Glueballs and mesons from functional equations

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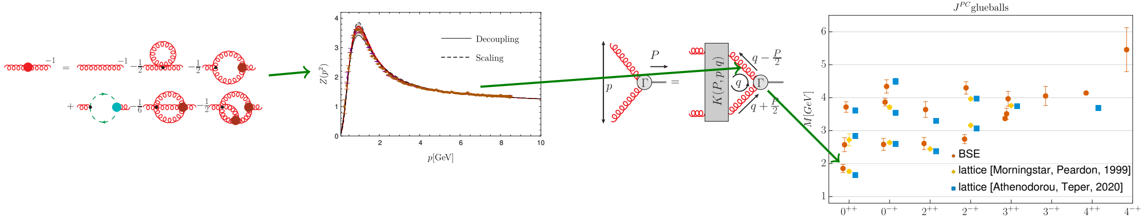


75th Annual Meeting of the Austrian Physical Society and 32nd Meeting of the Condensed Matter Division of the European Physical Society

Sept. 23, 2026

Graz, Austria

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

DFG Deutsche Forschungsgemeinschaft

Glueballs

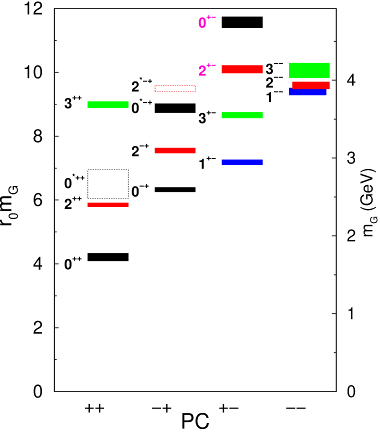
Glueballs are...

- color neutral states. $\rightarrow$ Observables?
- possible due to non-Abelian nature of QCD. $\rightarrow$ Exist in pure gauge theory.
- pure radiation. (No QED equivalent. Geons in gravity?)
- experimentally elusive.
- theoretically not fully understood (existence, mixing, decays).
- a missing piece in the puzzle of hadron spectroscopy.

Status of glueball results (quenched)

no quarks

Pure gauge theory glueballs known [Morningstar, Peardon, Phys. Rev. D60 (1999)].



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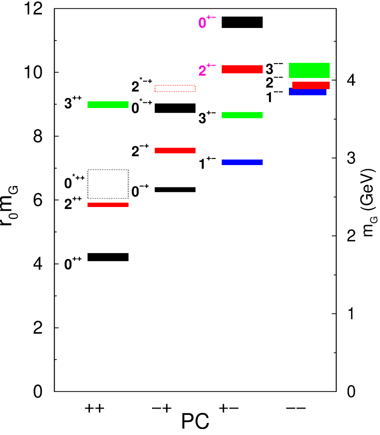

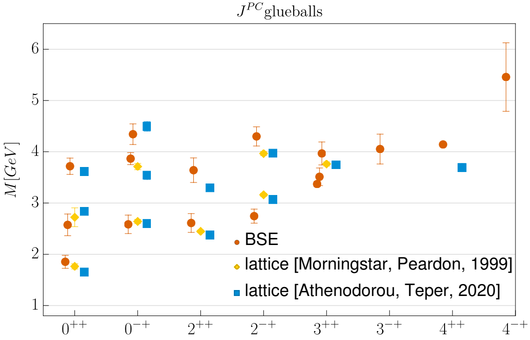

Lattice update: [Athenodorou, Teper, JHEP11 (2020)]

Functional results: [MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C81 (2021)]

$\rightarrow$ Agreement with lattice results.

Hadron calculations with functional methods

- Continuum
- Nonperturbative
- Computational complexity:
  - integral equations: complexity depends on # loops, legs, kinematic variables, . . .

    simple $\leftrightarrow$ complex
- Infinitely large systems $\rightarrow$ Truncations

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2 approaches:

- Phenomenologically motivated, model-based calculations
  - mesons, baryons
  - tetraquarks
  - five- and six-quark systems
- From first-principles $\rightarrow$ e.g. glueballs

Correlation functions:
functional renormalization group (FRG),
Dyson-Schwinger equations (DSEs), *n*PI effective action

Bound state equations (BSEs) $\rightarrow$ Spectra

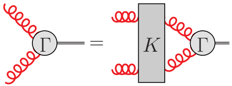
$\rightarrow$ [Eichmann, "Hadron physics with functional methods", 2503.10397, link; MQH, "A beginner's guide to functional methods in particle physics", 2510.18960, link]

Glueball bound state equations

Details of derivation

n-particle bound state: Pole in a 2*n*-point function ***G*** (or the scattering matrix ***T***).

