Impact of Dynamical Fermions on the Centre-Vortex Structure of QCD Ground-State Vacuum Fields

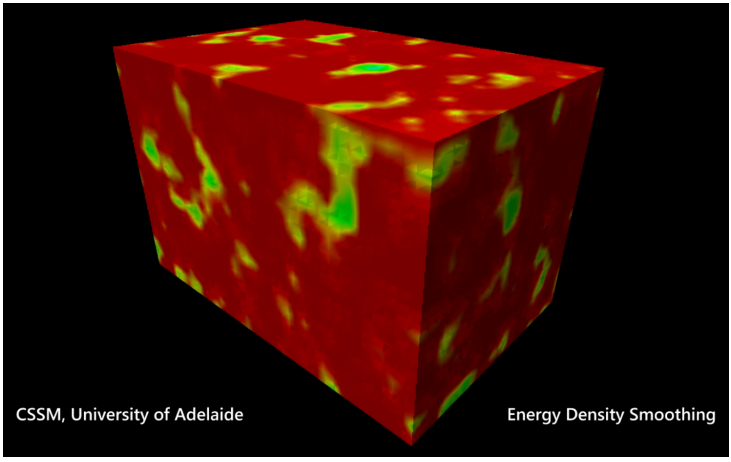
Derek Leinweber

In collaboration with:

James Biddle, Waseem Kamleh,

Amalie Trewartha, & Adam Virgili

Introduction: CSSM Visualisations on YouTube



Introduction

Is there something more fundamental that captures the salient features of QCD?

- Confinement.
- Dynamical generation of mass via Chiral Symmetry breaking.

Centre-Vortices in the Ground-State QCD-Vacuum Fields

- What are Centre Vortices?

Centre-Vortices in the Ground-State QCD-Vacuum Fields

- What are Centre Vortices?
- What is the phenomenology of the Centre-Vortex model in SU(3) gauge theory?
  - Static-quark confinement – P. Bowman *et. al.* Phys. Rev. D **84** (2011) 034501.
  - Gluon propagator – J. C. Biddle, W. Kamleh and DBL, Phys. Rev. D **98** (2018) 094504.
  - Quark propagator – A. Trewartha, W. Kamleh and DBL, Phys. Lett. B **747** (2015) 373.
  - Chiral Symmetry – A. Trewartha, W. Kamleh and DBL, J. Phys. G **44** (2017) 12, 125002.

Centre-Vortices in the Ground-State QCD-Vacuum Fields

- What are Centre Vortices?
- What is the phenomenology of the Centre-Vortex model in SU(3) gauge theory?
  - Static-quark confinement – P. Bowman *et. al.* Phys. Rev. D **84** (2011) 034501.
  - Gluon propagator – J. C. Biddle, W. Kamleh and DBL, Phys. Rev. D **98** (2018) 094504.
  - Quark propagator – A. Trewartha, W. Kamleh and DBL, Phys. Lett. B **747** (2015) 373.
  - Chiral Symmetry – A. Trewartha, W. Kamleh and DBL, J. Phys. G **44** (2017) 12, 125002.
- What do Centre Vortices look like?
  - Interesting features: percolation, monopoles, secondary loops, singular points, ...
  - J. C. Biddle, W. Kamleh and DBL, Phys. Rev. D **102** (2020) 034504 [arXiv:1912.09531 [hep-lat]].
  - What is the impact of dynamical fermions on centre-vortex structure?

Centre-Vortices in the Ground-State QCD-Vacuum Fields

- What are Centre Vortices?
- What is the phenomenology of the Centre-Vortex model in SU(3) gauge theory?
  - Static-quark confinement – P. Bowman *et. al.* Phys. Rev. D **84** (2011) 034501.
  - Gluon propagator – J. C. Biddle, W. Kamleh and DBL, Phys. Rev. D **98** (2018) 094504.
  - Quark propagator – A. Trewartha, W. Kamleh and DBL, Phys. Lett. B **747** (2015) 373.
  - Chiral Symmetry – A. Trewartha, W. Kamleh and DBL, J. Phys. G **44** (2017) 12, 125002.
- What do Centre Vortices look like?
  - Interesting features: percolation, monopoles, secondary loops, singular points, ...
  - J. C. Biddle, W. Kamleh and DBL, Phys. Rev. D **102** (2020) 034504 [arXiv:1912.09531 [hep-lat]].
  - What is the impact of dynamical fermions on centre-vortex structure?
- What is the origin of dynamical mass generation and confinement in QCD?

Vortex Structure in the Colour Fields of the QCD Vacuum

What Are Centre Vortices?

- Centre vortices in 3D are tube-like topological defects present in the QCD vacuum.
- We locate thin vortex lines on the lattice.
- The vortex line can be thought of as the 'axis of rotation' of the vortex.

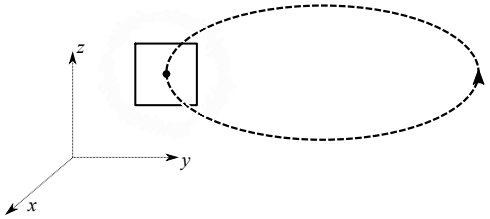


Figure: A centre vortex (dashed line) intersecting a lattice plaquette (solid square).

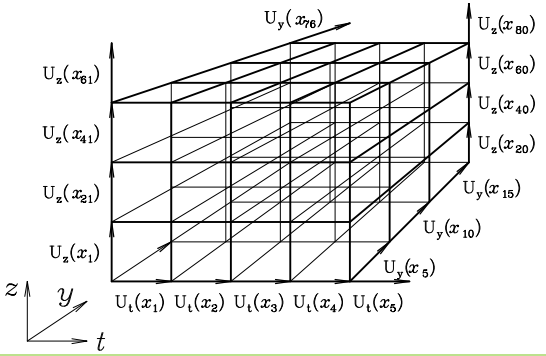
How do you find centre vortices?

Lattice Links

- On the lattice, the gluon-field is encoded in terms of the link variable

$$U_\mu^{ab}(x) \simeq \exp\left(i\, a\, g\, A_\mu^{ab}(x)\right) ,$$

  a 3×3 complex special-unitary matrix.



1. Maximal Centre Gauge

- Gauge transformations bring the links close to an element of the group centre.
- The centre elements of $SU(3)$ are the three cube roots of 1, namely

$$Z(3) = \exp\left(\frac{2\pi i}{3}\, m\right)\, I\,,\ \ m \in \{-1,\, 0,\, +1\}$$

- This is done by maximising the functional

$$R = \sum_{x} \sum_{\mu} |\, \mathrm{tr}[U_{\mu}(x)]\, |^2$$

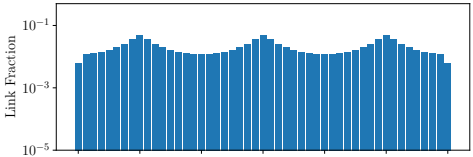
- This is called **Maximal Centre Gauge**

1. Maximal Centre Gauge

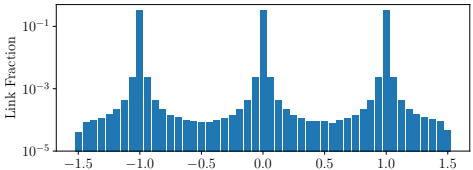
- Distribution of link phases following gauge fixing to Maximal Centre Gauge.

$$\operatorname{tr} U_\mu^{\mathrm{MCG}}(x) \;=\; \underbrace{r_\mu(x)}_{\text{real}} \exp \underbrace{\left(\frac{2\pi i}{3}\,\phi_\mu(x)\right)}_{-\pi \,<\, \text{phase} \,\leq\, \pi}, \quad -\frac{3}{2} < \phi_\mu(x) \leq \frac{3}{2}\,.$$

- $\phi_\mu(x)$ before gauge fixing.



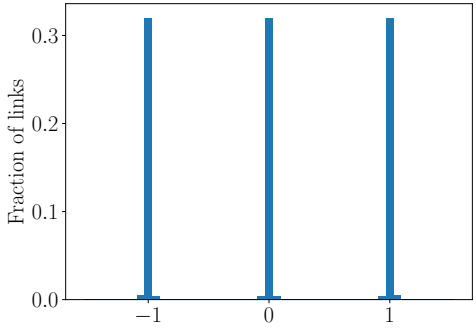
- $\phi_\mu(x)$ after gauge fixing.



1. Maximal Centre Gauge

- Distribution of link phases following gauge fixing to Maximal Centre Gauge.

$$\mathrm{tr}\, U_\mu^{\mathrm{MCG}}(x) \;=\; \underbrace{r_\mu(x)}_{\text{real}}\; \exp\underbrace{\left(\frac{2\pi i}{3}\,\phi_\mu(x)\right)}_{-\pi\,<\,\text{phase}\,\leq\,\pi}, \quad -\frac{3}{2} < \phi_\mu(x) \leq \frac{3}{2}\,.$$



2. Centre Projection

- Project onto $Z(3)$

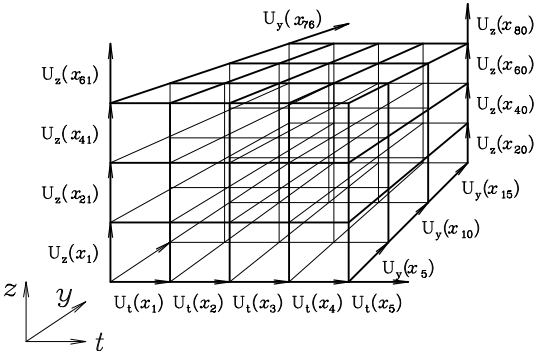
$$U_\mu^{\mathrm{MCG}}(x) \to Z_\mu(x) = \exp\left(\frac{2\pi i}{3}\, m_\mu(x)\right) I\,,\ \ m_\mu(x) \in \{-1,\, 0,\, +1\}\,,$$

  i.e. a cube-root of 1 times the identity matrix.

- Eight degrees of freedom are replaced by one of the three cube-roots of 1.

