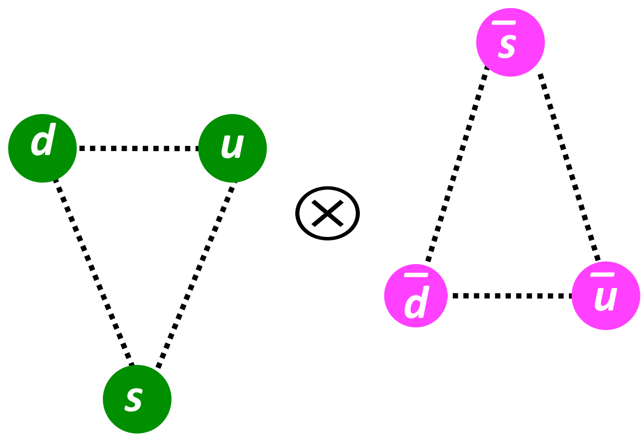
A New Hadron Spectroscopy

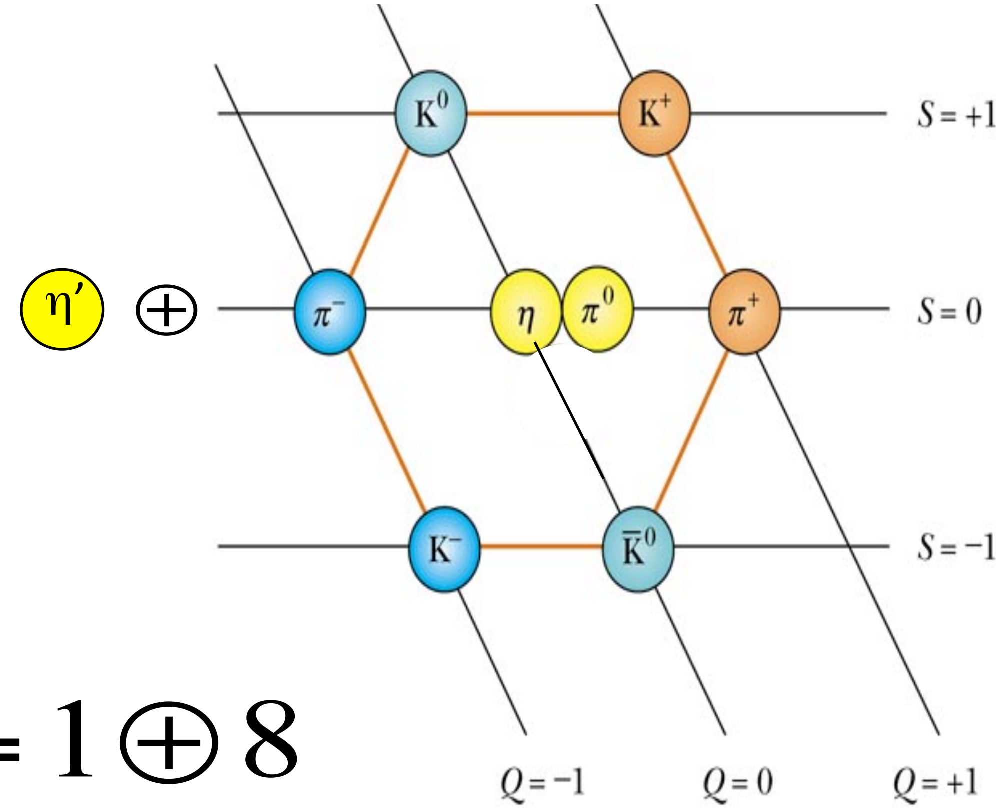
Stephen Lars Olsen ibs Institute for Basic Science **Daejeon KOREA**

53rd International Meeting on Nuclear Physics,

Bormio Italy, Jan 26-30, 2015

“Old Hadron Spectroscopy”:
mesons = q triplet $\otimes$ $\overline{\text{q triplets}}$





$$3 \otimes \overline{3} = 1 \oplus 8$$

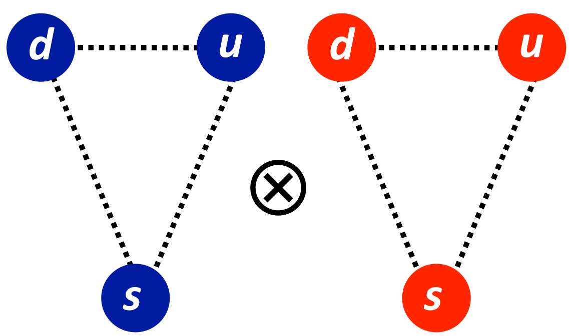
QCD "diquarks" ?

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

R. J. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [$\epsilon(700), S^*, \delta, \kappa$] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L = 1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.



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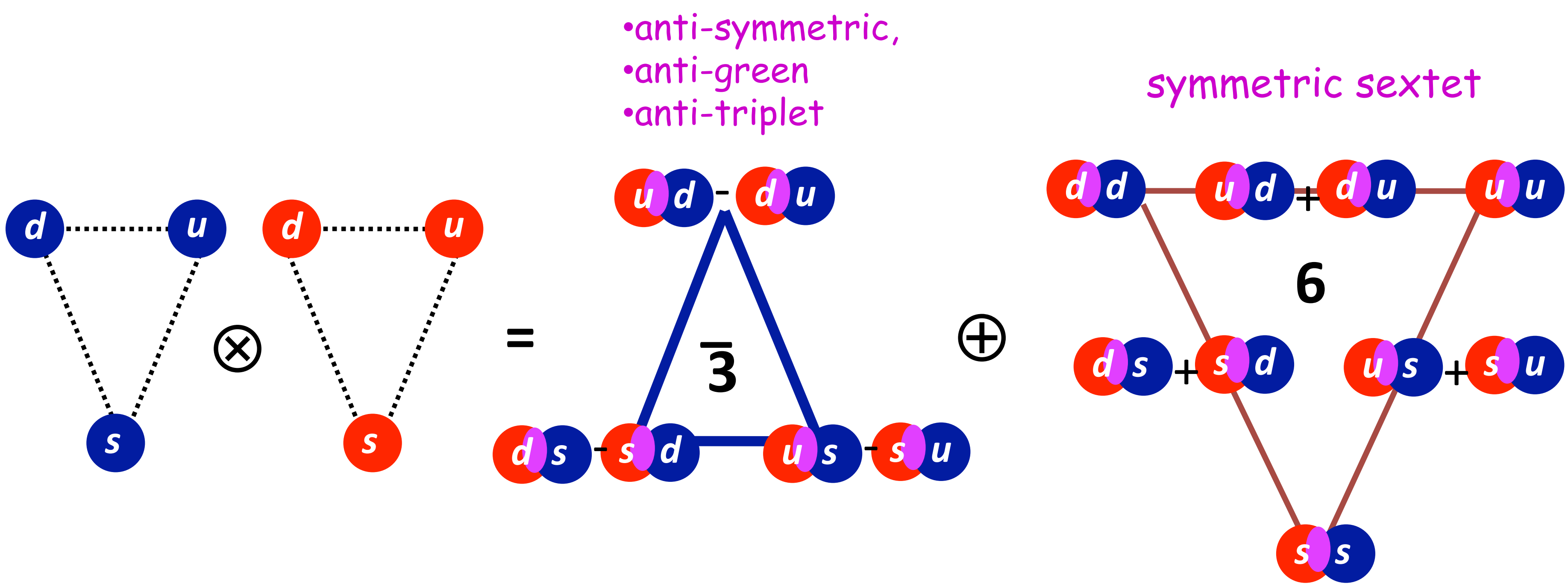


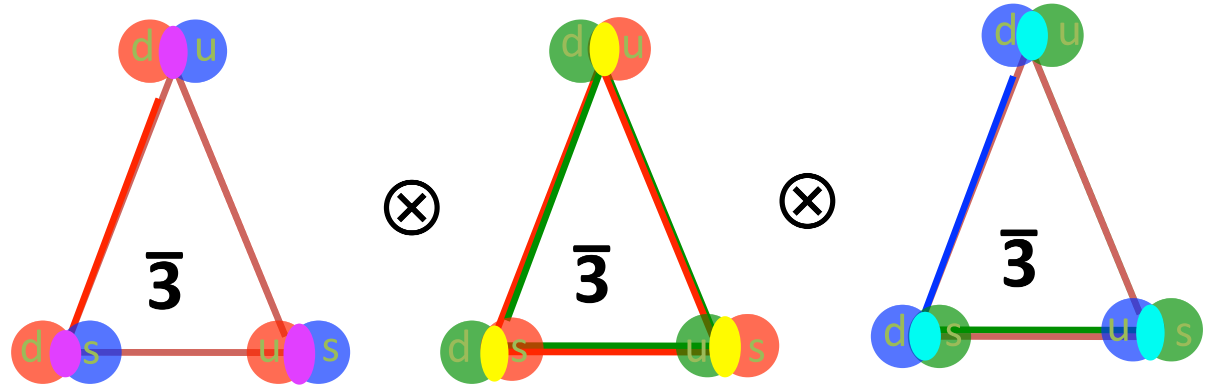
$$3 \otimes 3 = \bar{3} \oplus 6$$

multiquark states from diquarks & diantiquarks

red-blue diquark

green-red diquark

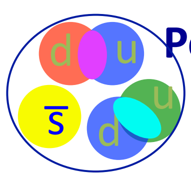
blue-green diquark



magenta (anti-green)
anti-triplet

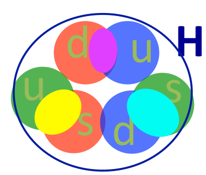
yellow (anti-blue)
anti-triplet

cyan (anti-red)
anti-triplet



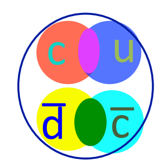
Pentaquark

magenta-cyan-yellow
color singlet 5-q state



H-dibaryon

magenta-cyan-yellow
color singlet 6-q state

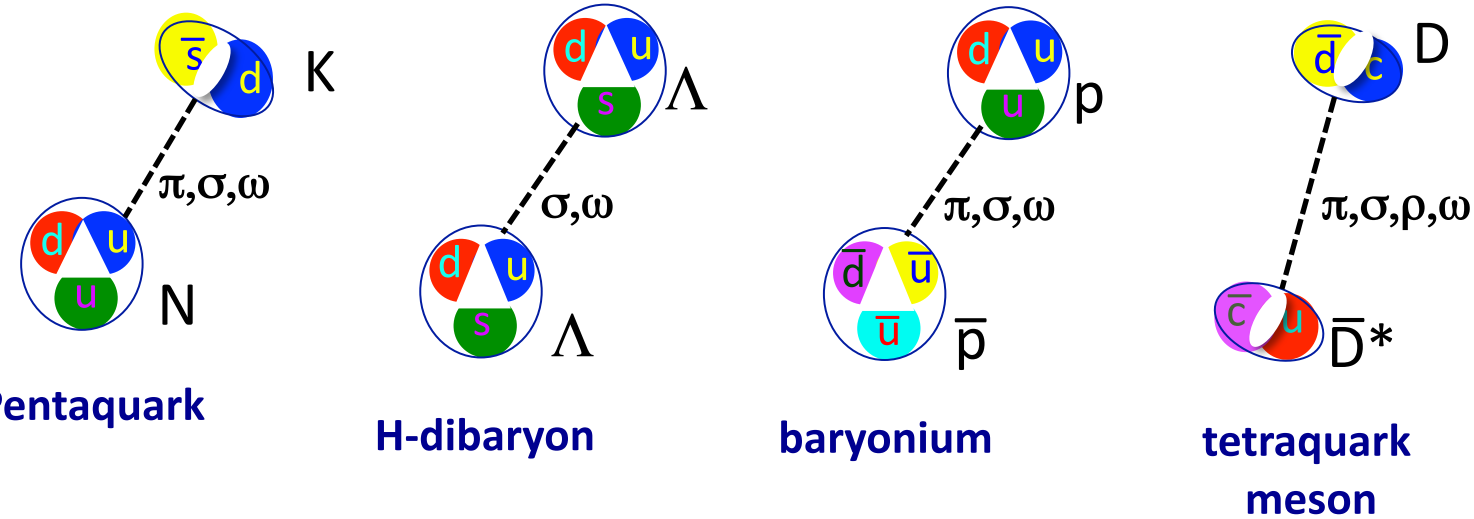


tetraquark meson

green-magenta (anti-green)
color singlet 4-q state

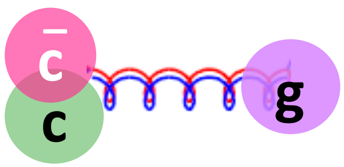
"exotic" hadrons that particle theorists love

multiquark states from “molecules”



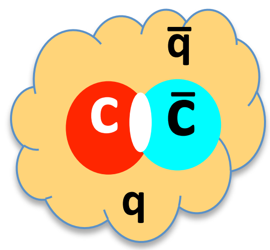
“exotic” hadrons that nuclear theorists love

Other proposed non-$q\bar{q}$ mesons

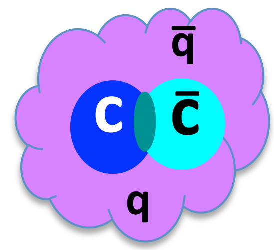


QCD hybrid

Glueball



hadrocharmonium



adjoint charmonium

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

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Where are they??

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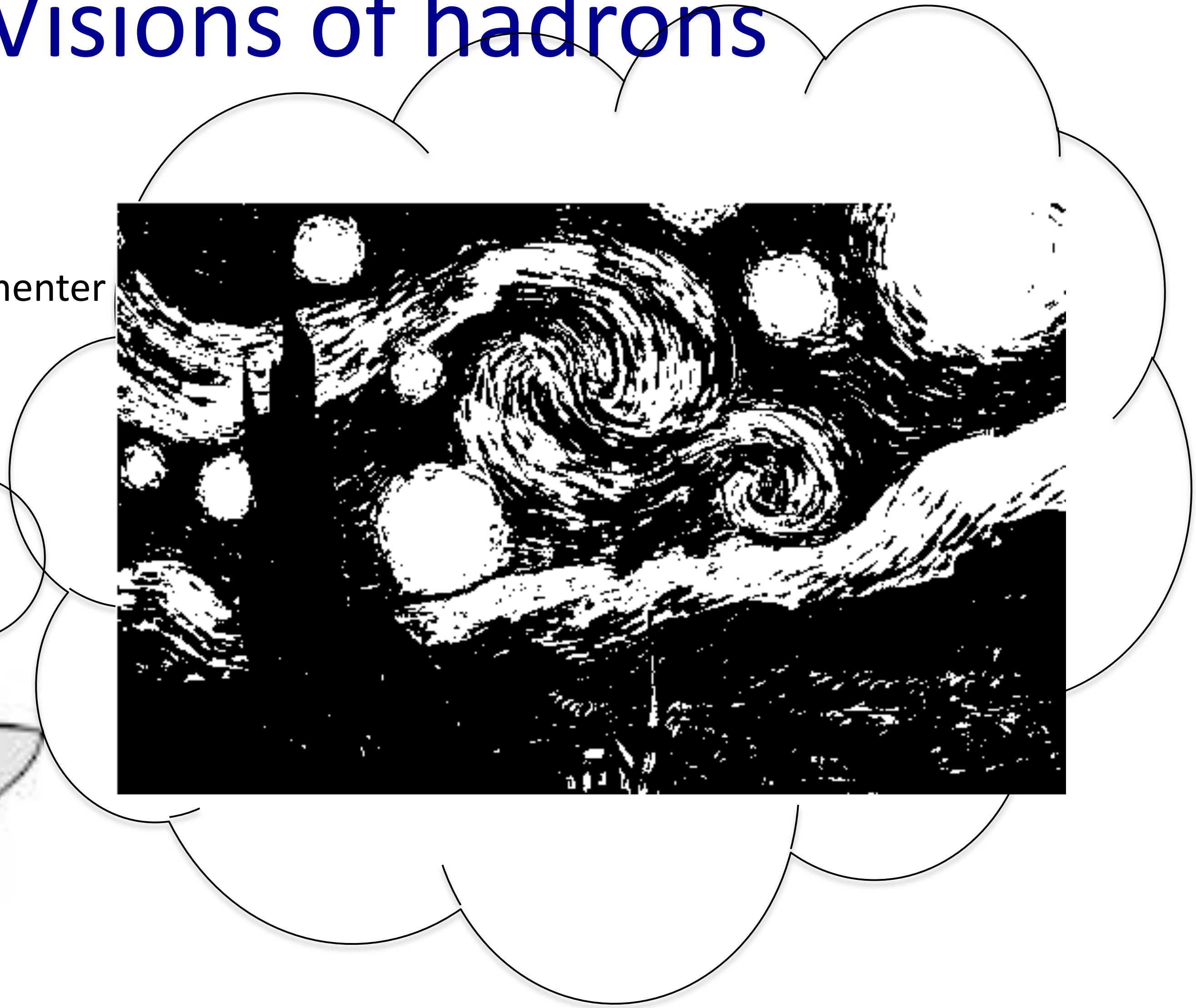
Visions of hadrons

Through a theorist‘s mind

van Gogh prediction of B-mode polarization in 1889?

Visions of hadrons

What is seen by an experimenter



The list keeps growing

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [82, 89] , BaBar [85], LHCb [90]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [83, 91, 92, 125], D0 [84]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [94] , BaBar [59]
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [95] , BaBar [96]
				$B \to K + (J/\psi\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$B \to K + (\psi'\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [86], CMS [87]
$X(3915)$	3917.4 ± 2.7	$28^{+10}_{-\ 9}$	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [58] , BaBar [59]
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [60] , BaBar [61]
$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [64] , BaBar [65]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
				$e^+e^- \to J/\psi + (...)$	Belle [26]
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar [129], Belle [130]
$Y(4008)$	$4008^{+121}_{-\ 49}$	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [32]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [74, 75], CMS [77]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
$Y(4260)$	4263^{+8}_{-9}	95±14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar [30, 131], CLEO [132] , Belle [32]
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [133]
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [133]
$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [75], CMS [77]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [81]
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar [31], Belle [33]
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [134]
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle [33]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [39], Belle [40]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [56]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [41]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [42]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [51]
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [44, 46, 47], LHCb [48]
				$B \to K + (J\psi\,\pi^+)$	Belle [51]
$Y_b(10890)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [117]
$Z_b^+(10610)$	10607.2±2.0	18.4±2.4	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1, 2, 3$	Belle [119, 122]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n = 1, 2$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (B\bar{B}^*)^+$, $n = 1, 2$	Belle [123]
$Z_b^0(10610)$	10609± 6		1^{+-}	"$\Upsilon(5S)$" $\to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n = 1, 2, 3$	Belle [121]
$Z_b^+(10650)$	10652.2±1.5	11.5±2.2	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1, 2, 3$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n = 1, 2$	Belle [119]
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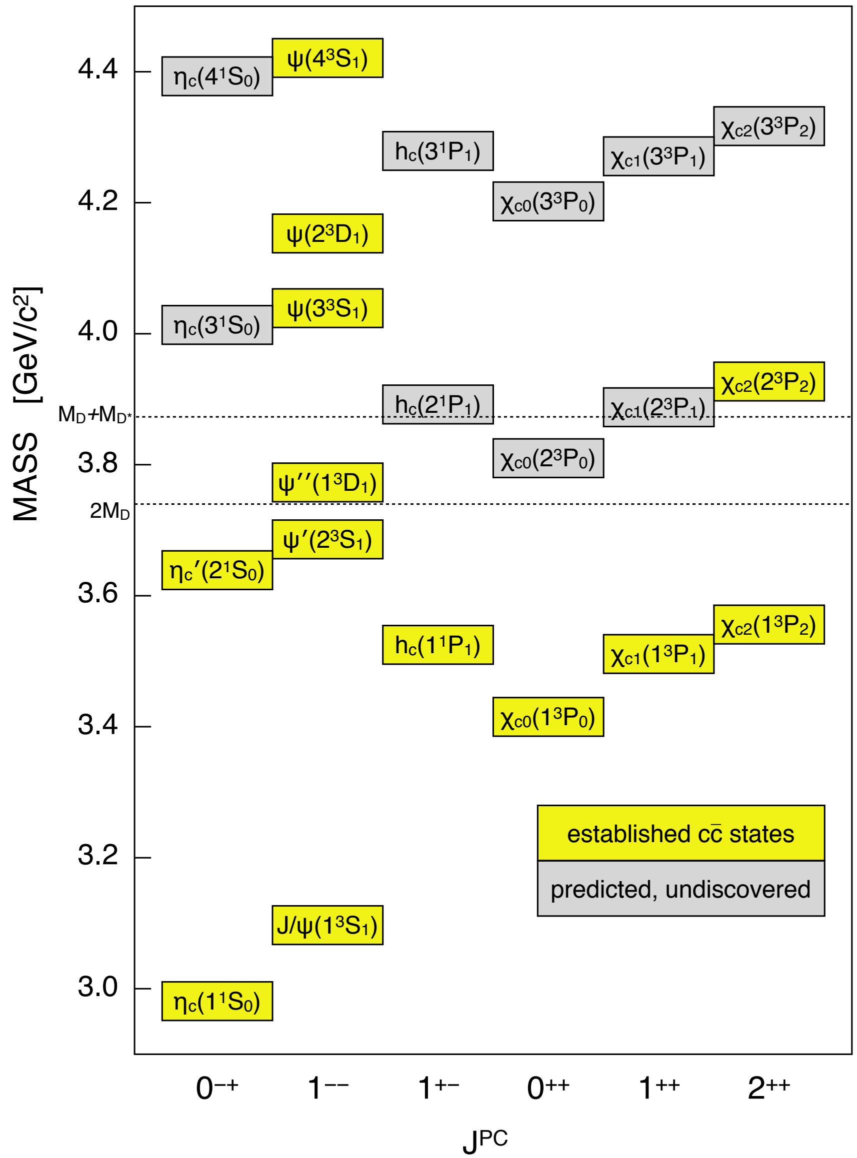
Now lots of charged Z_c mesons

and two Z_b mesons

$c\bar{c}$ assignments for the XYZ mesons?



c$\bar{c}$ assignments for the XYZ mesons?

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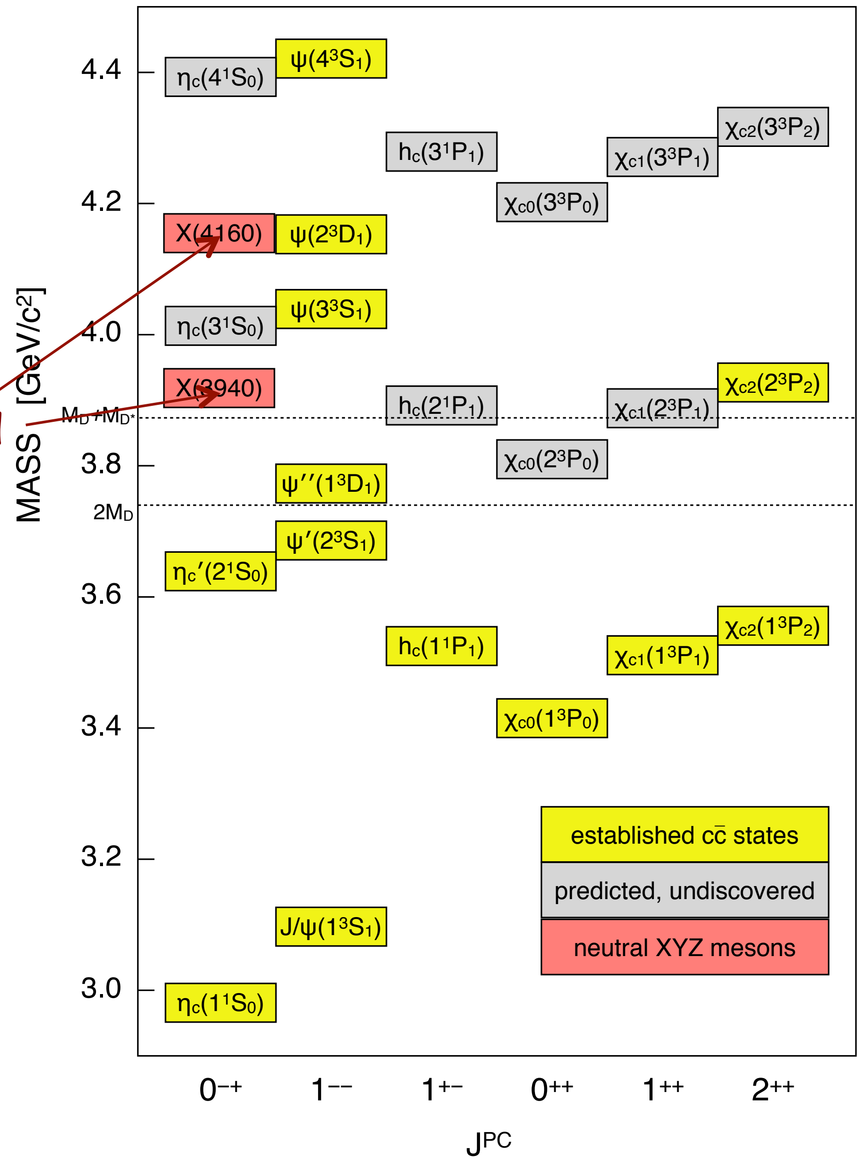

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no unassigned levels for the 1^{--} Y(4260) & Y(4360)

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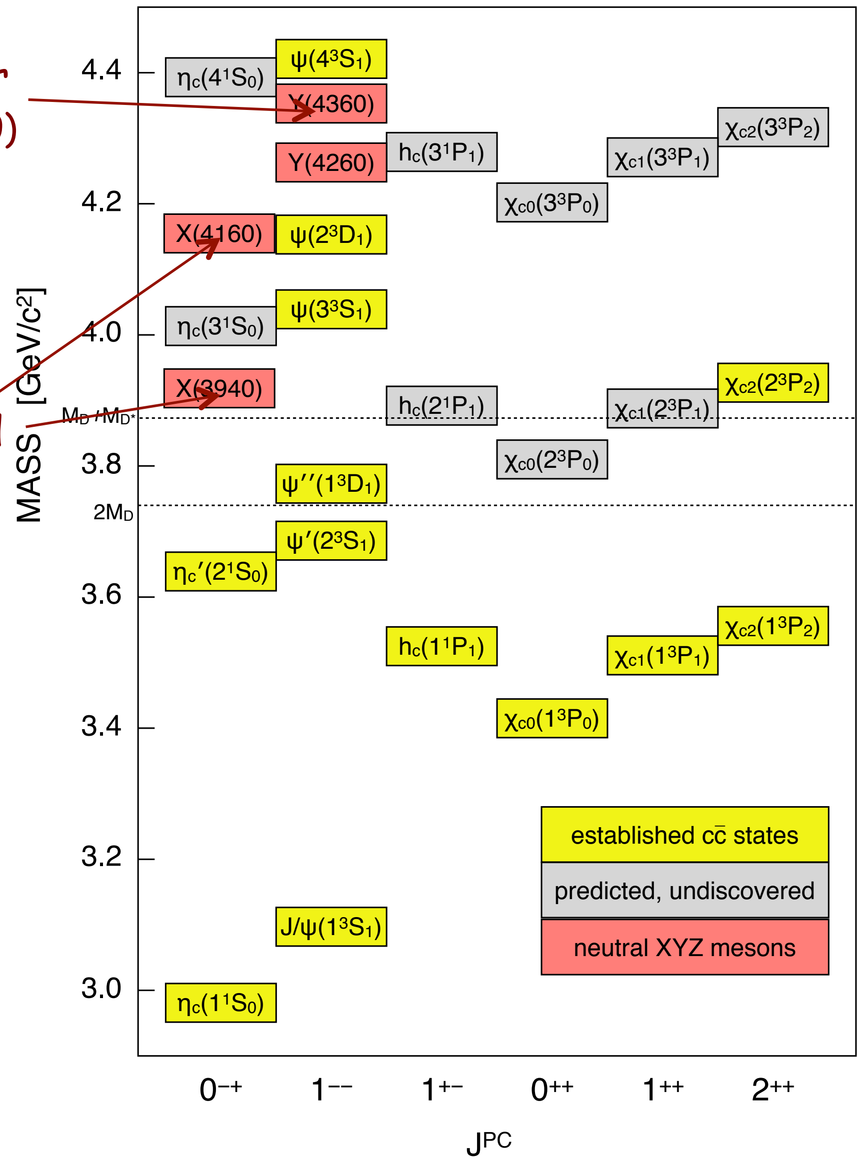

