Selected Results from STAR Beam Energy Scan Program

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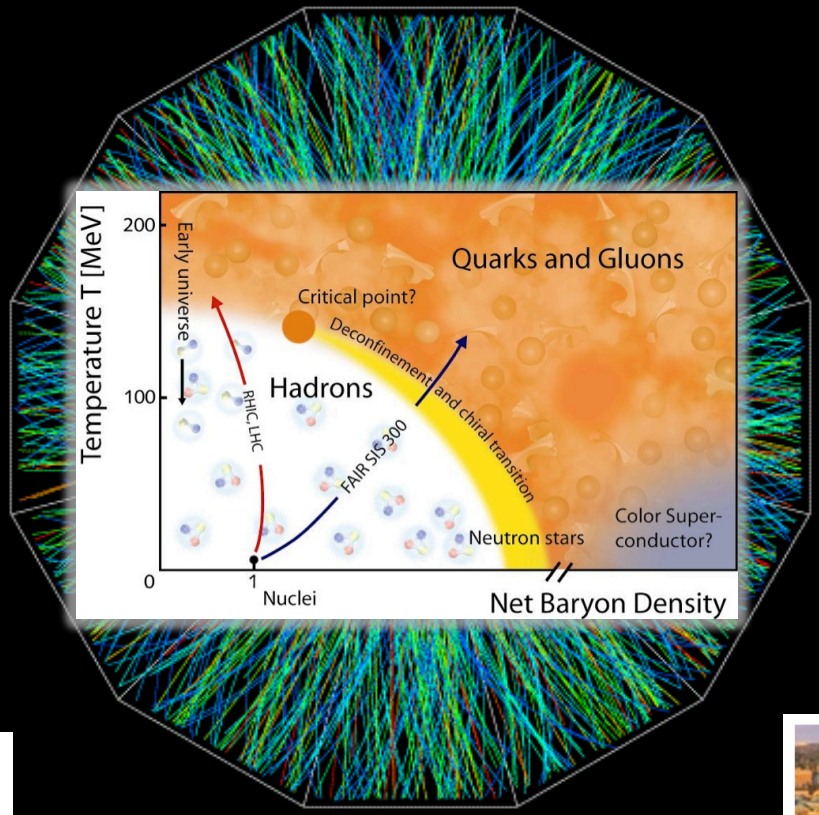
(for the STAR Collaboration)



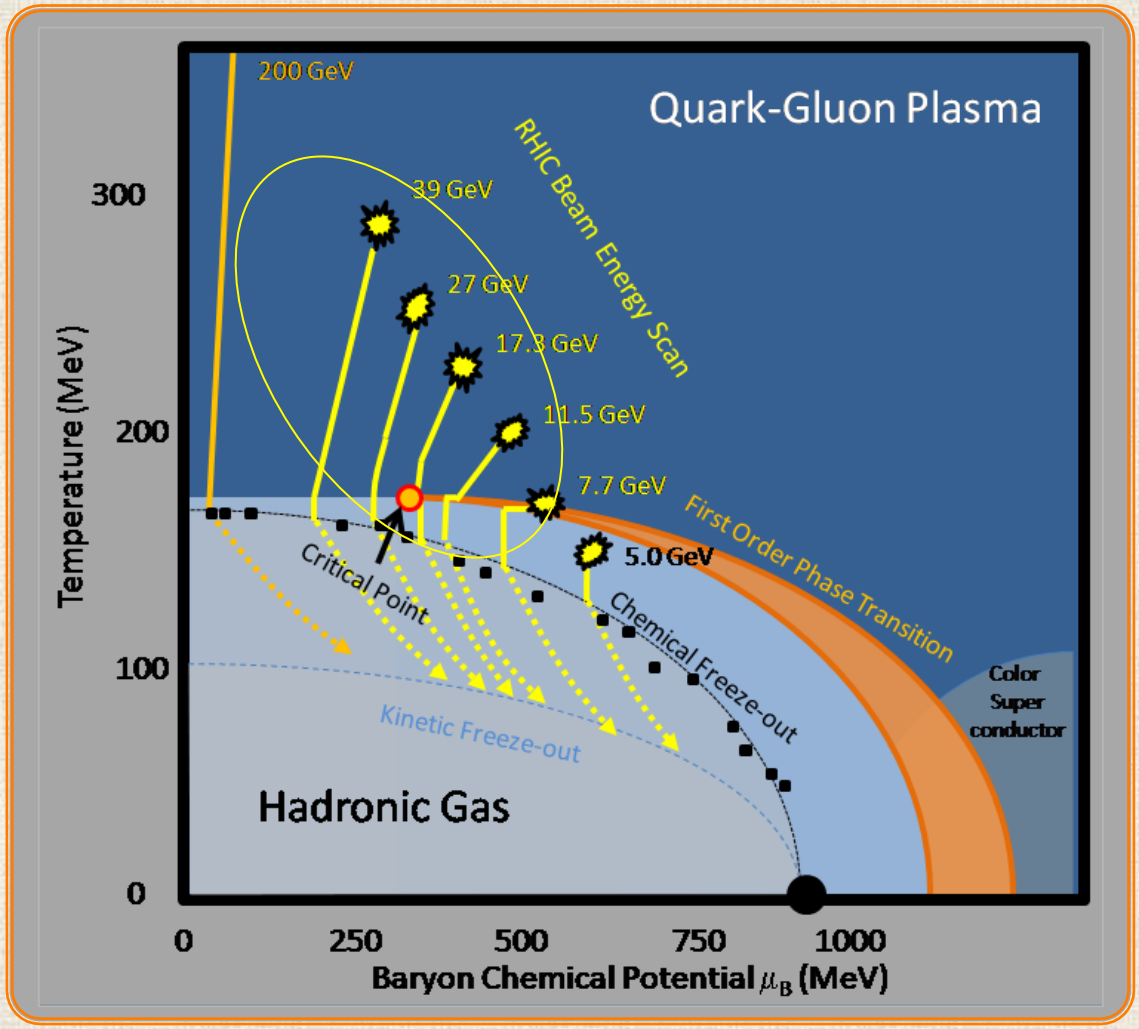
HEP 2013
Stockholm
18-24 July 2013

The RHIC Beam Energy Scan Motivation

1) Turn-off of sQGP signatures

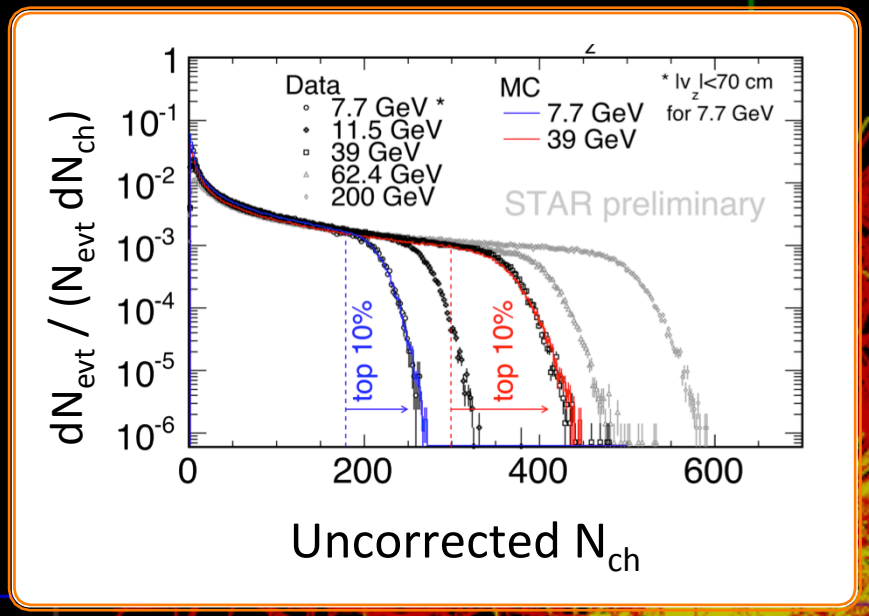
2) Search for the signals of phase boundary

3) Search for the QCD critical point



http://arxiv.org/abs/1007.2613

BES Au+Au Data Taking



BES-I Data:

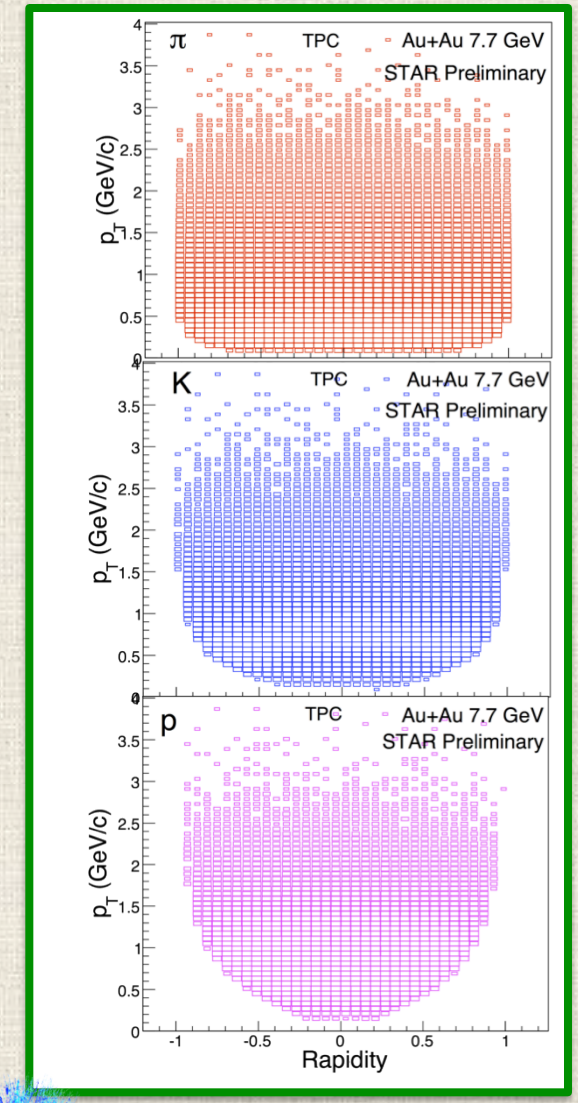
Year	$\sqrt{s_{NN}}$ [GeV]	events(10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5
2012*	5	Test Run

Triggering required effort, but was a solvable problem. Geometric acceptance remains the same, track density gets lower. Detector performance generally improves at lower energies.

