STAR results from RHIC Beam Energy Scan

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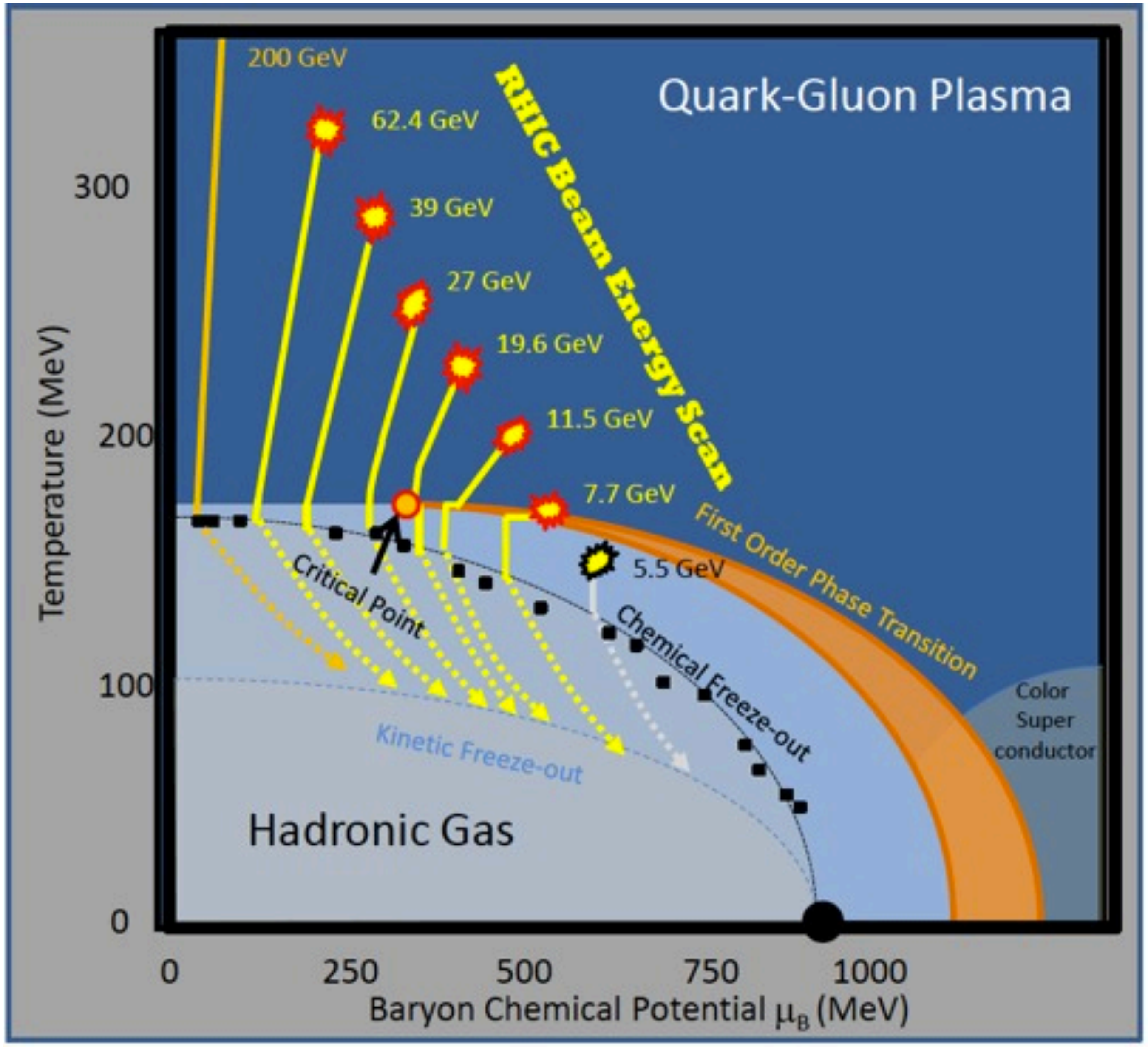
RHIC Beam Energy Scan (BES)



- Study the structure of QCD phase diagram
  - large baryon chemical potential ~ low beam energy

➡ Beam Energy Scan !

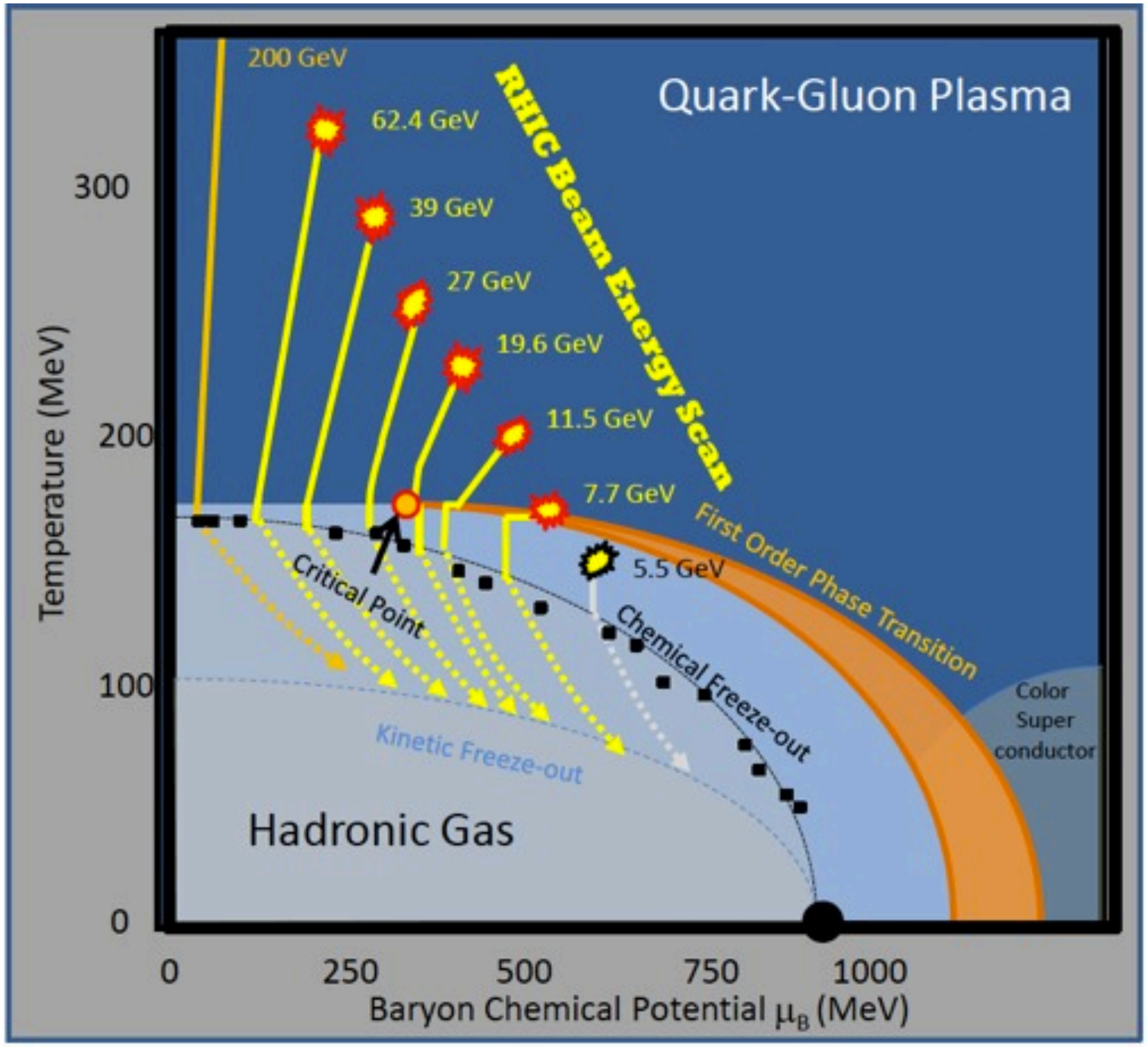
- History & timeline
  - 2008: Test run at $\sqrt{s_{NN}}$ = 9.2 GeV (***PRC81***, *024901, 2010*)
  - 2009: Proposal for BES Phase-I (arXiv:1007.2613)
  - 2010: First year of RHIC BES (7.7, 11.5, 39 and 62 GeV)
  - 2011: Two further energies (19.6 and 27 GeV)
  - 2012: Test run at 5 GeV

Goals

- At small baryon density, produced matter is characterized by
  - initial energy densities > critical values from lattice QCD
  - ~ ideal fluid flow (~ small shear viscosity to entropy density ratio)
  - opacity of jets

