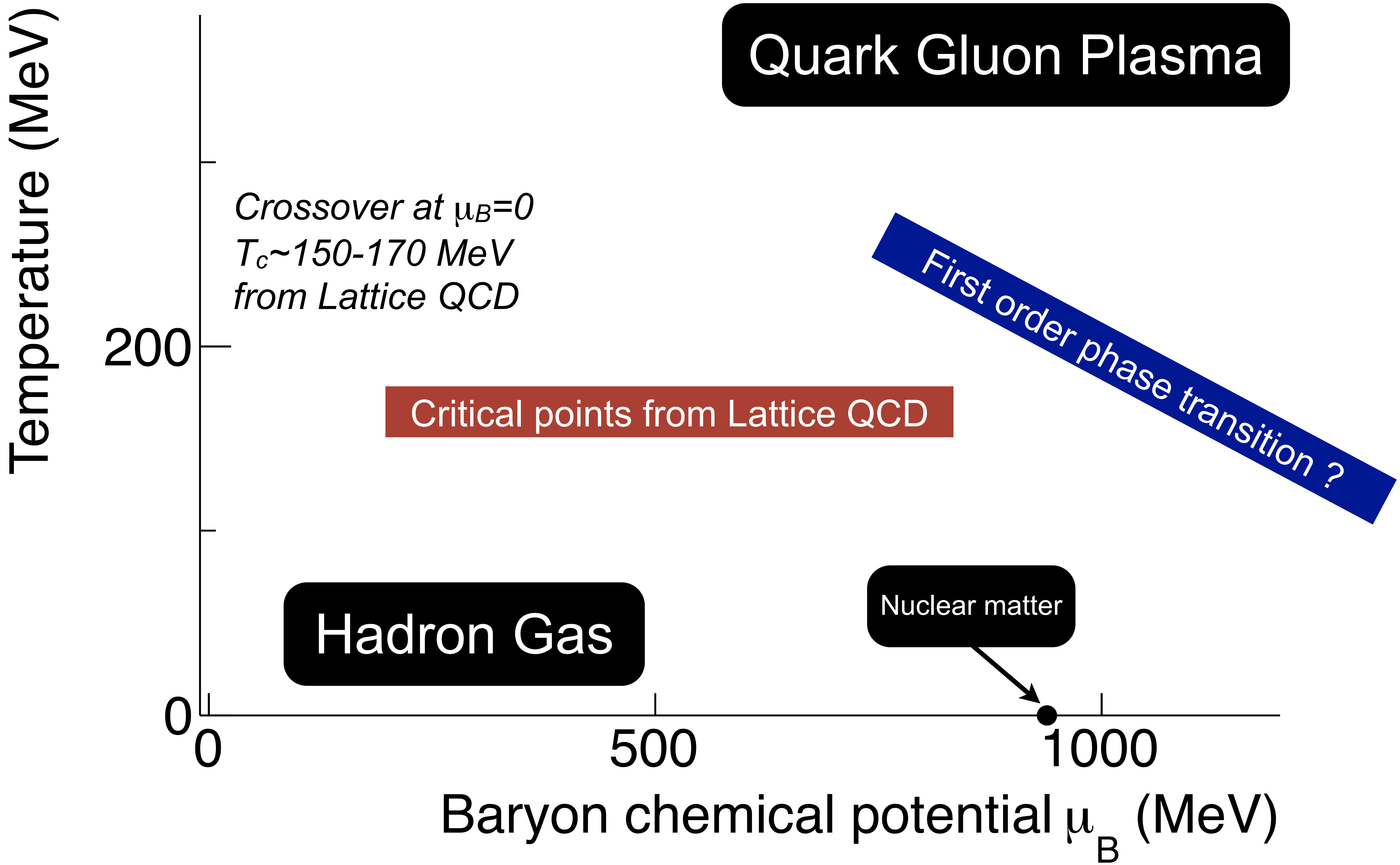

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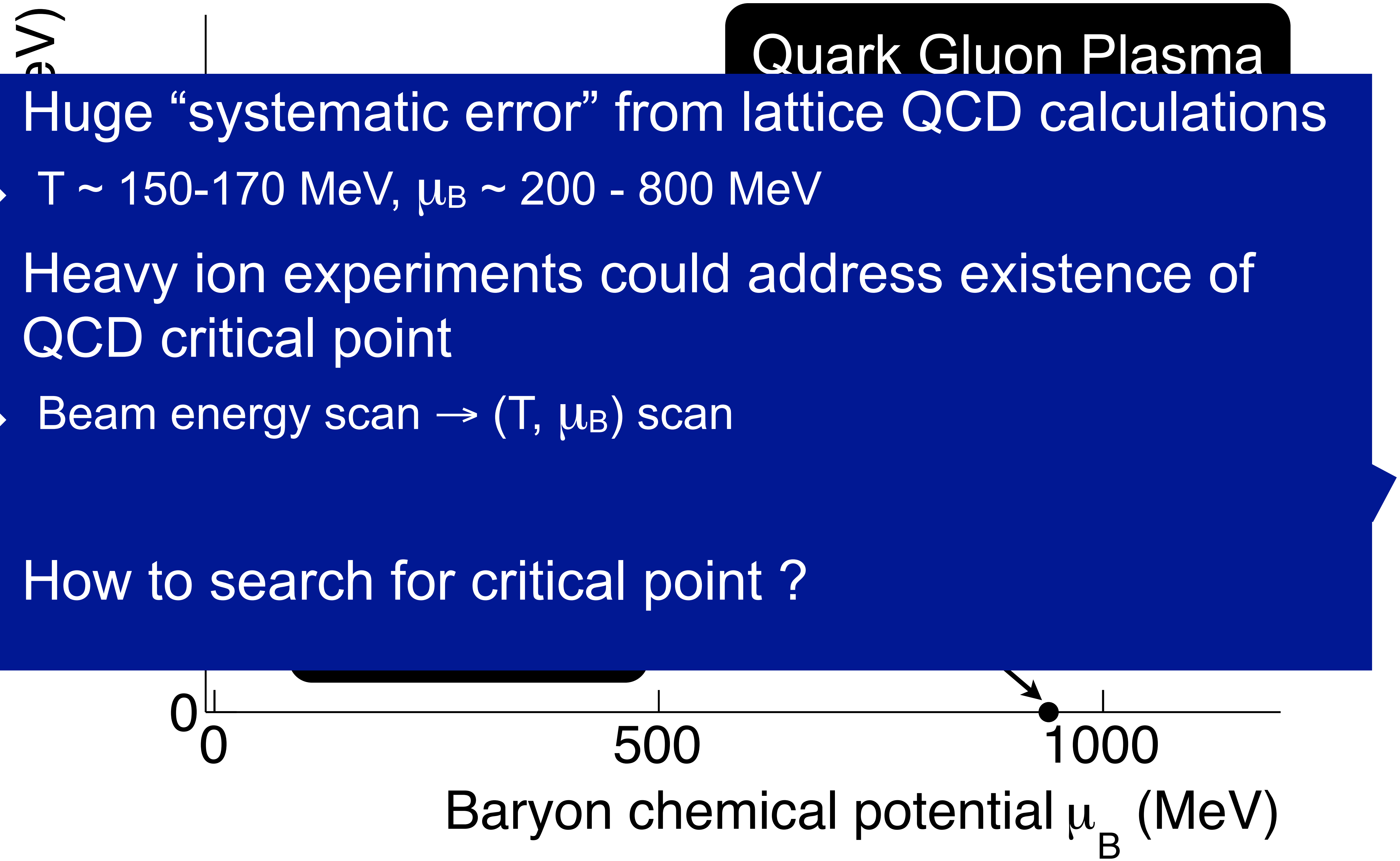


- Huge "systematic error" from lattice QCD calculations
  - T ~ 150-170 MeV, μ_B ~ 200 - 800 MeV
- Heavy ion experiments could address existence of QCD critical point
  - Beam energy scan → (T, μ_B) scan
- How to search for critical point ?

