BNL, February 29, 2008

# Quark Matter 2008: Theory summary

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Note:

this presentation file differs from the version presented in my talk on Friday, February 29, 2008 which unfortunately got corrupted due to a software compatibility problem*

- Mac users beware: PowerPoint for Mac release 1 does not save files under the latest Mac OS 10.5 “Leopard” (even though it tells you it does...)

# Disclaimers:

- Not a systematic summary of all theory talks but a biased personal view on a few selected topics

- Emphasis on open problems rather than on the achievements

# Outline

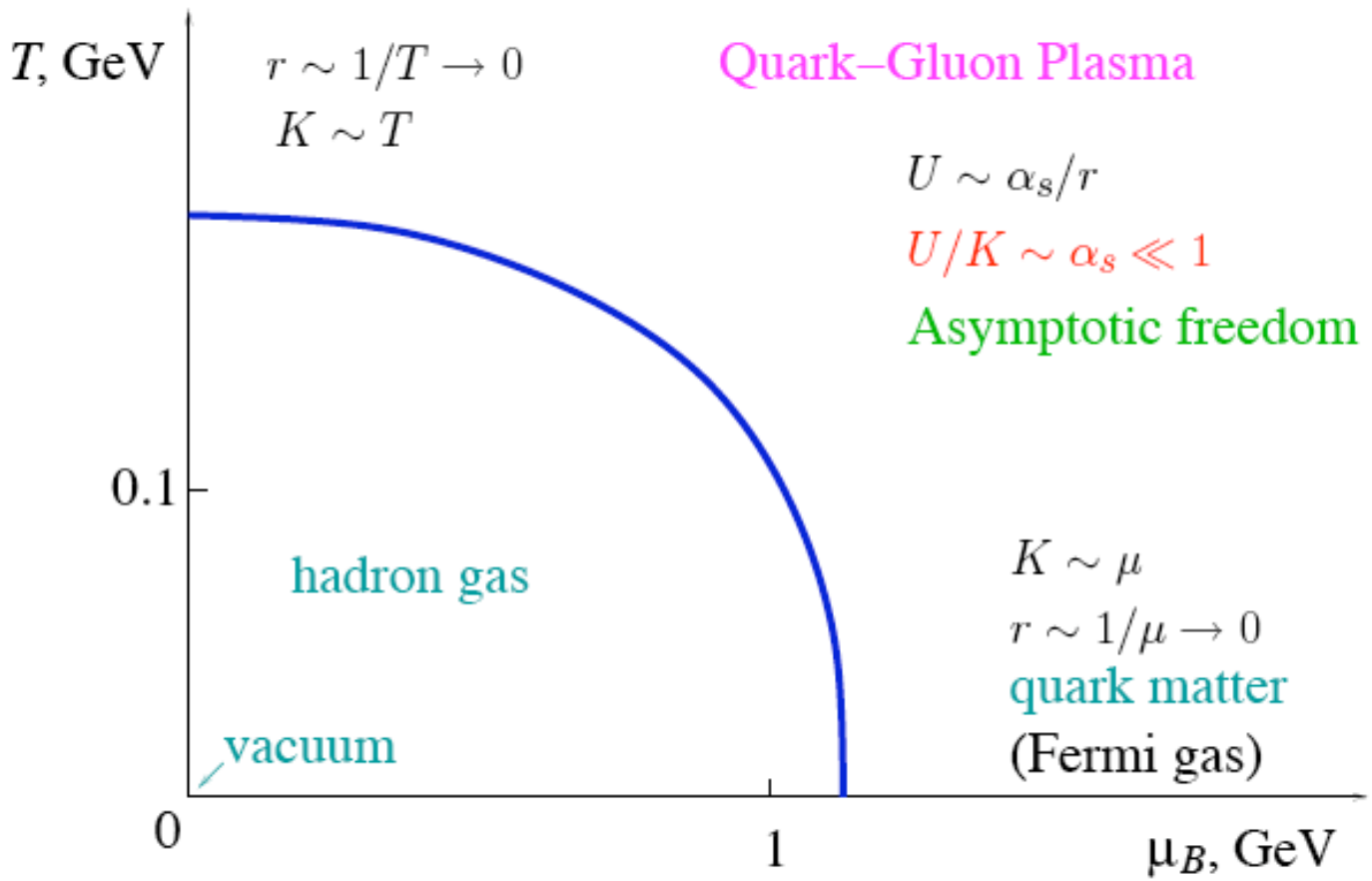
- The QCD phase diagram
- The critical point
- Quantum anomalies and sQGP
- What are the constituents of sQGP?
- How is sQGP produced?
- How does it react to external probes?
- What do we still need to know?

- The QCD phase diagram

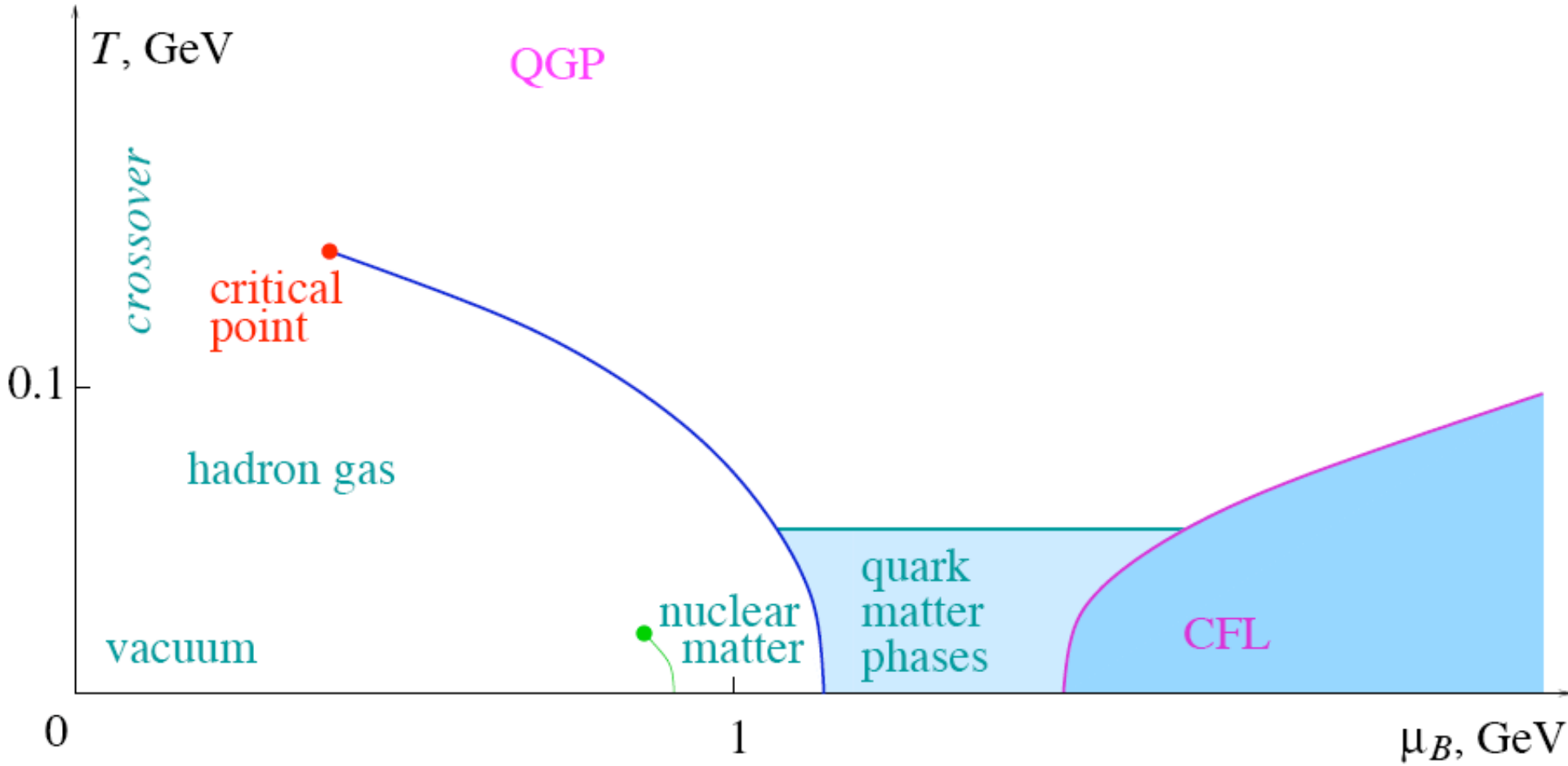
Early expectations:

M. Stephanov

Simple arguments lead to the sketch:

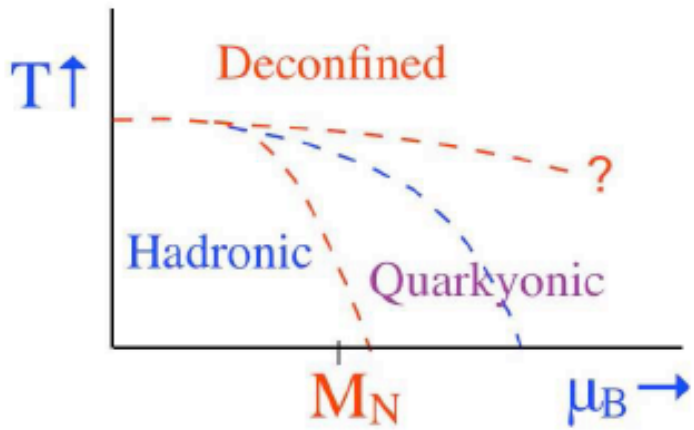


# QCD phase diagram (contemporary view)



# Insights from large $N_c$

McLerran, Pisarski



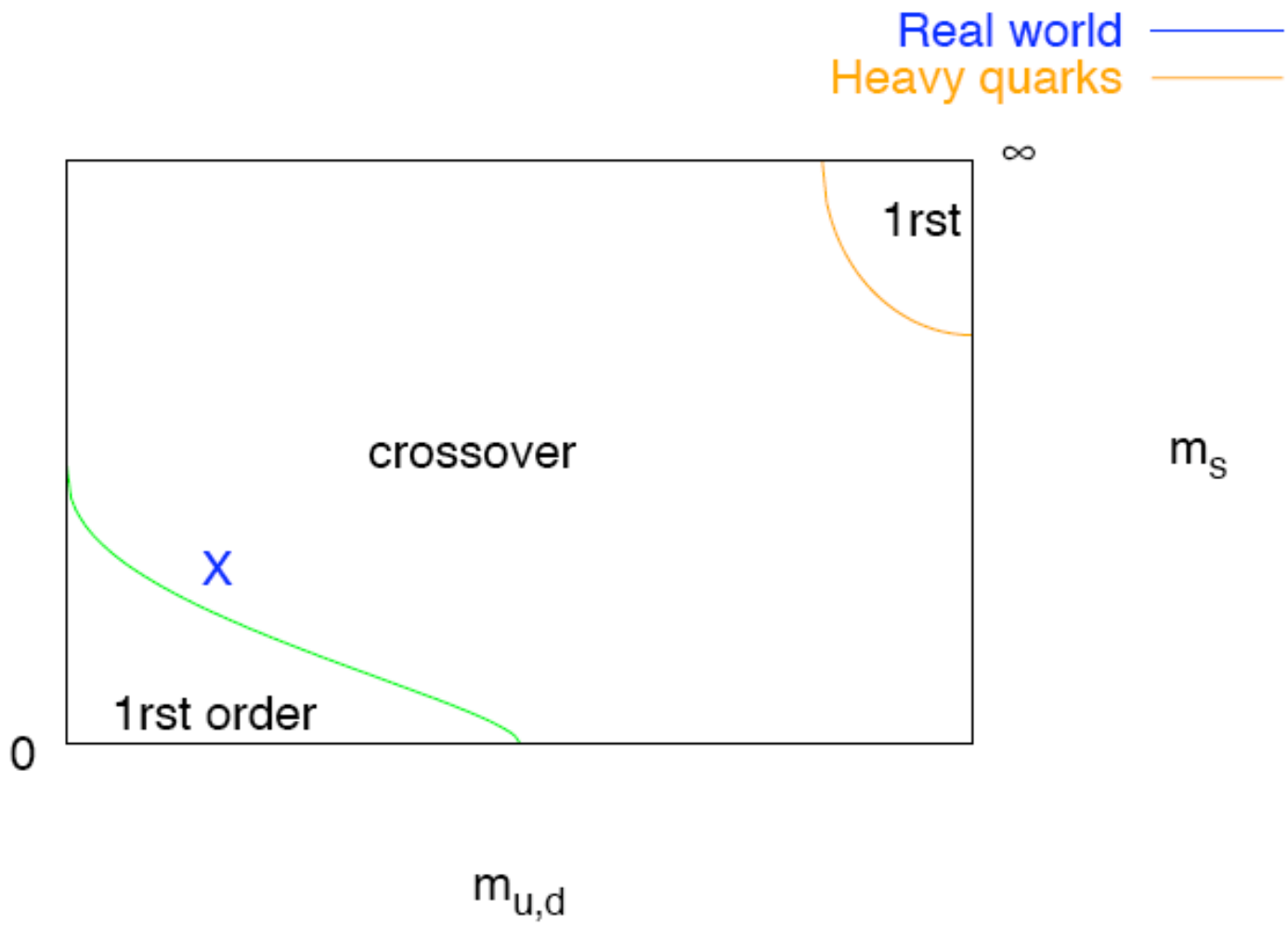

- Large $N_c$ is different from QCD in many aspects:
  - crossover at $\mu = 0$ in QCD, not 1st order;
  - CFL needs $N_c = N_f = 3$, not $N_c \gg N_f$.

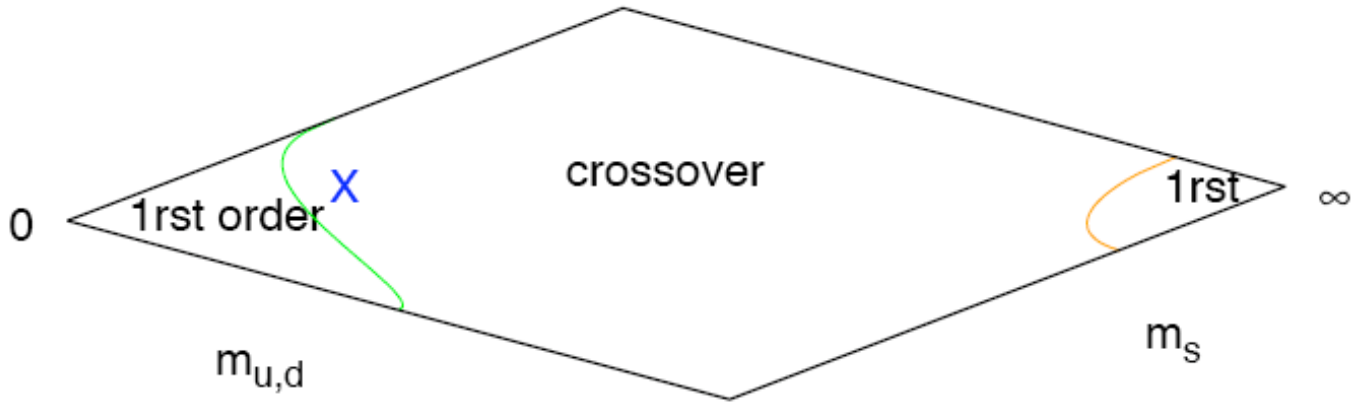
- Some features might be present in QCD, however.

Quarkyonic phase (quark matter with baryon-like excitations)?