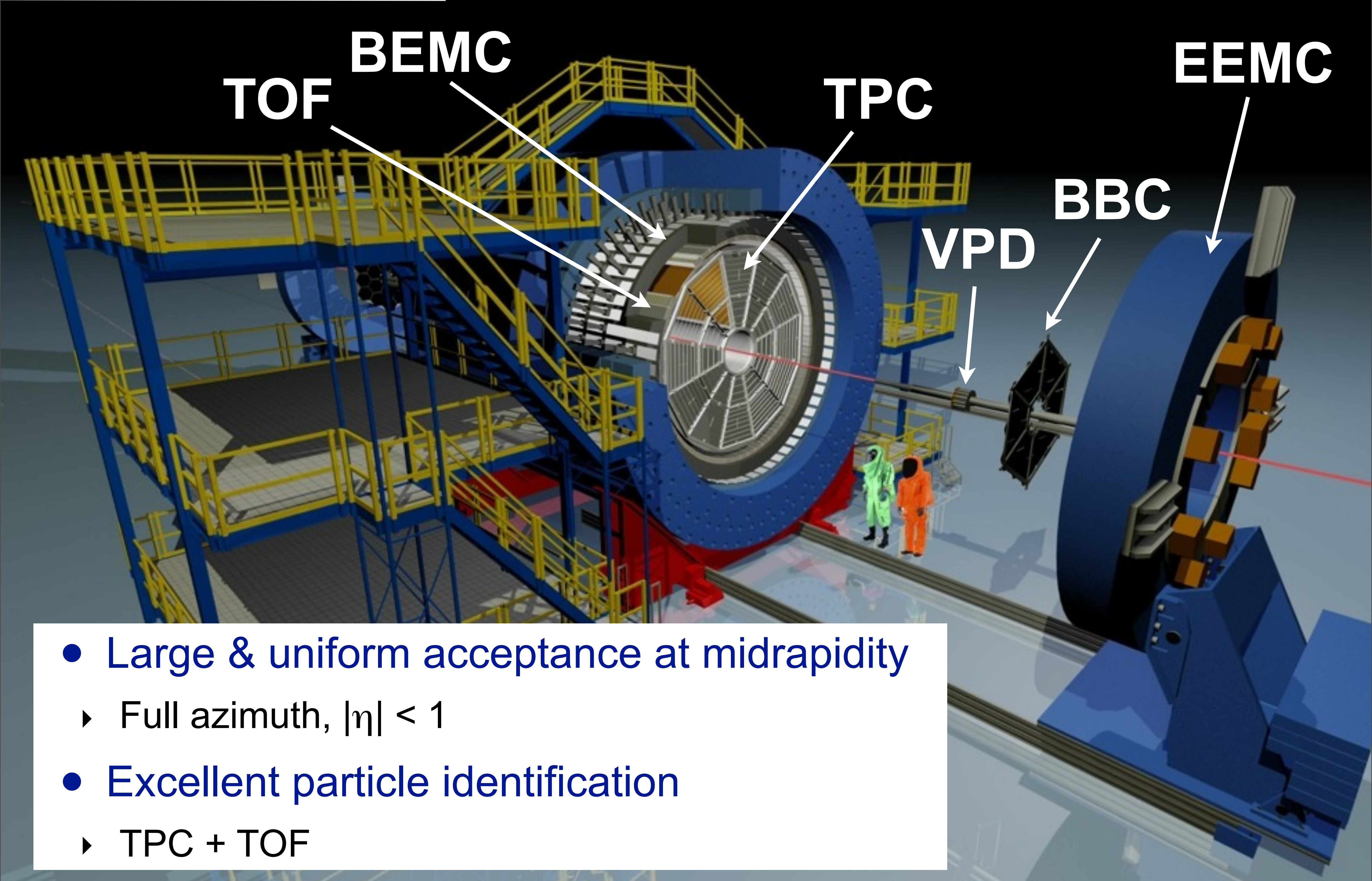
- 3 main goals for Beam Energy Scan at STAR
  - Search for ‘turn-off’ signals of Quark-Gluon Plasma (QGP)
    - or onset of the QGP
  - Search for signals of phase boundary
  - Search for QCD critical point

Observables



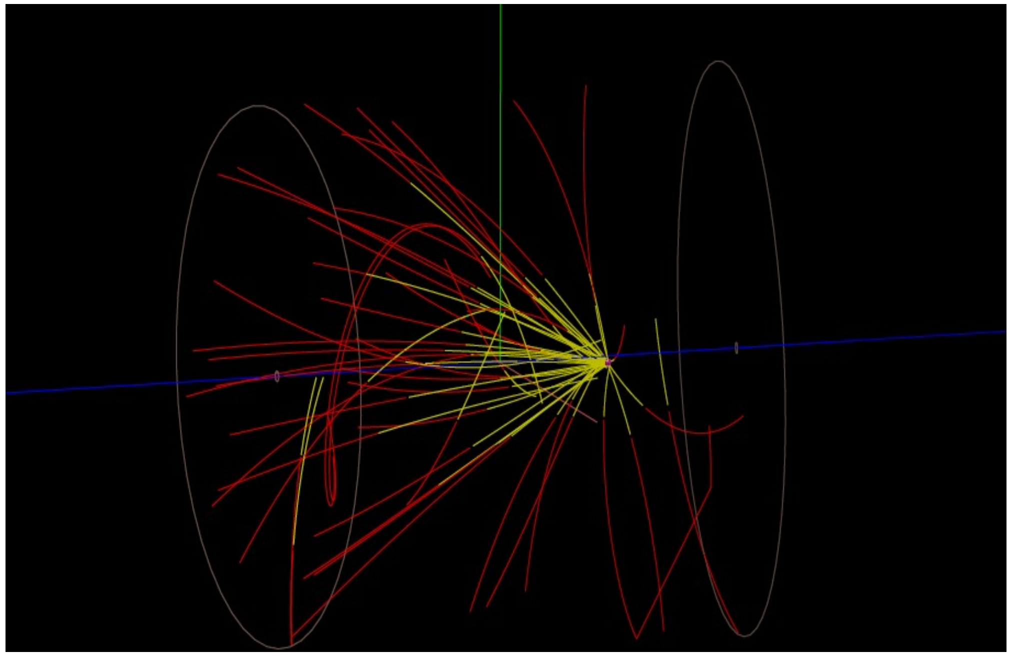
- Search for 'turn-off' signals of Quark-Gluon Plasma
  - Number of Constituent Quark (NCQ) scaling of v_2
  - High p_T suppression
  - Chiral magnetic effect
- Search for signals of phase boundary
  - Directed flow
  - Azimuthal sensitive HBT
- Search for QCD critical point
  - Fluctuations

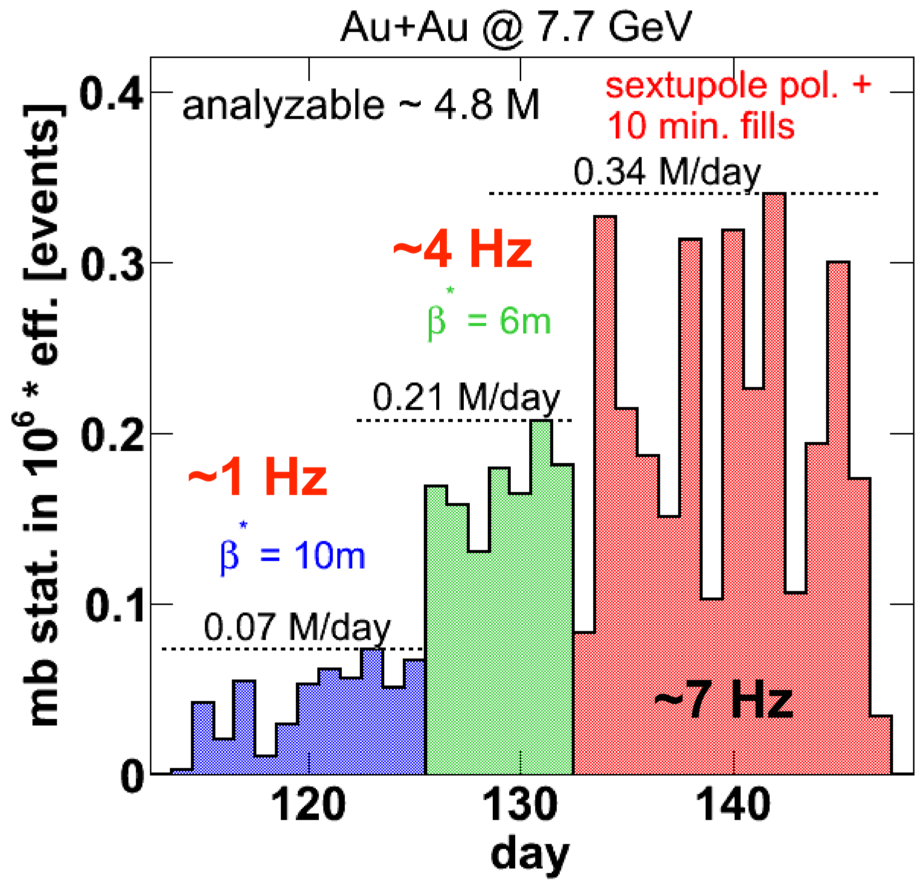
Solenoidal Tracker At RHIC

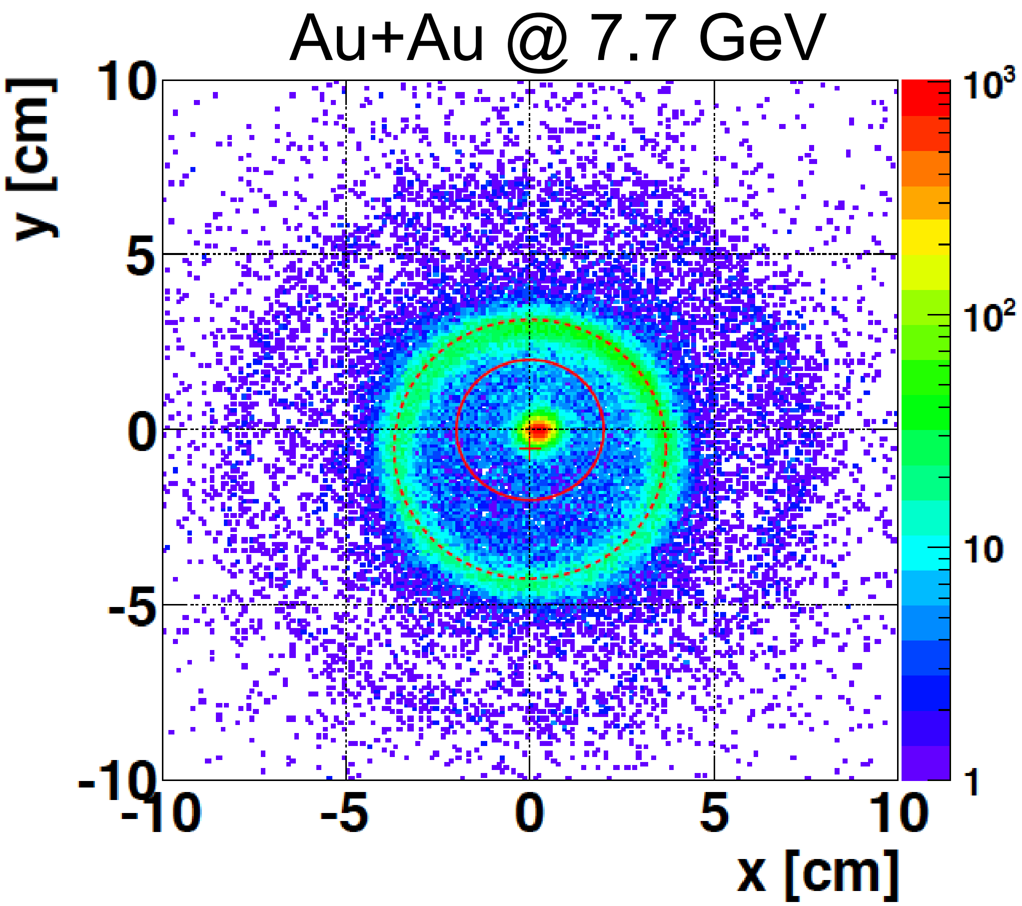


- Large & uniform acceptance at midrapidity
  - Full azimuth, $|\eta| < 1$
- Excellent particle identification
  - TPC + TOF

