Investigating the structure of the new mesons: $D_{s0}(2317)$, $D_{s1}(2460)$ and $X(3872)$

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Low x workshop

light scalars

new mesons: BaBar $D_{s0}(2317)$, CLEO $D_{s1}(2460)$, Belle $X(3872)$

masses and $X(3872)$ decay width

Scalar Mesons Spectroscopy

$\sigma(480)$, $\kappa(800)$, $f_0(980)$ and $a_0(980)$

$q\bar{q}$ states

$\Downarrow$

two isoscalars

$$f_0 = \cos(\alpha) s\bar{s} + \frac{\sin(\alpha)}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

$$\sigma = \frac{\cos(\alpha)}{\sqrt{2}}(u\bar{u} + d\bar{d}) - \sin(\alpha) s\bar{s}$$

$$a_0^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \quad a_0^+ = u\bar{d} \quad a_0^- = d\bar{u}$$

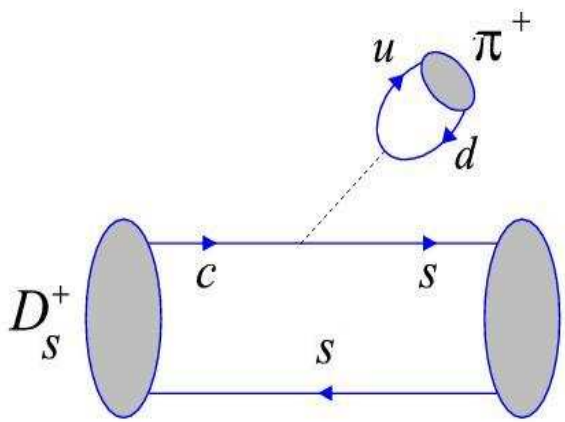
$$\kappa^+ = u\bar{s}, \quad \kappa^0 = d\bar{s}, \quad \bar{\kappa}^0 = s\bar{d}, \quad \kappa^- = s\bar{u}$$

we cannot understand the mass hierarchy

copious $\phi \to f_0(980)\gamma$ and $\phi \to a_0^0(980)\gamma$ decay

$$f_0 = \cos(\alpha) s\bar{s} + \frac{\sin(\alpha)}{\sqrt{2}}(u\bar{u} + d\bar{d}), \quad a_0^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

α small ?????

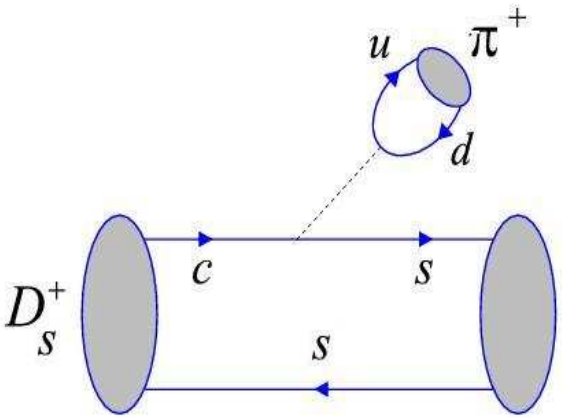


Bediaga, MN
PRD68 (03)

: $\frac{\Gamma(D_s^+ \to f_0(980)\pi^+)}{\Gamma(D_s^+ \to \phi\pi^+)}$ $(0.44 \pm 0.18)\cos^2\alpha$

$$\left(\frac{\Gamma(D_s^+ \to f_0(980)\pi^+)}{\Gamma(D_s^+ \to \phi\pi^+)}\right)^{E791} = (0.21 \pm 0.07) \Rightarrow \alpha \sim 36^0$$

$$\sigma_0 = -\sin(\alpha) s\bar{s} + \frac{\cos(\alpha)}{\sqrt{2}}(u\bar{u} + d\bar{d})$$



$$\frac{\Gamma(D_s^+ \to \sigma\pi^+)}{\Gamma(D_s^+ \to f_0(980)\pi^+)} \propto \tan^2(\alpha)$$

E791 do not see $D_s^+ \to \sigma\pi^+$

$$R = \frac{\Gamma(D_s^+ \to f_0(980)\pi^+)}{\Gamma(D^+ \to f_0(980)\pi^+)} = \frac{46 \pm 2}{\tan^2(\alpha)},$$ (Bediaga, Navarra, MN, PLB579(0

E791 Coll. → $R = 13.3 \pm 0.4$

→ $\alpha \sim 62^0$ *too large!*

Light Scalars $\Rightarrow$ Tetraquarks?

Jaffe (PRD15(77)) $\Rightarrow$ scalars as diquark-antidiquark states

$$\sigma = ud\bar{u}\bar{d}, \qquad f_0 = \frac{1}{\sqrt{2}}(us\bar{u}\bar{s} + ds\bar{d}\bar{s})$$

$$a_0^0 = \frac{1}{\sqrt{2}}(us\bar{u}\bar{s} - ds\bar{d}\bar{s}), \quad a_0^+ = us\bar{d}\bar{s}, \quad a_0^- = ds\bar{u}\bar{s},$$

$$\kappa^+ = ud\bar{d}\bar{s}, , \quad \kappa^0 = ud\bar{u}\bar{s}, \quad \bar{\kappa}^0 = us\bar{u}\bar{d}, \quad \kappa^- = ds\bar{u}\bar{d}$$

