

Lattice QCD Studies of Glueballs

Connecting Yang–Mills glueballs to production, decay and mixing

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Outline and scope

Focus: understanding glueballs through lattice studies of their spectrum, production, and mixing.

1. From the glueball concept to the Yang–Mills spectrum
2. Beyond spectroscopy: production and decay
3. Dynamical quarks and glueball–meson mixing

Further reading: broader perspectives

General / phenomenology: Mathieu, Kochelev and Vento, *The Physics of Glueballs*, IJMPE **18**, 1 (2009), [arXiv:0810.4453](#).

Experimental review: Crede and Meyer, *The Experimental Status of Glueballs*, PPNP **63**, 74 (2009), [arXiv:0812.0600](#).

Recent lattice overview: Morningstar, *Update on Glueballs* (2025), [arXiv:2502.02547](#).

$X(2370)$ experimental perspective: Huang, Jin and Zhang, *Discovery of a glueball-like particle $X(2370)$ at BESIII*, IJMPA **40**, 2530007 (2025), [doi:10.1142/S0217751X25300078](#).

The glueball idea

- In 1972, Fritzsche and Gell-Mann discussed pure-gluon states in the emerging quark–gluon field theory.
- The proposed states were color-singlet hadrons built from gluonic degrees of freedom, beyond the usual $q\bar{q}$ mesons and qqq baryons.
- Fritzsche and Minkowski (1975) developed the phenomenology of “glue mesons,” including mixing and Zweig-rule-violating decays.

The original physical question

Can the fields that mediate the strong interaction themselves form observable hadrons?

Fritzsche–Gell-Mann, ICHEP 1972, pp. 135–165 (reprinted as hep-ph/0208010); Fritzsche–Minkowski, Nuovo Cim. A 30, 393 (1975).

Glueballs in QCD

$$\mathcal{L}_{\text{QCD}} = \bar{q}(i\not{D} - m_q)q - \frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu}, \quad F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc}A_\mu^b A_\nu^c.$$

- Gluons carry color: the non-Abelian term generates three- and four-gluon interactions.
- Gauge-invariant gluonic operators can carry hadronic quantum numbers, e.g. $\text{Tr } F^2$ (0^{++}) and $\text{Tr } \tilde{F}F$ (0^{-+}).
- Self-interaction motivates the possibility of bound states; their existence, masses and ordering require nonperturbative dynamics.

To isolate the binding dynamics of the gluonic fields, we first consider pure Yang–Mills theory, without dynamical quarks.

Fritzsch–Gell-Mann–Leutwyler, PLB 47, 365 (1973); Chen et al., PRD 73, 014516 (2006).

Massless gluons, massive glueballs

$$\mathcal{L}_{\text{YM}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu}.$$

- Gauge symmetry forbids an explicit gluon mass term. In symmetry-preserving perturbation theory, gluons remain massless at any finite order.
- Pure Yang–Mills theory nevertheless has a dynamically generated scale. Massive color-singlet glueballs arise from nonperturbative gluonic dynamics.
- Determining the glueball spectrum requires a nonperturbative calculation: lattice gauge theory provides such a method.

From massless perturbative fields to a massive nonperturbative spectrum.

Emergence of mass in the gauge sector of QCD, CPC 46, 112001 (2022); Chen et al., PRD 73, 014516 (2006).

Glueball masses on the lattice

1. **Generate gauge-field configurations.** Sample $U_\mu(x)$ with the Euclidean pure-gauge weight $e^{-S_g[U]}$.
2. **Construct purely gluonic operators.** Combine gauge-invariant Wilson loops, project to definite lattice quantum numbers, and sum over space for $\mathbf{p} = 0$.
3. **Compute two-point correlators.** Average operator products over the gauge ensemble:

$$C_{ij}(t) = \langle \tilde{O}_i(t) \tilde{O}_j^\dagger(0) \rangle, \quad \tilde{O}_i = O_i - \langle O_i \rangle.$$

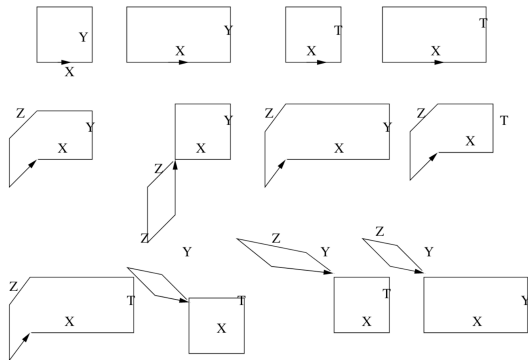
4. **Fit the time dependence to extract masses.** For periodic temporal extent T ,

$$C_{ij}(t) \simeq \sum_n A_{ij}^{(n)} [e^{-m_n t} + e^{-m_n(T-t)}].$$

At zero momentum, Vacuum subtraction matters in the scalar channel.

