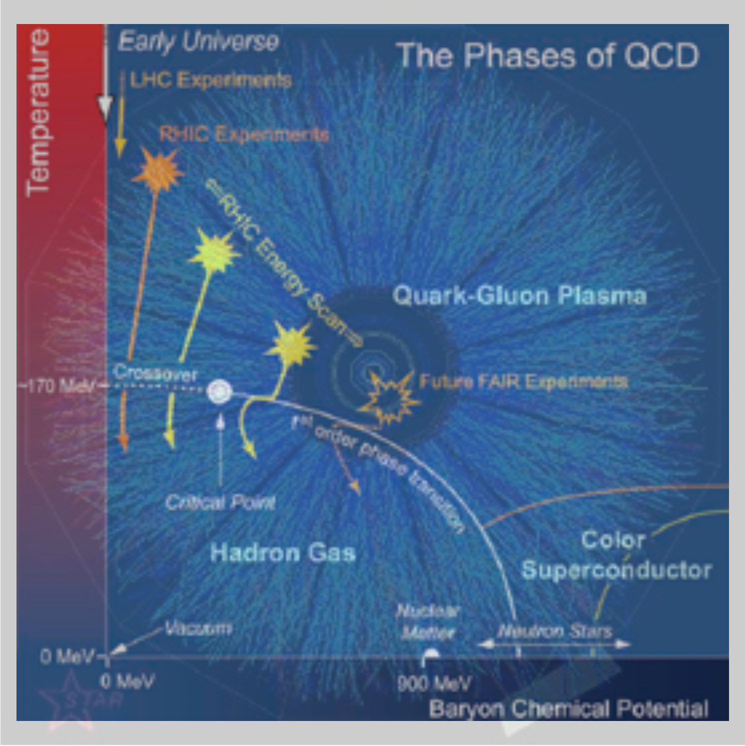
The Beam Energy Scan at RHIC



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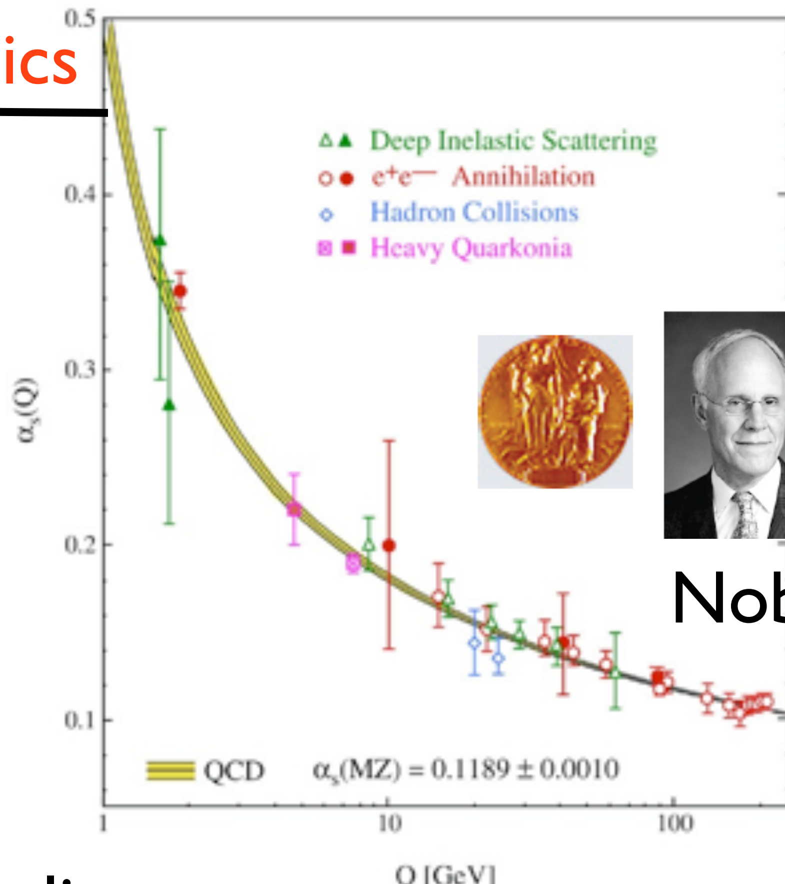
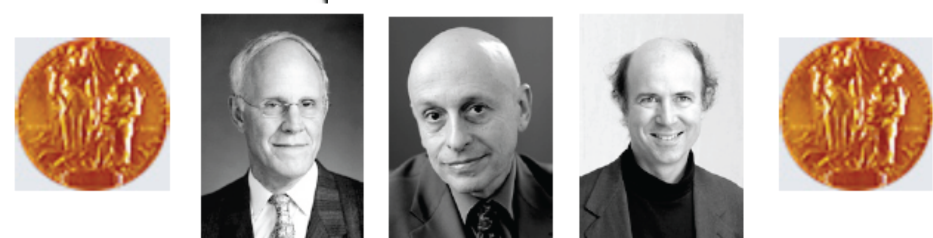
Outline

- Brief Intro: High Energy Heavy Ion Collisions
- The RHIC Beam Energy Scan
- EOS Toward Nonzero Density
- Summary

40 Years of Asymptotic Freedom

Nuclear Physics





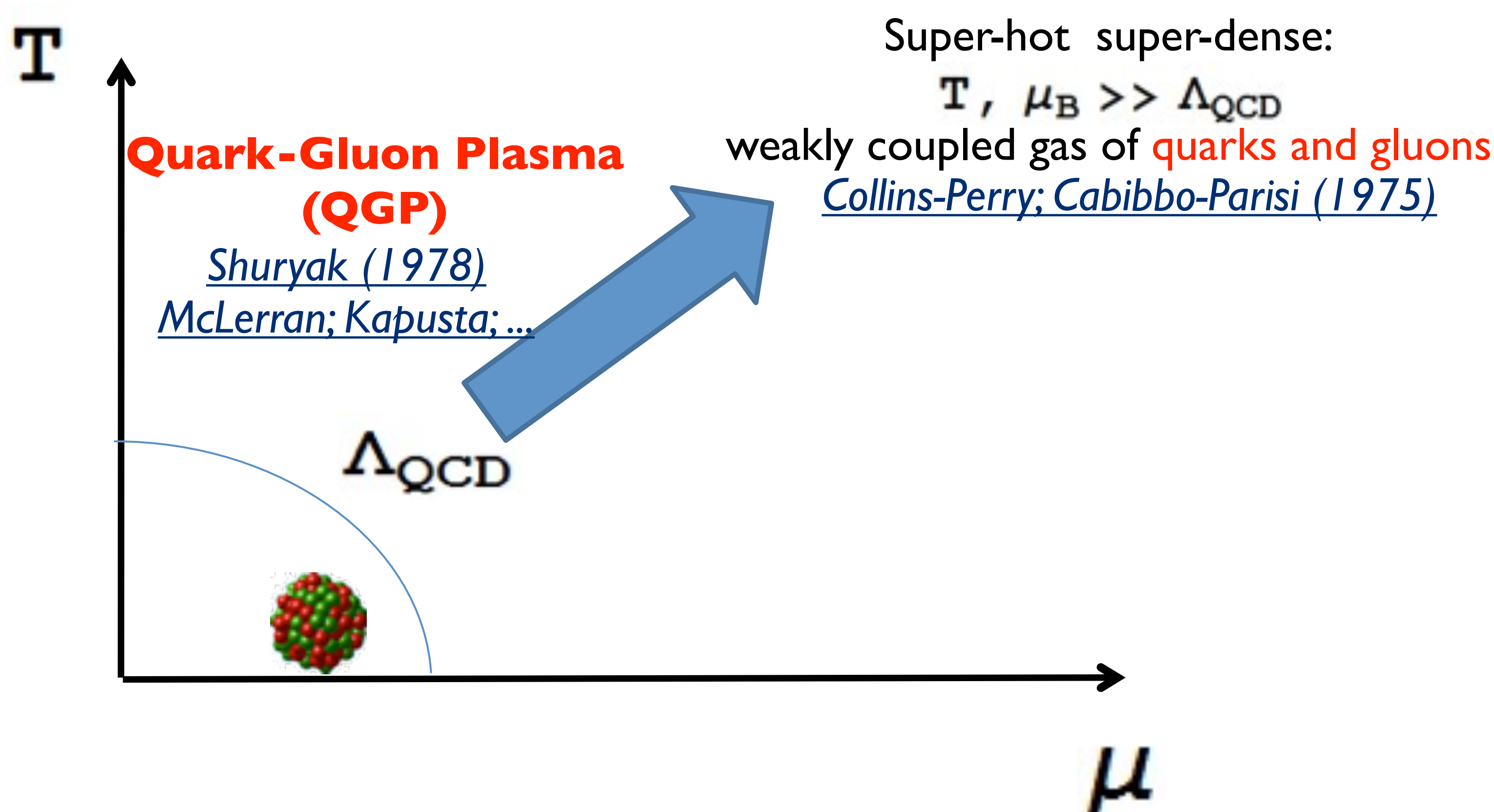
Nobel Prize 2004

Running coupling:

$$\alpha_s = g^2/4\pi$$

$$\alpha_s(r) = \frac{2\pi N_c}{(11N_c - 2N_f)\log(1/r\Lambda_{QCD})}$$

Asymptotically Free Matter



* There exists a limiting temperature/density for hadronic matter.
* Quark-gluon matter should be expected at very high temperature/density.
* Such early visions have developed into one of today's major frontiers in nuclear physics: **to study the "condensed matter physics of QCD"**.
* Major tools:

heavy ion collisions; lattice QCD; compact star observations; models...

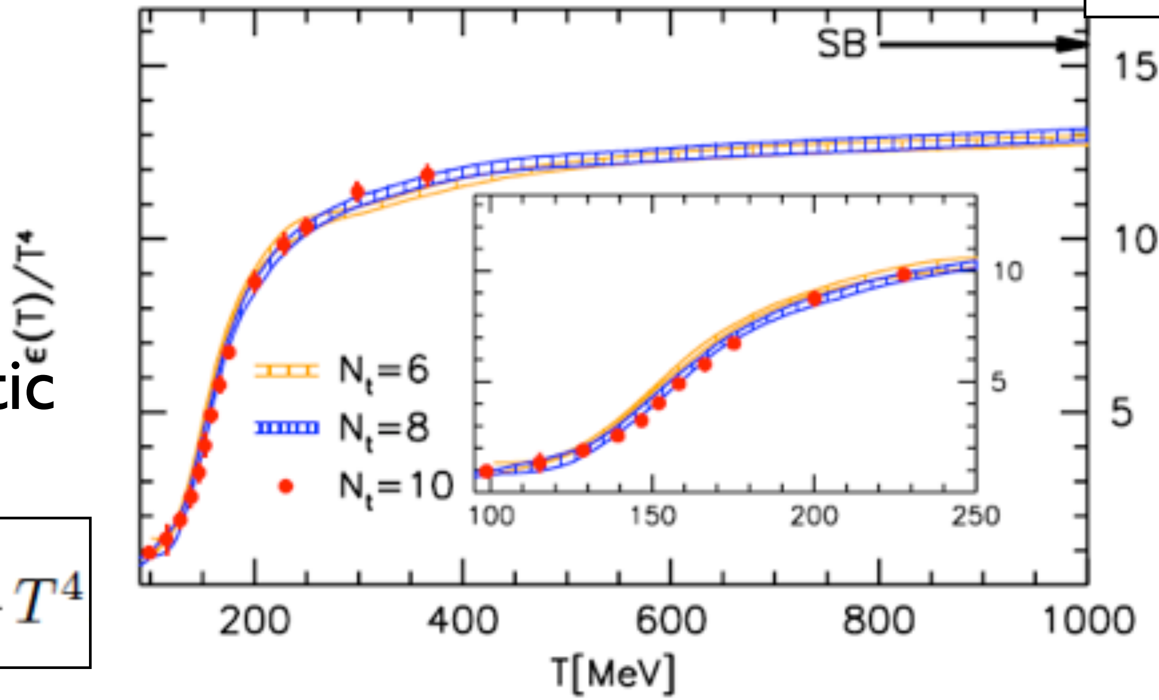
Thermodynamic Transitions

from Lattice QCD (Wuppertal-Budapest)

RHIC LHC

$$\epsilon = 47.5 \times \frac{\pi^2}{30} T^4$$

free QGP



a relativistic pion gas

$$\epsilon = 3 \times \frac{\pi^2}{30} T^4$$

More precisely,
Hadron Resonance Gas

* Two benchmarks at low/high T
* A transition regime in the middle
* Rapid CROSSOVER --- not 1st or 2nd

Heavy Ion Collisions

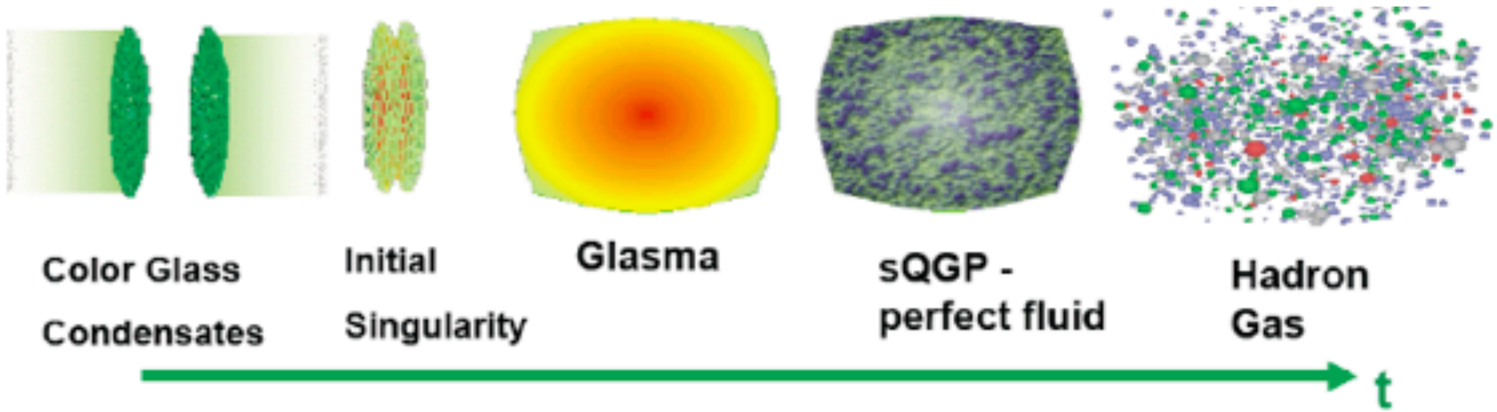
RHIC

LHC

Many others in the past and future:
AGS, SPS, CSR, NICA, FAIR, FRIB, ...