$\boxed{\text{we do understand the mass hierarchy}}$

New scalar charmed mesons

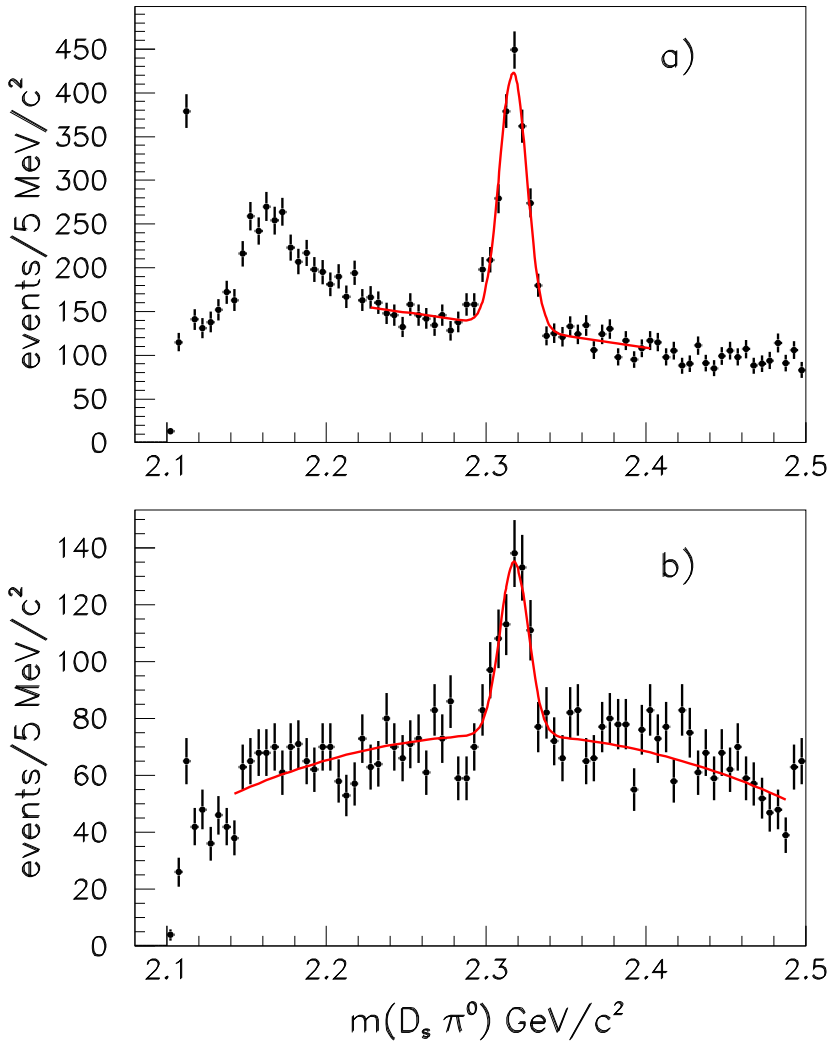
BABAR @ SLAC: (PRL90 (2003))

very narrow ($\Gamma < 5$ MeV) meson $\rightarrow D_s^+\pi^0$
$Q = 1,\ C = 1,\ S = 1 \Rightarrow$

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

$D_{s0}^+(2317),\ J^P = 0^+$

confirmed by CLEO, Belle, FOCUS



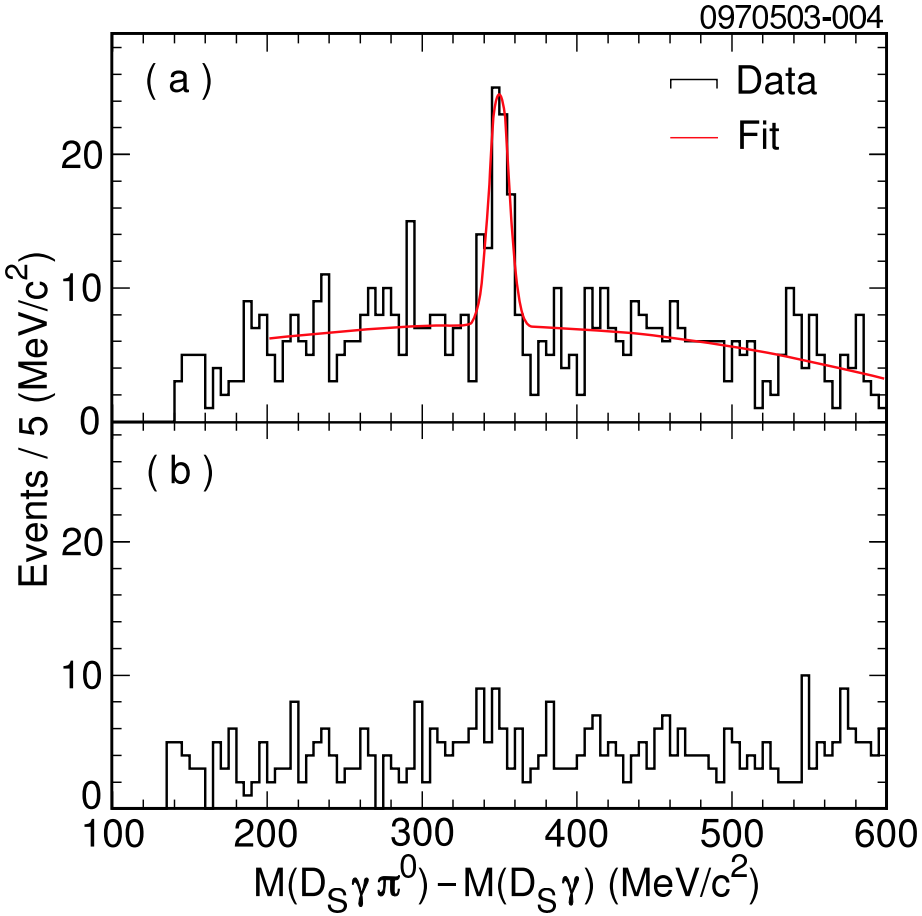
CLEO @ Cornell: (PRD68 (2003))

very narrow ($\Gamma < 7$ MeV) meson $\rightarrow D_s^{*+}\pi^0$
$Q = 1,\ C = 1,\ S = 1 \Rightarrow$

