Overview and highlights of bulk correlations at STAR

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for the STAR Collaboration

University of Houston

January 28, 2015

Winter Workshop on Nuclear Dynamics

Outline:

U+U results

BES results

Overview/outlook

UNIVERSITY of HOUSTON DEPARTMENT OF PHYSICS

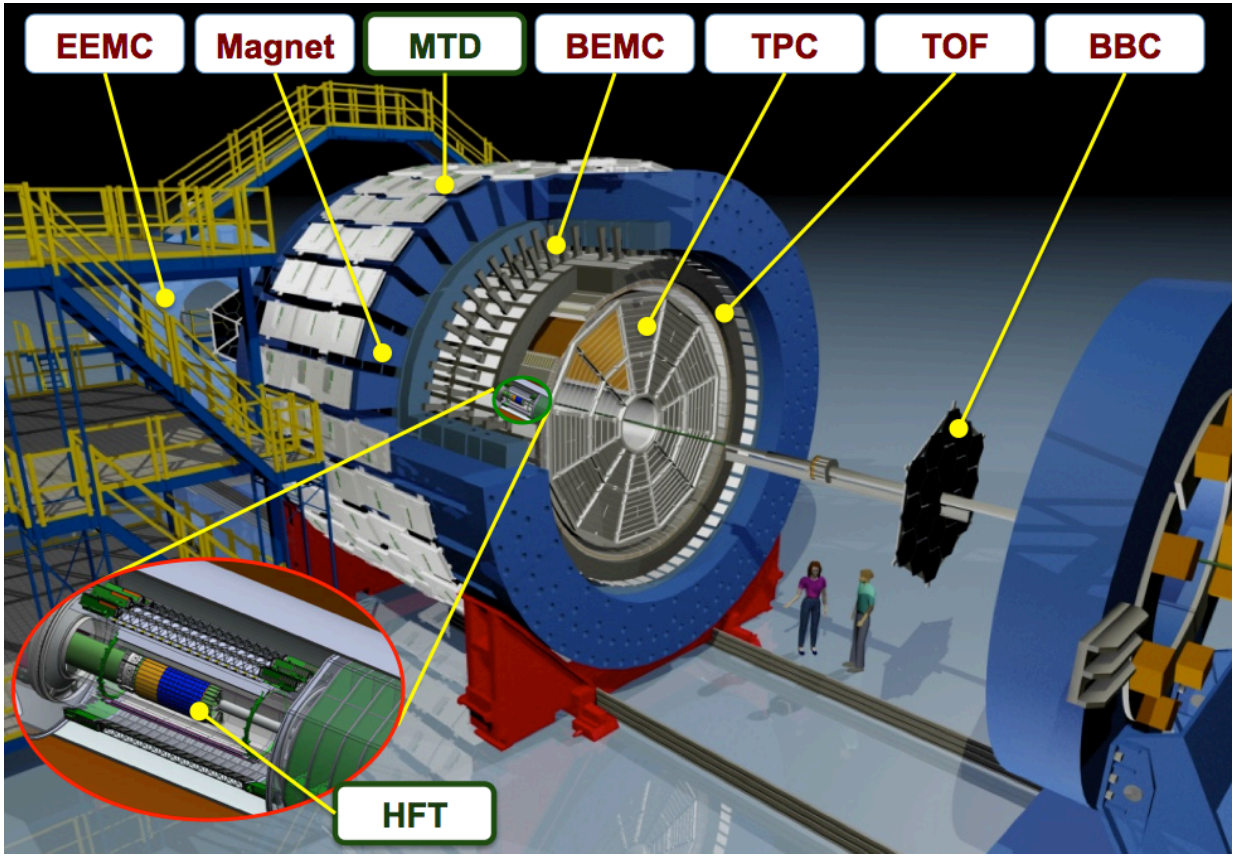
STAR

U.S. DEPARTMENT OF ENERGY

Office of Science

RHIC and a new collision species

Relativistic Heavy-Ion Collider (RHIC) successfully collided Uranium +Uranium in 3 week exploratory run in 2012, ~360M min bias, 13M central 1% ZDC



Large acceptance, mid-rapidity detector

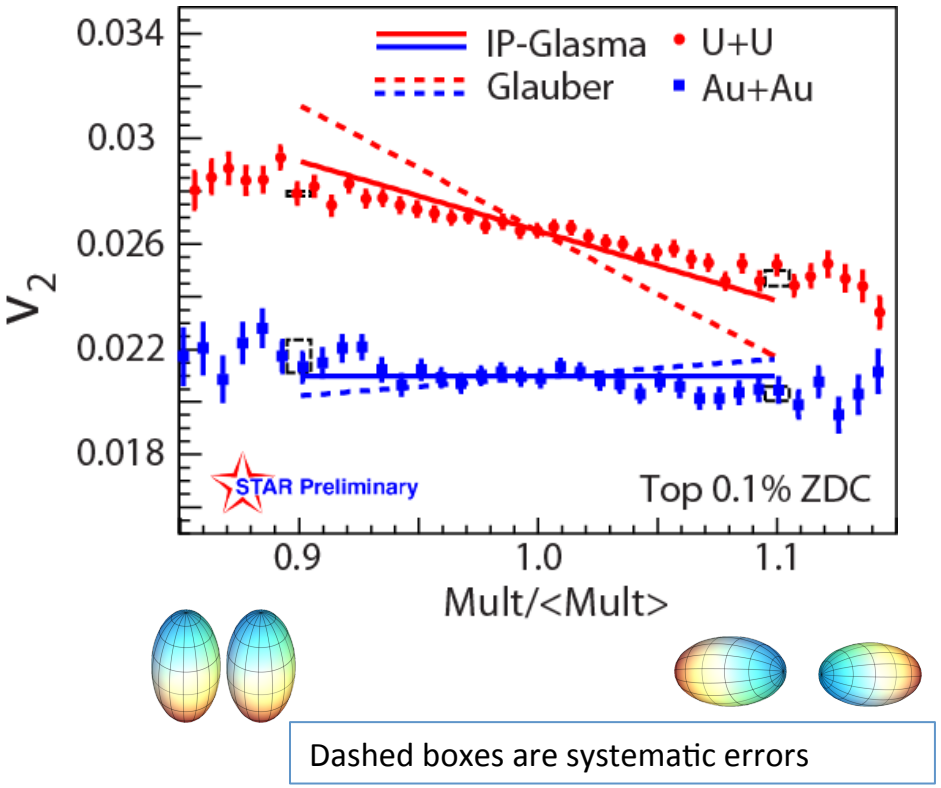
Full azimuthal coverage ($|\eta|<1.0$)

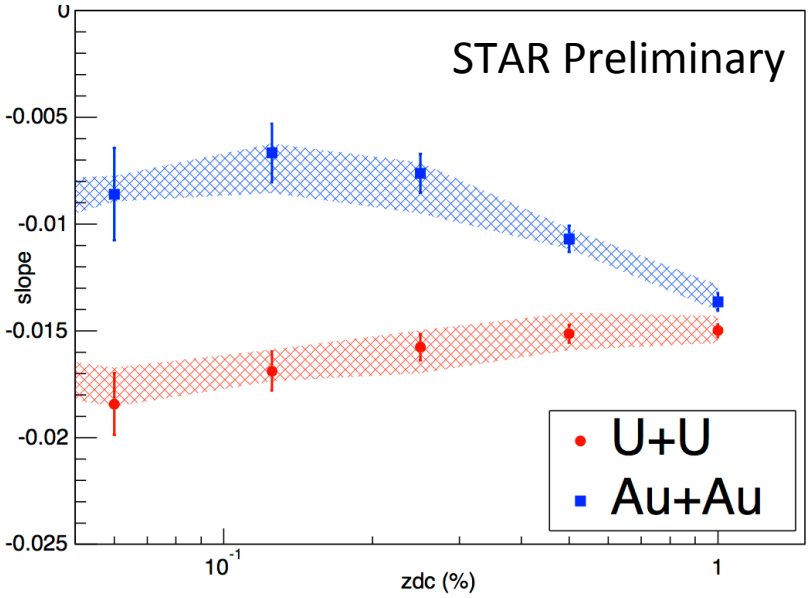
Excellent particle identification!

Analyses are still underway, but some interesting results thus far

- v_2
- Local Parity Violation

v_2 in U+U collisions at 193 GeV

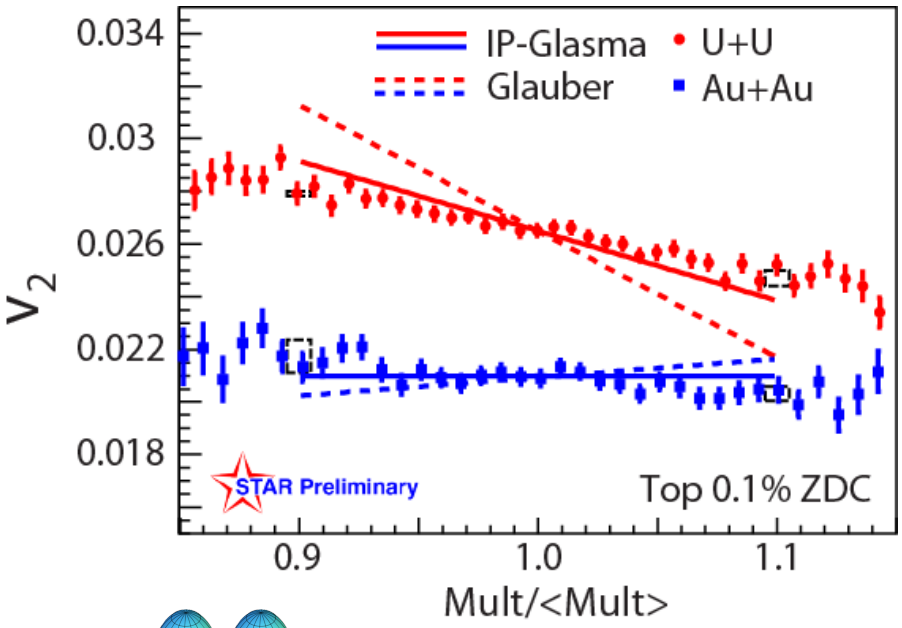


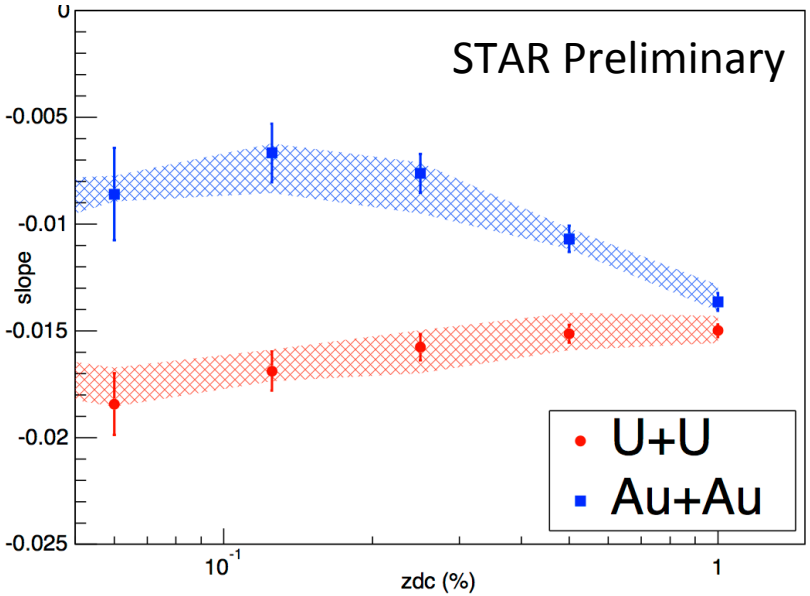


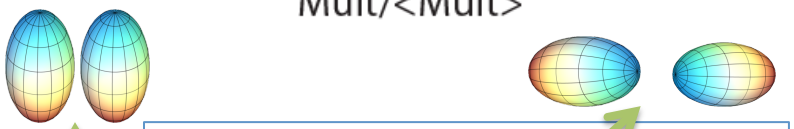
Dashed boxes are systematic errors

- U+U collisions studied in order to investigate effects of geometry. Uranium's unique prolate shape allows different collision geometries.

