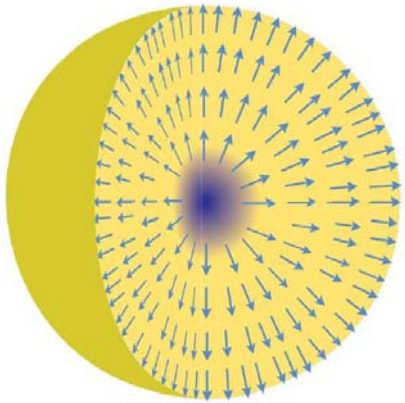
CP-ODD Workshop @ BNL , Apr, 2010

Probing the Topological Components of Strongly Coupled Quark-Gluon Plasma



Jinfeng Liao
Lawrence Berkeley National Laboratory

Outline

- Chiral Magnetic Effect:

  Data, **"Problem"** & New Probe

  (in collaboration with A. Bzdak and V. Koch)

- Thermal Monopoles &

  Postconfinement in sQGP

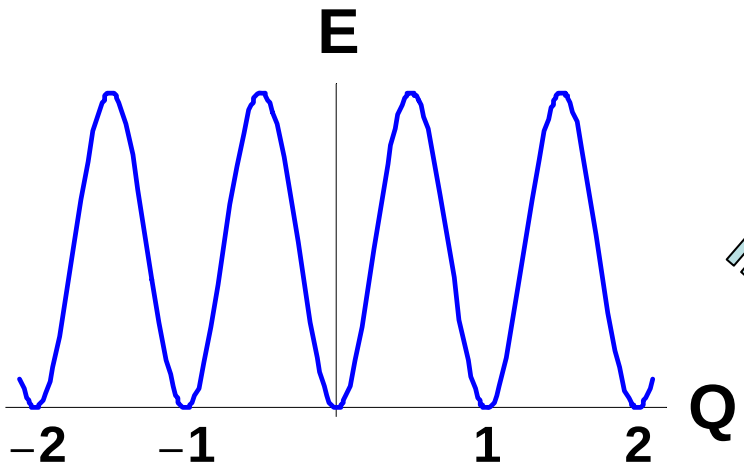
  (in collaboration with E. Shuryak)

Part. 1

- Chiral Magnetic Effect:

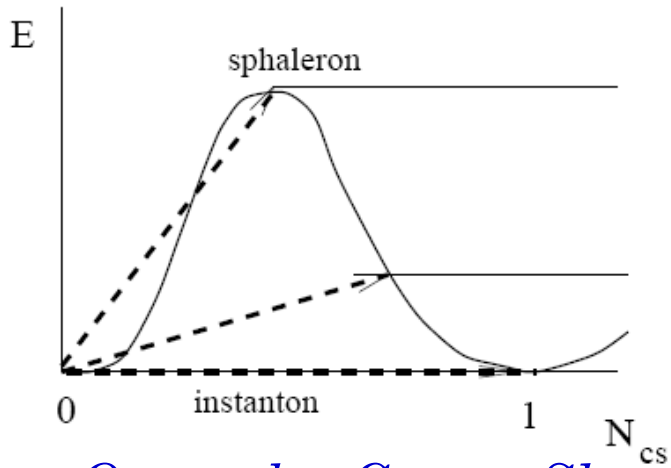
  Data, "**Problem**" & New Probe

Picking the Topology



The QCD Theta Vacua

When adequate energy is available …
(collisions; hot plasma)

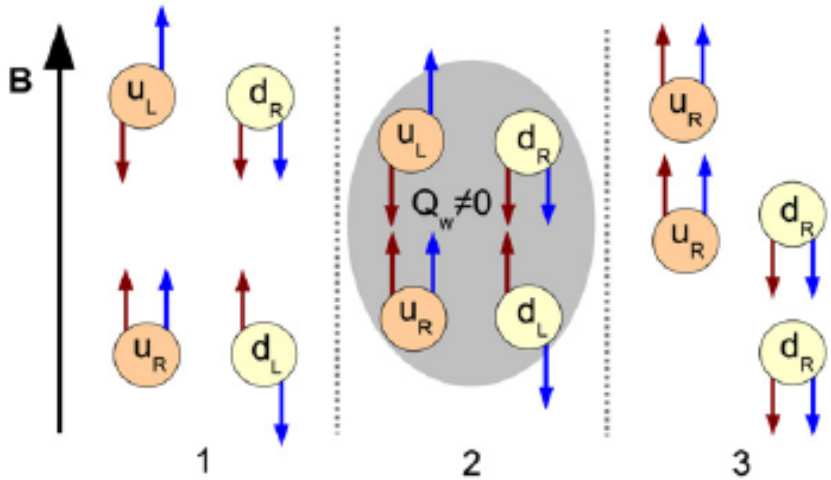


"Vacuum Engineering "
T.D. Lee (early 70's)

Ostrovsky, Carter, Shuryak, (02)
Kuchiev (09) "Energon"

The CME @ RHIC

Kharzeev, McLerran, Warringa (08)

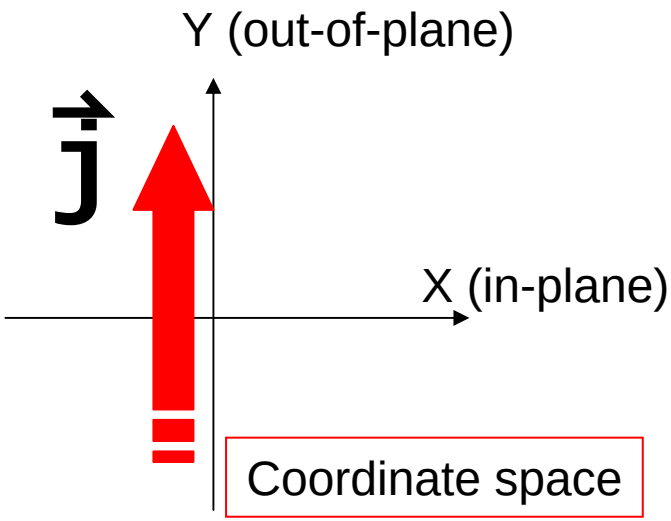


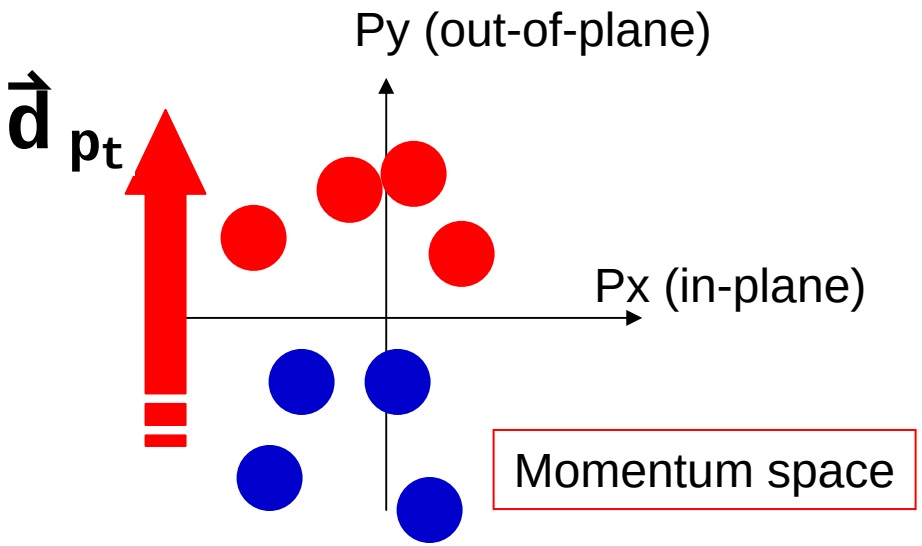
$$\vec{j} \propto (N_L - N_R)\,\vec{B} \propto Q\,\vec{B}$$

Q:
Theta vacua; sphaleron transition;
Flipping → ***exp. difficulty***

B:
Non-central; strong at very early time;
Out-of-plane → ***exp. difficulty***

Possible CME Signal





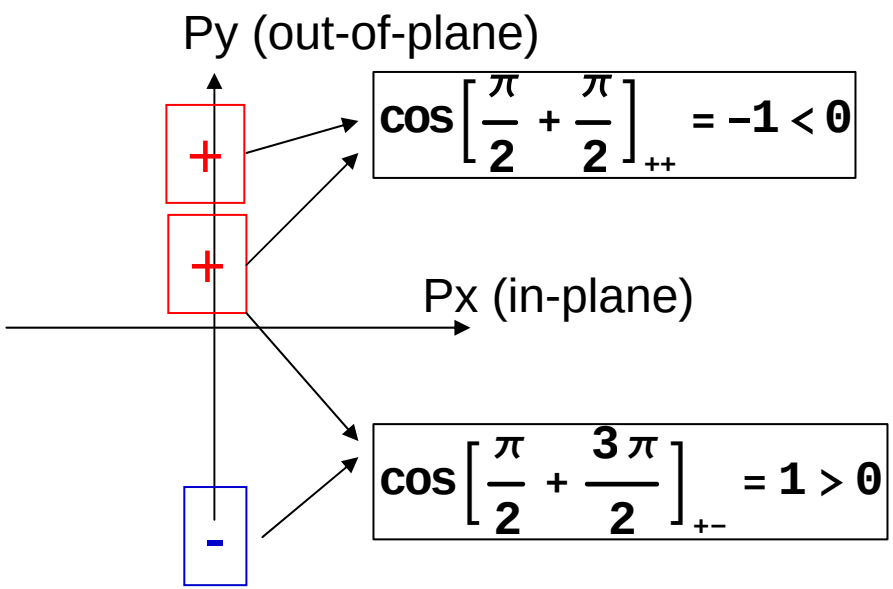
Charge Separation *or*
Electric Dipole in Pt Space
(along out-of-plane)