Signatures of critical point

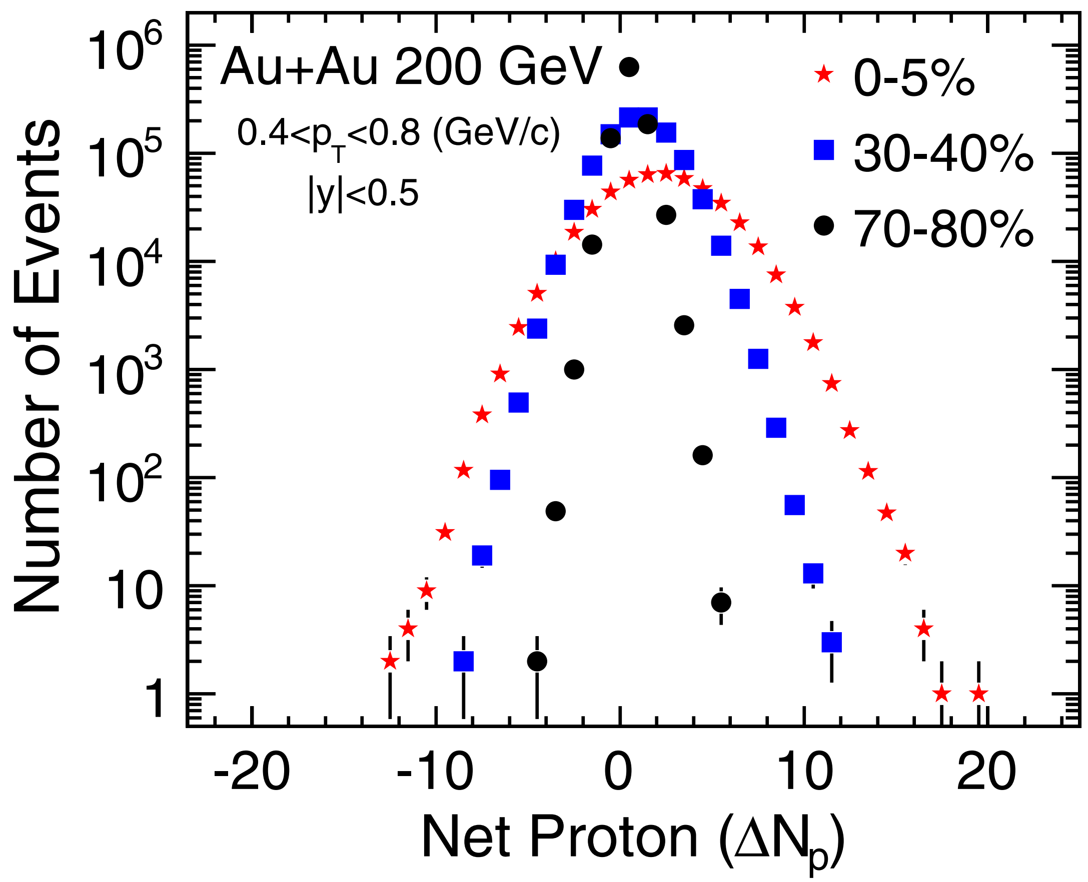
- Second order phase transition at critical point
  - ***A divergent susceptibility, an infinite correlation length***, and a power-law decay of correlations near criticality
- Ratio of susceptibilities ↔ ***product of moments (or ratio of cumulants)***

*M. A. Stephanov, PRL**102**, 032301 (2009),*
*C. Athanasiou et al, PRD**82**, 074008 (2010)*

  - ***"Higher" moments*** (3rd, 4th, ...) show stronger sensitivity on correlation length
- Critical point search at STAR
  - Measure product of moments for (proxy of) conserved quantities as a function of beam energy
  - Non-monotonic behavior of these observables will be the signature of QCD critical point

Experimental observables

STAR, PRL**105**, 022302 (2010)



$$\kappa_2 \equiv \langle(\delta x)^2\rangle \sim \xi^2, \kappa_3 \equiv \langle(\delta x)^3\rangle \sim \xi^{4.5},$$

$$\kappa_4 \equiv \langle(\delta x)^4\rangle - 3\langle(\delta x)^2\rangle^2 \sim \xi^7$$

$$\delta x \equiv x - \langle x\rangle \,,$$

$$S = \frac{\kappa_3}{\kappa_2^{3/2}} \text{ (Skewness)}, \quad K = \frac{\kappa_4}{\kappa_2^2} \text{ (Kurtosis)}$$

Observables

$$S\sigma = \kappa_3/\kappa_2, \quad K\sigma^2 = \kappa_4/\kappa_2$$

$$S\sigma \sim \chi^{(3)}/\chi^{(2)}, \quad K\sigma^2 \sim \chi^{(4)}/\chi^{(2)}$$

- Higher order cumulants scale with higher powers of correlation length
  - sensitive to critical point induced fluctuations
- Use product of moments (cancel volume effect)
  - Related to ratio of susceptibilities

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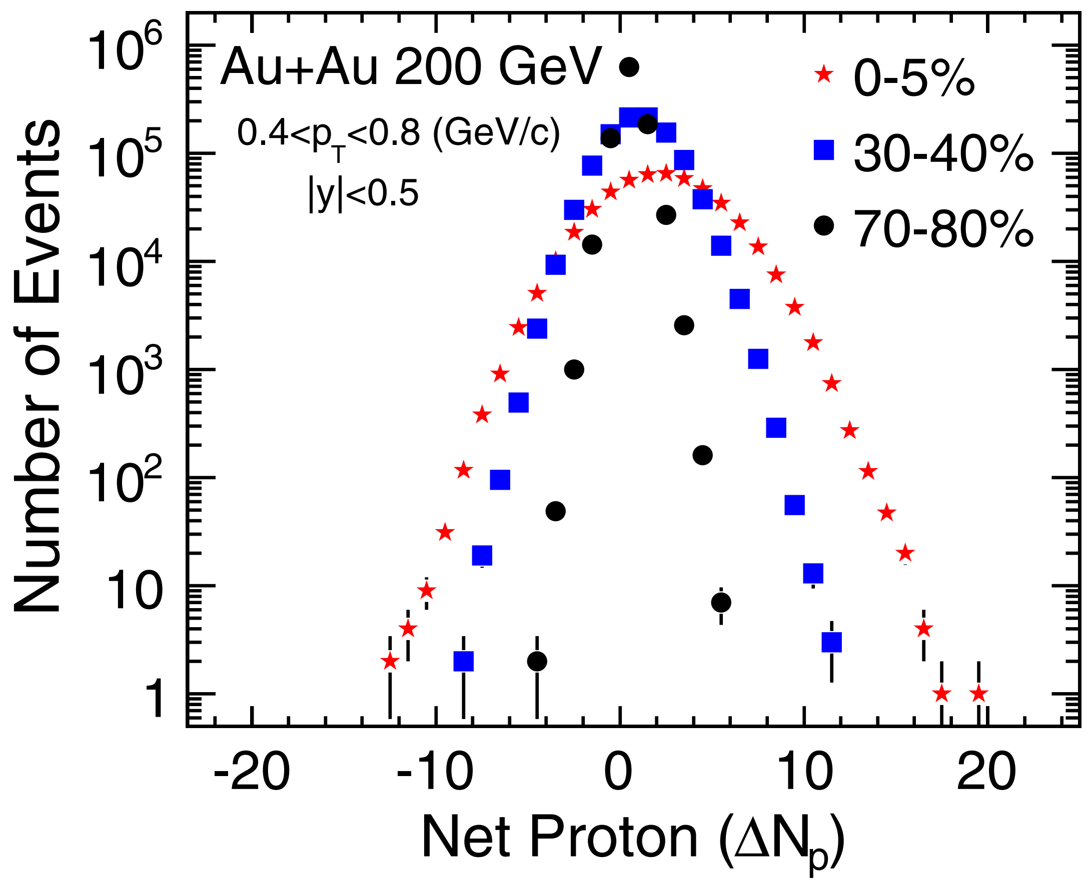