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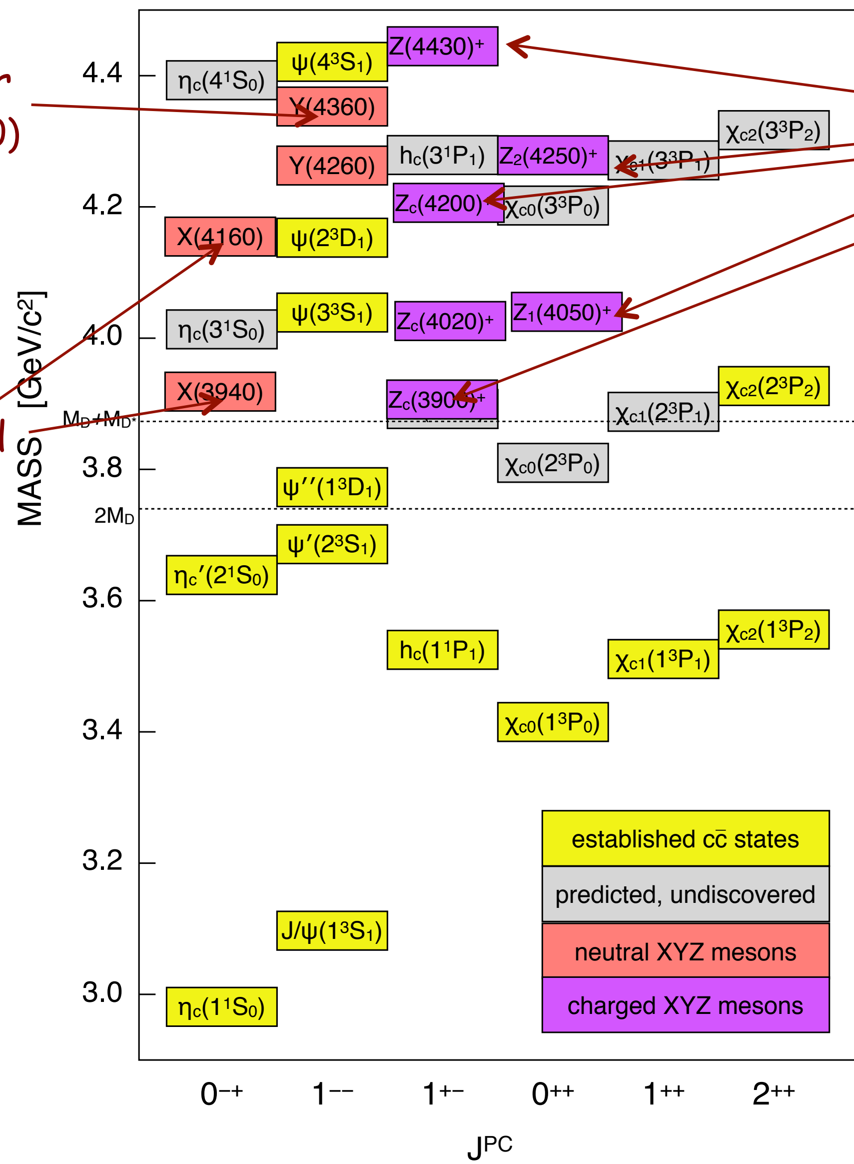

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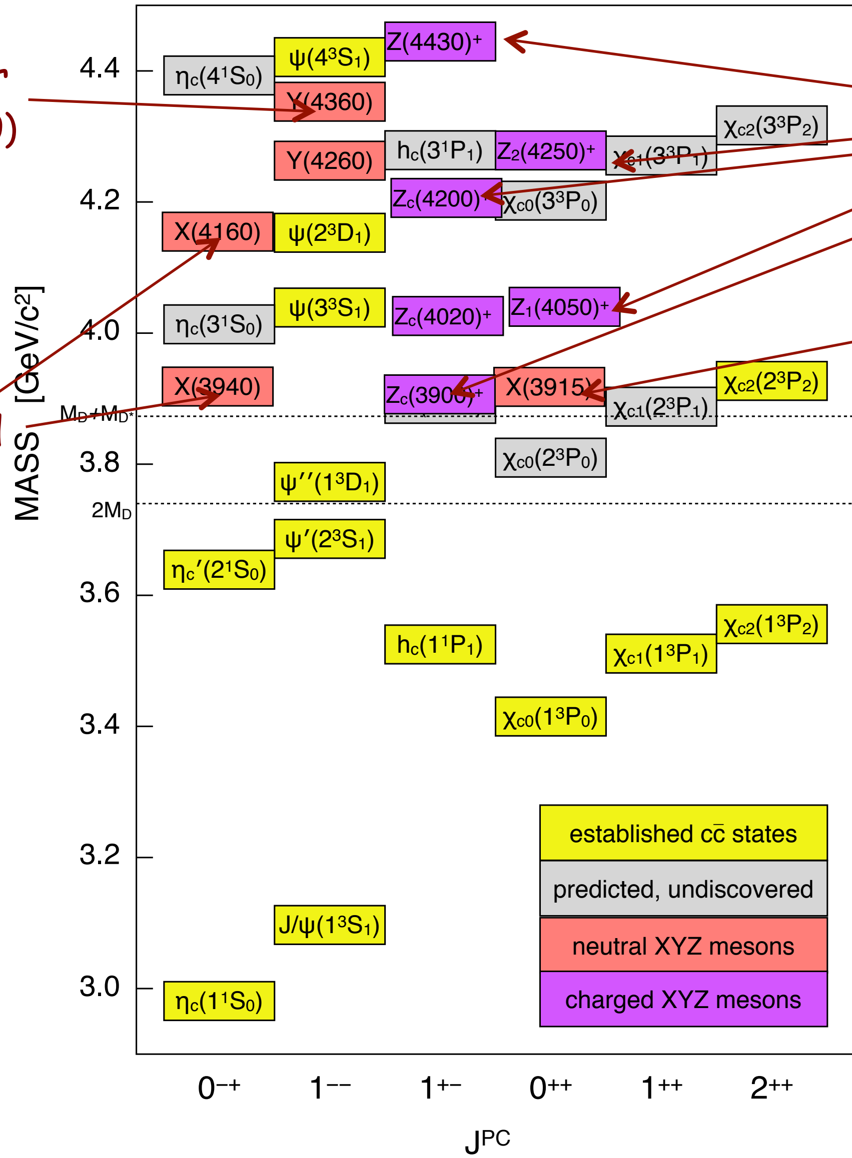

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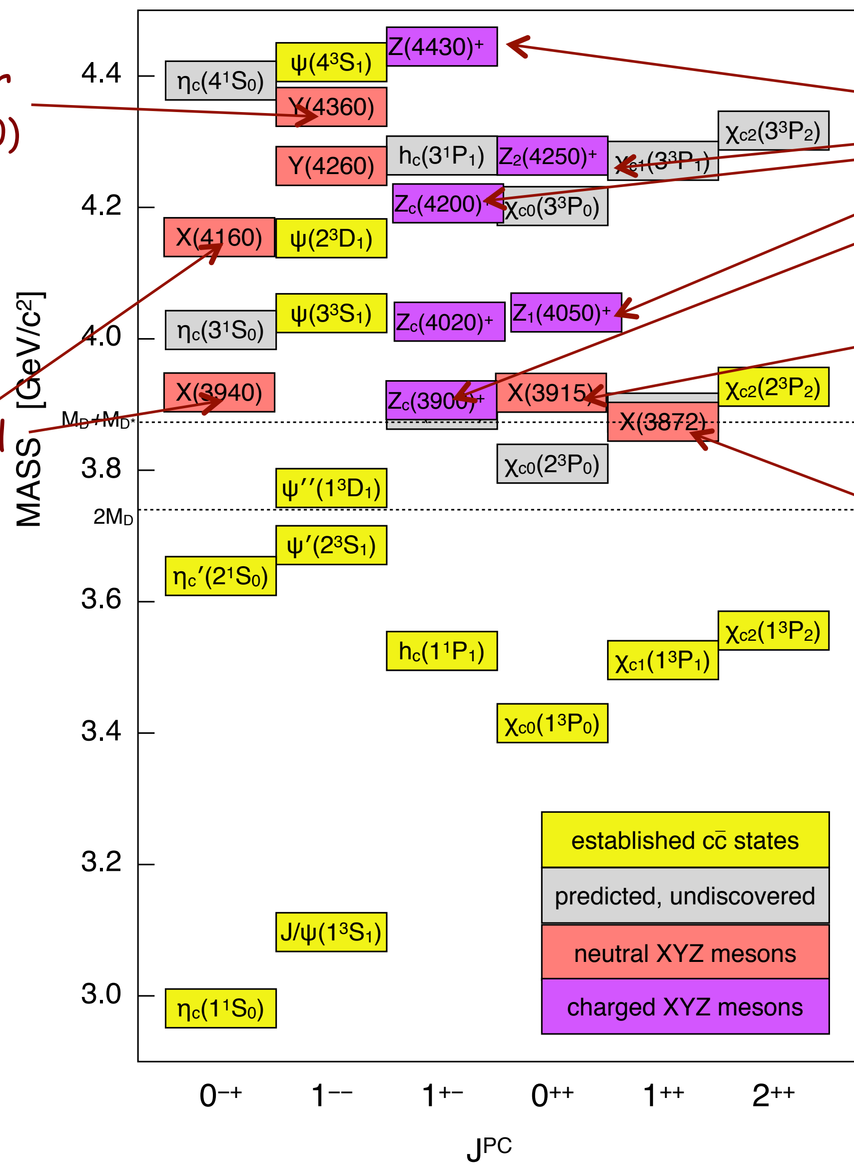

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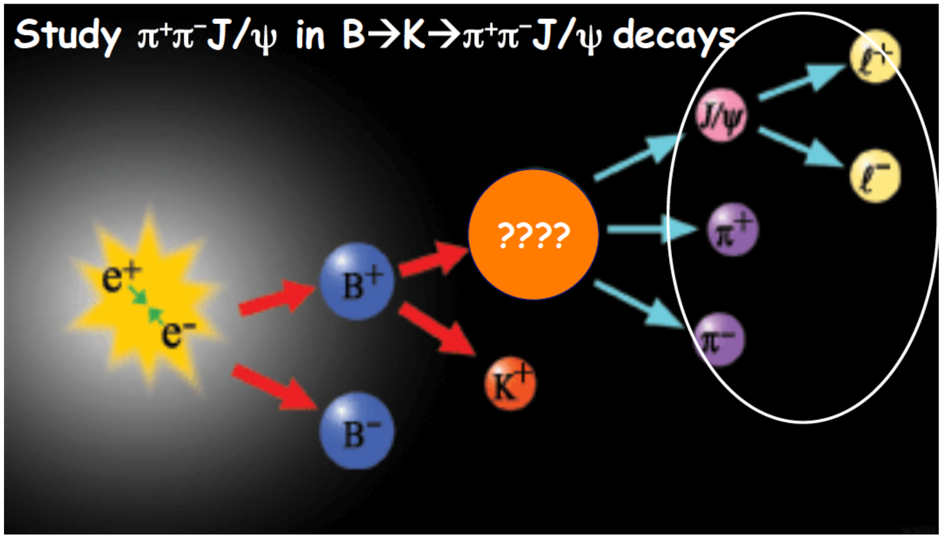
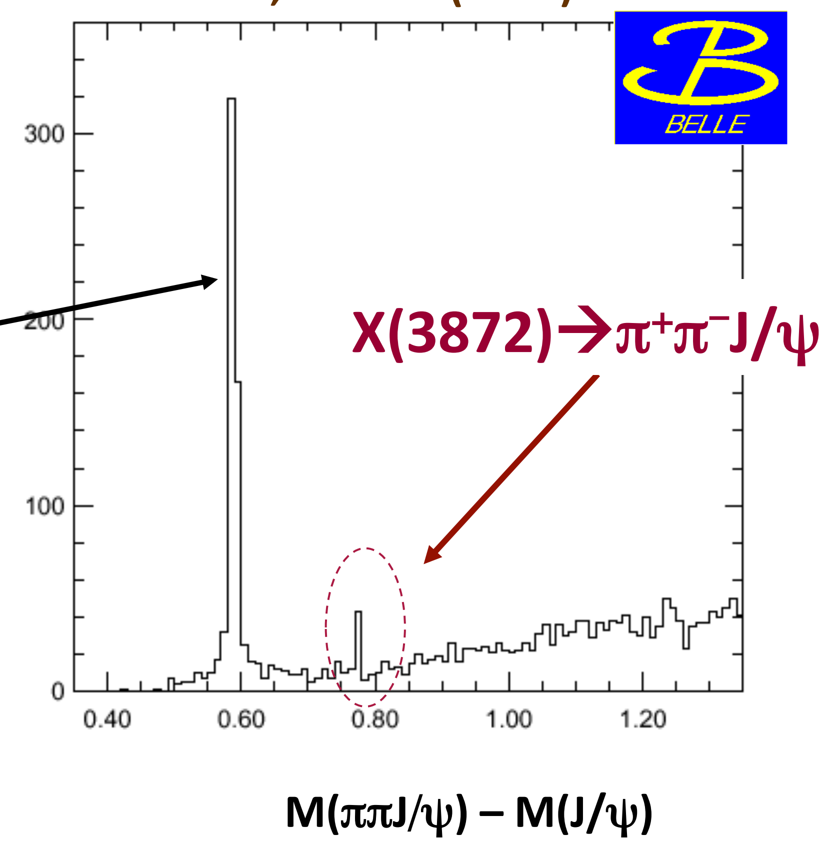
the X(3872) is a long complex story

The X(3872)

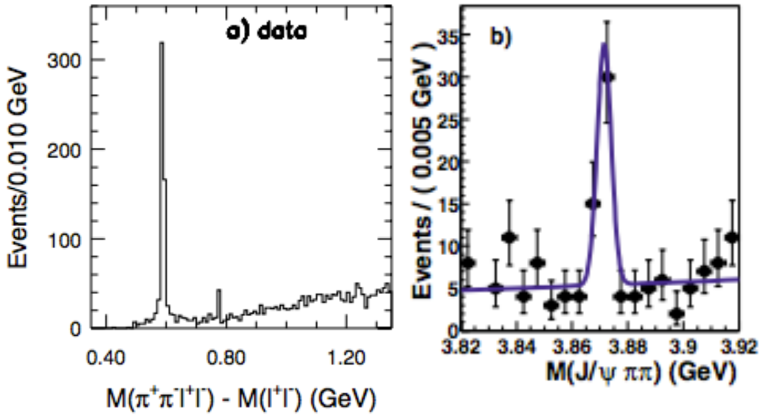


PRL 91, 262001 (2003)

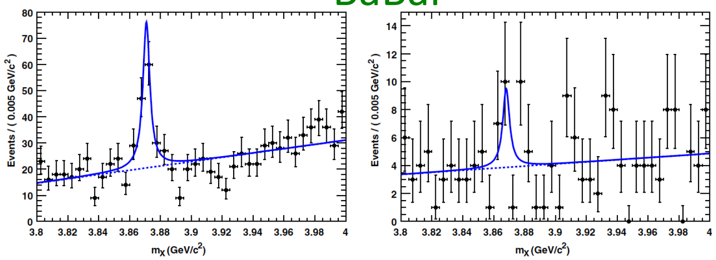


Seen by 7 experiments

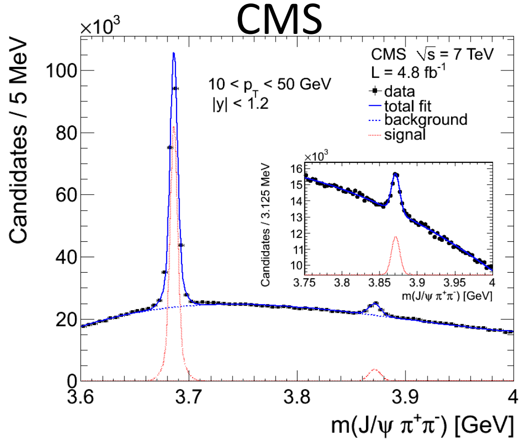
Belle

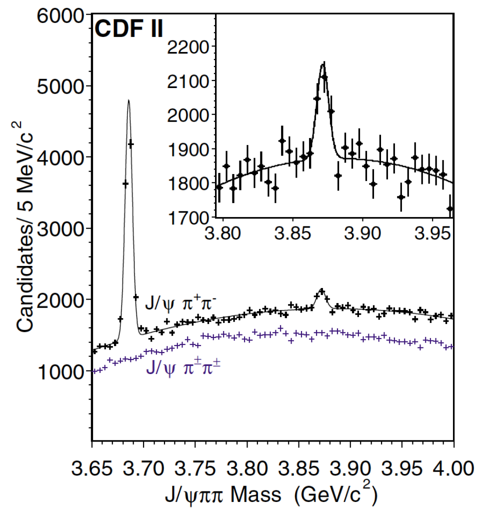


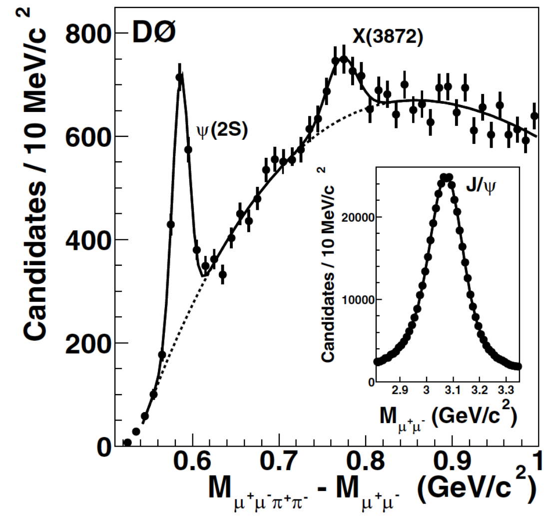
BaBar

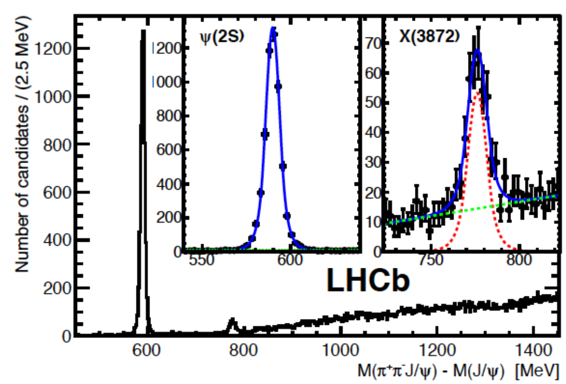


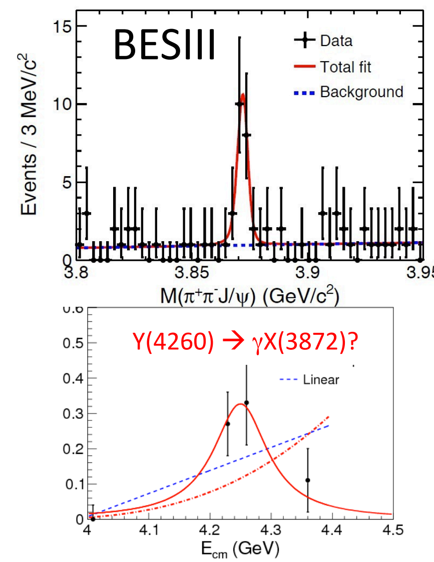
CMS











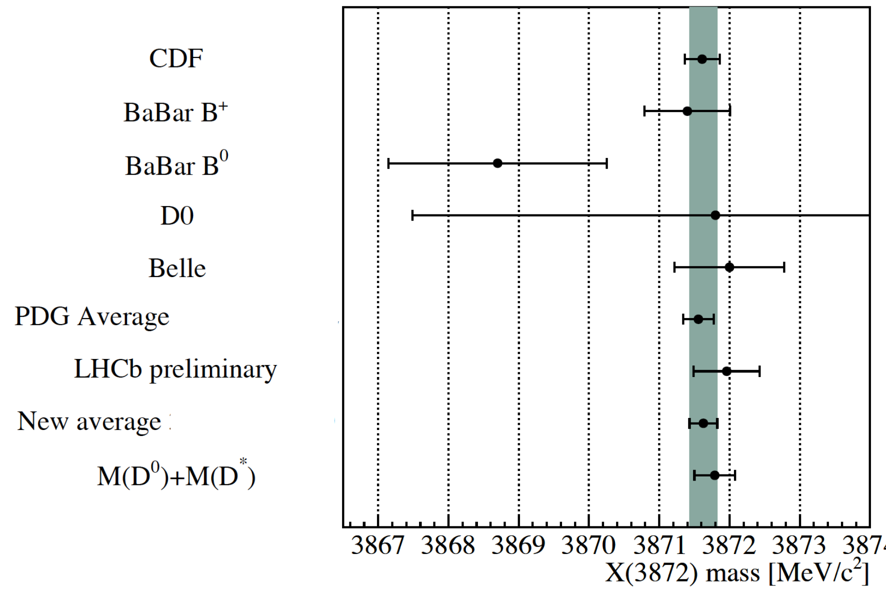
What is known about the X(3872)?

Mass and Width

$M_{X(3872)} = 3871.68 \pm 0.17$ MeV
$m_{D0} + m_{D^{*}0} = 3871.693 \pm 0.090$ MeV

➔ "B.E." = 3 ± 192 keV

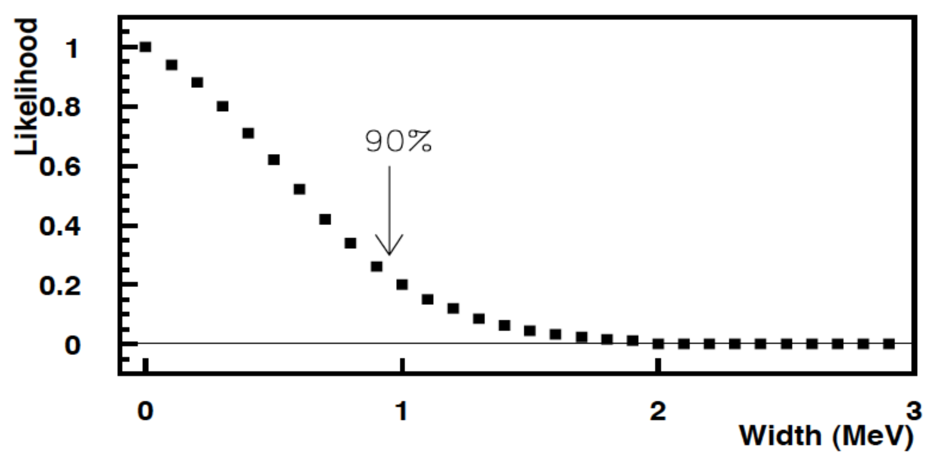
Tomaradze et al., arXiv:1501.01658



Near equality of $M_{X(3872)}$ & $m_{D0} + m_{D^{*}0}$
-- ≲1 part/10^4 --

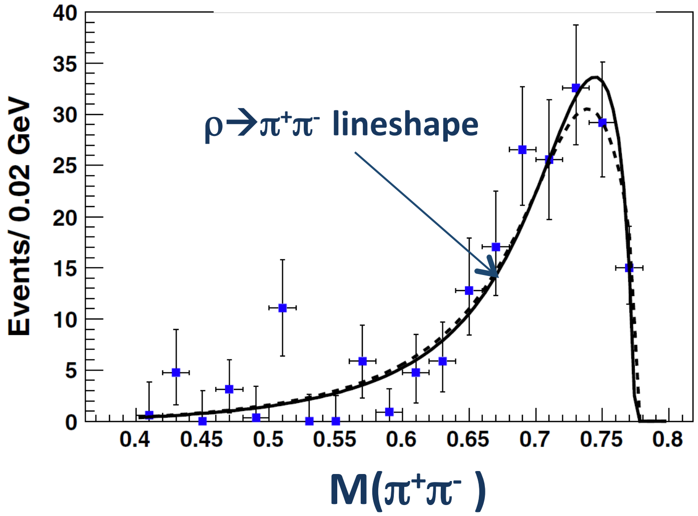
Accident???.... Dynamics??

$\Gamma_{X(3872)} < 1.2$ MeV (90% CL)

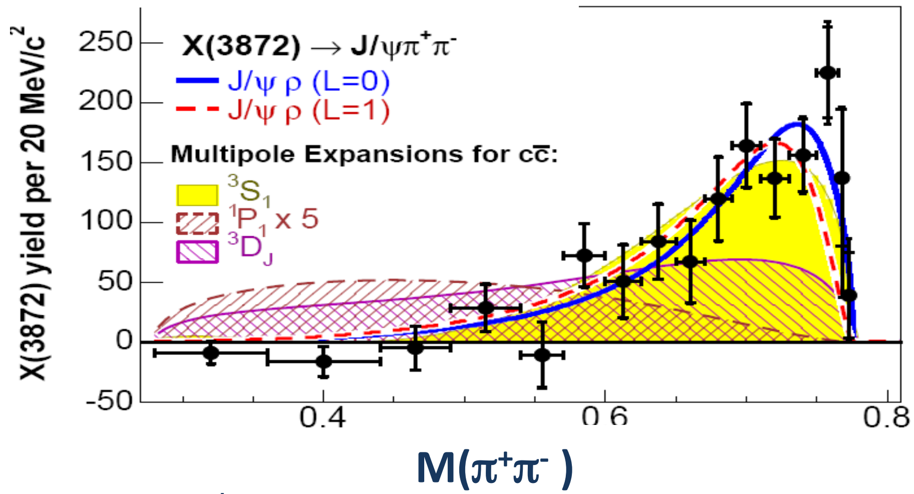


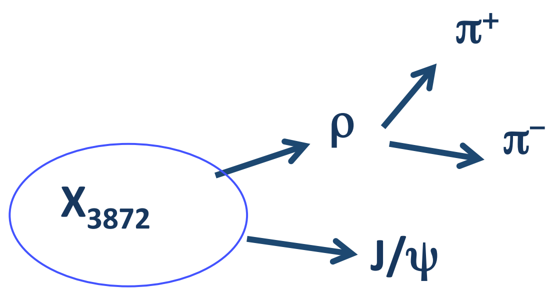
$\pi^+\pi^-$ system in X(3872)→$\pi^+\pi^-$J/ψ comes from ρ→$\pi^+\pi^-$

Belle: PRD 84 052004



CDF: PRL 96 102002

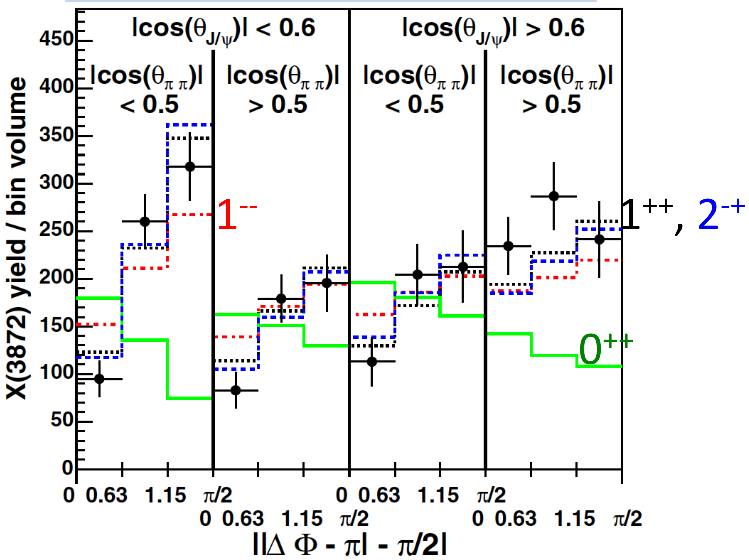




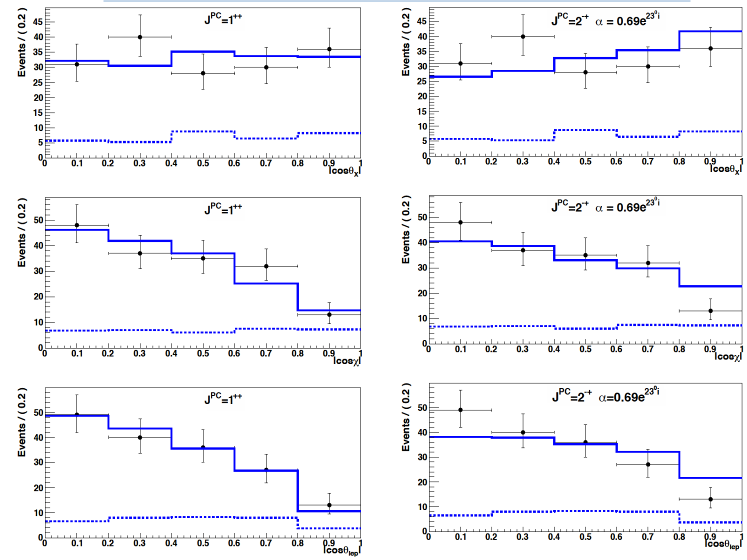
Problem: $(c\bar{c})$→ρ J/ψ violates Isospin
and should be strongly suppressed

