Quantum Chromo-Dynamics at the high energy/density frontier

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Quarks and the Standard Model

1/2 of all "elementary" particles of the Standard Model are not observable;

they are confined within hadrons by "color" interactions

Theoretical notion of color:

"The red-haired man"

by Daniil Kharms (1905-1942)

from "Blue Notebook No.10"

Once there was a red-haired man who had no eyes or ears.

Neither did he have any hair,

so he was called "red-haired" only theoretically

…

Therefore there's no knowing whom we are even talking about.

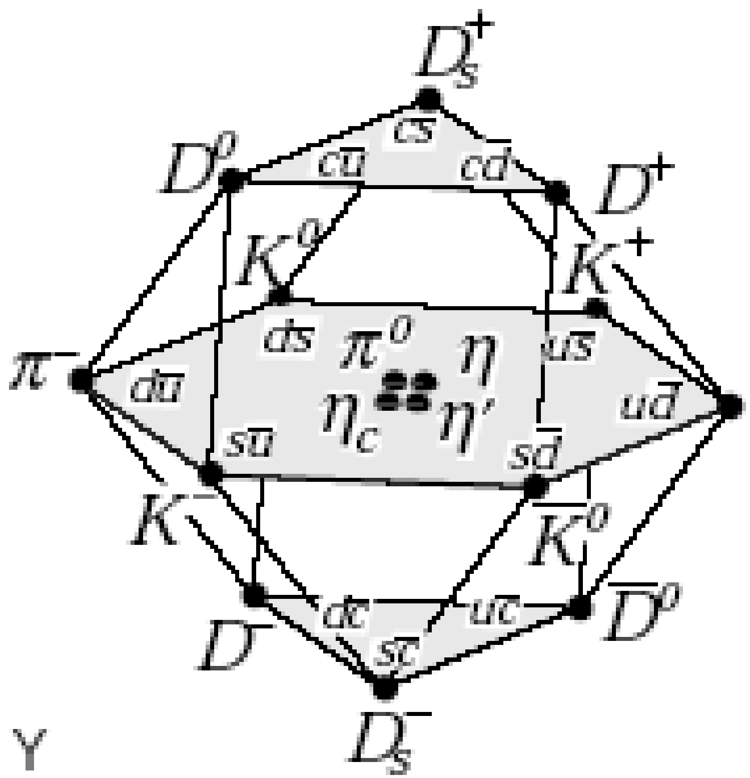
In fact we better not say anything about him...

Outline

- Quantum Chromo-Dynamics - the theory of strong interactions
- QCD at high energies
- QCD at high temperatures
- A glimpse of RHIC results
- New facets of QCD at RHIC and LHC:
  - Color Glass Condensate & thermalization
  - (strongly coupled) Quark-Gluon Plasma
  - topological effects at finite T

What is QCD?

QCD = Quark Model + Gauge Invariance



local gauge transformation:

$$q(x) \rightarrow \exp\left(i\omega_a(x)T^a\right)\ q(x),$$

$$[T^a, T^b] = if^{abc}T_c$$

QCD and the origin of mass

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

$$D_\mu = \partial_\mu - i g A^a_\mu t^a$$

gluons

quarks

Invariant under scale ($x \to \lambda x$) and chiral Left ⟷ Right

transformations in the limit of massless quarks

Experiment: u,d quarks are almost massless…

… but then… all hadrons must be massless as well!

Where does the “dark mass” of the proton come from?

QCD and quantum anomalies

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

Classical scale invariance is broken by quantum effects:

scale anomaly

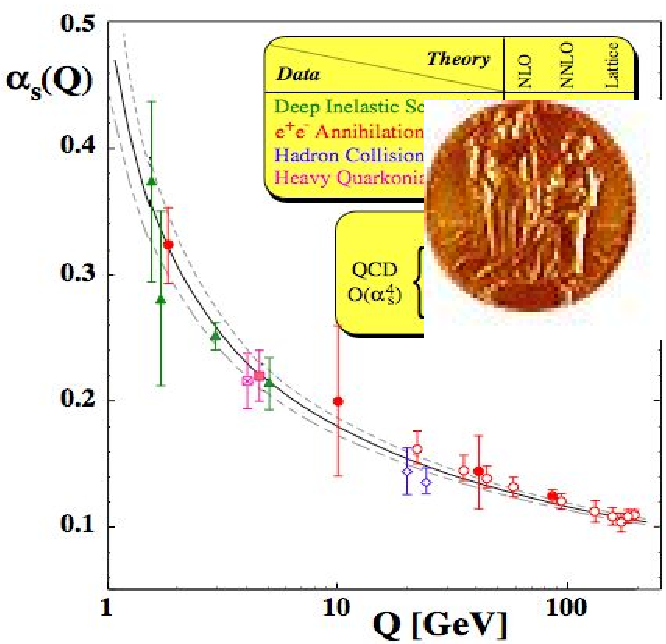
$$\theta^\mu_\mu = \frac{\beta(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_q m_q \bar{q} q$$

trace of the energy-momentum tensor

"beta-function"; describes the dependence of coupling on momentum

Hadrons get masses ⟺ coupling runs with the distance

Asymptotic Freedom



At short distances,
the strong force becomes weak
(anti-screening) -
one can access the "asymptotically free" regime in hard processes

and in super-dense matter
(inter-particle distances ~ 1/T)

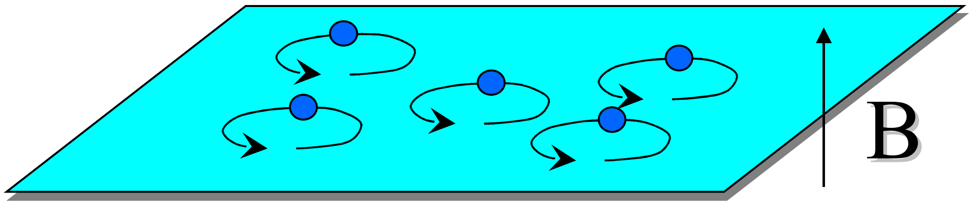
$$\alpha_s(Q) \simeq \frac{4\pi}{b \ln(Q^2/\Lambda^2)}$$

number of colors

number of flavors

$$b = (11N_c - 2N_f)/3$$

Asymptotic freedom and Landau levels of 2D parton gas

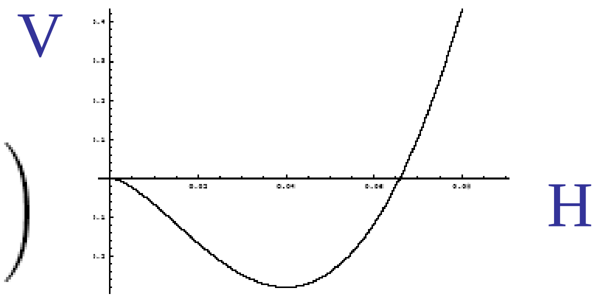


The effective potential: sum over 2D Landau levels

$$V_{\rm pert}(H) = \frac{g\,H}{4\,\pi^2} \int dp_z \sum_{n=0}^{\infty} \sum_{s_z=\pm 1} \sqrt{2\,g\,H\,(n+1/2-s_z)+p_z^2}.$$

Paramagnetic response of the vacuum:

$${\rm Re}\,V_{\rm pert}(H) = \frac{1}{2}\,H^2 + (g\,H)^2\,\frac{b}{32\,\pi^2}\left(\ln\frac{g\,H}{\mu^2} - \frac{1}{2}\right)$$



1. The lowest level n=0 of radius $\sim (gH)^{-1/2}$ is unstable!

2. Strong fields ⟷ Short distances

QCD and the classical limit

Classical dynamics applies when the action $S = \int d^4x \;\; \mathcal{L}(x)$ is large in units of the Planck constant (Bohr-Sommerfeld quantization)

$$\frac{S_{QCD}}{\hbar} \sim \frac{1}{g^2\hbar} \int d^4x \; \mathrm{tr}\; G^{\mu\nu}(x) G_{\mu\nu}(x) \gg 1$$

(equivalent to setting $\hbar \longrightarrow 0$)

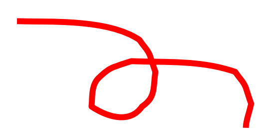
=> Need weak coupling and strong fields

$$D_\mu = \partial_\mu - igA_\mu^a t^a$$

$$A^2 \ll \frac{p^2}{g^2}$$

weak field

$$A^2 \sim \frac{p^2}{g^2}$$



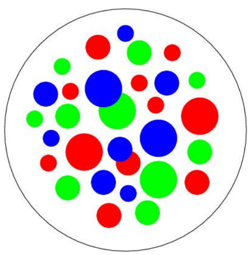
strong field

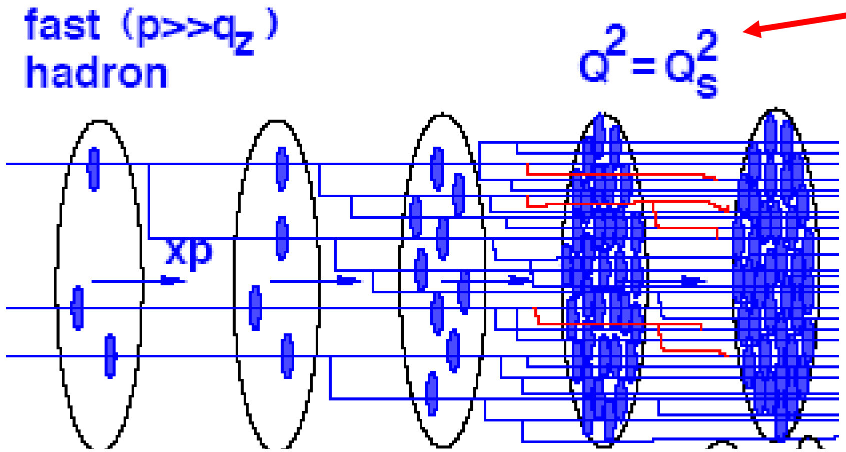
Building up strong color fields: small x (high energy) and large A (heavy nuclei)

Bjorken x : the fraction of hadron's momentum carried by a parton; high energies s open access to small $x = Q^2/s$

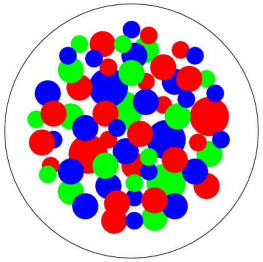
the boundary of non-linear regime: partons of size $1/Q > 1/Q_s$ overlap

Large x





small x

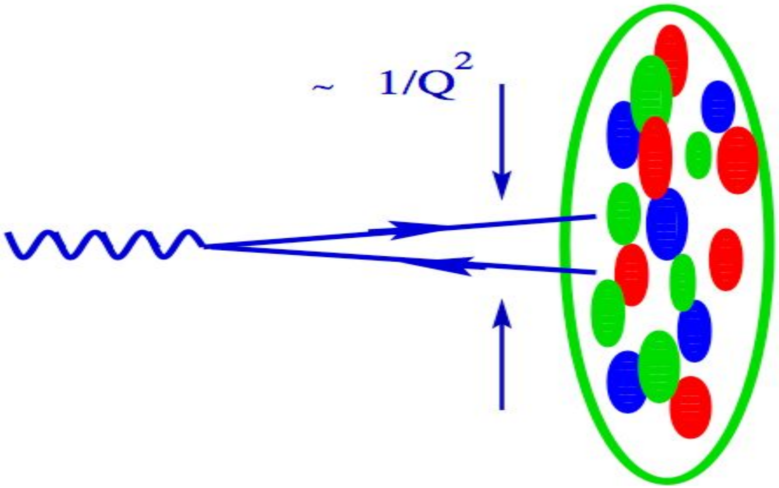


Because the probability to emit an extra gluon is ~ $\alpha_s \ln(1/x)$ ~ 1, the number of gluons at small x grows; the transverse area is limited

→ transverse density becomes large

Strong color fields in heavy nuclei

At small Bjorken x, hard processes develop over large longitudinal distances $l_c \sim \frac{2\nu}{Q^2} = \frac{1}{mx}$



Density of partons in the transverse plane as a new dimensionful parameter Q_s ("saturation scale")

Gribov, Levin, Ryskin

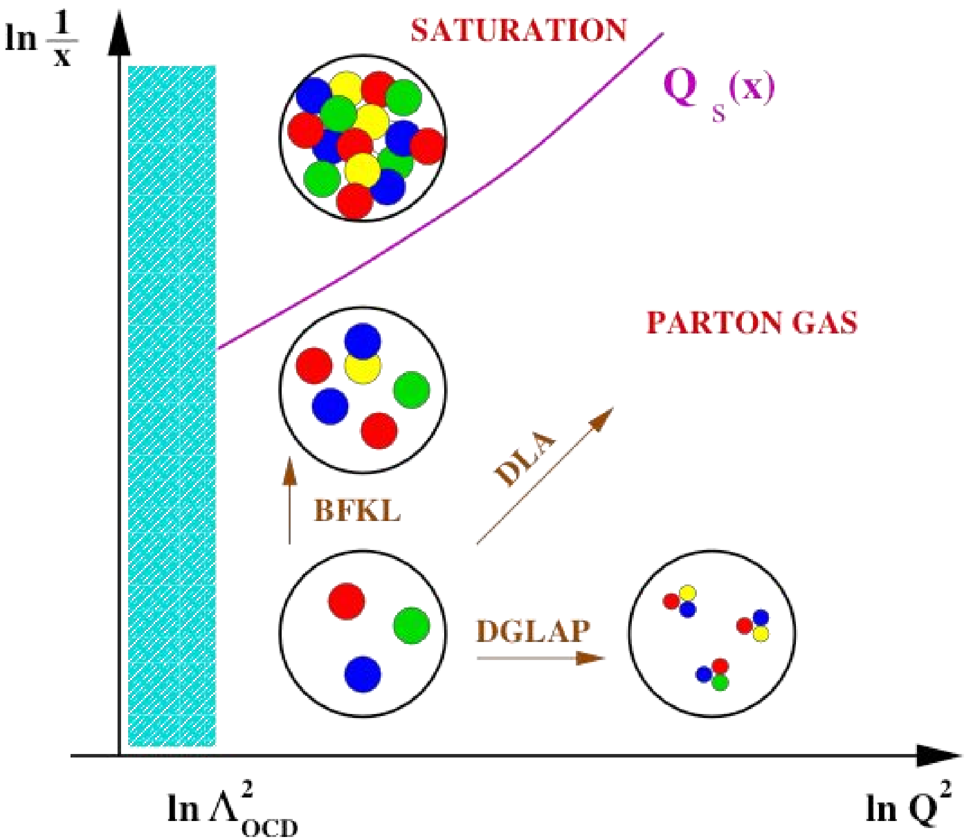
All partons contribute coherently => at sufficiently small x and/or large A strong fields, weak coupling!

McLerran, Venugopalan

Non-linear QCD evolution and population growth

Color glass condensate

time $t \to \ln \frac{1}{x} \equiv y$ rapidity



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Linear evolution: T. Malthus (1798)

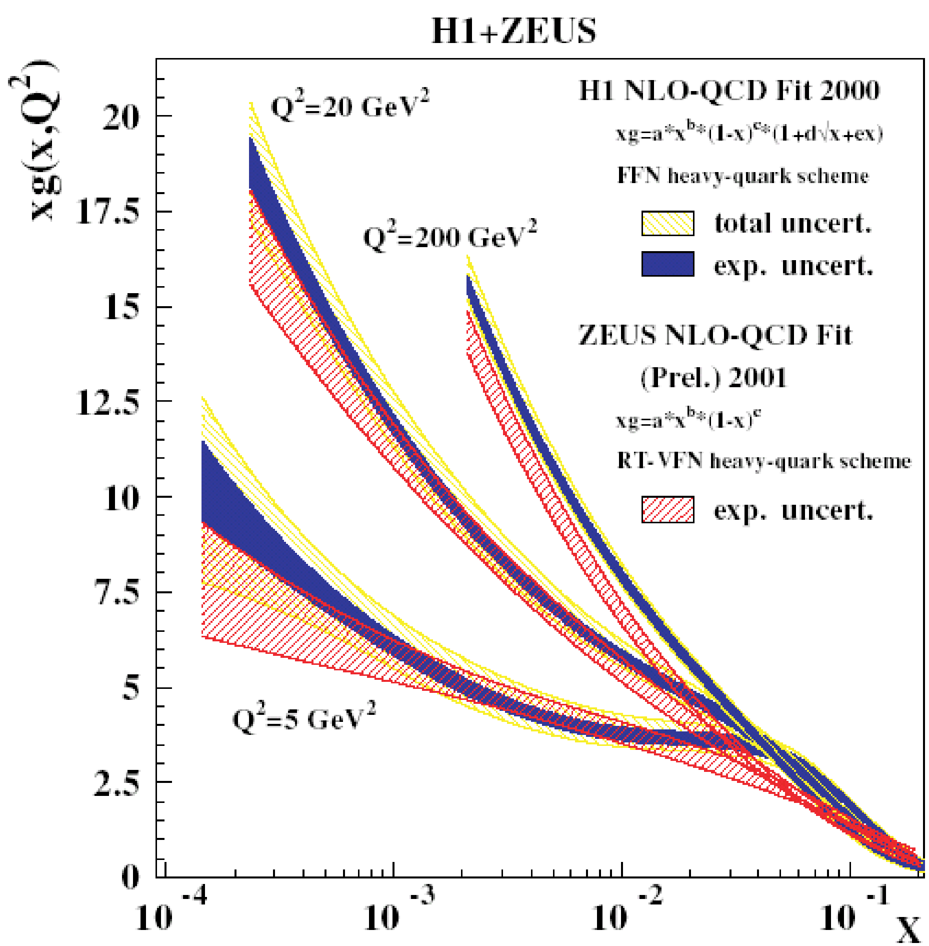
$$\frac{d}{dt} N(t) = r\ N(t)$$

r - rate of maximum population growth

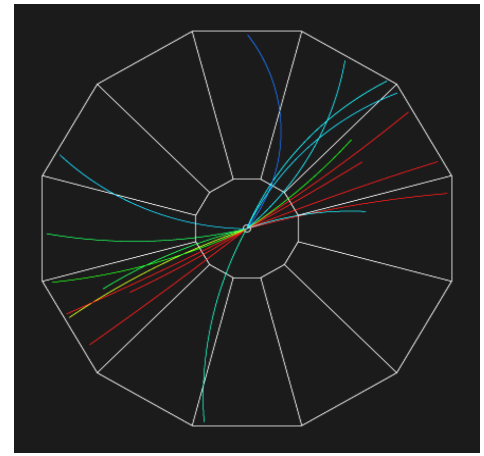
$$N(t) = N_0\ \exp(r\ t)$$

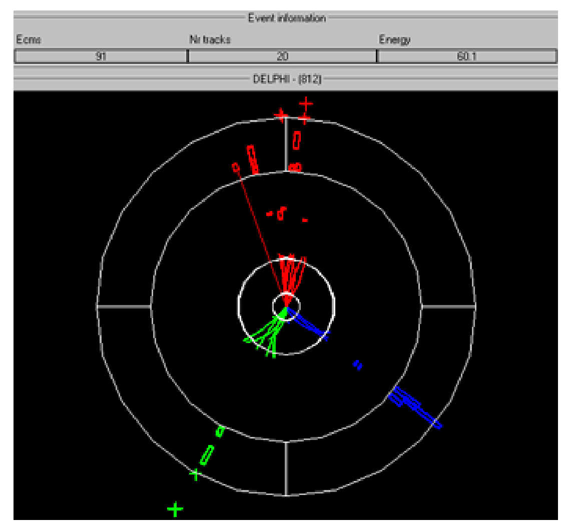
Unlimited growth!

Resolving the gluon cloud at small x and short distances ~ $1/Q^2$



number of gluons





"jets": high momentum partons

Population growth in a limited environment

$$\frac{dN(t)}{dt} = \frac{rN(K-N)}{K}$$ "logistic equation"

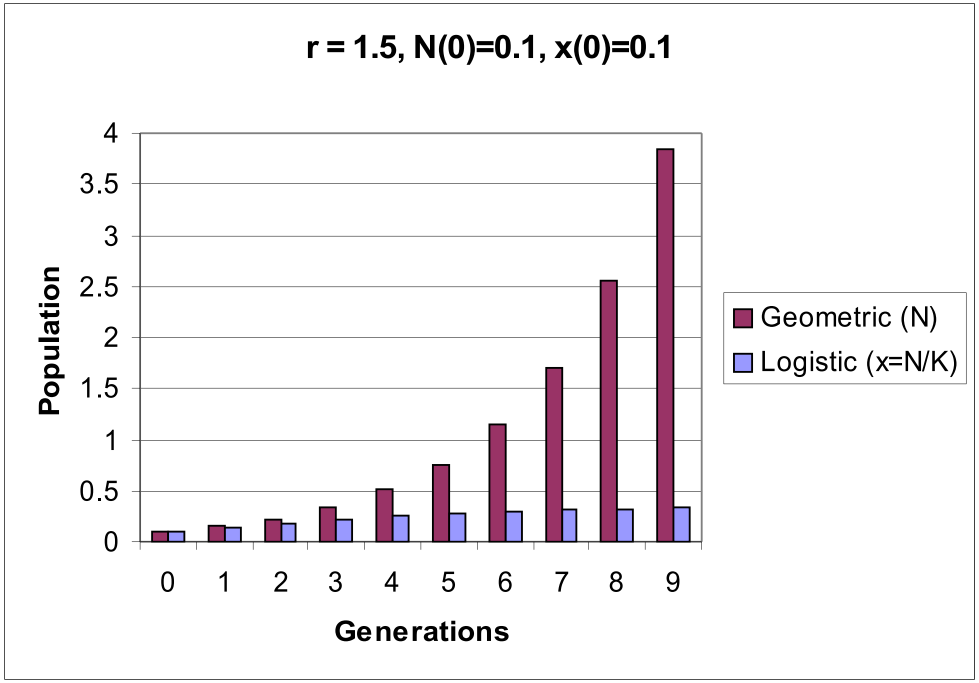
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

K - maximum sustainable population; define $x = \frac{N}{K}$

Pierre Verhulst (1845)

$$\frac{dx}{dt} = rx(1-x)$$

$$x(t) = \frac{1}{1+\left(\frac{1}{x_0}-1\right)e^{-rt}}$$



Stable population: $N(t) \to K, \quad \frac{dN}{dt} \to 0 \quad \text{as } t \to \infty$

The limit is universal (no dependence on the initial condition)

Population growth in a limited environment: a (short) path to chaos

QuickTime™ and a
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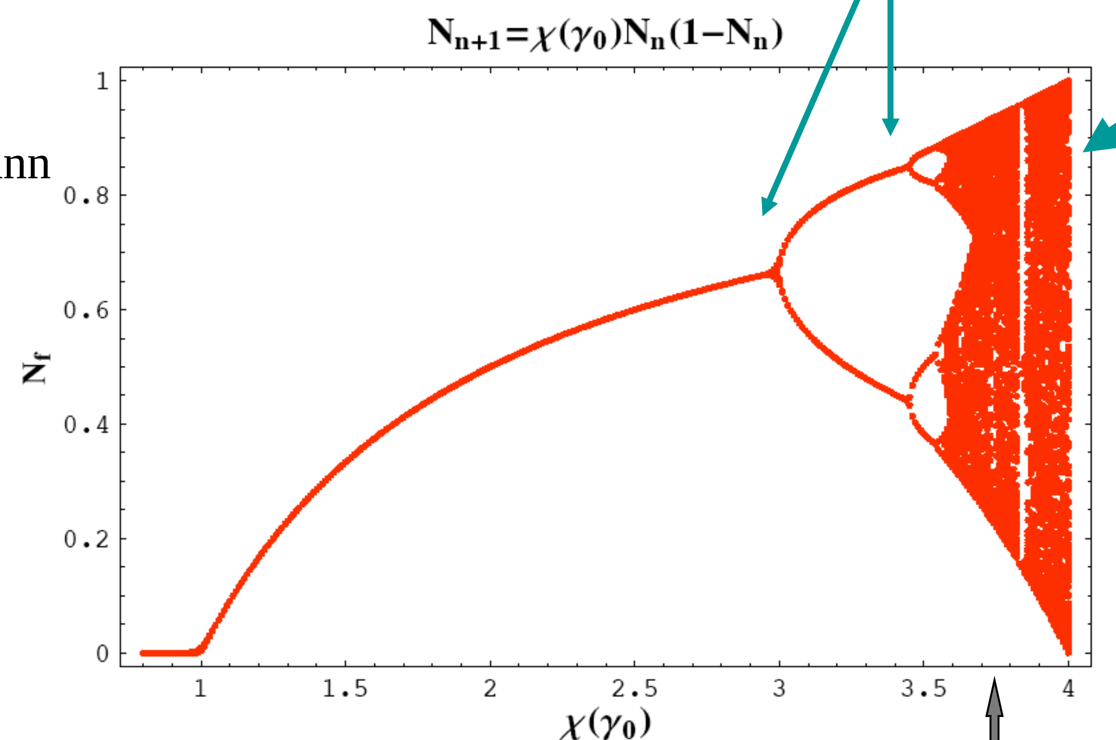
are needed to see this picture.

John von Neumann

Discrete version: bifurcations leading to chaos



Fixed points

($t \to \infty$ limit of the population)

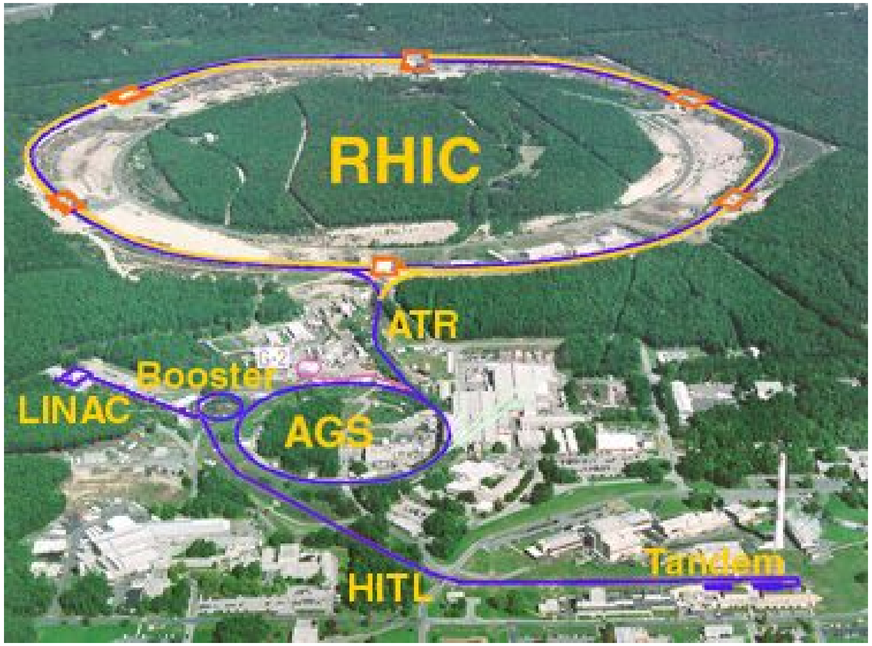
"logistic map"

Rate of growth (the value of $\alpha_s\ y$)

High energy evolution starts here (?)

