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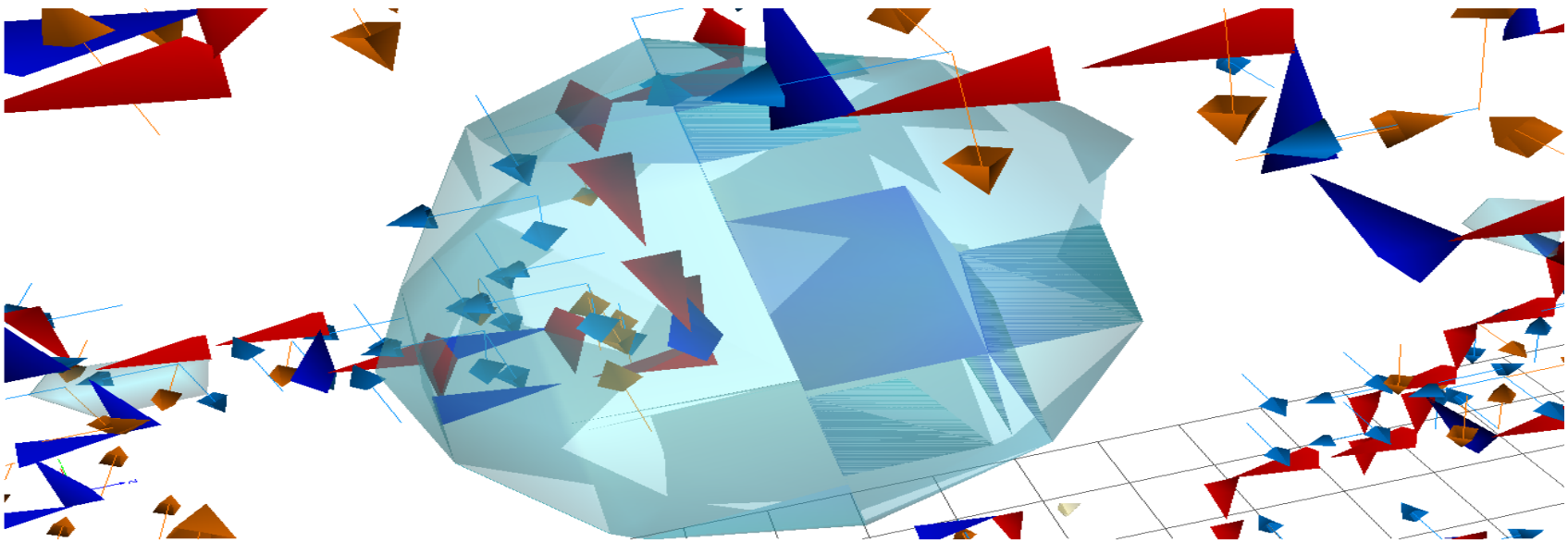
Emergent phenomena from centre vortices

Waseem Kamleh

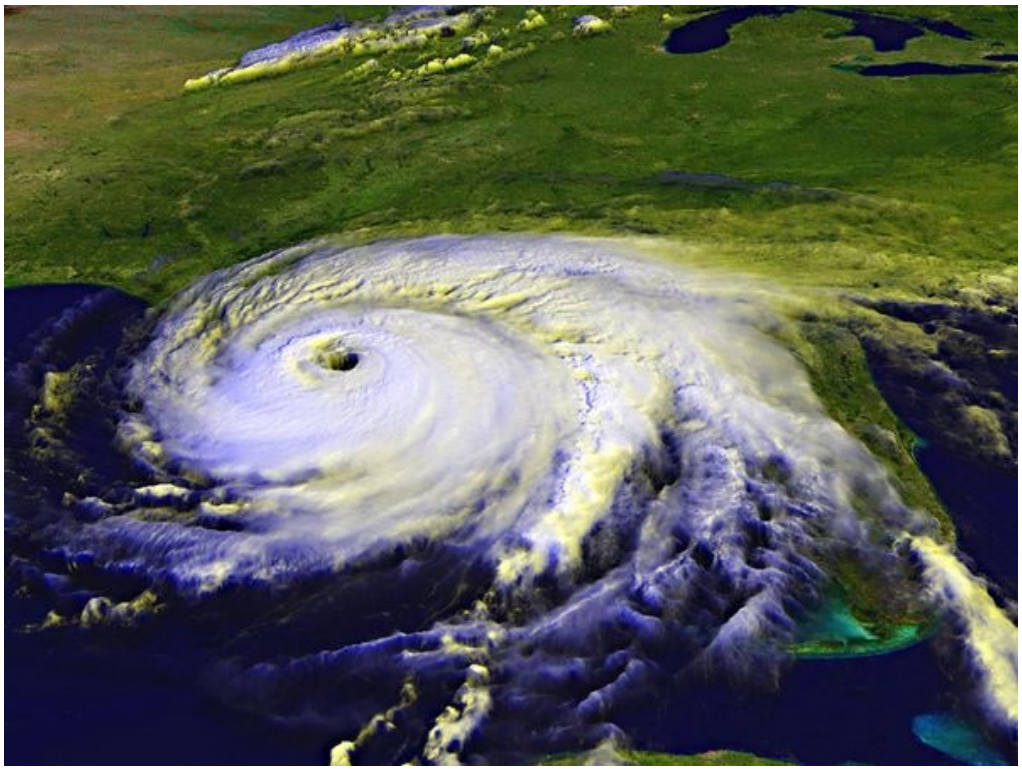
Collaborators

James Biddle, Derek Leinweber, Adam Virgili, Amalie Trewartha



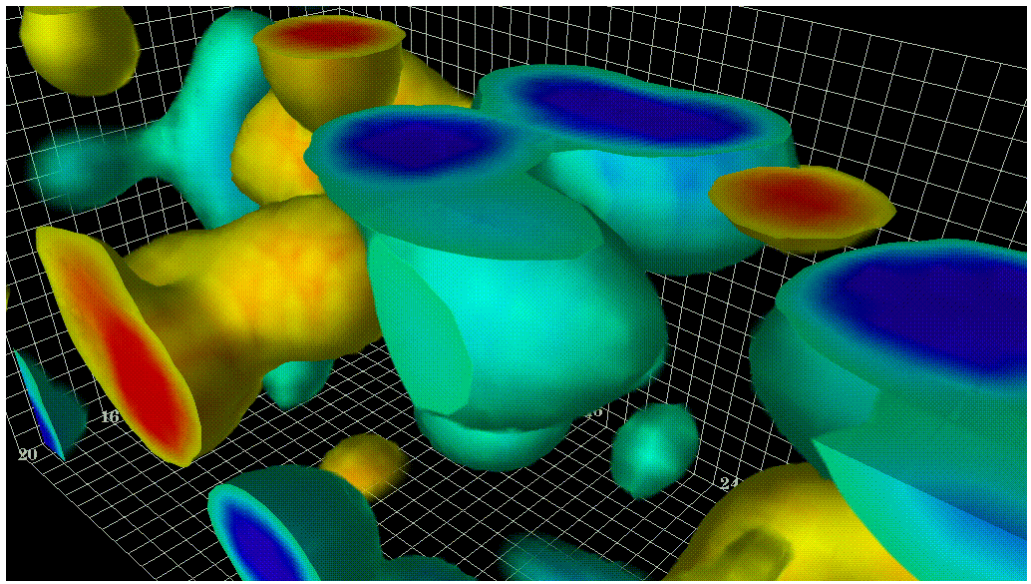
38th International Symposium on Lattice Field Theory
Zoom/Gather@MIT, 26-30 July 2021

Emergent Phenomena



An emergent behaviour or emergent property can appear when a number of simple entities (agents) operate in an environment, forming more complex behaviors as a collective.

