New charmonium states discovered at the B-factories

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B-factories

e^+e^- colliders at CM $\sim$ 10.6 GeV $\nearrow$ PEPII @ SLAC, $\searrow$ KEKB @ KEK

constructed to test CP violation
$B - \bar{B}$ pairs produced $\Rightarrow$ Belle (KEK) and BaBar (SLAC)

bonnus: observation of many new charmonium states

simplest charmonium producing B-meson decay: $B \longrightarrow K(c\bar{c})$

other form: initial state radiation (ISR) process
e^+ or e^- radiates a high energy γ-ray: $E_{\gamma_{ISR}} \sim 5000$ MeV

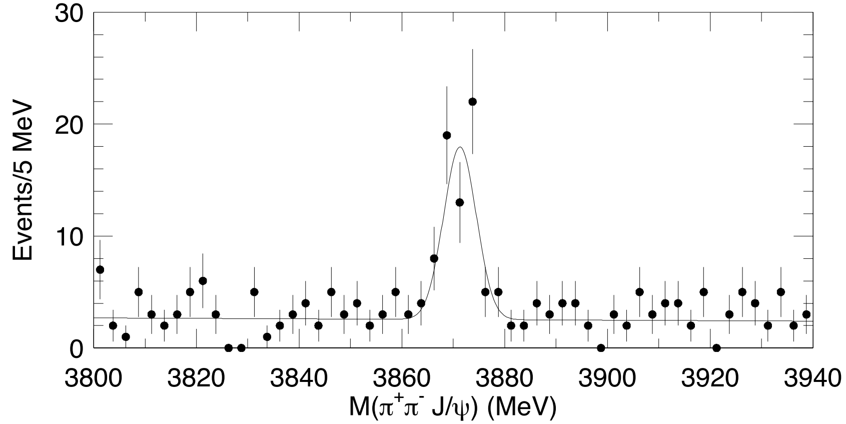
$$e^+e^- \longrightarrow c\bar{c} \quad \text{with} \quad J^{PC} = 1^{--}$$

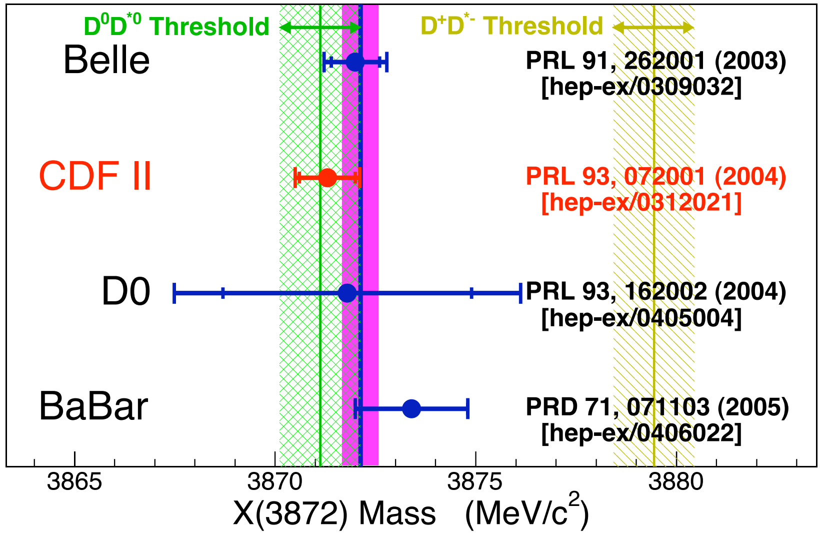
New charmonium mesons

$X(3872)$: Belle @ KEK (PRL91 (2003))

very narrow ($\Gamma < 2.3$ MeV) meson observed in B decay:

$$B^\pm \to K^\pm (J/\psi \pi^+ \pi^-)$$





confirmed by CDFII, D0, BaBar

$M(J/\psi \pi^+ \pi^-) = 3871.4 \pm 0.6$ MeV (world average)

$$\mathbf{X(3872)} \begin{cases} X(3872) \to \gamma J/\psi \Rightarrow C = + \\ \text{not seen in } e^+e^- \to X(3872) \Rightarrow J^P \neq 1^- \\ \text{angular distribution favors } J^{PC} = 1^{++} \end{cases}$$

$c\bar{c}$ spec. for $J^{PC} = 1^{++}$ (Barnes & Godfrey, PRD69 (2004))

- $\nearrow$ $2\ {}^3P_1\ (3990)$
- $\searrow$ $3\ {}^3P_1\ (4290)$

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

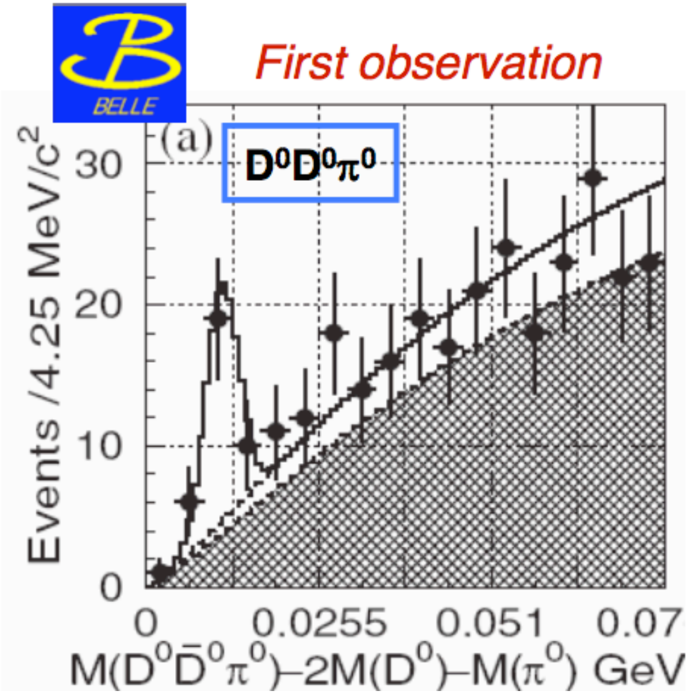
$$\frac{X \to J/\psi\pi^+\pi^-\pi^0}{X \to J/\psi\pi^+\pi^-} \sim 1 \Rightarrow \text{ strong isospin and } G \text{ parity violation}$$

$X(3872)$ can not be a simple $c\bar{c}$ state!

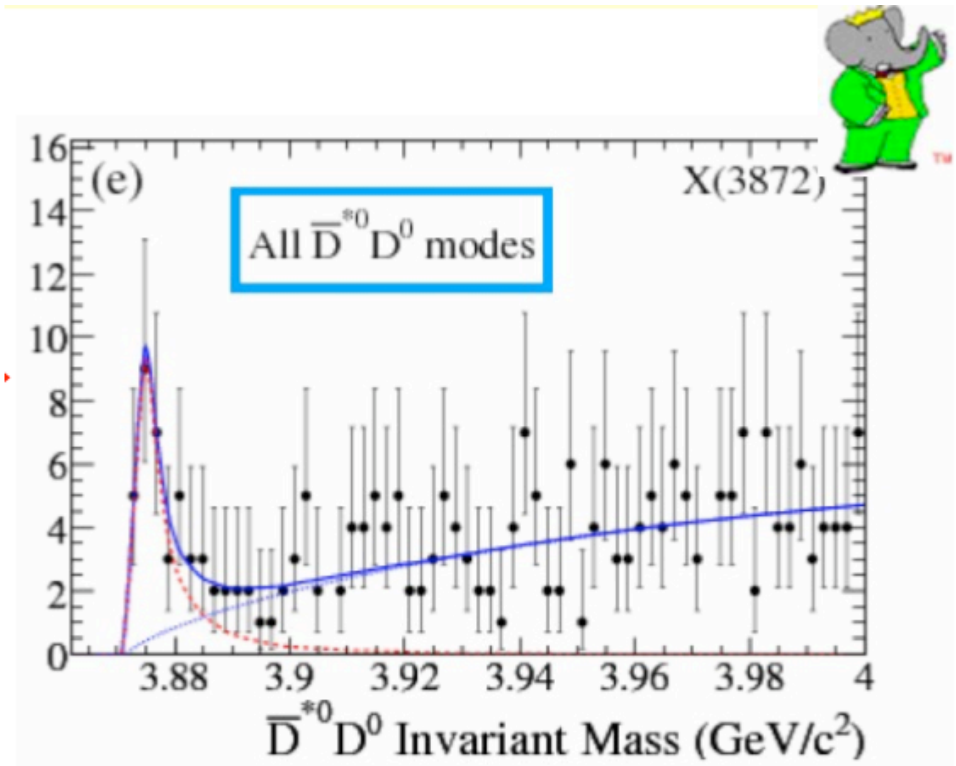
$$M(D^{*0}\bar{D}^0) = (3871 \pm 1) \Rightarrow$$

$X(3872)$: molecular $(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$ state (Close and Page PLB57(2004))

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



PRL97, 162002 (06)



PRD77, 011102 (08)

$$M_{belle} = 3875.2 \pm 0.7 \pm 0.8 \qquad M_{babar} = 3875.1 \pm 1.1 \pm 0.5$$

higher masses than $X \to J/\psi\pi\pi$

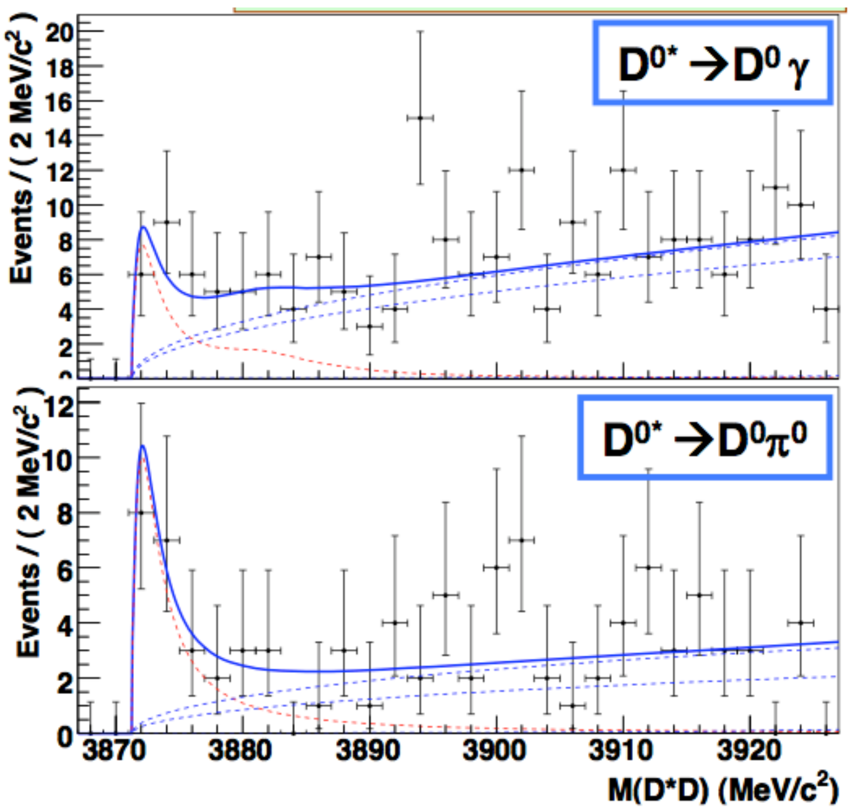
two particles? threshold effect?

