Exploring center symmetry with electrically charged quarks

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HIC for FAIR
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Outline

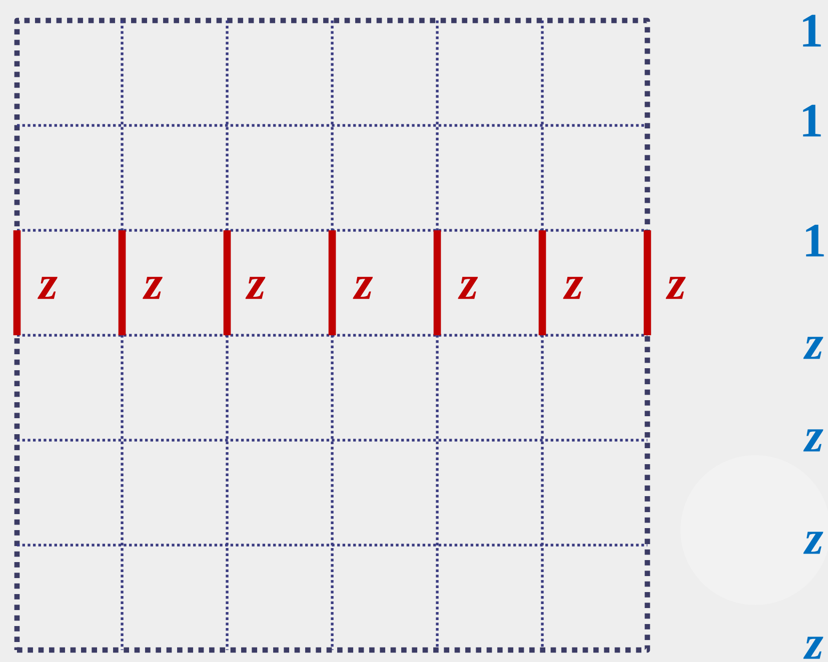
- Center symmetry
  - glue
  - dynamical quarks
- Including electromagnetism
- Our model
  - disordering
  - preliminary results

Center symmetry

- Symmetry of **pure** SU(*N*) gauge theory

$$SU(N)/\mathbb{Z}_N, \quad z = e^{in2\pi/N} \in \mathbb{Z}$$

- **Center transformation** - gauge trans. periodic only up to center phase in time direction



- action invariant

$$\Box \longrightarrow z^* z \, \Box = \Box$$

- Polyakov loop picks up phase

$$P = \mathrm{Tr} \uparrow \; \rightarrow z \, \mathrm{Tr} \uparrow$$

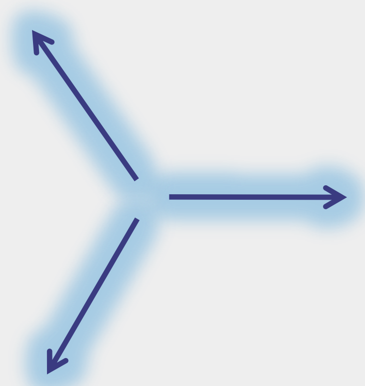
Center symmetry - Confinement

- VEV determines whether center symmetry is realized

- low *T*, confined, center symmetric phase

$$\langle P \rangle = 0$$

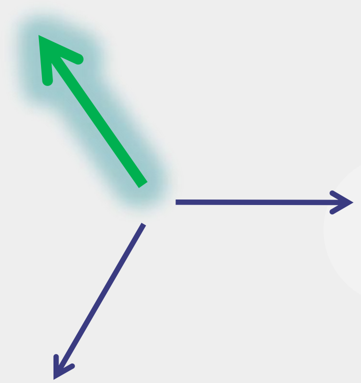
average to zero
 - disordered by **center vortices**



- high *T*, deconfined, center broken phase

$$\langle P \rangle \neq 0$$

sector spontaneously chosen



Center symmetry - Confinement

- deconfinement for pure SU(N) is a **center symmetry breaking** phase transition

- VEV of Polyakov loop is an **order parameter**
  - (see also vortex free energy)

- **infinitely heavy quarks**, i.e. static

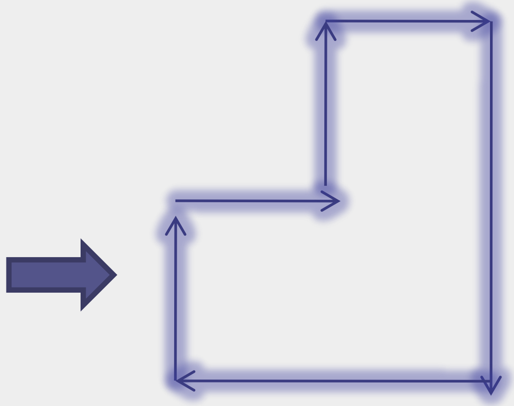
DYNAMICAL QUARKS (WILSON)

- explicitly break center symmetry

- Hopping expansion

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

$(1-\gamma_\mu)U_\mu$



closed loops

Dynamical quarks (Wilson)

- explicitly break center symmetry
- Hopping expansion

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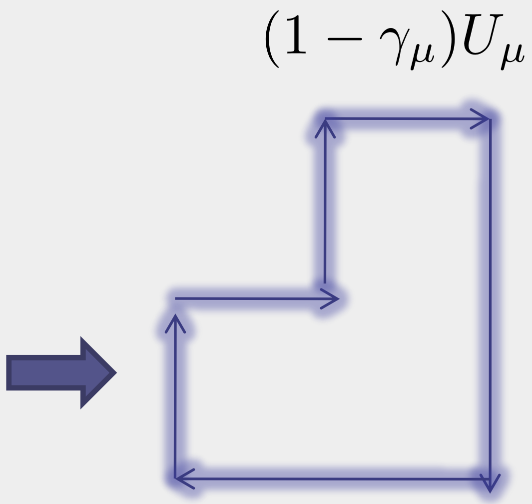


closed loops

- $N_t = 4$ – plaquettes & Polyakov loops

$$\det M = \exp(8\kappa^4 \sum_{\square} 2\mathrm{Re}\ \mathrm{Tr}\,\square + 32\kappa^4 \sum_{\vec{x}} 2N_c \mathrm{Re}\ P(\vec{x}) + \ldots)$$