Emergent features of QCD



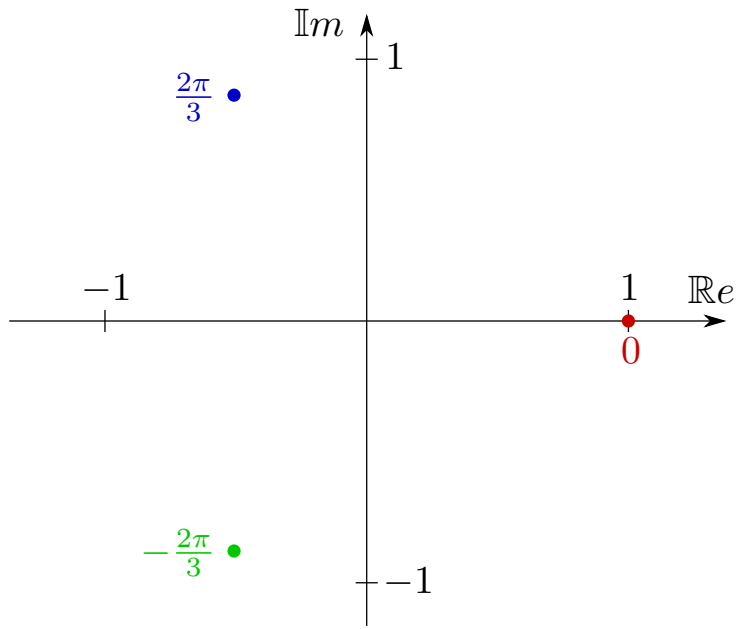
- Non-trivial QCD vacuum state (c.f. QED).
  - Requires a non-perturbative description.
- Two key *emergent* features
  - Confinement of quarks
  - Dynamical mass generation
- Can centre vortices explain the emergent features of QCD?

Centre group of SU(3)

- Centre elements commute with every group element,

$$z = \exp(\frac{2\pi i}{3} m) I, \quad m \in \{-1, 0, 1\} \simeq \mathbb{Z}_3.$$

- Three centre phases, associated with the three centre elements of SU(3),

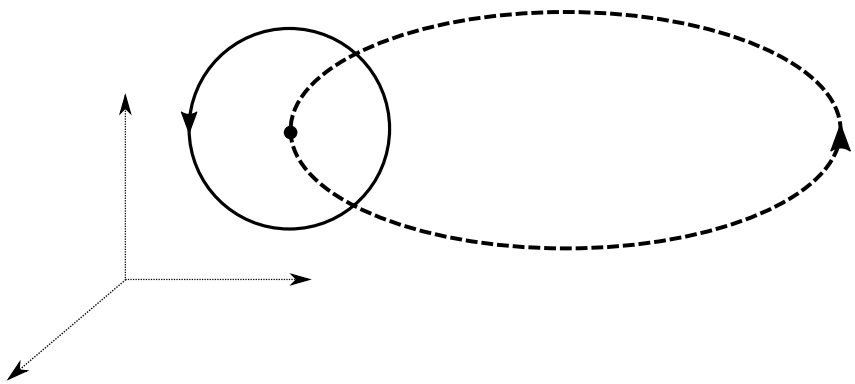


Centre Vortices

- A singular gauge transformation, discontinuous on a 3-volume, defines a (thin) *centre vortex* on the 2-dimensional boundary surface.
- We can generalise this to define centre vortices on arbitrary surfaces C, with topologically linked Wilson loops transforming as

$$U(C) \to zU(C),$$

where $U(C)$ is linked if it crosses the surface only once.



Identifying Centre Vortices

- Transform to Maximal Centre Gauge, where links are brought close to centre elements

$$Z_\mu = \exp\left[\frac{2\pi i}{3} m_\mu(x)\right] \mathrm{I}, \quad m_\mu(x) \in \{-1, 0, 1\}$$

- Require transformation $\Omega(x)$ maximising overlap between gauge links and centre elements

$$\sum_{x,\mu} \mathrm{Re}\,\mathrm{Tr}\left[U^\Omega_\mu(x) Z^\dagger_\mu(x)\right] \to \mathrm{Max}$$

- Then we project onto Z_3

$$\frac{1}{3}\mathrm{Tr} U^\Omega_\mu(x) = r_\mu(x) \exp(i\phi_\mu(x))$$

by choosing $m_\mu(x) \in \{-1, 0, 1\}$ closest to $\frac{3\phi_\mu(x)}{2\pi}$.

Identifying Centre Vortices

- The centre flux through an elementary plaquette $P_{\mu\nu}$ is given by:

$$P_{\mu\nu}(x) = \exp\left(\frac{\pi i}{3}\,\epsilon_{\kappa\lambda\mu\nu} m_{\kappa\lambda}(\bar{x})\right)$$

- The centre vortex field lives on the dual lattice,

$$\bar{x} = x + \frac{a}{2}(\hat{\mu} + \hat{\nu} - \hat{\lambda} - \hat{\kappa})$$

- Identify vortices via centre projection;

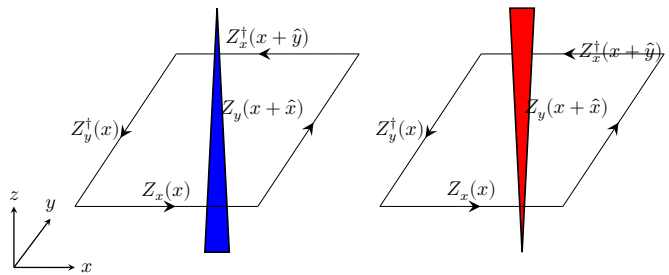
$$P_{\mu\nu}(x) = Z_\mu(x) Z_\nu(x+\mu) Z_\mu^\dagger(x+\nu) Z_\nu^\dagger(x),$$