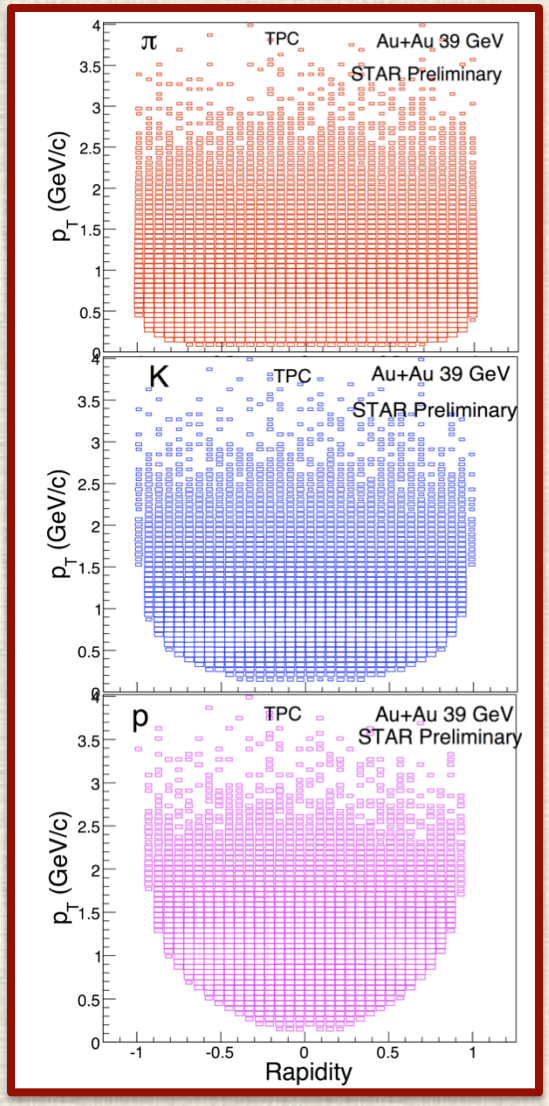
Central Au+Au at 7.7 GeV in STAR TPC

STAR TPC - Uniform Acceptance over all RHIC Energies

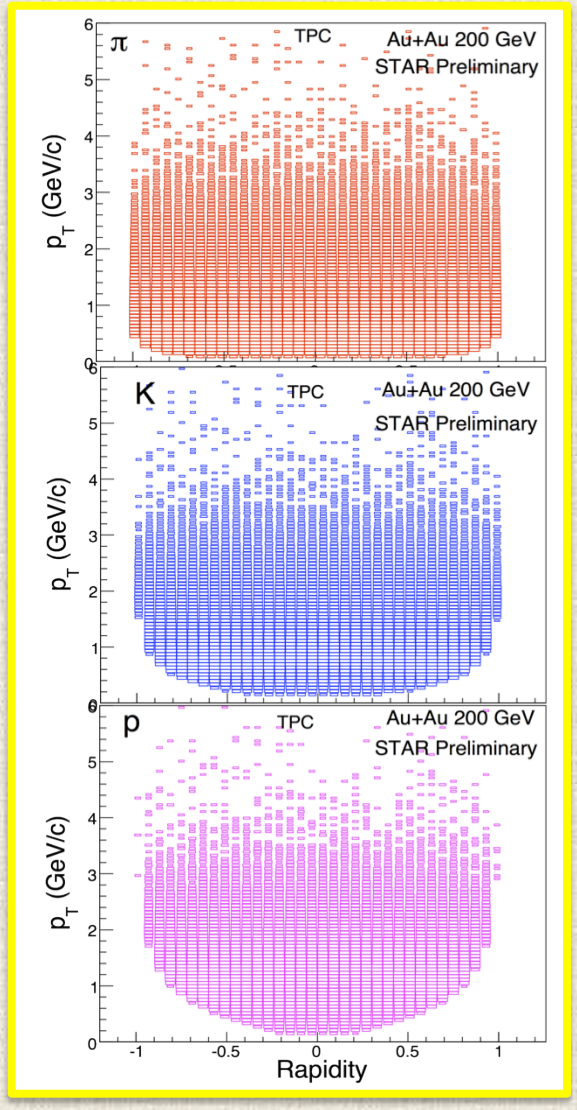
Au+Au at *7.7* GeV



Au+Au at *39* GeV



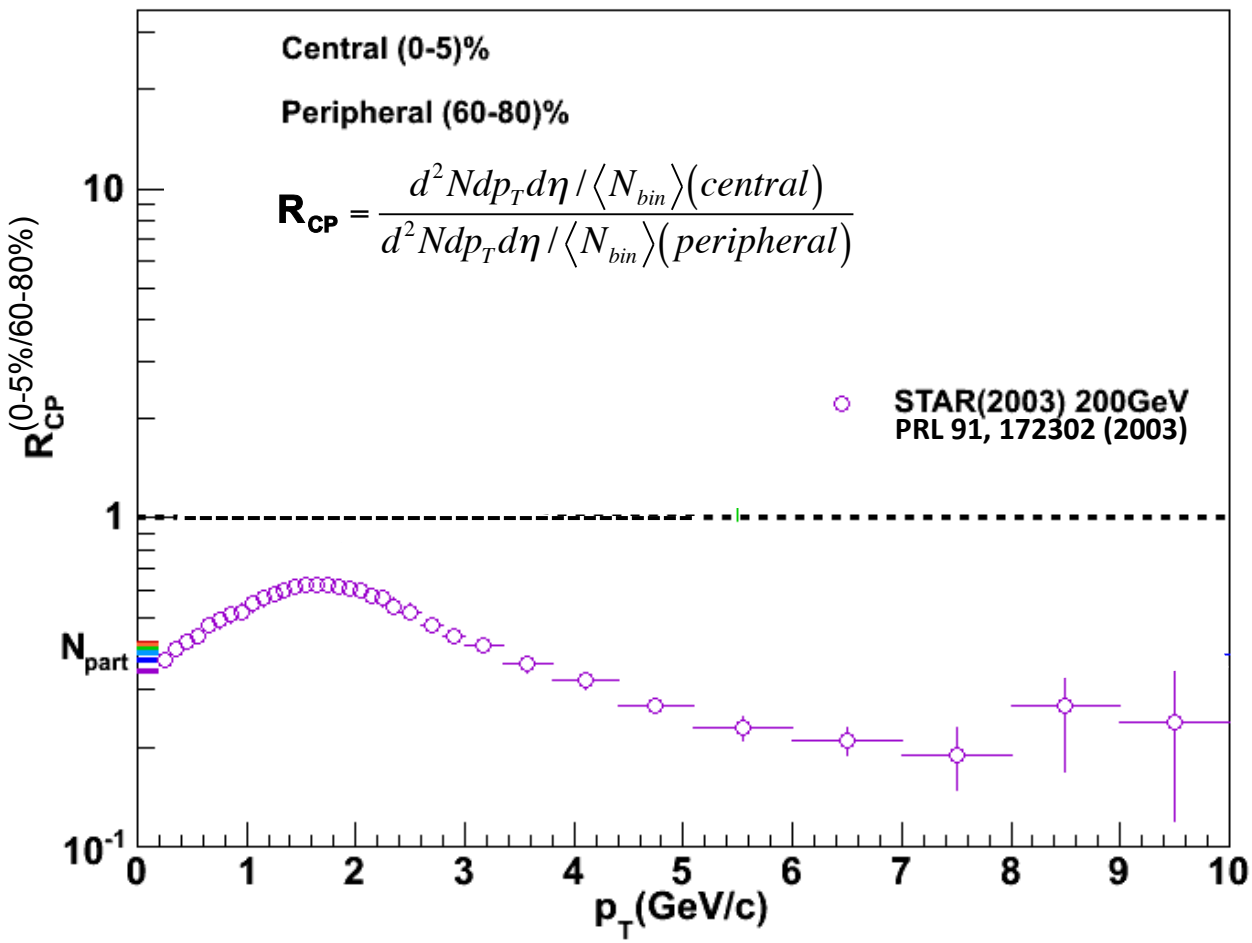
Au+Au at *200* GeV



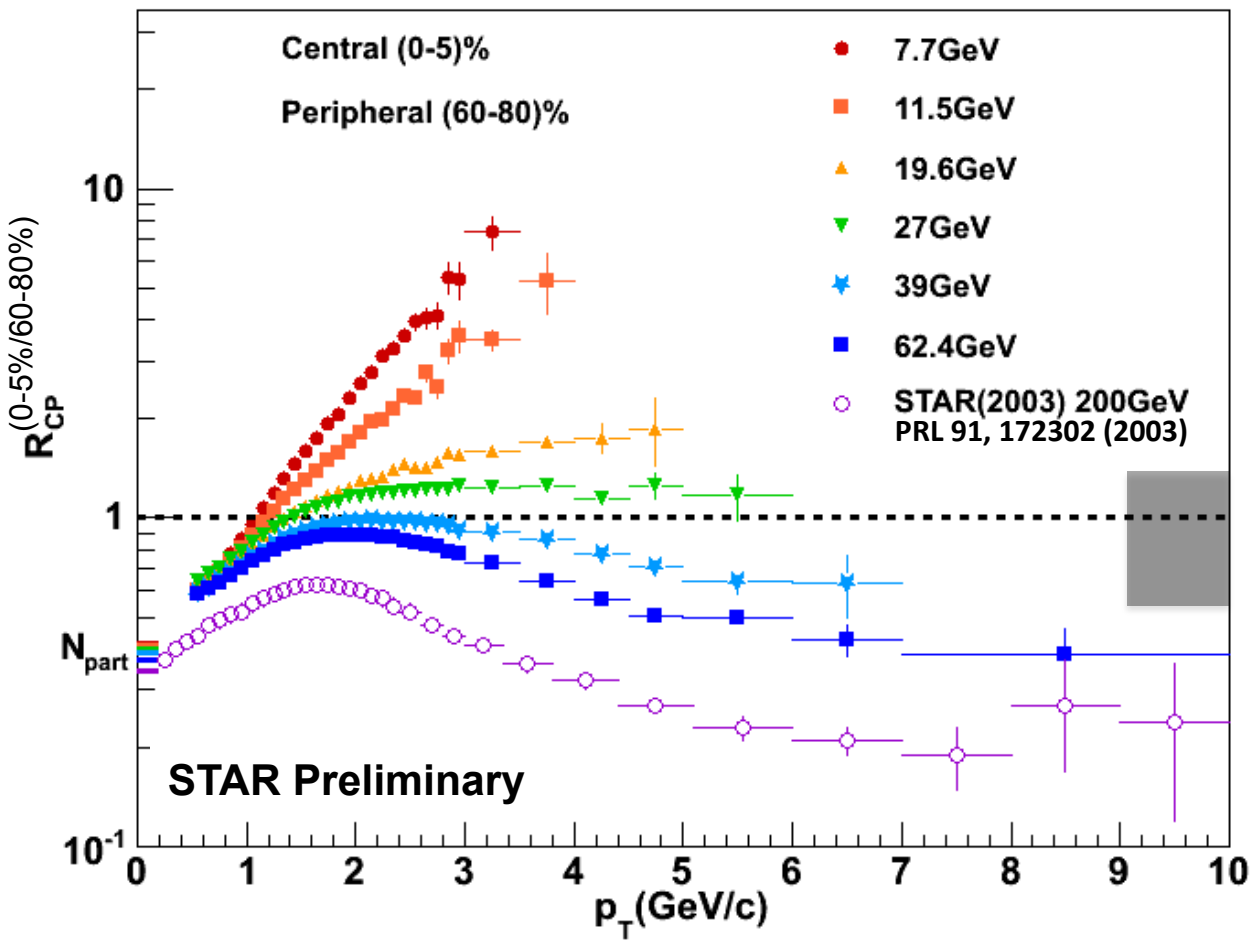
- Crucial for all analyses

Selected Results

Suppression of Charged Hadrons …

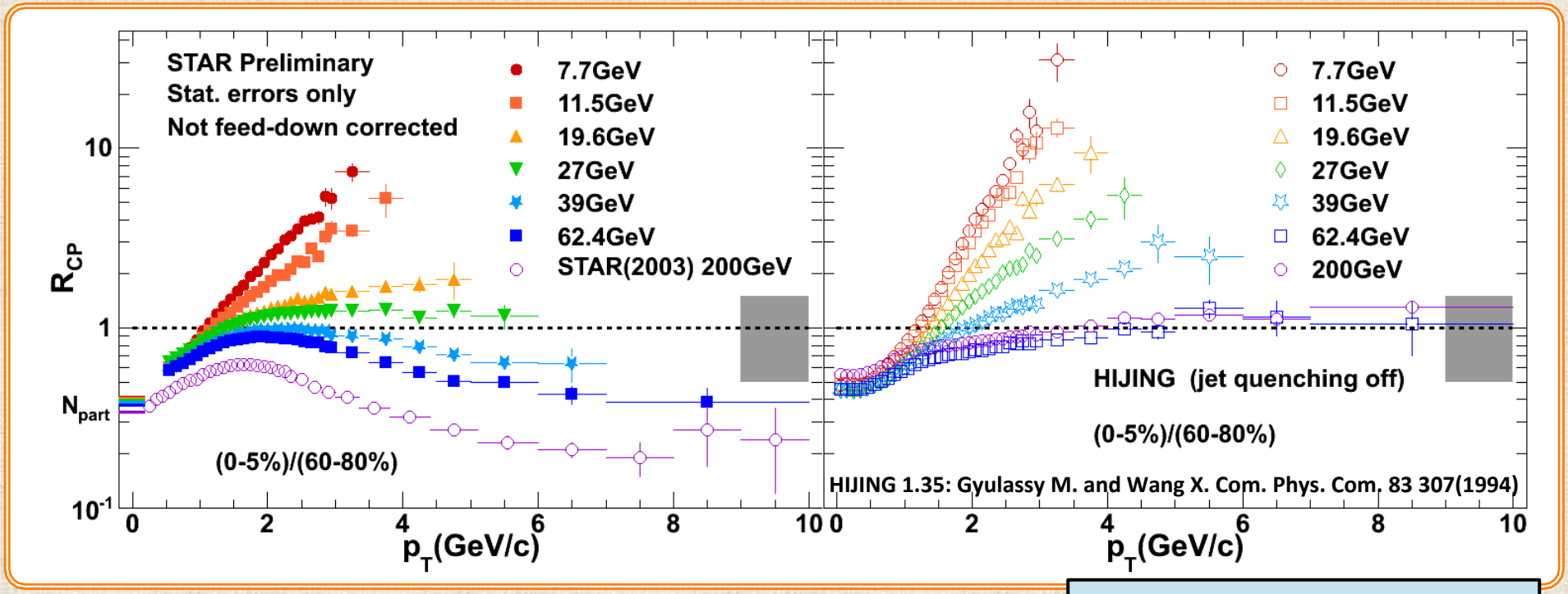


… and its Disappearance



$R_{CP} \geq 1$ at lower energies - Cronin effect?

Enhancement vs. QGP suppression

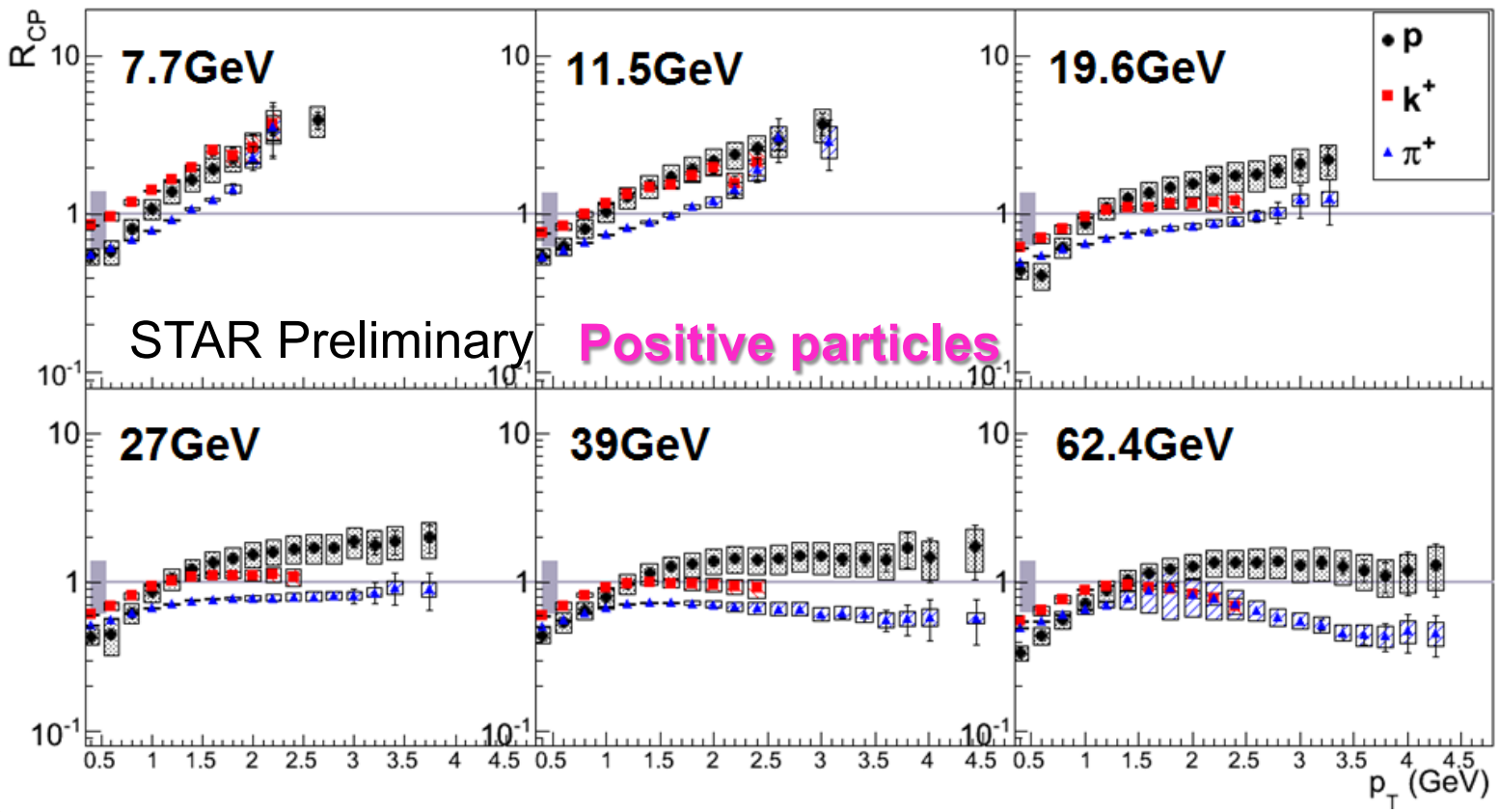


S. Horvat (STAR): arXiv: 1303.7260

