Lattice QCD at Extreme Conditions

International Conference
"Gauge Fields. Yesterday, Today, Tomorrow"
dedicated to the 70-th anniversary of
Andrei Alekseevich Slavnov

M.I. Polikarpov, ITEP

Plan

- Lattice QCD at finite temperature

DESY – ITEP – Kanazawa collaboration

- Confining string breaking
- Deconfining phase transition

- Strong magnetic fields in heavy ion collisions

- Lattice simulations with magnetic fields
- Chiral Magnetic Effect [generation of the electric current of quarks directed along the magnetic field]
- Chiral symmetry breaking
- Magnetization of the vacuum
- Electric dipole moment of quark along the direction of the magnetic field

Confining string breaking

DESY 02–135
ITEP-LAT/2002–16
KANAZAWA 02–26

ITEP Lattice

1

Thermodynamics and heavy quark potential in $N_f = 2$ dynamical QCD *

V. Bornyakov [a,b], Y. Nakamura [a], M. Chernodub [a,b], Y. Koma [a], Y. Mori [a], M. Polikarpov [b], G. Schierholz [c], A. Slavnov [d], H. Stüben [e], T. Suzuki [a], P. Uvarov [b], A. Veselov [b]

[a]Institute for Theoretical Physics, Kanazawa University, Kanazawa 920-1192, Japan

[b]Institute for Theoretical and Experimental Physics, B.Cheremushkinskaya 25, Moscow 117259, Russia

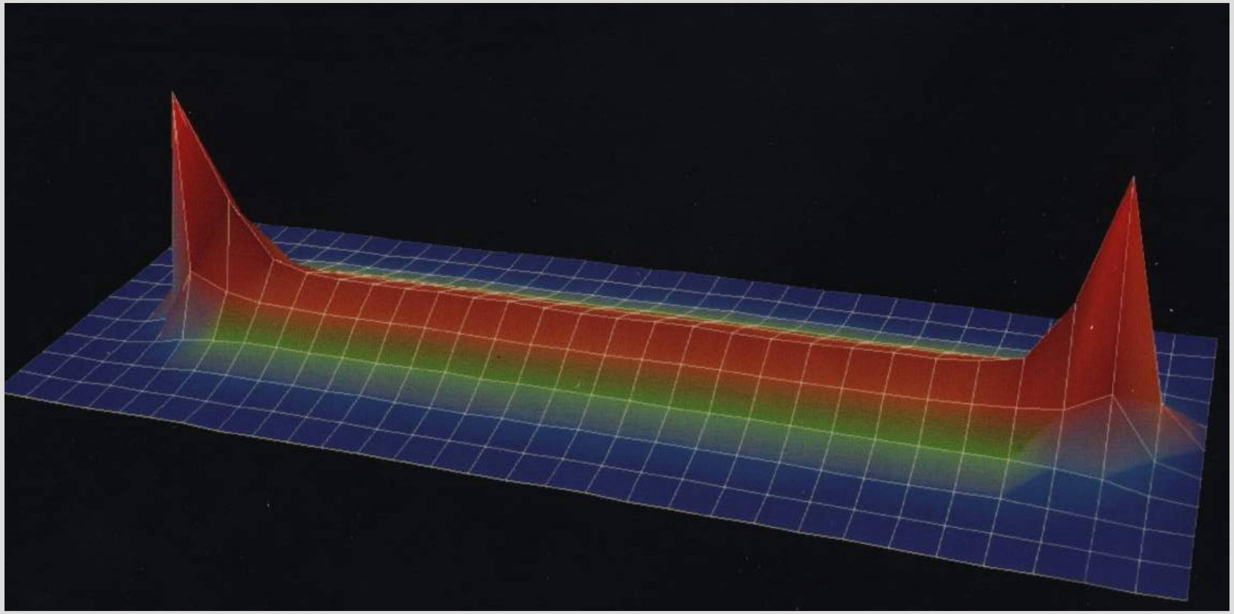
[c]NIC/DESY Zeuthen, Platanenallee 6, 15738 Zeuthen, Germany and
Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

[d]Steklov Mathematical Institute, Vavilova 42, 117333 Moscow, Russia

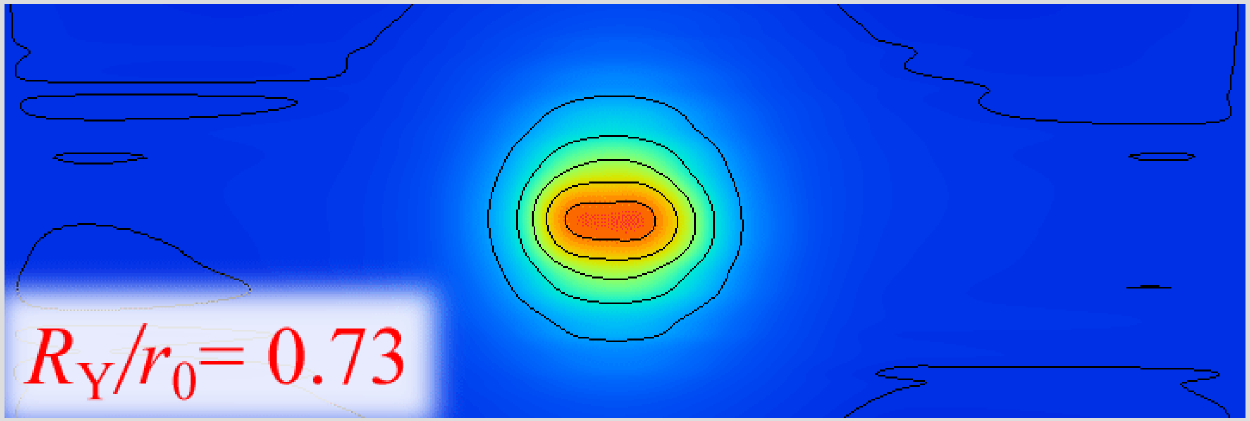
[e]Konrad-Zuse-Zentrum für Informationstechnik Berlin, D-14195 Berlin, Germany

We study $N_f = 2$ lattice QCD with nonperturbatively improved Wilson fermions at finite temperature on $16^3 \cdot 8$ lattices. We determine the transition temperature at $\frac{m_\pi}{m_\rho} \sim 0.8$ and lattice spacing as small as $a \sim 0.12$fm. The string breaking at $T < T_c$ is also studied. We find that the static potential can be fitted by a simple expression involving string model potential at finite temperature.

Confining string breaking

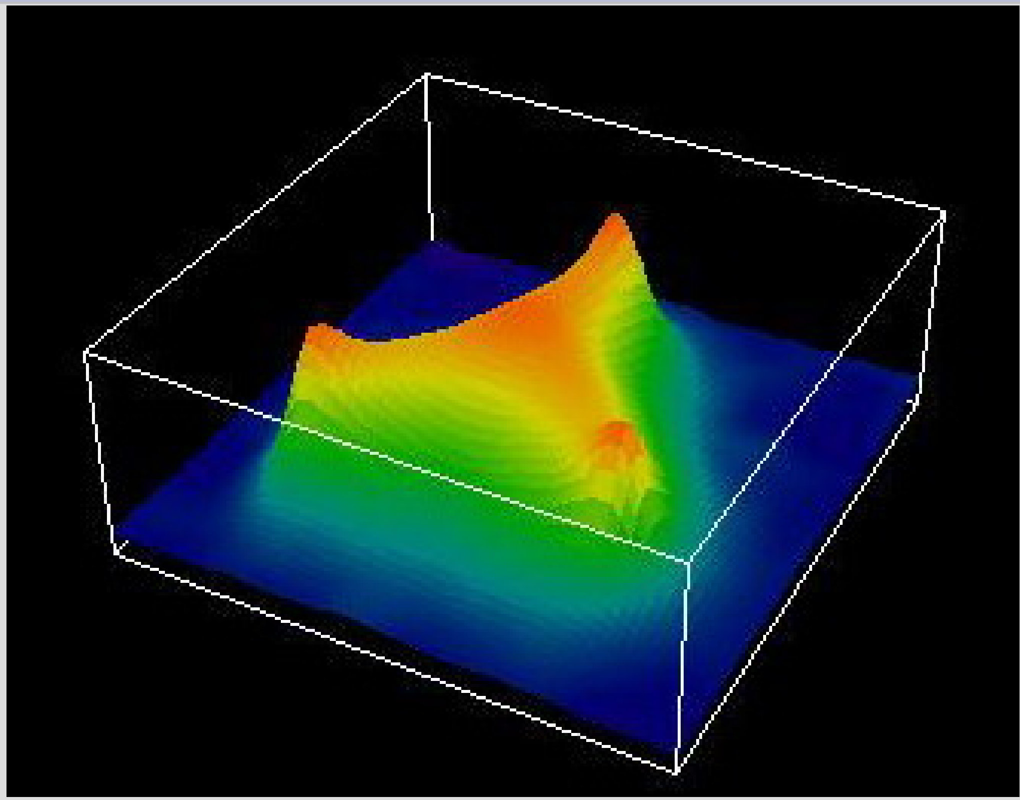


No dynamical quarks



Full QCD

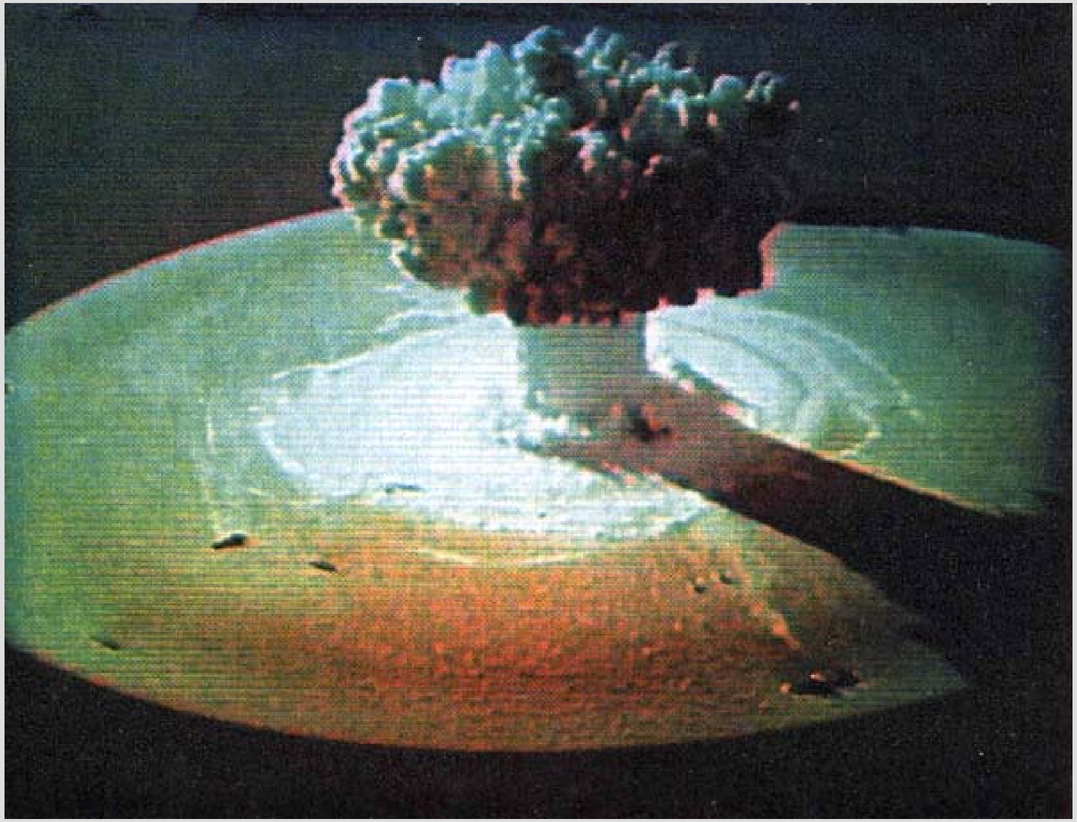
Baryon flux tube, Delta or Y type?