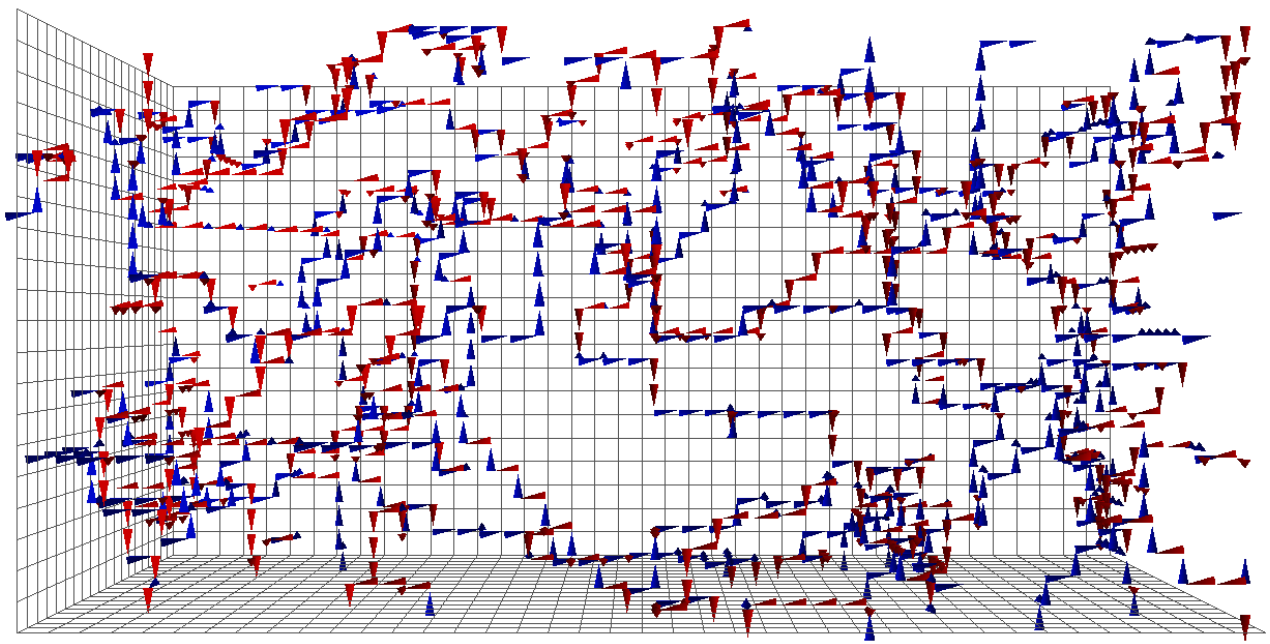
plaquette pierced by a centre vortex if

$$P_{\mu\nu}(x) = \exp\left(\frac{\pm 2\pi i}{3}\right) I$$

Identifying Centre Vortices

Example of $m = +1$ (left) and $m = -1$ (right) vortices.





Centre Vortices on the Lattice

3 ensembles:

- Untouched configurations

$$U_\mu(x)$$

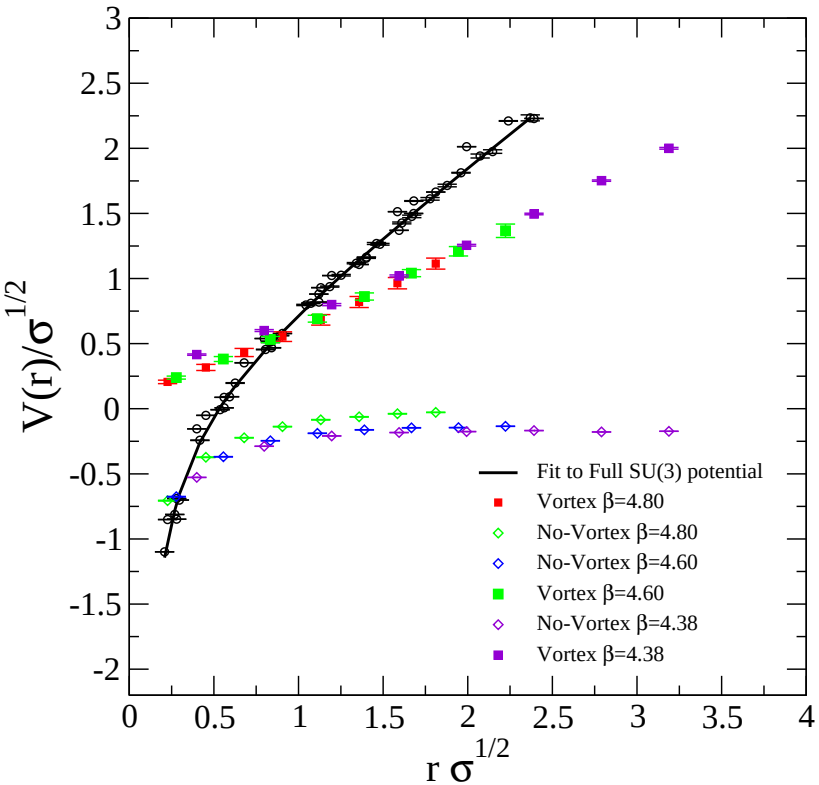
- Vortex-only configurations

$$Z_\mu(x) = \exp\left[\frac{2\pi i}{3} m_\mu(x)\right] \mathrm{I}$$

- Vortex removed configurations

$$R_\mu(x) = Z_\mu^\dagger(x) U_\mu^\Omega(x)$$

Static Quark Potenial

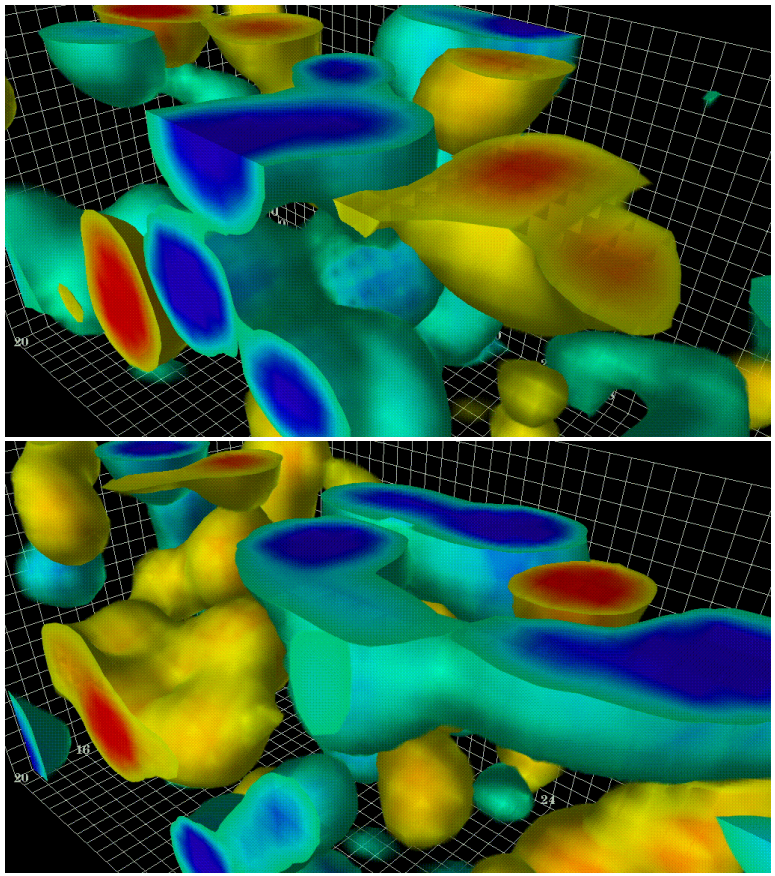


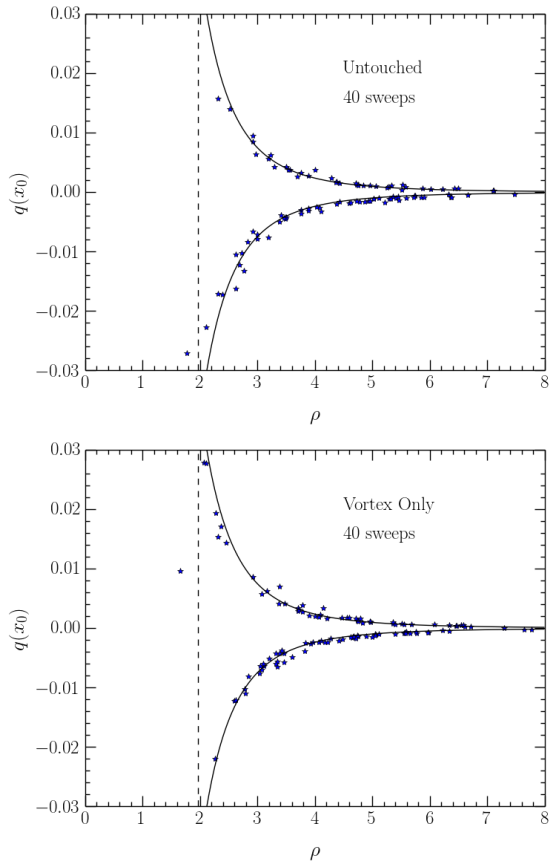
- Confinement:
  - Wilson loop falls off with asymptotic area law.
  - Static quark potential is linear.

$$V(r) \sim \sigma r \leftrightarrow W(\mathcal{C}) \sim e^{-\sigma A}$$

Role of center vortices in chiral symmetry breaking in SU(3) gauge theory
Bowman et al, Phys. Rev. D 84, 034501 (2011)