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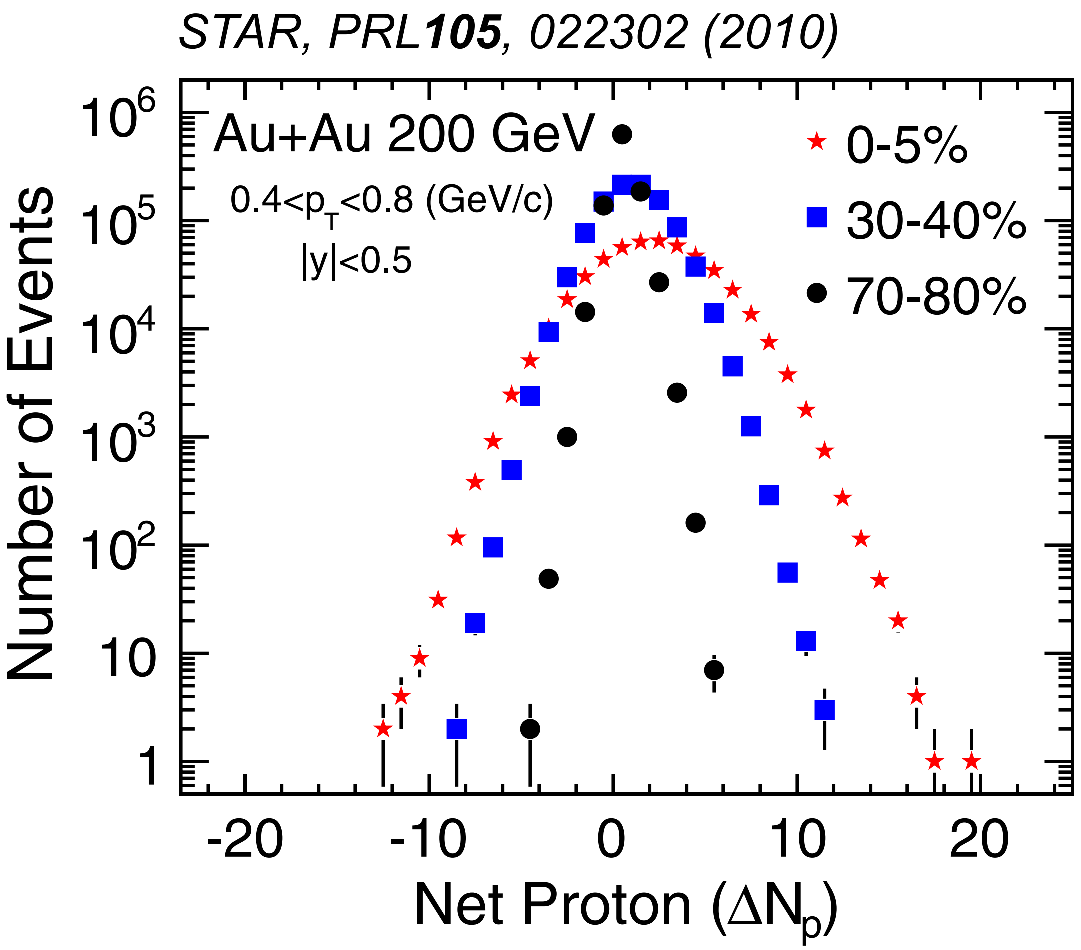

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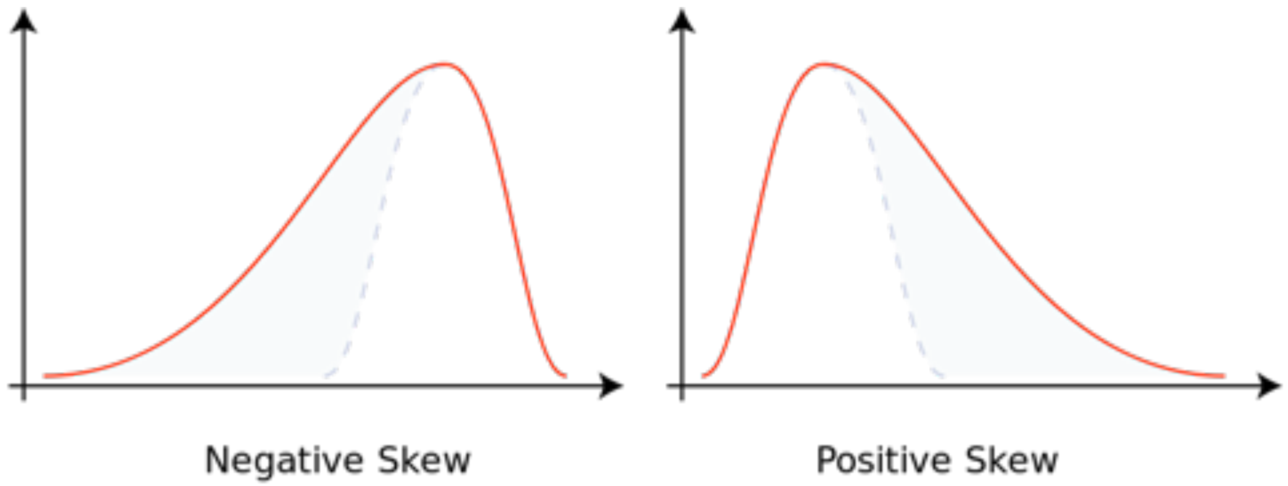
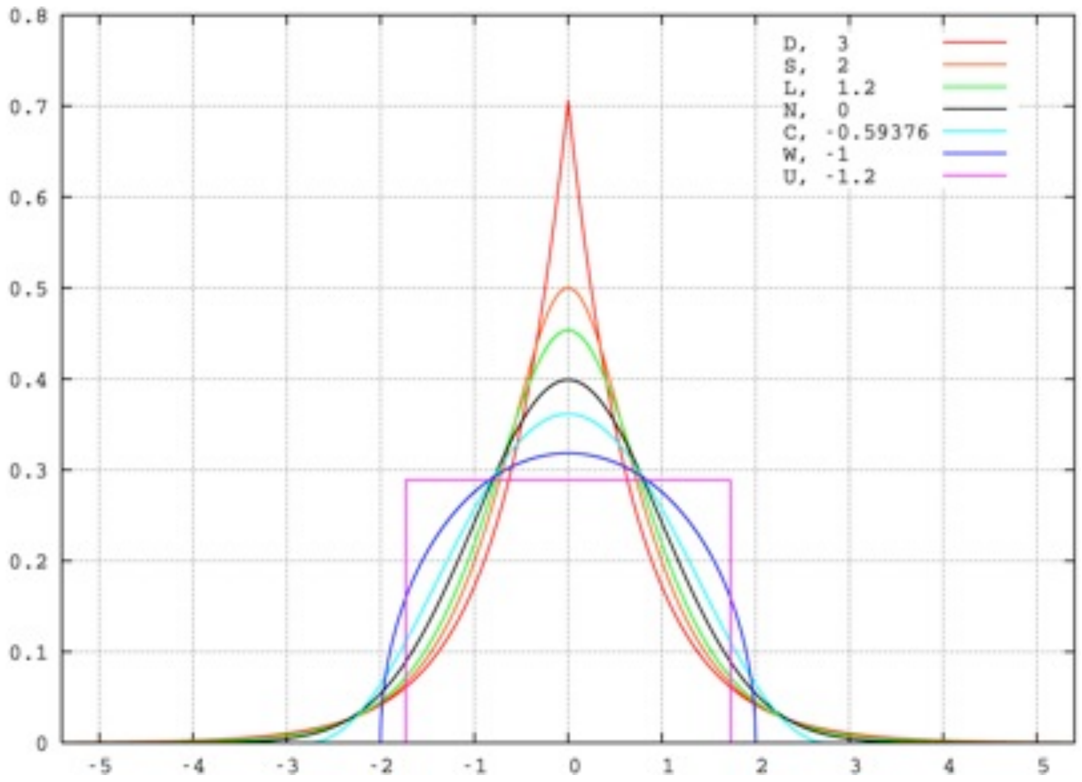
Non-gaussian fluctuations

