Study the QCD Phase Structure with Beam Energy Scan at STAR

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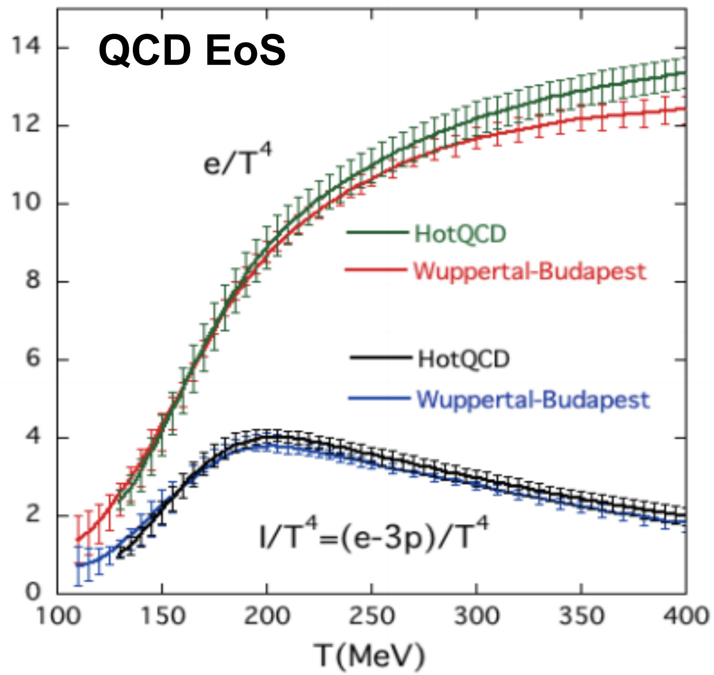
Outline

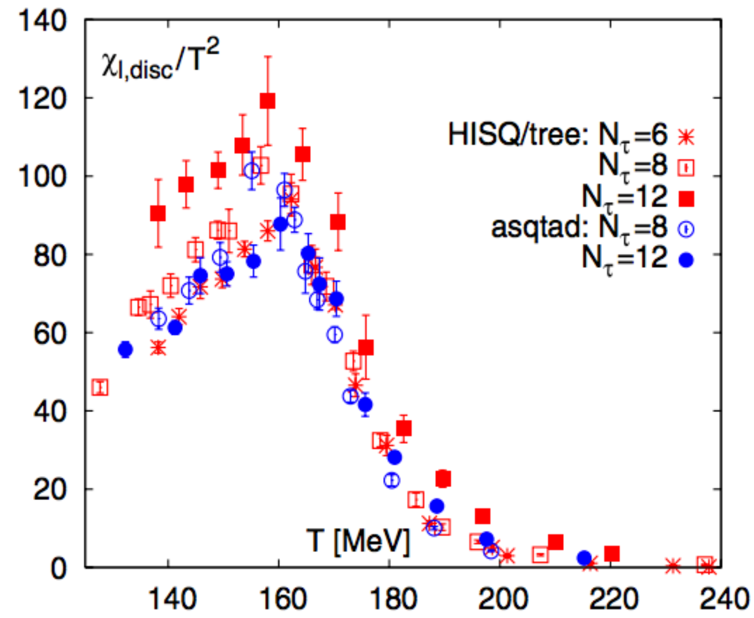
- Introduction
- Experimental Facility
- Selected Experimental Highlights
- Summary and Outlook

QCD Thermodynamics (μ_B=0)

Akira Ukawa, arXiv:1501.04215



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



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

Rapid rise of the energy density:

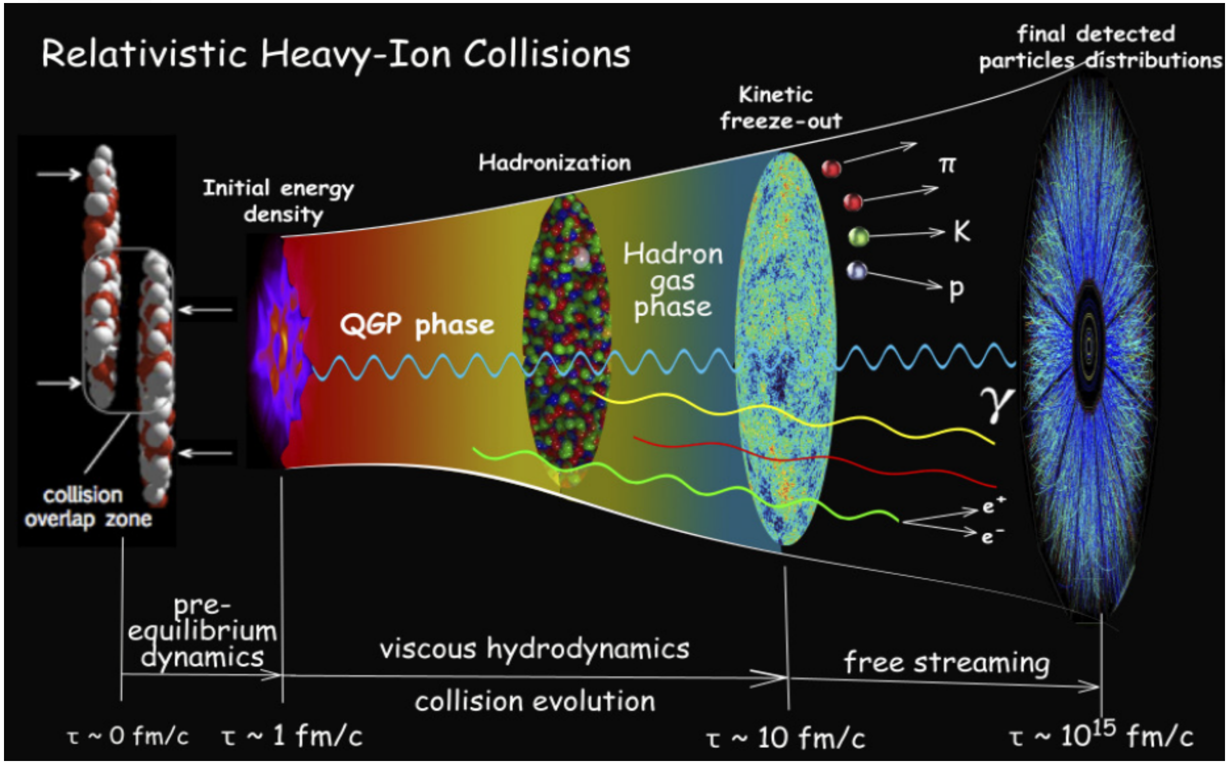
- Rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons.
- Smooth crossover transition.

Chiral susceptibility peaks at T_c:

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

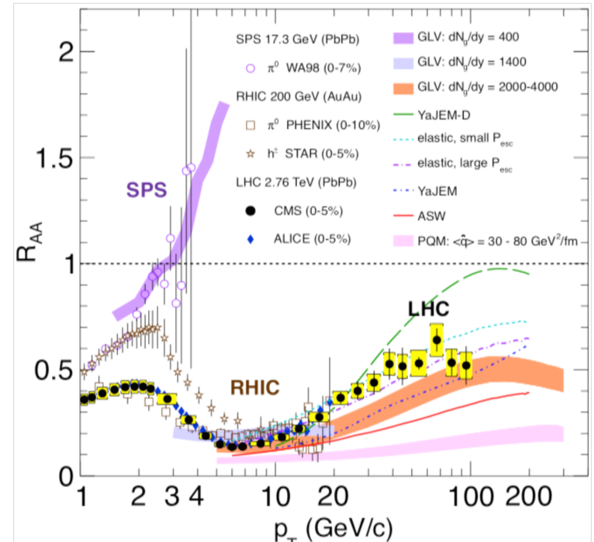
Chiral symmetry restoration: temperature: T_c~154+/-9 MeV

Relativistic Heavy–ion Collisions: Little Bang



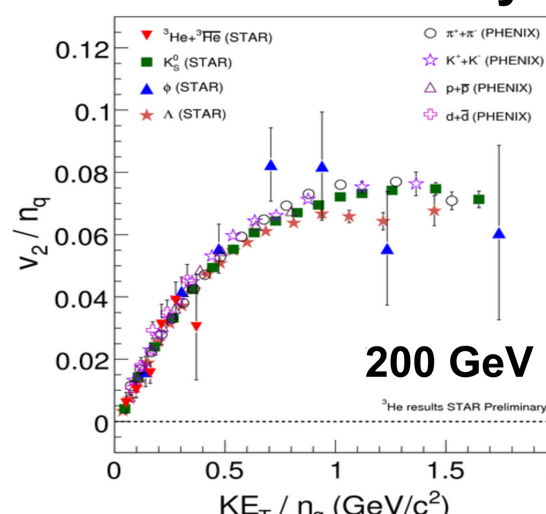
Courtesy of Paul Sorensen and Chun Shen

Jet Quenching



Eur.Phys.J. C72, 1945 (2012).

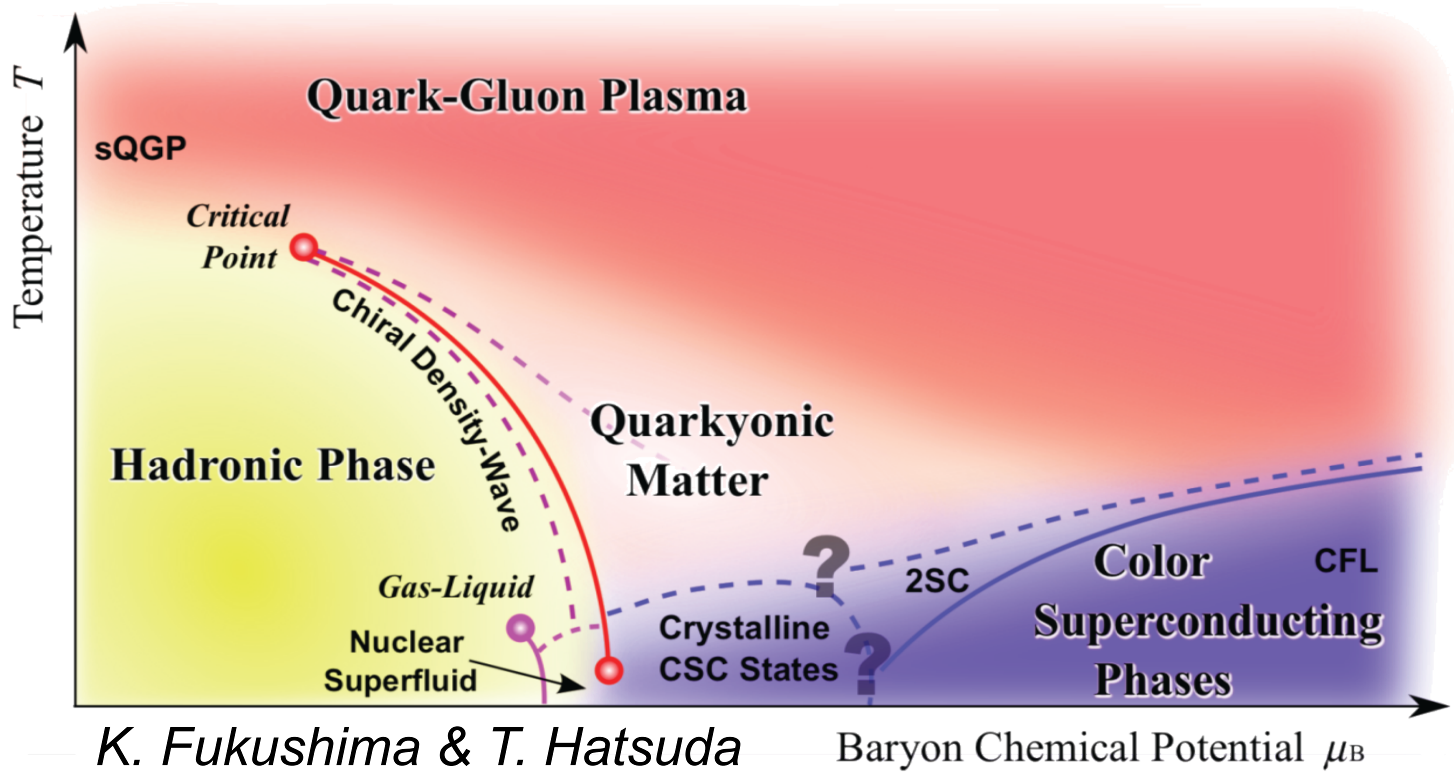
Partonic Collectivity v_2



- ➢ 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 TeV.
- ➢ Indirect evidences for strongly couple and liquid like QGP formed in high energy nuclear collisions.

