Glueballs

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Outline

- Glueballs?
- Theoretical studies
- Production and decays
- Favored candidate: $f_0(1710)$
- A new one? X(3020)
- Conclusions

Glueballs?

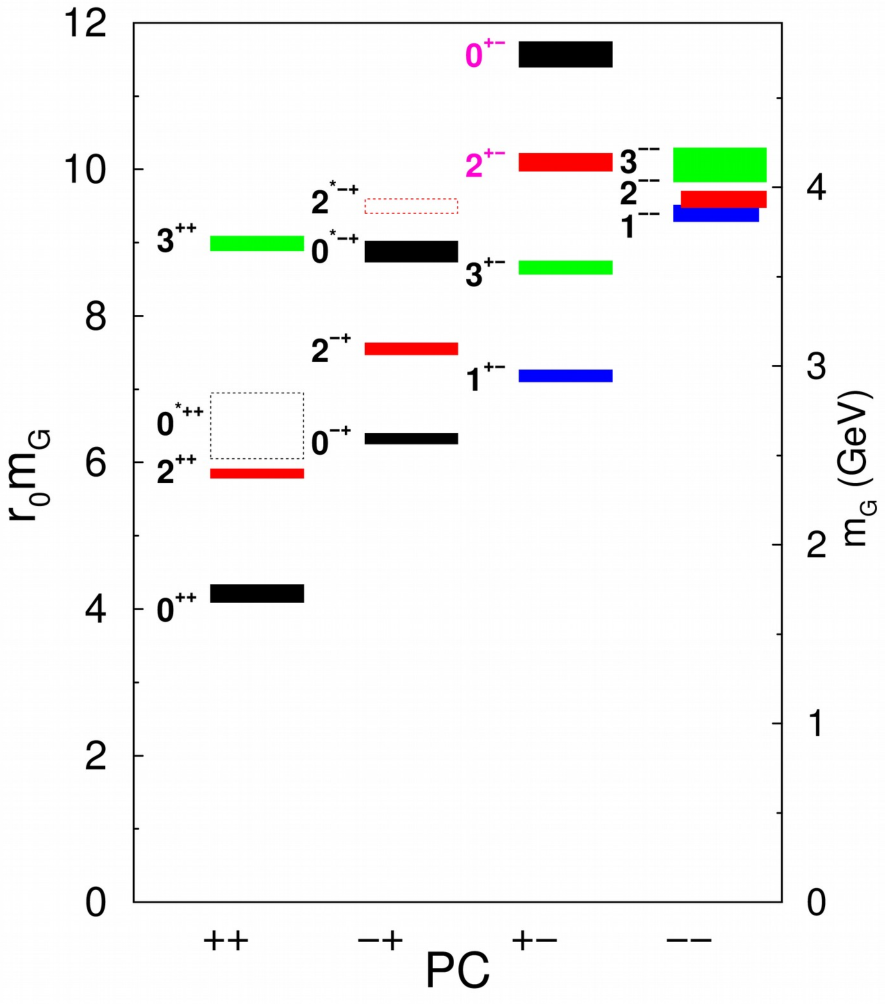
- QCD: Gluons have color, can interact directly
  - Bound states possible
- 2- and 3-gluon glueballs usually considered
  - Ground-state J = 0, 1, 2, 3
  - Excited states also possible
- Theorists agree that glueball states exist, but...
- Spectrum, decays uncertain (QCD is hard)
  - Mass range: 1 – 5 GeV; $J^{PC} = 0^{++}$ the lightest
- Observation hampered by mixing with ordinary mesons

Making predictions

- Various techniques to study glueball properties:
  - Lattice QCD
  - Constituent models (MIT bag model; potential models)
  - QCD sum rule approach (operator product expansion)
  - AdS/CFT (holography)
- All involve approximation, so results don’t always agree
- But they all predict a wide range of glueball states with qualitatively similar features