Challenges





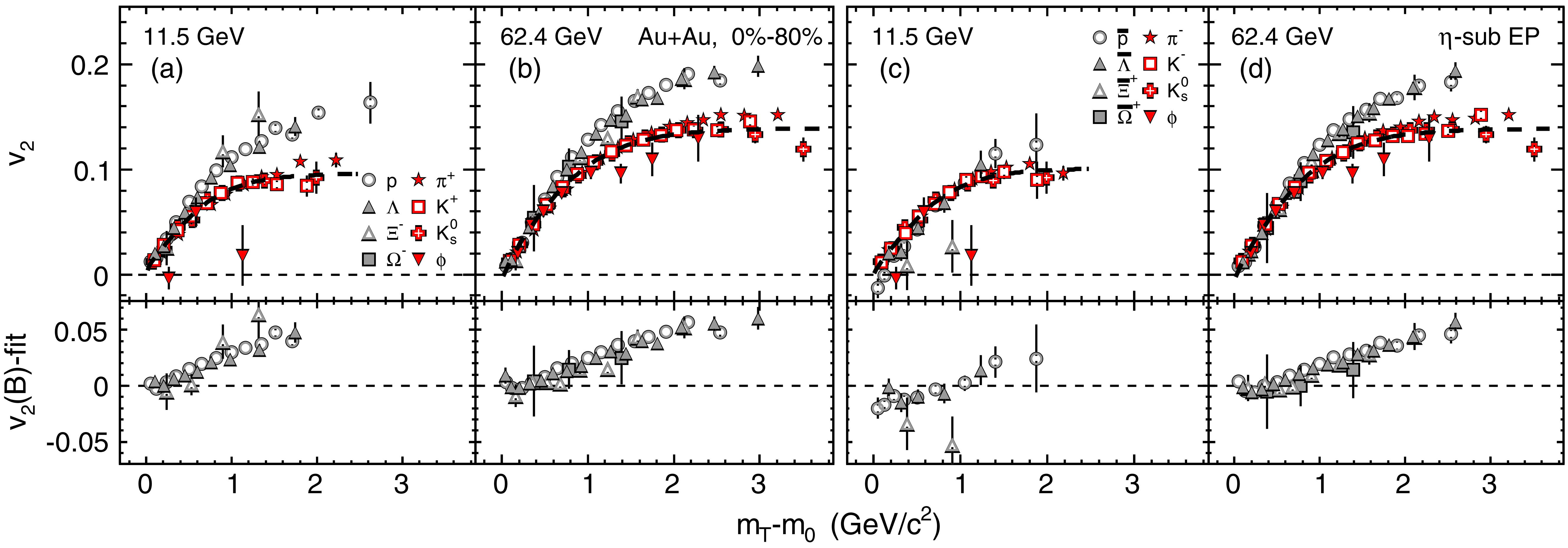


- Event rate ~ O(1) Hz, fill length ~ O(10) minutes
  - Significant improvement towards the end of runs (thanks to RHIC)
- Huge background from beam-beampipe collisions
  - e.g. total 100M events collected in ~ a month, ~95% is background at 7.7 GeV

Search for Turn-off signals of QGP

Breakdown of NCQ scaling

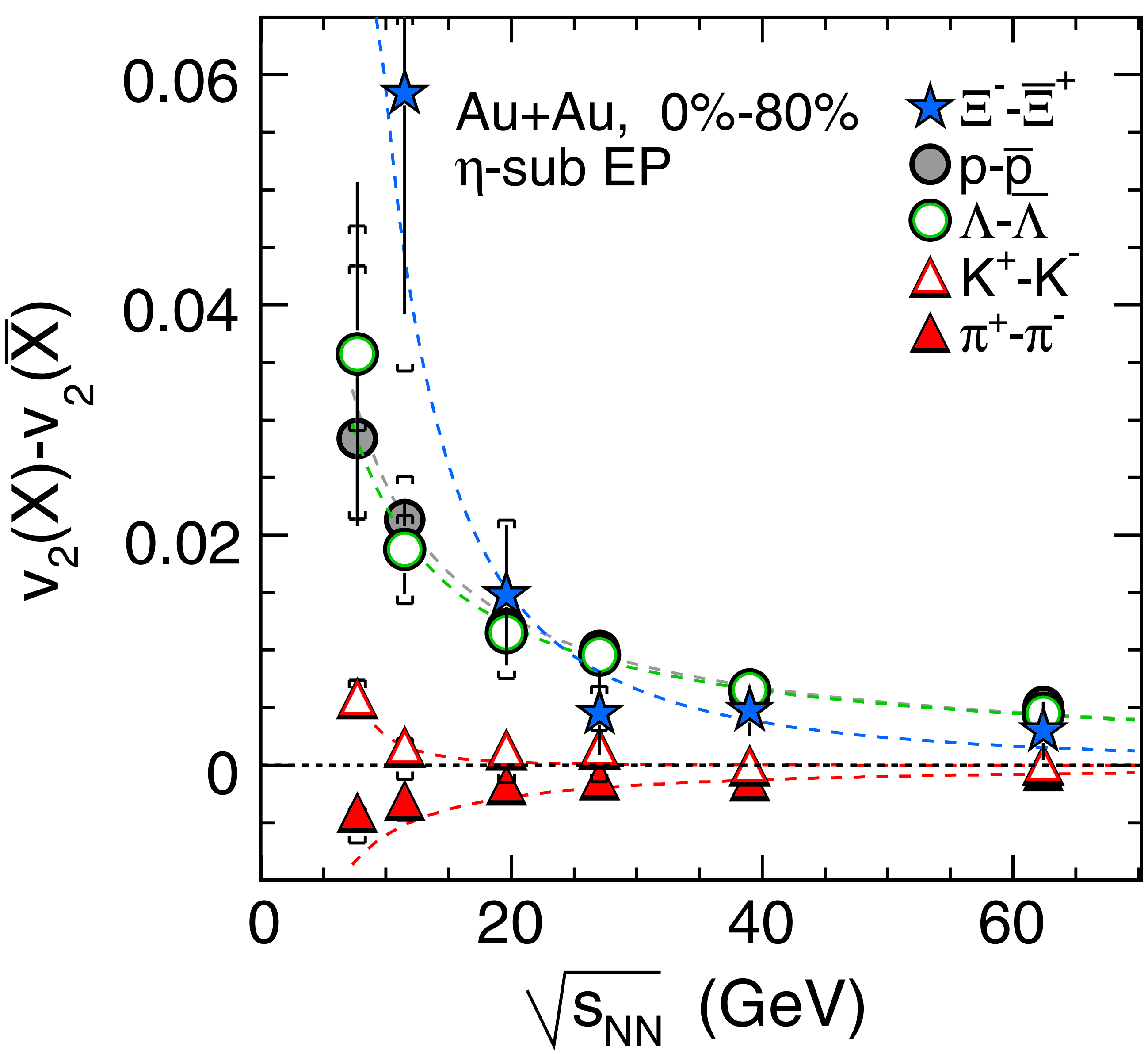
STAR ***PRL110**, 143201 (2013)*
see also ***PRC88**, 014902 (2013)*



- Meson-baryon splitting at 62 GeV - NCQ scaling of v_2
  - No difference between particles and anti-particles
- Meson-baryon splitting is gone for anti-particles at 11.5 GeV
- NCQ scaling is broken between particles and anti-particles

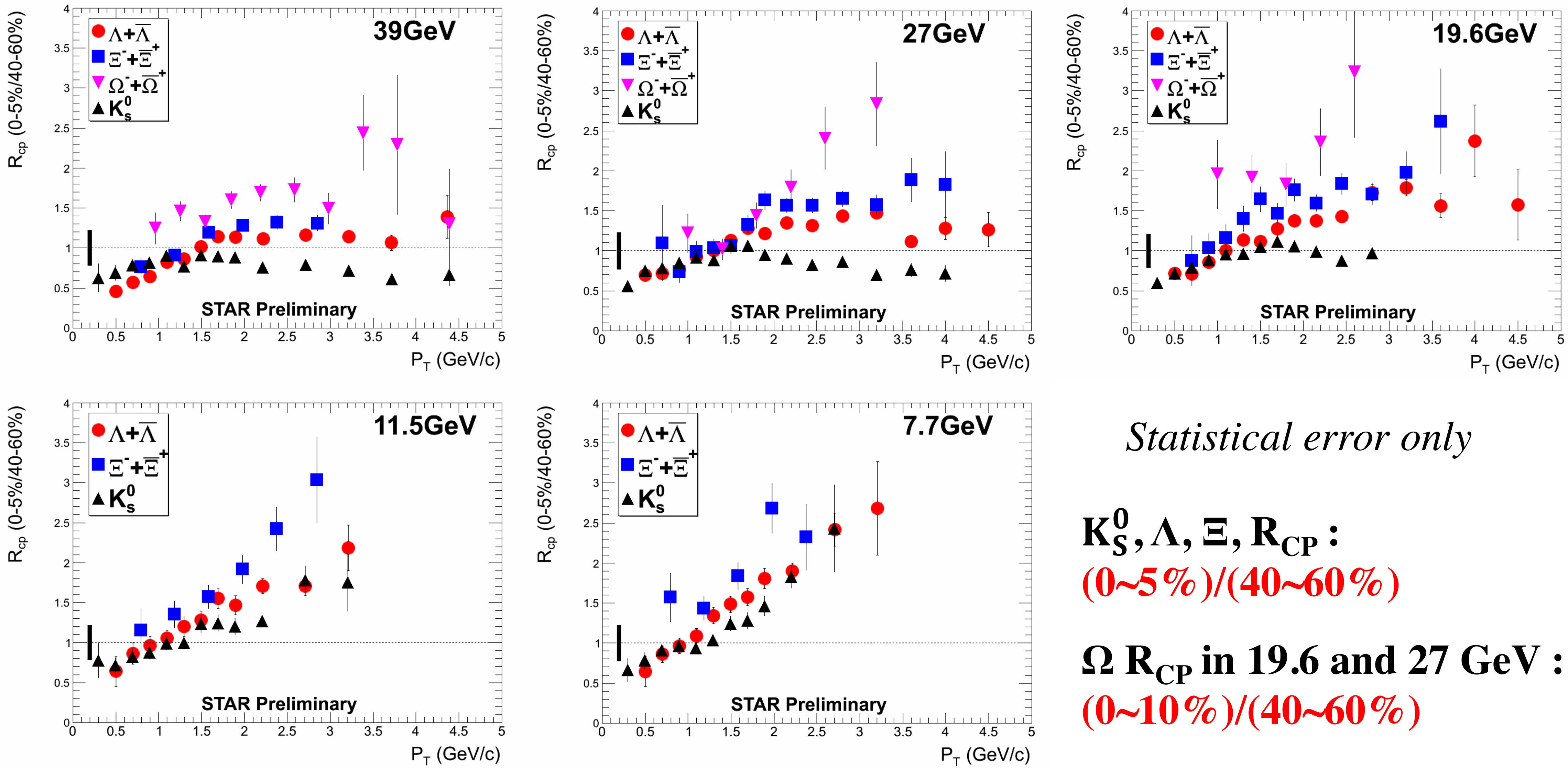
Large v_2 difference for baryons

STAR ***PRL110**, 143201 (2013)*
see also ***PRC88**, 014902 (2013)*



- Difference of v_2 between particles and anti-particles increase in lower energies
- Baryons show larger difference than mesons

