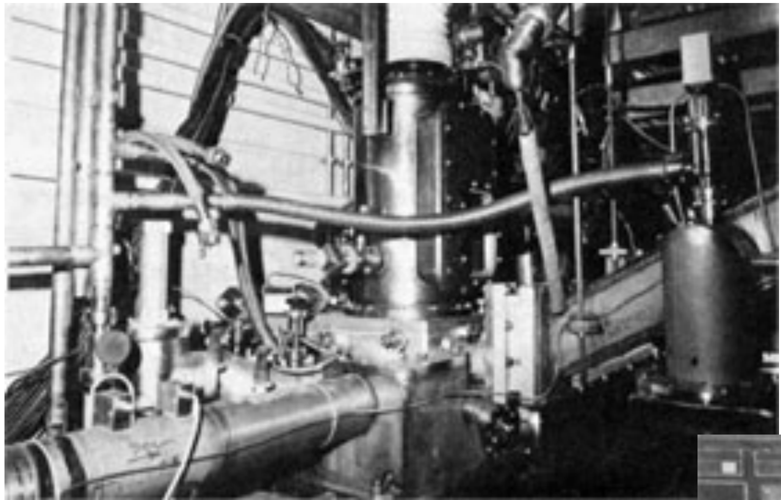
A New Hadron Spectroscopy

Stephen Lars Olsen Institute for Basic Science Daejeon KOREA

Baldin Seminar, JINR Dubna Sept 18 , 2014

E36 Gas Jet Target Experimental Group

Fermilab 1972-74



Real Part of the Proton-Proton Forward-Scattering Amplitude from 50 to 400 GeV

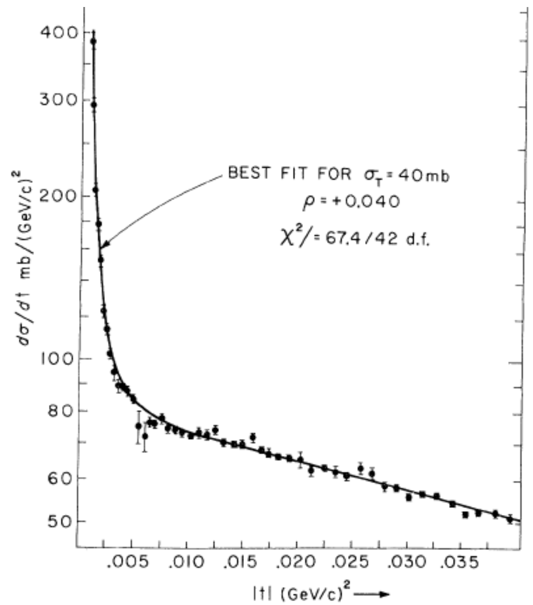
V. Bartenev, R. A. Carrigan, Jr., I-Hung Chiang,* R. L. Cool, K. Goulianos, D. Gross, A. Kuznetsov, E. Malamud, A. C. Melissinos, B. Morozov, V. Nikitin, S. L. Olsen,† Y. Pilipenko, V. Popov, R. Yamada, and L. Zolin

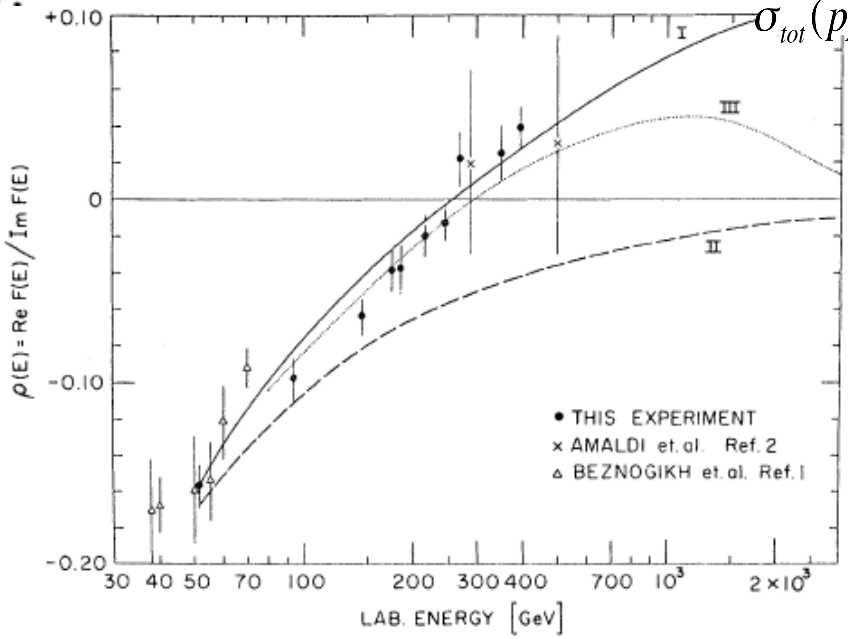
The State Committee for Utilization of Atomic Energy of the U.S.S.R., Moscow, U.S.S.R., and National Accelerator Laboratory, Batavia, Illinois 60510, and Rockefeller University, New York, New York 10021,‡ and University of Rochester, Rochester, New York 14627§

(Received 11 October 1973)

From measurements of proton-proton elastic scattering at very small momentum transfers where the nuclear and Coulomb amplitudes interfere, we have deduced values of ρ, the ratio of the real to the imaginary forward nuclear amplitude, for energies from 50 to 400 GeV. We find that ρ increases from -0.157 ± 0.012 at 51.5 GeV to $+0.039 \pm 0.012$ at 393 GeV, crossing zero at 280 ± 60 GeV.

$$\sigma_{tot}(pp) \propto \ln^2(s/s_0)$$



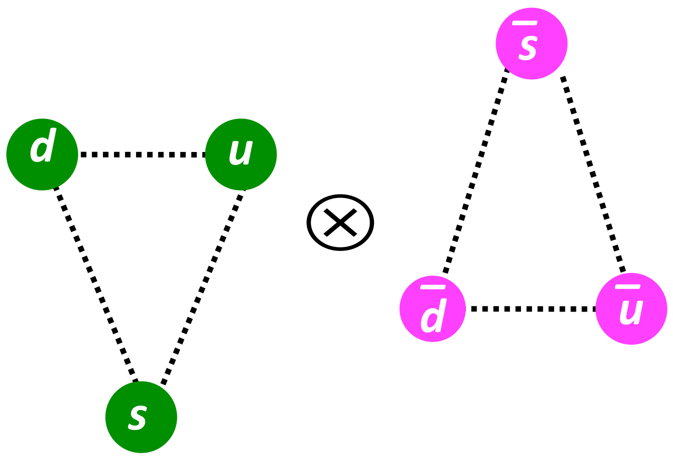


Alexander Michailovich Baldin

1926 - 2001

"Old spectroscopy":

mesons = q triplet ⊗ $\overline{\text{q triplets}}$



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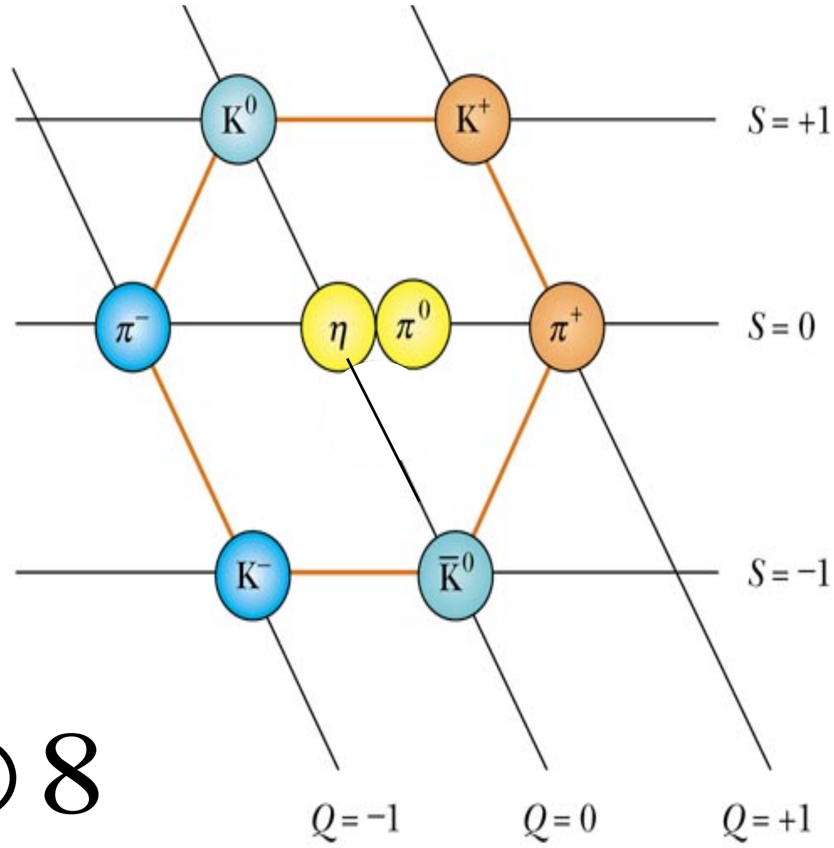
η' ⊕



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

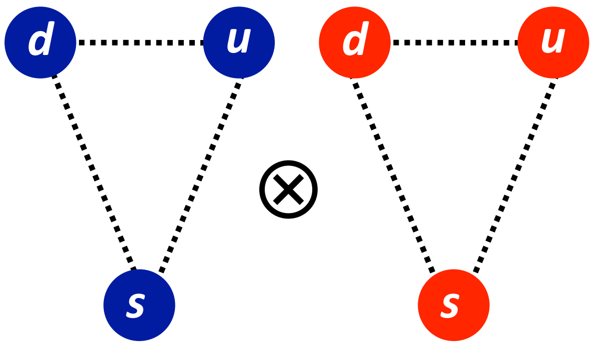
QCD “diquarks” ?

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 [ϵ(700), S^*,δ,κ] 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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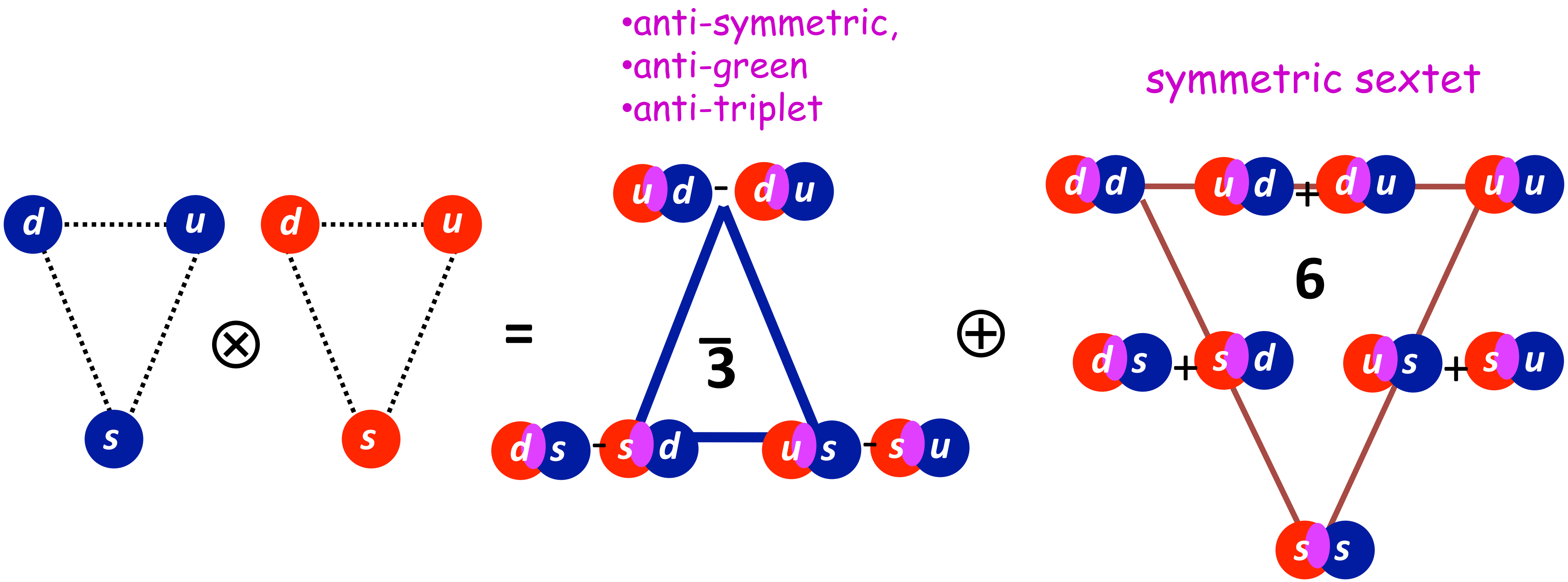
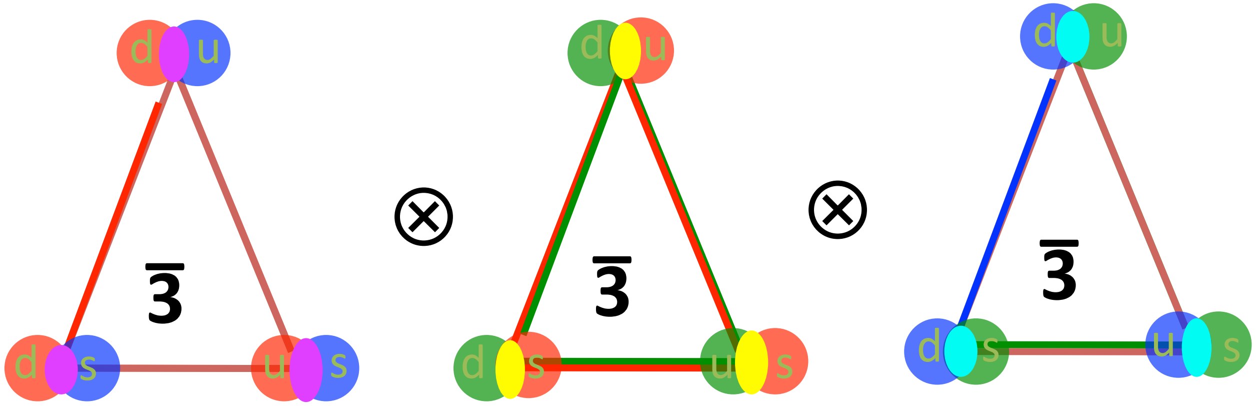


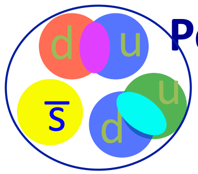
$$3 \otimes 3 = \bar{3} \oplus 6$$

multiquark states from diquarks & diantiquarks

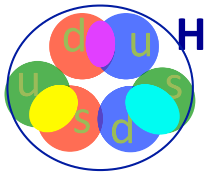
red-blue diquark | green-red diquark | blue-green diquark



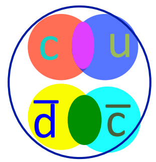
magenta (anti-green) **anti-triplet** | **yellow** (anti-blue) **anti-triplet** | **cyan** (anti-red) **anti-triplet**



Pentaquark



H-dibaryon



tetraquark meson

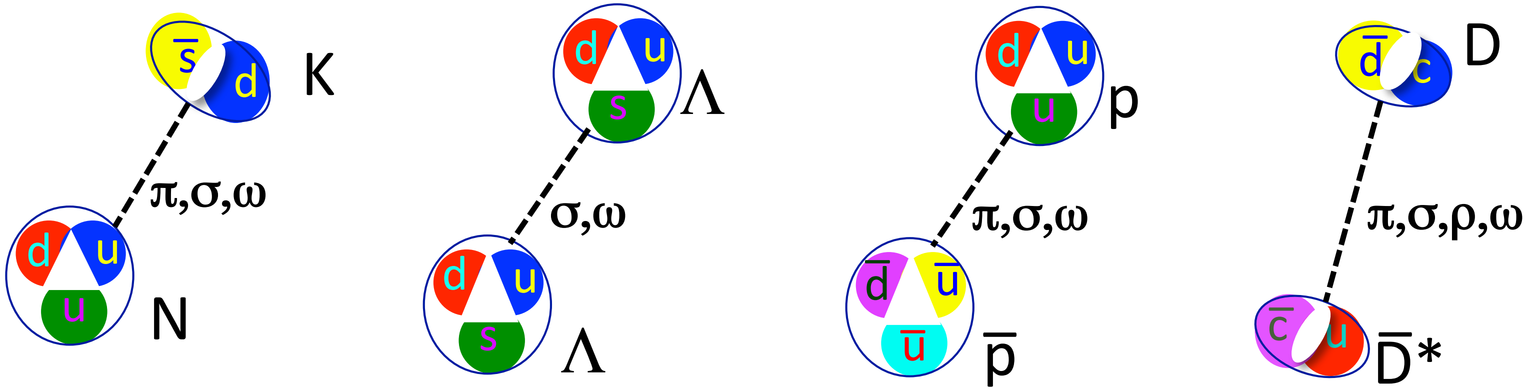
magenta-cyan-yellow
color singlet 5-q state

magenta-cyan-yellow
color singlet 6-q state

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

"exotic" hadrons that particle theorists love

multiquark states from "molecules"



Pentaquark **H-dibaryon** **baryonium** **tetraquark meson**

"exotic" hadrons that nuclear theorists love

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**.

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

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Where are they??

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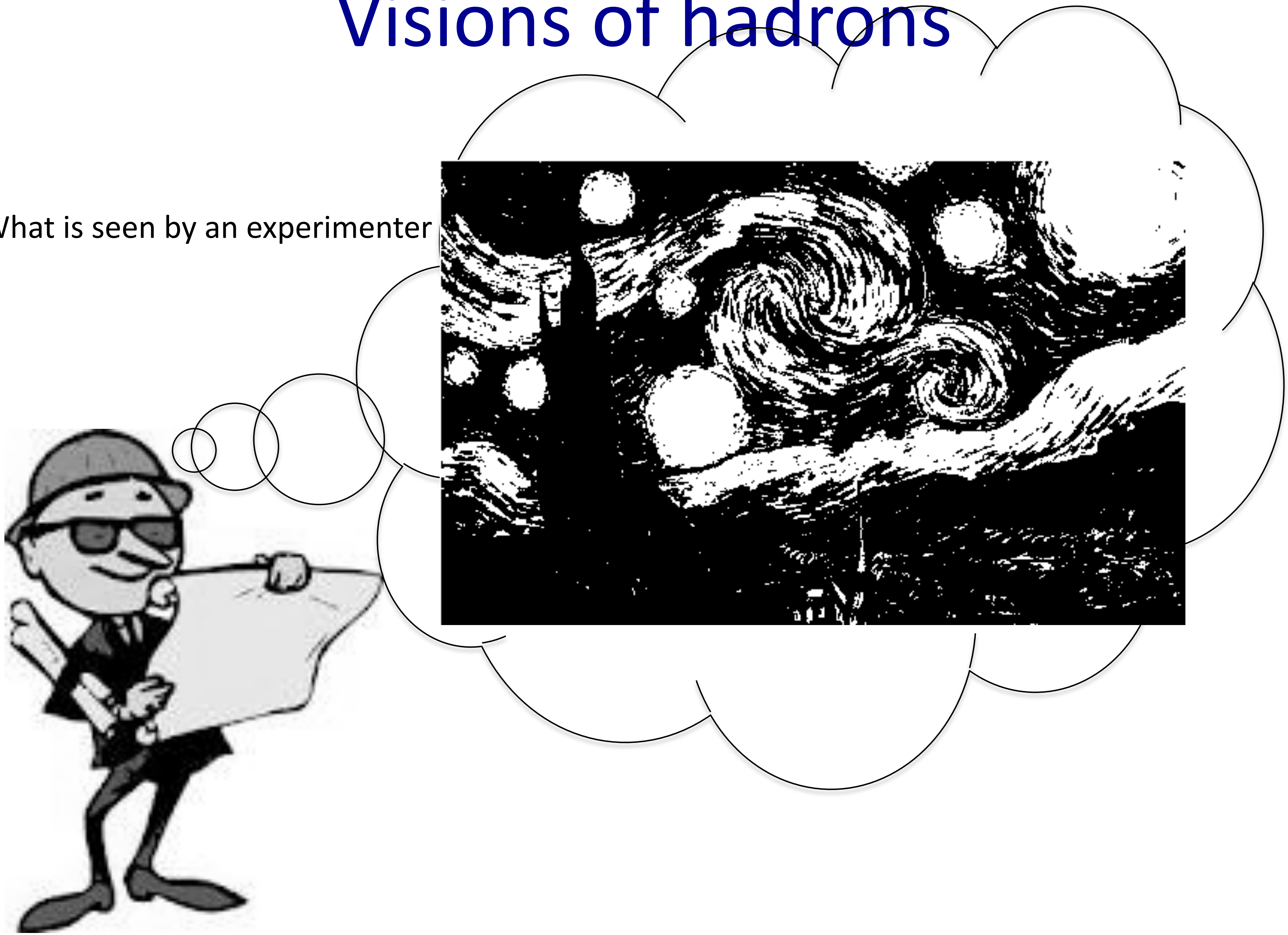
Visions of hadrons

Through a theorist‘s mind

van Gogh prediction of B-mode polarization in 1889?

Visions of hadrons

What is seen by an experimenter

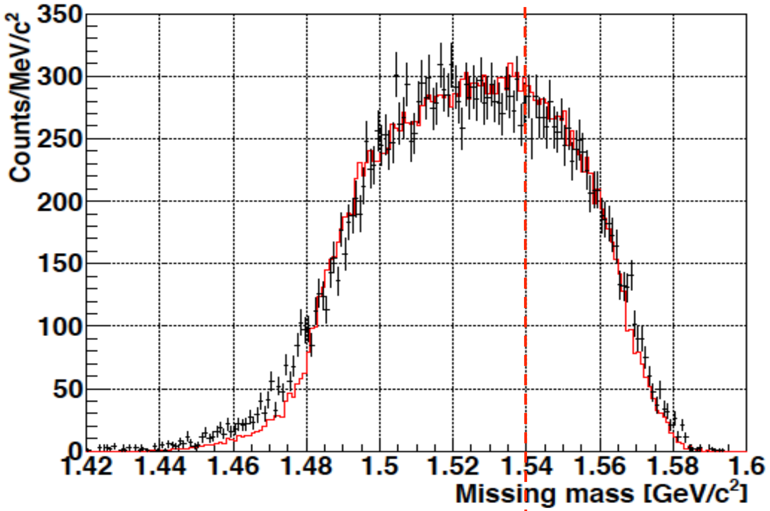


No Pentaquarks

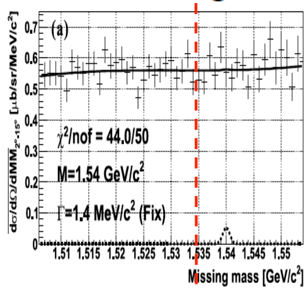
J-PARC E19 - 2012 PRL 109, 132002

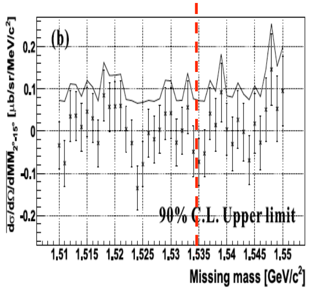
(Tanida-san)

$\pi^- p \to K^- X \;@\; 1.92 GeV/c$



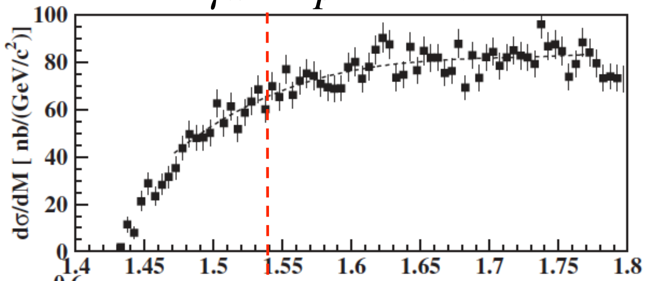
$$\frac{d\sigma}{d\Omega} < 0.26 \mu b / sr$$

