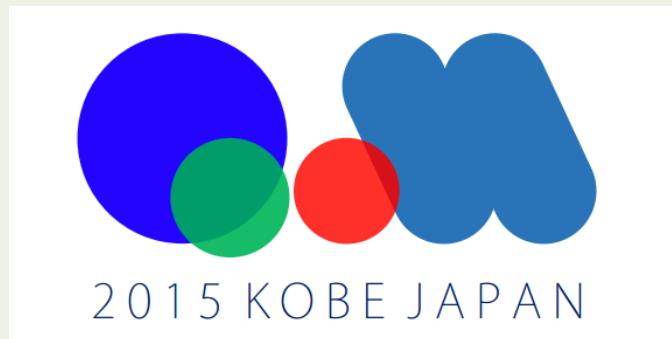


Exploring the QCD Phase Structure with Beam Energy Scan in Heavy-ion Collisions



Xiaofeng Luo (罗晓峰)

Central China Normal University, Wuhan
Oct. 1st, 2015



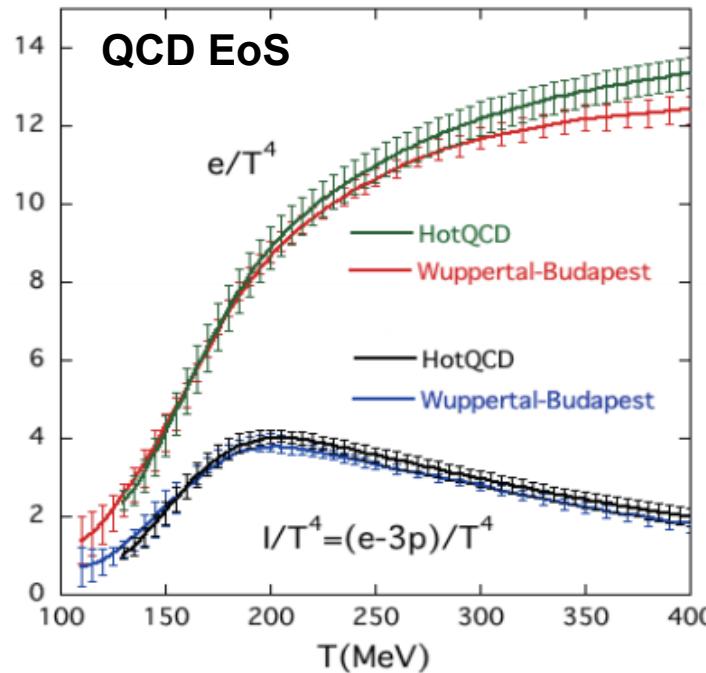


Outline

- **Introduction**
- **Experimental Facility**
- **Selected Experimental Highlights**
- **Summary**

QCD Thermodynamics ($\mu_B=0$)

Akira Ukawa, arXiv:1501.04215

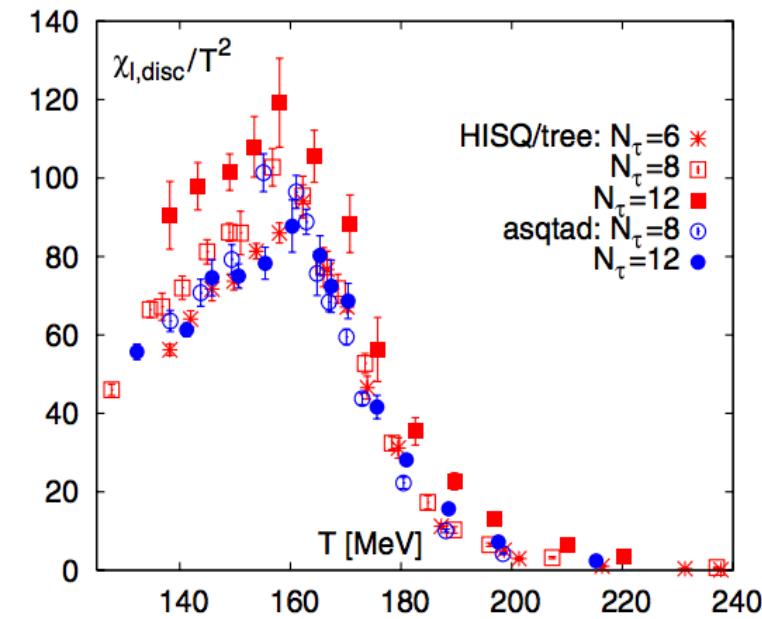


QCD EoS : Major goals in LQCD since 1980s,
Different groups approach similar conclusion.

Rapid rise of the energy density:

- Rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons.
- Smooth crossover transition.

WuppertalBudapest, JHEP 1009, 073 (2010).
HotQCD, Phys.Rev. D85, 054503 (2012).



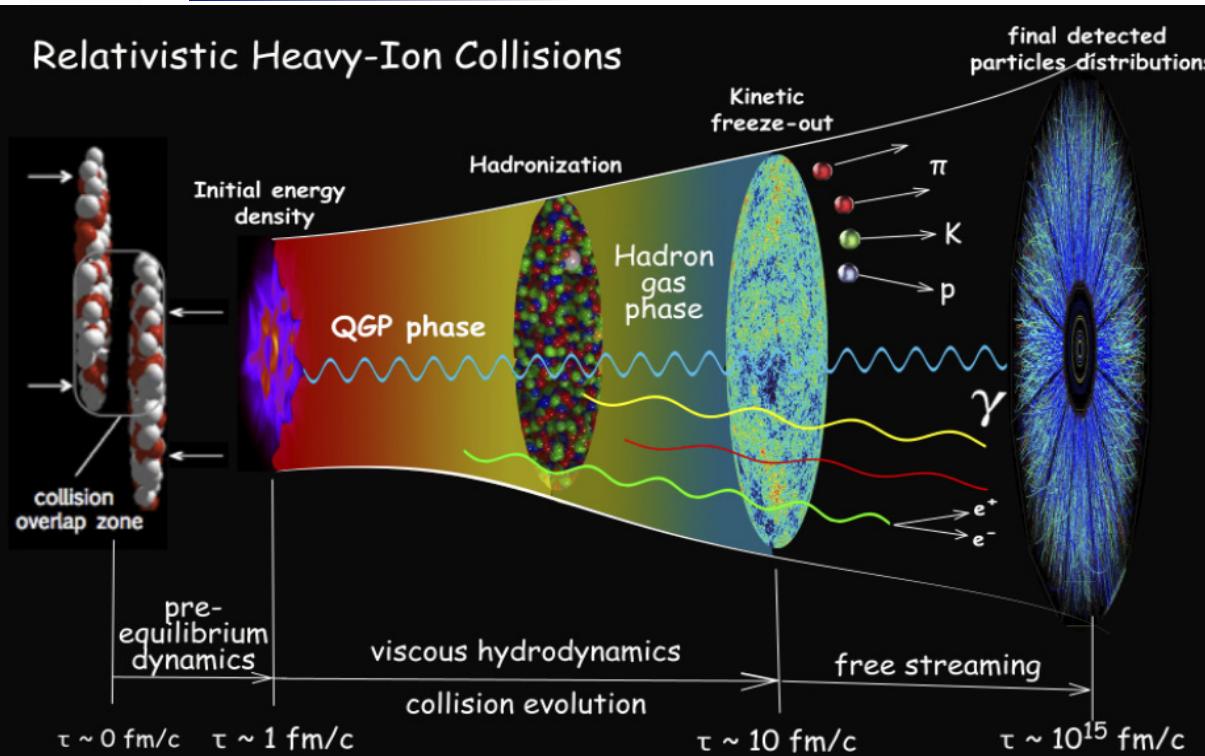
Chiral susceptibility peaks at T_c :

$$\chi_{\bar{\Psi}\Psi} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial m^2}$$

Chiral symmetry restoration:
temperature: $T_c \sim 154 \pm 9$ MeV

Little Bang

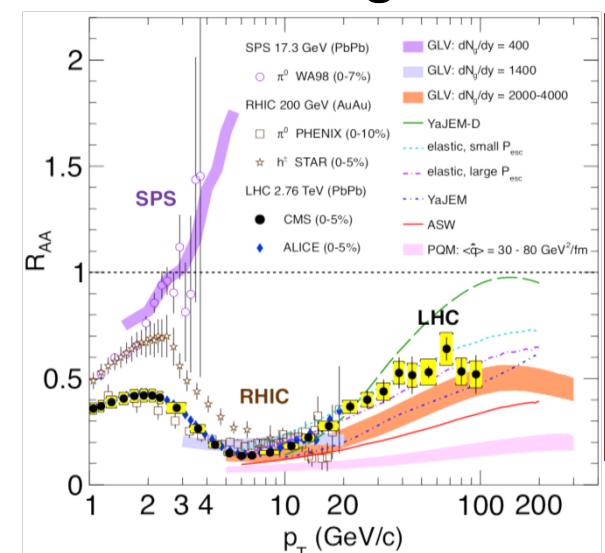
Relativistic Heavy-Ion Collisions



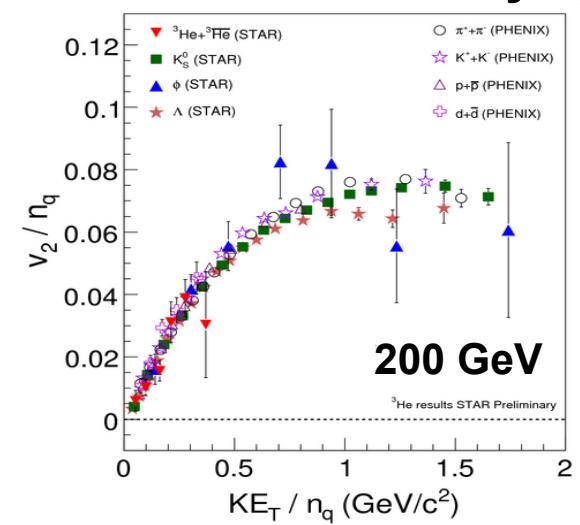
Courtesy of Paul Sorensen and Chun Shen

- QGP and phase diagram studied in high energy collisions of nuclei since 1987 at **AGS (5 GeV)**, 1996 at **SPS (17 GeV)**, since 2000 at **RHIC (200 GeV)**, since 2010 at the LHC at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$.
- Indirect evidences for strongly couple and liquid like QGP formed in high energy nuclear collisions.

Jet Quenching



Partonic Collectivity v_2

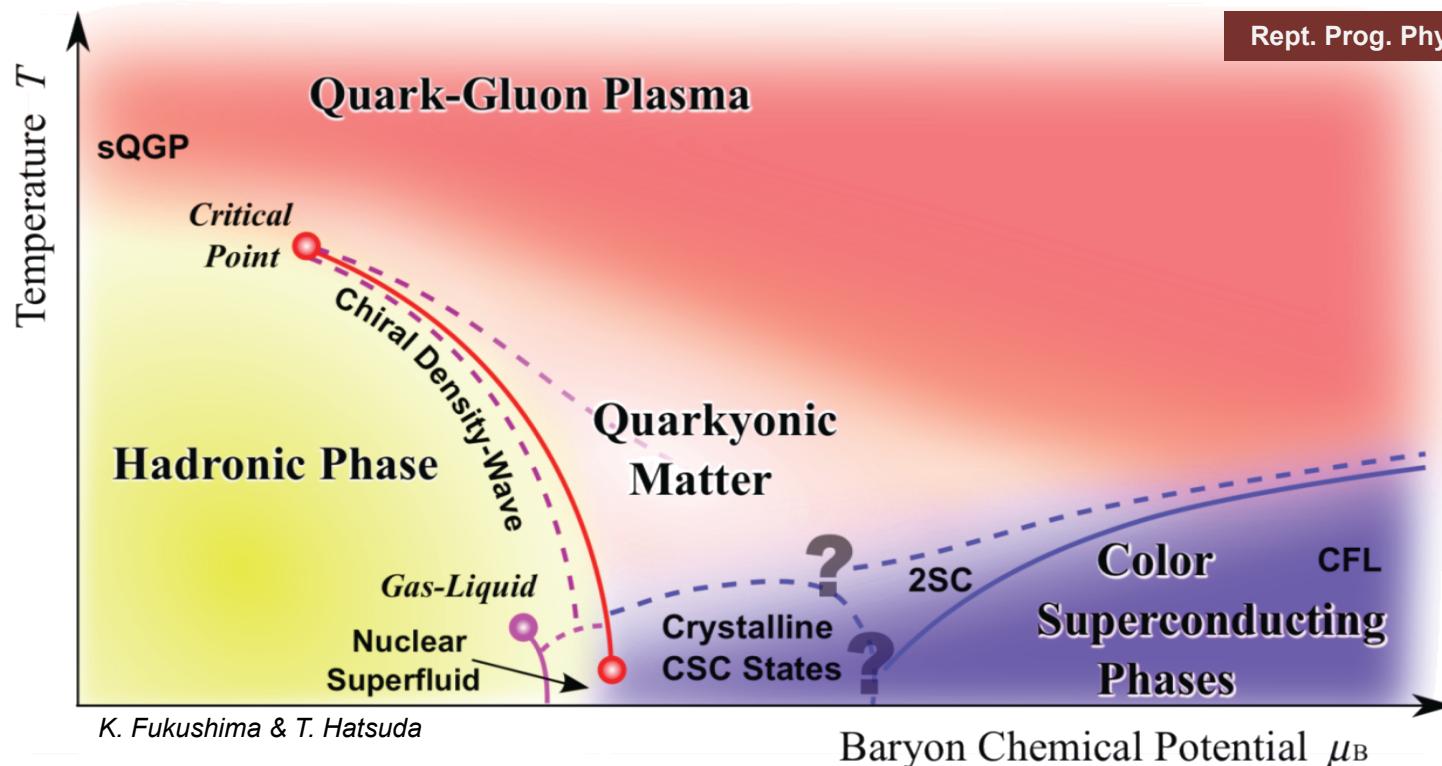




It is time to study the QCD Phase Structure !

