WORKSHOP

Studies of the QCD Phase Structure in High-Energy Nuclear Collisions

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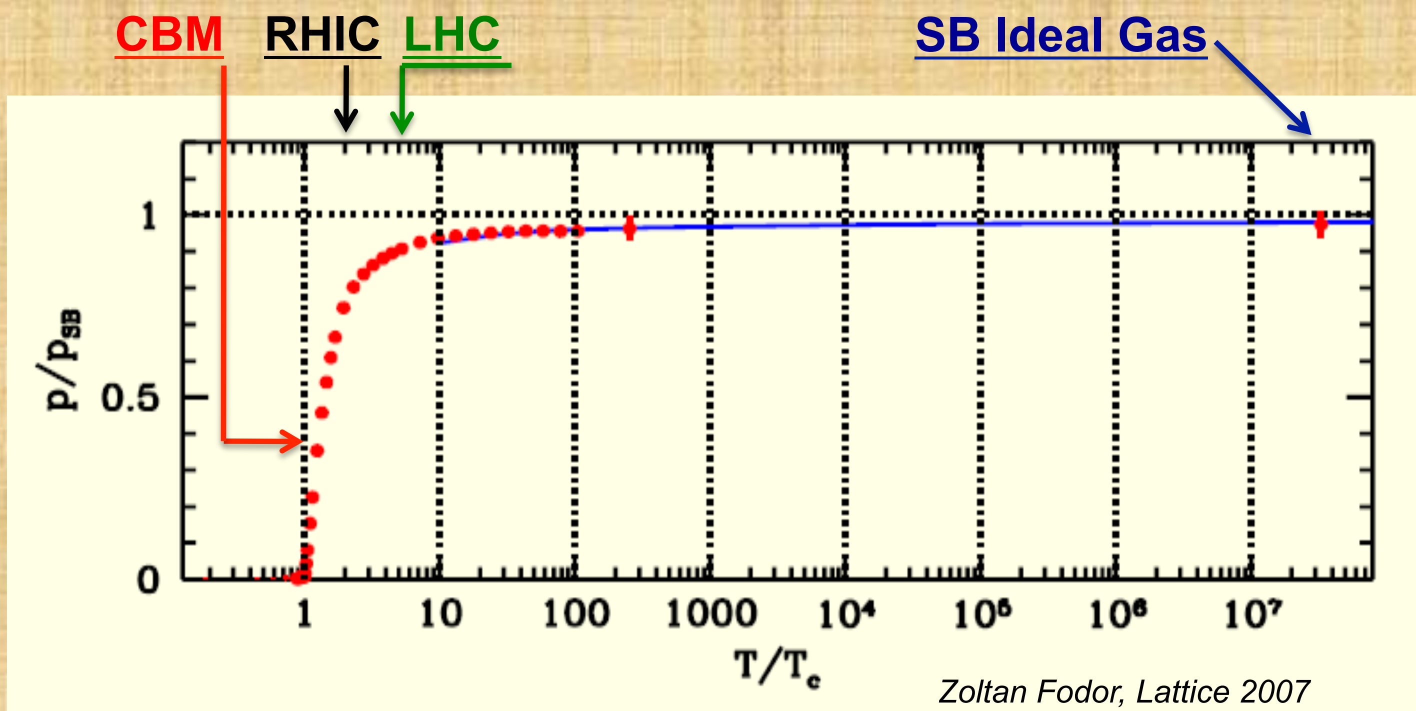
QCD Thermodynamics



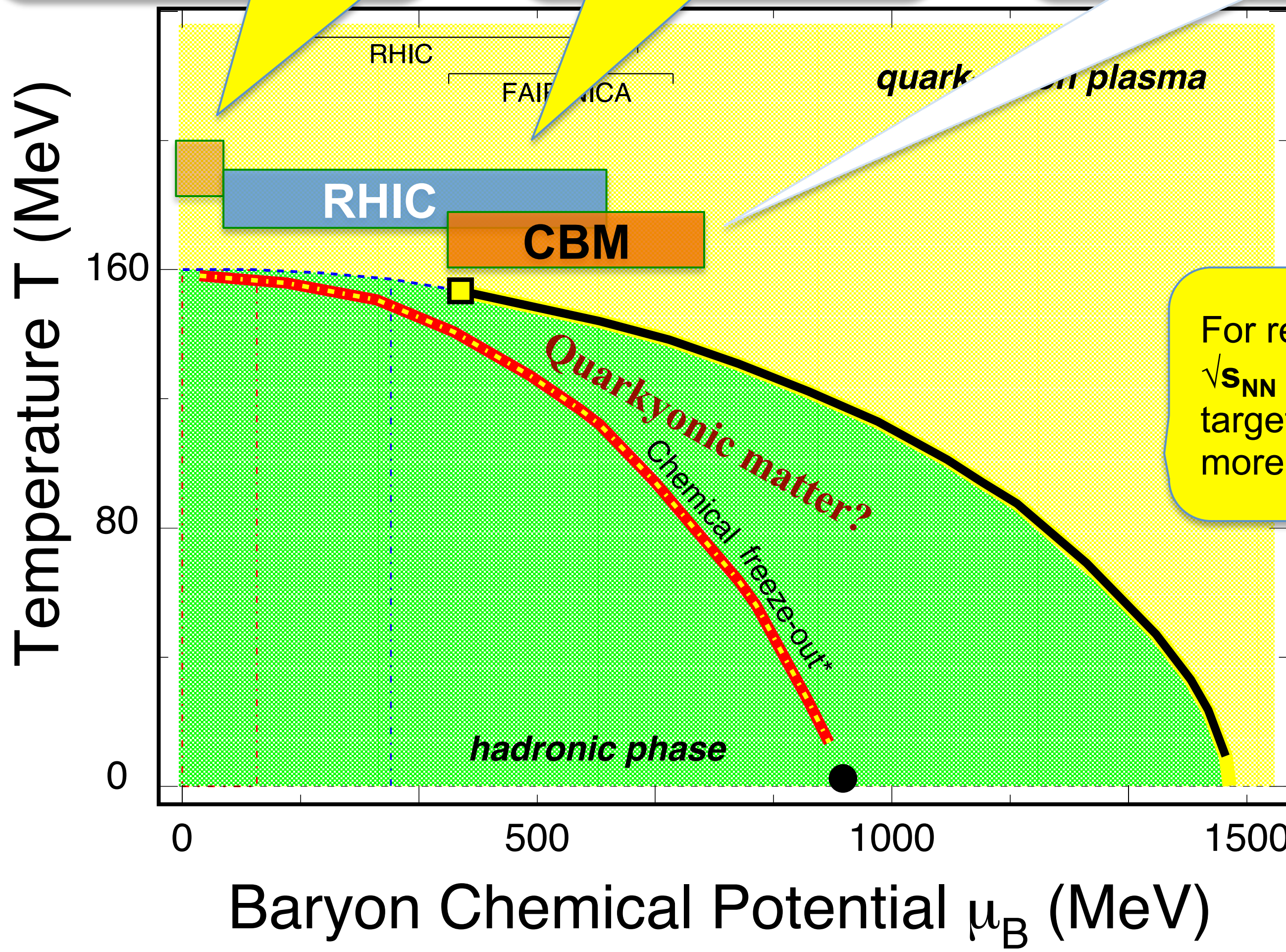
1) At $\mu_B = 0$: cross over transition, *150 < T_c < 200 MeV*
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) T_{ini}(LHC) ~ 2-3*T_{ini}(RHIC)
4) Thermodynamic evolutions are similar for RHIC and LHC

Exploring QCD Phase Structure

LHC+RHIC
Property of sQGP
$0.2 \leq \sqrt{s_{NN}} \leq 5.4$ TeV

RHIC BES-II
Critical Point
$7.7 \leq \sqrt{s_{NN}} \leq 20$ GeV

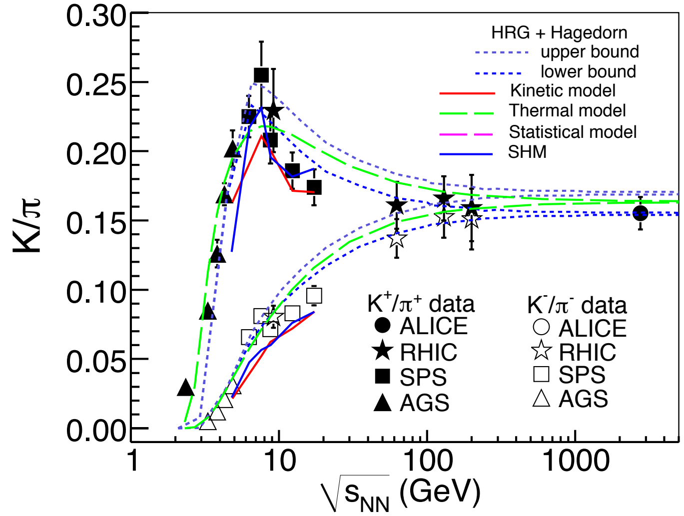
RHIC + FAiR
CP, 1st phase boundary, Quarkyonic Matter
$\sqrt{s_{NN}} \leq 8$ GeV

