Employing spin symmetry to disentangle different models for the XYZ states

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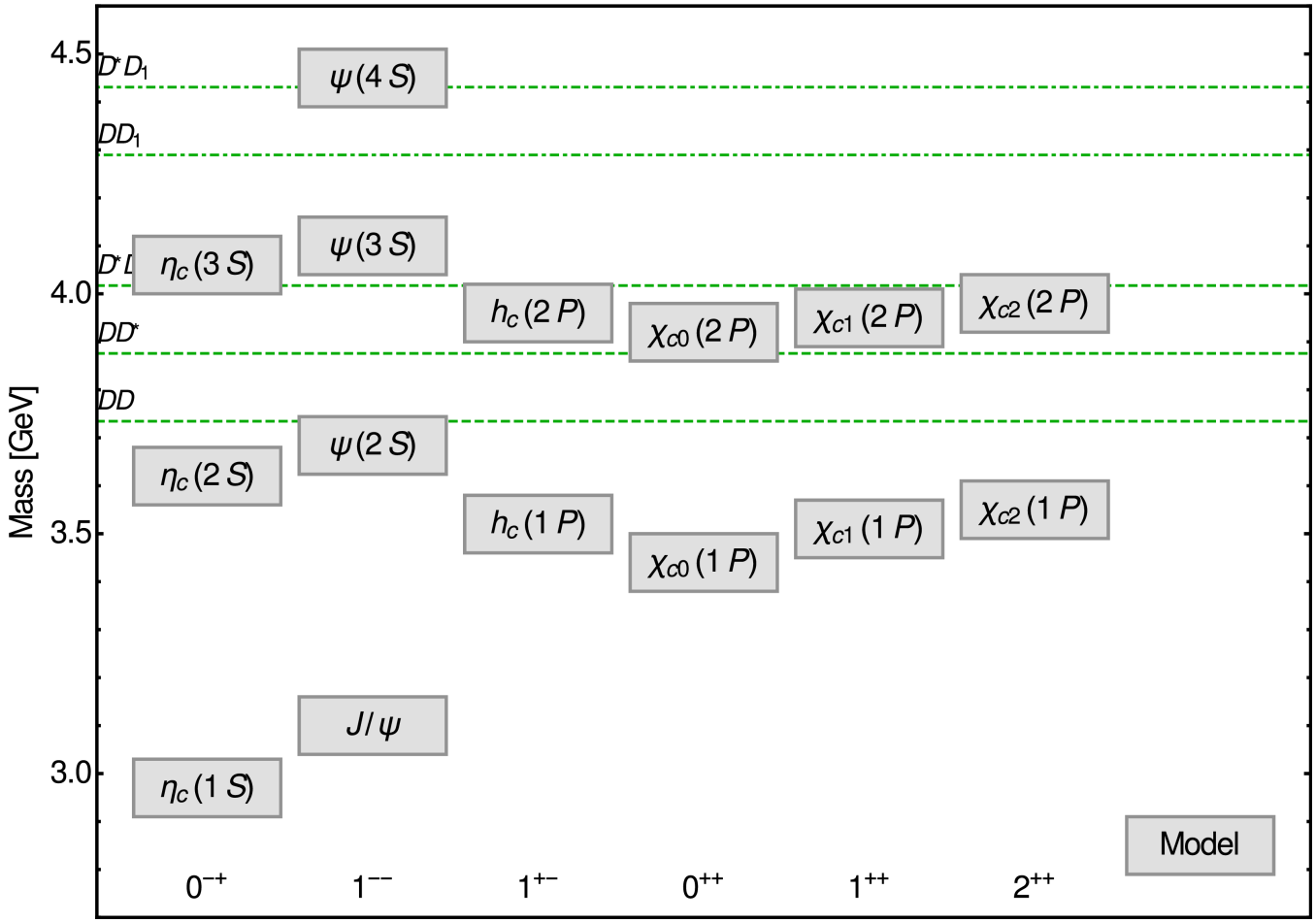
S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985), PDG

Charmonium Spectrum

Addittional states not shown here



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Charmonium Spectrum below open thresholds in perfect agreement with Quark Models (here: Godfrey-Isgur-Wise)

