Lessons from the heavy-quarkonium spectrum

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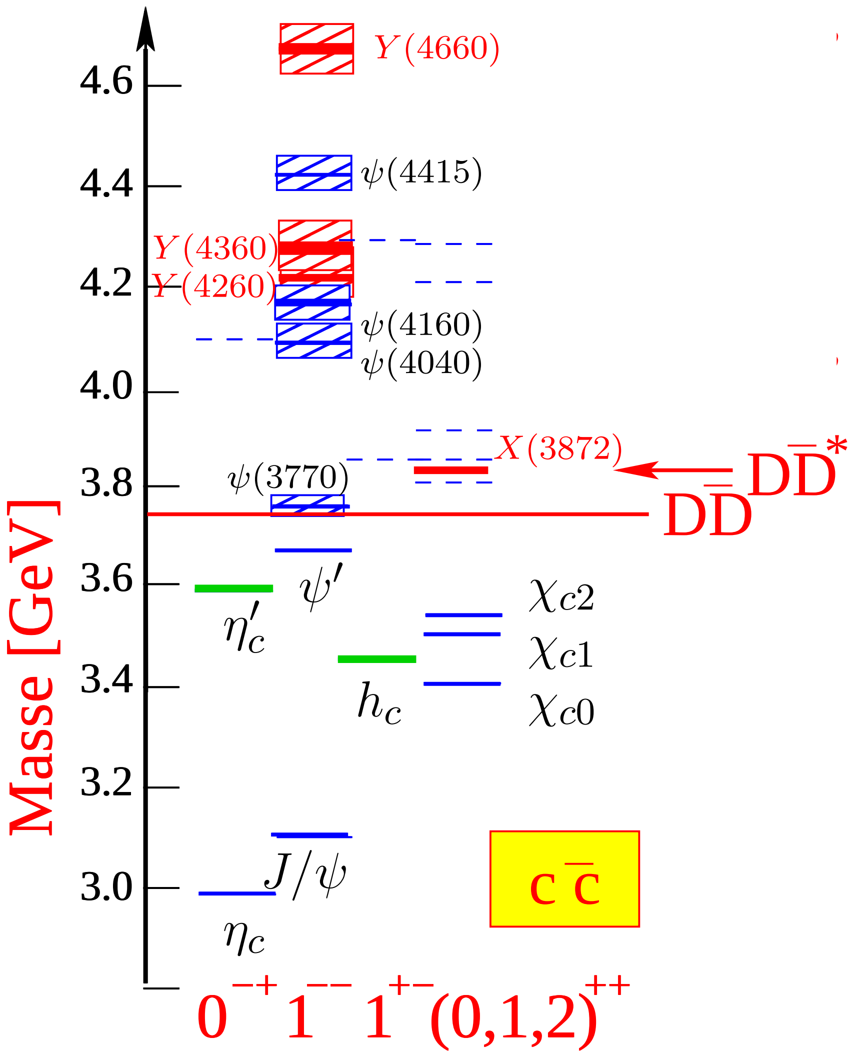
Charmonium after 2002

A new particle Zoo!

only established states shown



Quark-Model: Eichten et al. PRD 17 (1978)

→ missing low lying states found

→ Above the $\bar{D}D$ threshold:

- ▷ Many new states
- ▷ incompatible with quark model in mass and properties

→ Quark model states seem also present

Charged states

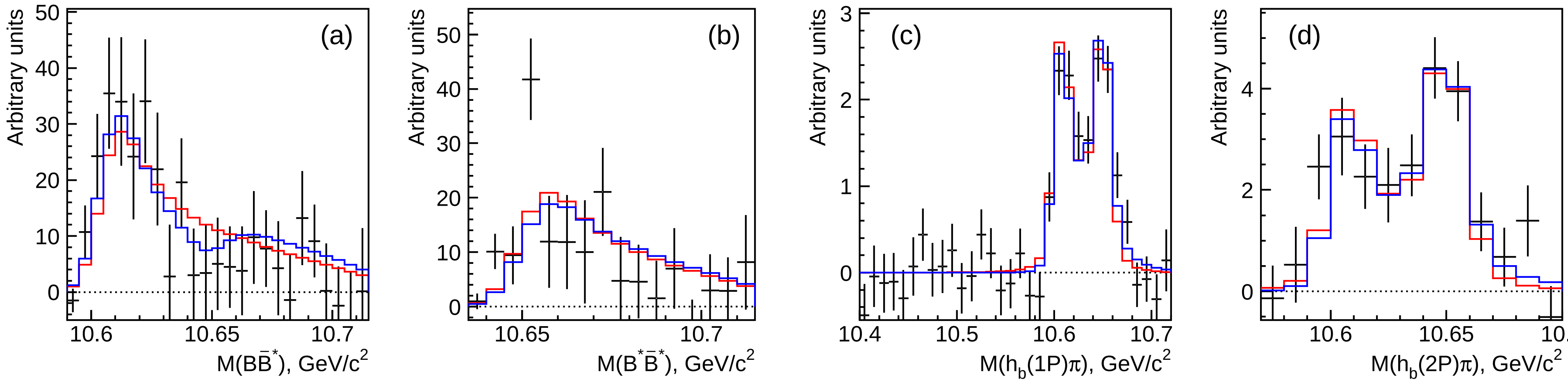
2011: Discovery of charged states that

→ have masses in the quarkonium regime;

→ decay with $\bar{Q}$ und Q in the final state

→ must contain at least 4 quarks

E.g. $Z_b(10610)^+$ and $Z_b(10650)^+$ in $e^+e^- \to \pi\pi(\bar{Q}Q)$ at $\Upsilon(5S)$

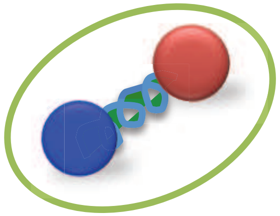


Data by Belle: A. Garmash *et al.*, `arXiv:1512.07419` & A. Bondar et al., PRL 108(2012)122001

Talk by Qian Wang at this conference

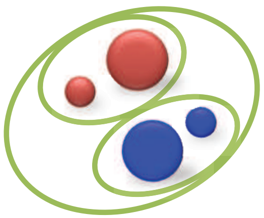
more of the kind: $Z_c(3900)^+$, $Z_c(4020)^+$, $Z_c(4430)^+$, ...

