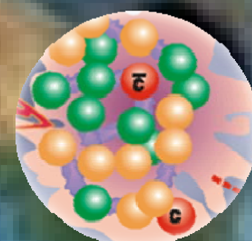
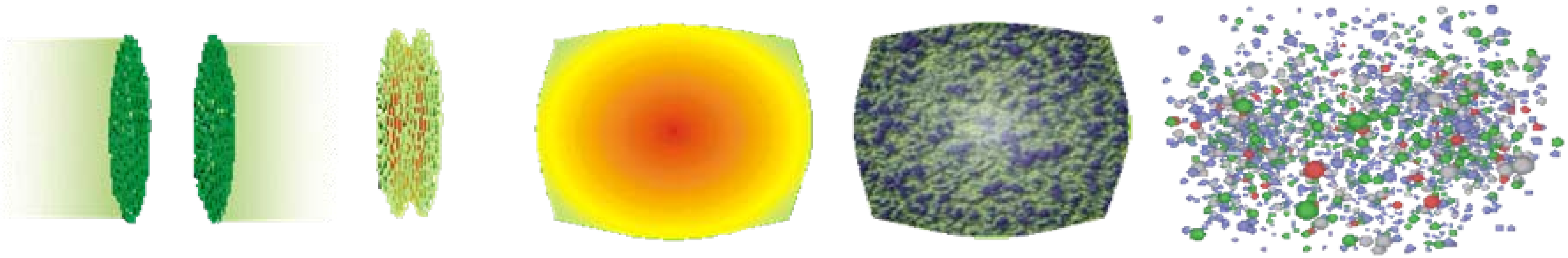
Quark-Gluon Plasma and Relativistic Heavy Ion Collisions



G.Zinovjev

Bogolyubov Institute for Theoretical Physics, Kiev, UKRAINE

June 23-25, Bautzen, GERMANY



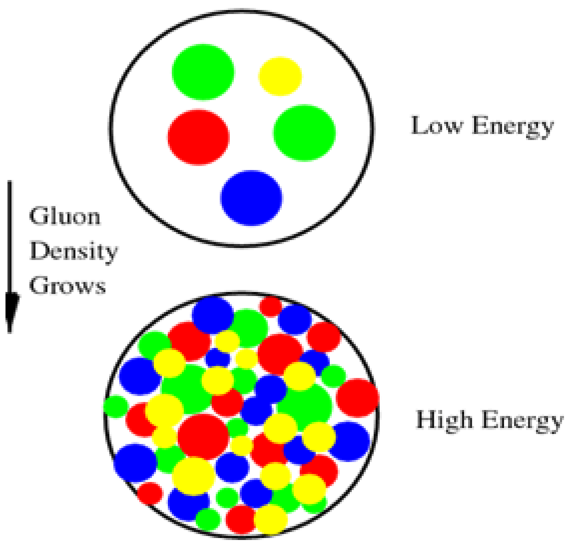
CGC

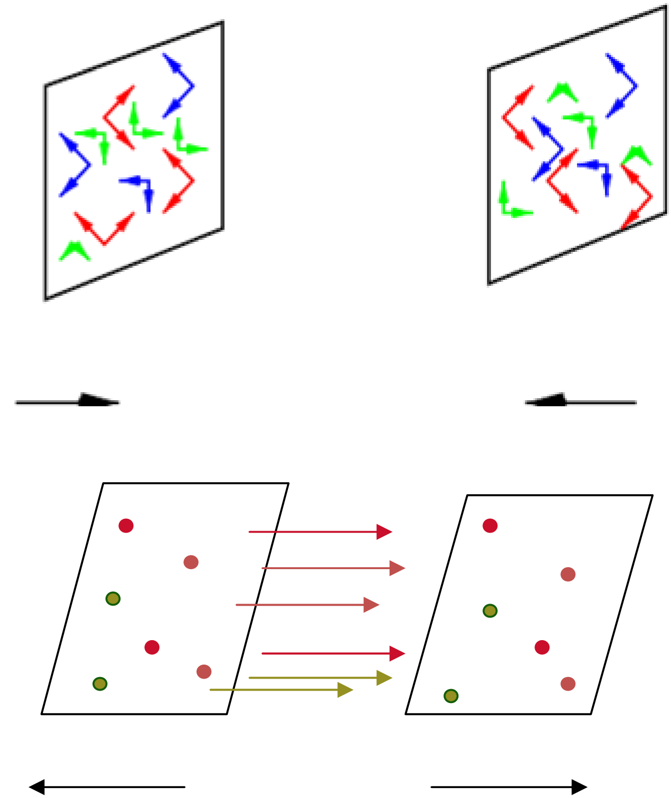
Initial Singularity

Glasma

sQGP

Hadron Gas

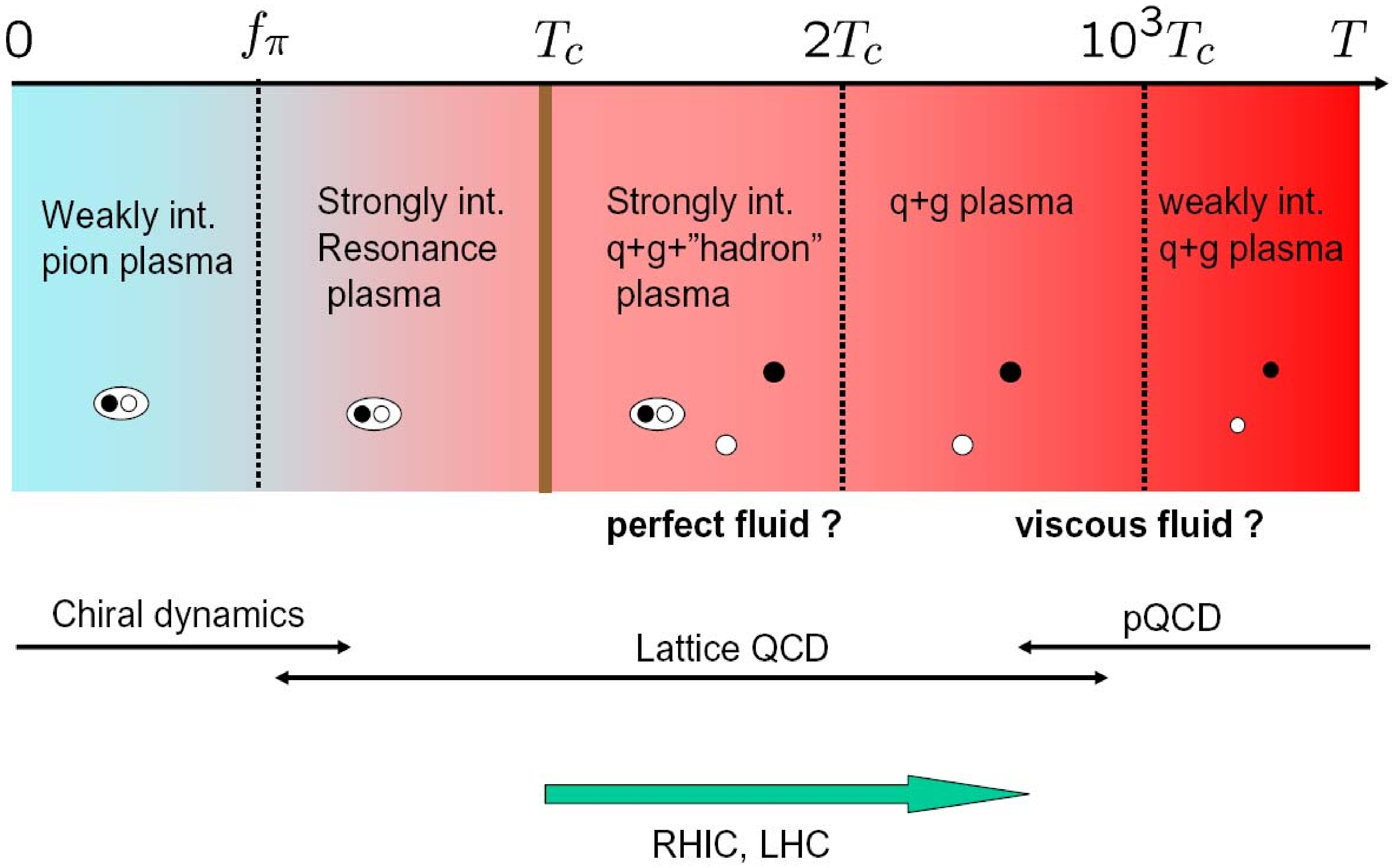




High Energy Density Gluonic Matter

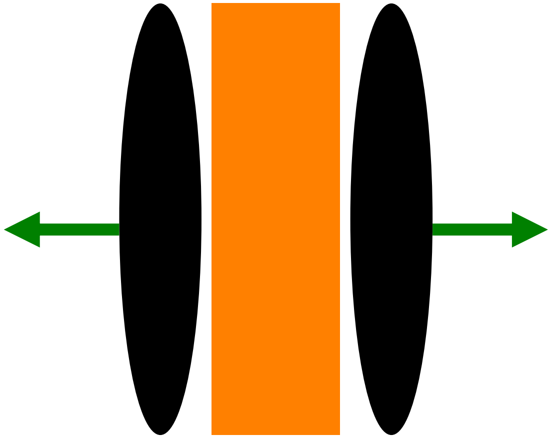
Thermalization?

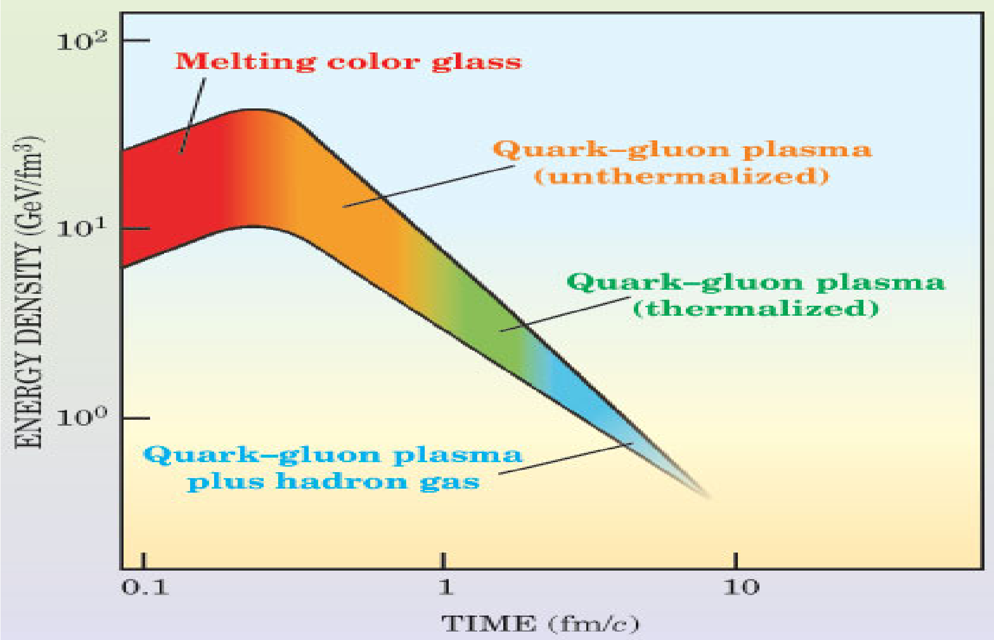
Possible structure of QCD plasma



What is the Glasma ?

Ludlam, McLerran, Physics Today (2003)



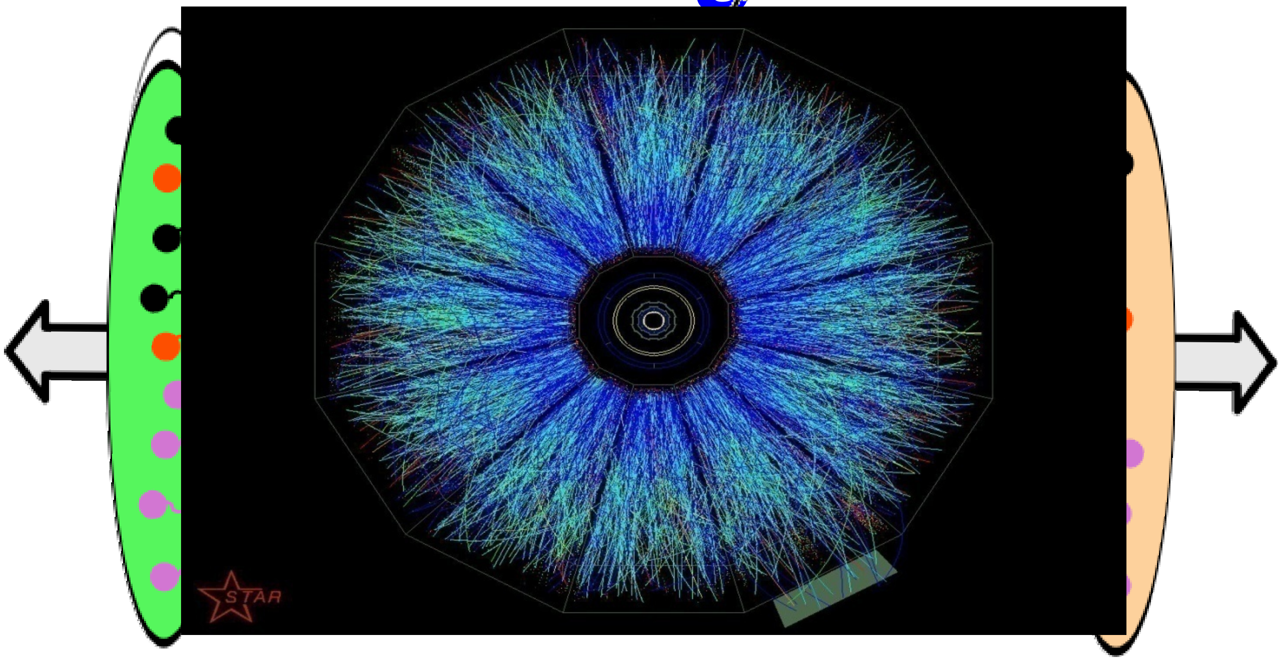


Glasma :

Noun: **non-equilibrium matter between Color Glass Condensate (CGC) & Quark Gluon Plasma (QGP)**

$$\varepsilon \approx 20 - 40\,\mathrm{GeV}/\mathrm{fm}^3 \text{ at } \tau \sim 0.3 \text{ fm}$$

How is Glasma formed in a Little Bang ?



❖ **Problem: Compute particle production in field theories with *strong time dependent* sources**

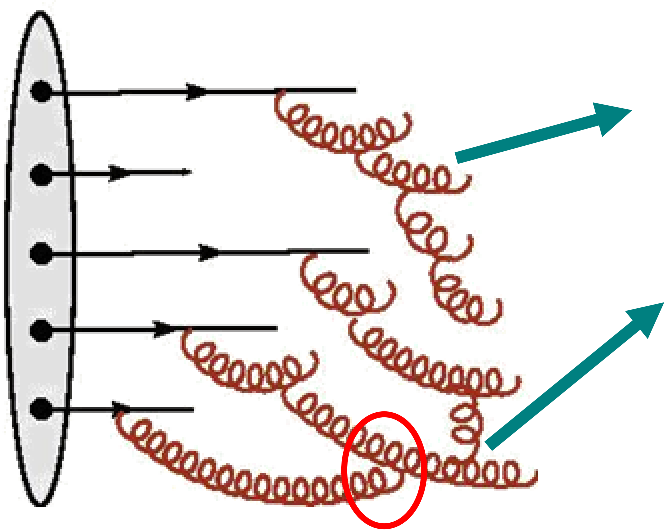
perturbative vs non-perturbative

Even if the QCD coupling constant is small the explosive growth in the number of partons with increasing energy makes the physics non-perturbative

strong coupling vs weak coupling

Before the Little Bang

- Nuclear wave function at high energies



Bremsstrahlung $\propto \alpha_S \ln\left(\frac{1}{x}\right)$ $\equiv \alpha_S Y$

+

Recombination $\propto \alpha_S \rho$

= Saturation: $E^2 \sim B^2 \sim \frac{1}{\alpha_S}$

- **Renormalization Group (JIMWLK/BK) equations sum leading logs** $(\alpha_S Y)^n$ **and high parton densities** $(\alpha_S \rho)^n$

- **Successful CGC phenomenology of HERA e+p; NMC e+A; RHIC d+A & A+A**

Review: RV, arXiv:0707.1867, DIS 2007

There are two major questions in this field

from point of view of experimentalists (and practising physicists)

- how to relate the thermodynamical properties. (temperature, energy density, entropy ...) of QGP or hot nuclear matter to properties that can be measured in the laboratory
- how the QGP can be detected

There are two major challenges in this field

- to find signatures that are unique to QGP so that this new state of matter can be distinguished from the "ordinary physics" of relativistic nuclear collisions

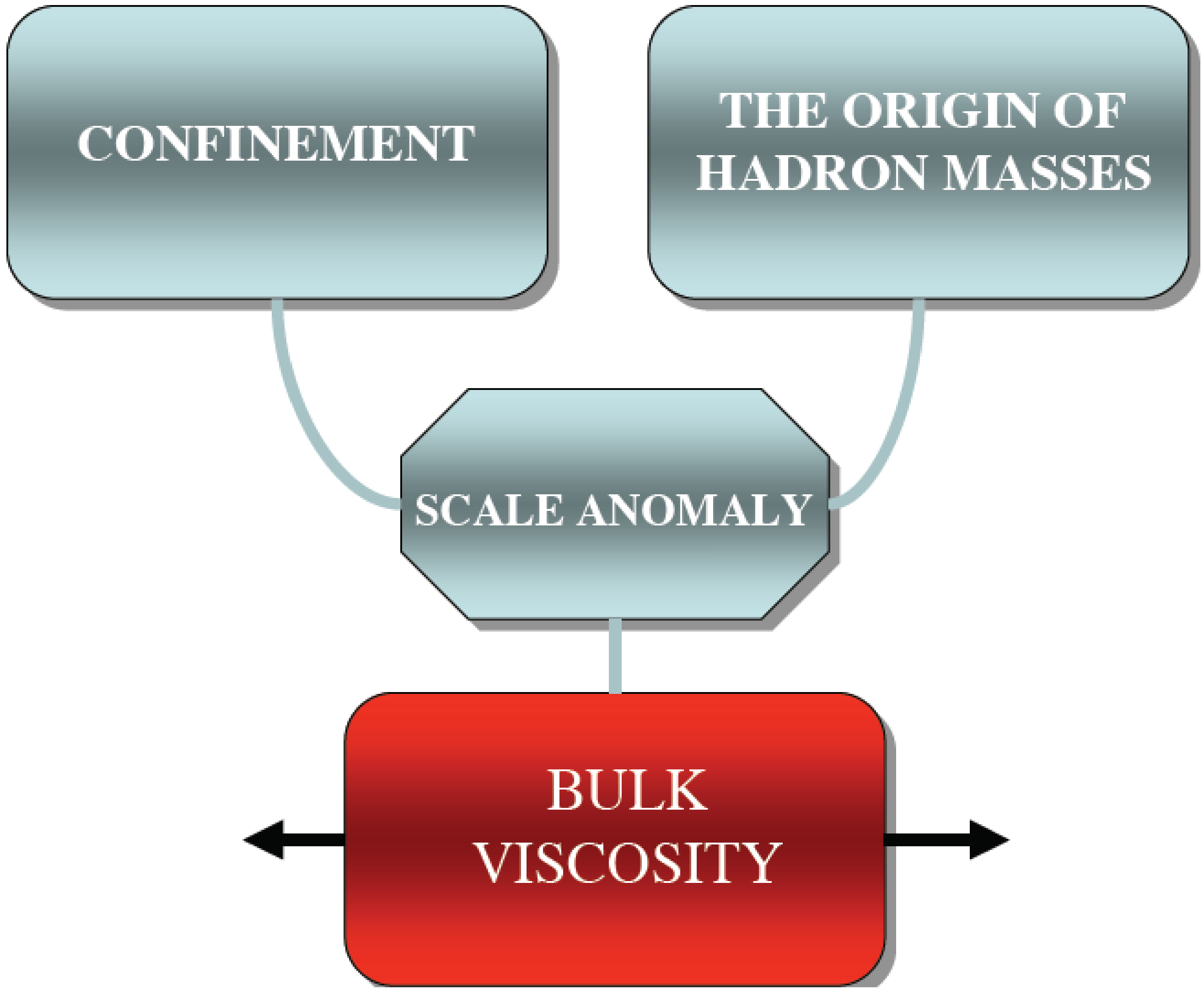
- to find effects which are specific to A+A collisions such as collective or coherent phenomena in distinction to cases for which A+A collisions can be considered as merely an incoherent superposition of nucleon-nucleon collisions

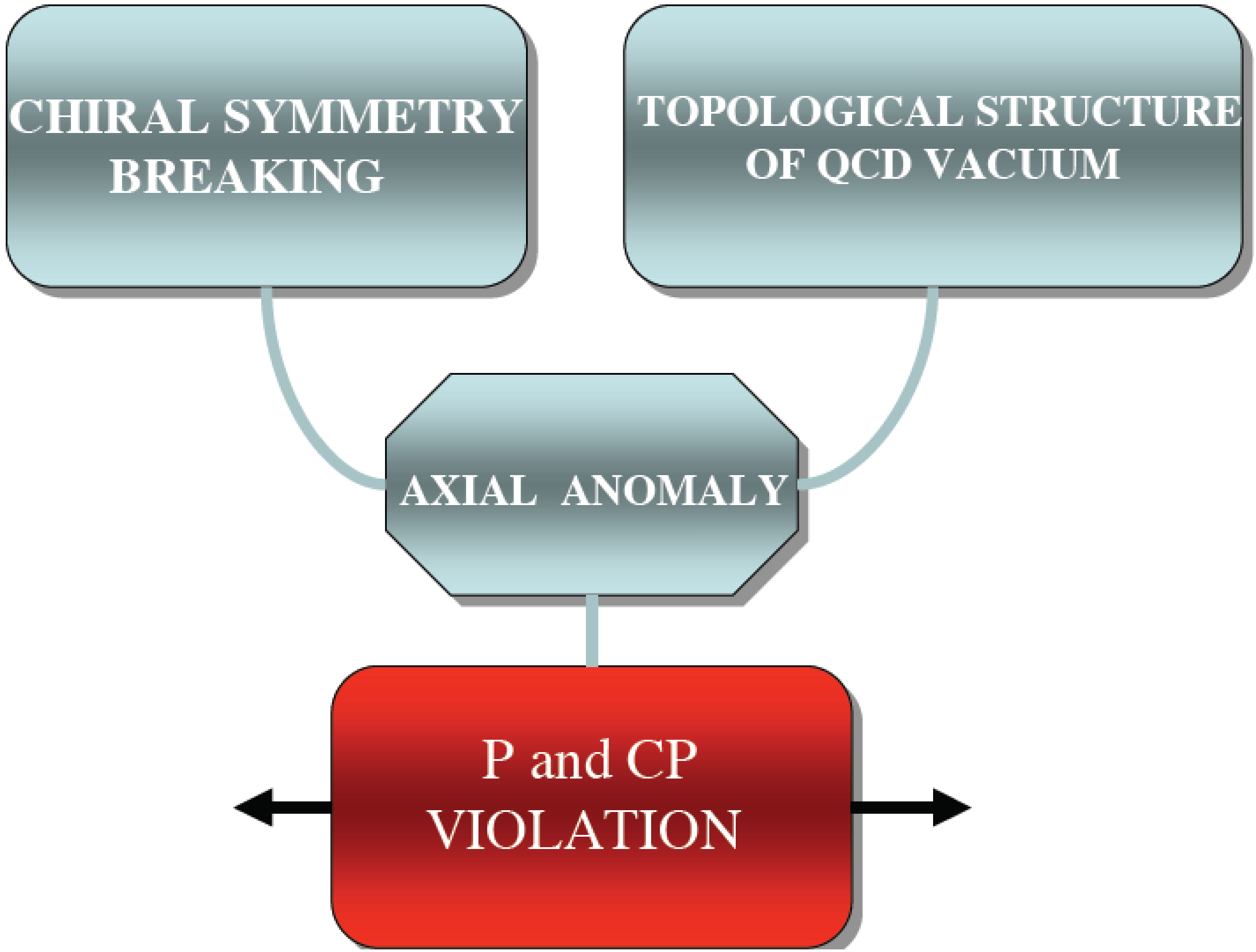
At the same time

Even a fully successful and quantitative model of heavy ion collisions will be of limited value to the broad scientific community if it does not bring us closer to answering the fundamental physics questions, such as:

What is the mechanism of confinement?
What is the origin of chiral symmetry breaking?
What is the origin of mass?

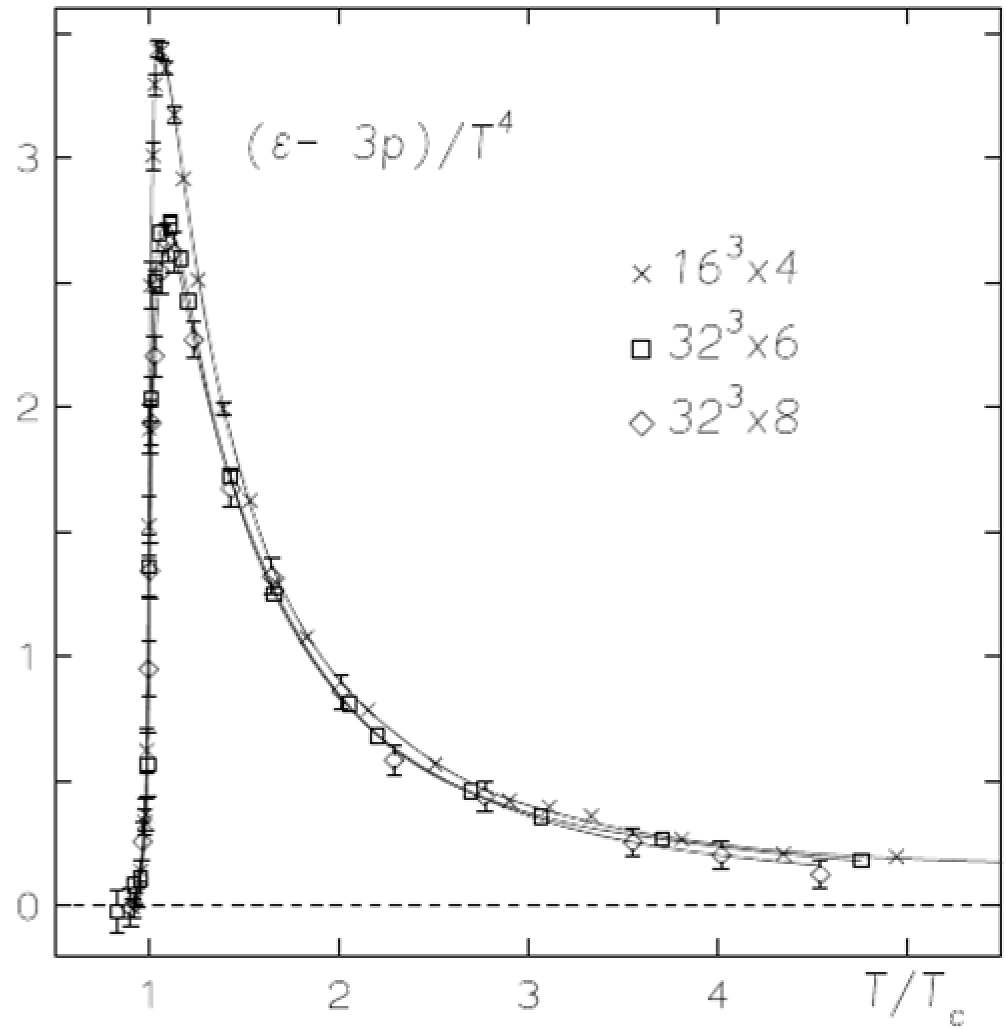
ambitious


CONFINEMENT
THE ORIGIN OF HADRON MASSES
SCALE ANOMALY
BULK VISCOSITY


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

Scale anomaly at finite T

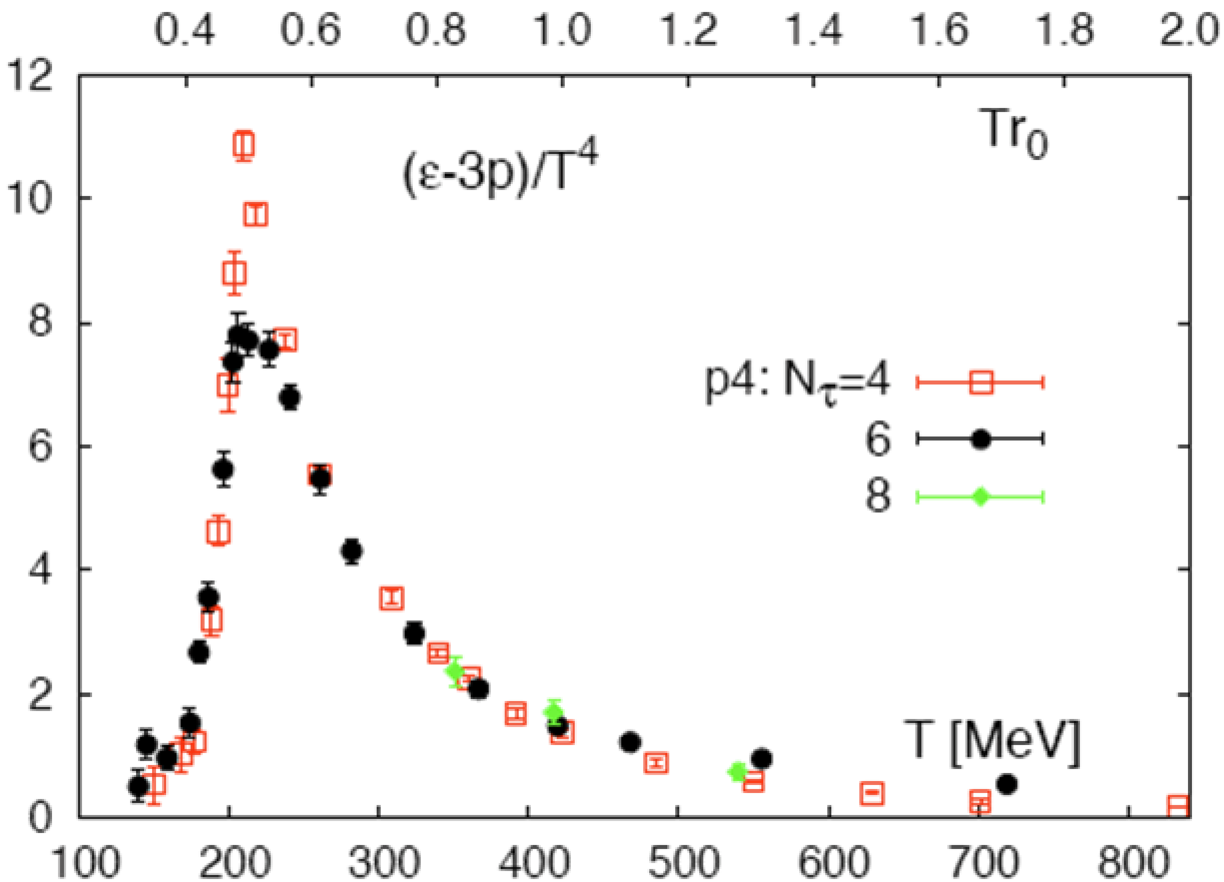
SU(3), pure gauge



Interactions are important; deviation from conformal behavior

Lattice data from G.Boyd, J.Engels, F.Karsch, E.Laermann, C.Legeland, M.Lutgeimer, B.Petersson,

Full QCD

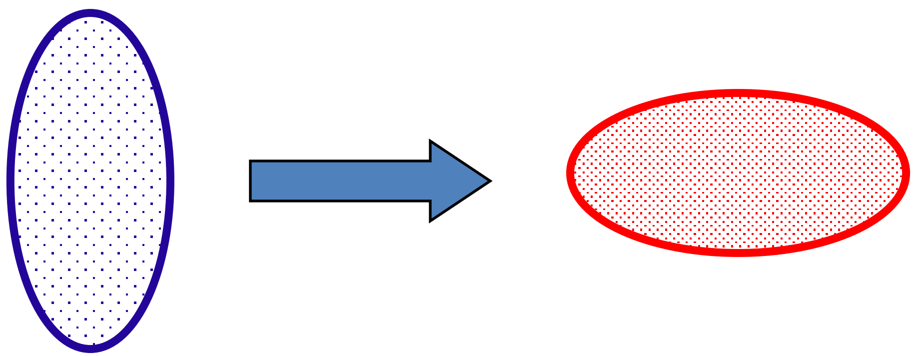


RBC-B Coll., M.Cheng et al., arXiv:0710.0354

What does this mean for transport properties?