DYNAMICAL QUARKS – $N_T = 4$

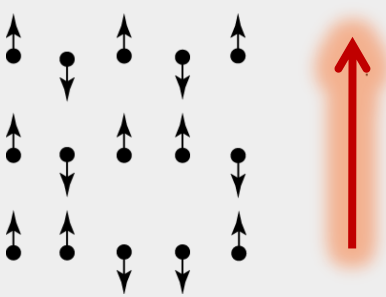
in partition f^{n} e^{-S}

$$S_{eff} = -\frac{\tilde{\beta}}{N_c}\sum_{\Box} \mathrm{Re\ Tr}\,\Box - 32\kappa^4 \sum_{\vec{x}} 2N_c \mathrm{Re}\ P(\vec{x}) + \ldots)$$

modify gauge coupling

ordering effect (S_{eff} minimized for P=1)

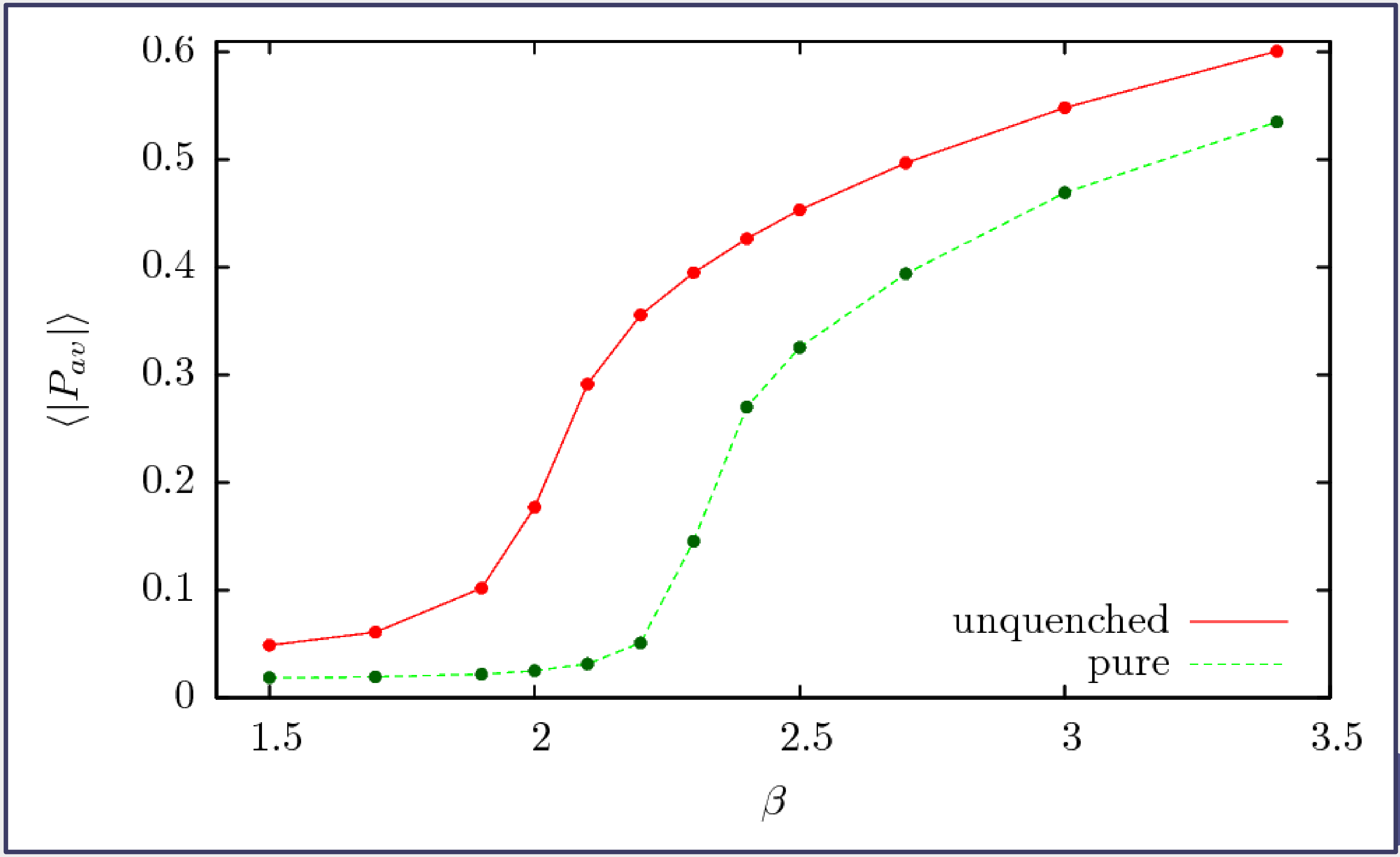
c.f. spin system in magnetic field



Effect of fermions - ordering external field

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

DYNAMICAL FERMIONS – SU(2)



