Overview of results from phase I of the Beam Energy Scan Program at RHIC

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RHIC and the Beam Energy Scan (BES)

Relativistic Heavy-Ion Collider (RHIC) discovered and studies the Quark Gluon Plasma (QGP), a deconfined phase of nuclear matter

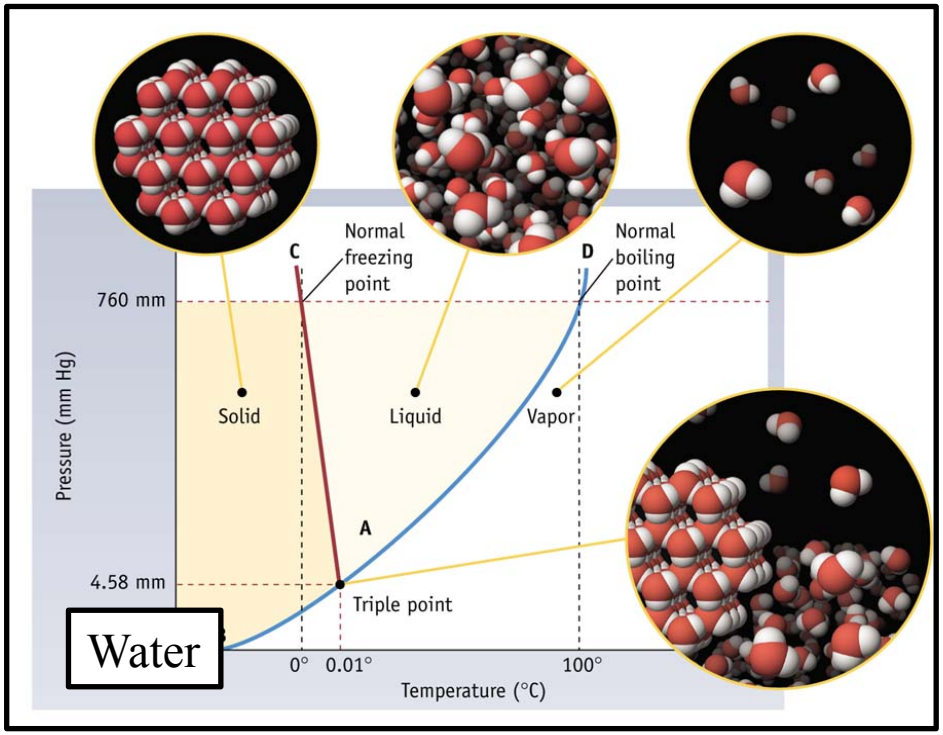
- QGP existed in the early universe
- Little is known about properties of nuclear matter
- RHIC uniquely able to explore phase diagram of nuclear matter

Phase Diagram of Nuclear Matter

• Can we see the signatures of the QGP turn off?

• Does the nuclear phase diagram have boundaries?

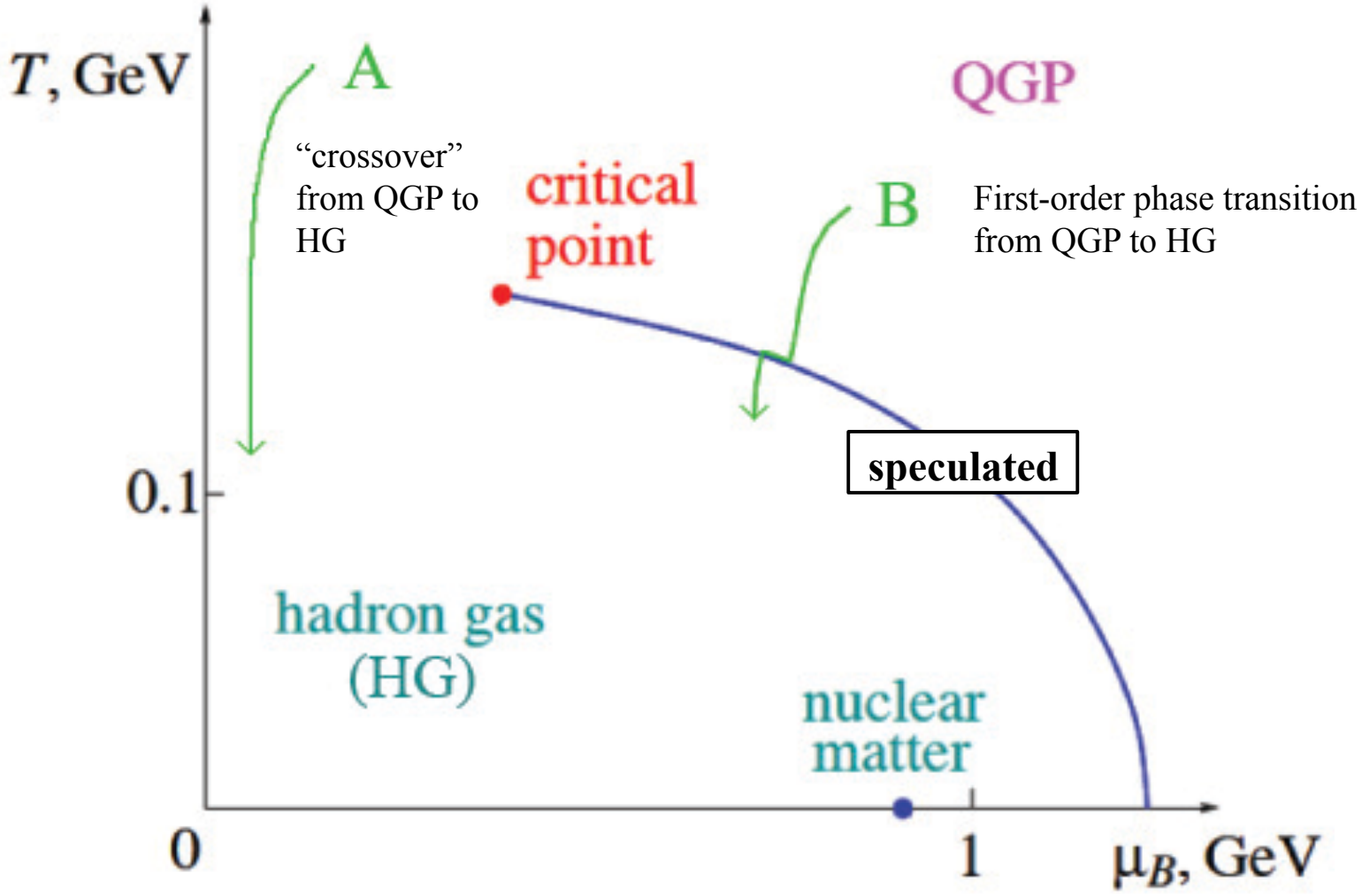
• Is there a critical point (CP)?



QCD phase diagram

STAR, arXiv:1007.2613 [nucl-ex]

At ~1 fm/c after a heavy-ion collision, excited nuclear systems with some local equilibrium are formed somewhere in the "phase diagram."

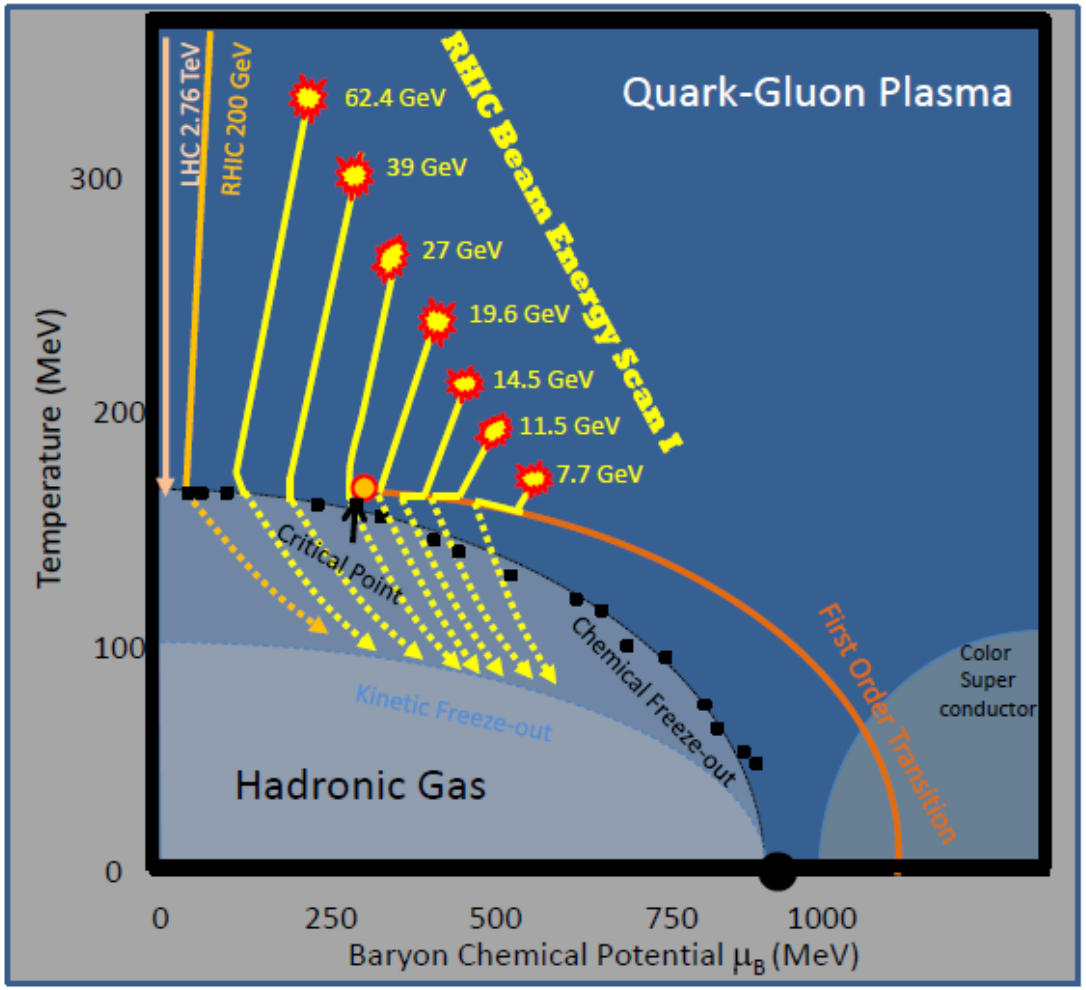


RHIC Beam Energy Scan (BES)

By varying the beam energy, one can experimentally explore the phase diagram.