Complications:
- hard to identify R.P. E-by-E
- dipole directions flip E-by-E

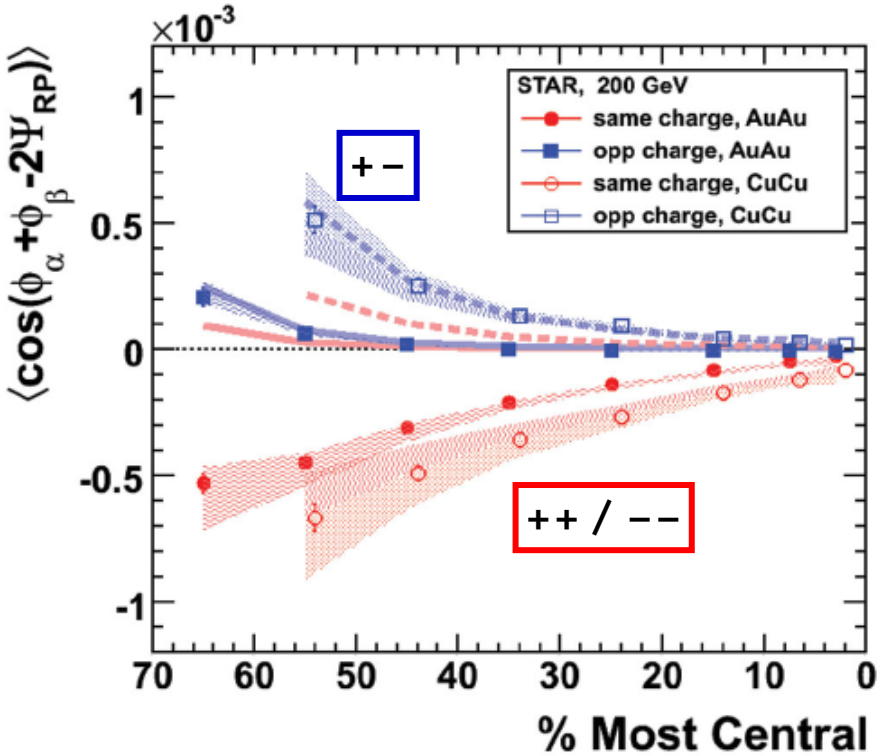
STAR Observable & Data

3P correlations: *Voloshin (04)*

$$\langle \cos(\phi_a + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos(\phi_a + \phi_\beta - 2\phi_c) \rangle / v_{2,c}.$$



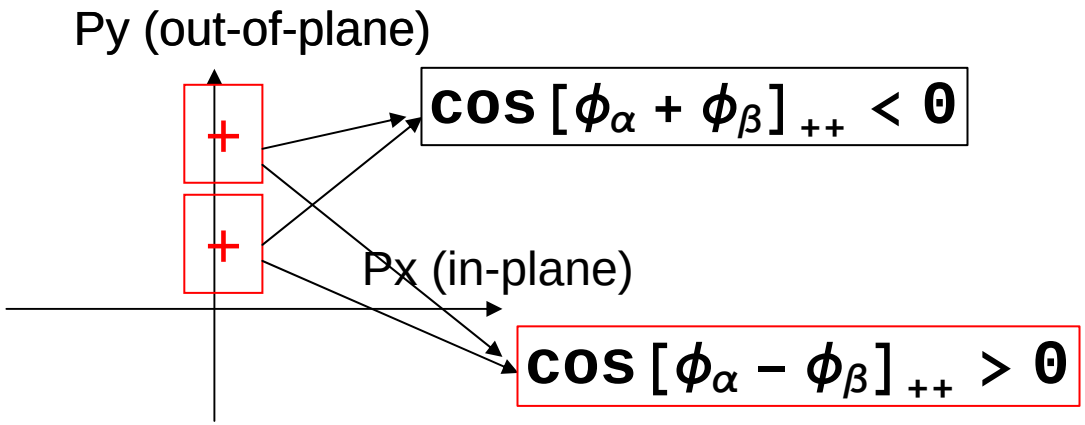
CME expectation



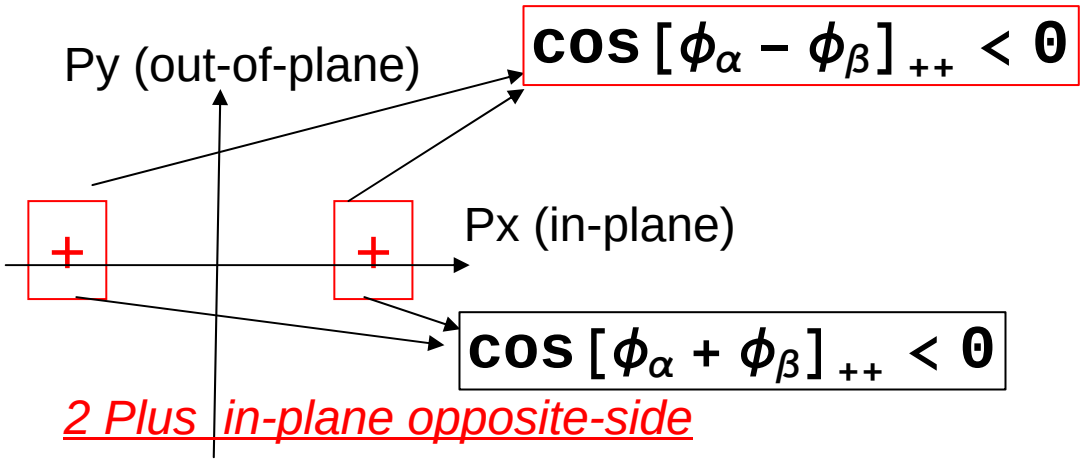
STAR (09)

In-plane v.s. Out-of-plane

Focus on the same charge pair

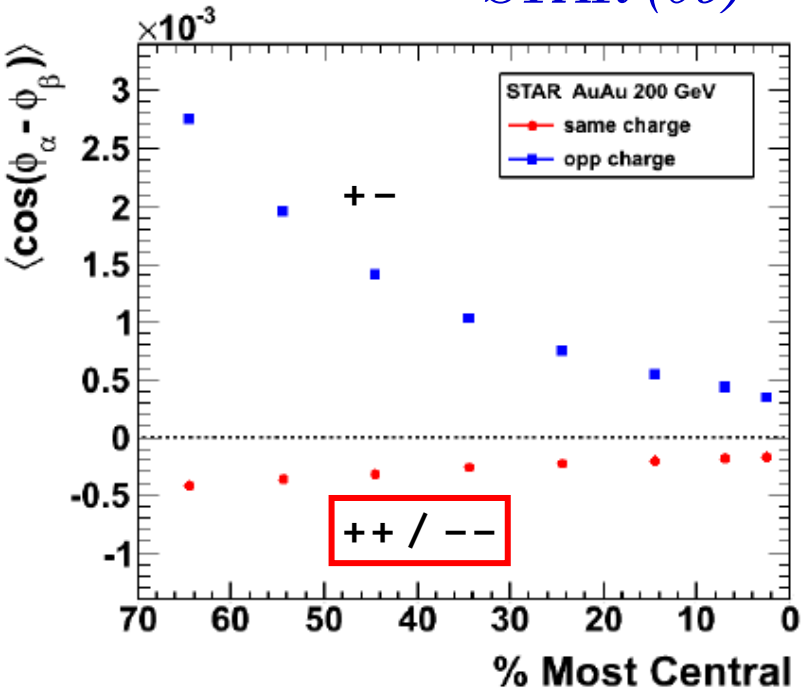


2 Plus out-of-plane same-side



2 Plus in-plane opposite-side

STAR (09)

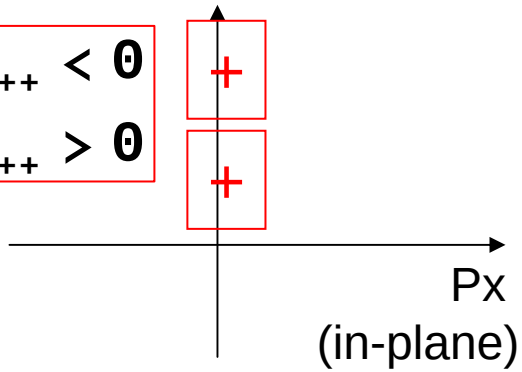


The data favors in-plane configuration.

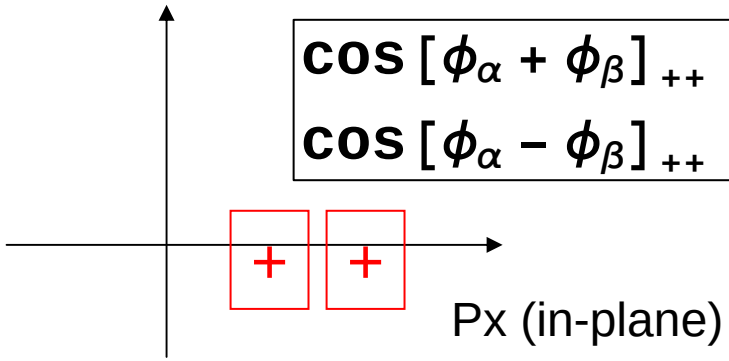
In-plane v.s. Out-of-plane

$\cos[\phi_\alpha + \phi_\beta]_{++} < 0$

$\cos[\phi_\alpha - \phi_\beta]_{++} > 0$



CME

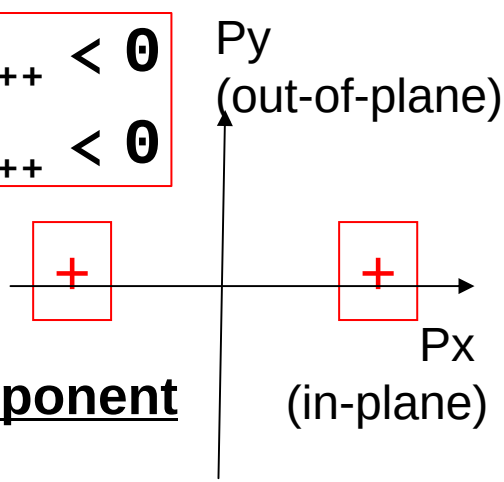


$\cos[\phi_\alpha + \phi_\beta]_{++} > 0$

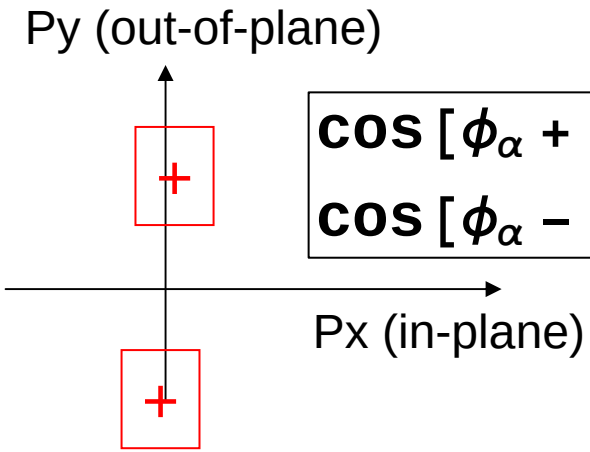
$\cos[\phi_\alpha - \phi_\beta]_{++} > 0$

$\cos[\phi_\alpha + \phi_\beta]_{++} < 0$

$\cos[\phi_\alpha - \phi_\beta]_{++} < 0$



Dominant component seen in DATA



$\cos[\phi_\alpha + \phi_\beta]_{++} > 0$

$\cos[\phi_\alpha - \phi_\beta]_{++} < 0$

Projected Correlations

$$\langle \cos[\phi_\alpha - \phi_\beta] \rangle = \langle \cos[\phi_\alpha - \Psi_{RP}] * \cos[\phi_\beta - \Psi_{RP}] \rangle + \langle \sin[\phi_\alpha - \Psi_{RP}] * \sin[\phi_\beta - \Psi_{RP}] \rangle$$

$$\langle \cos[\phi_\alpha + \phi_\beta - 2\Psi_{RP}] \rangle = \langle \cos[\phi_\alpha - \Psi_{RP}] * \cos[\phi_\beta - \Psi_{RP}] \rangle - \langle \sin[\phi_\alpha - \Psi_{RP}] * \sin[\phi_\beta - \Psi_{RP}] \rangle$$

BOTH ARE NEEDED AND IMPORTANT !

