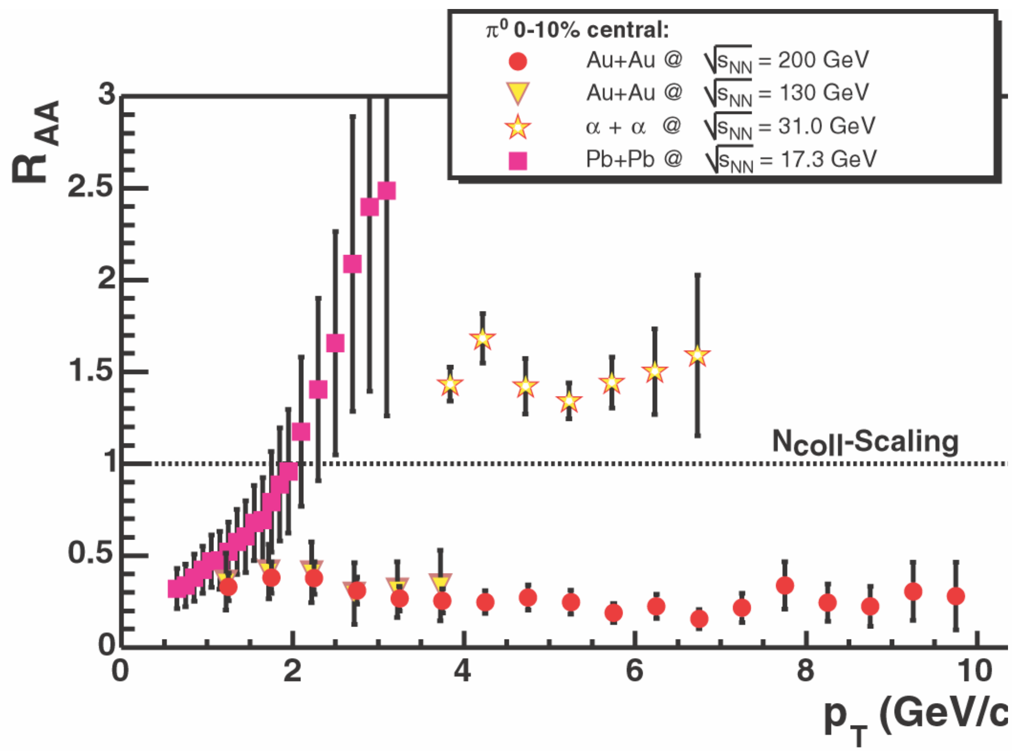
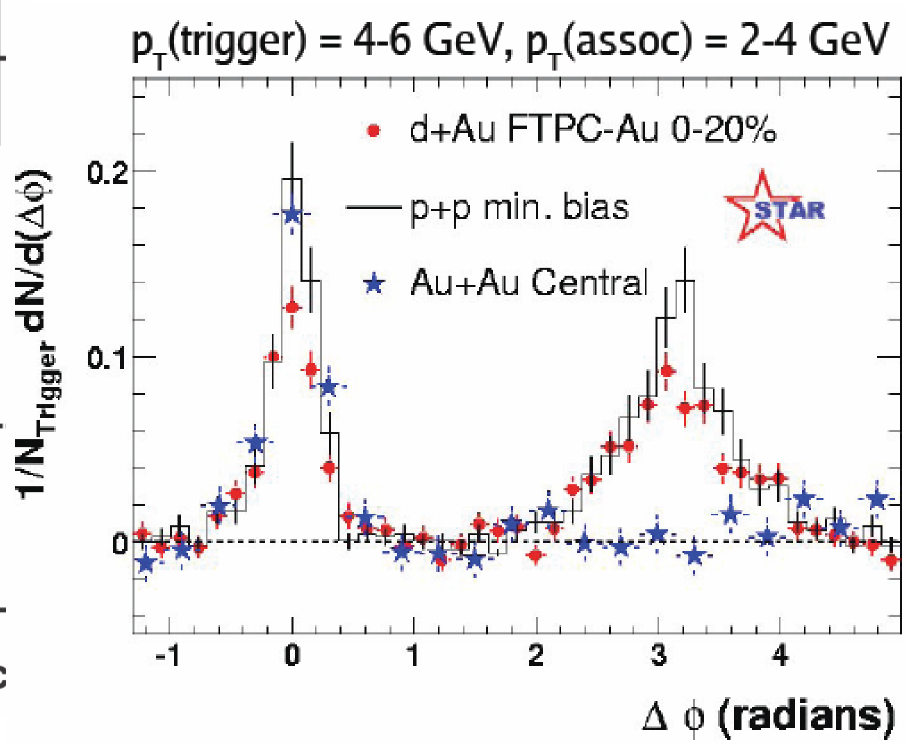
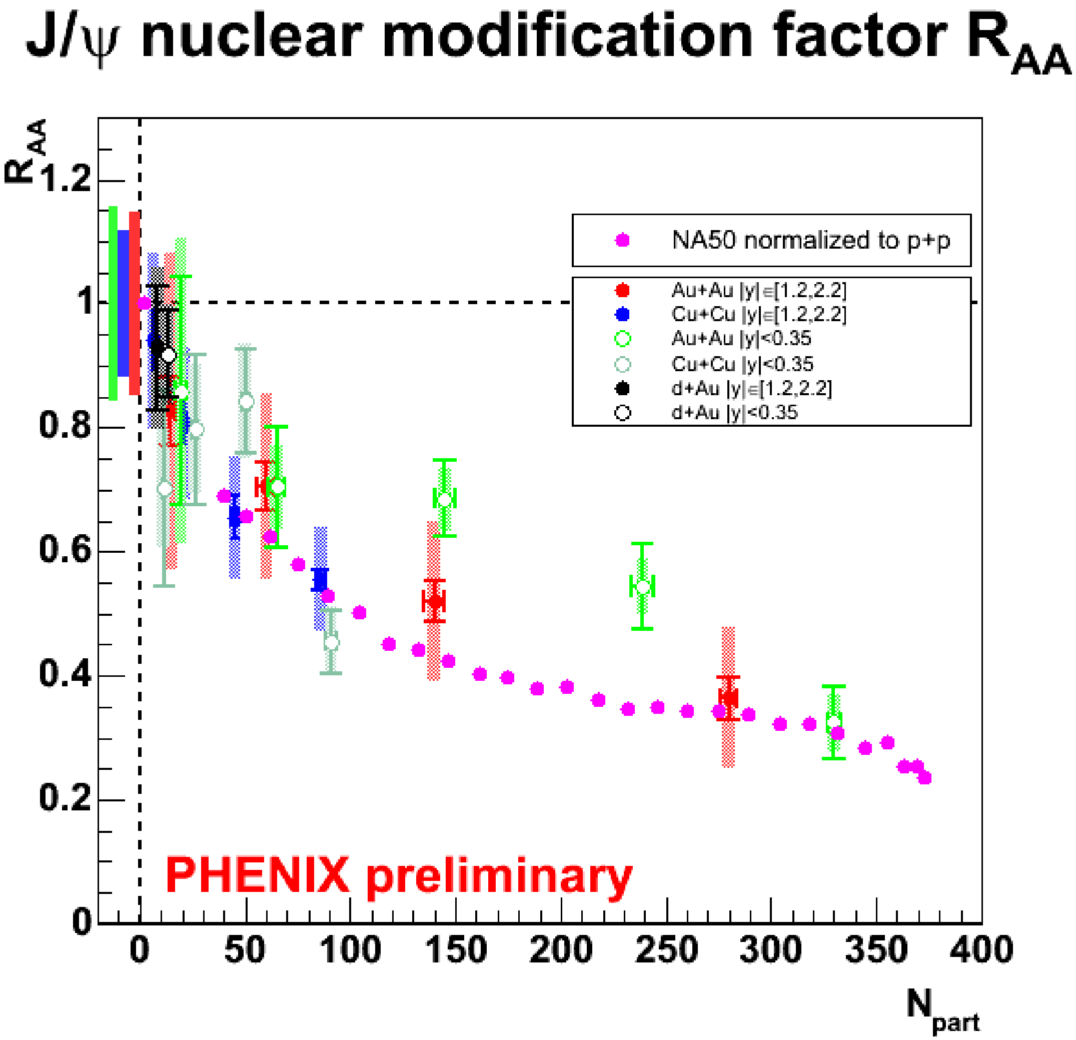
Do we see the QCD matter at RHIC?

II. Suppression of high p_T particles =>
consistent with the predicted parton energy loss from induced gluon radiation in dense QCD matter





III. J/ψ suppression at RHIC



"same as at SPS"?

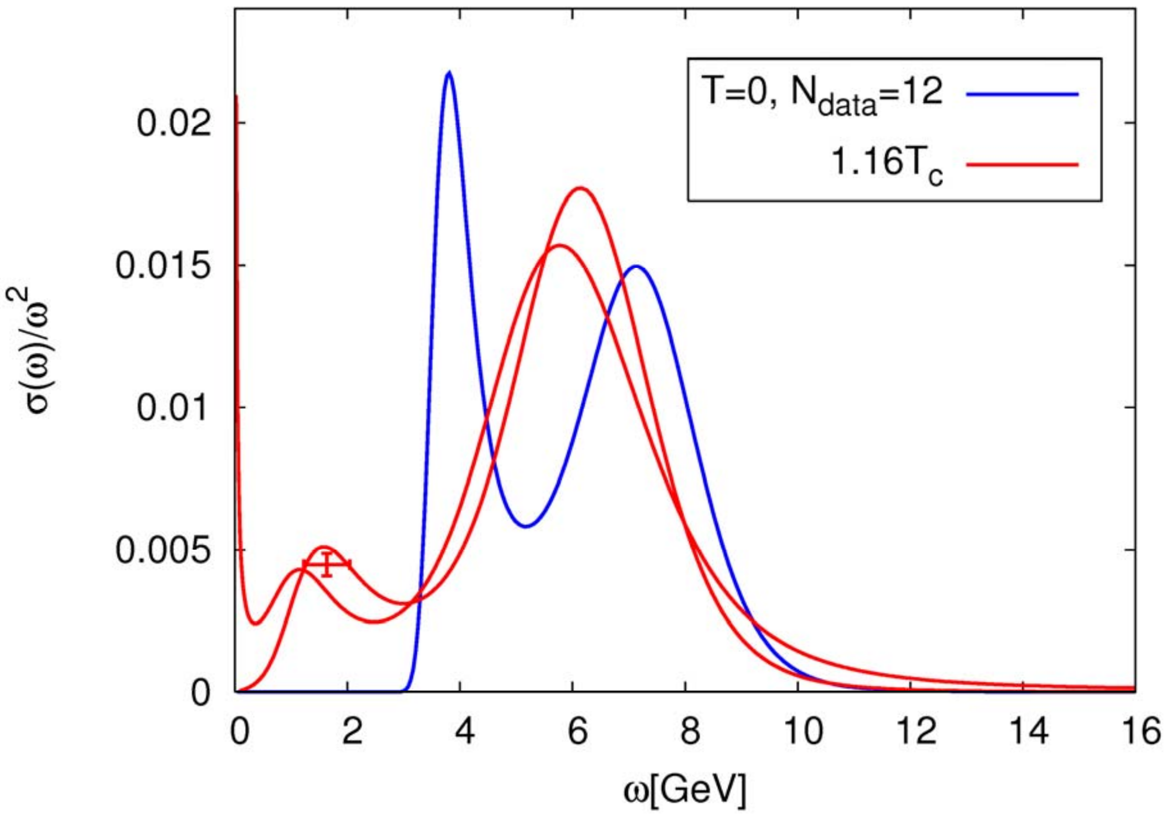
Sequential charmonium dissociation?

Both the absence of J/ψ suppression up to ~ 2 T_c in
the lattice QCD data and
the apparent similarity of the magnitude of suppression
at RHIC and SPS are puzzling;

However, the two puzzles may be consistent with each other

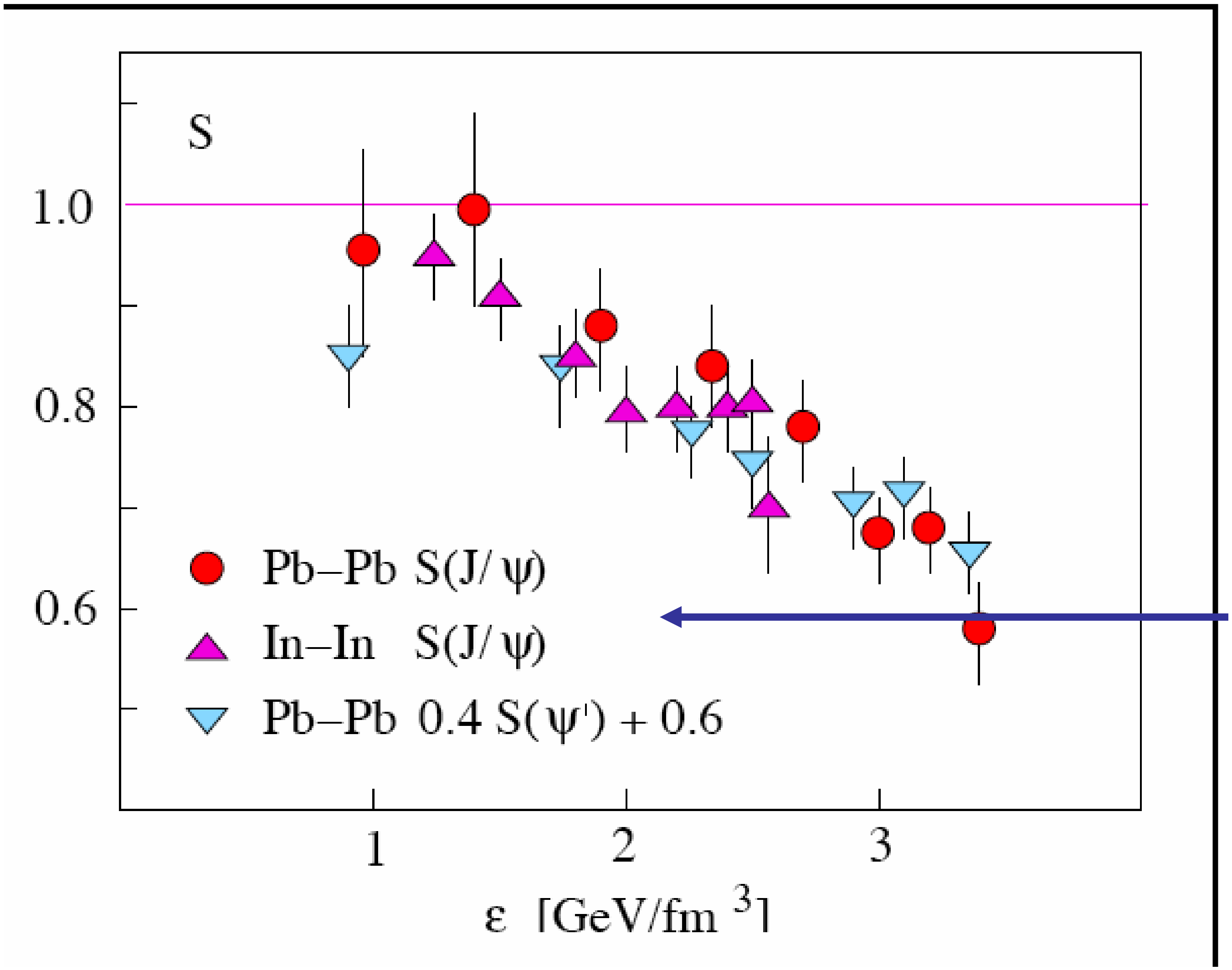
F.Karsch, DK, H.Satz,
hep-ph/0512239

Excited states dissapear at T ~ T_c???