v_2 in U+U collisions at 193 GeV







Dashed boxes are systematic errors

- U+U collisions studied in order to investigate effects of geometry. Uranium's unique prolate shape allows different collision geometries.
- Body-body and tip-tip samples selected via ZDC multiplicity cut.
- IP-Glasma models fit better

Bjoern Schenke, et al. arXiv:1403.2232
Maciej Rybczyński, et. al. PRC87,044908(2013)

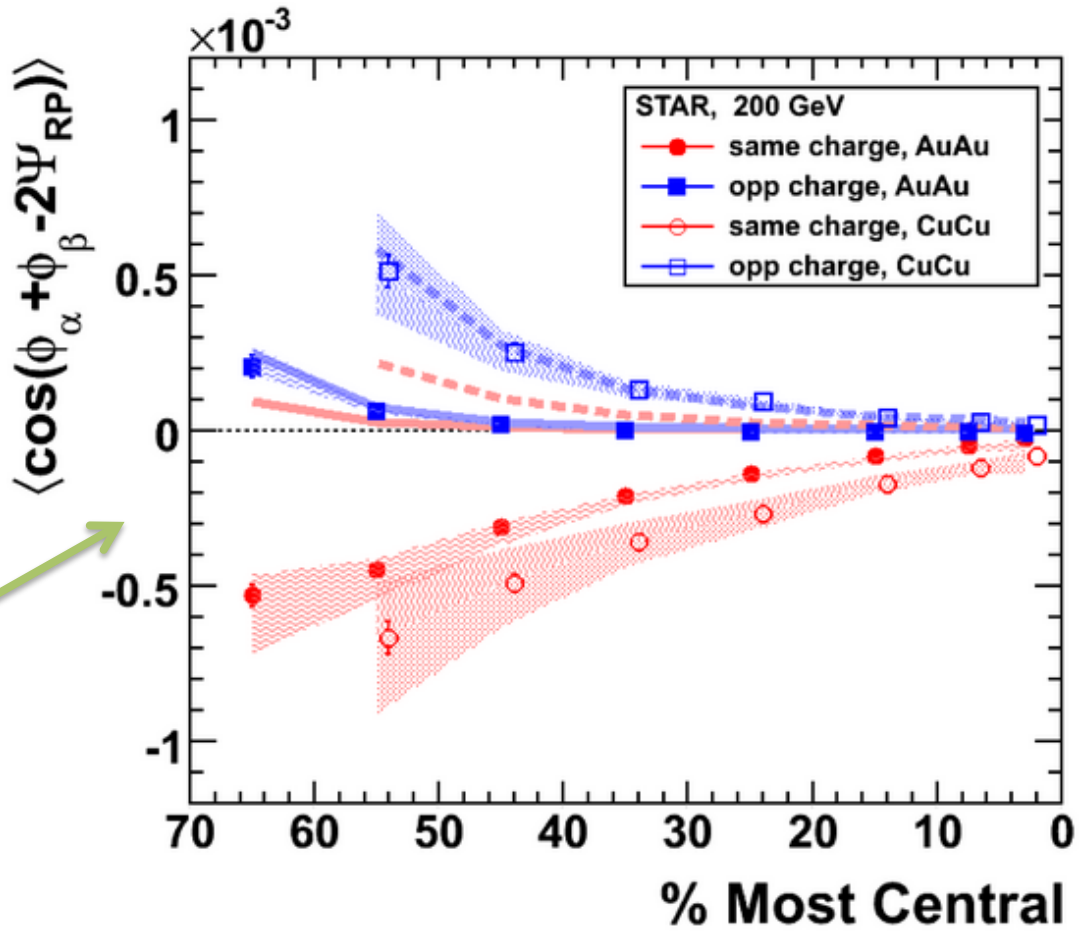
Local Parity Violation (LPV)

CME is phenomenon where separation of charges occurs from large magnetic fields in non-central collisions.

Can be explained by Local Parity Violation (LPV) or elliptic flow (v_2) + local charge conservation (LCC).

Seen at 200 GeV at STAR.

Central U+U would provide collision system with elliptic flow but little magnetic field.



Khareev D. PLB 633:260-264, 2006

STAR Collaboration. Phys.Rev.C81:054908,2010

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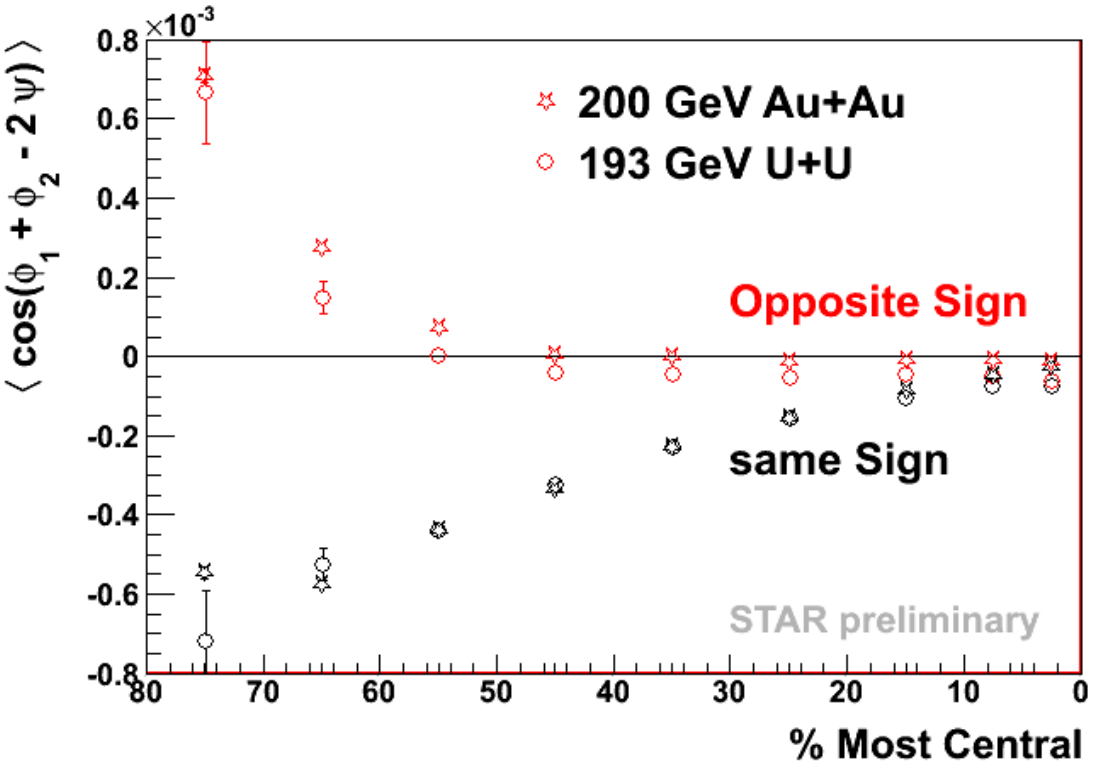


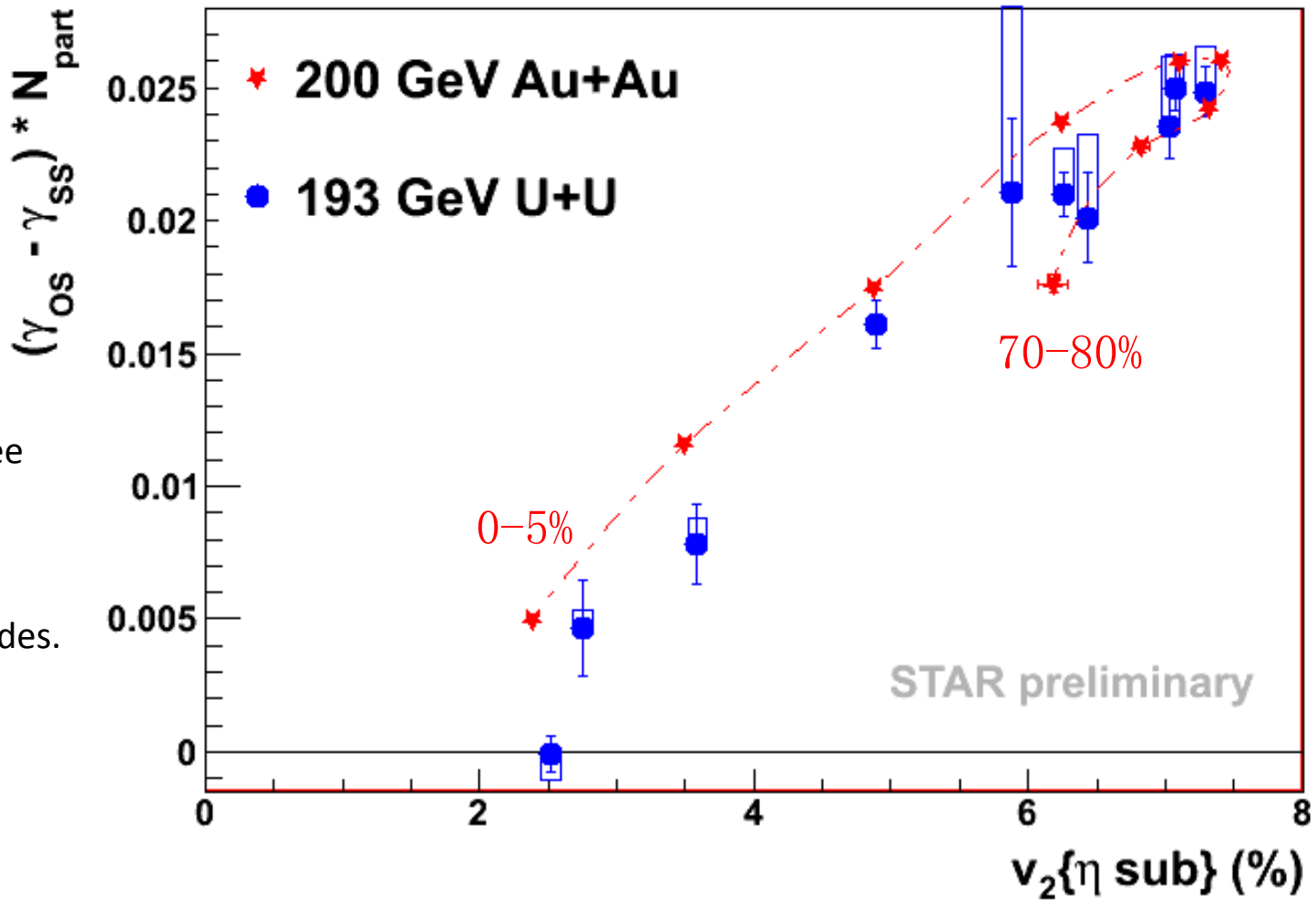
Still see clear charge separation in non-central collisions in U+U

Kharzeev D. PLB 633:260-264, 2006

STAR Collaboration. Phys.Rev.C81:054908,2010

Local Parity Violation (LPV)

γ is the three point correlator shown on previous slides.