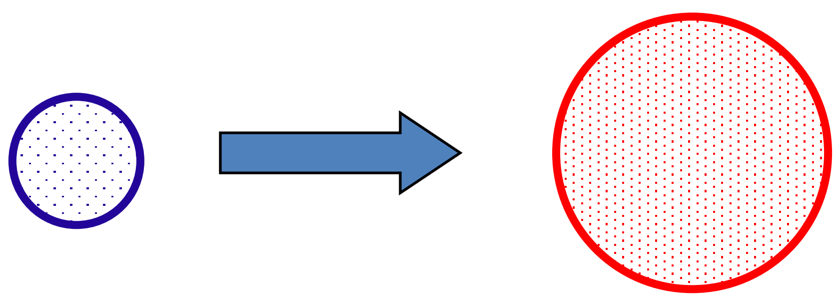
Physical picture:

Shear viscosity: how much entropy is produced by transformation of shape at constant volume



Generated by translations

Bulk viscosity: how much entropy is produced by transformation of volume at constant shape



Generated by dilatations

Shear and bulk viscosities: the definitions

The energy-momentum tensor:

$$\theta_{ij} = P_{eq}(\epsilon)\delta_{ij} - \eta \left(\partial_i u_j + \partial_j u_i - \frac{2}{3}\delta_{ij}\partial_k u_k\right) - \zeta\, \delta_{ij}\vec{\nabla}\cdot\vec{u}$$

↑ shear viscosity

↑ bulk viscosity

Kubo's formula:

$$\eta(\omega)\left(\delta_{il}\delta_{km}+\delta_{im}\delta_{kl}-\frac{2}{3}\delta_{ik}\delta_{lm}\right)+\zeta(\omega)\delta_{ik}\delta_{lm}$$
$$=\frac{1}{\omega}\lim_{\mathbf{k}\to\mathbf{0}}\int d^3x\int_0^\infty dt\, e^{i(\omega t-\mathbf{kr})}\langle[\theta_{ik}(t,\mathbf{r}),\theta_{lm}(0)]\rangle$$

Bulk viscosity is defined as the static limit of the correlation function:

$$\zeta=\frac{1}{9}\lim_{\omega\to 0}\frac{1}{\omega}\int_0^\infty dt\int d^3r\, e^{i\omega t}\langle[\theta_{ii}(x),\theta_{kk}(0)]\rangle$$

Bulk viscosity is determined by the correlation function of the trace of the energy-momentum tensor

In perturbation theory shear viscosity is “large”:

$$\frac{\eta}{s} \sim \frac{1}{\alpha_s^2}$$

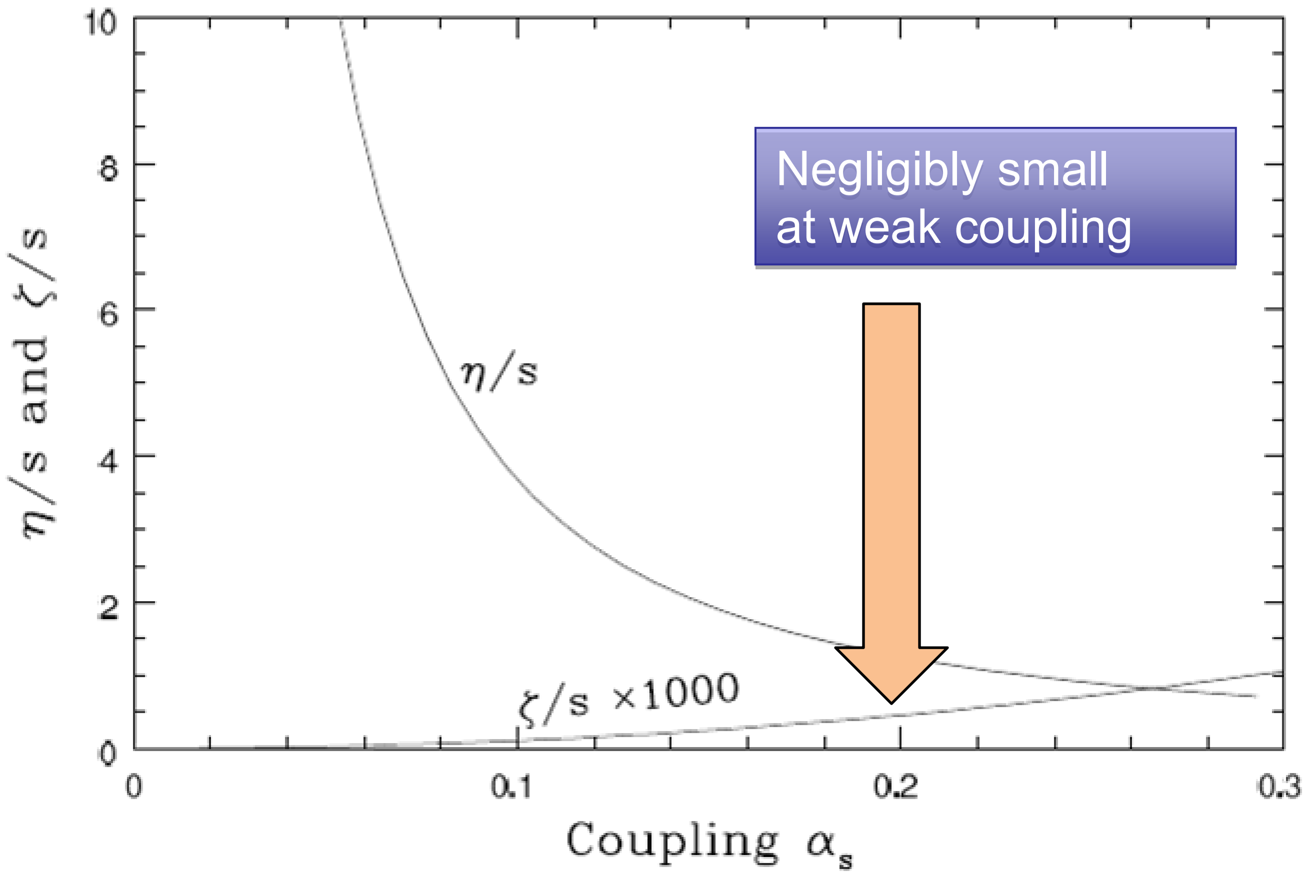
and bulk viscosity is “small”:

$$\frac{\zeta}{s} \sim \alpha_s^2$$

At strong coupling η is apparently small;

can ζ get large?

What about bulk viscosity?

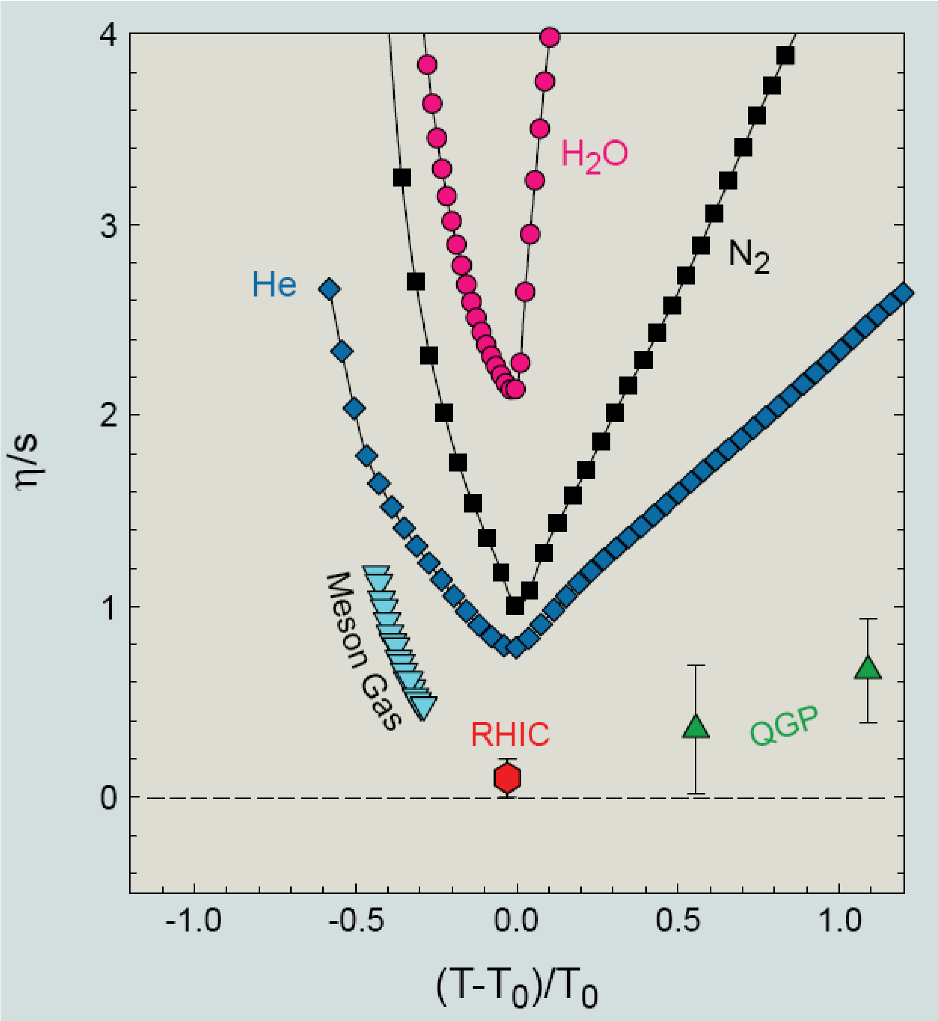


$\zeta/\eta < 10^{-3}$

$$\zeta \sim \frac{\alpha_s^2 T^3}{\log[1/\alpha_s]} \quad (m_0 \ll \alpha_s T)$$

P.Arnold, C.Dogan, G.Moore, hep-ph/0608012

Shear viscosity has attracted a lot of attention



Lattice QCD:
H. Meyer, 0704.1801

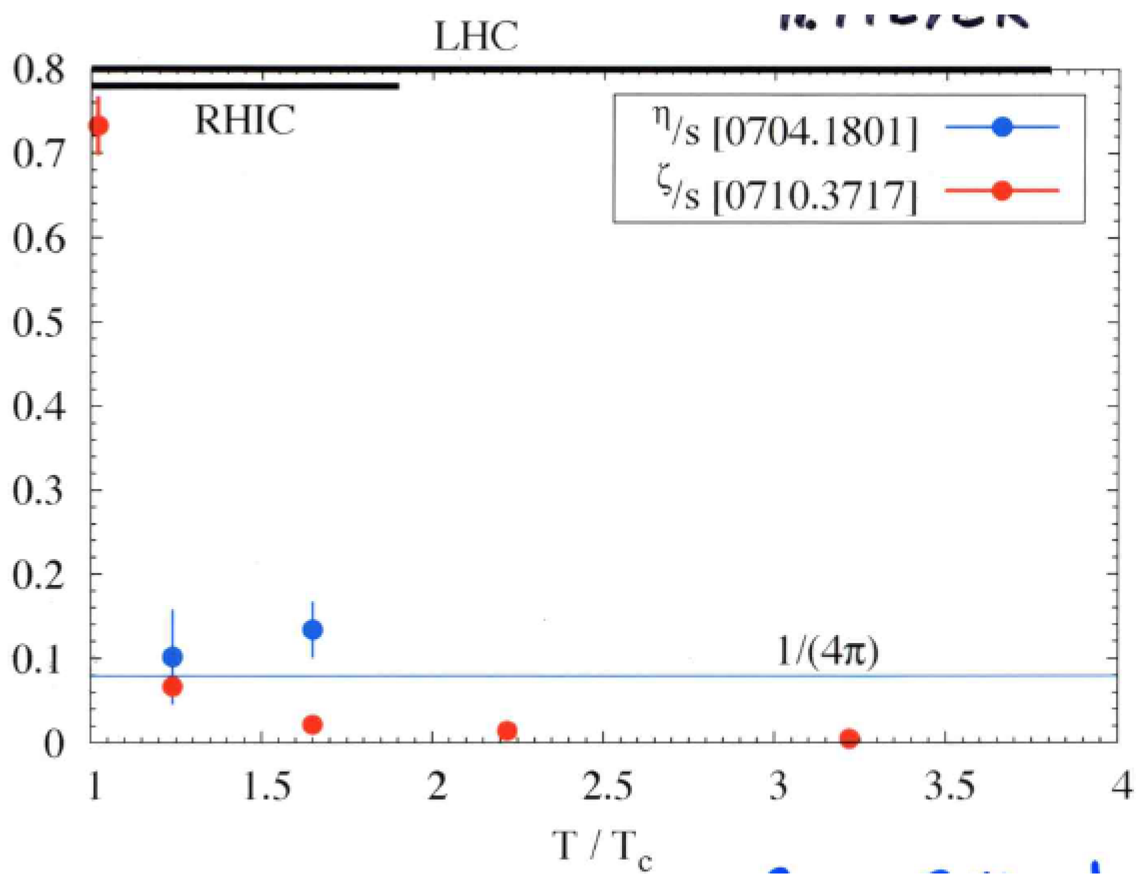
$$\eta/s = \begin{cases} 0.134(33) & (T = 1.65T_c) \\ 0.102(56) & (T = 1.24T_c) \end{cases}$$

Is quark-gluon plasma a perfect liquid close to T_c?

perturbative caculation gives~ 1

Kovtun - Son - Starinets bound: $\eta/s = 1/4\pi$
strongly coupled SUSY QCD = classical supergravity

LATTICE CALCULATION of BULK and SHEAR in GLUODYNAMICS
is perfect for thermodynamics (for static properties) and perturbative QCD is right theory but wrong approximation here

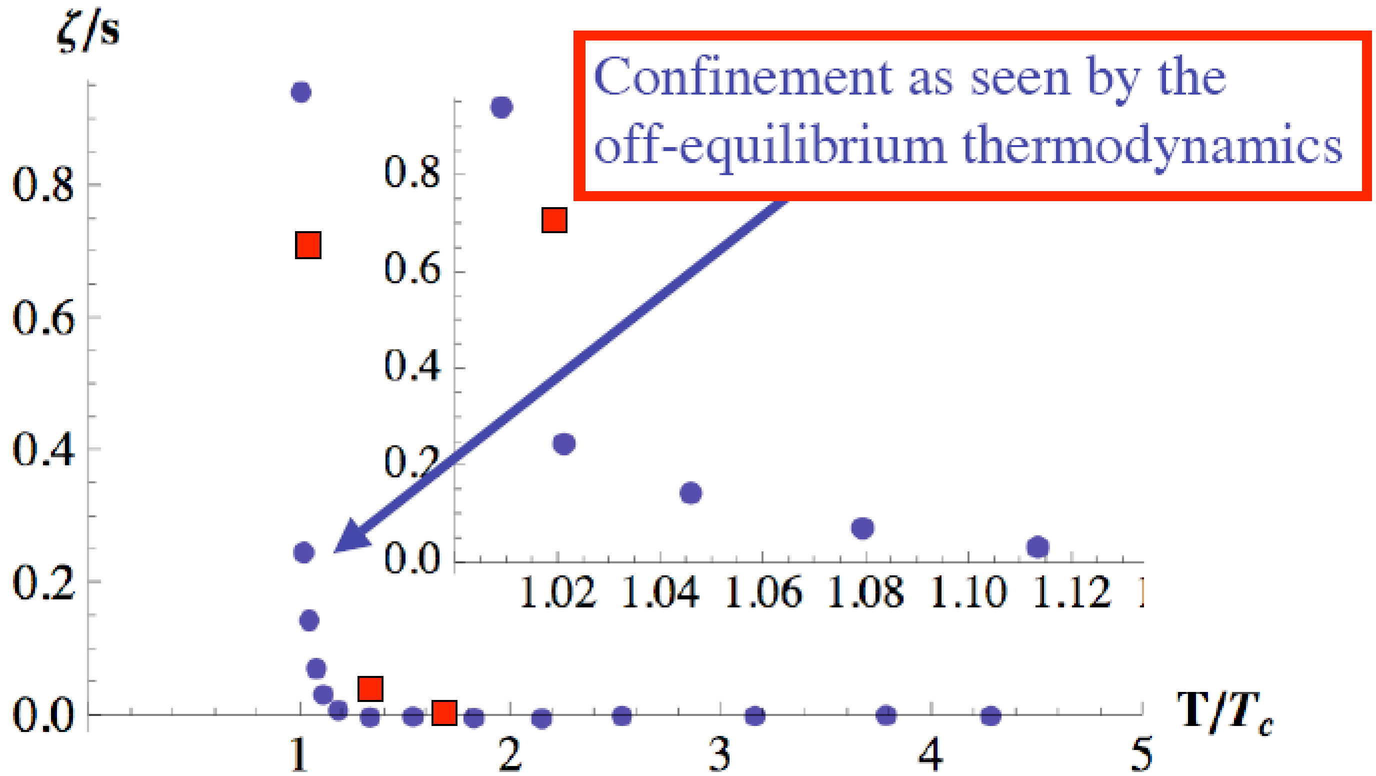


it suggests QGP is conformal (?) and should be liquid-like at LHC as at RHIC

Bulk viscosity

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

■ Meyer arXiv:0710.3717[hep-lat]

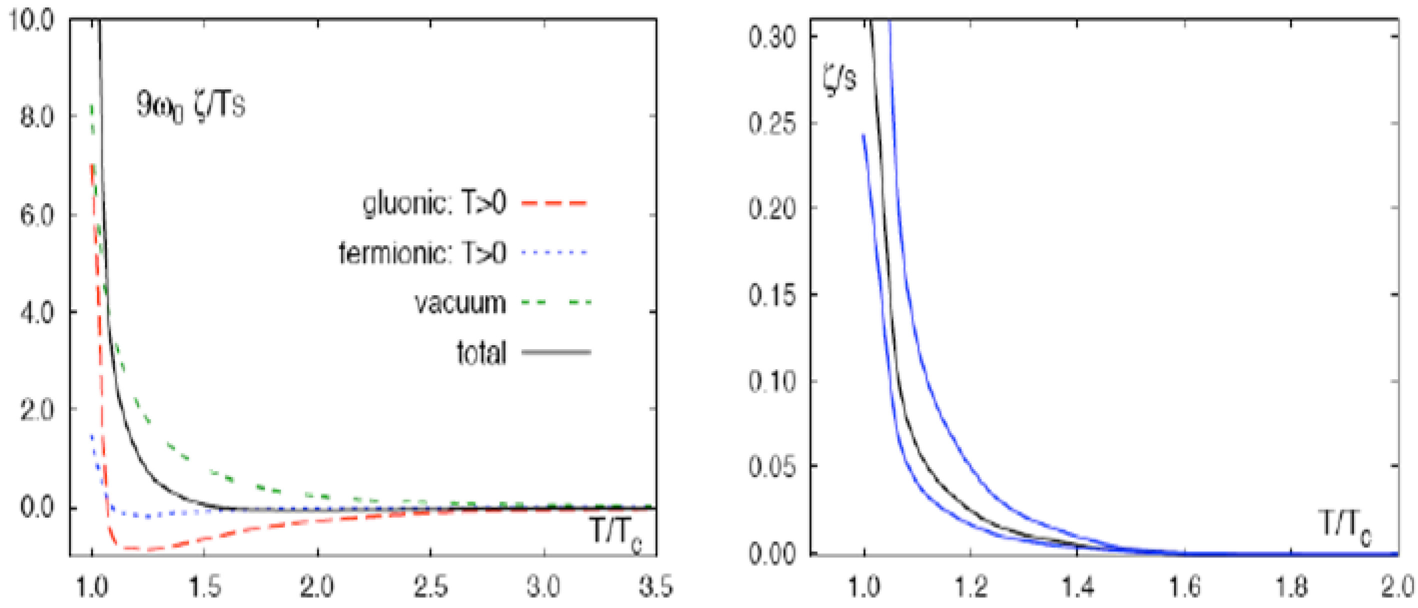


Model studies: Mizutani, Muroya, Namiki, '88; Paech, Pratt '06; Chen, Wang '07

Bulk viscosity in full QCD

Qualitatively similar results:

F.Karsch, DK, K.Tuchin, arXiv:0711.0914



+ Near the chiral critical point: divergence of bulk viscosity

Example: ^{3}He near the critical point at $(T-T_c)/T_c = 10^{-4}$ on the critical isochore shear viscosity is $\eta=17\ 10^{-6}$ Poise, whereas bulk viscosity is $\zeta=50$ Poise

The ratio ζ/η is in excess of a million

Are some dynamical properties universal (i.e. the same for strongly coupled plasmas in large class of theories) ? What properties ? What theories ?

Calculate QGP properties in other theories that are analyzable at strong coupling

N=4 supersymmetric Yang-Mills theory

- gauge theory specified by two parameters N_c and $g^2 N_c \equiv \lambda$
- conformal (λ does not run)
- if we choose λ large then at nonzero T we have strongly coupled plasma
- this 3+1 – dimensional gauge theory is equivalent to a particular string theory in a particular space-time $AdS_5 \times S_5$
- in the limit $N_c \to \infty, \lambda \to \infty$ the string theory reduces to classical gravity in which calculations easy at strong coupling and thermodynamics of very weakly and very strongly coupled plasmas could be rather similar

$$\varepsilon_{\lambda=\infty} / \varepsilon_{\lambda=0} = P_{\lambda=\infty} / P_{\lambda=0} = S_{\lambda=\infty} / S_{\lambda=0} = 3/4$$

- it means an approximate conformality above T_c does not need to be at weak coupling

duality setting

- CFT (conformal gauge theory) N=4 SYM a cousin of QCD (chromodynamics=theory of strong interaction) in which the coupling $\lambda=g^2N_c$ does not run
- It lives on flat 4-dim boundary of 5-d curved AdS (anti-de-Sitter) space where **weakly coupled** (super)gravity is a description of (super) string theory
- **Strategy: calculate in the "bulk", then project on the boundary**
- **Hint; think of extra dimension as a complex variable trick: instead of functions on the real axes one may think of poles in a complex plane**

AdS/CFT

now we know of infinite classes of different gauge theories whose QGP

- are equivalent to string theories in higher dimensional space-times that $\varepsilon / T^4 = (3/4)(\varepsilon / T^4)_D, \eta / s = 1/4\pi$
  contain a black hole
- all have in the limit of **strong coupling** and large number of colors

not known whether QCD in this class

is there a new notion of universality for strongly coupled (nearly) scale invariant liquids ?

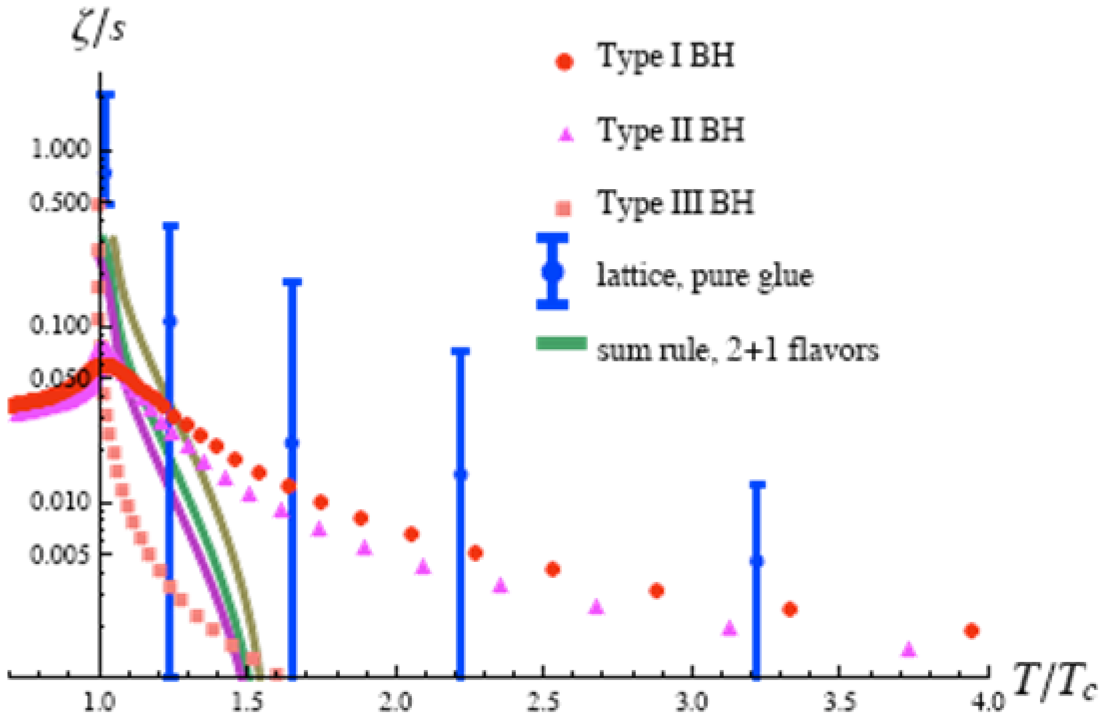
to what system does it apply ?

- quark-gluon plasma dual to string theory + black hole
- QCD quark-gluon plasma
- gas of fermionic atoms in the unitary regime (strongly coupled and scale invariant)

to what quantities does it apply?

- η / s ? Charmonium suppresion ?
- jet quenching ?

Bulk viscosity in AdS/QCD



S. Gubser, A. Nellore, S. Pufu and F.Rocha, arXiv:0804.1950

THEN MAY BE

LHC people dream about a black hole formation …

but it does happen in each AuAu event at RHIC but in the 5th direction …

what we see at RHIC is its 4-dim hologram…

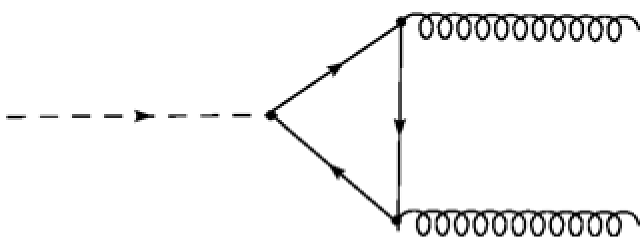
Axial anomaly

Vafa-Witten theorem necessarily true anymore at finite temperatures and/or chemical potentials

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:

$$\partial^\mu J_{\mu 5} = 2 m_f i \bar{\psi}_f \gamma_5 \psi_f - (N_f g^2 / 16\pi^2) G_\alpha^{\mu\nu} \tilde{G}_{\alpha\mu\nu}$$



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

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

P- and CP-violating transitions

Color fields with winding number

$$Q_w = \frac{g^2}{8\pi^2}\int d^4x\, \vec{E}_a \cdot \vec{B}_a = 0, \pm 1, \pm 2, \dots$$

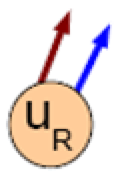
Integer for a vacuum solution at $t = \pm\infty$

induce difference between number of left- and right-handed fermions.

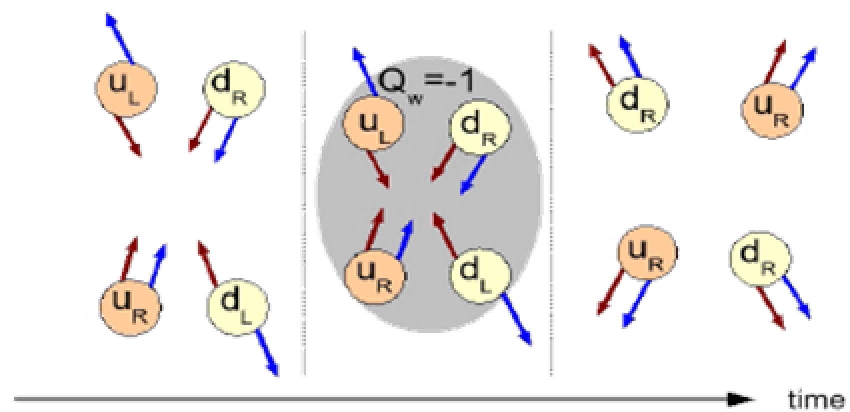
Nonperturbative P- and CP-violating transition

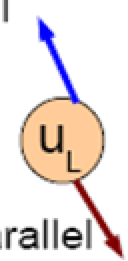
$t = \pm\infty$

In chiral limit:

Right-handed fermions 

have spin and momentum parallel



Left-handed fermions 

have spin and momentum anti-parallel

$$[N_L - N_R]_{t=\infty} - [N_L - N_R]_{t=-\infty} = 2N_f Q_w$$

Axial Ward Identity at work

chirality = helicity for massless quarks
which could be changed by interacting with gluons but not in perturbative QCD

strong CP problem

$$L_\theta = -(\theta / 32\pi^2) g^2 G_\alpha^{\mu\nu} \tilde{G}_{\alpha\mu\nu}$$

P and CP violation discovered will be a direct proof for the existence of topologically non-trivial gluon fields

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

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

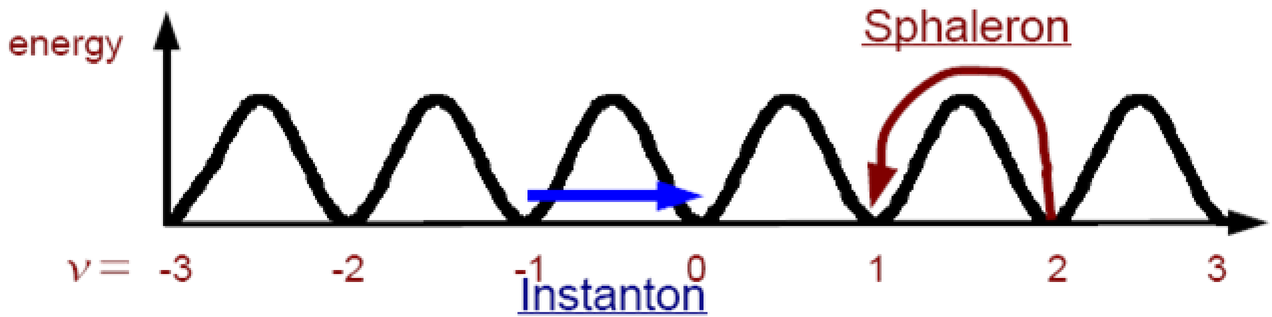
Why is θ so small?
QCD vacuum dynamics?

