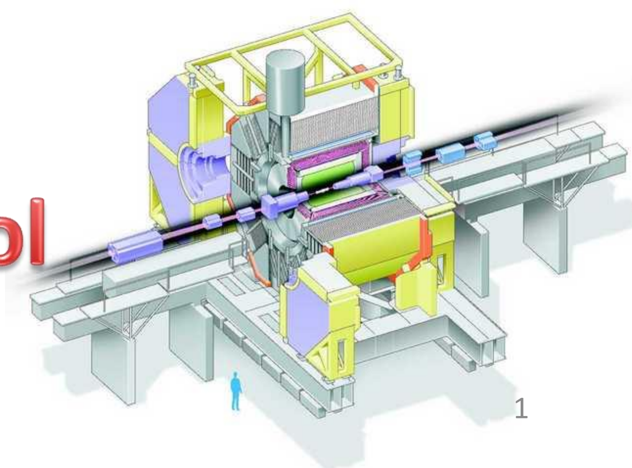
eXoTi$c\bar{c}$ states

Vishal Bhardwaj

IISER Mohali

Post CKM school

Mumbai, Dec. 2016



eXoTi$c\bar{c}$ states

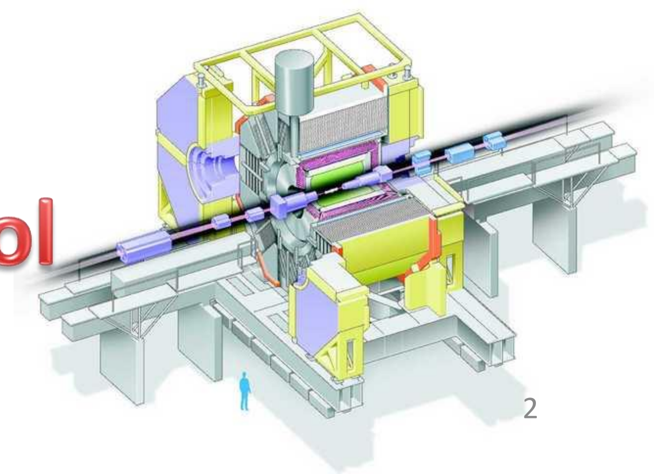
The "*chosen*" ones

Vishal Bhardwaj

IISER Mohali

Post CKM school

Mumbai, Dec. 2016



Outline

- Quark Model
- Charmonium
- X(3872) – Most studied and not well understood
- Z_c → “I got a charge in me”
- Summary

Hadrons in 1963

REVIEWS OF MODERN PHYSICS VOLUME 35, NUMBER 2 APRIL 1963

Tables of Elementary Particles and Resonant States

Matts Roos
Nordisk Institut for Teoretisk Atomfysik, Copenhagen, Denmark

Stable hadrons

Table I. Elementary Particles, March 1963.

Class	Symbol Charge	Antiparticle found	Isospin T	T_3	Spin Parity	Strangeness	Mass (MeV)	(m_{π^+})	Magnetic moment ($e/2m_p$)	Mean life (sec)	($1/m_{\pi^+}$)	Common decay modes
Hyperons	Ξ^-	$\bar\Xi^+$	½	−½	½	−2	1320.8 ± 0.4	9.46		$1.4(+0.6/-0.2)\times10^{-10}$	3×10^{13}	$\Lambda\pi^-$
	Ξ^0			+½		−2	1316	9.43		$3.9(+1.4/-0.9)\times10^{-10}$	8×10^{13}	$\Lambda\pi^0$
	Σ^-	$\bar\Sigma^+$	1	−1	½+	−1	1195.96 ± 0.30	8.57		$(1.59\pm0.05)\times10^{-10}$	3.4×10^{13}	$n\pi^-$
	Σ^0	$\bar\Sigma^0$		0	½+	−1	1191.5 ± 0.5	8.54		$10^{-11}>\tau>10^{-22}$	$10^{12}>\tau>10$	$\Lambda\gamma$
	Σ^+			1	½+	−1	1180.40 ± 0.20	8.52		$(0.78\pm0.03)\times10^{-10}$	1.65×10^{13}	$p\pi^0$, $n\pi^+$
		$\bar\Sigma^-$		−1		1						
	Λ^0		0	0	½+	−1	1115.38 ± 0.10	7.991	−1.5 ± 0.5	$(2.57\pm0.30)\times10^{-10}$	5.4×10^{13}	$p\pi^-$, $n\pi^0$
		$\bar\Lambda^0$		0		1	1115.44 ± 0.32	7.991		$(1.9\pm1.0)\times10^{-10}$	4×10^{13}	
Nucleons	n^0	$\bar n$	½	−½	½+	0	939.507 ± 0.01	6.731	−1.9128	1013 ± 26	2.15×10^{26}	$pe^-\bar\nu_e$
	p^+			½	½+	0	938.213 ± 0.01	6.722	2.792816 ± 0.000034	∞	∞	
		$\bar p$		−½		0			−1.8 ± 1.2			
Mesons	K^+		½	½	0−	1	493.98 ± 0.14	3.539	0	$(1.227\pm0.008)\times10^{-8}$	2.60×10^{15}	$\mu^+\nu_\mu(\mu2)$, $\pi^+\pi^0(\pi2)$, $\mu^+\pi^0\nu_\mu(\mu3)$, $e^+\pi^0\nu_e(e3)$, $\pi^+\pi^+\pi^-(\tau^+)$, $\pi^+\pi^0\pi^0(\tau'^+)$
	K^0	K^-, $\bar K^0$		−½	0−	−1, 1, −1	497.9 ± 0.6	3.57	<0.04 he/m_K	K_1^0 $(0.90\pm0.02)\times10^{-10}$; K_2^0 $6.3(+1.6/-1.0)\times10^{-8}$	1.9×10^{13}; 1.3×10^{16}	$\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^+\pi^-\pi^0$, $3\pi^0$, $\pi^\pm e^\mp\nu_e$, $\pi^\pm\mu^\mp\nu_\mu$
	π^+	π^-	1	1, −1	0−	0	139.58 ± 0.05	1	0	$(2.547\pm0.027)\times10^{-8}$	5.48×10^{15}	$\mu^+\nu_\mu$
	π^0			0	0−	0	134.97 ± 0.05	0.967	0	$(1.05\pm0.18)\times10^{-16}$	2.23×10^{7}	2γ, γe^+e^-
Leptons	μ^-	μ^+			½		105.65	206.765 ± 0.002 m_e	(1.001162 ± 0.000005) $e/2m_\mu$	$(2.210\pm0.002)\times10^{-6}$	4.69×10^{17}	$e^-\bar\nu_e\nu_\mu$
	e^-	e^+			½		0.510976 ± 0.000007	$1m_e$	(1.0011609 ± 0.0000024) $e/2m_e$	∞	∞	
	ν_μ	$\bar\nu_\mu$			±½		< 2.5	< $5m_e$				
	ν_e	$\bar\nu_e$			±½		< 0.000025	< $5\times10^{-4}m_e$				
Photon	γ				1	0	0	0				

Meson resonances

Table IIb. Mesonic Resonant States, March 1963.

Symbol	Charge	Isospin	Spin	Parity G-parity	S	Mass (MeV)	(m_{π^+})	Full width Γ (MeV)	Life-time Γ^{-1} ($1/m_{\pi^+}$)	Production Process	k_{lab} (MeV)	Modes
K^*	−	> ½			1	1630 ± 100	11.7			π^-p	3534	$(K^*\pi\pi)^-$, $(K^*\rho)^-$, $(K\pi\rho)^-$, others
K^*	+				1							same, charge +
χ_0	0				0	1340 ± 70	9.6			π^-p	2287	$(\rho\pi\pi)^0$ others
κ_1	0				0	1275 ± 25	9.1			π^-p	2125	$K^0\bar K^0$, K^+K^-
K^{**}					1	1260	9.0			π^-N		$K(\pi\pi)$
f	0	0	2	++	0	1253 ± 20	9.0	100 ± 50	1.4	π^-p	2070	$\pi^-\pi^+$
K^*		½			1, 1	1150 ± 50	8.2			π^-p	2250	$K^0\pi^+\pi^-$, $K^+\pi^-\pi^-$
χ_1, χ_1	−, 0	1			0, 0	1050, 1040	7.5, 7.4			π^-p	1620	$\pi^-\pi^-\pi^+\pi^0$, $\pi^+\pi^-(\pi\pi)^0$
κ_0	0	0	even	++	0	1040 ± 40	7.4			K^-p	1780	K_1K_1, even number π's
κ_1	0	0	odd	−−	0	1020	7.3	< 3	> 47	K^-p	1760	K_1K_2, odd number π's
ψ	−−, 0, ++	2			0, 0, 0	990	7.2			π^-p	1490	$\pi^-\pi^-$, $\pi^-\pi^+$, $\pi^+\pi^+$
K_1^*	−	½	1	−	−1	888 ± 3	6.4	50 ± 10	2.8	K^-p	1074	$\bar K^0\pi^-$, $K^-\pi^0$
K_1^*	0				−1					K^-p	1078	$K^-\pi^+$
K_1^*	+				1					π^-p	1834	$K^0\pi^+$, $K^+\pi^0$
K_1^*	0				1					π^-p	1657	$K^+\pi^-$, $K^0\pi^0$
φ_3	0				0	885 ± 10	6.3			π^-p	1284	$\pi^+\pi^-$
ω	0	0	1	− −	0	781.1 ± 0.8	5.6	< 12	> 12	$\bar pp$		neutr., $\pi^+\pi^-\pi^0$, others
ρ	−	1	1	− +	0	757 ± 5	5.4	120 ± 10	1.2	π^-p	1029	$\pi^-\pi^0$
ρ	0				0	751 ± 6	5.4	110 ± 10	1.3	πN	1029	$\pi^+\pi^-$, neutrals
ρ_1	0				0	780	5.6	60	2.3	πN	1085	$\pi^+\pi^-$, neutrals
ρ_1	0				0	720	5.2	20	7	πN	975	$\pi^-\pi^+$, neutrals
ρ	+				0					π^+p	1066	$\pi^+\pi^0$
ψ_4	−−, 0, ++	2			0, 0, 0	760	5.4			π^-p	1310, 1055, 1590	$\pi^-\pi^-$, $\pi^-\pi^+$, $\pi^+\pi^+$
K_1^*	0	½	> 1		1	730 ± 10	5.2	≤ 20	≥ 7	π^-p	1485	$K^+\pi^-$, $K^0\pi^0$
K_1^*	+				1							$(K\pi)^+$
δ	−, 0, +	1 or 2			0, 0, 0	645 ± 25	4.5			π^-p	810	$\pi^-\pi^0$, $\pi^+\pi^-$, $\pi^+\pi^0$
α	0, +	1 or 2			0, 0	625	4.5	< 80	> 1.7	pp		$\pi^+\pi^-\pi^0$, $\pi^+\pi^+\pi^-$
ψ_2	−−, 0, ++	2	0 or 2		0, 0, 0	605 ± 25, 580	4.3, 4.2	75	1.9	π^-p	1025, 733, 1235	$\pi^-\pi^-$, $\pi^-\pi^+$, $\pi^+\pi^+$
ζ	−, +, +	1			0, 0, 0	564 ± 9, 541 ± 18	4.0, 3.9	< 43	> 3.2	π^-p, π^-p, π^+p	707, 672	$\pi^-\pi^0$, $\pi^+\pi^-$, $\pi^+\pi^0$

Table IIb. Mesonic Resonant States, March 1963. (Continued)

Symbol	Charge	Isospin	Spin	Parity G-parity	S	Mass (MeV)	(m_{π^+})	Full width Γ (MeV)	Life-time Γ^{-1} ($1/m_{\pi^+}$)	Production Process	k_{lab} (MeV)	Modes
η	0	0	0	− +	0	548.5 ± 0.6	3.93	≤ 7	> 20	πp	685	$\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$, $3\pi^0$, $\pi^0\gamma$, 2γ, others
φ_2	0	0			0	520 ± 20	3.7	70 ± 30	2.0	π^-p	639	$\pi^+\pi^-$
ψ_3	−−, 0, ++	2			0, 0, 0	440, 420–440, 440	3.1, 3.1, 3.1			π^-p	735, 515, 975	$\pi^-\pi^-$, $\pi^-\pi^+$, $\pi^+\pi^+$
φ_1	0	0			0	395 ± 10	2.8	50 ± 20	2.8	π^-p	446	$\pi^+\pi^-$
ψ_1	−−, 0, ++	2			0, 0, 0	330, 330, 330	2.4, 2.4, 2.4			π^-p	557, 346, 790	$\pi^-\pi^-$, $\pi^-\pi^+$, $\pi^+\pi^+$
ω_{ABC}	0	0			0	317 ± 6	2.3	≤ 16	≥ 9	pd		$\pi^+\pi^-$

Baryon resonances

Table IIa. Baryonic Resonant States, March 1963.

Class	Symbol	Charge	Isospin	Spin	Parity	S	Mass (MeV)	(m_{π^+})	Full width Γ (MeV)	Life-time Γ^{-1} ($1/m_{\pi^+}$)	Production Process	k_{lab} (MeV)	Modes
Hyperonic States	Y_{05}^*	0	0	3/2 or 5/2		−1	1815	13.0	120	1.16	K^-p	1050	K^-p others
	Y^{**}	0				−1	1770 ± 100	12.7			π^-p	2260	$Y_1^*\pi^-$, $\Lambda\pi^+\pi^-$
	Y^*	0				−1	1715	12.2			π^-p	2185	K^0n
	Y_0^{**}	0	0			−1	1680	12.0	< 20	> 7	K^-p	760	$\Lambda\eta$
	Y_{13}^{**}	+	1	3/2		−1	1660 ± 10	11.9	40 ± 10	3.5	K^-p	715	$\bar K^0p$, $(\Sigma\pi)^+$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Sigma^0\pi^+\pi^+$
	Y_1^*		1 or 2			−1	1550 ± 20	11.1	125	1.75	π^-p	1770	$\Sigma\pi$
	Ξ_1^*	−	½	3/2	+	−2	1533 ± 3	10.98	≤ 7	≥ 20	K^-p	1512	$\Xi^-\pi^0$, $\Xi^0\pi^-$
	Ξ_1^*	0				−2						1521	$\Xi^-\pi^+$
	Y_{03}^*	0	0	3/2	−	−1	1520 ± 3	10.89	16	8.7	K^-p	395	$(\bar KN)^0$, $(\Sigma\pi)^0$, $\Lambda\pi^+\pi^-$
	Y_0^*	0	0			−1	1404.7 ± 0.4	10.1	< 1.4	> 100	K^-p	445	$(\Sigma\pi)^0$, $\Lambda\pi\pi$
	Y_{11}^*	−	1	½ or 3/2	+	−1	1385 ± 5	9.92	50 ± 10	2.8	K^-p	408	$(\Sigma\pi)^-$, $\Lambda\pi^-$
	Y_{11}^*	0				−1						395	$(\Sigma\pi)^0$, $\Lambda\pi^0$
	Y_{11}^*	+				−1						408	$(\Sigma\pi)^+$, $\Lambda\pi^+$
Nucleonic States	N_3^*		3/2			0	2360 ± 25	16.9	200 ± 25	0.7	π^+p	2510	πN others
	N_1^*		½			0	2190 ± 25	15.7	200 ± 20	0.7	π^-p	2080	πN others
	Z_1^*	0	½	> ½		0	1920 ± 20	13.8	15	9	$\pi^-(A)$		$K^0\Lambda$, $(K\Sigma)^0$
	N_{37}^*		3/2	7/2		0	1900	13.6	200	0.7	$\pi^-(A)$	1440	πN, $K\Sigma$
	N_{11}^*		½	½	+	0	1690	12.1			π^-p	1030	πN
	N_{15}^*		½	5/2	+	0	1683 ± 5	12.06	80	1.7	π^-p	1020	πN, $K\Lambda$, others
	Z_1^*	0	½	> ½		0	1650 ± 20	11.8	< 7	> 20	$\pi^-(A)$		$K^0\Lambda$
	N_{13}^*		½	3/2	−	0	1517 ± 3	10.87	60	2.3	π^-p	731	πN others
	N_{33}^*	−, 0, +, ++	3/2	3/2	+	0, 0, 0, 0	1237	8.86	90 ± 20	1.6	πN	303	π^-n, π^-p, π^0n, π^0p, π^+n, π^+p

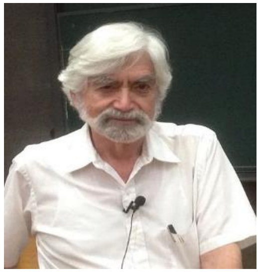
Two "flavors" of hadrons

"non-strange" : n, p, π, ρ,…
"strange": Λ, Σ, K, K*,…

Quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

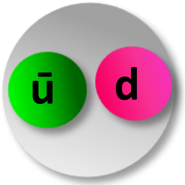
M. GELL-MANN
California Institute of Technology, Pasadena, California



1964 M. Gell-Mann, Phys.Lett. 8, 214 (1964) Received 4 January 1964 CERN preprint 8182/TH.401, Jan. 17, 1964

Independently Gell-Mann (and Zweig) develop quark model to explain the particles with three fundamental building blocks named quarks (and aces) up (u), down (d) and strange (s)

Mesons : bound state of 2 quarks

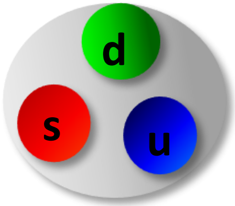


$\pi^+ = u\bar{d}$, $\pi^0 = 1/\surd 2(u\bar{u} - d\bar{d})$ and $\pi^- = d\bar{u}$

$K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\bar{K}_0 = s\bar{d}$ and $K^+ = s\bar{u}$

Baryons : bound state of 3 quarks

p=uud, n=udd and Λ=uds



$\bar{p} = \bar{u}\bar{u}\bar{d}$, $\bar{n} = \bar{u}\bar{d}\bar{d}$ and $\bar{\Lambda} = \bar{u}\bar{d}\bar{s}$

$\Delta(1232)^{++}$ made of 3 s quarks, color of quark comes to rescue from Pauli's principle.

The first paper discussing the idea of quark, also mention the idea of constituent particle having more than 3 quarks.

A SCHEMATIC MODEL OF BARYONS AND MESONS *

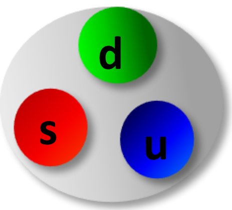
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

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**.

Still we have not seen particle with more than three quarks making matter ?

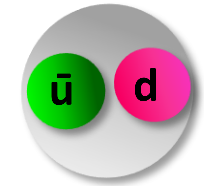
QCD : real particles are color singlet



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

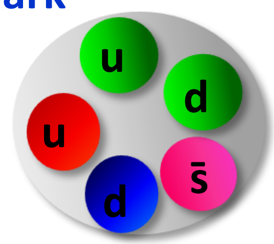


π=ūd

Other possible combinations of quarks and gluons :

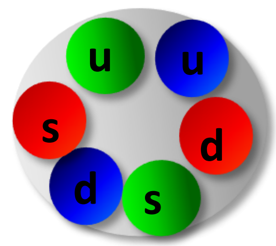
Pentaquark

S= +1 Baryon



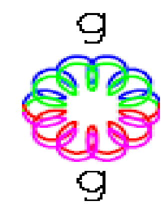
H di-Baryon

Tightly bound 6 quark state



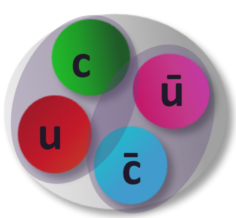
Glueball

Color-singlet multi-gluon bound state



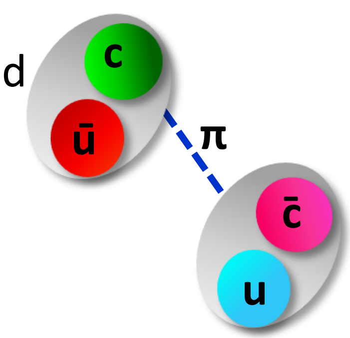
Tetraquark

Tightly bound diquark & anti-diquark

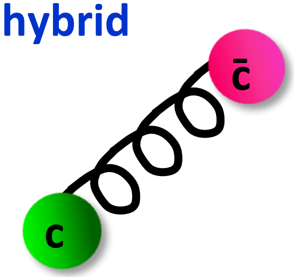


Molecule

loosely bound meson-antimeson "molecule"



qq̄ -gluon hybrid mesons



artistic illustration

$X(3872)$	3871.68 ± 0.17	<1.2	1^{++}	$B\to K+(J/\psi\pi^+\pi^-)$	[32, 33, 34, 35]
				$p\bar{p}\to(J/\psi\pi^+\pi^-)+\ldots$	[36, 37, 38, 39, 40]
				$B\to K+(J/\psi\pi^+\pi^-\pi^0)$	[41, 42]
				$B\to K+(D^0D^0\pi^0)$	[43, 44]
				$B\to K+(J/\psi\gamma)$	[45, 46, 47]
				$B\to K+(\psi'\gamma)$	[45, 46, 47]
				$pp\to(J/\psi\pi^+\pi^-)+\ldots$	[48, 49]
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B\to K+(J/\psi\omega)$	[50, 42]
				$e^+e^-\to e^+e^-+(J/\psi\omega)$	[51, 52]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^-\to J/\psi+(D^*D)$	[53]
				$e^+e^-\to J/\psi+(\ldots)$	[54]
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^-\to\gamma+(D\bar{D})$	[55, 56]
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^-\to\gamma+(J/\psi\pi^+\pi^-)$	[57]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B\to K+(J/\psi\phi)$	[58, 59, 60]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^-\to J/\psi+(D^*D)$	[53]
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^-\to\gamma+(J/\psi\pi^+\pi^-)$	[61, 62, 63, 57]
				$e^+e^-\to(J/\psi\pi^+\pi^-)$	[64]
				$e^+e^-\to(J/\psi\pi^0\pi^0)$	[64]
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^-\to\gamma+(\psi'\pi^+\pi^-)$	[65, 66]
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$	[67]
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma+(\psi'\pi^+\pi^-)$	[66]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260)\to\pi^-+(J/\psi\pi^+)$	[68, 69]
				$Y(4260)\to\pi^-+(D\bar{D}^*)^+$	[70]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260)\to\pi^-+(h_c\pi^+)$	[71]
				$Y(4260)\to\pi^-+(D^*\bar{D}^*)^+$	[72]
$Z_c^0(4020)$	4024 ± 4	10 ± 3	$1(?)^{+(?)-}$	$Y(4260)\to\pi^0+(h_c\pi^0)$	[73]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B\to K+(\chi_{c1}\pi^+)$	[74, 75]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B\to K+(J/\psi\pi^+)$	[76]
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B\to K+(\chi_{c1}\pi^+)$	[74, 75]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B\to K+(\psi'\pi^+)$	[77, 78, 79, 80]
				$B\to K+(J\psi\pi^+)$	[76]
$Y_b(10890)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^-\to(\Upsilon(nS)\pi^+\pi^-)$	[81]
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S)\to\pi^-+(\Upsilon(1,2,3S)\pi^+)$	[82, 83]
				$\Upsilon(5S)\to\pi^-+(h_b(1,2P)\pi^+)$	[82]
				$\Upsilon(5S)\to\pi^-+(B\bar{B}^*)^+$	[84]
$Z_b^0(10610)$	10609 ± 6		1^{+-}	$\Upsilon(5S)\to\pi^0+(\Upsilon(1,2,3S)\pi^0)$	[85]
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S)\to\pi^-+(\Upsilon(1,2,3S)\pi^+)$	[82]
				$\Upsilon(5S)\to\pi^-+(h_b(1,2P)\pi^+)$	[82]
				$\Upsilon(5S)\to\pi^-+(B^*\bar{B}^*)^+$	[84]

S. Olsen arXiv:1511.01589v1 [hep-ex]

$X(3872)$	3871.68 ± 0.17	<1.2	1^{++}	$B\to K+(J/\psi\pi^+\pi^-)$	[32, 33, 34, 35]
				$p\bar{p}\to(J/\psi\pi^+\pi^-)+\ldots$	[36, 37, 38, 39, 40]
				$B\to K+(J/\psi\pi^+\pi^-\pi^0)$	[41, 42]
				$B\to K+(D^0D^0\pi^0)$	[43, 44]
				$B\to K+(J/\psi\gamma)$	[45, 46, 47]
				$B\to K+(\psi'\gamma)$	[45, 46, 47]
				$pp\to(J/\psi\pi^+\pi^-)+\ldots$	[48, 49]
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B\to K+(J/\psi\omega)$	[50, 42]
				$e^+e^-\to e^+e^-+(J/\psi\,\omega)$	[51, 52]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^-\to J/\psi+(D^*D)$	[53]
				$e^+e^-\to J/\psi+(\ldots)$	[54]
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^-\to\gamma+(D\bar{D})$	[55, 56]
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^-\to\gamma+(J/\psi\pi^+\pi^-)$	[57]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B\to K+(J/\psi\phi)$	[58, 59, 60]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^-\to J/\psi+(D^*D)$	[53]
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^-\to\gamma+(J/\psi\pi^+\pi^-)$	[61, 62, 63, 57]
				$e^+e^-\to(J/\psi\pi^+\pi^-)$	[64]
				$e^+e^-\to(J/\psi\pi^0\pi^0)$	[64]
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^-\to\gamma+(\psi'\pi^+\pi^-)$	[65, 66]
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$	[67]
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma+(\psi'\pi^+\pi^-)$	[66]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260)\to\pi^-+(J/\psi\pi^+)$	[68, 69]
				$Y(4260)\to\pi^-+(D\bar{D}^*)^+$	[70]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260)\to\pi^-+(h_c\pi^+)$	[71]
				$Y(4260)\to\pi^-+(D^*\bar{D}^*)^+$	[72]
$Z_c^0(4020)$	4024 ± 4	10 ± 3	$1(?)^{+(?)-}$	$Y(4260)\to\pi^0+(h_c\pi^0)$	[73]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B\to K+(\chi_{c1}\pi^+)$	[74, 75]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B\to K+(J/\psi\pi^+)$	[76]
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B\to K+(\chi_{c1}\pi^+)$	[74, 75]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B\to K+(\psi'\pi^+)$	[77, 78, 79, 80]
				$B\to K+(J\psi\pi^+)$	[76]
$Y_b(10890)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^-\to(\Upsilon(nS)\pi^+\pi^-)$	[81]
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S)\to\pi^-+(\Upsilon(1,2,3S)\pi^+)$	[82, 83]
				$\Upsilon(5S)\to\pi^-+(h_b(1,2P)\pi^+)$	[82]
				$\Upsilon(5S)\to\pi^-+(B\bar{B}^*)^+$	[84]
$Z_b^0(10610)$	10609 ± 6		1^{+-}	$\Upsilon(5S)\to\pi^0+(\Upsilon(1,2,3S)\pi^0)$	[85]
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S)\to\pi^-+(\Upsilon(1,2,3S)\pi^+)$	[82]
				$\Upsilon(5S)\to\pi^-+(h_b(1,2P)\pi^+)$	[82]
				$\Upsilon(5S)\to\pi^-+(B^*\bar{B}^*)^+$	[84]

X(3872)

X(3915)

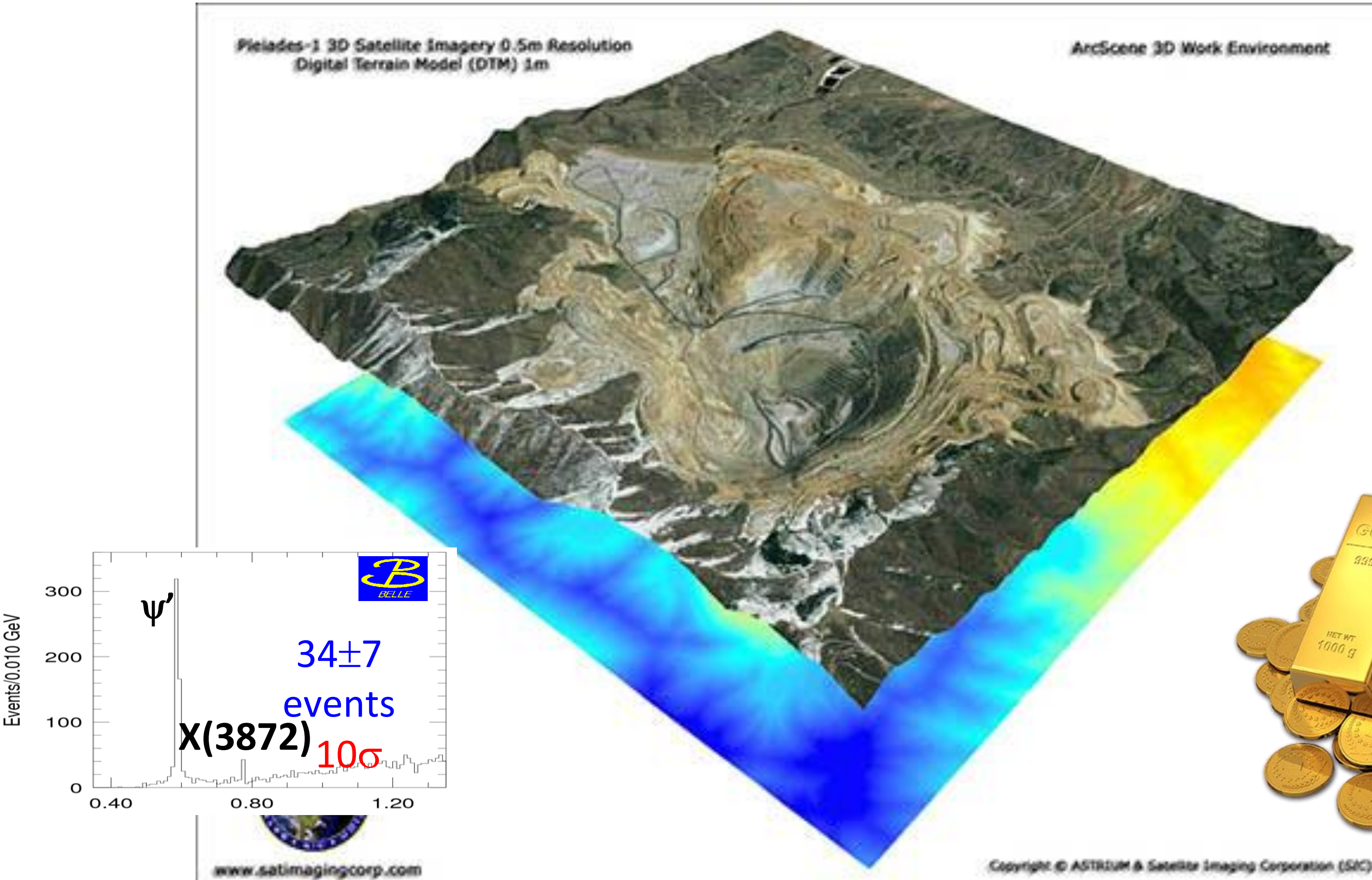
Y(4260)

Z_c^+

S. Olsen arXiv:1511.01589v1 [hep-ex]

Strategy

Image from http://www.satimagingcorp.com/applications/energy/mining/



This is how **signal** (gold) looks on paper/presentations.

