QCDSR studies of exotic hadrons

M. Nielsen
Universidade de São Paulo

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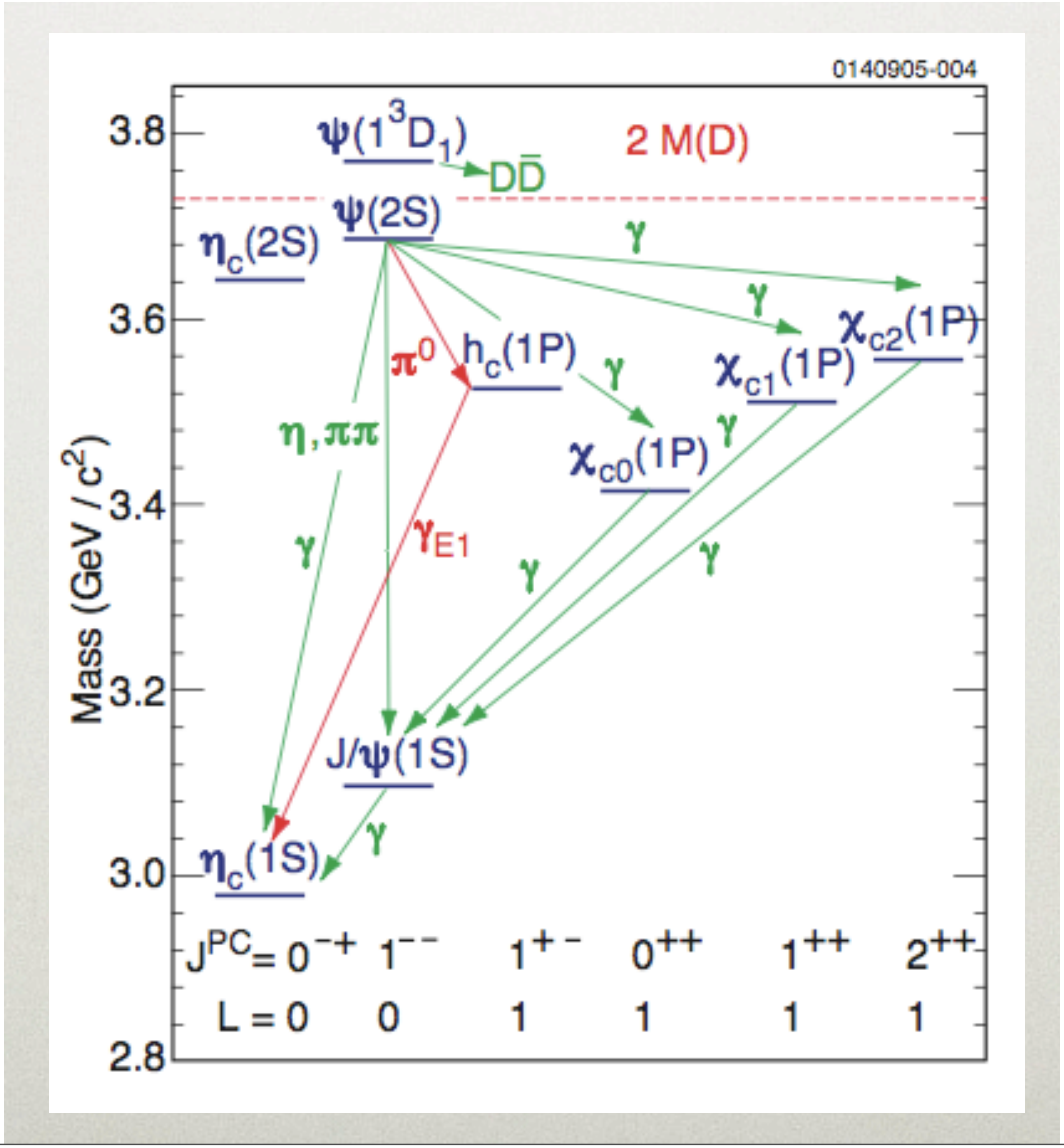
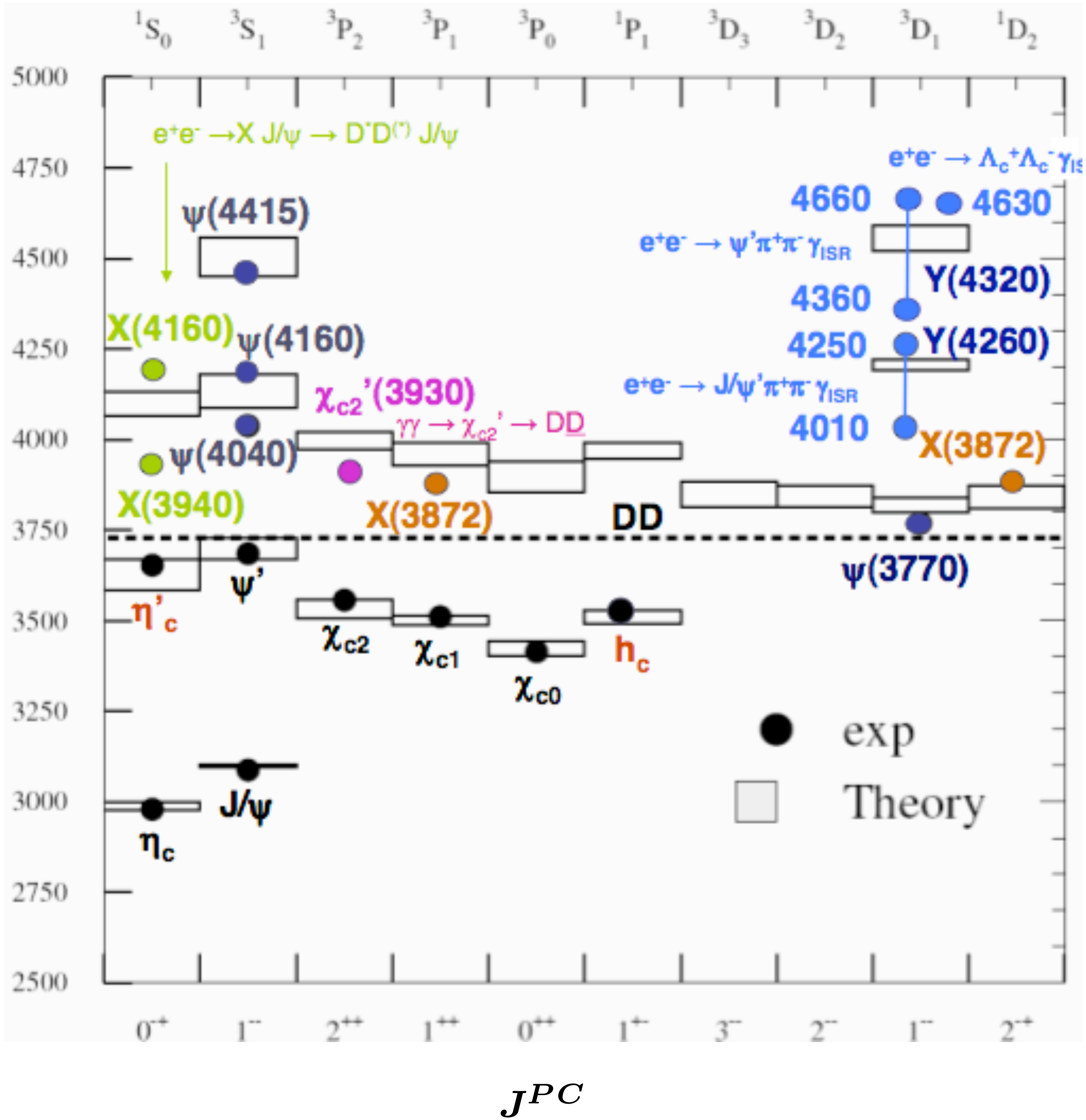
Charmonium spectroscopy before the B-factories



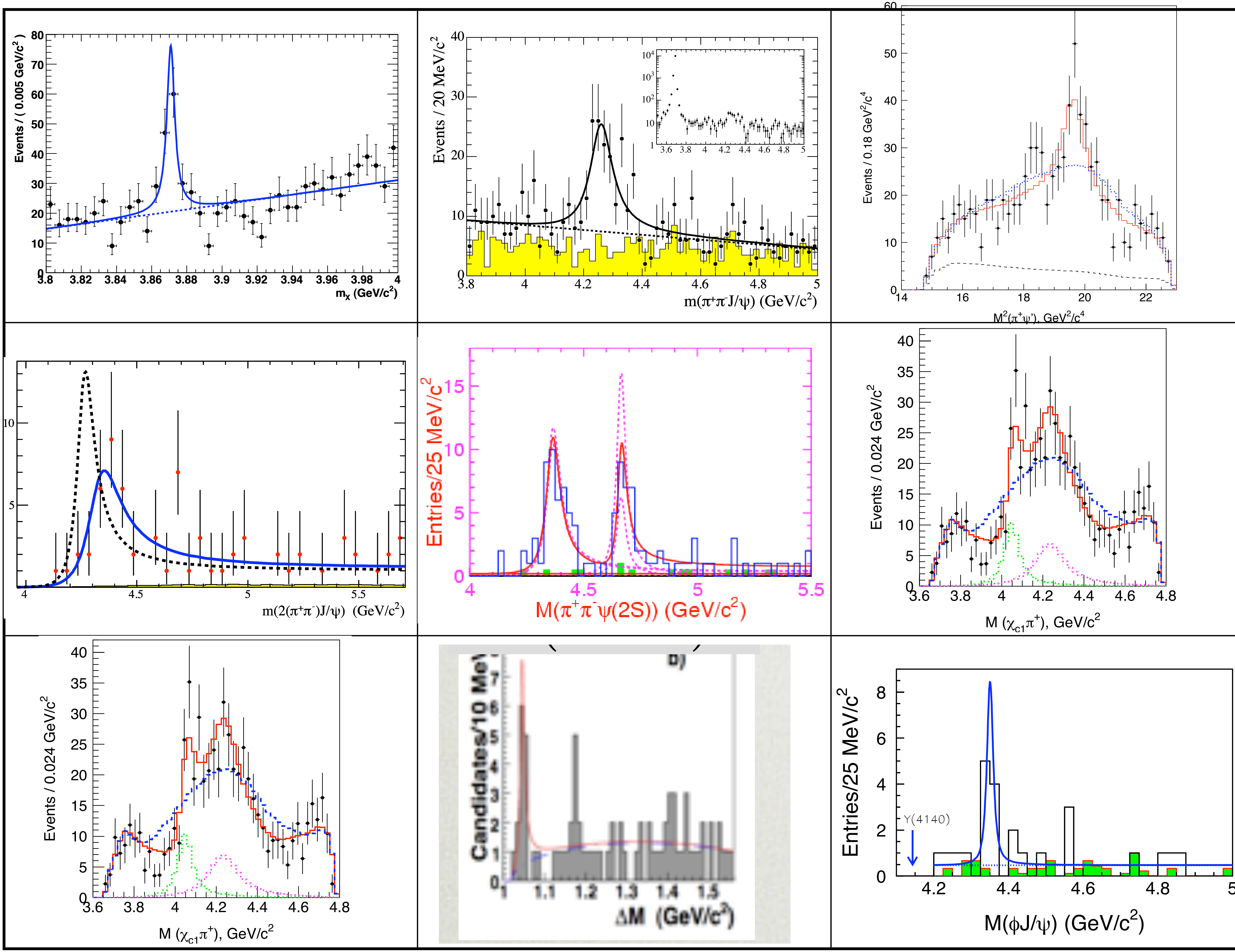
Charmonium spectroscopy after the B-factories



X(3872) 2003	Y(4260) 2005	Z^+(4430) 2007
Y(4360) 2006	Y(4660) 2007	Z_1^+(4050) 2008
Z_2^+(4250) 2008	Y(4140) 2009 $\gamma\gamma$	X(4350) 2009

X(3872) hep-ex/0309032	Y(4260) hep-ex/0506081	$Z^+(4430)$ arXiv:0708.1790
Y(4360) hep-ex/0610057	Y(4660) arXiv:0709.3699	$Z_1^+(4050)$ arXiv:0806.4098
$Z_2^+(4250)$ arXiv:0806.4098	Y(4140) arXiv:0903.2229	X(4350) arXiv:0912.2383

X(3872) $\boldsymbol{B^{\pm} \to K^{\pm}(J/\psi\pi^{+}\pi^{-})}$	Y(4260) $e^{+}e^{-} \to \gamma_{IRS}(J/\psi\pi^{+}\pi^{-})$	Z^{+}(4430) $\bar{B}^{0} \to K^{-}(\psi'\pi^{+})$
Y(4360) $e^{+}e^{-} \to \gamma_{IRS}(\psi'\pi^{+}\pi^{-})$	Y(4660) $e^{+}e^{-} \to \gamma_{IRS}(\psi'\pi^{+}\pi^{-})$	Z_1^{+}(4050) $\bar{B}^{0} \to K^{-}(\chi_{c1}\pi^{+})$
Z^{+}_2(4250) $\bar{B}^{0} \to K^{-}(\chi_{c1}\pi^{+})$	Y(4140) $B^{+} \to K^{+}(\phi J/\psi)$	X(4350) $\gamma\gamma \to (\phi J/\psi)$

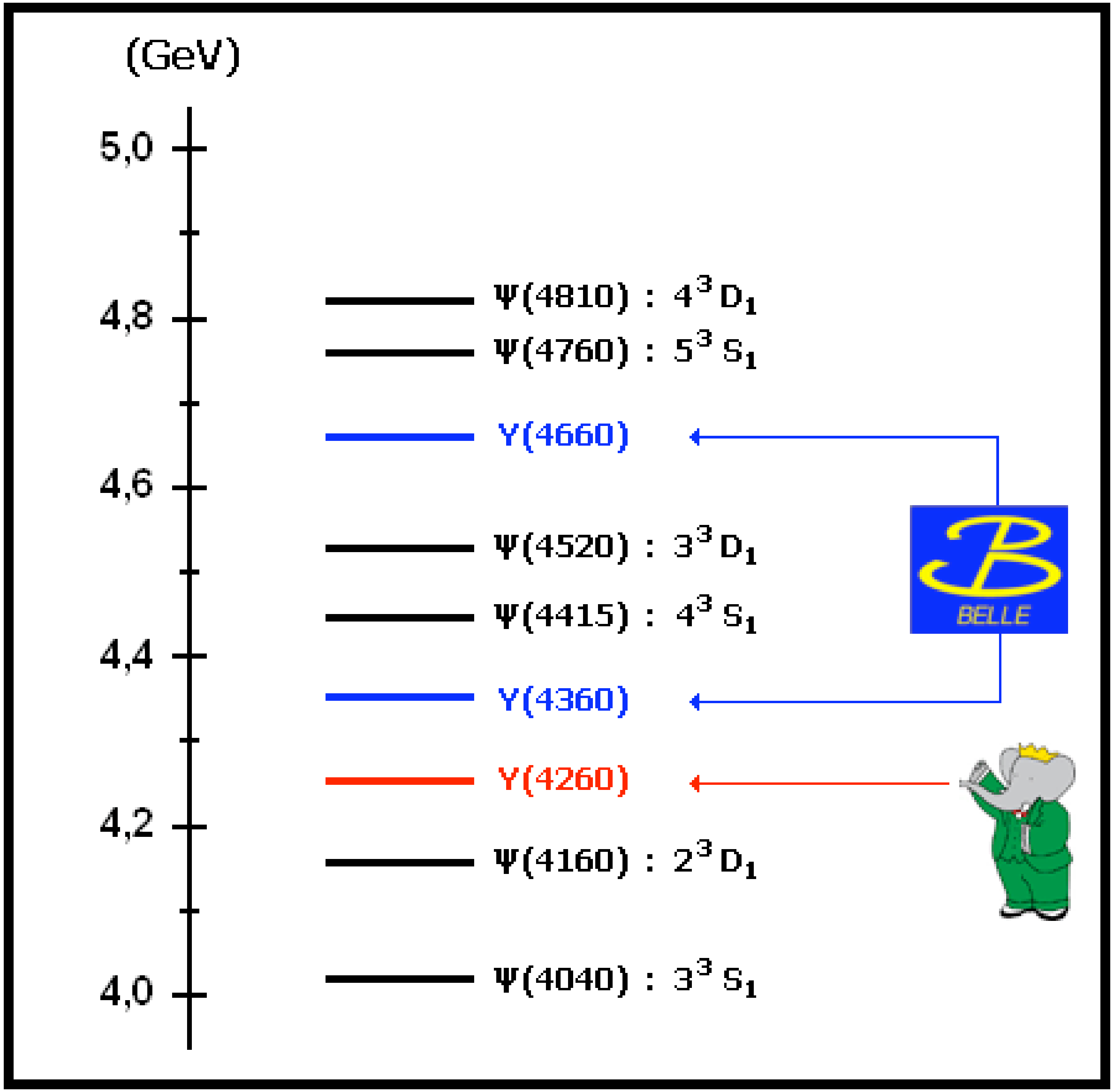

Events / (0.005 GeV/c^2)
m_X (GeV/c^2)
Events / 20 MeV/c^2
m($\pi^+\pi^-$J/ψ) (GeV/c^2)
Events / 0.18 GeV^2/c^4
M^2($\pi^+\psi'$), GeV^2/c^4
m(2($\pi^+\pi^-$)J/ψ) (GeV/c^2)
Entries/25 MeV/c^2
M($\pi^+\pi^-\psi$(2S)) (GeV/c^2)
Events / 0.024 GeV/c^2
M ($\chi_{c1}\pi^+$), GeV/c^2
Events / 0.024 GeV/c^2
M ($\chi_{c1}\pi^+$), GeV/c^2
ΔM (GeV/c^2)
Entries/25 MeV/c^2
Y(4140)
M(ϕJ/ψ) (GeV/c^2)