(I will be focusing on the high energy end.)

Some Basics of Heavy Ion Collisions

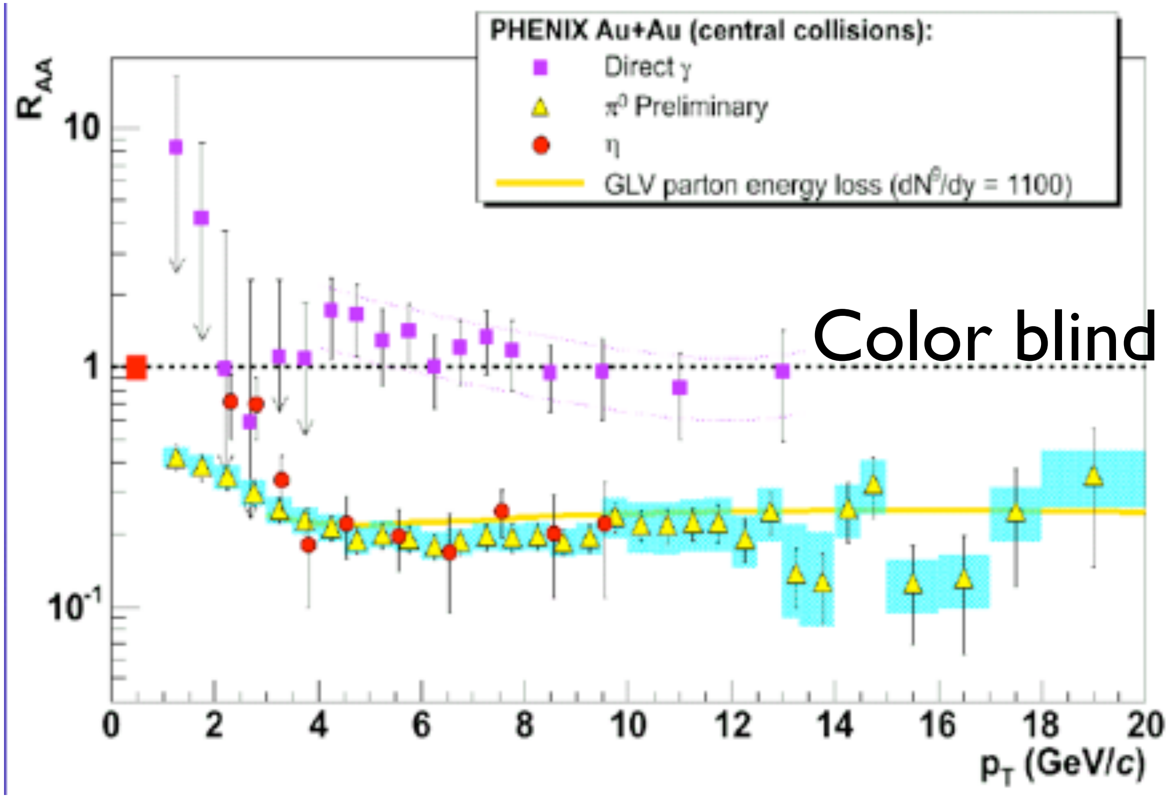


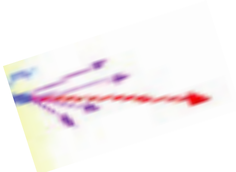
To give some ideas (taking Gold-Gold 200GeV at RHIC as example):

- 197 (79p+118n) nucleons colliding with 197 nucleons
  (Nuclei A as a handle)
- 100GeV/nucleon, 200GeV N-N C.M. energy, 42mb x-section
  (Collision Energy as a handle)
- 39TeV in, about 28TeV left in the middle → creating ~7500 particles
- **We observe the final state hadrons' identity and 3-momentum**
- Estimated initial temperature ~300MeV **(Trillion Kelvin)** > Tc ~170MeV
- Estimated initial energy density 5-10GeV/fm^3 > H.G. threshold 1GeV/fm^3

Involving the
Thermal (EoS,fluctuations,etc), Near-Thermal (transport, e.g. viscosity, q-hat), and Far-From-Thermal (the thermalization in galsma) properties of such strongly interacting quark-gluon matter

A Color-Opaque Plasma





Color blind probe

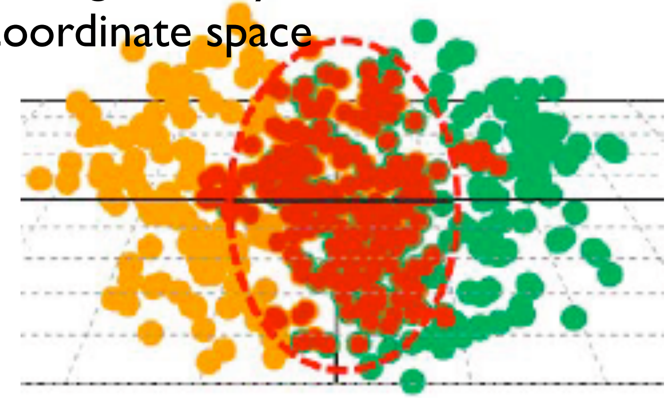
Colorful probe

$$R_{A\text{-}A}(p_t) \equiv \frac{d^2N^{A\text{-}A}/dp_t d\eta}{T_{A\text{-}A} d^2\sigma^{N\text{-}N}/dp_t d\eta}$$

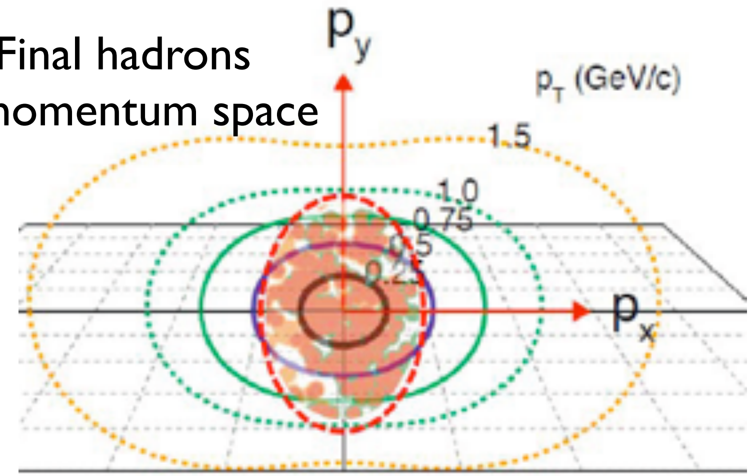
Strong jet quenching:
a qualitatively different medium

The Nearly Perfect Fluid

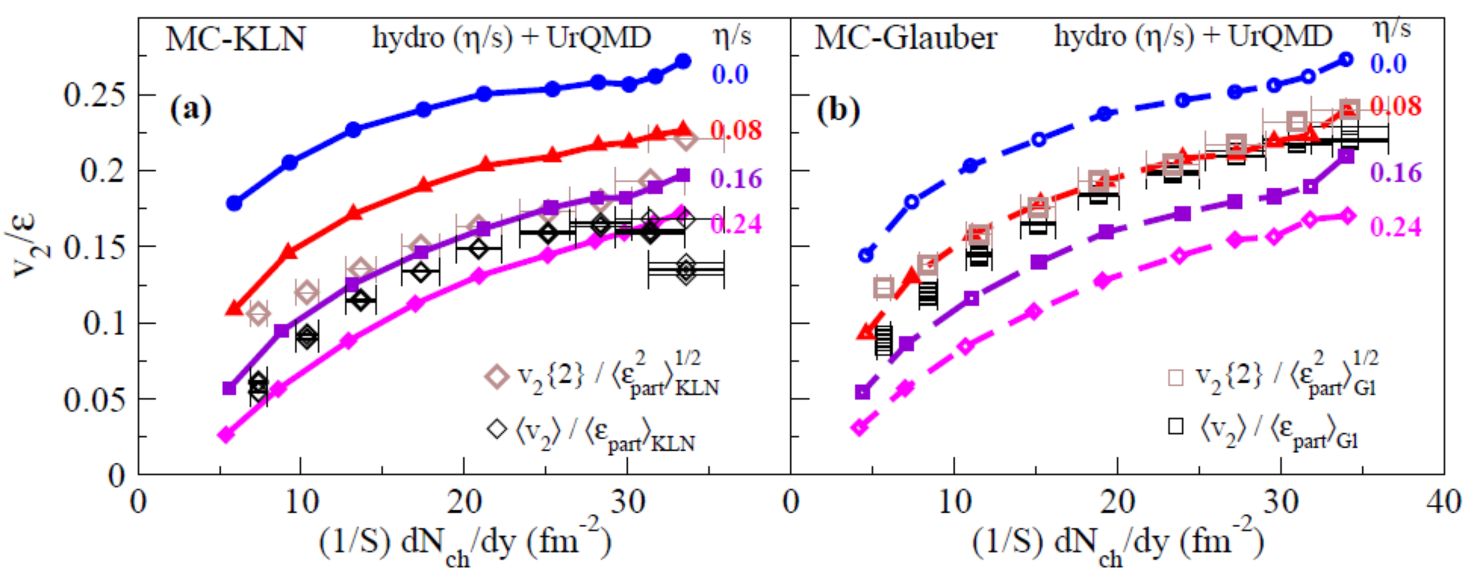
Initial geometry in coordinate space



Final hadrons in momentum space

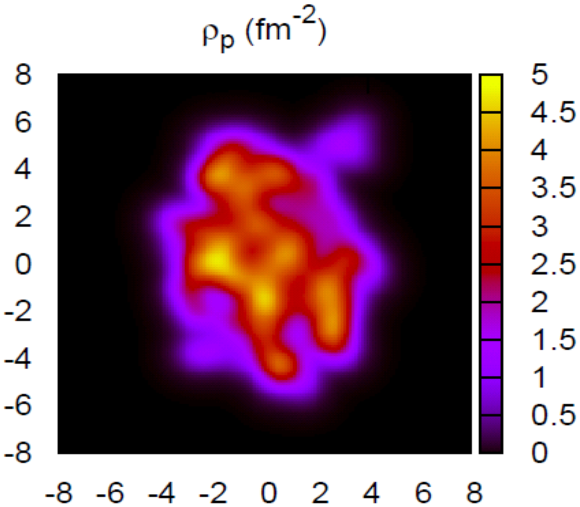


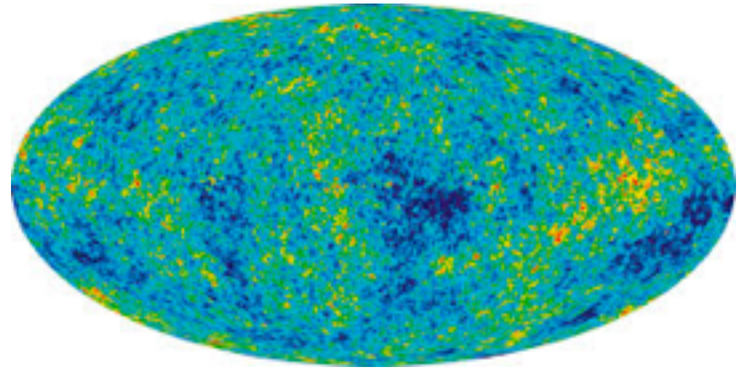
Collective Flow: sensitive to viscosity!

