Estados Exóticos do Charmonium

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New charmonium mesons

Belle @ KEK: (PRL91 (2003))

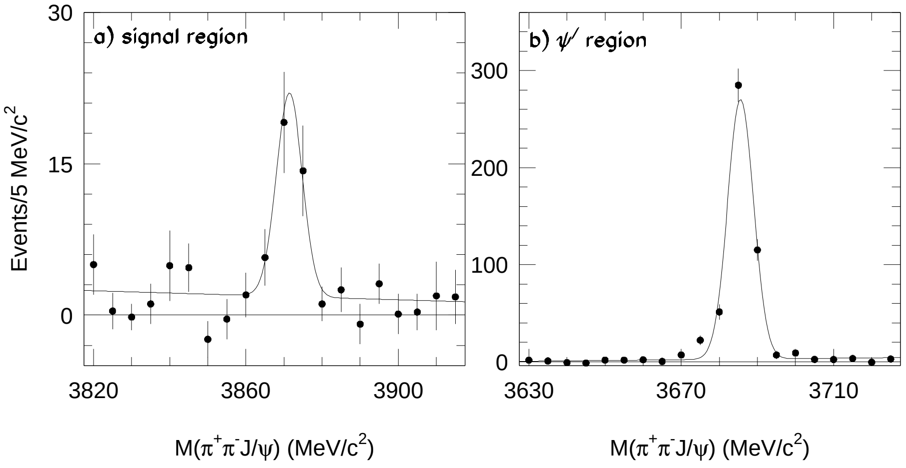
very narrow ($\Gamma < 2.3$ MeV) meson observed in B decay: $B^{\pm} \to K^{\pm}(J/\psi\pi^{+}\pi^{-})$

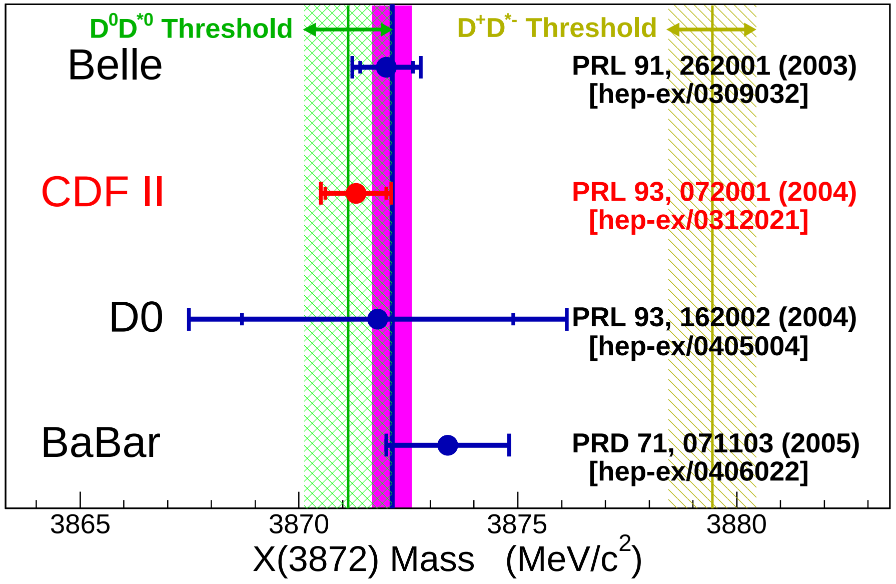
$Q = 0, \; c = 0, \; s = 0 \Rightarrow$

minimum quark content: $c\bar{c}$

$X(3872), \; J^{PC} = 1^{++}$

confirmed by CDFII, D0, BaBar





$$X(3872) \to \gamma J/\psi \Rightarrow C = +$$

$c\bar{c}$ spec. (Barnes & Godfrey, PRD69 (2004)) $\nearrow 2\,{}^3P_1\ (3990)$

$\searrow 3\,{}^3P_1\ (4290)$

if $X(3872) = c\bar{c} \Rightarrow I = 0,\ G = +$

$\dfrac{X \to J/\psi\pi^+\pi^-\pi^0}{X \to J/\psi\pi^+\pi^-} \sim 1 \Rightarrow$ strong isospin and G parity violatio

can not be a simple $c\bar{c}$ state. $M(D^{*0}\bar{D}^0) = (3871 \pm 1)$

$$\Downarrow$$

molecular $D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0$ bound state

Tetraquark state?

Maiani et al. (PRD71 (05)) tetraquark $J^{PC} = 1^{++}$ states:

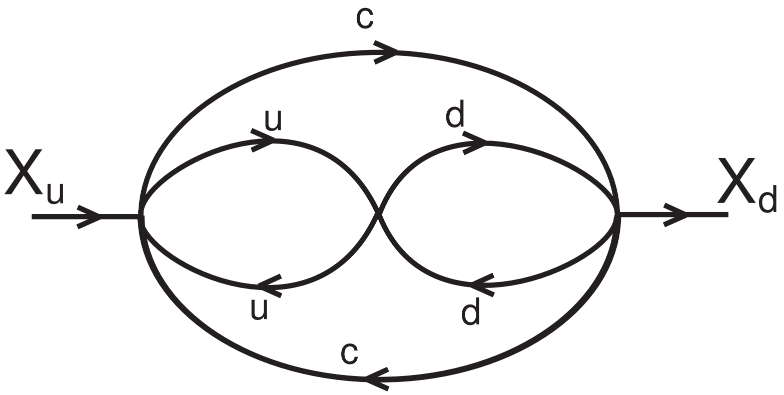
$$X_q = [cq]_{S=1}[\bar{c}\bar{q}]_{S=0} + [cq]_{S=0}[\bar{c}\bar{q}]_{S=1}$$

isospin eigenstates

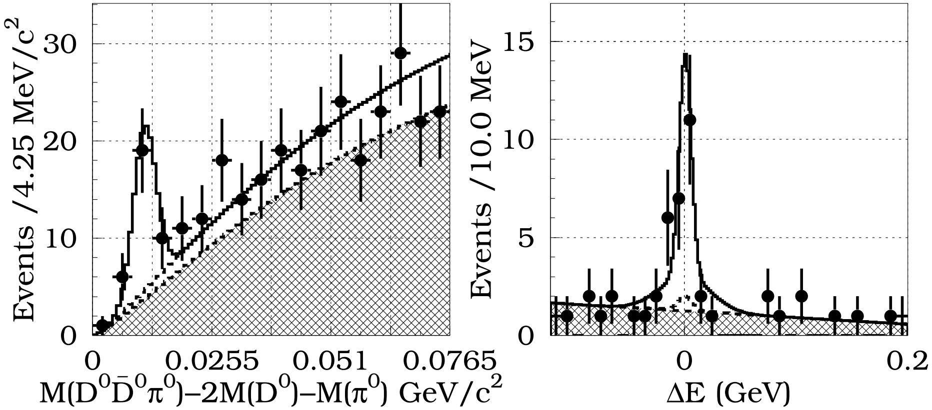
$$\nearrow X(I=0) = \frac{X_u + X_d}{\sqrt{2}}$$

$$\searrow X(I=1) = \frac{X_u - X_d}{\sqrt{2}}$$

charm quark mass scale ⇒ annihilation diagrams are suppressed ⇒ states are close to mass eigenstates, no longer isospin eigenstates



most general $\mathbf{X(3872)}$ states
$$\begin{cases} X_l = X_u \cos\theta + X_d \sin\theta \\ X_h = -X_u \sin\theta + X_d \cos\theta \\ \text{both can decay into } 2\pi,\ 3\pi \end{cases}$$

