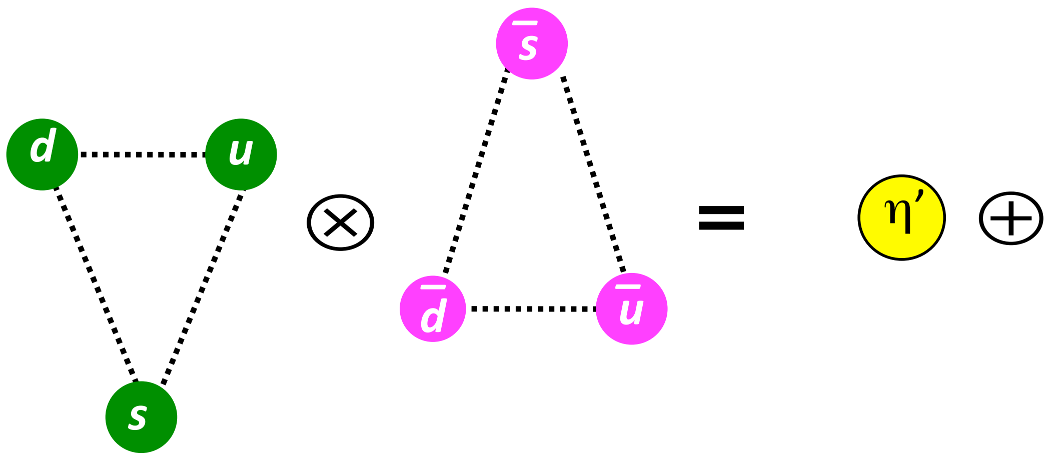
(A New) Hadron Spectroscopy

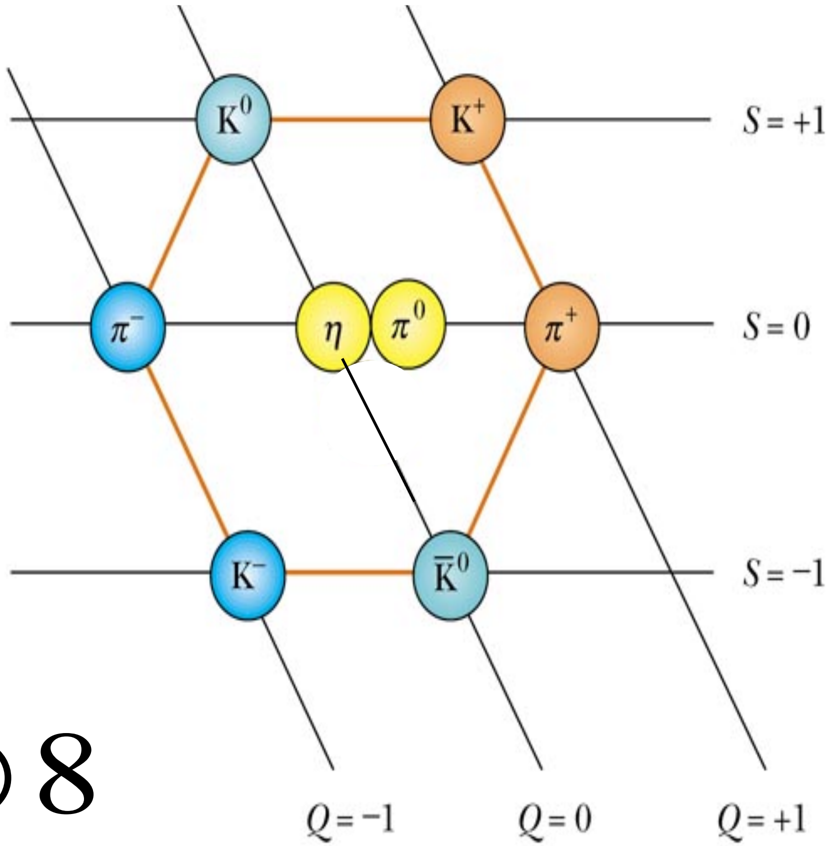
Stephen Lars Olsen ibs Institute for Basic Science Daejeon KOREA

ICFA Seminar, IHEP Beijing October 28, 2014

"Old spectroscopy":

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





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

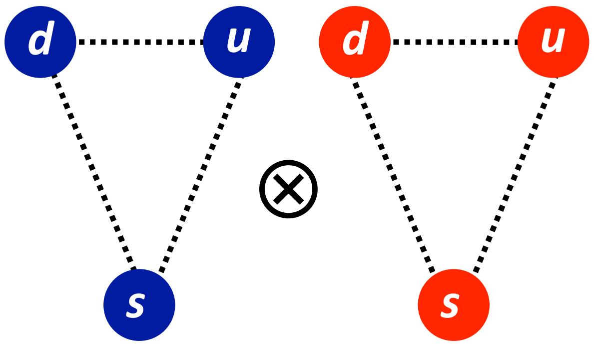
QCD "diquarks" ?

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 [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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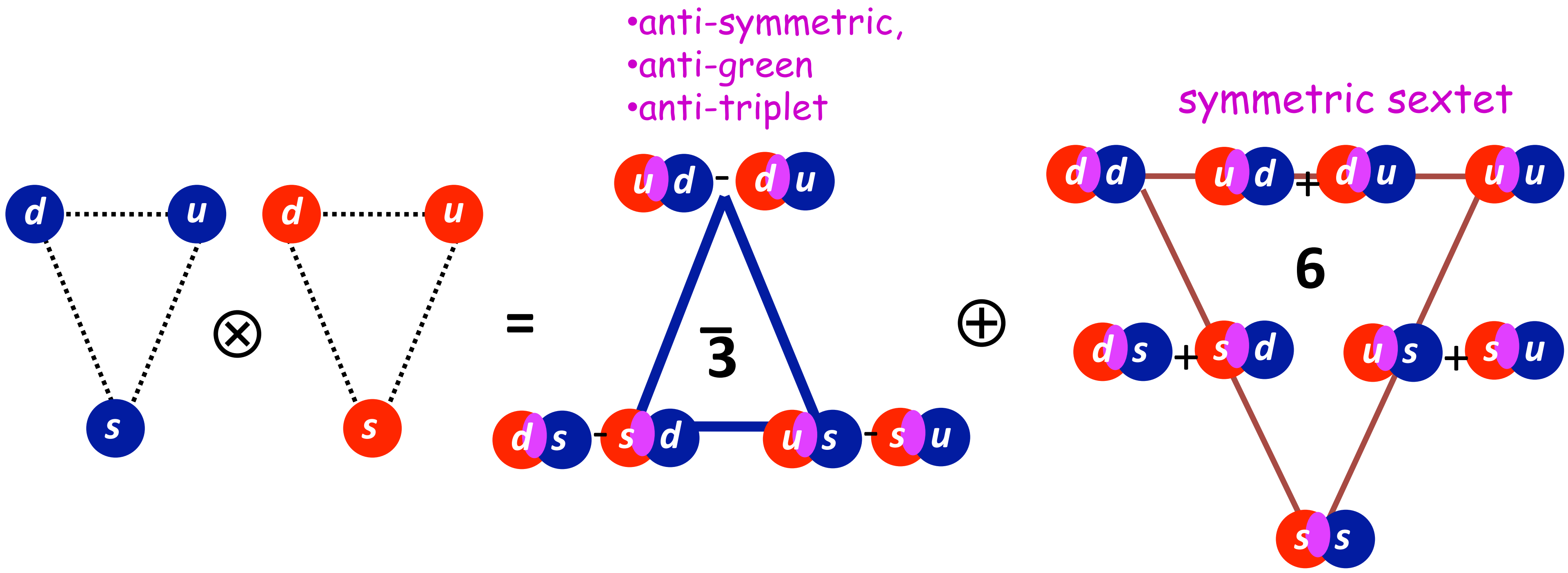

$$3 \otimes 3 = \bar{3} \oplus 6$$

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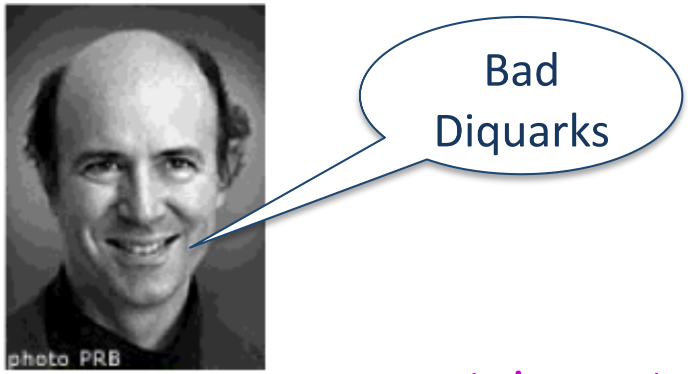

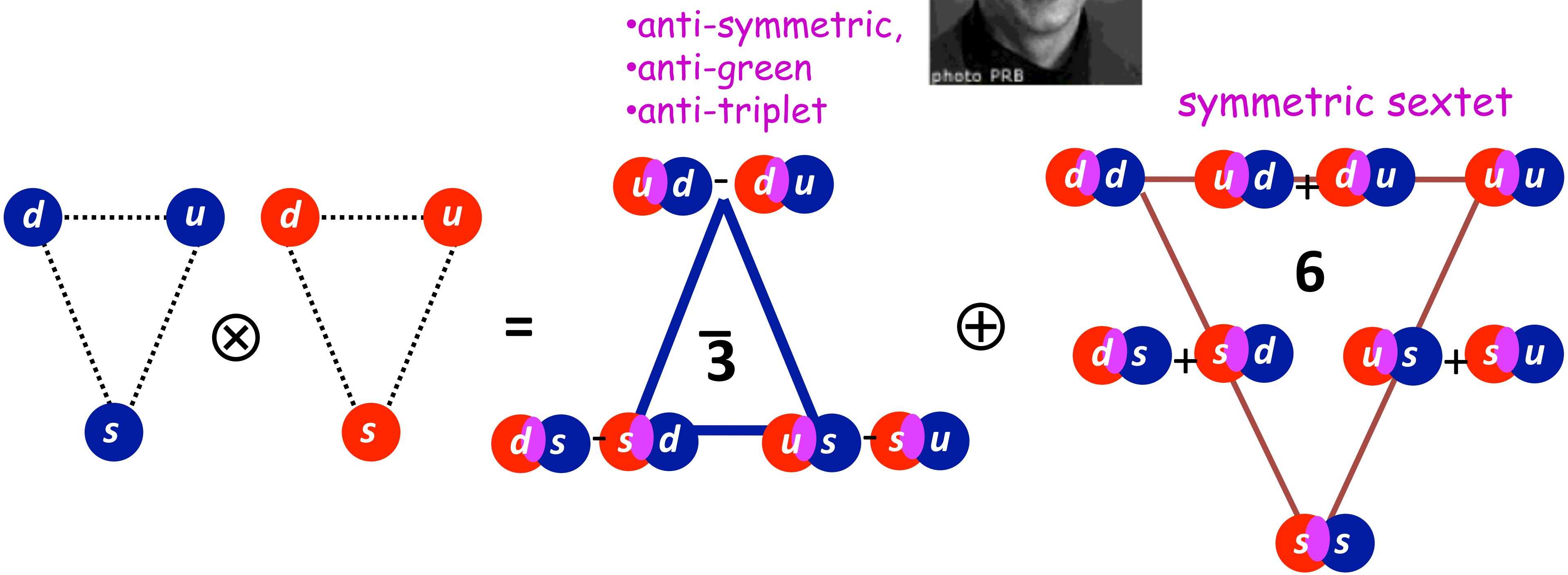

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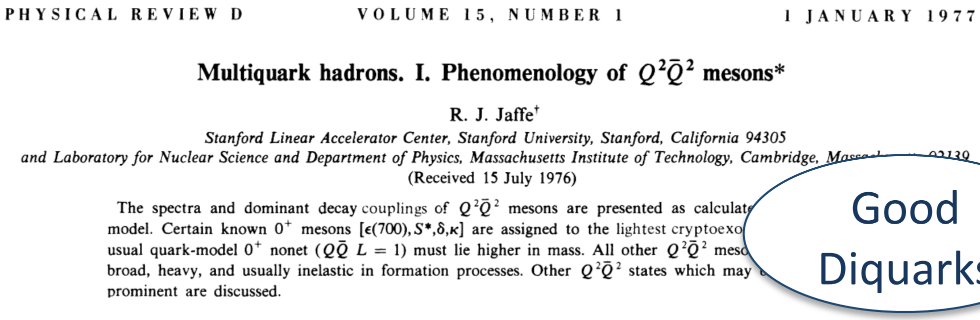
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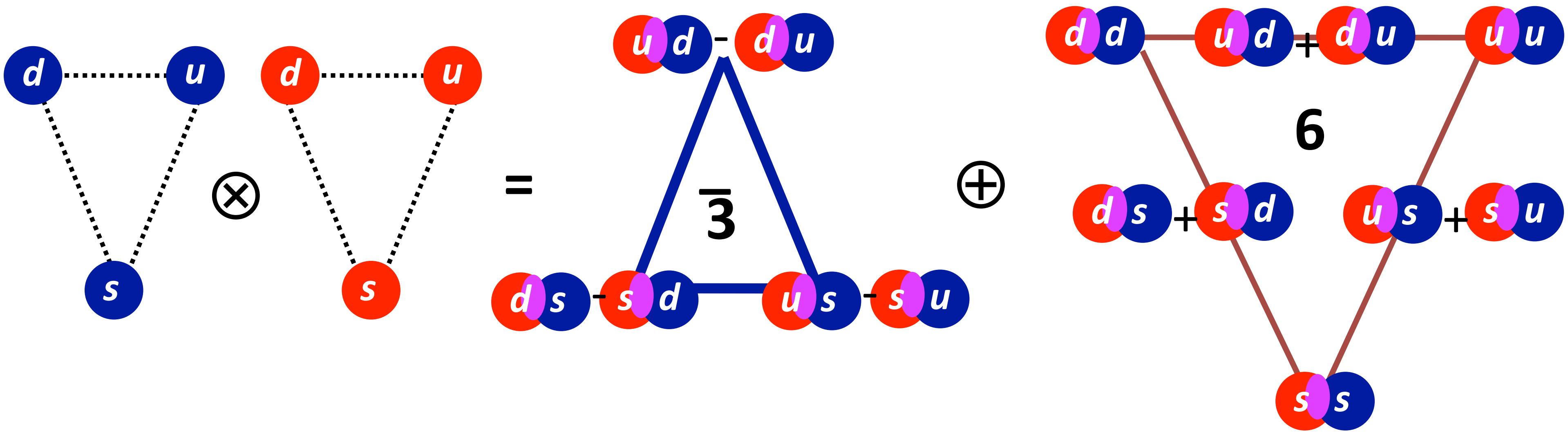
Good Diquarks

- anti-symmetric,
- anti-green
- anti-triplet

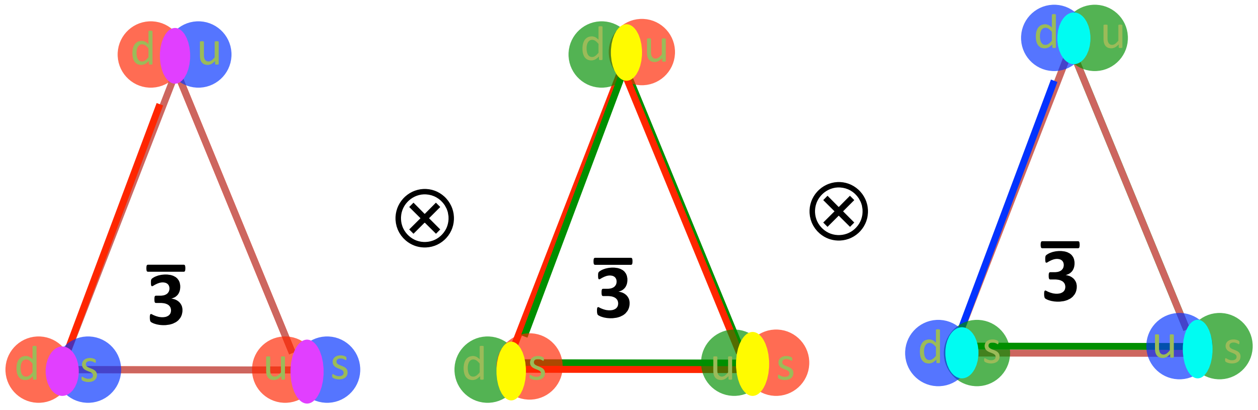
symmetric sextet



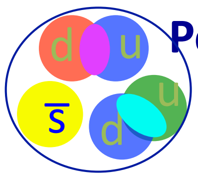
$$3 \otimes 3 = \bar{3} \oplus 6$$

multiquark states from diquarks & diantiquarks

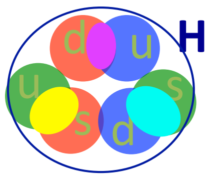
red-blue diquark　　　green-red diquark　　　blue-green diquark



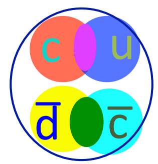
magenta (anti-green) **anti-triplet**　　　**yellow** (anti-blue) **anti-triplet**　　　**cyan** (anti-red) **anti-triplet**



Pentaquark



H-dibaryon

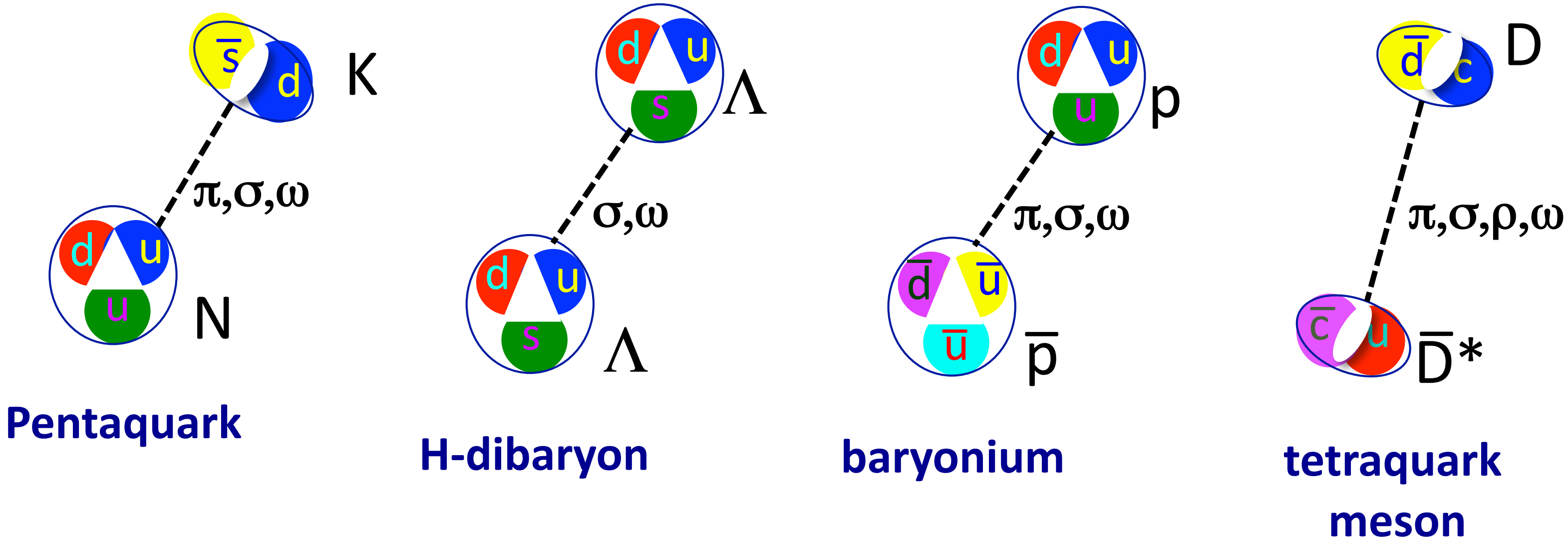


tetraquark meson

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”



“exotic” hadrons that nuclear theorists love

Multiquark states have been discussed since page 1 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**.

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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Where are they??

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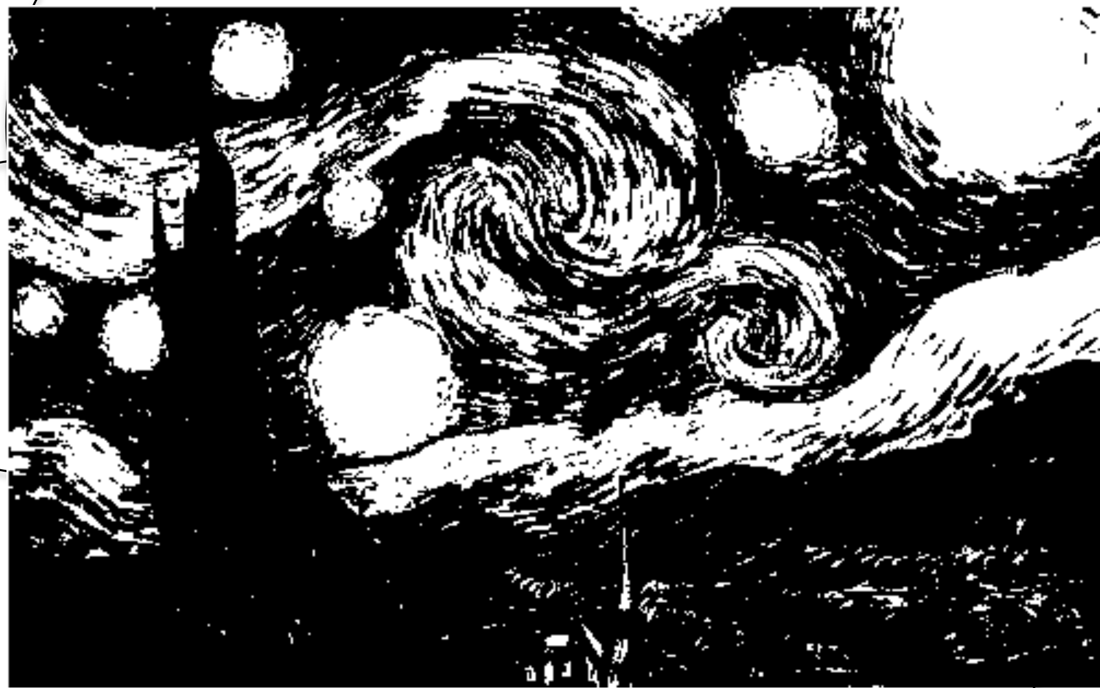
Visions of hadrons

Through a theorist's mind

van Gogh prediction of B-mode polarization in 1889?