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

$D_{s1}^{+}(2460),\ J^P = 1^+$

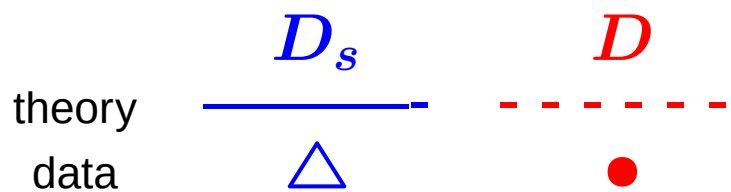
confirmed by BaBar, Belle



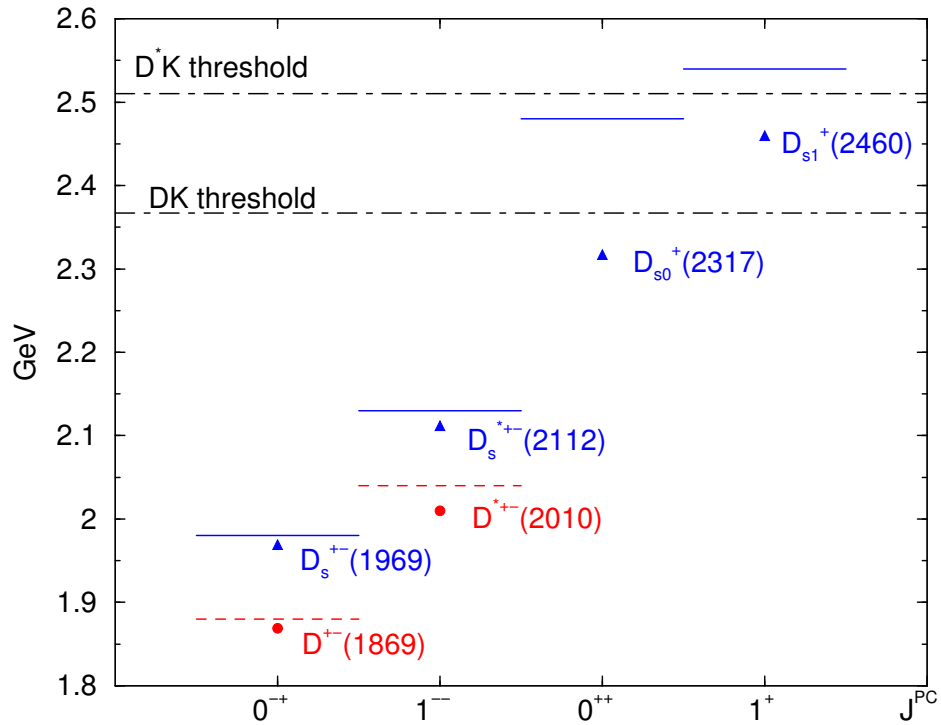
Bardeen, Eichten & Hill (PRD68 (2003) 054024): Goldberger-Treiman relation for $(0^+, 1^+) \rightarrow (0^-, 1^-) + \pi$ transition

using: $\Delta M(m_c) = M(0^+) - M(0^-) = 2.317 - 1.968 = 0.349$ GeV $\Rightarrow\ M(D_s(1^+)) = 2.46$ MeV

Meson D spectroscopy



theory: potencial model
Godfrey & Isgur, PRD32 (1985)



Tetraquark states?

New charmonium mesons

Belle @ KEK: (PRL91 (2003))

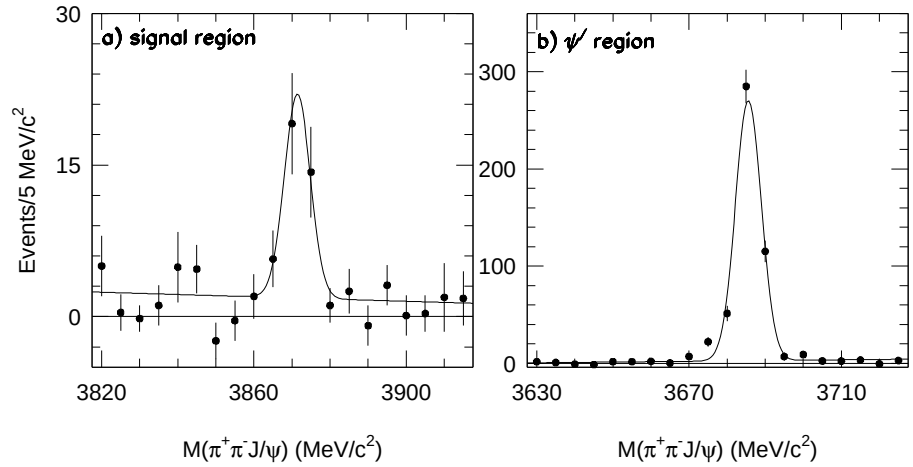
very narrow ($\Gamma < 2.3$ MeV) meson $\rightarrow J/\psi\pi^+\pi^-$

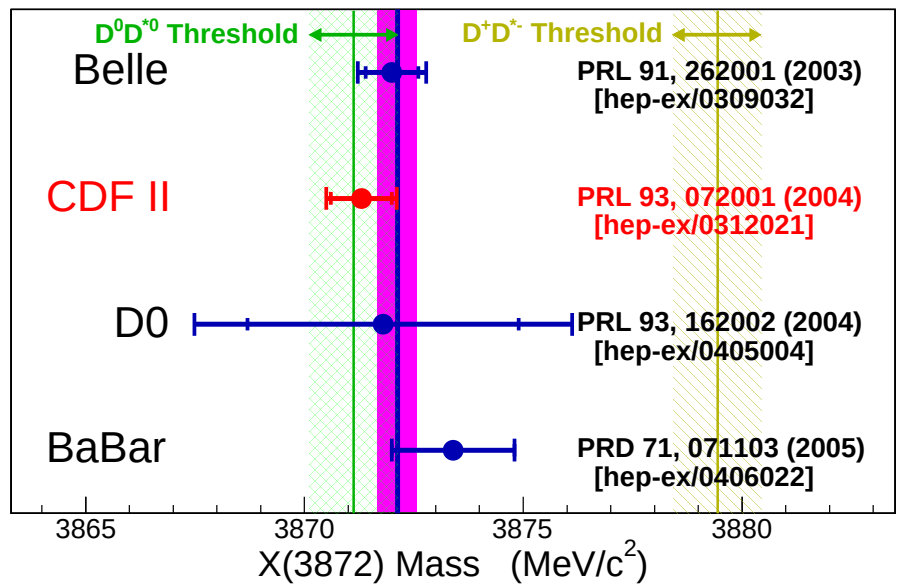
$Q = 0,\ c = 0,\ s = 0 \Rightarrow$

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

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

confirmed by CDFII, D0, BaBar





$c\bar{c}$ spec. (Barnes & Godfrey, PRD69 (2004)) $\nearrow 2\ ^3P_1\ (3990)$, $\searrow 3\ ^3P_1\ (4290)$

$$X(3872) = c\bar{c} \Rightarrow I = 0$$

$$\frac{X \to J/\psi\pi^+\pi^-\pi^0}{X \to J/\psi\pi^+\pi^-} \sim 1 \Rightarrow$$ strong isospin violation

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

$$\frac{B^0 \to XK^0}{B^+ \to XK^+} = 1.62 \pm 0.54,$$ molecular model < 0.1!