Wilson, PRD 10, 2445 (1974); Morningstar–Peardon, PRD 60, 034509 (1999); Chen et al., PRD 73, 014516 (2006).

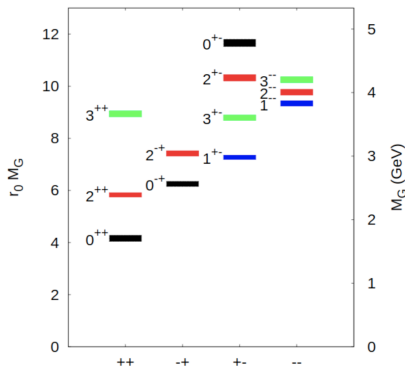
Lattices and gluonic operators



- $a_t < a_s$ provides finer resolution of rapidly decaying correlators.
- Smeared Wilson loops projected into cubic irreps R^{PC} .
- Variational optimization improves the overlap with low-lying states.

Liu, Wu and Chen, hep-lat/0011087; Chen et al., PRD 73, 014516 (2006).

Pure Yang–Mills spectrum



Chen et al., Phys. Rev. D **73**, 014516 (2006).

Chen et al. (2006)

J^{PC}	M [GeV]
0^{++}	1.710(50)(80)
2^{++}	2.390(30)(120)
0^{-+}	2.560(35)(120)

pure-SU(3) glueball results

Bali et al. (UKQCD), Phys. Lett. B **309**, 378–384 (1993).

Morningstar–Peardon, Phys. Rev. D **60**, 034509 (1999).

Vaccarino–Weingarten, Phys. Rev. D **60**, 114501 (1999).

Chen et al., Phys. Rev. D **73**, 014516 (2006).

Athenodorou–Teper, JHEP **11** (2020) 172.

From spectrum to production

- Pure Yang–Mills theory supplies reference masses and quantum numbers.
- Agreement of a mass with an experimental candidate is an initial clue.
- Radiative J/ψ decays provide a gluon-rich production environment, favoring isoscalar, $C = +$ hadronic systems in the dominant strong mechanism.
- Lattice transition matrix elements predict production strengths, providing quantitative benchmarks for experimental searches; electromagnetic glueball decays offer complementary information.

Radiative production requires transition matrix elements beyond the mass spectrum.

Gui et al., PRL 110, 021601 (2013); Yang et al., PRL 111, 091601 (2013); Gui et al., PRD 100, 054511 (2019).

Radiative production

Three-point transition

$$J/\psi(\mathbf{p}_i) \xrightarrow{J_\mu^{(c)}} G(\mathbf{p}_f)$$

$$q = p_i - p_f, \quad Q^2 = -q^2.$$

$$\langle G(\mathbf{p}_f) | J_\mu^{(c),R} | \psi(\mathbf{p}_i, \lambda) \rangle$$

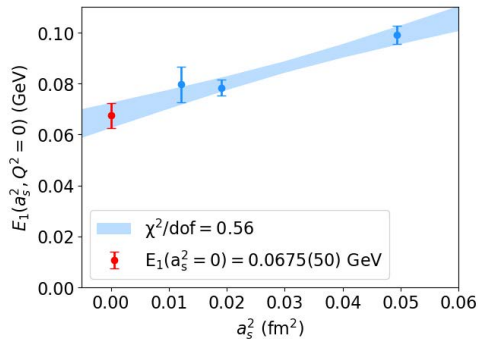
$$= \sum_a K_{\mu a}(p_i, p_f, \lambda) F_a(Q^2).$$

Gui et al., PRL 110, 021601 (2013); PRD 100, 054511 (2019).

$$C^{(3)} = \langle O_G(t_f) J_\mu^{(c)}(t) O_\psi^\dagger(0) \rangle.$$

- Optimize the glueball sink and extract transition form factors.
- Interpolate to the real-photon point, then extrapolate in lattice spacing.
- Multiply the local spatial charm current by its renormalization factor: $J_i^{(c),R} = Z_V^{(s)} J_i^{(c),\text{lat}}$.