X(3872) $J^{PC}=1^{++}$ 3871.4±0.6 $\Gamma<2.3$ MeV	Y(4260) $J^{PC}=1^{--}$ 4252±7 $\Gamma=88\pm24$	$Z^+(4430)$ $J^{PC}=?$ 4433±14 $\Gamma=44\pm17$
Y(4360) $J^{PC}=1^{--}$ 4361±13 $\Gamma=74\pm18$	Y(4660) $J^{PC}=1^{--}$ 4664±12 $\Gamma=48\pm15$	$Z_1^+(4050)$ $J^{PC}=?$ 4051±14 $\Gamma=82\pm21$
$Z_2^+(4250)$ $J^{PC}=?$ 4248±44 $\Gamma=177\pm54$	Y(4140) $J^{PC}=?^{?+}$ 4143±3 $\Gamma=11.7\pm8$	X(4350) $J^{PC}=?^{?+}$ 4350±5 $\Gamma=13\pm9$

Common features

- All these states decay into J/ψ or $\psi(2S)$ ➔ they have a $c\bar{c}$ pair in their quark components
- Their masses are not compatible with quark model calculations for charmonium states
- Absence of open charm production in their decays is inconsistent with $c\bar{c}$ interpretation
- Candidates for exotic (not quark-antiquark) states

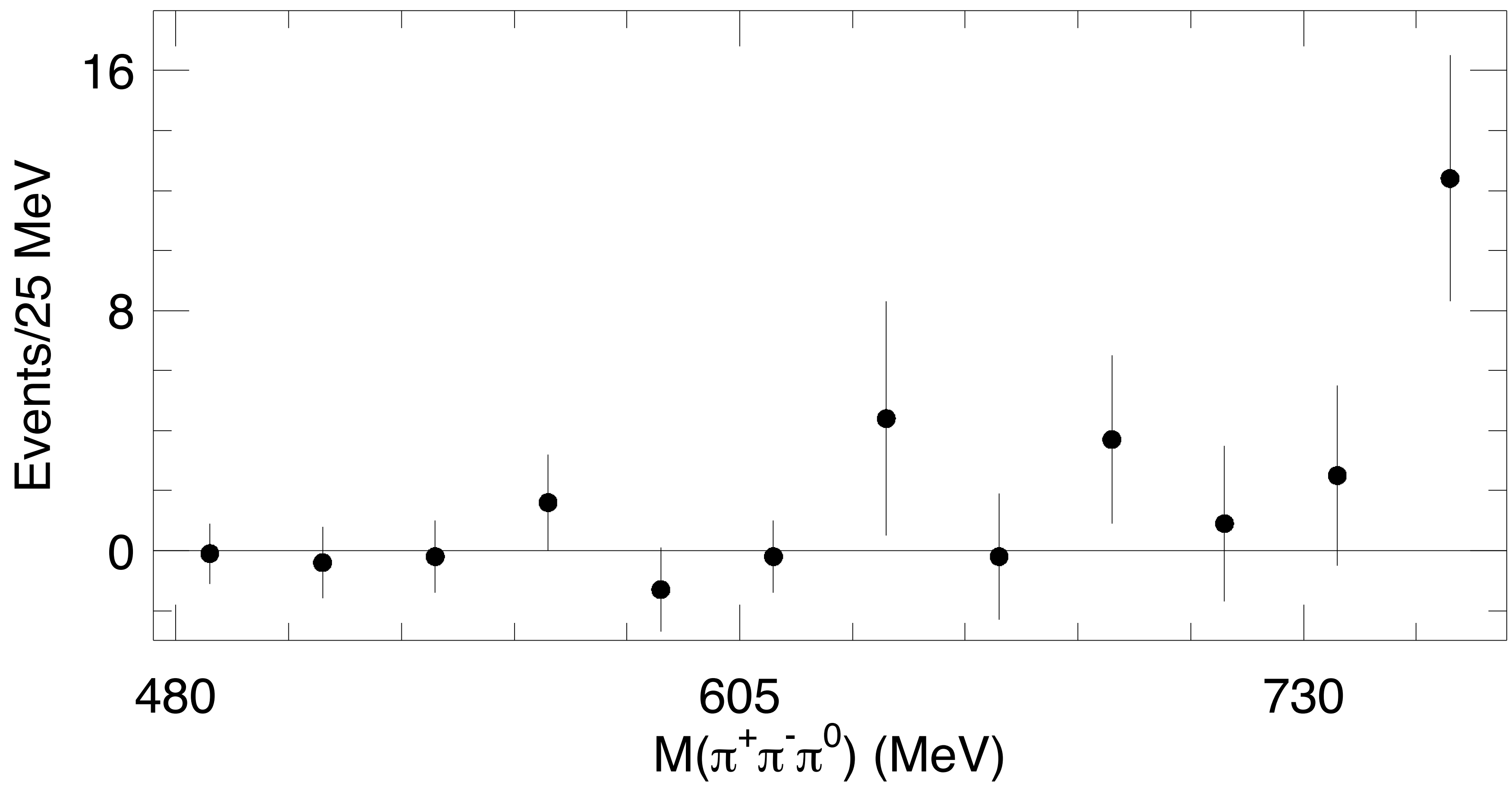
masses and widths of the Y states are not consistent with any of the 1^{--} charmonium states



X(3872) DD^* molecular state tetraquark state mixed charmonium- -molecular state threshold effect	Y(4260) charmonium hybrid J/ψ-f_0 bound state tetraquark state D_0D^* molecular state S wave threshold effect	$Z^+(4430)$ D_1D^* molecular state baryonium state tetraquark state threshold effect
Y(4360) charmonium hybrid	Y(4660) charmonium hybrid ψ'-f_0 bound state tetraquark state	$Z_1^+(4050)$ D^*D^* molecular state hadro-charmonium not a resonance
$Z_2^+(4250)$ D_1D molecular state	Y(4140) $D_s^*D_s^*$ molecular state tetraquark state not a resonance	X(4350) $D_s^*D_{s0}^*$ molecular state tetraquark state P-wave charmonium mixed charmonium- -molecular state

X(3872)

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



BELLE hep-ex/0505037

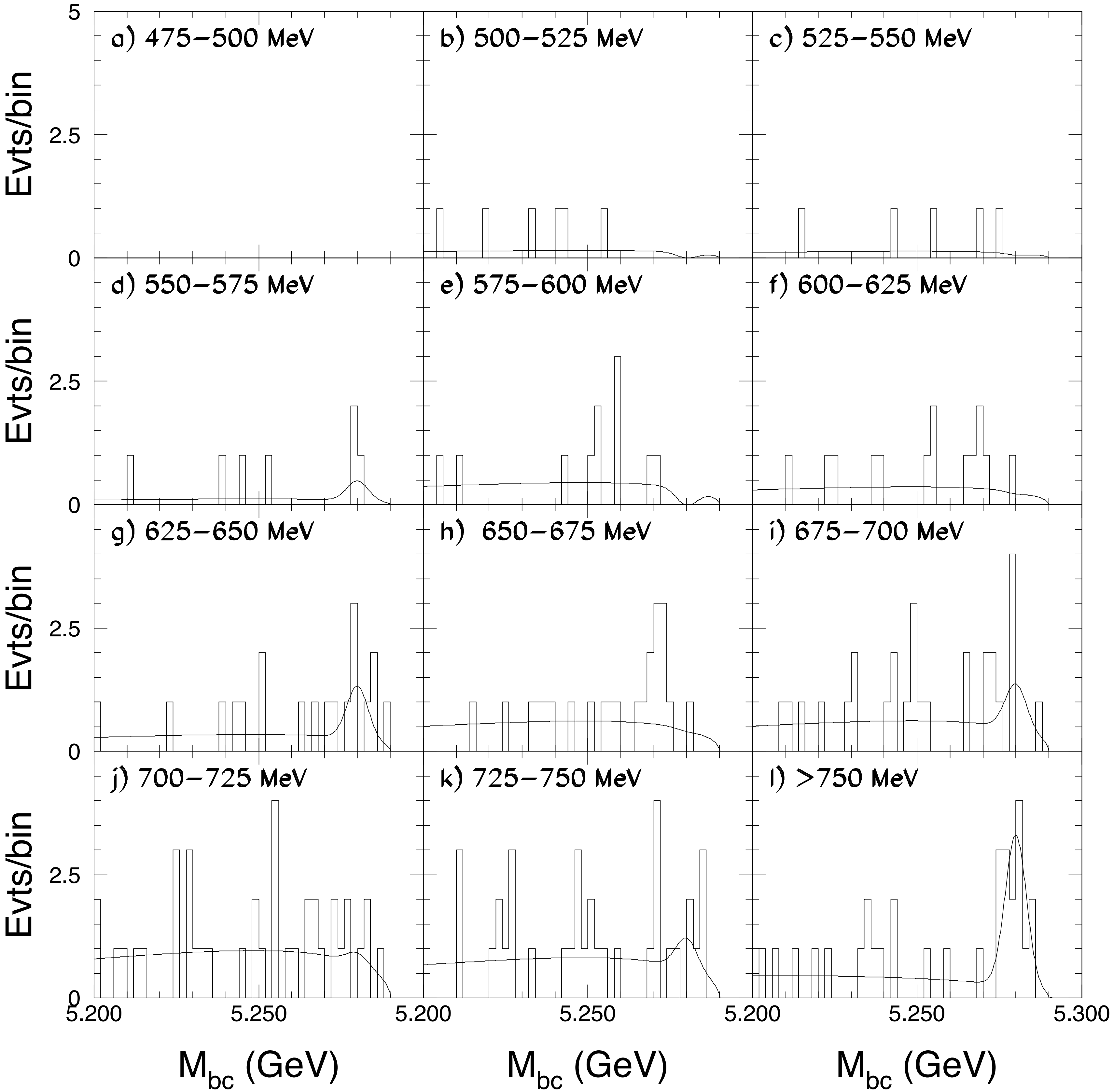
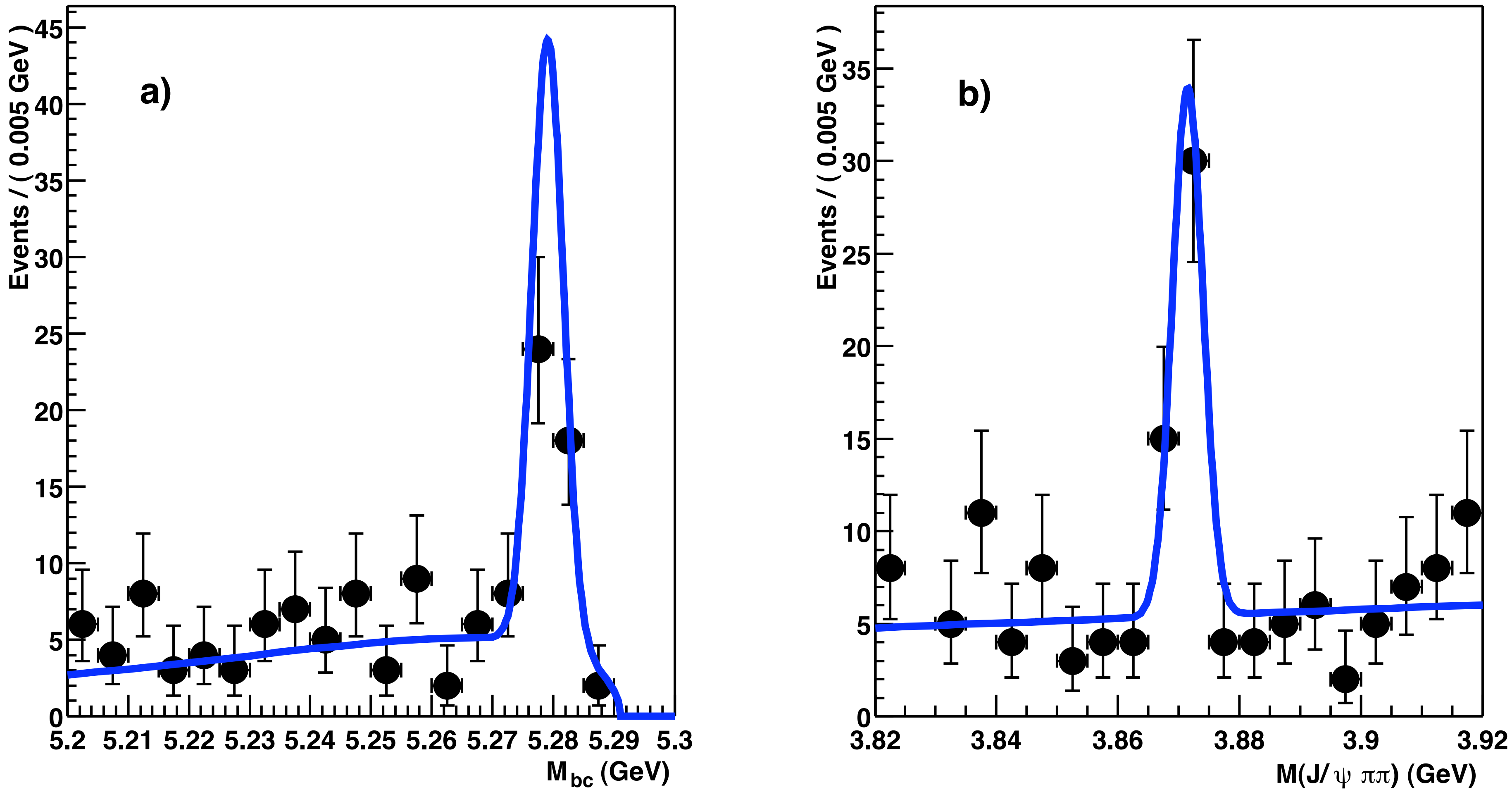
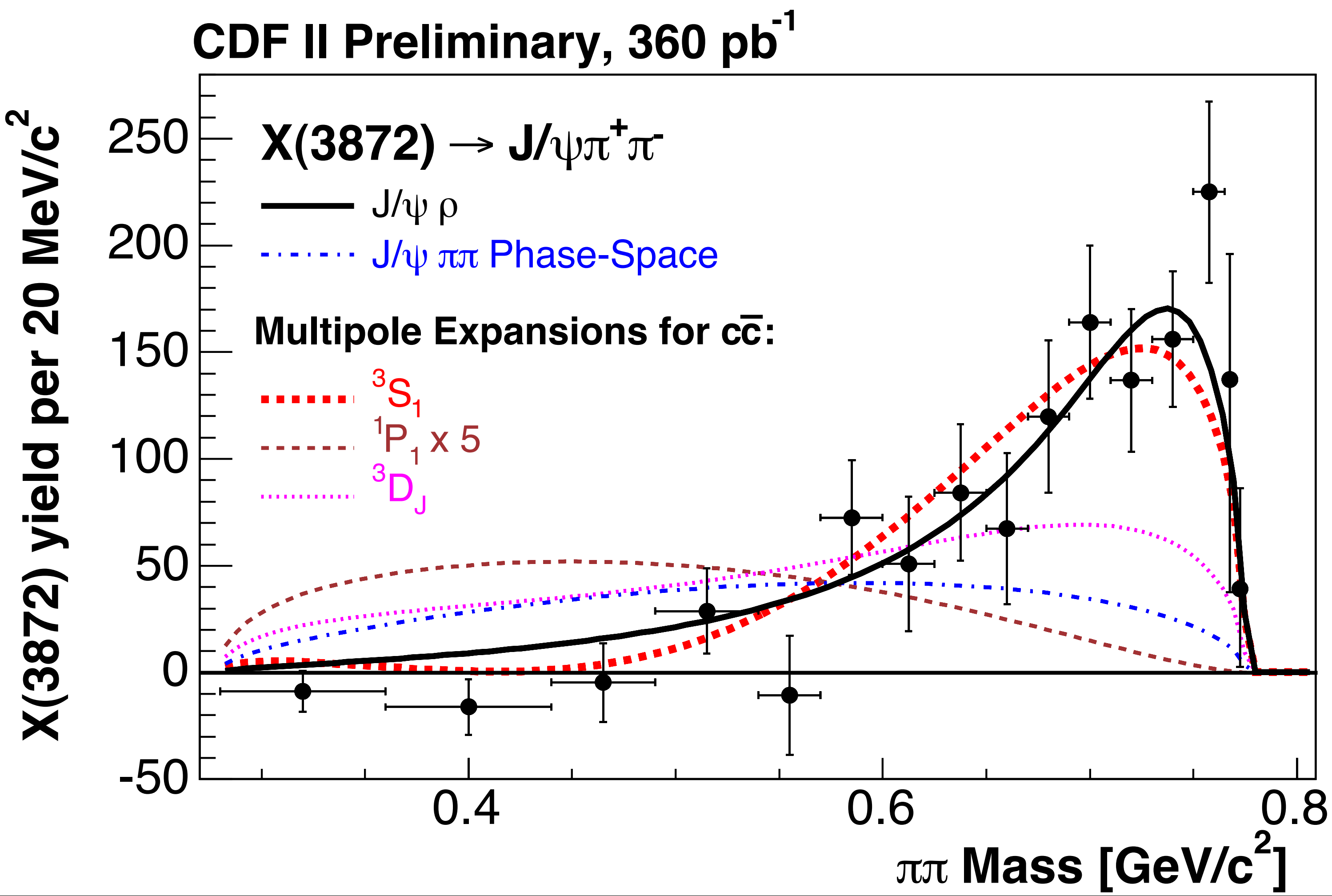


FIG. 3: $M_{\rm bc}$ distributions for $B^- \to K^-\pi^+\pi^-\pi^0 J/\psi$ candidates in the ΔE and $X \to \pi^+\pi^-\pi^0 J/\psi$ signal regions for 25 MeV-wide $\pi^+\pi^-\pi^0$ invariant mass bins.



hep-ex/0309032, PRL91(2003)



$$M(D^{*0}\bar{D}^0) = (3871 \pm 1)$$

X(3872): molecular $(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$ state (Swanson, Close, Voloshin, Wong ...)