Tetraquark state?

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

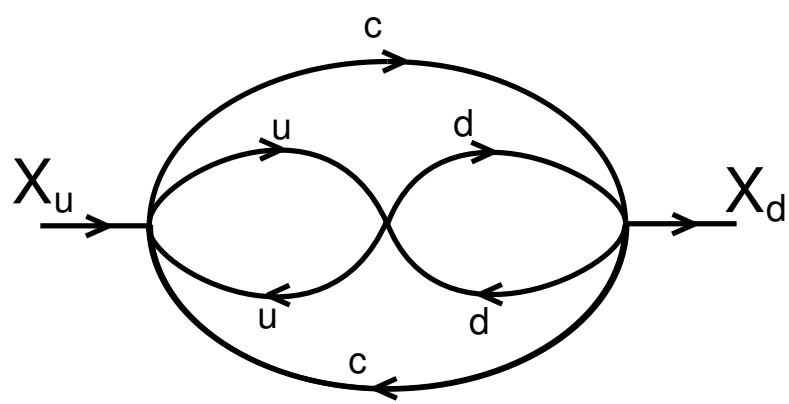
$$X_q = [cq]_{S=1}[\bar{c}\bar{q}]_{S=0} + [cq]_{S=0}[\bar{c}\bar{q}]_{S=1}$$

isospin eigenstates

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

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

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



most general $\mathbf{X(3872)}$ states

$$X_l = X_u \cos\theta + X_d \sin\theta$$

$$X_h = -X_u \sin\theta + X_d \cos\theta$$

both can decay into $2\pi,\ 3\pi$

$$\frac{B^0 \to X K^0}{B^+ \to X K^+} \sim 1$$

QCD Sum Rules

light scalars

$D_{s0}^+(2317),\ \ D_{s1}^+(2460),\ \ X(3872)$

as four-quark states

diquark antidiquark structure

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

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

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 $\left\{ \begin{array}{l} \text{eliminates subtraction terms} \\ \text{suppresses higher order condensates} \\ \text{increases importance pole contribution} \end{array} \right.$

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

good Sum Rule $\Rightarrow$ Borel window such that:

- pole contribution > continuum contribution
- converging OPE

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

Light Scalars

$$j_\sigma = \epsilon_{abc}\epsilon_{dec}(u_a^T C\gamma_5 d_b)(\bar{u}_d\gamma_5 C\bar{d}_e^T)$$

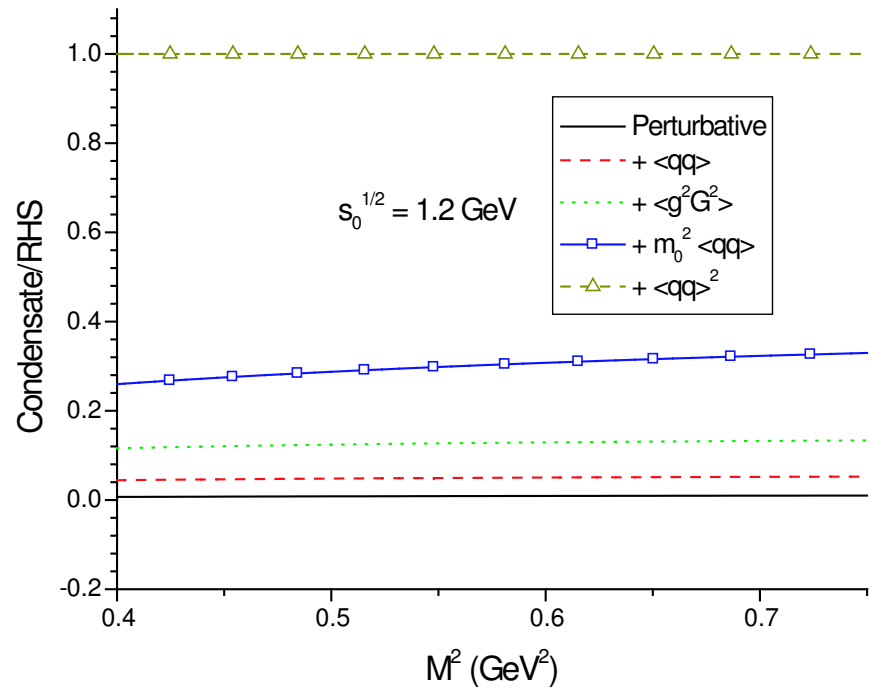
$$j_{f_0,a_0} = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\left[(u_a^T C\gamma_5 s_b)(\bar{u}_d\gamma_5 C\bar{s}_e^T) \pm u \leftrightarrow d\right],$$

$$j_\kappa = \epsilon_{abc}\epsilon_{dec}(u_a^T C\gamma_5 d_b)(\bar{q}_d\gamma_5 C\bar{s}_e^T), \quad \bar{q} = \bar{u}, \bar{d}.$$