Braaten (arXiv:0808.2948): combination
→ $X(3872)$ below threshold
→ threshold enhancement

two particles? threshold effect?

Braaten (arXiv:0808.2948): combination → $X(3872)$ below threshold / → threshold enhancement

New Belle Results $X(3872) \to D^0 D^{0*}$



simultaneous fit for both $D^{0*} \to D^0(\gamma, \pi^0)$:

$$M = 3872.6^{+0.5}_{-0.4} \pm 0.4$$

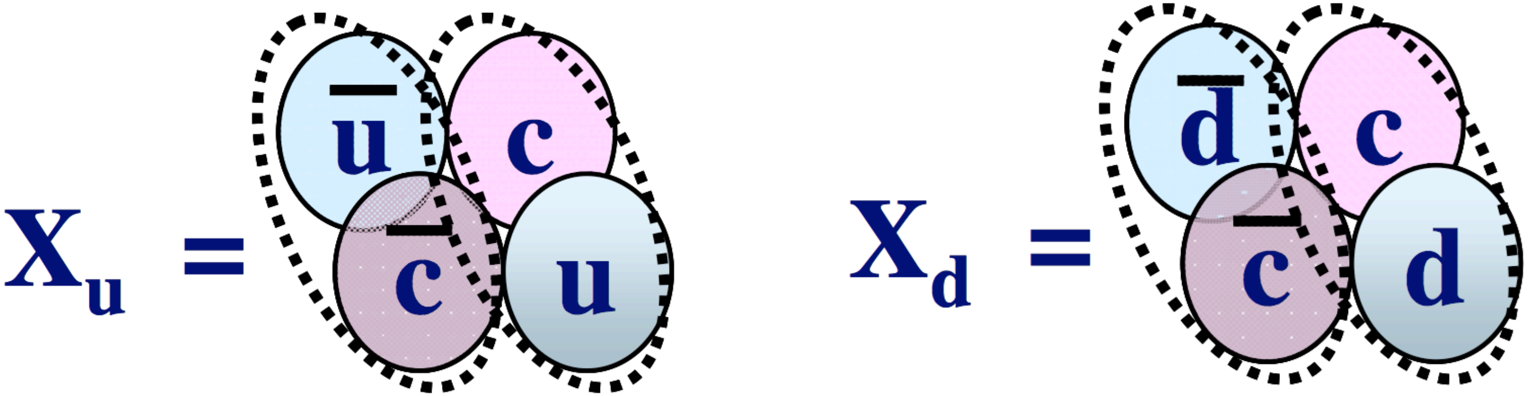
No mass shift!

arXiv:0810.0358

Tetraquark state?

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

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

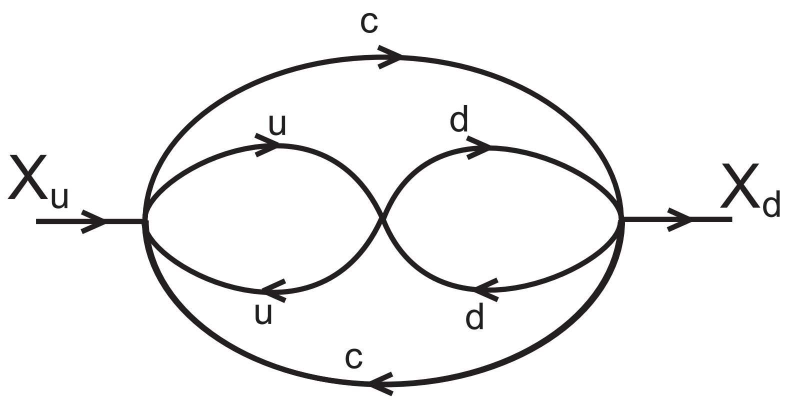


isospin eigenstates

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

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

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



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

$$\boldsymbol{X_l = X_u \cos\theta + X_d \sin\theta}$$

$$\boldsymbol{X_h = -X_u \sin\theta + X_d \cos\theta}$$

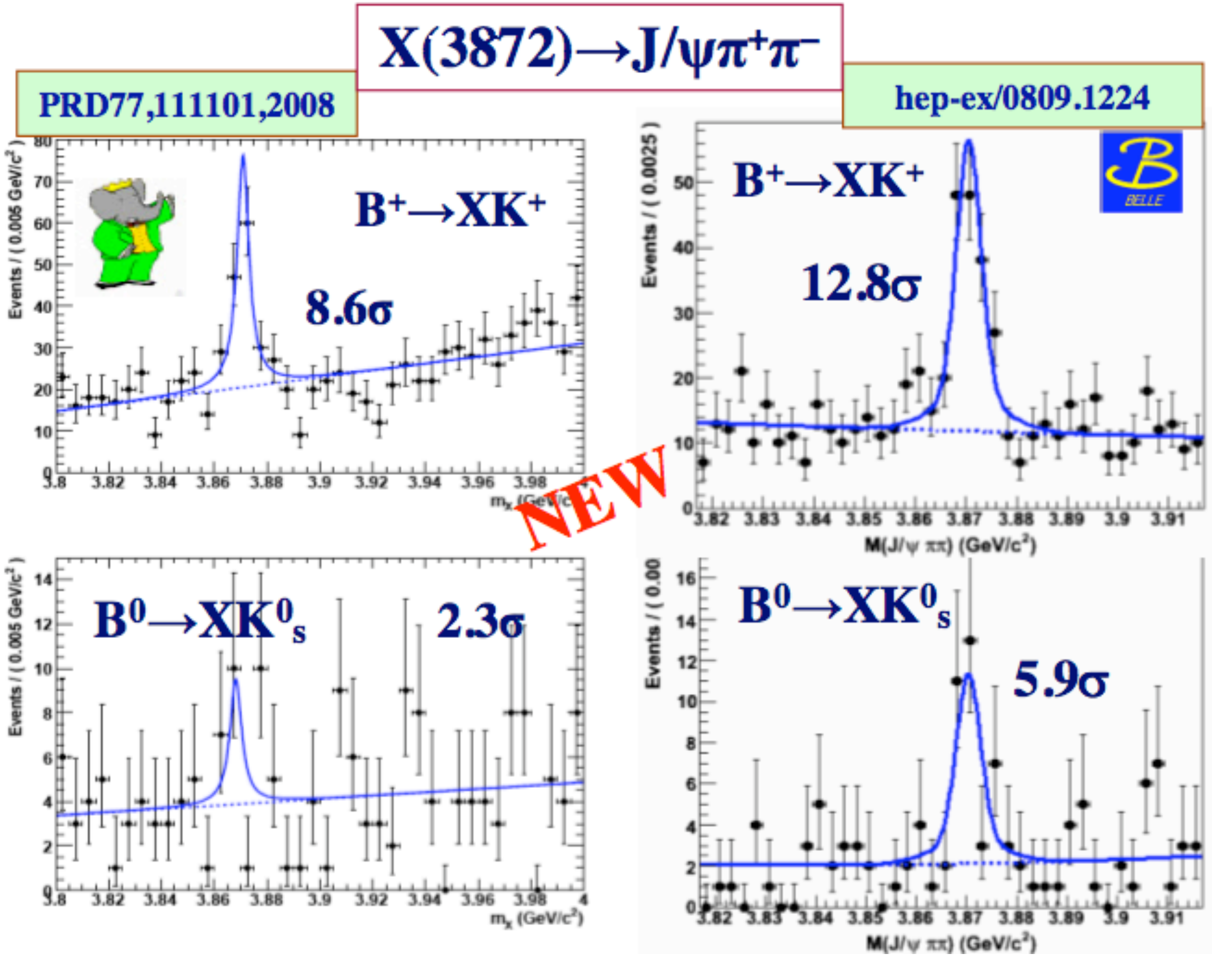
both can decay into $\boldsymbol{2\pi,\ 3\pi}$