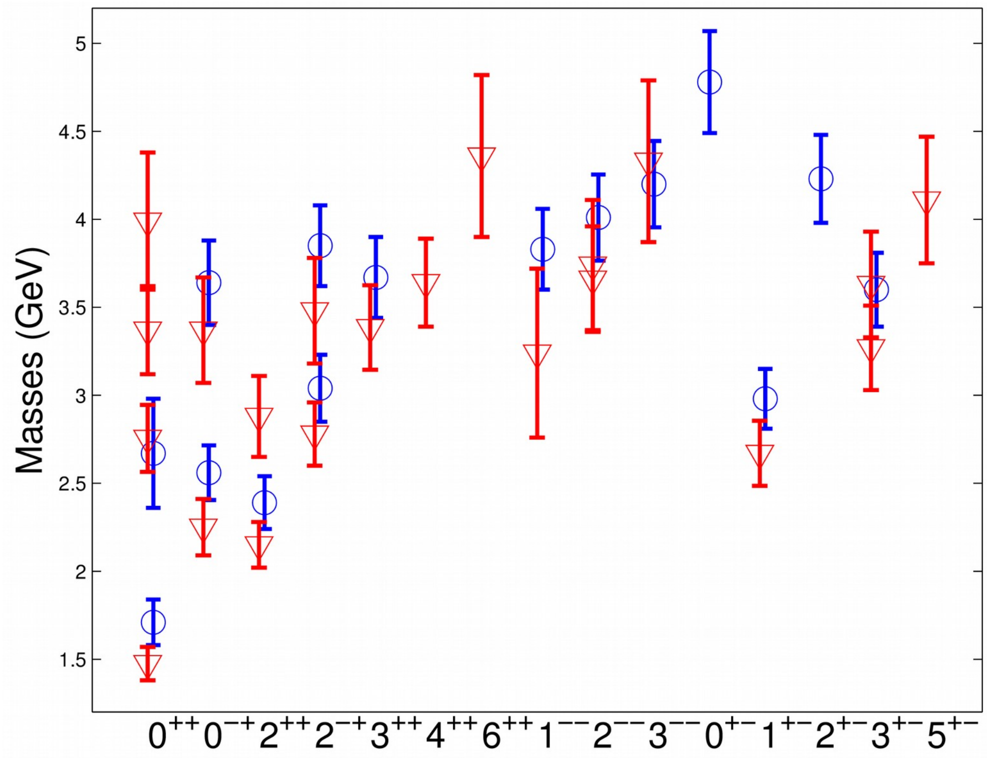
Lattice QCD

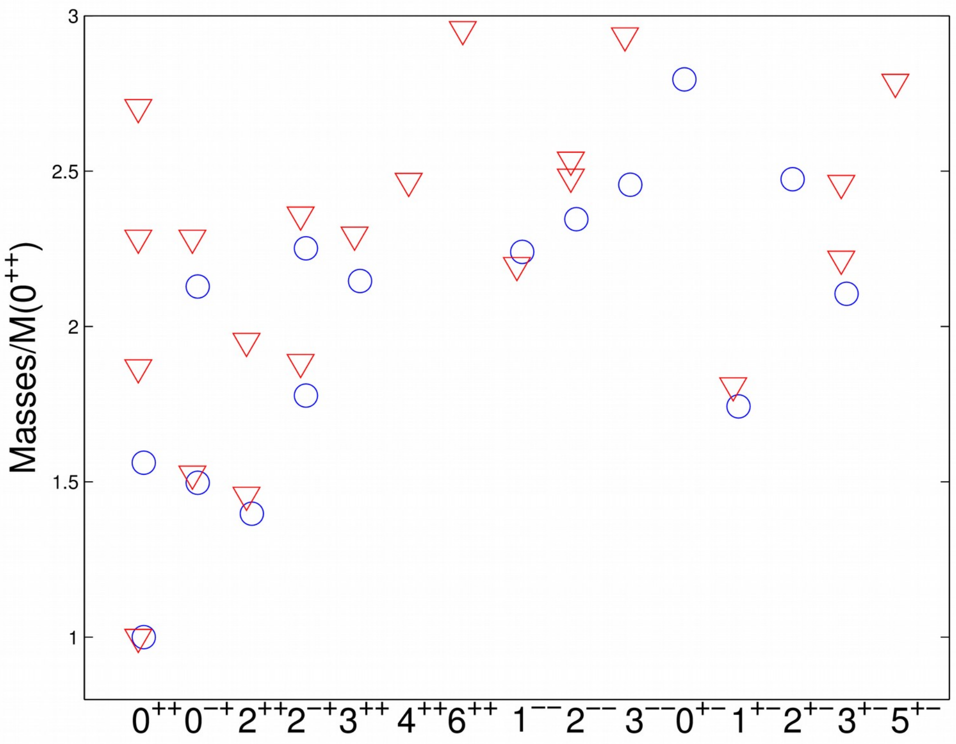
- Good for calculating spectra
- Decay properties much more difficult
  - Euclidean time has no concept of asymptotic states
- Traditional results from pure SU(3), no quarks
- Quenched models: Static quarks (not shown)
- Unquenched models: Full quark dynamics (not shown)



Glueball spectrum from “pure” (quarkless) lattice SU(3)