In-plane projected correlation

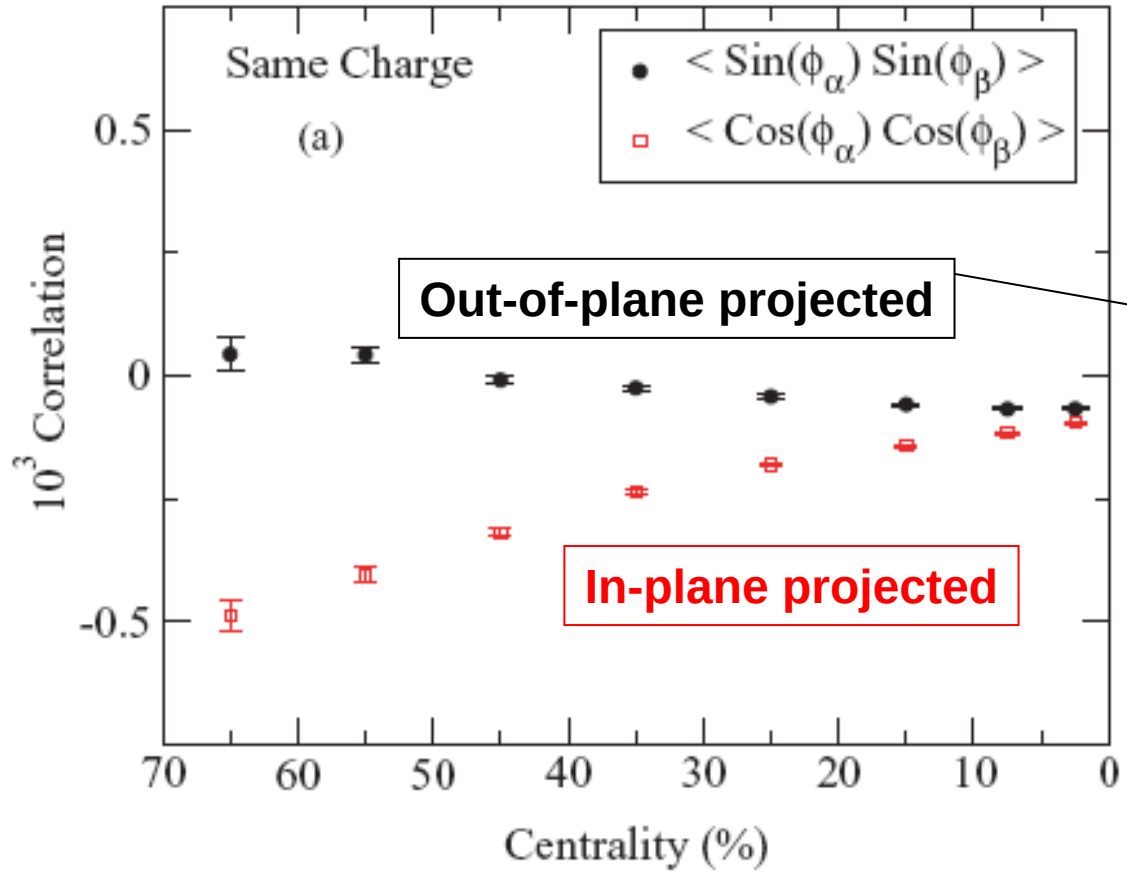
$$\langle \cos[\phi_\alpha - \Psi_{RP}] * \cos[\phi_\beta - \Psi_{RP}] \rangle$$

Out-of-plane projected correlation

$$\langle \sin[\phi_\alpha - \Psi_{RP}] * \sin[\phi_\beta - \Psi_{RP}] \rangle$$

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

Same-Charge Projected Correlations

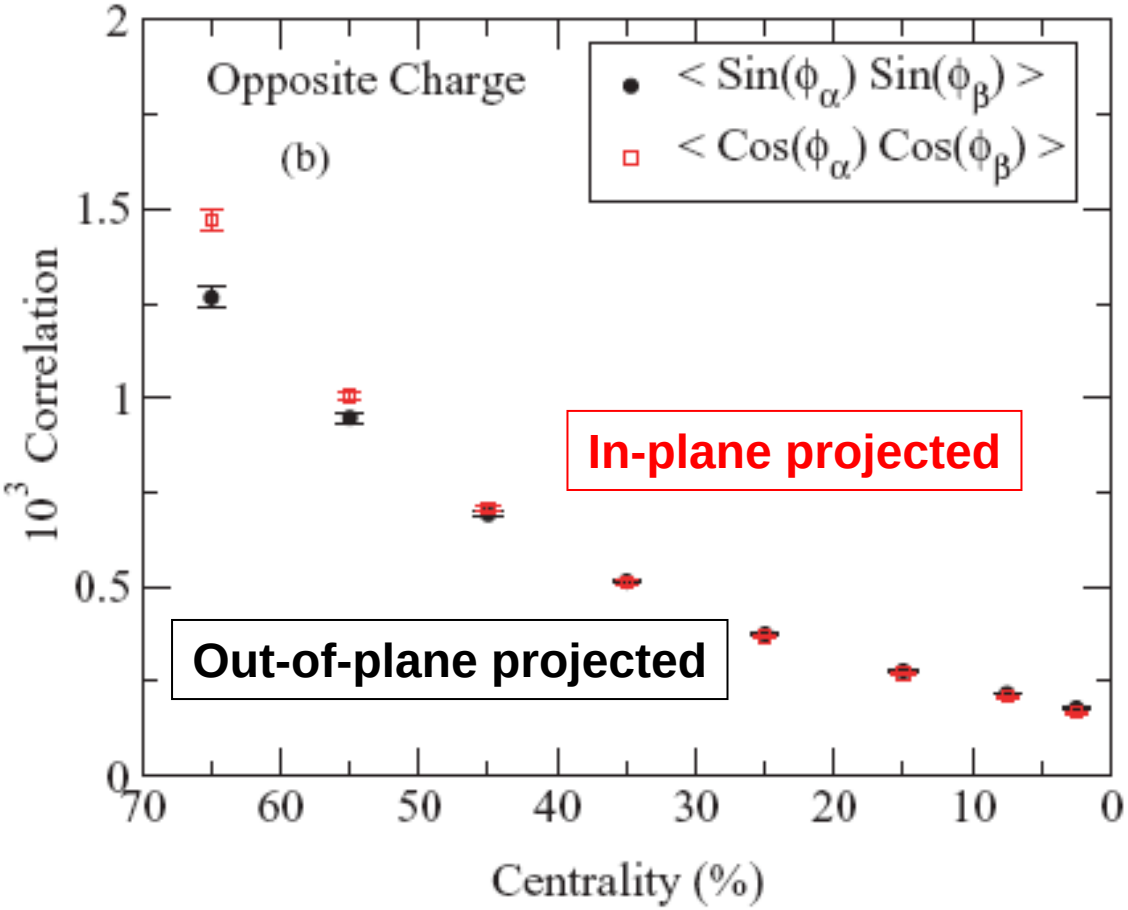


<sin*sin> ~ 0
A very strong constraint we have to live with !

In-plane-dominant, back-to-back

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

Opposite-Charge Projected Correlations



In/out-plane the same, same-side aligned

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

Background Dilemma

The "background" argument as per STAR papers

$$< \sin[\phi_\alpha - \Psi_{RP}] * \sin[\phi_\beta - \Psi_{RP}] > \; = \; B_{out} + P$$

$$< \cos[\phi_\alpha - \Psi_{RP}] * \cos[\phi_\beta - \Psi_{RP}] > \; = \; B_{in}$$

$$B_{in} = B_{out} \; ?$$

What data do show: $B_{out} \approx -P$

Call for critical and detailed investigation:

- what is in the background?
- fine-tuning cancellation? What? Why?
- Pt & eta differential study of projected correlations
- Projected correlations in CuCu
- **Other observables?**

NEED BOTH !

$\cos[\phi_\alpha + \phi_\beta]$

$\cos[\phi_\alpha - \phi_\beta]$

Charged Dipole Deformation

Azimuthal distribution:

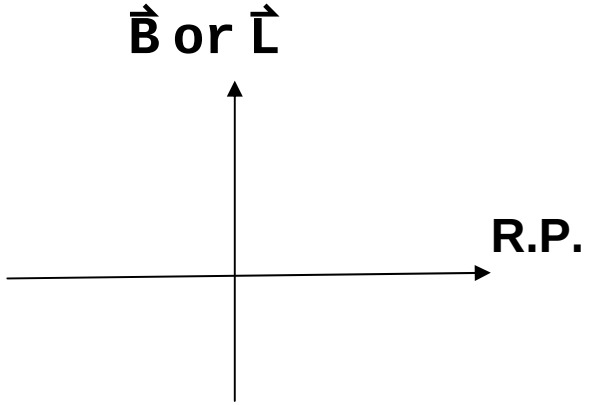
$$f_\chi(\phi, q) \propto 1 + 2\,v_2 \cos(2\phi - 2\Psi_{R.P.}) + 2\,q\,\chi\,d_1 \cos(\phi - \Psi_{C.S.})$$

Quadruple deformation

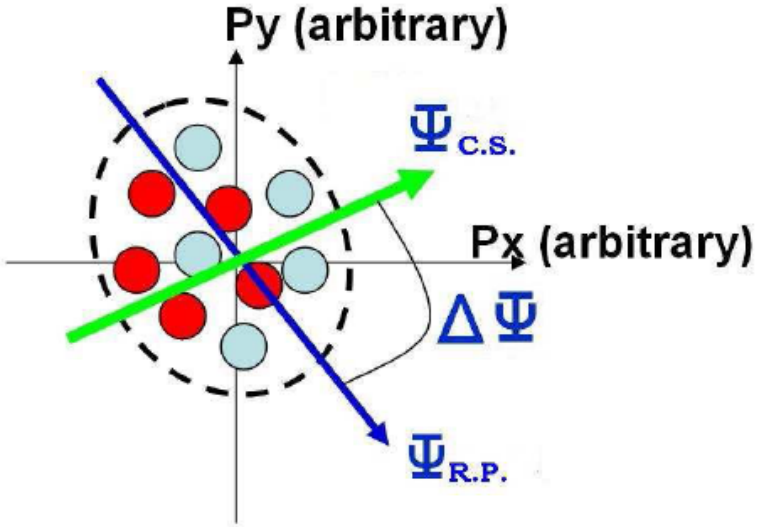
Reaction Plane angle

Charged dipole deformation

Charged dipole angle



The ideal world



The real world

Pinpoint the Dipole

In each event : N particles, (η_i, $p_{t\,i}$, ϕ_i, q_i)

Recall Q2 analysis for elliptic flow:
looking for the maximal quadruple

$$Q_2 \cos 2\Psi_2 \equiv \sum_i \cos 2\phi_i$$

$$Q_2 \sin 2\Psi_2 \equiv \sum_i \sin 2\phi_i$$

In analogy, Q^c_1 analysis:
looking for the maximal dipole

$$Q_1^c \cos \Psi_1^c \equiv \sum_i q_i \cos \phi_i$$

$$Q_1^c \sin \Psi_1^c \equiv \sum_i q_i \sin \phi_i$$

In each event ⇒ (Q_2, Ψ_2) & (Q^c_1, Ψ^c_1)

Relative orientation !