Possible to assign to each classical vacuum a topological invariant N_{cs}

$$Q_W = N_{CS}(t=\infty) - N_{CS}(t=-\infty)$$

Color fields with a winding number

Change topological charge vacuum



Instantons: Configuration with finite action. Tunneling through barrier

Suppression of rate at finite temperature 't Hooft ('76), Pisarski and Yaffe ('80)

Sphaleron: Configuration with finite energy. Go over barrier.

Only possible at finite temperature, rate not suppressed.

$$\frac{d N_t^{\pm}}{d^3 x \, d t} \sim 385 \, \alpha_S^5 T^4$$ Bödeker, Moore and Rummukainen ('00)

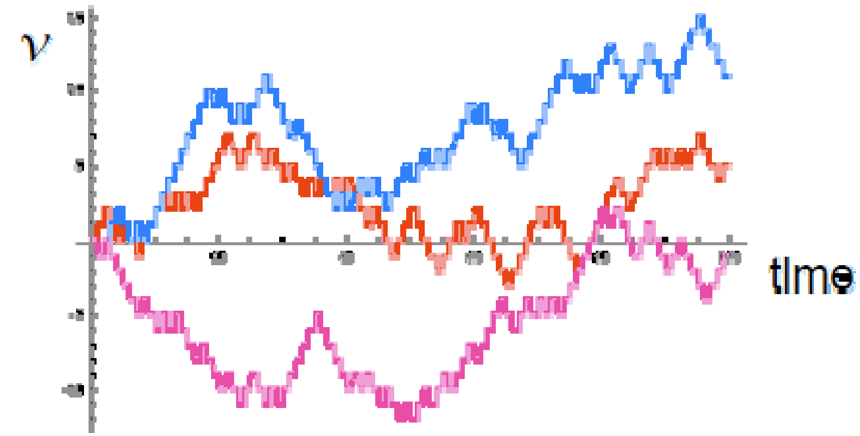
Chirality change and P- and CP – violation are directly related to the topology of gluon field

If one observes a difference between left and right handed fermions it signals P and CP violation on event-by-event basis

Topological charge change

Topological charge changing transitions can occur after each other

Dynamics is that of a
random walk in one dimension



Average total topological charge change vanishes $\langle \nu \rangle = 0$

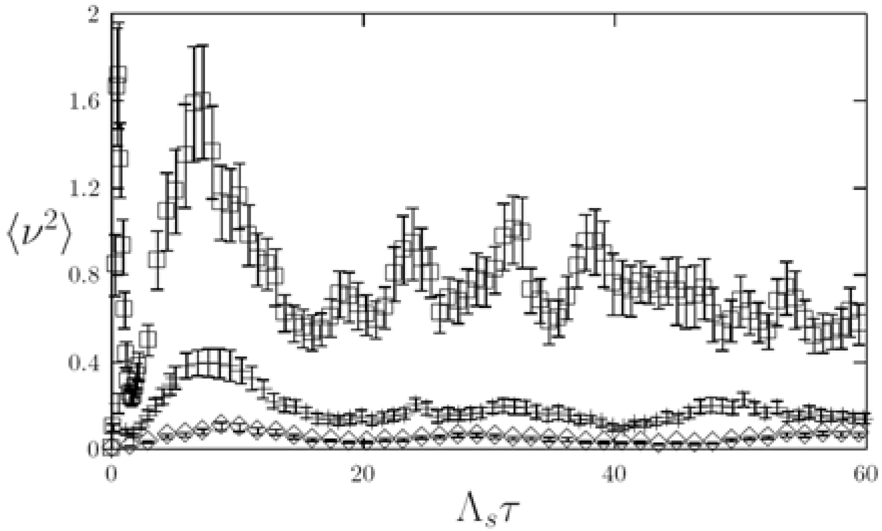
But the variance is equal to the total number of transitions

$$\langle \nu^2 \rangle = N_t$$

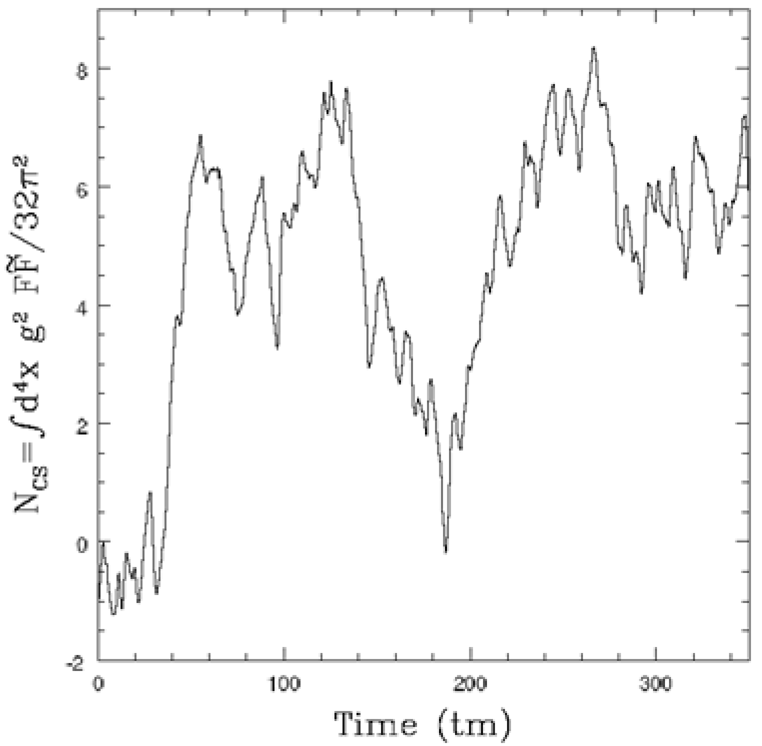
A nonzero topological charge change means P and CP-violation

To detect P- and CP-violation one has to understand
to what physical effects topological charge change can lead

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

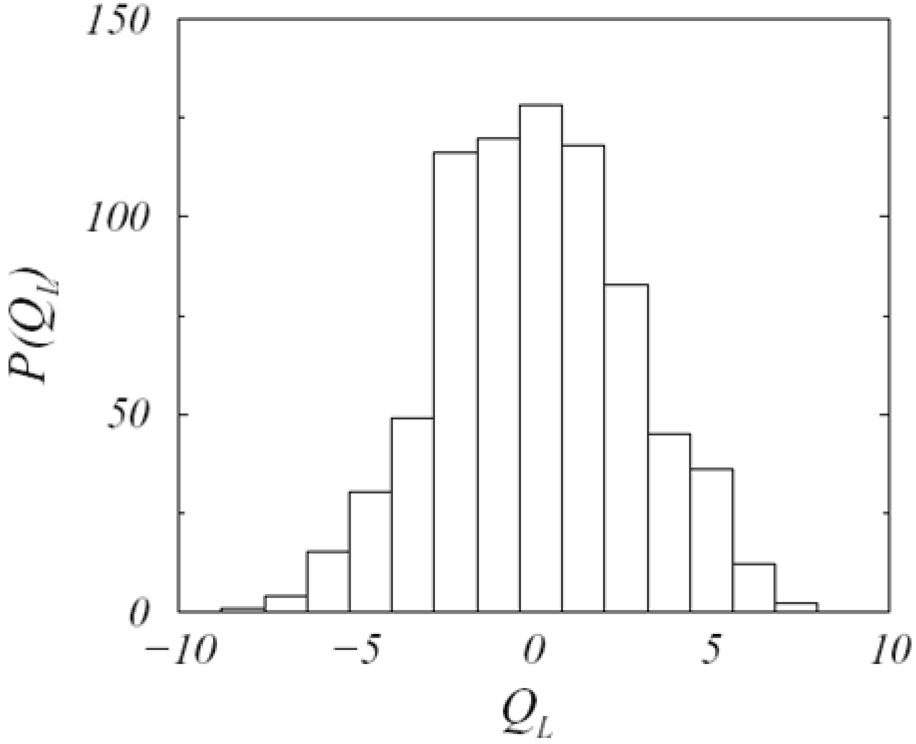


DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002



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

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

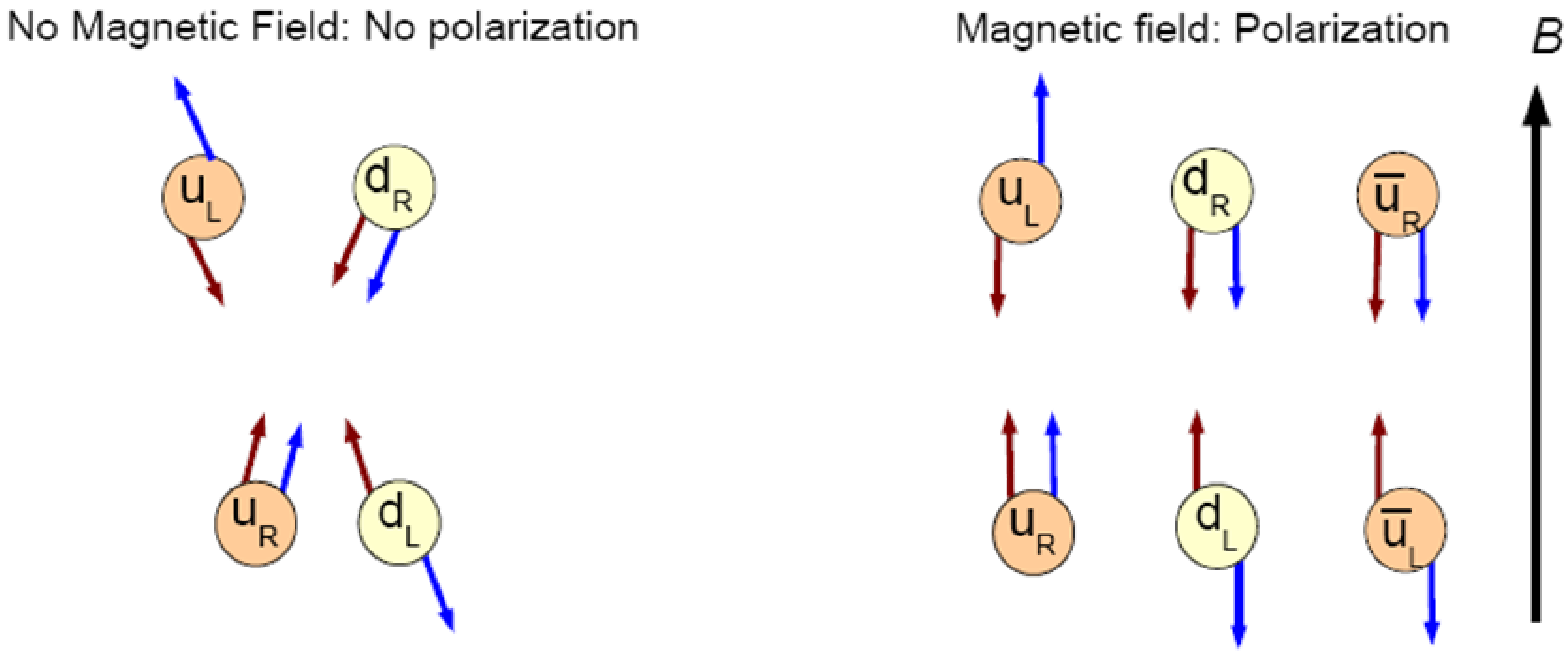


B.Alles, M.D'Elia and A.DiGiacomo, hep-lat/0004020

Adding a Magnetic Field

A magnetic field will align the spins, depending on their electric charge

Impossible to measure helicity then solution is polarization

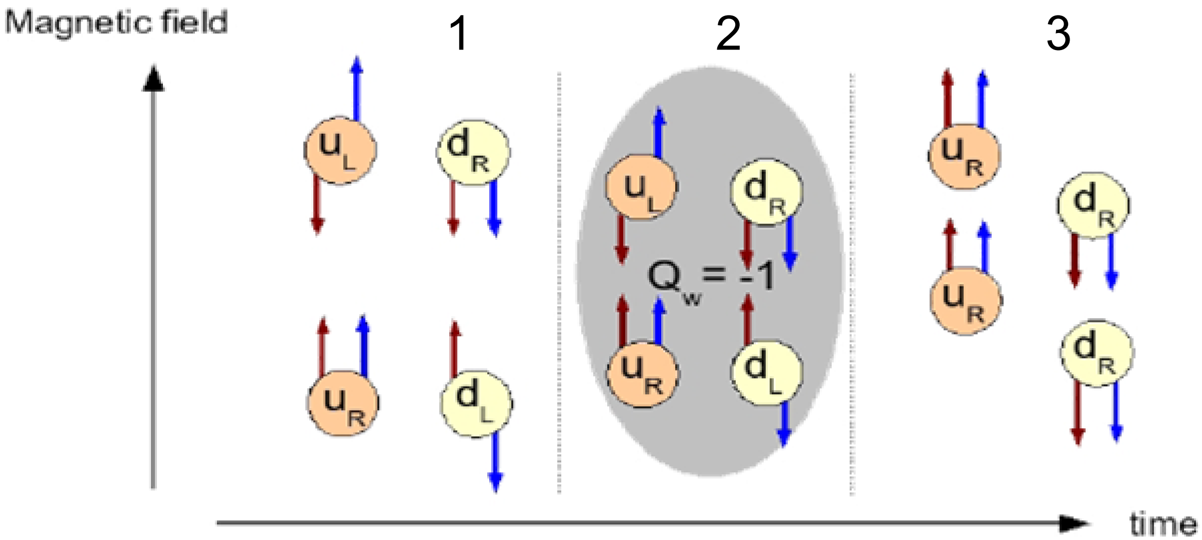


In the chiral limit the momenta align along the magnetic field

A right-handed up quark will have momentum opposite to a left-handed one

In this way the magnetic field can distinguish between left and right!

The Chiral Magnetic Effect



Charge difference:

$$Q = 2 Q_w \sum_f |q_f|$$

Same sign for antiparticles!

$$[N_L - N_R]_{t=\infty} - [N_L - N_R]_{t=-\infty} = 2 N_f Q_w$$

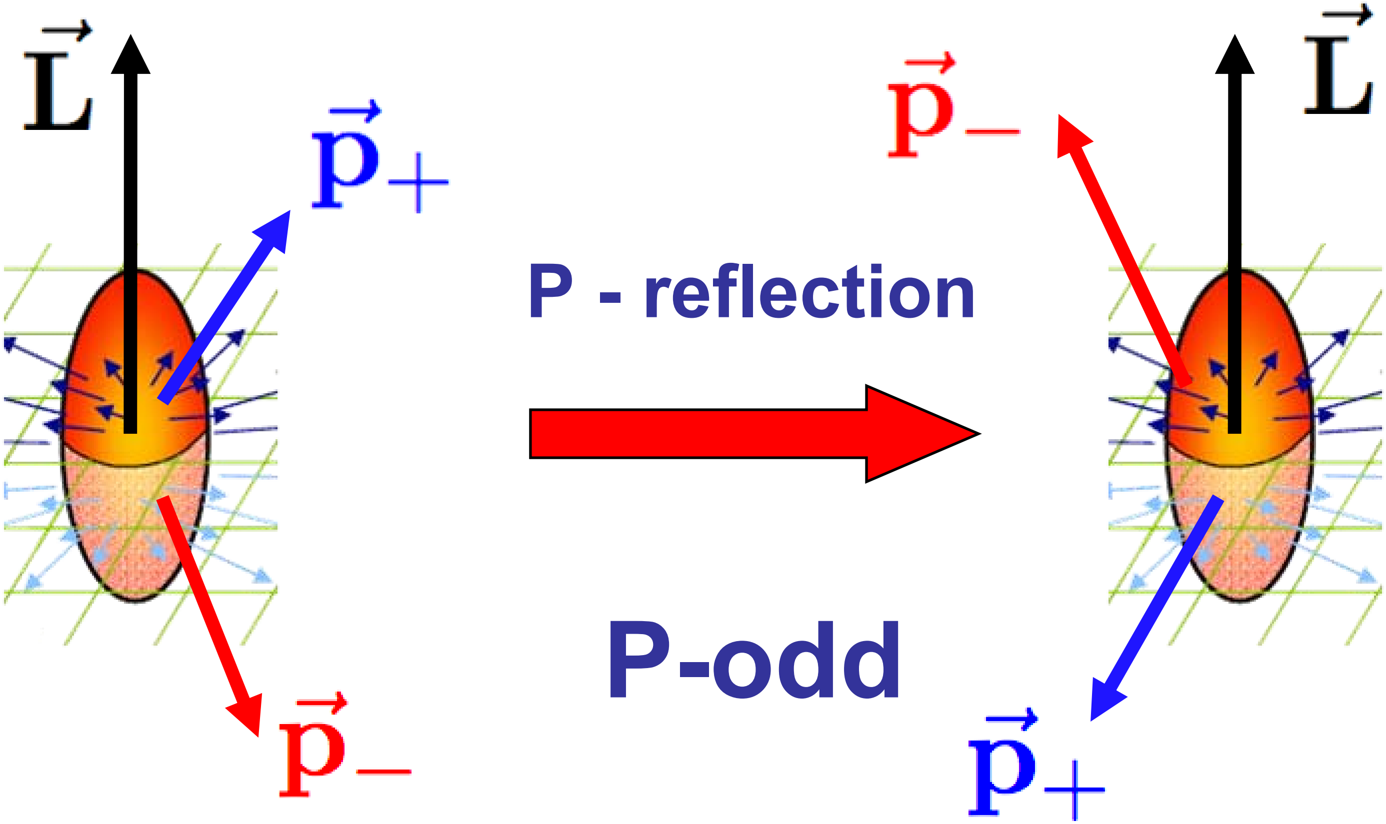
Topological charge charging transition induces Chirality

In presence of Magnetic field this induces Electromagnetic Current

In finite volume this causes separation of positive from negative charge

Red arrow - momentum; blue arrow - spin;
In the absence of topological charge no asymmetry between left and right (fig.1) ; the fluctuation of topological charge (fig.2) in the presence of magnetic field induces electric current (fig.3)

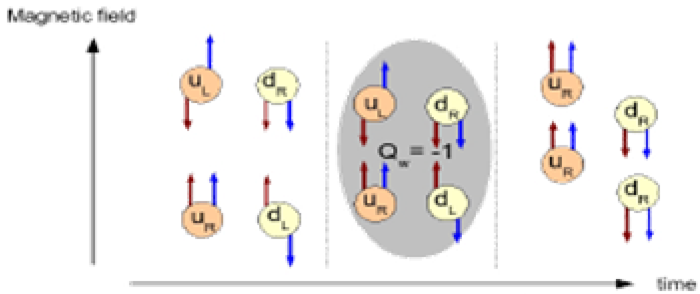
Charge separation = parity violation:



$$\mathbf{P}: \quad \vec{p} \to -\vec{p}; \quad \vec{L} = \vec{r} \times \vec{p} \to \vec{L}$$

The Chiral Magnetic Effect

In a moderate magnetic field (some polarization)



$$[N_L - N_R]_{t=\infty} - [N_L - N_R]_{t=-\infty} = 2 N_f Q_w$$

Charge difference:

$$Q = 2 Q_w \sum_f |q_f| \, \text{polarization}(q_f)$$

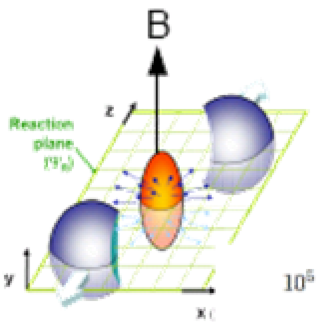
Quarks with energy smaller than inverse size of sphaleron are changing chirality

$$\text{polarization}(q_f) = \frac{|N_\uparrow - N_\downarrow|}{N_\uparrow + N_\downarrow} \approx 2 |q_f e B| \rho^2$$

Size of sphalerons is of order $\rho \sim \dfrac{1}{\alpha_s T}$

To get reasonable polarization we need $eB \sim \dfrac{1}{\rho^2} \sim \alpha_s^2 T^2 \sim 10^3 - 10^4 \text{ MeV}^2$

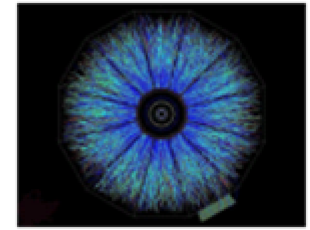
Magnetic Field in Heavy Ion Collisions

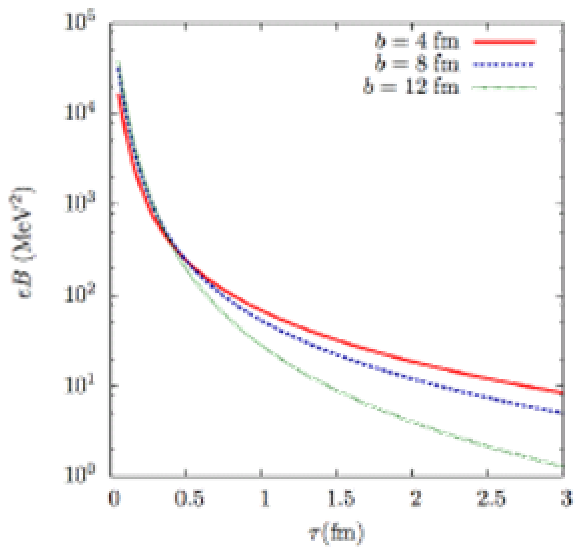


Computed numerically at origin in pancake approximation

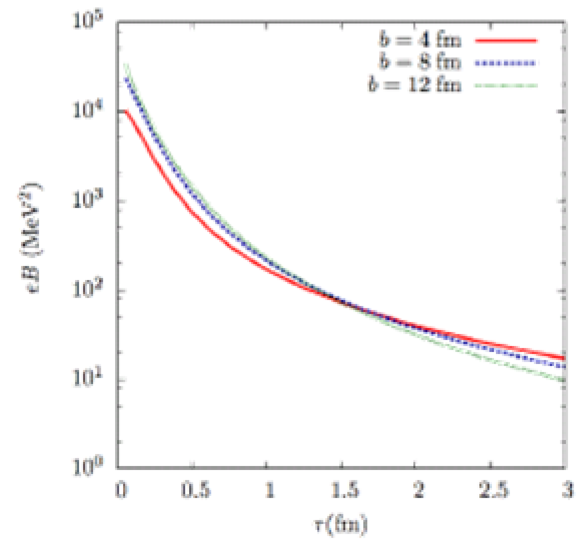
RHIC@BNL

$$eB(\tau = 0.2\,\mathrm{fm}) = 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{G}$$





100 GeV per Nucleon

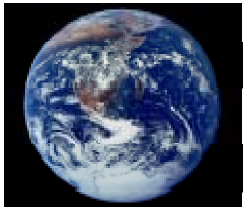


31 GeV per Nucleon

Low energy quarks which are produced in early stages will be polarized in the direction perpendicular to reaction plane to some degree.

Magnetic field falls off rapidly: Chiral Magnetic Effect is early time dynamics

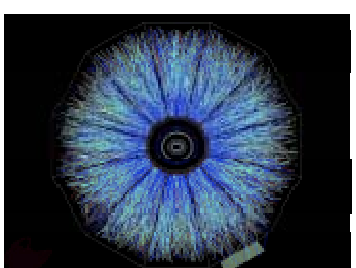
Comparison of magnetic fields



The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^{6} Gauss
The strongest man-made fields ever achieved, if only briefly	10^{7} Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{16} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html

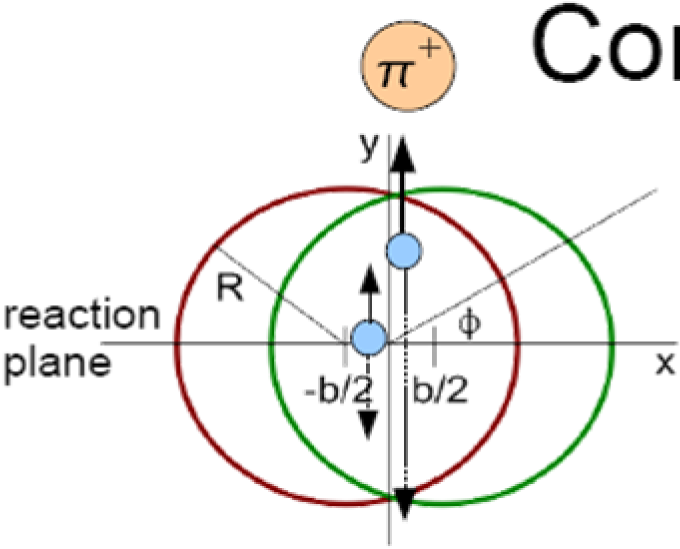
Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory



Off central Gold-Gold Collisions at 100 GeV per nucleon

$$e\,B(\tau = 0.2\ \mathrm{fm}) \;=\; 10^{3} \sim 10^{4}\ \mathrm{MeV}^{2} \sim 10^{17}\ \mathrm{Gauss}$$

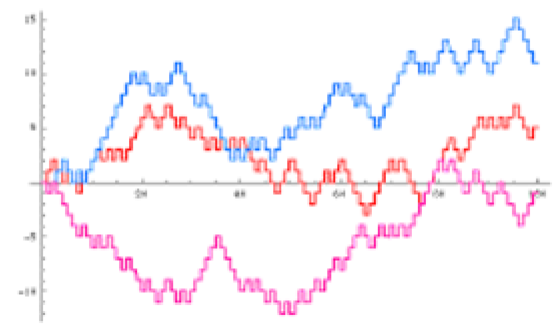
Computing observables



The Chiral Magnetic Effect is a near the surface effect

Medium causes screening

1-d random walk



The variances are the observables

Variance topological charge change equal to total number of transitions

Variance of charge difference between both sides reaction plane:

$$\langle \Delta_{\pm}^2 \rangle = 2\int_{t_i}^{t_f} \mathrm{d}t \int_V \mathrm{d}^3x \; \frac{\mathrm{d}N_t}{\mathrm{d}^3x\,\mathrm{d}t} \; [\xi_+^2(x_\perp)+\xi_-^2(x_\perp)] \; \left(\sum_f q_f^2 e B \rho\right)^2$$