The QCD Phase Diagram

Rept. Prog. Phys. 74 (2011).



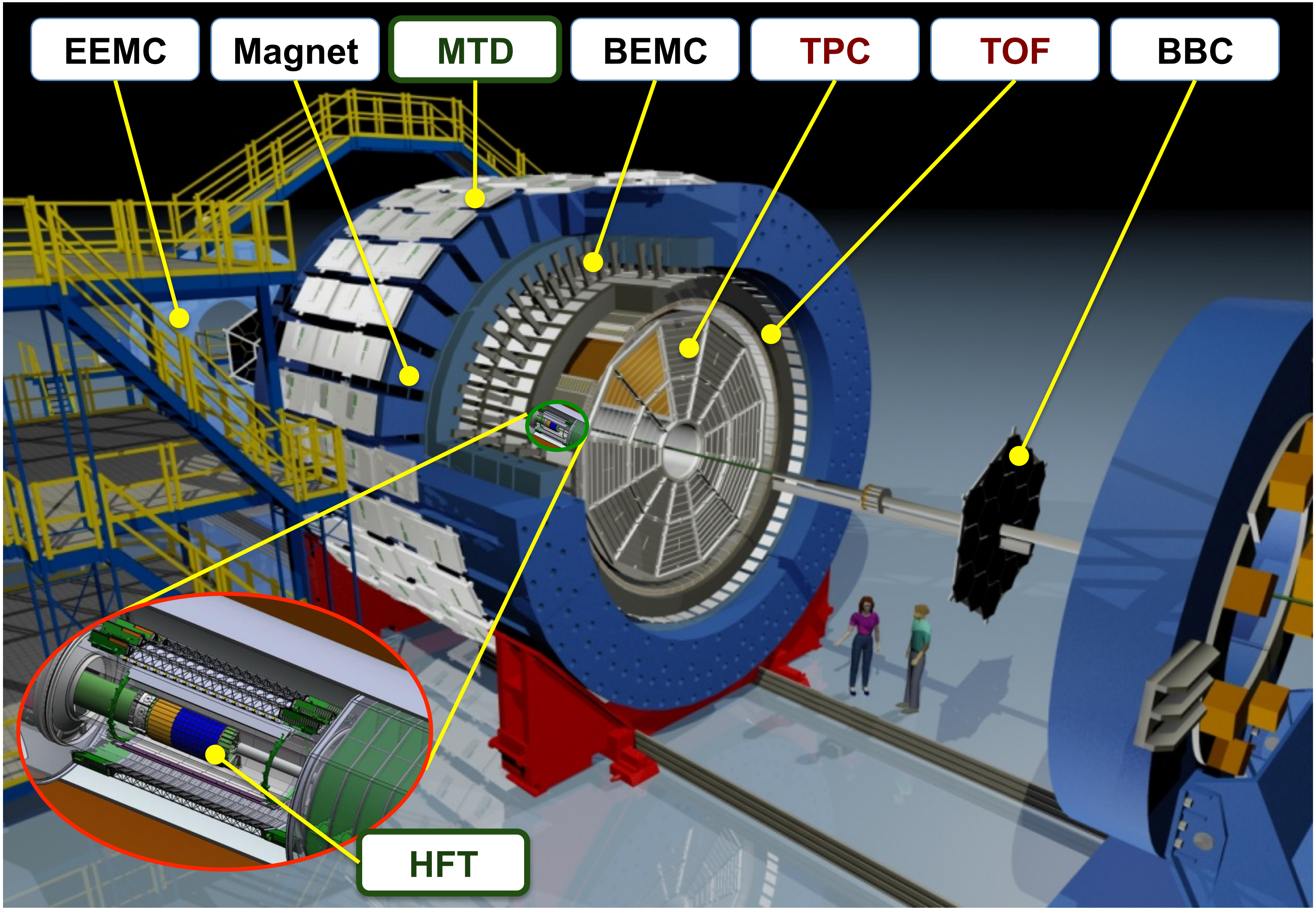
K. Fukushima & T. Hatsuda

1. Properties of QGP ?: T dependence, at $\mu_B \sim 0$, of EoS, η/s, q^, etc.

2. Turning off the QGP signals at low energies ?

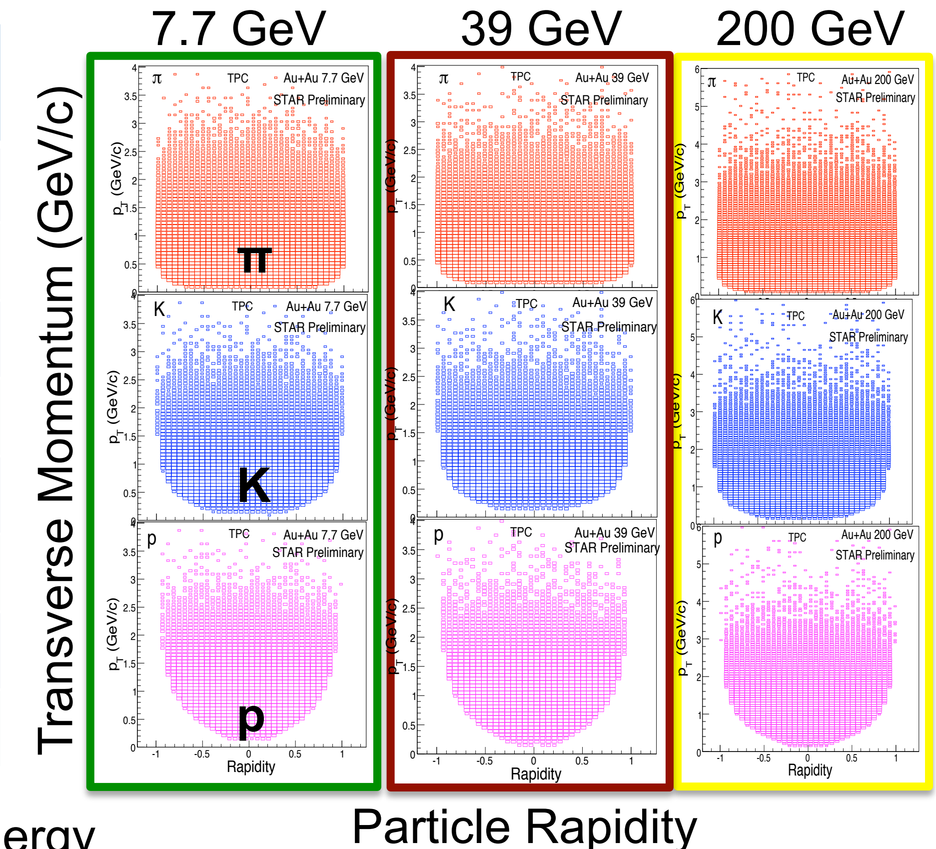
3. 1st order phase boundary and QCD critical point ?

STAR Detector System



RHIC Beam Energy Scan- I (2010-2014)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	μ_B (MeV)	T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140



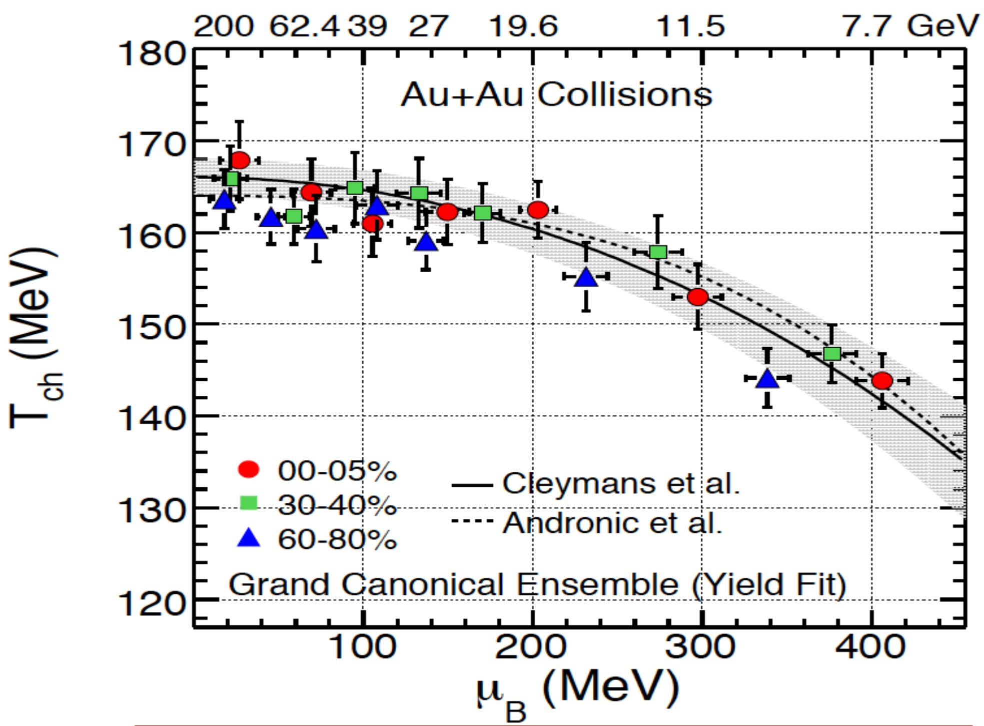
1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Important for fluctuation analysis!