From Wikipedia

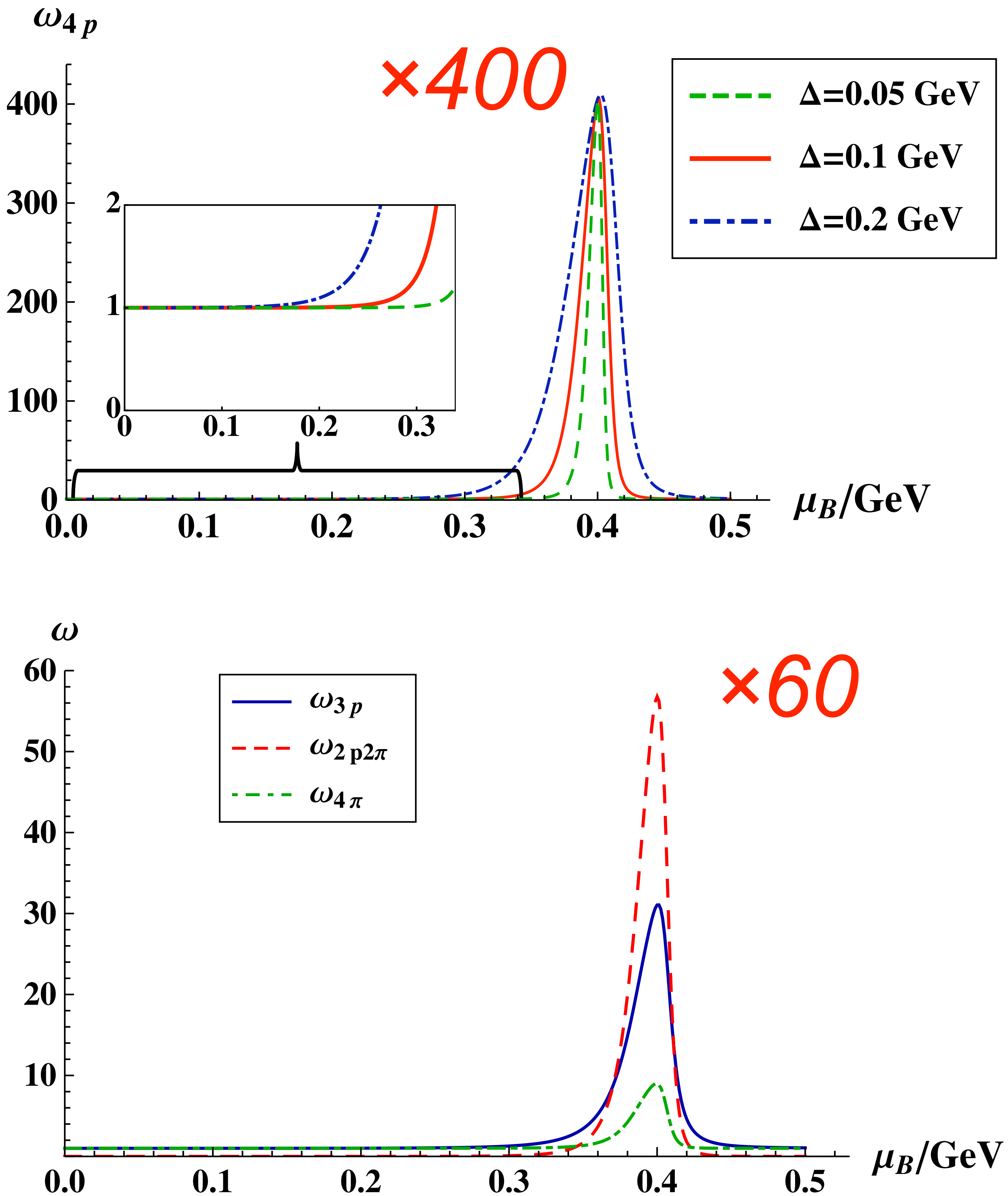




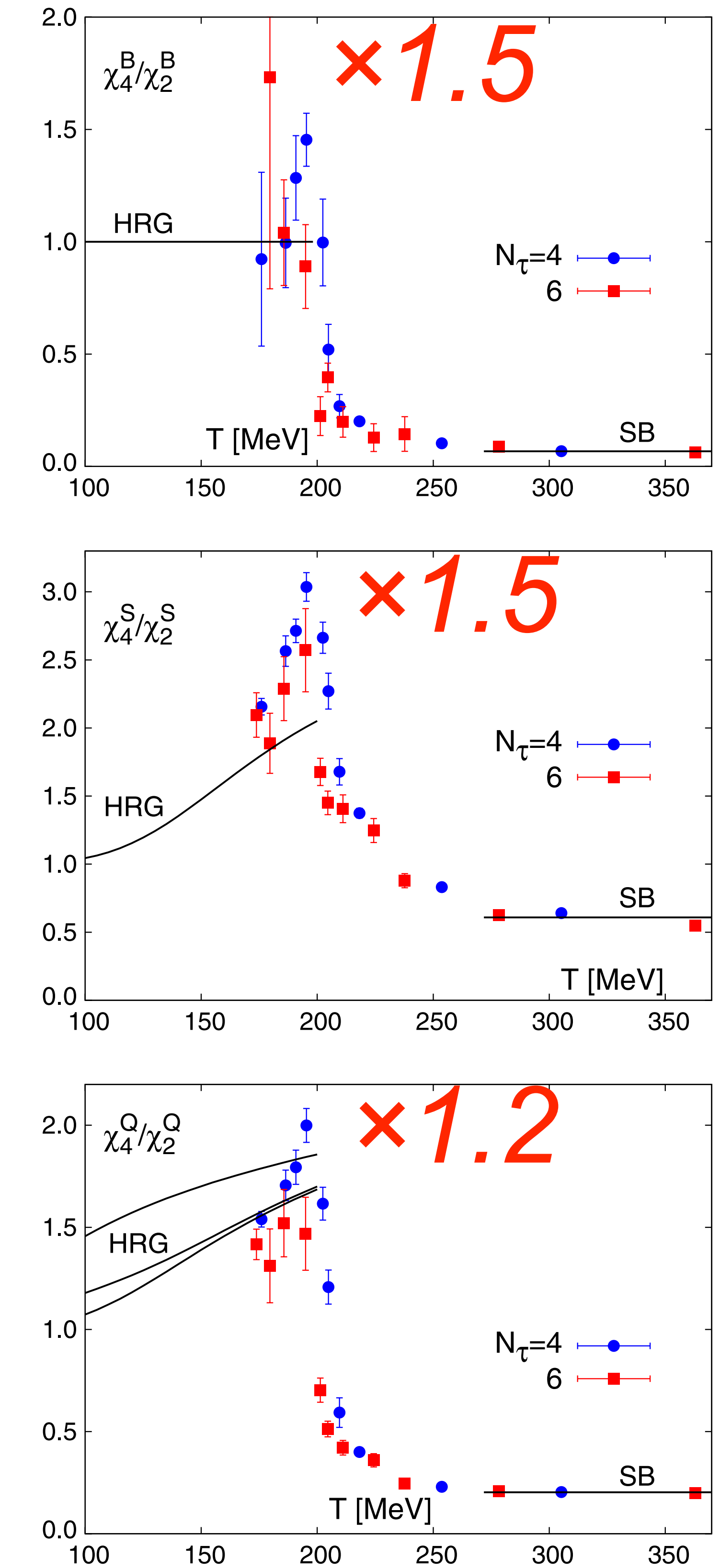
- 3rd moment = Skewness, *S*
  - Asymmetry of the distribution
- 4th moment = Kurtosis, *K*
  - Peakedness of the distribution
- Both moments are 0 for gaussian
- Critical point induce non-gaussian fluctuation