3. Identifying Vortices

- Examine the product of $Z_\mu(x)$ around each elementary square (plaquette).
- Each plaquette takes a value from $Z(3)$.



3. Identifying Vortices

- Non-trivial plaquettes with values

$$\exp\left(\frac{2\pi i}{3}\, m\right) \neq 1\,, \quad i.e.\ m \in \{-1, +1\}\,,$$

  identify our thin vortices.

- Thin vortices locate the centre of the physical thick vortices

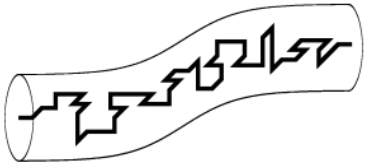


Figure: An example of a vortex path embedded within a thick vortex.
M. Engelhardt, H. Reinhardt, Nuclear Physics B **585** (2000) 597

Configurations

- This projection allows us to define 3 sets of configurations:
  - Untouched - $U_\mu(x)$
  - Vortex Only - $Z_\mu(x)$
  - Vortex Removed - $R_\mu(x) = Z_\mu^\dagger(x)\, U_\mu(x)$

Configurations

- This projection allows us to define 3 sets of configurations:
  - Untouched - $U_\mu(x)$
  - Vortex Only - $Z_\mu(x)$
  - Vortex Removed - $R_\mu(x) = Z_\mu^\dagger(x)\, U_\mu(x)$

- 4 ensembles
  - $20^3 \times 40$ pure gauge (PG), spacing $a = 0.125$ fm
  - $32^3 \times 64$ pure gauge (PG), spacing $a = 0.100$ fm
  - $32^3 \times 64$ dynamical $2+1$ flavour, spacing $a = 0.1022$ fm, $m_\pi = 701$ MeV
  - $32^3 \times 64$ dynamical $2+1$ flavour, spacing $a = 0.0933$ fm, $m_\pi = 156$ MeV
  - S. Aoki, *et al.* (PACS-CS), Phys. Rev. D **79**, 034503.

Phenomenology of Centre Vortices

Static Quark Potential

- Measures the potential energy between two massive, static quarks at separation r.
- Serves as an indicator of confining behaviour in the form of a linear long-range potential.
- Typically described via the Cornell potential

$$V(r) = V_0 - \frac{\alpha}{r} + \sigma\, r$$

Centre Vortices and Confinement – Pure Gauge Sector

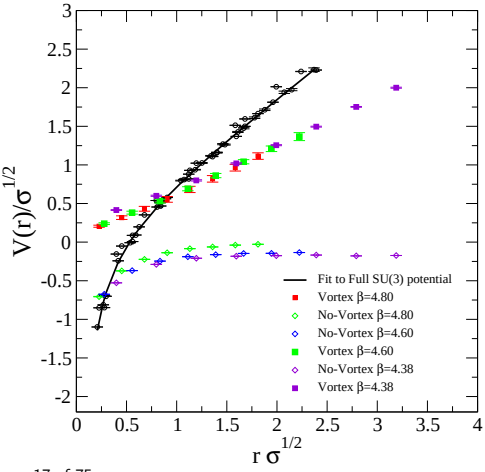


Figure from

Bowman et al, Phys. Rev. D **84**, *034501 (2011).*

MCG procedure cannot simultaneously identify all SU(3) vortex matter.

O'Cais et al, Phys. Rev. D **82**, *114512 (2010).*

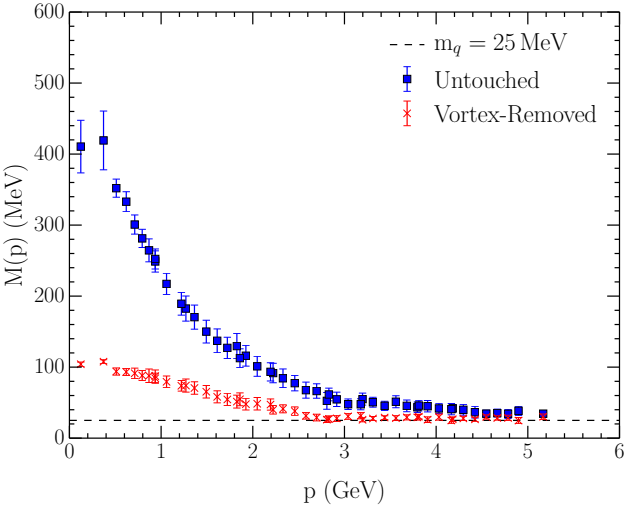
Centre Vortices and the Landau-Gauge Quark Propagator

- Probe dynamical mass generation using the quark propagator

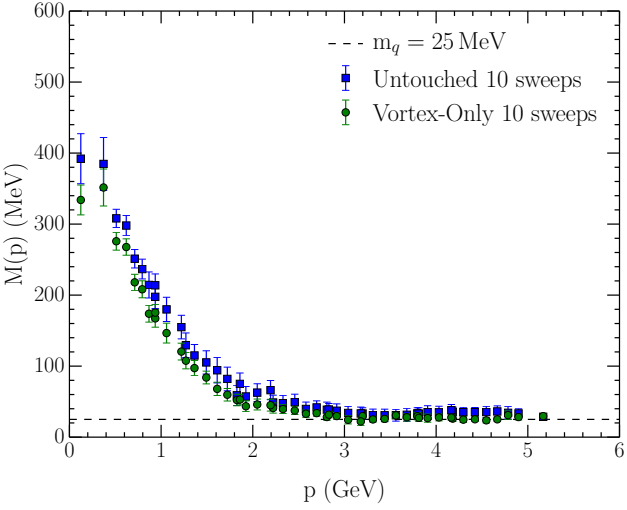
$$S(p) = \frac{Z(p)}{i\not{p} + M(p)},$$

- Enhancement of the mass function, $M(p)$, at low momenta indicates dynamical mass generation.
- Renormalisation function, $Z(p)$, is typically infrared suppressed.
- Consider the Overlap-Dirac fermion action
  - Provides a lattice implementation of chiral symmetry,
  - No additive mass renormalisation,
  - Sensitive to the topological structure of the gauge fields.

Quark Mass Function in Pure Gauge Theory



Vortex-Only Mass function, 10 sweeps of cooling



Restoration of Chiral Symmetry

- If vortices are responsible for $D\chi SB$, then their removal should restore chiral symmetry

$$\mathrm{SU}\,2_\mathrm{L} \times \mathrm{SU}\,2_\mathrm{R} \times \mathrm{U}(1)_\mathrm{A}$$

- Expect hadrons related by chiral transformations to become degenerate

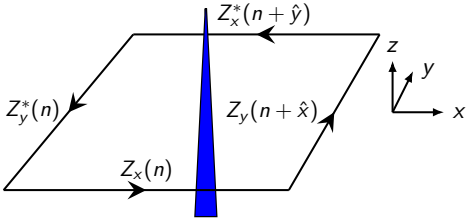
$$\begin{array}{ccc} \pi & \xleftrightarrow{\mathrm{U}(1)_\mathrm{A}} & a_0 \\ \rho & \xleftrightarrow{\mathrm{SU}\,2_\mathrm{L}\times\mathrm{SU}\,2_\mathrm{R}} & a_1 \\ N & \xleftrightarrow{\mathrm{SU}\,2_\mathrm{L}\times\mathrm{SU}\,2_\mathrm{R}} & \Delta \end{array}$$

- At light quark masses, all symmetries are observed to be restored.
- A. Trewartha, W. Kamleh and DBL, J. Phys. G **44** (2017) 125002 [arXiv:1708.06789 [hep-lat]].

What do centre vortices look like?

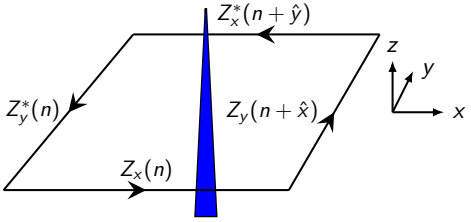
Rendering Projected Vortices

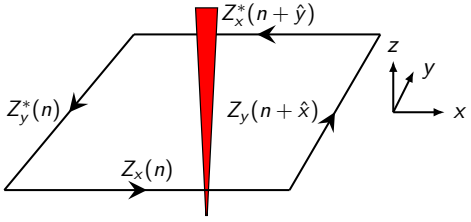
- Vortex directions are indicated using a right-handed coordinate system.
- For example,
  - An $m = +1$ vortex in the x-y plane is plotted in the $+\hat{z}$ direction as a blue jet.



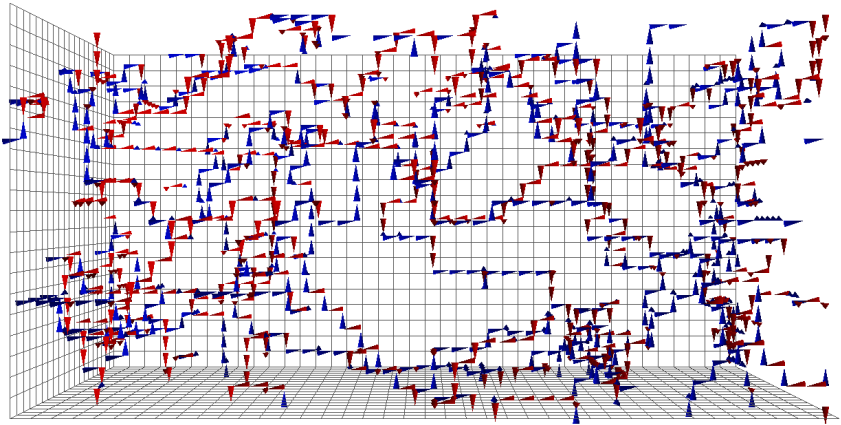
Rendering Projected Vortices

- Vortex directions are indicated using a right-handed coordinate system.
- For example,
  - An $m = +1$ vortex in the x-y plane is plotted in the $+\hat{z}$ direction as a blue jet.
  - An $m = -1$ vortex in the x-y plane is plotted in the $-\hat{z}$ direction as a red jet.





