How can we unravel the mysteries of the XYZ states?

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QCD vs. QED

't Hooft; Politzer; Gross, Wilczek

QCD as well as QED are local gauge theories

QED: one charge (U(1)); QCD: three charges (= colors) (SU(3))

The Lagrangian reads

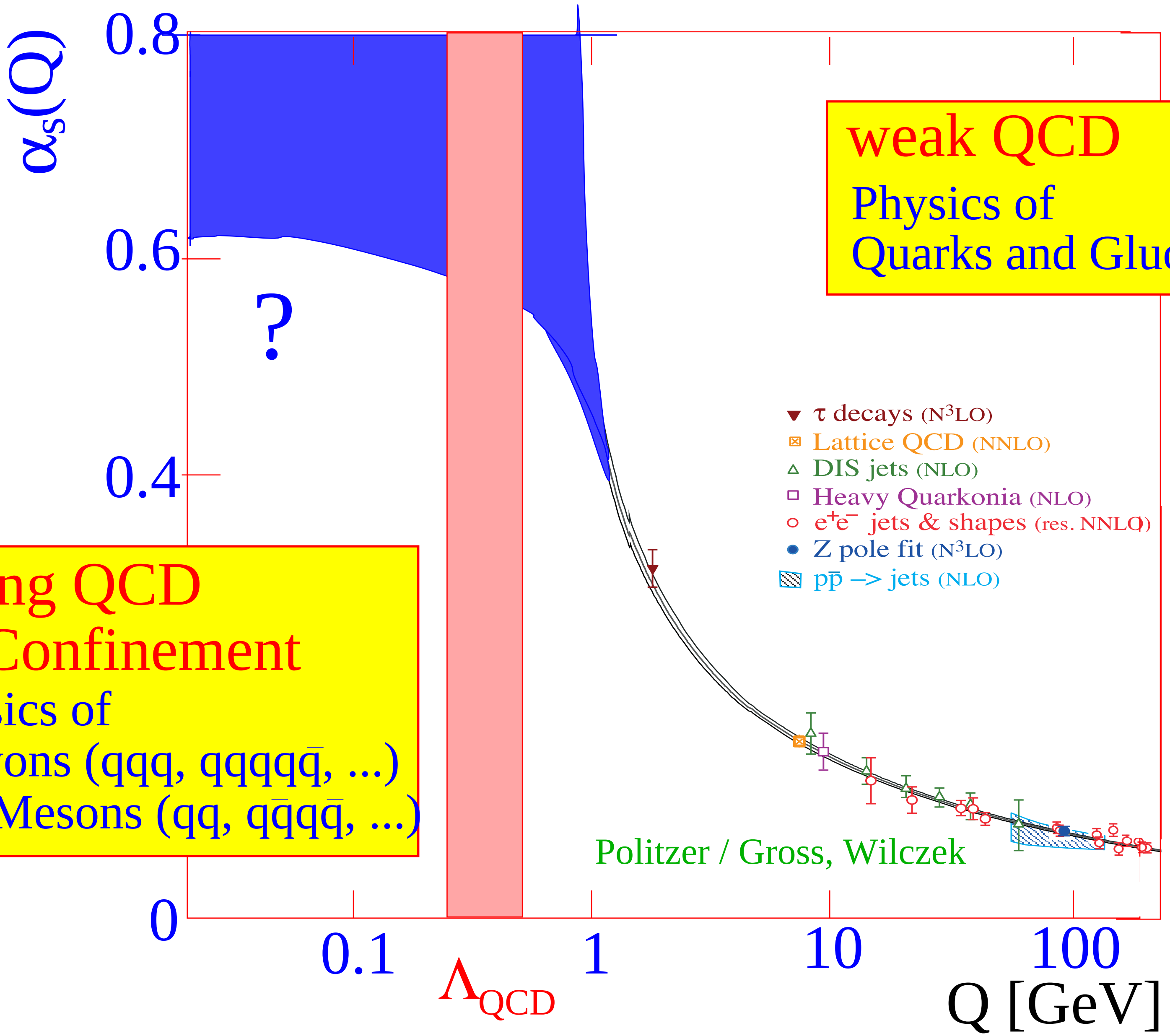
$$\boxed{\mathcal{L}_{\mathrm{QCD/QED}} = \bar{\psi}\left(\gamma_\mu D^\mu - M\right)\psi - \frac{1}{4T}\mathrm{Tr}\left(F^{\mu\nu}F_{\mu\nu}\right)}$$

where the covariant derivative and field strength tensor read

$$\begin{aligned} D_\mu &= \partial_\mu - igG_\mu = \partial_\mu - ig\sum_a G^a_\mu T^a\,, \\ F_{\mu\nu} &= \frac{i}{g}\left[D_\mu, D_\nu\right] = \partial_\mu G_\nu - \partial_\nu G_\mu - ig\left[G_\mu, G_\nu\right] \end{aligned}$$

where $T^a =$ generators of the gauge group with Tr $\left(T^a T^b\right) = T\delta^{ab}$

The faces of QCD



weak QCD

Physics of
Quarks and Gluons

strong QCD

➛ Confinement

Physics of
Baryons (qqq, qqqq$\bar{q}$, ...)
and Mesons (qq, q$\bar{q}$q$\bar{q}$, ...)

Particle data group 2014

Properties and Open questions

→ Confinement:

only color neutral objects travel long distances

→ Only certain quark/anti-quark combinations are allowed:

Mesons:

$\bar{q}q$ (regular), $\bar{q}\bar{q}qq$ (tetraquark), $\bar{q}\bar{q}\bar{q}qqq$ (baryonium), ...
GG, GGG, ... (glueball)

Baryons:

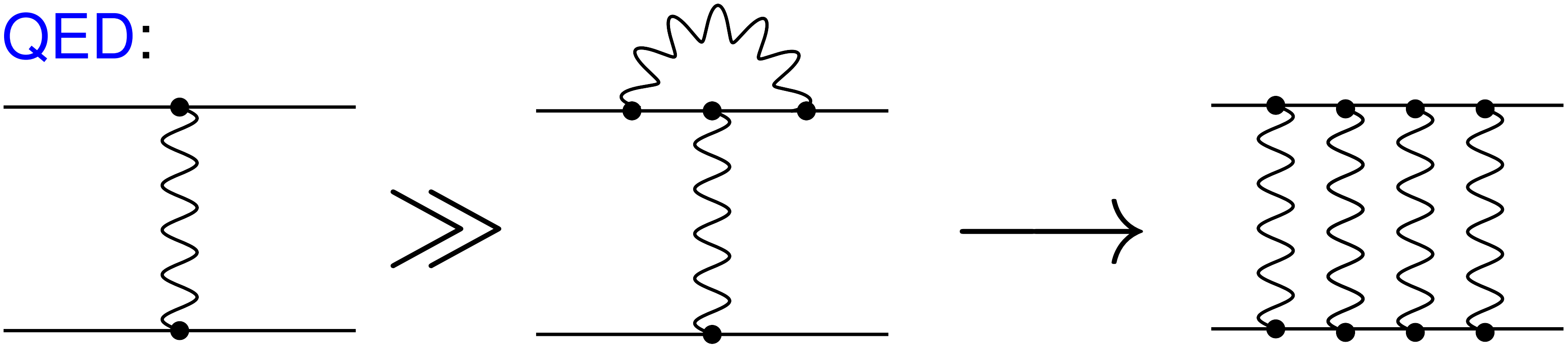
qqq (regular), $\bar{q}qqqq$ (penta-quark), $qqqqqq$ (di-baryon), ...

All those are expected; ~~only regular ones observed~~

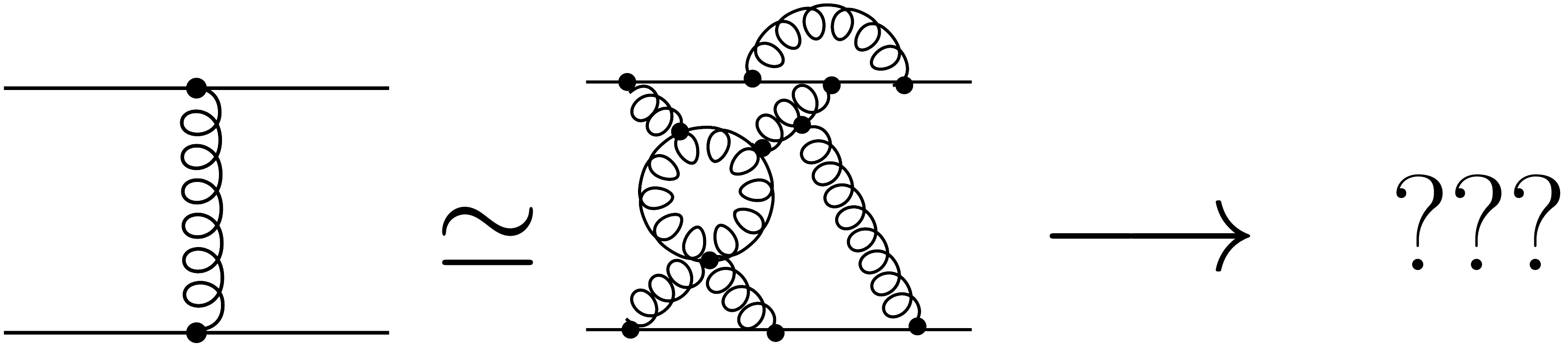
The problem:

Potential Bound states

QED:



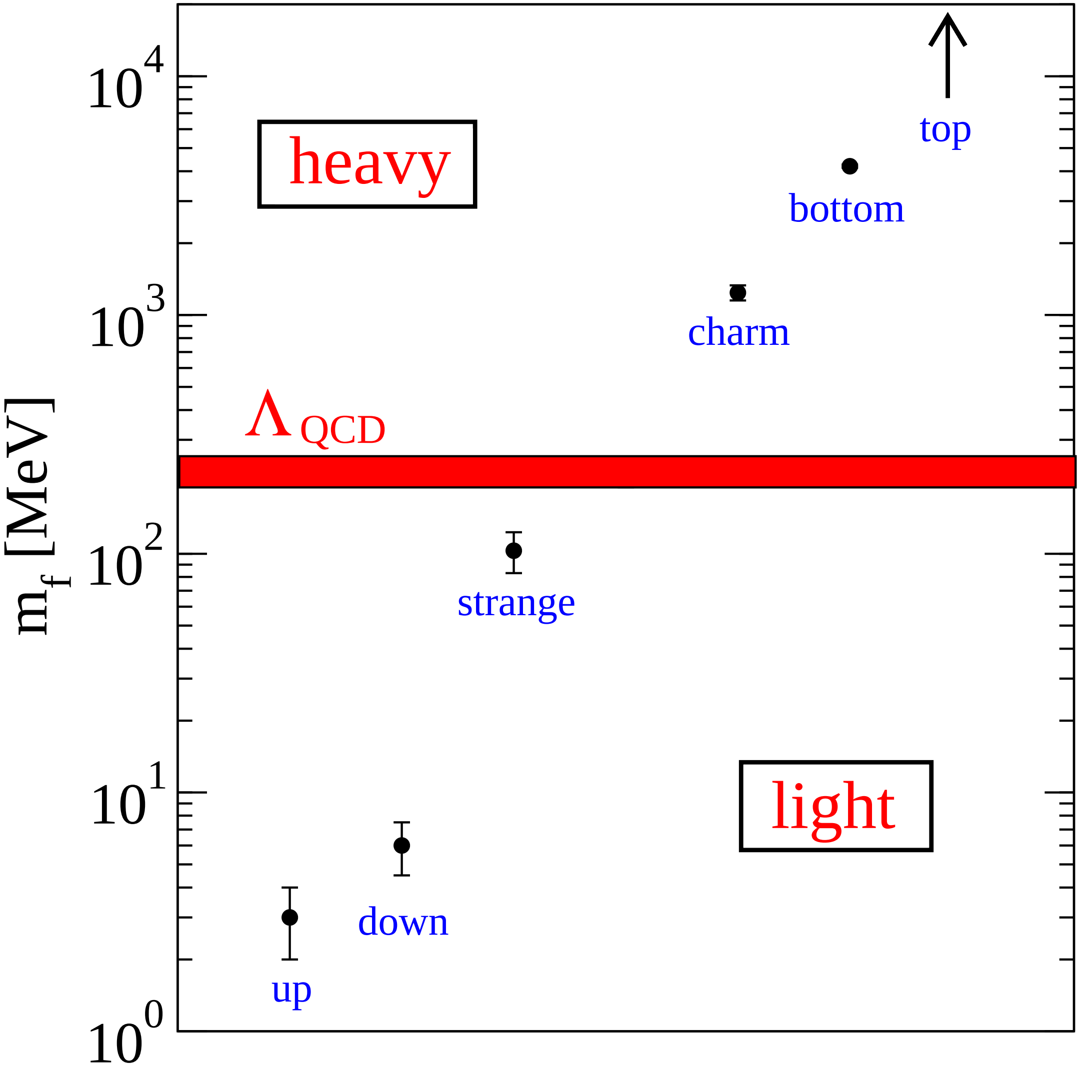
QCD at intermediate or large distances:



exception: low lying states between heavy quarks (see below)