To reduce mutual background, difference of opposite sign and same sign taken, plotted versus v_2. In 0-1% U+U, signal disappears at finite v_2.

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

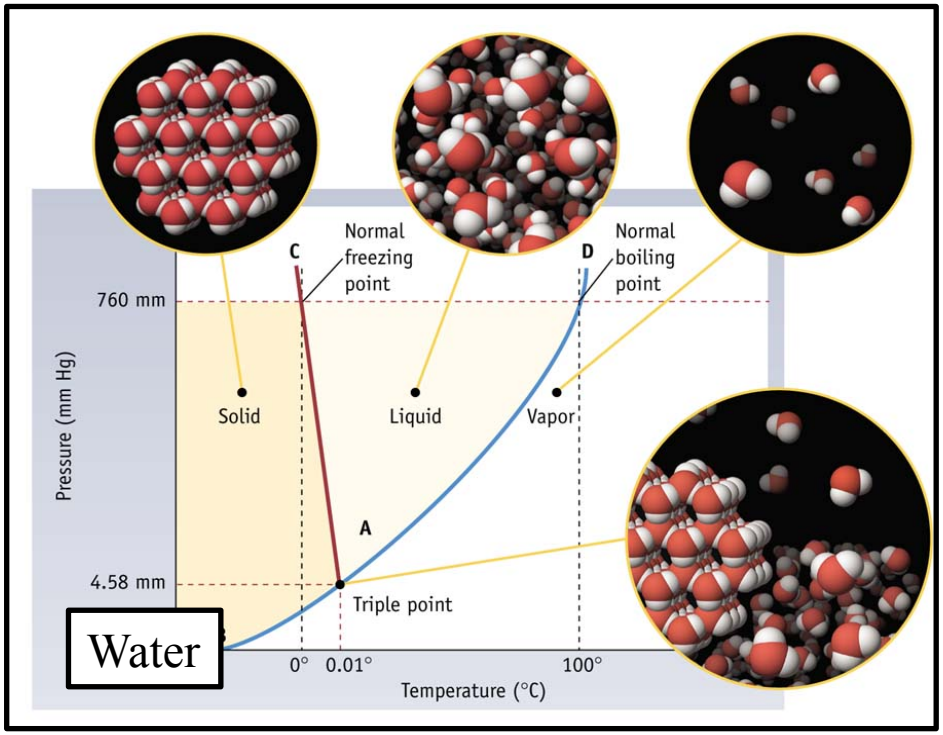
- QGP existed in the early universe
- Little is known about properties of nuclear matter
- RHIC uniquely able to explore phase diagram of nuclear matter

Phase Diagram of Nuclear Matter

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

• Does the nuclear phase diagram have boundaries?

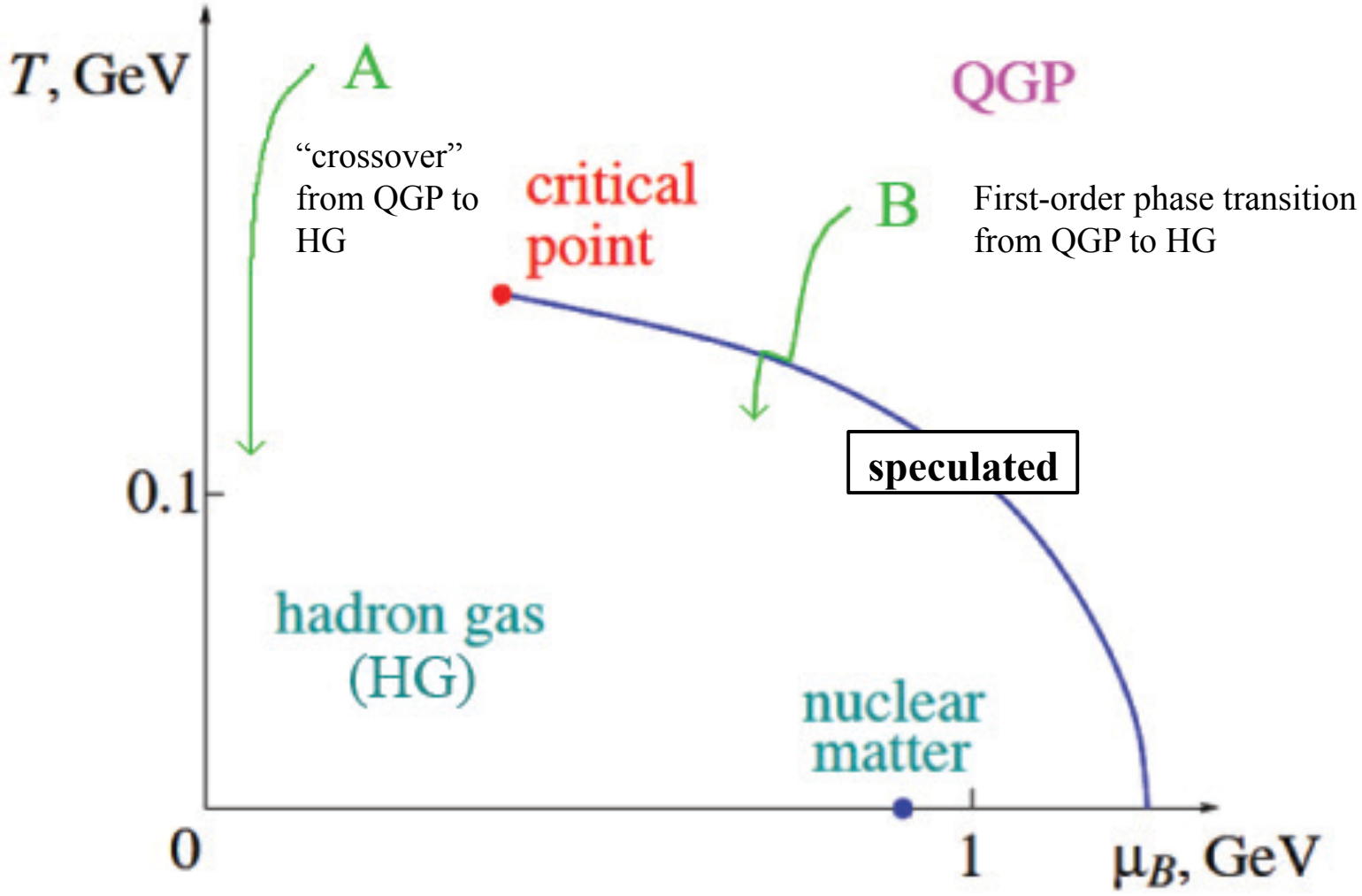
• Is there a critical point (CP)?



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."

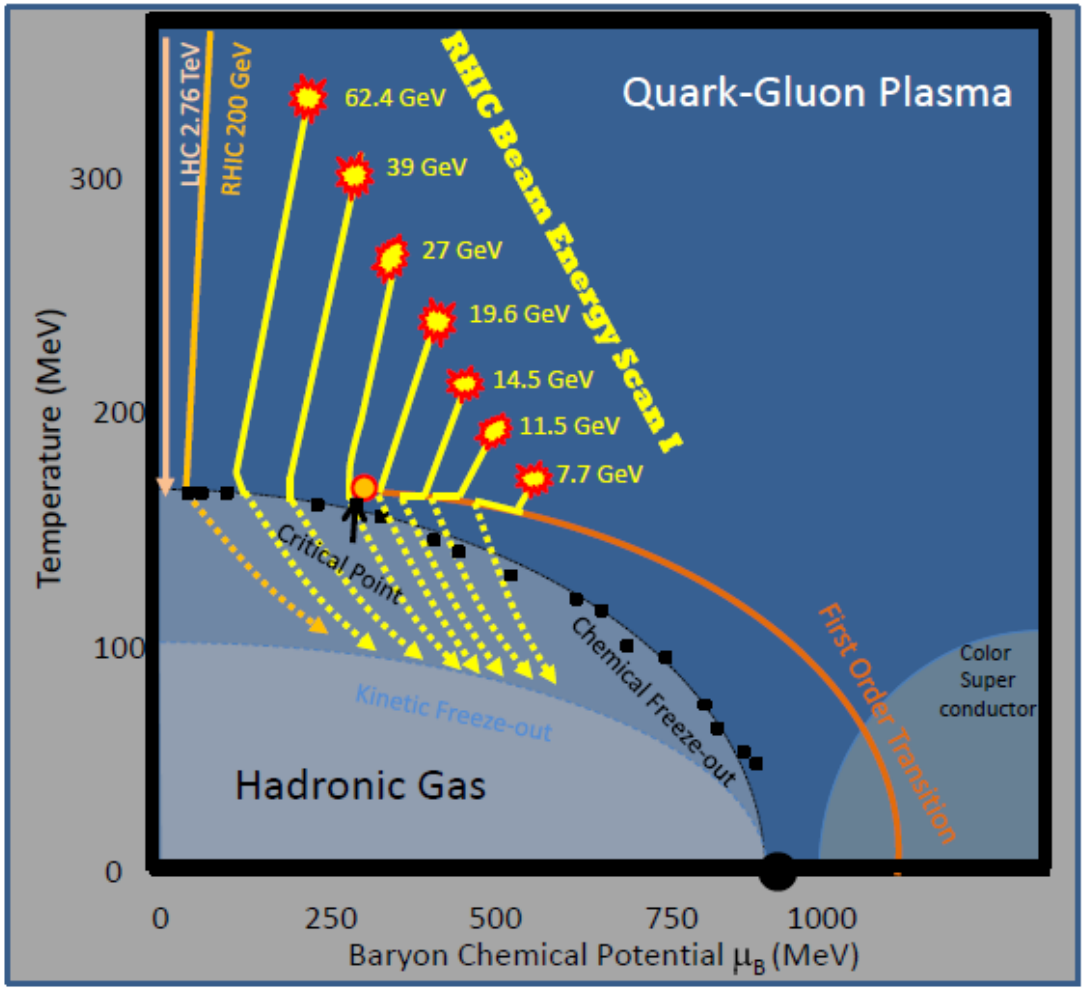


RHIC Beam Energy Scan (BES)

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.