Strategy

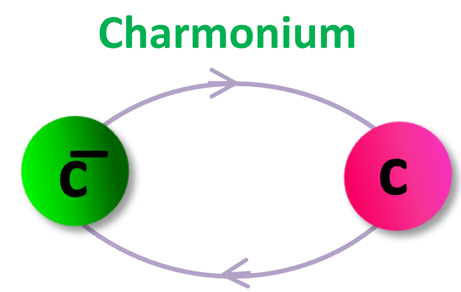
This is how one really dig gold !

You dig or study decay modes systematically and if you find some interesting particle.

Study till you are sure that there is no more gold left.

Many time where others are not expecting, you may hit a jackpot !!!

Charmonium



Bound state of c and $\bar{c}$

Spin : ½ and ½ = 0,1

Orbital angular momentum: L =0,1,2,…

Parity (P) = $(-1)^{L+1}$

Charge Conjugation (C) = $(-1)^{L+S}$

Total Spin : $\vec{J} = \vec{L} + \vec{S}$

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

(Cornell potential)

Quark model quantum numbers

L=0, S=0 : J=0 J^{PC}=

L=0, S=1 : J=1 J^{PC}=

L=1, S=0 : J=1 J^{PC}=

L=1, S=1 : J=0,1,2 J^{PC} =

L=2, S=0 : J=1 J^{PC}=

L=2, S=1 : J=1,2,3 J^{PC}=

and so on..

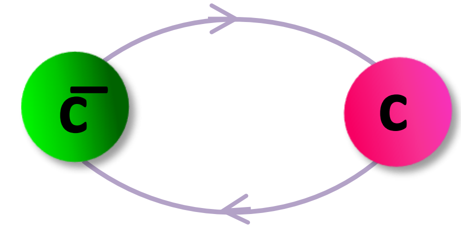
Spectrum based on this, with spin-orbital, spin-spin and tensor term.

States not easily accommodated, candidates for exotic nature.

Charmonium

Bound state of c and $\bar{c}$
Spin : ½ and ½ = 0,1
Orbital angular momentum: L =0,1,2,…
Parity (P) = $(-1)^{L+1}$
Charge Conjugation (C) = $(-1)^{L+S}$
Total Spin : $\vec{J} = \vec{L} + \vec{S}$

Charmonium



$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

(Cornell potential)

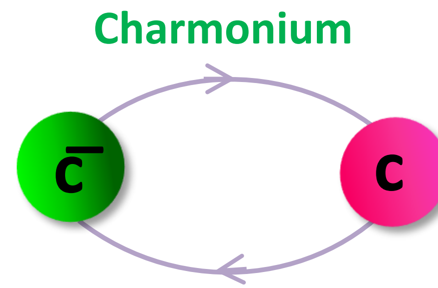
Quark model quantum numbers

L=0, S=0 : J=0 — $J^{PC}=0^{-+}$
L=0, S=1 : J=1 — $J^{PC}=1^{--}$
L=1, S=0 : J=1 — $J^{PC}=1^{+-}$
L=1, S=1 : J=0,1,2 — $J^{PC} = 0^{++}\ 1^{++}\ 2^{++}$
L=2, S=0 : J=1 — $J^{PC}= 2^{-+}$
L=2, S=1 : J=1,2,3 — $J^{PC}=1^{--}\ 2^{--}\ 3^{--}$
and so on..

Spectrum based on this, with spin-orbital, spin-spin and tensor term.

States not easily accommodated, candidates for exotic nature.

Charmonium



Bound state of c and c̄
Spin : ½ and ½ = 0,1
Orbital angular momentum: L =0,1,2,…
Parity (P) = $(-1)^{L+1}$
Charge Conjugation (C) = $(-1)^{L+S}$
Total Spin : $\vec{J} = \vec{L} + \vec{S}$

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

(Cornell potential)

Quark model quantum numbers

L=0, S=0 : J=0	**$J^{PC}=0^{-+}$**
L=0, S=1 : J=1	**$J^{PC}=1^{--}$**
L=1, S=0 : J=1	**$J^{PC}=1^{+-}$**
L=1, S=1 : J=0,1,2	**$J^{PC} = 0^{++}\ 1^{++}\ 2^{++}$**
L=2, S=0 : J=1	**$J^{PC}= 2^{-+}$**
L=2, S=1 : J=1,2,3	**$J^{PC}=1^{--}\ 2^{--}\ 3^{--}$**

and so on..

Spectrum based on this, with spin-orbital, spin-spin and tensor term.

Exotic quantum number
0^{+-}, 0^{--}, 1^{-+}, 2^{+-} and so on..

States not easily accommodated, candidates for exotic nature.

S,P,D corresponds to relative orbital angular momentum L=0,1,2 between quark and antiquark

Spin of quark can couple to either S=0 (spin-singlet) or S=1(spin-triplet) states.
Parity of quark-antiquark state with orbital angular momentum L is

$P = (-1)^{L+1}$

Charge conjugation is

$C = (-1)^{L+S}$

States are denoted by $n^{2S+1}L_J$ [17]

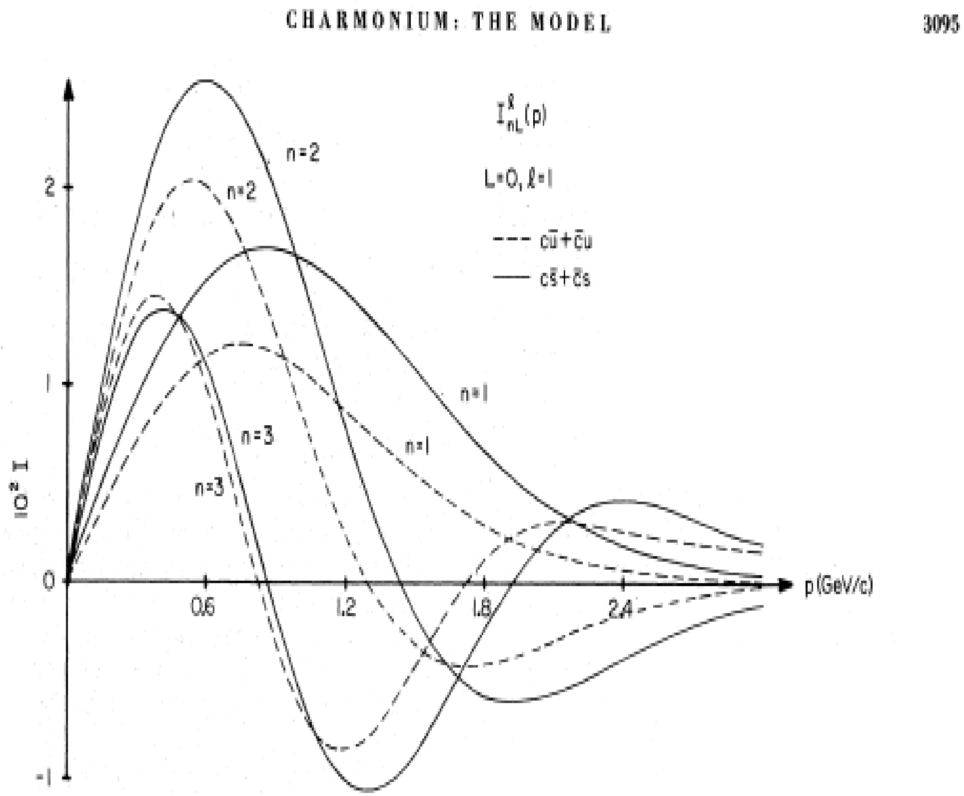
L=0 states can be $^1S_0$ or $^3S_1$
L=1 states can be $^1P_1$ or $^3P_{0,1,2}$
L=2 states can be $^1D_2$ or $^3D_{1,2,3}$

Radial quantum number denoted by n

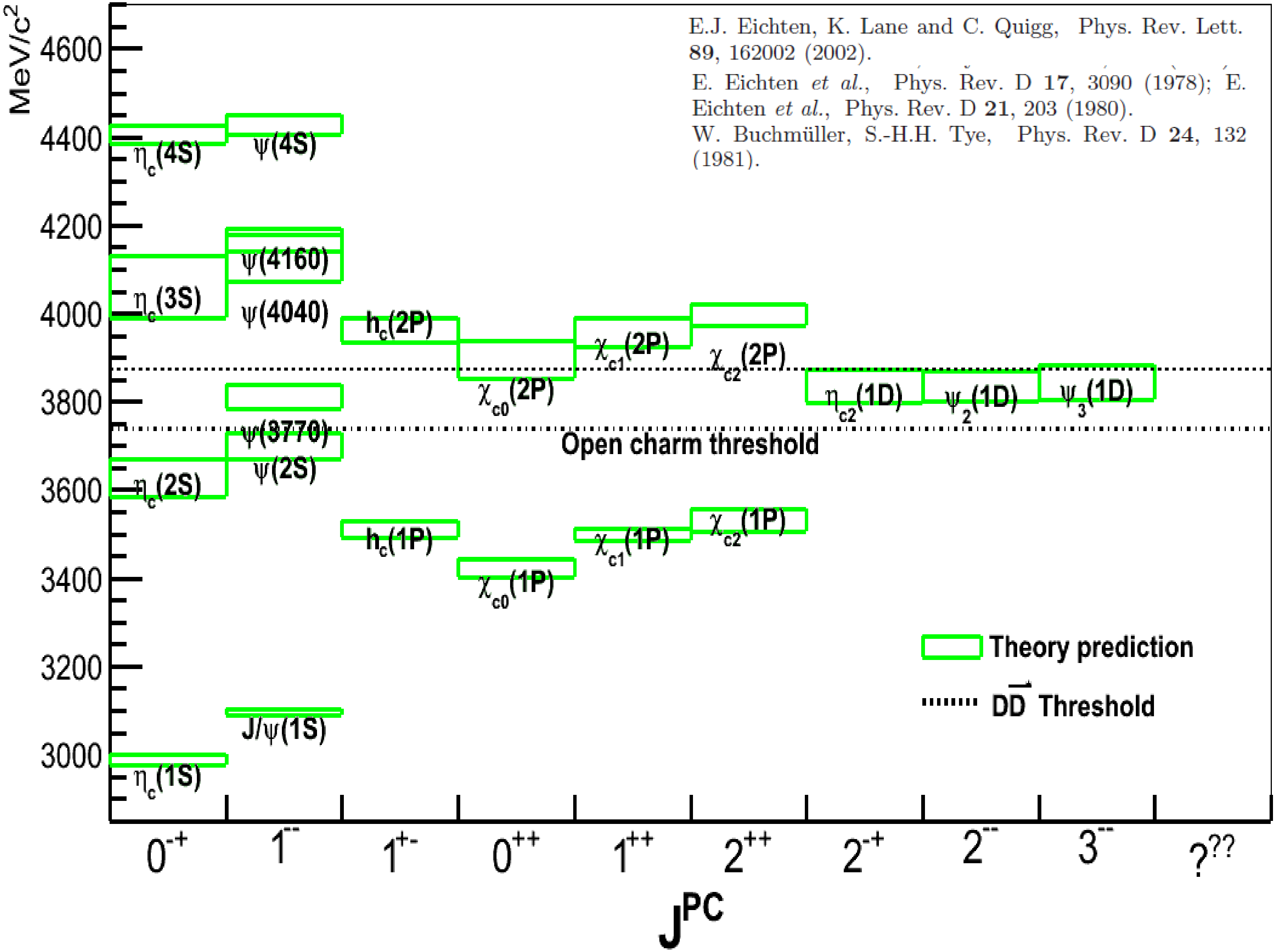
Quark model quantum numbers

L=0, S=0 : J=0	**$J^{PC}=0^{-+}$**
L=0, S=1 : J=1	**$J^{PC}=1^{--}$**
L=1, S=0 : J=1	**$J^{PC}=1^{+-}$**
L=1, S=1 : J=0,1,2	**$J^{PC} = 0^{++}\ 1^{++}\ 2^{++}$**
L=2, S=0 : J=1	**$J^{PC}= 2^{-+}$**
L=2, S=1 : J=1,2,3	**$J^{PC}=1^{--}\ 2^{--}\ 3^{--}$**

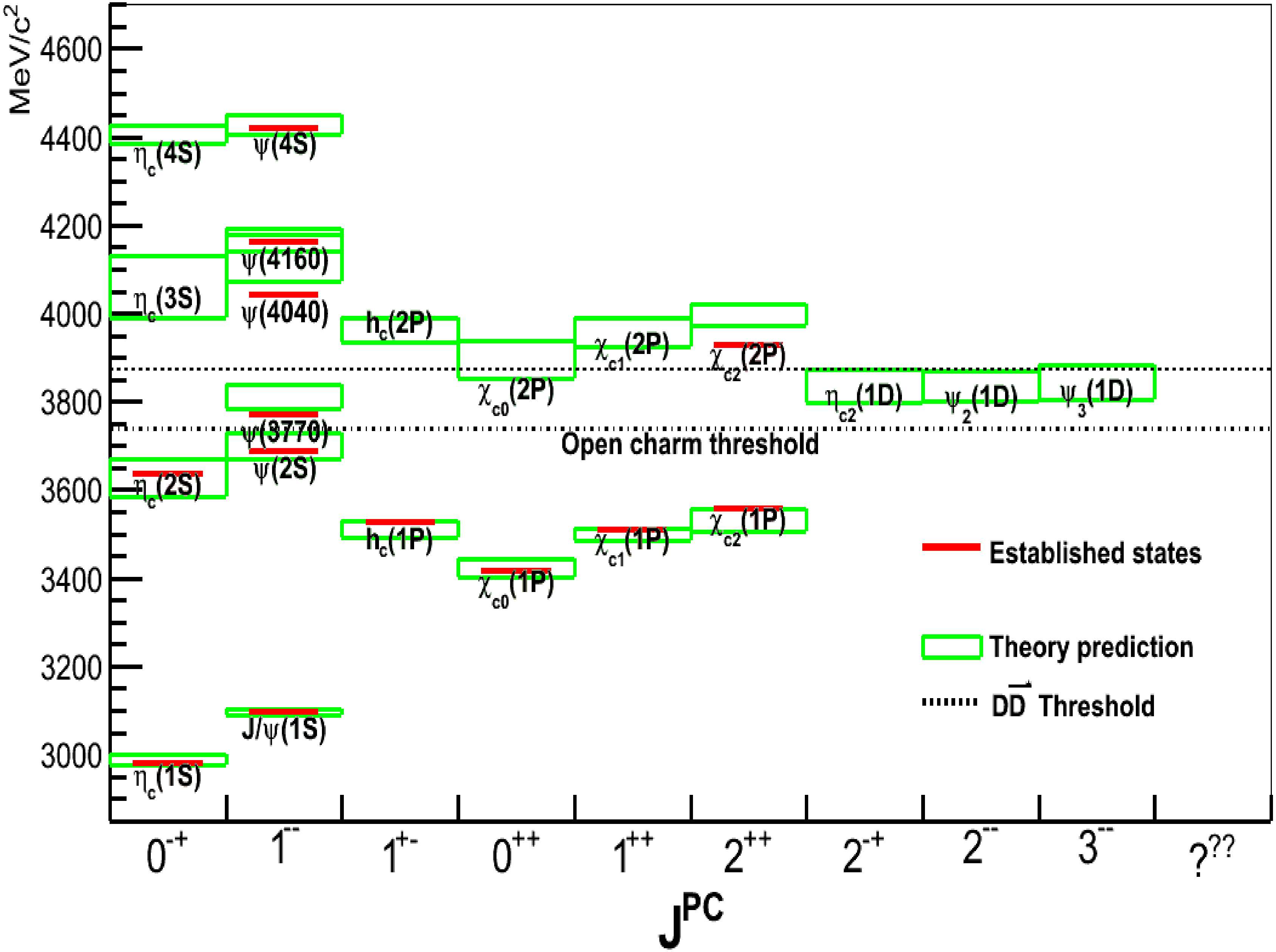
and so on..



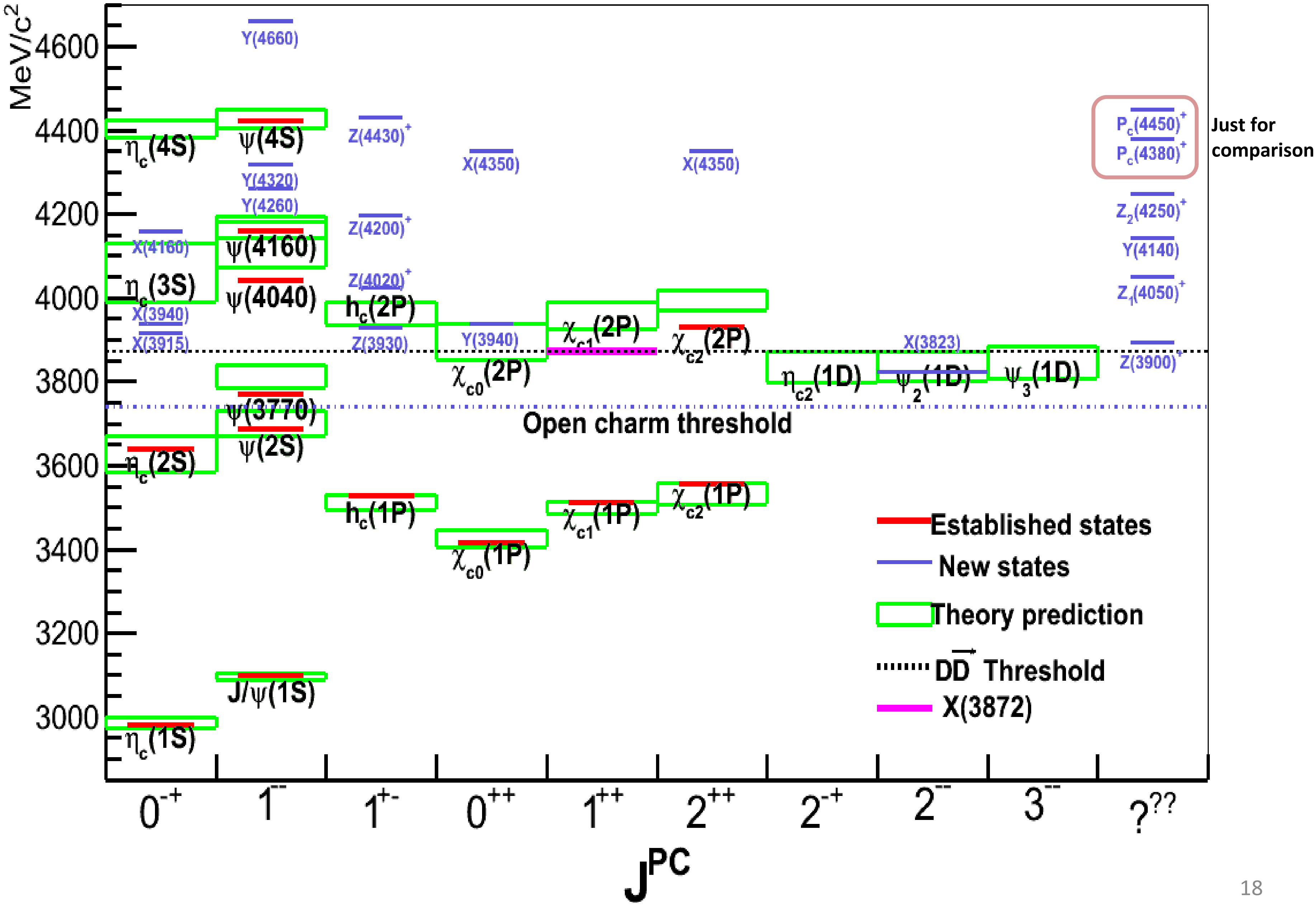
$c\bar{c}$ spectrum (theory)



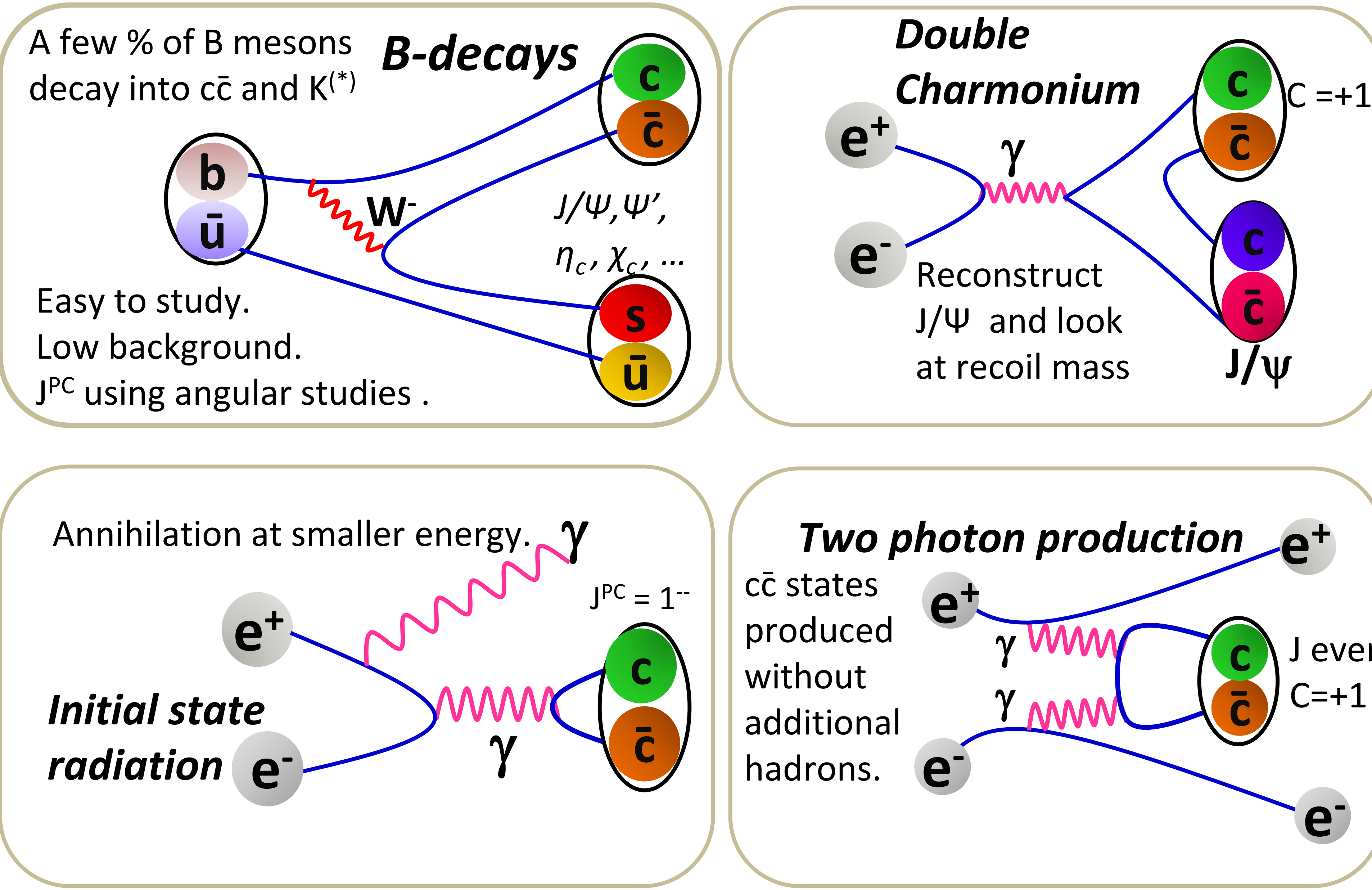
$c\bar{c}$ spectrum (established)



$c\bar{c}$ spectrum (exotics?)