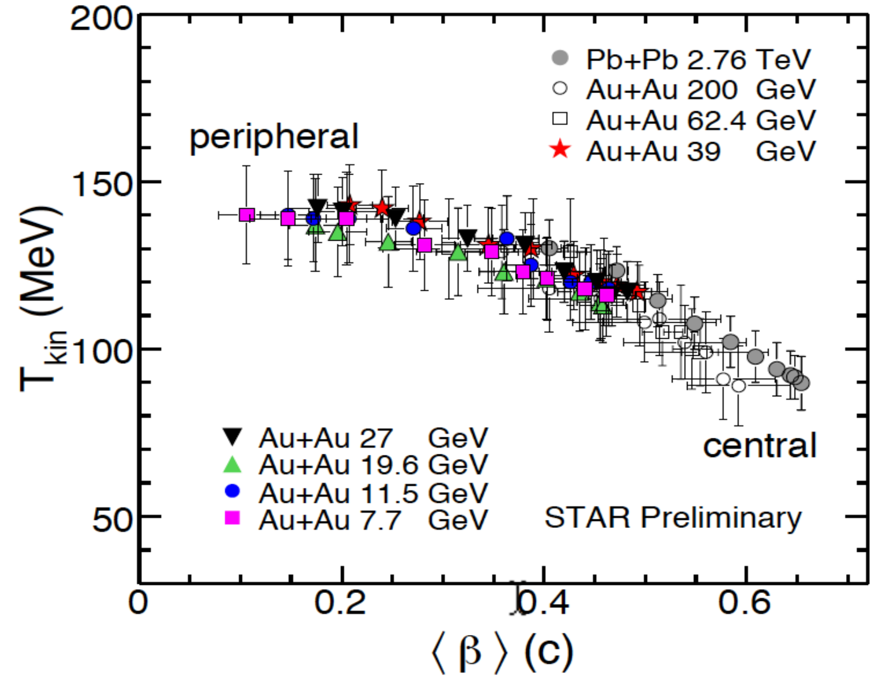
(μ_B, T_{CH}) : J. Cleymans et al., PRC 73, 034905 (2006)

arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Main Goals: Study QCD Phase Structure
- Search for the 1st order phase transition.
- Search for the **critical point.**

Freeze Out Dynamics





Chemical Freeze-out: (GCE)

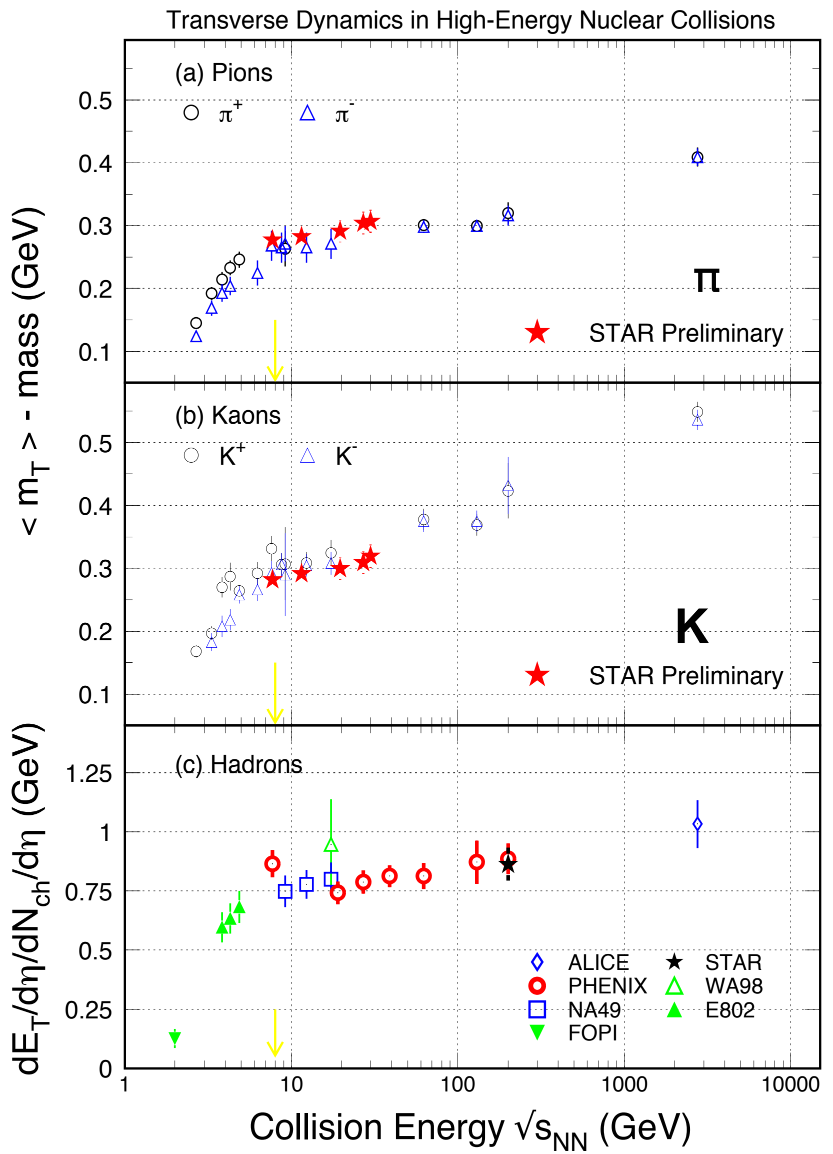
- Weak temperature dependence
- Centrality dependence μ_B!
- Lattice prediction on CP around $\mu_B \sim 300 - 400$ MeV

Kinetic Freeze-out:

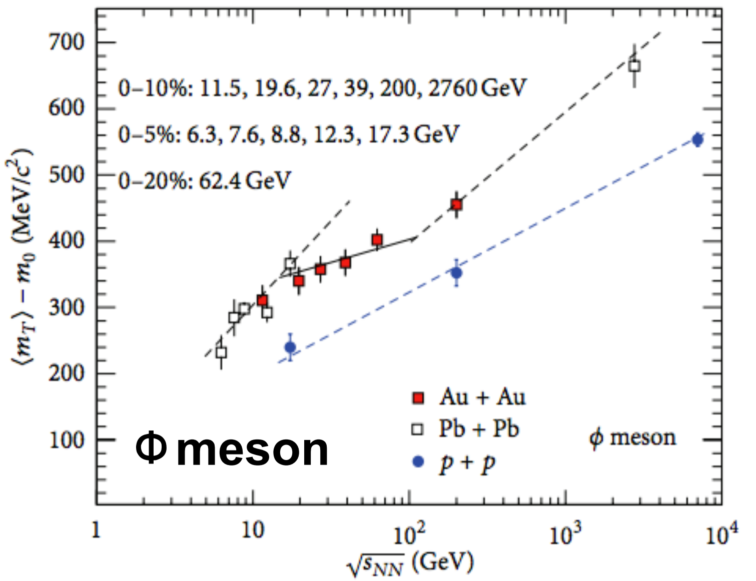
- Central collisions => lower value of T_{fo} and larger collectivity β_T
- Stronger collectivity at higher energy, even for peripheral collisions

ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(2013).
STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)

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).



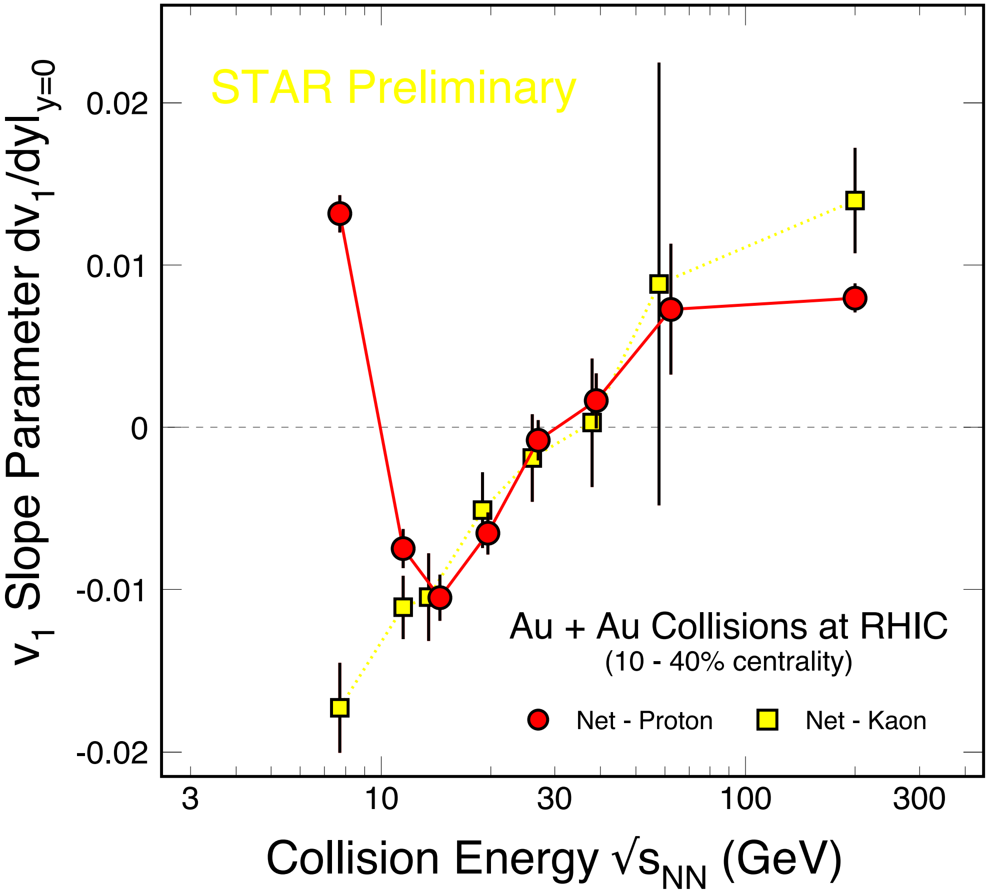
- Excitation function of particle $<m_T>-m_0$ and transverse energy/mul. show a flat pattern above ~ 8 GeV.

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: $<m_T>-m_0 \sim T$
Entroy：$dN/d\eta \sim \log(\sqrt{s_{NN}})$.