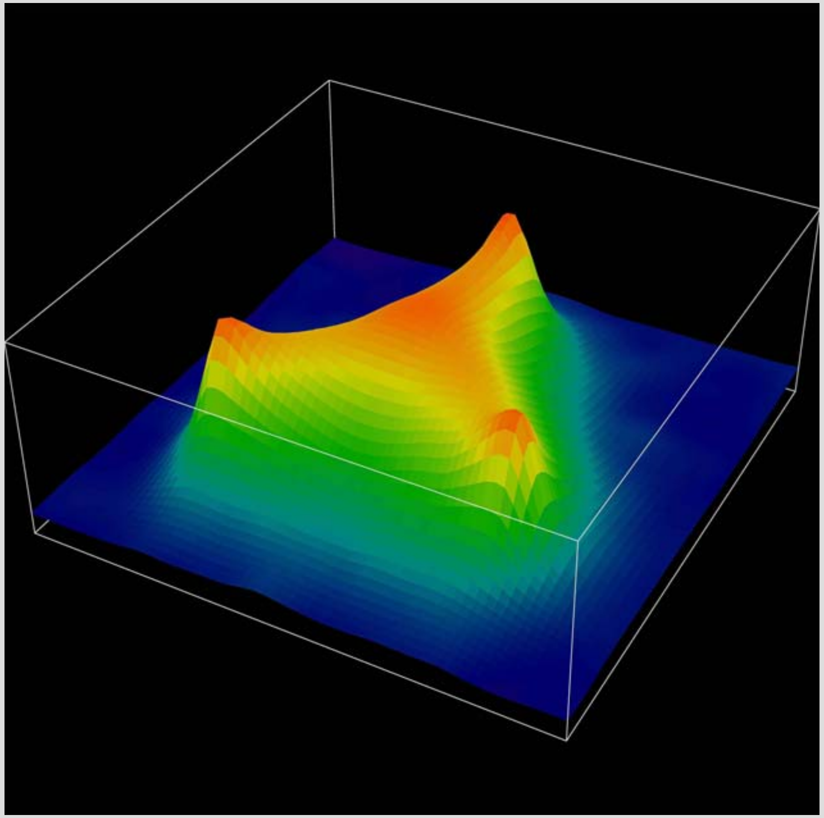


Genuine 3-body forces! (DIK collaboration results)

$$V(r_1, r_2, r_3) \neq V(r_1 - r_2) + V(r_2 - r_3) + V(r_3 - r_1)$$

The masses of all material objects around us are due to gluon tubes in baryons





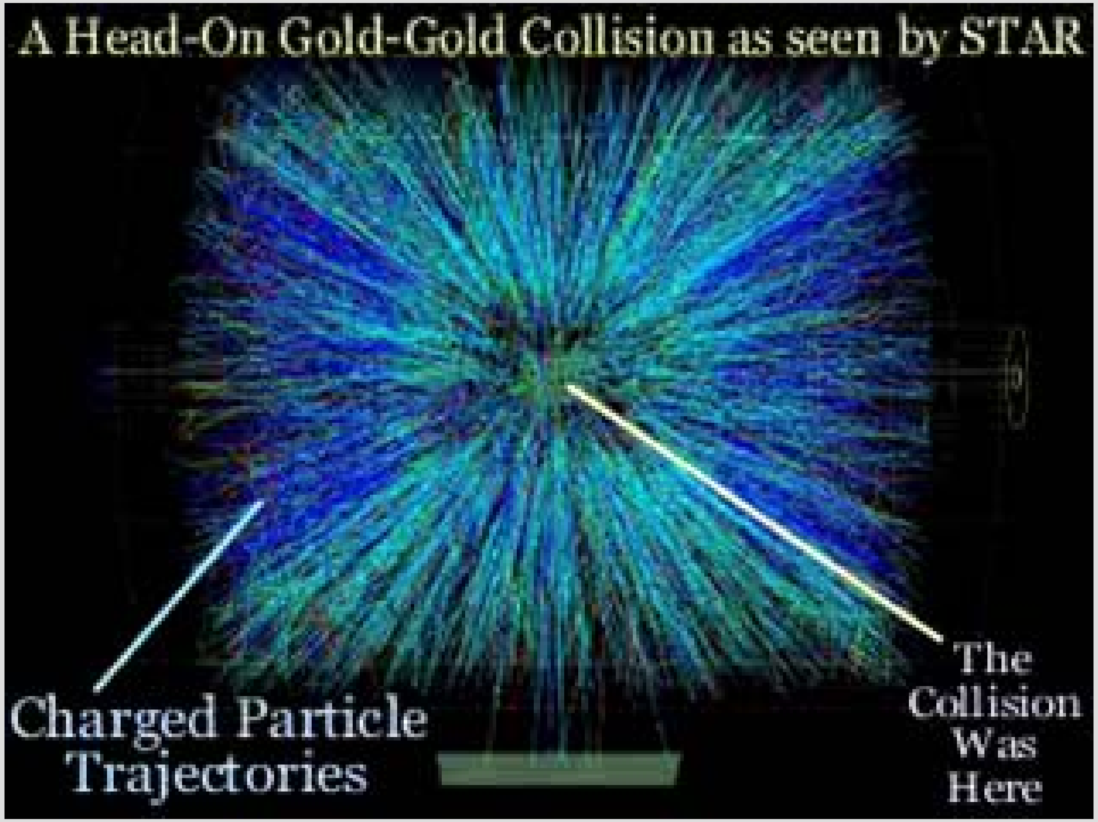
$$E = m_0 c^2$$

$$3m_q / m_{baryon} \approx 1/100$$

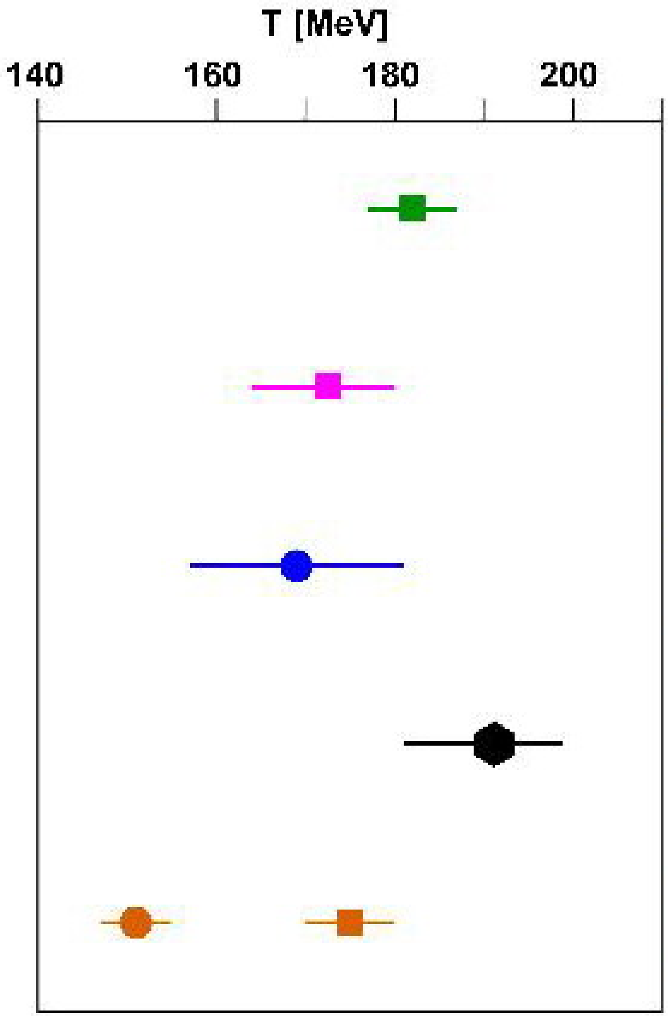
$$m_0 = \frac{E}{c^2}$$

Critical temperature, Tc

At T>Tc we have deconfining phase:
quark-gluon plasma, glasma, quark-gluon matter



Summary of recent results on T_c



use T=0 scale: r0=0.469fm

Nf=2:

V.G. Bornyakov et al, POS Lat2005, 157 (2006)
(improved Wilson, Nt=8, 10; input: r0=0.5 fm)
(added Nt=12, Lattice'07) (rescaled to r0)

Y. Maezawa et al., hep-lat/0702005 (QM'2006)
(improved Wilson, Nt=4, 6; input: m-rho)
(no cont. exp. yet)

Nf=2=1:

C. Bernard et al., Phys.Rev. D71, 034504 (2005)
(improved staggered (asqtad), Nt=4,6,8, input r1)
(rescaled to r0)

M. Cheng et al., Phys.Rev D74, 054507 (2006)
(improved staggered (p4), Nt=4,6; input r0)

Y. Aoki et al., Phys. Lett. B643, 46 (2006)
(staggered (stout), Nt=4,6,8,10; input fK)
(converted to r0)

● chiral ■ deconfinement ⬢ chiral+deconfinement

F. Karsch hep-lat/0711/0661; Talk at Lattice 2007

Tc by DIK (DESY-ITEP-Kanazawa) collaboration

V.G. Bornyakov, M.N. Chernodub, Y. Mori , S.M. Morozov, Y. Nakamura,
M.I. Polikarpov, G. Schierholz, A.A. Slavnov, H. Stüben, T. Suzuki, MIP (2006)

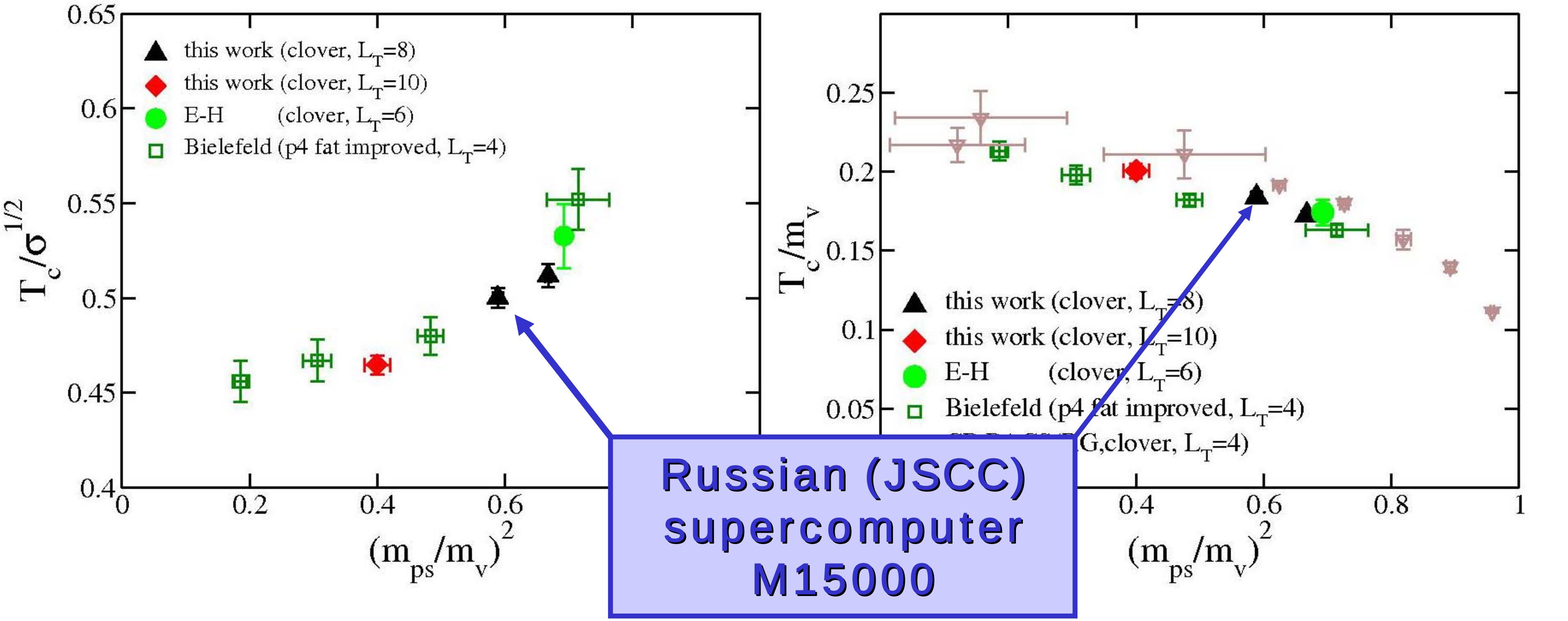
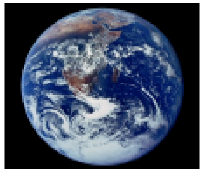


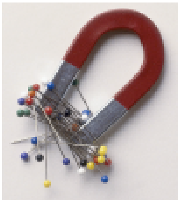
Figure 5: (left) The transition temperature T_c in units of the string tension $\sigma(T=0)$ as a function of $m_{\rm ps}/m_{\rm v}$ and (right) T_c in units of $m_{\rm v}$ as a function of $(m_{\rm ps}/m_{\rm v})^2$ (right). The data is from this work (the up triangles and the diamond), Ref. [1] (the squares), Ref. [6] (the circle), and Ref. [5] (the down triangles).

