Exploring center symmetry with electrically charged quarks

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The Gist

- Could the **fractional electric charge** of quarks relevant be to the phase diagram?

  (esp. deconfinement)

- We think 'yes, there might be a way'

This talk – finite temperature only

Outline

- Lattice based – lean heavily on analogy of Polyakov loops as spins
- Standard picture of (de)confinement
- Inclusion of electromagnetism
- Results from our 2-color model

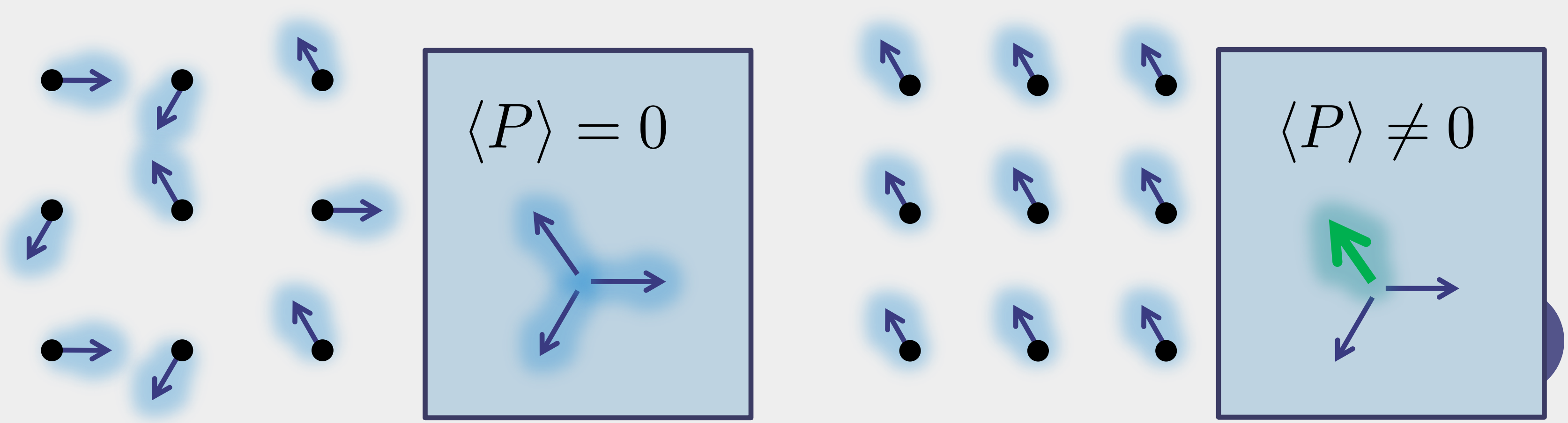
(DE)CONFINEMENT FOR PURE GLUE

- **Center symmetry**

  ... glue is blind to phases $z = e^{in2\pi/3} \in \mathbb{Z}_3$

- gauge group $SU(3)/\mathbb{Z}_3$

- **Polyakov loop** - order parameter for Z_3 breaking transition



space

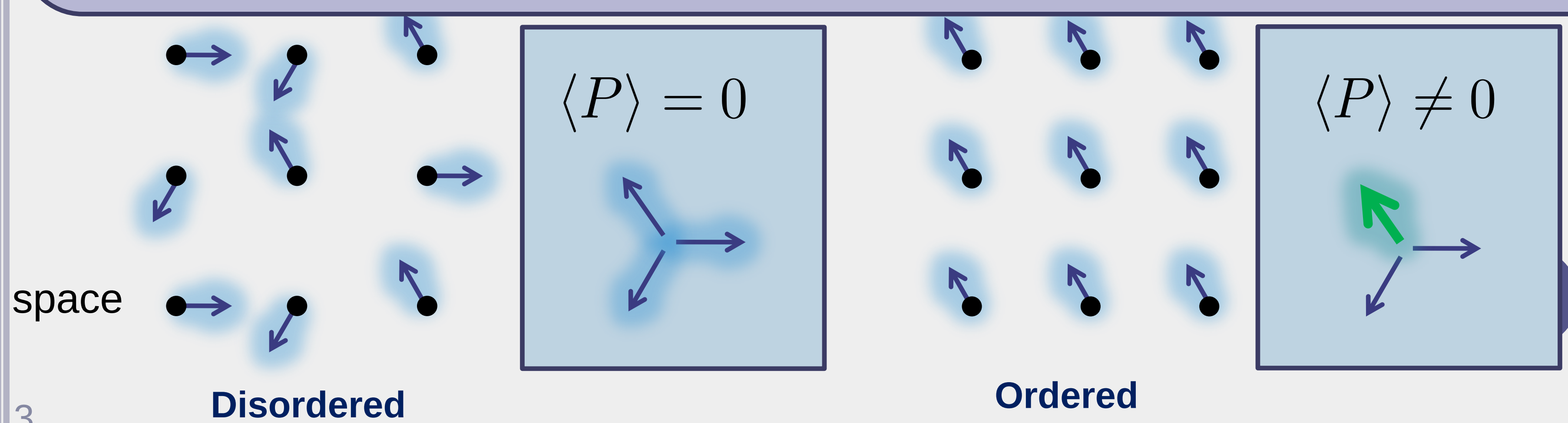
Disordered **Ordered**

(DE)CONFINEMENT FOR PURE GLUE

- **Center symmetry**

… glue is blind to phases $z = e^{in2\pi/3} \in \mathbb{Z}_3$

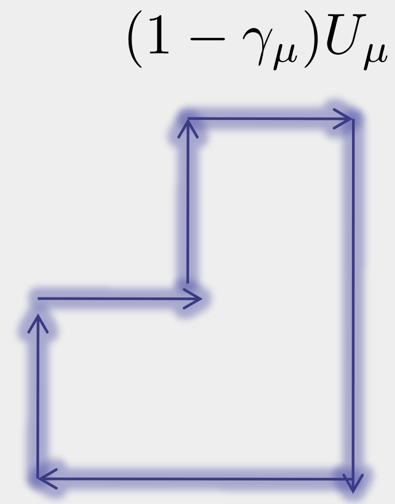
c.f. spontaneous magnetization of a spin system