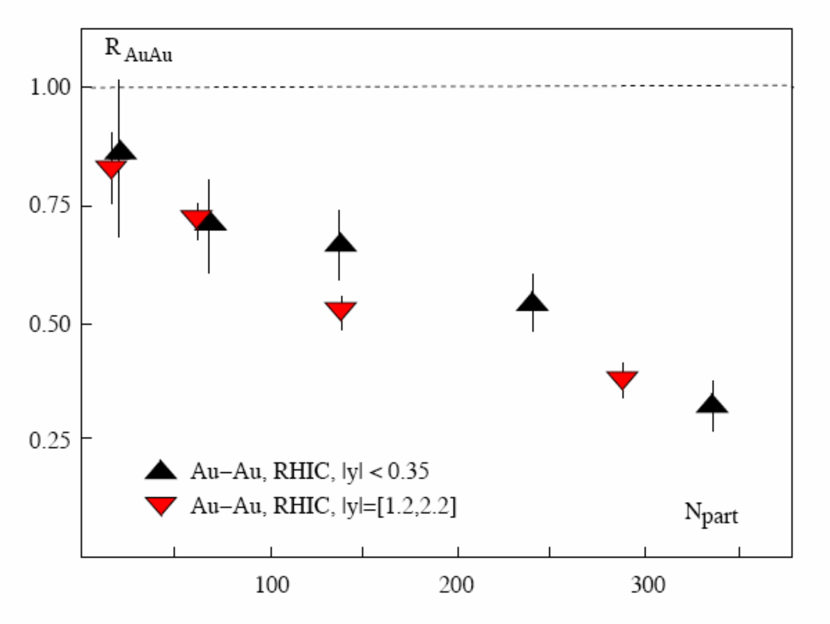
Scalar channel; from A.Jakovac et al., hep-lat/0611017

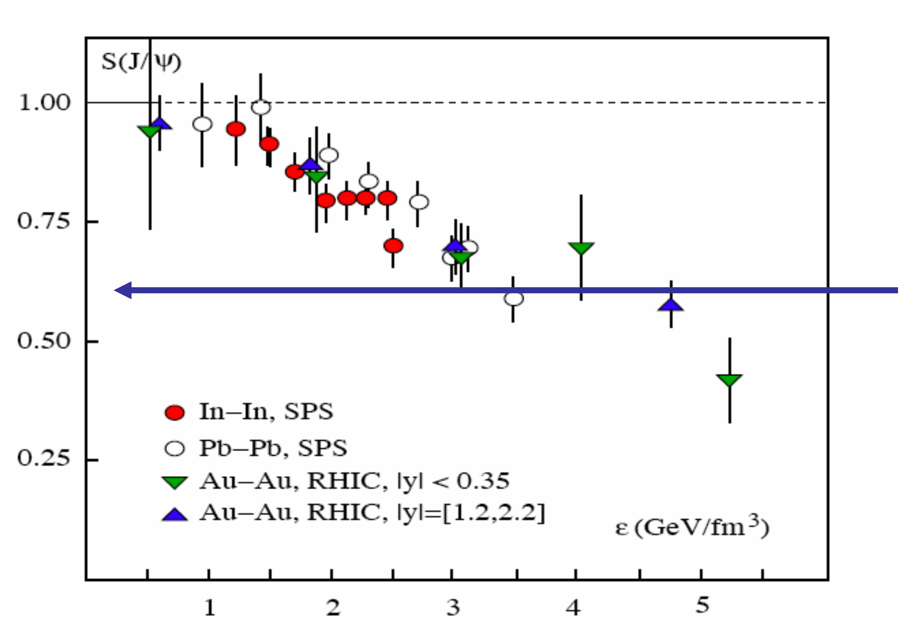
Is there a “direct” J/ψ suppression at SPS?



~ 40%
of observed
J/ψ ‘s
originate
from χ and ψ
decays;
they should
be gone above T_c

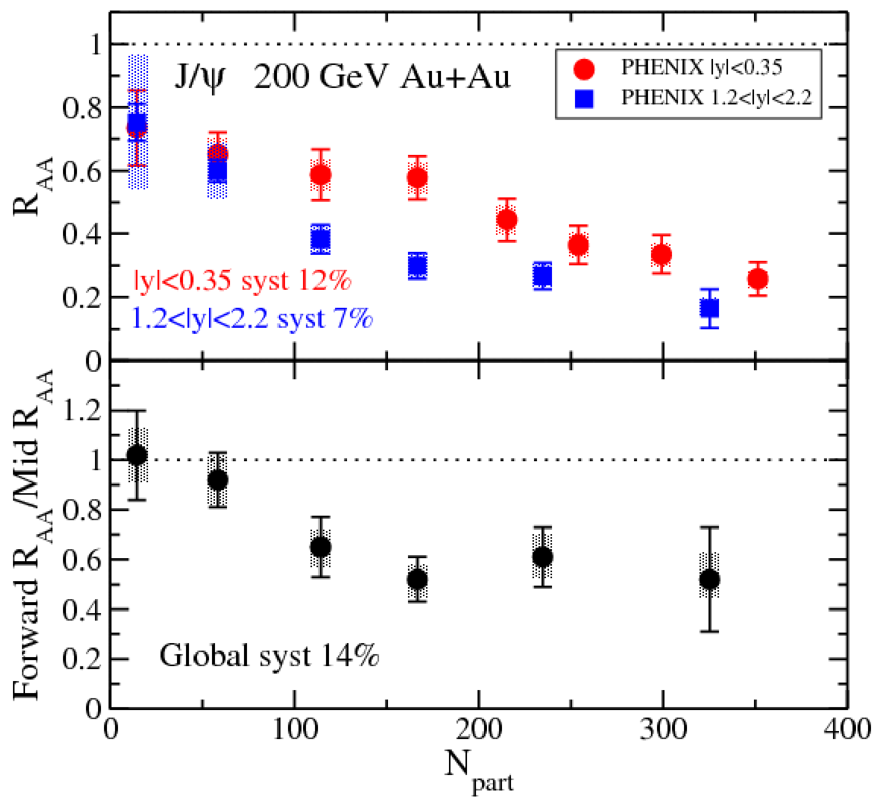
Is there a "direct" J/ψ suppression at RHIC?

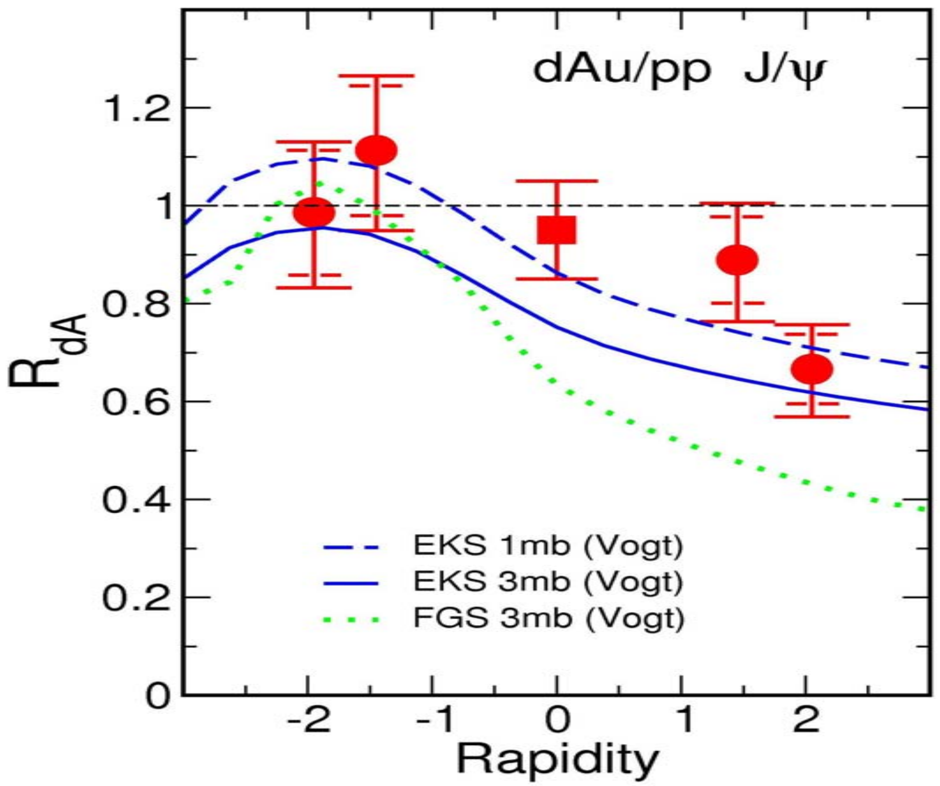




Data: PHENIX, NA50, NA60

Recent PHENIX results: suppression is stronger away from y=0

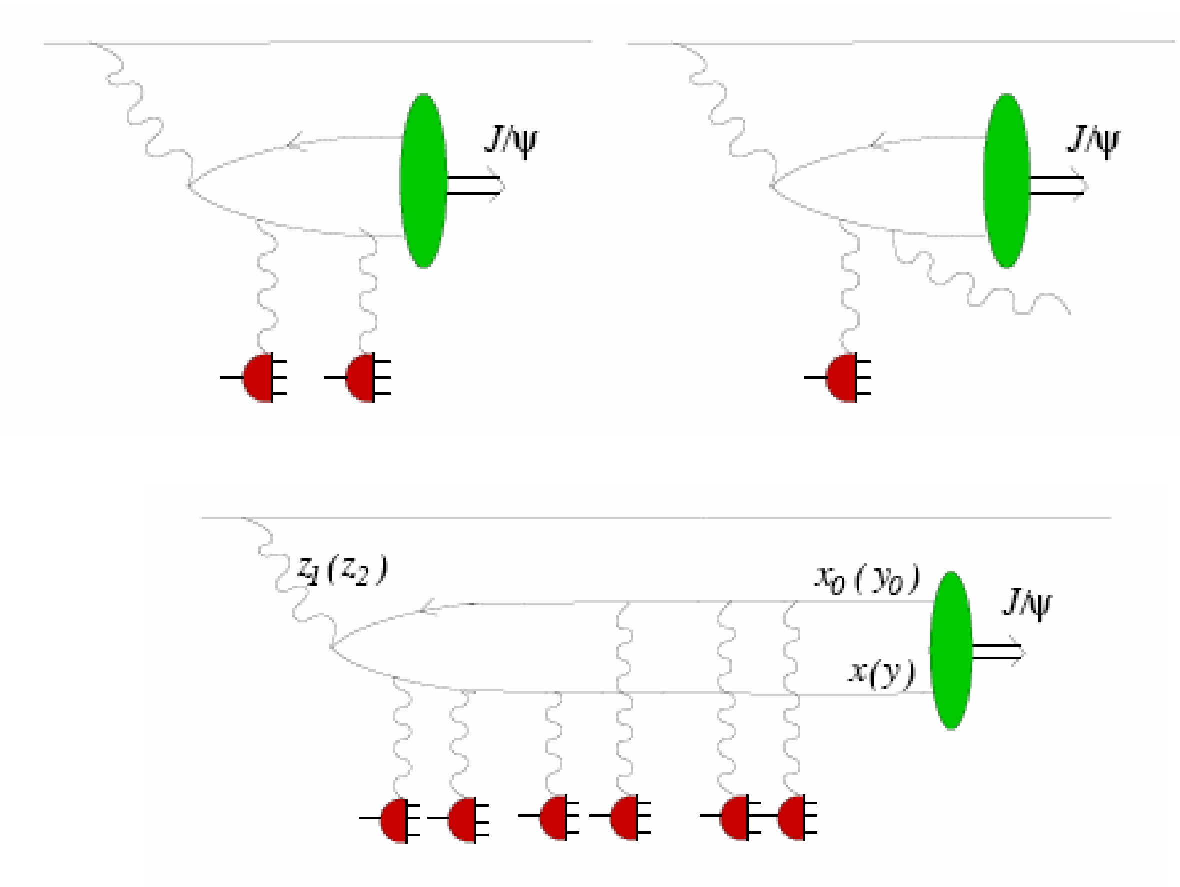




Initial state effect? Need better dA data

J/Ψ in strong color fields: “initial state effects”

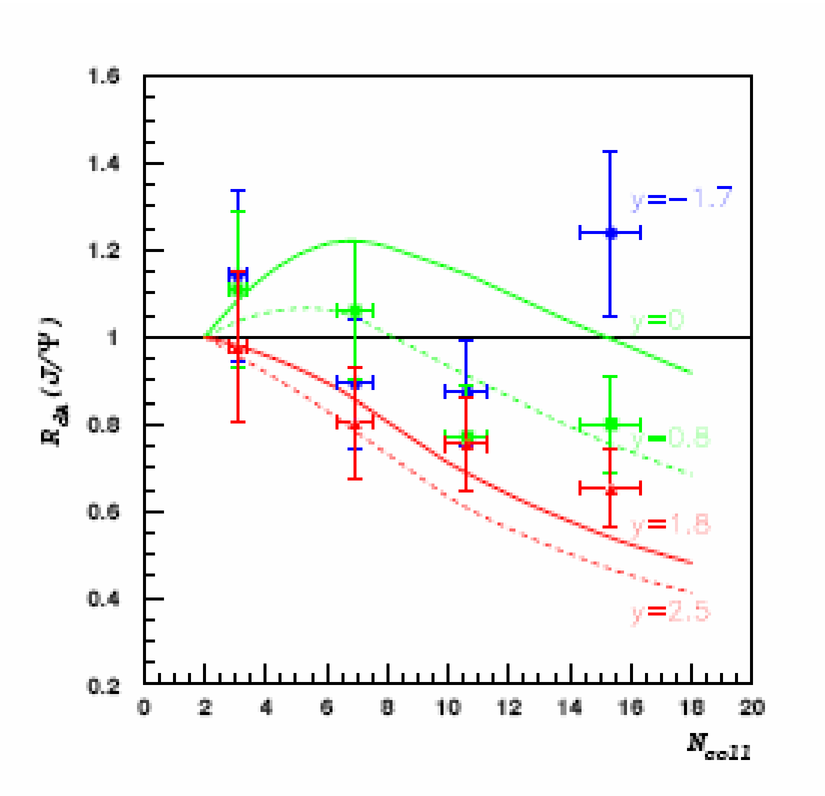
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