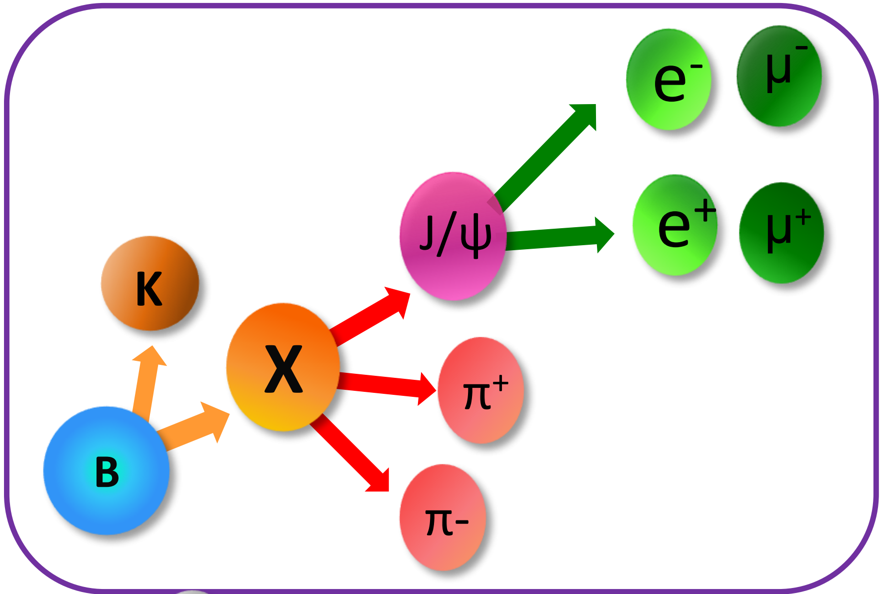


Production of $c\bar{c}$ (-like) *@ B-factories*



Analysis procedure

Reconstruct $B^{\pm}$ (of interest)



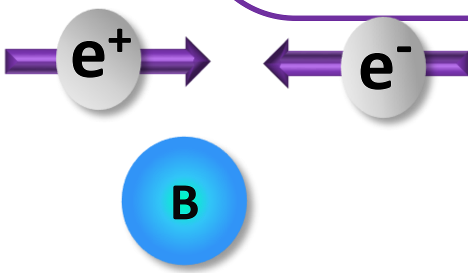
Common variable used in analyses *in this talk*

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$

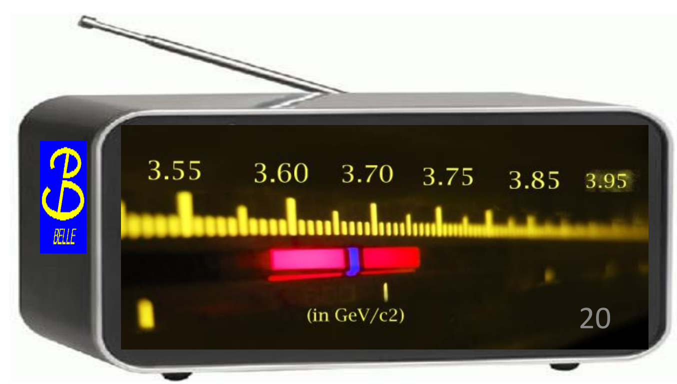
$$\Delta E = E_B - E_{beam}$$

$M_{J/\psi\pi\pi}$ or

$M_{final\ state\ of\ interest}$



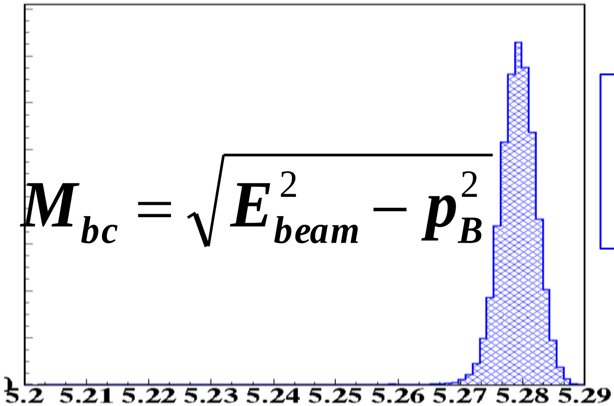
Scan the data ($M_{finalstate}$) in order to search for any exciting exotic signal (particle)



Simplified example

X(3872) → J/ψ ππ

↳ $e^+ e^-$ or $\mu^+\mu^-$

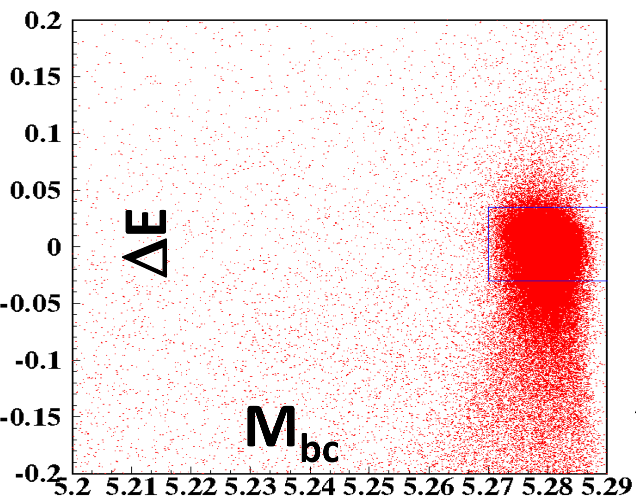


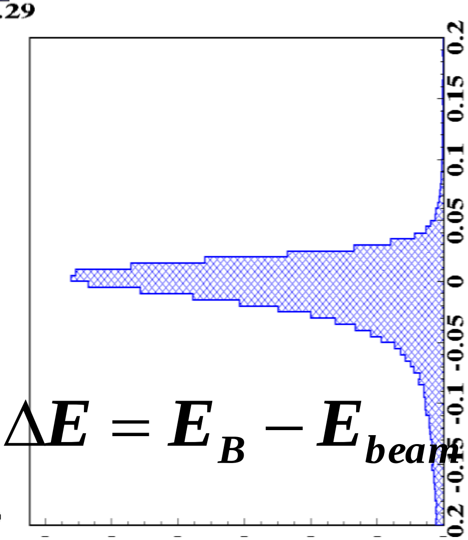
$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$

Reconstruction of B

X(3872) K

↳ B





$$\Delta E = E_B - E_{beam}$$

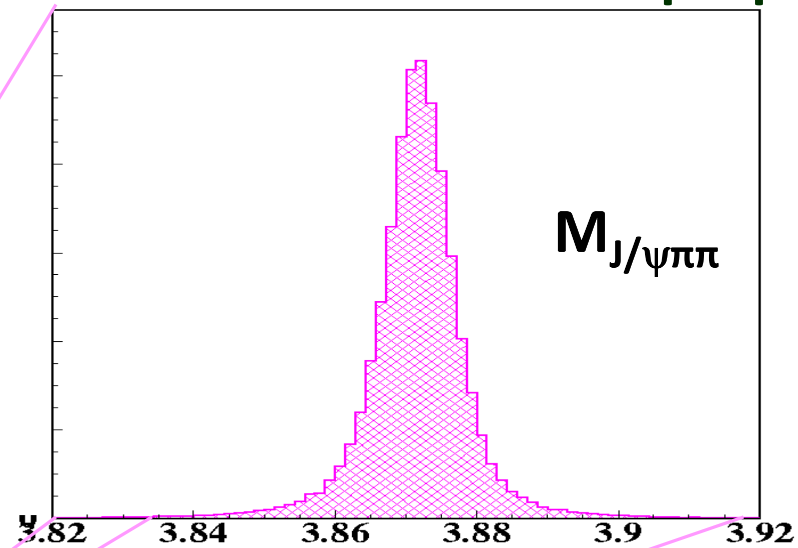
Signal window cut in ΔE & M_{bc}

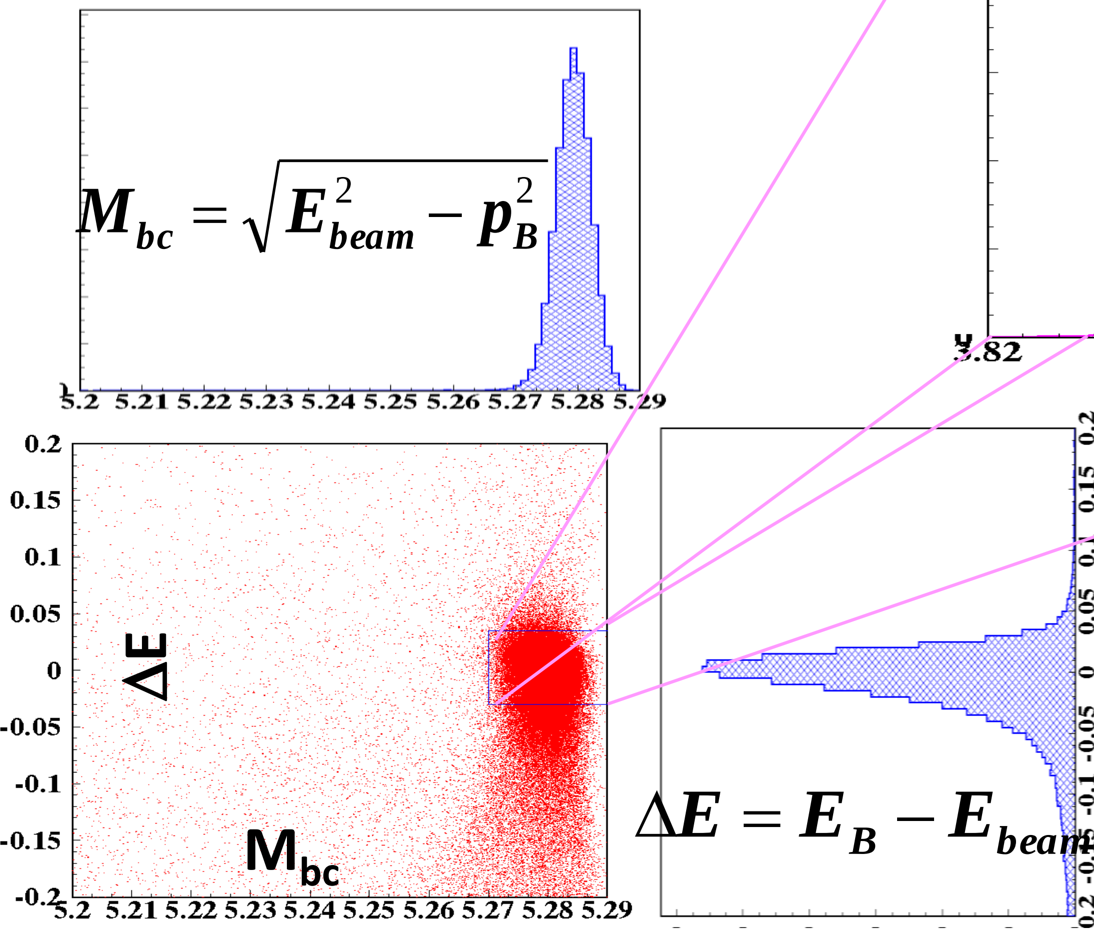
MC for illustration purpose

Simplified example

MC for illustration purpose

X(3872) → J/ψ ππ
↳ $e^+ e^-$ or $\mu^+\mu^-$



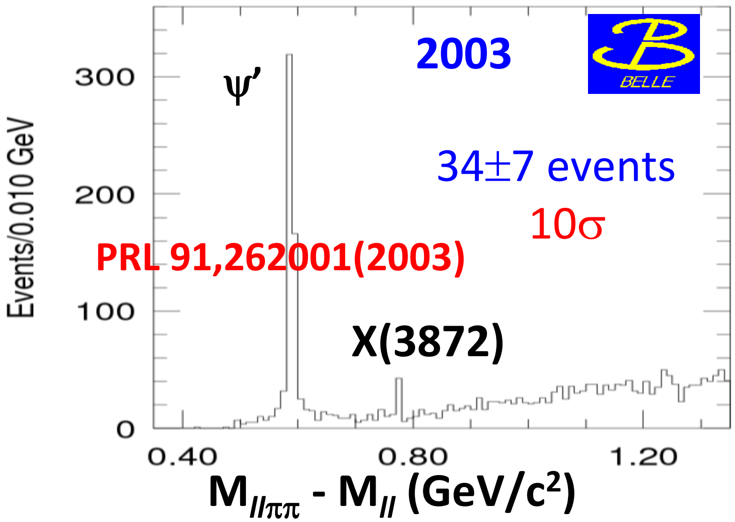


Signal window cut in ΔE & M_{bc}

Peak will be at the mass of the resonance.

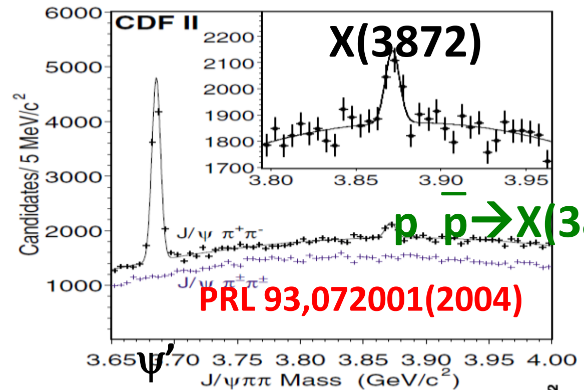
X(3872) Most famous $c\bar{c}$ (-like) state

Discovered by Belle in $J/\psi\pi\pi$ decay mode

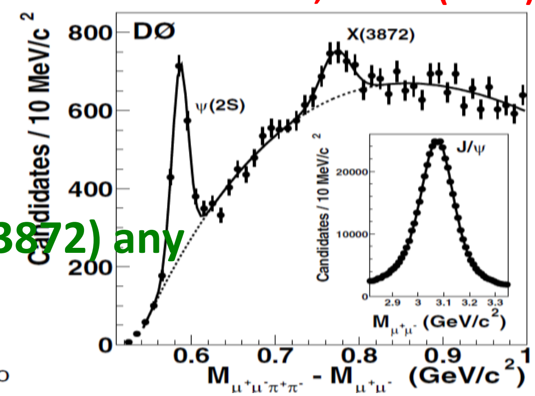


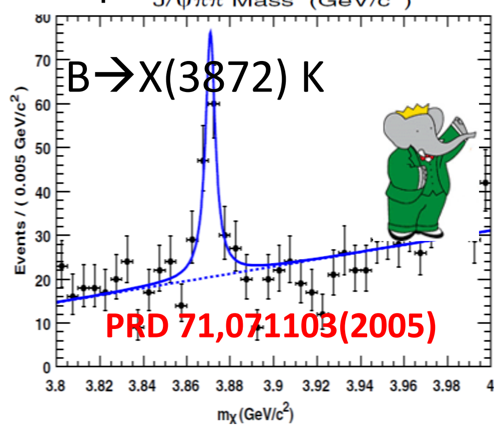
$B^+ \to X(3872) K^+$,
$X(3872) \to J/\psi\pi^+\pi^-$

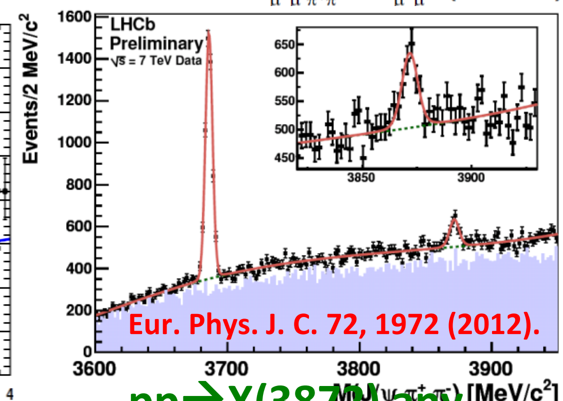
$\Gamma < 2.5$ MeV
(90%CL)

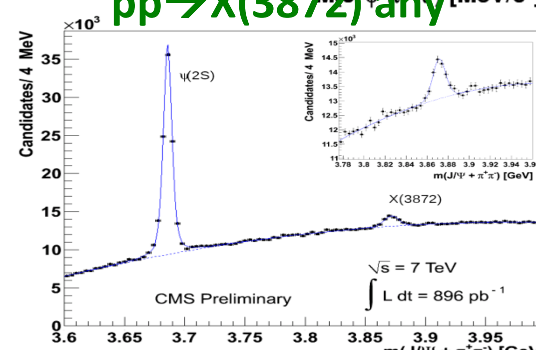


PRL 93,162002(2004)









arXiv:hep-ex/1201.6677

Difficult to assign to a conventional charmonium state.

Confirmed by CDF, DO, BaBar, CMS and LHCb.

Lets check the mass of X(3872)

X(3872) found in $J/\psi\pi\pi$ → similar to ψ' Another charmonium ?

VALUE (MeV)	EVTS		DOCUMENT ID		TECN	COMMENT
$\mathbf{3871.69 \pm 0.17}$	**PDG Average**					
$3871.9 \pm 0.7 \pm 0.2$	20 ± 5		ABLIKIM	2014	BES3	$e^+ e^- \to J/\psi\pi^+\pi^-\gamma$
$3871.95 \pm 0.48 \pm 0.12$	0.6k		AAIJ	2012H	LHCB	$p\,p \to J/\psi\pi^+\pi^- X$
$3871.85 \pm 0.27 \pm 0.19$	~ 170	1	CHOI	2011	BELL	$B \to K\pi^+\pi^- J/\psi$
$3873\,^{+1.8}_{-1.6} \pm 1.3$	27 ± 8	2	DEL-AMO-SANCHEZ	2010B	BABR	$B \to \omega J/\psi K$
$3871.61 \pm 0.16 \pm 0.19$	6k	3, 2	AALTONEN	2009AU	CDF2	$p\,\overline{p} \to J/\psi\pi^+\pi^- X$
$3871.4 \pm 0.6 \pm 0.1$	93.4		AUBERT	2008Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
$3868.7 \pm 1.5 \pm 0.4$	9.4		AUBERT	2008Y	BABR	$B^0 \to K^0_S\, J/\psi\pi^+\pi^-$
$3871.8 \pm 3.1 \pm 3.0$	522	4, 2	ABAZOV	2004F	D0	$p\,\overline{p} \to J/\psi\pi^+\pi^- X$

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

Mass(D^0)= (1864.83±0.05)MeV/c^2

\+ Mass($\overline{D}^{*0}$)= (2006.85±0.05)MeV/c^2

Mass near D^0 and $\overline{D}^{*0}$ threshold → 3871.68± 0.07 MeV/c^2 PDG

How is it related to $D^0\,\overline{D}^{*0}$? $D^0\,\overline{D}^{*0}$ molecule or something else ?

X(3872) much narrower width (Γ< 1.2MeV @ 90% CL) than other charmonium states above $D\,\overline{D}$ threshold.

Belle PRD 84, 052004 (2011)

D⁰D*⁰ molecule?

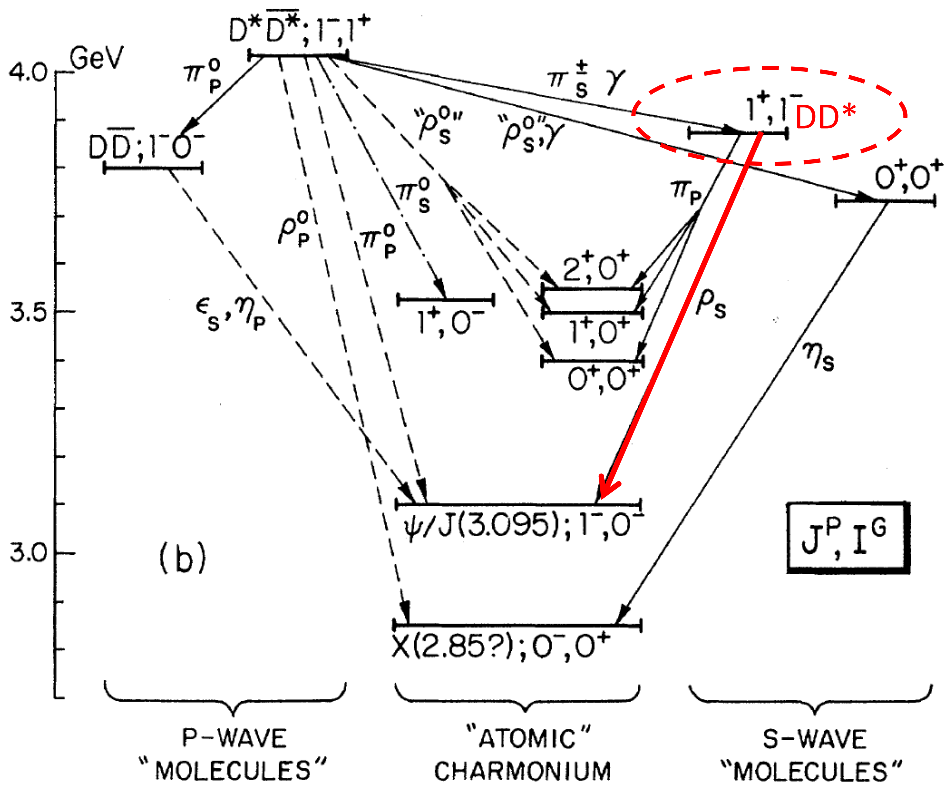
Not a recent idea, old idea

Molecular Charmonium: A New Spectroscopy?*

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 23 November 1976)

PRL 38, 317 (1976)

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.



predictions:

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

$(DD^*)_{mol} \rightarrow \rho J/\psi$

$\rightarrow \pi^+\pi^-$

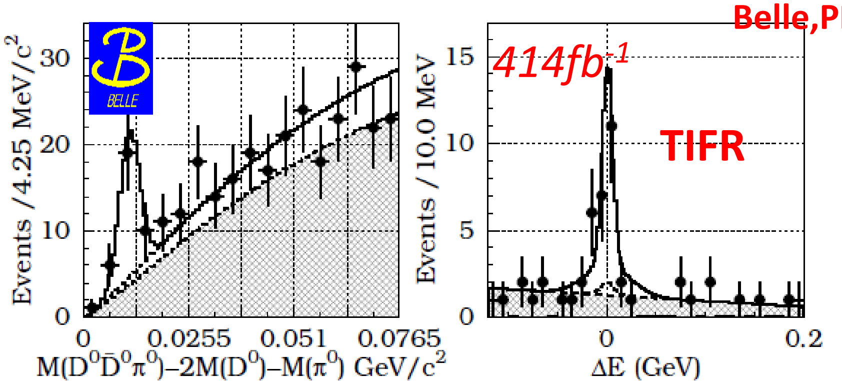
L. Okun & M. Voloshin JETP Lett. 23, 333 (1974)

Slide stolen from Olsen

X(3872)→$D^{*0}\bar{D}^0$

$D^{*0}\bar{D}^0$ molecule ?

X(3872) loosely bound molecule → enhancement in $D^{*0}\bar{D}^0$ invariant mass near



Belle,PRL 97,162002 (2006)

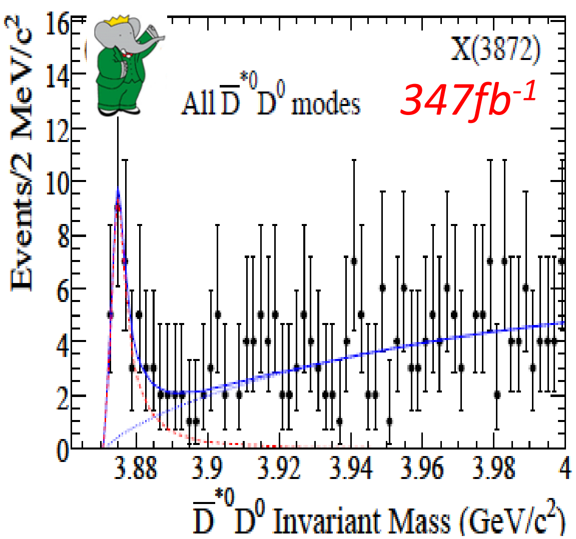
$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^0_S\pi^+\pi^-, K^+K^-$

Signal	$\epsilon\mathcal{B}\times10^4$	N_{obs}	sig, σ	$\mathcal{B}\times10^4$
$B\to D^0\bar{D}^0\pi^0K$	2.12±0.10	24.1±6.1	6.4	$1.27\pm0.31^{+0.22}_{-0.39}$
$B^+\to D^0\bar{D}^0\pi^0K^+$	3.62±0.14	17.4±5.2	5.0	$1.07\pm0.31^{+0.19}_{-0.33}$
$B^0\to D^0\bar{D}^0\pi^0K^0$	0.84±0.04	6.5±2.6	4.6	$1.73\pm0.70^{+0.31}_{-0.53}$

Mass→ $3875.4\pm0.7^{+0.4}_{-1.7}\pm0.9\ \mathrm{MeV}/c^2$ MeV/c^2

Mass is 2σ higher than mass observed in X(3872)→J/Ψππ

PRD 77,011102 (2008)



BaBar also observed X(3872)→$D^0\bar{D}^{*0}$, along with shift in the mass

Mass→ $3875.1^{+0.7}_{-0.5}\pm0.5$ MeV/c^2

$D^0\to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^-$
$D^{*0}\to D^0\pi^0, D^0\gamma$

Belle & BaBar both observe X(3872)→$D^{*0}\bar{D}^0$ but they got slight shift in mass

Same X(3872) or what ?

3 times larger sample

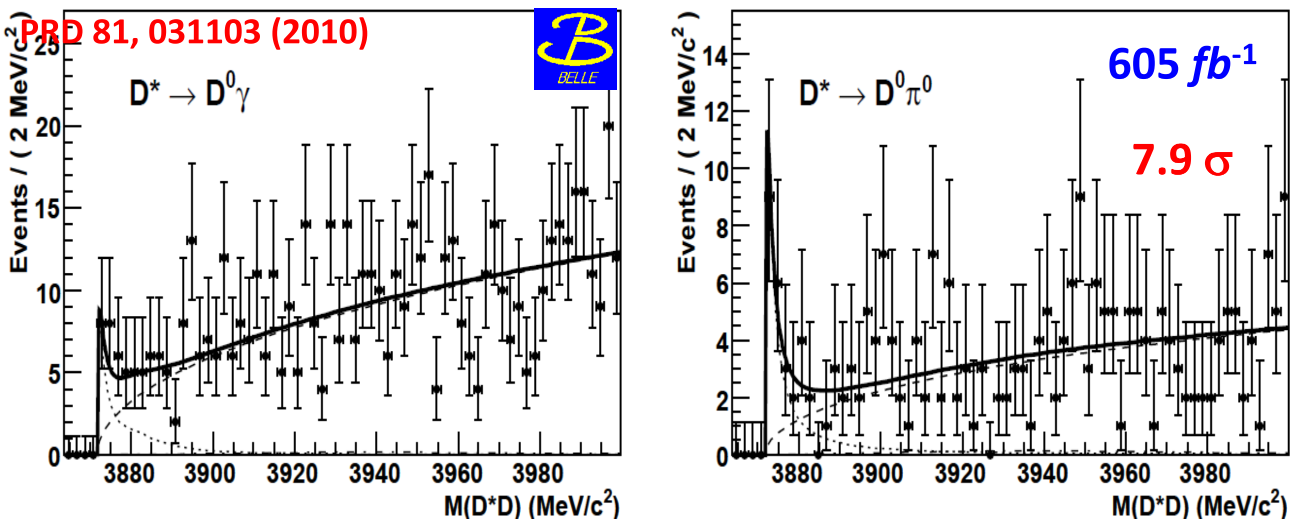
Different X(3875) ??

Mass of $D^0\bar{D}^0\pi^0$ is away from X(3872) by 4.5σ

→ Difference due to threshold effect PRD 76,014007 (2007) PRD 76,034007(2007)

→ Evidence for X(3872) partner state as predicted by diquark-antidiquark model.

PRL 99,182003(2007)



...... Signal
- - - Background
- · - Y(3940)

PRD 81, 031103 (2010)

Increased statistics and fit with improve Flatte function returned

Mass → $3872.9^{+0.6}_{-0.4}{}^{+0.4}_{-0.5}$ MeV/c^2 Discrepancy <2σ

More sophisticated fitting procedure including a mass-dependent resolution function and a 2DUML fit with two different shapes, the relativistic Breit-Wigner function and the Flatt´e distribution

Difficult to fit this spectrum, due to threshold

Obtained BR consistent with Belle previous result

Mass is 1.8σ lower.

Consistent with Belle previous result !!!

Molecular Avatar

As, X(3872) has narrow width < 1.2 MeV

If the X couples to $D^0 \bar{D}^{*0}$ in an S-wave:

X(3872) is charm meson molecule

$$X(3872) = \frac{1}{\sqrt{2}}(D^{*0}\bar{D}^0 + D^0\bar{D}^{*0})$$

E. Braaten, J. Stapleton PRD81, 0140189

Mass(X(3872))= (3871.69±0.17)MeV/c^2

Mass(D^0)= (1864.83±0.05)MeV/c^2

Mass($\bar{D}^{*0}$)= (2006.85±0.05)MeV/c^2

Binding Energy (E_b)= Mass(D^0) + Mass($\bar{D}^{*0}$) – Mass(X3872)

Minimum radius= $\sqrt{2\mu_x E_b}$

Reduced mass $\mu_x = \frac{M_{D0} M_{\bar{D}*}}{M_{D0} + M_{\bar{D}*}}$

Molecular Avatar

As, X(3872) has narrow width < 1.2 MeV

If the X couples to $D^0 \bar{D}^{*0}$ in an S-wave:

X(3872) is charm meson molecule

$$X(3872) = \frac{1}{\sqrt{2}}(D^{*0}\bar{D}^0 + D^0\bar{D}^{*0})$$

E. Braaten, J. Stapleton PRD81, 0140189

Measurement	Unit	SI value of unit
Energy	eV	$1.602\ 176\ 565(35) \times 10^{-19}$ J
Mass	eV/c^2	$1.782\ 662 \times 10^{-36}$ kg
Momentum	eV/c	$5.344\ 286 \times 10^{-28}$ kg·m/s
Temperature	eV/k_B	$1.160\ 4505(20) \times 10^4$ K
Time	$\hbar$/eV	$6.582\ 119 \times 10^{-16}$ s
Distance	$\hbar c$/eV	$1.973\ 27 \times 10^{-7}$ m

Mass(X(3872))= (3871.69 ± 0.17)MeV/c^2

Mass(D^0)= (1864.83 ± 0.05)MeV/c^2

Mass($\bar{D}^{*0}$)= (2006.85 ± 0.05)MeV/c^2

Binding Energy (E_b)= Mass(D^0) + Mass($\bar{D}^{*0}$) – Mass(X3872)

Minimum radius= $\sqrt{2\mu_x E_b}$

Reduced mass $\mu_x = \frac{M_{D0}M_{\bar{D}*}}{M_{D0}+M_{\overline{D*}}}$

The E_b of (-10 ± 180)keV one expect 170keV

Which tell that it has a minimum radius of ~ 10 fm

Molecular Avatar

As, X(3872) has narrow width < 1.2 MeV

If the X couples to $D^0\,\bar{D}^{*0}$ in an S-wave:

X(3872) is charm meson molecule

$$X(3872) = \frac{1}{\sqrt{2}}\left(D^{*0}\bar{D}^{0} + D^{0}\bar{D}^{*0}\right)$$

E. Braaten, J. Stapleton PRD81, 0140189

Measurement	Unit	SI value of unit
Energy	eV	$1.602\,176\,565(35) \times 10^{-19}$ J
Mass	eV/c^2	$1.782\,662 \times 10^{-36}$ kg
Momentum	eV/c	$5.344\,286 \times 10^{-28}$ kg·m/s
Temperature	eV/k_B	$1.160\,4505(20) \times 10^{4}$ K
Time	ħ/eV	$6.582\,119 \times 10^{-16}$ s
Distance	ħc/eV	$1.973\,27 \times 10^{-7}$ m

Mass(X(3872))= $(3871.69\pm0.17)\,MeV/c^2$

Mass(D^0)= $(1864.83\pm0.05)\,MeV/c^2$

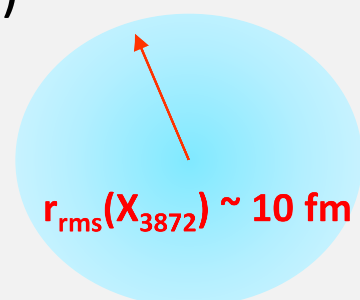
Mass($\bar{D}^{*0}$)= $(2006.85\pm0.05)\,MeV/c^2$

$r_{rms}(\psi') \approx 0.8$ fm

ψ'

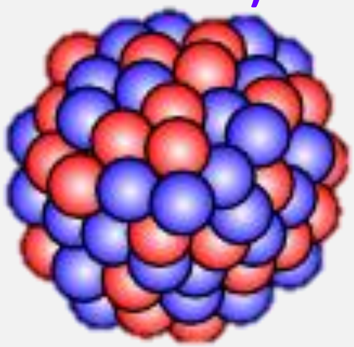
More than 10 times

X(3872)



$r_{rms}(X_{3872})$ ~ 10 fm

$r_{rms}(^{208}Pb$ nucleus$) \approx 5.56$ fm



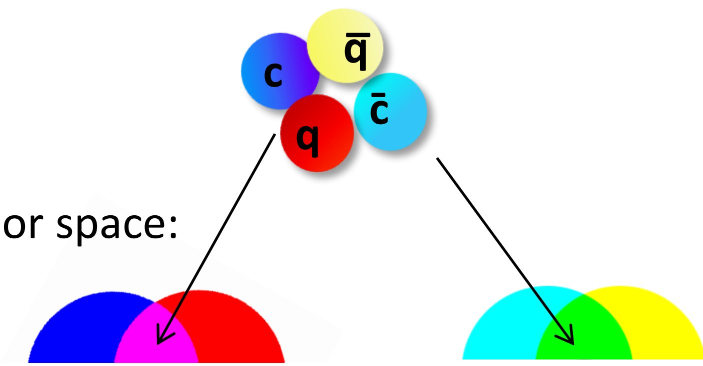
The E_b of (-10 ± 180)keV one expect 170keV

Which tell that it has a minimum radius of ~ 10 fm

Tetraquark as avatar in X(3872)

Tightly bound
diquark-diantiquark

In color space:



R.L.Jaffe PRD 15, 267 (1977)

red+blue=magenta
(antigreen)

cyan yellow=green
(antimagenta)

A colored diquark
is like a antiquark

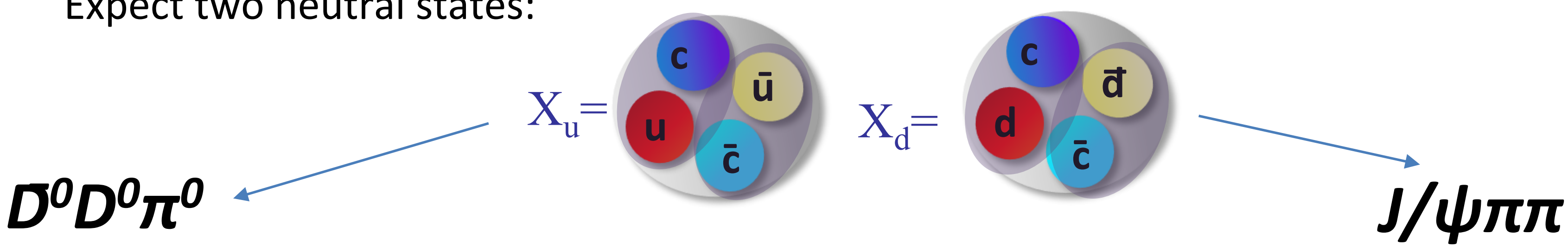
A colored diantiquark
is like a quark

diquark-diantiquark?