The QCD Phase Diagram

Rept. Prog. Phys. 74 (2011).

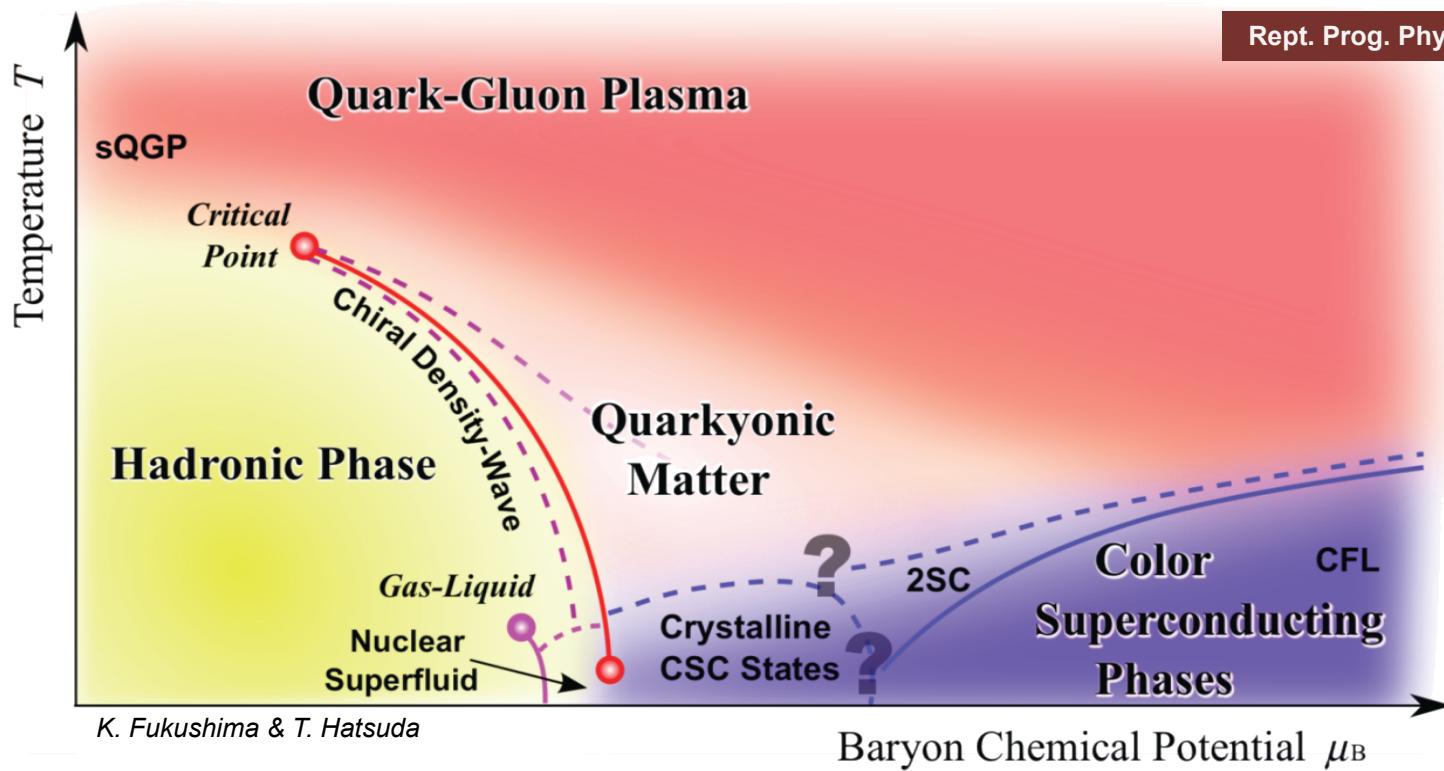


1. Properties of QGP ?: T dependence, at $\mu_B \sim 0$, of EoS, η/s , q^\wedge , etc.
2. Turning off the QGP signals and/or onset of deconfinement at low energies ?
3. 1st order phase boundary and QCD critical point ?
4. Quarkyonic phase at high baryon density ? Triple point ?



The QCD Phase Diagram

Rept. Prog. Phys. 74 (2011).



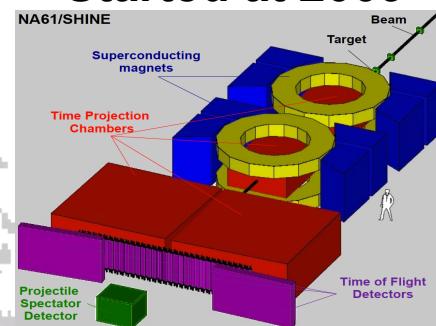
Emergent Properties of QCD !



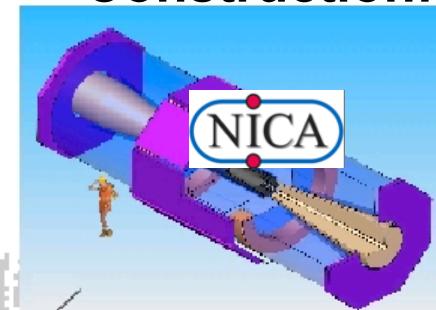
Experimental Facility for the Beam Energy Scan

NA61/SPS

Started at 2009



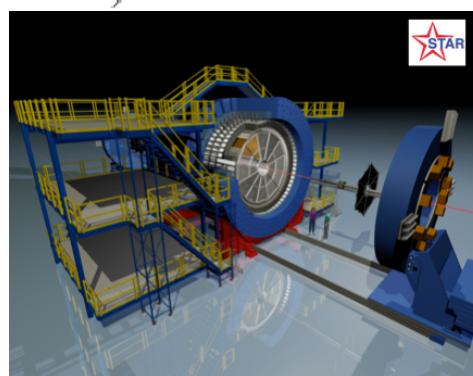
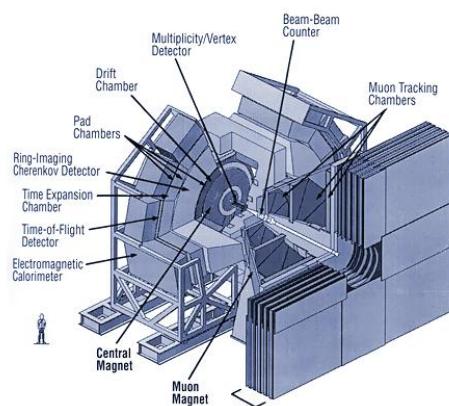
Construction....



Fix target
 $\sqrt{s_{NN}} = 5\text{-}17 \text{ GeV}$

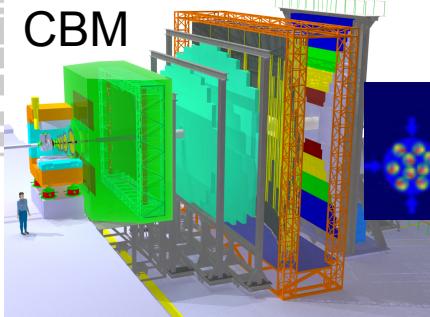
RHIC Beam Energy Scan

BES-I (2010-2014) is complete.



Collider $\sqrt{s_{NN}} = 7.7\text{-}200 \text{ GeV}$

Construction....



The Compressed Baryonic Matter experiment

Fix target

$\sqrt{s_{NN}} = 2\text{-}8 \text{ GeV}$

The Beam Energy Scan Program at RHIC and SPS

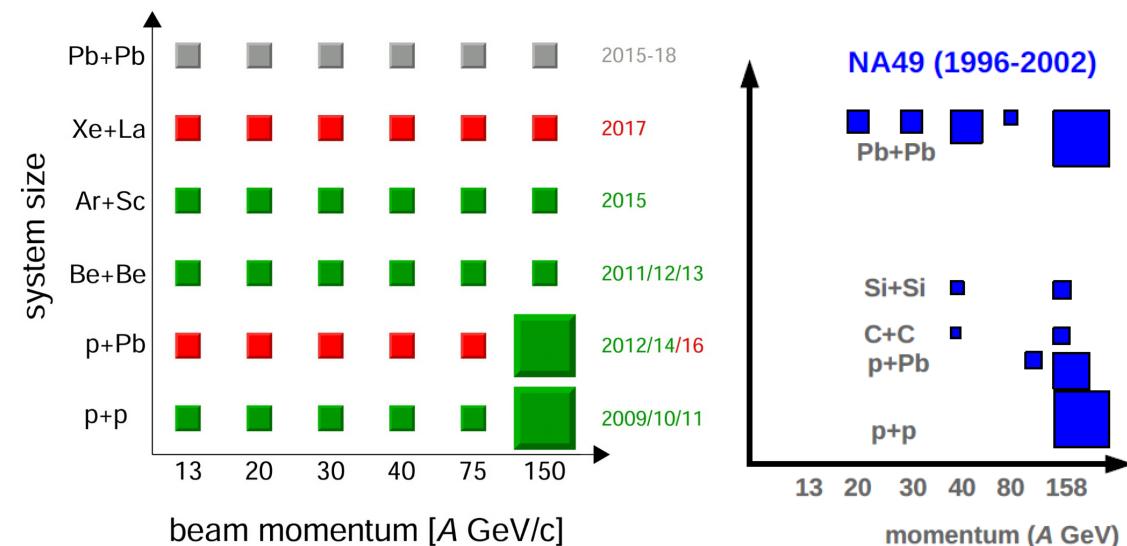
**RHIC: STAR and PHENIX (Collider)
Au+Au Collisions**

\sqrt{s} (GeV)	Statistics(10^6)	μ_B (MeV)
7.7	~4	420
11.5	~12	315
14.5	~ 20	266
19.6	~36	205
27	~70	155
39	~130	115
62.4	~67	70
200	~350	20

arXiv:1007.2613

<https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493>

<https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598>



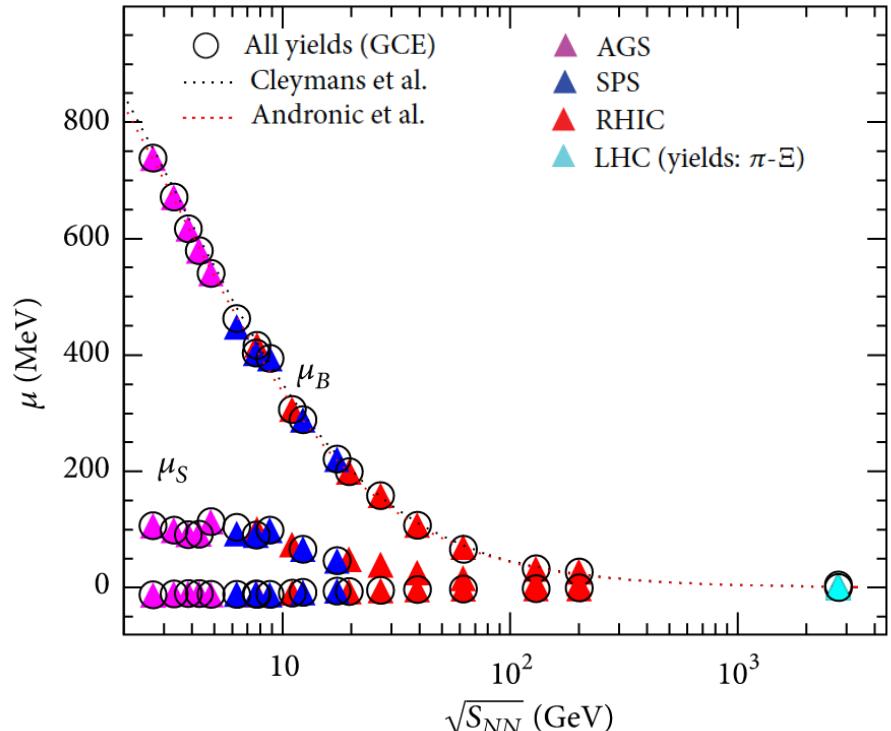
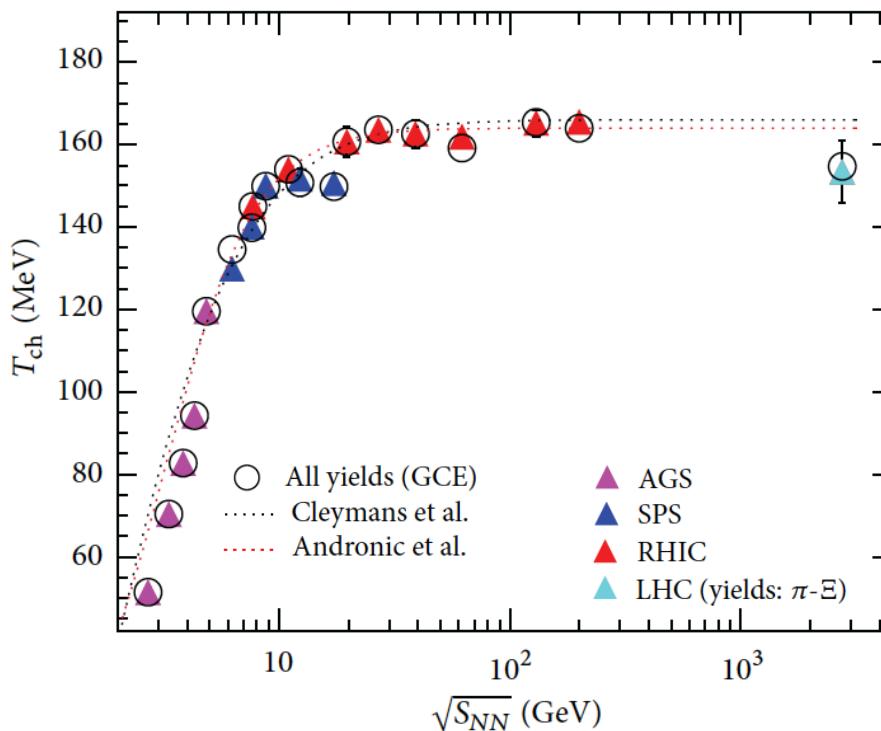
$$\sqrt{s}_{NN} = 5-17 \text{ GeV}$$

JINST 9 (2014) P06005 [arXiv:1401.4699]

Finish Ar+Sc collisions in 2015

Exploring the QCD phase structure by varying the collision energy and/or system size to change temperature and baryon chemical potential.