RHIC BES collected data at seven different beam energies in 2010, 2011, and 2014.

Energy (GeV)	Events (Millions)	Time (Weeks)
200	350	11
62.4	67	1.5
39.0	130	2
27.0	70	1
19.6	36	1.5
14.5	20	3
11.5	12	2
7.7	4	4



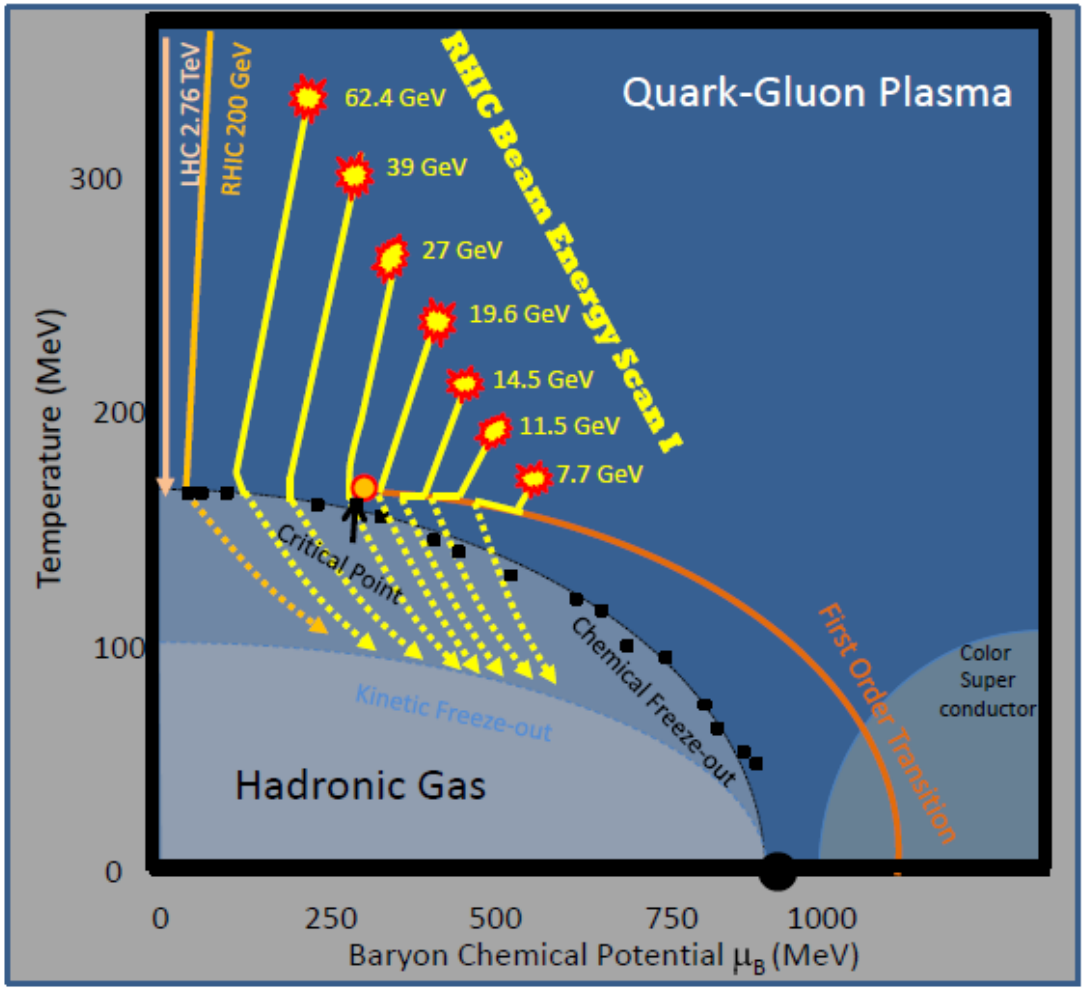
RHIC Beam Energy Scan (BES)

Goals of BES are to locate:

Turn-off of QGP signatures

First-order phase transition

Critical Point



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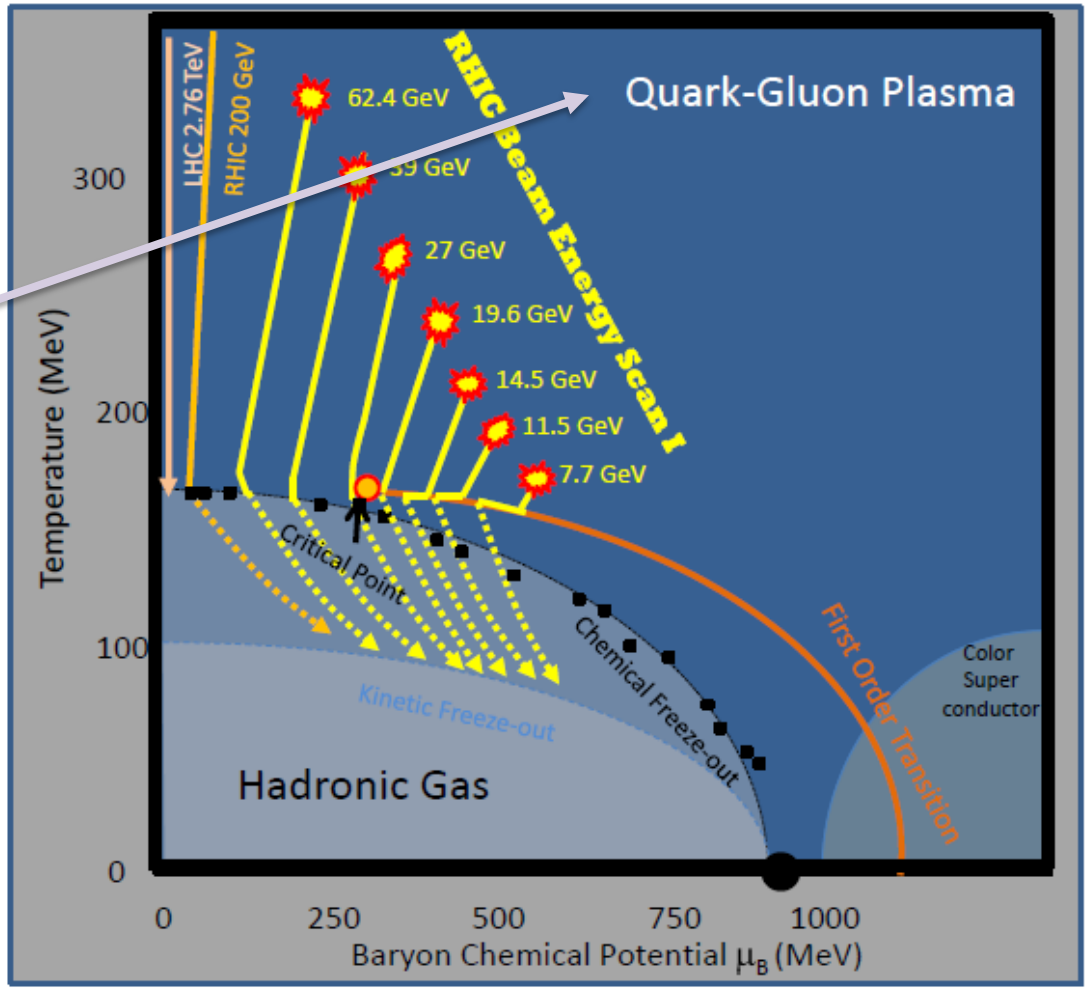


Turn-off of QGP signatures: R_{CP}

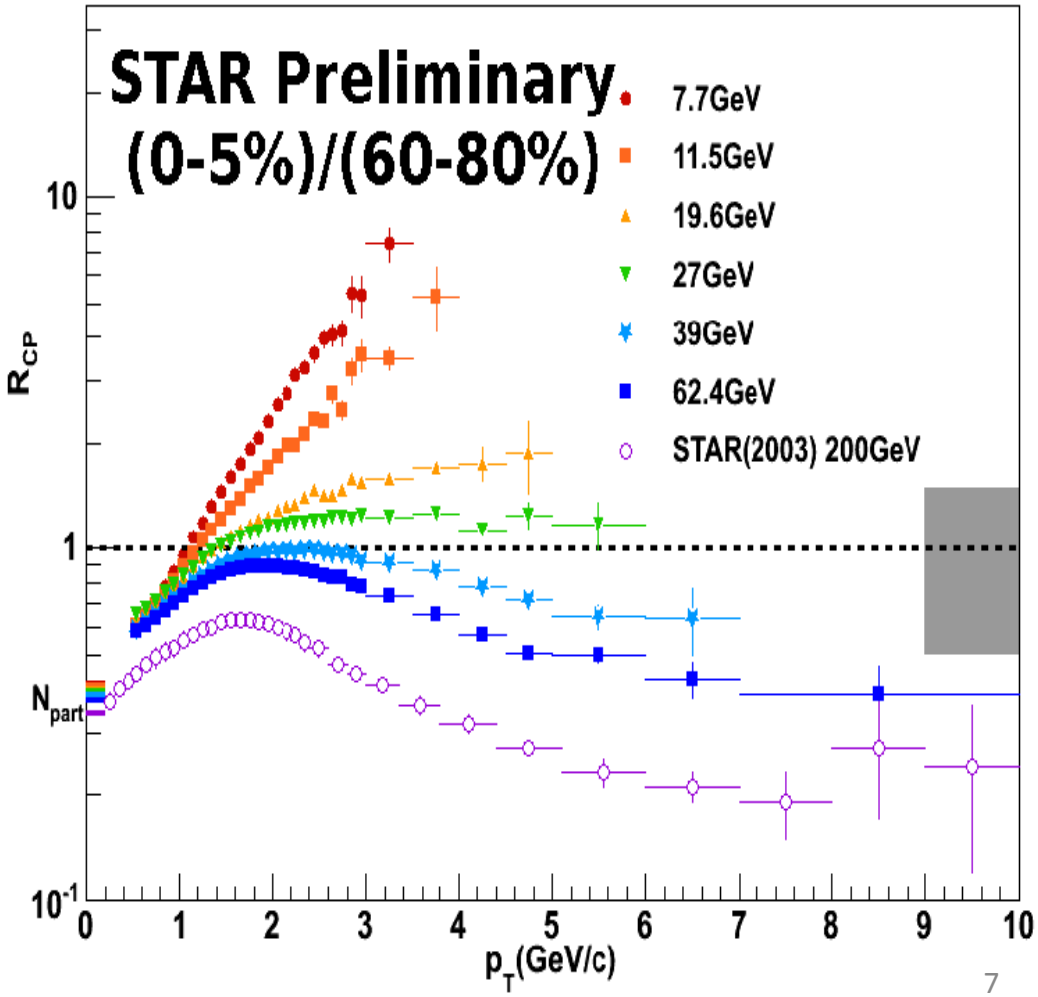
$$R_{CP} = \langle N_{bin}^{peri} \rangle \frac{d^3 N_{AA}^{cen}}{d\eta d^2 p_T} \Big/ \langle N_{bin}^{cen} \rangle \frac{d^3 N_{AA}^{peri}}{d\eta d^2 p_T}$$

R_{CP} is seen as a measure of the parton energy loss in the medium.