Instantons

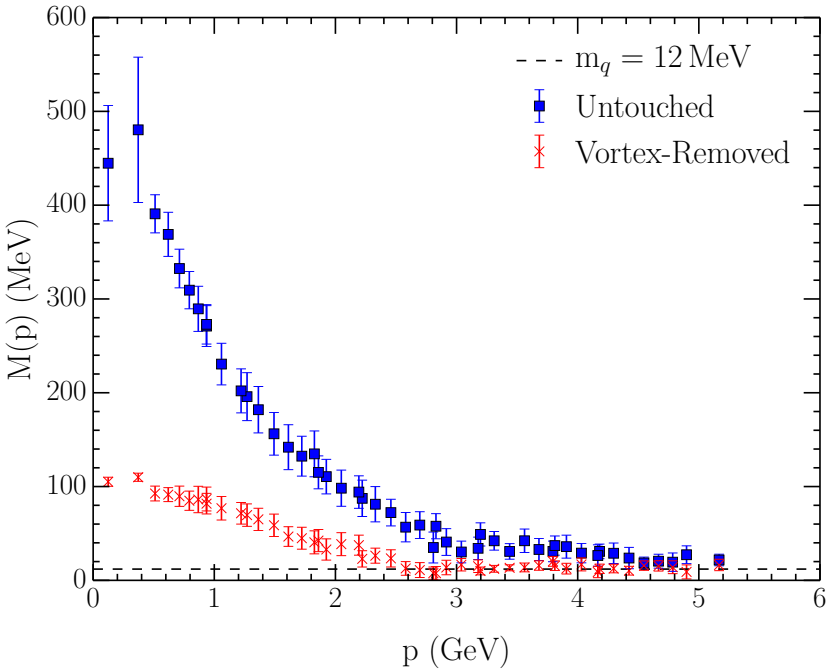


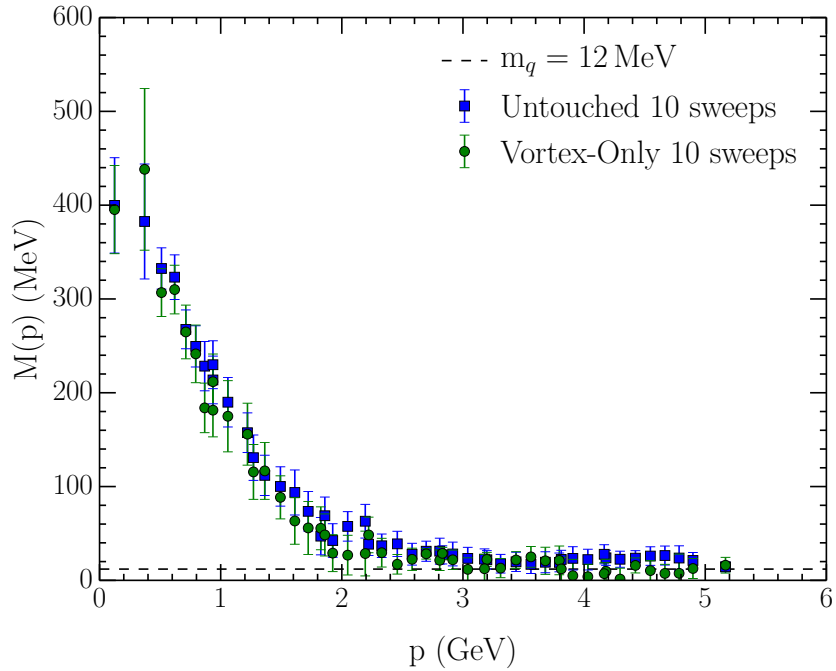


Connection between center vortices and instantons through gauge-field smoothing

A. Trewartha, WK, D.B. Leinweber, Phys. Rev. D 92 (2015) 7, 074507

Overlap Quark Propagator

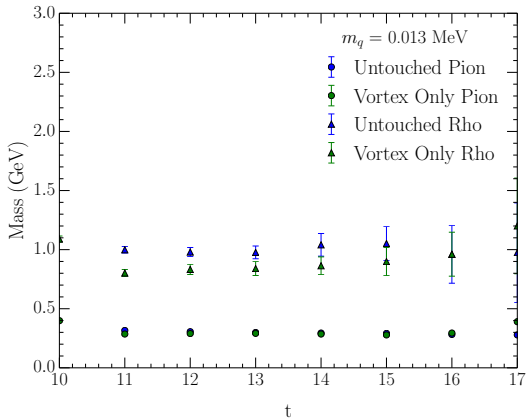


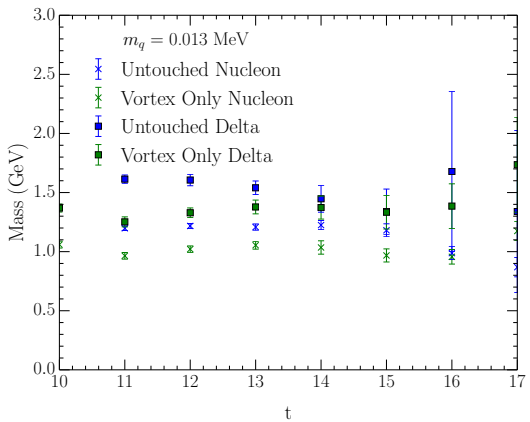


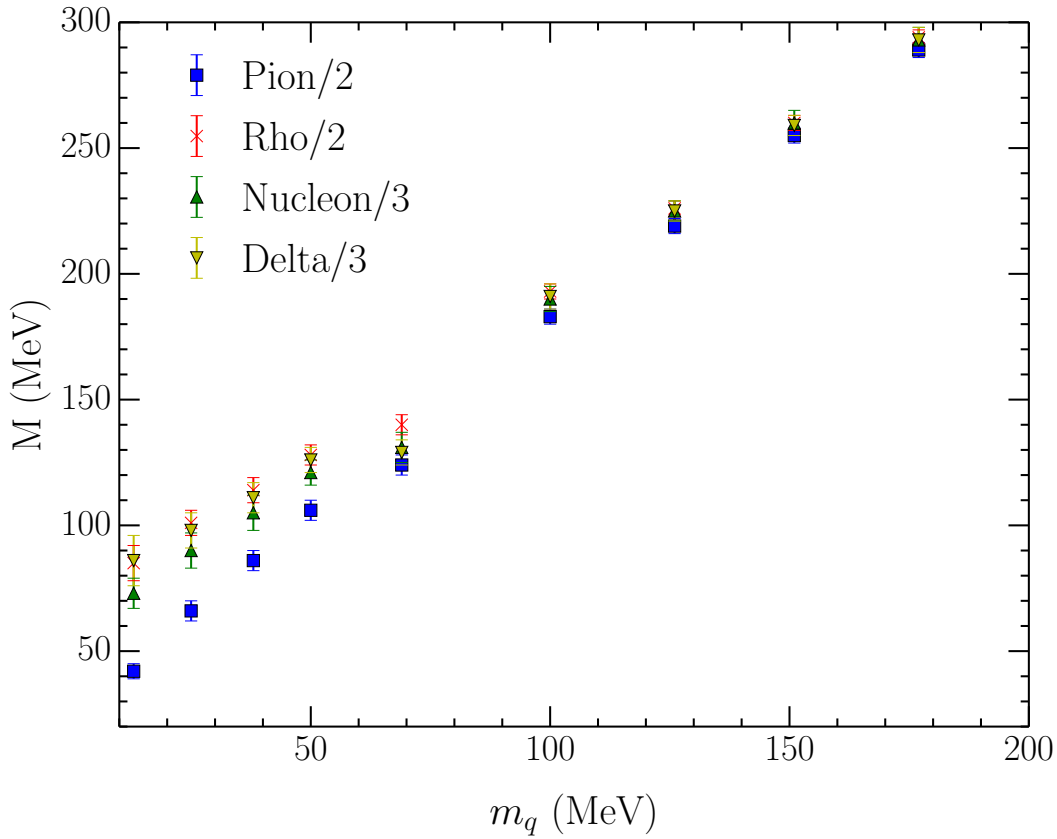
Evidence that centre vortices underpin dynamical chiral symmetry breaking in SU(3) gauge theory

A. Trewartha, WK, D.B. Leinweber, Phys. Lett. B 747 (2015) 373-377

Hadron spectrum



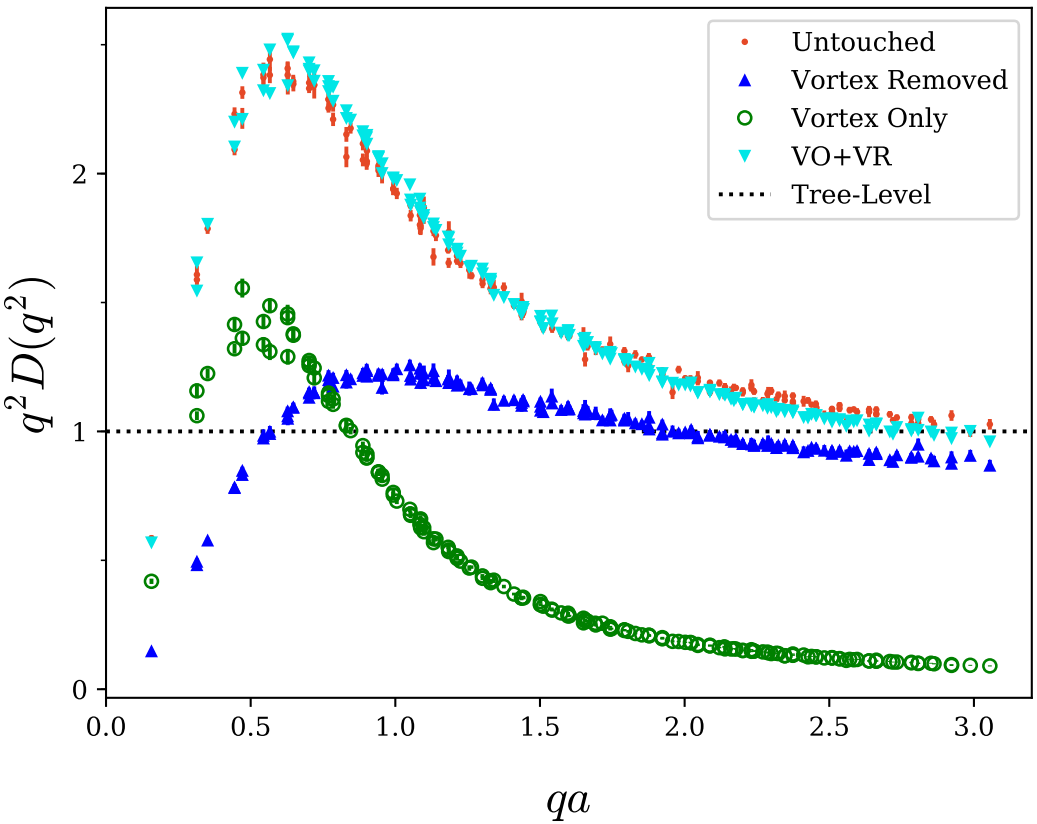




Centre vortex removal restores chiral symmetry

A. Trewartha, WK, D.B. Leinweber, J. Phys. G 44 (2017) 12, 125002

Gluon Propagator



Gluon propagator on a center-vortex background

J.C. Biddle, WK, D.B. Leinweber, Phys. Rev. D 98 (2018) 9, 094504

$SU(3)$ Pure Gauge Results

- Static quark potential;
  - Vortex removal removes linear potential.
  - Vortex-only field recreates $\sim 2/3$ of string tension.
- Connection to instanton degrees of freedom
  - Vortex removal destabilizes instantons under cooling.
  - Vortex-only field creates instantons under cooling.
- Overlap quark propagator;
  - Vortex removal causes loss of dynamical mass generation.
  - Vortex-only field reproduces dynamical mass generation.
- Hadron spectrum;
  - Vortex removal restores chiral symmetry at light masses.
  - Vortex-only field reproduces ground state spectrum.
- Gluon propagator;
  - Vortex removal causes loss of infrared strength.
  - Vortex-only field recreates $\sim 2/3$ of infrared strength.