Visions of hadrons

What is seen by an experimenter

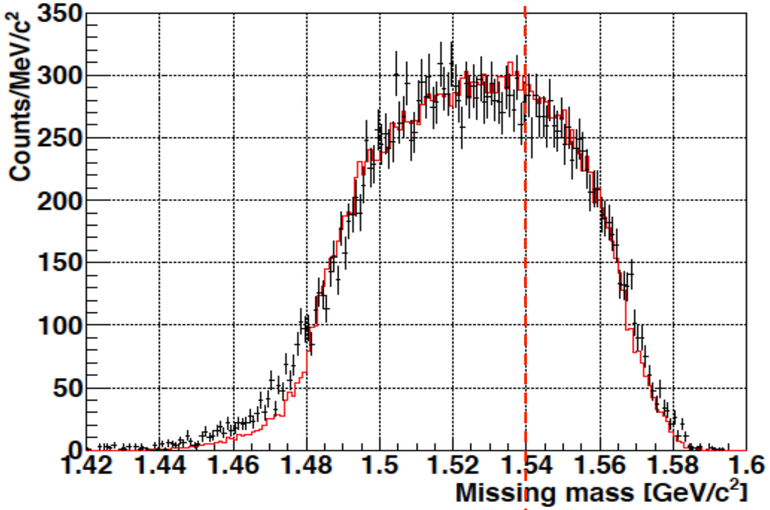


No Pentaquarks

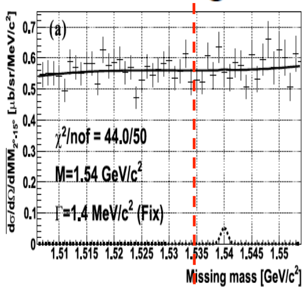
J-PARC E19 - 2012 PRL 109, 132002

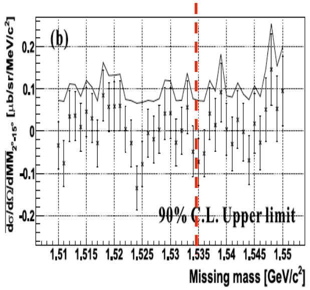
(Tanida-san)

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



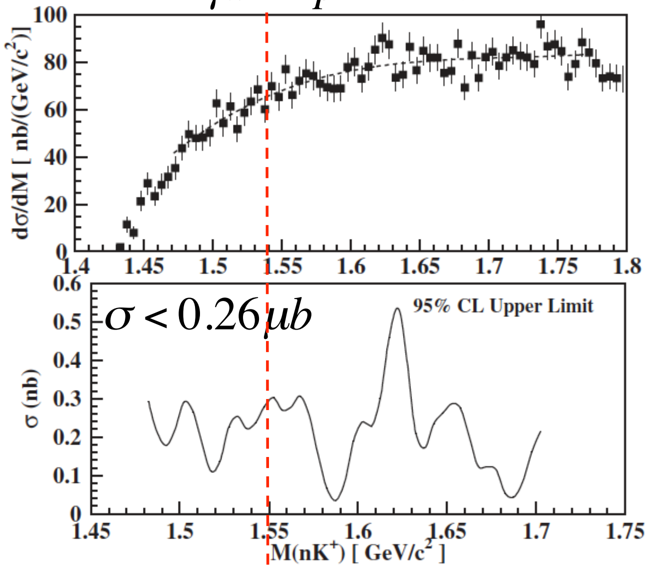
$$\frac{d\sigma}{d\Omega} < 0.26 \mu b/sr$$

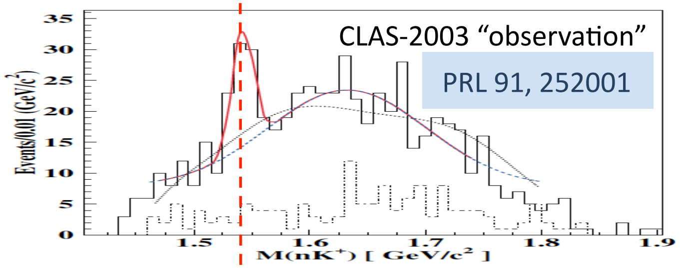




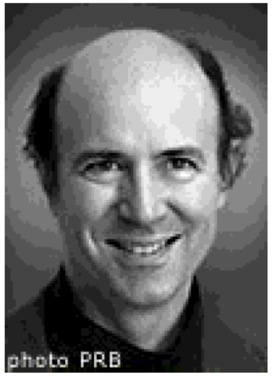
JLab CLAS -2006 PRL 96, 212001

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



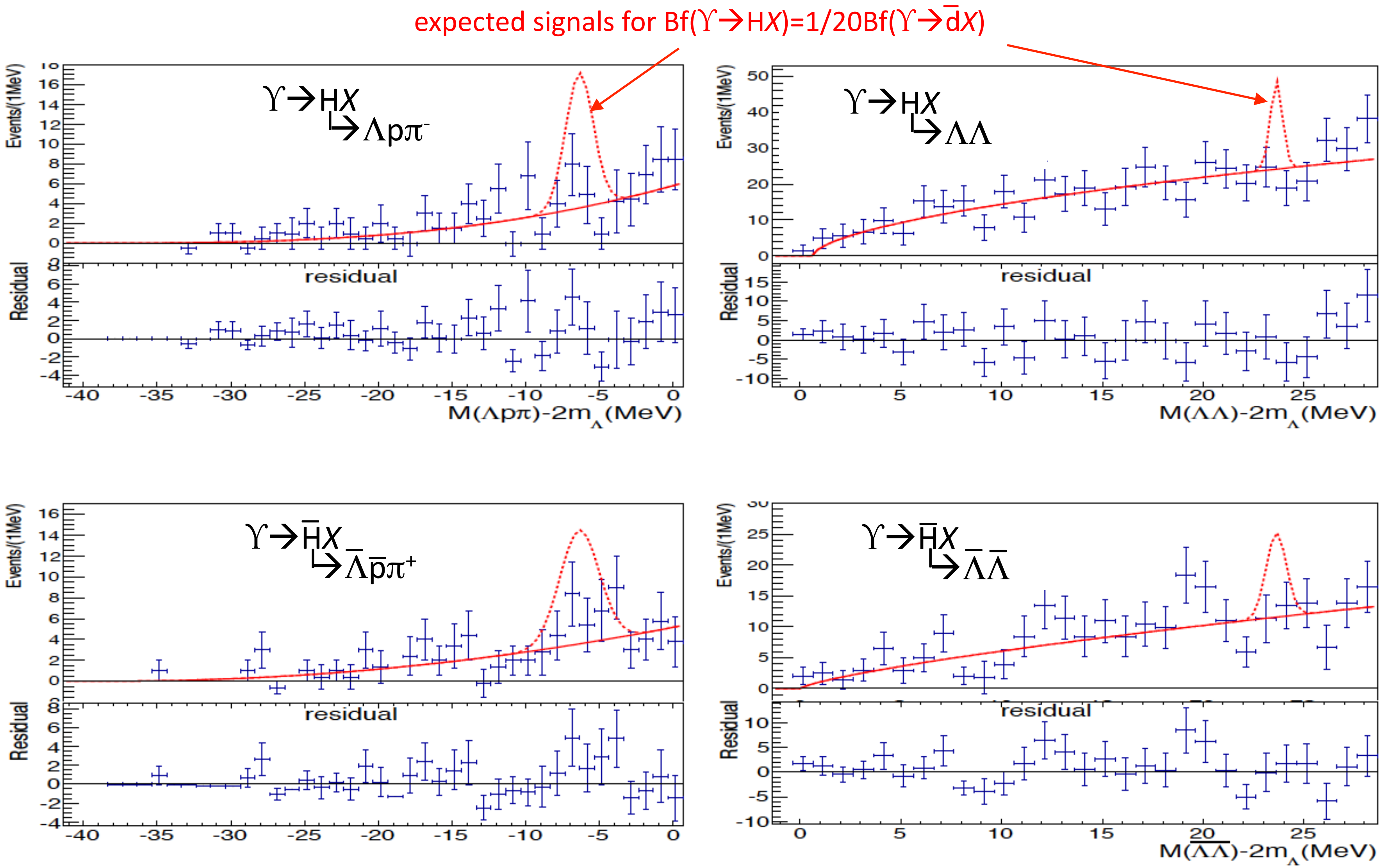


“The story of pentaquark shows how poorly we understand QCD” – F. Wilczek, 2005



Frank Wilczek

No H dibaryon

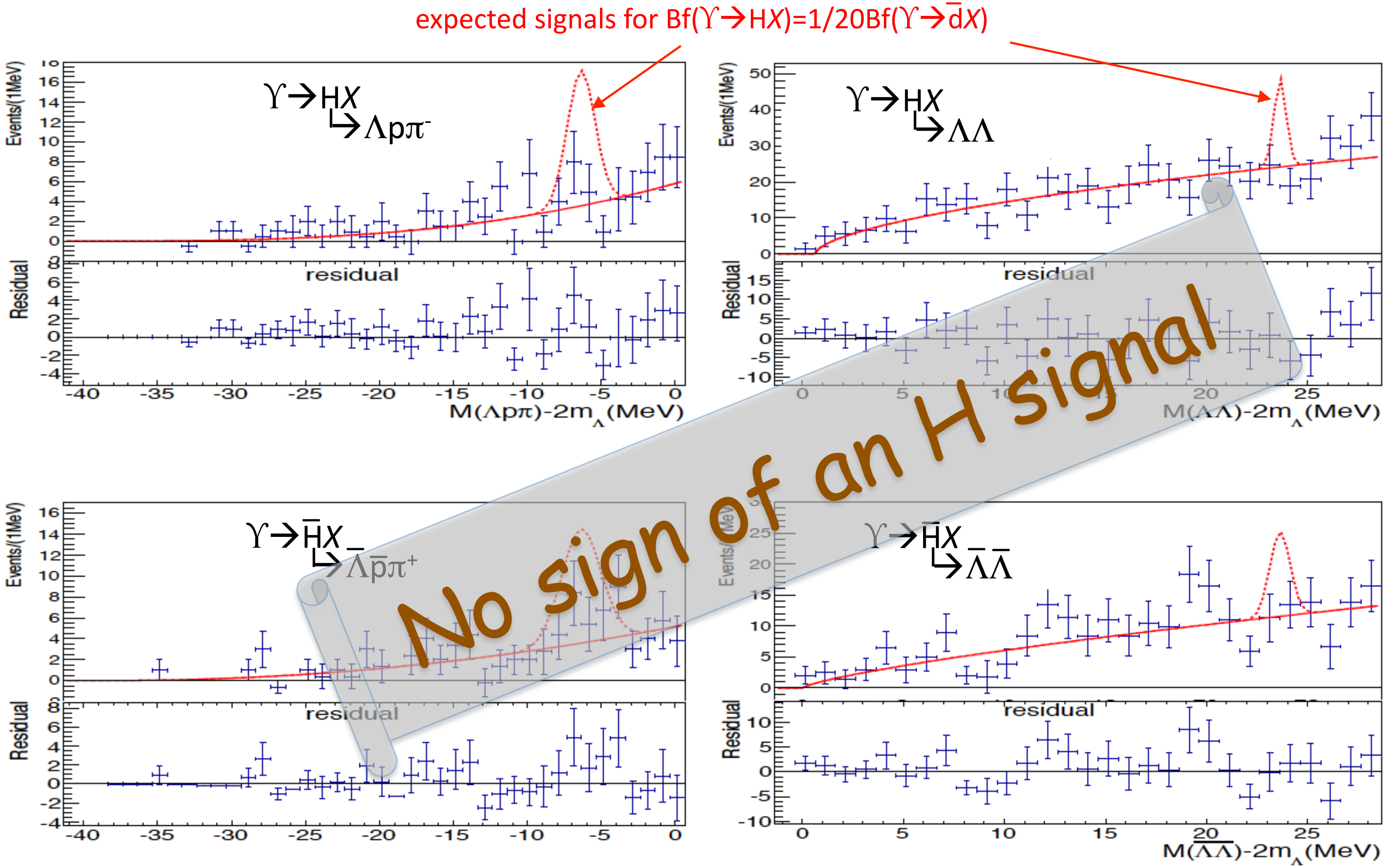


$M(\Lambda p\pi^-)-2m_\Lambda$

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

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

No H dibaryon



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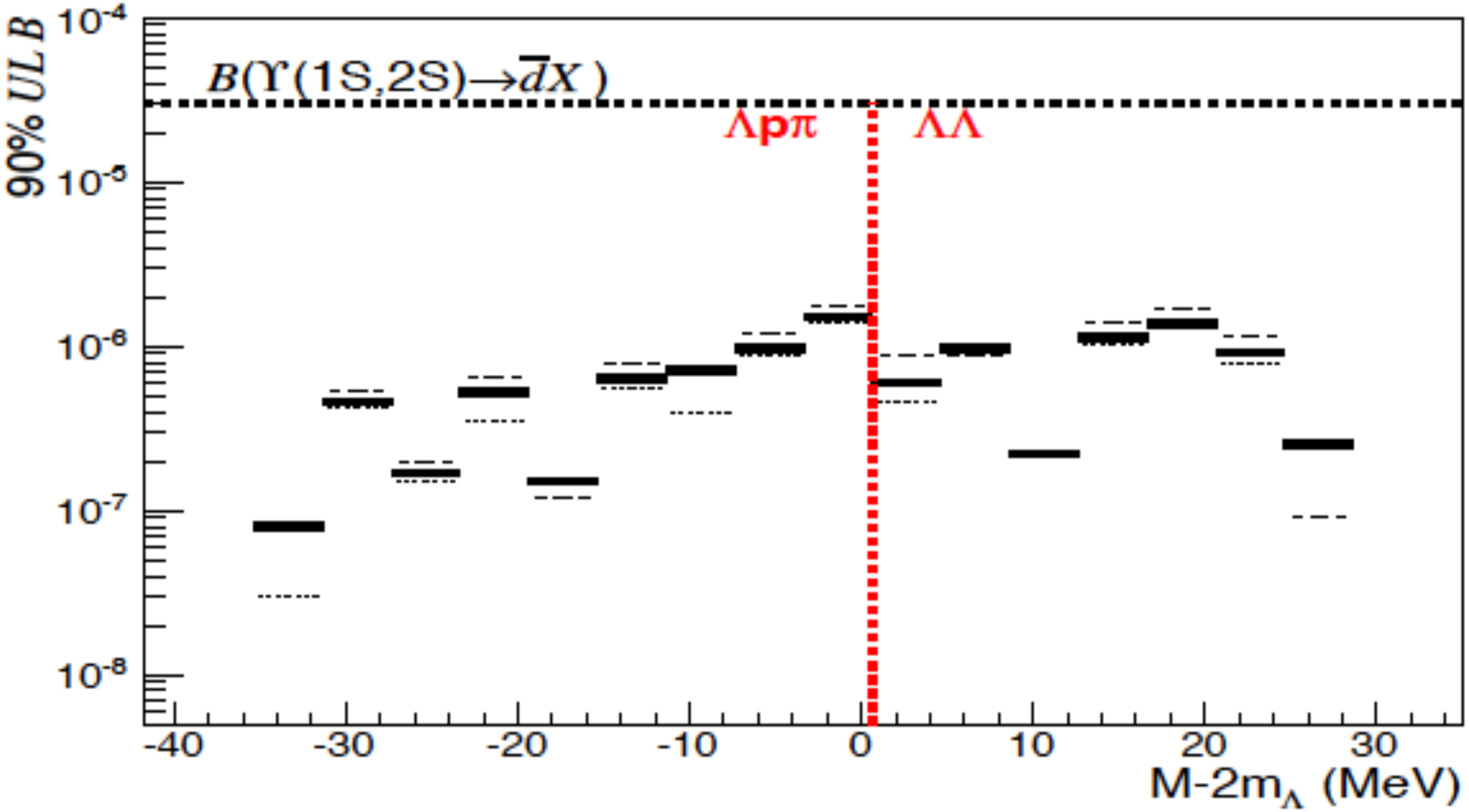
90% CL upper limits on $\Upsilon(1S,2S) \rightarrow H\ X$



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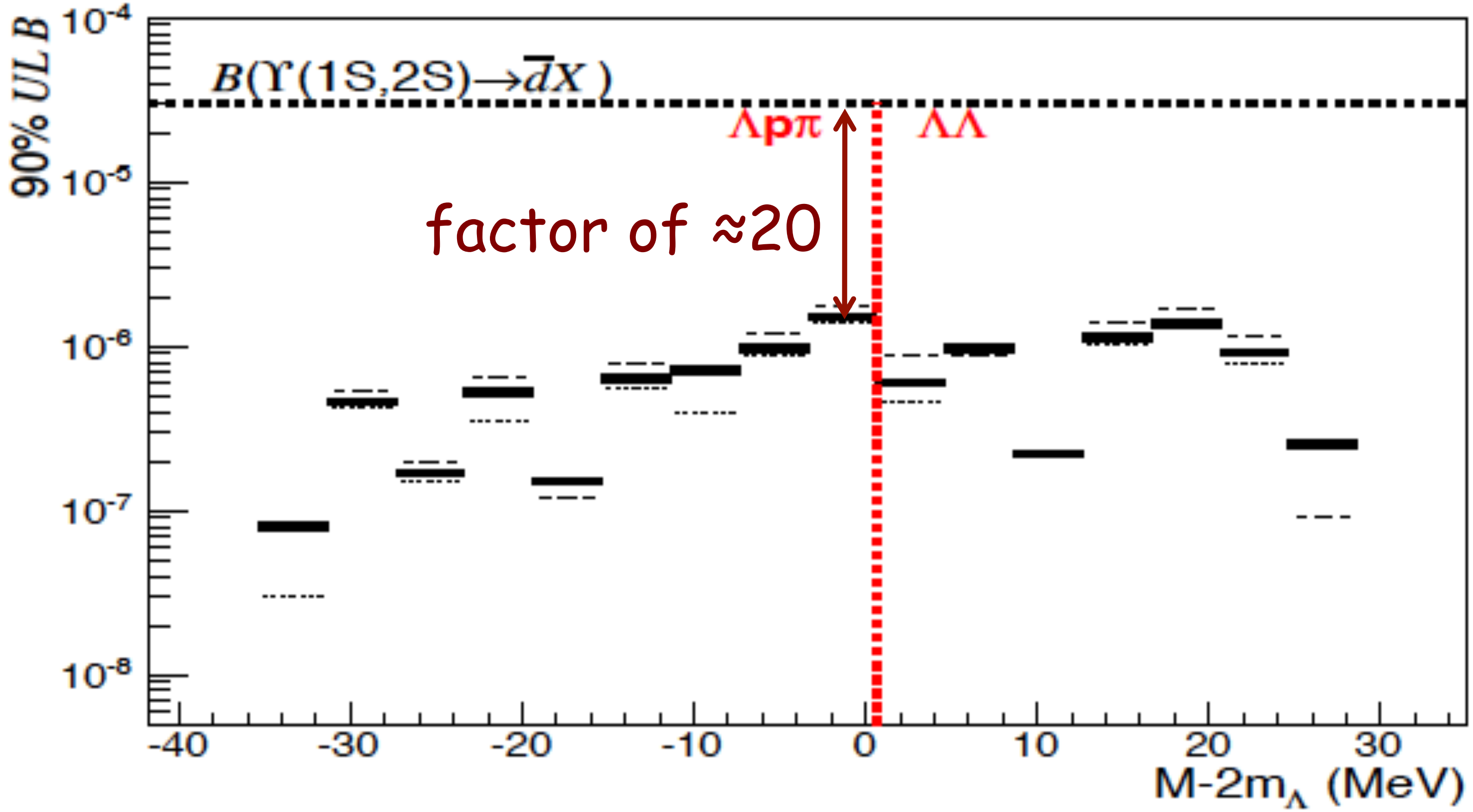
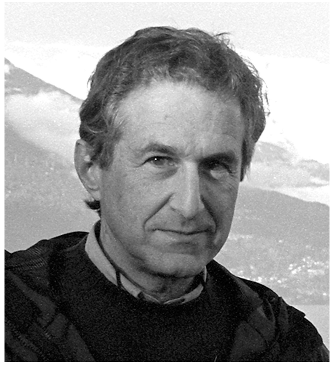


B.H. Kim *et al* (Belle) PRL 110, 222002 (2013)

QCD-motivated multiquark states are not seen!

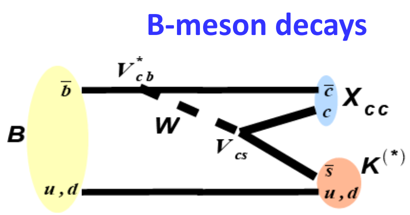
“The absence of exotics is one of the most obvious features of QCD, R. Jaffe 2005

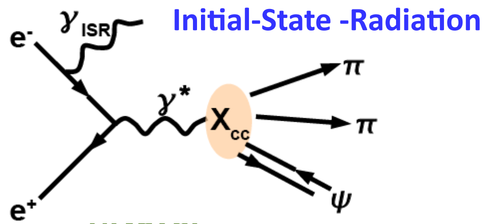


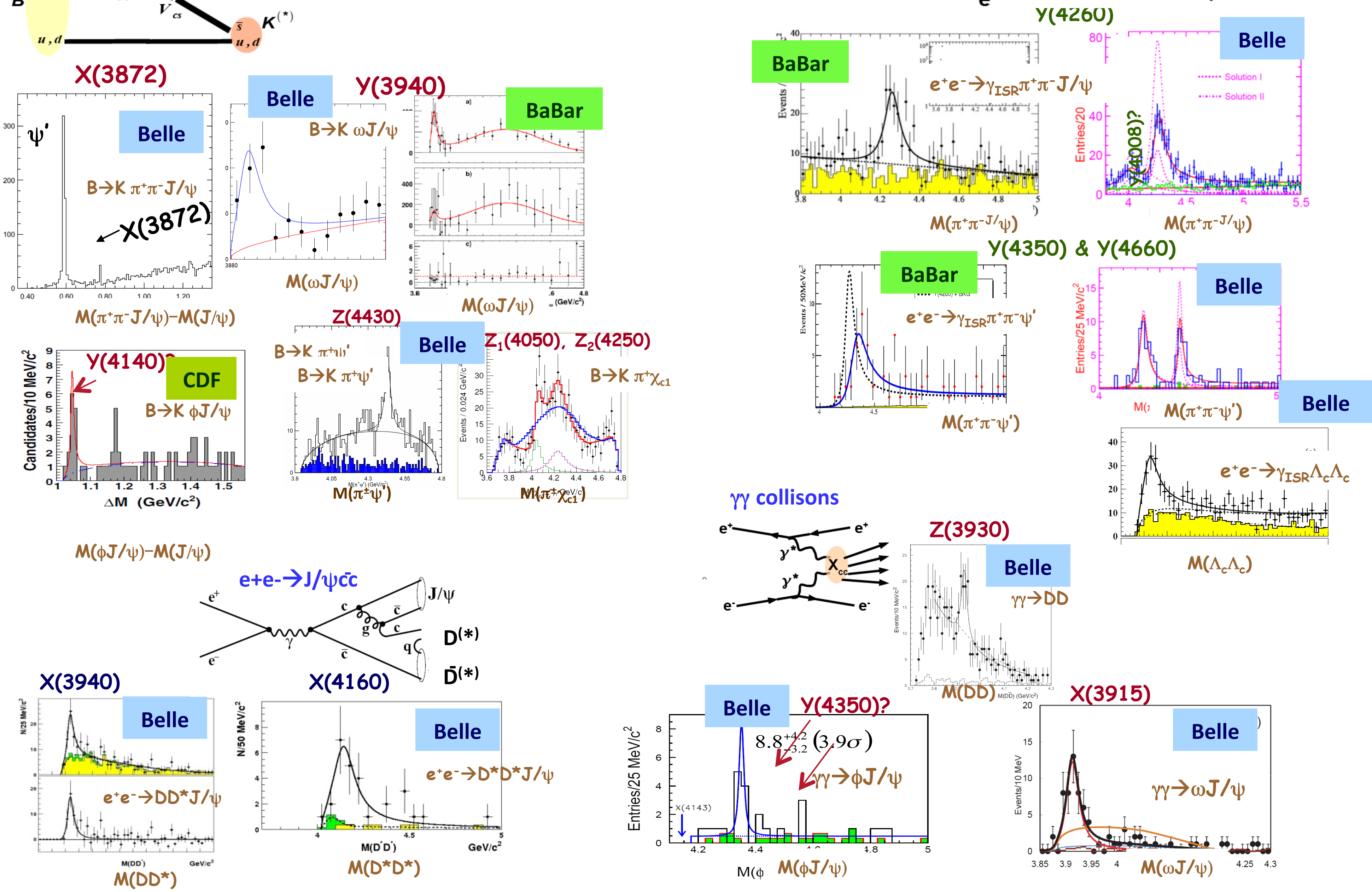
Robert Jaffe

What do we see?