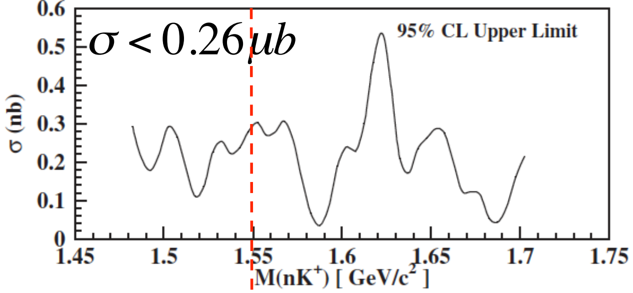


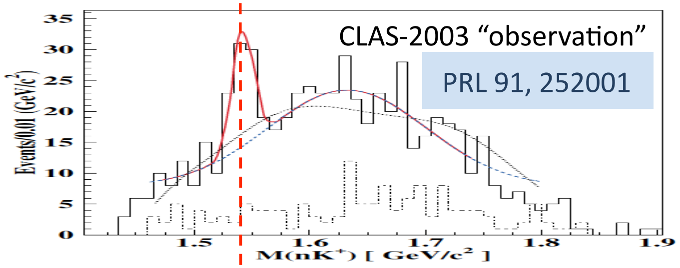


JLab CLAS -2006 PRL 96, 212001

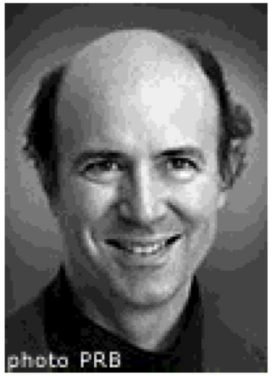
$\gamma d \to p K^- K^+ n$





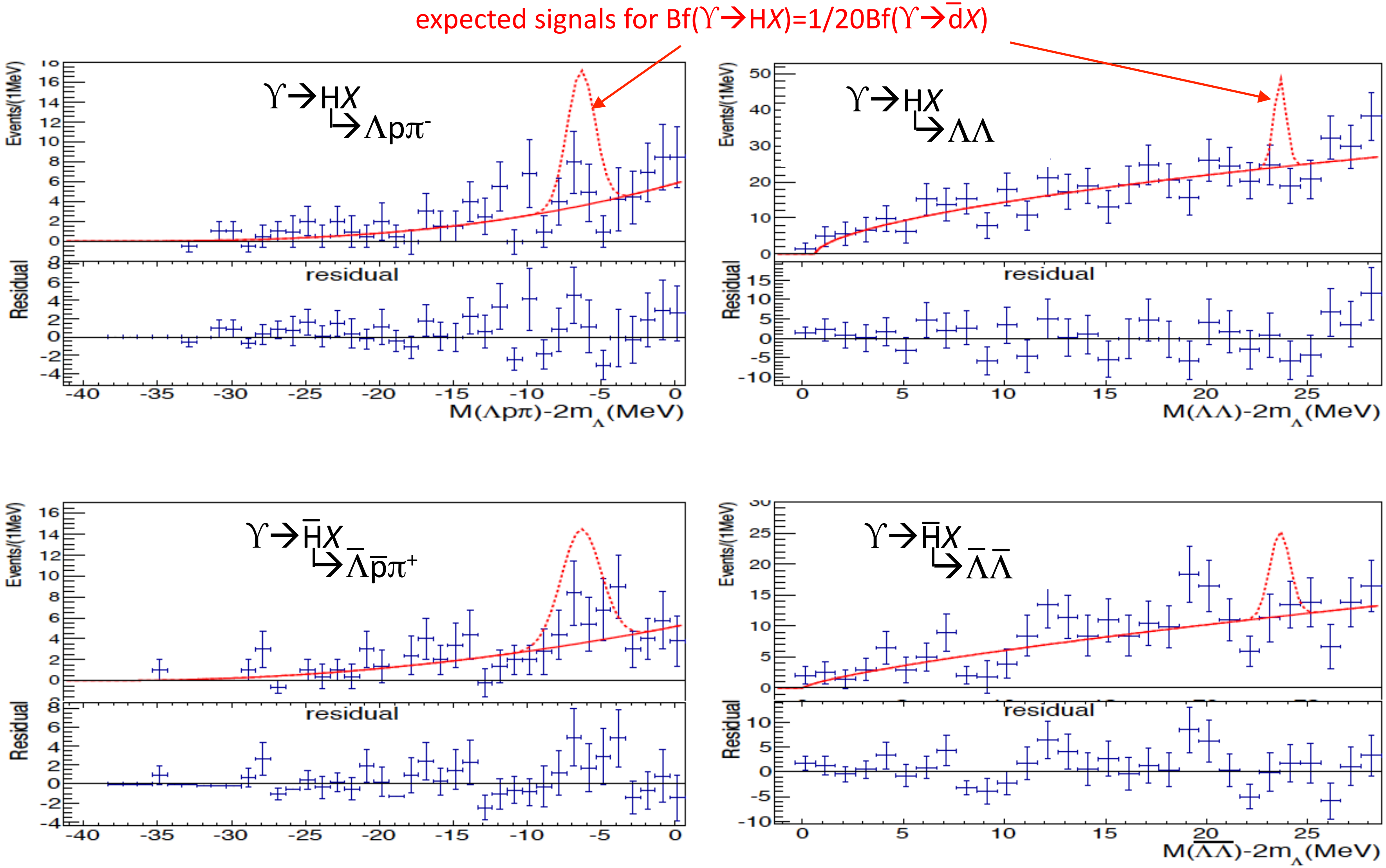


“The story of pentaquark shows how poorly we understand QCD” – F. Wilczek, 2005



Frank Wilczek

No H dibaryon

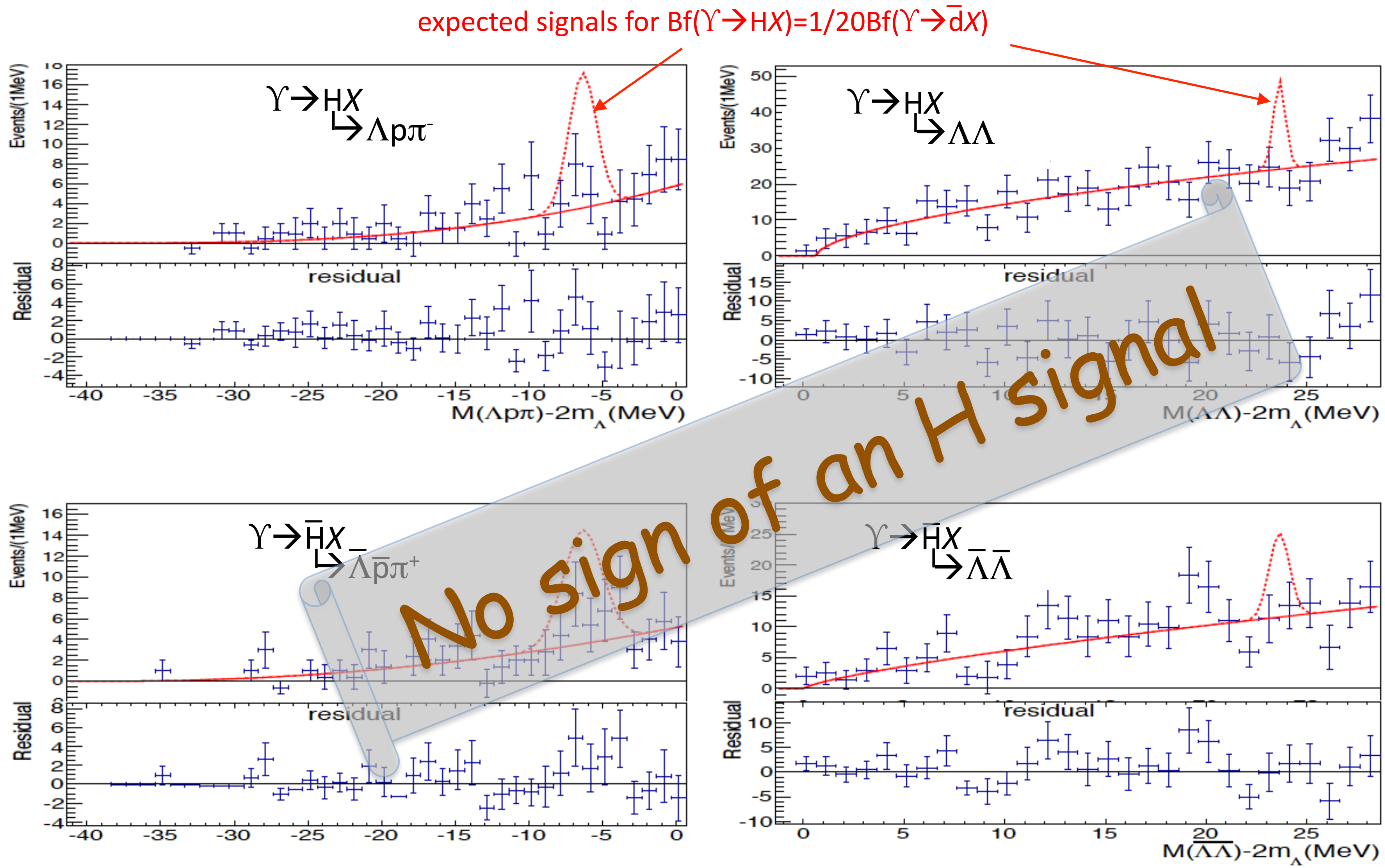


B.H. Kim *et al* (Belle) PRL 110, 222002 (2013)

$M(\Lambda p \pi^-)-2m_\Lambda$

$M(\Lambda\Lambda)-2m_\Lambda$

No H dibaryon

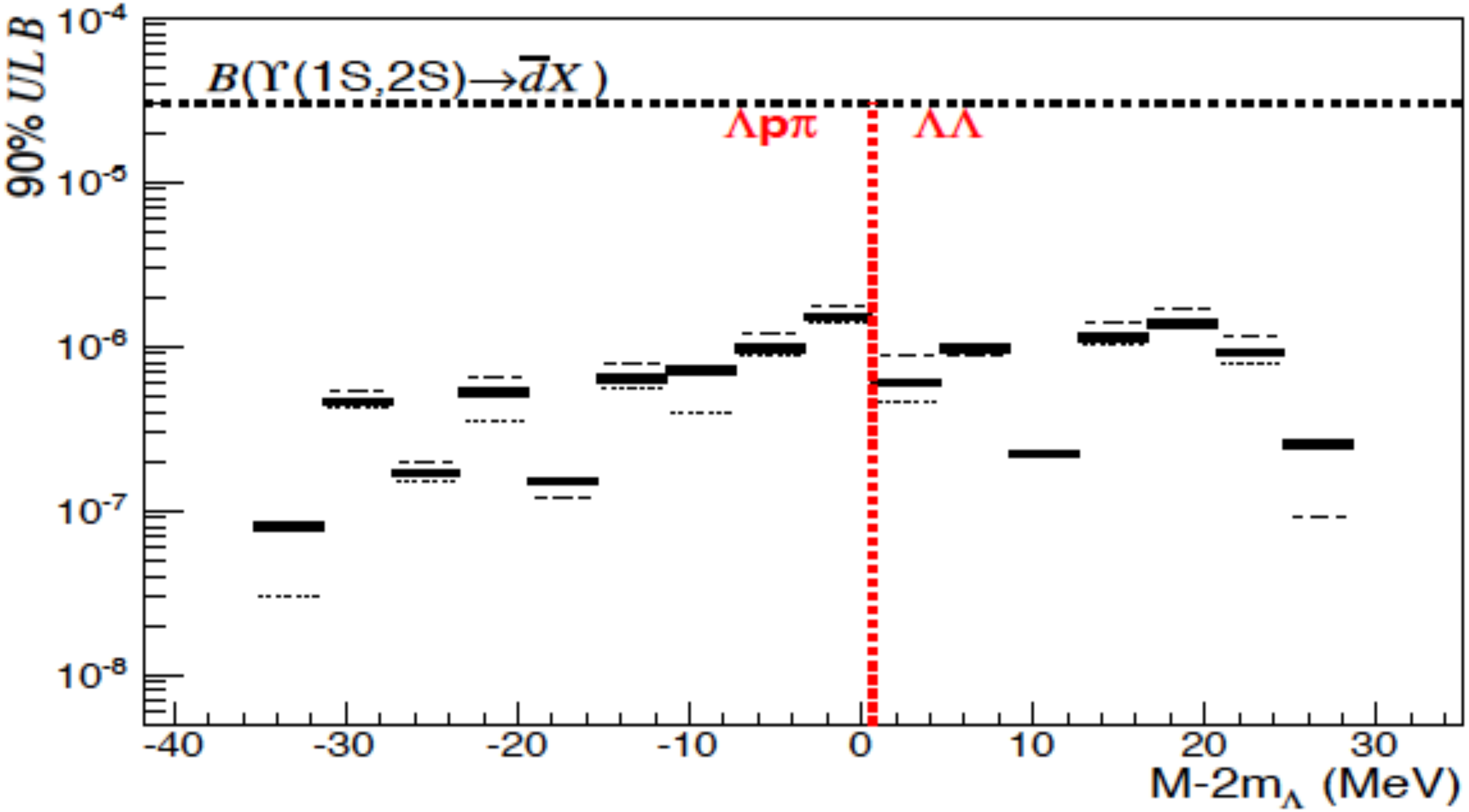


M($\Lambda p\pi^-$)-2m_Λ

B.H. Kim *et al* (Belle) PRL 110, 222002 (2013)

M($\Lambda\Lambda$)-2m_Λ

90% CL upper limits on $\Upsilon(1S,2S) \rightarrow H\,X$



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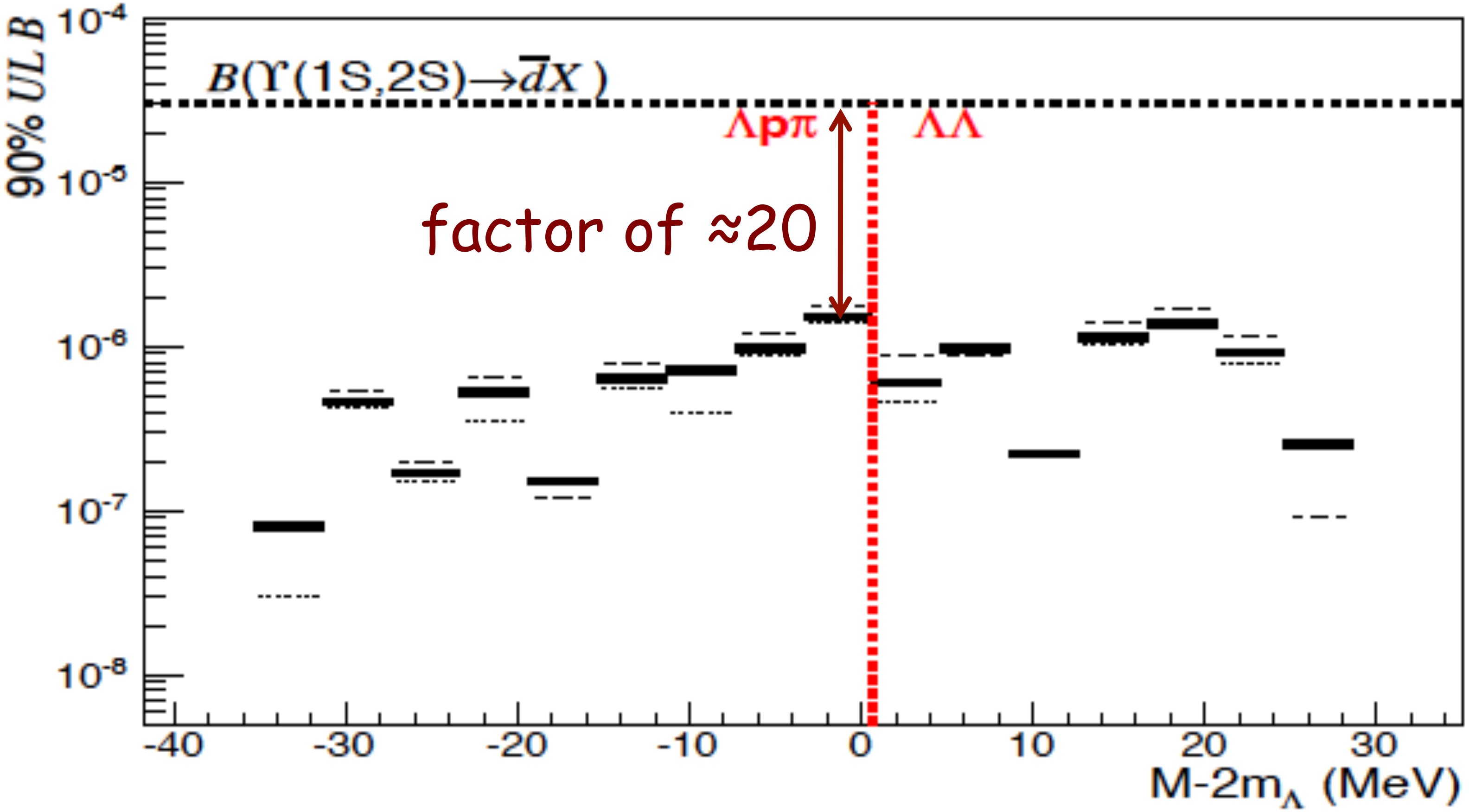
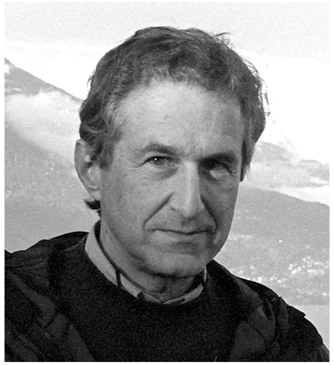


B.H. Kim *et al* (Belle) PRL 110, 222002 (2013)

QCD-motivated multiquark states are not seen!

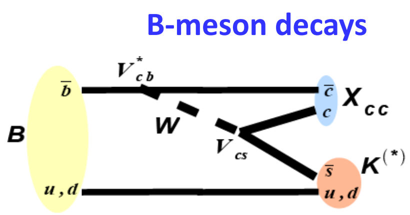
"The absence of exotics is one of the most obvious features of QCD, R. Jaffe 2005

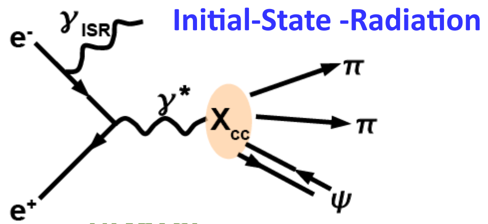


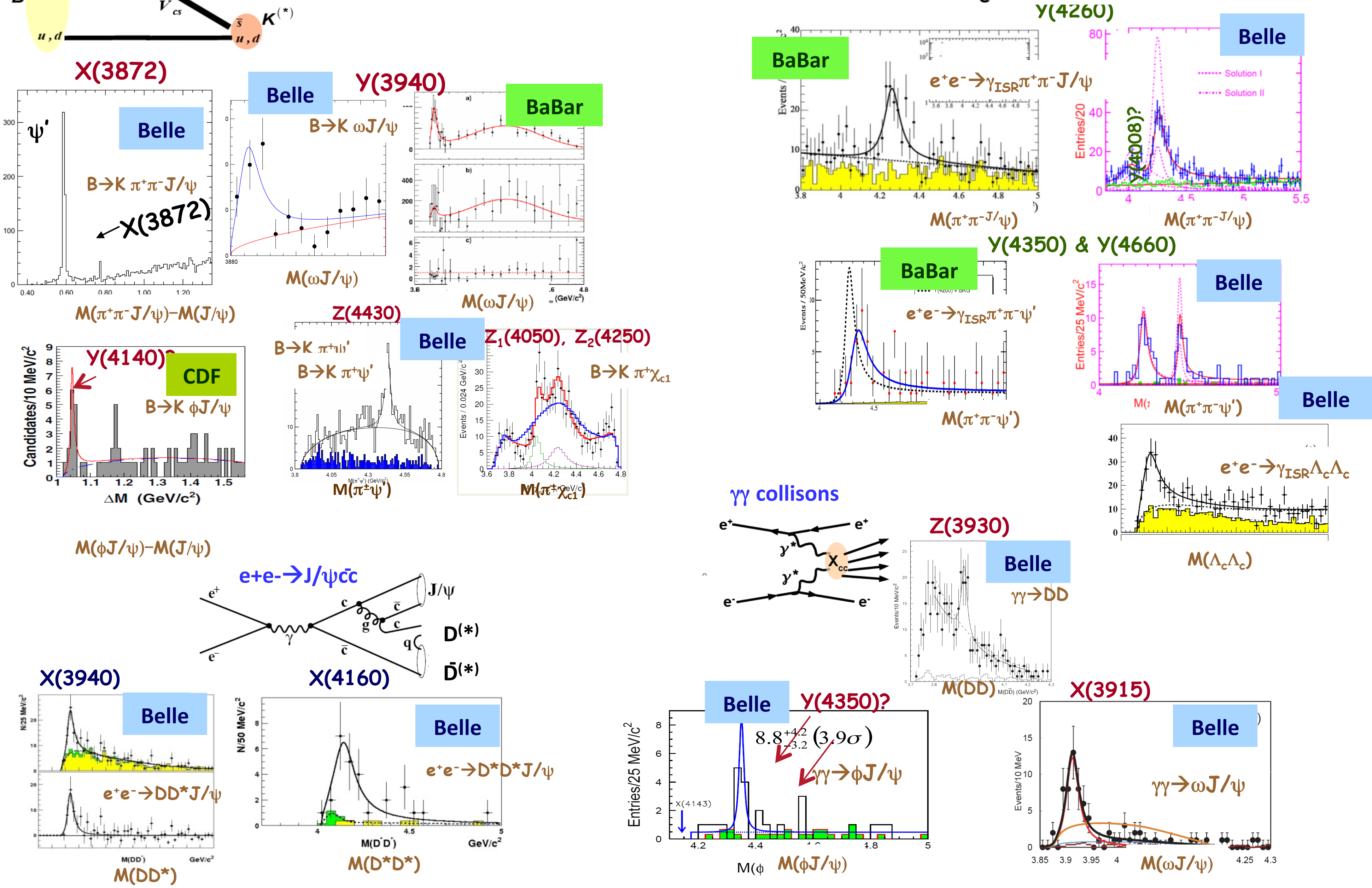
Robert Jaffe

What do we see?

The XYZ quarkonium-like mesons







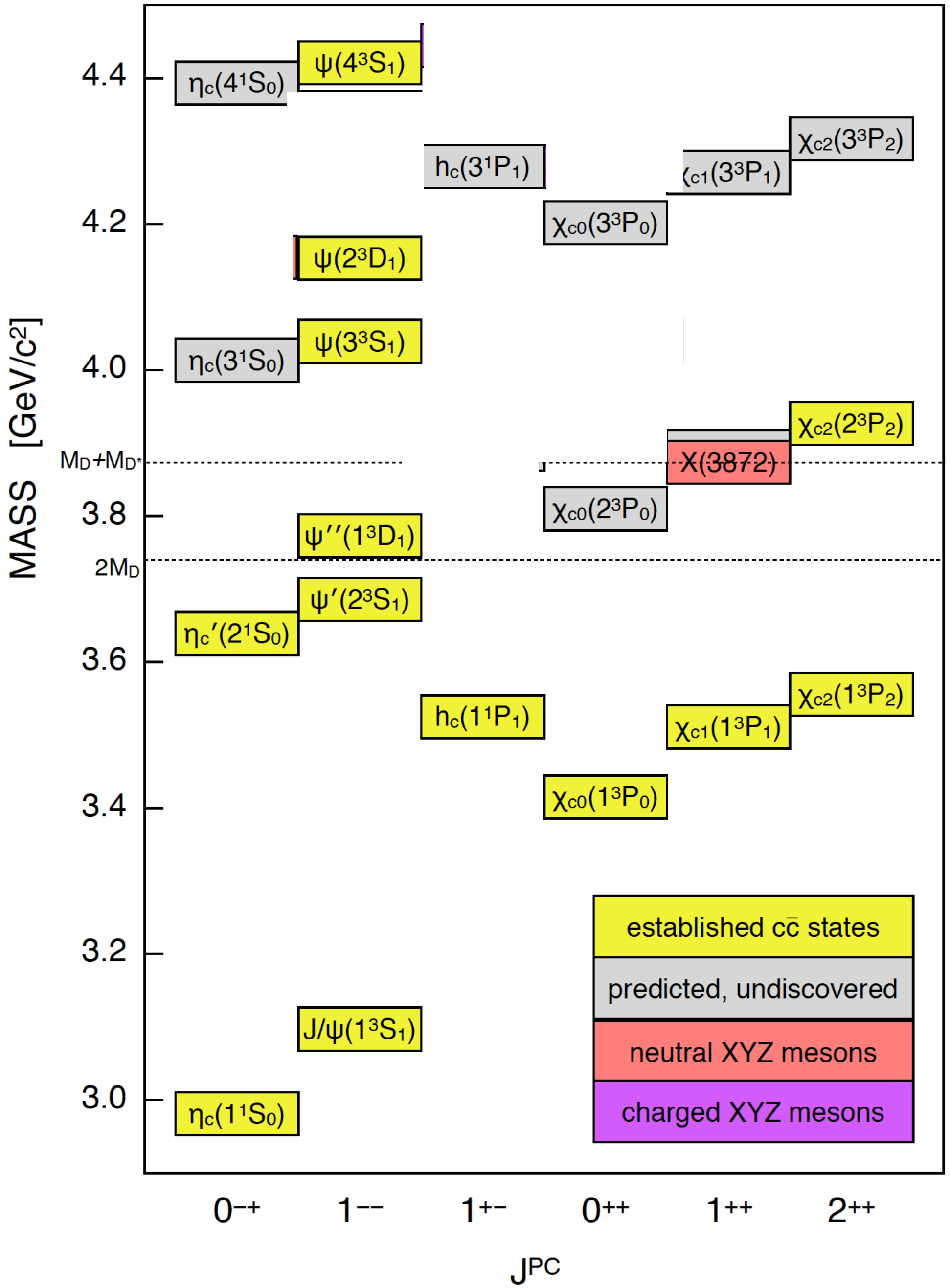
The list keeps growing

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]
				"$\Upsilon(5S)$" $\to \pi^- + (B^*\bar{B}^*)^+$, $n = 1,2$	Belle [123]