Tornqwist (ZPC61(94)) predict a $\bar{D}D^*$ molecule with $J^{PC} = 0^{-+}$ or 1^{++}

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

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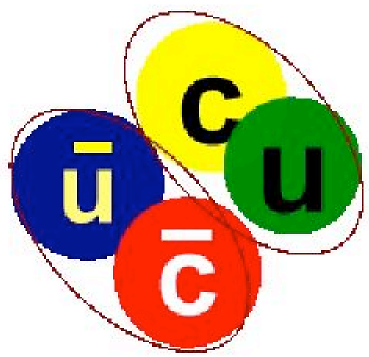
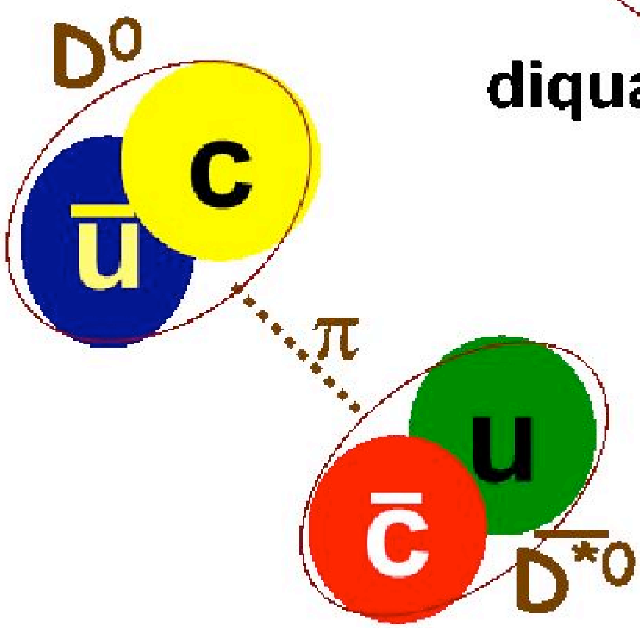


diquark-diantiquark

molecular and tetraquark interpretations differ by the way quarks are organized in the state

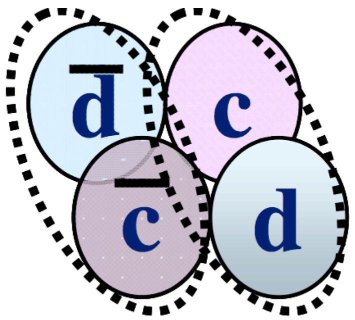


$D^0 - \overline{D^{*0}}$ "molecule"

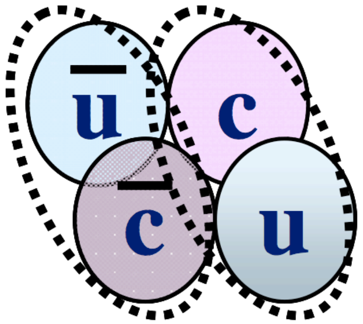
production rate for a pure molecule should be two orders of magnitude smaller than exp. (Bignamini et. al., PRL103(09)162001)

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

$\mathbf{X_d}$ =



$\mathbf{X_u}$ =



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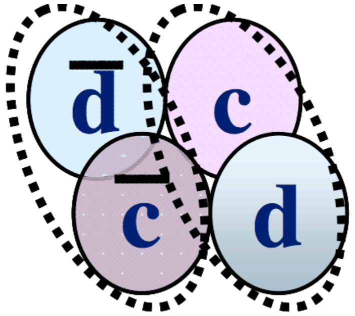
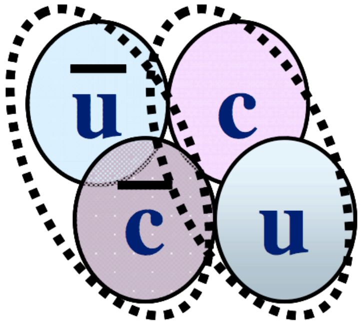
$\mathbf{X_d}$ = 

$\mathbf{X_u}$ = 

isospin eigenstates

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

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

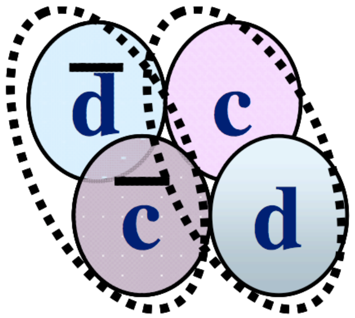
most general $\mathrm{X}(3872)$ states

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

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

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

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

$\mathbf{X_d}$ = 

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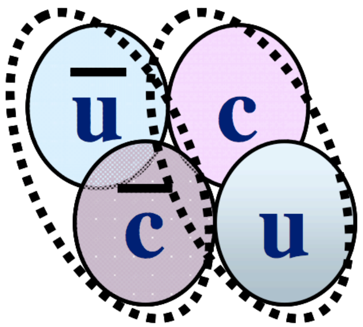
$\mathbf{X_u}$ = 

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

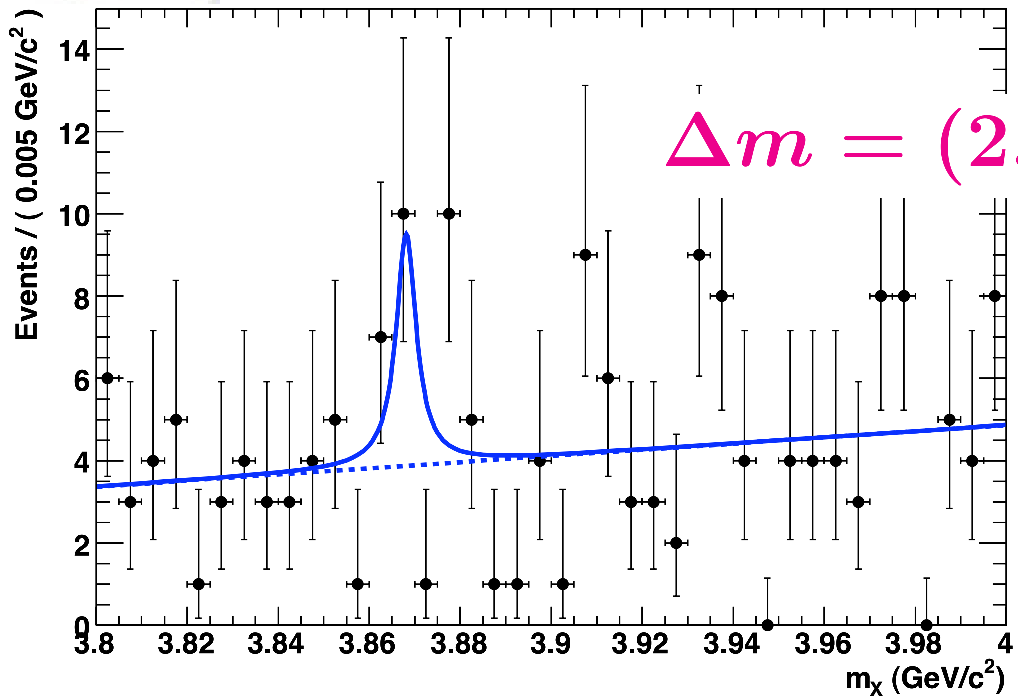
- $X_l = X_u \cos\theta + X_d \sin\theta$
- $X_h = -X_u \sin\theta + X_d \cos\theta$
- both can decay into $2\pi,\ 3\pi$

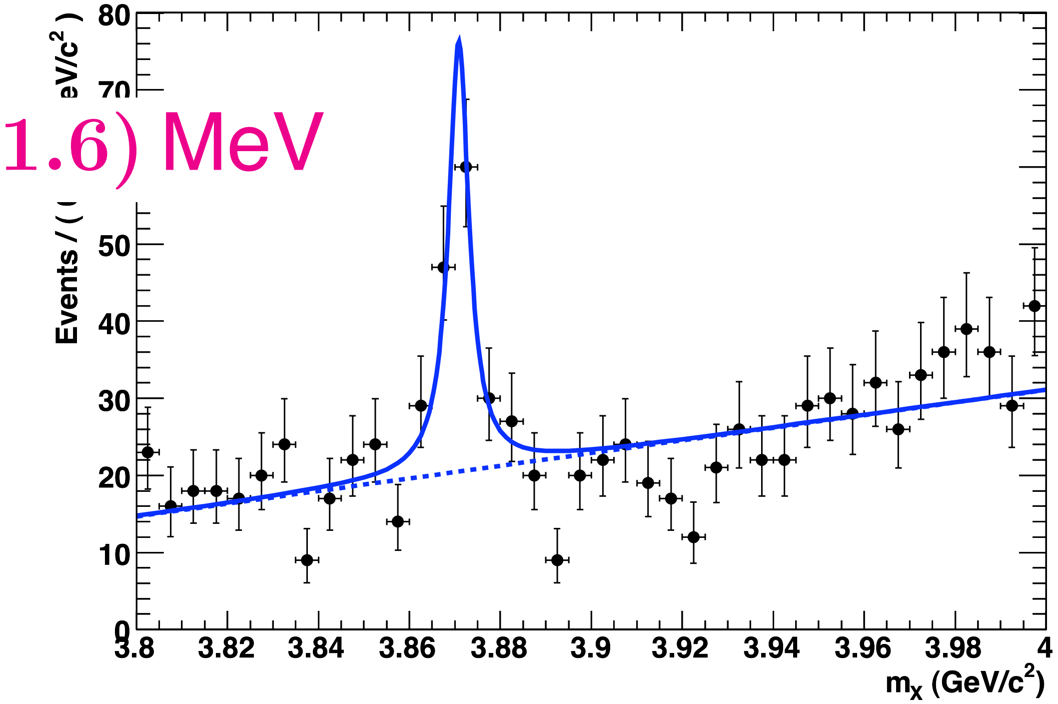
From $\dfrac{X \to J/\psi\pi^+\pi^-\pi^0}{X \to J/\psi\pi^+\pi^-} \sim 1 \quad \Rightarrow \quad \theta \sim\ 20^0$

Only one is produced in $B^\pm \to K^\pm X \Rightarrow$ the other appear in

$$B^0 \to K^0 X$$

BaBar Collaboration PRD77, 111101 (2008)

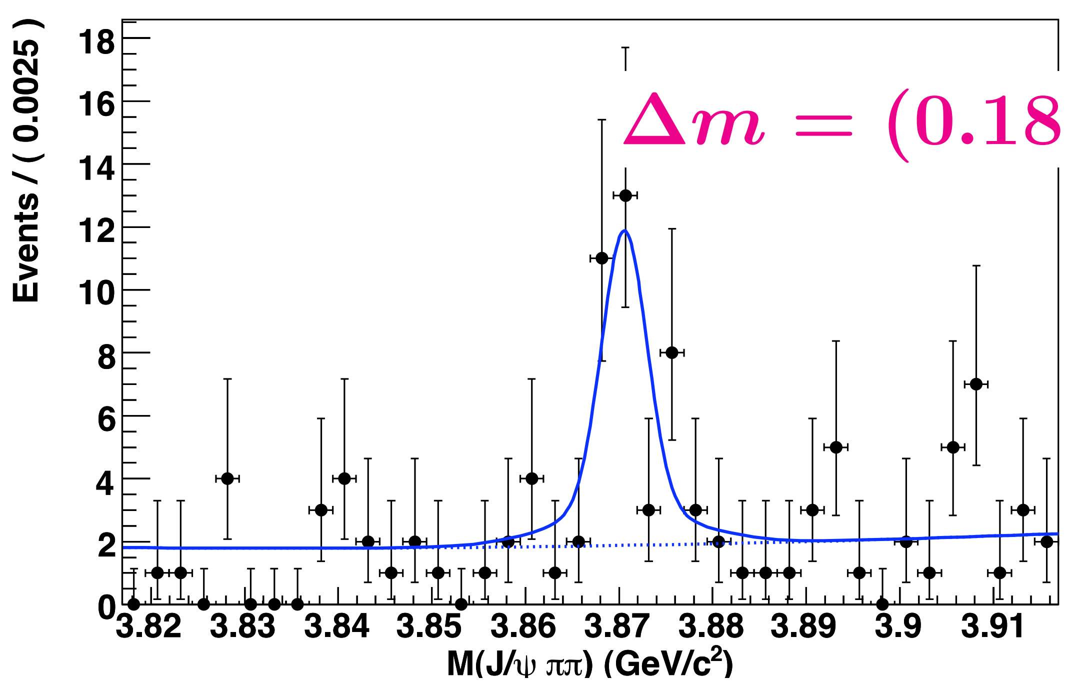


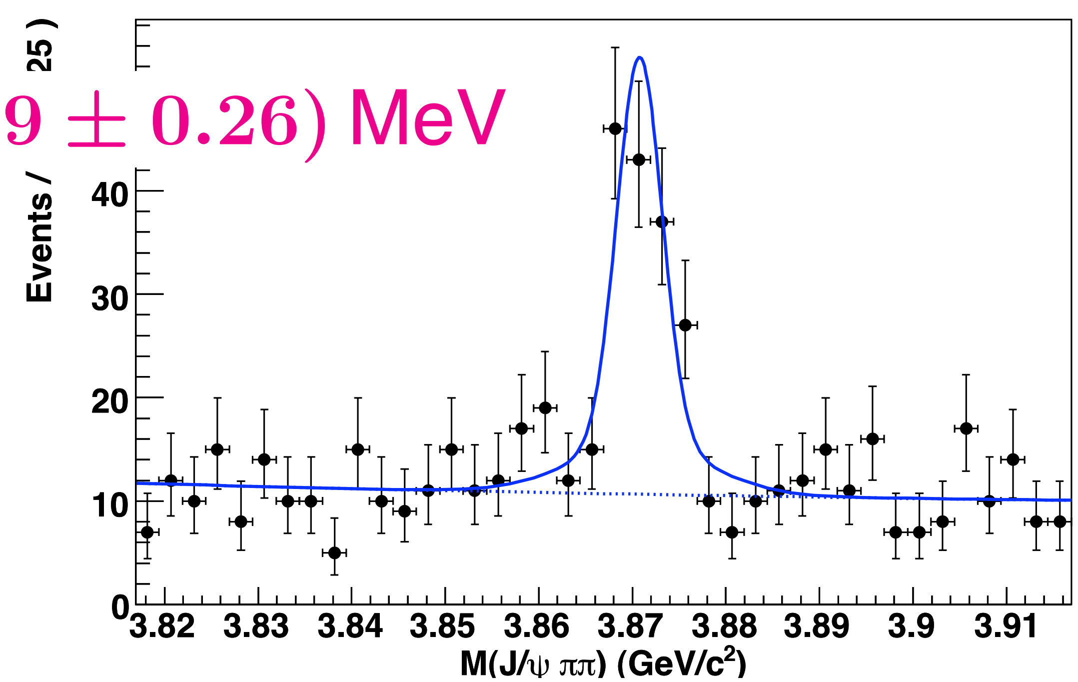


$\Delta m = (2.7 \pm 1.6)$ MeV

$B^0 \to XK^0$ $\qquad$ $B^+ \to XK^+$

Belle Collaboration: arXiv/0809.1224





$\Delta m = (0.18 \pm 0.89 \pm 0.26)$ MeV

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

QCD Sum Rule

Fundamental Assumption: Principle of Duality

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

Theoretical side Phenomenological side

Theoretical side

$$\Pi(q) = i \int d^4x\, e^{iq\cdot x} \langle 0|T[j(x)j^\dagger(0)|0\rangle \;= \sum_n C_n(Q^2)\hat{O}_n$$

Phenomenological side

$$\Pi(q^2) = -\int ds\, \frac{\rho(s)}{q^2 - s + i\epsilon} + \cdots$$

$$\rho(s) = \lambda^2 \delta(s - m^2) + \rho_{cont}(s)$$

$$\langle 0|j|H\rangle = \lambda$$

$$\rho_{cont}(s) = \rho^{OPE}(s)\Theta(s - s_0)$$

s_0: continuum parameter

$$\Pi^{phen}(Q^2) \leftrightarrow \Pi^{OPE}(Q^2)$$

➡ Borel transform

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

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$$\langle 0|j|H\rangle = \lambda \qquad\qquad \rho_{cont}(s) = \rho^{OPE}(s)\Theta(s - s_0)$$

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➡ Borel transform

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Good Sum Rule ➡ Borel window such that:

- pole contribution > continuum contribution
- good OPE convergence
- good Borel stability

$$m^2 = \frac{\int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ s\ \rho^{OPE}(s)}{\int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ \rho^{OPE}(s)}$$

QCD sum rules calculation for $\boldsymbol{X(3872)}$

Matheus, Narison, MN, Richard: PRD75 (07)

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

$$m^2 = \frac{\int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ s\ \rho^{OPE}(s)}{\int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ \rho^{OPE}(s)}$$