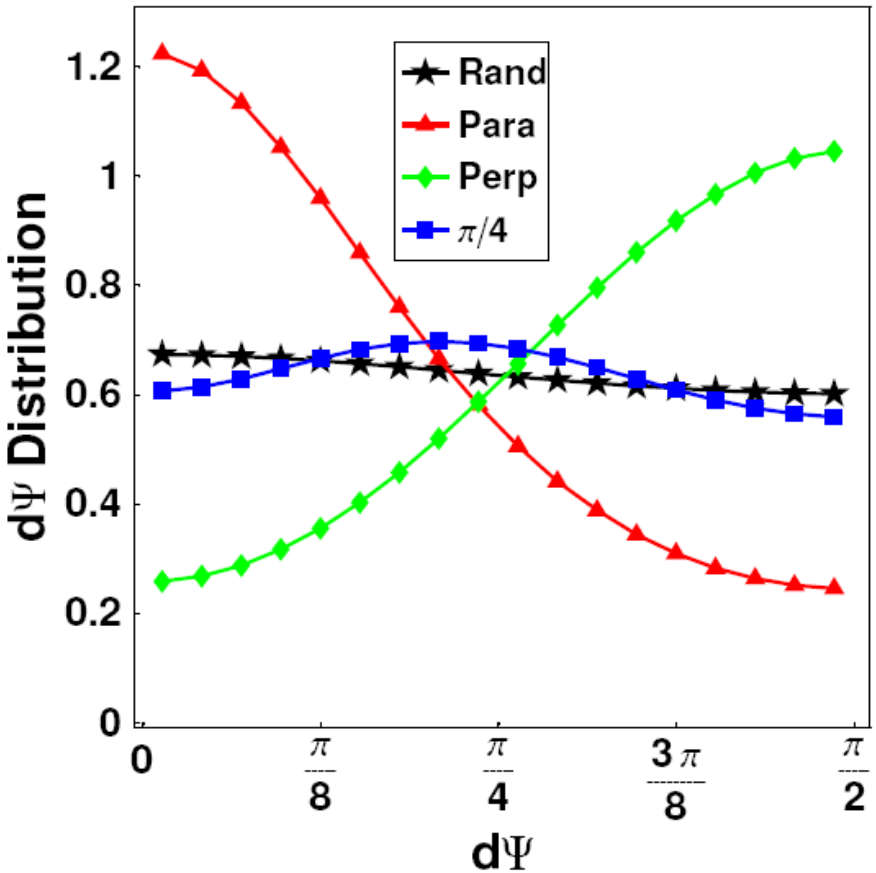
Discriminating the Angular Pattern

JL, Koch, Bzdak (to appear)

Azimuthal distribution:

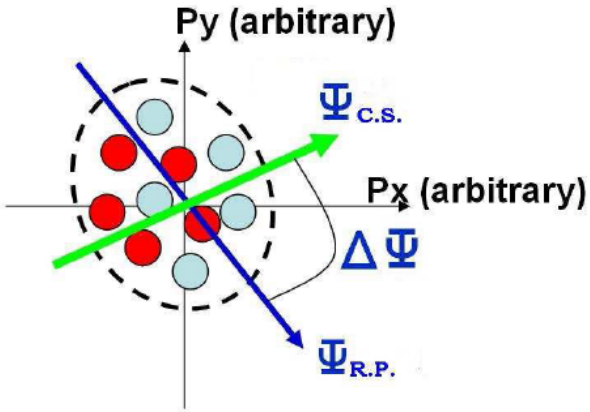
$$f_\chi(\phi, q) \propto 1 + 2\, v_2 \cos(2\phi - 2\Psi_{R.P.}) + 2\, q\, \chi\, d_1 \cos(\phi - \Psi_{C.S.})$$

Monte Carlo sampling of events according the above with different relative orientation:
(a) Random (b) parallel
(c) perpendicular (d) 45deg.
Then applying the
joint Q2 & Q^c_1 analysis !
[details: 200 +, 200 -, v2 =0.1 , d1=0.05]



* Great discriminating power, may clarify the situation;
* Robust: surviving tests with built-in cluster type correlations.

Measure the Relative Orientation



$$Q_1^c \cos \Psi_1^c \equiv \sum_i q_i \cos \phi_i$$

$$Q_1^c \sin \Psi_1^c \equiv \sum_i q_i \sin \phi_i$$

$$Q_2 \cos 2\Psi_2 \equiv \sum_i \cos 2\phi_i$$

$$Q_2 \sin 2\Psi_2 \equiv \sum_i \sin 2\phi_i$$

in a given event

$$\cos[2*(\Psi^c{}_1 - \Psi_2)] = \frac{N_{ch} + 2\sum q_i q_j \cos(\phi_i - \phi_j) + \sum \cos(2\phi_i - 2\phi_j) + \sum q_i q_j \cos(\phi_i + \phi_j - 2\phi_k)}{[N_{ch} + \sum \cos(2\phi_i - 2\phi_j)]^{1/2} * [N_{ch} + \sum q_i q_j \cos(\phi_i - \phi_j)]}$$

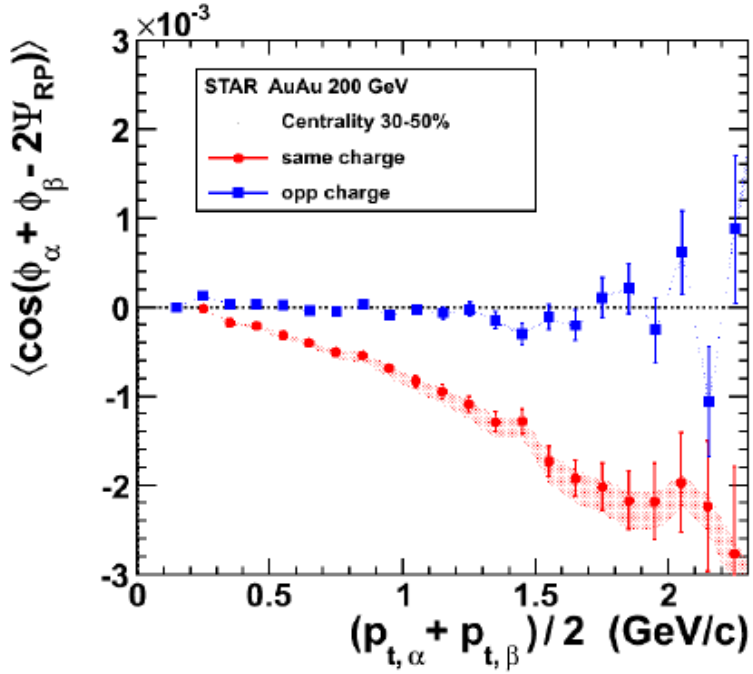
$$< \cos[2*(\Psi^c{}_1 - \Psi_2)] >$$

-1 ——— +1

Out-of-plane ——— In-plane

- involves all 2P,3P correlations in a complicated way
- current data can NOT tell about it: please measure !

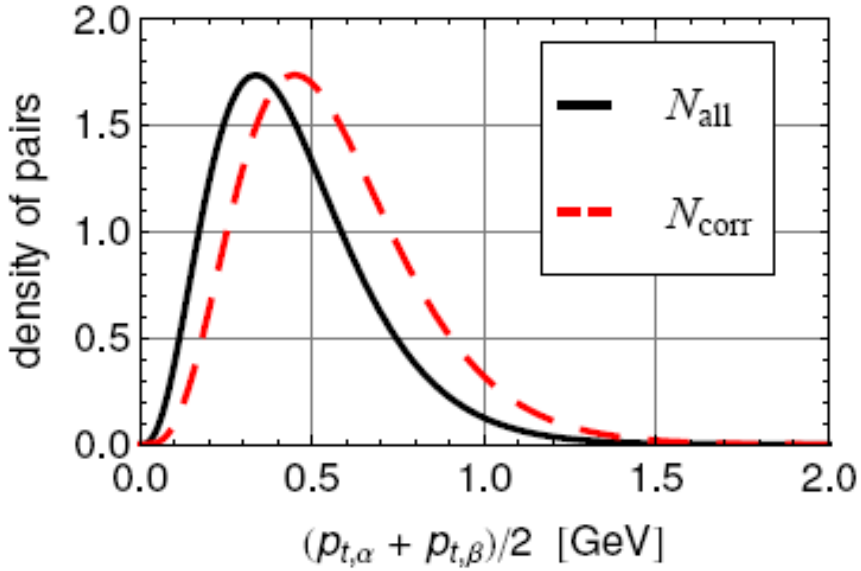
Interesting Pt Pattern



Bzdak, Koch, JL (09)
PRC81,031901(R),2010

$$< \cos[\phi_\alpha + \phi_\beta - 2\,\Psi_{RP}] > \;\propto\; \frac{N_{corr}}{N_{all}}$$

$$N_{all}(p_+) \propto \int d^2p_{t,\alpha} d^2p_{t,\beta} \exp\left(-\frac{p_{t,\alpha}}{T}\right) \exp\left(-\frac{p_{t,\beta}}{T}\right) \times \delta(2p_+ - [p_{t,\alpha} + p_{t,\beta}]) \propto p_+^3 e^{-2p_+/T},$$