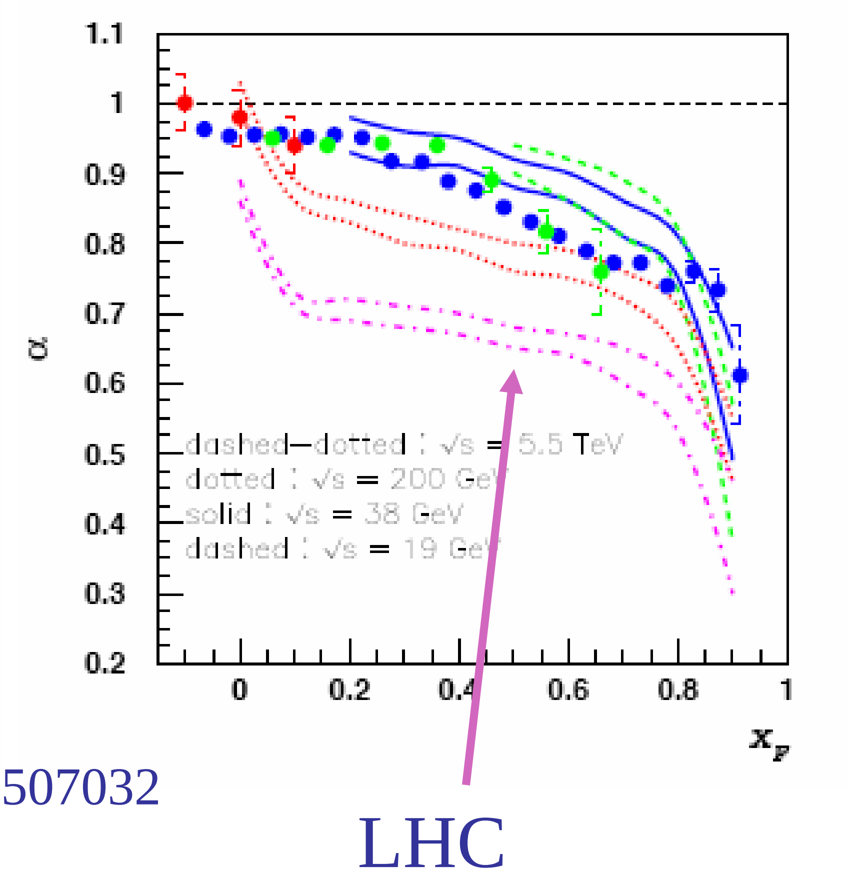


J/Ψ suppression in the Color Glass Condensate

Somewhat like screening in the plasma, $Q_s \longleftrightarrow 2\pi T$

"x_F scaling"

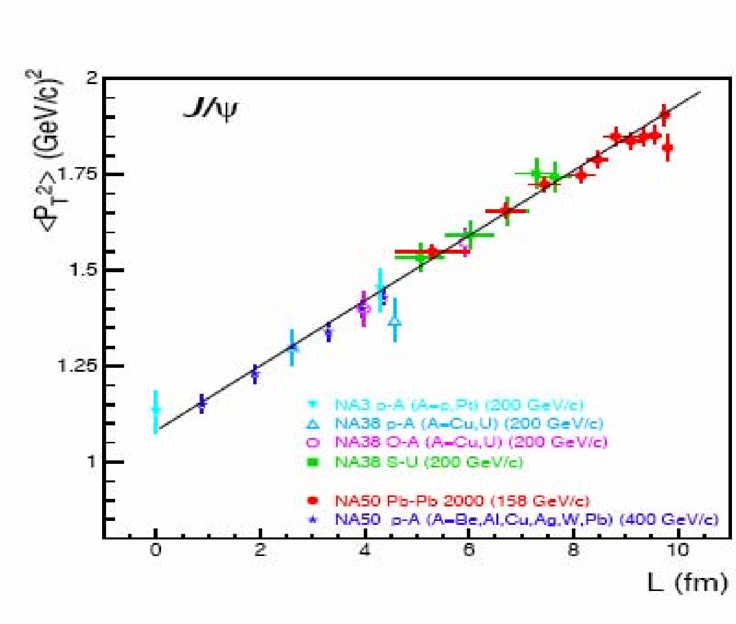


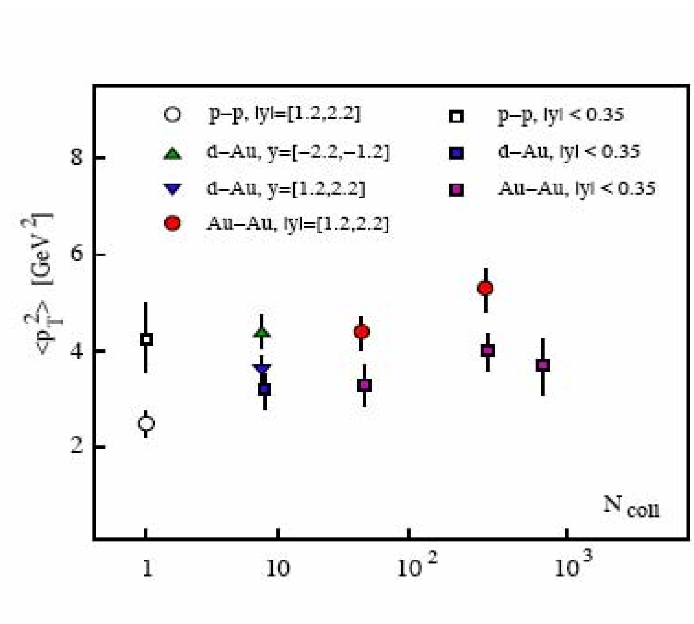


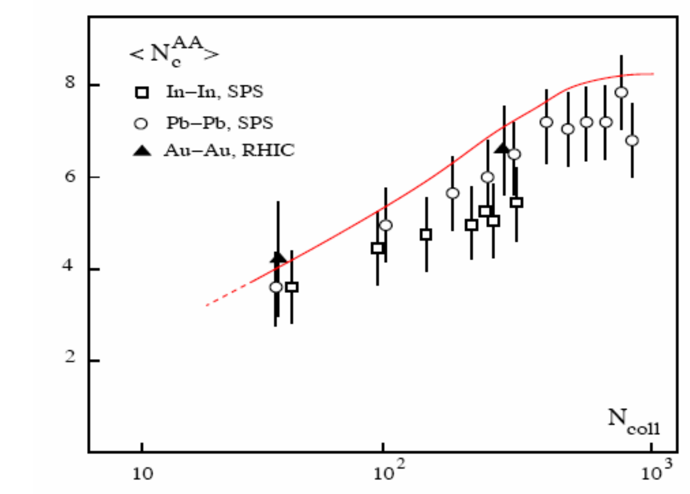
Data: PHENIX Coll., nucl-ex/0507032

DK, K.Tuchin, hep-ph/0510358

Transverse momentum distributions







Glauber model analysis

Screening at finite momentum

* Weak coupling: enhanced screening in the direction of momentum

M.Chu & T.Matsui ‘89, M.Mustafa et al ‘04

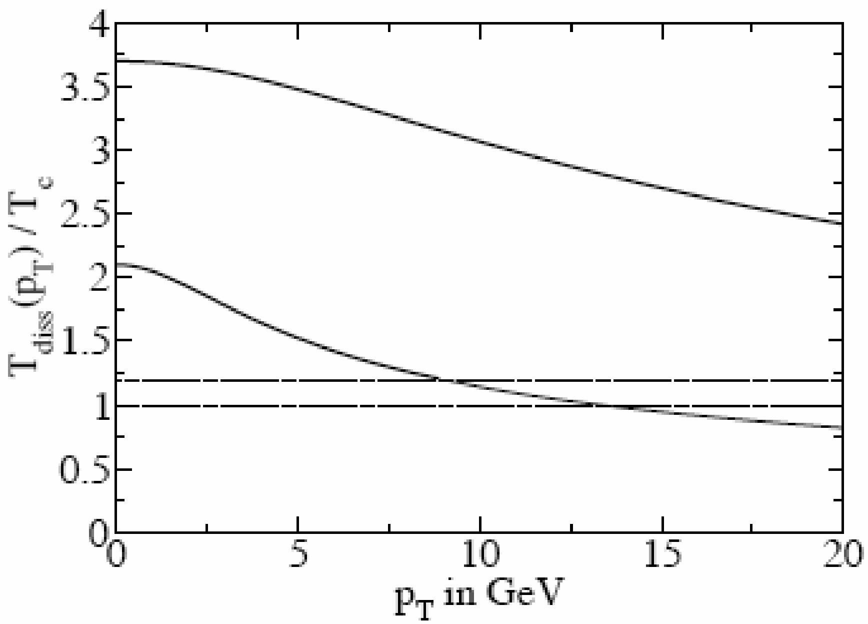


FIG. 3: A $1/\sqrt{\gamma}$-velocity scaling of the screening length in QCD would imply that the J/Ψ dissociation temperature $T_{\rm diss}(p_T)$ decreases significantly with transverse momentum.

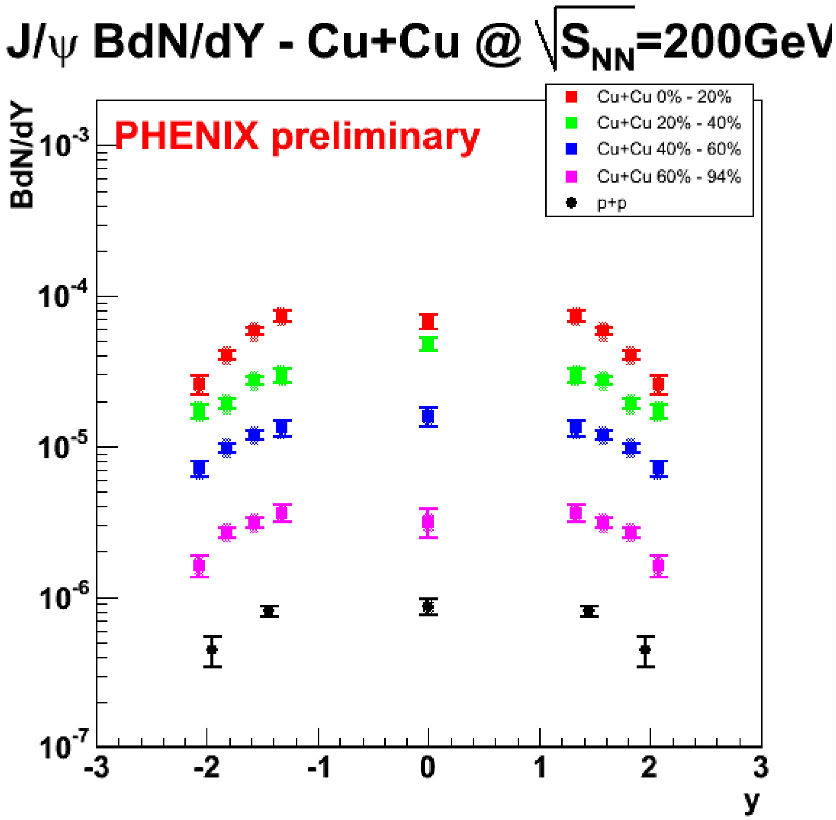
* AdS/CFT: Lorentz contraction of the screening length, enhanced screening

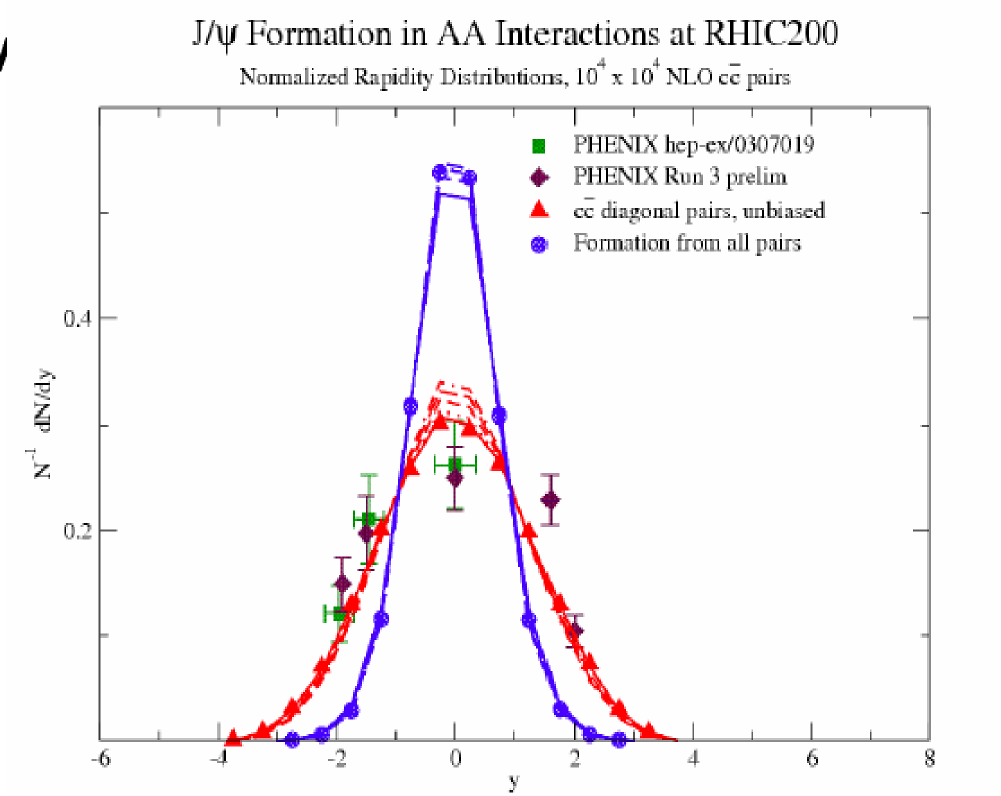
H.Liu, K.Rajagopal, U.Wiedemann ‘06

* Lattice calculations so far limited to p/T < 5;

* Experiment: how to disentangle from the suppression due to gluon fragmentation?

Recombination of charm quarks?