$t = 1$ J. Biddle, W. Kamleh and DBL, Phys. Rev. D **102**, 034504 [arXiv:1912.09531 [hep-lat]]



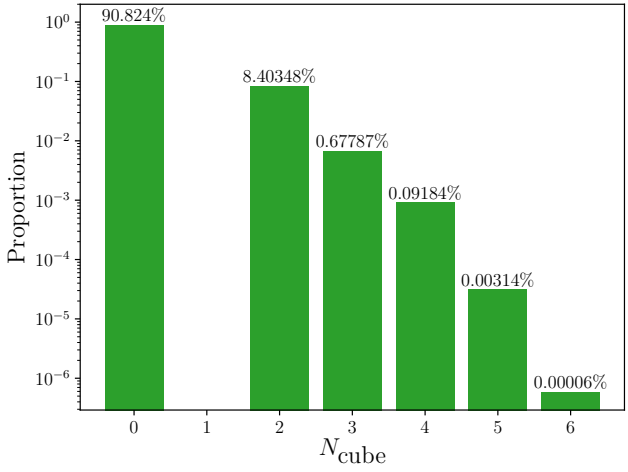
Visualising Centre Vortices

- Consider the number of vortices entering a 3D cube on the dual lattice.

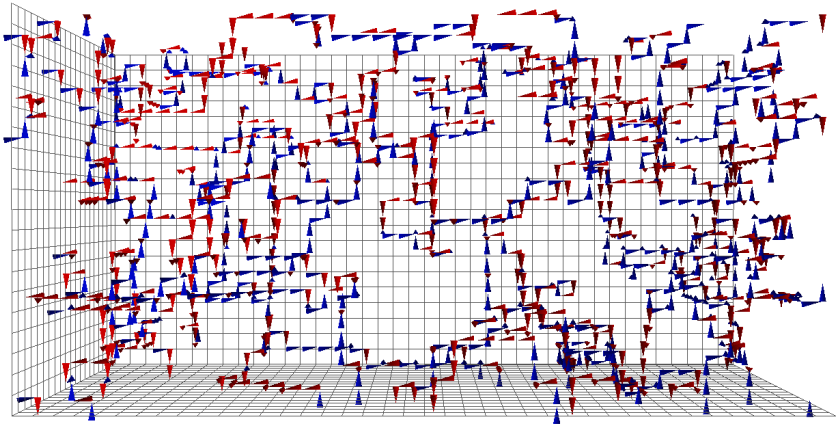
$N_{\text{cube}}(\tilde{x})$	Interpretation
0	No vortices present.
1	Terminating vortex, forbidden by Bianchi*.
2	Vortex line flowing through the cube.
3	Simple three-way vortex monopole.
4	Vortex intersection.
5	Complex five-way monopole path.
6	Vortex intersections or double monopoles.

*Bianchi identity implies a continuous flow of centre vortex flux through a spatial cube.

Visualising Centre Vortices

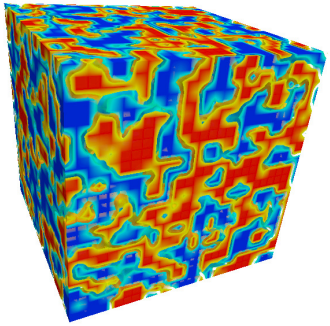


$t = 2$ J. Biddle, W. Kamleh and DBL, Phys. Rev. D **102**, 034504 [arXiv:1912.09531 [hep-lat]]

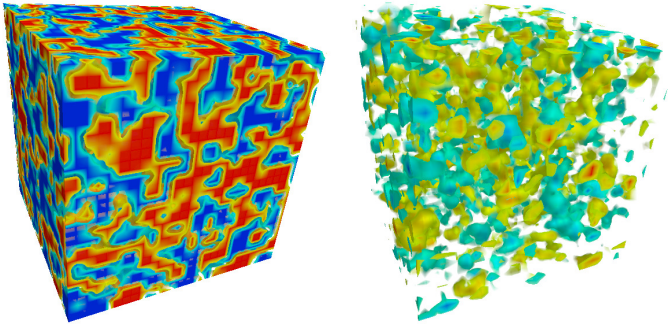


Impact of Dynamical Fermions on Centre Vortex Structure

Visualisations of the Topological Charge Density

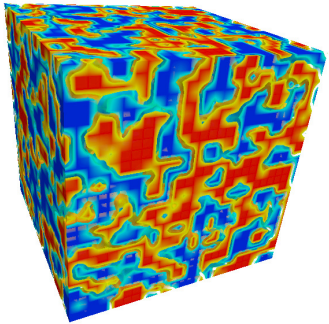


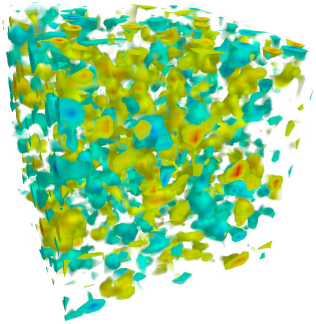
Visualisations of the Topological Charge Density

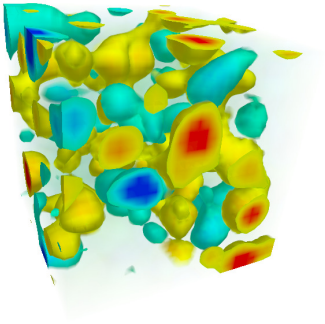


- See "Buried treasure in the sand of the QCD vacuum," P. J. Moran and DBL, [arXiv:0805.4246 [hep-lat]].

Visualisations of the Topological Charge Density

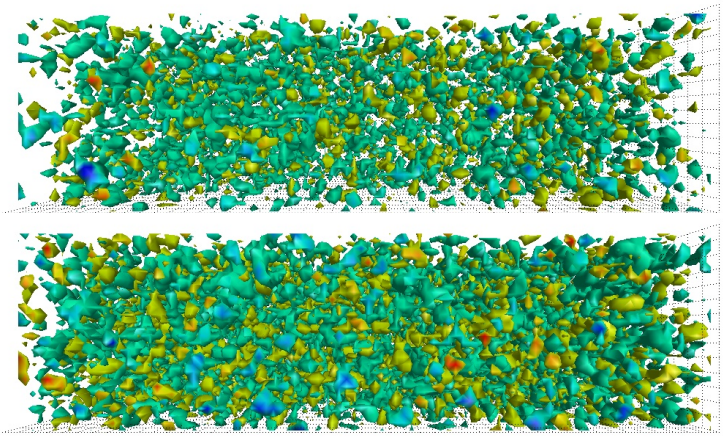






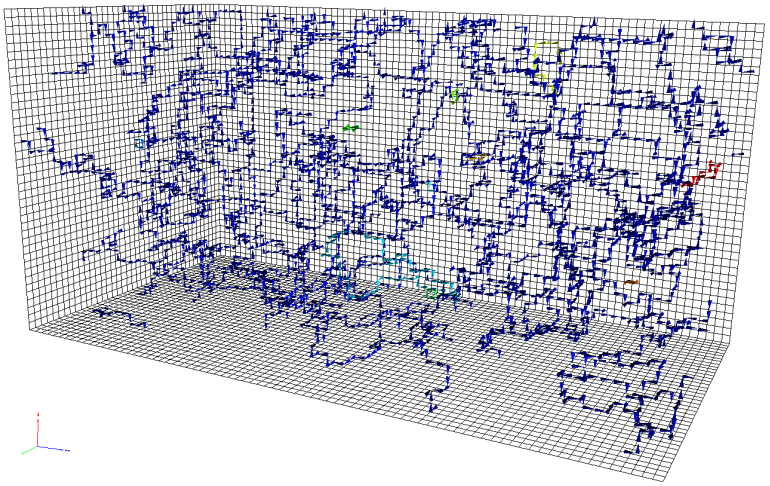
- See "Buried treasure in the sand of the QCD vacuum," P. J. Moran and DBL, [arXiv:0805.4246 [hep-lat]].

Pure Gauge versus MILC $2+1$-Flavour QCD: $m_{u,d} = 27.1$ MeV

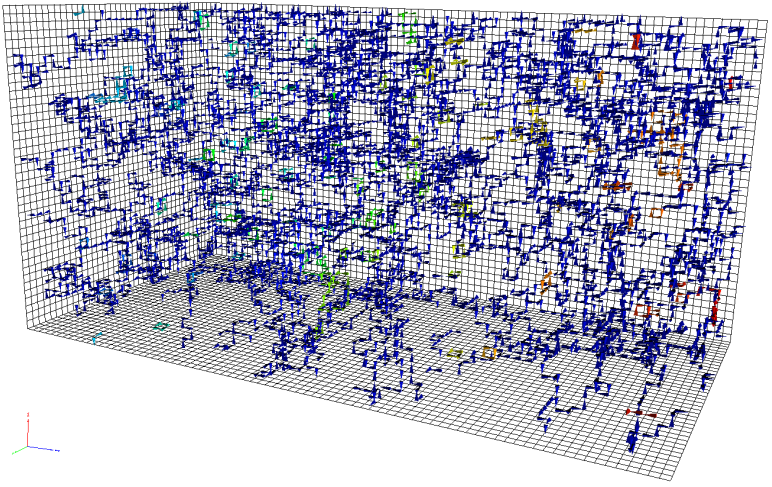


- "Impact of Dynamical Fermions on QCD Vacuum Structure," P. J. Moran and DBL, Phys. Rev. D **78** (2008) 054506 [arXiv:0801.2016 [hep-lat]].