Quark Masses

Quark Masses (in $\overline{\mathrm{MS}}$ at μ=2 GeV)



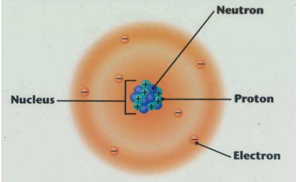
Particle Data Group (2008)

Expect very different phenomena for light (u,d,s) and heavy (c,b) quarks

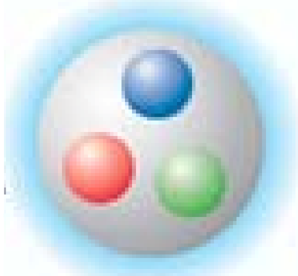
- What are the spectra? Where are the poles?
- What structures are there?

Study systematically particle properties, decays, and interactions!

Origin of hadron masses



$$\mathrm{M}_{\mathrm{Atom}} = (\Sigma_i m_i) \times \left(1 - \mathcal{C}_1 \times 10^{-8}\right)$$
$$\mathrm{M}_{\mathrm{Kern}} = (\Sigma_i m_i) \times \left(1 - \mathcal{C}_2 \times 10^{-3}\right)$$



$$\mathrm{M}_{\mathrm{Hadron}} = \mathcal{C}_3(\Sigma_i m_i) + E_{\mathrm{field}}/c^2$$

for light quarks: $E_{\mathrm{field}}/c^2 \gg \mathcal{C}_3(\Sigma_i m_i)$

for heavy quarks: $E_{\mathrm{field}}/c^2 \ll \mathcal{C}_3(\Sigma_i m_i)$

Higgs mechanism responsible for 10% of light hadron masses,
but for over 90% of heavy hadron masses

Heavy systems are expected to be easier to understand ...

Heavy Quark Symmetry

see, e.g., Neubert Phys. Rep. 245(1994)259

One may derive from the QCD Lagrangian:

$$\mathcal{L}_{\rm QCD} = \bar{q}_f \left\{ iv\cdot\partial + gv\cdot A^a t^a \right\} q_f + \mathcal{O}(\Lambda_{\rm QCD}/m_f)$$

At leading order interaction spin and flavor independent!

heavy quark spin and $J_{\rm light}$ of light quarks conserved independently

Terms at $\mathcal{O}(\Lambda_{\rm QCD}/m_f)$ contain

→ kinetic energy of heavy quark

→ term breaking spin symmetry

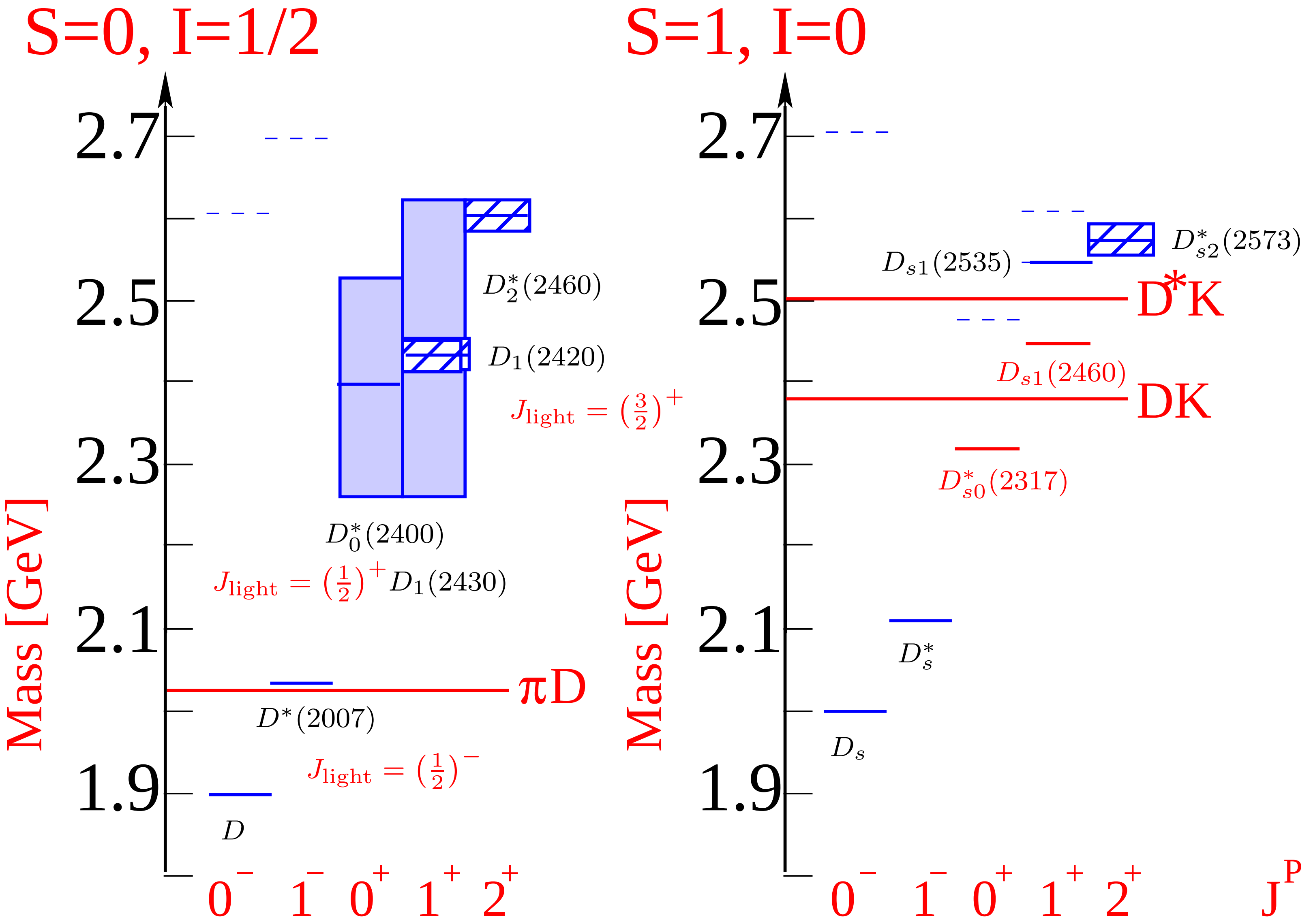
Consequence: mesons form spin multiplets with

$$m_{D^*} - m_D \sim \Lambda_{QCD} \ , \quad m_{B^*}^2 - m_B^2 \simeq m_{D^*}^2 - m_D^2$$

which works nicely - also for excited states

→ Amount of spin symmetry violation important diagnostic tool!