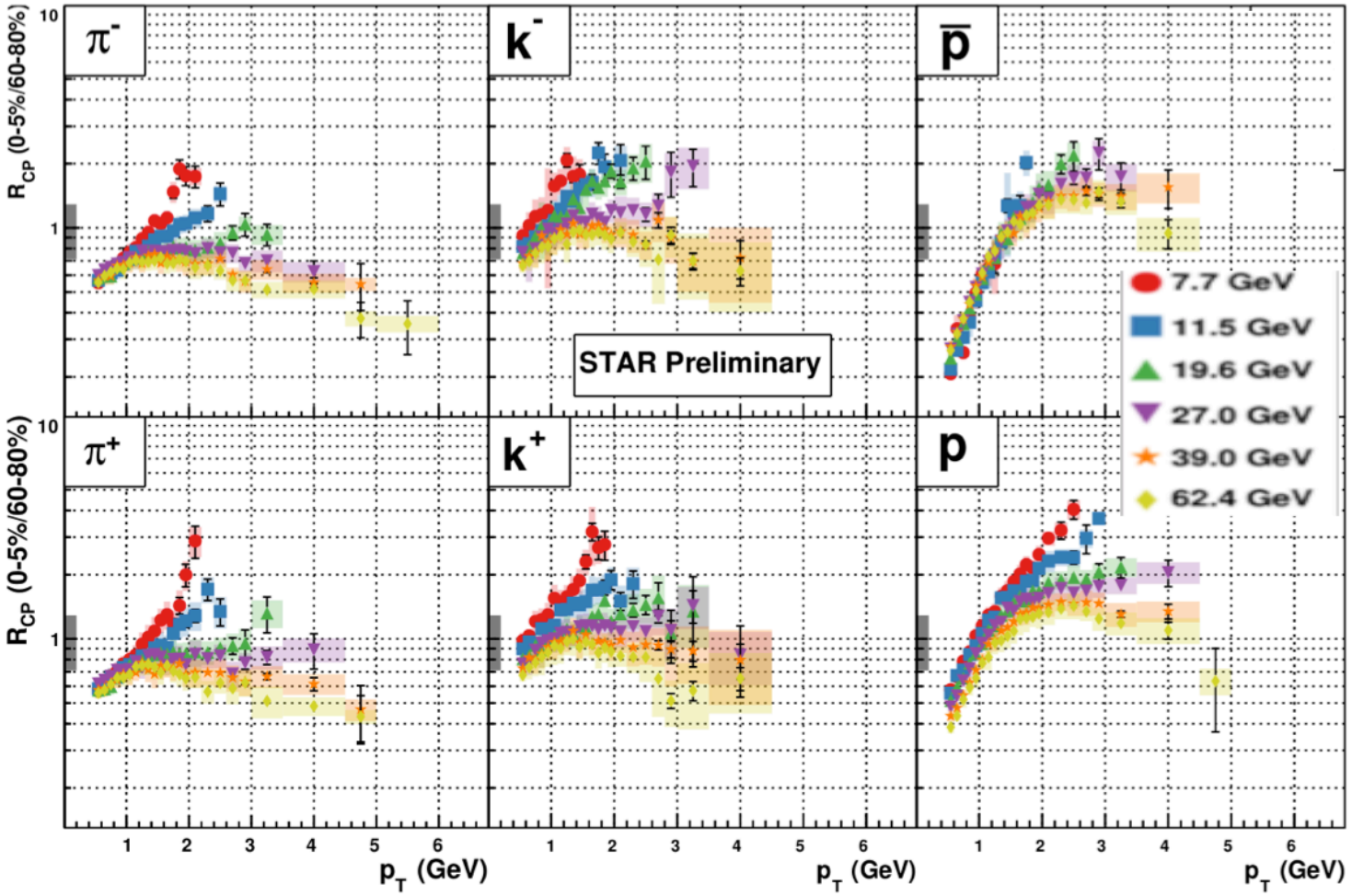
- Suppression at high p_T indicative of QGP formation.

No suppression of R_{CP} is seen below ~39 GeV.

The p_T reach at lower energies is limited by statistics.

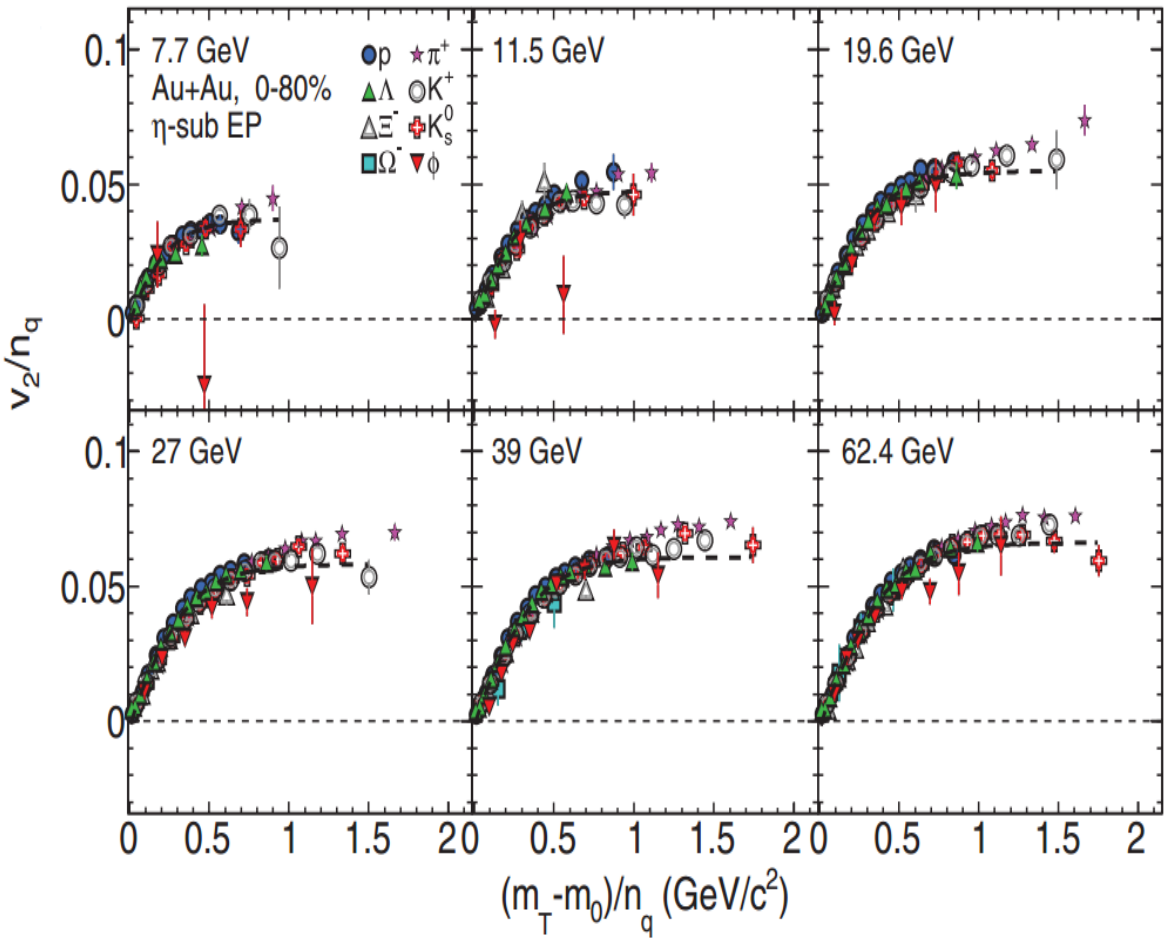


Turn-off of QGP signatures: R_{CP}



- Pion R_{CP} is suppressed at ~27 GeV.
- Proton R_{CP} is not suppressed.
- The p_T reach at lower energies is limited by statistics.