Predictions

*C. Athanasiou et al, PRD**82**, 074008 (2010)*
Non-linear sigma model

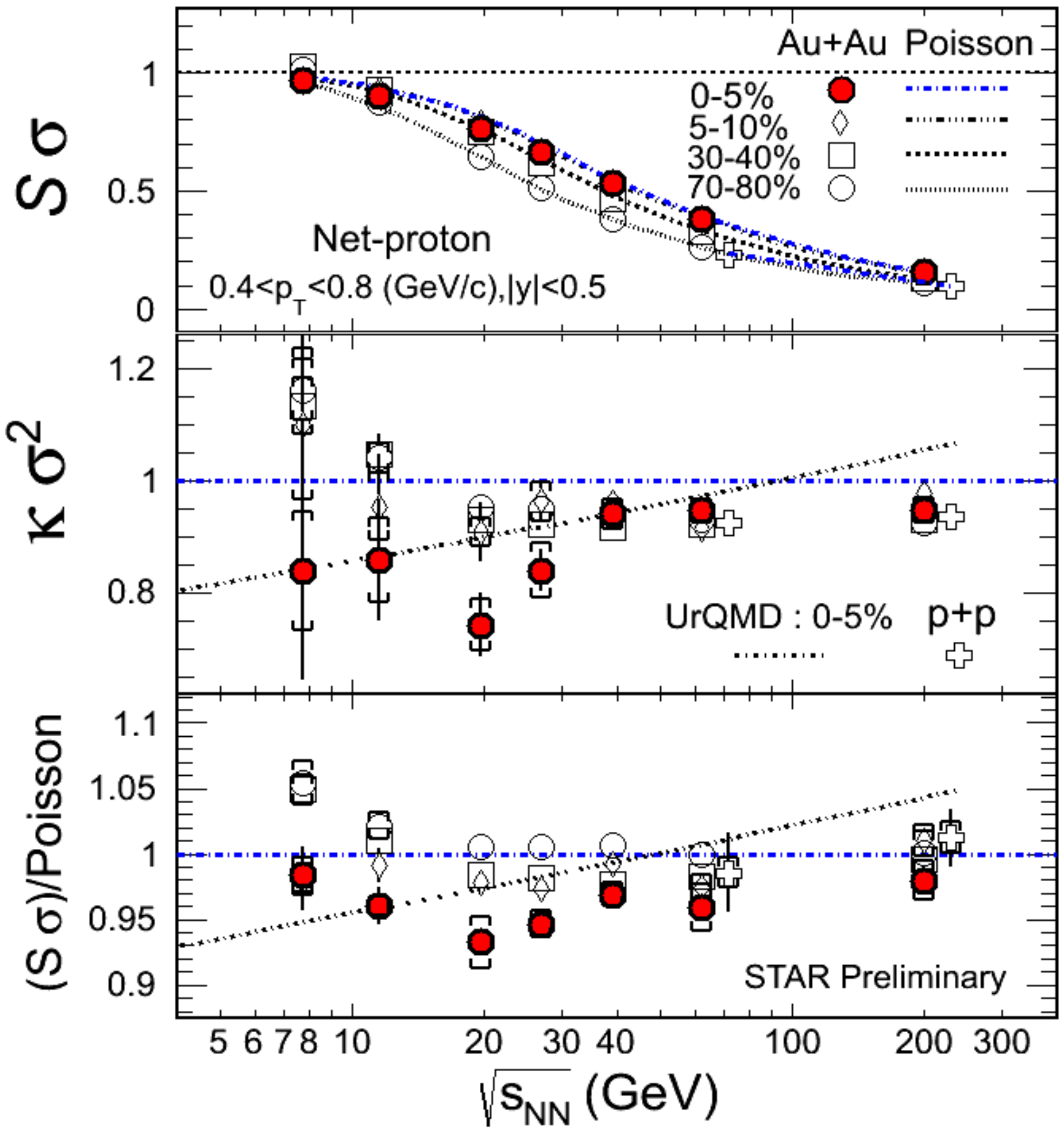


*M. Cheng et al, PRD**79**, 074505 (2009)*
Lattice QCD

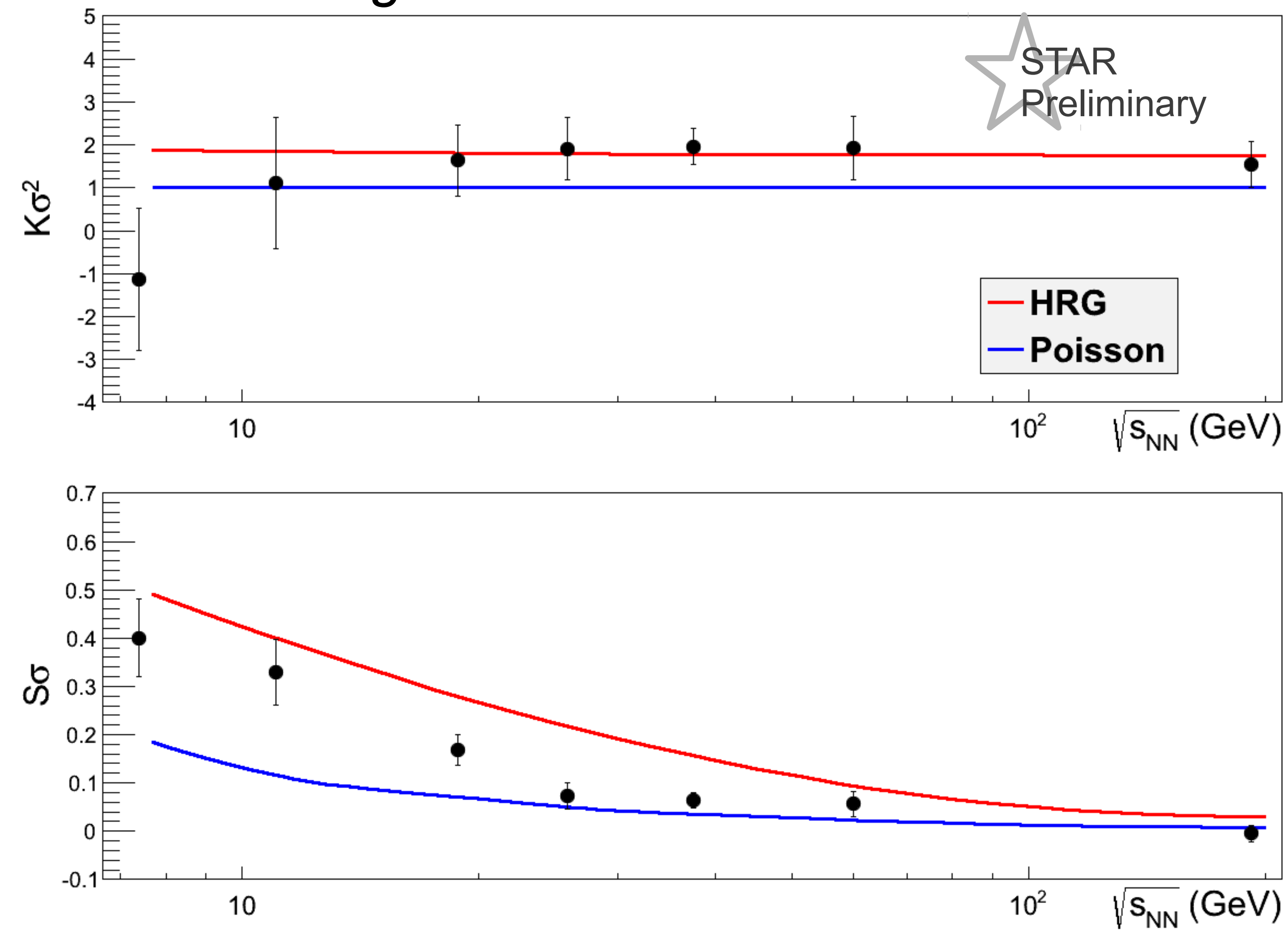


Results

net-proton



net-charge



Poisson expectation

$S\sigma = (M_x - M_{\bar{x}})/(M_x + M_{\bar{x}})$

$K\sigma^2 = 1$

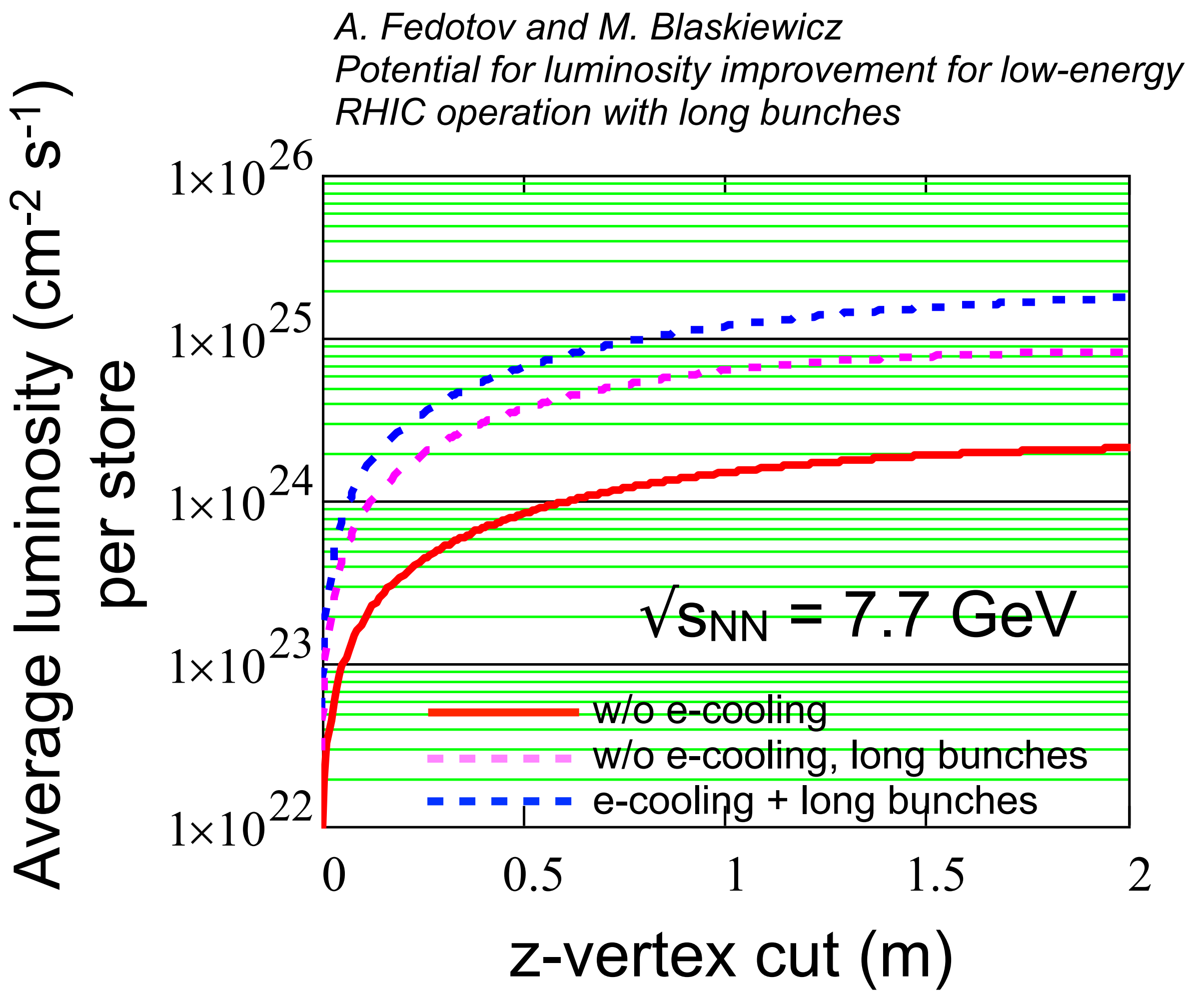
- A factor of 1.5-100 enhancement not seen compared to the Poisson and HRG expectations