pole > continuum

$\Downarrow$

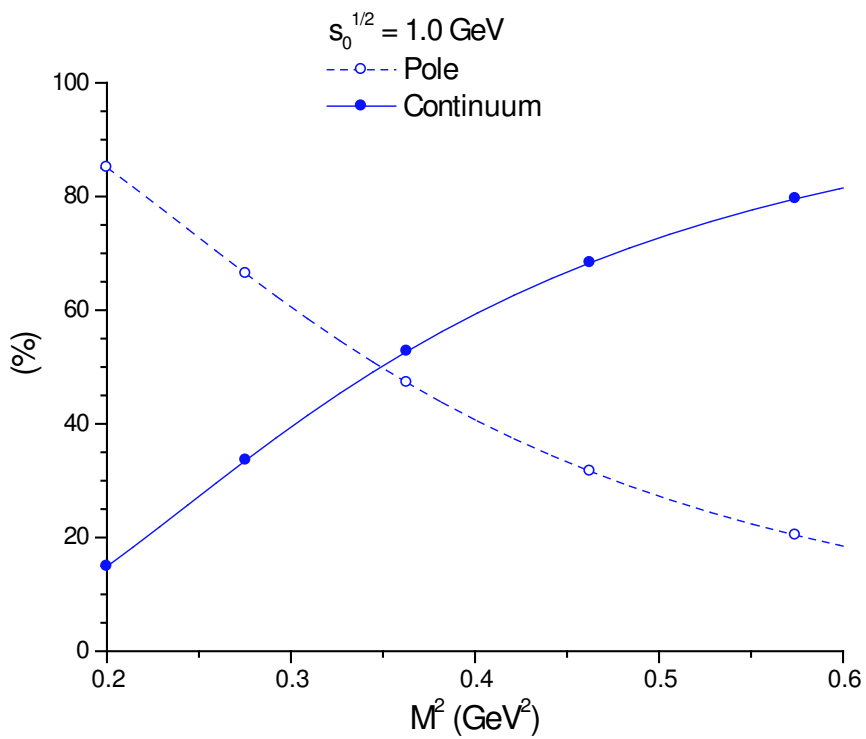
$M^2 < 0.6$ GeV

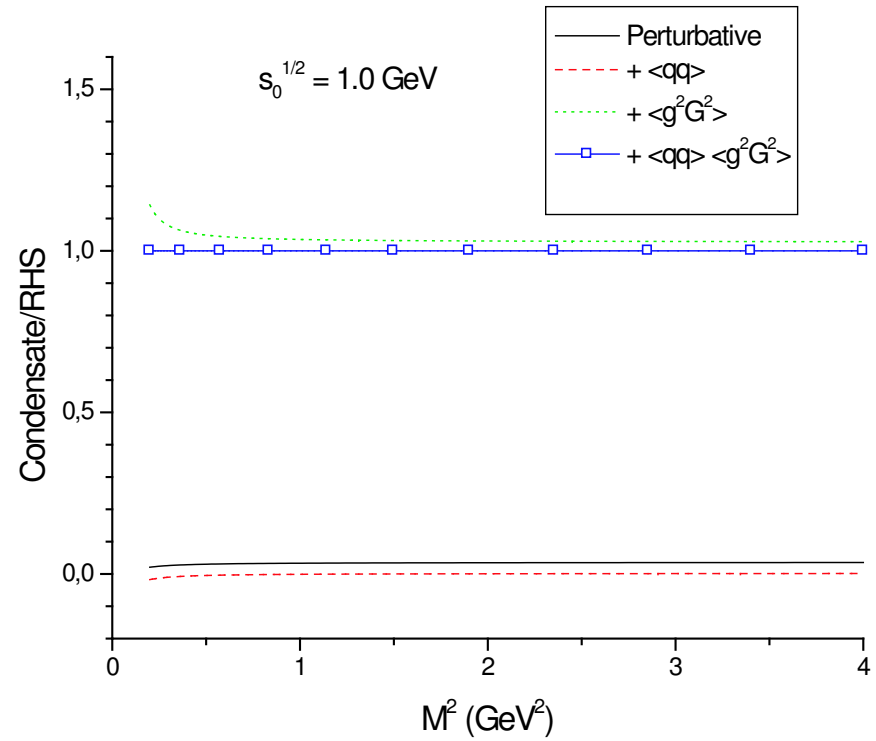


no Borel window

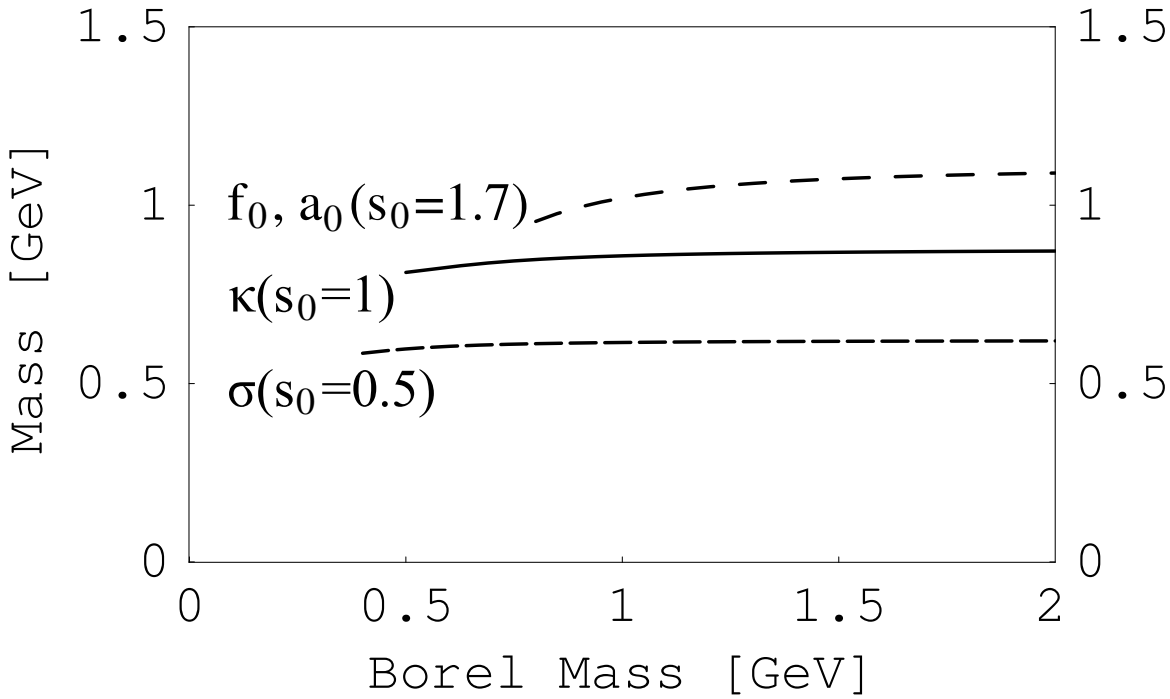
Chen, Hosada, Zhu hep-ph/0609163, $j_\sigma = (A_6^\sigma + \sqrt{2} V_3^\sigma)/\sqrt{3}$

$$A_6^\sigma = (u_a^T C \gamma_\mu d_b)(\bar{u}_a \gamma^\mu C \bar{d}_b^T - \bar{u}_b \gamma^\mu C \bar{d}_a^T) \,,$$
$$V_3^\sigma = (u_a^T C \gamma_\mu \gamma_5 d_b)(\bar{u}_a \gamma^\mu \gamma_5 C \bar{d}_b^T - \bar{u}_b \gamma^\mu \gamma_5 C \bar{d}_a^T)$$





small Borel window for $M^2 < 0.35\,\mathrm{GeV}^2$



OPE: $\sum_n A_n (M^2)^{\frac{10-n}{2}}$

$\Downarrow$

higher dimension condensates not suppressed!