Directed Flow v_1



STAR: PRL**112**, 162301(2014)
Talk by P. Shanmuganathan at QM2015

1) Mid-rapidity net-proton dv_1/dy published in 2014 by STAR, except the point at 14.5 GeV

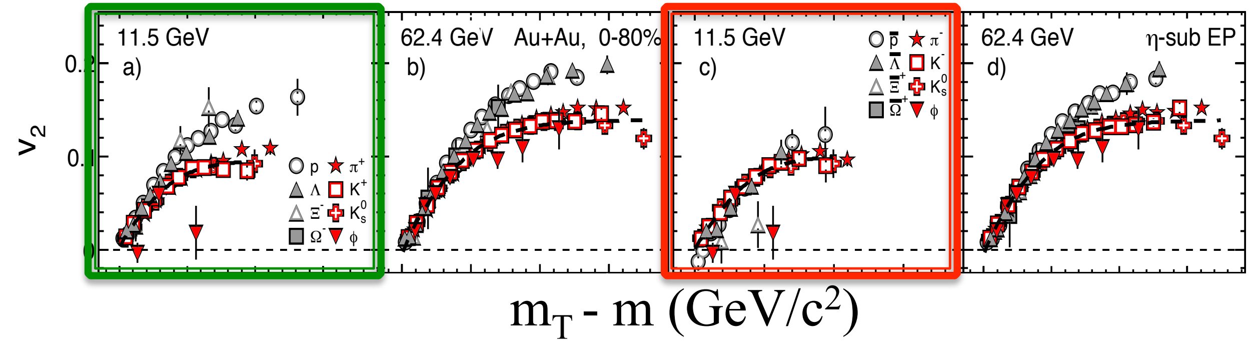
2) Minimum at $\sqrt{s_{NN}}$ = 14.5 GeV for net-proton, but net-Kaon data continue decreasing as energy decreases

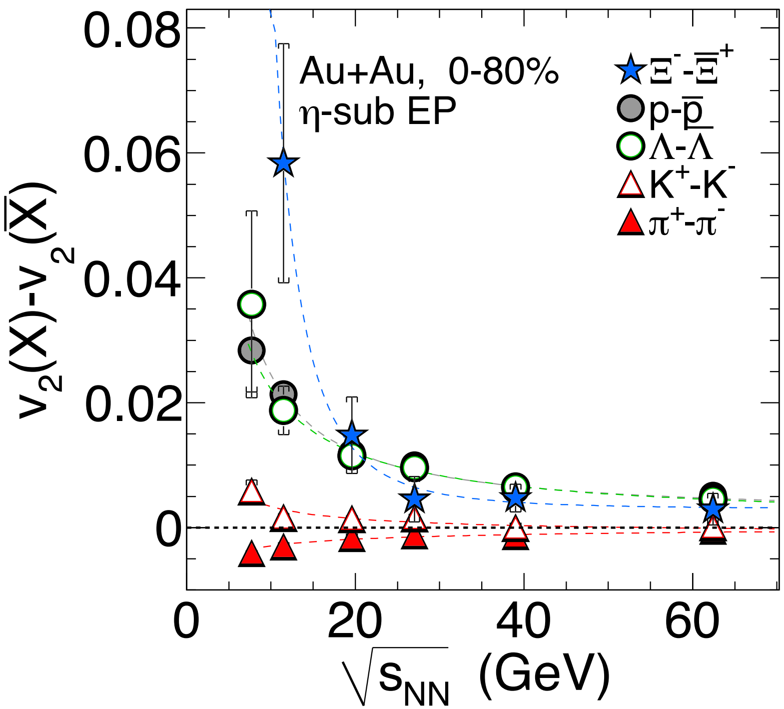
3) At low energies, baryon stopping effects are important.

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

Indicate softening of EoS due to the first order phase transition ?

Elliptic flow v_2



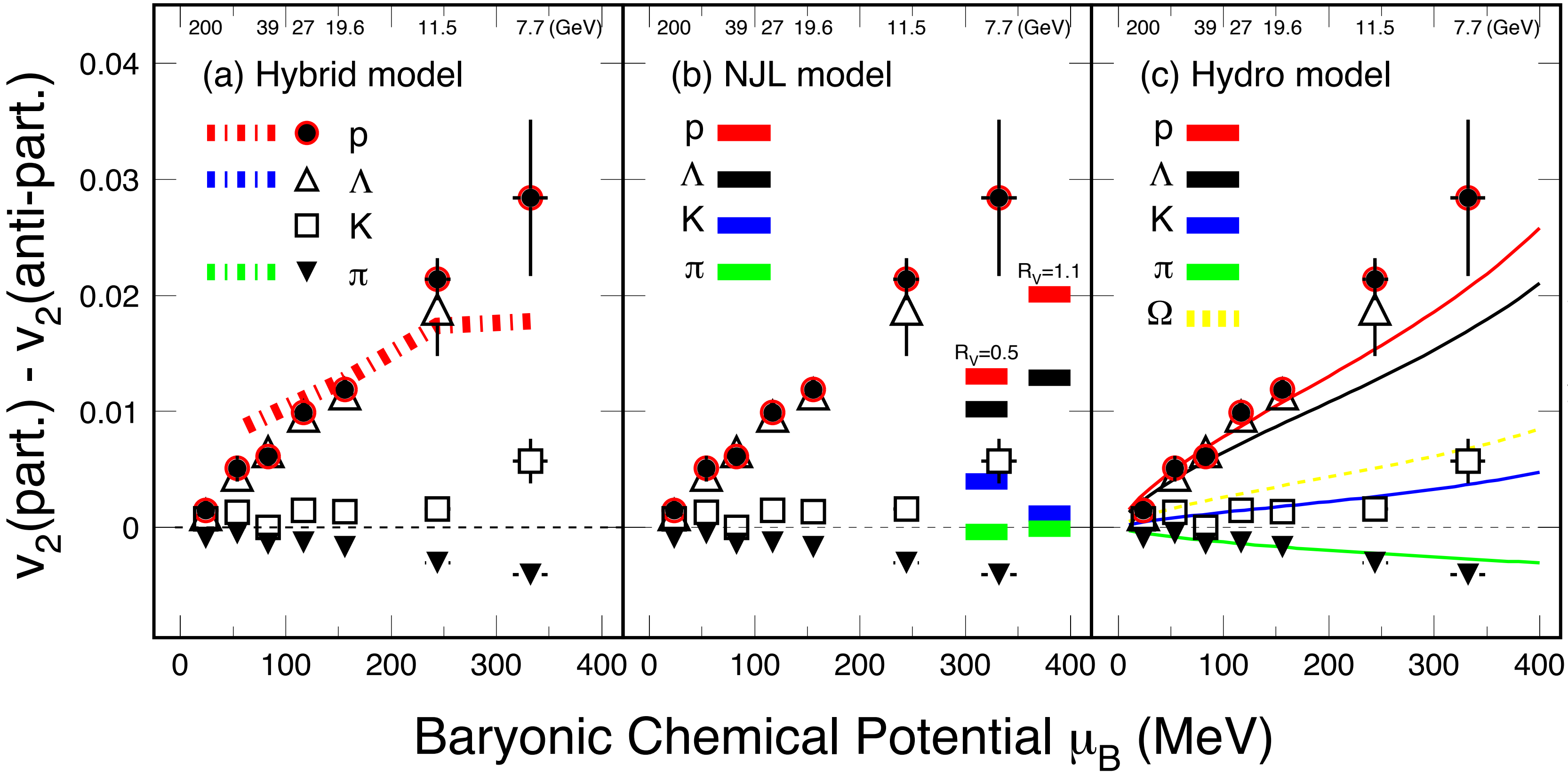


STAR: PR**110** (2013) 142301

1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

2) At $\sqrt{s_{NN}}$ < 11.5 GeV, the universal **NCQ scaling in** v_2 **is broken,** consistent with hadronic interactions becoming dominant

v_2 and Model Comparison

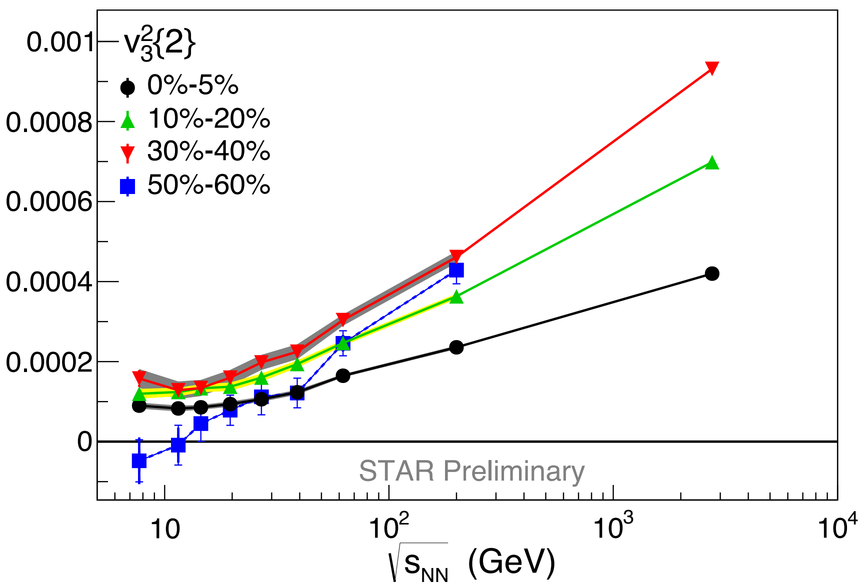


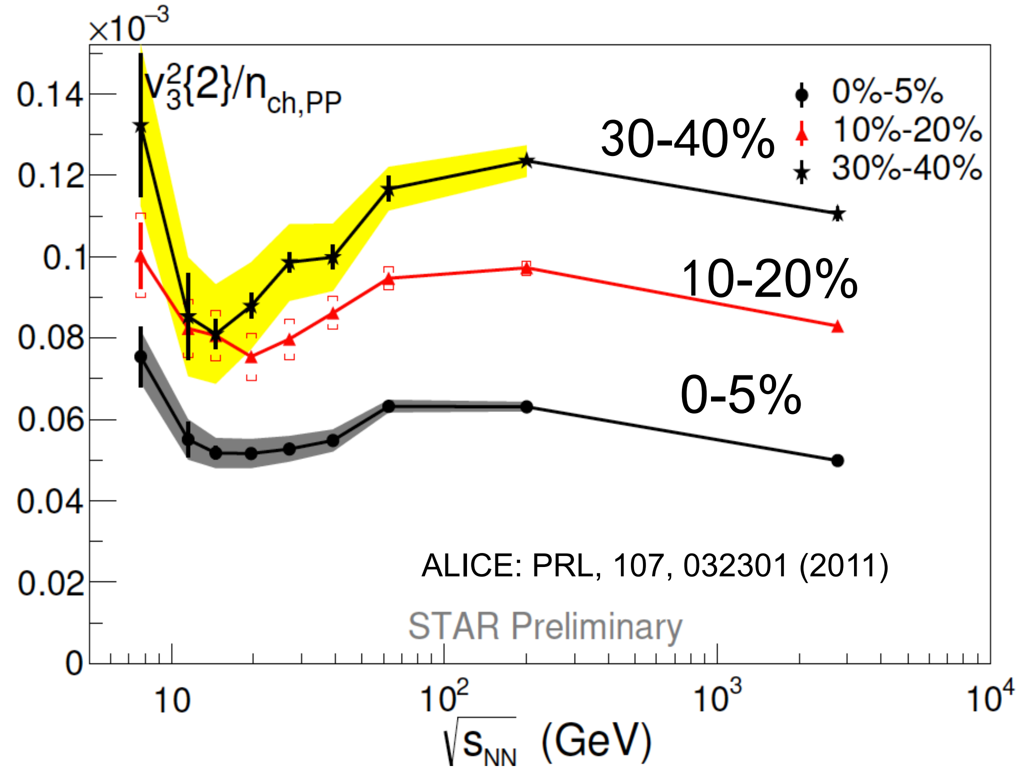
(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PRC86, 44902(13)]

(b) NJL model:. Sensitive to hadronic potential. [J. Xu, et al., PRL112.012301(14)]