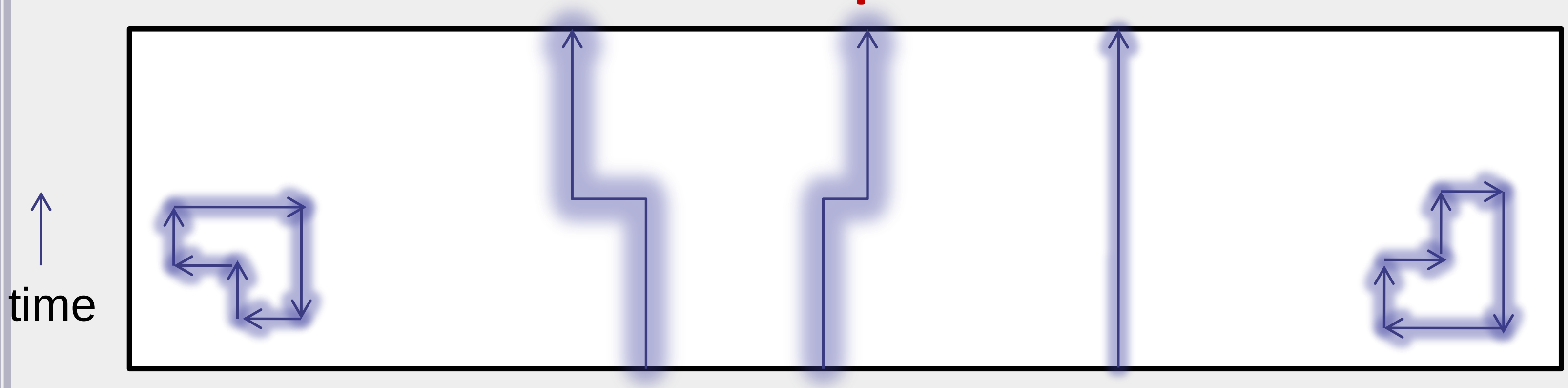
Add dynamical quarks (Wilson)

- explicitly break center symmetry
- Hopping expansion of determinant

$$\det M = \exp(-\sum_j \frac{\kappa^j}{j} \mathrm{Tr} H^j), \quad \kappa = \frac{1}{2am+8}$$



Finite temperature

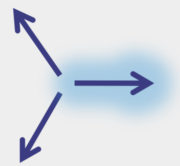


in partition fⁿ $e^{-S_{eff}}$

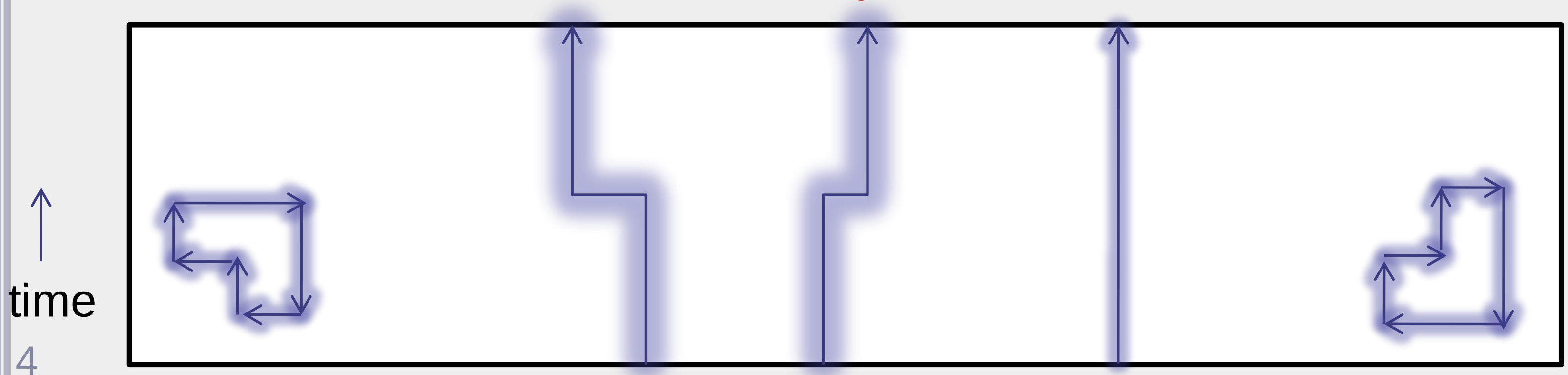
- plaquette-like terms terms don't affect symmetry
- Polyakov loop terms pick center sector

$$\propto -\kappa^{N_t} \sum_{\vec{x}} \mathrm{Re}\ \mathrm{Tr} P(\vec{x})$$

favors $P = 1$



Finite temperature



$e^{-S_{eff}}$ in partition f[n]

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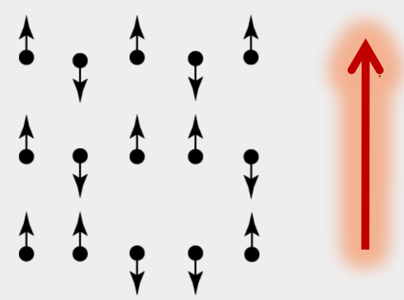
favors

$$P = 1$$

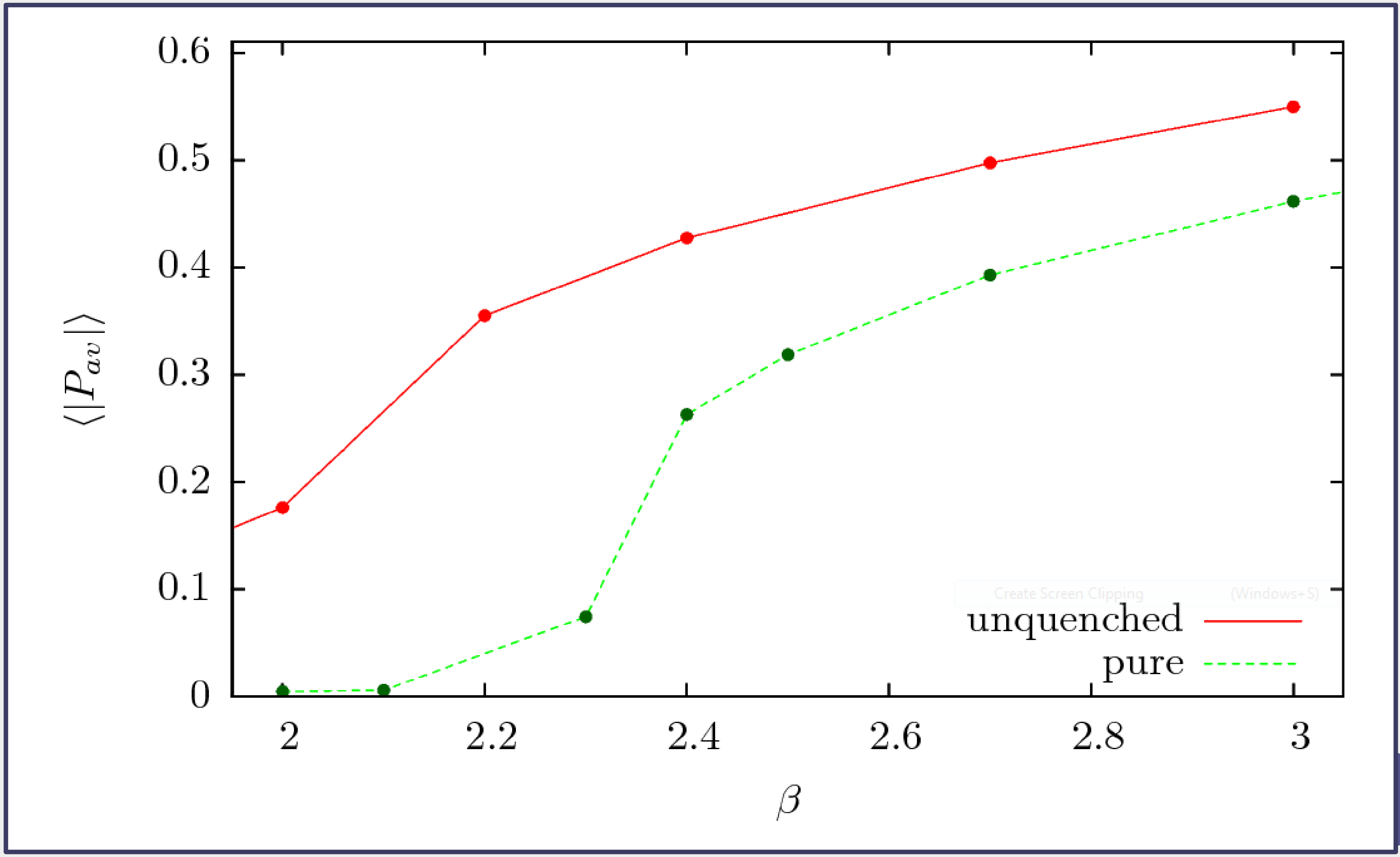
Like coupling spins to an ext. magnetic field