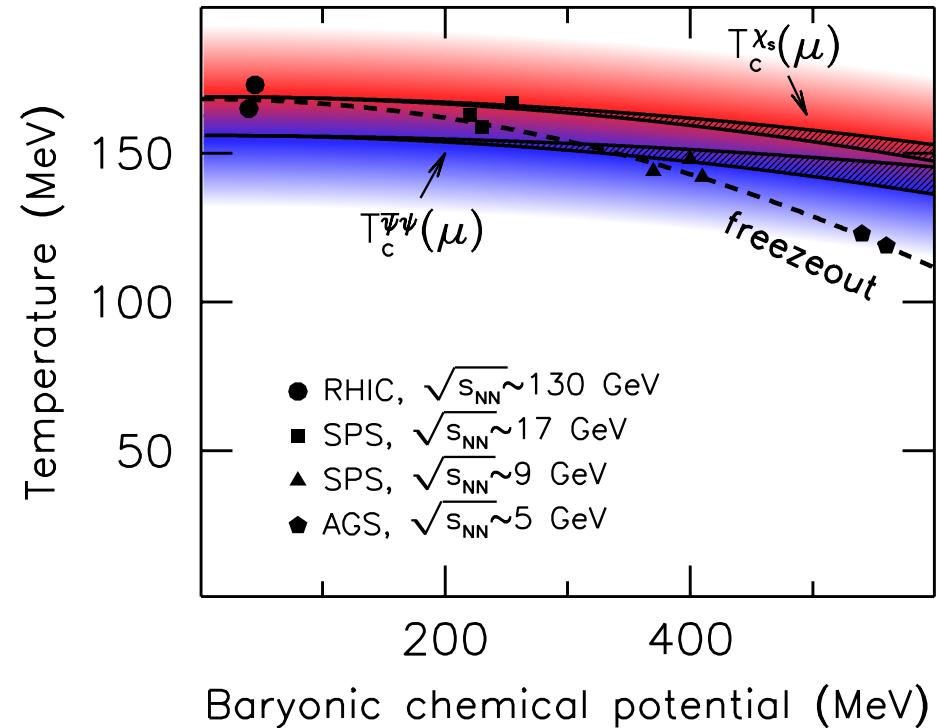
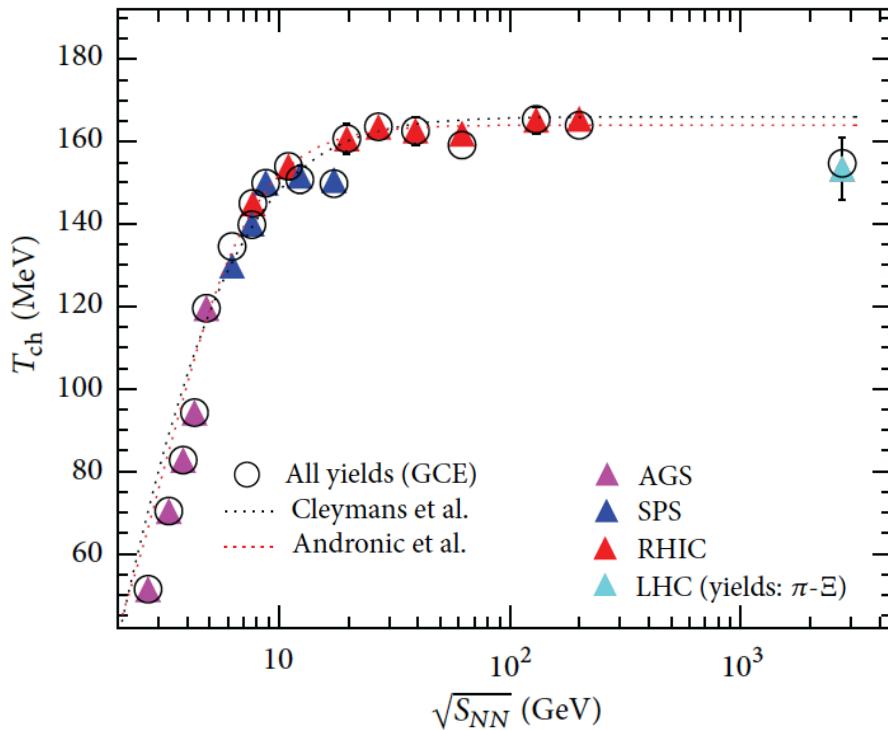
Chemical Freeze Out



Vipul, Wed, 9:40 am, [492]
 Lokesh Kumar, QM2014

- T_{ch} increase with energy and saturate above ~ 10 GeV ($T_{lim} \sim 160$ MeV, depict the phase boundary ($\mu_B < 300$ MeV)? How about higher baryon density region ?) PBM and Johanna, arXiv: 1101.3167

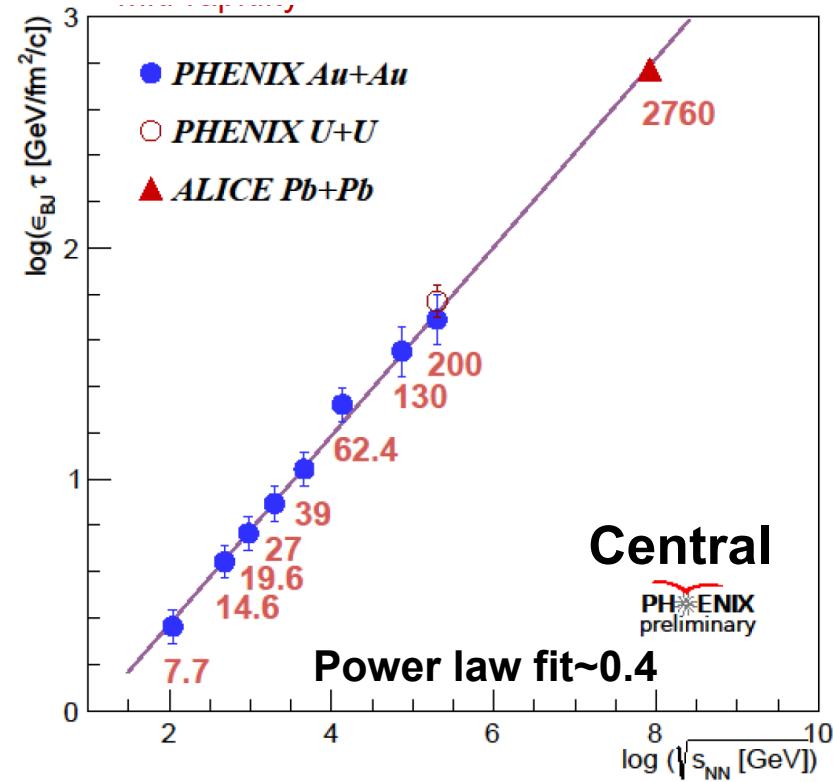
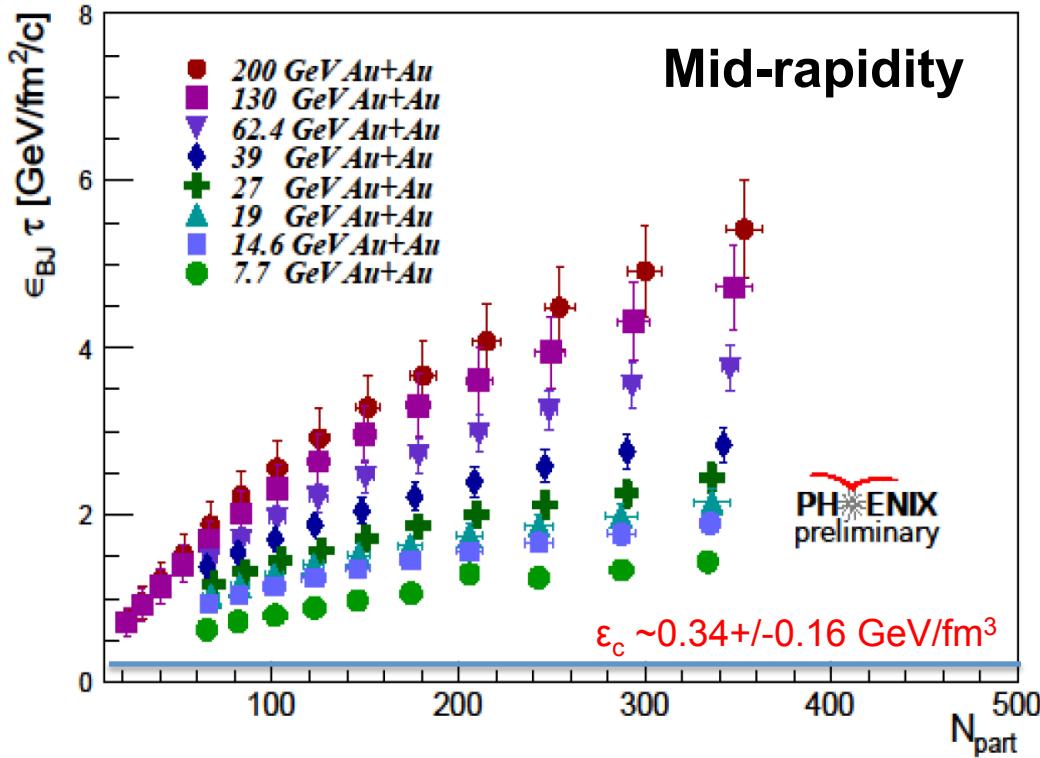
Chemical Freeze Out: Close to the Transition Lines



JHEP 1104 (2011) 001

- T_{ch} increase with energy and saturate above ~ 10 GeV ($T_{lim} \sim 160$ MeV, depict the phase boundary ($\mu_B < 300$ MeV)? How about higher baryon density region ?) PBM and Johanna, arXiv: 1101.3167

Initial Energy Density



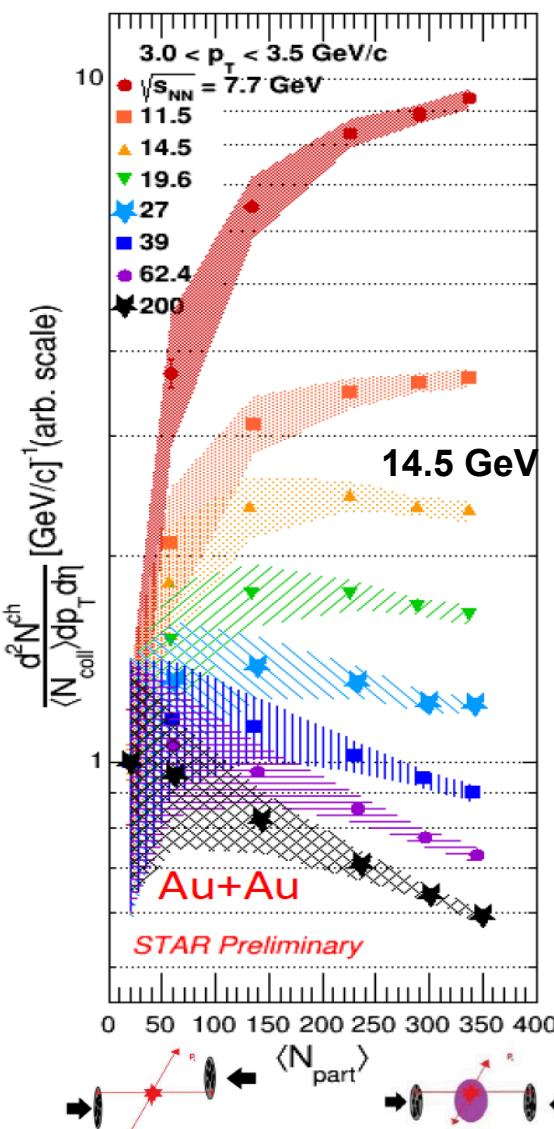
Bjorken Energy Density: $\epsilon_{BJ} = \frac{1}{A_{\perp} \tau} \frac{dE_T}{dy}$

PHENIX, Jeffery T. Mitchell, CPOD2014.
ALICE data, arXiv:1106.6324

Caveat: 1. Boost invariant may not hold at low energy. 2, The critical energy density here is estimated at $\mu_B=0$, may be different at large μ_B (>300 MeV).