Correlated pairs are a bit
HARDER
than average medium pairs

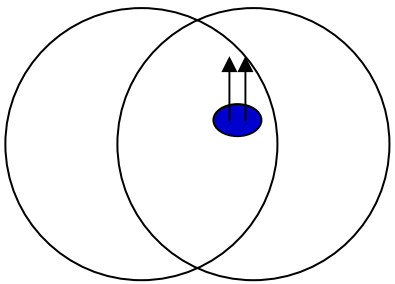
Radial Flow & Geometric Bias

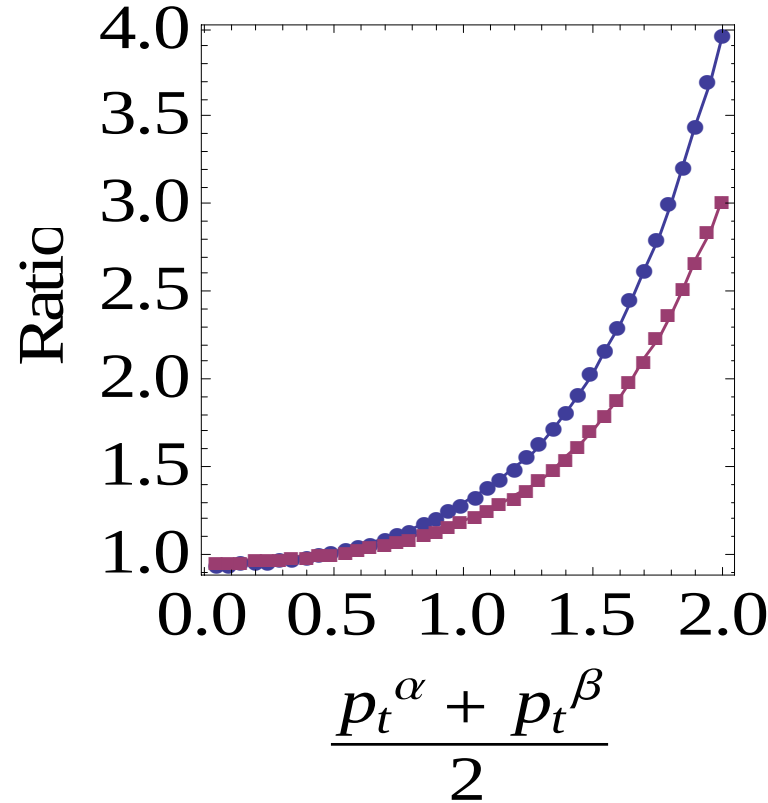
Harder spectra → picking up a larger radial flow → bias toward surface

Similar idea in the hard ridge: Shuryak (07)

Convolution of initial generation & subsequent attenuation

- *Initial bias :* Npart v.s. Ncoll v.s. whatever ?
  could shift inward/outward/same
- *Localization bias:*
  all pairs -- ***n(r1)*n(r2)***
  correlated pairs --- ***n(r) if bubble small***
  the "all pairs" weighed more in the center
- *Quenching bias (or screening in K.M.W. paper):*





More in progress…

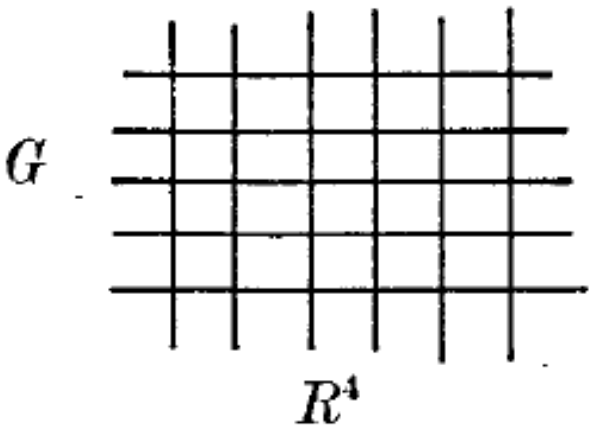
Part. II

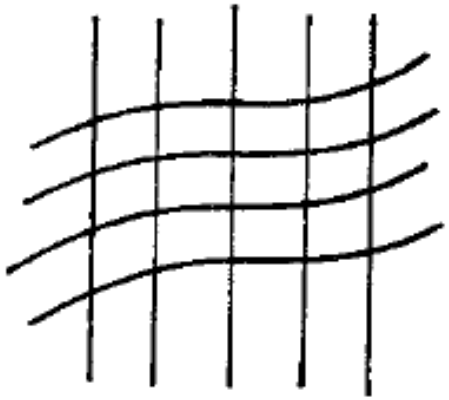
- Thermal Monopoles &

  Postconfinement in sQGP

Gauge Fields as Geometry

from M. Atiyah





Twisting gauge fields across space-time → topological structure

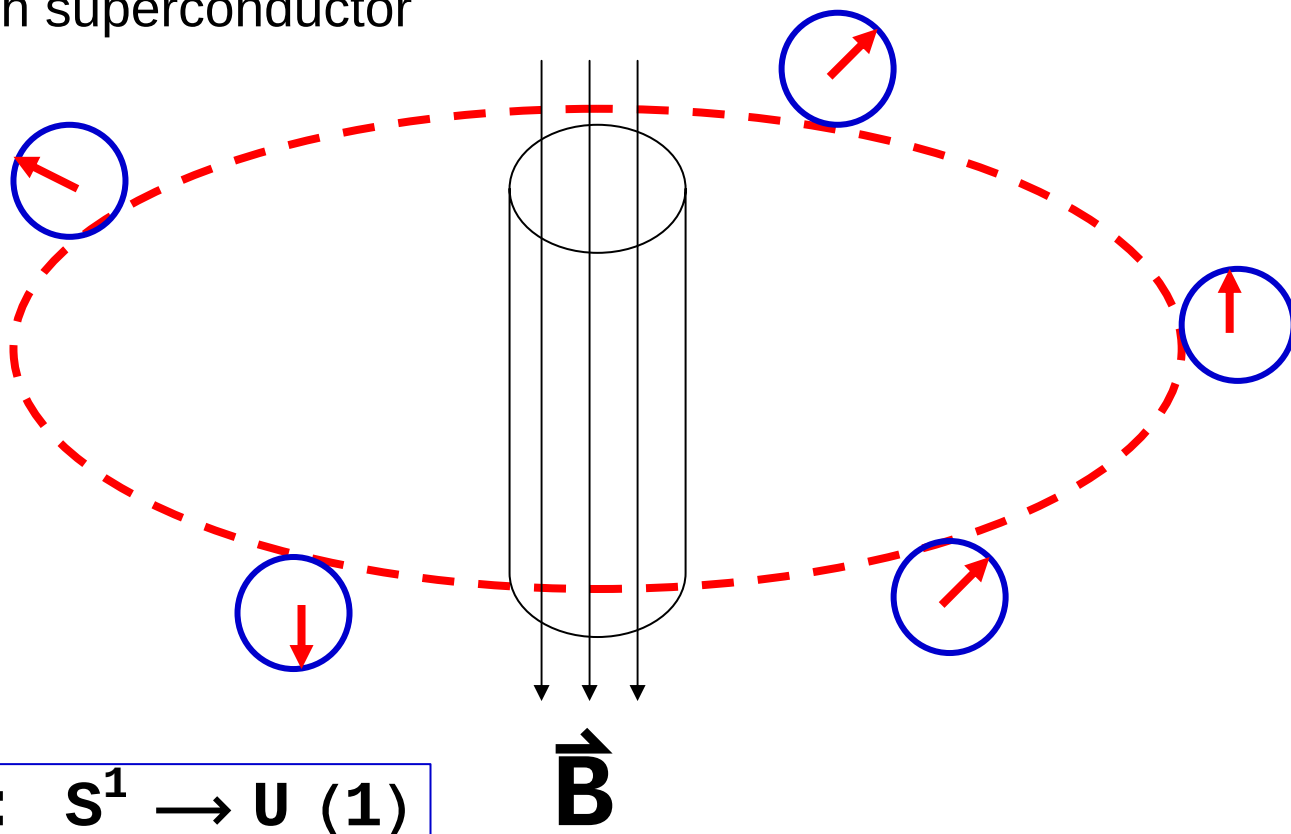
Vortex in 2D

Magnetic flux through superconductor

$$|\vec{x}| \longrightarrow \infty$$

$$|\Phi e^{i\theta}| = v \neq 0$$

E-charged condensate



$$\boxed{\text{Mapping}: \; S^1 \longrightarrow U(1)}$$

HOMOTOPY CLASSES & GROUP: times of covering
(see the excellent chapter in Rubakov's book)

Magnetic Monopole in 3D

't Hooft-Polyalov monopole in George-Glashow model with SU(2)

$$L = -\frac{1}{2}\mathrm{Tr}\ F_{\mu\nu}F^{\mu\nu} + \mathrm{Tr}\ D_\mu\phi D^\mu\phi - V(\phi)$$ with higgs-type condensate