The XYZ quarkonium-like mesons







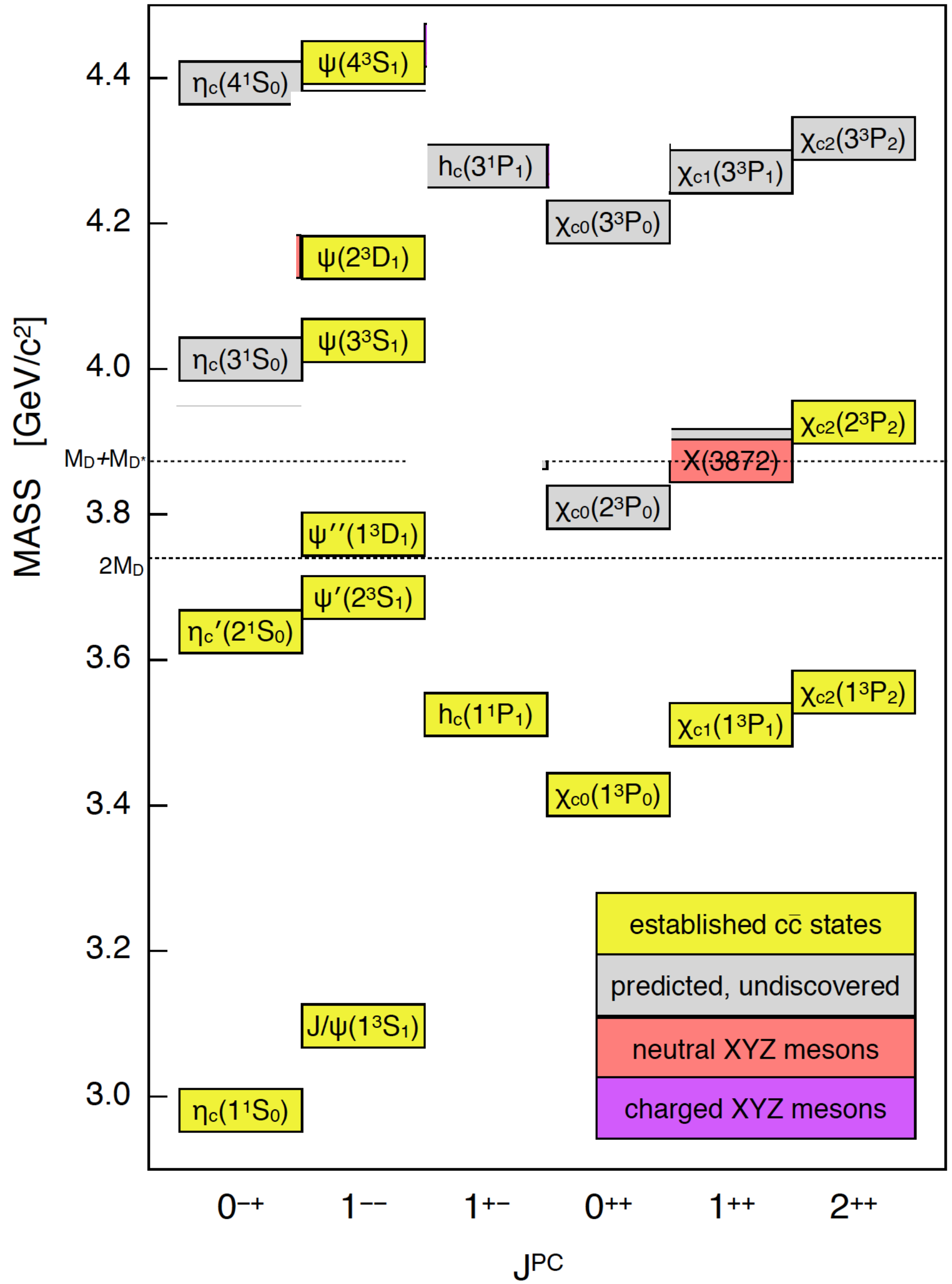
The list keeps growing

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

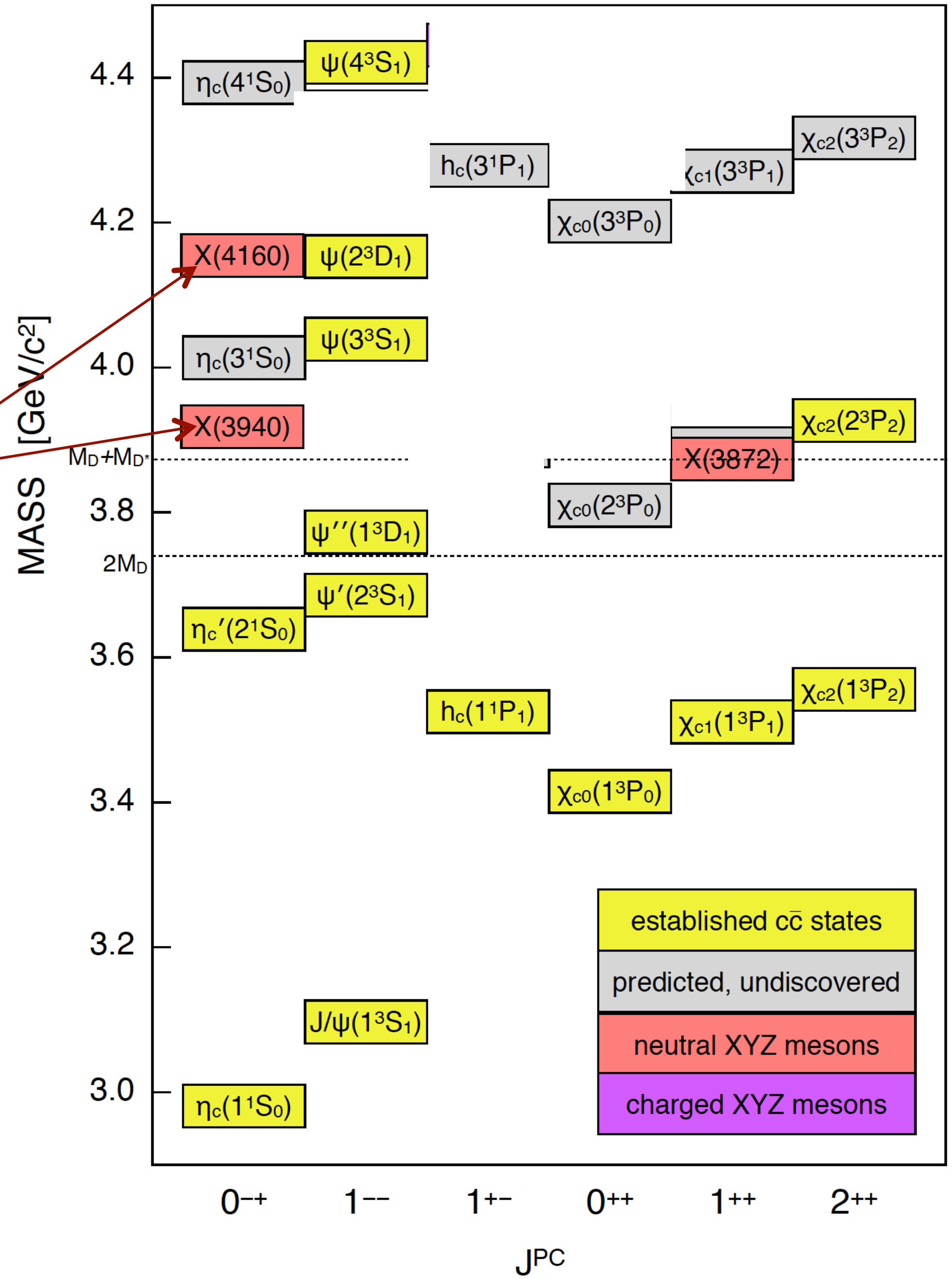
and two Z_b mesons

$c\bar{c}$ 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



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

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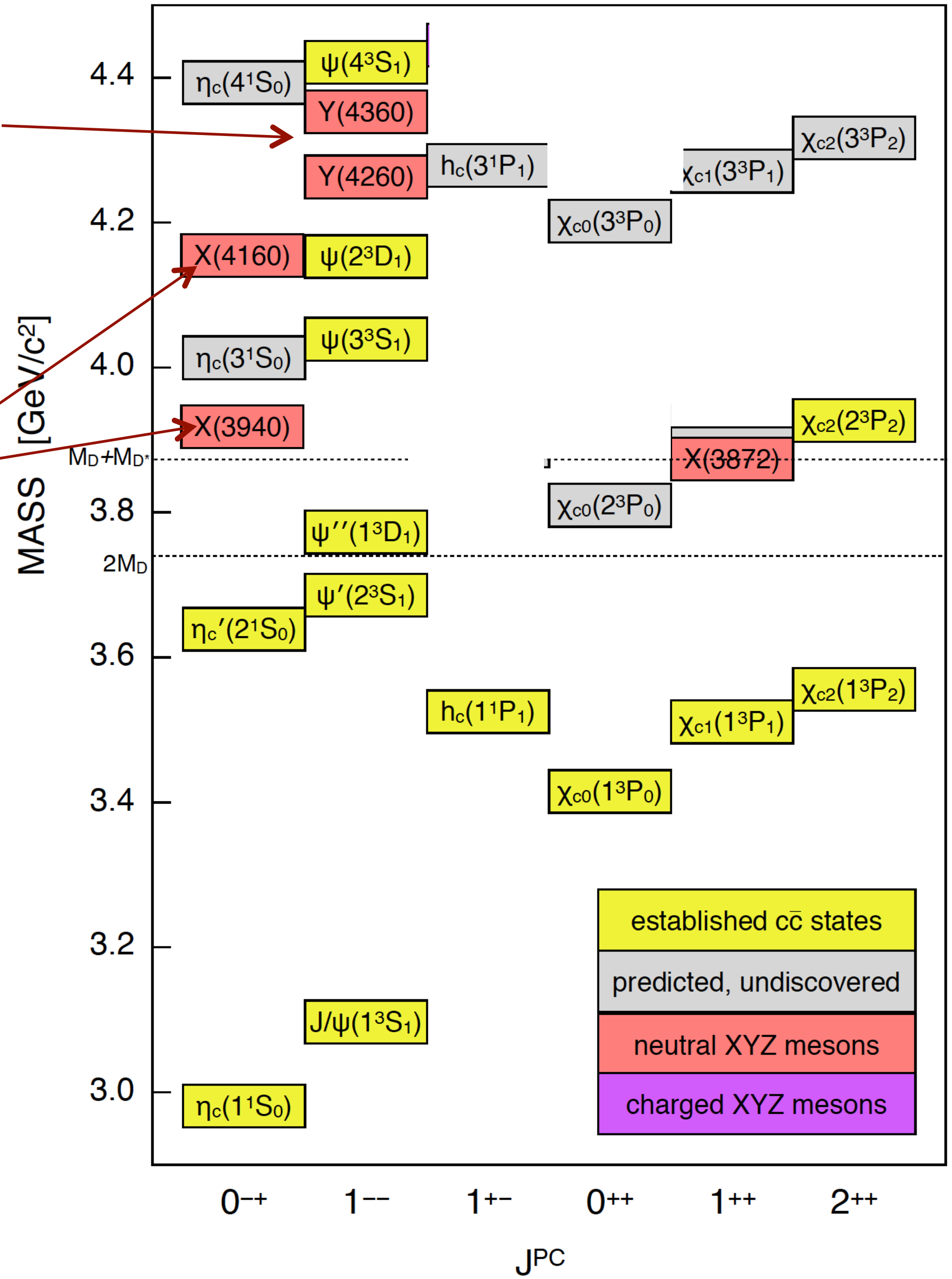

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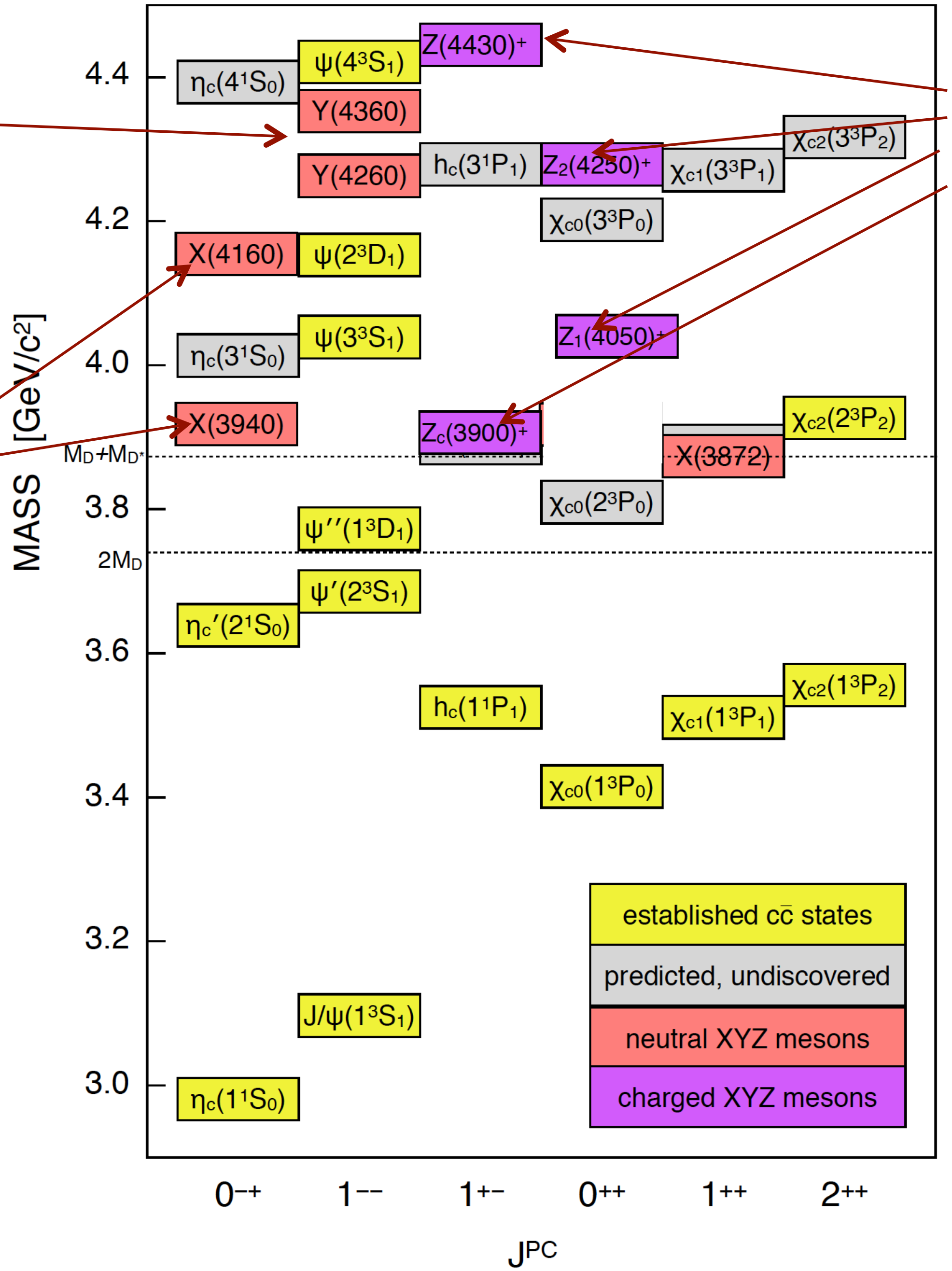

the (4) charged Zs must have a minimal quark content of $c\bar{c}u\bar{d}$

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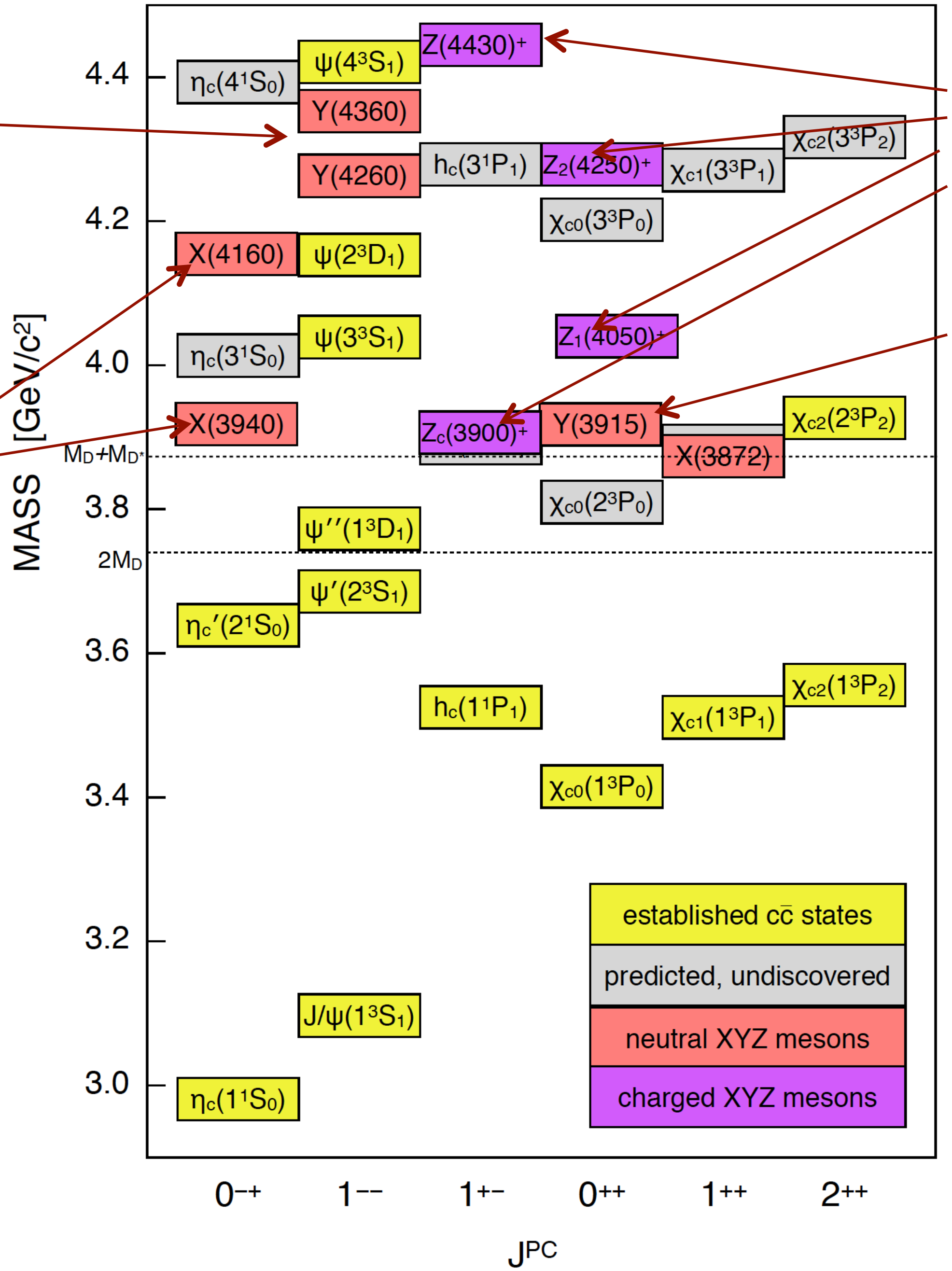

the (4) charged Zs must have a minimal quark content of $c\bar{c}u\bar{d}$

the X(3915) mass and $\Gamma(X \rightarrow \omega J/\psi)$ too high & $\Gamma(X \rightarrow D\bar{D})$ too low for the $\chi_{c0}(2P)$ (see arXiv:1410.6534).

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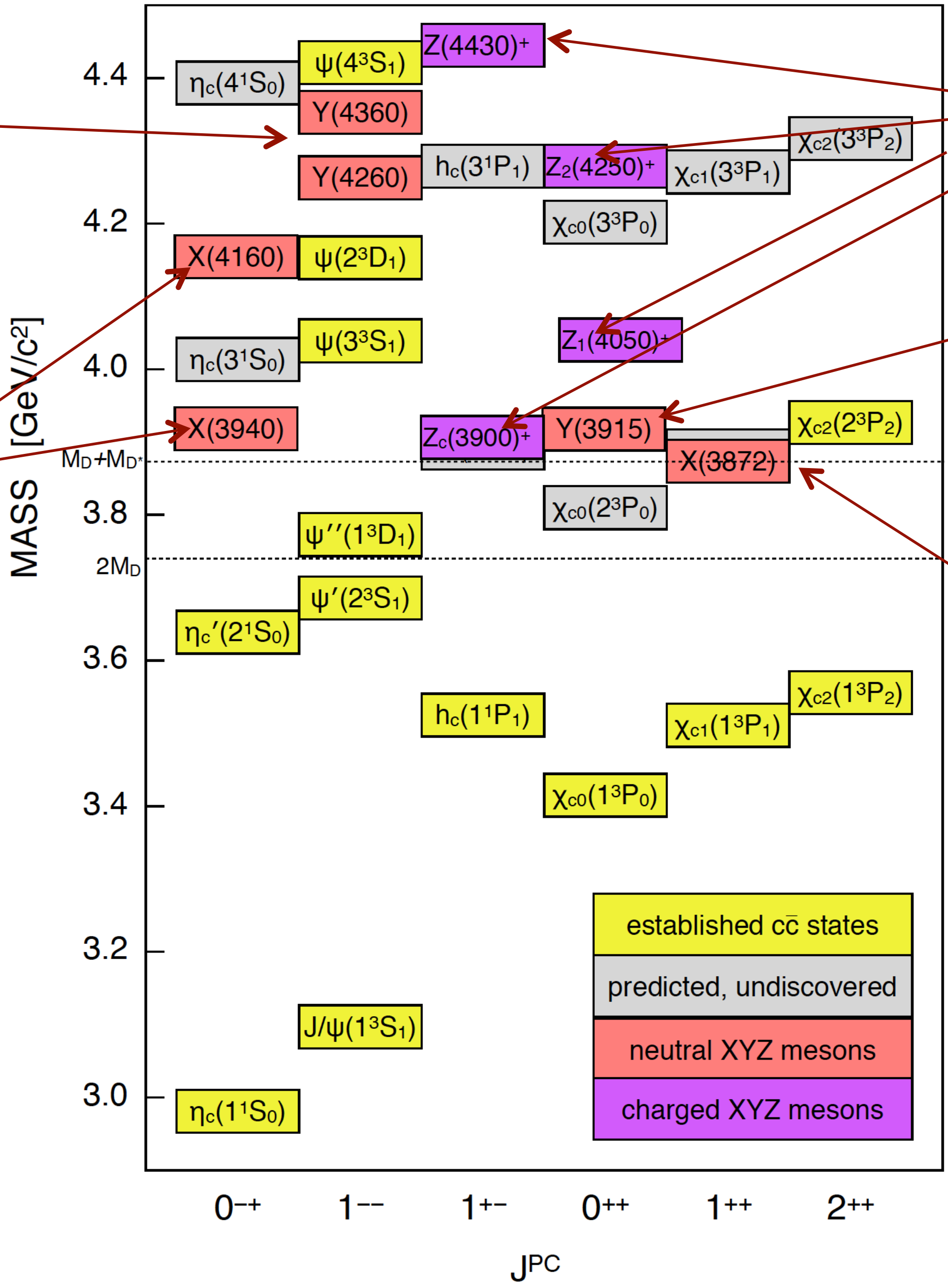

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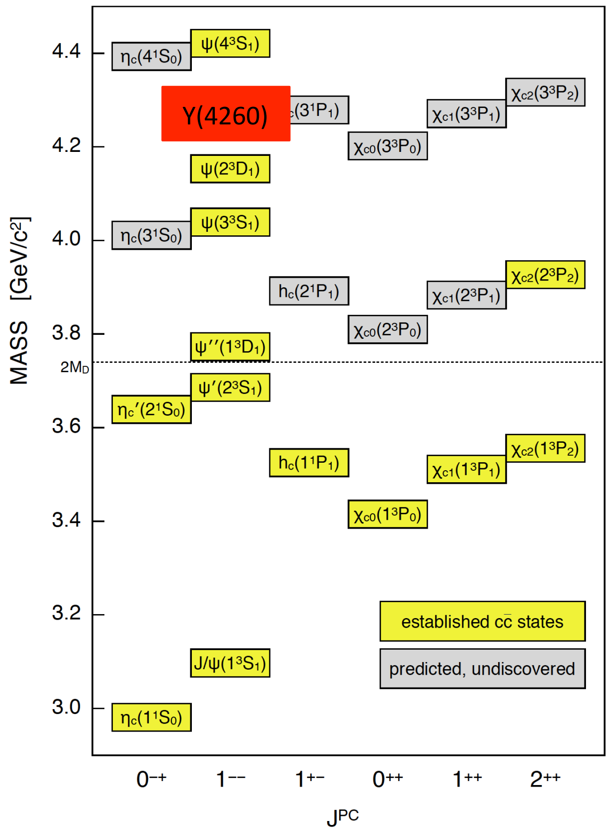
the X(3872) is a long complex story