(c) Pure Hydro solution with μ_B, viscosity: **Chemical potential μ_B and viscosity η/s driven!** [Hatta et al. arXiv:1502.05894//1505.04226//1507.04690]

Triangle Flow : $v_3^2\{2\}$





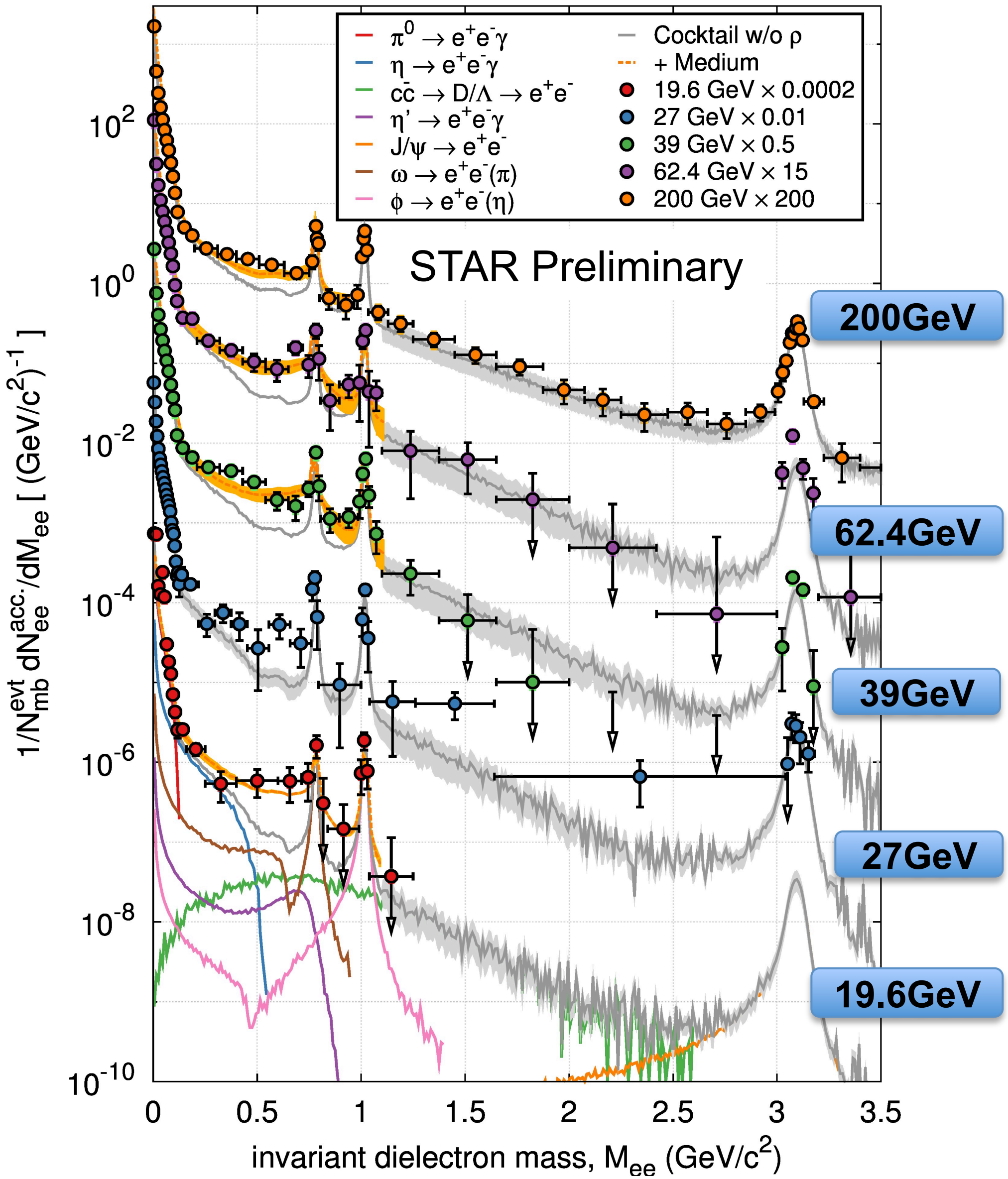
$$n_{ch,PP} = (2/N_{part})dN_{ch}/d\eta$$

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

STAR, arXiv:1601.01999.

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

Energy Dependence of Di-electrons



Bulk-penetrating probe:

1) **$M_{ee} \leq 1GeV/c^2$:** In-medium broadened ρ, model results* are consistent with exp. data. (* driven by the baryon density in the medium)

2) **$1 \leq M_{ee} \leq 3GeV/c^2$:** QGP thermal radiation?
HFT: Charm contributions.

3) High statistics data are needed, **BES-II!**

- STAR: (200GeV data) sub. to PRL. 1312.7397
- R. Rapp: PoS CPOD13, 008(2013)
- O. Linnyk et al, PRC85, 024910(12)

Fluctuations Probes the QCD Phase Transition

Fluctuations are sensitive to the thermodynamic properties of the system and can be used to probe the QCD phase transition.

1. Fluctuations signals the QCD Critical Point.

M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. Lett. 81, 4816 (1998). Cited:928
M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. D 60, 114028 (1999). Cited:708

Probe singularity of the equation of state: Divergence of the fluctuations.

2. Fluctuations signals the Quark Deconfinement.

S. Jeon and V. Koch, Phys. Rev. Lett. 83, 5435 (1999). Cited: 193.
S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000). Cited: 470.
M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000). Cited:443.

Proposed experimental observables:

1. **Pion multiplicity fluctuations.**
2. **Mean p_T fluctuations.**
3. **Particle ratio fluctuations**
4. **Fluctuations of conserved quantities.**

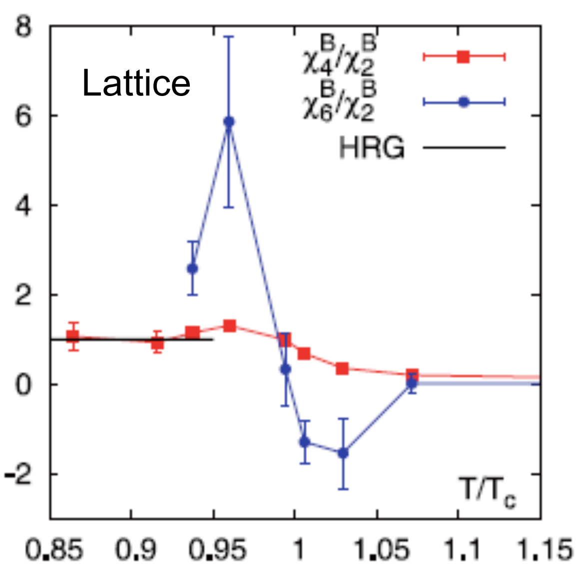
Higher Order Fluctuations of Conserved Quantities

1. Higher sensitivity to correlation length (ξ) and probe non-gaussian fluctuations near the Critical Point.

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

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

2. Direct connection to the susceptibility of the system.



$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q)^n}, q = B, Q, S$$

S. Ejiri et al, Phys.Lett. B 633 (2006) 275.
Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694.
F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2012).
A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

Observables: Higher Moments (fluctuations)

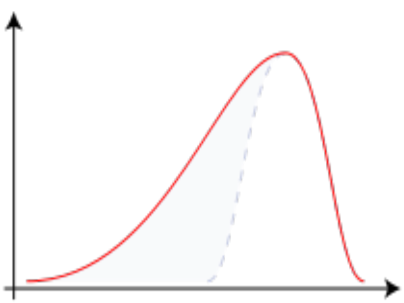
"Shape" of the fluctuations can be measured: non-Gaussian moments.

$$C_{1,x} = \langle x \rangle, C_{2,x} = \langle (\delta x)^2 \rangle,$$

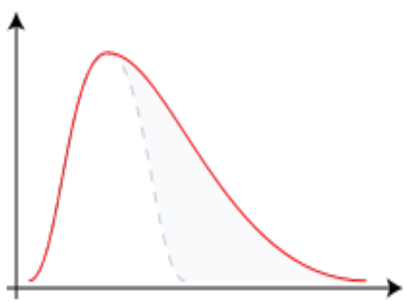
$$C_{3,x} = \langle (\delta x)^3 \rangle, C_{4,x} = \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2$$

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$$

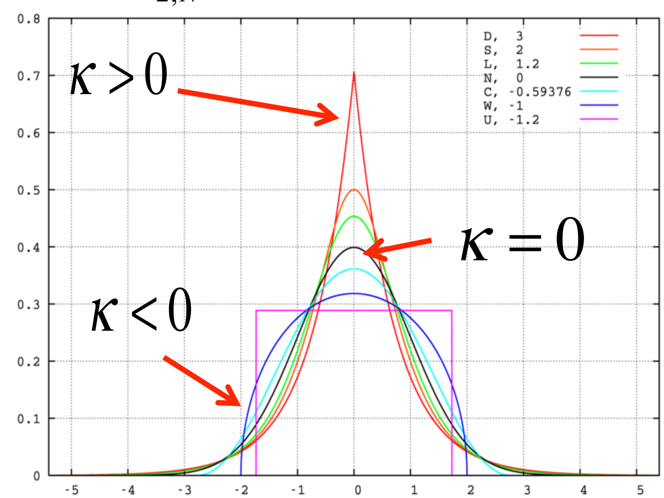
$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$$