Motivation: Agreement between the simulation and the data at low beam energies and its break down at higher energies could help to find the energy at which QGP becomes dominant.

- In HIJING (jet quenching off) R_{CP} at lower energies is enhanced, but there is no quantitative agreement with charged hadron R_{CP} from data.
- No suppression at higher energies observed, as expected (quenching was turned off).

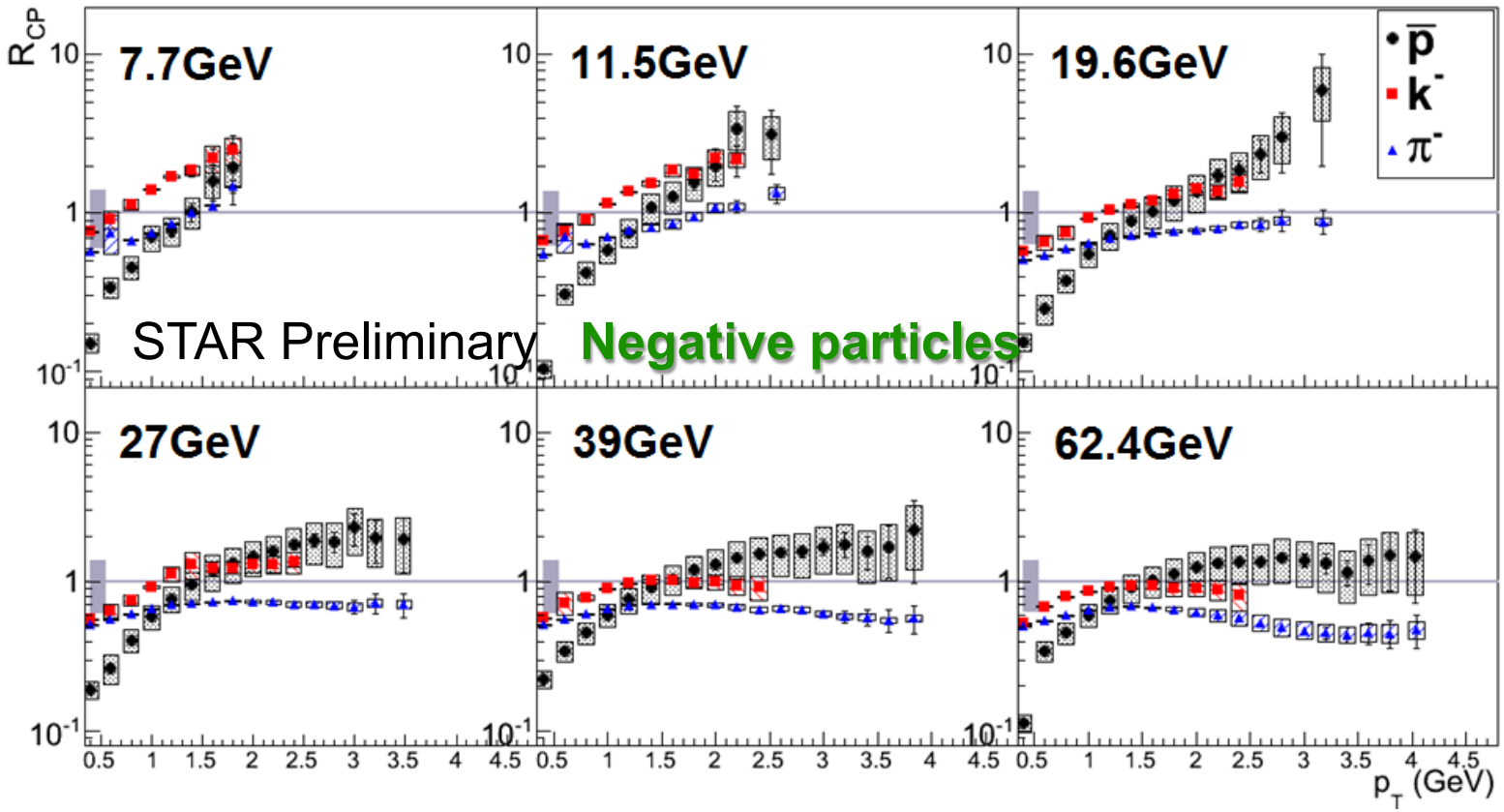
R_{CP} : Identified Particles



- Proton R_{CP} > pion R_{CP}, similar to d+Au at $\sqrt{s_{NN}}$=200 GeV

⇒Pions may serve as a better gauge for jet quenching within the p_T range available through particle identification.