Maiani *et al* PRD71, 014028 (2005)

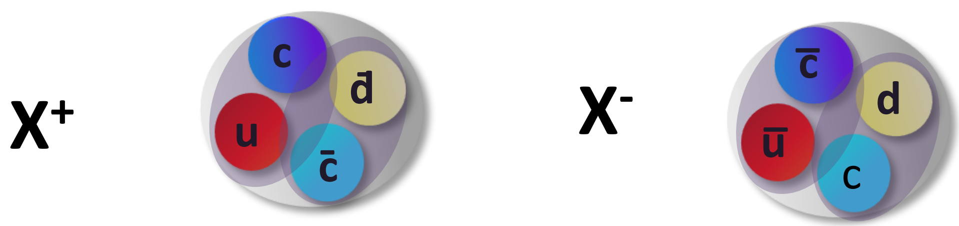
diquark-diantiquark (tetra-quark) model

Expect two neutral states:



Predict : $\Delta M(M_x(B^+)-M_x(B^0))$ =8±3 MeV

It also predicts charged partners:



Isospin relations:

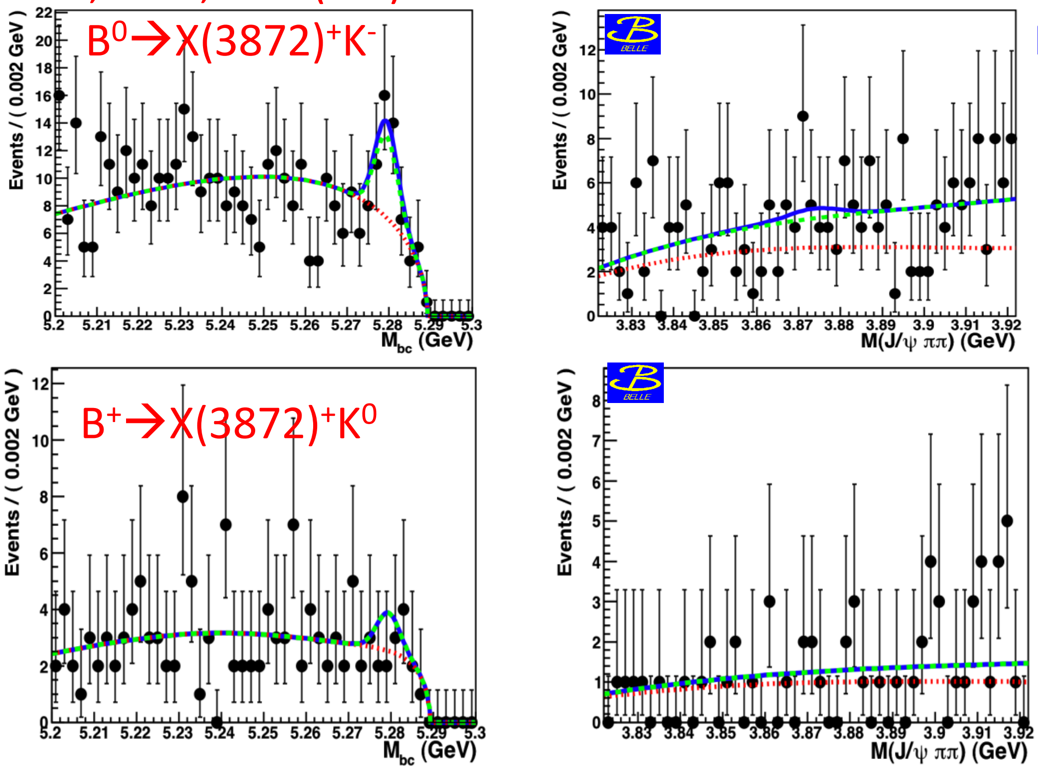
$$B(B^+ \rightarrow K^0 X(3872)^+) = 2 \times B(B^0 \rightarrow K^0 X(3872)^0)$$

$$B(B^0 \rightarrow K^- X(3872)^+) = 2 \times B(B^+ \rightarrow K^+ X(3872)^0)$$

$X(3872)^+$ existence ?

Tetraquark model predicts the existence of isospin triplet : $X(3872)^+$

Belle, PRD 84,052004 (2011)



Mass diff. b/w charged and neutral B decay

$\Delta M_{X(3872)} = (-0.69 \pm 0.97 \pm 0.19)$ MeV

Prediction: $\Delta M(M_x(B^+)-M_x(B^0)) = (8 \pm 3)$ MeV

Maiani *et al.*, PRD71, 014028(2005)

$\mathcal{BR}(B^+ \rightarrow X(3872)^+K^0) = 2 \times \mathcal{BR}(B^0 \rightarrow X(3872)K^0)$

- Reconstruct $X(3872)^+ \rightarrow J/\Psi \pi^+\pi^0$
- No signal is seen
- UL (@90% CL) is provided

$\mathcal{BR}(B^0 \rightarrow X^+K^-) \times \mathcal{BR}(X^+ \rightarrow \pi^+\pi^0 J/\psi) < 3.9 \times 10^{-6}$

No charged partner

$\mathcal{BR}(B^+ \rightarrow X^+K^0) \times \mathcal{BR}(X^+ \rightarrow \pi^+\pi^0 J/\psi) < 4.5 \times 10^{-6}$

Rule out isospin triplet model ?

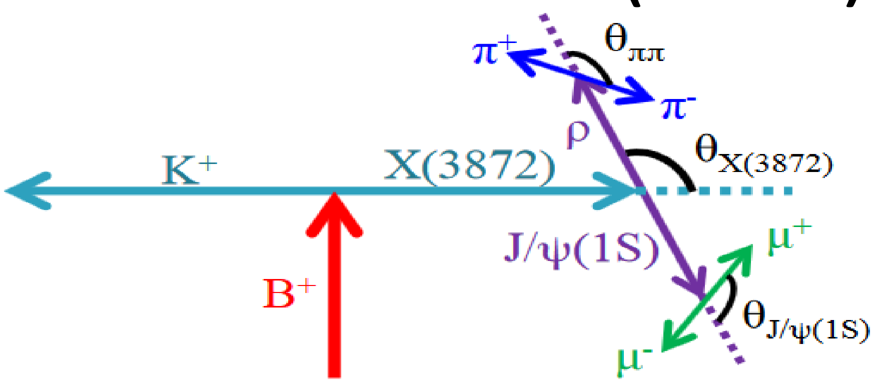
Few tetraquark models predict $X(3872)^+$ to be broad, non-observed yet because of low statistics (?).

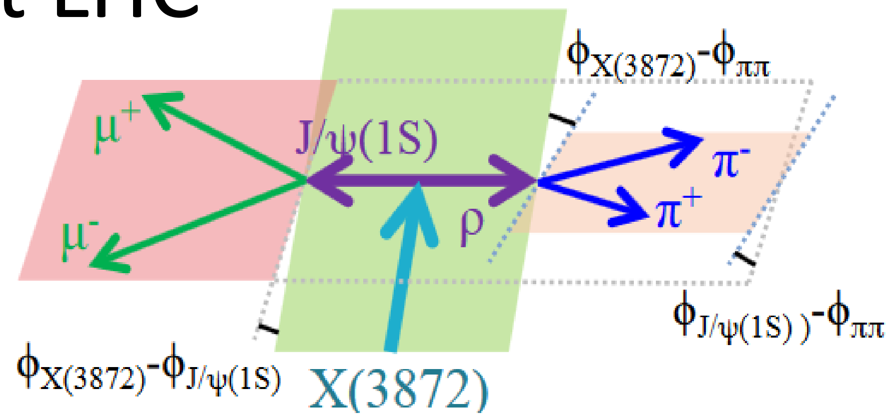
K. Terasaki, arxiV : 1107.5868v2

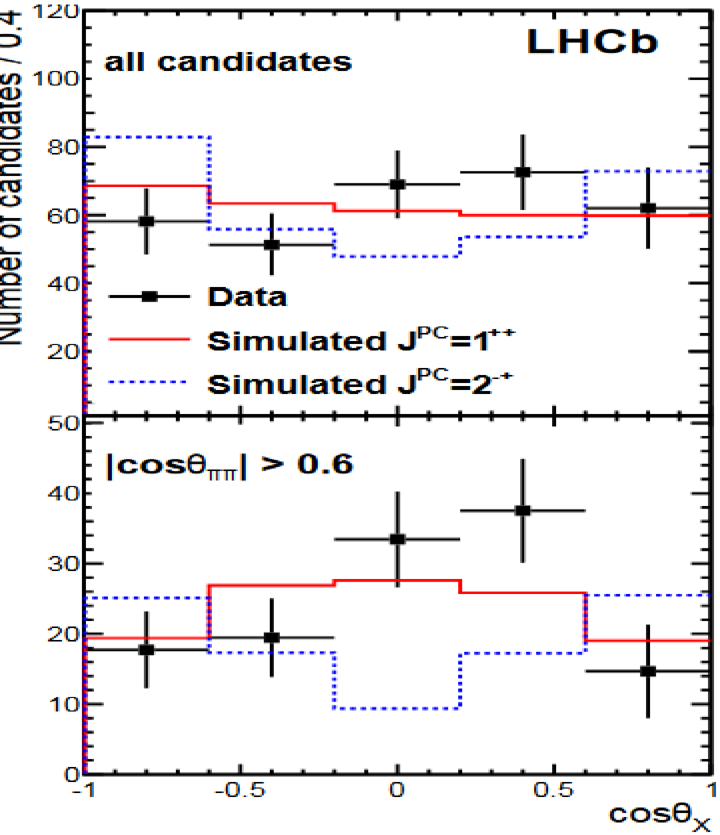
If X(3872) is tetraquark, than X(3872) has C-odd partner which can decay into

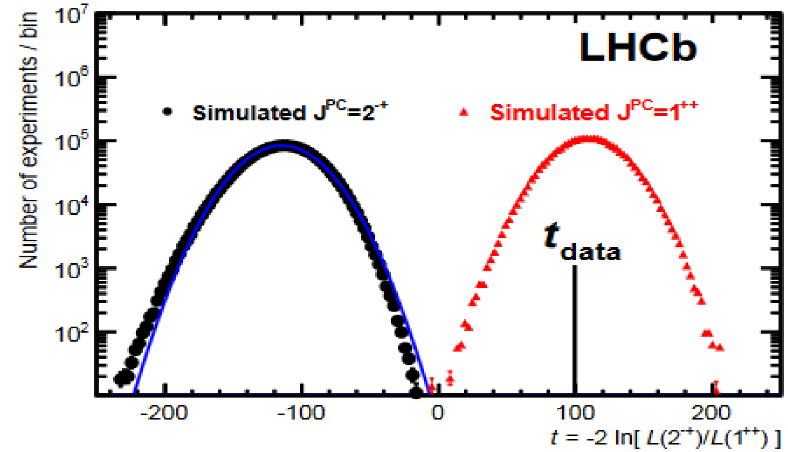
✓ $X(3872)^{C-} \rightarrow \chi_{c1}\gamma$

X(3872) at LHC









$$D = -2\ln\left(\frac{\text{likelihood for null model}}{\text{likelihood for alternative model}}\right)$$
$$= 2\ln\left(\frac{\text{likelihood for alternative model}}{\text{likelihood for null model}}\right)$$
$$= 2 \times [\ln(\text{likelihood for alternative model}) - \ln(\text{likelihood for null model})]$$

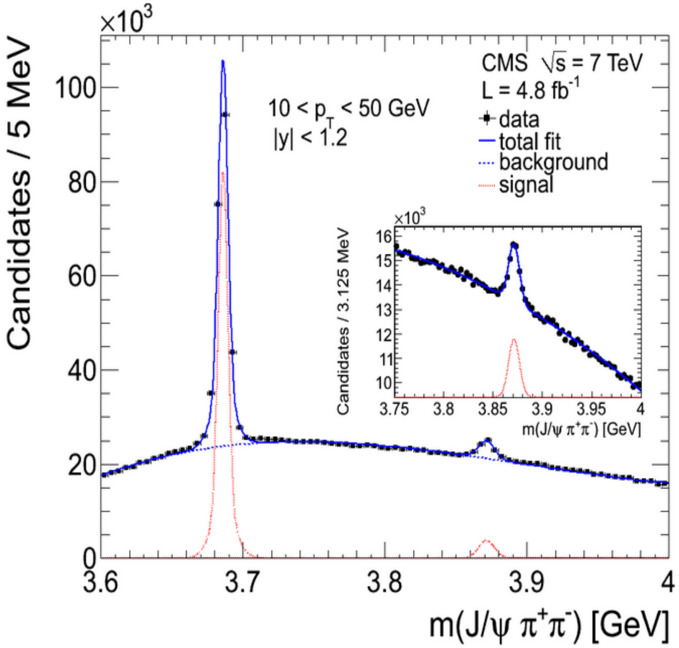
One get this likelihood from Fit (RooFit return it)

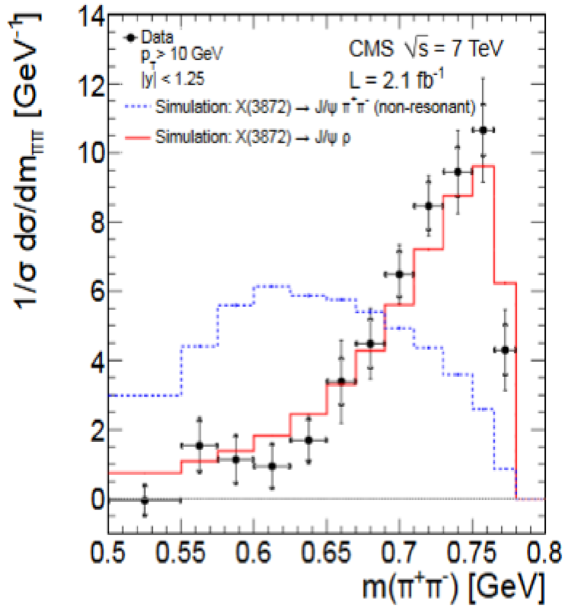
Chisquare value with the degree of freedom

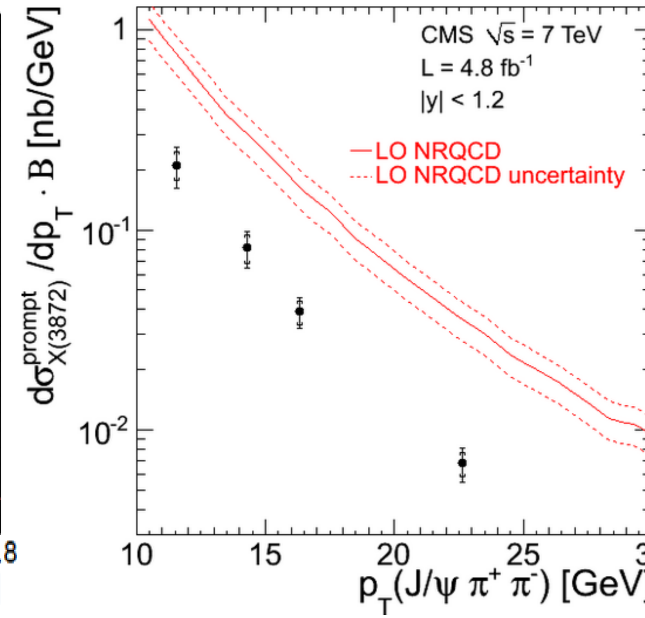
Rejected 2^{-+} with more than 8σ significance

CMS, JHEP 04, 154(2013)

X(3872) at LHC





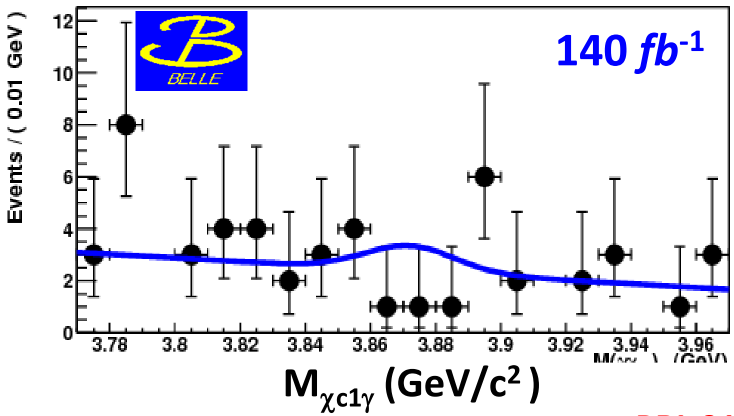


•The X(3872) is more copiously produced through "prompt" processes and only 26% of the production rate is observed from decays of B hadrons.

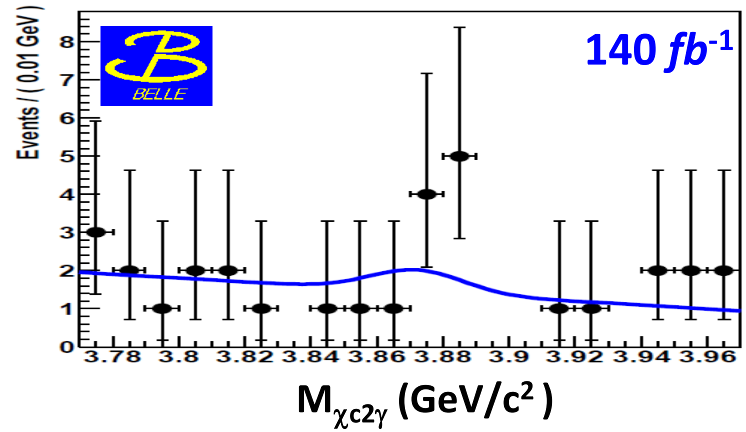
•A measurement of the mass spectrum of the pion pairs produced in X(3872) decays indicates that the decay into the two charged pions proceeds via an intermediate ρ state.

Radiative decays to understand X(3872)

$X(3872) \to \chi_{c1}\gamma$



$X(3872) \to \chi_{c2}\gamma$

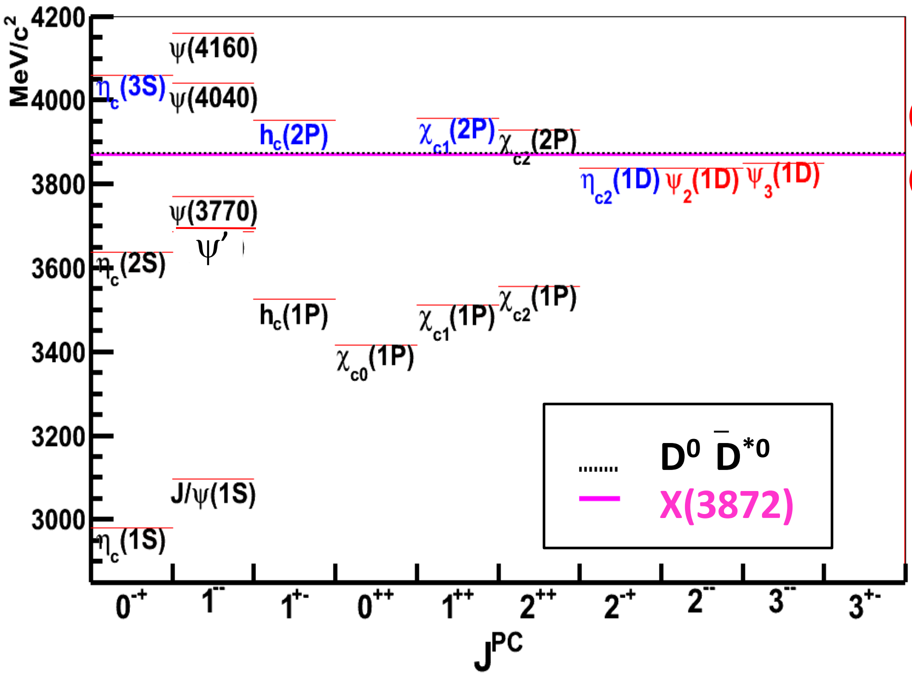


PRL 91, 262001 (2003)

$$\frac{\Gamma(X(3872)\to\chi_{c1}\gamma)}{\Gamma(X(3872)\to J/\psi\pi\pi)} < 0.9 \quad (90\% CL)$$

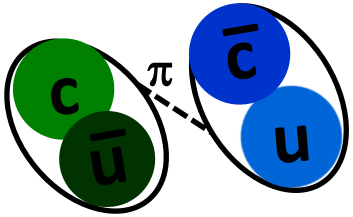
arXiv:0408116

$$\frac{\Gamma(X(3872)\to\chi_{c2}\gamma)}{\Gamma(X(3872)\to J/\psi\pi\pi)} < 1.1 \quad (90\% CL)$$



- ψ_2 → $\Gamma(\gamma\chi_{c1})$ too small
- ψ_3 → $\Gamma(\gamma\chi_{c2})$ too small
- h_c' → Ruled out by angular distribution
- χ_{c1}' → $\Gamma(\gamma J/\psi)$ too small
- η_{c2} → BR($X \to J/\psi\pi\pi$) should be small
- η_c'' → should have high mass and large width

Not obvious charmonium candidate



Radiative decay and X(3872) structure

Belle found evidence for X(3872)→ J/ψγ in B^+→X(3872) K^+

+ve C parity

Belle, arXiv:0505037

Phys.Rept. 429,243(2006)

If pure molecular : $\mathcal{BR}$(X(3872)→ ψ'γ) < $\mathcal{BR}$(X(3872)→ J/ψγ)

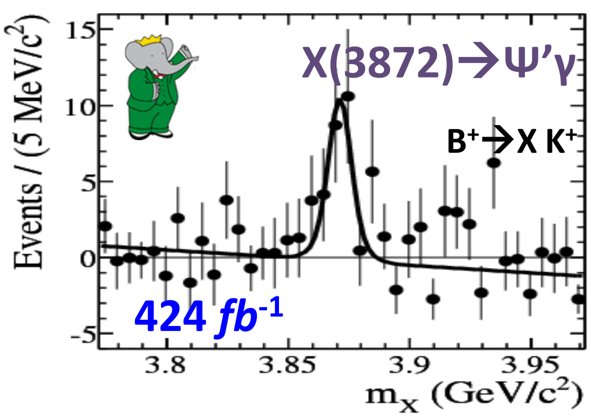
If X(3872) is 2^{-+} $c\bar{c}$: $\mathcal{BR}$(X(3872)→ ψ'γ) < $\mathcal{BR}$(X(3872)→ J/ψγ) **arXiV:1007.4541**

If X(3872) is 1^{++} $c\bar{c}$: $\mathcal{BR}$(X(3872)→ ψ'γ) > $\mathcal{BR}$(X(3872)→ J/ψγ) **PRD 73,014014(2006)**

If X(3872) is admixture of $D^0\bar{D}^{*0}$ bound state with a $c\bar{c}$ meson :

$\mathcal{BR}$(X(3872)→ ψ'γ) /$\mathcal{BR}$(X(3872)→ J/ψγ) will suggest the admixture ratio.

PRD 83, 094009 (2011) , arXiv:1107.0443v3
PLB 697,3, 233-237 (2011)



BaBar, PRL 102, 132001 (2009)

BaBar found signal in X(3872)→Ψ'γ

$\mathcal{BR}$(X(3872)→ ψ' γ) /$\mathcal{BR}$(X(3872)→ J/ψ γ) = 3.5 ±1.4

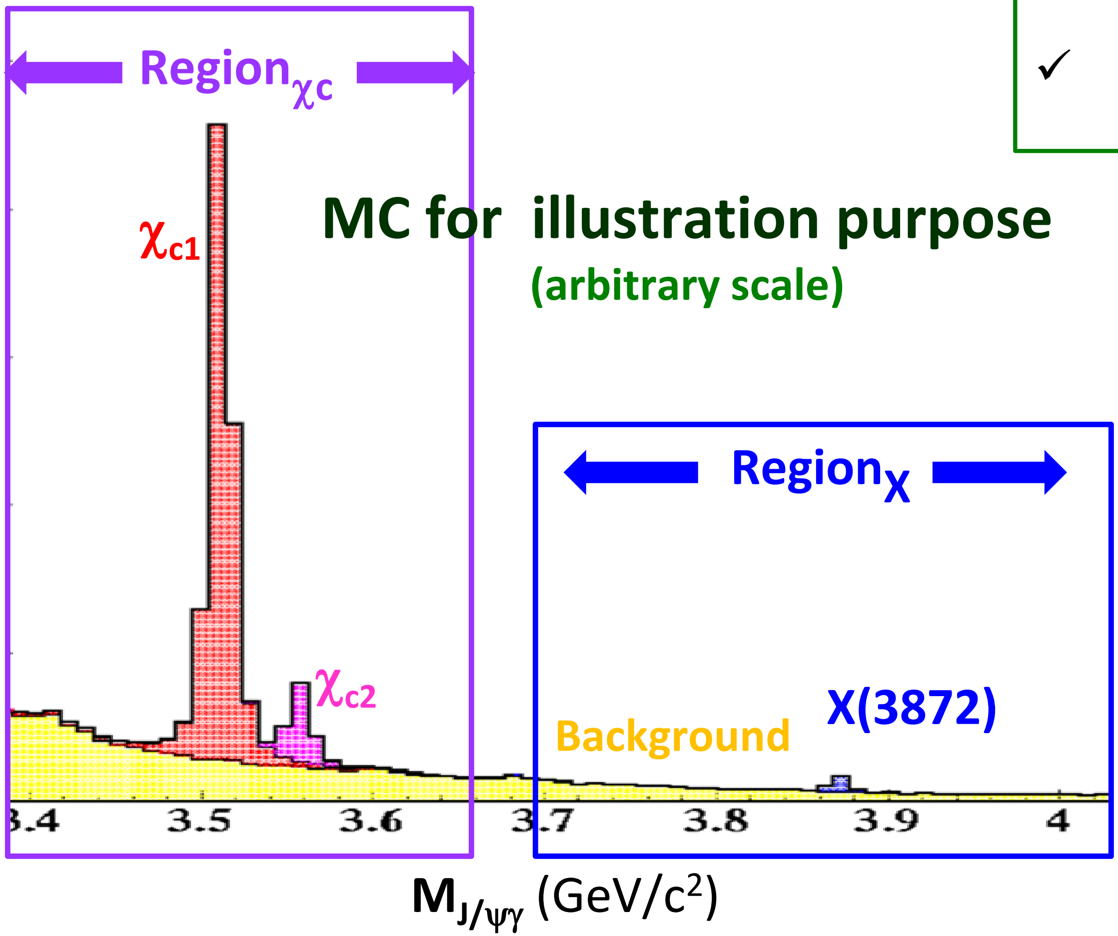
Resolving this admixture ratio is important to understand X(3872) nature

Study of B→(J/ψγ) K

- χ_{c1} K^+ good control sample
- Same final state : J/ψ γ

Photon selection

- ✓ E_γ > 290 MeV for $\chi_{c1,c2}$
  E_γ > 470 MeV for X(3872)
- ✓ π^0 veto
- ✓ $\cos\theta_{hel}$ cut to reduce the background