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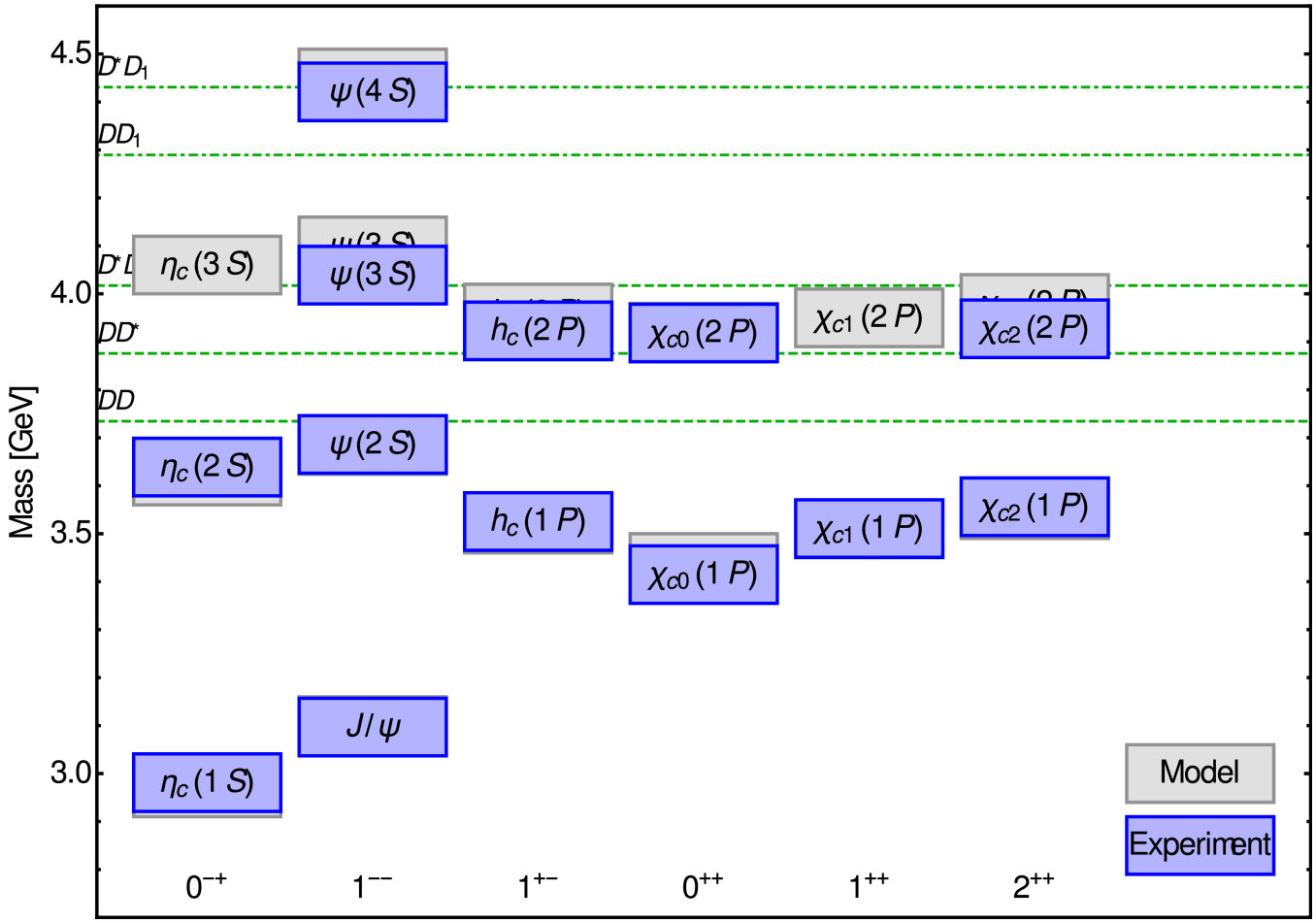