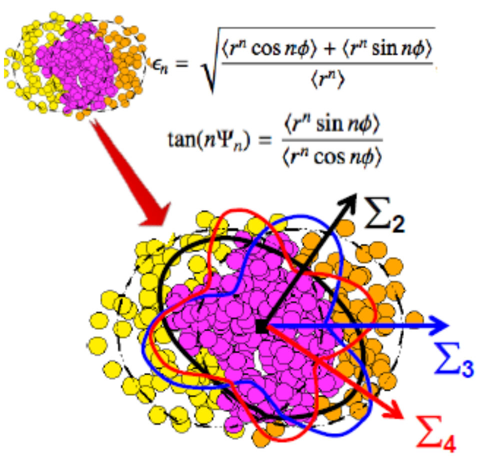


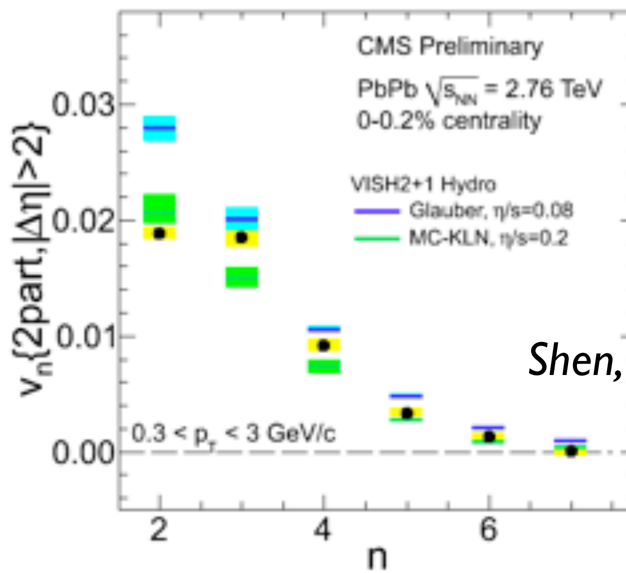
from: Heinz, et al

The Nearly Perfect Fluid







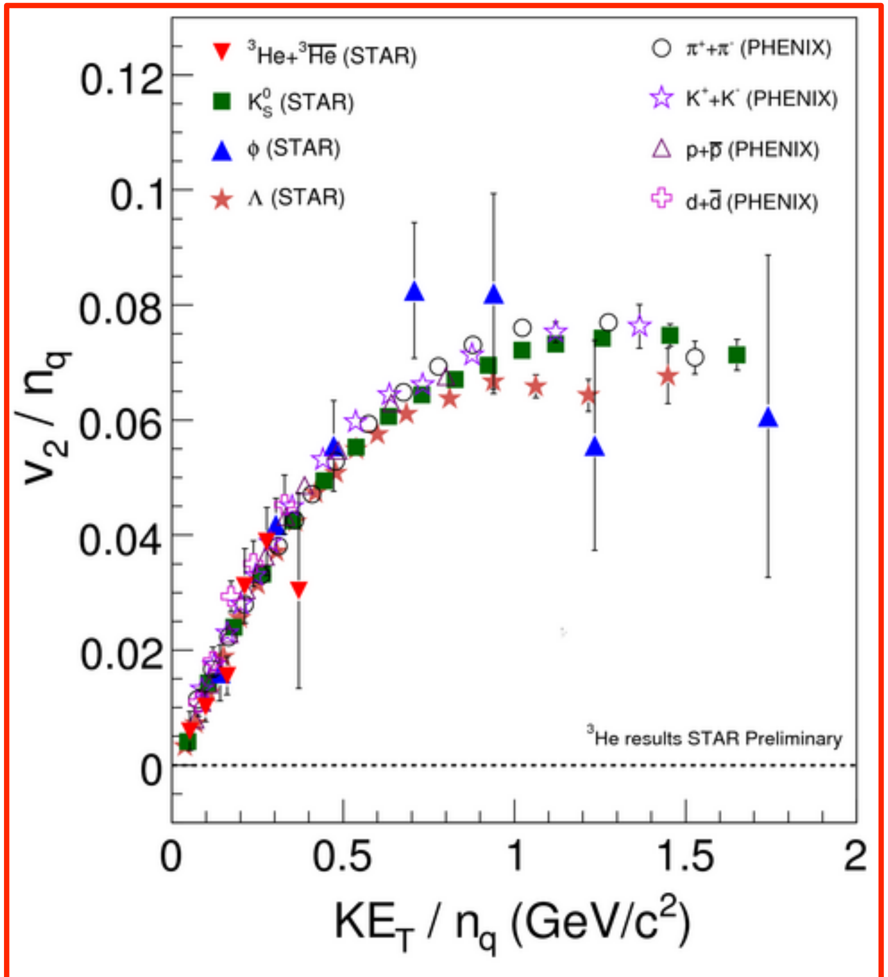


Shen, Qiu, Heinz

The fluid is so perfect that it even carries initial state fluctuations toward final state harmonic flow! --- **strong constraints on shear viscosity!**

$$\frac{1}{4\pi} < \left\{\frac{\eta}{s}\right\}_{QGP} < \frac{2.5}{4\pi}$$

Partonic Collectivity



The observed flow of various hadrons scales with the Number of Constituent Quarks (NCS)!

(Even for phi and Omega)

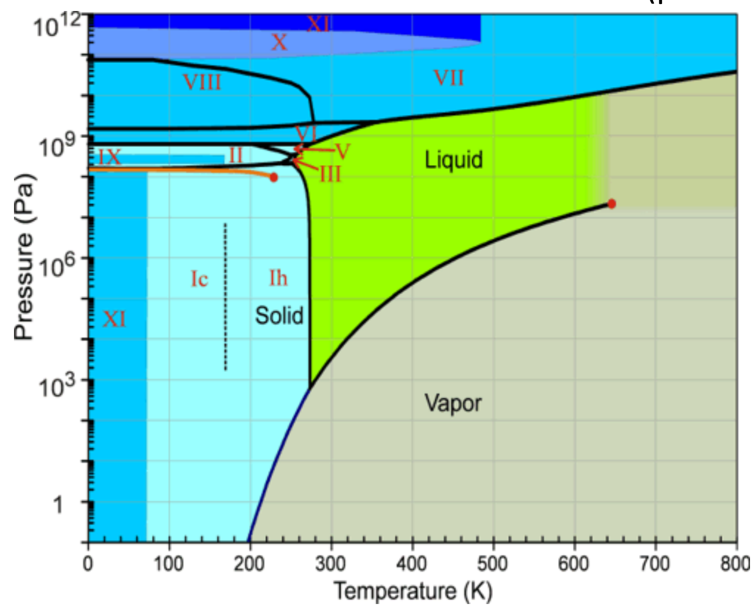
Strong evidence for a significant partonic stage where the flow is developed.

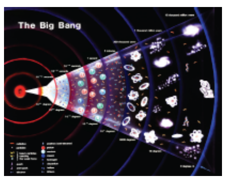
The Beam Energy Scan at RHIC

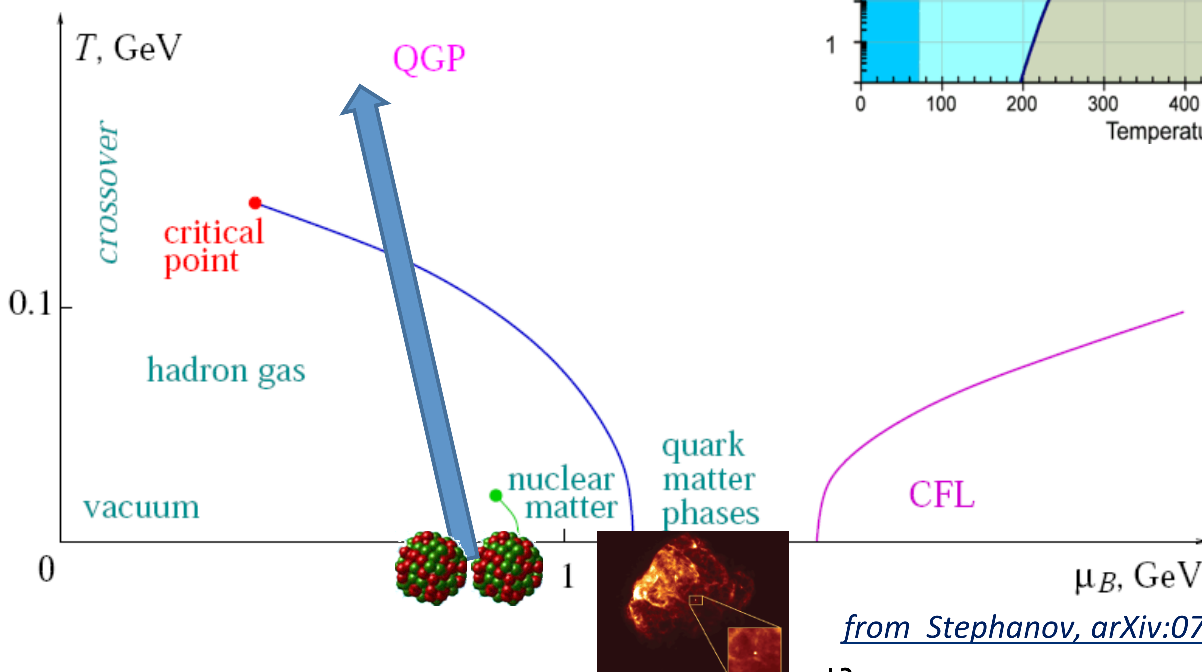
Explore Phase Diagram of QCD

Can we know as much about QCD matter as we know about water?

(phase diagram of water)



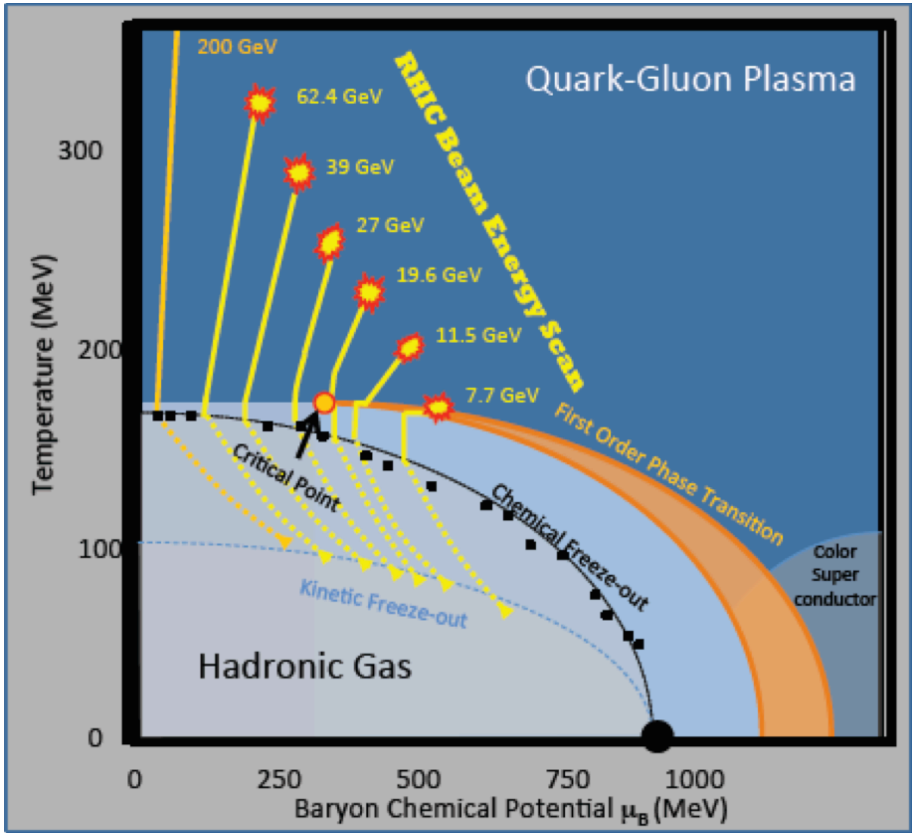




from Stephanov, arXiv:0701002

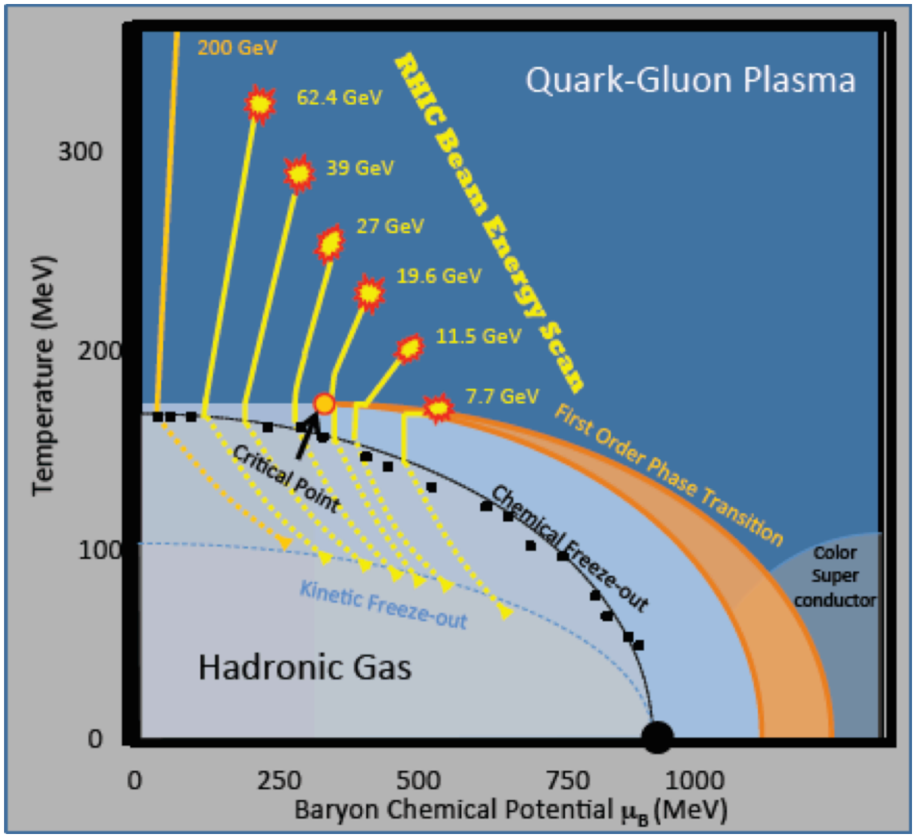
Different regions are connected by one and same QCD theory!