Proposals



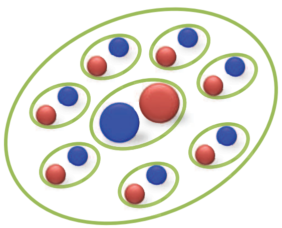
Hybrid

$\rightarrow$ Compact with active gluons and $\bar{Q}Q$



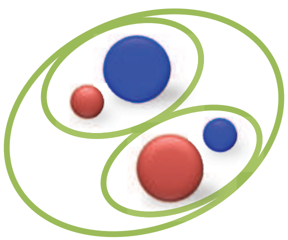
Tetraquark

$\rightarrow$ Compact object formed from (Qq) and $(\bar{Q}\bar{q})$



Hadro-Quarkonium

$\rightarrow$ Compact $(\bar{Q}Q)$ surrounded by light quarks



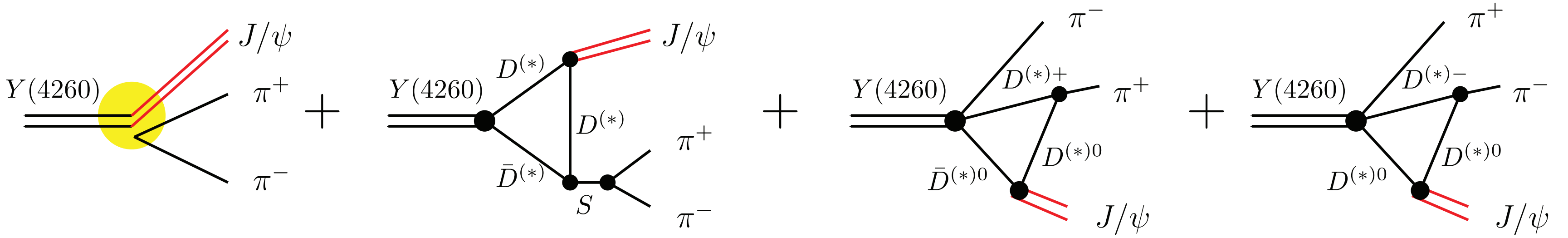
Hadronic-Molecule

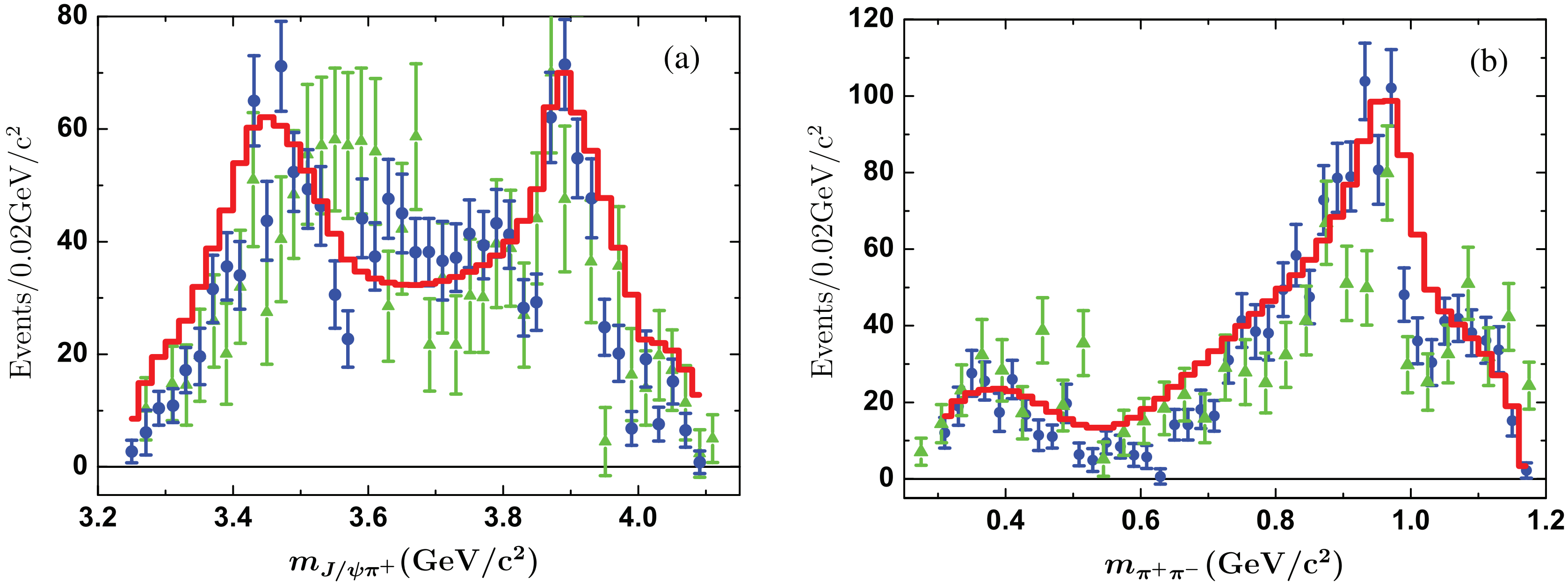
$\rightarrow$ Extended object made of $(\bar{Q}q)$ and $(Q\bar{q})$

... or simply a threshold effect?

(Some) XYZ-states threshold effects?

Bugg PLB598(2004)8; Chen et al. PRD84(2011)094003; Swanson PRD91(2015)034009





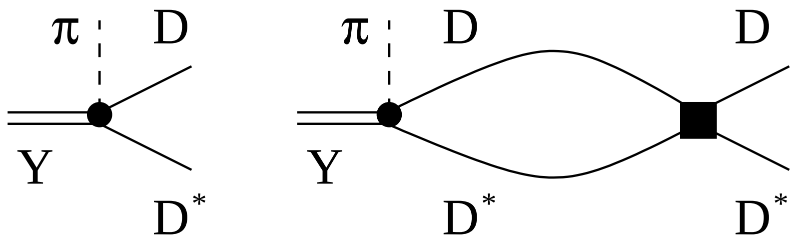
Chen et al., PRD88(2013)036008

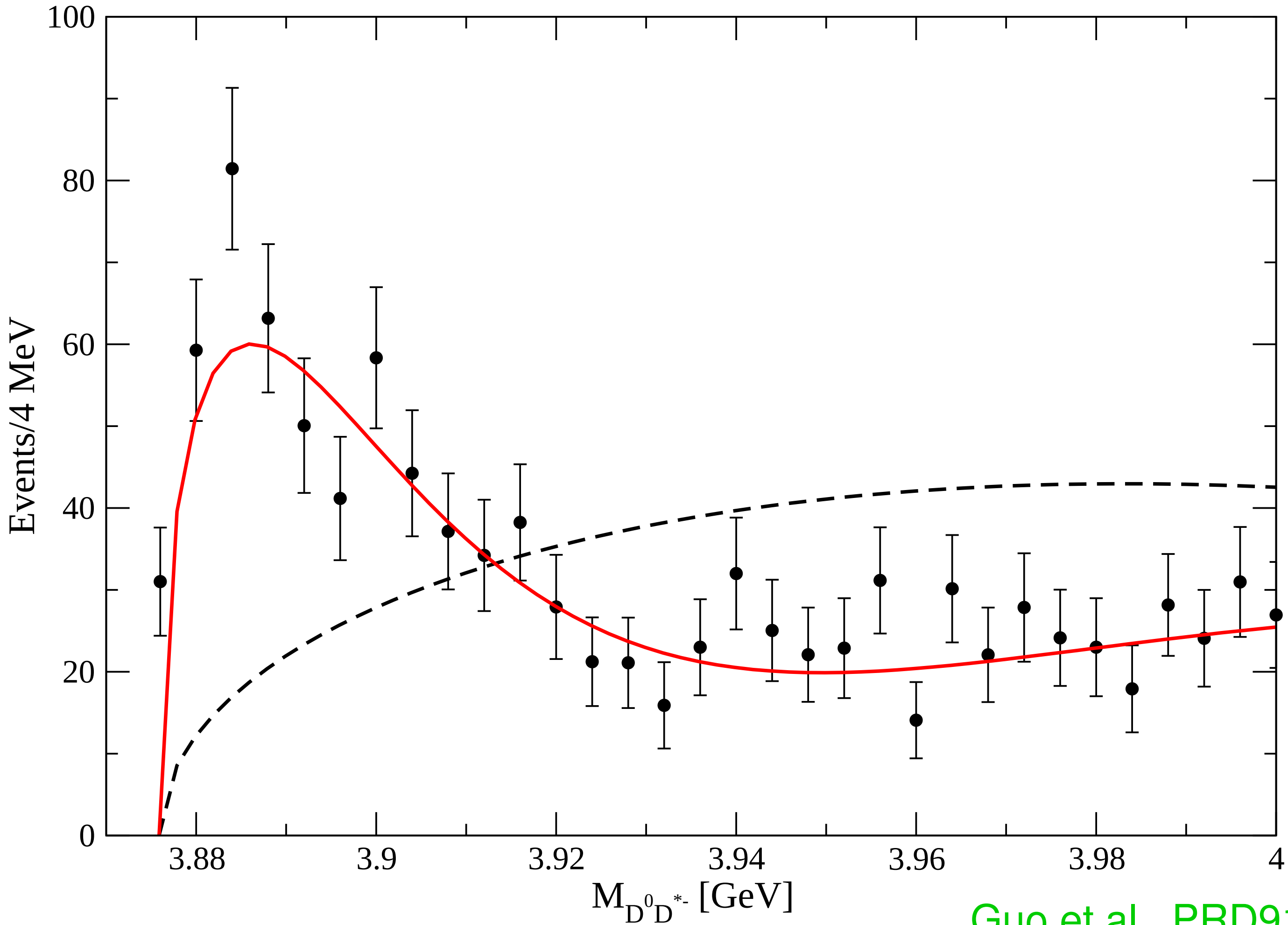
Could it be that the origin of $Z(3900)$ is a threshold cusp