R_{CP} : Identified Particles



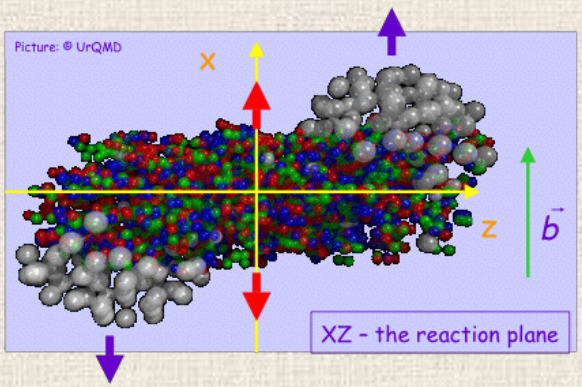
- Antiproton R_{CP} < pion R_{CP} for p_T <1GeV/c
- Pion R_{CP} suppressed for $\sqrt{s_{NN}}$ ≥39GeV

Azimuthal Anisotropy

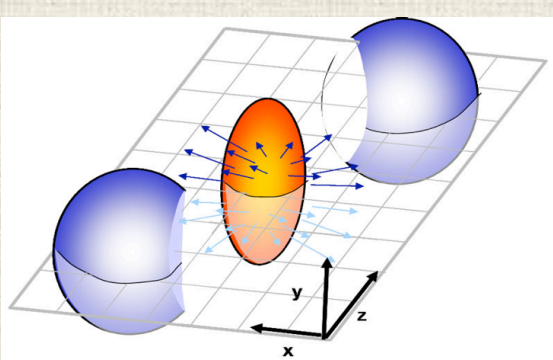
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n-1}^{+\infty} v_n \cos\left[n\left(\phi - \Psi_r\right)\right]\right)$$

$$v_n = \left\langle \cos(n\phi - \Psi_r) \right\rangle$$

$$\phi = \tan^{-1}\left(\frac{p_x}{p_y}\right)$$

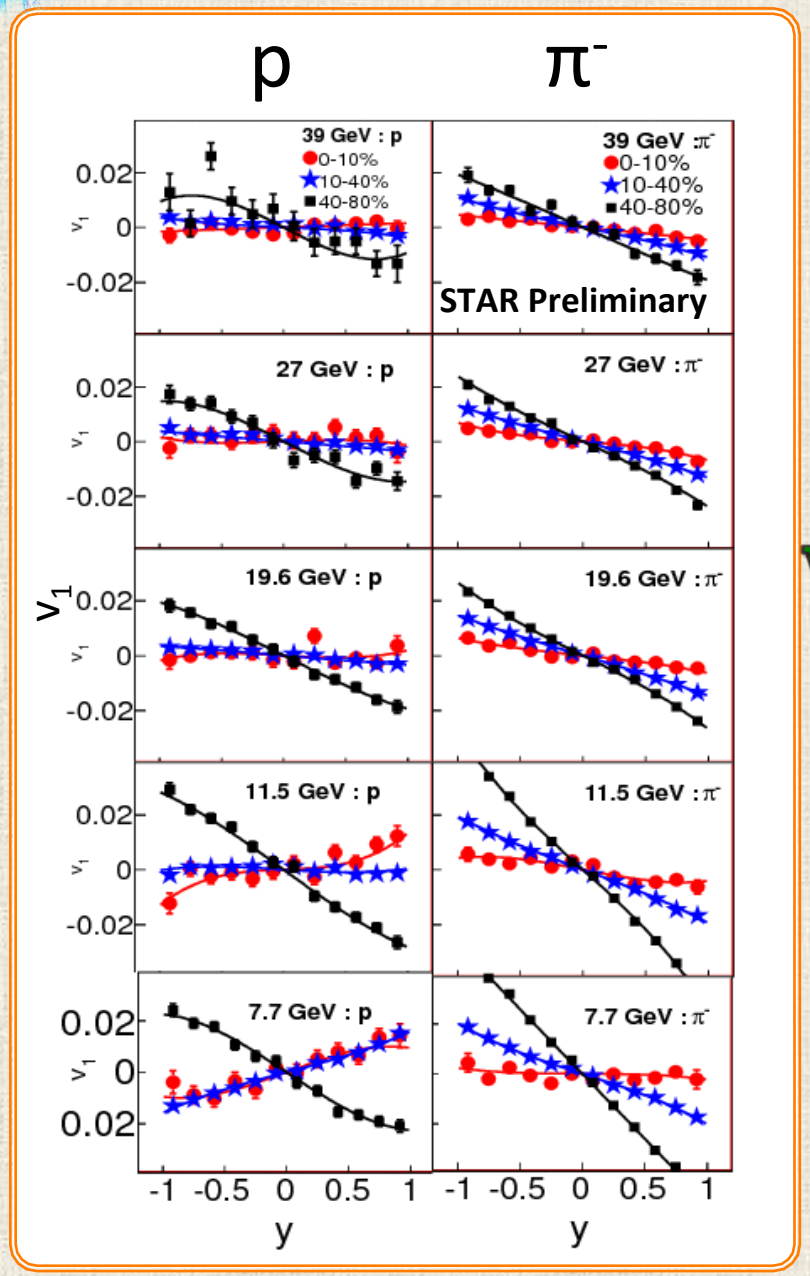


- Directed flow v_1 is due to the sideward motion of the particles within the reaction plane. It is sensitive to baryon transport, space-momentum correlations and QGP formation.

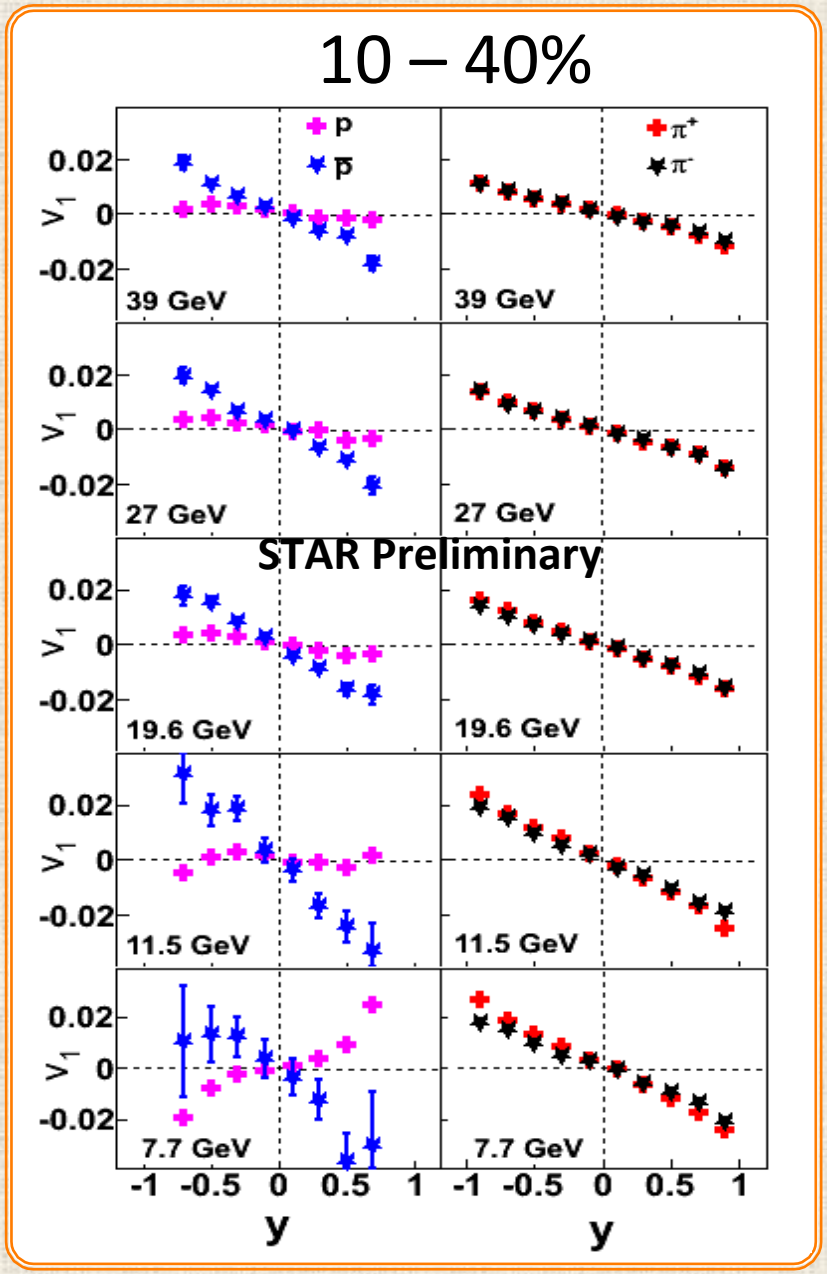


- Elliptic flow v_2 results from the interaction among produced particles and is directly related to transport coefficients of produced matter.

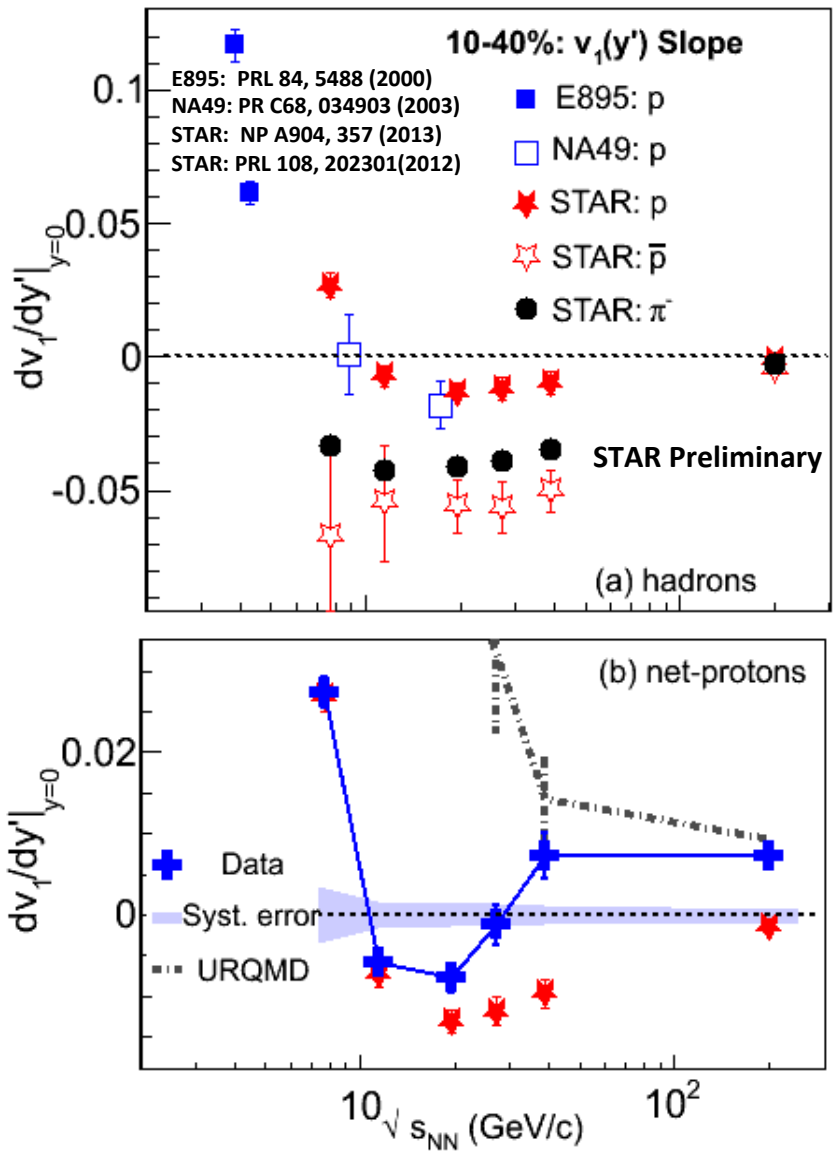
Directed Flow of p and π



$\sqrt{s_{NN}}$



Directed Flow of p and π: mid-central



Proton v_1 slope: changes sign from positive at 7.7 GeV to negative at 11.5 GeV and remains small negative up to $\sqrt{s_{NN}}$ =200GeV.