From lattice, critical $\epsilon_c = 0.34 \pm 0.16 \text{ GeV}/\text{fm}^3$: lowest energy 7.7 GeV still likely to be above transition region. A. Bazavov et al. (hotQCD), Phys. Rev. D90 (2014) 094503

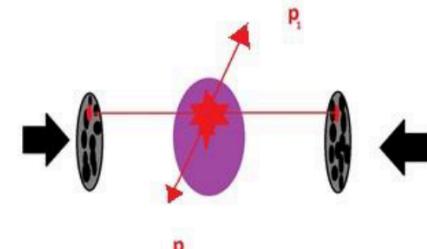
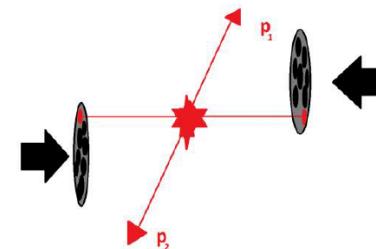
Charged Particle Yield Per Binary Collisions



Au + Au
Peripheral

Au + Au
Central

$$S(N_{\text{part}}) = \left(\frac{d^2N}{N_{\text{coll}} dp_T d\eta} \right)_{\text{high-}p_T \text{ bin}}$$

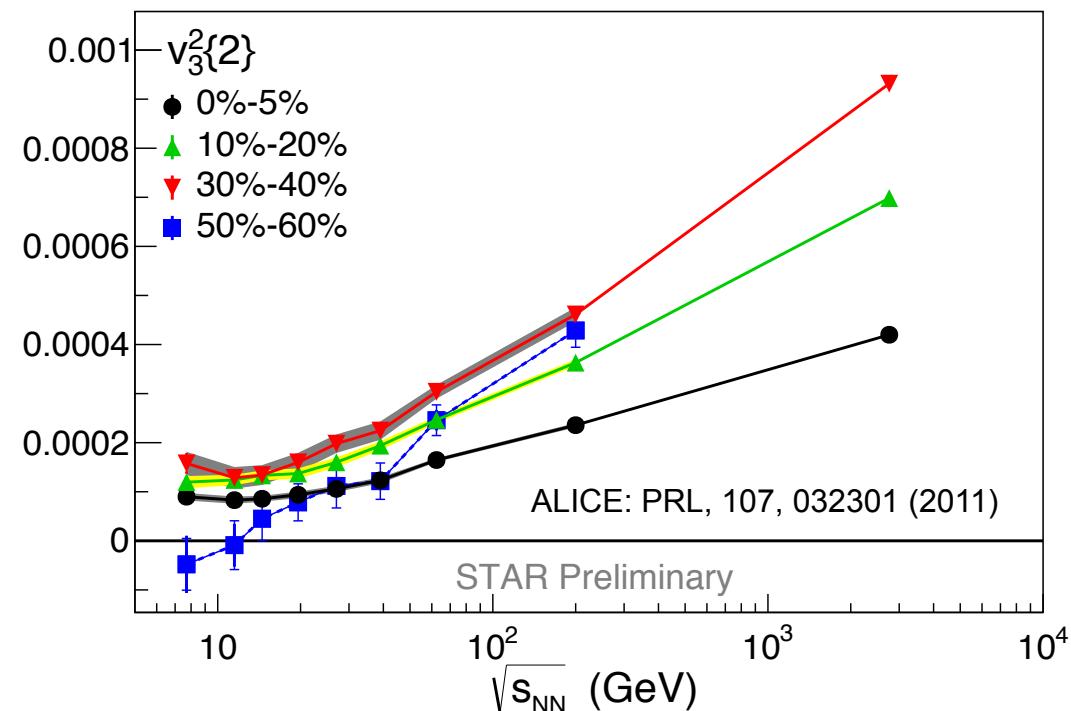
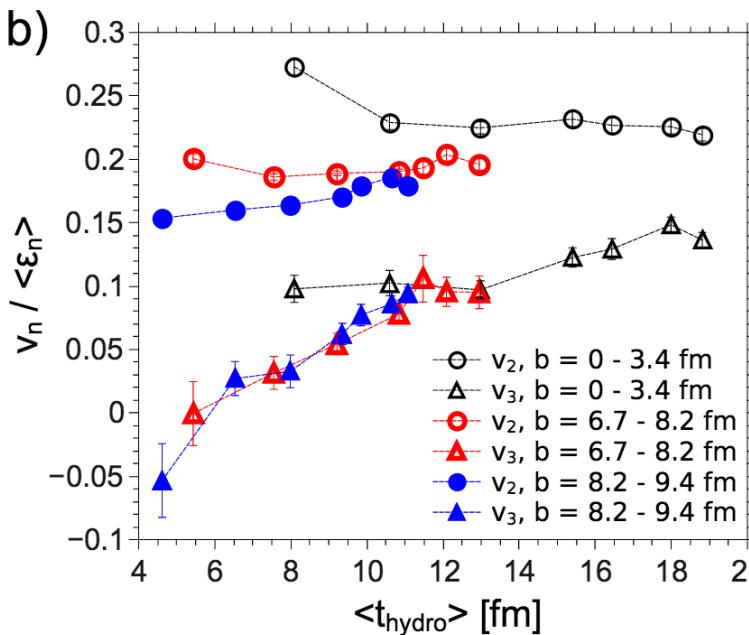
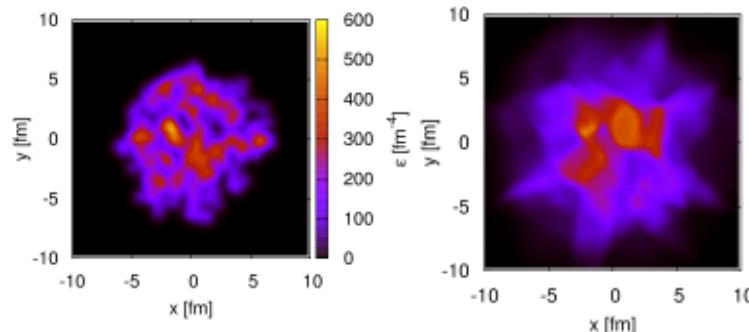


Enhancement : Cronin, Radial Flow etc.
 Suppression: Jet Quenching

- Sensitive to quenching and provides possible evidence for where a QGP **is** formed.
- Central data are suppressed for energy above 14.5 GeV. This does not rule out the formation of a QGP at lower energies than 14.5 GeV.

S. Horvat, Baryon Rich QCD Matter (323)

Triangle Flow v_3



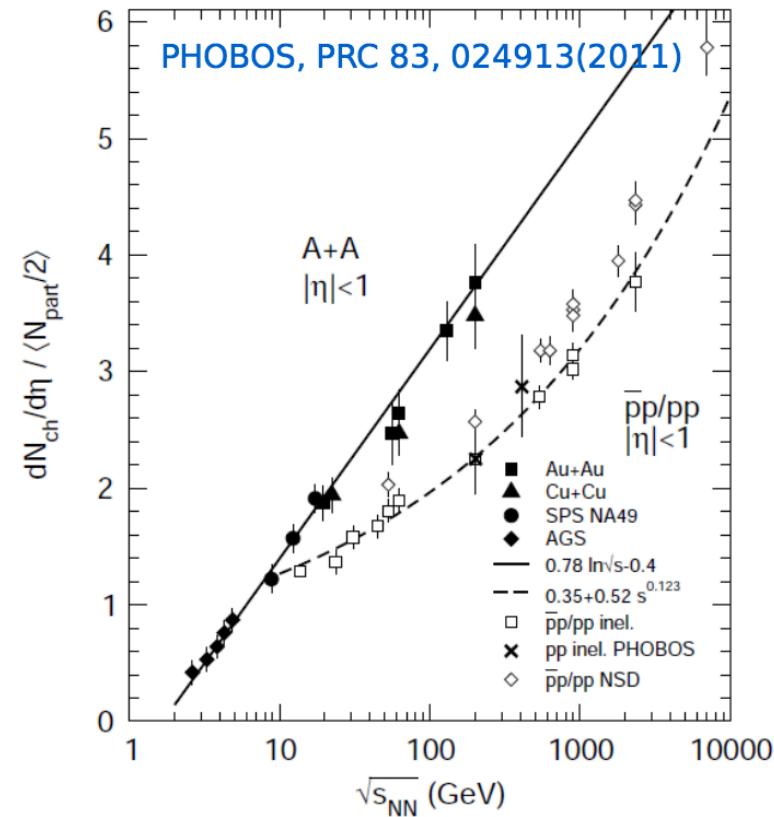
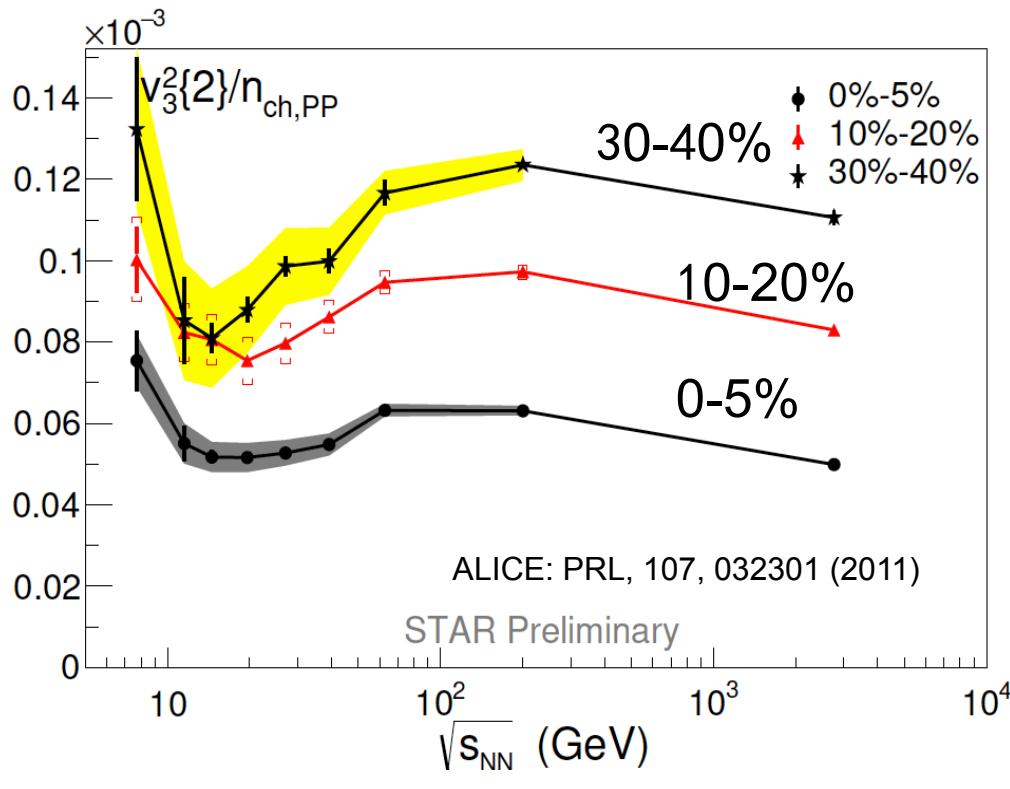
Liao Song, Tue, 14:40 pm, [258]

Steven Horvat, Wed, 11:00am, [323]

- Require low η/s early QGP phase to transfer initial fluctuations to a significant v_3 .
- v_3 vanishes for peripheral collisions at lowest RHIC BES energy.

J. Auvinen and H. Petersen, Phys. Rev. C88, 397 (2013).

v_3^2 Scaled by Energy Density

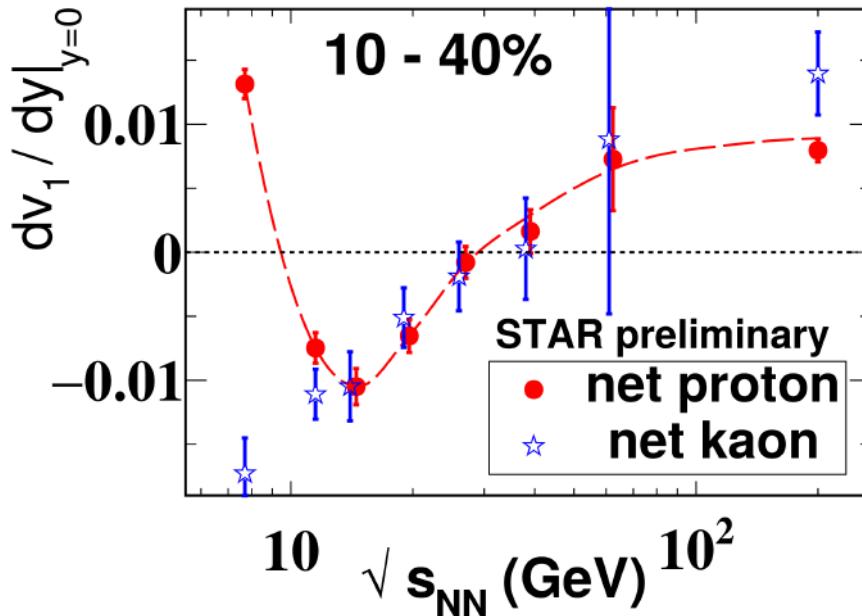


$$n_{ch,PP} = (2/N_{part}) dN_{ch}/d\eta \quad \text{Estimation for energy density}$$

- Minimum are observed for centralities bins in 0-50% collisions for $v_3^2/n_{ch,pp}$.
- Softening of EoS ?