- ✓ Region$_{\chi c}$ studied first
- ✓ Then Region$_X$

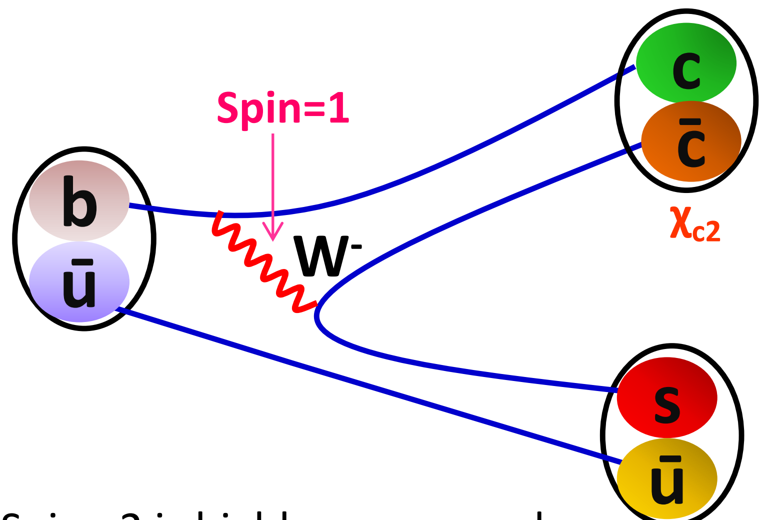
772 M $B\bar{B}$

First Evidence for $B^+ \rightarrow \chi_{c2} K^+$

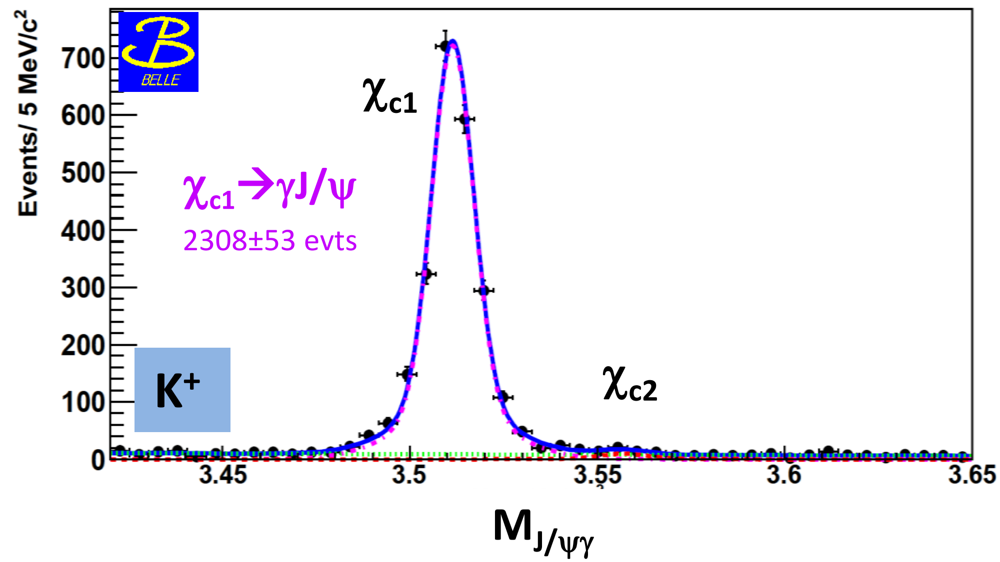
$B \rightarrow (J/\psi\gamma) K$

Calibration mode

Spin =2



Spin =2 is highly suppressed



Belle PRL 107, 091803 (2011)

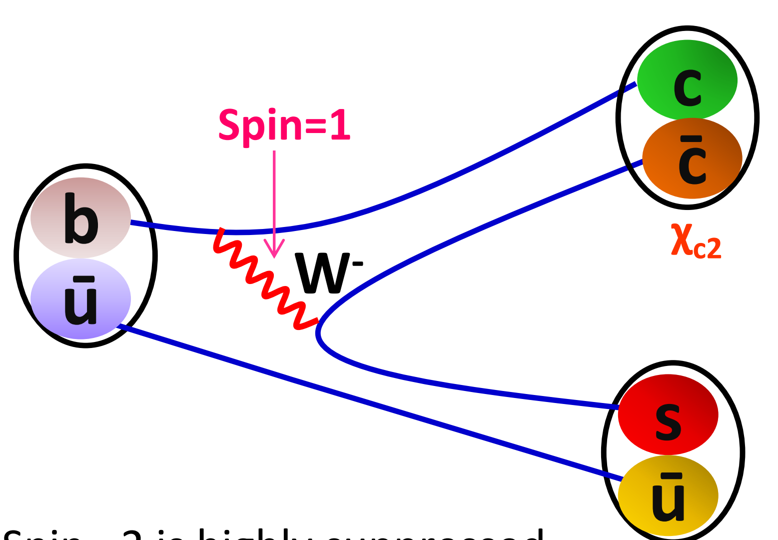
772 M $B\bar{B}$

First Evidence for $B^+ \rightarrow \chi_{c2} K^+$

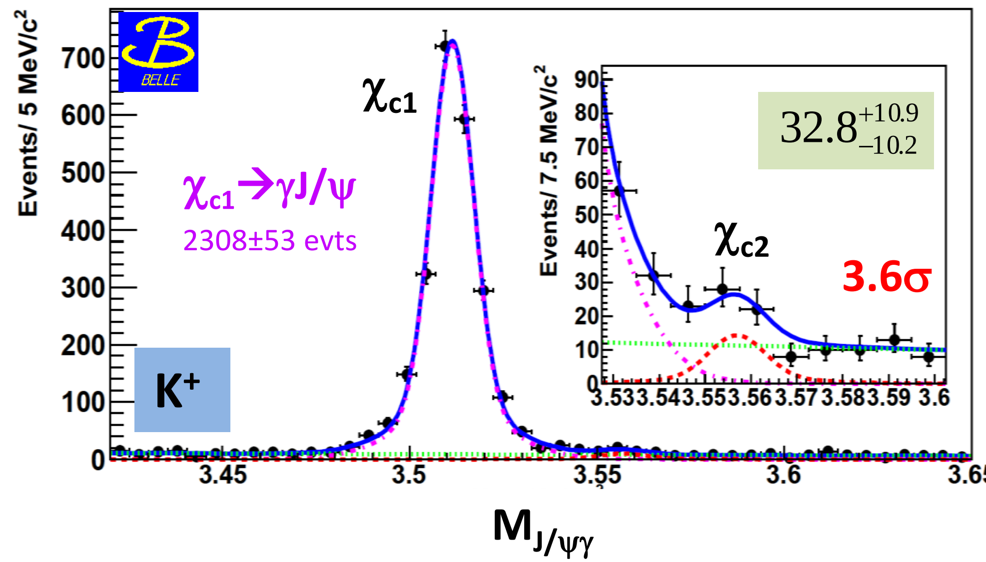
$B \rightarrow (J/\psi\gamma) K$

Calibration mode

Spin =2



Spin =2 is highly suppressed



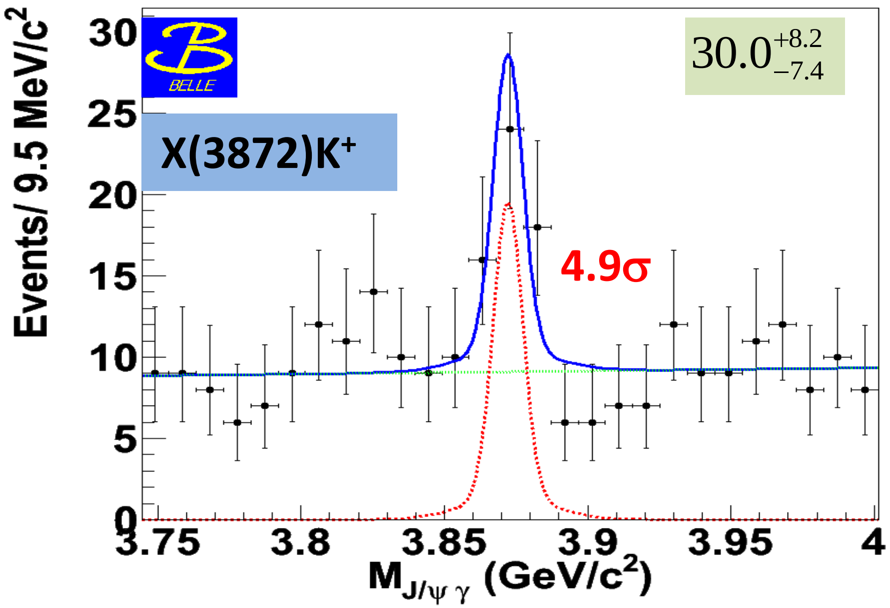
Belle PRL 107, 091803 (2011)

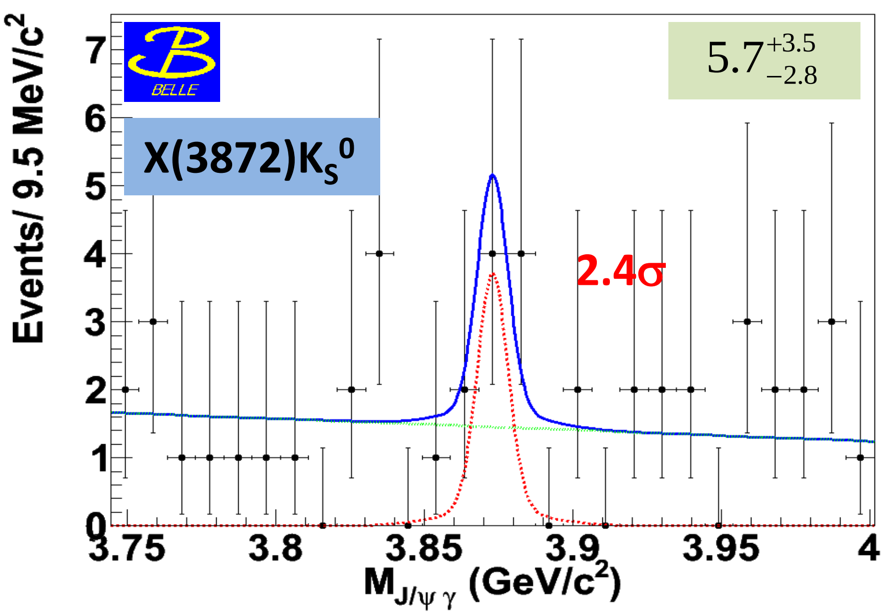
$$\frac{\mathcal{B}(B \rightarrow \chi_{c2} K)}{\mathcal{B}(B \rightarrow \chi_{c1} K)} = 2.2 \pm 0.7\ \%$$

772 M $B\bar{B}$

B→X(3872)K

PRL 107, 091803 (2011)





Mode	Events	Significance
$B^+ \to X(3872)\,K^+$	$30.0^{+8.2}_{-7.4}$	4.9 σ
$B^0 \to X(3872)\,K_S^0$	$5.7^{+3.5}_{-2.8}$	2.4 σ

Clear observation of X(3872) → J/ψγ in $B^+ \to X(3872)K^+$

- $\mathcal{BR}$ ($B^+ \to X(3872)\,K^+$) x $\mathcal{BR}$(X(3872) → J/ψγ) is (1.78±0.46±0.12) x 10^{-6}

Consistent with Belle previous Evidence as well as BaBar

arXiv:0505037

PRL 102, 132001 (2009)

$$\frac{\mathrm{BR}(X(3872) \to J/\psi\gamma)}{\mathrm{BR}(X(3872) \to J/\psi\pi\pi)} = 0.21 \pm 0.06$$

Using Belle X(3872)→J/ψππ result from

Belle, PRD 84,052004 (2011)

- $\mathcal{BR}$ ($B^0 \to X(3872)\,K^0$) x $\mathcal{BR}$(X(3872) → J/ψγ) is < 2.4 x 10^{-6} (@ 90% CL)

Combining both, 5.5σ significance is obtained

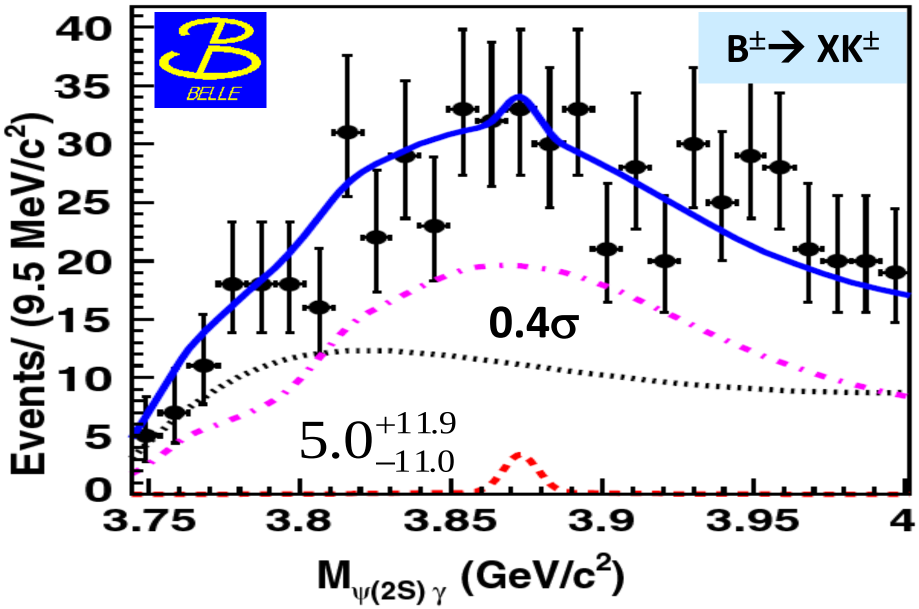
✓ **X(3872)→J/ψγ is well established decay mode**

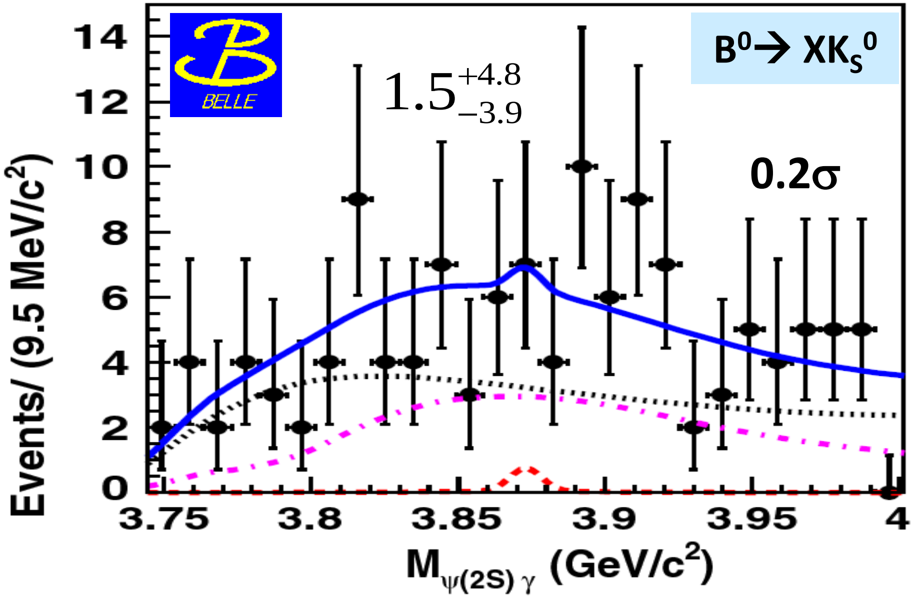
772 M $B\overline{B}$

Belle PRL 107, 091803 (2011)

X(3872)→Ψ'γ

B→(ψ'γ) K





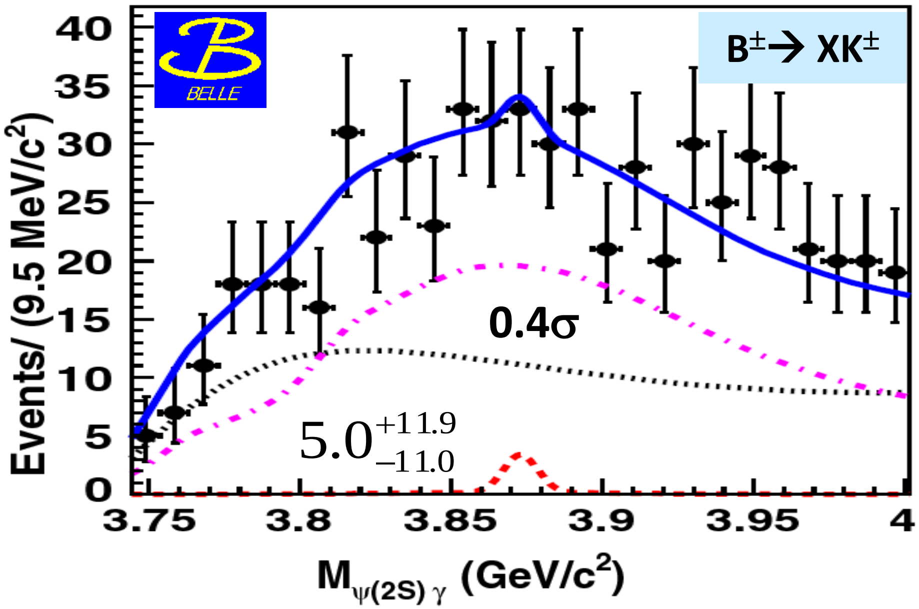
Signal **Combinatorial background** **ψ'K*, ψ'K background component**

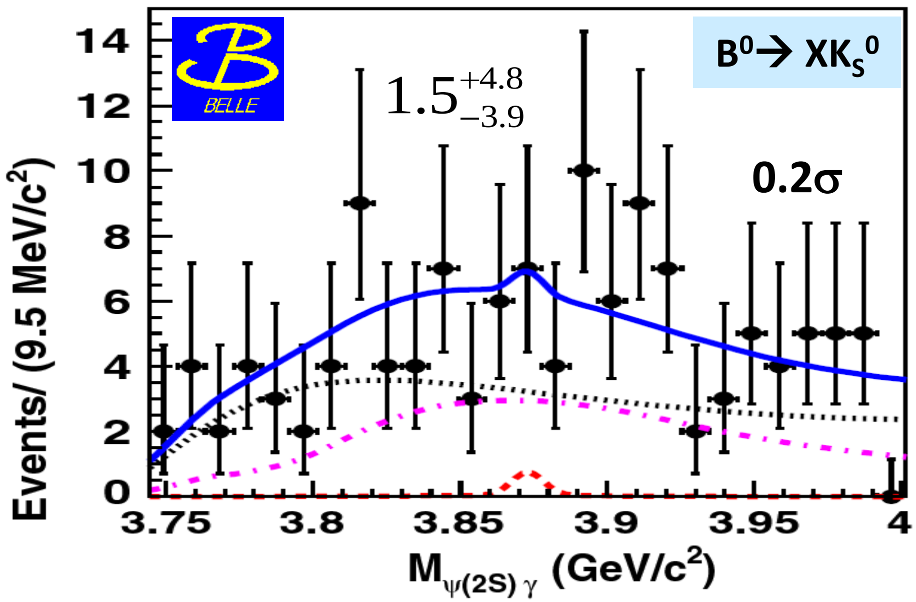
$X(3872) \to \Psi'\gamma$

772 M $B\overline{B}$

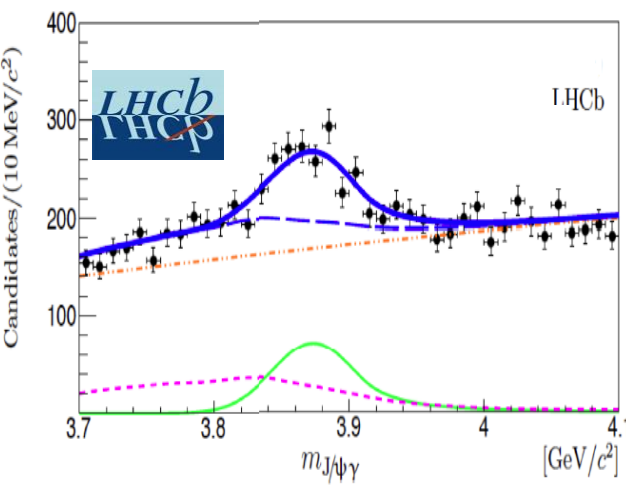
Belle PRL 107, 091803 (2011)

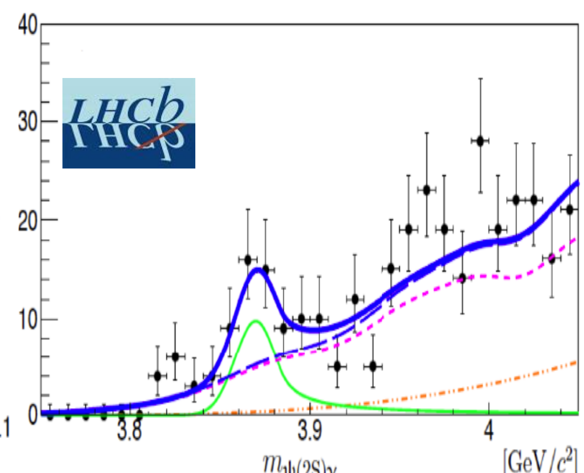
$B \to (\psi'\gamma)\,K$





Signal   Combinatorial background   ψ'K*, ψ'K background component





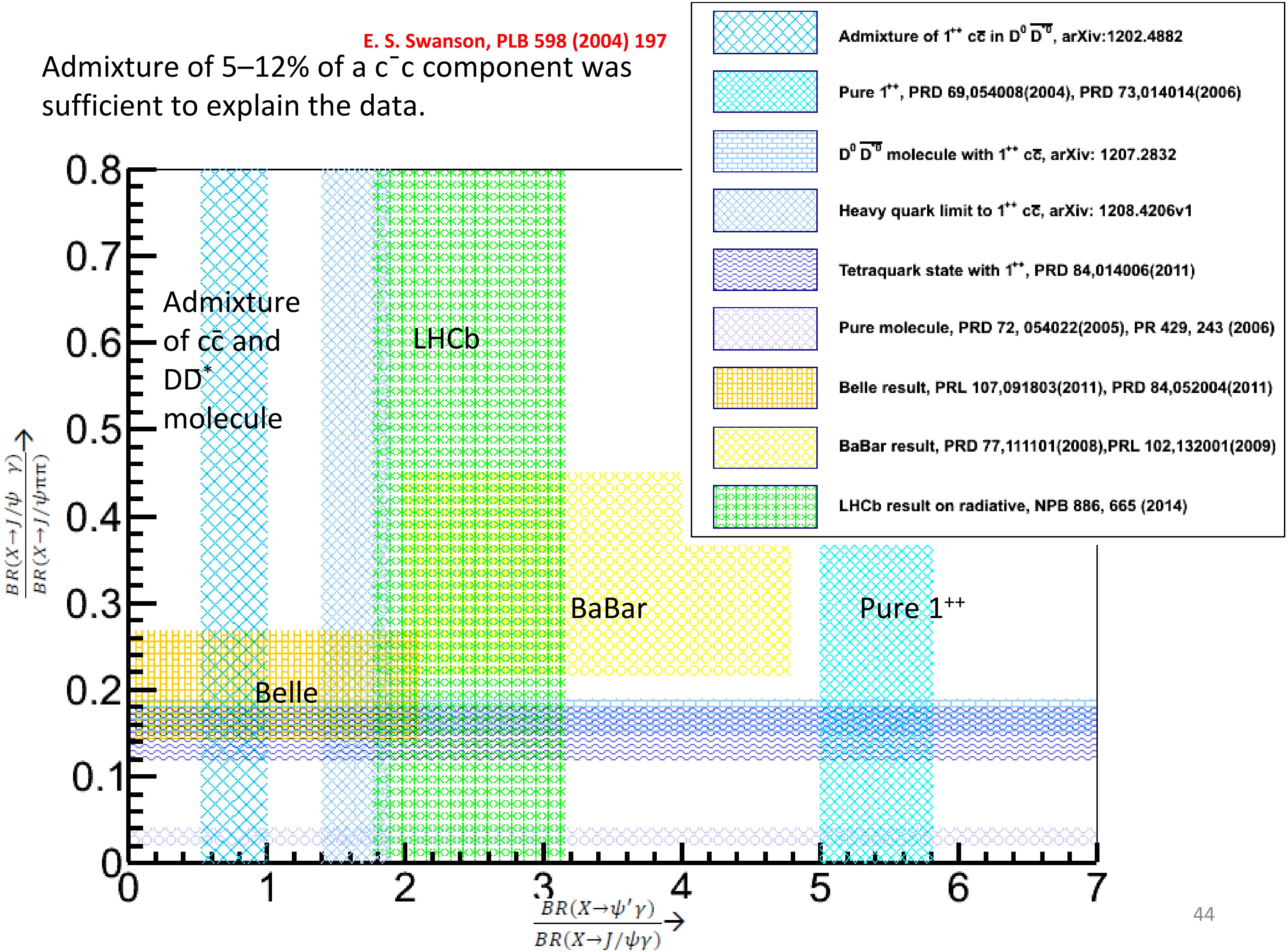
LHCb NPB 886, 665 (2014)

LHCb saw signal in $X(3872) \to \Psi'\gamma$, consistent with Belle and BaBar

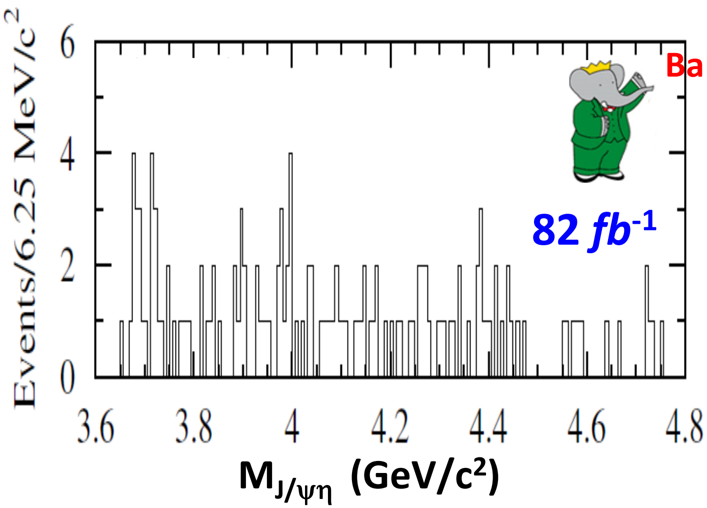
$$\frac{\mathcal{B}(X \to \psi'\gamma)}{\mathcal{B}(X \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

E. S. Swanson, PLB 598 (2004) 197

Admixture of 5–12% of a $\bar{c}c$ component was sufficient to explain the data.

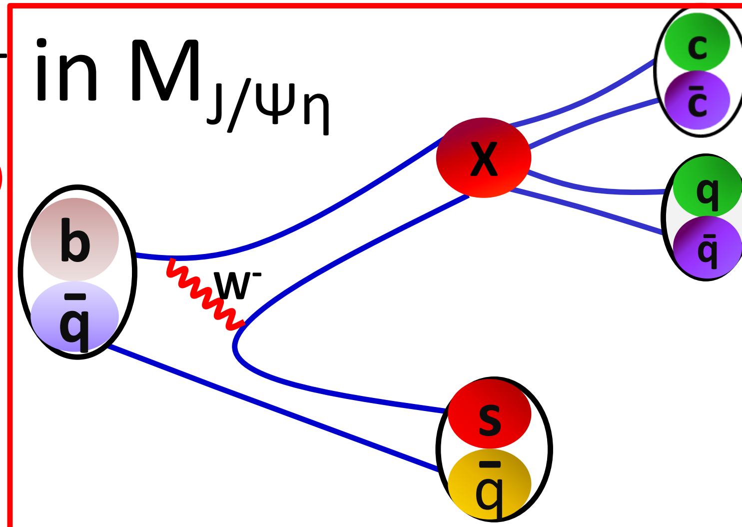


Search for X(3872)$^{c-}$ in $M_{J/\psi\eta}$



BaBar,PRL 93, 041801 (2004)

No signal was seen in X(3872) region.