DK, K. Tuchin

Semi-classical QCD: experimental tests



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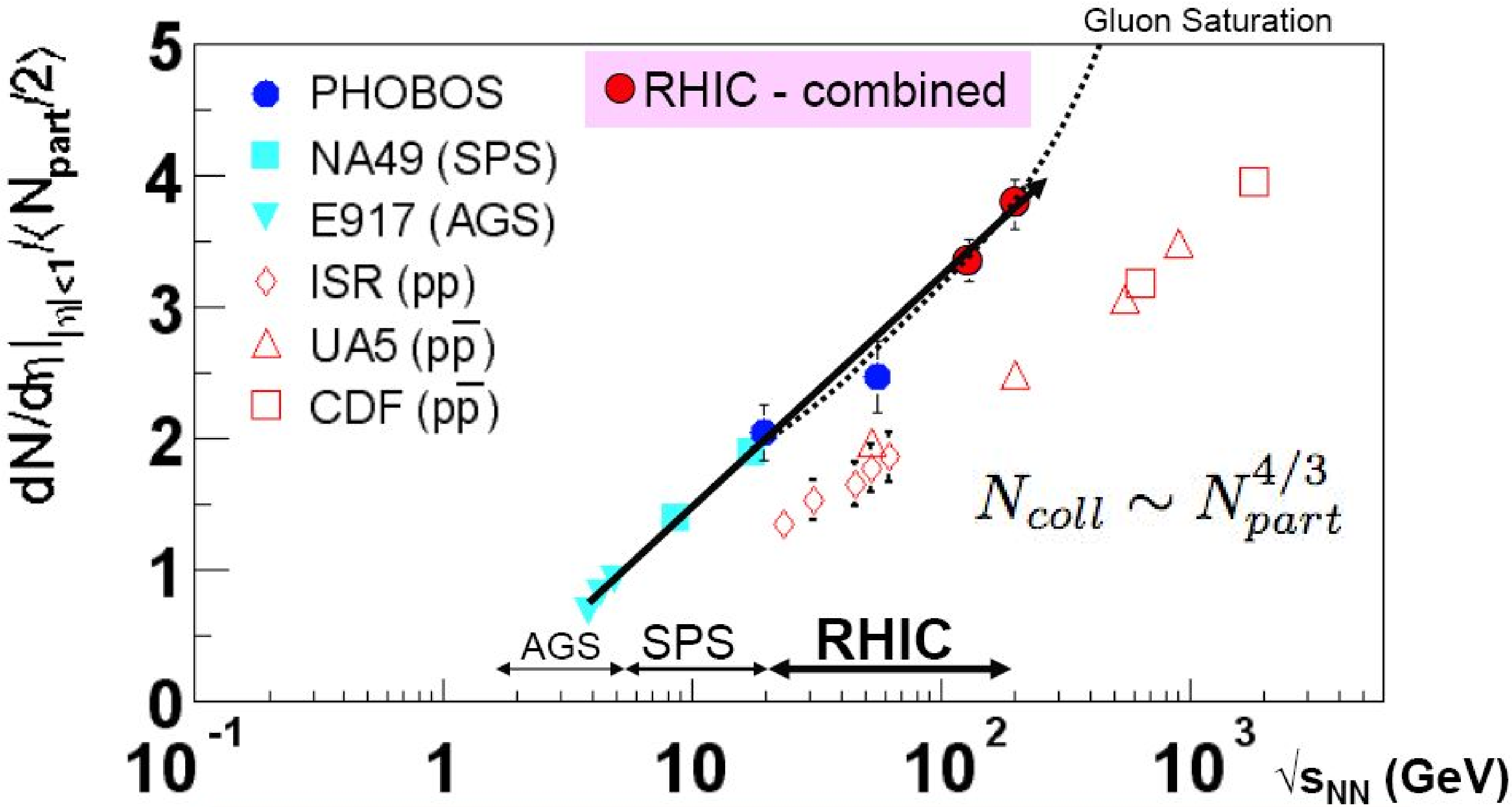
Hadron multiplicities: the effect of parton coherence

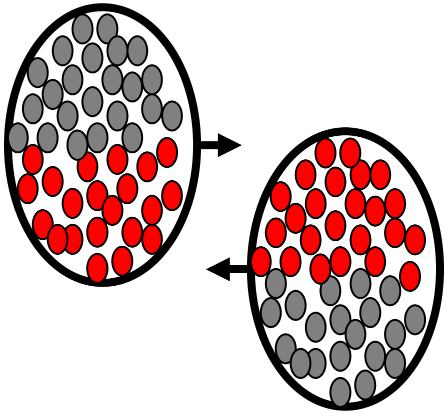


Semi-classical QCD and total multiplicities in heavy ion collisions

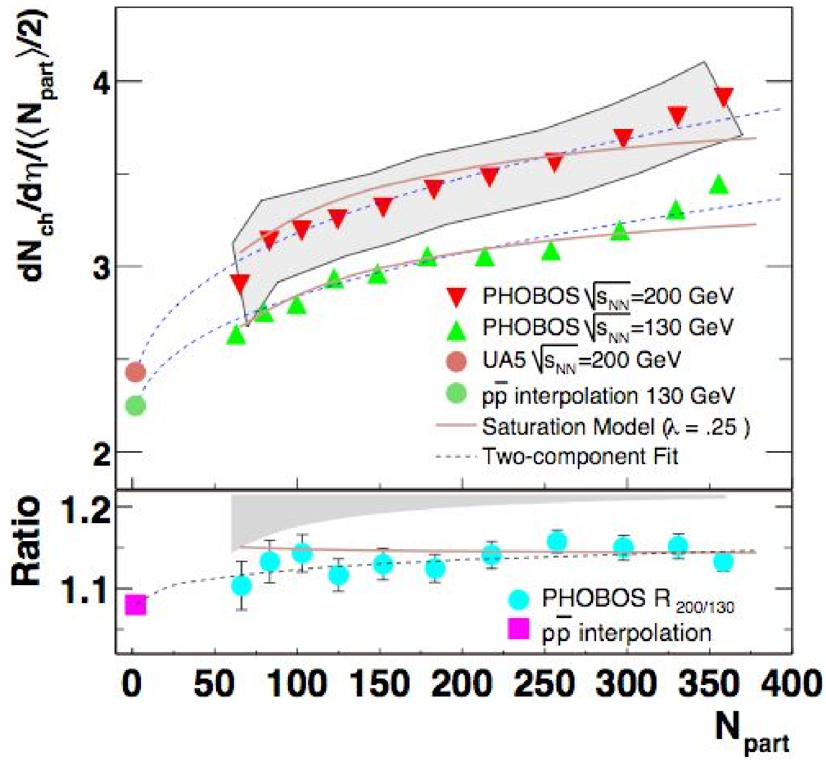
Expect very simple dependence of multiplicity on atomic number A / N_{part}:

$$n \sim \frac{S_A Q_s^2}{\alpha_s(Q_s^2)} \sim N_{part} \ \ln N_{part}$$

N_{part}:



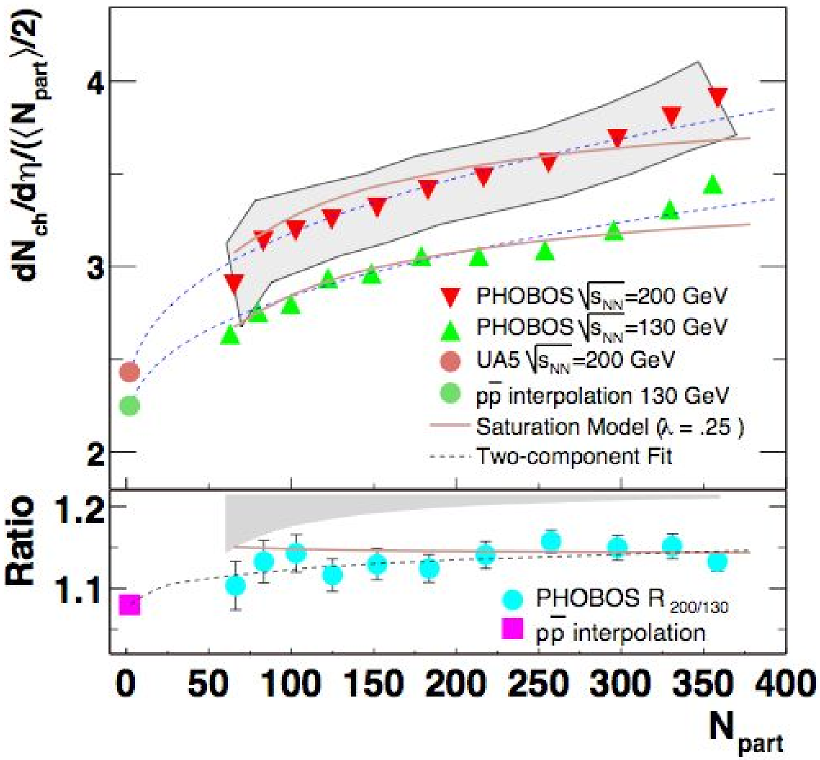
Almost the wounded nucleon model!

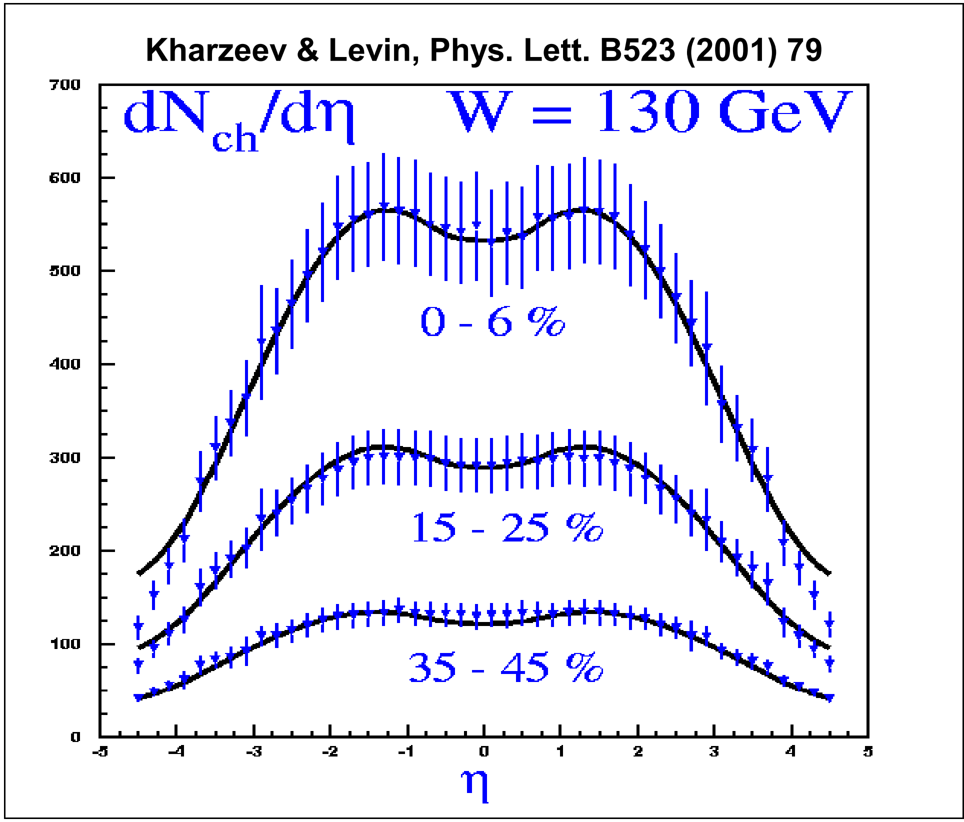


$$\frac{1}{N_{part}}\ \frac{dN}{d\eta} \sim \frac{1}{\alpha_s(Q_s^2)}$$

Classical QCD dynamics in action

The data on hadron multiplicities in Au-Au and d-Au collisions support the quasi-classical picture





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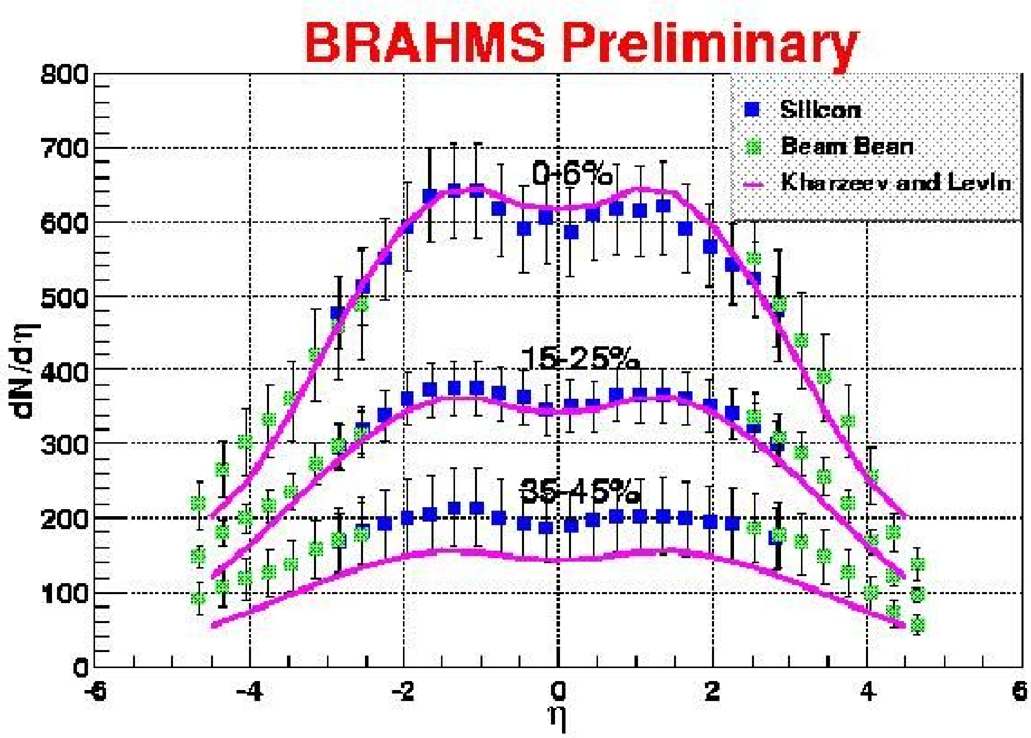
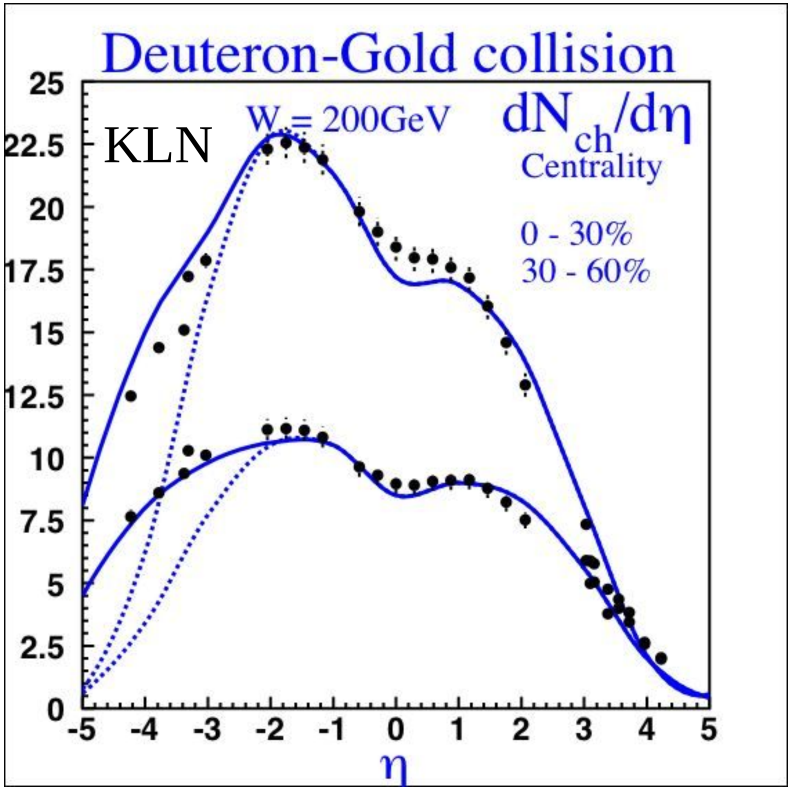
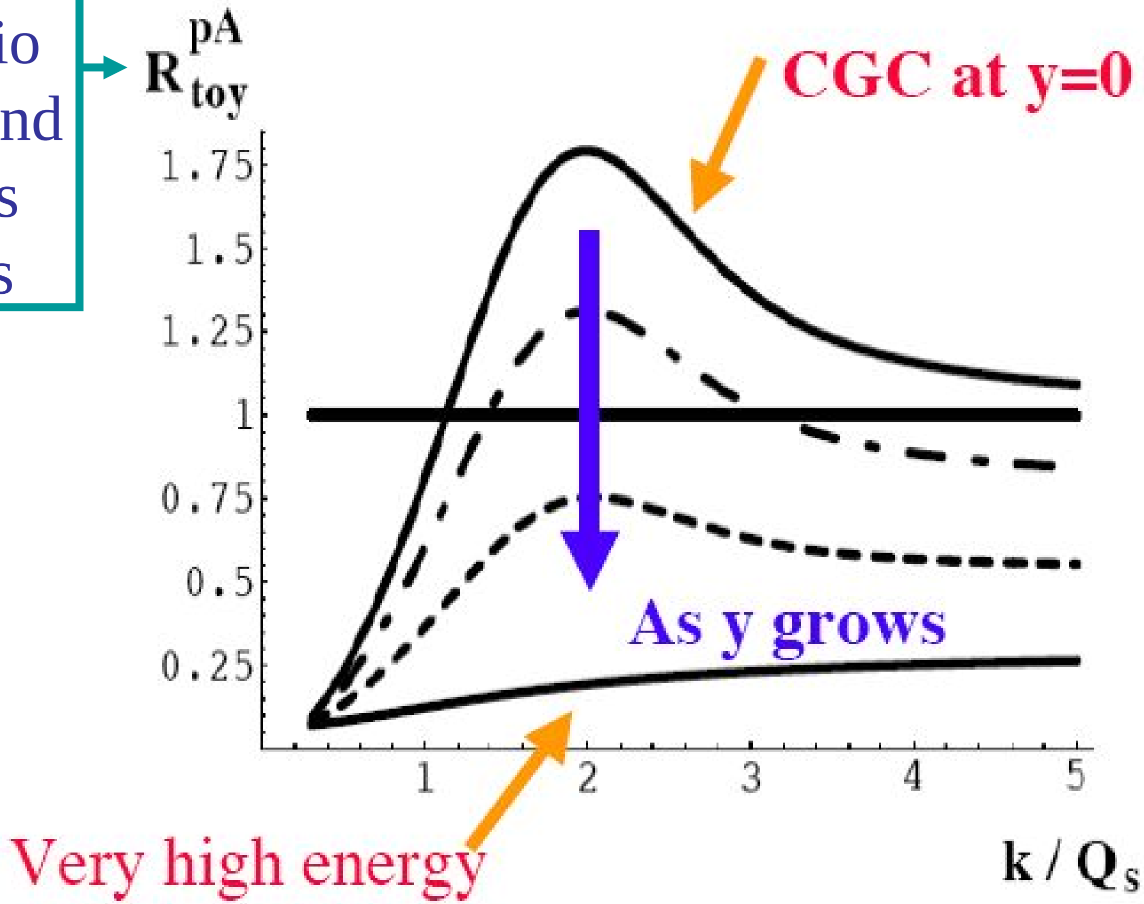




Gluon multiplication in a limited (nuclear) environment

The ratio of pA and pp cross sections

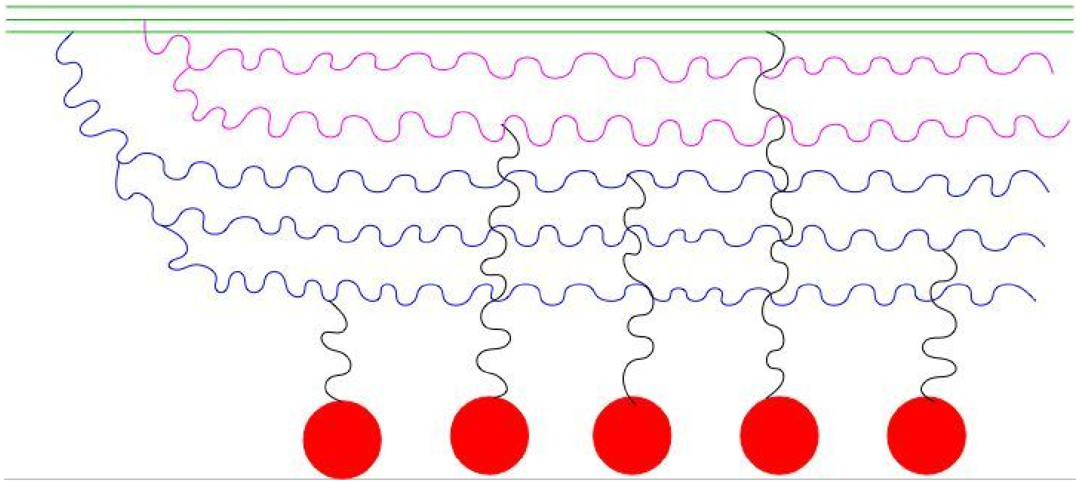


transverse momentum

At large rapidity y (small angle) expect suppression of hard particles!

DK, Levin, McLerran; KKT; Albacete et al

Quantum regime at short distances: the effect of the classical background



1) Small x evolution leads to anomalous dimension

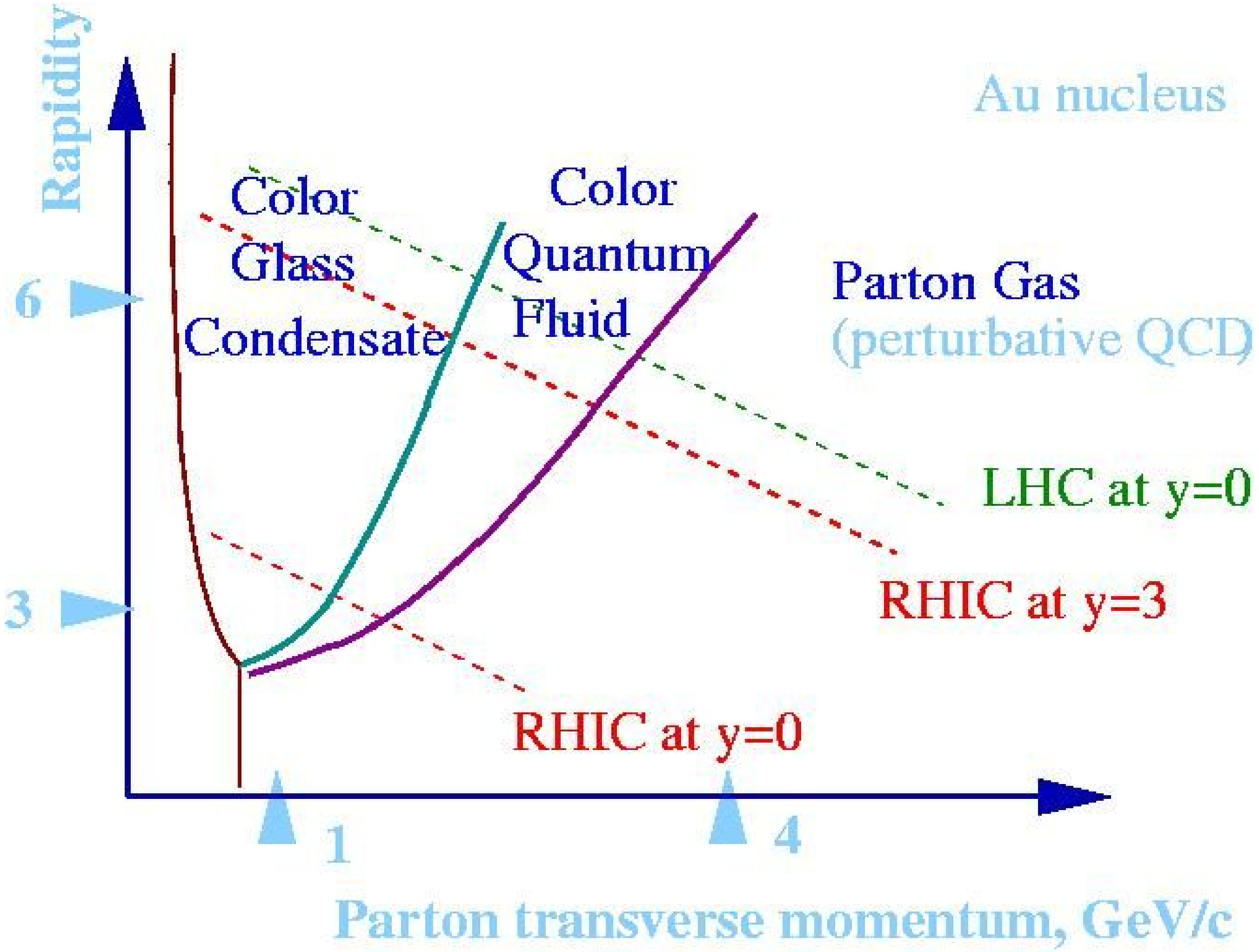
$$\frac{1}{Q^2} \rightarrow \left(\frac{1}{Q^2}\right)^{\gamma} \qquad \gamma \simeq 1/2$$

2) Q_s is the only relevant dimensionful parameter in the CGC; thus everything scales in the ratio Q_s^2/Q^2

