Theoretical Review on Exotics Charmonium

M. Nielsen
Universidade de São Paulo

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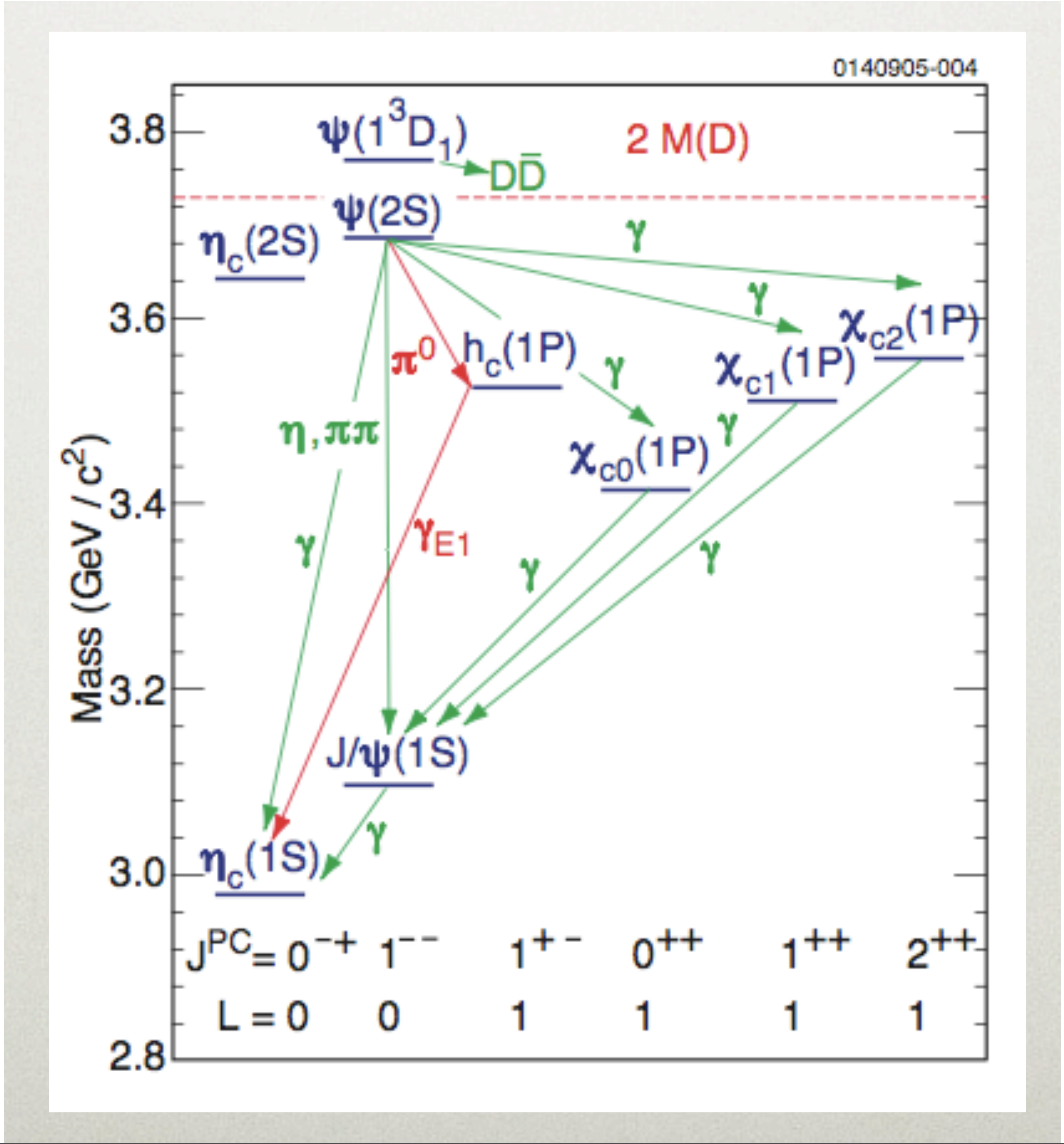
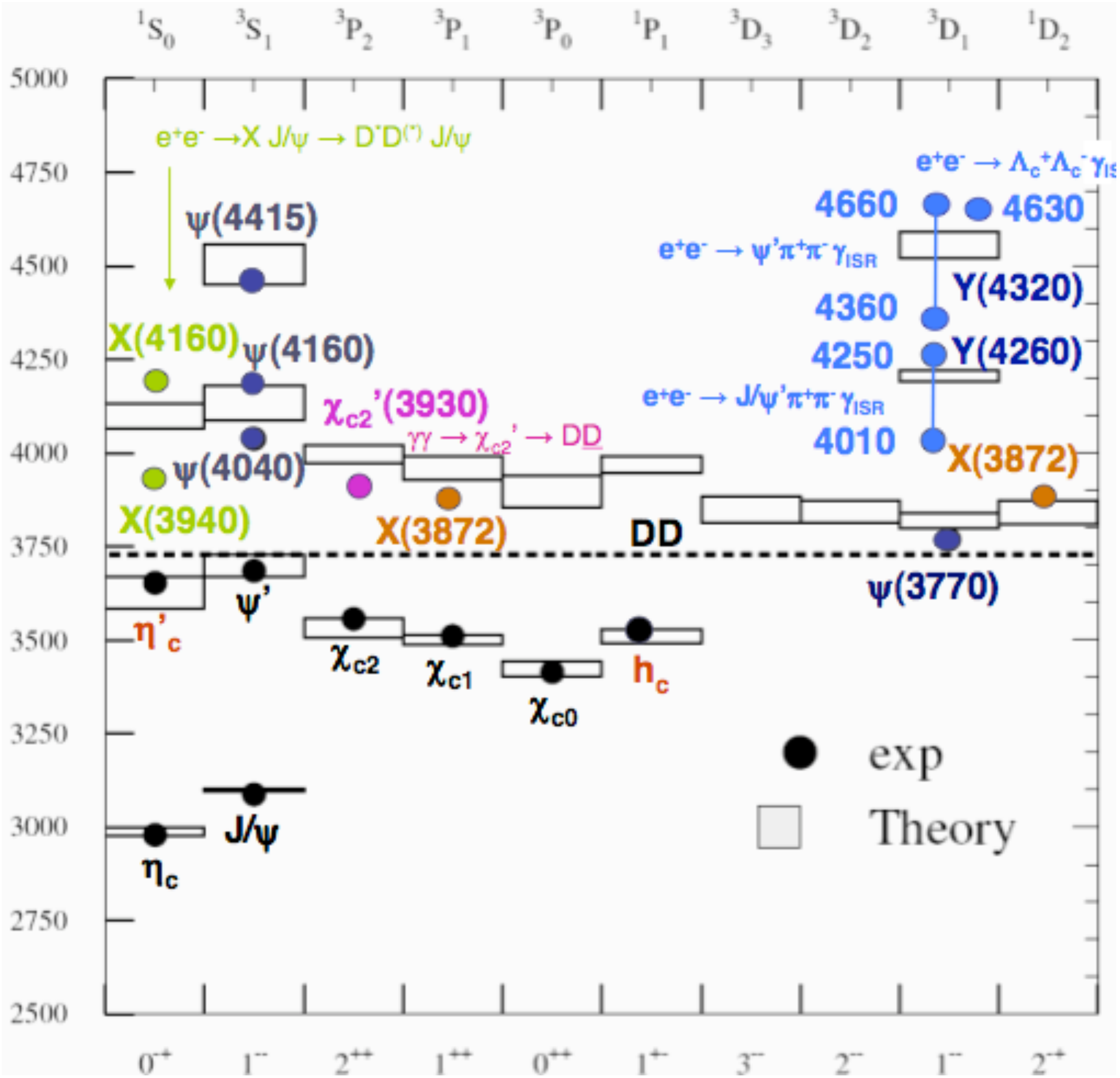
Charmonium spectroscopy before the B-factories



