Centre Vortices in the Presence of Dynamical Fermions

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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Introduction

- It is an open question how the QCD Standard Model gives rise to key non-perturbative features of QCD, namely:
  - Confinement
  - Chiral symmetry breaking (χ_{SB}), resulting in dynamical generation of mass.
- Is there a single, unifying property of QCD that gives rise to these features?
- Many models (Abelian monopoles, instantons, etc...).
- Most successful is the centre vortex model.

What are we aiming to explain?

- The lattice provides an excellent framework in which to test the performance of the centre vortex model.
- Confinement can be probed by studying the
  - **String tension** (P. Bowman *et. al.* Phys. Rev. D **84** (2011) 034501)
  - **Gluon propagator** (J. C. Biddle, W. Kamleh and D. B. Leinweber, Phys. Rev. D **98** (2018))
- χ_{SB} can be probed by studying the
  - Hadron mass spectrum (A. Trewartha *et. al.* J. Phys. G **44** (2017) 12, 125002)
  - Quark propagator (A. Trewartha *et. al.*, Phys. Lett. B **747** (2015) 373)

Previous centre vortex work

- Current understanding of centre vortices comes primarily from studies in pure Yang-Mills theory.
- In $SU(2)$, the centre vortex model is nearly flawless.
- In pure gauge $SU(3)$, things aren't so simple.

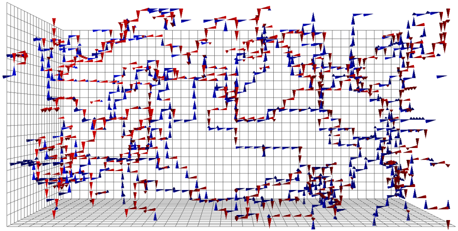

Figure: J. Biddle *et. al.* Phys. Rev. D **102**, 034504

Previous centre vortex work (cont.)

- Despite the aforementioned discrepancy, the vortex model has proved remarkably capable of reproducing the salient features of QCD.
- Naturally, one might then want to see what happens when dynamical fermions are introduced.

Configurations

- Centre vortex projection allows us to define 3 sets of configurations:
  - Untouched - U_μ
  - Vortex Only - Z_μ
  - Vortex Removed - $R_\mu = Z_\mu^\dagger \, U_\mu$

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

Static Quark Potential

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

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

Static Quark Potential on the Lattice

- On the lattice, the static quark potential is calculated by considering Wilson loops $W(r, t)$ with spatial extent r and temporal extent t.
- The static quark potential E_0 is obtained through the relationship:

$$\langle W(r,t)\rangle = \sum_i a_i e^{-E_i(r)\,t}$$

- E_0 is extracted via a variational analysis.

Static Quark Potential in pure-gauge QCD

- Original:

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

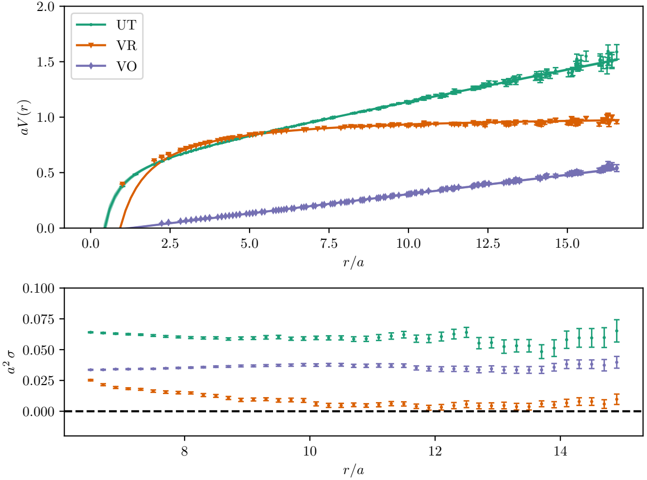
- Vortex-only:

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

- Vortex-removed:

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

- Vortex-only reproduces about 62% of the static quark potential.

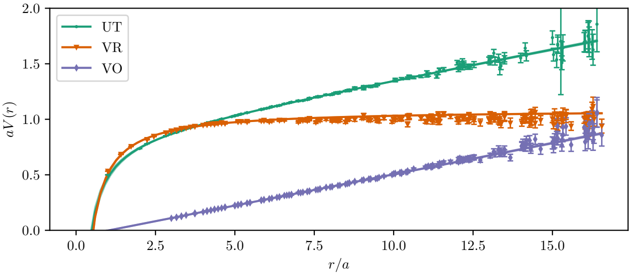


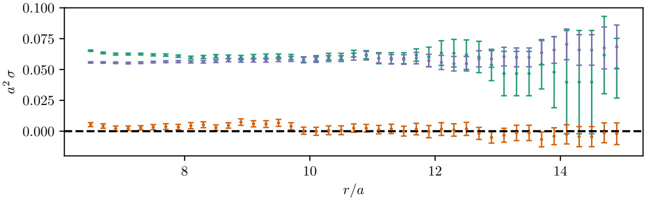
Introducing Dynamical Fermions ($m_\pi = 701$MeV)

- In the presence of dynamical fermions, this issue seems to vanish!

$$\sigma_{\mathrm{PG}} = 0.0562(9)$$
$$\sigma_{\mathrm{dynamical}} = 0.054(1)$$

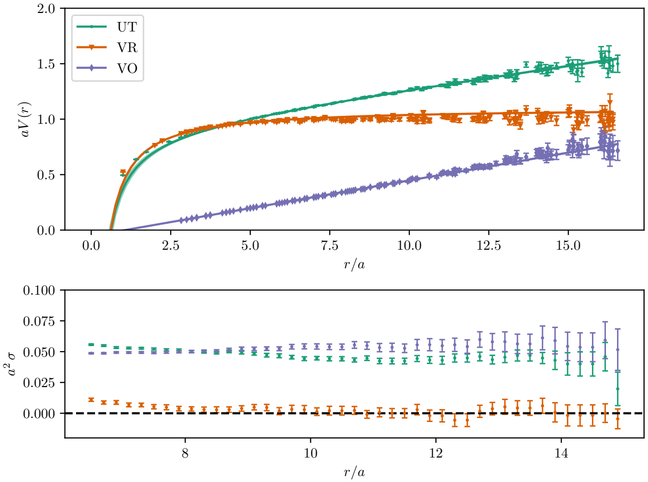
- Even at a very heavy pion mass, centre vortices now capture the full string tension.
- The vortex removed also now has no residual strength.