Now lots of charged Z_c mesons

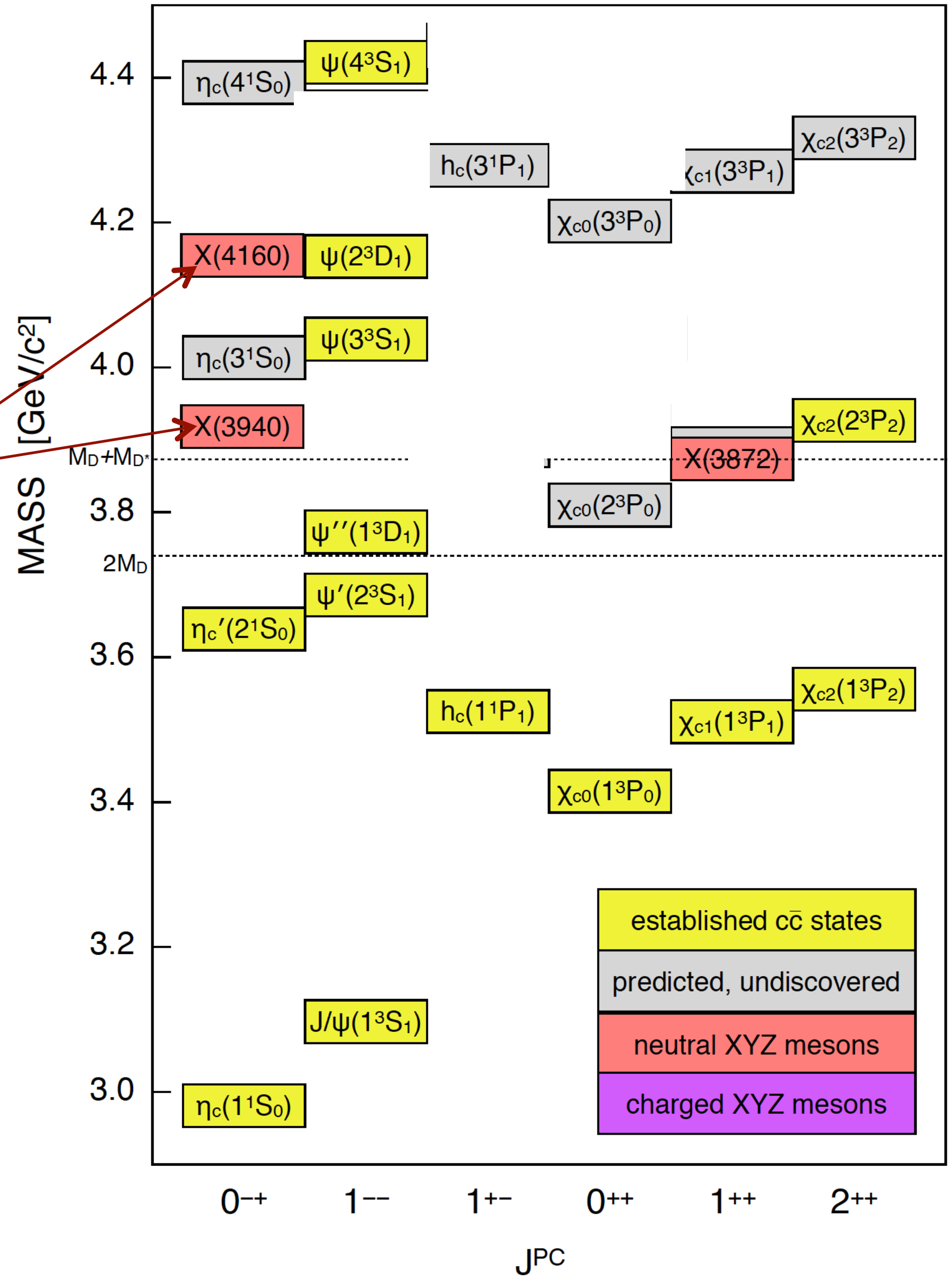
and two Z_b mesons

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



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

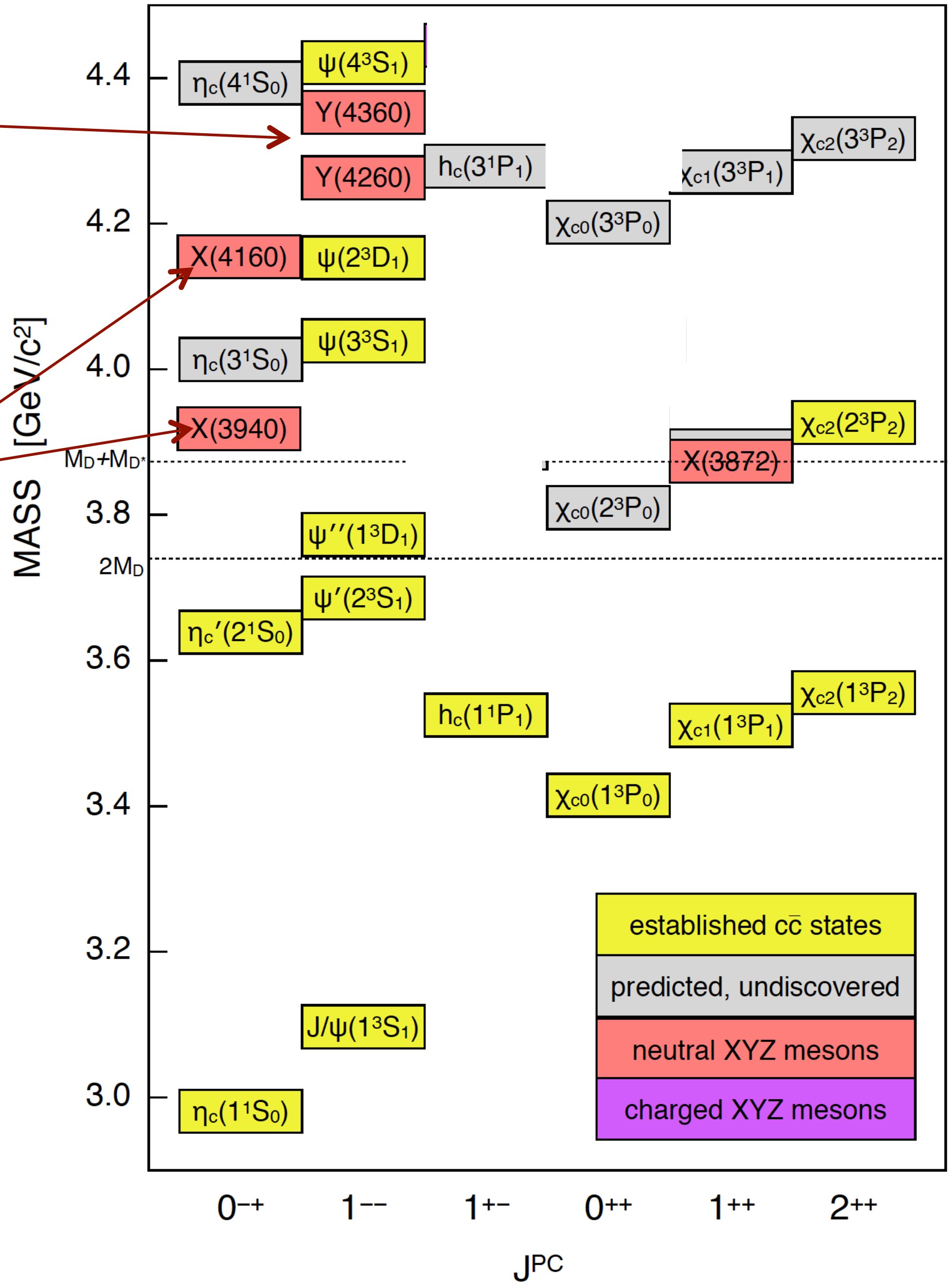
the X(3940) & X(4160) as the $\eta_c(3S)$ & $\eta_c(4S)$ would imply huge hyperfine splittings for n=3&4



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

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

the X(3940) & X(4160) as the $\eta_c(3S)$ & $\eta_c(4S)$ would imply huge hyperfine splittings for n=3&4



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

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

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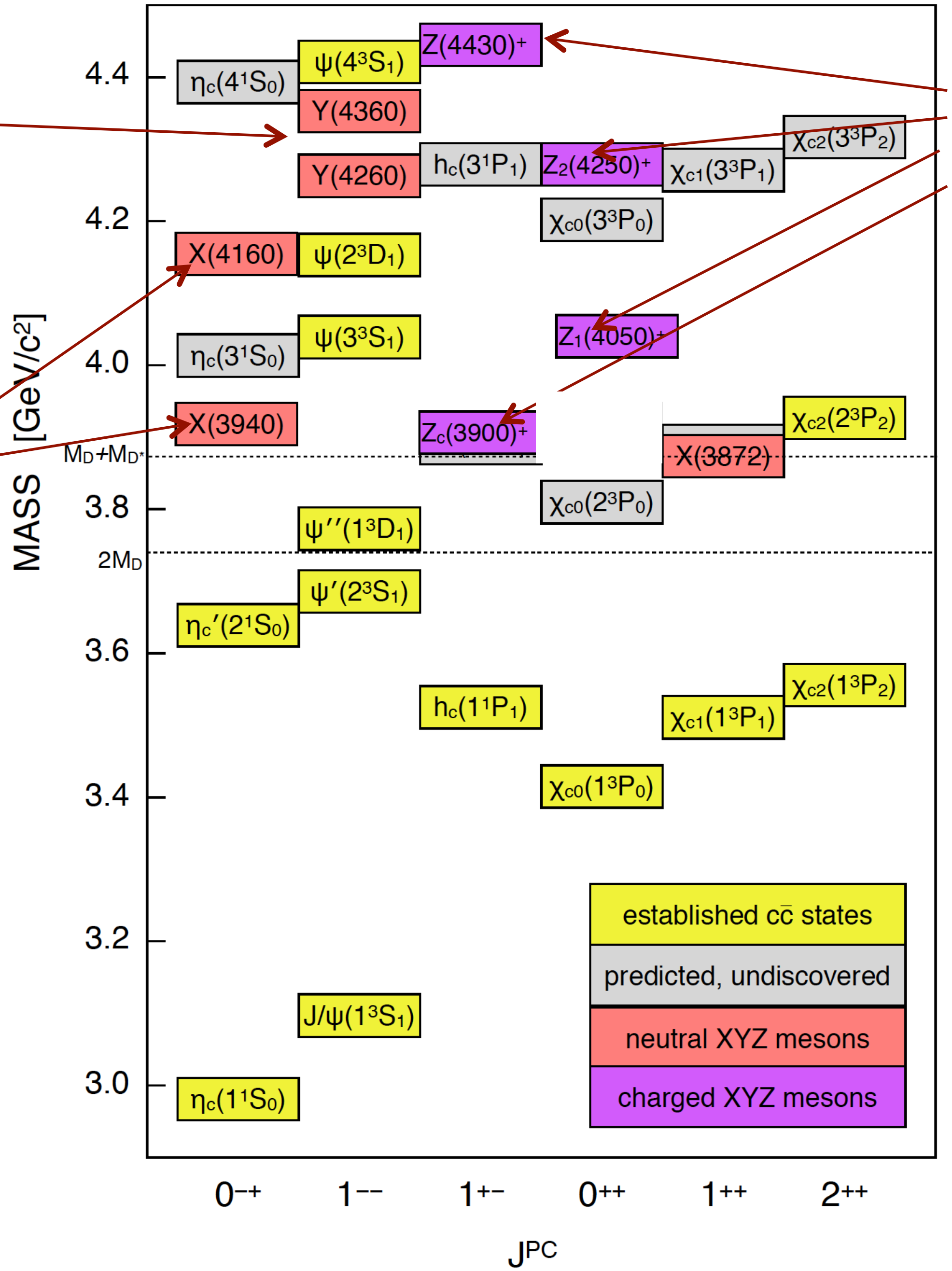
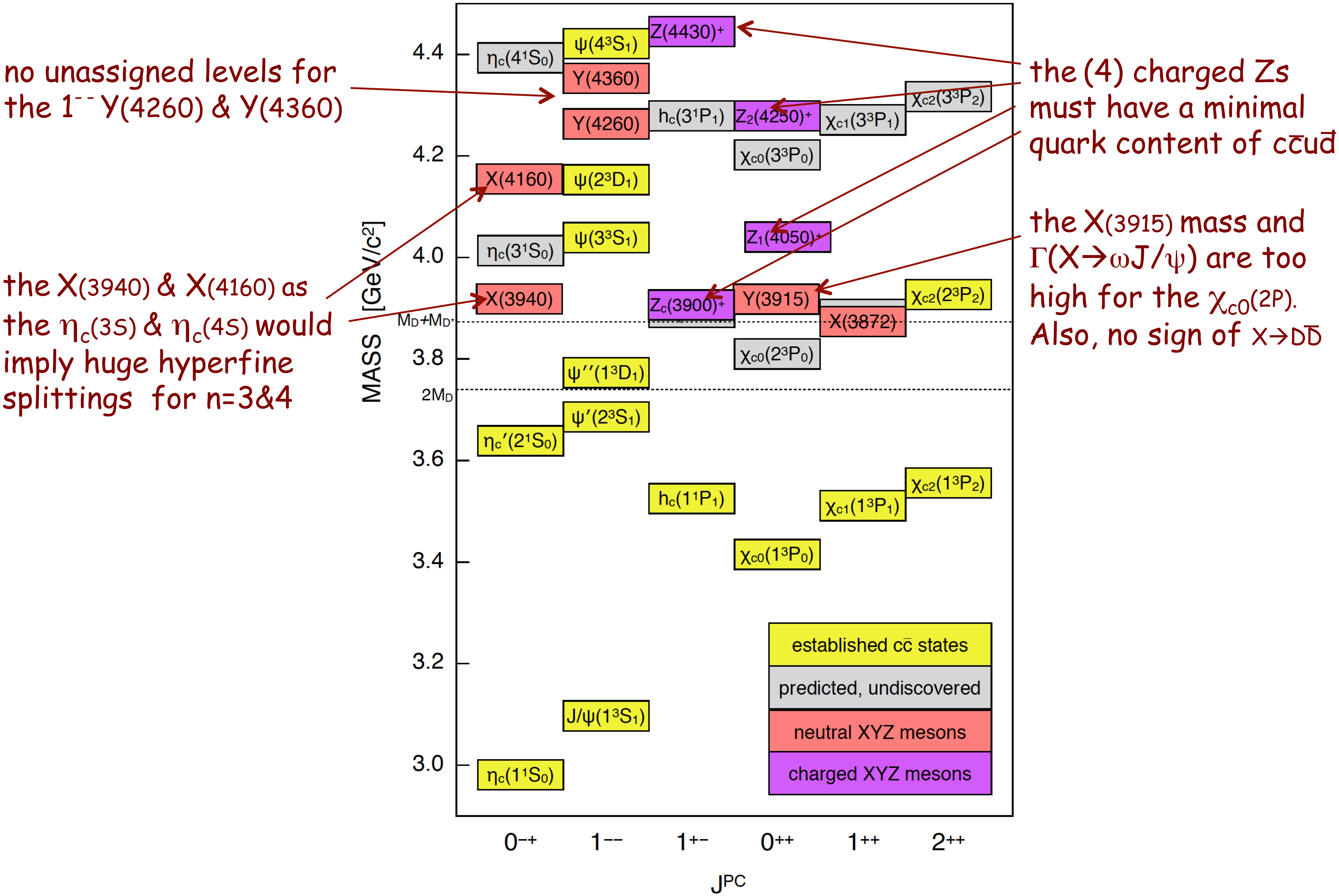


the (4) charged Zs must have a minimal quark content of $c\bar{c}u\bar{d}$

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



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

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

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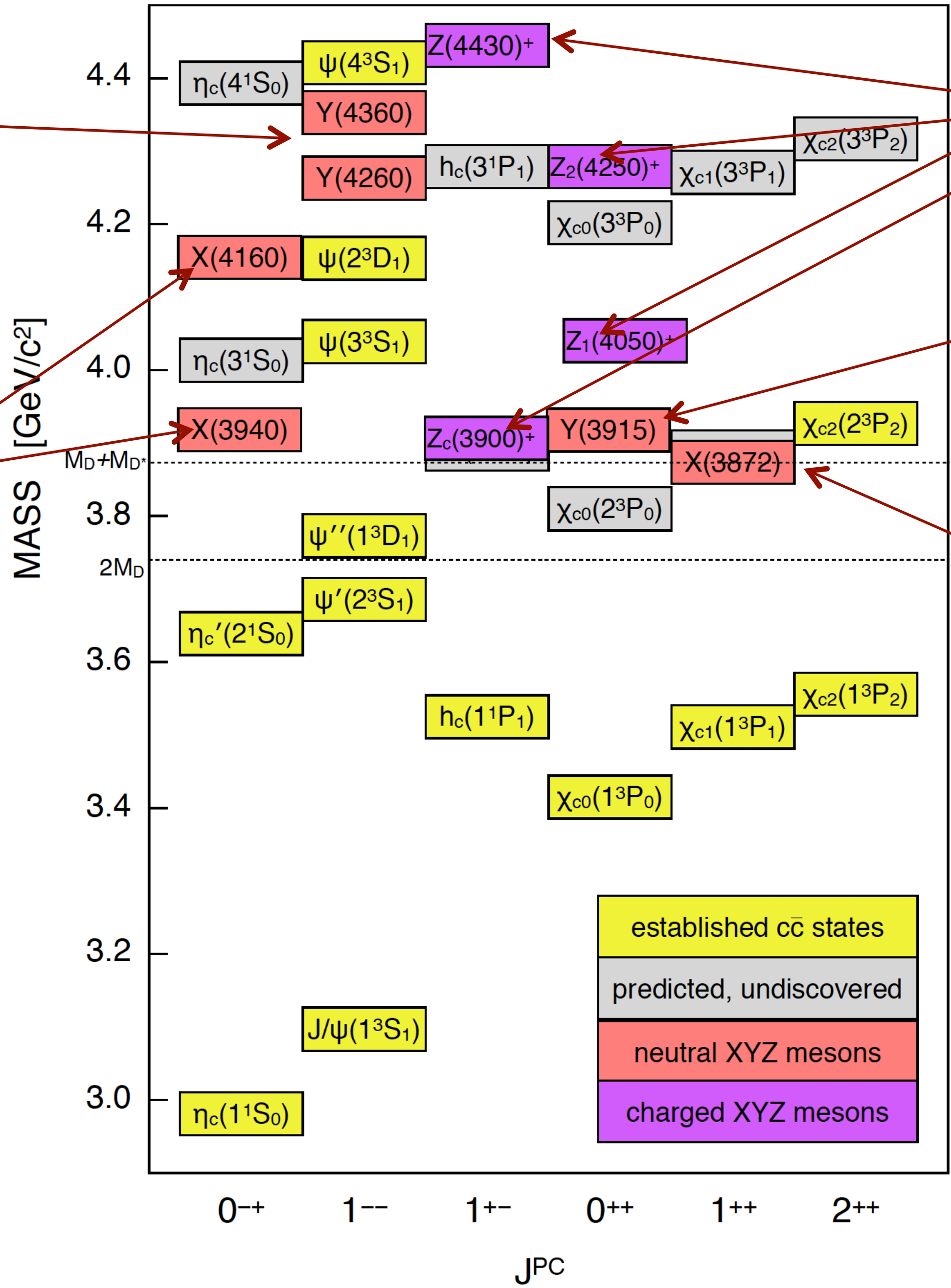
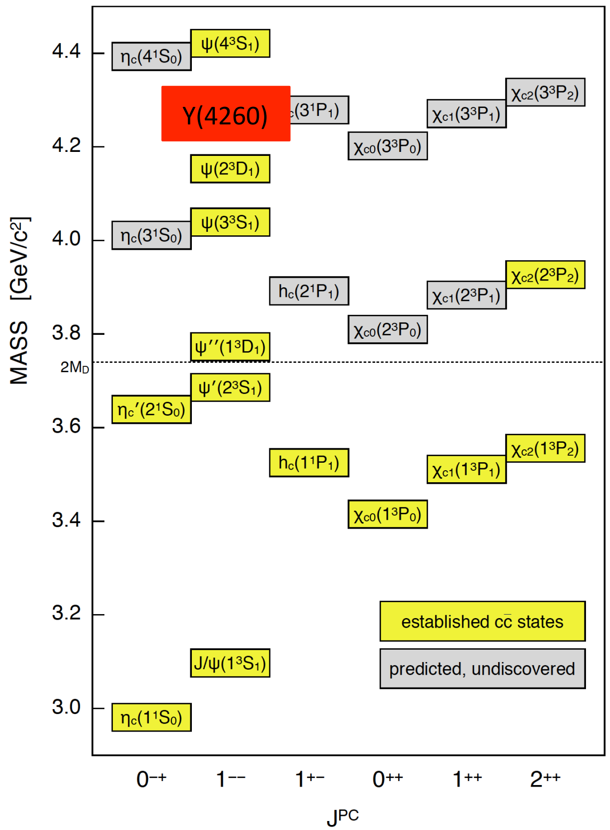


the (4) charged Zs must have a minimal quark content of $c\bar{c}u\bar{d}$

the Y(3915) mass and $\Gamma(X \rightarrow \omega J/\psi)$ are too high for the $\chi_{c0}(2P)$. Also, no sign of $X \rightarrow D\bar{D}$

the X(3872) is a long complex story

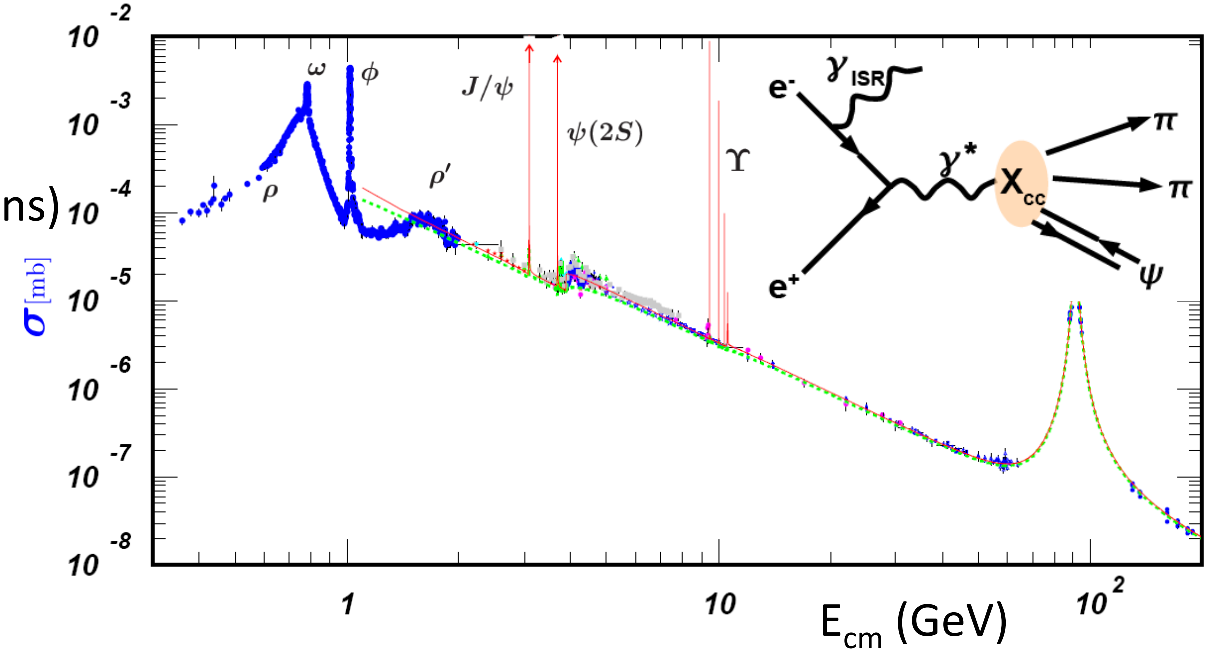
The Y(4260)



Y(4260)
ηc(4¹S₀)
ψ(4³S₁)
(3¹P₁)
χc2(3³P₂)
χc1(3³P₁)
χc0(3³P₀)
ψ(2³D₁)
ηc(3¹S₀)
ψ(3³S₁)
hc(2¹P₁)
χc2(2³P₂)
χc1(2³P₁)
χc0(2³P₀)
ψ''(1³D₁)
2M_D
ψ'(2³S₁)
ηc'(2¹S₀)
hc(1¹P₁)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
established cc̄ states
predicted, undiscovered
J/ψ(1³S₁)
ηc(1¹S₀)
MASS [GeV/c²]
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
J^PC

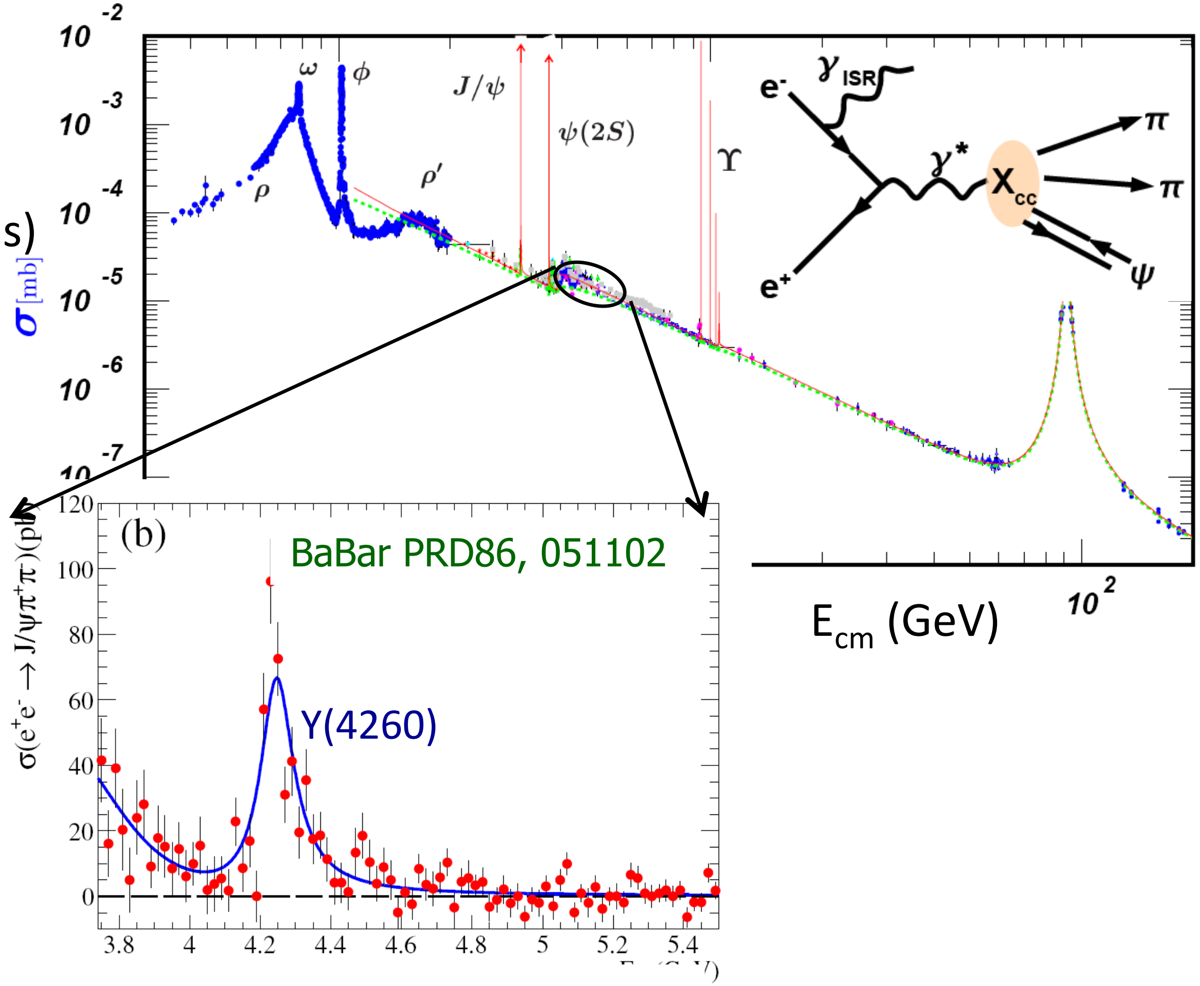
found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$

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



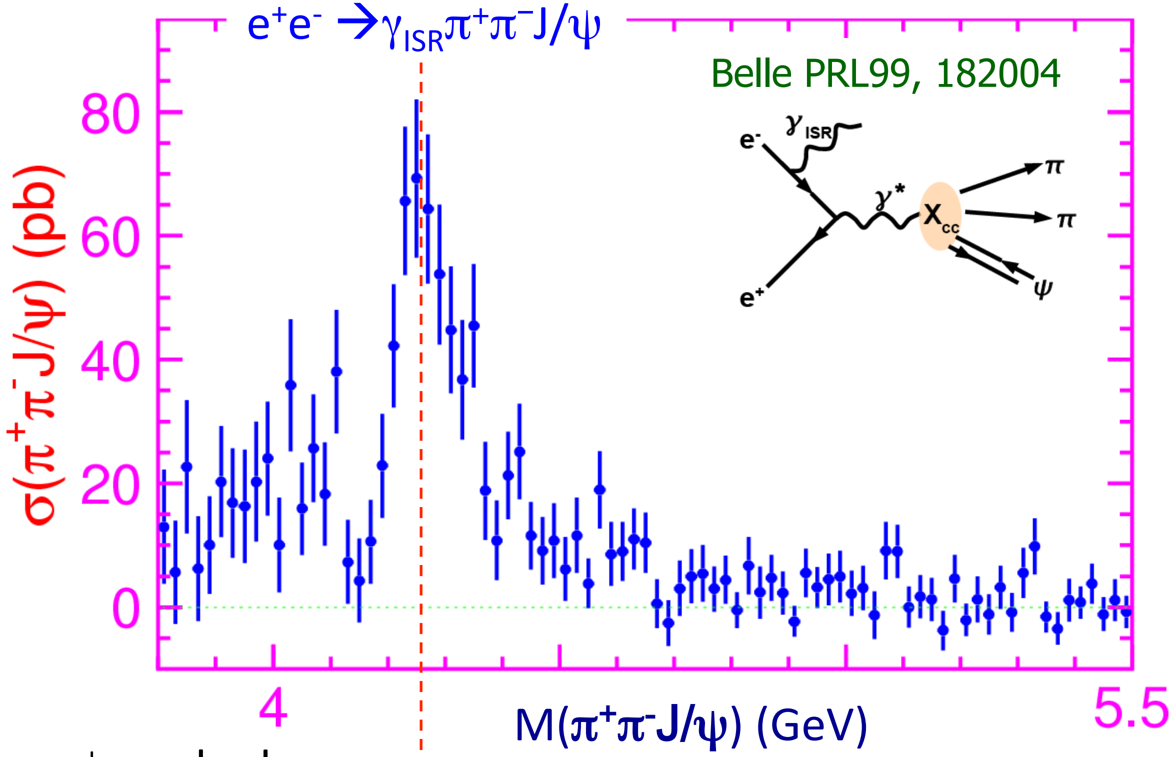
found by BaBar in $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$