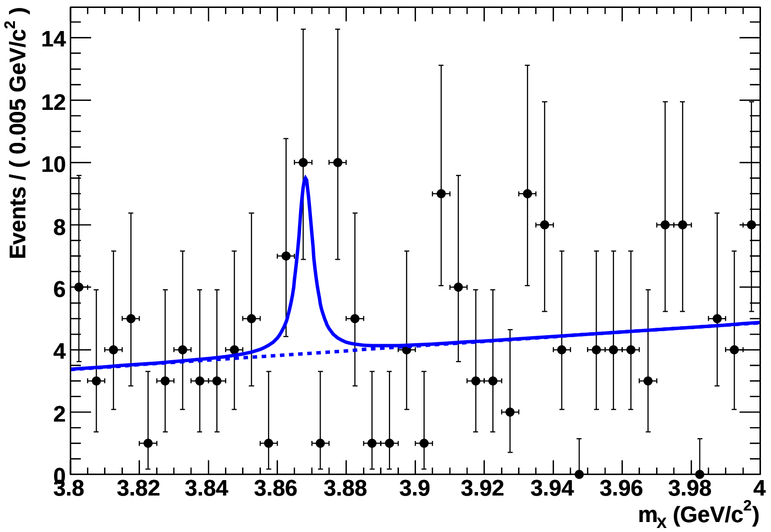


observation of an state decaying into $D^0\bar{D}^0\pi^0(DD^*)$ with mass $3875.4 \pm 07^{+1.2}_{-2.0}$ (Belle hep-ex/0606055)

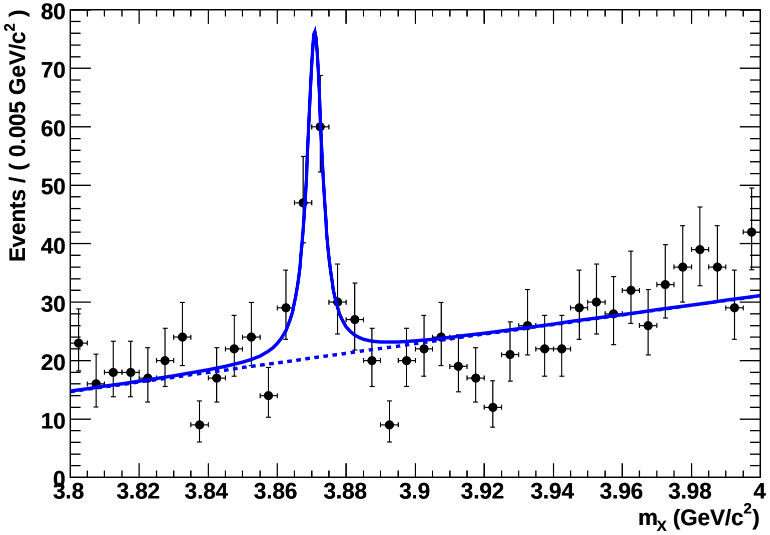
$$M(J/\psi\pi^+\pi^-) = 3871.2 \pm 0.5 \text{ MeV (world average)}$$

$$M(D^0\bar{D}^0\pi^0) \begin{cases} 3875.4 \pm 0.7^{+1.2}_{-2.0} \text{ MeV (Belle)} \\ 3875.1 \pm 0.5^{+0.7}_{-0.5} \text{ MeV (BaBar)} \end{cases}$$

BaBar Collaboration arXiv:0803.2838,



$$B^0 \to XK^0$$



$$B^+ \to XK^+$$

$$\frac{B^0 \to XK^0}{B^+ \to XK^+} = 0.41 \pm 0.24 \pm 0.05, \quad \text{molecular model} \sim \ 0.1$$

$$m(X)_{B^+} = (3871.4 \pm 0.6)\ \text{MeV}, \quad m(X)_{B^0} = (3868.7 \pm 1.6)\ \text{Me}$$

$$\Delta m = (2.7 \pm 1.6)\ \text{MeV}$$

$Y(J^{PC} = 1^{--})$ family

BaBar @ SLAC: (PRL91 (2005))

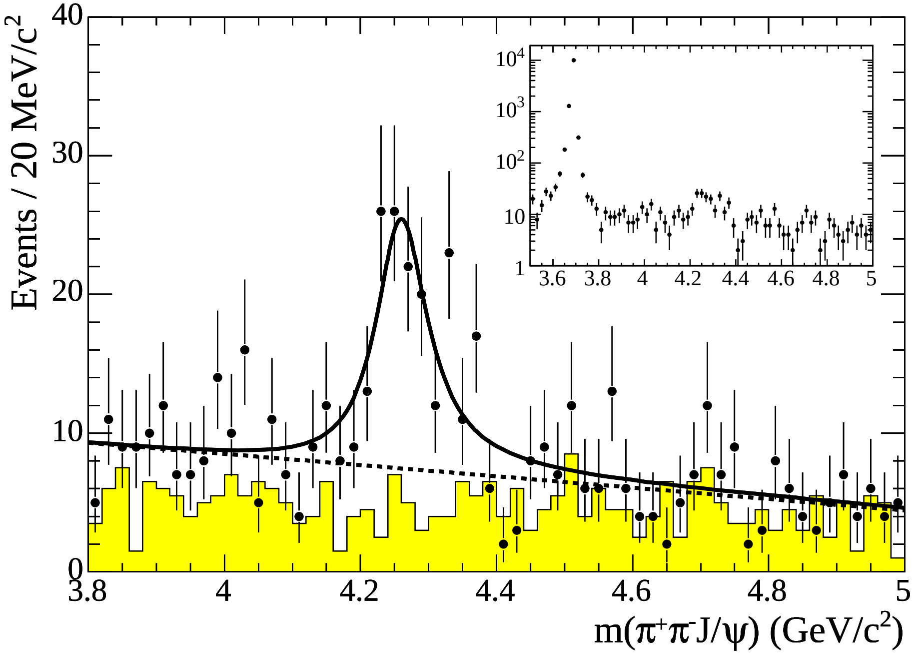
distinct peak ($\Gamma \sim 90$ MeV) meson observed in e^+e^- annihilation:
$e^+e^- \to \gamma_{IRS}(J/\psi\pi^+\pi^-)$
$Q = 0,\ c = 0,\ s = 0 \Rightarrow$