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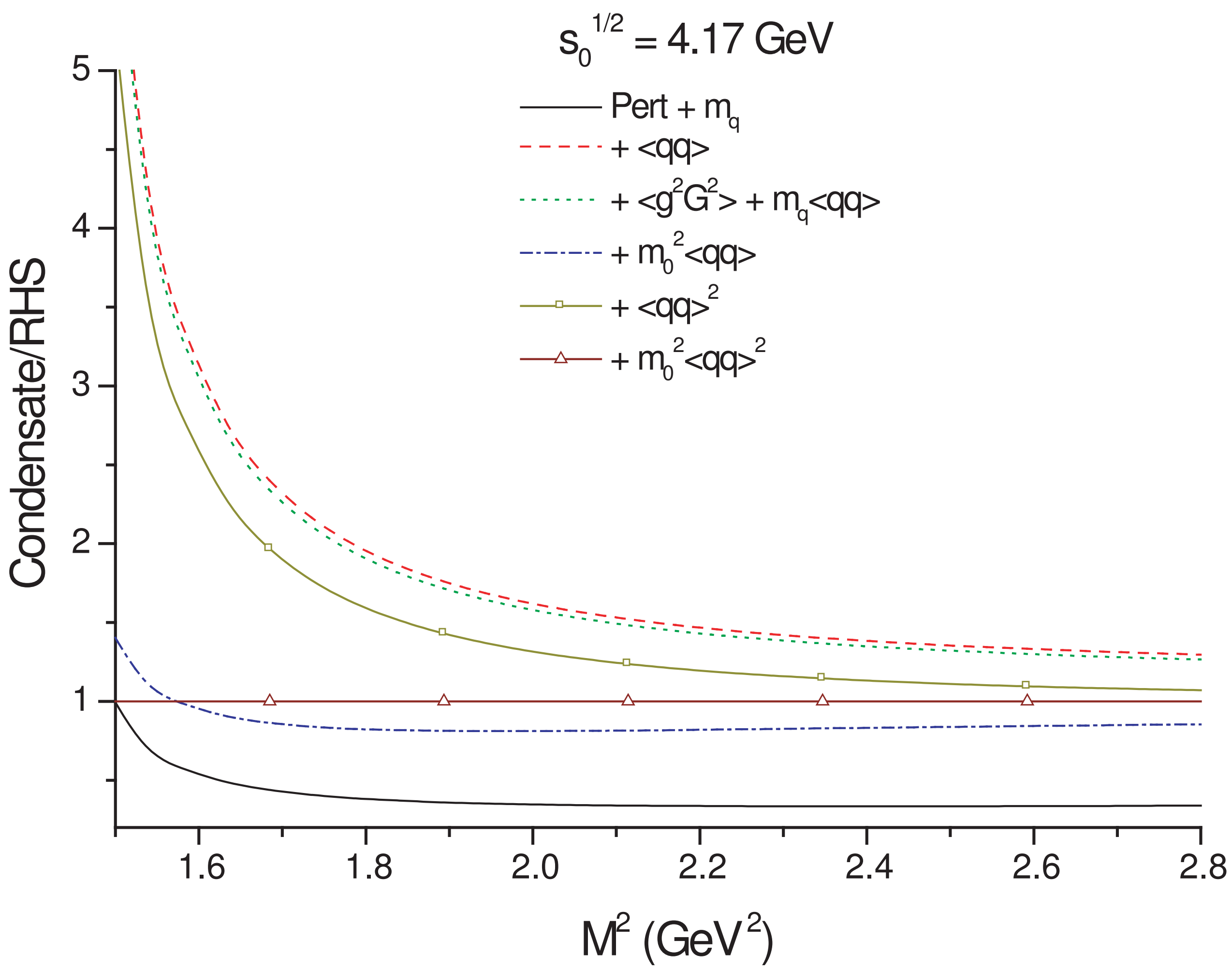
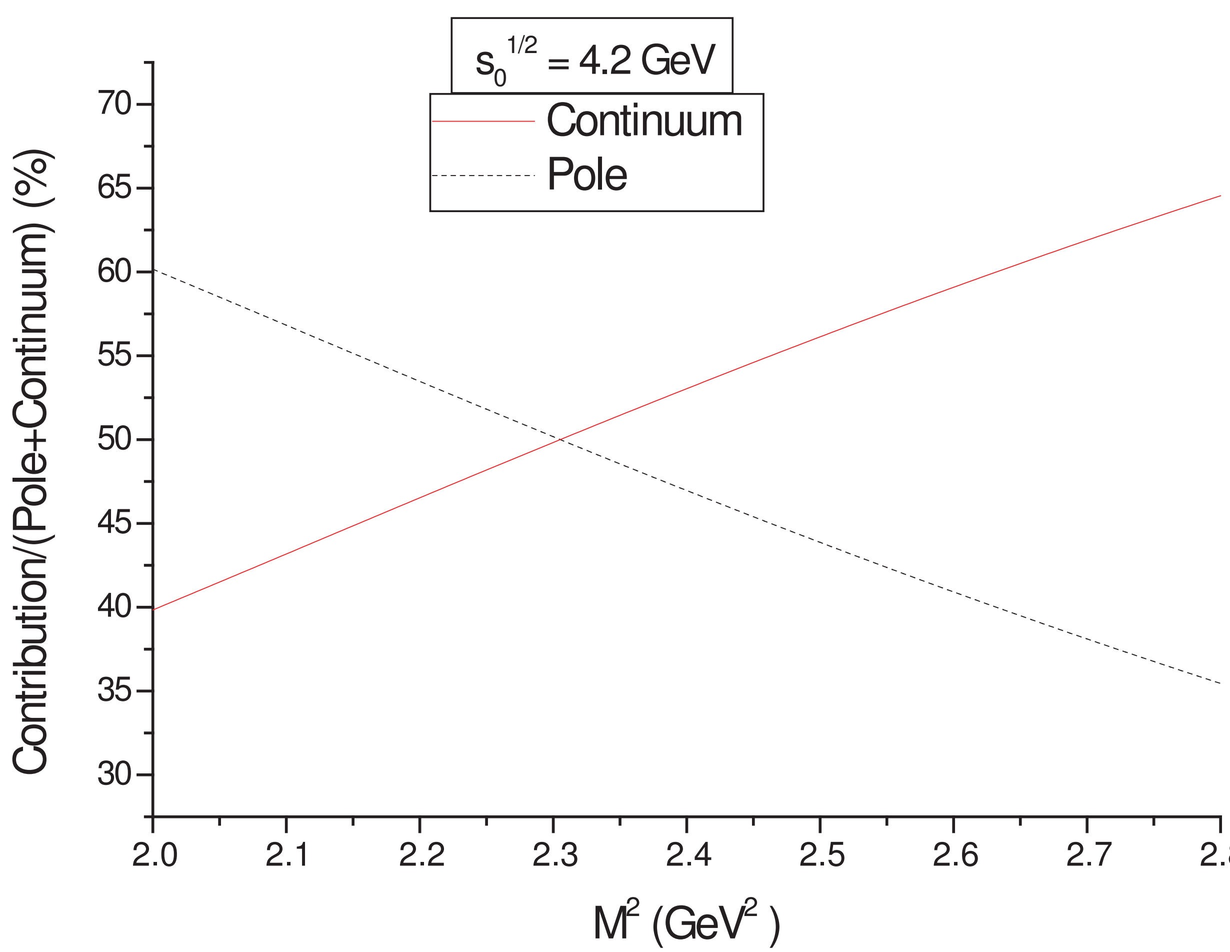
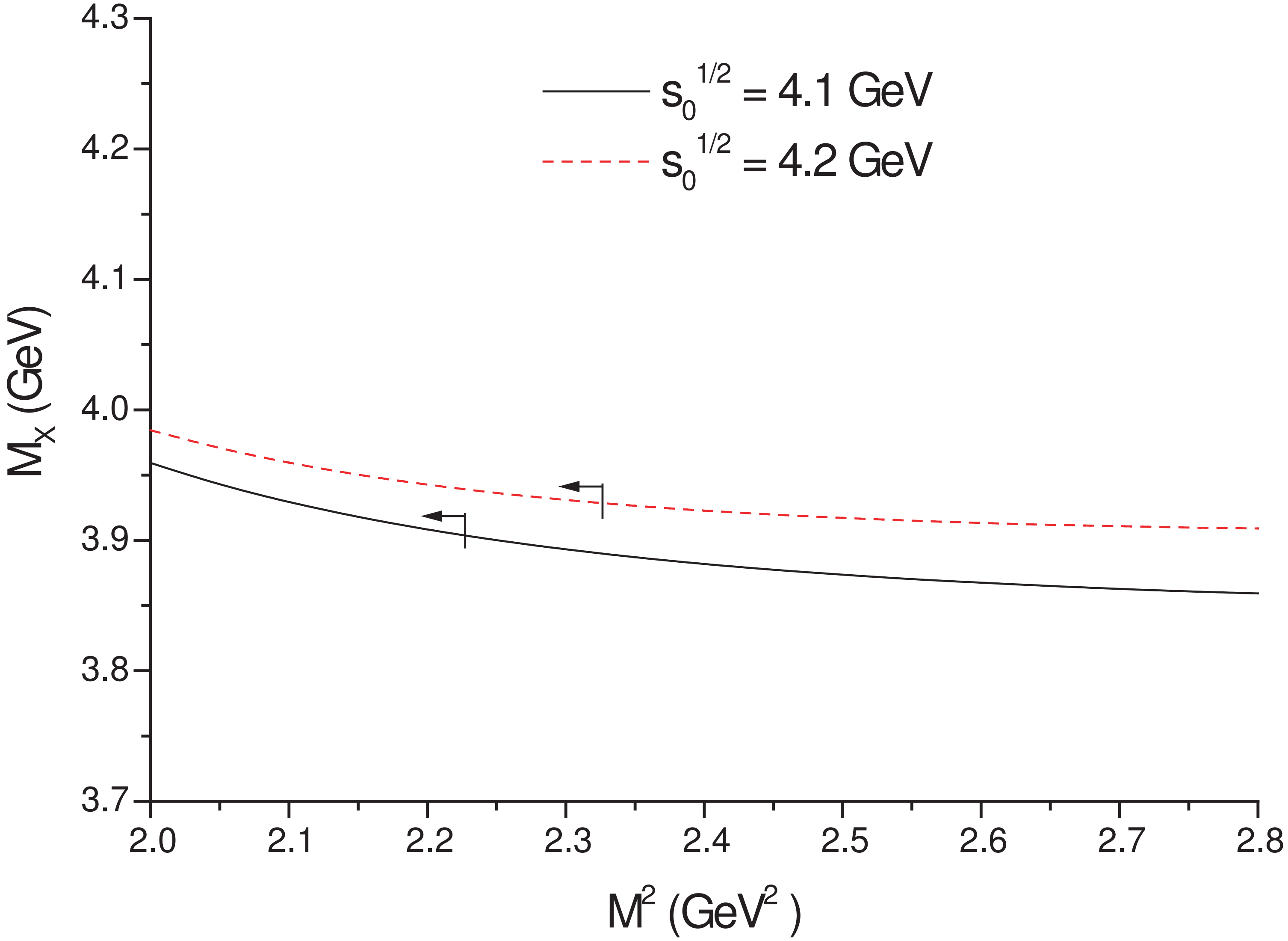
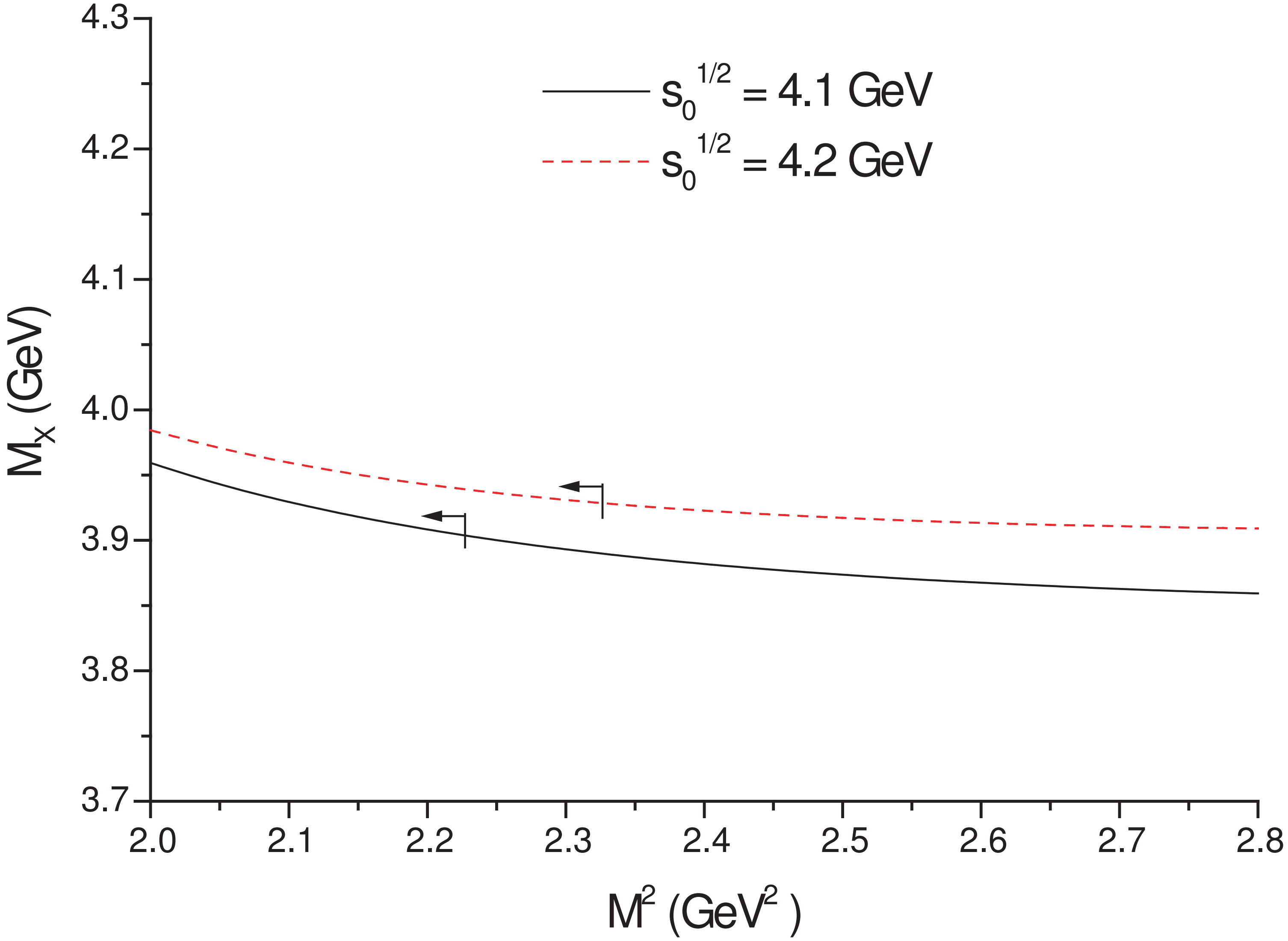






$$m_X = (3.92 \pm 0.13)\ \text{GeV}$$

$$M(X_h) - M(X_l) \begin{cases} \nearrow (8 \pm 3)\ \text{MeV (quark model)} \\ \searrow (2.6\ -\ 3.9)\ \text{MeV (QCD sum rule)} \end{cases}$$



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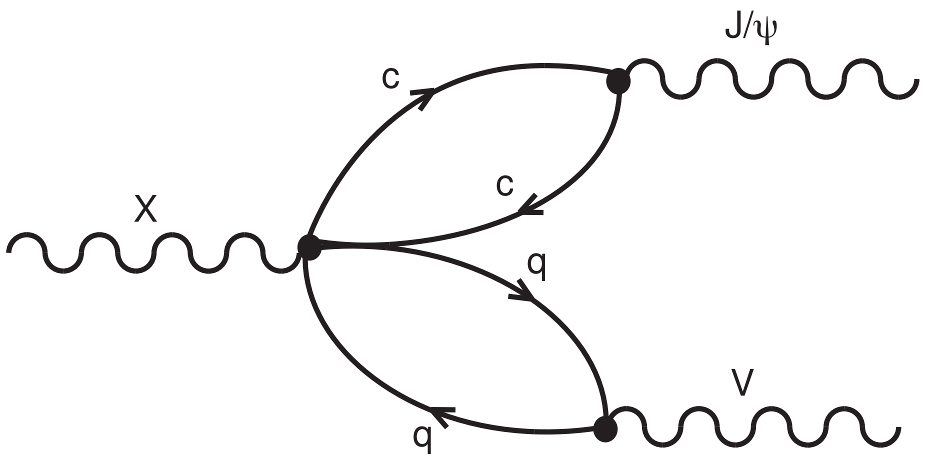
Belle Collaboration: arXiv/0809.1224 ➡ $\Delta m = (0.18 \pm 0.89 \pm 0.26)$ MeV

Lee, MN, Wiedner: $D^0\bar{D}^{*0}$ molecular current (arXiv:0803.1168)

$$j_\mu^{(q,mol)}(x) = \frac{1}{\sqrt{2}}\left[(\bar{q}_a(x)\gamma_5 c_a(x)\bar{c}_b(x)\gamma_\mu q_b(x)) - (\bar{q}_a(x)\gamma_\mu c_a(x)\bar{c}_b(x)\gamma_5 q_b(x)) \right]$$

$$\boldsymbol{m_X = (3.87 \pm 0.07)}\ \text{GeV}$$

better agreement with the molecular current



Problem: decay width X → J/ψππ

~ 50 MeV (Navarra, MN, PLB639 (06)272)

arXiv:0810.1073: $X(3872)$ observed in two different channels

$$\left(\frac{X\to\psi(2S)\gamma}{X\to J/\psi\gamma}\right)_{exp} = 3.4 \pm 1.4, \quad \left(\frac{X\to\psi(2S)\gamma}{X\to J/\psi\gamma}\right)_{mol} \sim 4\times 10^{-3}$$

indication of a significant mixing of the $c\bar{c}$ and $D_0\bar{D}^{*0}$ molecular components

