Gluon structure of spin-1 meson as it becomes unstable using variationally optimized operators

Jefferson Lab

Dimitra A Pefkou

William & Mary
CHARTERED 1693

Collaborators

- Phiala Shanahan (MIT Center for Theoretical Physics)
- Raul Briceño (Old Dominion University/Jefferson Lab)
- Robert Edwards (Jefferson Lab)

Hadron structure in QCD

- How to correctly describe a QCD state?
  e.g $|n> = c_0 q\bar{q} + c_1 q\bar{q}q\bar{q} + c_2 q\bar{q}g + \ldots$
- Which one to choose? It there a hierarchy?
- Quantifying internal structure might help
- GPDs (Generalized Parton Distributions)
- Encode 3D distribution of partons in hadrons

Gluonic structure

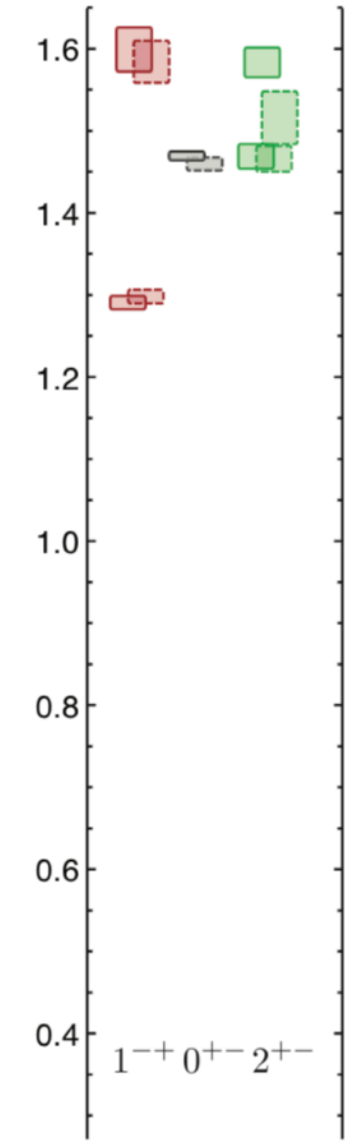
- Gluons are essential in hadron and nuclear structure
- Gluon GPDs harder to measure experimentally than quark
- Better understanding of gluons goal of current and future experiments (GlueX, EIC)

Gluon GPDs in Lattice QCD

- Moments of GPDs (GFFs) directly related to matrix elements calculable on the lattice for **bound states**
- Analogous quark functions (e.g form factors) have been studied extensively in Lattice QCD
- Gluon GFFs less understood. In recent years they have been investigated for pion, phi, nucleon and nuclei
- Goal: understand the gluonic structure of unstable states (resonances)

Exotic mesons

- Spin addition and symmetry transformation of fermion wavefunctions
- Not all J^{PC} combinations can be built from $q\bar{q}$
- However multiple experimental candidates (e.g π1(1600) at COMPASS)
- Possible explanations: Tetraquark states, meson molecules, glueballs, hybrids



Dudek et al 1004.4930

Hybrids $q\bar{q}g$

- Flux tube model (Isgur & Paton PRD 31 (1965), 2910)