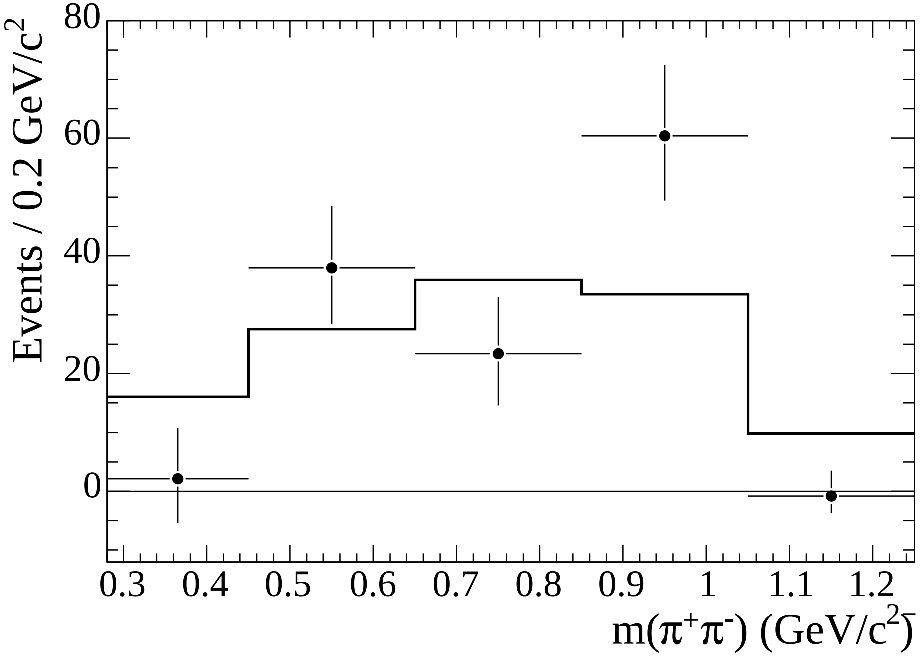
minimum quark content: $c\bar{c}$

$Y(4260),\ J^{PC} = 1^{--}$

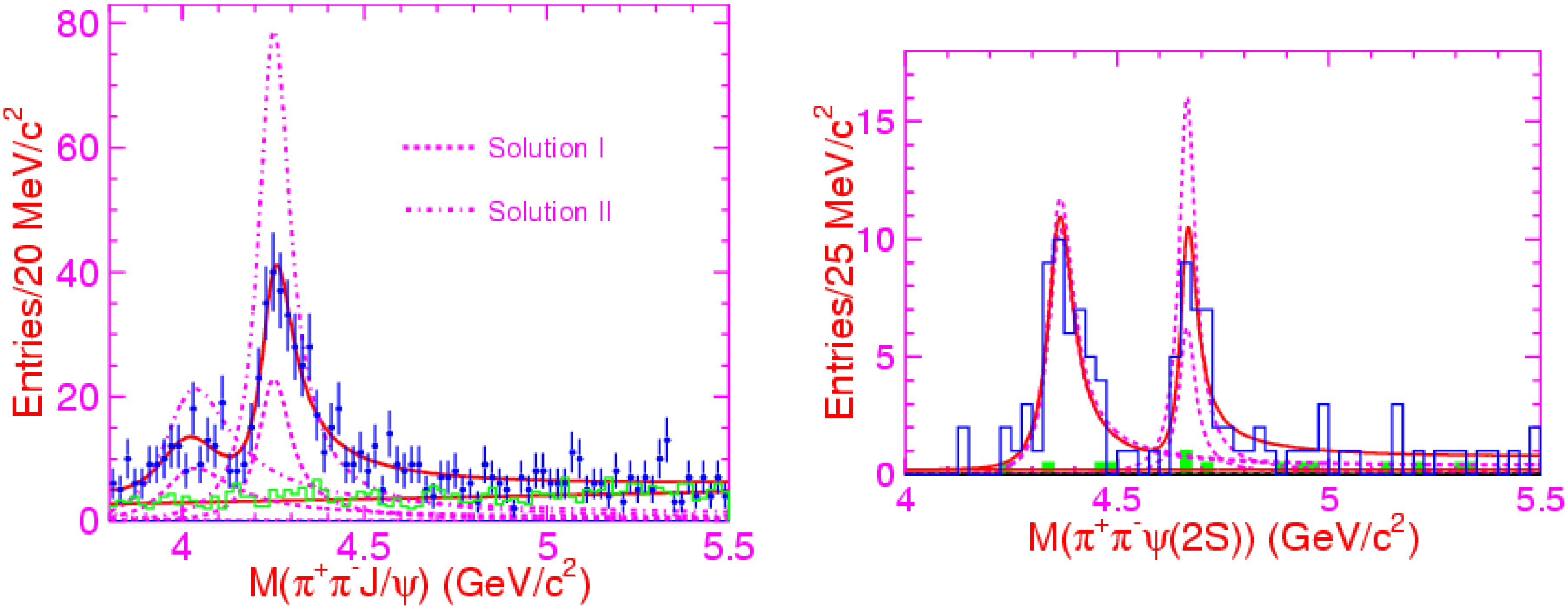
confirmed by CLEO and Belle

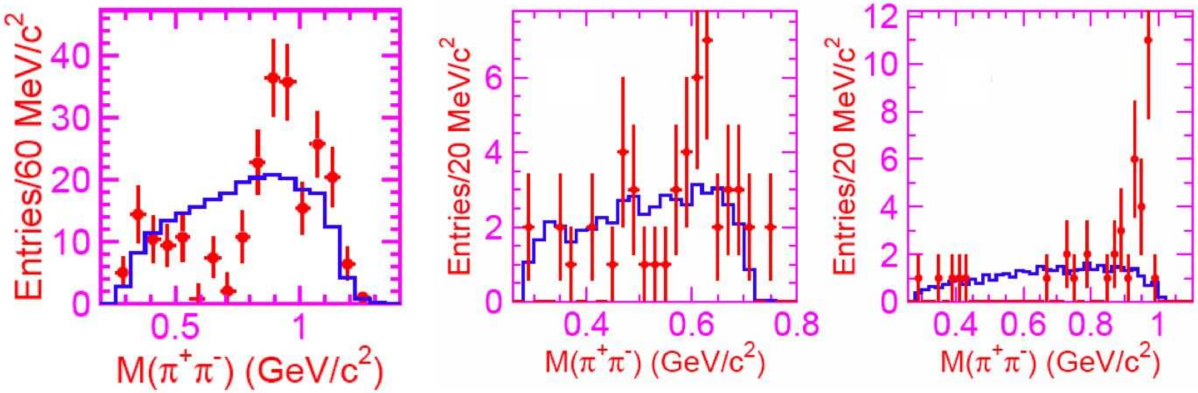
$\pi^+\pi^-$ distribution mass consistent with $f_0(980)$