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



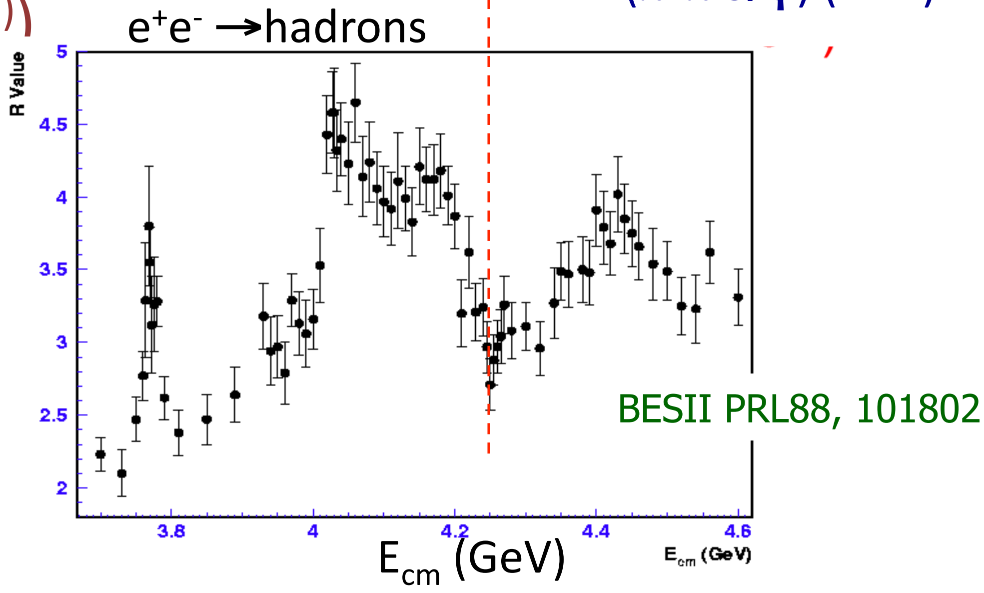
$M(\pi^+\pi^- J/\psi)$ (GeV)

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



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

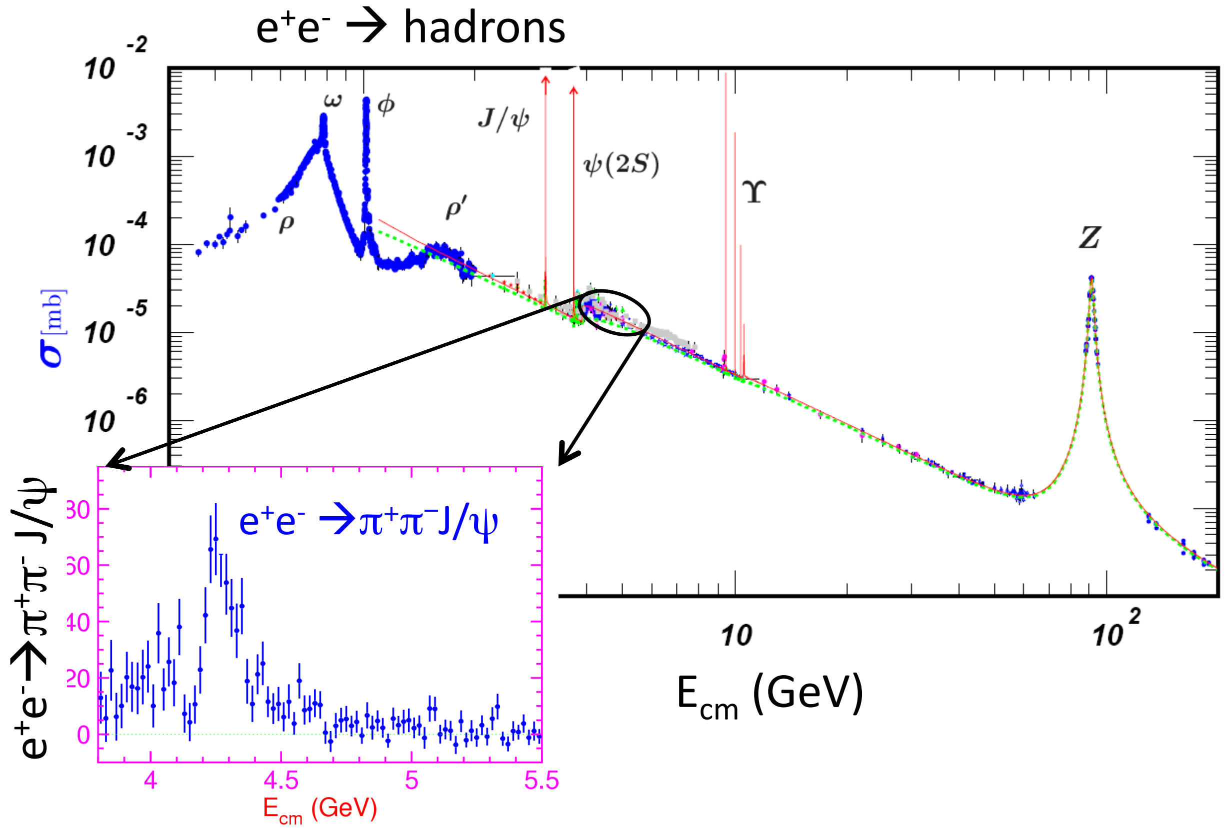
Y(4260) peak in σ $(\pi^+\pi^- J/\psi)$ occurs at a dip in $\sigma(D^{(*)}\bar{D}^{(*)})$



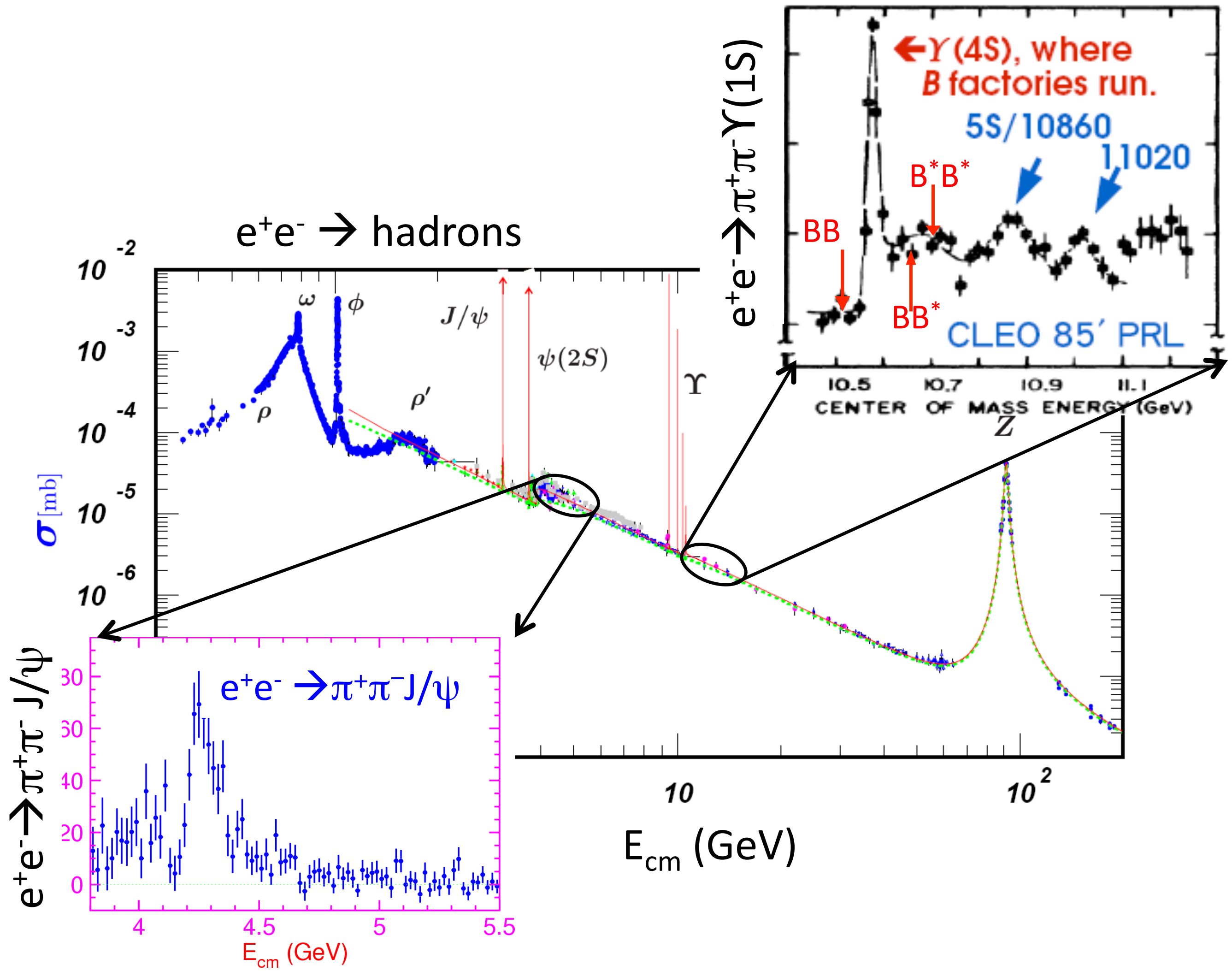
→$\Gamma(\pi^+\pi^- J/\psi)$ is large,
but OZI suppressed for $c\bar{c}$

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

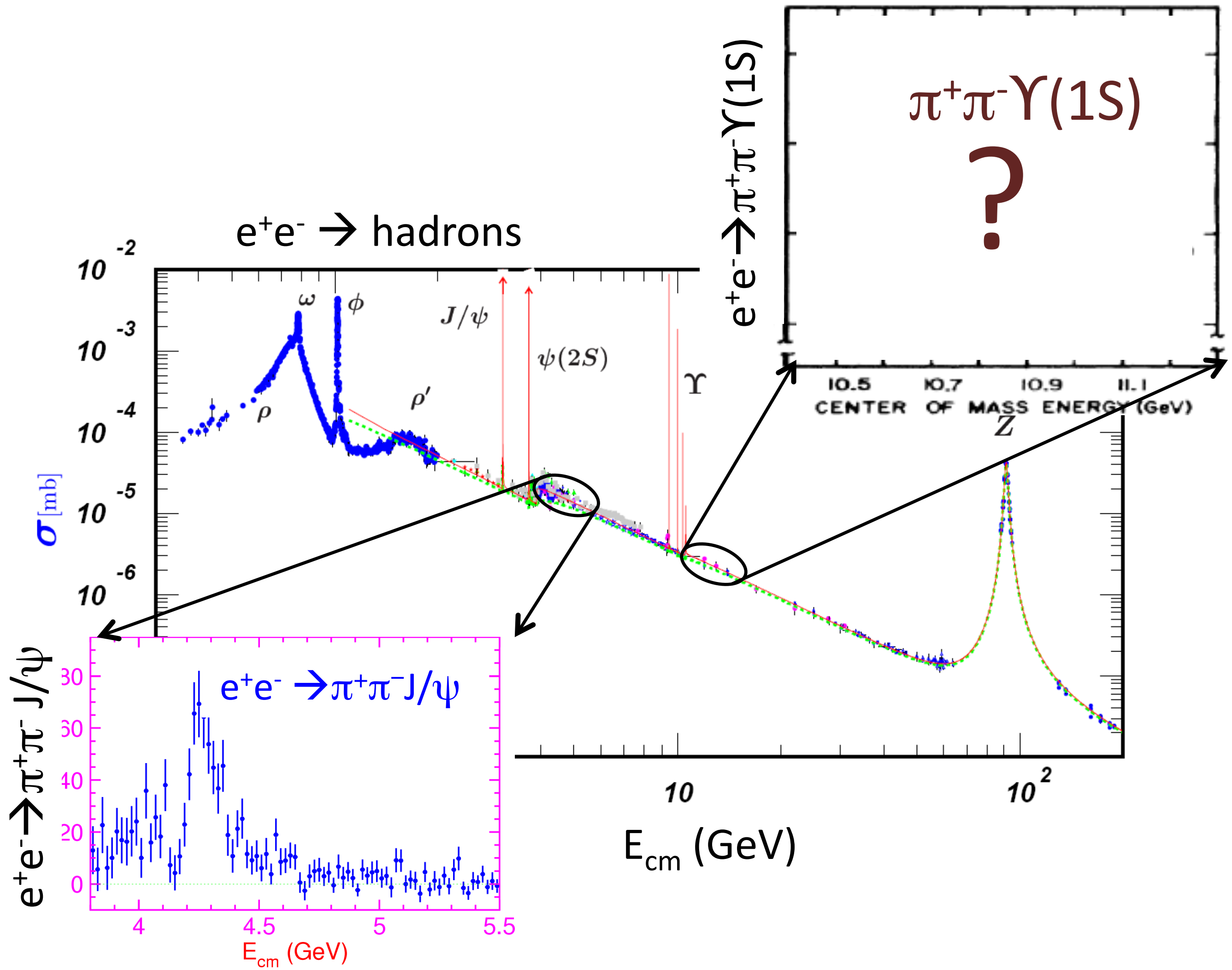
Is there a b-quark version of Y(4260)?



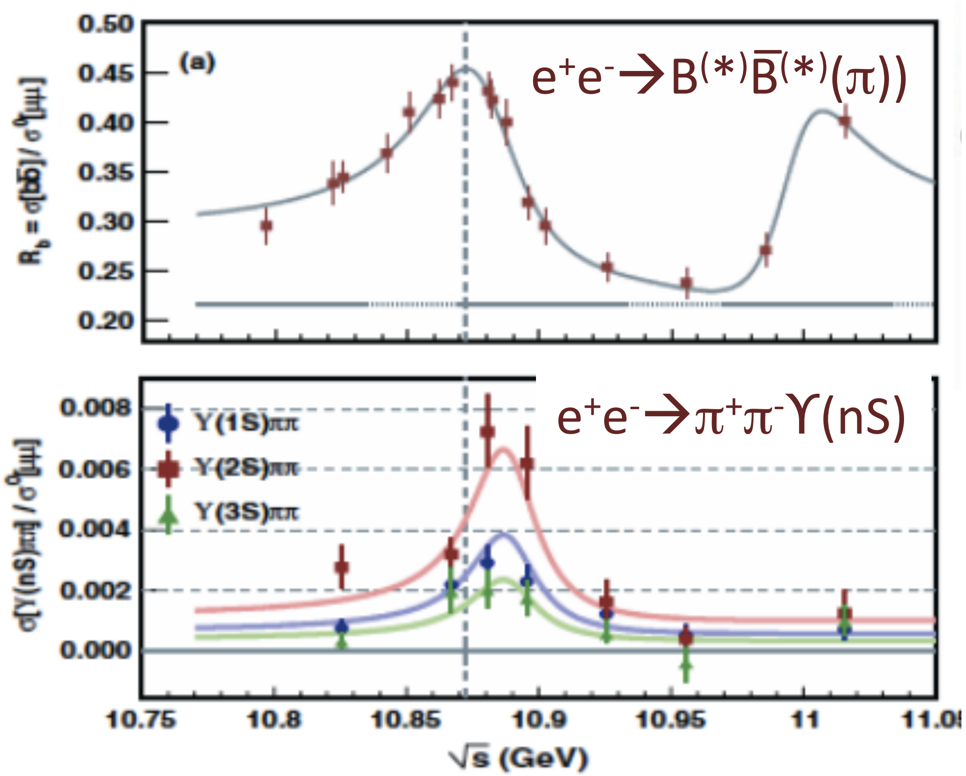
Is there a b-quark version of Y(4260)?



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



Yes

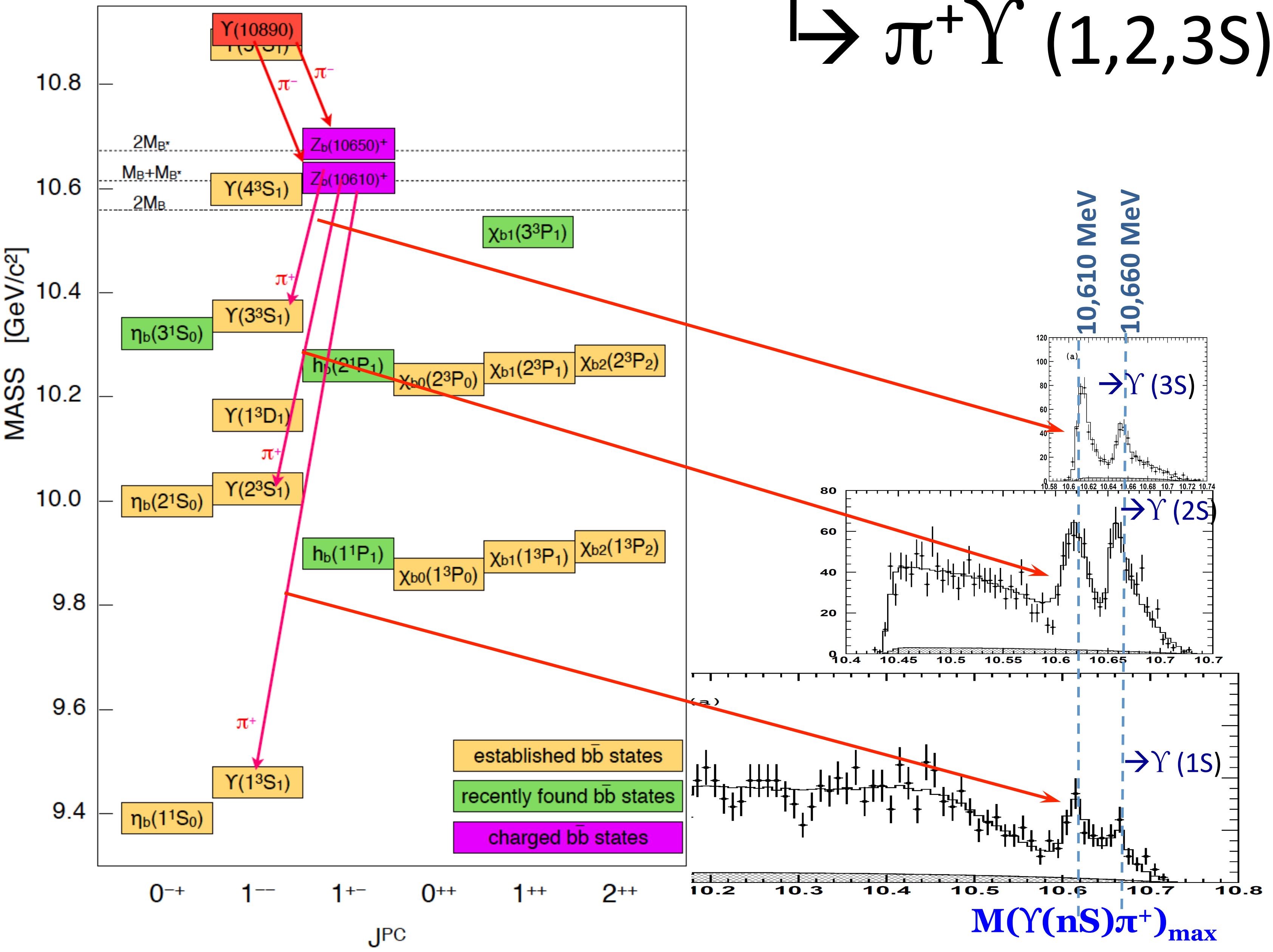


PRD82,091106(2010)

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

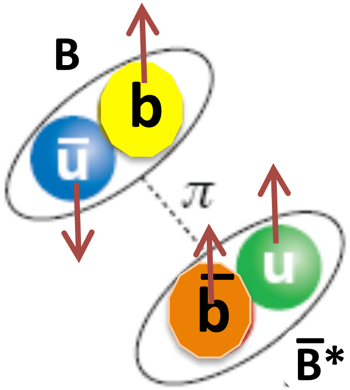
"$\Upsilon(5S)$" → $\pi^- Z^+_{b1,2}$
↳ $\pi^+ \Upsilon(1,2,3S)$

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



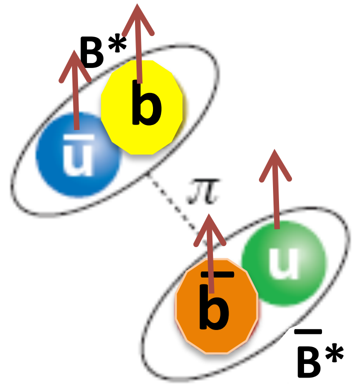
B-$\bar{B}$* & B*-$\bar{B}$* molecules??

$Z_b(106010)^{\pm}$



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

$Z_b(106050)^{\pm}$



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

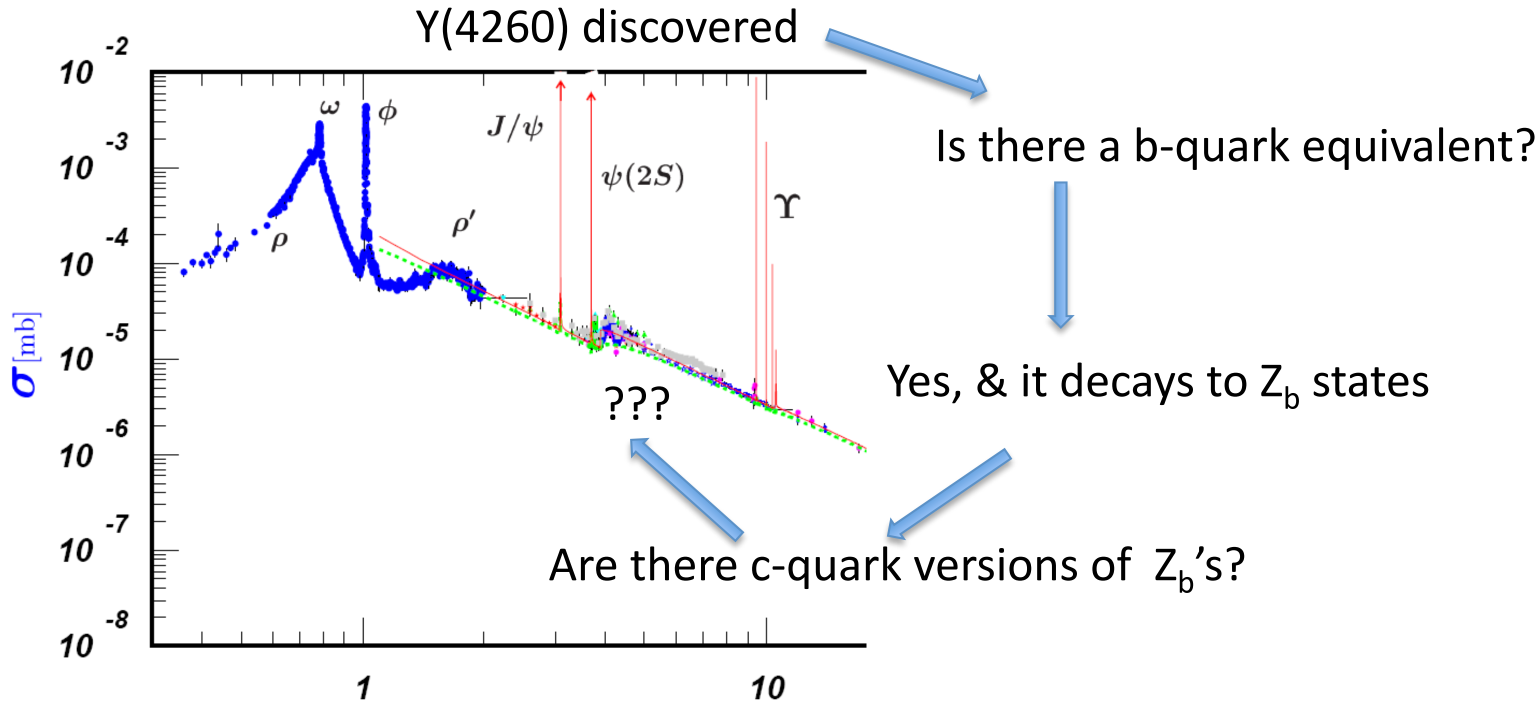
$M_{Z_b(106010)} - (M_B + M_{B*}) = +\,3.6 \pm 1.8$ MeV