Example 1: Open Charm states

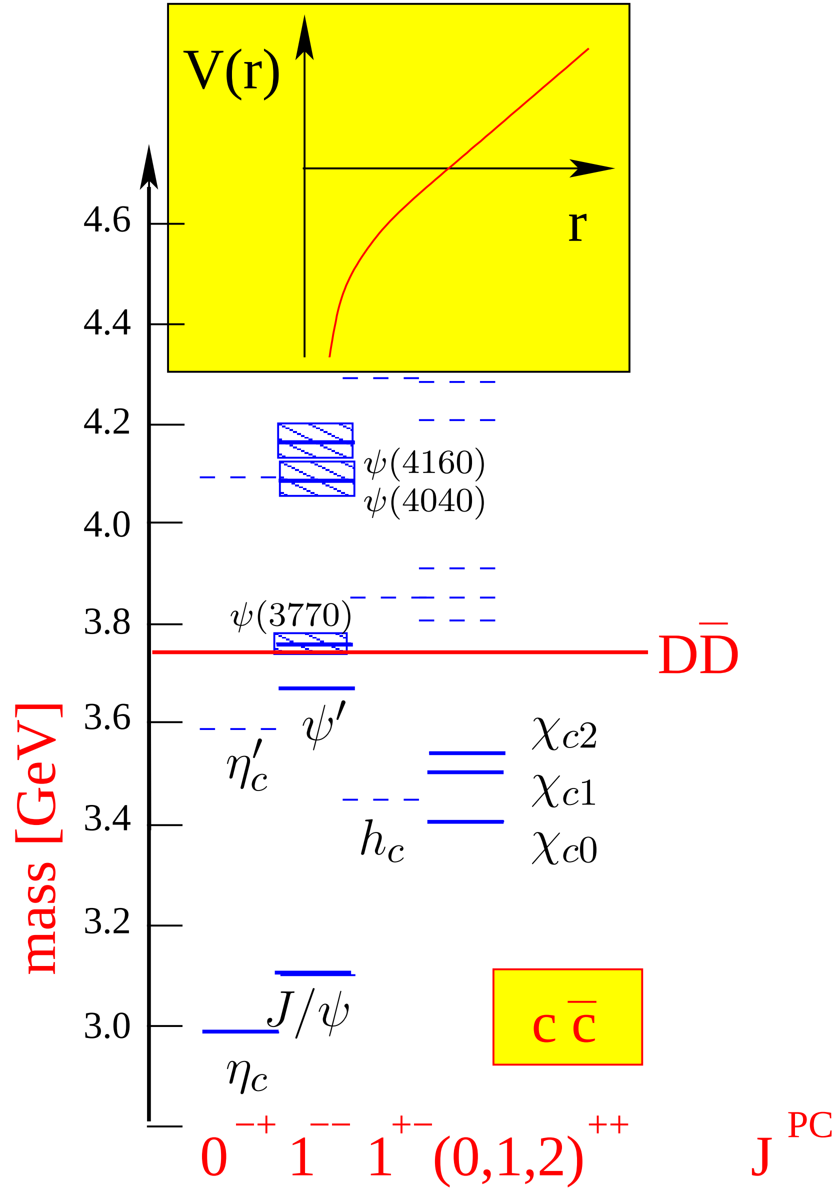


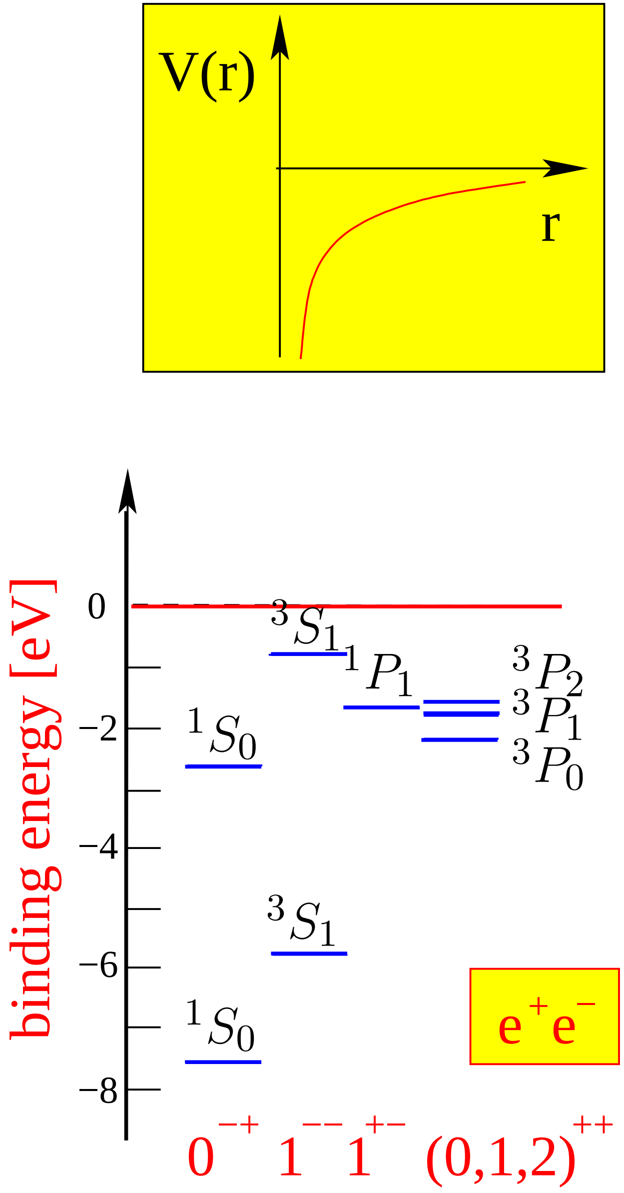
Quark Modell: M. Di Pierro and E. Eichten, PRD 64 (2001) 114004

Quark model predicts quantum number dependent spin symmetry violations

Example 2: Charmonium before 2002

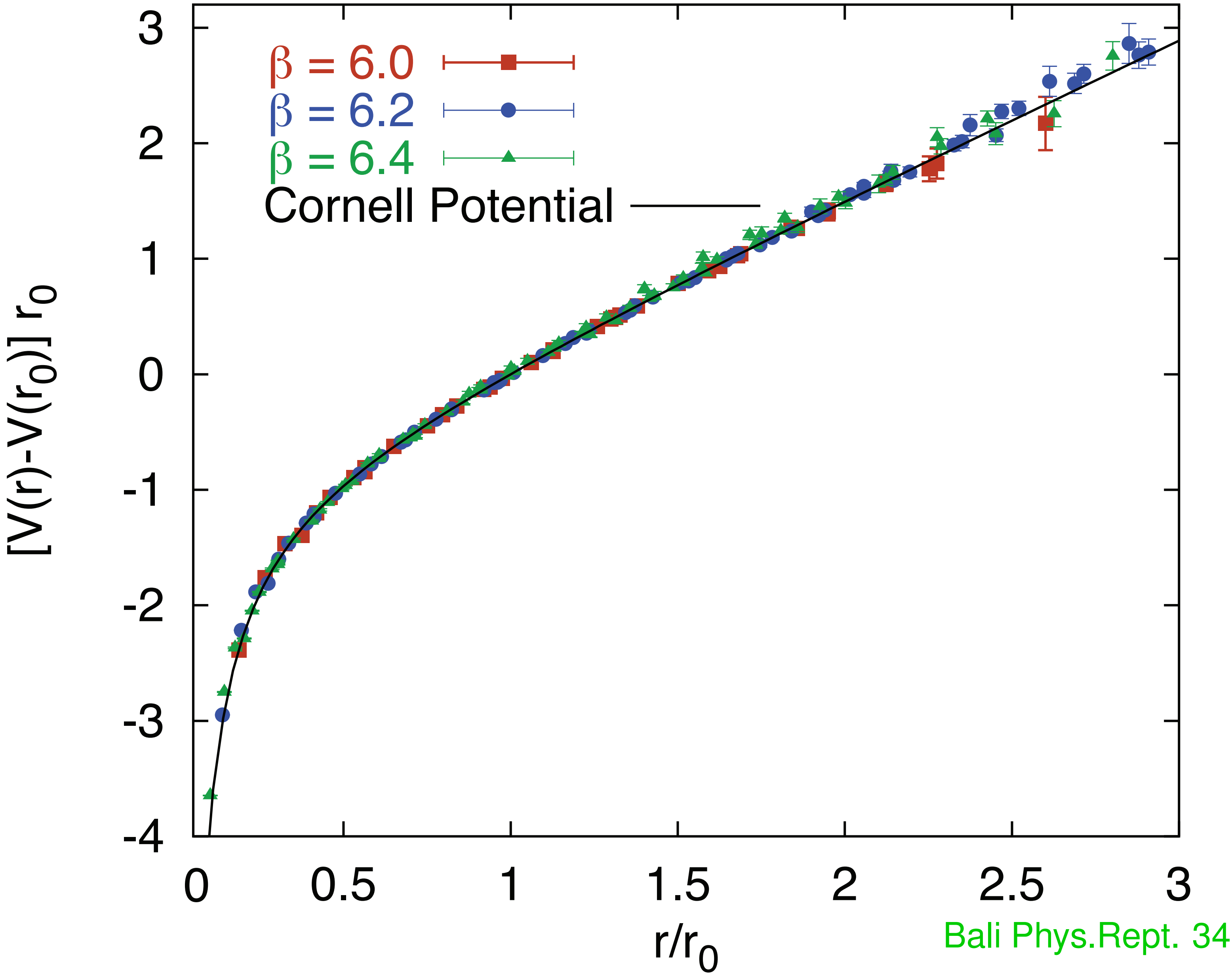
Quark-Model: Eichten et al. PRD 17 (1978)





Heavy quarkonia

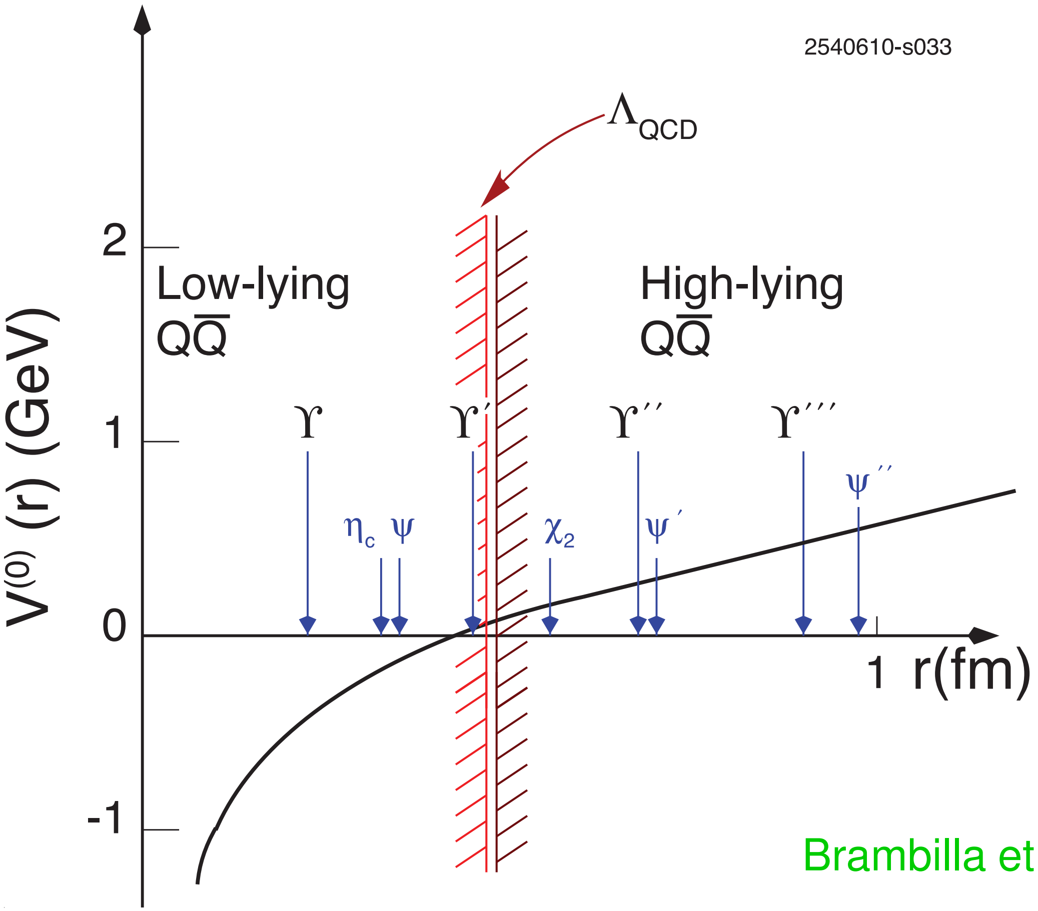
Potential of two static color sources



Bali Phys.Rept. 343(2001)1

(p)NRQCD

Relevant scales: $M_Q \gg p \sim M_Q v \sim 1/r \gg E \sim M_Q v^2$



Brambilla et al., EPJC71(2011)1534

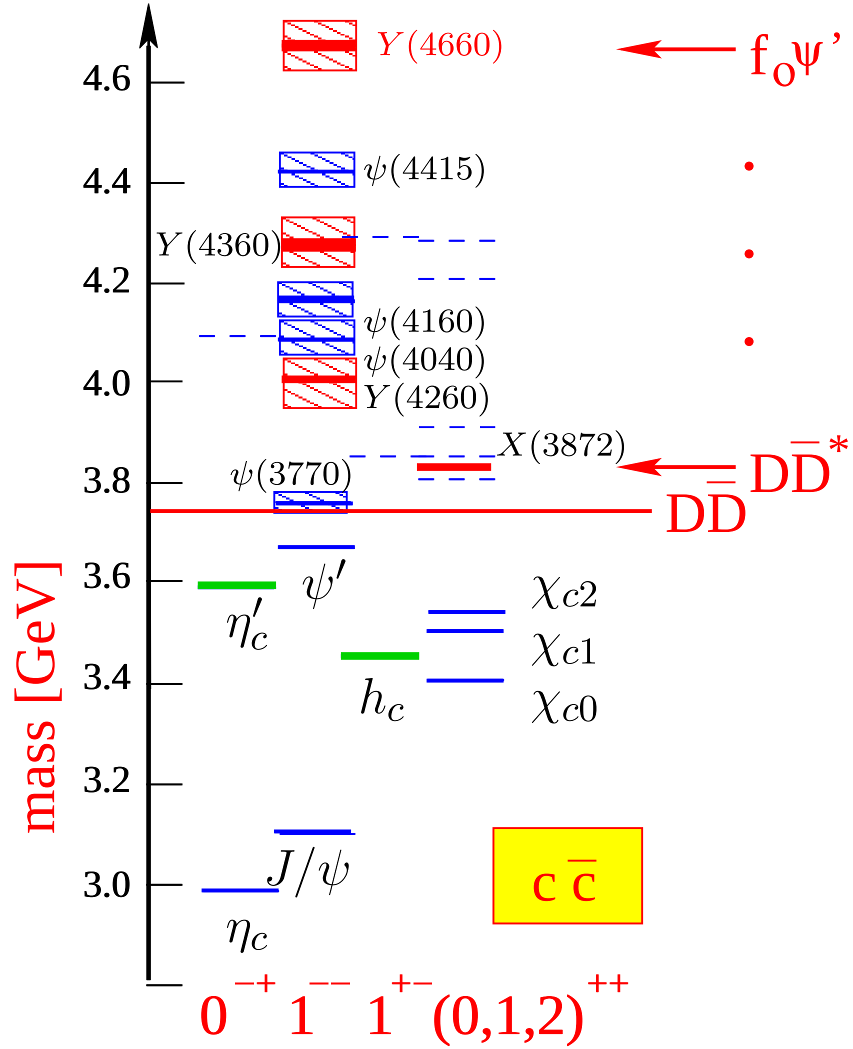
→ For systems with small radii: precision calculations

→ Transition to non-perturbative regime can be studied

Charmonium after 2002

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

A new particle Zoo!