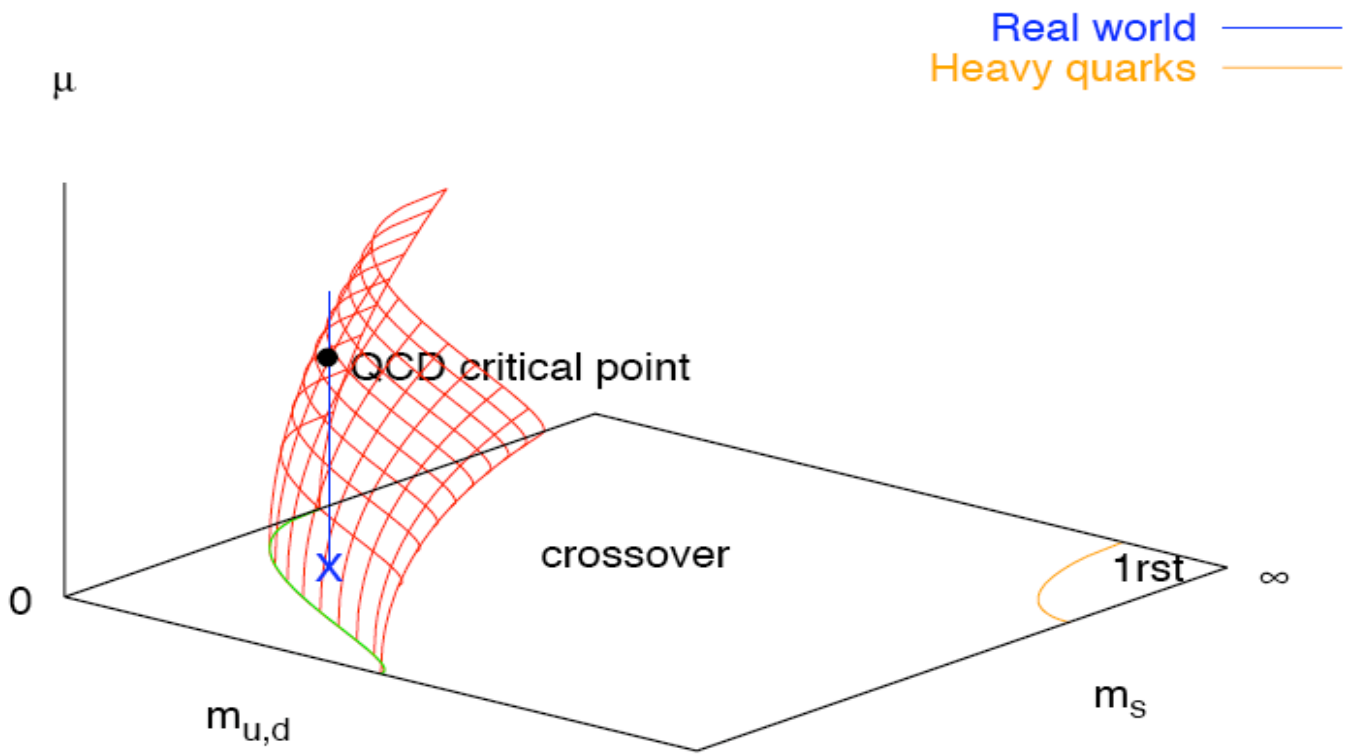
- The critical point

P. de Forcrand

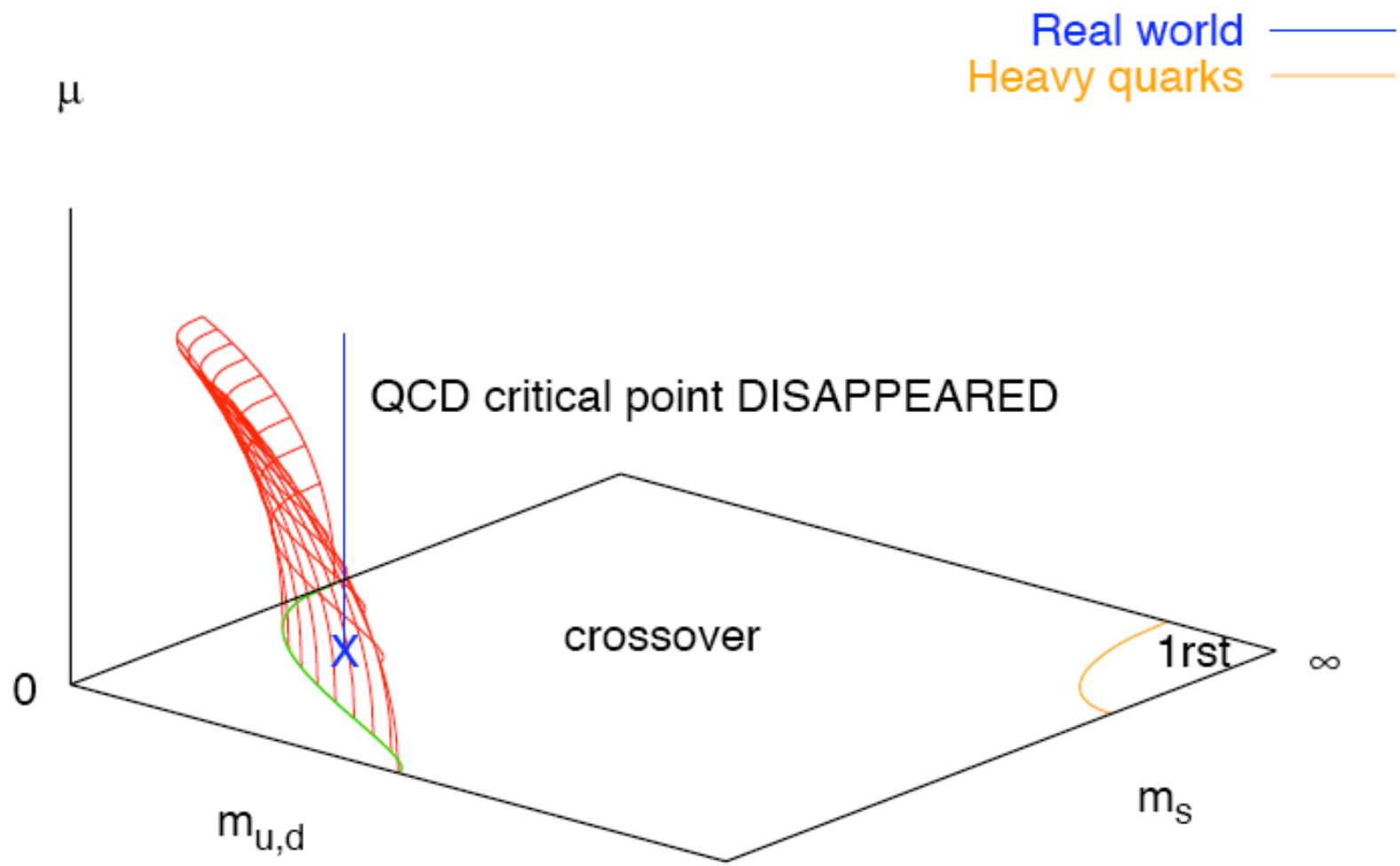





## Now turn on $\mu$




Conventional wisdom: first-order region expands with real $|\mu|$

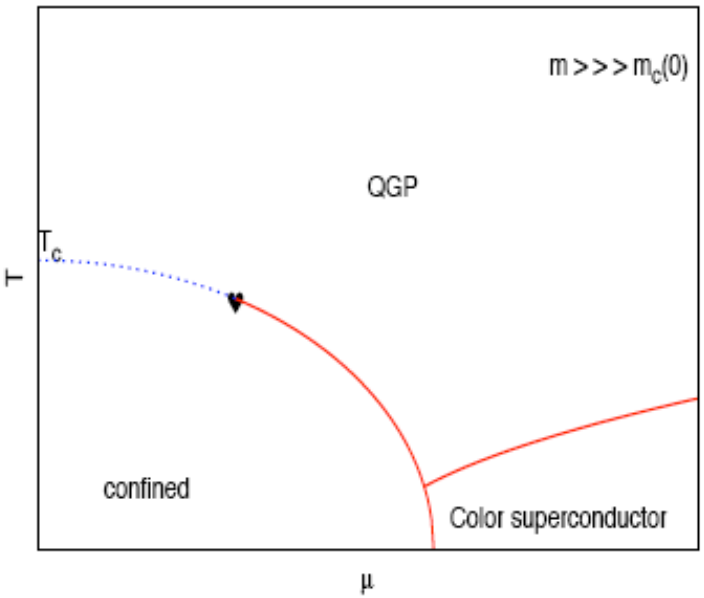


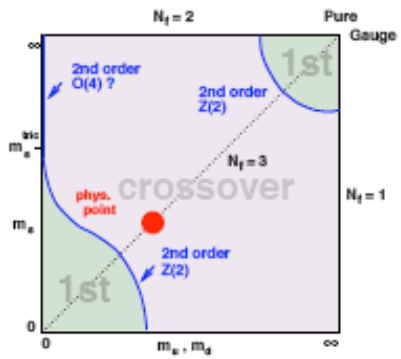

Exotic scenario: first-order region shrinks with real $|\mu|$ $\frac{d\ m_c}{d\mu^2}|_{\mu=0} < 0$

de Forcrand, Philipsen

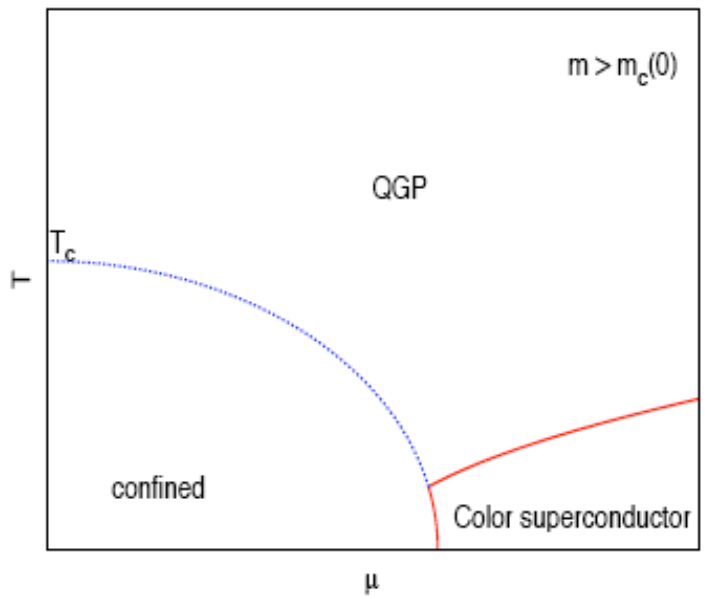
Talks by P. de Forcrand, M. Lombardo

**Standard scenario**




**Exotic scenario**

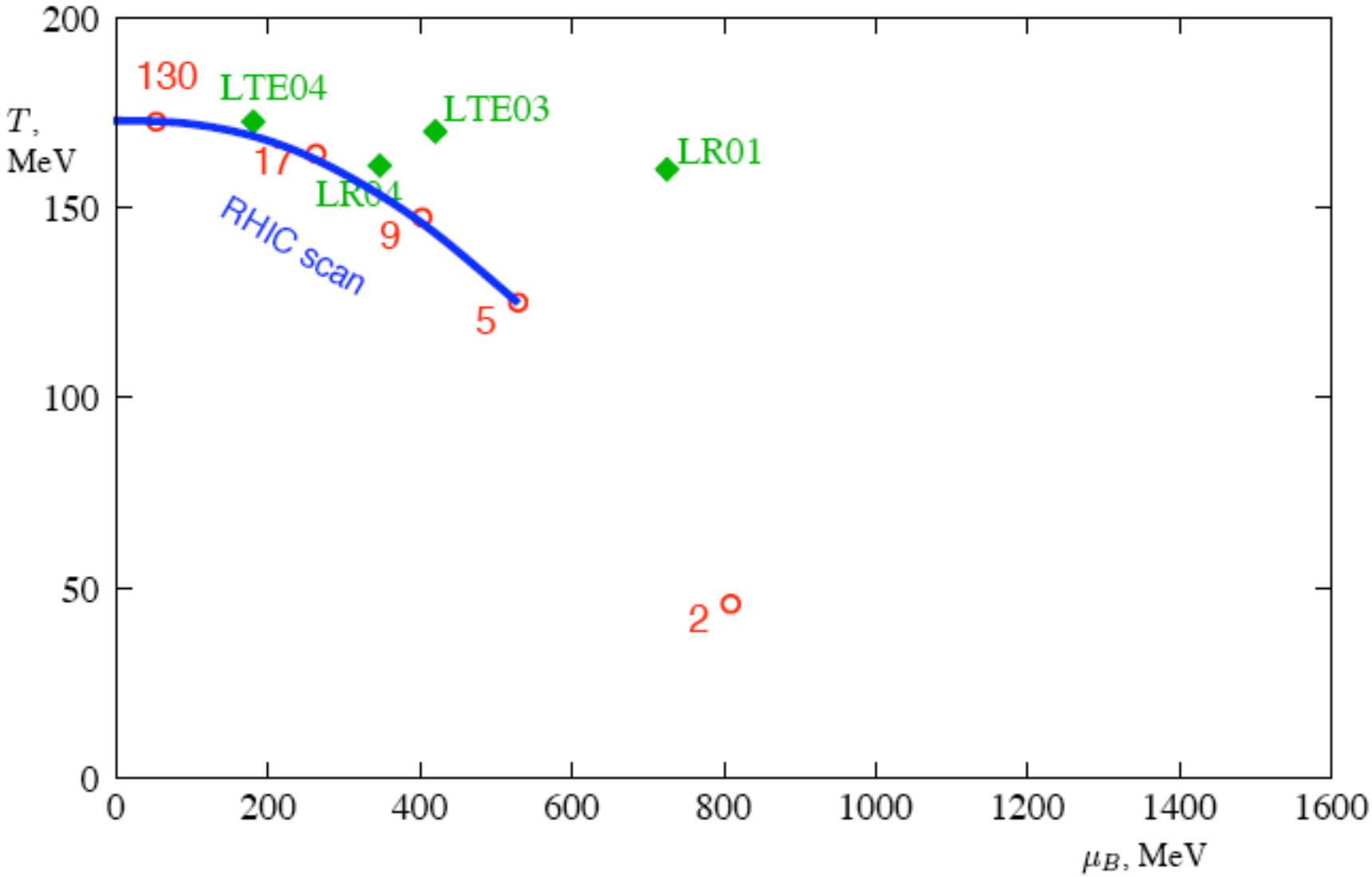



Critical point is not seen in de Forcrand - Philipsen lattice simulation at $N_t$=4;

Is this physics or an artifact of a coarse lattice?

we need to know!

# Can we discover the critical point?



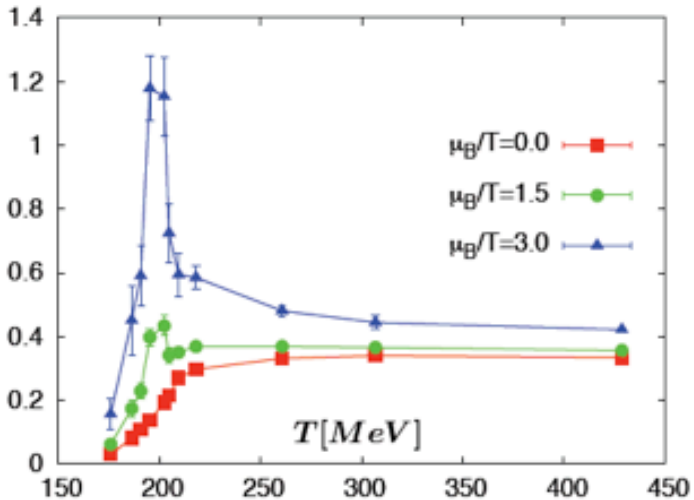

M. Stephanov

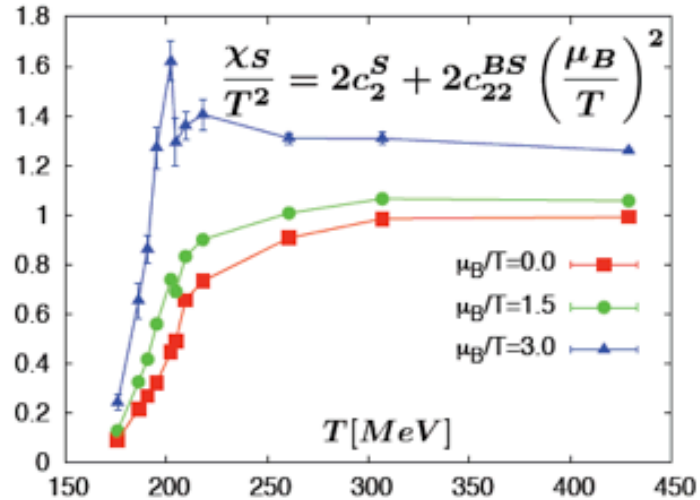
# Observables for CP and co-existence

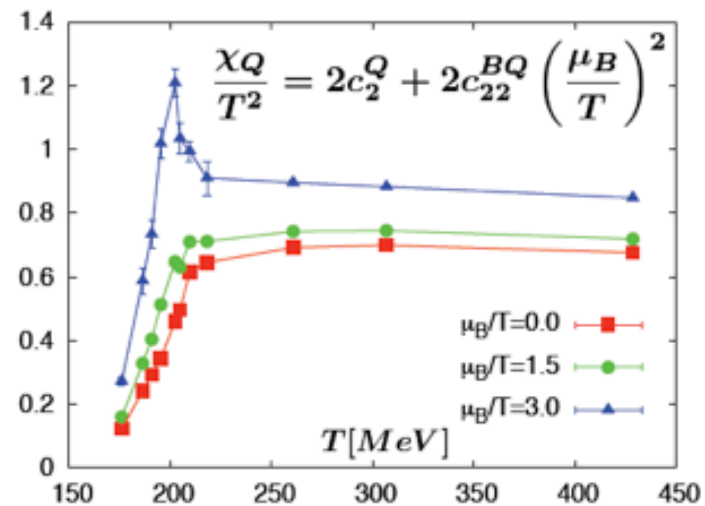
- Fluctuations (probably not of conserved charges)
- Correlations (spiondal blobs)
- Energy scan
- System size dependence (finite volume scaling)
  - centrality may not do
- Good, HOMOGENIOUS acceptance
- Be prepared to measure everything
  - not clear (yet?) which observable couples strongest to baryon density
  - want to see finite volume scaling in more than one observable
- Get you hands dirty now!