Generic form for 2-particle bound state:



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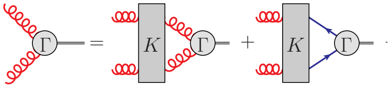

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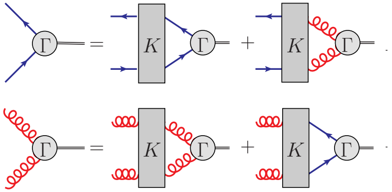

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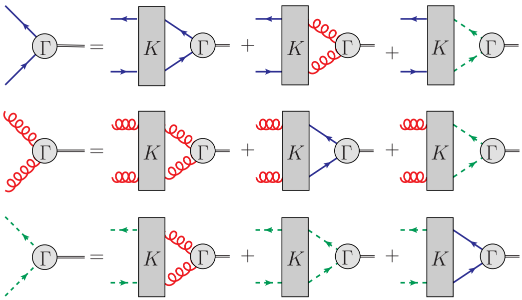

Gluons, quarks (u, d, s, . . .) and ghosts all couple.

(Landau gauge)

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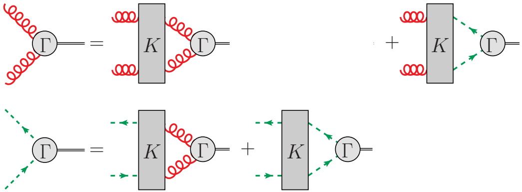
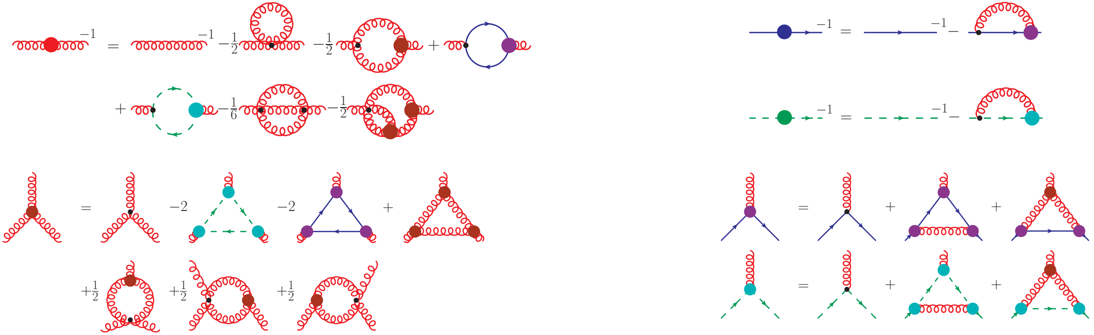
Focus on pure glueballs.



- Conceptually simpler: fewer terms, only glueballs (ghosts *do not* lead to additional states)
- Benchmark: Lattice results

Equations of motion from 3PI 3-loop

Stationarity conditions: $\frac{\delta\Gamma}{\delta D}=0,\ \frac{\delta\Gamma}{\delta\Gamma^{(3)}}=0 \rightarrow$ Equations of motion (already truncated):



$\rightarrow$ Self-consistent treatment of propagators and three-point functions. Including two-loop diagrams.

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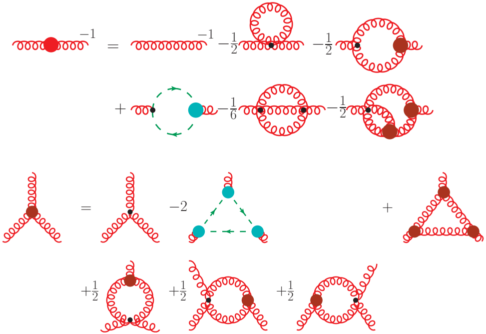

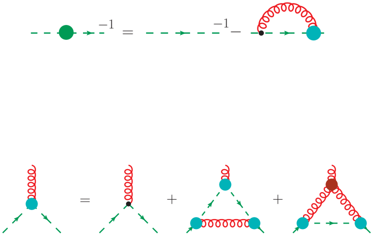

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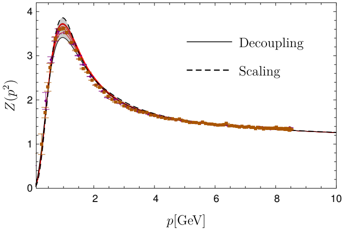
Input for bound state equations: Pure gauge theory

[MQH, Phys. Rev. D 101 (2020)]

Gluon dressing function:



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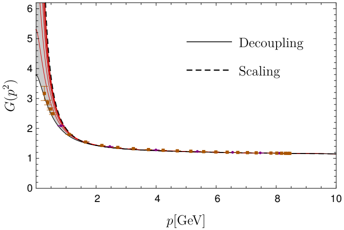

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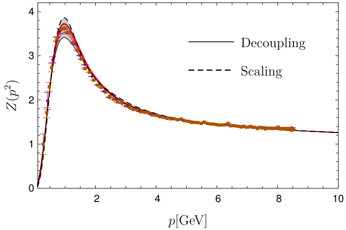

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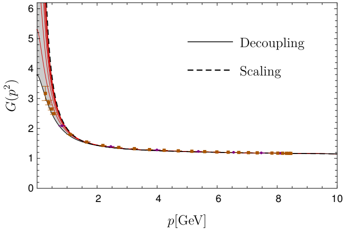
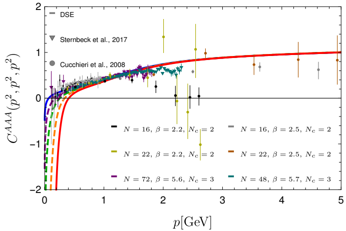


Three-gluon vertex [Cucchieri, Maas, Mendes, Phys. Rev. D 77 (2008); Sternbeck et al., Pos LATTICE2016; MQH, Phys. Rev. D 101 (2020)]:



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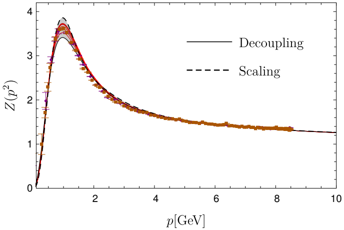

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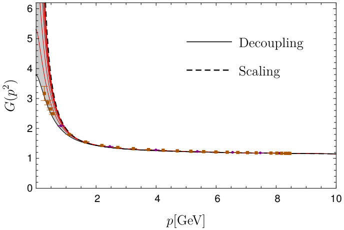

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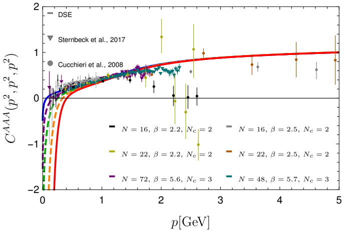


Still truncations in equations...

How far should we trust the results? → [MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C85 (2026)]

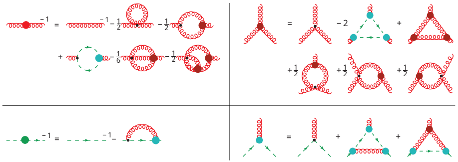
Testing truncations

Pragmatic approach

Enlarging the truncation until changes small enough. $\rightarrow$ Apparent convergence

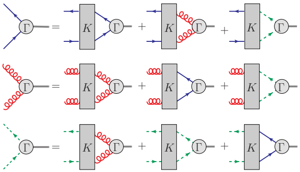
<u>Two sets to test:</u>

Correlation functions



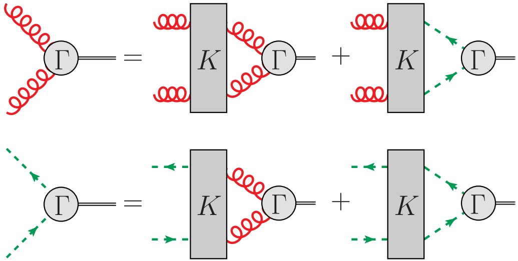
$\rightarrow$ List of tests in [MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C85 (2026)]

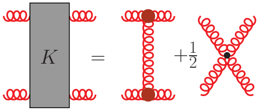
Bound state equations



Approximations in kernels

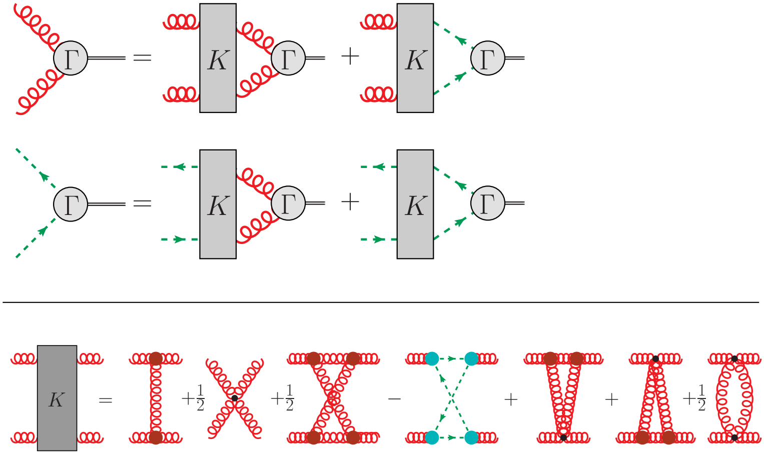
- Only one-particle exchanges (2020)