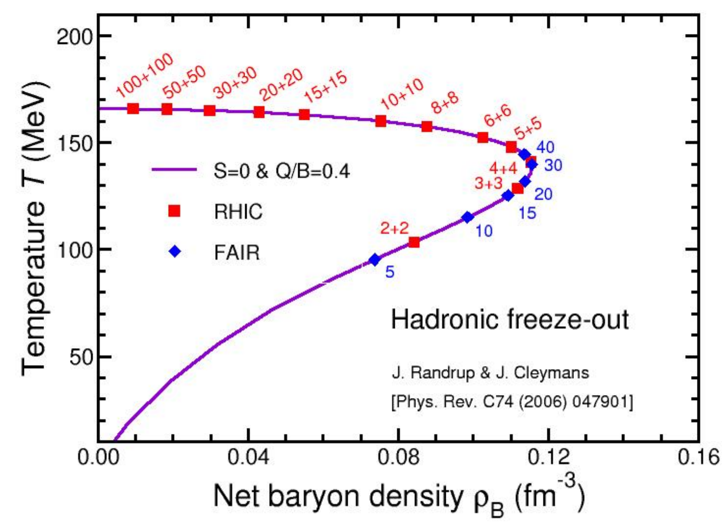


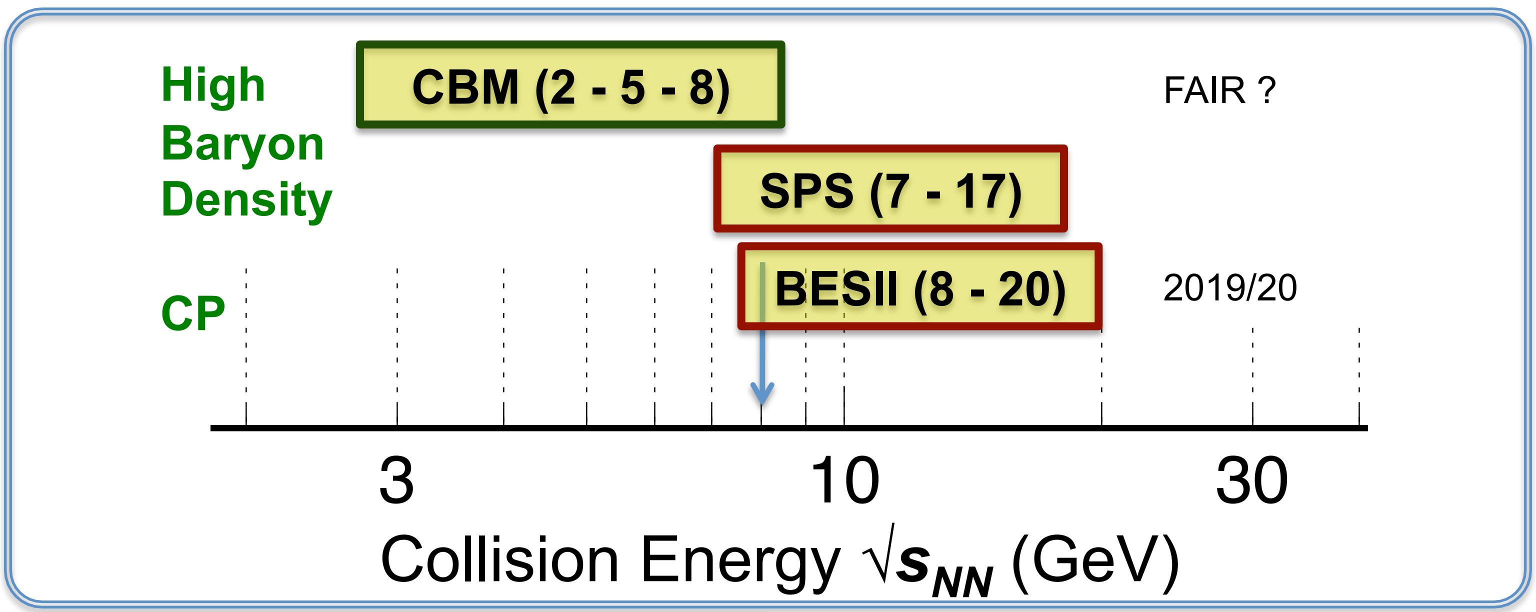
For region $\mu_B > 500$ MeV, $\sqrt{s_{NN}} \leq 5$ GeV, fixed-target experiments are more efficient

Baryon Density Peaks at ~ $\sqrt{s_{NN}}$ = 8 GeV

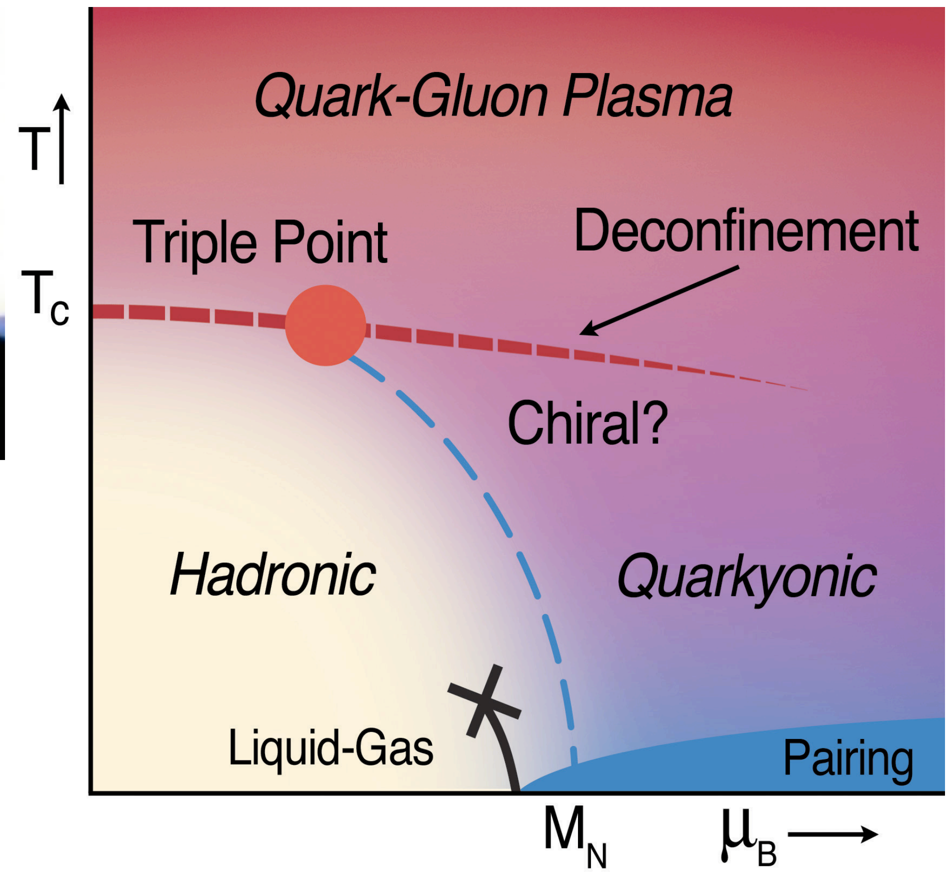
1304.2969, Adv.High Energy Phys. 2013 (2013) 761474







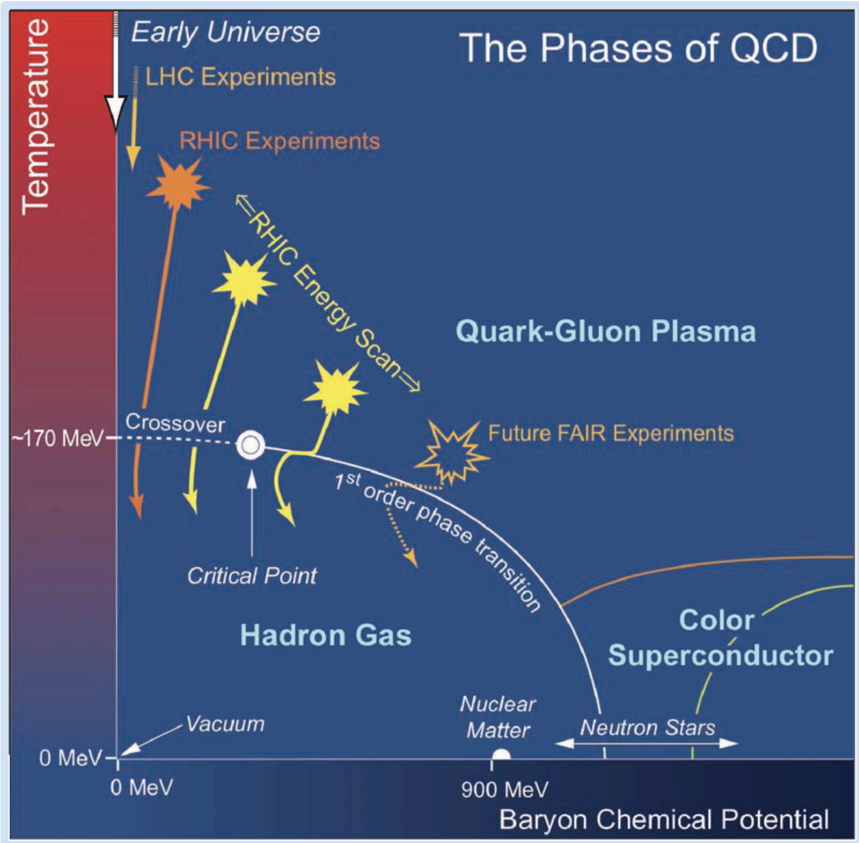
QCD Phase Diagram (2009)



nucl-th: 0907.4489, ***NPA830***,709(09) *L. McLerran*

NPA837, 65(2010) nucl-th 0911.4806*: A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel*