Lighter pion ($m_\pi = 156\text{MeV}$)

- This trend continues at lighter pion masses.
- Ligher pion masses lead to overall suppression of the potential, $\sigma = 0.040(1)$.
- The vortex-only results slightly overestimate the original.
- Could be residual excited state contamination.
- Regardless, results overlap well and are considerably closer than the pure-gauge values.



Gluon Propagator

Centre Vortices and the Landau-Gauge Gluon Propagator

- $D(q^2)$ is characterised by an infrared peak, with a UV tail
- The nonperturbative scalar gluon propagator in momentum space is

$$D(q^2) \equiv \frac{Z(q^2)}{q^2} \to \frac{1}{q^2} \,.$$

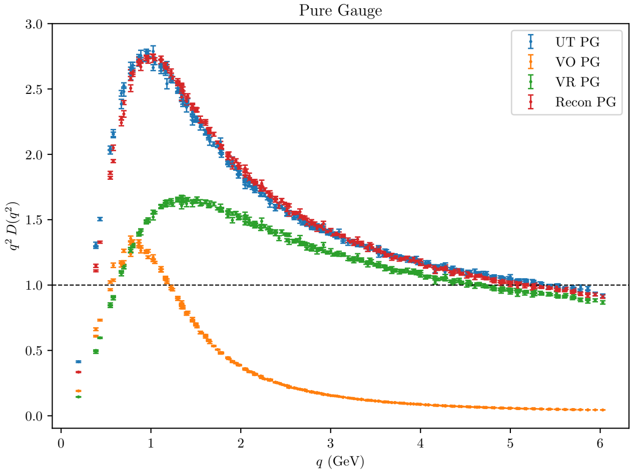
- Consider the renormalisation function

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

- Renormalise by setting $Z(q^2) = 1$ at $q = 5.5$ GeV.

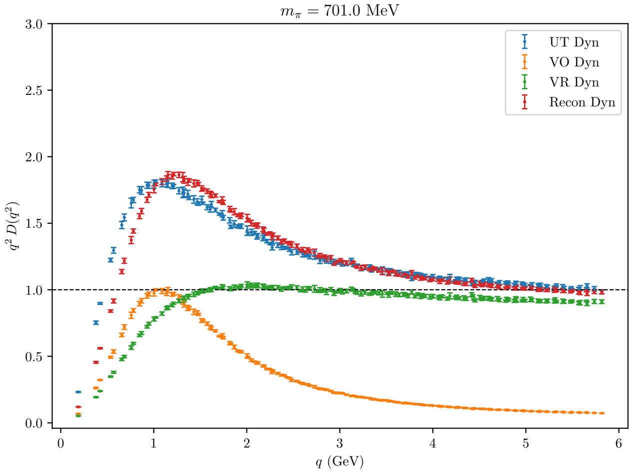
Gluon Propagator – Pure Gauge Sector

- 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.



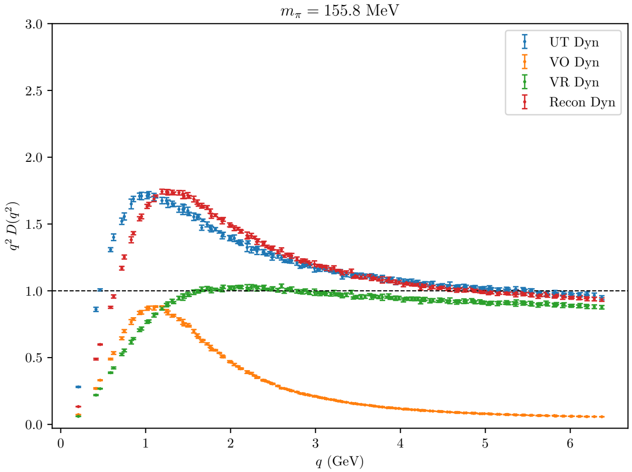
Gluon Propagator – Dynamical Fermions $m_\pi = 701$ MeV

- 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 effects of dynamical fermions in QCD.



Conclusions

- Dynamical fermions, even at heavy pion masses, radically alter the behaviour of the vortex vacuum
- Vortex removal has an amplified effect.
- The vortex-only gluon propagator captures a greater fraction of the infrared strength.
- The static quark potential is fully reproduced by vortices.

Conclusions

- Dynamical fermions, even at heavy pion masses, radically alter the behaviour of the vortex vacuum
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- Further exploration is needed to fully explore how other quantities are impacted.
- Searching for signs of string-breaking with other operators would also be of interest.

Supplementary Slide

Table: The static quark potential as extracted from the original and vortex-only ensembles.

m_π (MeV)	σ_{UT}	σ_{VO}	$\sigma_{\mathrm{VO}}/\sigma_{\mathrm{UT}}$
Pure gauge	0.0562(9)	0.0349(4)	0.62(1)
701	0.054(1)	0.0563(7)	1.04(3)
155.8	0.040(1)	0.0499(7)	1.24(4)