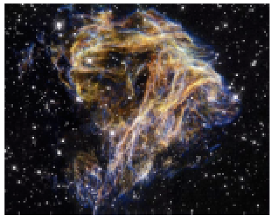
Strong Magnetic Fields in Heavy Ion Collisions

P.V.Buividovich, M.N.Chernodub, E.V.Luschevskaya, M.I.Polikarpov

Comparison of magnetic fields

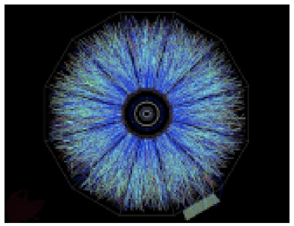






The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

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



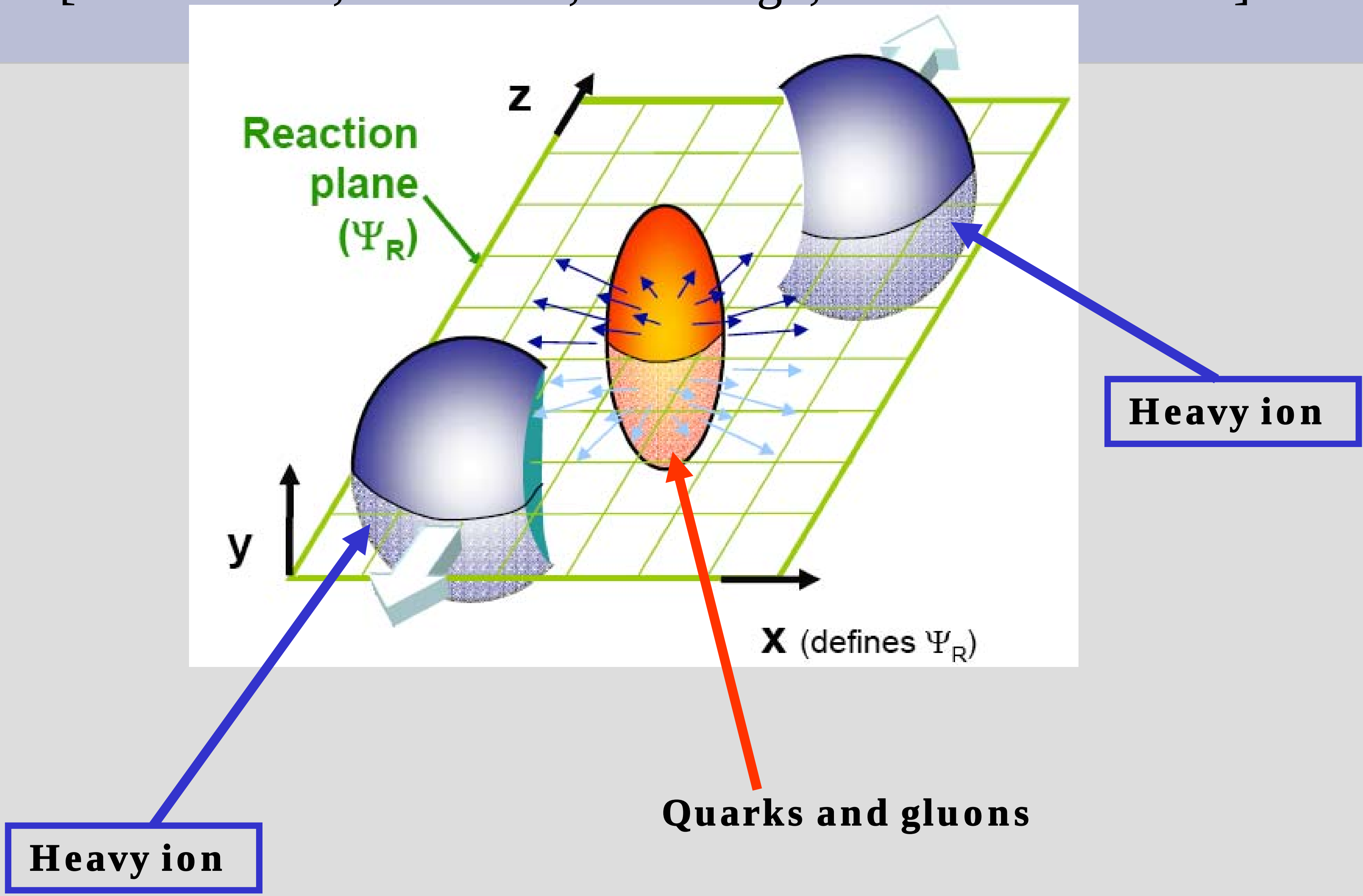
At BNL we beat them all!

Off central Gold-Gold Collisions at 100 GeV per nucleon

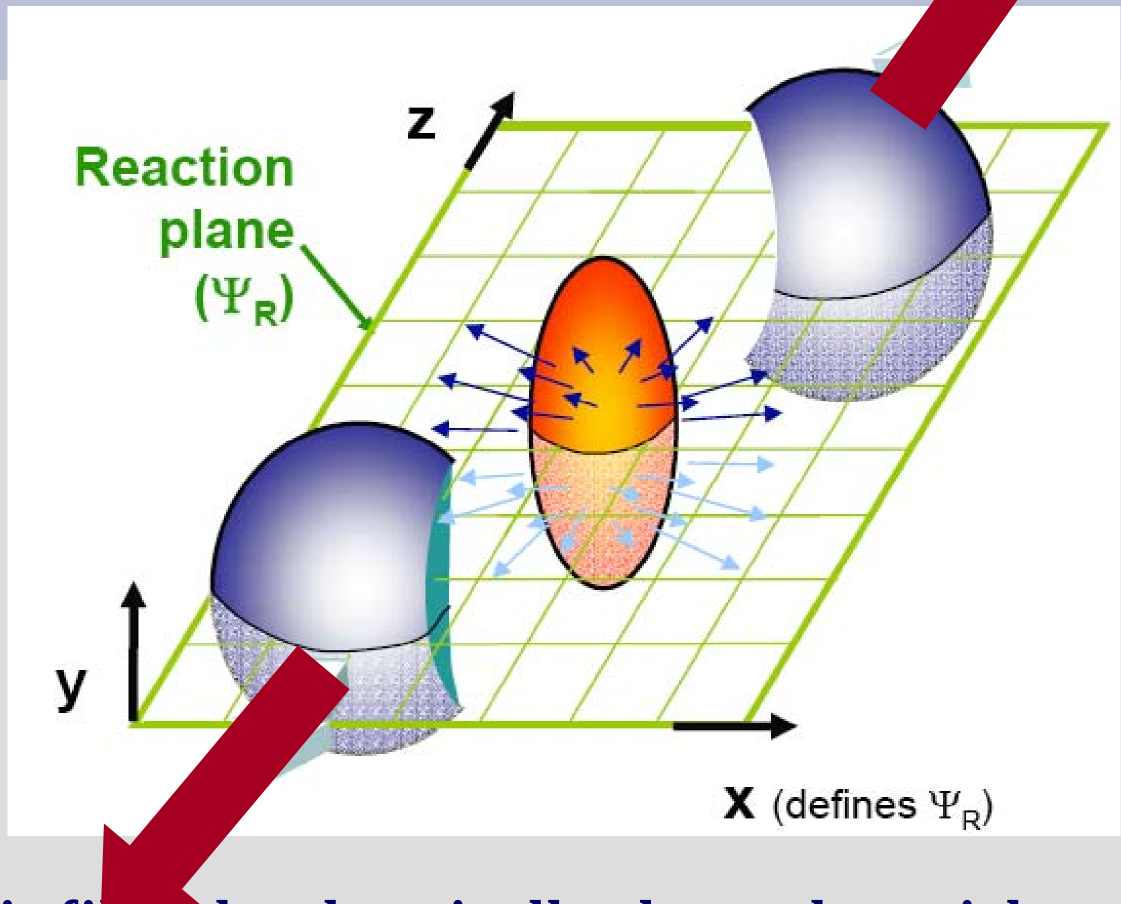
$$e\,B(\tau = 0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

Magnetic fields in non-central collisions

[Fukushima, Kharzeev, Warringa, McLerran ’07-’08]