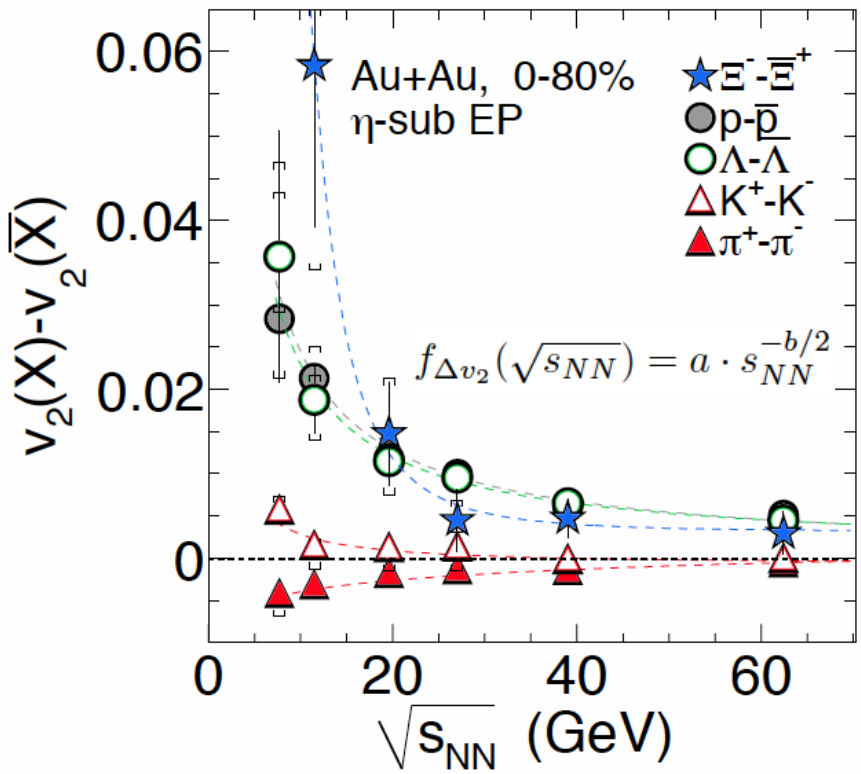
Pion and antiproton v_1 slope: always negative.

⇒ For $\sqrt{s_{NN}} \geq 11.5$ GeV contradicts baryon stopping picture predicting opposite slope for protons and pions.

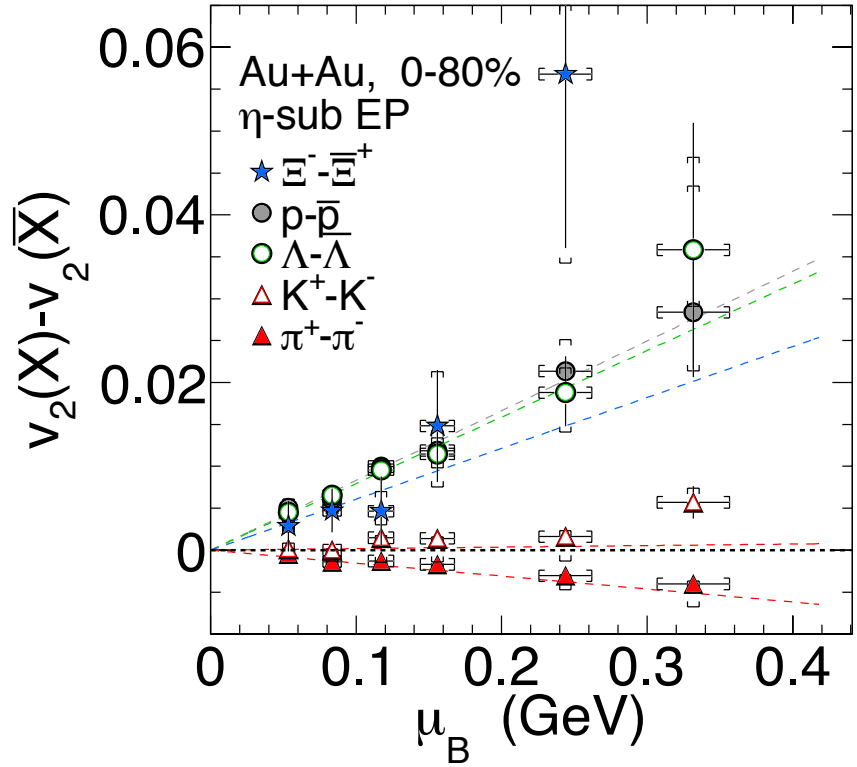
Net-proton v_1 slope: shows double sign change. Can not be explained by URQMD model but is qualitatively consistent with a prediction of hydrodynamic model with a first order phase transition*.

*)H. Stocker, Nucl. Phys. A 750, 121 (2005).

Δv_2: v_2(Particles) - v_2 (Antiparticles)



STAR: PRL 110 (2013) 142301

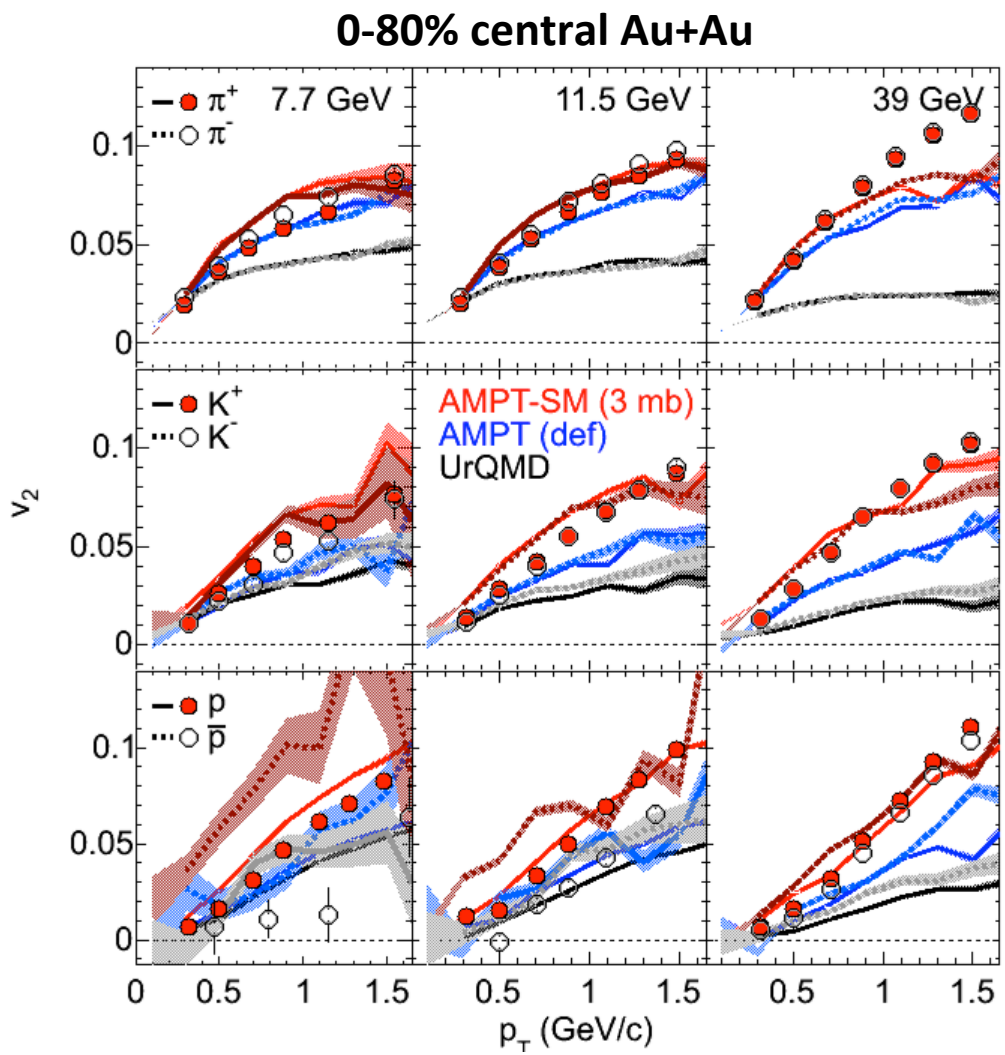


STAR: Phys.Rev. C88, 014902 (2013)

- The difference between particles and anti-particles is observed.
- A linear increase $\Delta v_2 = a \times \mu_B$ for all particle species for 7.7 GeV ≤ $\sqrt{s_{NN}}$ ≤ 62.4 GeV.

⇒ The baryon chemical potential is directly connected to the difference in v_2 between particles and antiparticles.