Beam Energy Scan at RHIC



Study QCD Phase Structure

- Onset of sQGP
- Phase boundary and critical point
- Chiral symmetry

BES-I:

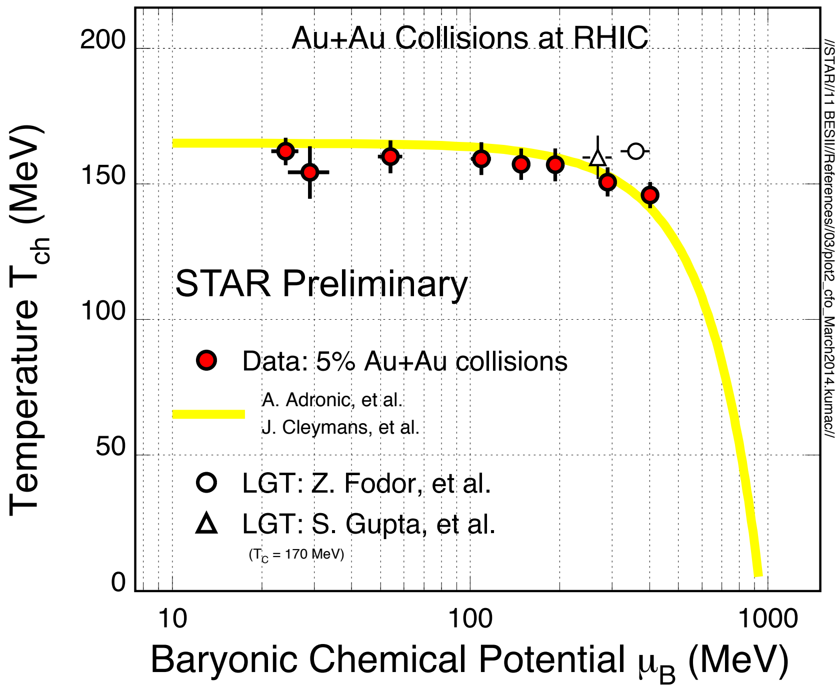
$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39GeV

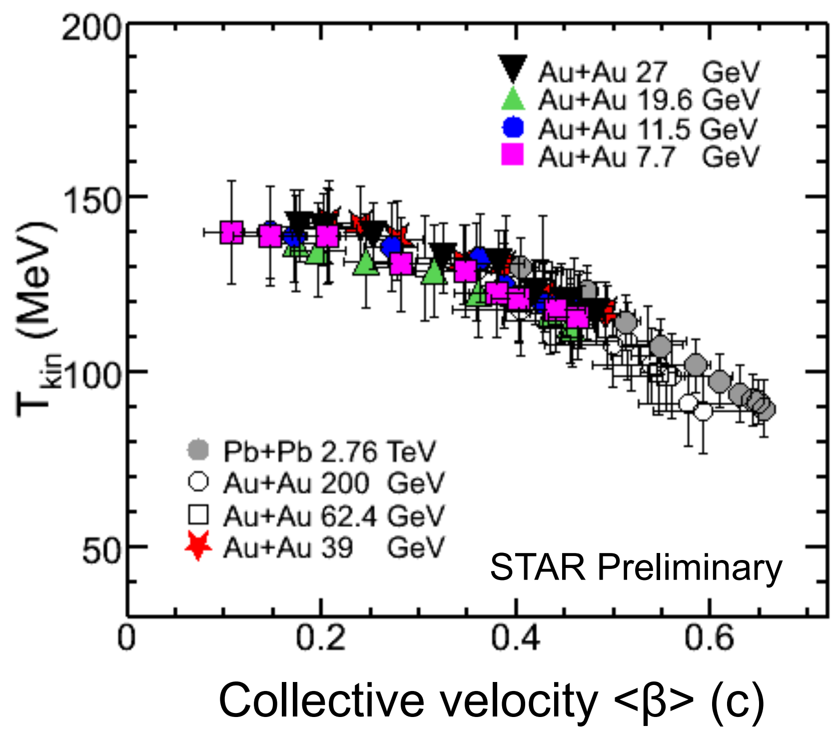
BES-II: $\sqrt{s_{NN}} \leq$ 20GeV

(1) Chiral symmetry: **Baryon & charge separation**

(2) Critical point* (critical region): **High order cumulants**

Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)
- Central collisions.
- Centrality dependence, not shown, of T_{ch} and μ_B!

Kinetic Freeze-out:
- Central collisions => lower value of T_{kin} and larger collectivity β
- Stronger collectivity at higher energy

Outline

(1) Introduction

(2) Search for CME, CVE

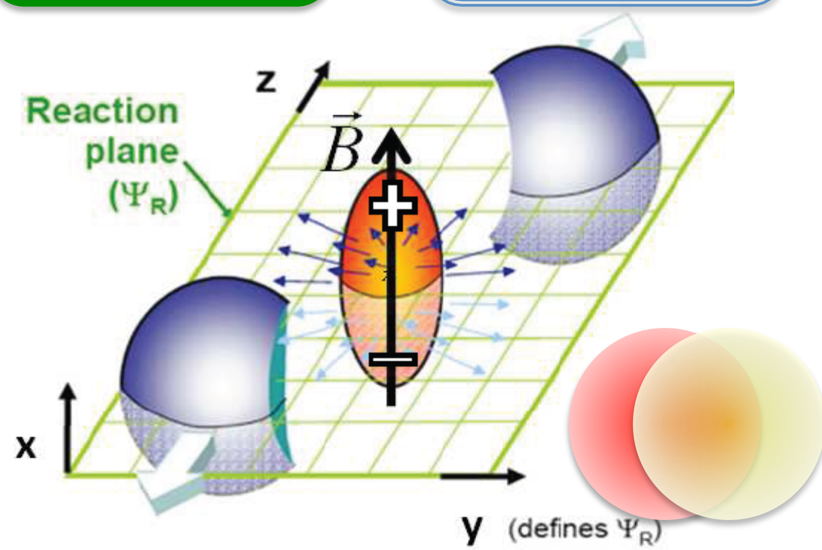
(3) Search for QCD CP

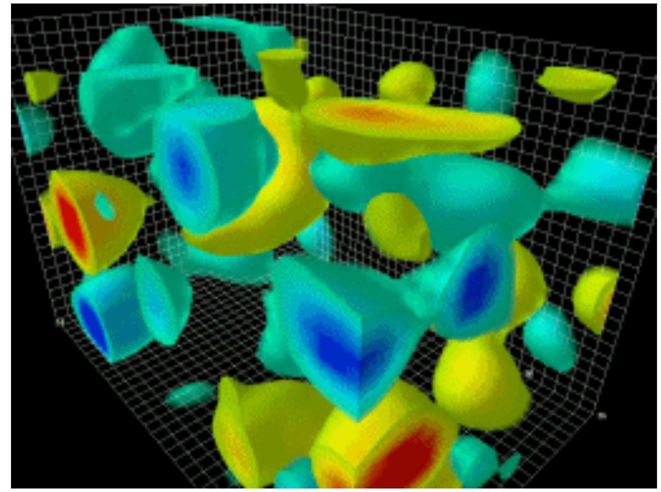
Study QCD Topological Structure

Hot/dense QCD Medium
Parity odd domains form

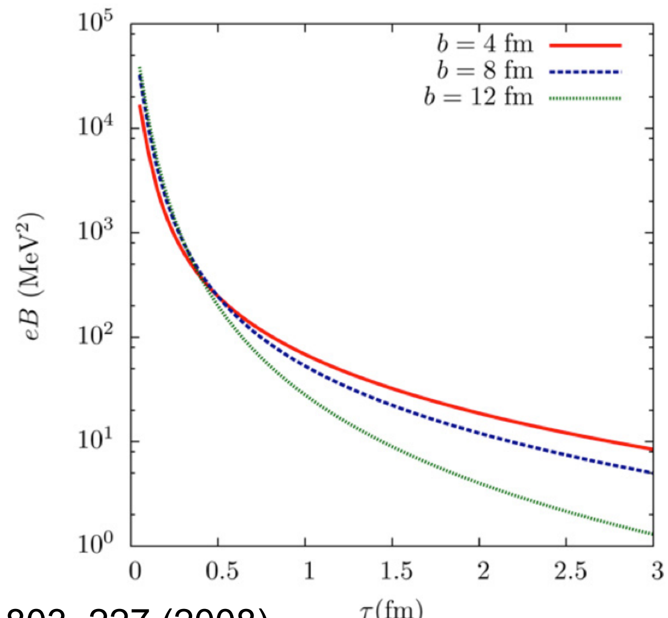
External Magnetic Field → Chiral magnetic effect (**CME**) (electric charge)

External Angular Momentum ➔ Fluid Vorticity → Chiral vortical effect (**CVE**) (baryonic charge)