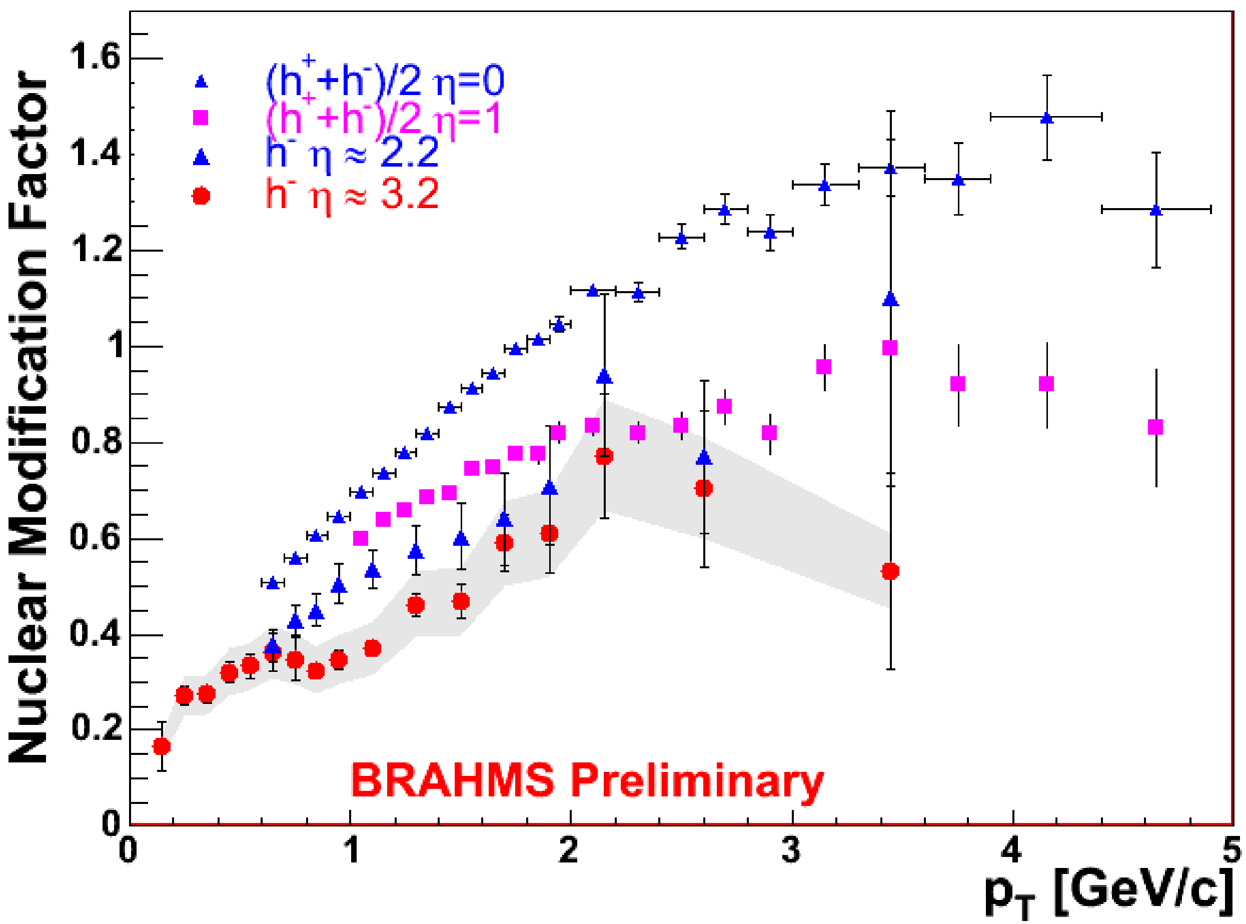
3) Since $Q_s^2 \sim A^{1/3}$ the A-dependence is changed

→ Expect high p_T suppression at sufficiently small x

Phase diagram of high energy QCD

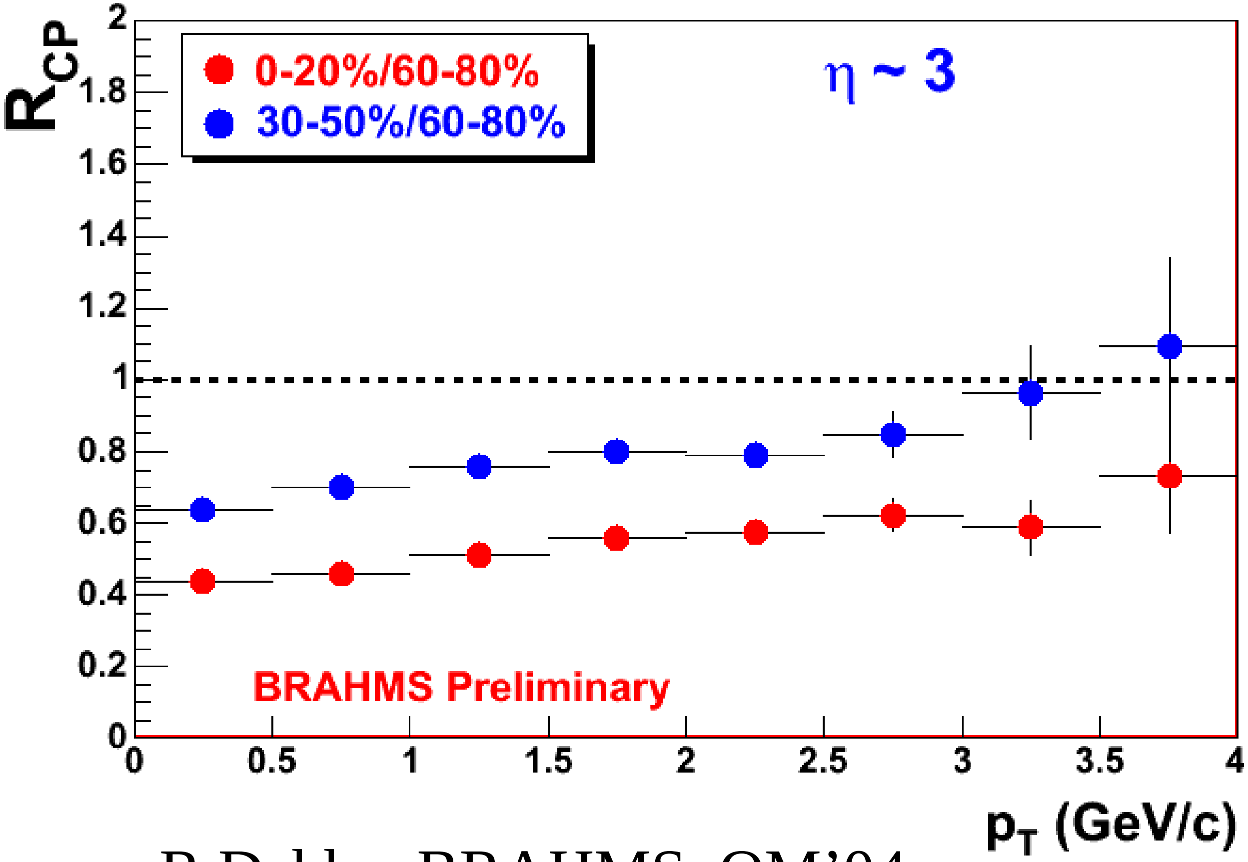


Nuclear Modification of Hard Parton Scattering

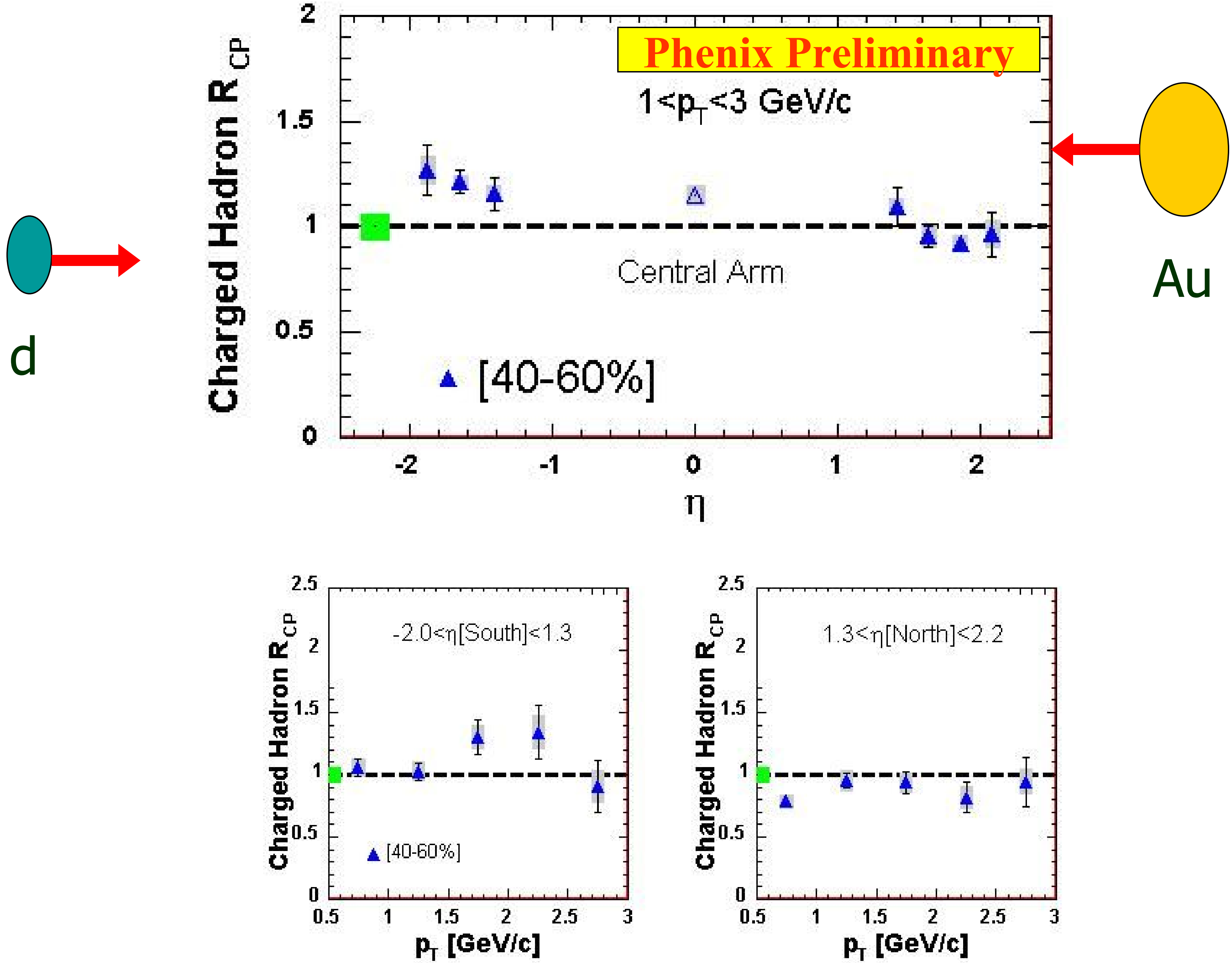


R.Debbe, BRAHMS, QM'04

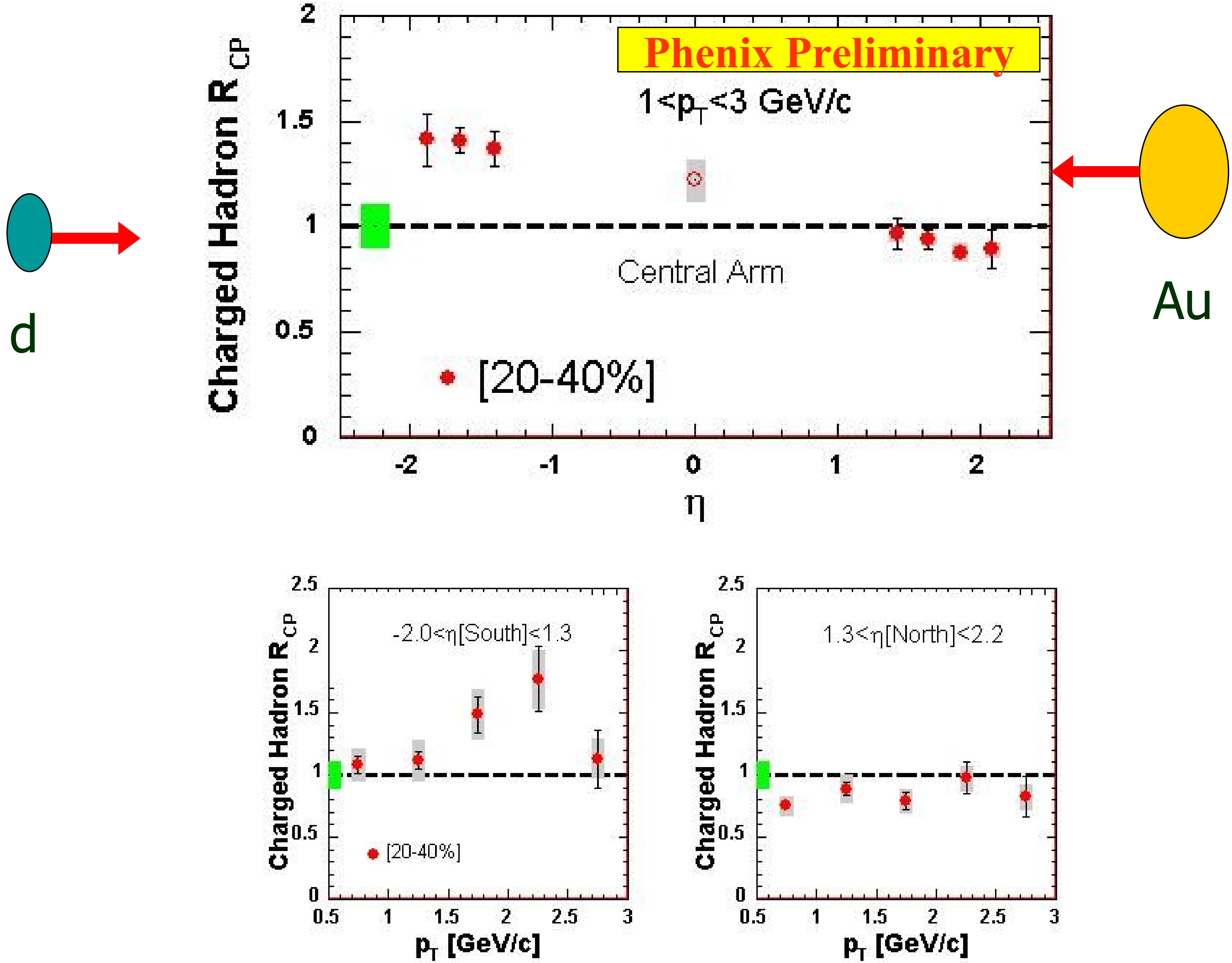
Centrality dependence



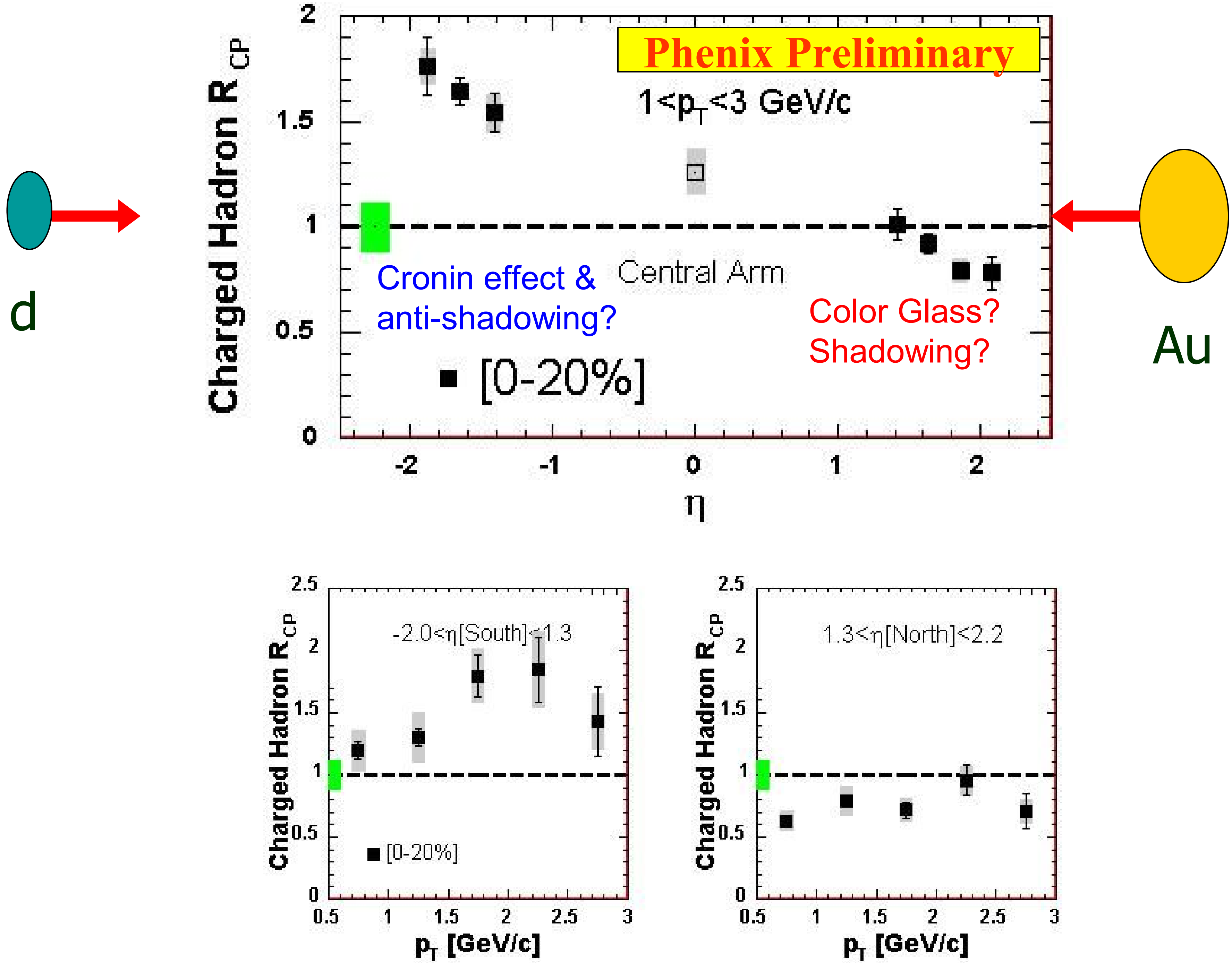
R.Debbe, BRAHMS, QM’04



Phenix Preliminary
1<p_T<3 GeV/c
Central Arm
[40-60%]
Charged Hadron R_CP
η
d
Au
-2.0<η[South]<1.3
[40-60%]
1.3<η[North]<2.2
p_T [GeV/c]

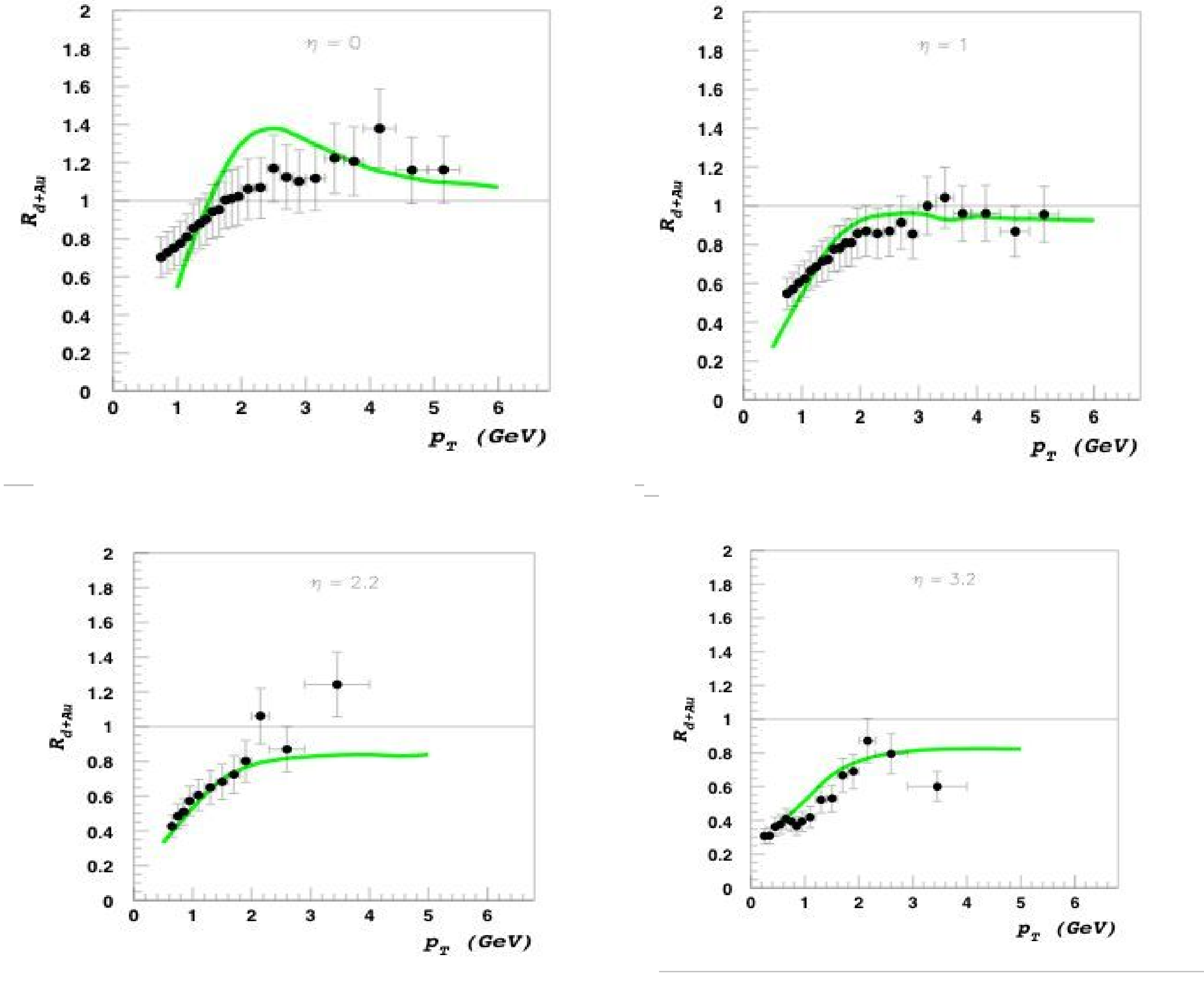


Phenix Preliminary
1<p_T<3 GeV/c
Charged Hadron R_CP
Central Arm
[20-40%]
η
d
Au
-2.0<η[South]<1.3
1.3<η[North]<2.2
p_T [GeV/c]



Phenix Preliminary
1<p_T<3 GeV/c
Charged Hadron R_CP
η
Central Arm
Cronin effect &
anti-shadowing?
Color Glass?
Shadowing?
[0-20%]
d
Au
-2.0<η[South]<-1.3
1.3<η[North]<2.2
p_T [GeV/c]

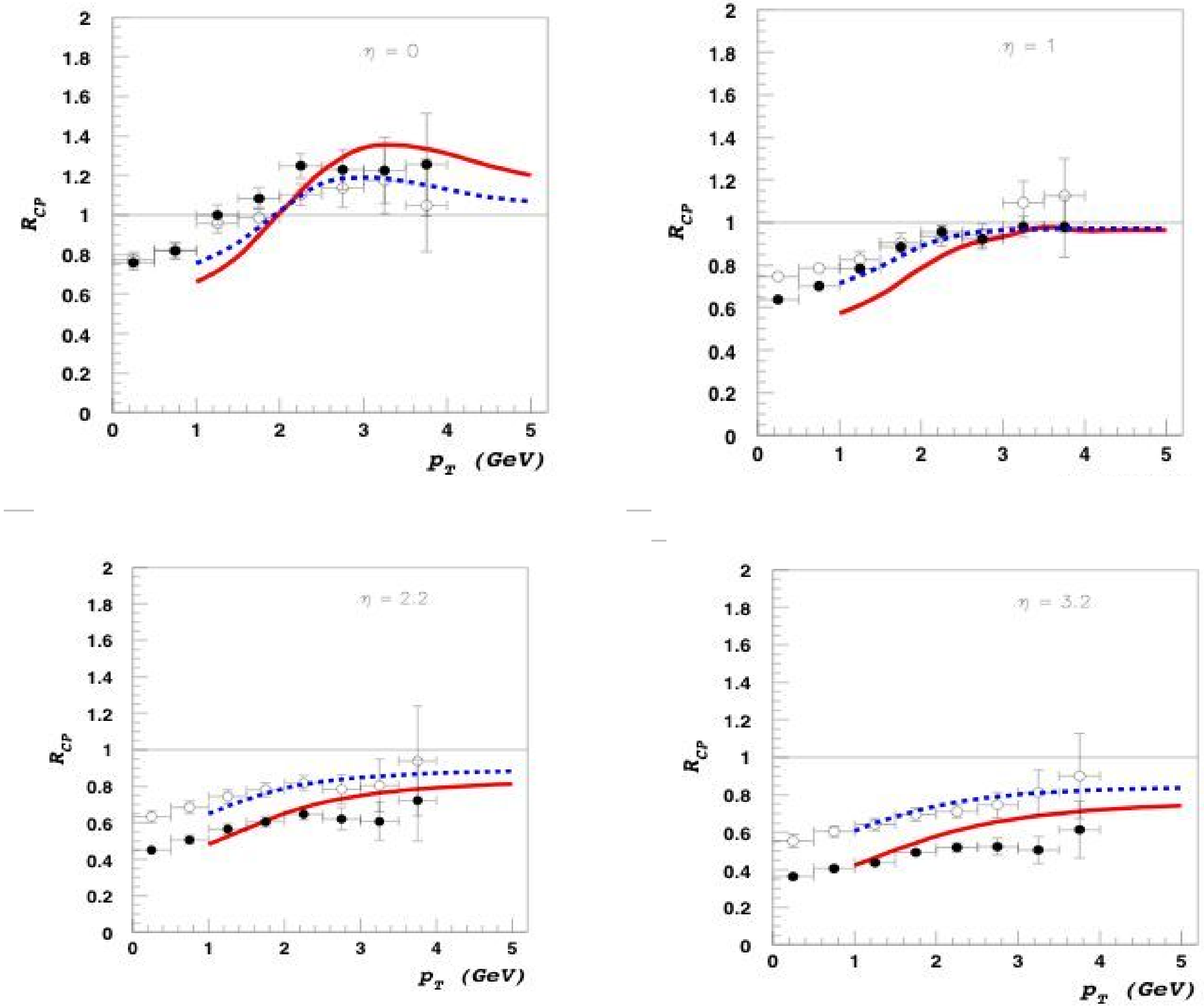
Color Glass Condensate: confronting the data



BRAHMS data,
η= 0, 1,
2.2, 3.2

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

Color Glass Condensate: confronting the data



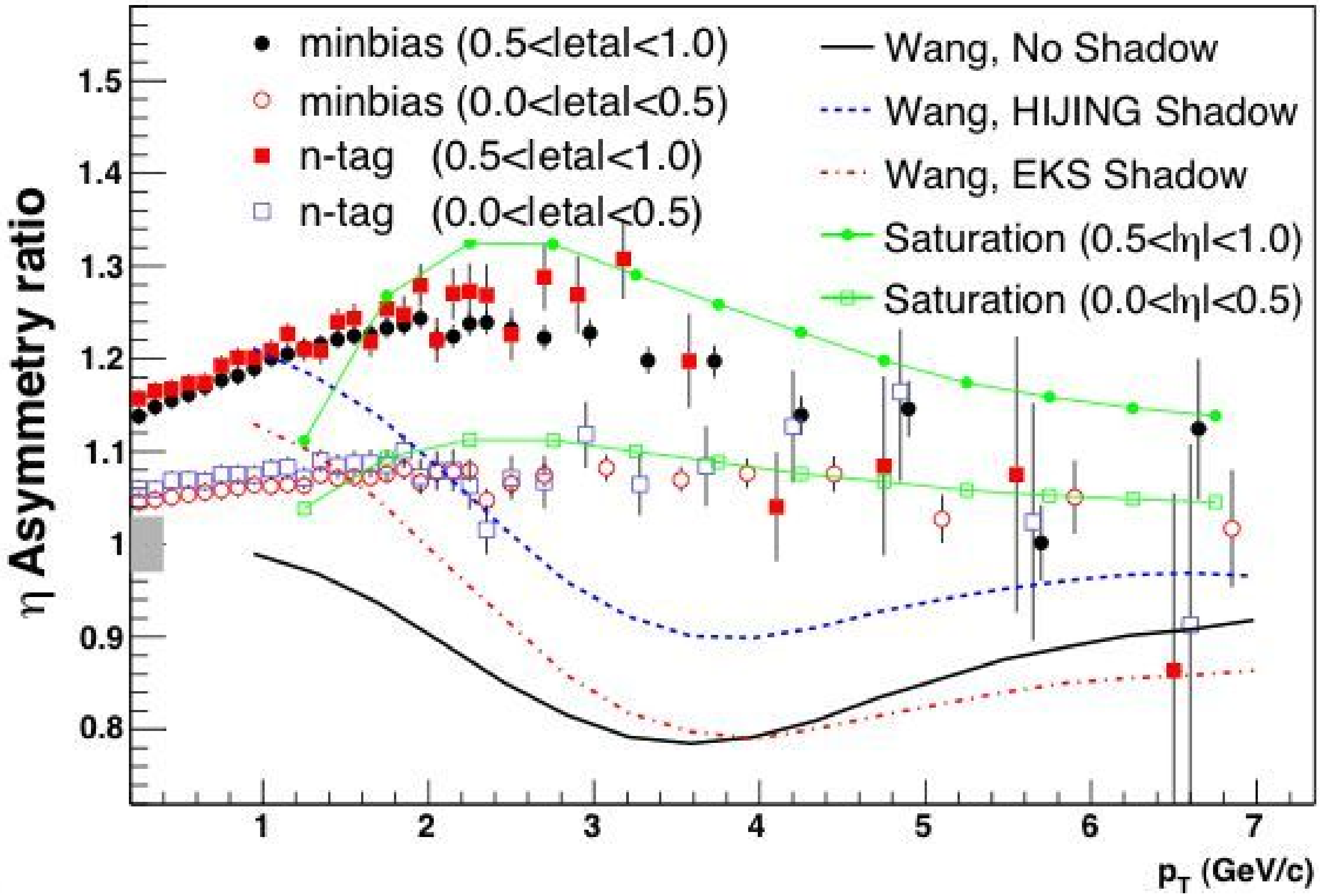
BRAHMS data, R_{CP}

η= 0, 1, 2.2, 3.2

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

Confronting the RHIC data

STAR Collaboration



How dense is the produced matter?