$v_2(p_T)$: Transport model comparisons

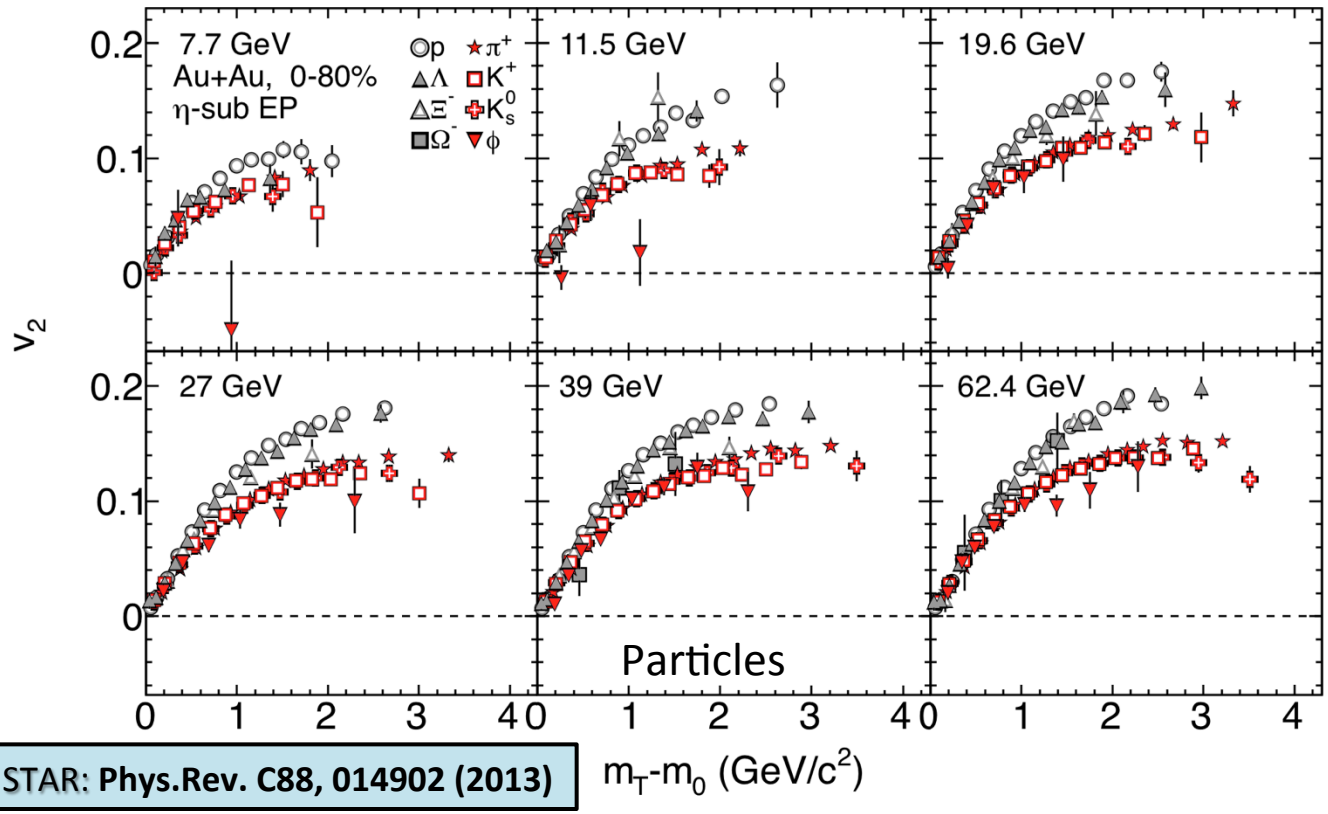


STAR: **Phys.Rev. C88, 014902 (2013)**

- **Purely hadronic system (UrQMD) does not explain relatively large elliptic flow at these energies.**
- **AMPT-SM provides the best description of the data (except of protons and anti-protons @ 7.7 GeV).**
- **In all other cases both AMPT and UrQMD under-predict $v_2(p_T)$.**

UrQMD 2.23: M. Bleicher et al, J. Phys. G 25, 1859 (1999).
AMPT 1.11: Z.-W. Lin et al., Phys. Rev. C 72, 064901 (2005).
AMPT-SM: string melting version

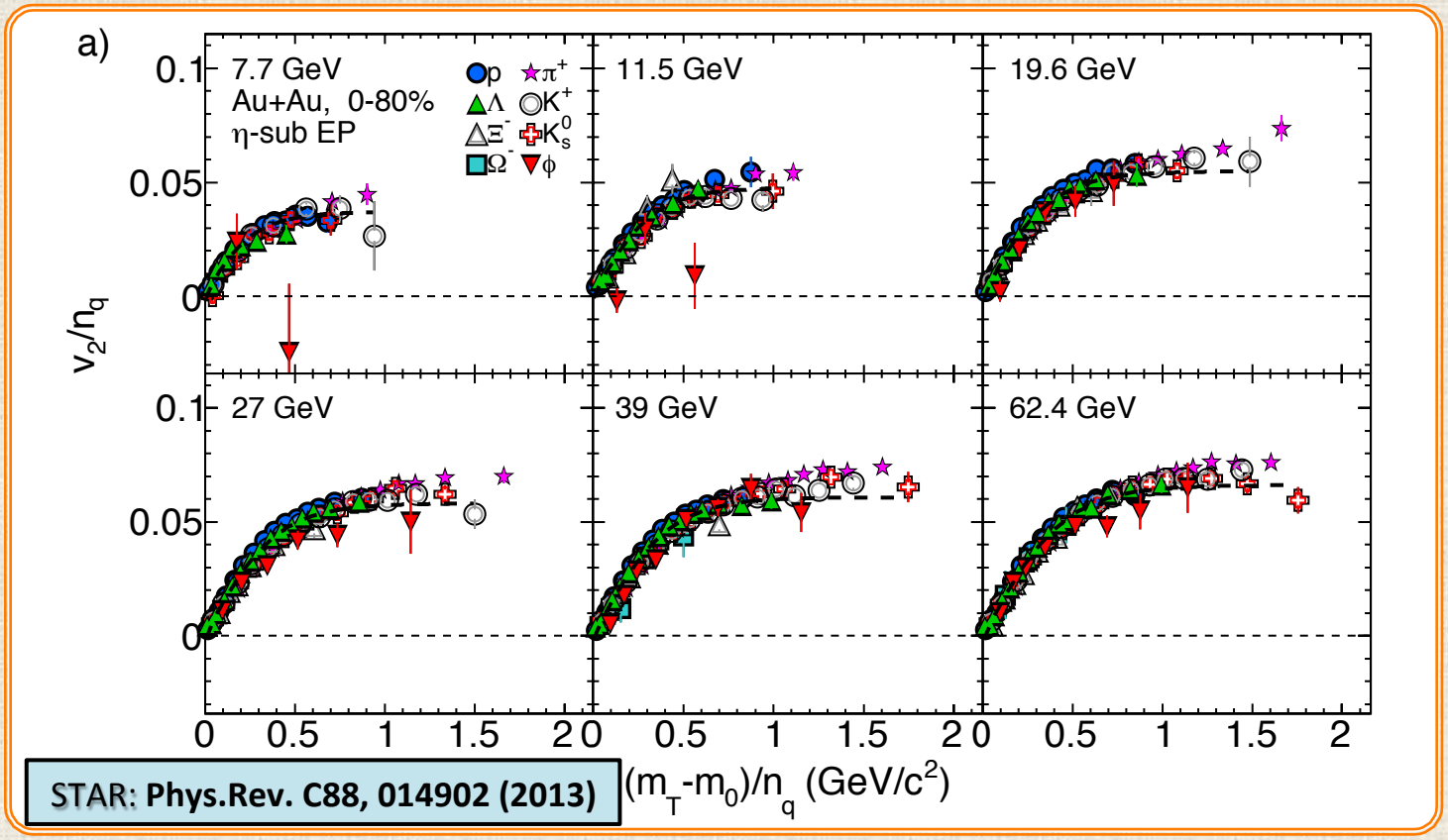
v_2 vs. m_T-m_0



STAR: **Phys.Rev. C88, 014902 (2013)**

- Baryon–meson splitting is observed when collisions energy ≥ 19.6 GeV for both particles and the corresponding anti-particles
- For anti-particles the splitting is almost gone within errors at 11.5 GeV

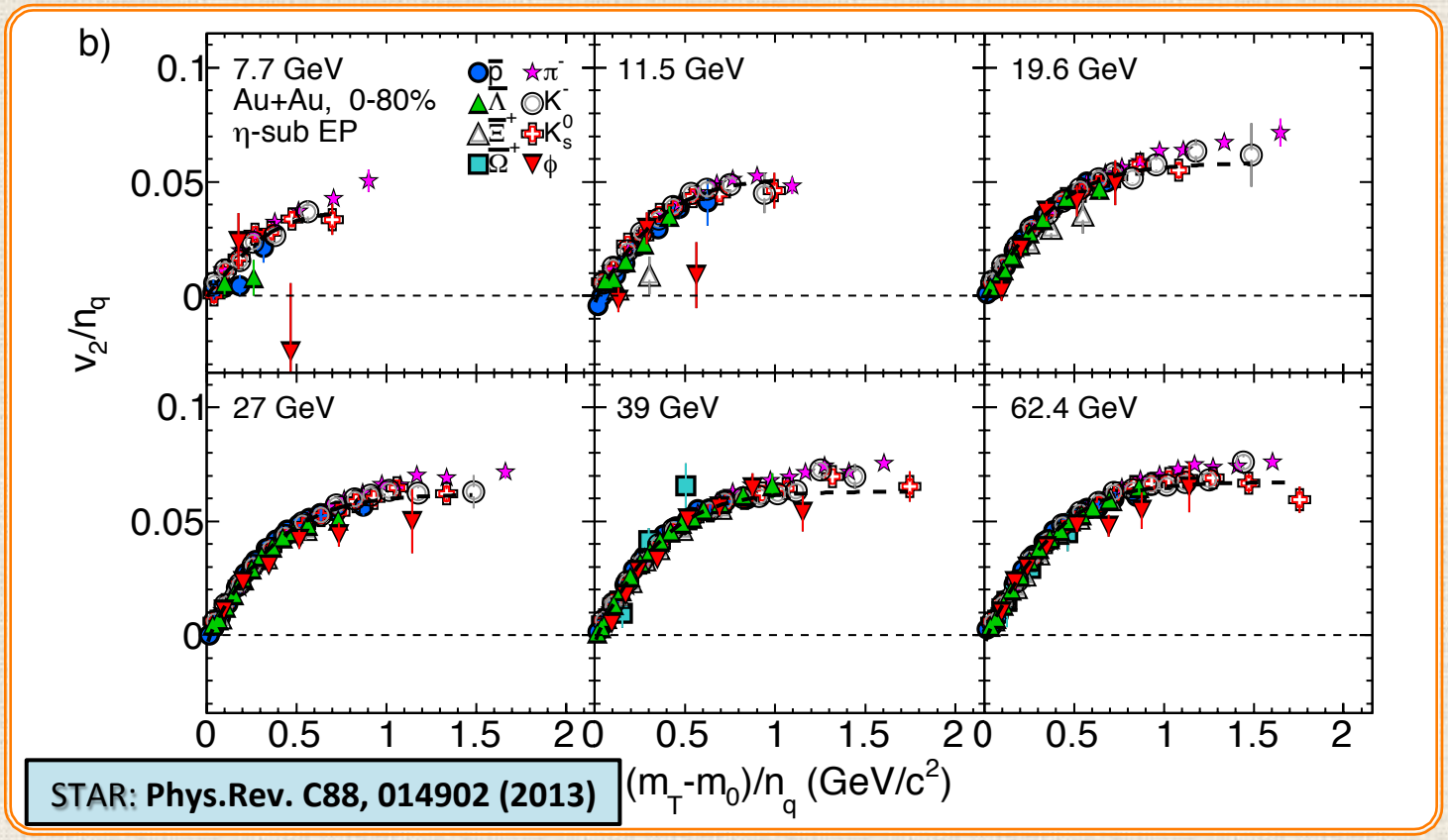
NCQ Scaling Test: particles



- Universal trend for most of particles – n_{cq} scaling not broken at low energies
- ϕ meson v_2 deviates from other particles in Au+Au@(11.5 & 7.7) GeV: ~ 2σ at the highest p_T data point. Needs more data to make clear conclusion.