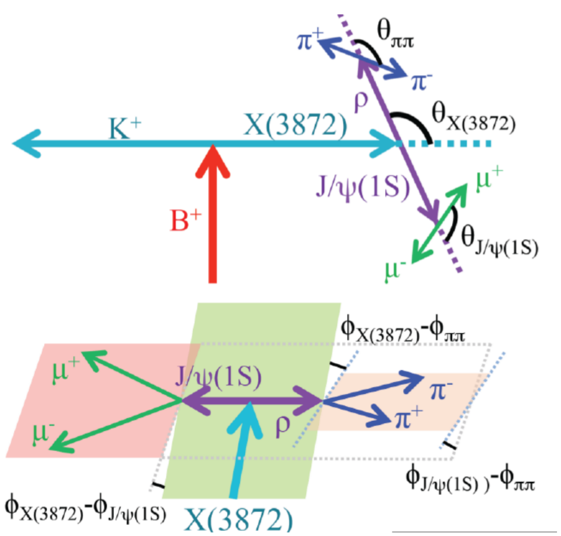
$J^{PC}=1^{++}$

CDF PRL 98, 132002: J^{PC} = 1^{++} or 2^{-+}

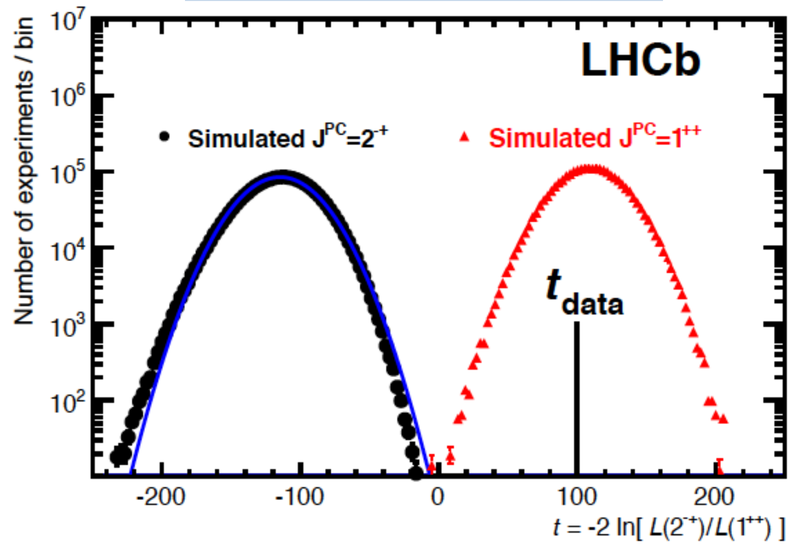


Belle PRD 84, 052004(R): J^{PC} = 1^{++} or 2^{-+}



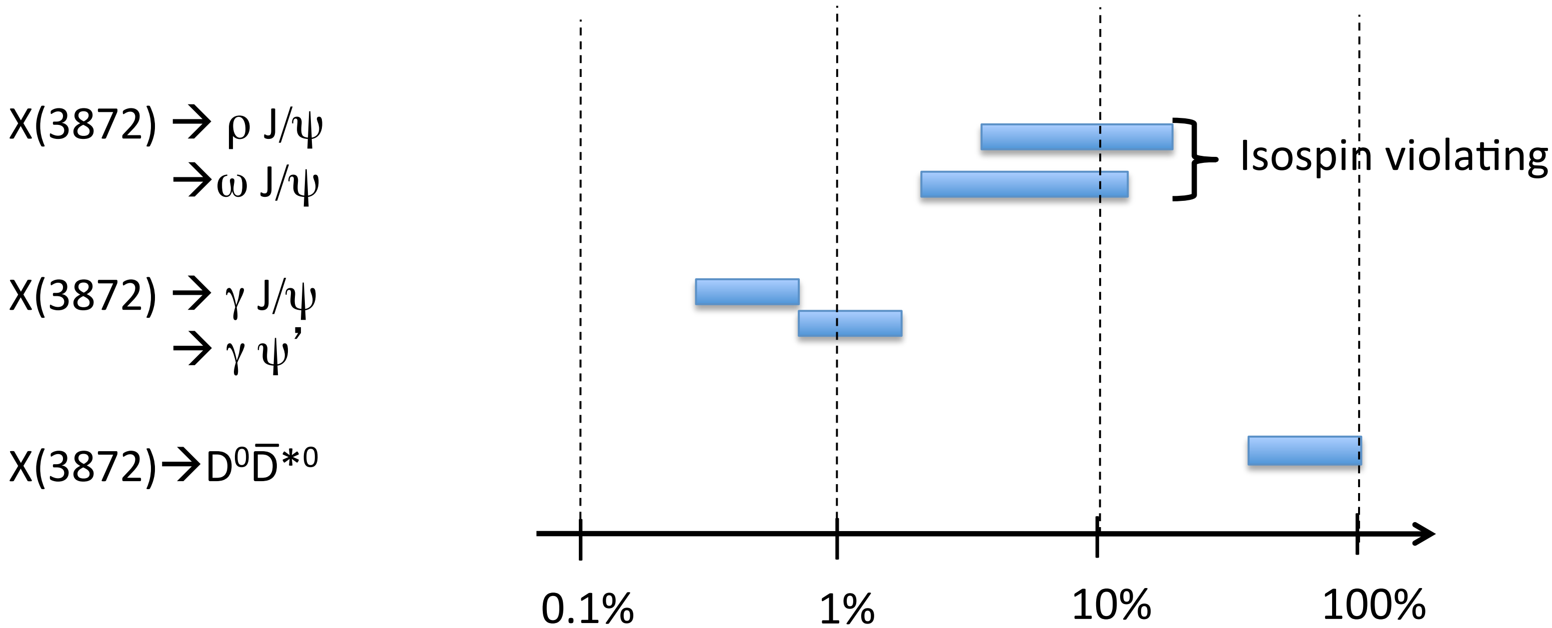


LHCb PRL 110, 222001: J^{PC} = 1^{++}



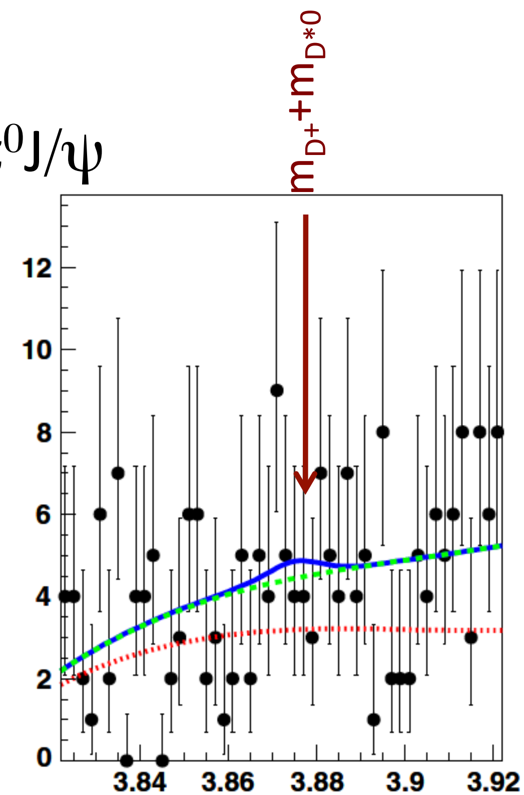
Decay modes

my rough estimates



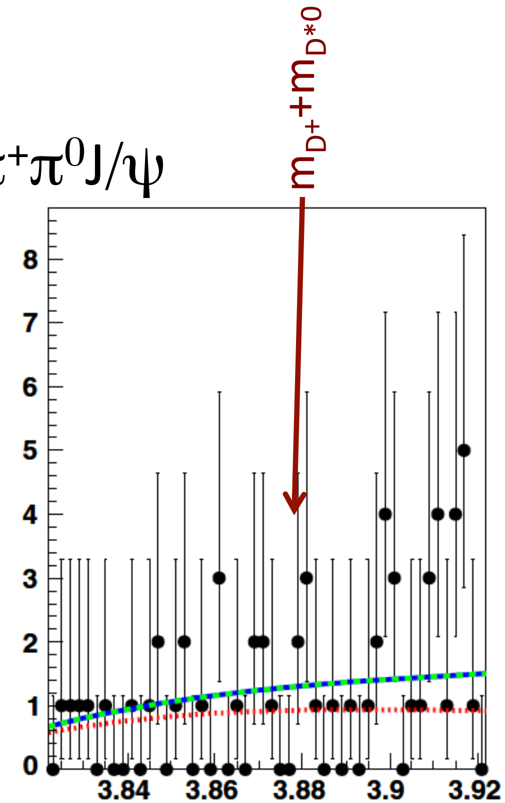
No X(3872)$^+$ in B$\rightarrow$K$\pi^+\pi^0$J/ψ

B$^0\rightarrow$K$^-\pi^+\pi^0$J/ψ



M($\pi^+\pi^0$J/ψ) (GeV)

B$^+\rightarrow$K$^0\pi^+\pi^0$J/ψ



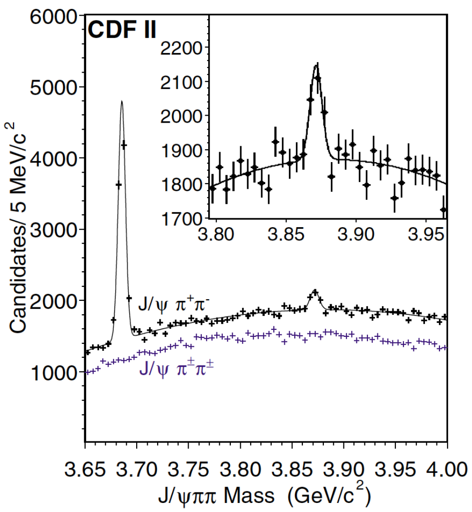
M($\pi^+\pi^0$J/ψ) (GeV)

BaBar PRD 71, 031501

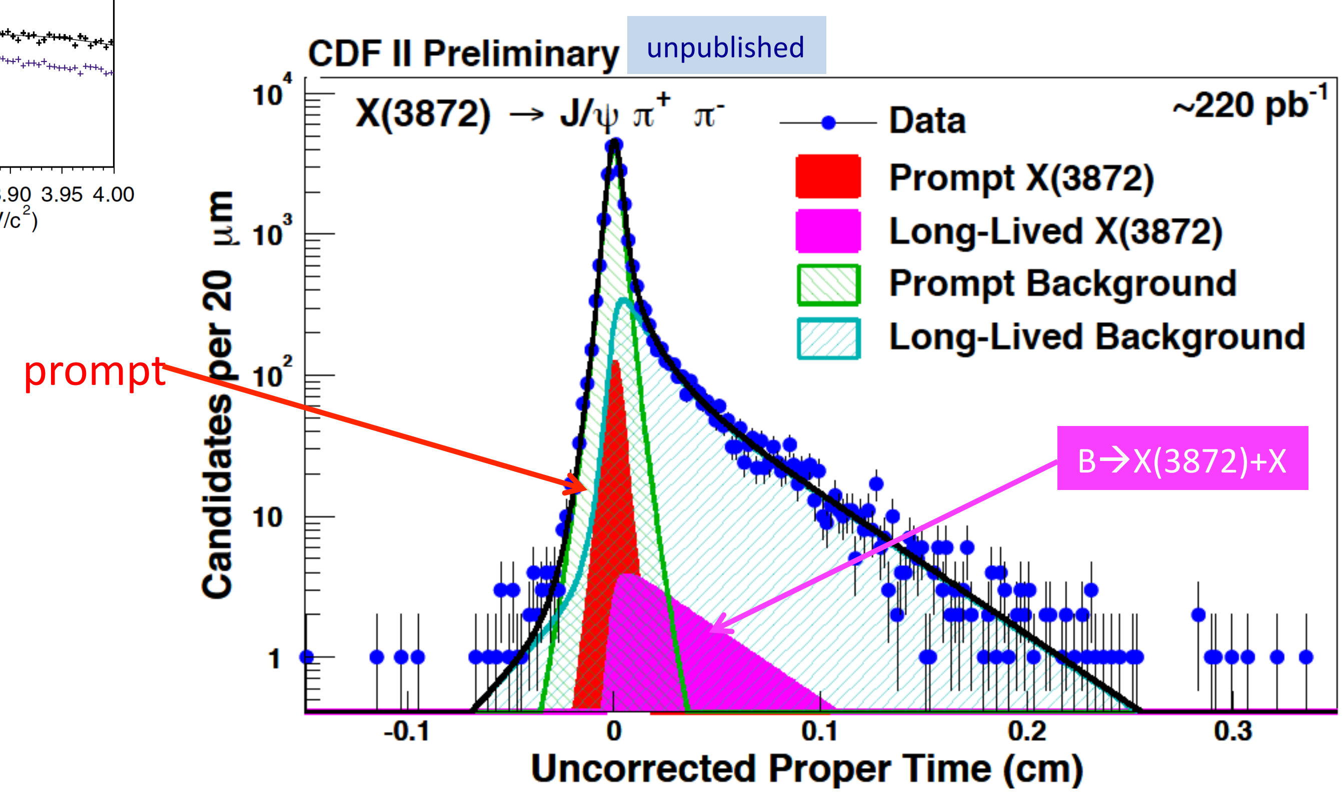
Belle PRD 84, 052004(R)

(If M(X$^+$) > $m_{D^+}+m_{D^{*0}}$ ≈ 3877 MeV, Γ(X$^+$) may be wide)

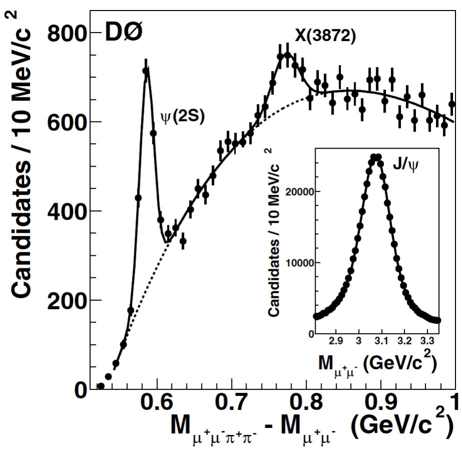
CDF: ~85% of $p\bar{p} \rightarrow X(3872)$ is prompt



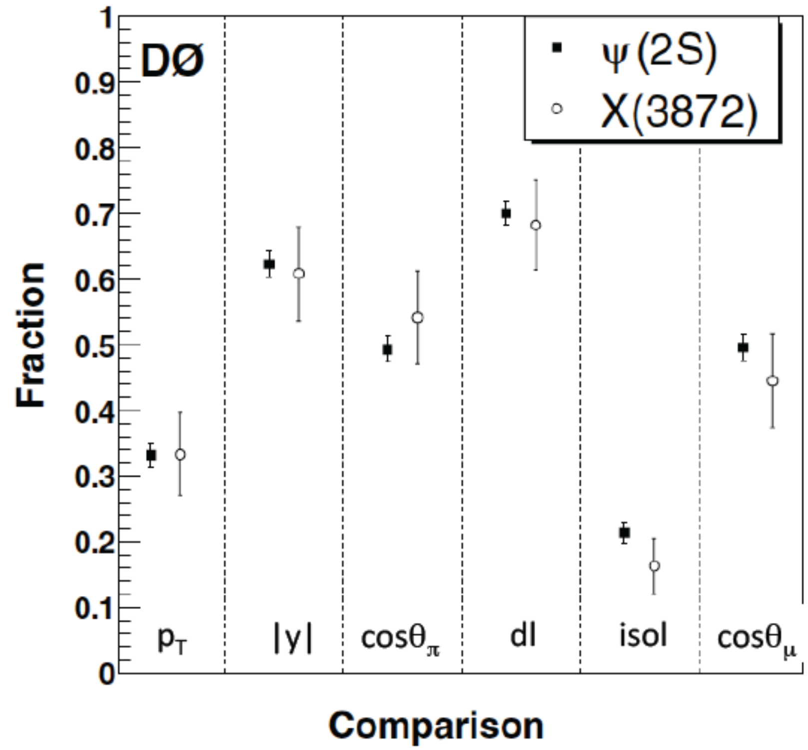
~75% @ LHC: CMS JHEP 04 (2013) 154



D0: prompt $p\bar{p} \rightarrow X(3872)X \approx p\bar{p} \rightarrow \psi'X$



D0: PRL 93, 162002

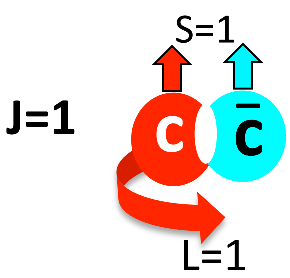


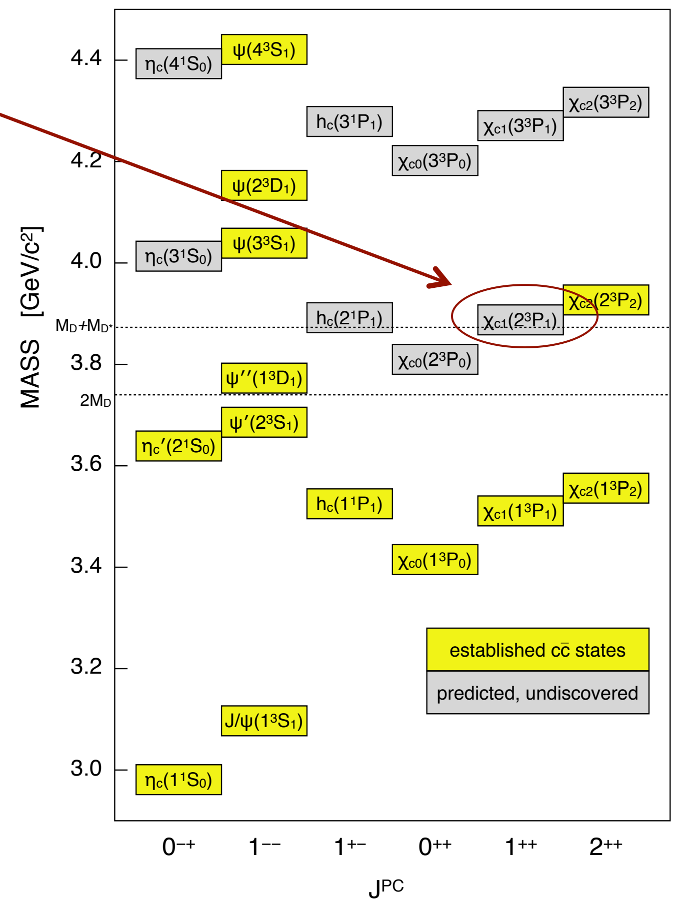
X(3872) & ψ' have similar cross sections & production characteristics: p_T- & $|y|$-dependence, isolation, etc.

See, also, CMS: JHEP 04 (2013) 154

What is the X(3872)? I

Charmonium: (χ_{c1}') ?





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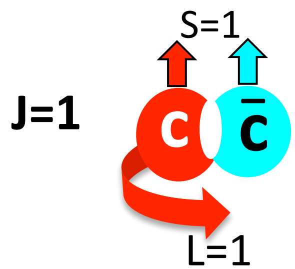
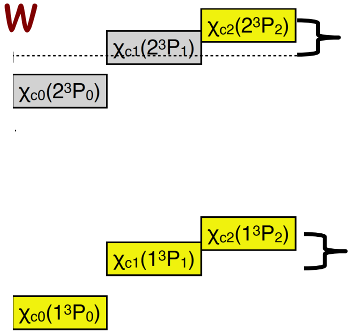


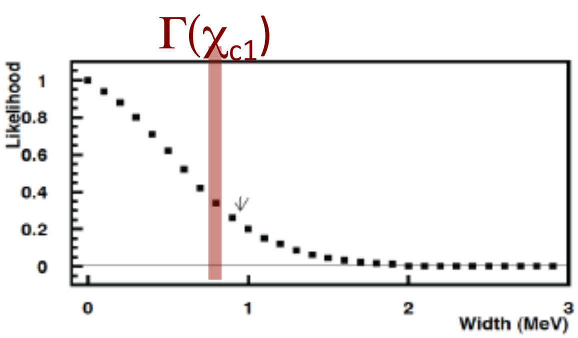
- mass is too low



$\Delta M(2P)=55\pm3$ MeV

$\Delta M(1P)=45.6$ MeV

Theory: $\Delta M(2P)<\Delta M(1P)$



- width is too narrow

more phase space & decay channels → $\Gamma(X(3872))<1.2\text{ MeV}<1.4\Gamma(\chi_{c1})$

($\Gamma(\chi_{c1}) = 0.86$ MeV)

expect: $\Gamma(\chi_{c1}')> 1.7\ \Gamma(\chi_{c1})$

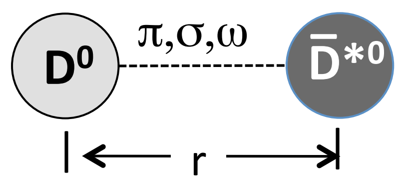
- Isospin violation

$$\underset{I=0}{\chi_{c1}'} \rightarrow \underset{I=1}{\rho}\ \underset{I=0}{J/\psi}$$

$\Delta I=1$

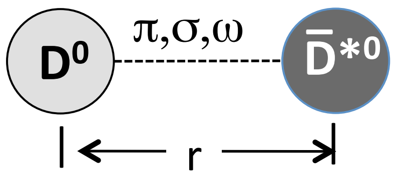
What is the X(3872)? II

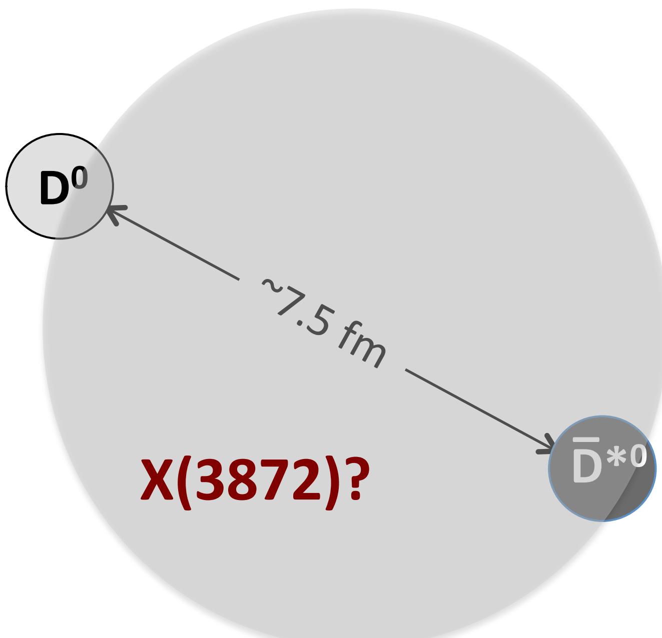
Molecule: $\frac{1}{\sqrt{2}}\left(\left|D^0\overline{D}^{*0}\right\rangle + \left|D^{*0}\overline{D}^0\right\rangle\right)$?



What is the X(3872)? II

Molecule: $\frac{1}{\sqrt{2}}\left(\left|D^0\bar{D}^{*0}\right\rangle + \left|D^{*0}\bar{D}^0\right\rangle\right)$?



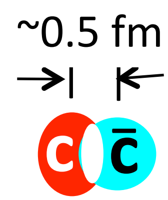


"binding energy":

$$\left|\delta M_{00}\right| = \left|M_{X(3872)} - (m_{D^0} + m_{D^{*0}})\right| \leq 0.2 \text{ MeV}$$

size ≈ scattering length

$$\left\langle r_{00}\right\rangle_{rms} \approx \sqrt{\frac{1}{2m_D\left|\delta M_{00}\right|}} \geq 7.5 \text{ fm}$$



ψ'

produced with similar cross sections
in highest energy $p\bar{p}$ collisions?

What is the X(3872)? III

QCD tetraquark: $\left| cq\bar{c}\bar{q} \right\rangle$?

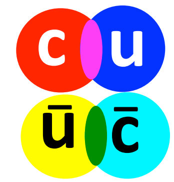
What is the X(3872)? III

QCD tetraquark: $\left| c q \bar{c} \bar{q} \right\rangle$?

tetraquark meson

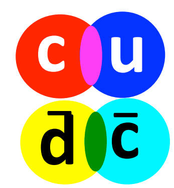
should be others:

$\left| c u \bar{c} \bar{u} \right\rangle \Leftarrow \mathrm{X_u}(3872)$

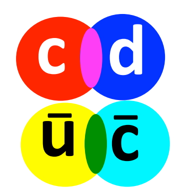


$\left| c d \bar{c} \bar{d} \right\rangle \Leftarrow \mathrm{X_d}(3872)$

$\left| c u \bar{c} \bar{d} \right\rangle \Leftarrow \mathrm{X^+}(3872)$



$\left| c d \bar{c} \bar{u} \right\rangle \Leftarrow \mathrm{X^-}(3872)$

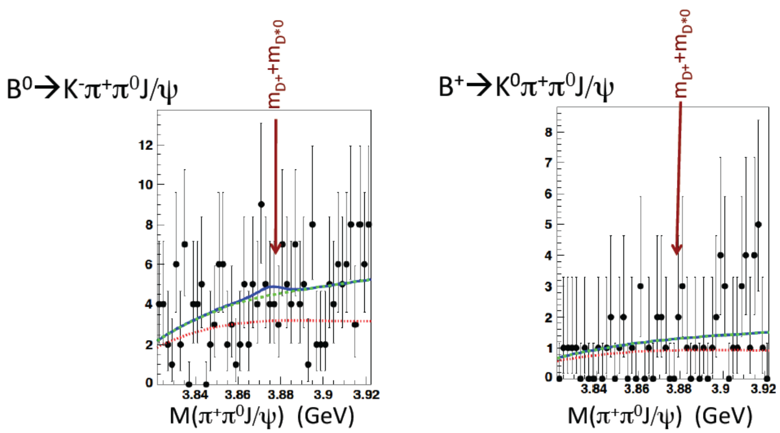


What is the X(3872)? III

QCD tetraquark: $\left|cq\bar{c}\bar{q}\right\rangle$?

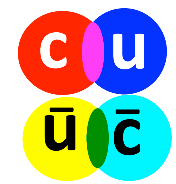
tetraquark meson

not seen



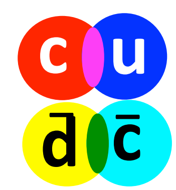
should be others:

$\left|cu\bar{c}\bar{u}\right\rangle \Leftarrow X_u(3872)$

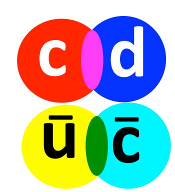


$\left|cd\bar{c}\bar{d}\right\rangle \Leftarrow X_d(3872)$

$\left|cu\bar{c}\bar{d}\right\rangle \Leftarrow X^+(3872)$



$\left|cd\bar{c}\bar{u}\right\rangle \Leftarrow X^-(3872)$



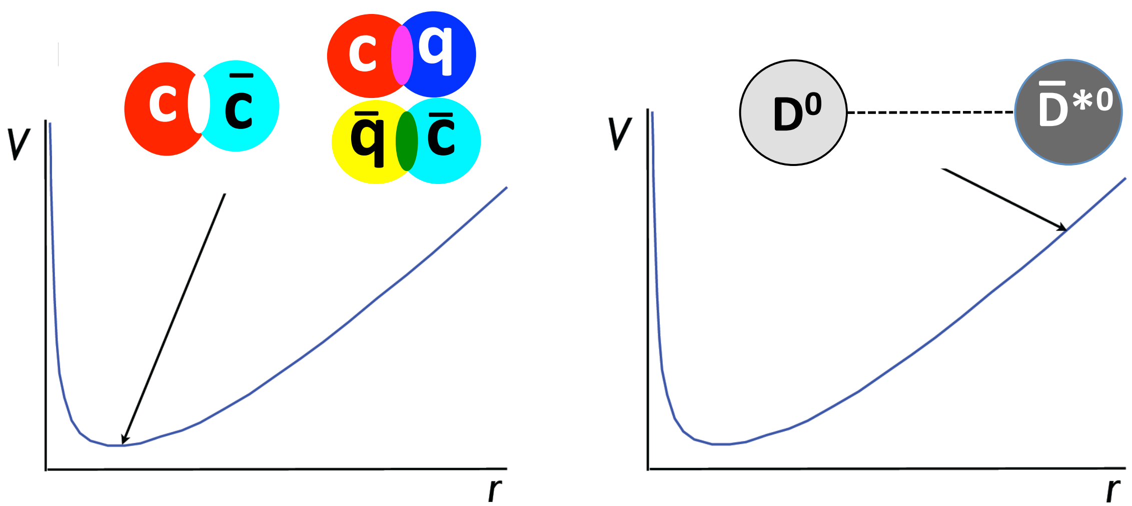
What is the X(3872)? IV

QM-mixture of the above ?