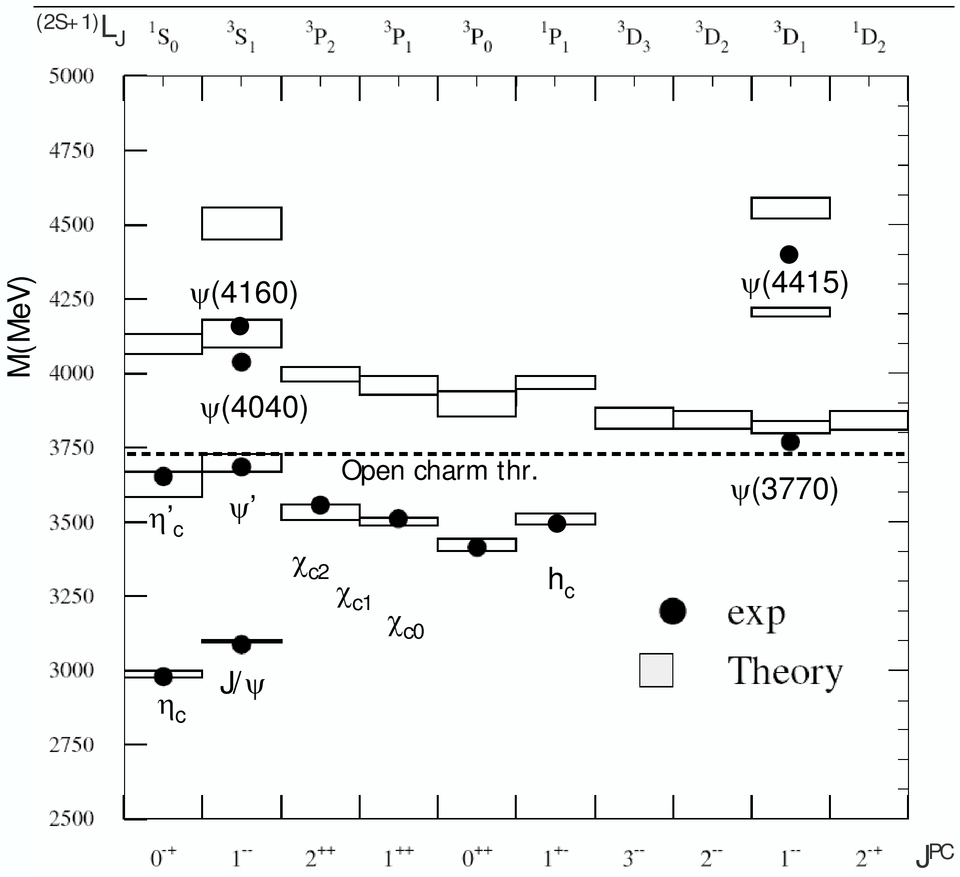


Belle Collaboration arXiv:0707.3699

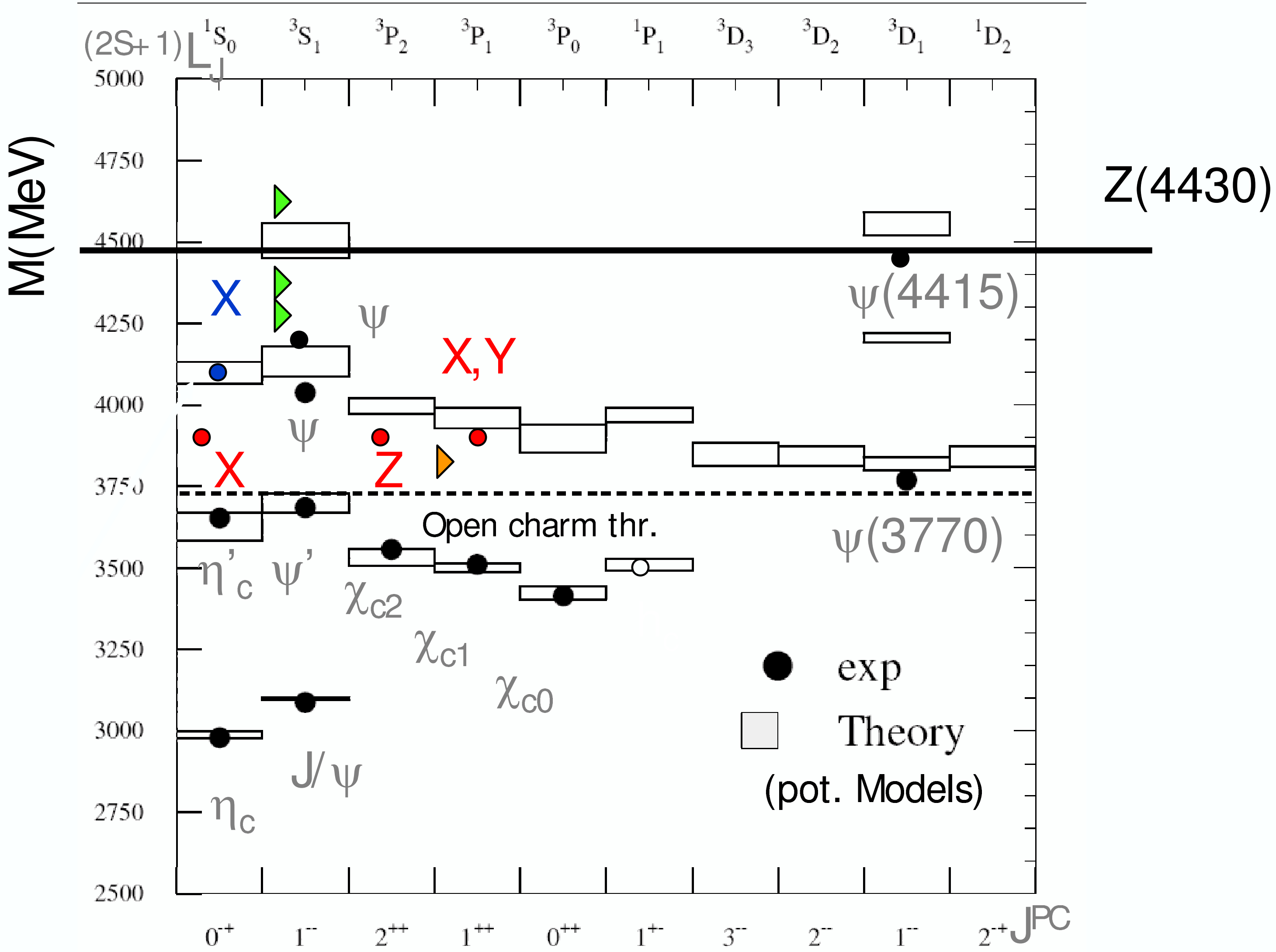




$Y(4260)$ **$Y(4350)$** **$Y(4660)$**



(2S+1)L_J
¹S₀
³S₁
³P₂
³P₁
³P₀
¹P₁
³D₃
³D₂
³D₁
¹D₂
M(MeV)
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
ψ(4160)
ψ(4040)
ψ(4415)
Open charm thr.
ψ(3770)
η'c
ψ'
χc2
χc1
χc0
hc
ηc
J/ψ
exp
Theory
0⁻⁺
1⁻⁻
2⁺⁺
1⁺⁺
0⁺⁺
1⁺⁻
3⁻⁻
2⁻⁻
1⁻⁻
2⁻⁺
J^PC



M(MeV)
(2S+1)L_J
1S0
3S1
3P2
3P1
3P0
1P1
3D3
3D2
3D1
1D2
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
Z(4430)
X
ψ
X,Y
ψ(4415)
ψ
X
Z
Open charm thr.
ψ(3770)
η'c
ψ'
χc2
χc1
χc0
J/ψ
ηc
● exp
Theory
(pot. Models)
0-+
1--
2++
1++
0++
1+-
3--
2--
1--
2-+
JPC

Tetraquark states?

Maiani et al. (PRD72 (05)) tetraquark $J^{PC} = 1^{--}$ states:

$$Y(4260) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{\text{P-wave}}$$

$$M_Y \sim 2M_{D_s} + 600 \ \text{MeV} \sim 4540 \ \text{MeV}$$

$$Y(?) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=1} + [cs]_{S=1}[\bar{c}\bar{s}]_{S=0})$$

molecule ↗ $(D_s\bar{D}_s)_{\text{P-wave}} \ (m \sim 3940 + L)$

molecule ↘ $(D_s^*\bar{D}_{s0}) \ (m \sim 4430 \ \text{MeV})$

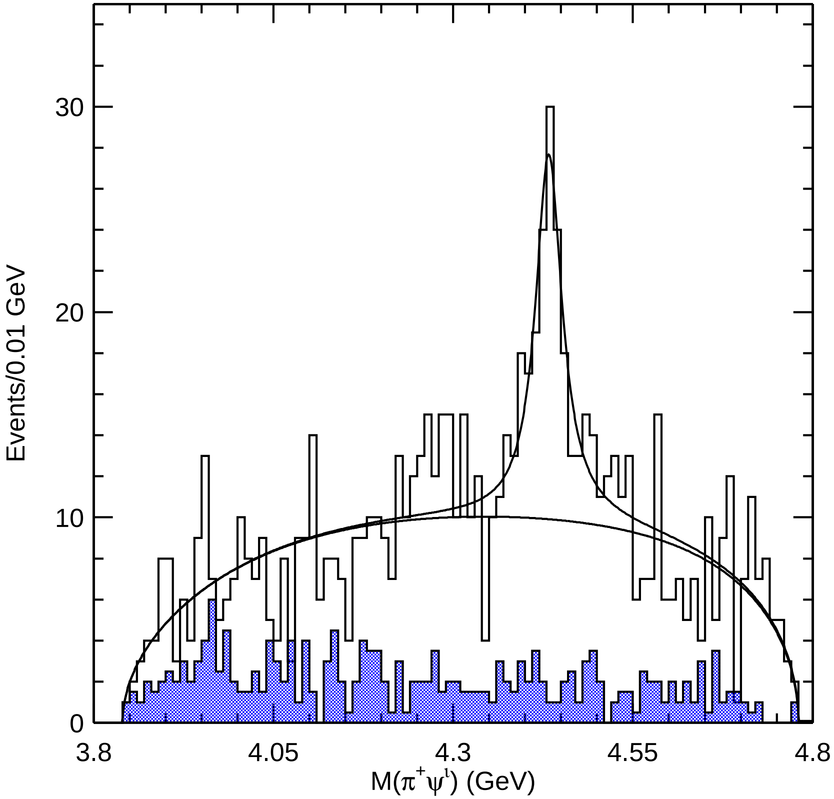
Belle @ KEK: (arXiv:0708.1790)

distinct peak ($\Gamma \sim 45$ MeV) observed in the decay mode $\bar{B}^0 \to K^-(\psi'\pi^+)$