followed by perturbative rescattering? —- NO!

For criticism to our point of view see Swanson arXiv:1504.07952

Why the argument is wrong





Guo et al., PRD91(2015)051504

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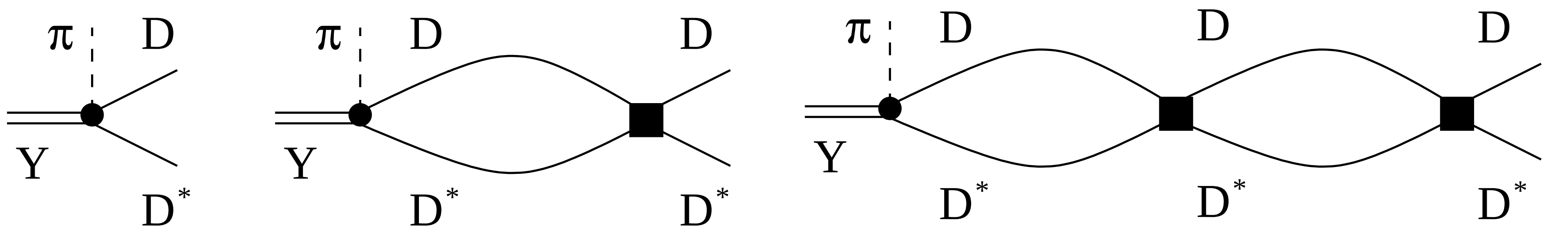