Physics Motivation



* To reach the high baryon density regime
* To map out the parton/hadron phase boundary
* To search for a possible critical end point (CEP)

BES Runs



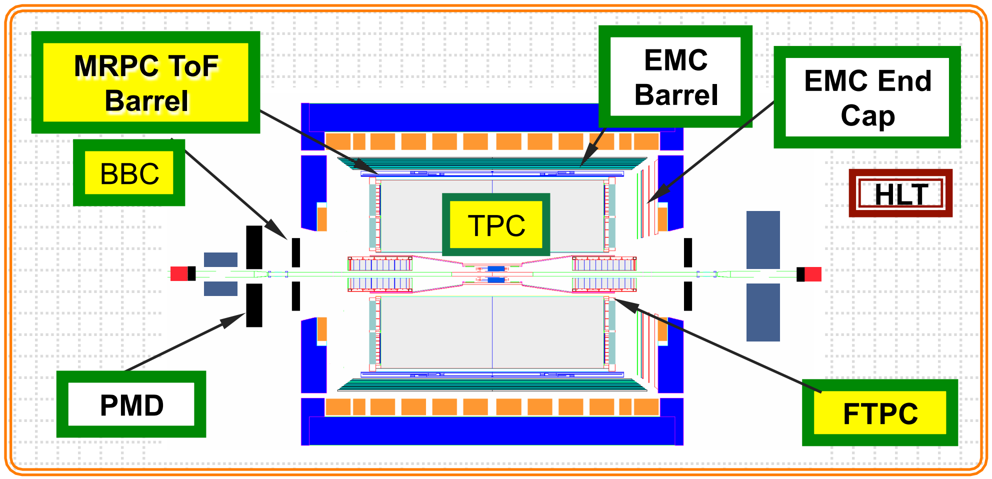
* RHIC top energy:
200 GeV (130 GeV)

* Beam Energy Scan
(BES Phase-I)
2010 (Run10):
62.4 GeV; 39 GeV; 7.7 GeV
2011 (Run11):
27 GeV; 19.6 GeV

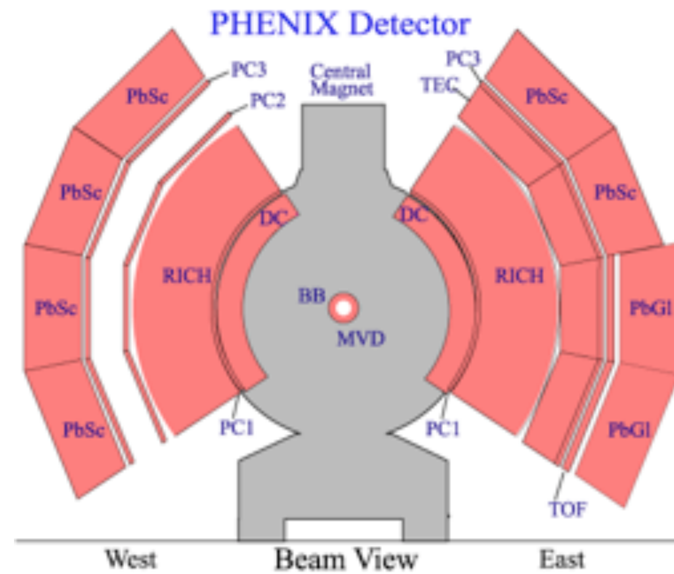
* Beam Energy Scan
(Phase-II) 2015~2017:
~10 times more luminosity;
additional collision energies;
other species? fixed target?

Measurements

STAR

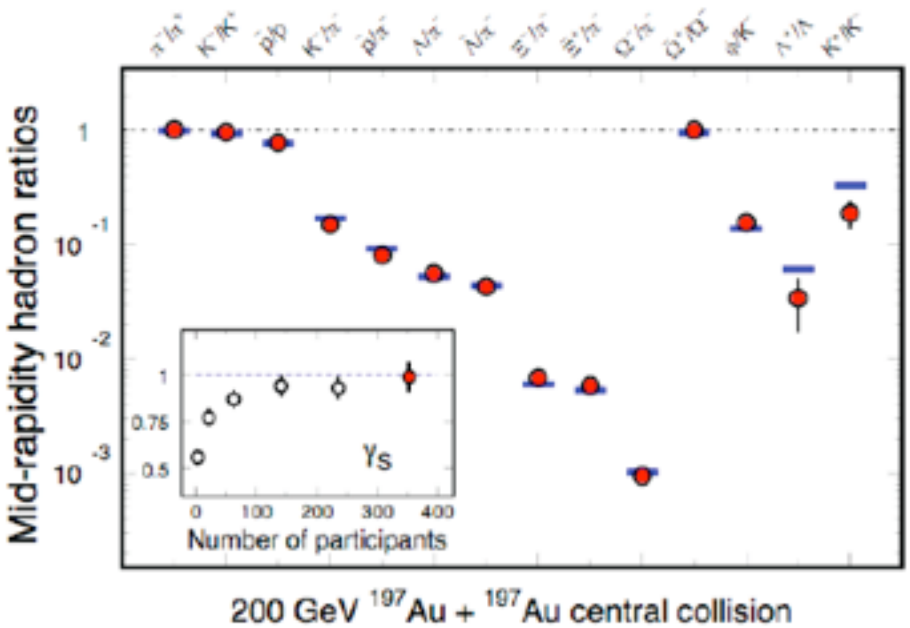


PHENIX

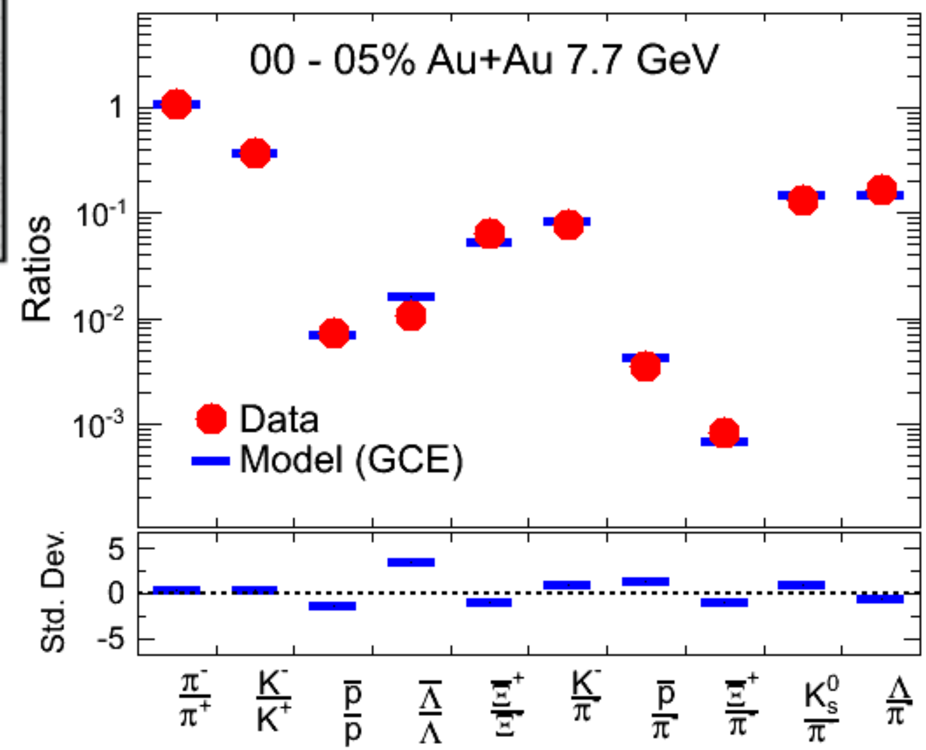


Many particle species have been measured:
pions, kaons, protons, Xi, Lambda, phi, Omega, heavy flavor;
yields, flow, correlations,...

Particle Ratios

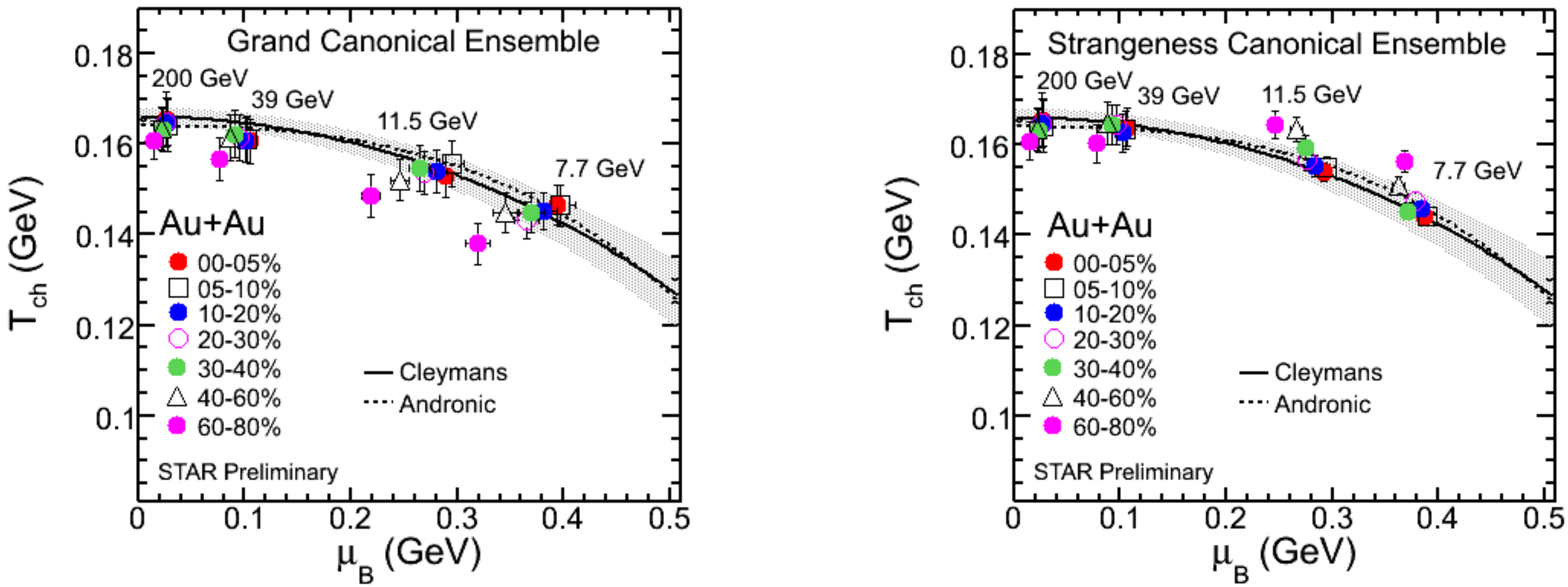


pi-/pi+: not much change
p-bar/p: clear decrease



from: STAR

Chemical Freeze-Out Condition



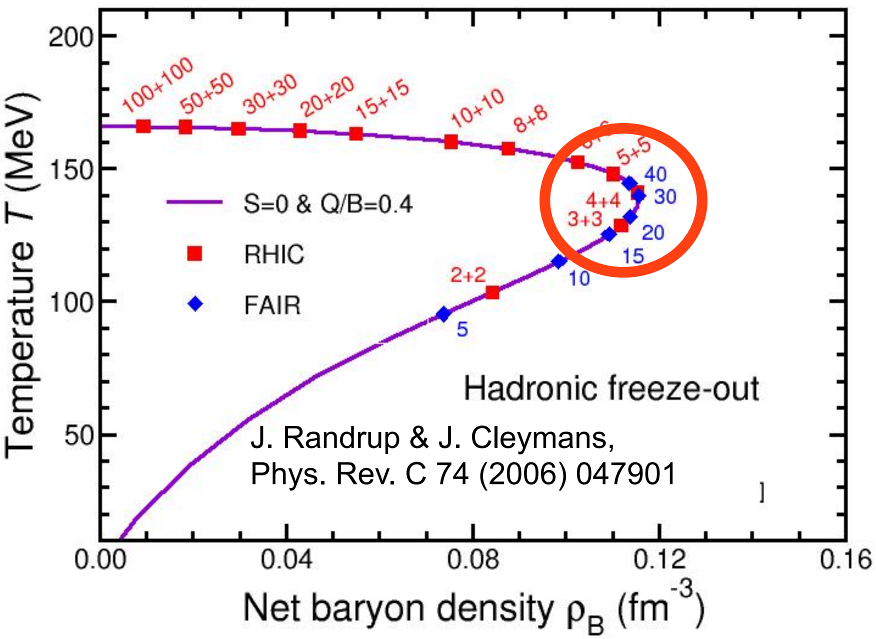
$$T[\mathrm{MeV}] = T_{lim}\left(1 - \frac{1}{0.7 + (\exp(\sqrt{s_{NN}}(\mathrm{GeV})) - 2.9)/1.5}\right)$$

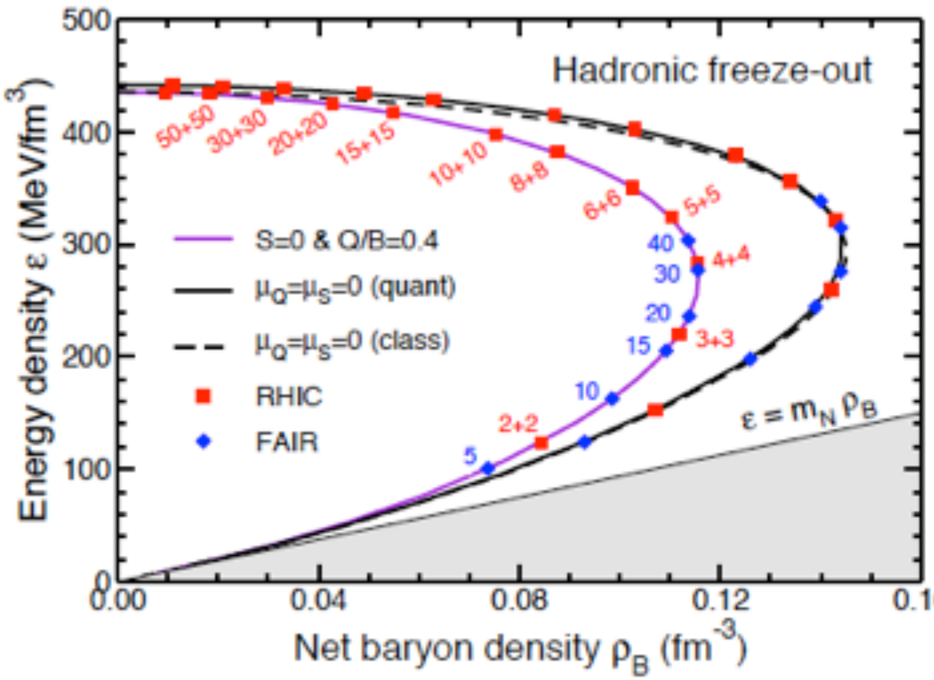
$$\mu_b[\mathrm{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\mathrm{GeV})},$$

$$a = 1303 \pm 120 \text{ MeV and } b = 0.286 \pm 0.049 \text{ GeV}^{-1}$$

Andronic, et al, arXiv:0511071

How Far Can We Reach?