$Q = +,\ c = 0\ \Rightarrow$

minimum quark content: $c\bar{c}u\bar{d}$

$Z^+(4430),\ J^P = ?^?$



$$Z^+(4430) \to \psi'\pi^+ \Rightarrow I^G = 1^+$$

$$M(\bar{D}_1^0(2420)D^{*+}(2010)) = 4430 \text{ MeV}$$

$Z^+(4430)$

- threshold effect in the $D_1 D^*$ channel
  Rosner, arXiv:0708.3496
- four-quark radial excitation with $J^{PC} = 1^{+-}$
  Maiani, Polosa & Riquer, arXiv:0708.3997
- radial excitation of $\Lambda_c - \Sigma_c^0$ bound state
  Qiao, arXiv:0709.4066
- $D_1 D^*$ molecular state with $J^P = 0^-, 1^-, 2^-$
  Meng & Cheng, arXiv:0708.4222

2^+ suppressed in $B \to Z(4430)K$ due to small phase space

$1^- \Rightarrow J^{PC}[Z^0] = 1^{--}$. Why was not seen in e^+e^- annihilation? ($Y(4260)$, $Y(4350)$, $Y(4660)$)

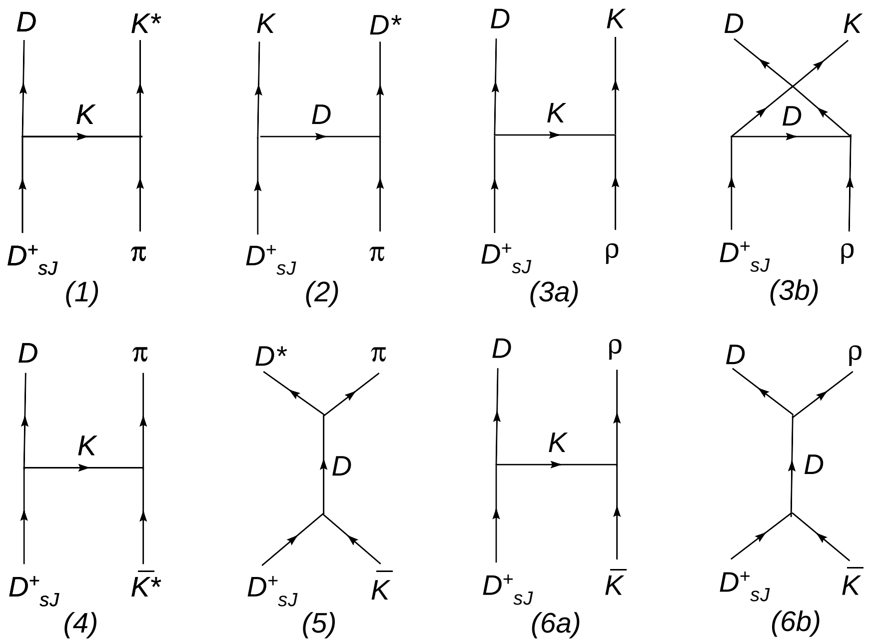
Is there an experimental way to test the structure?

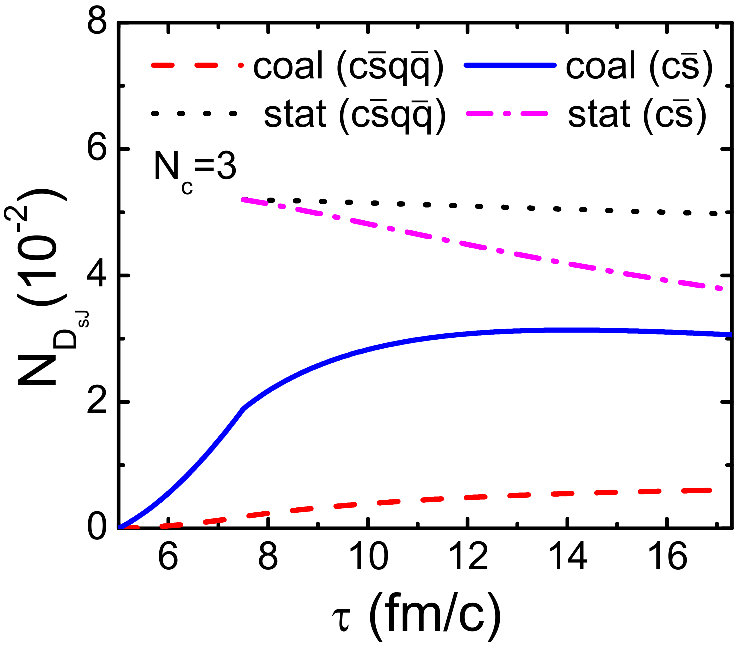
$$g^{two}_{D_{s0}DK} = 9.2\ \text{GeV}, \qquad g^{four}_{D_{s0}DK} = 3.15\ \text{GeV}$$

Wang & Wan PRD73(2006)

MN hep-ph/0610320

time evolution of $D_{s0}(2317)$ abundance in central Au+Au collision - arXiv:0705.1697

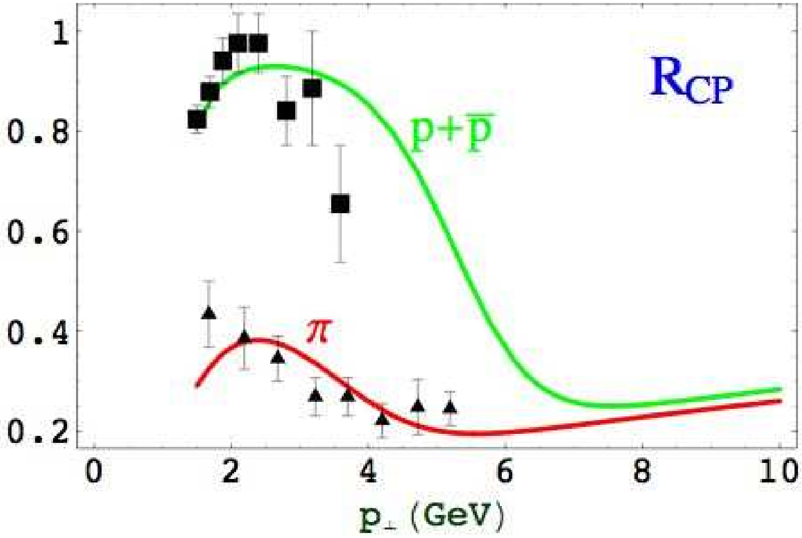


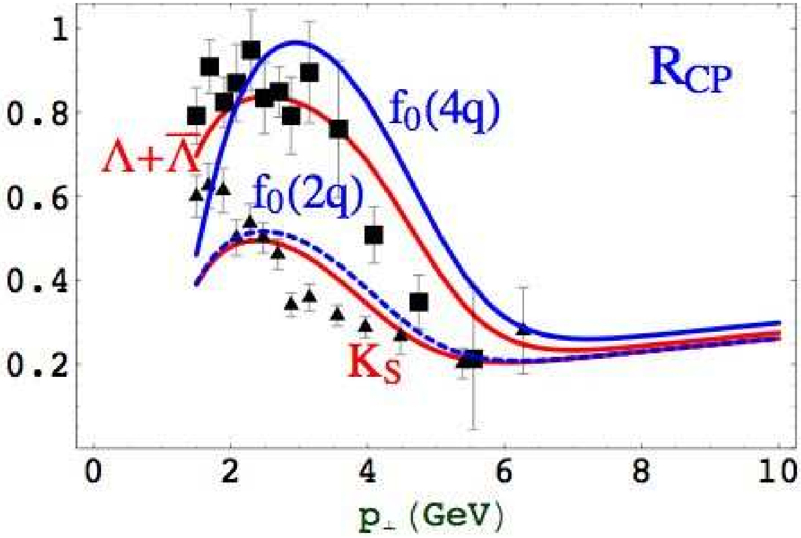


Counting quarks

recombination/fragmentation model (Maiani et al. PLB645(2007)):