# Hadronic fluctuations $\mu_B > 0$ $(\mu_S = \mu_Q = 0)$

$$\frac{\chi_B}{T^2} = 2c_2^B + 12c_4^B\left(\frac{\mu_B}{T}\right)^2$$




Talk by
C. Schmidt

→ large baryon number fluctuations

→ enhanced strangeness and electric charge fluctuations (~ factor 3 at Tc)

# Critical Point and viscosities

CP is in universality class of liquid gas (Son, Stephanov)

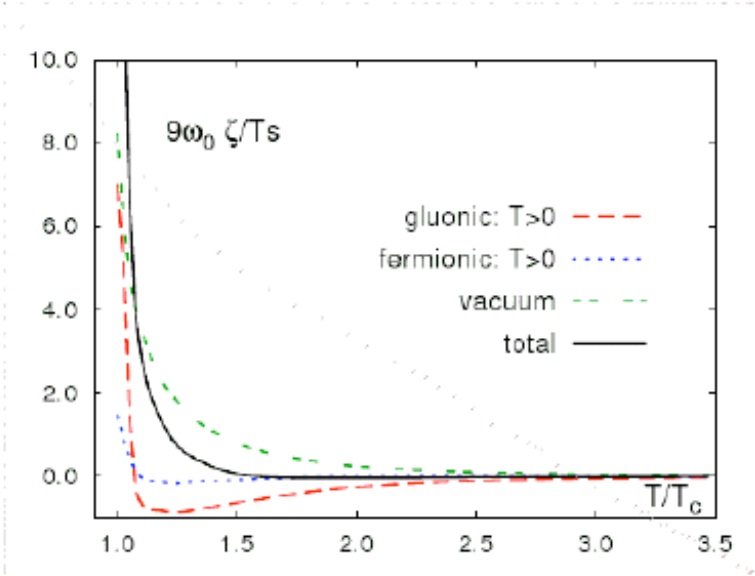
Hohenberg - Halperin Model H (Rev. Mod. Phys 49 (1977)):

$$\eta \sim \xi^{0.065}, \qquad \xi = \text{Correlation Length}$$

Shear viscosity diverges at CP

Bulk viscosity also diverges:
(Kharzeev, Turchin, Karsch arXiv:0711.0914)

Note: even large increase without PT
due to vacuum contribution



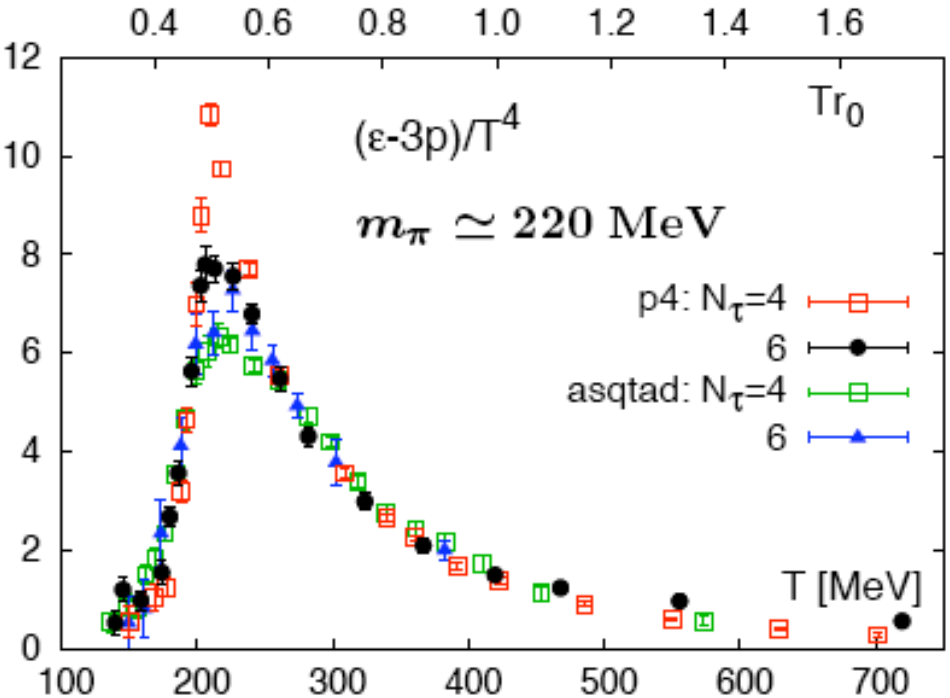
Growth of bulk and shear viscosities
as a signature of the critical point?

Reduction of the radial and elliptic flow
in the vicinity of the critical point?

need to do a realistic viscous hydro
calculation to check this

- Quantum anomalies and sQGP: bulk viscosity and parity violation

# sQGP is not conformally invariant; quantum effect - running coupling




p4 vs. asqtad: overall good agreement

However: We still need to...

| | |
|---|---|
| $T < T_c$ | make contact to hadron gas phenomenology |
| $T < 2T_c$ | analyze large deviation from conformal limit ($\epsilon = 3p$) |
| $T > 2T_c$ | make contact to (resummed) perturbation theory |

p4-data: RBC-Bielefeld
M. Cheng et al, PRD77, 014511 (2008)

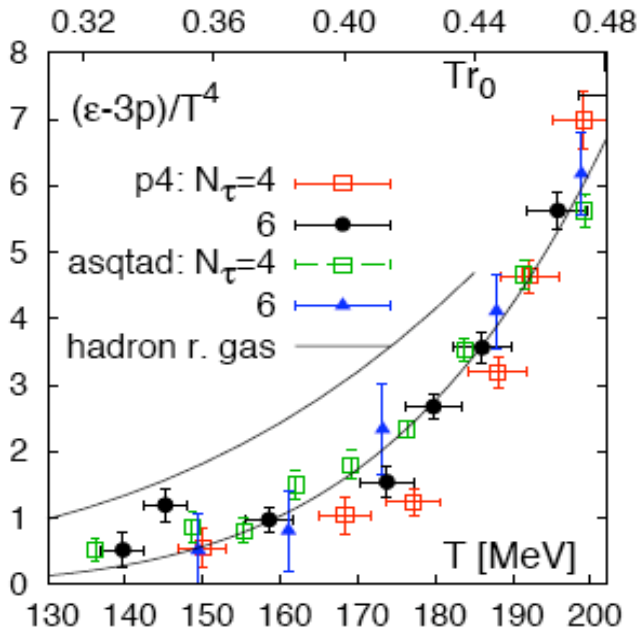
asqtad data: MILC
C. Bernard et al., PRD 75, 094505 (2007)

F. Karsch; RBCB and hotQCD Collaborations

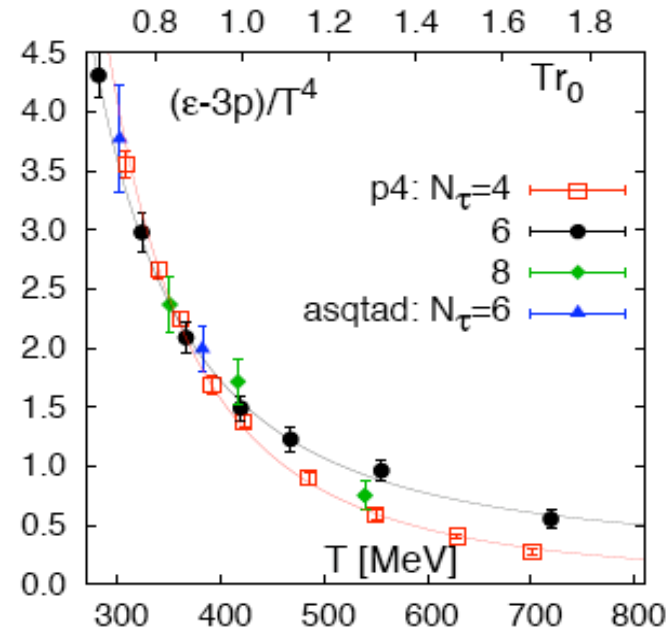
Deviations from conformal limit may be understood at low ($T < T_c$) and high ($T > 2 - 3\ T_c$) temperatures;

What is the physics at $T_c < T < 3\ T_c$ ?

F. Karsch




LGT vs resonance gas




LGT vs. pert. theory

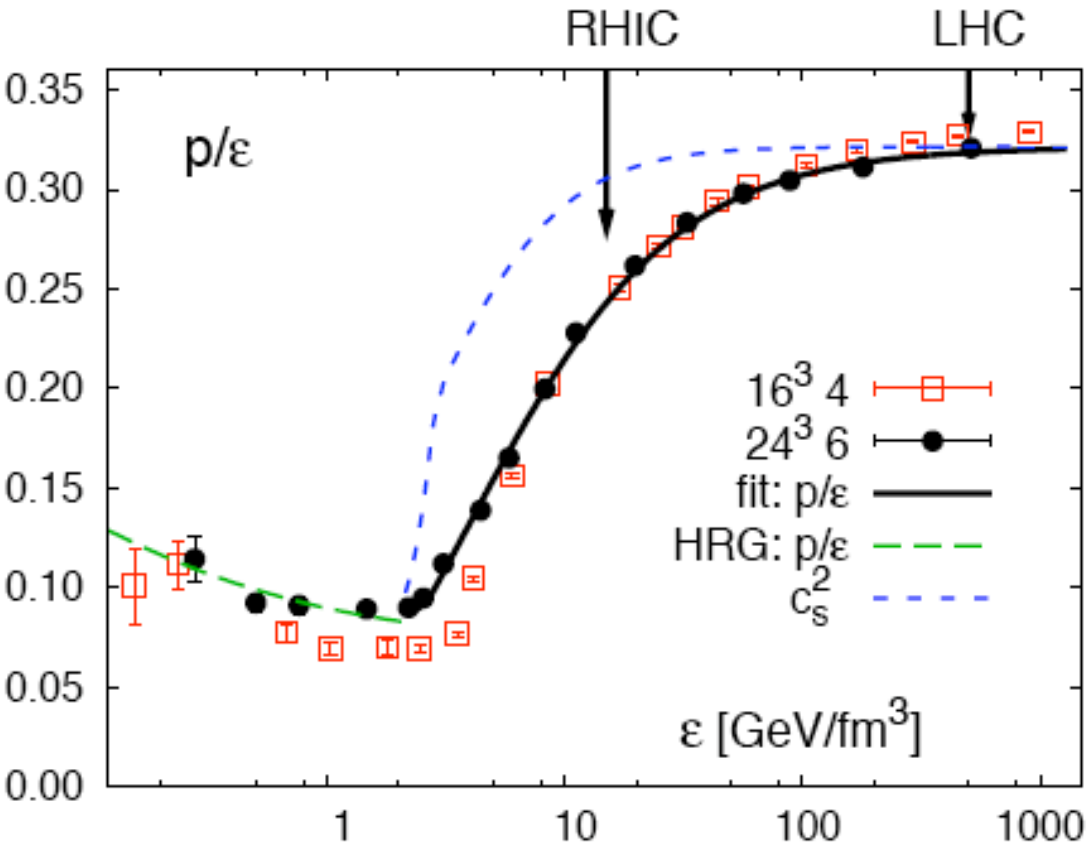
- approach to physical quark masses
  $\rightarrow\ \mathcal{O}(5MeV)$ shift of $T$-scale
- approach to continuum limit
  $\rightarrow\ N_\tau = 8, ..$
  hotQCD collaboration, ongoing

- strong deviations from conformal limit: find $(\epsilon - 3p)/T^4 \sim a/T^2 + b/T^4$ for $300\mathrm{MeV} \lesssim T \lesssim 700\mathrm{MeV}$
- need to control cut-off dependence for $T \gtrsim 400$ MeV to establish contact to (resummed) perturbative QCD

- $p/\epsilon \Rightarrow$ velocity of sound:

$$c_s^2 = \frac{\mathrm{d}p}{\mathrm{d}\epsilon} = \epsilon \frac{\mathrm{d}(p/\epsilon)}{\mathrm{d}\epsilon} + \frac{p}{\epsilon} \equiv \frac{s}{c_V}$$

F. Karsch




needs to be confirmed on larger lattices, closer to the continuum limit;

e.g. $N_\tau = 8$, ...

hotQCD-collaboration

M. Cheng et al. (RBC-Bielefeld), PRD77, 014511 (2008)

cf talk by H. Caines: $c_s^2 = 0.04$

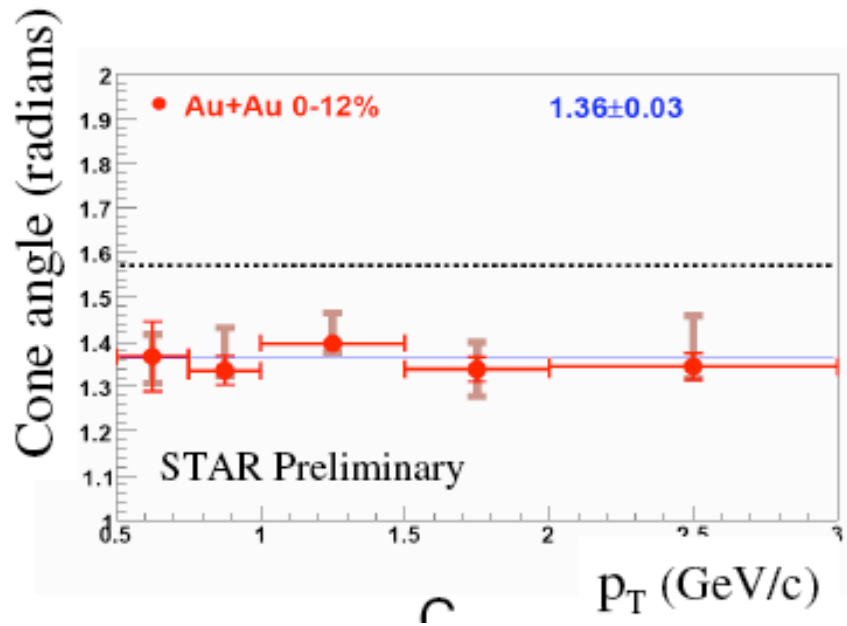
- a factor of ~ 2 discrepancy with the lattice ?