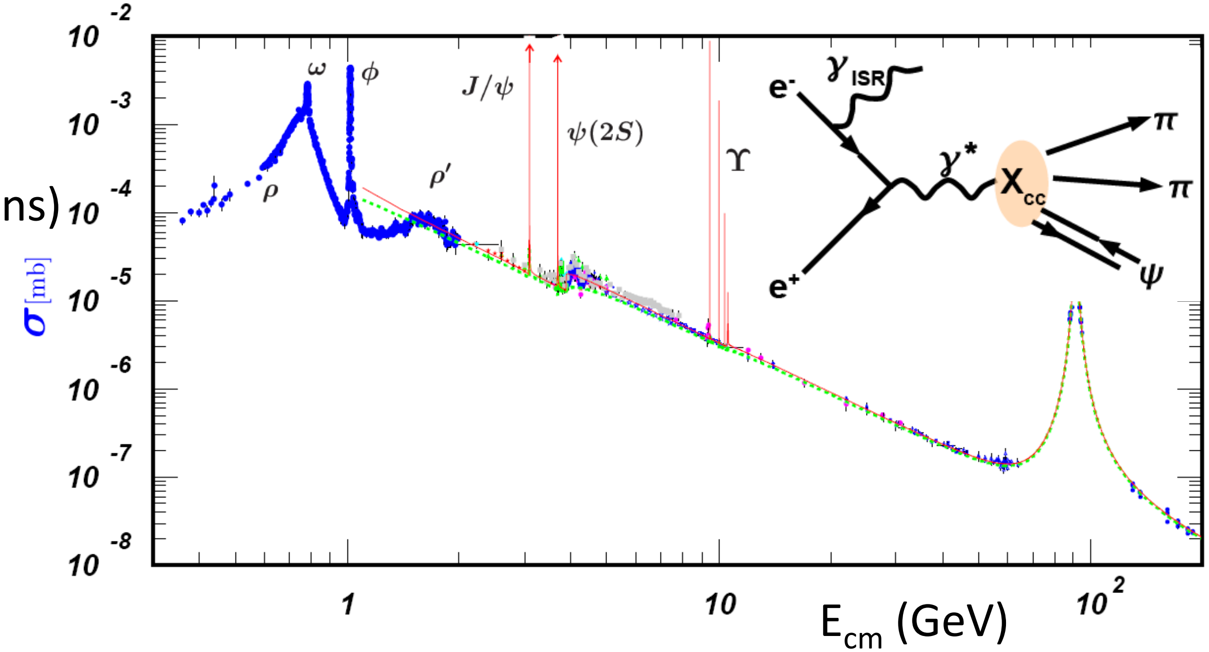
The Y(4260)



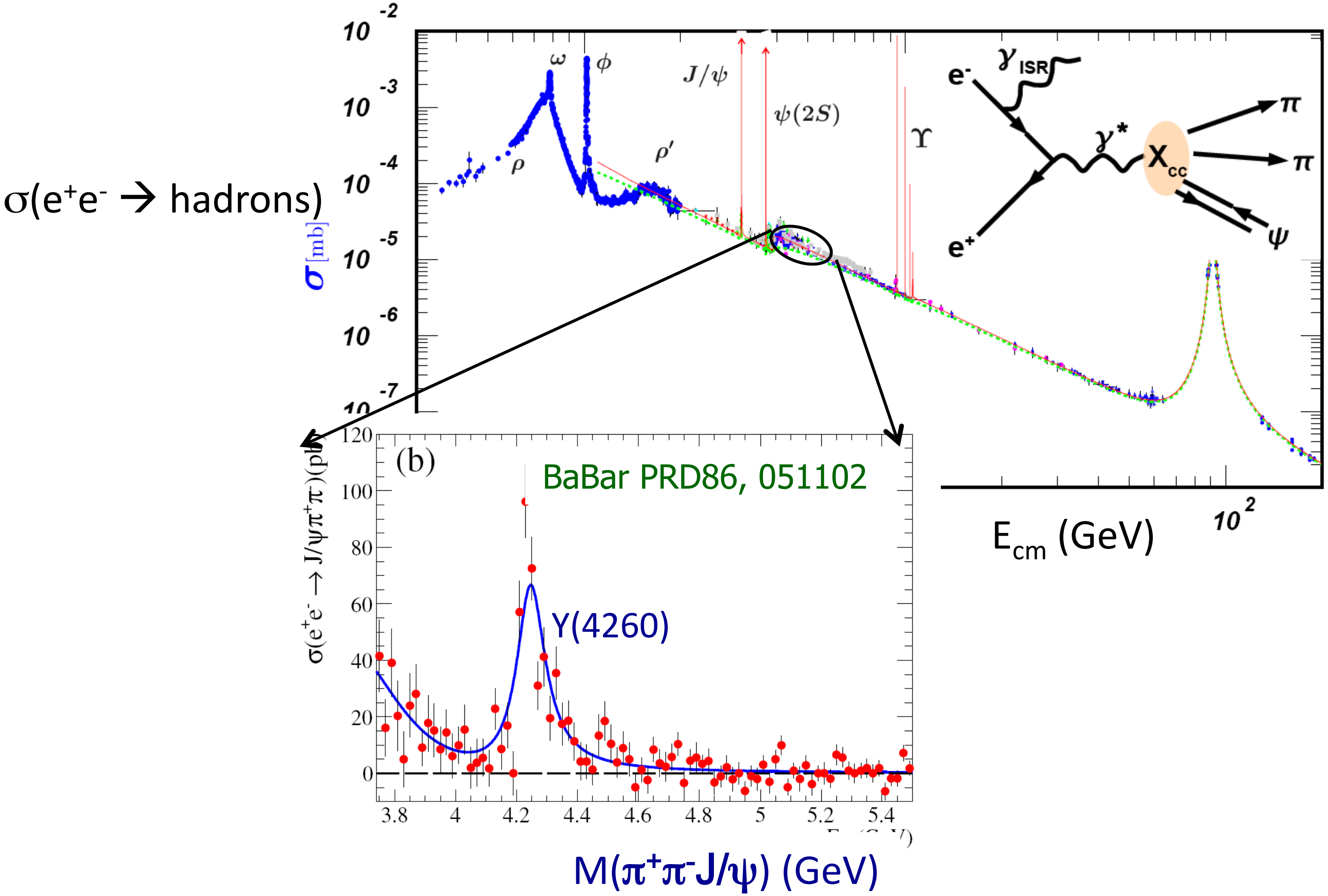
Y(4260)
ηc(4¹S0)
ψ(4³S1)
(3¹P1)
χc0(3³P0)
χc1(3³P1)
χc2(3³P2)
ψ(2³D1)
ηc(3¹S0)
ψ(3³S1)
hc(2¹P1)
χc1(2³P1)
χc2(2³P2)
χc0(2³P0)
ψ''(1³D1)
2MD
ψ'(2³S1)
ηc'(2¹S0)
hc(1¹P1)
χc1(1³P1)
χc2(1³P2)
χc0(1³P0)
established cc̄ states
predicted, undiscovered
J/ψ(1³S1)
ηc(1¹S0)
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
MASS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

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

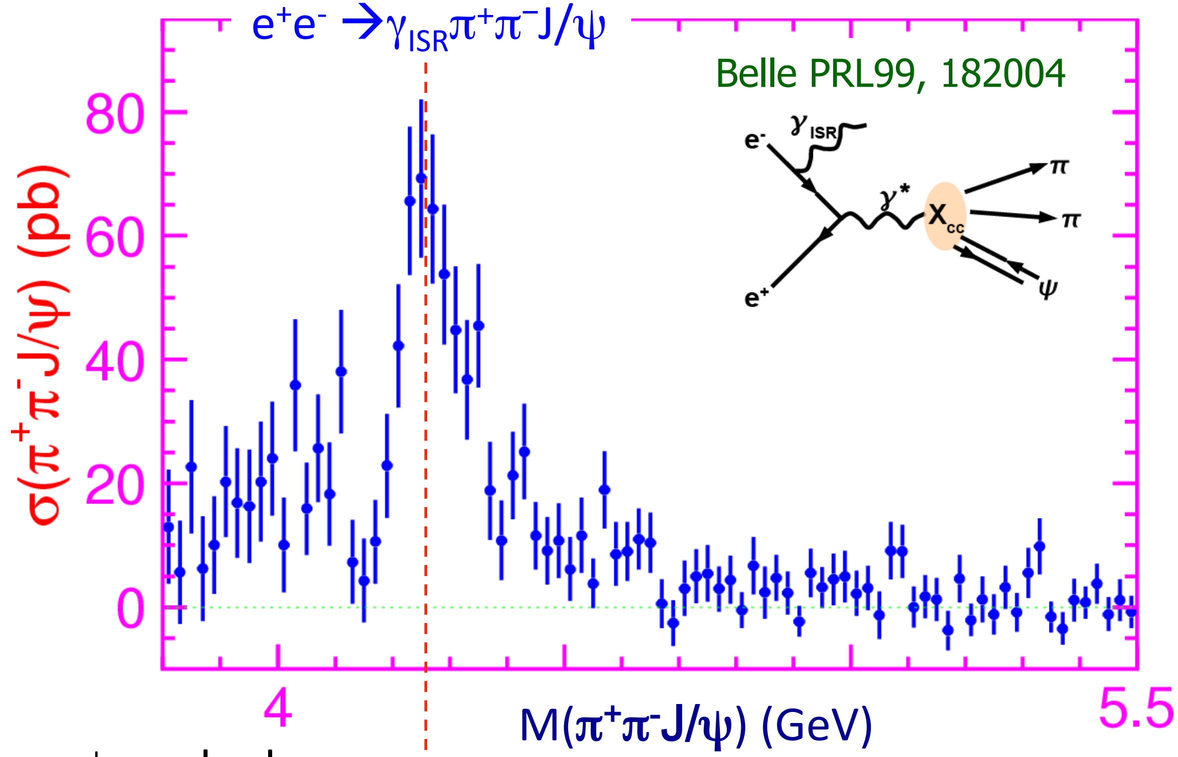
σ(e⁺e⁻ → hadrons)



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

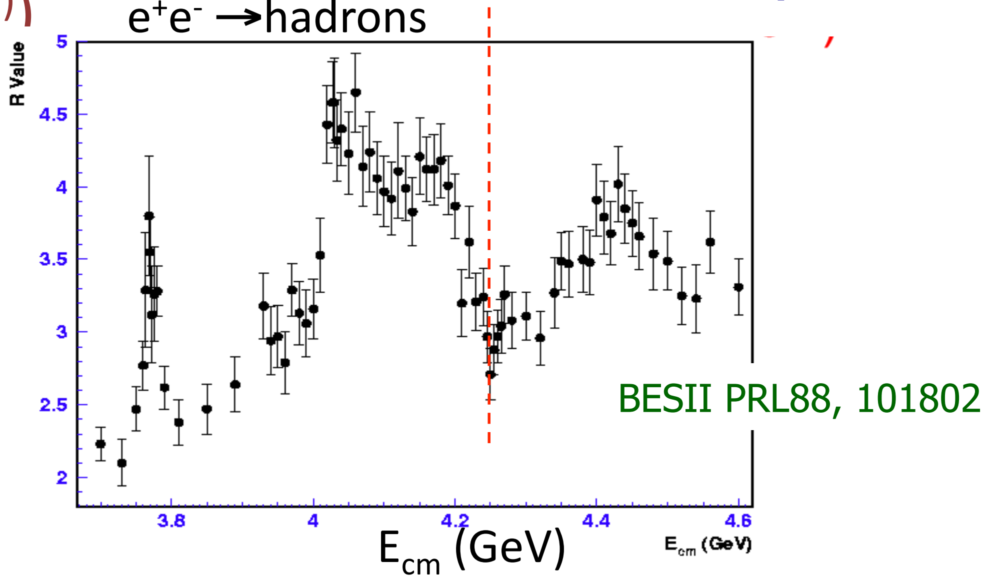


Y(4260) → $\pi^+\pi^- J/\psi$ confirmed by Belle



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

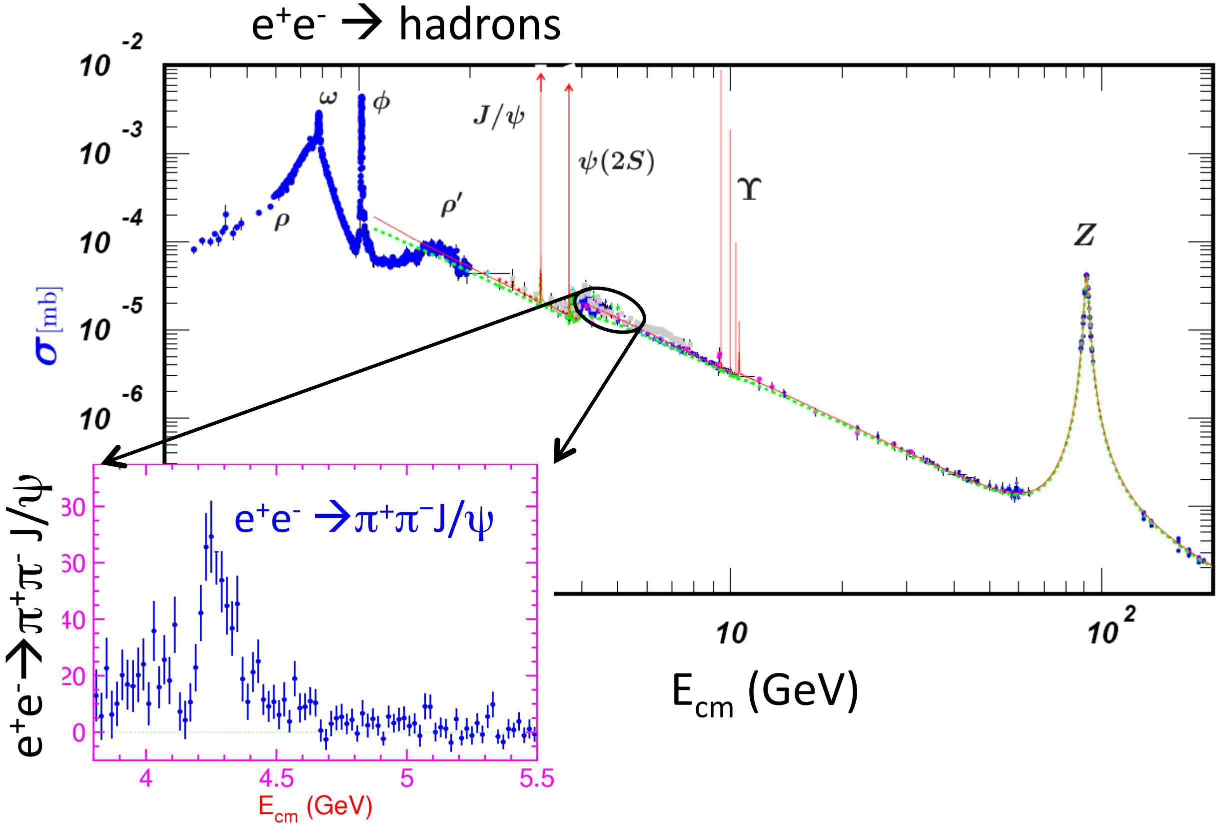
Y(4260) peak in $\sigma(\pi^+\pi^- J/\psi)$ occurs at a dip in $\sigma(D^{(*)}\bar{D}^{(*)})$



→$\Gamma(\pi^+\pi^- J/\psi)$ is large,
an OZI suppressed mode 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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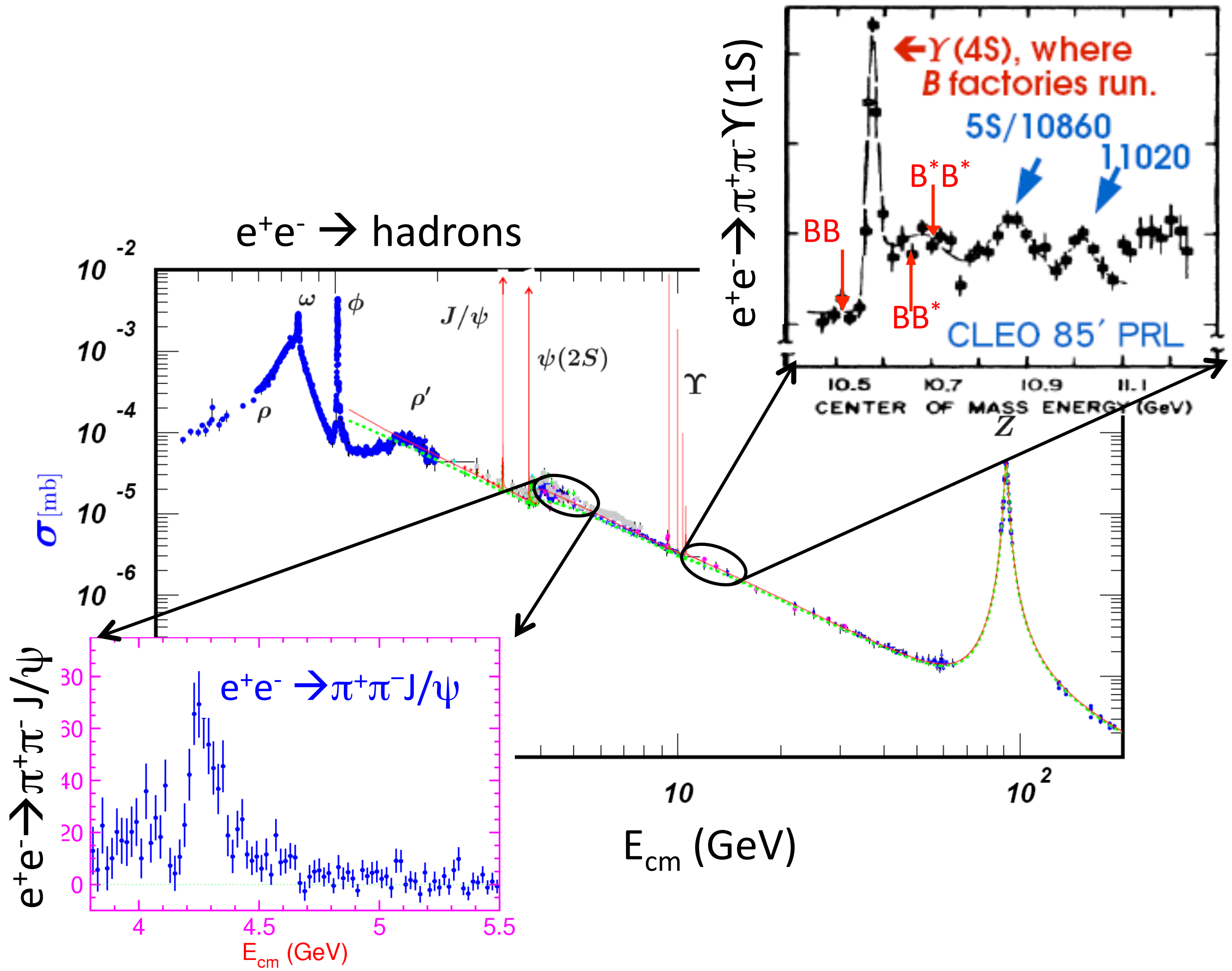

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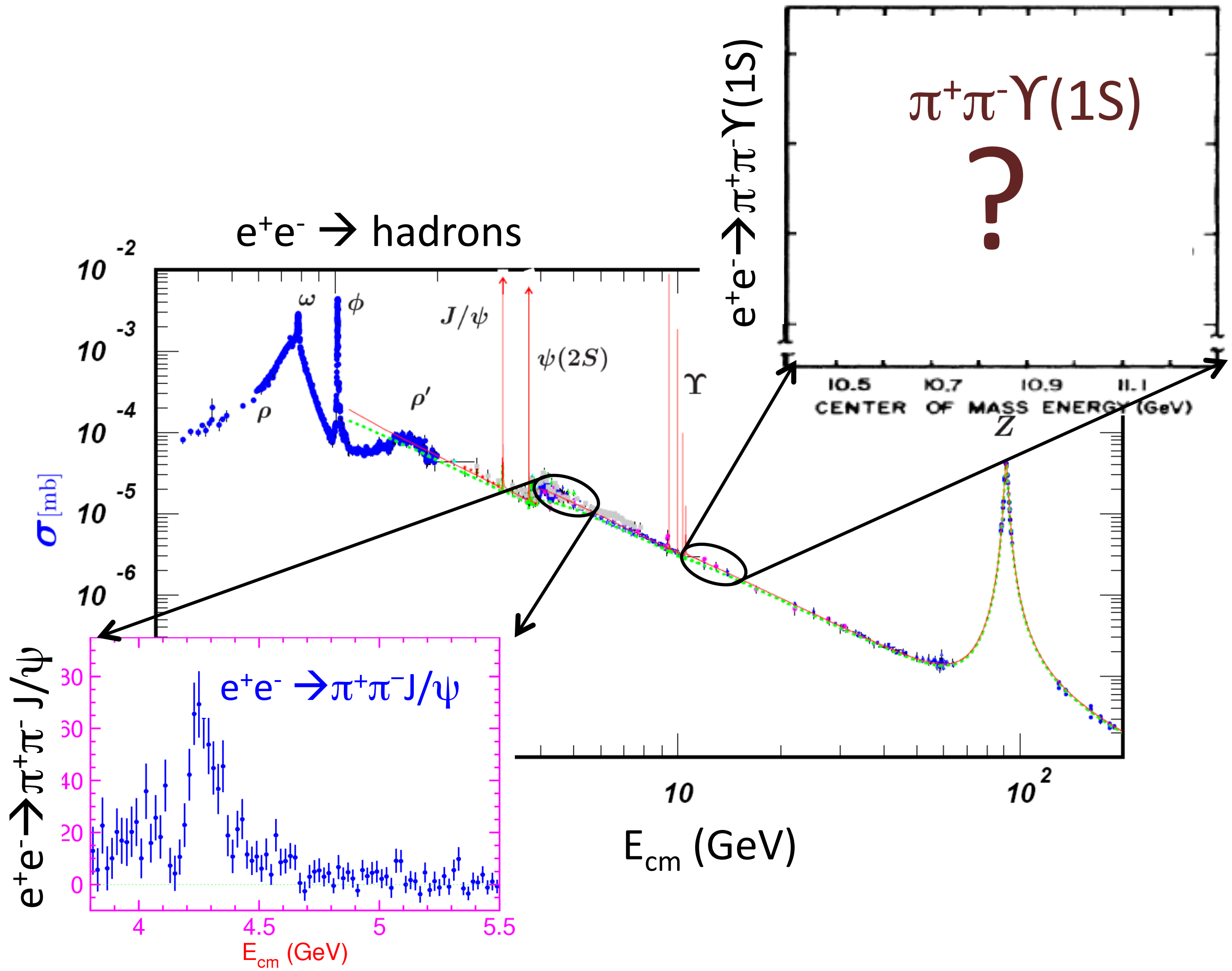
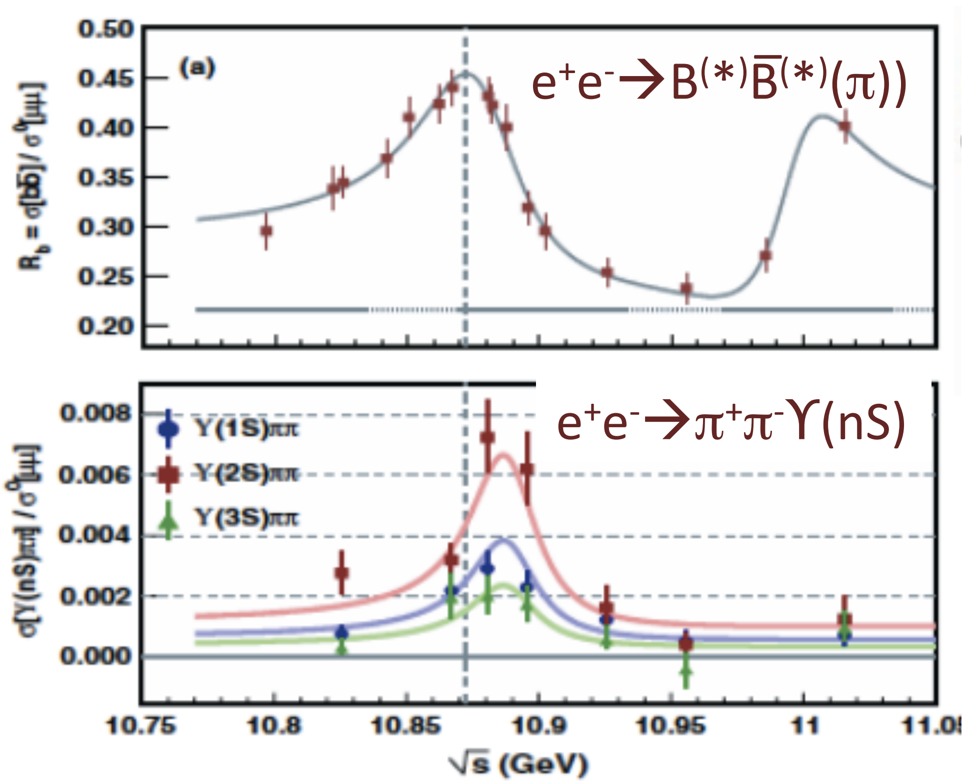