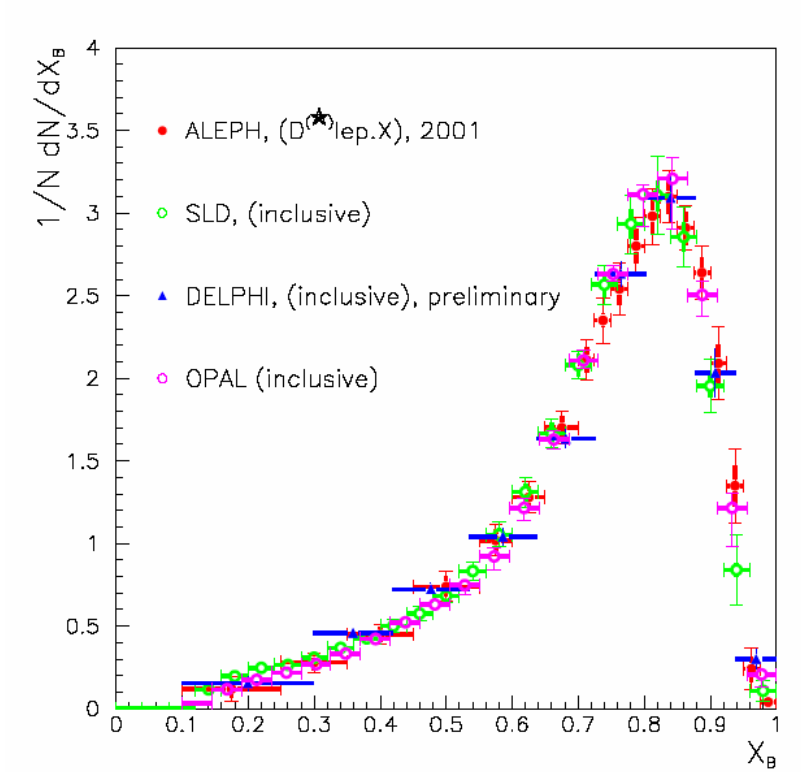
R.Thews

Recombination narrows the rapidity distribution; is this seen?

Are high p_t charmonia suppressed stronger than open charm?

Heavy quarks in QCD vacuum

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



OPAL Collaboration

Heavy quarks produce a larger number of particles

and carry a larger fraction of jet momentum

Heavy quark colorimetry of QCD matter

col·or·im·e·try *noun*
col·or·im·e·ter *noun* **:**
an instrument or device for determining and specifying colors; *specifically* **:** one used for chemical analysis by comparison of a liquid's color with standard colors

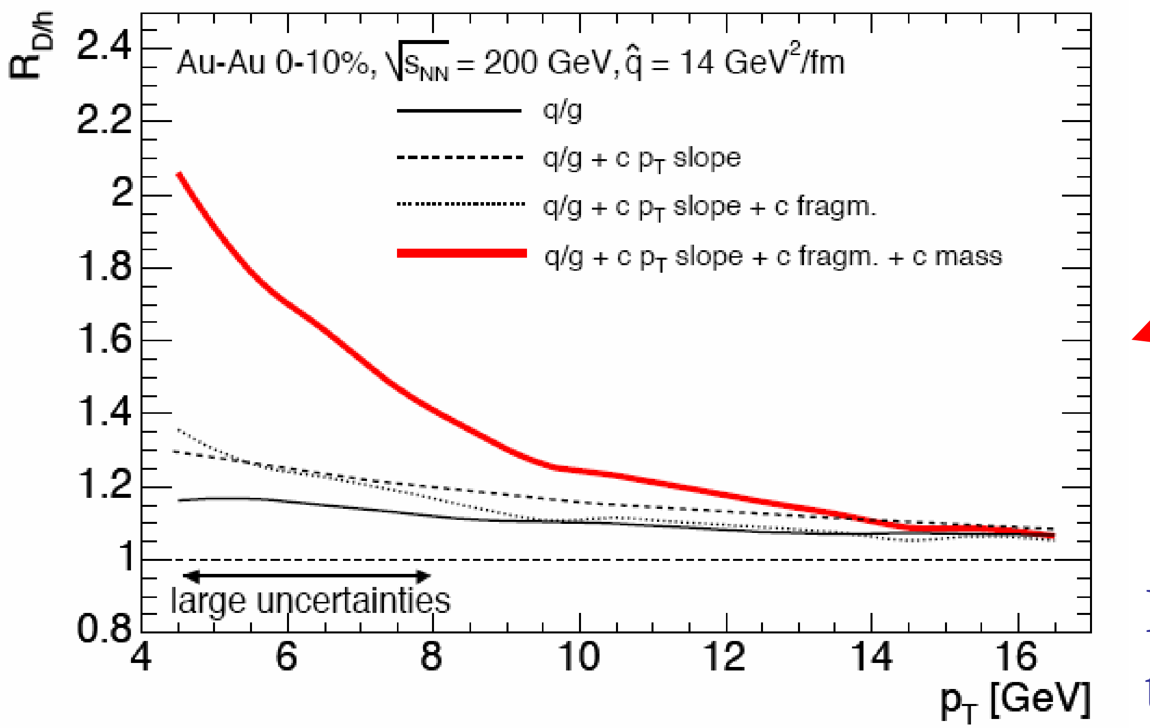
Merriam-Webster Dictionary

The propagation of heavy quarks in QCD matter is strongly affected by the interplay of the "dead cone" and quantum interference effects (LPM) at energies up to

$$E \leq M\sqrt{\hat{q}L^3}$$

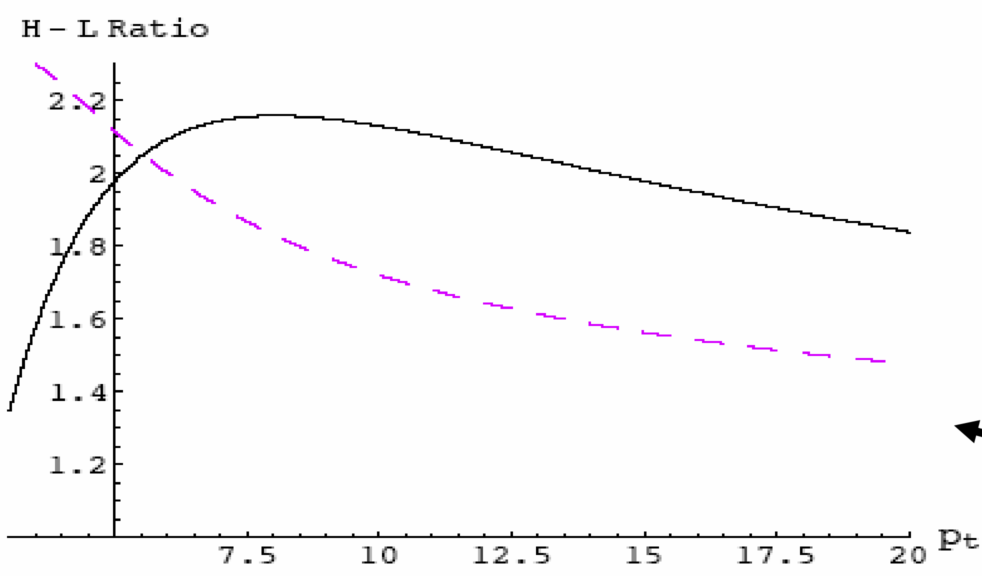
(a consequence of quantum mechanics & causality)

Yu.Dokshitzer, DK
hep-ph/0106202



N.Armesto, A.Dainese, C.Salgado, U.Wiedemann, hep-ph/0303185

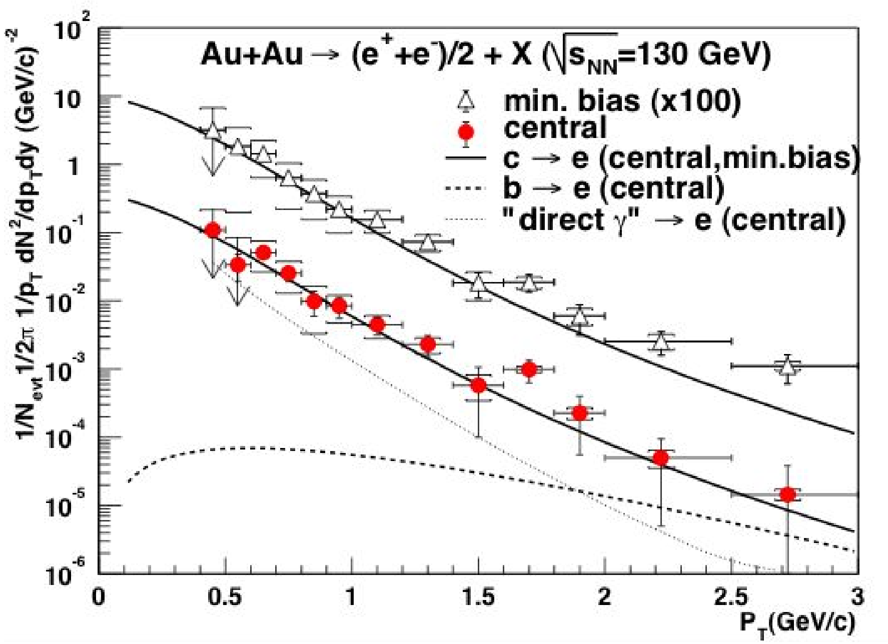
Enhancement of the D/h ratio as a signature of the radiative energy loss in the QGP: Heavy quarks lose less

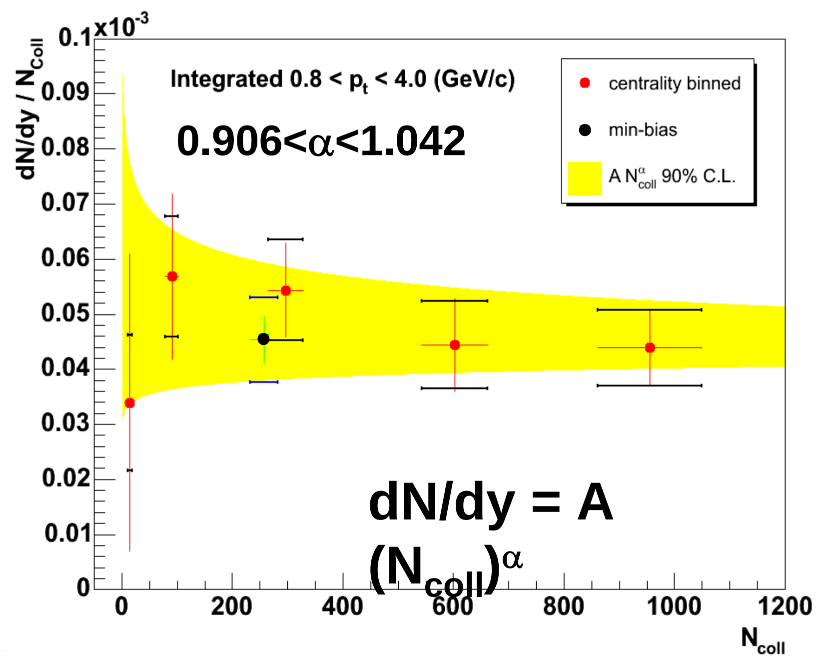


Yu.L.Dokshitzer and DK, Phys.Lett.B519 (2001) 199

For heavy quarks the induced gluon radiation should be suppressed; is it?

Recent work:
M.Djordjevic, M.Gyulassy ‘03-
B.Zhang, E.Wang, X.-N. Wang’04
N.Armesto, C.Salgado, U.Wiedemann’04-

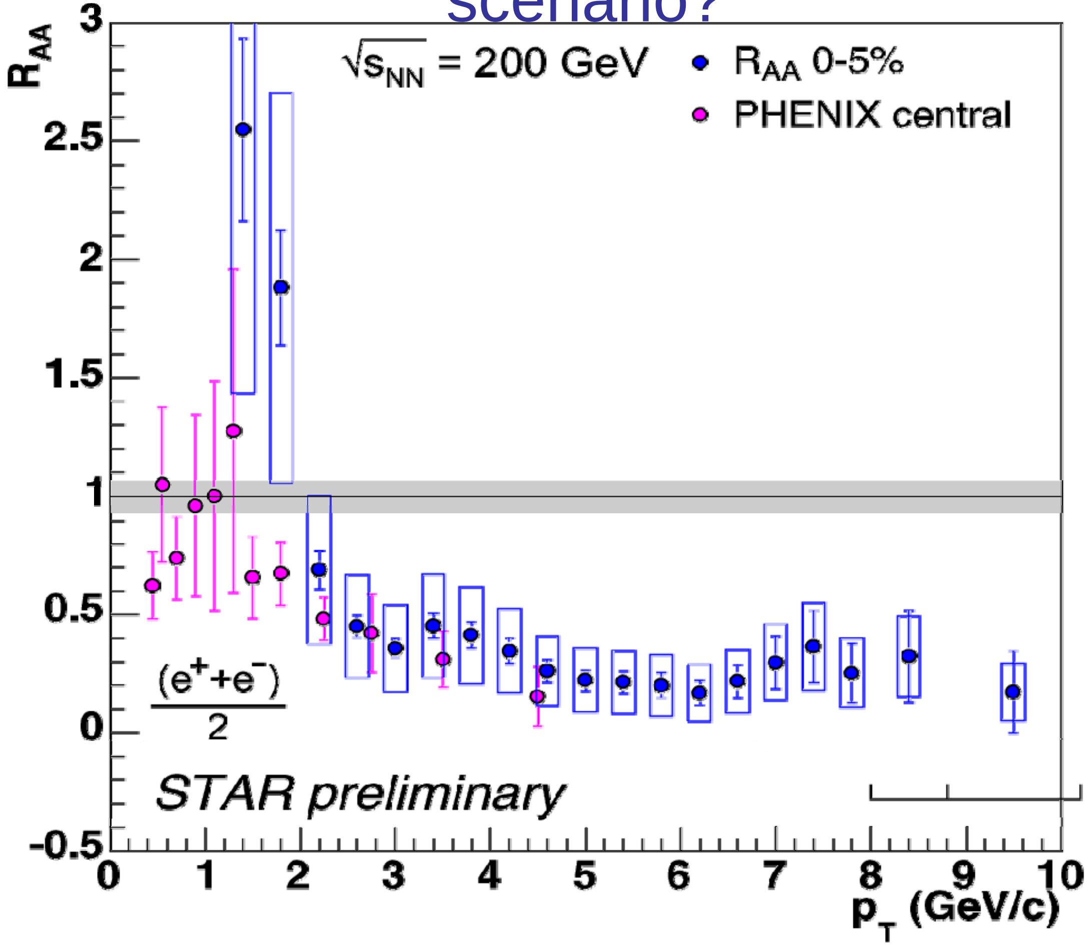




Data from PHENIX

AuAu collisions: charm is quenched!?