Turn-off of QGP signatures: n_Q scaling



Phys Rev C 88 (2013) 014902

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle,$$

φ = azimuthal angle

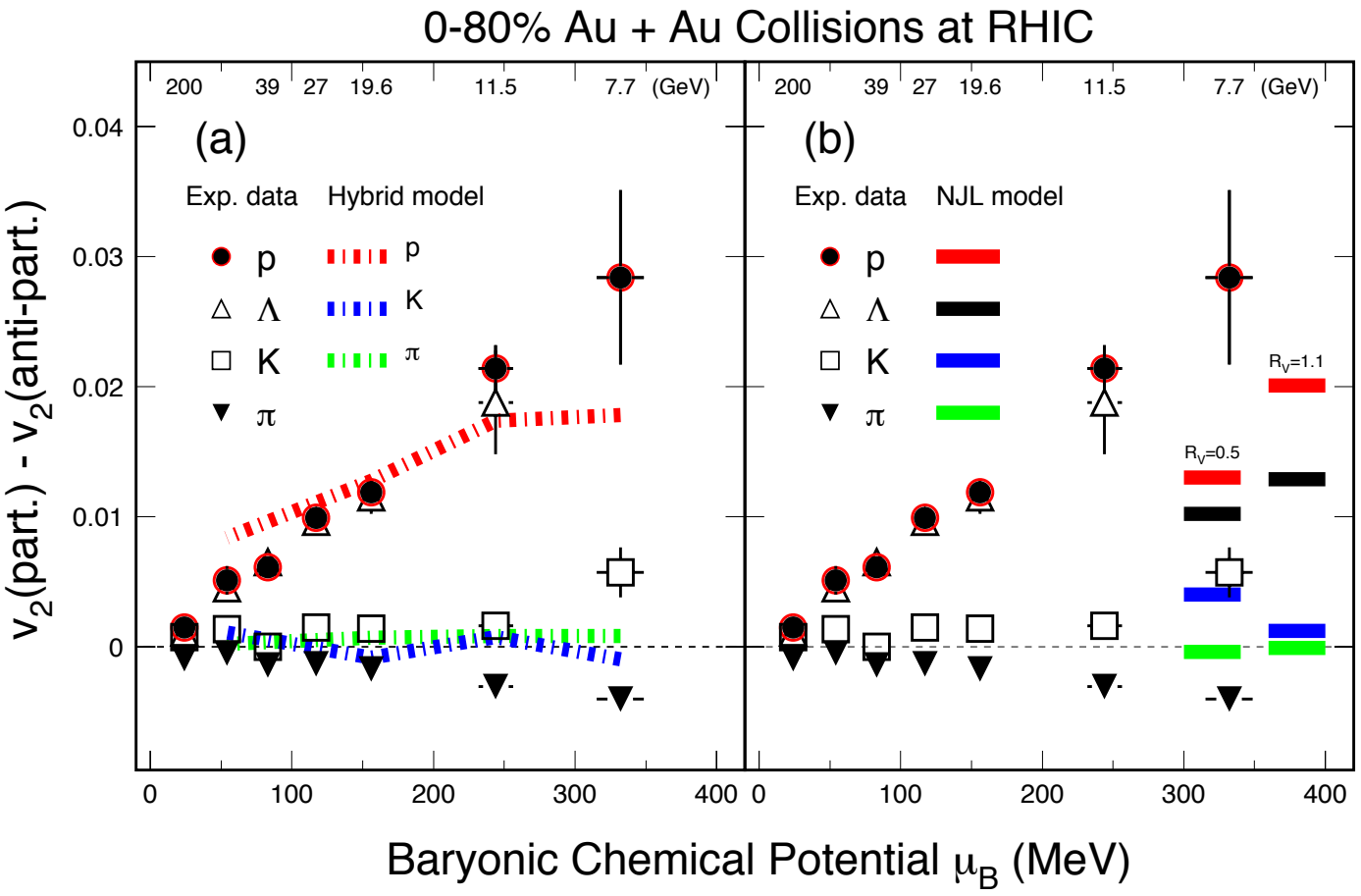
n_Q = #constituent quarks

n_Q scaling is seen as a possible indicator of partonic behavior.

n_Q scaling holds for particles to within ~10%.

The ϕ meson may not follow the trends at 11.5 or 7.7 GeV. More data needed.

Turn-off of QGP signatures: Δv_2



Data: Phys. Rev. Lett. 110, 142301 (2013)

Hybrid: Phys. Rev. C 86, 044903 (2012)

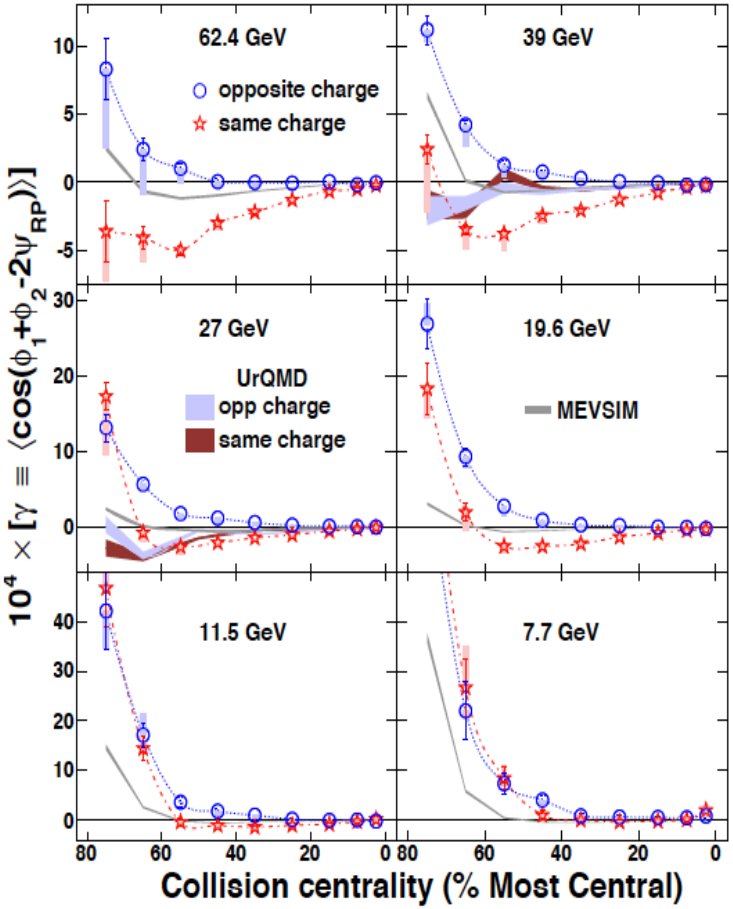
NJL: Acta Phys.Polon.Supp. 7 (2014) 1, 183

At 200 GeV, particle and antiparticle v_2 agree well.

As beam energy decreases, difference between particle and antiparticle v_2 increases.

Turn-off of QGP signatures: Chiral Magnetic Effect (CME)

CME is phenomenon where separation of charges occurs from large magnetic fields in non-central collisions. It would require the system to be deconfined.

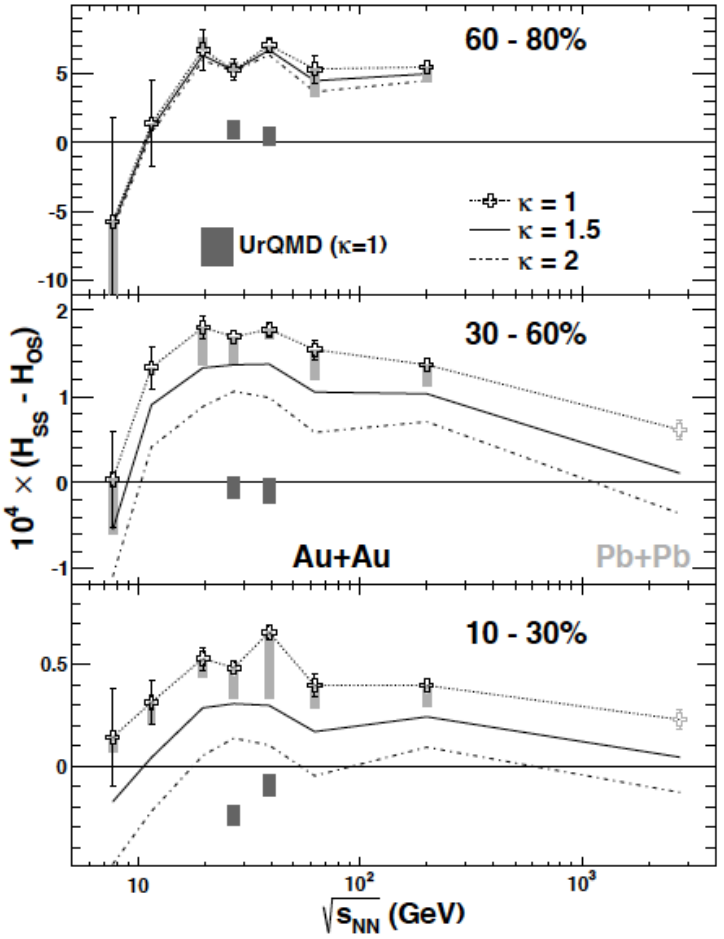


Charges separately

γ may be sensitive to CME.

Effect goes away at low beam energy.

arXiv:1404.1433, Accepted by PRL



Signal-Background

RHIC Beam Energy Scan (BES)