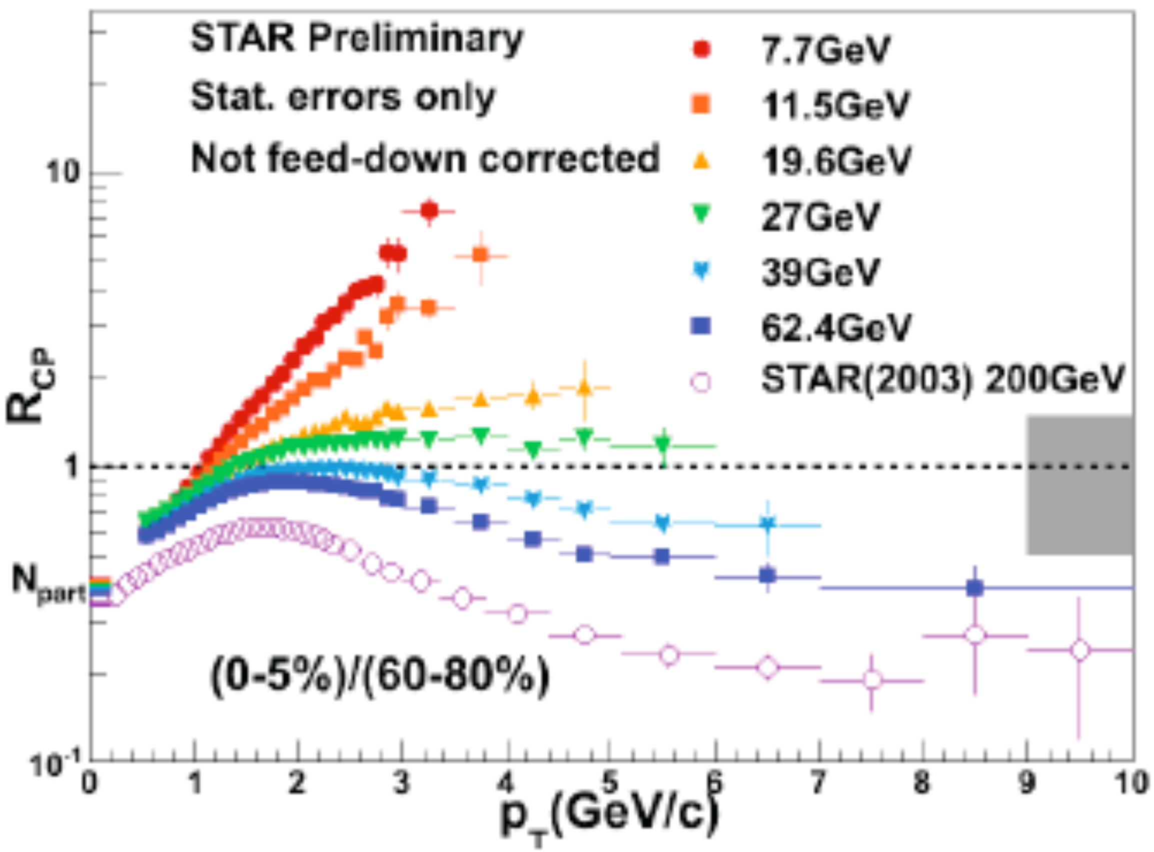




Computed with freezeout parameters, assuming hadron resonance gas model

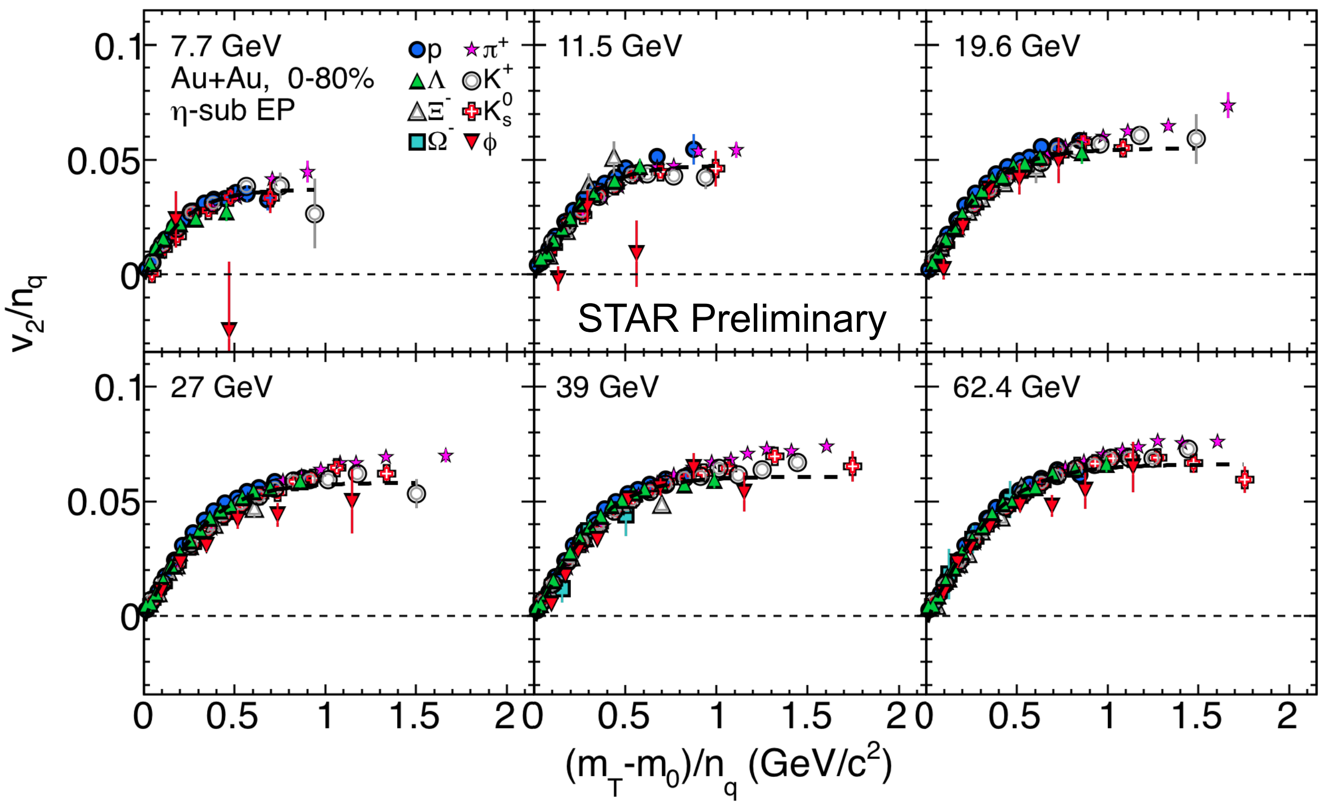
Randrup & Cleymans, arXiv:0607065

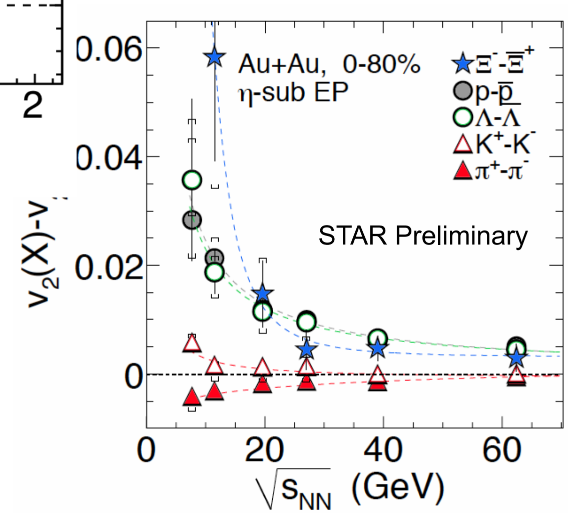
Phase Boundary: Jet Quenching



Suppression turning off around 10~20GeV

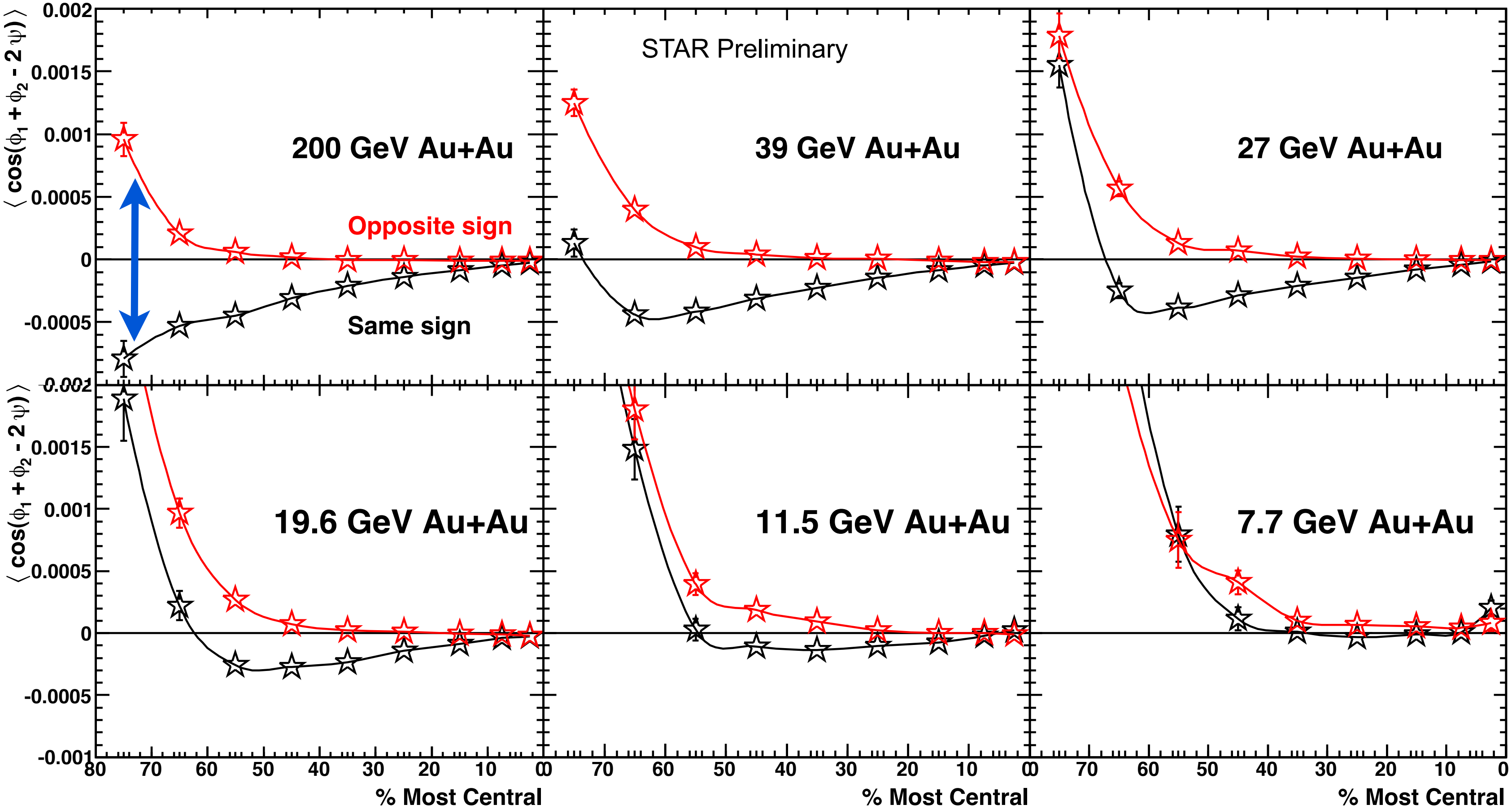
Phase Boundary: NCQ Scaling





Partonic collectivity turing off around 10~20GeV

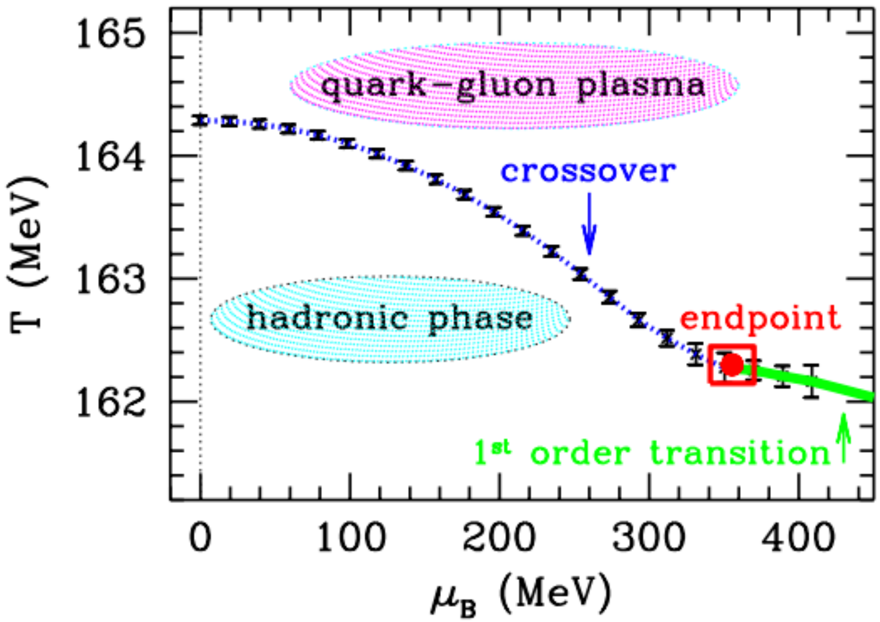
Dynamical Correlations



* Azimuthal angle correlations of same-charge and opposite-charge pairs
* The same-/opposite-charge pair correlations' difference may come from mechanisms specific to QGP formation (e.g. Chiral-Magnetic-Effect)
* Such difference disappears around 10~20GeV