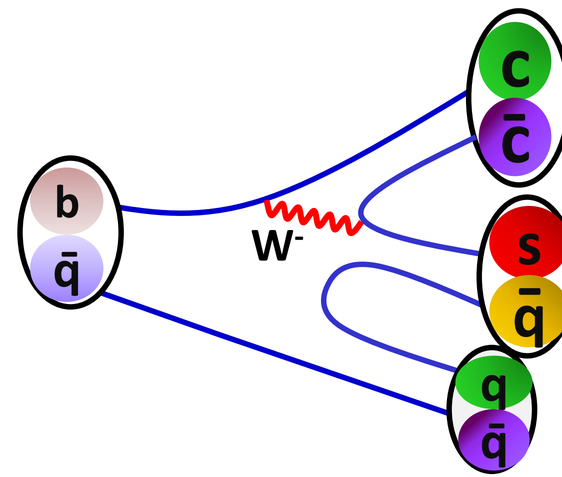


Most interesting

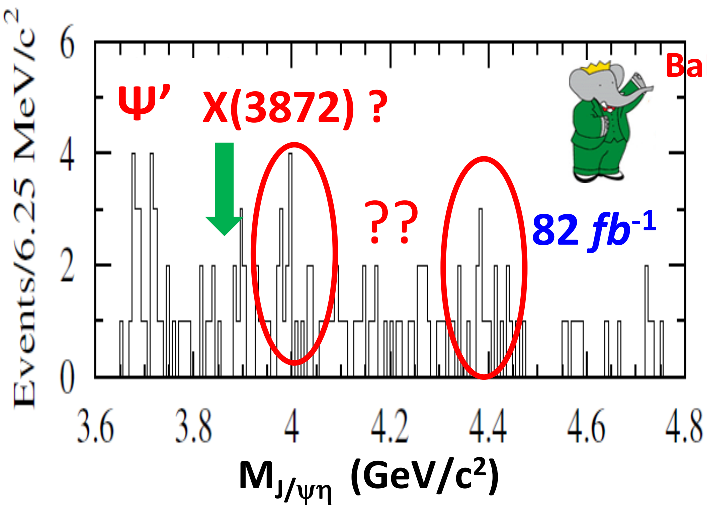
$\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow J/\psi\eta) < 7.7 \times 10^{-6}$ (90% CL)

BaBar observed $B^+ \rightarrow J/\Psi\eta K^+$ and provided

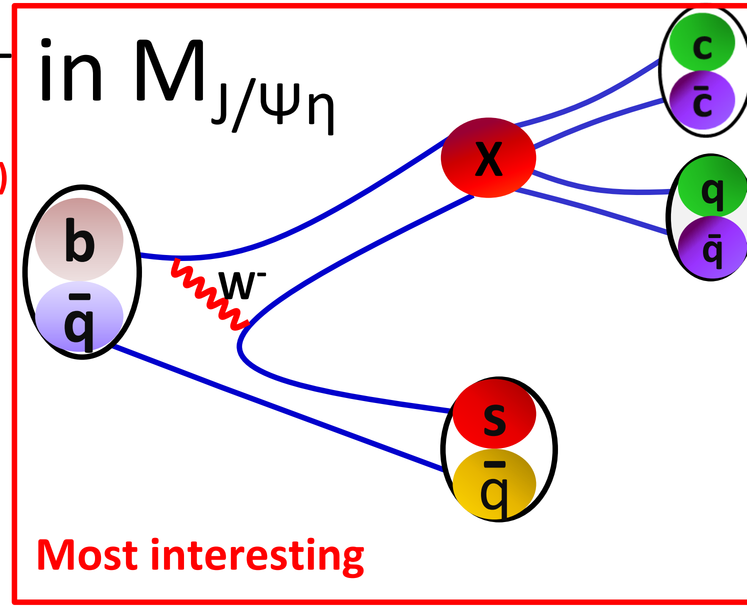
$\mathcal{B}(B^+ \rightarrow J/\psi\eta\ K^+) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$



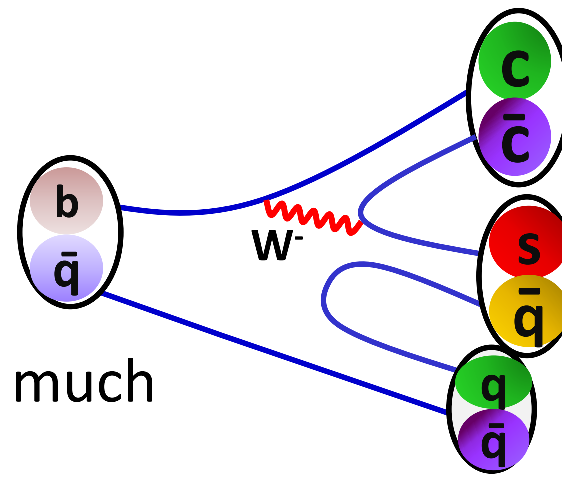
Search for X(3872)$^{c-}$ in $M_{J/\psi\eta}$



No signal was seen in X(3872) region.



$\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to J/\psi\eta) < 7.7 \times 10^{-6}$ (90% CL)



BaBar observed $B^+ \to J/\Psi\eta K^+$ and provided

$$\mathcal{B}(B^+ \to J/\psi\eta\, K^+) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$$

With more data (9x), we can either rule out or put much tighter constraint on the X(3872)$^{c-}$ partner.

Above 3.9 GeV, some hint of new states?

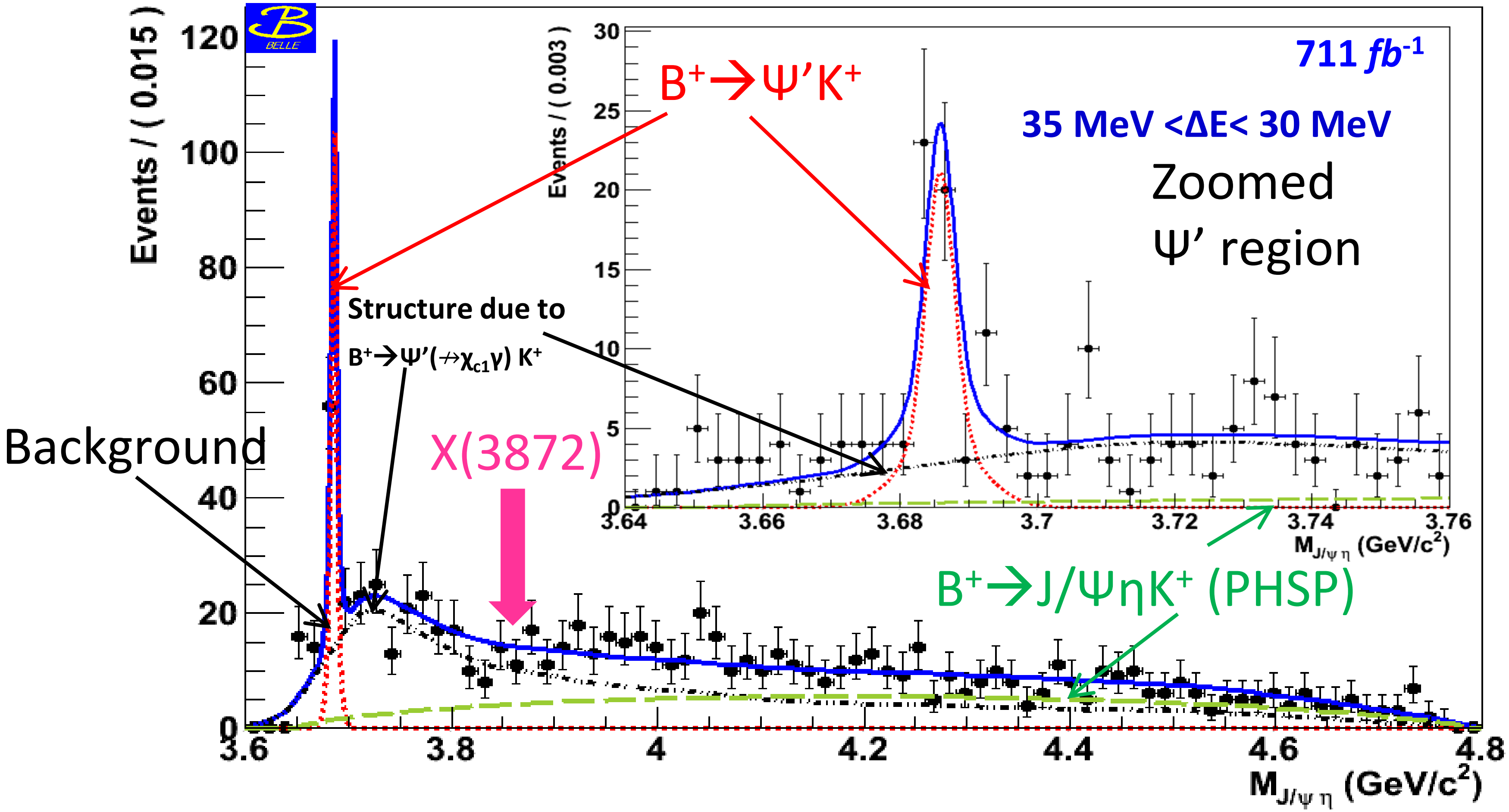
Additional motivation

"Search for new state in $M_{J/\psi\eta}$"

(Belle) PTEP 2014, 043C01 (2014)

$M_{J/\Psi\eta}$ distribution

$B^{\pm} \to J/\Psi\eta K^{\pm}$



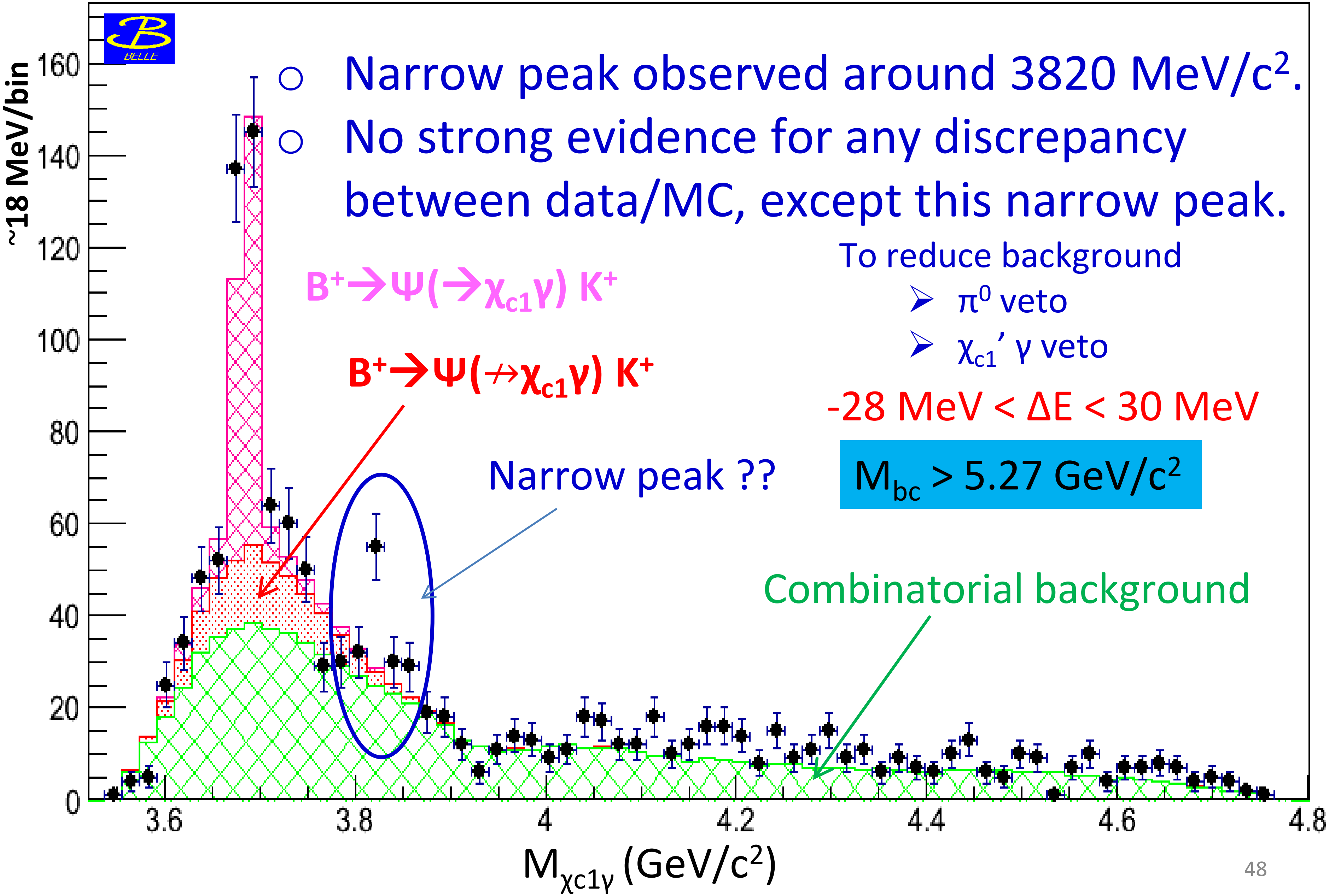
- After including phase space (PHSP) component of $B \to J/\Psi\eta K$, data/MC agrees quite well.

Much tighter constraint to the C-odd partner of X(3872).

711 fb^{-1}

$M_{\chi c1 \gamma}$ distribution

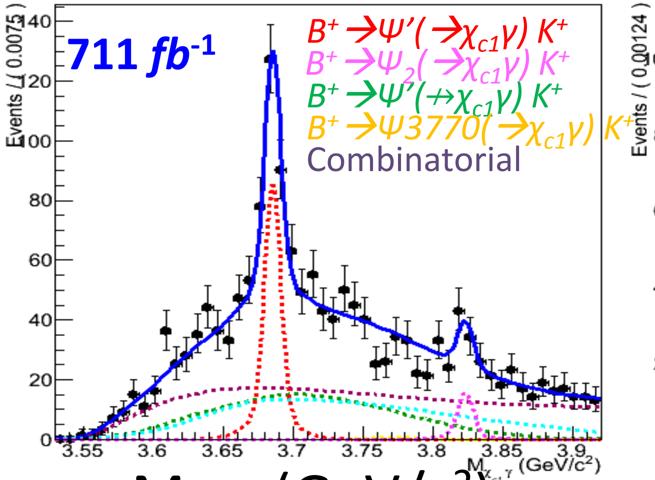
$B^{\pm} \rightarrow \chi_{c1} \gamma K^{\pm}$



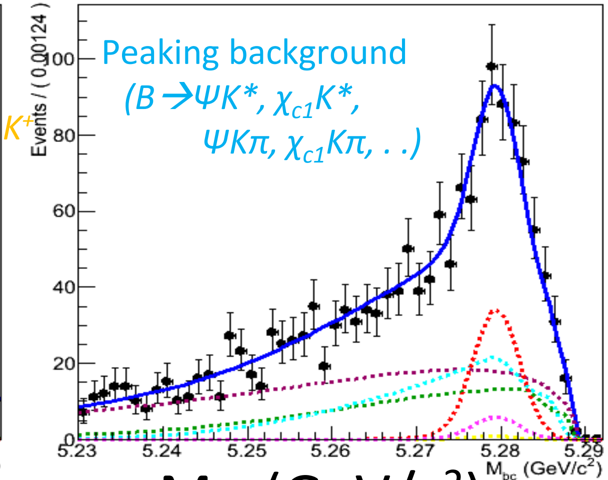
(Belle) PRL 111,032001(2013)

New state @ 3823

$B^{\pm} \to \chi_{c1}\gamma K^{\pm}$



$M_{\chi c1\gamma}$ (GeV/c²)



M_{bc} (GeV/c²)

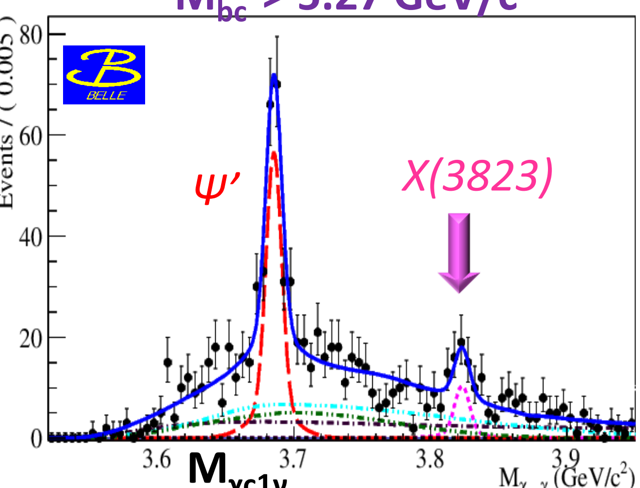
Clear evidence of a peak at 3823MeV/c²

Yield: 3.8σ (syst. Included)
33.2±9.7 events

Γ = 1.7±5.5 MeV if fitted, poor sensitivity

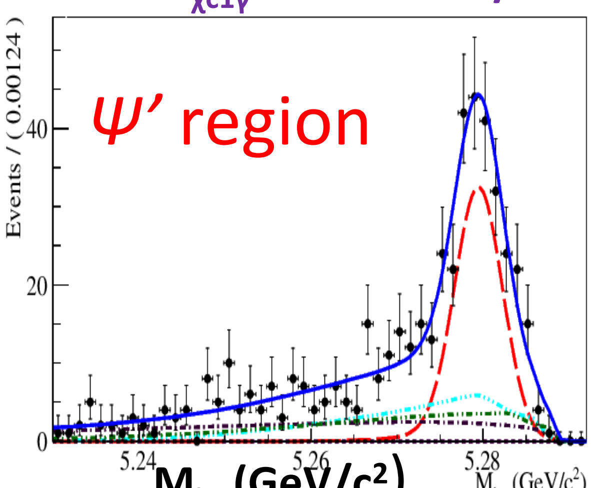
Projection in signal region

M_{bc} > 5.27 GeV/c²



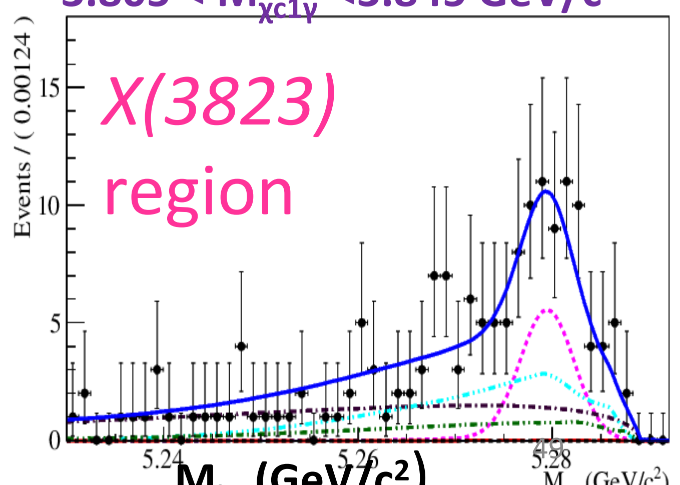
$M_{\chi c1\gamma}$

3.66 < $M_{\chi c1\gamma}$ <3.708 GeV/c²



M_{bc} (GeV/c²)

3.805 < $M_{\chi c1\gamma}$ <3.845 GeV/c²



M_{bc} (GeV/c²)

(Belle) PRL 111,032001(2013)

Interpretation of *X(3823)* as Ψ_{2D}

TABLE III: Charmonium spectrum, including the influence of open-charm channels. All masses are in MeV. The penultimate column holds an estimate of the spin splitting due to tensor and spin-orbit forces in a single-channel potential model. The last column gives the spin splitting induced by communication with open-charm states, for an initially unsplit multiplet.

State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	$2\,979.9^a$	$3\,067.6^b$	−90.5	+2.8
1^3S_1	$3\,096.9^a$		+30.2	−0.9
1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	+5.9
1^3P_1	$3\,510.5^a$		-11.6^e	−2.0
1^1P_1	3 525.3		$+1.5^e$	+0.5
1^3P_2	$3\,556.2^a$		-31.9^e	−0.3
2^1S_0	$3\,637.7^a$	$3\,673.9^b$	−50.4	+15.7
2^3S_1	$3\,686.0^a$		+16.8	−5.2
1^3D_1	$3\,769.9^{ab}$	$(3\,815)^d$	−40	−39.9
1^3D_2	3 830.6		0	−2.7
1^1D_2	3 838.0		0	+4.2
1^3D_3	3 868.3		+20	+19.0
2^3P_0	3 931.9	$3\,968^d$	−90	+10
2^3P_1	4 007.5		−8	+28.4
2^1P_1	3 968.0		0	−11.9
2^3P_2	3 966.5		+25	−33.1

S. Godfrey & N. Isgur, PRD 32, 189 (1985)
E. Eichten et al., PRL 89,162002 (2002), PRD 69, 094019 (2004)

Three states with similar mass (predicted): $^3D_2$, $^1D_2$, $^3D_3$

- $^1D_2$ excluded due to C conservation in EM decays.
- $^3D_3$ doesn't have transition to $\chi_{c1}\gamma$
- $^3D_2$ seems to be appropriate

- Ψ_2 below $D\bar{D}^*$ threshold: expected to be narrow
- Mostly decaying into $\chi_{c1}\gamma$.

The observed peak (@3823) has not been seen in $D\bar{D}$ ($^3D_2 \nrightarrow DD$ is expected).

$\frac{\Gamma(X(3823)\to\chi_{c2}\gamma)}{\Gamma(X(3823)\to\chi_{c1}\gamma)}$ <0.41 (@ 90% CL) , Expected $\frac{\Gamma(\Psi_2\to\chi_{c2}\gamma)}{\Gamma(\Psi_2\to\chi_{c1}\gamma)}$ ~ 0.2 (model dependent)

PRL 89, 162002 (2002); PRD 67, 014027 (2003)

If we assume, $B(\Psi_2\to\chi_{c1}\gamma) = 0.64$ PRD 55, 4001 (1997), PLB 395, 107 (1997)

$\frac{\mathcal{B}(B\to\Psi_2 K)}{\mathcal{B}(B\to\Psi' K)} \sim 0.02$

Factorization penalty similar to the one observed in $B\to\chi_{c2}K$

$\frac{\mathcal{B}(B\to\chi_{c2}K)}{\mathcal{B}(B\to\chi_{c1}K)} = 0.022\pm0.007$

Belle, PRL 107, 091803 (2011)

Suppression w.r.t. to $J^{PC}=1^{--}$, similar to the observed suppression of $J^{PC}=2^{++}$ w.r.t. $J^{PC}=1^{++}$.

X(3823) seems to be the missing $\Psi_{2D}(1^3D_2)$ from the charmonium spectrum .

4.67fb^{-1}

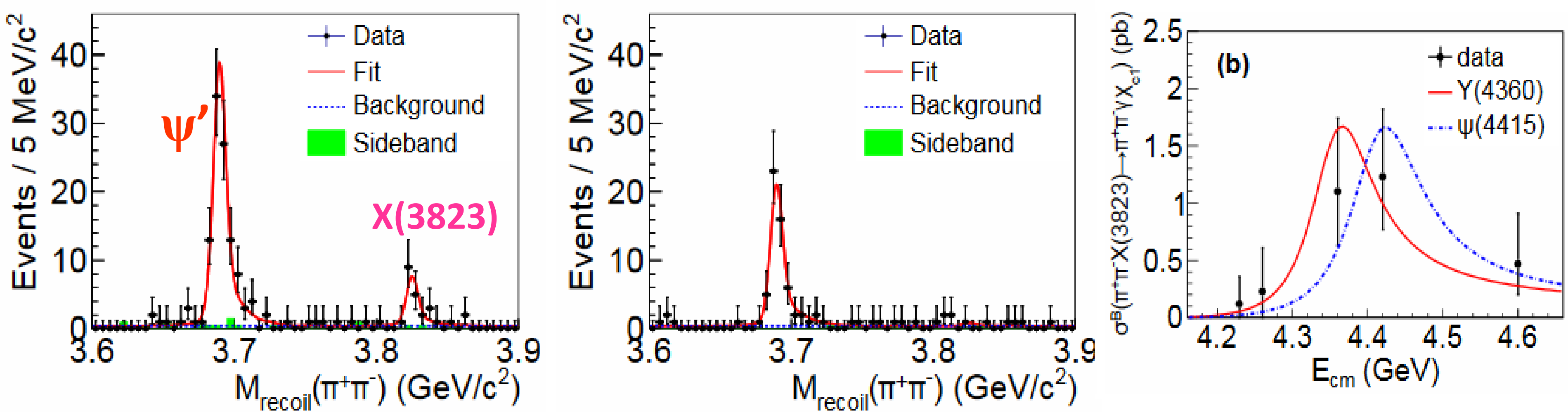
Confirmation of X(3823) by BES III !

BESIII, PRL 115,011803(2015)

$$e^+e^- \to \boxed{\pi^+\pi^-} X$$

$\sqrt{s}$ = 4.19 to 4.60 GeV

Reconstruct the two pions and look at the recoil mass



X(3823) has been confirmed by BES III with 6.2σ significance.

$M_{X(3823)}$=3821.7±1.3 ±0.7 MeV

$\Gamma_{X(3823)}$ < 16 MeV (90% CL)

$$\frac{\Gamma(X(3823)\to\chi_{c2}\gamma)}{\Gamma(X(3823)\to\chi_{c1}\gamma)} < 0.42 \text{ (@ 90\% CL)}$$

X(3823) is now a confirmed state !

BESIII also prefer $\Psi_{2D}(1^3D_2)$

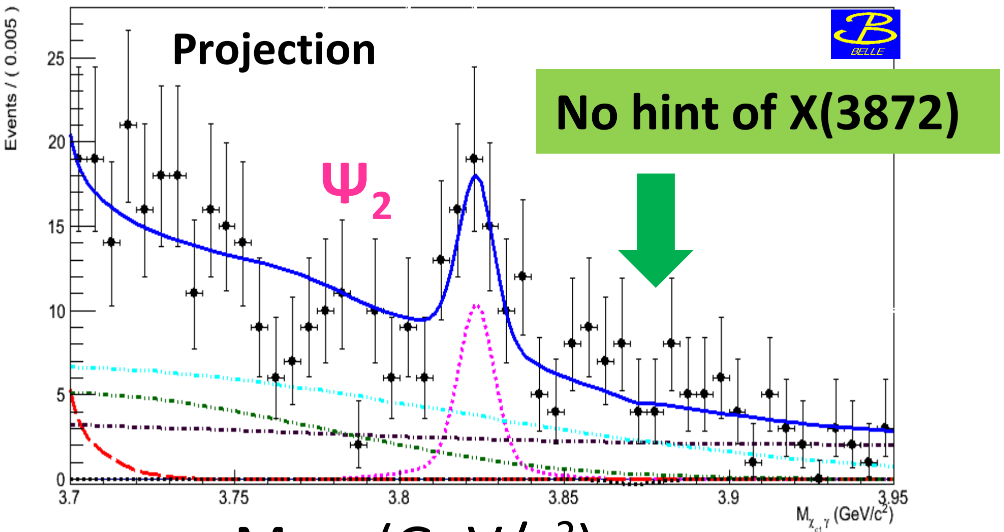
$B^{\pm} \to \chi_{c1}\gamma K^{\pm}$

$X(3872)^{C-}$

711 fb^{-1}

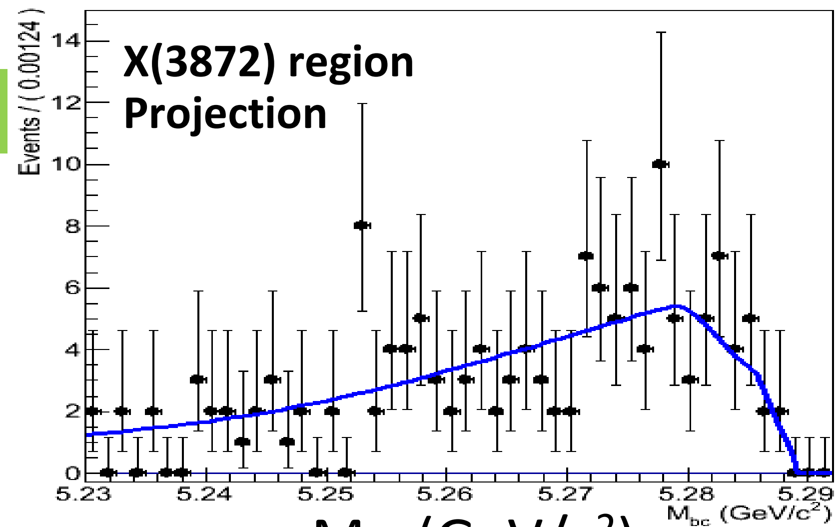
X(3872) yield : -0.9±5.1 events

Belle PRL 111,032001(2013)



$M_{\chi c1\gamma}$ (GeV/c²)

M_{bc} > 5.27 GeV/c²



M_{bc} (GeV/c²)

3.84< $M_{\chi c1\gamma}$< 3.9 GeV/c²

No signal is observed in the X(3872) region.

$\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \times \mathcal{B}(X(3872) \to \chi_{c1}\gamma) < 2.0 \times 10^{-6}$ (@90% CL)

$$\frac{\Gamma(X3872 \to \chi_{c1}\gamma)}{\Gamma(X3872 \to J/\Psi\pi\pi)} < 0.26$$

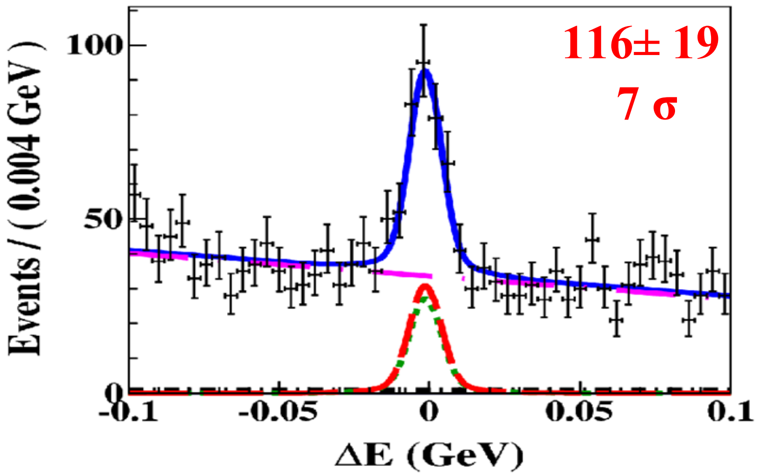
Belle, PRD 85,052004 (R) (2011)

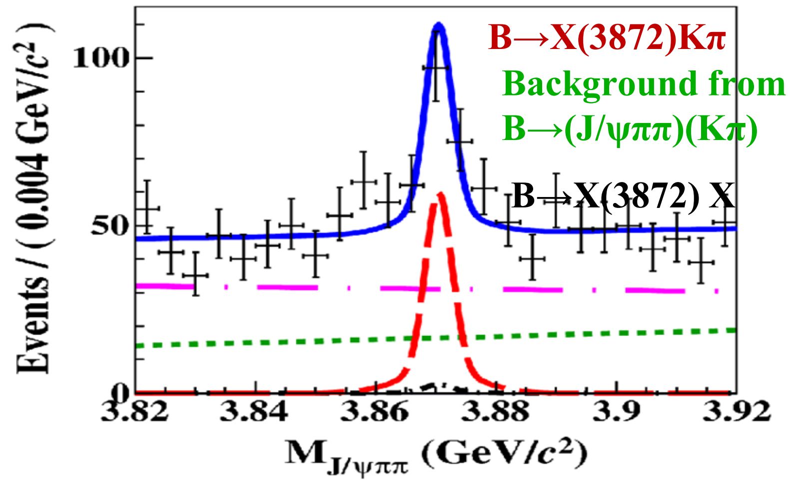
* Recent Belle result used for BR(B→X3872K)*BR(X3872→J/Ψπ⁺π⁻).