The initial energy density achieved:

$$\epsilon_{initial} \simeq \frac{< k_t >}{\tau_0} \frac{d^2N}{d^2b\ d\eta} \simeq Q_s^2 \frac{d^2N}{d^2b\ d\eta} \simeq 18\ \mathrm{GeV/fm^3}$$

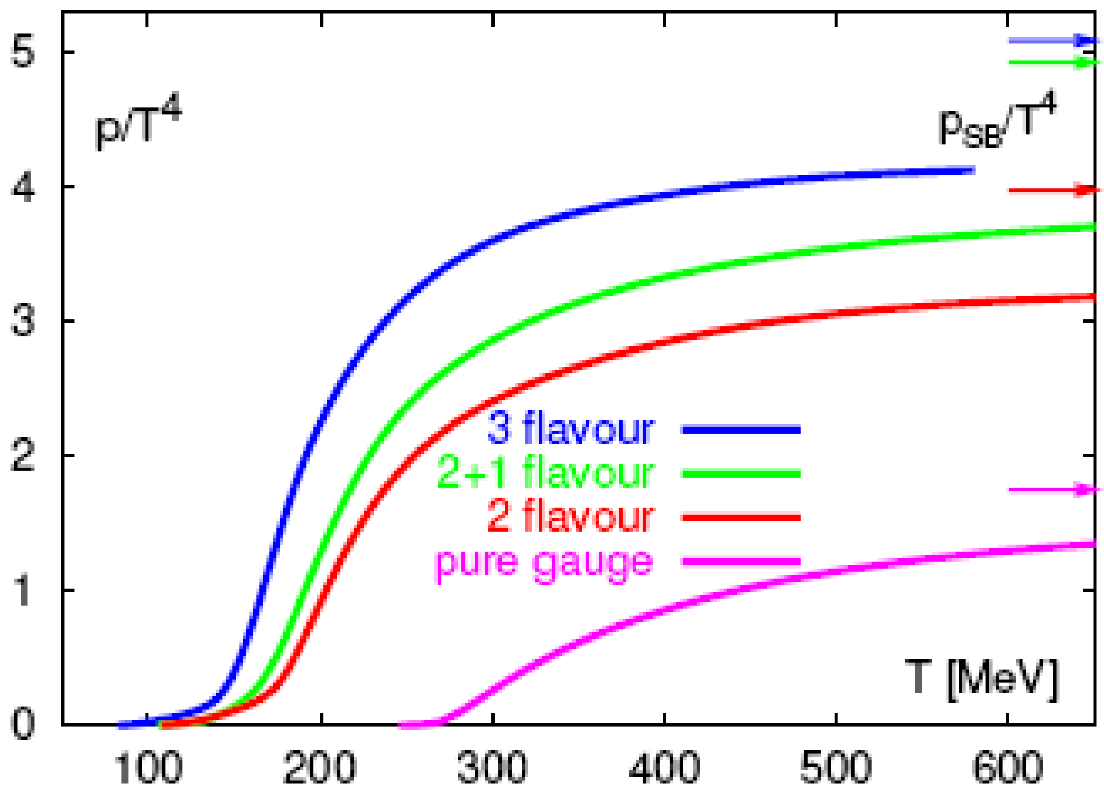
mean transverse momentum of produced gluons

gluon formation time

the density of the gluons in the transverse plane and in rapidity

about 100 times nuclear density !

What happens at such energy densities?



Phase transitions:

deconfinement

Chiral symmetry restoration

$U_A(1)$ restoration

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

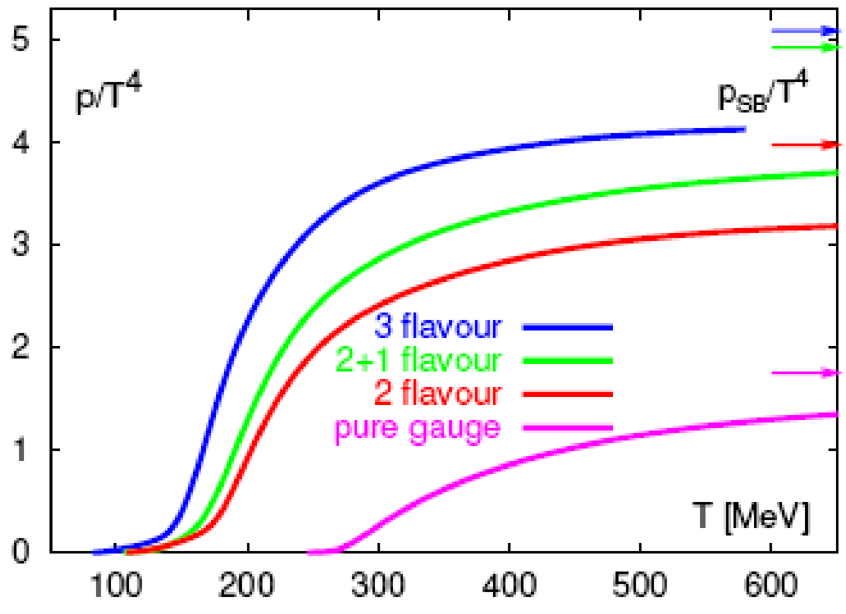
Data from lattice QCD simulations F. Karsch et al

critical temperature ~ 10^{12} K; cf temperature inside the Sun ~ 10^{7} K

Strongly coupled QCD plasma

$$\langle \theta^\mu_\mu \rangle = \epsilon - 3P \neq 0$$

Interactions are important!
(strongly coupled
Quark-Gluon Plasma)

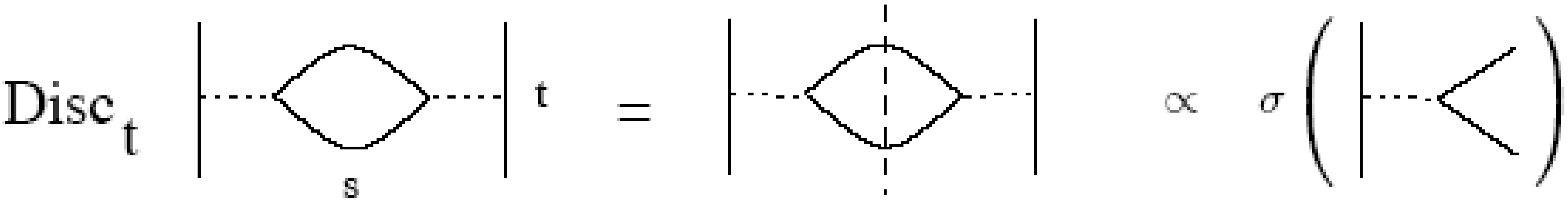


C. Bernard, T.Blum, ‘97

F. Karsch, P.Petreczky,

Coulomb potential in QCD

Spectral representation in the t-channel: $V(R) = \sum_m \sigma(m^2)\,\frac{\exp(-mR)}{R}$



If physical particles can be produced (positive spectral density), then unitarity implies screening

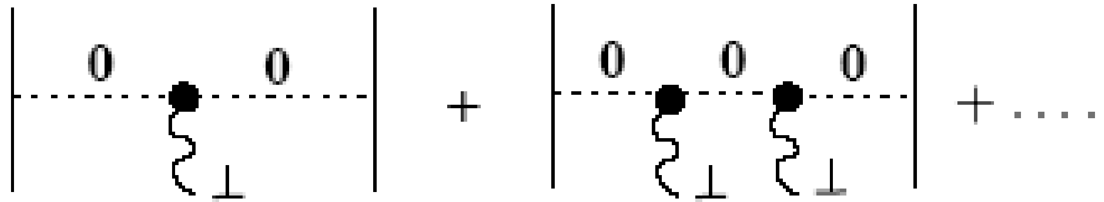
$$\left\{ \frac{d\,\alpha_s^{-1}(R)}{d \ln R} \right\}^{\text{phys}} \propto \frac{1}{3} N + \frac{2}{3} n_f$$

Gluons (transverse) Quarks

Coulomb potential in QCD - II

Missing non-Abelian effect: instantaneous Coulomb exchange dressed by (zero modes of) transverse gluons

$$\sum_n \left[0 + \perp \rightarrow 0\right]^n =$$



Negative sign
(the shift of the ground level
due to perturbations - unstable vacuum!):

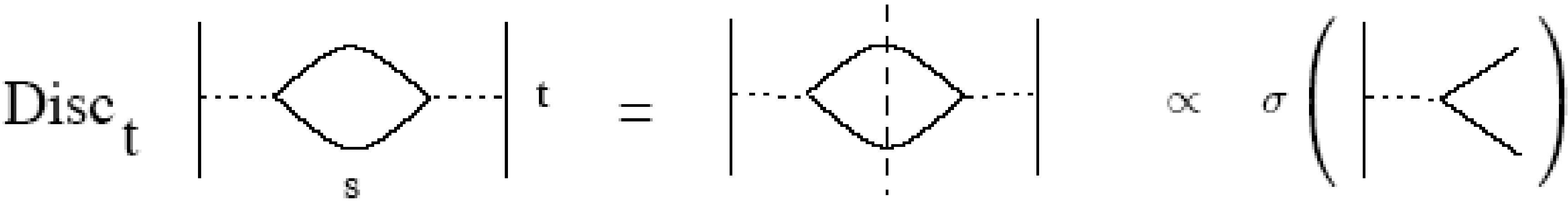
$$\delta E \equiv E - E_0 = \sum_n \frac{|\langle 0|\delta V|n\rangle|^2}{E_0 - E_n} < 0$$

Anti-screening

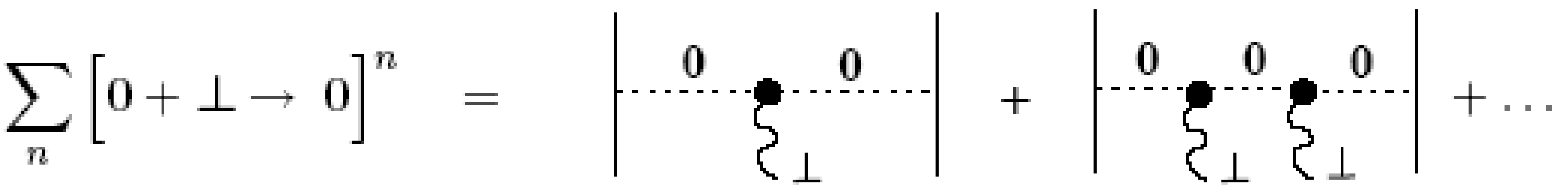
$$\left\{ \frac{d\,\alpha_s^{-1}(R)}{d \ln R} \right\}^{\rm stat} \propto -4N$$

Screening in Quark-Gluon Plasma

These diagrams are enhanced at finite temperature:
(scattering off thermal gluons and quarks)

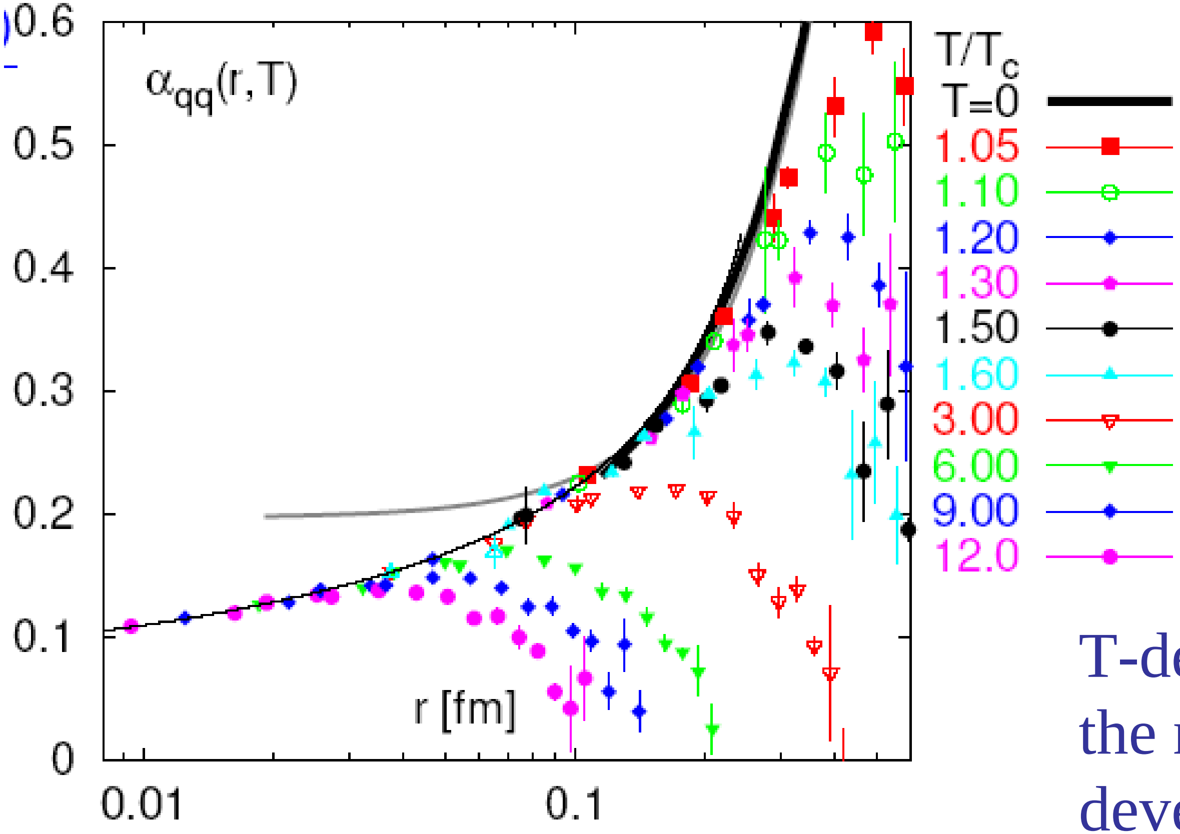


This diagram is not:



=> At high enough T, screening wins

Screening in QGP



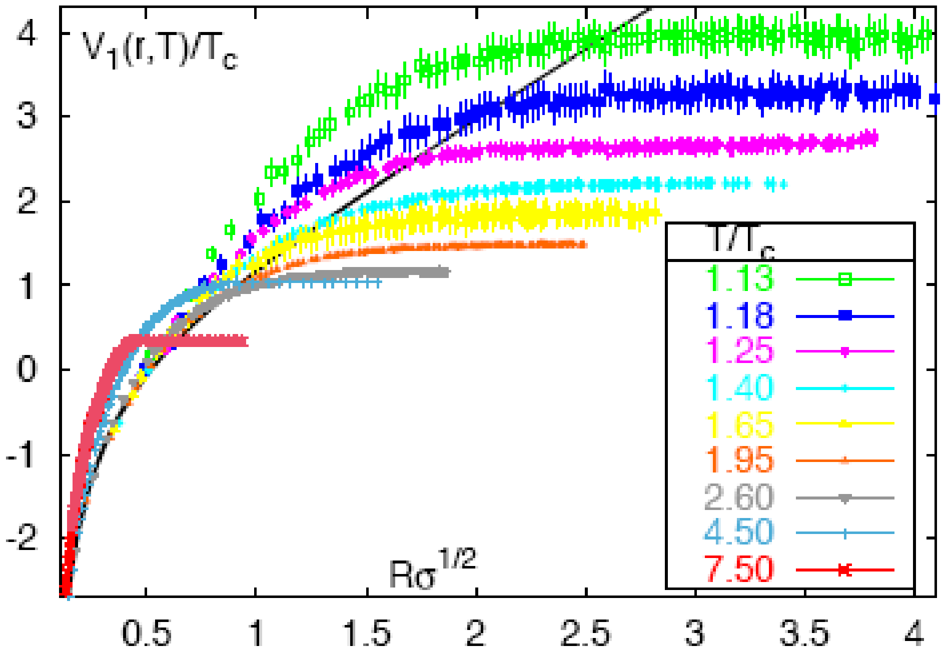
F.Karsch et al

Strong force is screened by the presence of thermal gluons and quarks

T-dependence of the running coupling develops in the non-perturbative region at $T < 3\ T_c$; $\Delta E/T > 1$

- “cold” plasma

Heavy quark internal energy above T



O.Kaczmarek, F. Karsch, P.Petreczky,
F. Zantow, hep-lat/0309121

J/Ψ as a probe:

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
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and

H. SATZ
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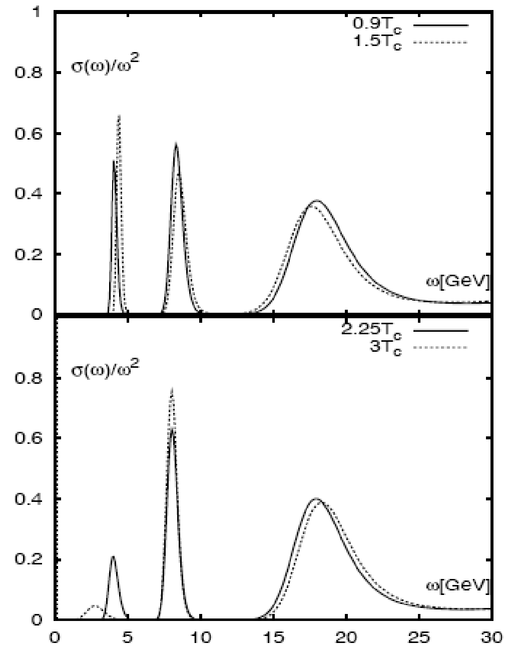
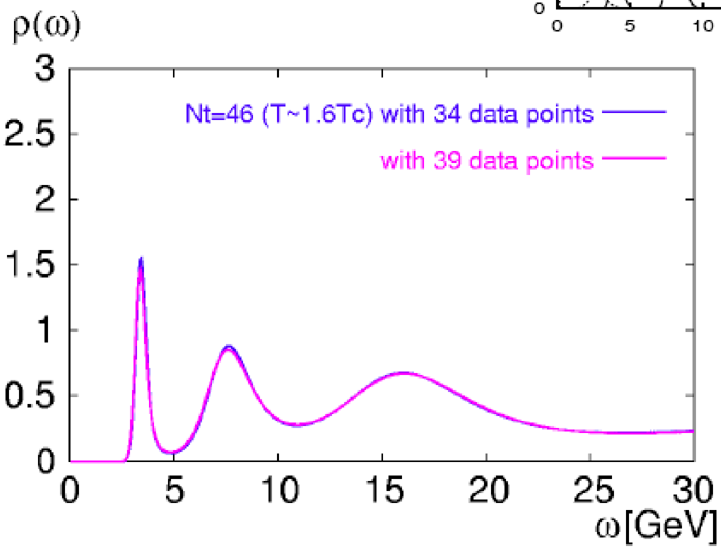
Received 17 July 1986

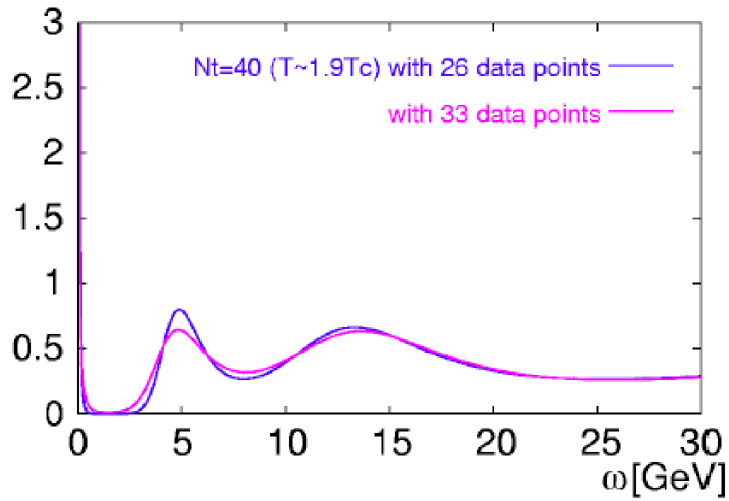
If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

J/Ψ above T_c: alive and well?



S.Datta,
F.Karsch,
P.Petreczky,
I.Wetzorke

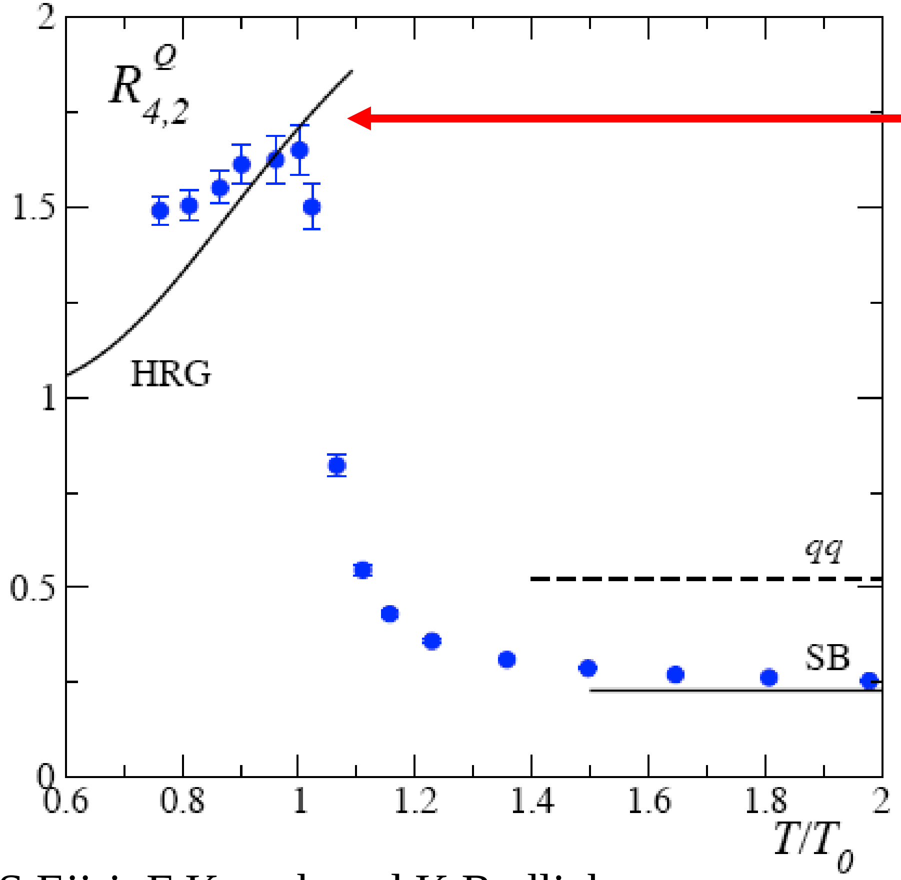




M.Asakawa,
T.Hatsuda

What are the dynamical degrees of freedom in the plasma?