→ missing low lying states found

→ Above the $\bar{D}D$ threshold:

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

What are they?

Charged states

2012: Discovery of charged states that

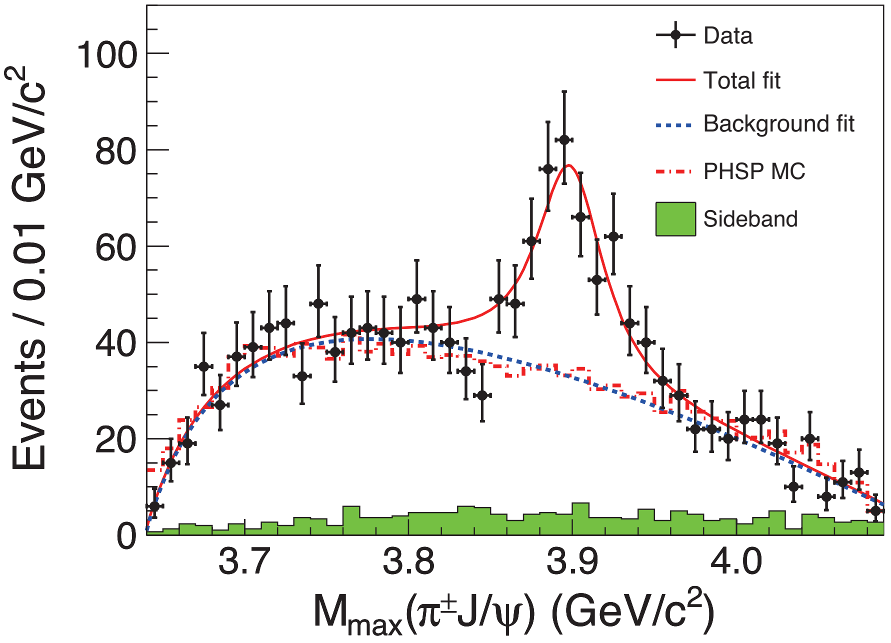
→ have masses in the quarkonium regime;

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

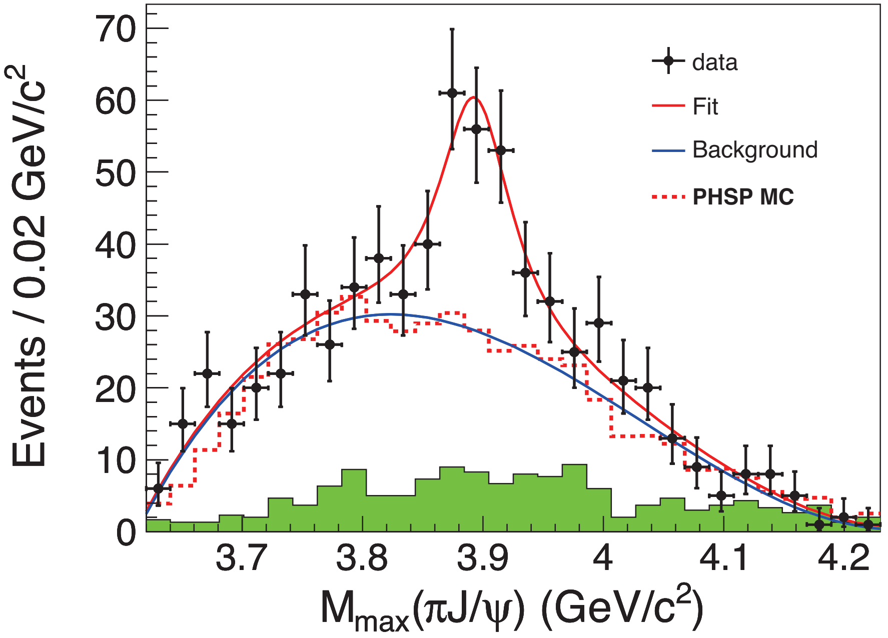
→ must contain at least 4 quarks

Example: $Z_c(3900)$ close to $\bar{D}D^*$ threshold

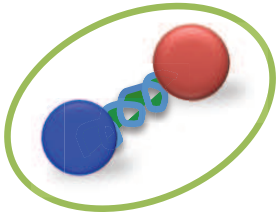
BES-III (China), 2013



Belle (Japan), 2013

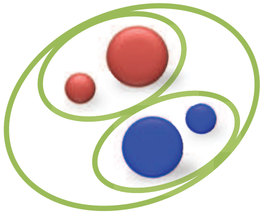


Proposals



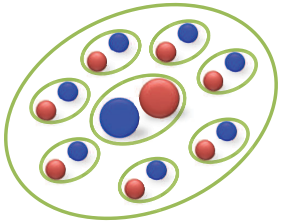
Hybrid

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



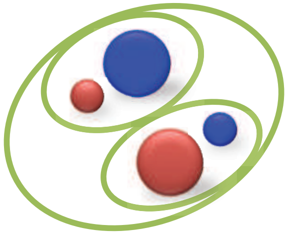
Tetraquark

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



Hadro-Quarkonium

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



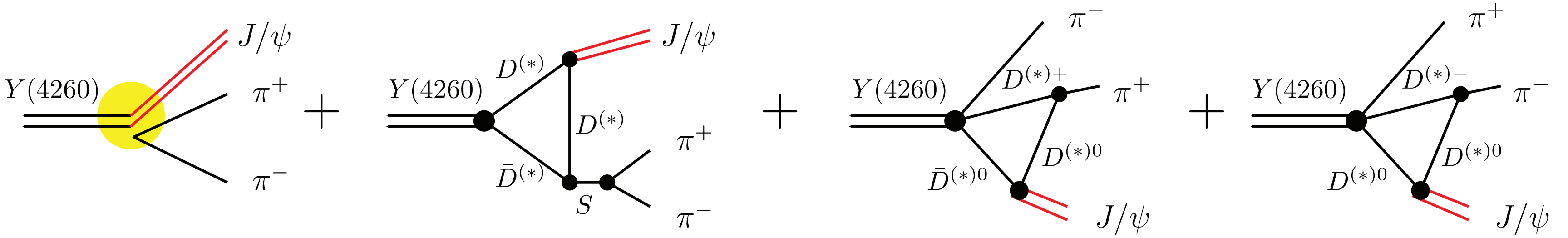
Hadronic-Molecule

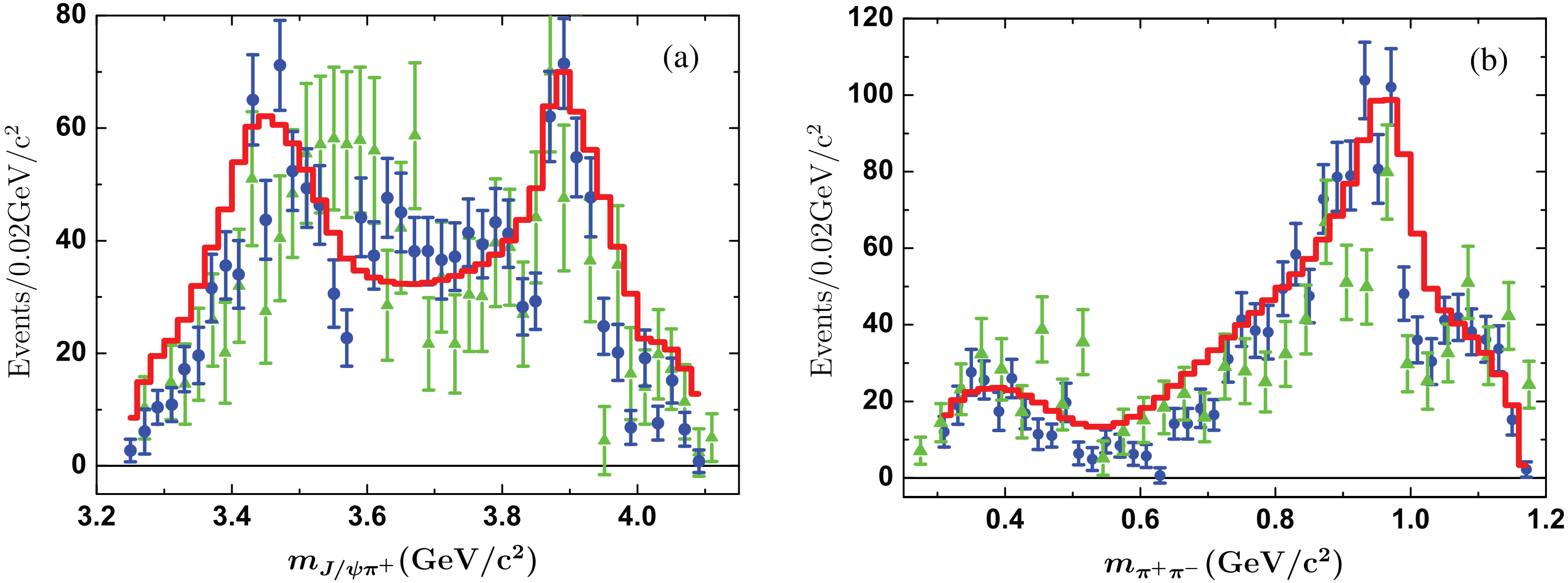
→ Extended object made of $(\bar{Q}q)$ and $(Q\bar{q})$

... or simply a threshold effect?

(Some) XYZ-states threshold effects?