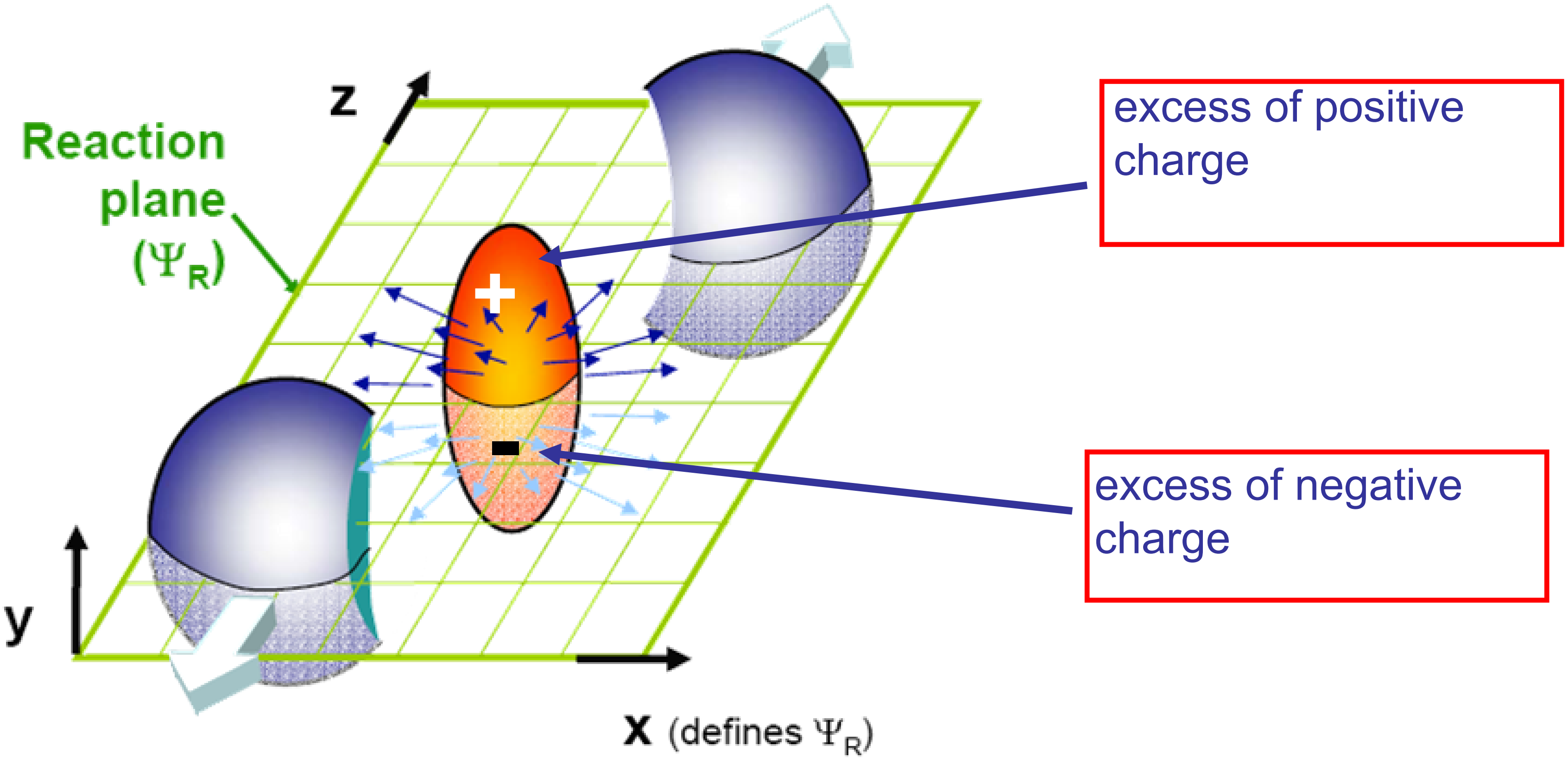
Time & Volume integral Overlap region

Rate of Transitions

Screening Functions

Square of Change Charge difference

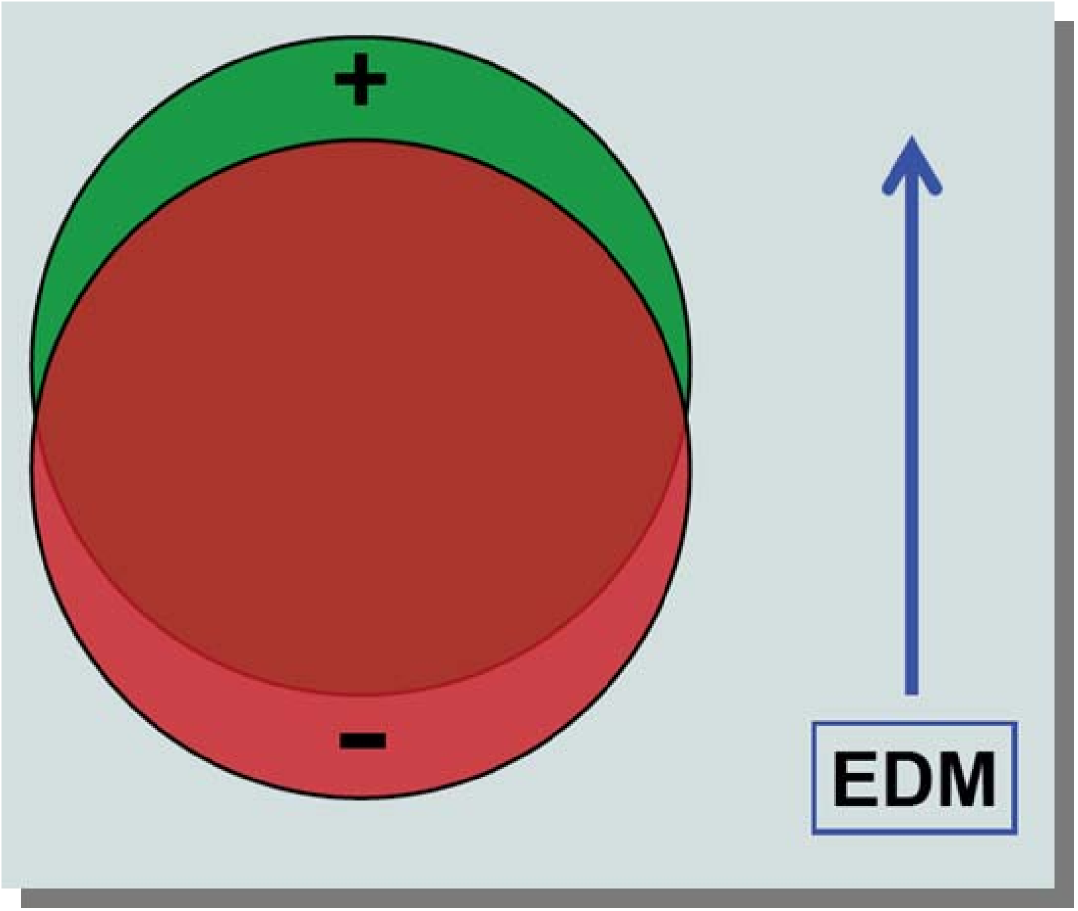
Charge asymmetry with respect to reaction plane as a signature of strong P violation



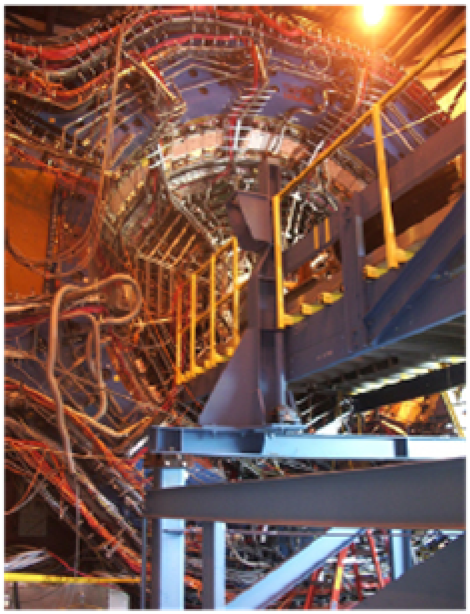
Electric dipole moment of QCD matter!

D.Kharzeev; Phys.Lett.B633(2006)260

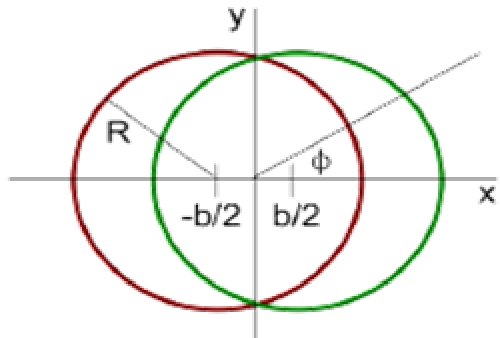
Measuring the electric dipole moment of the quark-gluon plasma



OBSERVABLES



STAR detector
Full azimuthal coverage



ϕ : angle between particle and reaction plane

$$\frac{\mathrm{d}N_{\pm}}{\mathrm{d}\phi} = \frac{N_{\pm}}{2\pi} + a_{\pm}\sin\phi + v_2\cos 2\phi + \ldots.$$

Average over many equivalent events
(to cancel statistical fluctuations) can give us

$\langle a_+^2 \rangle \sim \langle \Delta_+^2 \rangle$ Pref. emission positive on one side

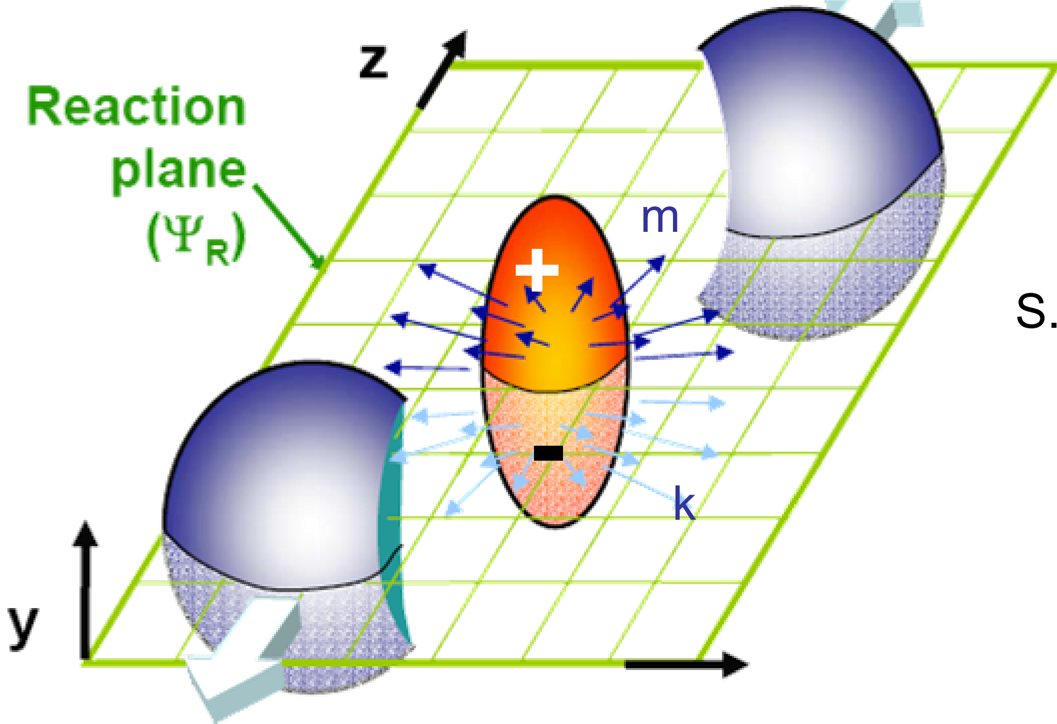
$\langle a_-^2 \rangle \sim \langle \Delta_-^2 \rangle$ Pref. emission negative on one side

$\langle a_+ a_- \rangle \sim \langle \Delta_+ \Delta_- \rangle$ Correlations between positive on one and negative on other side

Preliminary analysis performed by STAR collaboration

Observables are not P and CP-odd, understand possible backgrounds

Charge asymmetry with respect to reaction plane: how to detect it?



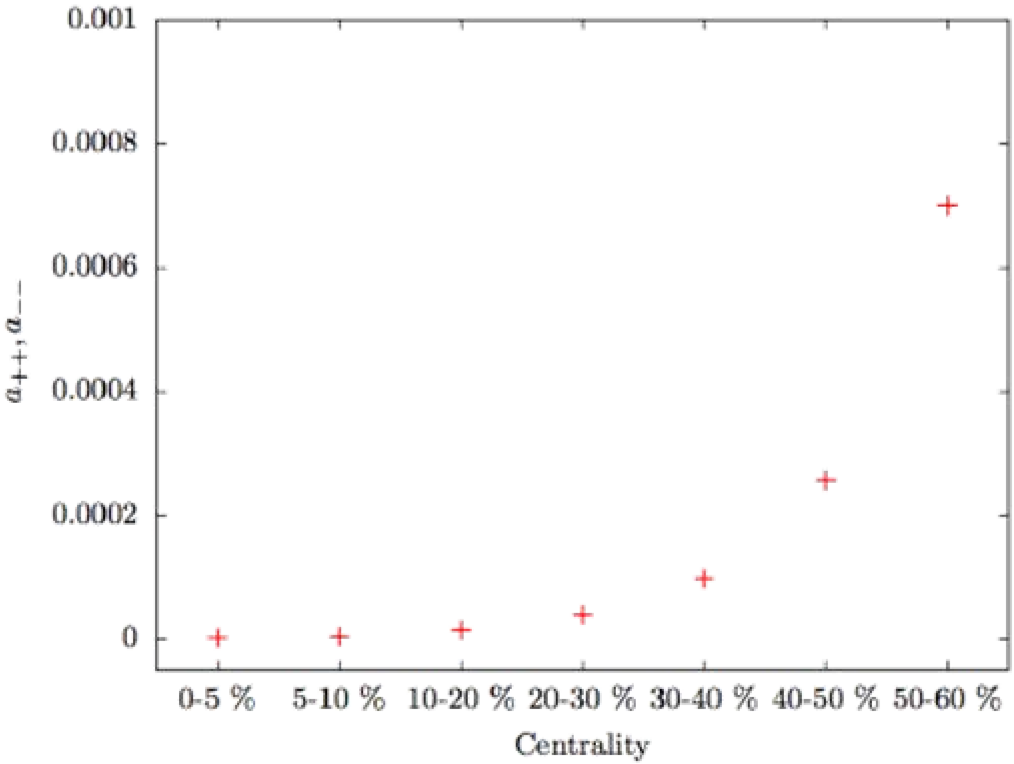
S.Voloshin, hep-ph/0406311

A sensitive measure of the asymmetry:

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

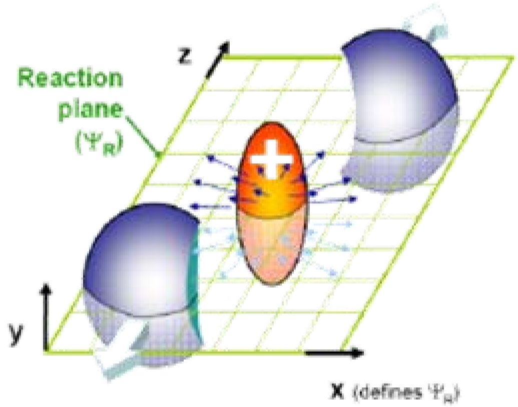
Expect $\quad a^+ a^+ = a^- a^- > 0; \quad a^+ a^- < 0$

Correlators vs. Centrality



$\langle a_+^2 \rangle \sim \langle \Delta_+^2 \rangle$

Preferential emission of positively charged particles around $\phi = \pi/2$ or $\phi = 3\pi/2$



A possible result of the Chiral Magnetic Effect in Gold-Gold collisions at 130 GeV per nucleon

Strong CP violation at high T ?

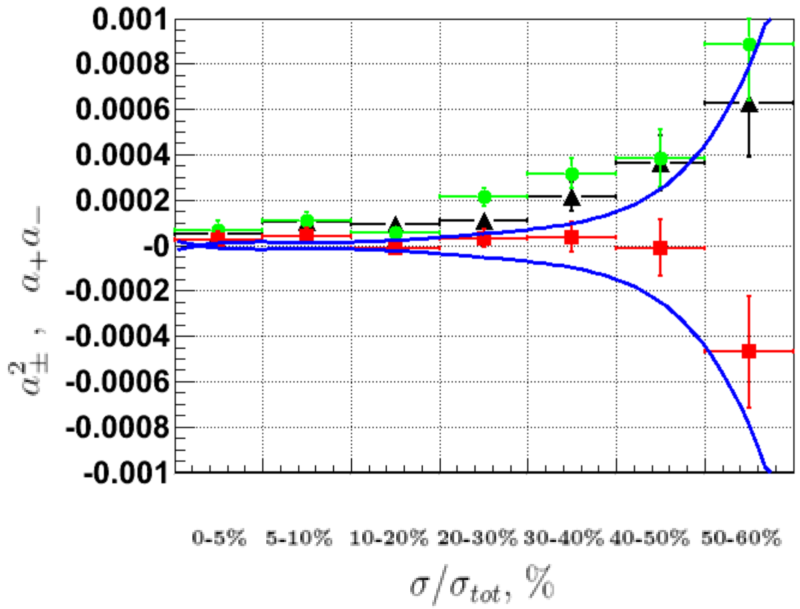
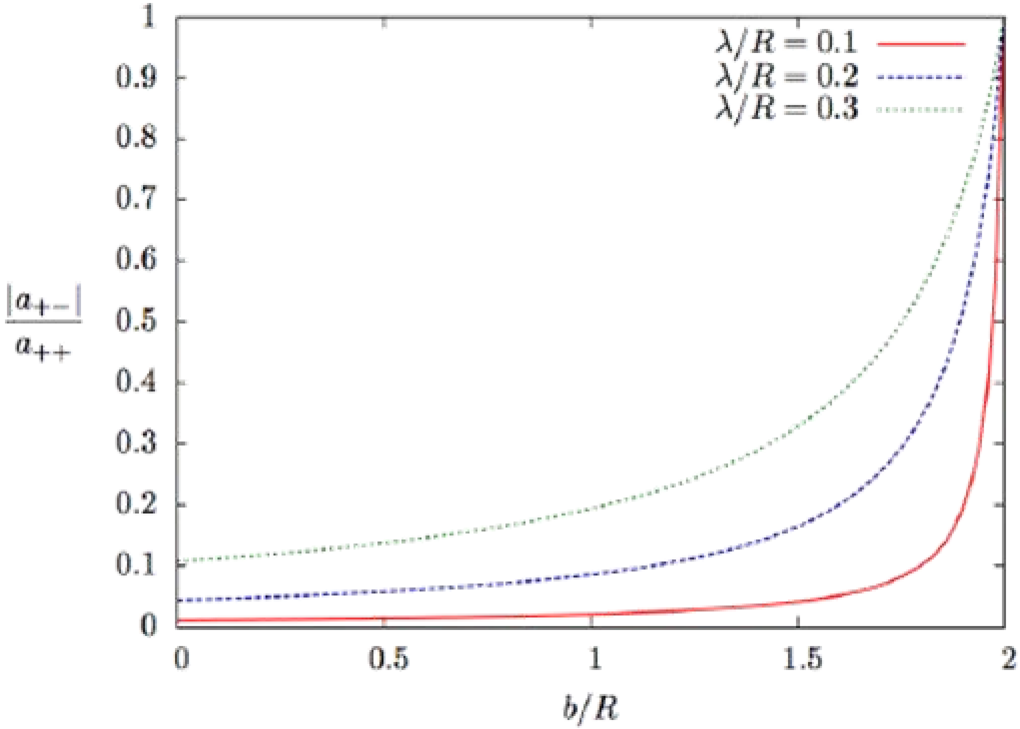


Figure 2: Charged particle asymmetry parameters as a a function of standard STAR centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares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

preliminary result by I. Selyuzhenkov et al., STAR Collaboration

Suppression of +/- correlations



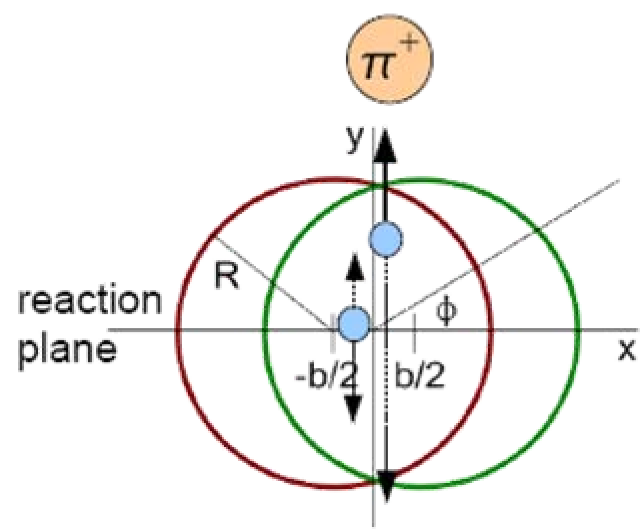
Suppression of correlations

between positively charged particles on one side and

negatively charged particles on other side of reaction plane

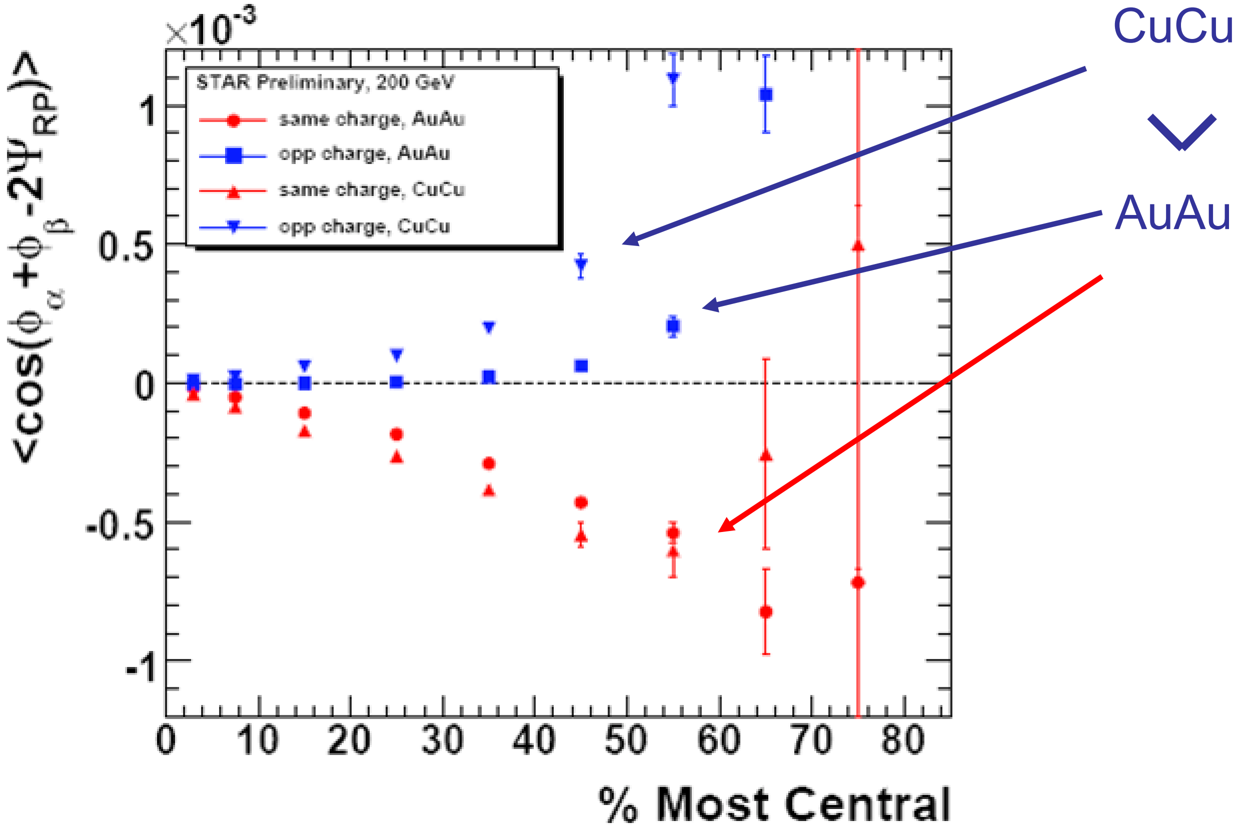
due to screening.

A possible result of the Chiral Magnetic Effect



Strong P, CP violation at high T ?

Charge asymmetry w.r.t. reaction plane,
~ - $a^k a^m$



S. Voloshin et al [STAR Coll.]

This analysis is currently being finalized

Many signatures of QGP have been proposed over past two decades which cover experimental programs at AGS, SPS, RHIC and soon LHC

several features of the AGS and CERN measurements were consistent with the expected properties of the QGP at that time (2000)

As to the RHIC results the BNL press release on April 2005 declared :

instead of behaving like a gas of free quarks or/and gluons the matter created in RHIC's heavy ion collisions appears to be more like a liquid

this state of matter interacts much more strongly than expected

sQGP

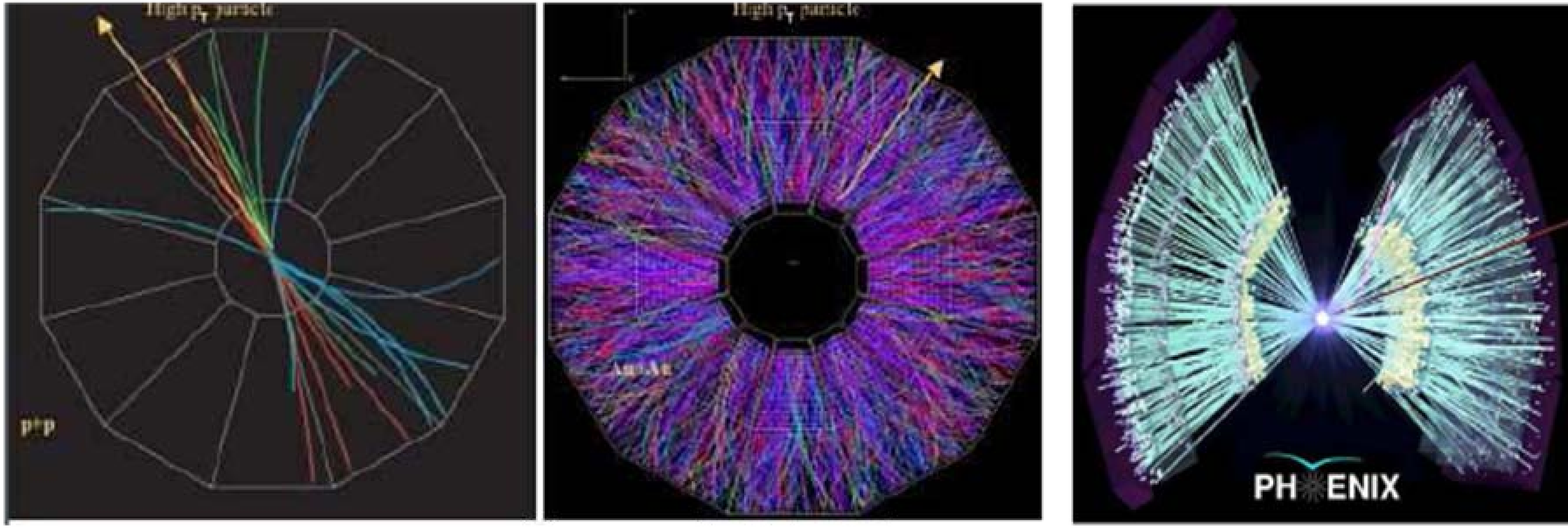
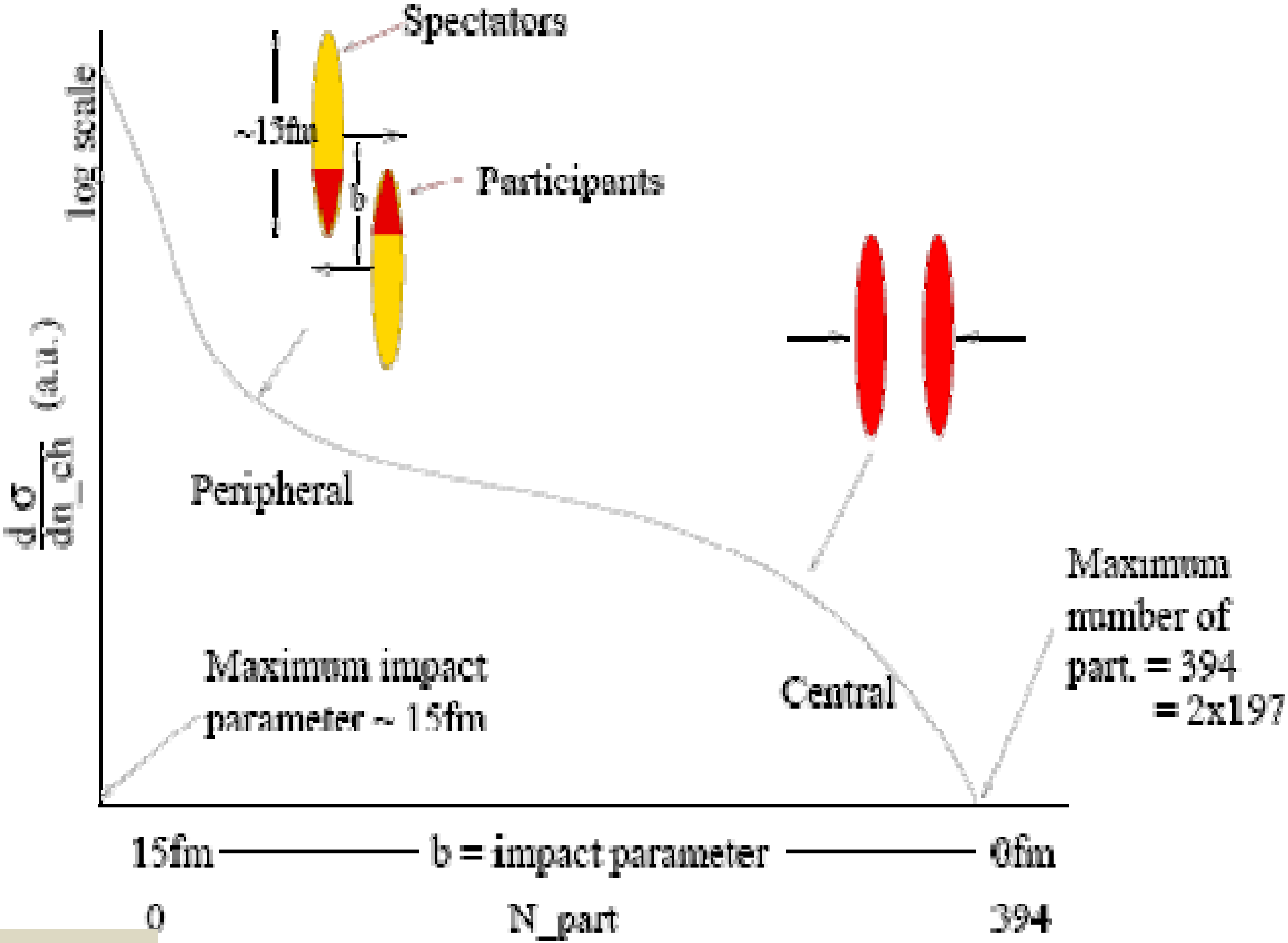


Fig. 5. a) (left) A p-p collision in the STAR detector viewed along the collision axis; b) (center) Au+Au central collision at $\sqrt{s_{NN}} = 200$ GeV in the STAR detector; c) (right) Au+Au central collision at $\sqrt{s_{NN}} = 200$ GeV in the PHENIX detector

In c.m.s. of AA collision two Lorentz-contracted nuclei of radius *R* approach each other with impact parameter *b, i*n region of overlap the "participating" nucleons interact with each other, while in the non-overlap region "spectator" nucleons simply continue on their original trajectories and can be measured in ZDC so that the number of participants can be determined.

Degree of overlap is called the centrality of collision, with $b \sim 0$, being most central and $b \sim 2R$, most peripheral. The maximum time of overlap is $\tau_O = 2R/\gamma c$ where γ is Lorentz factor and c is velocity of light. Energy of inelastic collision is predominantly dissipated by multiple particle production.