Lattice comparisons



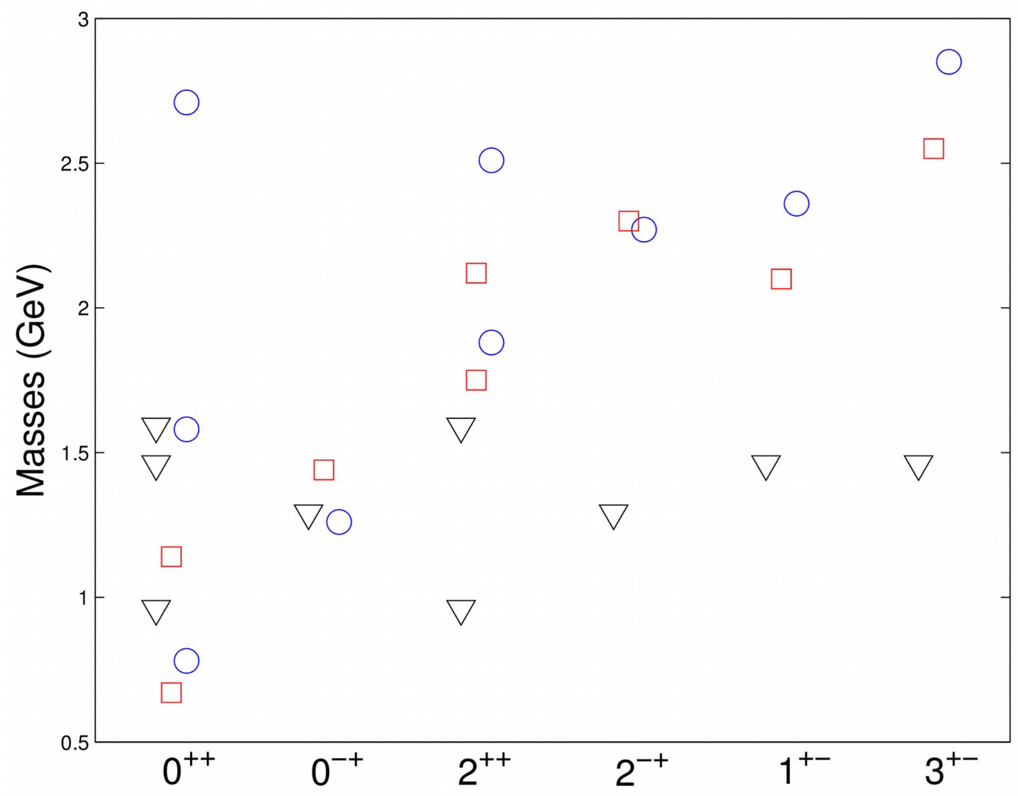


Comparison of two independent quarkless lattice QCD calculations (triangles vs circles)

Left: Absolute masses; Right: Mass ratios vs. lowest state

MIT bag model

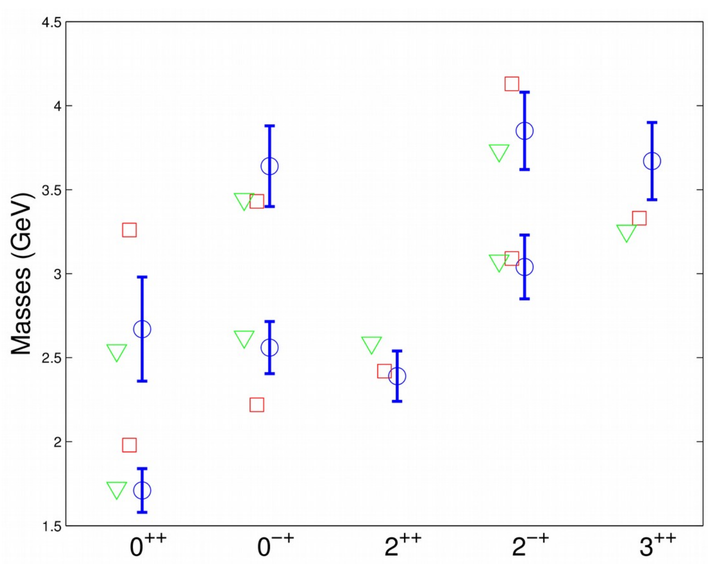
- Model hadronic system as (spherical) region with boundary condition
  - Color flux disappears at bounday
- Fit parameters to known hadron masses etc.
- Then solve for energies of normal modes of gluon field (TE, TM, etc.)

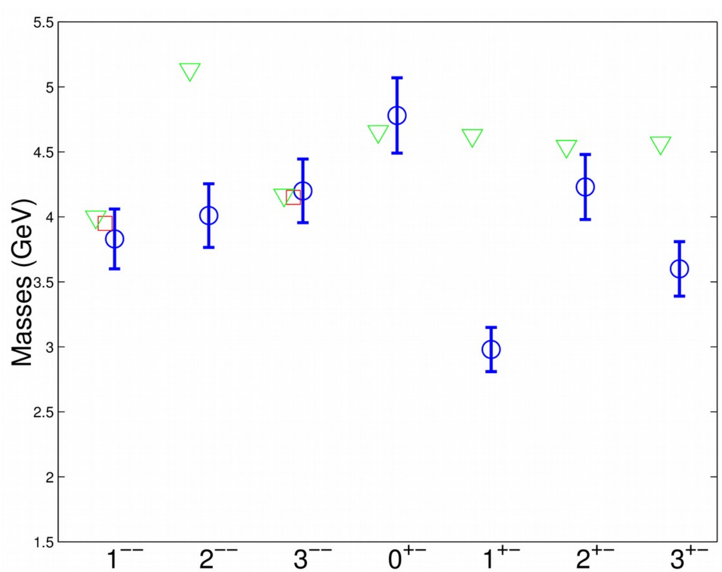


Glueball spectrum from three different bag models (square/circle/triangle)