Effect of fermions - ordering external field

$$P_{av} = \frac{1}{V}\sum_{\vec{x}} P$$

DYNAMICAL FERMIONS – SU(2)



24^3 x 4, κ = 0.15, 2 flavors

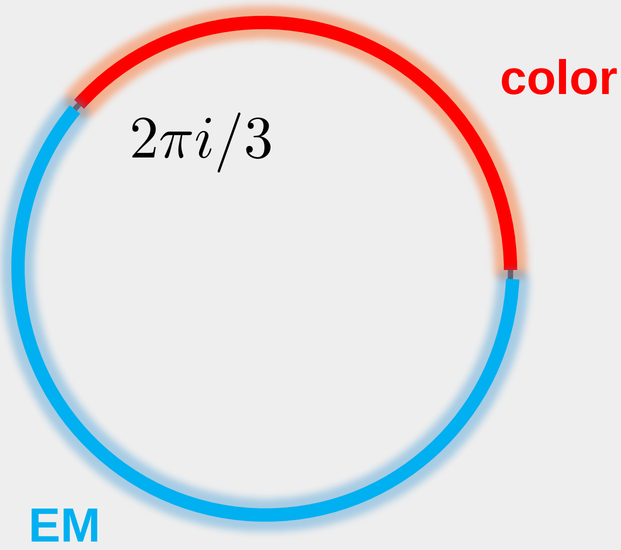
...BUT QUARKS HAVE ELECTRIC CHARGE

- What if we include electromagnetism?

$$q_u = +\frac{2}{3}e, \quad q_d = -\frac{1}{3}e$$

- Exactly compensate color center phase by U(1) phase

$$\left(e^{i2\pi/3}, e^{i2\pi Q/e}\right), \; \left(e^{-i2\pi/3}, e^{-i2\pi Q/e}\right)$$



- **Symmetry**

$$SU(3) \times U(1)_{em}/\mathbb{Z}_3$$

HIDDEN SYMMETRY

- ‘True’ Standard Model symmetry group

$$SU(3) \times SU(2) \times U(1)/\mathbb{Z}_6$$

before electroweak trans.

- Importance
  - unification, e.g. SU(5), SO(10) GUT
  - topological objects - color-EM monopoles/vortices

A global center symmetry with fermions!

- What can it do for us?

electroweak trans. – Zubhov, Veselov, Bakker

TOY MODEL FOR SIMPLICITY

- 2 colors, 2 flavors of dynamical Wilson fermions, gauge group

$$SU(2) \times U(1)_{em}/\mathbb{Z}_2$$

  - u/d quarks with **± ½ charge** relative to $U(1)_{em}$ gauge action

$$S = -\sum_{\Box} \left(\frac{\beta_{col}}{2} \mathrm{Re}\ \mathrm{Tr}\ \Box_{SU(2)} + \beta_{em} \cos \Box_\theta \right) + S_{f,W}$$

$$U_\mu \exp i \frac{\theta}{2}$$

parallel transporters give both color and electromagnetic contribution to quarks – e.g. -1 x -1 = 1

HMC

Color disorder through U(1) disorder

- Quark loops get additional U(1) factor

  e.g. Polyakov loop terms from Hopping expansion

$$\propto -\sum_{\vec{x}} \mathrm{Re}\,\mathrm{Tr}\,\uparrow \cdot \mathrm{Re}\,\uparrow$$

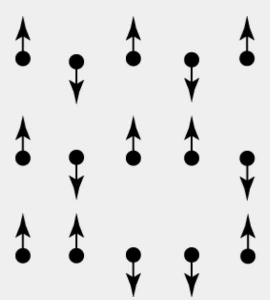
color   EM

transporter for quarks

$$\exp i\frac{\theta}{2}$$

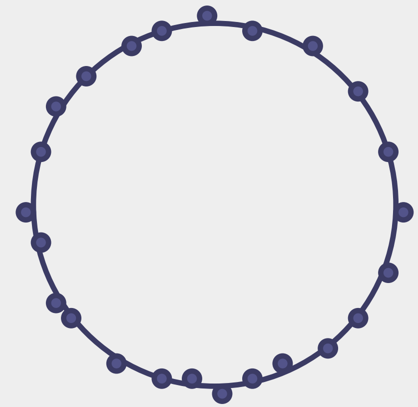
- if U(1) disordered - c.f. spin model in a **random external field**