Reduction of v_2 for ϕ meson and absence of n_{cq} scaling ➔ during the evolution the system remains in the hadronic phase [B. Mohanty and N. Xu: J. Phys. G 36, 064022(2009)]

NCQ Scaling Test: antiparticles



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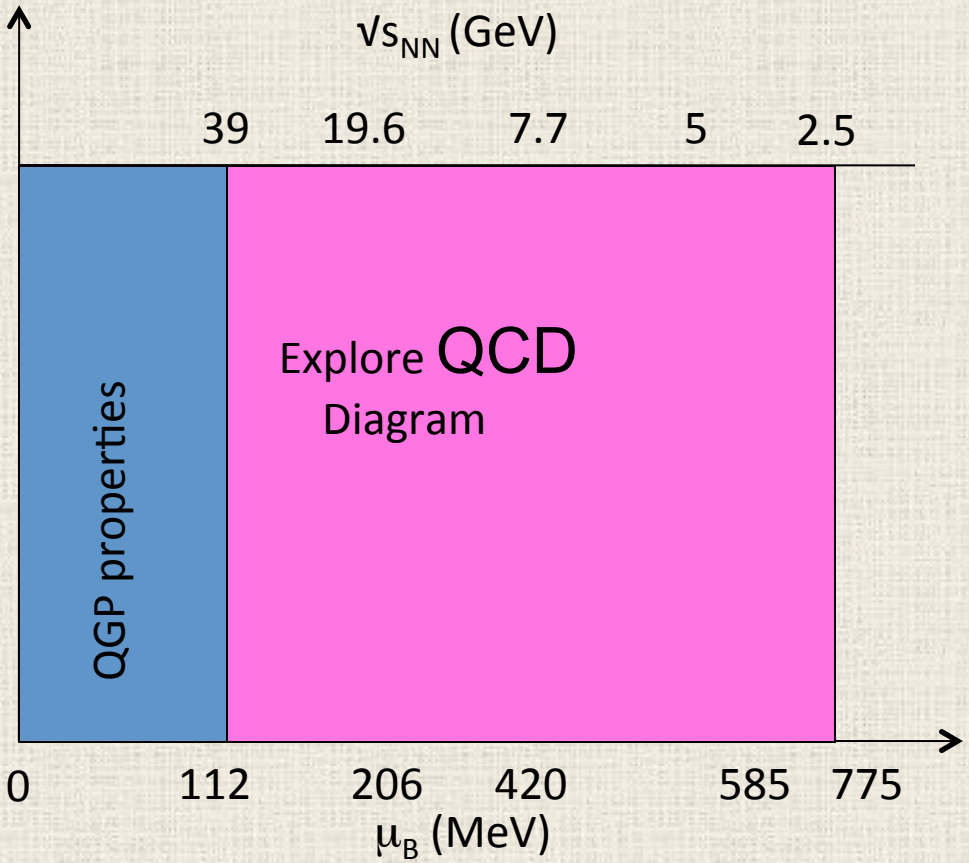
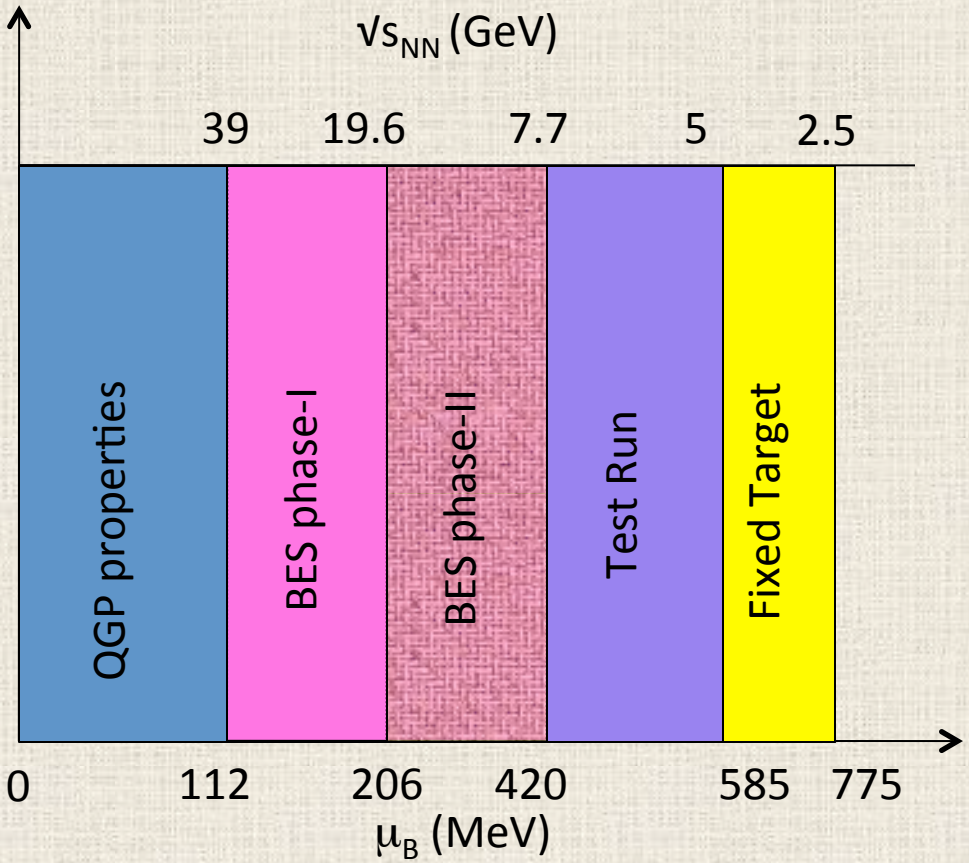
Beam Energy Scan Phase- II

STAR BES Program Summary



Large range of μ_B in the phase diagram !!!

STAR BES Program Summary



Large range of μ_B in the phase diagram !!!

Summary

- ★ STAR results from BES program covering large μ_B range provide important constraint on QCD phase diagram:
  - **R_{CP} of unidentified charged hadrons turns-off near 39 GeV.**
  - **Identified R_{CP} is qualitatively similar and suggests that pions are less affected by (still unquantified) sources of enhancement.**
  - **Proton v_1 slope changes sign between 7.7 GeV and 11.5 GeV.**
  - **Net-proton v_1 slope shows double sign change between 7.7 GeV and 39 GeV.**
  - **Particles-antiparticles v_2 difference increases with decreasing $\sqrt{s_{NN}}$ and is directly connected to baryon chemical potential.**
  - **Baryon–meson splitting is observed when collisions energy ≥ 19.6 GeV for both particles and the corresponding anti-particles.**
  - **...and many other results not covered in this talk.**

- ★ Search for the critical point continues:
  - **Proposed BES-II program**
  - **Fixed target proposal to extend μ_B coverage up to 800 MeV**

STAR Collaboration

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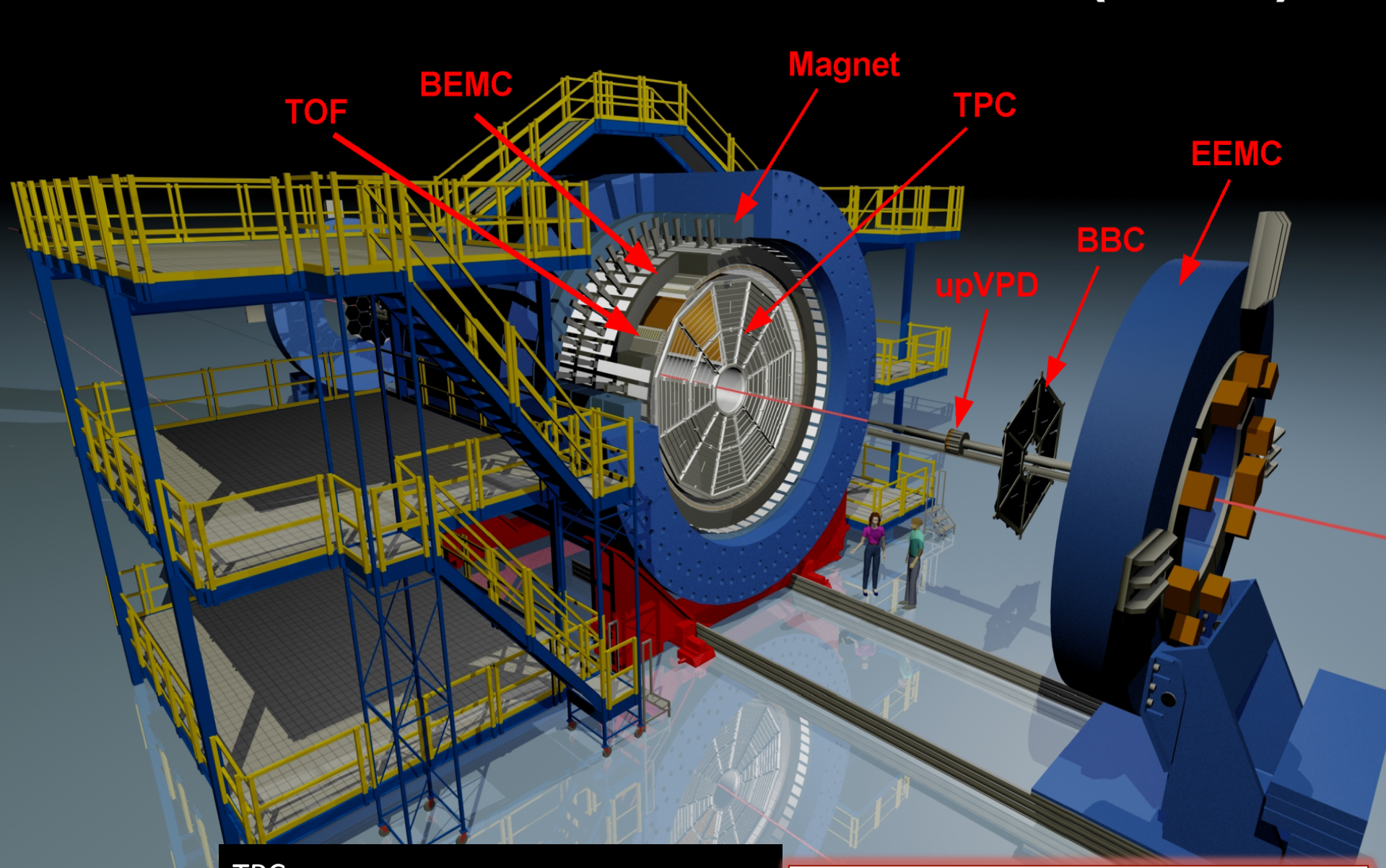
Thank you