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

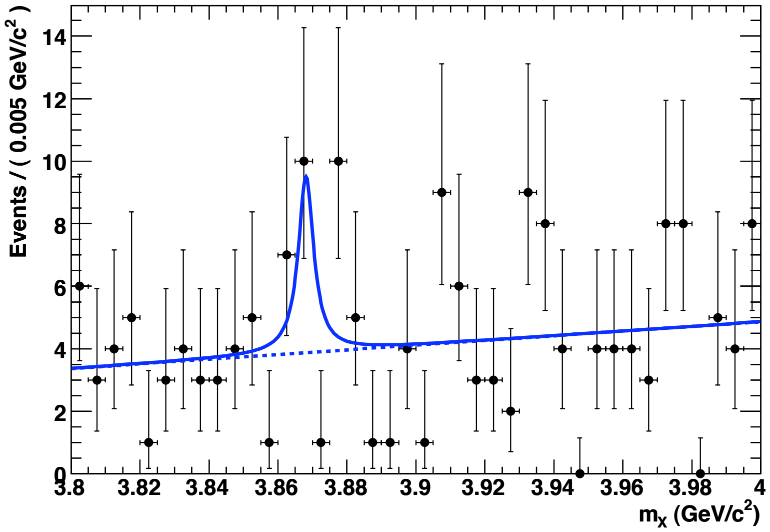
$$\boldsymbol{B^0 \to K^0 X}$$

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

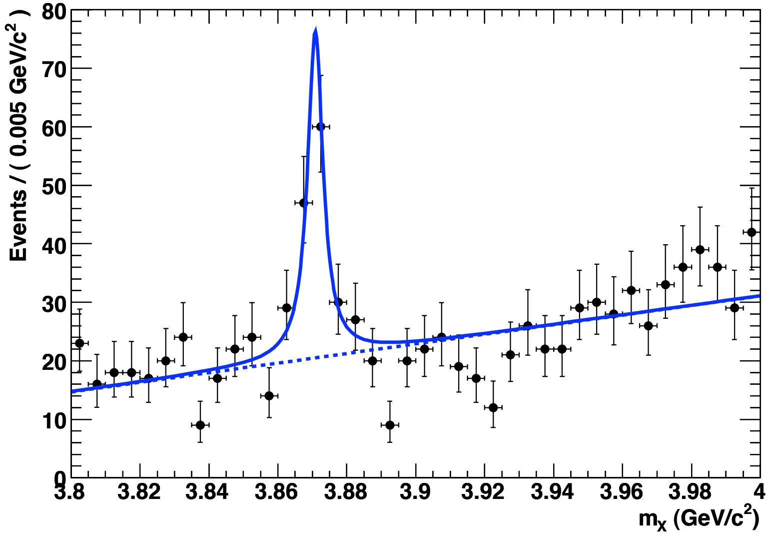
$$M(X_h) - M(X_l) \begin{cases} \nearrow (8 \pm 3) \text{ MeV (quark model)} \\ \searrow (2.6 \;-\; 3.9) \text{ MeV (QCD sum rule)} \end{cases}$$



BaBar Collaboration PRD77, 111101 (2008),



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



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

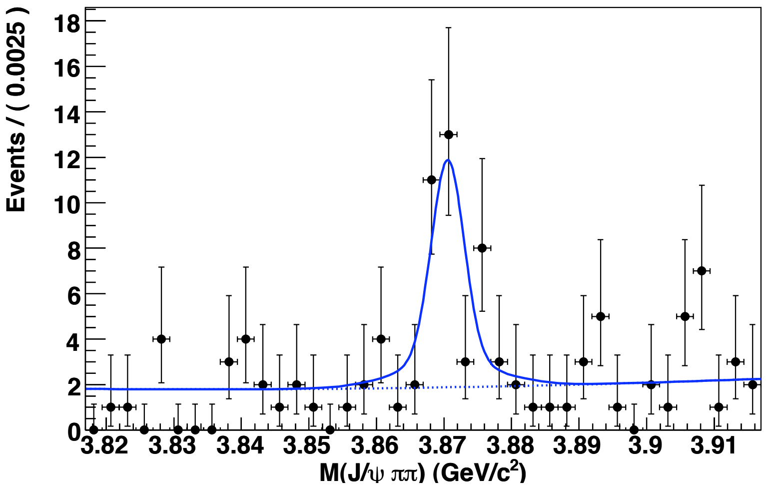
$$\frac{B^0 \to XK^0}{B^+ \to XK^+} = 0.41 \pm 0.24 \pm 0.05$$

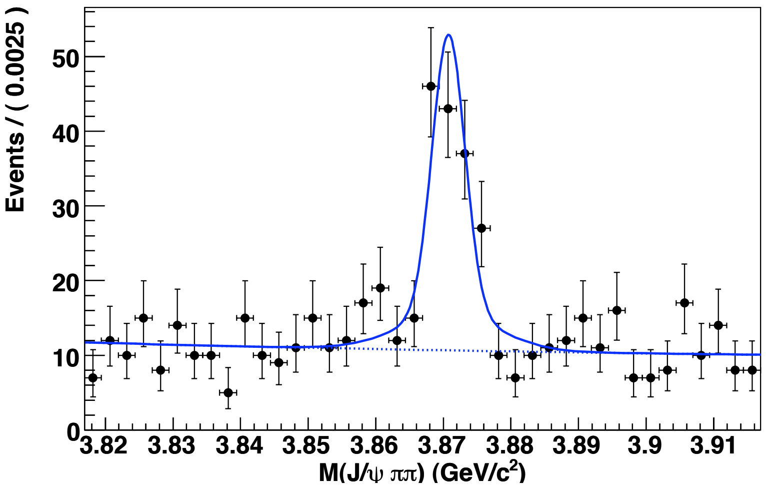
molecular model $\sim$ 0.1, tetraquark model $\sim$ 1

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

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

Belle Collaboration: arXiv/0809.1224,



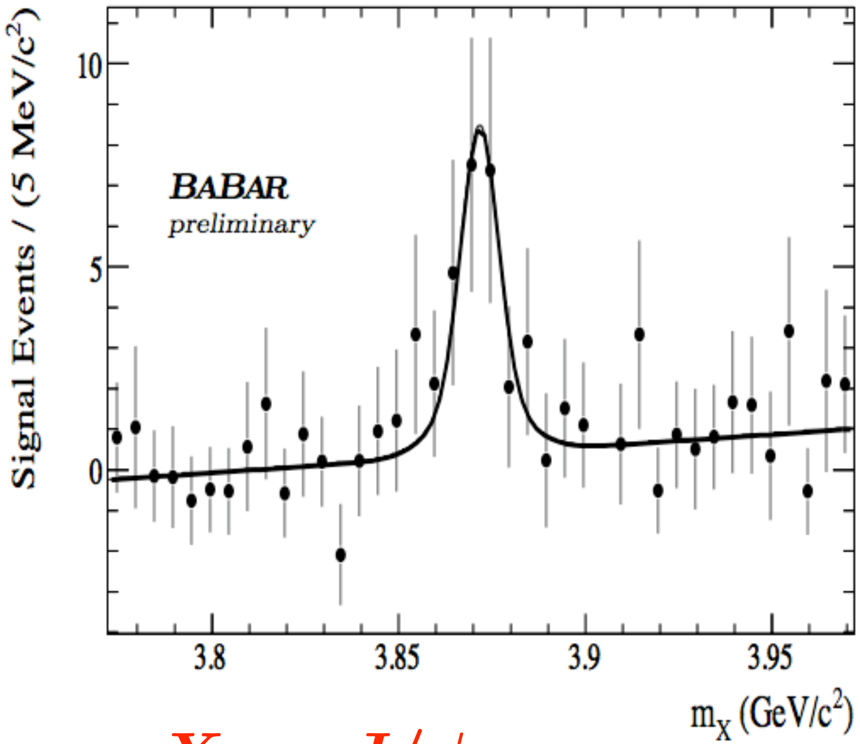


$B^0 \to XK^0$ $\qquad$ $B^+ \to XK^+$

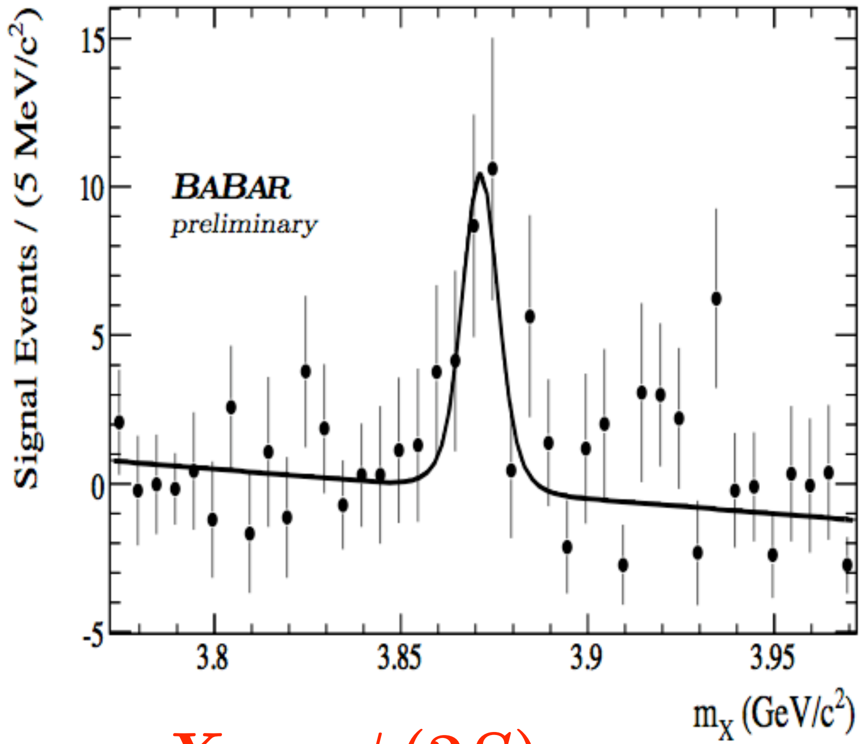
$$\frac{B^0 \to XK^0}{B^+ \to XK^+} = 0.82 \pm 0.22 \pm 0.05$$

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

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



$X \to J/\psi\gamma$



$X \to \psi(2S)\gamma$

$$\frac{X \to J/\psi\gamma}{X \to \psi(2S)\gamma} \sim 0.283 \Rightarrow$$ contradicts theoretical expectation

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

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

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

condensates up to dimension 8 {
- quark condensate
- gluon condensate
- mixed condensates
- four-quark condensate

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

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

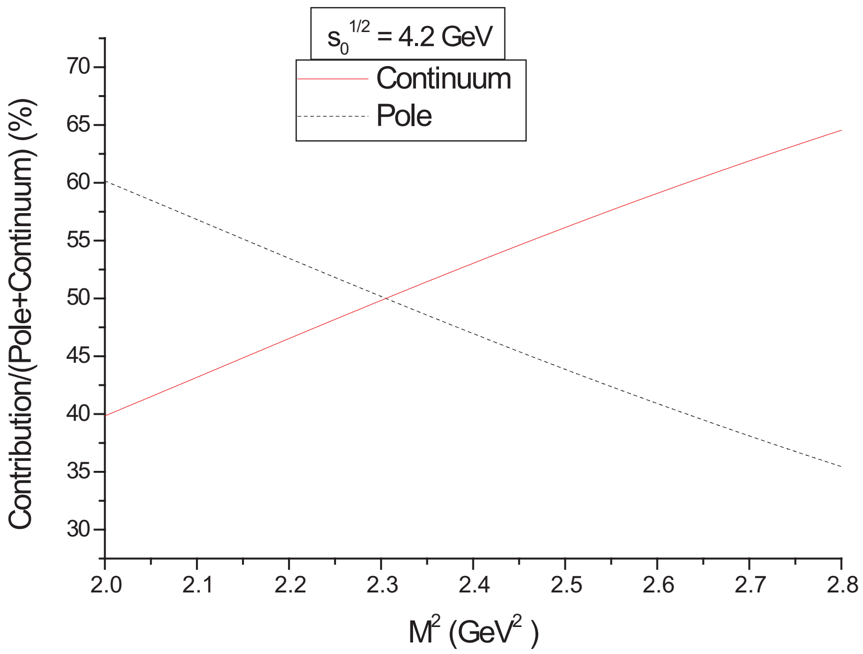
$$\lambda^2 e^{-m_S^2/M^2} = \int_{m_c^2}^{s_0} ds \, \rho^{OPE}(s) \, e^{-s/M^2}$$