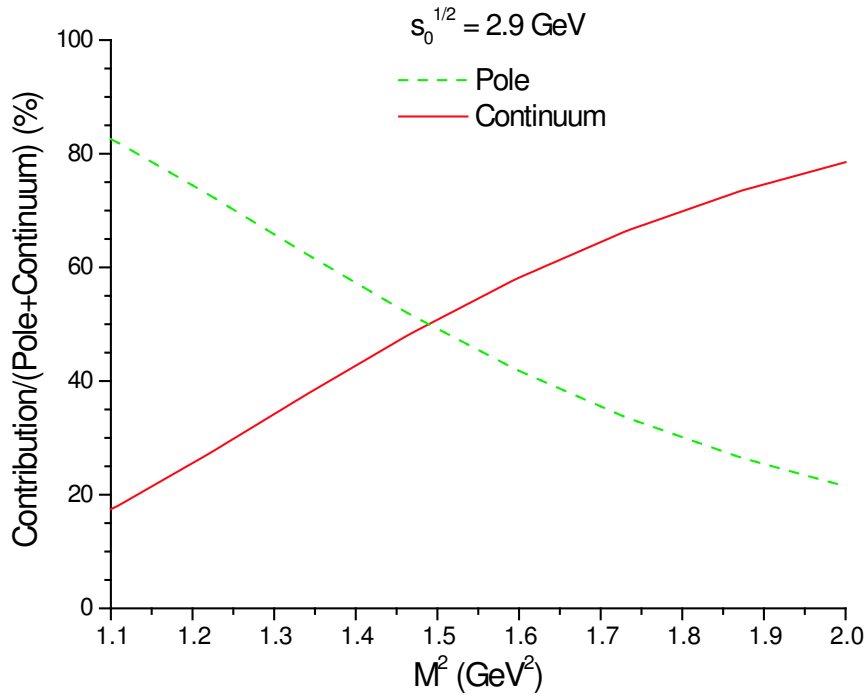
light many-quark states can not be considered

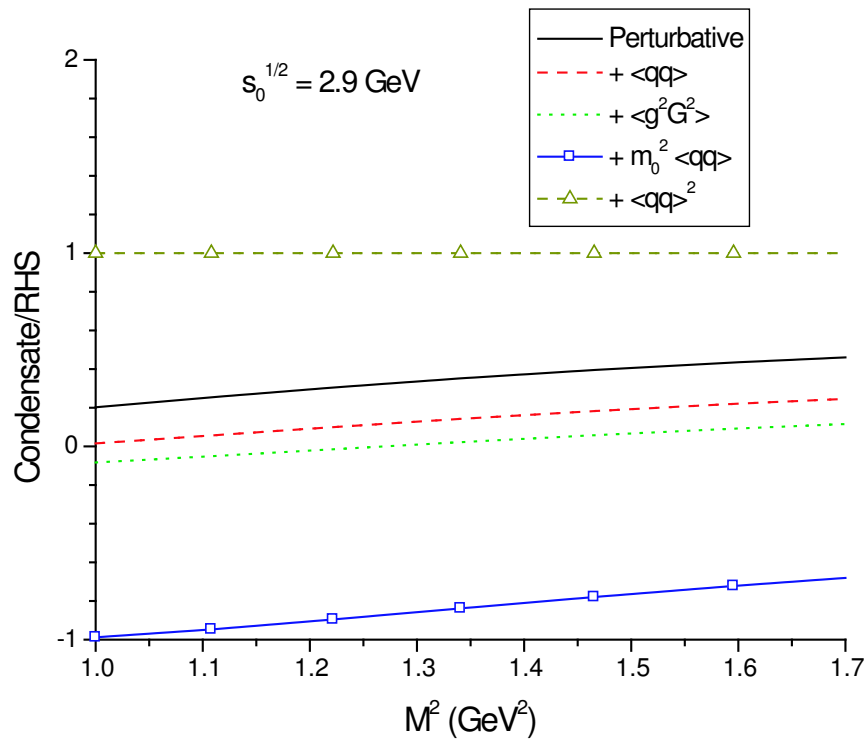
resonances separated from the continuum

Charmed Mesons

$$D_{s1}(2460): \; j_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(u_a^T C\gamma_5 c_b)(\bar{u}_d\gamma_\mu C\bar{s}_e^T) + u \leftrightarrow d]$$

$$D_{s0}(2317): \; j = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(u_a^T C\gamma_5 c_b)(\bar{u}_d\gamma_5 C\bar{s}_e^T) + u \leftrightarrow d]$$





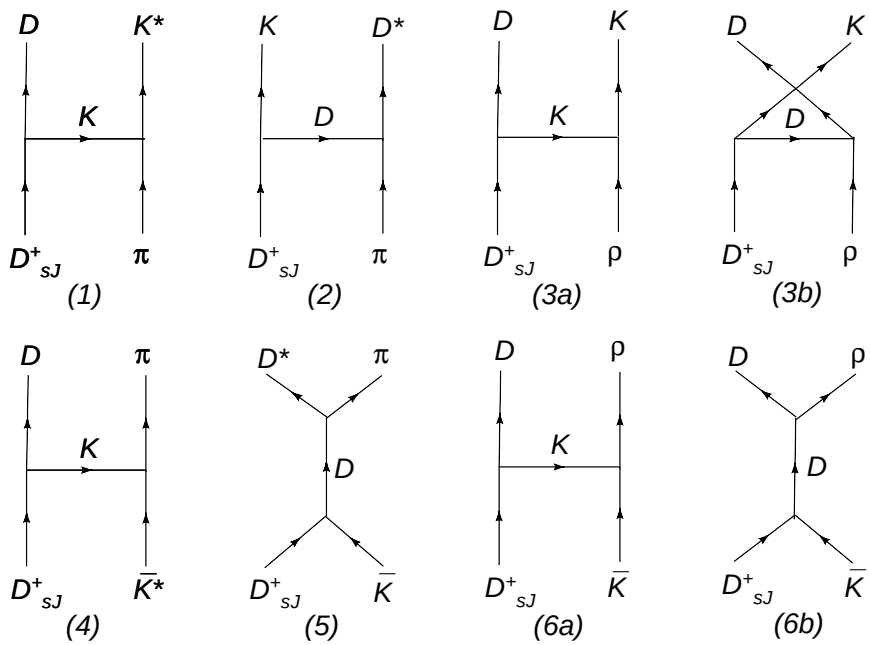
possible to reproduce experimental masses, but no Borel window