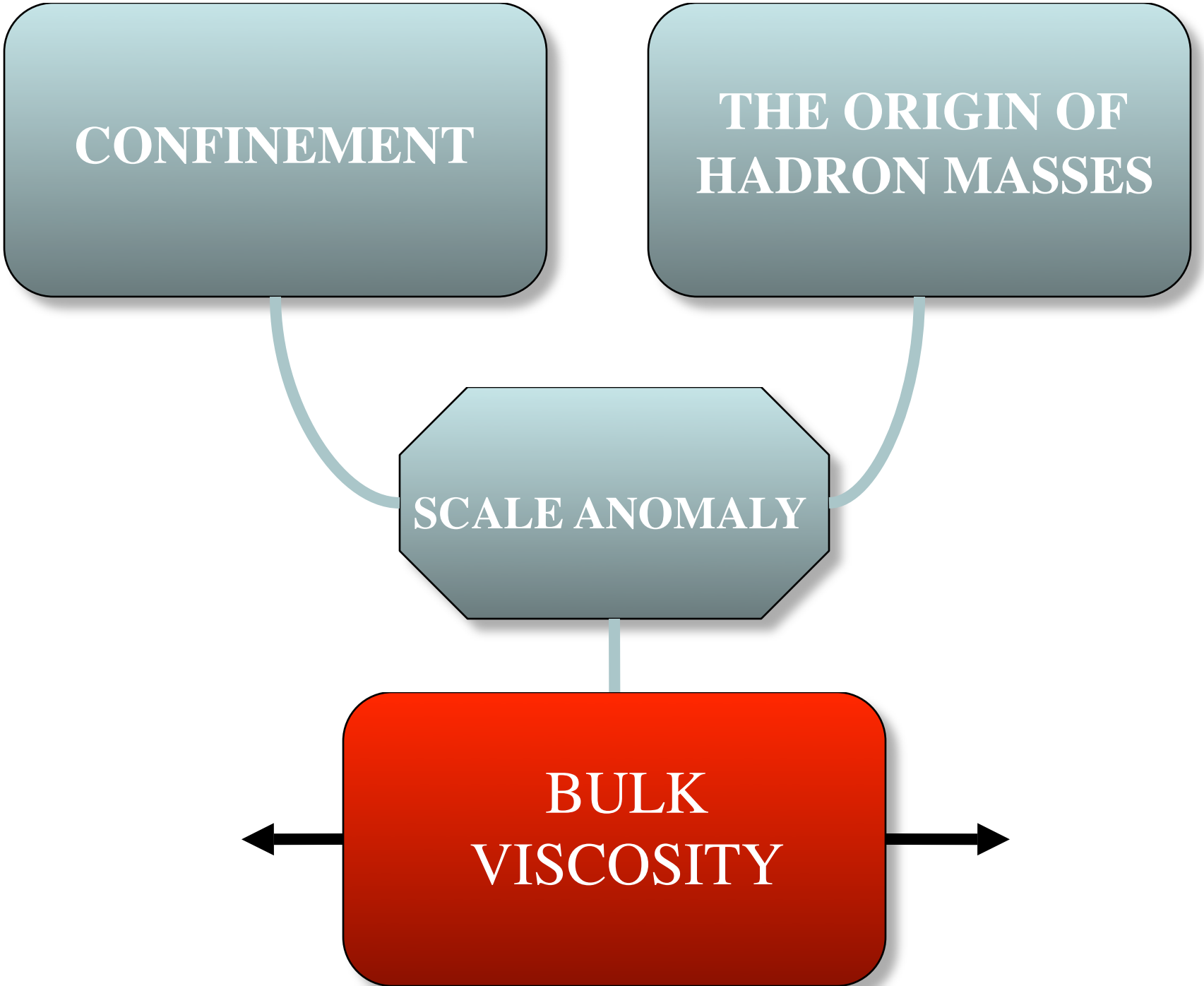
Naive calc. of time averaged velocity of sound in medium:

$$\frac{c_s}{v_{parton}} = \cos(\theta_M) \ , \ v_{parton} = c$$

Cone angle ~ 1.36 radians

$c_s$ = 0.2c!

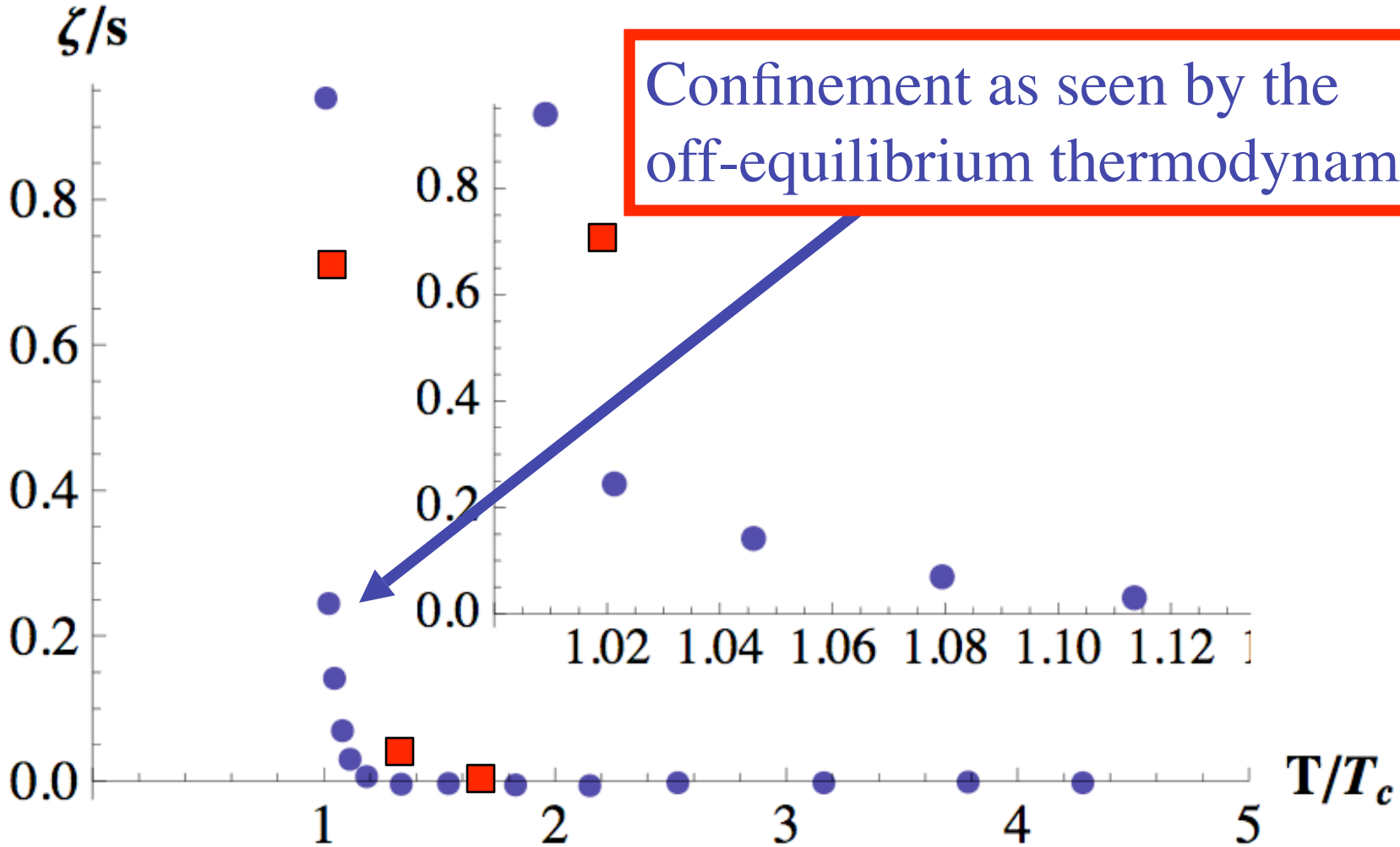



CONFINEMENT
THE ORIGIN OF HADRON MASSES
SCALE ANOMALY
BULK VISCOSITY

# Bulk viscosity

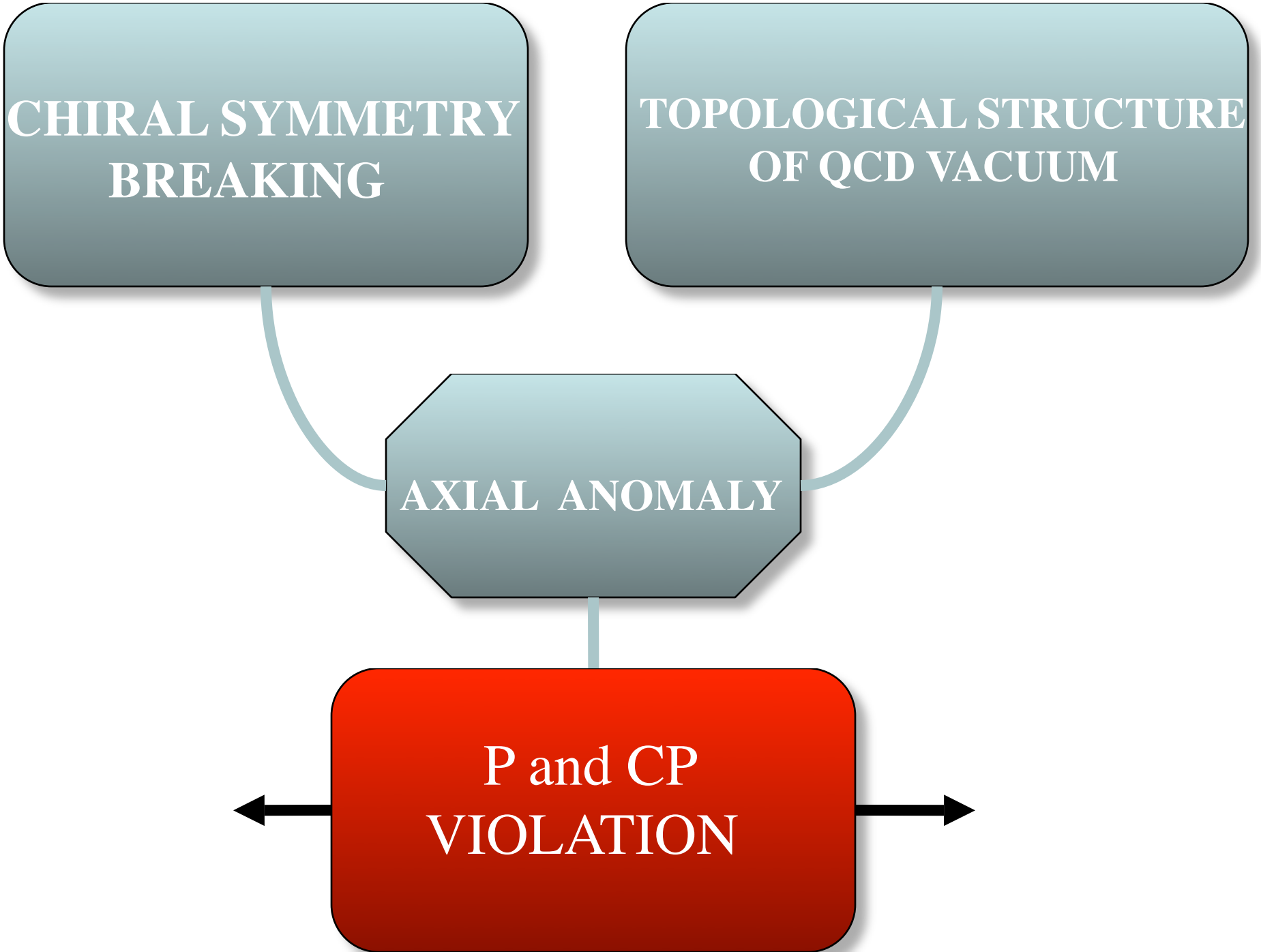
● Kharzeev-Tuchin arXiv:0705.4280 [hep-ph]

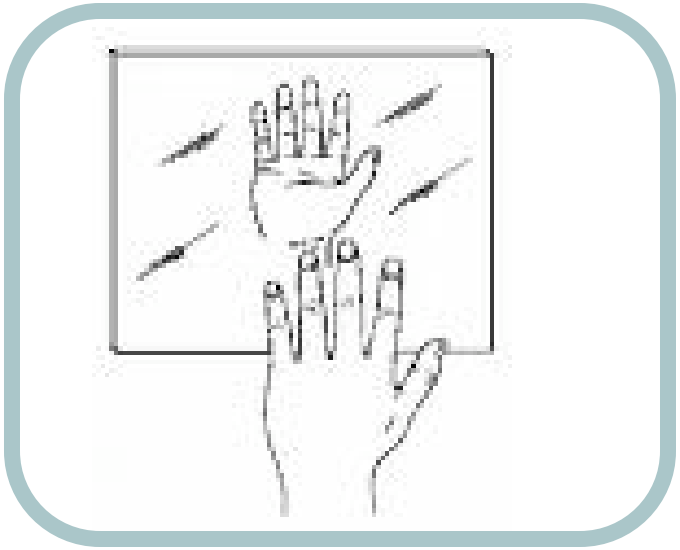
■ Meyer arXiv:0710.3717[hep-lat]

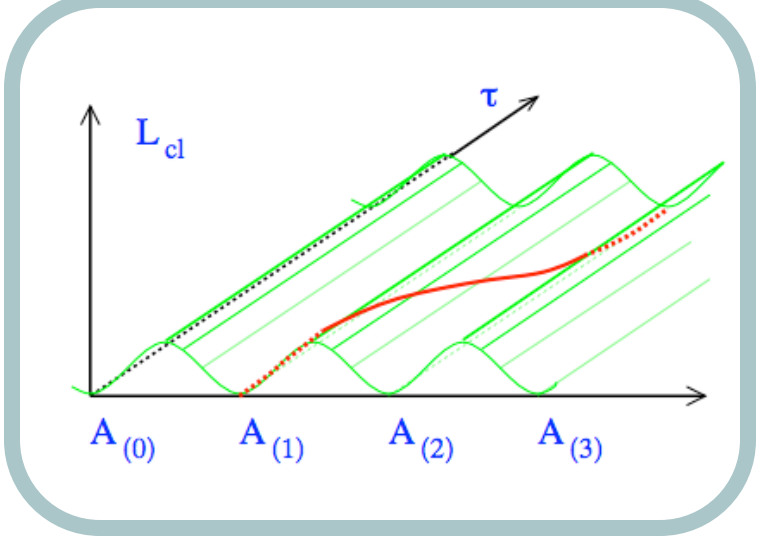


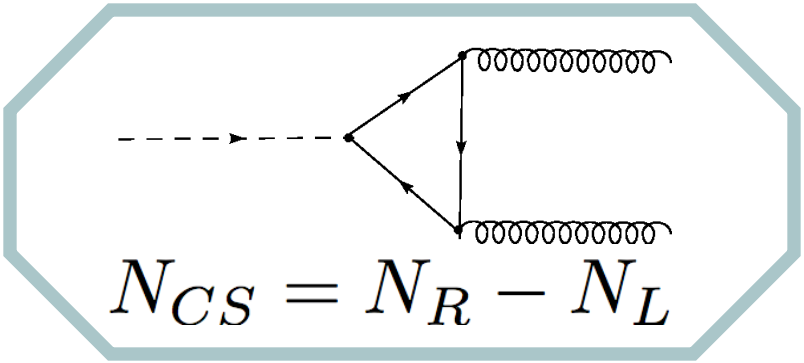

Confinement as seen by the off-equilibrium thermodynamics

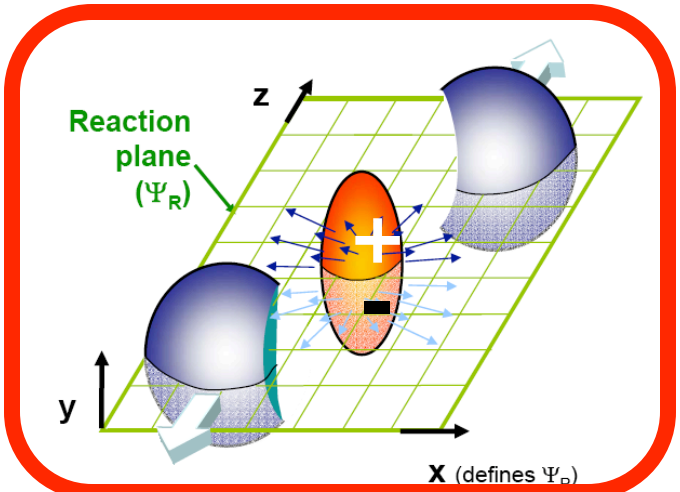
Talks by K. Rajagopal, V. Koch, S. Gupta, ..