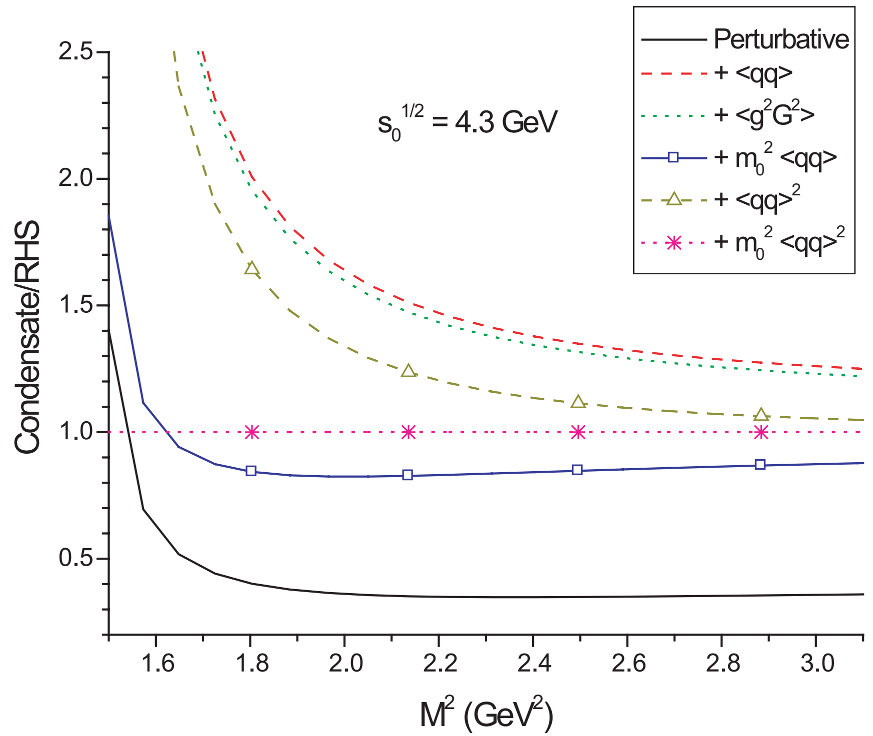
good Sum Rule $\Rightarrow$ Borel window such that:

- pole contribution > continuum contribution
- converging OPE

QCD sum rules calculation for $X(3872)$

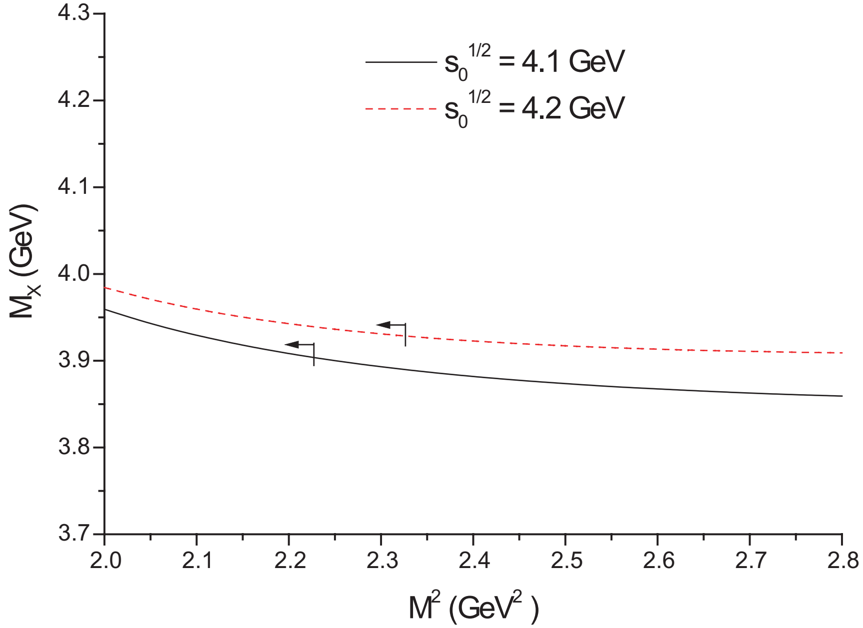
$$j_\mu^X = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\left[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T)+(q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)\right]$$





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

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



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

good agreement $X(3872)$

molecular state (arXiv:0803.1168)

$$j^X = D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0$$

better OPE convergence, bigger Borel window

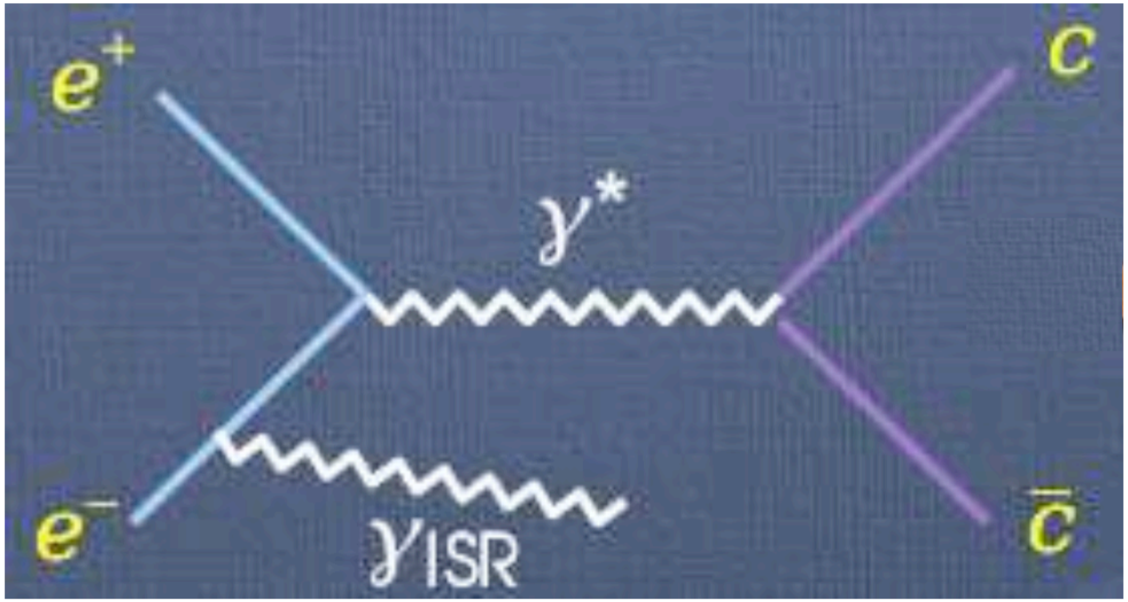
$$m_X = (3.87 \pm 0.07)\ \text{GeV}$$

Better agreement with the molecular model

$e^+e^- \rightarrow 1^{--}$ Final States

via Initial State Radiation (ISR)

$$e^+e^- \rightarrow \gamma_{IRS}(c\bar{c})$$

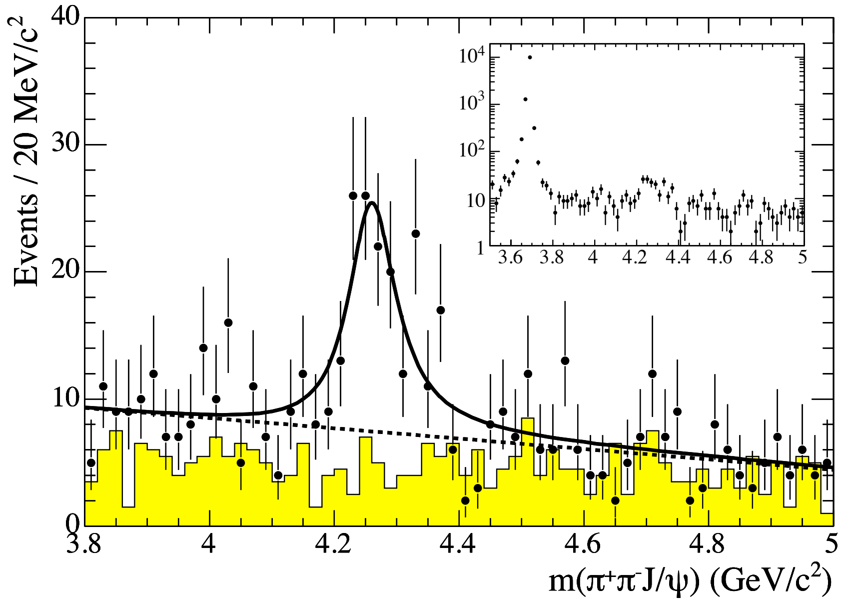


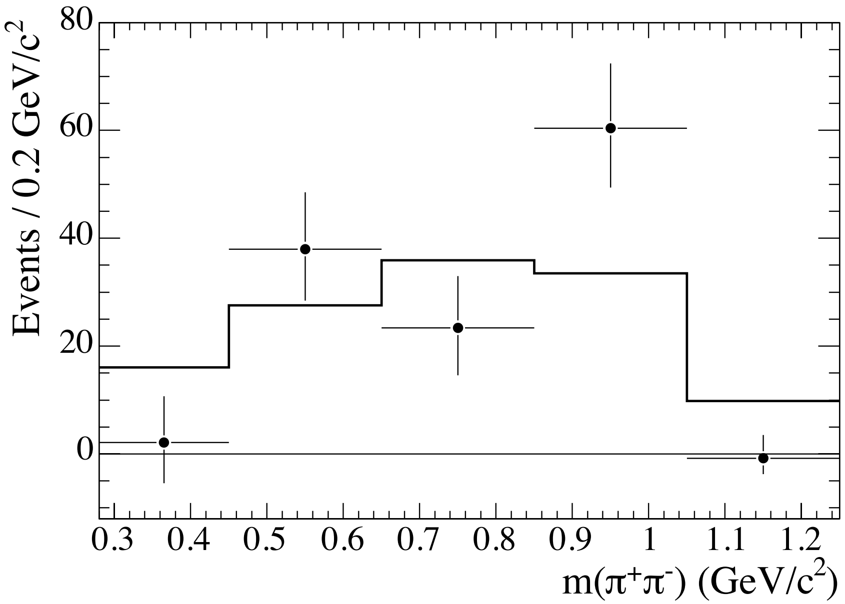
$Y(J^{PC} = 1^{--})$ family

$Y(4260)$: BaBar @ SLAC: (PRL91 (2005))