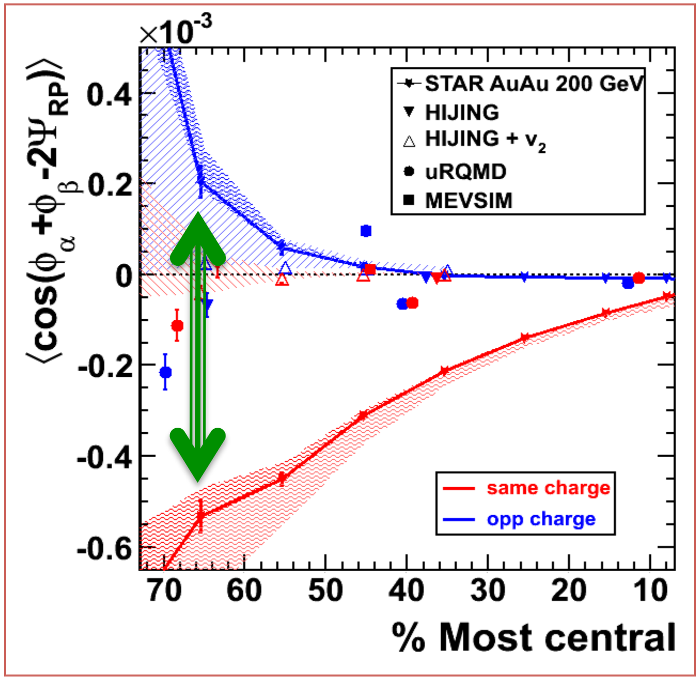


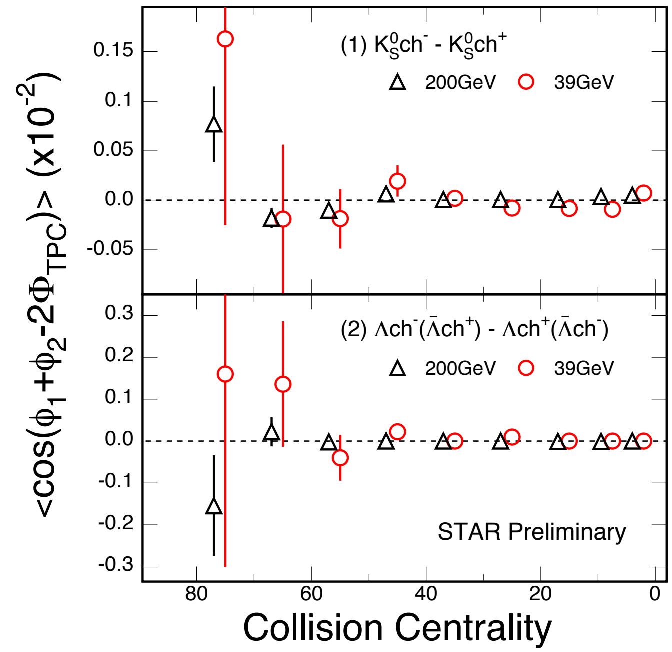
Animation by *Derek Leinweber*

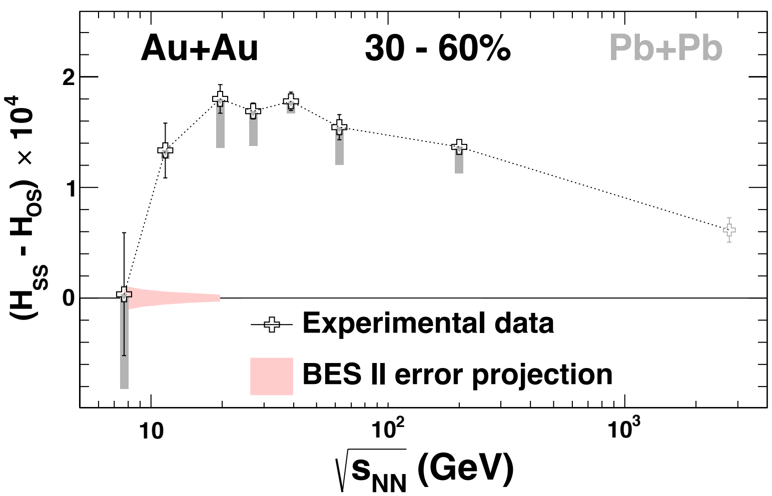


NPA 803, 227 (2008).

Charge Separation wrt Event Plane (CME)







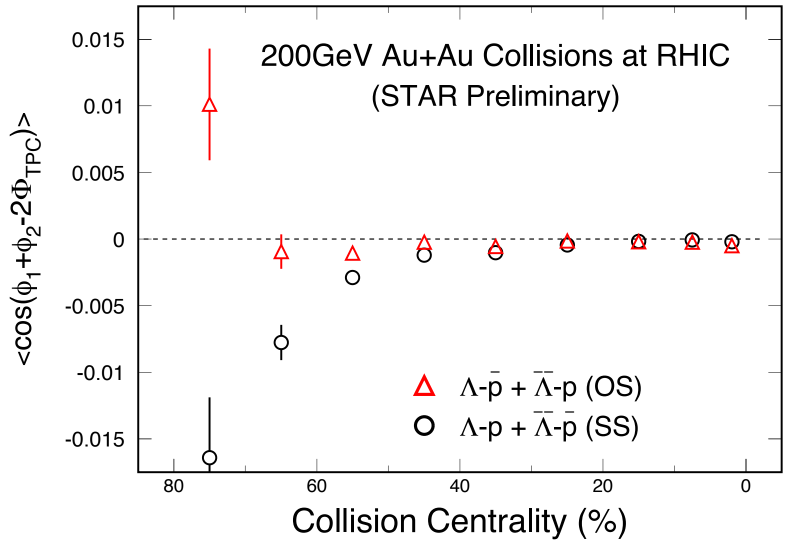
CME disappears: with neutral hadrons:

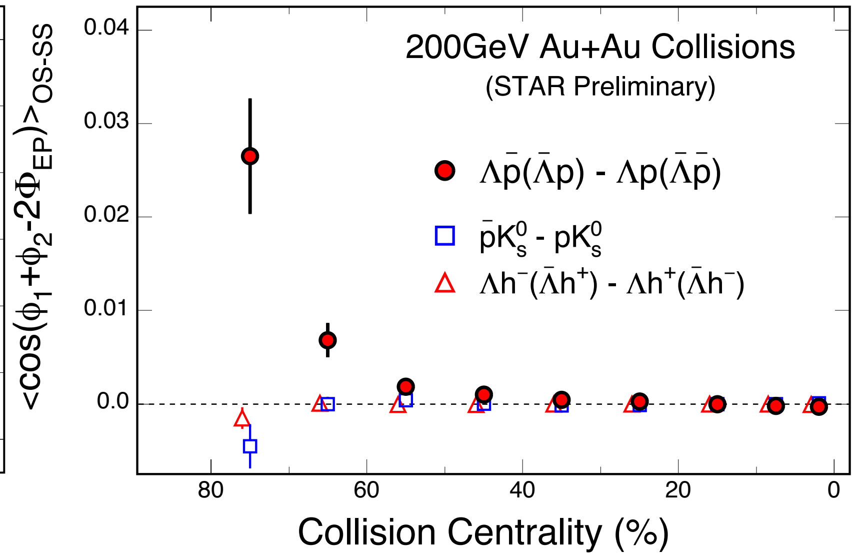
At low energy, no csr, no CME:
➔ hadronic interactions become dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: ***PRL103***, *251601(09);* ***PRL113***, *052302(14)*
D. Kharzeev, **PLB633**, 260 (06)
D. Kharzeev, et al. **NPA803**, 227(08)

Baryon Separation wrt Event Plane (**CVE**)

Λ-proton correlation: Λ contains the same B-charge as p but no e-charge

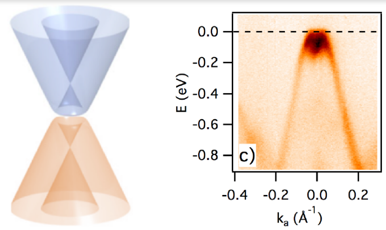




1) The opposite baryon-charge correlations (OS) are similar, ~ zero. But the same baryon-charge correlations (SS) are lower than that of the OS. The difference OS-SS is non-zero, ***baryon-charge separation***, as expected from the CVE
2) Neither p-K_0 nor Λ-charge hadron correlations show any separation effect, consistent with CVE

STAR: F. Zhao, QM2014 Proceedings **NPA931**, 746(14)
Kharzeev, D.T. Son, **PRL106**, 062301(11); D. Kharzeev. **PLB633**, 260 (06); D. Kharzeev, et al. **NPA803**, 227(08)

Chiral Symmetry is Life



“Observation of the chiral magnetic effect in $ZrTe_5$”

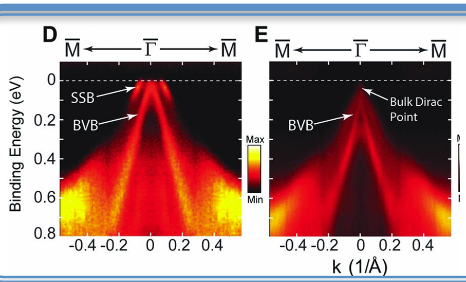
Q. Li et al., arXiv: 1412.6543 [cond-mat.str-el]

“Force of nature gave life its asymmetry”

'Left-handed' electrons destroy certain organic molecules faster than their mirror versions.