CHIRAL SYMMETRY BREAKING
TOPOLOGICAL STRUCTURE OF QCD VACUUM
AXIAL ANOMALY
P and CP VIOLATION





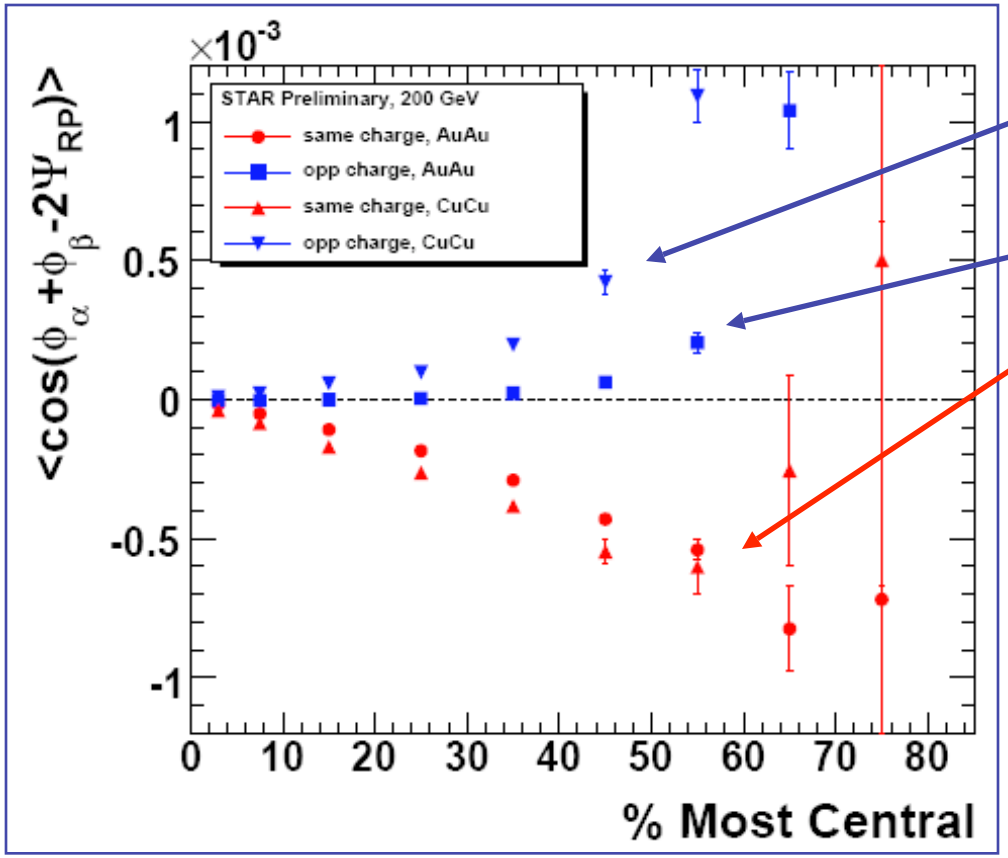




Talk by H. Warringa

Charge asymmetry w.r.t. reaction plane,

$\sim - a^k a^m$




CuCu

<

AuAu

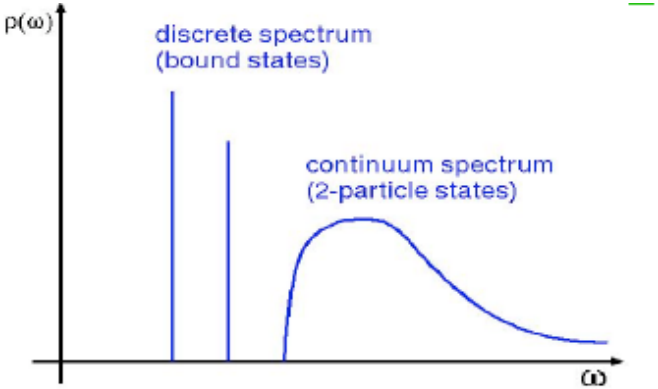
Need to analyze the systematics and backgrounds - vigorous ongoing work!

S. Voloshin [STAR Coll.] Poster 205, QM'08

- What are the constituents of the sQGP?

“Constituents” - well-defined quasi-particles may not exist at strong coupling -

width ~ (coupling)$^2$




So may not see peaks in the spectral densities

Moreover, soft gluon and quark propagators may not even have a spectral representation at all! (Gribov copies, etc)

Are "constituent partons" consistent with small viscosity?

Indeed, "constituent parton" in the plasma implies the existence of a quasiparticle with

$$\frac{\text{Width}}{\text{Energy}} \sim (\text{coupling})^2 \ll 1$$

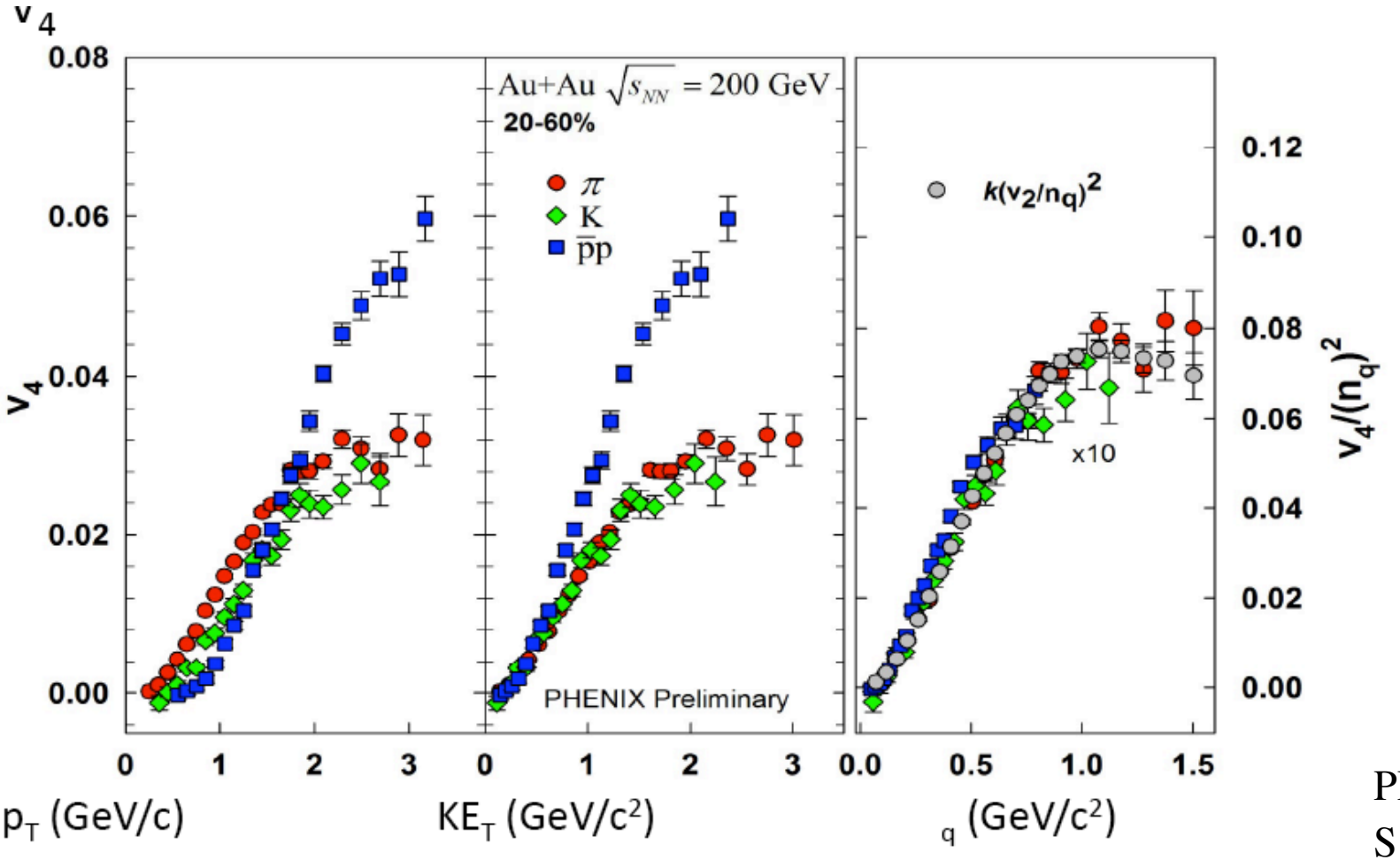
Is this consistent with "perfect liquid", where

$$\frac{\text{Shear viscosity}}{\text{Entropy}} \sim \frac{1}{(\text{coupling})^2} \ll 1$$

and with

$$\frac{\text{Bulk viscosity}}{\text{Entropy}} \sim (\text{coupling})^2 \gg 1 \quad ?$$

# But: the "constituent quark scaling" is well established




$v_2$ scales with $n_q$, $v_4$ with $n_q^2$ partonic degree of freedom

PHENIX:
S Huang,
Summary by
J. Frantz

Is the constituent quark recombination
(an off-equilibrium phenomenon) consistent
with the thermal abundances of the produced hadrons?

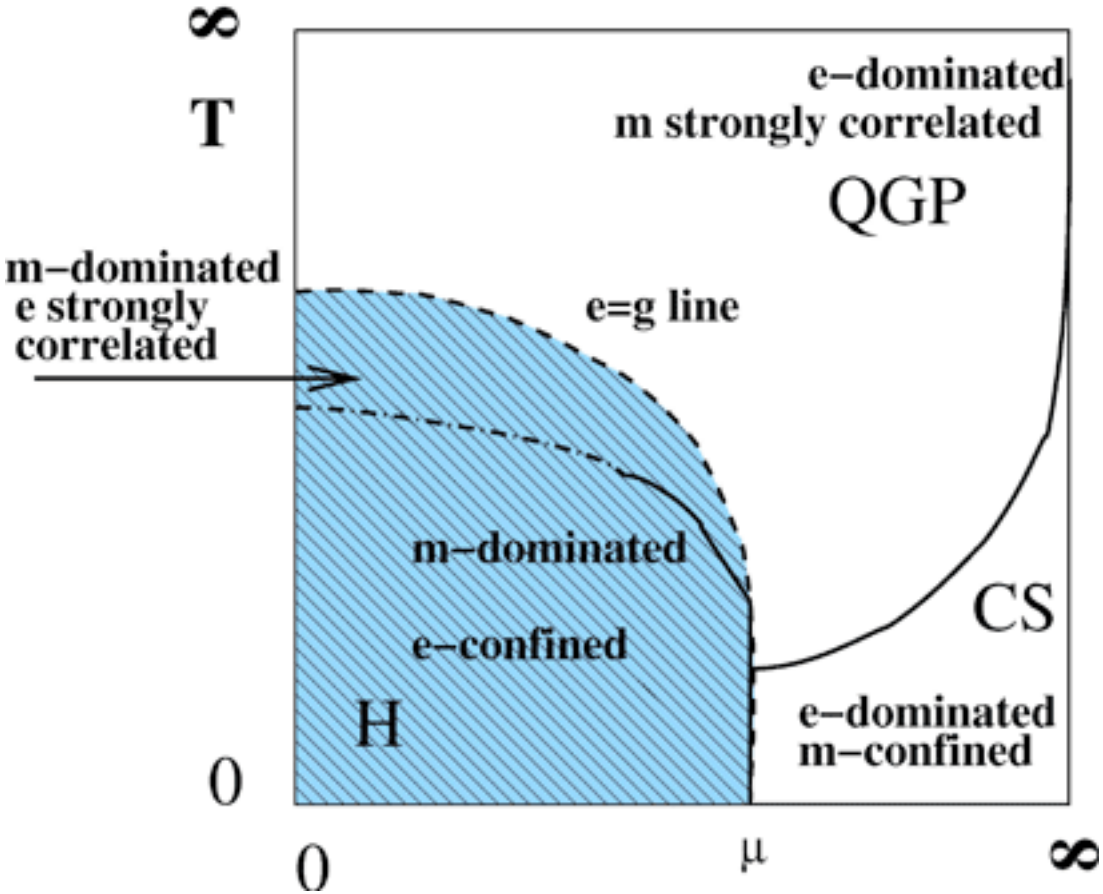
Perhaps, the constituent quark scaling is telling us
something about the mechanism of hadronization
rather than about the degrees of freedom in sQGP?

AND, how is the constituent quark recombination (an off-equilibrium phenomenon) consistent with the thermal abundances of the produced hadrons?

Perhaps, the constituent quark scaling is telling us something about the mechanism of hadronization rather than about the degrees of freedom in sQGP?

e.g. recombination of partons produced <u>at hadronization</u> (recall the peak in bulk viscosity)?

# Extended field configurations as the relevant degrees of freedom in sQGP?

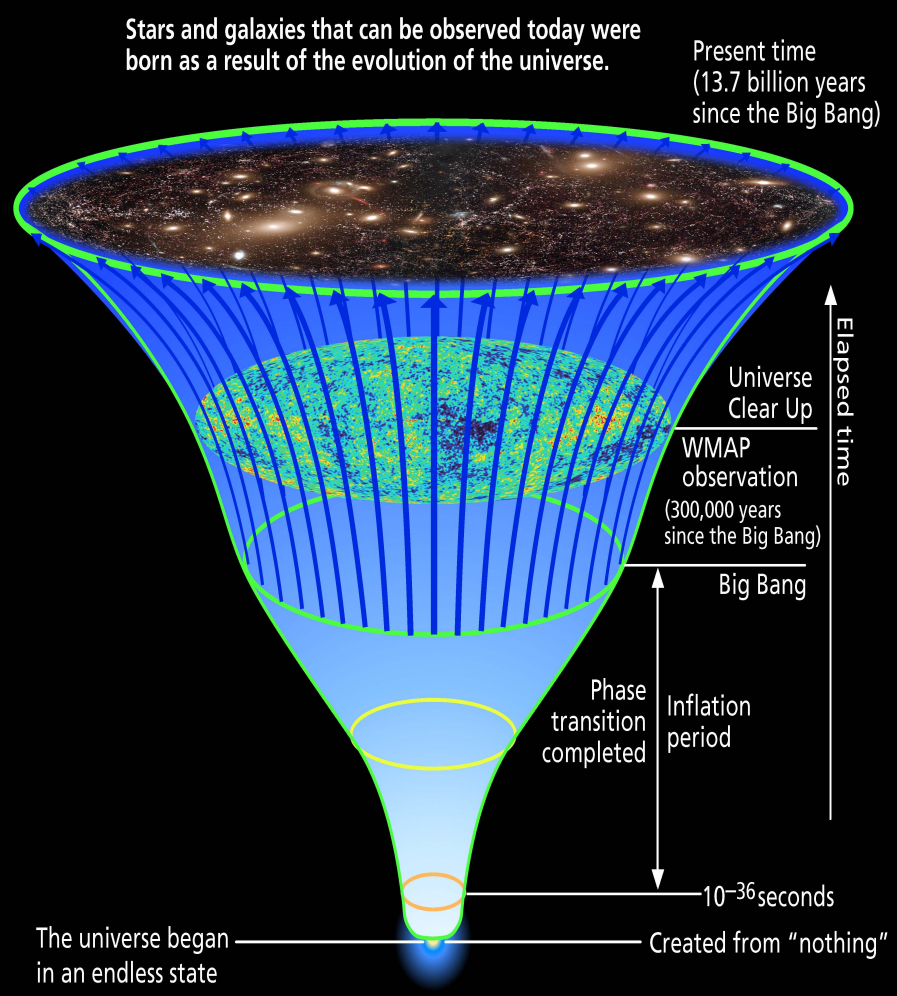


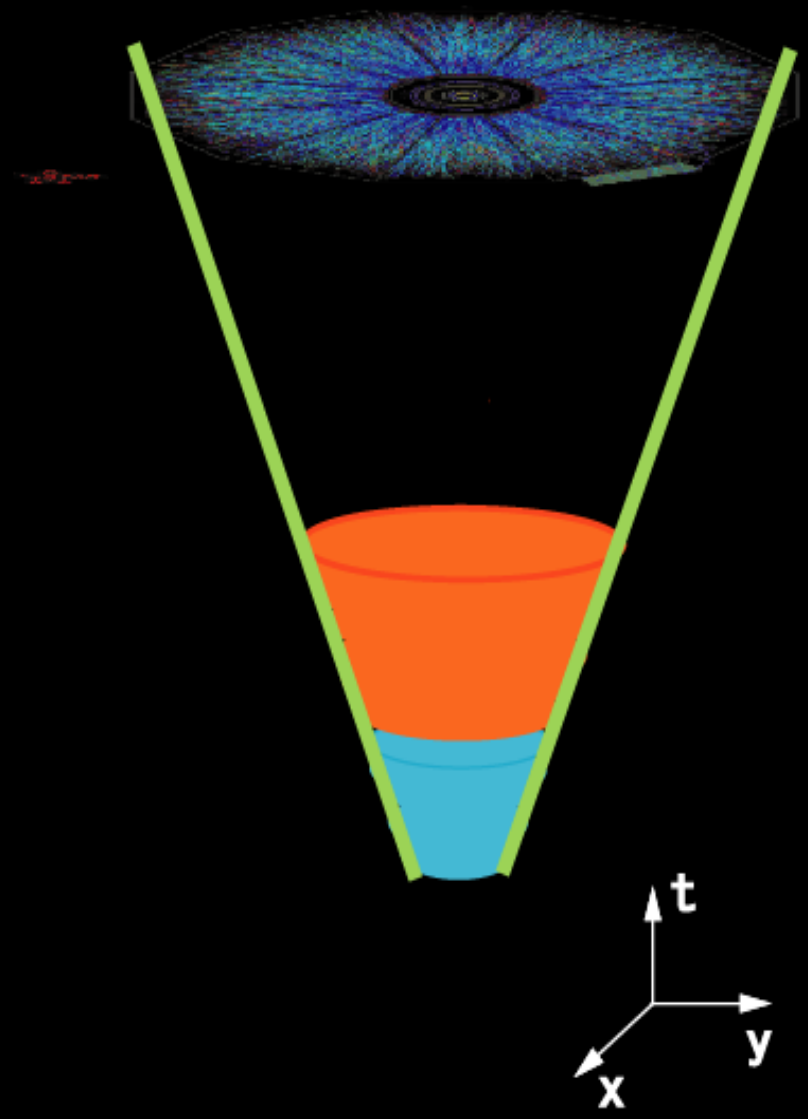

E. Shuryak:

Magnetic monopoles

- How is the sQGP produced?