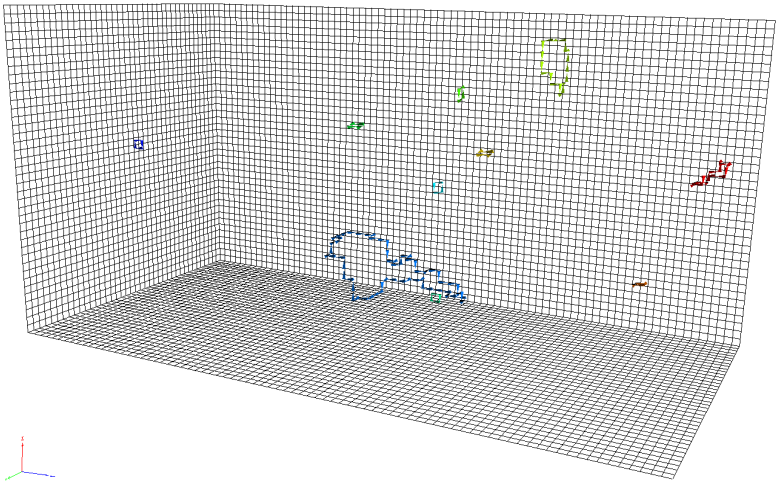
Vortices on a Pure-Gauge $32^3 \times 64$ Lattice



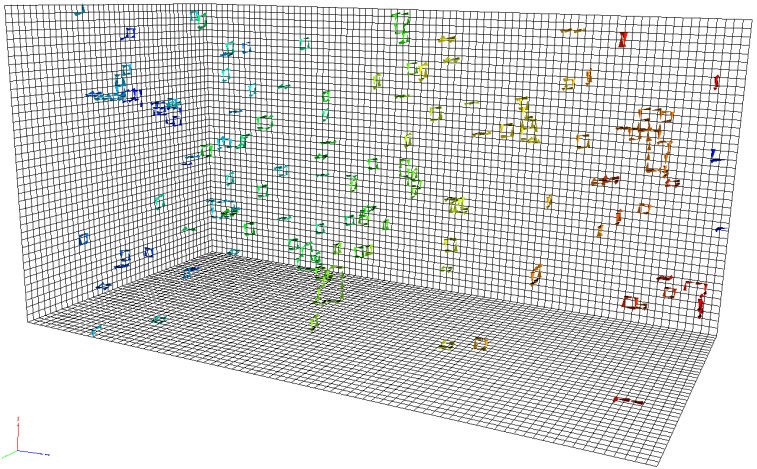
$2+1$ Flavour $32^3 \times 64$ Dynamical-Fermion Lattice $m_\pi = 156$ MeV



Secondary Loops on a Pure-Gauge $32^3 \times 64$ Lattice



$2+1$ Flavour $32^3 \times 64$ Dynamical-Fermion Lattice $m_\pi = 156$ MeV



Impact of Dynamical Fermions on Centre Vortex Structure

- The vortex vacuum is typically dominated by a single large percolating cluster.

Impact of Dynamical Fermions on Centre Vortex Structure

- The vortex vacuum is typically dominated by a single large percolating cluster.
- Dynamical fermions significantly increase the number of vortices observed.

Impact of Dynamical Fermions on Centre Vortex Structure

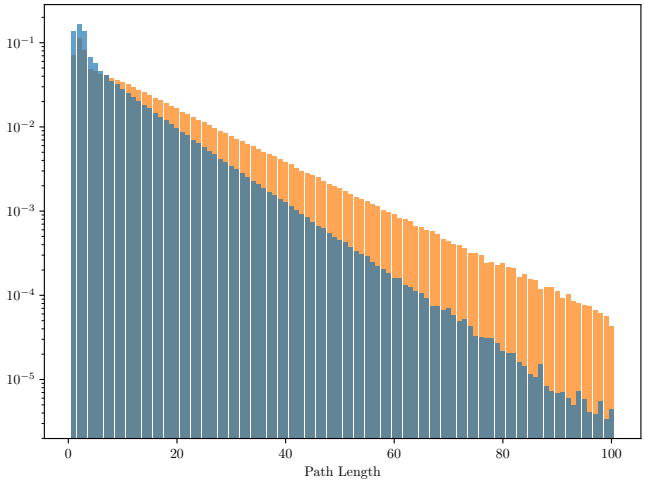
- The vortex vacuum is typically dominated by a single large percolating cluster.
- Dynamical fermions significantly increase the number of vortices observed.
- The number of vortices composing the primary cluster is
  - $3,277 \pm 156$ vortices in the Pure Gauge theory.
  - $5,924 \pm 239$ vortices in Full QCD.

Impact of Dynamical Fermions on Centre Vortex Structure

- The vortex vacuum is typically dominated by a single large percolating cluster.
- Dynamical fermions significantly increase the number of vortices observed.
- The number of vortices composing the primary cluster is
  - $3,277 \pm 156$ vortices in the Pure Gauge theory.
  - $5,924 \pm 239$ vortices in Full QCD.
- There is further enhancement of the secondary loop structure,
  - Both in number and in complexity via monopoles.

Impact of Dynamical Fermions: Vortex Path Lengths

- Histogram of vortex path lengths in the percolating cluster.
- Pure Gauge and Dynamical Fermion ensembles are illustrated.
- Path length is the number of jets from one branching point to the next.
- Distributions are normalised.
- Moderate size loops are exponentially distributed.
  - Fixed probability of branching .
  - Branching is independent of length.



Impact of Dynamical Fermions on the Centre-Vortex Structure of the Gluon Propagator

Centre Vortices and the Landau-Gauge Gluon Propagator

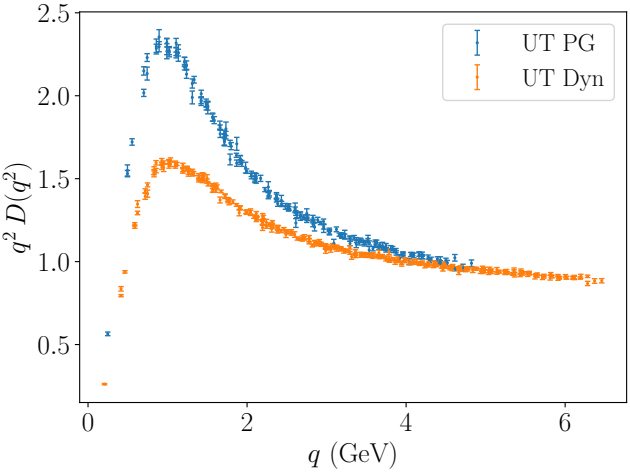
- The nonperturbative scalar gluon propagator in momentum space is

$$D(q^2) \equiv \frac{Z(q^2)}{q^2} \to \frac{1}{q^2} \text{ at tree level.}$$

- Consider the renormalisation function

$$Z(q^2) = q^2\, D(q^2)\,.$$

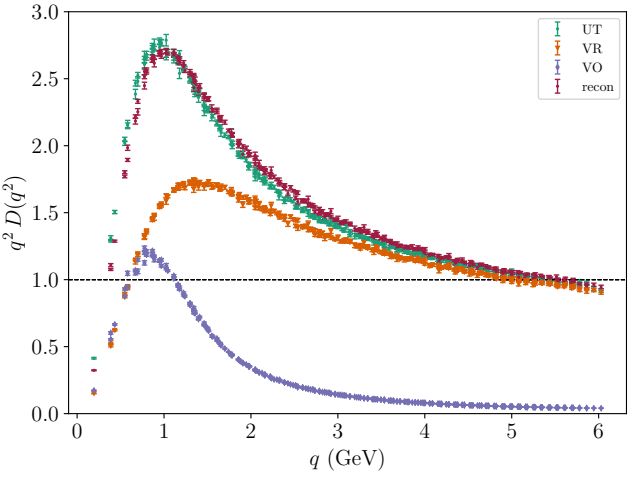
- Renormalise by setting $Z(q^2) = 1$ at $q = 5.5$ GeV.
- $32^3 \times 64$ lattices. $m_\pi = 156$ MeV.



J. C. Biddle, W. Kamleh and DBL, in preparation.

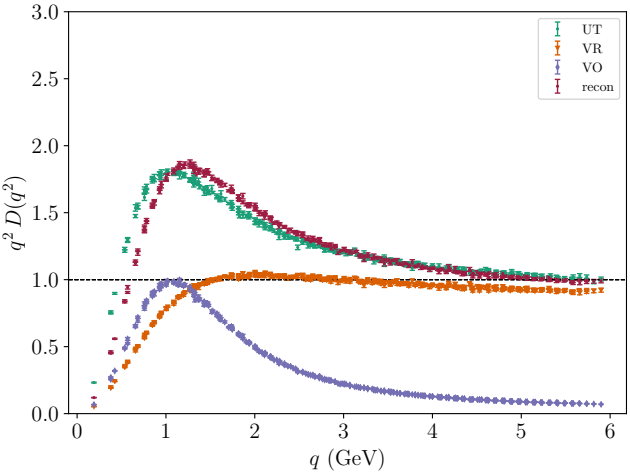
Gluon Propagator – Pure Gauge Sector

- Vortex Removal (VR) suppresses infrared enhancement whilst preserving UV perturbative behaviour.
- Vortex-Only (VO) configurations capture the long-distance physics.
- Reconstruction of the propagator as a linear combination of the vortex-modified parts recovers full propagator.
- Residual infrared enhancement in the vortex-removed result is undesirable.



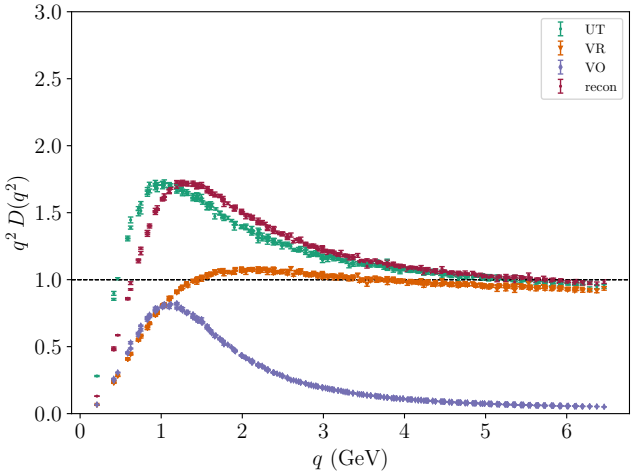
Gluon Propagator – Dynamical Fermions $m_\pi = 701$ MeV

- Dynamical fermions (UT) suppress the overall infrared strength.
- Vortex Removal (VR) almost eliminates infrared enhancement.
- Vortex-Only (VO) configurations capture the long-distance physics.
- Reconstruction is less perfect.