Approximations in kernels

- Only one-particle exchanges (2020)
- Gluonic two-loop diagrams (2025)



Effect of approximations (for 0^{++})

[MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C 85 (2026)]

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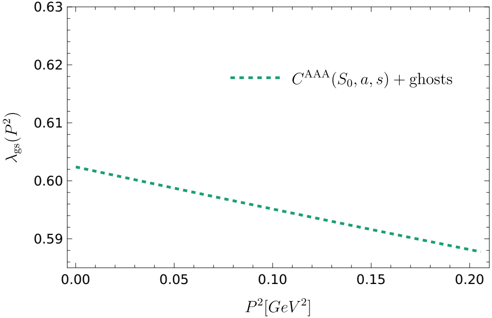

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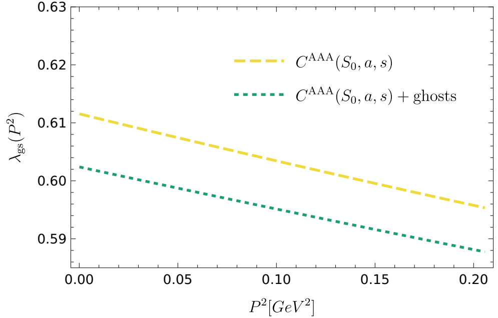

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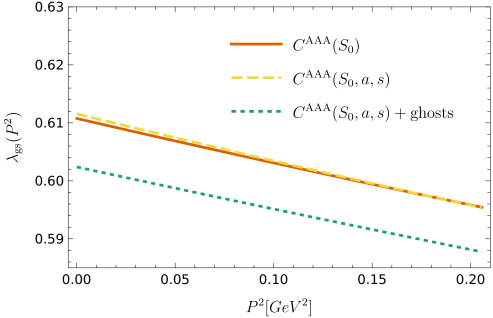

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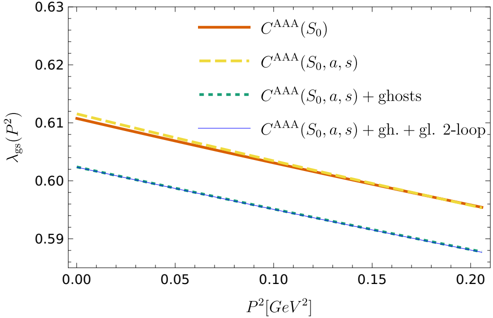
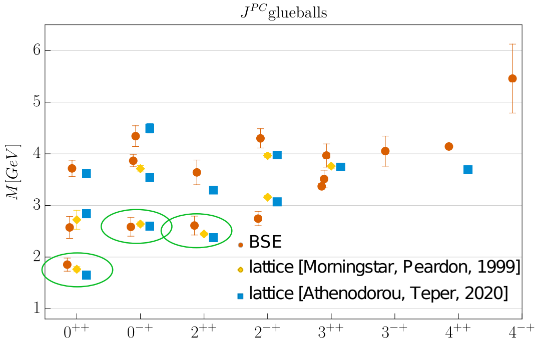


- Ghost diagrams essential: $\Delta m \approx 200 - 350\,\text{MeV}$
- Small influence of three-gluon kinematics (S_0 only vs. S_0, a, s) $\rightarrow \Delta m \approx 50\,\text{MeV}$
- Two-loop diagrams negligible: $\Delta m/m < 2\%$ (also for 0^{-+}, 2^{++})

Glueball results



[MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C 81 (2021)]

- Agreement with lattice results
- Consensus: **0^{++}** is lightest state
- Next: 0^{-+}, 2^{++}, 0^{++*}

- Cf. experimental states $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ as scalar and $X(2370)$ as pseudoscalar glueball candidates

Description of mesons with BSEs

Chiral symmetry $\to$ Goldstone bosons: K, π, η
$\to$ Important test: $m_q = 0 \Rightarrow M_\pi = 0$?

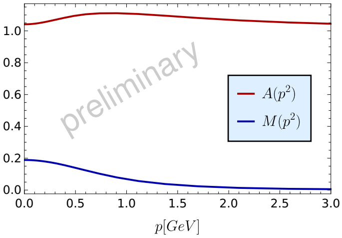
Functional methods: Relation between quark selfenergy and kernel!
$\to$ Nontrivial to fulfill!