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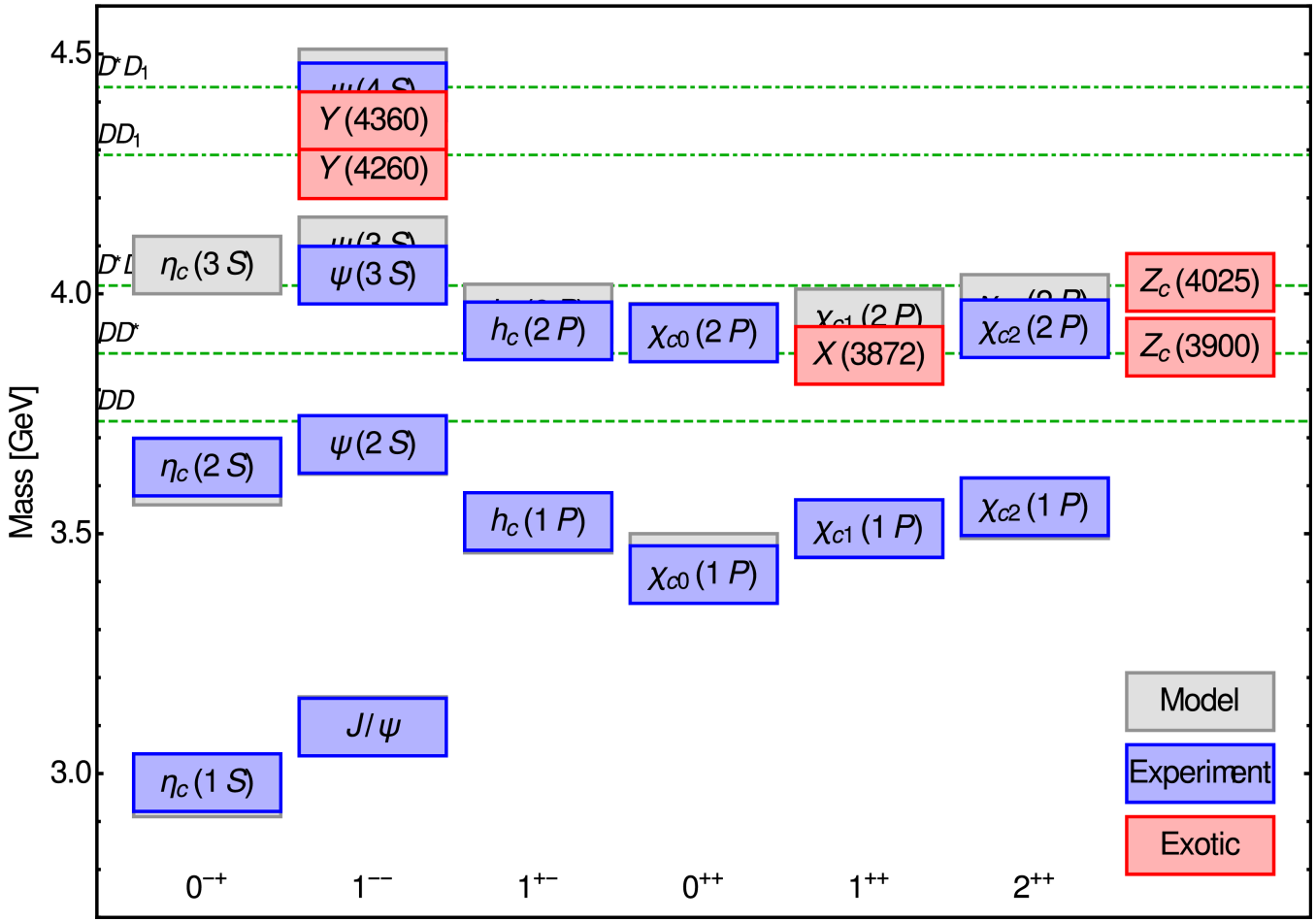

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Many new states at odds with potential models → Exotics