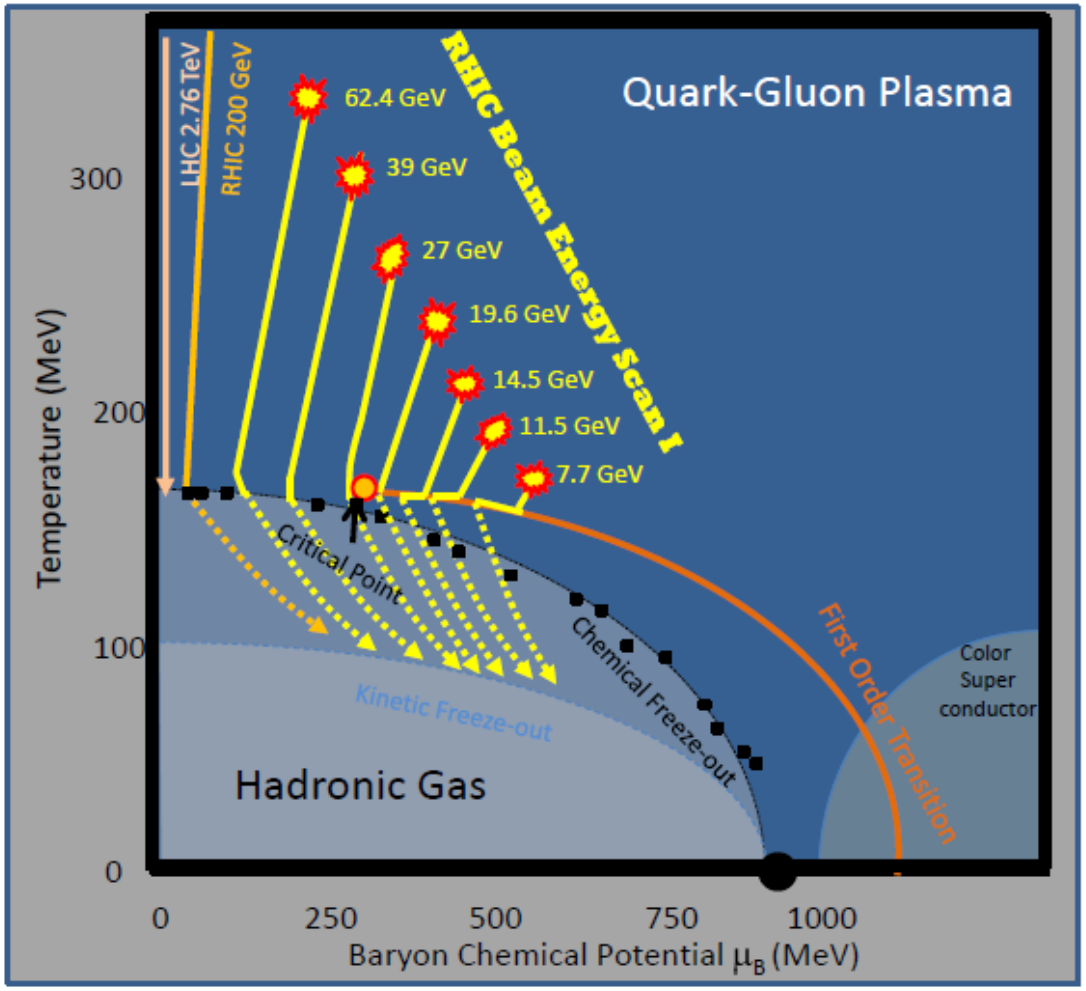
Energy (GeV)	Events (Millions)	Time (Weeks)
200	350	11
62.4	67	1.5
39.0	130	2
27.0	70	1
19.6	36	1.5
14.5	20	3
11.5	12	2
7.7	4	4



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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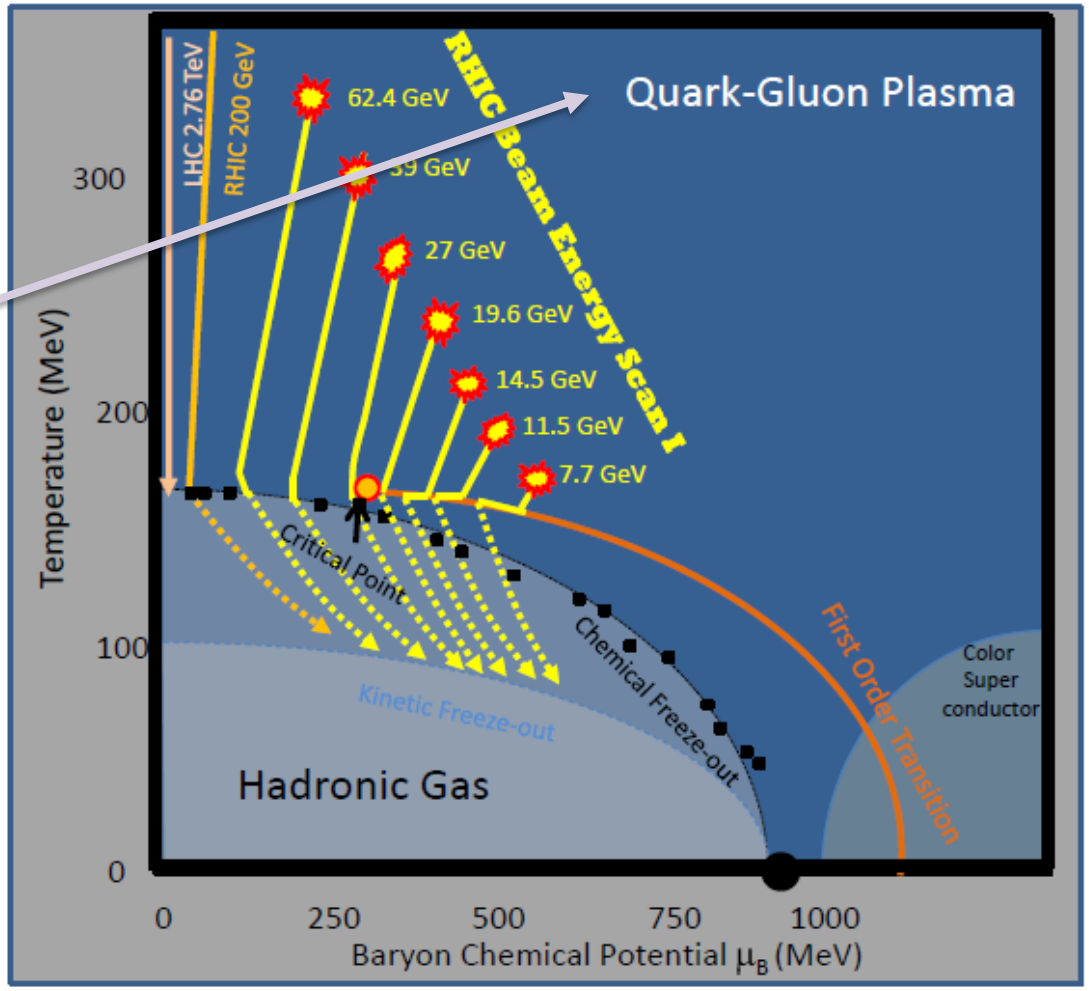


Turn-off of QGP signatures: R_{CP}

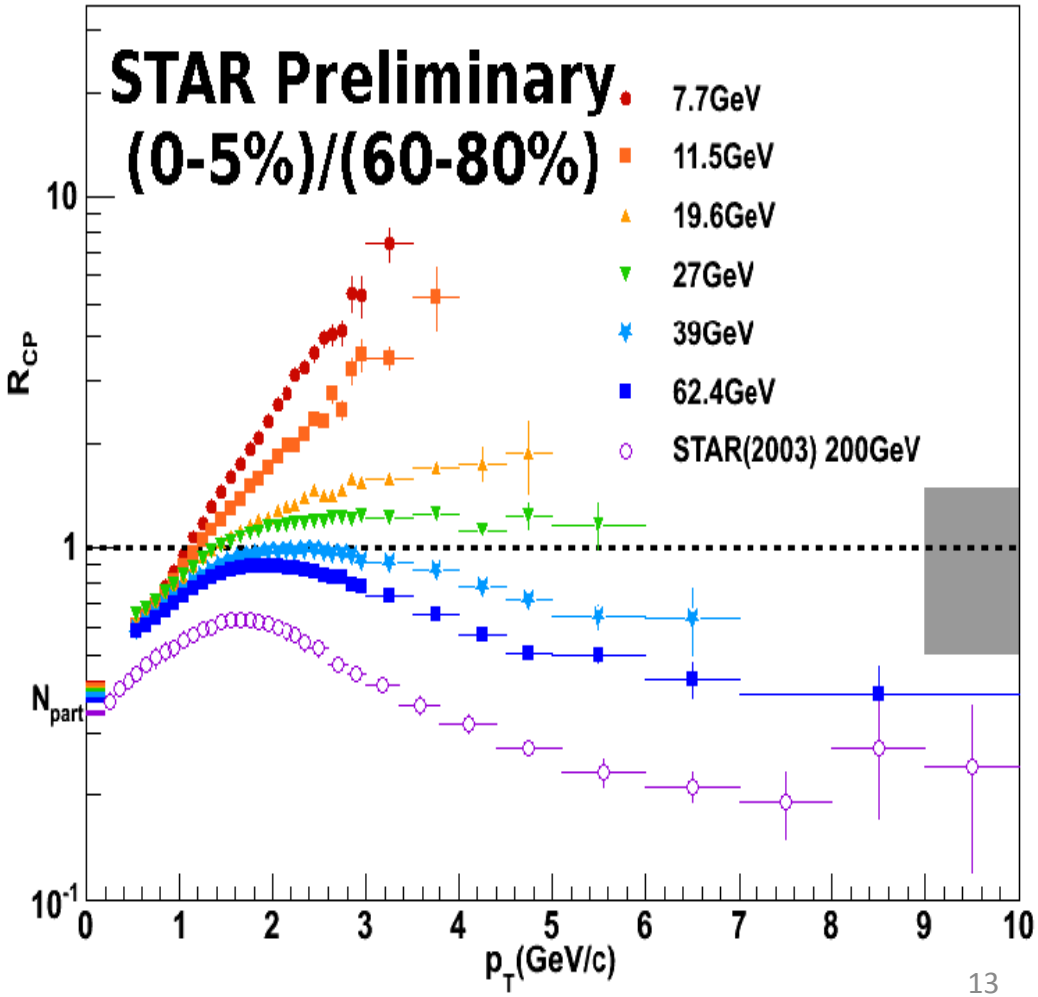
$$R_{CP} = \langle N_{bin}^{peri} \rangle \frac{d^3 N_{AA}^{cen}}{d\eta d^2 p_T} \Big/ \langle N_{bin}^{cen} \rangle \frac{d^3 N_{AA}^{peri}}{d\eta d^2 p_T}$$