$$R_{CP} = \frac{N_{\mathrm{coll}}(b)\, d^2 N_{\mathrm{Au+Au}}(b=0)/dP_\perp^2}{N_{\mathrm{coll}}(b=0)\, d^2 N_{\mathrm{Au+Au}}(b)/dP_\perp^2}$$





QCD Sum Rules

- **$X(3872)$, $Y(?)$**
  as four-quark states
  diquark antidiquark structure
- **$Z^+(4430)$**
  as molecular $D_1 D^*$ state with $J^P = 0^-$

QCD Sum Rules

- powerful framework investigate masses
- vector mesons
- barionic octet

QCD Sum Rule

Fundamental Assumption: Principle of Duality

$$\Pi(q) = i \int d^4x \, e^{iq.x} \, \langle 0 | T[j(x) j^\dagger(0)] | 0 \rangle$$

Theoretical side	Phenomenological side
↓	↓
quark level quark and gluon degrees of freedom	hadron level hadron parameters (masses, couplings, form-factors,...)
↓	↓
Wilson OPE	dispersion relation

To improve the matching $\Rightarrow$ Borel transform

Phenomenological side

$$\Pi^{phen} = \lambda^2 \frac{1}{m_S^2 - q^2} + continuum, \qquad \lambda = \langle 0 | j | S \rangle$$

Theoretical Side

$$\Pi^{OPE}(q^2) = \int_{m_c^2}^{\infty} ds\, \frac{\rho(s)}{s - q^2}, \qquad \rho(s) = \frac{1}{\pi}\mathrm{Im}[\Pi^{OPE}]$$

$$\text{condensates up to dimension 6} \left\{ \begin{array}{l} \text{quark condensate} \\ \text{gluon condensate} \\ \text{mixed condensate} \\ \text{four-quark condensate} \end{array} \right.$$

$$continuum = \int_{s_0}^{\infty} ds\, \frac{\rho^{OPE}(s)}{s - q^2}$$

Borel Transform {
eliminates subtraction terms
suppresses higher order condensates
increases importance pole contribution

$$\lambda^2 e^{-m_S^2/M^2} = \int_{m_c^2}^{s_0} ds\ \rho^{OPE}(s)\ e^{-s/M^2}$$

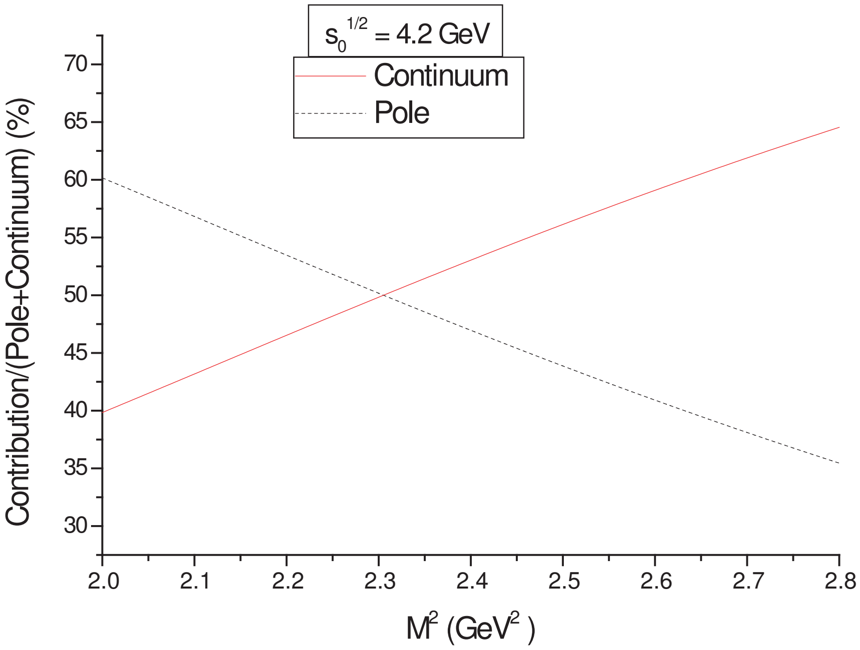
good Sum Rule ⇒ Borel window such that:

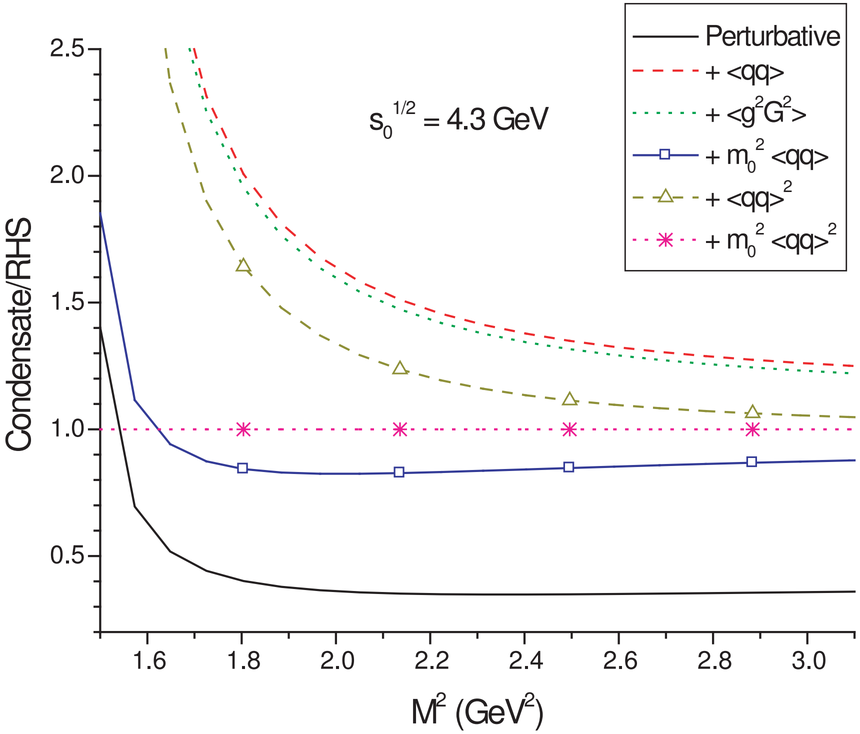
- pole contribution > continuum contribution
- converging OPE

QCDSR
light scalars
: $q\bar{q}$ states ⇒ m > 1.5 GeV
$(q\bar{q})^2$Latorre & Pascual (JPG-85), Narison (PLB-86)
no attempt to control OPE or pole contribution