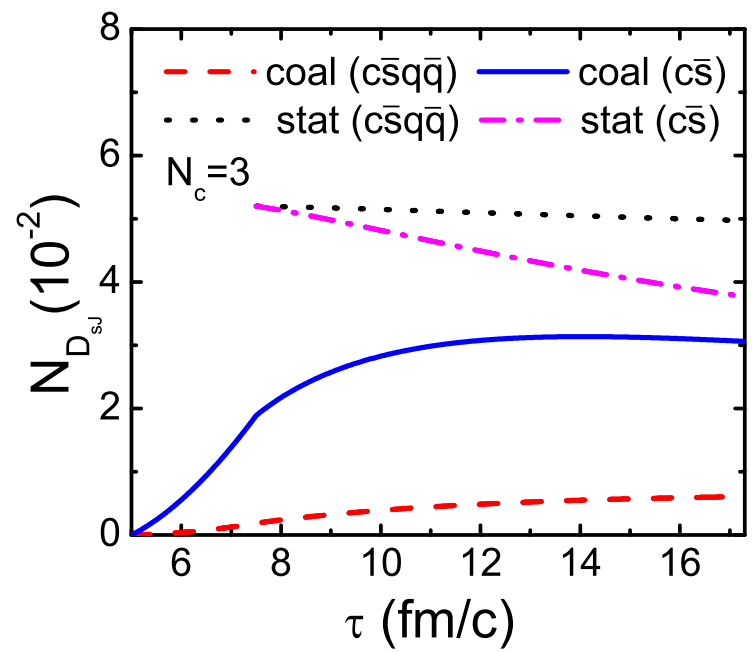
Is there an experimental way to test the structure?

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

Wang & Wan PRD73(2006) MN hep-ph/0610320

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

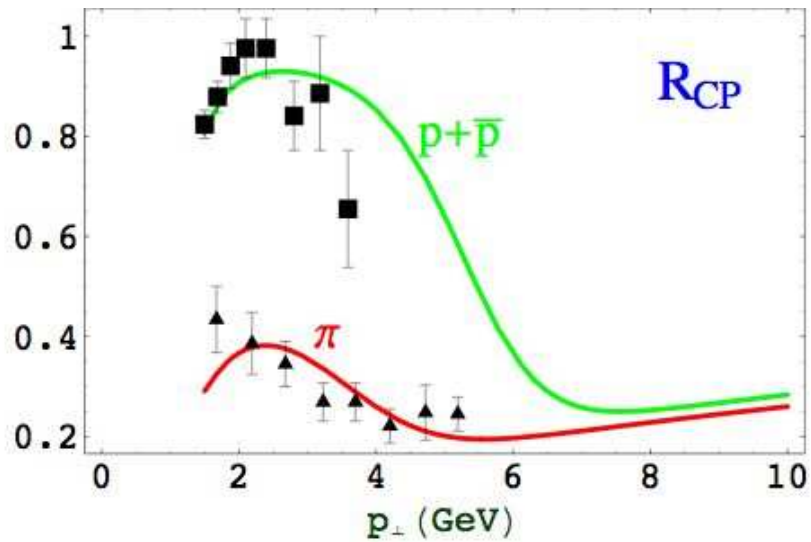


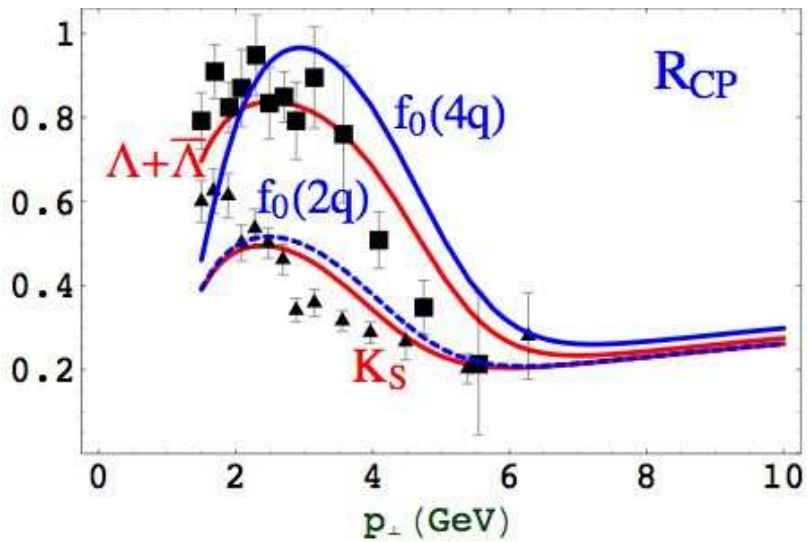


Counting quarks

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

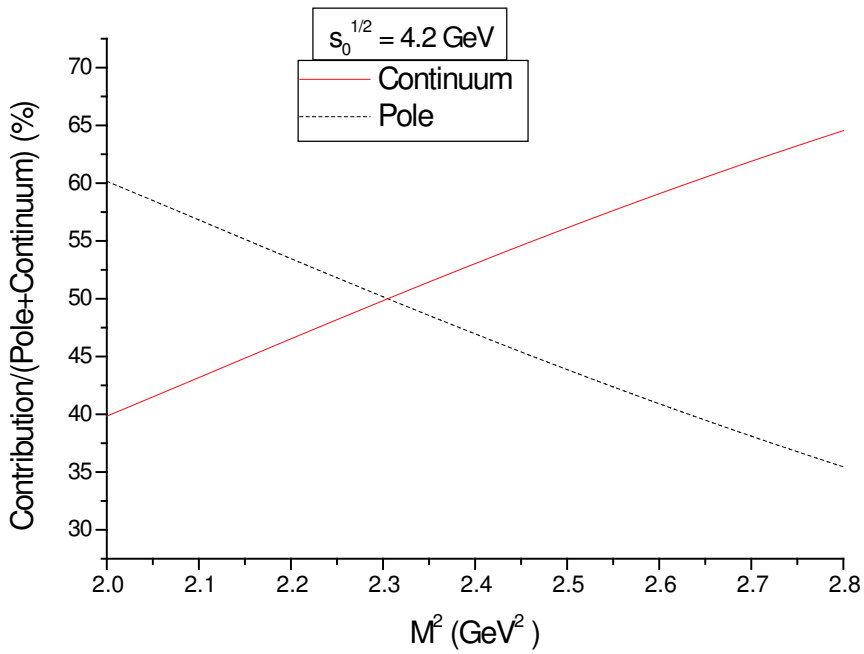
$$R_{CP} = \frac{N_{\rm coll}(b)\, d^2 N_{\rm Au+Au}(b=0)/dP_\perp^2}{N_{\rm coll}(b=0)\, d^2 N_{\rm Au+Au}(b)/dP_\perp^2}$$