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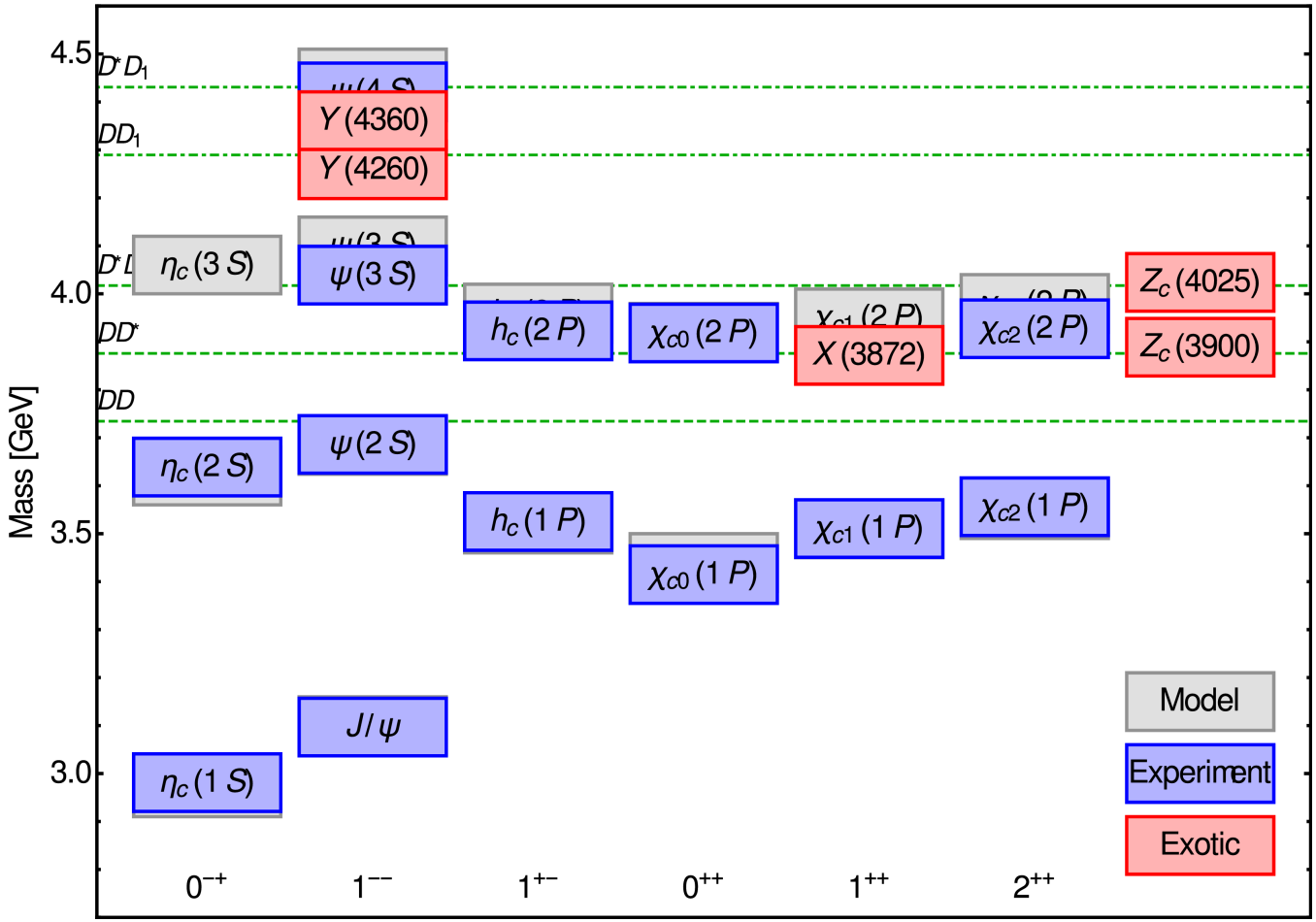

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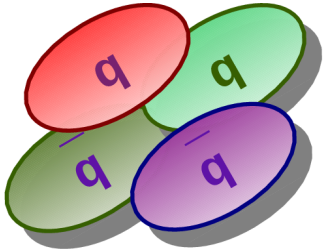
Heavy Quark Spin Symmetry: Spin Multiplets

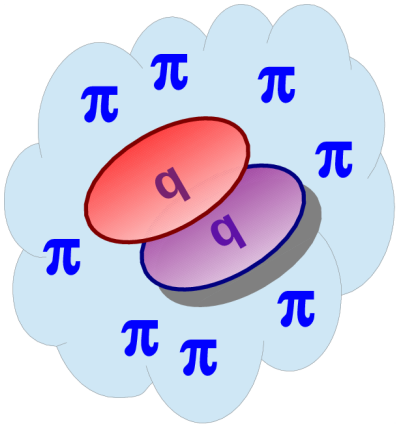
$$(D, D^*) \quad (D_1, D_2) \quad (J/\psi, \eta_c) \quad (h_c, \chi_{cJ})$$

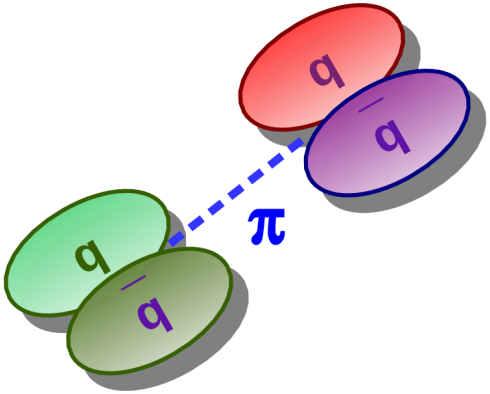
Color-Neutral Objects: Exotic Configurations