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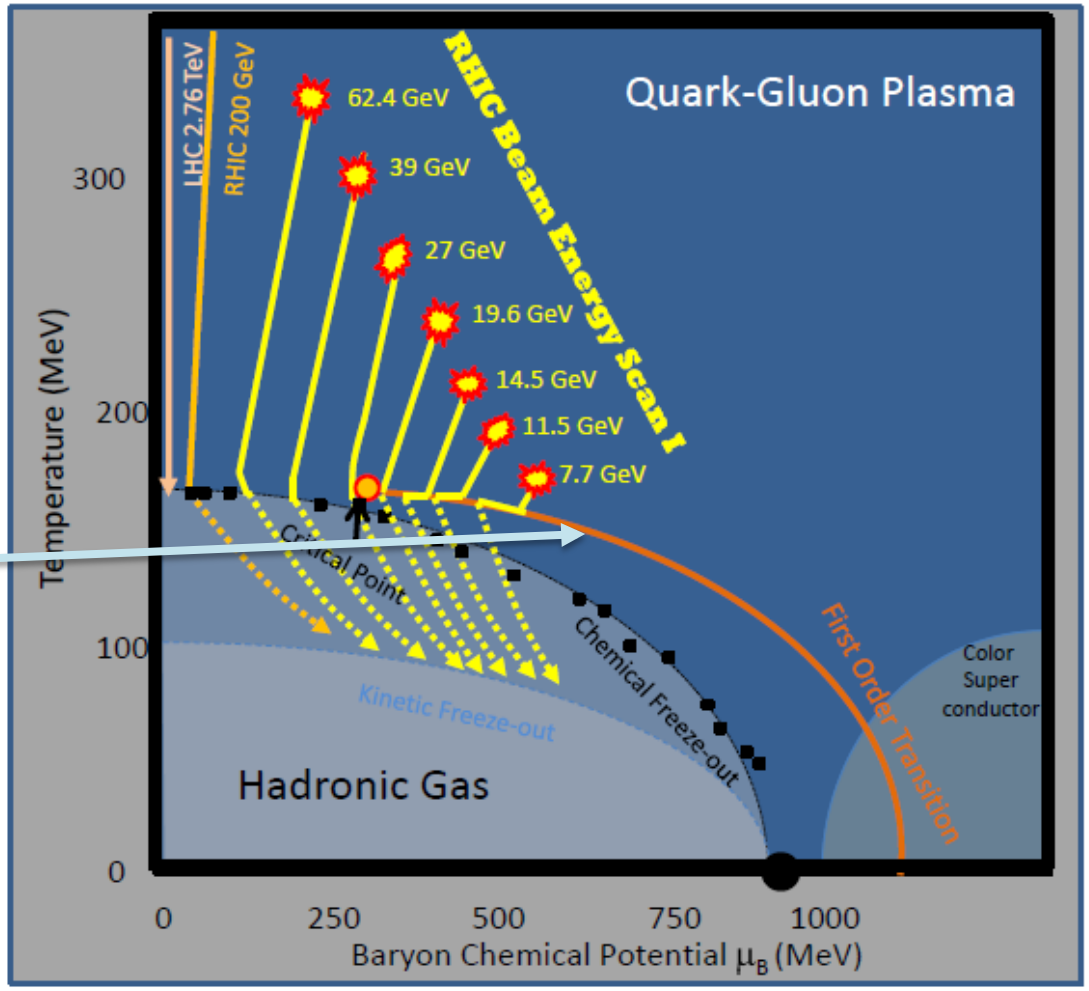
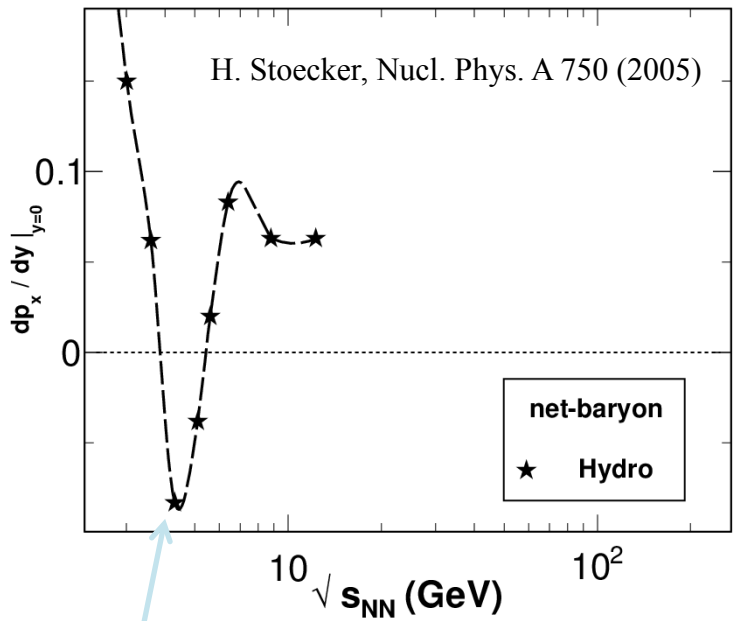
First-order phase transition

Critical Point

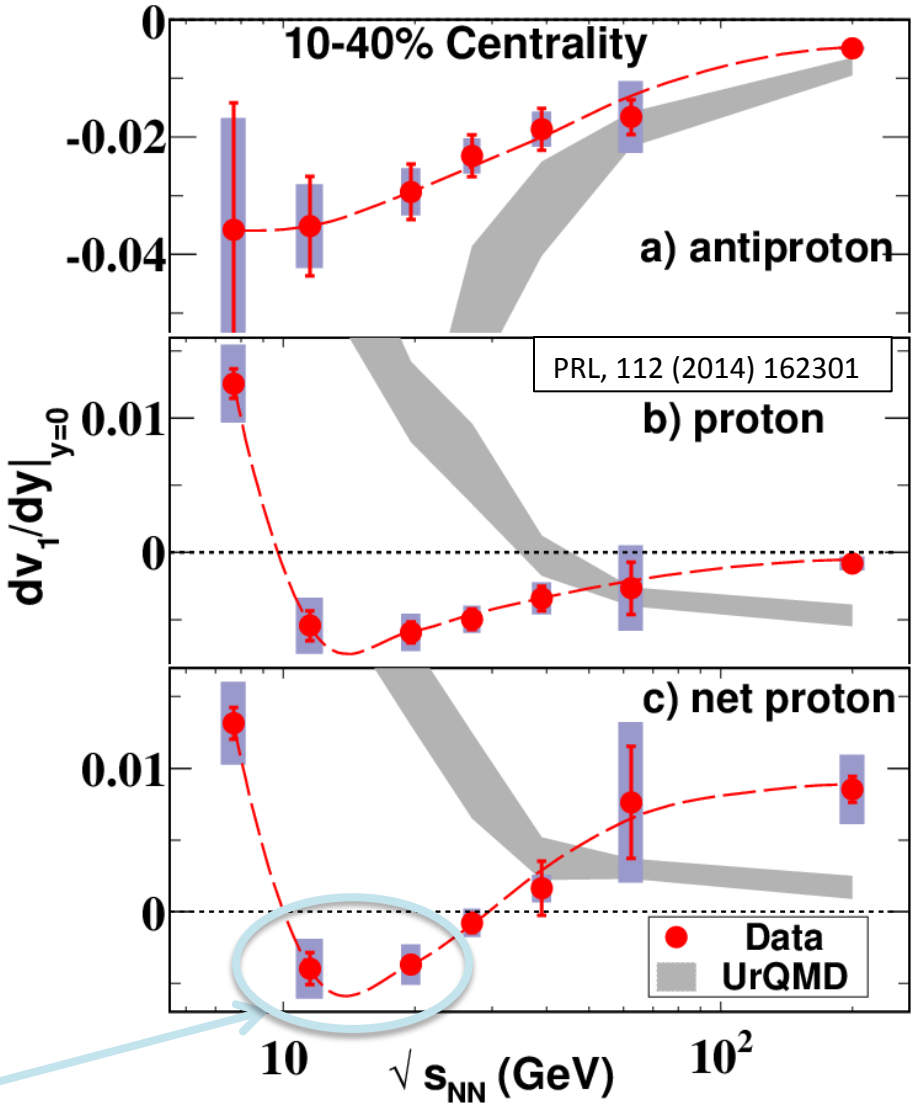


First-order phase transition: v_1



A 1st order phase transition would be characterized by a region with the lowest compressibility.

The v_1 would show early pressure of system. Softest point?

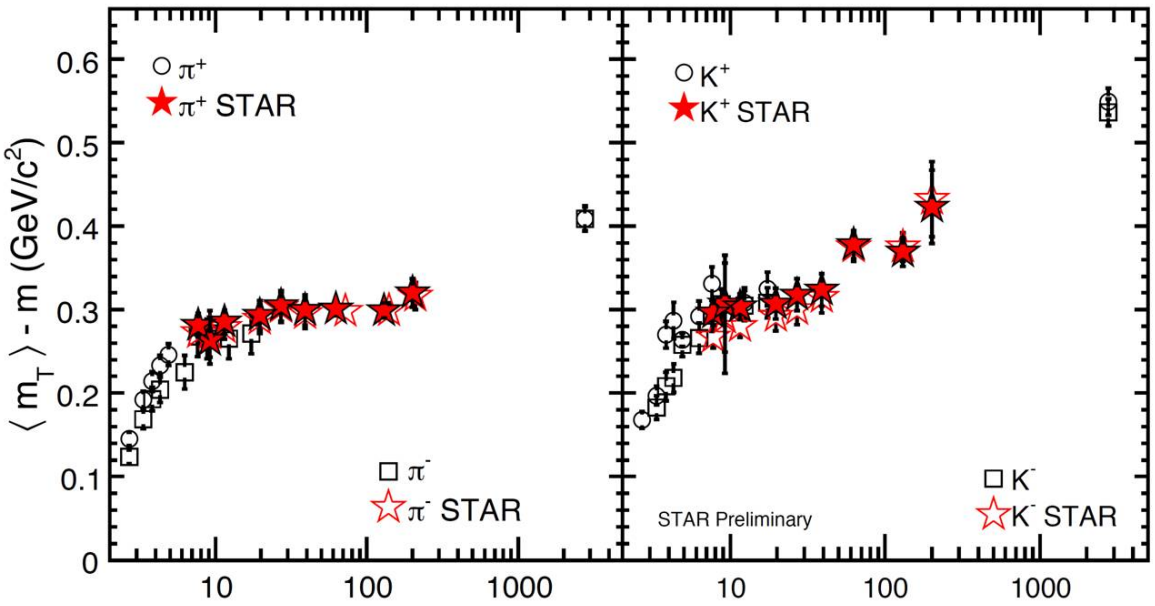


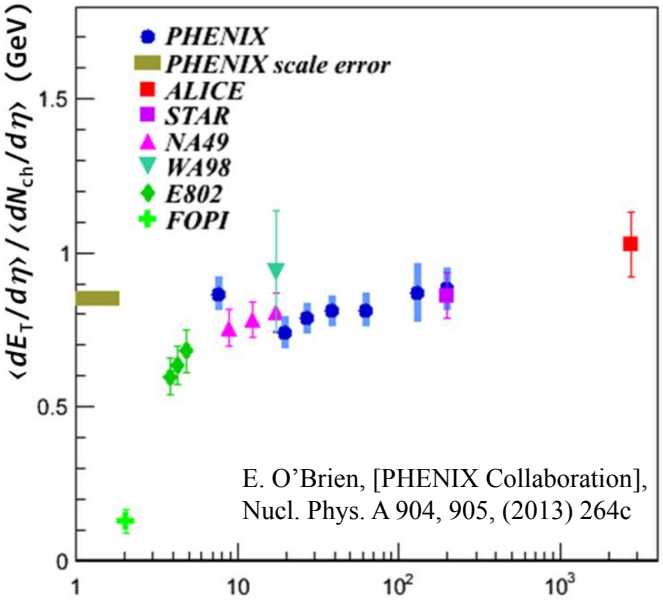
First-order phase transition: $\langle m_T \rangle$

$\langle m_T \rangle$ is related to the temperature of the system.

The saturation of $\langle m_T \rangle$ is indicative of a 1st order phase transition region.