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





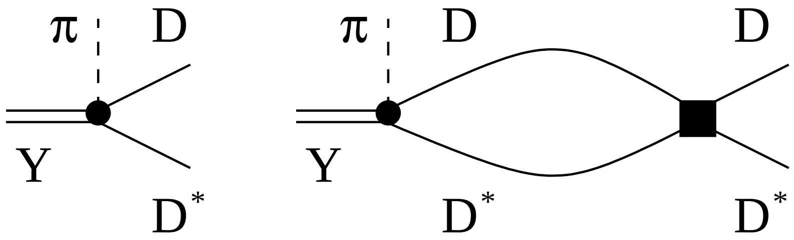
Chen et al., PRD88(2013)036008

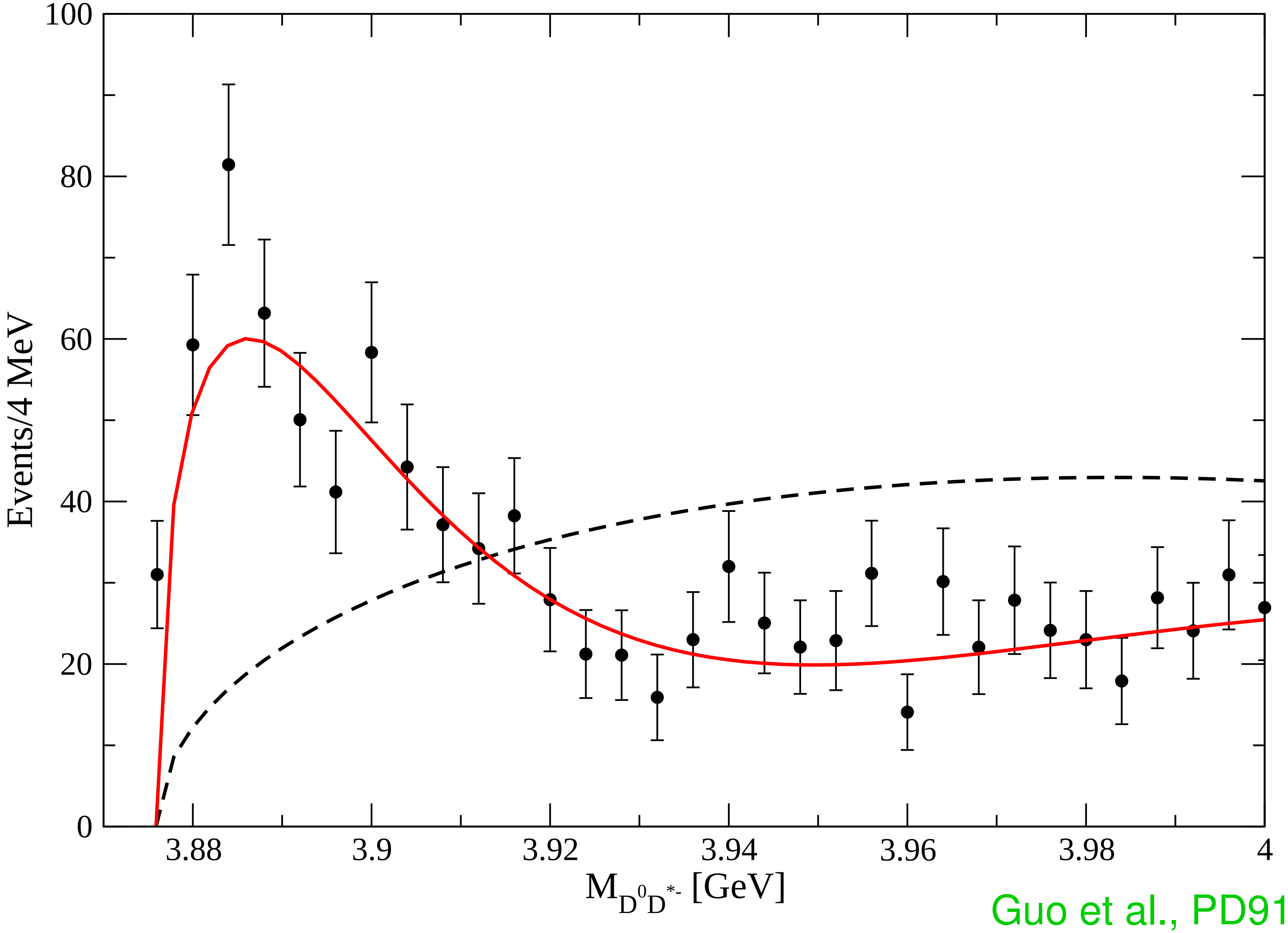
Could it be that the origin of $Z(3900)$ is a threshold cusp

followed by perturbative rescattering? —- NO!