Matheus, Navarra, MN, Zanetti

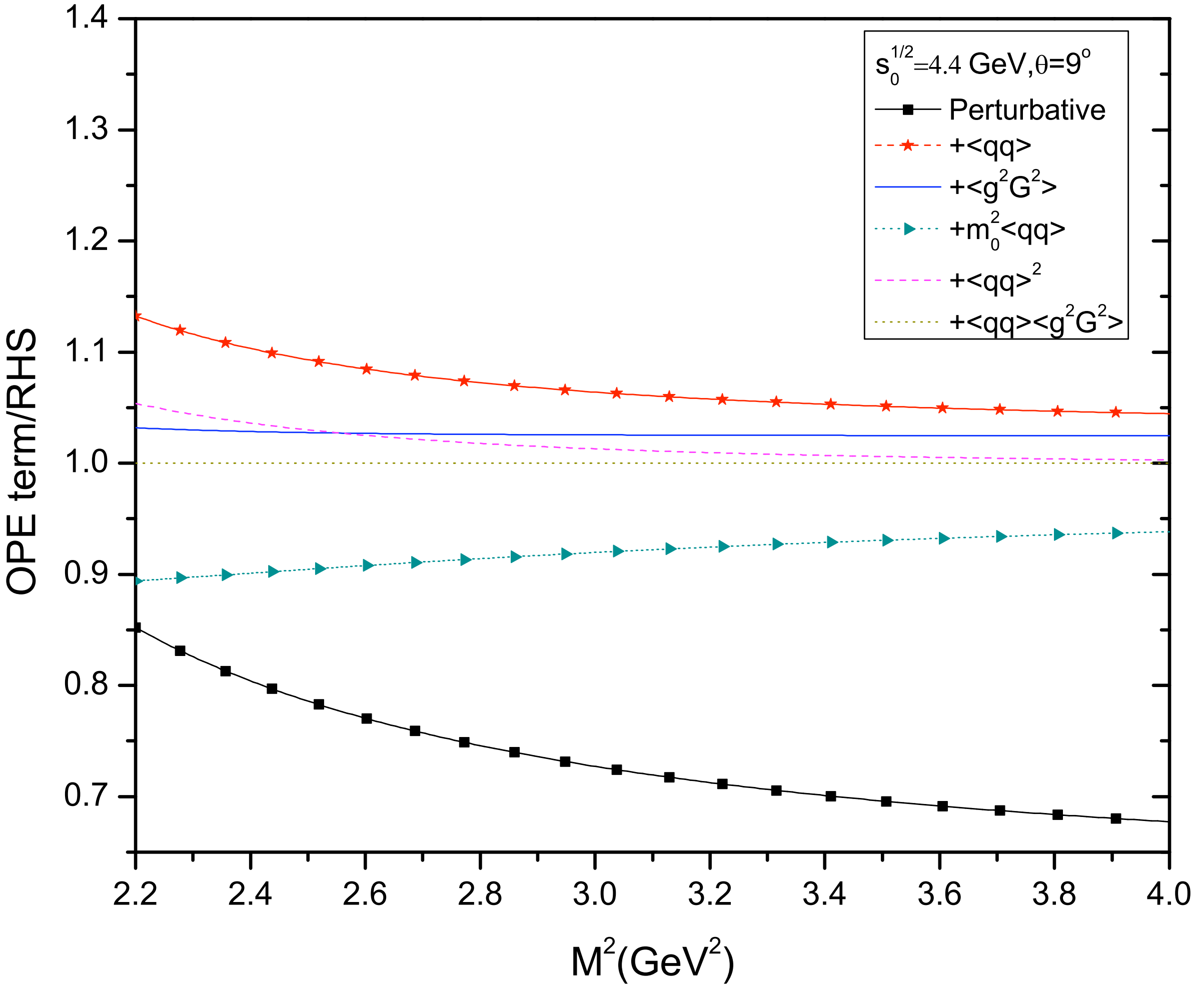
(arXiv:0907.2683)

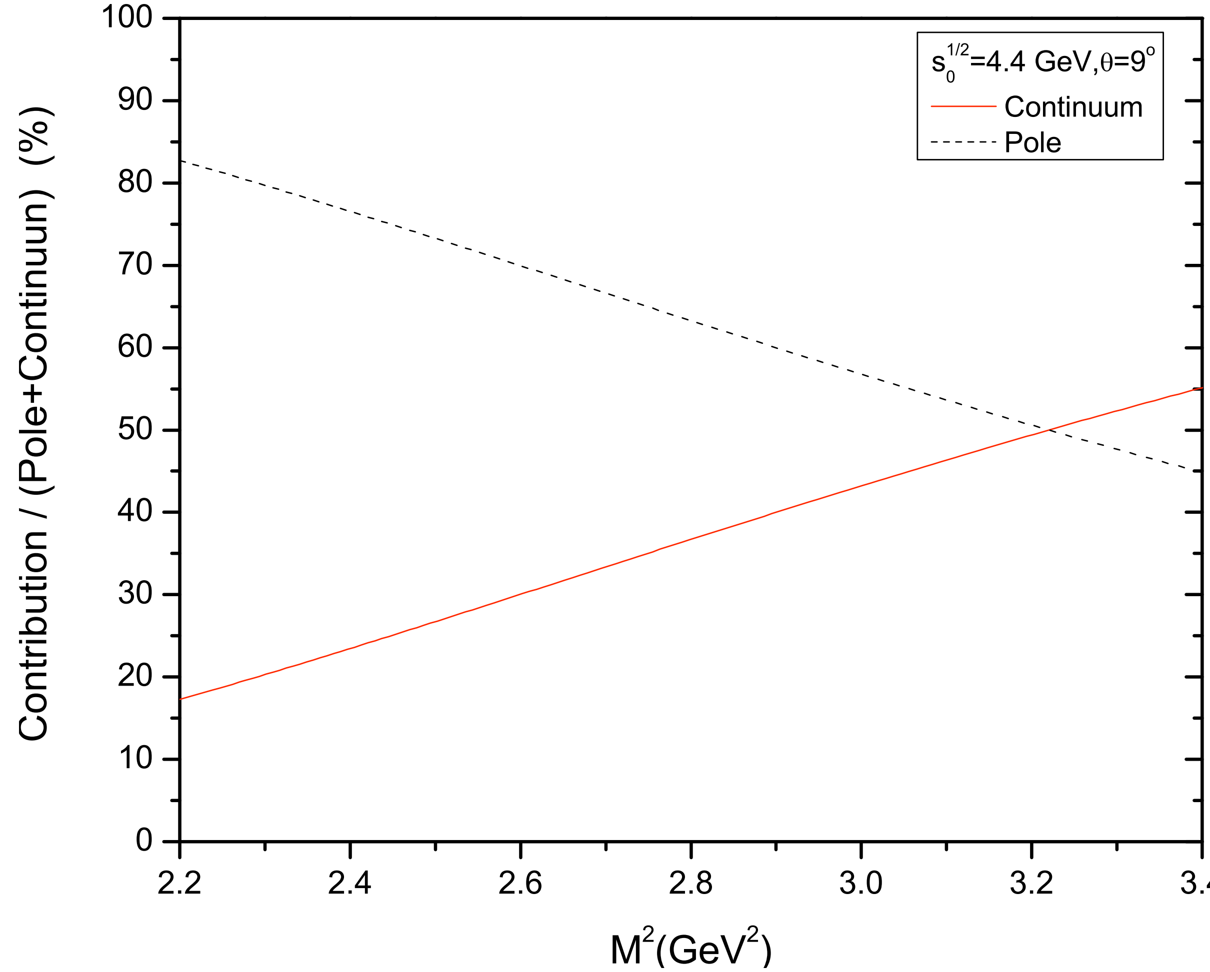
$$J_\mu^q(x) = \sin\theta j_\mu^{(q,mol)}(x) + \cos\theta j_\mu^{(q,2)}(x)$$

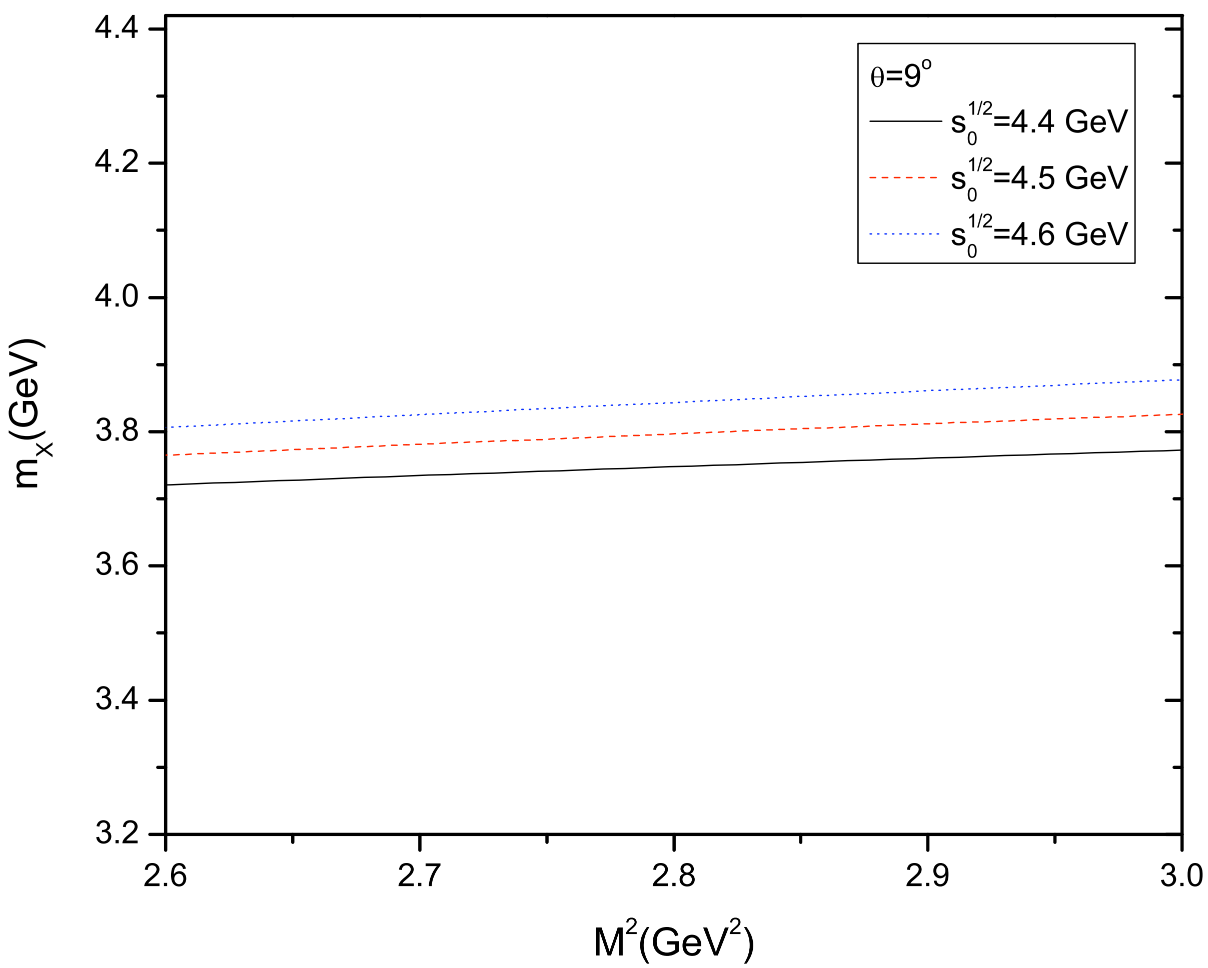
$$j_\mu^{(q,2)}(x) = \frac{1}{6\sqrt{2}}\langle\bar{q}q\rangle[\bar{c}_a(x)\gamma_\mu\gamma_5 c_a(x)]$$

Sugiyama, Nakamura, Ishii, Nishikawa, Oka (arXiv:0707.2533)