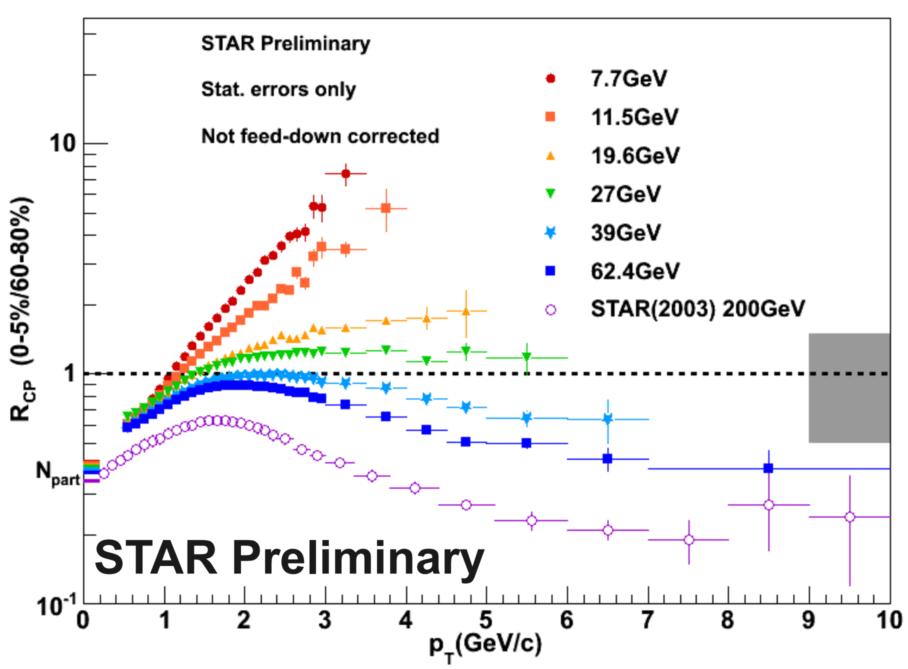
Disappearance of R_{cp} suppression



Statistical error only

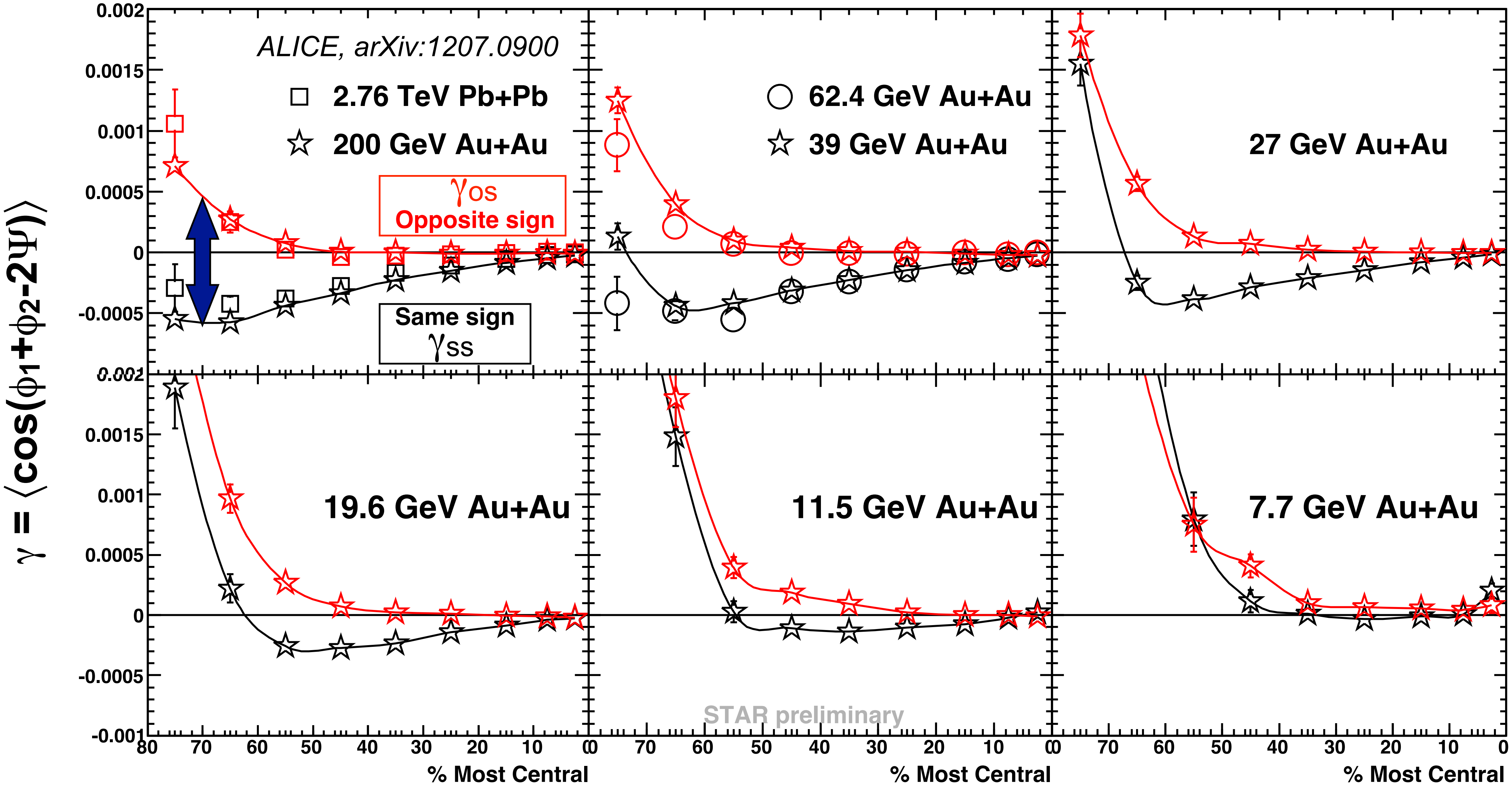
K^0_S, Λ, Ξ, R_{CP} :
(0~5%)/(40~60%)

Ω R_{CP} in 19.6 and 27 GeV :
(0~10%)/(40~60%)



- Significant suppression at 200 GeV
- R_{cp} increases with decreasing beam energies
- Baryon-meson splitting reduces at low energies

Disappearance of charge separation

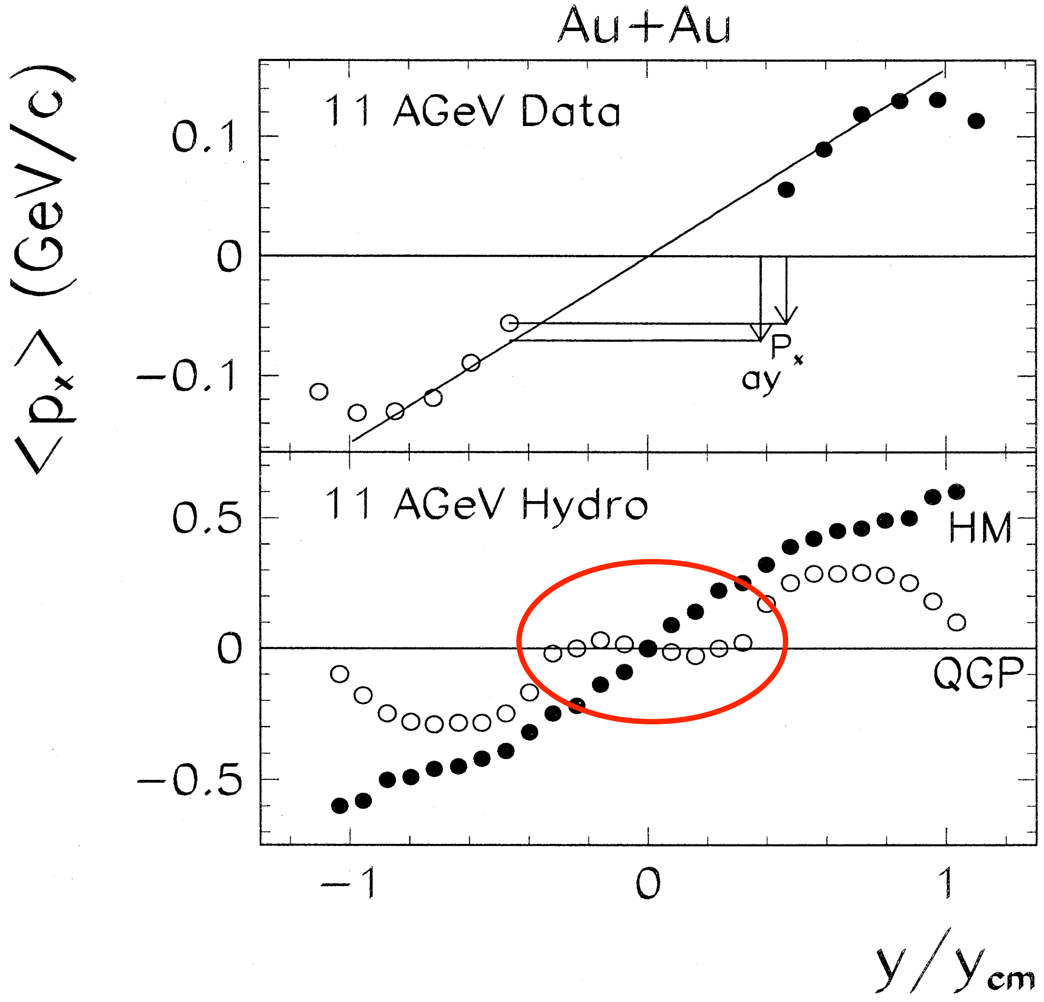


- Charge separation (γ_{OS}-γ_{SS}) at 200 GeV
  - chiral magnetic effect (deconfinement+chiral symmetry restoration) ?
- Separation decreases with decreasing beam energies. Disappears at $\sqrt{s_{NN}}$ = 11.5 GeV or less