Scalar production



$$\Gamma(\psi \rightarrow \gamma G_{0++}) = \frac{4\alpha}{27} \frac{k}{M_\psi^2} |E_1(0)|^2.$$

2013

$$\Gamma = 0.350(80) \text{ keV}$$

$$\mathcal{B} = 3.80(90) \times 10^{-3}$$

2024

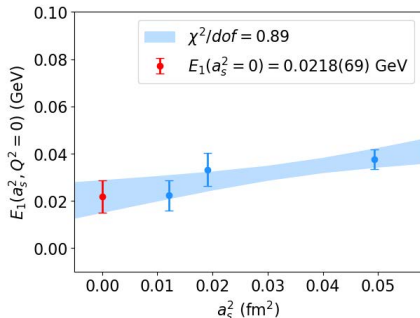
$$\Gamma = 0.578(86) \text{ keV}$$

$$\mathcal{B} = 6.20(90) \times 10^{-3}$$

Three spacings; revised current normalization.

Gui et al., PRL 110, 021601 (2013); Zou et al., Sci. China Phys. Mech. Astron. 67, 111012 (2024).

Scalar decays: $\gamma\phi$ and $\gamma\gamma$



Three-spacing extrapolation in a_s^2 .
 $E_1(0) = 0.0218(69)$ GeV.

Direct lattice result

$$\Gamma(G \rightarrow \gamma\phi) = 0.074(47) \text{ keV}.$$

For a total width of order 100 MeV,
 $\mathcal{B}(J/\psi \rightarrow \gamma G \rightarrow \gamma\gamma\phi) \sim 10^{-9}$. Difficult to observe with 10^{10} J/ψ events; compatible with BESIII's analysis.

Lattice input + VMD

$$\Gamma(G \rightarrow \gamma\gamma) \simeq 0.53(46) \text{ eV}.$$

A model estimate, not a direct two-current lattice calculation.

Zou et al., Sci. China Phys. Mech. Astron. 67, 111012 (2024); BESIII, Phys. Rev. D 111, 052011 (2025).

Scalar candidates and gluonic content

- All three isoscalar 0^{++} resonances lie in the scalar glueball mass region.
- The quenched scalar benchmark is $\mathcal{B}(J/\psi \rightarrow \gamma G) = 6.20(90) \times 10^{-3}$. Experiment finds stronger $f_0(1710)$ than $f_0(1500)$ signals in several radiative J/ψ channels.
- The measured-channel sums quoted give lower bounds of 2.1×10^{-3} for $f_0(1710)$ and 1.9×10^{-4} for $f_0(1500)$.
- Small quenched radiative-decay widths offer complementary search benchmarks.

These comparisons favor $f_0(1710)$ as a candidate with a substantial glueball component

Gui et al., PRL 110, 021601 (2013); Zou et al., Sci. China Phys. Mech. Astron. 67, 111012 (2024).

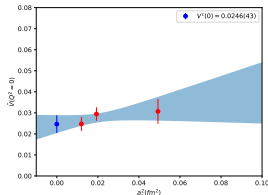
Tensor production

$$\Gamma(\psi \rightarrow \gamma \mathbf{G}_{2++}) = \frac{4\alpha}{27} \frac{k}{M_\psi^2} (|E_1(0)|^2 + |M_2(0)|^2 + |E_3(0)|^2) .$$

- Form factors: $E_1 = 0.1140(120)(60) \text{ GeV}$, $M_2 = -0.0110(50)(10) \text{ GeV}$, $E_3 = 0.0230(80)(10) \text{ GeV}$.
- $\mathcal{B}(J/\psi \rightarrow \gamma \mathbf{G}_{2++}) = 1.1(2) \times 10^{-2}$.
- The large predicted production rate in radiative J/ψ decays motivates experimental searches for glueball candidates in the tensor channel.

Yang et al., PRL 111, 091601 (2013).