Schematic of collision of two nuclei with radius R and impact parameter b. The curve with the ordinate labeled $d\sigma/dn_{ch}$ represents the relative probability of charged particle multiplicity n_{ch} which is directly proportional to the number of participating nucleons, N_{part}.

for any observed particle of momentum p, energy E, the momentum can be resolved into transverse (p_T) and longitudinal (p_L) components, in many cases the mass (m) of particle can be determined and longitudinal momentum is conveniently expressed in terms of rapidity

$$y = \ln\left(\frac{E + p_L}{m_T}\right), \cosh y = E / m_T \qquad \sinh y = p_L / m_T \qquad dy = dp_L / E$$

$$m_T = \sqrt{m^2 + p_T^2} \quad \text{and} \quad E = \sqrt{p_L^2 + m_T^2} = \sqrt{p^2 + m^2}.$$

in the limit when (m<< E) the rapidity reduces to the pseudorapidity (η)

$$\eta = -\ln \tan \theta / 2, \quad \cosh \eta = \csc \theta \qquad \sinh \eta = \cot \theta,$$

θ is the polar angle of emission. The rapidity is additive under a Lorentz transformation.

for any collision c.m.s. – in which the momenta of the incident projectile and target are equal and opposite – is at rapidity y^{cm} and its total energy $\sqrt{s}$ is also the "invariant mass". For a collision of an incident projectile of energy E_1, mass m_1, in lab. system where the target, of mass m_2, is at rest (appropriate for fixed-target experiments)

$$s = m_1^2 + m_2^2 + 2E_1 m_2 .$$

The c.m. rest frame moves in lab. system (along the collision axis) with a velocity $\beta^{\mathrm{cm}} c$ corresponding to

$$\gamma^{cm} = \frac{E_1 + m_2}{\sqrt{s}} \quad \text{and} \quad y^{cm} = \cosh^{-1} \gamma^{cm} \quad , \gamma^2 = 1/(1-\beta^2).$$

useful quantity is y^{beam}, rapidity of the incident particle in lab. system

$$y^{\text{beam}} = \cosh^{-1}\frac{E_1}{m_1},$$ for equal mass projectile and target $$y^{\text{cm}} = y^{\text{beam}}/2.$$

in the region near the projectile or target rapidity, the Feynman x fragmentation variable is also used

$$x_F = 2p_L^* / \sqrt{s},$$ p^*_L is the longitudinal momentum of particle in c.m. frame

kinematics is considerably simpler in NN c.m. frame in which two nuclei approach each other with the same γ (it is the reference frame of detectors at RHIC and LHC). The nucleon-nucleon c.m. energy is $\sqrt{s_{NN}}$ and the total c.m. energy is $\sqrt{s} = A \cdot \sqrt{s_{NN}}$ for symmetric A+A collisions, the colliding nucleons approach each other with energy $\sqrt{s_{NN}}/2$ and equal and opposite momenta. The rapidity of the nucleon-nucleon center of mass is $y_{NN}=0$ and taking $m_1=m_2=m_N$ projectile and target nucleons are at equal and opposite rapidities:

$$y^{\text{proj}} = -y^{\text{target}} = \cosh^{-1}\frac{\sqrt{s_{NN}}}{2m_N} = y^{\text{beam}}/2.$$

average transverse momentum $\langle p_T \rangle$ or mean transverse kinetic energy, $\langle m_T \rangle - m$ or asymptotic slope are taken as measures of temperature T of reaction

important to be aware that the integral of single particle inclusive cross section over all variables is not equal to σ_I the interaction cross section, but rather is equal to the mean multiplicity times the interaction cross section:

$$\langle n \rangle \times \sigma_I$$

then the mean multiplicity per interaction is

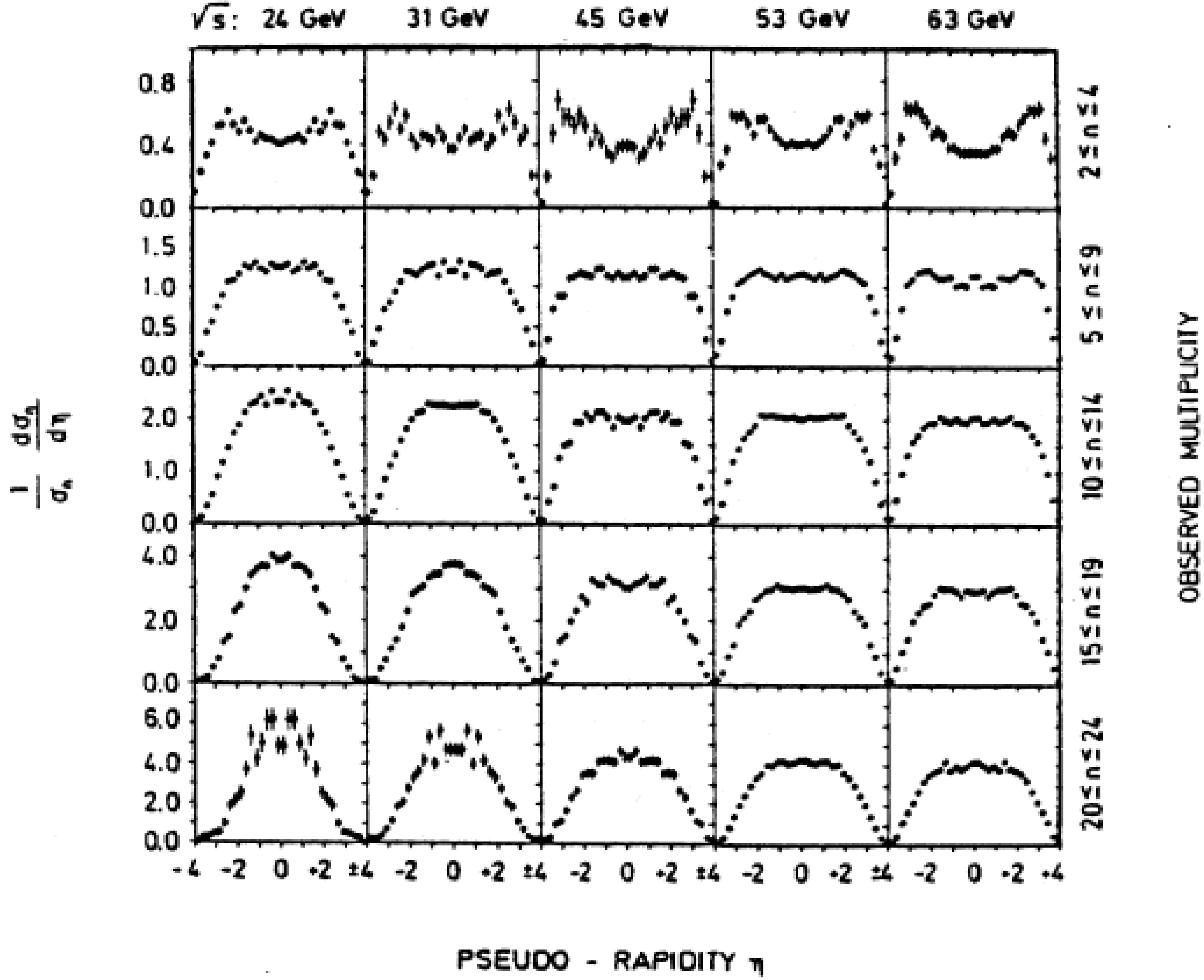
$$\langle n \rangle = \frac{1}{\sigma_I} \int \frac{d\phi}{2\pi} dy\, dp_T\ p_T\ \mathbf{f}(p_T, y) = \frac{1}{\sigma_I} \int dy \frac{d\sigma}{dy} = \int dy\ \rho(y)$$

where the terminology for the multiplicity density in rapidity is

$$(1/\sigma_I) d\sigma / dy = \rho(y) = dn / dy$$

for identified particles (m known), $dn/d\eta$ for non-identified particles (unknown, m assumed massless). The total charged particle multiplicity is taken as a measure of the total entropy, S and $dn/d\eta$ is taken as a measure of the entropy density in restricted intervals of rapidity

shape and evolution with $\sqrt{s}$ of charged particle density in rapidity dn/dy provide a graphic description of high energy collisions



Data from a classical measurement in a streamer chamber from p-p collisions at the CERN ISR

- statistical hadronization model - as effective model describing hadron formation in high energy collisions at scales where perturb QCD is not applicable longer
- if complex dynamical process driven by QCD which eventually forms extended massive colourless objects clusters or fireballs, their masses, momenta, charges are determined by those processes but statistical hadronization postulates - hadrons are formed from decay of each cluster in statistical way

any multi-hadronic state localized within fireball and obeying conservation laws is equally probable principal point of SHM - cluster possesses finite spatial size as MIT bag model

- should not expect statistical approach to work in situation where number of particles is rather small because wisdom is hadronic thermalization process takes long time if governed by hadronic collisions
- waiting for answer for why non-thermal system shows remarkably thermal behaviour

- **Neglecting quantum statistics effect the decay rate of fireball into N secondary particles is proportional to microcanonical partition function**

$$\Omega_{\{N_j\}} = \frac{V^N}{(2\pi)^{3N}} \left(\prod_{j=1}^{K} \frac{(2S_j+1)^{N_j}}{N_j\,!} \right) \int d^3p_1 \ldots \int d^3p_N \, \delta^4\left(P_0 - \sum_i p_i \right) \langle |0| P_V \,|0\rangle$$

- ***S_j* - spin, *V* - fireball proper volume,** M**, - its mass** $P_0 = (M, \vec{0})$

- ***S* –matrix formulation of statistical mechanics (R. Dashen, E. Ma and H. Bernstein, Phys.Rev. 187 (1969) 345) allows us**

  - to calculate microcanonical partition function of interacting system in thermodynamic limit

  -justifies hadron-resonance gas model

  -helps in appraising multi-body interactions to thermalize

  -holds multi-particle generating functions not only for microcanonical

decay rate of massive cluster into some multi-hadronic channel is proportional to its phase space volume *$d^3p\, d^3x$* but in field theory *$d^3p/2E$* invariant momentum space (quantitatively different from standard one)

define four-volume $\Upsilon = Vu$, *V*- cluster rest frame volume, *u* – its four-velocity vector then decay rate of fireball into *N* – body channel

$$\Gamma_N \propto \sum_{\sigma_1,\ldots\sigma_N} \frac{1}{(2\pi)^{3N}} \left(\prod_j \frac{1}{N_j\,!} \right) \int \frac{d^3p_1}{2\varepsilon_1} \ldots \int \frac{d^3p_N}{2\varepsilon_N} |M_{fi}|^2\, \delta^4\left(P_0 - \sum_i p_i \right)$$

then dynamical matrix element in statistical hadronization model

$$|M_{fi}|^2 \propto \prod_{i=1}^{N} \Upsilon \cdot p_i$$

dynamics is defined by common factor for each emitted particle and linearly hinges upon cluster spatial size which is proportional to four-momentum of fireball through inverse of energy density

$$|M_{fi}|^2 \propto \frac{1}{\rho^N} \prod_{i=1}^{N} P \cdot p_i$$

-separation of kinematics and dynamics; just inverse density determines the scale of particle production which, in principle should be related to fundamental QCD parameter;

- calculating observables implies then summing up microcanonical averages over all produced fireballs what requires to know their four-momenta and charges, it is not in stat model for hadrons;
- if interested in calculating invariant observables (average multiplicities) cluster momenta are immaterial and only conserved charges and masses matter;
- assume their distributions are the same for N different clusters, it means should be calculated for one fireball (whose volume and charge are the sums of all proper volumes and their charges);
- mass and charge become large enough justifying application of canonical ensemble (introduction of temperature) as good approximation, estimate for mass is 8 GeV to validate canonical ensemble what corresponds to energy density 0,5 GeV/fm^3 ;
- a temperature can be introduced to replace more fundamental description in terms of energy density and this density is related to fireball hadronization;

-

temperature T implies value of energy density at which fireball hadronize and any observable related to hadronization is determined by this temperature
multiplicity of every hadron species

$$\langle n_j \rangle = \frac{VT(2S_j+1)}{2\pi^2} \sum_{n=1}^{\infty} \gamma_S^{N_s n} (\mp 1)^{n+1} \frac{m_j^2}{n} \mathrm{K}_2\left(\frac{n m_j}{T}\right) \frac{Z(\vec{Q} - n\vec{q}_j)}{Z(\vec{Q})}$$

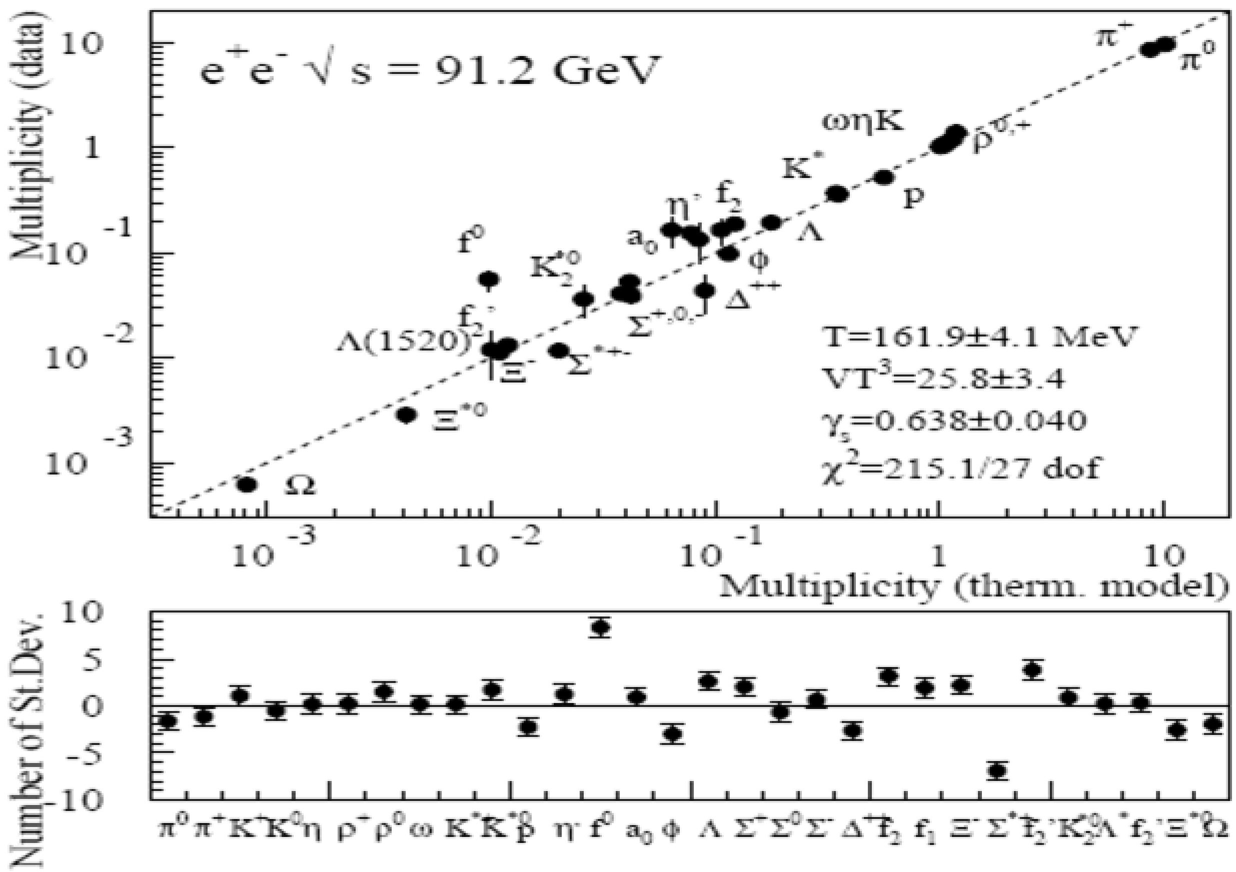
V - (mean) volume, *T* - temperature of the equivalent global cluster, *Z*(**Q**) canonical partition function (chemical factor) depending on initial abelian charges **Q** = (*Q,N,S,C,B*), i.e., electric charge, baryon number, strangeness, charm and beauty; m_j and S_j - mass and spin of hadron *j;* $\mathbf{q}_j = (Q_j, N_j, S_j, C_j, B_j)$ its corresponding charges; upper sign applies to bosons and lower sign to fermions; resonance decays should be added

$$Z(\vec{Q}) = \frac{1}{(2\pi)^N} \int_{-\pi}^{+\pi} d^N\phi \, \mathrm{e}^{i\vec{Q}\phi} \exp\left[\frac{V}{(2\pi)^3} \sum_j (2S_j+1) \int d^3p \log\left(1 \pm \gamma_s^{N_{sj}} e^{-\sqrt{p^2+m_j^2}/T_i - i\vec{q}_i\cdot\phi}\right)^{\pm 1}\right]$$

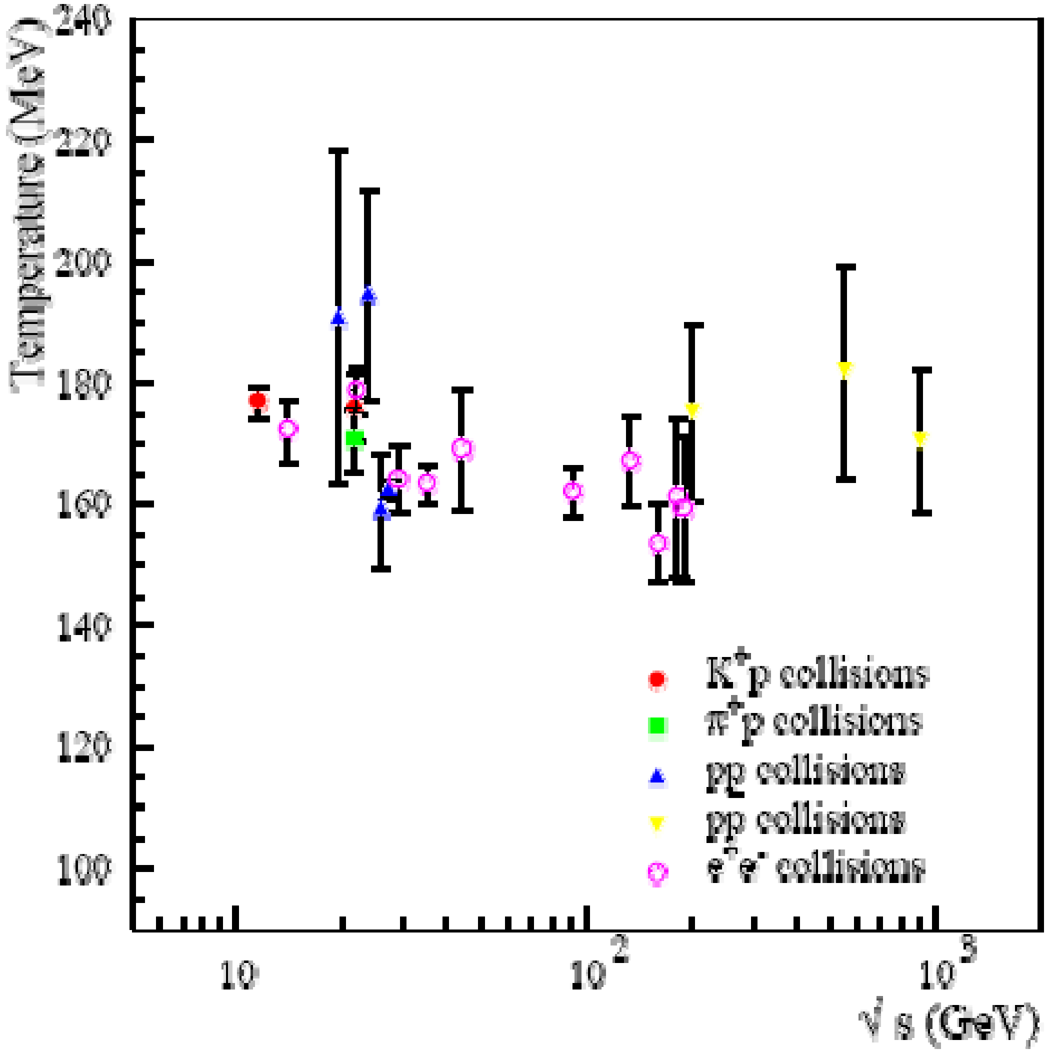
γ_s extra phenomenological factor implementing suppression of hadrons with N_s strange valence quarks with respect to equilibrium value, outside of pure thermodynamical approach and necessary to reproduce data

Canonical statistical model for $e^+ e^-$ - annihilation

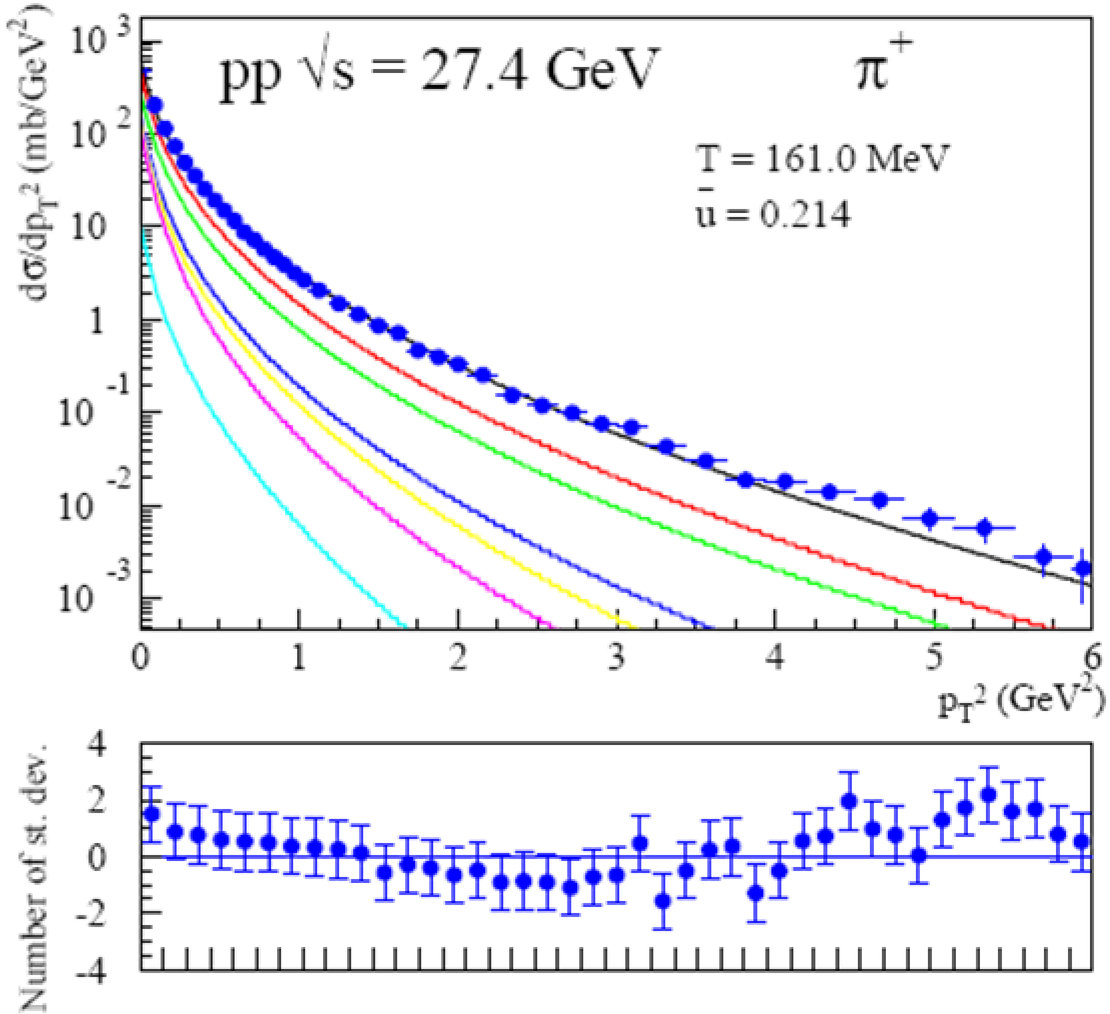
for temperature values of 160 MeV or higher, Boltzmann statistics, corresponding to term n = 1 only is very good approximation (within 1.5%) for all hadrons but pions; for resonances it should be folded with relativistic Breit-Wigner distribution for the mass m_j , γ_S = 0,7.



Temperature is approximately constant over two orders of magnitude in c.m.e. With value 160 – 170 Mev and close to critical and hadronization is a universal process at critical density 0,5 Gev/fm ^{3}



Reproduces transverse momentum spectra in hadronic collisions, in particular, accounts for m_t scaling observed in pp collisions



Energy density can not directly measured

-for example, at SPS projectile energy of 158 Gev/nucleon for Pb+Pb the overall c.m. rapidity is about 2,9
-this is where most of created transv energy should gather if, indeed, initial energy gets stopped down – in lab. frame the target and projectile initial positions are y=0 and 5,8 and a fused reaction volume should be centered about mid-rapidity = 2,9
-high cross section at low E_T results from grazing collisions; shoulder corresponds to gradually increasing overlap, leading to a rapid fall-off indicating that a head-on configuration is reached and no further increase can be expected by mere impact geometry
-tail slope reflects a mean variation resulting from spread of inelasticity in microscopic collisions
-extrapolation to full rapidity space leads to the result that head-on Pb+Pb collisions create a total transverse energy about 1 TeV, this energy is carried on average by about 2500 hadrons created
-detailed kinematical analysis shows this amount of total transverse energy is about 60% of conceivable maximum E_T that would correspond to "complete stopping" of all incoming energy in a single fireball isotropic in momentum space and centered at mid-rapidity
-the remaining fraction of c.m.energy resides in longitudinal motion
-then Bjorken estimate for energy density gives $\varepsilon \approx 3 GeV/fm^3$ (even uncertainties)

$$dE_T / dy \approx \langle p_T \rangle (dn / dy)$$

transverse energy density is related to multiplicity and usually measured in calorimeters by summing over all particles on event in fixed but relatively large solid angle

$E_T = \sum_i E_i \sin\theta_i$ and dE_T / dy is thought to be related to co-moving energy density in longitudinal expansion

$$\varepsilon_{Bj} = (\partial \langle E_T \rangle / \partial y)(1 / \tau_F \pi R^2)$$

Bjorken definition of a measure of energy density in space $\tau_F \approx 1 fm$ and πR^2 effective area of collision

transverse energy distribution in relativistic heavy ion collisions being sensitive to nuclear geometry is used to measure the centrality of individual interactions on event-by-event basis

In heavy ion collisions two possibilities are envisaged:

1) hadronizing systems (fireballs) are much larger

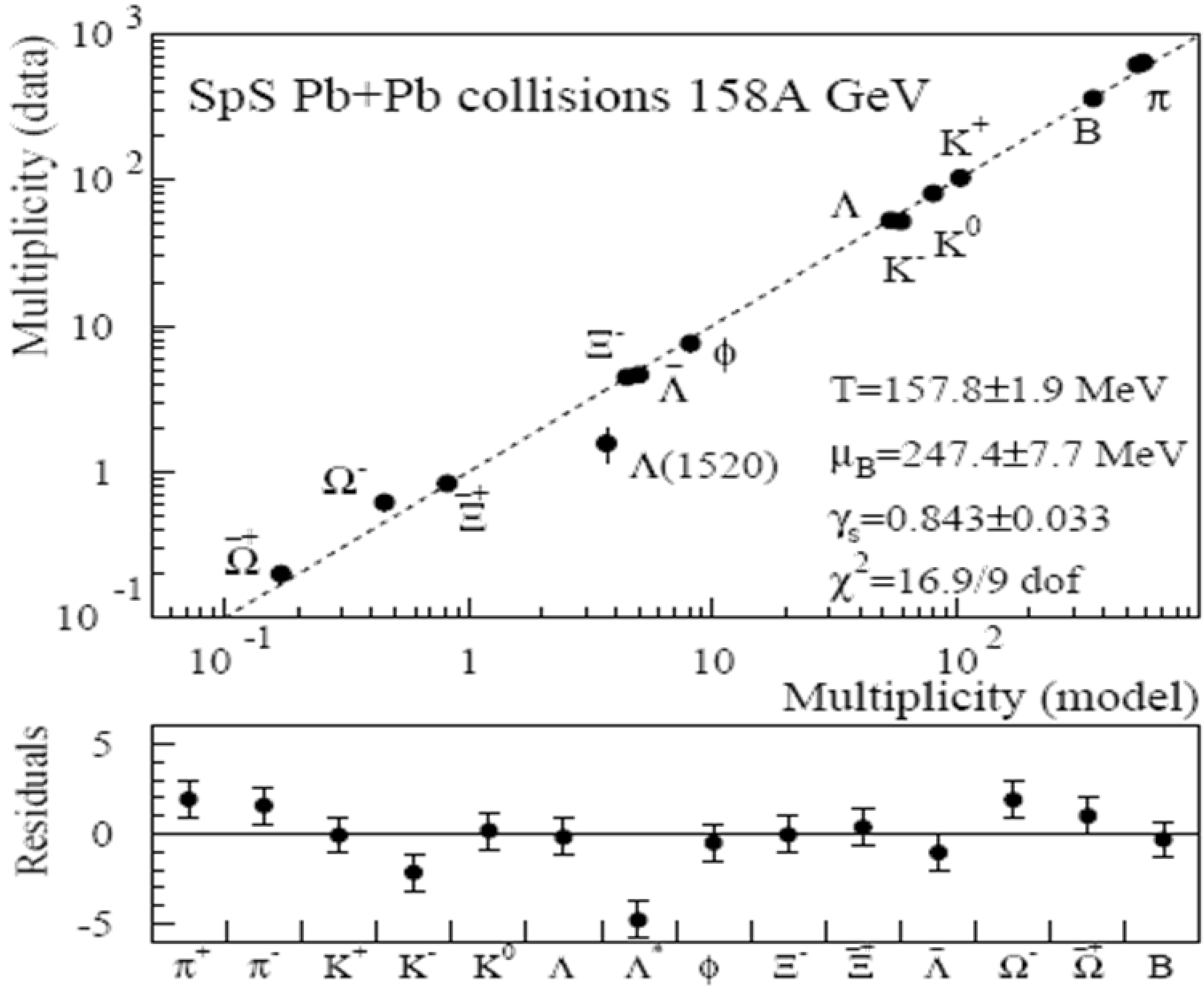
2) hydro, i.e. they are small but in thermal contact with each other due to thermalization which implies strong correlations between their momenta, positions and charge densities

canonical or grand-canonical formalisms apply to individual fireball; transition from canonical to grand-canonical effectively takes place when cluster volume is of order 100 fm^3 at energy density of 0,5 GeV/fm^3 temperature and chemical potential depend on space-time

$$\langle n_j \rangle = \frac{VT(2S_j+1)}{2\pi^2} \sum_{n=1}^{\infty} \gamma_S^{N_s n} (\mp 1)^{n+1} \frac{m_j^2}{n} \mathrm{K}_2\left(\frac{n m_j}{T}\right) \exp\left[n \vec{\mu} \cdot \vec{q}_j / T \right]$$

hydro description is principal feature of heavy ion collisions due to early thermalization in partonic phase, phenomenon which does not occur in elementary collisions

if rapidity distributions are wide enough and small variations of thermo parameters of fireballs around midrapidity it gives rapidity densities as well; valid for RHIC but not AGS and SPS where rapidity distributions as in pp-collis


SpS Pb+Pb collisions 158A GeV
Multiplicity (data)
Multiplicity (model)
T=157.8±1.9 MeV
μB=247.4±7.7 MeV
γs=0.843±0.033
χ2=16.9/9 dof
π
B
K+
K0
K-
Λ
φ
Ξ-
Λ̄
Λ(1520)
Ω-
Ξ̄+
Ω̄+
Residuals
π+ π- K+ K- K0 Λ Λ* φ Ξ- Ξ̄ Λ̄ Ω- Ω̄ B