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

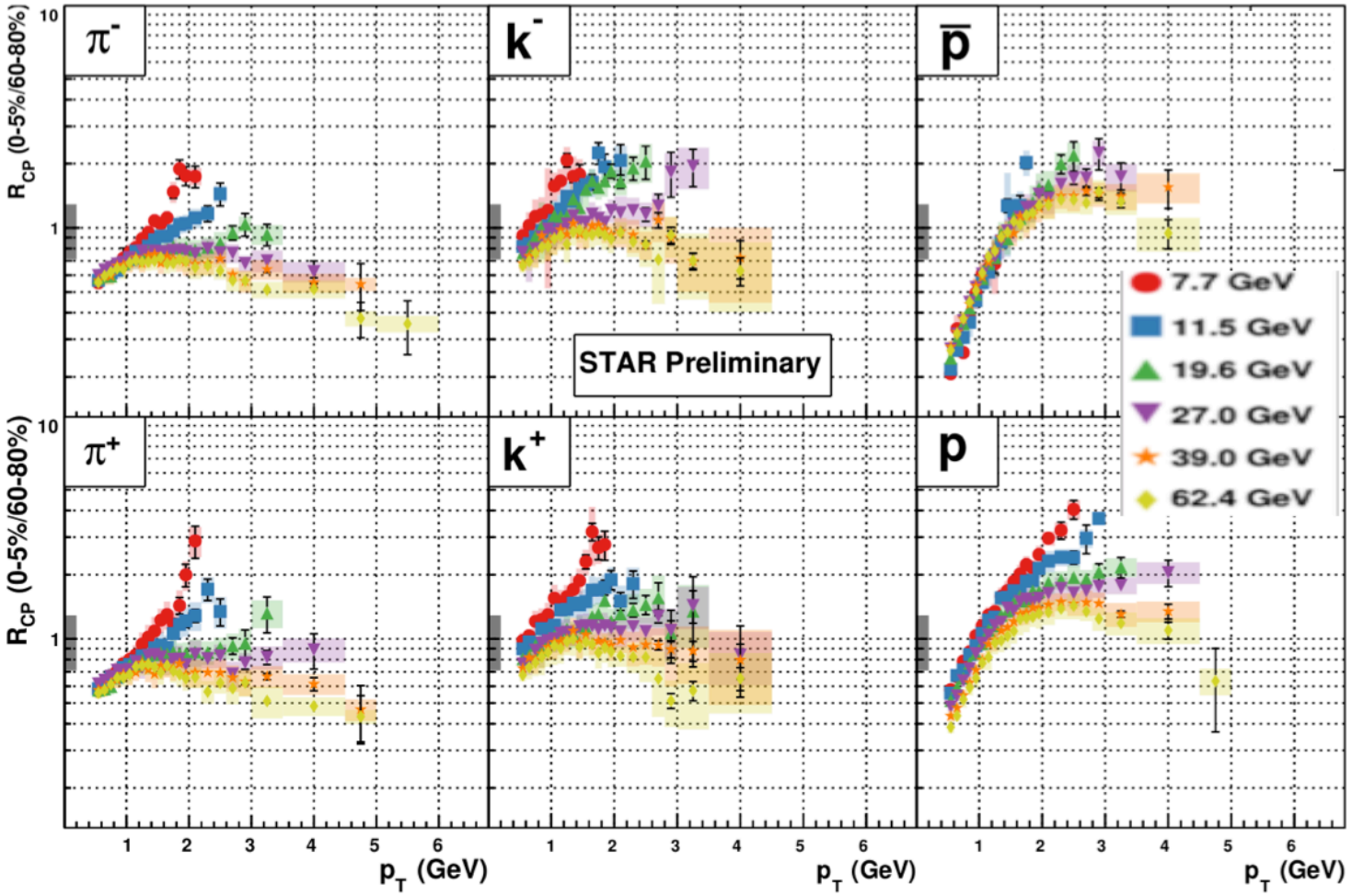
- Suppression at high p_T indicative of QGP formation.

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

The p_T reach at lower energies is limited by statistics.

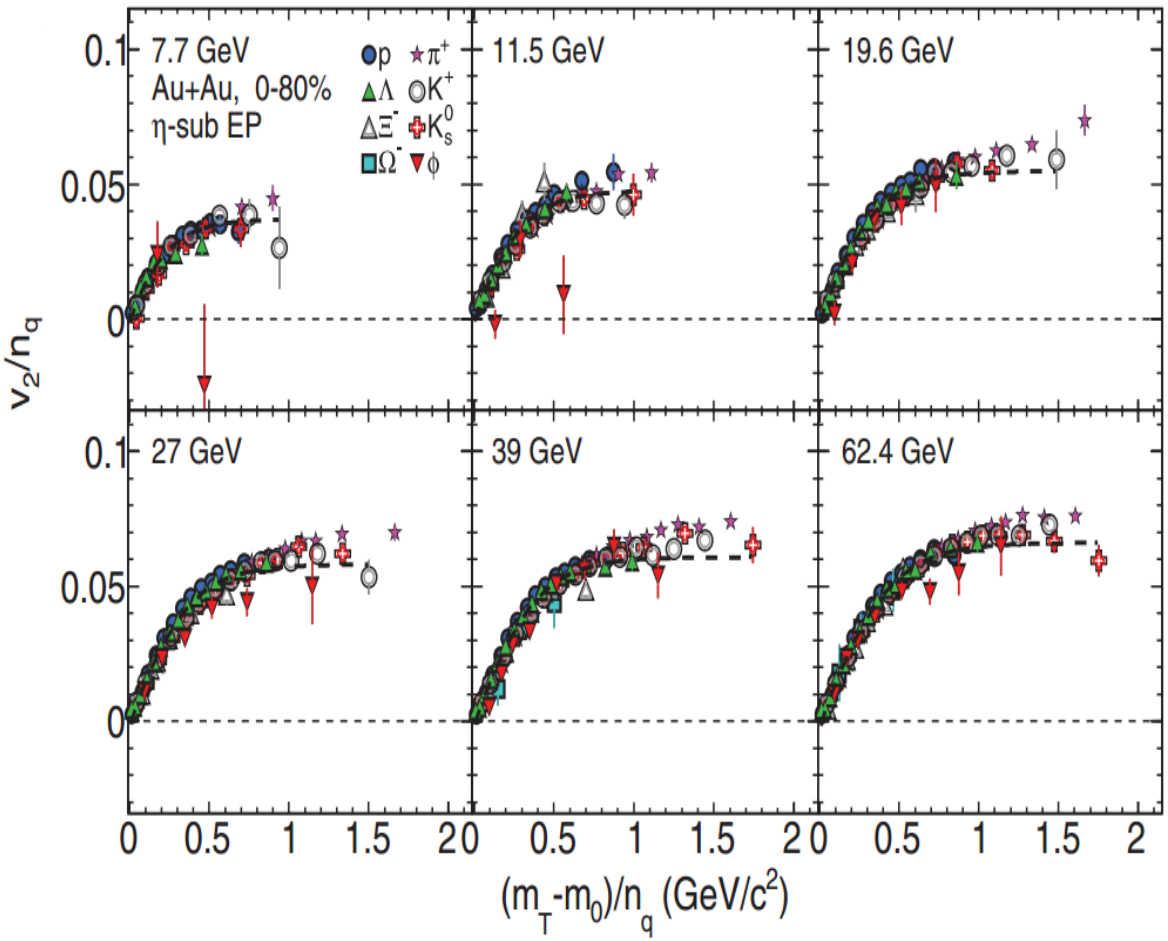


Turn-off of QGP signatures: R_{CP}



- 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

$$v_n = \langle \cos[n(\varphi - \Psi_2)] \rangle,$$

φ = azimuthal angle

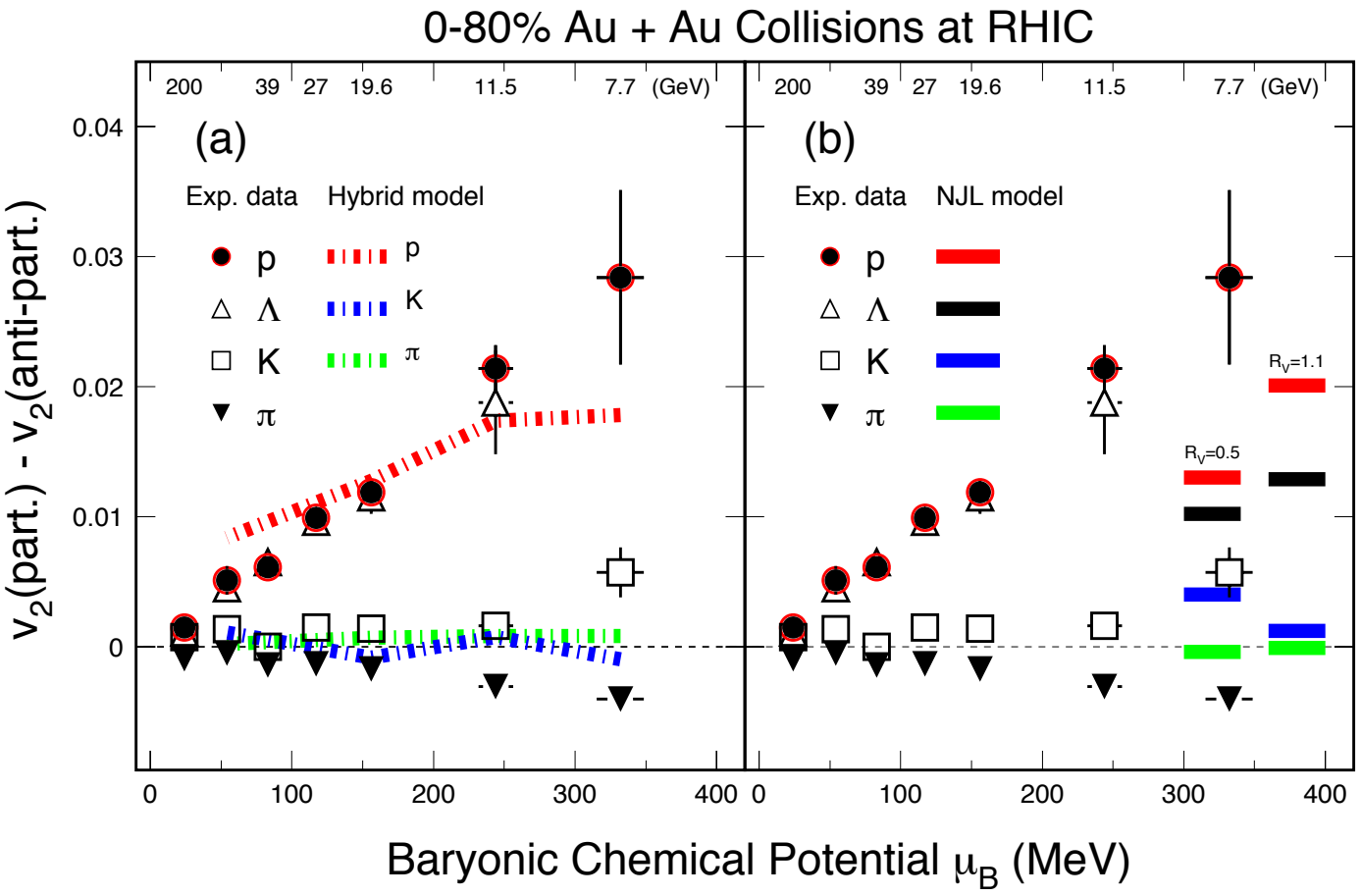
n_Q = #constituent quarks

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

n_Q scaling holds (separately for particles, antiparticles) 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)