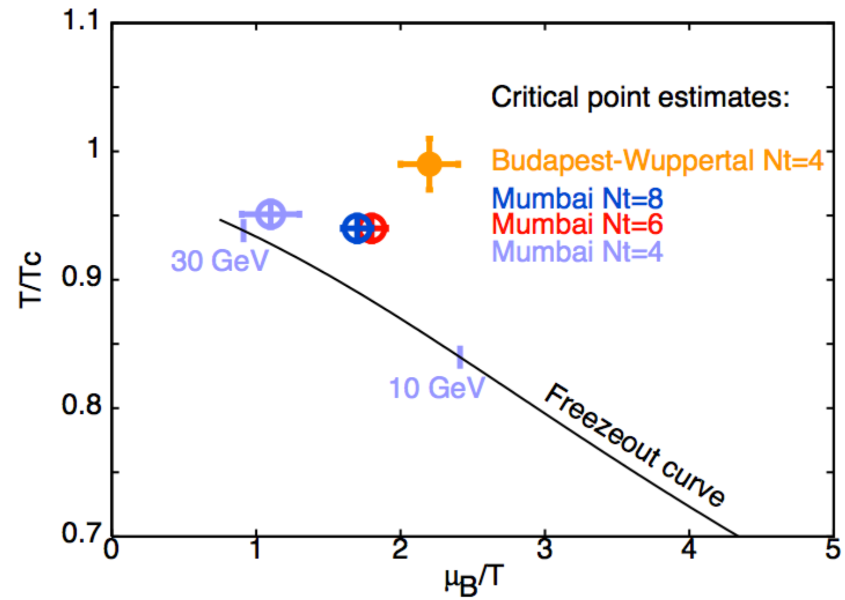
The QCD Critical End Point (CEP)

Fodor&Katz, 2004



T_E=162+/-2 MeV
μ_E=360+/-40 MeV

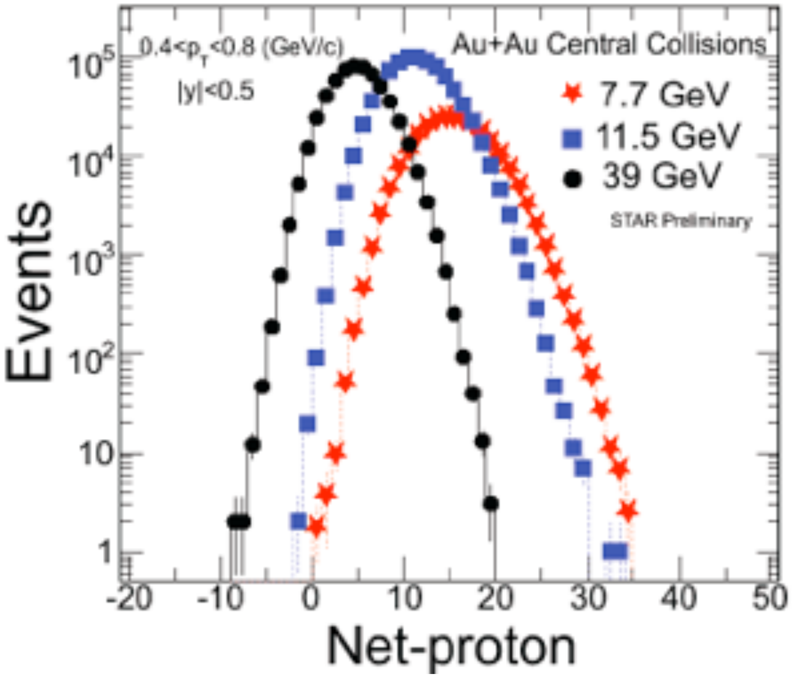
Gavai&Gupta, 2008



T_E/T_c=0.94+/-0.01
μ_E/T_E=1.8+/-0.1

Experimentally accessible region!

Observables for CEP



Look for specific patterns of conserved charge fluctuations which scale with correlation length (Stephanov)

$$< (\delta N)^2 > \sim \xi^2 \qquad < (\delta N)^3 > \sim \xi^{4.5}$$

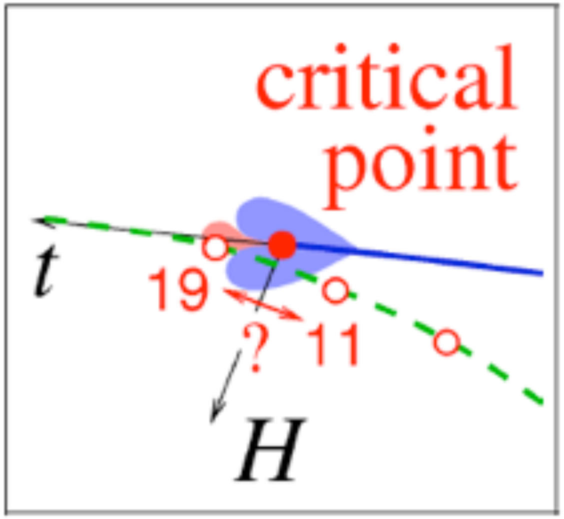
$$< (\delta N)^4 > - \ 3 < (\delta N)^2 >^2 \sim \xi^7$$

Skewness

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

Kurtosis

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



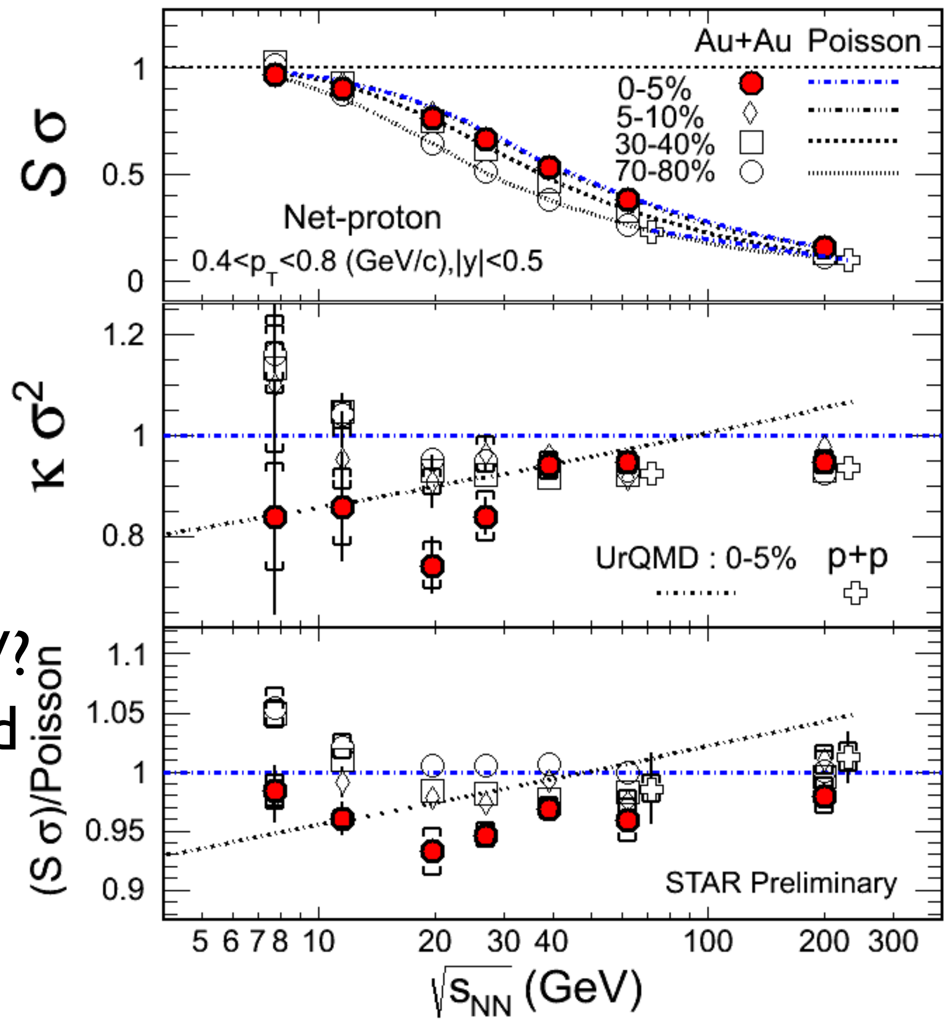
Non-monotonic dependence of skewness with collision energy

Results from BES

$$\sigma = \sqrt{<(N-<N>)^2>}$$

$$s = \frac{<(N-<N>)^3>}{\sigma^3}$$

$$\kappa = \frac{<(N-<N>)^4>}{\sigma^4} - 3$$

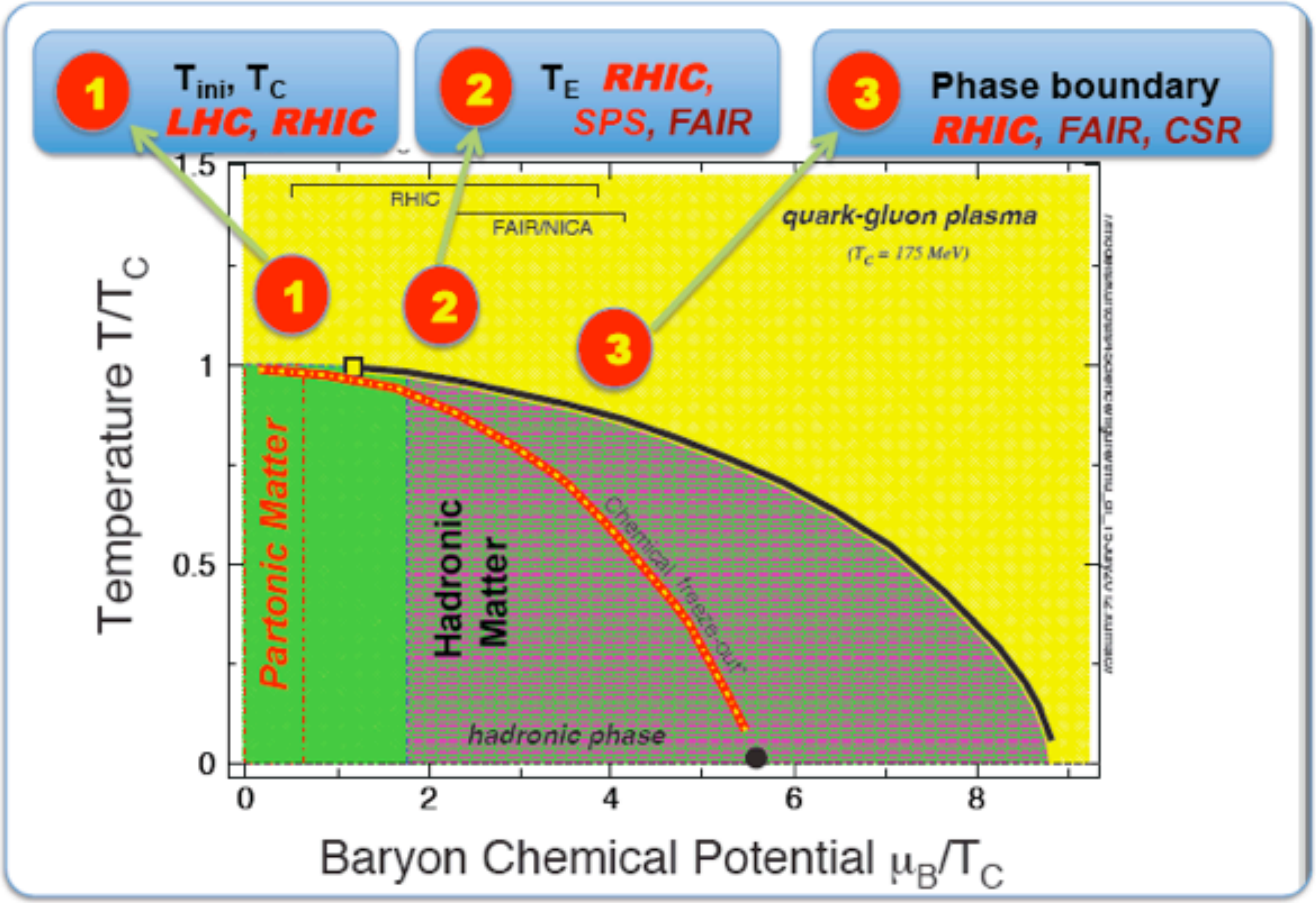


Indications around 10~20GeV?