Statistical model explains increase of relative strangeness production with respect to hadronic collisions

effect of global volume increase at transition from pp to AA-collisions;

in elementary collisions a volume is small for chemical factors of strange particles

and canonical suppression,requires increase of γ_C

because neutral mesons with

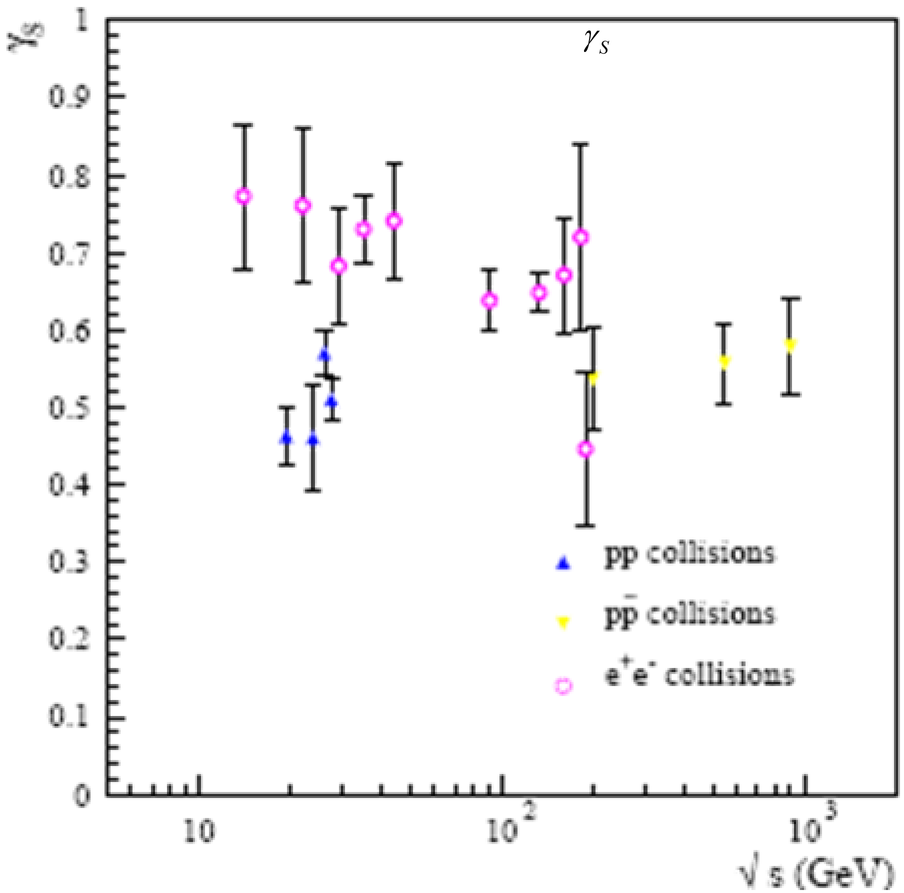
strange quarks and not suffering from canonical

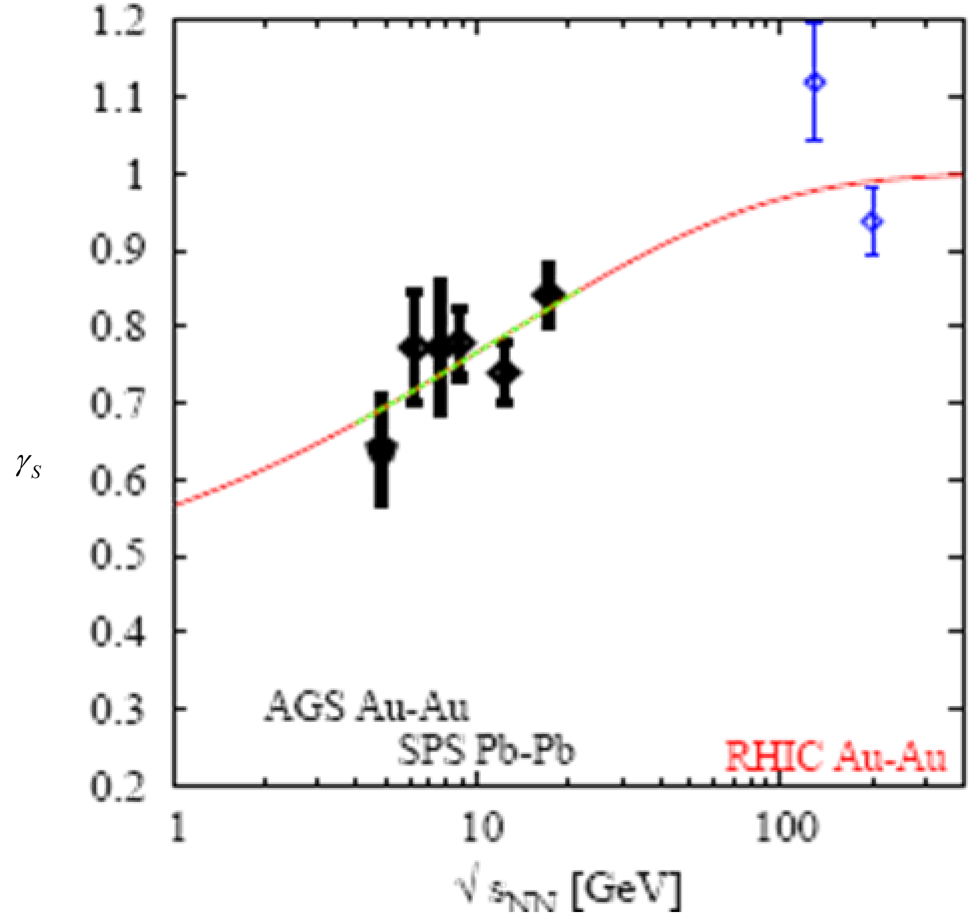
suppression are more abundant in AA-collisions;

at RHIC energies γ_C =1 in central collisions but it is

purely empirical parameter;

this observation does not clarify strangeness enhancement





γ_S does not show special regularities in elementary collisions

Centrality dependence of strangeness production provides interpolation from pp–collisions at large values of impact parameter to head-on heavy ion collisions at low values

- highest enhancement for Ω^-, lowest for Λ
- model in which possible to take canonical – grand-canonical approach mixed (strangeness is enforced by γ_s) but electric and baryon are introduced by chemical potentials
- it means (to explain $\gamma_s < 1$) small sub-regions within large fireball where only strangeness is exactly vanishing even for central collisions
- no tendency of volume of S=0 to increase

Canonical suppression has no effect on ϕ -meson consisting strange quarks, its relative yield increases from peripheral to central

- geometric explanation based on superposition of emission from hadron-resonance gas at full chemical equilibrium with γ_S=1 defined as core (highly dense volume area) and from NN-collisions at boundary of overlapping region defined as corona (low density area) from which produced particles escape unscathed
- difference in centrality dependence between AuAu at RHIC and PbPb at SPS and centrality dependence of strangeness enhancement finds a natural explanation in core-corona model
- this second source reproduces centrality dependence of ϕ - meson relative yield to increase from peripheral to central
- thermalization occcurs at relatively early stage over large region in heavy ion collisions but at late stage (close to hadroniz) over small region

Hadron production at chemical equilibrium

A.Andronic, P.Braun-Munzinger, J.Stachel, NPA 772 (2006) 167, PLB 673 (2009) 142

from E_{beam}/A=2 GeV to $\sqrt{s_{NN}}$=200 GeV

(central collisions)

- conservation (on average) of the quantum numbers:
  i) baryon number: $V\sum_i n_i B_i = N_B$
  ii) isospin: $V\sum_i n_i I_{3i} = I_3^{tot}$
  iii) strangeness: $V\sum_i n_i S_i = 0$
  iv) charm: $V\sum_i n_i C_i = 0.$
- interactions: excluded volume correction
- widths of resonances taken into account
- minimize: $\chi^2 = \sum_i \frac{(R_i^{exp} - R_i^{therm})^2}{\sigma_i^2}$

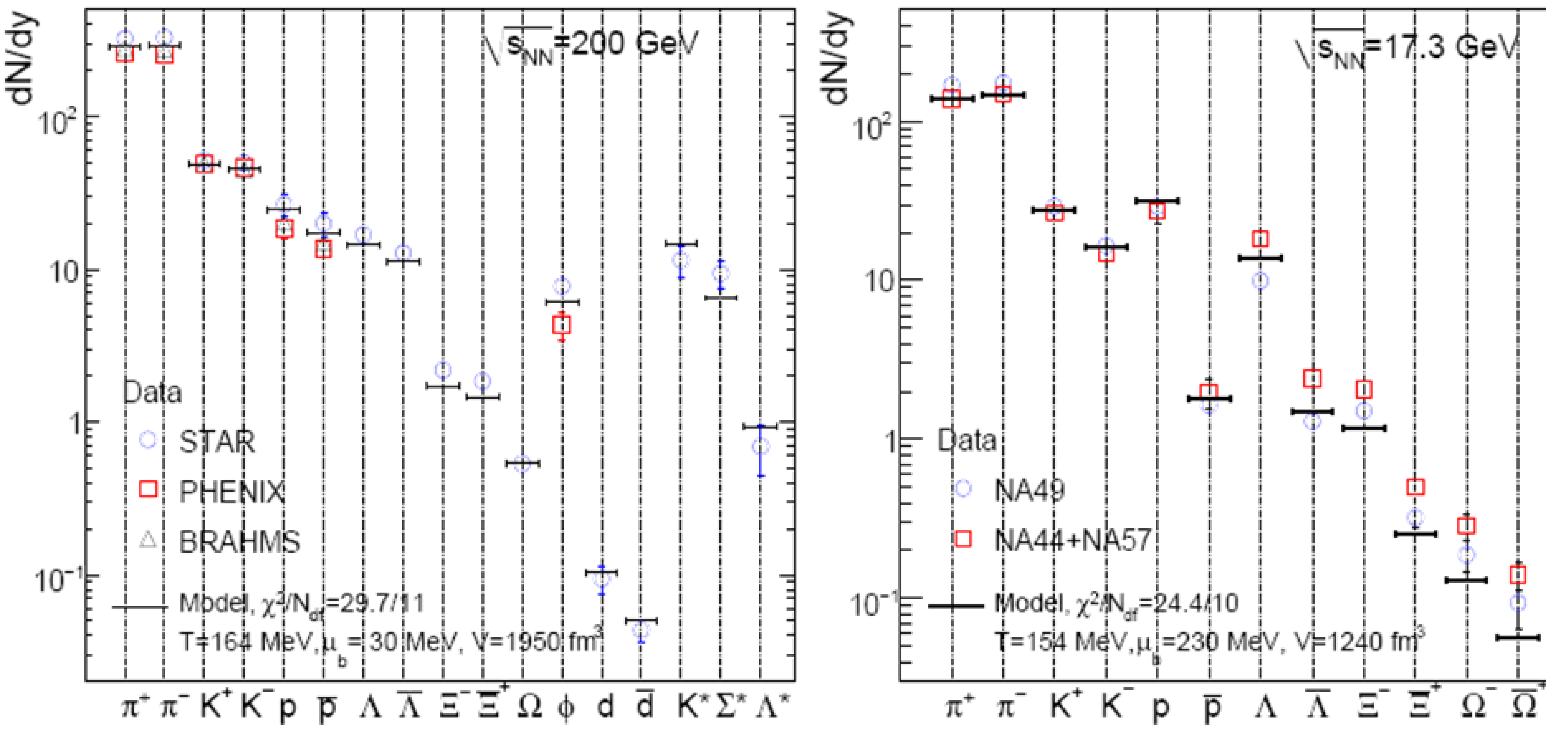
▷ R_i: hadron yield ($\Rightarrow T$, μ_b, V) or yield ratio (no V)

▷ Data: 4π or $\mathrm{d}N/\mathrm{d}y$ data (our choice, unless stated 4π)

? extra parameters: γ_S, λ's (physical meaning?)

Latest PDG hadron mass spectrum (up to 3 GeV)

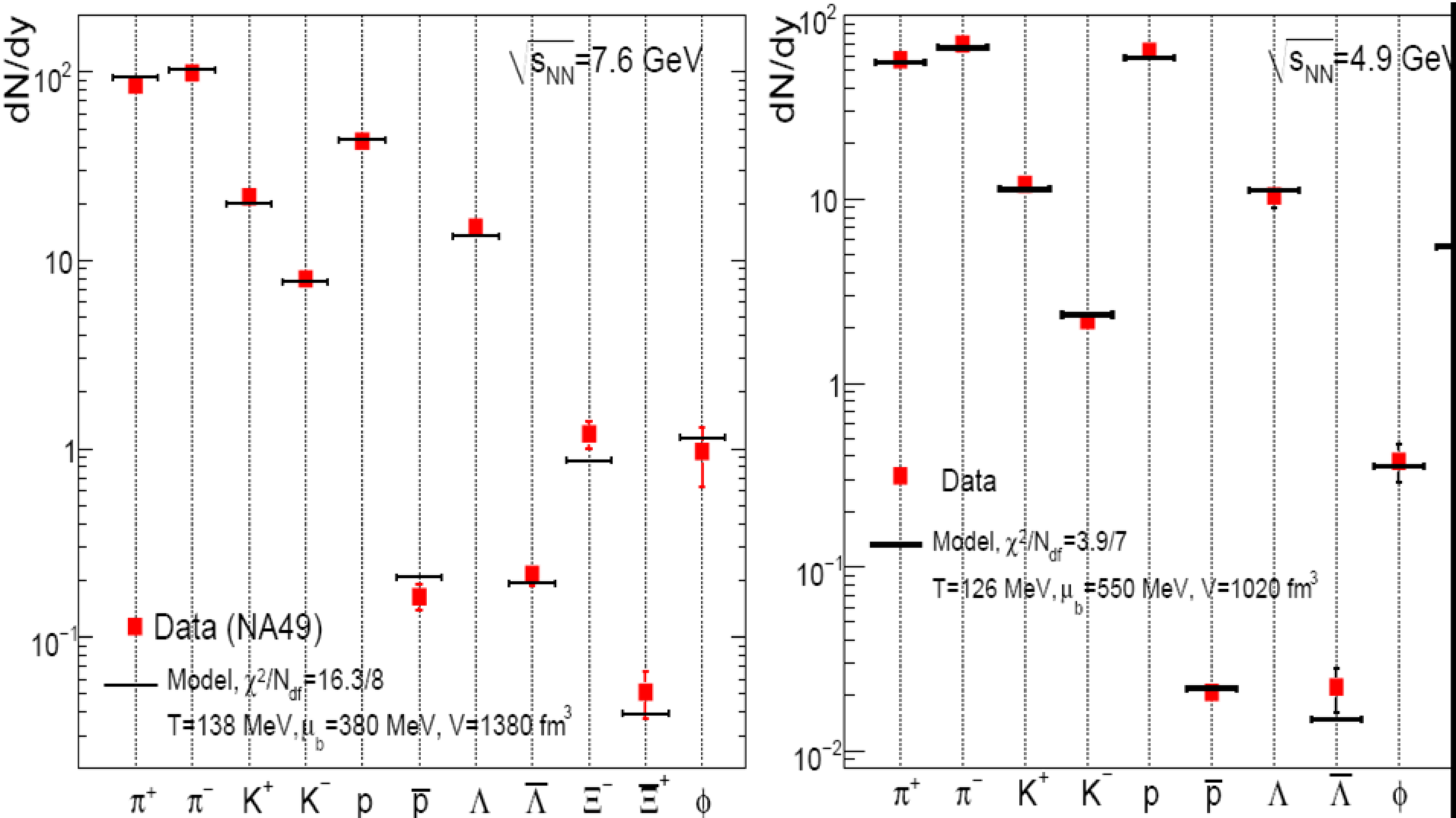
RHIC (200 GeV) and SPS (17.3 GeV)



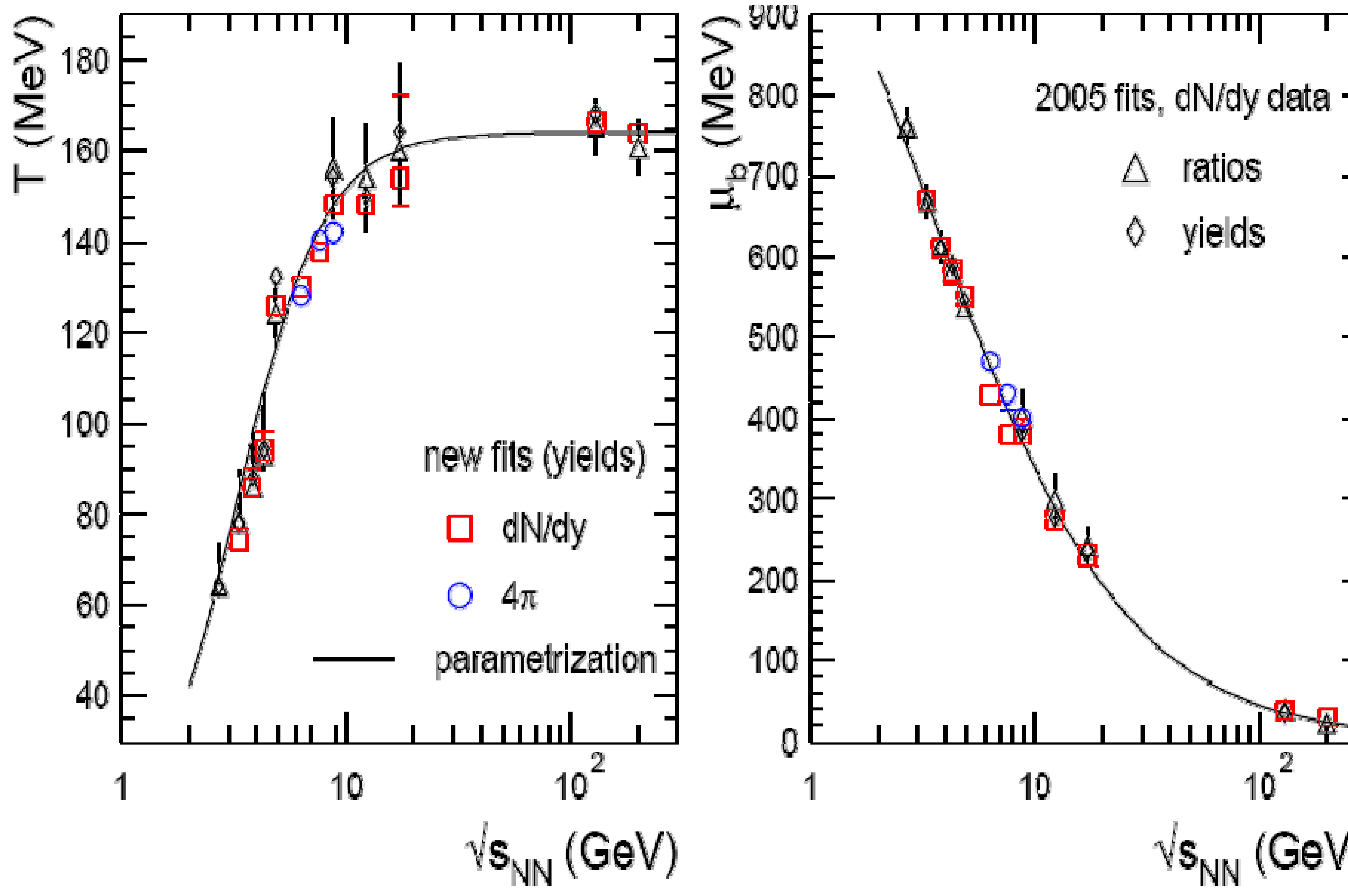
only STAR data: T=162 MeV, μ_b=32 MeV, V=2400 fm^3, χ^2/N_{df}=9.0/11

only NA49 data: T=148 MeV, μ_b=215 MeV, V=1660 fm^3, χ^2/N_{df}=36/10

SPS (30 AGeV) and top AGS (10.5 AGeV)

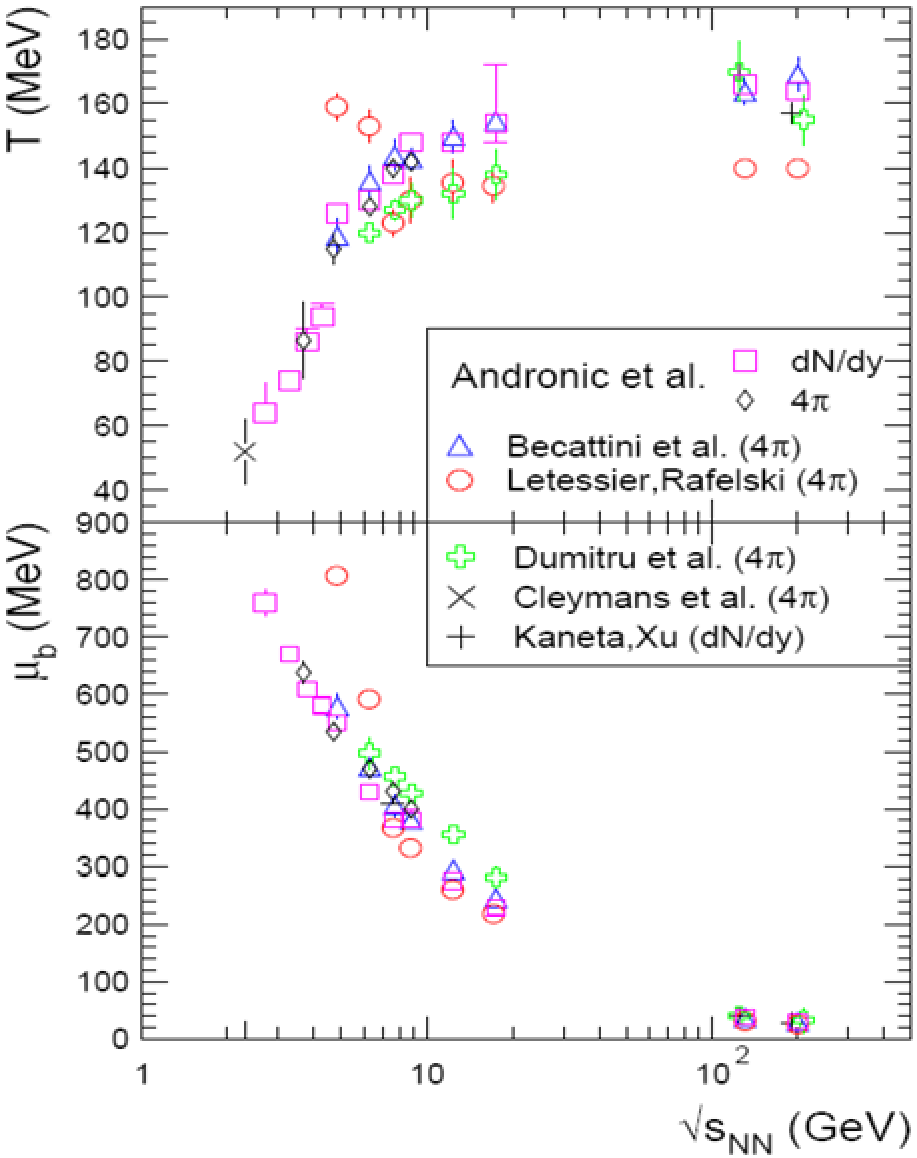


Energy dependence of T, μ_b (parametrizations)



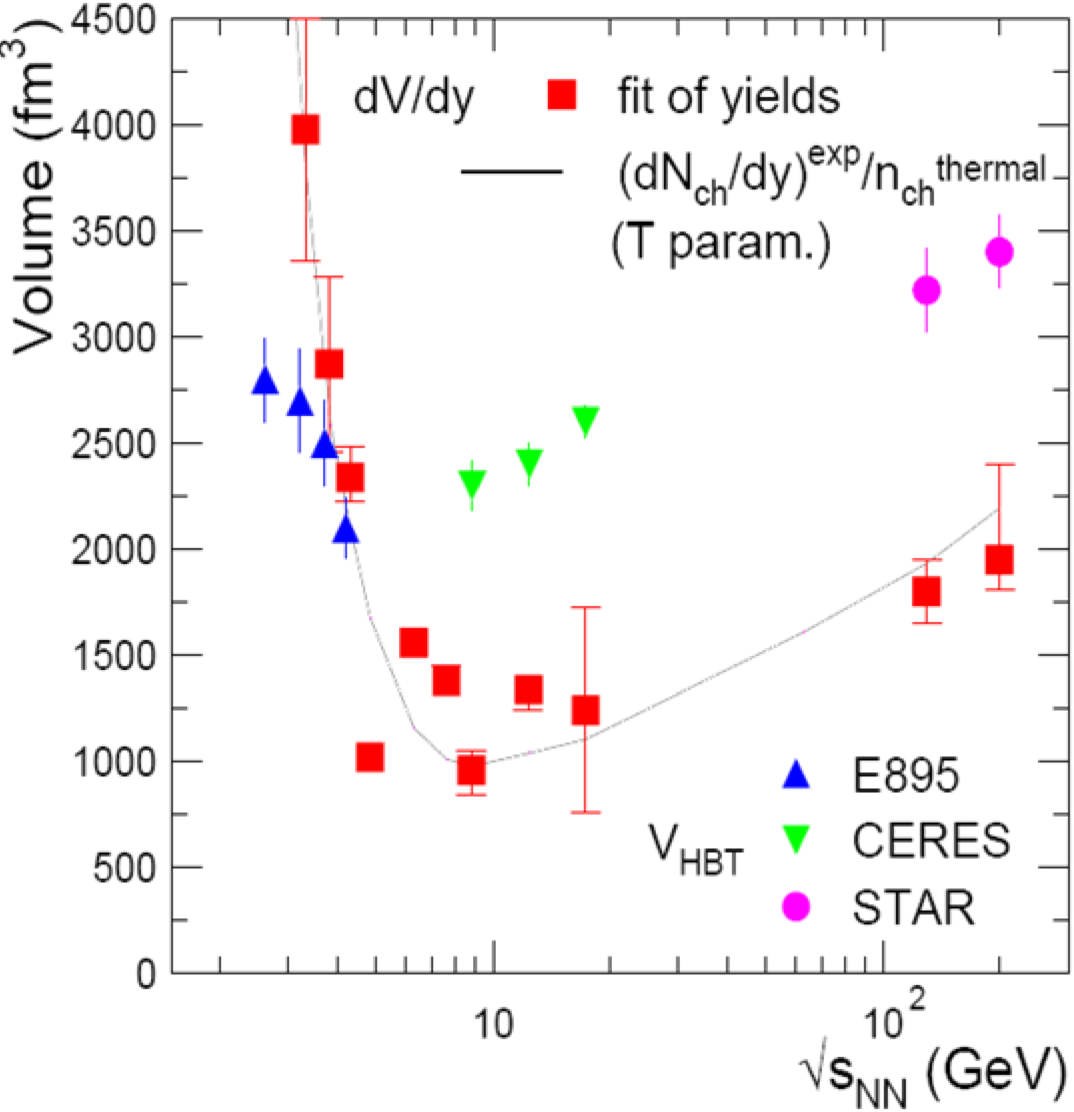
thermal fits exhibit a limiting temperature: $T_{lim} = 164 \pm 4$ MeV

Energy dependence of the thermal parameters



- Becattini et al.: $+\gamma_S$ - hep-ph/0511092,0806.4100
- Rafelski et al.: $+\gamma_{S,q}$, λ_{q,S,I_3} - nucl-th/0504028
  γ_S=0.18,0.36,1.72,1.64,...
  γ_q=0.33,0.48,1.74,1.49,1.39,1.47...
- Dumitru et al.: inhomogeneous freeze-out (δT, $\delta\mu_B$) - nucl-th/0511084

Energy dependence of the freeze-out volume



dV/dy: volume for one unit rapidity (at midrapidity)

minimum at $T \to T_{lim}$

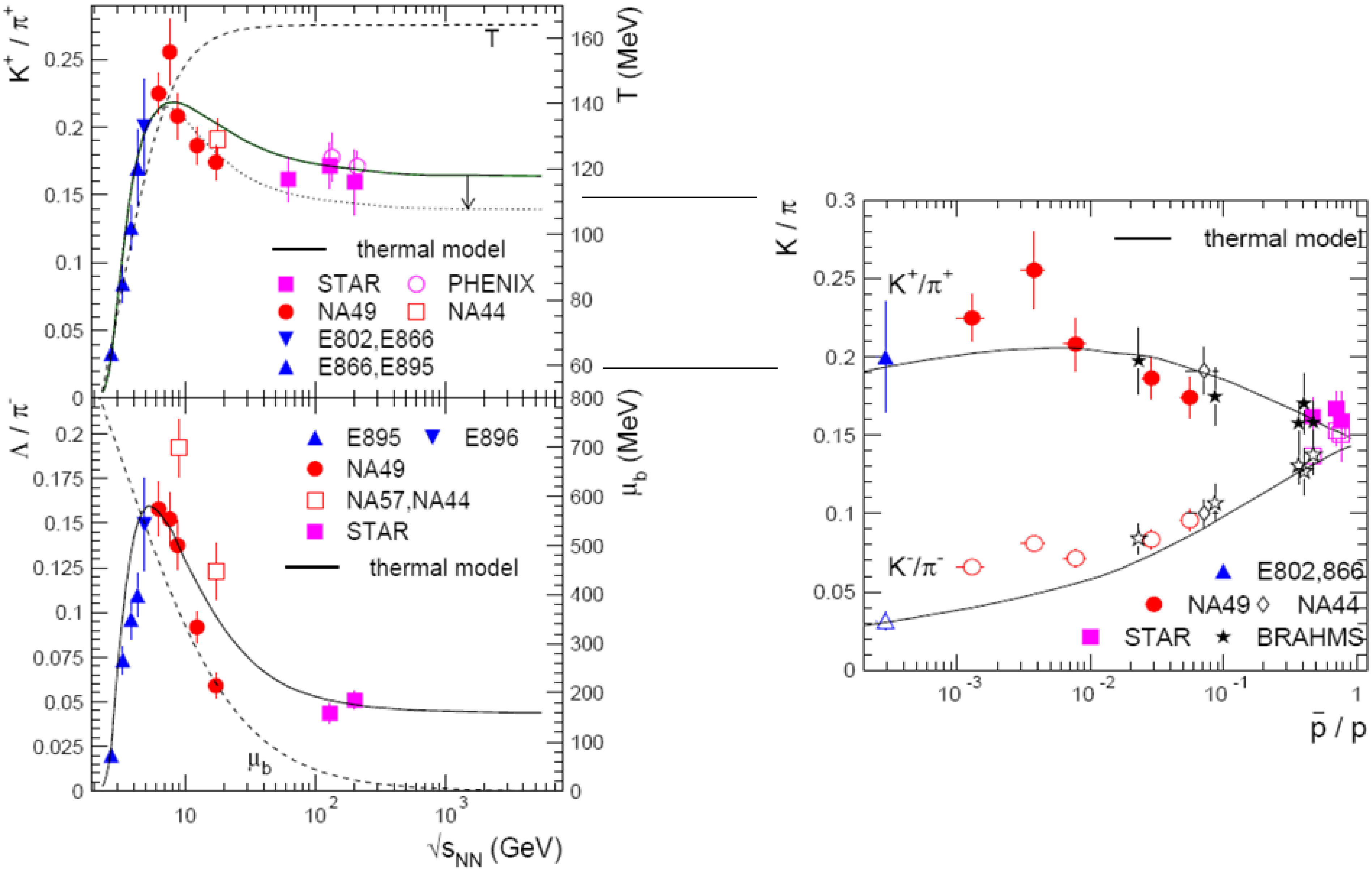
V_{HBT}:

CERES, PRL, 90 (2003) 022301

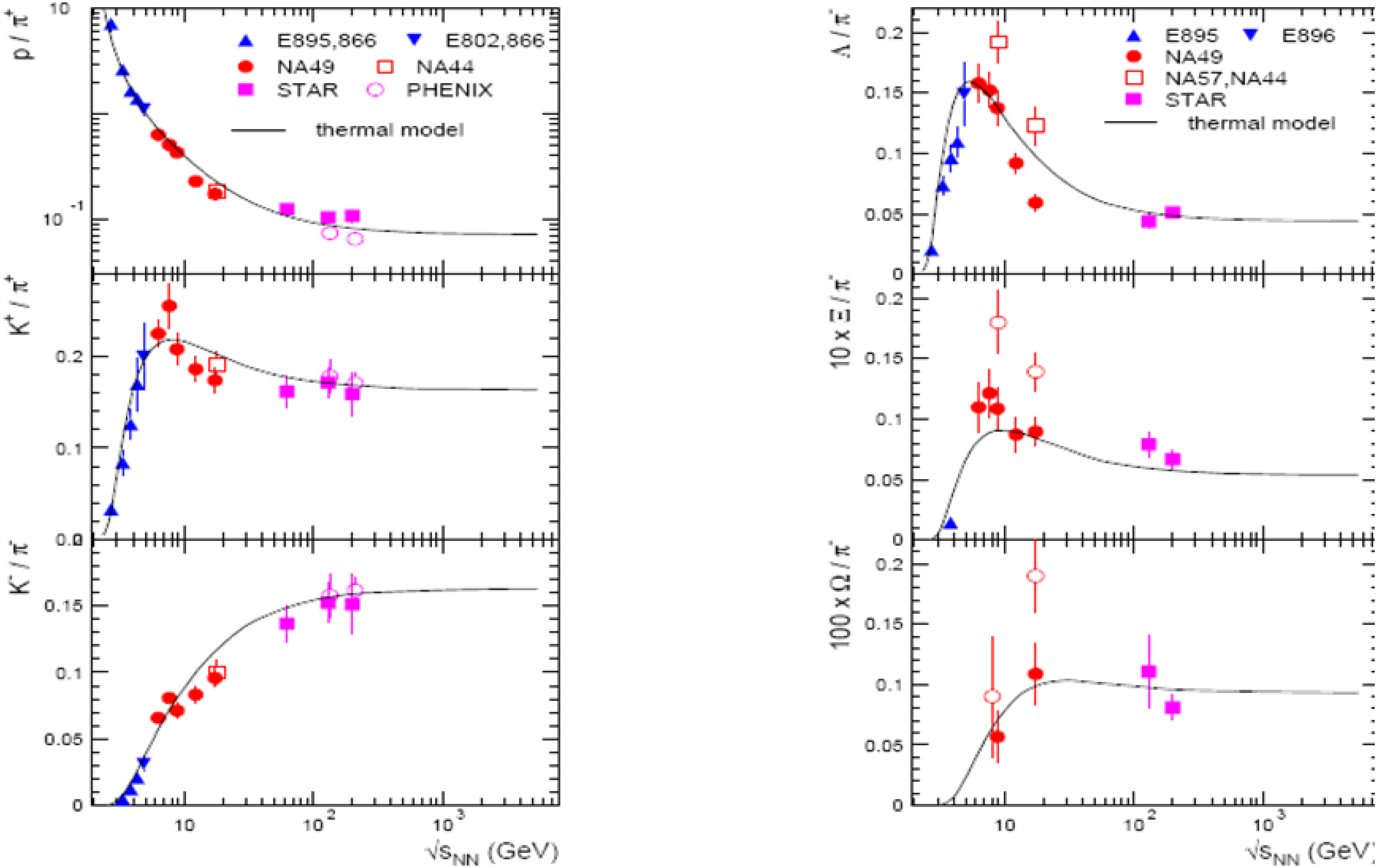
($\lambda_f \simeq$1 fm)

not fully understood dependen

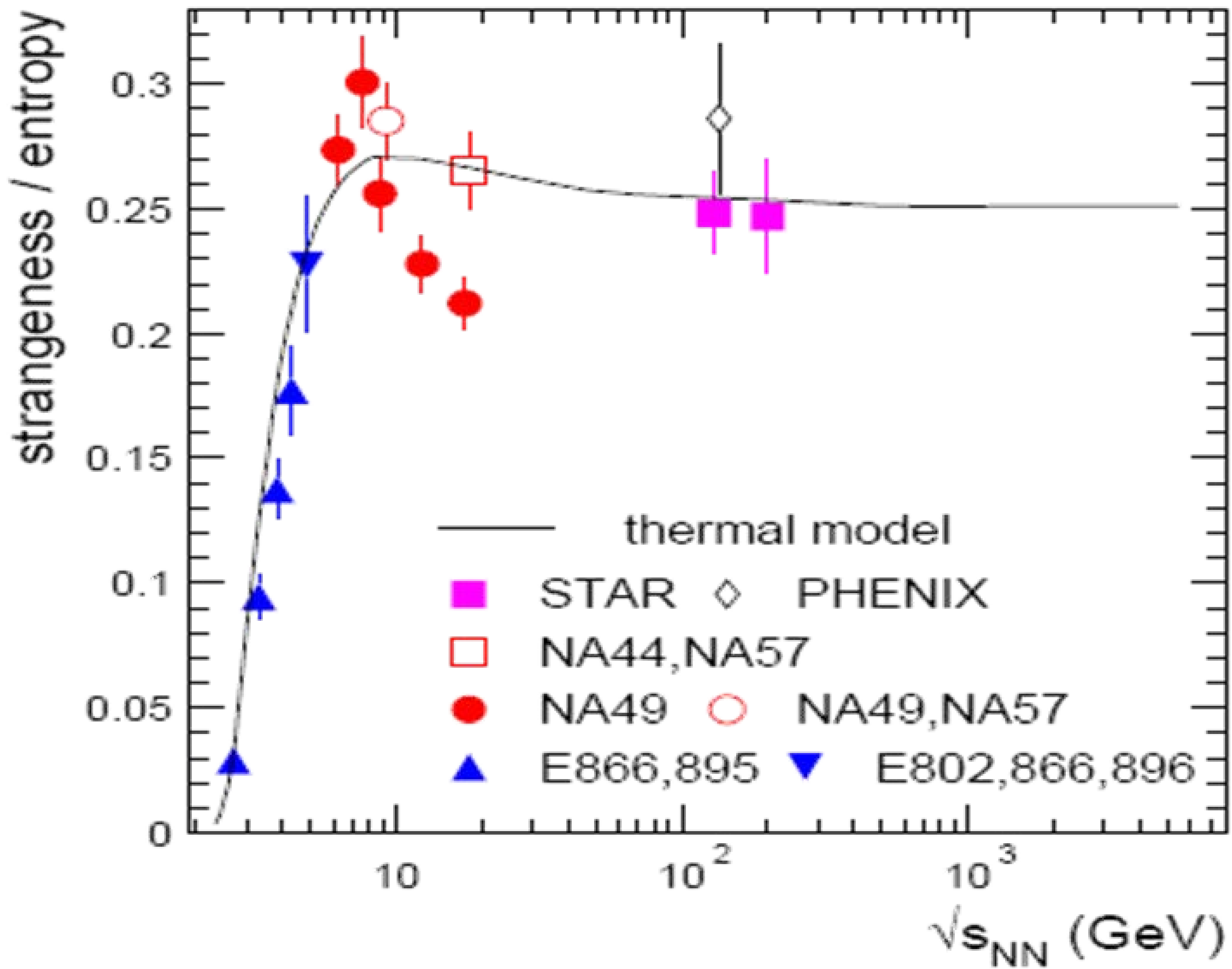
Particle ratios



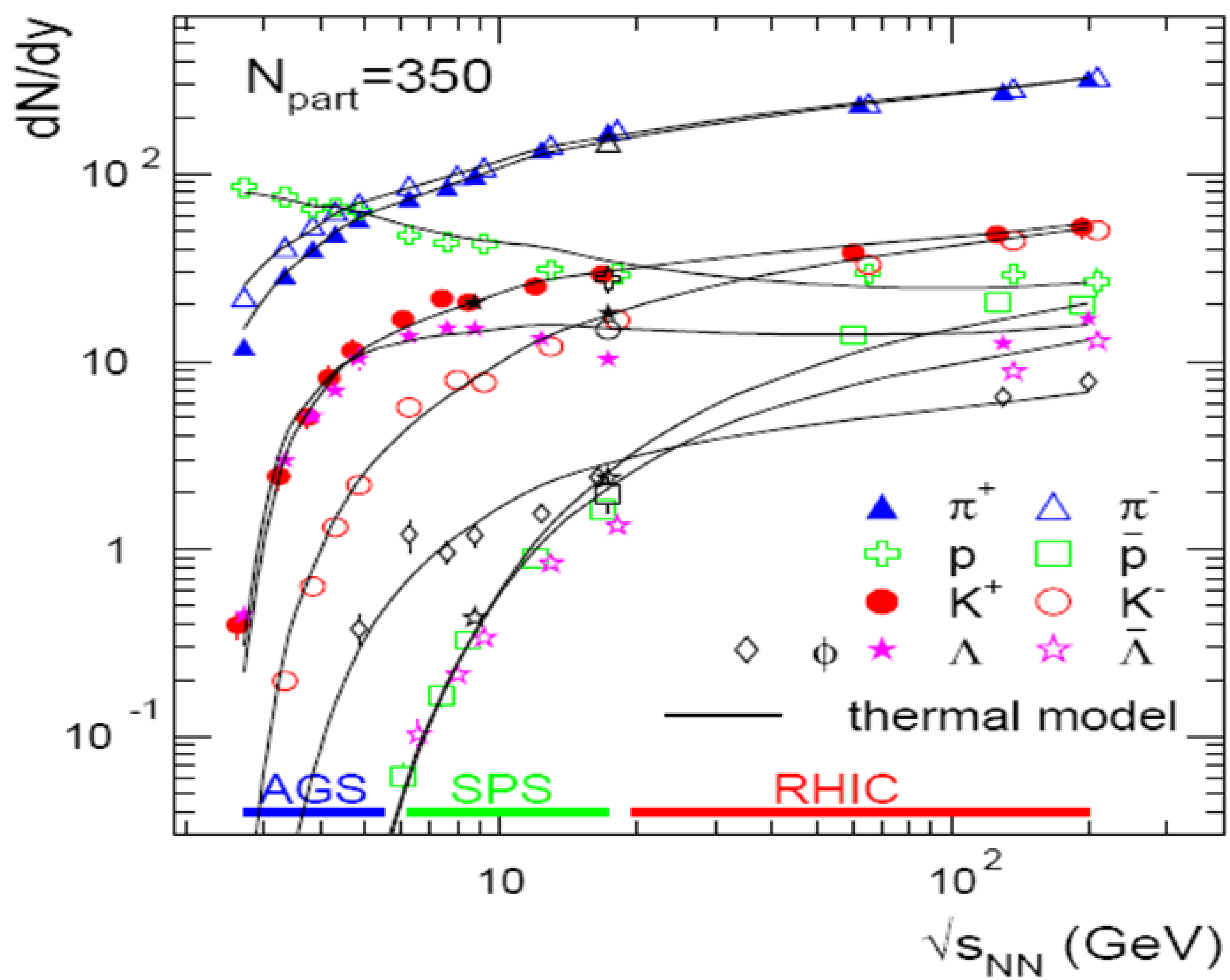
More particle ratios



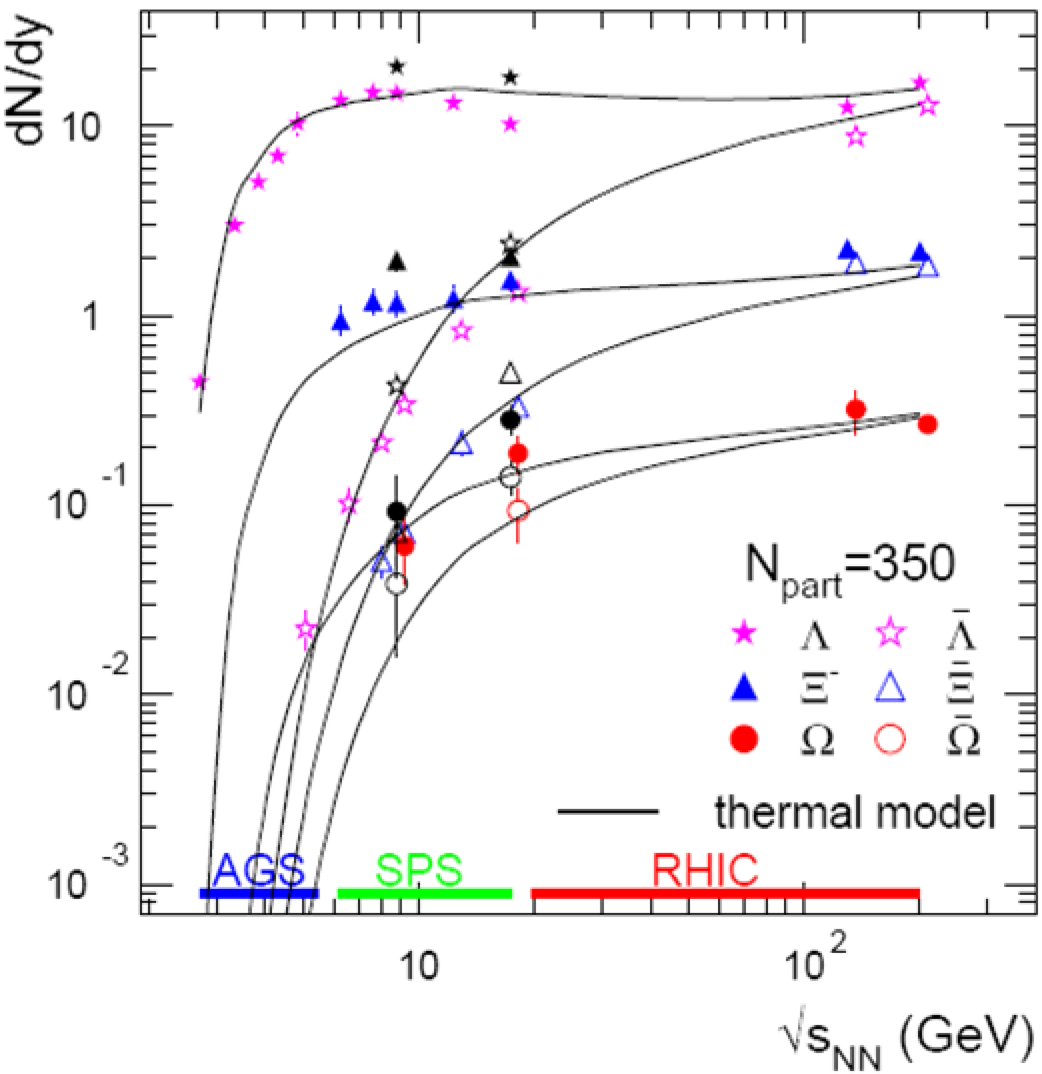
A global ratio: strangeness/entropy



Yields at mid-rapidity



Yields at mid-rapidity: hyperons



production (dN/dy) at 8 AC

Λ: 9.0	$\bar{\Lambda}$: $1.4 \cdot 10^{-3}$
Ξ: 0.27	$\bar{\Xi}$: $3.2 \cdot 10^{-4}$
Ω: $5.4 \cdot 10^{-3}$	$\bar{\Omega}$: $5.4 \cdot 10^{-5}$

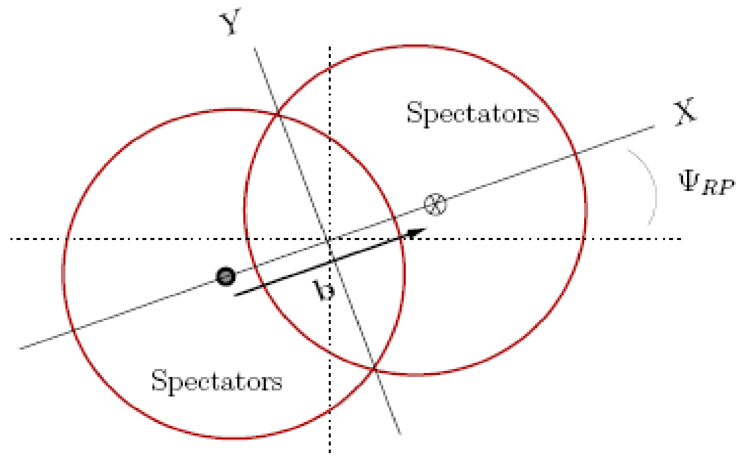
- thermal fits work remarkably well (AGS-RHIC) $\Rightarrow$ (T, μ_b, V)
- limiting temperature $\Rightarrow$ phase boundary (LQCD)

  $\rightarrow$ for the skeptics... *LHC case will be decisive* ("bigger,...")
- indications (bad fits) for the critical point? ...maybe, at SPS...

  ...but not a strong case due to disagreements between experiments

indications for strangeness non-equilibrium (γ_S) in central collisions?
NOT (others: not at SIS and RHIC, *some* at AGS-SPS, *some* at RHIC)

two nuclei collide off-center at impact parameter **b** and oriented at an angle Ψ_{RP} with respect to lab axes as shown, spectator nucleons continue down beam pipe leaving behind excited almond shaped region. The impact parameter **b** is a transverse vector **b**=(b_x, b_y) pointing from center of one nucleus to the center of the other, X and Y are reaction plane coordinates, not the lab coordinates.

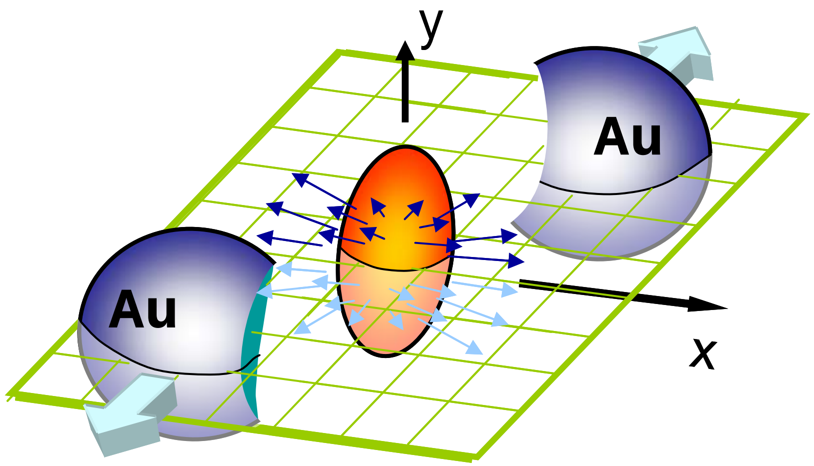


elliptic flow is defined as anisotropy of particle production with respect to the reaction plane

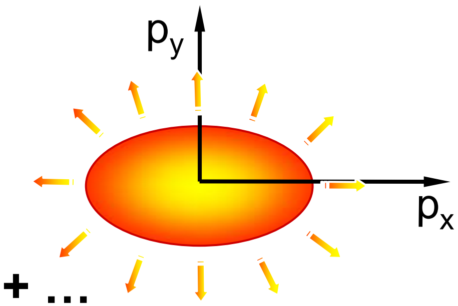
$$v_2 \equiv \left\langle \frac{p_X^2 - p_Y^2}{p_X^2 + p_Y^2} \right\rangle,$$

or second Fourier coefficient of azimuthal distribution $\langle \cos(2(\phi - \Psi_{RP})) \rangle$. Elliptic flow can also be measured as a function of transverse momentum $p_T = \sqrt{p_X^2 + p_Y^2}$ by expanding the differential yield of particles in a Fourier series

$$\frac{1}{p_T}\frac{dN}{dy\,dp_T\,d\phi} = \frac{1}{2\pi p_T}\frac{dN}{dy\,dp_T}\left(1 + 2v_2(p_T)\cos 2(\phi - \Psi_{RP}) + \ldots\right).$$



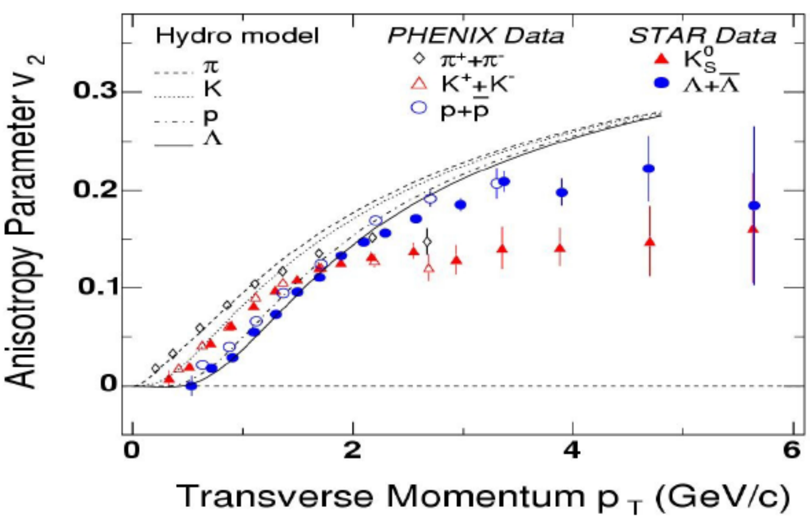
Elliptic Flow (V2)

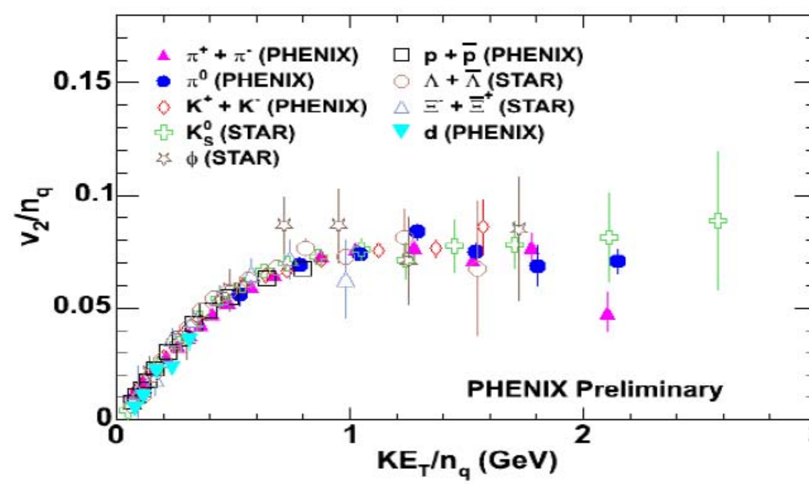


$$dN/d\phi = 1 + 2\, V_2 \cos 2\,(\phi - \psi) + \ldots$$

ellipses denote still higher harmonics, v_4, v_6 and on, flow can be measured as a function of impact parameter, particle type and rapidity

Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**





for a mid-peripheral collision $(b \simeq 7\,\text{fm})$ the average elliptic flow $\langle v_2 \rangle$ is approximately 7% Surprising large!

For instance, ratio of particles in the X direction to the Y is $1+2v_2 : 1-2v_2 \simeq 1.3:1$. At higher transverse momentum the elliptic flow grows and at $p_T \sim 1.5$ GeV elliptic flow can be as large as 15%.

such a useful observable because it is rather direct probe of the response of QCD medium to high energy density created during the event. If mean free path is large compared to the size of interaction region then produced particles will not respond to the initial geometry. If the transverse size of nucleus is large compared to interaction length scales involved, hydrodynamics is appropriate theoretical framework to calculate the response of medium to the geometry.

calculations based on ideal hydrodynamics do a fair reasonable job in reproducing observed elliptic flow, there has never been even remotely successful model of flow if $\eta/s > 0.4$

the reaction plane angle, Ψ_{RP}, is also determined experimentally, for example, by event plane method which is conceptually the simplest one

Traditionally the average <···> is taken with respect to the number of participants in the transverse plane, for example

$$\langle y^2 - x^2 \rangle = \frac{1}{N_p}\int \mathrm{d}x\,\mathrm{d}y\,(y^2 - x^2)\frac{\mathrm{d}N_p}{\mathrm{d}x\,\mathrm{d}y}$$

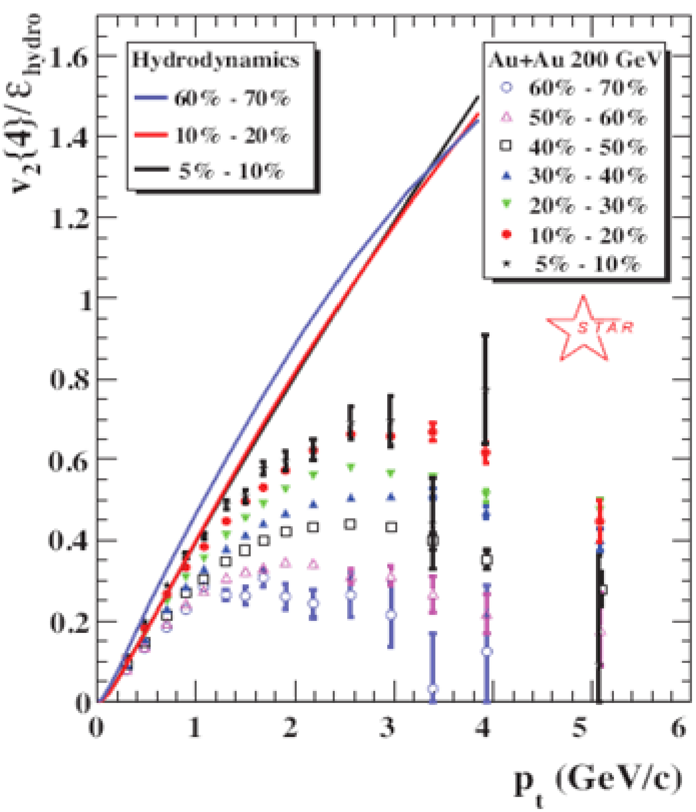
viscous correction

$$(p_T / T)^2 (\ell_{mfp} / L)$$

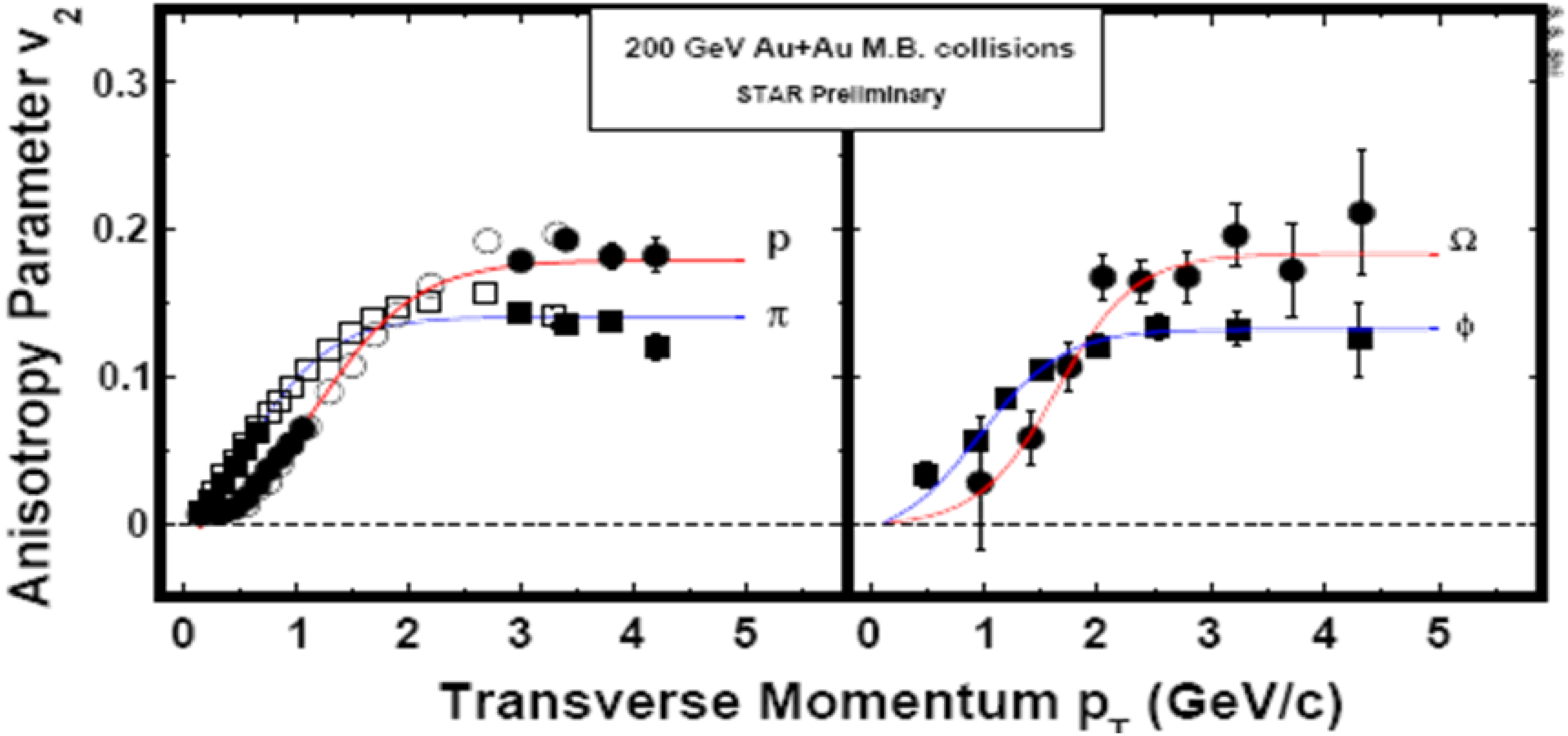
L characteristic length scale

Then for the moment returning to previous Fig. which plots the asymmetry parameter versus centrality and may also find root mean square radius $R_{\mathrm{rms}} = \sqrt{\langle x^2 + y^2 \rangle}$

which is important for categorizing the size of viscous corrections.