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

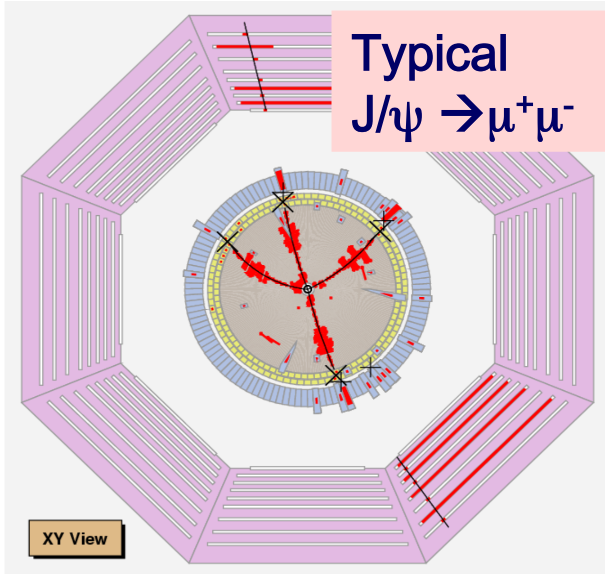
Are there c-quark versions of Z_b's



run BEPCII/BESIII as a Y(4260) factory

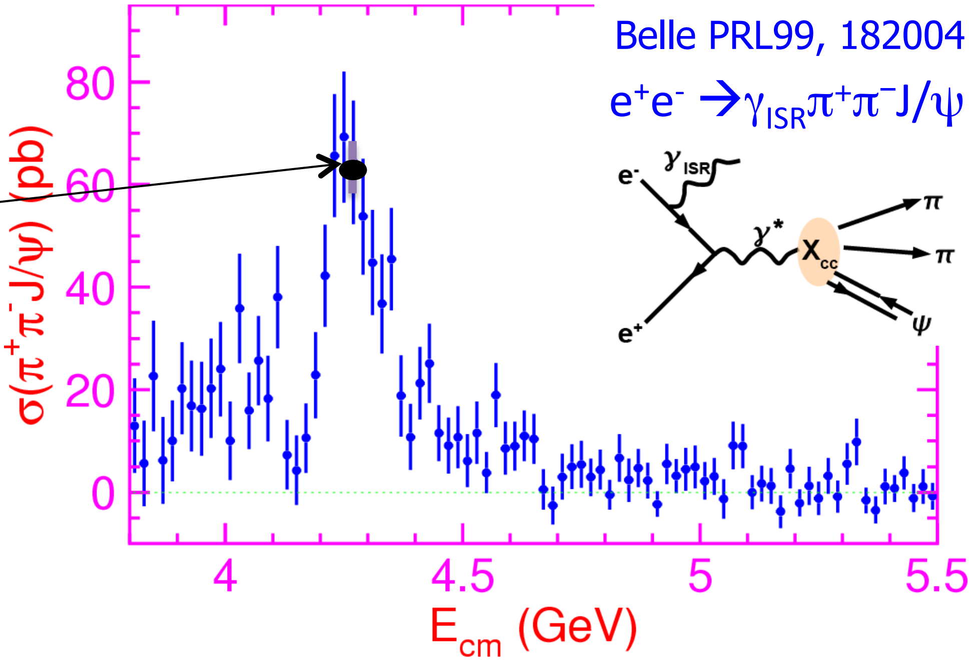
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$

$@E_{cm}=4260$ MeV

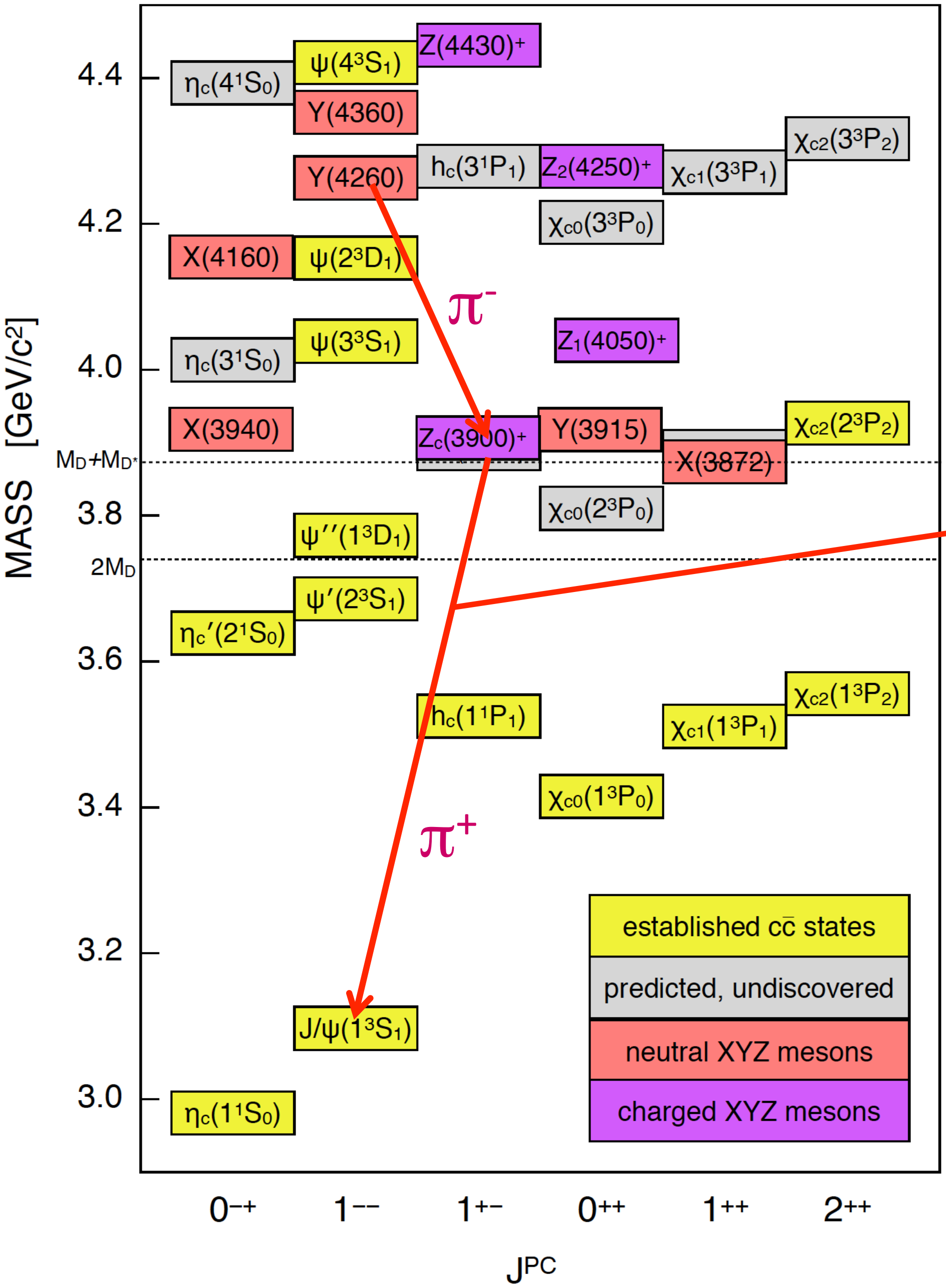


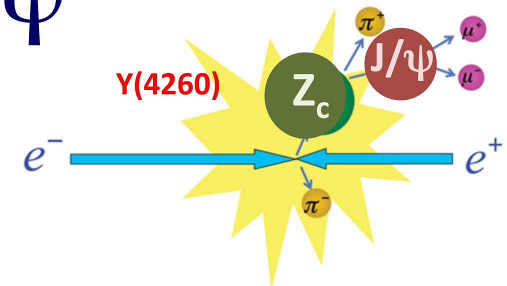
BESIII: PRL 110, 252001 (2013)

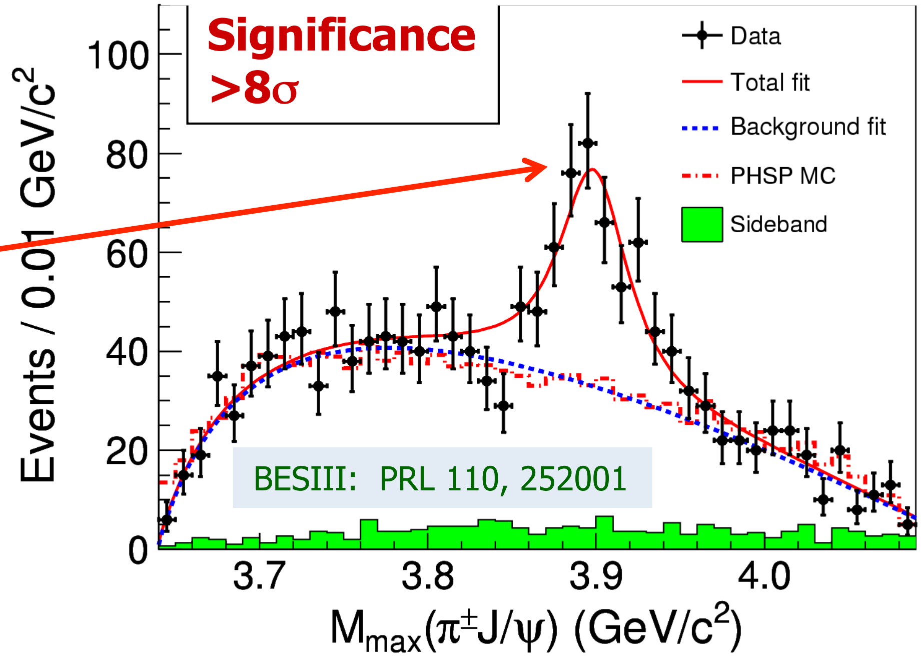
$\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb



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



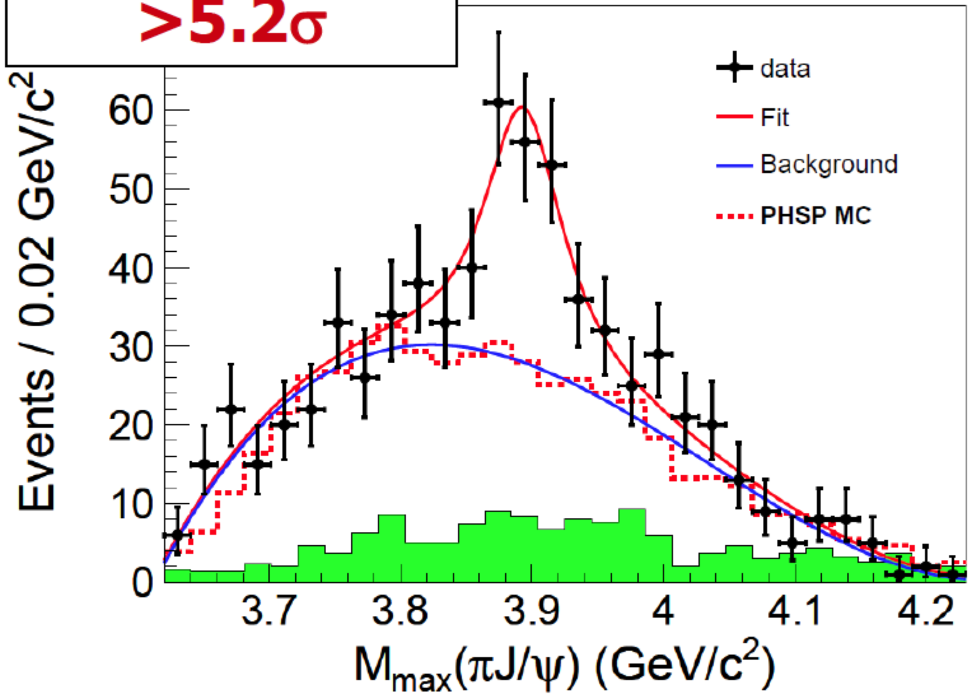




- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

$Z_c(3900)$ confirmed by Belle

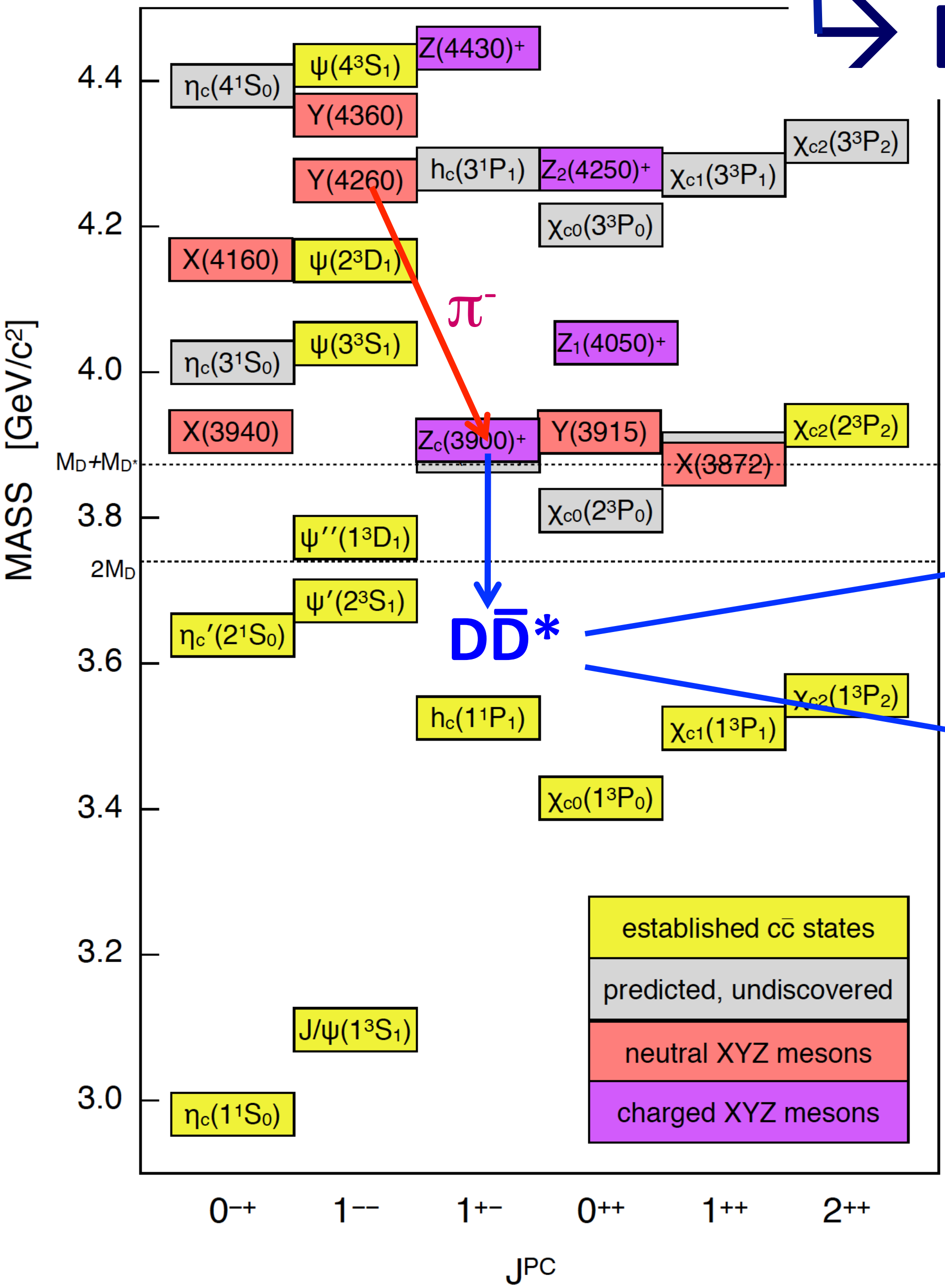
Significance >5.2σ

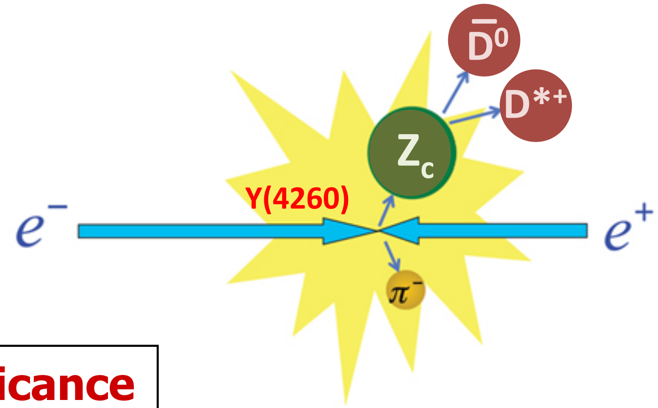


Mass = (3894.5 ± 6.6 ± 4.5) MeV
Width = (63 ± 24 ± 26) MeV
Fraction = (29.0 ± 8.9)% (stat. err. only)

Belle: PRL 110, 252002

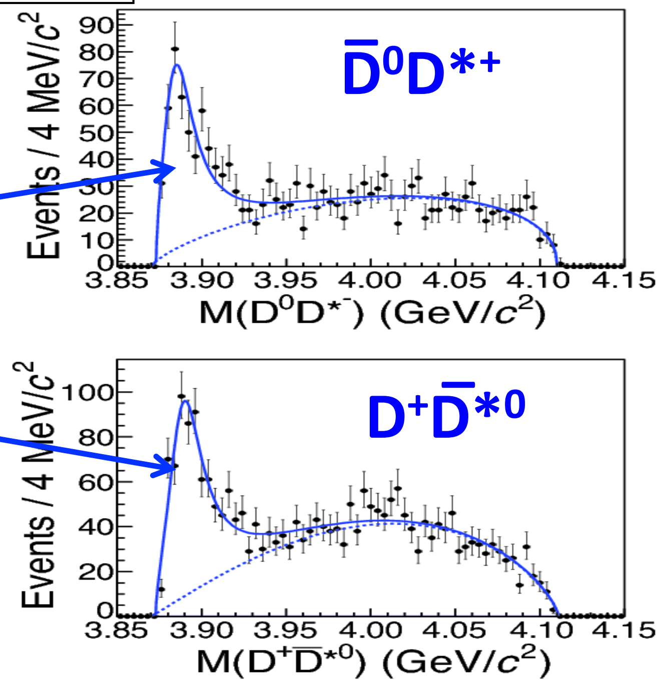
$Y(4260) \rightarrow \pi^- Z_c(3900)^+$
↳ $\bar{D}D^*$





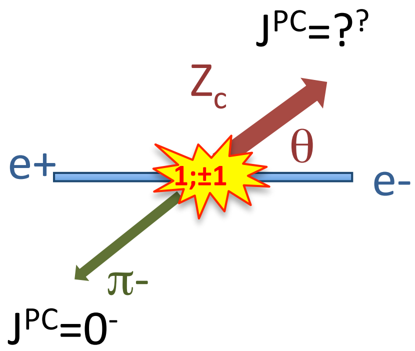
Significance >18σ

BESIII PRL 112, 022001 (last month)



- Mass = (3883.9 ±1.5 ±4.2) MeV
- Width = (24.8 ±3.3 ±11.0) MeV
- $D\bar{D}^*/\pi^+\pi^- J/\psi$ = 6.2 ± 1.1 ± 2.7

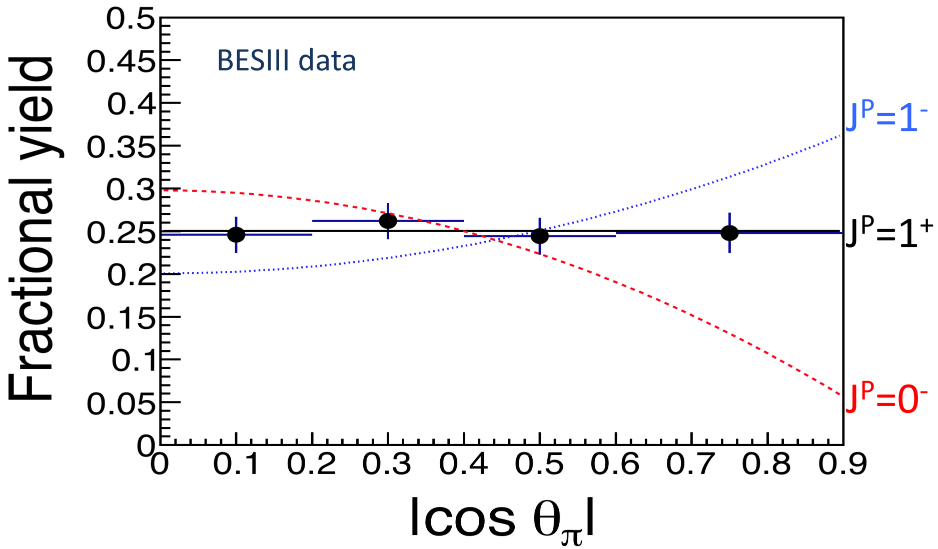
J^P of the $Z_c(3900)$?



initial state: $|J;J_z\rangle = |1;\pm1\rangle \; P = -1$

final state:

π	Z_c	$\|L;L_z\rangle\|S;S_z\rangle$	$dN/d\|\cos\theta\|$
0^-	0^+	forbidden by Parity	---
0^-	0^-	$\|1;\pm1\rangle\|0;0\rangle$	$\propto \sin^2\theta$
0^-	1^+	$\|0;0\rangle\|1;\pm1\rangle$	flat
0^-	1^-	$\|1;\pm1\rangle\|1;0\rangle - \|1;0\rangle\|1;\pm1\rangle$	$\propto 1+\cos^2\theta$



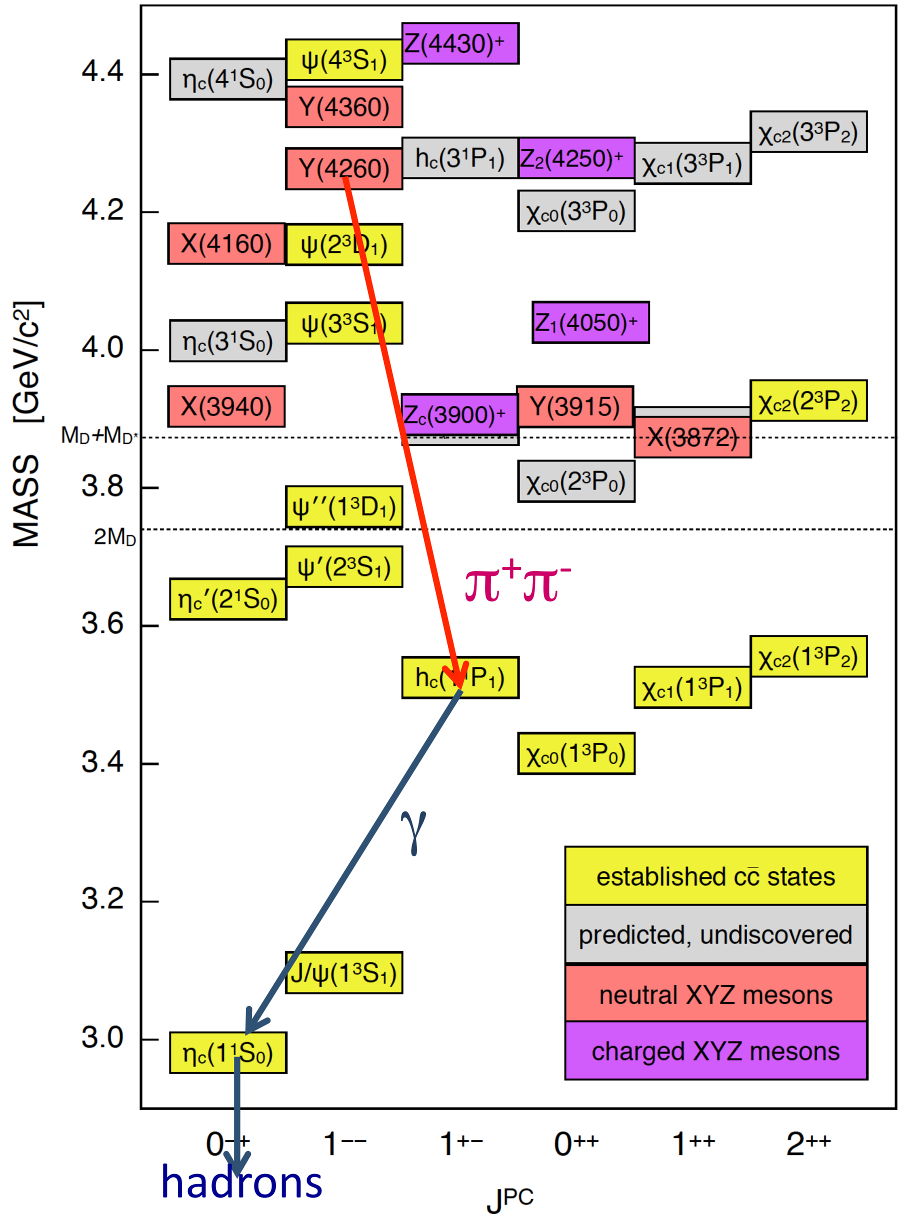
The data clearly establish $J^P=1^+$

Are there others?