Massive gluons, potential models

- Nonperturbative effects (confinement) can be described by a “dynamical” mass for the gluon
  - Derived e.g. from dressed gluon propagator
  - Typical result: Gluon “mass” ~ 500 MeV
- Take two or three massive gluons, assign interaction potential, study bound states





Left: Lattice results (blue) vs. 2-gluon potential models

Right: 3 gluons

QCD sum rules

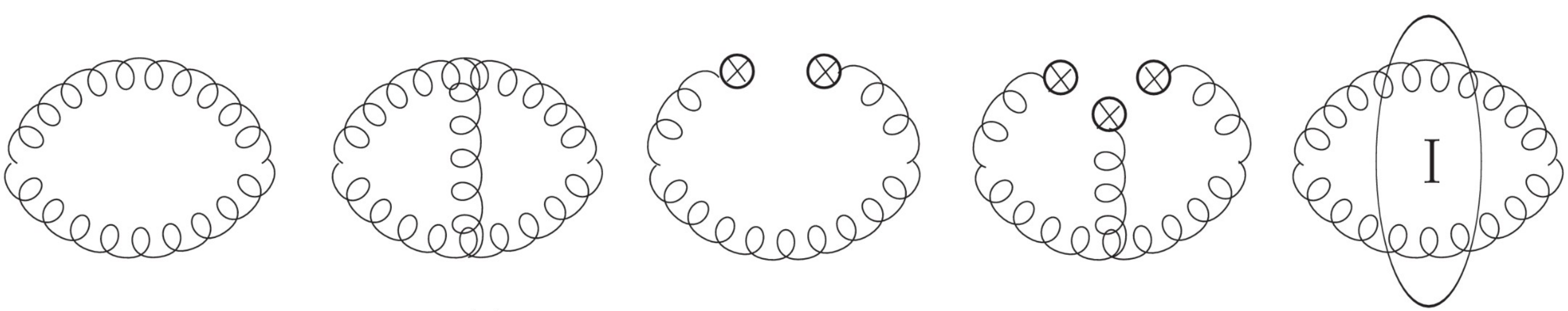
- Popular approach. Basic idea: Take, say, glueball current correlator

$$\Pi(Q^2) = i \int d^4x \; e^{iq\cdot x} \langle 0 | T J_G(x) J_G(0) | 0 \rangle$$

- And rewrite it using really horrific QFT black magic (operator product expansion) until you get an expression involving desired observables, like glueball masses:

$$\mathrm{Im}\Pi(s)^{\mathrm{phen}} = \sum_i \pi f_{G_i}^2 m_{G_i}^4 \delta(s - m_{G_i}^2) + \pi\theta(s - s_0) \; \mathrm{Im}\Pi(s)^{\mathrm{theor}}$$

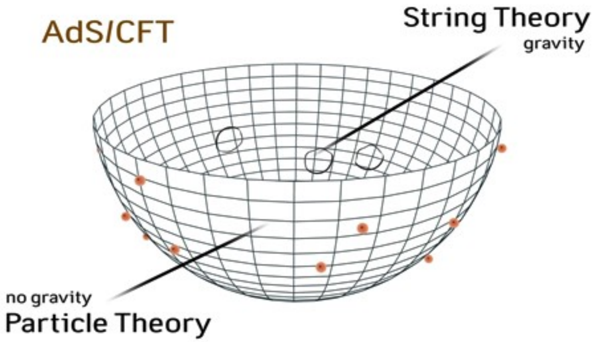
- Calculation is sensitive to vacuum structure: condensates, instantons, etc. Results very uncertain for most glueball states (except “clean” 2^{++} state)