Let us look at the charge fluctuations in sQGP:



Hadron resonance gas

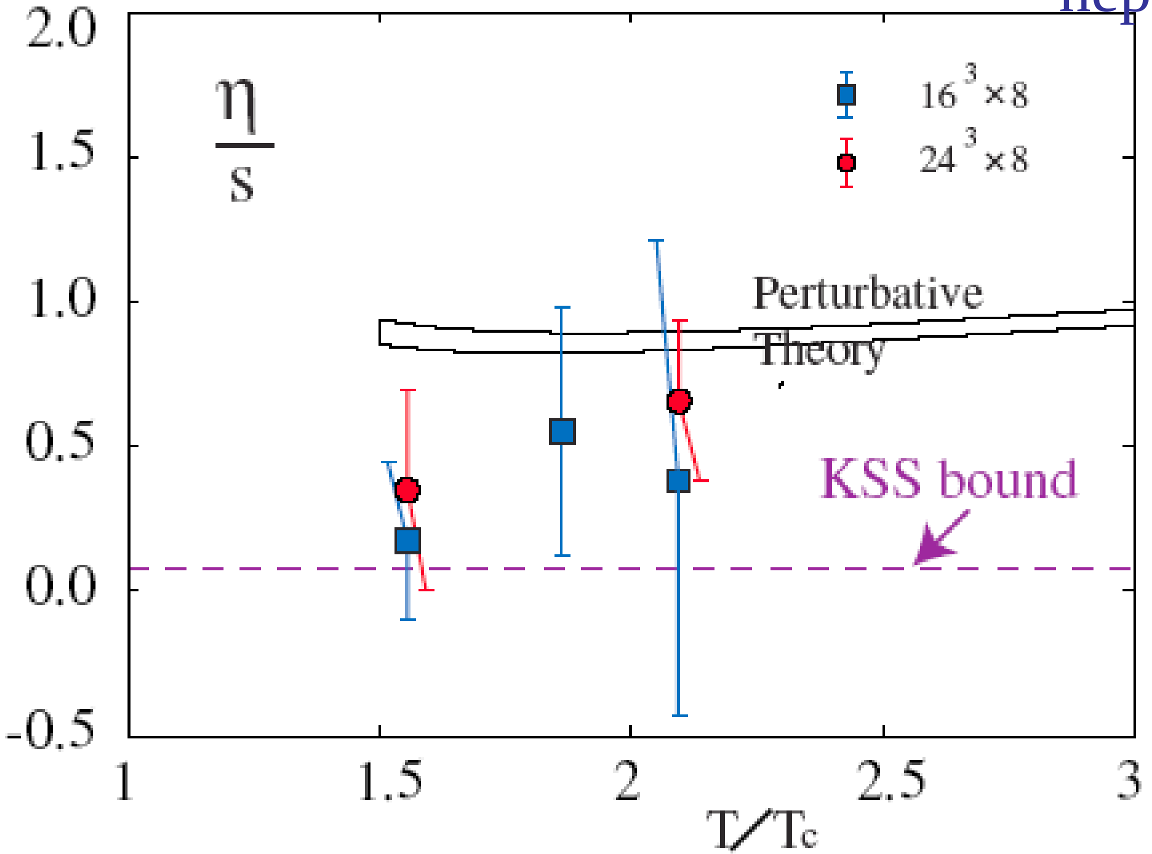
QQ bound states

Dynamical quarks

S.Ejiri, F.Karsch and K.Redlich

Viscosity of sQGP

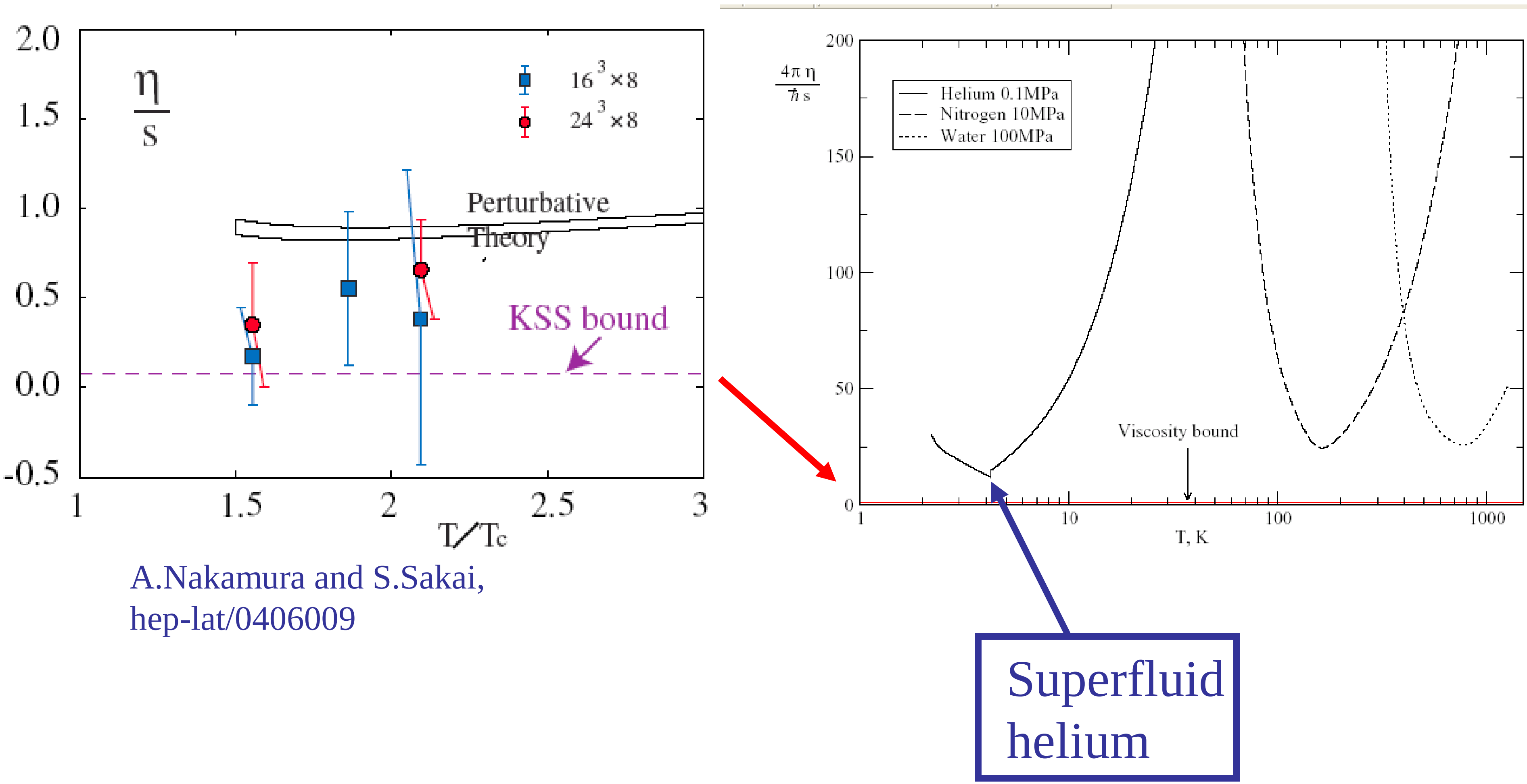
A.Nakamura and S.Sakai, hep-lat/0406009



Perfect fluid

KSS bound:
strongly coupled SUSY QCD = classical supergravity

Quark-gluon plasma: more fluid than water?



A.Nakamura and S.Sakai, hep-lat/0406009

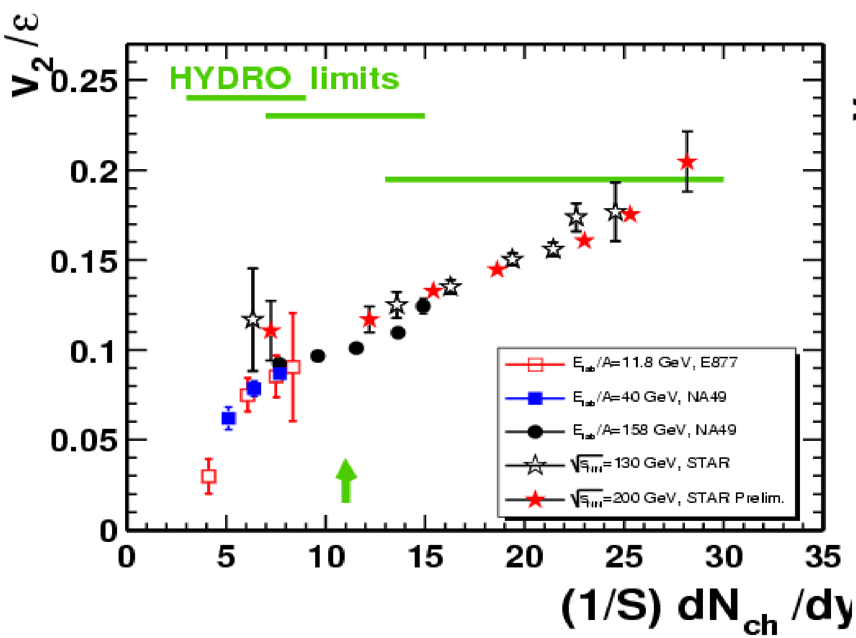
Do we see the QCD matter at RHIC ?

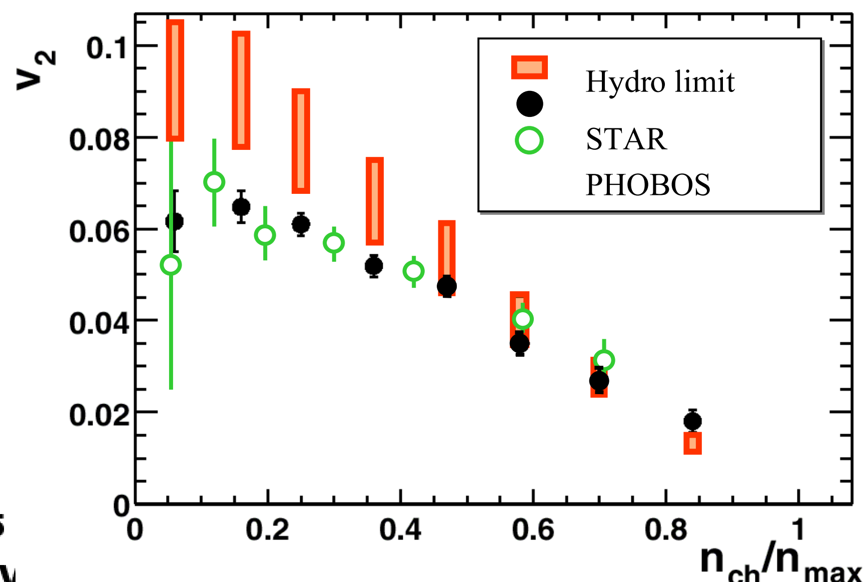
I. Collective flow =>

Au-Au collisions at RHIC produce strongly interacting matter

shear viscosity - to - entropy ratio

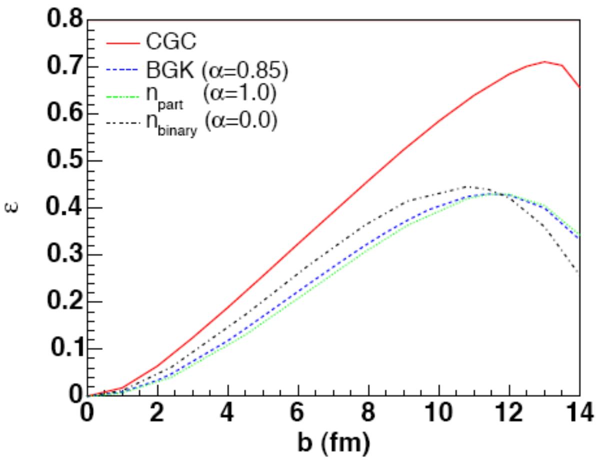
hydrodynamics: QCD liquid is more fluid than water

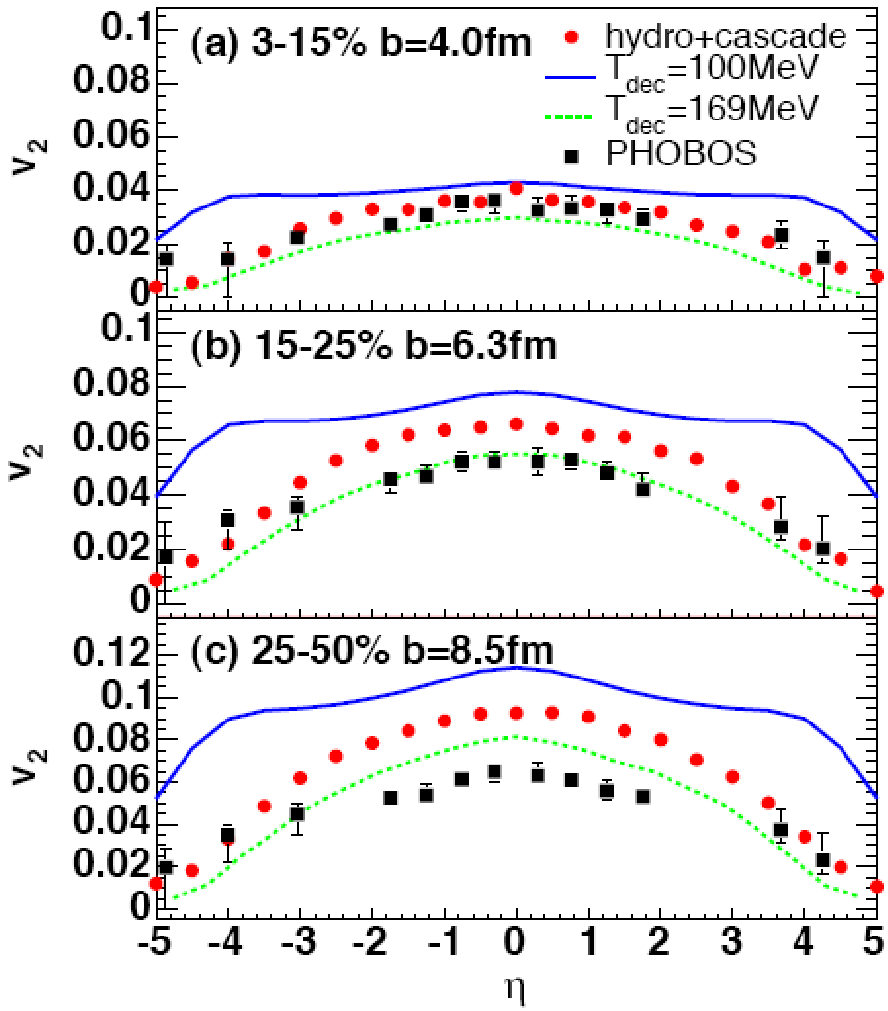




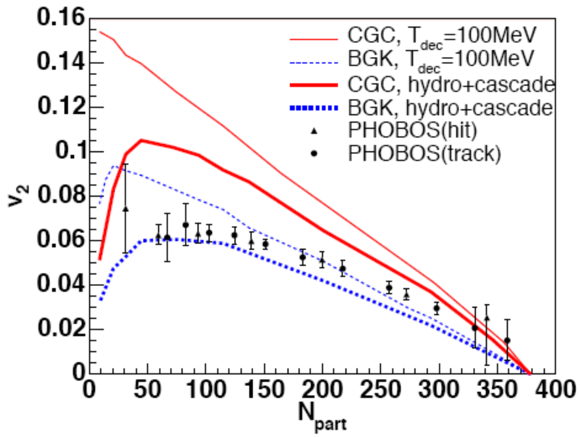
How small is really the viscosity?

CGC initial conditions lead to larger ellipticity,





require some viscous effects:

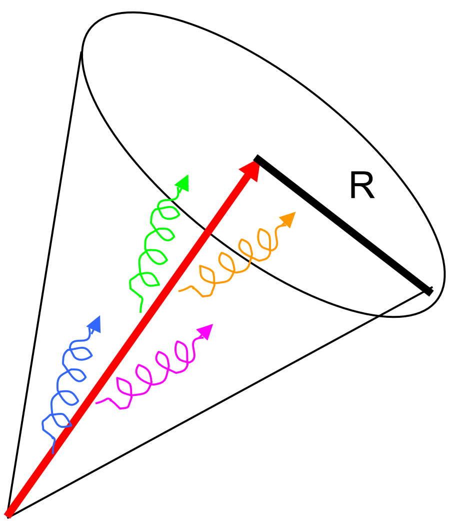


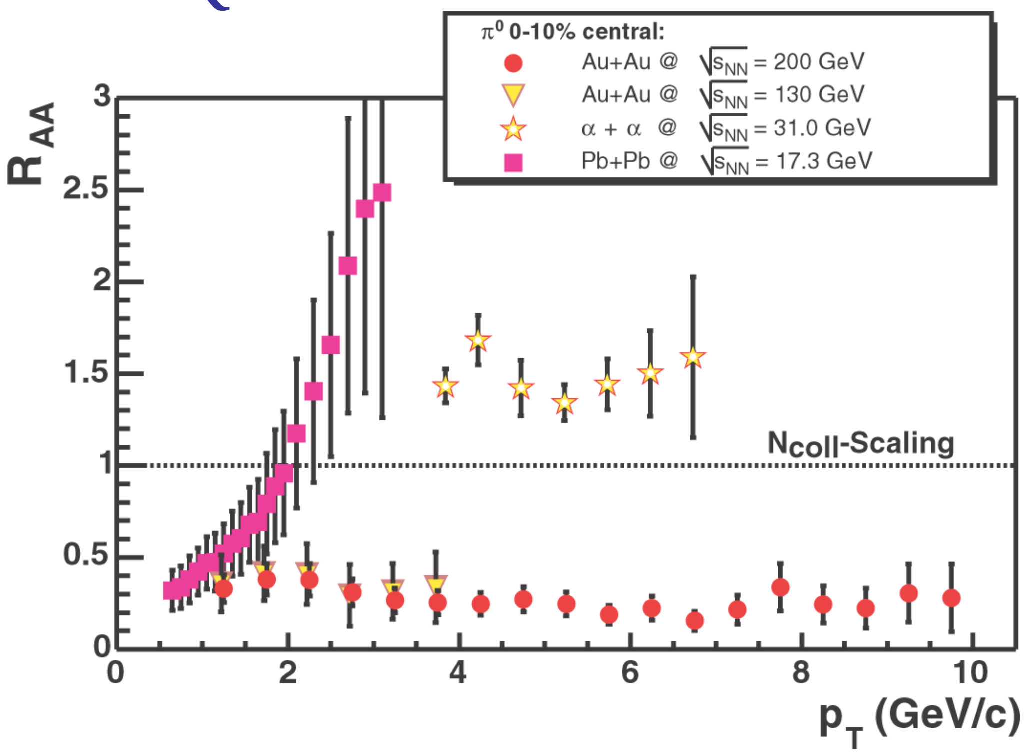
T.Hirano, U.Heinz, DK, R.Lacey, Y. Nara, hep-ph/0511046

Do we see the QCD matter at RHIC?

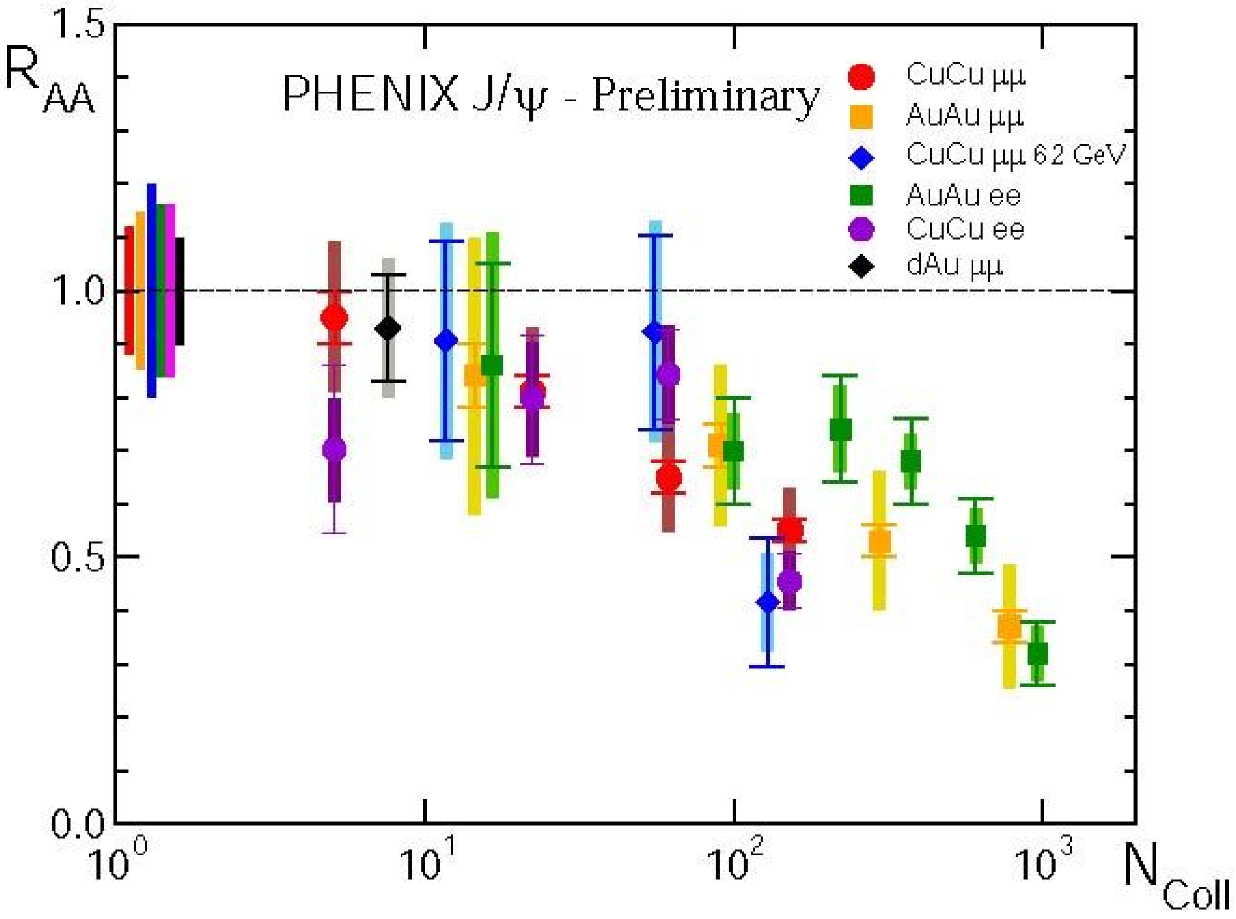
II. Suppression of high p_T particles =>

consistent with the predicted parton energy loss from induced gluon radiation in dense QCD matter





J/ψ suppression at RHIC



“same as at SPS”?

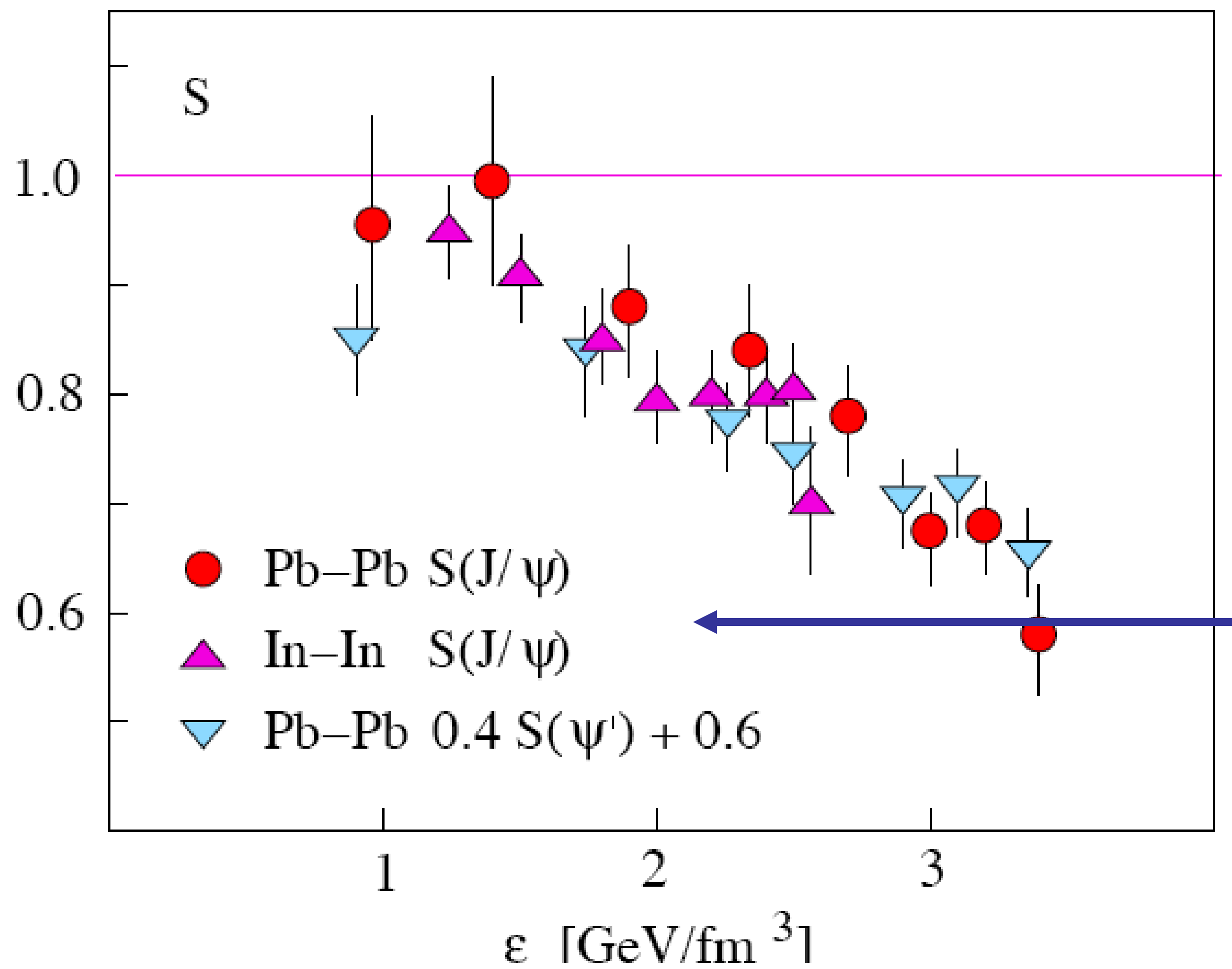
Sequential charmonium dissociation?

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

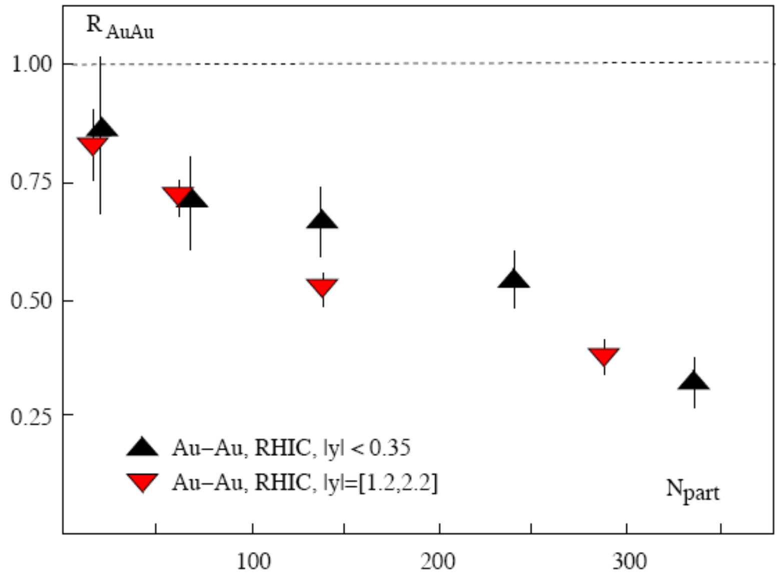
F.Karsch, DK, H.Satz,
hep-ph/0512239

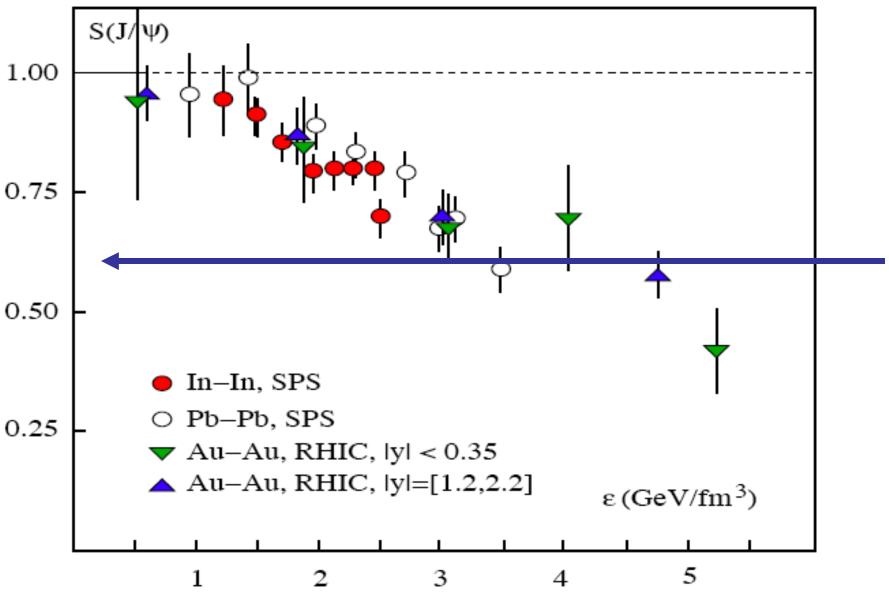
Is there a "direct" J/ψ suppression at SPS?