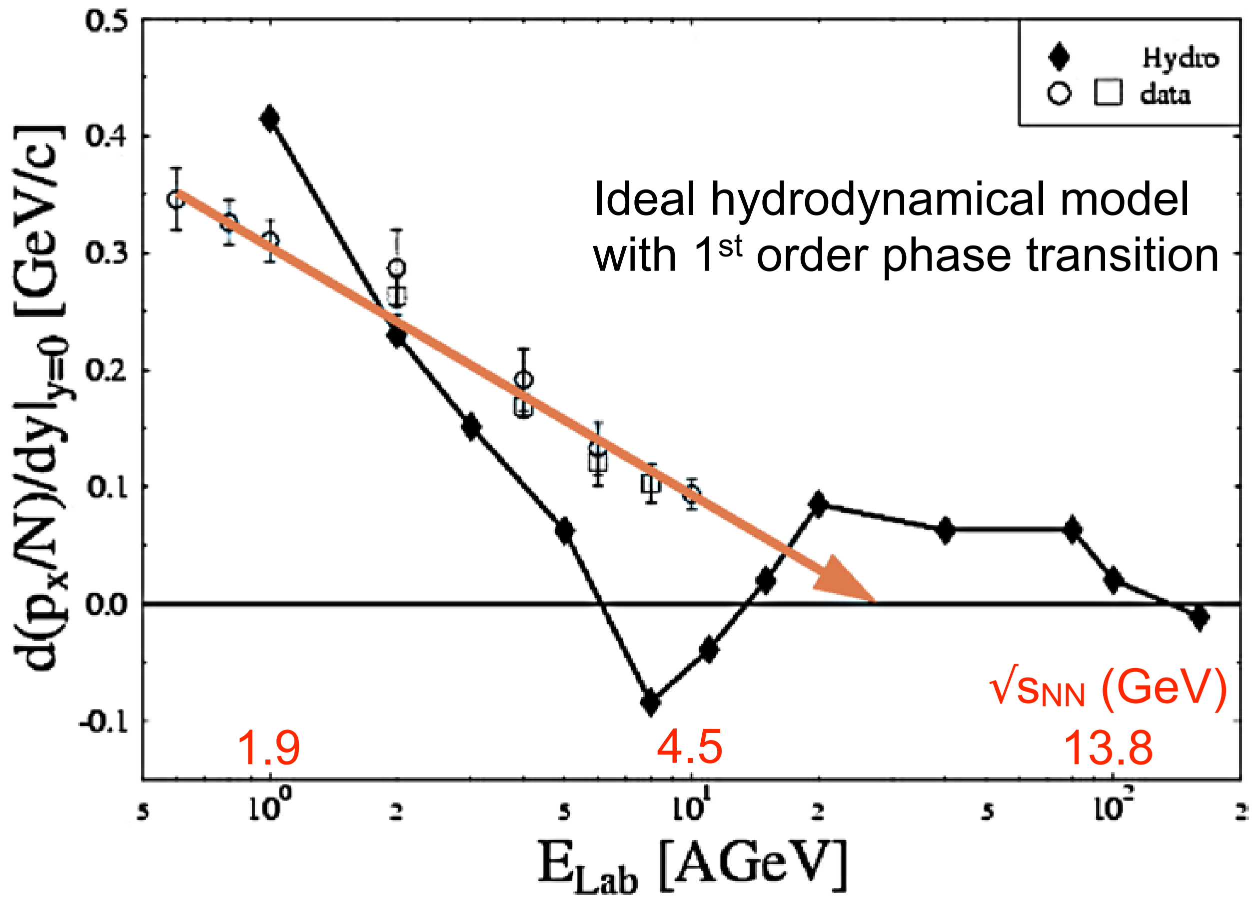
Search for signals of phase boundary

Directed flow - early predictions

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

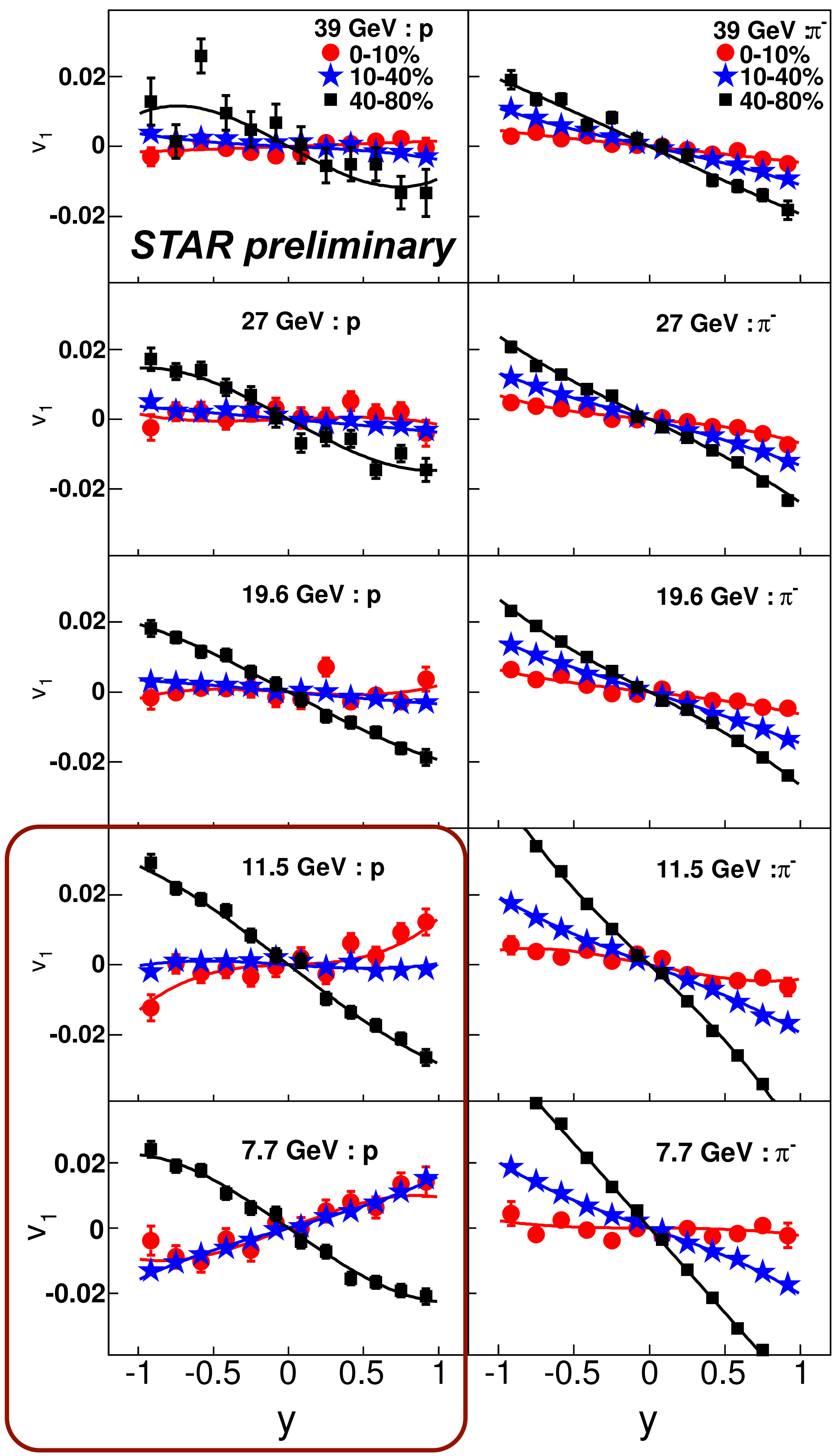


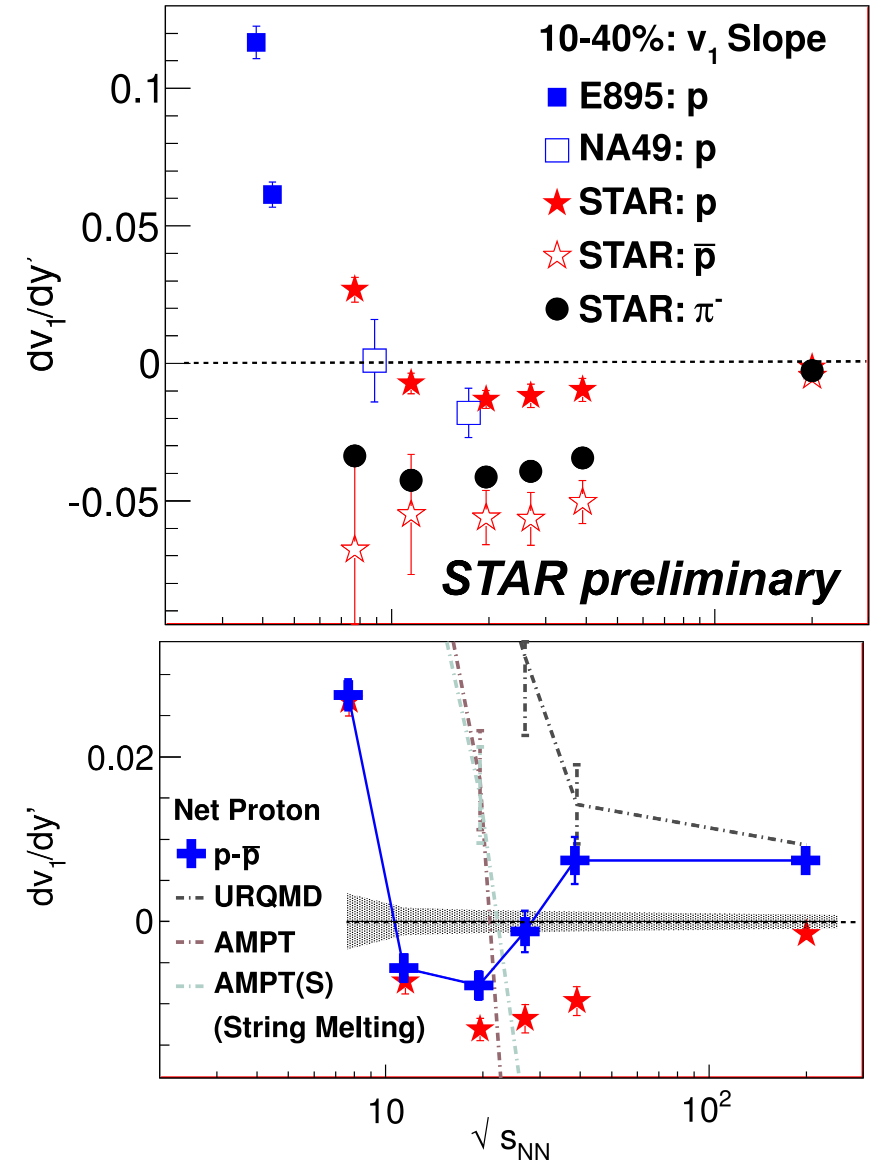
*H. Stocker, NPA**750**, 121 (2005)*



- 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

Non-monotonic behavior of v_1 slope

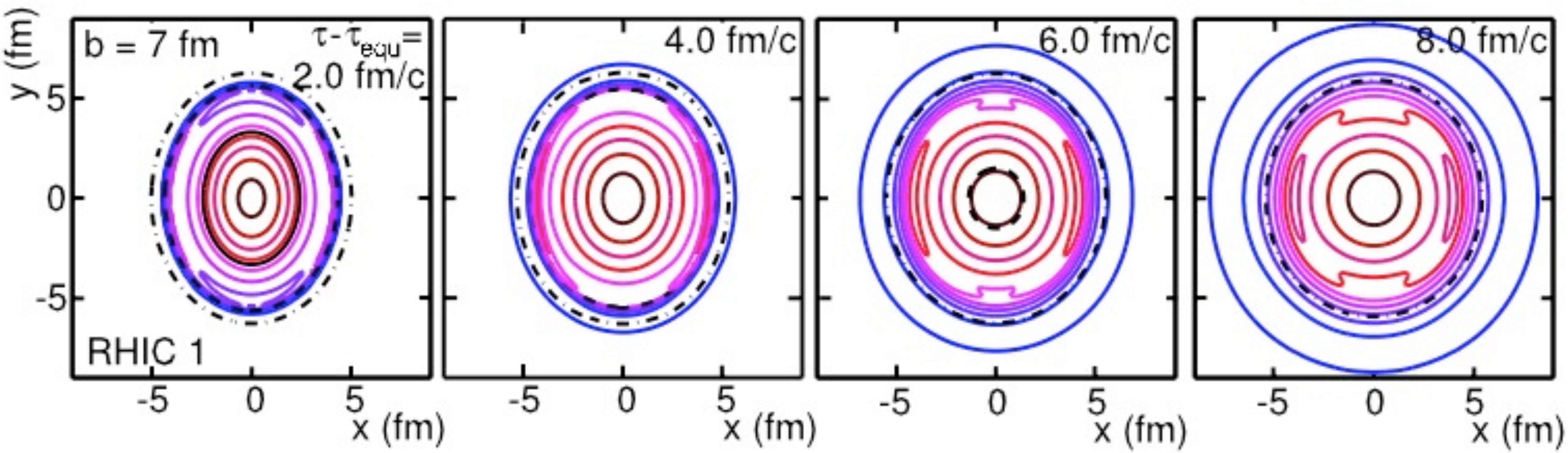


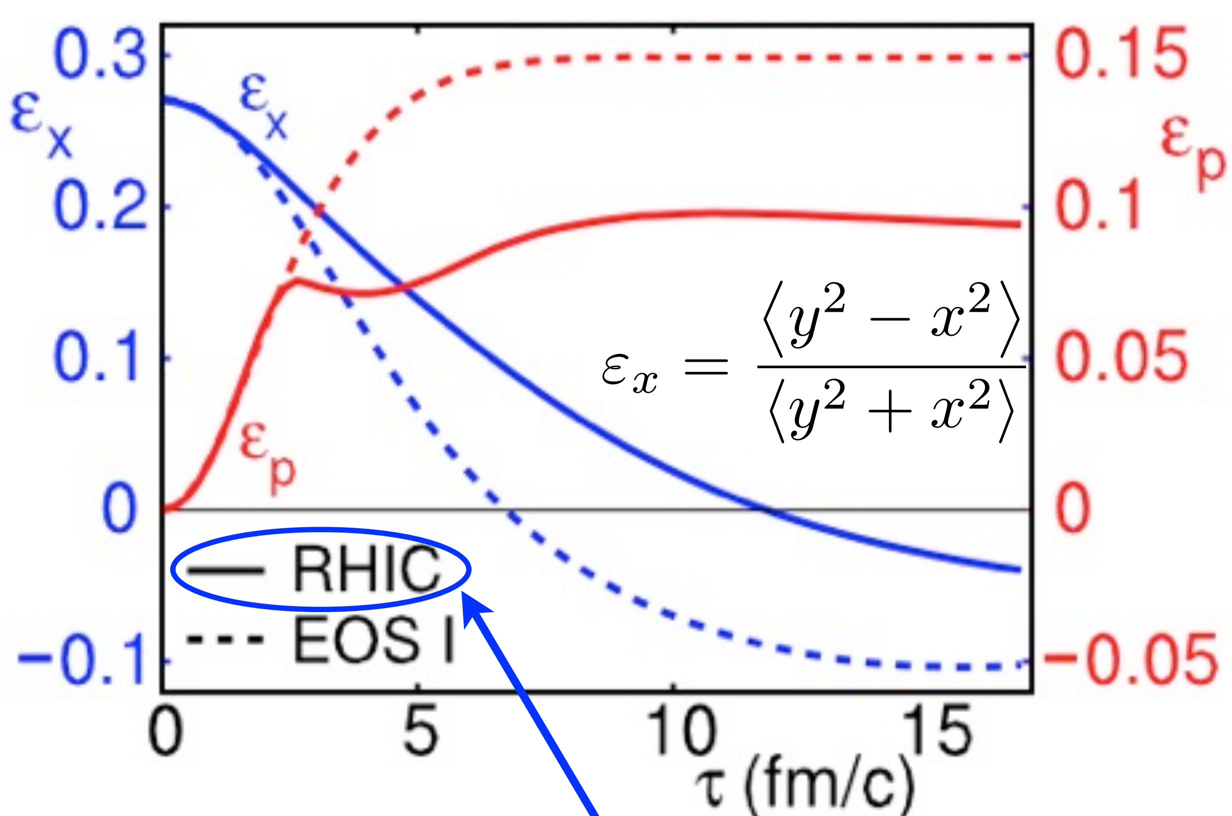


- v_1 slopes (dv_1/dy') are negative