Pseudoscalar production



$$\Gamma(\psi \rightarrow \gamma \mathbf{G}) = \frac{16\alpha}{27} \frac{k^3}{(M_\psi + M_G)^2} |\hat{V}(0)|^2.$$

$$M_G = 2.395(14) \text{ GeV}, \quad \hat{V}(0) = 0.0246(43).$$

$$\mathcal{B} = 2.31(80) \times 10^{-4}.$$

Effective radiative couplings

$$\Gamma(\psi \rightarrow \gamma X) = \frac{\alpha}{3} g_X^2 \frac{k^3}{M_\psi^2}, \quad [g_X] = 1.$$

X	g_X
η	0.01080(20)
η'	0.02590(80)
$\eta(1405/1475)$	0.0313(41)
$\eta(1760)$	0.0255(25)
$X(1835)$	0.0123(12)
$\eta(2225)$	0.0167(17)
G_{0-+}	0.0126(22)

The pseudoscalar glueball coupling is not substantially larger than the pseudoscalar meson couplings.

Gui et al., Phys. Rev. D 100, 054511 (2019).

The X(2370) connection

- BESIII established $J^{PC} = 0^{-+}$ in 2024. Combining measurements in three decay channels gives $M_X = 2359^{+13}_{-14}$ MeV, compatible with our lattice prediction for the pseudoscalar glueball. Its measured decay properties are naturally understood in the glueball picture, leading BESIII to favor a pseudoscalar-glueball-dominated interpretation.

- Measured exclusive channels constrain products:

$$b_f = \mathcal{B}(\psi \rightarrow \gamma X) \mathcal{B}(X \rightarrow f), \quad f = K\bar{K}\pi, \pi\pi\eta, \pi\pi\eta', K\bar{K}\eta'.$$

- Channel sums and isospin relations motivate $\mathcal{B}(\psi \rightarrow \gamma X) \gtrsim 10^{-3}$.

The pure-glue reference $2.31(80) \times 10^{-4}$ motivates studying quark dynamics and coherent mixing.

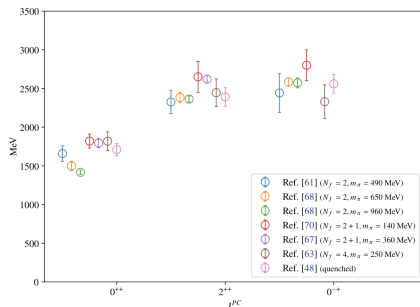
BESIII, PRL 132, 181901 (2024); arXiv:2605.26495; arXiv:2607.20366; alternative interpretation: arXiv:2609.01342.

From production to mixing

- Quenched calculations provide quantitative benchmarks for the glueball spectrum and radiative transitions.
- Glueballs are well defined in pure Yang–Mills theory; ultimately, we need to understand how they manifest themselves in the hadron spectrum of full QCD.
- Dynamical quarks allow glueball–meson mixing and open additional hadronic decay channels.

Zhang et al., PLB 827, 136960 (2022); Jiang et al., PRD 107, 094510 (2023); Chen–Gui–Li–Sun, arXiv:2605.01757.

Gluonic spectra with dynamical quarks



References in the plot

[61] Bali et al., PRD 62, 054503 (2000).

[63] Athenodorou et al., PoS LATTICE2022, 057 (2023).

[67] Gregory et al., JHEP 10 (2012) 170.

[68] Wei Sun et al., CPC 42, 093103 (2018).

[70] Feiyu Chen et al., CPC 47, 063108 (2023).

[48] Ying Chen et al., PRD 73, 014516 (2006).

Vadacchino, arXiv:2305.04869 (2023)

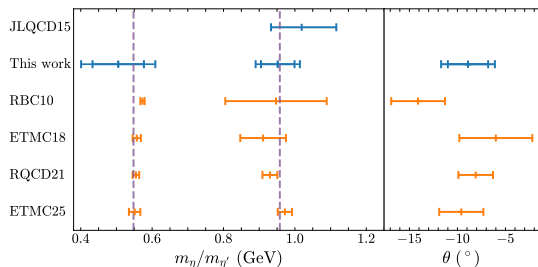
Gluonic operators and meson states

$$q(x) = \frac{g^2}{32\pi^2} F_{\mu\nu}^a \tilde{F}^{a\mu\nu}, \quad A_\mu^0 = \sum_{f=1}^{N_f} \bar{q}_f \gamma_\mu \gamma_5 q_f.$$

$$\partial^\mu A_\mu^0 = 2 \sum_f m_f \bar{q}_f i \gamma_5 q_f + 2N_f q(x).$$

- The flavor-singlet axial anomaly connects gluonic topology with the pseudoscalar meson sector.
- In $N_f = 2 + 1$ QCD, $\langle 0 | q | \eta \rangle$ and $\langle 0 | q | \eta' \rangle$ can be nonzero: a gluonic interpolator does not select only glueball states.
- Wilson loops and topological charge density can emphasize different states in the same finite-volume spectrum.