--- Not conclusive and in need of more data.

--- Also caveats (e.g. only measuring net protons)

Exploring Phases of QCD



from: Nu Xu

EOS Toward Nonzero Density

Charge Fluctuations & Correlations

Conserved charges in QCD:

Baryon number, Isospin, Strangeness, Electric Charge, ...

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q;$$
$$\mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q;$$
$$\mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S.$$

$$\frac{p}{T^4} = \frac{1}{VT^3}\ln Z(V,T,\mu_B,\mu_S,\mu_Q)$$

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}p/T^4}{\partial(\mu_B/T)^l\partial(\mu_S/T)^m\partial(\mu_Q/T)^n}.$$

Susceptibilities

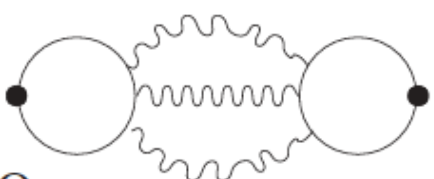
$$Z \sim \int [\ldots]e^{-\mu_X N_X}e^{-\mu_Y N_Y}[...]$$

O$_2$

$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2\rangle$$

$$\partial^2_{\mu_X} Z \sim \int [\ldots]N_X^2 e^{-\mu_X N_X}e^{-\mu_Y N_Y}[...] \sim < N_X^2 >$$

$$\partial_{\mu_X}\partial_{\mu_Y} Z \sim \int [\ldots]N_X N_Y e^{-\mu_X N_X}e^{-\mu_Y N_Y}[...] \sim < N_X N_Y >$$



O$_{11}$

$$\chi_{11}^{XY} = \frac{1}{VT^3}\langle N_X N_Y\rangle$$

Taylor expansion can be used to extrapolate to nonzero density!

Two Benchmarks of The Susceptibilities

Let us take baryonic number fluctuation as an example,
and examine two simple cases:

A gas of heavy fermions with charge B (e.g. as baryonic gas)

$$n_B^{\rm free}|_{\rm NR} = B N_i \left(\frac{MT}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{M}{T}} [e^{\frac{B\mu}{T}} - e^{-\frac{B\mu}{T}}],$$

$$d_n^{\rm free}|_{\rm NR} = N_i \left(\frac{M}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{M}{T}} \times 2B^n \equiv \mathcal{F}\left[\frac{M}{T}\right] B^n.$$

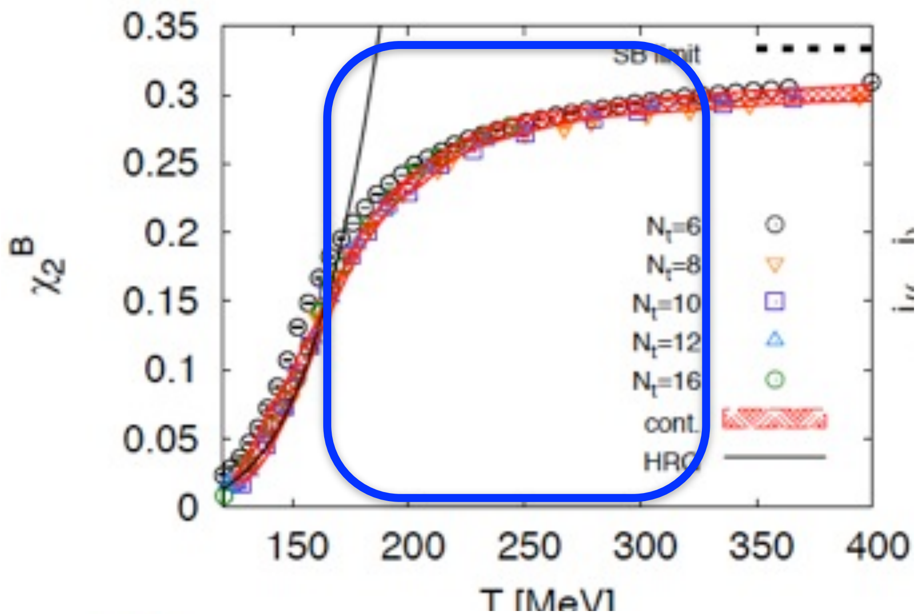
A gas of massless fermions with charge B (e.g. as S.B. limit)

$$n_B^{\rm free}|_{\rm UR} = N_i \frac{T^3}{6\pi^2}\left[B^4\left(\frac{\mu}{T}\right)^3 + \pi^2 B^2 \left(\frac{\mu}{T}\right)\right],$$

$$d_2^{\rm free}|_{\rm UR} = N_i \frac{B^2}{6}, \qquad d_4^{\rm free}|_{\rm UR} = N_i \frac{B^4}{\pi^2}, \qquad d_{n>4}^{\rm free}|_{\rm UR} = 0.$$

N-th order susceptibilities ~ B^n : quarks B=1/3, baryons B=1

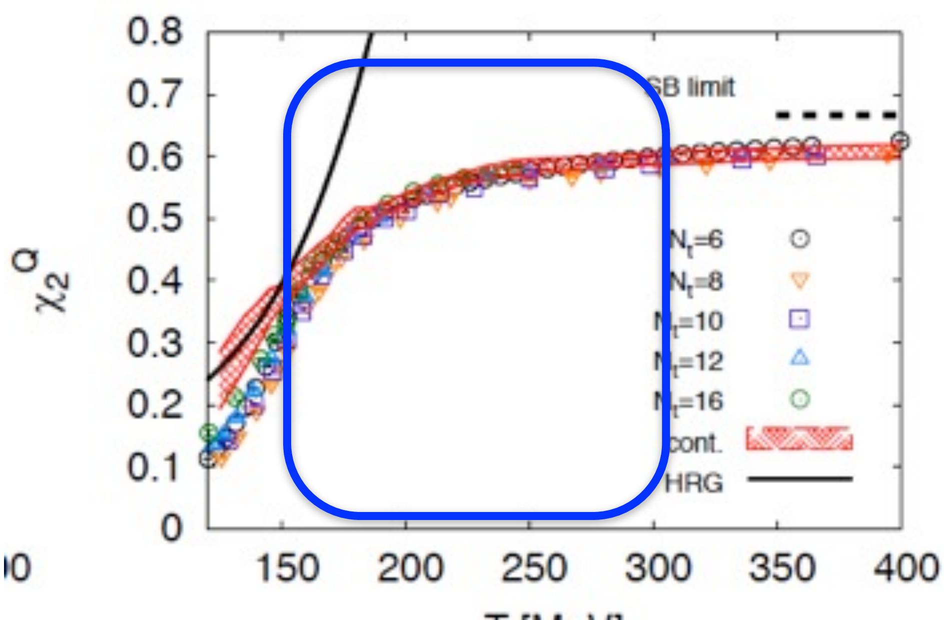
Quadratic Susceptibilities from (2+1)-f Lattice QCD

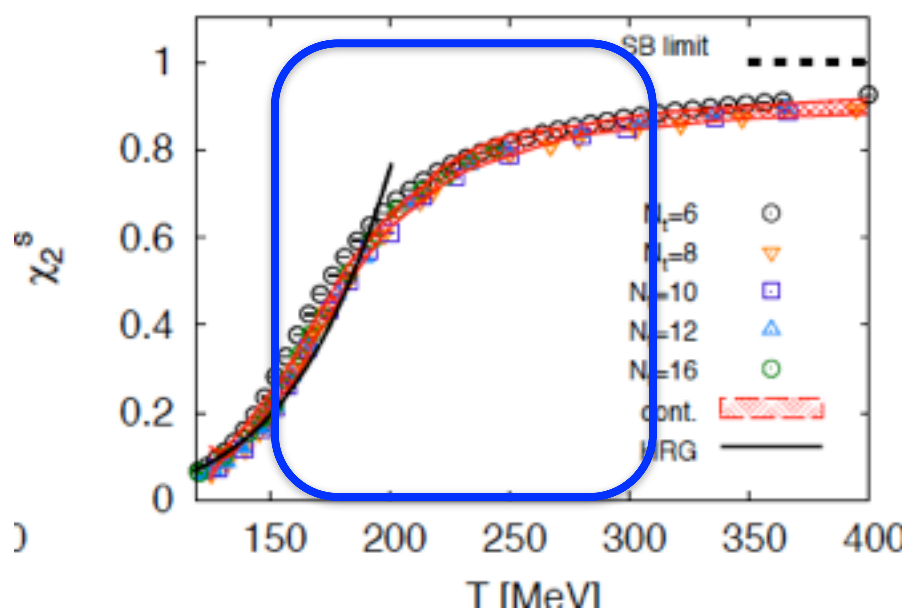


* HRG at low T
* SB limit at high T
* nontrivial pattern
in transition regime

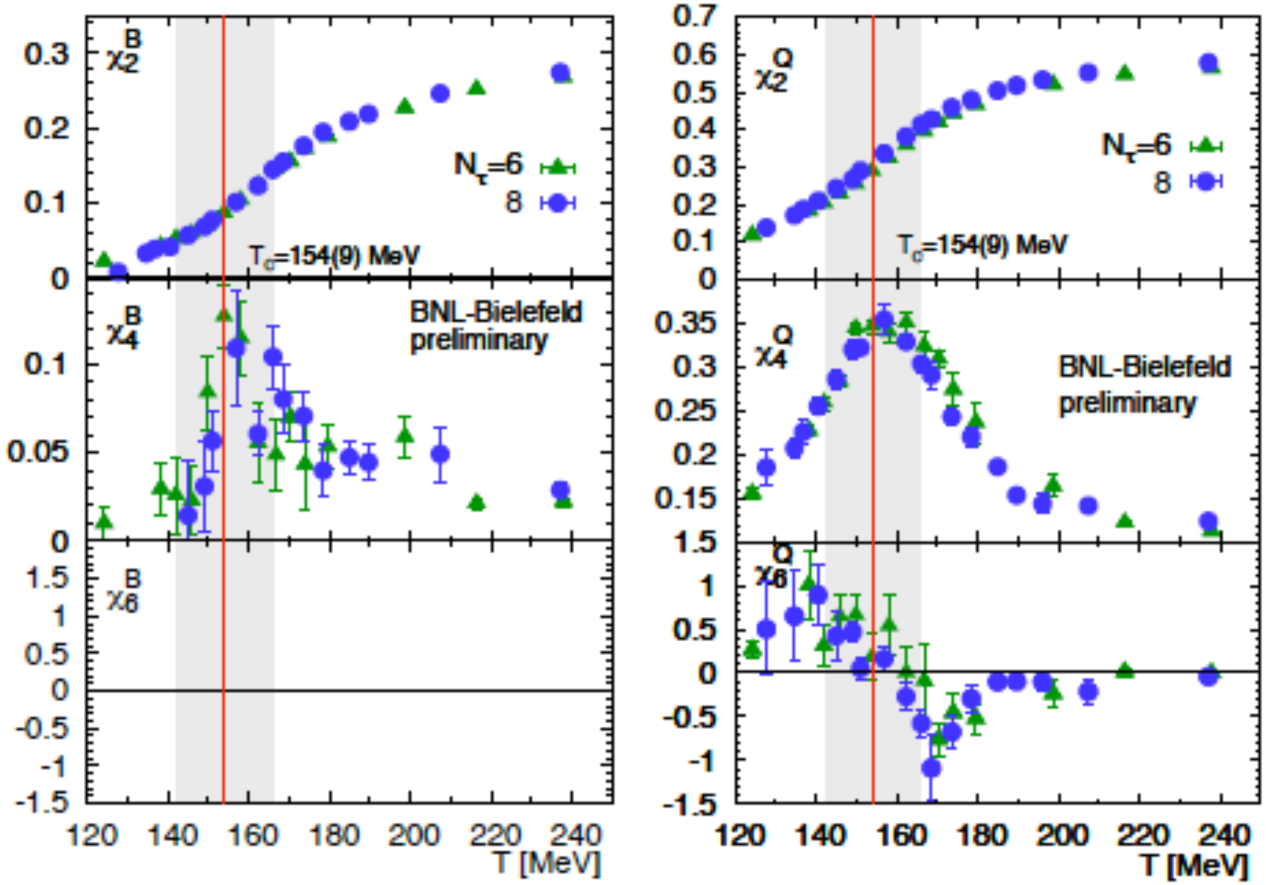
JL, et al, PRD2007,NPB2009,JHEP2013

Wuppertal-Budpast group results
(BNL-Bielefield results are consistent)