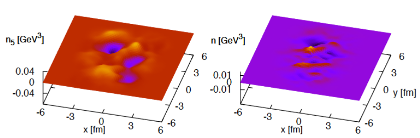
E. Gibney, ***Nature***, 25 September 2014

J.M. Dreiling and T.J. Gay, ***PRL113***, 118103(2014)



“Discovery of a Three-Dimensional Topological Dirac Semimetal, Na_3Bi”

Z.K. Liu et al., ***Science***, 343, 864(2014)

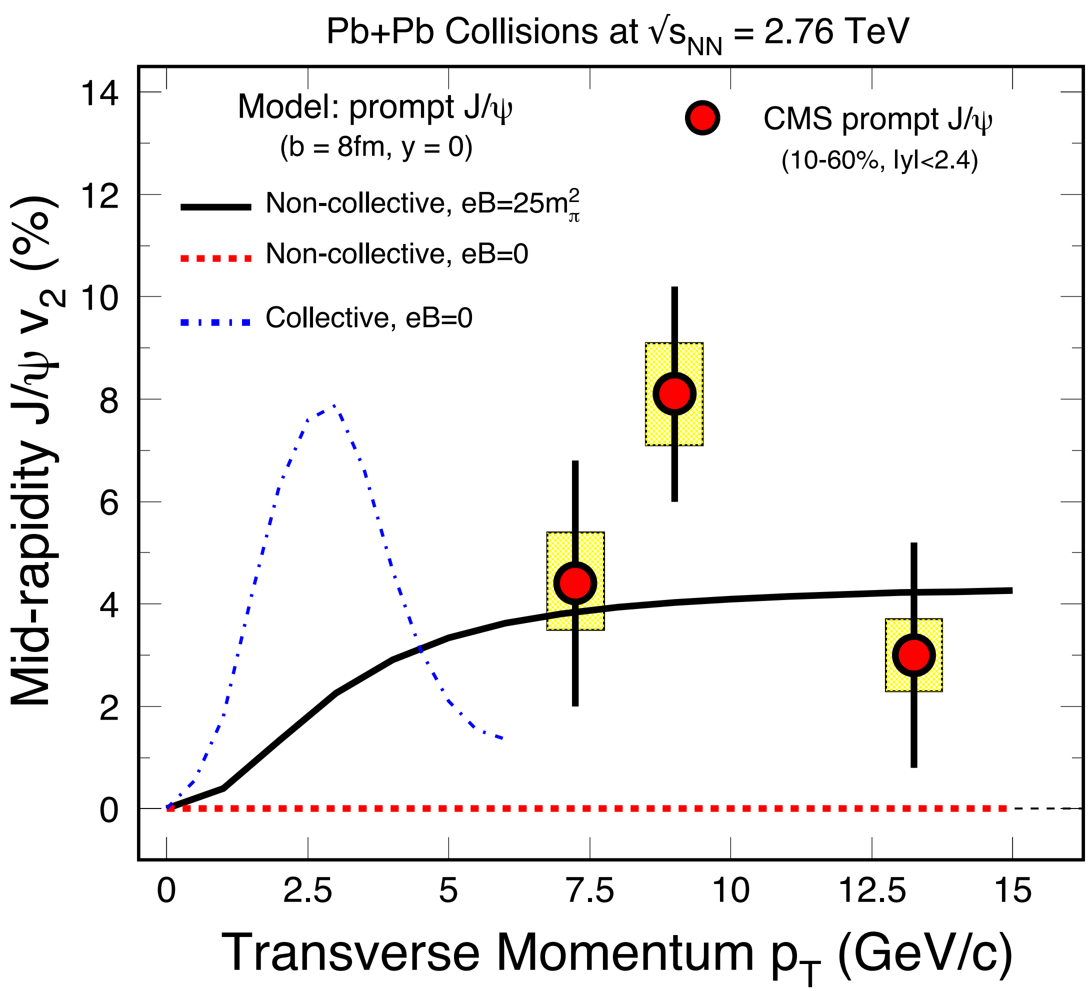


“The Chiral magnetic effect in heavy-ion collisions from event-by-event anomalous hydrodynamics”

Y. Hirono et al., arXiv: 1412.0311 [hep-ph]

Assess the Initial Field

X.Y. Guo, P.F. Zhuang, *et al,* 1502.04407



1) Very strong external magnetic filed at the beginning of the heavy-ion collisions
2) Early production of the high p_T quarkonia are sensitive to the initial field
3) Measurements of the large p_{T}, non-collective v_2 of J/ψ, from Pb+ Pb collisions at LHC, seems consistent
4) Future tests:
   - Upsilon v_2 from LHC
   - Collectivity of J/ψ
   - J/ψ v_2 from RHIC

W.T. Deng and X.G. Huang, Phys. Rev. **C85**, 044907 (2012)
U. Gursoy, D. Kharzeev, K. Rajagopal, Phys. Rev. **C89**, 054905 (2014)

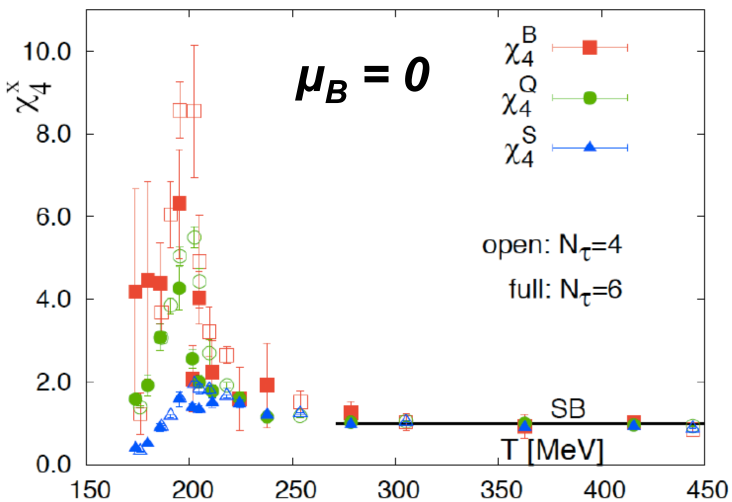
Summary I

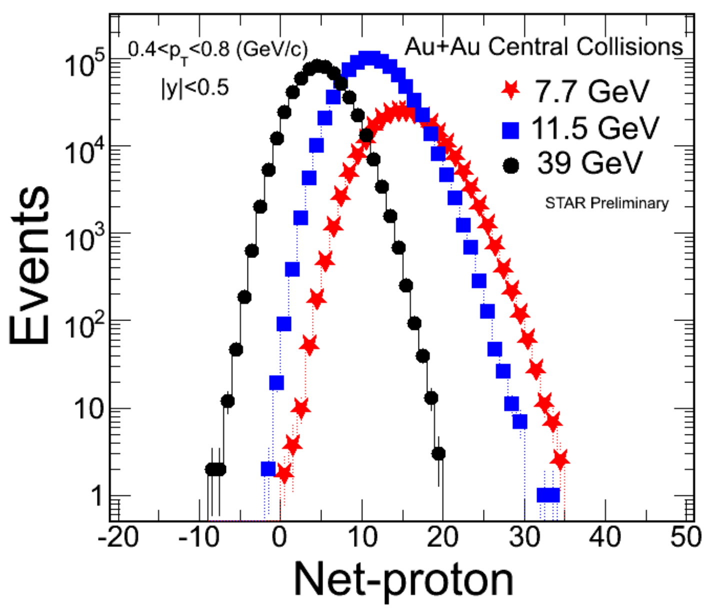
(1) Centrality dependence of the charge separation vs. collision energy consistent with the CME. The effect disappears at low collision energy

(2) Baryon separations observed in Au+Au collisions at 39 and 200 GeV, consistent with CVE

(3) High p_T quarkonia could help to access the initial magnetic field

Higher Moments





1) Higher moments of conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \quad \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