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

…BUT QUARKS HAVE ELECTRIC CHARGE

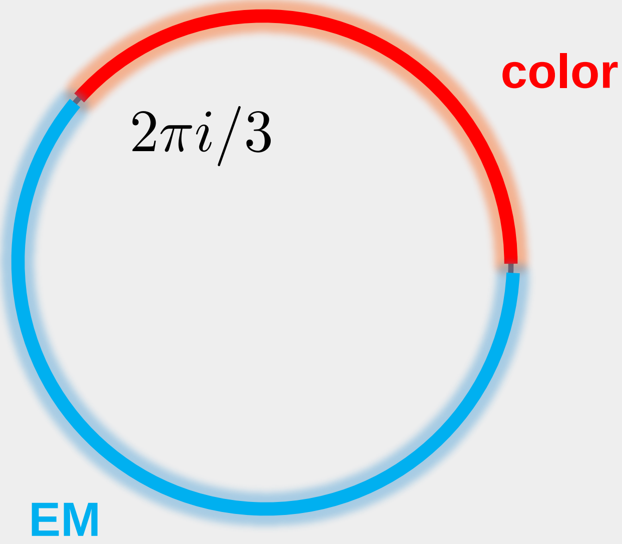
- What if we include electromagnetism?

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

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

- **Gauge group**

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



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

- Existence of a **global gauge symmetry** that may be spontaneously broken

  - relevant to **confinement**?

electroweak trans. – Zubhov, Veselov, Bakker

Toy lattice model

- 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

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

  - implement via HMC

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

parallel transporters give both color and electromagnetic contribution to quarks – no net phase for -1 x -1 = 1

Effect of the U(1)

- Expect $U(1)_{em}$ to have a **disordering effect**

- Recall Polyakov loop term from Hopping expansion

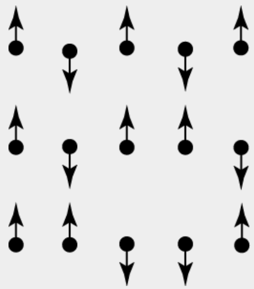
$$\propto \text{-Re Tr} \uparrow \cdot \ \text{Re} \uparrow$$

color EM

transporter for quarks

- If U(1) loop random over space → c.f. spin model in a **random external field**

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

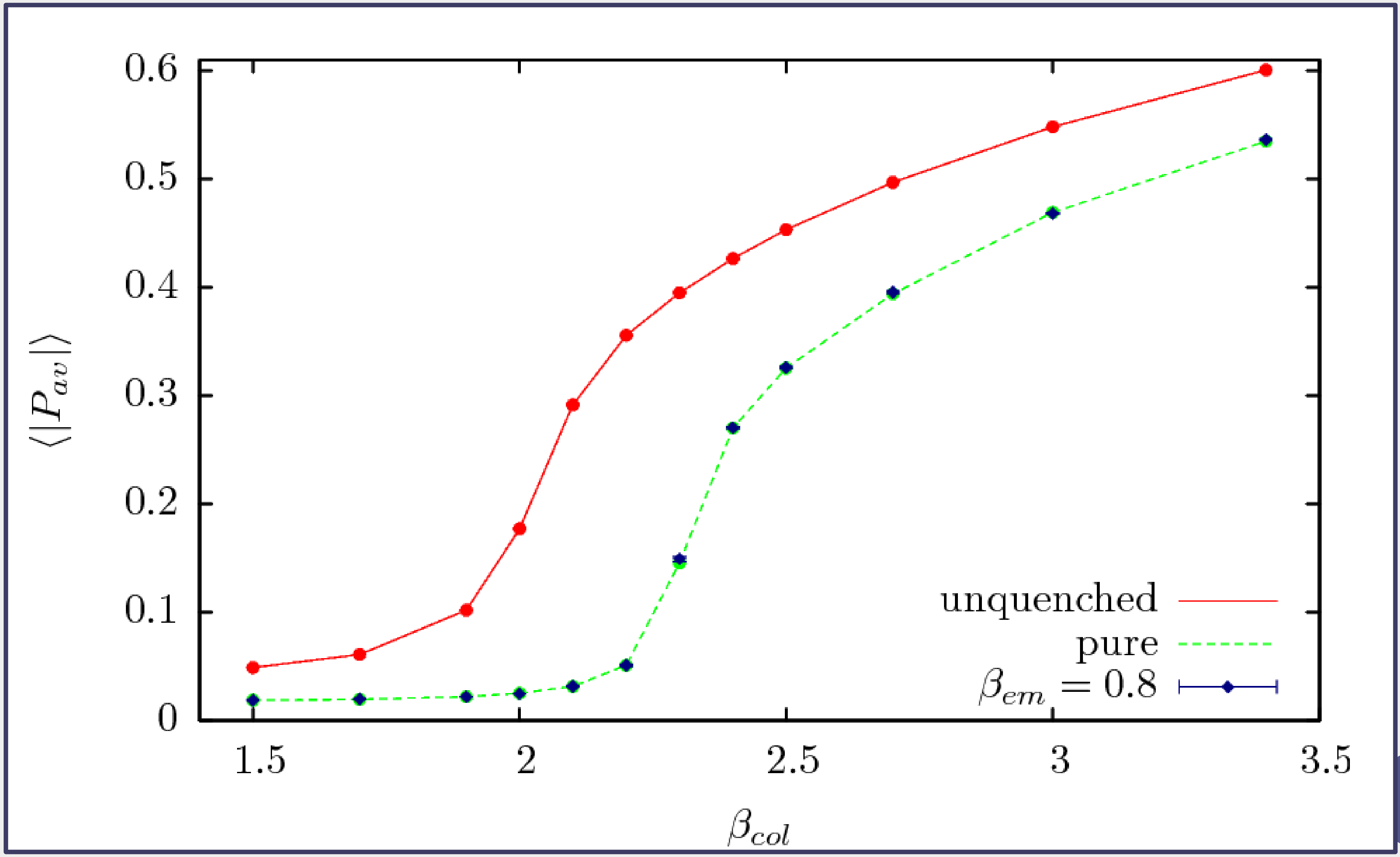


A word on (pure) compact QED

- Confining at small values of the lattice coupling
  (i.e. **strong** coupling)
  - i.e. **disordered phase** for EM Polyakov loop
- Phase transition to Coulomb phase at $\beta \approx 1.01$
- Expect U(1) to have large effect for small lattice coupling