Magnetic fields in non-central collisions



Charge is large
Velosity is high

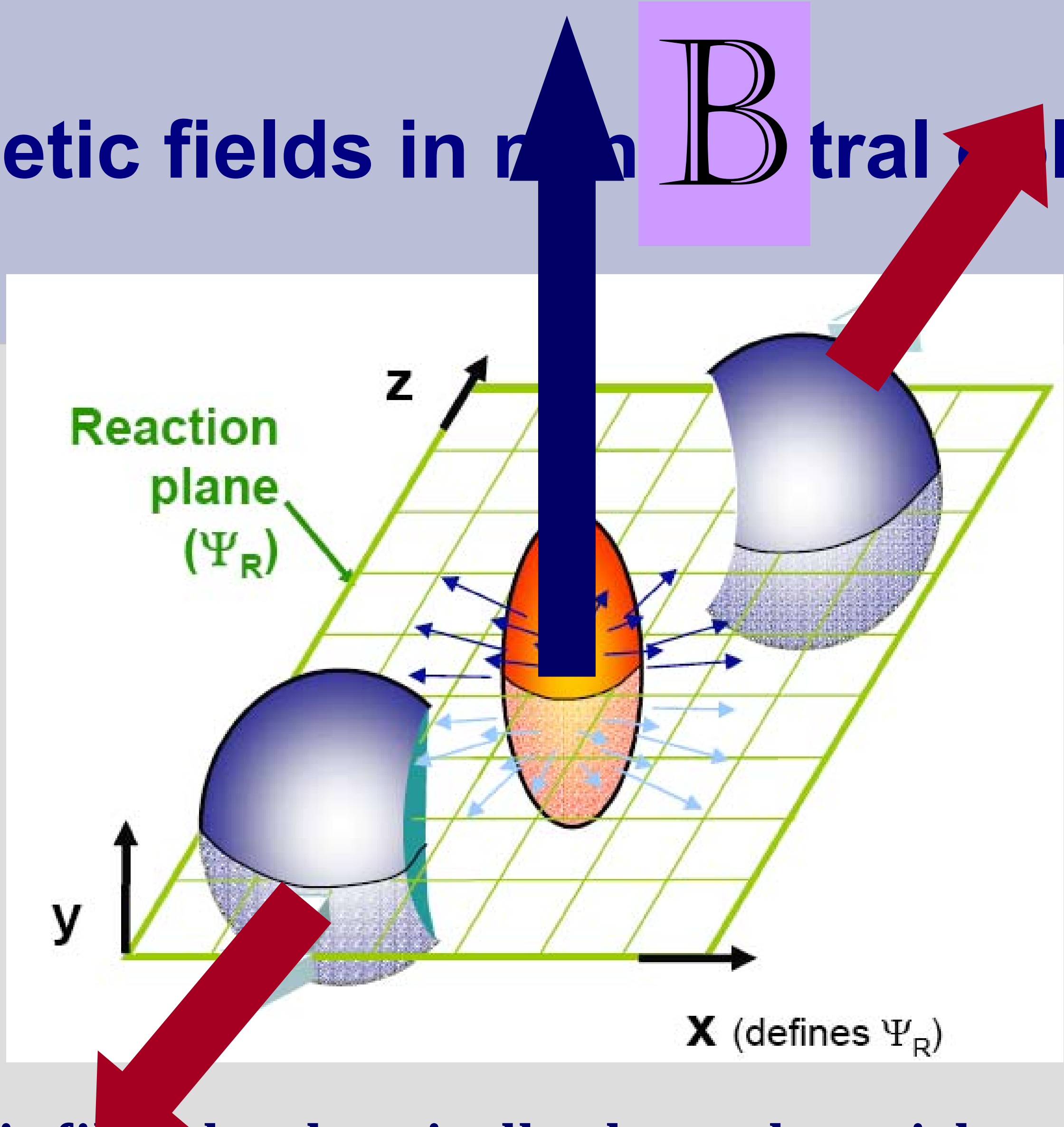
Thus we have two very big currents

The medium is filled by electrically charged particles

Large orbital momentum, perpendicular to the reaction plane

Large magnetic field along the direction of the orbital momentum

Magnetic fields in n … tral … llisions



Two very big currents produce a very

big magnetic field

The medium is fi… by electrically charged particles

Large orbital momentum, perpendicular to the reaction plane

Large magnetic field along the direction of the orbital momentum

Magnetic forces are of the order of strong interaction forces

first time in my life I see such effect

$$eB \approx \Lambda_{QCD}^{2}$$

Magnetic forces are of the order of strong interaction forces

first time in my life I see such effect

$$eB \approx \Lambda^2_{QCD}$$

We expect the influence of magnetic field on strong interaction physics

Magnetic forces are of the order of strong interaction forces

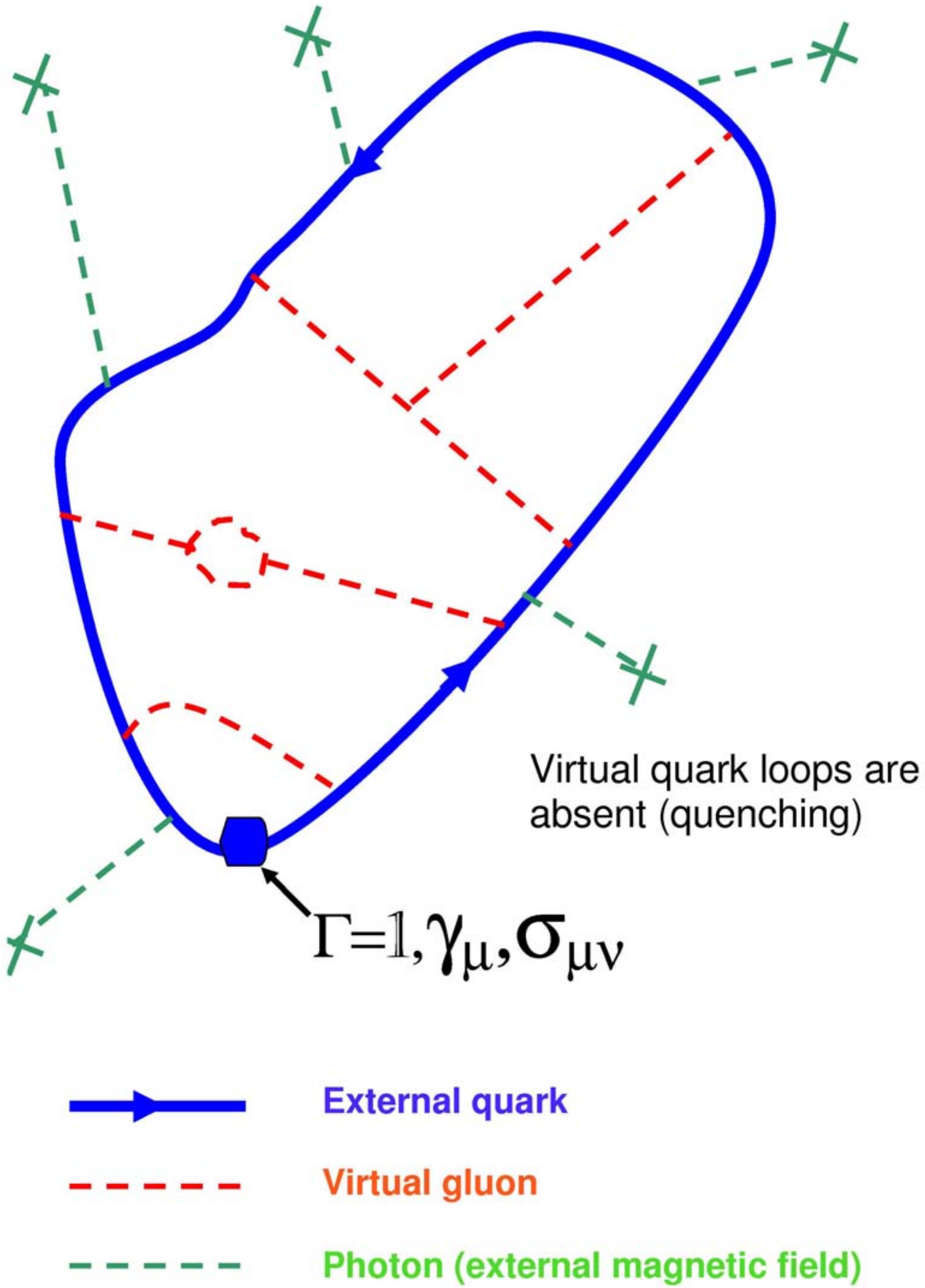
first time in my life I see such effect

$$eB \approx \Lambda^2_{QCD}$$

We expect the influence of magnetic field on strong interaction physics

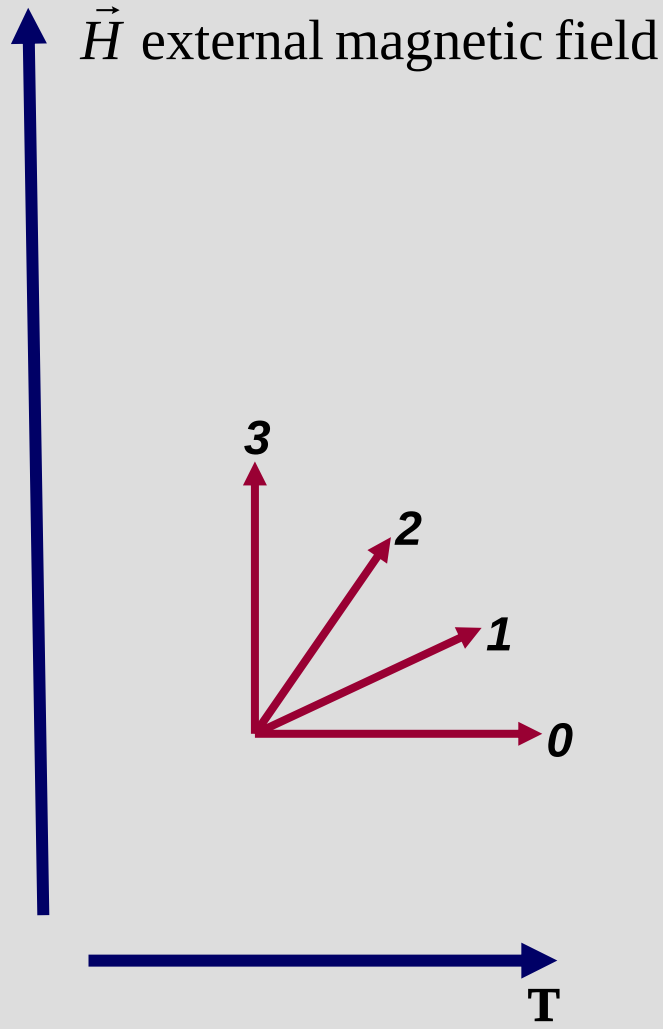
The effects are nonperturbative,
it is impossible to perform analytic calculations
and we use

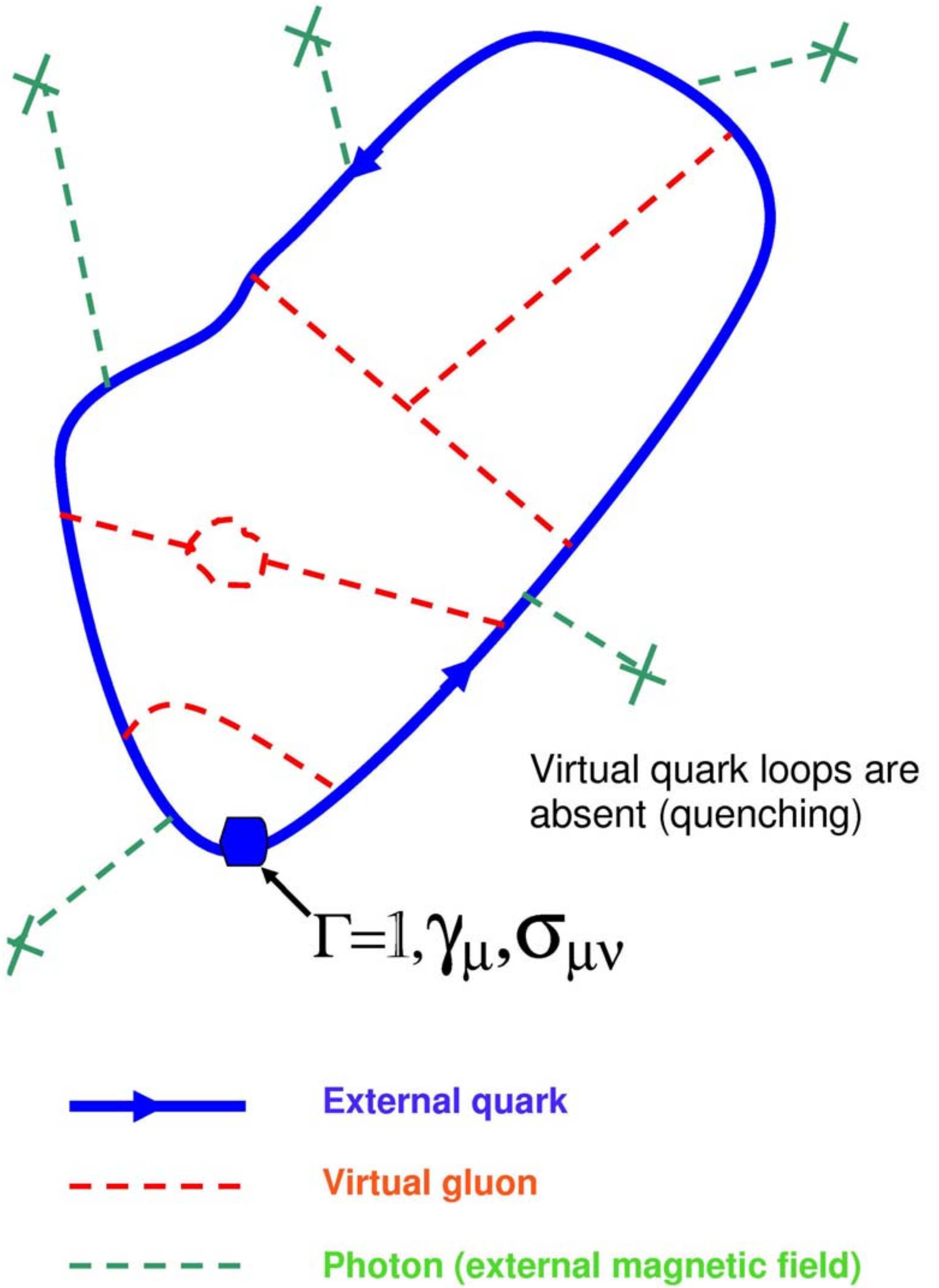
LATTICE CALCULATIONS



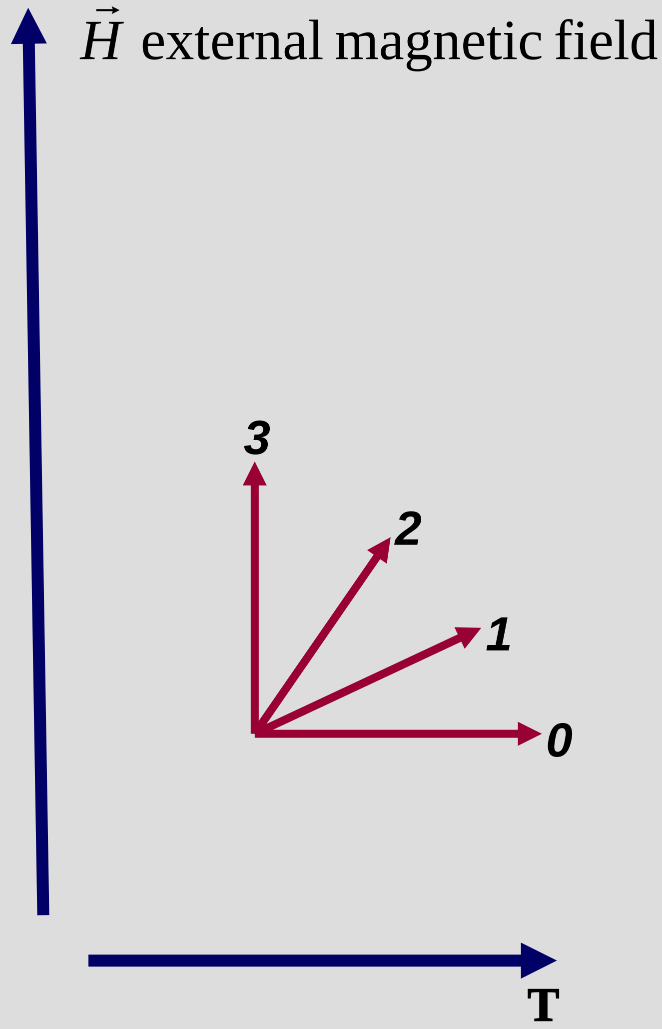
We calculate $< \overline{\psi}\, \Gamma \psi >; \ \Gamma = 1, \gamma_\mu, \sigma_{\mu\nu}$