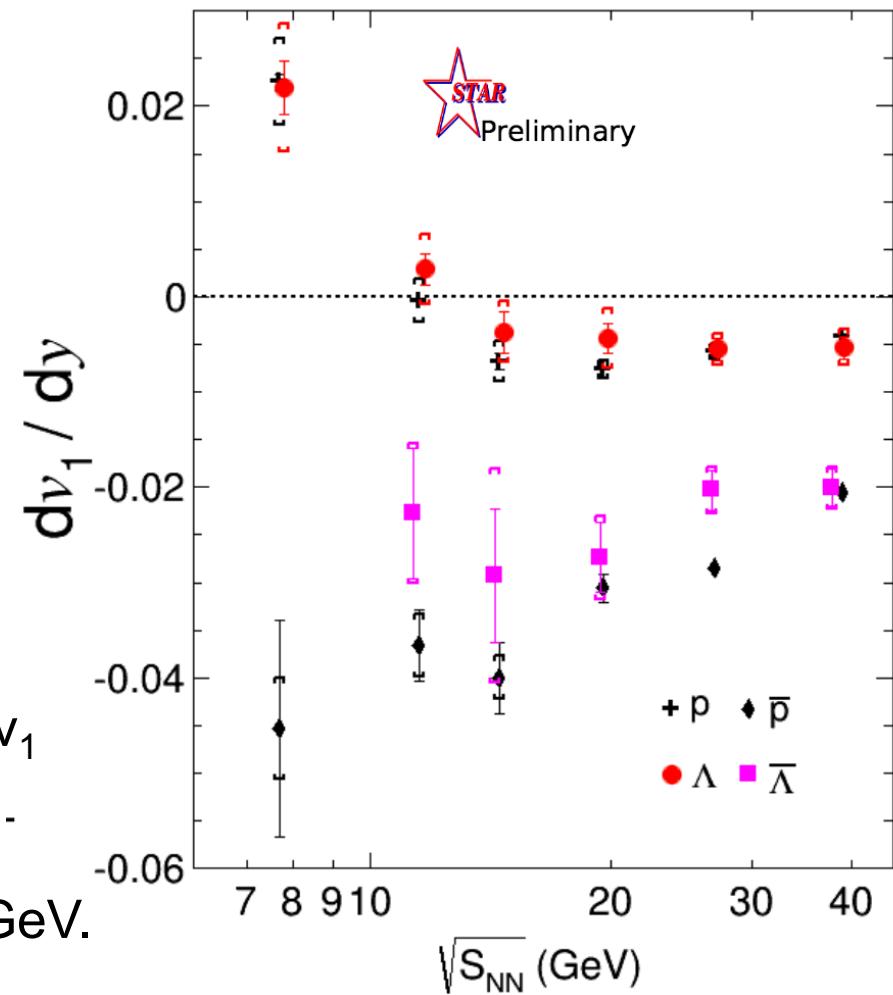
Liao Song, Tue, 14:40 pm, [258]

Directed Flow v_1



Net-proton v_1 : STAR, PRL 112, 162301 (2014);

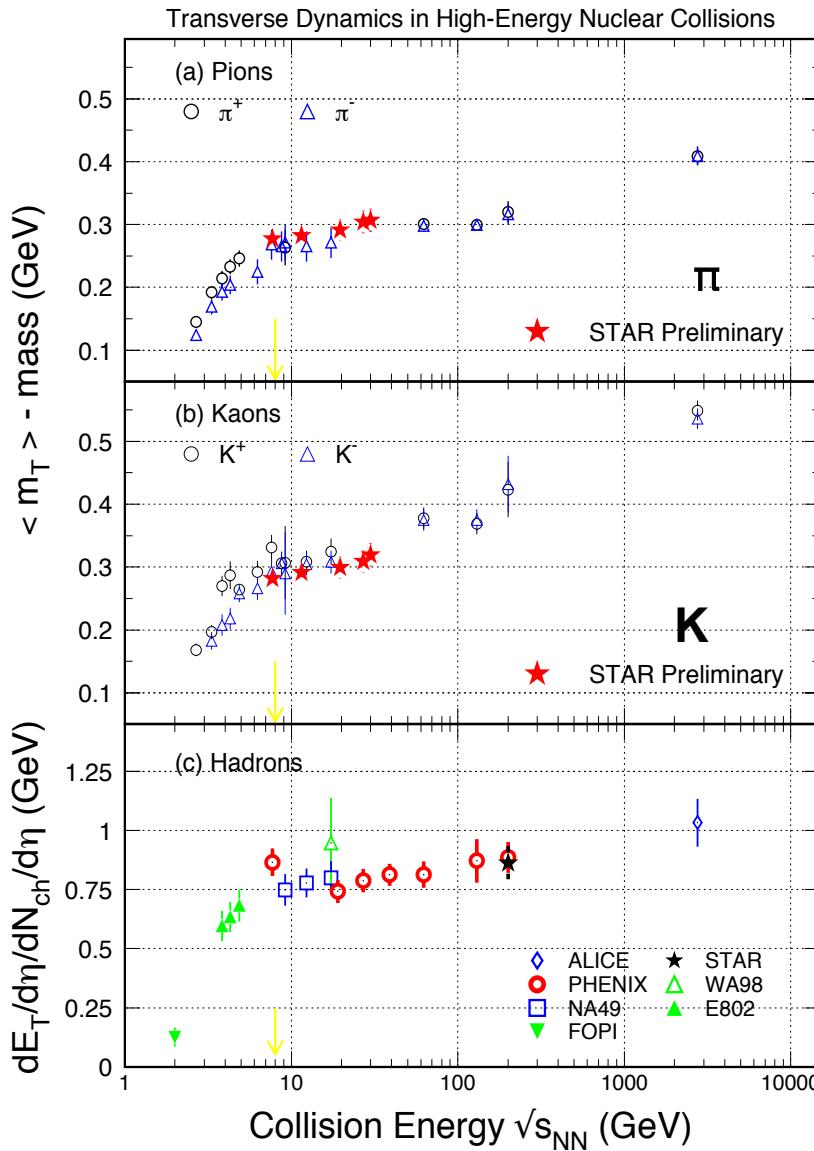
- Non-monotonic behavior in net-proton v_1 indicate 1st order phase transition ?
- Split of net-p and net-K v_1 below 14.5 GeV.



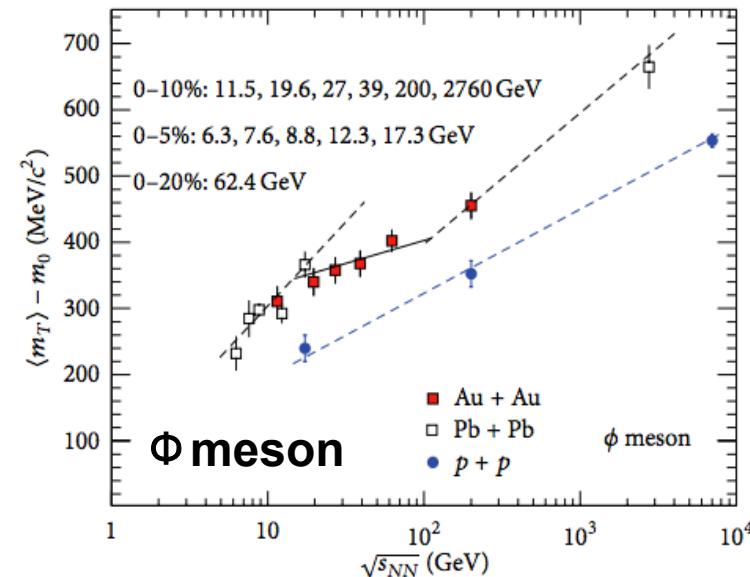
H. Stoecker, Nucl. Phys. A 750, 121 (2005).
D.H. Rischke et al. HIP1, 309(1995)
J. Steinheimer et al., arXiv:1402.7236
P. Konchakovski et al., arXiv:1404.276

Prashanth Shanmuganathan,
Tue, 9:20am, [398]

Transverse Dynamics



NA49: Phys. Rev. C 78, 4 (2008), Physics Lett. B 491, 59 (2000).
 STAR: Phys. Rev. C 49, 064903 (2009).
 ALICE: Phys. Rev. C91, 024609 (2015).
 M. Nasim et al., Advances in High Energy Physics, 197930 (2015).



- Excitation function of particle $\langle m_T \rangle - m_0$ and transverse energy/mul. show a flat pattern above ~ 8 GeV.

L. van Hove, PLB 118, 138 (1982).

- Indication of 1st order phase transition ?

Fit spectra: $1/m_T dN/dm_T \sim \exp(-m_T/T)$.

Temperature: $\langle m_T \rangle - m_0 \sim T$

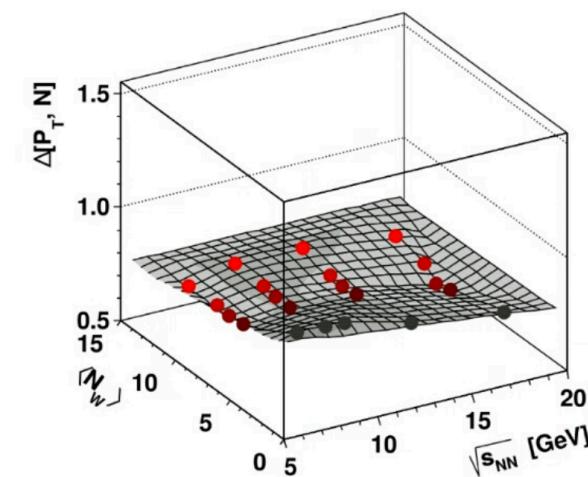
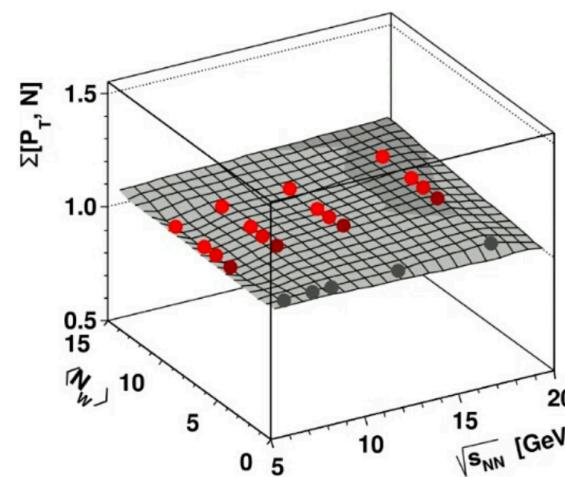
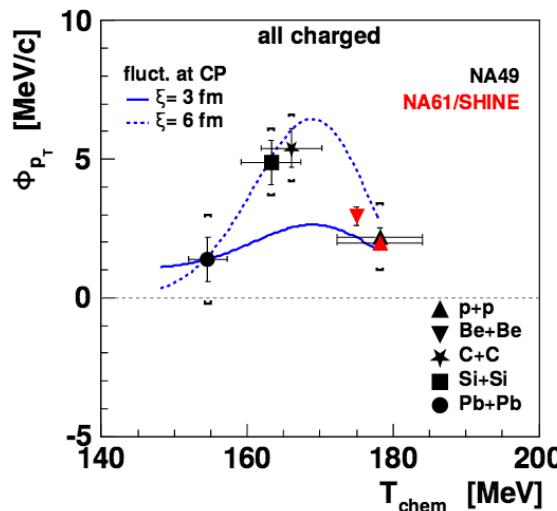
Entropy: $dN/d\eta \sim \log(\sqrt{s_{NN}})$.

Search for the Criticality

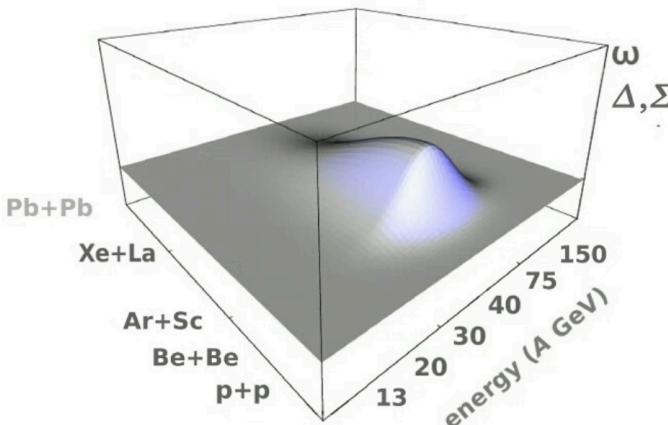
- Strongly intensive measure and p_T fluctuations – NA49/NA61.
- Finite Size Scaling analysis for HBT Radii.
- Fluctuations of Conserved Quantities: Net-Q, Net-S, Net-B.

Fluctuations measure from NA49/NA61: 2D Scan

SPS: Scan Nuclear Mass and Collision Energy (2D Scan)



Strongly intensive measure: p+p and Be+Be



$$\Delta^{P_T, N} = \frac{1}{C_\Delta} [\langle P_T \rangle \omega(N) - \langle N \rangle \omega(P_T)]$$

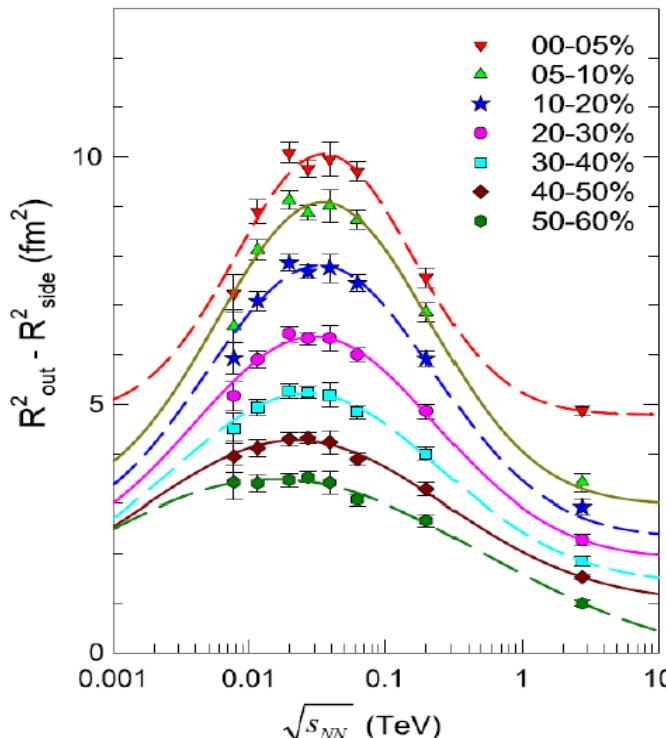
$$\Sigma^{P_T, N} = \frac{1}{C_\Sigma} [\langle P_T \rangle \omega(N) + \langle N \rangle \omega(P_T) - 2(\langle N \cdot P_T \rangle - \langle N \rangle \langle P_T \rangle)]$$

Gorenstein, Gazdzicki, Phys.Rev. C84 (2011) 014904
Gazdzicki, et al., Phys.Rev. C88 (2013) 024907

No clear evidence of CP signal.