“core” state

Charmonium, QCD tetraquark

molecule

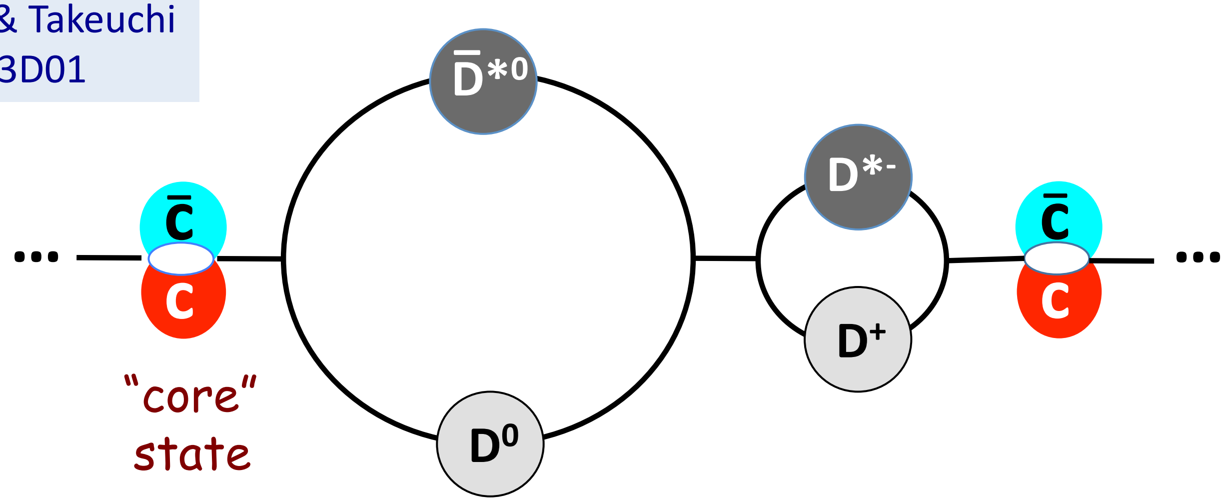


See Eric Braaten’s talk at QWG 2014, CERN

“hybrid” model for the X(3872)

Example calculation:

Takizawa & Takeuchi
PTEP 9, 093D01

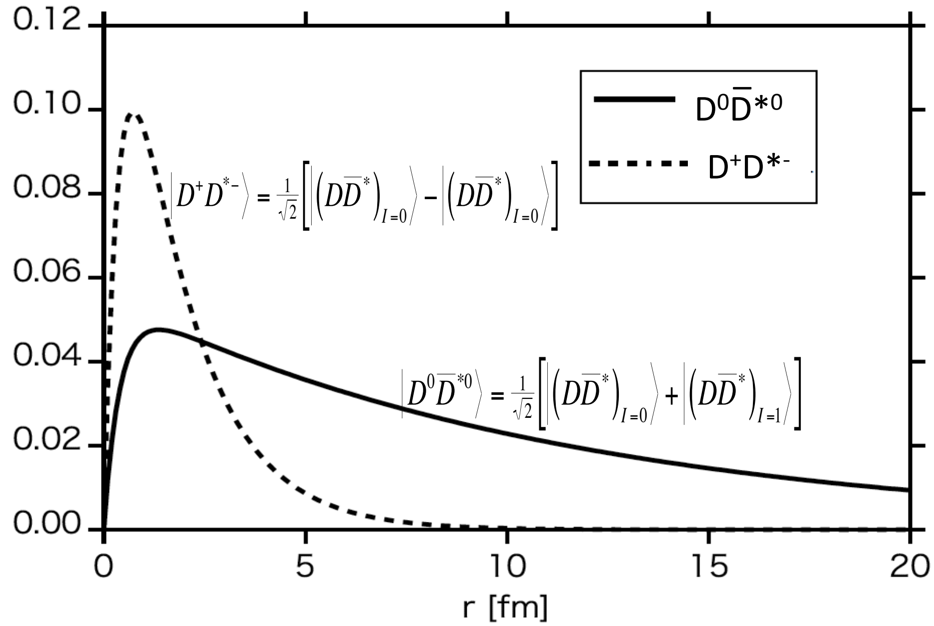


$$\left|X(3872)\right\rangle = \underbrace{0.94\left|D^0\overline{D}^{*0}\right\rangle}_{89\%} + \underbrace{0.23\left|D^+D^{*-}\right\rangle}_{5\%} - \underbrace{0.24\left|c\overline{c}\right\rangle}_{6\%} \approx \left|\chi'_{c1}\right\rangle$$

Looks like a molecule, but binding comes from

$c\bar{c}$-$D\bar{D}^*$ couplings (not from D-$\bar{D}^*$ attraction)

$D^0\bar{D}^{*0}$ and D^+D^{*-} radial wave functions



$$|X(3872)\rangle = 0.94\left|D^0\bar{D}^{*0}\right\rangle + 0.23\left|D^+D^{*-}\right\rangle - 0.24|c\bar{c}\rangle$$

$$|X(3872)\rangle = 0.83\left|\left(D\bar{D}^*\right)_{I=0}\right\rangle + 0.51\left|\left(D\bar{D}^*\right)_{I=1}\right\rangle - 0.24|c\bar{c}\rangle$$

mostly I=0

X→ωJ/ψ decays

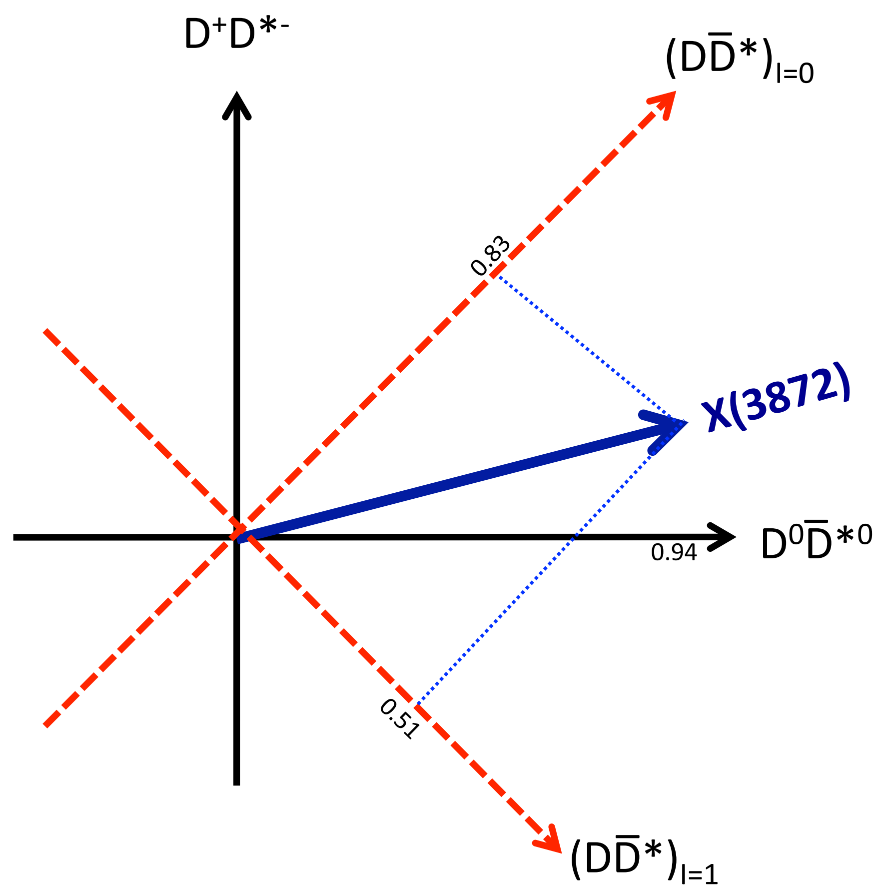
X→ρJ/ψ decays

production

X(3872): not a pure Isospin state

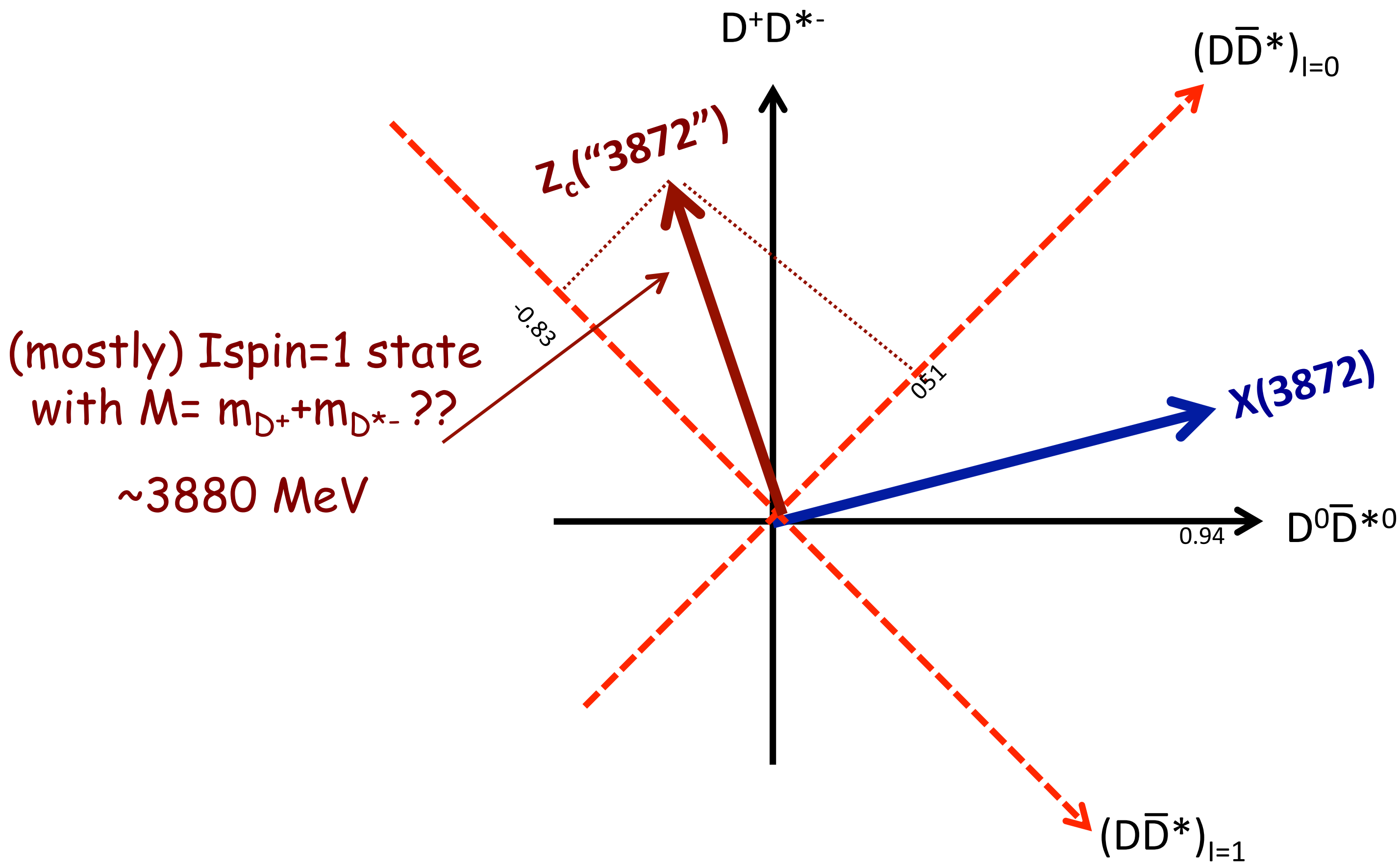
69% 26% 6%

$$\left|X(3872)\right\rangle = 0.83\left|\left(D\overline{D}^{*}\right)_{I=0}\right\rangle + 0.51\left|\left(D\overline{D}^{*}\right)_{I=1}\right\rangle - 0.24\left|c\overline{c}\right\rangle$$

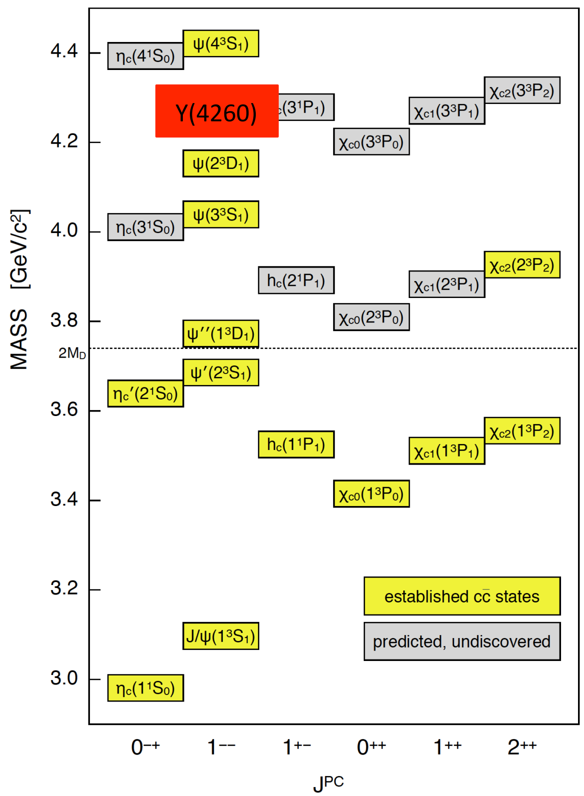


Is there an orthogonal I≈1 state?

$$\left|Z_c(\text{"}3872\text{"})\right\rangle = 0.51\left|\left(D\overline{D}^*\right)_{I=0}\right\rangle - 0.83\left|\left(D\overline{D}^*\right)_{I=1}\right\rangle - 0.24\left|c\overline{c}\right\rangle$$

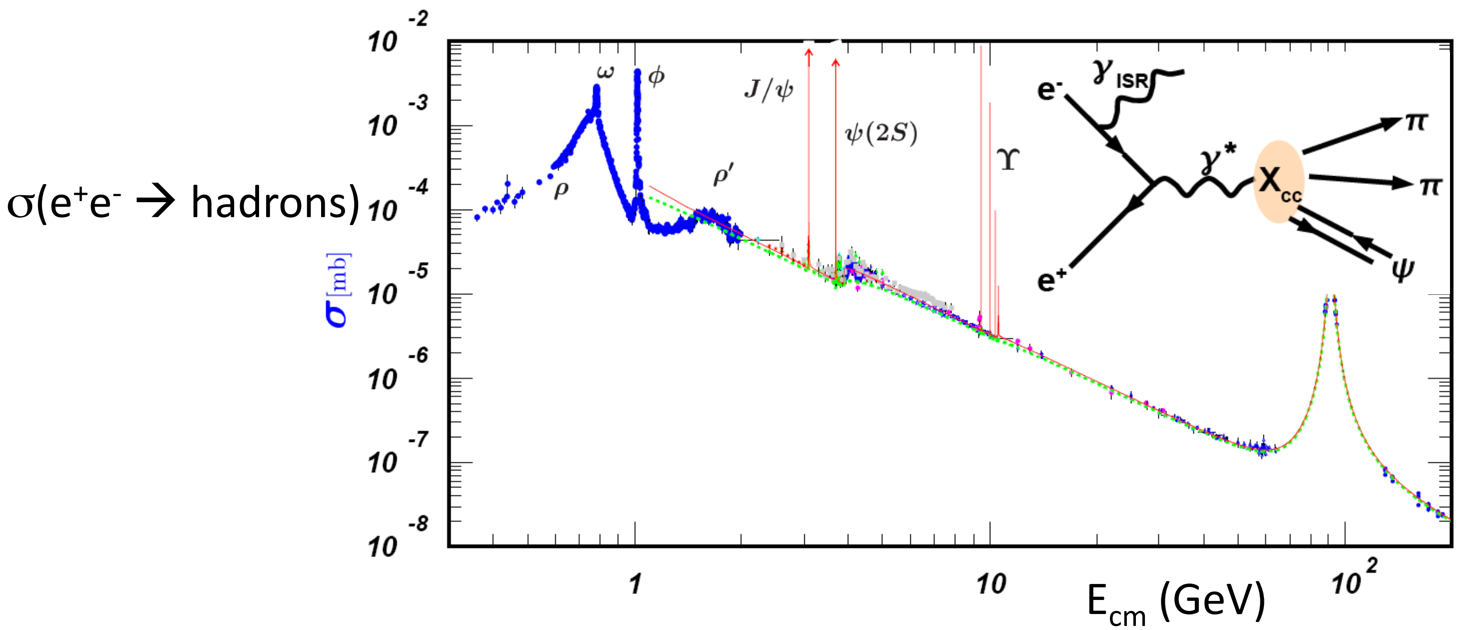


The Y(4260)



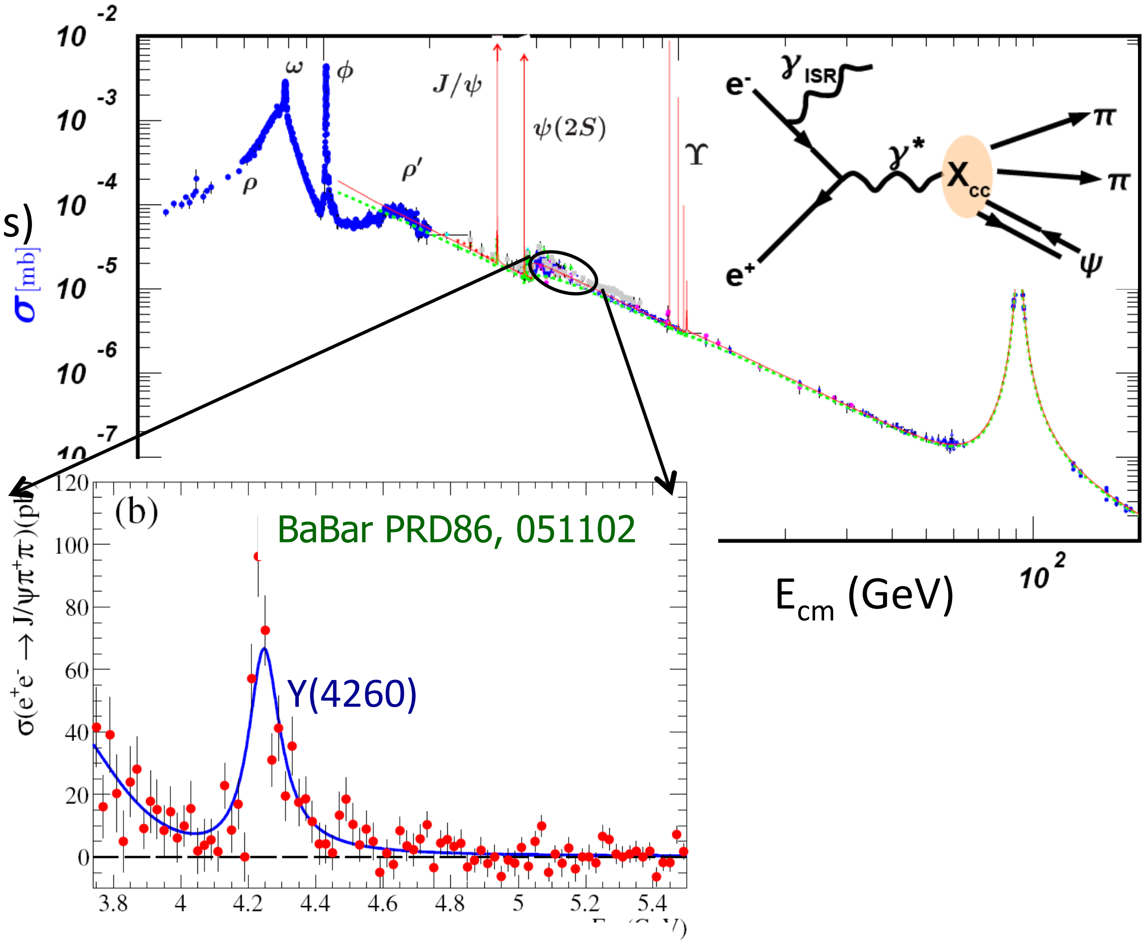
Y(4260)
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
(3^1P_1)
$\chi_{c1}(3^3P_1)$
$\chi_{c2}(3^3P_2)$
$\chi_{c0}(3^3P_0)$
$\psi(2^3D_1)$
$\eta_c(3^1S_0)$
$\psi(3^3S_1)$
$h_c(2^1P_1)$
$\chi_{c1}(2^3P_1)$
$\chi_{c2}(2^3P_2)$
$\chi_{c0}(2^3P_0)$
$\psi''(1^3D_1)$
$2M_D$
$\psi'(2^3S_1)$
$\eta_c'(2^1S_0)$
$h_c(1^1P_1)$
$\chi_{c1}(1^3P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c0}(1^3P_0)$
$J/\psi(1^3S_1)$
$\eta_c(1^1S_0)$
established $c\bar{c}$ states
predicted, undiscovered
MASS [GeV/c^2]
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
J^{PC}

found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$



found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$

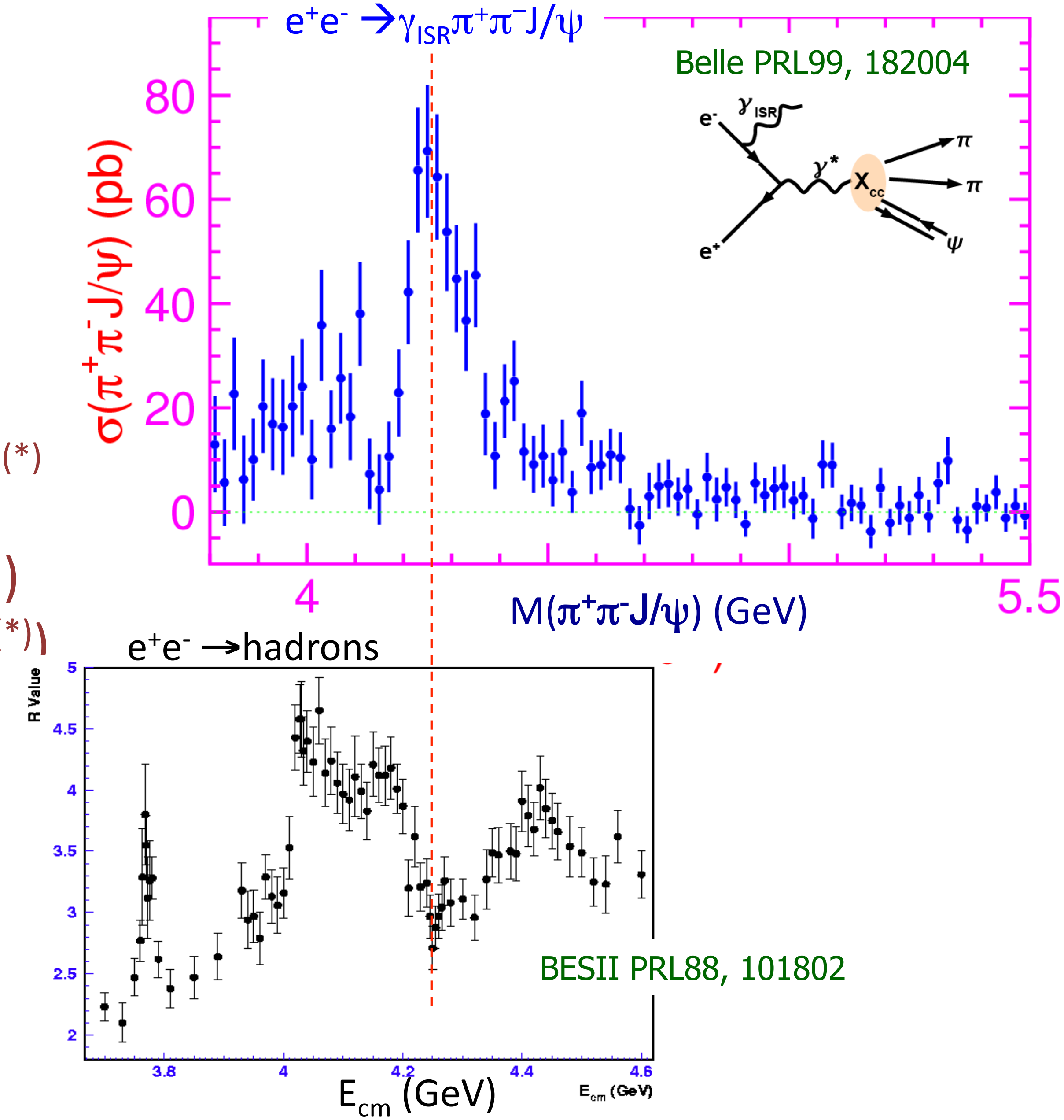
$\sigma(e^+e^- \rightarrow \text{hadrons})$



E_{cm} (GeV)

$M(\pi^+\pi^- J/\psi)$ (GeV)

$Y(4260) \to \pi^+\pi^- J/\psi$ confirmed by Belle



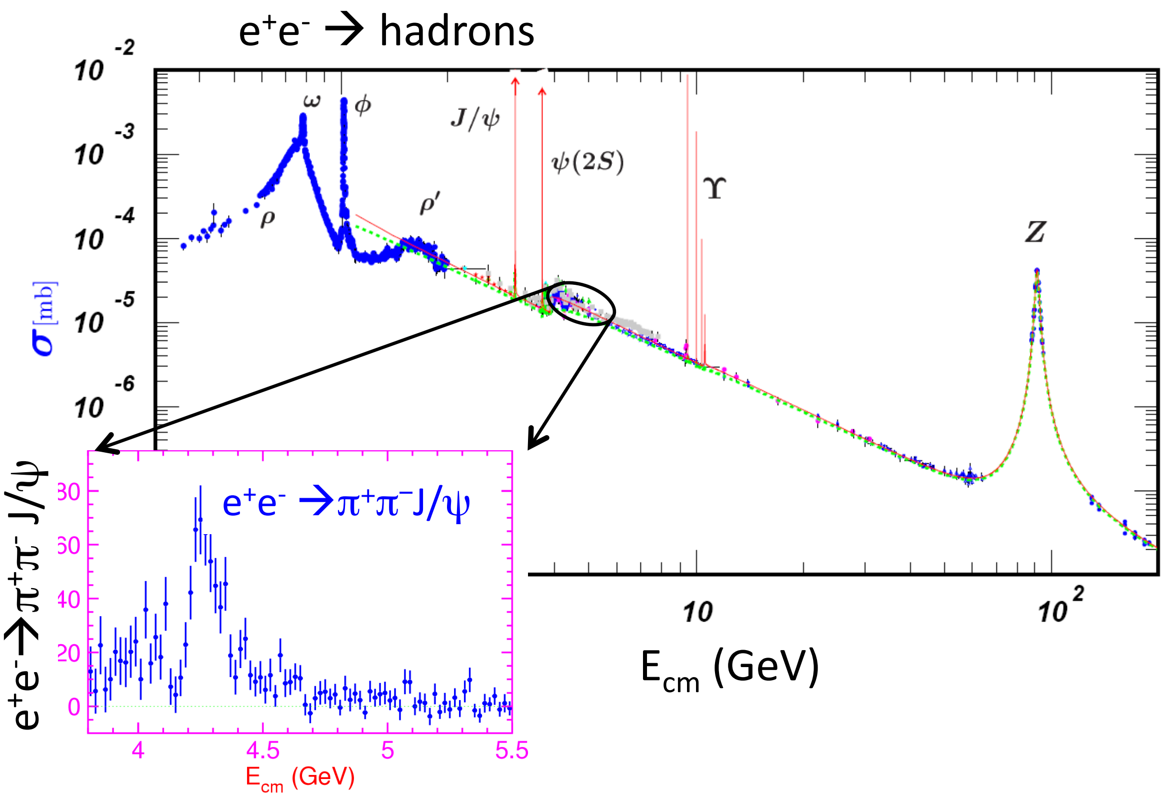
No sign of $Y(4260) \to D^{(*)}\bar{D}^{(*)}$

$Y(4260)$ peak in $\sigma(\pi^+\pi^- J/\psi)$ occurs at a dip in $\sigma(D^{(*)}\bar{D}^{(*)})$

$\to \Gamma(\pi^+\pi^- J/\psi)$ is large, but OZI suppressed for $c\bar{c}$

X. H. Mo et al., PLB 640, 182

Is there a b-quark version of Y(4260)?