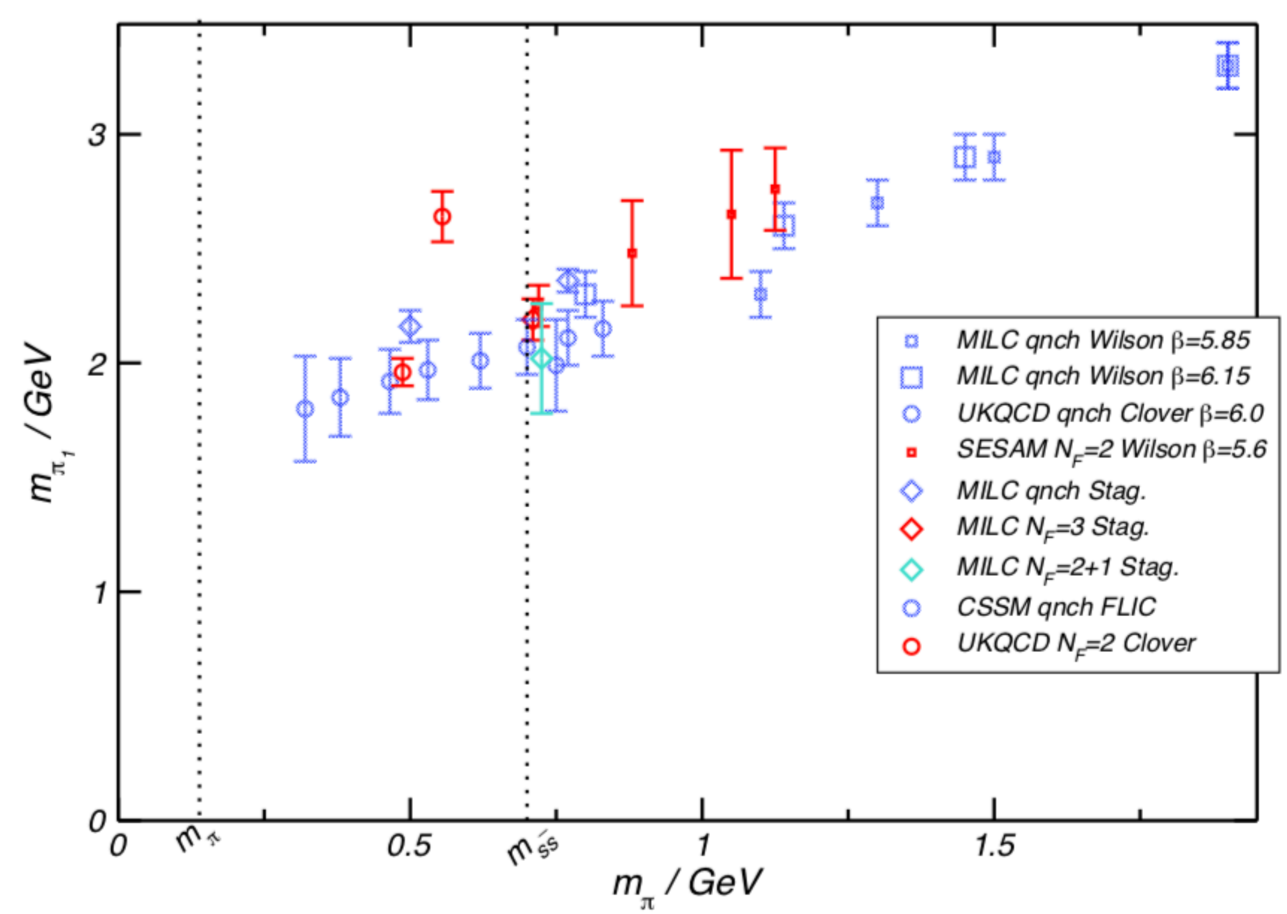
→ supported by Lattice (Bali et al PRD 62 (2000) 054503):

- Gluonic flux tube between quark and antiquark
- Excitations of tube results in hybrid states, some exotic
- Model predicts allowed J^{PC} and decay modes

Hybrids $q\bar{q}g$

ζ	L	S	J^{PC}
+	1	0	1^{++}
+	1	1	$(\underline{2}, 1, \underline{0})^{+-}$
+	2	0	2^{--}
+	2	1	$(\underline{3}, 2, \underline{1})^{-+}$
-	1	0	1^{--}
-	1	1	$(2, \underline{1}, 0)^{-+}$
-	2	0	2^{++}
-	2	1	$(3, \underline{2}, 1)^{+-}$

Meyer & Swanson arXiv:1502.07276



From GlueX Collaboration (presentation to PAC30)

GlueX search for light hybrids

First case study: ρ meson

- Mellin moments of GPDs related to gluonic operator matrix elements

$$\bar{O}_{\mu_1 \ldots \mu_n} = S[G_{\mu_1 \alpha} i\overleftrightarrow{D}_{\mu_3} \ldots i\overleftrightarrow{D}_{\mu_n} G^{\alpha}_{\mu_2}]$$ **Spin-independent**

$$\tilde{O}_{\mu_1 \ldots \mu_n} = S[\tilde{G}_{\mu_1 \alpha} i\overleftrightarrow{D}_{\mu_3} \ldots i\overleftrightarrow{D}_{\mu_n} \tilde{G}^{\alpha}_{\mu_2}]$$ **Helicity**

$$O_{\nu_1 \nu_2 \mu_1 \ldots \mu_n} = S[G_{\nu_1 \mu_1} i\overleftrightarrow{D}_{\mu_3} \ldots i\overleftrightarrow{D}_{\mu_n} G_{\nu_2 \mu_2}]$$ **Transversity**