# Talk by R. Venugopalan




Plot by T. Hatsuda

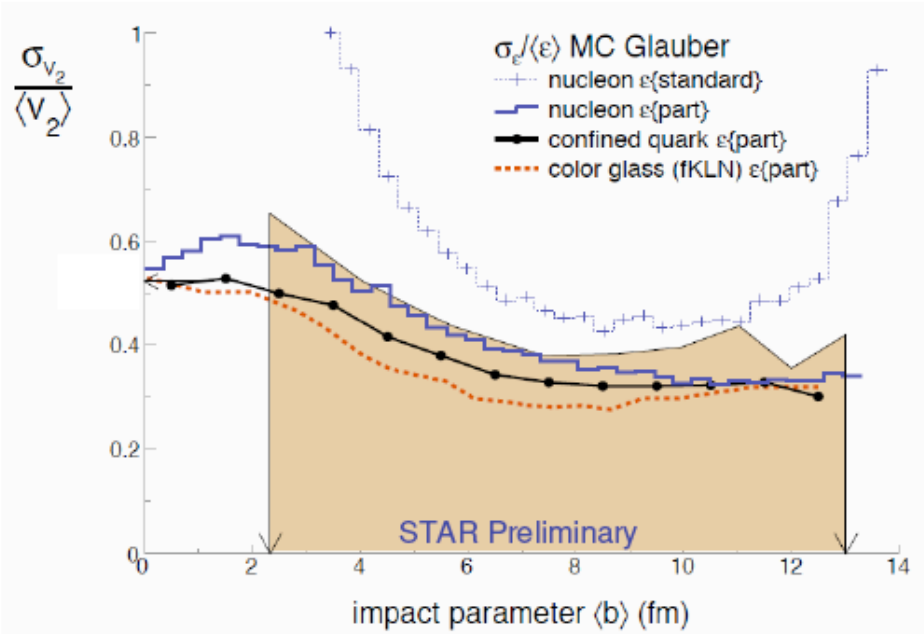
# Big Bang vs. Little Bang

| | | |
|---|---|---|
| **Decaying Inflaton field with occupation # $1/g^2$** | ⟷ | **Decaying Glasma field with occupation # $1/g^2$** |
| **Explosive amplification of low mom. small fluctuations (preheating)** | ⟷ | **Explosive amplification of low mom. small fluctuations (Weibel instability ?)** |
| **Interaction of fluct./inflaton - thermalization** | ⟷ | **Interaction of fluct./Glasma - thermalization ?** |

**Other common features: topological defects, turbulence ?**

# Initial conditions: Glauber or CGC?

$v_2$ fluctuations may provide some insight/constraints



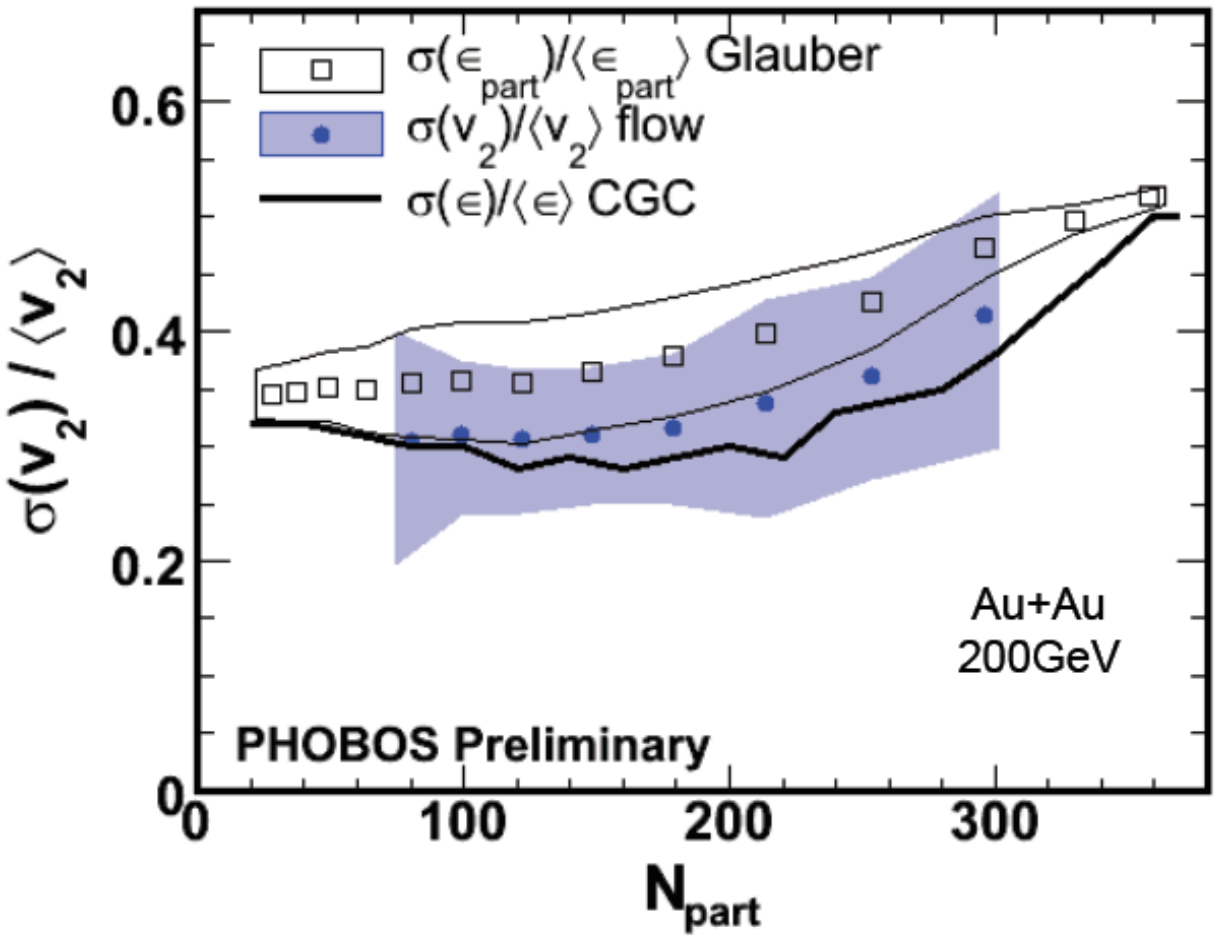

$$\left(\frac{\sigma_{v_2}}{\langle v_2 \rangle}\right)_{meas.} \approx \left(\frac{\sigma_\varepsilon}{\langle \varepsilon \rangle}\right)_{calc.}$$

P.Sorensen, H. Caines

Confined quark MC:
- constituent quark participants
- decreases ε fluctuations

Color glass MC:
- includes effects of saturation
- increases the mean ε

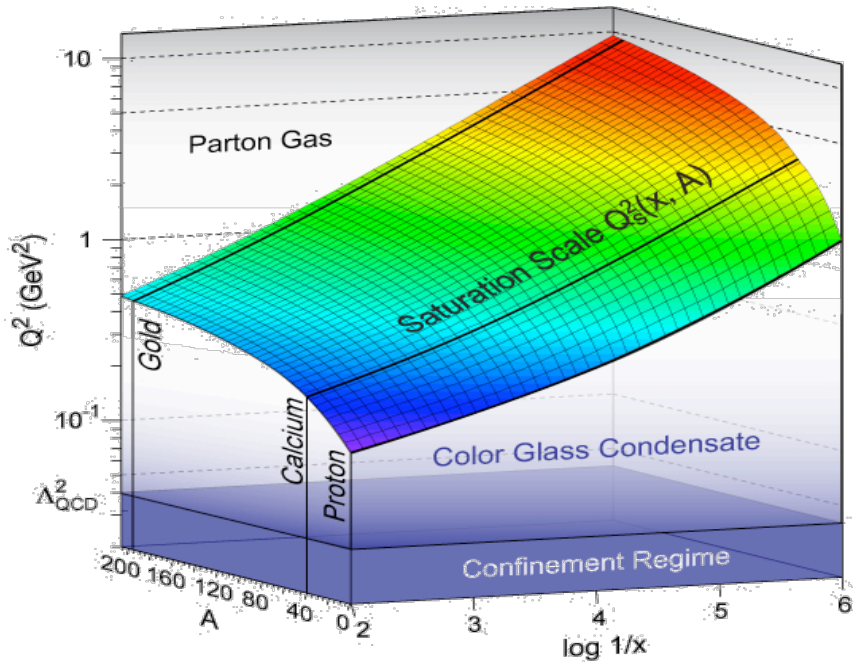
- Upper limit challenges models of initial eccentricity fluctuations
- Nucleon Glauber leaves no room for other fluctuations & correlations
- Data calls for different model of initial eccentricity (e.g. CGC)



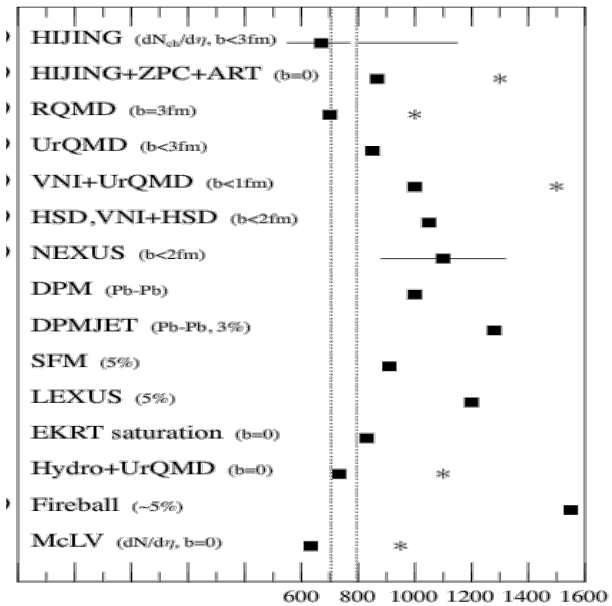

In agreement with both Glauber and CGC calculations within errors

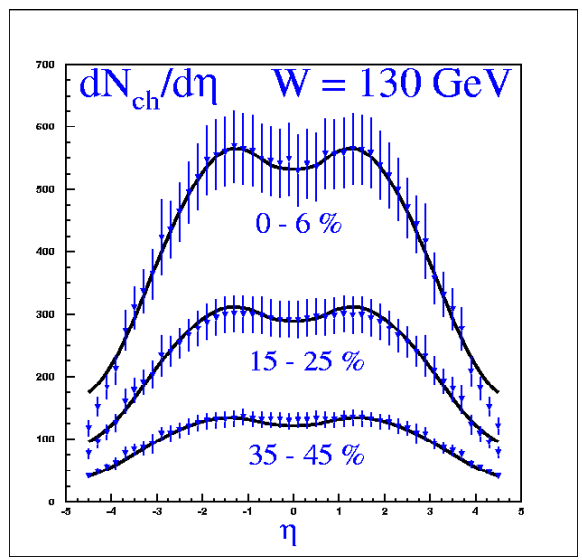
PHOBOS:
talk by G. Stephans

# From the initial wave functions to the quark-gluon plasma

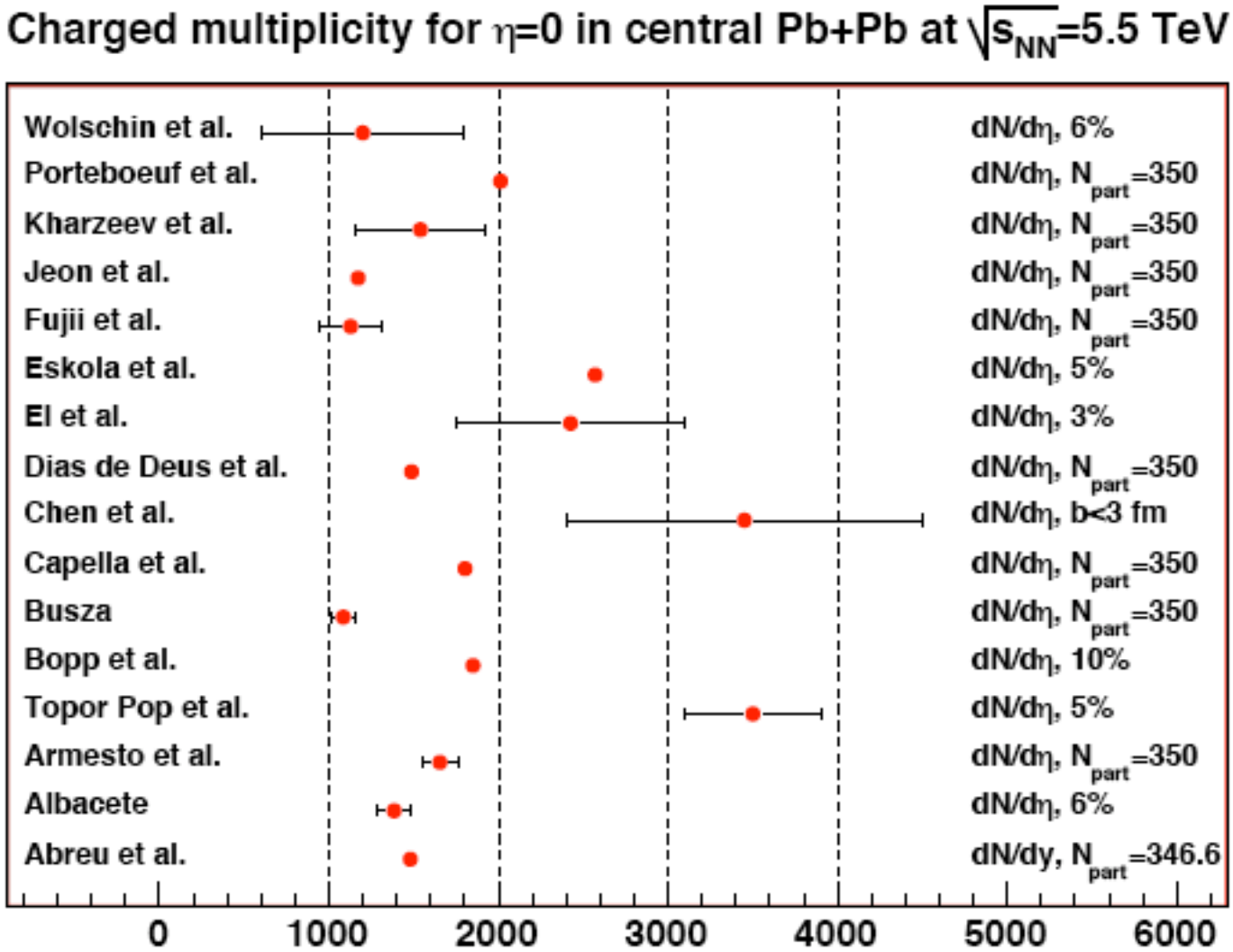



T. Ullrich, R. Venugopalan



# Predictions for the LHC - talk by N. Armesto

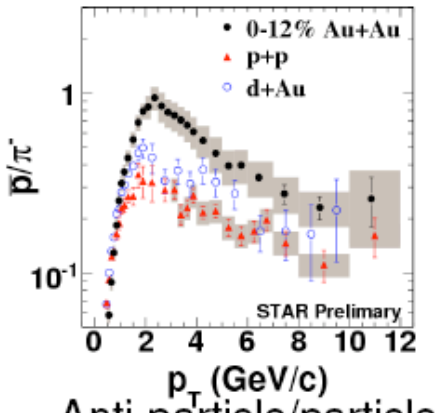


- How does the sQGP react to external probes?