Topology probes η and η'



RBC/UKQCD 48I and 64I, $N_f = 2 + 1$,
physical pion mass.

$$m_\eta = 0.505(72)(75) \text{ GeV}$$

$$m_{\eta'} = 0.952(47)(40) \text{ GeV}$$

$$\theta_q = -8.9(2.1)(1.8)^\circ.$$

$$\tan \theta_q = -\frac{\langle 0 | \mathbf{q} | \eta \rangle}{\langle 0 | \mathbf{q} | \eta' \rangle}.$$

Blue: topological-charge operators (JLQCD15 and this work); orange: quark-bilinear operators.

A purely gluonic correlator can resolve meson states.

Su et al., Phys. Rev. D 112, 114516 (2025).

A framework for glueball–meson mixing

A common spectrum, probed by quark and gluonic operators

$$C_{XY}(t) = \sum_n Z_X^{(n)} Z_Y^{(n)*} e^{-E_n t}, \quad Z_X^{(n)} = \langle 0 | O_X | n \rangle, \quad X, Y = Q, G.$$

An effective mixing description in a chosen reference basis

$$H_{\text{eff}} = \begin{pmatrix} m_Q & x \\ x & m_G \end{pmatrix}, \quad |\tan 2\theta| = \frac{2|x|}{|m_G - m_Q|}.$$

- Assumptions: two-state dominance, orthogonal reference states, and approximate operator-sector isolation:

$$\langle 0 | O_Q | G \rangle \simeq 0, \quad \langle 0 | O_G | Q \rangle \simeq 0.$$

- For weak mixing, $|\theta| \simeq |x|/|m_G - m_Q|$: both the coupling and the level separation matter.

Zhang et al., PLB 827, 136960 (2022); Jiang et al., PRD 107, 094510 (2023); Gui et al., arXiv:2607.17294 (2026).

Pseudoscalar glueball–meson mixing

	Ensemble I	Ensemble II
$m_{J/\psi}$ [GeV]	2.7430(10)	3.0680(10)
m_{η_1} [GeV]	2.7030(10)	3.0310(30)
m_{g_1} [GeV]	2.286(50)	2.323(55)
Mass separation [GeV]	$\simeq 0.417$	$\simeq 0.708$
$ \theta $	$6.60(90)^\circ$	$4.30(40)^\circ$
x [MeV]	48.0(90)	49.0(60)

- Two degenerate dynamical charm flavors, $16^3 \times 128$, $a_s \simeq 0.1026$ fm.
- Light $N_f = 2$, $m_\pi \simeq 350$ MeV: $|x| = 107(15)(2)$ MeV, $|\theta| = 3.46(46)^\circ$.

Zhang et al., PLB 827, 136960 (2022); Jiang et al., PRD 107, 094510 (2023).

Charm mixing and X(2370) production

$$\langle P(k) | \bar{c} \gamma^\mu c | \psi(p, \lambda) \rangle = M^{(P)}(Q^2) \epsilon^{\mu\nu\rho\sigma} p_\nu k_\rho \epsilon_\sigma(p, \lambda), \quad Q^2 = -(p - k)^2.$$

$$M^{(P)}(Q^2) = \frac{2\hat{V}^{(P)}(Q^2)}{M_\psi + M_P}, \quad [\hat{V}] = 1, \quad [M^{(P)}] = \text{GeV}^{-1}.$$

$$M^{\bar{c}c}(0) = 1.2270(70) \text{ GeV}^{-1}, \quad M^G(0) = 0.0090(16) \text{ GeV}^{-1}.$$

$$M^X(0) = \cos \theta M^G(0) - \sin \theta M^{\bar{c}c}(0).$$

- The charm amplitude is about two orders of magnitude larger: even a few-degree admixture can strongly change $J/\psi \rightarrow \gamma X(2370)$.
- Depending on the relative phase, mixing can enhance or suppress the rate. This offers a possible explanation of the large observed production.

The analysis combines lattice inputs with a mixing model.

Chen–Gui–Li–Sun, arXiv:2605.01757.

