A new method for measuring high-spin glueball states on the lattice

Kieran Twaites Mike Teper

Rudolf Peierls Centre for Theoretical Physics
University of Oxford

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Outline

Regge trajectories

For $2 \to 2$ scattering, $\mathcal{A}(s,t) \sim s^{\alpha(t)}$ $(s \gg |t|)$ has poles where $\alpha(t) \in \mathbb{N}$

Bound states at these points with $\alpha(m_i^2) = J_i$

Experimentally, $\alpha(t) = \alpha(0) + \alpha' t$

For ρ meson,

- $\alpha_\rho(0) \approx 0.5$
- $\alpha'_\rho \approx 1\ \text{GeV}^{-2}$

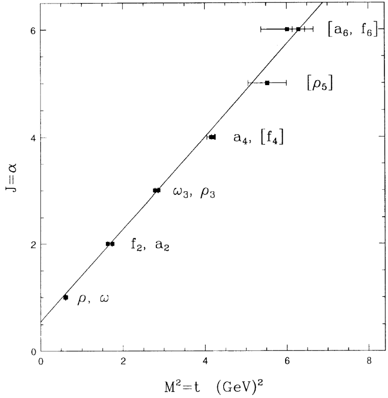

Figure: Chew & Frautschi (1961, 1962)

The Pomeron (in 3+1D)

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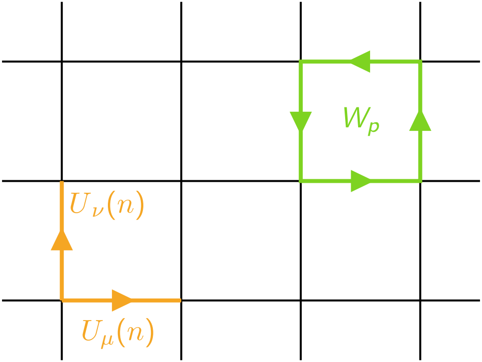
$\alpha_P(0) > 1 \quad \Leftrightarrow \quad$ exchange of vacuum quantum numbers
(Pomeranchuk, 1956)
Glueballs are only candidates in QCD that could lie on the Pomeron trajectory

This project:

Aims to find accurate masses for high-J glueballs and see if they lie on the Pomeron trajectory

Lattice field theory - a brief reminder



$$W_p = \prod_{l \in p} U_l$$

$$S = \beta \sum_p \mathrm{Re}\,\mathrm{Tr}\,(W_p)$$

$$\mathcal{Z} = \int \prod_l dU_l \; e^{-S[U]}$$

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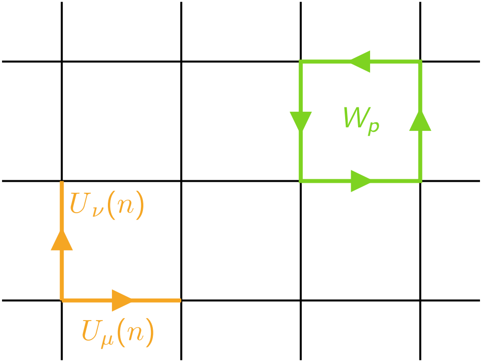

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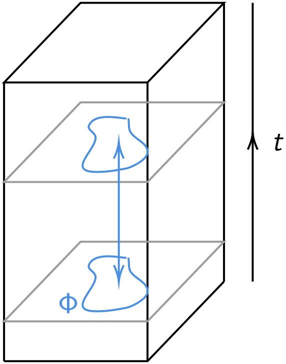
We work in 2+1D, although we hope to generalise to 3+1D in the future

Measuring glueball states



Use Cabbibo-Marinari heatbath to generate field configurations

Measure 2-point functions of closed-loop operators $\Phi(t)$

$$\langle \Phi(t)\Phi(0)\rangle = \sum_{\text{states } \alpha} |c_\alpha|^2 \, e^{-m_\alpha t}$$

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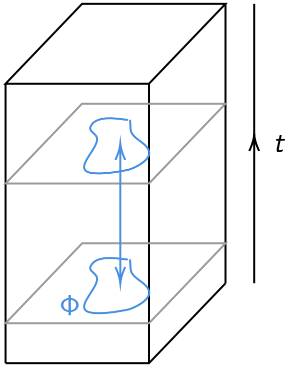