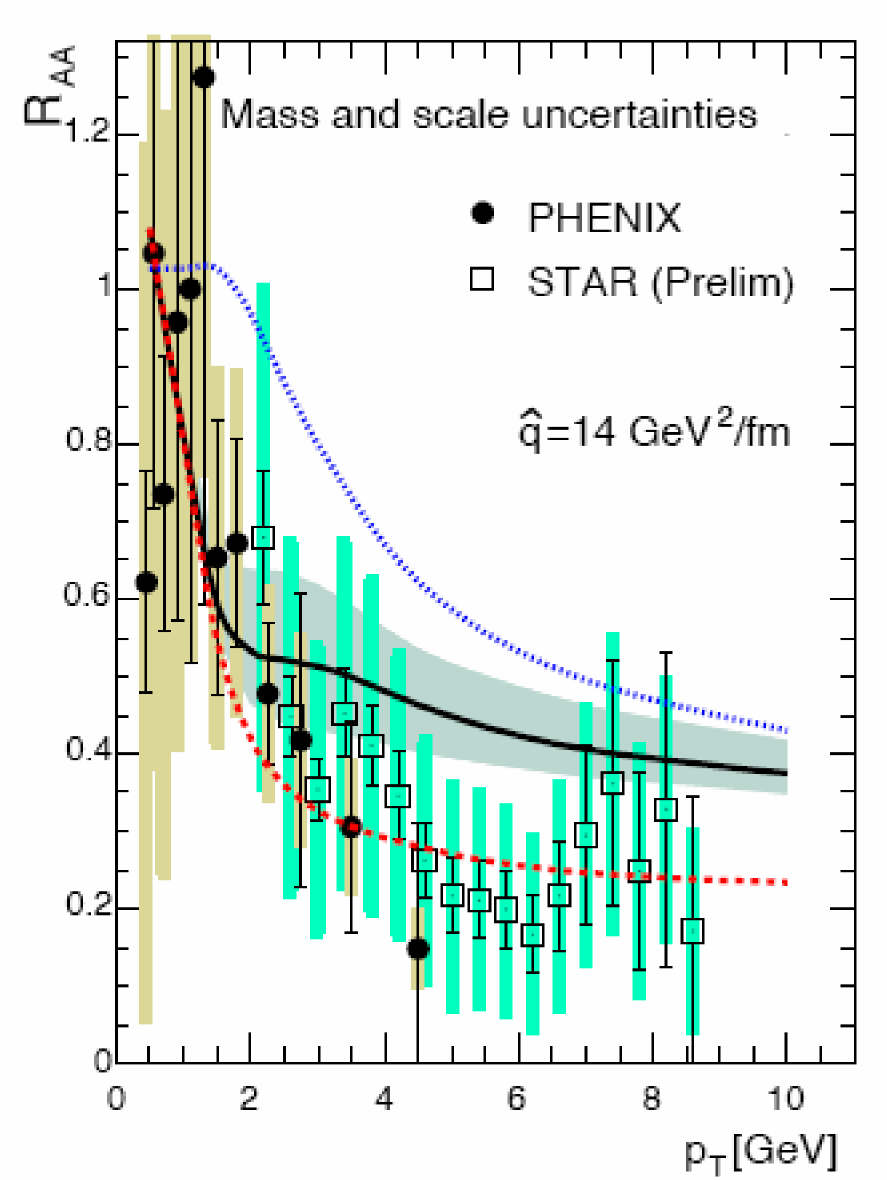
a serious problem for the naïve radiative energy loss scenario?



STAR Coll., Quark Matter'05

AuAu collisions: charm is quenched!?

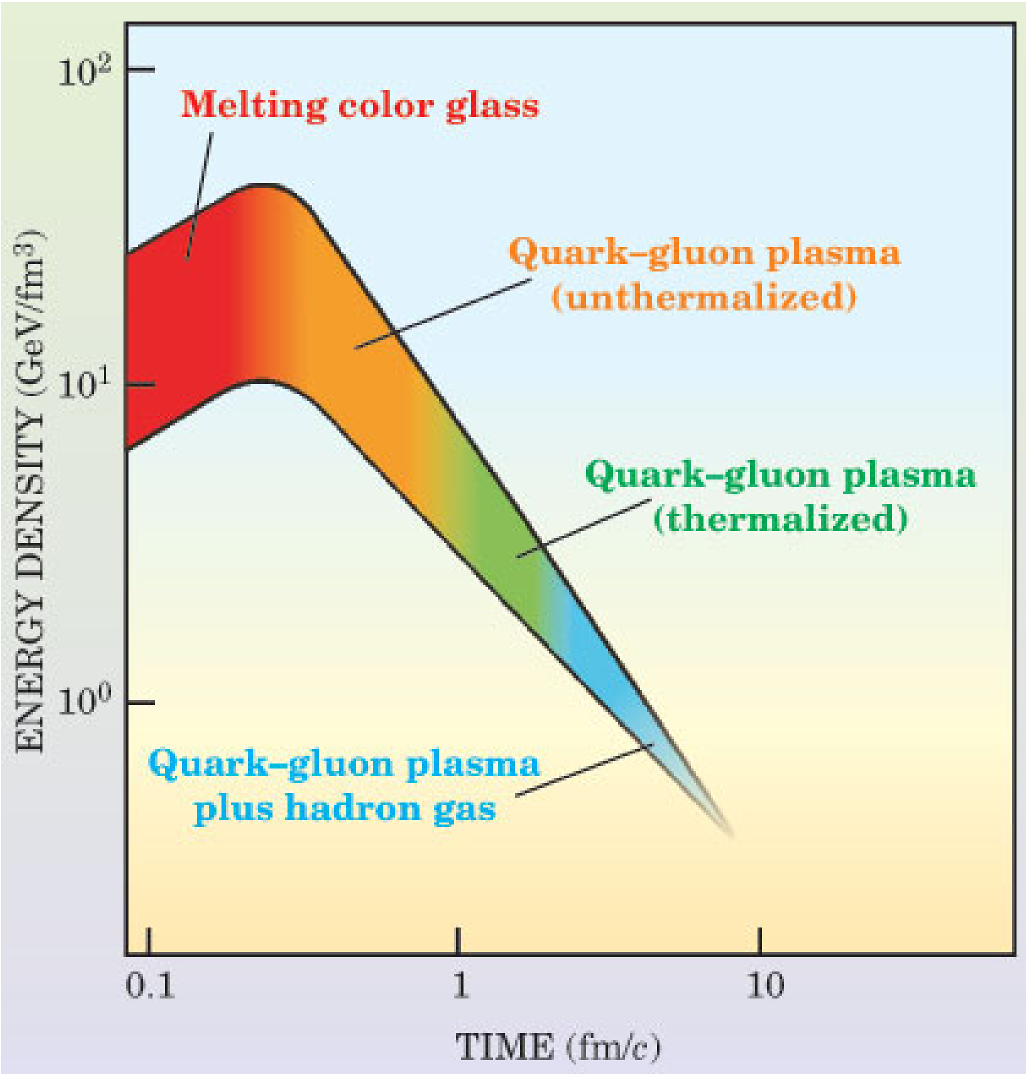
a problem for the naïve radiative energy loss scenario?



N.Armesto. M.Cacciari, A.Dainese, C.Salgado,U.Wiedemann, hep-ph/0511257

Need to separate
b and c contributions!

The emerging picture



Big question:

How does the produced matter thermalize so fast?

Perturbation theory + Kinetic equations

→ $\tau_{therm} \sim 50\ fm$

Topological effects in QGP?

$$\mathcal{L} = -\frac{1}{4} F_{\alpha}^{\mu\nu} F_{\alpha\mu\nu} + \sum_f \bar{\psi}_f \left[i\gamma^{\mu} (\partial_{\mu} - igA_{\alpha\mu} t_{\alpha}) - m_f \right] \psi_f$$

$U_A(1)$ problem:

Invariant under chiral Left $\longleftrightarrow$ Right transformations in the limit of massless quarks

$U_L(N_f) x U_R(N_f)$ chiral symmetry $\Longrightarrow$ parity doubling in the hadron spectrum (not seen!)

If broken spontaneously, $N_f^2 = 9$ Goldstone bosons.

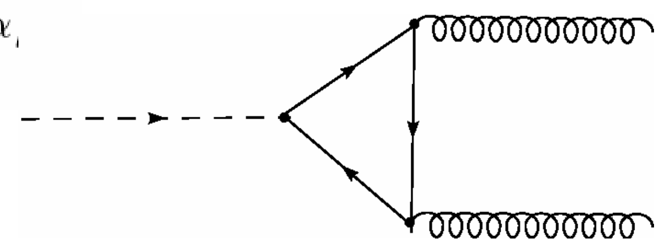
Only 8 exist; the ninth, η' is heavier than the proton!

Axial anomaly

Consider the flavor singlet current $J_{\mu 5} = \bar{\psi}_f \gamma_\mu \gamma_5 \psi_f$

It is not conserved even in the m -> 0 limit due to quantum effects:

$$\partial^\mu J_{\mu 5} = 2 m_f i \bar{\psi}_f \gamma_5 \psi_f - \frac{N_f g^2}{16\pi^2} F^{\mu\nu}_{\alpha} \tilde{F}_{\alpha}$$



Divergence can be written down as
a surface term, and so is seemingly irrelevant:

$$F^{\mu\nu}_{\alpha} \tilde{F}_{\alpha\mu\nu} = \partial_\mu K^\mu$$

ABJ

Instantons and the $U_A(1)$ problem

But: sometimes, surface terms are important

Instantons: classical Euclidean solutions of QCD which map color SU(2) onto the sphere S_3; in Minkowski space, describe quantum tunneling between degenerate vacua with different topological Chern-Simons numbers

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

$$\nu = \int_{-\infty}^{+\infty} dt \frac{dQ_5}{dt} = 2N_f q[F]$$

$$q[F] = \frac{g^2}{32\pi^2} \int d^4x F_{\alpha}^{\mu\nu} \tilde{F}_{\alpha\mu\nu}$$

As a result, chiral charge is no longer conserved

$$Q_5 = \int d^3x \; K_0$$

QCD vacuum as a Bloch

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

“θ - vacuum”

$$|\theta\rangle = \sum_q e^{i\theta q}|q\rangle$$

$$\langle\mathcal{O}\rangle = \sum_q f(q)\int_q D[\psi]D[\bar{\psi}]D[A]\exp(iS_{QCD})\mathcal{O}(\psi,\bar{\psi},A)$$

$$f(q_1+q_2) = f(q_1)f(q_2) \longrightarrow f(q) = \exp(i\theta q)$$

“quasi-momentum” “coordinate”

The lost symmetries of QCD

The prescription

$$\langle \mathcal{O} \rangle = \sum_q f(q) \int_q D[\psi] D[\bar{\psi}] D[A] \exp(i S_{QCD}) \mathcal{O}(\psi, \bar{\psi}, A)$$

with the "Bloch" weight $f(q) = \exp(i\theta q)$

is equivalent to adding to the Lagrangian a new piece $\mathcal{L}_{QCD} \rightarrow \mathcal{L}_{QCD} + \mathcal{L}_\theta$

$$\mathcal{L}_\theta = -\frac{\theta}{32\pi^2} g^2 F_\alpha^{\mu\nu} \tilde{F}_{\alpha\mu\nu}$$

which is odd under P, T, CP symmetries !

The strong CP problem

$$\mathcal{L}_\theta = -\frac{\theta}{32\pi^2} g^2 F_\alpha^{\mu\nu} \tilde{F}_{\alpha\mu\nu}$$

Unless θ=0, P, T and CP invariances are lost!

Experiment: (e.d.m. of the neutron) $\theta \lesssim 3 \times 10^{-10}$

Why θ is so small?
Axions?

- PVLAS -recent evidence?

Will assume θ=0 for the rest of the talk

The strong CP problem and the structure of QCD vacuum

Vafa-Witten theorem: P and CP cannot be broken spontaneously in QCD

But:
1. it does not constrain metastable states
2. it does not apply at finite temperature, finite baryon density, finite isospin density

θ–vacuum in the presence of light quarks: chiral description

Non-linear σ-model with $U_A(1)$ anomaly:

$$\mathcal{L} = \frac{f_\pi^2}{4}\,\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U) + \Sigma\,\mathrm{Re}\left[\mathrm{tr}(\mathcal{M}\,U^\dagger)\right] - \frac{\chi}{2}(\theta + i\,\log\det U)^2$$

mass matrix   quark condensate   chiral unitary matrix $N_f \times N_f$

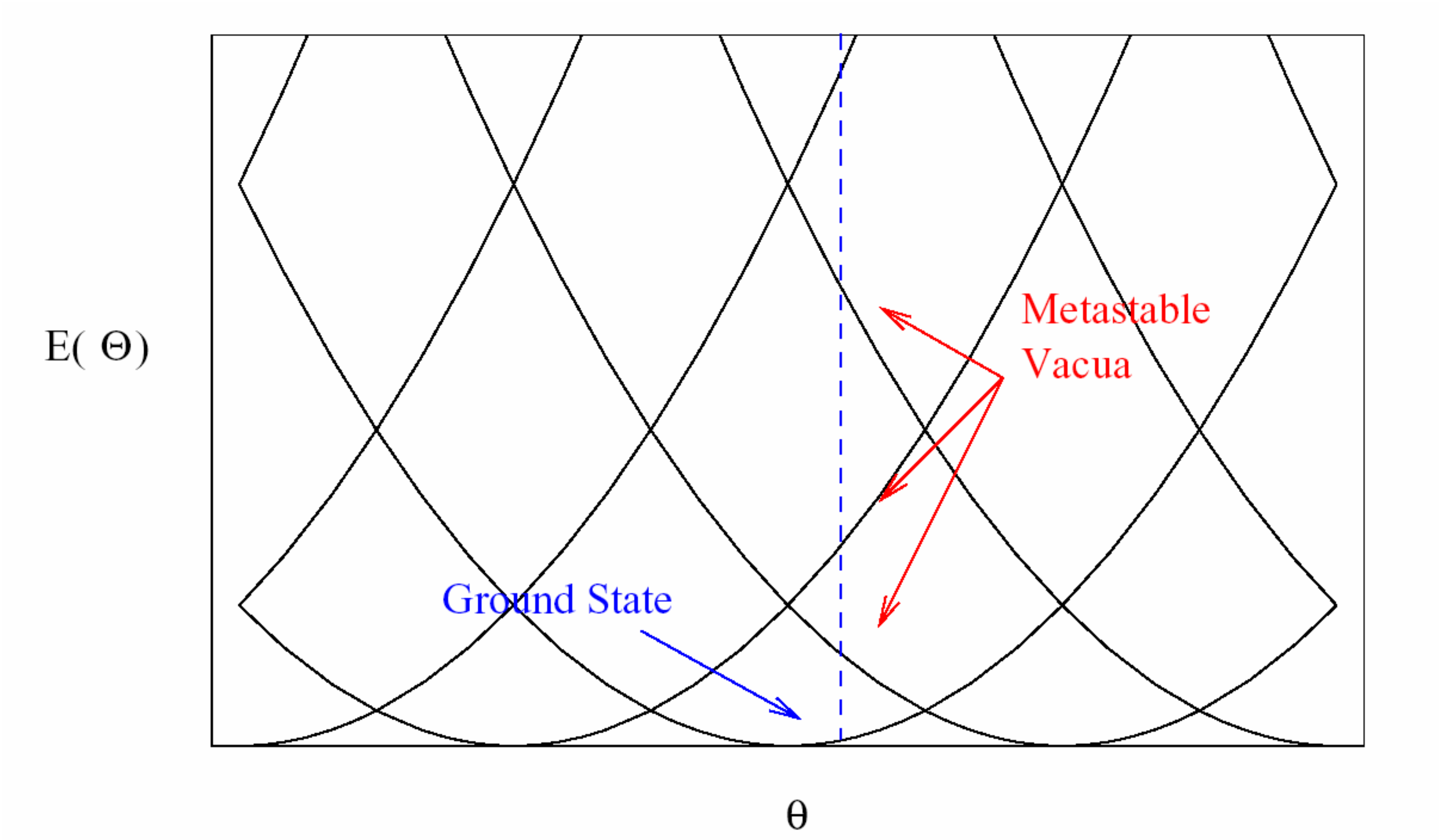
$$\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s) \qquad U = \exp i\phi^a\lambda^a/f_\pi$$

topological susceptibility $\chi = \int d^4x\ \langle q(x)q(0)\rangle$

The effective potential:

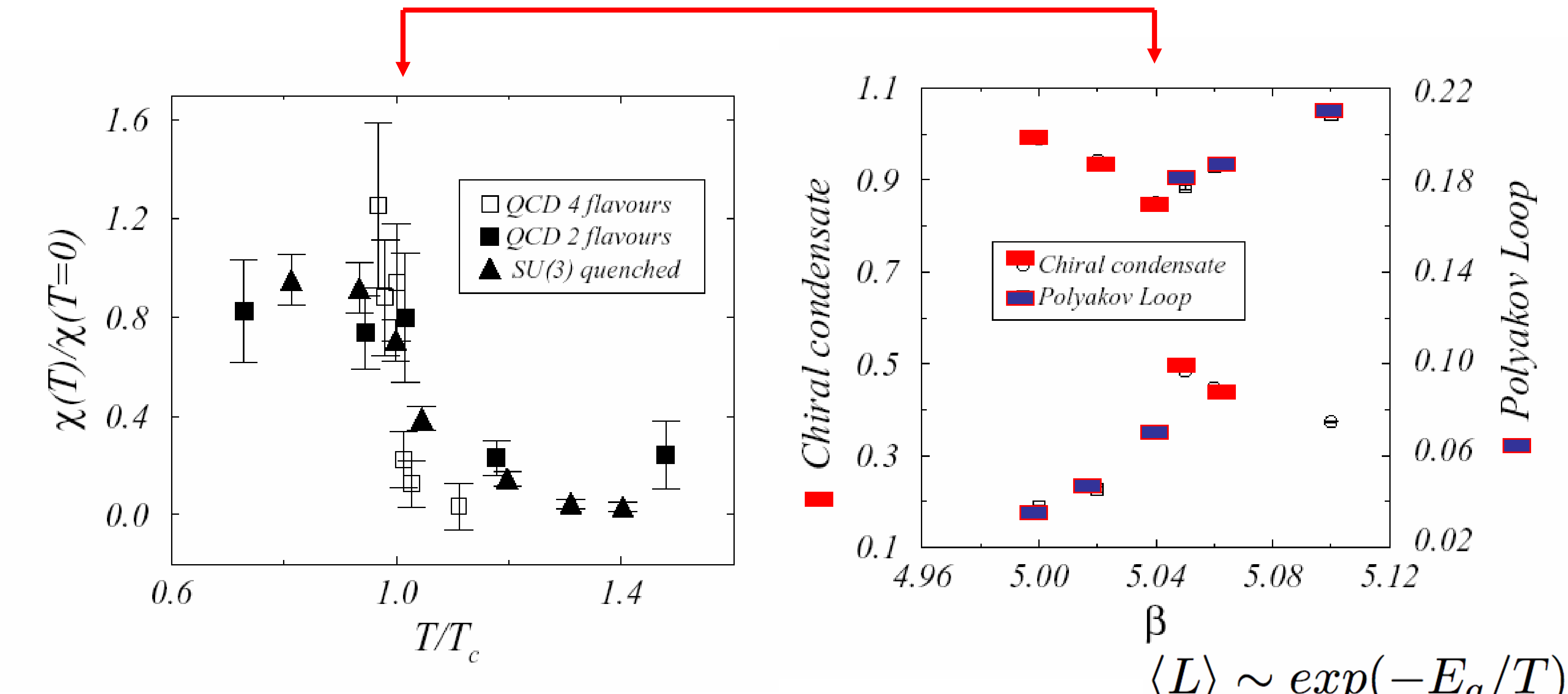
$$\mathcal{V} = -\sum_{i=u,d,s} m_i\Sigma\cos\frac{\phi_i}{f_\pi} + \frac{\chi}{2}(\theta - \sum_{i=u,d,s}\phi_i/f_\pi)^2$$

θ–vacua



Multi-valued potential => a family of vacuum states

Topological susceptibility at finite temperature

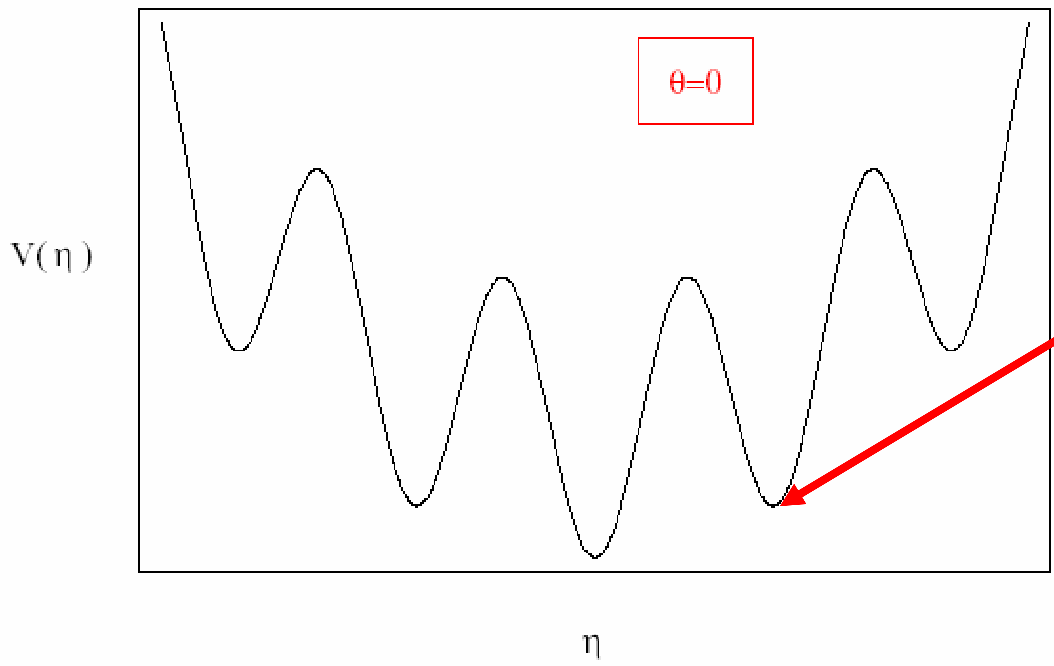


$$\langle L \rangle \sim exp(-E_q/T)$$

Rapid decrease of susceptibility at the deconfinement phase transition

B.Alles, M.D'Elia and A.DiGiacomo, hep-lat/0004020

θ–vacuum in the presence of light quarks: chiral description



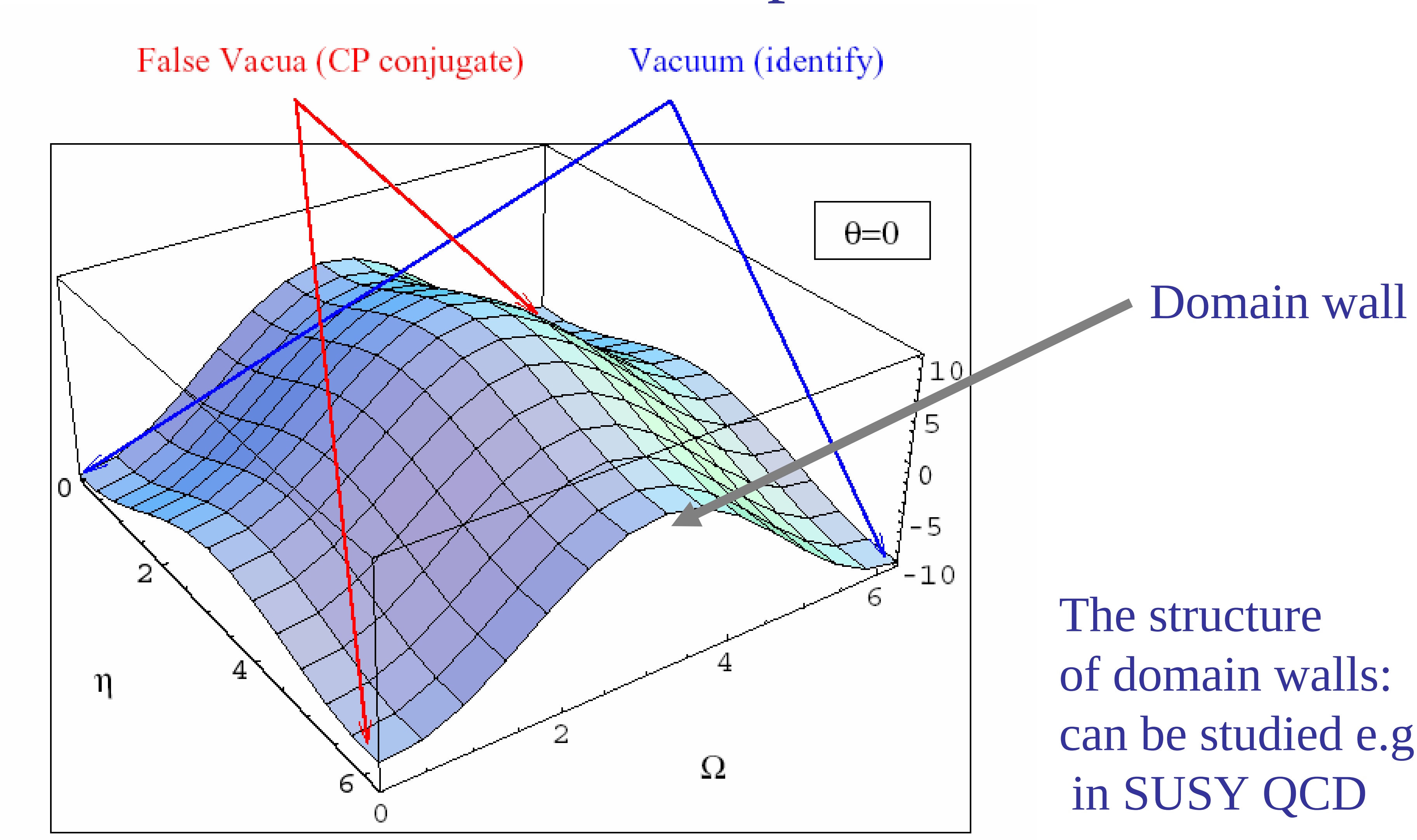
Decrease of χ results in the appearance of metastable CP-odd domains

DK, Pisarski, Tytgat '97

$$\mathcal{V} = -\sum_{i=u,d,s} m_i \Sigma \cos\frac{\phi_i}{f_\pi} + \frac{\chi}{2}(\theta - \sum_{i=u,d,s} \phi_i/f_\pi)^2$$

v.e.v. of the η field is equivalent to non-zero θ

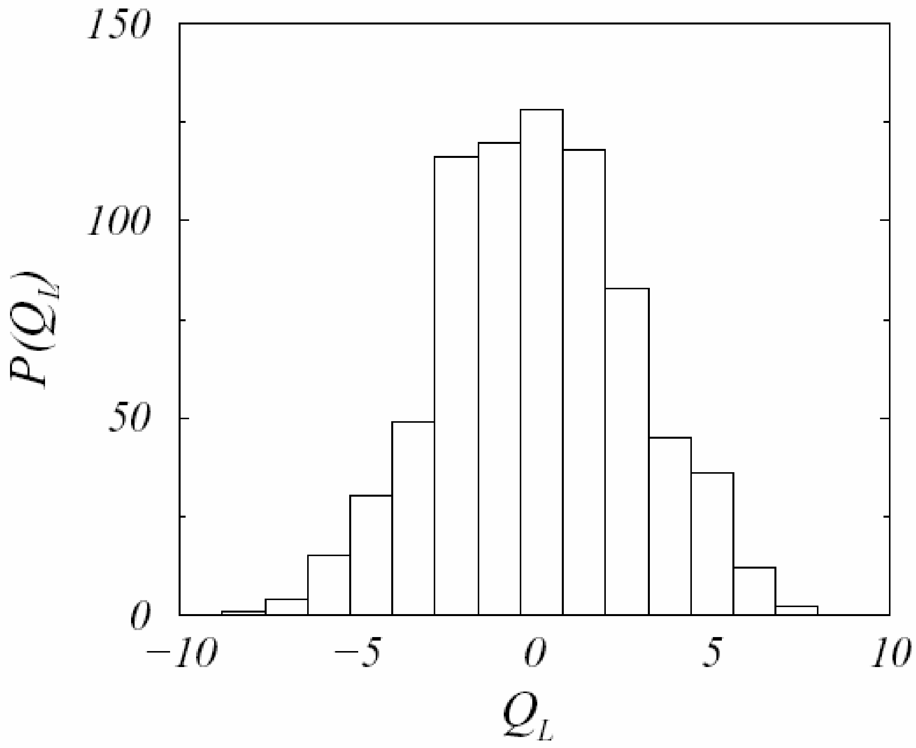
θ–vacuum in the presence of light quarks: chiral description