- Subduce into appropriate irreps of hypercubic rotation/reflection symmetry

- Lowest twist (n=2) decomposition into Lorentz structure for spin-1 meson gives 7 spin-independent, 7 helicity + 8 transversity GFFs

- Each structure function defines a gluonic radius (slope at zero momentum transfer)

Forward limit spin independent GFFs

$$\bar{O}_{\mu_1\mu_2} = G_{\mu_1\alpha}G^{\alpha}_{\mu_2} - \frac{1}{4}g_{\mu_1\mu_2}G^{\alpha}_{\alpha}$$ ⟶ Traceless part of gluon energy momentum tensor

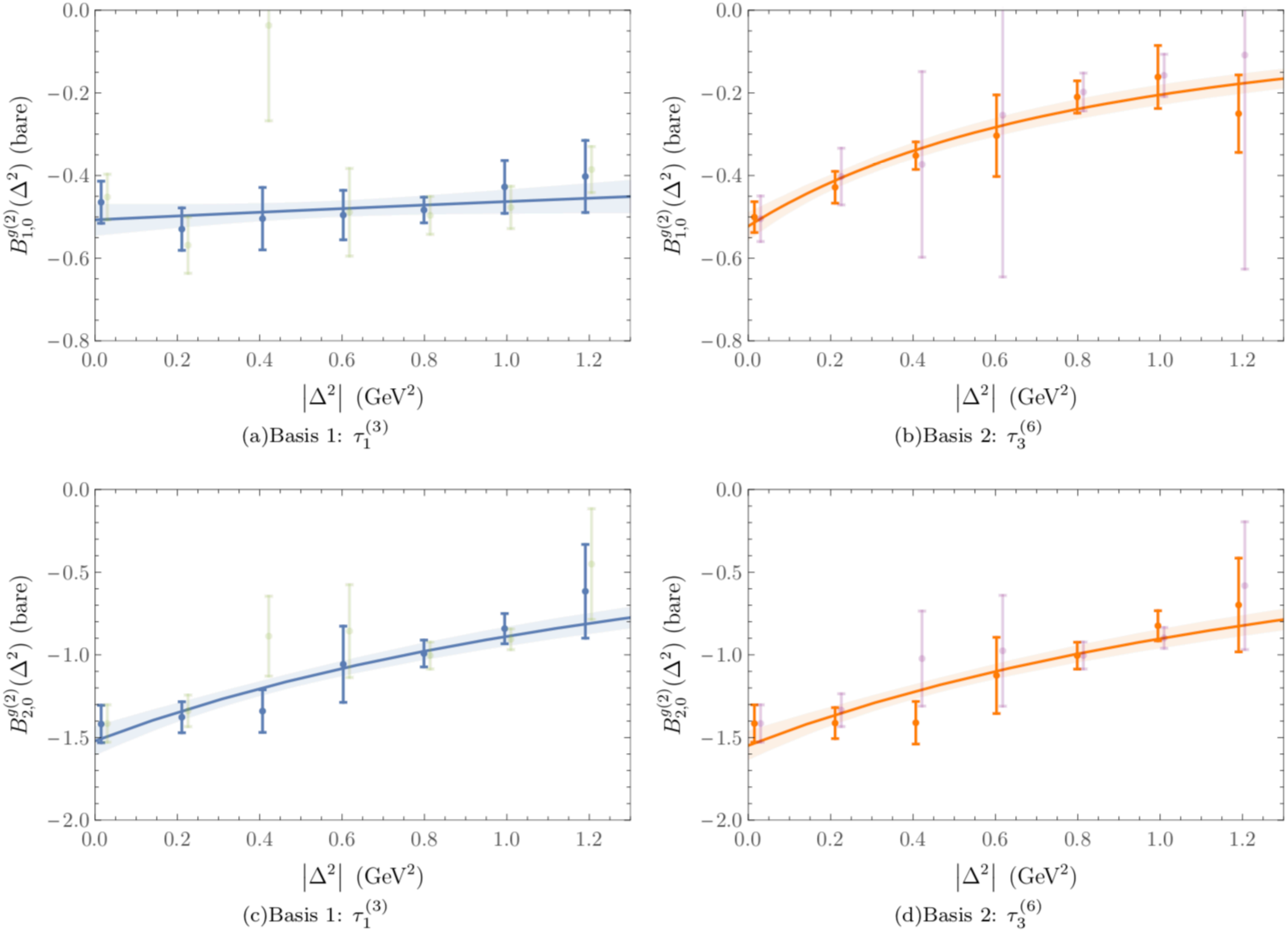
$$< pE'|S[\bar{O}_{\mu_1\mu_2}]|pE > = S[M^2 E'^{*}_{\mu_1}E_{\mu_2}]B_{2,1} + S[(E\cdot E'^{*}p_{\mu_1}p_{\mu_2})]B_{2,2}$$ ⟶ Directly related to gluon momentum fraction in forward limit