Negative Skew



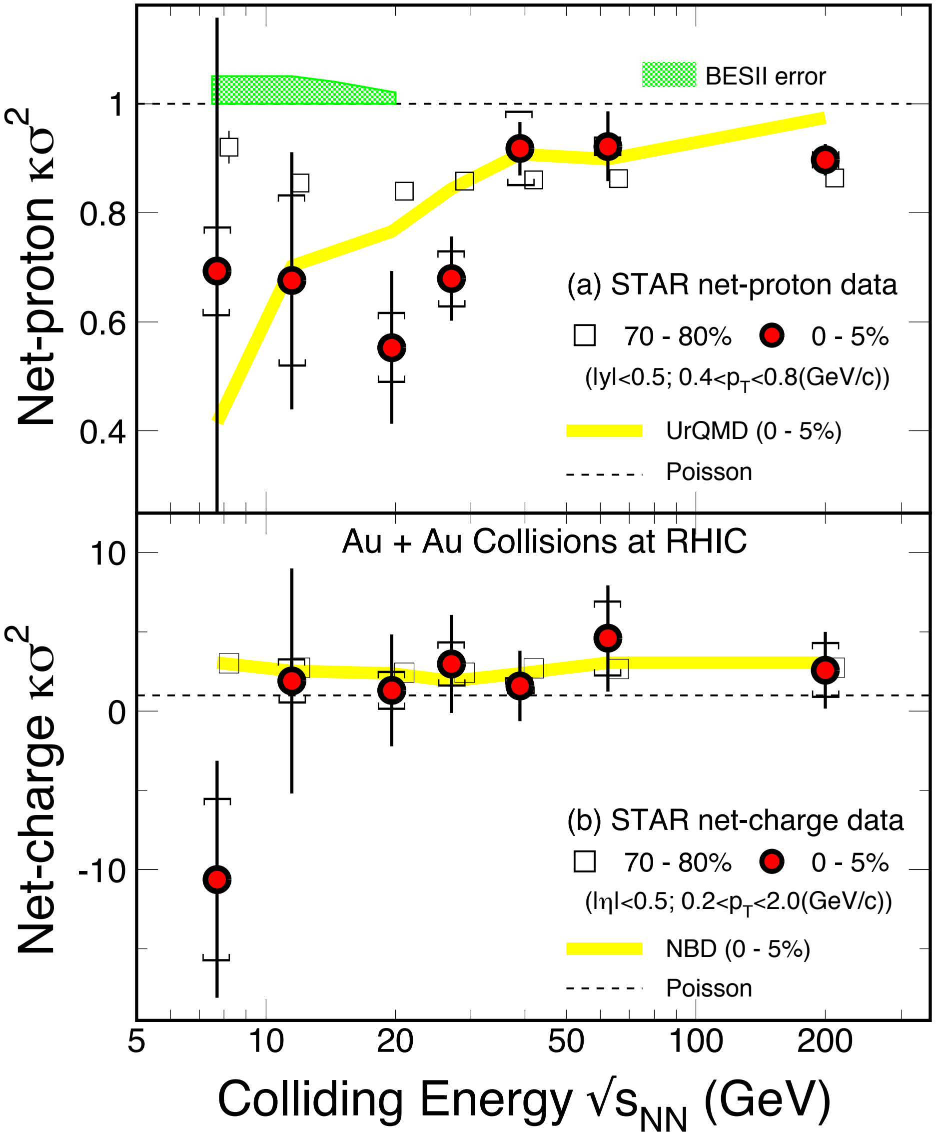
Positive Skew



- **Susceptibility ratios ⇔ Cumulant Ratios (Cancel V dependence)**

$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}}, \qquad \text{(q=B, Q, S)}$$

Results Published in 2014



Net-proton ($0.4<p_T<0.8$ GeV/c):

All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}} \sim 20$ GeV

Net-charge ($0.4<pT<2$ GeV/c)

Need more statistics.

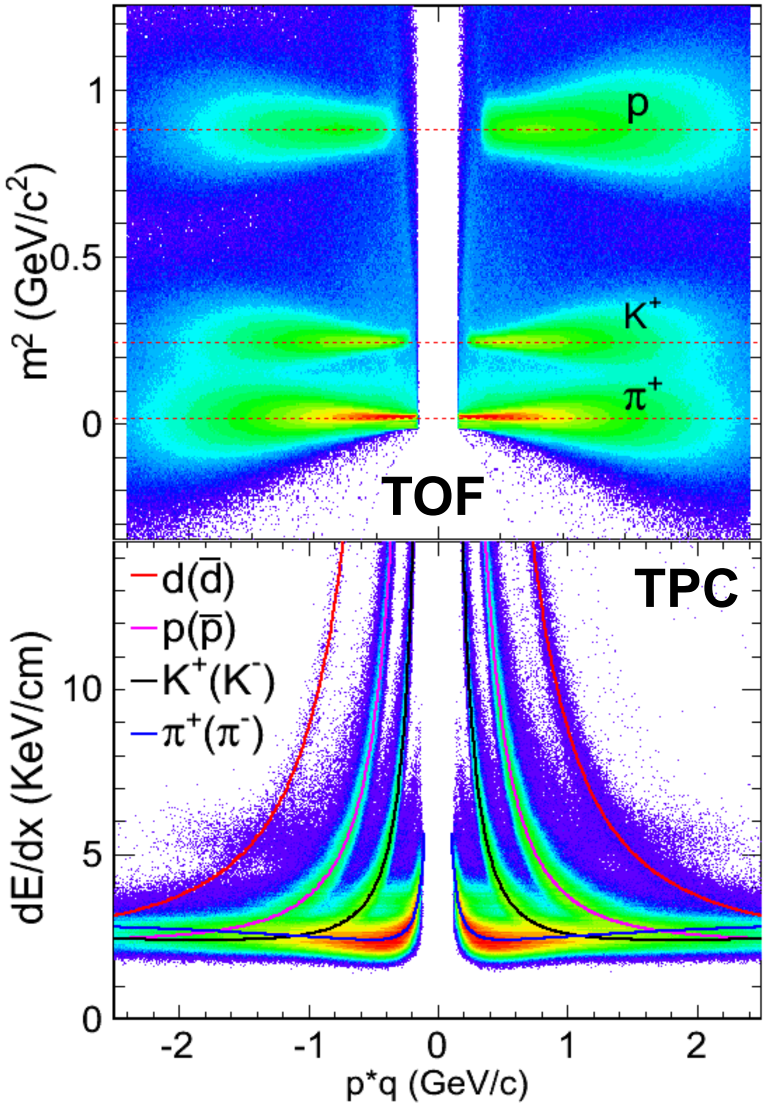
Poisson: $\kappa\sigma^2=1$

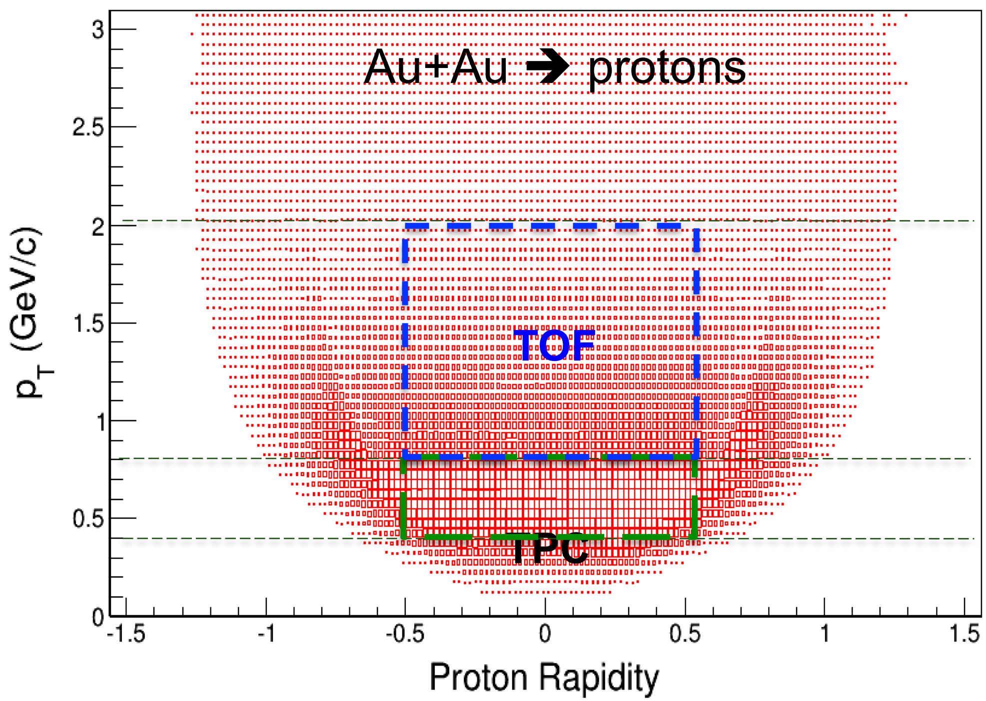
Net-proton: STAR: **PRL112**, 32302(2014)

Net-charge: STAR: **PRL113**,092301(2014)

New Net-proton Analysis: Larger p_T Acceptance

TOF is used for Identify p/pbar in addition with TPC to extend the p_T coverage.





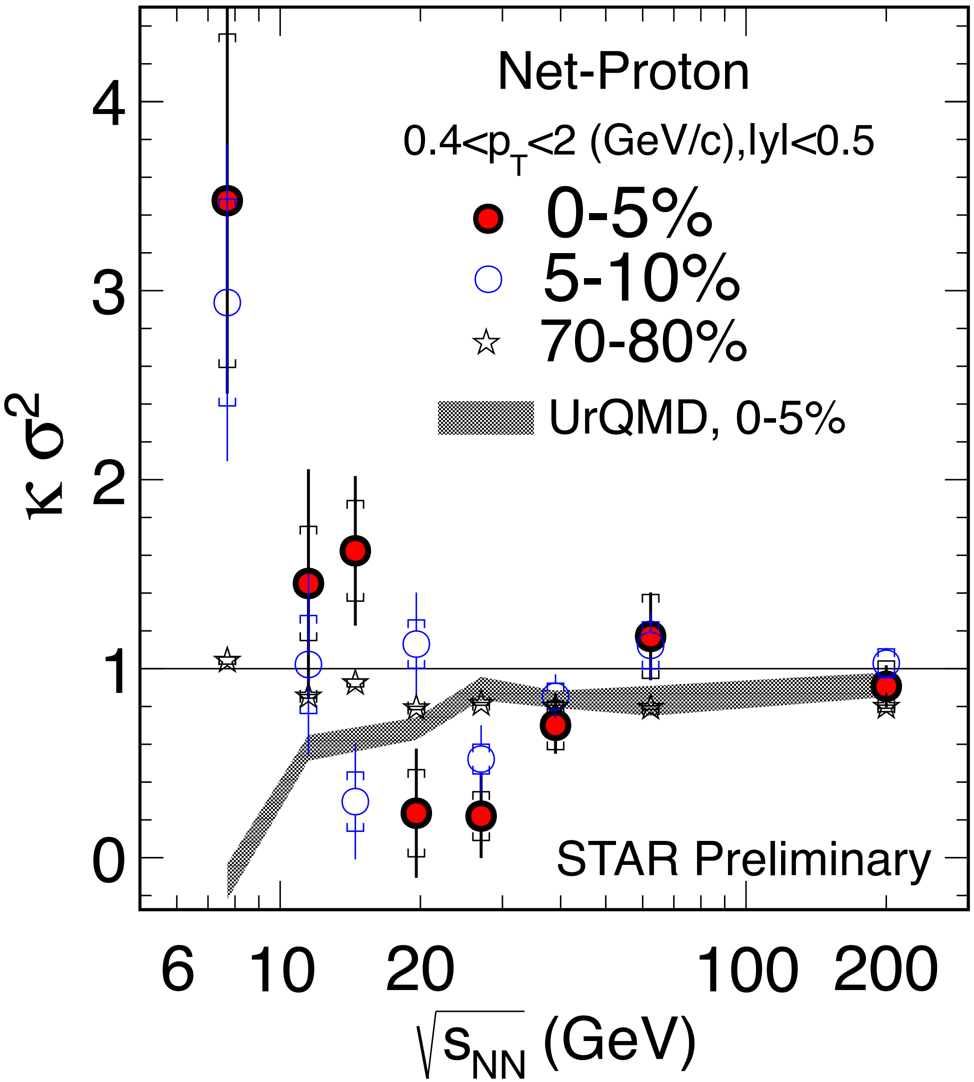
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

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): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

Forth Order Fluctuations: Net-proton



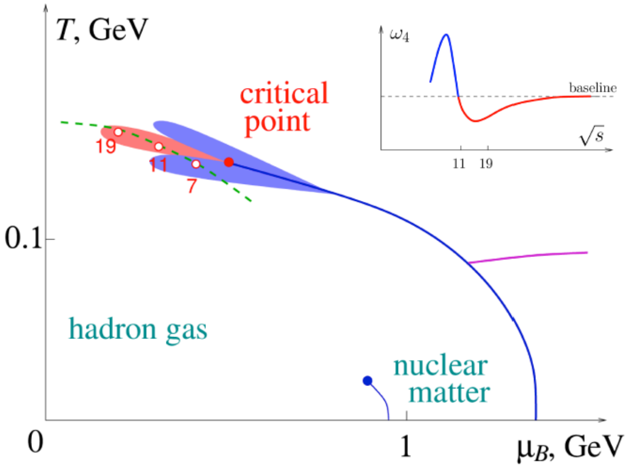
$$\kappa\sigma^2 = C_4/C_2$$

- Non-monotonic trend is observed for the 0-5% most central Au+Au collisions. Dip structure is observed around 19.6 GeV.
- Separating and flipping for the results of 0-5% and 5-10% centrality are observed at 14.5 and 19.6 GeV. (**Oscillation Pattern observed !**)
- UrQMD (no CP) results show suppression at low energies. Consistent with the effects of baryon number conservation.