Charmonium spectroscopy after the B-factories

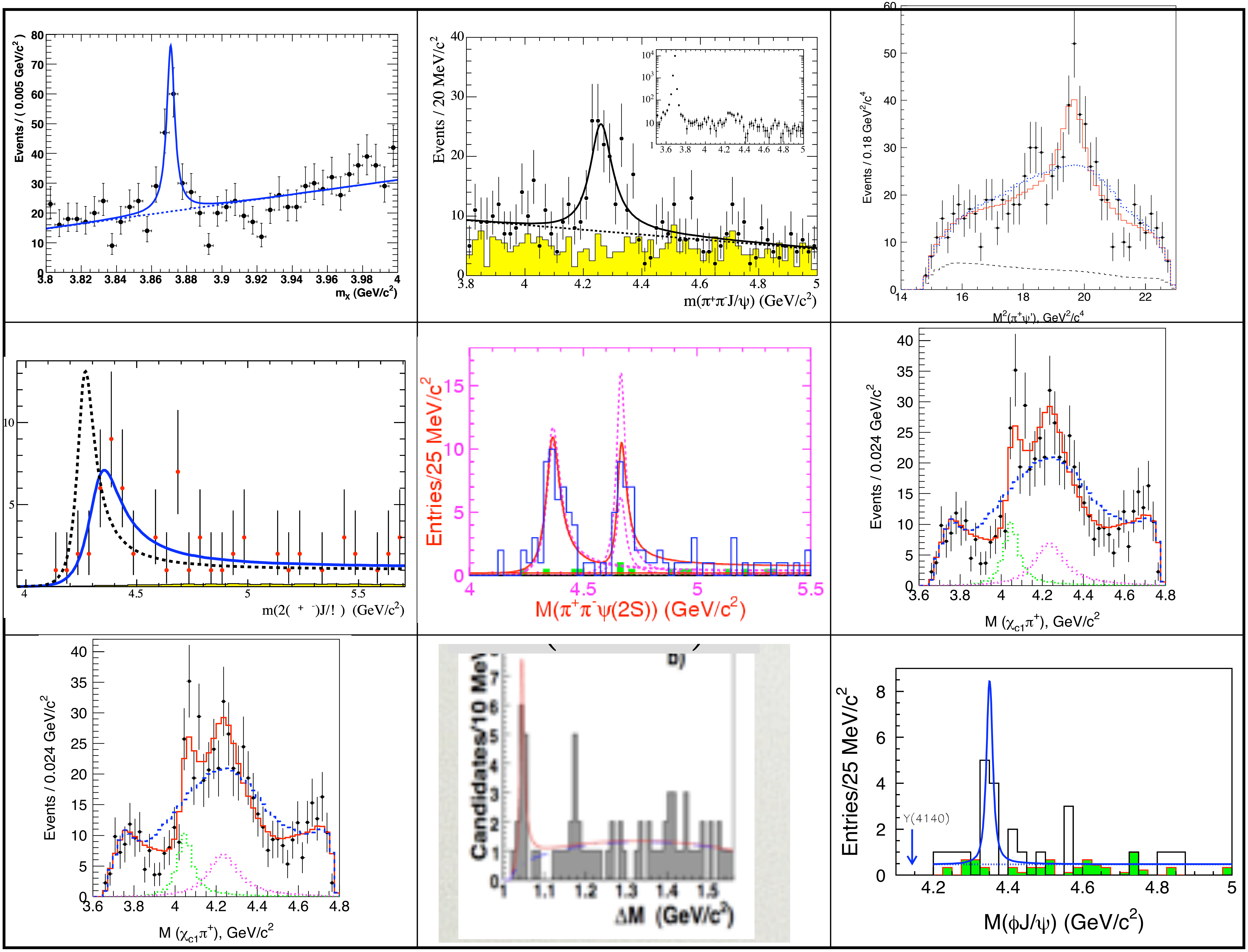


J^{PC}

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

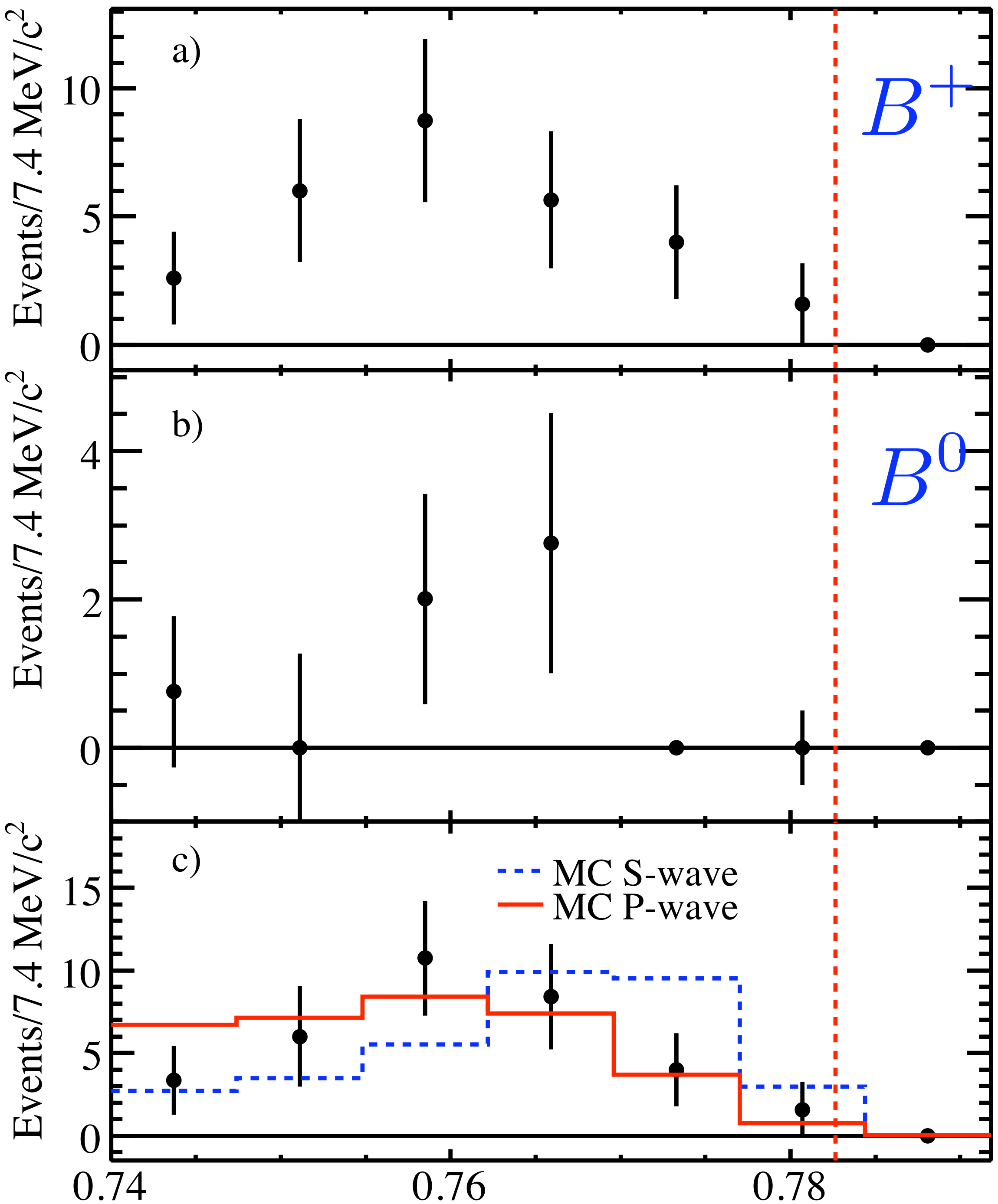


Events / (0.005 GeV/c^2)
m_X (GeV/c^2)
Events / 20 MeV/c^2
m($\pi^+\pi^-$J/ψ) (GeV/c^2)
Events / 0.18 GeV^2/c^4
M^2($\pi^+\psi'$), GeV^2/c^4
m(2(+ -)J/!) (GeV/c^2)
Entries/25 MeV/c^2
M($\pi^+\pi^-\psi$(2S)) (GeV/c^2)
Events / 0.024 GeV/c^2
M ($\chi_{c1}\pi^+$), GeV/c^2
Events / 0.024 GeV/c^2
M ($\chi_{c1}\pi^+$),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