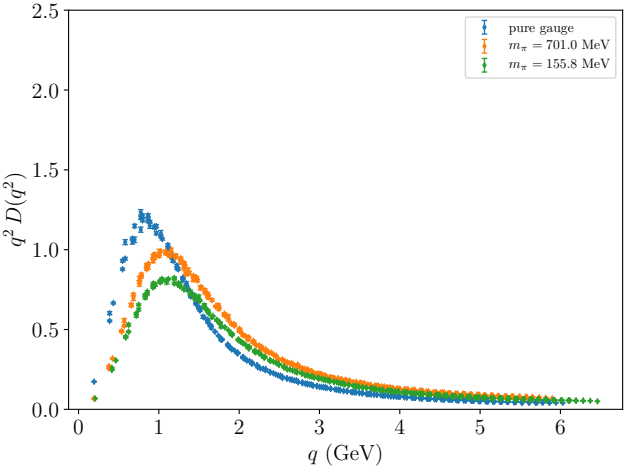


Gluon Propagator – Dynamical Fermions $m_\pi = 156$ MeV

- Lighter dynamical u and d quarks further suppress the infrared enhancement.
- Centre Vortex degrees of freedom are able to capture the screening effects of dynamical fermions in QCD.



Dynamical-Fermion Screening Effects in Vortex-Only Configurations



The Gluon Propagator and Confinement

- The 1-dimensional Fourier transform of the gluon propagator at zero spatial momentum defines the wall-to-wall correlator

$$C(t) = \int_0^\infty dm\, \rho(m^2)\, e^{-mt}\,.$$

  - C(t) is negative in QCD.

The Gluon Propagator and Confinement

- The 1-dimensional Fourier transform of the gluon propagator at zero spatial momentum defines the wall-to-wall correlator

$$C(t) = \int_0^\infty dm\, \rho(m^2)\, e^{-mt}\,.$$

  - C(t) is negative in QCD.
- The spectral density, $\rho(m^2)$, cannot be a positive spectral function.
  - A physical state does not have negative norm contributions in its propagator.
  - There is no Källen-Lehmann representation.
  - The corresponding states cannot appear in the physical particle spectrum.

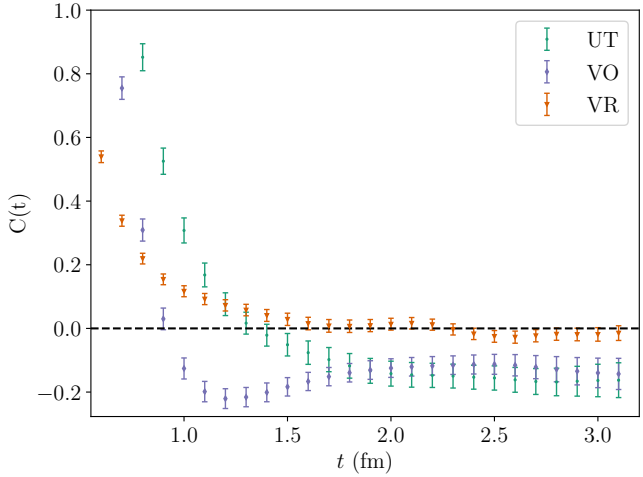
The Gluon Propagator and Confinement

- The 1-dimensional Fourier transform of the gluon propagator at zero spatial momentum defines the wall-to-wall correlator

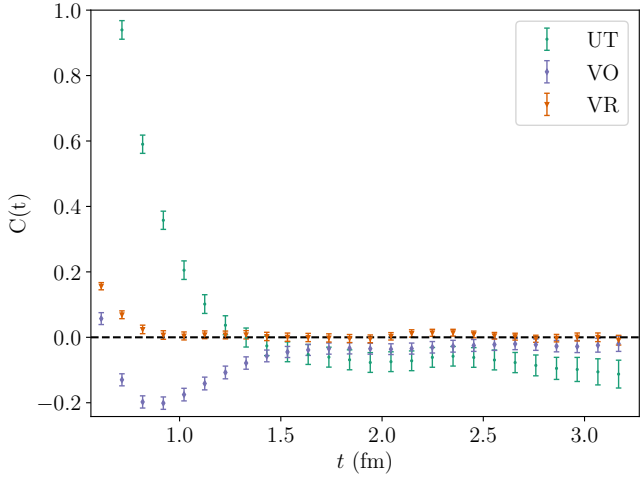
$$C(t) = \int_0^\infty dm\, \rho(m^2)\, e^{-mt}\,.$$

  - C(t) is negative in QCD.
- The spectral density, $\rho(m^2)$, cannot be a positive spectral function.
  - A physical state does not have negative norm contributions in its propagator.
  - There is no Källen-Lehmann representation.
  - The corresponding states cannot appear in the physical particle spectrum.
- The states are confined from the physical world.
  - J. E. Mandula and M. Ogilvie, Phys. Lett. **B185**, 127 (1987).
  - C. A. Aubin and M. C. Ogilvie, Phys. Lett. **B570**, 59 (2003), hep-lat/0306012.
  - P. O. Bowman, *et al.* Phys. Rev. D **76**, 094505 (2007) [arXiv:hep-lat/0703022 [hep-lat]].

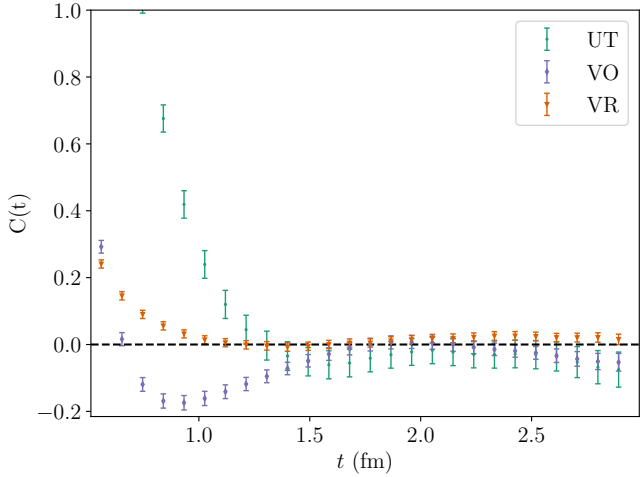
Positivity Violation in the Pure-Gauge Sector



Positivity Violation in QCD: $m_\pi = 701$ MeV



Positivity Violation in QCD: $m_\pi = 156$ MeV



Impact of Dynamical Fermions on the Centre-Vortex Structure of the Quark Propagator

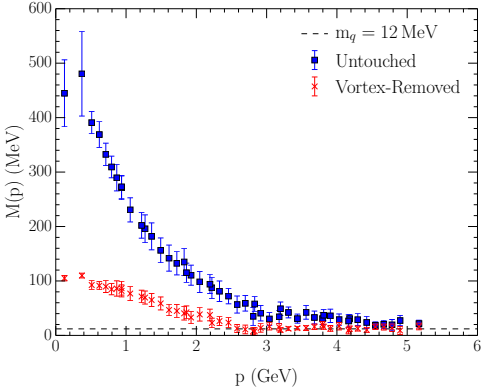
Centre Vortices and the Landau-Gauge Quark Propagator

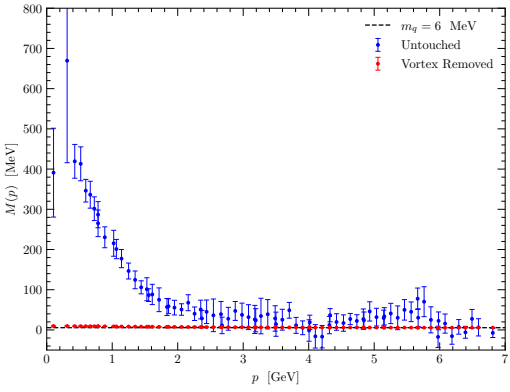
- Probe dynamical mass generation using the quark propagator

$$S(p) = \frac{Z(p)}{i\not{p} + M(p)},$$

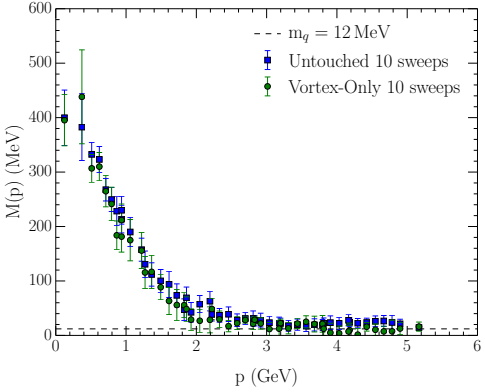
- Enhancement of the mass function, $M(p)$, at low momenta indicates dynamical mass generation.
- Renormalisation function, $Z(p)$, is typically infrared suppressed.
- Consider the Overlap-Dirac fermion action
  - Provides a lattice implementation of chiral symmetry,
  - No additive mass renormalisation,
  - Sensitive to the topological structure of the gauge fields.