$$|\vec{x}| \longrightarrow \infty$$

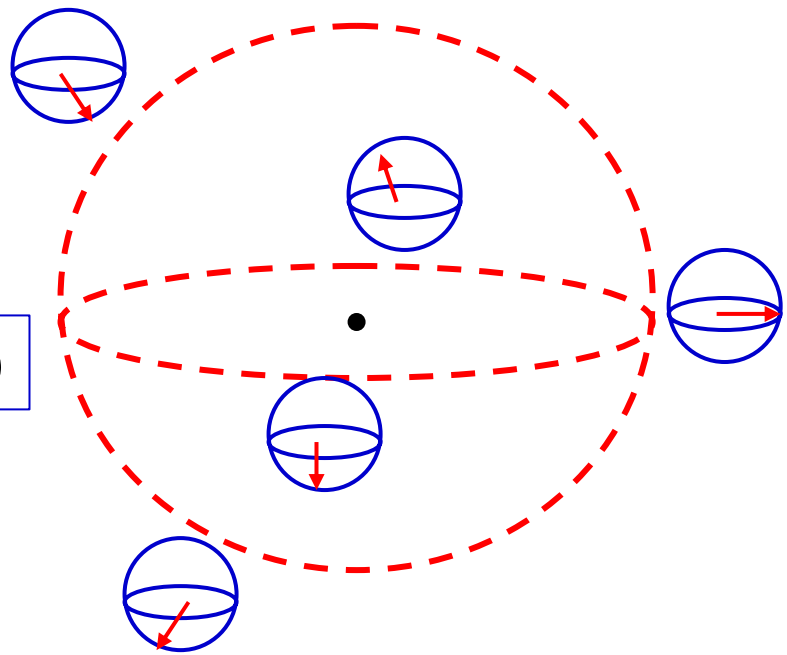
$$|U\Phi U^{-1}| = v \neq 0$$

$$\boxed{\text{Mapping}: \quad S^2 \longrightarrow SU(2)}$$

↓

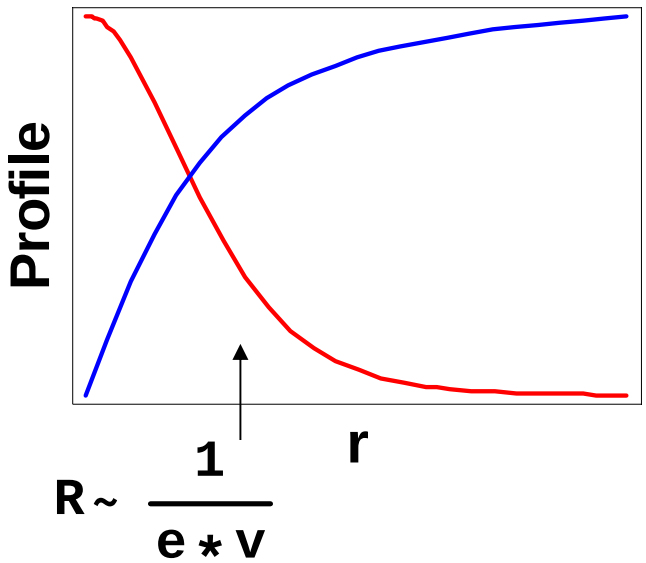
Topological charge &
Magnetic charge

$$g = \frac{4\pi n}{e}, \qquad n \in \mathbb{Z}$$



BPS limit:
$V \rightarrow 0$

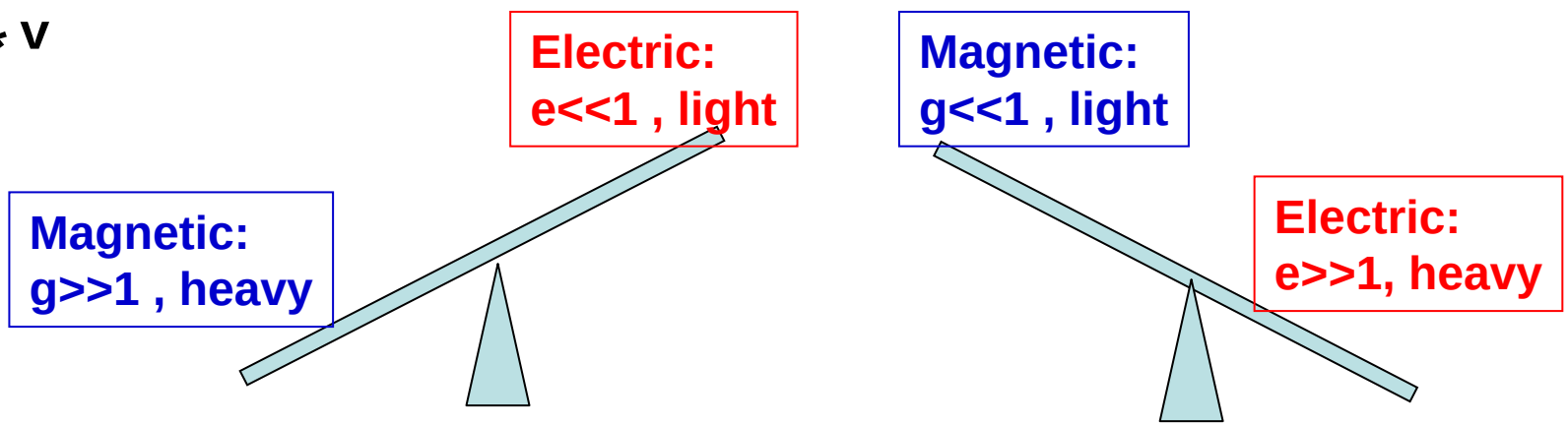
Electric-Magnetic See-Saw



Gluon/W-boson mass: $M_w = e * v$

Magnetic monopole mass: $M_m = g * v$

$$\text{Dirac}: \; e * g = 1$$

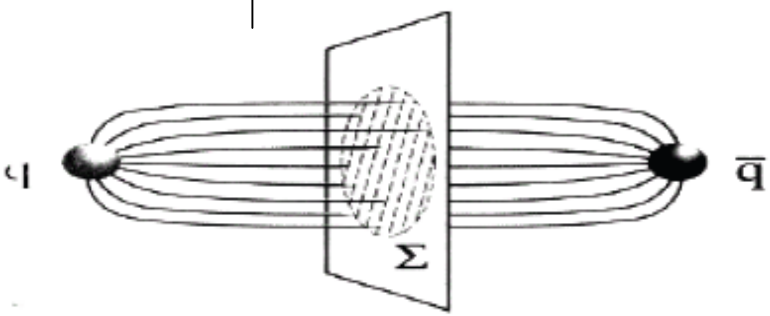


Montonen, Olive, 77
Seiberg, Witten, 94

QCD Confinement

Vacuum: confined | Tc | sQGP | wQGP | T

RHIC



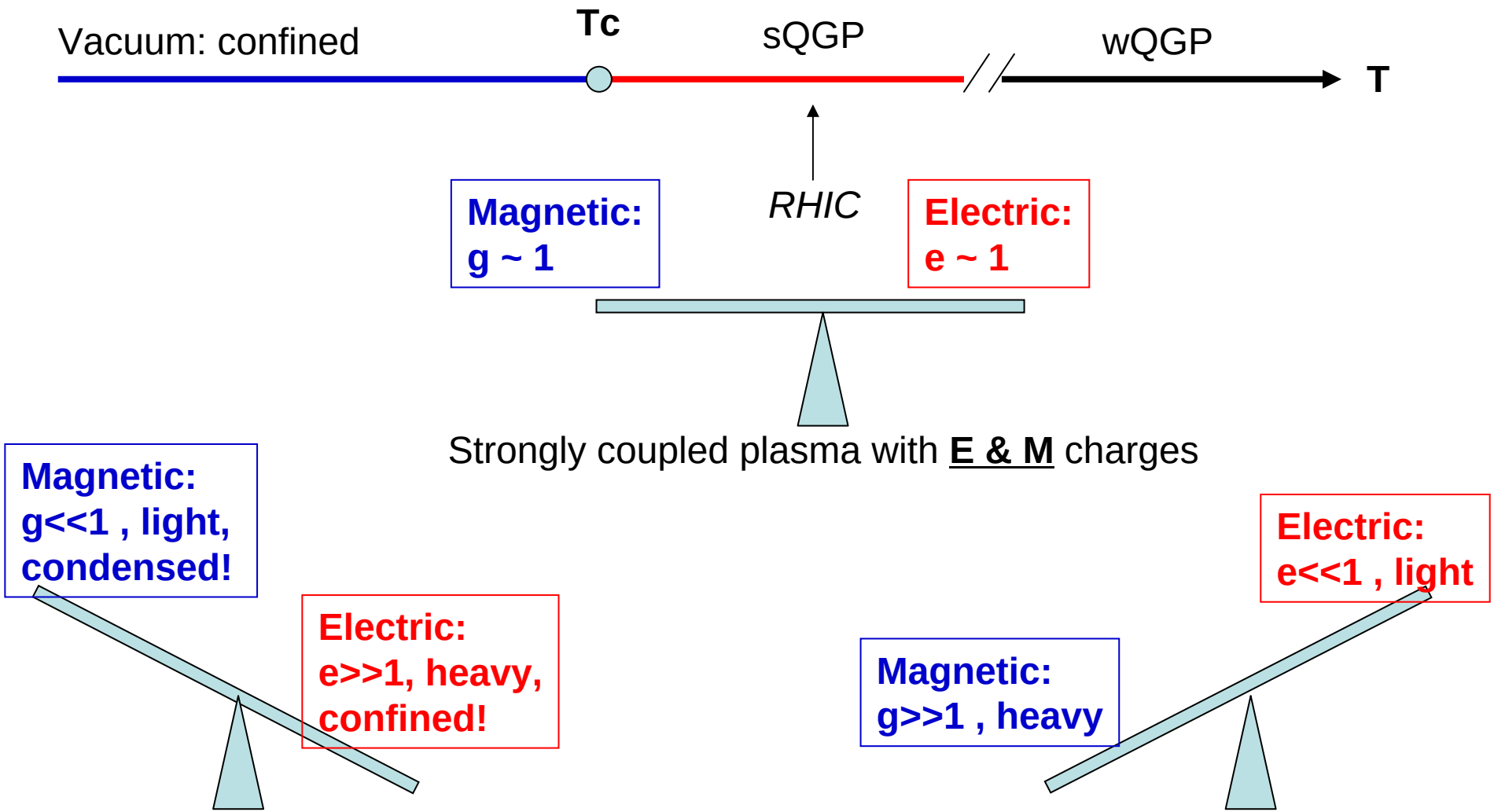
?

Electric Flux Tube:
Magnetic Condensate

Plasma of E-charges
E-screening: g T
M-screening: g^2 T

Dual superconductor
't Hooft ; Mandelstam late 70's

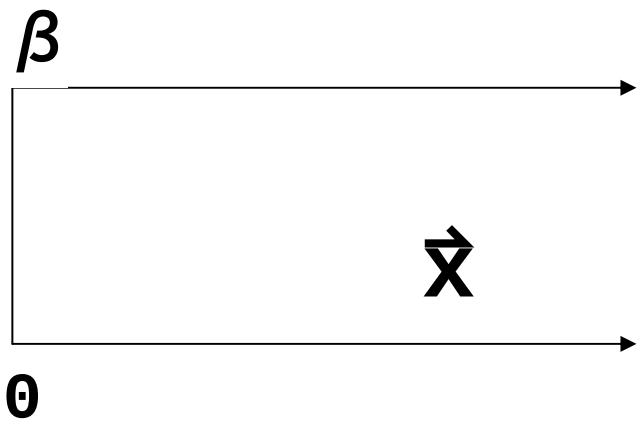
QCD See-Saw ? !