E_T includes mass and is associated with the energy density.





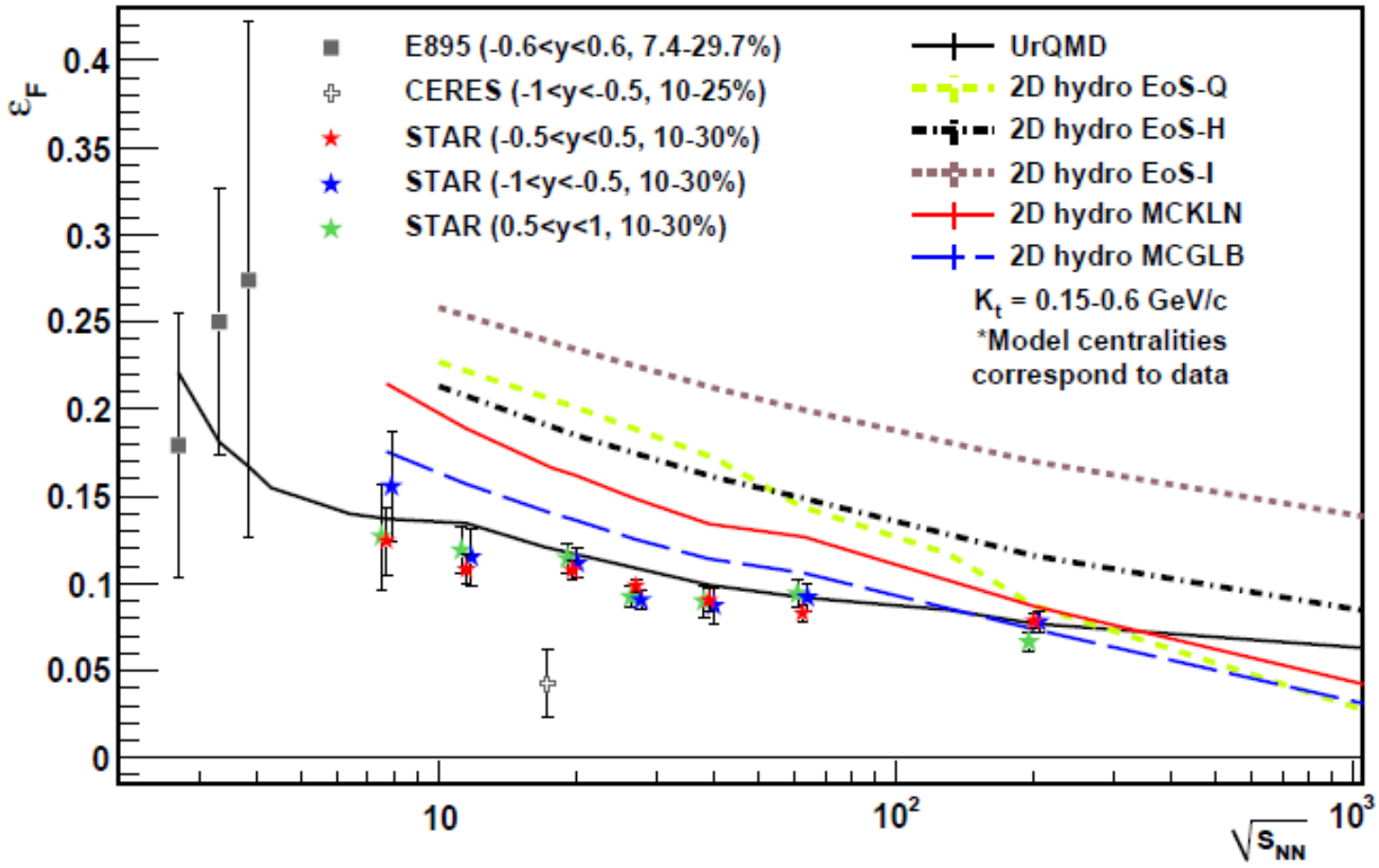
Center of Mass Collision Energy $\sqrt{s_{NN}}$ (GeV)

First-order phase transition: azimuthal HBT

Pion azimuthal HBT allows the study of the coordinate space "almond shape" (ε_F) after expansion

No minimum observed.

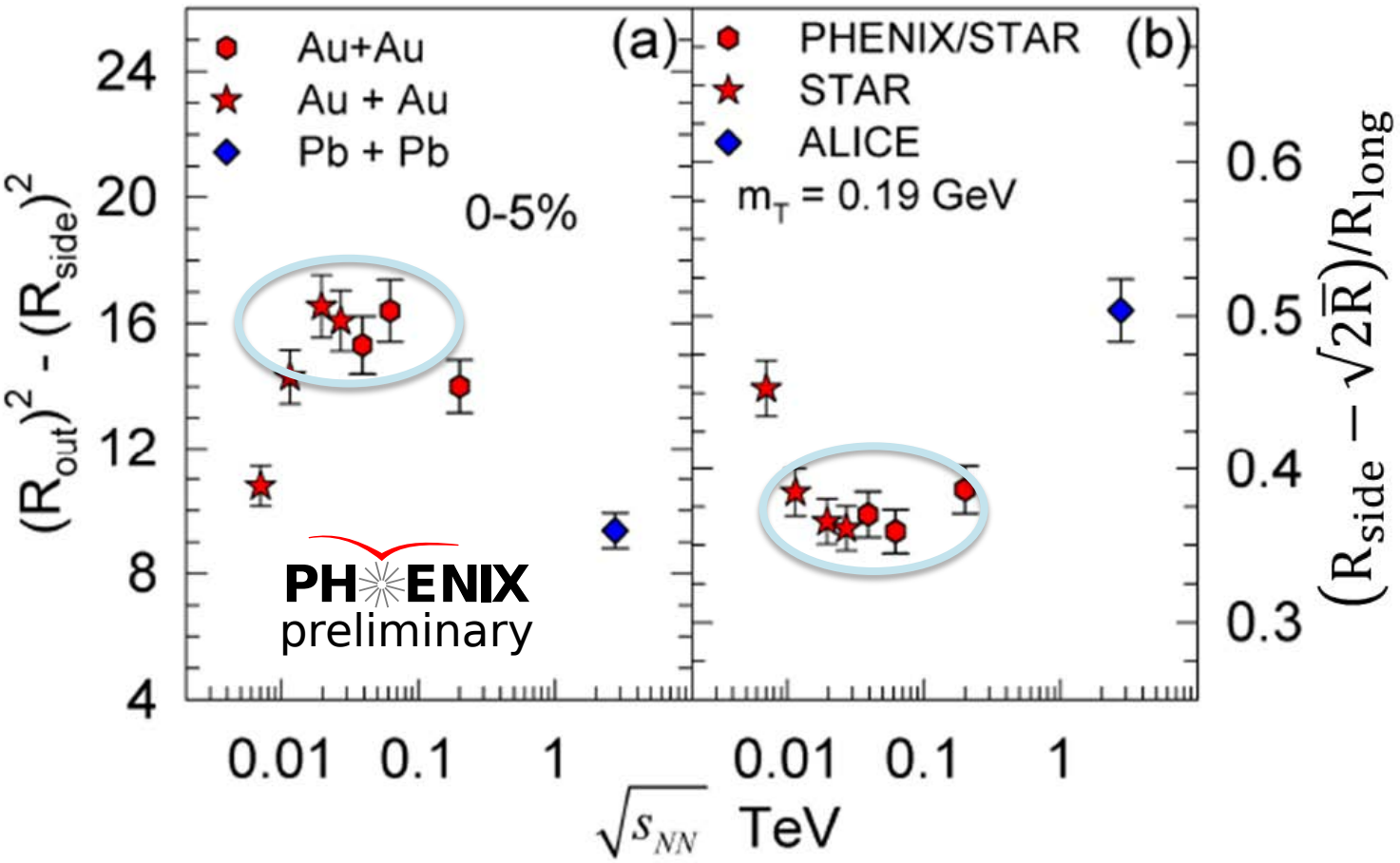
Dip, such as at the CERES point, would be indicative of phase transition.



arXiv:1403.4972

First-order phase transition: HBT

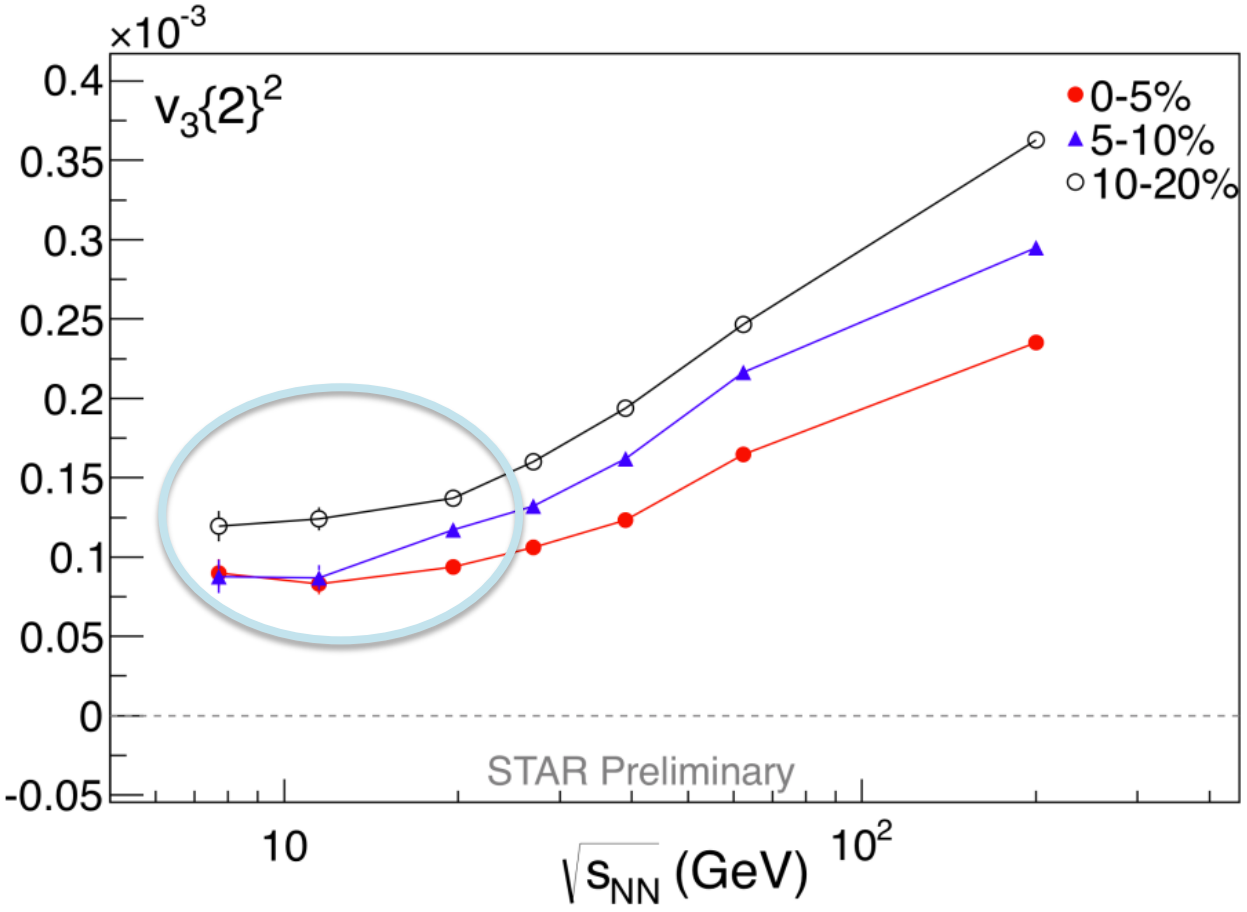
The peak and minimum of the HBT ratios and differences could be indicative of changes to reaction dynamics, such as at a phase transition or near a critical point.