$SU(3)$ Pure Gauge Results

Centre vortices contain all information necessary to reproduce confinement and DχSB in $\mathrm{SU}(3)$ gauge theory.

> *It would be tempting to abolish the SU(3) color theory for hadrons altogether, replacing it by a Z(3) theory on a Euclidean lattice and taking the continuum limit close to the critical point.*

"On the phase transition towards permanent quark confinement"
G. 't Hooft, 1978

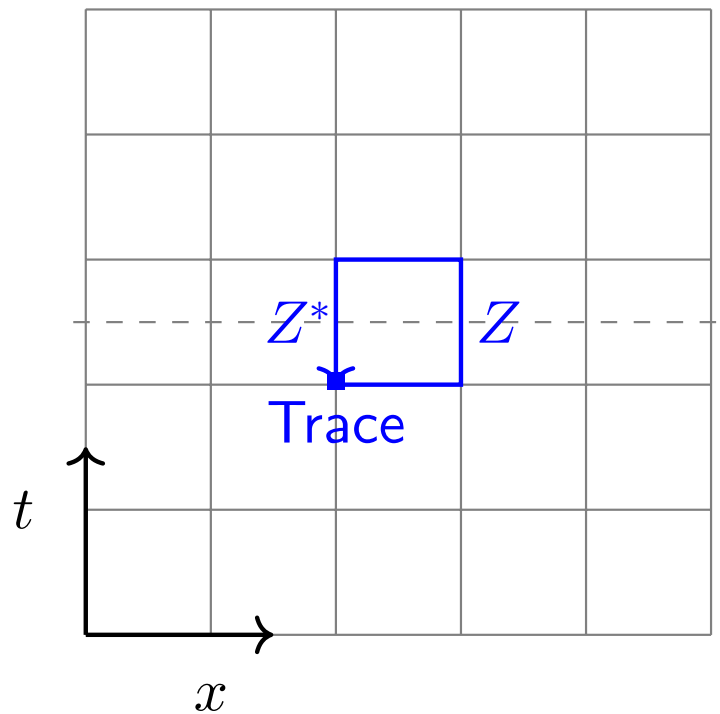
What happens in the presence of dynamical fermions?