  - except for protons at low energies
- Net-proton v_1 slope shows a minimum around 11.5-19.5 GeV

Evolution of initial spatial anisotropy

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

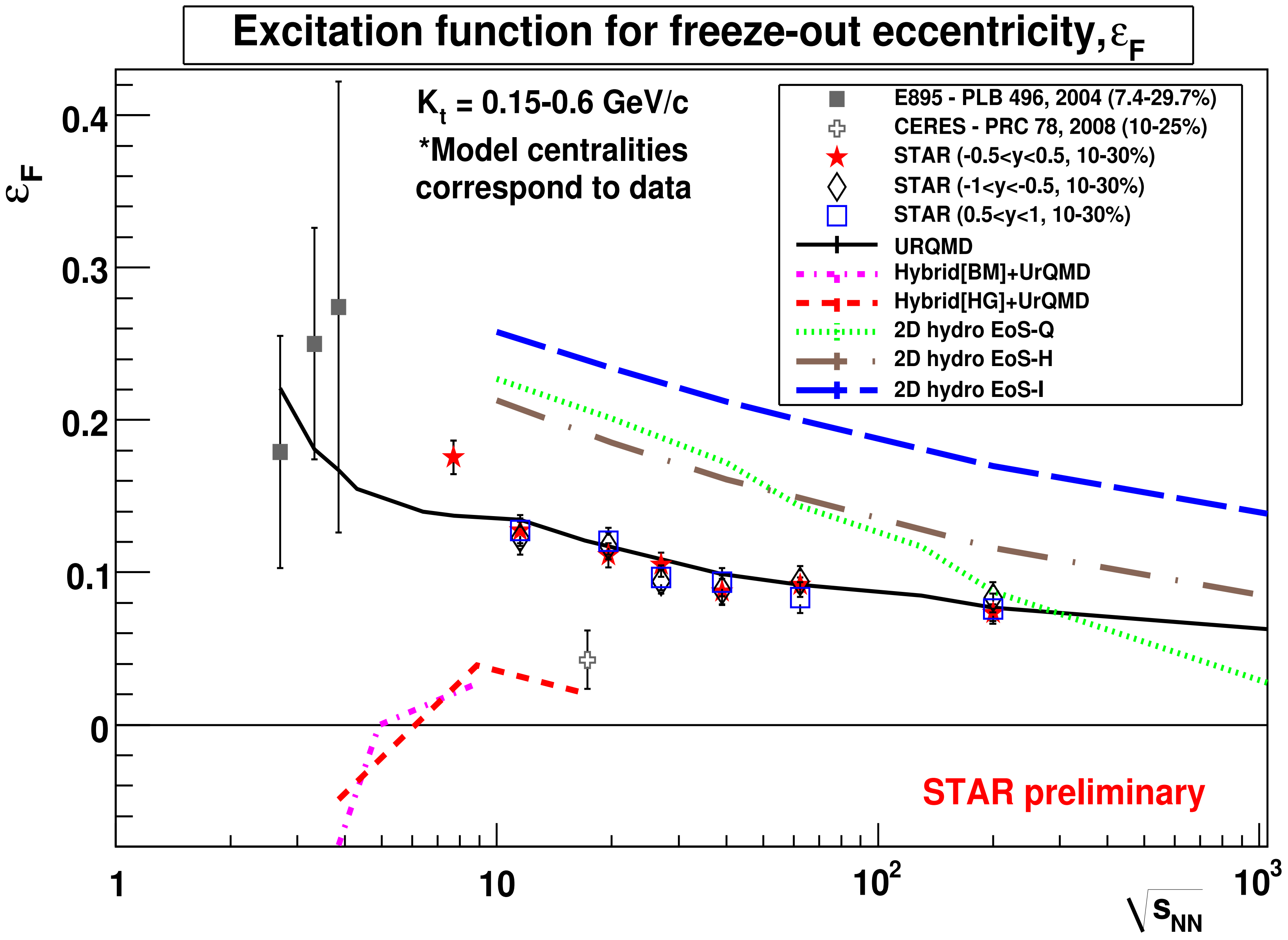




with 1st order phase transition

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

Monotonic decrease of freeze-out eccentricity



- Pion freeze-out eccentricity smoothly decrease as a function of beam energy
  - Rapidity dependence also studied to try to compare with CERES