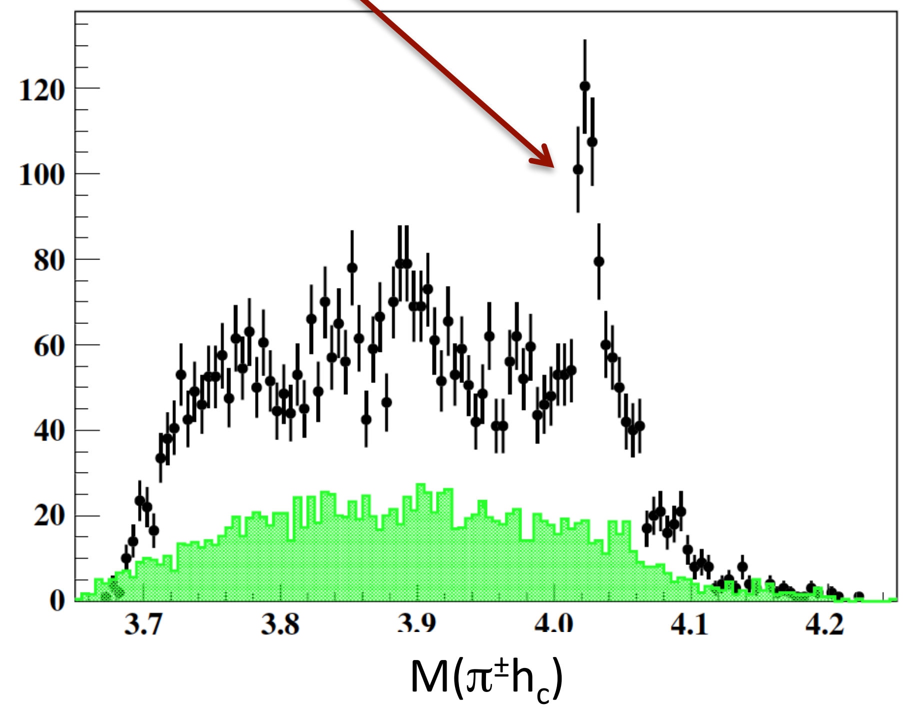
Study Y(4260)→$\pi^+\pi^-$ h_c decays

→ $\gamma\eta_c$

→ 16 channels

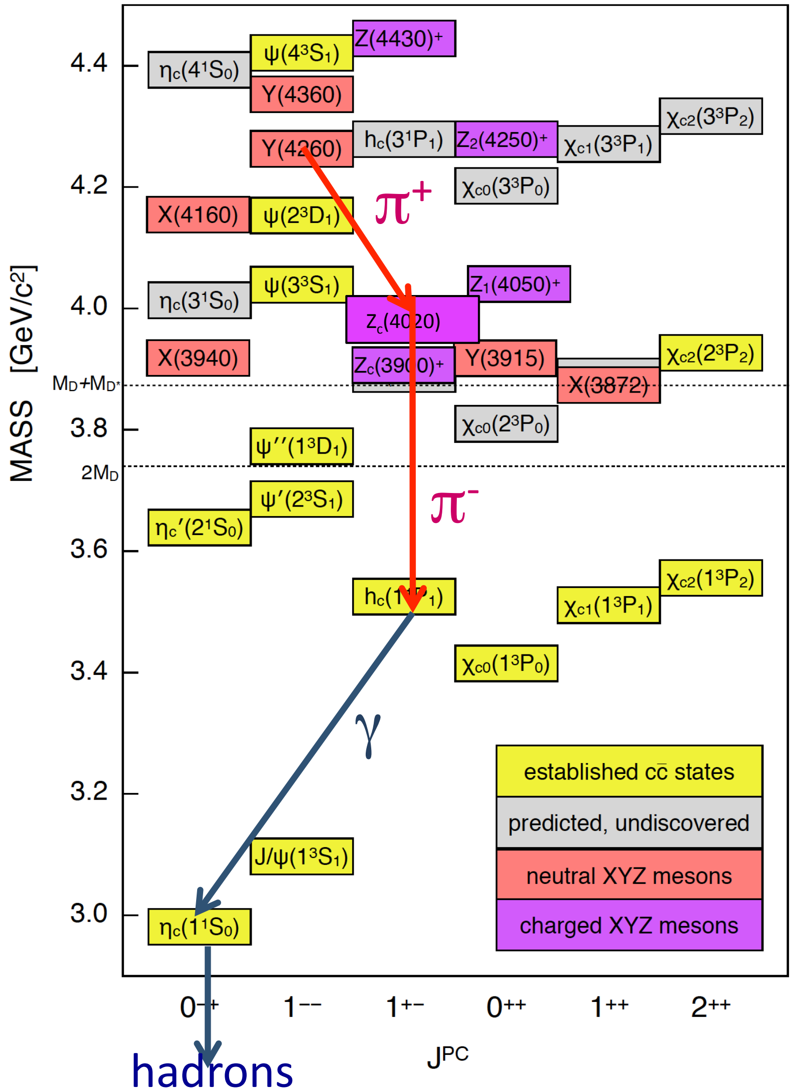


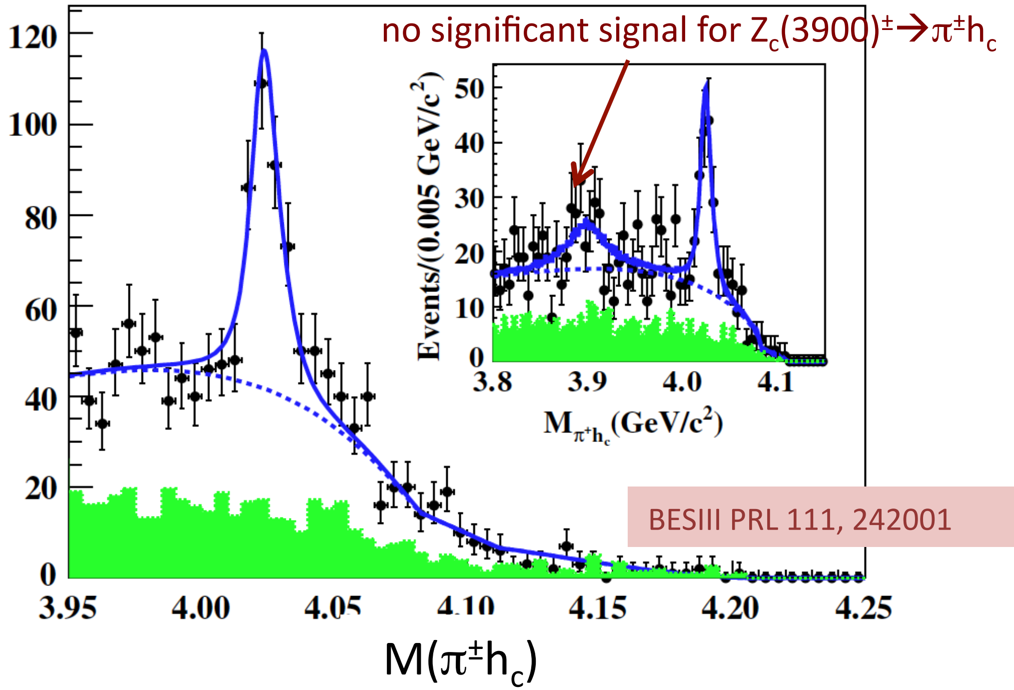
sharp M(πh_c) peak but not near ~3900 MeV



BESIII PRL 111, 242001 (2 months ago)

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





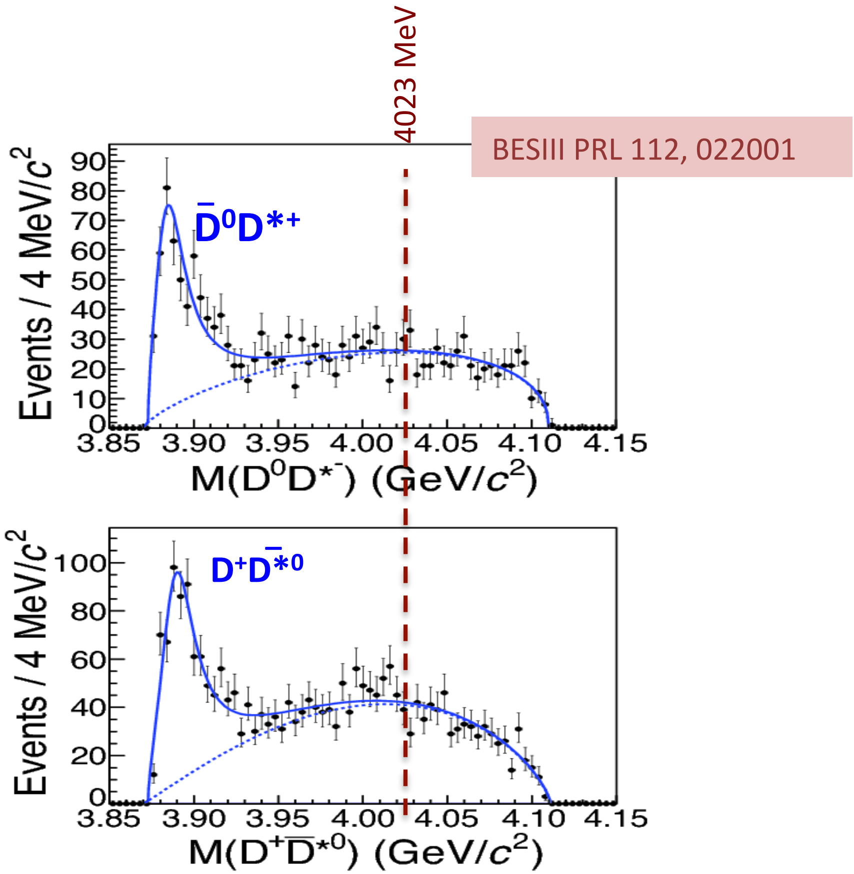
5.6 ± 2.8 MeV above $D^{*0}D^{*-}$ thresh.
= 4017.3 ±0.3 MeV

Fit results:

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

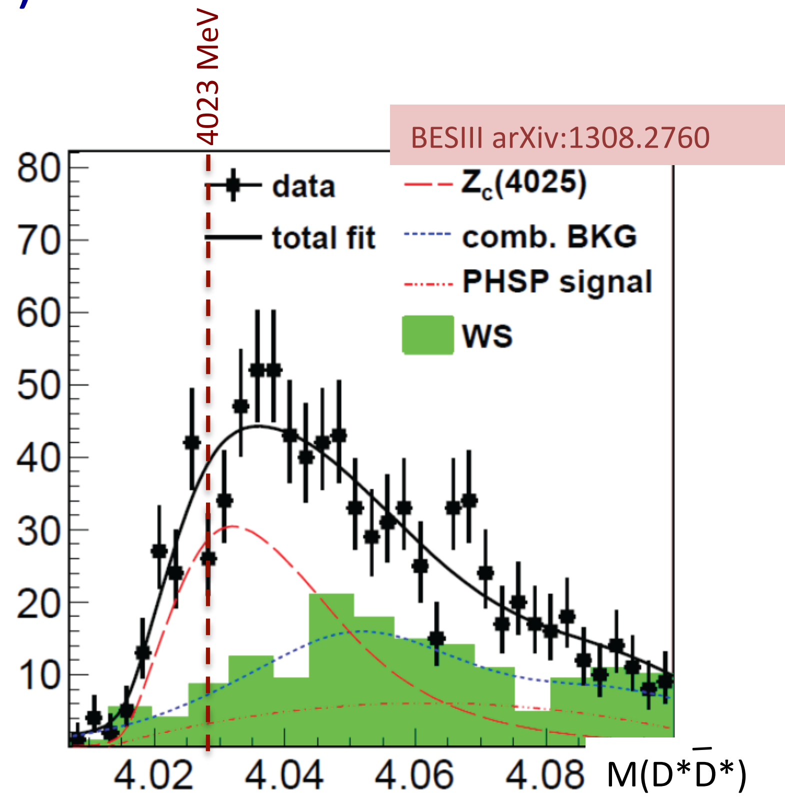
Does the $Z_c(4020) \rightarrow D\bar{D}^*$? … $D^*\bar{D}^*$?

$Z_c(4020) \rightarrow D\bar{D}^*$?



No sign of $Z_c(4020) \rightarrow D\bar{D}^*$

$Z_c(4020) \rightarrow D^*\bar{D}^*$?



Something there (~10σ!), but …

Fit results:
- Mass = (4026.3 ± 2.6 ± 3.7) MeV
- Width = (24.8 5 ± 5.6 ± 7.7) MeV

… higher mass (~1.5σ) and width (~1.5σ) than $Z_c(4020) \rightarrow \pi h_c$ signal

Big news from last month

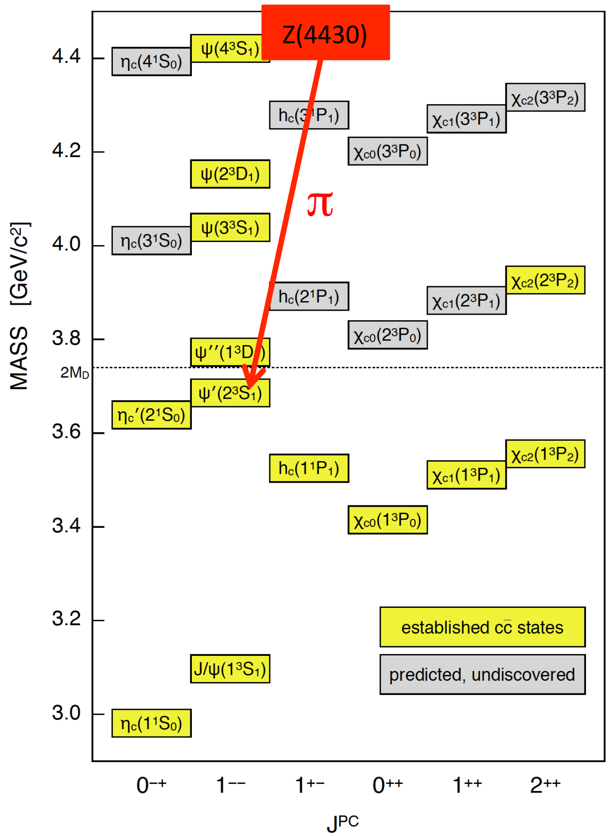
April 14, 2014

CERN's LHCb experiment sees exotic particle

An analysis using LHC data verifies the existence of an exotic four-quark hadron.

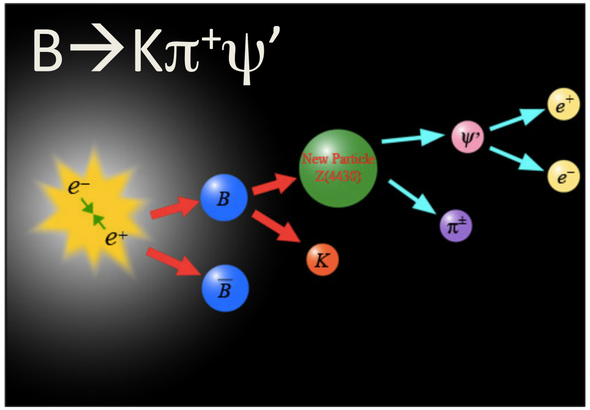
By Sarah Charley

The Z(4430)



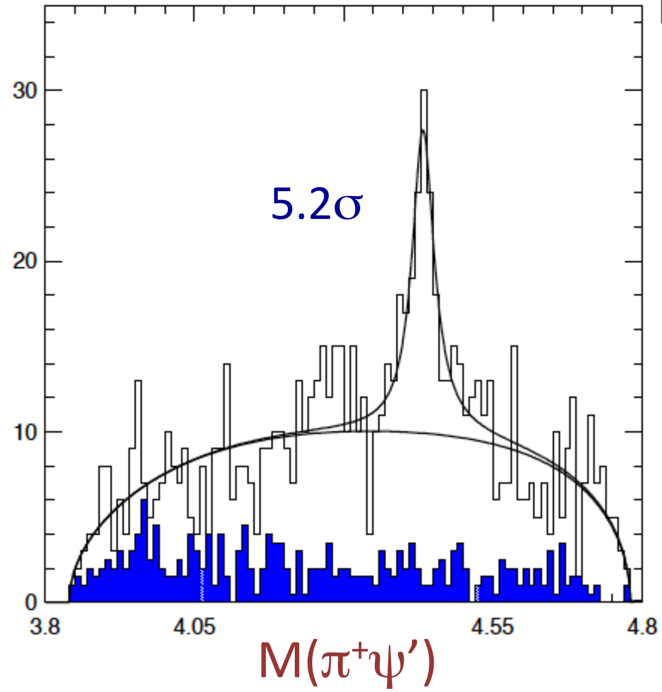
Z(4430)
π
MASS [GeV/c²]
4.4
4.2
4.0
3.8
2MD
3.6
3.4
3.2
3.0
ηc(4¹S₀)
ψ(4³S₁)
hc(3¹P₁)
χc1(3³P₁)
χc2(3³P₂)
χc0(3³P₀)
ψ(2³D₁)
ηc(3¹S₀)
ψ(3³S₁)
hc(2¹P₁)
χc1(2³P₁)
χc2(2³P₂)
χc0(2³P₀)
ψ''(1³D₁)
ψ'(2³S₁)
ηc'(2¹S₀)
hc(1¹P₁)
χc1(1³P₁)
χc2(1³P₂)
χc0(1³P₀)
J/ψ(1³S₁)
ηc(1¹S₀)
established cc̄ states
predicted, undiscovered
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
J^PC

Found by Belle in 2007



S-K Choi et al Belle: PRL 100 142001

2007 slice & dice analysis



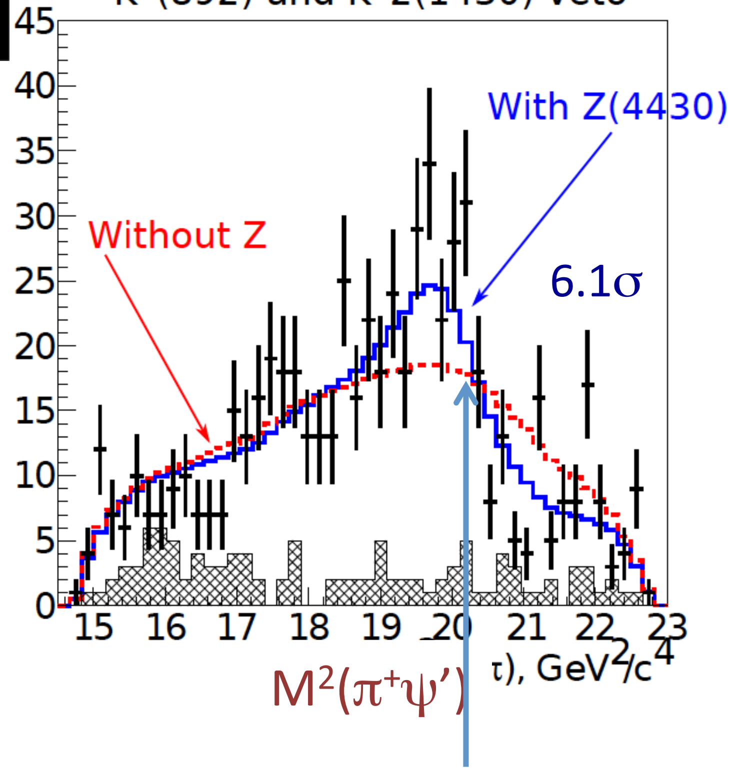
$$M = 4485^{+22+28}_{-22-11}\ \text{MeV}$$

$$\Gamma = 200^{+41+26}_{-46-35}\ \text{MeV}$$

K Chilikin et al Belle: PRD 88 074026

2013: 4-dim amplitude analysis

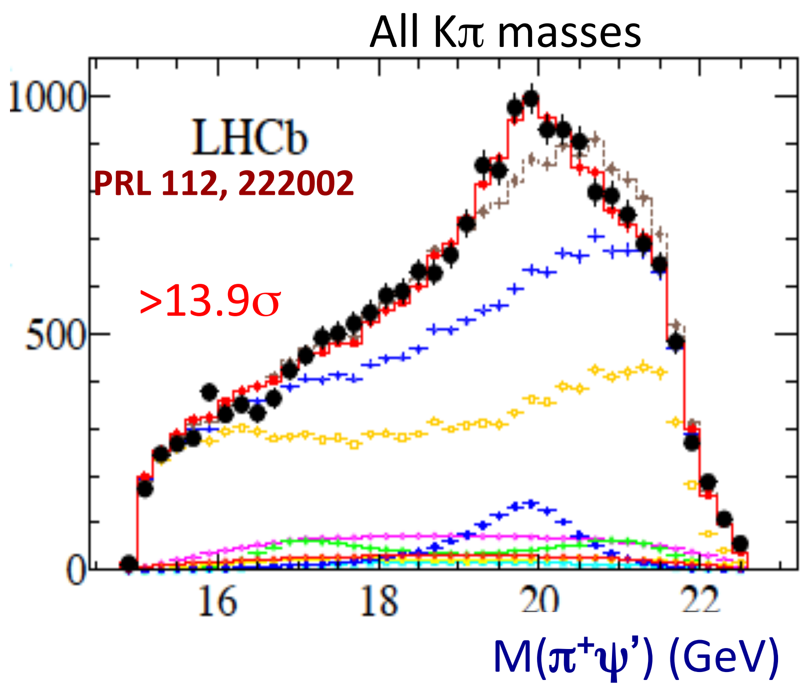
K*(892) and K*2(1430) veto

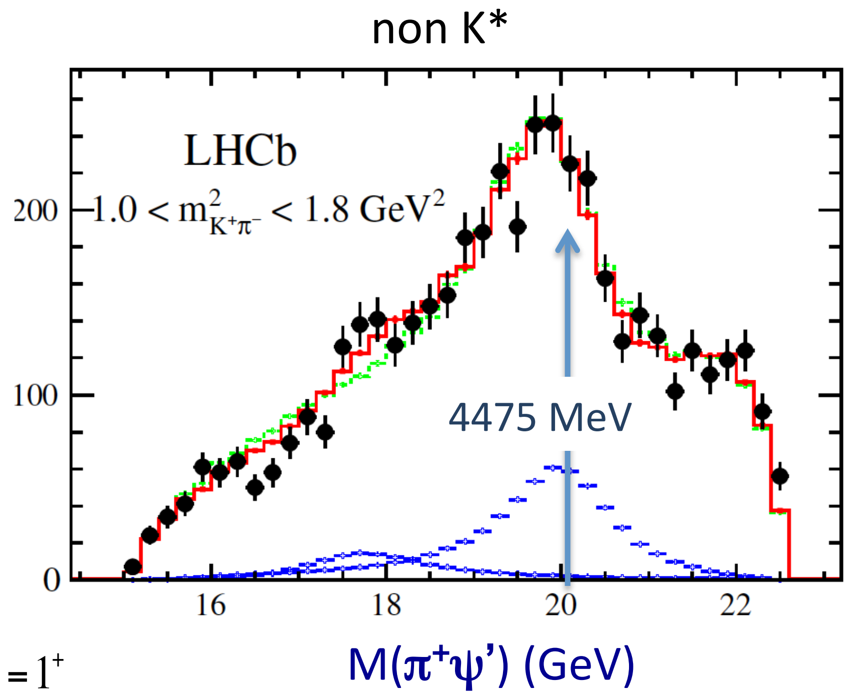


4485 MeV

Confirmed by LHCb last spring

B→Kπ$^+$ψ': 4-dim amplitude analysis





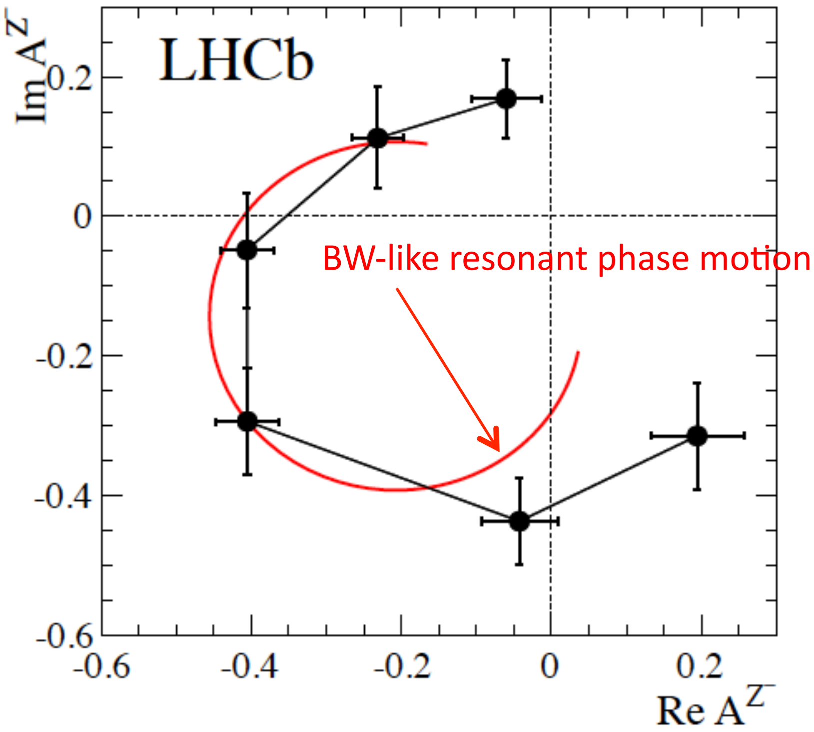
$J^P = 1^+$

$M = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Argand plot shows BW-like phase motion

BW Model-independent Argand plot



Any non-resonance explanation of the data requires an amplitude with:

- rapid 180° phase change near peak
- coherence with $K^*\psi'$ "background"

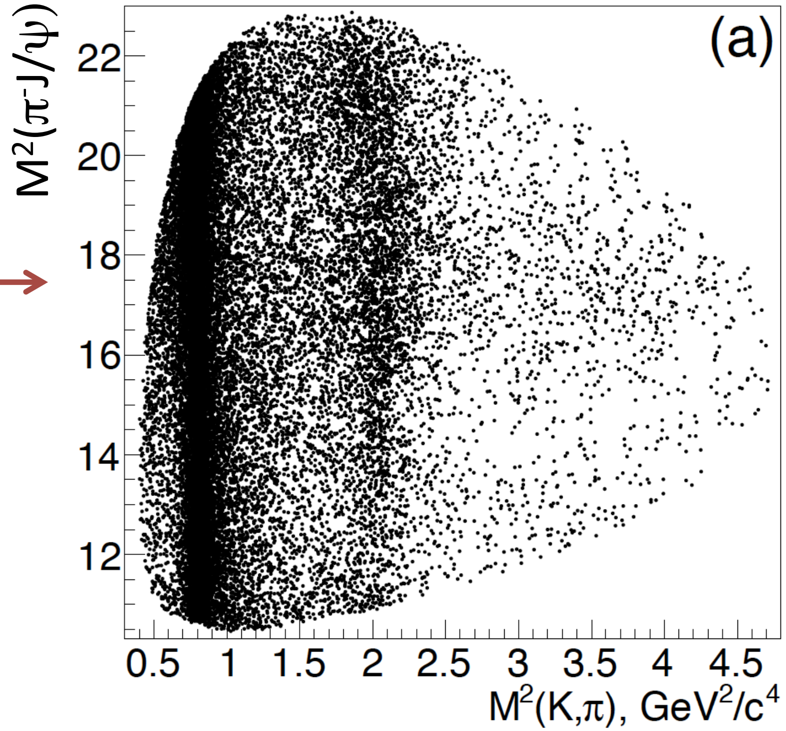
still some skeptics, see: Pakhlov & Uglov, arXiv:1408.5295

New from Belle:

$$Z_c(4200) \rightarrow \pi^+ J/\psi$$

New from Belle: 4-dim analysis of B→$K^+\pi^-J/\psi$

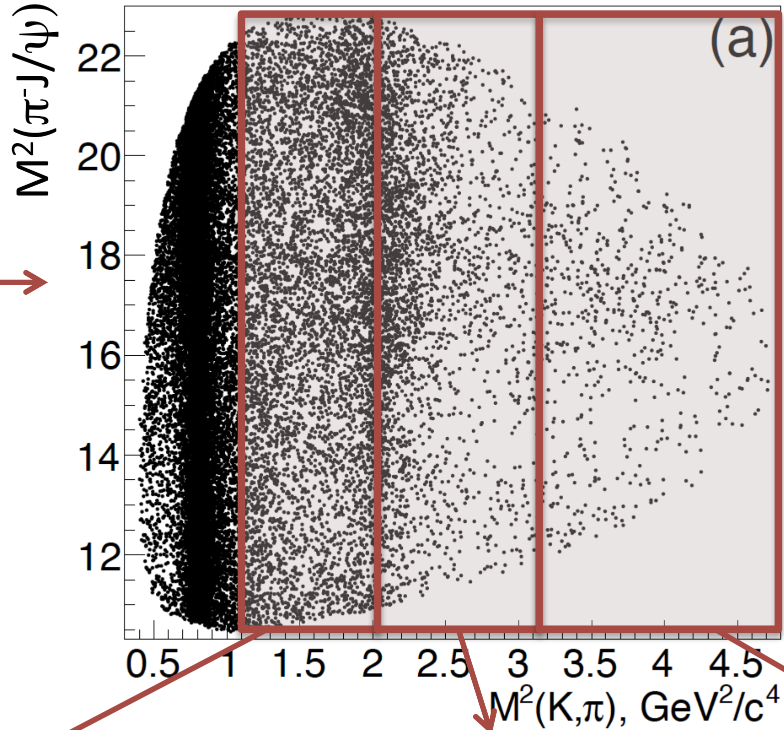
New state:
$Z_c(4200)^-\rightarrow\pi^-J/\psi$