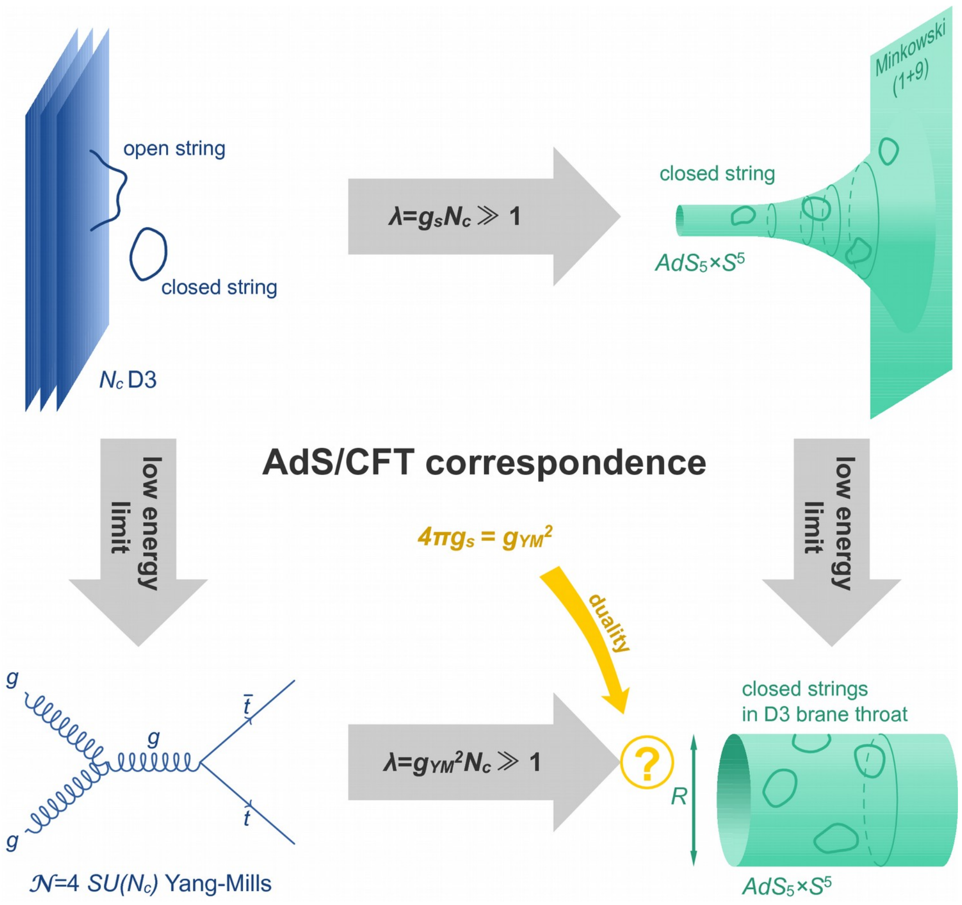


(a) (b) (c) (d) (e)