Maja Ma ckowskiak-Pawlowska, Mon., 17:00 pm

HBT Radii: Finite Size Scaling



R.Lacey, PRL114,142301(2015)

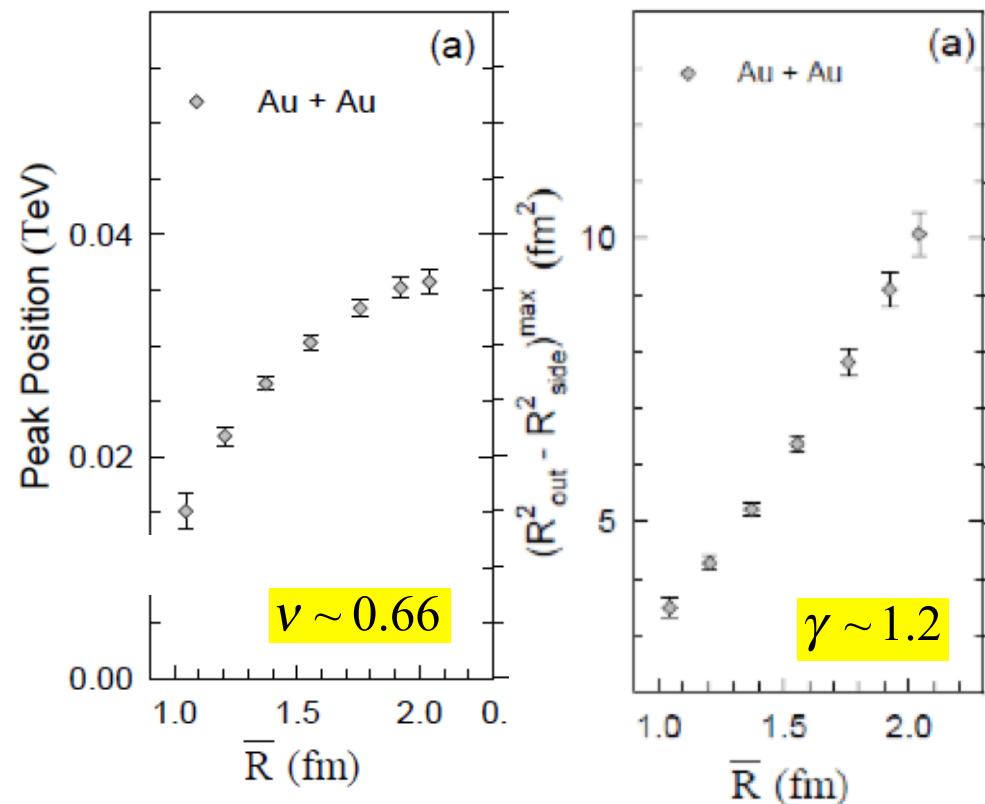
Order Parameter: $R_{\text{out}}^2 - R_{\text{side}}^2$

Emission duration and compressibility

$$(R_{\text{out}}^2 - R_{\text{side}}^2)^{\max} \propto \bar{R}^{\gamma/\nu}$$

$$\sqrt{s_{NN}}(V) = \sqrt{s_{NN}}(\infty) - k \times \bar{R}^{-(1/\nu)}$$

Fitted parameters suggest existence of CP at $\mu_B \sim 95$ MeV, $T \sim 165$ MeV.



$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)} \quad \sqrt{s_{CEP}} \sim 47.5 \text{ GeV}$$

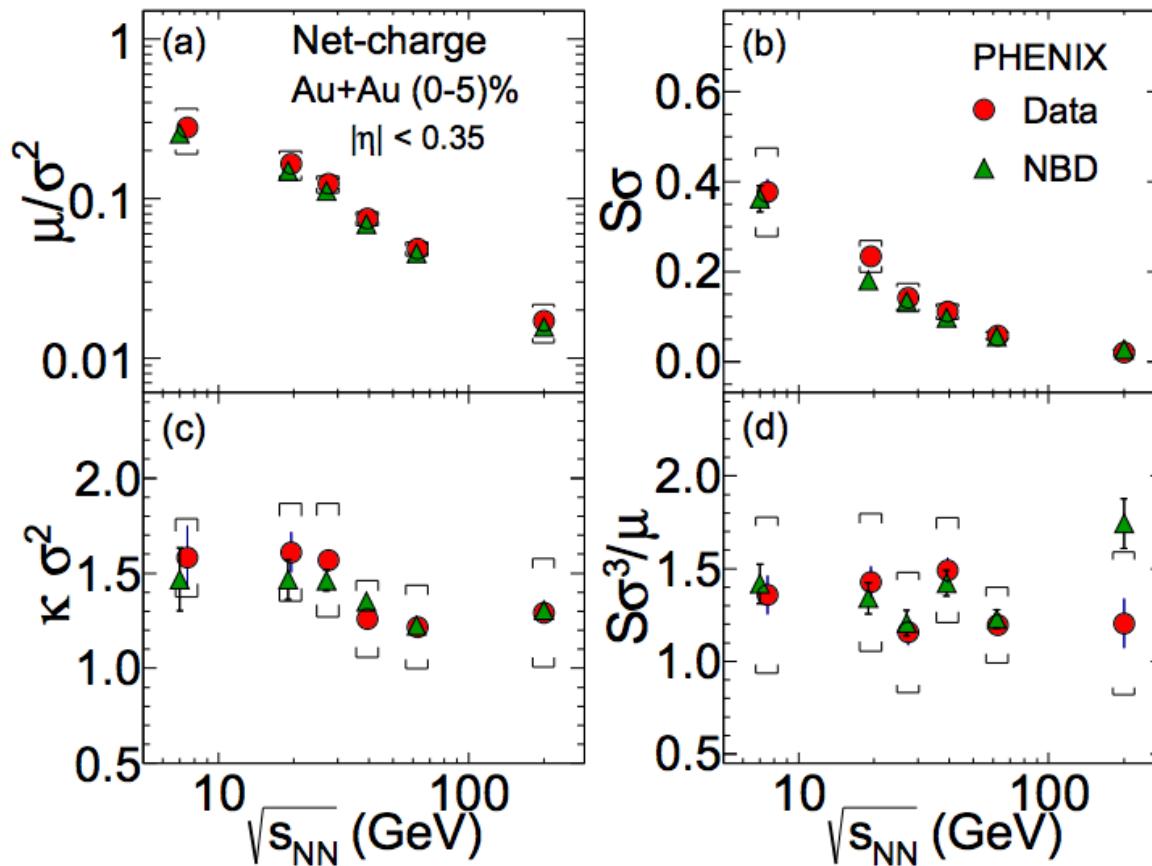
σ_x & $\sigma_y \rightarrow$ RMS widths of density distribution

Roy A. Lacey, Mon., 17:20pm

PHENIX: Moments of the Net-charge Multiplicity Distribution

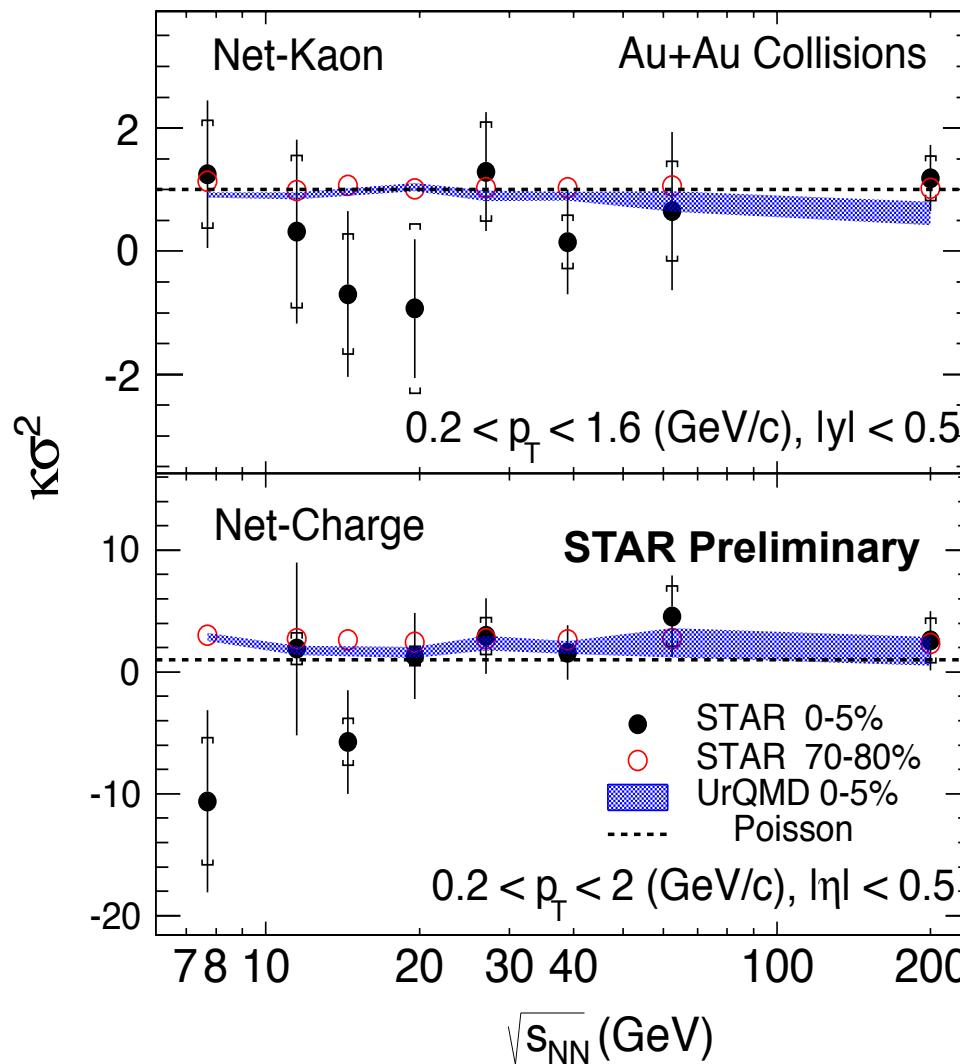
A.Adare et al.,arXiv:1506.07834(2015)

$|\eta| < 0.35, 0.2 < pT < 2.0 \text{ GeV}/c$



- Smaller error bars are solely due to small acceptance, both (η, φ) .
- “No clear evidence for structure attribute to the CP.” **Prakhar Garg, Tue., 10:50am.**

STAR: Moments of Net-Charge and Net-Kaon Distributions



- Net-Kaon and Net-Charge $\kappa\sigma^2$ are consistent with unity.
- More statistics are needed to make a conclusion.
- UrQMD (no CP), show no energy dependent.

$$\text{error}(\kappa\sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

σ : Measured width of distributions.
 ε : Efficiency.

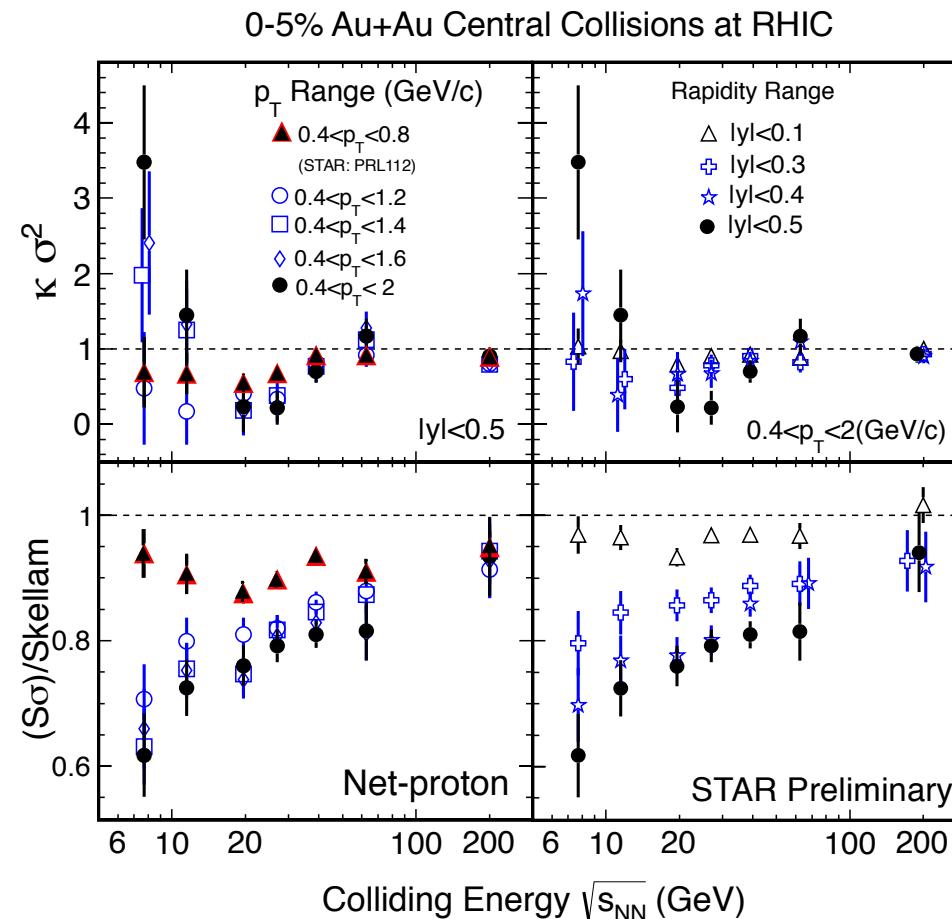
X. Luo, PRC91, 034907 (2015)