  - similar for net-kaons

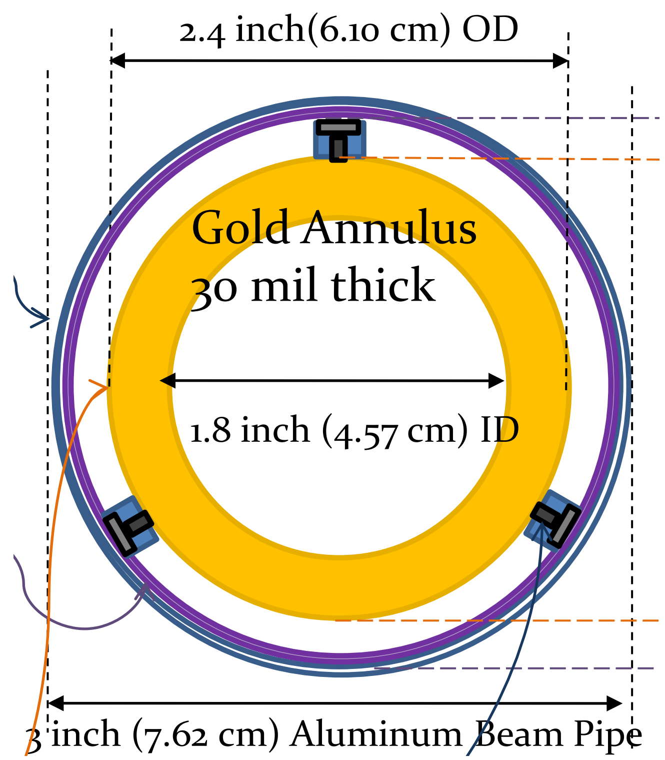
Summary

- Several observables turn off
  - v_2 (between particles and anti-particles), hint for ϕ meson v_2, R_{cp}, charge separation
- Non-monotonic behavior of dv_1/dy
  - Hadron or parton cascade models can't describe the data
- No clear signal for critical point
  - Lack of statistics below 20 GeV

- Hadronic phase plays more important role at lower energies
- Need precision measurements below 20 GeV