distinct peak ($\Gamma \sim 90$ MeV) observed in e^+e^- annihilation:

$$e^+e^- \to \gamma_{IRS}(J/\psi\pi^+\pi^-)$$

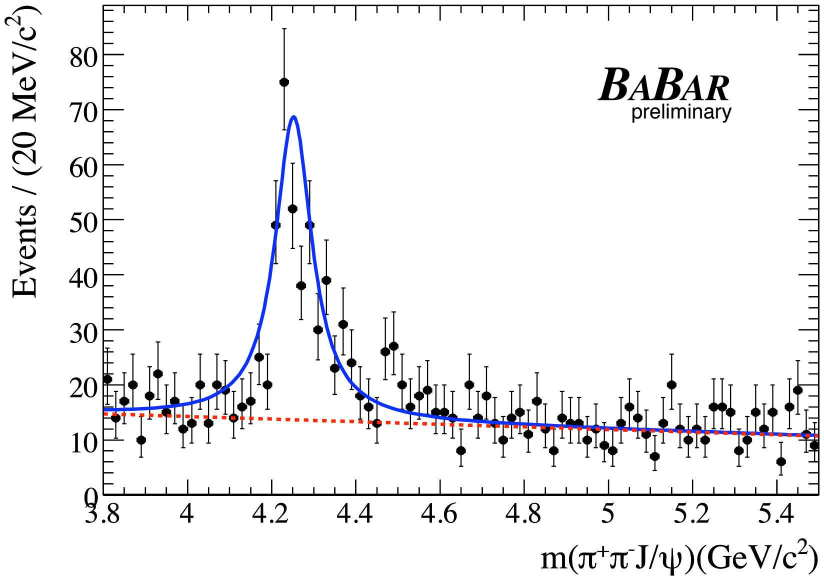


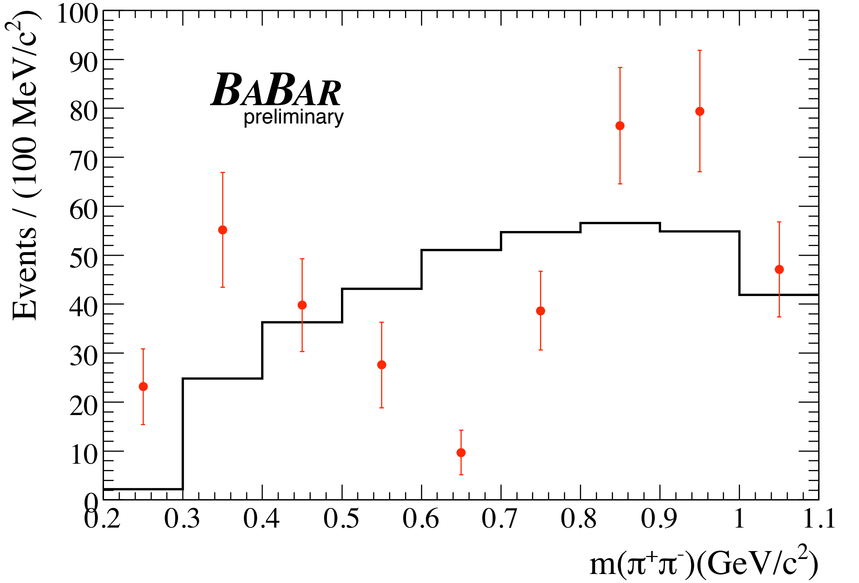


confirmed CLEO and Belle

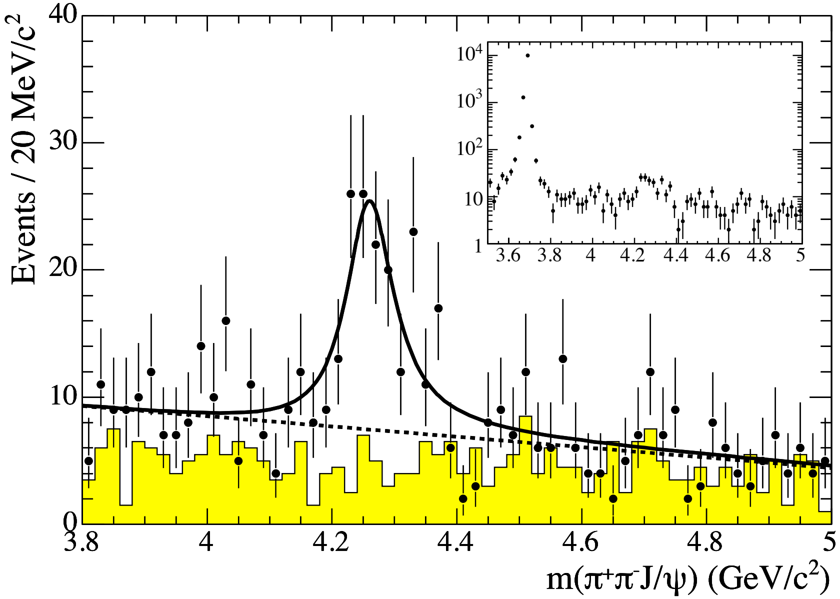
$\pi^+\pi^-$ distribution mass "consistent" with $f_0(980)$

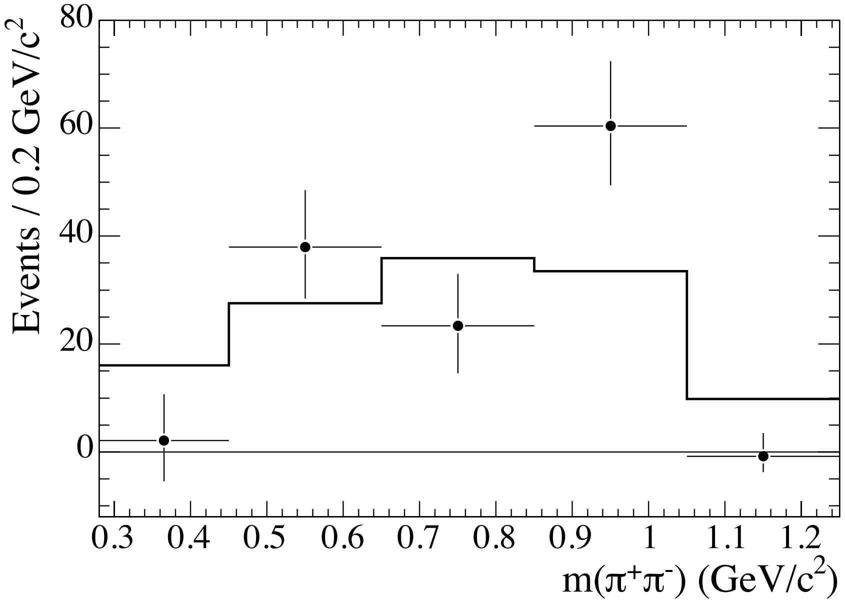
BaBar Collaboration arXiv:0808.1543



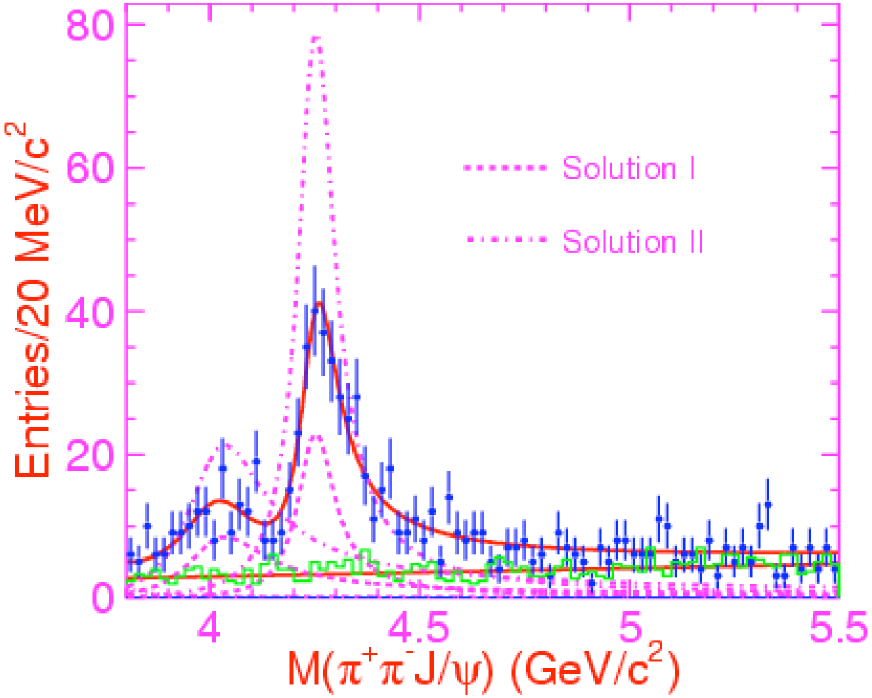


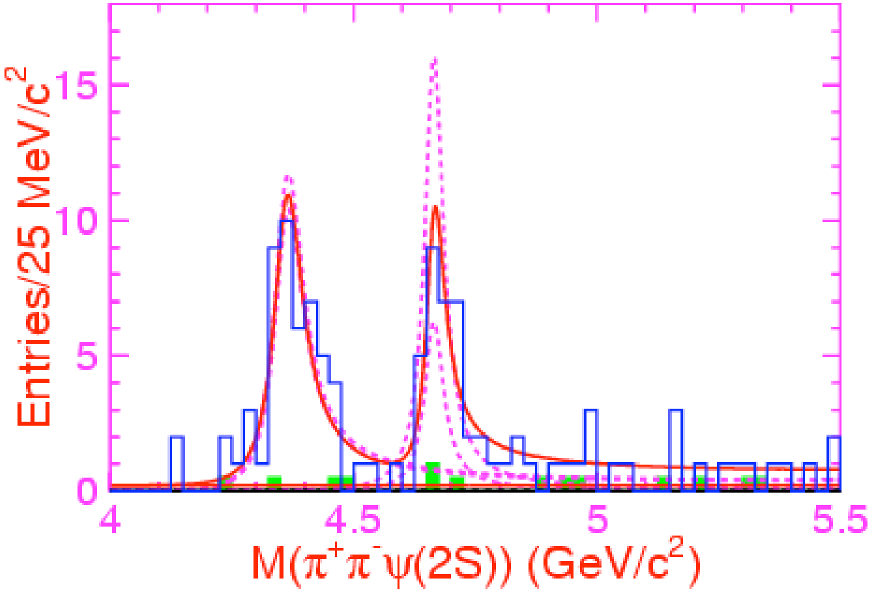
$$M = (4252 \pm 7)\ \text{MeV}, \quad \Gamma = (105 \pm 20)\ \text{MeV}$$