mixed 2-quark 4-quark current to study the light scalars

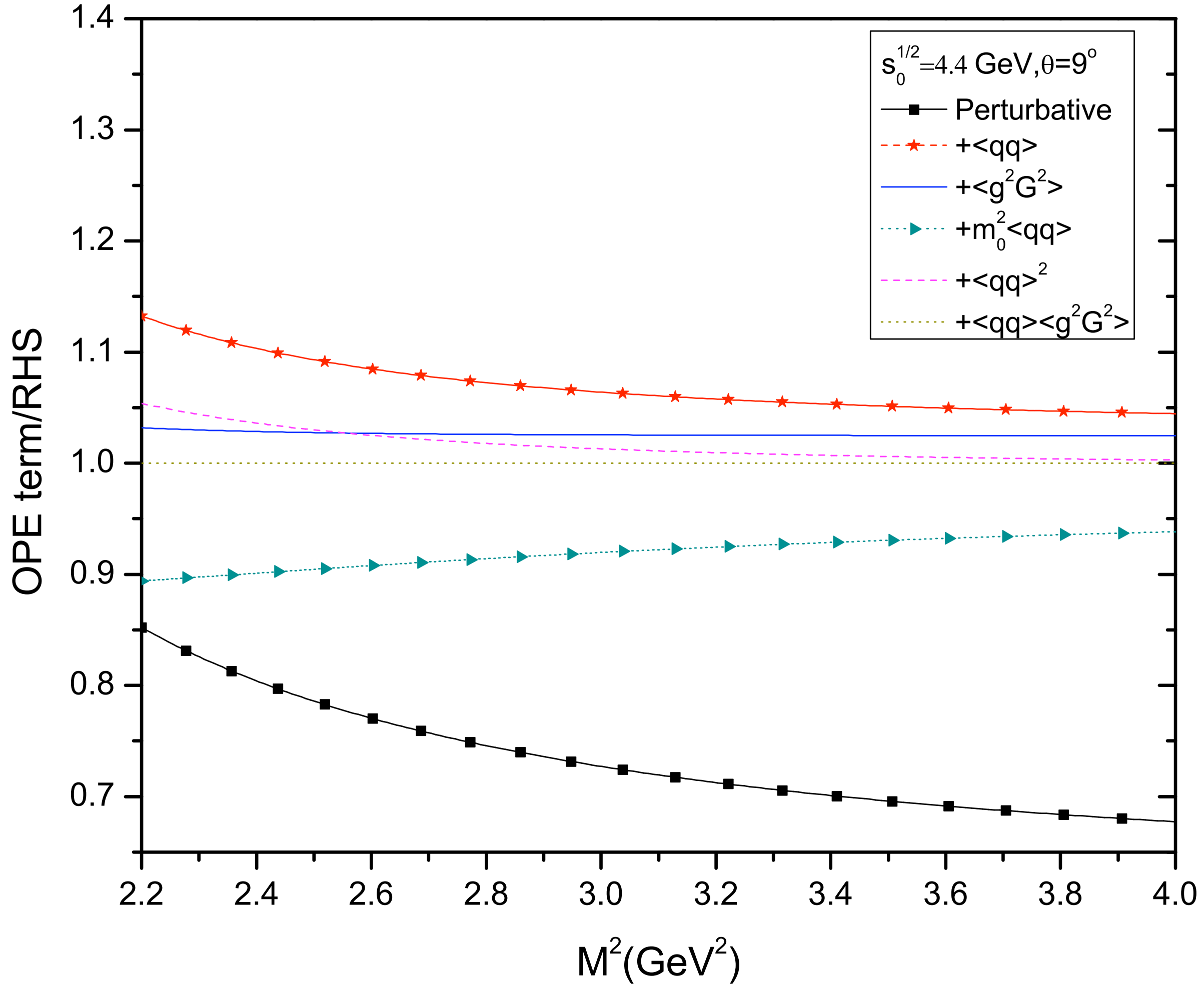


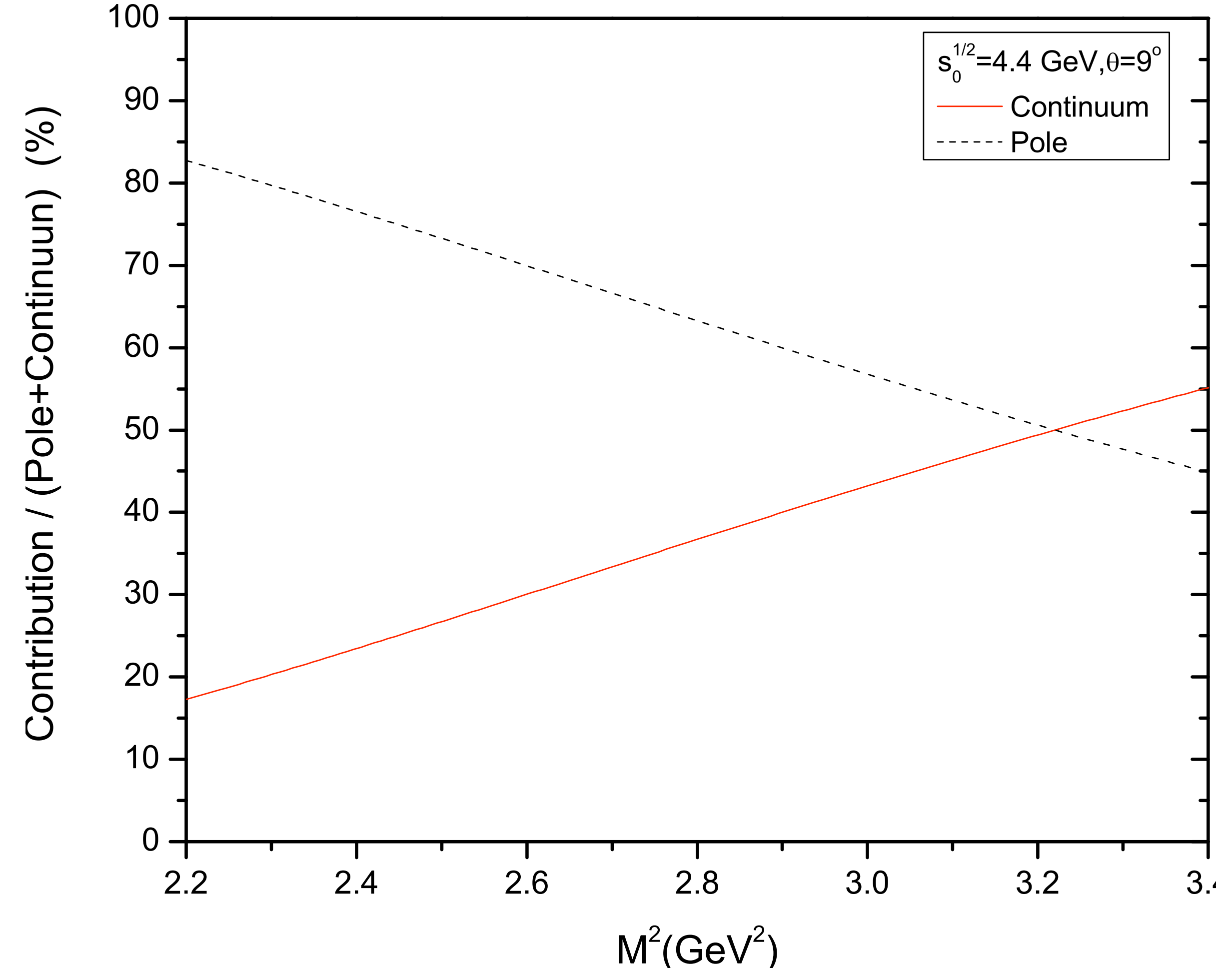


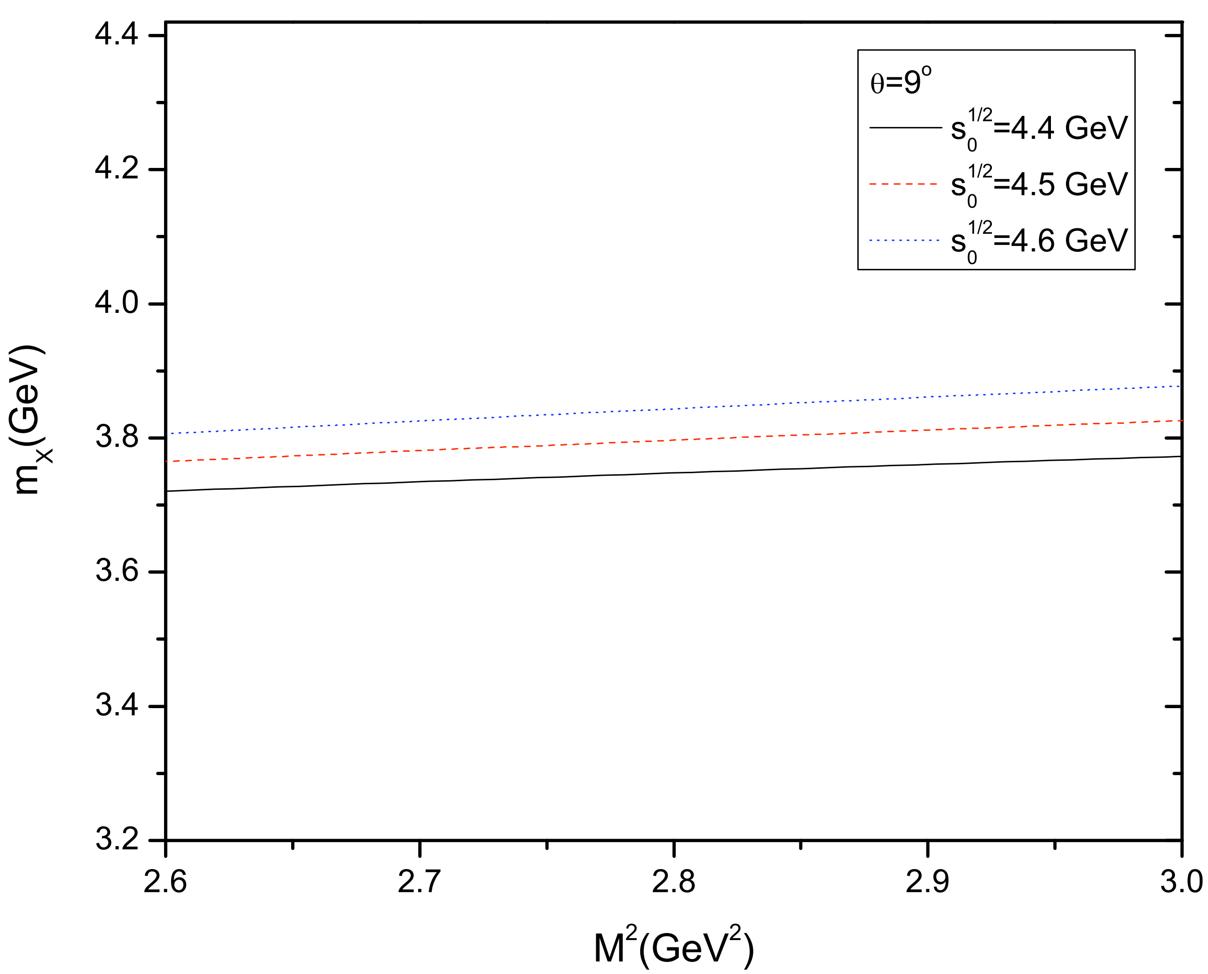


$$m_X = (3.77 \pm 0.18)\ \text{GeV}$$

$$9^0 \leq \theta \leq 13^0$$







$$m_X = (3.77 \pm 0.18)\ \text{GeV}$$

$$9^0 \leq \theta \leq 13^0$$

m_X increases with θ

Decay width $X \rightarrow J/\psi V$

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \ e^{ip'.x} \ e^{iq.y}\Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_\nu^V(y) j_\alpha^{X\dagger}(0)]|0\rangle$$

$$\Pi_{\mu\nu\alpha}(x,y) \ = \ \frac{\langle\bar{u}u\rangle}{2\sqrt{6}}\cos(\theta)\Pi^{c\bar{c}}_{\mu\nu\alpha}(x,y) \quad + \ \sin(\theta)\Pi^{mol}_{\mu\nu\alpha}(x,y)$$

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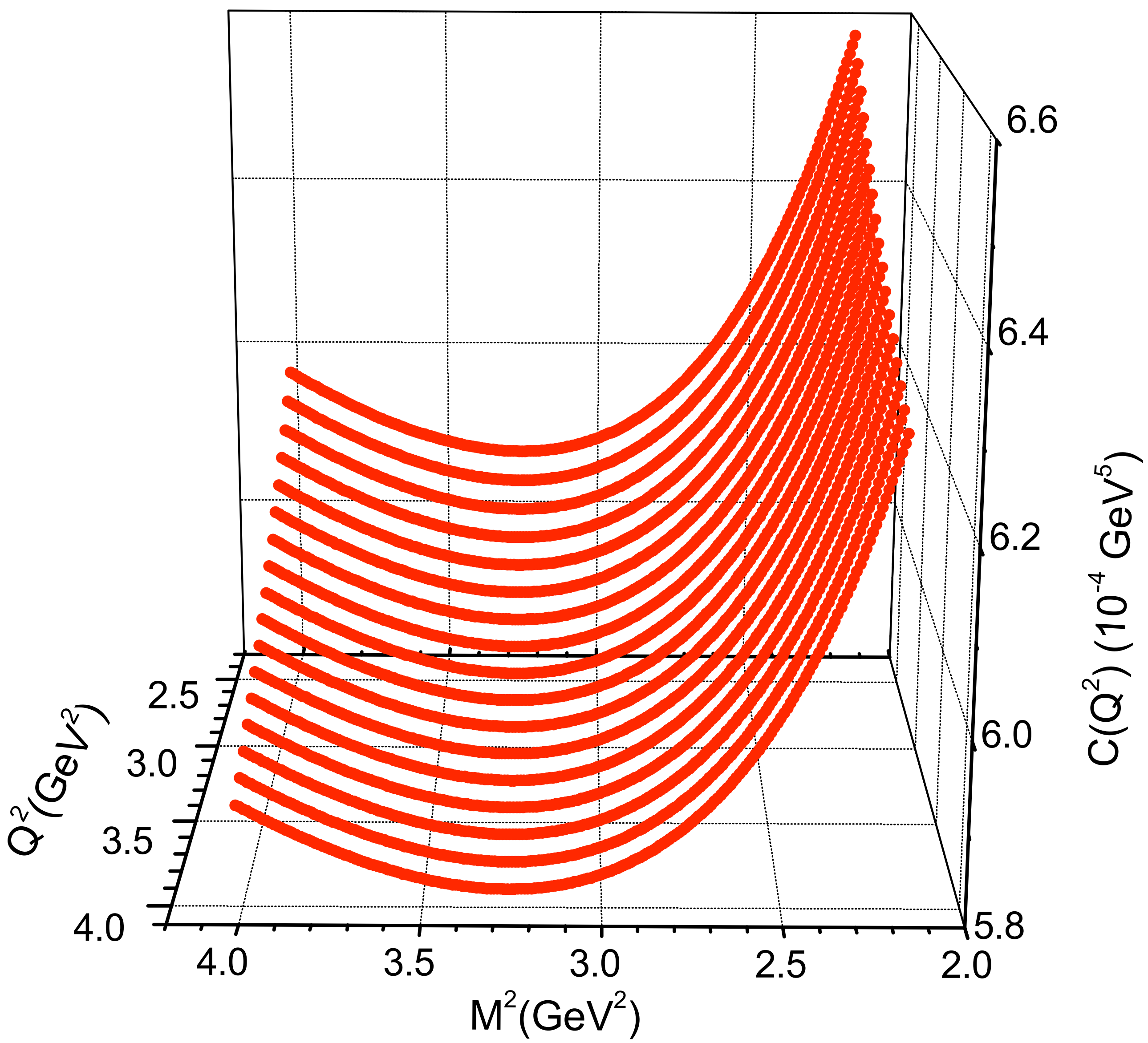
$$\frac{X \to J/\psi\,\pi^+\pi^-\pi^0}{X \to J/\psi\pi^+\pi^-} = 1.0 \pm 0.4 \pm 0.3 \Rightarrow j_\mu^X(x) = \cos\alpha J_\mu^u(x) + \sin\alpha J_\mu^d(x)$$

$$\frac{\Gamma(X \to J/\psi\,\pi^+\pi^-\pi^0)}{\Gamma(X \to J/\psi\,\pi^+\pi^-)} \simeq 0.15\left(\frac{\cos\alpha + \sin\alpha}{\cos\alpha - \sin\alpha}\right) \Rightarrow \quad \alpha \sim 20^0$$

$$\Pi^{(phen)}_{\mu\nu\alpha}(p,p',q) \rightarrow \langle J/\psi(p')V(q)|X(p)\rangle$$

$$\langle J/\psi(p')V(q)|X(p)\rangle = g_{X\psi V}(Q^2)\varepsilon^{\mu\nu\rho\sigma}p_\mu\varepsilon^*_\rho(p')\varepsilon^*_\sigma(q)\varepsilon_\nu(p)$$



$$g(Q^2) = \frac{A}{B+Q^2}$$

$$g_{X\psi\omega} = g_{X\psi\omega}(-m_\omega^2) = 5.4 \pm 2.4$$

$m_X = (3.77 \pm 0.18)$ GeV

$\Gamma = (9.3 \pm 6.9)$ MeV

$5^0 \leq \theta \leq 13^0$

Decay width $X \to J/\psi\Upsilon$

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y}\Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T j_\mu^\psi j_\nu^\gamma j_\alpha^{X^\dagger}]|0\rangle \qquad j_\mu^X = \sin\alpha J_\mu^d + \cos\alpha J_\mu^u$$

$$J_\mu^q(x) = \sin\theta j_\mu^{(q,mol)}(x) + \cos\theta j_\mu^{(q,2)}(x)$$

$$j_\mu^{(q,2)}(x) = \frac{1}{6\sqrt{2}}\langle\bar{q}q\rangle[\bar{c}_a(x)\gamma_\mu\gamma_5 c_a(x)]$$

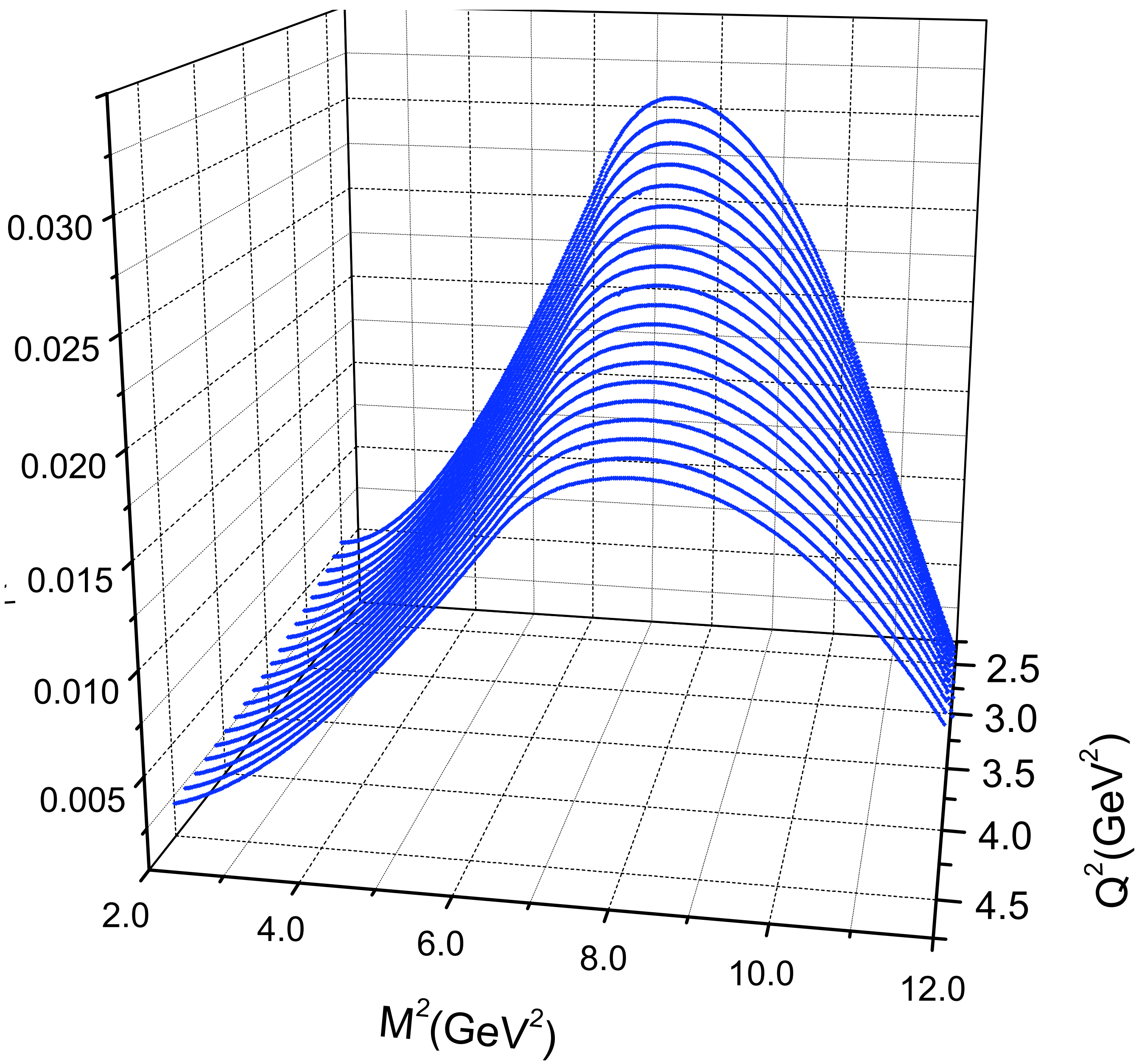
$$j_\mu^{(q,mol)}(x) = \frac{1}{\sqrt{2}}\Big[(\bar{q}_a(x)\gamma_5 c_a(x)\bar{c}_b(x)\gamma_\mu q_b(x)) - (\bar{q}_a(x)\gamma_\mu c_a(x)\bar{c}_b(x)\gamma_5 q_b(x)) \Big]$$

$$j_\mu^\gamma = \frac{2}{3}\bar{u}\gamma_\mu u - \frac{1}{3}\bar{d}\gamma_\mu d + \frac{2}{3}\bar{c}\gamma_\mu c$$

$$\Pi^{(phen)}_{\mu\nu\alpha}(p,p',q) \Rightarrow \langle J/\psi(p')|j^{\gamma}_{\nu}(q)|X(p)\rangle$$

$$\langle J/\psi(p')|j^{\gamma}_{\nu}(q)|X(p)\rangle = iM\left(X(p)\to J/\psi(p')\gamma(q)\right)\varepsilon^{*\gamma}_{\nu}(q)$$

$$M(X(p)\to\gamma(q)J/\psi(p')) = e\,\varepsilon^{mn\rho\sigma}\,\epsilon^{\alpha}_{X}(p)\,\epsilon^{\mu}_{J_\psi}(p')\,\epsilon^{\gamma}_{\rho}(q)\,\frac{q_\sigma}{m_X^2}\left(A\,g_{\mu n}g_{\alpha m}\,pq + B\,g_{\mu n}\,p_m q_\alpha + C\,g_{\alpha m}\,p_n q_\mu\right)$$



$$A(Q^2) = ae^{-bQ^2}$$

$$\begin{aligned} A &= A(Q^2=0) = 23.9 \pm 1.2 \\ A+B &= (A+B)(Q^2=0) - 0.9 \pm 0.4 \\ C &= C(Q^2=0) = -1.08 \pm 0.01 \end{aligned}$$

$$\Gamma(X(3872) \to \gamma J/\psi) = \frac{\alpha}{3}\frac{P^{*5}}{m_X^4}\left((A+B)^2 + \frac{m_X^2}{m_{J_\psi}^2}(A+C)^2\right)$$

$$P^* = (m_X^2 - m_{J_\psi}^2)/(2m_X)$$

$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi^+\pi^-)} = 0.31 \pm 0.22, \quad 5^0 \leq \theta \leq 13^0$$