On lattice proportional to 3-pt/2-pt function ratio:

$$\frac{< O_n \bar{O}^{E,\Lambda}_{\mu_1\mu_2} O^{\dagger}_n > - < O_n O^{\dagger}_n >< \bar{O}^{E,\Lambda}_{\mu_1\mu_2} >}{< O_n O^{\dagger}_n >}$$

- Λ denotes the hypercubic irrep that the operator has been reduced to. Two convenient choices: $\tau^{(3)}_1$ $\tau^{(6)}_3$ (Goeckeler et al PRD 54 (1996))
- Can mix with quark operator of same dimension. However mixing has been shown to be 10% (Alexandrou et al PRD 96 (2017) 054503)

Stable heavy ρ spin-indep GFFs



$24^3 \times 64$

$m_\pi \sim 450\, MeV$

Detmold, Pefkou, Shanahan PRD 95 (2017) 114515

Variationally optimized interpolators

- Use large basis of definite spin operators of form $\bar{\psi}\Gamma\overleftrightarrow{D}\ldots\overleftrightarrow{D}\psi$

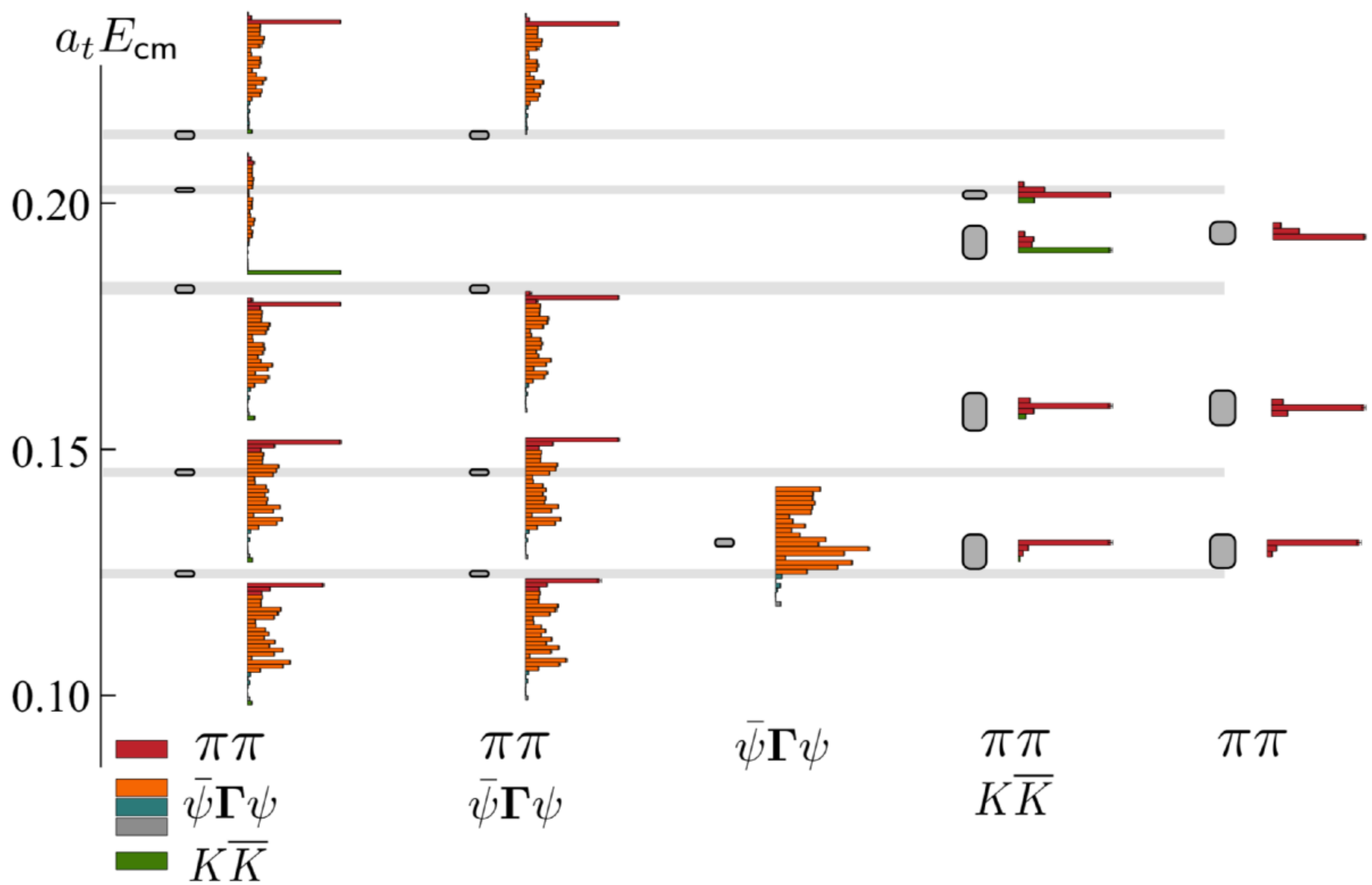
- Reduce into cubic irreps if at rest or little group if in flight