[Tetraquark]
Compact state of four quarks

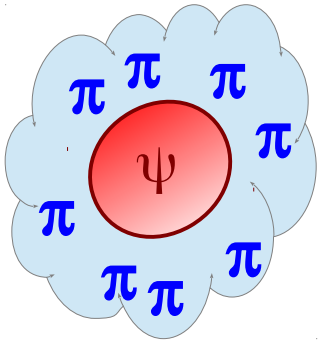
[Hadrocharmonium]
Heavy Quarkonium Core
Surrounded by pion cloud



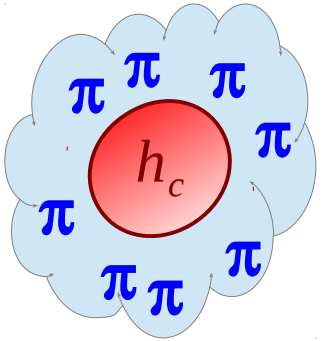


[Hadronic Molecule]
Formed from interactions of two hadrons
Classic Example for Baryons: Deuteron

M. B. Voloshin, PPNP 61, 455 (2008); S. Dubynskiy and M. B. Voloshin, PL B 666, 344 (2008); X. Li and M. B. Voloshin, MPL. A 29, 1450060



Hadro-Charmonium



- (Conventional) Quarkonium core
- Light quark cloud surrounding the core

Features

- Dominant decay mode: Core + pions
- Exotic quantum numbers possible

Problem for Y states:

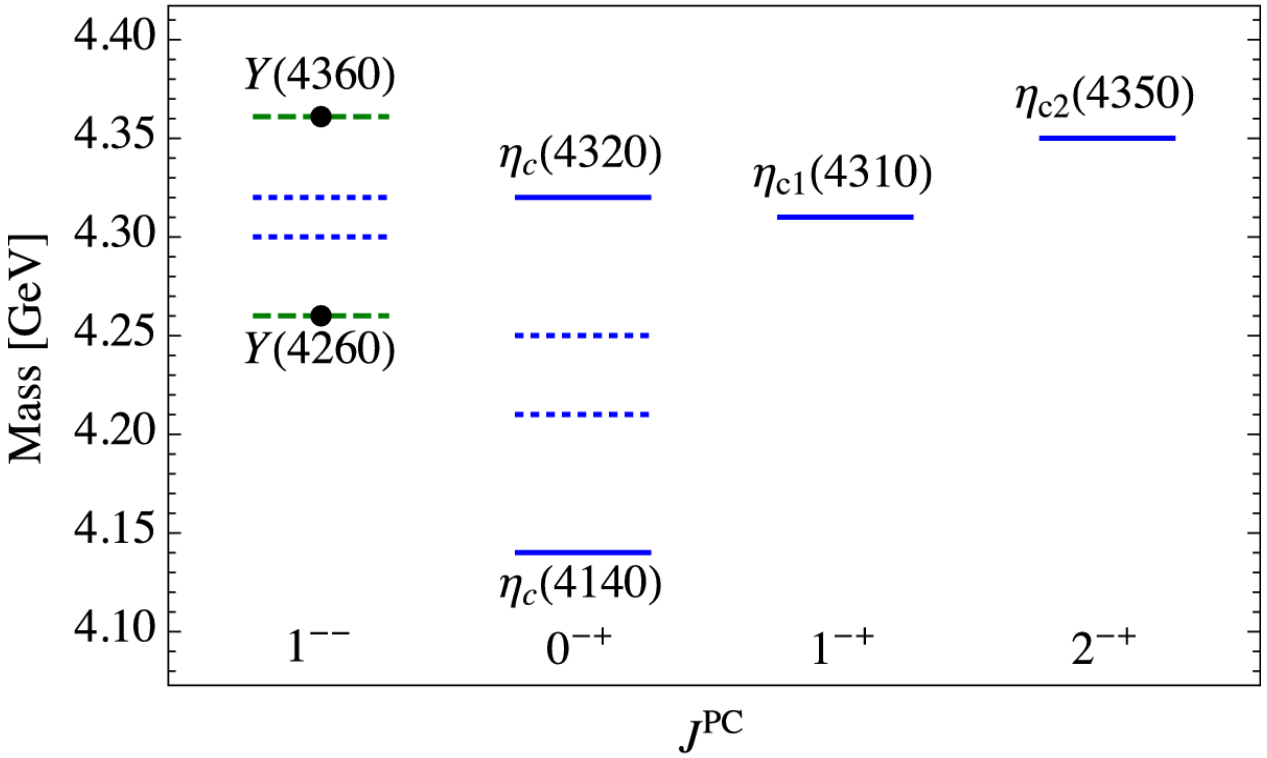
- Both Y(4260) and Y(4360) seen in final states
  $J/\psi\pi\pi$, $\psi'\pi\pi$ and $h_c\pi\pi$
  → Heavy Quark Spin Flip!