Belle PRD91, 051101 (R) (2015)

B→X(3872) Kπ decay mode

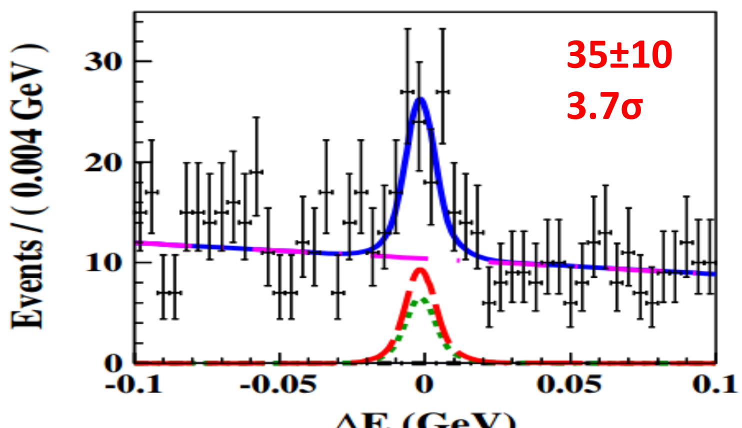
Production of X(3872) also provides an opportunity to understand its nature.

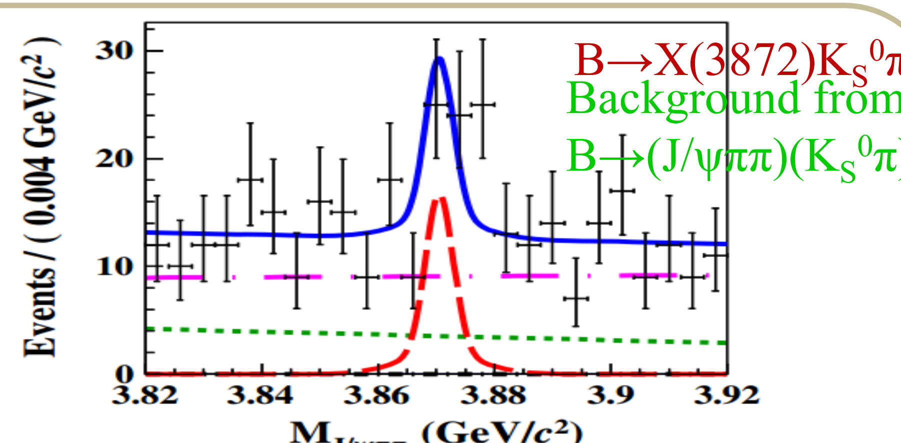




A clear signal peak is observed for $B^0 \to X(3872)K^+\pi^-$ decay mode

$\mathcal{B}(B^0 \to X(3872)K^+\pi^-)\times\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-) = (7.91 \pm 1.29 \pm 0.43)\times 10^{-6}$





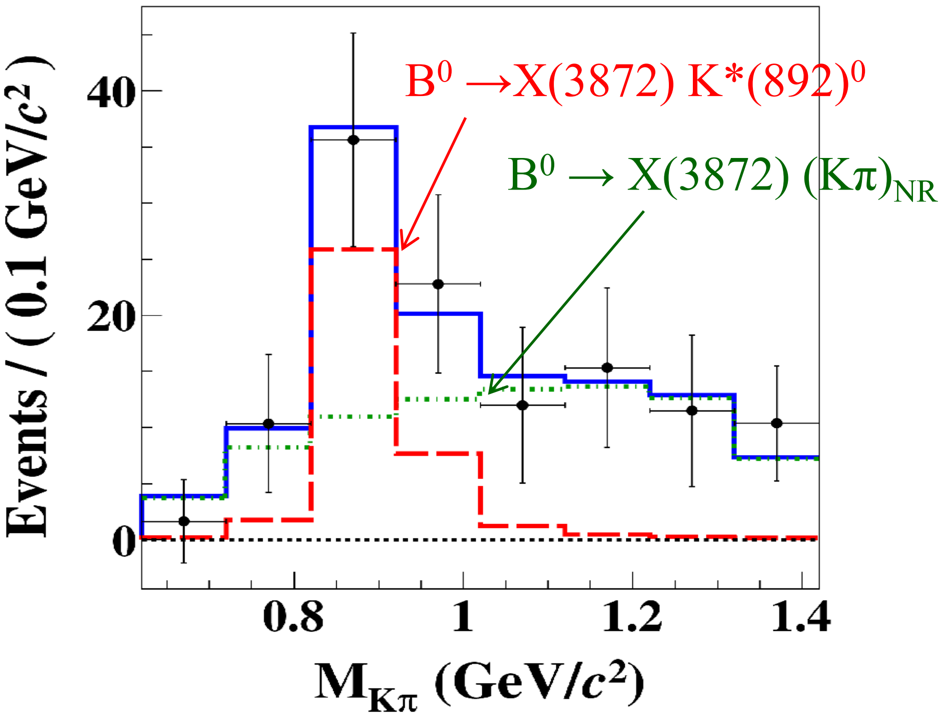
First evidence for $B^+ \to X(3872)K_S^0\pi^+$ decay mode

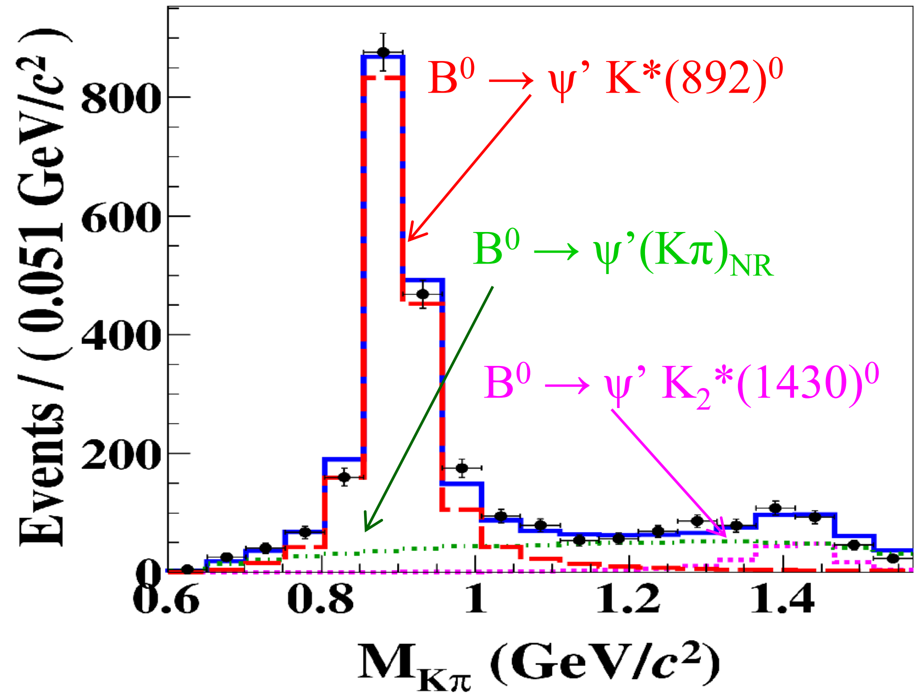
$\mathcal{B}(B^+ \to X(3872)K^0\pi^+)\times\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-) = (10.61 \pm 3.04\ (stat) \pm 0.85(syst))\times 10^{-6}$

$B^0 \to X(3872)K^+\pi^-$

Fit to background subtracted M(Kπ)

Belle PRD91, 051101 (R) (2015)





$$\frac{\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(K^*(892)^0 \to K^+\pi^-)}{\mathcal{B}(B^0 \to X(3872)K^+\pi^-)} = 0.34 \pm 0.09(\text{stat.}) \pm 0.02(\text{syst.})$$

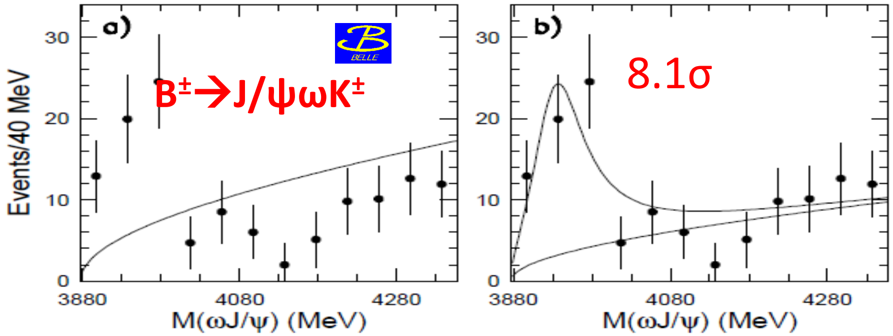
while

$$\frac{\mathcal{B}(B^0 \to \psi' K^*(892)^0) \times \mathcal{B}(K^*(892)^0 \to K^+\pi^-)}{\mathcal{B}(B^0 \to \psi' K^+\pi^-)} = 0.68 \pm 0.01(\text{stat.})$$

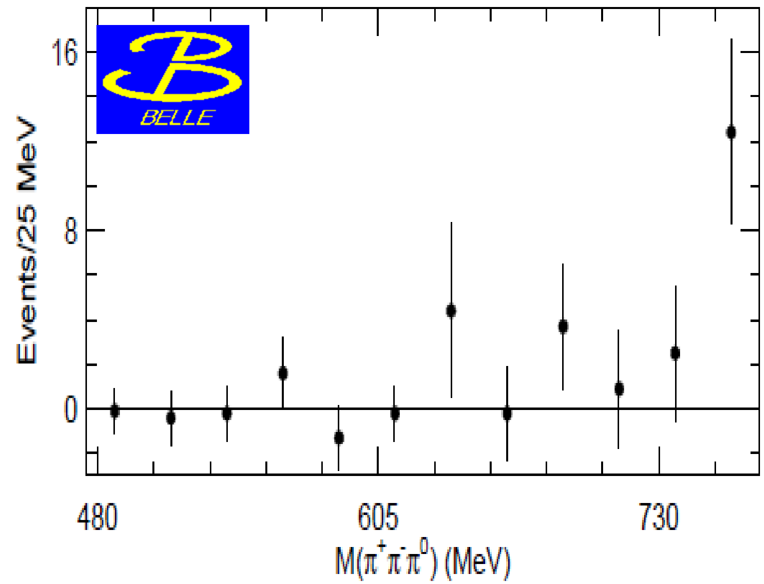
- Here $K^*(892)^0$ has less contribution as compared to the level seen in Ψ'.

$X(3872) \rightarrow J/\psi\omega$

275 BB̄ pairs

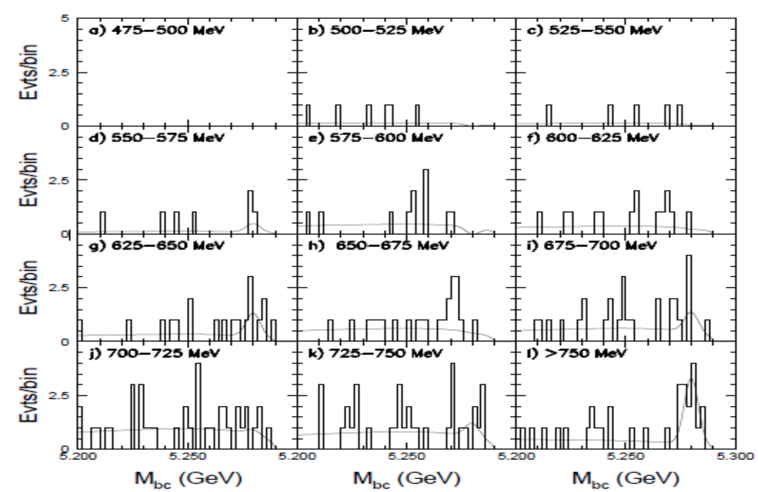


Belle found enhancement in $J/\psi\omega$ in $B^{\pm} \rightarrow J/\psi\omega K^{\pm}$ Y(3940). **Belle, PRL 94, 182002 (2005)**



- Re analysis by Belle, by cutting at $M_{J/\psi\pi^+\pi^-\pi^0}$ around X(3872) mass ±3σ
- This suggest that $X(3872) \rightarrow J/\psi\omega$

Belle, arXiv:hep-ex/0505037



$$\frac{BR(X(3872)\rightarrow J/\Psi\pi^+\pi^-\pi^0)}{BR(X(3872)\rightarrow J/\Psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

For $M(\pi^+\pi^-\pi^0) > 750$ MeV/c^2

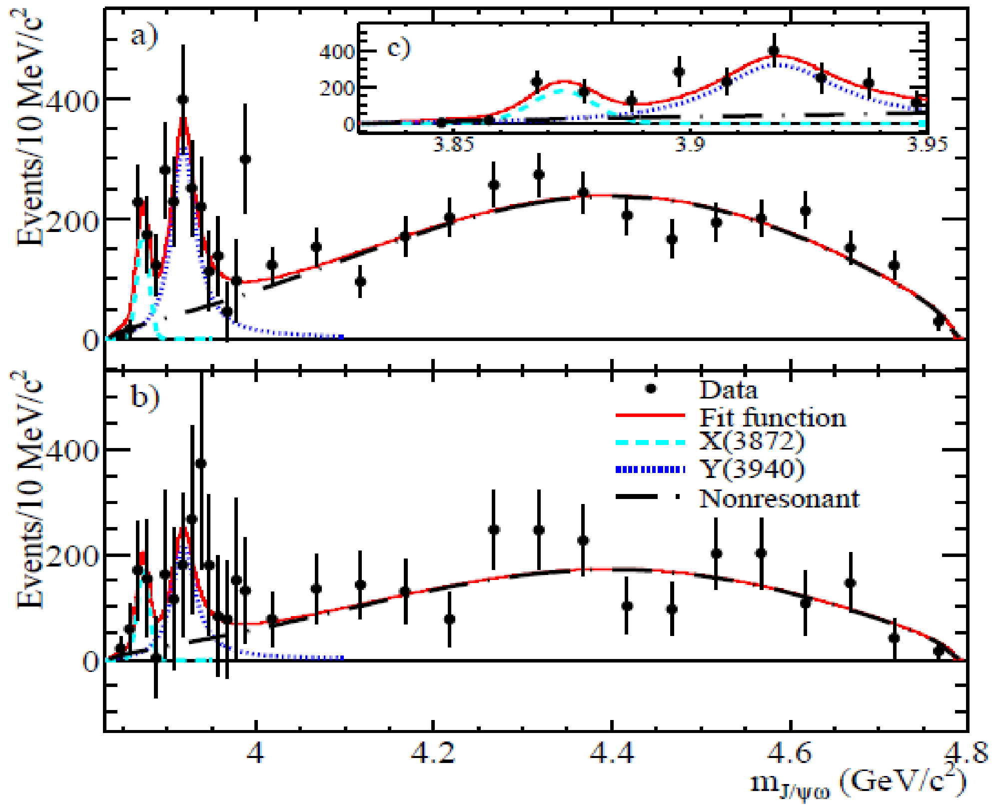
X(3872)→ J/ψω

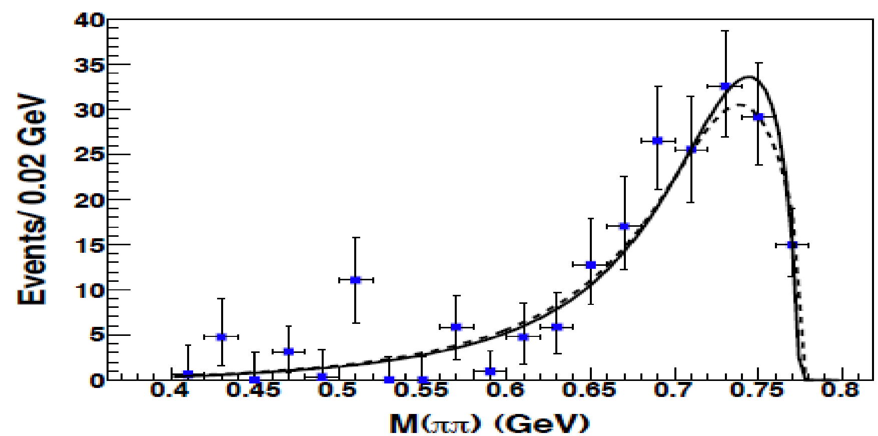
BaBar Full Data

- Analysis by BaBar with 467 $B\bar{B}$ pairs, observes a clear peak of X(3872)→J/ψω.

$$\frac{BR(X(3872)\rightarrow J/\Psi\omega)}{BR(X(3872)\rightarrow J/\Psi\pi^{+}\pi^{-})} = \mathbf{0.8 \pm 0.3}$$

Why this ratio is important ?





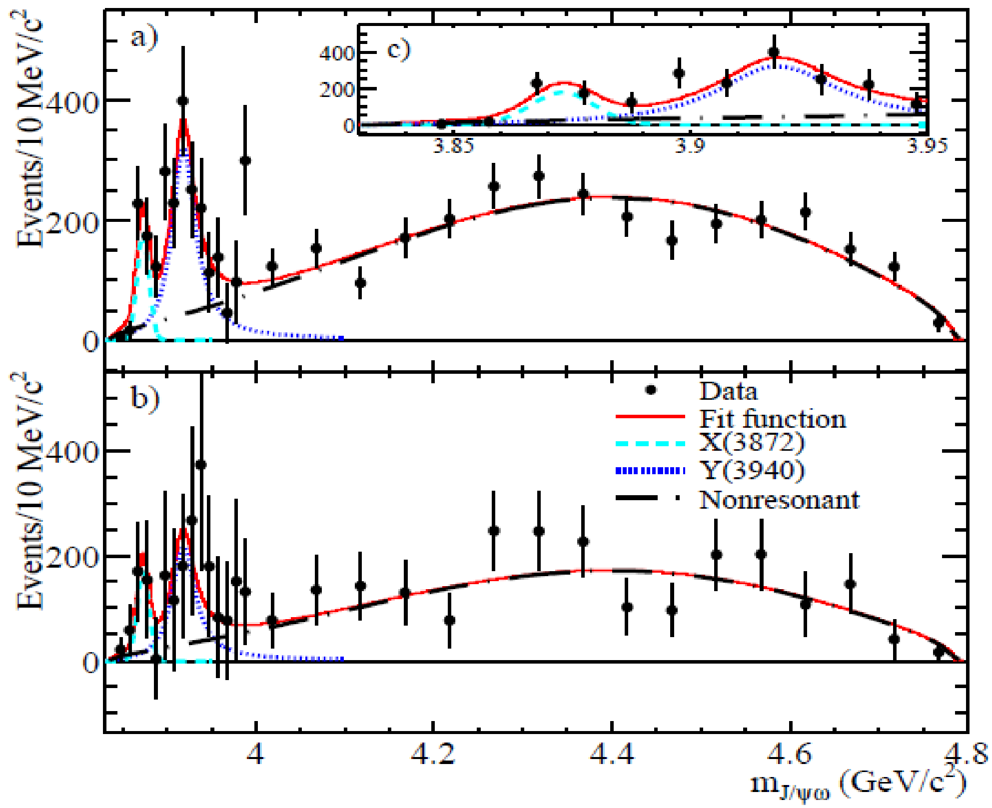
X(3872)→ J/ψω

BaBar Full Data

- Analysis by BaBar with 467 $B\bar{B}$ pairs, observes a clear peak of X(3872)→J/ψω.

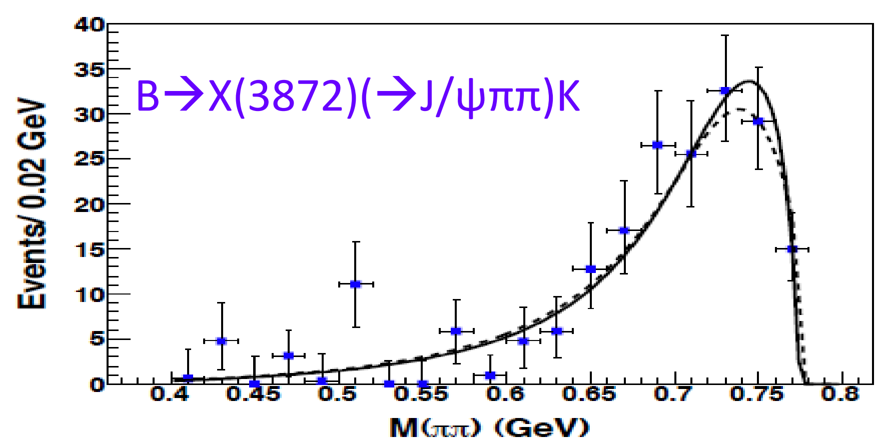
$$\frac{BR(X(3872)\rightarrow J/\Psi\omega)}{BR(X(3872)\rightarrow J/\Psi\pi^{+}\pi^{-})} = 0.8\pm0.3$$

Why this ratio is important ?



No charged partner of X(3872) is found, X(3872) iso-singlet state.
This implies that X(3872) →J/ψππ is isospin non-conserving.

This is another puzzling nature of X(3872) !



Admixture, most plausible interpretation ?

No signature for

- Charged partner in $J/\Psi\pi^+\pi^0$
- C=-1 partner in $J/\Psi\eta$, $\chi_{c1}\gamma$, $\eta_c\omega$ and $\eta_c\pi^+\pi^-$
  - Disfavor tetraquark hypothesis.

No signal in $X(3872)\rightarrow\chi_{c1}\pi^+\pi^-$ and $\chi_{c1}'\rightarrow\chi_{c1}\pi^+\pi^-$.

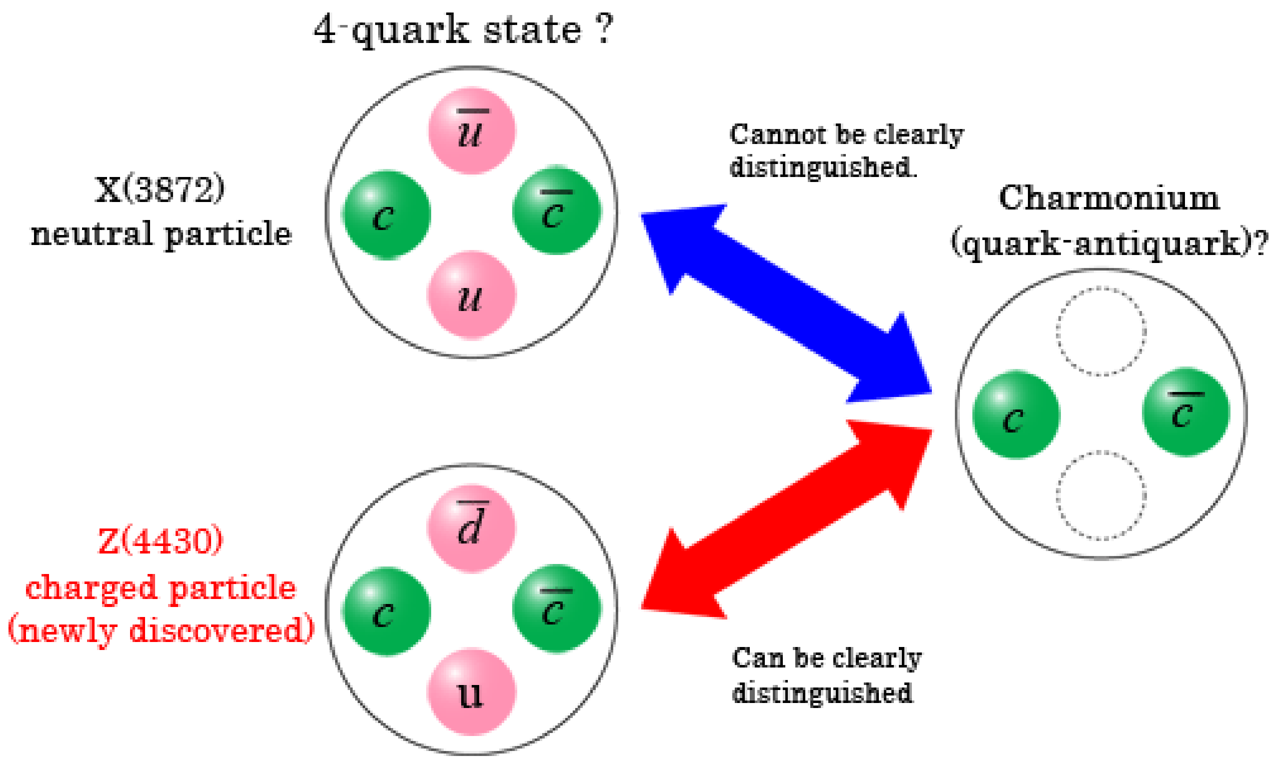
Remember $\chi_{c1}'\rightarrow J/\psi\rho$ violate isospin and is suppressed !

$D\bar{D}^*$ molecule is mixing with the same J^{PC} $c\bar{c}$, $\chi_{c1}(2P)$ (yet unseen).

- Explain $BR(X\rightarrow D^0\bar{D}^{*0})/BR(X\rightarrow J/\Psi\pi\pi)$ is about 10.
  - (pure molecule case, to be about 1000).

Pure molecule is too fragile to be produced in Tevatron/LHC.

Tetraquark searches



$Z(4430)^+$

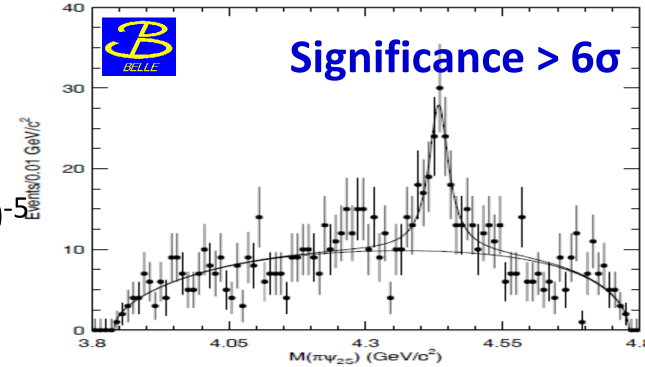
Belle, PRL 100, 142001 (2007)

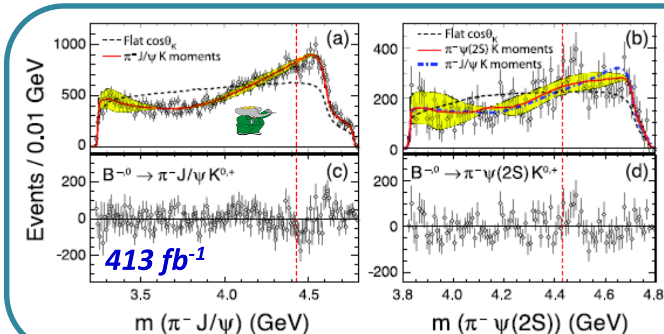
Veto $K^*(890)$ & $K_2^*(1430)$

$BR(B^0 \rightarrow K^- Z(4430)^+) \times BR(Z(4430)^+ \rightarrow \Psi'\pi^+) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

$M = (4433 \pm 4 \pm 2)$ MeV

$\Gamma = (45^{+18+30}_{-13-13})$ MeV





BaBar didn't found conclusive evidence for the $Z(4430)^+$

$BR(B^0 \rightarrow K^- Z(4430)^+) \times BR(Z(4430)^+ \rightarrow \Psi'\pi^+) < 3.1 \times 10^{-5}$

BaBar data (due to less statistics) doesn't refute the Belle observation of $Z^+(4430)$

BaBar, PRD79, 112001 (2009)

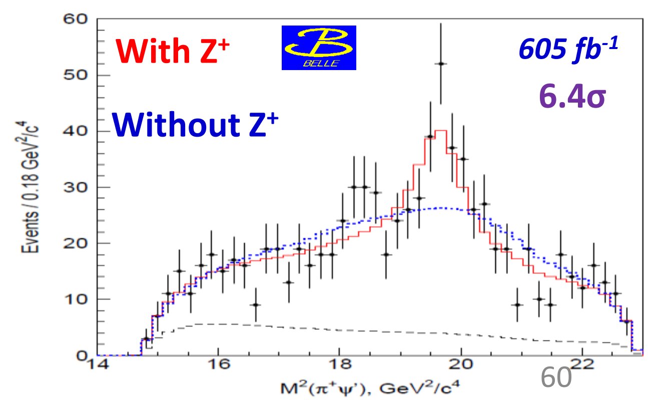
Re-analysis by Belle using sophisticated Dalitz fit

$M = (4443^{+15+17}_{-12-13})$ MeV

Belle, PRD80, 031104 (2009)

$\Gamma = (109^{+86+57}_{-43-52})$ MeV

$BR(B^0 \rightarrow K^- Z(4430)^+) \times BR(Z(4430)^+ \rightarrow \Psi'\pi^+) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$



$Z(4430)^+$

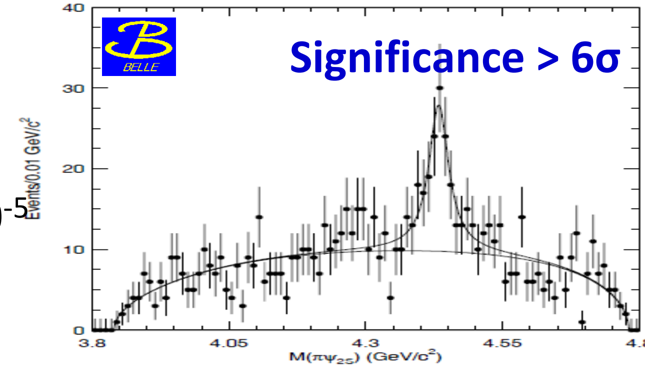
Belle, PRL 100, 142001 (2007)