$$\mathcal{H} = -J\sum_{\langle i,j\rangle} s_i s_j - h\sum_i h_i s_i$$



ref. *Spin glasses and random fields*, 1997

- Compact QED has a confining, disordered phase for $\beta_{em} < 1$



U(1) link angles

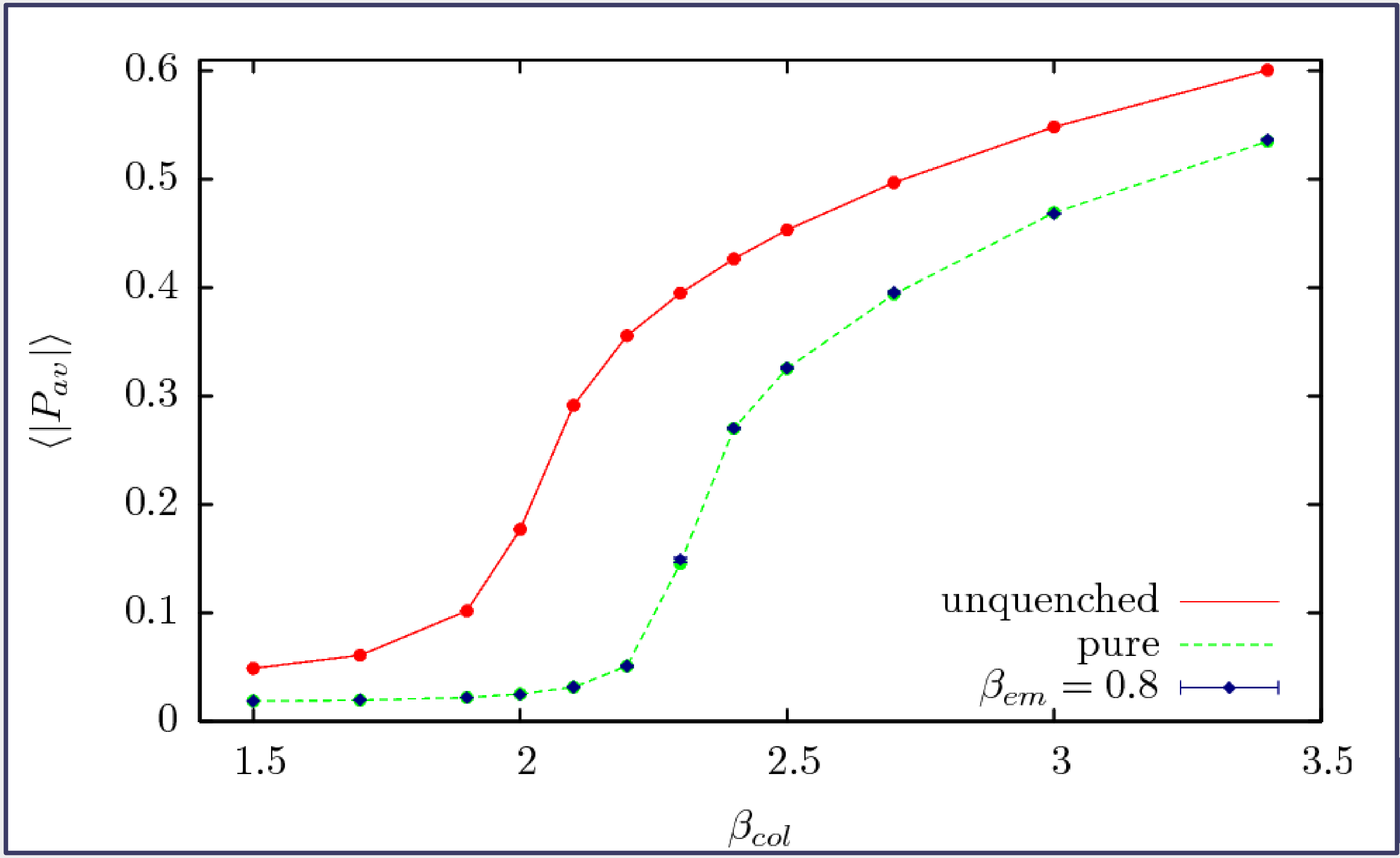
- Expect a large effect here

$$\propto \text{-Re Tr} \underbrace{\uparrow}_{\text{color}} \cdot \ \text{Re} \underbrace{\uparrow}_{\text{EM}}$$

c.f. Peccei-Quinn mechanism (strong CP)

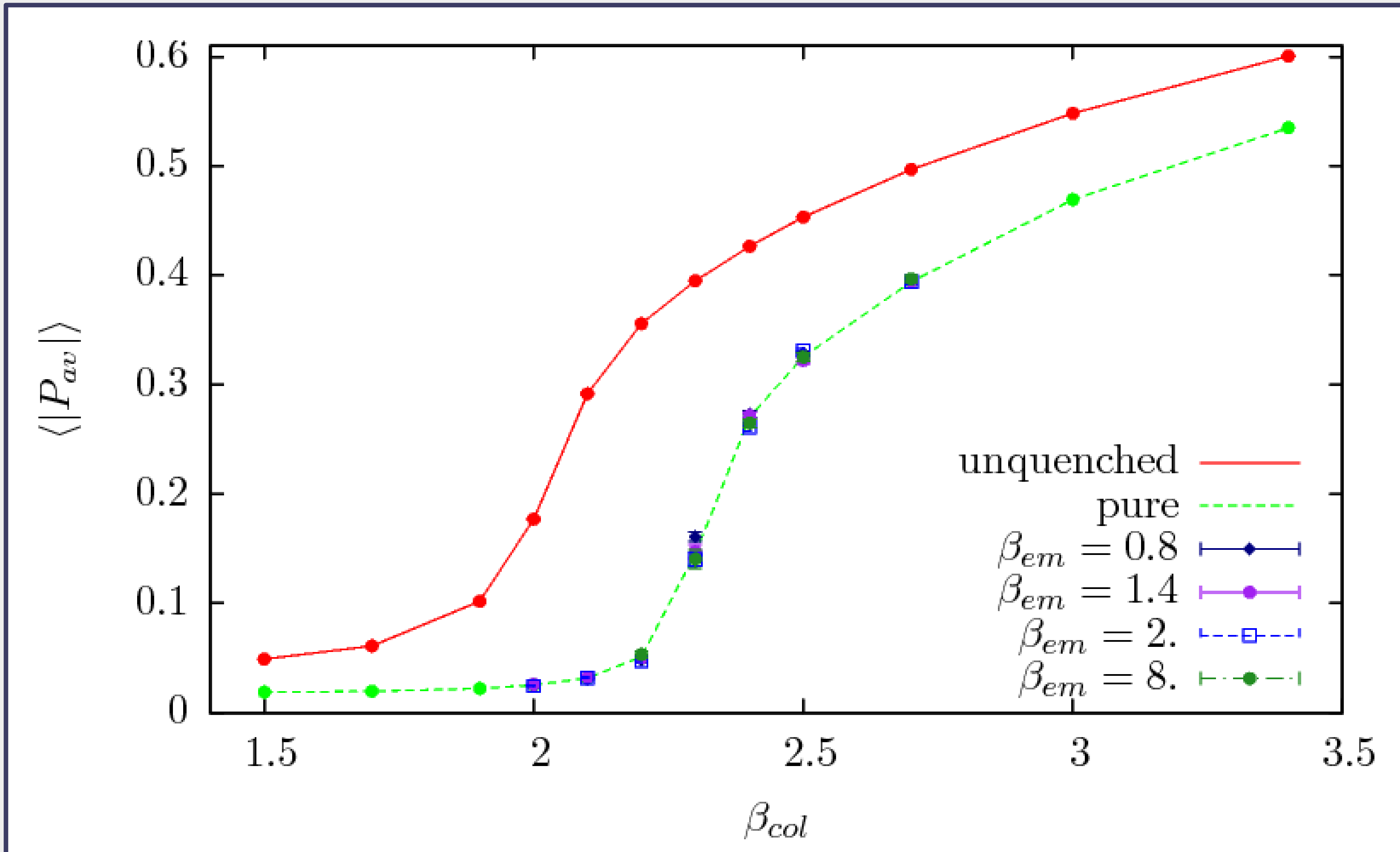
RESTORATION OF PURE GAUGE BEHAVIOR FOR $P_{SU(2)}$