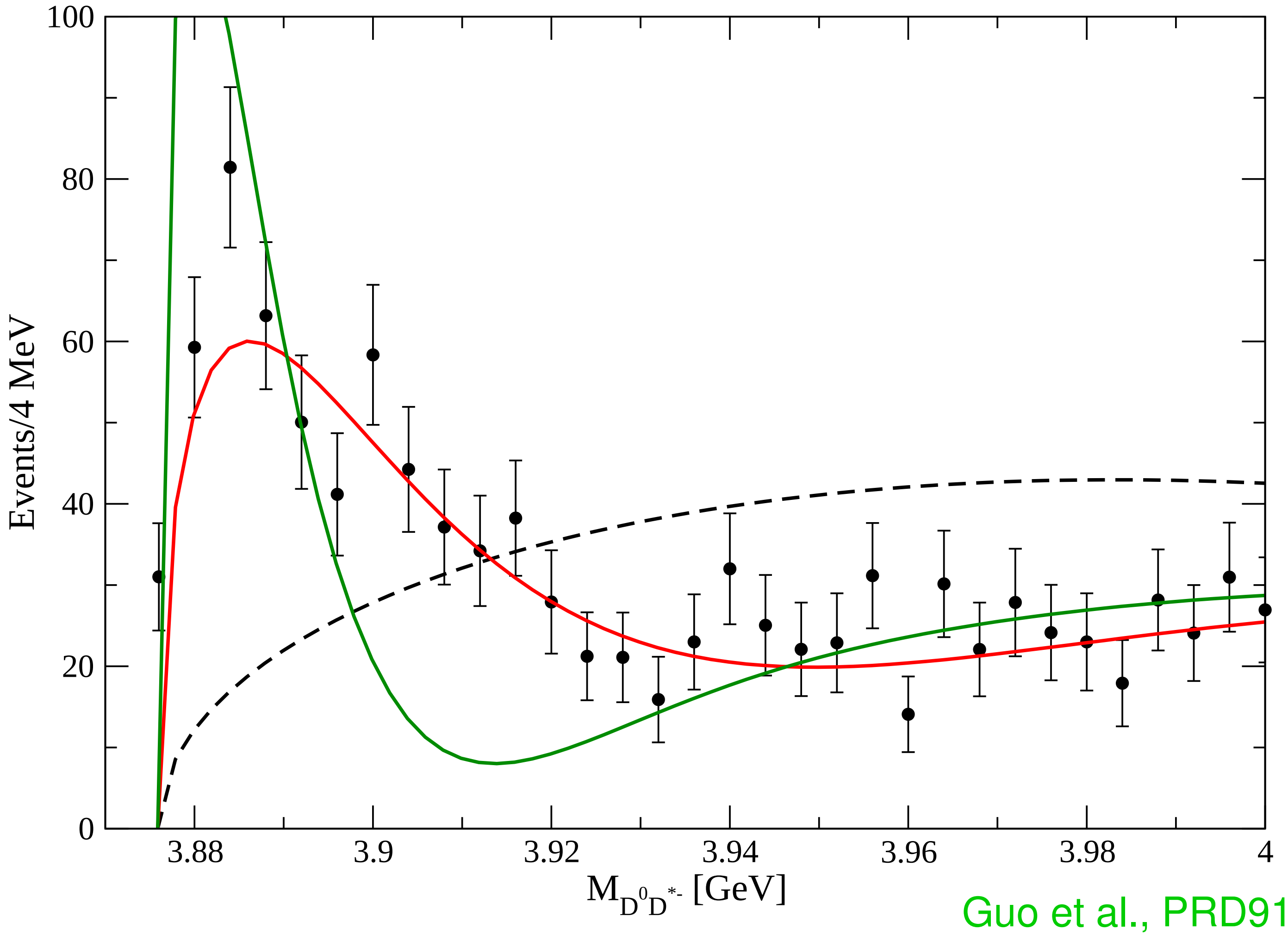

Guo et al., PRD91(2015)051504

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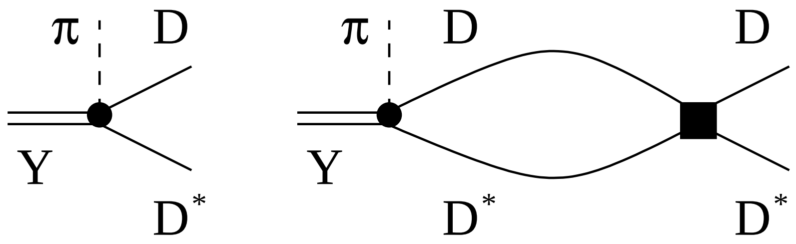
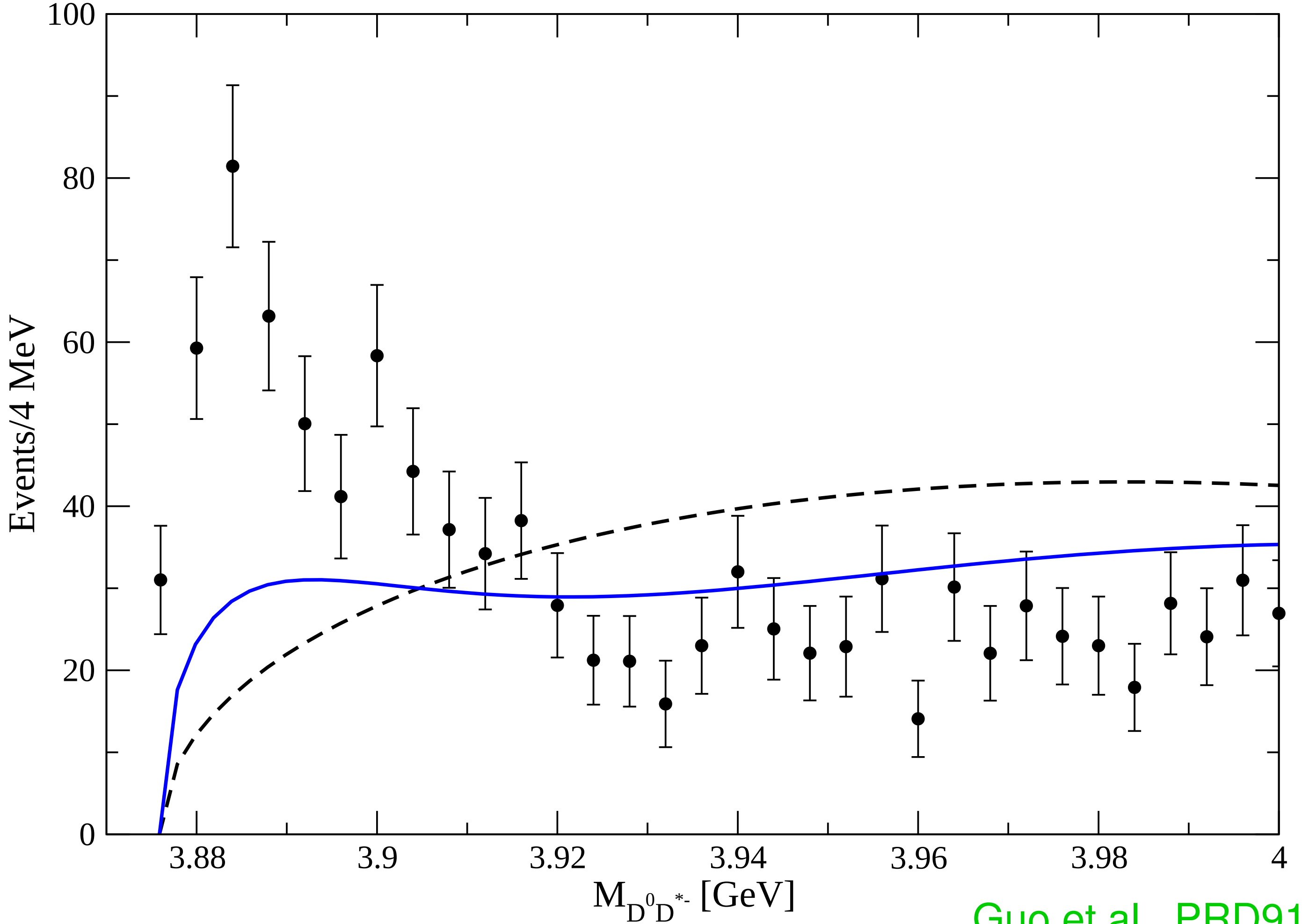
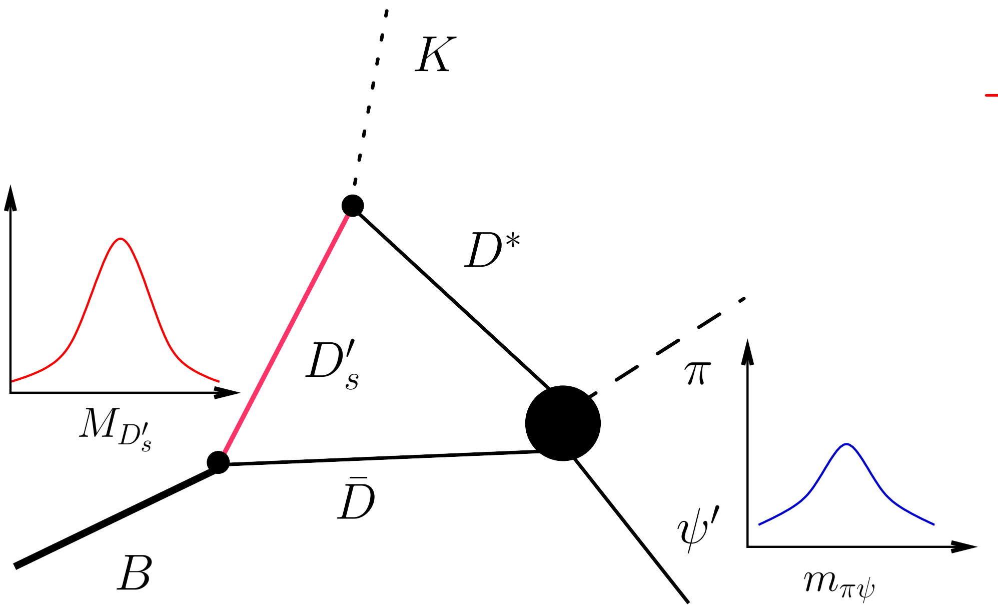




Guo et al., PRD91(2015)051504

(Some) driven by triangle–effects?



Pakhlov, PLB702(2011)139

→ if there are excited D_s in the proper mass range, they can produce the structure $Z(4430)$ in the $\pi\psi'$ invariant mass

... maybe — but certainly not for all XYZ–states, since

mechanism very sensitive to external invariant masses, and, e.g.,

→ $X(3872)$ is seen in B–decays and $Y(4260)$ radiative decays

→ $Z_c(3900)^+$ is seen at different energies in e^+e^-

→ not applicable to vectors states seen in e^+e^-

for more information see F.-K. Guos talk at this converence

Outline

From now on I assume the presence of poles is established

Question: What can we say about their nature?