Solution:

- Lin. Combinations of
  $\psi_1 \sim h_c \times (0^{-+})_{q\bar{q}}$ and $\psi_3 \sim \psi' \times (0^{++})_{q\bar{q}}$

MC et. al.,Phys.Rev. D92 (2015) 1, 014005

Predicted Spectrum based on HQSS



Spin Multiplets

(ψ, η_c) and (h_c, χ_{cJ})

Possible Final States

$\eta_c \pi\pi$, $\chi_{cJ} \pi\pi$

Decay Channels

$Y \to \gamma\, \eta_c/\chi_{cJ}\, \pi\pi$

$B \to K\, \eta_c/\chi_{cJ}\, \pi\pi$

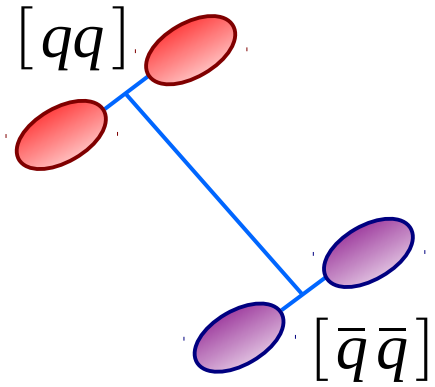
Distinct Features

- Exotic QN $J^{PC} = 1^{-+}$
- Two $J^{PC} = 0^{-+}$, one of them below Y(4260)

Tetraquark

L. Maiani et al., Phys. Rev. D 89, 114010 (2014)
A. Esposito et al., Int. J. Mod. Phys. A 30, 1530002 (2015)

Originally proposed to explain the mass hierarchy of the light scalar mesons



- Diquark-Antidiquark model
- Other (more sophisticated?) models exist
- General Properties remain

Hyperfine Splitting from Diquark/Antidiquark:

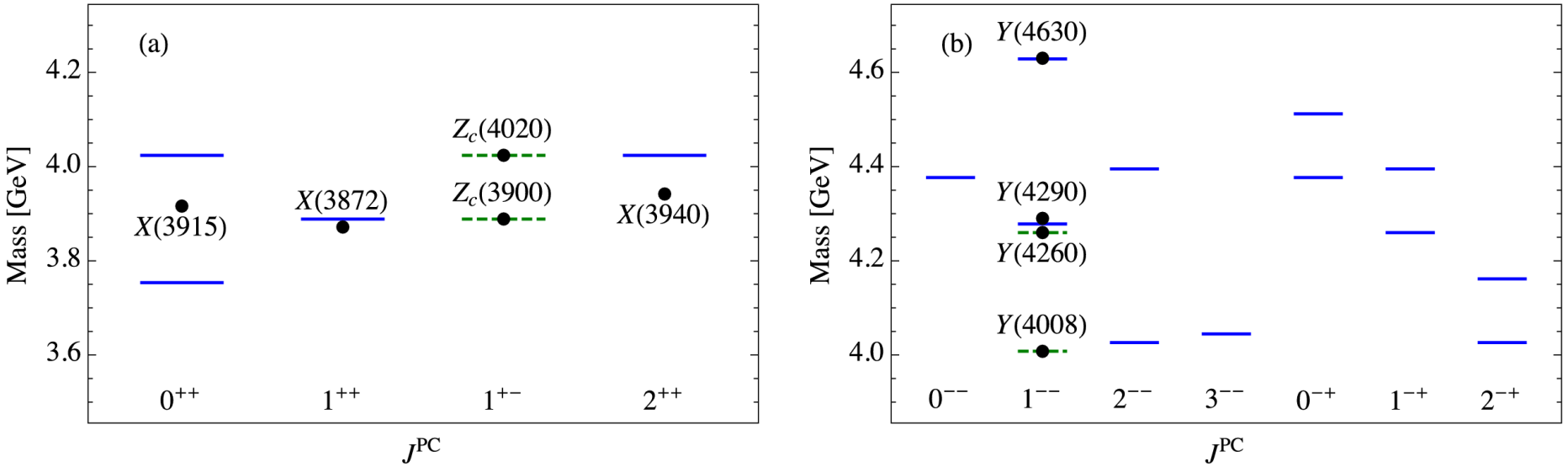
$$M = M_{00} + B_c \frac{L^2}{2} - 2a(L \cdot S) + 2\kappa_{cq}\left[(s_q \cdot s_c) + (s_{\bar{q}} \cdot s_{\bar{c}})\right]$$