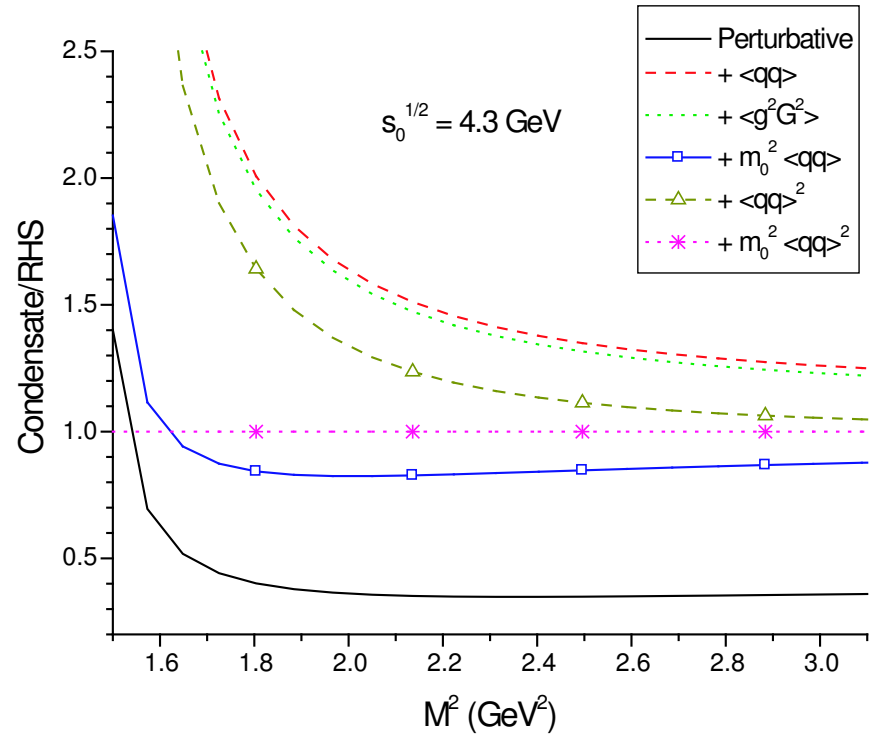




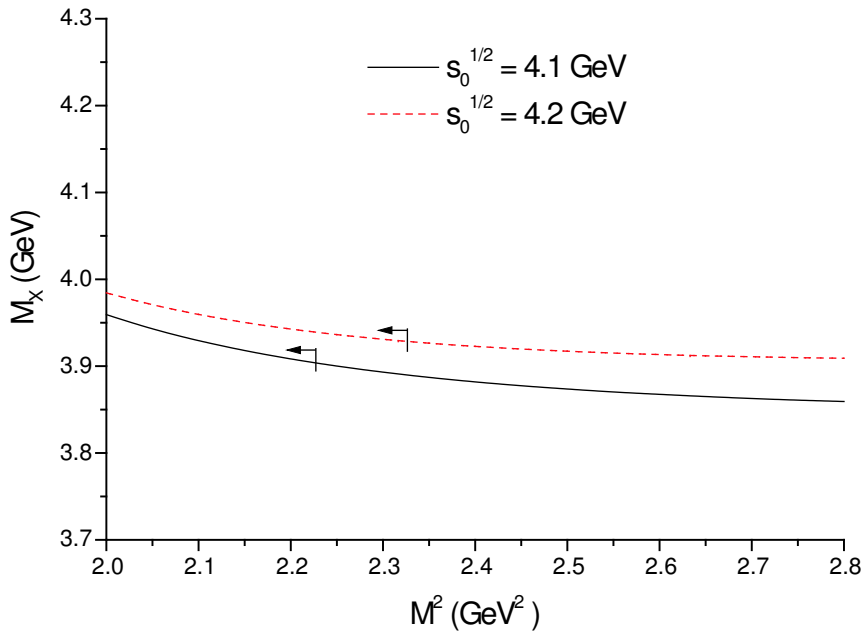
$X(3872)$

$$j_\mu^X = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\left[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T)+(q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)\right]$$





good Borel window $2.0 \leq M^2 \leq 2.3\,\text{GeV}^2$



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

good agreement $X(3872)$

same result for $X(3872) = D^0 \bar{D}^{*0} + \bar{D}^0 D^{*0}$ molecule

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

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

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

Decay Width

Decays

$$X(3872) \to J/\psi\omega \to J/\psi\pi^+\pi^-\pi^0$$

$$X(3872) \to J/\psi\rho \to J/\psi\pi^+\pi^-$$

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

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

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

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

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

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

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

$$\left(\frac{\Gamma(X_{l,h} \to J/\psi\, 3\pi)}{\Gamma(X_{l,h} \to J/\psi\, 2\pi)}\right) = 0.152 \left(\frac{\cos\theta \pm \sin\theta}{\cos\theta \mp \sin\theta}\right)^2 \Rightarrow \theta \sim \pm 23^0$$

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))

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

Conclusions

Evaluated masses of: light scalars, $D_{s0}(2317)$, $D_{s1}(2460)$ and $X(3872)$ as diquark-antidiquark states: good agreement with experimental masses, but good Borel window only for $X(3872)$.

Indication from QCDSR that light scalar and charmed mesons cannot be considered resonances separated from the continuum.

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

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

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