Vacuum: confined
Tc
sQGP
wQGP
T
RHIC
Magnetic:
g ~ 1
Electric:
e ~ 1
Strongly coupled plasma with E & M charges
Magnetic:
g<<1 , light,
condensed!
Electric:
e>>1, heavy,
confined!
Magnetic:
g>>1 , heavy
Electric:
e<<1 , light

Compelling Evidences

- L-suppression persists till ~1.6Tc while D.o.F liberated earlier (semi-QGP) → AND thermal monopoles
- E / M screening masses crossing ~1.4Tc
- Flux-tube in Q-bar-Q potential survives till ~1.3Tc → protected by thermal M-currents
- Direct lattice manifestation via MAG → density & BEC; spatial correlations and running coupling
- RHIC: small viscosity due to E-M mixture; strong enhancement of jet quenching near Tc → jet v2 puzzle; cone & ridge protected

How the monopoles arise in QCD



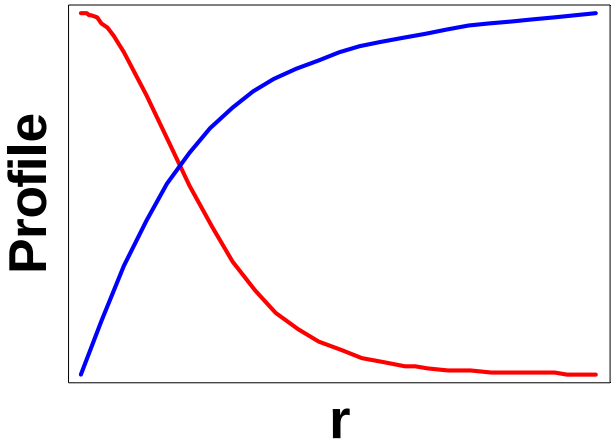
$$L(\mathbf{x}) = \mathcal{P}\,\exp\left(i\int_0^{\frac{1}{T}} dt\, A_4(t,\mathbf{x})\right)$$

$$L = \mathrm{diag}\left(e^{2\pi i\mu_1}, e^{2\pi i\mu_2}, \ldots, e^{2\pi i\mu_N}\right)$$

$L\,(\,|\,\vec{x}\,|\,\longrightarrow\infty)$

A_4 as adj – scalar

$$\mathcal{L} \sim -\frac{1}{4}\,\mathrm{Tr}F_{ij}\,F^{ij} + \mathrm{Tr}\,[D_i\,A_0]\,[D^i\,A_0]$$



However:

BPS ; long range E charge, i.e. dyon

$V[A_0]$ From dimensional reduction with fixed (nontrivial) holonomy;

Essential for an effective theory

Summary Part-1

- CME motivated measurements of charged 2P correlations
- Projected correlations dominated by

  same-charge: back-to-back, in-plane

  opposite-charge: aligned, in/out-plane similar
- New useful probe

  intuitive approach: relative angle between dipole/R.P.
- Genuine 2P correlations from localized source --- harder spectra due to localization & quenching bias

Summary Part-II

- E-M See-Saw at work in QCD
- sQGP in 1-1.5Tc as the "balanced regime" with both E & M players
- Lattice and phenomenological evidences
- Effective theory:

  holonomy + dim. reduction

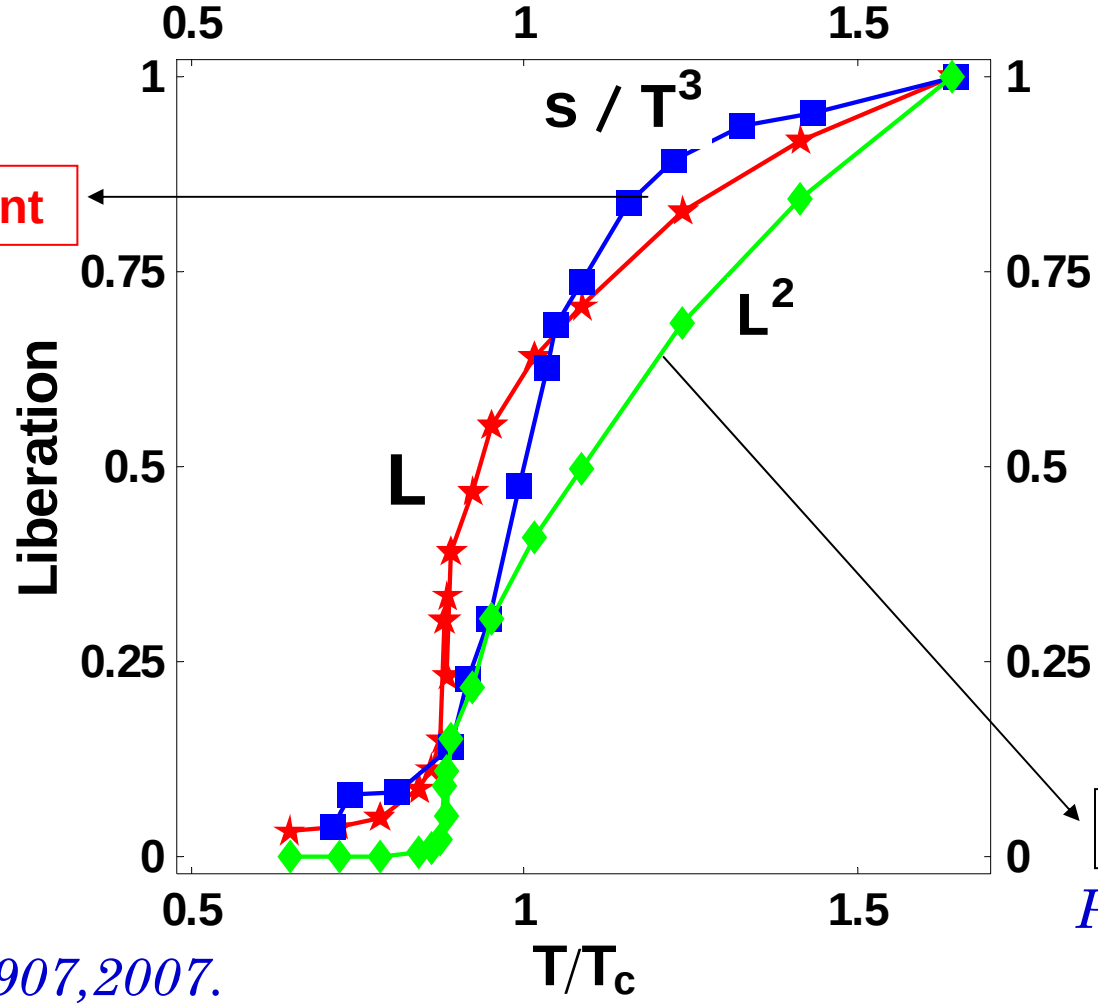
Thank you !

Backup Slides

Liberation of Color and D.o.F

Magnetic component

Postconfiment:
understand confinement physics in (partially) deconfined phase

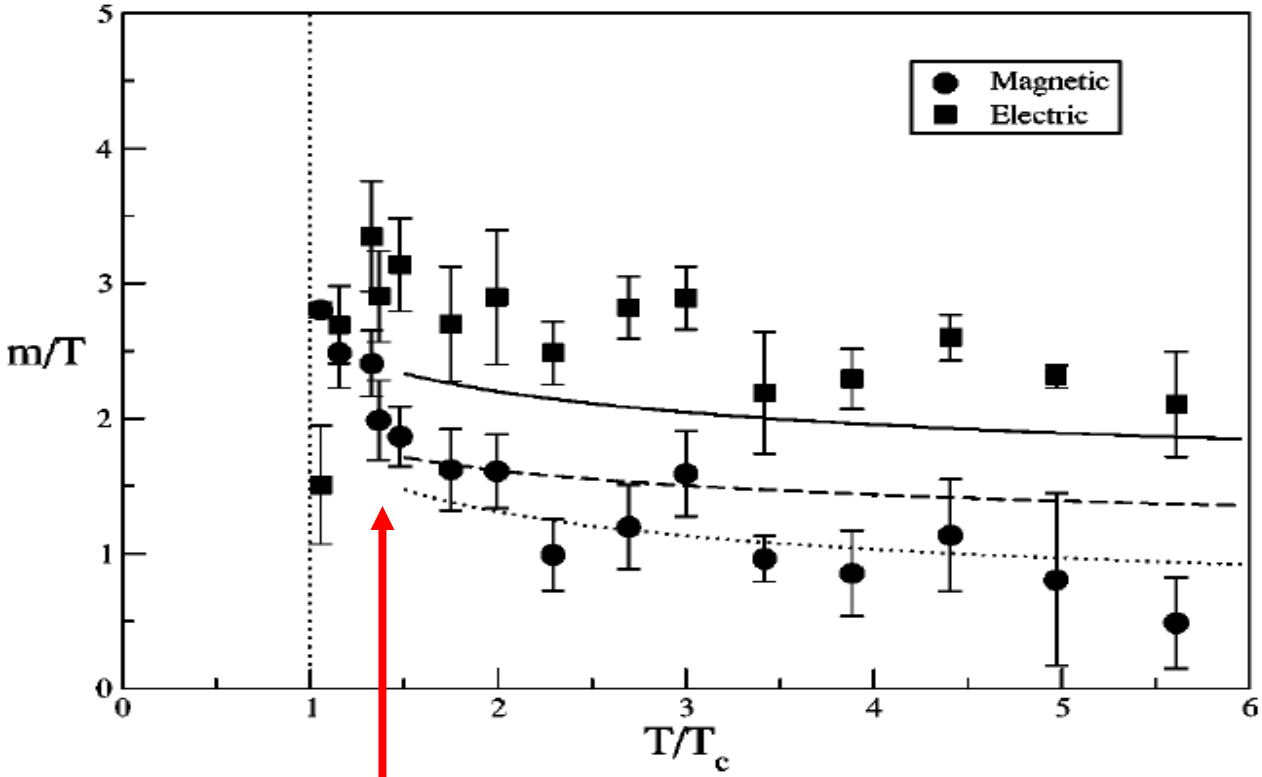


semi-QGP

JL & Shuryak, 06
Phys.Rev.C75,054907,2007.

Pisarski, et al

Electric & Magnetic Screening



E: g T

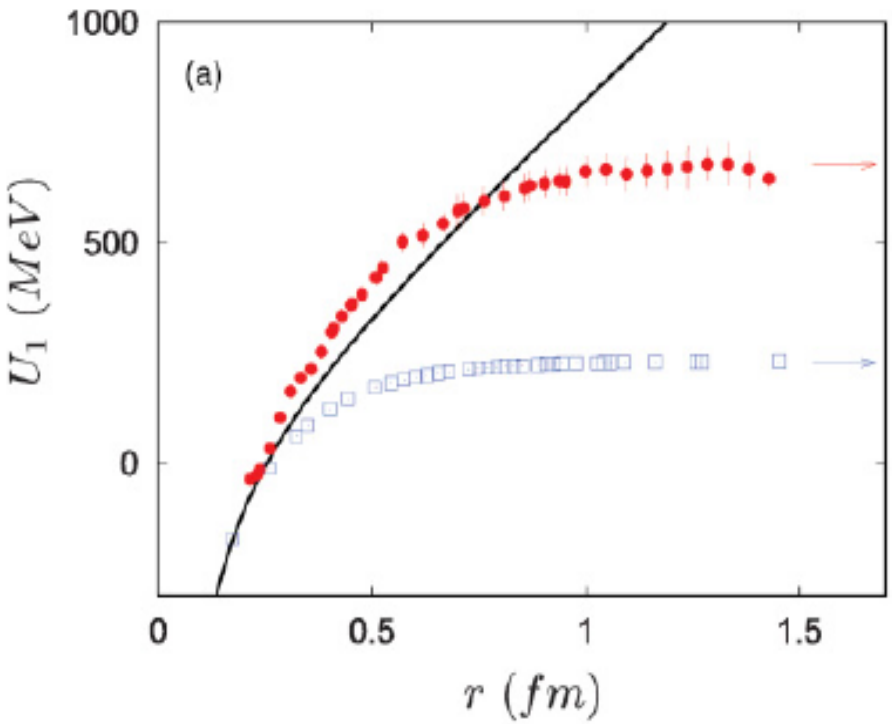
M: g^2 T

E / M crossing !