BaBar Collaboration arXiv:1005.5190

$$B \to K\omega J/\psi \to KJ\psi\pi^0\pi^+\pi^-$$



the 3π mass distribution strongly favors P-wave ⇒ $J^{PC} = 2^{-+}$

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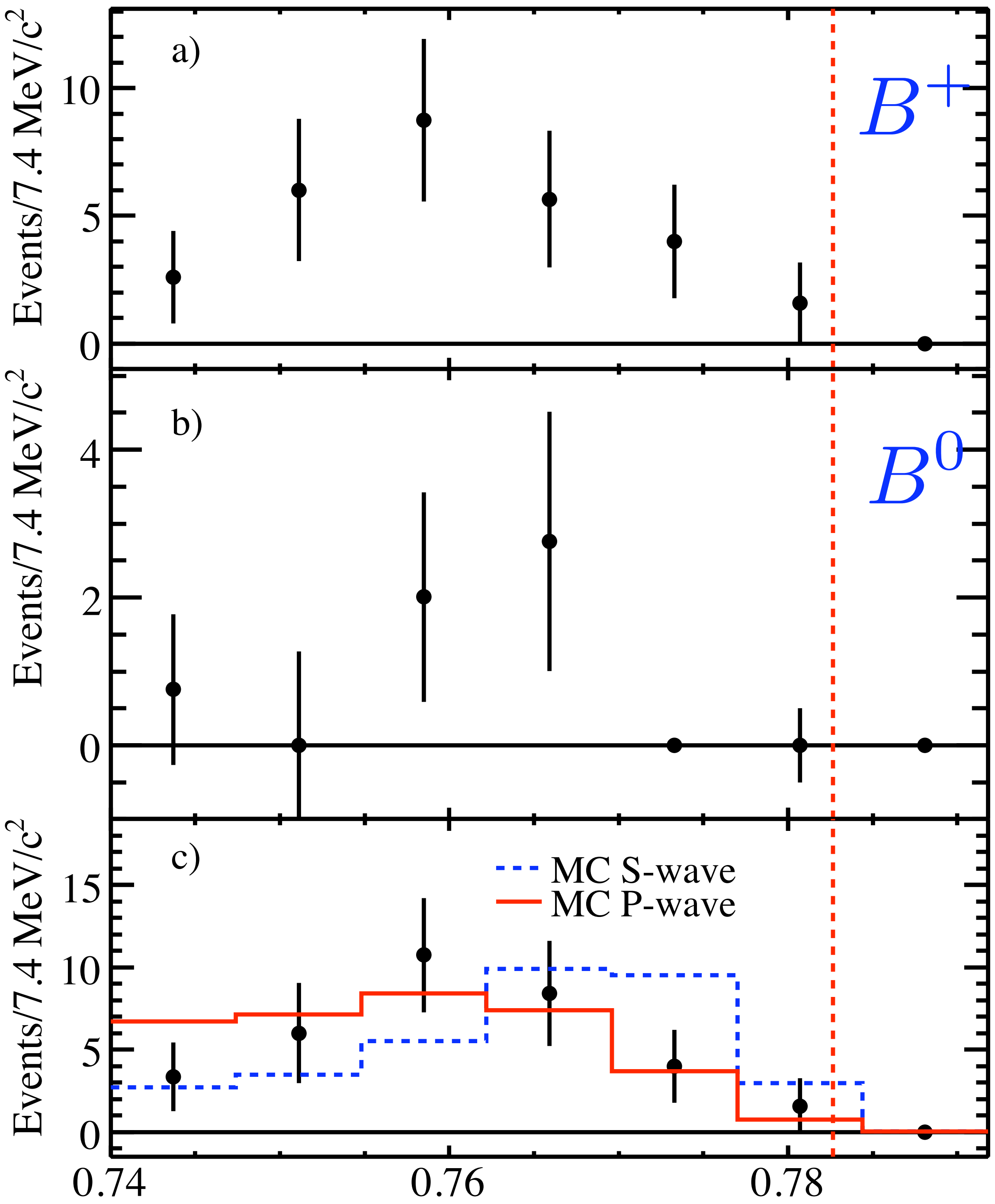

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Burns et al. (arXiv: 1008.0018): the production cross section at CDF is predicted to be much smaller than that observed