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

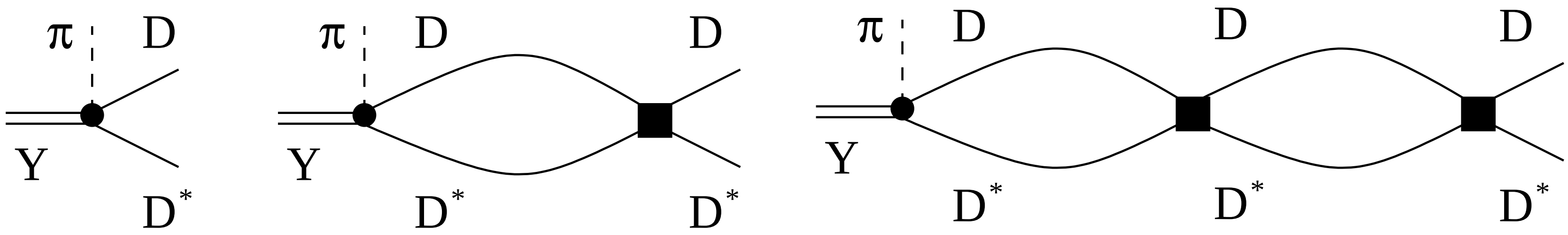
Why the argument is wrong

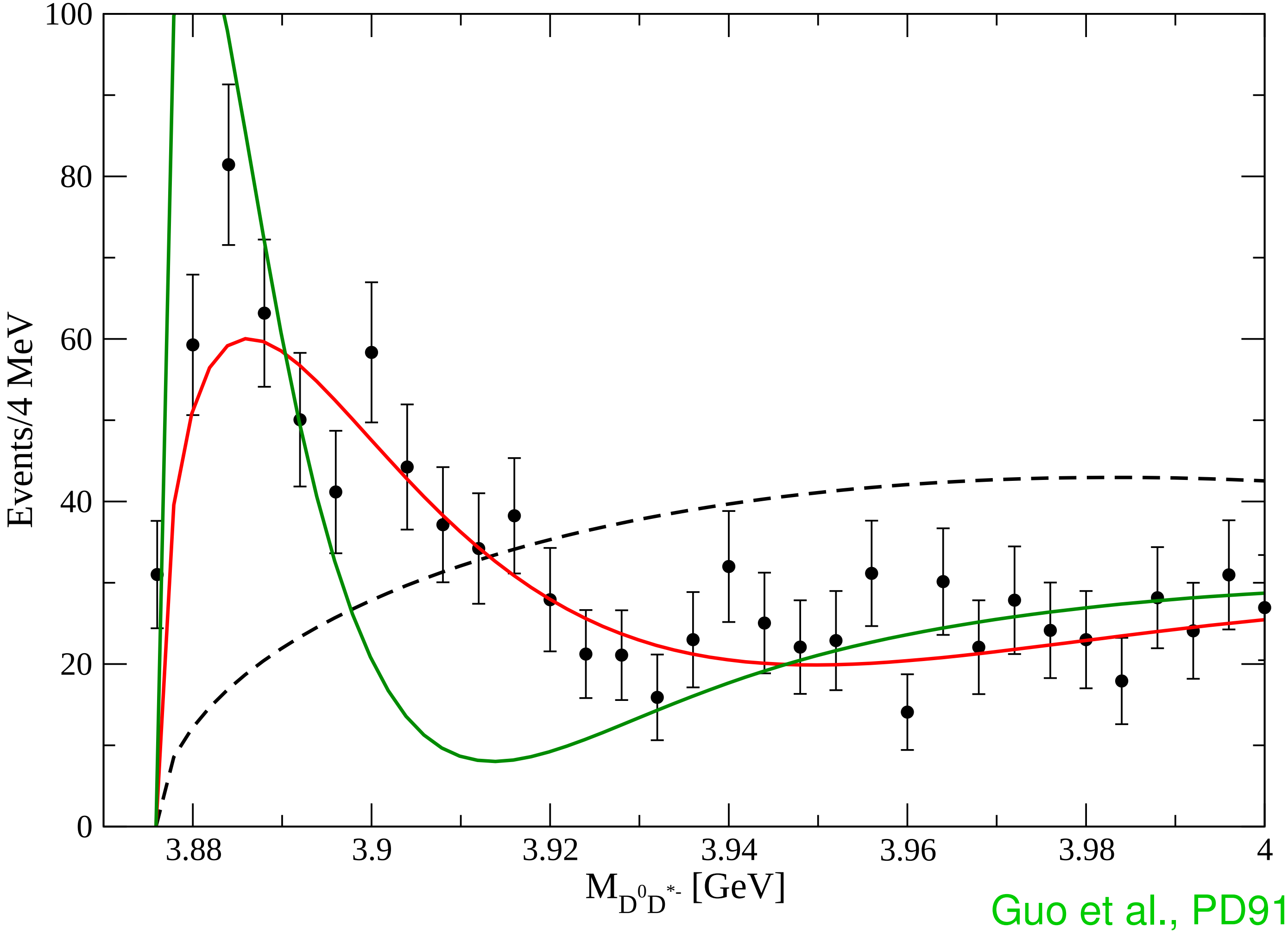




Guo et al., PD91(2015)051504

Why the argument is wrong





Guo et al., PD91(2015)051504

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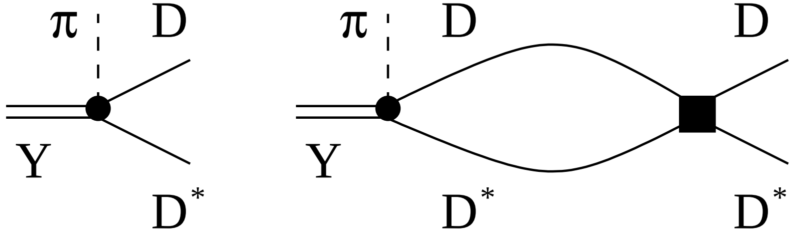
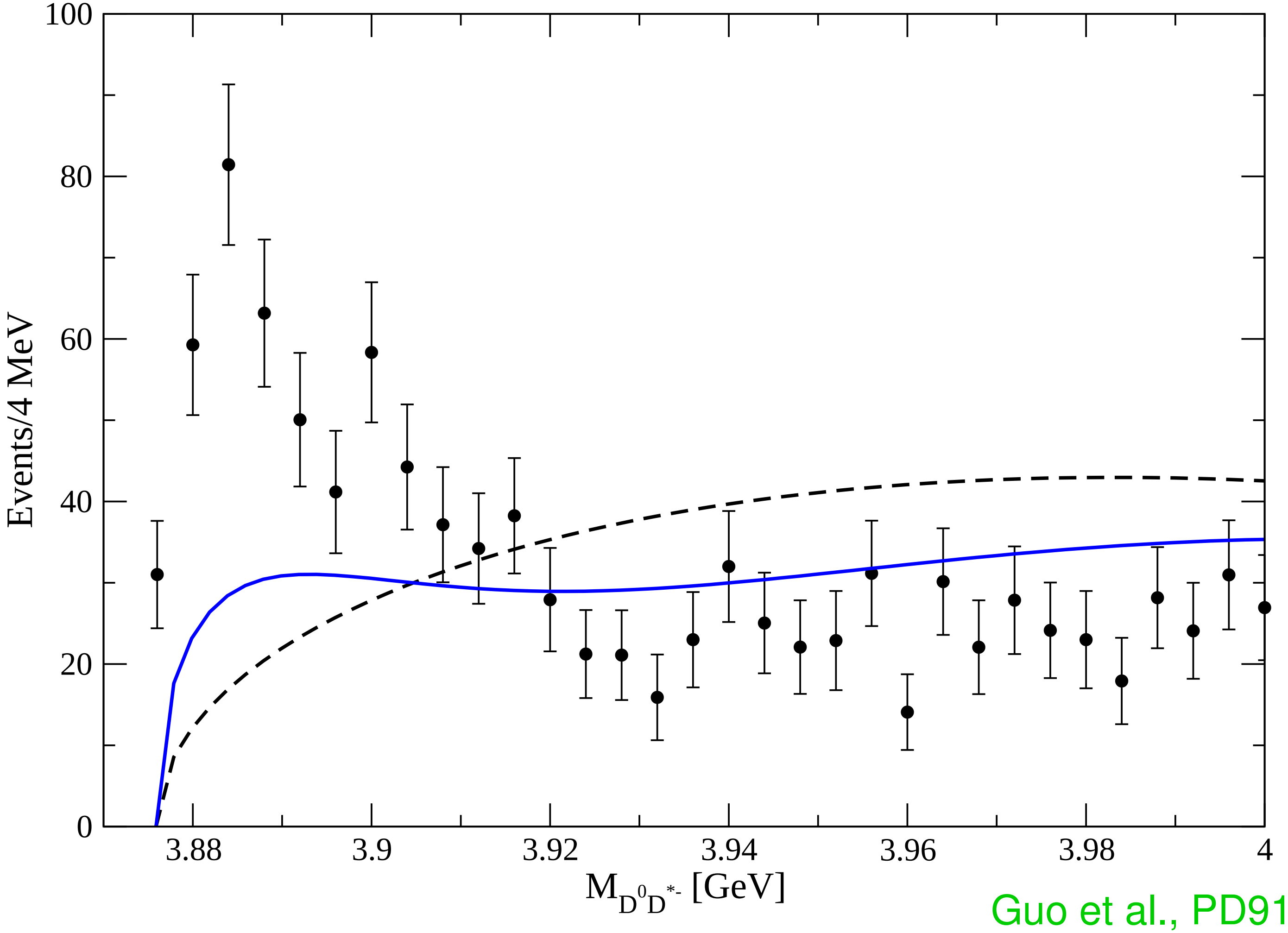
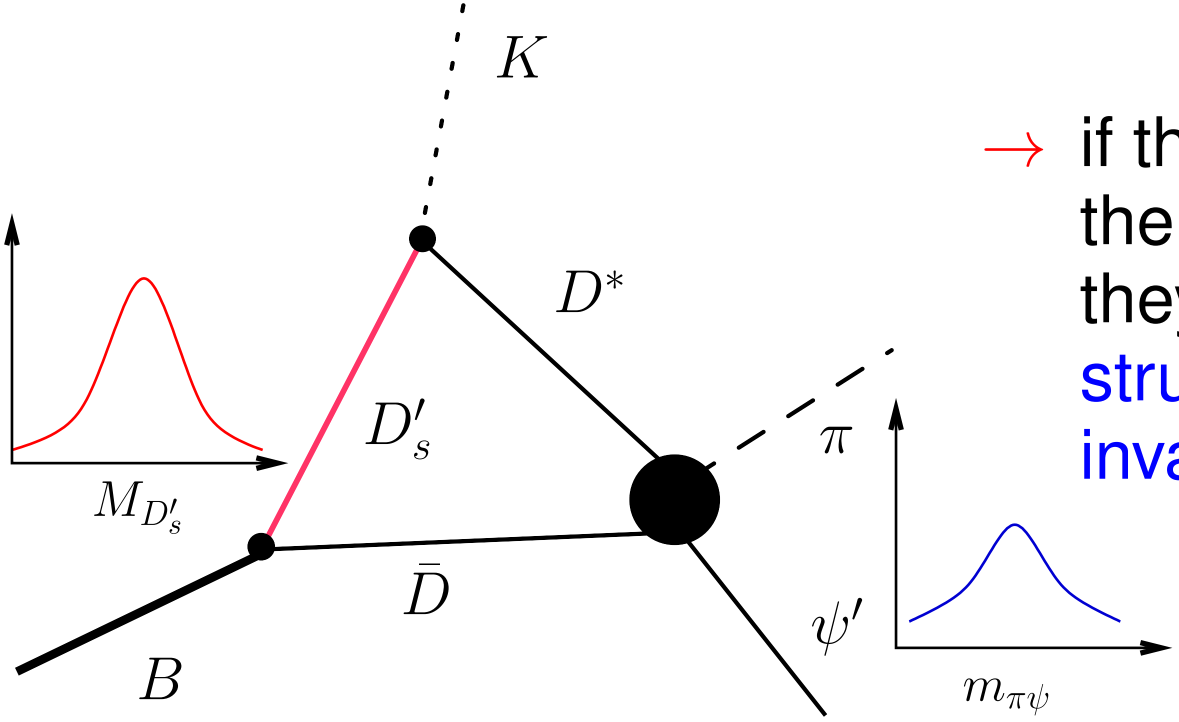




Guo et al., PD91(2015)051504

(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

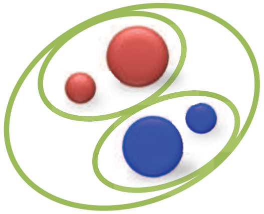
... maybe — but certainly not for all XYZ–states, since mechanism very sensitive to external invariant masses, and, e.g.,

→ $X(3872)$ 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^-

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 propose spin-spin interaction within diquarks dominant

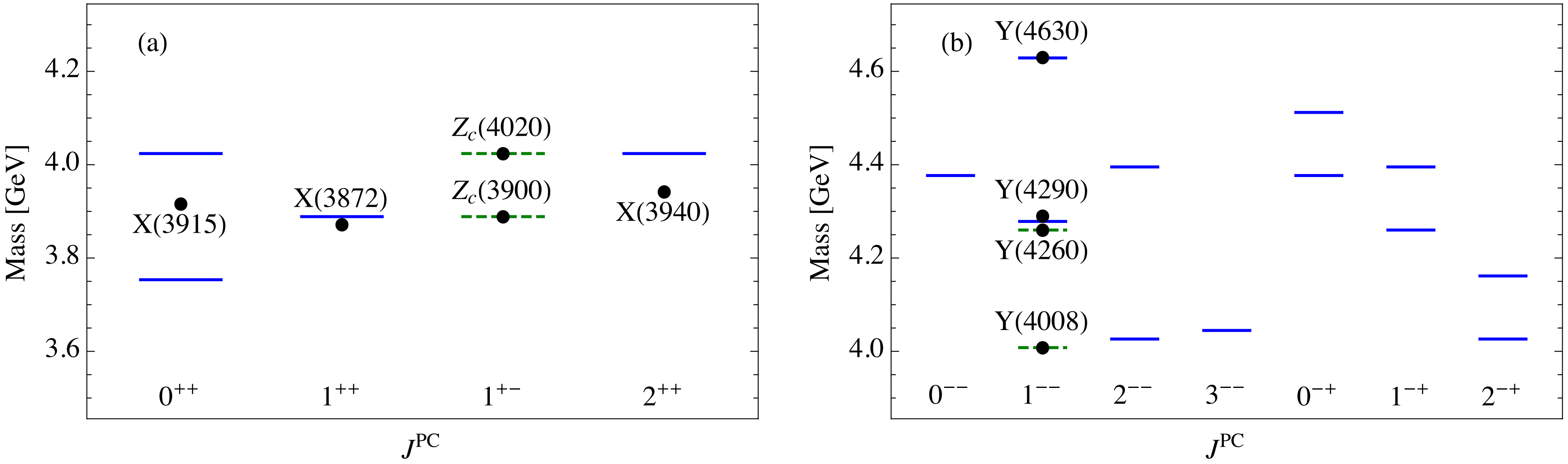
Maiani et al. PRD89(2014)114010

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

- 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)

Typical results and problems

Cleven et al., arXiv:1505.01771



Many more charged and neutral states predicted than observed!

67 among 80 ground states still to be discovered

In addition:

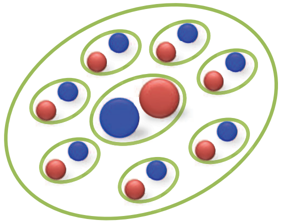
Proposed Hamiltonian without microscopic justification

Special feature: very light $J = 3$ state

Hadrocharmonium

M. B. Voloshin, PPNP61(2008)455

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

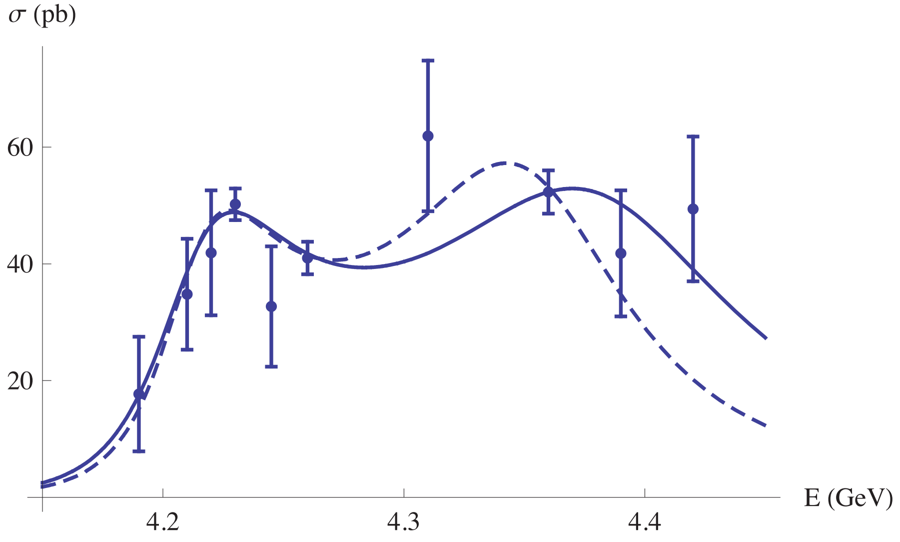


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ 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



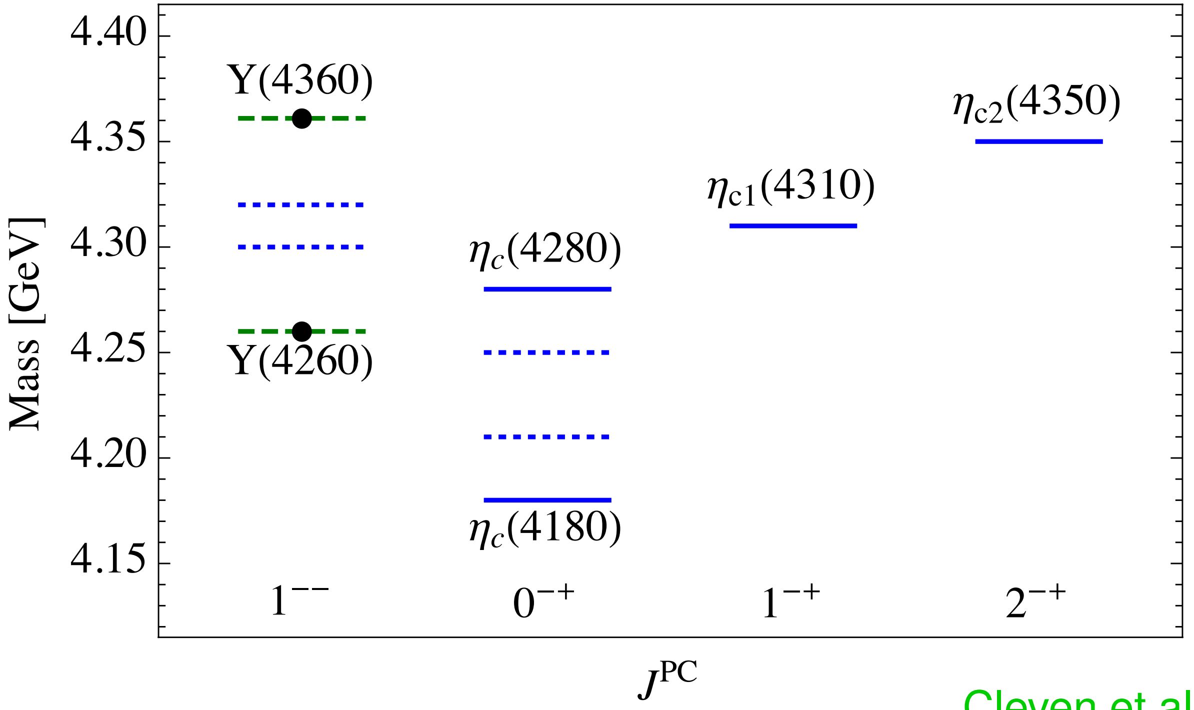
Hadrocharmonium: new states

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., arXiv:1505.01771

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

Molecular states

Are expected near thresholds of narrow particle pairs

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

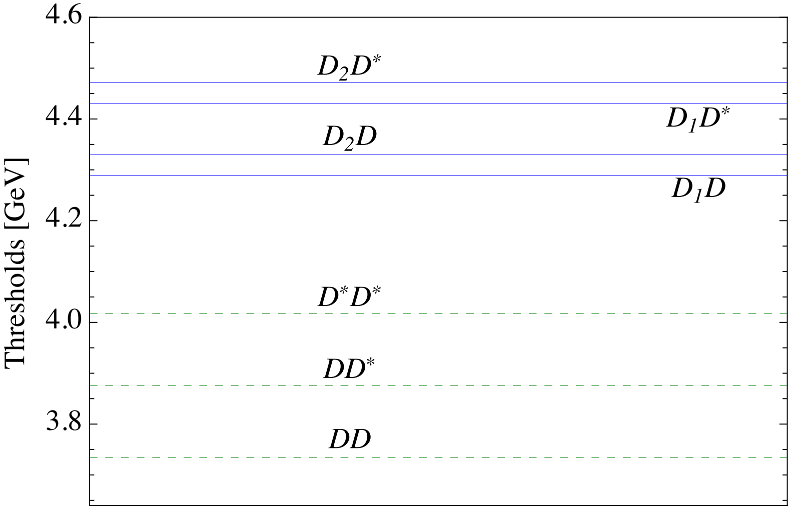
But not near all of them:

$\rightarrow$ Interaction not necessarily attractive

$\rightarrow$ 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}

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^* ($X(3872)$ $(I{=}0)$)

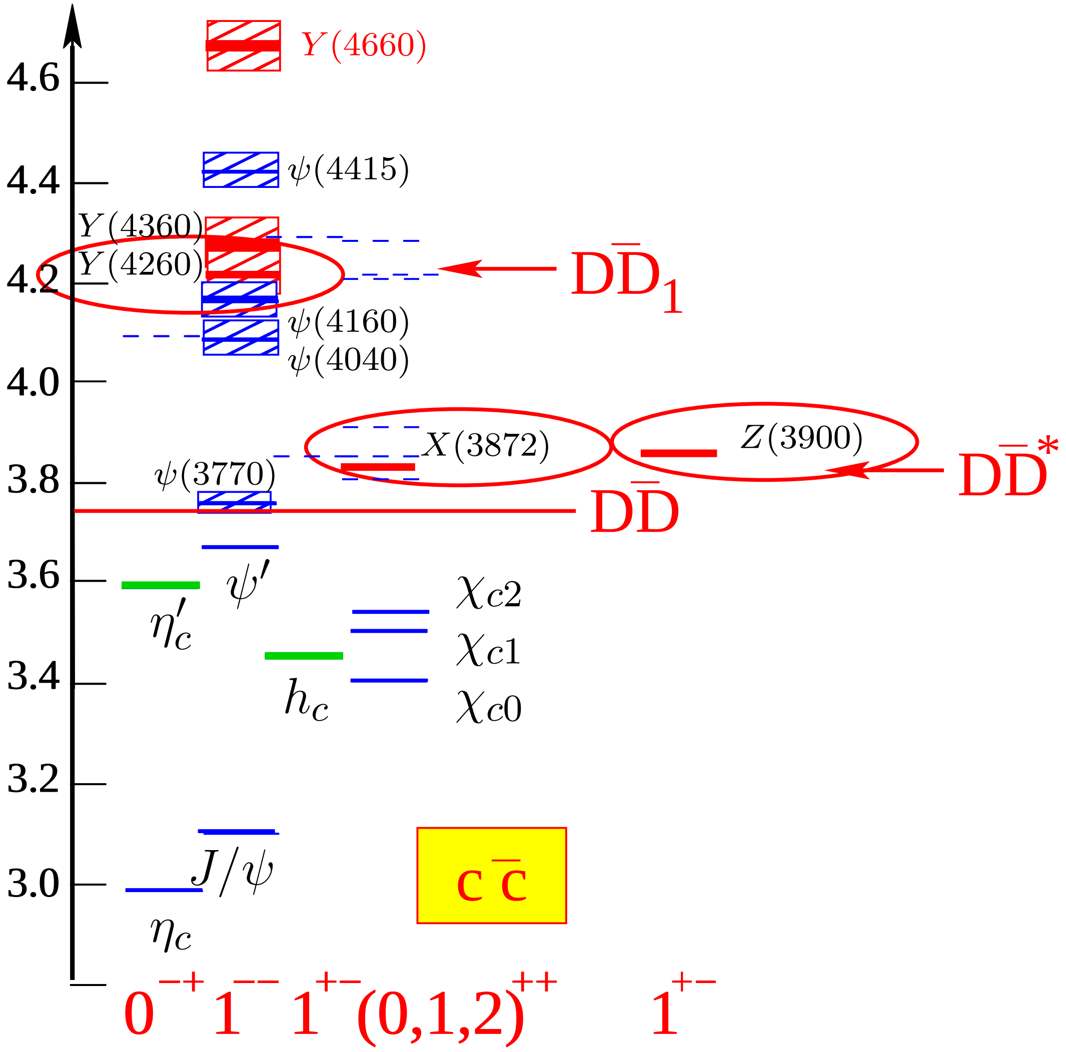
1^{+-}: $DD^* - D^*D^*$ ($Z_c(3900), Z_c(4020)$ $(I{=}1)$)

0^{++}: $DD - D^*D^*$;

Special feature: $1^{-\pm}$ states as lightest neg. parity states!

Molecular states: An example

Nontrivial statements from the molecular picture



Observation:

$|M_X - M_D - M_{D^*}| = (0.17 \pm 0.26)$ MeV

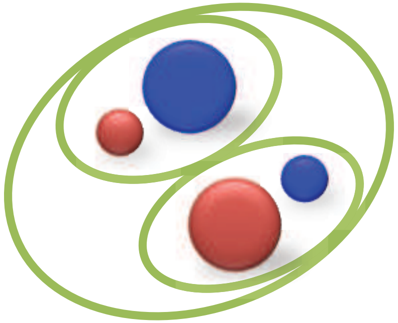
$|M_Y - M_D - M_{D_1}| \simeq 30$ MeV

$|M_Z - M_D - M_{D^*}| < 20$ MeV

What follows,

if these were

molecules?



→ for transitions and

→ line shapes

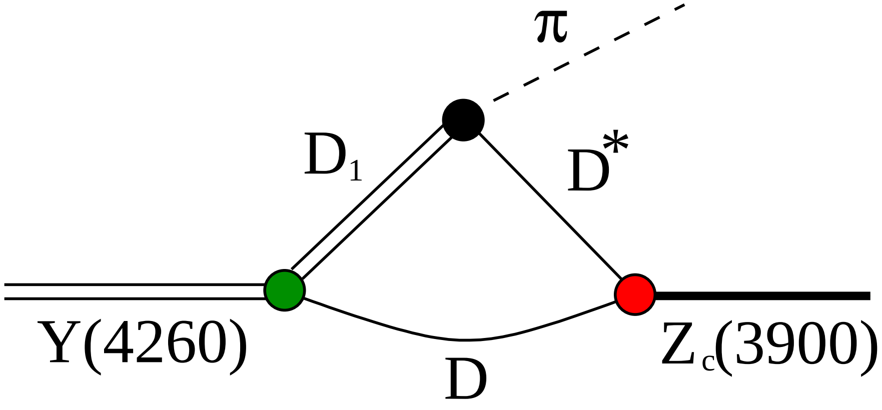
A possible scenario

We proposed:

- → $Y(4260)$ is a $D_1(2420)\bar{D}$–molecule
- → $Z_c(3900)$ is a $D^*\bar{D}$ molecule

A molecule decays via its constituents

Within this picture Z_c was found in $Y(4260)$ decays since the decay $D_1 \to D\pi$ provides many slow D^*D pairs



Q. Wang, CH and Q. Zhao, Phys. Rev. Lett. 111 (2013) 132003

Consequences I

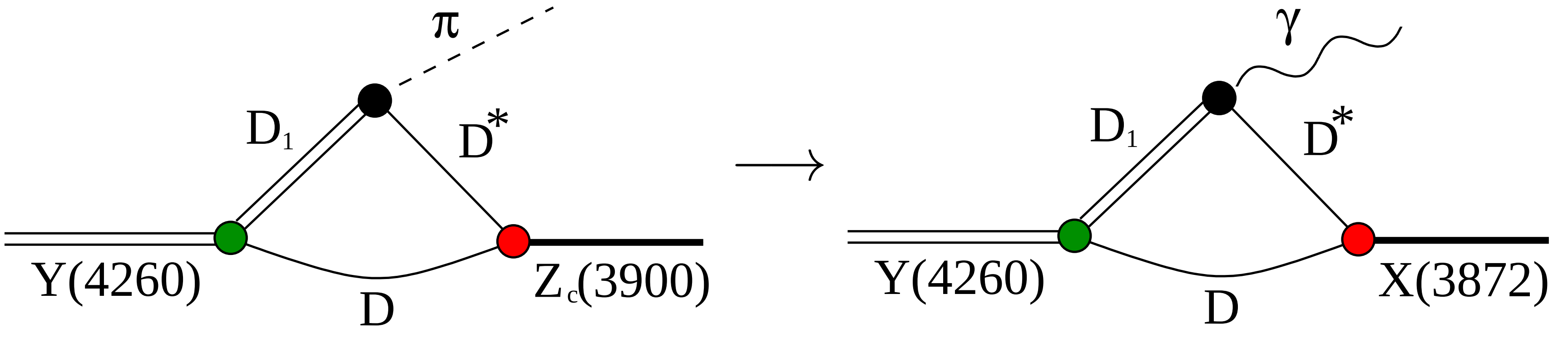
We claim that Z_c ($I(J^{PC}=1(1^{+-})$) is a $(\bar{D}^* D + D^* \bar{D})$ state with

$$Z_c^+ \sim D^{*+}\bar{D}^0\ ,\quad Z_c^0 \sim \frac{1}{\sqrt{2}}(D^{*+}D^- - D^{*0}\bar{D}^0)\ ,\quad Z_c^- \sim D^{*0}D^-$$