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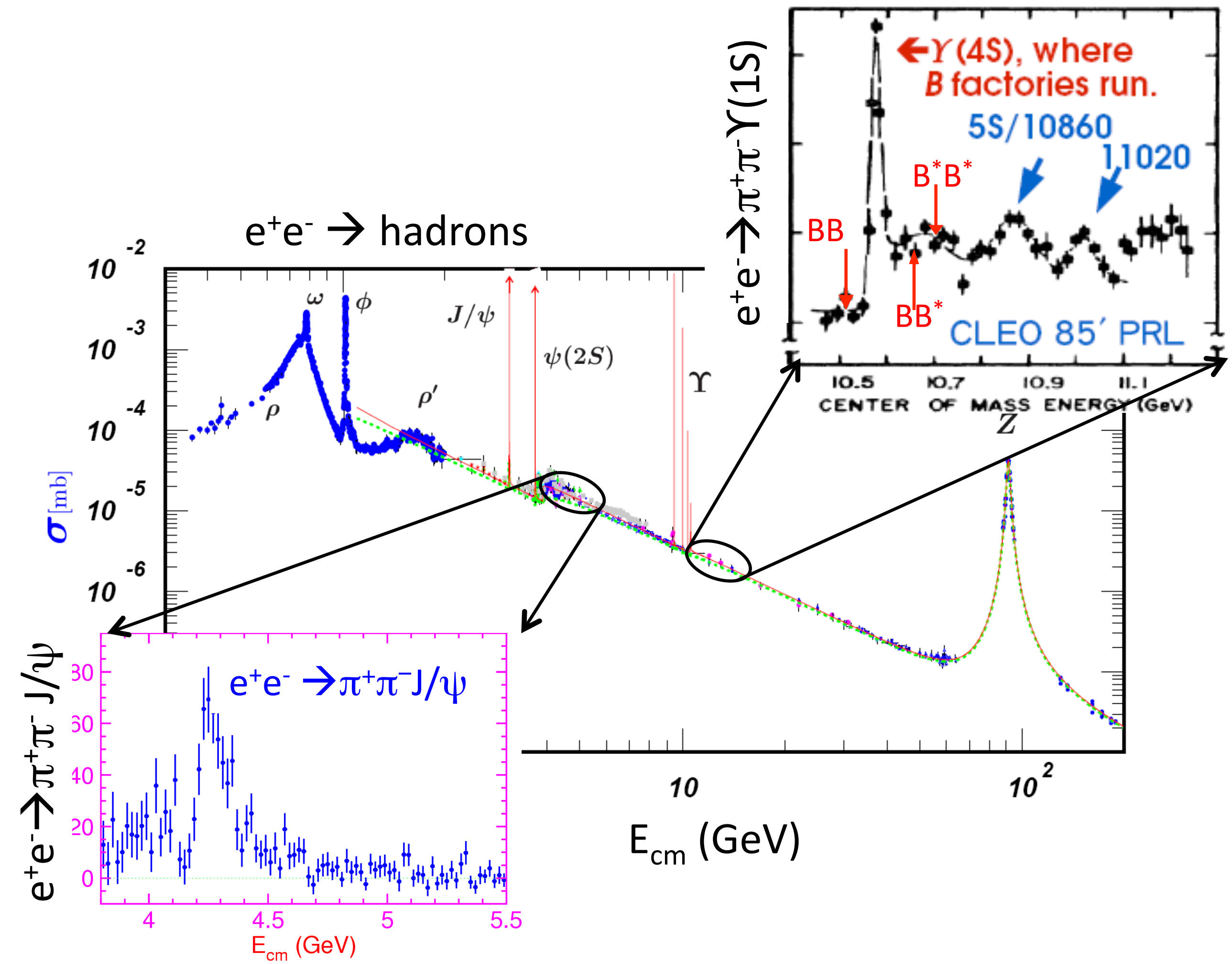

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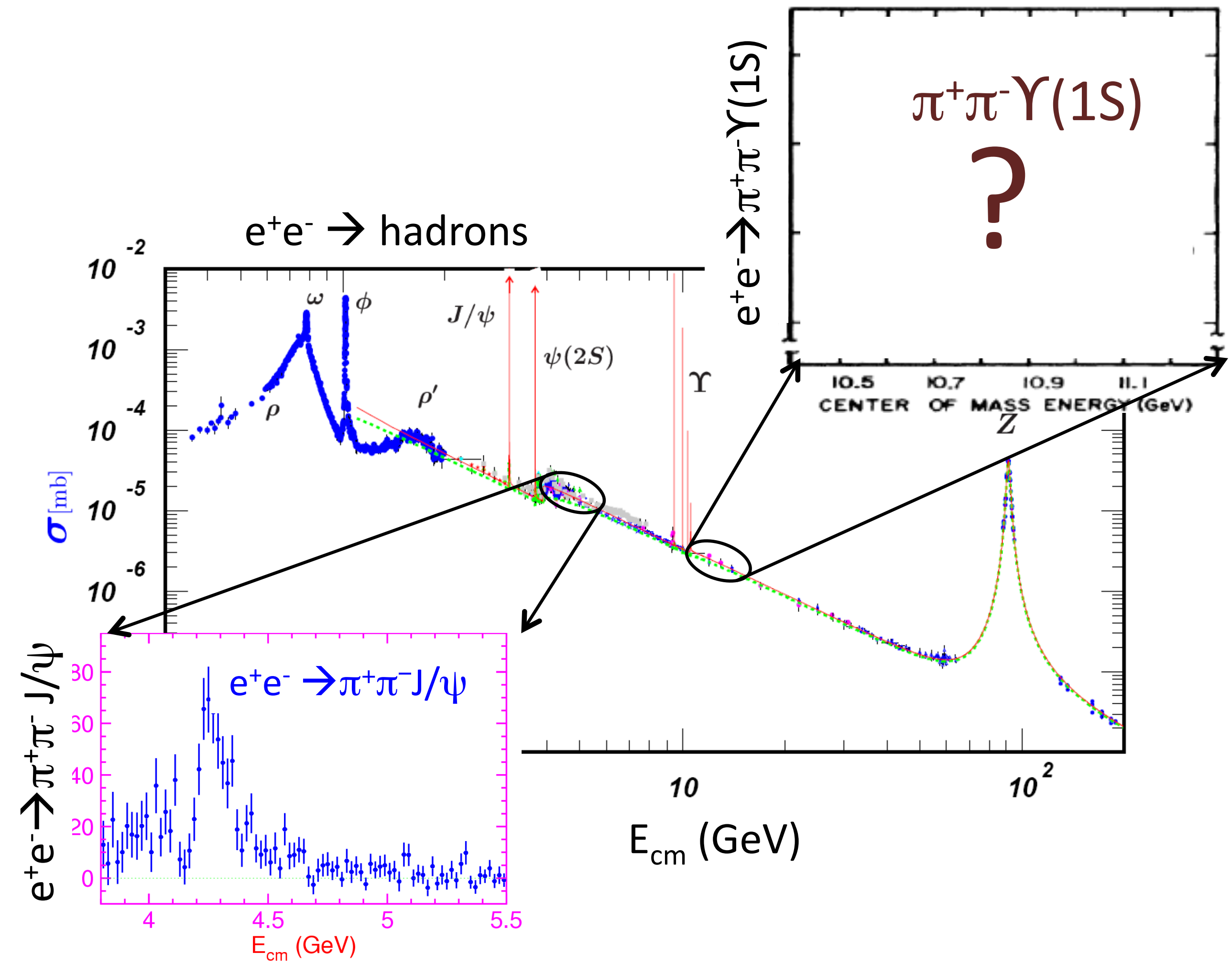
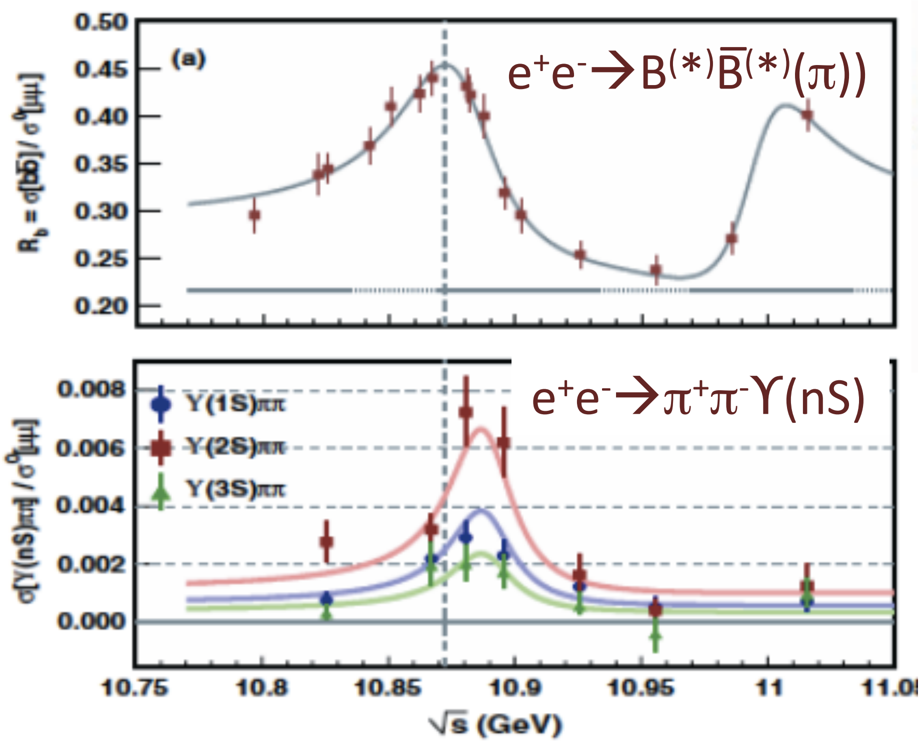


Yes



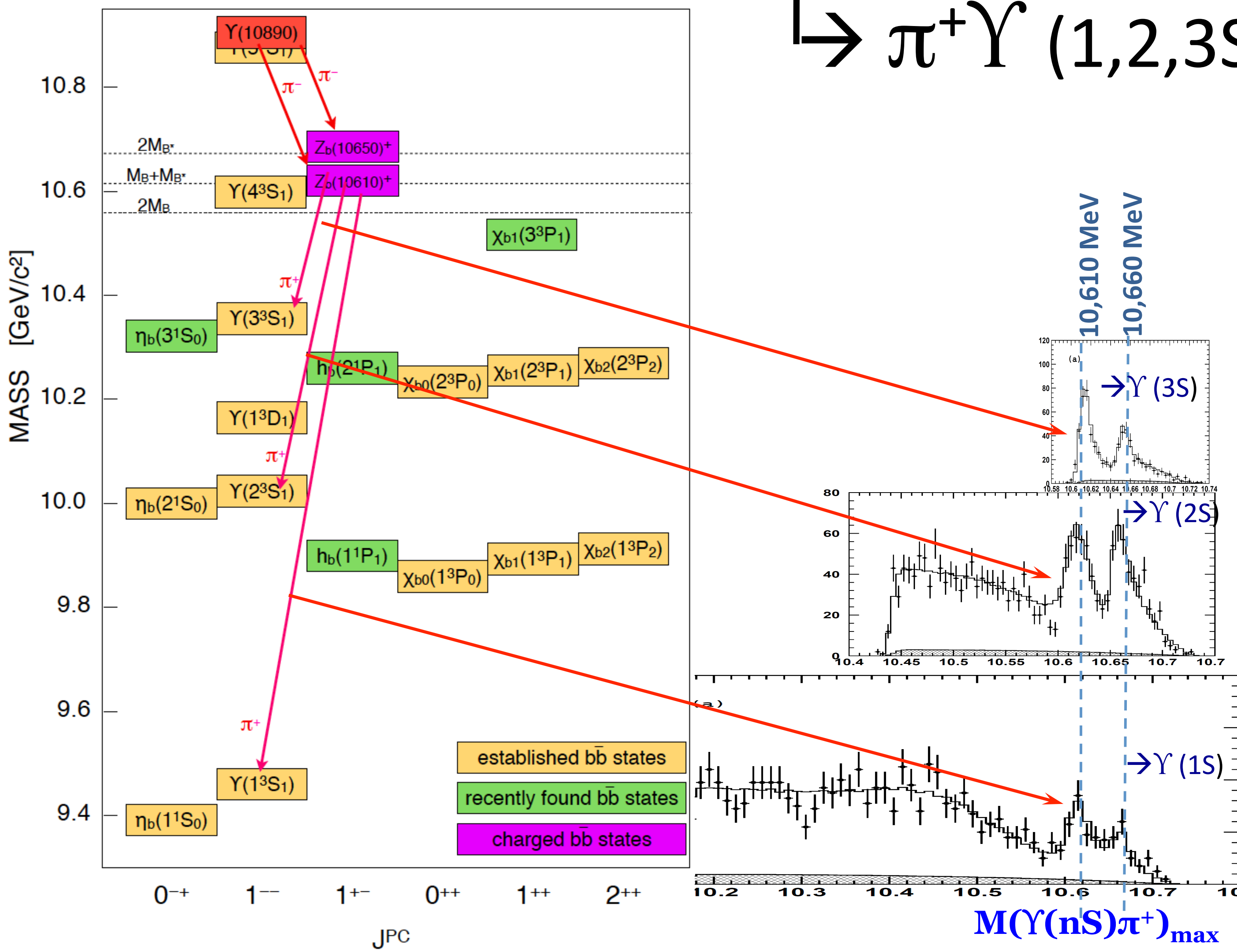
PRD82,091106(2010)

$\pi^+\pi^-\Upsilon(nS)$ rate is 100's of times bottomonium model expections

$“\Upsilon(5S)” \rightarrow \pi^- Z^+_{b1,2}$

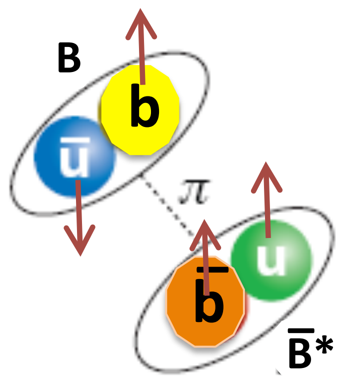
$\hookrightarrow \pi^+ \Upsilon(1,2,3S)$

Belle PRL 108, 122001 (2012)
121.4 fb^{-1}



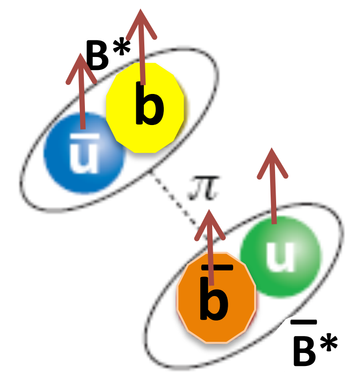
B-$\bar{B}$* & B*-$\bar{B}$* molecules??

$Z_b(106010)^{\pm}$



B-$\bar{B}$* "molecule"

$Z_b(106050)^{\pm}$



B*-$\bar{B}$* "molecule"

$M_{Z_b(106010)} - (M_B + M_{B*}) = +\,3.6 \pm 1.8$ MeV

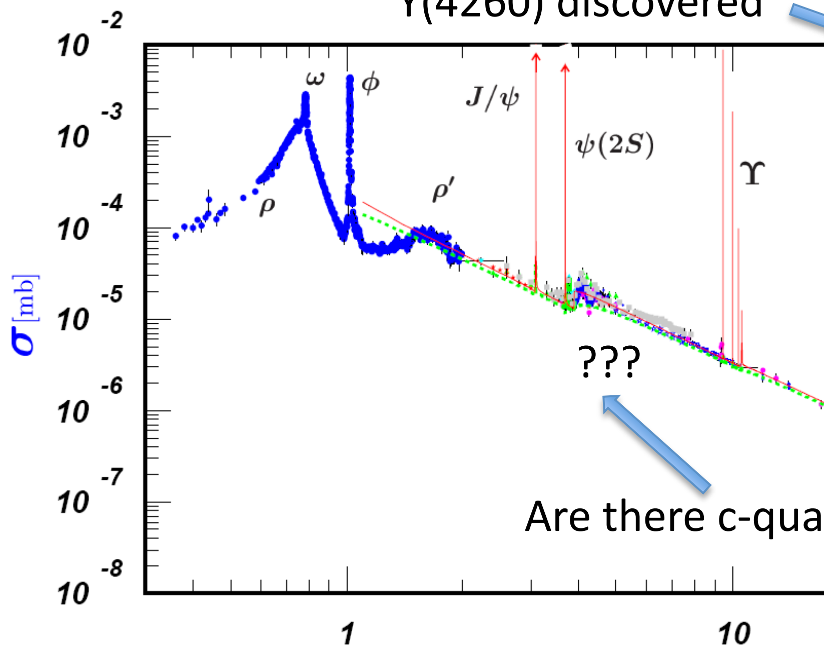
$M_{Z_b(106010)} - 2M_{B*} = +\,3.1 \pm 1.8$ MeV

Slightly unbound threshold resonances??

Belle:	M=10608.1±1.7 MeV Γ=15.5±2.4 MeV	M=10653.3±1.5 MeV Γ=14.0±2.8 MeV
PDG:	$M_B + M_{B*} = 10604.5 \pm 0.6$ MeV	$M_{B*} + M_{B*} = 10650.2 \pm 1.0$ MeV

Are there c-quark versions of Z_b's

Y(4260) discovered



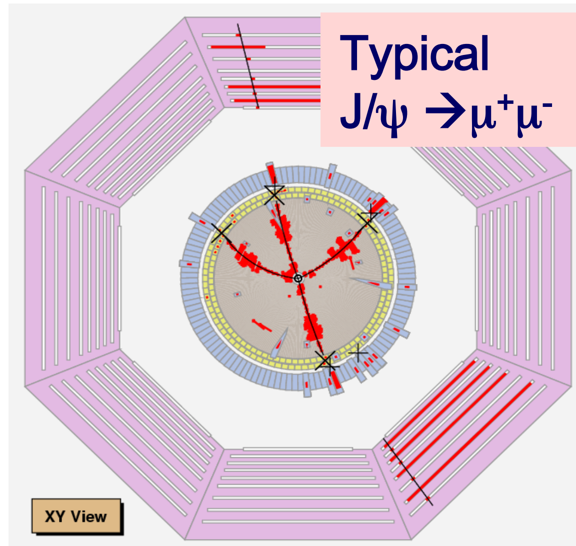
Is there a b-quark equivalent?

Yes, & it decays to Z_b states

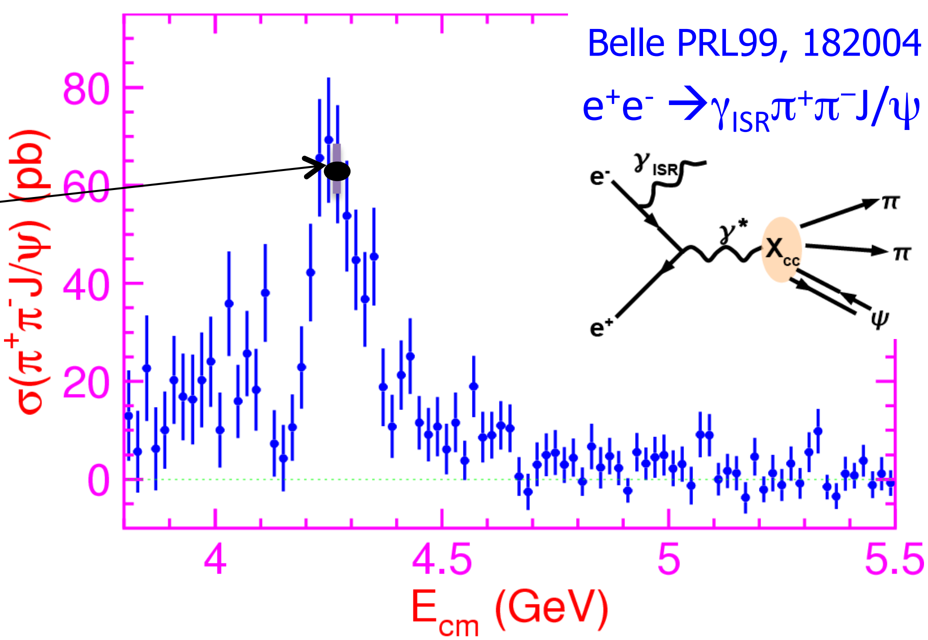
Are there c-quark versions of Z_b's?

run BEPCII/BESIII as a Y(4260) factory

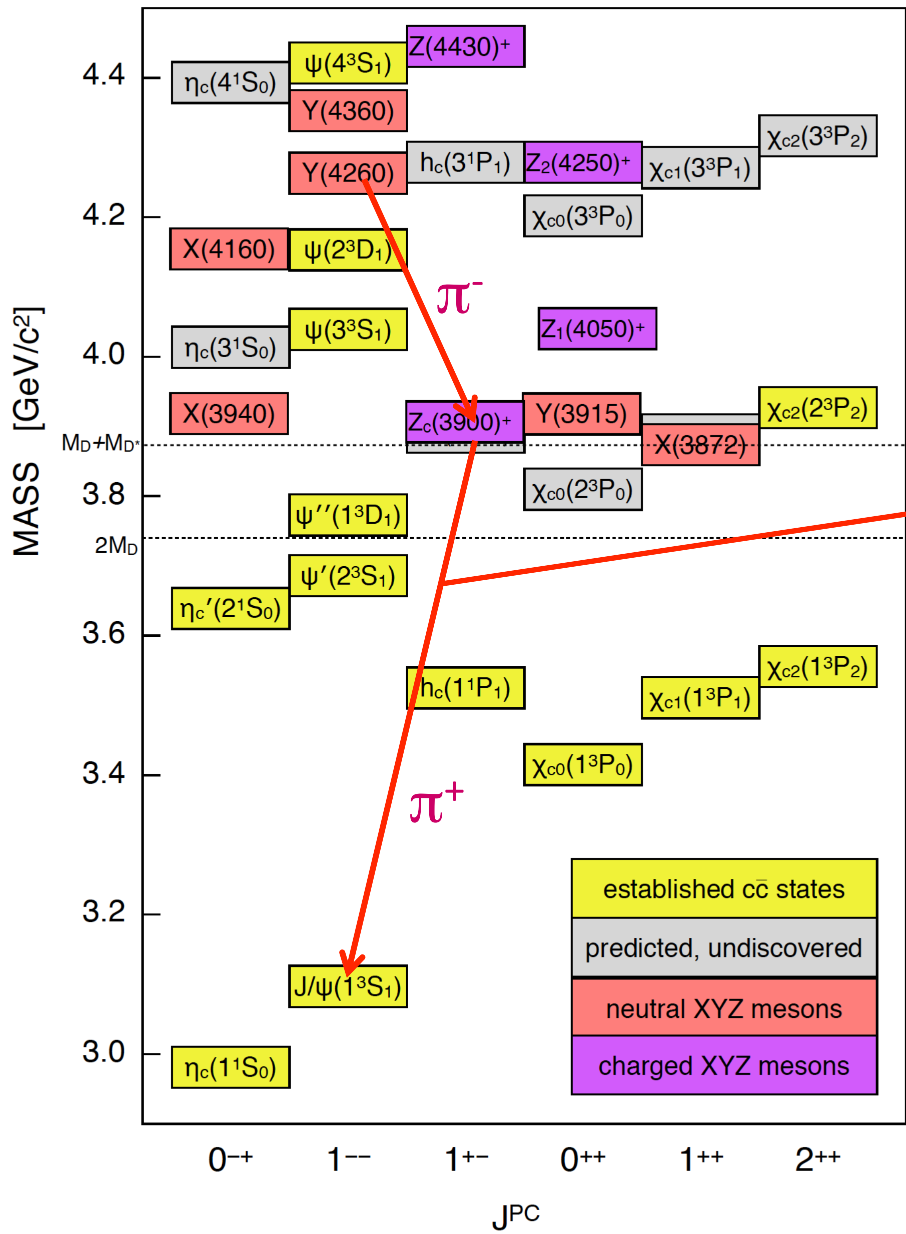
$e^+e^- \to \pi^+\pi^- J/\psi$
@E_{cm}=4260 MeV

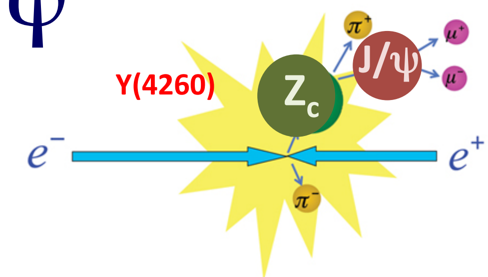


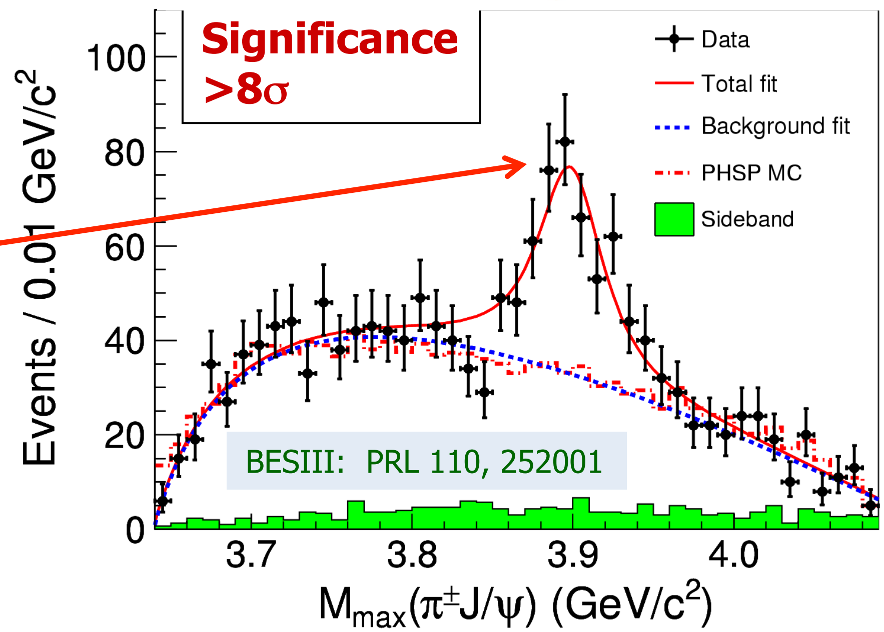
BESIII: PRL 110, 252001 (2013)
$\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ = (62.9±1.9±3.7) pb



$Y(4260) \rightarrow \pi^- Z_c(3900)^+$
$\hookrightarrow \pi^+ J/\psi$



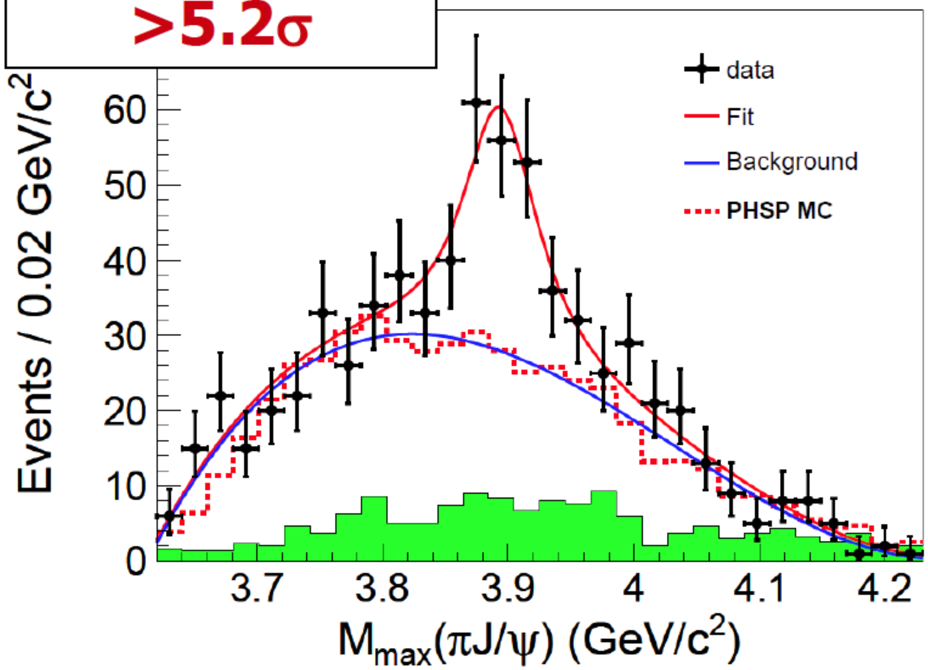




- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

Z_c(3900) also found by Belle

Significance >5.2σ



Mass = (3894.5 ± 6.6 ± 4.5) MeV
Width = (63 ± 24 ± 26) MeV
Fraction = (29.0 ± 8.9)% (stat. err. only)

Belle: PRL 110, 252002

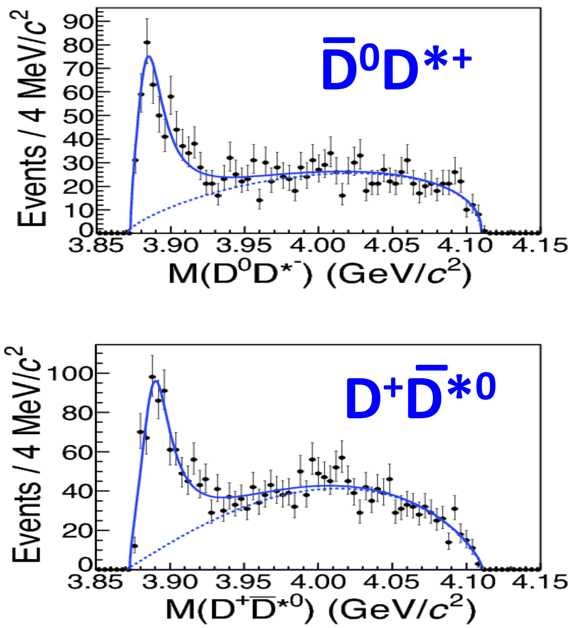
$Z_c(3900) \rightarrow D\bar{D}^*$

BESIII:

$e^+e^- \rightarrow Y(4260) \rightarrow \pi D\bar{D}^*$

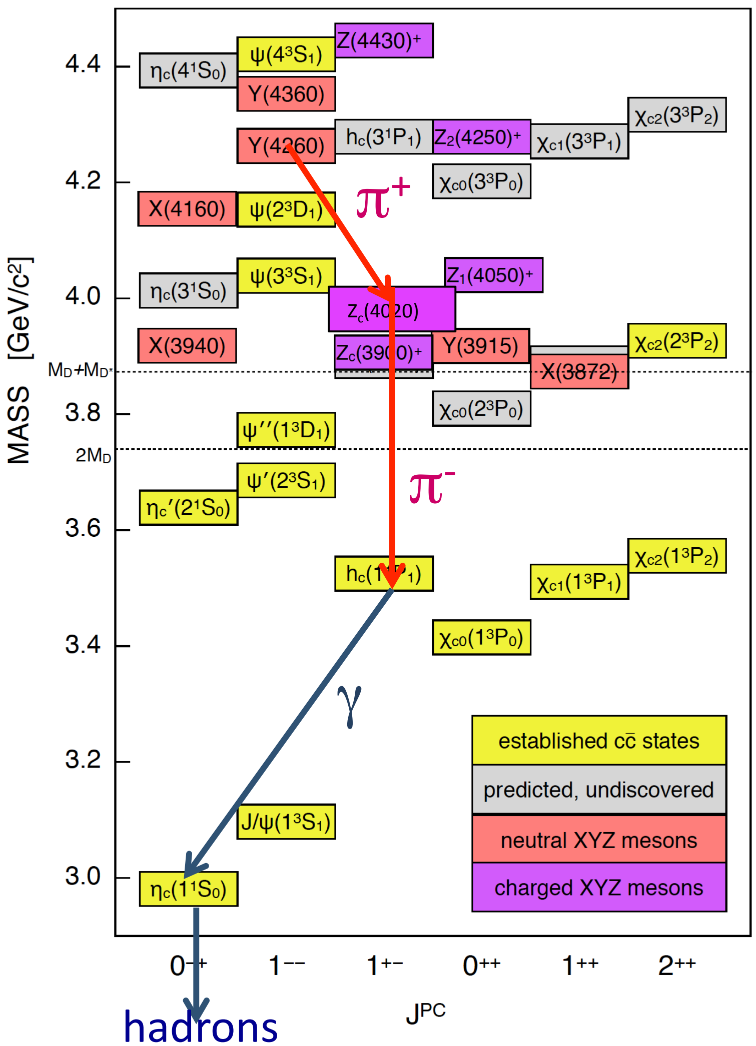
$Y(4260) \rightarrow \pi\, Z_c(3900)$

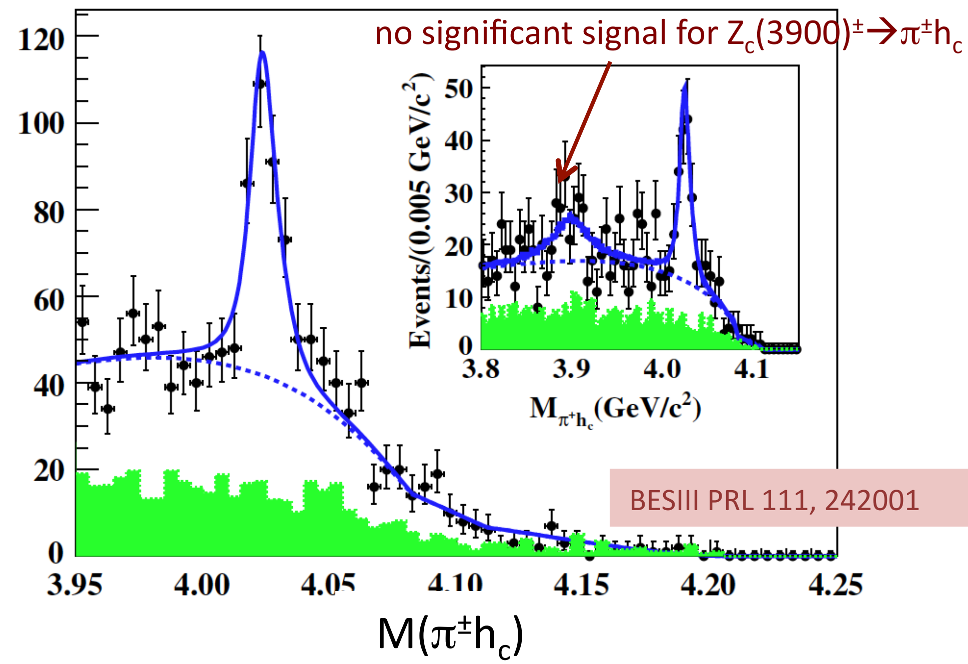
$\hookrightarrow D\bar{D}^*$



BESIII PRL 112, 022001

$Y(4260) \to \pi^+ Z_c(4020)^-$
$\hookrightarrow \pi^- h_c$

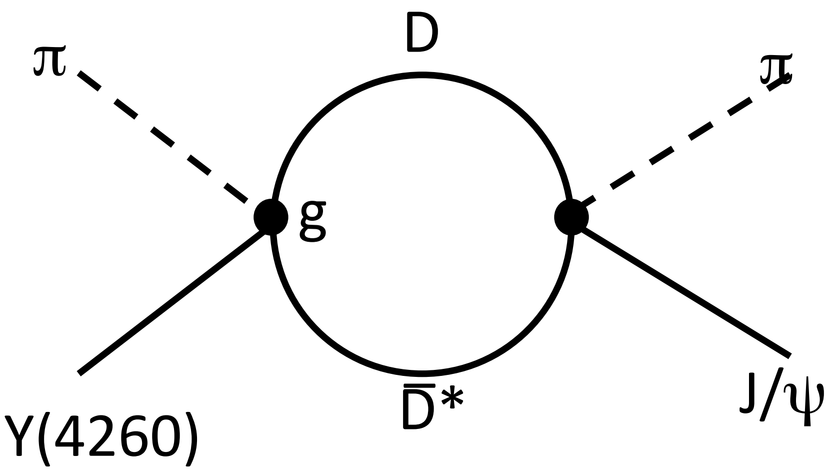




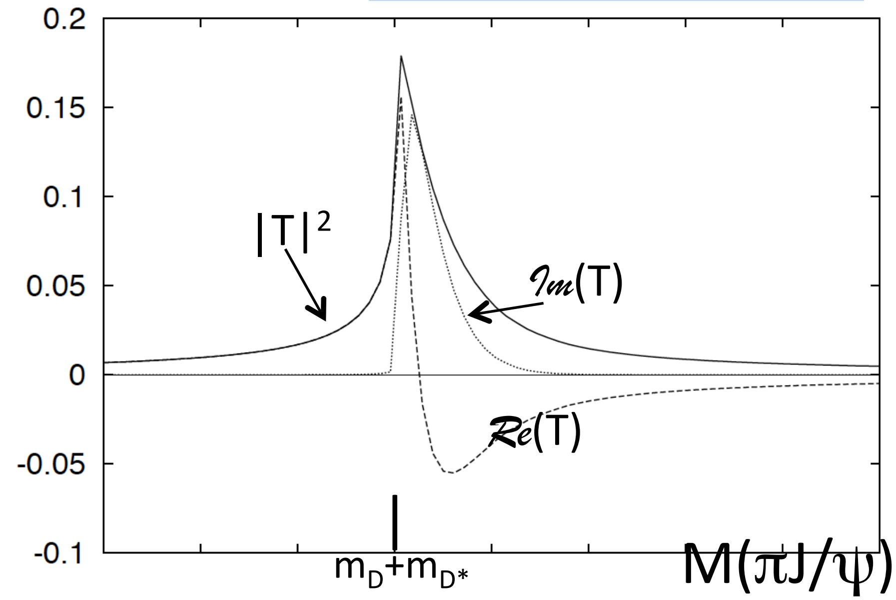
5.6 ± 2.8 MeV above $D^{*0}D^{*-}$ thresh.
= 4017.3 ±0.3 MeV

Fit results:
Mass = (4022.9 ±0.8 ±2.7) MeV
Width = (7.9 ±2.7 ±2.6) MeV
fraction = 0.18 ± 0.07

Could $Z_c(3900)$ be a threshold cusp?



Bugg: EPL 96 11002 (2011)

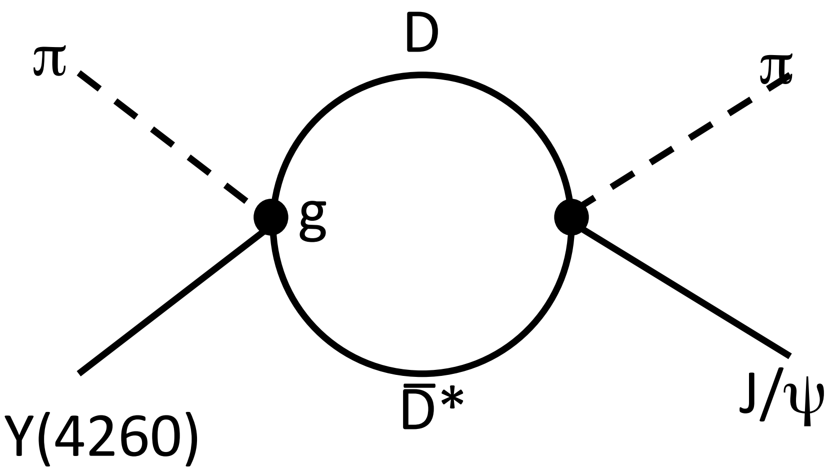


$$\mathrm{Im}\,T \propto g^2 \frac{2k}{\sqrt{s'}} FF(s')$$

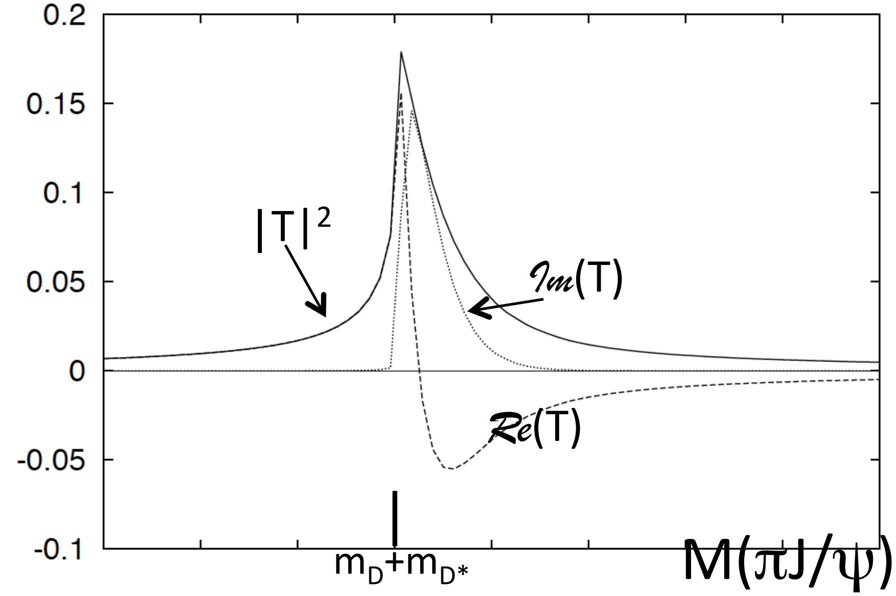
Analyticity:

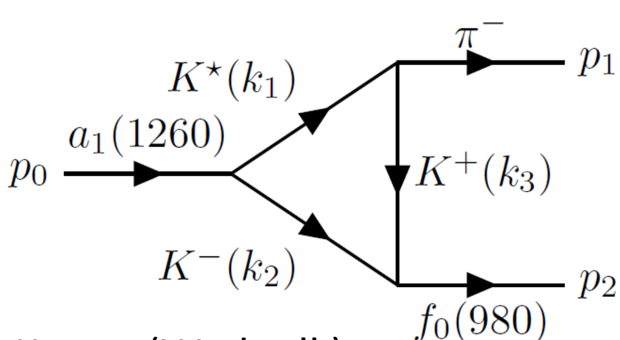
$$\mathrm{Re}\,T \propto \frac{1}{\pi} P \int_{s_{thr}}^{M_Y^2} \frac{\mathrm{d}s'\ \mathrm{Im}\,T}{s' - s}$$

Could $Z_c(3900)$ be a threshold cusp?



Bugg: EPL 96 11002 (2011)





B. Ketzer (Wed talk)

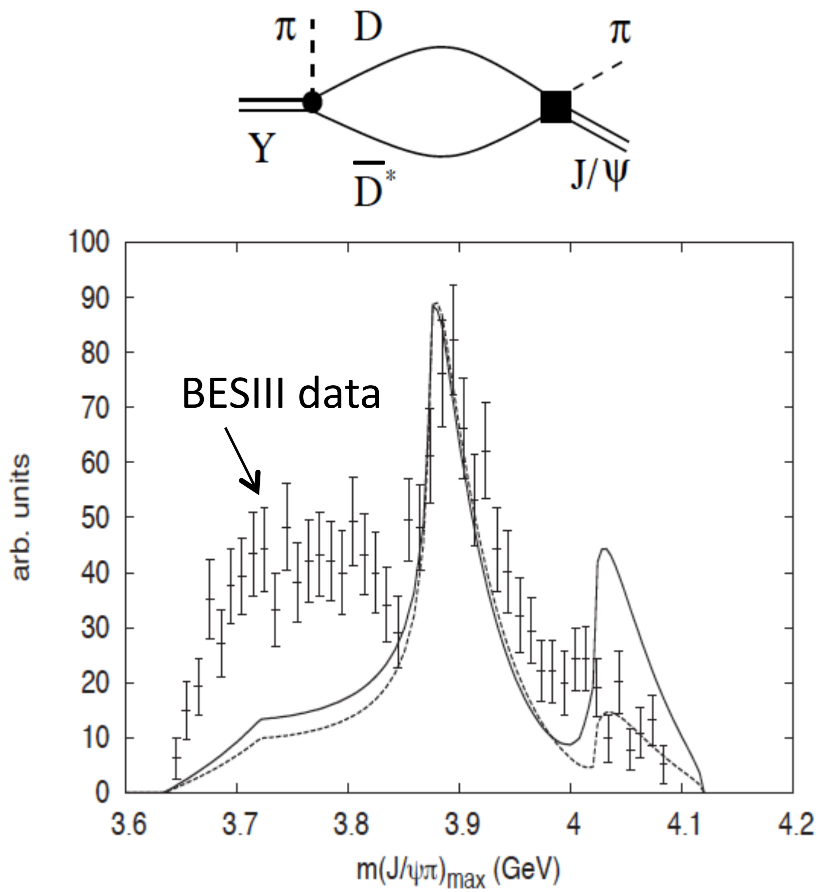
$$\mathrm{Im}\, T \propto g^2 \frac{2k}{\sqrt{s'}} FF(s')$$

Analyticity:

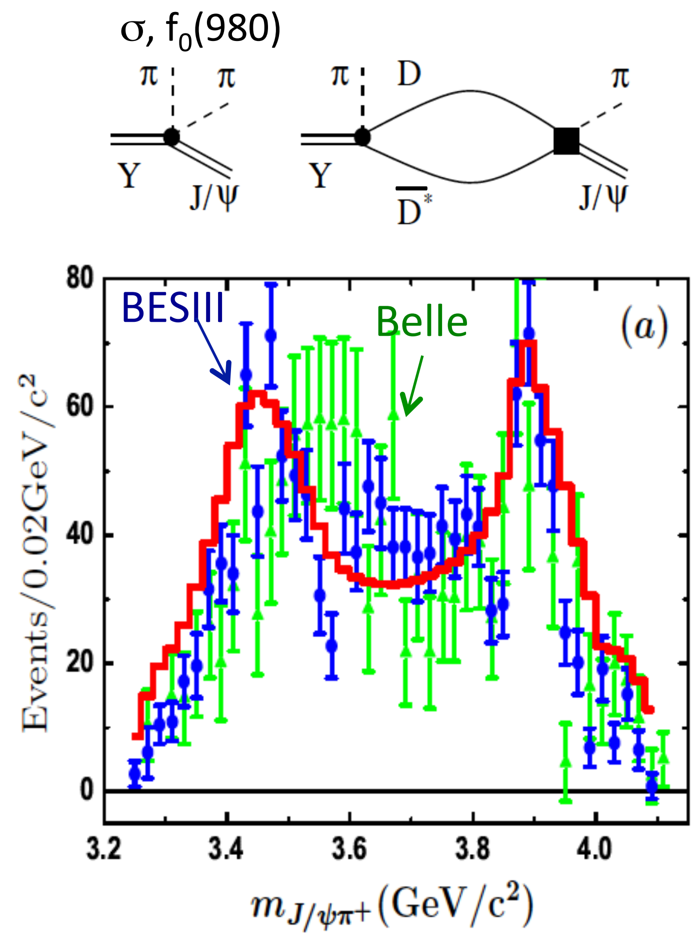
$$\mathrm{Re}\, T \propto \frac{1}{\pi} P \int_{s_{thr}}^{M_Y^2} \frac{ds' \ \mathrm{Im}\, T}{s' - s}$$

Comparisons with data

Swanson: arXiv:1409.3291

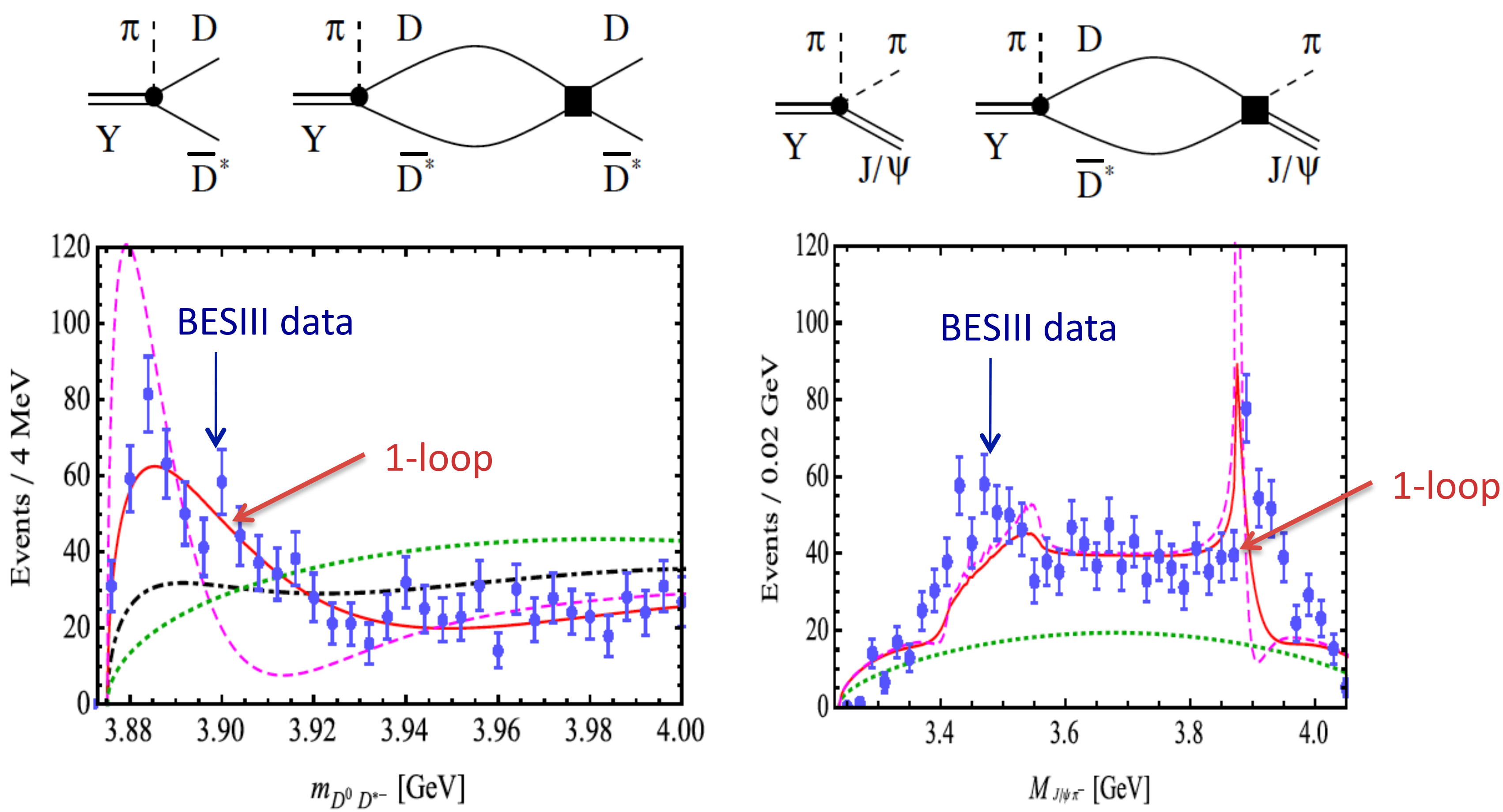


Chen et al. PRD 88 036008409.3291

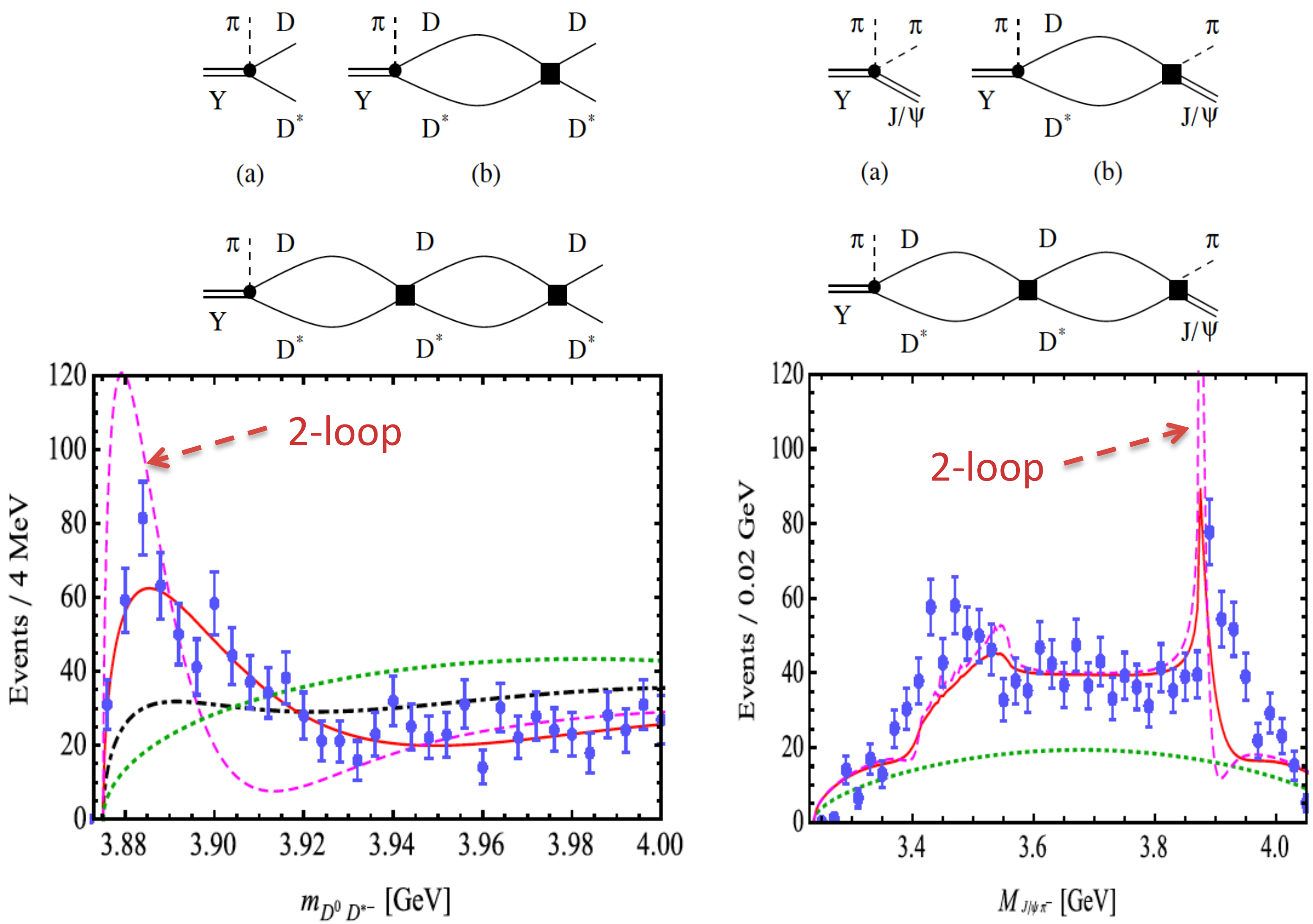


Combined fit to J/ψ & DD* channels

Guo, Hanhart, Wang, Zhao: arXiv:1411.5584

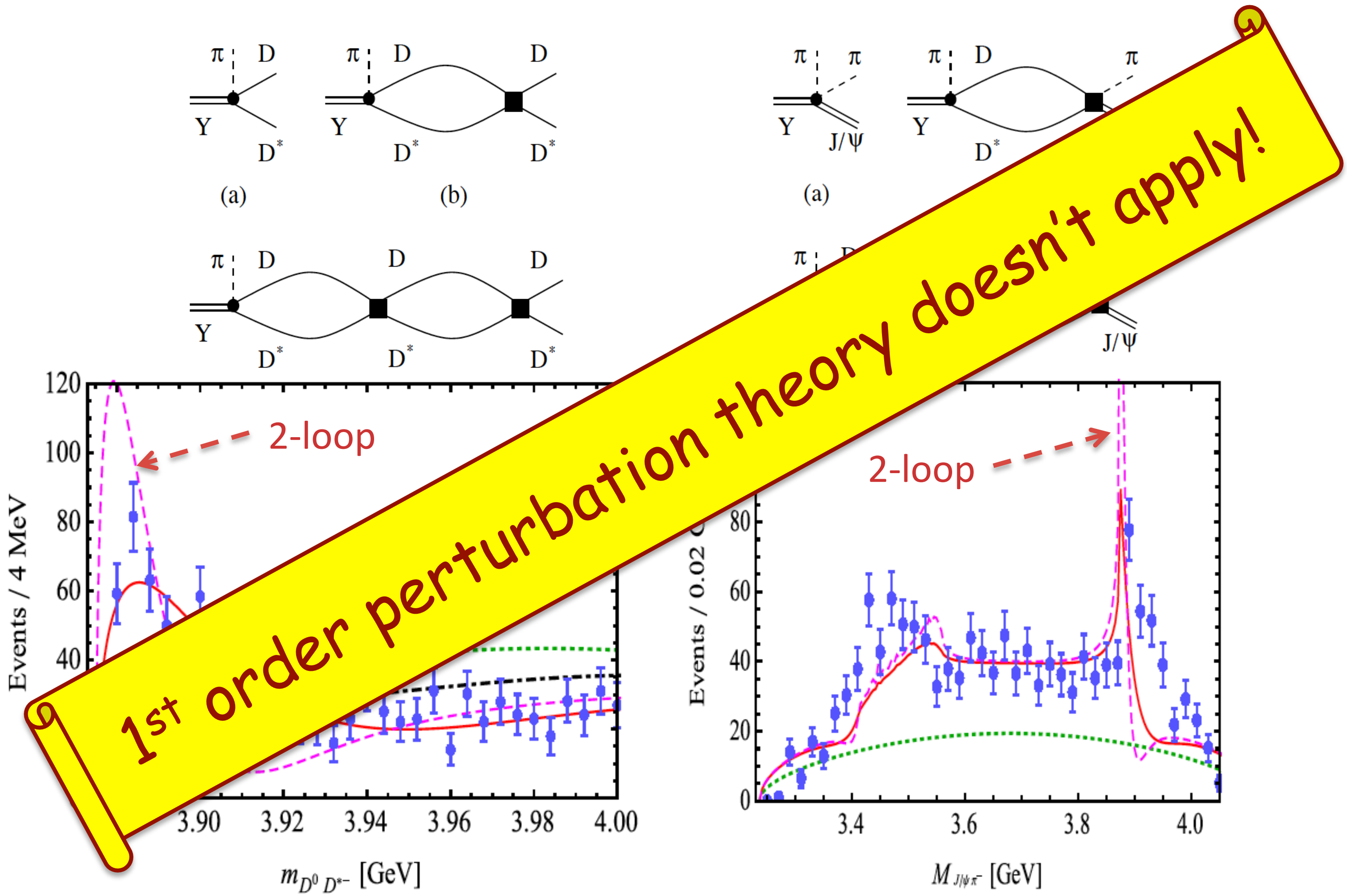


Add 2^{nd}-order perturbation terms



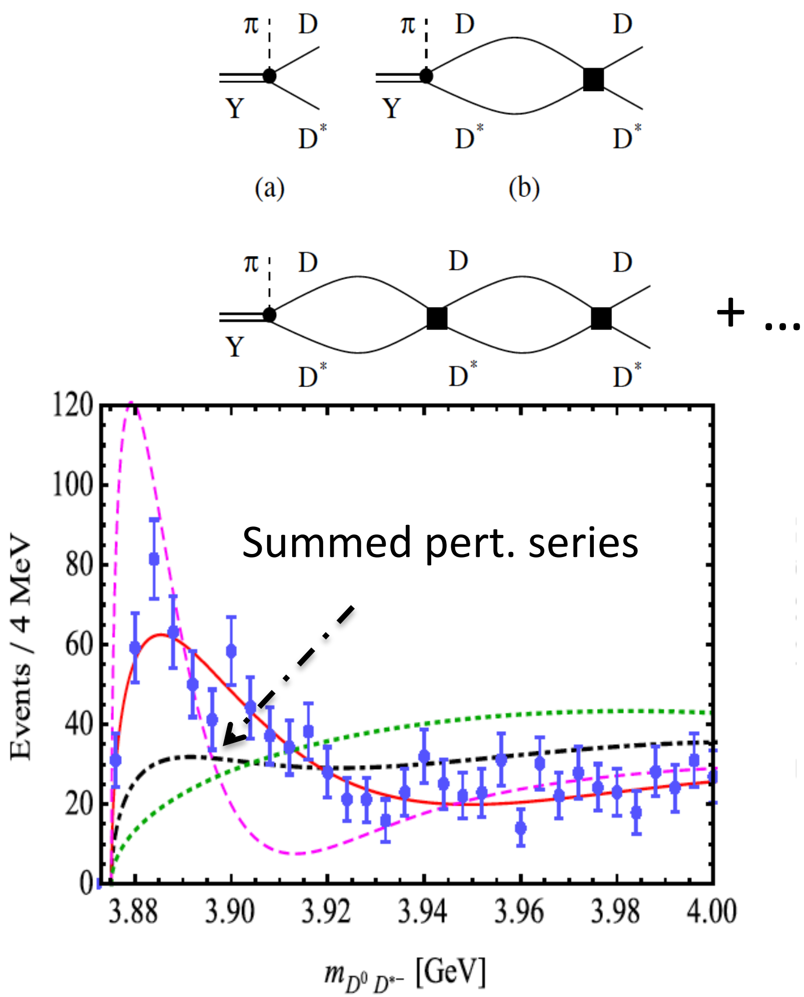
Guo, Hanhart, Wang, Zhao: arXiv:1411.5584