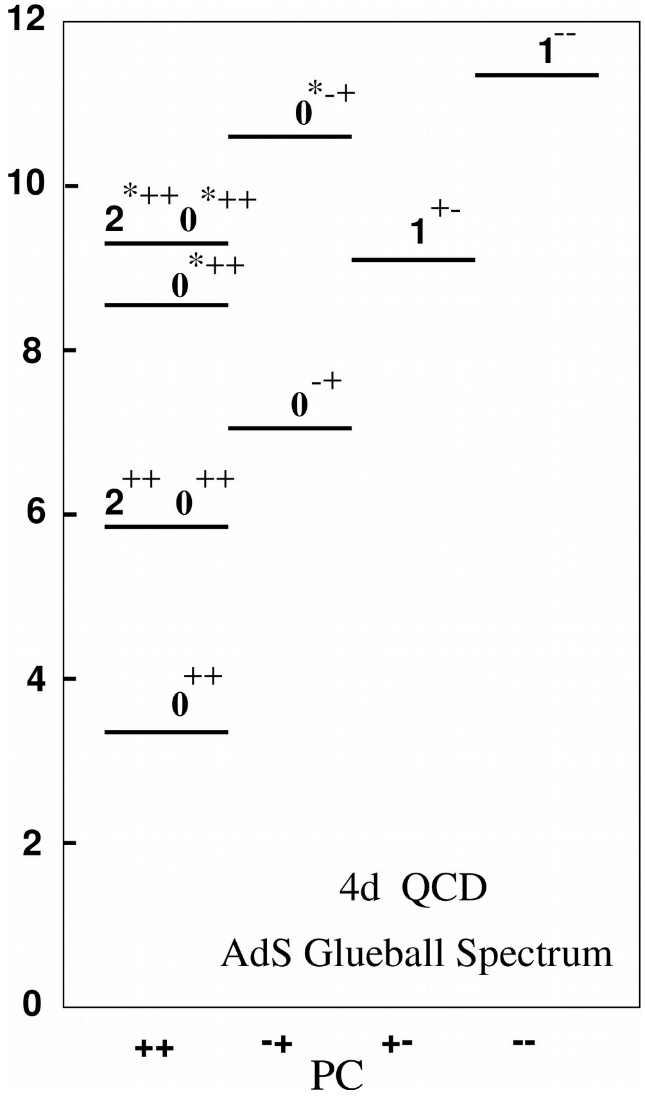
AdS/QCD

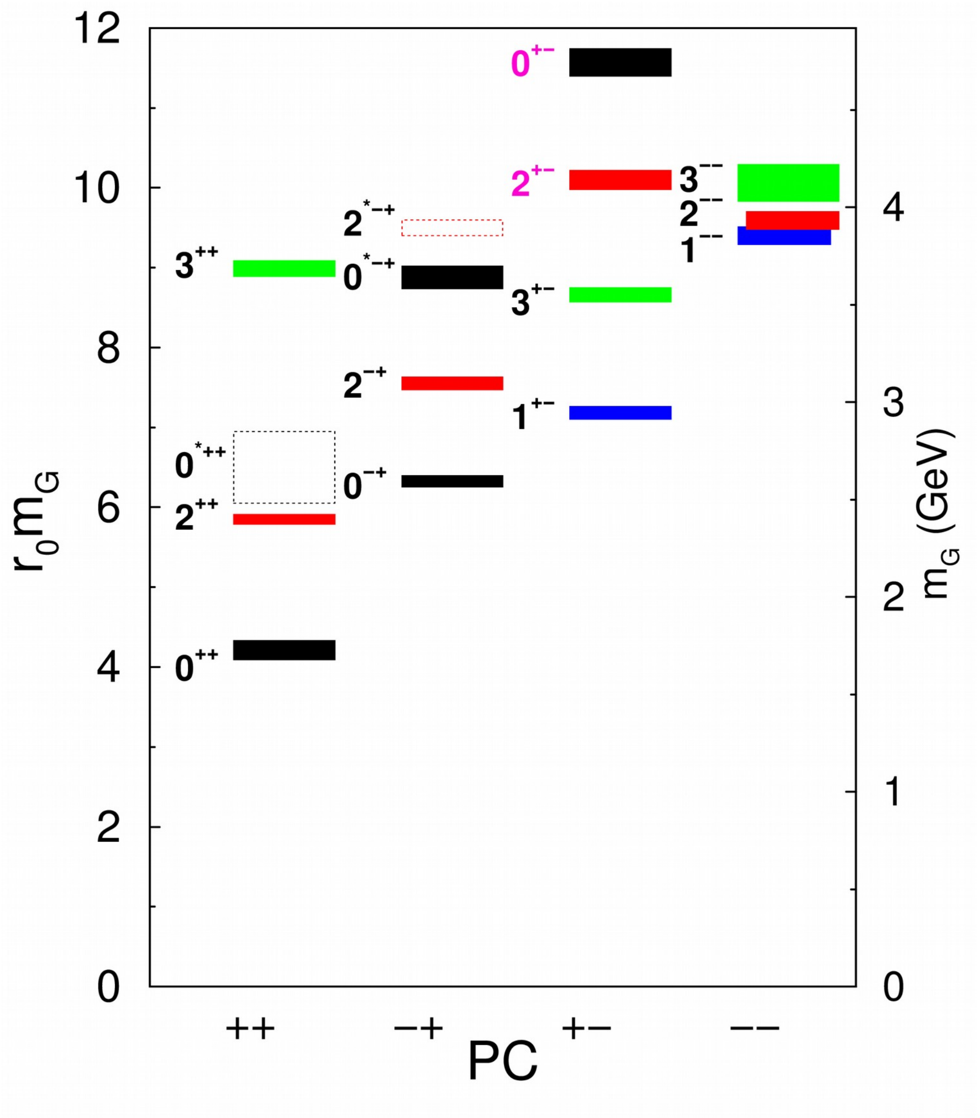
- Inspired by AdS/CFT: Anti de-Sitter/Conformal Field Theory
  - D-dim superstring theory equivalent to strongly-coupled (D-1)-dim conformal field theory on the boundary
- AdS/QCD: Break conformal invariance by e.g. introducing a black hole in the bulk
- Calculate in g, $N_c \rightarrow \infty$ limit, where we get "easy" classical supergravity in the bulk
- Glueball spectrum deduced from graviton modes in black hole background





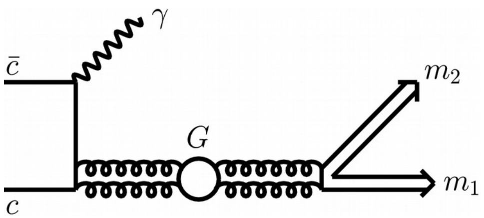
AdS/QCD vs. Lattice

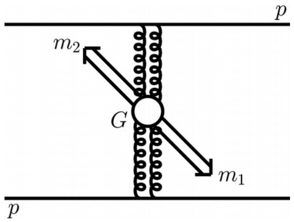


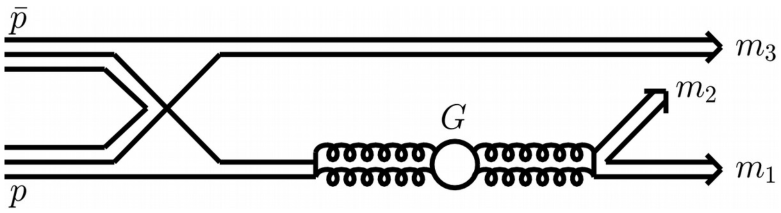


Glueball production/detection

- Production dominated by “gluon-rich” processes where quark channels are suppressed
  - Radiative J/ψ decays (BES III): To photon + pair of gluons (glueball)
  - Central production: Hadrons exhange gluons
  - $p\bar{p}$ annihilation: $p\bar{p} \rightarrow \pi^0 G$ ($\overline{\text{P}}$ANDA)
  - Photoproduction (GlueX)