Backup slides

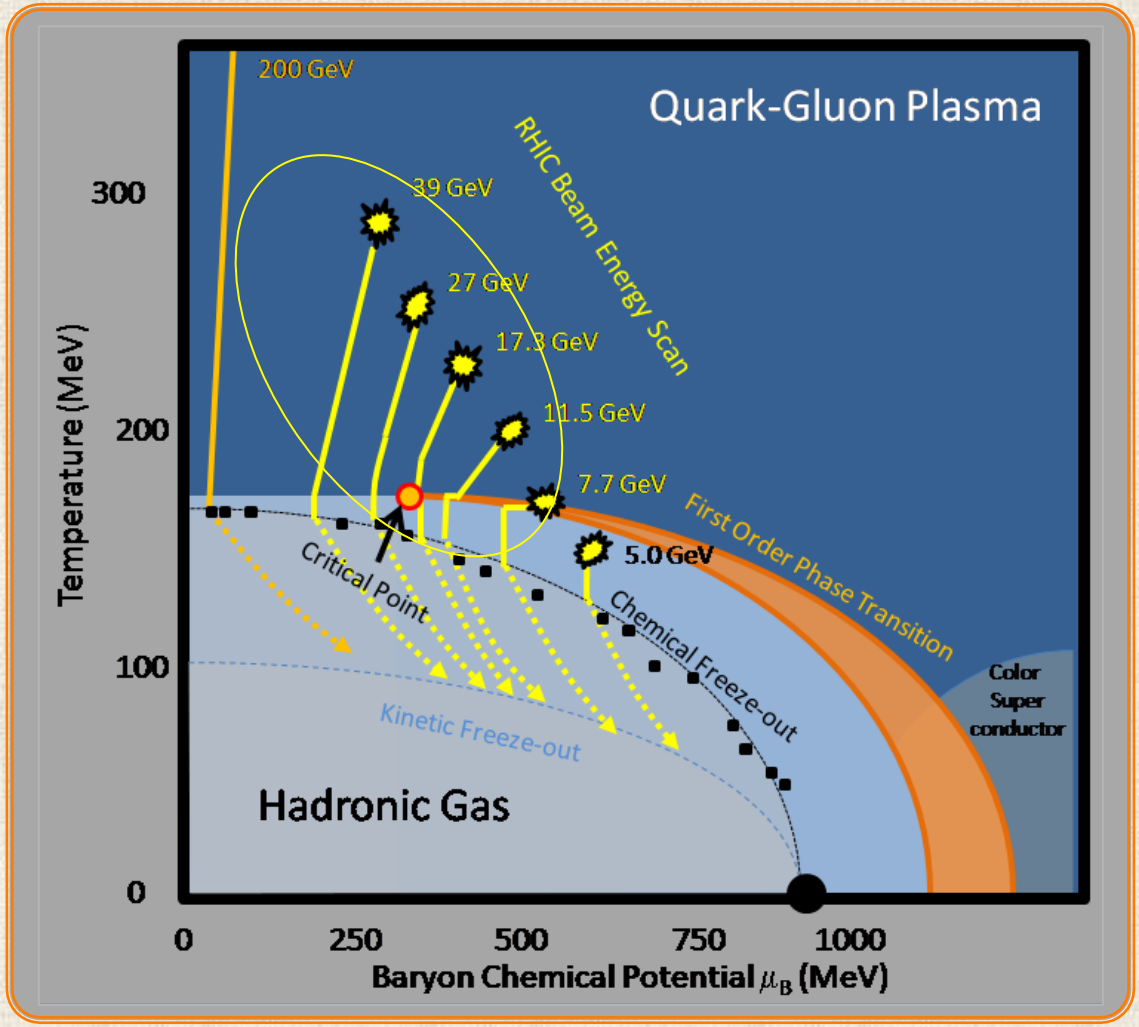


TPC:
Detects Particles in the $|\eta|<1$ range
π, K, p through dE/dx and TOF
K^0_s, Λ, Ξ, Ω, ϕ through invariant mass

Coverage: $0 < \phi < 2\pi$ $|\eta| < 1.0$
Uniform acceptance: All energies and particles

The RHIC Beam Energy Scan Project

- Since the original design of RHIC (1985), running at lower energies has been envisioned
- RHIC has studied the possibilities of running lower energies with a series of test runs: 19.6 GeV Au+Au in 2001, 22.4 GeV Cu+Cu in 2005, and 9.2 GeV Au+Au in 2008
- In 2009 the RHIC PAC approved a proposal to run a series of six energies to search for the critical point and the onset of deconfinement.
- These energies were run during the 2010 and 2011 running periods.



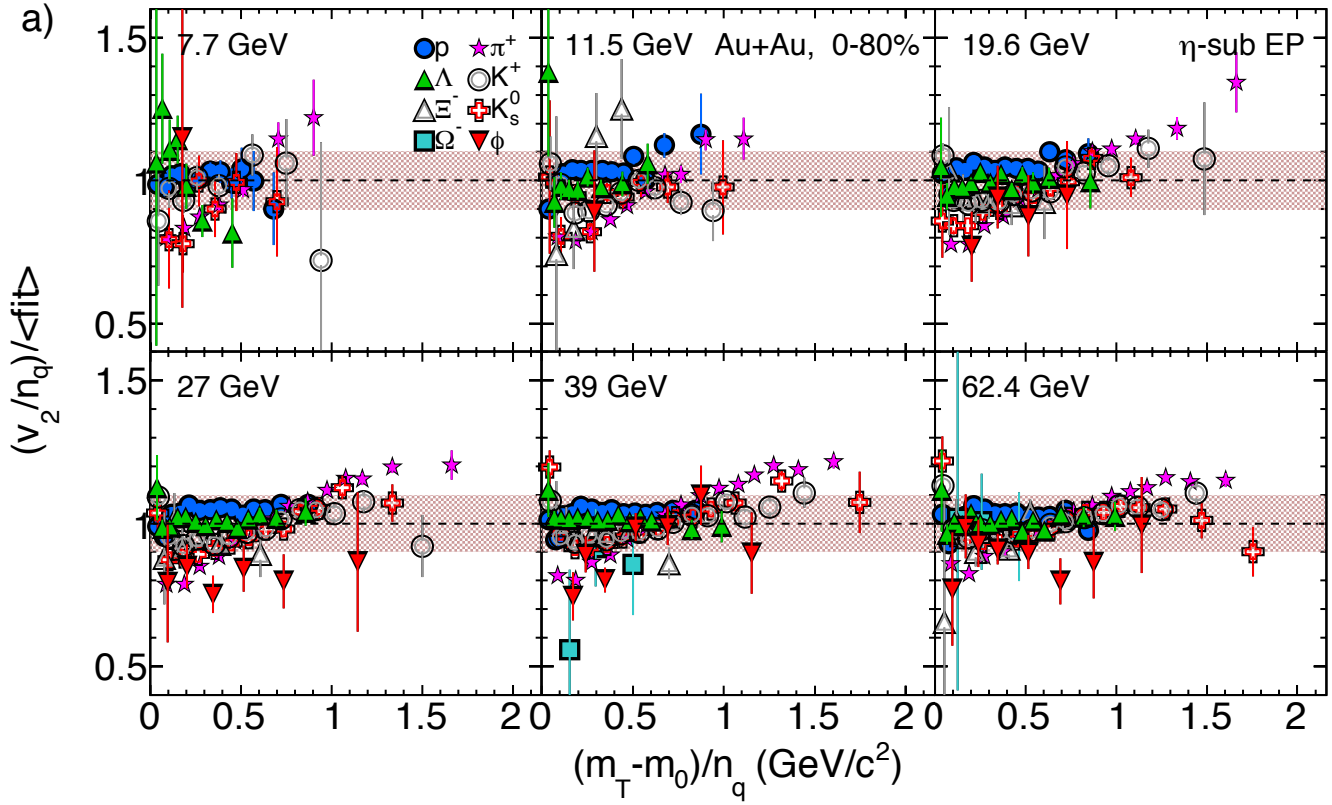
A landmark of the QCD phase diagram

Model summary

- HIJING captures beam energy dependence of spectra.
- Jet quenching as modeled in HIJING has a greater effect on higher beam energies.
- For AMPT, lower beam energies are better matched by SM off, while SM on better captures the beam energy dependence.

⇒Physics of hadronization shifts from coalescence to fragmentation?

NCQ Scaling Quality: particles



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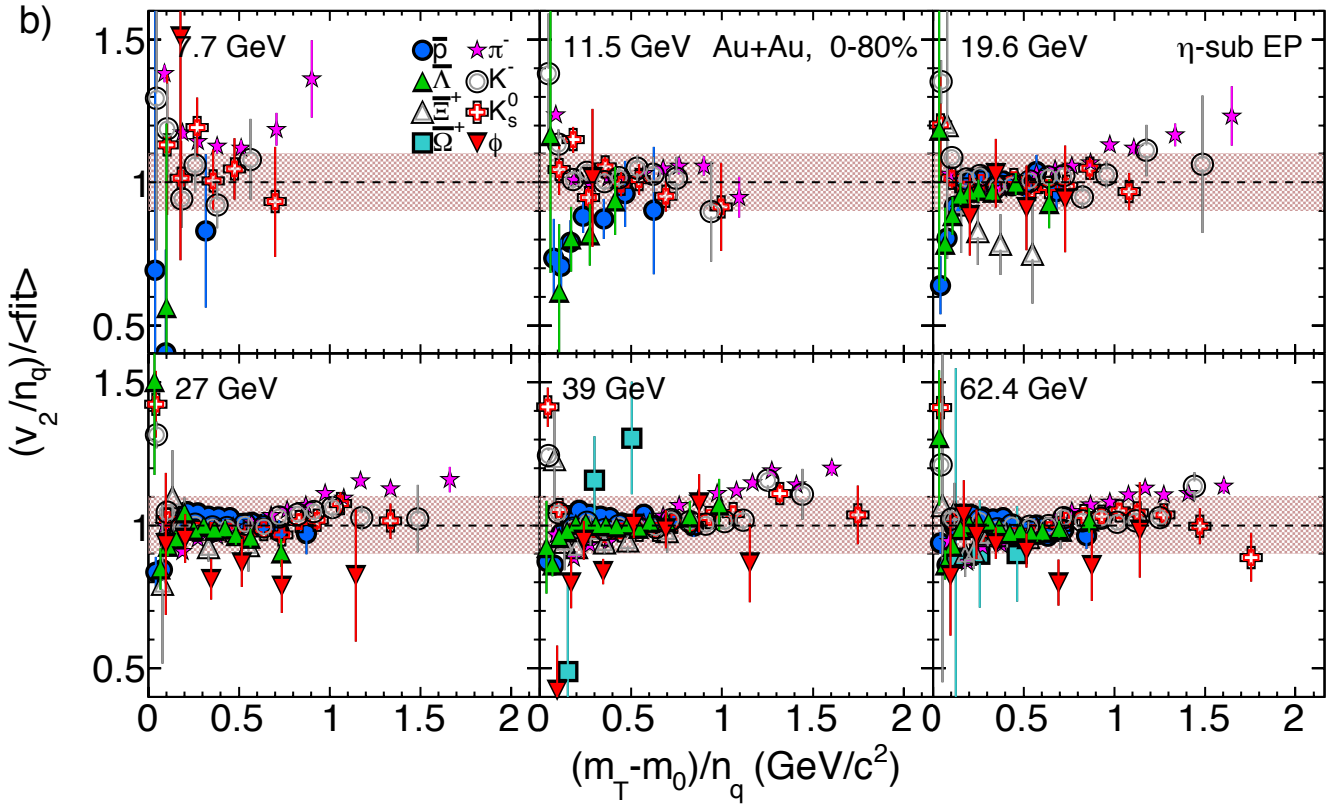
NCQ Scaling Quality: antiparticles



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