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

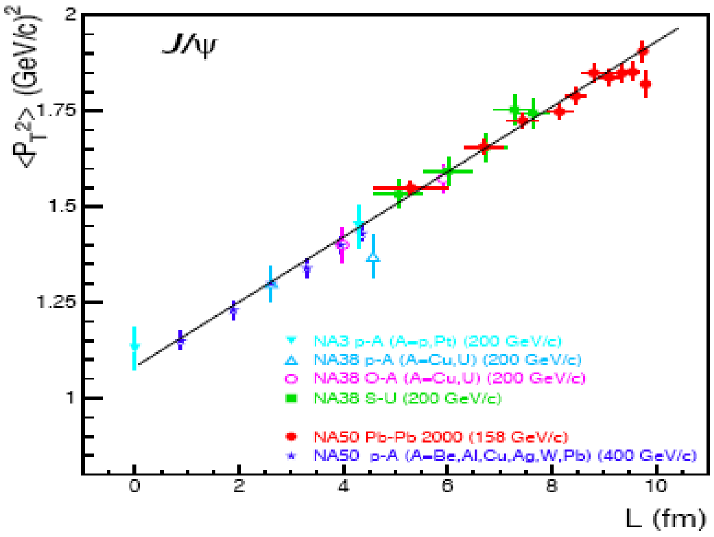
Is there a “direct” J/ψ suppression at RHIC?

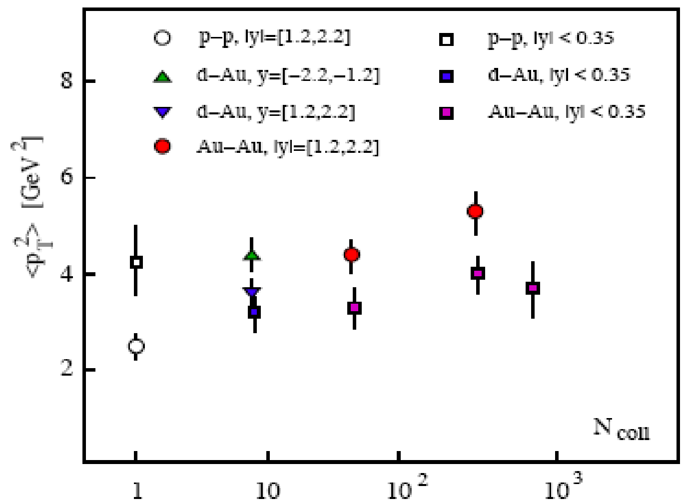


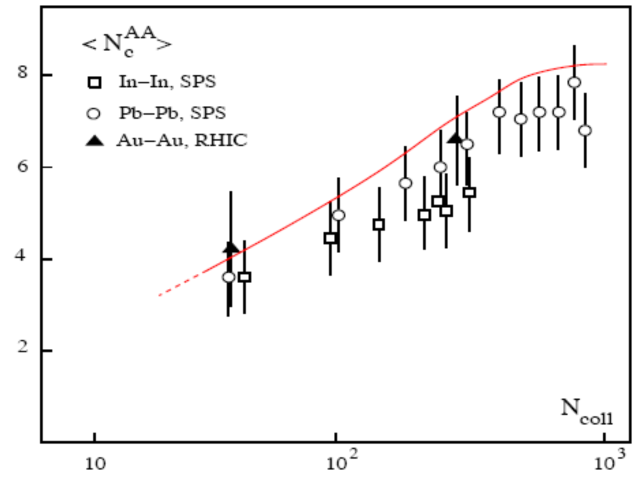


Data: PHENIX, NA50, NA60

Transverse momentum distributions

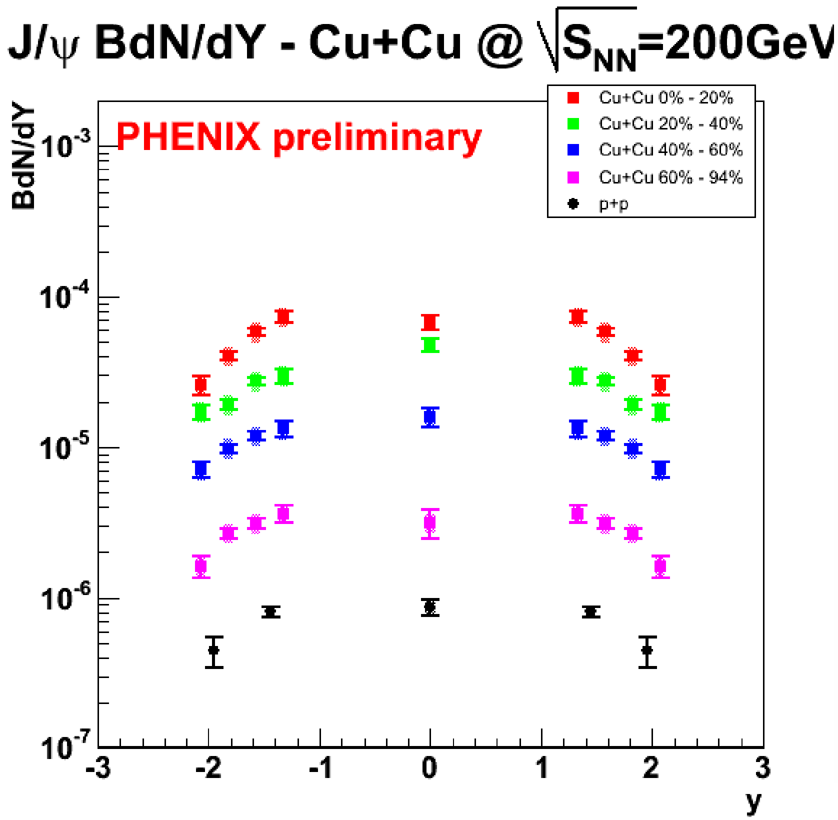


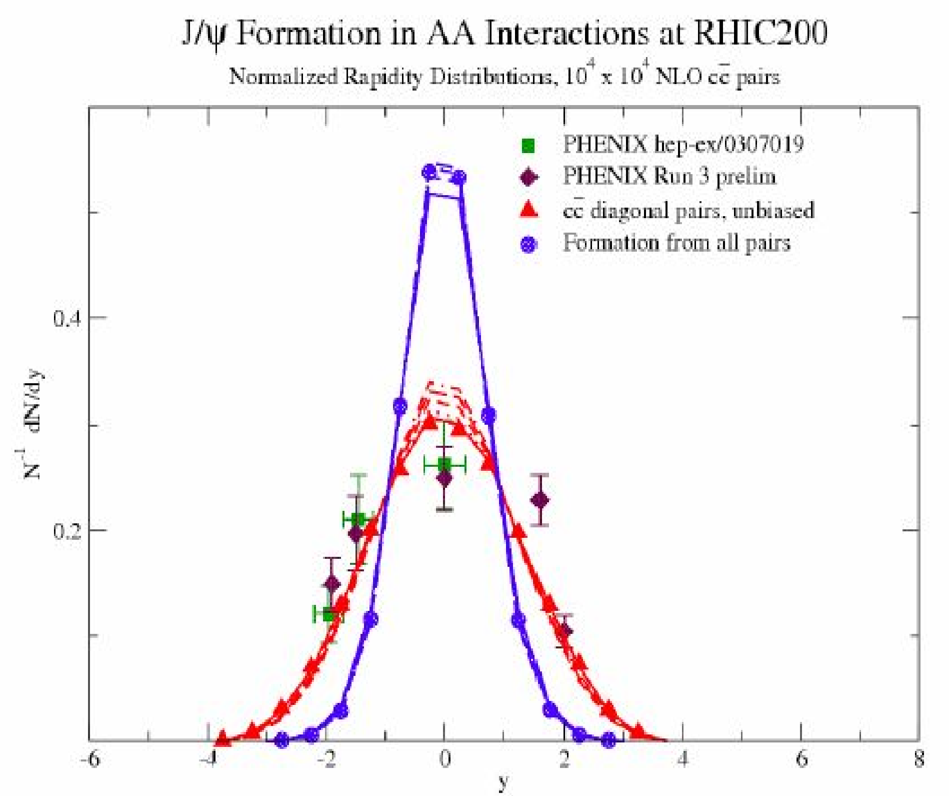




Glauber model analysis

Recombination of charm quarks?



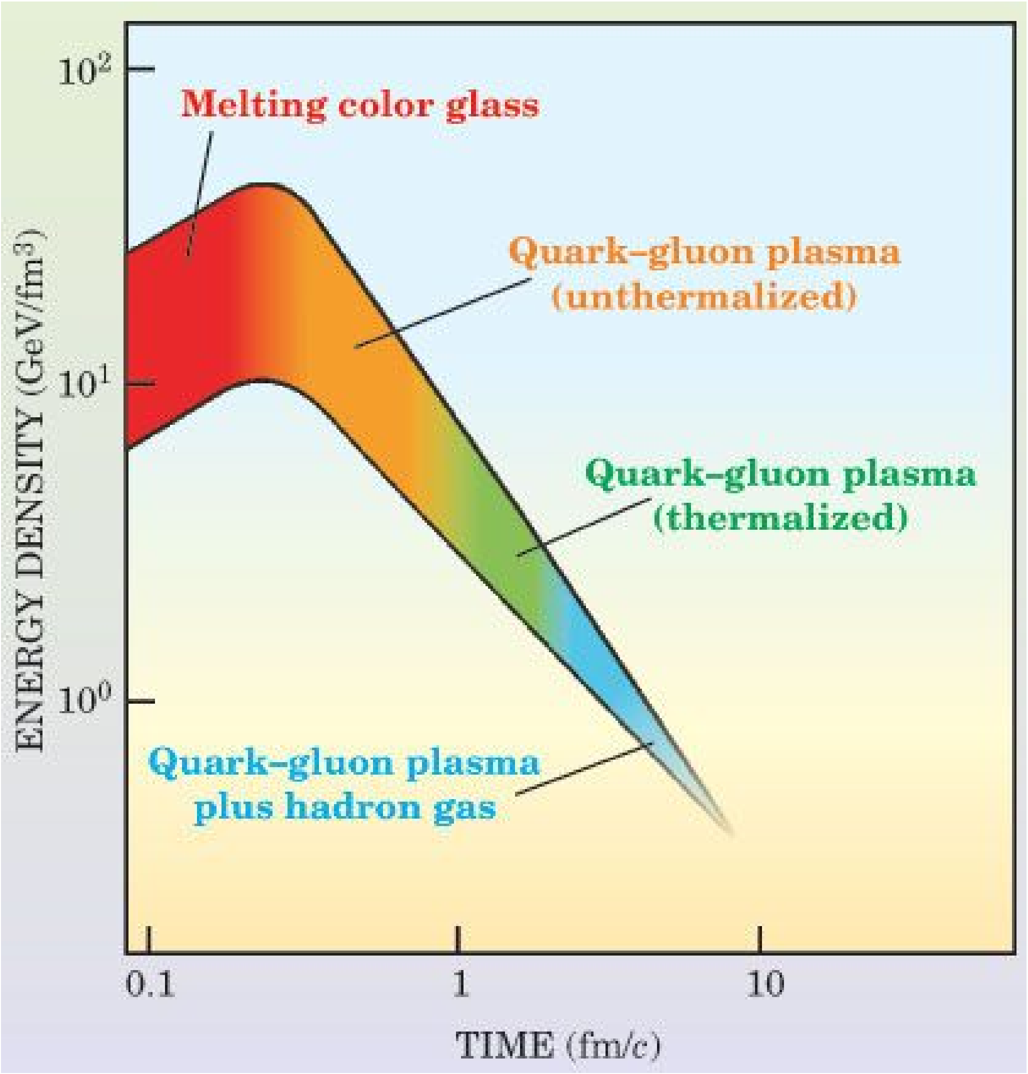


R.Thews

Recombination narrows the rapidity distribution; is this seen?

Are high p_t charmonia suppressed stronger than open charm?

The emerging picture



Big question:

How does the produced matter thermalize so fast?

Perturbation theory +
Kinetic equations

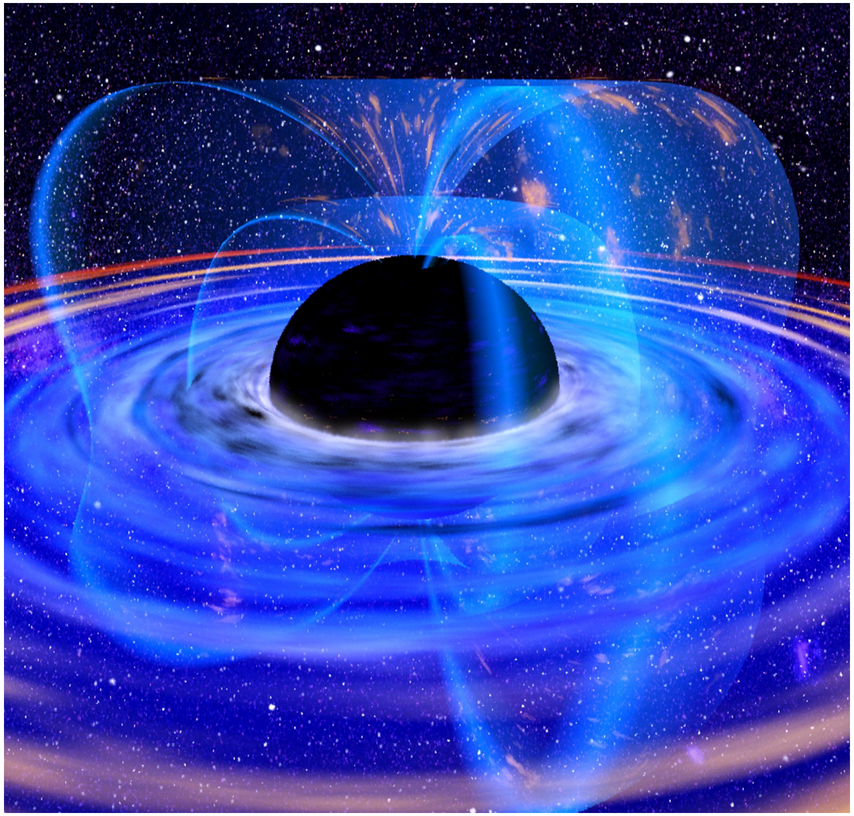
→ $\tau_{therm} \sim 50\ fm$

Instabilities?
Lectures by
L.McLerran, R.Venugopalan

What is the mechanism of fast equilibration?

Hawking radiation

S.Hawking '74



Black holes emit thermal radiation with temperature

$$T = \frac{\kappa}{2\pi}$$

acceleration of gravity at the surface

Similar things happen in non-inertial frames

Einstein's Equivalence Principle:

Gravity ⟷ Acceleration in a non-inertial frame

↓

An observer moving with an acceleration a detects a thermal radiation with temperature

$$T = \frac{a}{2\pi}$$

W.Unruh '76

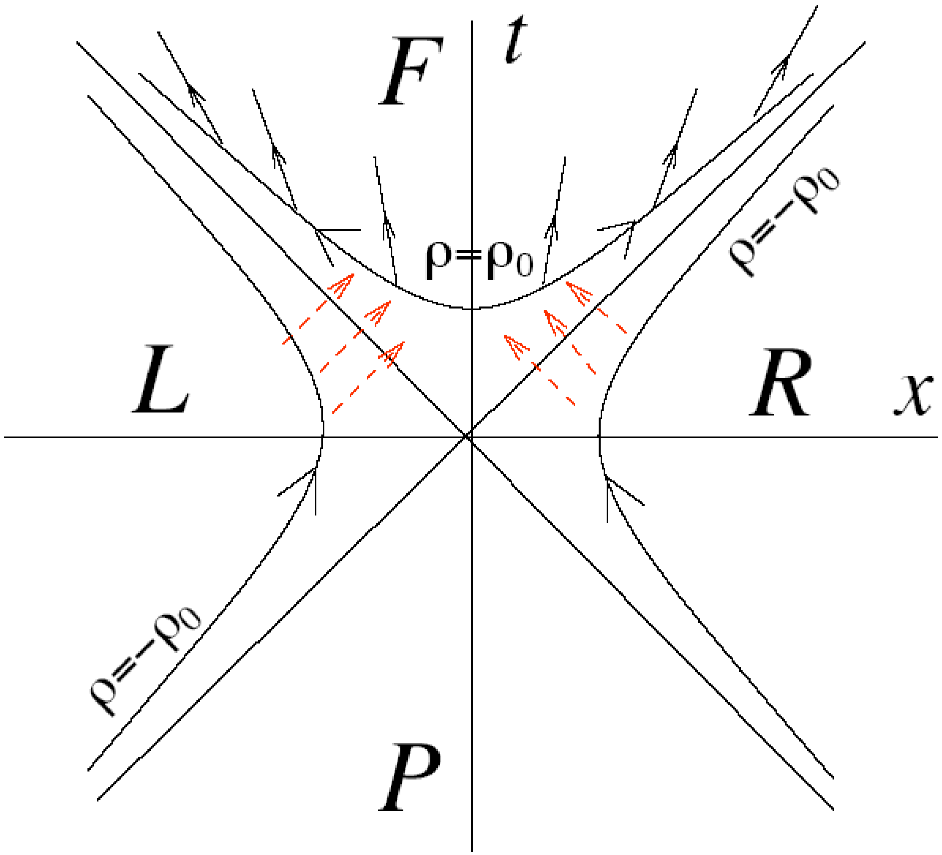
In both cases the radiation is due to the presence of event horizon

Black hole: the interior is hidden from an outside observer; Schwarzschild metric

Accelerated frame: part of space-time is hidden (causally disconnected) from an accelerating observer; Rindler metric

Quantum thermal radiation at RHIC

$$T = \frac{a}{2\pi} \simeq \frac{Q_s}{2\pi}$$



Rindler and Minkowski spaces

The event horizon emerges due to the fast decceleration $a \simeq Q_s$ of the colliding nuclei in strong color fields;

Tunneling through the event horizon leads to the thermal spectrum

DK, K.Tuchin;
DK, E.Levin, K.Tuchin

Rapid deceleration induces phase transitions

Nambu-
Jona-Lasinio model
(BCS - type)

Similar to phenomena in the vicinity of a large black hole:
Rindler space $\approx$ Schwarzschild metric

Topological effects in QGP?

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

$U_A(1)$ problem:

Invariant under chiral Left ⟷ Right transformations in the limit of massless quarks

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

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

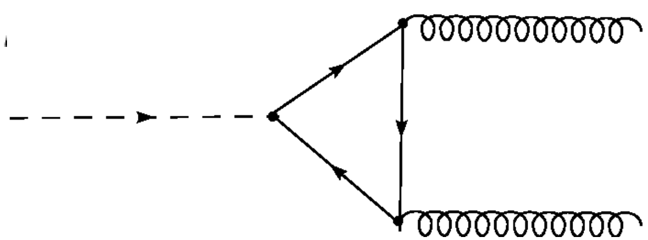
Only 8 exist; the ninth, η' is heavier than the proton!

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:

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



ABJ

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

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

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.

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

As a result, chiral charge is no longer conserved

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

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

QCD vacuum as a Bloch crystal

"θ - vacuum"

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

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

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

"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

$$\mathcal{L}_{QCD} \rightarrow \mathcal{L}_{QCD} + \mathcal{L}_\theta$$

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

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)

$$\bar{\theta} < 3 \times 10^{-10}$$

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 $N_f \times N_f$

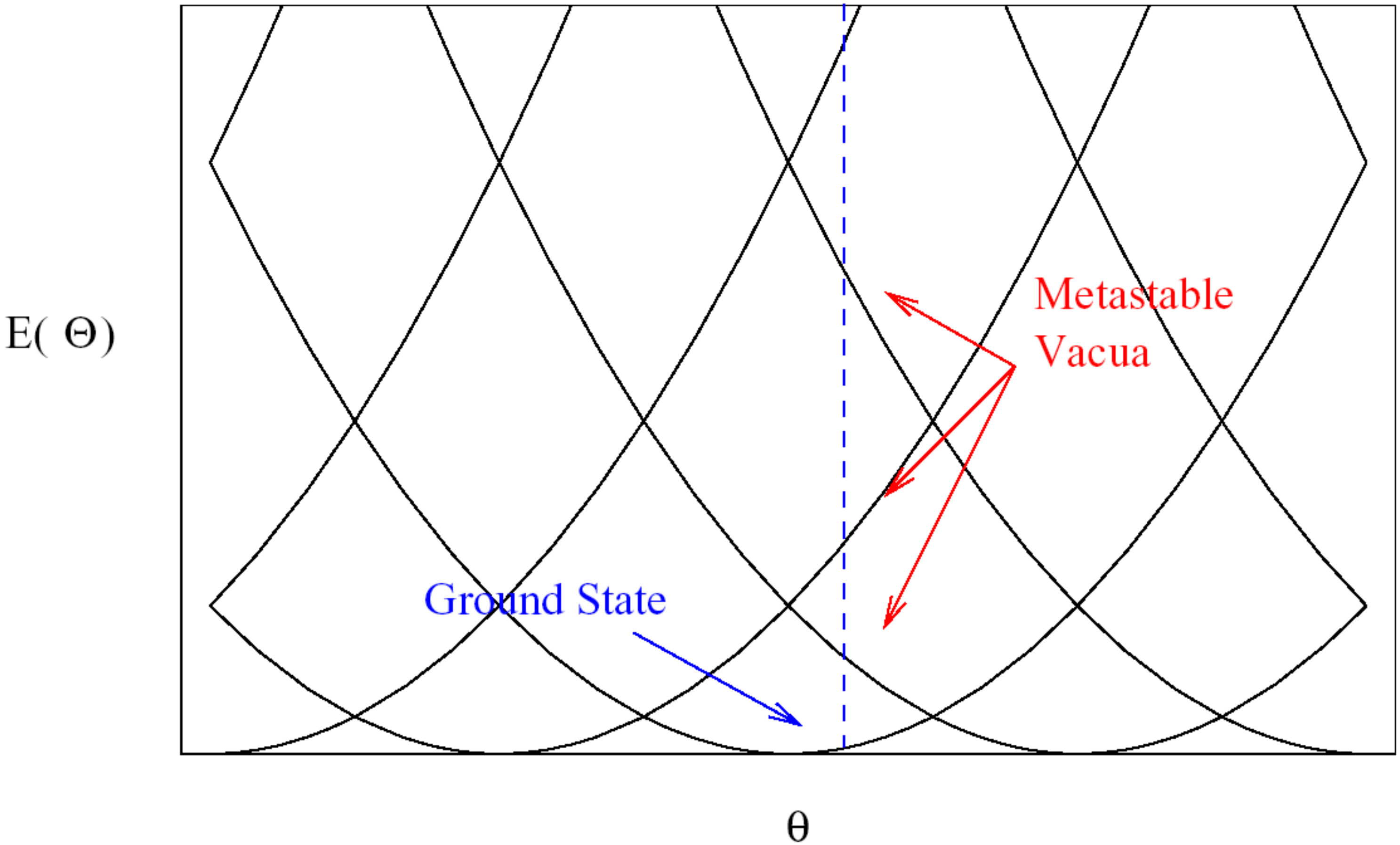
$$\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s) \qquad U = \exp i\phi^a\lambda^a/f_\pi$$

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

The effective potential:

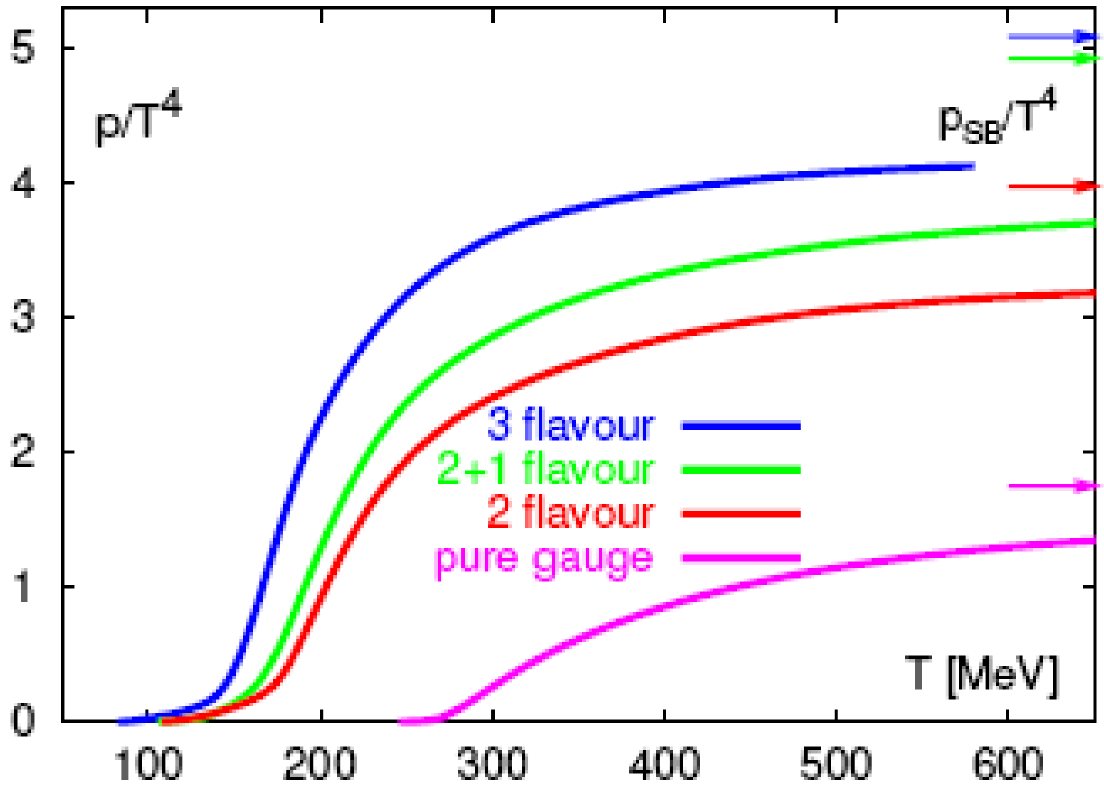
$$\mathcal{V} = -\sum_{i=u,d,s} m_i \Sigma \cos\frac{\phi_i}{f_\pi} + \frac{\chi}{2}(\theta - \sum_{i=u,d,s}\phi_i/f_\pi)^2$$

θ–vacua



Multi-valued potential => a family of vacuum states

What happens at high temperatures?