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Choose Φ to maximise $|c_\alpha|^2$
Extract m_α by looking for plateus in effective mass:

$$m_{\text{eff}} = -\log\left(\frac{\langle \Phi(t)\Phi(0)\rangle}{\langle \Phi(t-1)\Phi(0)\rangle}\right)$$

To extract excited states, first do a variational calculation over basis of operators

Conventional glueball operators

Multiply link variables is a closed loop:

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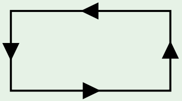
$\mathcal{O} =$ 

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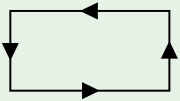
$\mathcal{O} =$ 

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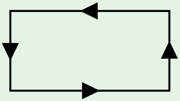
$\mathcal{O} =$ 

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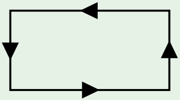
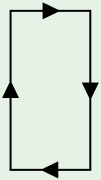
$\Phi_{\pm} = \mathrm{Re}\Big\{$  $\pm$  $\Big\}$

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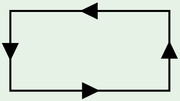
$\mathcal{O} =$ 

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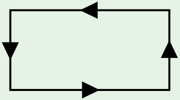
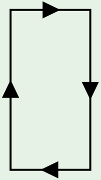
$\Phi_{\pm} = \mathrm{Re}\Big\{$  $\pm$  $\Big\}$

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Need loops which can be rotated by $\theta < \pi/2$

Method I - the path finder method

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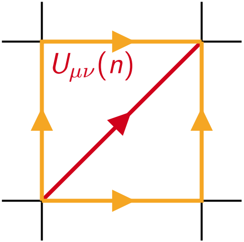

Construct diagonal links:

$$U_{\mu\nu}(n) = \mathcal{U}(U_\mu(n)U_\nu(n+\mu) + U_\nu(n)U_\mu(n+\nu))$$

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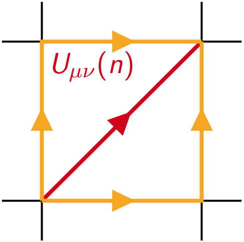

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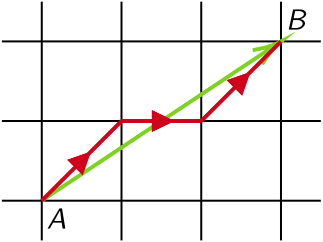

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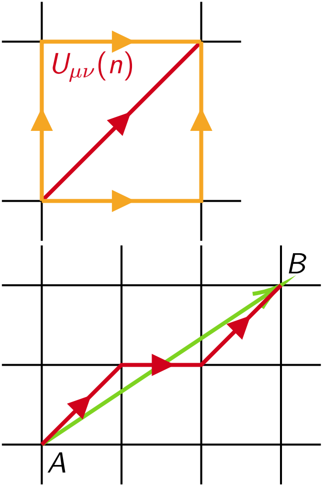

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- Fairly cheap
- Quickly becomes cumbersome for high spins

Method II - the matrix method

Add non-dynamical scalar field to $S[U]$ (later we will need to use staggered fermions instead):

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M_{ij}^{-1} gives lattice scalar propagator from site $i \to j$

We can also view M^{-1}_{ij} as a sum over paths:

$$\begin{aligned} M^{-1} &= (M_0 - \alpha)^{-1} \\ &= -\frac{1}{\alpha}\sum_{n=0}^{\infty}\frac{M_0^n}{\alpha^n} \end{aligned}$$

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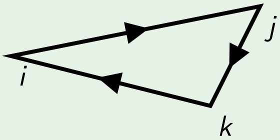
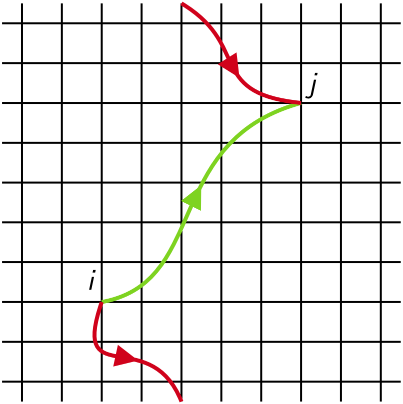
Construct operators as closed loops of propagators

Example

$$\mathcal{O} = \mathrm{Tr}\left(M_{ij}^{-1} M_{jk}^{-1} M_{ki}^{-1}\right) \quad =$$