First-order phase transition: $v_3\{2\}^2$

Flow observables motivated to check for potential softening

- Plot something proportional to pressure (e.g. v_3)
- Check if there is a softest spot
  - While multiplicity increases with energy, v_3 doesn't until ~20 GeV



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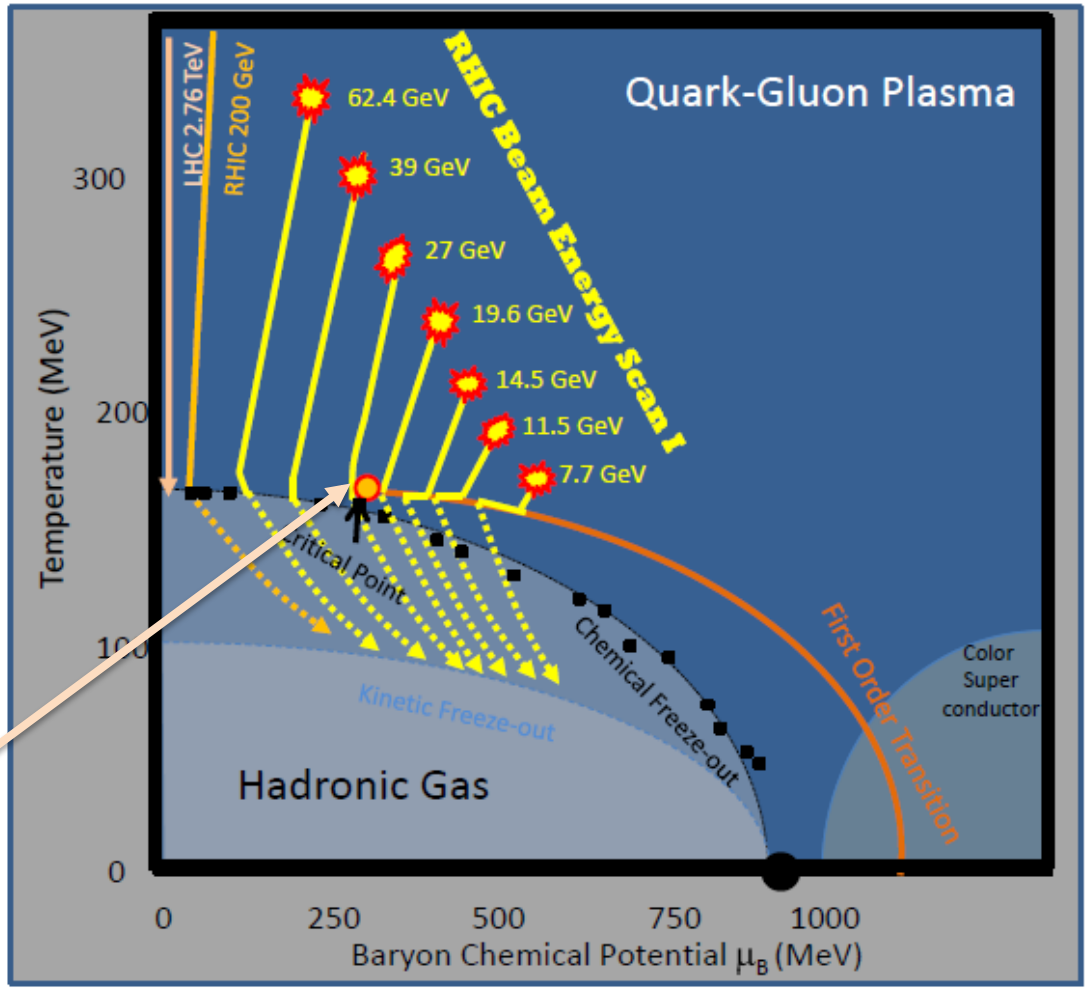


Critical Point: net-proton multiplicity moments

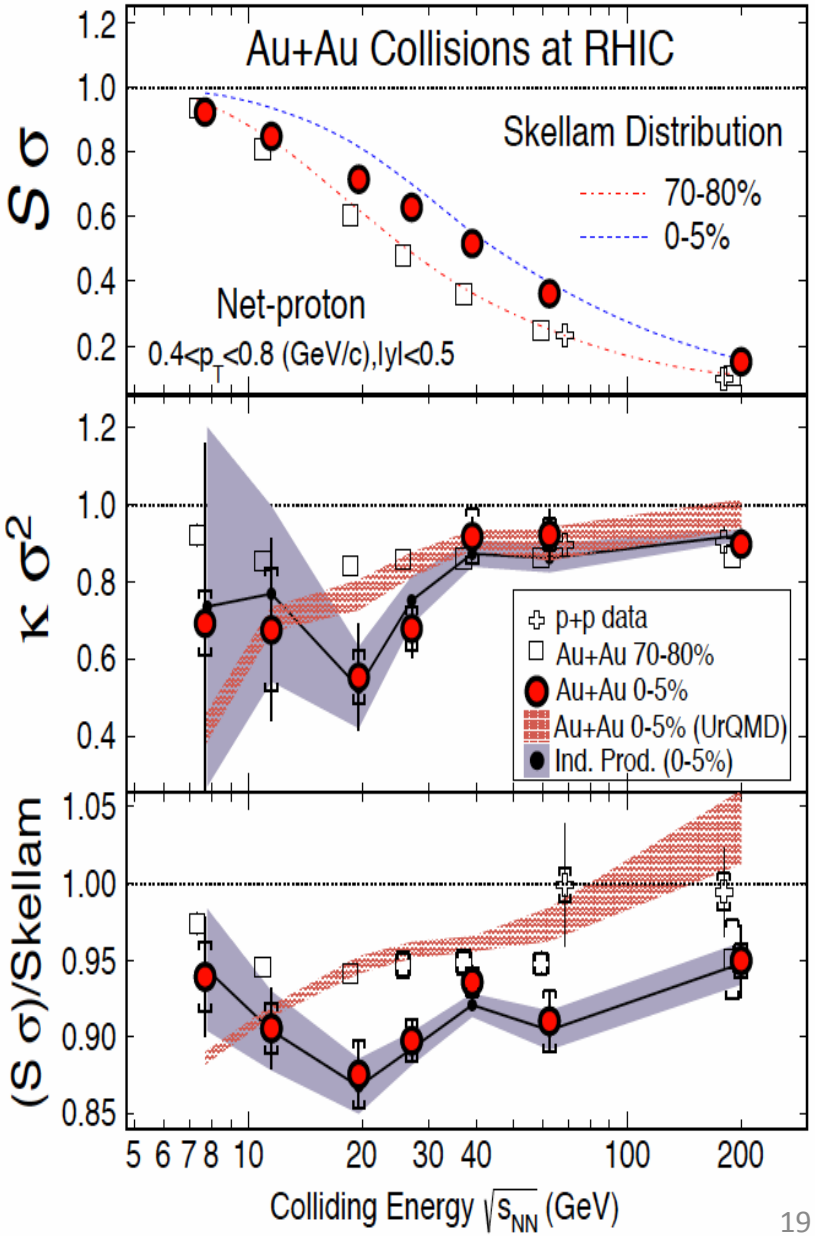
Susceptibility ratios of conserved quantities (χ_{BQS}) are related to the moments of experimentally measurable multiplicity distributions.