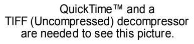


Phase transitions:

deconfinement

Chiral symmetry restoration

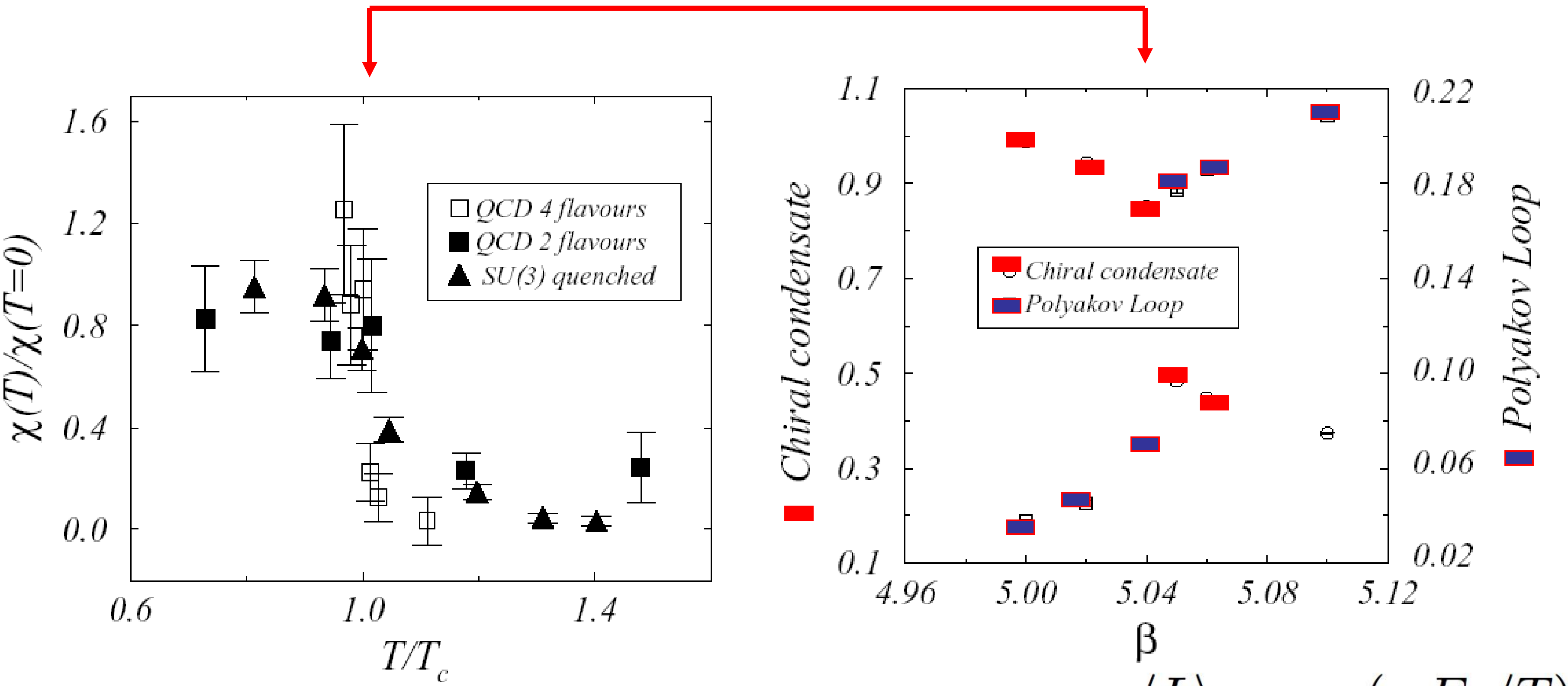
$U_A(1)$ restoration



Data from lattice QCD simulations F. Karsch et al

critical temperature ~ 10^{12} K; cf temperature inside the Sun ~ 10^7 K

Topological susceptibility at finite temperature

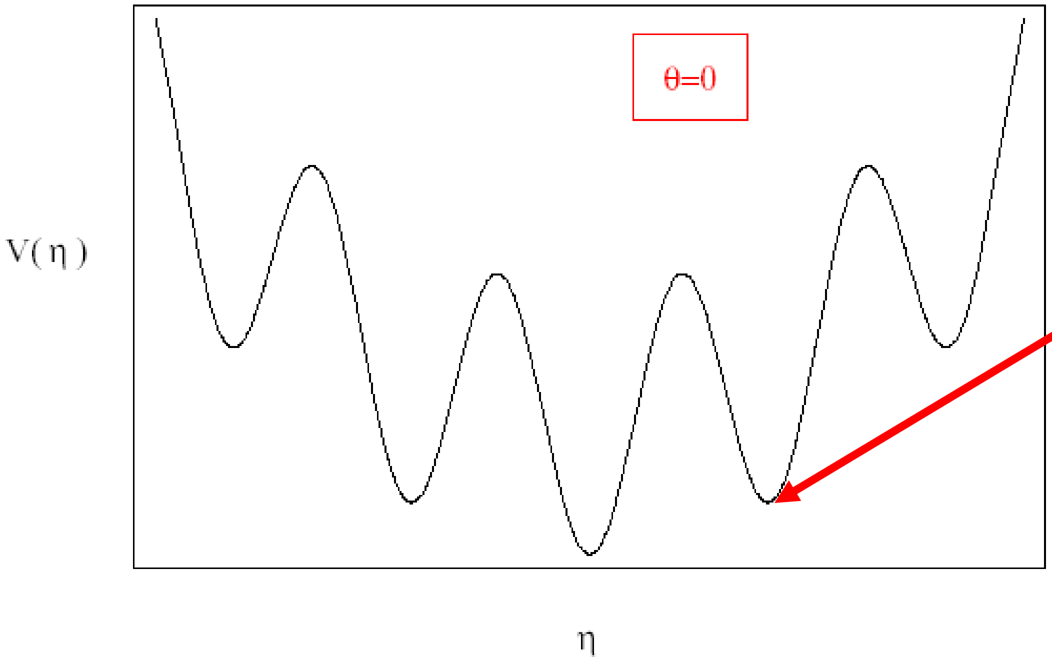


$$\langle L \rangle \sim exp(-E_q/T)$$

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



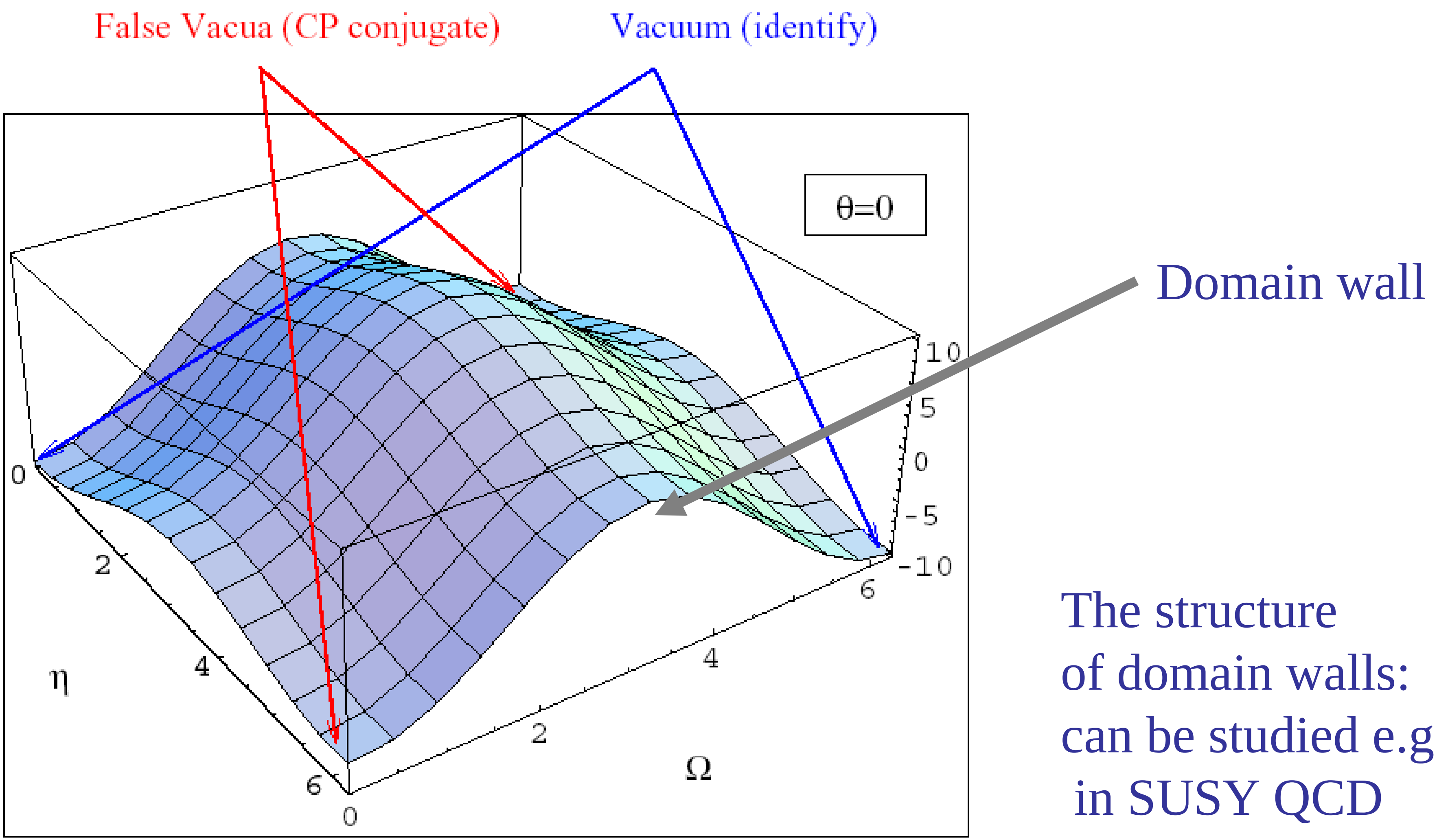
Decrease of χ results in the appearance of metastable CP-odd domains

DK, Pisarski, Tytgat '97

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

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

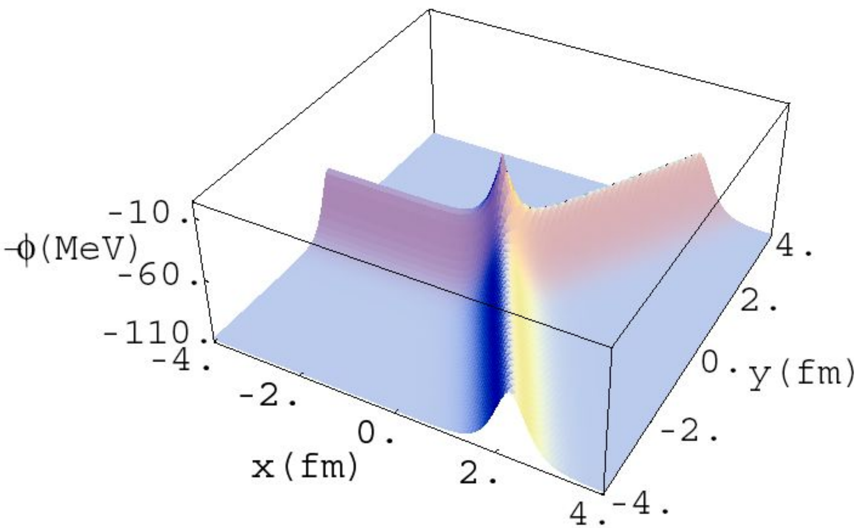
θ–vacuum in the presence of light quarks: chiral description

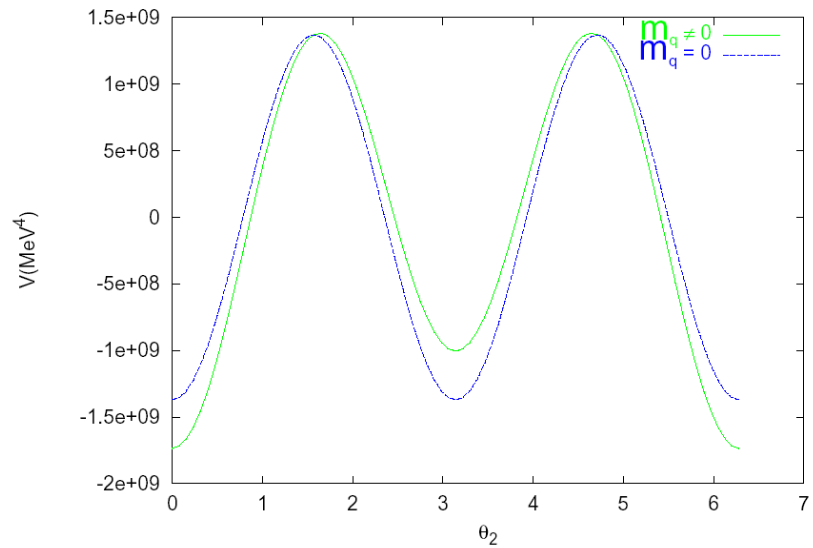


The structure of domain walls: can be studied e.g. in SUSY QCD

θ–vacuum in the presence of light quarks: linear σ model

"topological strings"; similar to Abrikosov vortices, "cosmic strings",..



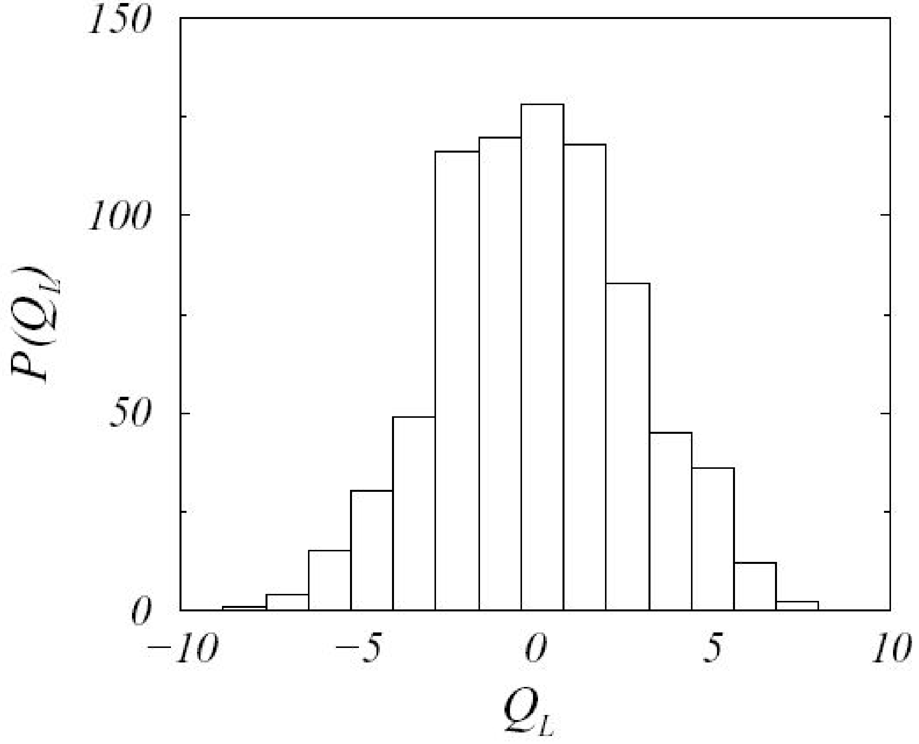


$$\mathcal{L}(\Phi) = \mathrm{Tr}\left(\partial_\mu \Phi^\dagger \partial^\mu \Phi - m^2\, \Phi^\dagger \Phi\right) - \lambda_1 \left[\mathrm{Tr}\left(\Phi^\dagger \Phi\right)\right]^2 - \lambda_2 \mathrm{Tr}\left(\Phi^\dagger \Phi\right)^2$$
$$+ c\left[\mathrm{Det}\,(\Phi) + \mathrm{Det}\left(\Phi^\dagger\right)\right] + \mathrm{Tr}\left[H(\Phi + \Phi^\dagger)\right] .$$

$$\Phi = T_a\, \phi_a = T_a\,(\sigma_a + i\pi_a)$$

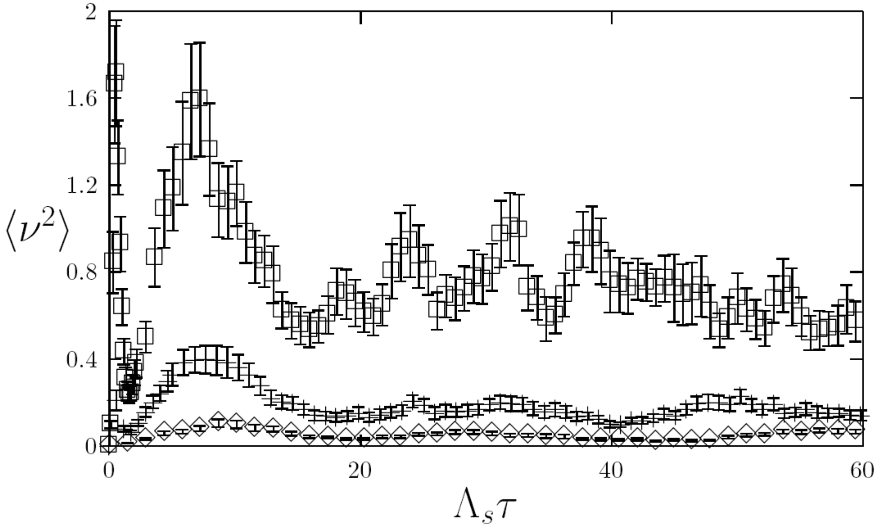
A.Balachandran and S.Digal, Phys.Rev.D66:034018,2002

Fluctuations of Chern-Simons number in hot QCD: numerical lattice simulations

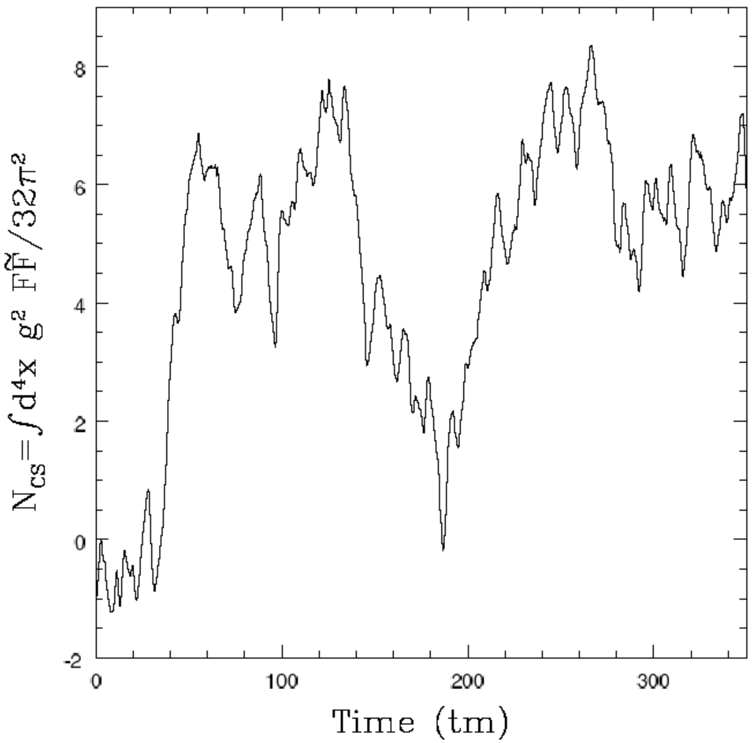


B.Alles, M.D'Elia and A.DiGiacomo,
hep-lat/0004020

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



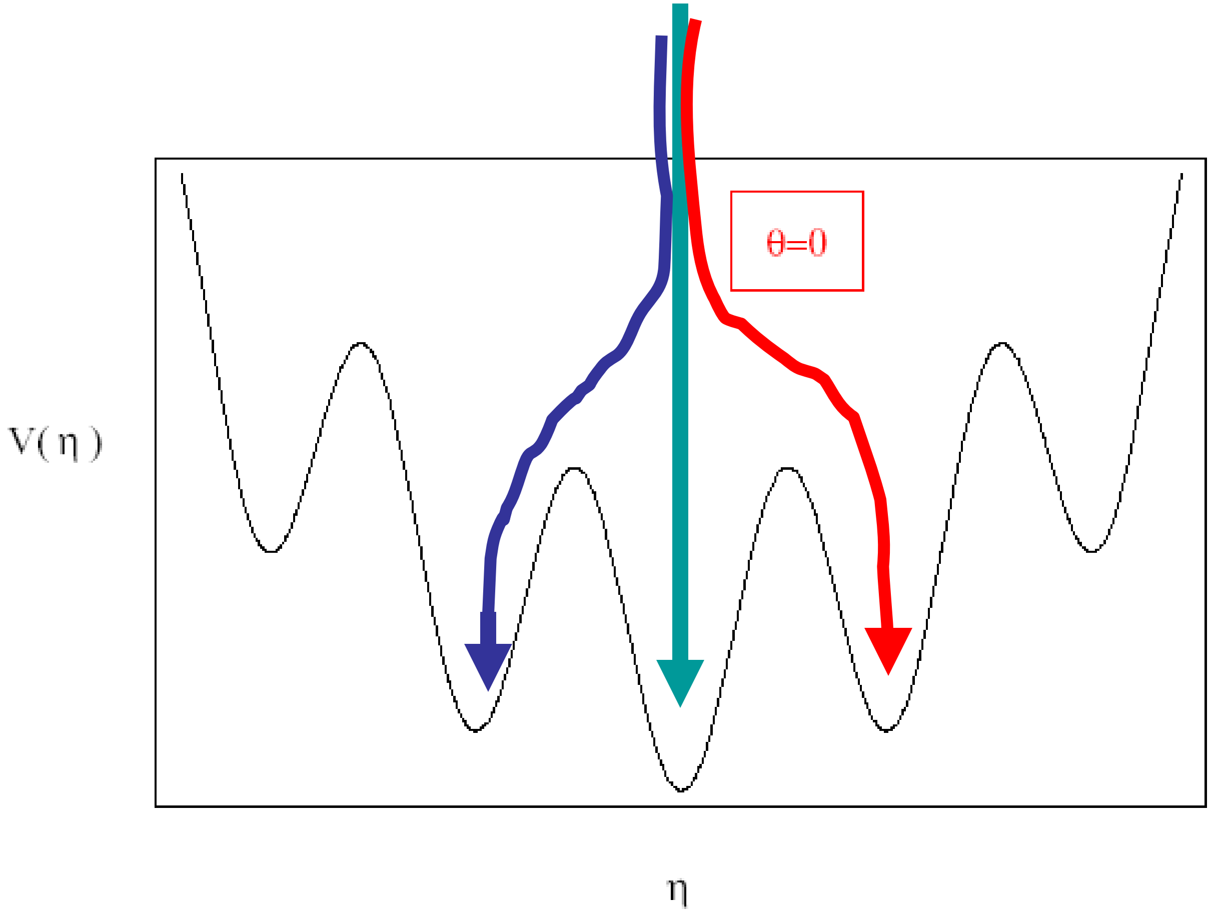
DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002



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

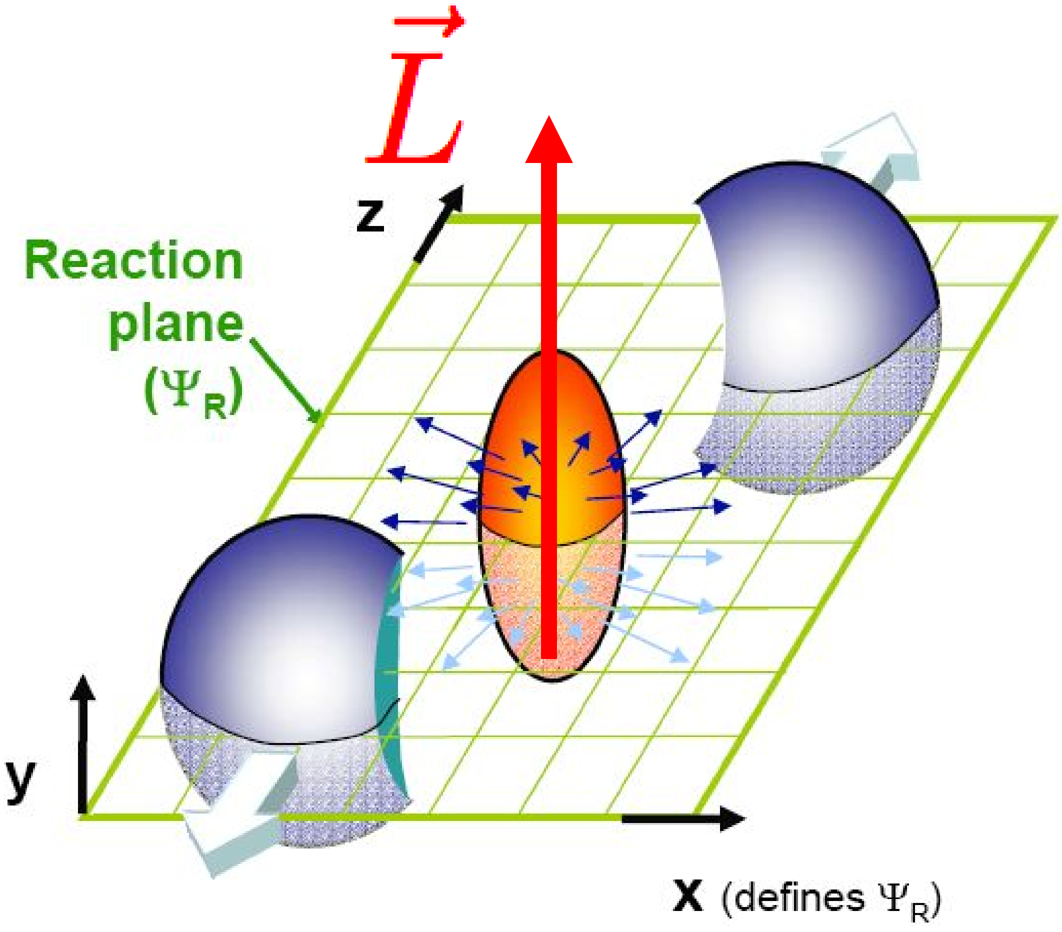
In a CP-odd domain, $\hat{m}(\mathbf{x}, t) = m \exp(i\theta(\mathbf{x}, t))$

This leads to the asymmetry between "left" and "right" quarks

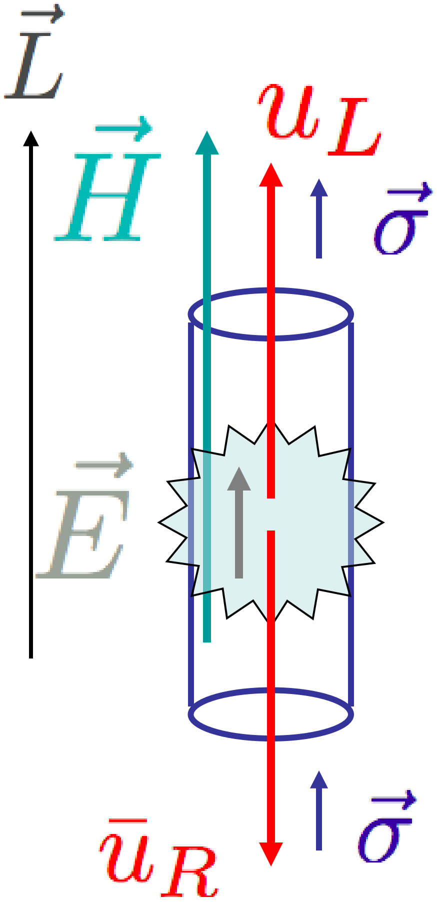
$$\mathcal{L}_\theta = -m\cos\theta \left(\bar{u}_L u_R + \bar{u}_R u_L\right) - im \sin\theta \left(\bar{u}_L u_R - \bar{u}_R u_L\right)$$