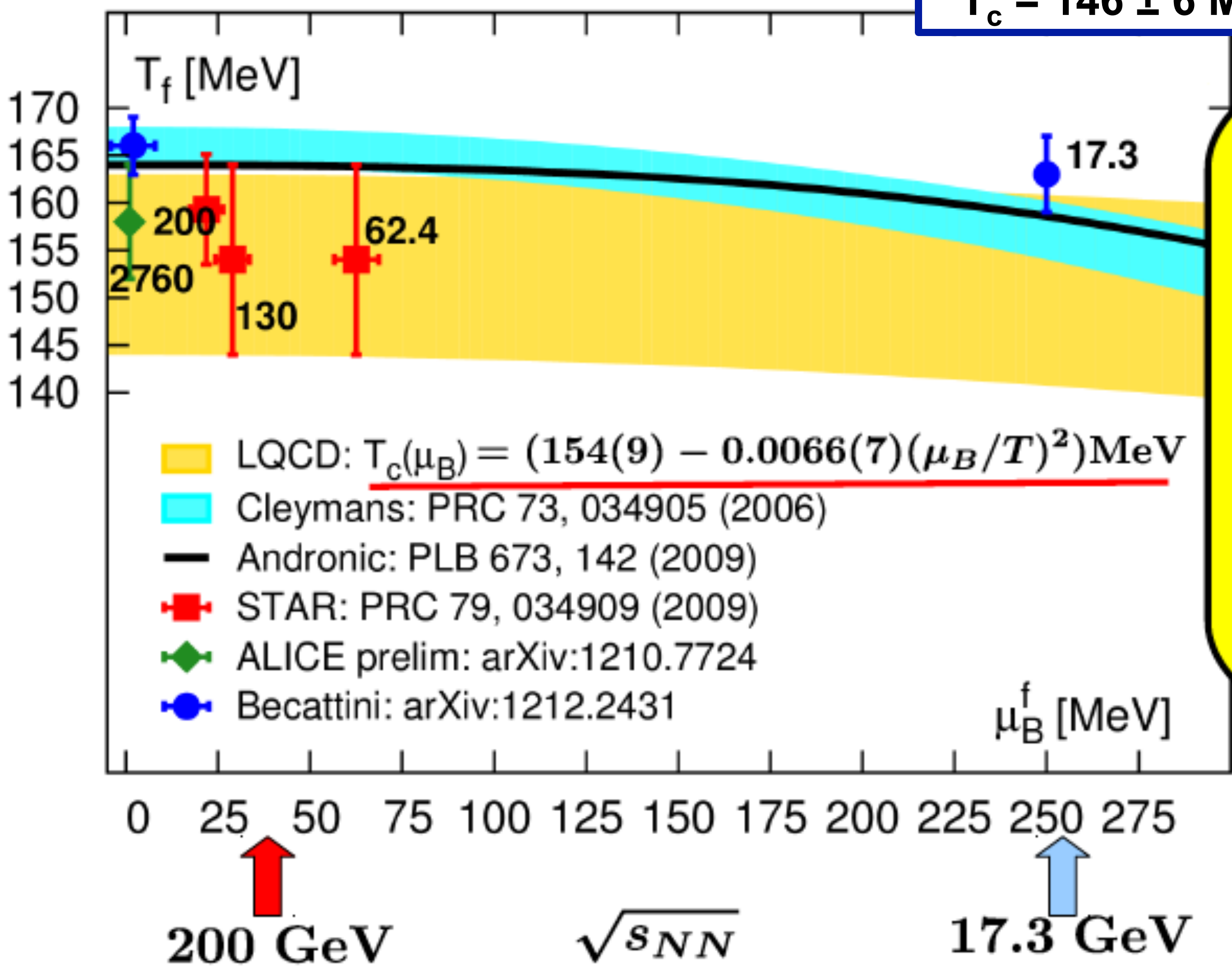
4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

References:

- STAR: ***PRL105***, 22303(10); *ibid*, ***PRL112***, 032302(14)
- M. Stephanov: ***PRL102***, 032301(09) // R.V. Gavai and S. Gupta, **PLB696,** 459(11) // F. Karsch et al, ***PLB695***, 136(11) // S.Ejiri et al, ***PLB633***, 275(06)
- A. Bazavov et al., ***PRL109***, 192302(12) // S. Borsanyi et al., ***PRL111***, 062005(13) // V. Skokov et al., ***PRC88***, 034901(13)

Chiral transition and freeze-out

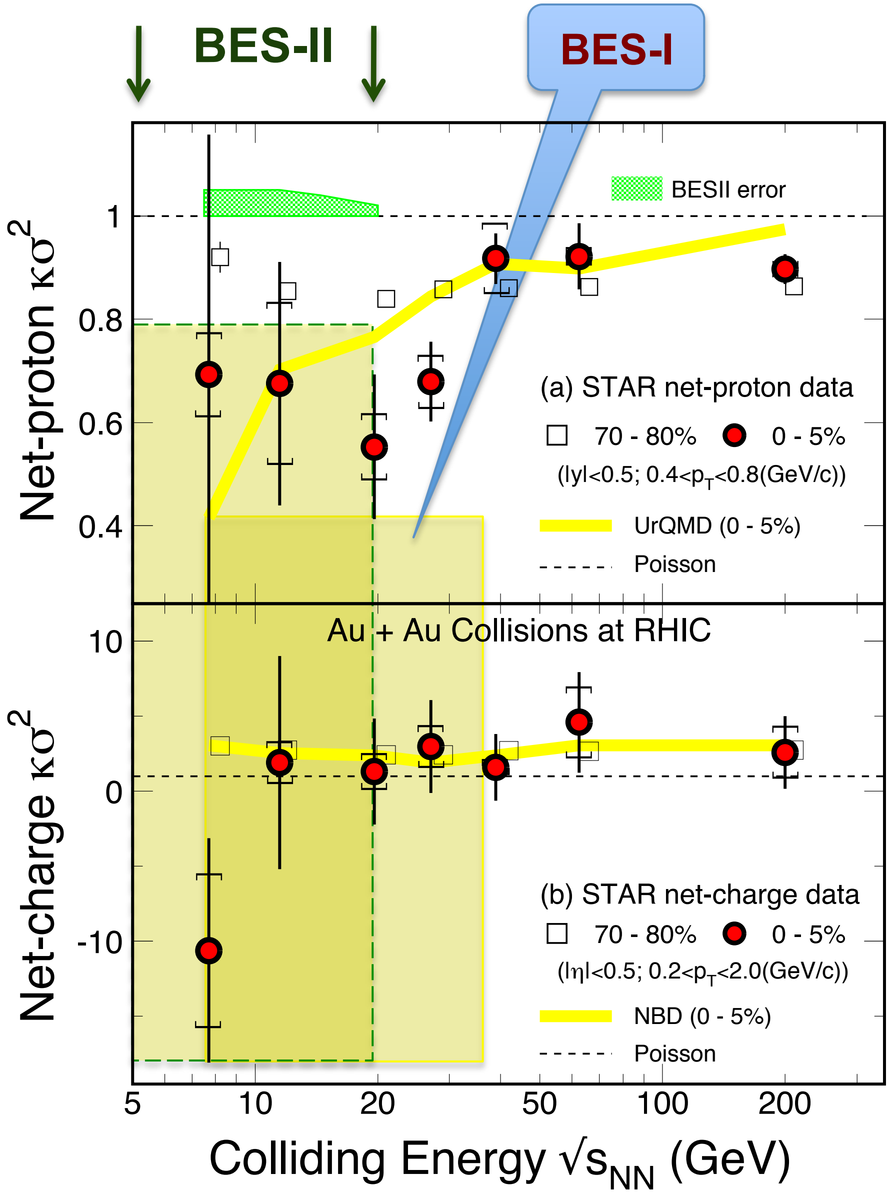
Comparing to LGT calculations
T_c = 146 ± 6 MeV, for $\sqrt{s_{NN}}$ > 39 GeV



phenomenological freeze-out / hadronization curve, QCD transition line and experimental data (obtained by assuming the validity of the HRG model) are consistent for

$$\mu_B/T \lesssim 2$$

Higher Moments Results



Net-proton results:

1) All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$~20GeV
2) UrQMD model shows monotonic behavior in the moment products

*STAR: **PRL112**, 32302(14)*

Net-charge results:

1) No non-monotonic behavior
2) More affected by the resonance decays

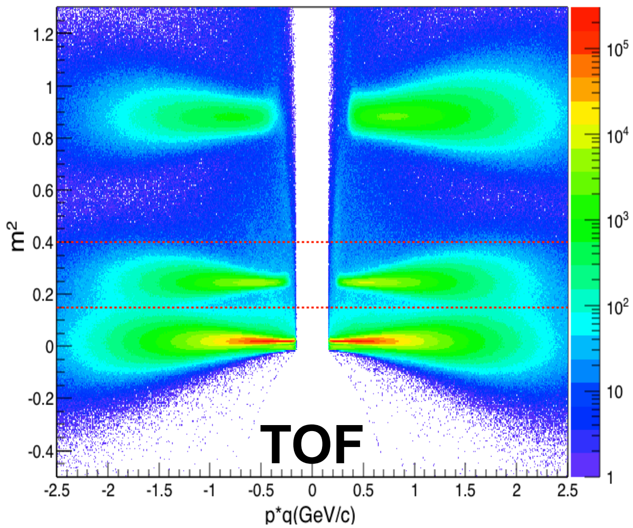
*STAR: **PRL113**, 92301(14)*
P. Garg et al, PLB726, 691(13)

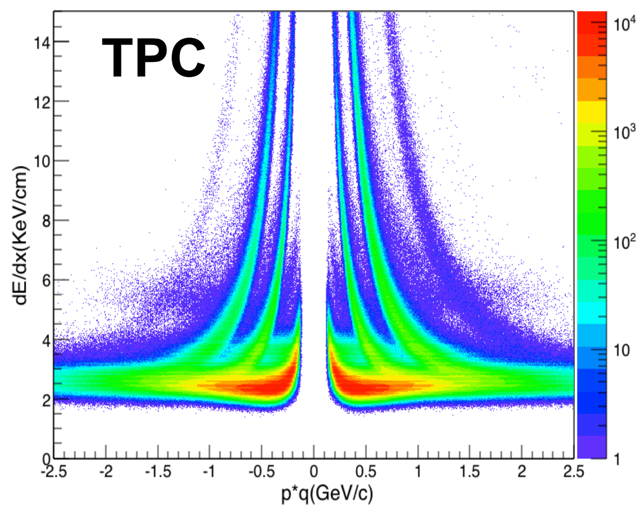
BES-II:

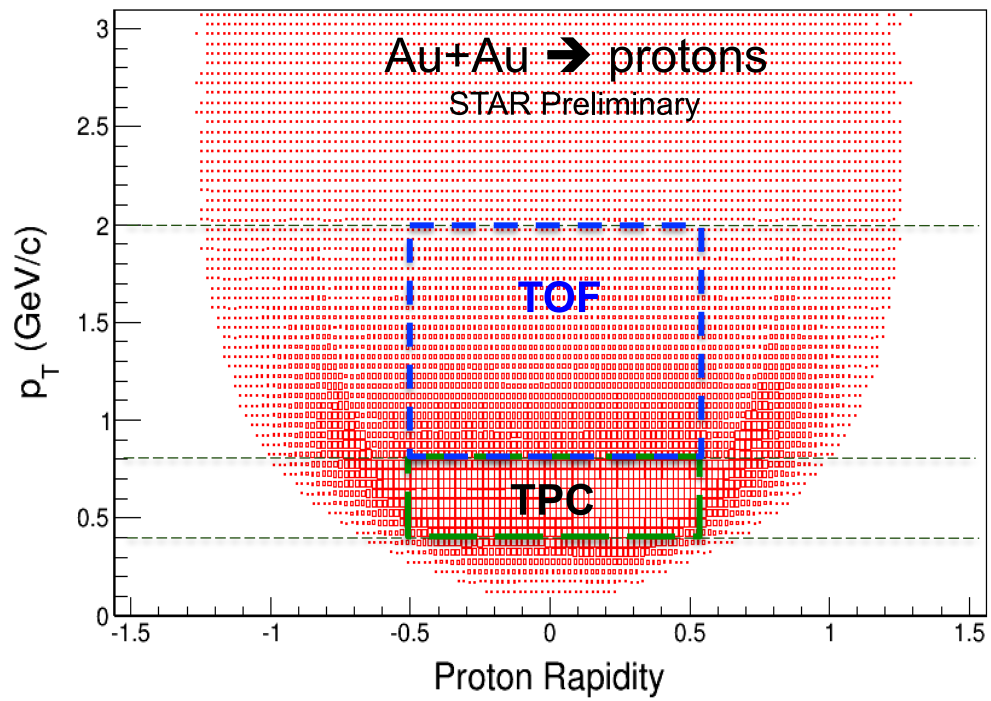
Higher statistics needed for collisions at $\sqrt{s_{NN}}$ < *20 GeV*

Extend Proton Identification with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.







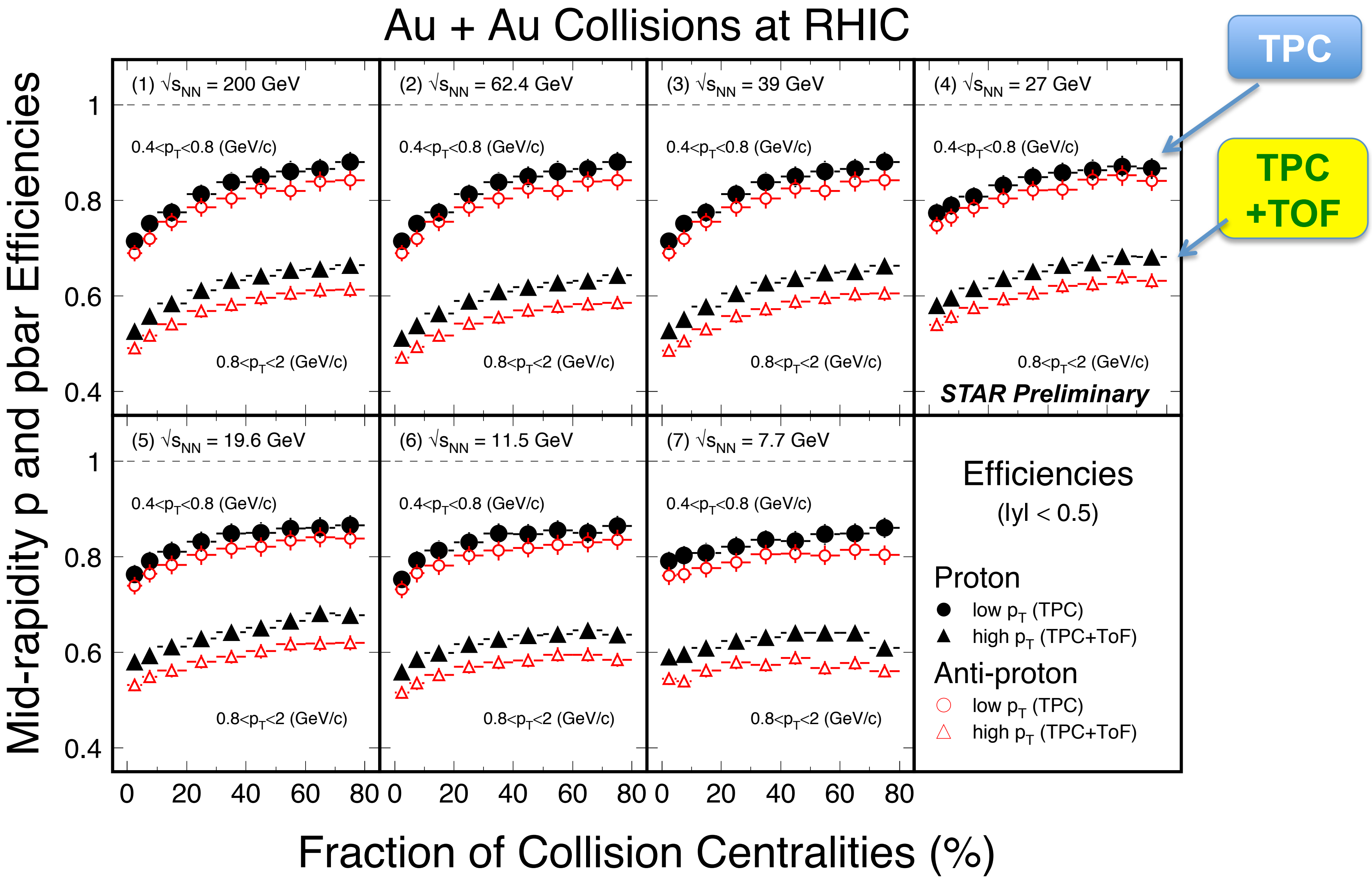
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

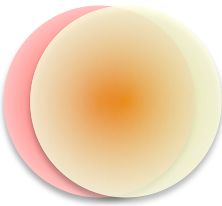
TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): **$\varepsilon_{TPC} \sim 0.8$**

TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

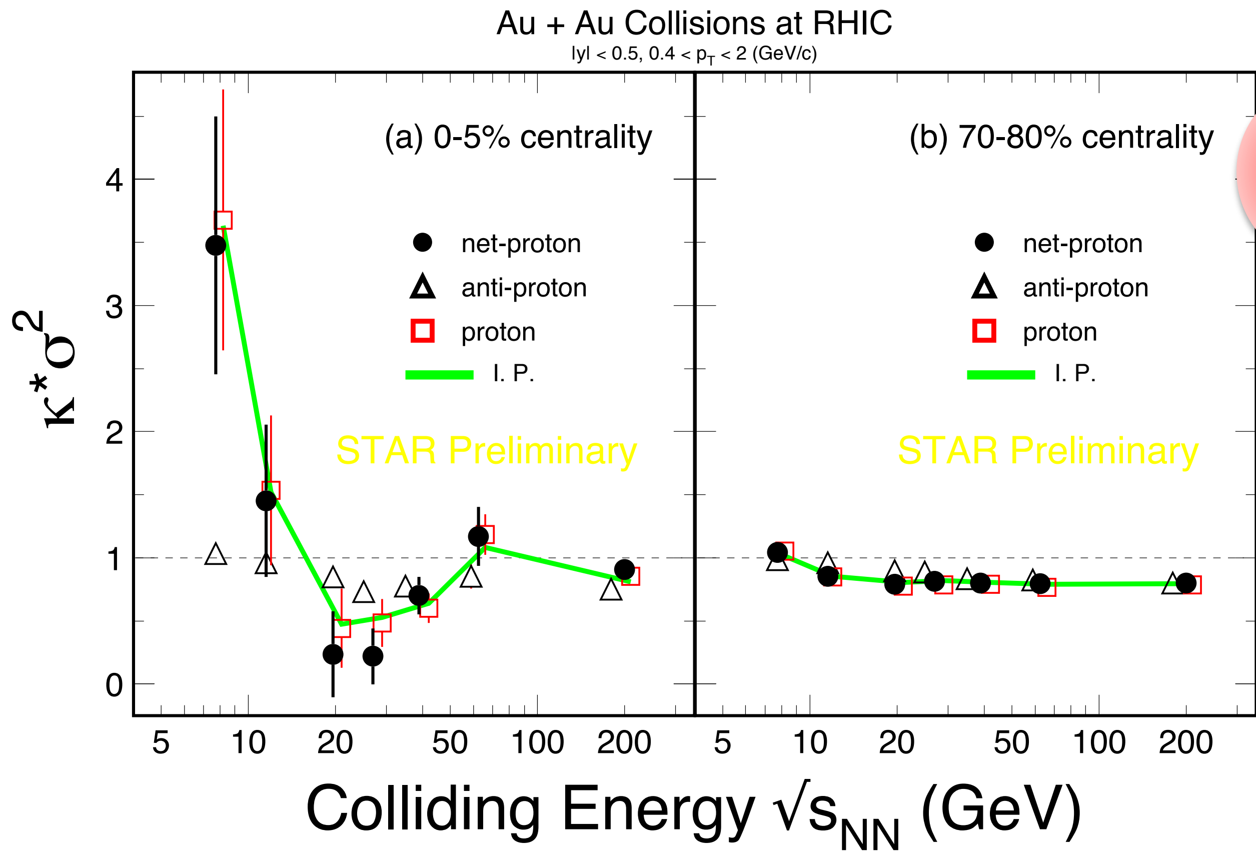
Efficiencies for Protons and Anti-protons