Yes

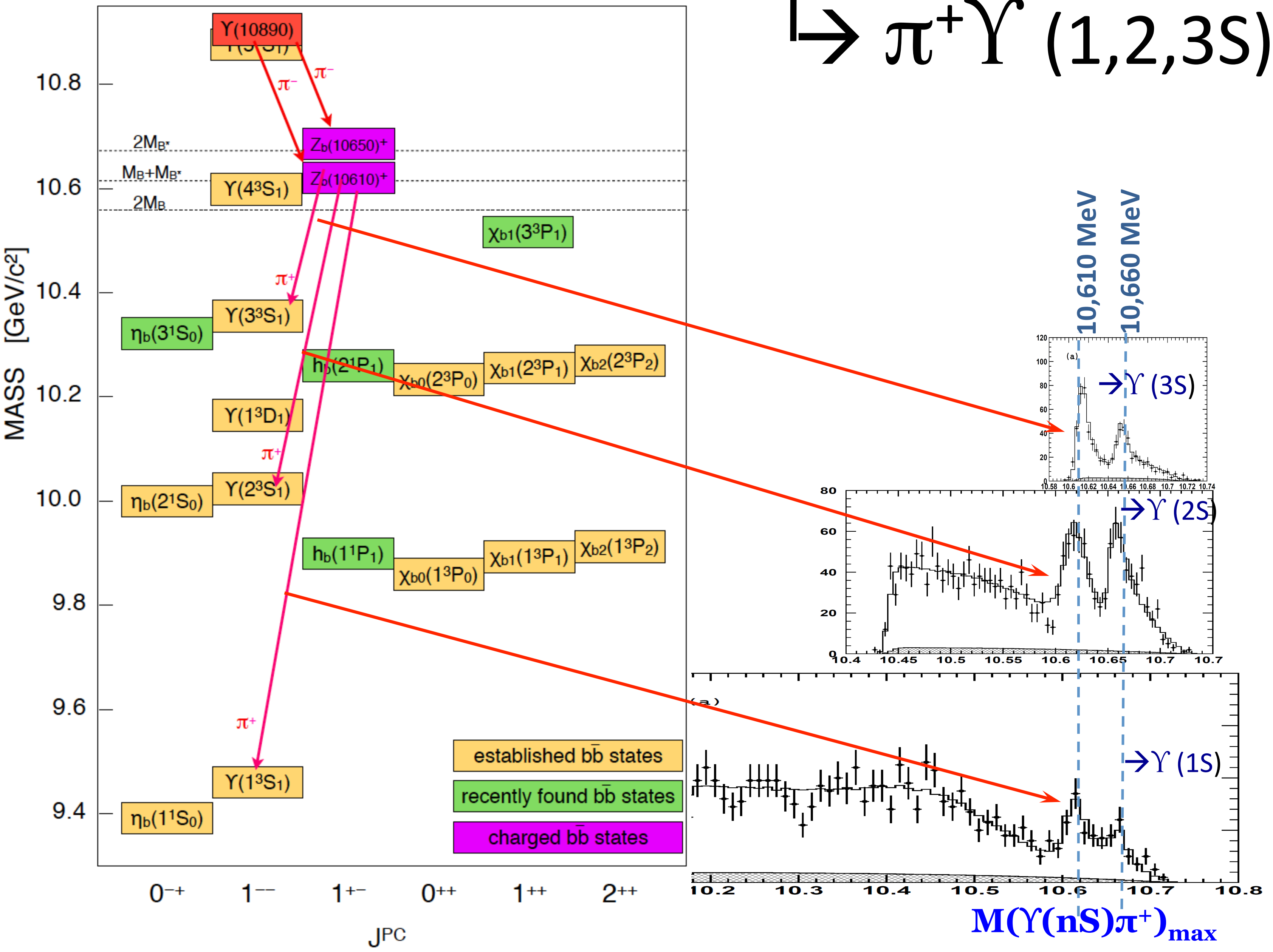


PRD82,091106(2010)

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

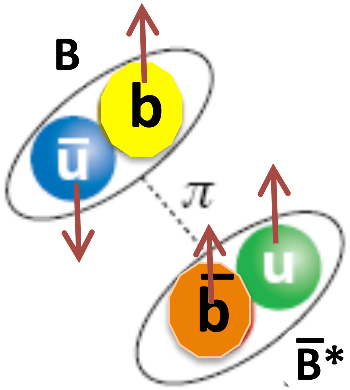
"Υ(5S)" → $\pi^- Z_{b1,2}^+$ → $\pi^+ \Upsilon$ (1,2,3S)

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



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

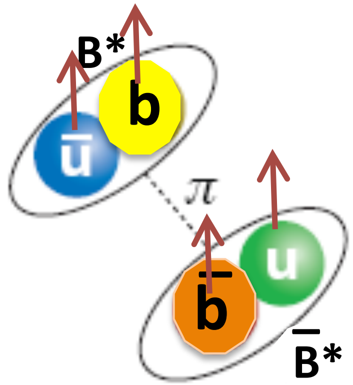
$Z_b(106010)^{\pm}$



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

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

$Z_b(106050)^{\pm}$



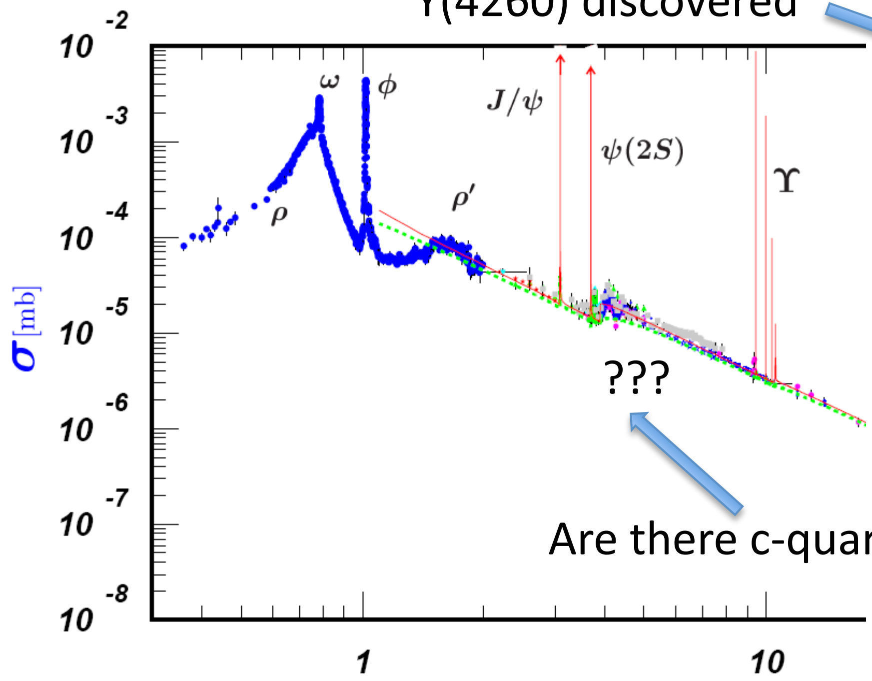
$B^*\text{-}\bar{B}^*$ "molecule"

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

Slightly unbound threshold resonances??

Amplitude analyses: both states have $J^P = 1^+$

Are there c-quark versions of Z_b's



Y(4260) discovered

Is there a b-quark equivalent?

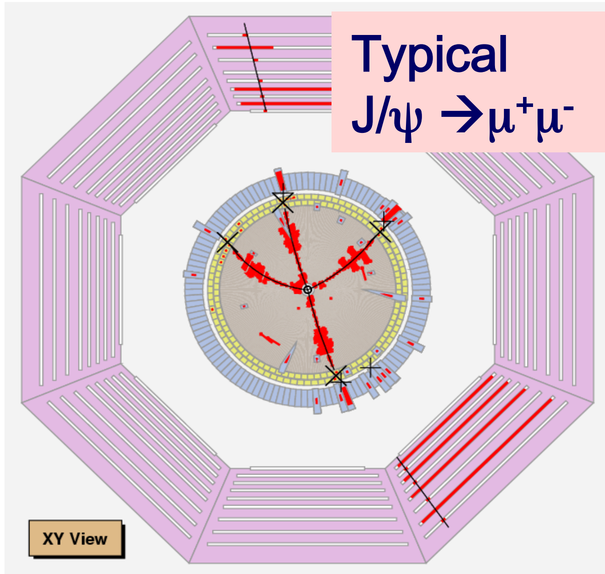
Yes, & it decays to Z_b states

Are there c-quark versions of Z_b's?

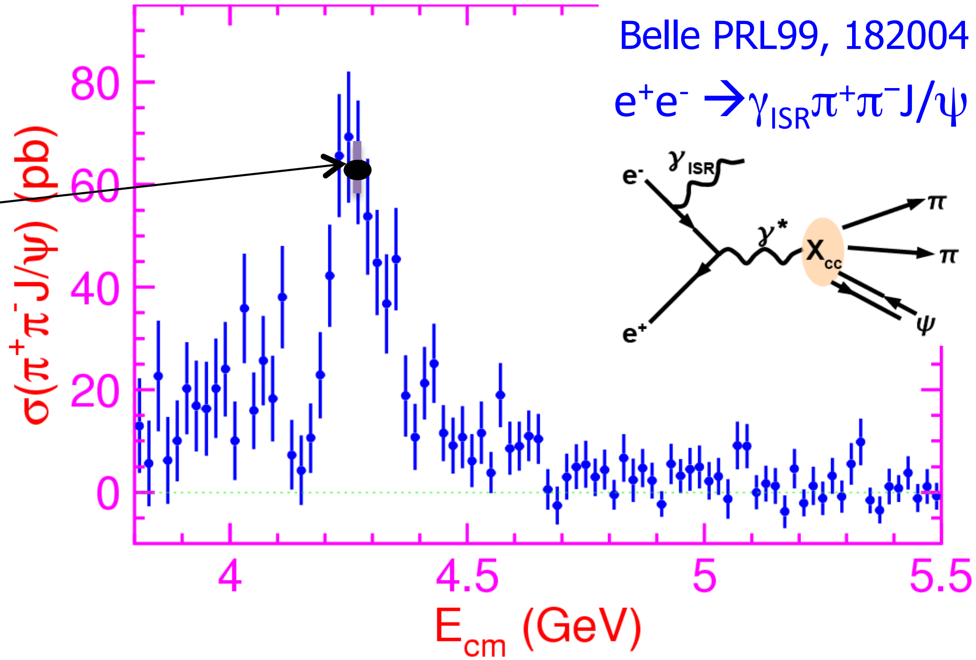
run BEPCII/BESIII as a Y(4260) factory

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

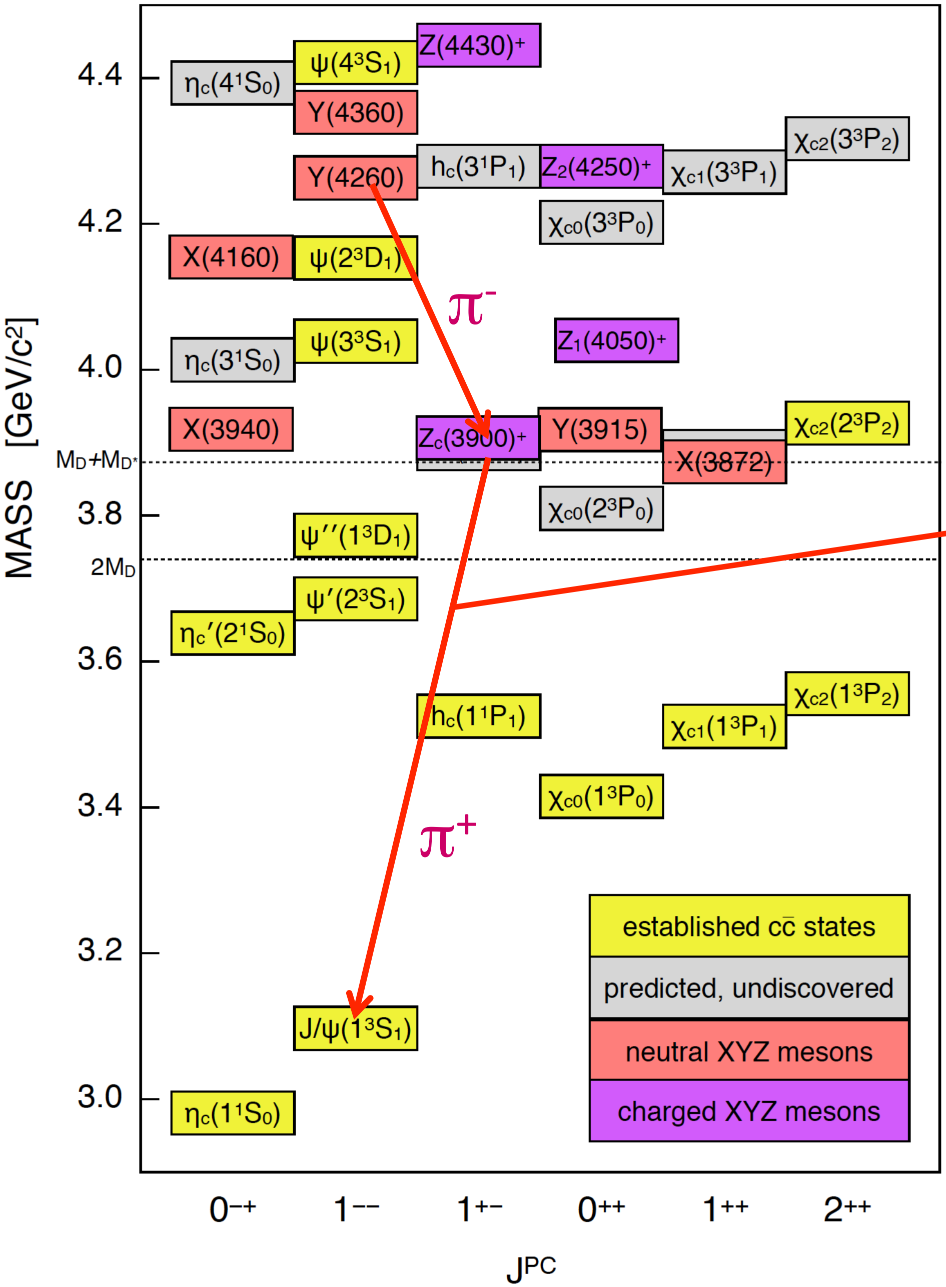
$@E_{cm}=4260$ MeV

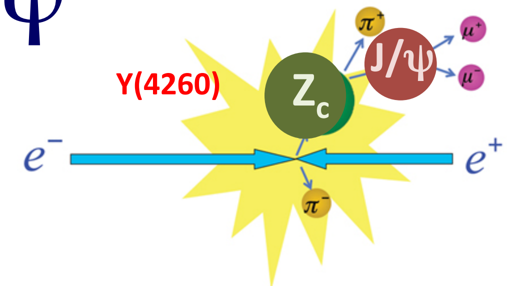


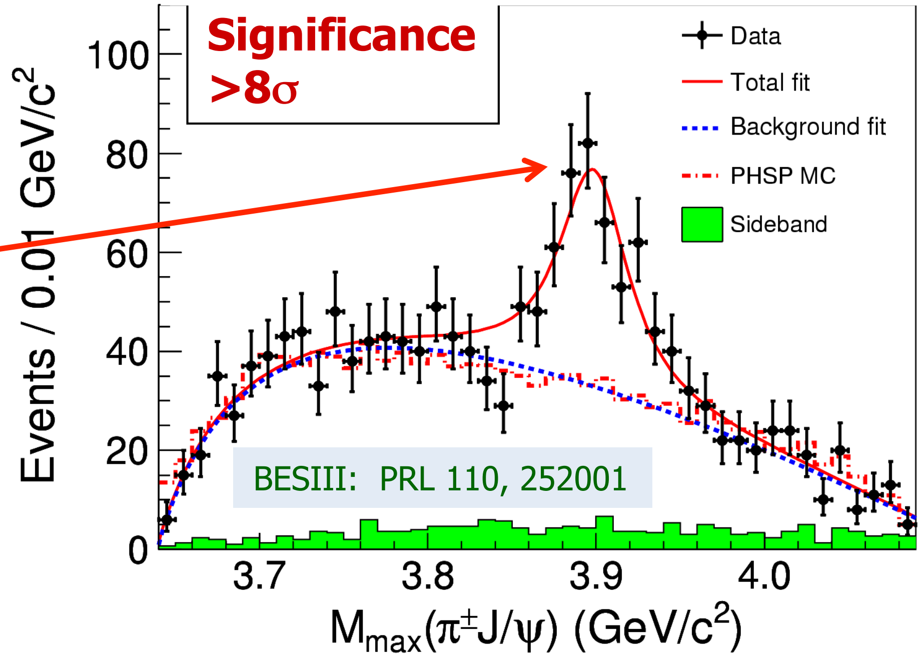
BESIII: PRL 110, 252001 (2013)
$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb



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



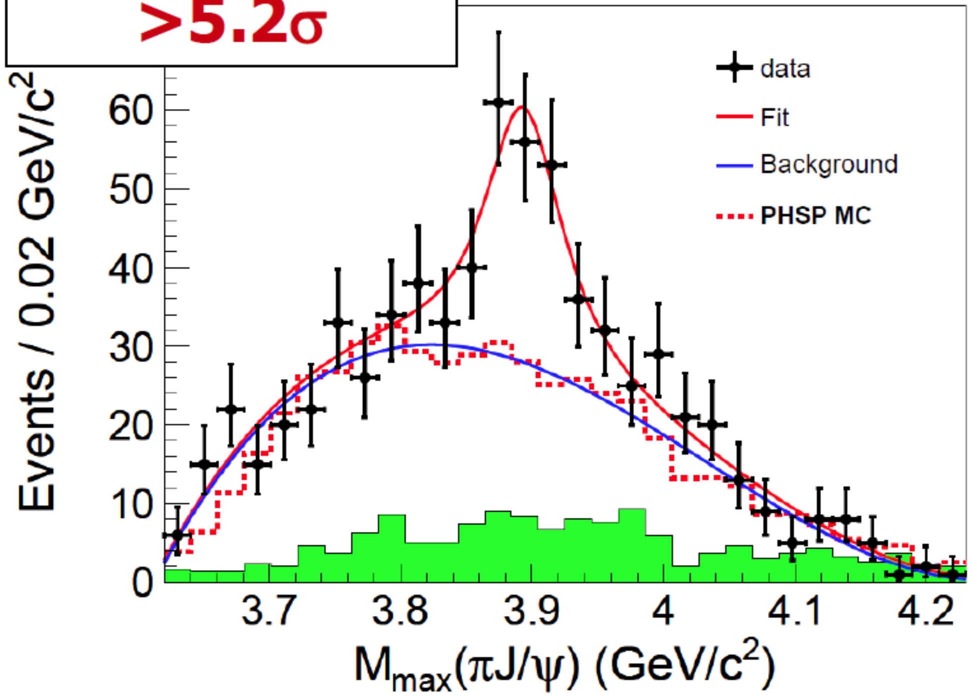




- Mass = $(3899.0 \pm 3.6 \pm 4.9)$ MeV
- Width = $(46 \pm 10 \pm 20)$ MeV
- Fraction = $(21.5 \pm 3.3 \pm 7.5)\%$

Z_c(3900) also seen by Belle

Significance >5.2σ

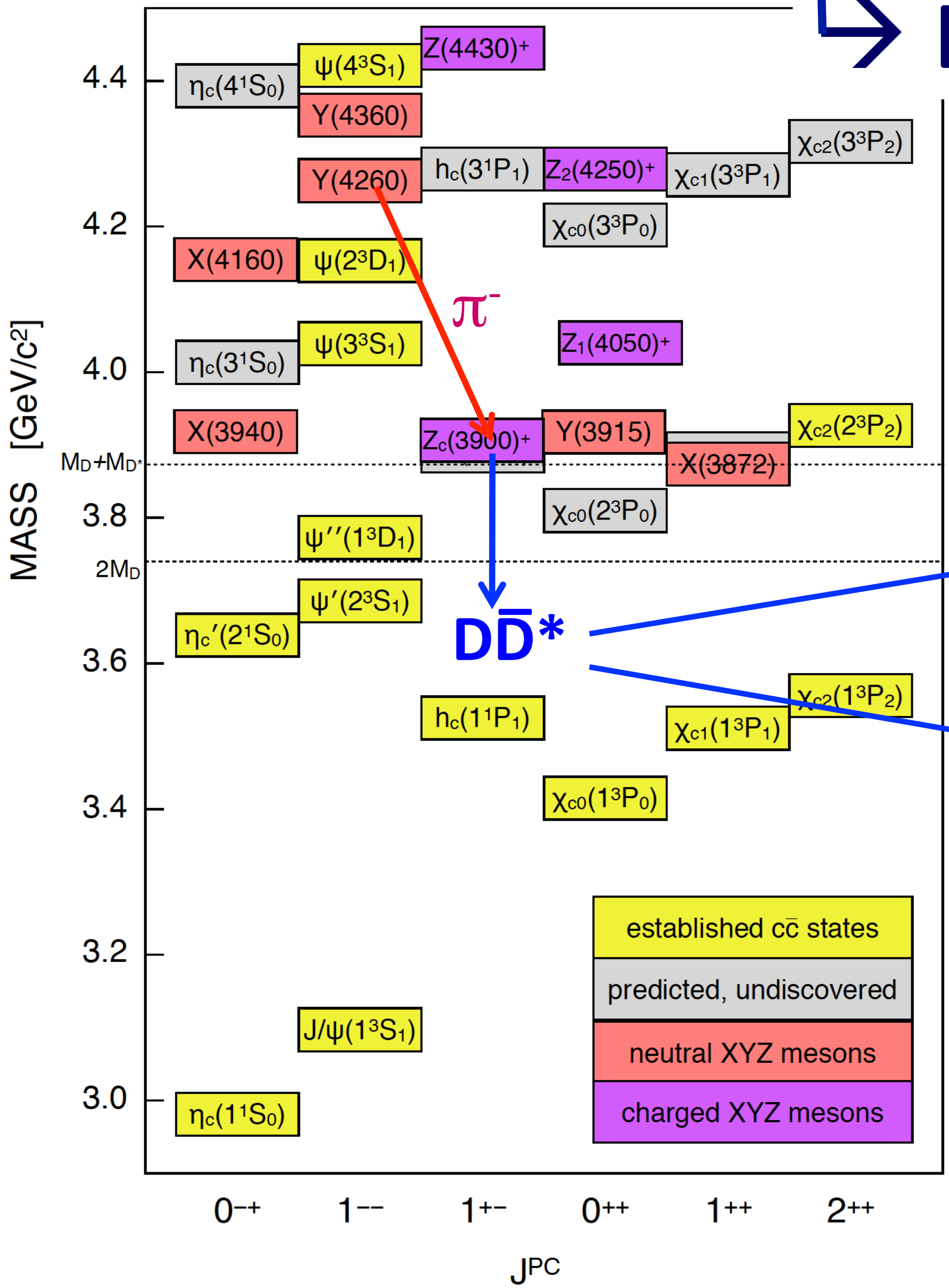


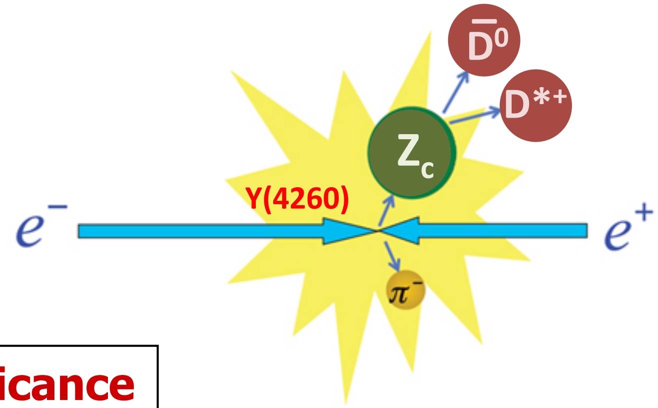
Mass = (3894.5 ± 6.6 ± 4.5) MeV
Width = (63 ± 24 ± 26) MeV
Fraction = (29.0 ± 8.9)% (stat. err. only)

Belle: PRL 110, 252002

$Y(4260) \rightarrow \pi^- Z_c(3900)^+$

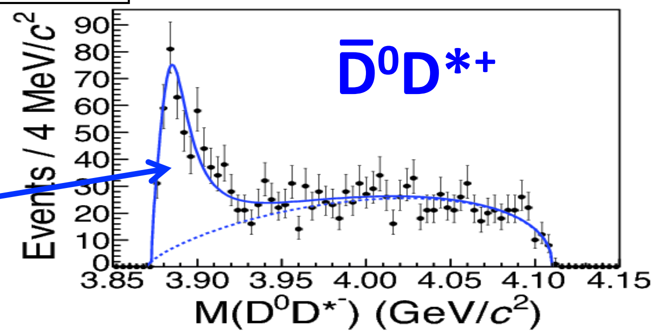
↳ $\bar{D}D^*$

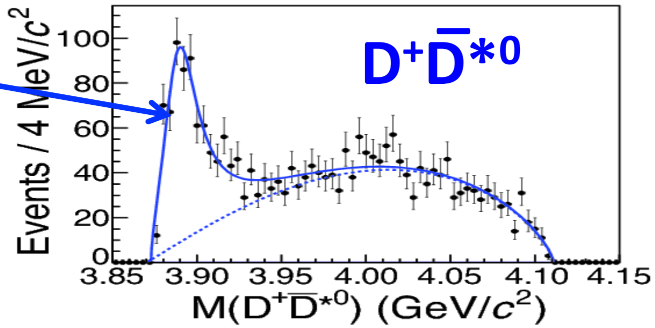




Significance >18σ

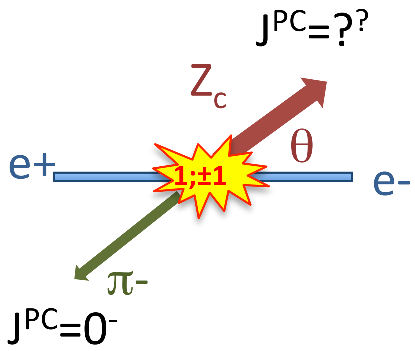
BESIII PRL 112, 022001 (last month)





- 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

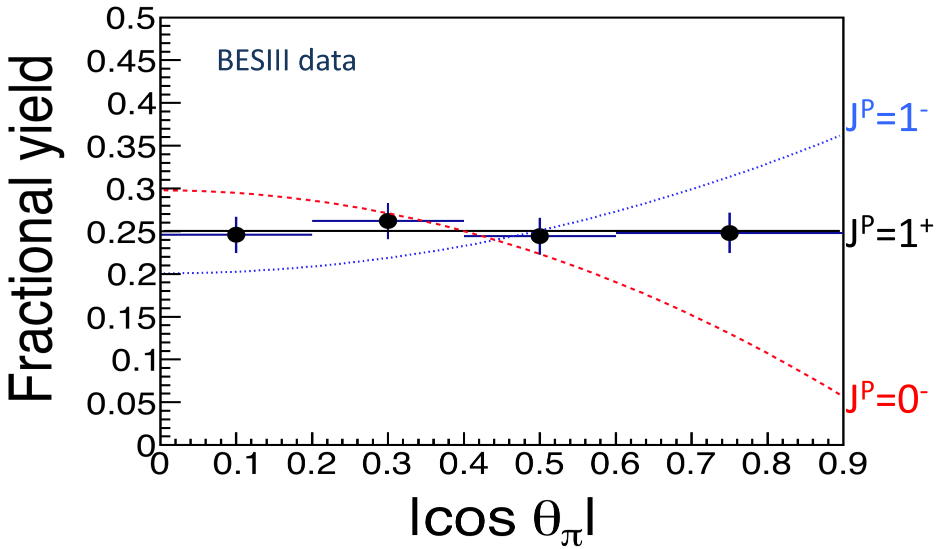
J^P of the $Z_c(3900)$?