Outlook - towards BES Phase II

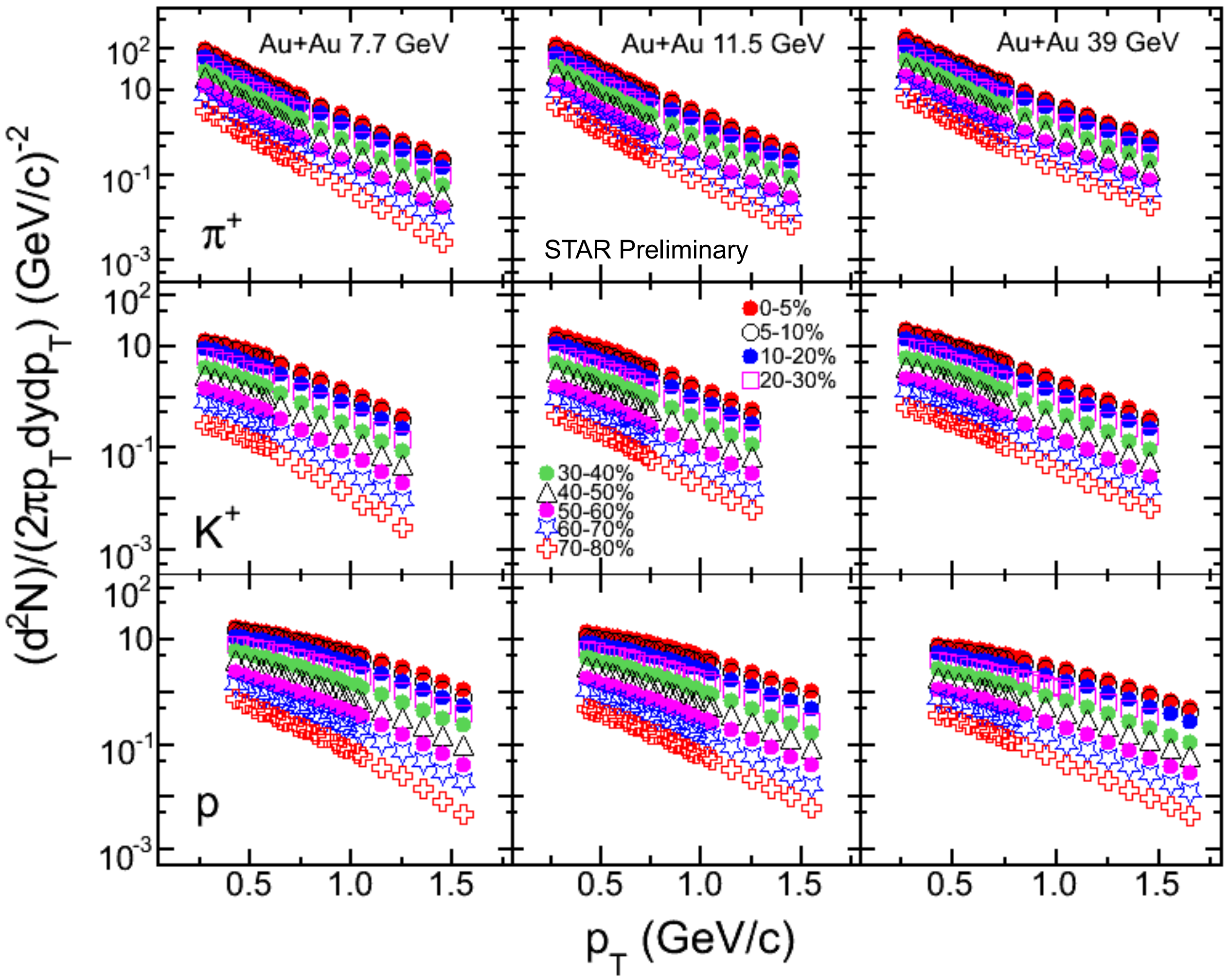


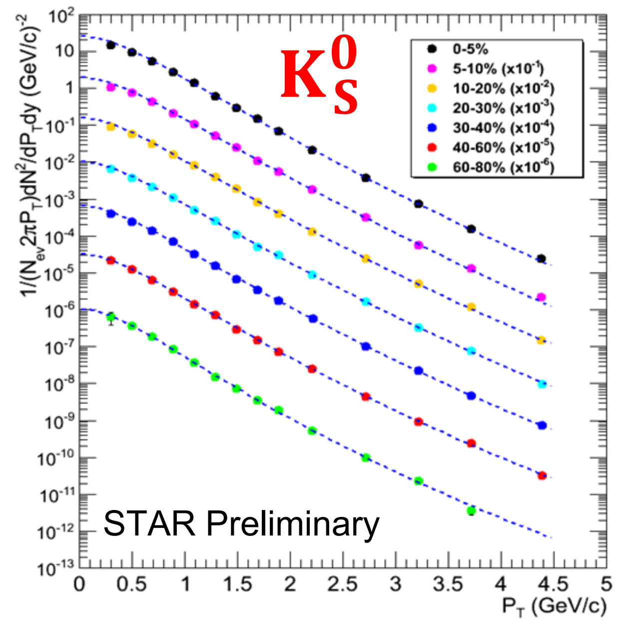


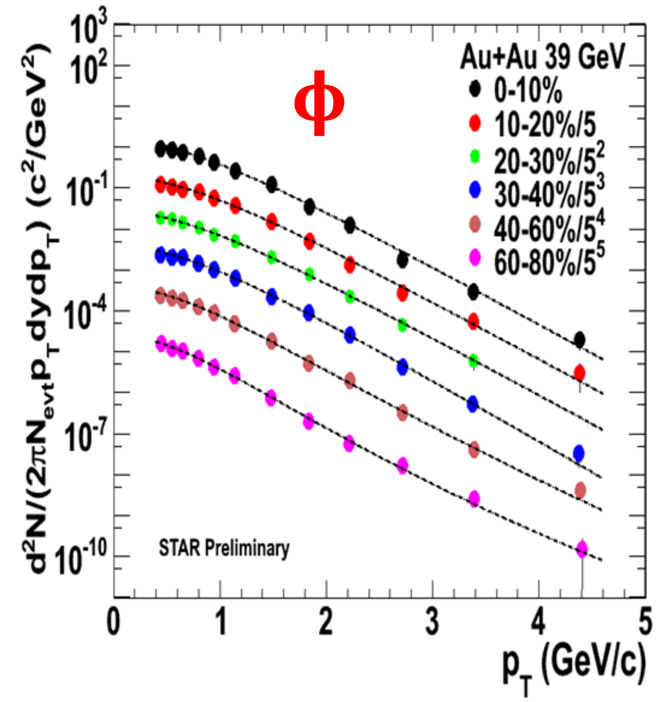
- BES phase II will likely cover the energy below ~ 20 GeV with improved statistics
  - Fill the gap between 11.5 and 19.6 GeV ($\Delta\mu_B$~100 MeV)
- Electron cooling + longer bunches will give 3-10 times higher luminosity
- Fixed target proposal - $\sqrt{s_{NN}}$ < 5 GeV
  - Annular gold target, 2m away from the center of the STAR
  - Data taking with collider mode at the beginning of each fill, no disturbance to normal RHIC running