$X(3872)$

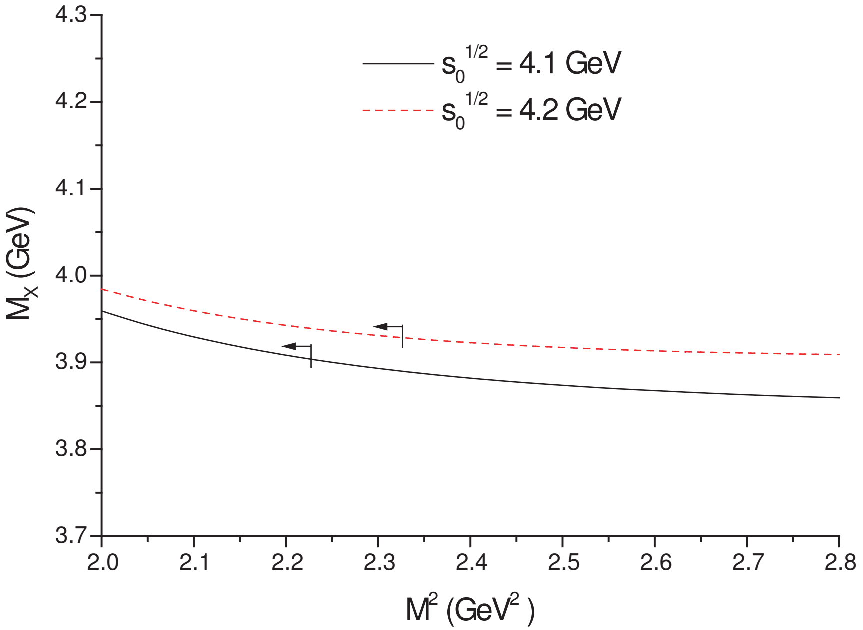
$$j^X_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\Big[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T)+(q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)$$





good Borel window $2.0 \le M^2 \le 2.3$ GeV^2

Matheus, Narison, M.N and Richard, Phys. Rev. D75 (2007)



$$m_X = (3.92 \pm 0.13)\ \text{GeV}$$

good agreement $X(3872)$

for $X(3872) = D^0\bar{D}^{*0} + \bar{D}^0 D^{*0}$: $m_X = (3.87 \pm 0.07)$ GeV

$$X_l = X_u \cos\theta + X_d \sin\theta, \quad X_h = -X_u \sin\theta + X_d \cos\theta$$

$M(J/\psi\pi^+\pi^-) = 3871.2 \pm 0.5$ MeV,
$M(D^0\bar{D}^0\pi^0) = 3875.3 \pm 0.7$ MeV

$\theta = 20^0 \Rightarrow \; |M(X_h) - M(X_l)| \sim (2.6 \;-\; 3.9)$ MeV

result very depending on $\gamma = \frac{\langle 0|\bar{d}d - \bar{u}u|0\rangle}{\langle 0|\bar{u}u|0\rangle}$

Prediction for $X_s = [cs][\bar{c}\bar{s}]$ $(2.0 \leq M^2 \leq 2.3$ GeV^2):

$$m_{X_s} < m_X : \;\; m_{X_s} - m_X = -(60 \pm 30) \text{ MeV}$$

Prediction for $X_b = [bq][\bar{b}\bar{q}]$ $(6.0 \leq M^2 \leq 7$ GeV^2):

$$m_{X_b} = (10.14 \pm 0.11) \;\text{ GeV}$$

Decay Width

Decays ↗ $X(3872) \longrightarrow J/\psi\omega \longrightarrow J/\psi\pi^+\pi^-\pi^0$

Decays ↘ $X(3872) \longrightarrow J/\psi\rho \longrightarrow J/\psi\pi^+\pi^-$

$$M_i(p) \longrightarrow M_1(p')M_2(q)$$

$$\Pi(p,p',q) = \int d^4x d^4y\, e^{ip'.x}\, e^{iq.y} \langle 0|T[j_{M_1}(x) j_{M_2}(y) j^\dagger_{M_i}(0)]|$$

$$\Pi^{phen} \propto g_{M_i M_1 M_2}$$

$$\Gamma(M_i \longrightarrow M_1 M_2) \propto g^2_{M_i M_1 M_2}$$

$$\frac{Br(X \to J/\psi\, \pi^+\pi^-\pi^0)}{Br(X \to J/\psi\, \pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

considering $3\pi \longrightarrow$ virtual ω, $2\pi \longrightarrow$ virtual ρ and the states

$$X_l = X_u \cos\theta + X_d \sin\theta, \quad X_h = -X_u \sin\theta + X_d \cos\theta$$

$$\left(\frac{\Gamma(X_{l,h} \to J/\psi\; 3\pi)}{\Gamma(X_{l,h} \to J/\psi\; 2\pi)}\right) = 0.152 \left(\frac{\cos\theta \pm \sin\theta}{\cos\theta \mp \sin\theta}\right)^2 \Rightarrow \theta \sim \pm 23$$

ref.	Γ (MeV)	$g_{X\psi\omega}$
Maiani et al., PRD71(2005)	~ 0.4	0.475
Navarra, MN, PLB639(2006)	50 ± 15	13.8 ± 2.0

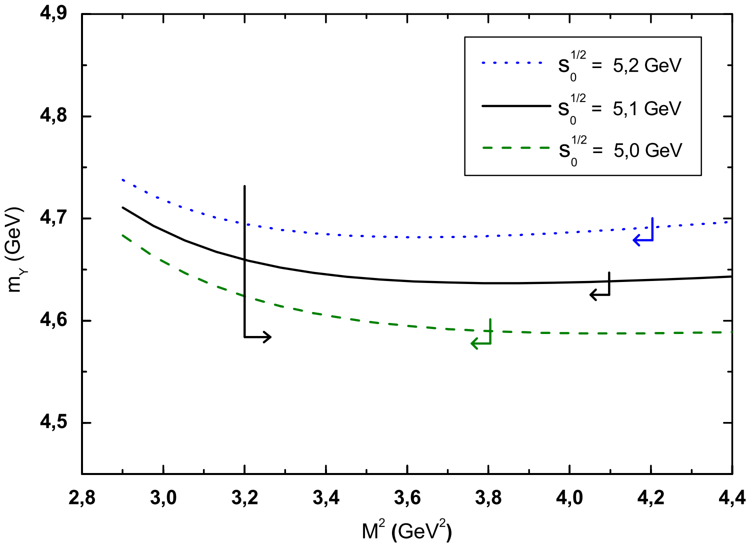
$\Gamma_{total} < 2.3$ MeV

Chromomagnetic model (Høgaasen, Richard & Sorba, PRD73(2006))

$$X \longrightarrow [c\bar{c}]_1^8 \otimes [q\bar{q}]_1^8$$

$Y(4???)$

$$j_\mu^Y = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\Big[(s_a^T C\gamma_5 c_b)(\bar{s}_d\gamma_\mu\gamma_5 C\bar{c}_e^T)+(s_a^T C\gamma_\mu\gamma_5 c_b)(\bar{s}_d\gamma_5 C$$

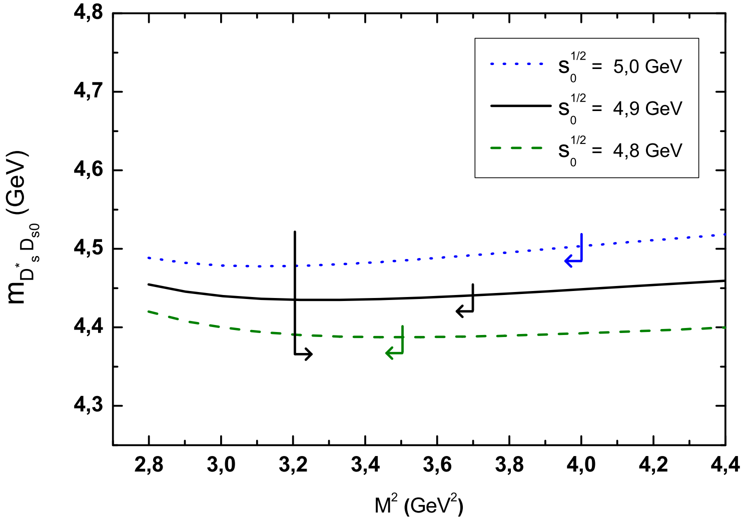


$m_Y = (4.65 \pm 0.10)$ GeV

good agreement $Y(4660)$

$s \leftrightarrow q \rightarrow m = (4.49 \pm 0.11)$ GeV: Y(4350)?