Search for signals of QCD critical point

Higher (n>2) moments (or cumulants)

- At critical point (with infinite system)
  - susceptibilities and correlation length diverge
    - both quantities cannot be directly measured
- Experimental observables
  - Moment (or cumulant) of conserved quantities: net-baryons, net-charge, net-strangeness, ...
  - Moment product (cumulant ratio) ↔ ratio of susceptibility

$$\kappa_2 = \left\langle (\delta N)^2 \right\rangle \sim \xi^2, \kappa_3 = \left\langle (\delta N)^3 \right\rangle \sim \xi^{4.5}, \kappa_4 = \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N) \right\rangle^2 \sim \xi^7$$

$$S\sigma = \frac{\kappa_3}{\kappa_2} \sim \frac{\chi_3}{\chi_2}, \; K\sigma^2 = \frac{\kappa_4}{\kappa_2} \sim \frac{\chi_4}{\chi_2}$$

- directly related to the susceptibility ratios (Lattice QCD)

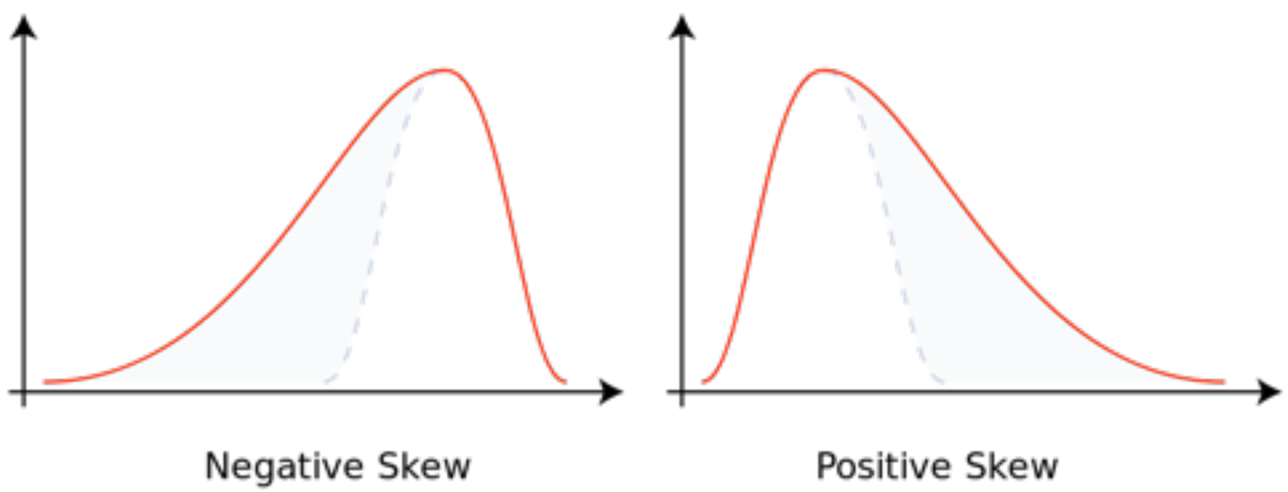
*M. A. Stephanov, PRL**102**, 032301 (2009)*

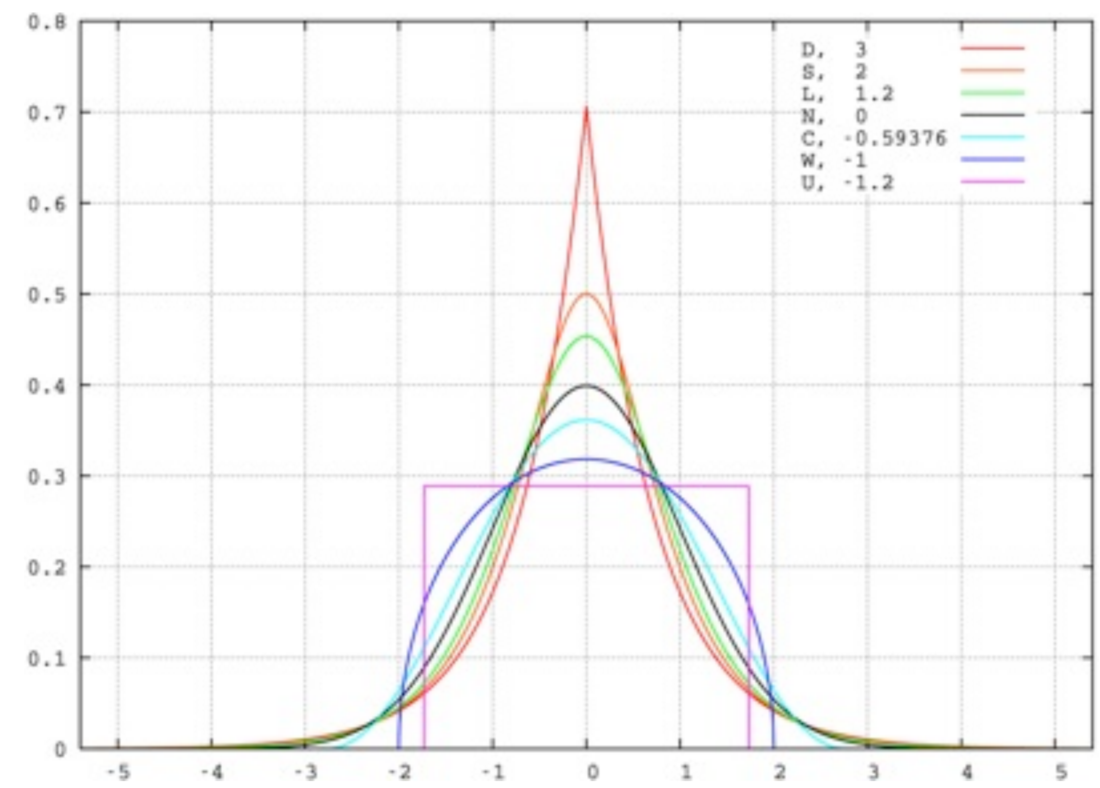
- higher moments (cumulants) have higher sensitivity to correlation length

- Signal = Non-monotonic behavior of moment products (cumulant ratios) vs beam energy

Non-gaussian fluctuations

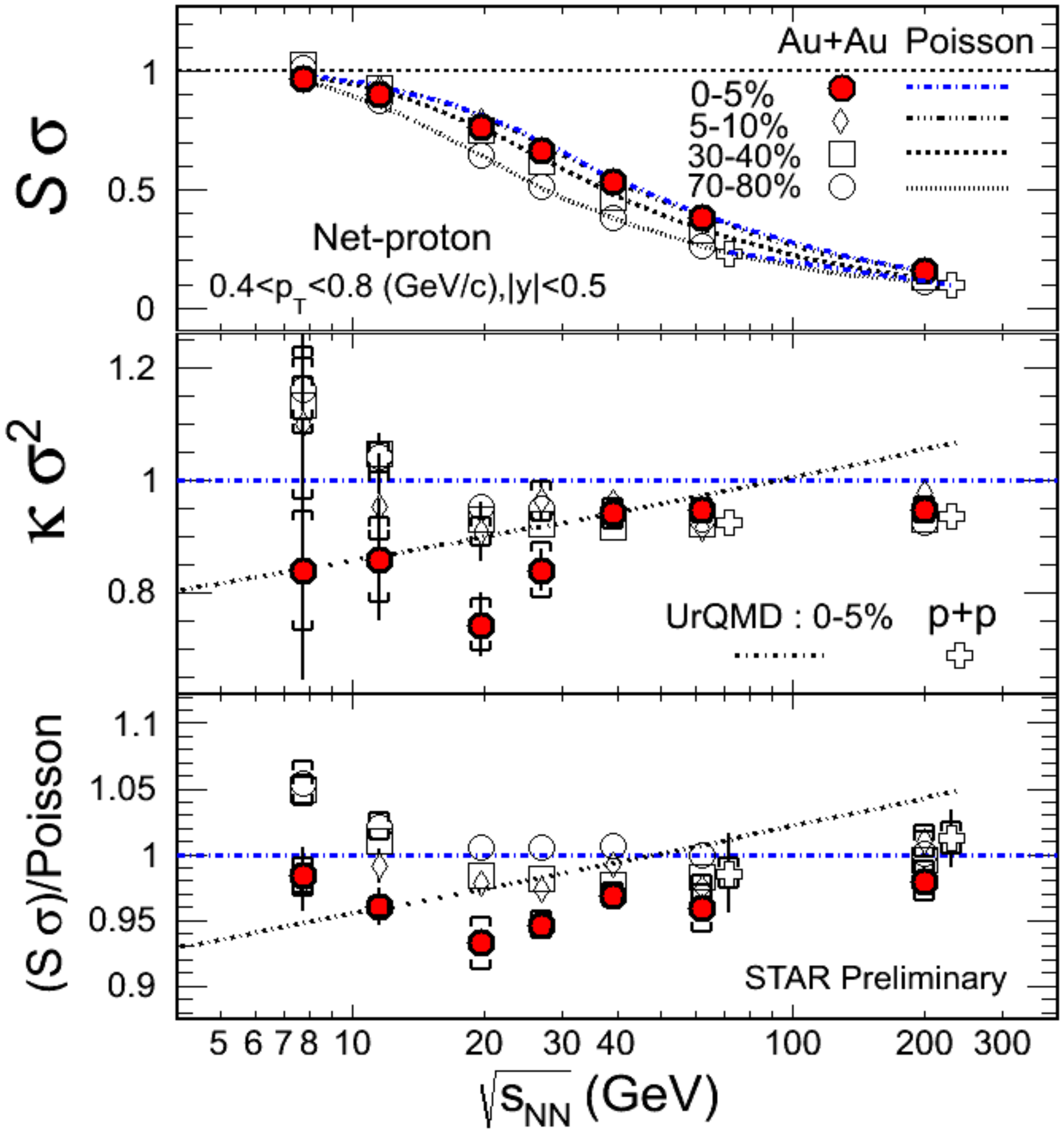
From Wikipedia





- 3rd moment = Skewness *S*
  - Asymmetry
- 4th moment = Kurtosis *K*
  - Peakedness
- Both moments = 0 for gaussian distribution
- Critical point induces non-gaussian fluctuations