Flux tube contributions



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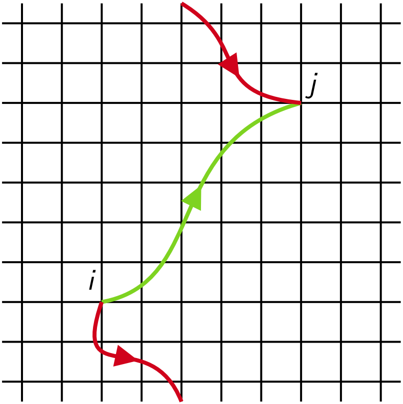

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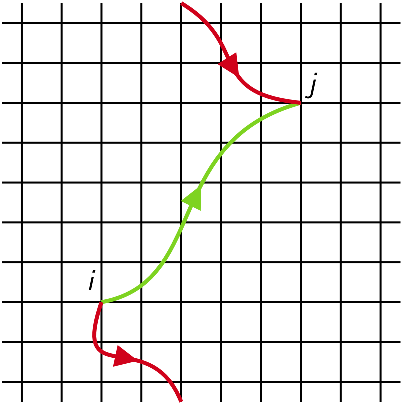

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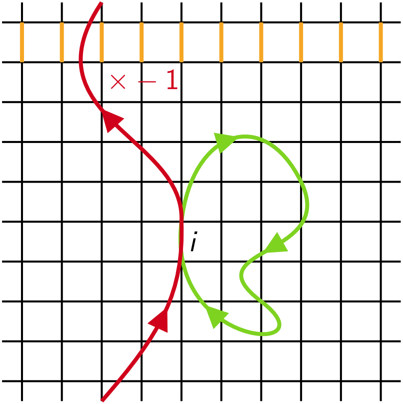
$$\mathcal{O} = \mathrm{Tr}\left(M_{ij}^{-1} M_{ji}^{-1}\right)$$

Therefore closed loops will project onto flux tube states

Flux tubes lighter than glueball states (on the volumes we are interested in), so will contaminate the spectrum

Removing flux tube contributions



For simplicity, consider an $SU(2)$ theory and $\mathcal{O} = \mathrm{Tr}\left(M_{ii}^{-1}\right)$
Winding paths charged under $\mathbb{Z}_2$ 1-form symmetry

Apply $\mathbb{Z}_2$ transformation:

$$U_y(x, y = L) \mapsto -U_y(x, y = L)$$

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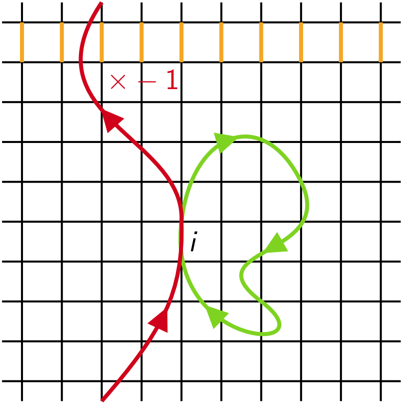

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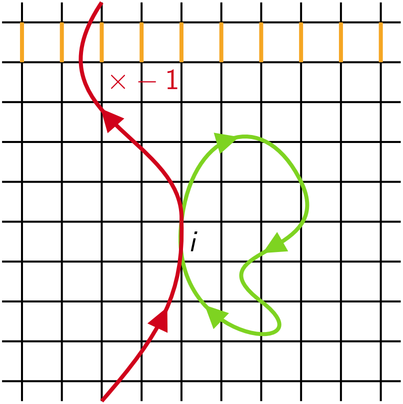

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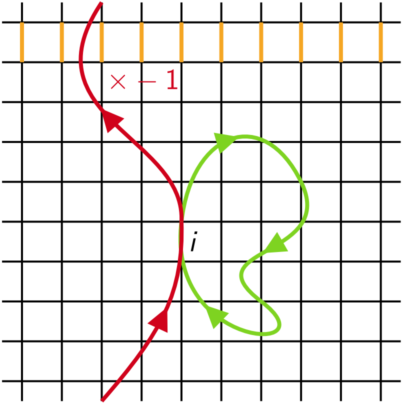

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In $SU(N)$, take the combination $\mathcal{O} = \mathrm{Tr}\left(\sum_{k_x,k_y=0}^{N-1} M(k_x,k_y)_{ii}^{-1}\right)$
This is in principle generalisable to multi-site operators

Matrix inversion performance

We use a standard version of the well-studied conjugate gradient algorithm
Efficiency determined by κ

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If any $\lambda_i \approx \alpha$, CG fails!