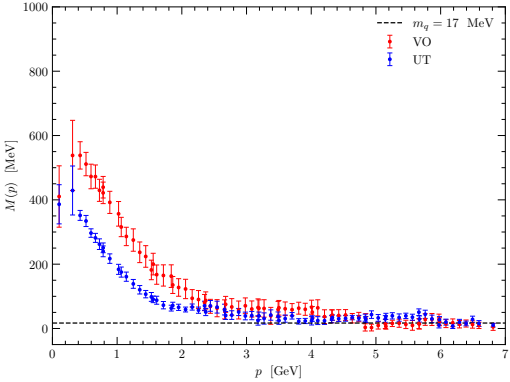
Pure Gauge vs Dynamical: Vortex-Removed Quark Mass Function





Pure Gauge vs Dynamical: Vortex-Only Mass Function

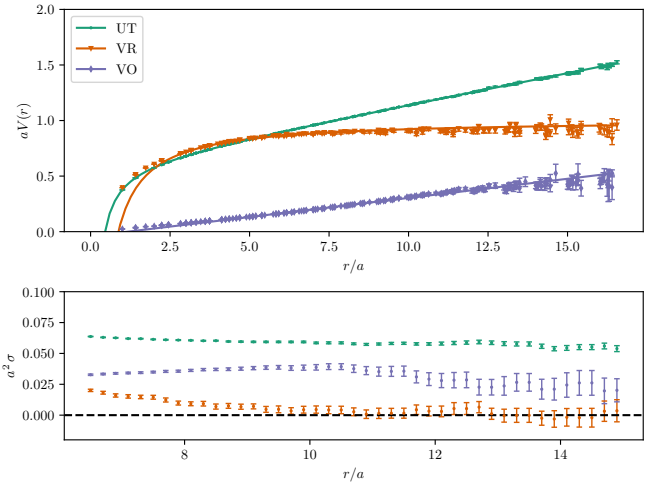




Impact of Dynamical Fermions on the Centre-Vortex Structure of the Static Quark Potential

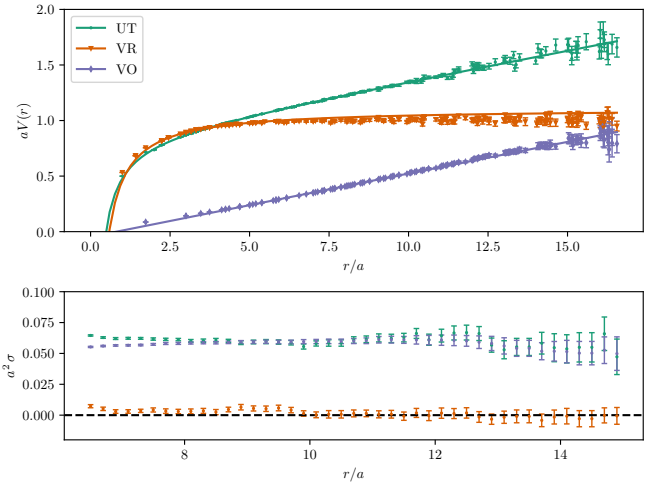
Static Quark Potential – Pure Gauge Sector

- Lower plot reports the local slope from fits to $V(r)$ over a window of $r \pm \frac{3}{2}\, a$.
- Vortex removal (VR) leaves no residual confining potential.
- Vortex-only (VO) reproduces only 62% of the original (UT) static quark potential.



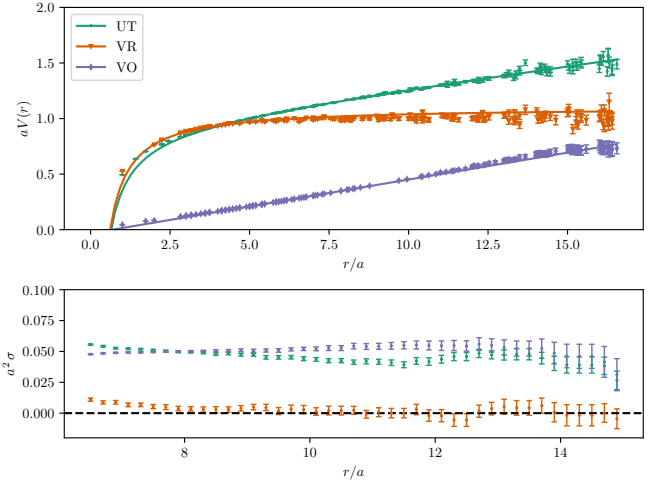
Introducing Dynamical Fermions ($m_\pi = 701$MeV)

- In the presence of dynamical fermions, vortices capture the full string tension.
- Vortex removal leaves no residual confining potential.
- Centre vortices are the origin of confinement in QCD.



Lighter dynamical fermions ($m_\pi = 156$MeV)

- Lighter quark masses screen the confining potential.
- Vortices continue to capture the full string tension.
- Vortex removal leaves no residual confining potential.
- Centre vortices are the origin of confinement in QCD.



Visualisation Conclusions

- Centre-vortex structure is complex.

Visualisation Conclusions

- Centre-vortex structure is complex.
- Observe a proliferation of monopoles in $SU(3)$ with further enhancement in QCD.

Visualisation Conclusions

- Centre-vortex structure is complex.
- Observe a proliferation of monopoles in $SU(3)$ with further enhancement in QCD.
- Each configuration is dominated by a long-distance percolating structure.

Visualisation Conclusions

- Centre-vortex structure is complex.
- Observe a proliferation of monopoles in $SU(3)$ with further enhancement in QCD.
- Each configuration is dominated by a long-distance percolating structure.
- Observe a doubling in the size of the percolating vortex structure in full QCD.
  - From $\sim 3,000 \rightarrow 6,000$ vortex links.

Visualisation Conclusions

- Centre-vortex structure is complex.
- Observe a proliferation of monopoles in $SU(3)$ with further enhancement in QCD.
- Each configuration is dominated by a long-distance percolating structure.
- Observe a doubling in the size of the percolating vortex structure in full QCD.
  - From $\sim 3,000 \rightarrow 6,000$ vortex links.
- Enhancement of small vortex paths upon introducing dynamical fermions.

Visualisation Conclusions

- Centre-vortex structure is complex.
- Observe a proliferation of monopoles in $SU(3)$ with further enhancement in QCD.
- Each configuration is dominated by a long-distance percolating structure.
- Observe a doubling in the size of the percolating vortex structure in full QCD.
  - From $\sim 3,000 \rightarrow 6,000$ vortex links.
- Enhancement of small vortex paths upon introducing dynamical fermions.
- Increased complexity in the vortex paths via monopole-antimonopole pairs.

Visualisation Conclusions

- Centre-vortex structure is complex.
- Observe a proliferation of monopoles in $SU(3)$ with further enhancement in QCD.
- Each configuration is dominated by a long-distance percolating structure.
- Observe a doubling in the size of the percolating vortex structure in full QCD.
  - From $\sim 3,000 \rightarrow 6,000$ vortex links.
- Enhancement of small vortex paths upon introducing dynamical fermions.
- Increased complexity in the vortex paths via monopole-antimonopole pairs.

- Dynamical fermions radically alter the centre-vortex structure of the vacuum fields.

Conclusions

- In QCD, vortex removal:
  - Suppresses the infrared enhancement of the gluon propagator.
  - Eliminates dynamical mass generation in the mass function of the quark propagator.
  - Eliminates the confinement potential of the static quark potential.

Conclusions

- In QCD, vortex removal:
  - Suppresses the infrared enhancement of the gluon propagator.
  - Eliminates dynamical mass generation in the mass function of the quark propagator.
  - Eliminates the confinement potential of the static quark potential.
- In QCD, the consideration of vortices alone:
  - Captures the infrared enhancement of the gluon propagator and positivity violation.
  - Demonstrates dynamical mass generation in the mass function of the quark propagator.
  - Fully reproduces the confining potential of the static quark potential.

Conclusions

- In QCD, vortex removal:
  - Suppresses the infrared enhancement of the gluon propagator.
  - Eliminates dynamical mass generation in the mass function of the quark propagator.
  - Eliminates the confinement potential of the static quark potential.
- In QCD, the consideration of vortices alone:
  - Captures the infrared enhancement of the gluon propagator and positivity violation.
  - Demonstrates dynamical mass generation in the mass function of the quark propagator.
  - Fully reproduces the confining potential of the static quark potential.
- Conclude that centre vortices provide a common origin for
  - Confinement, and the
  - Dynamical generation of mass via chiral symmetry breaking.

Conclusions

- In QCD, vortex removal:
  - Suppresses the infrared enhancement of the gluon propagator.
  - Eliminates dynamical mass generation in the mass function of the quark propagator.
  - Eliminates the confinement potential of the static quark potential.
- In QCD, the consideration of vortices alone:
  - Captures the infrared enhancement of the gluon propagator and positivity violation.
  - Demonstrates dynamical mass generation in the mass function of the quark propagator.
  - Fully reproduces the confining potential of the static quark potential.
- Conclude that centre vortices provide a common origin for
  - Confinement, and the
  - Dynamical generation of mass via chiral symmetry breaking.
- Centre Vortices capture the essence of nonperturbative QCD.

Interactive 3D Visualisation Techniques

- Rendered in AVS Express Visualisation Edition.
  `http://www.avs.com/solutions/express/`
- Exported in VRML.
- Converted to U3D format via pdf3d ReportGen.
  `https://www.pdf3d.com/products/pdf3d-reportgen/`
- Imported into LaTeX via media9 package.
- Viewed in Adobe acroread (Linux, use 9.4.1 when 3D support was maintained).
  `ftp://ftp.adobe.com/pub/adobe/reader/unix/9.x/9.4.1/`

Space-Time Oriented Vortices

Rendering Space-Time Oriented Projected Vortices

- Every link in the spatial volume has a forward and backward time-oriented plaquette associated with it.

Rendering Space-Time Oriented Projected Vortices

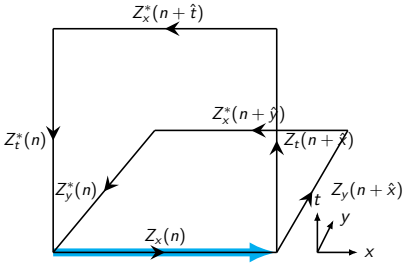
- Every link in the spatial volume has a forward and backward time-oriented plaquette associated with it.
- The three jets associated with the spatial x-y, y-z and z-x plaquettes, are complemented by
  - Jets in the three forward time x-t, y-t and z-t plaquettes, and
  - Jets in the three backward time x-t, y-t and z-t plaquettes.

Rendering Space-Time Oriented Projected Vortices

- Every link in the spatial volume has a forward and backward time-oriented plaquette associated with it.
- The three jets associated with the spatial x-y, y-z and z-x plaquettes, are complemented by
  - Jets in the three forward time x-t, y-t and z-t plaquettes, and
  - Jets in the three backward time x-t, y-t and z-t plaquettes.
- See "Visualization of center vortex structure," to link vortices to topological charge.
  J. C. Biddle, W. Kamleh and DBL, Phys. Rev. D **102** (2020) 034504 [arXiv:1912.09531 [hep-lat]].