- Rainbow-ladder (model-based): ✓
- Explicit constructions for beyond rainbow-ladder, e.g., [Bender, Roberts, von Smekal, Phys.Lett.B 380 (1996); Williams, Fischer, Heupel, Phys. Rev. D 93 (2016); Qin, Roberts, Chin.Phys.Lett. 38 (2021)].

Construct quark DSE "kernel-first": Kernel $\to$ selfenergy

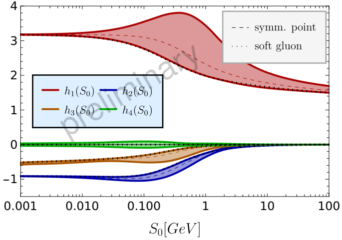
Equation for $B(p^2)$ modified by constraints from the kernel.

Quark correlation functions

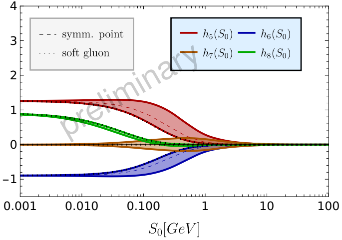


- Input: Yang-Mills results of [MQH, Phys. Rev. D 101 (2020)]
- Coupling fixed by $f_\pi \approx 123$ Mev (chiral limit)
- IR enhancement of dressings, chirally symmetry/breaking
- Bands: angular dependence!

Chirally symmetric



Chirally breaking



See also [Wieland, Alkofer, 2604.20235]

Chiral symmetry

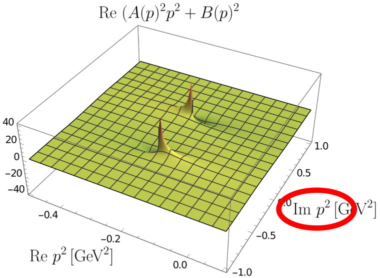
Test chiral symmetry:
$m_q = 0 \rightarrow M_\pi = 0 \rightarrow \lambda(P^2 = 0) = 1$

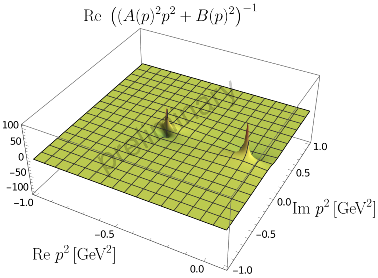
Quark propagator	Quark-gluon vertex	Eigenvalue $\lambda(\epsilon)$
Kernel-first	non-Abelian + Abelian	0.9997
3PI	non-Abelian + Abelian	0.9885
Kernel-first	non-Abelian	0.9997
3PI	non-Abelian	0.9637

For comparison:
Physical quark mass,
model-based
$\rightarrow \lambda(\epsilon) = 0.98259$.

Analytic structure of quark propagator

Schlessinger continued fraction method [Schlessinger, Phys.Rev.167 (1968)] with Euclidean data:
$\rightarrow$ Estimates of first quark propagator poles in complex plane.





Maris-Tandy: Complex conjugate poles.
[Dorkin, Kaptari, Kämpfer, Phys. Rev. C 91 (2015); Windisch, Phys. Rev. C 95, (2017);]

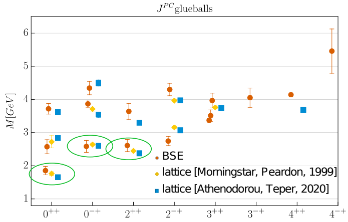
Kernel-first/3PI: $\rightarrow$ Only poles on real axis:

- $p^2 = -0.049 \pm 0.0004 \sim 222$ MeV
- $p^2 = -0.36 \pm 0.009 \sim 602$ MeV

See also [Wieland, Alkofer, 2604.20235; Alkofer, Ferreira, Miramontes, Morgado, Papavassiliou, 2606.28212].

Summary and conclusions

- Functional methods are versatile tools:
  - Qualitative: Study mechanisms, e.g., structure of tetraquarks
  - Quantitative: tailored for certain sectors; large sets of correlation functions, benchmarks and tests necessary



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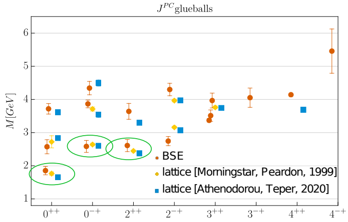

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- BSEs: two-loop diagrams ($0^{\pm+}$, 2^{++}) ✓
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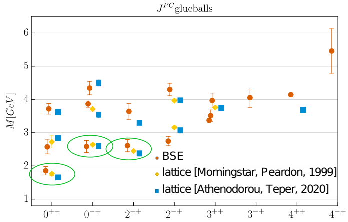

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Mesons

- Quark correlation functions from a truncation respecting chiral symmetry.
- Future: Mixing of glueballs and mesons.