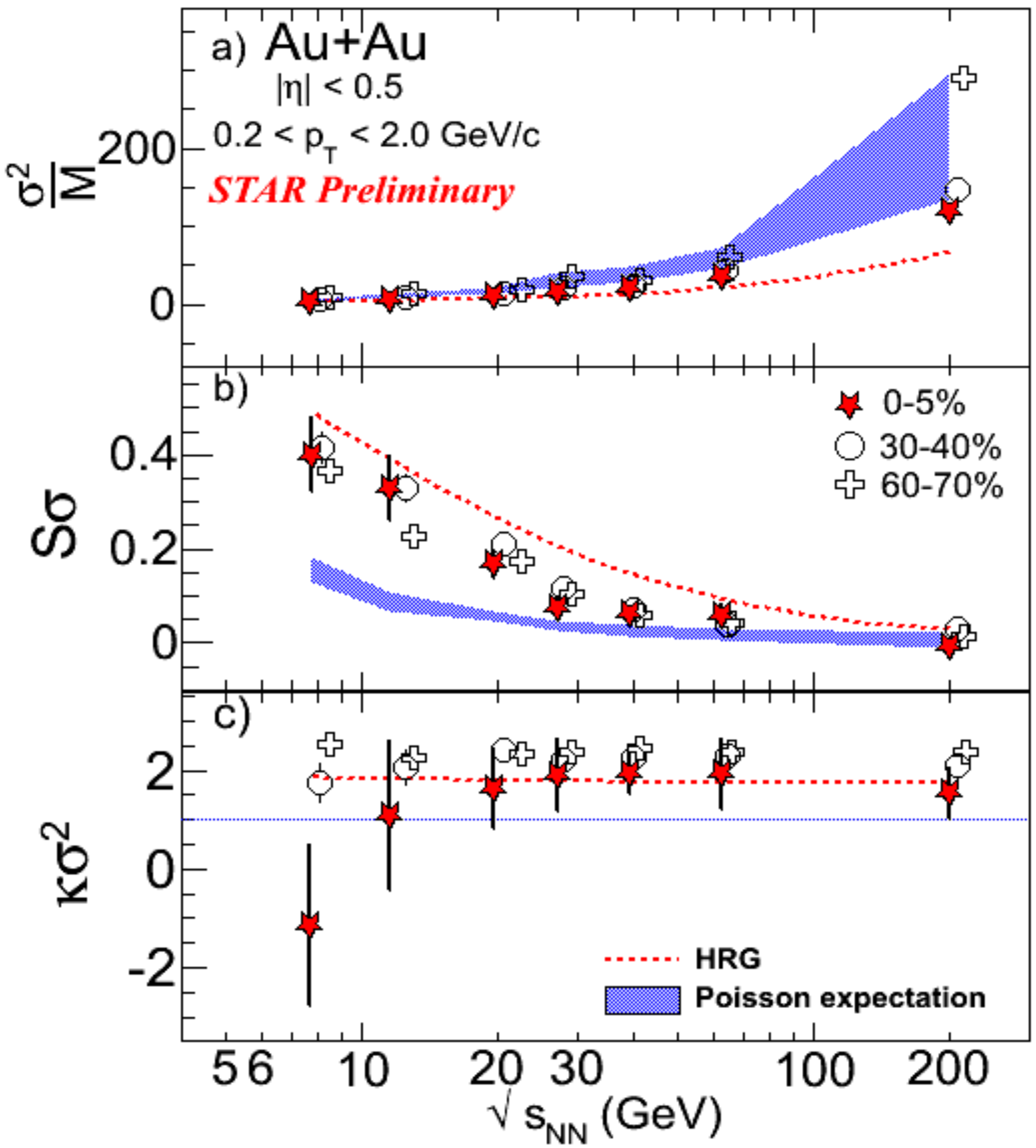
Net-protons



- Data
  - efficiency uncorrected*
- Data compared to various expectations
  - Poisson
  - (Negative-)Binomial*
  - Random sampling between p and pbar*
- UrQMD shows a monotonic energy dependence
- Need precision measurements at low energies

* under investigation (not shown here)

Net-charge



- Data
  - efficiency uncorrected*
- Data compared to various expectations
  - Poisson
  - (Negative-)Binomial*
- Need precision measurements at low energies

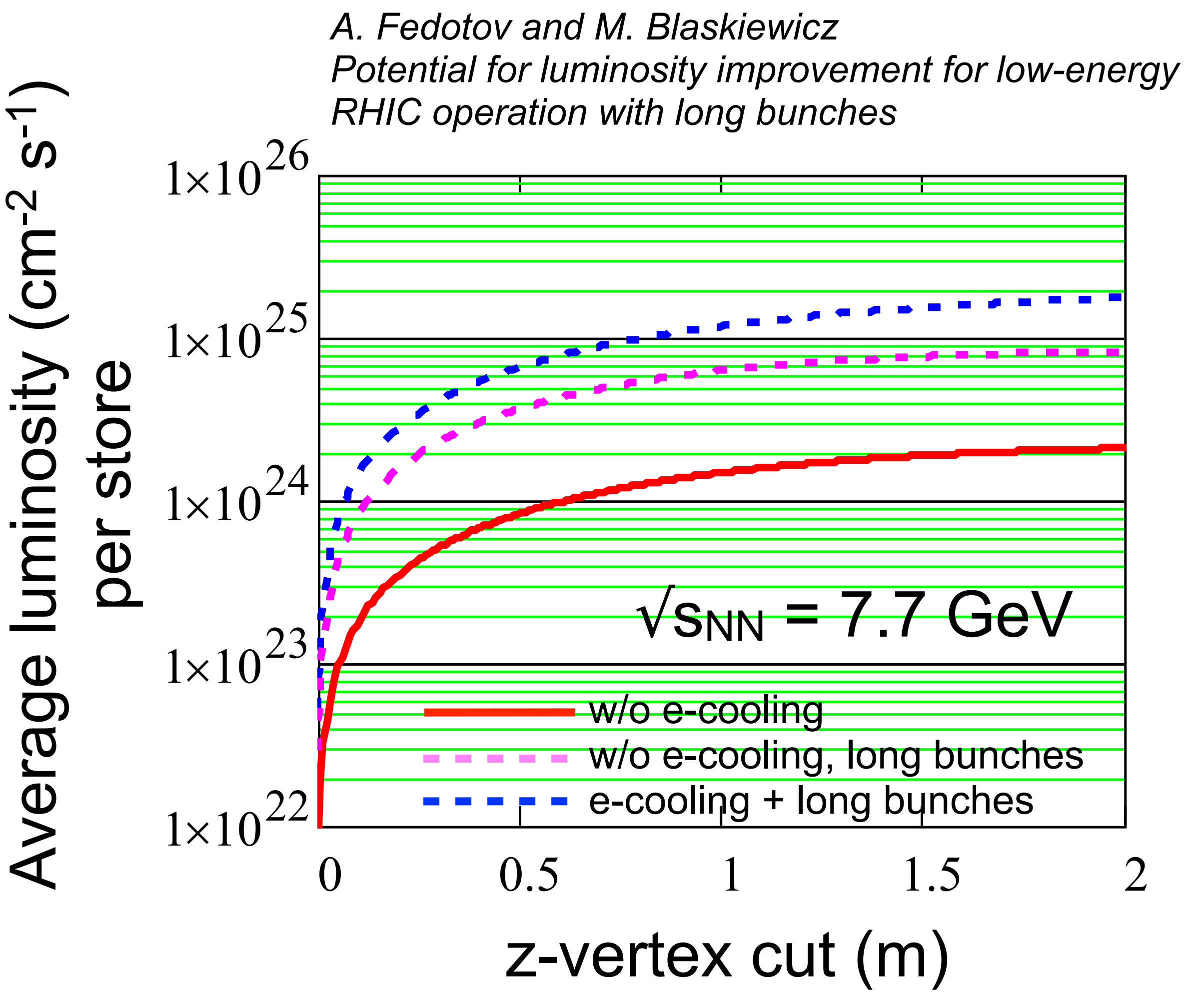
* under investigation (not shown here)

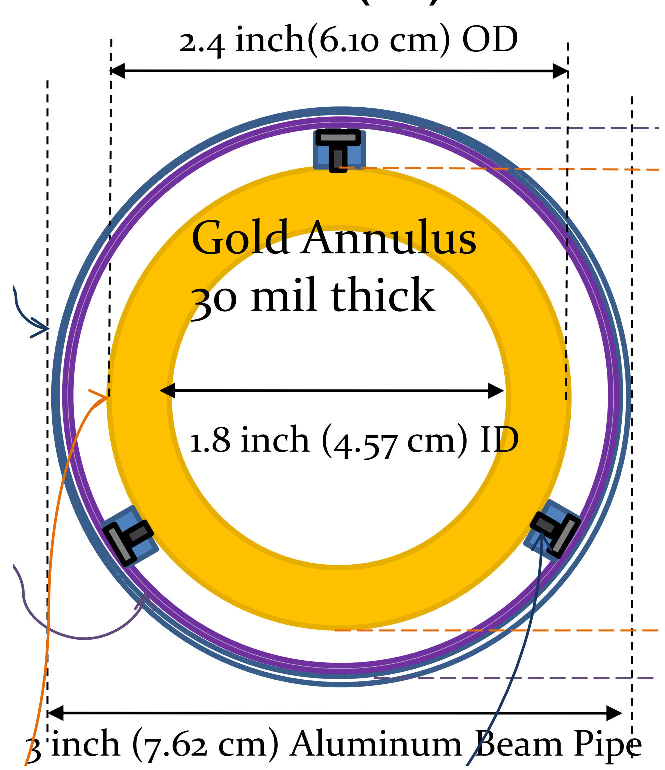
Summary on BES-I

- Turn-off QGP signals
  - Breakdown of NCQ scaling (particles vs anti-particles)
  - Disappearance of high p_T suppression
  - Disappearance of charge separation
- Signals of phase transition
  - Non-monotonic behavior of net-proton v_1 slope
  - Monotonic decrease of freeze-out eccentricity
- Signals of QCD critical point
  - Ongoing study on several aspects (efficiency, baseline, ...)
  - Need precision measurements at low beam energies

- BES phase-II will focus on beam energies below ~ 20 GeV

BES phase-II proposal





- BES phase-II (2017-) will 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 - down to $\sqrt{s_{NN}}$ ~ 3 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

Conclusions

- Several QGP signals turned off (v_2, R_{cp}, ...)

➡ ***hadronic interactions become more important at low energies***

- Non-monotonic behavior on v_1 slope
- Need precision measurements for higher moment analysis

- BES phase-II
  - Focus on $\sqrt{s_{NN}} < 20$ GeV
  - Precision measurements on bulk observables
    - especially event-by-event fluctuations to search for QCD critical point