Centre Symmetry

Confinement is the phase of unbroken global centre symmetry

- Consider a centre transformation on some timeslice,

$$U_t(t_0, \vec{x}) \to Z\, U_t(t_0, \vec{x}), \quad \forall \vec{x}$$



Centre Symmetry

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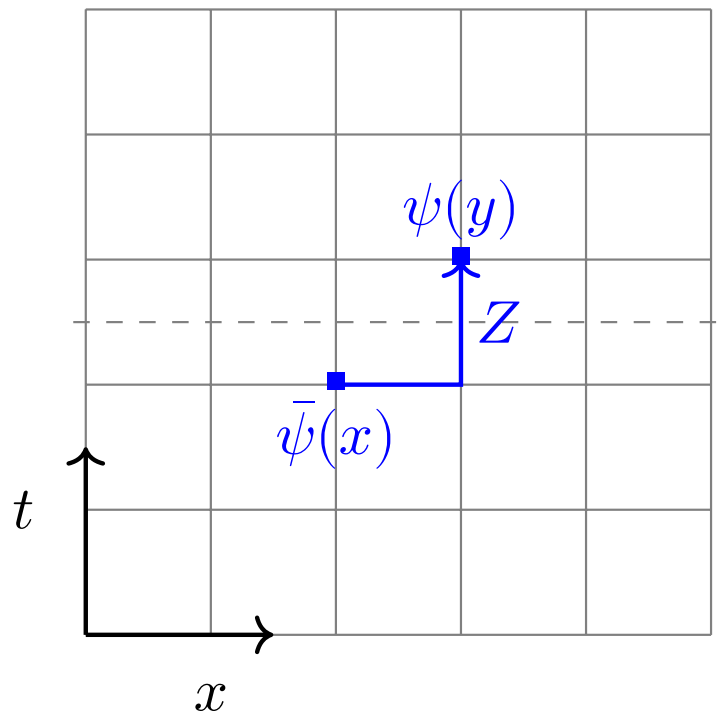
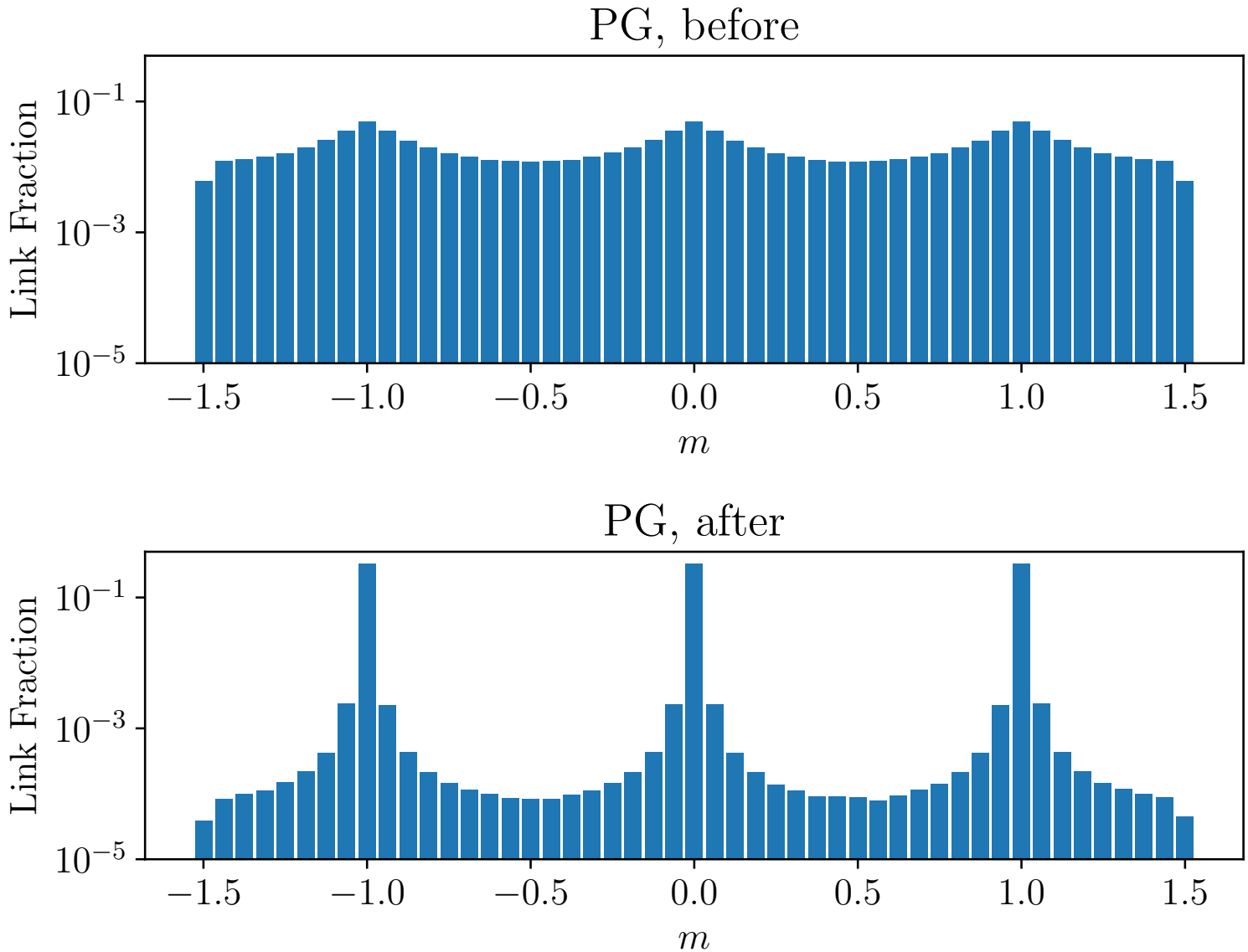
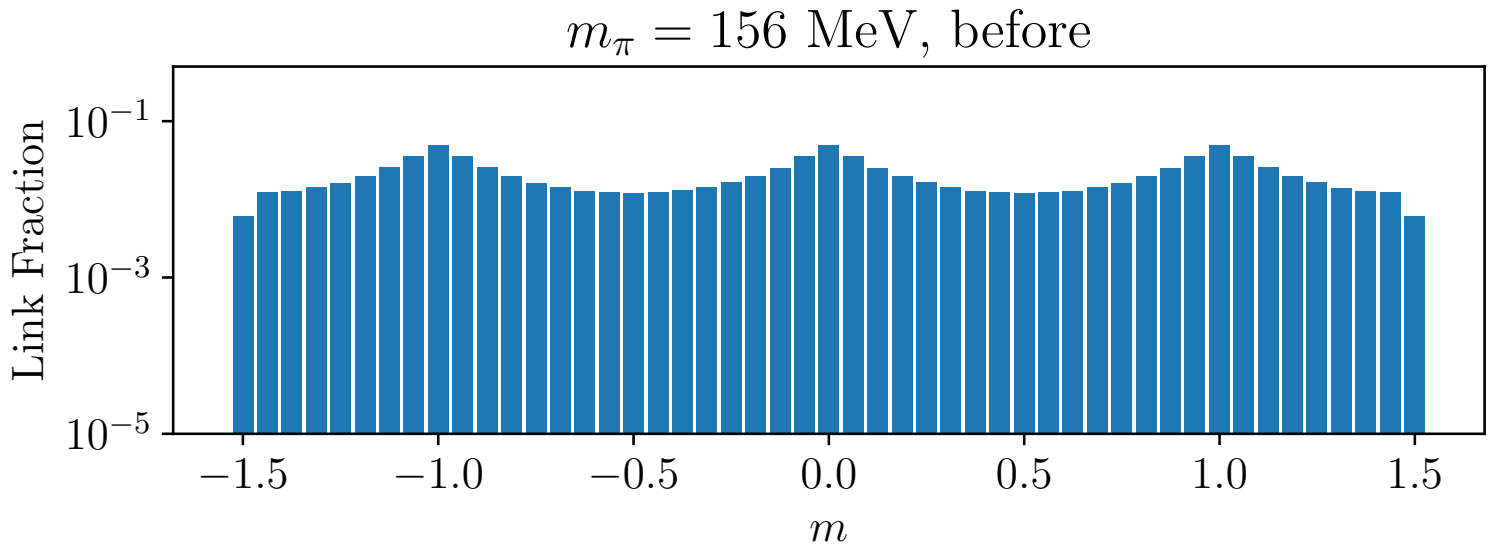
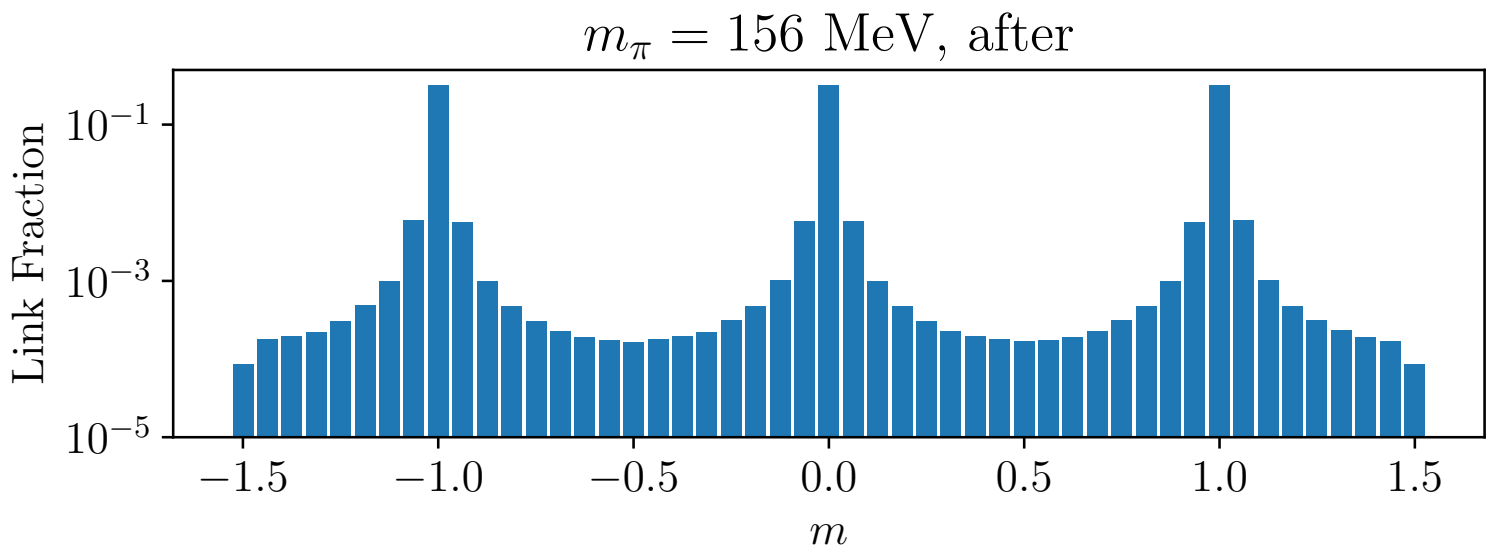