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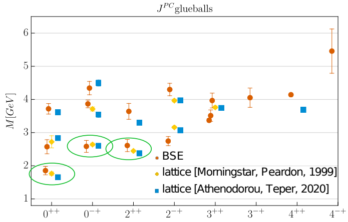

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Thank you for your attention.

Derivation of bound state equations I

For more details see [Eichmann, Sanchis-Alepuz, Williams, Alkofer, Fischer, Prog.Part.Nucl.Phys. 91 (2016)]

n-particle bound state

Pole in a $2n$-point function.

For simplicity here $n = 2$.

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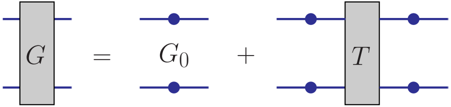

disconn. connected part

$\to$ scattering matrix T (amputated, conn. part of G)

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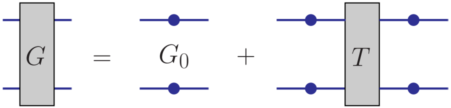

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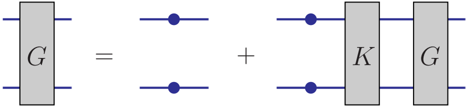
$\rightarrow$ scattering matrix T (amputated, conn. part of G)

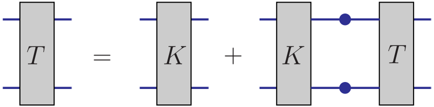
Dyson equations: nonperturbative resummations! Compare:

$$f(x) = \frac{1}{1-x} = 1 + x + x^2 + \ldots = 1 + x\, f(x) = 1 + x + x^2\, f(x)$$

$$G = G_0 + G_0\, K\, G$$



$$T = K + K\, G_0\, T$$



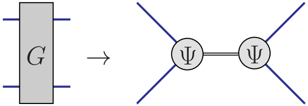
Scattering kernel K: 2-particle irreducible with respect to horizontal quarks lines (rest created by iteration)

Derivation of bound state equations II

Back

On-shell: at pole position $P^2 = -M^2$

$$G \to \frac{\Psi\,\overline{\Psi}}{P^2 + M^2}$$



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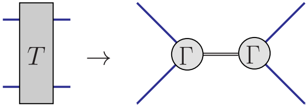

Bethe-Salpeter amplitude Γ is the amputated wave function, $\Psi = G_0 \Gamma$.

Pole position: mass M

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Derivation of bound state equations II

Back

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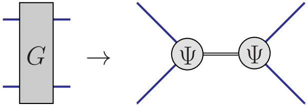

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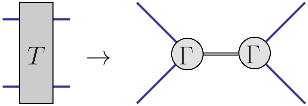

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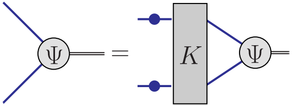
Plug into Dyson equations: homogeneous Bethe-Salpeter equations

$$\Psi = G_0\, K\, \Psi$$



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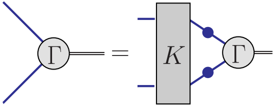

BSE calculations for glueballs

- Model based ($J = 0$):
  - [Meyers, Swanson, Phys.Rev.D87 (2013)]
  - [Sanchis-Alepuz, Fischer, Kellermann, von Smekal, Phys.Rev.D92, (2015)]
  - [Souza et al., Eur.Phys.J.A56 (2020)]
  - [Kaptari, Kämpfer, Few Body Syst.61 (2020)]

  $\rightarrow$ Calculations possible, but no quantitative prediction yet.

- Self-consistently calculated input:
  - [MQH, Sanchis-Alepuz, Fischer, Eur.Phys.J.C 80 (2020)]: $0^{\pm+}$
  - [MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C81 (2021)]: $0^{\pm+}$,$1^{\pm+}$,$2^{\pm+}$,$3^{\pm+}$,$4^{\pm+}$
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Convergence: Pragmatic approach

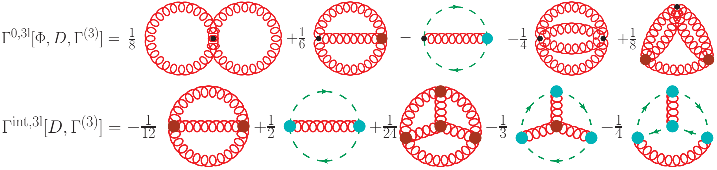
Enlarging the truncation until changes small enough. $\rightarrow$ Apparent convergence

3PI effective action

Back

- 3PI: propagators and three-point functions as dynamic quantities
- Natural expansion scheme in loops.