From pseudoscalar to scalar mixing

- Pseudoscalar studies demonstrate that a small mixing amplitude can substantially change radiative production.
- We now turn to a direct mixing calculation in the scalar channel.
- One-flavor QCD retains annihilation and G – $s\bar{s}$ coupling while simplifying the flavor structure.
- The objective is to extract energies and mixing parameters within an explicitly stated two-state description.

Scalar mixing in one-flavor QCD

Theory	$N_f = 1$
Lattice	$16^3 \times 128$
Configurations	4893
a_s	$\simeq 0.148$ fm
a_t^{-1}	6.660(50) GeV

- Simplifies the flavor structure while retaining annihilation diagrams.
- Optimized gluonic and scalar $s\bar{s}$ operators.
- Nonzero total momentum eliminates the vacuum contribution by momentum projection.

A well-defined theory with reduced channel complexity and a restricted operator basis.

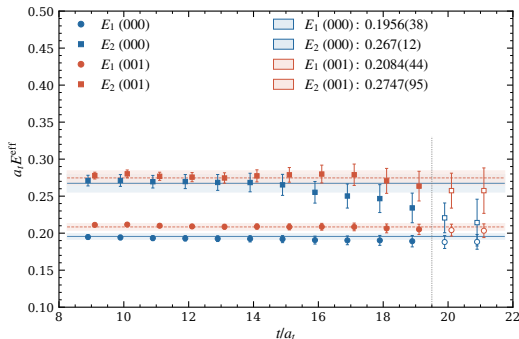
Gui et al., arXiv:2607.17294.

Scalar correlators and annihilation

$$C(t) = \begin{pmatrix} C_{GG}(t) & C_{Gs}(t) \\ C_{sG}(t) & C_{ss}(t) \end{pmatrix}.$$

- The scalar $s\bar{s}$ correlator contains both connected and annihilation contributions.
- The cross correlators directly probe coupling between the selected gluonic and quark-bilinear sectors.
- The connected-only scalar mass is used as an effective unmixed-sector input in a consistency check.

Scalar energy levels and masses



Blue: $\mathbf{n} = (0, 0, 0)$; red: $\mathbf{n} = (0, 0, 1)$. The vertical axis is $a_t E_{\text{eff}}$.

Gui et al., arXiv:2607.17294.

Energies in the two frames [GeV]

$$E_{1,2}(000) = 1.303(25), 1.781(79).$$

$$E_{1,2}(001) = 1.388(30), 1.829(63).$$

Moving-frame masses use

$$m_i = \sqrt{E_i^2 - \mathbf{p}^2}.$$

Combined rest masses [GeV]

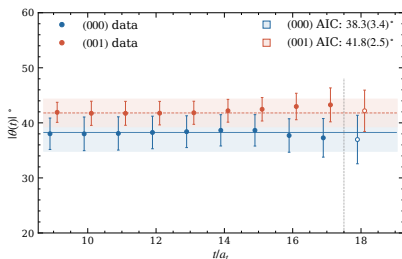
$$m_1 = 1.296(20), \quad m_2 = 1.768(48).$$

Correlations between frames and states are retained. Errors combine statistical uncertainty and fit-window/ t_0 variation.

Mixing angle from correlator ratios

$$|\tan \theta| \simeq \sqrt{-\frac{C_{s2}(t)C_{G1}(t)}{C_{s1}(t)C_{G2}(t)}},$$

$$C_{Xi} = \langle O_X(t) O_i^\dagger(0) \rangle.$$



Optimized states $i = 1, 2$; sectors $X = s, G$.

Approximate isolation of the two unmixed sectors makes the overlap normalizations cancel.

Combined rest- and moving-frame ratio analyses with AIC averaging yield $|\theta| = 40.5(2.2)^\circ$.

Interpretation assumes two-state dominance and approximate sector isolation.

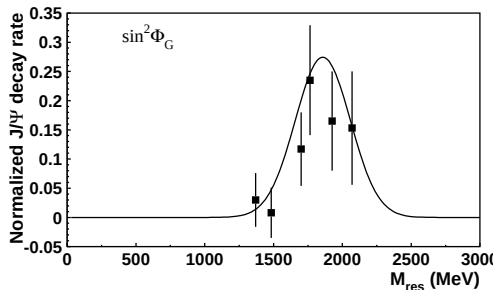
Gui et al., arXiv:2607.17294.