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^-	$\|1;\pm1\rangle\|1;0\rangle - \|1;0\rangle\|1;\pm1\rangle$	$\propto 1+\cos^2\theta$



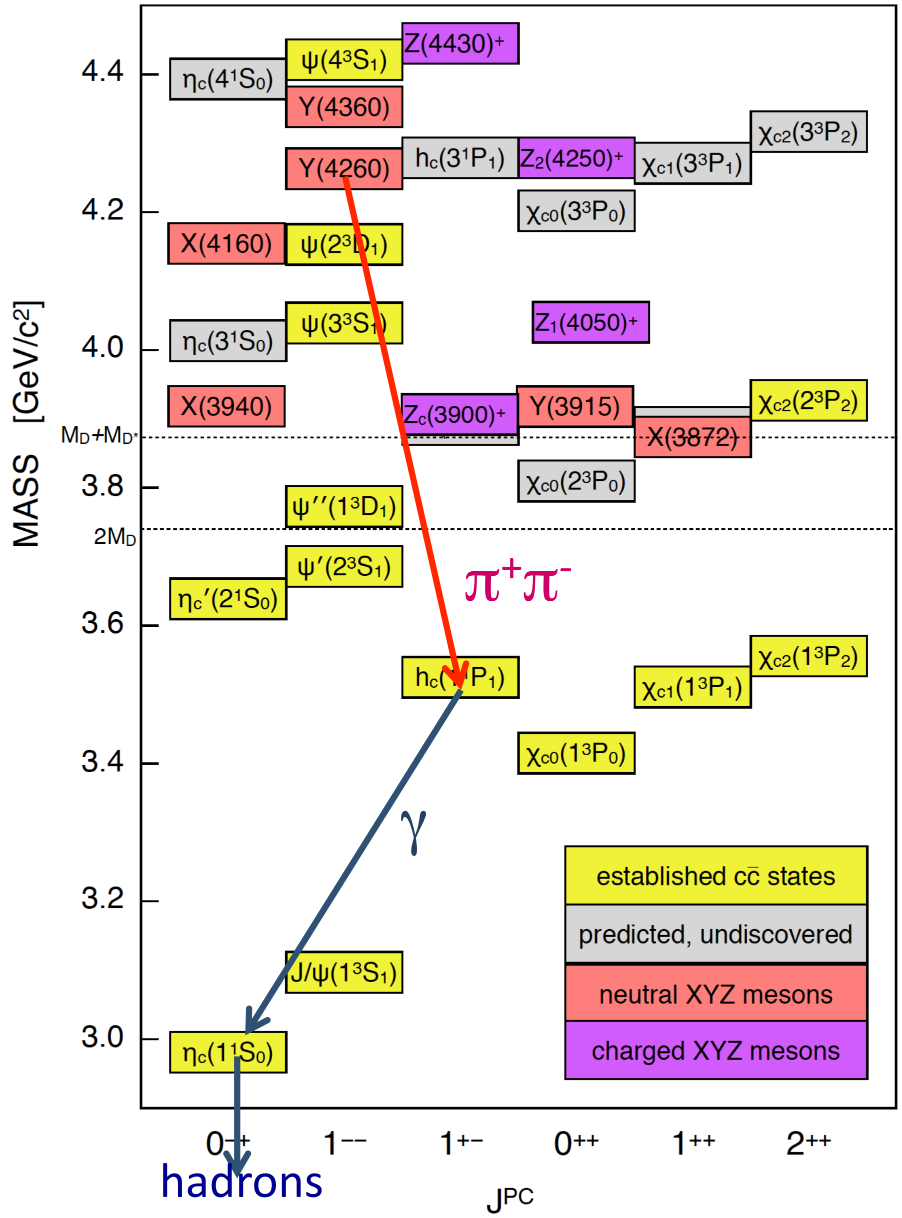
The data clearly establish $J^P=1^+$

Are there others?

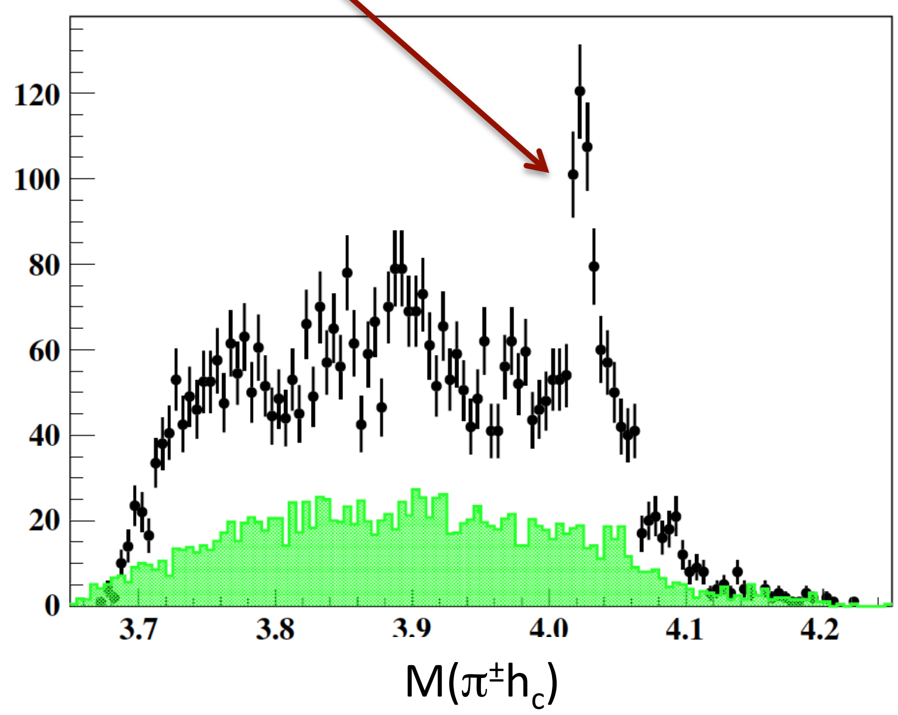
Study $Y(4260) \rightarrow \pi^+\pi^- h_c$ decays

$h_c \rightarrow \gamma\eta_c$

$\eta_c \rightarrow$ 16 channels

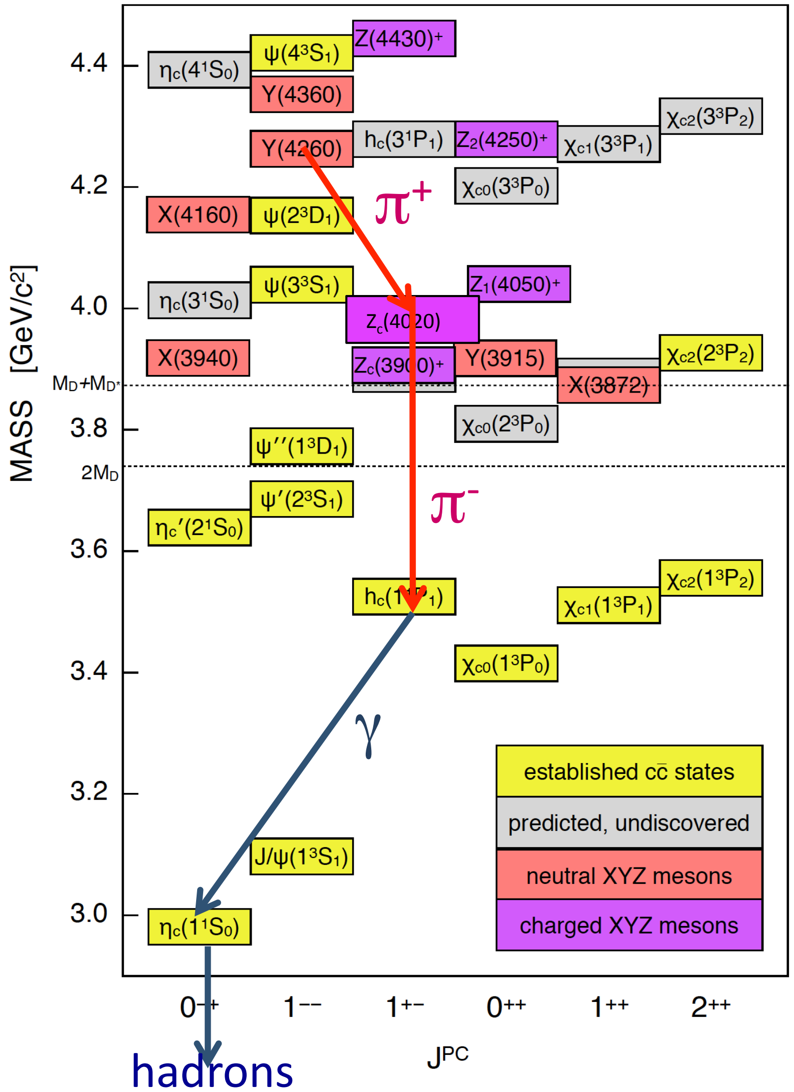


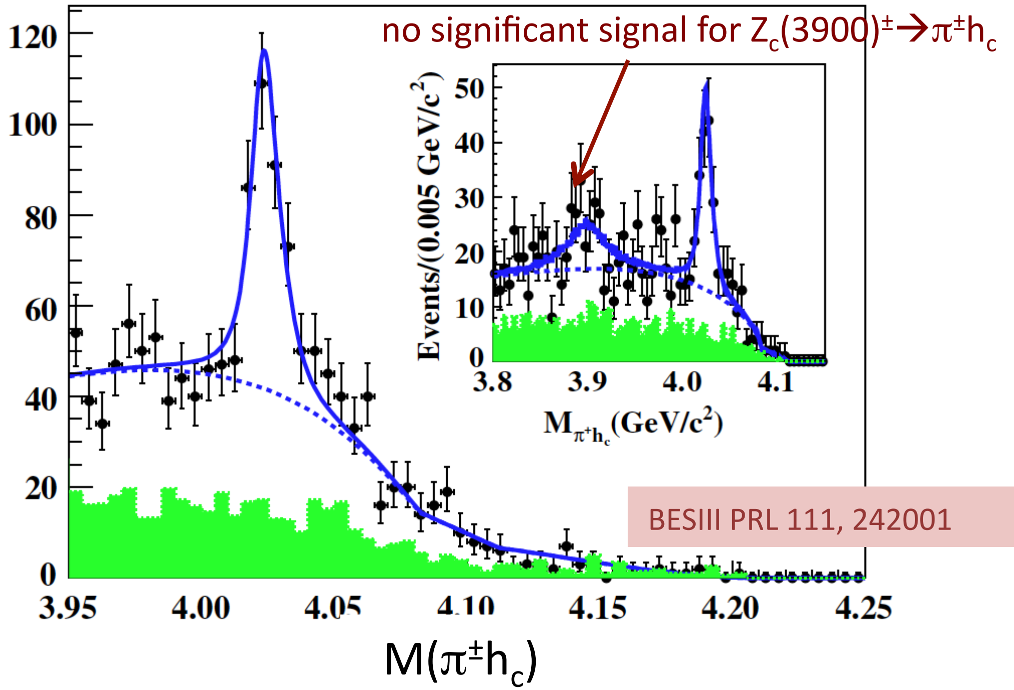
sharp $M(\pi h_c)$ peak but not near ~3900 MeV



BESIII PRL 111, 242001 (2 months ago)

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





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

= 4017.3 ±0.3 MeV

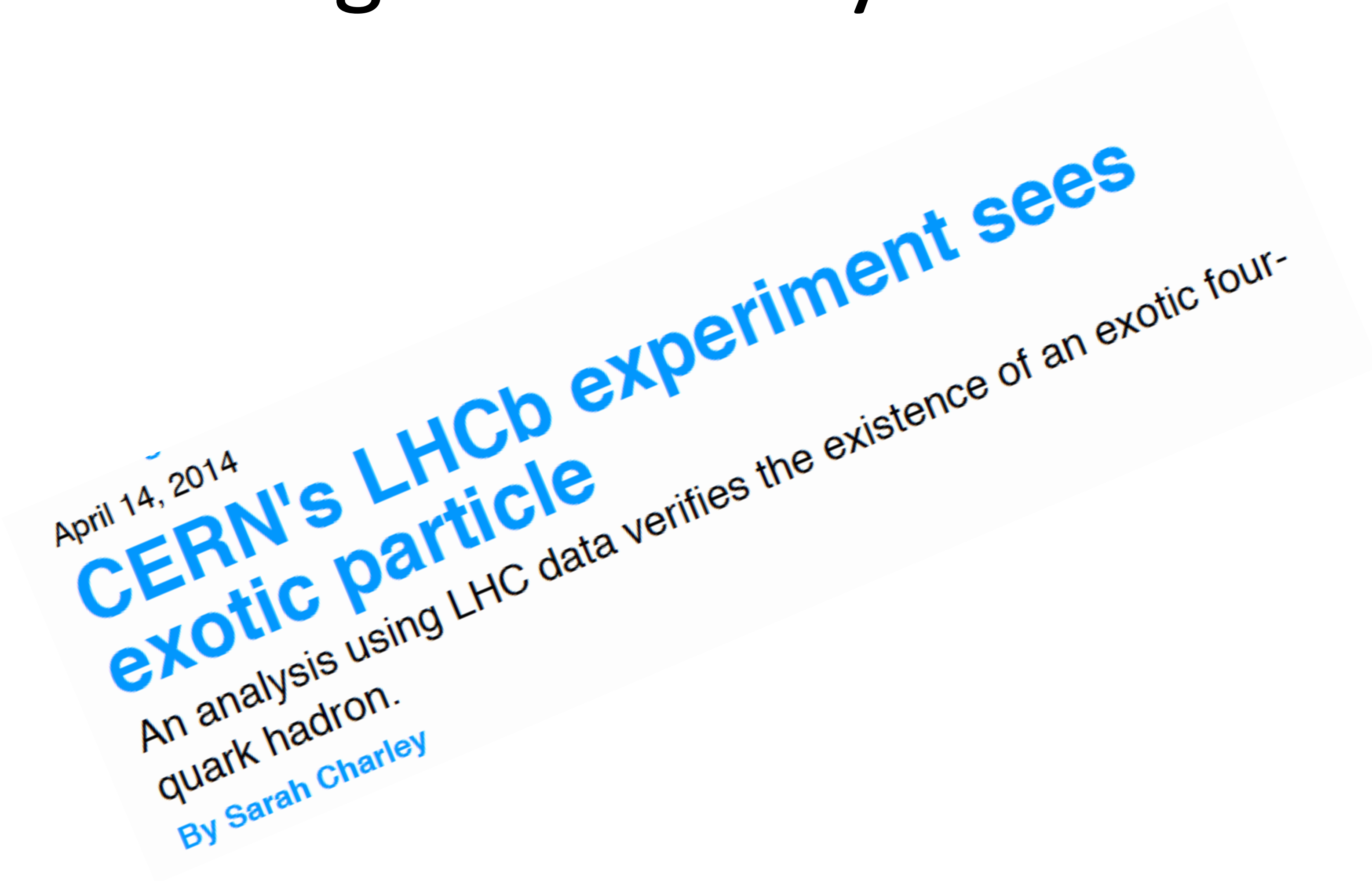
Fit results:

Mass = (4022.9 ±0.8 ±2.7) MeV

Width = (7.9 ±2.7 ±2.6) MeV

fraction = 0.18 ± 0.07

Big news this year

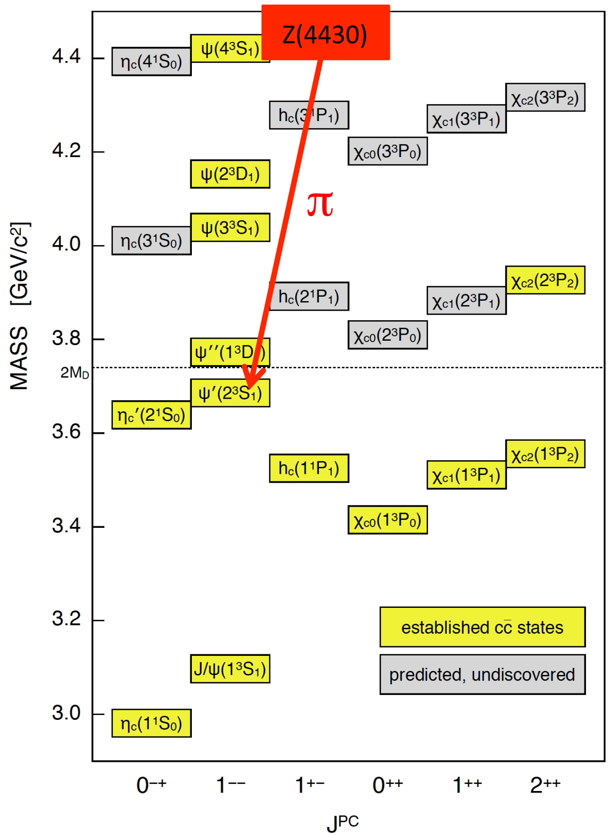

April 14, 2014

CERN's LHCb experiment sees exotic particle

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

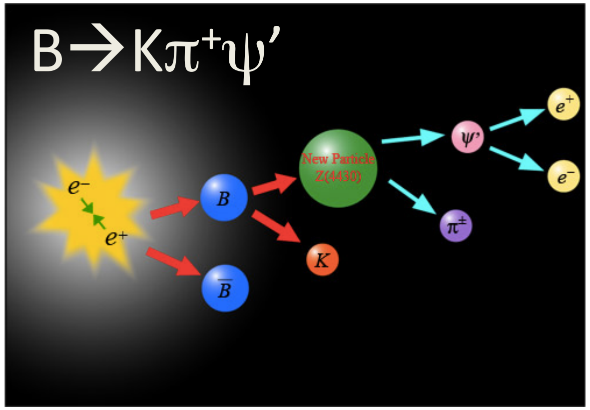
By Sarah Charley

The Z(4430)



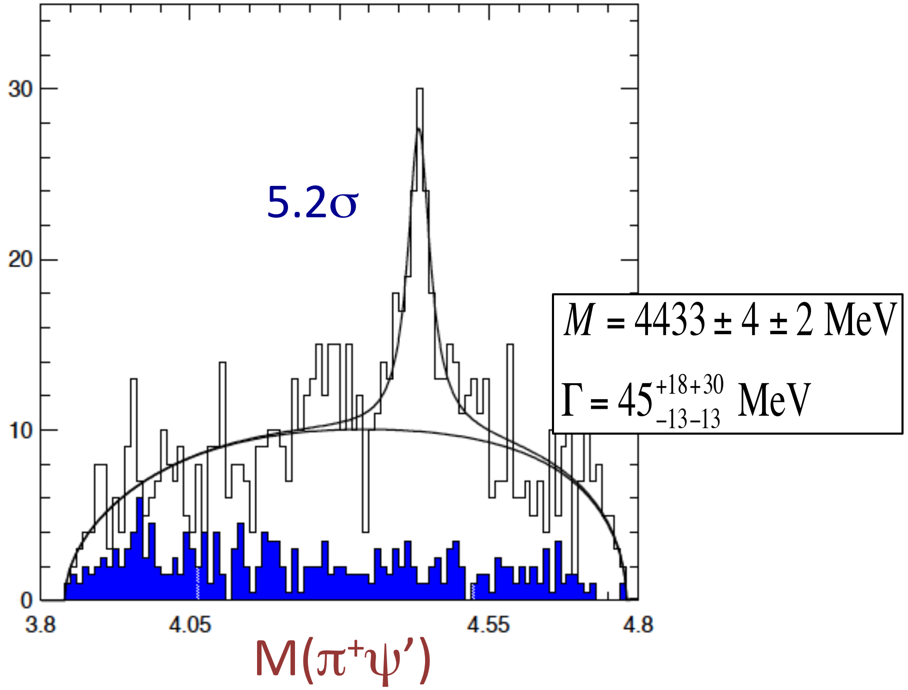
Z(4430)
π
MASS [GeV/c²]
4.4
4.2
4.0
3.8
2MD
3.6
3.4
3.2
3.0
ηc(4¹S₀)
ψ(4³S₁)
hc(3¹P₁)
χc2(3³P₂)
χc1(3³P₁)
χc0(3³P₀)
ψ(2³D₁)
ηc(3¹S₀)
ψ(3³S₁)
hc(2¹P₁)
χc2(2³P₂)
χc1(2³P₁)
χc0(2³P₀)
ψ''(1³D₁)
ψ'(2³S₁)
ηc'(2¹S₀)
hc(1¹P₁)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
established cc̄ states
predicted, undiscovered
J/ψ(1³S₁)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