Ji Xu, Poster ID, 0127.
 Jochen Thaeder, Mon, 14:30pm, [153]

In STAR, with the same # of events: $\text{error(Net-Q)} > \text{error(Net-K)} > \text{error(Net-P)}$

Moments of Net-proton Distribution at STAR

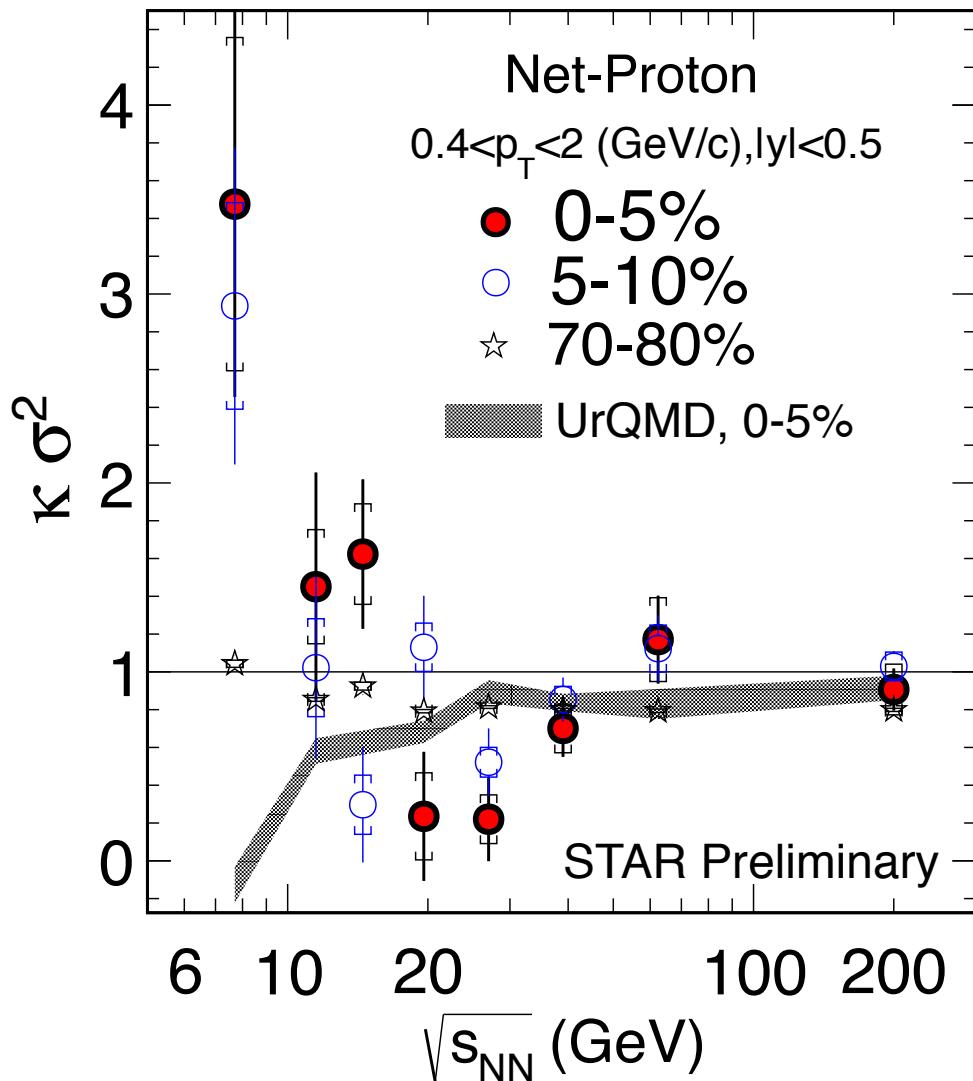
“More is different” – P. W. Anderson



**Large acceptance is crucial
for fluctuations analysis.**

**Xiaofeng Luo, CPOD 2014
arXiv: 1503.02558.**

Energy Dependence of Moments of Net-proton Distributions



Net-proton as proxy for net-baryon.

- Non-monotonic trend is observed for the 0-5% most central Au+Au collisions.
- Separation and flipping for the results of 0-5% and 5-10% centrality are observed at 14.5 and 19.6 GeV.
**(Oscillation Pattern observed !
Very Interesting !)**

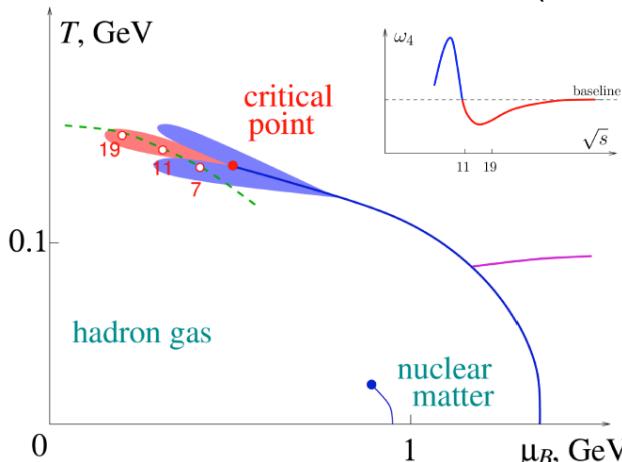
- UrQMD (no CP) results show suppression at low energies. Consistent with the effects of baryon number conservation.

Jochen Thaeder, Mon, 14:30pm, [153]
Xiaofeng Luo, CPOD2014.

Sign of Kurtosis :Model and Theoretical Calculations

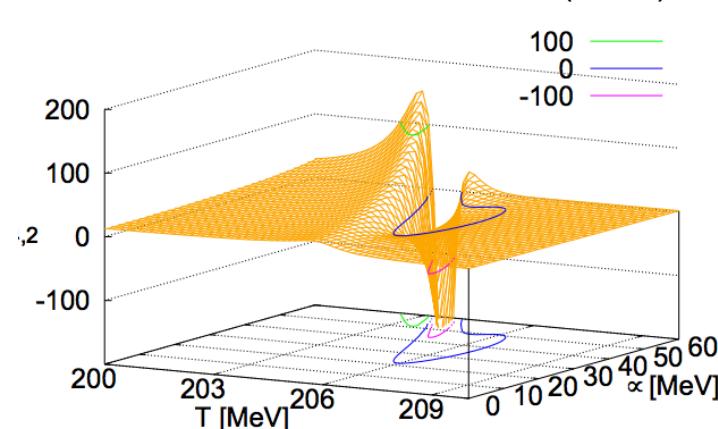
σ model

M.A. Stephanov,
PRL107, 052301 (2011).



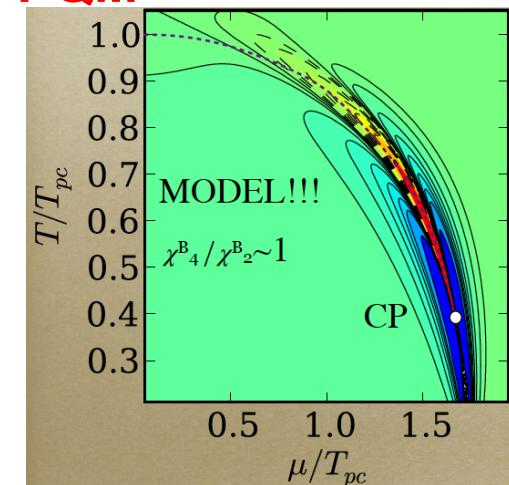
PQM

Schaefer&Wanger,
PRD 85, 034027 (2012)

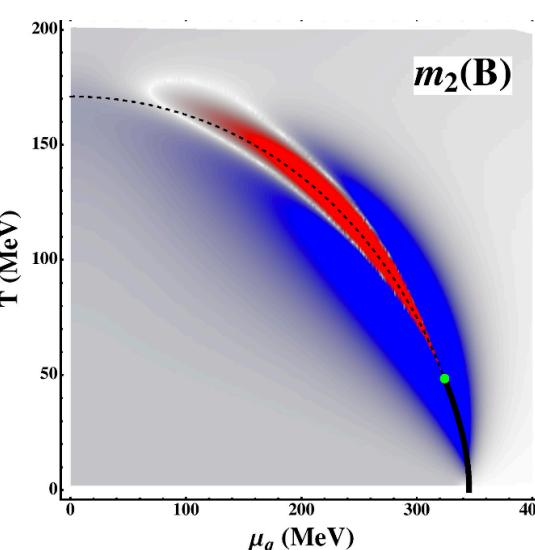


PQM

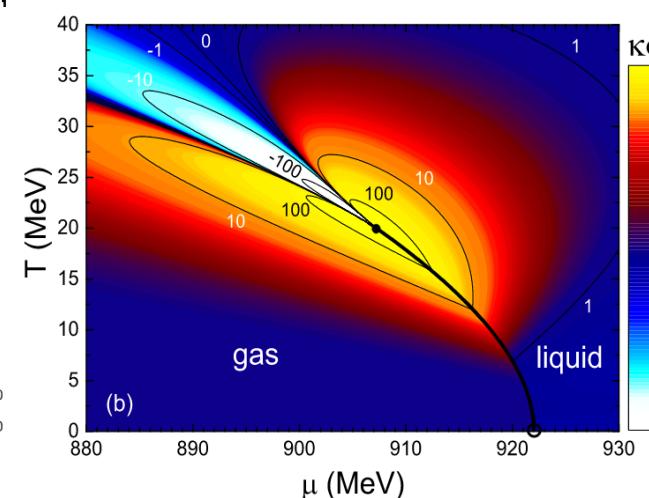
V. Skokov, QM2012



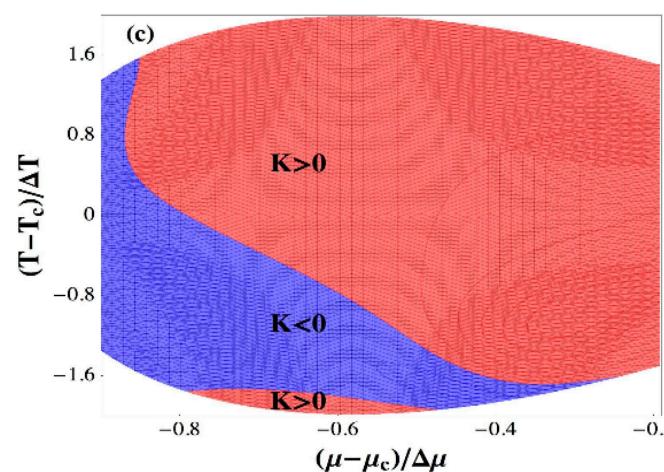
NJL



VDW



Memory Effects

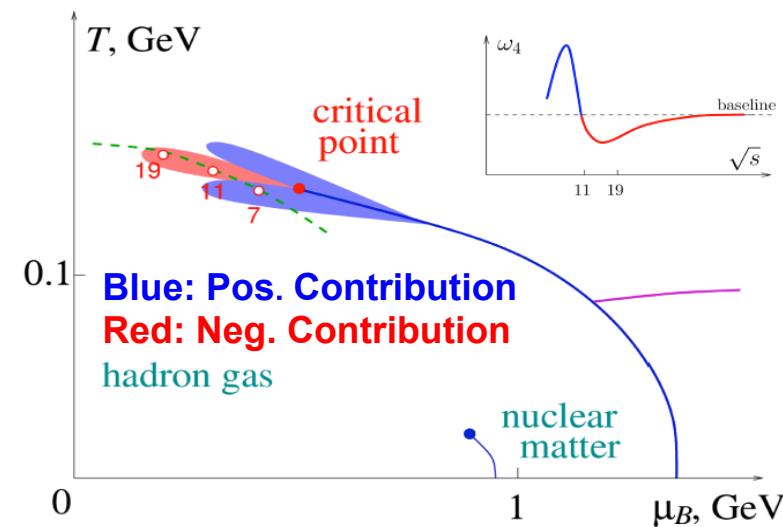
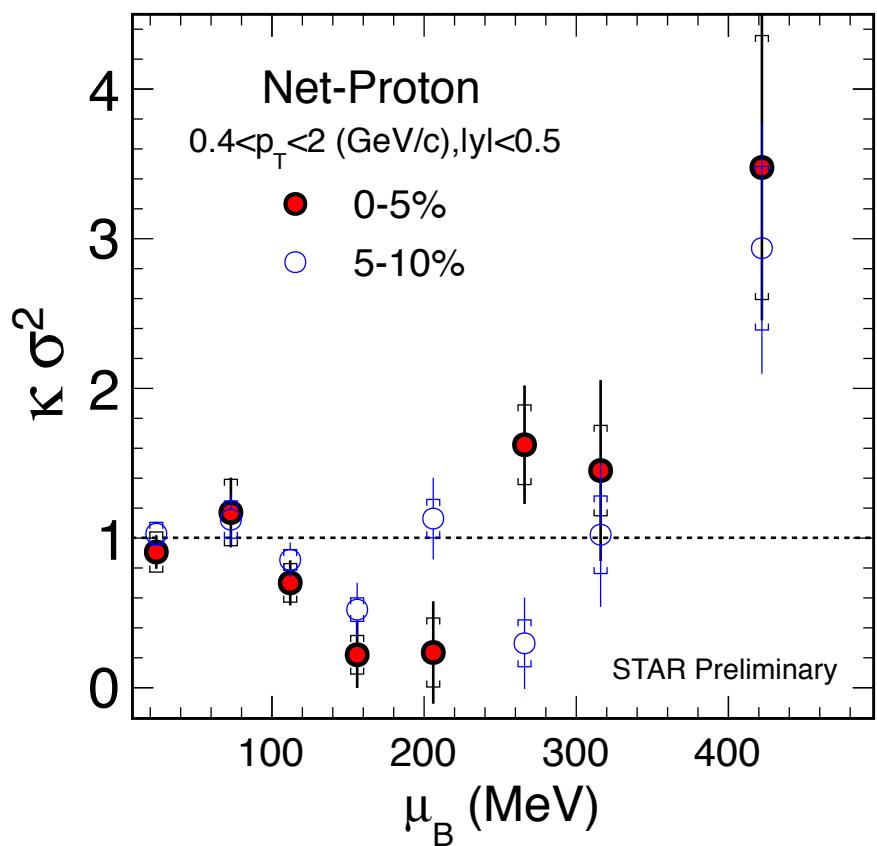


JW Chen et al., arXiv:1509.04968

Vovchenko et al., arXiv:1506.05763

Swagato, et al, PRC92,034912 (2015).