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

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



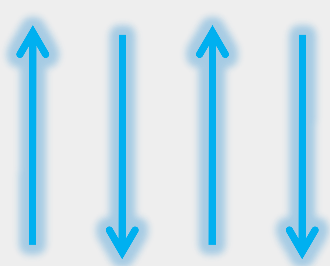
$8^3 \times 4$, $\kappa = 0.15$ (heavy quarks!)

Importance of quarks' fractional charge

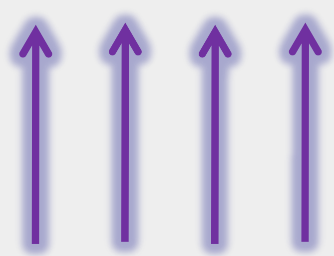
- U(1) angles in gauge action are **twice** those seen by quarks
  - phases differing by π for quarks are not distinguished by the U(1) action

- As we cross $\beta_{\rm em} \approx 1$, particles of unit electric charge should be deconfined - i.e. Polyakov loop of 'electron' becomes finite

- **BUT there is still room for Z_2 disorder in the links as seen by quarks**



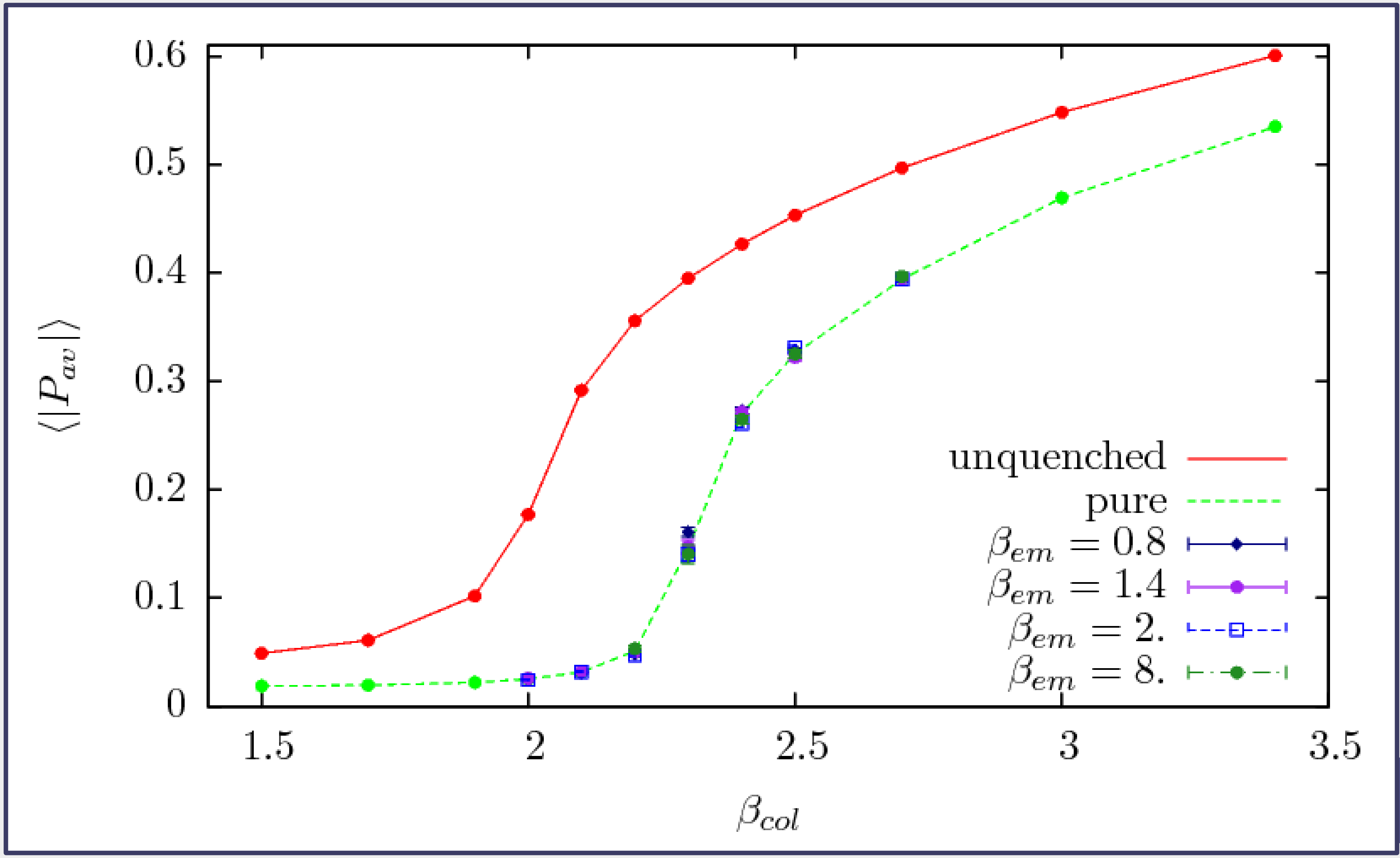
for quarks



for electrons / gauge action

Disorder SU(2) Polyakov loop in the Coulomb phase for unit electric charges?