- Optimized interpolators look like $\Omega_n^\dagger = \Sigma_i w_i^n O_i^\dagger$ where the weights are proportional to the eigenstates of the generalized eigenvalue problem $C(t)v^n = \lambda_n(t)C(t_0)v^n$

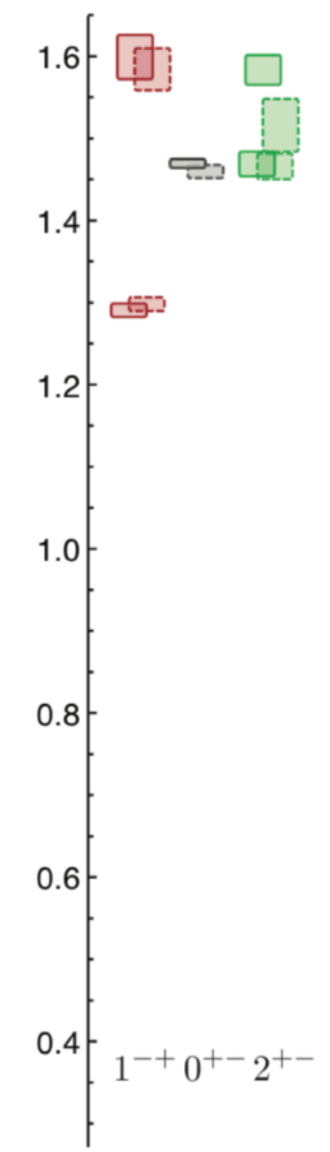
- Allows to probe in theory any state $\longrightarrow$ spectra + structure functions of bound states

- Lüscher: infinite volume spectra of resonances

Results from Hadron Spectrum Collaboration



Wilson, Briceno, Dudek, Edwards, Thomas PRD 92, 094502 (2015)



Dudek et al PRD 82, 034508 (2010)

spin-indep ρ matrix element

With variationally optimized operators

$m_\pi \sim 700\, MeV$

$24^3 \times 128$

$\frac{a_s}{a_t} \sim 3.5$

$\tau_1^{(3)}$

GFFs of unstable ρ

- Asymptotic state ⟶ Corresponds to complex valued pole
- No such thing in finite volume
- Several studies have looked into solving that problem
- In particular we will use the Briceno-Hansen formalism (non-perturbatively maps lattice matrix elements to infinite volume amplitudes)
- Necessary elements: π elastic FFs, ππ (↗ in p wave) matrix elements
- For more details see Alessandro Baroni's talk

Short term goals

- Calculate the infinite volume matrix element of ρ resonance using BH formalism
- Extract gluonic GFFs and renormalize results
- Parallel efforts on renormalization of gluonic operators by Yang et al (arxiv:1805.00531).
- Compare with stable ρ GFFs to interpret e.g gluon momentum fraction similarities and differences
- What happens to the gluon radius?

Long term goals

- Expand formalism to exotic states (hybrids)
- Predict 3D picture of gluonic structure of states with explicit gluonic degrees of freedom. How does it compare with conventional states?
- Combine with experimental efforts to get better understanding of QCD and nature

THANK YOU