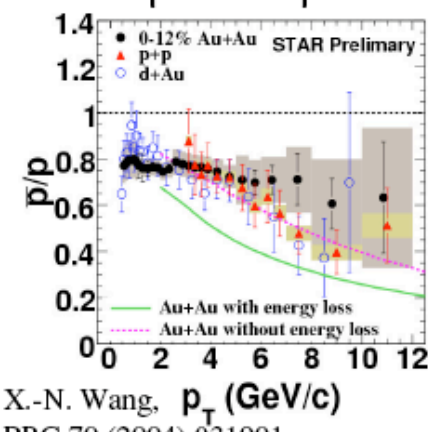
# Perturbative description of parton energy loss seems to be in a drastic contradiction with the data:

## Is there a difference in $E_{loss}$ of q and g

Anti-Baryon/meson




Anti-particle/particle




X.-N. Wang, PRC 70 (2004) 031901

Mechanism of energy loss : Medium induced gluon radiation

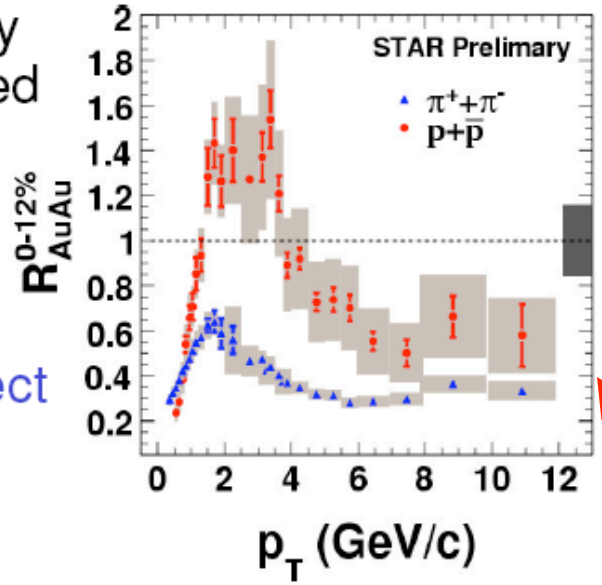
$$\langle \Delta E \rangle \sim \alpha_s C \langle \hat{q} \rangle L^2$$

The Color Factor Effect

$$\frac{\Delta E_g}{\Delta E_q} \sim 9/4$$

STAR : PLB 637 (2006) 161
PRL 97 (2006) 152301
PLB 655 (2007) 104

Baryon & meson NMF



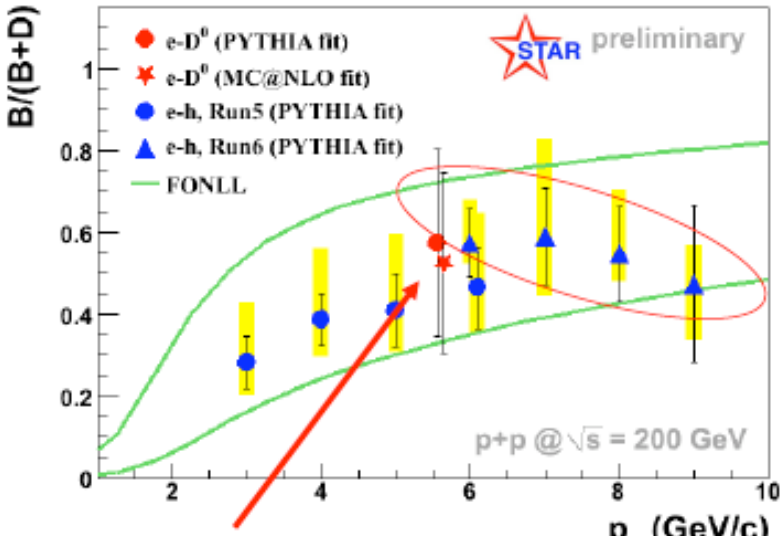

Factor 9/4 Color effects not observed up to $p_T$ ~ 12 GeV/c

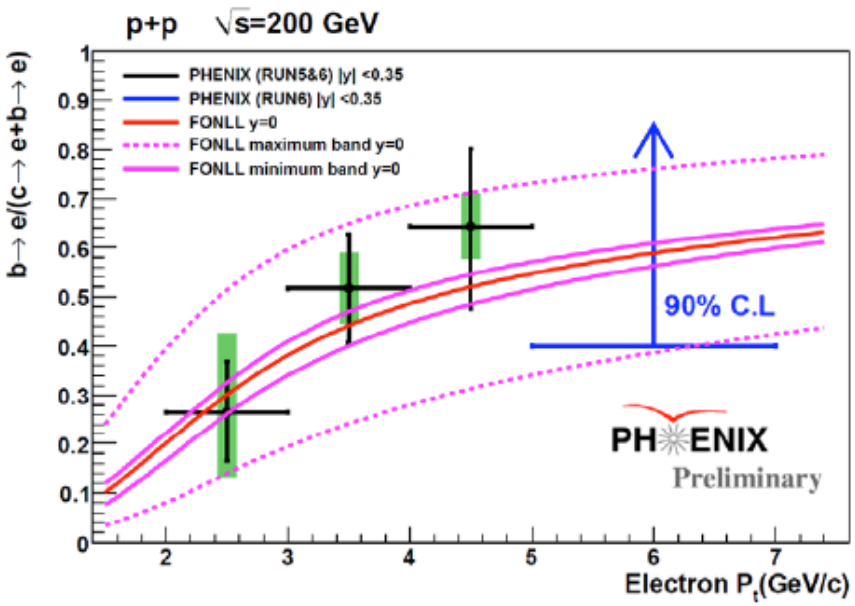
Maybe just not sensitive!

H. Caines, P. Fachini: STAR

gluons quenched less than quarks???

# Perturbative description of parton energy loss seems to be in a drastic contradiction with the data:



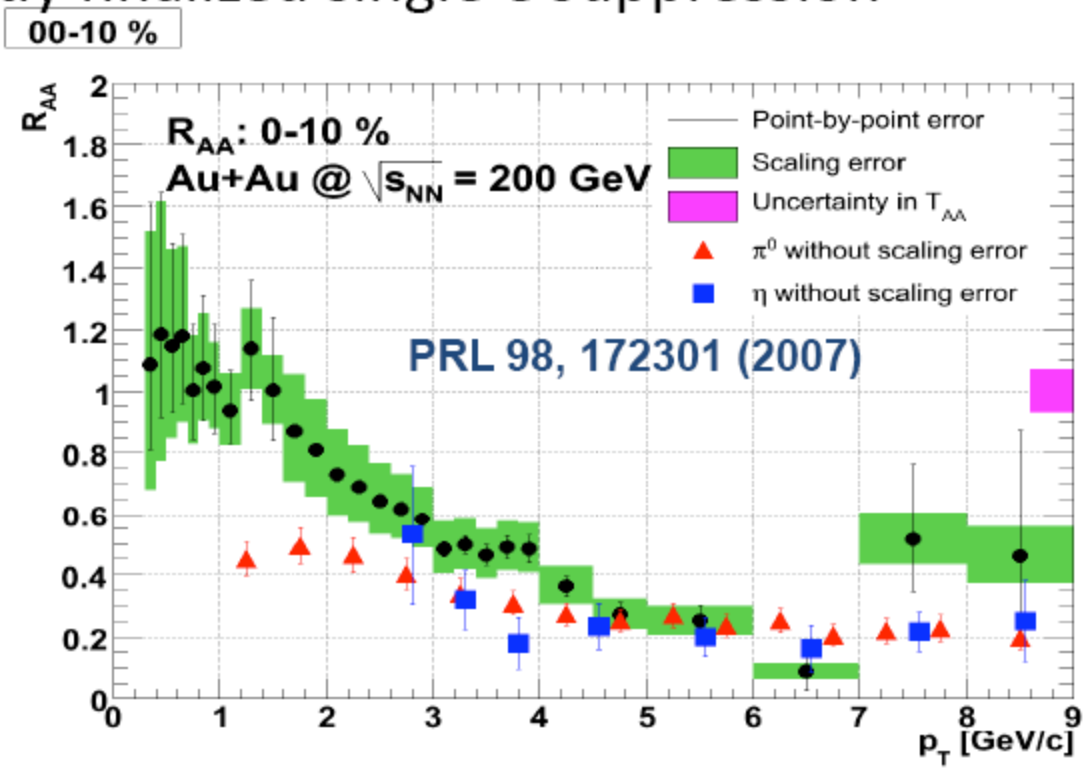

High $p_T$ electrons contain a large (dominant?) contribution from b-quarks;

High $p_T$ electrons are strongly suppressed;

b quarks must be quenched about as strongly as light quarks

(Almost?) impossible in pQCD

- Recently finalized single e suppression

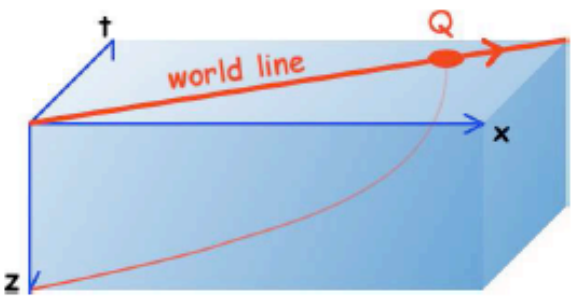


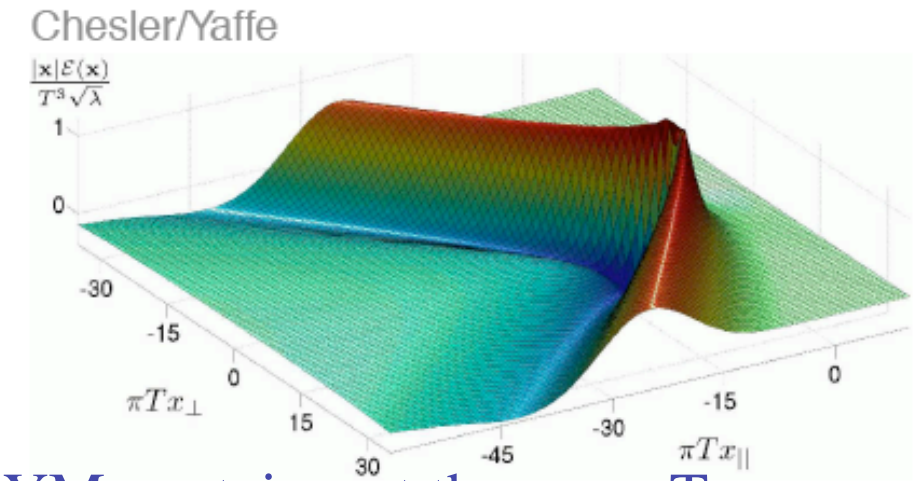

- Awaits further interpretation
  - Now quite well established b/c separation should help
- Collisional component of Eloss important?
- Non-perturbative components?

Perhaps;
but if so, should be
even more important
for light quarks!

PHENIX, J. Frantz

# Other energy loss mechanisms?




A word of caution: N=4 SUSY YM contains, at the same T, much higher density of particles than QCD; "rescaling" to QCD is not trivial (+ conformal invariance, etc )

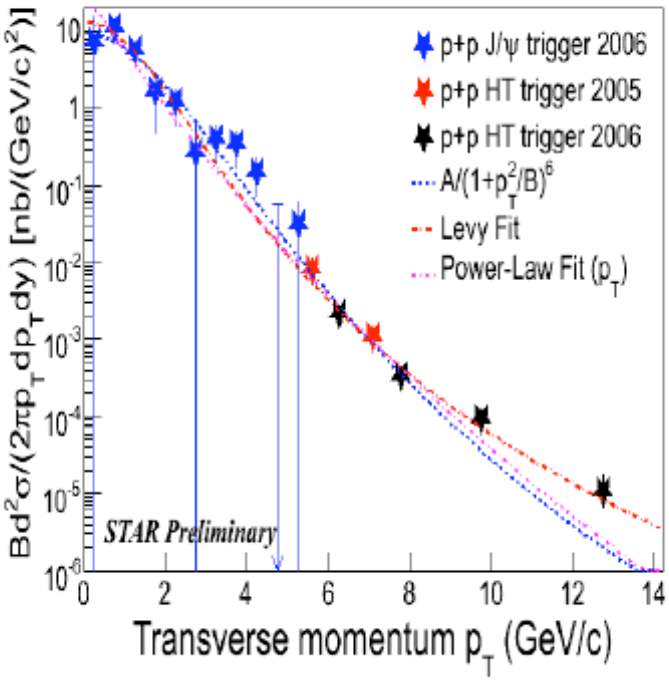
New experimental information: ridge, shoulder, … may provide a clue

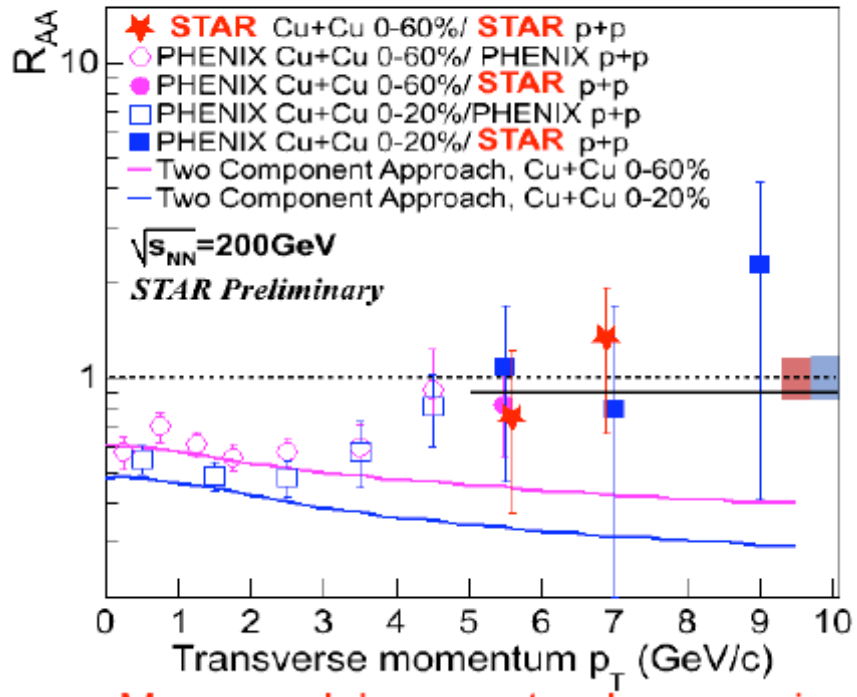
Talks by K.Rajagopal, R.Hwa, R.Venugopalan, …