- Decays:
  - To ordinary mesons, baryons
  - Distinguishing feature: No radiative decays, no decays to ηη’
    - Can be spoiled by mixing with quarkonia
  - Flavor independent? Traditional assumption, but quite possibly wrong
  - Dirty, broad resonances due to mixing
  - Many candidates, but hard to determine whether made from gluons or quarks

Hunting for glueballs

- Need good understanding of “ordinary” hadron spectrum to avoid false positives
- Simplest approach: Look for “oddballs”
  - $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$: Impossible for $q\bar{q}$
  - Narrow width, easy to identify
  - 4.3 GeV 2^{+-} state expected to be visible at $\overline{\text{P}}$ANDA
  - Lighter oddballs might mix with “hybrid” mesons ($q\bar{q}g$)

Prime candidate $f_0(1710)$

- 1.7 GeV state, ~100 MeV width, $J^{PC} = 0^{++}$ (not an oddball)
- Theory studies often predict lowest glueball near 1.7 GeV!
- A well-established resonance, but what is it?
- Decays biased toward strange quarks…
  - Uh oh! Assuming flavor SU(3), glueballs shouldn't distinguish between u, d, s
- Not so fast! TU Wien theoriests, using AdS/QCD, found that quark masses enhance strange decays
- Meanwhile, candidate $f_0(1500)$'s decays don't agree with AdS/QCD

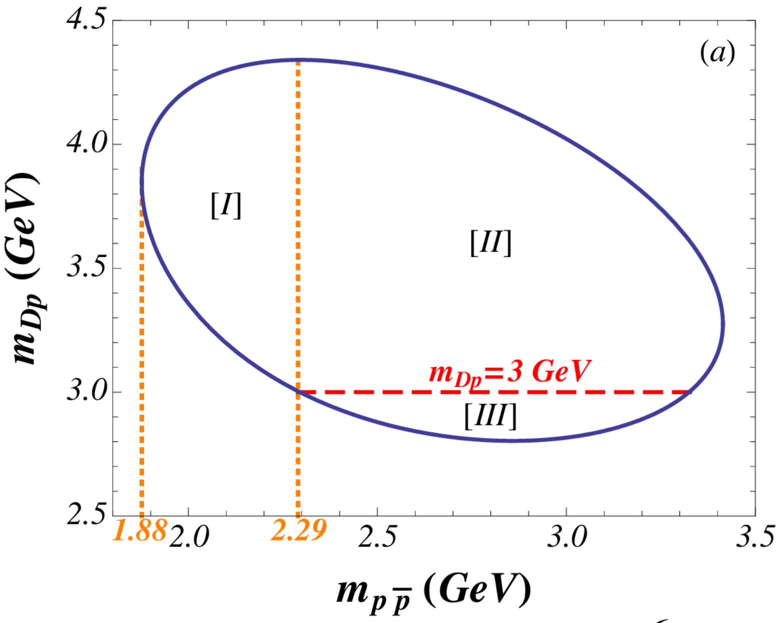
TU Wien AdS/QCD results

decay	Γ/M (exp. [8])	(WSS chiral [24])	(WSS massive)
$f_0(1500)$ (total)	0.072(5)	0.027...0.037	0.057...0.077
$f_0(1500) \to 4\pi$	0.036(3)	0.003...0.005	0.003...0.005
$f_0(1500) \to 2\pi$	0.025(2)	0.009...0.012	0.010...0.014
$f_0(1500) \to 2K$	0.006(1)	0.012...0.016	0.034...0.045
$f_0(1500) \to 2\eta$	0.004(1)	0.003...0.004	0.010...0.013
$f_0(1710)$ (total)	0.078(4)	0.059...0.076	0.083...0.106
$f_0(1710) \to 2K$	$* \begin{cases} 0.041(2) \\ 0.047(17) \end{cases}$	0.012...0.016	0.029...0.038
$f_0(1710) \to 2\eta$	$* \begin{cases} 0.020(10) \\ 0.022(11) \end{cases}$	0.003...0.004	0.009...0.011
$f_0(1710) \to 2\pi$	$* \begin{cases} 0.017(4) \\ 0.009(2) \end{cases}$	0.009...0.012	0.010...0.013
$f_0(1710) \to 2\rho, \rho\pi\pi \to 4\pi$	?	0.024...0.030	0.024...0.030
$f_0(1710) \to 2\omega \to 6\pi$	seen	0.011...0.014	0.011...0.014