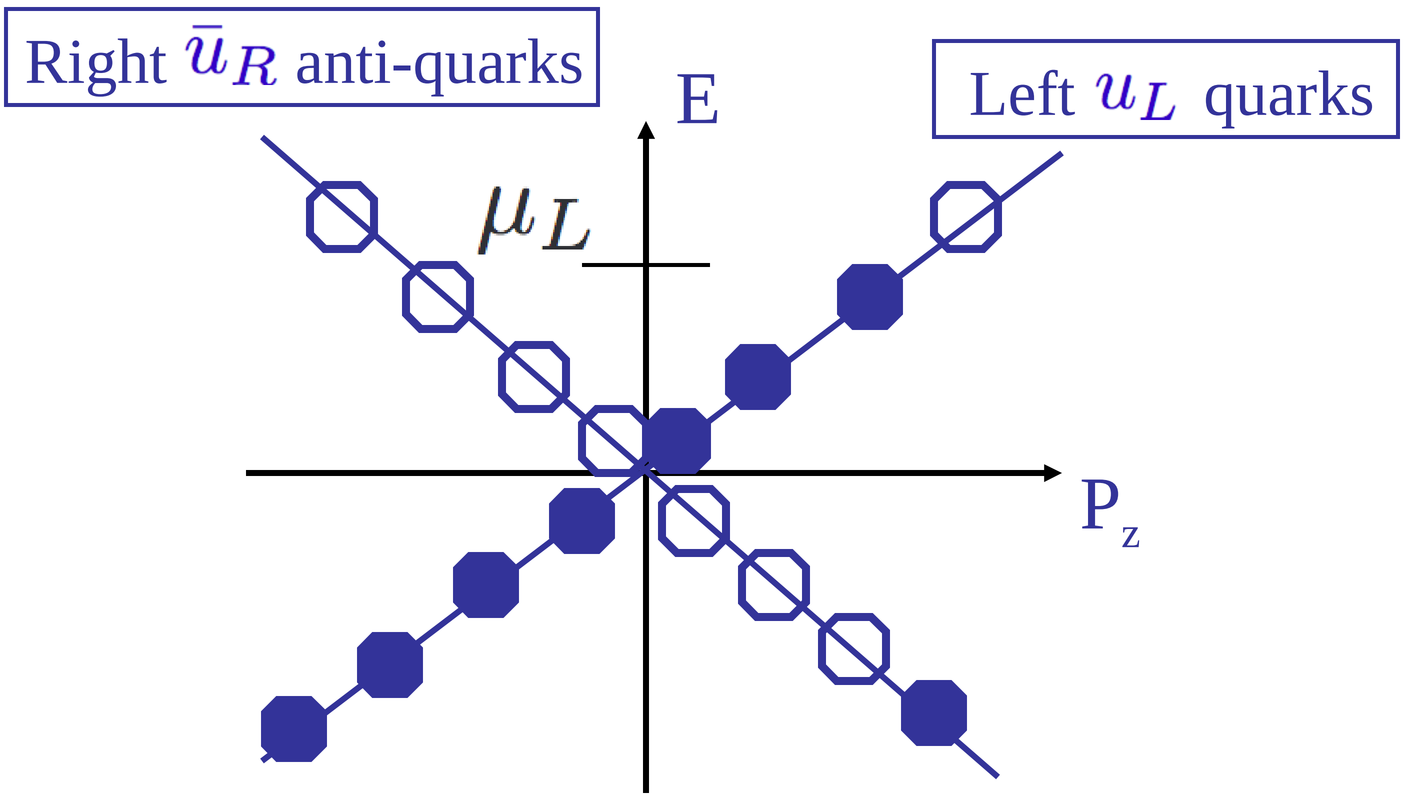
What is "left" and what is "right"? Quarks are massive,
so the definition of chirality depends on the frame…

Azimuthal anisotropy = angular momentum



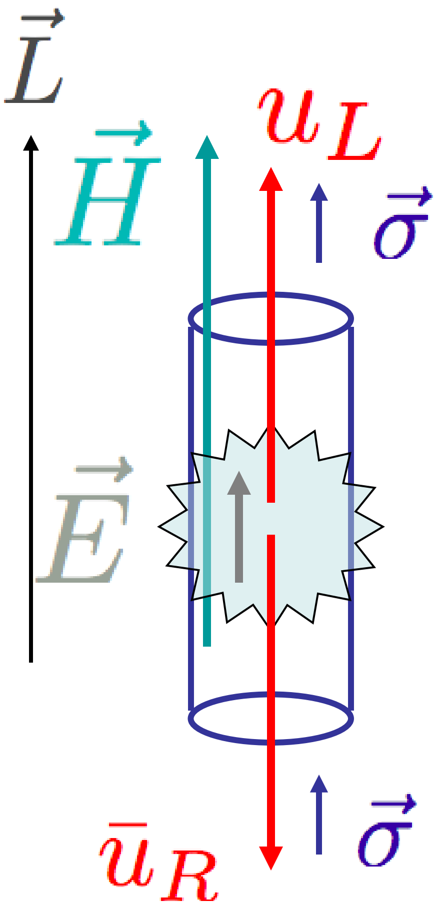
Magnetic vortices and CP violation





Fluctuation of chromo-electric field in the presence of chromo-magnetic vortex produces left quarks and right anti-quarks (level crossing at the 0th Landau level)

Magnetic vortices and CP violation



Analogous to cosmic strings, except not 1D

Left quarks: in the electric field, energy increases:

$$\Delta E_L = p_F^L = qEt$$

Decreases by the same amount for right anti-quarks.

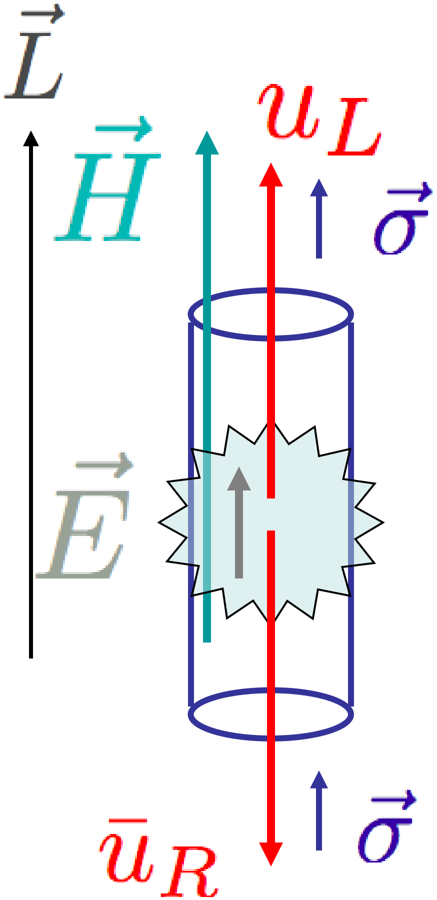
Density of states = longitudinal x transverse:

$$\frac{p_F}{2\pi} \cdot \frac{qH}{2\pi} = \frac{q^2}{4\pi^2} \; E \cdot H \; t$$

Rate of chirality generation:

$$\frac{d^4 N_L}{dt \;\, dz \;\, d^2 s} = \frac{q^2}{4\pi^2} \; E \cdot H$$

Magnetic vortices and CP violation



Analogs:

Dyons

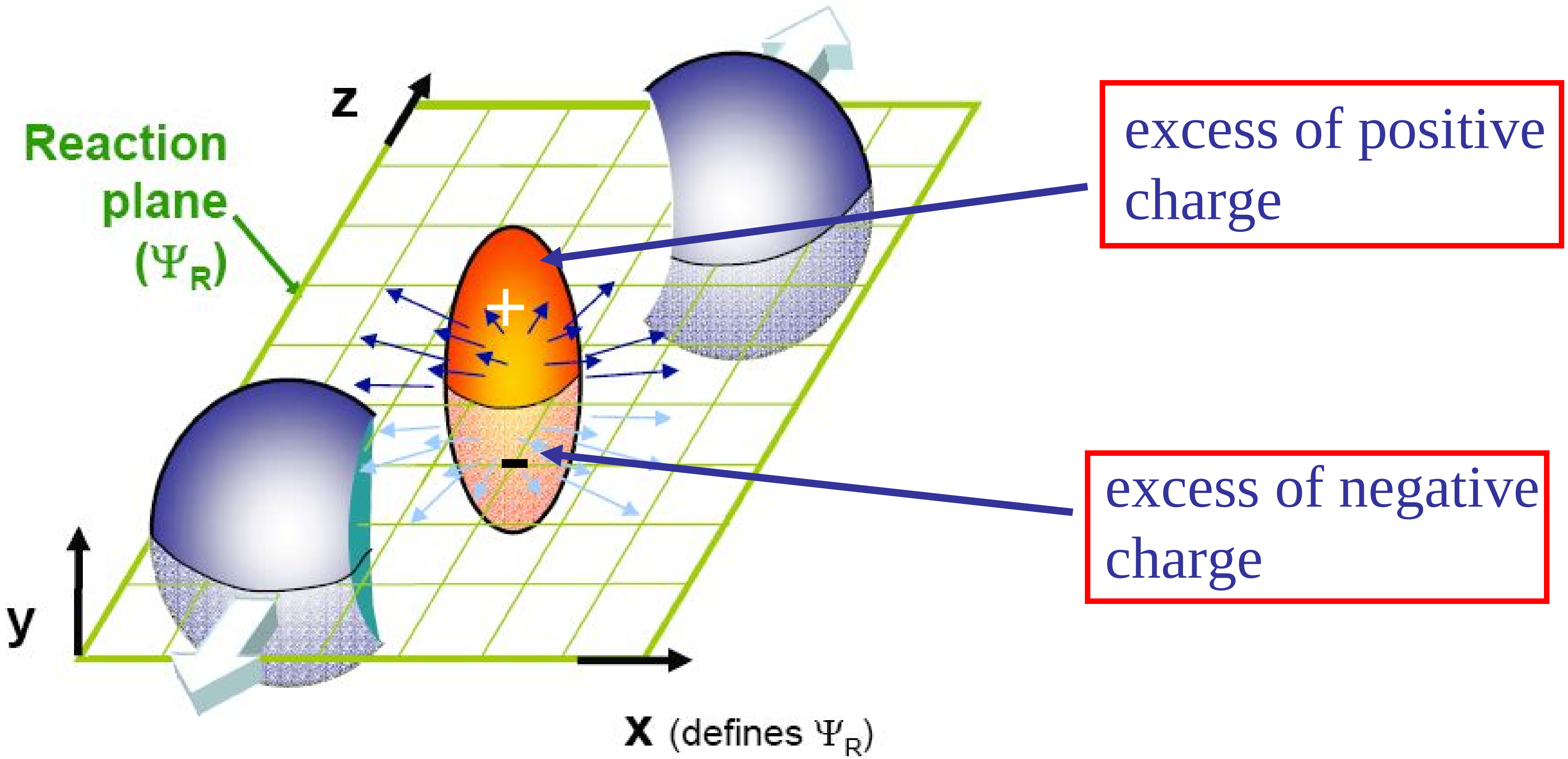
Magnetic monopole - induced baryon decay

Cosmic strings

Chirality generation in superfluid ^{3}He

....

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

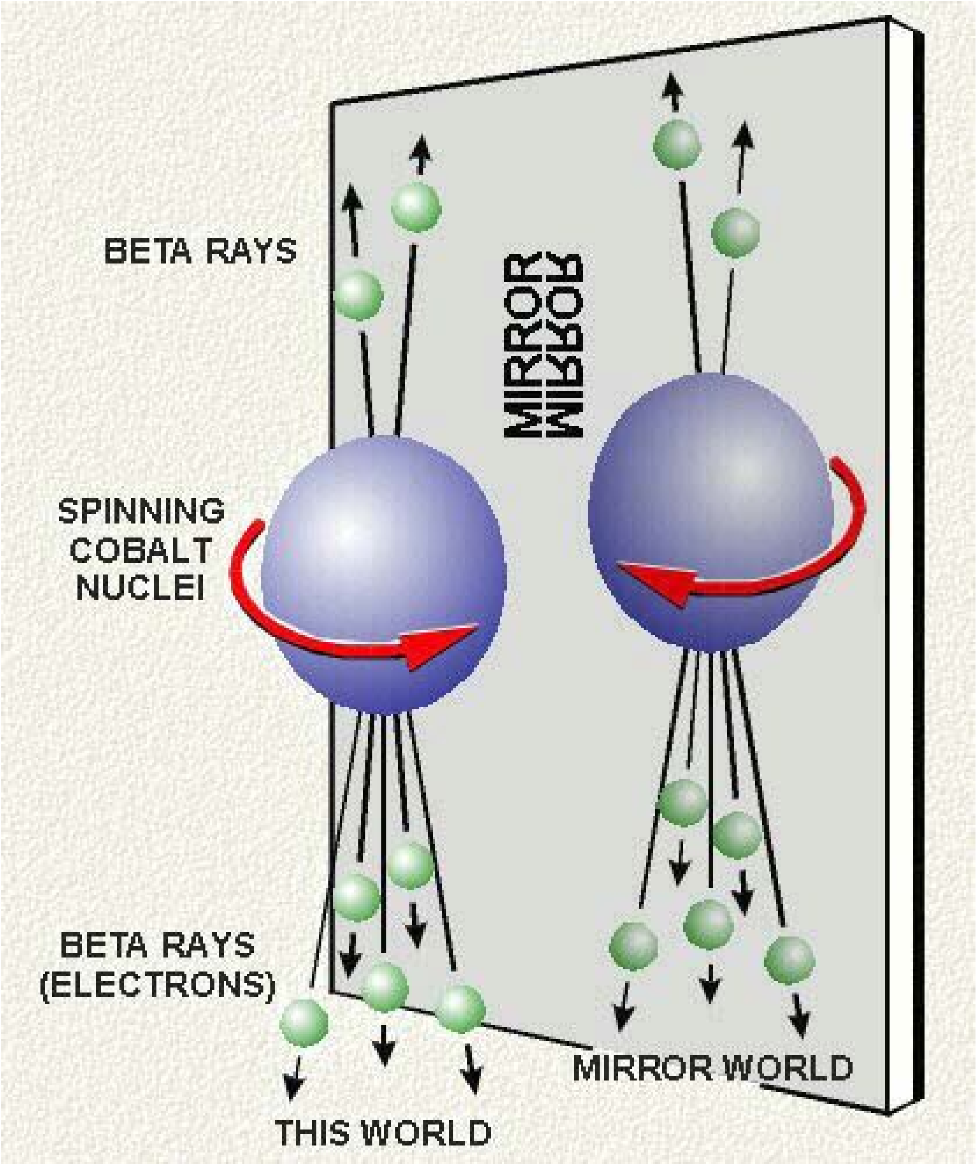


Electric dipole moment of QCD matter!

DK, hep-ph/0406125

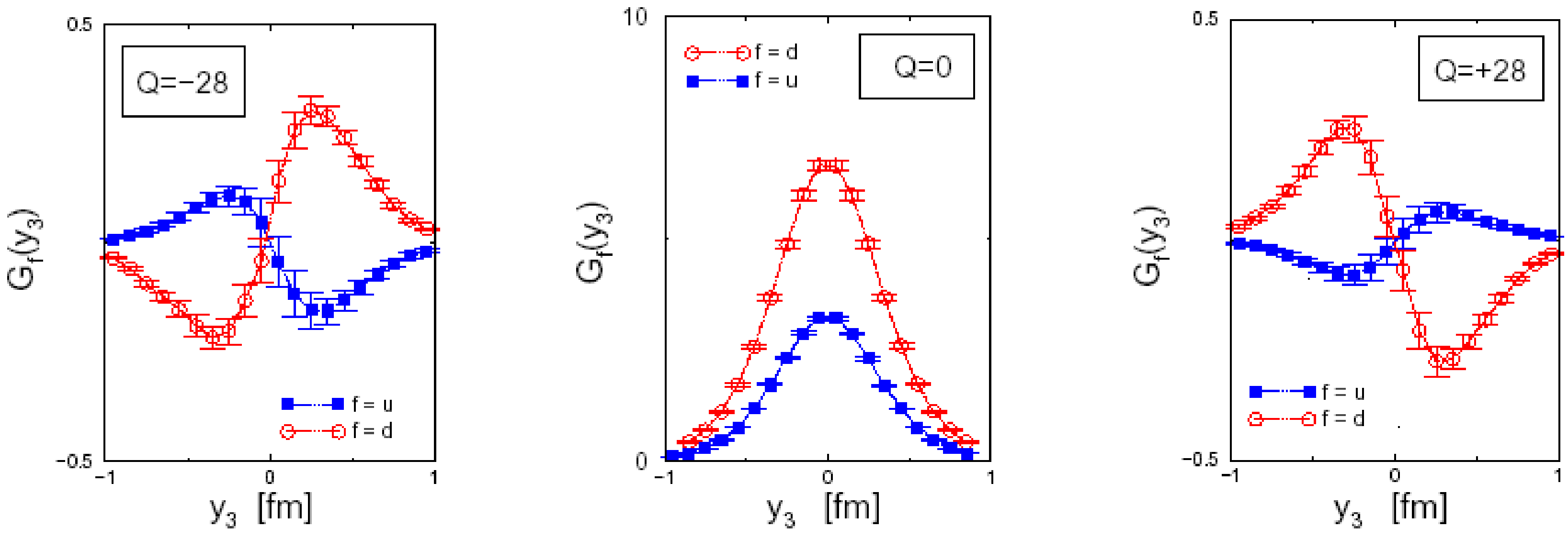
Charge asymmetry w. r.t. reaction plane violates T, P, and (by CPT theorem) CP:

Analogy to P violation in weak interactions



Charge asymmetry w.r.t. the direction of spin and the electric dipole moment of the neutron

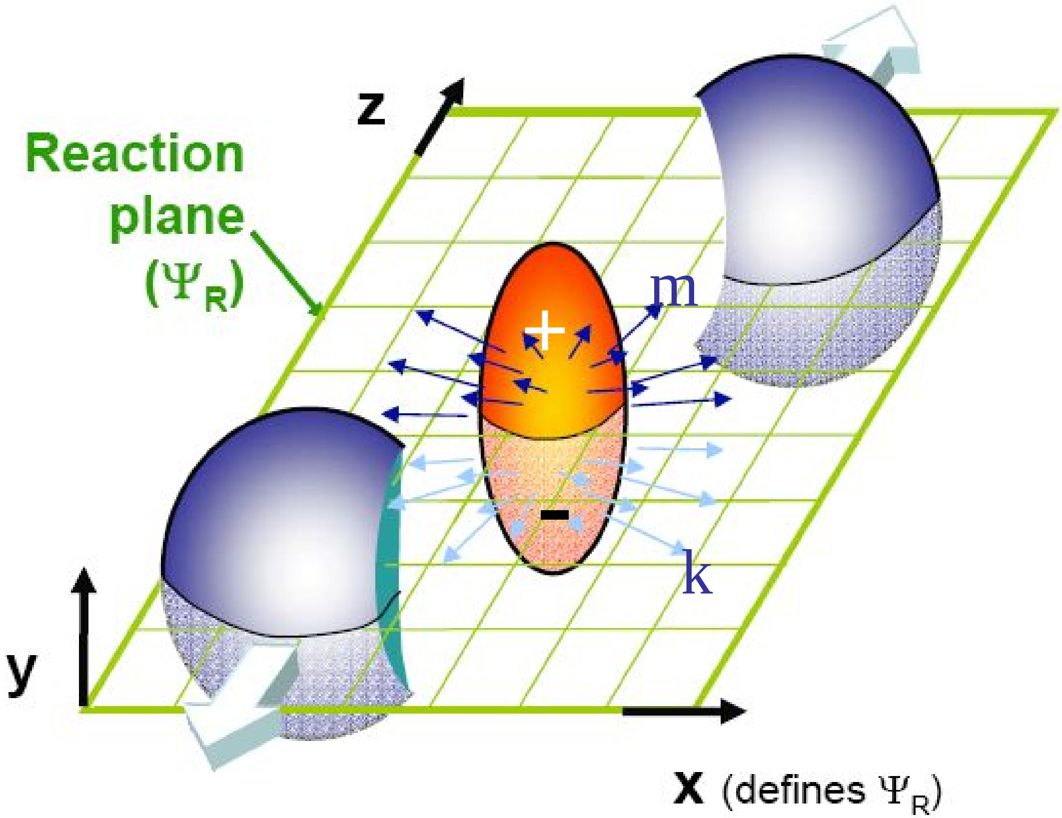
Analogy: e.d.m. of the neutron at finite θ



Lattice QCD simulation

P.Faccioli, Phys.Rev.D71:091502,2005

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 ?

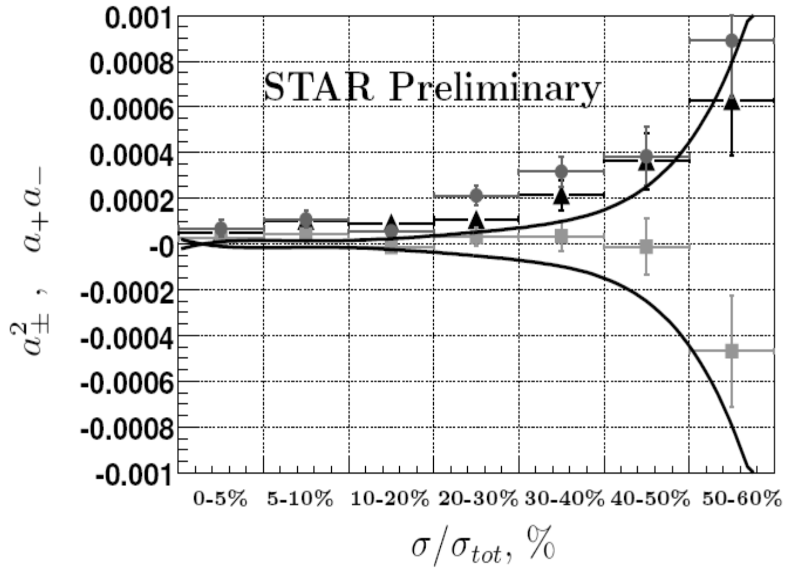
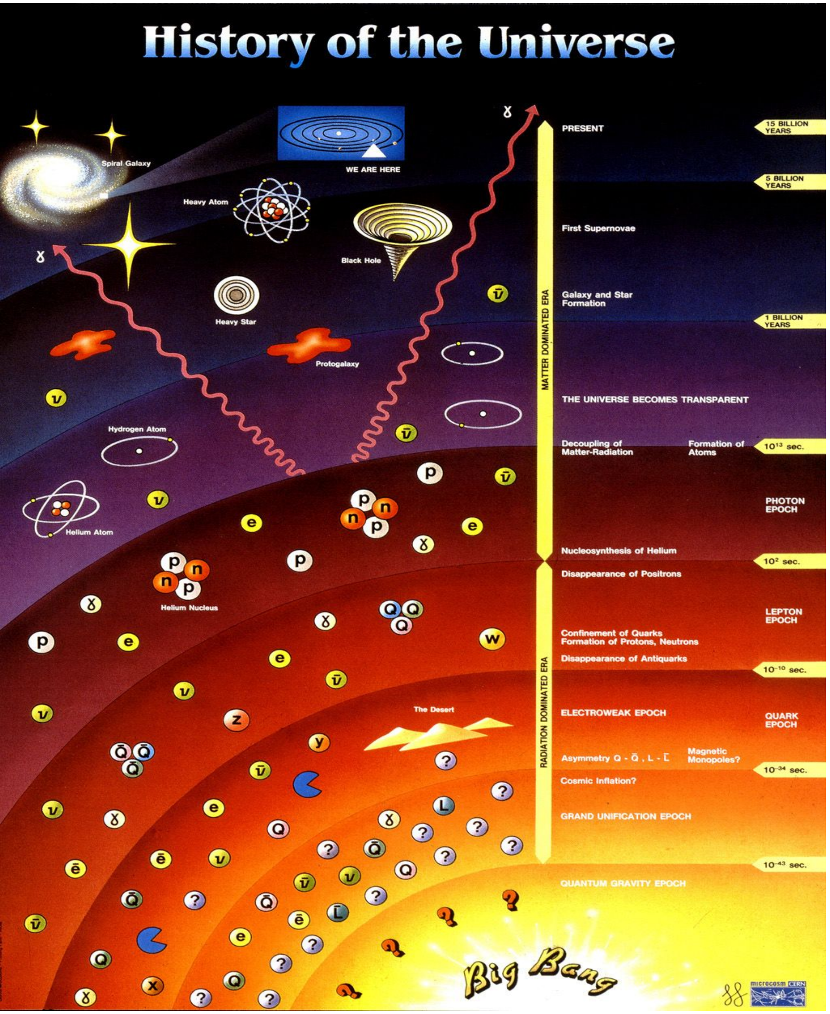


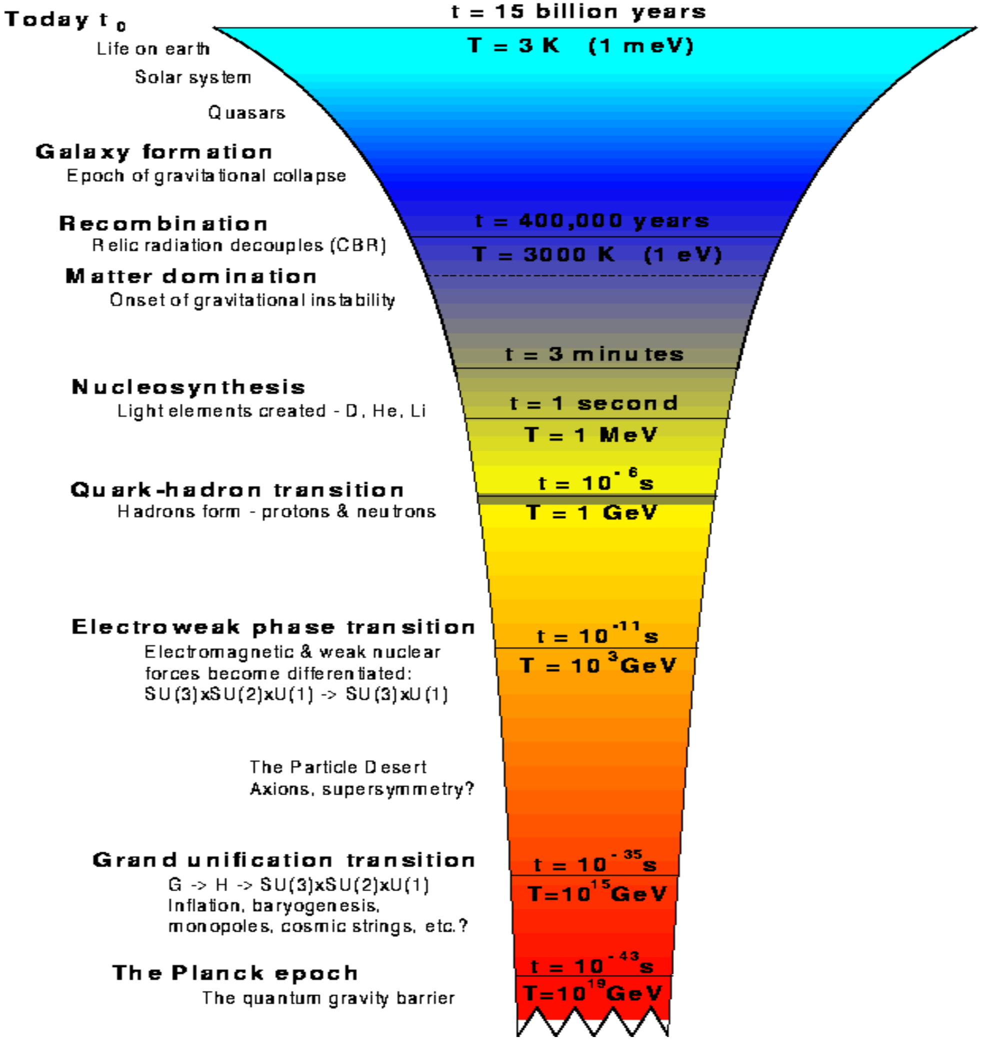
Figure 2: Charged particle asymmetry parameters as a a function of standard STAR centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares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