I will now focus on two important aspects

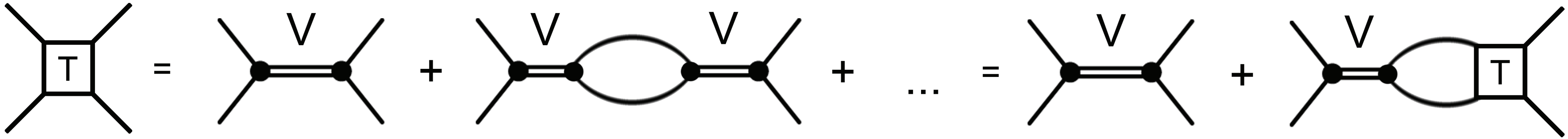
A Interplay of quark model states and hadronic continuum

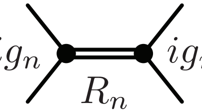
I. K. Hammer, C. H. and A. V. Nefediev, “Remarks on meson loop effects on quark models,” EPJA 52 (2016) 330 [arXiv:1607.06971 [hep-ph]]

B Distinct signatures of the different structures

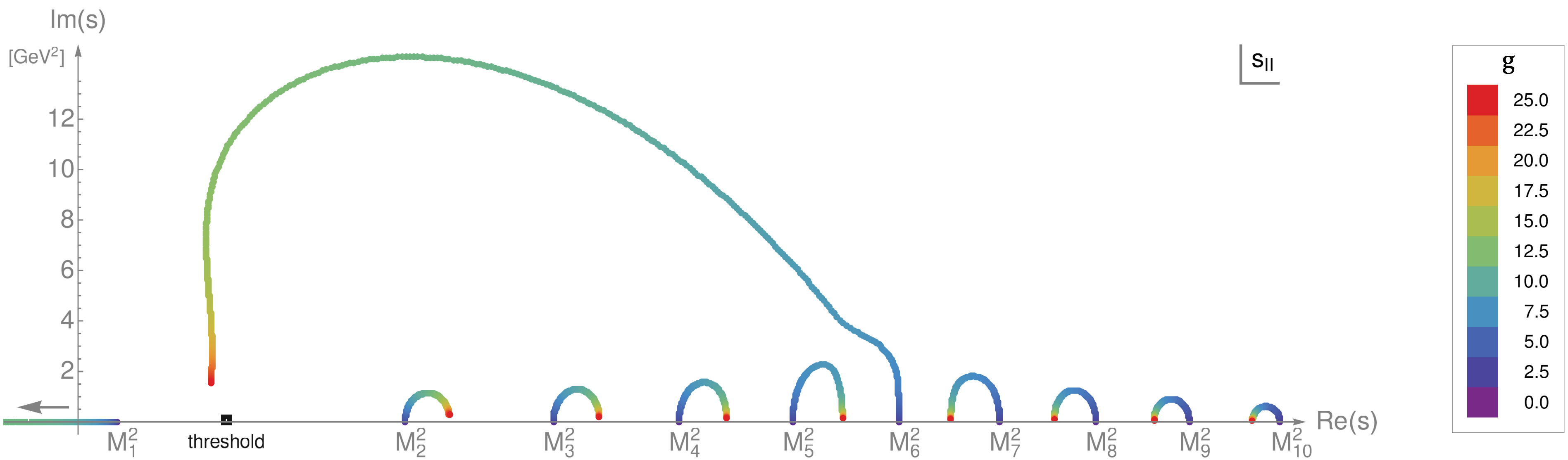
M. Cleven et al., “Employing spin symmetry to disentangle different models for the XYZ states,” PRD 92 (2015) 014005 [arXiv:1505.01771 [hep-ph]]

A: Unitarizing the quark model



with $V = \sum_{n=1}^{N}$ ig_n  ig_n $= -\sum_{n=1}^{N} \frac{g_n^2}{s - M_n^2}$ and $\Pi(s) = -\frac{i}{16\pi m}k - \Delta(g)$

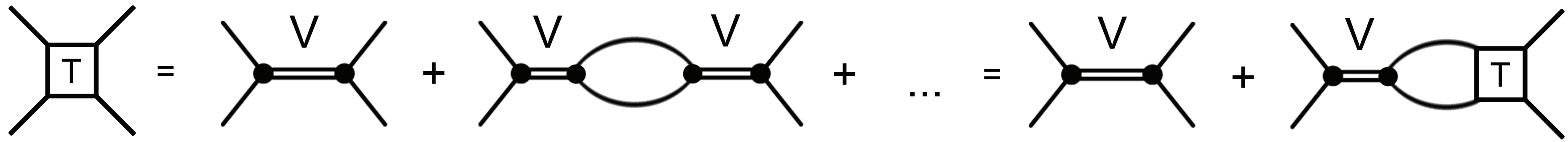
Pole trajectories: for $\Delta(g) = 0$ and increasing $g \equiv g_n$

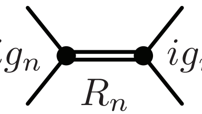


→ Most states decouple from continuum for $g = g_n \to \infty$

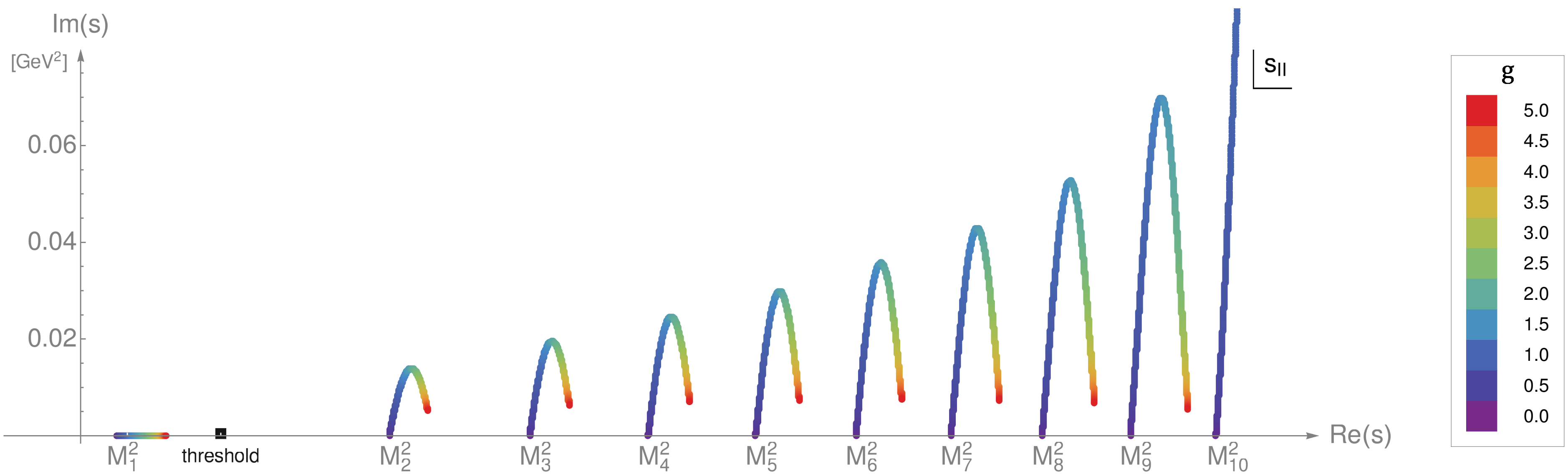
→ One state different - naturally close to threshold?