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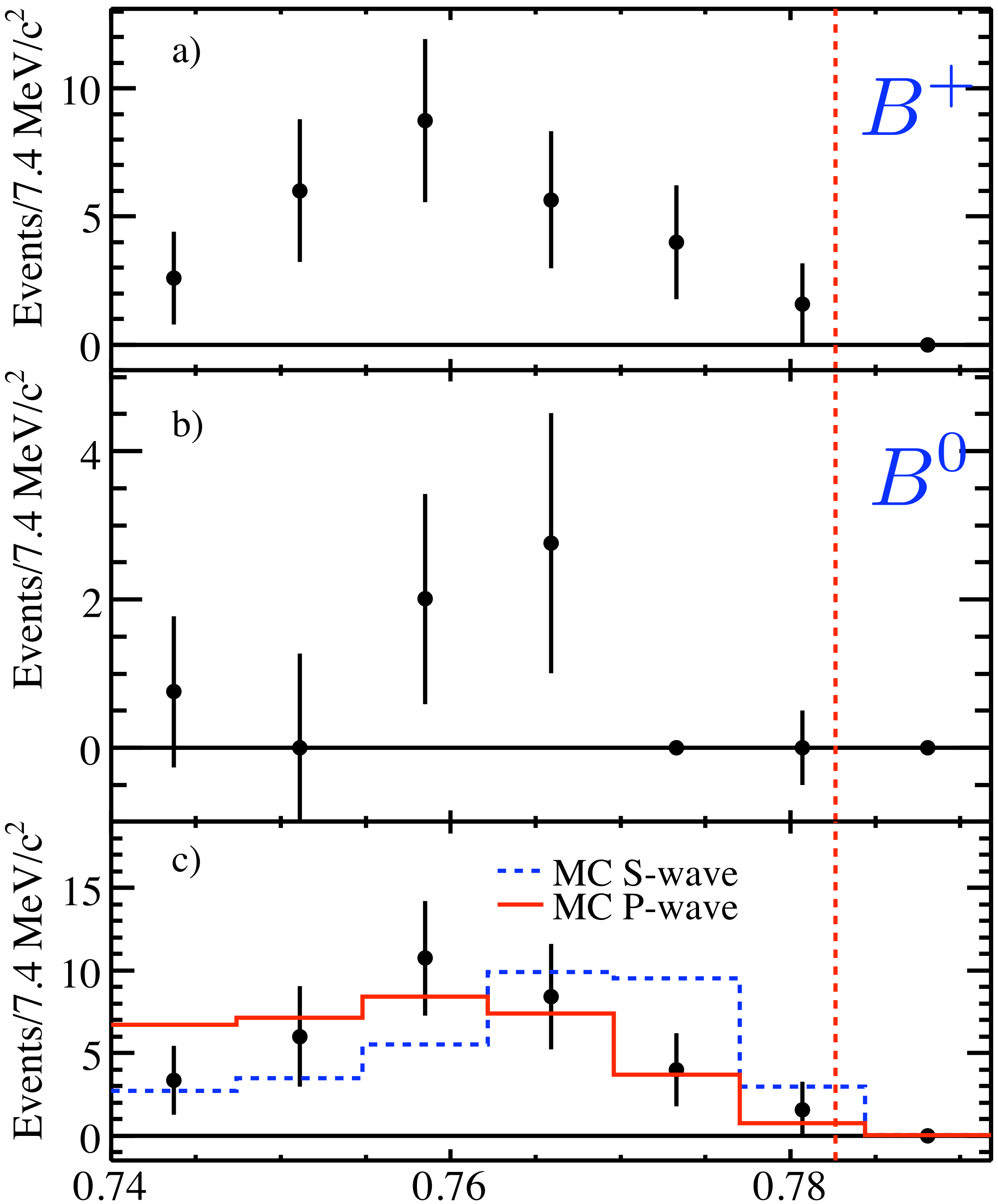

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Burns et al. (arXiv: 1008.0018): the production cross section at CDF is predicted to be much smaller than that observed

Kalashnikova, Nefediev (arXiv:1008.2895): stablished properties of the X(3872) are in conflict with the 2^{-+} assignment

Common features

- All these states decay into J/ψ or ψ(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

$c\bar{c}$ spec. for $J^{PC} = 1^{++}$ (Barnes & Godfrey, PRD69 (2004)) → $2\,^3P_1$ (3990) / → $3\,^3P_1$ (4290)

not compatible with the X(3872) mass

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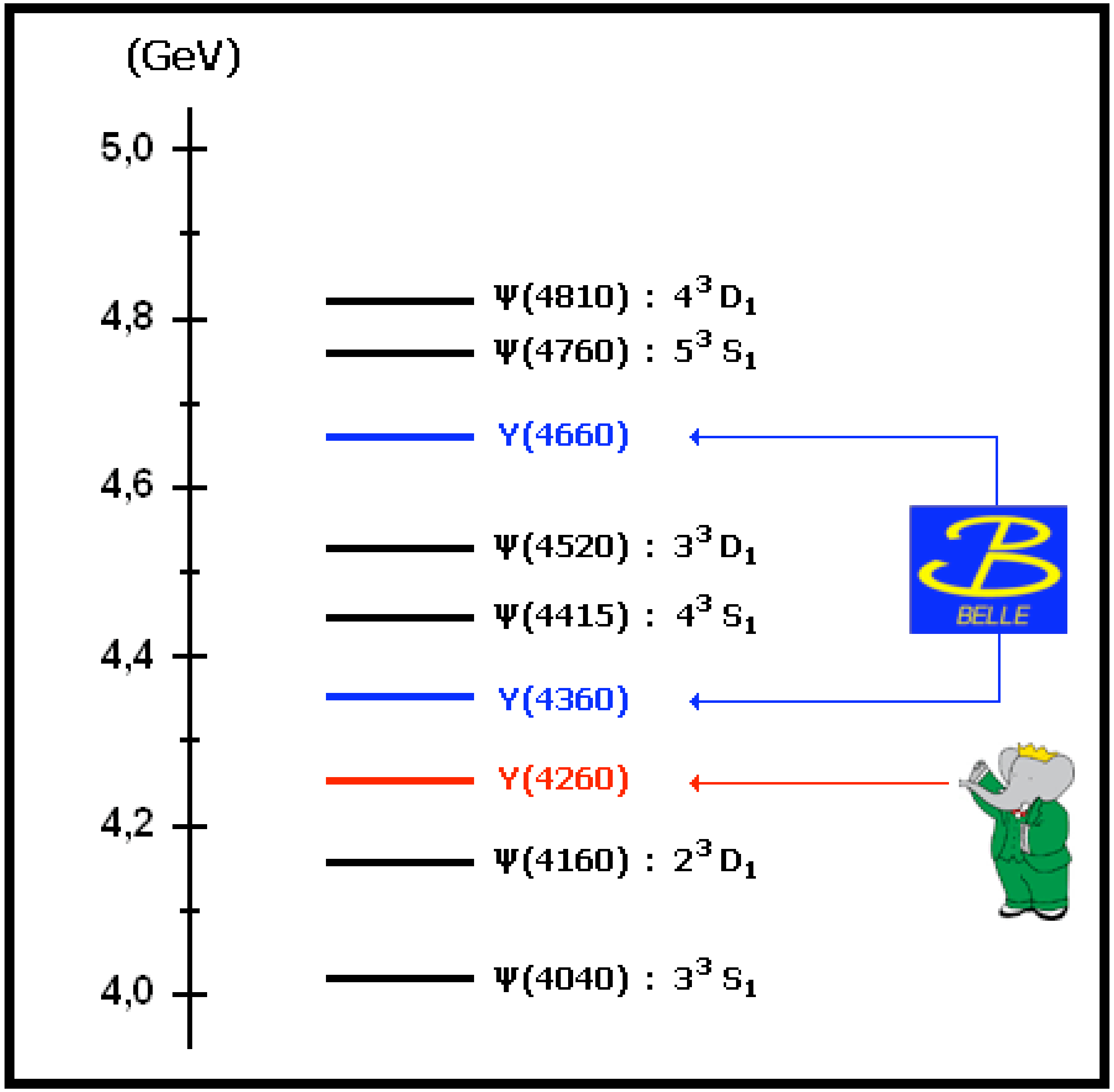