In general: *m*-loop for *n*PI, $m \geq n$, for a consistent description.



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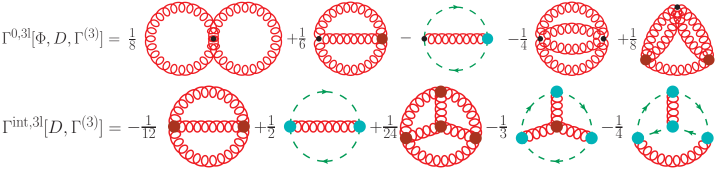

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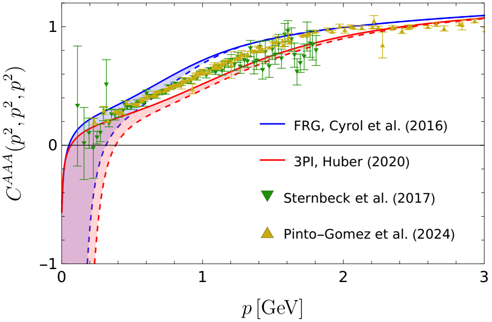
- Equations of motion from stationarity conditions $\rightarrow$ correlation functions ✓
- Kernels from stability conditions $\rightarrow$ BSEs ✓

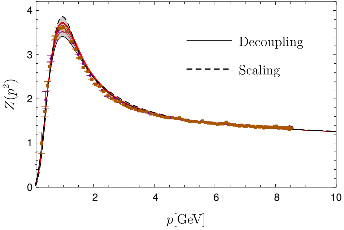
Example check: Three-gluon vertex

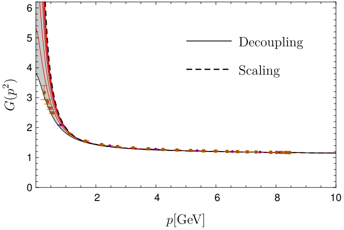
Agreement between lattice, FRG, DSE and 3PI.

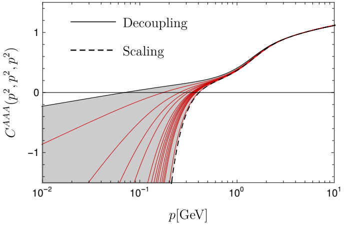


[Pinto-Gómez, de Soto, Rodríguez-Quintero, Phys.Lett.B 838 (2023); Sternbeck et al., Proc.Sci. LATTICE2016 (2017); Cyrol et al., Phys.Rev.D 94 (2016); MQH, Phys.Rev.D101 (2020); MQH, Fischer, Sanchis-Alepuz, Eur. Phys. J. C 85 (2025)]

Family of solutions







- Family of solutions [von Smekal, Alkofer, Hauck, PRL79 (1997); Aguilar, Binosi, Papavassiliou, Phys.Rev.D 78 (2008); Boucaud et al., JHEP06 (2008); Fischer, Maas, Pawlowski, Ann.Phys. 324 (2008); Alkofer, MQH, Schwenzer, Phys. Rev. D 81 (2010)]
- Nonperturbative completions of Landau gauge [Maas, Phys. Lett. B 689 (2010)]?

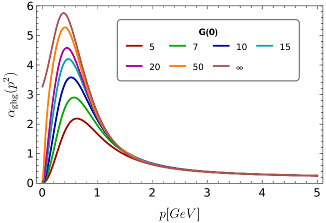
Spectrum for family of solutions

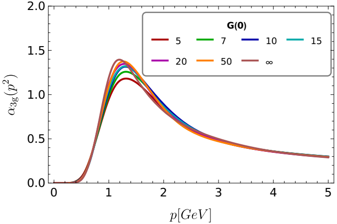
Couplings:

[MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C 85]

$$\alpha_{3g}(p^2) = \alpha(\mu^2)\left[D^{3g}(p^2)\right]^2\left[Z(p^2)\right]^3$$

$$\alpha_{ghg}(p^2) = \alpha(\mu^2)\left[D^{ghg}(p^2)\right]^2 Z(p^2)\left[G(p^2)\right]^2$$