Add 2nd-order perturbation terms

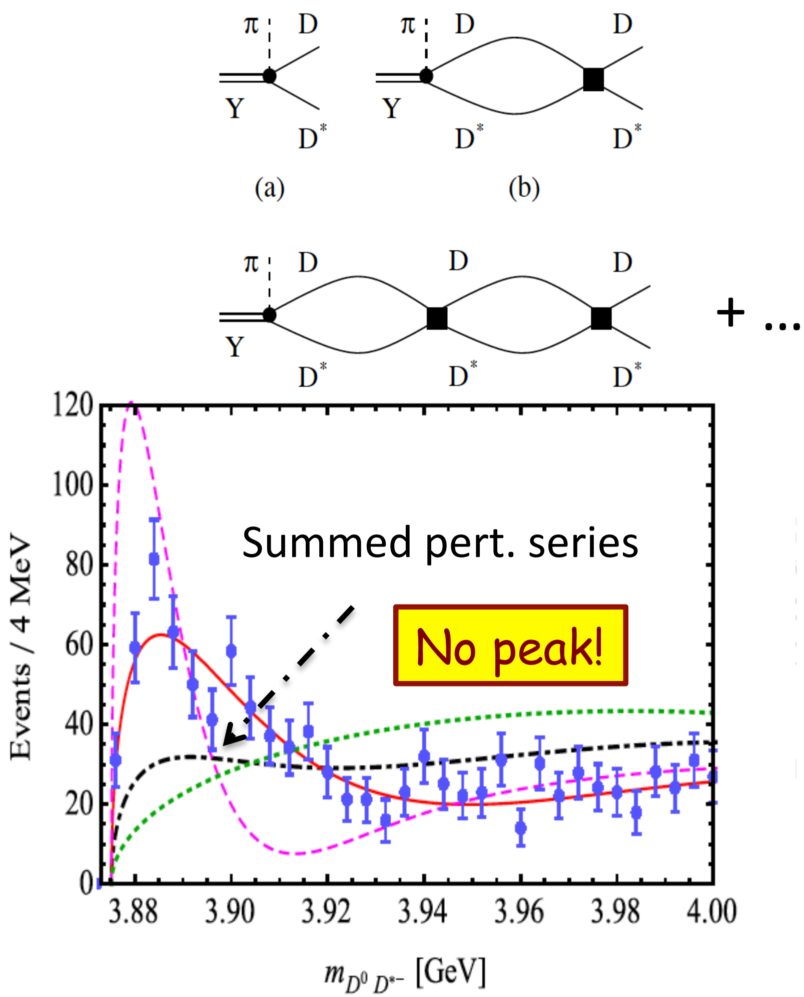


Guo, Hanhart, Wang, Zhao: arXiv:1411.5584

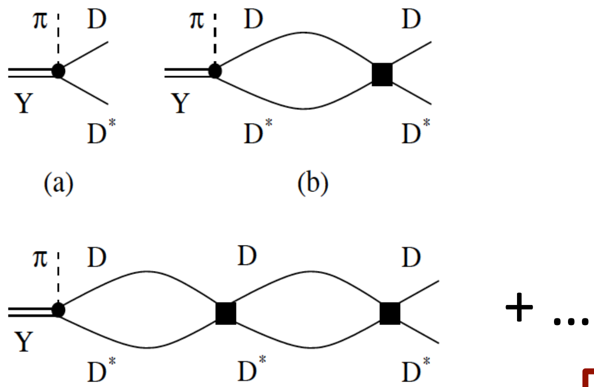
Require perturbation series to converge

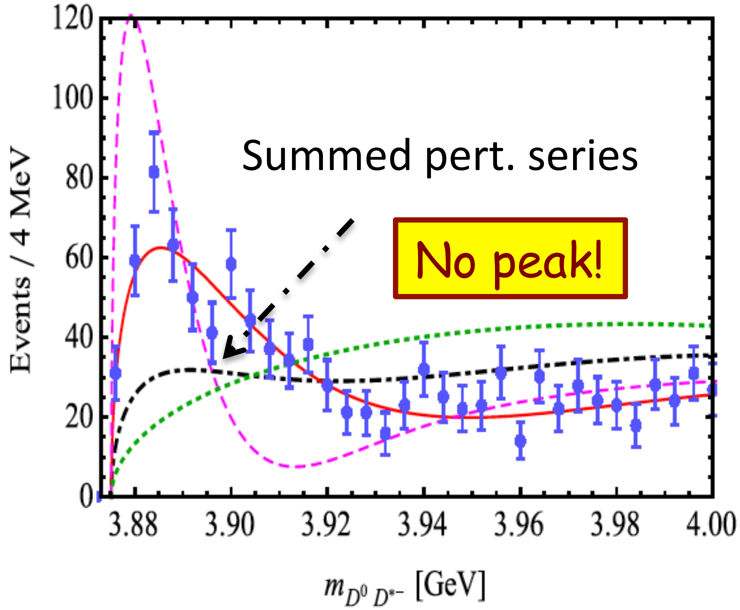


Require perturbation series to converge



Require perturbation series to converge





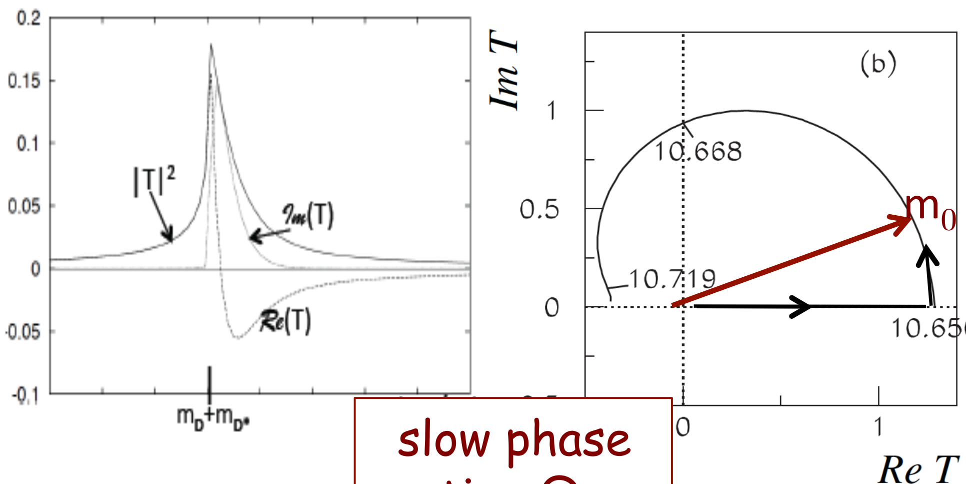
Guo, Hanhart, Wang, Zhao: arXiv:1411.5584

"...the approach used [by Swanson and Chen et al] is intrinsically inconsistent,"

"... there has to be a near-threshold pole."

cusp vs BW phase motion

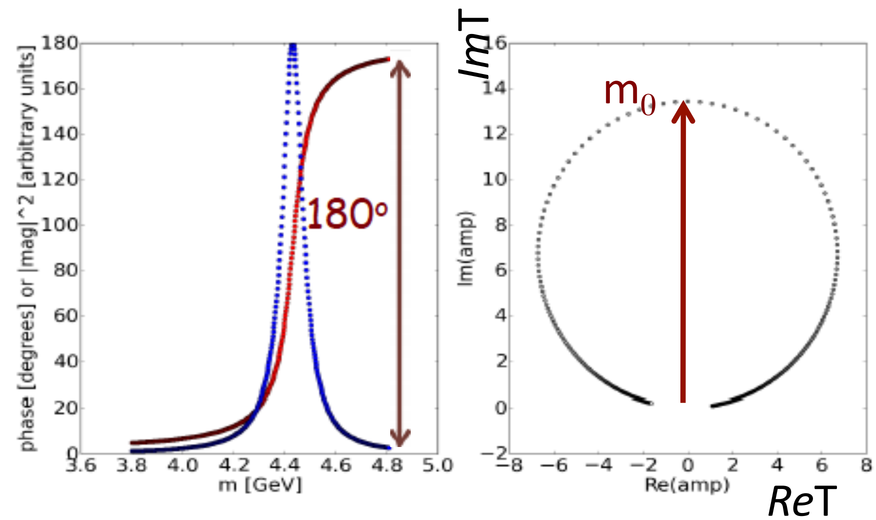
cusp



slow phase motion @ m_0

Bugg: EPL 96 11002 (2011)

BW



rapid phase motion @ m_0

$Z_c(3900) \rightarrow \pi^+ J/\psi$ amplitude analysis currently underway at BESIII, results soon?

Is the $Z_c(3900)$ the I≈1 X(3872) partner

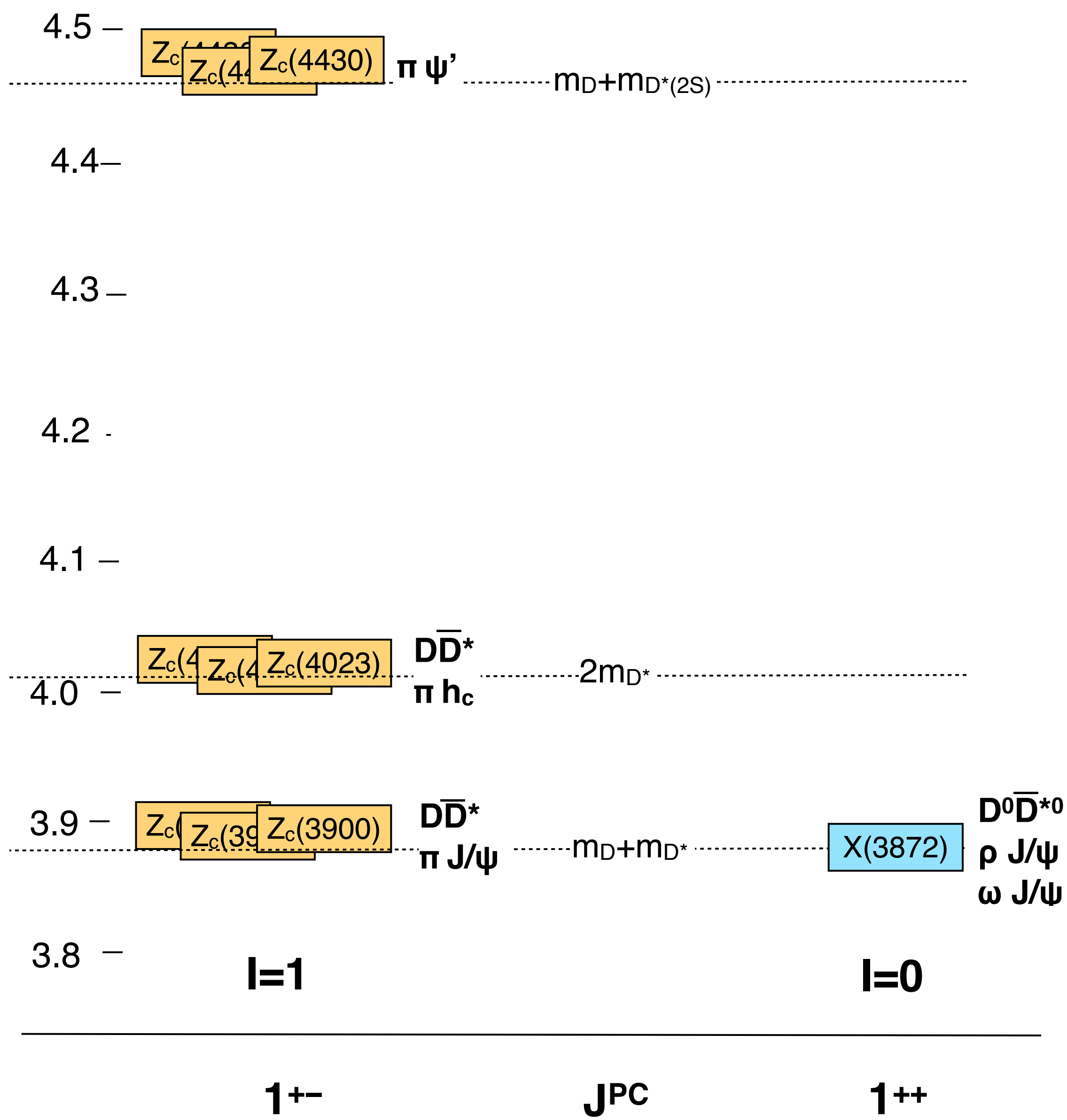
No! Wrong C (G) parity

	C	→ρJ/ψ?	→πJ/ψ?
$X(3872)^0$: $J^{PC}=1^{++}$	even	allowed	forbidden
$Z_c(3900)^0$: $J^{PC}=1^{+-}$	odd	forbidden	allowed

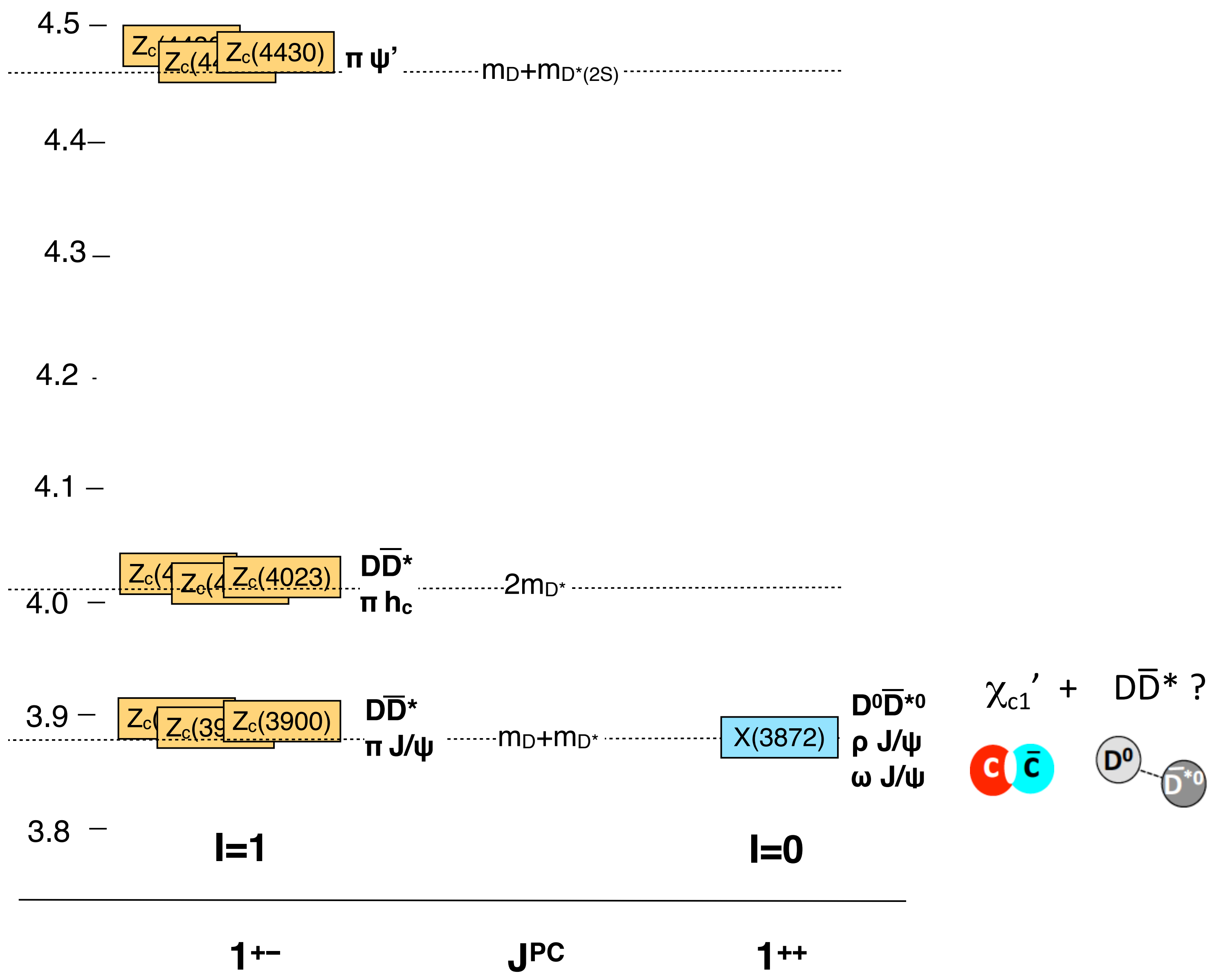
$$\left|X(3872)\right\rangle = a_0 \tfrac{1}{\sqrt{2}}\left[\left|\left(D\overline{D}^*\right)\right\rangle + \left|\left(D^*\overline{D}\right)\right\rangle\right]_{I=0} + a_1 \tfrac{1}{\sqrt{2}}\left[\left|\left(D\overline{D}^*\right)\right\rangle + \left|\left(D^*\overline{D}\right)\right\rangle\right]_{I=1} - a_c\left|\chi_{c1}'\right\rangle$$

$$\left|Z_c(3900)^0\right\rangle = b_0 \tfrac{1}{\sqrt{2}}\left[\left|\left(D\overline{D}^*\right)\right\rangle - \left|\left(D^*\overline{D}\right)\right\rangle\right]_{I=0} + b_1 \tfrac{1}{\sqrt{2}}\left[\left|\left(D\overline{D}^*\right)\right\rangle - \left|\left(D^*\overline{D}\right)\right\rangle\right]_{I=1} + b_c\left|h_c'\right\rangle$$