Tetraquark II

Resulting Spectrum

L. Maiani et al., Phys. Rev. D 89, 114010 (2014)
A. Esposito et al., Int. J. Mod. Phys. A 30, 1530002 (2015)
MC et. al.,Phys.Rev. D92 (2015) 1, 014005

$$M = M_{00} + \frac{B_c}{2} L(L+1)$$
$$+ a\left[L(L+1) + S(S+1) - J(J+1)\right] + \kappa_{Qq}\left[s(s+1) + \bar{s}(\bar{s}+1) - 3\right]$$



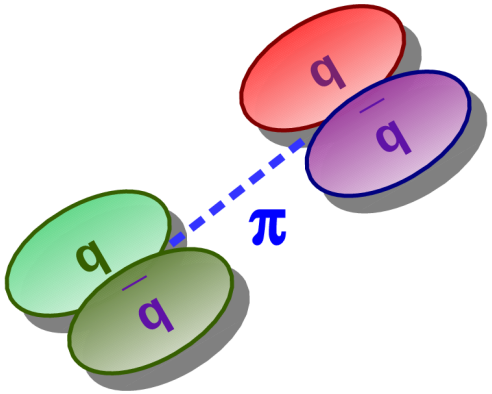
Consequences

- Extremely rich spectrum, degenerate for Isospin Singlet/Triplet
- E.g. Charged Partner of X(3872) expected
- Two 0^{-+} states > 4.4 GeV
- Low-lying state with $J^{PC}=3^{--}$

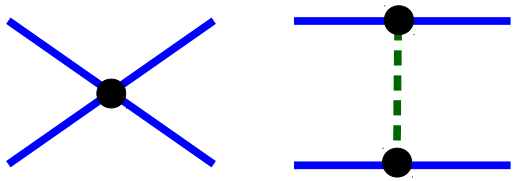
Molecules: Charmed Meson pairs

with Binding Energy <100 MeV

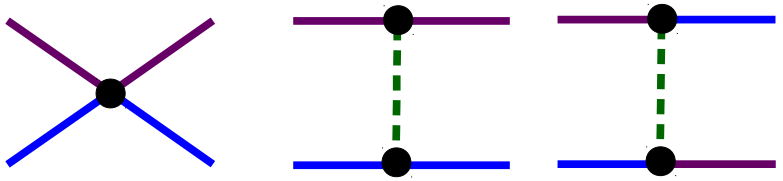
Classic Analogy: Deuteron as Proton-Neutron Bound State



- (D,D*) + (D,D*)



- (D_1,D_2) + (D,D*)



- Contact Term:
  - Short-ranged part
    – exchange of heavier mesons, s-channel...
  - Not enough data to fix all possible ones
    → drop here!
- One-pion exchange

  – some qualitative statements possible

- Isospin: $\langle I, I_3 | \vec{\tau}_{(1)} \cdot \vec{\tau}_{(2)} | I, I_3 \rangle = 2\left[I(I+1) - 3/2\right] = \begin{cases} -3 & I = 0 \\ 1 & I = 1 \end{cases}$