in the external magnetic field and in the presence of the vacuum gluon fields





We consider SU(2) gauge fields and quenching approximation



Quenched vacuum, overlap Dirac operator, external magnetic field

$$eB = \frac{2\pi qk}{L^2}; eB \geq 250\ Mev$$

Chiral Magnetic Effect

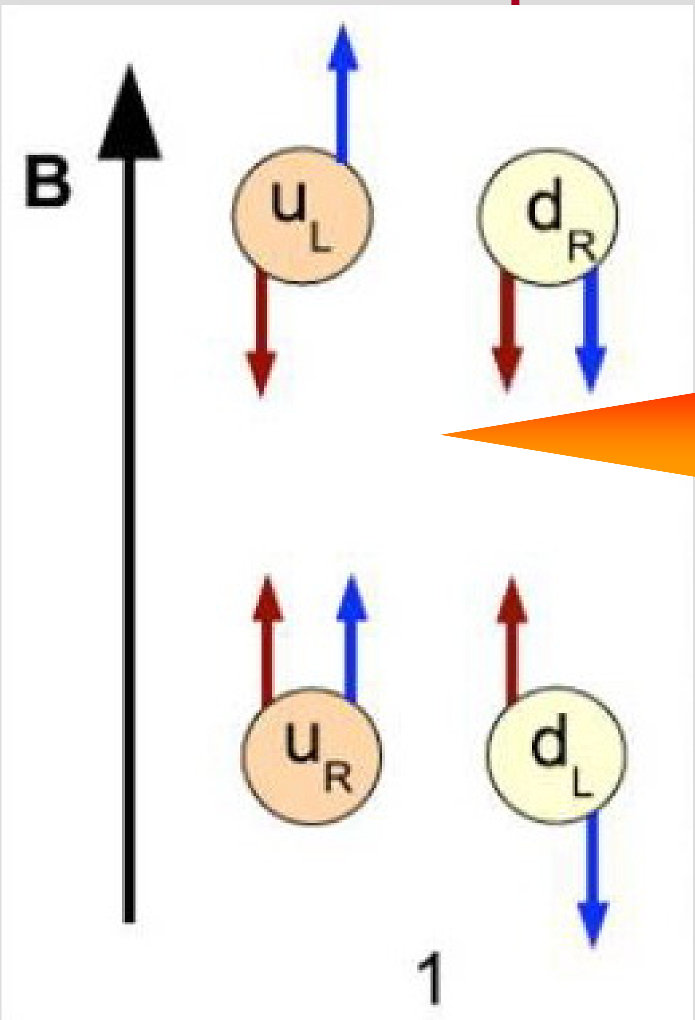
[Fukushima, Kharzeev, Warringa, McLerran '07-'08]

Electric current appears at regions
1. with non-zero topological charge density
2. exposed to external magnetic field

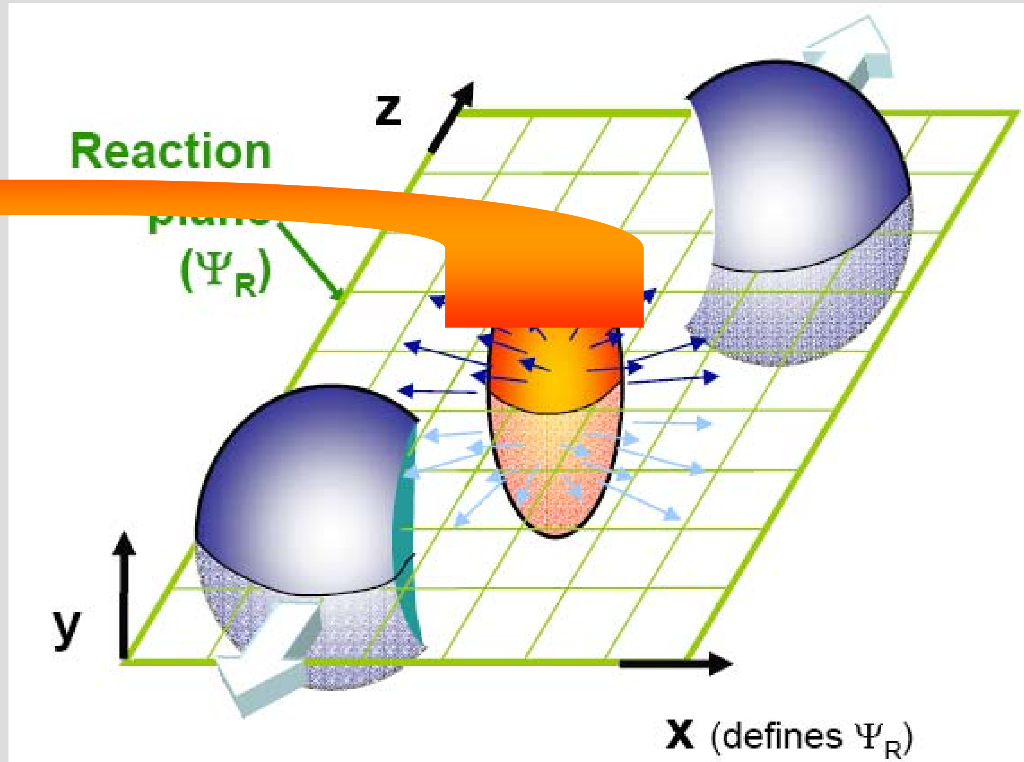
Experimentally observed at RHIC **:**
charge asymmetry of produced particles at heavy ion collisions