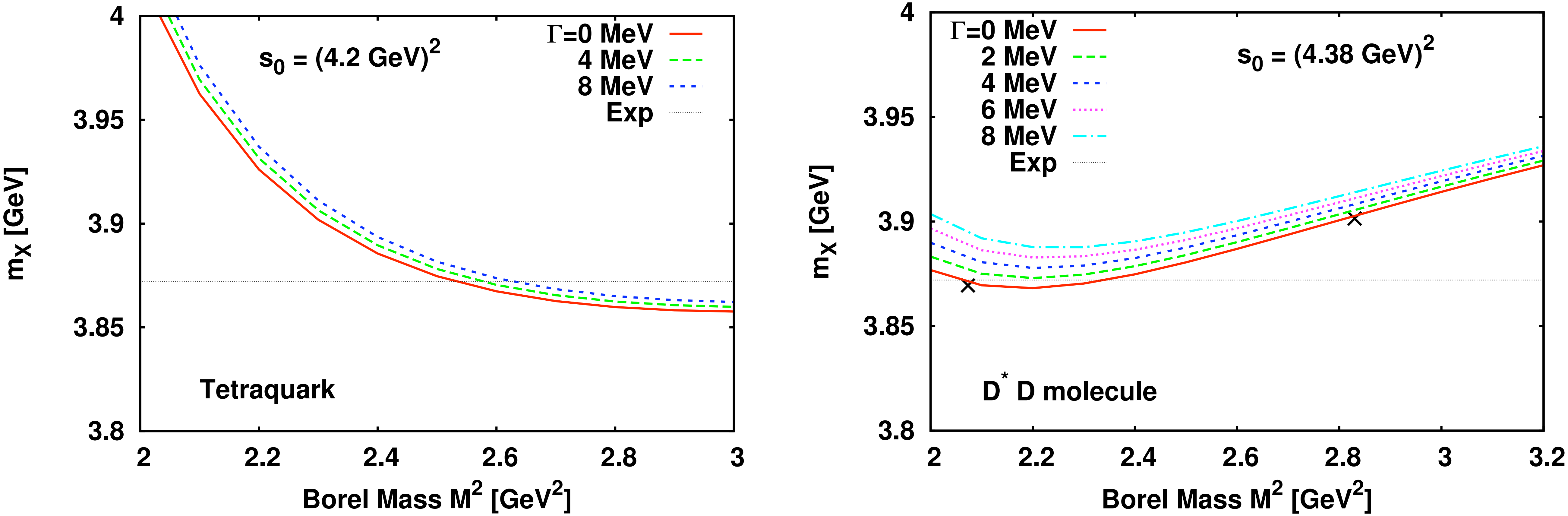
$$\left.\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi^+\pi^-)}\right|_{exp} = 0.14 \pm 0.05$$

QCDSR ➔ X is a mixed charmonium-molecular state

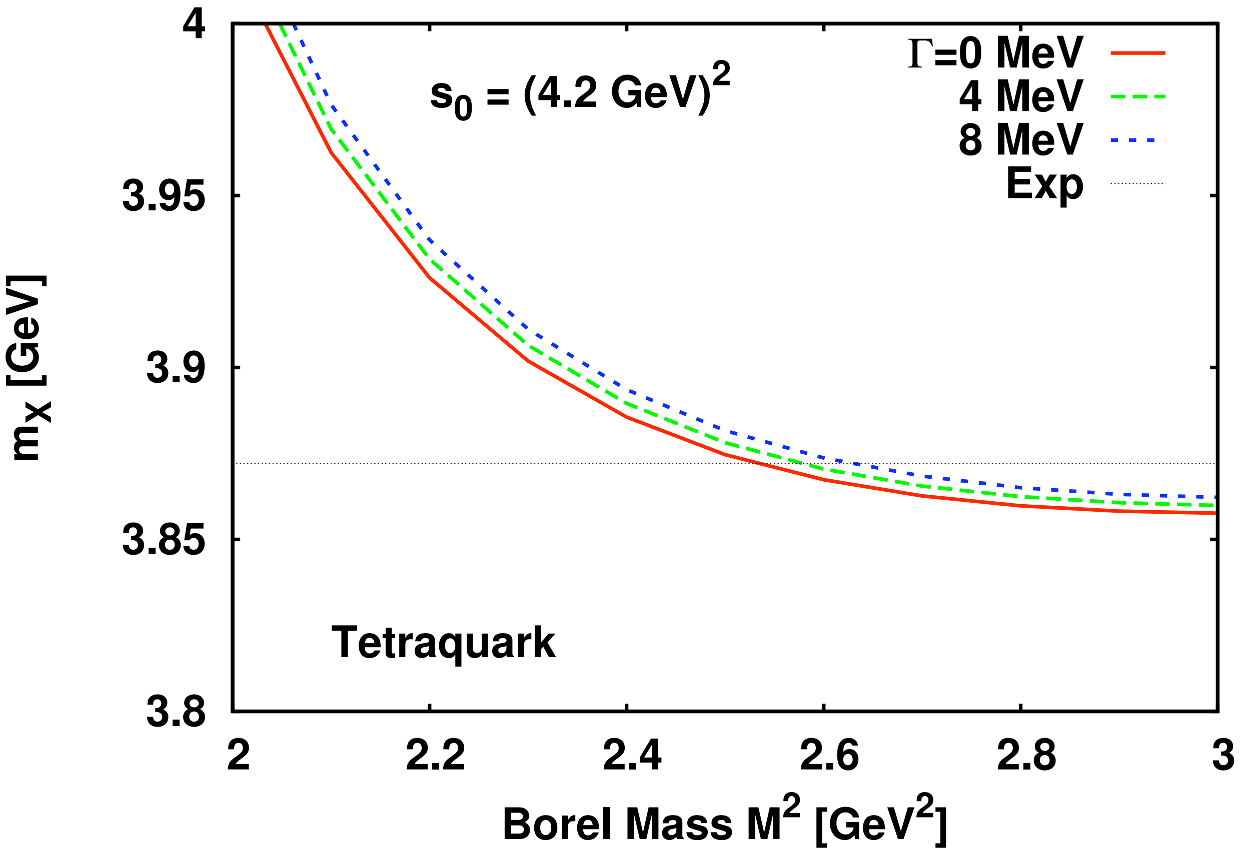
MN, Navarra & Lee, arXiv:0911.1958

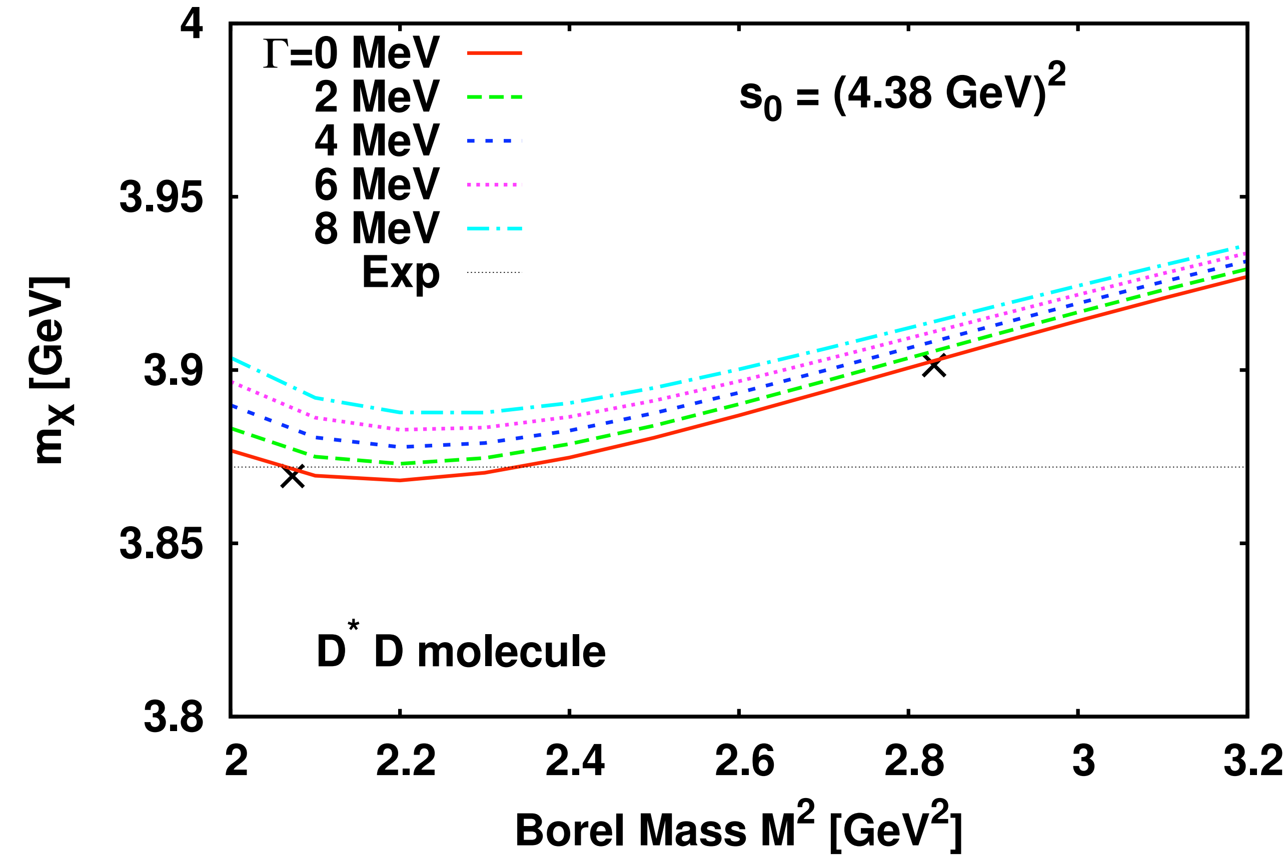
X(3872) mixed DD^* charmonium state $J^{PC}=1^{++}$ (3.77 ± 0.18) GeV	**Y(4260)** D_0D^* molecular state $J^{PC}=1^{--}$ (4.27 ± 0.10) GeV	**Z^+(4430)** D_1D^* molecular state $J^P=0^-$ (4.40 ± 0.10) GeV
Y(4360) not compatible with scalar-vector cq state neither with $D_{0s}D^*_s$ molecular state $J^{PC}=1^{--}$	**Y(4660)** scalar-vector cs tetraquark state $J^{PC}=1^{--}$ (4.65 ± 0.10) GeV	**Z_1^+(4050)** not compatible with D^*D^* molecular state $J^P=0^+$ (4.19 ± 0.18) GeV
Z_2^+(4250) D_1D molecular state $J^P=1^-$ (4.25 ± 0.10) GeV $40 < \Gamma < 60$ MeV	**Y(4140)** $D_s^*D_s^*$ molecular state $J^{PC}=0^{++}$ (4.14 ± 0.09) GeV	**X(4350)** not compatible with $D_s^*D_{s0}^*$ molecular state $J^{PC}=1^{-+}$ (5.05 ± 0.19) GeV

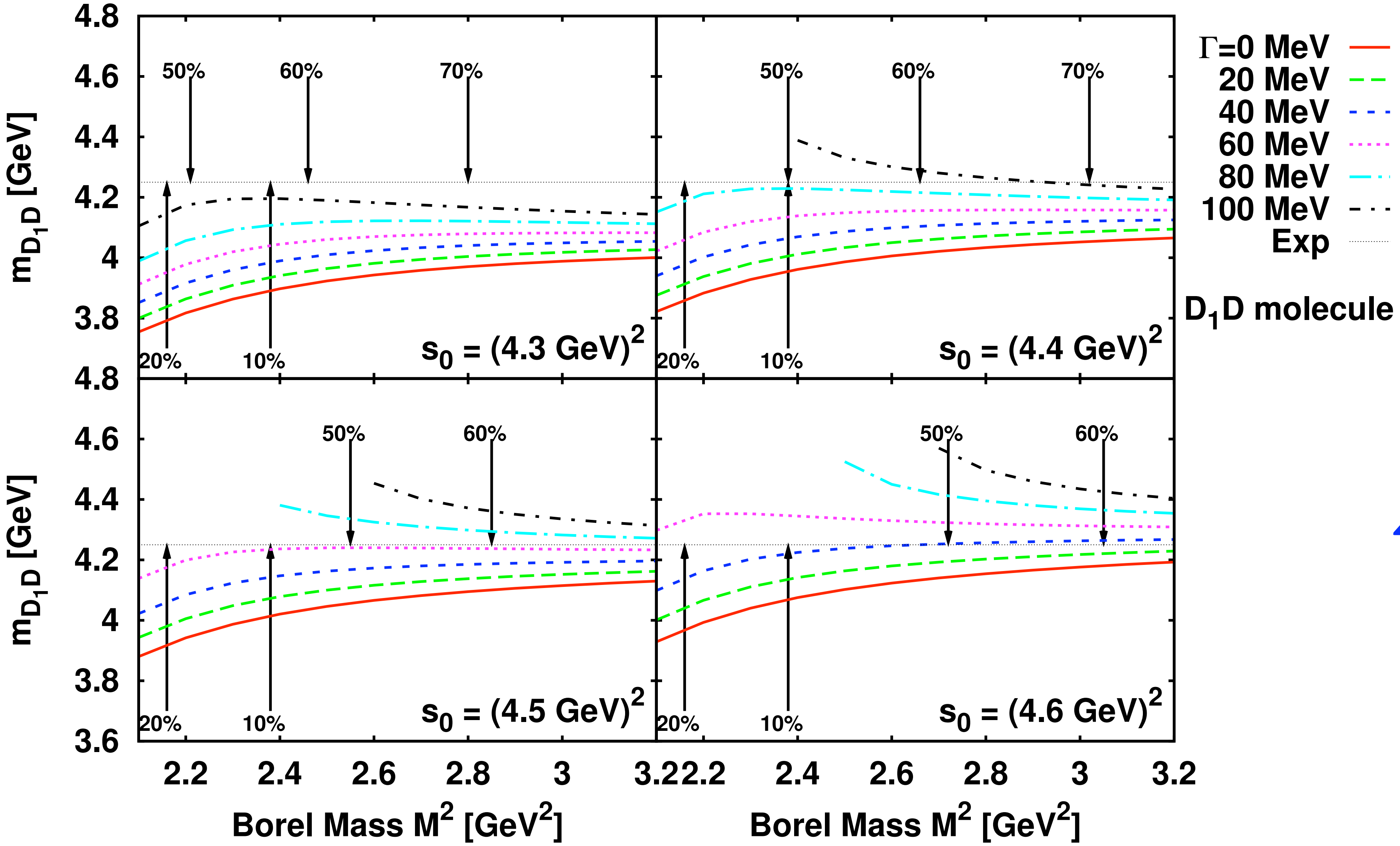
X(3872) $J^{PC} = 1^{++}$ 3871.4±0.6 Γ<2.3 MeV	Y(4260) $J^{PC} = 1^{--}$ 4252±7 Γ=88±24	$Z^+(4430)$ $J^{PC} = ?$ 4433±14 Γ=44±17
Y(4360) $J^{PC} = 1^{--}$ 4361±13 Γ=74±18	Y(4660) $J^{PC} = 1^{--}$ 4664±12 Γ=48±15	$Z_1^+(4050)$ $J^{PC} = ?$ 4051±14 Γ=82±21
$Z_2^+(4250)$ $J^{PC} = ?$ 4248±44 Γ=177±54	Y(4140) $J^{PC} = ?^{?+}$ 4143±3 Γ=11.7±8	X(4350) $J^{PC} = ?^{?+}$ 4350±5 Γ=13±9



Lee, Morita, MN, arXiv:0808.3168


$s_0 = (4.2\ \mathrm{GeV})^2$
Γ=0 MeV
4 MeV
8 MeV
Exp
Tetraquark
m_X [GeV]
Borel Mass M^2 [GeV^2]


Γ=0 MeV
2 MeV
4 MeV
6 MeV
8 MeV
Exp
$s_0 = (4.38\ \mathrm{GeV})^2$
$D^* D$ molecule
m_X [GeV]
Borel Mass M^2 [GeV^2]