$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial (\mu_B/T)^n}\right|_T$$

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$
$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

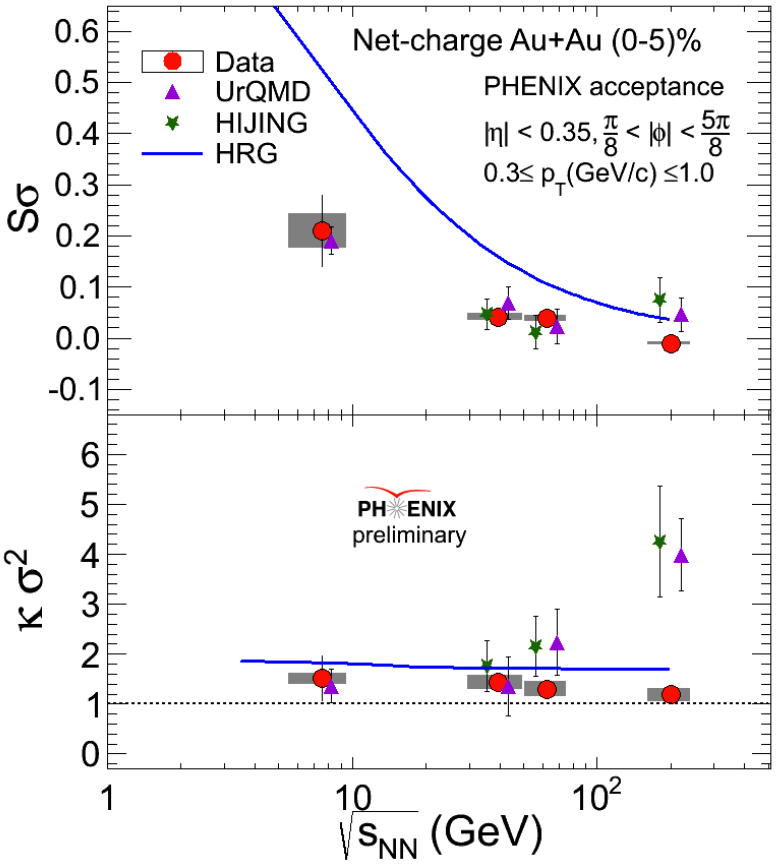
F. Karsch, PoS (CPOD07) 026, PoS (Lattice 2007) 015

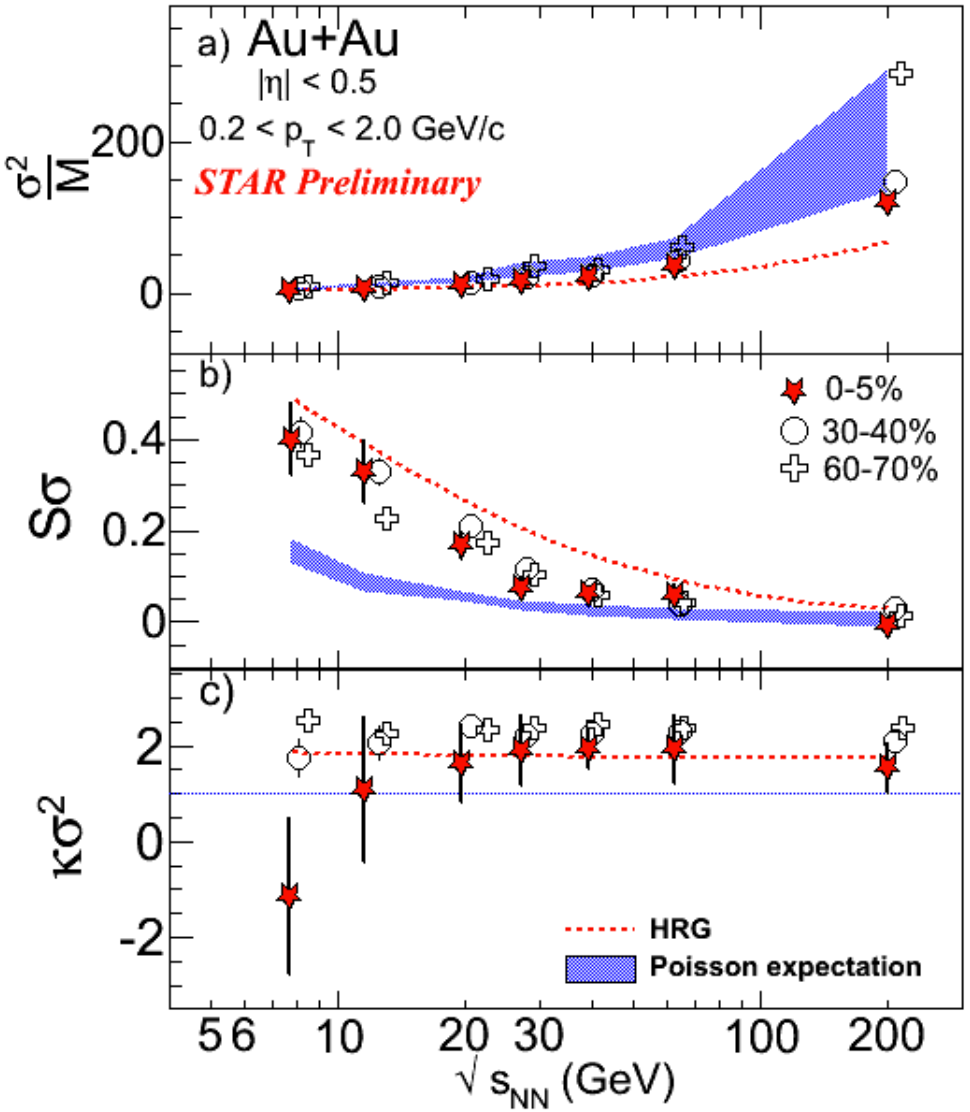
Higher statistics is necessary to further clarify net-proton results.



Phys. Rev. Lett. 112 (2014) 032302

Critical Point: net-charge multiplicity moments





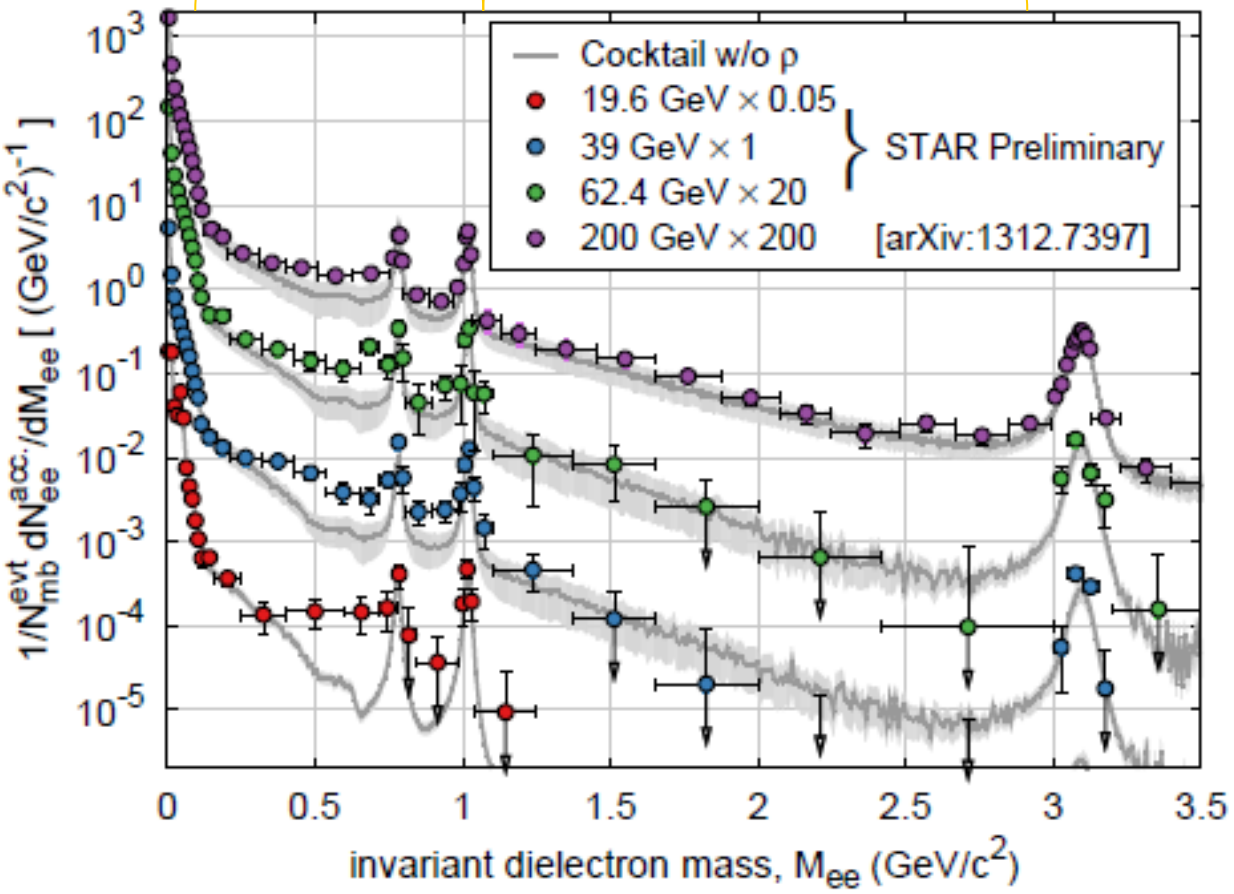
No evidence of non-monotonic behavior of net-charge moments products within statistical uncertainties

Dileptons: bulk penetrating EM probes

- No strong beam-energy dependence of LMR excess
  - Further comparison with SPS possible with energies below 19.6 GeV
  - Excess could spike near CP
- Not enough statistics for meaningful interpretation of results in IMR
  - Improved statistics would open up study of properties of QGP

Low Mass Region (LMR):
ρ in medium modification tied to chiral symmetry restoration

Intermediate Mass Region (IMR):
QGP Thermal Radiation



RHIC Beam Energy Scan (BES): overview

Goals of BES are to locate:

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First-order phase transition

Critical Point

Signs of deconfinement down to at least ~27 GeV.

Need more data at lower beam energies.

RHIC Beam Energy Scan (BES): overview

Goals of BES are to locate:

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Critical Point

Multiple observables point to potential softening of the equation of state/1st order phase transition in the region of ~20-40 GeV

- v_1
- $v_3\{2\}^2$
- HBT differences/ratios

RHIC Beam Energy Scan (BES): overview

Goals of BES are to locate:

Turn-off of QGP signatures

First-order phase transition

Critical Point

Further statistics at lowest energies still needed to reach more definitive conclusion.

Future directions: BES II

Some tantalizing hints of interesting phenomena in BES I.

- However, more statistics needed at lower beam energies.
- Smaller error bars would allow more definitive conclusions about:
  - Turn-off of QGP signatures (CME, n_Q scaling, v_2 of ϕ, R_{CP})
  - 1st order phase transition (HBT, v_1, $v_3\{2\}^2$)
  - Critical point
  - Bulk penetrating EM probes (dileptons)

Detector upgrades, such as iTPC, would increase luminosity, making extended runs significantly more feasible.

Would take ~22 weeks in 2018-2019 to collect BES II data at 7.7, 9.1, 11.5, 14.5 and 19.6 GeV.

Potential fixed-target program could collect data below 7.7 GeV.

Please see Grazyna Odyniec's talk, 16:35 on August 4th for BES II details.

Thanks!!