SU(2) x U(1)/Z_2



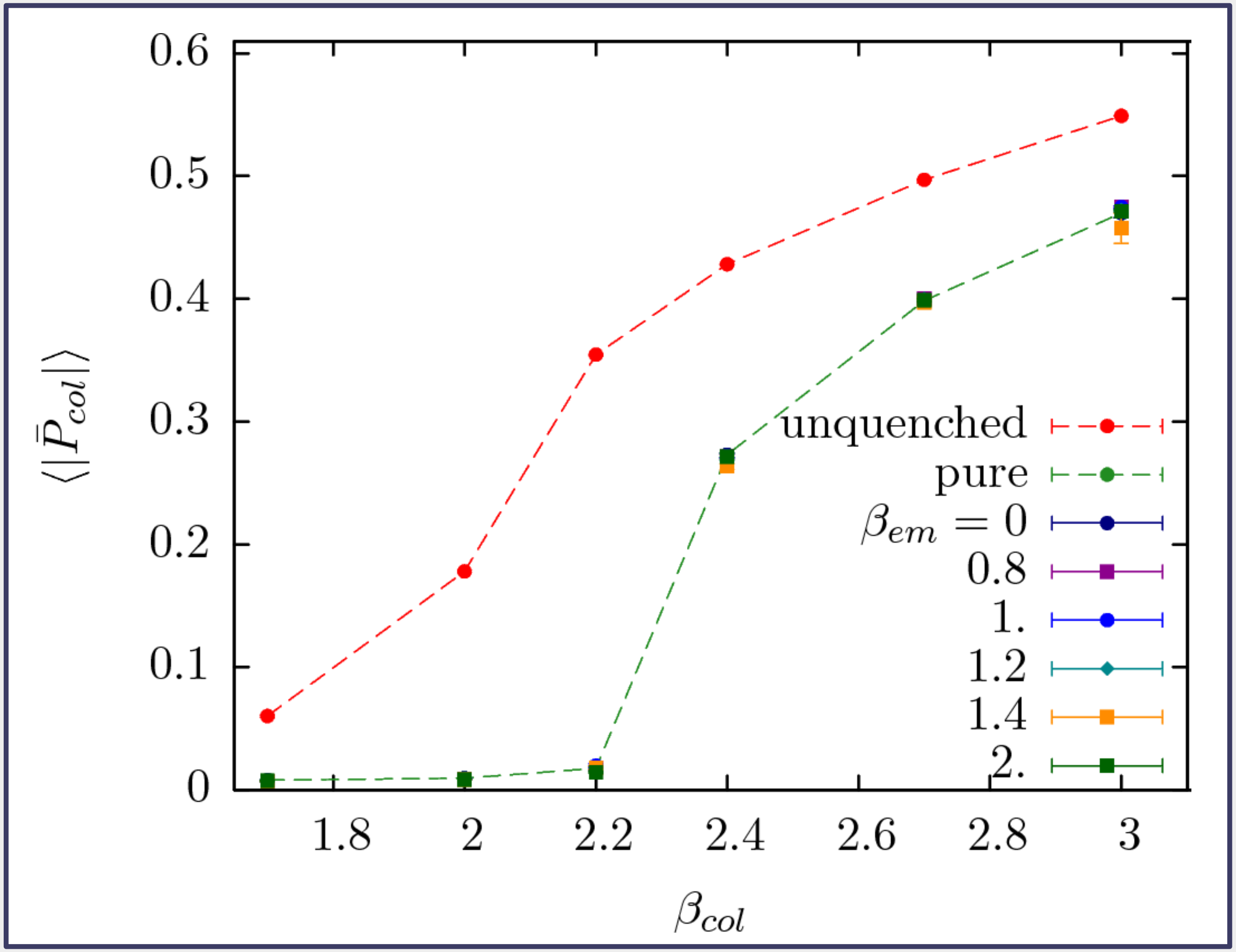
8^3 x 4 , κ = 0.15

Crank up U(1) coupling beyond the U(1) transition



$8^3 \times 4$, $\kappa = 0.15$, random start

…AND ON BIGGER LATTICES

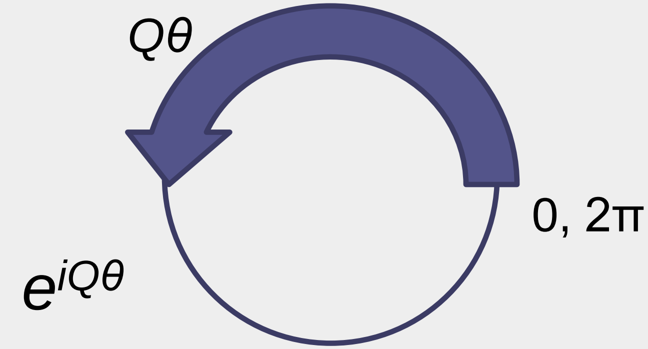


16^3 x 4
κ = 0.15
random start

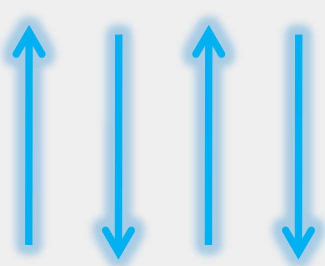
…and 24^3 x 4

Still U(1) disorder for the quarks deep in the Coulomb phase for unit charges…

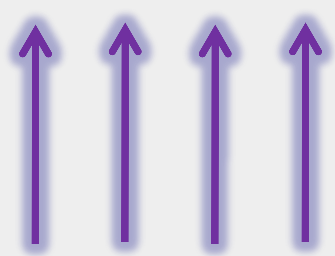
- Quarks have ***fractional*** charge



- See phases that integer charged particles and the gauge action do not
  - π for our quarks - 2π in U(1) action $e^{i\pi} = -1$ vs $e^{i2\pi} = 1$
- $\beta_{\mathrm{em}} > 1$, order w.r.t. U(1) action – links ~ 1 for int. particles
- **BUT there is still room for Z_2 disorder in the links as seen by quarks**