If now $X(3872)$ ($I(J^{PC}=0(1^{++})$) is a $(\bar{D}^* D - D^* \bar{D})$ state with

$$X \sim \frac{1}{\sqrt{2}}(D^{*+}D^- + D^{*0}\bar{D}^0)$$

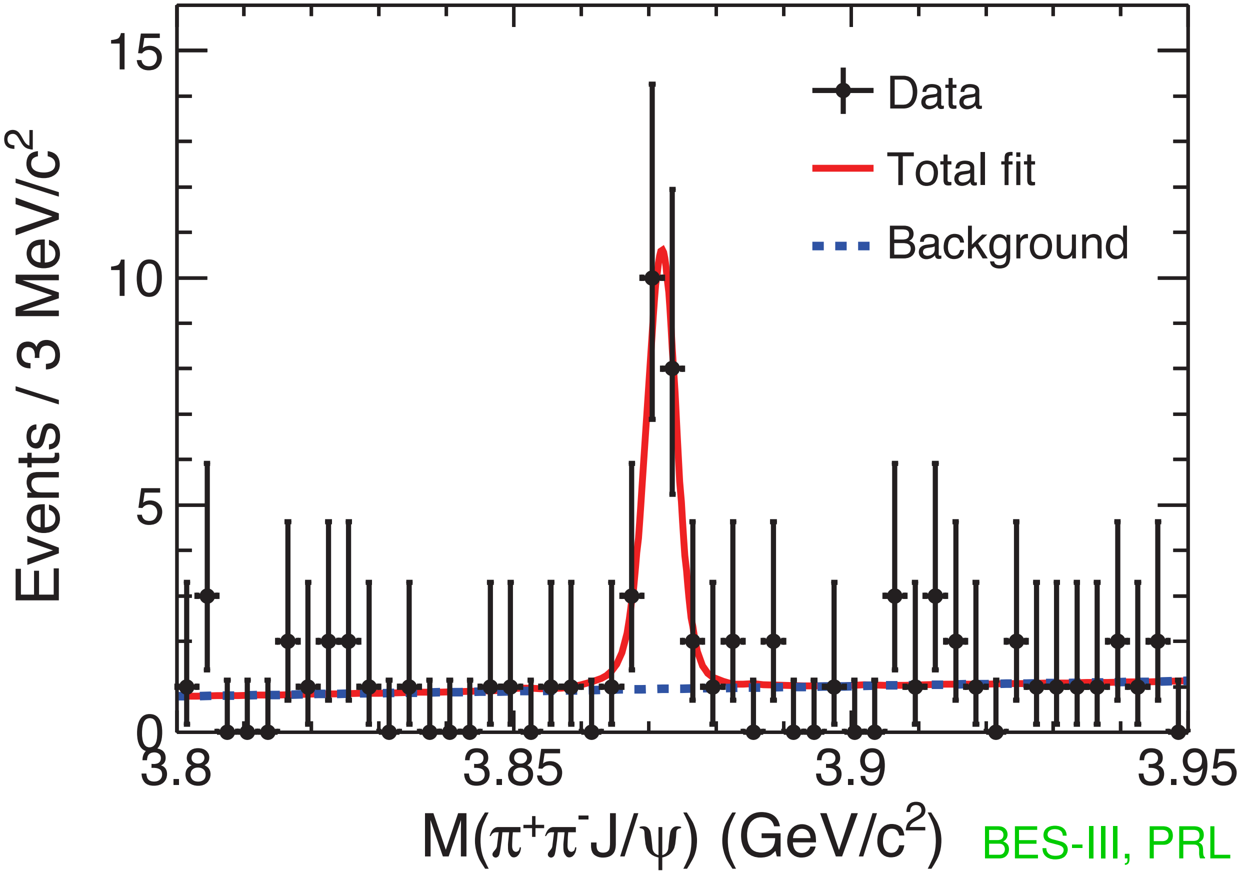
there must be $Y(4260) \to \gamma X(3872)$ F.-K. Guo et al., PLB 725 (2013) 127-133



and indeed ...

BES-III data for $Y(4260) \to \gamma X(3872) \to \gamma[\pi\pi J/\psi]$

fully in line with prediction

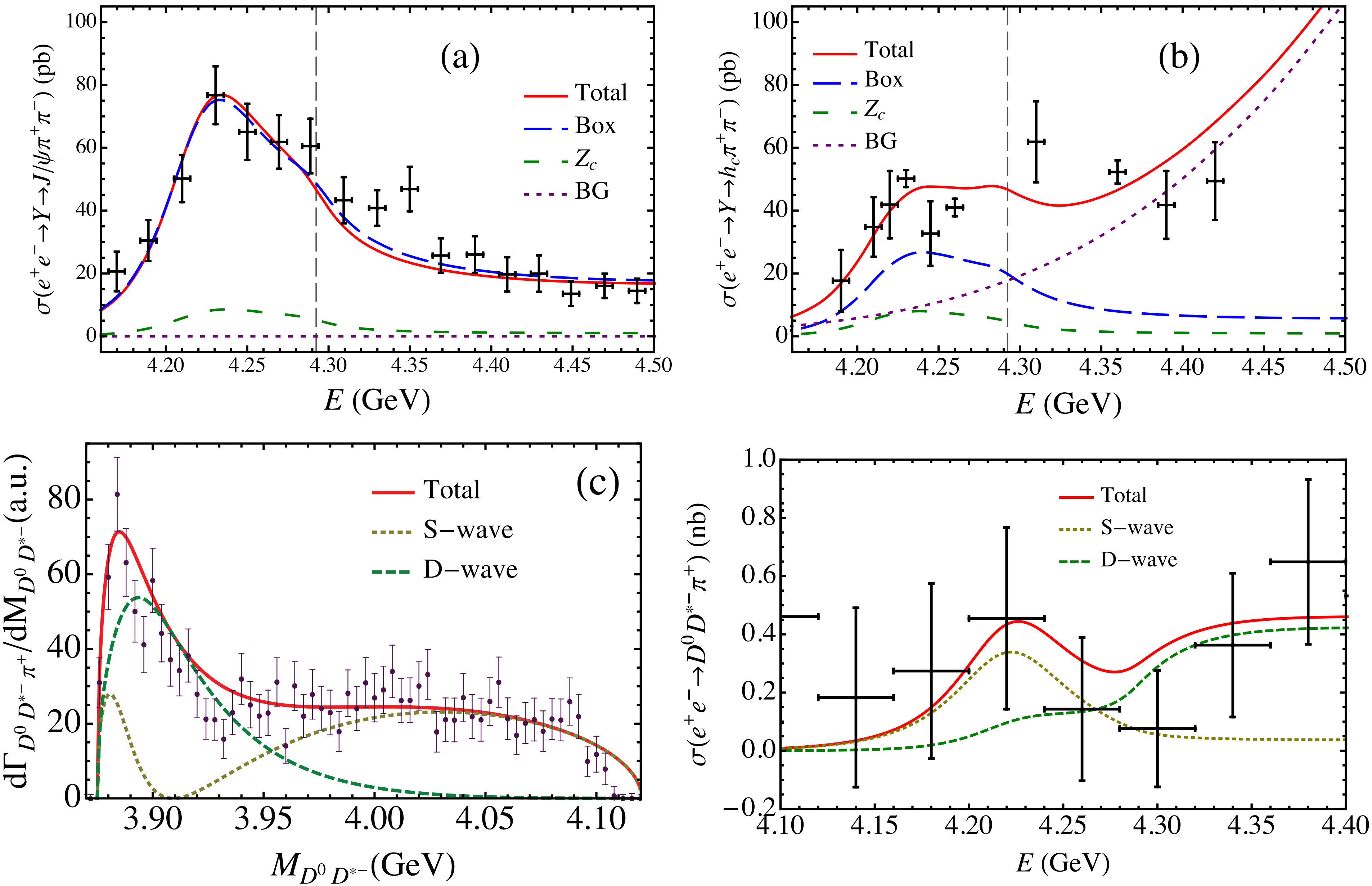


BES-III, PRL 112 (2014) 092001

Note: transition also natural within tetraquark picture

Maiani et al., PRD89(2014)114010

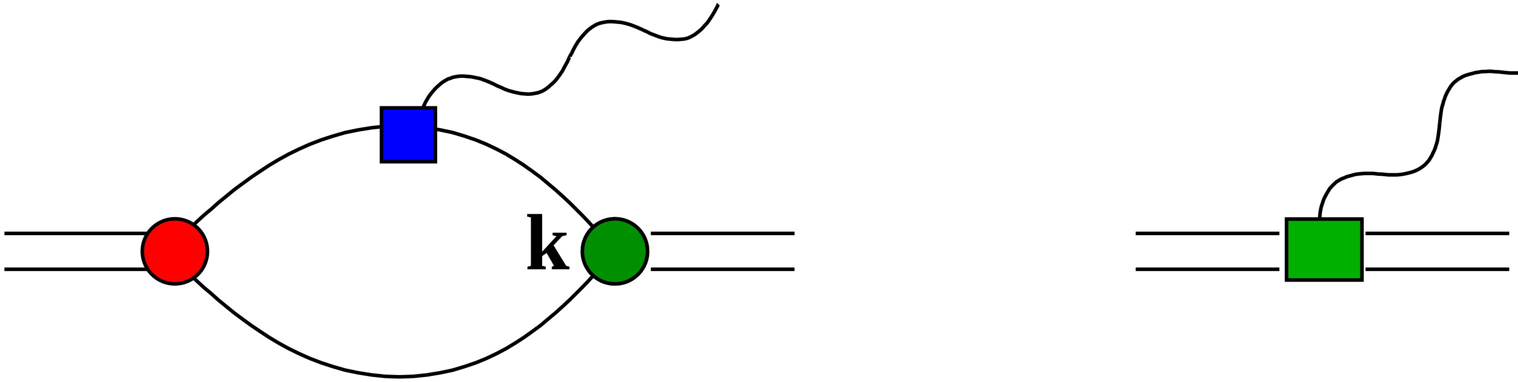
Consequences II ...



Vertical dashed line: nominal $D_1\bar{D}$ threshold

M. Cleven et al., PRD90(2014)074039

$\Gamma(X(3872) \to \gamma\psi')/\Gamma(X(3872) \to \gamma J/\psi)$



The ratio

$$\frac{\Gamma(X(3872) \to \gamma\psi')}{\Gamma(X(3872) \to \gamma J/\psi)} = 2.46 \pm 0.64 \pm 0.29$$

LHCb, NPB886(2014)665

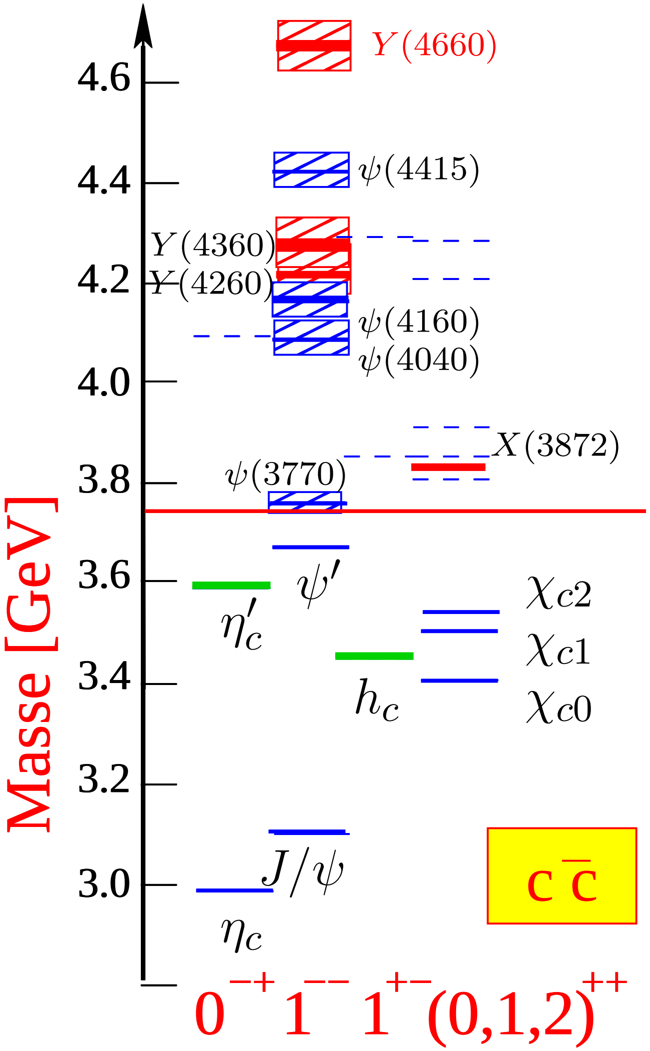
is not sensitive to the molecular component, since

→ the loop depends on $g_{\psi' DD}/g_{J/\psi DD}$

→ there is a leading order counter term

F.-K. Guo et al., PLB742(2015)394

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!

Summary

These are exciting times for strong interaction physics:

⟶ We are about to change the paradigms

What it takes is high quality experiments

analyzed with modern, controlled theory tools

The overall picture is still to come — and it promises to provide

deep insights into the inner workings of the Standard Model

... an probably beyond

Thank you very much for your attention