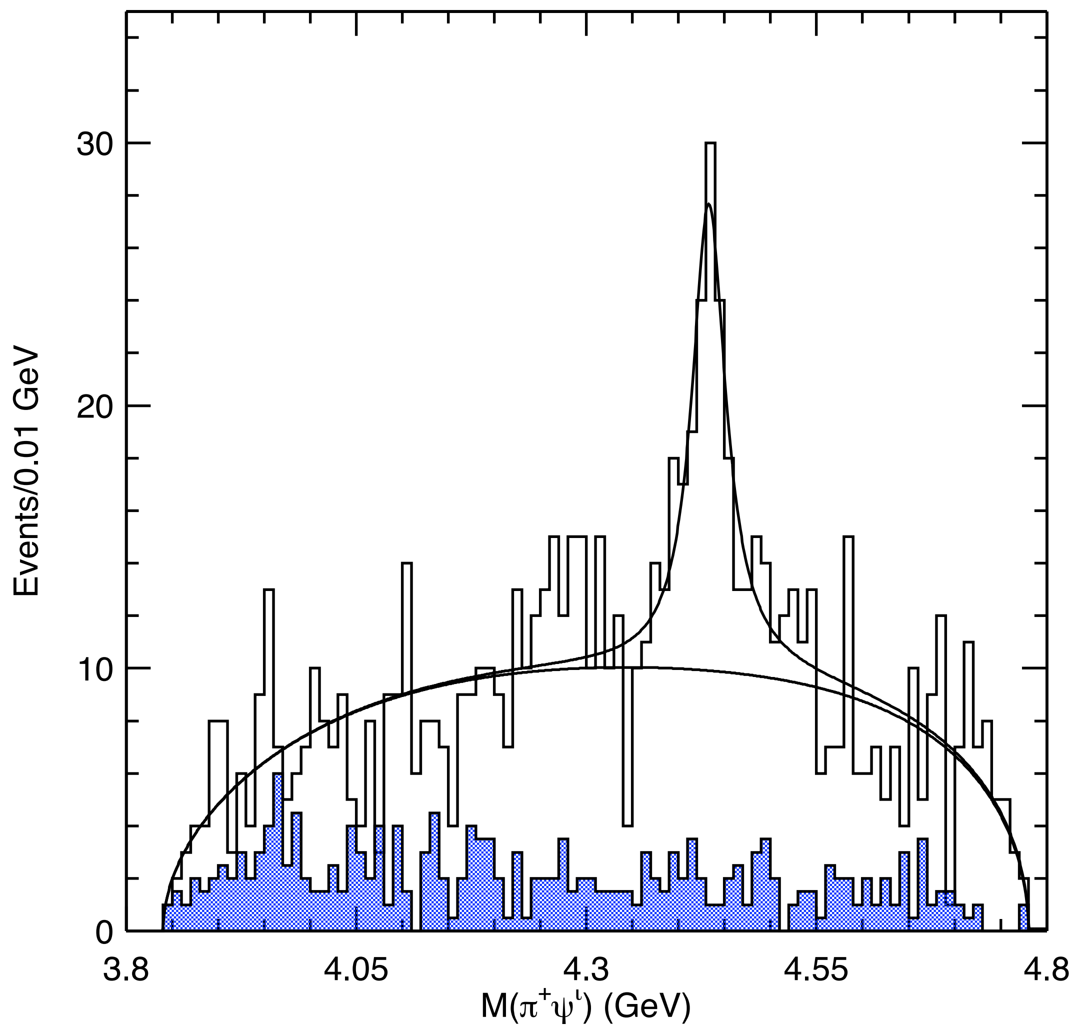

Γ=0 MeV
20 MeV
40 MeV
60 MeV
80 MeV
100 MeV
Exp
D_1D molecule
$s_0 = (4.3\ \mathrm{GeV})^2$
$s_0 = (4.4\ \mathrm{GeV})^2$
$s_0 = (4.5\ \mathrm{GeV})^2$
$s_0 = (4.6\ \mathrm{GeV})^2$
50%
60%
70%
20%
10%
m_{D_1D} [GeV]
Borel Mass M^2 [GeV^2]

$$Z_2^+(4250)$$

$Z^+(4430)$

$$B^+ \rightarrow Z^+ K \rightarrow \psi(2S)\pi^+ K$$

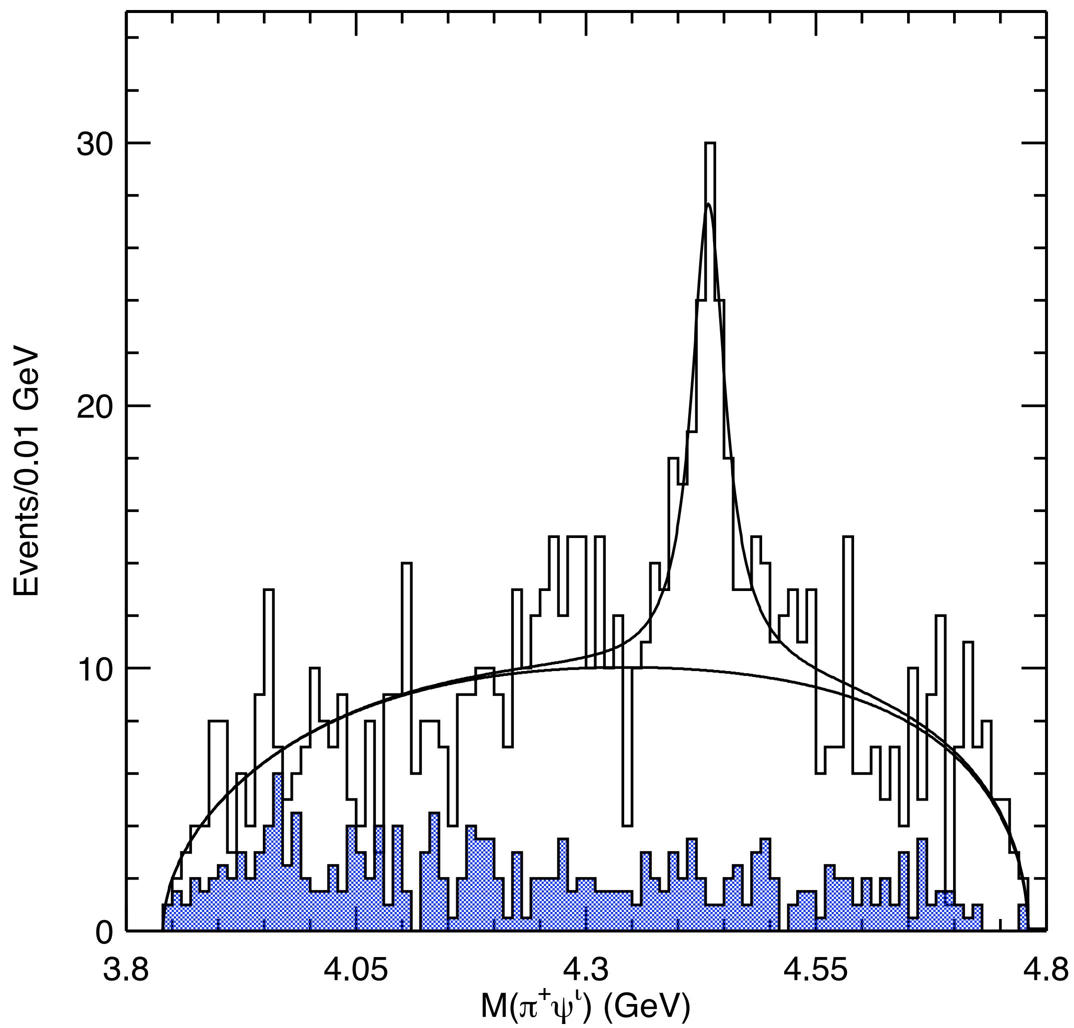
PRL100(08)142001

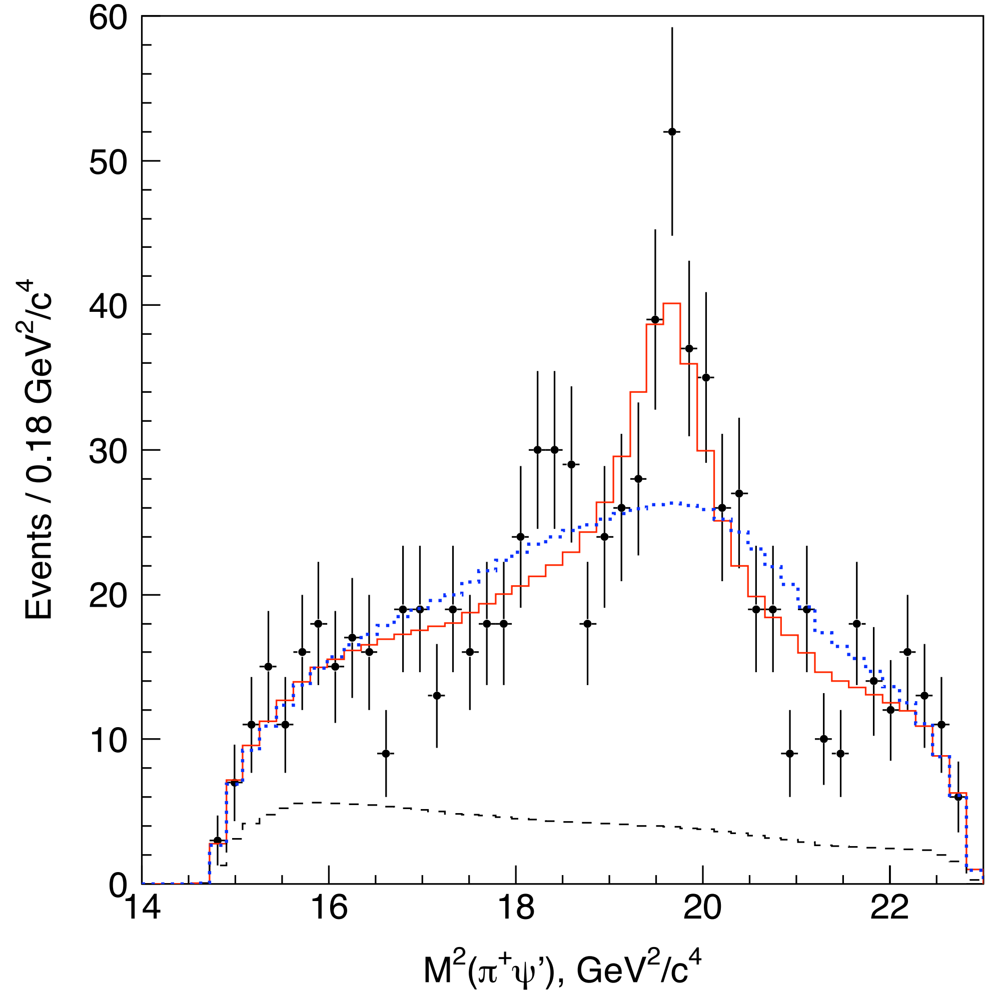


$Z^+(4430)$

$$B^+ \to Z^+ K \to \psi(2S)\pi^+ K$$

PRL100(08)142001





up-dated arXiv:0905.2869 confirmed the observation

M = (4433±22) MeV

Γ = (109±100) MeV

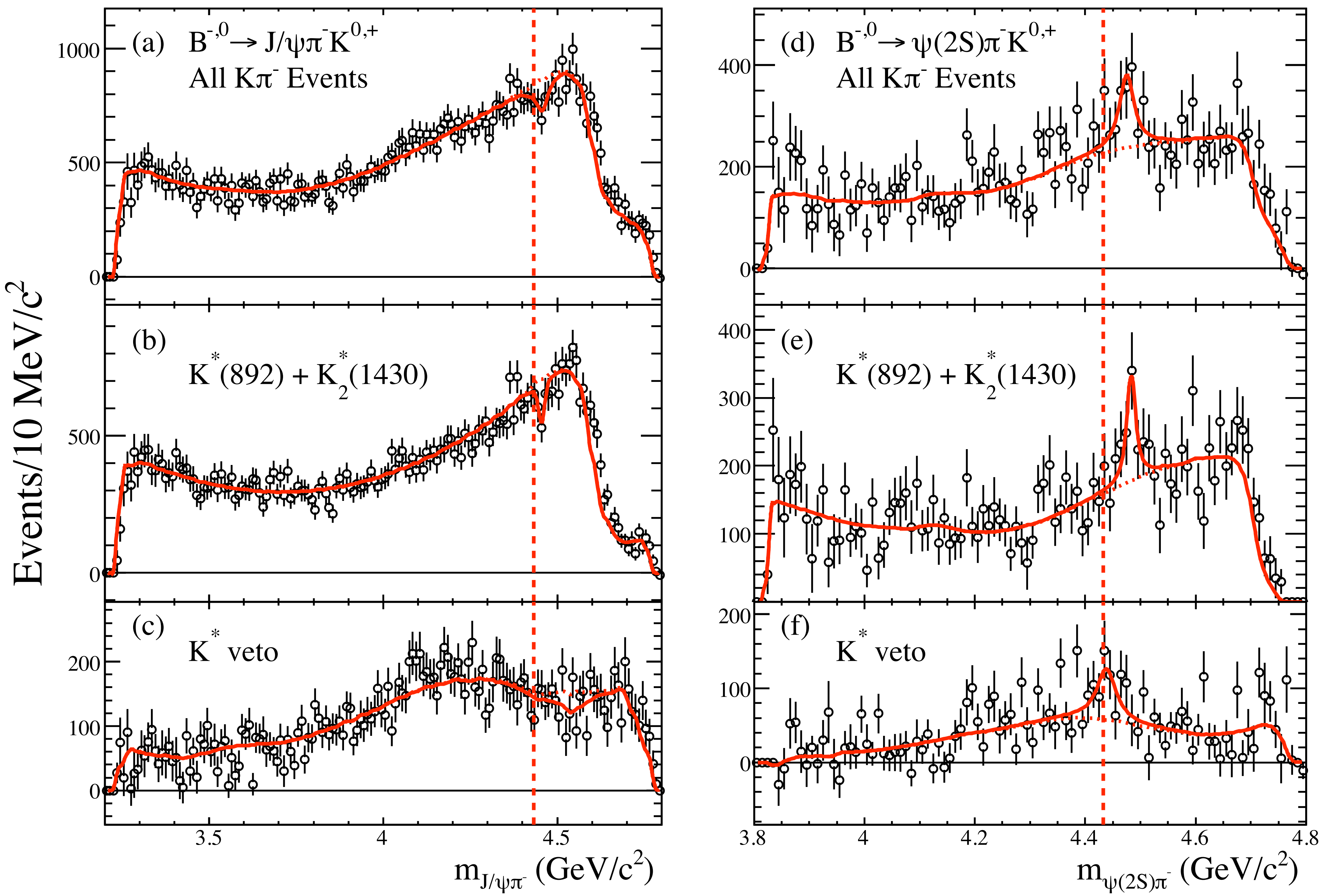
searched $Z^-(4430)$ in 4 decay modes:

arXiv:0905.2869

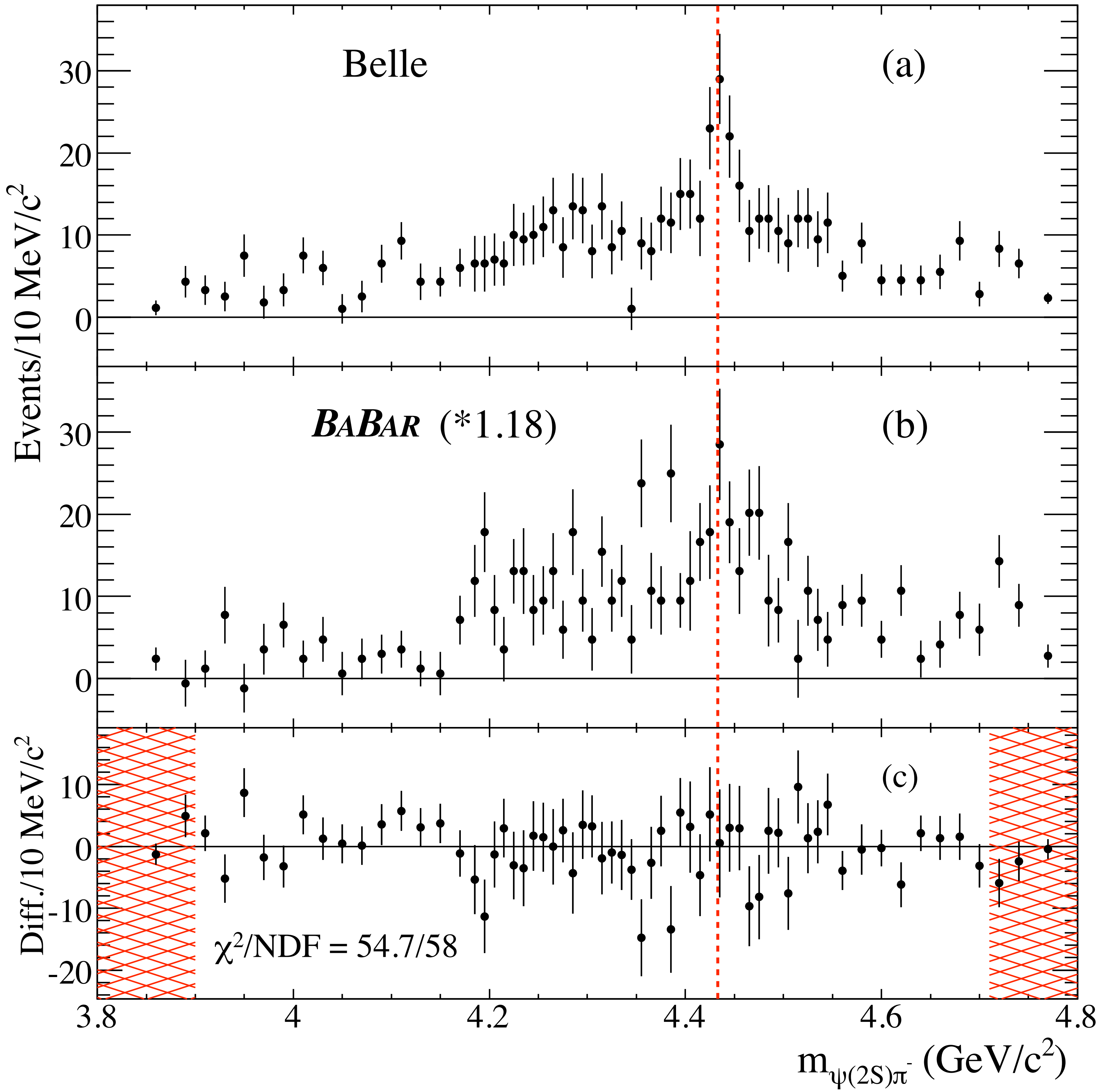
$$B \to \psi \pi^- K$$

$\psi = J/\psi,\ \psi(2S)$

$K = K_s^0,\ K^+$



no conclusive evidence for the existence of $Z^+(4430)$ seen by Belle arXiv:0912.0111 ➡ $\psi(2S)\pi^+$ invariant mass distribution



difference

almost same data but different conclusions

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

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

$$J^P = 1^+ \begin{cases} \nearrow \text{light antidiquark: } \epsilon_{abc}[\bar{u}_b\gamma_5 C\bar{d}_c^T] \\ \searrow \text{heavy diquark: } \epsilon_{aef}[c_e^T C\gamma_\mu c_f] \end{cases}$$

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

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

$$J^P = 1^+ \begin{cases} \nearrow \text{light antidiquark: } \epsilon_{abc}[\bar{u}_b\gamma_5 C\bar{d}^T_c] \\ \searrow \text{heavy diquark: } \epsilon_{aef}[c^T_e C\gamma_\mu c_f] \end{cases}$$

QCD sum rule study Navarra, MN, Lee, hep-ph/0703071

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

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

Conclusions

- Lots of charmonia in the last 7 years: a new spectroscopy?
  - Emerging consensus that X(3872) is a mixed charmonium-molecular state.
- Discovery of Y(4260), Y(4360) and Y(4660) represent an overpopulation of the 1^{--} states
  - Absence of open charm production in the Y decay is inconsistent with $c\bar{c}$ interpretation
- Z^+ states, need confirmation, but only molecule or tetraquark interpretations are possible