for quarks



for electrons / gauge action

+1 link w.r.t. the gauge action could be a -1 link for the quarks

frozen in

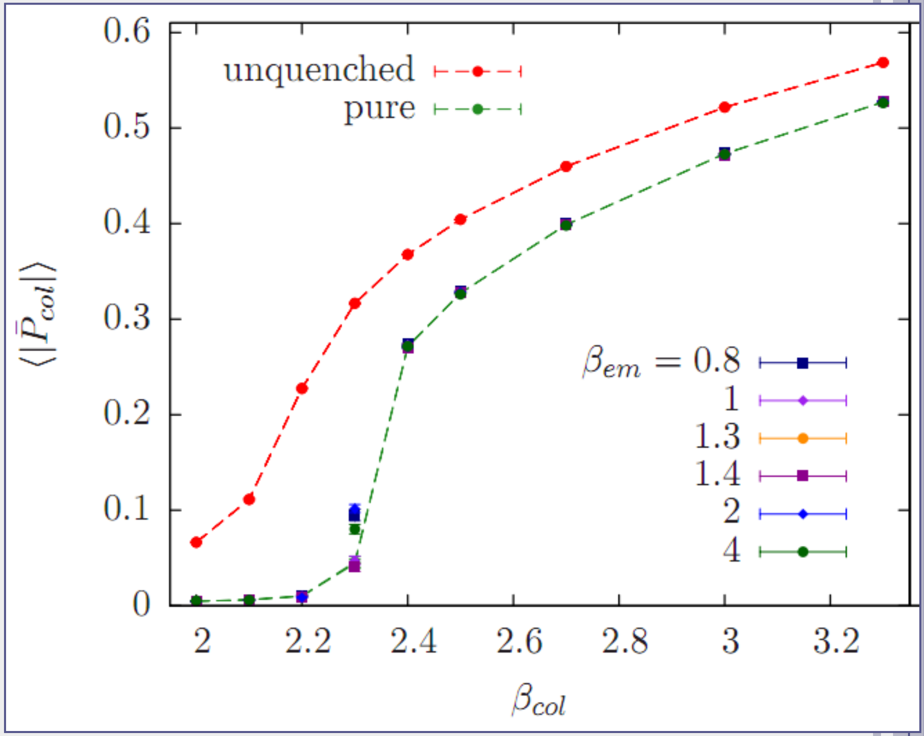
N_T=4 Hopping expansion

Fermions through κ⁴ terms

Poly-Poly $\propto \mathrm{Re\,Tr}\,\uparrow \cdot \mathrm{Re}\,\uparrow$

color EM

plaq-plaq $\propto \mathrm{Re\,Tr}\,\square\;\mathrm{Re}\,\square_{\theta/2}$



- Conspire to order color, U(1) links w.r.t. each other
- Compete with pure gauge terms

Play with relative strength

- Suggests coupled spin models
  XY - Ising

coupled energy densities and local spin-spin

~Nightingale et al, 1995

So…

- A **center symmetry** recovered when U(1) is added to QCD with dynamical quarks

- **Disordering** effect of U(1)
  - How much can the quarks' **fractional** electric charge influence color dynamics?

a lot in our model!

To think about

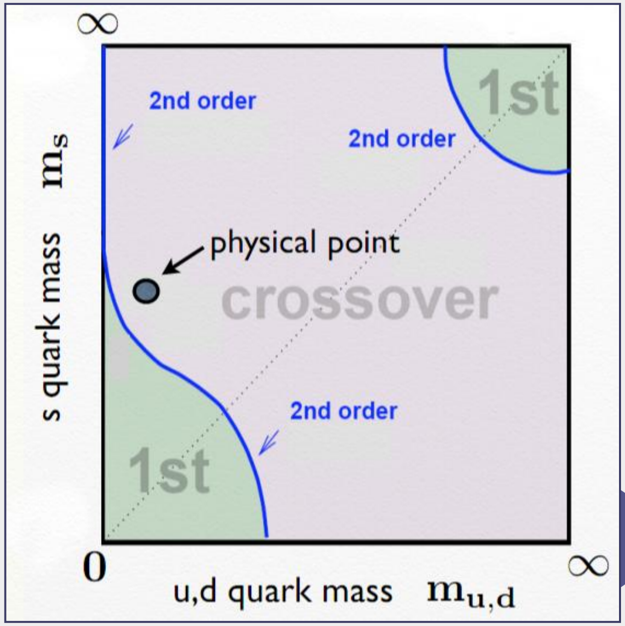
- Initial conditions – source of Z_2 disorder
- Quark mass dependence, lines of constant physics

Speculation for SU(3)xU(1) / Z_3

?

first order transition persists for lighter quarks?

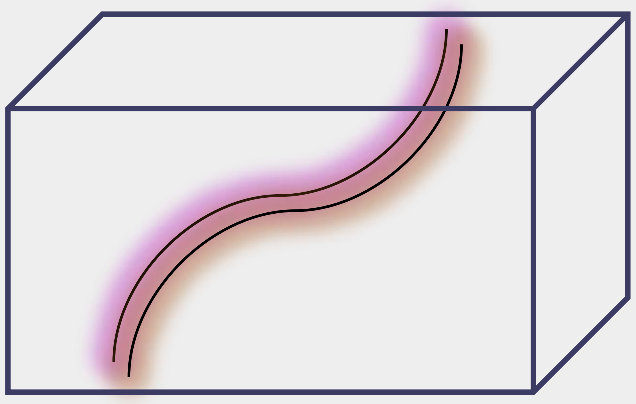
sharpen crossover if it doesn't reach physical quark masses?



… and if you like **vortices**…

't Hooft's twisted boundary conditions!