$Y = D_{s0}\bar{D}_s^* + \bar{D}_{s0}D_s^*$ molecule



$$m_Y = (4.42 \pm 0.10)\ \text{GeV}$$

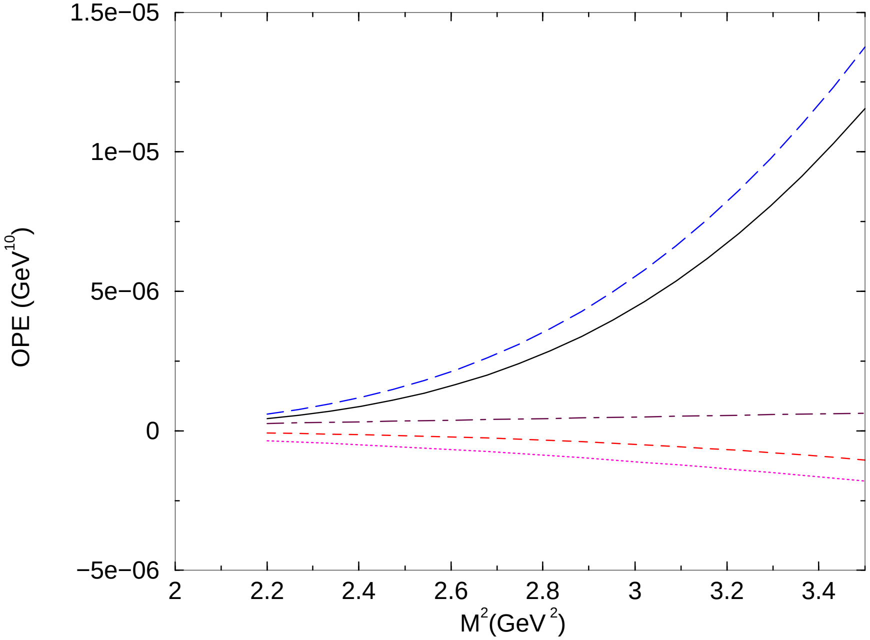
also in agreement with $Y(4530)$

$$s \leftrightarrow q \longrightarrow m = (4.27 \pm 0.11)\ \text{GeV: Y(4260)!}$$

$$Y(J^{PC} = 1^{--}) \begin{cases} (cs)(\bar{c}\bar{s}) \longrightarrow Y(4660) \\ (cq)(\bar{c}\bar{q}) \text{ or } D_{s0}\bar{D}_s^* \longrightarrow Y(4350) \\ D_0\bar{D}^* \text{ molecule } \longrightarrow Y(4260) \end{cases}$$

$Z^+(4430)$: D^*D_1 state with $J^P = 0^-$

$$j = \frac{1}{\sqrt{2}}\left[(\bar{d}_a\gamma_\mu c_a)(\bar{c}_b\gamma^\mu\gamma_5 u_b) + (\bar{d}_a\gamma_\mu\gamma_5 c_a)(\bar{c}_b\gamma^\mu u_b)\right]$$



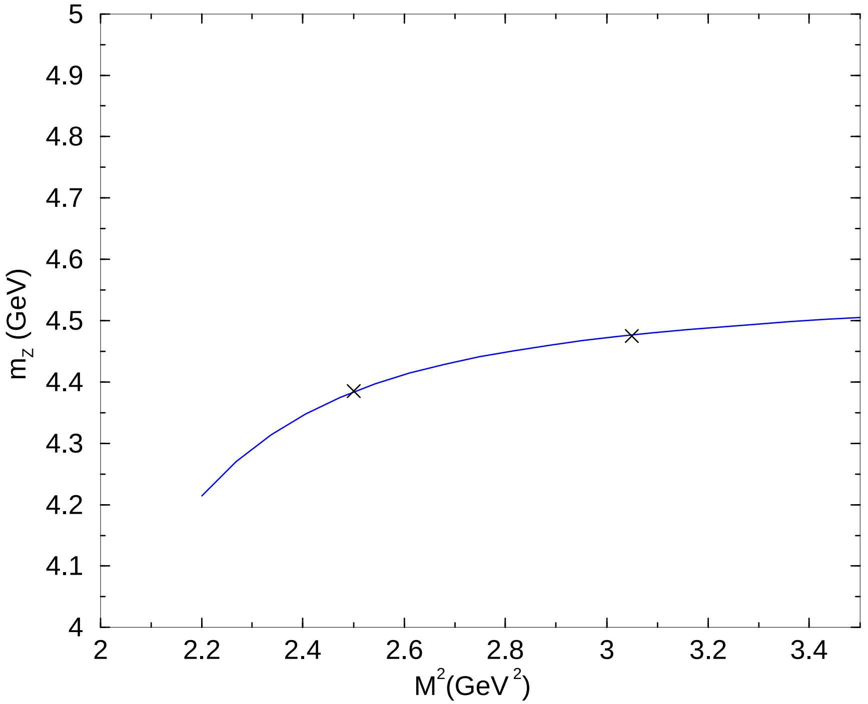
$s_0 = \sqrt{4.9}$ GeV

– – – – – – perturbative
- - - - - - - - $\langle g^2G^2\rangle$
· · · · · · · · $\langle\bar{q}q\rangle^2$
— · — · — · $\langle\bar{q}g\sigma.Gq\rangle\langle\bar{q}q\rangle$
—— total

pole cont. > continuum cont.
$\Rightarrow\ M^2 < 3.05$ GeV^2

good Borel window $2.5 \leq M^2 \leq 3.05$ GeV^2

Lee, Mihara, Navarra, MN, arXiv:0710.1029



$$m_Z = (4.43 \pm 0.08)\ \text{GeV}$$

good agreement $Z^+(4430)$

Prediction for $Z_{bb} = B_1 B^*$ $(8.0 \leq M^2 \leq 9.0\,\text{GeV}^2)$:

$$m_{Z_{bb}} = (10.74 \pm 0.12)\ \text{GeV}$$

Conclusions

Evaluated masses of: $\boldsymbol{X(3872)}$ and $\boldsymbol{Y(4660)}$ as diquark-antidiquark states and $\boldsymbol{Z^+(4430)}$ as a $\boldsymbol{D_1 D^*}$ state with $\boldsymbol{J^P = 0^-}$: good agreement with experimental masses, and good Borel window.

QCDSR $\Rightarrow$ $\boldsymbol{X(3872)}$ can be a four-quark state: remains to explain its narrow width.

What about the other molecules?

More study is needed to arrive at a conclusion about the tetraquark states.

Important to find experimental probes to test the structure of these mesons.

$T_{cc}^{+}([cc][\bar{u}\bar{d}])\ J^P = 1^+$

Stable against strong decay if $m < m[DD^*] = 3.875$ GeV:
$\not\to DD$ in S wave due to J nor in P wave due to P

Navarra, MN, Lee, hep-ph/0703071

$$m_{T_{cc}} = (4.0 \pm 0.2)\ \text{GeV}$$

particle	m (GeV)	J^{PC}
$X(3872)$	3.92 ± 0.13	1^{++}
$Z^+(4430)$	4.43 ± 0.08	0^-
T_{cc}	4.0 ± 0.2	1^+

T_{cc}: as easy to form in HIC at LHC as $X(3872)$
Lee, Yasui, Liu, Ko, arXiv:0707.1747