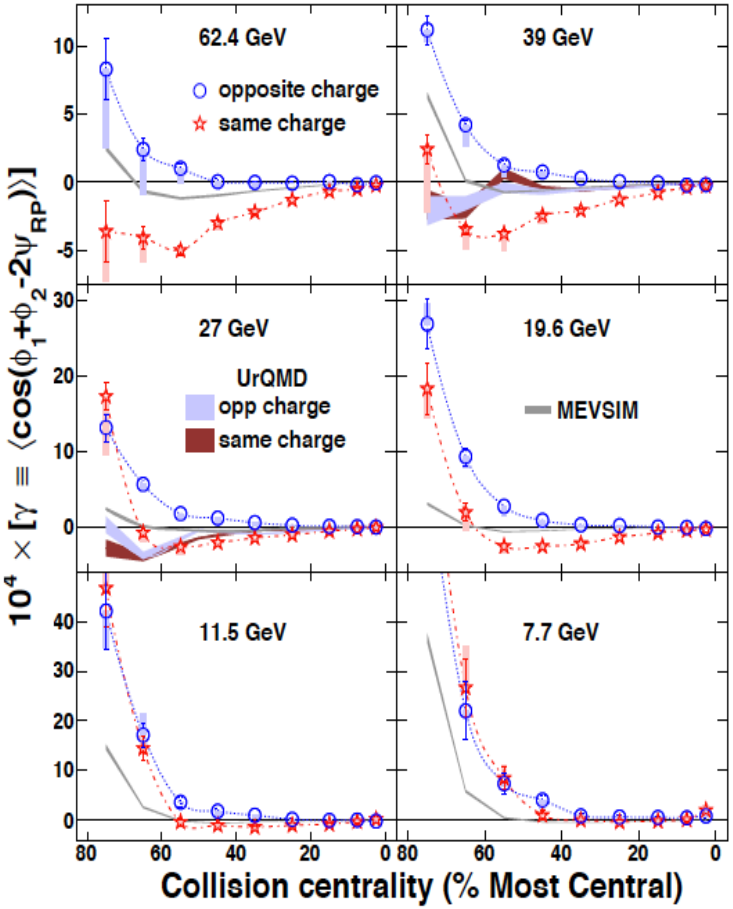
NJL: Acta Phys.Polon.Supp. 7 (2014) 1, 183

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.



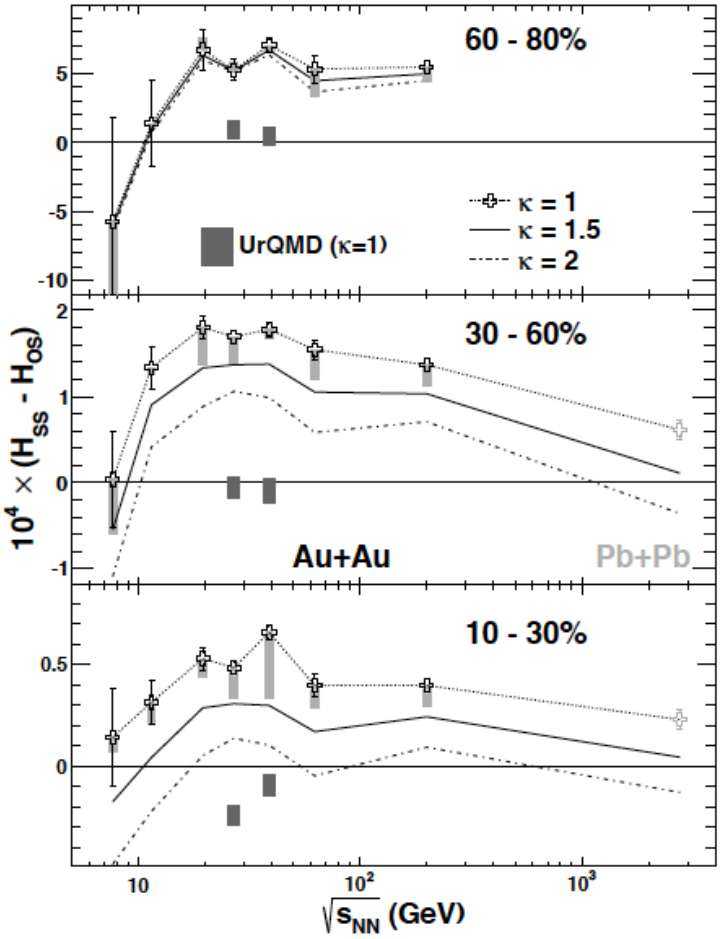
Charges separately

γ may be sensitive to CME.

H is CME background contribution

Effect goes away at low beam energy.

Phys. Rev. Lett. 113, 052302 (2014)



Signal-Background

RHIC Beam Energy Scan (BES)

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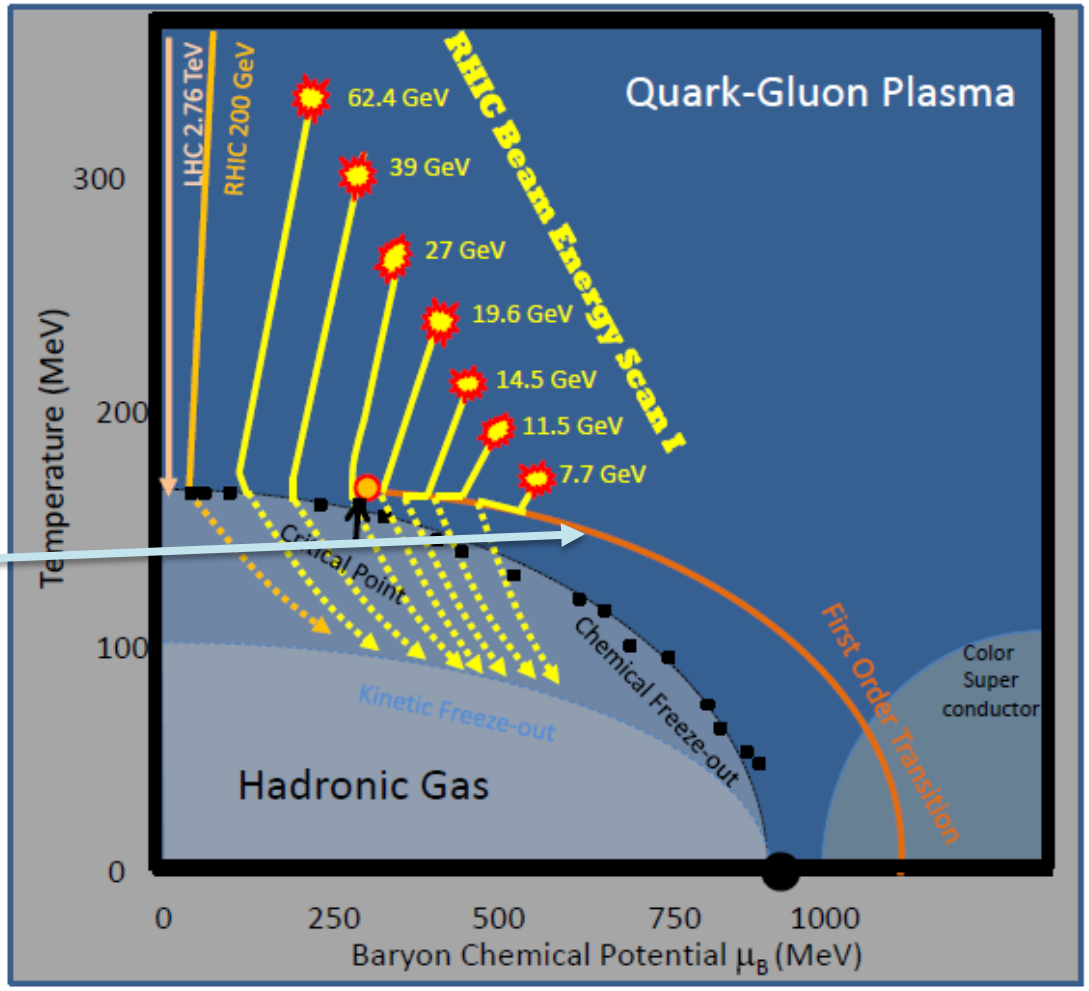
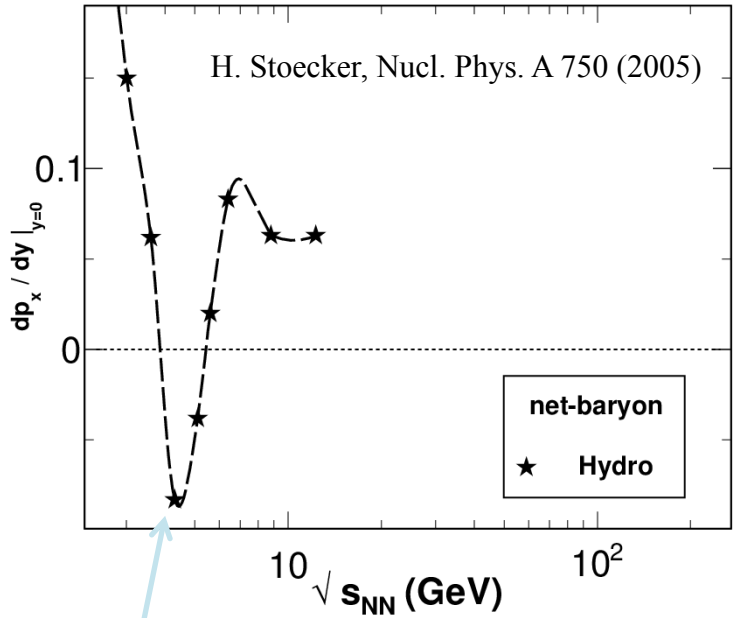
Turn-off of QGP signatures