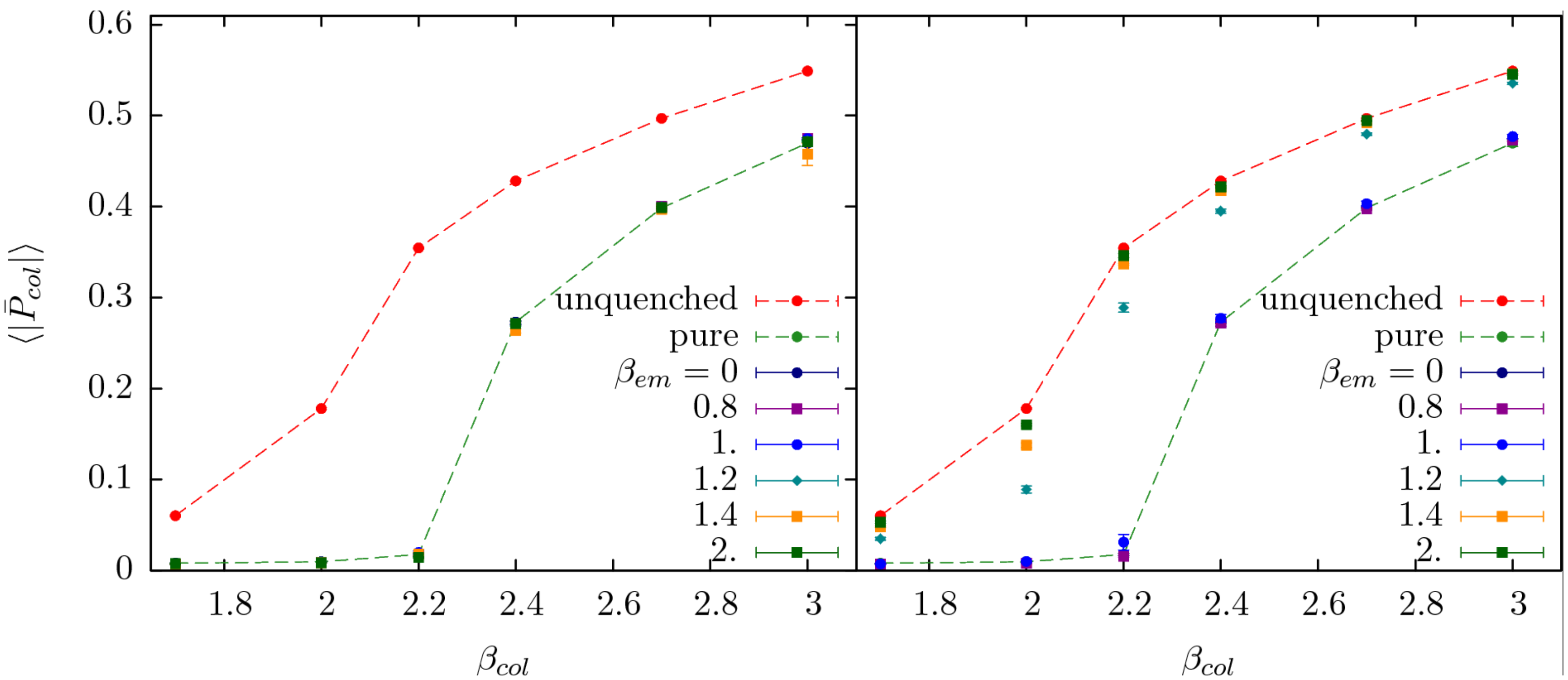
- in presence of dynamical fermions
- combined **vortices** carrying both color and EM flux