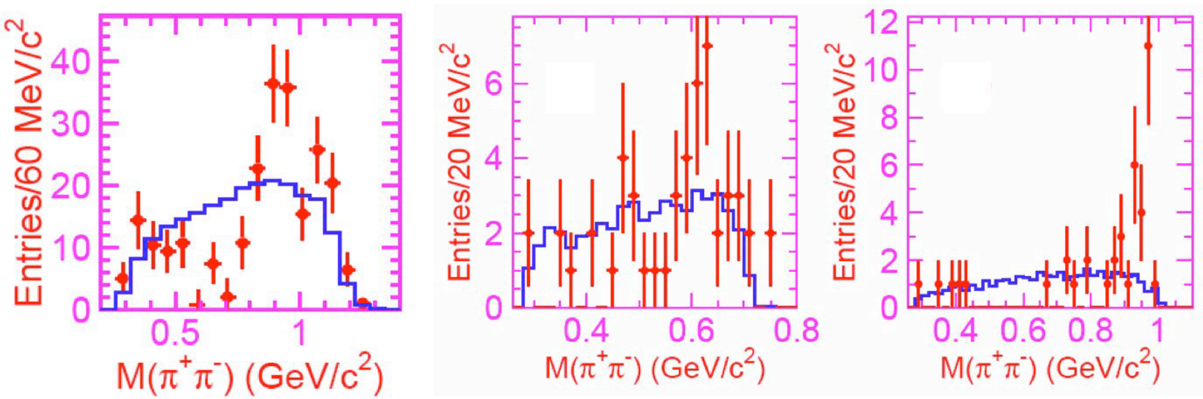




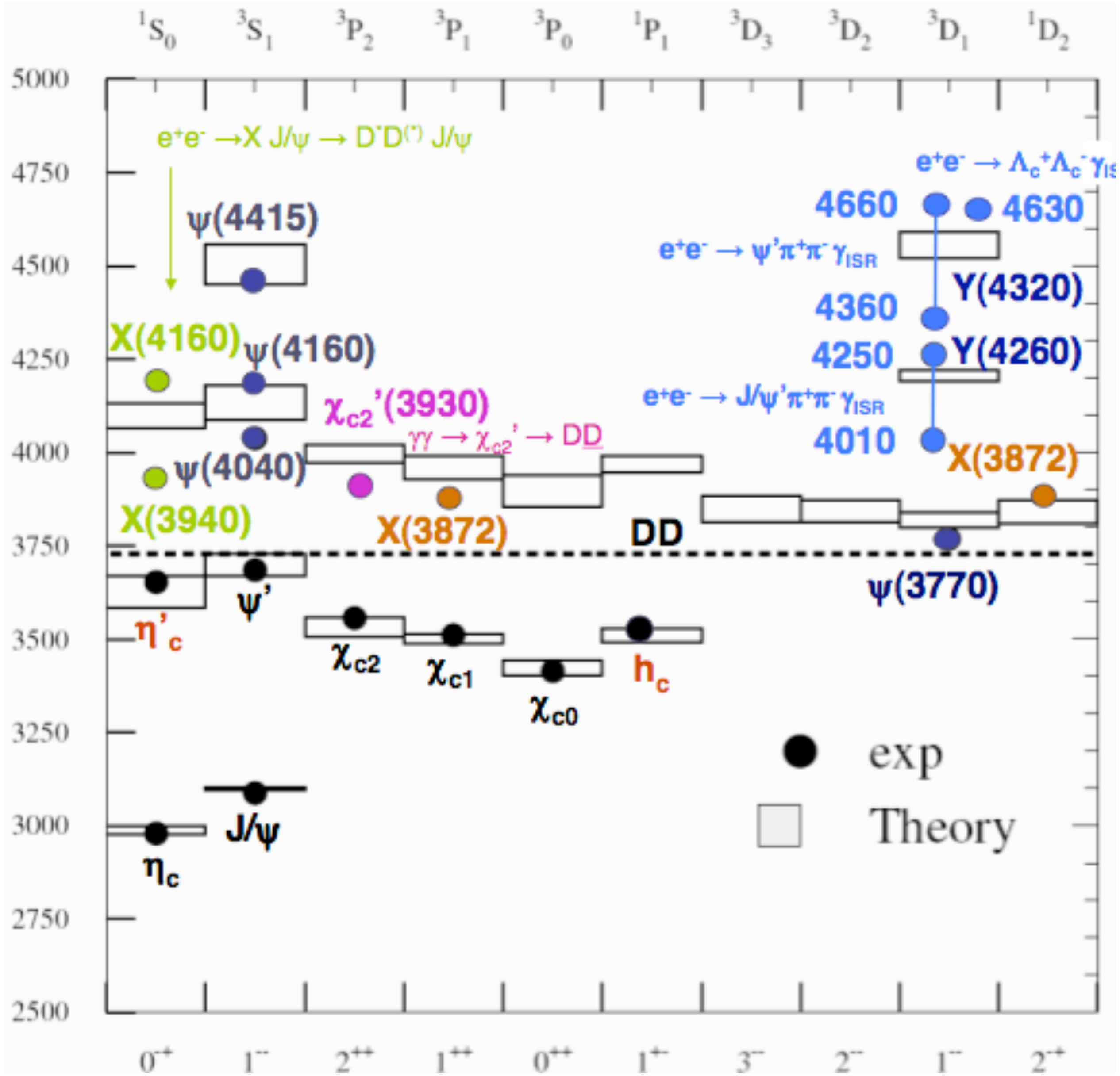
Belle Collaboration arXiv:0707.3699







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



J^{PC}

Charmonium Spectroscopy after the B-factories

Exotic states?

charmonium hybrids:
- Lattice (PRL82(99)): $M \sim 4200$ MeV
- flux tube (Barnes et al. (PRD52(95)) $M \sim 4200$ MeV

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

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

They arrive at $M_Y = 4160$ MeV$+$ orbital term = (4330 ± 70) MeV

Other Possibilities

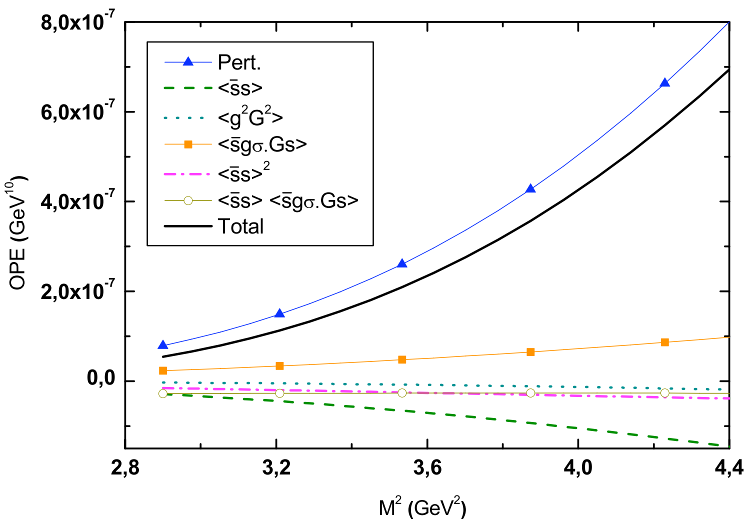
$$Y = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=1} + [cs]_{S=1}[\bar{c}\bar{s}]_{S=0}) \text{ or } s \leftrightarrow q$$

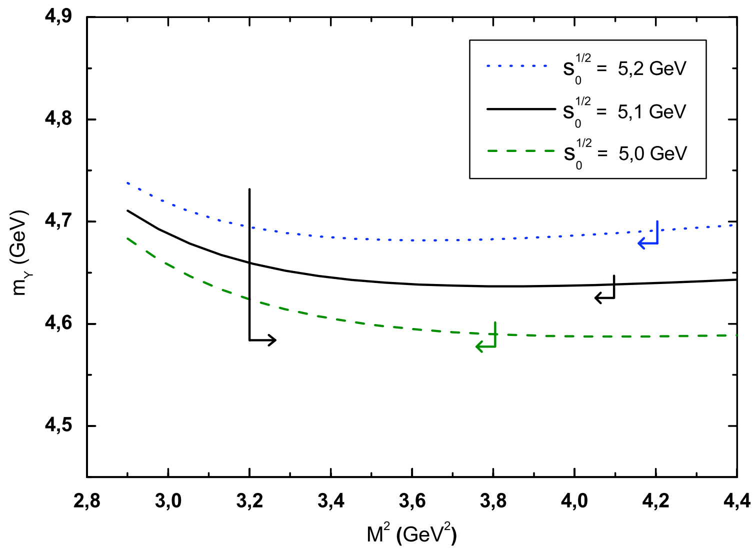
molecule
$$\begin{cases} D_s^*(2110)\bar{D}_{s0}(2317)\ (m_{thres} \sim 4430\ \text{MeV}) \\ D^*(2007)\bar{D}_0(2310)\ (m_{thres} \sim 4320\ \text{MeV}) \\ D(1865)\bar{D}_1(2420)\ (m_{thres} \sim 4285\ \text{MeV}) \end{cases}$$