First-order phase transition

Critical Point

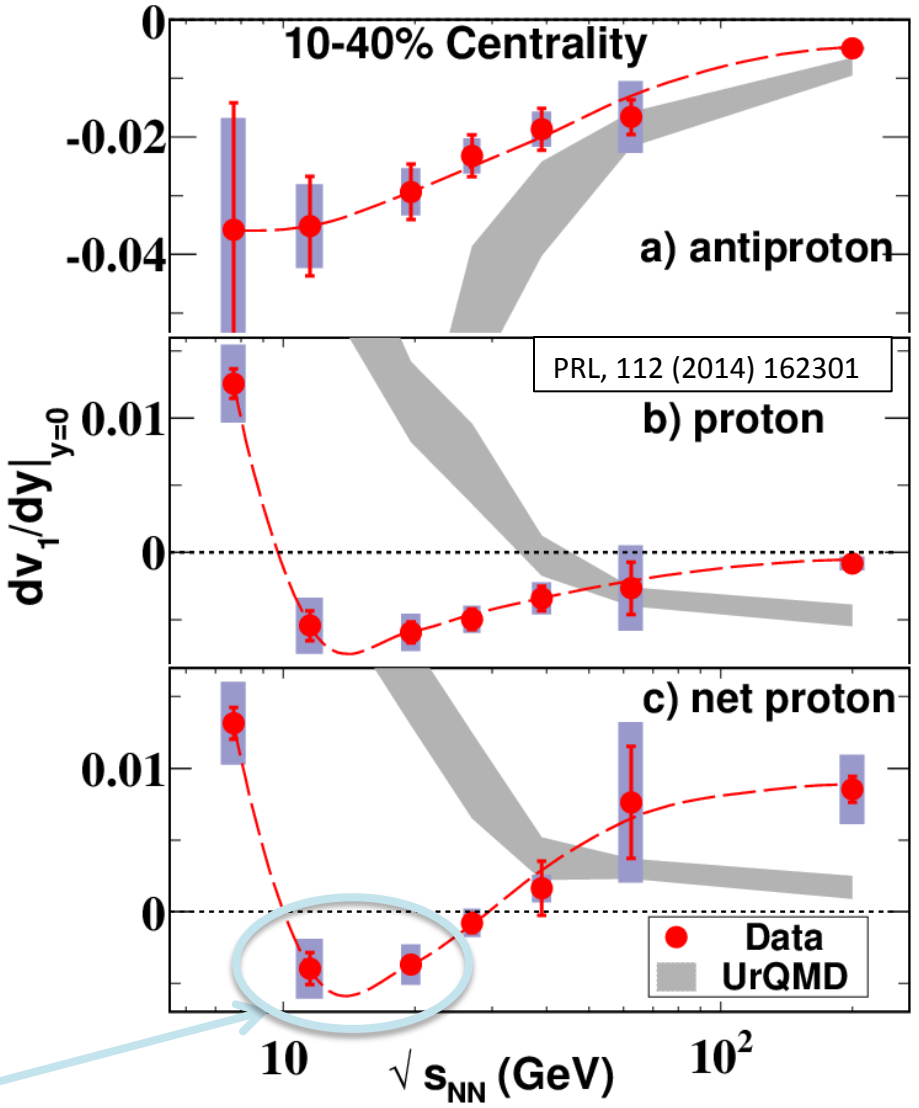


First-order phase transition: v_1



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?

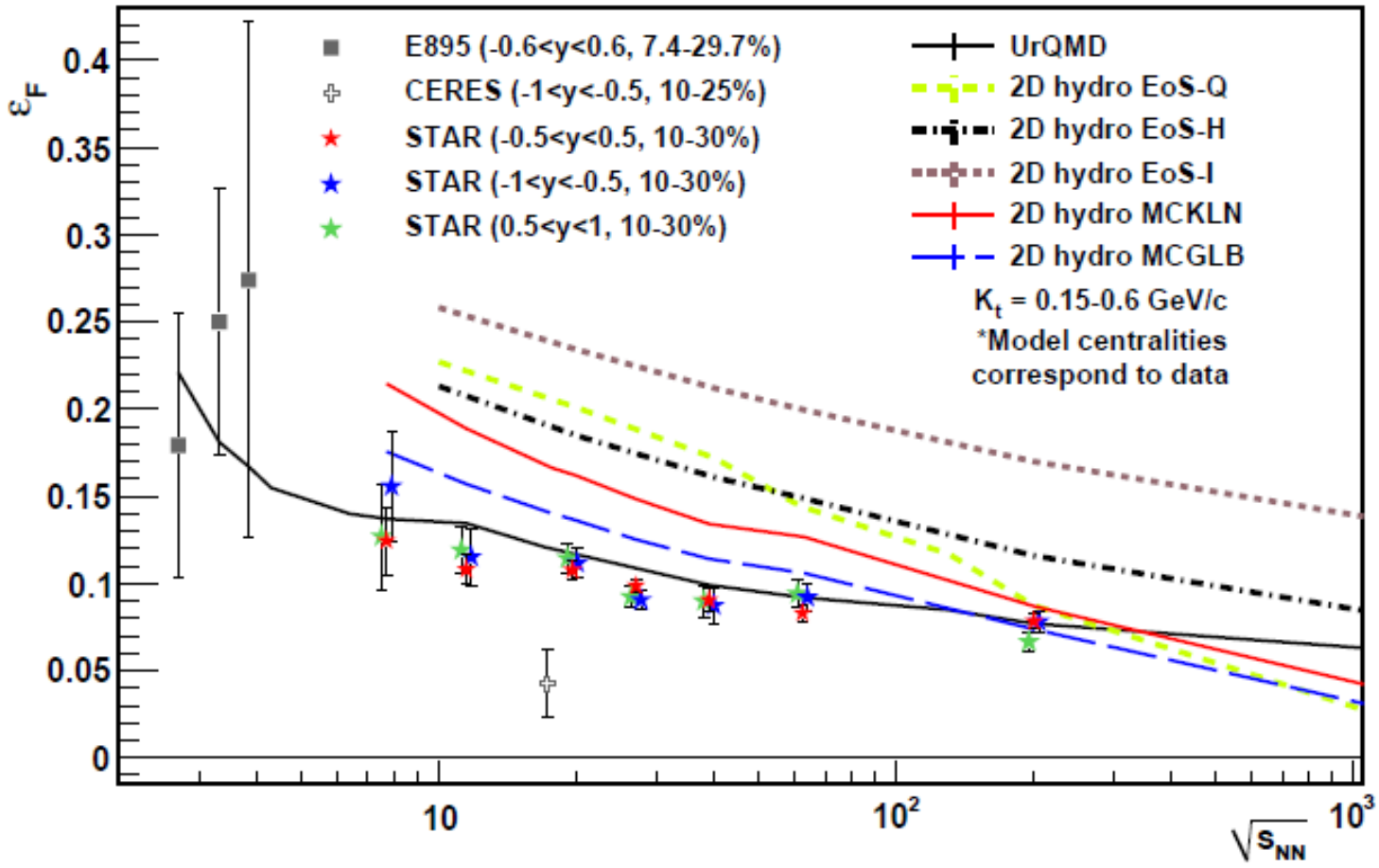


First-order phase transition: azimuthal HBT

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 1st-order phase transition.