New from Belle: 4-dim analysis of B→K⁺π⁻J/ψ

K. Chilikin et al. (Belle) arXiv:1408.6457

New state: $Z_c(4200)^- \to \pi^- J/\psi$



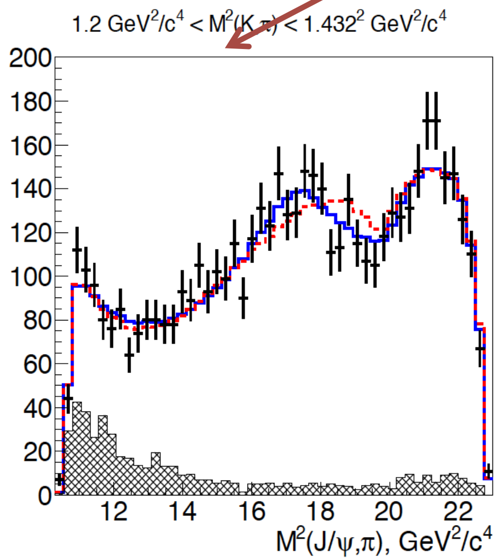
$M = 4196^{+31+17}_{-29-6}$ MeV

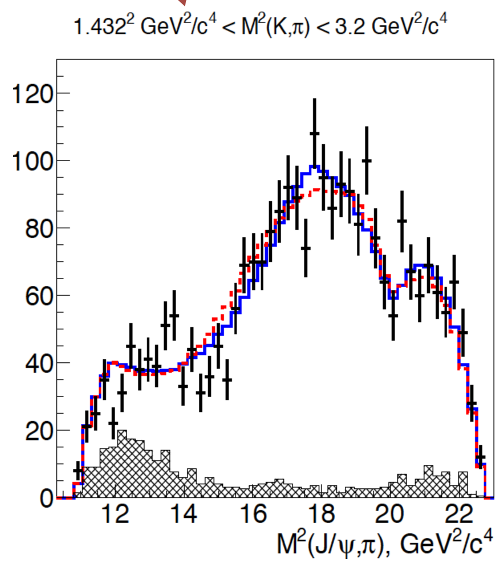
$\Gamma = 370^{+70+70}_{-70-80}$ MeV

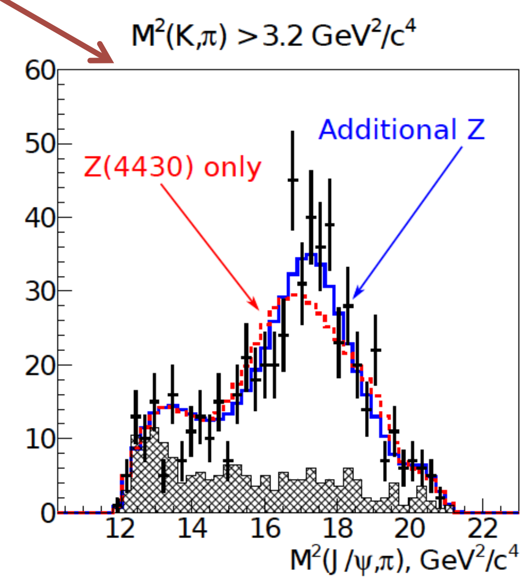
$J^P = 1^+$ preferred by ~ 4σ

signif : 7.2σ

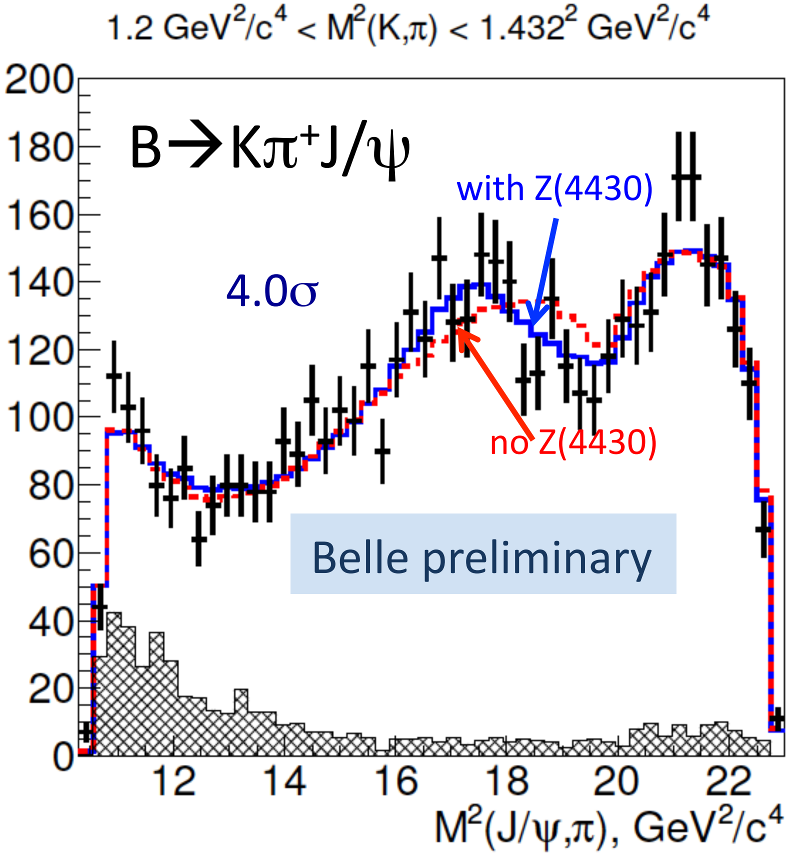
$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$,







Also: Z(4430)→$\pi^- J/\psi$ is seen (~4σ)



K. Chilikin et al. (Belle) arXiv:1408.6457

$$Bf(B^0 \to K^+ Z^-_{4430}) \times Bf(Z^-_{4430} \to \pi^- J/\psi) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$$

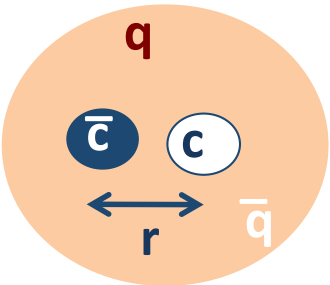
$$\frac{Bf(Z^-_{4430} \to \pi^- \psi')}{Bf(Z^-_{4430} \to \pi^- J/\psi)} \approx 10$$

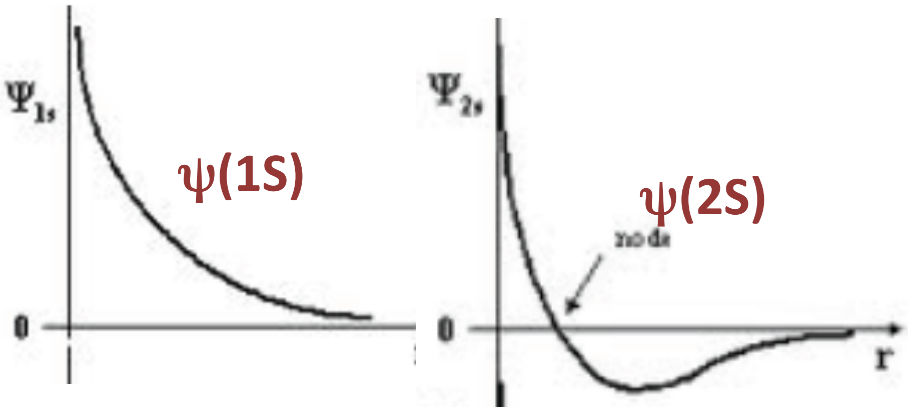
decays to ψ′ favored over those to J/ψ

Z(4430) = radial excitation of $Z_c(3900)$?

$$\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$$

Radial Wave Functions

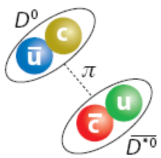




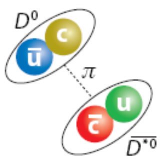
The $c\bar{c}$ part of the wave function of the Z(4430) likely has a node
➔ a radial excitation of the ground state: the $Z_c(3900)$?

$M(Z_c(4430))-M(Z_c(3900))$ = 589 ± 30 MeV
$M(\psi') - M(J/\psi)$ = 589 MeV

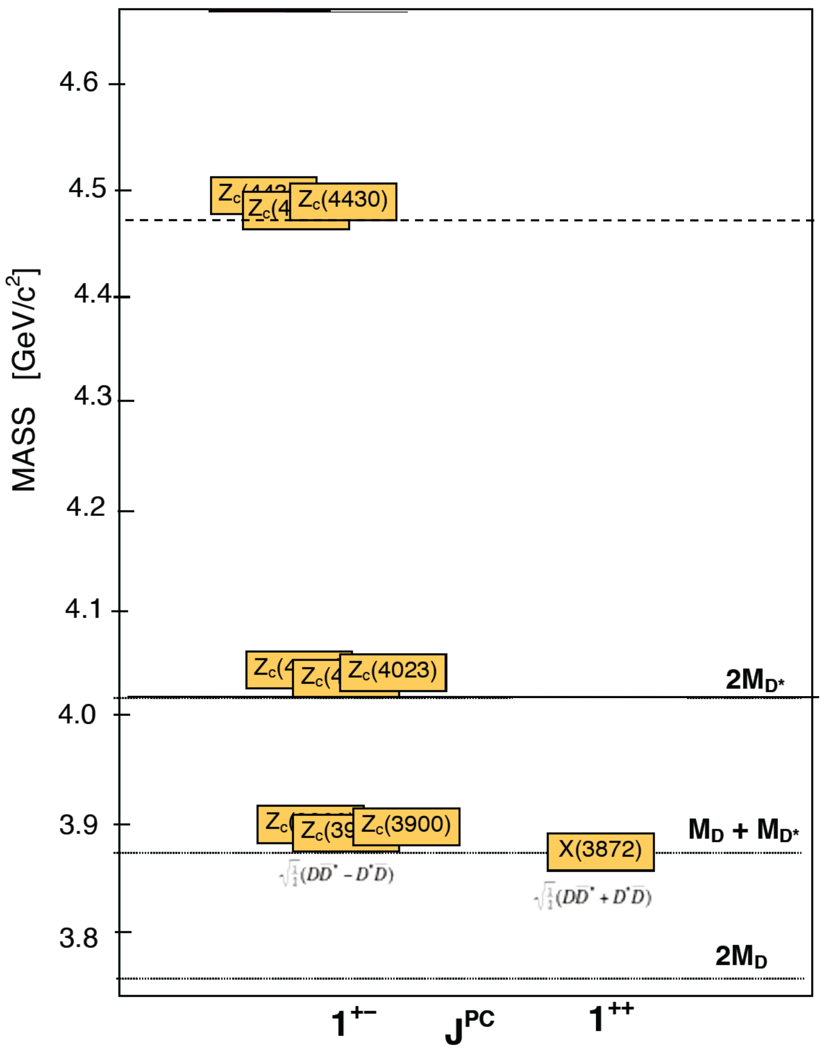
The $J^P=1^+$ charmoniumlike states



D*-D̄* molecule?

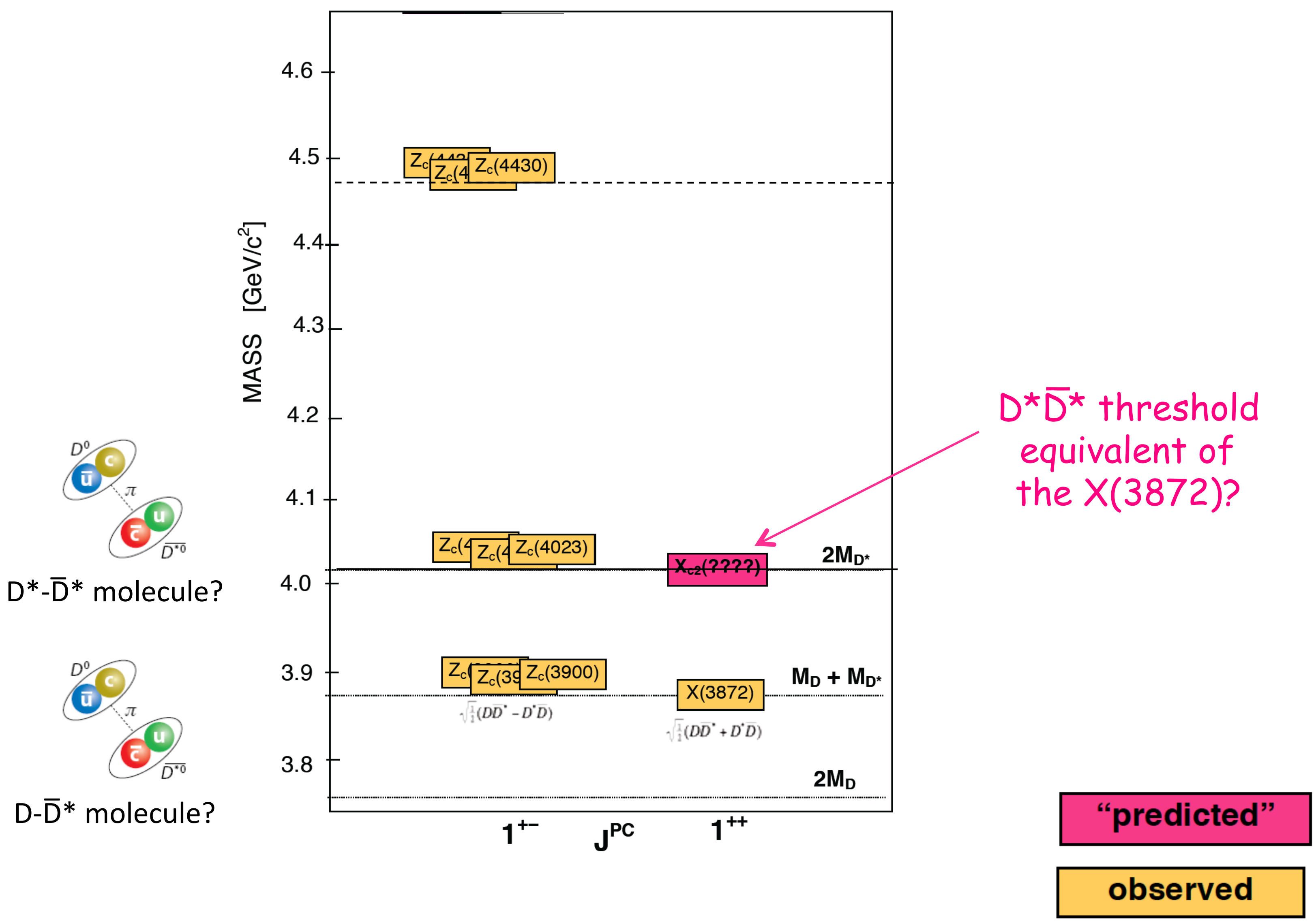


D-D̄* molecule?

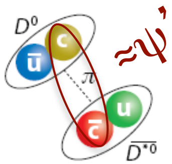


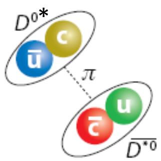
observed

The $J^P=1^+$ charmoniumlike states



The $J^P=1^+$ charmoniumlike states





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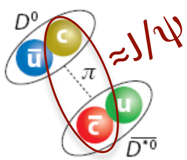
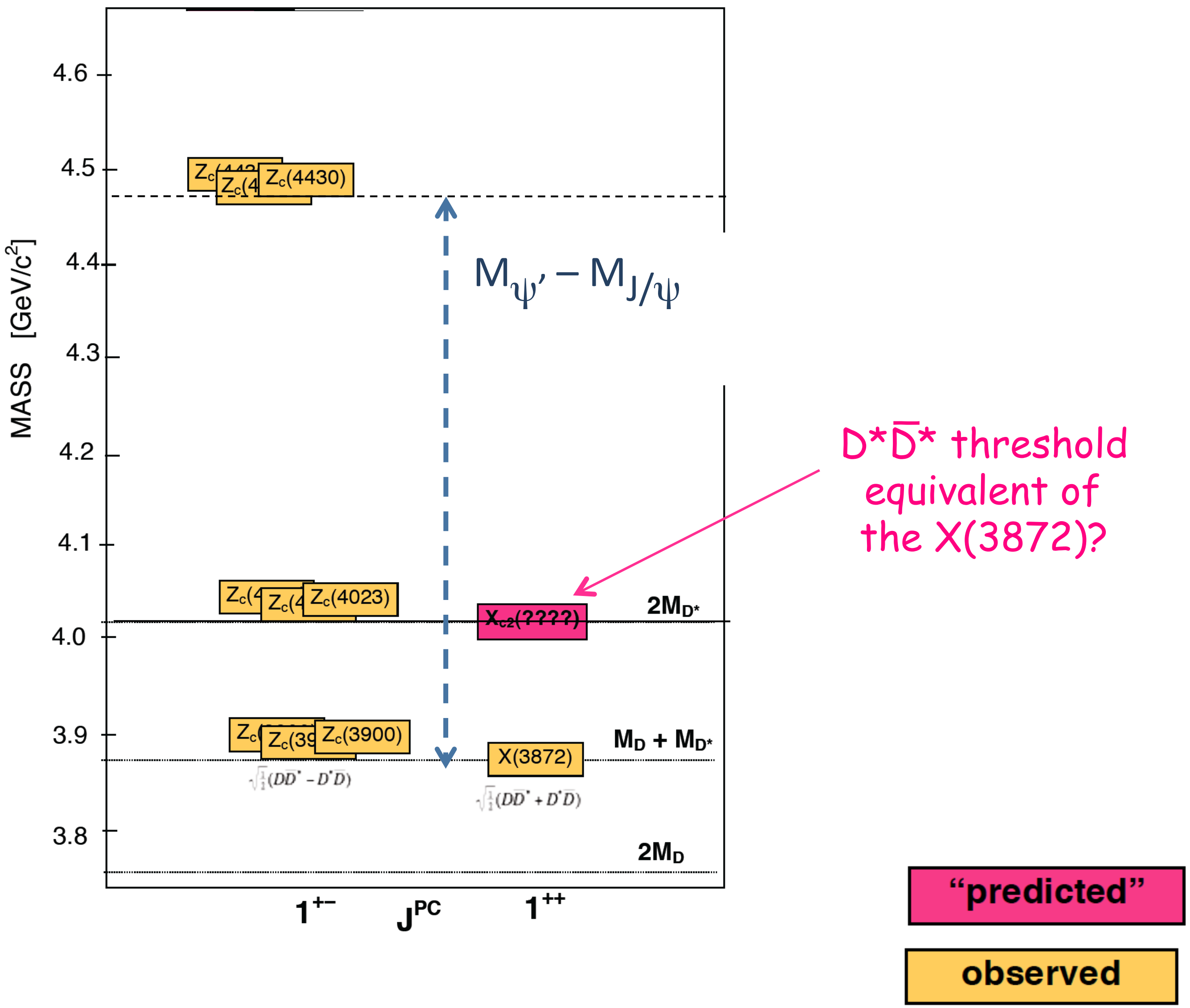


D-D̄* molecule?

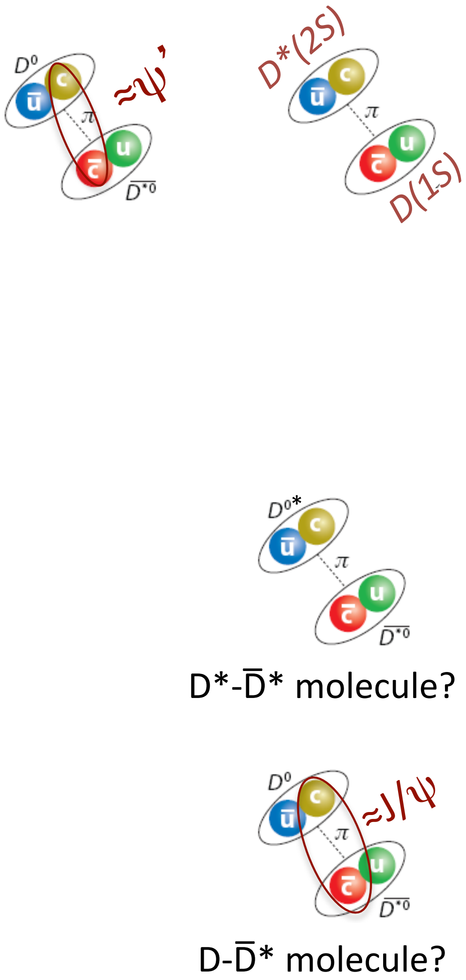


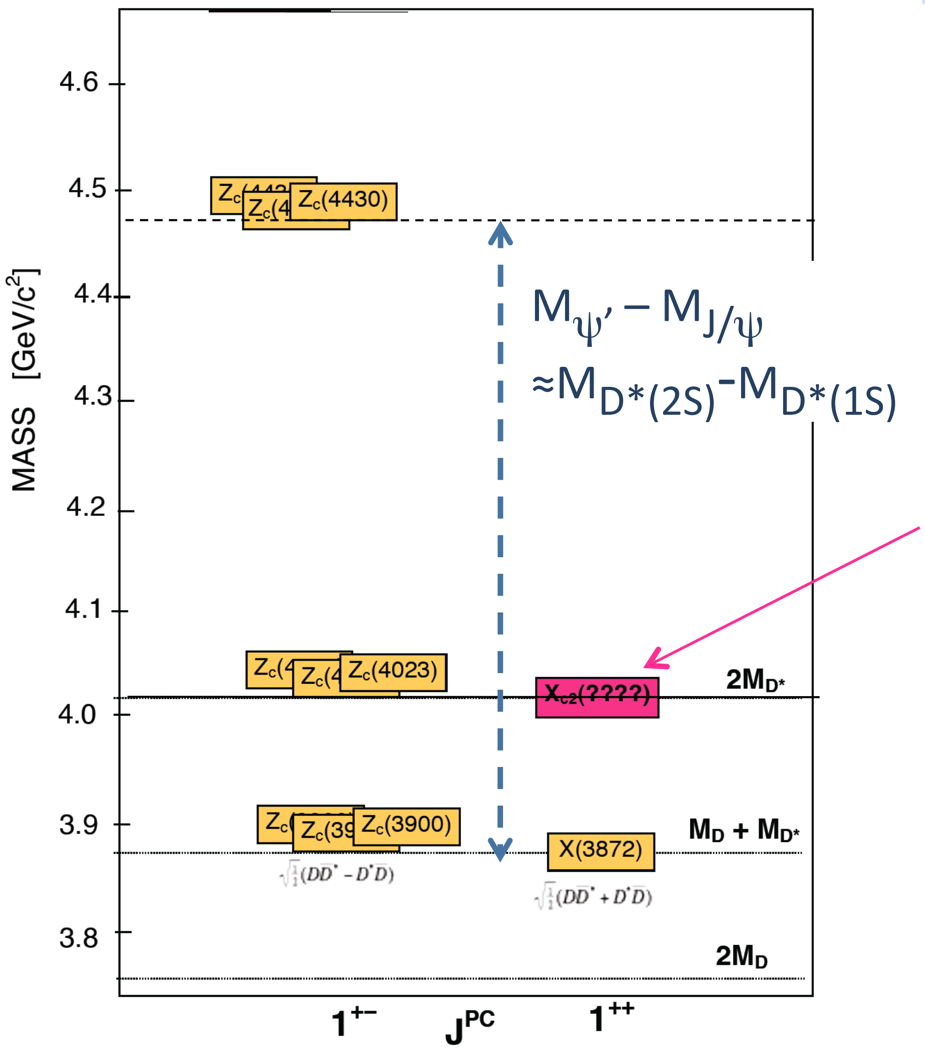
The $J^P=1^+$ charmoniumlike states

BaBar PRD 83, 032004 (2011)