# Quarkonium: as puzzling as ever

Provides means to investigate heavy quarkonium production mechanisms

Two Component Approach: *X. Zhao and R. Rapp, hep-ph/07122407*




$R_{AA}$ ($p_T$ < 4 GeV/c) : 0.5-0.6

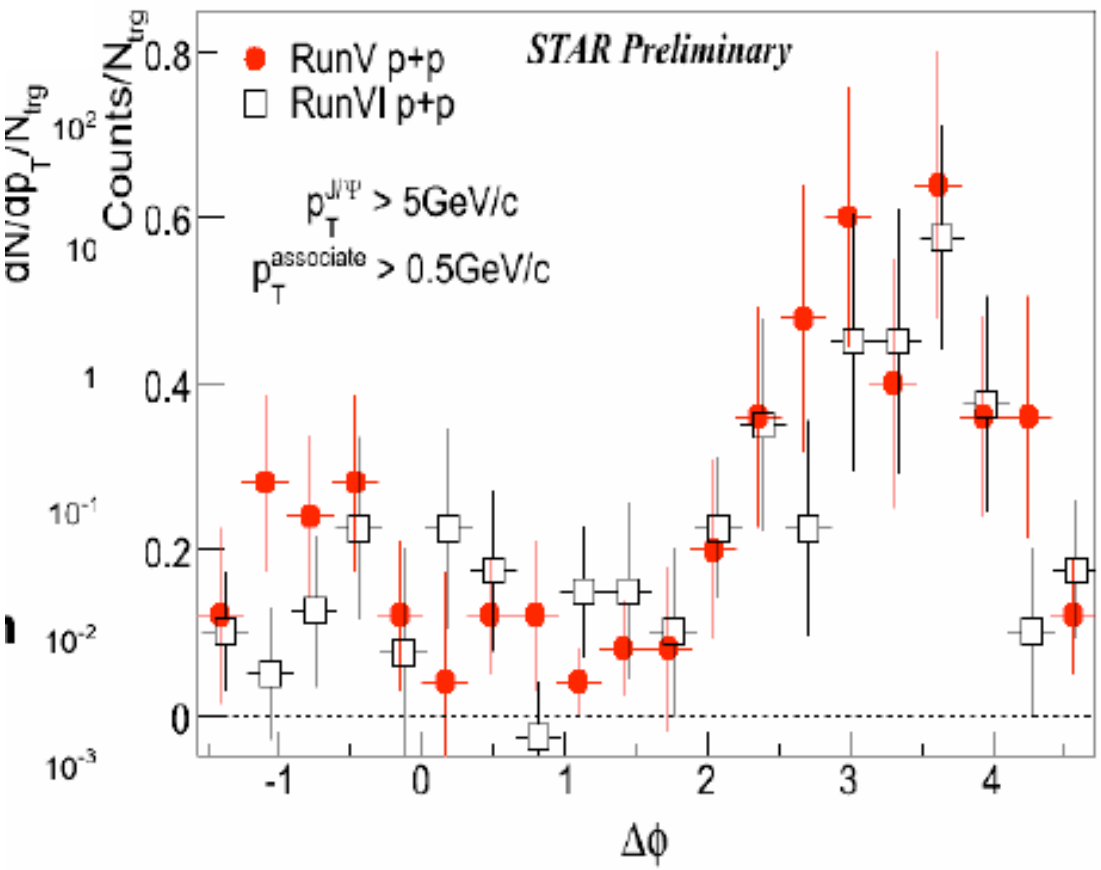
$R_{AA}$ ($p_T$ > 5 GeV/c) : 0.9±0.2

consistent with no suppression

Many models expect a decrease in $R_{AA}$ as function of $p_T$

Next step the ϒ - almost there

Lack of high $p_T$ suppression is consistent with the color singlet production mechanism, which also predicts the lack of near-side correlation: $g + g \rightarrow J/\psi + g$




No near side correlation seen!

BUT: how to understand the dominance of the color singlet mechanism at $p_T \sim 10$ GeV?

# What happens to quarkonium in sQGP?

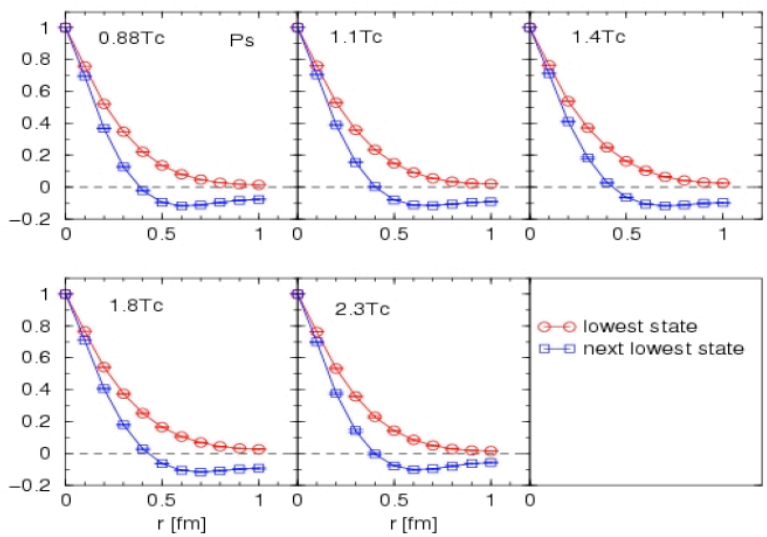
Still no clear answer:

lattice indicates that J/ψ correlation function does not change up to ~ 2 $T_c$

but this may still be consistent with dissociation (a threshold enhancement in the spectral density?)

Talk by A. Mocsy

a recent attempt to measure the quarkonium wave function:

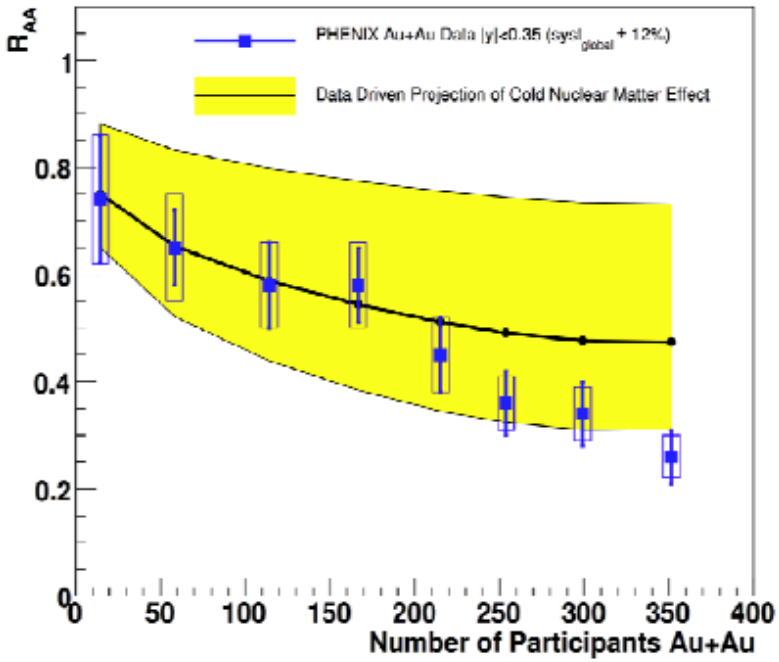


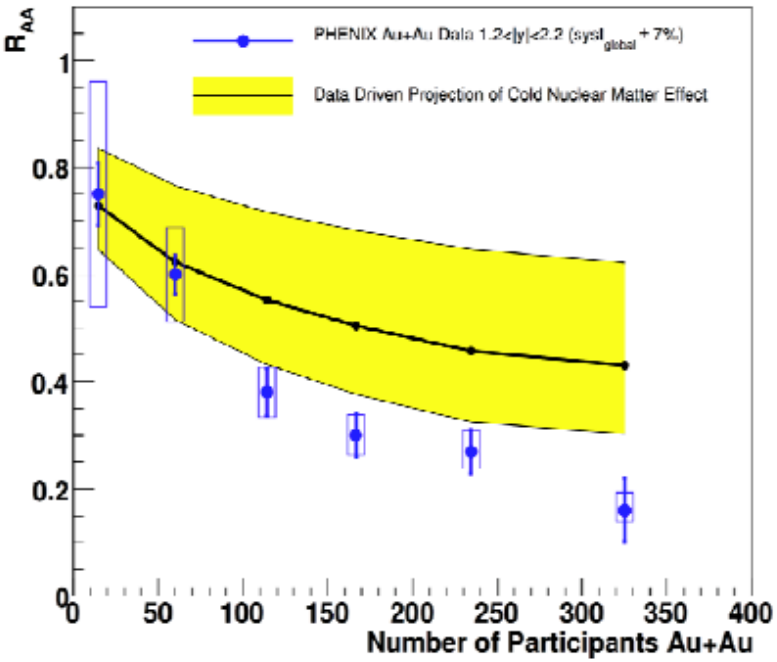

T. Umeda

Need to address also the real-time dynamics (diffusion etc) -
P. Petreczky

- No indication of scattering state up to 2.3Tc ( ! )

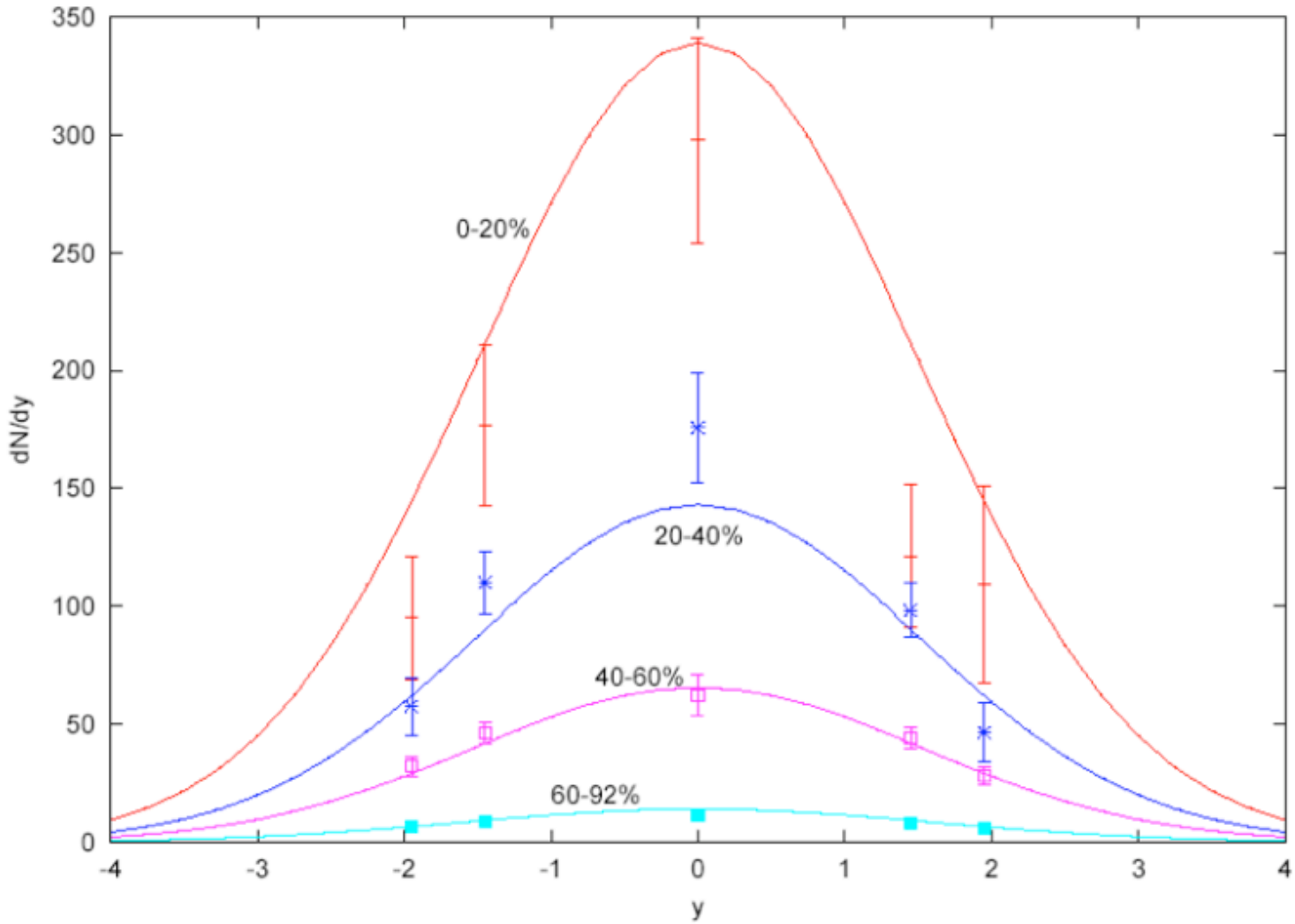
# J/ψ $R_{AuAu}$ 200 GeV (Run4)



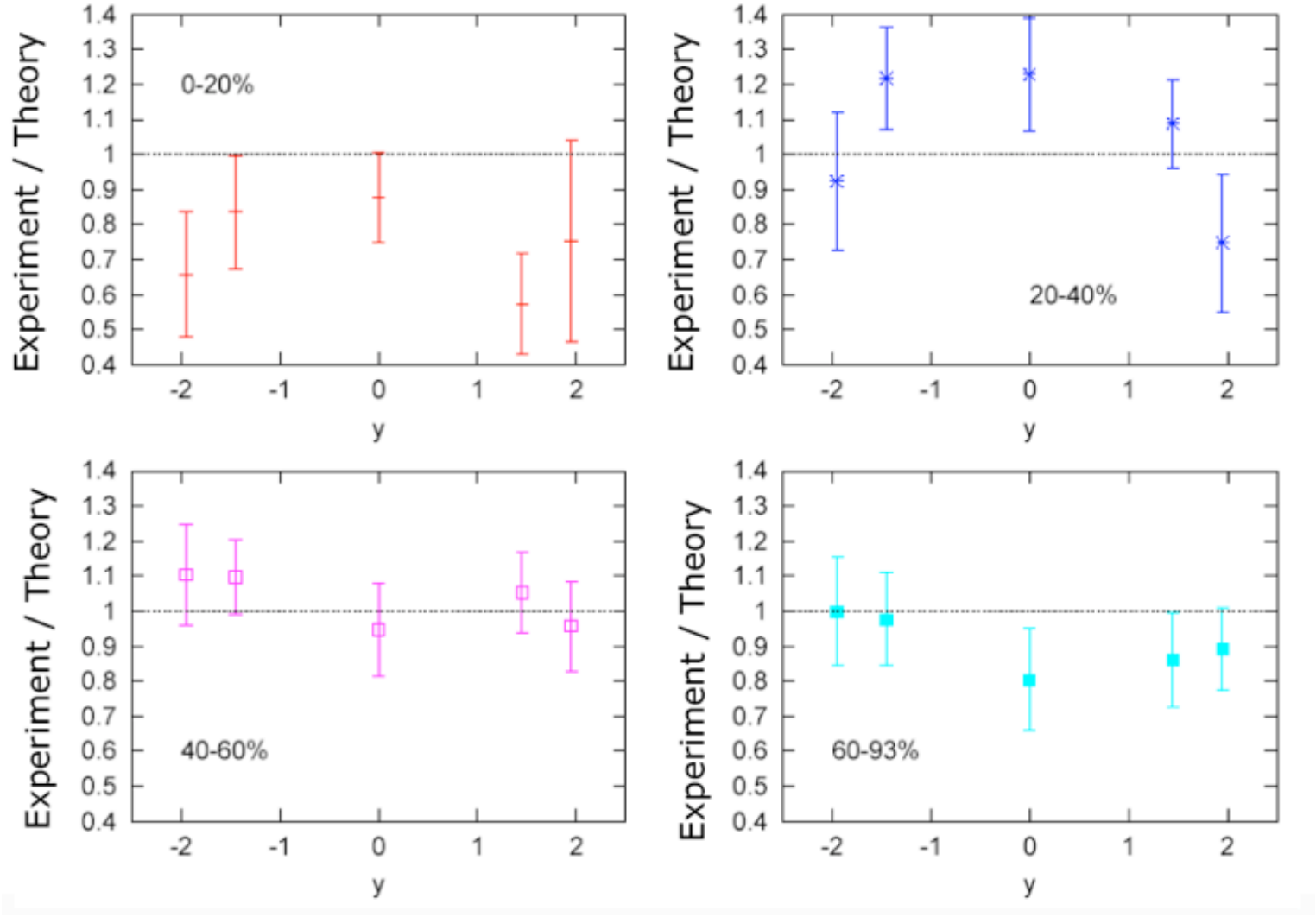




PHENIX: do we see more suppression at forward rapidity than is expected from "cold nuclear matter" effects?

R. Granier de Cassagnac




CGC predictions: talk by M. Nardi




The rapidity dependence is described quite well;
room for QGP effects in the central bin

# What do we still need to know?

- Are heavy quarks really quenched as strongly as light ones? (vertex detectors, more Au-Au data)
- Need to understand better the structure of the jets (ridge, cones, ...) and the color charge dependence of quenching
- Test the predictions of the CGC in dAu
- Need to understand better what is happening with the heavy quarkonia: production and suppression mechanisms
- Search for the critical point: the energy scan