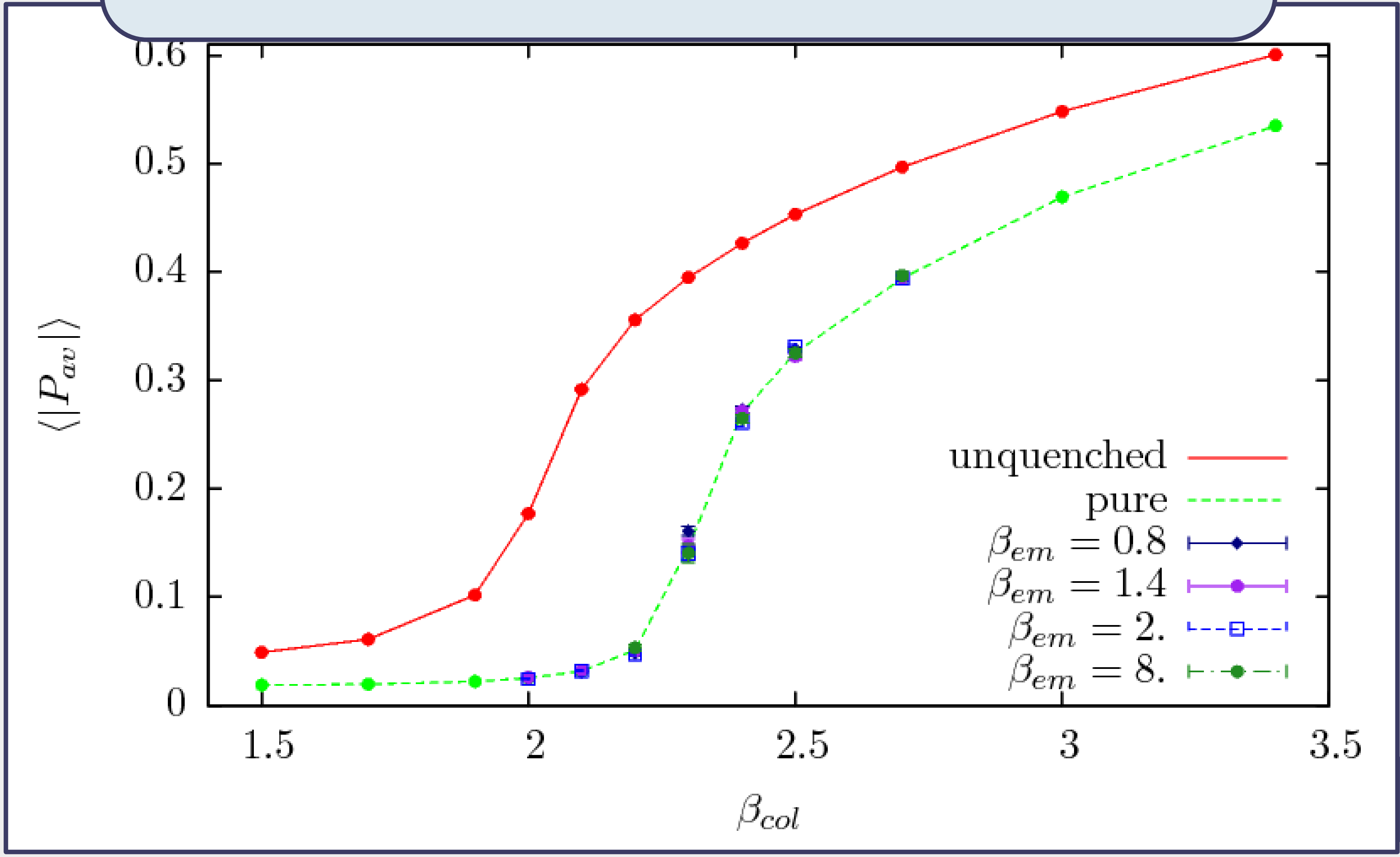
HOT START - $P_{SU(2)}$



8^3 x 4 , κ = 0.15, ~ 6000 traj.

U(1) gauge action is not able to remove the disorder for quarks, even deep in the Coulomb phase for unit charges

Ho



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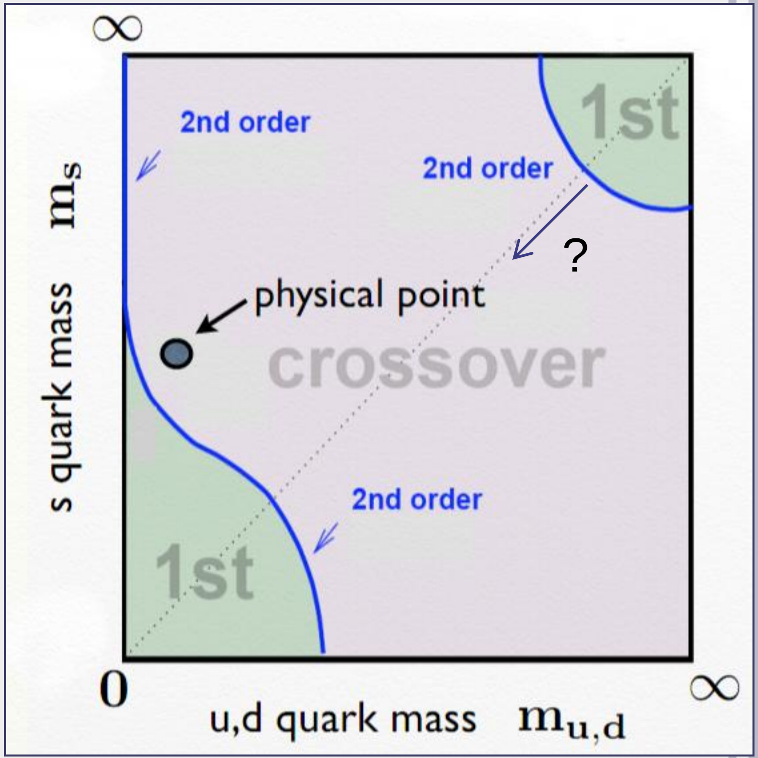
MUCH TO BE UNDERSTOOD…

- Cold starts – disorder for quarks only persists for a window beyond $\beta_{em} \approx 1$ – algorithmic issue only?