Higher Order Susceptibilities



BNL-Bielefeld

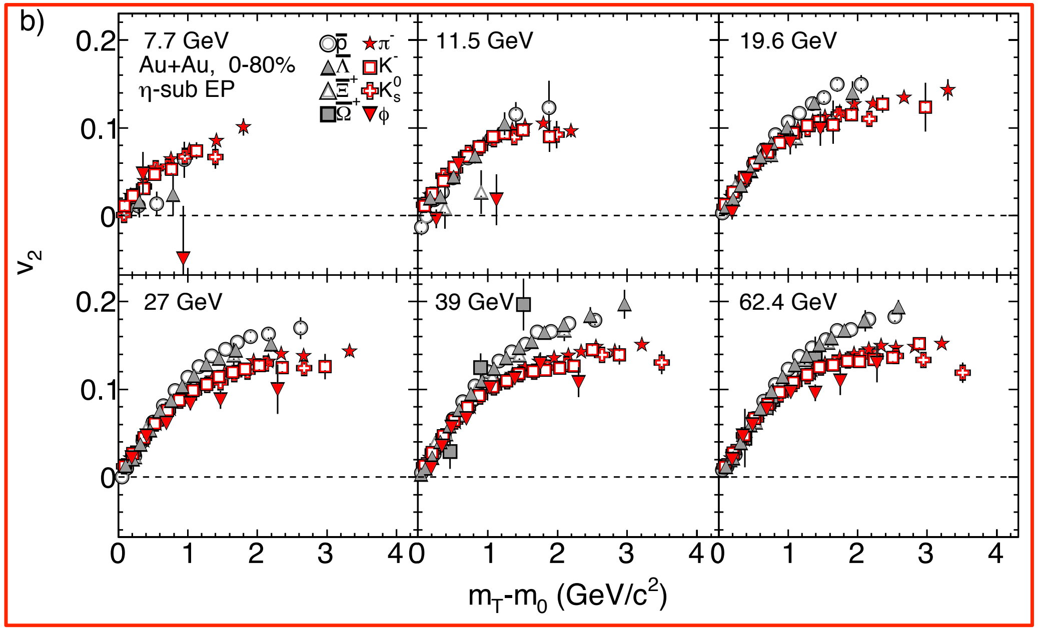
$$\frac{p}{T^4} = \frac{1}{VT^3}\ln Z = \sum_{i,j,k} \frac{1}{i!\ j!\ k!} \chi_{ijk,0}^{BQS}\ \hat{\mu}_B^i\ \hat{\mu}_Q^j\ \hat{\mu}_S^k$$

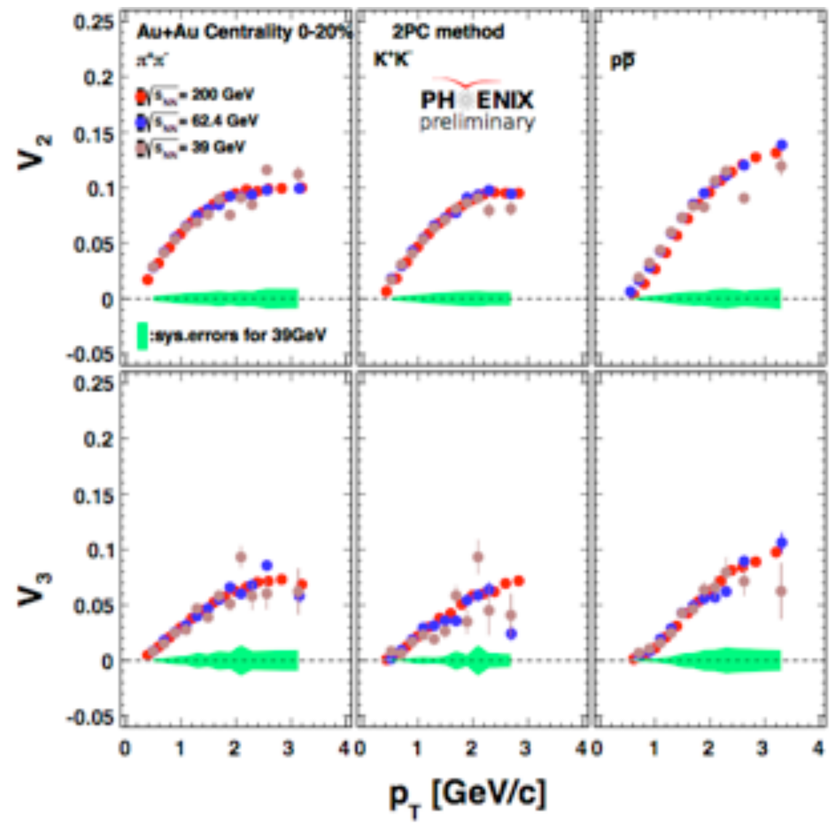
Constructing EOS with Taylor expansion
--- how far can we go?

$$\kappa\sigma^2 \sim \frac{\chi^{(4)}}{\chi^{(2)}}, S\sigma \sim \frac{\chi^{(3)}}{\chi^{(2)}}, \frac{\sigma^2}{M} \sim \frac{\chi^{(2)}}{\chi^{(1)}}$$

Connection with measured moments of net charge distributions

Constraining EOS: BES HIC vs Hydro





EOS is input for hydro --- however:

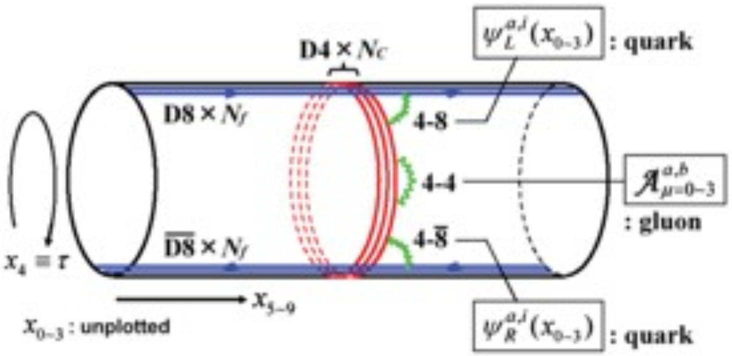
* significant contributions from hadronic reactions?

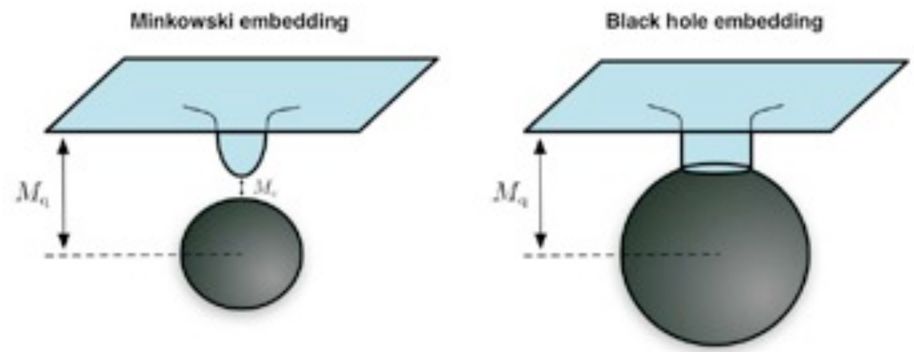
* uncertainty of thermalization, EOS, viscosity.

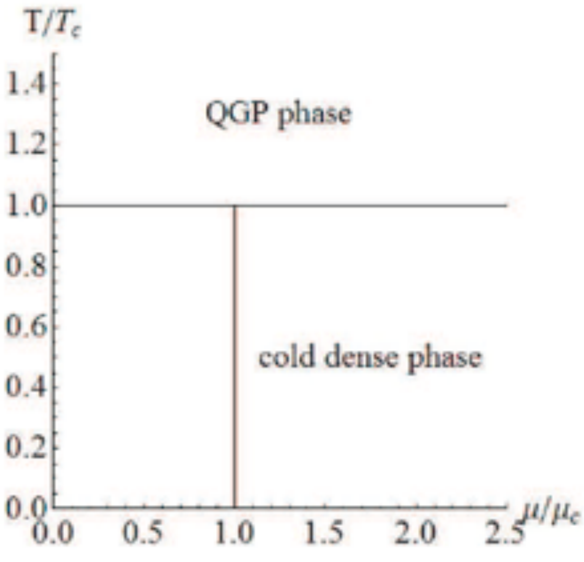
* nevertheless important and interesting approach

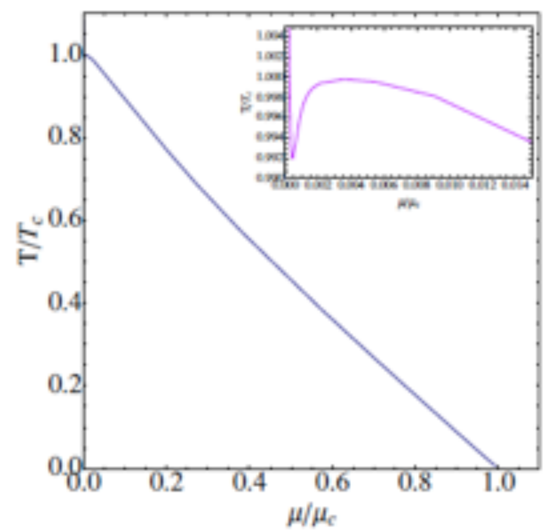
Holographic Models of QCD

We may use holography to extract insights about strongly interacting dense matter.





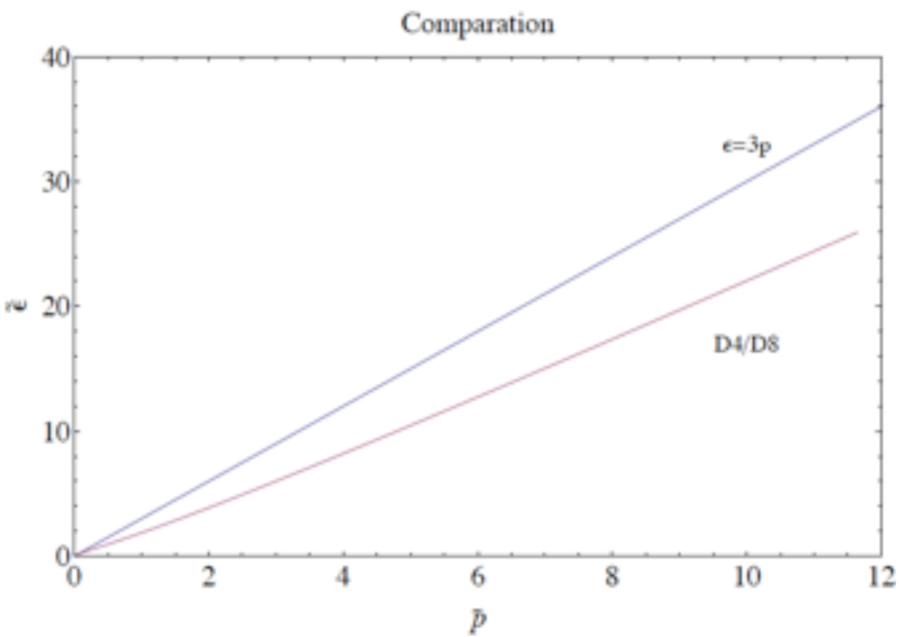


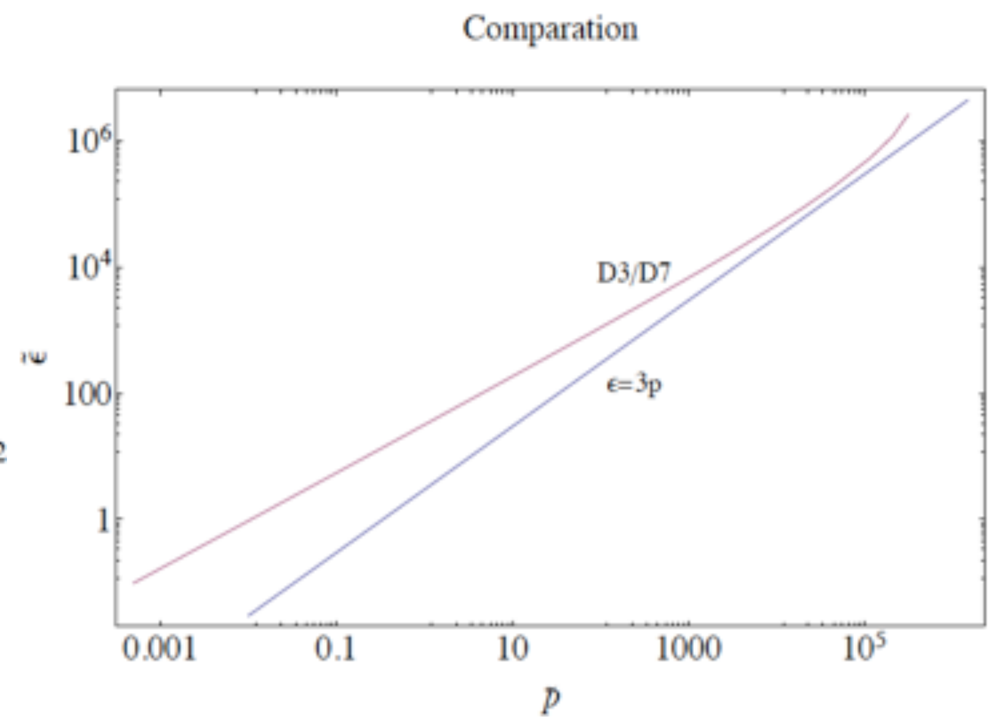


D4-D8 Model

D3-D7 Model

EOS of Dense Phase from Holography





(Preliminary Results)

Summary

RHIC top energy & LHC:
QGP as a color-opaque, nearly perfect fluid.

RHIC Beam-Energy-Scan:
reaching dense ~1/2 rho_0 (but still hot) regime;
constraining the phase boundary;
searching for QCD Critical End Point

Efforts toward finite density EOS:
lattice QCD determination of susceptibilities;
BES flow measurements against hydro;
QCD-related models.

THANK YOU!