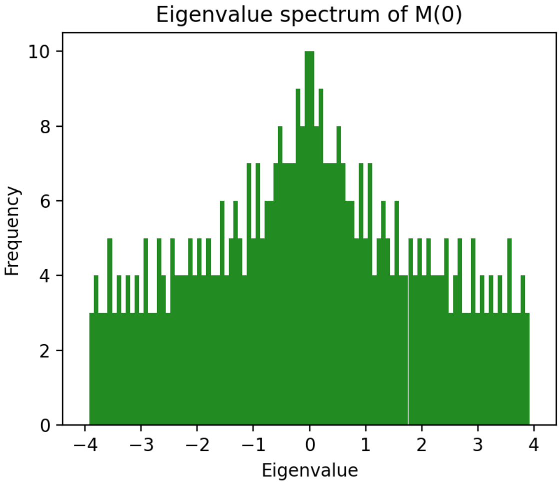

Figure: Eigenvalue spectrum of M_0

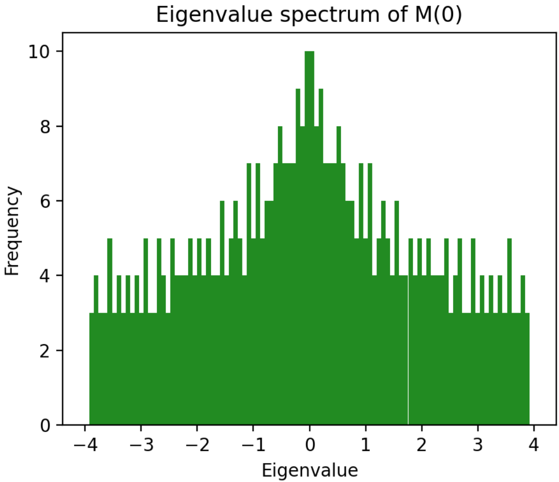

Figure: Eigenvalue spectrum of M_0

CG fails for $\alpha < 4$

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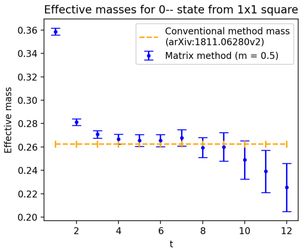
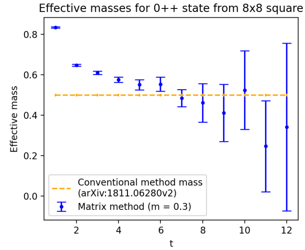
However, some paths subtracted in M_{ij}^{-1}

$U(1)$ results

$\beta = 2.2,\ 22^2 36$





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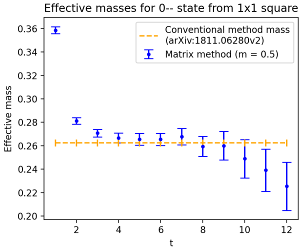
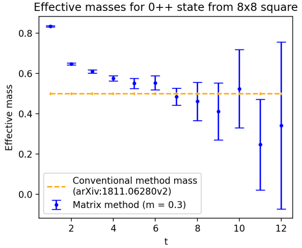
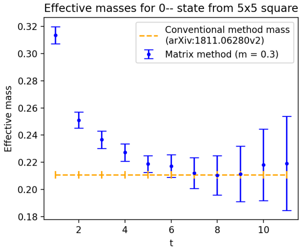
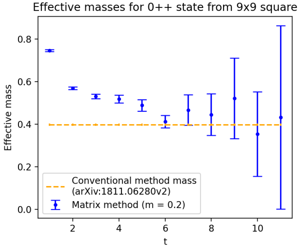