masses and widths of these states are not consistent with any of the 1^{--} charmonium states

(Zhu, IJMPE17(08)283)

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

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

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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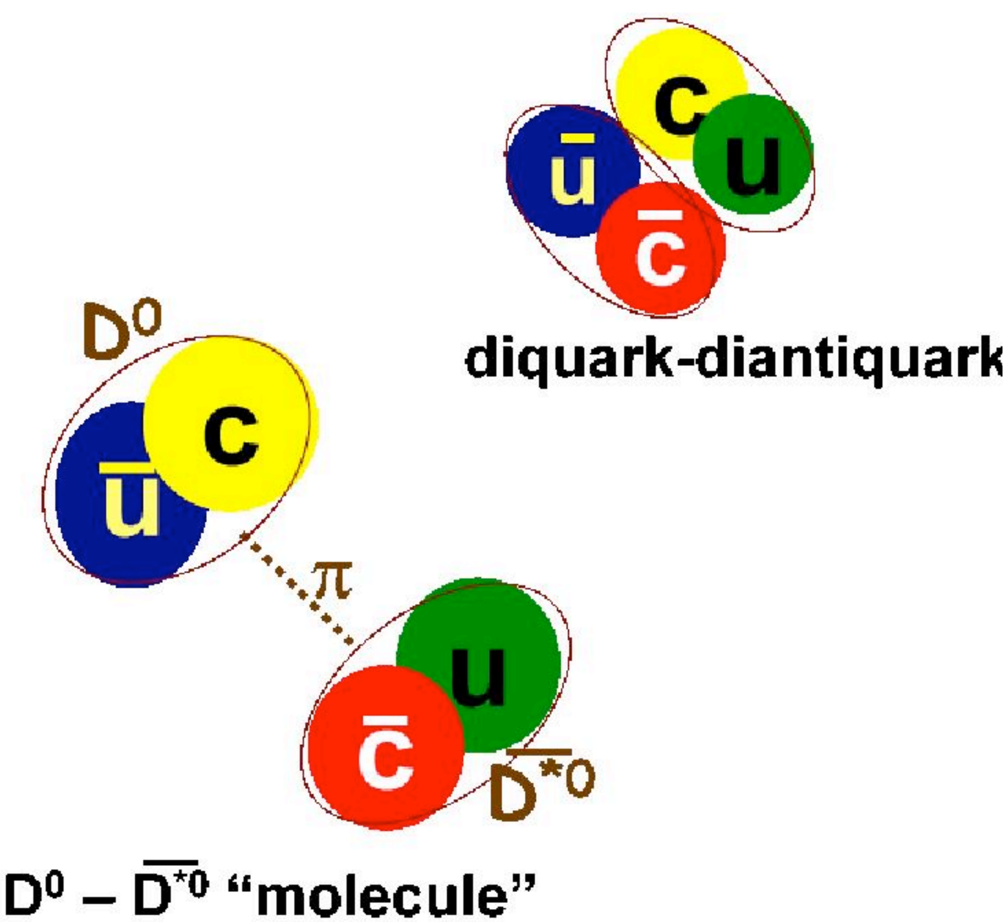

molecular and tetraquark interpretations differ by the way quarks are organized in the state

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

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Theoretical side Phenomenological side

Good Sum Rule ➡ Borel window such that:

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

QCD sum rules calculation for X (3872)

Matheus, Narison, MN, Richard: tetraquark current (PRD75(07)014005)

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

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

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

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

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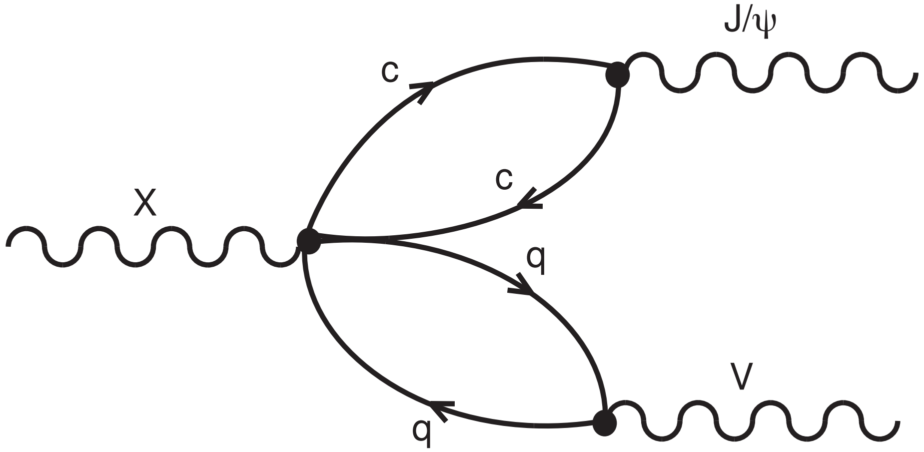