A: Unitarizing the quark model



with $V = \sum_{n=1}^{N} ig_n$  $ig_n = -\sum_{n=1}^{N} \frac{g_n^2}{s - M_n^2}$ and $\Pi(s) = -\frac{i}{16\pi m}k - \Delta(g)$

Pole trajectories: for $\Delta(g) = -0.5$ GeV and increasing $g \equiv g_n$



→ Most states decouple from continuum for $g = g_n \to \infty$

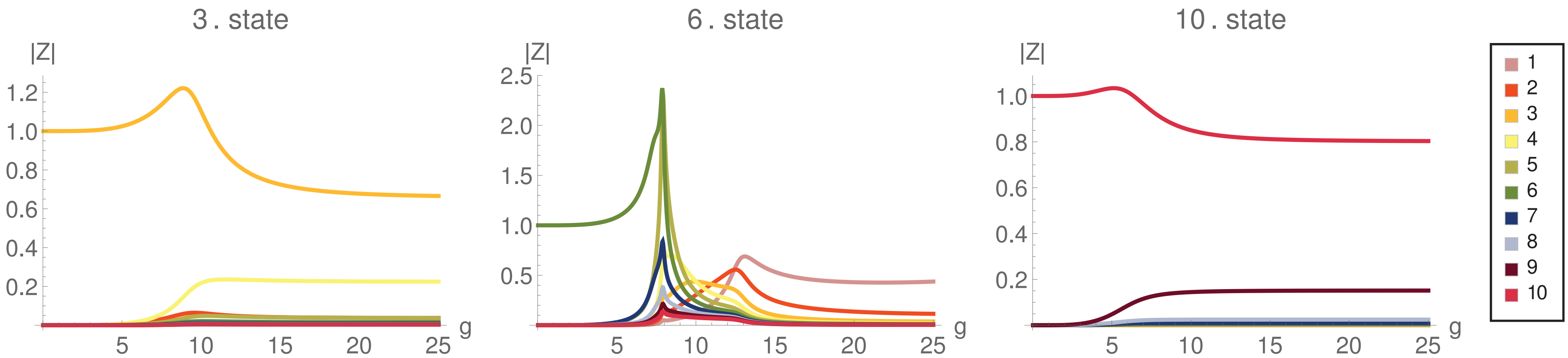
→ One state different - which one depends on Re(Π)

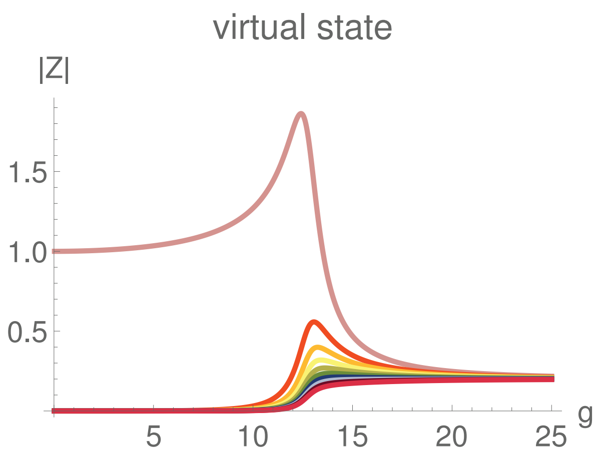
A: Residues

Residues: $Res\left(T(s_p^{(i)})\right) = \sum_{n,n'} g_n g_{n'} Z_{nn'}^{(i)}$

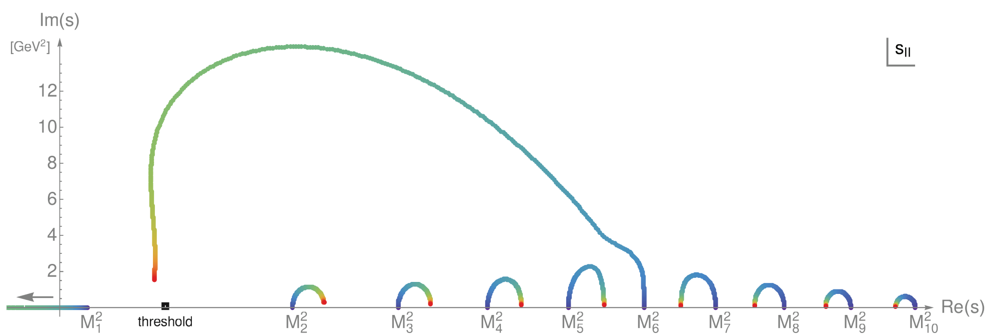
$|Z_{nn}^{(i)}|$: a measure of the admixture of the n$^{\text{th}}$ bare state in the i$^{\text{th}}$ physical state.

Absolute values of Z_{nn}: (for $N = 10$ and $\Delta = 0$)





Pole trajectories:



A: Summary

→ Most states decouple from continuum for $g \to \infty$

→ Most states predominantly feel nearest neighbor

→ At least one state behaves very different

→ This state feels all other states

→ Which state that is depends on renorm. cond.

Qualitatively these results are independent of N, shape of interaction, renormalization condition ...

see also G. Rupp, E. van Beveren, and S. Coito, Acta Phys. Polon. Supp. 8 (2015) 139

Are these extraordinary states the exotics?

$\to$ further studies necessary

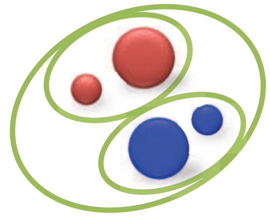
We now switch to part B: concrete models for exotics

Connection between part A and part B unclear ...

B: Heavy Tetraquarks

→ Mesons as anti-diquark–diquark systems

→ Straightforward extension of the quark model



→ Originally proposed by Jaffe for light quarks

Jaffe PRD15(1977)267

→ To account for spectrum spin-spin interaction needs to be dominant within diquarks

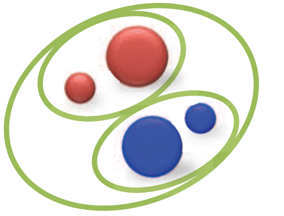
Maiani et al. PRD89(2014)114010

$$\hat{M} = \hat{M}_{00} + \frac{B_c}{2}\vec{L}^{\,2} - 2a\vec{L}\cdot\vec{S} + 2\kappa_{cq}\left[\vec{s}_c\cdot\vec{s}_q + \vec{s}_{\bar{c}}\cdot\vec{s}_{\bar{q}}\right]$$