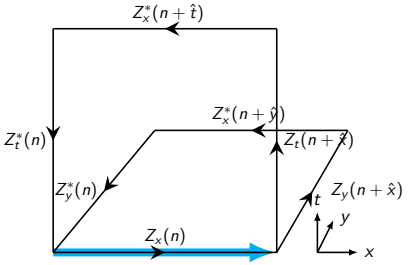
Rendering Space-Time Oriented Projected Vortices

- If a spatial link belongs to a vortex in a space-time plaquette then:
  - The link is rendered in cyan for an $m = +1$ vortex.



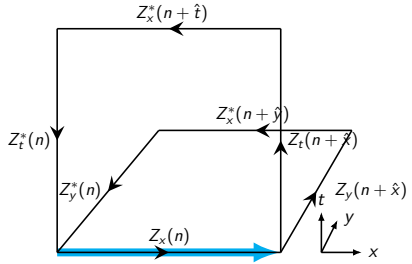
Rendering Space-Time Oriented Projected Vortices

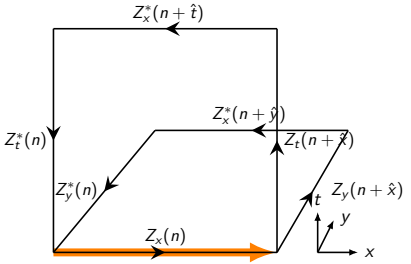
- If a spatial link belongs to a vortex in a space-time plaquette then:
  - The link is rendered in cyan for an $m = +1$ vortex.
  - The link is rendered as a positively-directed arrow for forward space-time plaquettes.



Rendering Space-Time Oriented Projected Vortices

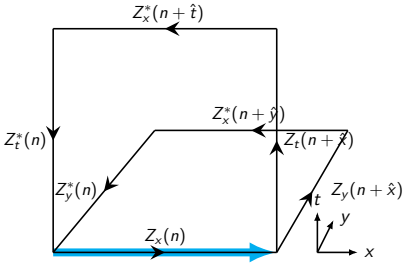
- If a spatial link belongs to a vortex in a space-time plaquette then:
  - The link is rendered in cyan for an $m = +1$ vortex, and in orange for $m = -1$.
  - The link is rendered as a positively-directed arrow for forward space-time plaquettes.

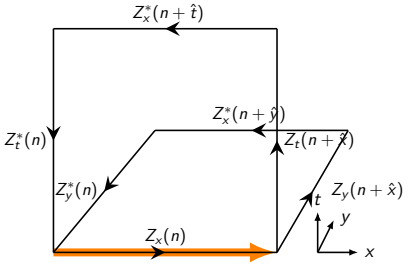




Rendering Space-Time Oriented Projected Vortices

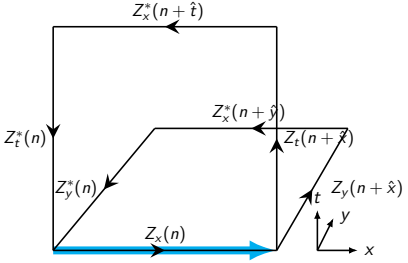
- If a spatial link belongs to a vortex in a space-time plaquette then:
  - The link is rendered in cyan for an $m = +1$ vortex, and in orange for $m = -1$.
  - The link is rendered as a positively-directed arrow for forward space-time plaquettes.
  - The link is rendered as a negatively-directed arrow for backward space-time plaquettes.

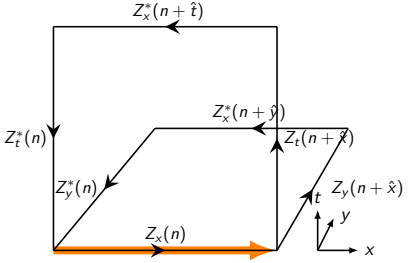




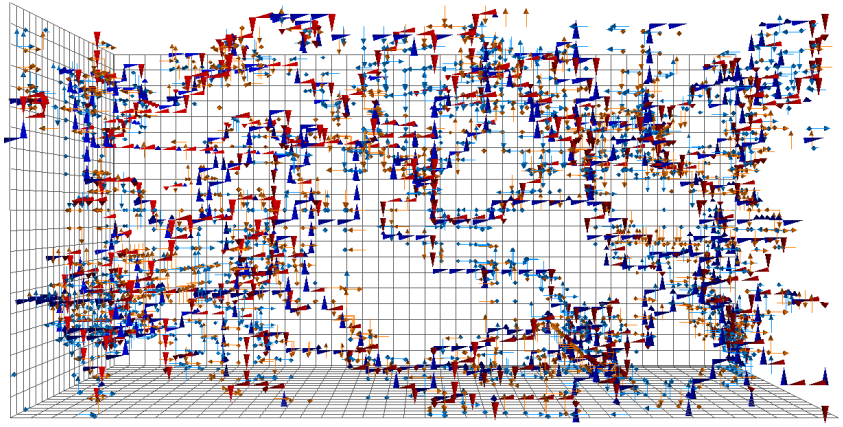
Rendering Space-Time Oriented Projected Vortices

- If a spatial link belongs to a vortex in a space-time plaquette then:
  - The link is rendered in cyan for an $m = +1$ vortex
  - The link is rendered as a positively-directed arrow for forward space-time plaquettes.
  - The link is rendered as a negatively-directed arrow for backward space-time plaquettes.
- As one steps forwards in time, positively-directed links become negatively-directed.

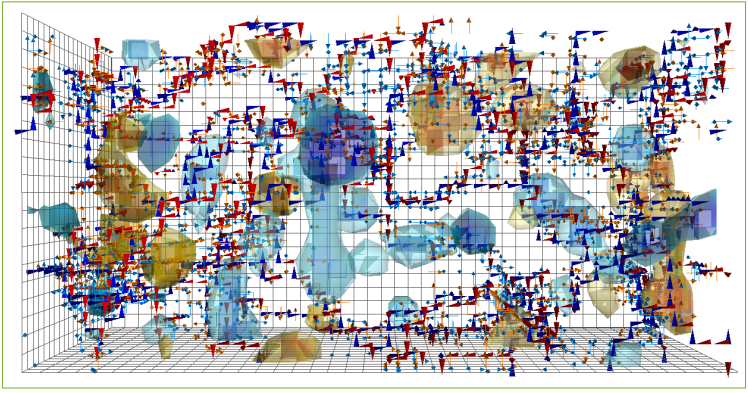




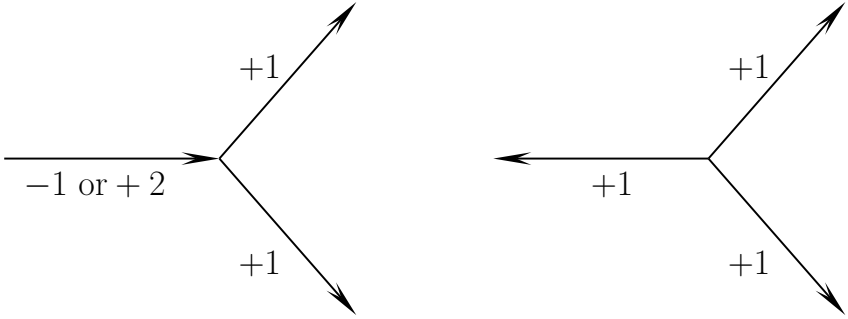
Time slice $t = 1$



Animation of Centre Vortex Structure Google: YouTube CSSM Visualisations



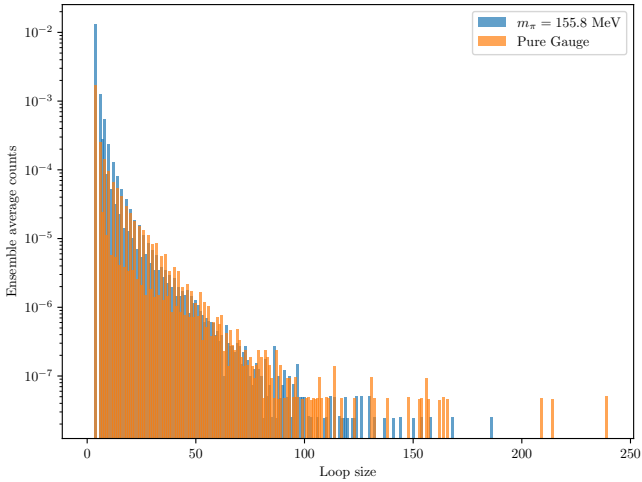
Visualising Centre Vortices



- A vortex branching point with centre charge $+2$ flowing into a vertex (left) is equivalent to a vortex monopole with charge $+1$ flowing out of the vertex (right). Arrows indicate the direction of flow for the labelled charge.
- Our convention illustrates the directed flow of charge $m = +1$.

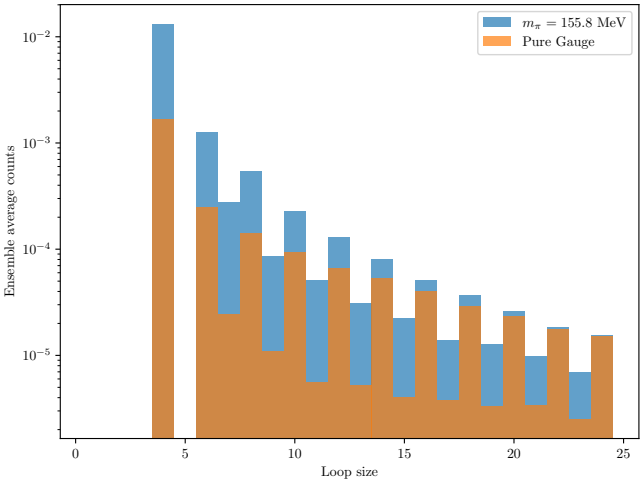
Impact of Dynamical Fermions: Secondary Loop Lengths

- Histogram of vortex path lengths for each structure within an ensemble.
- The relative proportion of each loop size is indicated.
- Moderate size loops are exponentially distributed.
- There is an order of magnitude increase in the number of small loops in QCD.
- Comb-like structure indicates lower probability of monopoles.