Found by Belle in 2007

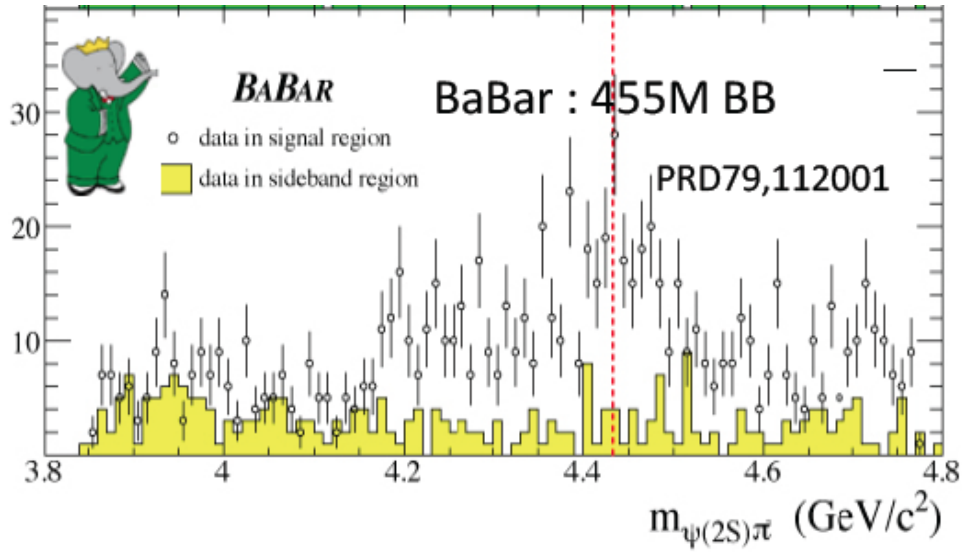


S-K Choi et al Belle: PRL 100 142001

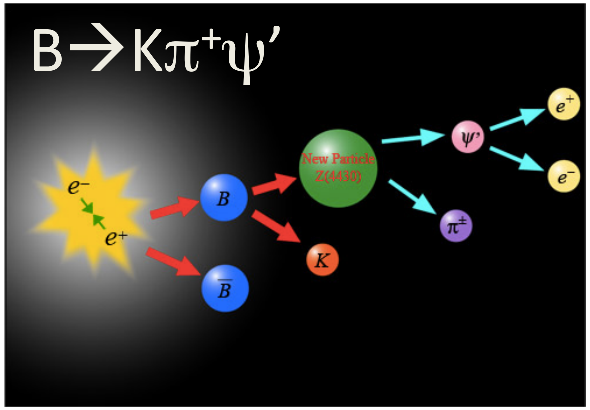
2007 slice & dice analysis



not confirmed by BaBar (only a 1.9σ "hint")

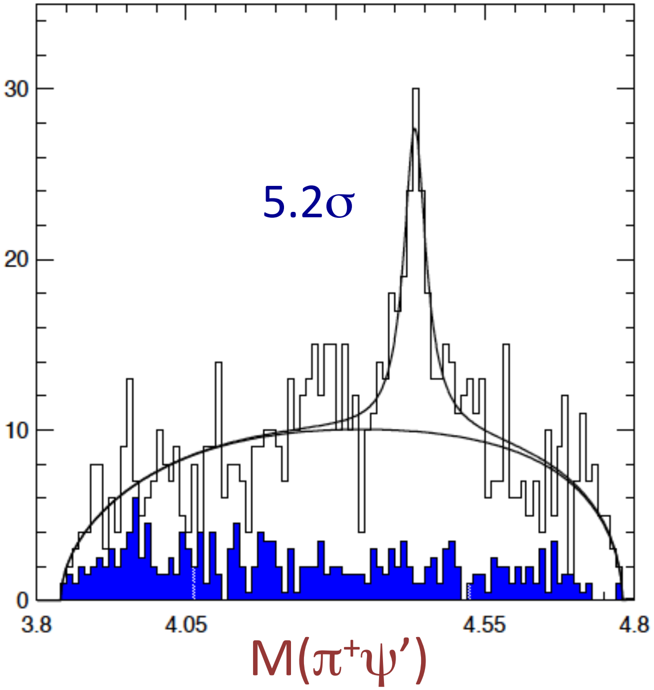


Belle 4-dim. amplitude analysis



S-K Choi et al Belle: PRL 100 142001

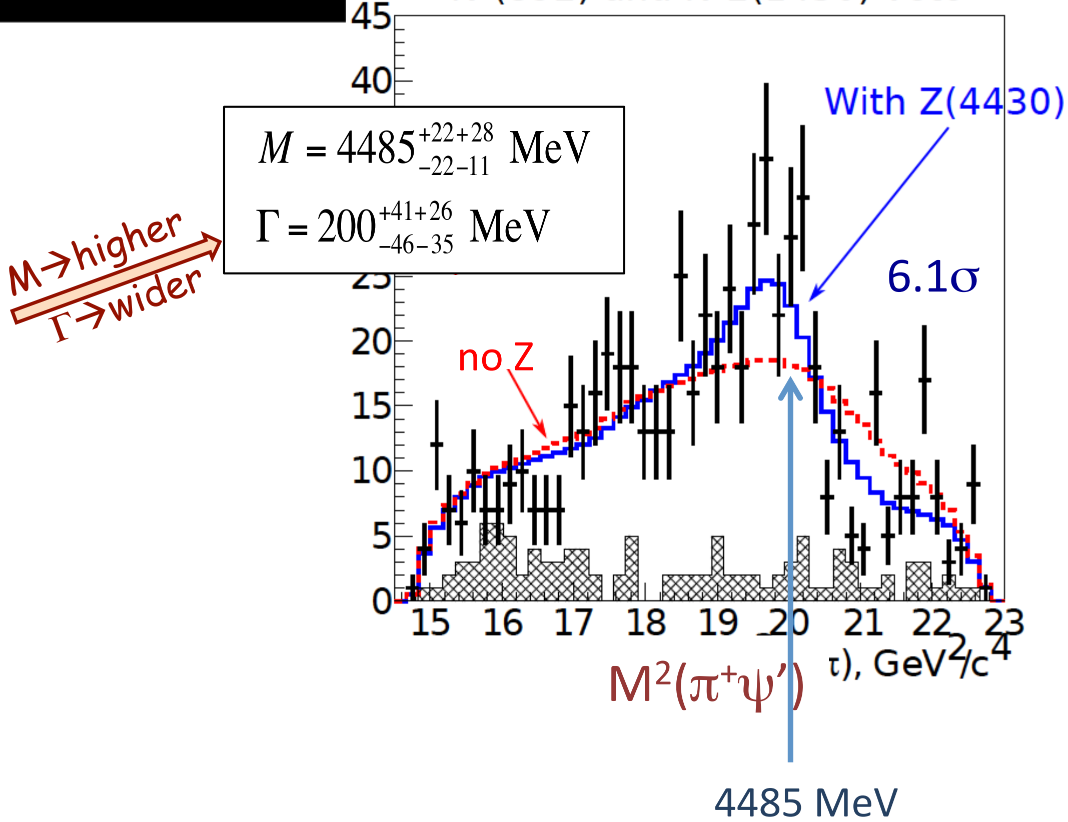
2007 slice & dice analysis



K Chilikin et al Belle: PRD 88 074026

2013: 4-dim amplitude analysis

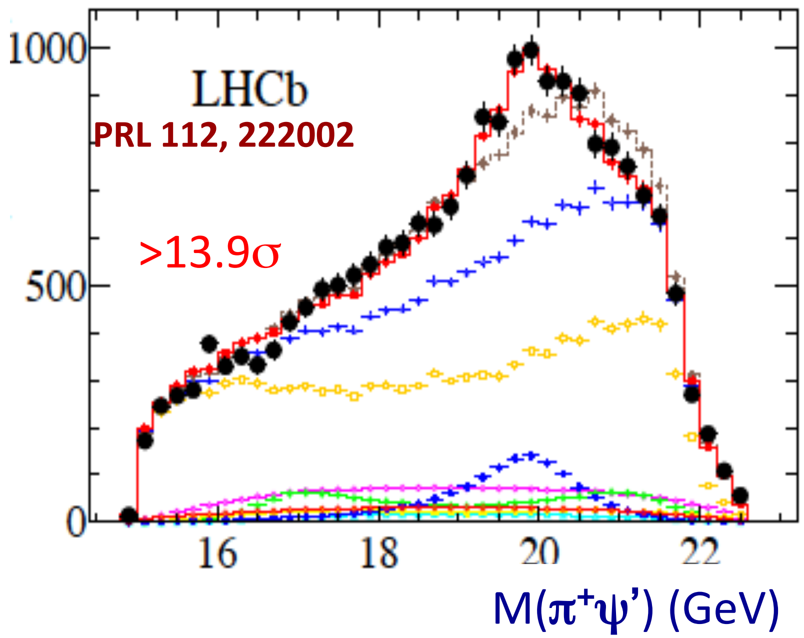
K*(892) and K*2(1430) veto



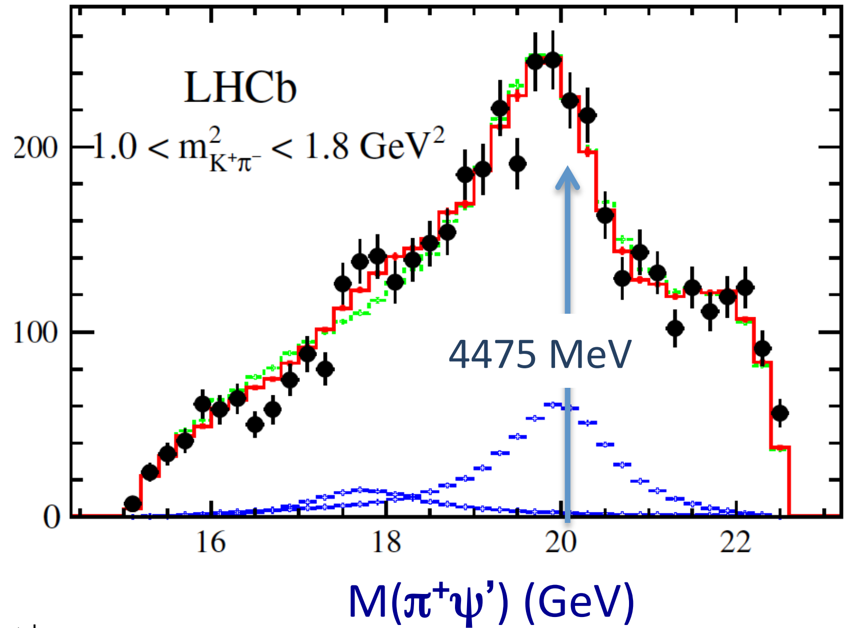
Confirmed by LHCb last spring

B→Kπ⁺ψ′: 4-dim amplitude analysis

All Kπ masses



non K*



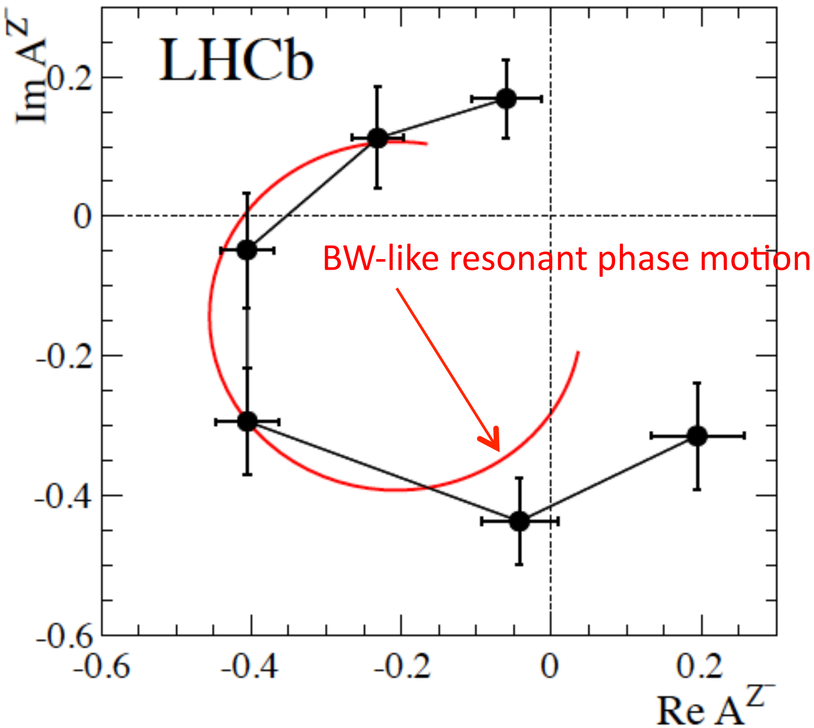
$$J^P = 1^+$$

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

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

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"

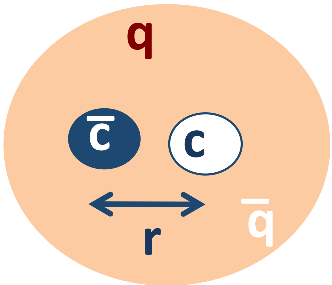
still some skeptics, see: Pakhlov & Uglov, arXiv:1408.5295

Curious feature

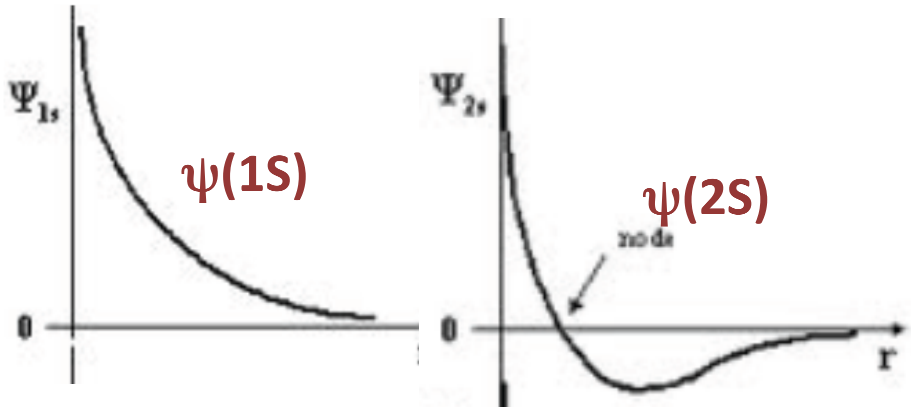
$$\frac{Bf\,(Z^-_{4430} \rightarrow \pi^- \psi')}{Bf\,(Z^-_{4430} \rightarrow \pi^- J/\psi)} \approx 10$$

decays to ψ' favored
over those to J/ψ

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



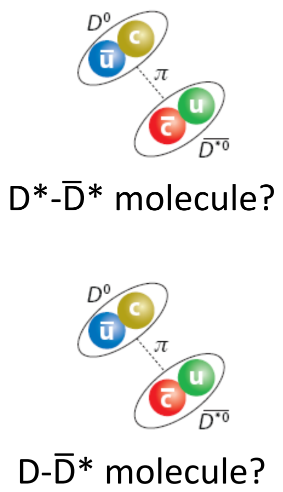
Radial Wave Functions

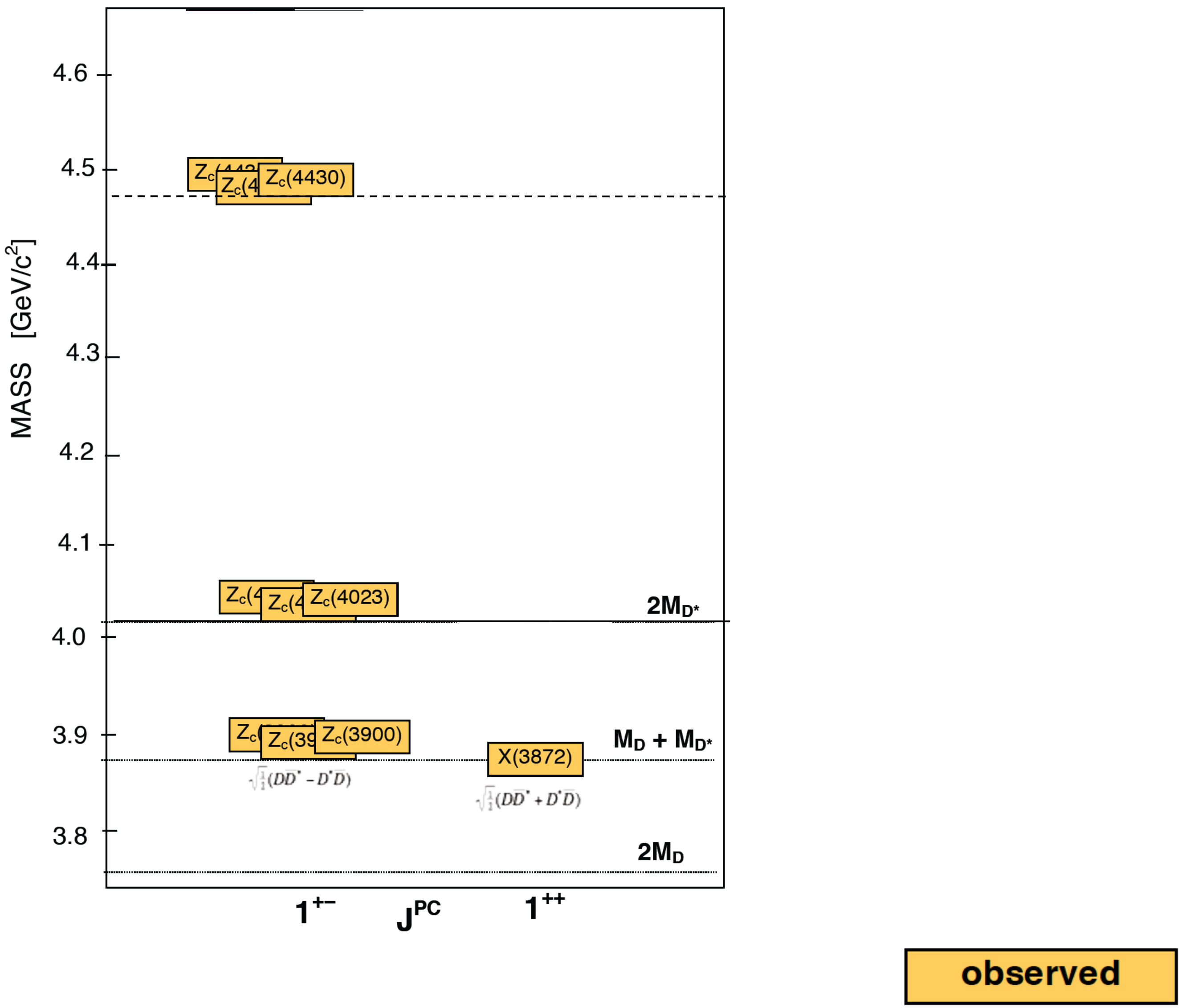


The $c\bar{c}$ part of the wave function of the Z(4430) likely has a node
➔ a radial excitation of the ground state: the $Z_c(3900)$?

$$M(Z_c(4430)) - M(Z_c(3900)) = 589 \pm 30 \text{ MeV}$$
$$M(\psi') - M(J/\psi) = 589 \text{ MeV}$$

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





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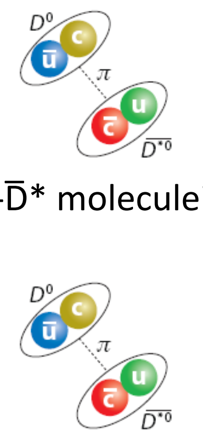
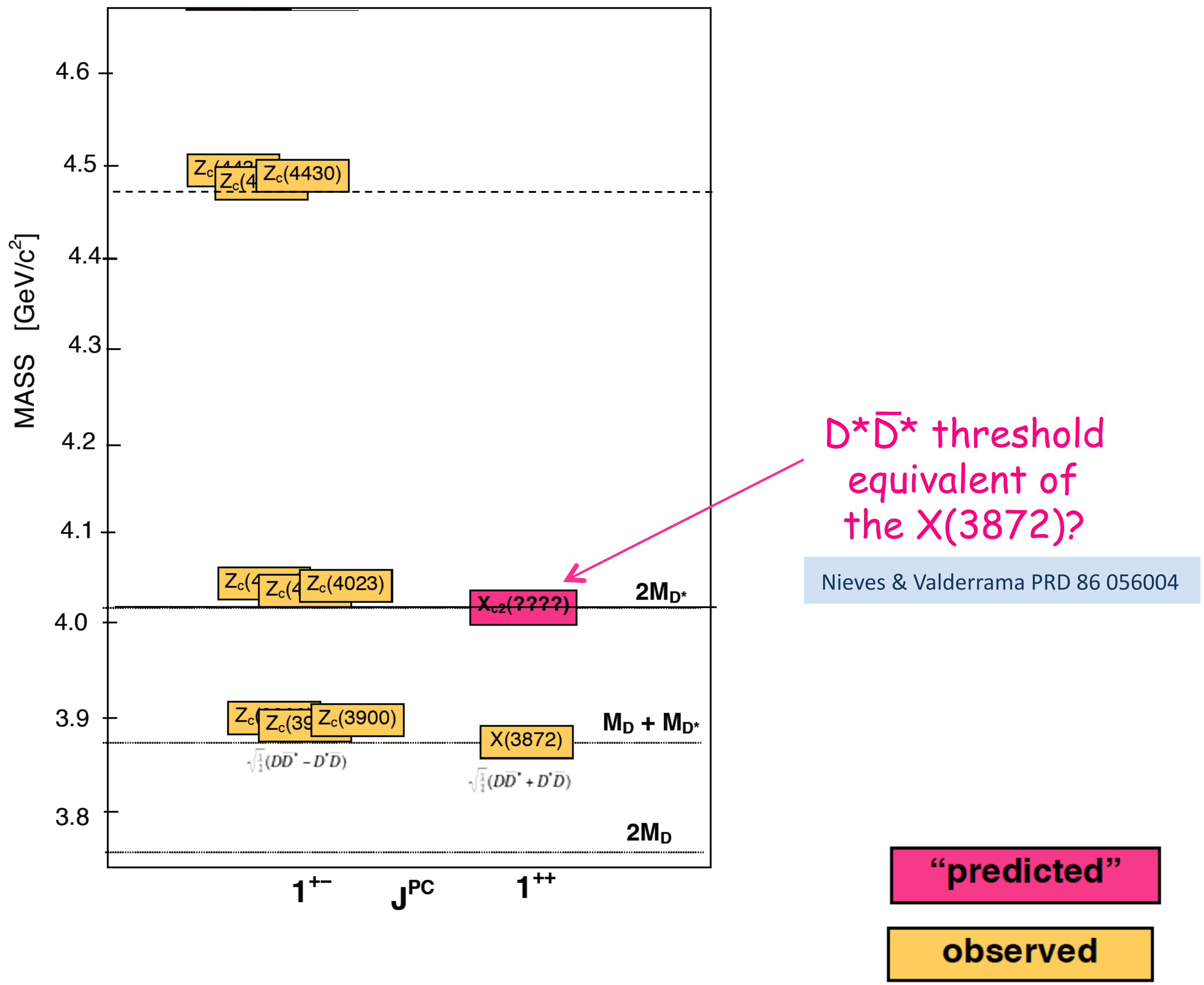
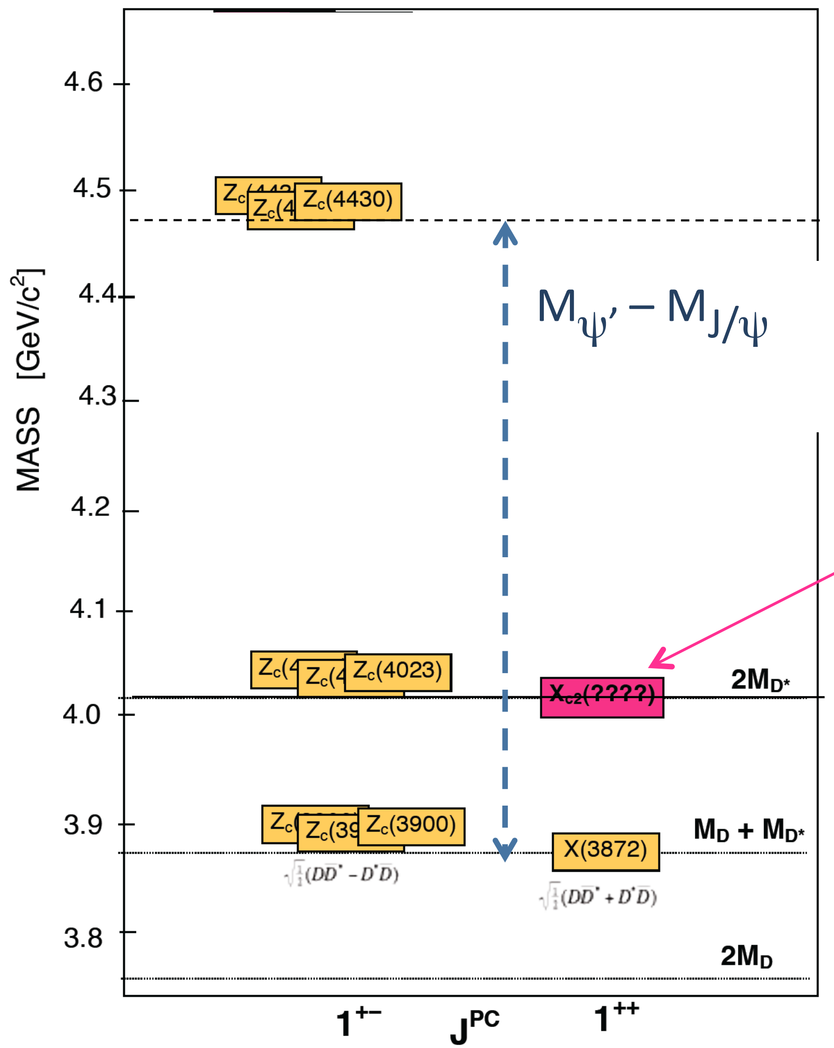
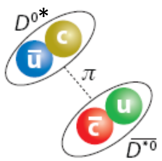


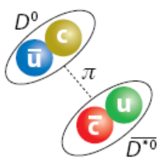


The $J^P=1^+$ charmoniumlike states





D*-D̄* molecule?