Problem: decay width $X \rightarrow J/\psi\pi\pi$
~ 50 MeV (Navarra, MN, PLB639 (06)272)

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

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

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

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Meng, Gao, Chao (arXiv:hep-ph/0506222) necessity of mixing

mixed charmonium-molecular state (arXiv:0907.2683)

$$j^X = \cos(\alpha)\ [c\bar{c}] + \sin(\alpha)\ j^X_{mol}$$

$m_X = (3.77 \pm 0.18)$ GeV

$5^0 \leq \alpha \leq 13^0$

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

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

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

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

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

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

m_X = (3.77 ± 0.18) GeV

Γ = (9.3 ±6.9) MeV

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

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

MN, Zanetti

(arXiv:1006.0467)

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

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

$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi^+\pi^-)} = 0.19 \pm 0.13, \quad 5^0 \leq \theta \leq 13^0$$

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

QCDSR ➔ X is a mixed charmonium-molecular state

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

charmonium hybrids:

→ Lattice (PRL82(99)): $M \sim 4200$ MeV

→ flux tube (Barnes et al. (PRD52(95)) $M \sim 4200$ MeV

more recent lattice (EPJA19(04)1) and string models calculations

(Kalashnikova et al., PRD77(08)054025) ➡ M ~ 4400 MeV

charmonium hybrid ➡ dominant decay mode $D\bar{D}_1$

(Close & Page, PRLB628(05)215)

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

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

Ebert et al. (EPJC58(08)) ➡ such state would have M ~ 4450 MeV

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Y(4260) →
- baryonium $\Lambda_c - \bar{\Lambda}_c$ state (Qiao, PLB639(06))
- *S*-wave threshold effect (Rosner, PRD74(06))
- molecular state (Ding, Liu et al.,Yuan et al., MN et al.,...)
- manifestations of Regee zeros (Beveren et al., arXiv:0811.1755)

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

tetraquark state (arXiv:0804.4817)

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

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

molecular state (arXiv:0804.4817)

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

$m_Y = (4.27 \pm 0.10)$ GeV in good agreement with $Y(4260)$

other states

$$\left\{ \begin{array}{l} D_s^*\bar{D}_{s0} \Rightarrow m = (4.42 \pm 0.10)\ \text{GeV} \\ D\bar{D}_1 \Rightarrow m = (4.12 \pm 0.09)\ \text{GeV} \\ [cq]_{S=0}[\bar{c}\bar{q}]_{S=1} \Rightarrow m = (4.49 \pm 0.11)\ \text{GeV} \end{array} \right.$$

$Z^+(4430)$

charged state ➡ not a $c\bar{c}$!

PRL100(08)142001

arXiv:0905.2869

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

no conclusive evidence for the existence of $Z^+(4430)$ seen by Belle

$Z^{+}(4430)$

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PRL100(08)142001

arXiv:0905.2869

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$Z^{+}(4430)$ {

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

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 $Z_2^+(4250)$

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

$M(\bar{D}_1^0 D^+) \sim 4285$ MeV

Liu et al. (arXiv:0808.0073)

→ strong atraction in $D^*\bar{D}^*$

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

Ding (arXiv:0905.1188): $Z_1^+(4050)$ molecular interpretation not favored

QCD sum rule (arXiv:0808.0690)

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

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

$$M_{D^*D^*} = (4.15 \pm 0.12)\ \text{GeV} > (D^*\bar{D}^*)_{thre}$$

$$M_{D_1 D} = (4.19 \pm 0.22)\ \text{GeV} < (\bar{D}_1 D)_{thre}$$

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

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

$M_{D^*D^*} = (4.15 \pm 0.12)\ \text{GeV} > (D^*\bar{D}^*)_{thre}$

$M_{D_1 D} = (4.19 \pm 0.22)\ \text{GeV} < (\bar{D}_1 D)_{thre}$

including the width (Lee et al., PRD78(08)):

M = (4.25±0.15) GeV

40 ≤ Γ ≤ 60 MeV

consistent with $Z_2^+(4250)$

Y(4140)

CDF $c\bar{c}$ ➡ large decay width into open charm pair

Liu & Zhu (arXiv:0903.2529): $D_s^* \bar{D}_s^*$ molecular state, $J^{PC} = 0^{++}$ or 2^{++}

Ding (arXiv:0904.1782): boson exchange model supports $D_s^* \bar{D}_s^*$

Stancu (arXiv:0906.2485): tetraquark $cs\bar{c}\bar{s}$ 1^{++} state

Beveren et al. (arXiv:0906.2278): is not a resonance

QCD sum rules Y(4140)

- Wang (arXiv:0903.5200)
- Albuquerque, Bracco, MN (PLB678(09))
- Zhang, Huang (arXiv:0905.4178)

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Wang (arXiv:0903.5200)

Albuquerque, Bracco, MN (PLB678(09))