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

1. Massless quarks in external magnetic field.

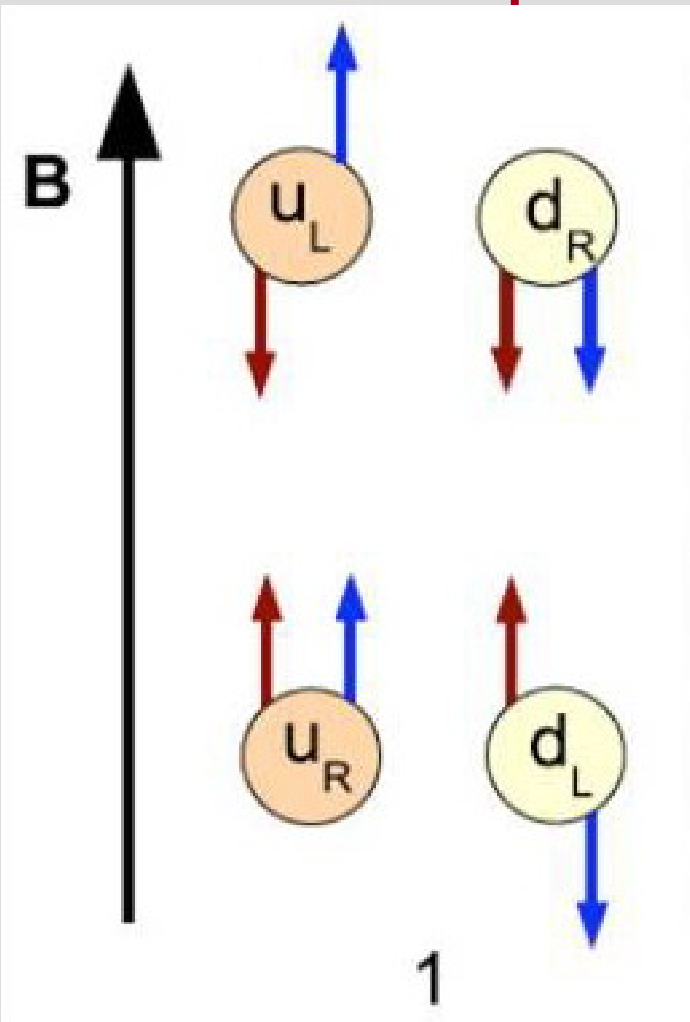


Red: momentum **Blue: spin**

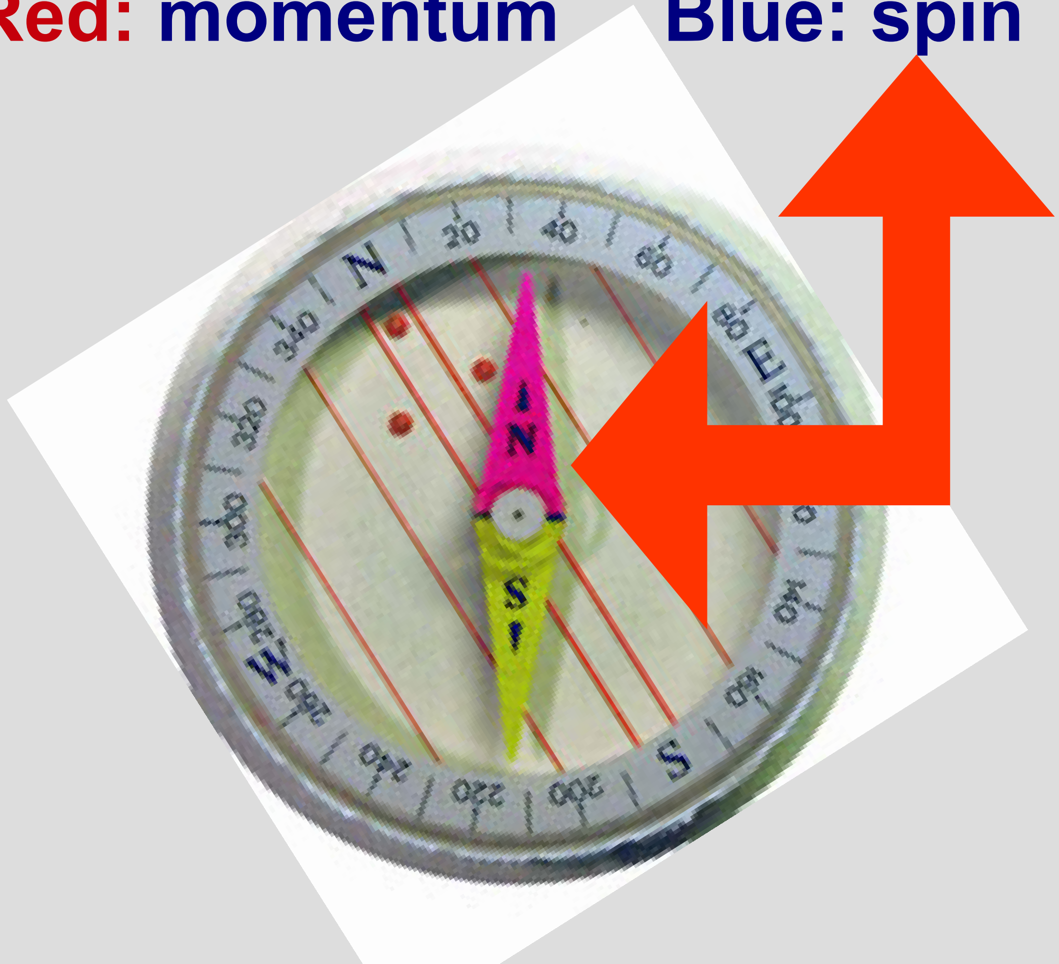


Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

1. Massless quarks in external magnetic field.

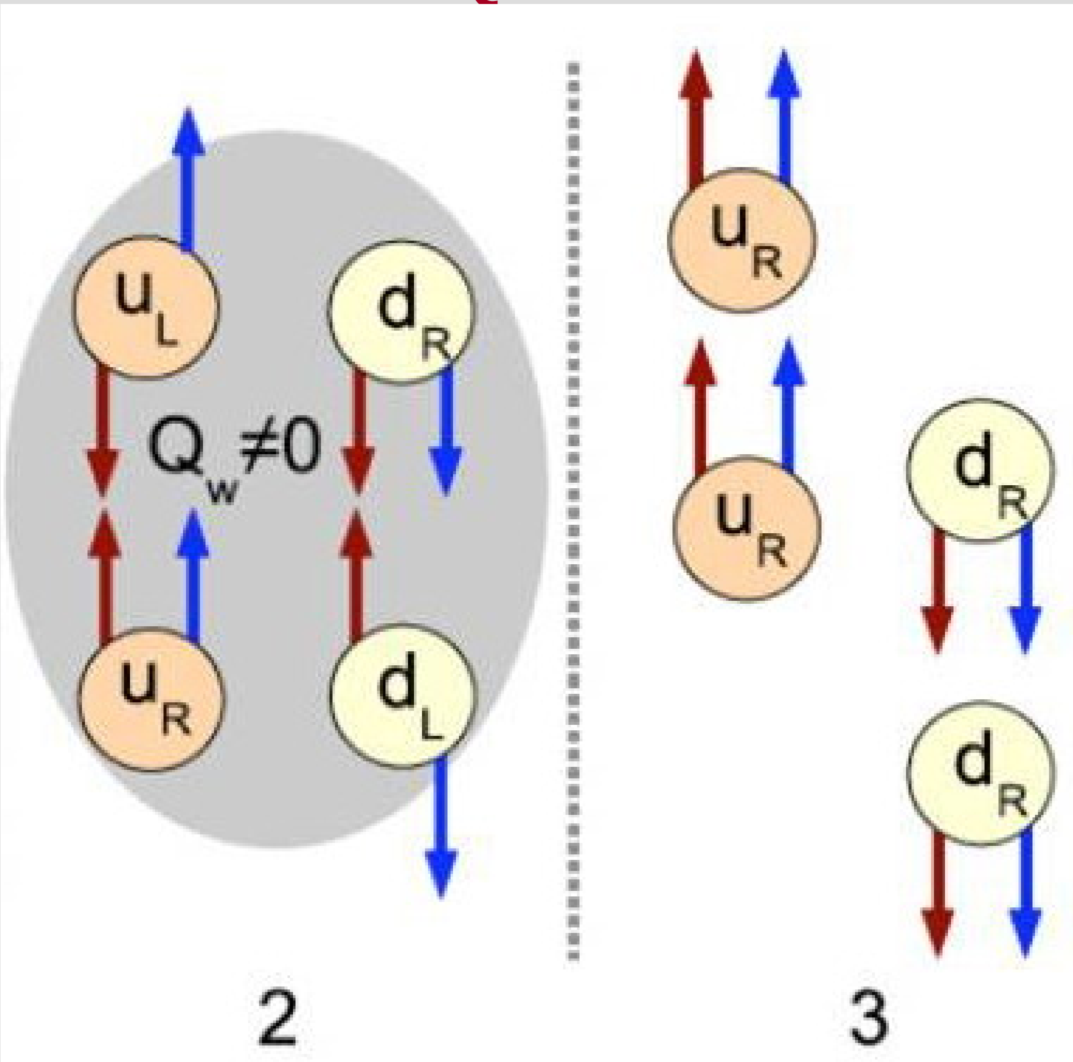


Red: momentum Blue: spin



Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

2. Quarks in the instatnton field.



Red: momentum
Blue: spin

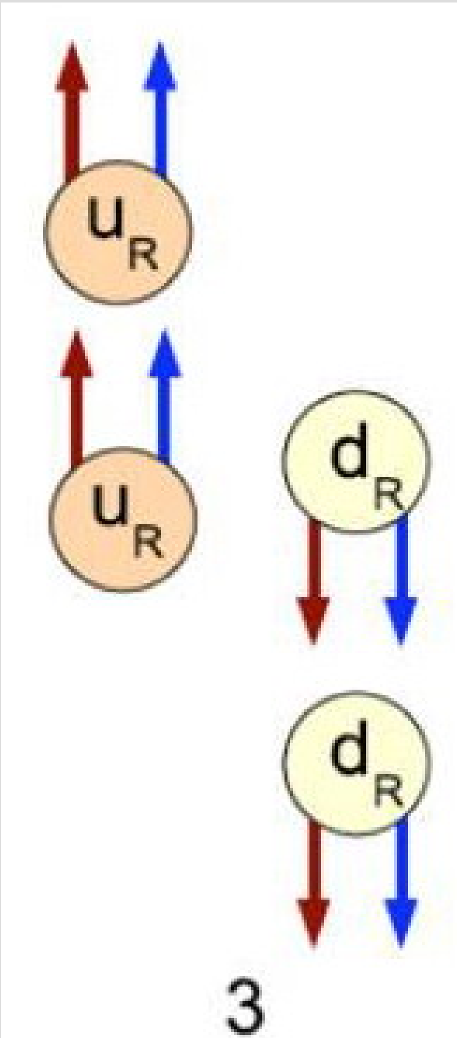
Effect of topology:

$u_L \rightarrow u_R$

$d_L \rightarrow d_R$

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

3. Electric current along magnetic field



Red: momentum
Blue: spin

Effect of topology:

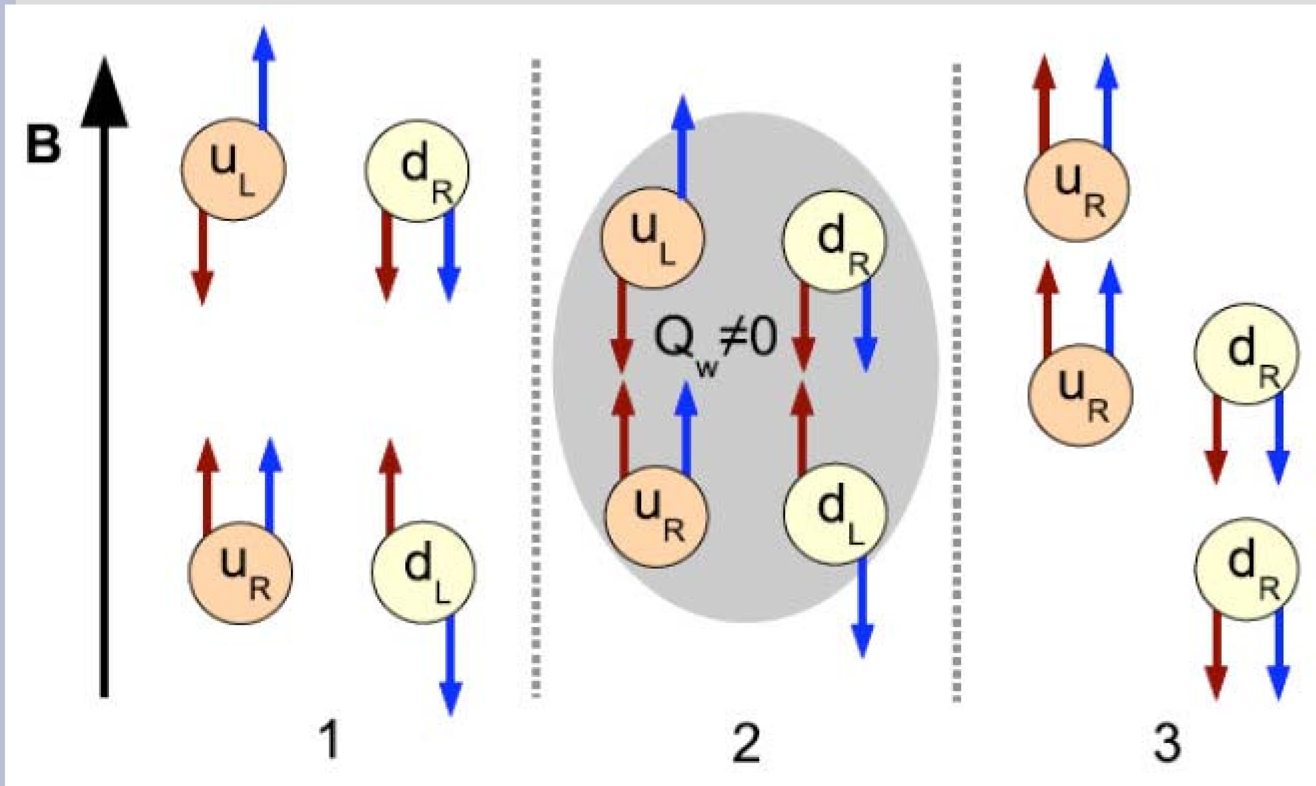
$u_L \rightarrow u_R$

$d_L \rightarrow d_R$

u-quark: q=+2/3
d-quark: q= - 1/3

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

3. Electric current is along magnetic field In the *instanton* field

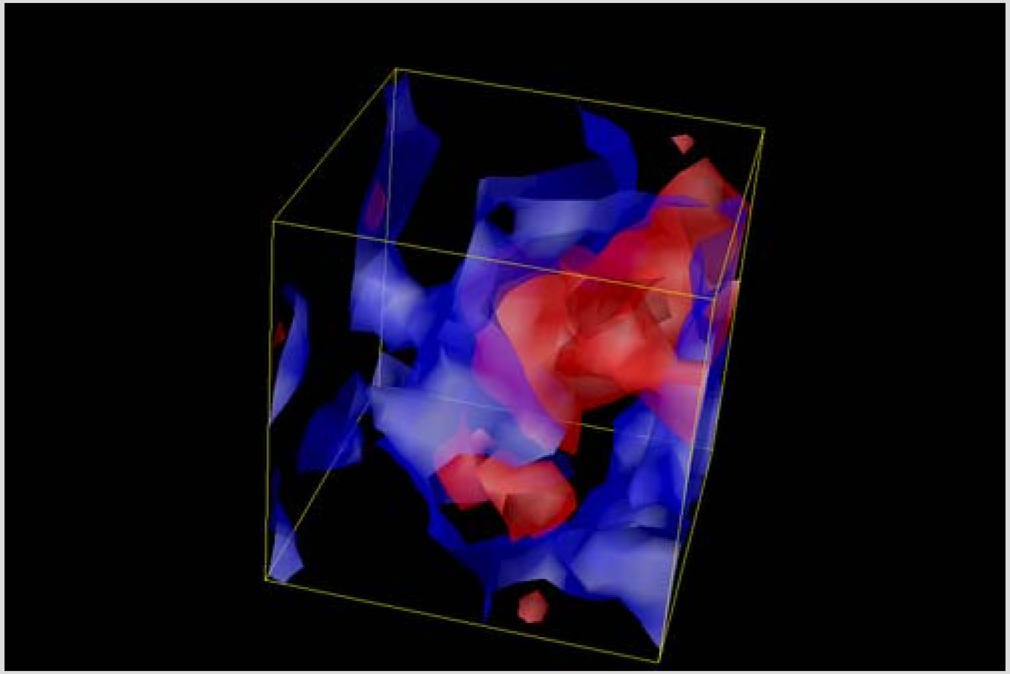


Red: momentum
Blue: spin

Effect of topology:
$u_L \rightarrow u_R$
$d_L \rightarrow d_R$

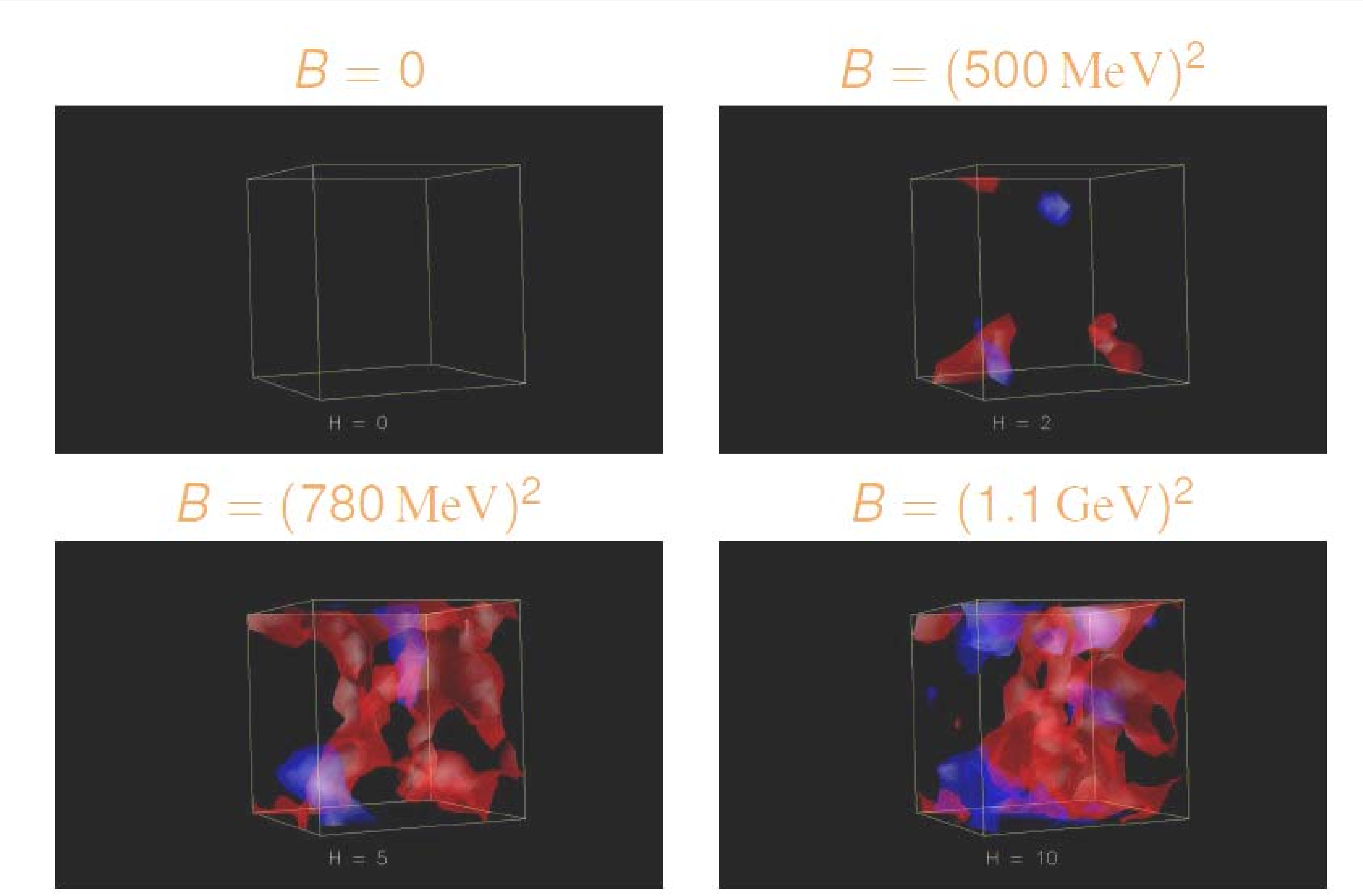
u-quark: q=+2/3
d-quark: q= - 1/3

Topological charge density in quantum QCD vacuum has fractal structure

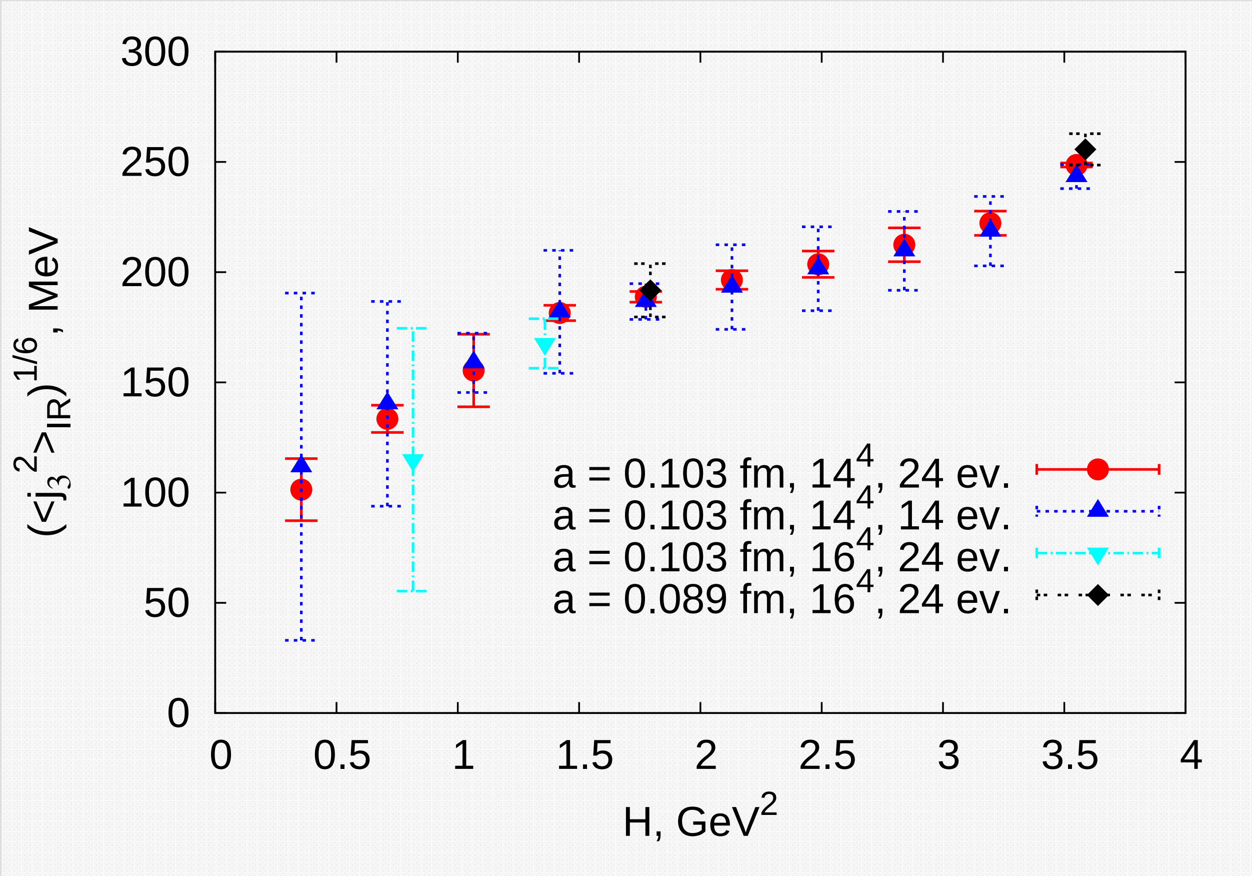


Chiral Magnetic Effect on the lattice, charge separation

Density of the electric charge vs. magnetic field



Chiral Magnetic Effect on the lattice, numerical results



Regularized electric current:

$$< j_3^2 >_{IR} = < j_3^2(H,T) > - < j_3^2(0,0) >, \quad j_3 = \overline{\psi}\gamma_3\psi$$

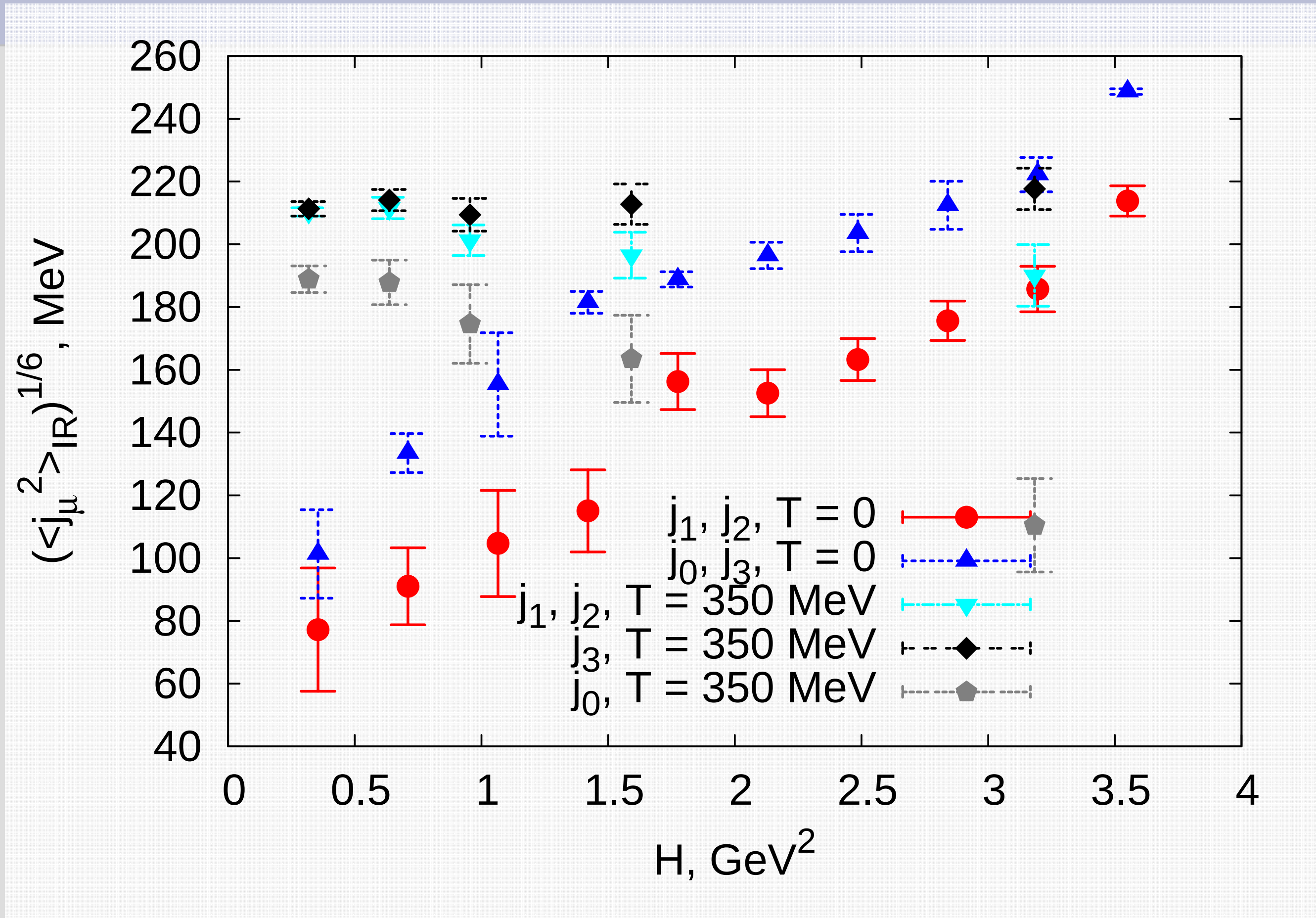
Chiral Magnetic Effect on the lattice, numerical results

$T=0$

$F_{12} \neq 0$

$< j_1^2 > = < j_2^2 >$

$< j_3^2 > = < j_0^2 >$



$T>0$

$F_{12} \neq 0$

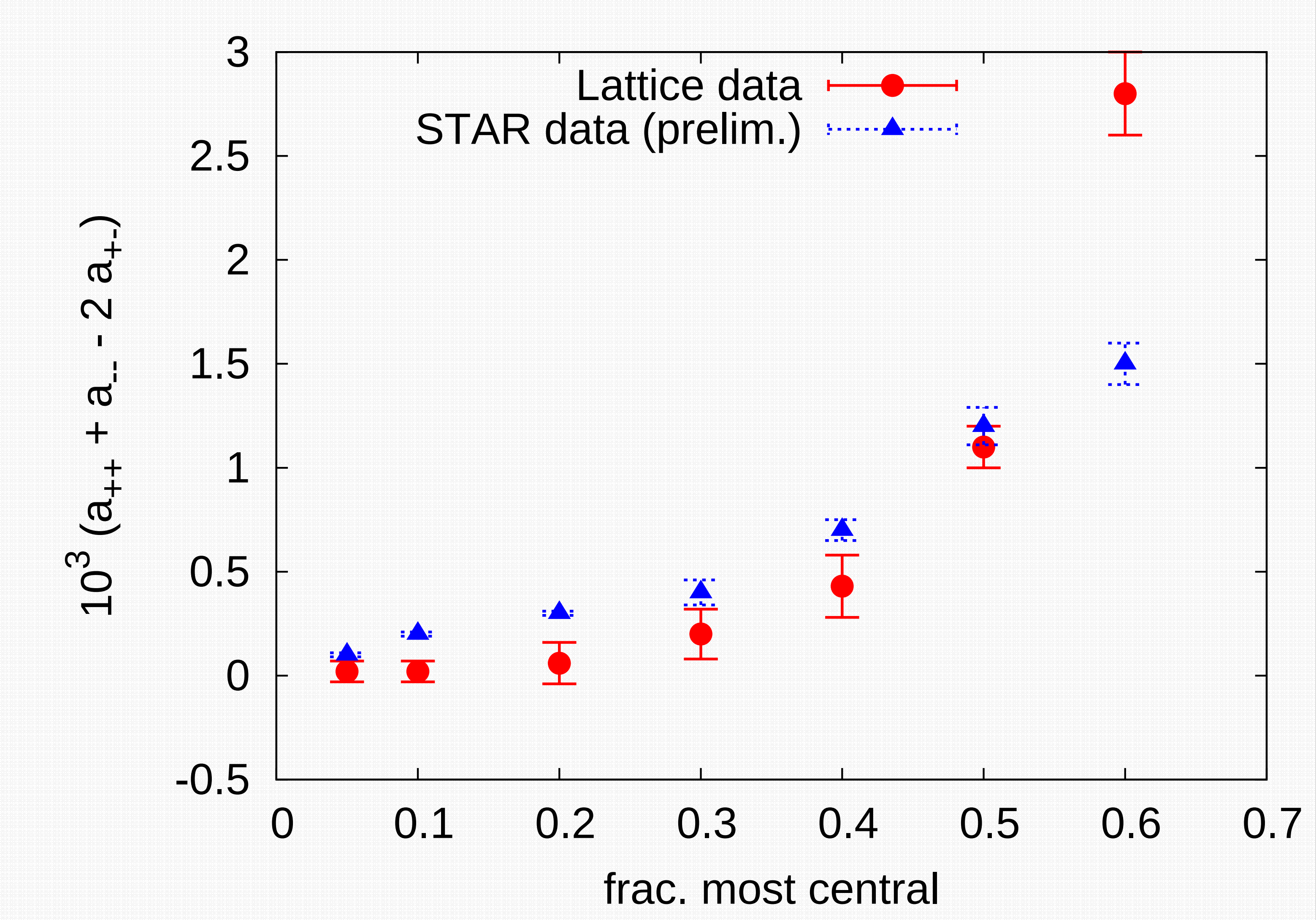
$< j_1^2 > = < j_2^2 >$

$< j_3^2 > \neq < j_0^2 >$

Regularized electric current:

$$< j_i^2 >_{IR} = < j_i^2(H,T) > - < j_i^2(0,0) >, \quad j_i = \overline{\psi} \gamma_i \psi$$