Two-state Hamiltonian check

$$H = \begin{pmatrix} m_s & x_s \\ x_s & m_G \end{pmatrix}, \quad \tan 2\theta = \frac{2x_s}{m_G - m_s}.$$

- Overlap-ratio angle: $40.5(2.2)^\circ$; Hamiltonian check: $39.4(3.6)^\circ$.
- The effective mixing energy is $x_s = 231(14)$ MeV.
- Connected-only input $m_s = 1.486(2)$ GeV gives an effective unmixed-sector mass parameter $m_G \simeq 1.578(64)$ GeV.
- These are parameters of the specified two-state description, with assumptions about sector isolation and orthogonality.

Scalar glueball strength across several mesons



Model-extracted glueball contributions, Klempt–Sarantsev (2022).

Phenomenological picture

BESIII radiative J/ψ data + hadronic constraints.

Fits to scalar decay couplings distribute the glueball component over several f_0 resonances.

Distribution: $M \simeq 1.865$ GeV, $\Gamma \simeq 0.370$ GeV.

Radiative production yield

Phenomenological extraction: $5.8(1.0) \times 10^{-3}$.

Our updated quenched benchmark:

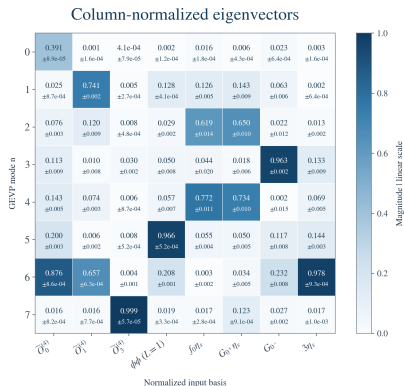
$6.20(90) \times 10^{-3}$.

Consistent within uncertainties.

Our strong G – $s\bar{s}$ mixing supports the qualitative picture of shared gluonic strength.

Sarantsev et al., PLB 816, 136227 (2021), arXiv:2103.09680; Klempt–Sarantsev, PLB 826, 136906 (2022), arXiv:2112.04348, Fig. 3.

Ongoing multi-hadron studies



Pseudoscalar sector: $N_f = 1$

Eight-operator GEVP,
 $(t_0, t_d)/a_t = (2, 3)$.

Rows: GEVP modes $n = 0, \dots, 7$.
Columns: normalized input
operators.

Each operator column is normalized
to $\sum_n |b_{ni}|^2 = 1$.

The gluonic operator G_{0-+} column
is concentrated in mode $n = 3$
($|b| \simeq 0.963$).

Liu, Chen, Gui, Gong and Sun, ongoing work. Preliminary eight-operator GEVP.

Ongoing scalar studies: towards a scattering analysis

A joint operator basis in the scalar channel

Two-pseudoscalar operators $\oplus$ **Scalar-meson operators** $\oplus$ **Gluonic operators**

$$\{[\eta^{(1)}\eta^{(1)}]_{\mathbf{p}}, S_i, G_i\} \longrightarrow C_{ij}(t) \longrightarrow \text{GEVP}$$

- We are extending the scalar spectrum study across multiple lattice ensembles with a joint GEVP analysis of these operators.
- The resulting finite-volume spectra will provide input for a scattering analysis of scalar glueball-related resonances.

Joint GEVP $\longrightarrow$ finite-volume spectra $\longrightarrow$ scattering amplitudes and resonance poles

Ongoing one-flavor scalar studies. $\eta^{(1)}$ denotes the pseudoscalar singlet including annihilation.

Summary

1. Over the past decades, we have systematically studied glueball spectroscopy, production, decays and glueball–meson mixing.
2. Our pseudoscalar mass, radiative J/ψ production and $G-\eta_c$ mixing studies provide important theoretical input for interpreting $X(2370)$.
3. Our scalar studies support a mixing picture in which gluonic strength can be shared among several scalar states; the physical distribution remains to be determined.
4. Our next step is to extend the spectrum analysis with multi-hadron operators and investigate glueball-related resonances through scattering.

Local computing support for lattice QCD



- The growth of AI increases competition for computing resources available to lattice QCD.
- Where institutional policies permit, small local computing servers may offer a practical complement.
- An indicative hardware budget of **RMB 50,000–200,000** can provide storage and computing capacity for small to medium-scale workloads, depending on the configuration.

Our Xiangjiang cluster: an expansion rack.