QCD sum rules calculation for $Y(J^{PC} = 1^{--})$

tetraquark state (arXiv:0804.4817)

$$j^Y = [cs]_{S=1}[\bar{c}\bar{s}]_{S=0} + [cs]_{S=0}[\bar{c}\bar{s}]_{S=1}$$



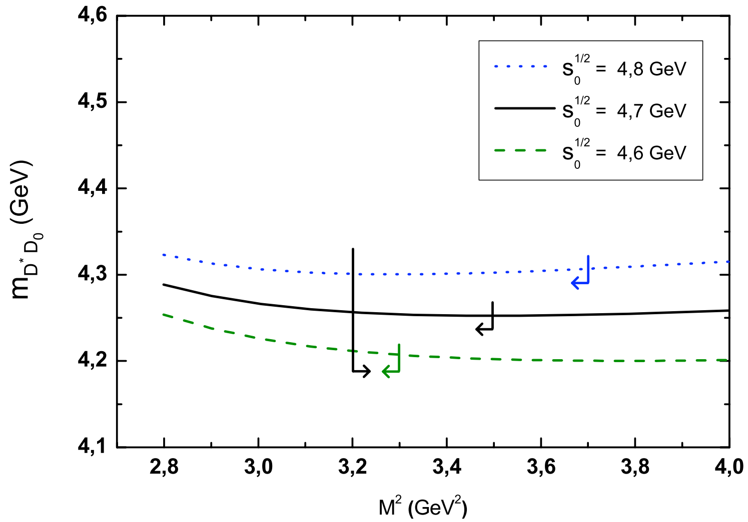


good OPE convergence for $M^2 \geq 3.2\,\text{GeV}^2$

$m_Y = (4.65 \pm 0.10)$ GeV in good agreement with $Y(4660)$

molecular state (arXiv:0804.4817)

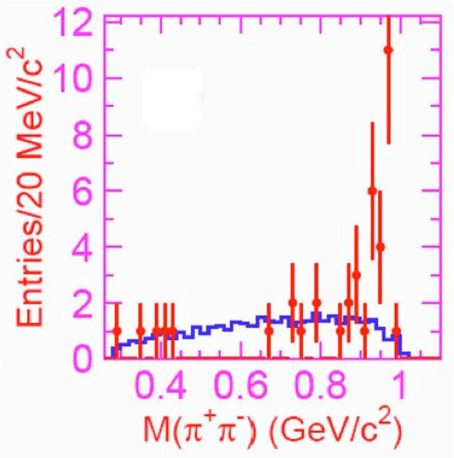
$$j^Y = D_0\bar{D}^* + \bar{D}_0 D^*$$



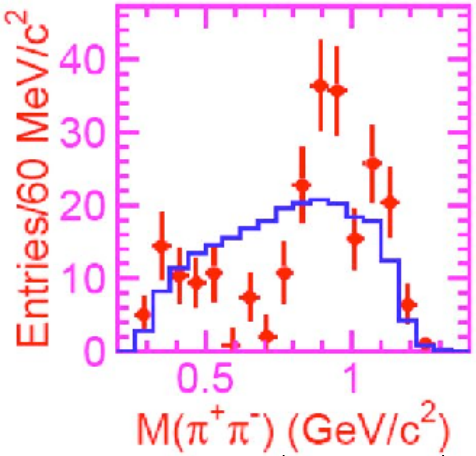
similar OPE convergence

$m_Y = (4.27 \pm 0.10)$ GeV

good agreement $Y(4260)$



$Y(4660)$



$Y(4260)$

$Z^+(4430)$

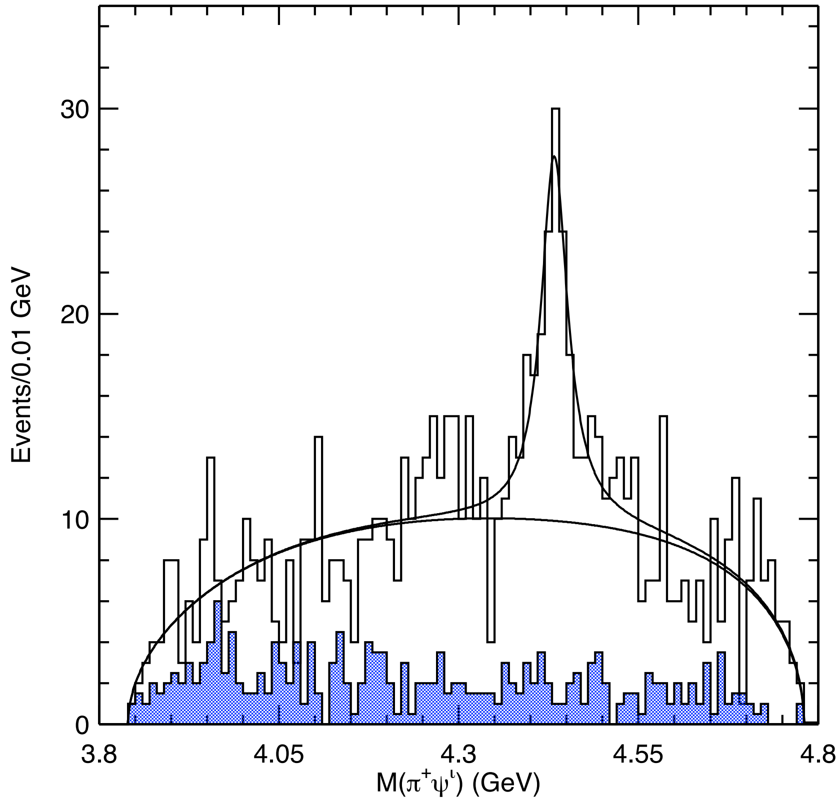
Belle @ KEK: (arXiv:0708.1790)

distinct peak observed in the decay mode:

$$\bar{B}^0 \rightarrow K^-(\psi'\pi^+)$$

$Q = + \Rightarrow$ minimum quark content: $\boxed{c\bar{c}u\bar{d}}$

$$M = (4433 \pm 14)\text{ MeV}$$
$$\Gamma = (44 \pm 17)\text{ MeV}$$
$$J^P = ??$$

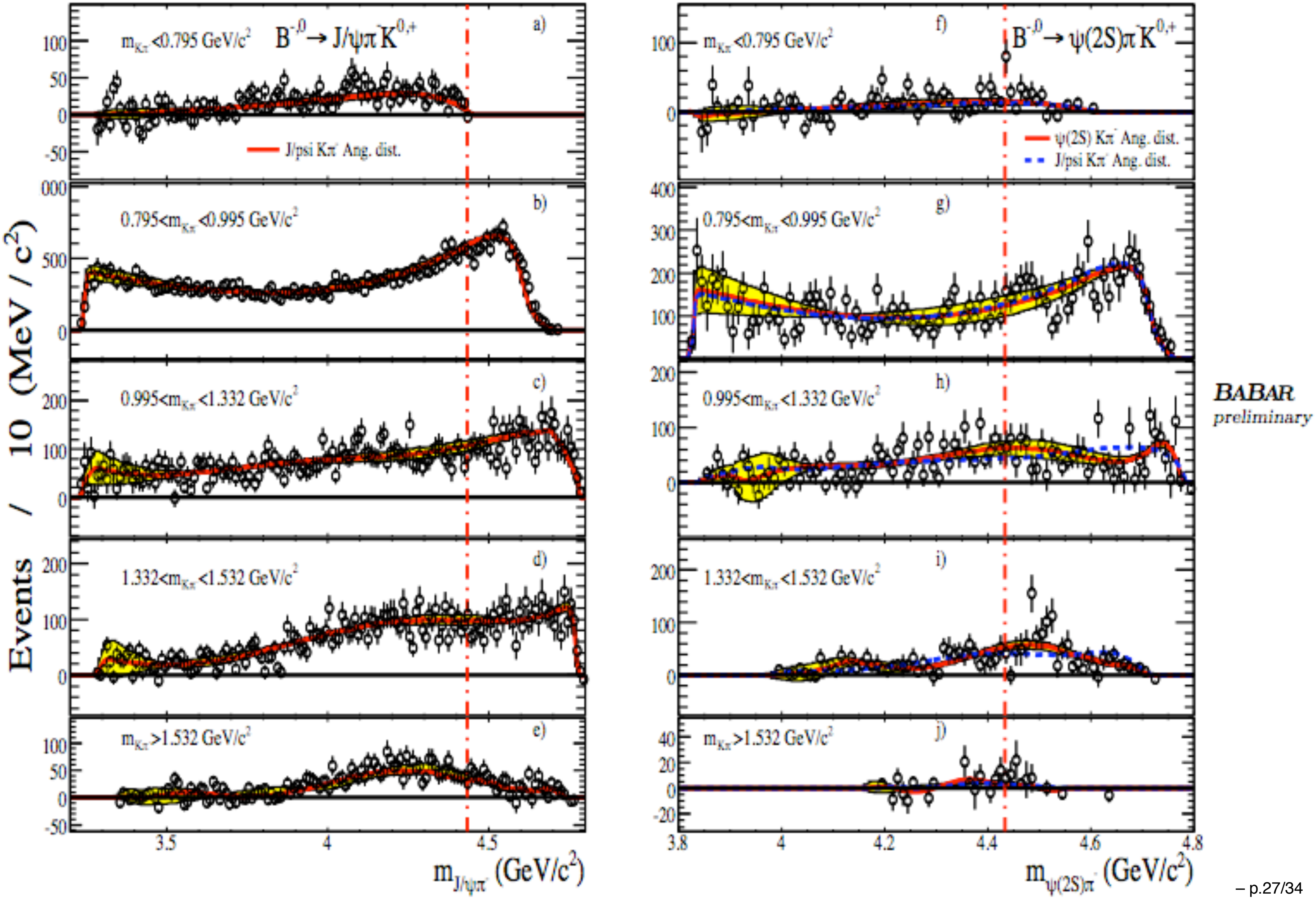


$$Z^+(4430) \rightarrow \psi'\pi^+ \Rightarrow I^G = 1^+$$

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

New results from BaBar (arXiv:0810.1073)