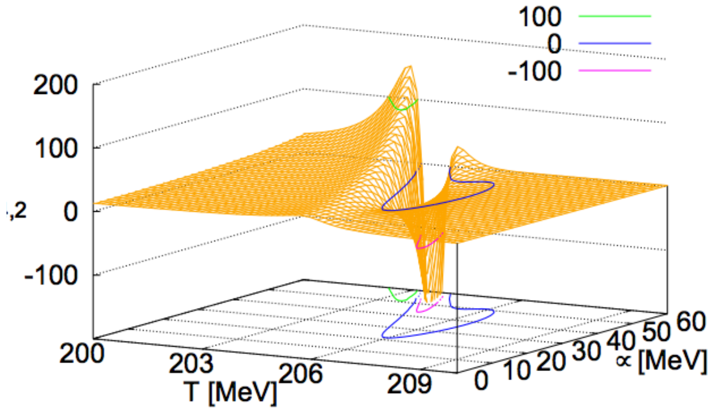
Systematic errors: 1) Uncertainties on efficiency, 2) PID, 3) Track Cuts.

Sign of Kurtosis :Model and Theoretical Calculations

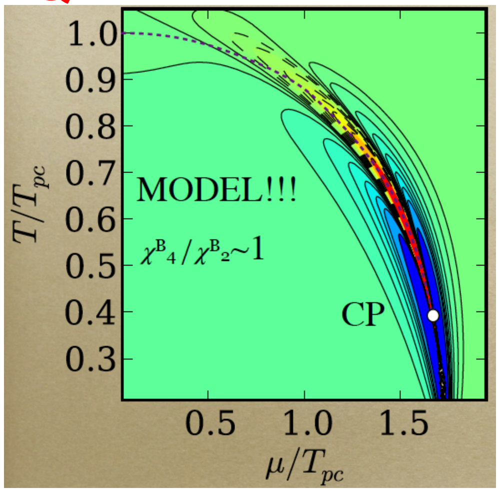
σ model M.A. Stephanov, PRL107, 052301 (2011).



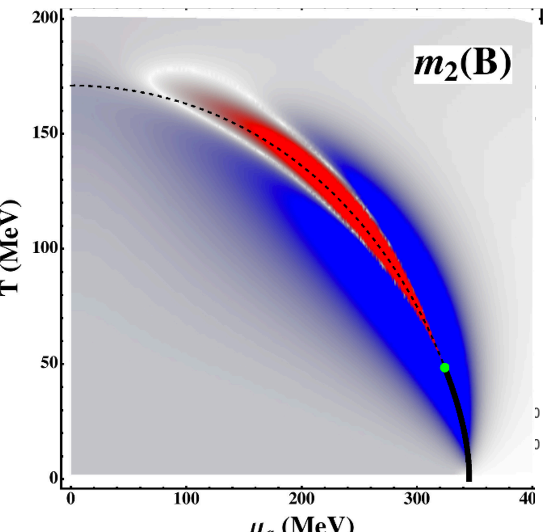
PQM Schaefer&Wanger, PRD 85, 034027 (2012)



PQM V. Skokov, QM2012

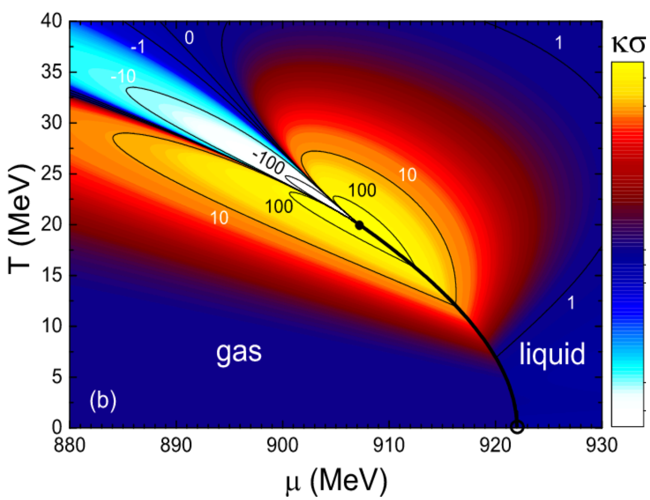


NJL



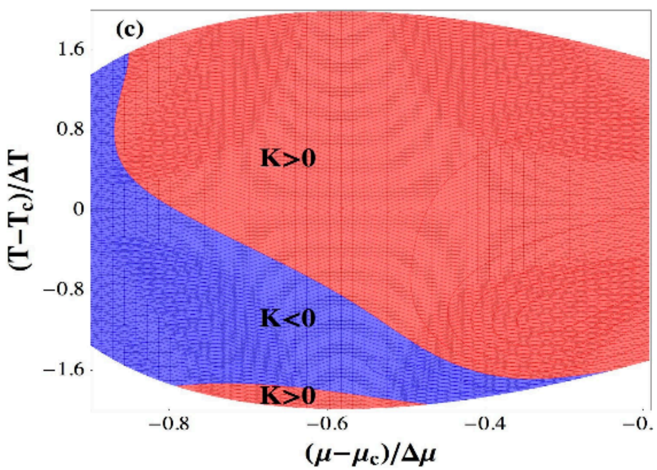
JW Chen et al., arXiv:1509.04968

VDW



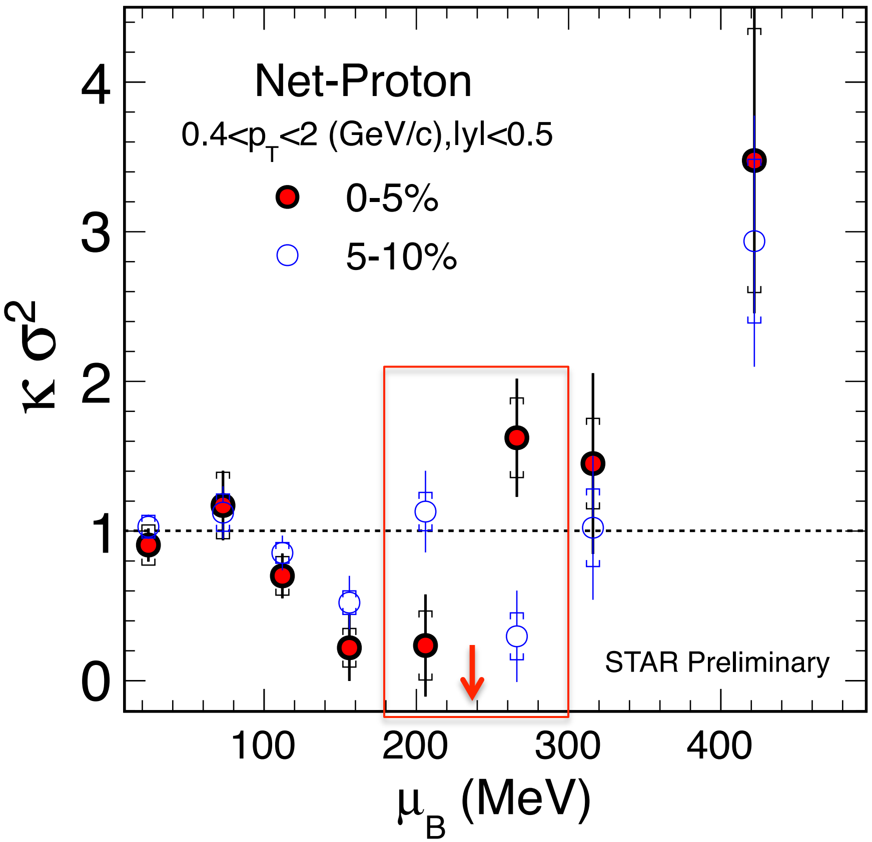
Vovchenko et al., arXiv:1506.05763

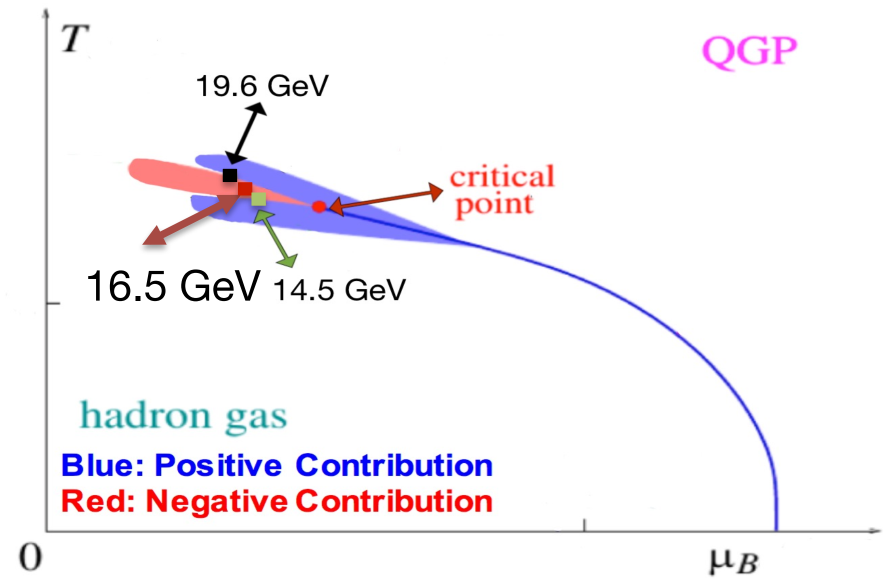
Memory Effects



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

Oscillation Pattern: Signature of Critical Region ?