the signs are chosen such that after the fit the coefficients are positive

B: Heavy Tetraquarks

→ Mesons as anti-diquark–diquark systems



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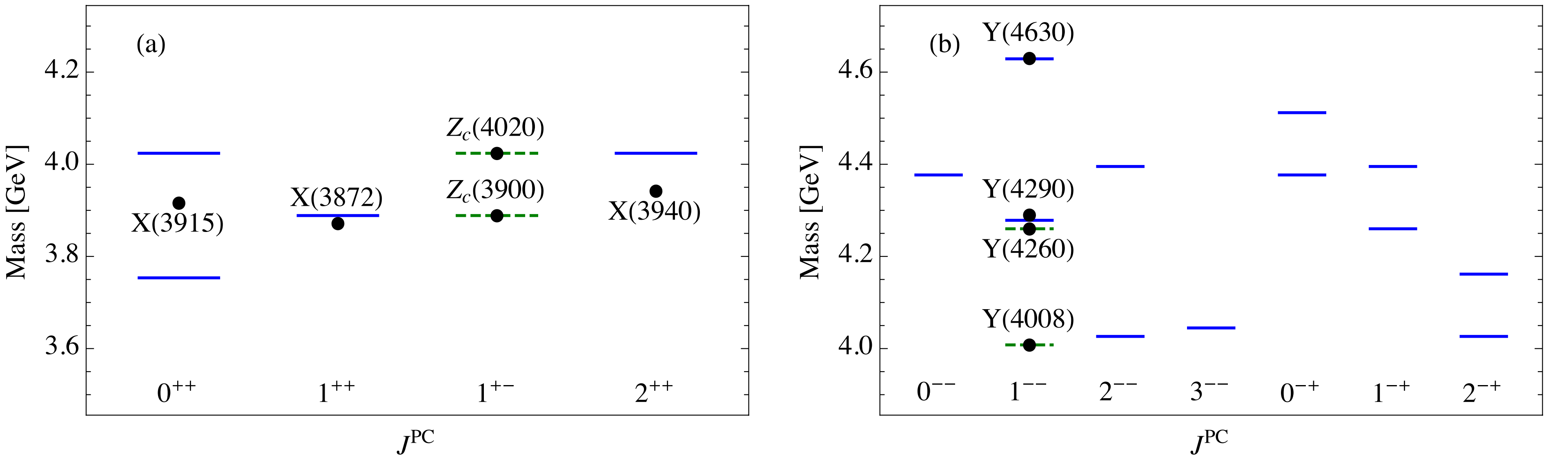
Maiani et al. PRD89(2014)114010

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

- Already many ground states
- Each level has isovector and isoscalar state ($cf.$ ρ and ω)
- The larger J the lighter the state ($a > 0$ from the fit)

B: Typical results and problems

Cleven et al., PRD 92(2015)014005



Many more charged and neutral states predicted than observed!

Special features:

$\rightarrow$ very light $J = 3$ state

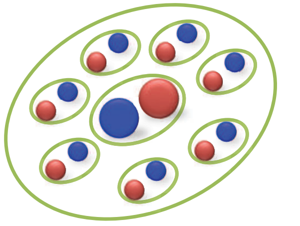
$\rightarrow$ lightest vector state close to $X(3872)$

... however: $Y(4008)$ not seen by BESIII PRL118(2017)092001

B: Hadrocharmonium

M. B. Voloshin, PPNP61(2008)455

→ Extra states are viewed as compact $\bar{Q}Q$ surrounded by light quarks

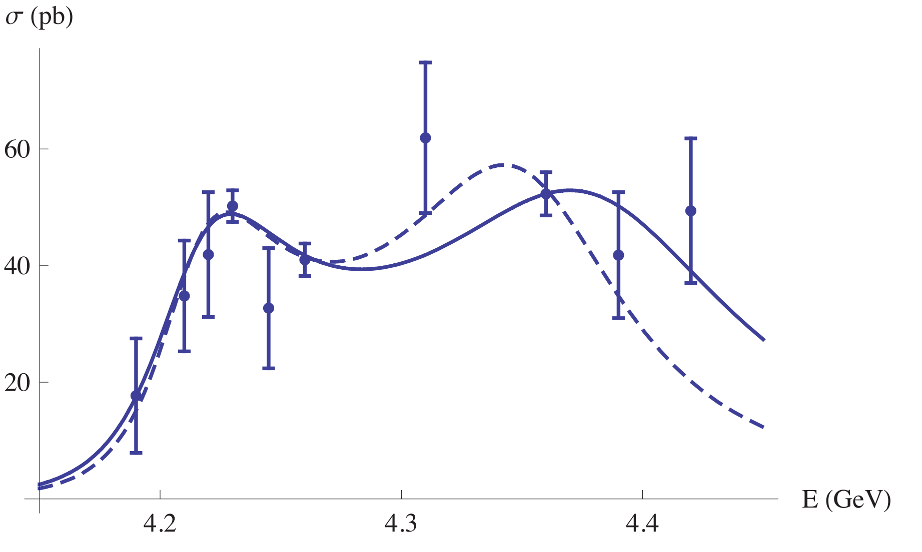


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ Heavy quark spin symmetry demands that spin of the core is conserved in decay to charmonia

→ Explaining $e^+e^- \to h_c\pi\pi$ needs mixing between states with $s_{\bar{c}c} = 0$ and $s_{\bar{c}c} = 1$ leading to $Y(4260)$ and $Y(4360)$

Li & Voloshin MPLA29(2014)1450060



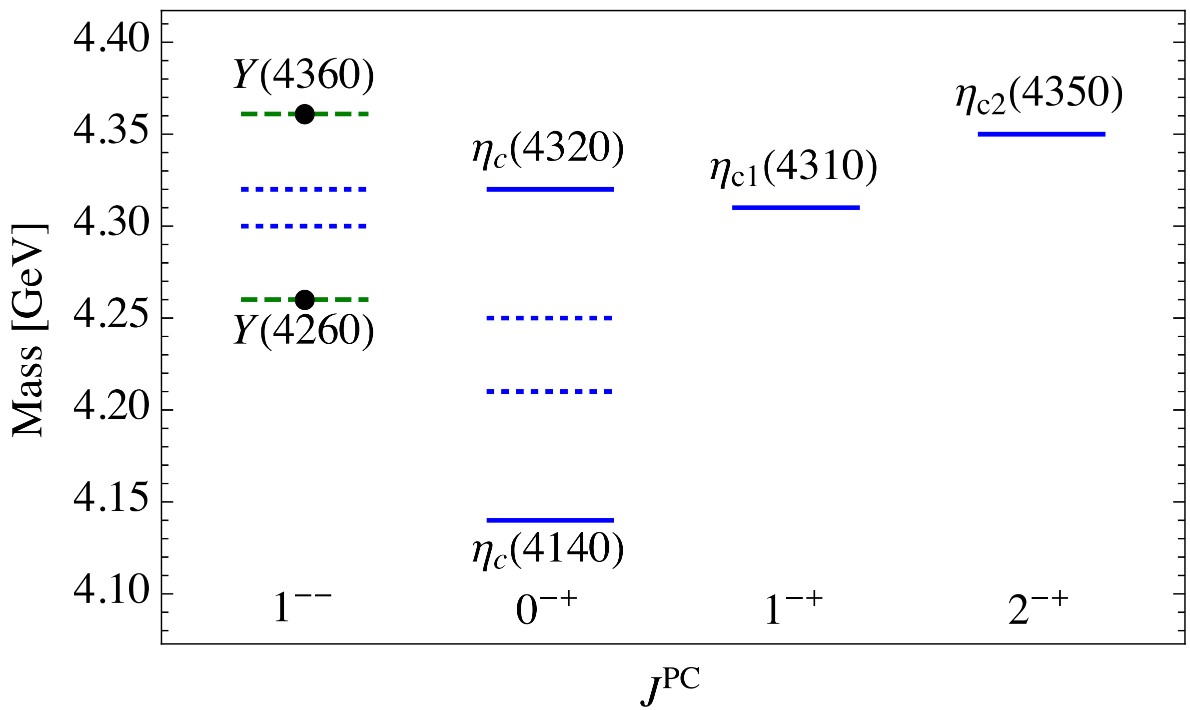
B: Hadrocharmonium: new states

The above mentioned mixing suggests for the unmixed states:

$$\Psi_3 \sim (1^{--})_{c\bar{c}} \otimes (0^{++})_{q\bar{q}} \qquad \Psi_1 \sim (1^{+-})_{c\bar{c}} \otimes (0^{-+})_{q\bar{q}} \ ,$$

where the heavy cores are ψ' and h_c.