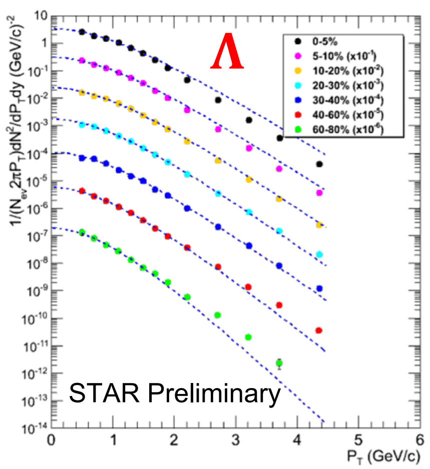
Back up

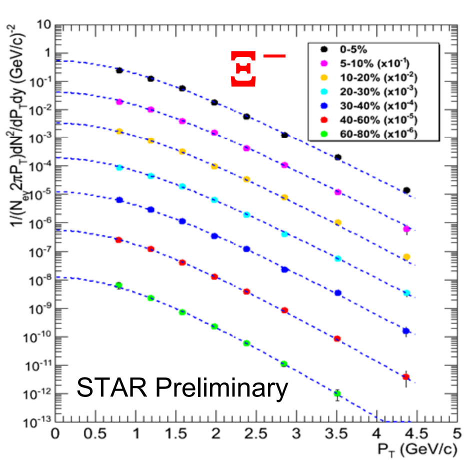
Identified particle spectra

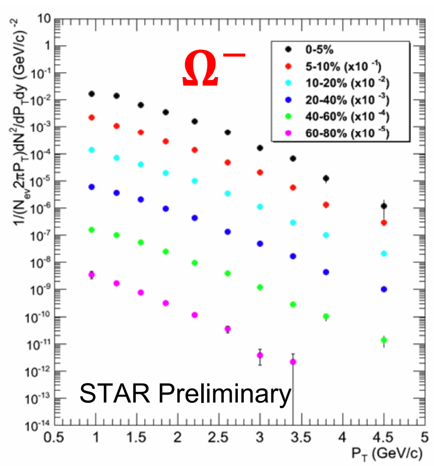






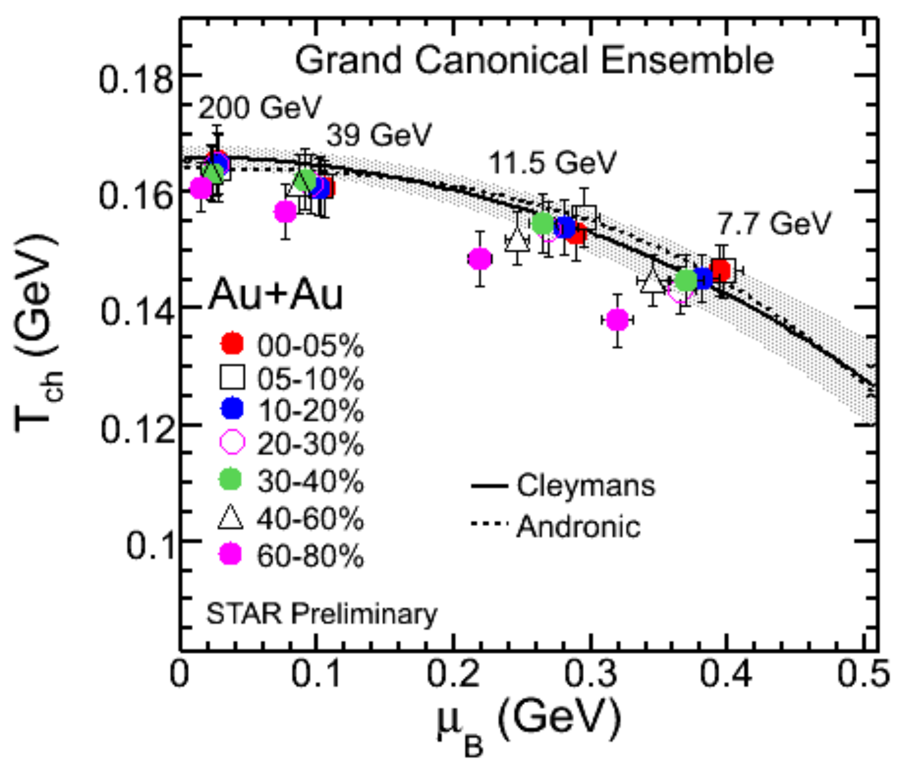


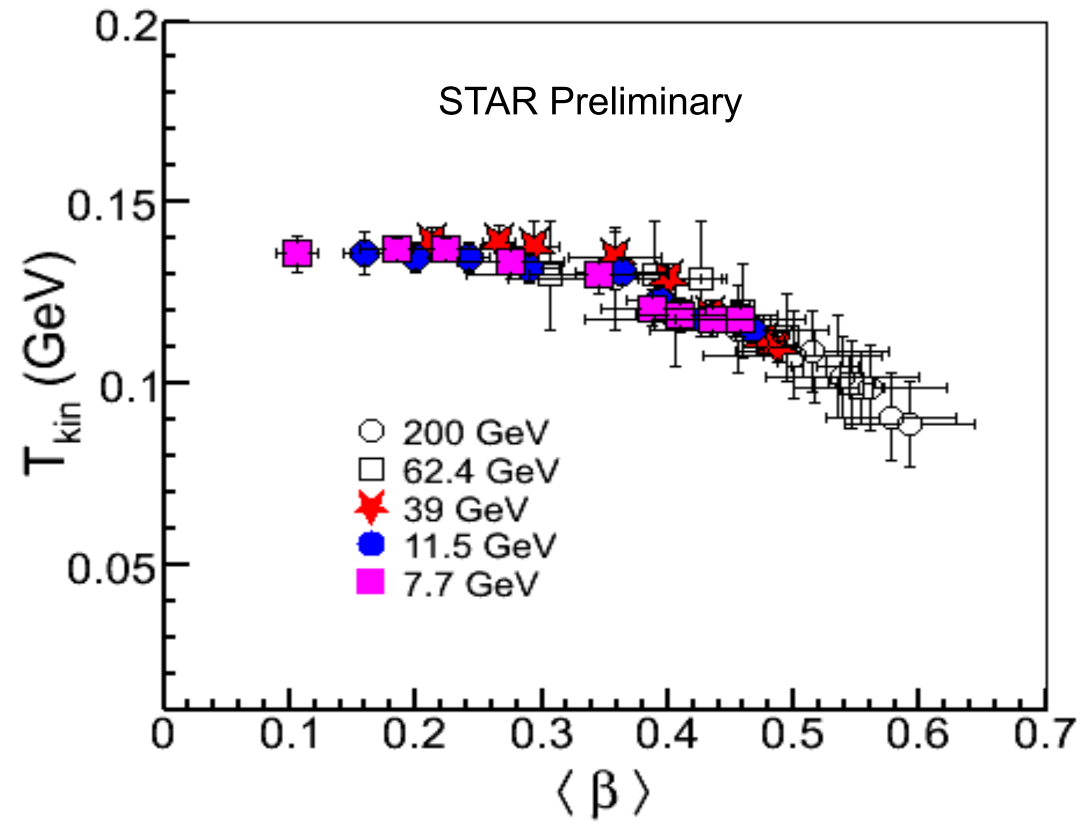


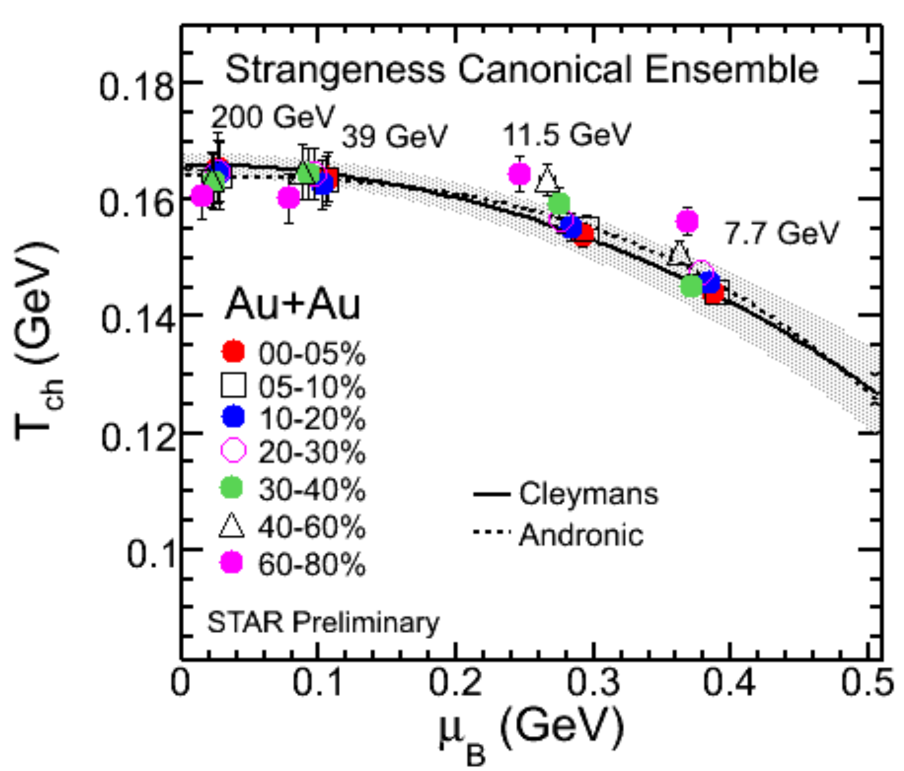


- Feed down from weak decays
  - corrected for Λ, others are not corrected

Kinetic & chemical freeze-out







- Kinetic freeze-out
  - Blast-wave fit for π, K and p spectra
- Chemical freeze-out
  - THERMUS fit for π, K, K^0_S, p, Λ and Ξ
  - Centrality dependence are under investigation