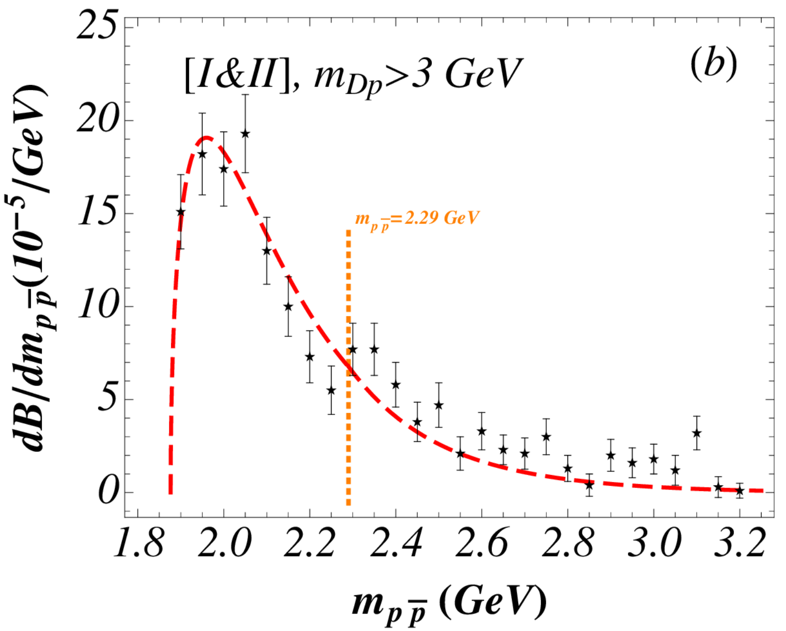
Another one: X(3020)?

- Unexpected “resonance” at 3.02 GeV observed in BaBar data for $\bar{B}^0 \rightarrow p\bar{p}D^0$
- So far only reported by one(?) group in Taiwan
- Charmonium interpretation excluded based on known J/ψ properties
- Light $q\bar{q}$ excluded; too damn heavy
- J^{PC} could be 2^{-+}, 1^{--}, 1^{+-} ...

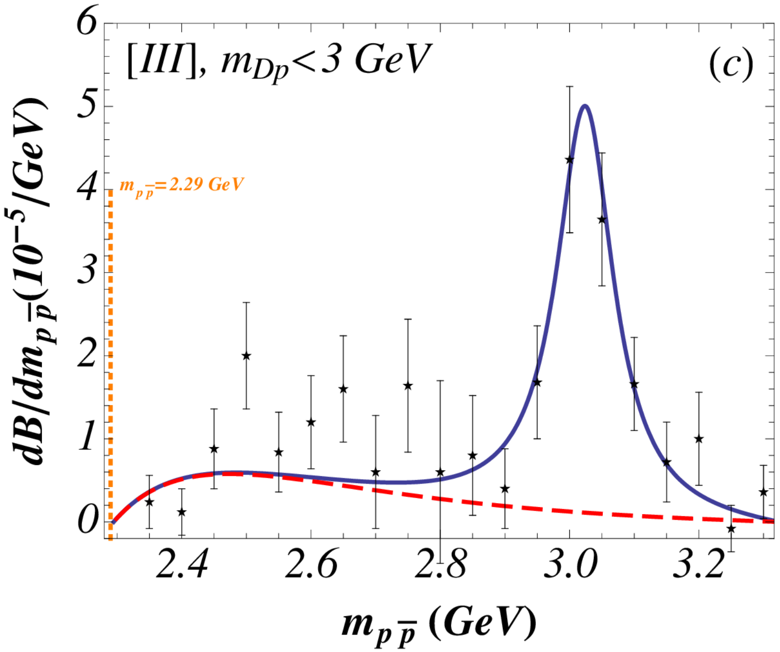
X(3020) evidence



Dalitz plot showing kinematic regions considered



p̄p invariant mass in "background" regions I+II



The money plot. 3 GeV enhancement can't be explained by perturbative QCD, must be a resonance

Conclusions

- Glueballs *should* exist
- Predictions are difficult
- Various candidates proposed
- If confirmed, would be another victory for QCD
- Ongoing/future experiments ($\overline{\text{P}}$ANDA, BES III, GlueX) will hopefully provide the necessary data

Further reading

- *The Physics of Glueballs,* **0810.4453**
- AdS/QCD: *Nonchiral enhancement of scalar glueball decay in the Witten-Sakai-Sugimoto model,* **1504.05815**
- *Identifying Glueball at 3.02 GeV in Baryonic B Decays,* **1302.3351**
- *Search for Glueballs,* http://www.slac.stanford.edu/cgi-wrap/getdoc/ssi96-006.pdf (old, 1996)