- Suppression of -1 transporters for light quarks? Competition between plaquette like terms



- **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?

Summary

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

- **Disordering** effect of U(1)
  - How much can electromagnetism influence color dynamics?

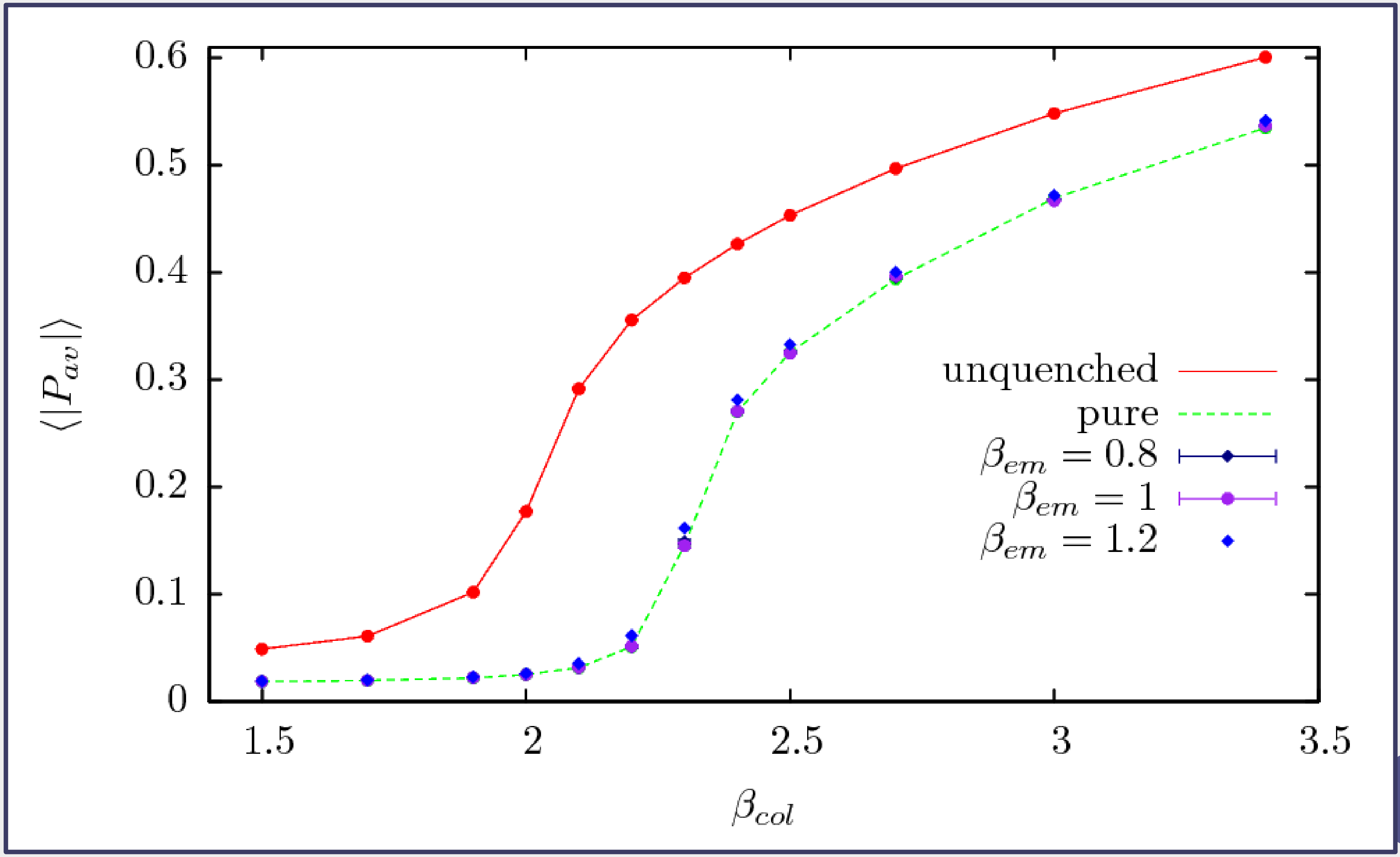
- First steps in a toy SU(2)xU(1)/Z_2 model

OUTLOOK

- Production runs – respectable masses and volumes
- Related spin models – random field Ising/Potts
- Hopping expansion – baby simulations

- **Twisted boundary conditions**!
  - in prescence of dynamical fermions
  - combined **vortices** carrying both color and EM flux