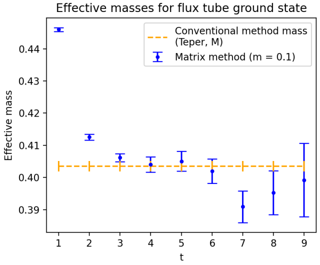
$\beta = 2.3,\ 30^2 36$

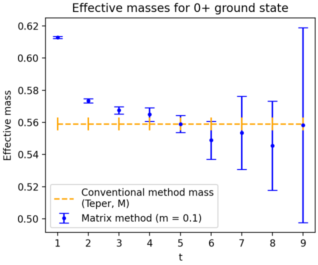


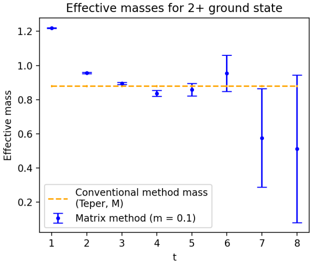


$SU(2)$ results

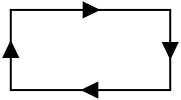
$$\beta = 12.0,\ 30^2 36$$



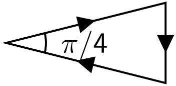




Higher spin states on the lattice

 $\rightarrow$ irreps of $D4 \subset O(2)$ $\rightarrow$ $J = 0, \cdots, 2$

Irrep	Dimension	Continuum glueball content (J^P)
A_1	1	$0^+, 4^+, \cdots$
A_2	1	$0^-, 4^-, \cdots$
B_1	1	$2^+, 6^+, \cdots$
B_2	1	$2^-, 6^-, \cdots$
E	2	$1^\pm, 3^\pm, \cdots$



$\rightarrow$ irreps of $D8 \subset O(2)$ $\rightarrow$ $J = 0, \cdots, 4$

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A_1	1	$0^+,\ 8^+, \cdots$
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E_1	2	$1^\pm,\ 7^\pm, \cdots$
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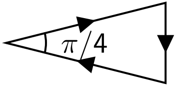
E_3	2	$3^\pm,\ 5^\pm, \cdots$



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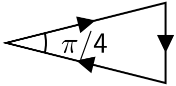
0^+ states: add all rotations

$$\Phi = \sum_{n=1}^{8} \mathcal{O}\left(\theta = \frac{n\pi}{4}\right)$$

4^+ states: alternating sum

$$\Phi = \sum_{n=1}^{8} (-1)^n \, \mathcal{O}\left(\theta = \frac{n\pi}{4}\right)$$



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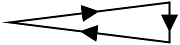

$\rightarrow$ irreps of $DN \subset O(2)$ $\rightarrow$ $J = 0, \cdots, N/2$

Symmetry breaking

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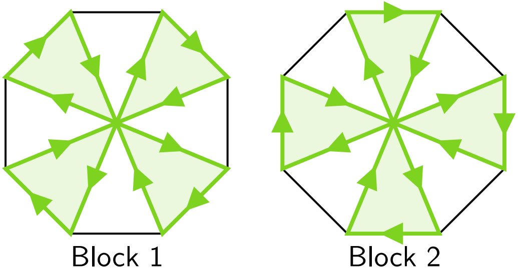

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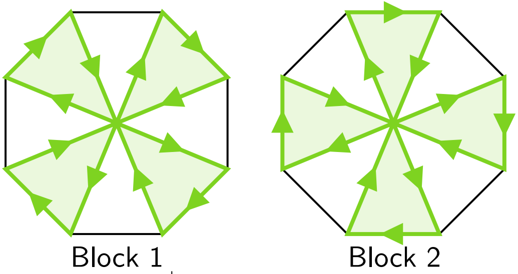

Decompose trial unbroken 4^+ operator:

$$\Phi = \sum_{n=1}^{8} (-1)^n \mathcal{O}\left(\frac{n\pi}{4}\right)$$

$$= \underbrace{-\sum_{n=1,3,5,7} \mathcal{O}\left(\frac{n\pi}{4}\right)}_{\Phi_1} + \underbrace{\sum_{n=2,4,6,8} \mathcal{O}\left(\frac{n\pi}{4}\right)}_{\Phi_2}$$

Define weight vector $\vec{w}_0$:

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For higher spins, choose $\vec{w}$ such that:

- $\langle \Phi[\vec{w}] \rangle = 0$
- $\max(\vec{w} \cdot \vec{w}_0)$

$\Rightarrow \vec{w} = \vec{w}_0 - \frac{\vec{w}_0 \cdot \vec{\Phi}}{\vec{\Phi} \cdot \vec{\Phi}} \vec{\Phi}$

Conclusions and Outlook

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Questions for the audience...

- How can we increase the speed of the Conjugate Gradient algorithm?
- Can we exploit the symmetries of staggered fermions to improve/speed up the calculation?