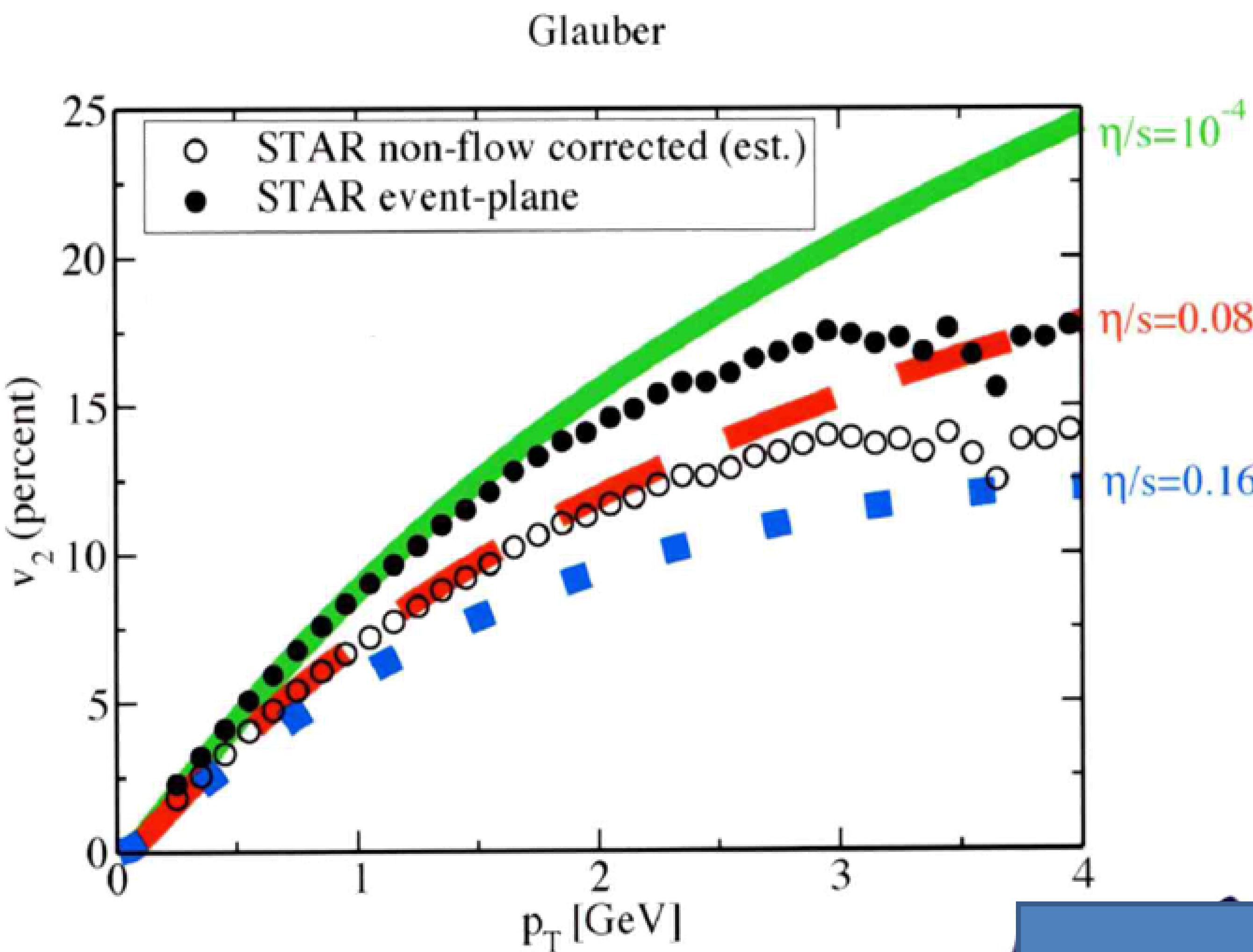


collected all essential definitions of $\varepsilon_{s,part}$, centrality and v_2, and are now in a position to return to the physics. The scaled elliptic flow v_2/ε measures the response of medium to the initial geometry. Fig. shows $v_2(p_T)/\varepsilon$ as a function of centrality, 0–5% being the most central and 60 - 70% being the most peripheral and we see a gradual transition from a weak to a strong dynamic response with growing system size because of transitioning from kinetic to hydro regime. Elliptic flow $v_2(p_T)$ as measured by the STAR for different centralities. The measured elliptic flow has been divided by the eccentricity $-\varepsilon_{hydro} \approx \varepsilon_{s,part}$. Curves are ideal hydro calculations



compares elliptic protons

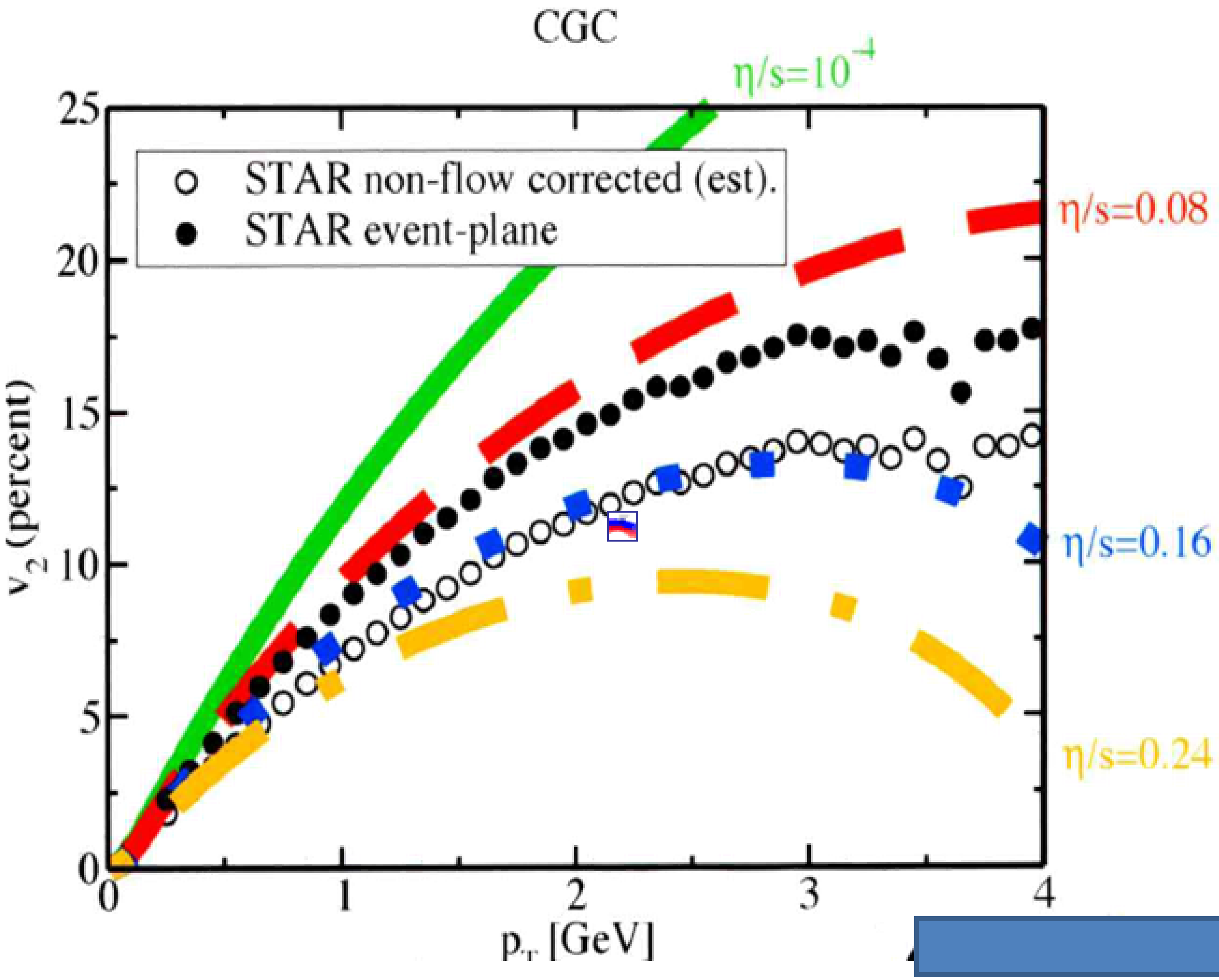
and pions to the flow of the multi-strange hadrons Ω^- and ϕ. (These hadrons have valence quark content sss and $s\bar{s}$ respectively.) The important point is that the Ω^- is nearly twice as heavy as the proton and more importantly, does not have a strong resonant interaction analogous to the Δ. For these reasons the hadronic relaxation time of the Ω^- is expected to be much longer than the duration of the heavy ion event. Nevertheless the Ω shows nearly the same elliptic flow as the protons. This provides fairly convincing evidence that the majority of the elliptic flow develops during a deconfined phase which hadronizes to produce a flowing Ω^- baryon.



entropy is proportional to participant number $s(\tau_0, \vec{x}_{tr}) \propto dN_p / dxdy$

hydrodynamic fields are initialized at a time $\tau_0 \sim 1 fm/c$

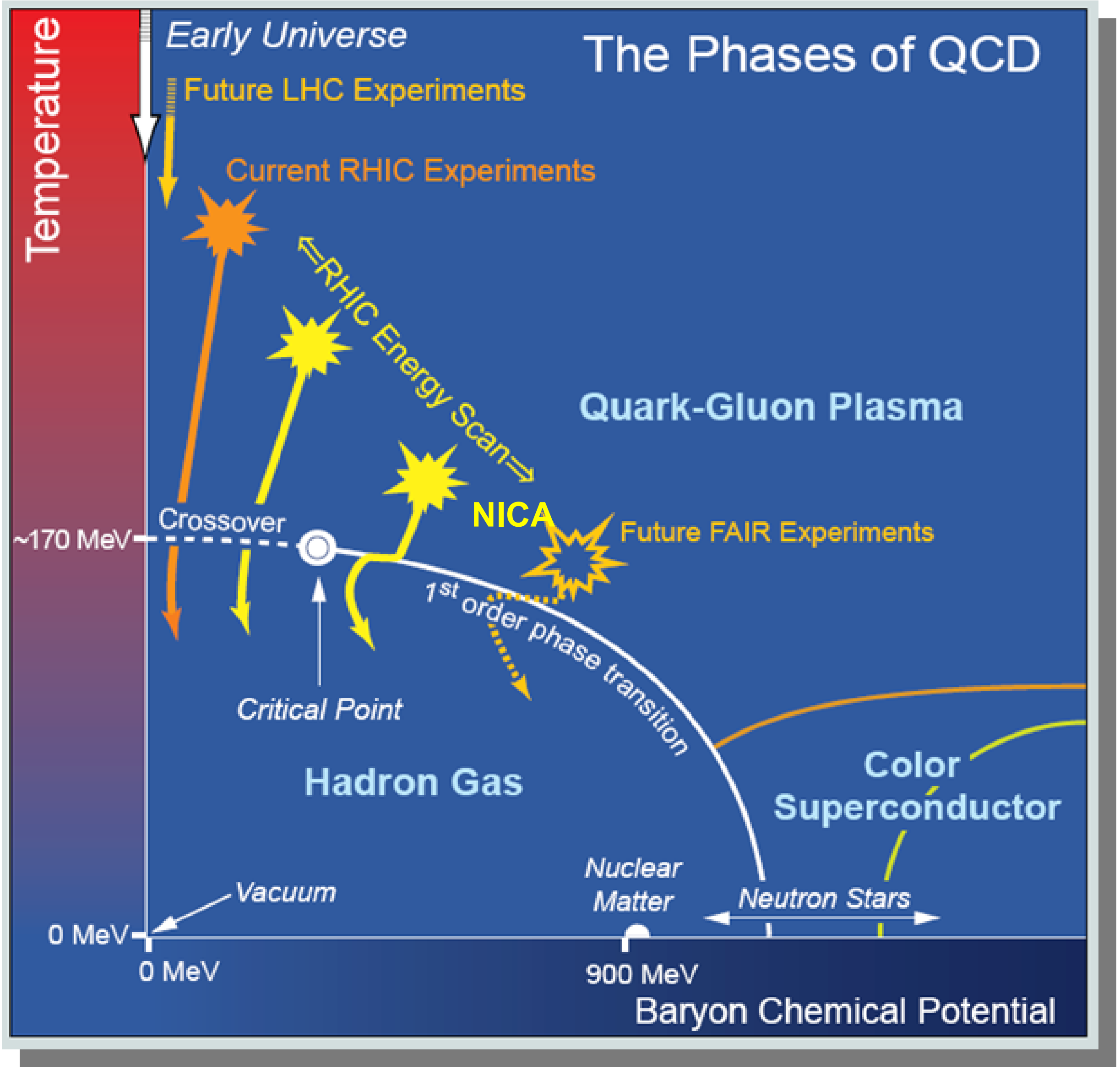
which is arbitrary in a sense but final results are not sensitive this value both in kinetic theory and hydrodynamics



Initial transverse flow is zero

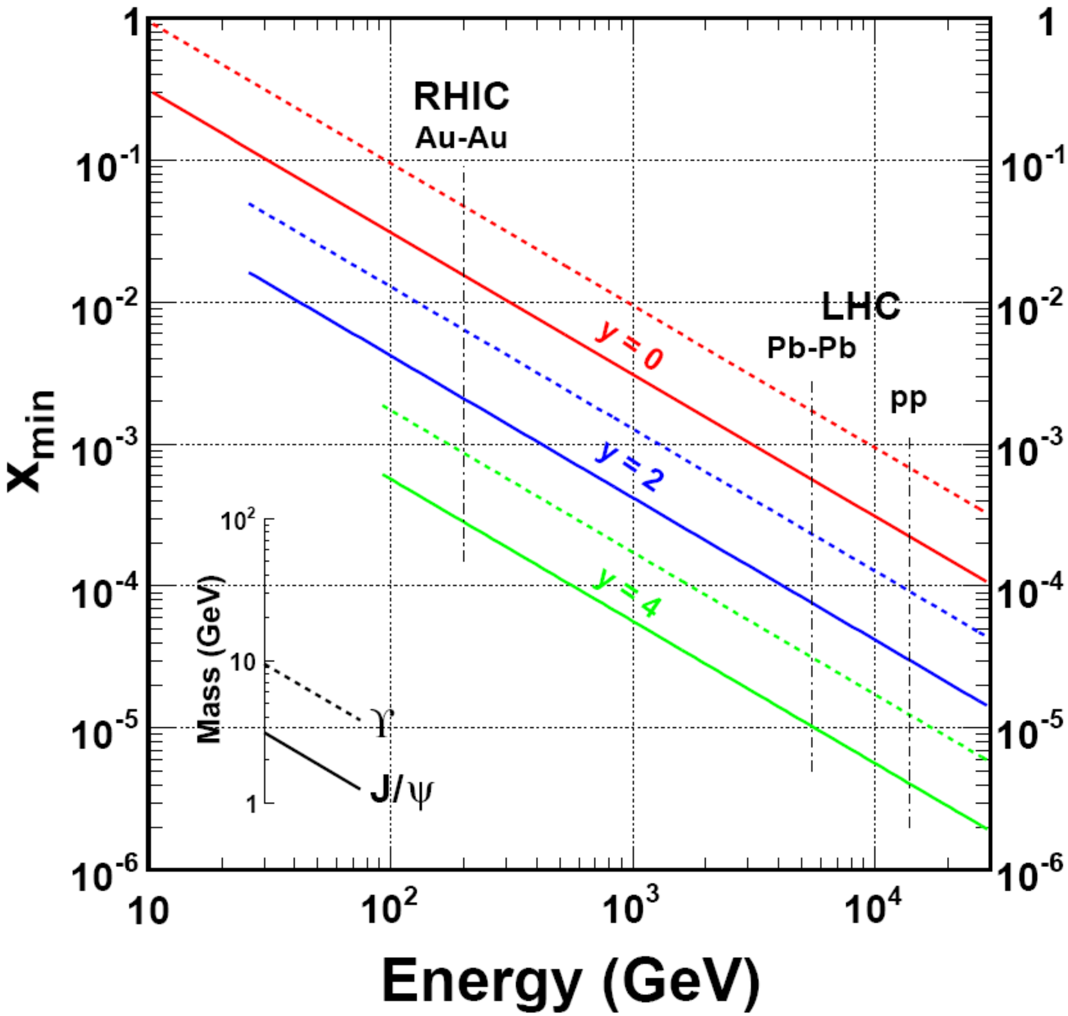
$$u_x(\tau_0, \vec{x}_{tr}) = u_y(\tau_0, \vec{x}_{tr}) = 0$$

The phase diagram of hot and dense QCD



NSAC LRP 2008

LHC: extending the low-x Reach

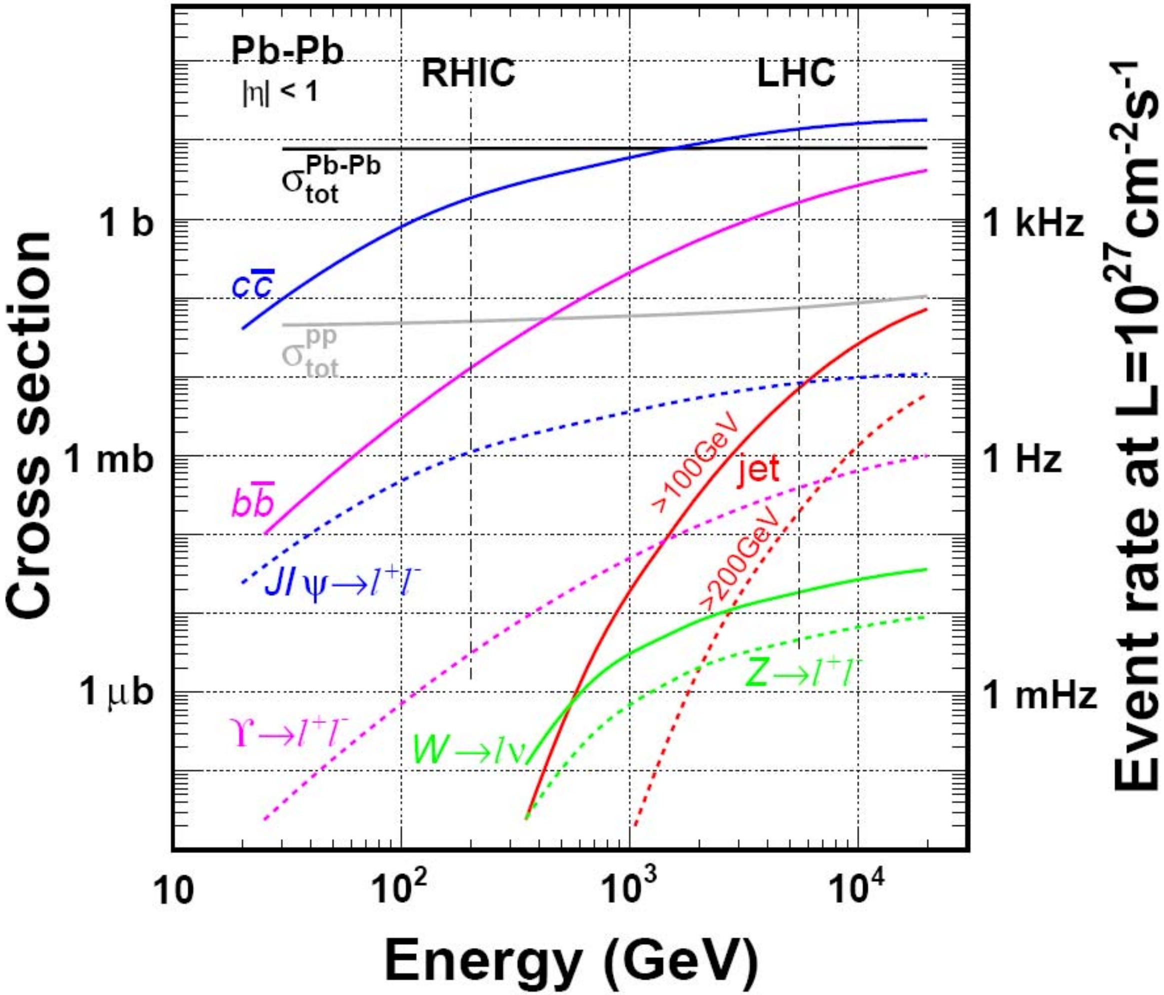


RHIC as opened the low-x frontier finding indications for new physics (CGC ?)

LHC will lower the x- frontier by another factor 30

Can reach $x = 3 * 10^{-6}$ in pp,
10^{-5} in PbPb

LHC: Cross-sections and Rates



Cross-sections of interesting probes expected to increase by factors

~ 10 ($c\bar{c}$) to

~ 10^2 ($b\bar{b}$) to

~ > 10^5 (very high p_T jets)

I. Physics of relativistic heavy ion collisions

NICA characteristics providing the unique possibilities for relativistic heavy ion experiments

1. Wide interval of heavy ion beams at various energies

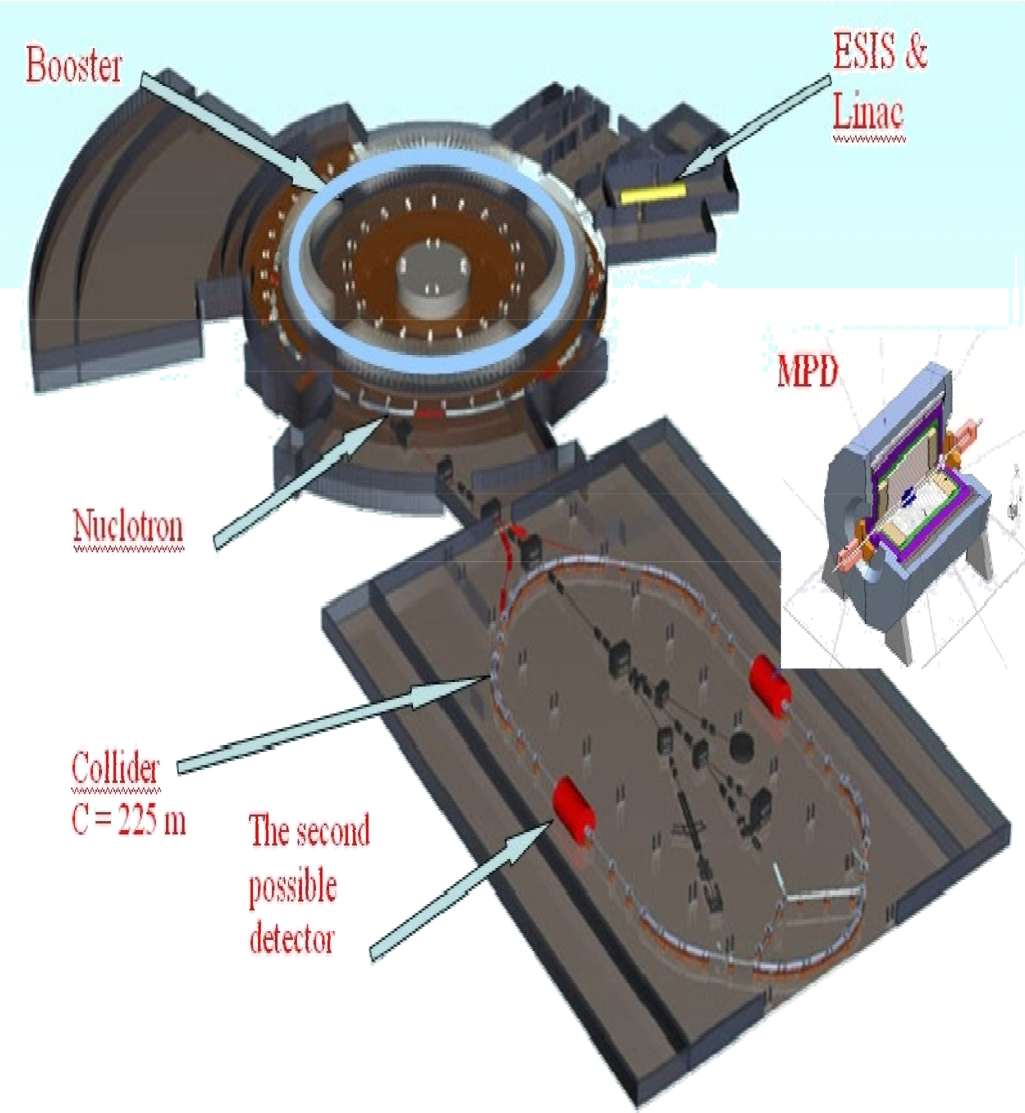
$$\sqrt{s} = 2 - 9\,A\mathrm{GeV}$$

- Possibility of centrality and atomic number scanning

3. Wide and stable the detector acceptance as collision energy function

4. Constructing the 4 π geometry detector

5. High luminosity L=1027 см-2с-1



NICA/MPD Physics Goals

Studying hadron properties in medium and nuclear matter EoS.
Searching the signals of deconfinement, chiral symmetry restoration phase transition, mixed phase and critical phenomena

Observables:

Corresponding measurements will be done by scanning in collision energy, centrality and atomic number of heavy ions

First stage:

- ♣ **Multiplicities and global characteristics of registrated** hadrons including multi-strange hadrons.
- ♣ **Fluctuations of multiplicity and transvers momentum**.
- ♣ Elliptic and other flows.
- ♣ Correlations of particles.

Second stage:

- ♣ **Dileptons and direct photons**

Experimental programs

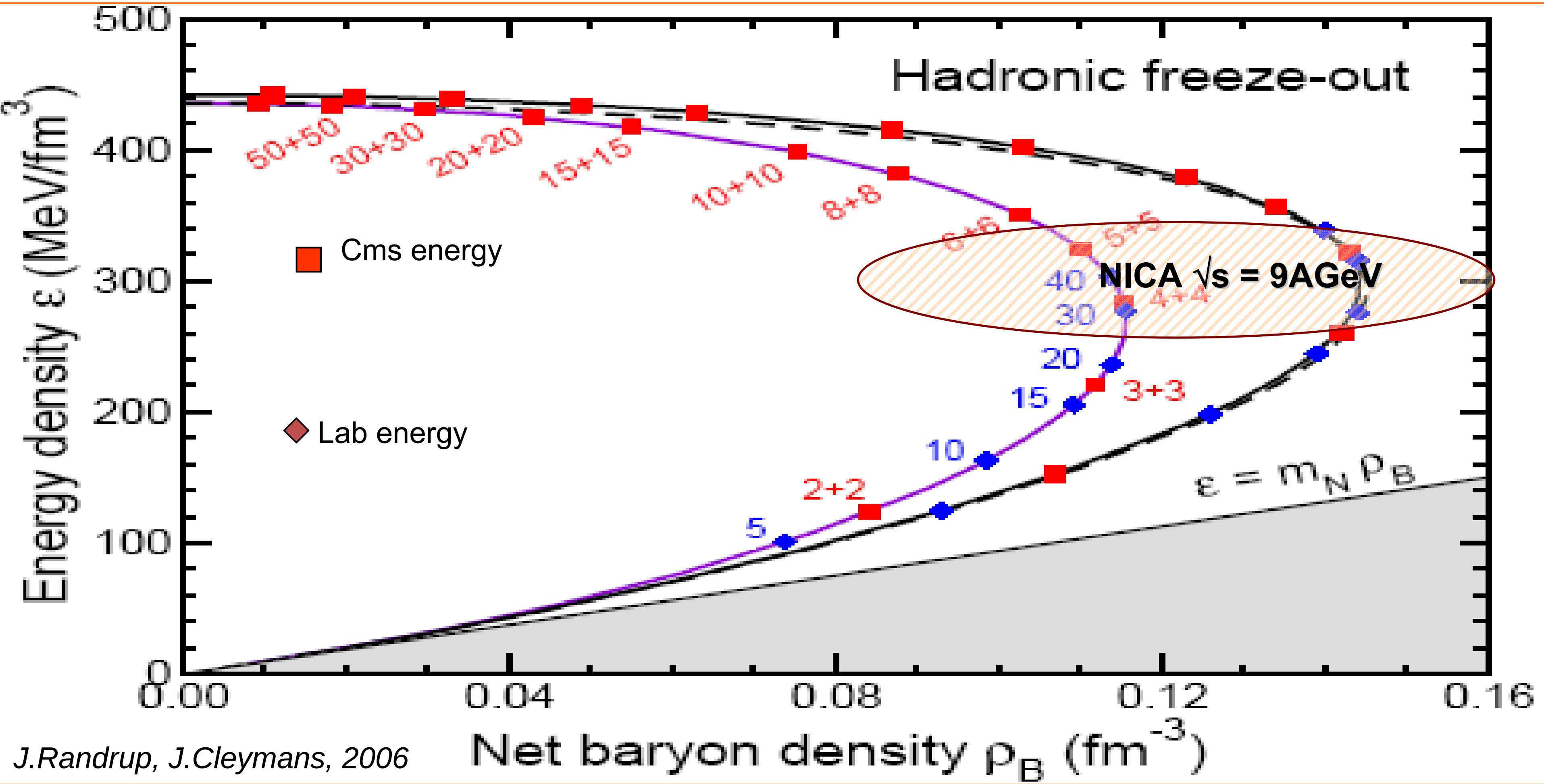
Accelerator	SPS	RHIC	NICA	SIS-300
Experiment	NA61	STAR PHENIX	MPD	CBM
Year of start	2010	2010	2013	2015
Energy (Pb ions) GeV/nucleon	4.9-17.3	4.9-50	≤ 9	≤ 8.5
Event frequency (8 GeV/nucleon	100 Hz	1 Hz (?)	≤ 10 КГц	≤ 10 MHz
4 π geometry	✗	✗	✓	✓
Physics	CP,OD	CP,OD	CP,OD,HDM	CP,OD,HDM

CP – critical point research

OD – phase transition research

HDM – hadron properties in dense matter

Unique baryon densities



J.Randrup, J.Cleymans, 2006

Maximal baryon densities at the chemical freeze-out curve!

⇨ **High densities at the interaction stage!?**

What we have learned from heavy ion physics during last five years

- New form of matter with qualitatively unexpected (?) features
- Stimulating challenges to theory from new experimental data, becomes "data-driven field"
- New principal questions and theoretical responses including new calculational techniques
- Theorists and experimentalists together yielding answers of new questions arising
- New unanticipated links to other areas (like string theory or cold atoms)

What to wait for … (in another 5(?) years)

From RHIC

c and b – quarks

charmonium at higher transverse momentum

identified jets and their modification because o f medium response

low energy scan for critical point in QCD phase diagram

From ALICE at LHC

V_2 to understand if QGP is strongly coupled at temperature $\sim 3T_c$

charmonium and bottonium

identified jets up to 200 Gev and their modification

. . . everything

From NICA

critical point

mixed phase, quarkyonic matter etc