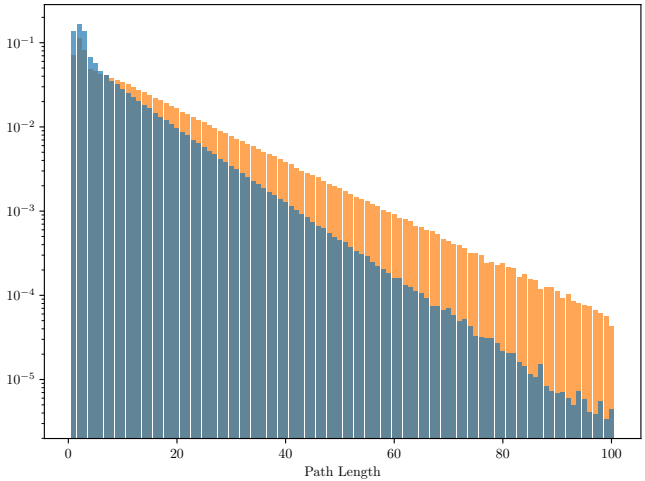
Impact of Dynamical Fermions: Secondary Loop Lengths

- Path lengths 1, 2, 3 and 5 don't close.
  - Bianchi identity forbidden.
- Odd link-path lengths require a monopole-antimonopole pair.
- Greater relative abundance of monopole-antimonopole pairs in QCD.
  - Tines of the comb are shorter in QCD.



Impact of Dynamical Fermions: Vortex Path Lengths

- Histogram of vortex path lengths in the percolating cluster.
- Pure Gauge and Dynamical Fermion ensembles are illustrated.
- Path length is the number of jets from one branching point to the next.
- Distributions are normalised.
- Moderate size loops are exponentially distributed.
  - Fixed probability of branching .
  - Branching is independent of length.



Potential Models: Lighter dynamical fermions ($m_\pi = 156$MeV)

- Lattice QCD results characterised well by simple models.
- Original (UT):

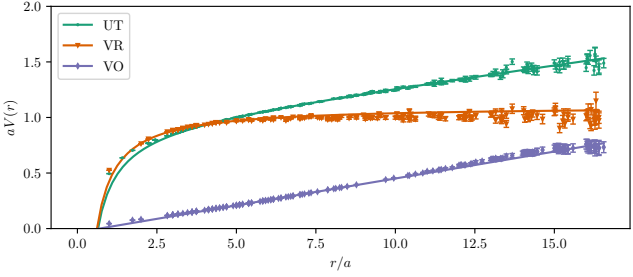
$$V(r) = V_0 - \frac{\alpha}{r} + \sigma\, r$$

- Vortex-removed (VR):

$$V(r) = V_0 - \frac{\alpha}{r}$$

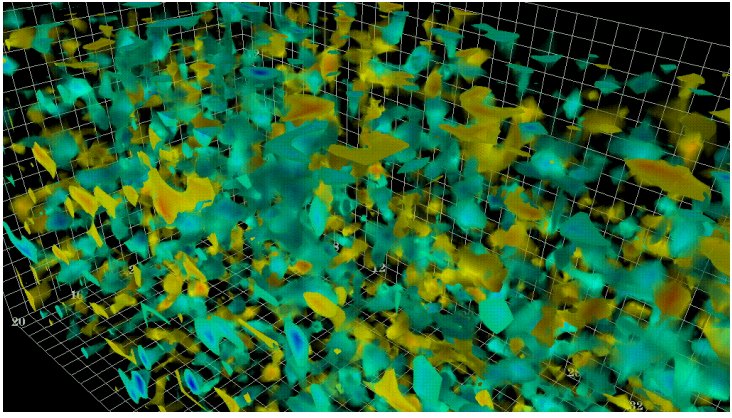
- Vortex-only (VO):

$$V(r) = V_0 + \sigma\, r$$

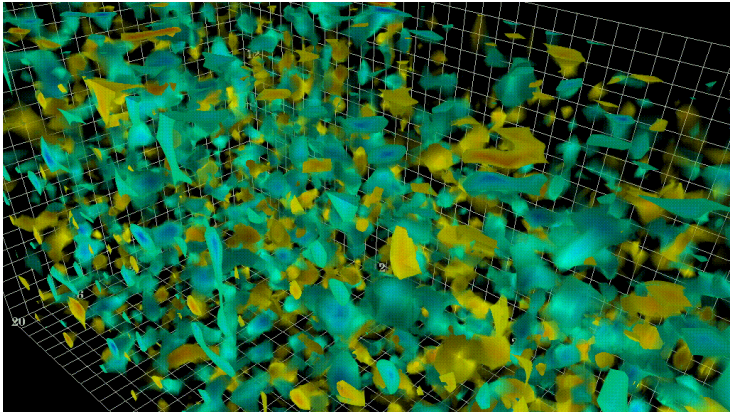


Centre Vortices Versus Instantons

Untouched Configurations with Cooling



Vortex Removed Configurations with Cooling



Smoothed Vortices vs Instantons

Quark propagator on vortex only fields

- Vortex only configurations consist only of centre elements

$\Rightarrow$ very rough

- The Overlap operator has a smoothness condition

$\Rightarrow$ 10 sweeps of cooling on vortex only configurations.

Does 10 sweeps of cooling recreate instantons?

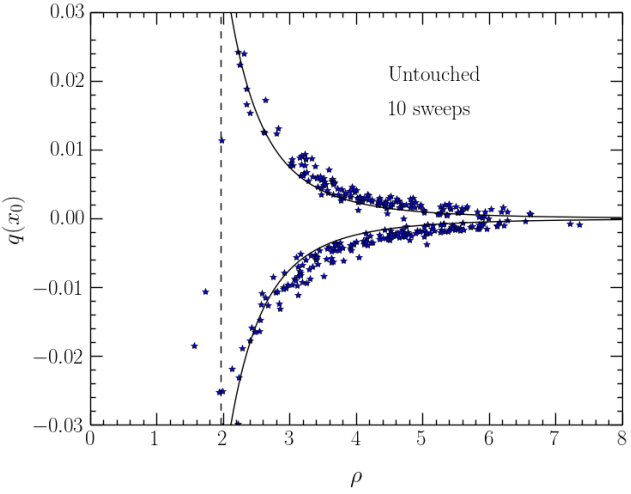
- Scan each configuration for local maxima of the action.
- Fit the instanton profile around them to learn the radius ρ

$$S_0(x) = \xi \frac{6}{\pi^2} \frac{\rho^4}{((x - x_0)^2 + \rho^2)^4} .$$

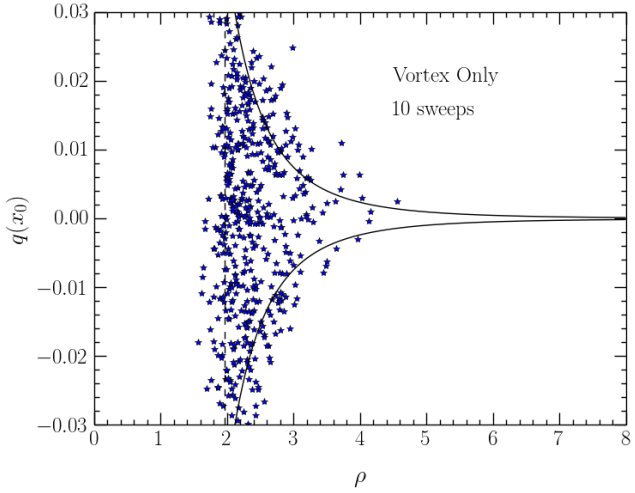
- Compare lattice value for $q(x_0)$ to the theoretical relationship

$$q(x_0) = Q \frac{6}{\pi^2 \rho^4} .$$

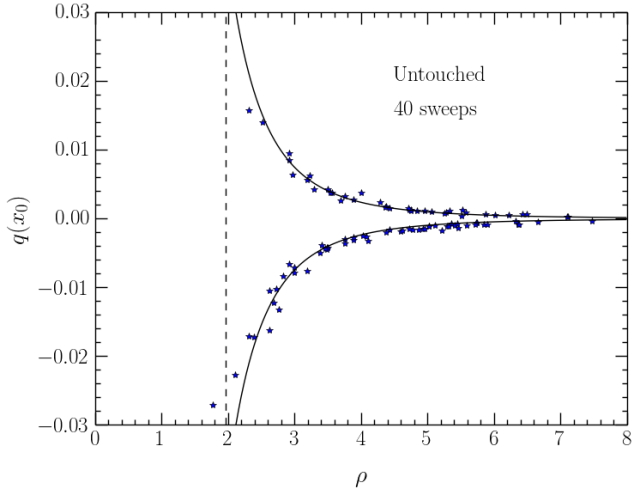
Instanton ρ vs $q(x_0)$



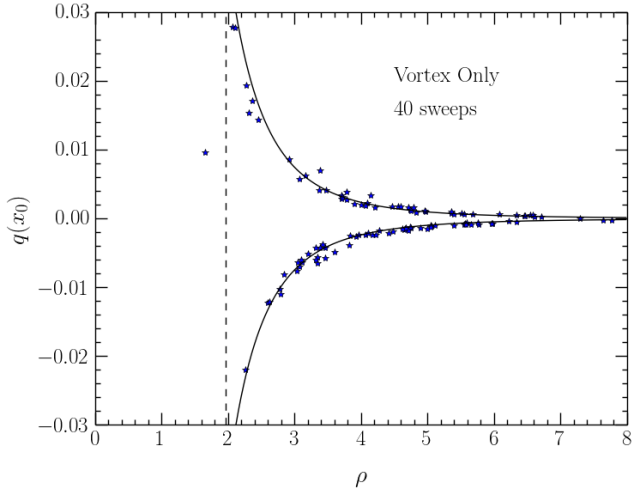
Instanton ρ vs $q(x_0)$



Instanton ρ vs $q(x_0)$



Instanton ρ vs $q(x_0)$



Untouched (left) and Vortex-Only comparison (10 sweeps)