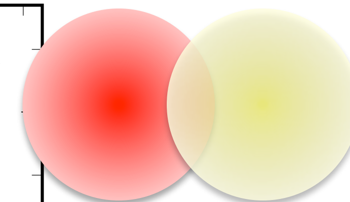


Net-proton Higher Moment



central





peripheral

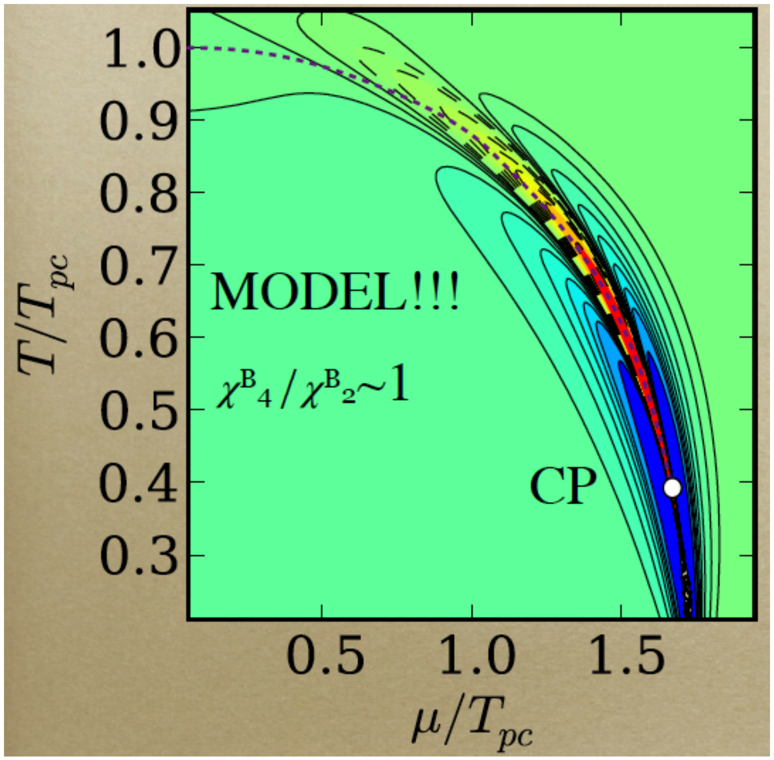
Net-proton results: All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$ ~ 20 GeV.

Non-monotonic behavior in central collision! *X.F. Luo, CPOD2014*

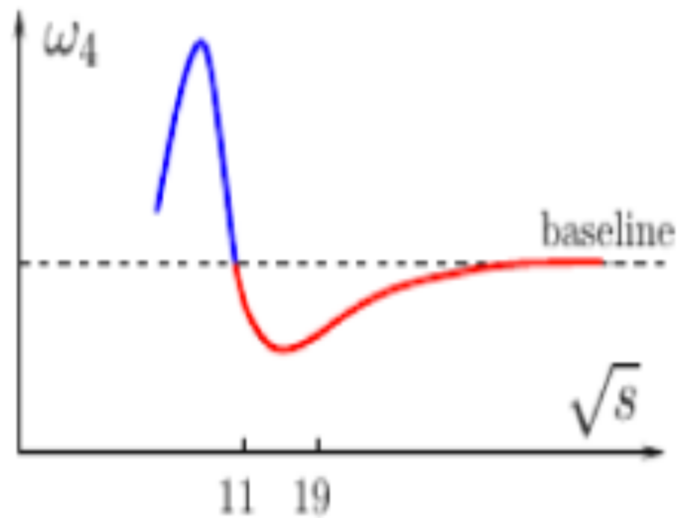
Question: What will happen at even lower collision energy?

Expectation from Calculations

V. Skokov, Quark Matter 2012

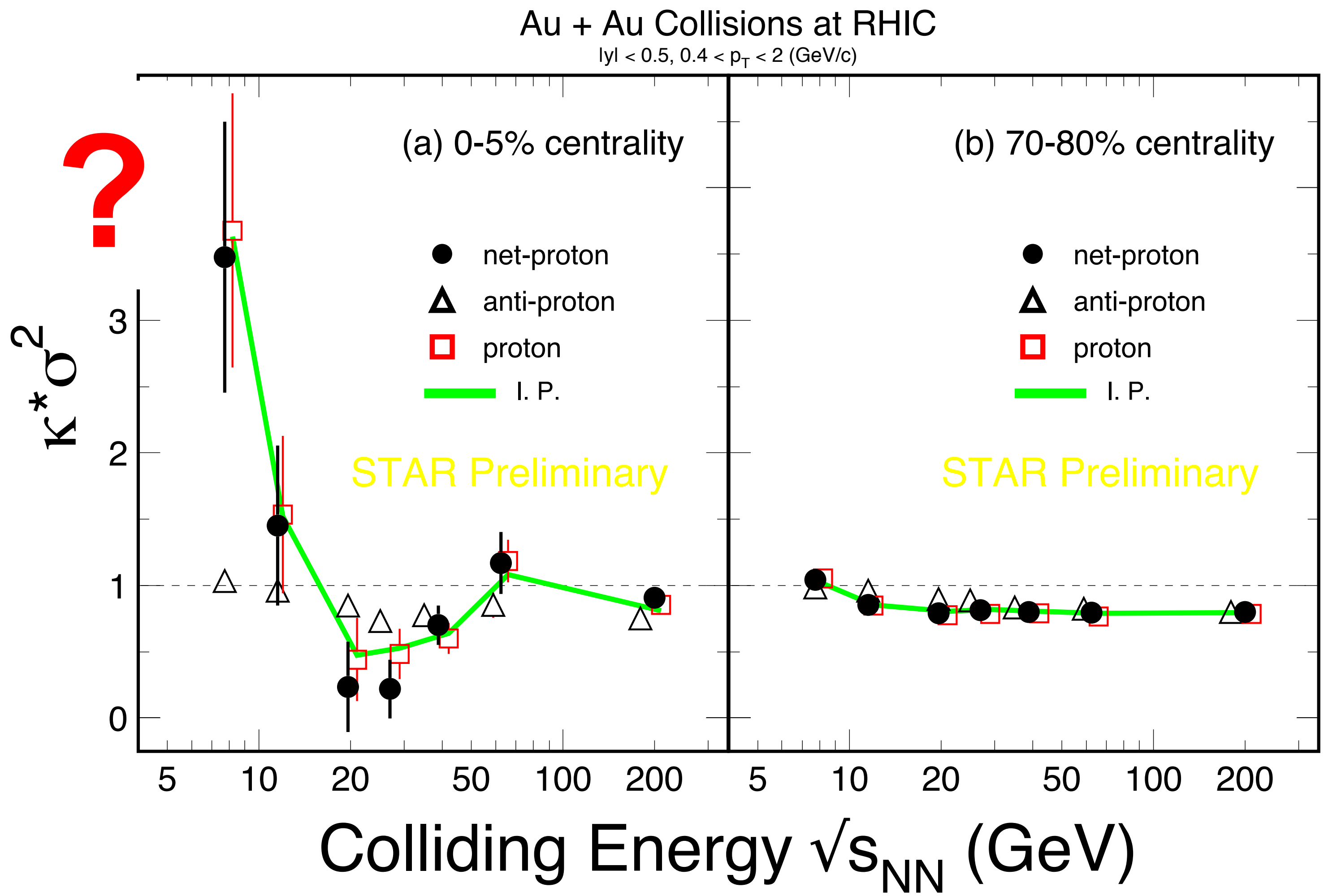


M. Stephanoc, ***PRL107***, 052301(2011)



"Oscillating pattern" around the reference is expected.

Net-proton Higher Moment



Question: What will happen at even lower collision energy?

Summary-II

1) Net-proton high order moments show **non-monotonic behavior** in 5% central Au+Au collisions

2) RHIC BES-II: focus at $\sqrt{s_{NN}} \leq 20$ GeV region
run19 and 20: RHIC e-cooling upgrade, luminosity increase ~10
STAR detector upgrade iTPC+RPD

3) STAR HFT physics analysis have started

Best wishes from Feng Liu, Daicui Zhou, et al., CCNU

Happy Birthday, Johanna!