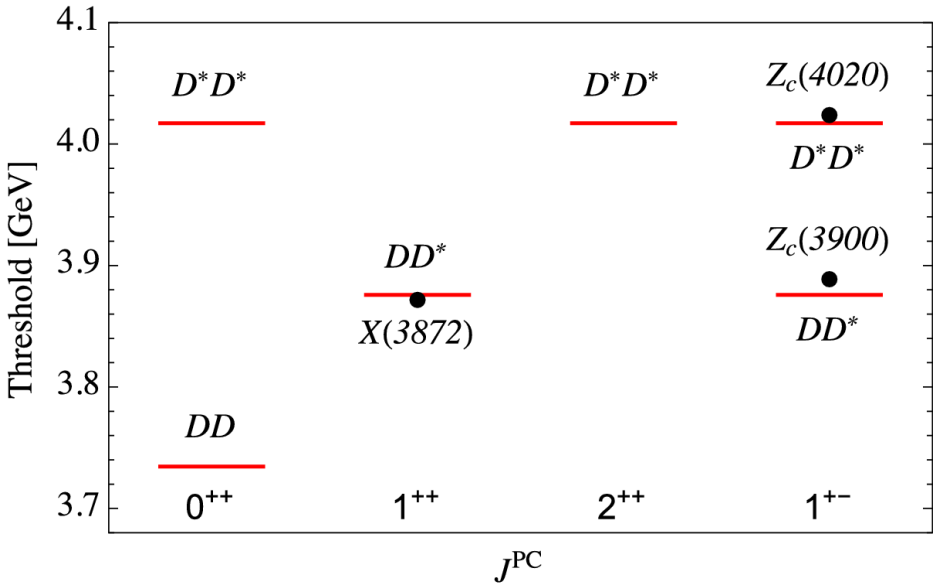
Either Isosinglet OR Isotriplet states!

Hadronic Molecules II

MC et. al.,Phys.Rev. D92 (2015) 1, 014005

Qualitative Only: Lines represent thresholds available for certain QN

Possible S-wave States

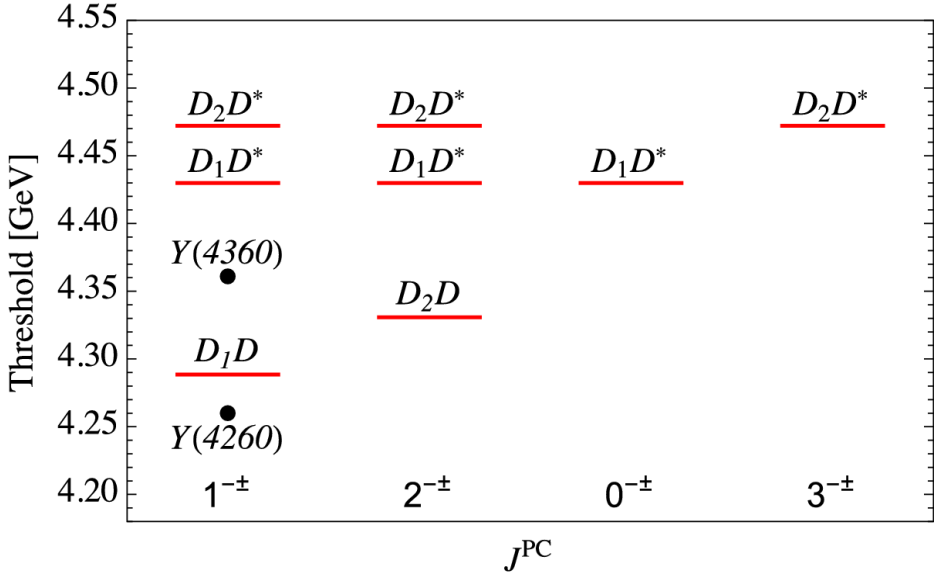


- X(3872) Isosinglet 1^{++}
- Contact Terms $V_{2^{++}} = V_{1^{++}} \rightarrow X_2$

  J.Nieves, et. al., PRD86(2012)056004,

  F.K.Guo, et. al., PRD88(2013)054007,
- $Z_c(3900)$ & $Z_c(4025)$ Isotriplet

Possible P-wave States



- Spin 3 state significantly higher than for tetraquarks
- Single 0^{-+}, significantly higher than for HC
- Isoscalar 0^{--} and 3^{-+}
- Isovector 0^{-+} and 3^{--}

Smoking Guns

- Charged partner of X(3872)
  - Strong Support for Tetraquark
  - Impossible for Hadronic Molecule or Hadro-charmonium
- States with 0^{-+}
  - Hadro-Charmonium: Two states 4.1 GeV and 4.3 GeV
  - Tetraquark: Two states > 4.4 GeV
  - Hadronic Molecule: One state near D_2D^* thr. (4.4 GeV)
- Spin 3 state
  - $M_{3^-} < 4.1$ GeV → Tetraquark, $M_{3^-} > 4.4$ GeV → Molecule