Chiral Magnetic Effect,
EXPERIMENT VS LATTICE DATA (Au+Au)

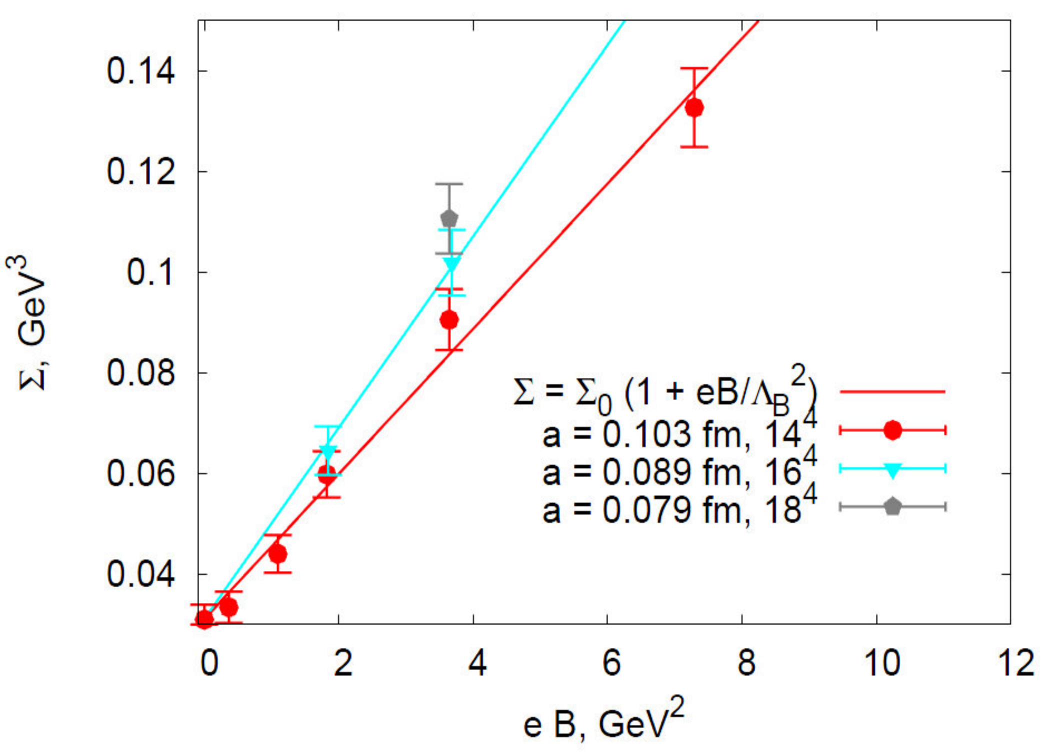


2. Chiral condensate in QCD

$$\Sigma = -<\bar{\psi}\psi>$$

$$m_\pi^2 f_\pi^2 = m_q <\bar{\psi}\psi>$$

Chiral condensate vs. field strength



$$\Sigma = \Sigma_0 \left(1 + \frac{eB}{\Lambda_B^2}\right)$$

- Our value for Λ_B:

$$\Lambda_B^{\text{fit}} = (1.41 \pm 0.14 \pm 0.20)\ \text{GeV}$$

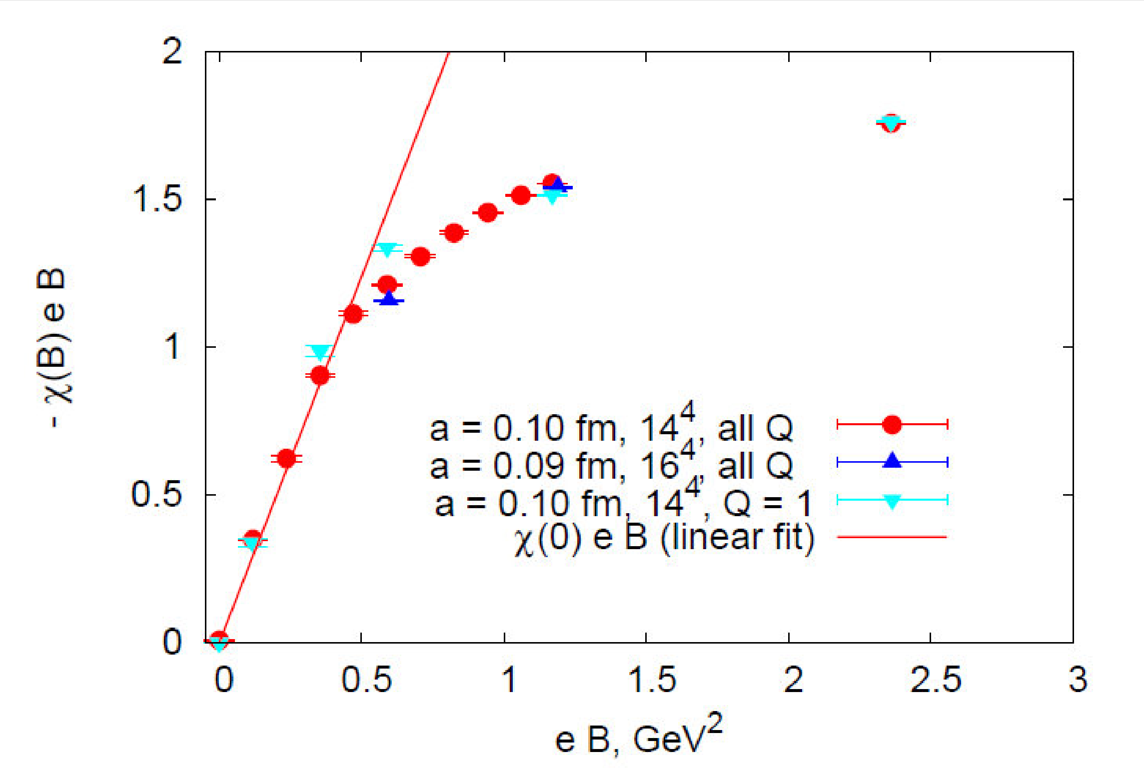
- χPT result:

$$\Lambda_B^{\chi PT} = 1.96\ GeV \quad (F_\pi = 130\ MeV - real\ world)$$
$$\Lambda_B^{\chi PT} = 1.36\ GeV \quad (F_\pi = 90\ MeV - quenched)$$

- Chiral condensate at $B = 0$: $\Sigma_0^{\text{fit}} = [(310 \pm 6)\ \text{MeV}]^3$

We are in agreement with the chiral perturbation theory: the chiral condensate is a linear function of the strength of the magnetic field!

3. Magnetization of the vacuum as a function of the magnetic field



Spins of virtual quarks turn parallel to the magnetic field

$$< \bar{\psi}\psi > \chi = -46(3) Mev \leftrightarrow \text{our result}$$

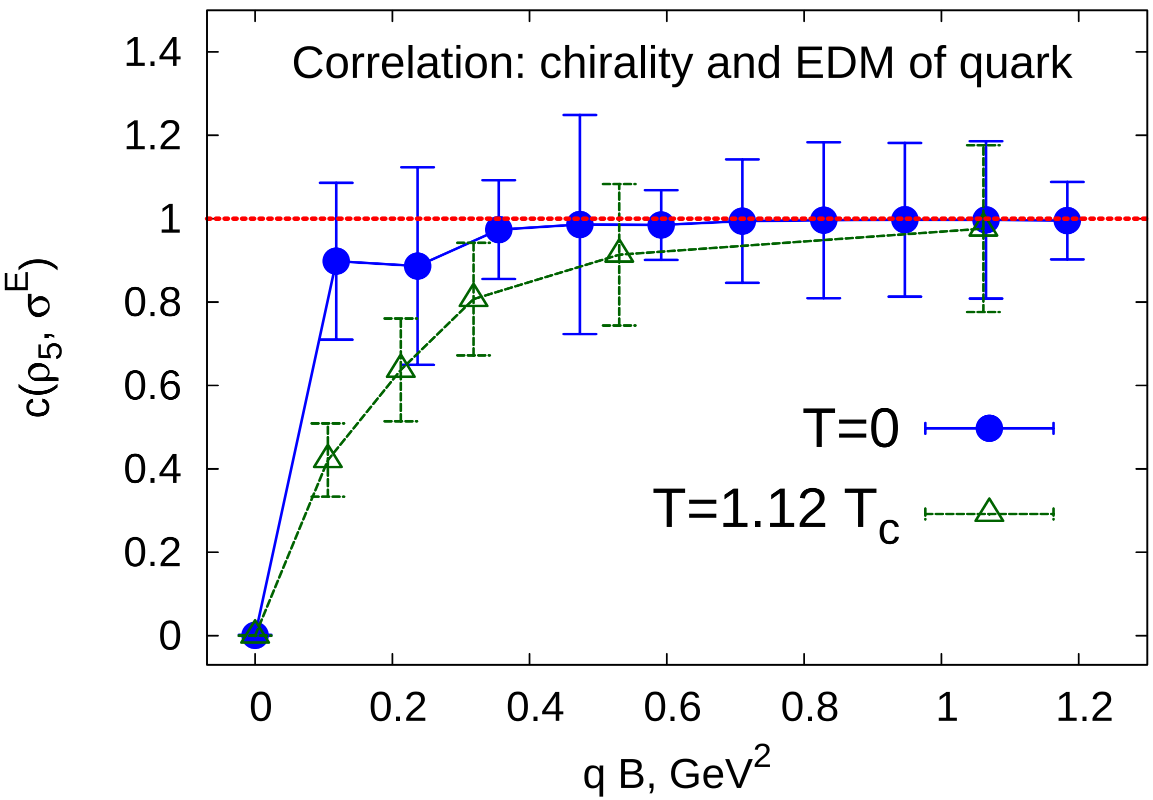
$$< \bar{\psi}\psi > \chi \approx -50 Mev \leftrightarrow \text{QCD sum rules}$$

(I. I. Balitsky, 1985, P. Ball, 2003.)

4. Generation of the anomalous quark electric dipole moment along the axis of magnetic field

- **Large correlation between square of the electric dipole moment**

$\sigma_{0i} = i\overline{\psi}[\gamma_0, \gamma_i]\psi$ **and chirality** $\rho_5 = \overline{\psi}\gamma_5\psi$



Results

1. We obsreve signatures of the Chiral Magnetic Effect, but the physics may differ from the model of Kharzeev, McLerran and Warringa (arXiv:0907.0494, Phys.Rev.D79:106003,2009)

2. We observe that the chiral condensate is proportional to the strength of the magnetic field, the coefficient of the proportionality agrees with Chiral Perturbation Theory. Microscopic mechanism for the chiral enhancement is the localization of fermion modes in the vacuum (arXiv:0812.1740, Phys.Lett. B)

3. The calculated vacuum magnetization is in a qualitative agreement with model calculations (arXiv:0906.0488, Nucl.Phys. B 826 (2010) 313)

4. We observe very large correlation between electric dipole moment of quark and chirality (arXiv:0909.2350)

arXiv:0909.1808

Conclusions

1. In QCD with dynamical quarks we

a) Observe confining string breaking

b) Find the structure of flux tubes inside baryon

c) Calculate the critical temperature

2. In QCD with external magnetic field we

a) Observe charge separation, but the physics may differ from the model of Kharzeev, McLerran and Warringa

b) The charge separation is weaker for heavy quarks, thus it is interesting to measure in experiments charge asymmetry for S and C quarks

c) The strong magnetic field exists only very short time $\lesssim 1$ *fm* still it can influence physics of strong interactions