The structure
of domain walls:
can be studied e.g.
in SUSY QCD

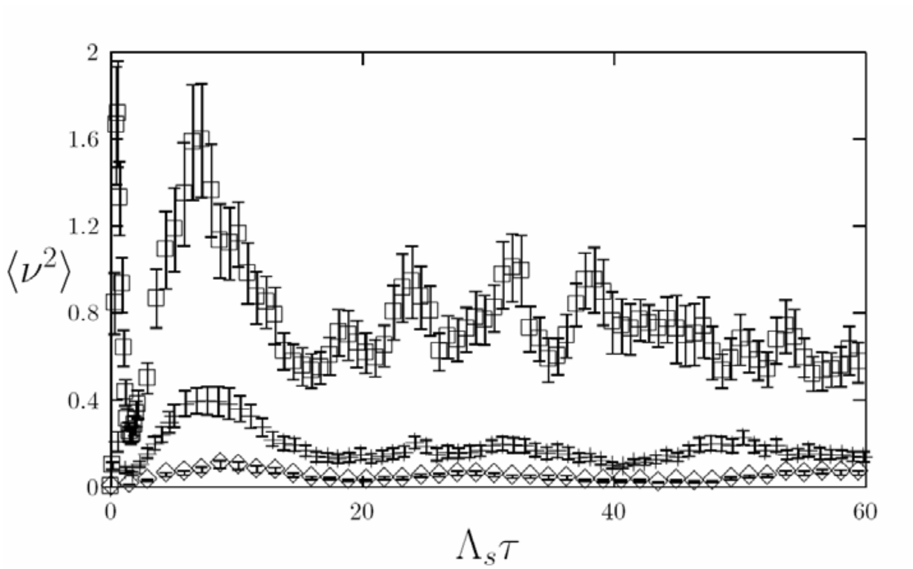
Fluctuations of Chern-Simons number in hot QCD:

numerical lattice simulations

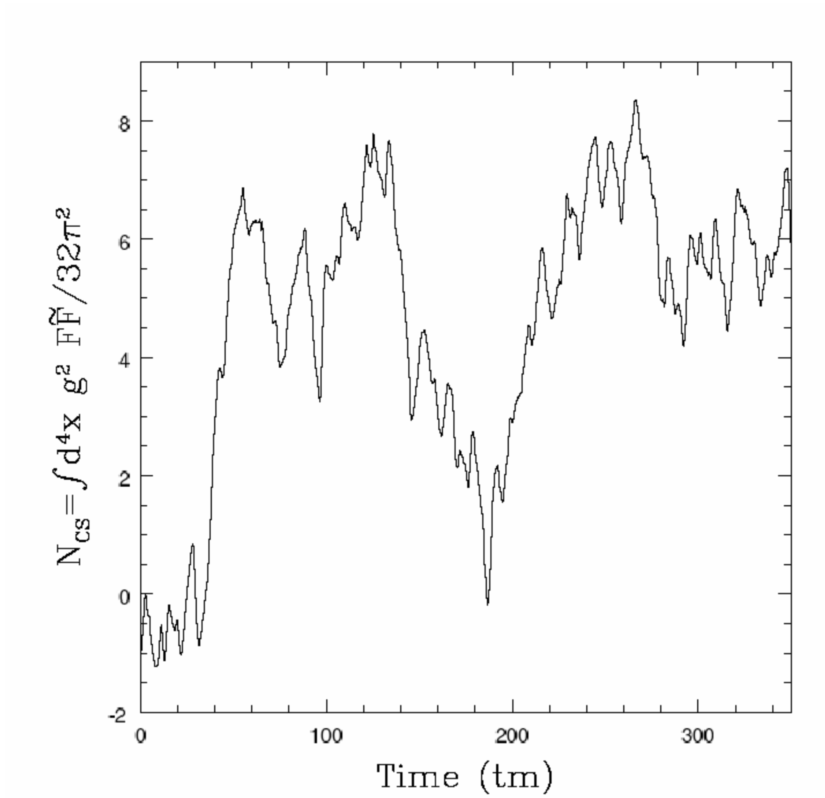


B.Alles, M.D'Elia and A.DiGiacomo,
hep-lat/0004020

Diffusion of Chern-Simons number in QCD: real time lattice simulations



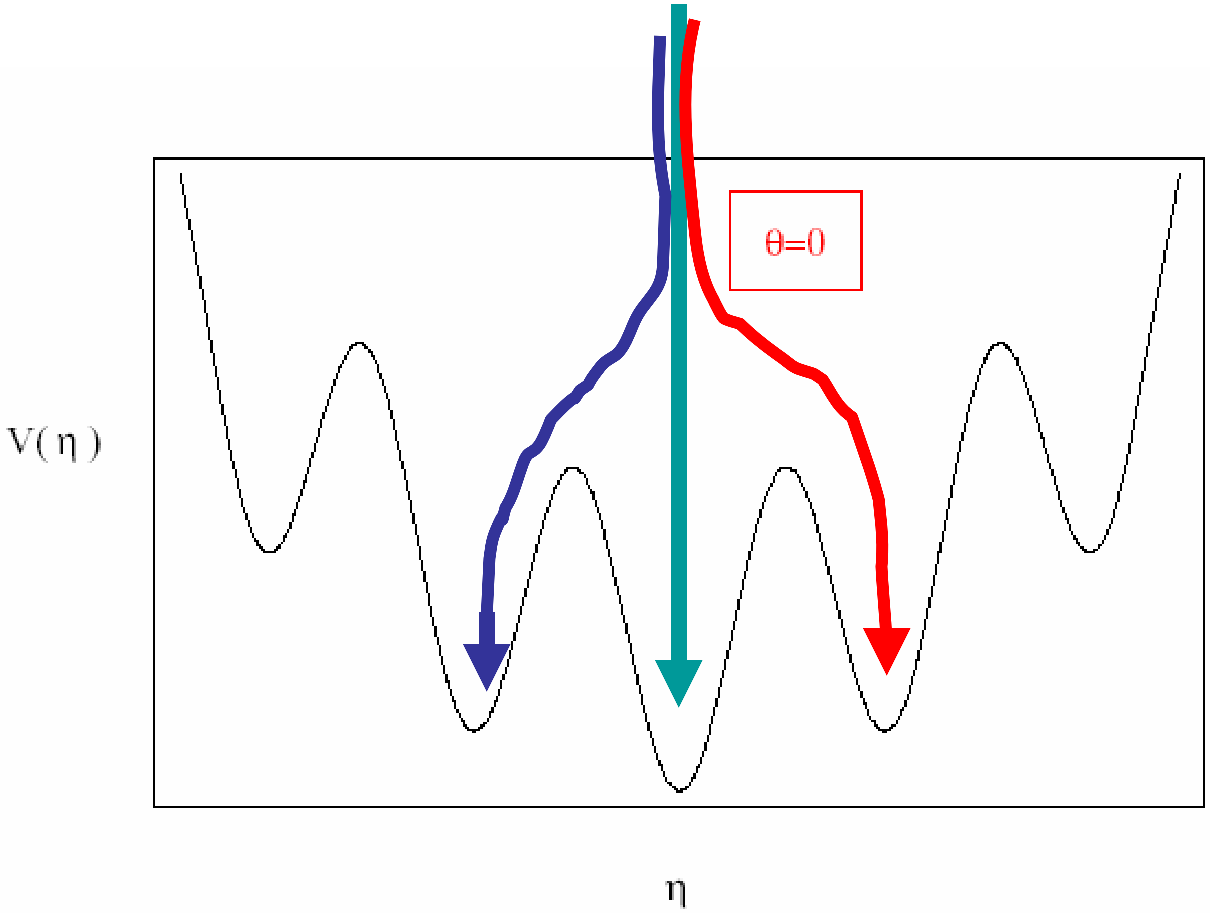
DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002



P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

What are the experimental signatures?

CP-odd domains in heavy ion collisions: how to look for them?



Similar to DCC

v.e.v. of the η field is equivalent to non-zero θ

What are the observable signatures of strong CP violation?

rotate all CP violating phase into the quark piece of the Lagrangian:

$$\mathcal{L}_{quark} = -\sum_f \left(\hat{m}_f \; \bar{\psi}_{L,f}\psi_{R,f} + \hat{m}_f^* \; \bar{\psi}_{R,f}\psi_{L,f}\right)$$

$\hat{m} = m\exp(i\theta)$ is a complex mass parameter

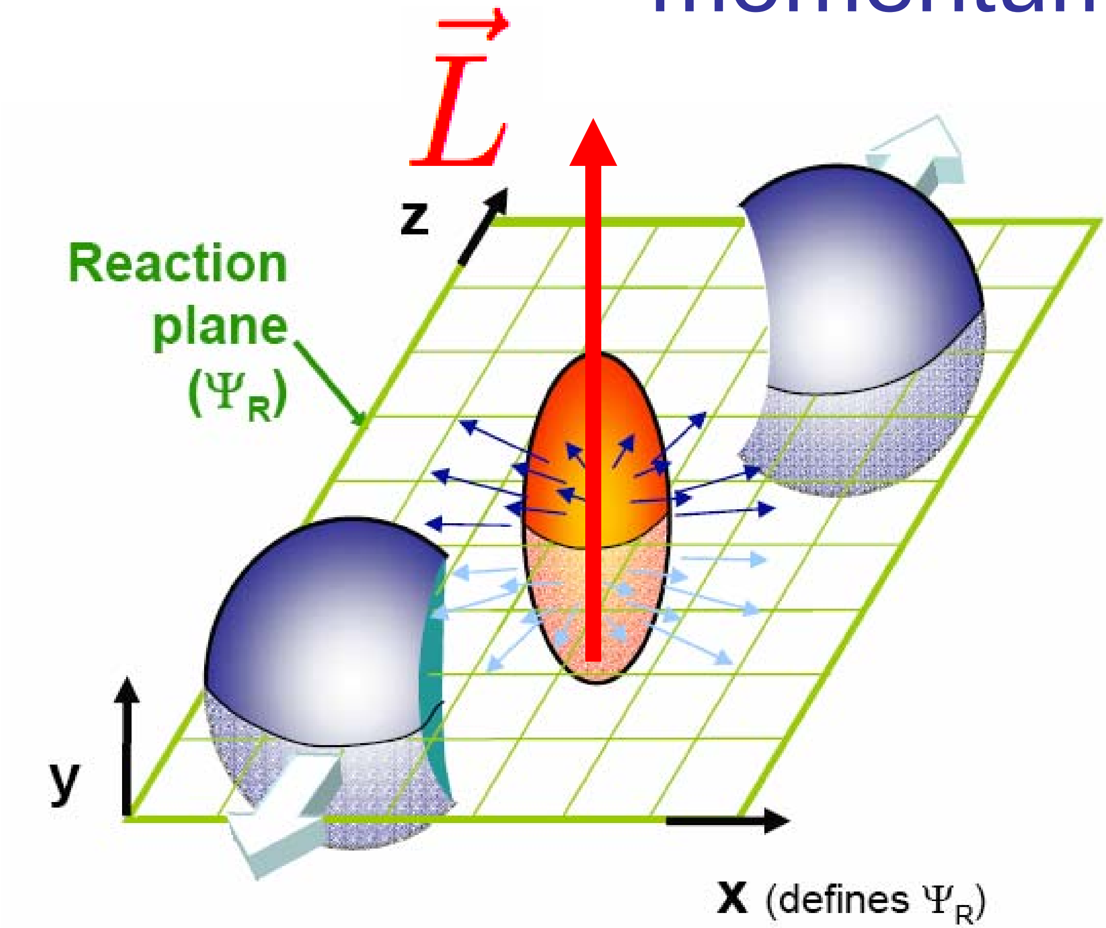
In a CP-odd domain, $\hat{m}(\mathbf{x},t) = m\exp(i\theta(\mathbf{x},t))$

This leads to the asymmetry between “left” and “right” quarks

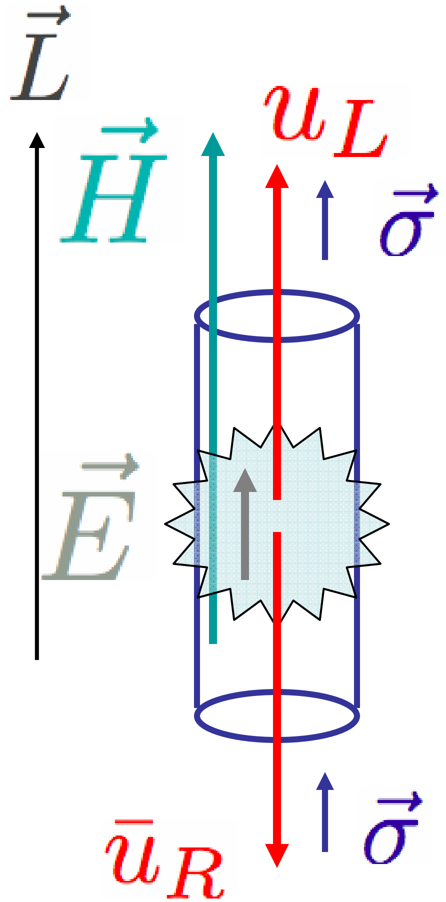
$$\mathcal{L}_\theta = -m\cos\theta\,(\bar{u}_L u_R + \bar{u}_R u_L) - im\sin\theta\,(\bar{u}_L u_R - \bar{u}_R u_L)$$

What is “left” and what is “right”? Quarks are massive, so the definition of chirality depends on the frame…

Azimuthal anisotropy = angular momentum



Magnetic vortices and CP violation



Analogs:

Dyons

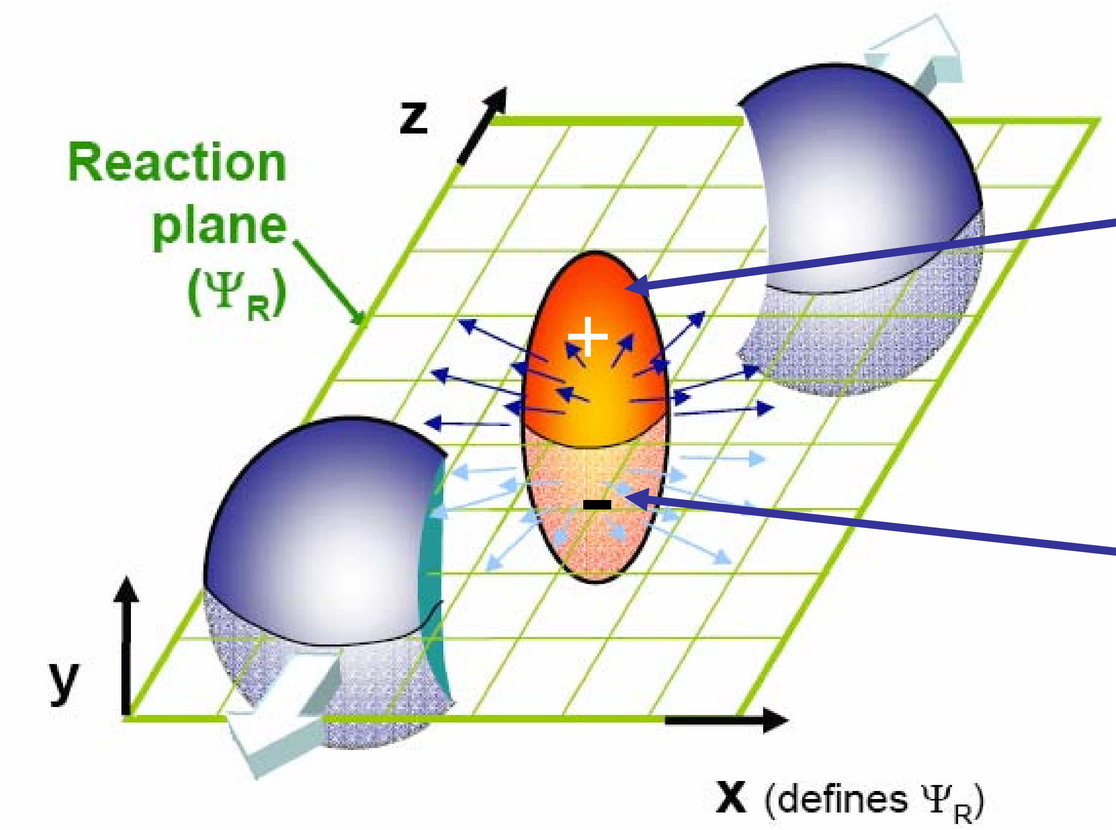
Magnetic monopole - induced baryon decay

Cosmic strings

Chirality generation in superfluid ^{3}He

....