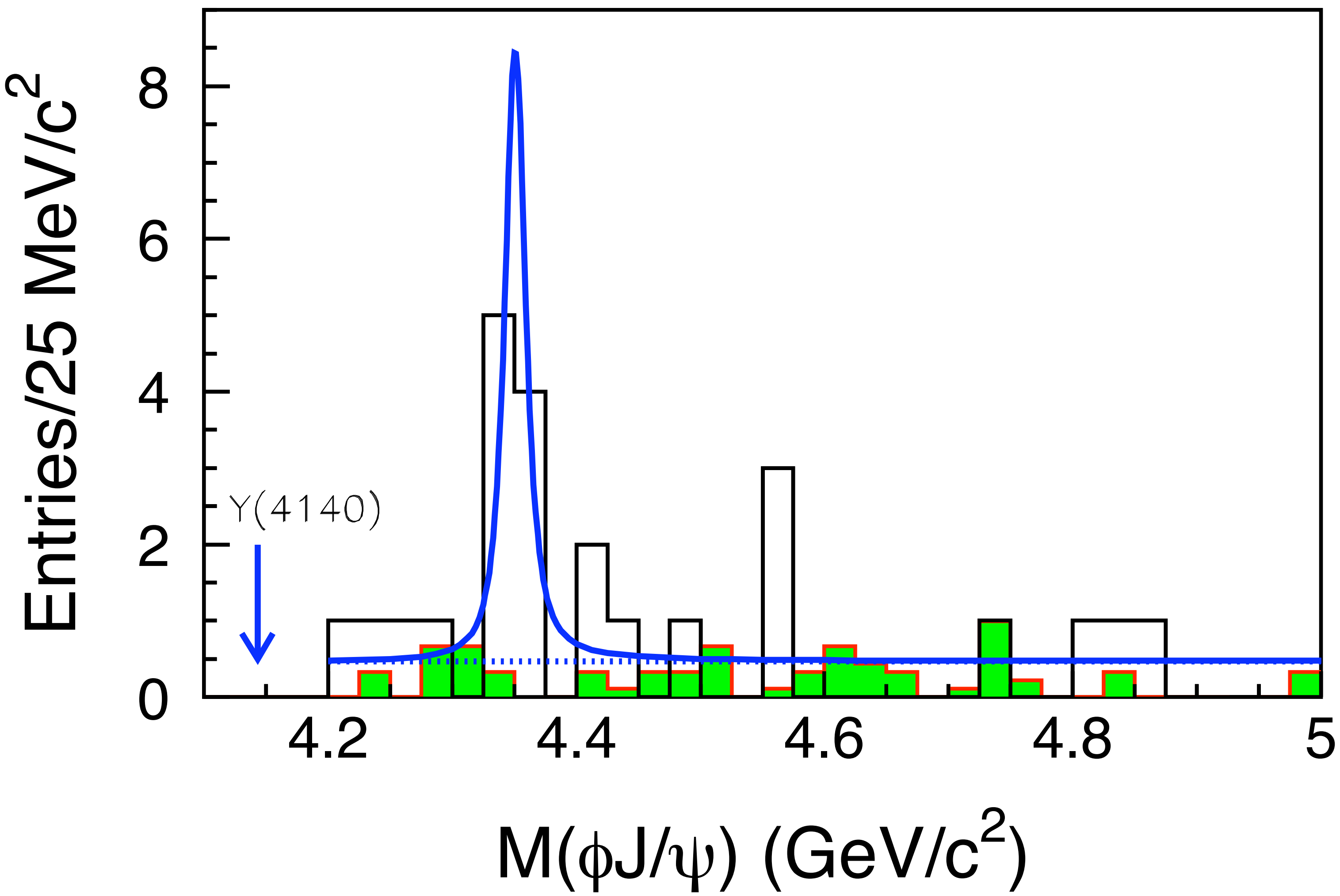
Zhang, Huang (arXiv:0905.4178)

$D_s^*\bar{D}_s^*$ with $J^{PC} = 0^{++}$ ➡ **M = (4.14 ± 0.09) GeV** arXiv:0903.5424 ➜ if Y(4140) is a $D^*_s D^*_s$ molecule, it should be seen in the $\gamma\gamma$ process arXiv:0903.5424 ➜ if Y(4140) is a $D^*_s D^*_s$ molecule, it should be seen in the γγ process

BELLE arXiv:0912.2383

searched for Y(4140) in

$\gamma\gamma \to \phi J/\psi$



no signal of Y(4140) but evidence for a new X(4350) state

point against the molecular assignement?

$X(4350) \to J/\psi\phi$ ➡ possible quantum numbers: $0^{++},\ 1^{-+},\ 2^{++}$

1^{-+} ⇒ exotic: not consistent with constituent quark model

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- Stancu (arXiv:0906.2485): 2^{++} $cs\bar{c}\bar{s}$ tetraquark state
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- Wang. (arXiv:0912.4626): mixed 0^{++} charmonium- $D_s^* \bar{D}_s^*$ state
- Ma (arXiv:1006.1276): 0^{++} $D_s^* D_{s0}^*$ molecular state

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QCD Sum Rule (arXiv:1001.3092): 1^{-+} $D_s^*\bar{D}_{s0}^*$ current

M = (5.05 ± 0.19) GeV

not compatible with the mass of the narrow structure observed by BELLE

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

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

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

$J^P = 1^+$ →

- light antidiquark: $\epsilon_{abc}[\bar{u}_b \gamma_5 C \bar{d}_c^T]$
- heavy diquark: $\epsilon_{aef}[c_e^T C \gamma_\mu c_f]$

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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

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