Oscillation Pattern: Signature of Critical Region ?

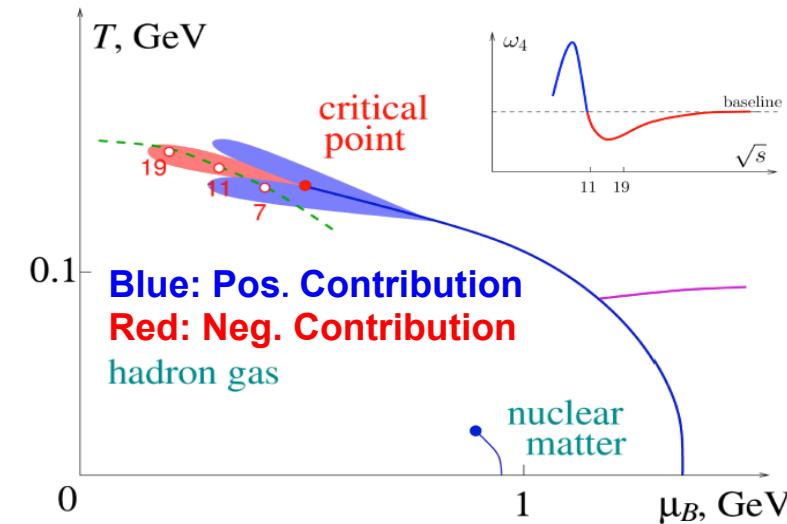
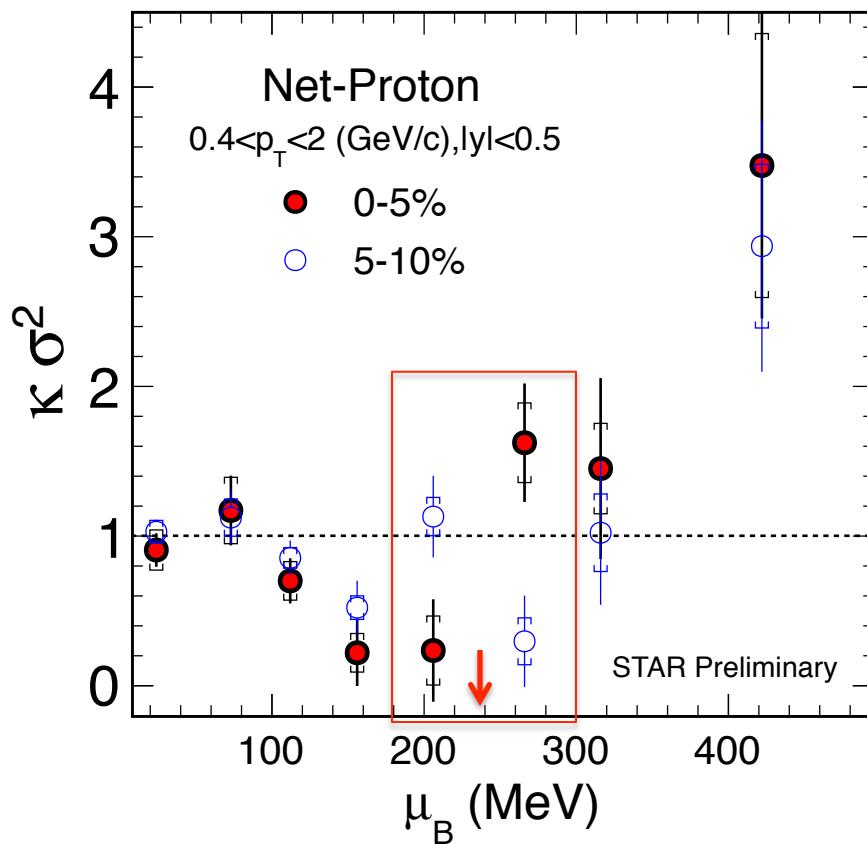


Depending on relative position between reaction trajectories/freeze out position and critical region.

$\kappa\sigma^2$	0-5%	5-10%
14.5 GeV	1+Pos.	1+Neg.
19.6 GeV	1+Neg.	1+Pos.

“Oscillation pattern” around baseline for Kurtosis
may indicate a signature of critical region.

Oscillation Pattern: Signature of Critical Region ?



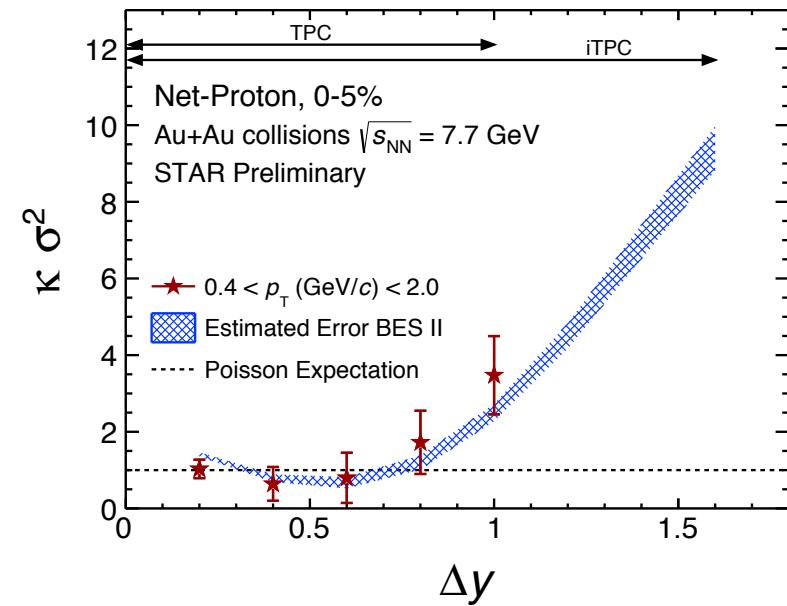
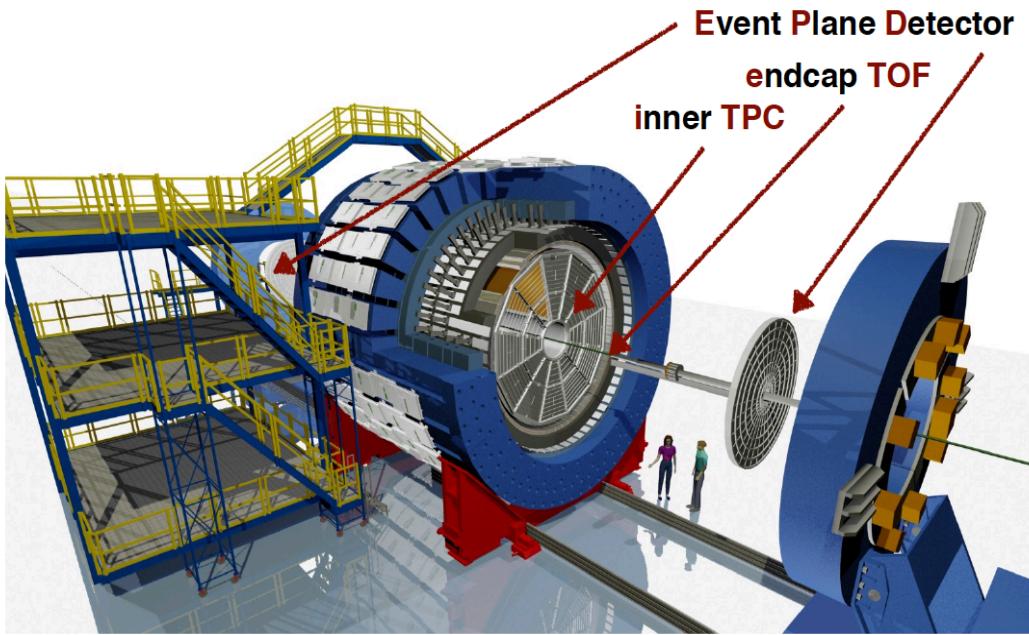
Depending on relative position between reaction trajectories/freeze out position and critical region.

$\kappa\sigma^2$	0-5%	5-10%
14.5 GeV	1+Pos.	1+Neg.
19.6 GeV	1+Neg.	1+Pos.

“Oscillation pattern” around baseline for Kurtosis
may indicate a signature of critical region.

Propose to scan **16.5 GeV ($\mu_B = 238$ MeV)** or even finer step between 14.5 and 19.6 GeV, expect to see bigger dip and no separation for the results of the 0-5% and 5-10%.

STAR Upgrades and BES Phase-II (2019-2020)



iTPC proposal: <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619>

BES-II whitepaper: <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598>

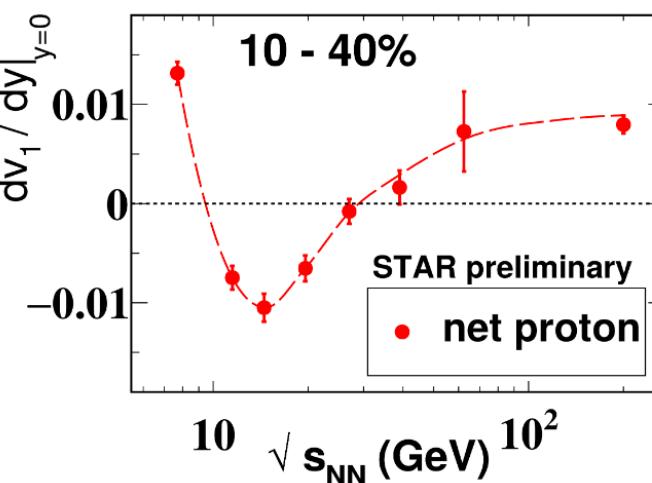
Larger rapidity acceptance crucial for further critical point search with net-protons

- Electron cooling upgrade will provide increased luminosity $\sim 3\text{-}10$ times.
- Inner TPC(iTPC) upgrade : $|\eta| < 1$ to $|\eta| < 1.5$. Better dE/dx resolution.
- Forward Event Plane Detector (EPD): Centrality and Event Plane Determination. $1.8 < |\eta| < 4.5$

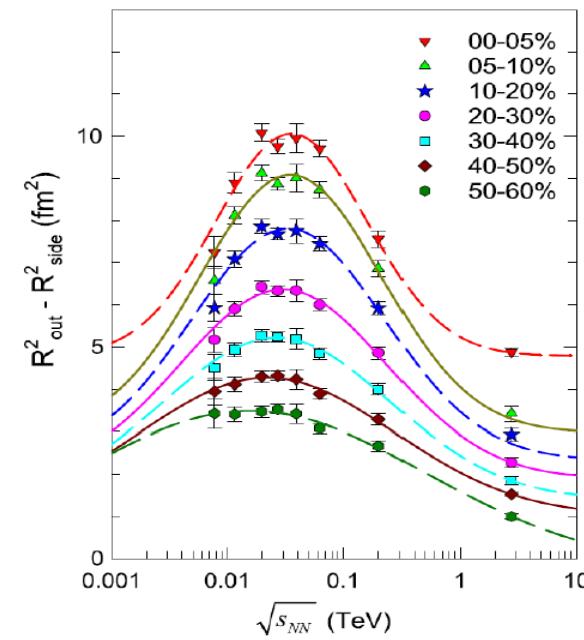
Summary

Intriguing structures are observed at low energies.

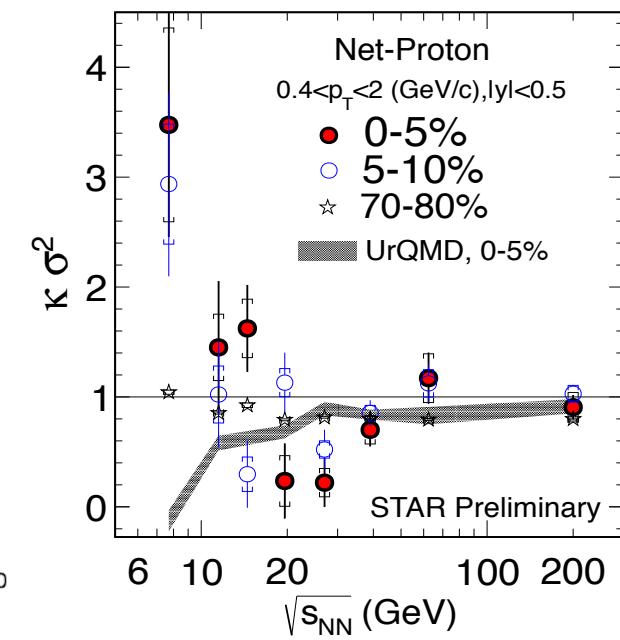
Dip



Peak



Oscillation



Discovery Potential at High Baryon Density:

First order phase transition and QCD Critical Point etc.

The Race is on.....

Thank you !