$SU(2) \times U(1)/Z_2$

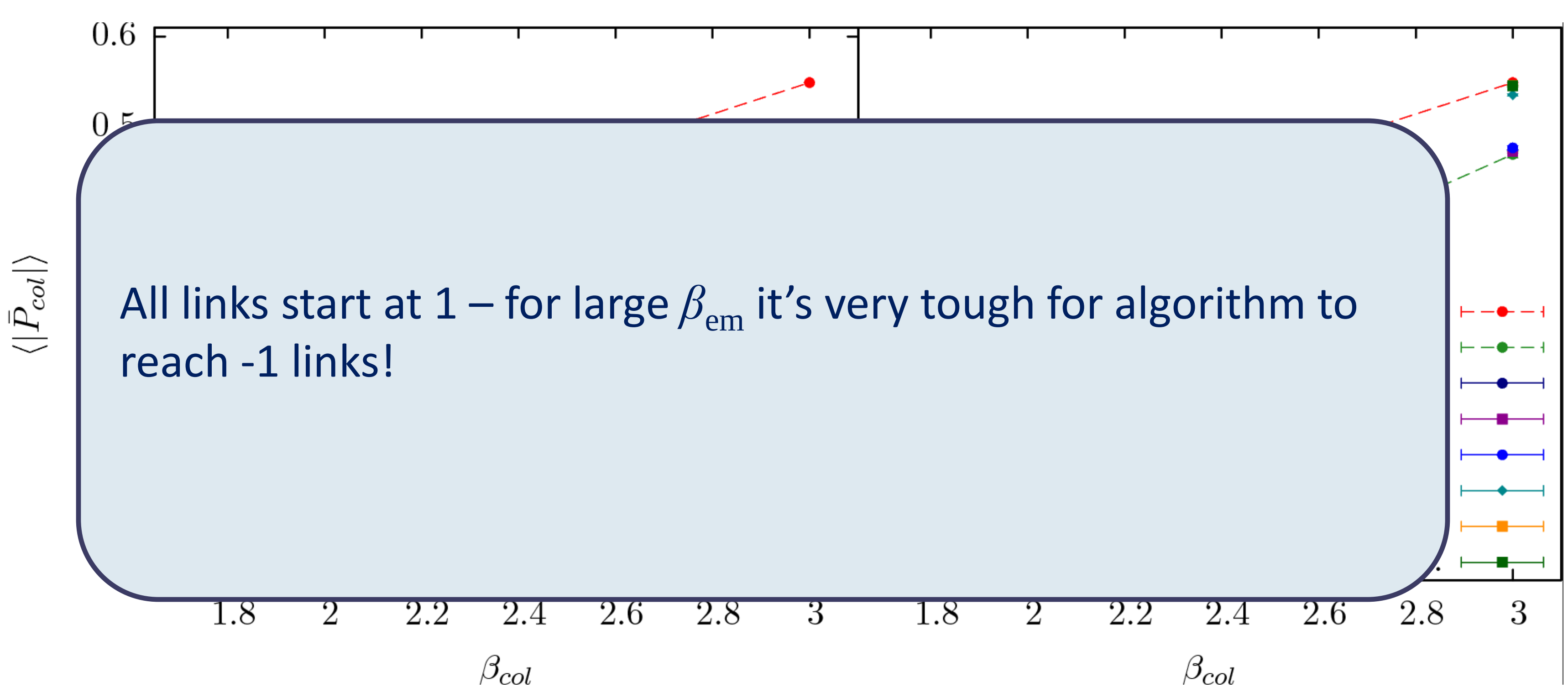
twist simultaneously

HOT VS COLD START - $P_{SU(2)}$

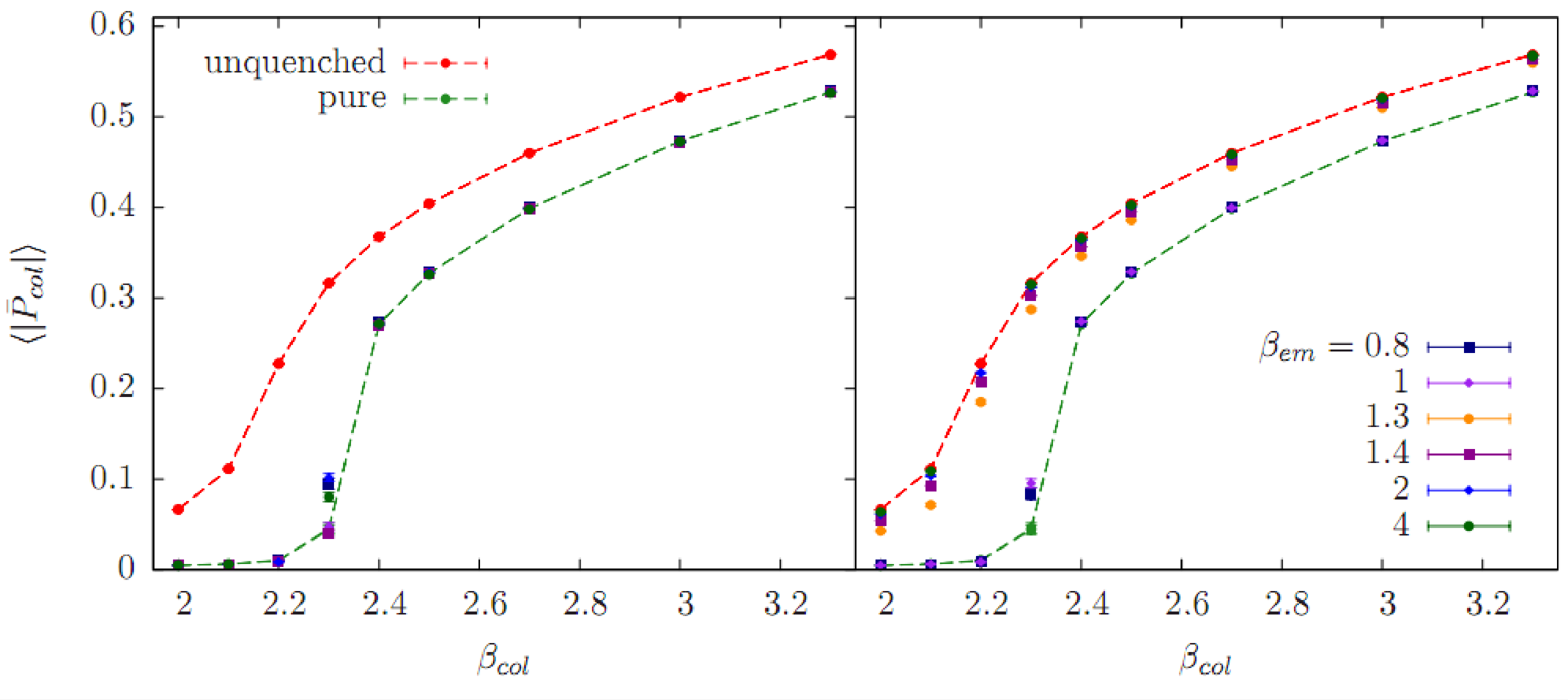


$16^3 \times 4$, $\kappa = 0.15$

Hot vs Cold start - $P_{SU(2)}$

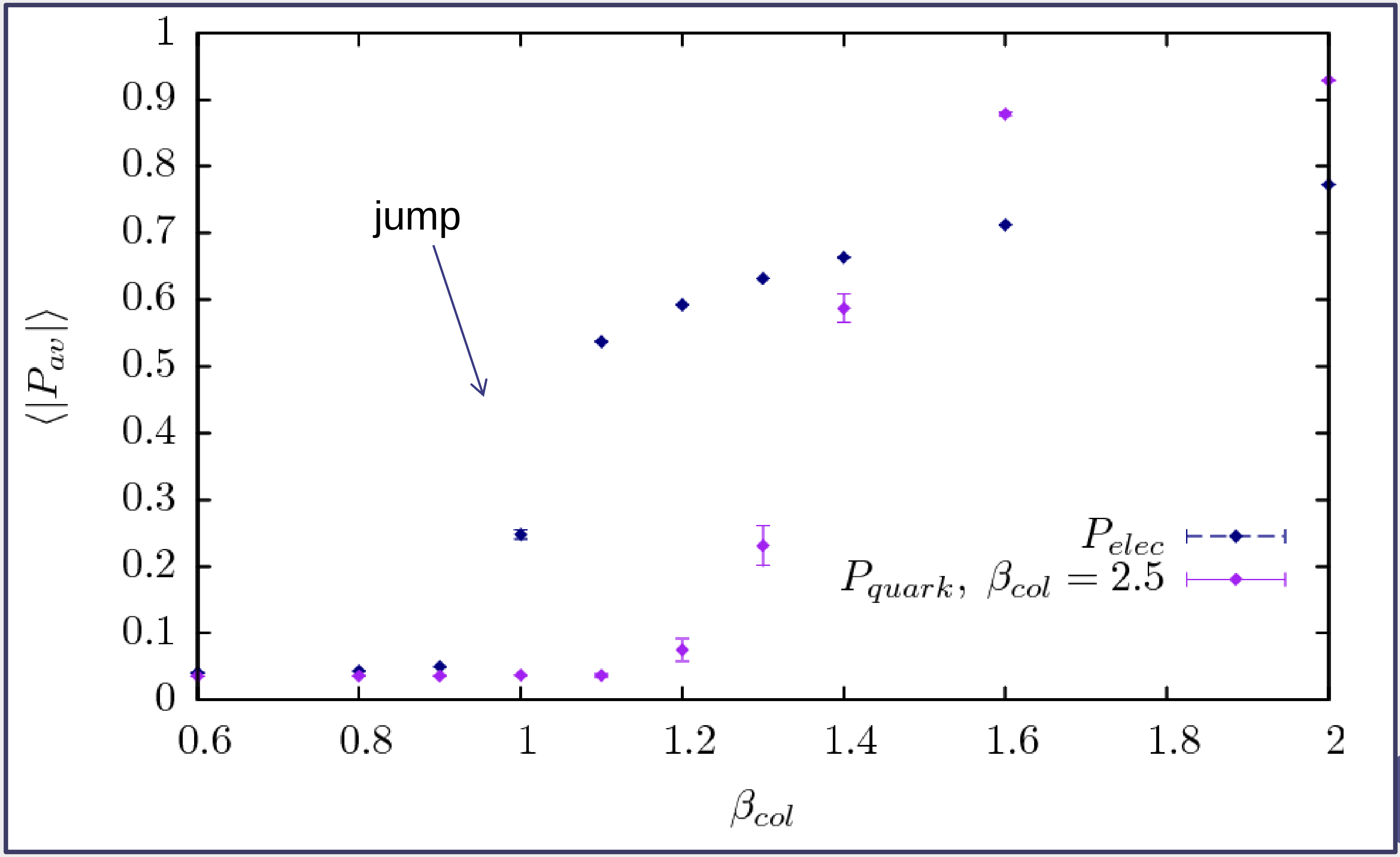


16^3 x 4 , $\kappa = 0.15$



0.6
0.5
0.4
0.3
0.2
0.1
0
$\langle|\bar{P}_{col}|\rangle$
unquenched
pure
2
2.2
2.4
2.6
2.8
3
3.2
β_{col}
$\beta_{em} = 0.8$
1
1.3
1.4
2
4

CHECKING U(1) POLYAKOV LOOPS – COLD START



Plaq-plaq competition

$$\propto -\kappa^4 \ \mathrm{Re} \ \mathrm{Tr} \ \square \ \ \mathrm{Re} \ \square_{\theta/2}$$

color EM

$$\propto -\kappa^4 \ \mathrm{Re} \ \mathrm{Tr} \ \square \ \ \mathrm{Re} \ \square_{\theta/2}$$

color EM