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



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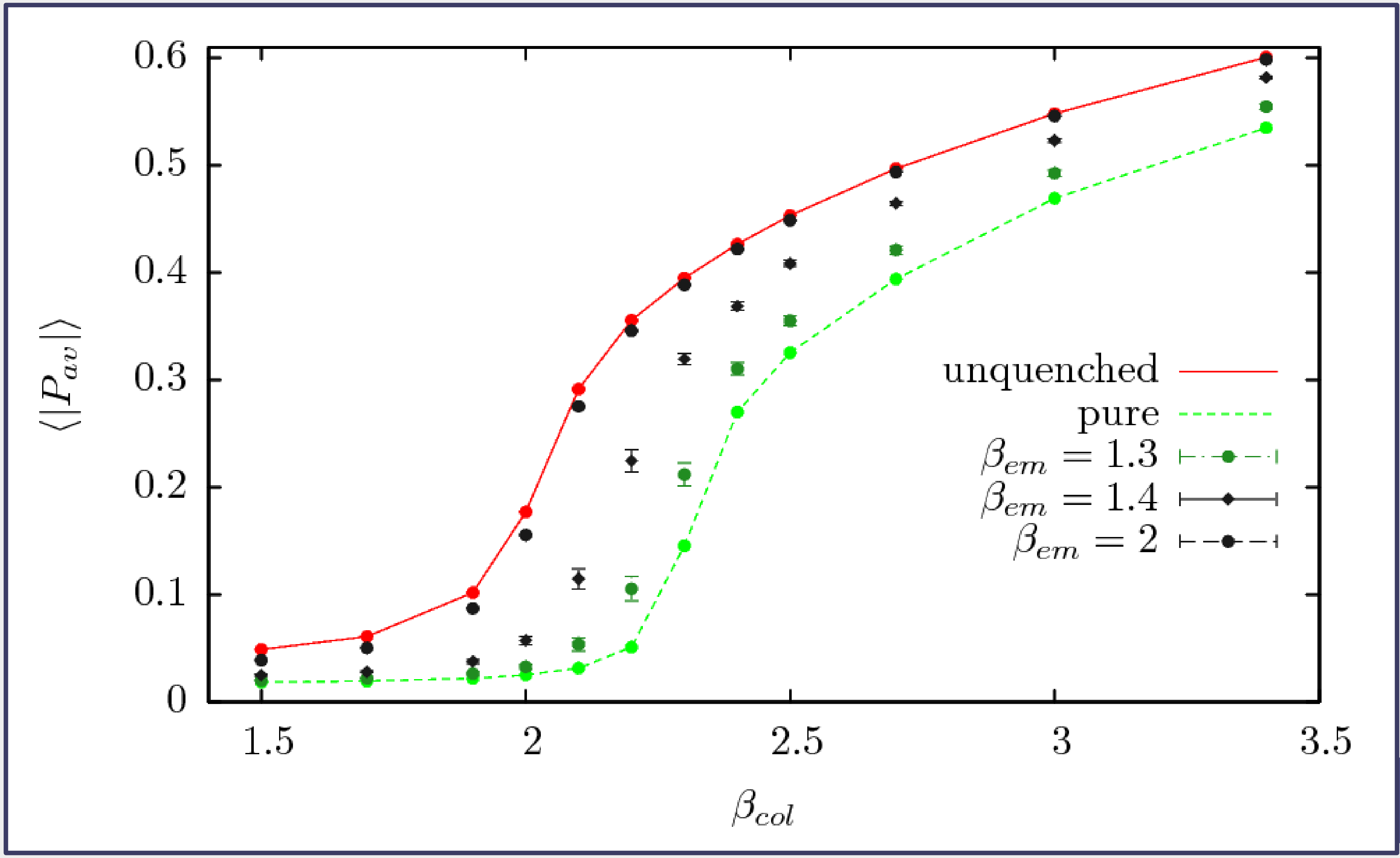