$$M_{D(2S)} = 2540 \pm 8 \text{ MeV}$$

$$M_{D^*(2S)} = 2609 \pm 4 \text{ MeV}$$





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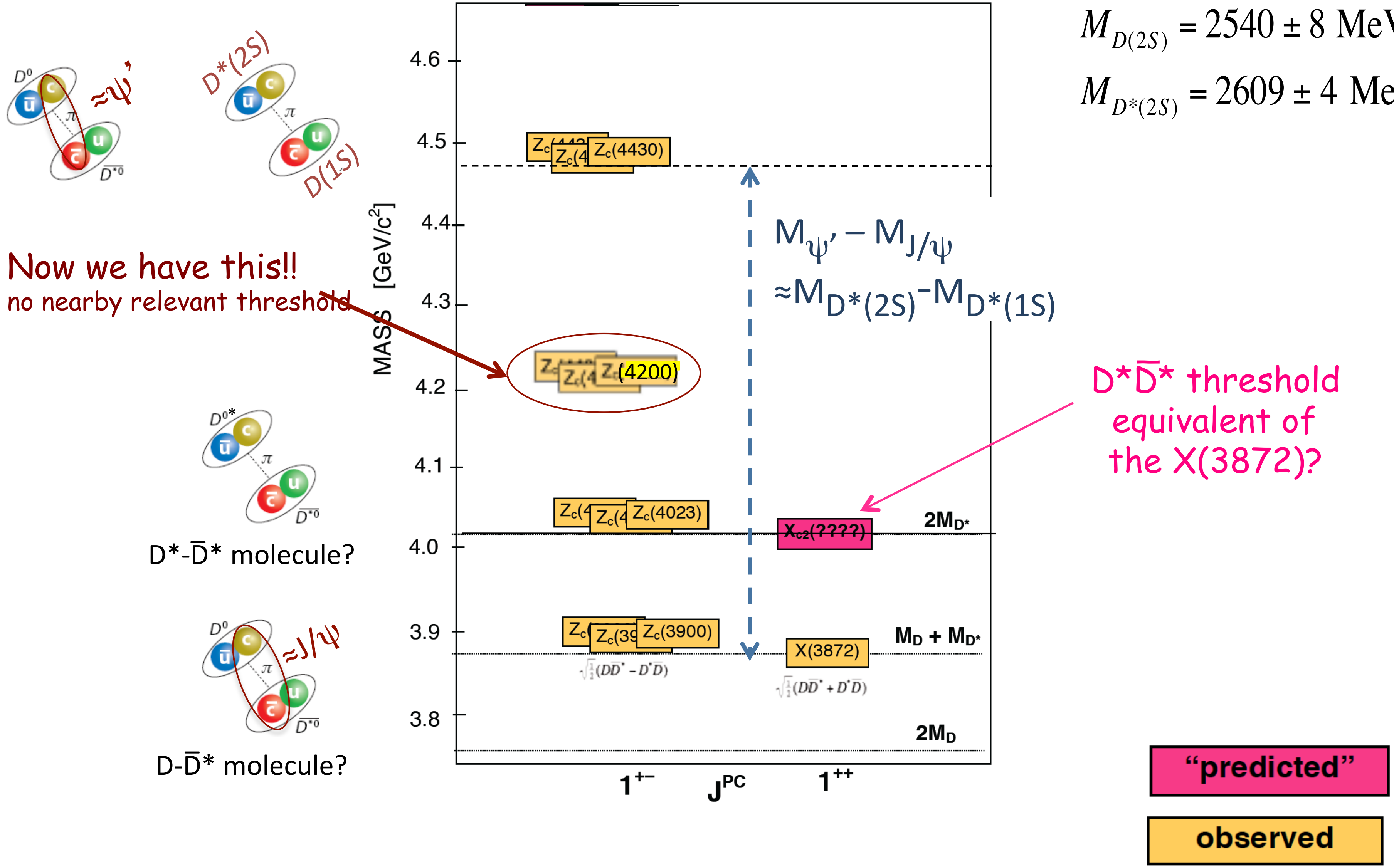
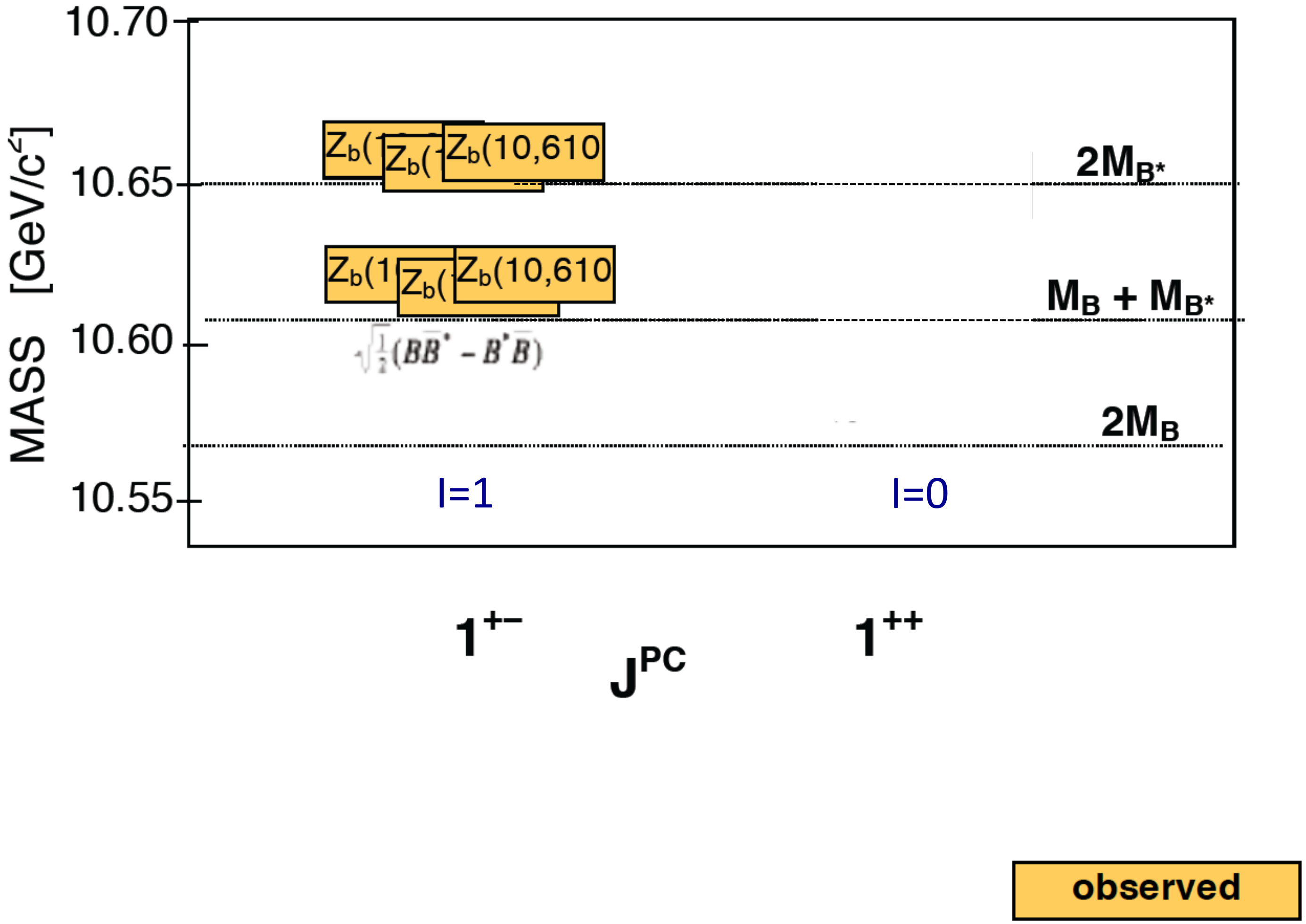
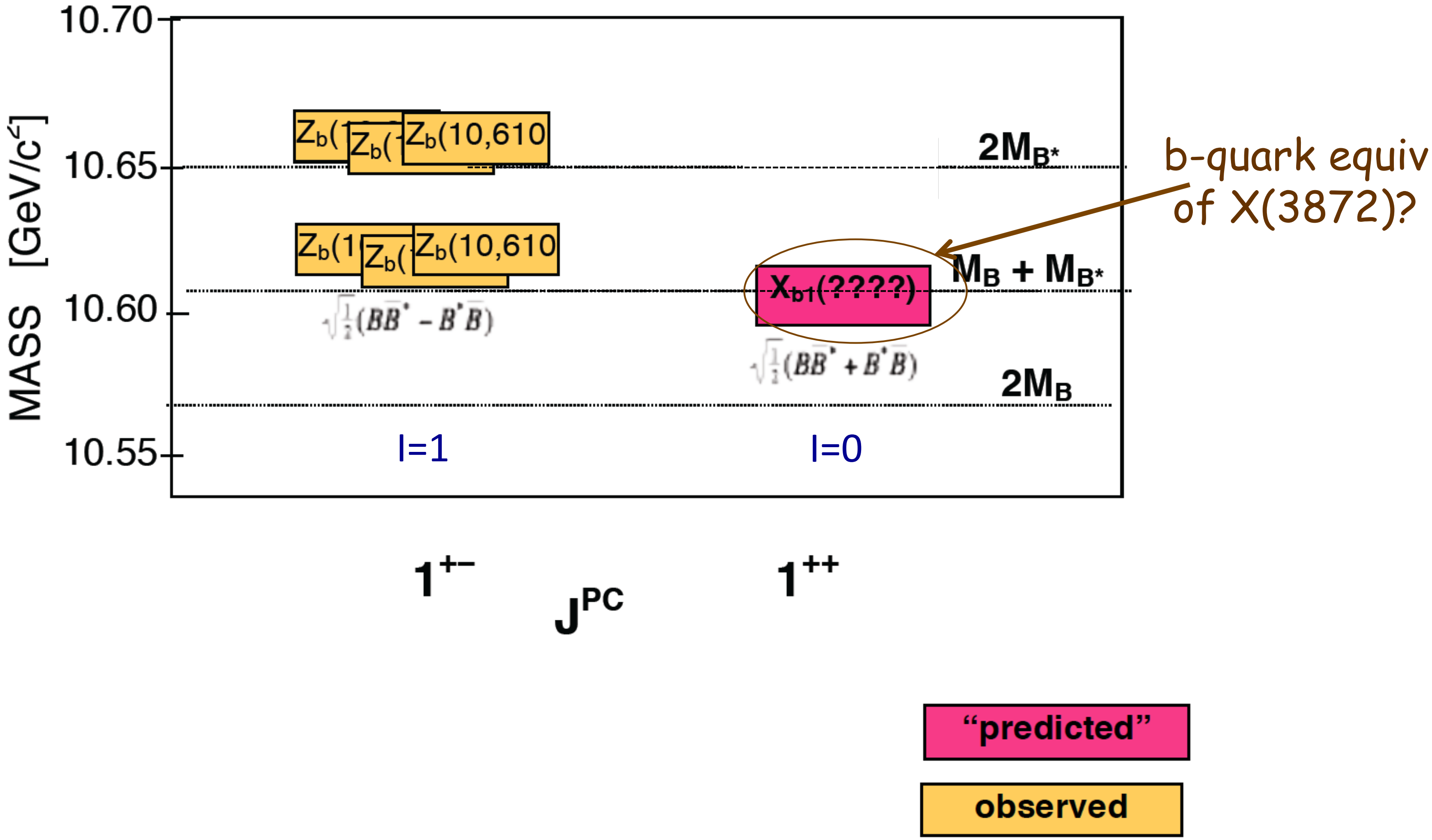


The $J^P=1^+$ bottomonium states?

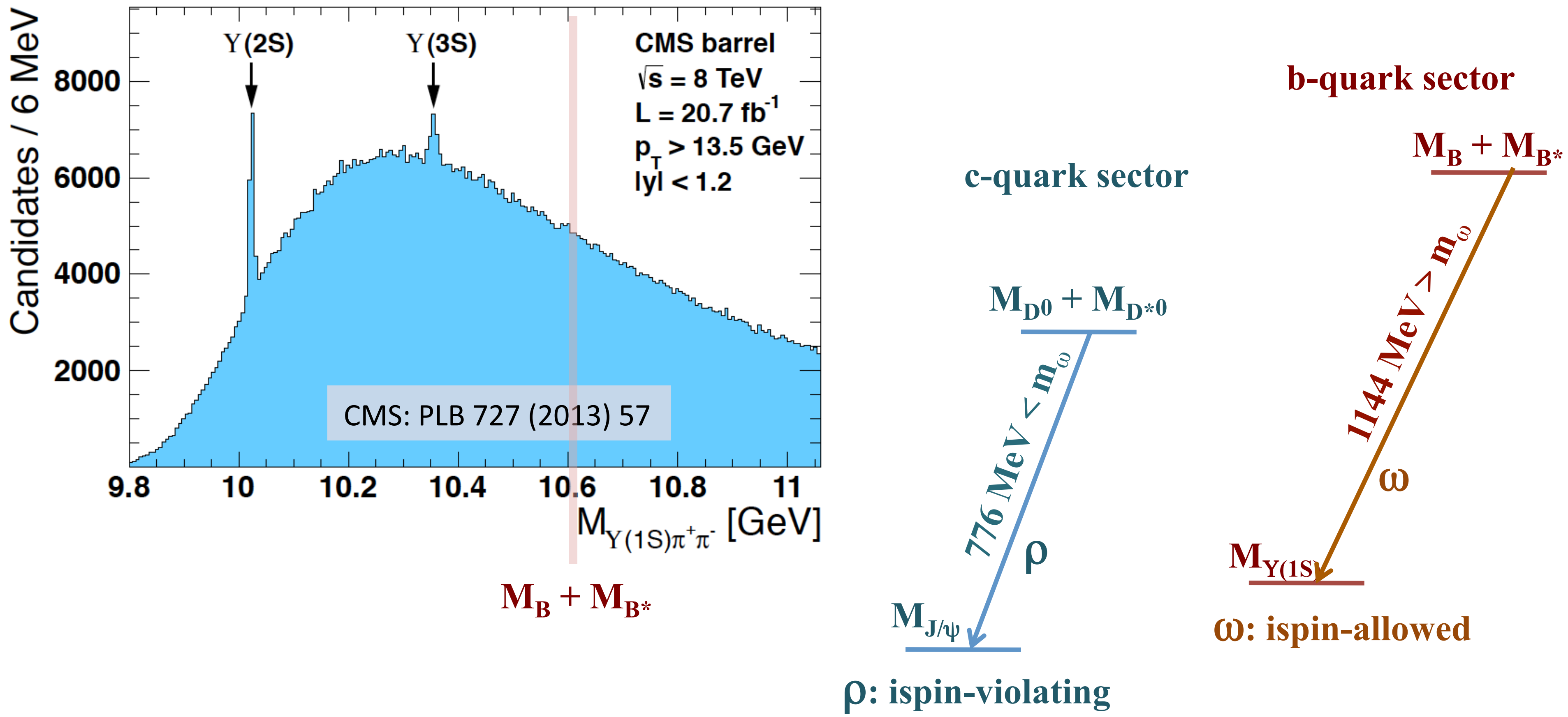


The $J^P=1^+$ bottomonium states?



CMS search for b-sector version of X(3872)

$pp \to \pi^+\pi^-\Upsilon(1S) + anything$

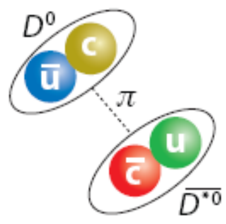


relevant X_b transition is ispin-allowed $X_b \to \omega\Upsilon(1S)$

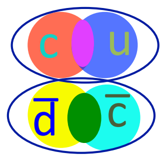
can LHCb &/or CMS do this?

Proposed structures for the new mesons

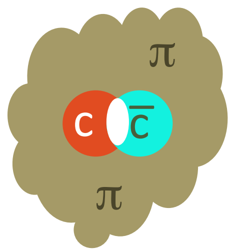
Molecules



QCD tetraquarks



Hadrocharmonium



(NB: QCD-hybrids & glueballs have no charged quarkoniumlike states)

Molecules?

good points: -- many (most?) states are close to thresholds

-- sometimes very close: $M_{X(3872)}=m_{D^0}+m_{D^{0*}}$ to one part in 10^4

-- decay patterns reflect nearby thresholds

-- states near $2m_{D^*}$ ($2m_{B^*}$) like to decay $Z \rightarrow D^*\bar{D}^*$ ($B^*\bar{B}^*$) & not $D\bar{D}^*$ ($B\bar{B}^*$)

--decays to $\pi J/\psi$ ($\pi\Upsilon(ns)$) and πh_c (πh_b) occur with similar strengths

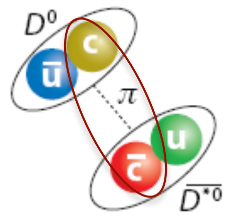
problems: -- some states are not close to thresholds

-- difficult to account for large decays to hidden quarkonium

$$\text{e.g.}\ \frac{\Gamma(Z_c \to \pi J/\psi)}{\Gamma(Z_c \to D\bar{D}^*)} = 0.16 \pm 0.07$$

$$\Rightarrow \Gamma(Z_c \to \pi J/\psi) \approx \text{a few MeV}$$

not so small



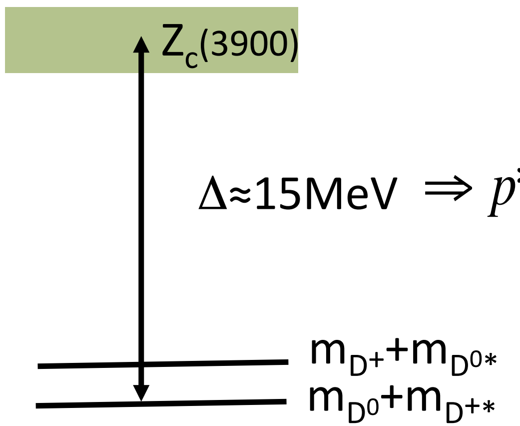
the c and $\bar{c}$ quarks:
--don't have much overlap
--colors are uncorrelated

-- X(3872) production in high energy pp collisions similar to that for ψ'

$Z_c(3900)$ is not so close to $m_D+m_{D^*}$

Not so close to threshold:

$M_{Zc(3900)} = 3890 \pm 3$ MeV



$m_{D^0} + m_{D^{*+}} = 3875$ MeV

$\Delta \approx 15\text{MeV} \Rightarrow p^* = \sqrt{2\mu_D \Delta} \approx 170$ MeV

pretty large for an S-wave resonance
(no centrifugal barrier)

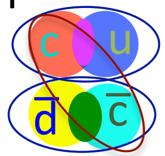
QCD tetraquarks?

good points:

-- decays to hidden charmonium not suppressed

  -- c and $\bar{c}$ have large overlap

  -- colors are correlated



-- mass & ψ' affinity of the $Z_c(4430)$ is ok

  --predicted the $Z_c(3900)$

-- masses not restricted to thresholds

--- production in high energy pp collisions okay

-- many detailed predictions

problems:

-- many of the detailed predictions were wrong

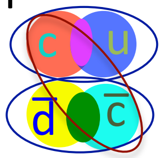
prediction	experiment
-- X(3872) doublet	only 1 X(3872)
-- $Z_c(3900)$ partner at M≈3800 MeV	$M_{Zc(4020)}$= 4023 MeV
-- $\frac{\Gamma(Z_c \to \pi J/\psi)}{\Gamma(Z_c \to D\bar{D}^*)} \approx 7$	$\frac{\Gamma(Z_c \to \pi J/\psi)}{\Gamma(Z_c \to D\bar{D}^*)} = 0.16 \pm 0.07$

QCD tetraquarks?

good points:

-- decays to hidden charmonium not suppressed

- -- c and $\bar{c}$ have large overlap
- -- colors are correlated



-- mass & ψ' affinity of the $Z_c(4430)$ is ok

- --predicted the $Z_c(3900)$

-- masses not restricted to thresholds

--- production in high energy pp collisions o...y

-- many detailed predictions

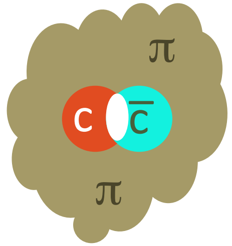
problems:

-- many of the detailed ... ...ong

prediction	...periment
-- X(38...	only 1 X(3872)
	$M_{Zc(4020)}$= 4023 MeV
...MeV	
$\frac{...\omega J/\psi)}{...(Z_c \to D\bar{D}^*)} \approx 7$	$\frac{\Gamma(Z_c \to \pi J/\psi)}{\Gamma(Z_c \to D\bar{D}^*)} = 0.16 \pm 0.07$

NB: These predictions are for specific models & probably not fatal to the tetraquark scenario.

Hadrocharmonium?



good points:

large hadronic transitions to hidden quarkonium are ok

explains mass and ψ' affinity of the $Z_c(4430)$

problems:

mass patterns should track quarkonium levels

predicts very (too) large value for $\Gamma(Z(3900)) \rightarrow \pi^- J/\psi)$

has trouble with $\Gamma(Z_{b1,2} \rightarrow \pi^- \Upsilon(nS))_{(n=1,2,3)} \approx \Gamma(Z_{b1,2} \rightarrow \pi^- h_b(mP))_{(m=1,2)}$

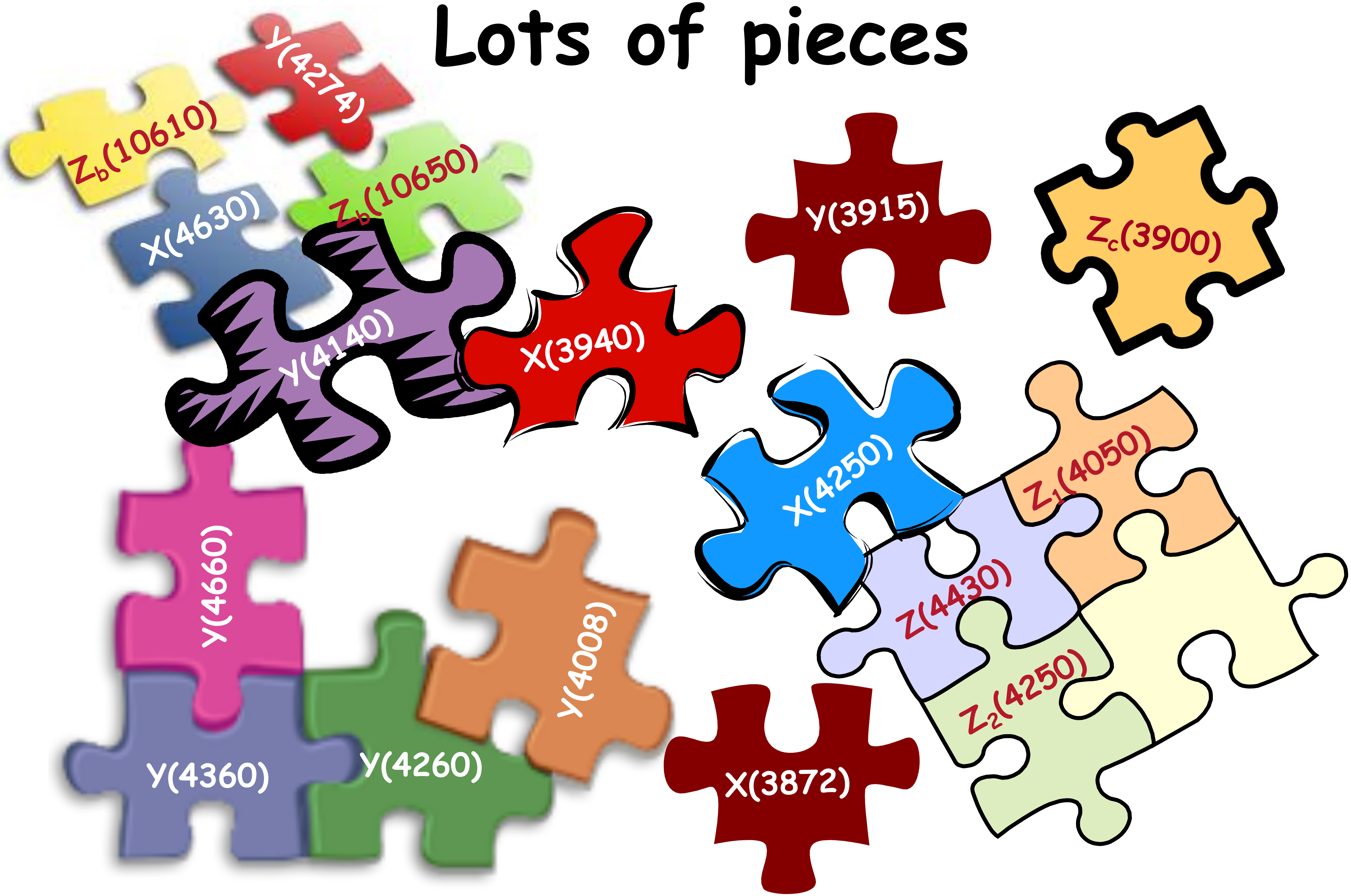
predicted a $Z_c(3900)$ partner at lower mass

Summary

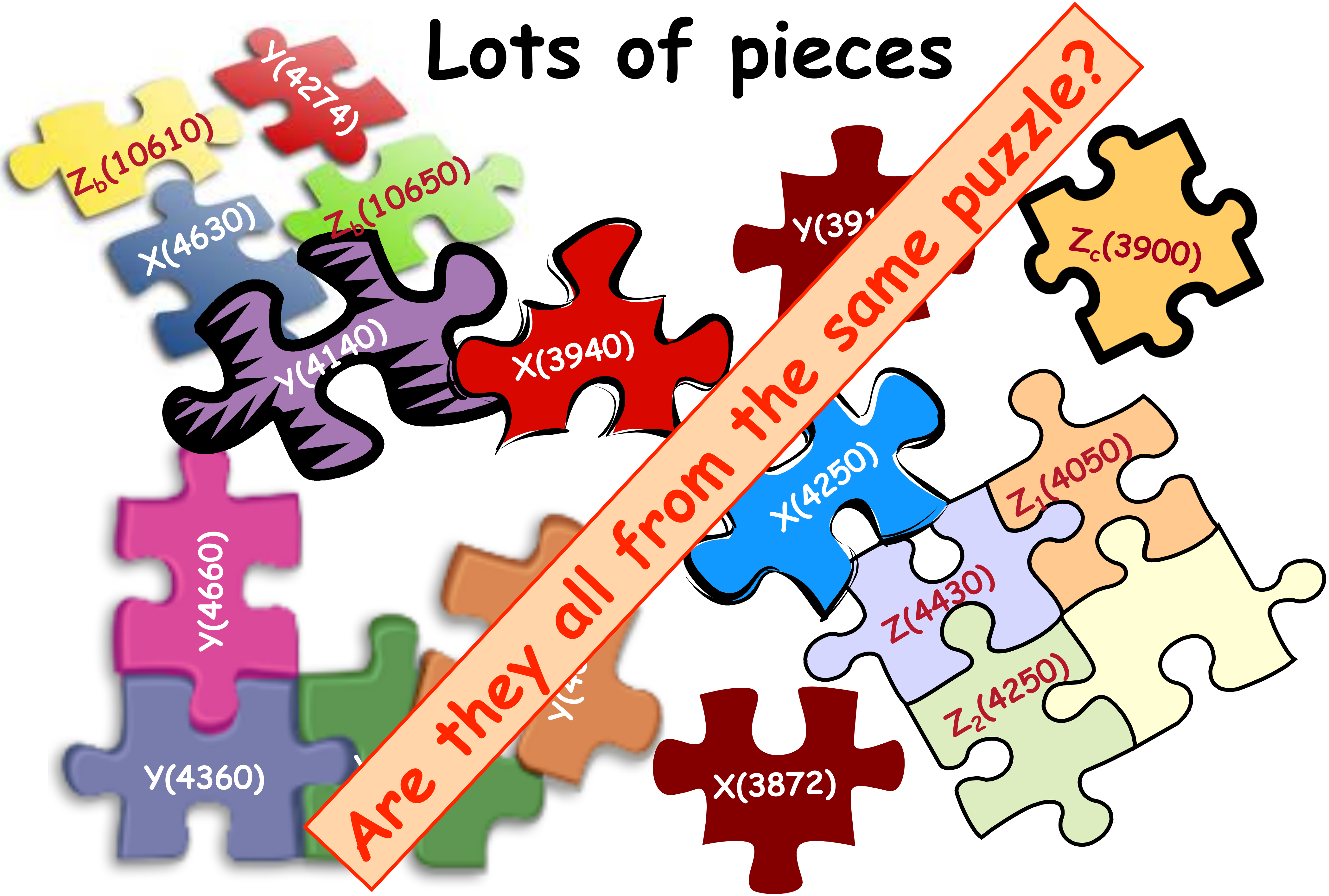
- Numerous 4-quark meson candidates not specific to QCD have been found
  - XYZ mesons containing $c\bar{c}$ and $b\bar{b}$ pairs, some of which are charged.
  - $Z(4430)^-$ confirmed by LHCb, BW-like resonant behavior established
  - Large partial widths for hadronic transitions to quarkonium
    - *e.g.* $\Gamma(Z(4430)^- \rightarrow \pi^- \psi') > 7.5$ MeV, $\Gamma(Z(3900)^- \rightarrow \pi^- J/\psi) \approx 2$ MeV
  - $Z(4430)^- \rightarrow \pi^- J/\psi$ seen: $Bf(Z(4430)^- \rightarrow \pi^- J/\psi) << Bf(Z(4430)^- \rightarrow \pi^- \psi')$
  - Many states are near thresholds (àla molecules), but not all.

- No single model reproduces the observed properties of all states
  - molecule models have trouble with:
    - large $(\pi^+)\pi^- J/\psi$ & $(\pi^+)\pi^- \Upsilon(nS)$ decay widths
    - states not near threshold
    - production (at least for the $X(3872)$)
  - QCD tetraquark-based (& hadrocharmonium) models have trouble with:
    - mass and decay-width predictions

Lots of pieces



Lots of pieces



Thank You

Спснбо

감사합니다

どもう　ありがとう

Back-up slides

Event in the Belle Detector