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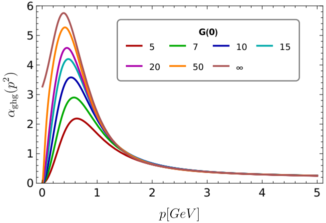
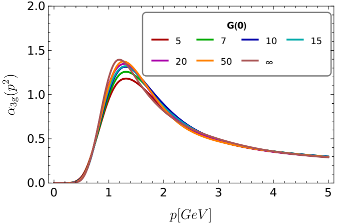
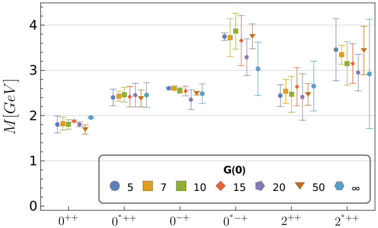




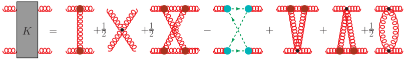


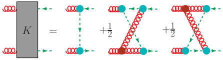
- Invariant spectrum $\rightarrow$ Nonperturbative gauge hypothesis supported.
- Invariance lost when deforming the input. $\rightarrow$ Consistency relevant.

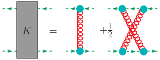
Kernels from the 3PI 3-loop effective action

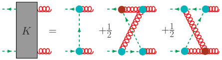
3PI effective action

Systematic derivation from 3PI effective action [Berges, PRD70 (2004); Carrington, Guo, PRD83 (2011)].









[Fukuda, Prog. Theor. Phys 78 (1987); McKay, Munczek, Phys. Rev. D 40 (1989); Sanchis-Alepuz, Williams, J. Phys: Conf. Ser. 631 (2015); MQH, Fischer, Sanchis-Alepuz, Eur.Phys.J.C 80 (2020)]

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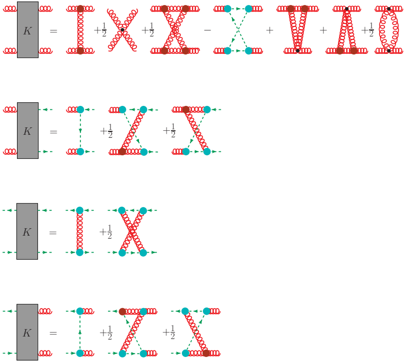

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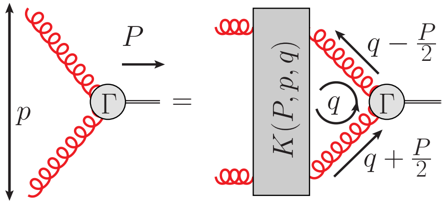
Solving a BSE



(pseudoscalar glueball)

$$\boldsymbol{\lambda(P)}\Gamma(P) = \mathcal{K}\cdot\Gamma(P)$$

$\rightarrow$ Eigenvalue problem for $\Gamma(P)$:

1. Solve for $\lambda(P)$.
2. Find P with $\lambda(P)=1$.
   $\Rightarrow M^2 = -P^2$

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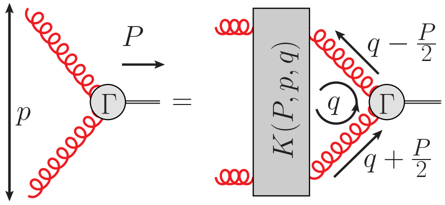

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However:

Propagators are probed at $\left(q \pm \frac{P}{2}\right)^2 = \frac{P^2}{4} + q^2 \pm \sqrt{P^2\, q^2} \cos\theta = -\frac{M^2}{4} + q^2 \pm \boldsymbol{i}\, M \sqrt{q^2} \cos\theta$

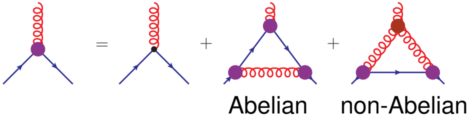
$\rightarrow$ Complex for $P^2 < 0$!

Time-like quantities ($P^2 < 0$) $\rightarrow$ Correlation functions for complex arguments.

Equations for quark correlation functions

$$\Gamma^{a,ij}_{\mu}(k;p,q) = -i\,g\,T^{a,ij}\Gamma_{\mu}(k;p,q),$$

$$\Gamma_{\mu}(k;p,q) = \sum_{l=1}^{12} G_l(k;p,q)\tau^l_{\mu}(k;p,q).$$



- Landau gauge $\rightarrow$ 8 transverse dressings
- Kinematics: 3 variables
  base on $S_3 \rightarrow (S_0), (a, s)$ [Eichmann, Williams, Alkofer, Vujinovic, Phys.Rev.D89 (2014)]