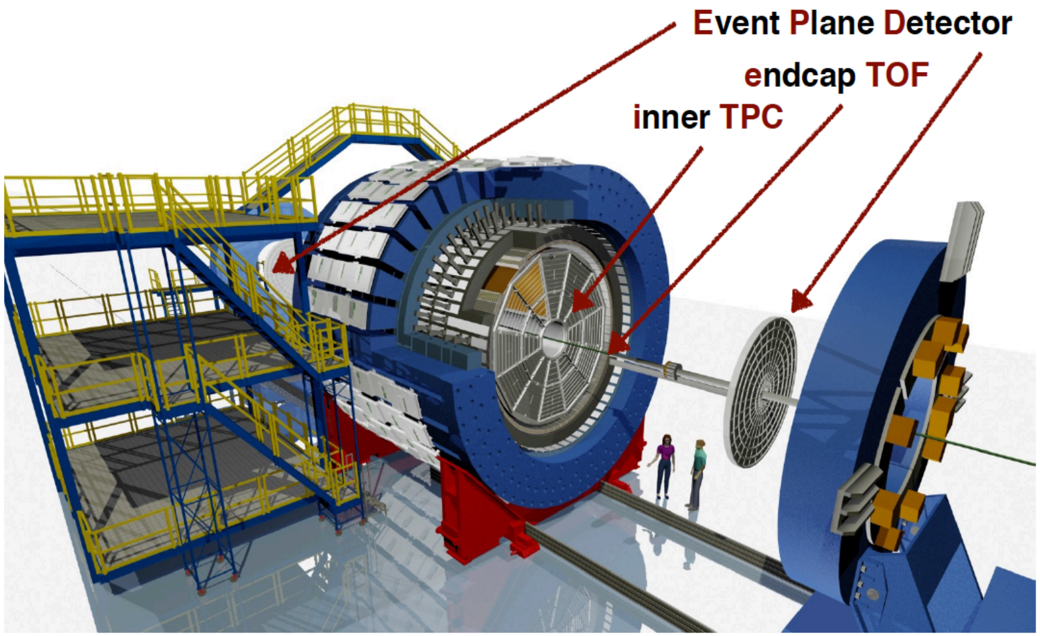
Depending on relative position between reaction trajectories/freeze out position and critical region.

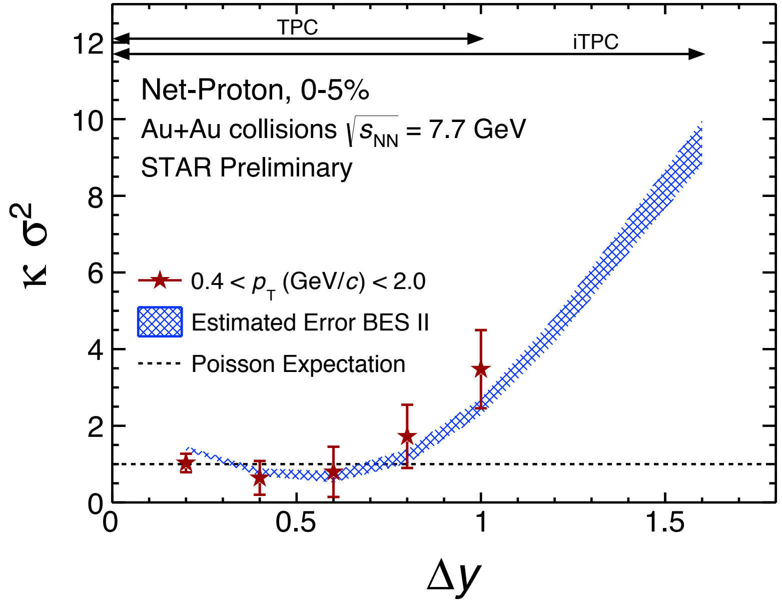
"Oscillation pattern" around baseline for Kurtosis **may indicate a signature of critical region.**

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

Propose to scan **16.5 GeV (μ_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

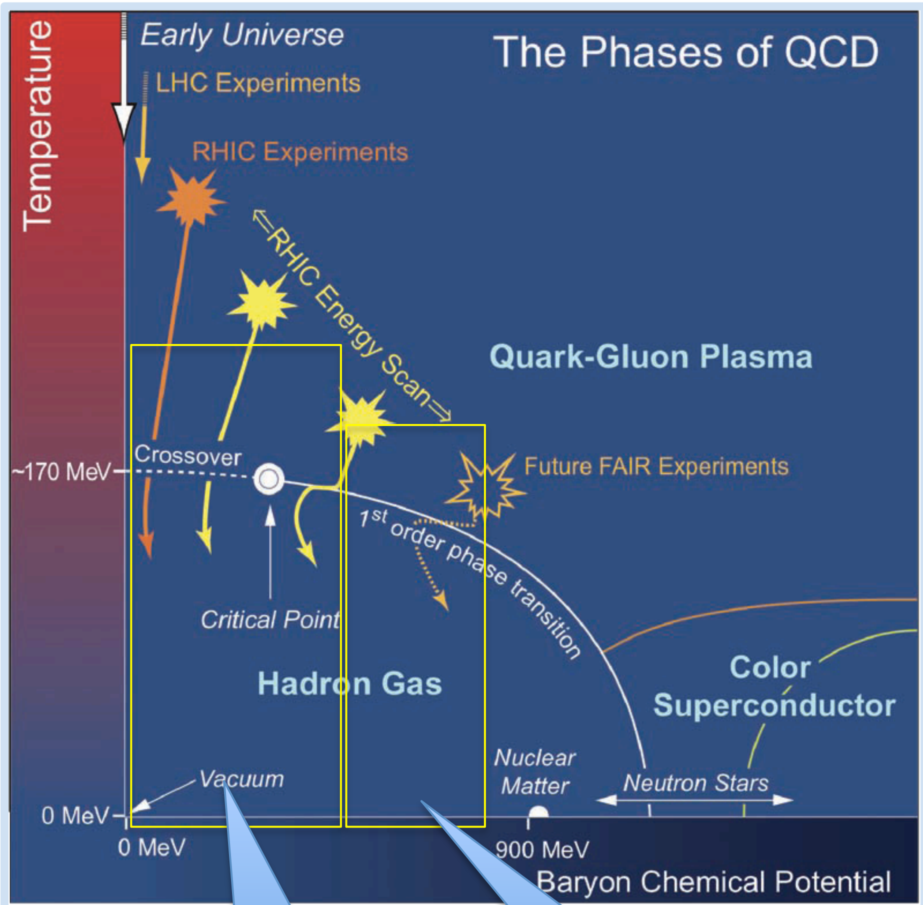
- Electron cooling upgrade will provide increased luminosity ~ 3-10 times.
- Inner TPC(iTPC) upgrade : |η| < 1 to | η |< 1.5. Better dE/dx resolution.
- Forward Event Plane Detector (EPD)：Centrality and Event Plane Determination. 1.8 < |η| < 4.5

Event Statistics for BES II at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

1) Event statistics driven by QCD CP search and di-electron measurements

Summary



RHIC BESII collider mode
200 < μ_B < 420 MeV

Fixed-target
400 < μ_B < 700 MeV

RHIC e-cooling and iTPC upgrades bring BES-II: a **new era** for study the QCD phase structure at high net-baryon region (200 < μ_B < 420 MeV).

Fixed-target experiment at extreme large net-baryon density, 2 < $\sqrt{s_{NN}}$ < 5 GeV for a systematic study of critical behavior with high precision.

Discovery potential at high baryon density region:

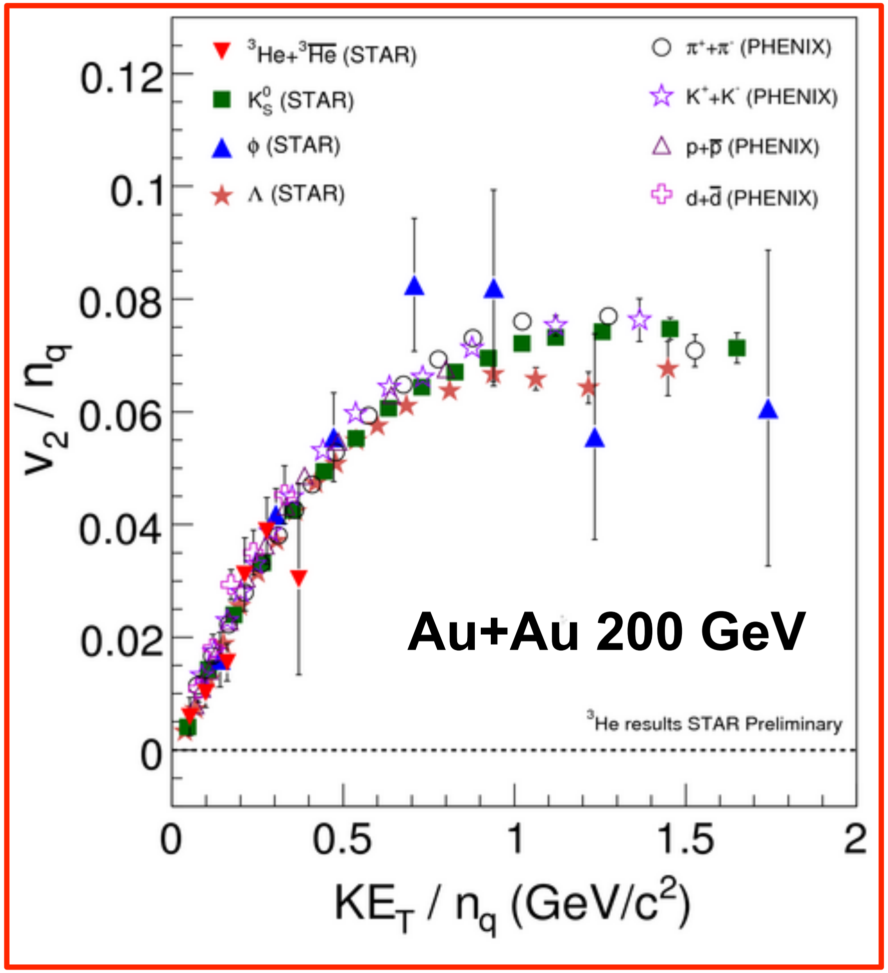
1) The QCD critical point (region) and phase boundary.

2) Properties with Chiral symmetry.

Thank you !

Establishing Quark Gluon Plasma (II): Partonic Collectivity

Number of constituent quark (NCQ) scaling

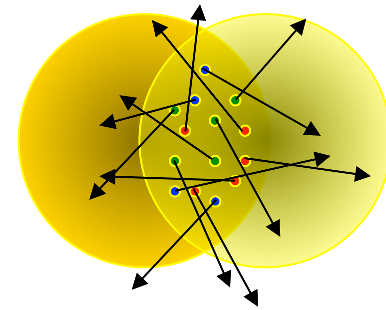


n_q = 2 for mesons

n_q = 3 for baryons

Initial spatial anisotropy

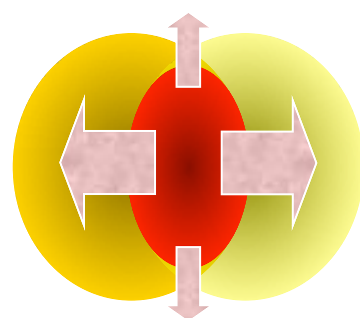
$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$



INPUT

Interaction among produced particles → Pressure Gradient

OUTPUT



Momentum Anisotropy $v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$

Partonic Collectivity at Early Stage.