$\longrightarrow$ get spin partners via $\psi' \to \eta_c'$ and $h_c \to \{\chi_{c0},\ \chi_{c1},\ \chi_{c2}\}$



Cleven et al., PRD 92(2015)014005

Special feature: very light 0^{-+} state that should not decay to $D^*\bar{D}$

B: Molecular states

→ Are expected near thresholds of narrow particle pairs

Filin et al., PRL 105, 019101 (2010); Guo et al., PRD 84, 014013 (2011)

→ Interaction not necessarily attractive
Note: Potential the strongest in S–waves

→ Isovector meson exchanges give $\langle\vec{\tau}_{(1)}\cdot\vec{\tau}_{(2)}\rangle = 2I(I+1)-3$
Expect either $I=1$ or $I=0$ states (not both) for given J^{PC}

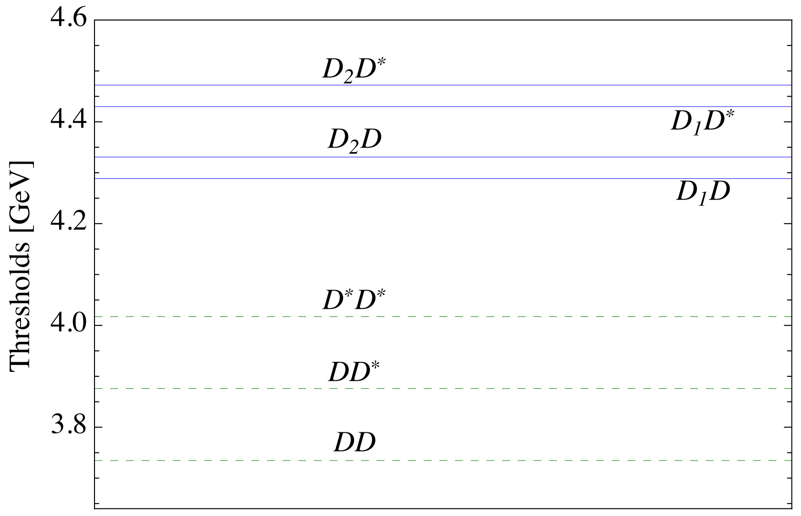
→ Switching C also induces sign change

→ Role of spin symmetry violation non–trivial,
e.g.: π-exchange in 2^{++}: $D^*\bar{D}^*\big|_S \to \ D\bar{D}\big|_D \ \to D^*\bar{D}^*\big|_S$
vs. π-exchange in 0^{++}: $D\bar{D}\big|_S \to D^*\bar{D}^*\big|_{S,D} \to D\bar{D}\big|_S$
feel strongly $M_D - M_{D^*}$

see talk by Vadim Baru at this conference

B: Concrete example:

Example: $1/2^+$ multiplet $\{D, D^*\}$ and $3/2^-$ multiplet $\{D_1, D_2\}$ $\rightarrow$



$3^{-\pm}$: D^*D_2
$0^{-\pm}$: D^*D_1
$2^{-\pm}$: $D^*D_1 - D^*D_2 - DD_2$
$1^{-\pm}$: $DD_1 - D^*D_1 - D^*D_2$ ($Y(4260), Y(4360)$ ($I=0$))

2^{++}: D^*D^*
1^{++}: DD^* ($X(3872)$ ($I=0$))
1^{+-}: $DD^* - D^*D^*$ ($Z_c(3900)^+, Z_c(4020)^+$ ($I=1$))
0^{++}: $DD - D^*D^*$;

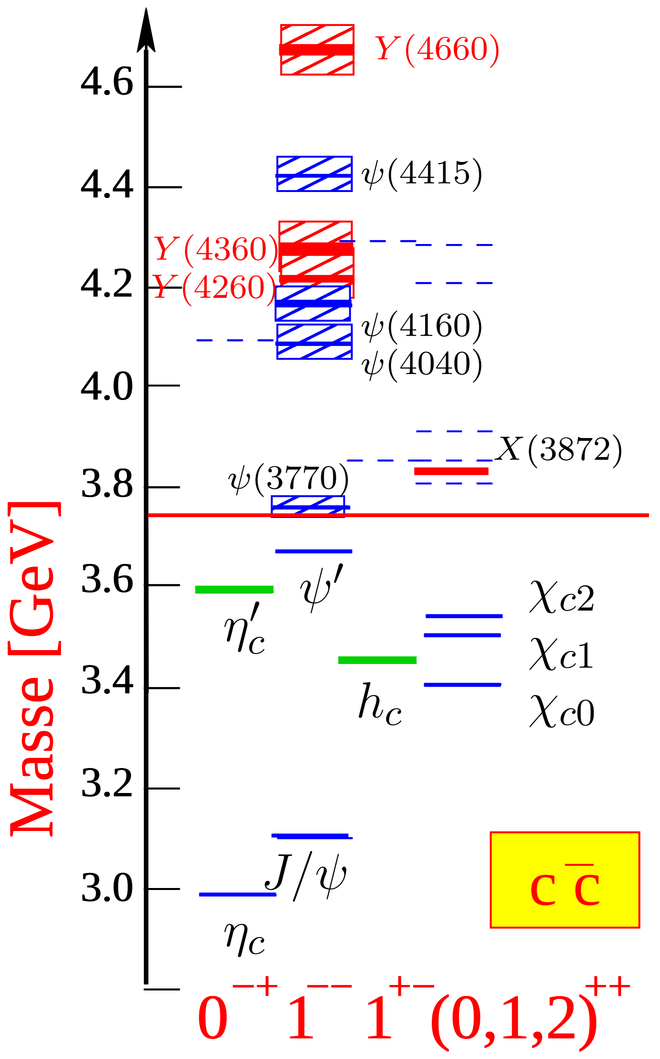
$\rightarrow$ $1^{-\pm}$ states as lightest neg. parity states!

$\rightarrow$ Explains mass gap between 1^+ and 1^- states:
$M_{Y(4260)} - M_{X(3872)} = 388$ MeV $\simeq$ $M_{D_1(2420)} - M_{D^*} = 410$ MeV

$\rightarrow$ Natural explanation for $Y(4260) \rightarrow \pi Z_c(3900)$ and $Y(4260) \rightarrow \gamma X(3872)$

Q. Wang, C. H., Q. Zhao, PRL111 (2013) no.13, 132003
F.-K. Guo et al., PLB 725 (2013) 127-133

What's next?



Different scenarios give different predictions, for

→ spin partner(s)

→ the decay rates

Theory needs to provide predictions for all scenarios

... and we need more data especially in other channels! and in the bottom sector!

Thank you very much for your attention