D-D̄* molecule?

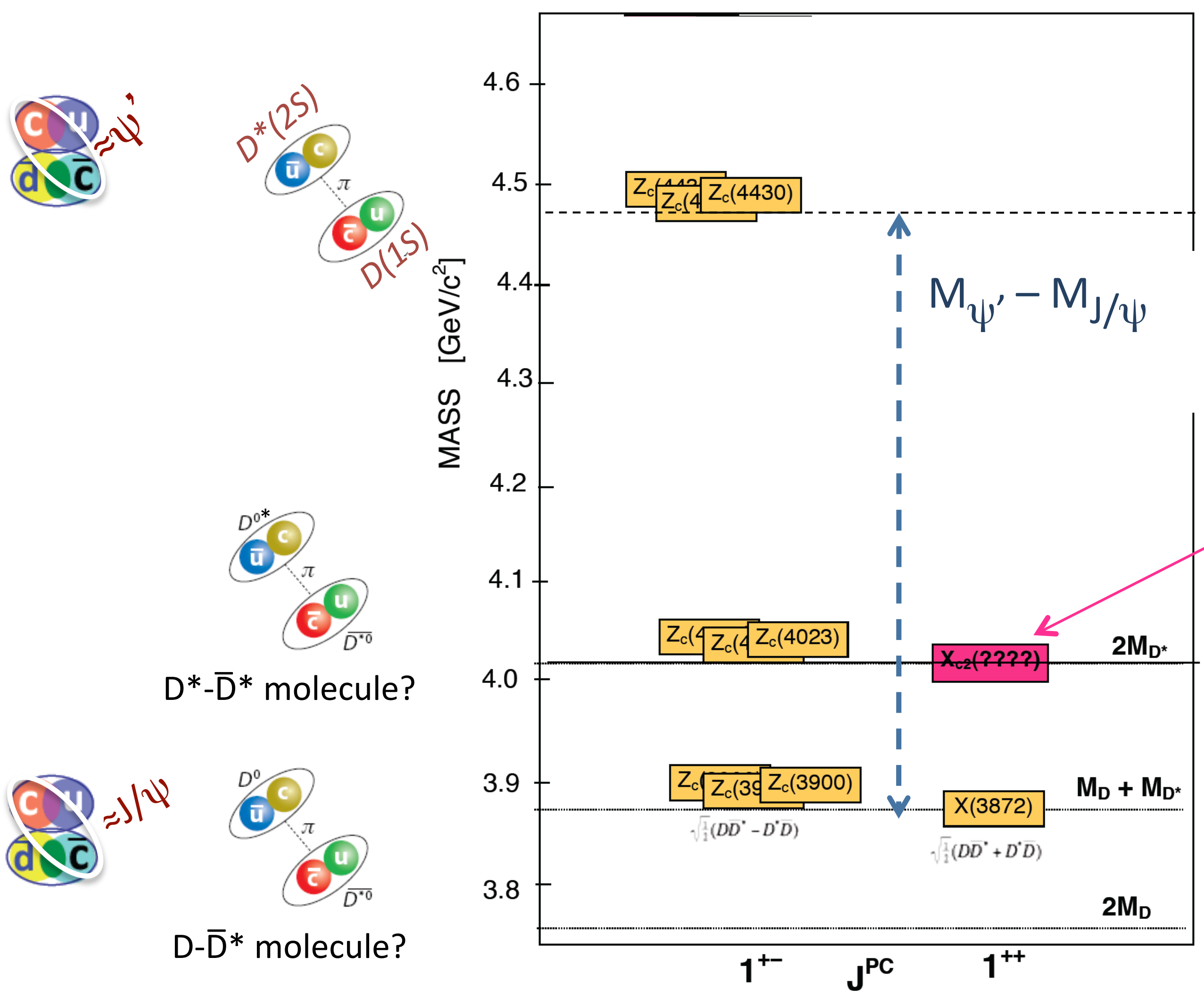
D*D̄* threshold equivalent of the X(3872)?

Nieves & Valderrama PRD 86 056004

"predicted"

observed

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



BaBar PRD 83, 032004 (2011)

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

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

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

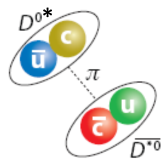
BaBar PRD 83, 032004 (2011)

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

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

Now we have this!!
no nearby relevant threshold

Belle arXiv:1408.6457



D*-D̄* molecule?

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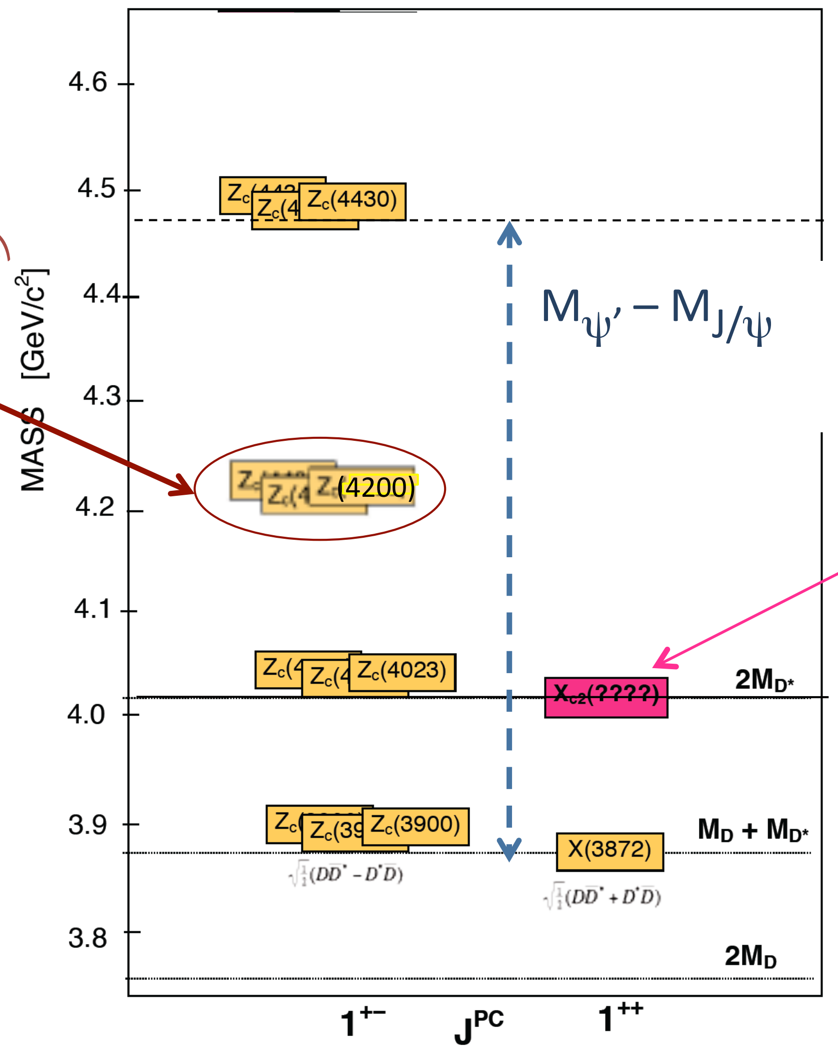

D*D̄* threshold
equivalent of
the X(3872)?

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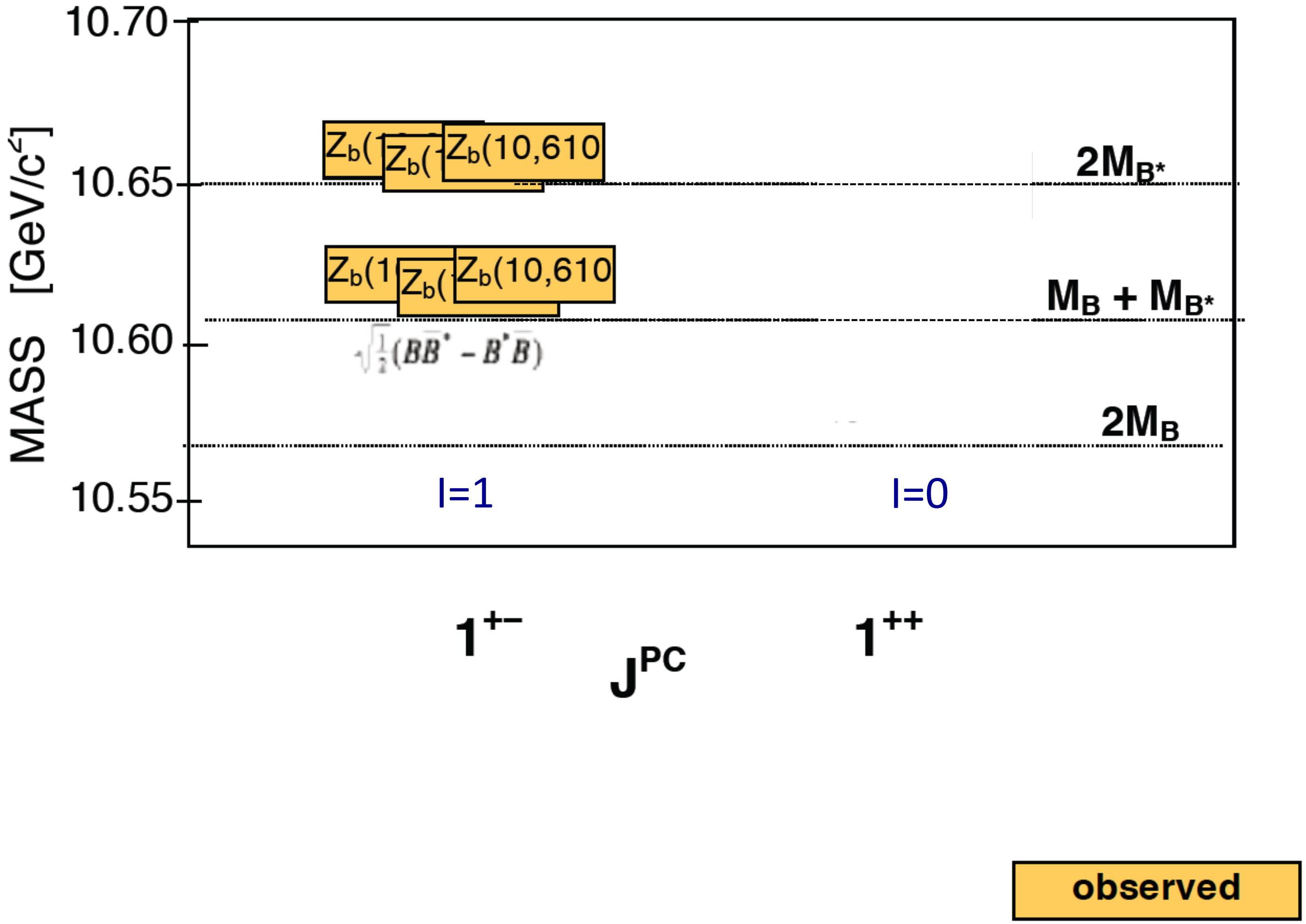
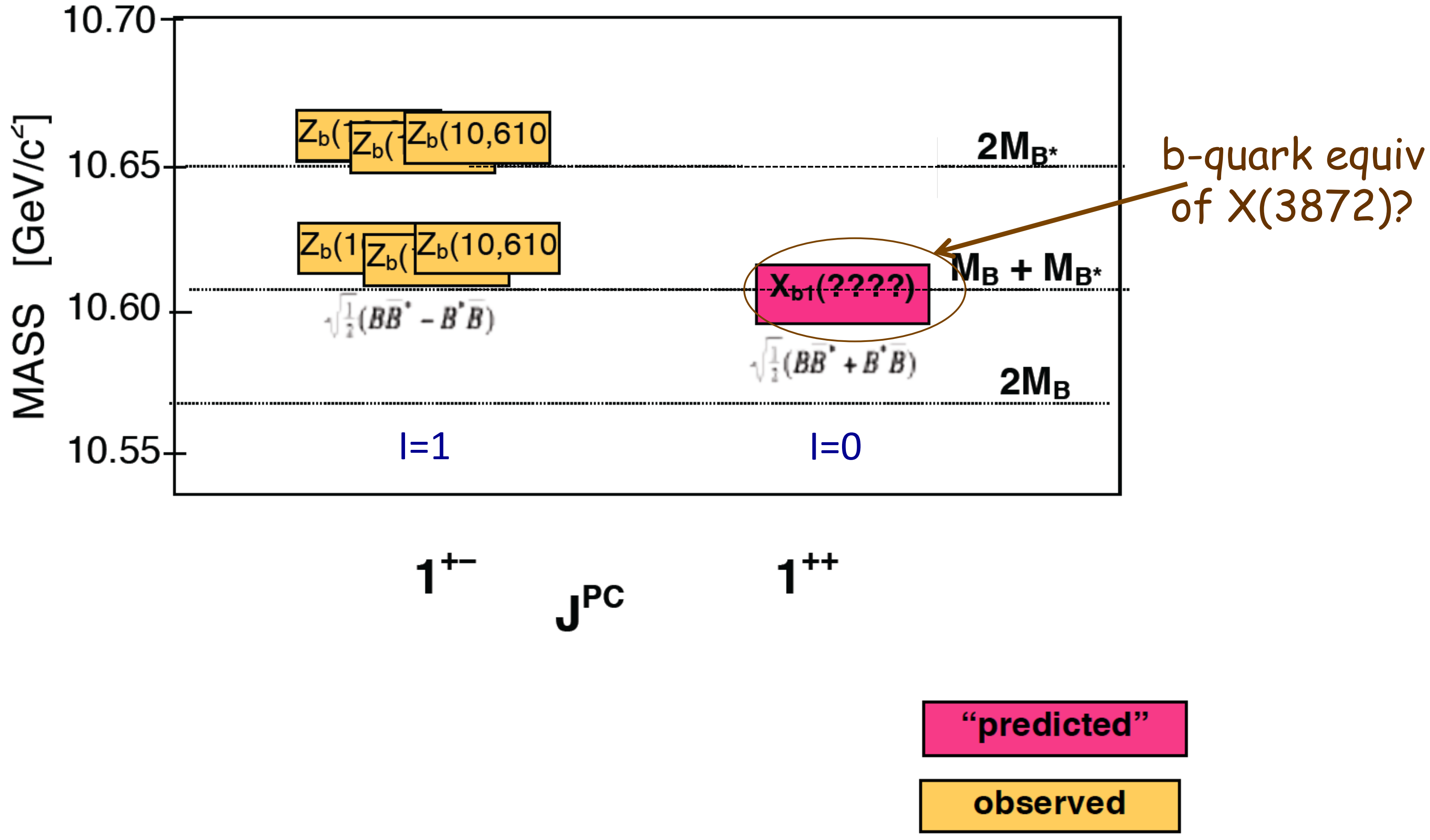
"predicted"

observed

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

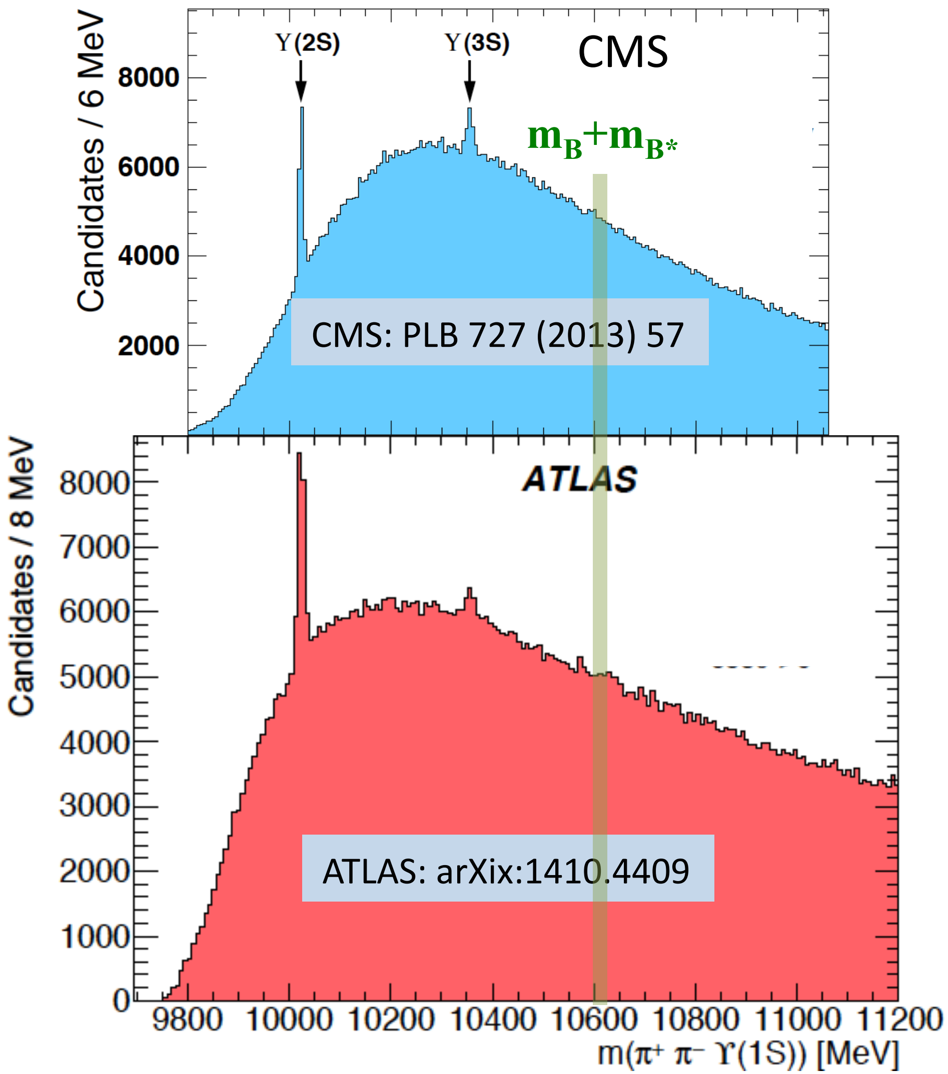


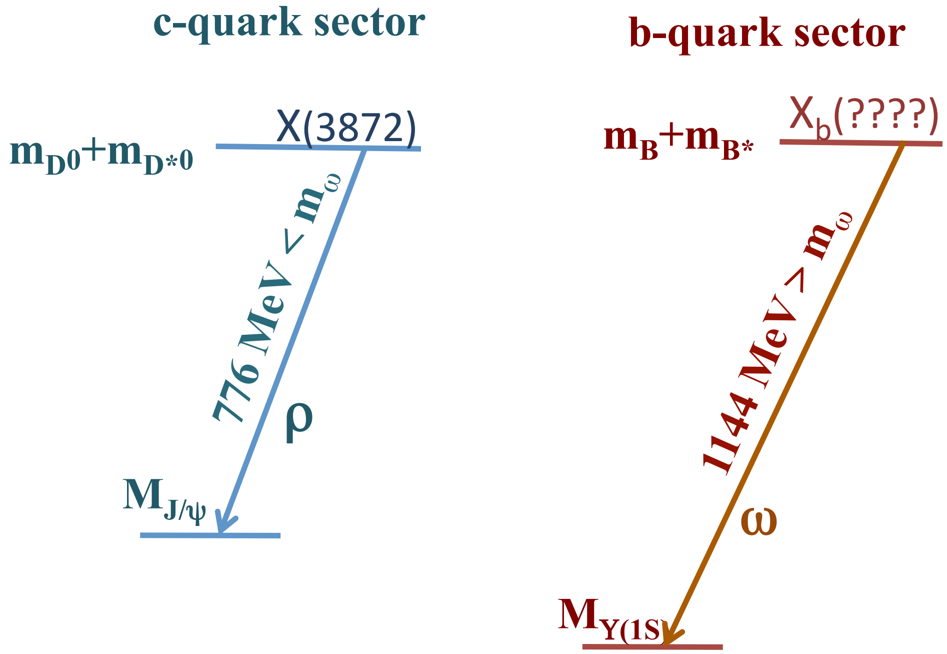
The $J^P=1^+$ bottomonium states?



LHC searches for b-sector version of X(3872)

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





ρ: isospin-violating

ω: isospin-allowed

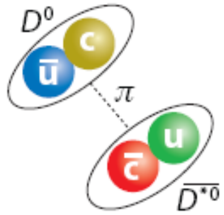
relevant X_b transition:

isospin-allowed $X_b \to \omega\Upsilon(1S)$

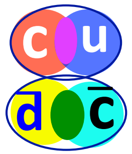
can ATLAS, CMS &/or LHCb do this?

Proposed structures for the new mesons

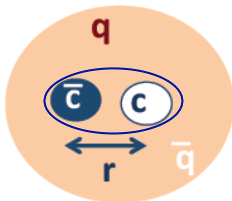
Molecules



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

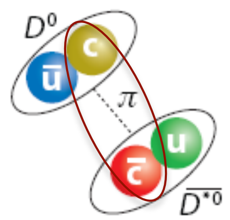
problems: -- some states are not close to thresholds

-- 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



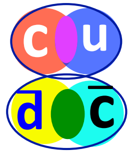
the c and $\bar{c}$ quarks:
--don't have much overlap
--colors are uncorrelated

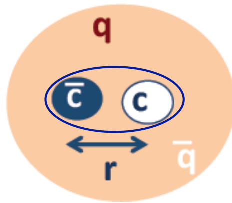
-- X(3872) production in high energy pp collisions similar to that for ψ'

QCD tetraquarks? … hadrocharmonium?

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

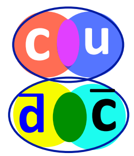
prediction	experiment
-- X(3872) is 1 of a doublet	only 1 X(3872)
-- $Z_c(3900)$ partner at M≈3800 MeV	$M_{Zc(4020)}$= 4023 MeV
-- $\frac{\Gamma(Z_c \to \pi J/\psi)}{\Gamma(Z_c \to D\bar{D}^*)} \approx 7$	$\frac{\Gamma(Z_c \to \pi J/\psi)}{\Gamma(Z_c \to D\bar{D}^*)} = 0.16 \pm 0.07$

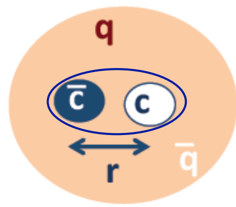
QCD tetraquarks? … hadrocharmonium?

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 ol

-- many detailed predictions

problems:

-- many of the detailed ong

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

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

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.* $\Gamma(Z(4430)^- \to \pi^-\psi') > 7.5$ MeV, $\Gamma(Z(3900)^- \to \pi^- J/\psi) \approx 2$ MeV
- $Z(4430)^- \to \pi^- J/\psi$ seen: $Bf(Z(4430)^- \to \pi^- J/\psi) << Bf(Z(4430)^- \to \pi^-\psi')$
- 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

◆ All the labs are involved: JLAB, JPARC, BESIII, BaBar, Belle, CDF, D0, LHCb, CMS, ATLAS,…

Thank You

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감사합니다