Charge asymmetry w.r.t. reaction plane as a signature of strong CP violation



excess of positive charge

excess of negative charge

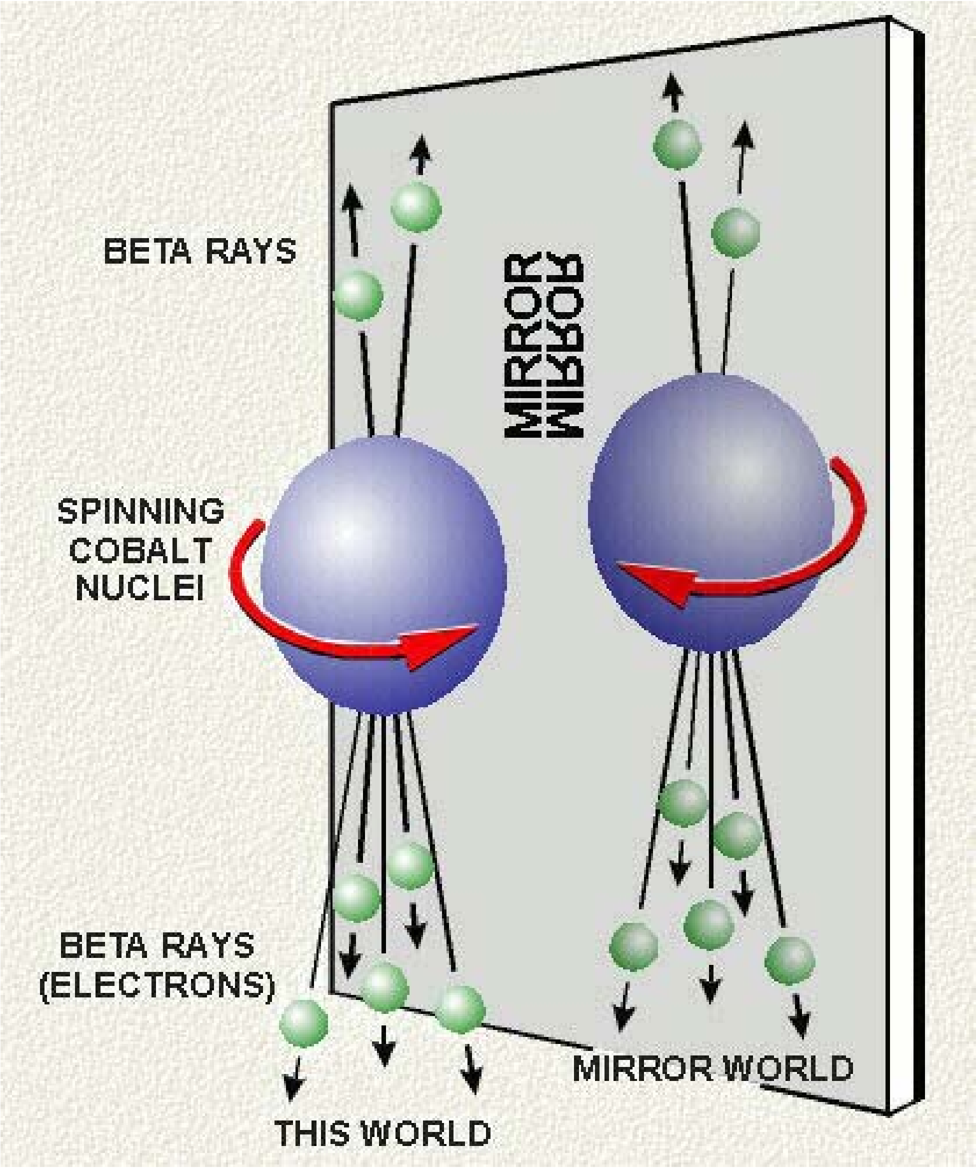
Electric dipole moment of QCD matter!

DK, hep-ph/0406125

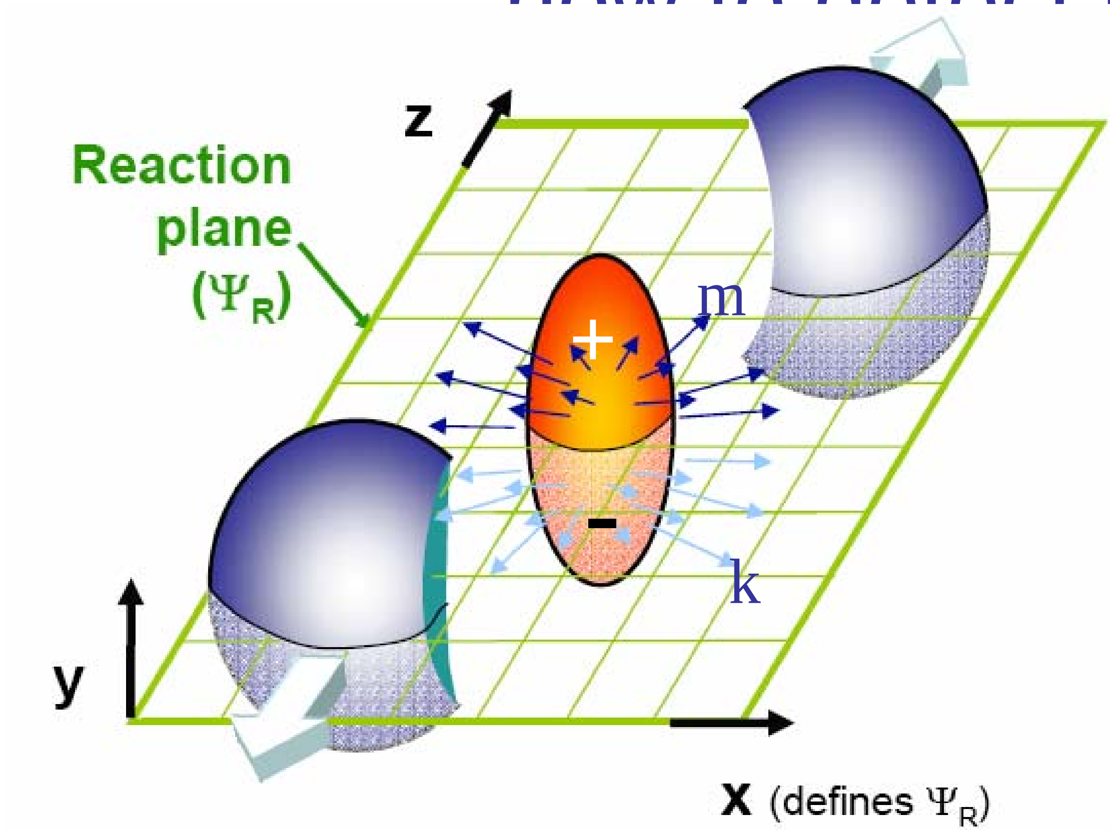
Charge asymmetry w. r.t. reaction plane violates T, P, and (by CPT theorem) CP:

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Analogy to P violation in weak interactions



Charge asymmetry w.r.t. reaction plane: how to detect it?



We need
a sensitive measure
of the asymmetry

Improved method:
"mixed harmonics"
S.Voloshin, hep-ph/0406311

$$a^k a^m = \langle \sum_{ij} \sin(\varphi_i^k - \Psi_R)\ \sin(\varphi_j^m - \Psi_R) \rangle$$

Expect $a^+ a^+ = a^- a^- > 0; \quad a^+ a^- < 0$

Strong CP violation at high T ?

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

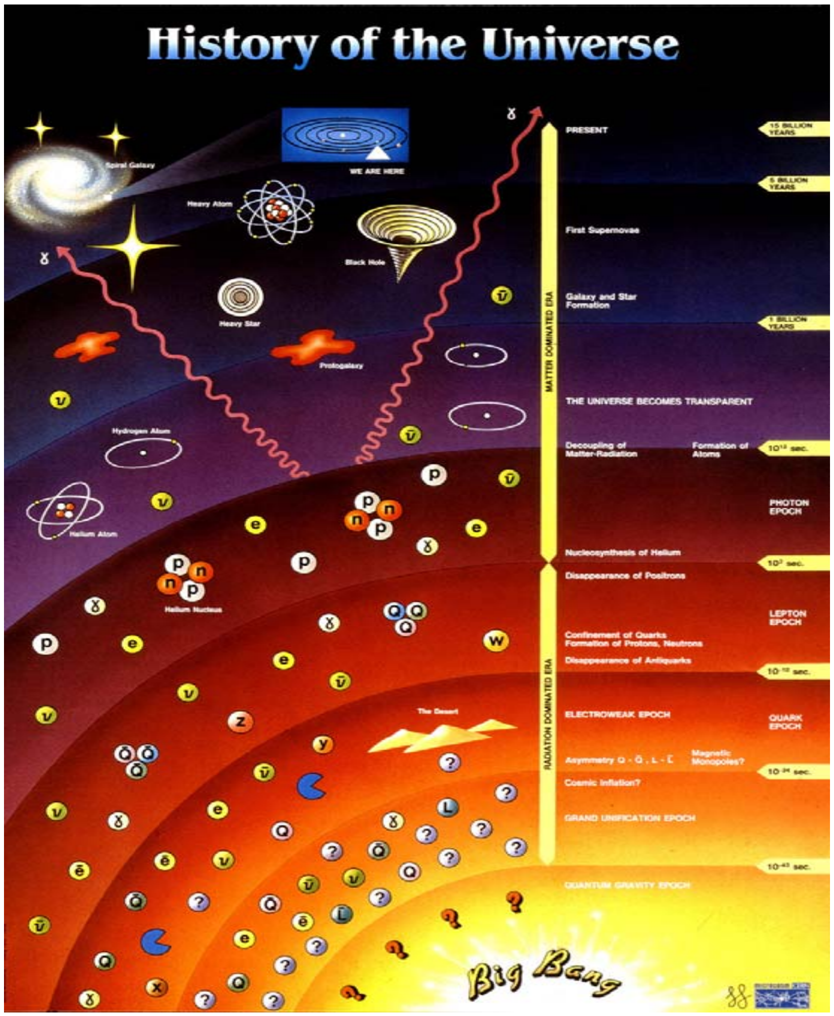
σ/σ_{tot}, %

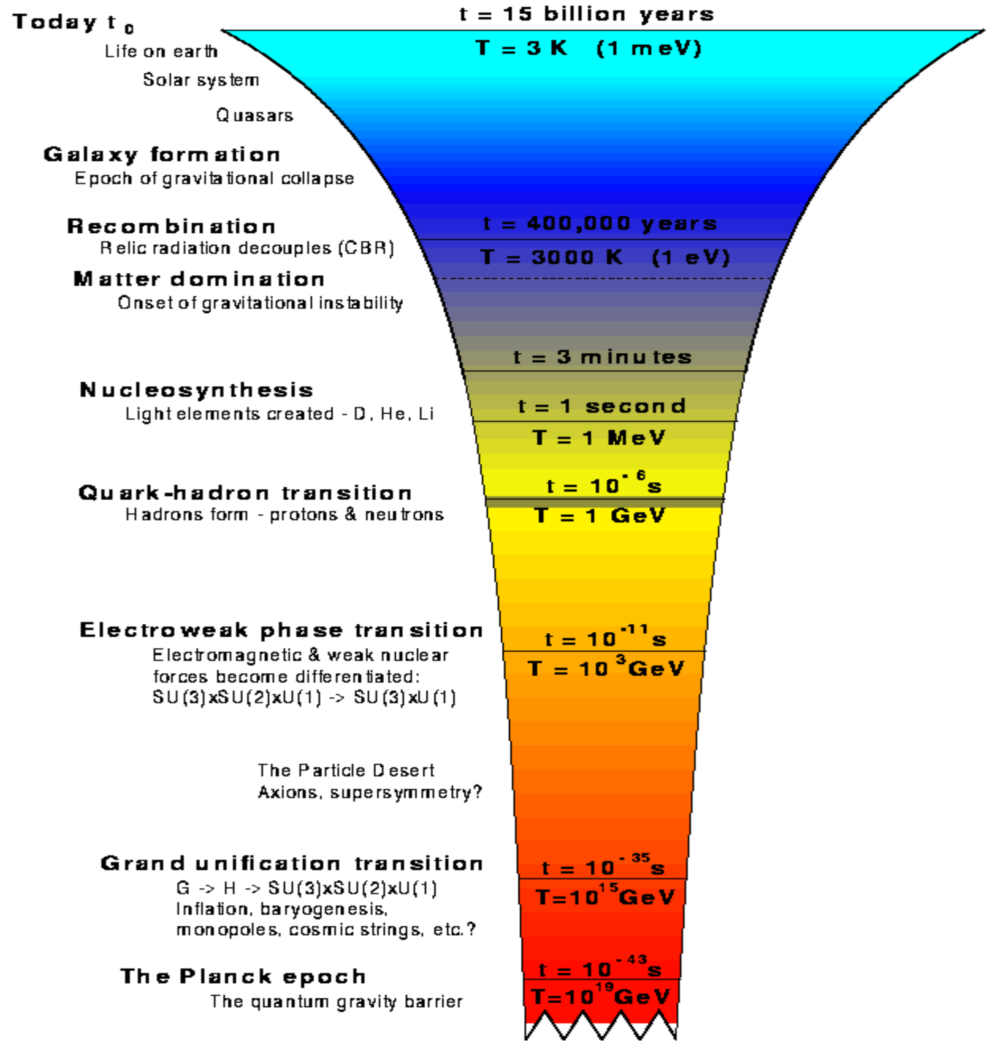
Figure 2: Charged particle asymmetry parameters as a a function of standard STAR centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are a_+a_-. Black lines are theoretical prediction [1] corresponding to the topological charge $|Q| = 1$.

STAR Coll., nucl-ex/0510069;   October 25, 2005

Need to analyze the systematics, improve statistics - vigorous ongoing work!

What are the implications for the Early Universe?





Summary

1. Quantum Chromo-Dynamics is
an established and consistent field theory
of strong interactions
but it's properties are far from being understood

2. High energy nuclear collisions test the predictions
of strong field QCD and probe
the properties of super-dense matter

Many surprises; a lot more work needs to be done!