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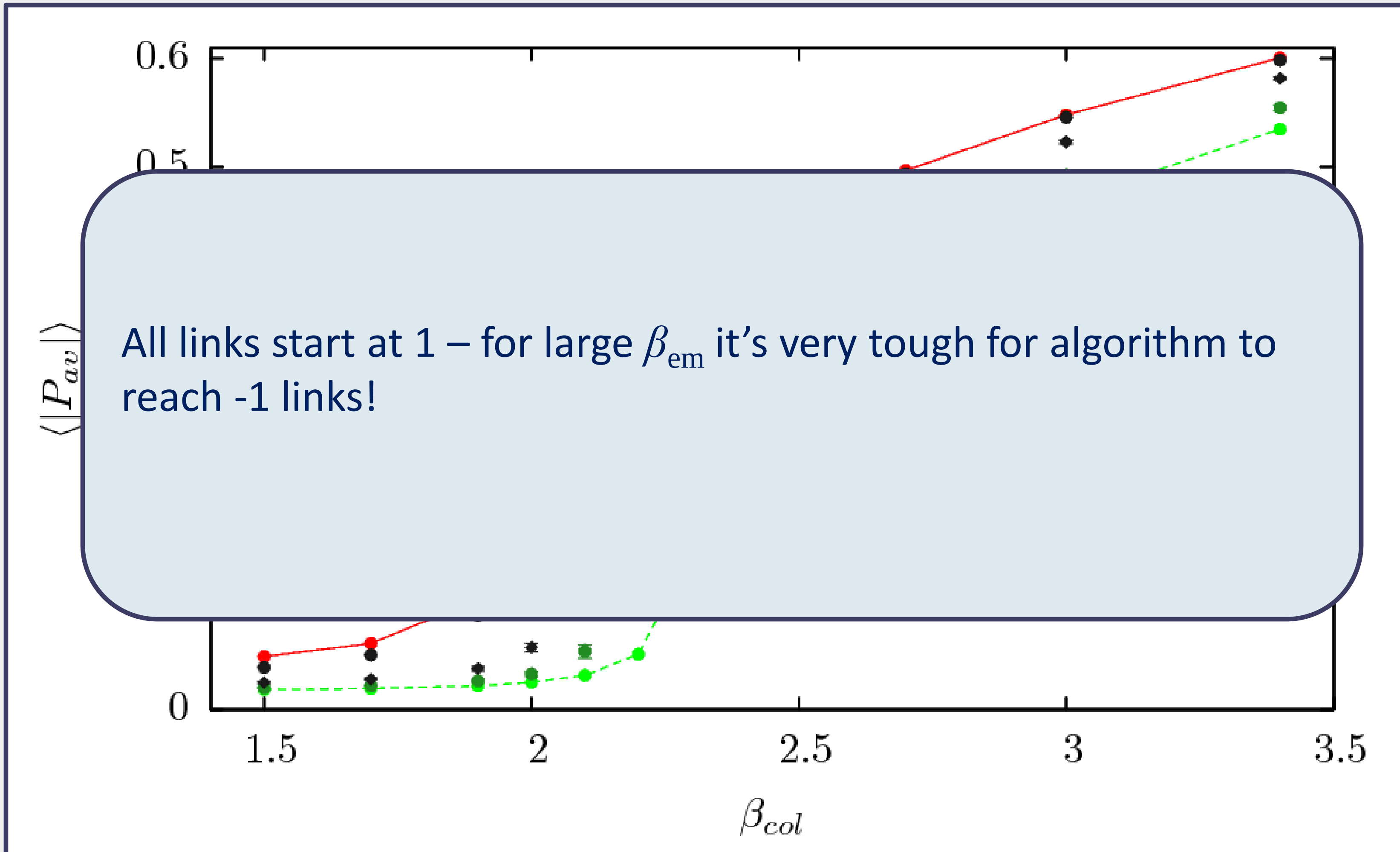
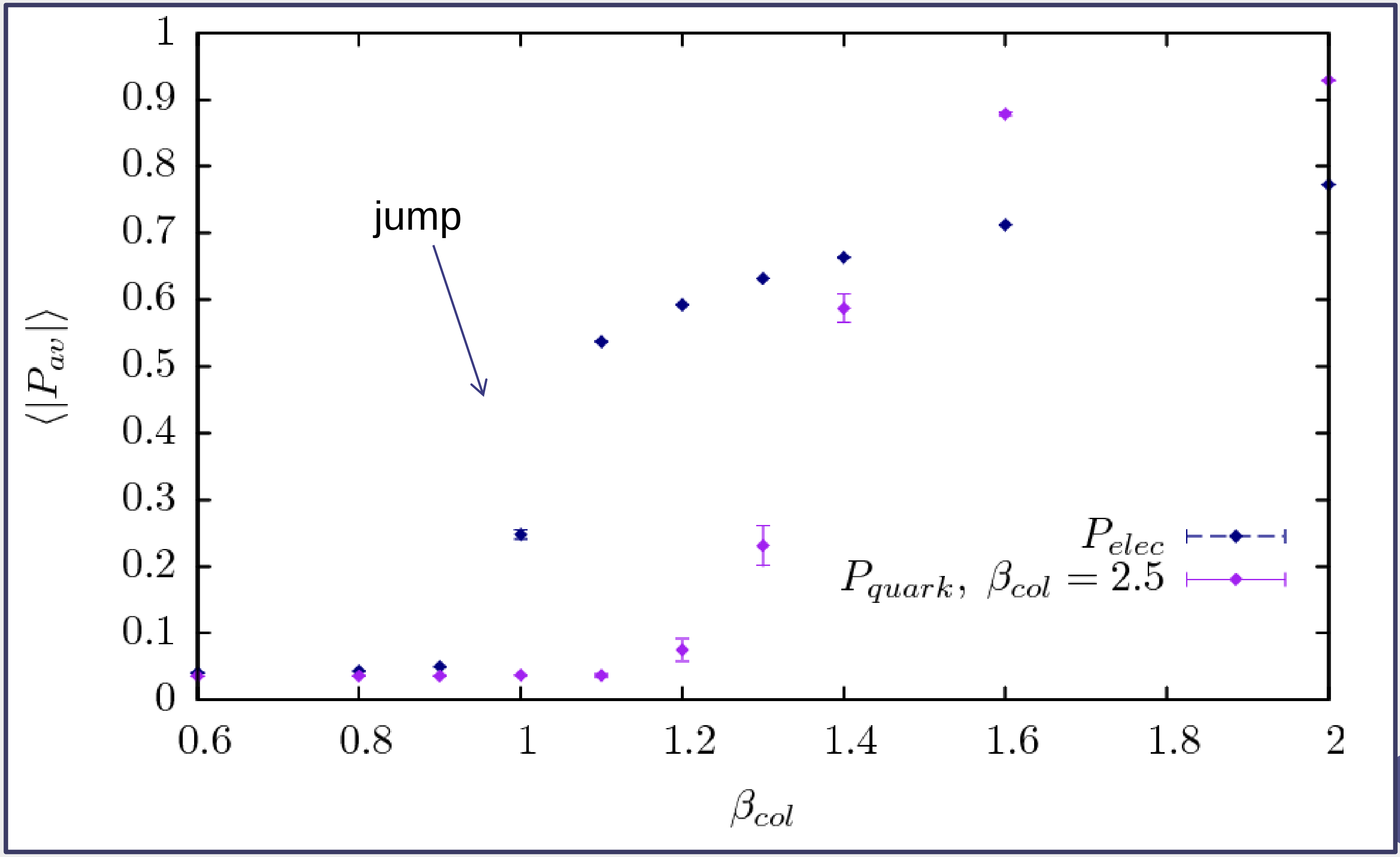
Cold start - $P_{SU(2)}$



All links start at 1 – for large β_{em} it's very tough for algorithm to reach -1 links!

$8^3 \times 4$, $\kappa = 0.15$, ~ 40000 traj.

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