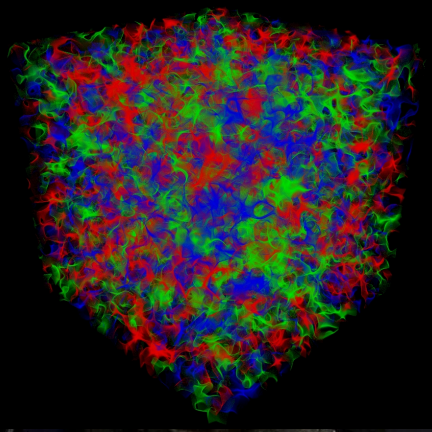
Centre Phase Distribution (Pure Gauge)

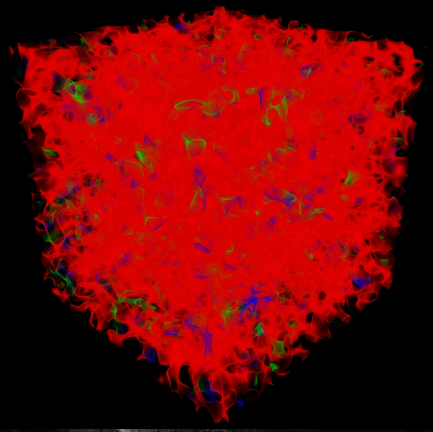


Centre Phase Distribution (Dynamical)

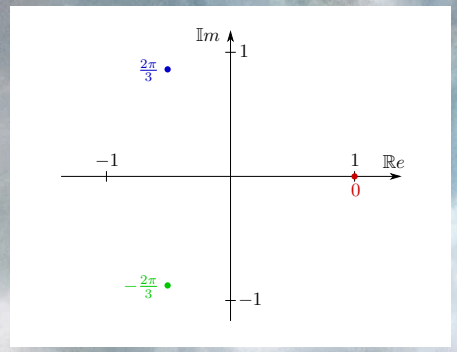




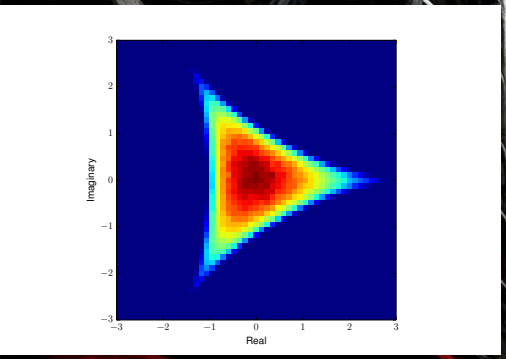


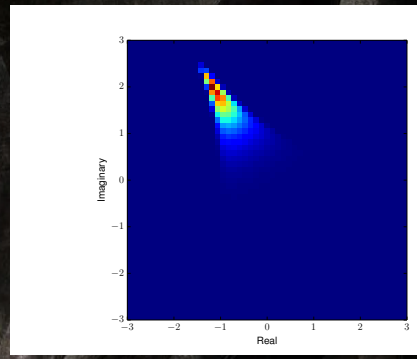


EQUALITY
SYMMETRY
CONFINEMENT



DOMINANCE
ASYMMETRY
DECONFINEMENT





CENTRE

PROTECT

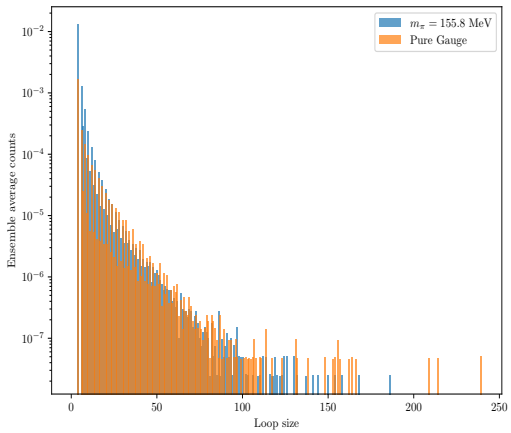
DESTROY

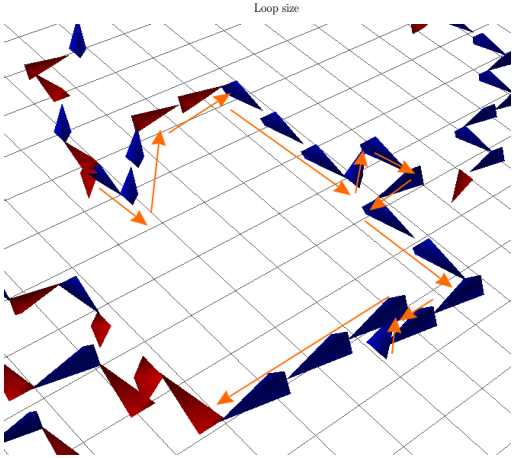
TRANSFORMERS

Confinement is an emergent feature of QCD that is realised when the vacuum phase embodies global centre symmetry.

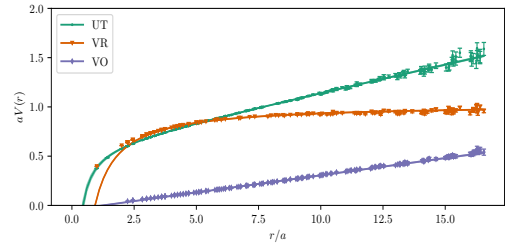
Coming up ...

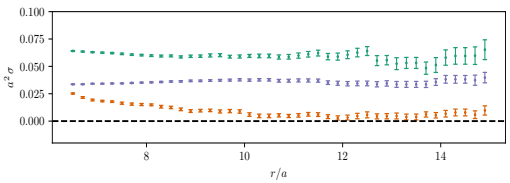
Next
Derek Leinweber

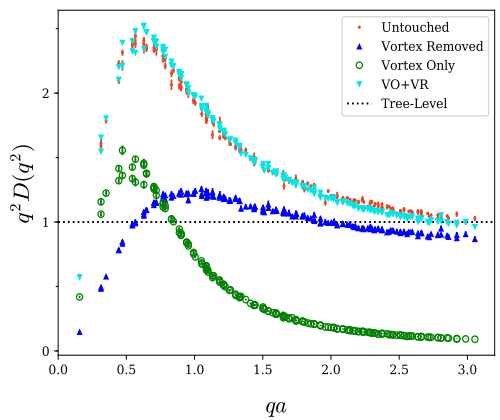




Next + 1
James Biddle







Next + 2
Adam Virgili