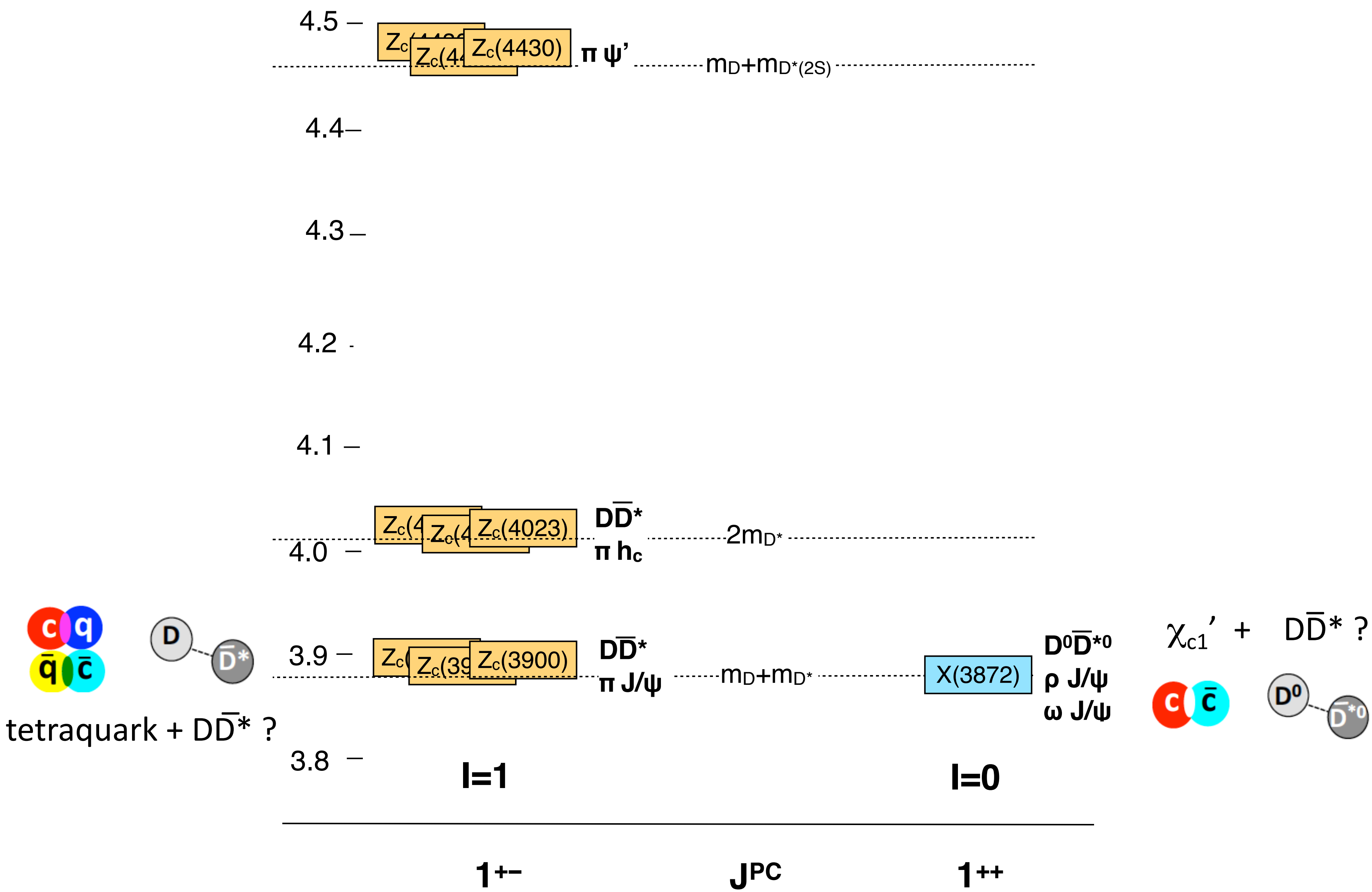
1^+ states: what we see



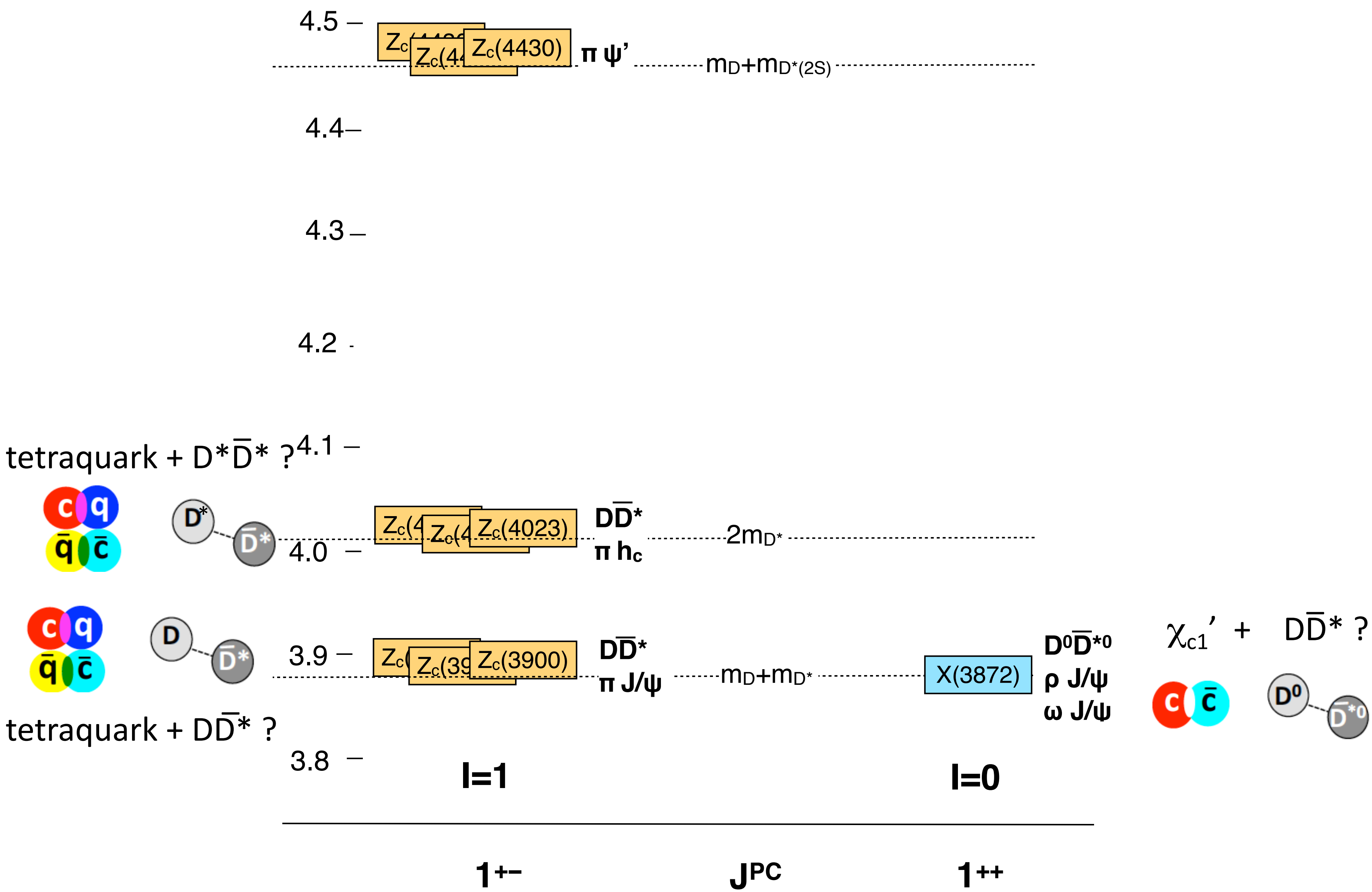
1^+ states: what we see



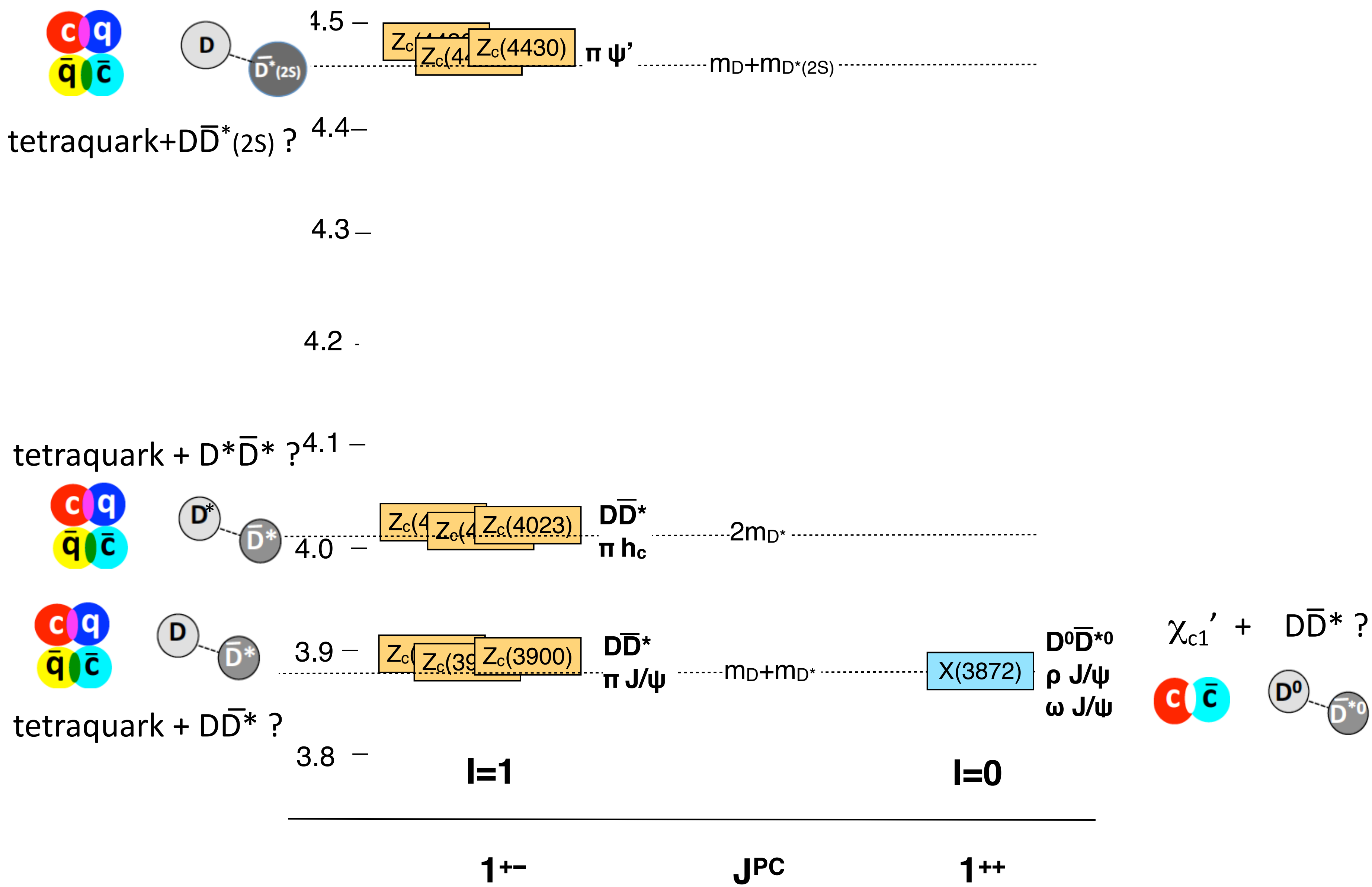
1^+ states: what we see



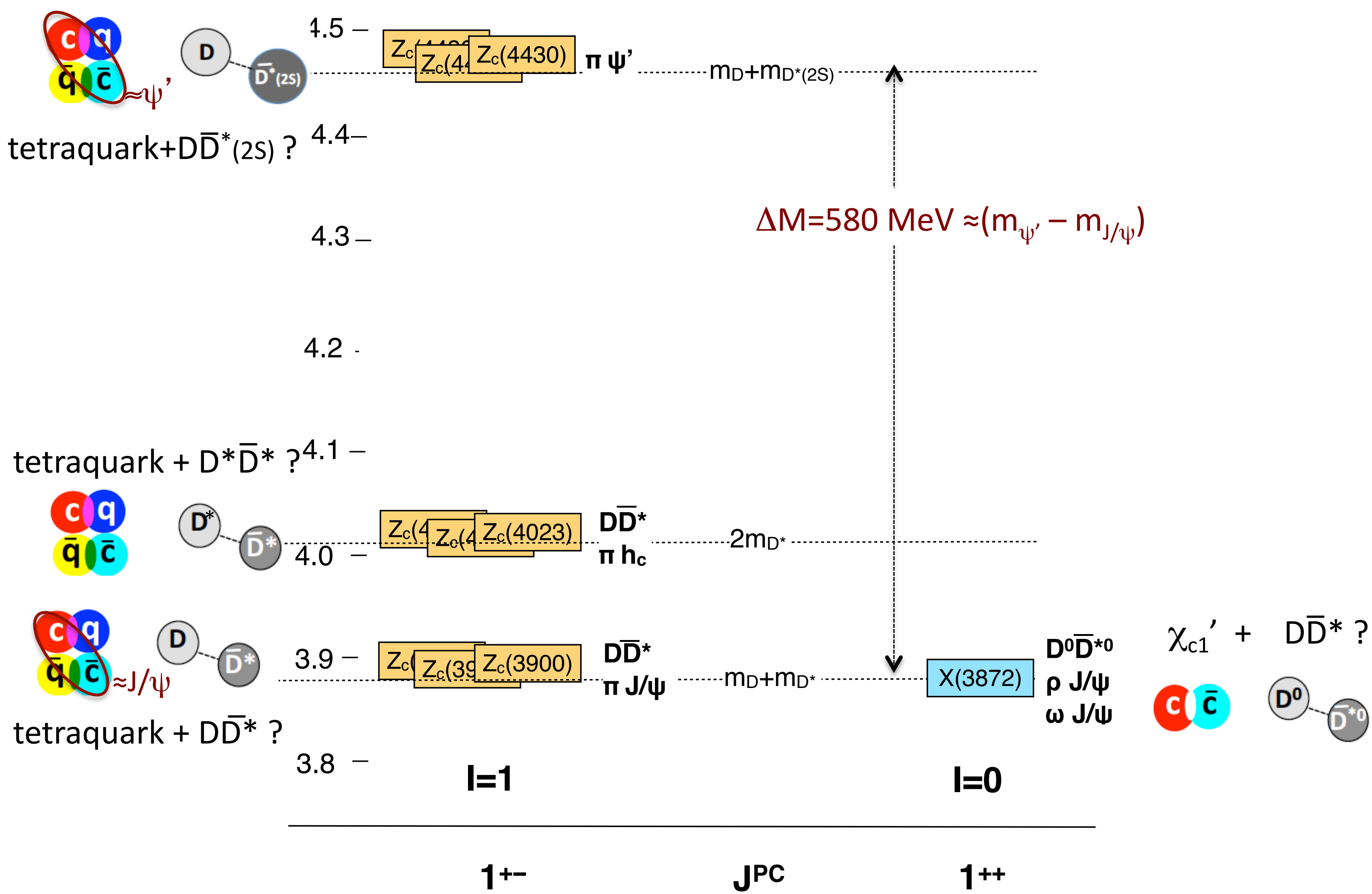
1⁺ states: what we see



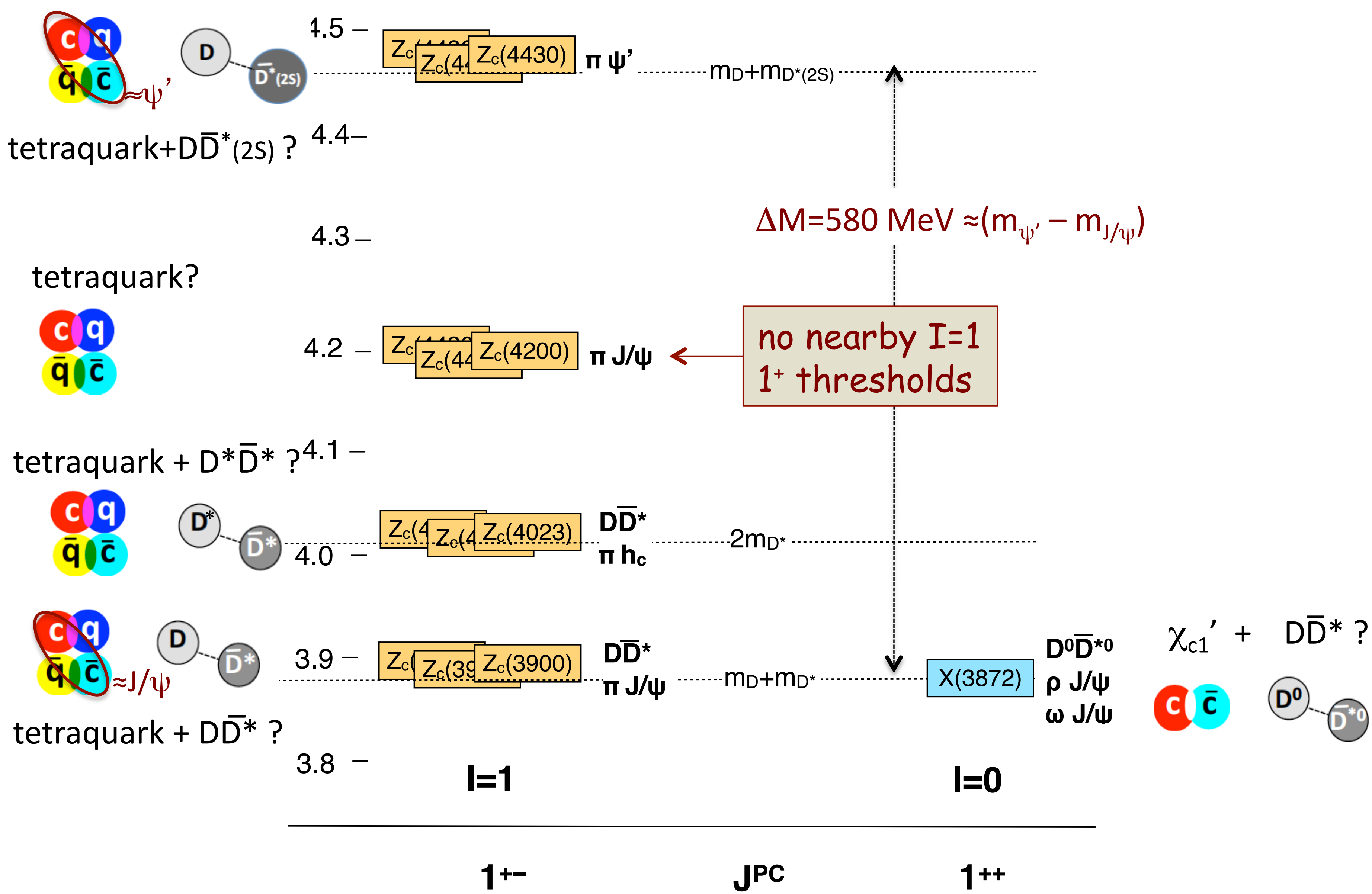
1+ states: what we see



1^+ states: what we see



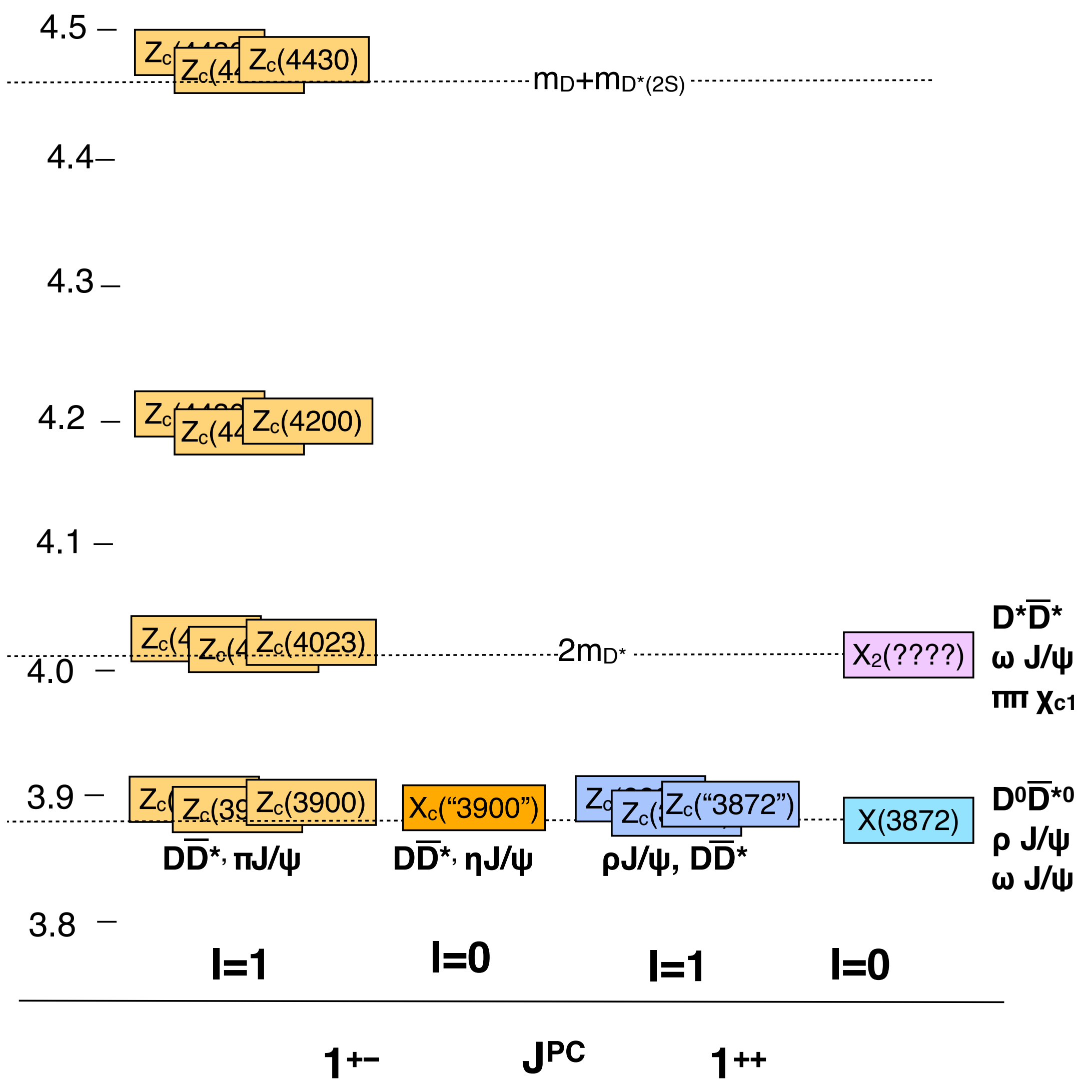
1^+ states: what we see



Future

- Look for associated states
- XYZ physics without guilt

Are there other 1^+ states?



XYZ physics without guilt

What is common to (almost) all of the charmonium-like XYZ mesons?

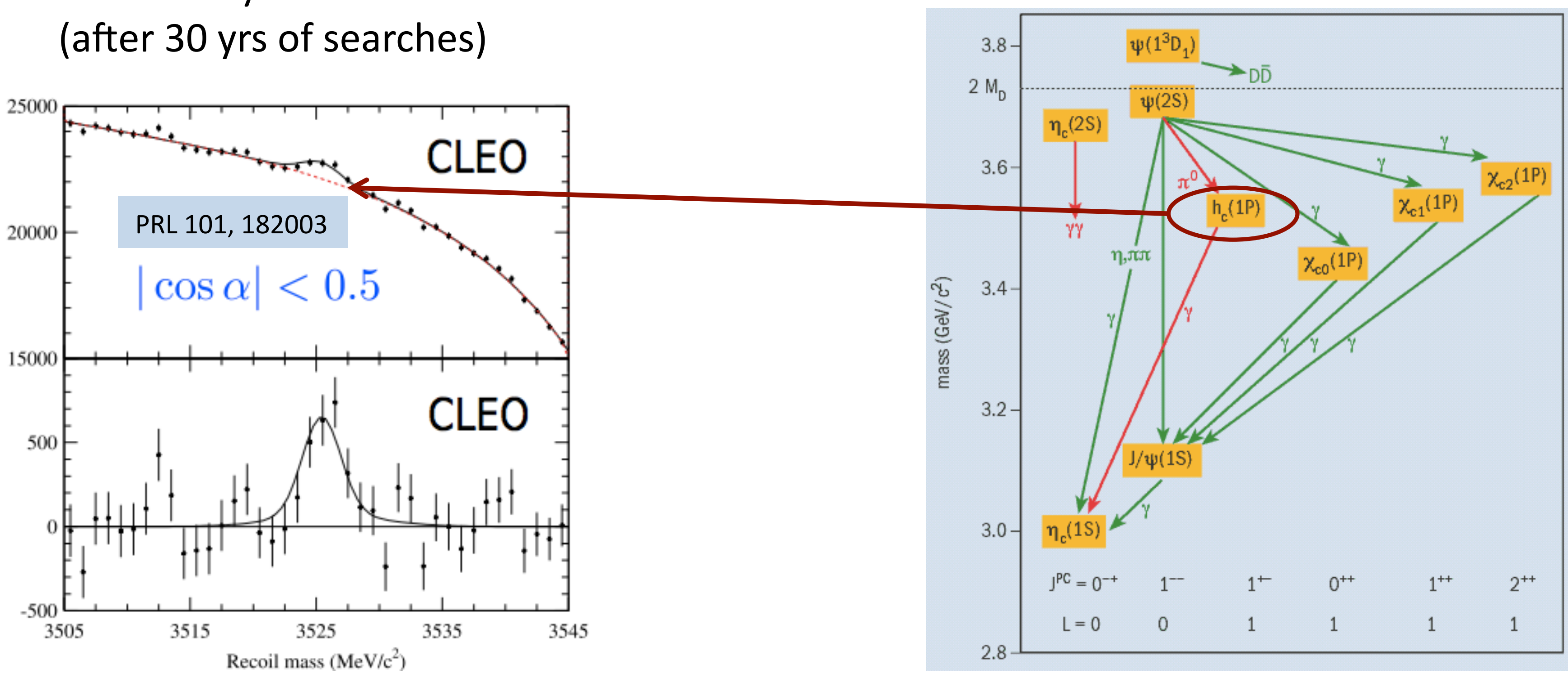
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [82, 89] , BaBar [85], LHCb [90]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [83, 91, 92, 125], D0 [84]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [94] , BaBar [59]
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [95] , BaBar [96]
				$B \to K + (J/\psi\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$B \to K + (\psi'\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [86], CMS [87]
$X(3915)$	3917.4 ± 2.7	$28^{+10}_{-\ 9}$	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [58] , BaBar [59]
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [60] , BaBar [61]
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [64] , BaBar [65]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
				$e^+e^- \to J/\psi + (...)$	Belle [26]
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar [129], Belle [130]
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [32]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [74, 75], CMS [77]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar [30, 131], CLEO [132] , Belle [32]
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [133]
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [133]
$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [75], CMS [77]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [81]
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar [31], Belle [33]
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [134]
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle [33]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [39], Belle [40]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [56]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [41]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [42]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [51]
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [44, 46, 47], LHCb [48]
				$B \to K + (J\psi\,\pi^+)$	Belle [51]
$Y_b(10890)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [117]
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1, 2, 3$	Belle [119, 122]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n = 1, 2$	Belle [119]

J/ψ (ψ')

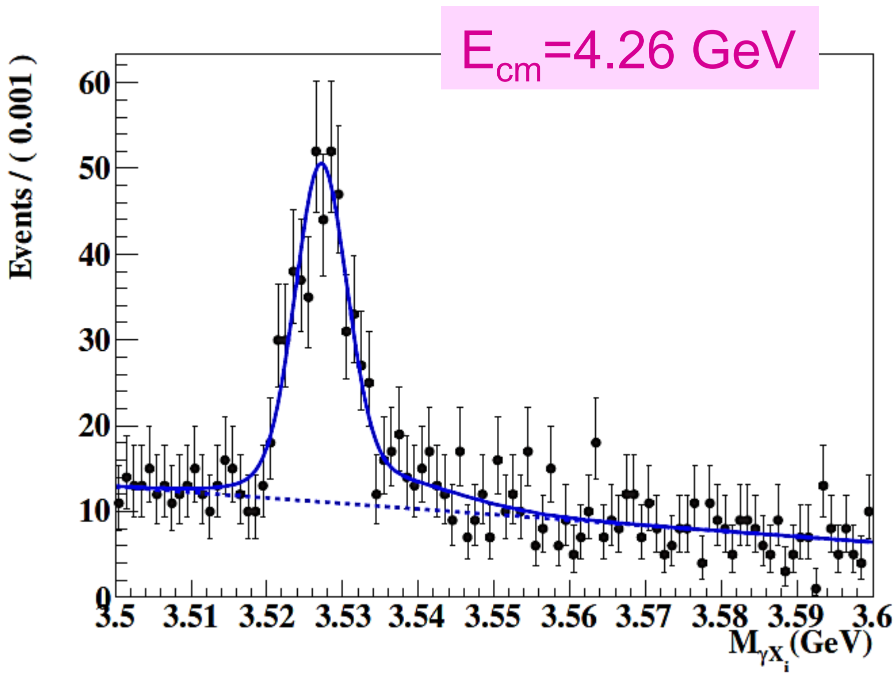
XYZ physics without g~~uil~~t

h_c: from discovery→important tool

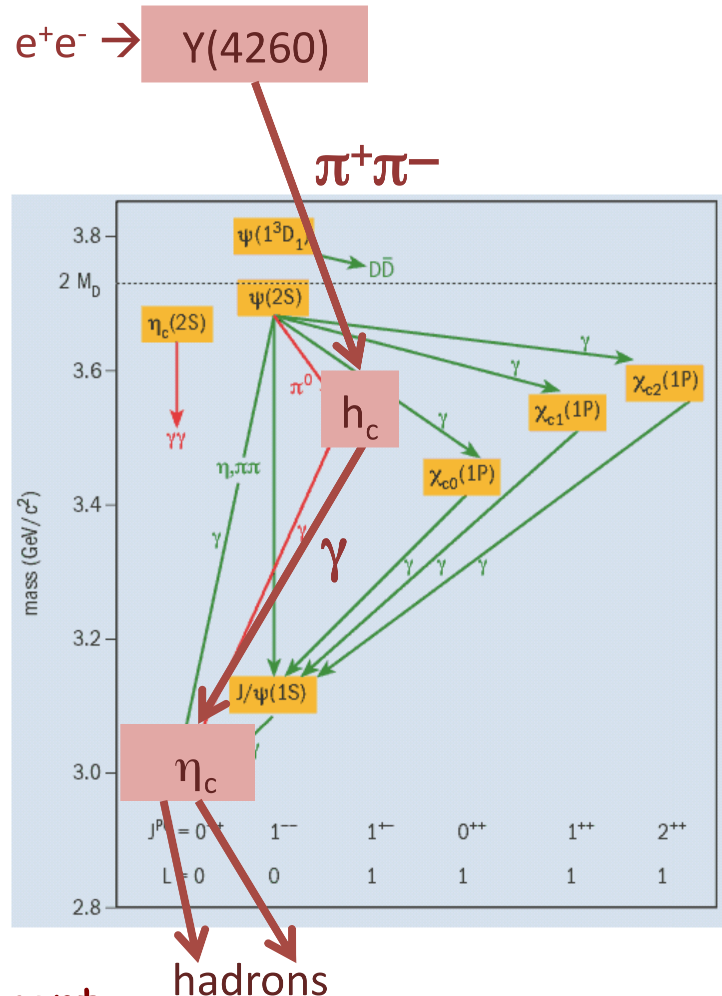
Discovered by CLEO-c in 2005
(after 30 yrs of searches)



h_c signal in BESIII



$N(h_c)$=416±28   Lum=827/pb



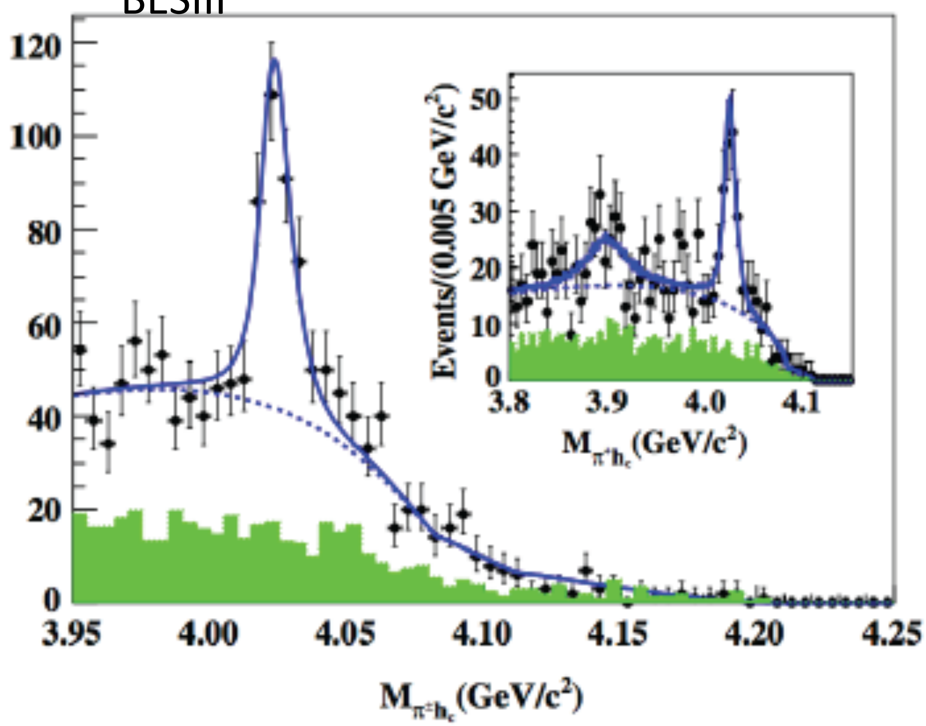
Reconstruct 16 different
η_c decay channels

Discovery of $Z_c(4020)$ in πh_c channels

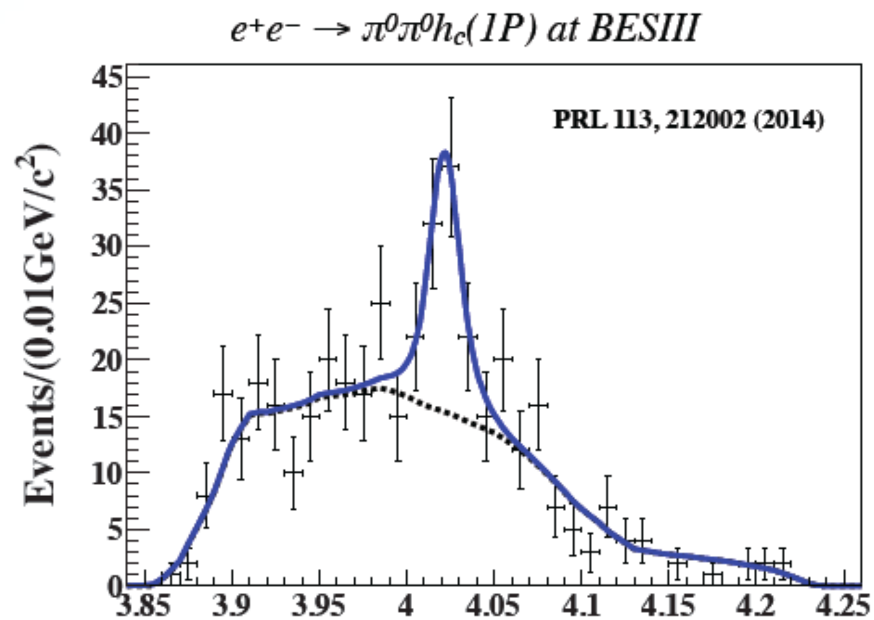
$Z_c(4020)^+ \rightarrow \pi^+ h_c$

PRL 111, 242001 (2013)

BESIII



$Z_c(4020)^+ \rightarrow \pi^0 h_c$

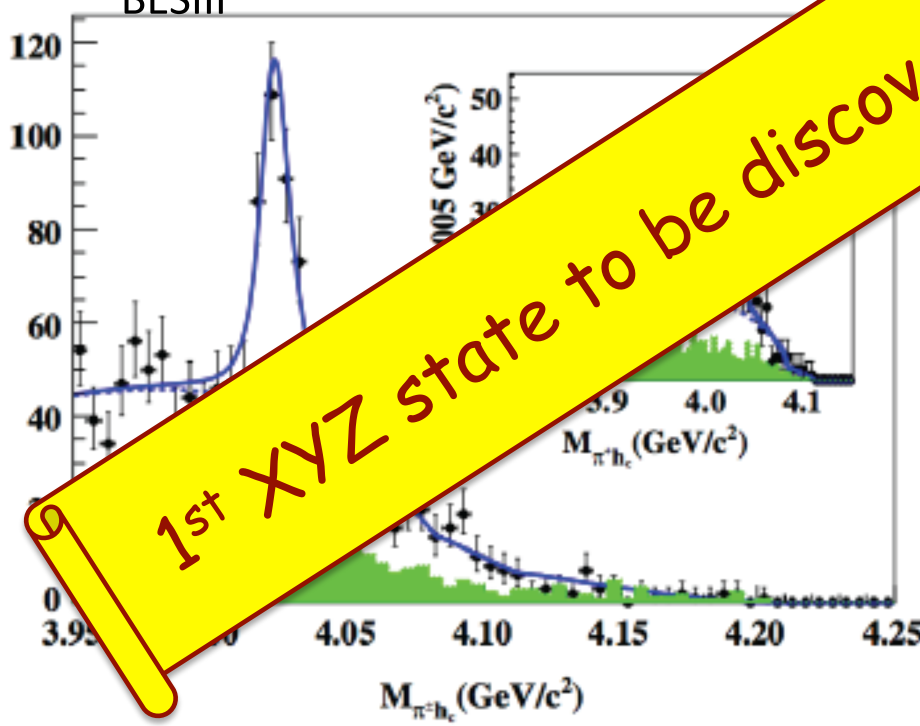


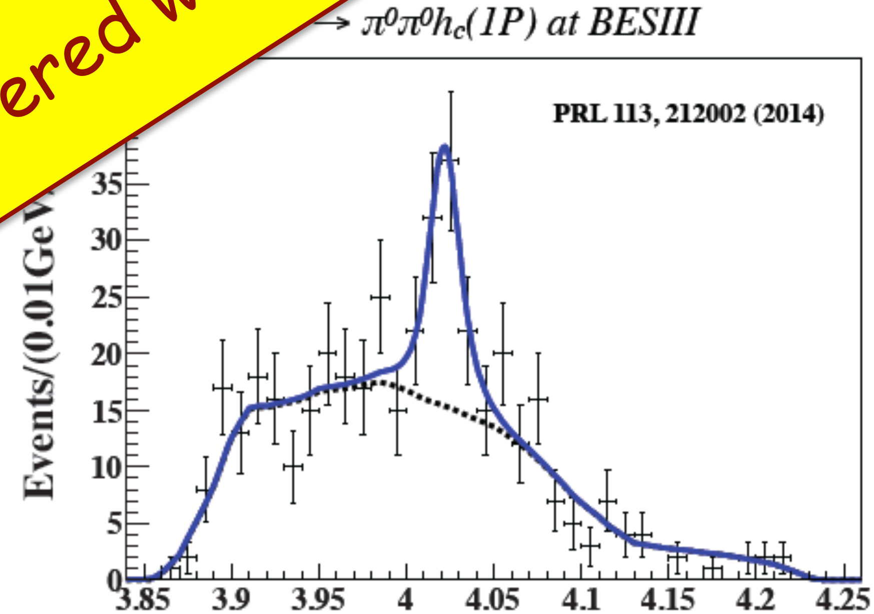
Discovery of $Z_c(4020)$ in πh_c cha

$Z_c(4020)^+ \rightarrow \pi^+ h_c$

$\rightarrow \pi^0 h_c$

PRL 111, 242001 (2013)





1st XYZ state to be discovered with no J/ψ (ψ') or Υ

Expect more XYZ states with non-J/ψ (ψ') decay modes from BESIII in the future

Summary

- 4-quark, charmonium-like mesons have been observed
  - -large partial widths to $(c\bar{c})$+hadrons
  - -many, but not all, have mass near $D^{(*)}\bar{D}^{(*)}$ thresholds

- To date, searches have been confined to XYZ mesons that decay to J/ψ or ψ' final states
  - -BESIII is examining more complex final states

- Kinematic "cusp" explanations of near-threshold peaks have some troubles under close scrutiny

- Lots to do at BESIII, LHCb, BelleII, PANDA, etc