$$B^- \to Z^- K^0 \to \psi(\psi')\pi^- K^0$$



$Z^+(4430)$ $\left\{\right.$

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

QCD sum rules calculation for $Z^+(4430)$

tetraquark states with $J^P = 0^-,\ 1^-$ (arXiv:0807.3275)

$$j_Z(1^-) = [cu]_{S=1}[\bar{c}\bar{d}]_{S=0} + [cu]_{S=0}[\bar{c}\bar{d}]_{S=1}$$

$$m_Z = (4.84 \pm 0.14)\ \text{GeV}$$

$$j_Z(0^-) = [cu]_{S=0}[\bar{c}\bar{d}]_{S=0}$$

$$m_Z = (4.52 \pm 0.12)\ \text{GeV}$$

molecular state with $J^P = 0^-$ (PLB661(2008)28)

$$j_Z = D_1^0 D^{*+} + D_1^+ D^{*0}$$

$m_Z = (4.40 \pm 0.10)$ GeV in good agreement with $Z^+(4430)$

Better agreement with the molecular model

$Z_1^+(4050)$ and $Z_2^+(4250)$

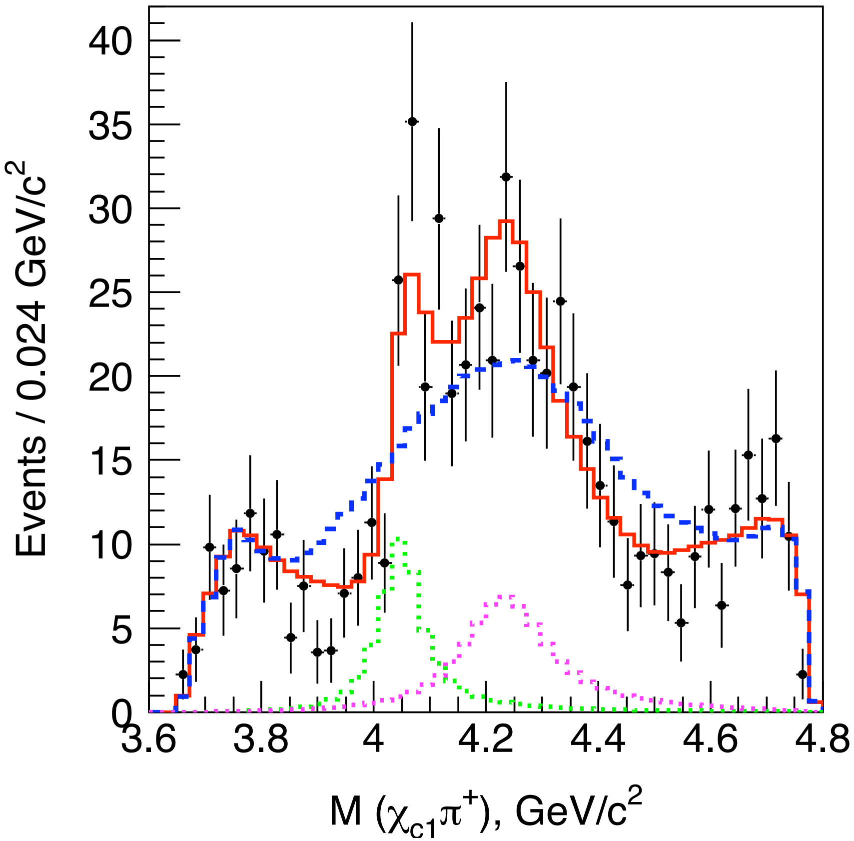
Belle @ KEK: (arXiv:0806.4098)

observation of two resonance-like structures:

$$\bar{B}^0 \to K^-(\chi_{c1}\pi^+)$$

$$M_1 = (4051 \pm 14)\ \text{MeV}$$
$$\Gamma_1 = (82 \pm 21)\ \text{MeV}$$

$$M_2 = (4248 \pm 44)\ \text{MeV}$$
$$\Gamma_2 = (177 \pm 54)\ \text{MeV}$$



$$Z_{1,2}^+ \to \chi_{c1}\pi^+ \Rightarrow I^G = 1^-$$

If confirmed $\Rightarrow$ multiquark states!

$M(\bar{D}_1^0 D^+) \sim 4200$ MeV, $M(\bar{D}^{*0} D^{*+}) \sim 4020$ MeV

$Z_2^+(4250)$ $Z_1^+(4050)$

Liu et al. (arXiv:0808.0073) → strong atraction in $D^*\bar{D}^*$

→ $Z_1^+(4050) \Rightarrow D^*\bar{D}^*$ state, $J^P = 0^+$

$M(\bar{D}_1^0 D^+) \sim 4200$ MeV, $M(\bar{D}^{*0} D^{*+}) \sim 4020$ MeV

$Z_2^+(4250)$ $Z_1^+(4050)$

Liu et al. (arXiv:0808.0073)
→ strong atraction in $D^* \bar{D}^*$
→ $Z_1^+(4050) \Rightarrow D^* \bar{D}^*$ state, $J^P = 0^+$

QCD sum rule (arXiv:0808.0690)

$D^* \bar{D}^*$ molecule with $J^P = 0^+$

$M_{D^* D^*} = (4.15 \pm 0.07)$ GeV $> (D^* \bar{D}^*)_{thre}$

$\bar{D}_1 D$ molecule with $J^P = 1^-$

$M_{D_1 D} = (4.12 \pm 0.10)$ GeV $< (\bar{D}_1 D)_{thre}$

$Z_2^+(4250)$: molecular $D^+ \bar{D}_1^0$ state with $J^P = 1^-$

Other Multiquark states

$X(3872)$, $Y(4260)$, $Y(4660)$, $Z^+(4430)$ molecules $\Rightarrow$
many other molecules should exist!

$\mathrm{B}^+ \rightarrow \pi^+(\mathrm{J}/\psi\pi^-\mathrm{K}^+)$ $\begin{cases} \text{similar to } B^+ \rightarrow K^+(J/\psi\pi^+\pi^-) \\ (J/\psi\pi^-K^+) \Rightarrow (D_s\bar{D}^*) \text{ molecule} \\ J^P = 1^+ \end{cases}$

QCD sum rule study $D_s\bar{D}^*$ molecule (arXiv:0803.1168)

$$m_{D_sD^*} = (3.97 \pm 0.08) \text{ MeV}$$

~ 100 MeV bigger than $X(3872)$ mass
very close to the $D_s\bar{D}^*$ threshold: ~ 3980 MeV

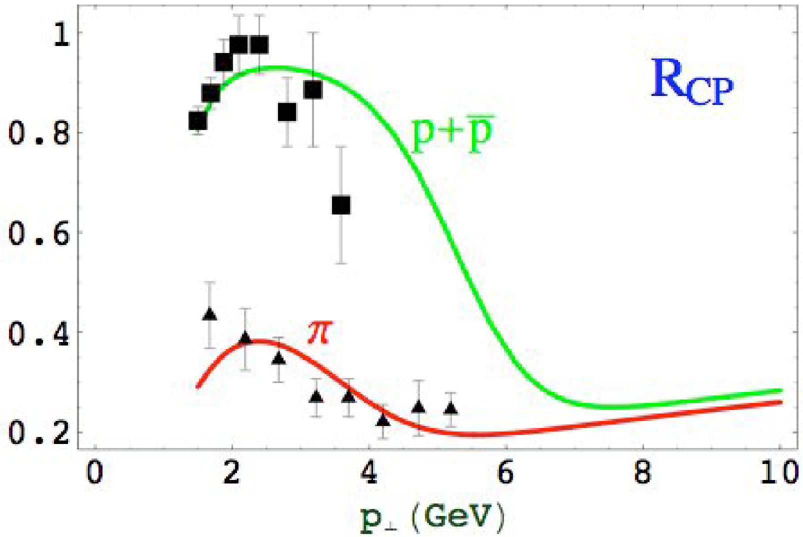
Conclusions

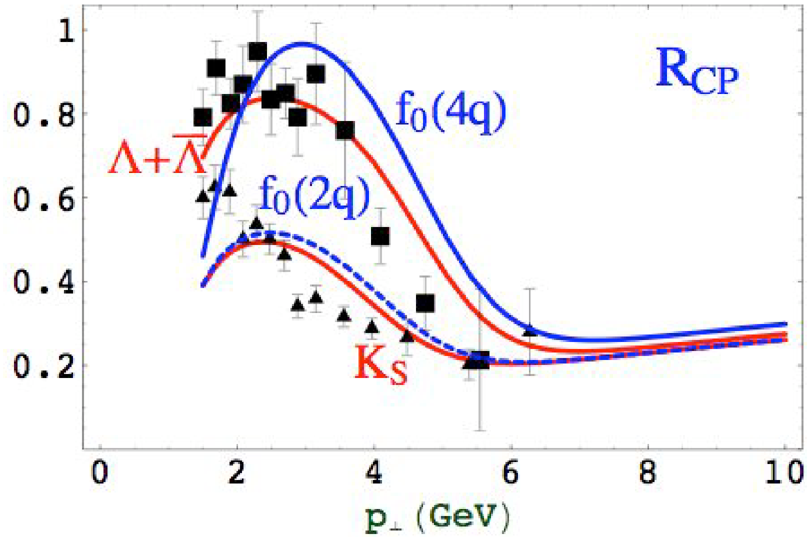
- Lots of new 'charmonia' in the last 5 years $\Rightarrow$ a new spectroscopy
- Emerging consensus that $X(3872)$ is a multiquark state
- Discovery of $Y(4260),\ Y(4360),\ Y(4660)$ represent overpopulation of the 1^{--} states
- Absence of open charm production in the Y decay is inconsistent with conventional $c\bar{c}$ explanation
- Possible to interpret $Y(4260)$ as a molecular $D_0\bar{D}^*$ state or $c\bar{c}$-hybrid
- Current situation of the 1^{--} states is unsettled
- If confirmed: $Z^+(4430) \rightarrow$ first genuine multiquark state
- QCD sum rules favor a molecular $D_1\bar{D}^*$ interpretation with $J^P = 0^-$

Counting quarks

Is there an experimental way to test the structure?

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





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