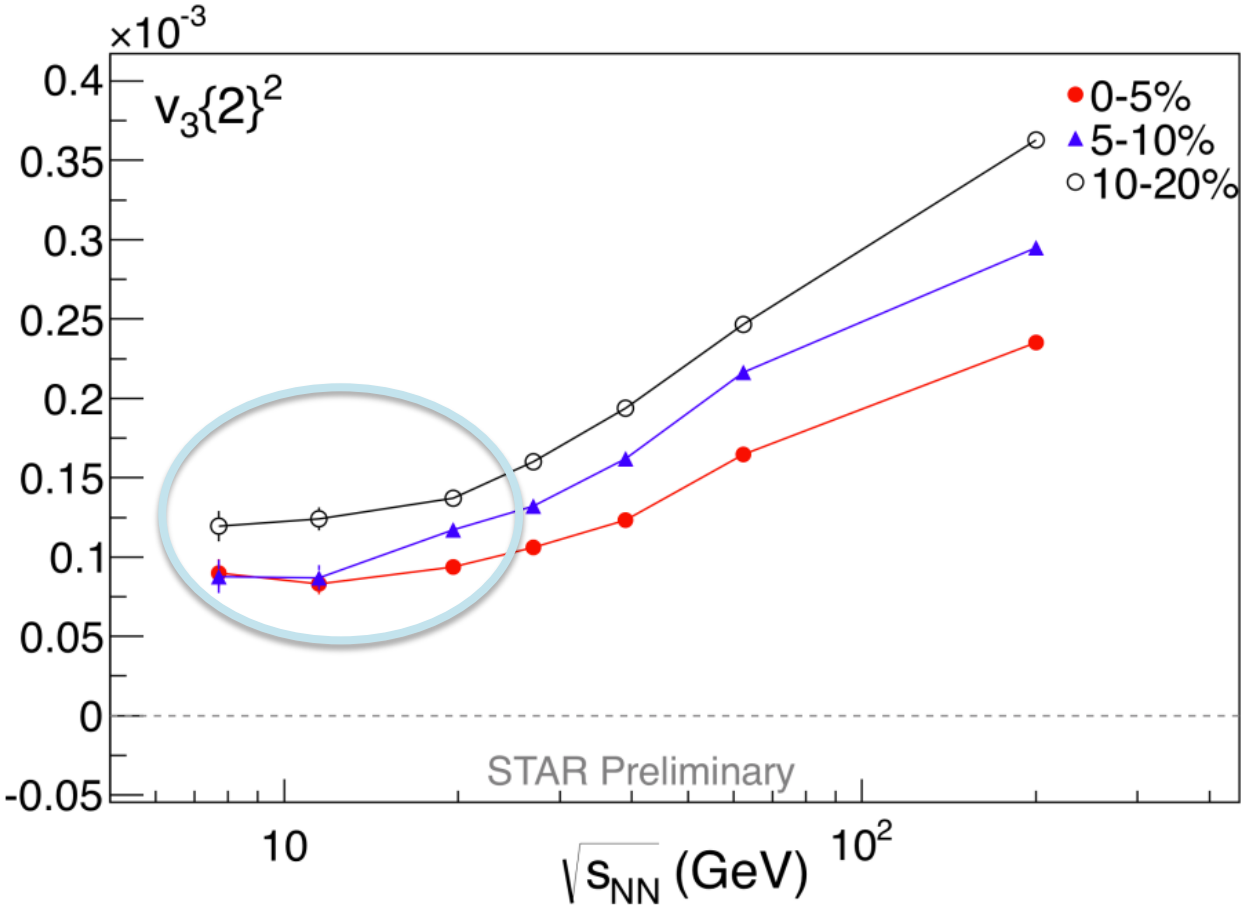


arXiv:1403.4972

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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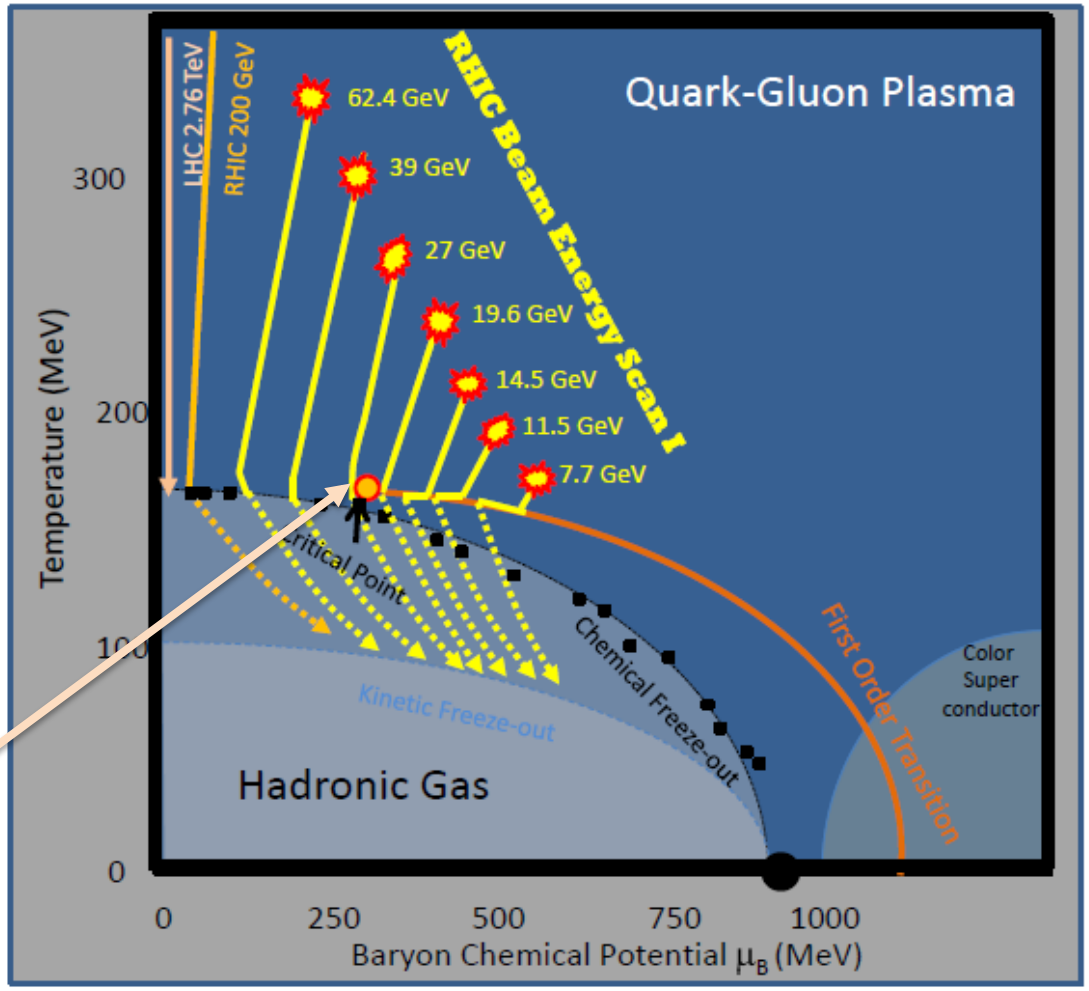


Critical Point: net-proton multiplicity moments

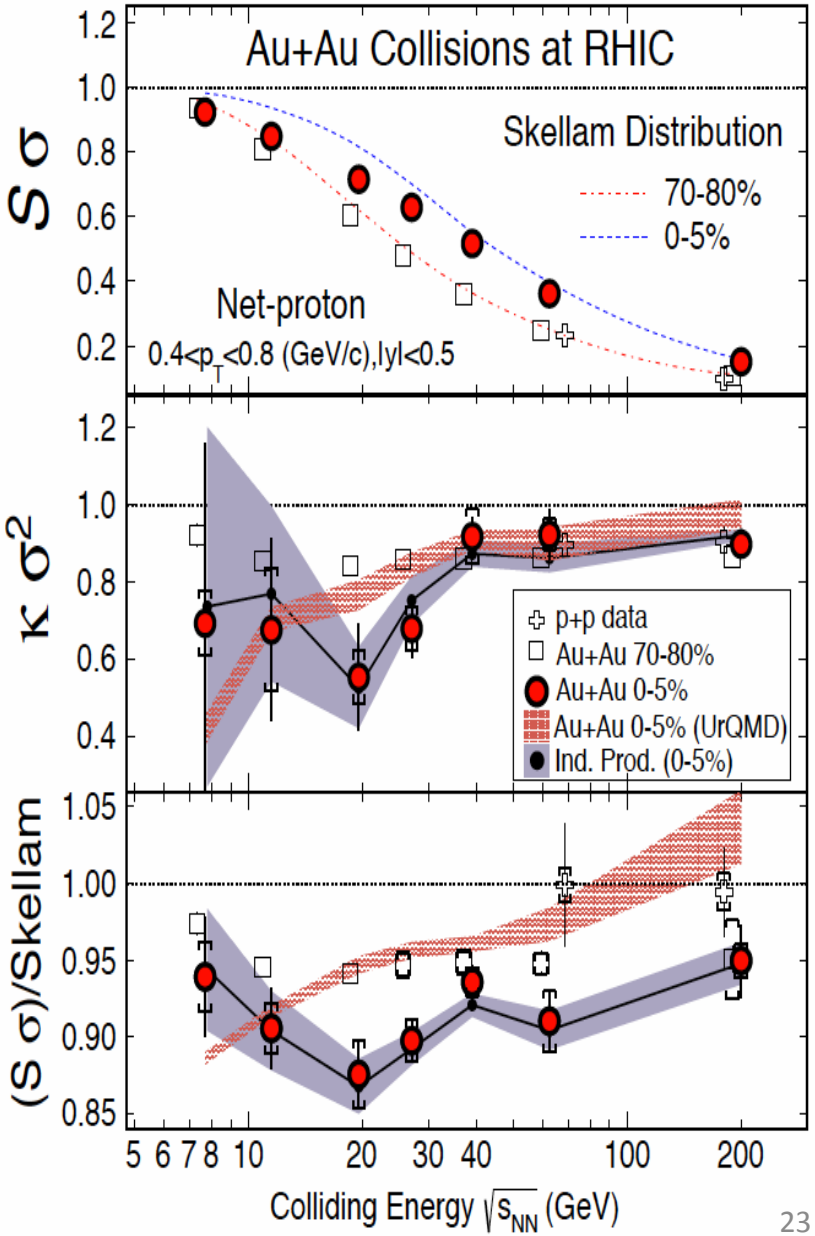
Susceptibility ratios of conserved quantities (χ_{BQS}) are related to the moments of experimentally measurable multiplicity distributions.

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

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

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

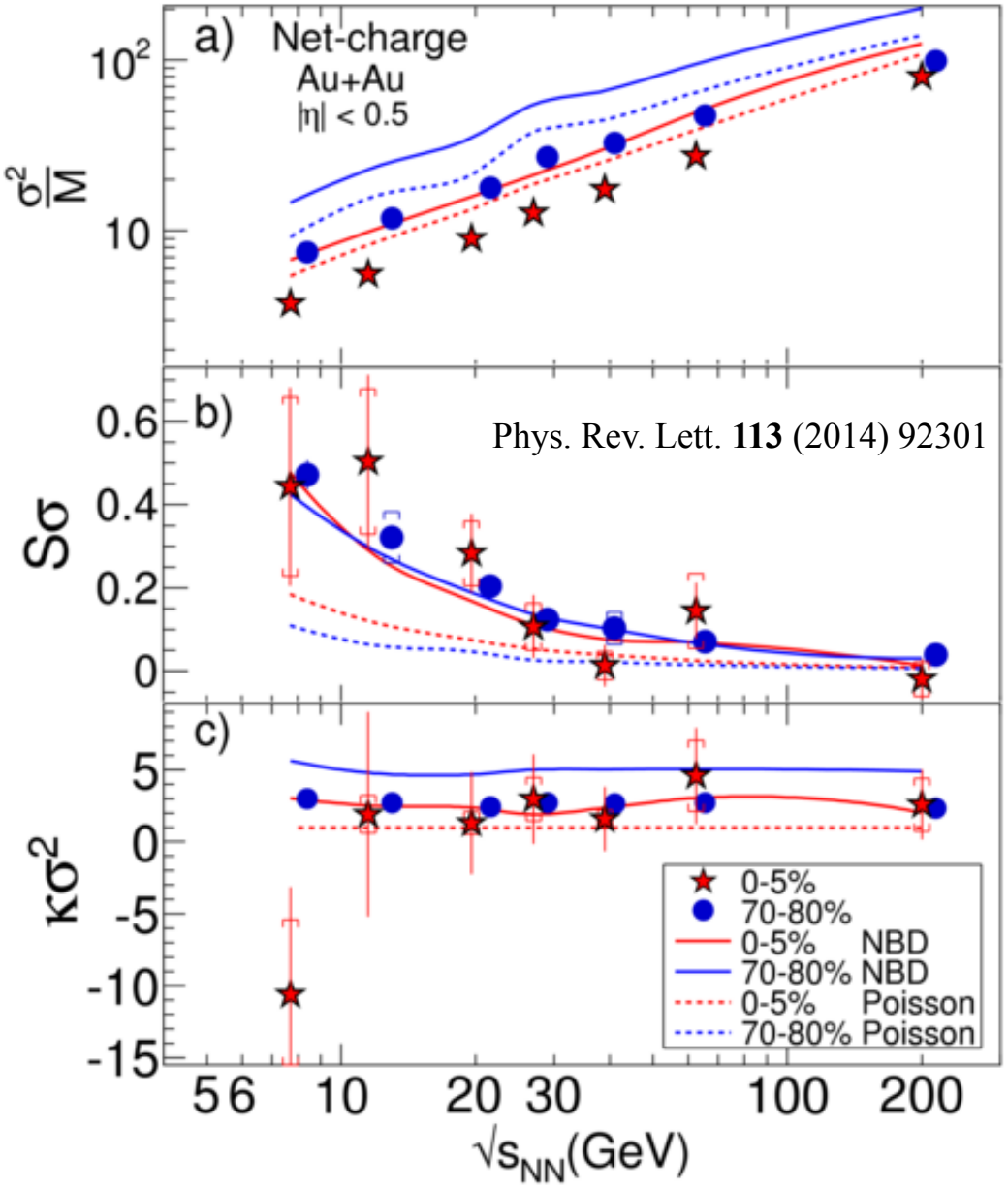
Higher statistics is necessary to further clarify net-proton results.



Phys. Rev. Lett. 112 (2014) 032302

Critical Point: net-charge multiplicity moments

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



RHIC Beam Energy Scan (BES): overview

Goals of BES are to locate:

Turn-off of QGP signatures

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:

Turn-off of QGP signatures

First-order phase transition

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
- $v_3\{2\}^2$

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.

Summary

200 GeV U+U results shown: v_2 and LPV.

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
- New data point at 14.5 GeV coming, **official production completed**

Future results hopefully coming from new colliding species:

Cu+Au (run 12) and Au+He3 (run 14)

Outlook:

- BES-II, focusing on beam energies below ~20 GeV, planned for run 18-19
- Collider upgrades with e-cooling and STAR upgrades underway

Thanks!!