Nakamura, Saito, Sakai, 03;
Digal, Fortunato, Petreczky, 03

Q-bar-Q Potential

Kaczmarek, Zantow, 05

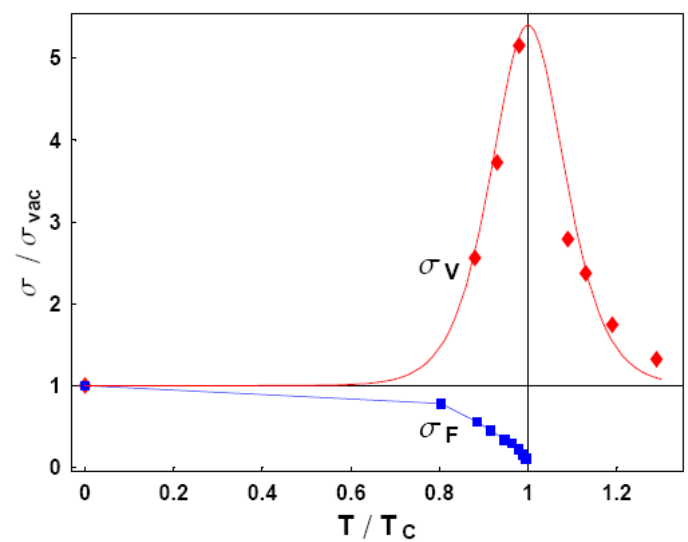


Flux tube survives till about 1.3Tc :

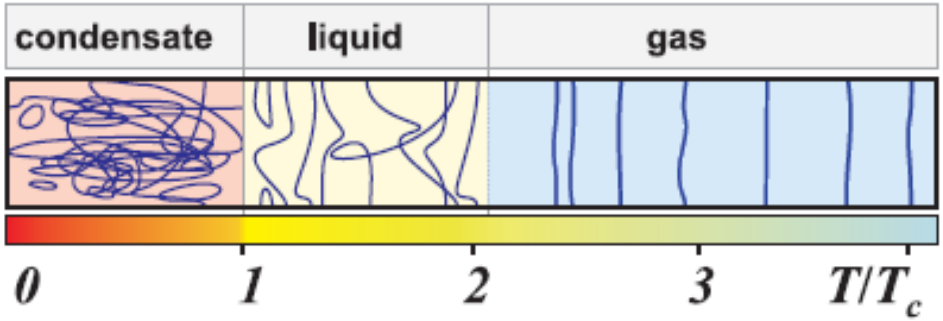
Metastable, alive on short time scale;
Protected by thermal monopole current !
→

Phenomenological consequences:

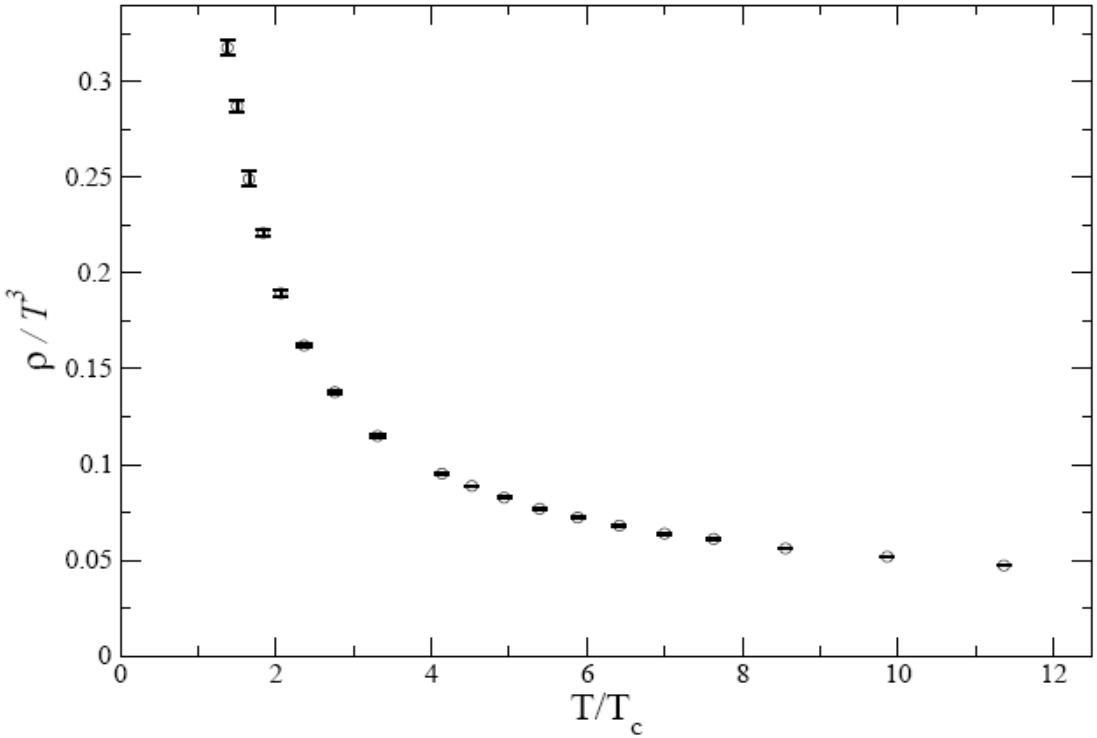
Jet quenching, strong near Tc,
resolving the jet v2 puzzle;
Cone & ridge, also protected



Direct Lattice Manifestation



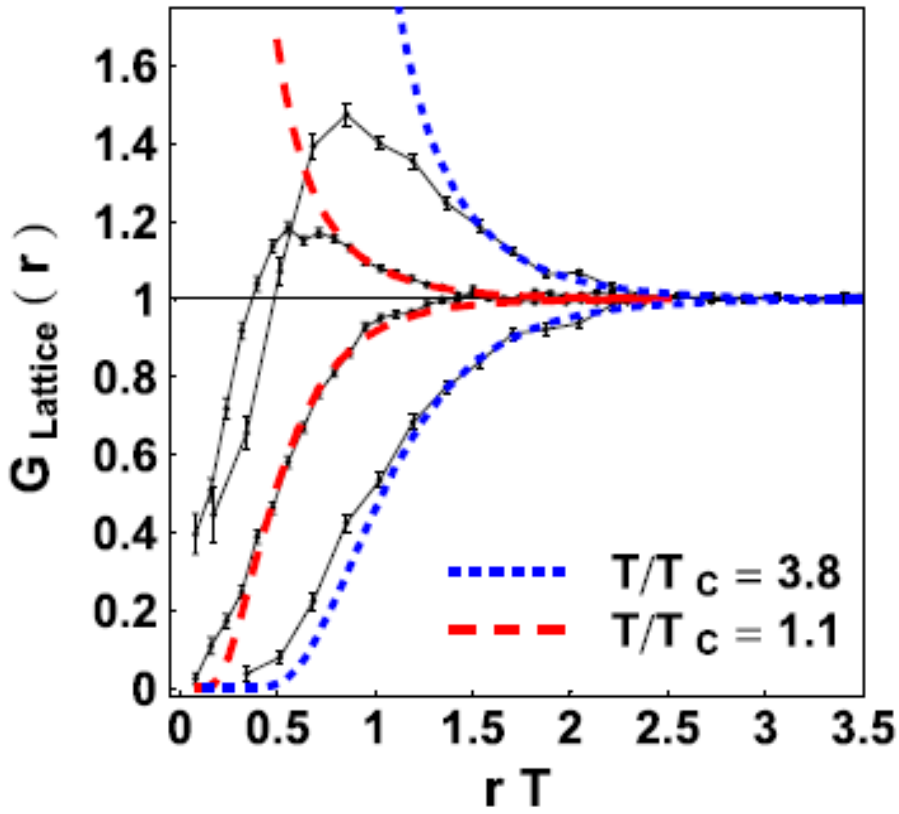
Chernodub, Zakharov, 06;
D'Alessandro, D'Elia , 07;
D'Alessandro, D'Elia, Shuryak, 10.

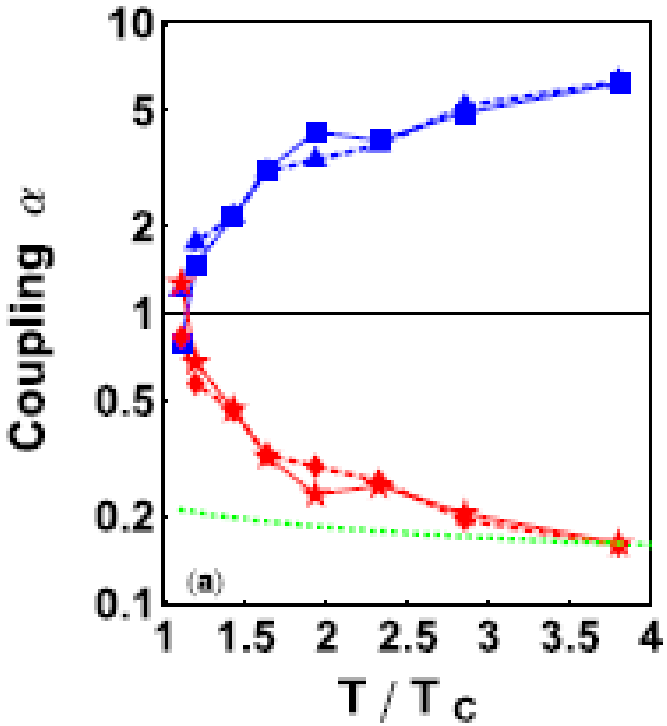


Direct Lattice Manifestation

$$\alpha_E * \alpha_M = 1.$$

JL & Shuryak, 08.





See-Saw is there !