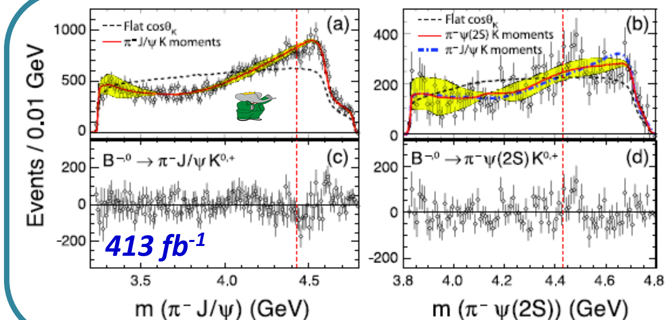
Veto $K^*(890)$ & $K_2^*(1430)$

$BR(B^0 \to K^- Z(4430)^+) \times BR(Z(4430)^+ \to \Psi'\pi^+) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

$M = (4433 \pm 4 \pm 2)$ MeV

$\Gamma = (45^{+18+30}_{-13-13})$ MeV





BaBar didn't found conclusive evidence for the $Z(4430)^+$

$BR(B^0 \to K^- Z(4430)^+) \times BR(Z(4430)^+ \to \Psi'\pi^+) < 3.1 \times 10^{-5}$

BaBar data (due to less statistics) doesn't refute the Belle observation of $Z^+(4430)$

BaBar, PRD79, 112001 (2009)

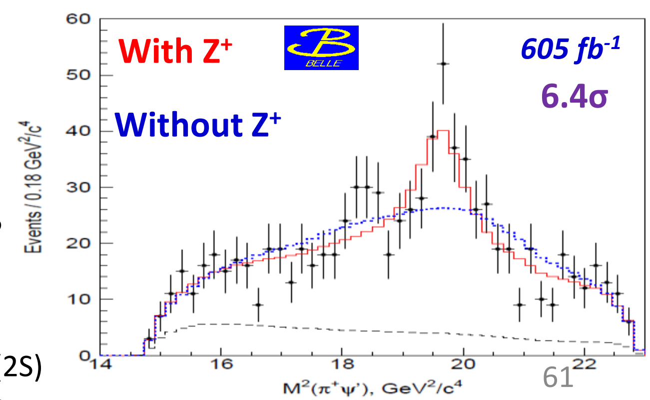
Re-analysis by Belle using sophisticated Dalitz fit

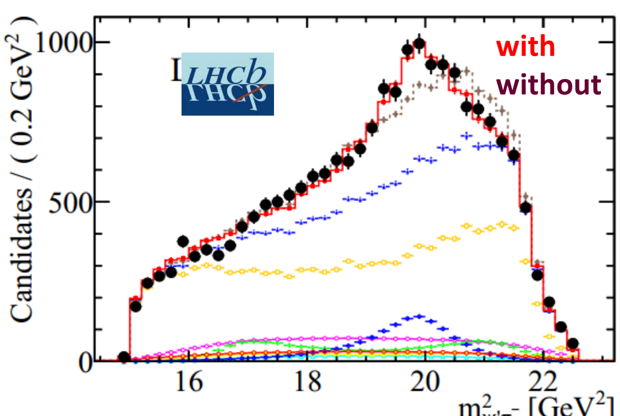
$M = (4443^{+15+17}_{-12-13})$ MeV

$\Gamma = (109^{+86+57}_{-43-52})$ MeV

Belle, PRD80, 031104 (2009)

$BR(B^0 \to K^- Z(4430)^+) \times BR(Z(4430)^+ \to \Psi'\pi^+) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$





LHCb, PRL112, 222002 (2014)

4D fit ($M_{\Psi(2S)\pi^+}$, $M_{K\pi}$, $\cos\Theta_{\Psi(2S)}$ and ϕ) by LHCb confirm the Existence of $Z^+(4430)$

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

$\Gamma = (109 \pm 13^{+37}_{-34})$ MeV

$Z(4430)^+$

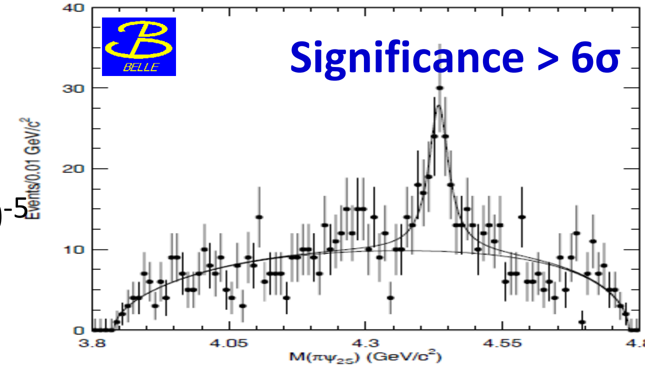
Belle, PRL 100, 142001 (2007)

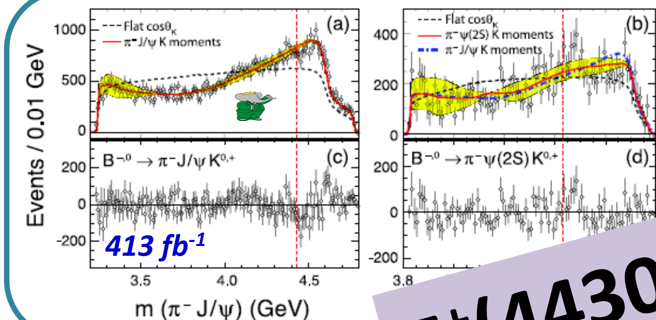
Veto K*(890) & K_2*(1430)

$BR(B^0 \rightarrow K^- Z(4430)^+) \times BR(Z(4430)^+ \rightarrow \Psi' \pi^+) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

$M = (4433 \pm 4 \pm 2)$ MeV

$\Gamma = (45^{+18+30}_{-13-13})$ MeV





BaBar didn't found conclusi… he $Z(4430)^+$

$BR(B^0 \rightarrow K^- Z(443$… $\pi^+) < 3.1 \times 10^{-5}$

BaB… atistics) doesn't refute the Belle … Z (4430)

BaBar, PRD79, 112001 (2009)

$Z^+(4430)$ is confirmed state now!

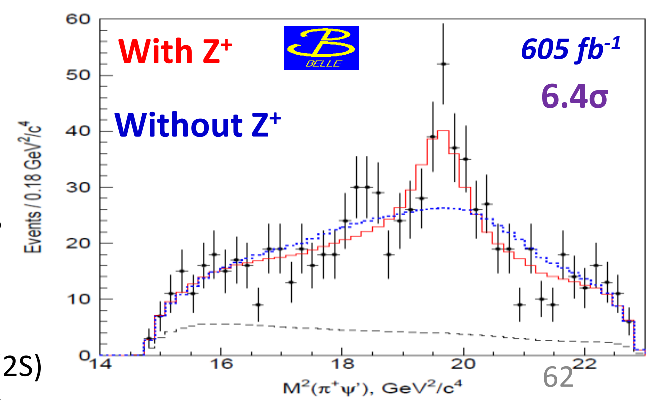
Re-analysis by Belle u… g sophisticated Dalitz fit

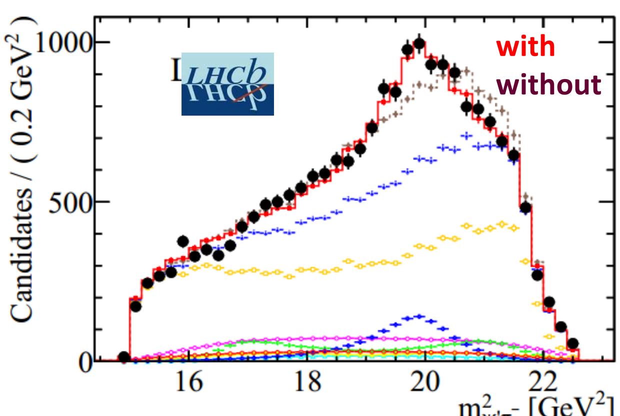
$M = (4443^{+15+17}_{-12-13})$ MeV

$\Gamma = (109^{+86+57}_{-43-52})$ MeV

Belle, PRD80, 031104 (2009)

$BR(B^0 \rightarrow K^- Z(4430)^+) \times BR(Z(4430)^+ \rightarrow \Psi' \pi^+) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$





LHCb, PRL112, 222002 (2014)

4D fit ($M\Psi_{(2S)\pi+}$, $M_{K\pi}$, $\cos\Theta_{\Psi(2S)}$ and ϕ) by LHCb confirm the Existence of $Z^+(4430)$

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

$\Gamma = (109 \pm 13^{+37}_{-34})$ MeV

Quantum number of Z(4430)+

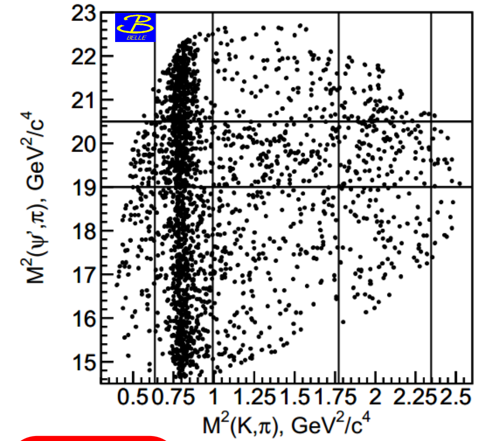
711 fb^{-1}

Belle,PRD 88, 074026 (2013)

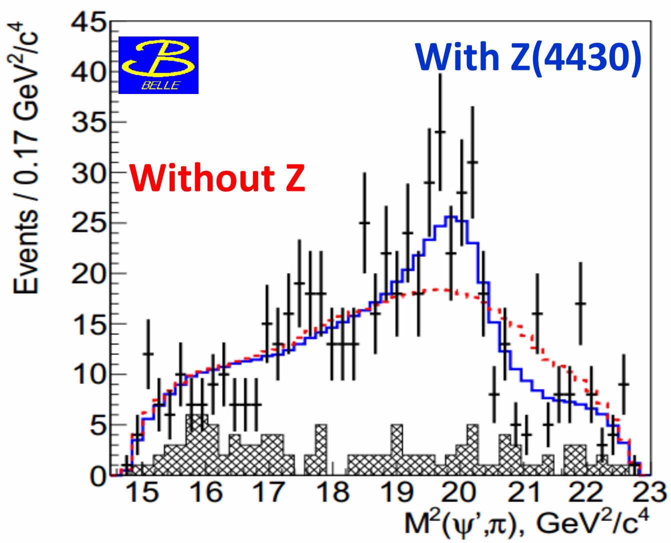
$B^0 \rightarrow (\Psi'\pi^+)K^-$ decay mode

Amplitude analysis in 4D space is performed

M(Kπ), M(Ψ'π),Ψ' helicity and angle between Ψ' and K*

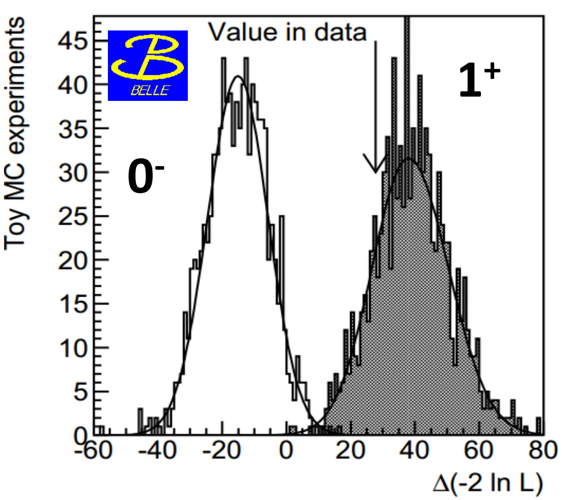


Projection of the fit results with K* veto



Mass and width consistent with previous Belle result

J^P	0^-	1^-	1^+	2^-	2^+
Mass,MeV/c^2	4479±16	4477±4	4485±20	4478±22	4384±19
Width,MeV	110±50	22±14	200±40	83±25	52±28
Significance	4.5σ	3.6σ	6.4σ	2.2σ	1.8σ



1^+ hypothesis is favored

Exclusion levels calculated from toy MC

- **1^+ is favored over 0^- by 3.4σ**
- **1^-, 2^- and 2^+ are excluded at levels of 3.7σ,4.7σ and 5.1σ**

$BR(B^0 \rightarrow \Psi' K^+\pi^-) = (5.80 \pm 0.39) \times 10^{-4}$

$BR(B^0 \rightarrow \Psi' K^*(892)) = (5.55^{+0.22+0.41}_{-0.23-0.84}) \times 10^{-4}$

$BR(B^0 \rightarrow Z(4430)^- K^+) \times BR(Z(4430)^- \rightarrow \Psi'\pi^-) = (6.0^{+1.7+2.5}_{-2.0-1.4}) \times 10^{-5}$

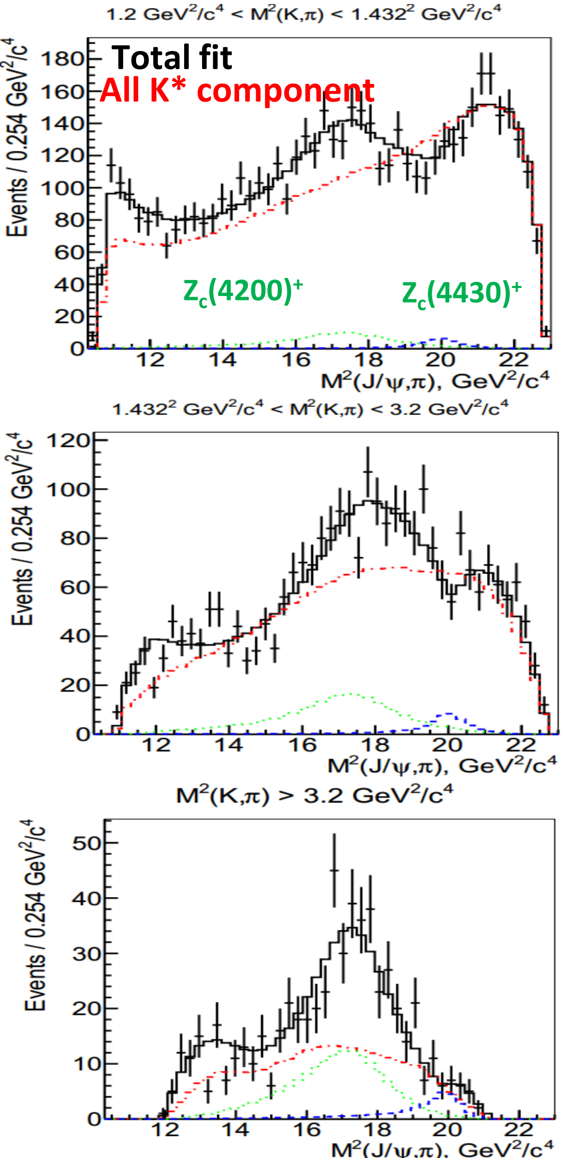
Amplitude analysis of B→J/ΨKπ

Belle, PRD 90, 112009 (2014)

Analysis similar to $Z_c(4430)^+$ quantum number.

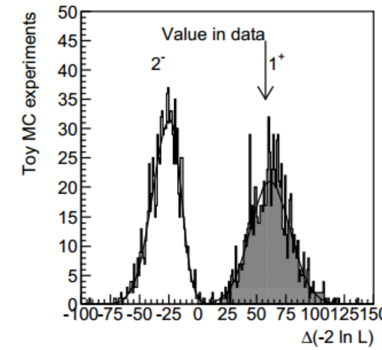
Resonances added : all K^*(10 resonances) and $Z_c(4430)^+$

Search for another Z_c^+ is performed



J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

New Z_c^+ is found ($J^P = 1^+$), $Z_c(4200)^+$



$M = (4196^{+31+17}_{-29-23})$ MeV

$\Gamma = (370^{+70+70}_{-70-132})$ MeV

- $J^P = 1^+$ favored
- While J^P having 0^-, 1^-, 2^- and 2^+ are excluded at the levels of 6.1σ, 7.4σ, 4.4σ and 7.0σ

$BR(B^0 \to J/\Psi K^+\pi^-) = (1.15 \pm 0.01 \pm 0.05) \times 10^{-3}$

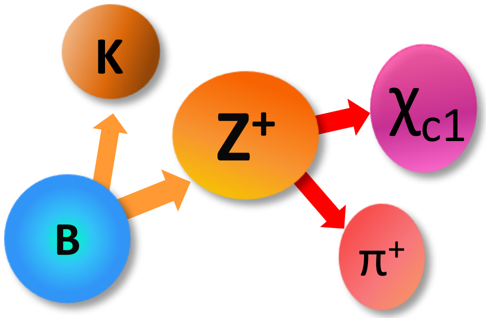
$BR(B^0 \to J/\Psi K^*(892)) = (1.19 \pm 0.01 \pm 0.08) \times 10^{-3}$

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

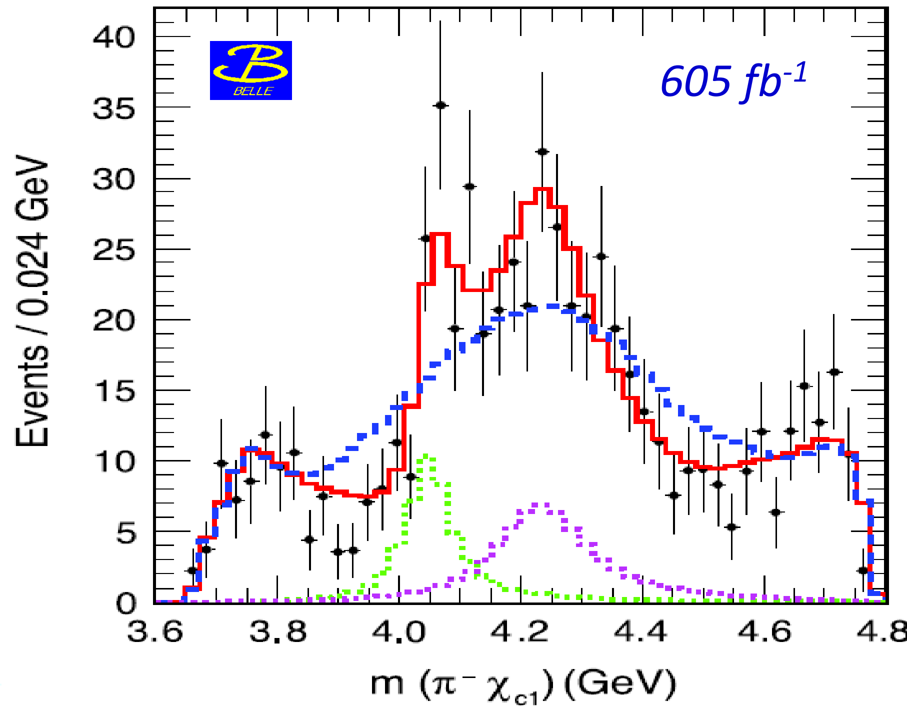
$BR(B^0 \to Z_c(4200)^- K^+) \times BR(Z_c(4200)^- \to J/\Psi\pi^-) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$

$BR(B^0 \to Z_c(3900)^- K^+) \times BR(Z_c(3900)^- \to J/\Psi\pi^-) < 9 \times 10^{-7}$ (90% CL)

$Z^+(4050)$ & $Z^+(4250)$



Belle, PRD80, 031104 (2009)



Isobar model :
$\chi_{c1}\pi$- resonance+ known $K^-\pi^+$

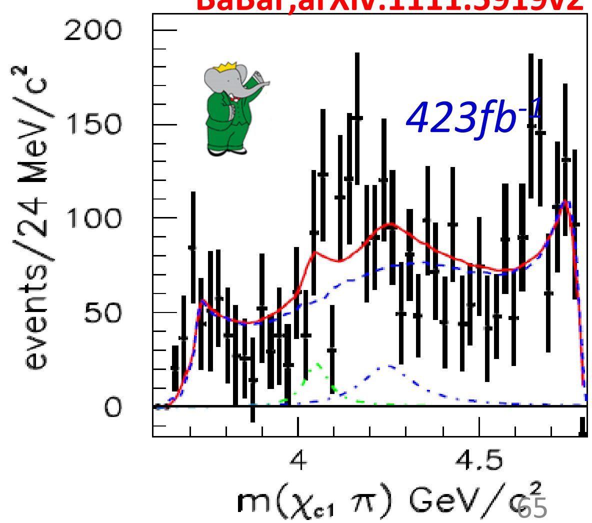
Without two Z^+ resonance

With two Z^+ resonance

Two resonance preferred at > 5σ

	Z_1^+	Z_2^+
M (MeV)	$4051 \pm 14^{+20}_{-41}$	$4248^{+44}_{-29}{}^{+180}_{-35}$
Γ (MeV)	$82^{+21}_{-17}{}^{+47}_{-22}$	$177^{+54}_{-39}{}^{+316}_{-61}$
$B_{\overline{B}^0} \times B_{Z^+}$ $(\times 10^{-5})$	$(3.1^{+1.5}_{-0.9}{}^{+3.7}_{-1.7})$	$(4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5})$

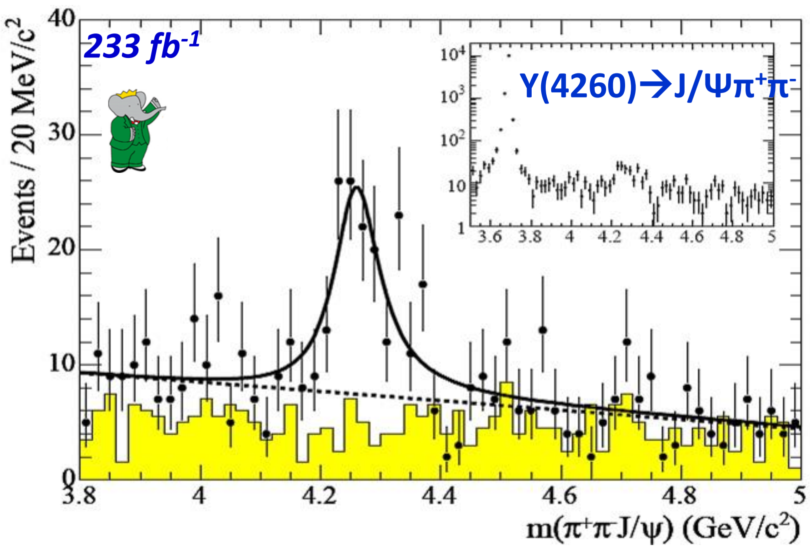
BaBar,arXiv:1111.5919v2

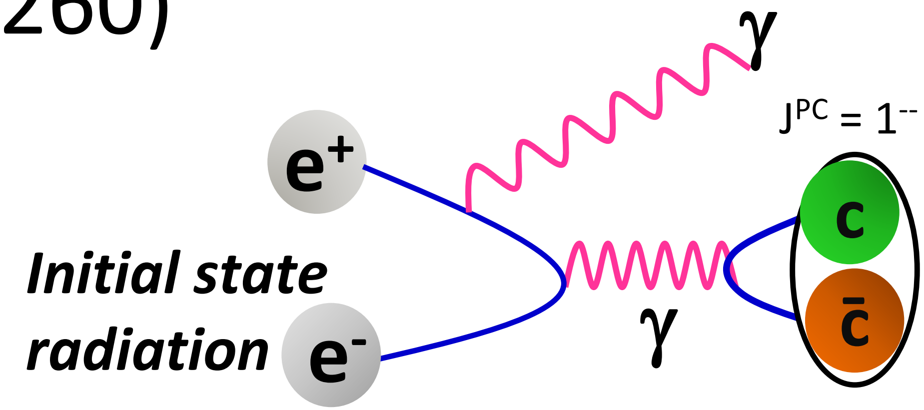


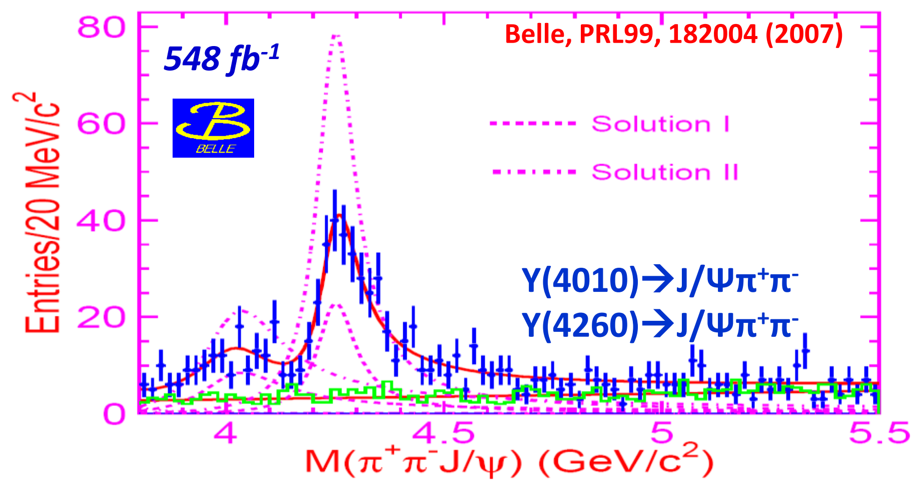
BaBar didn't find any strong evidence (in their search). However, they are limited by less statistics.

Y(4260)

BaBar, PRL95, 142001 (2005)





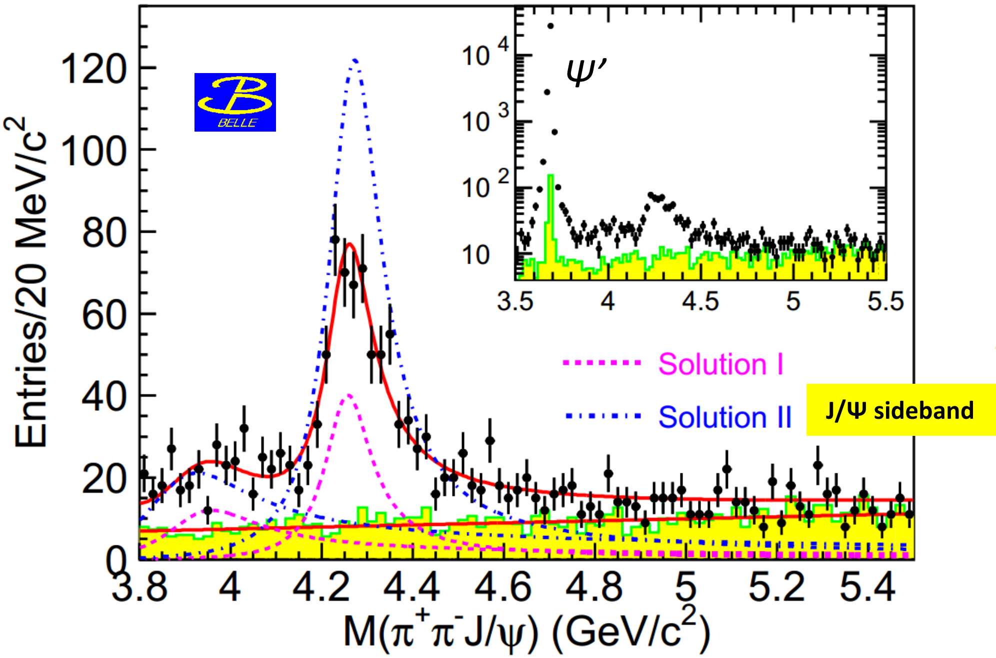


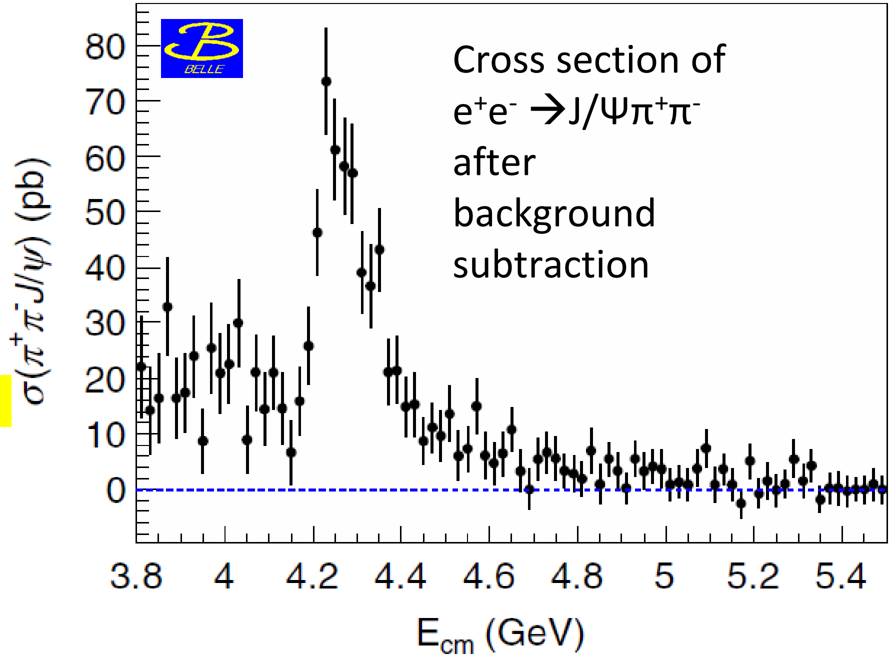
	Name	Process	M (MeV/c²)	Γ (MeV)
BaBar(233 fb⁻¹)	Y(4260)	J/Ψππ	$4259\pm8^{+2}_{-6}$	$88\pm23^{+6}_{-4}$
Belle (548 fb⁻¹)	Y(4260)	J/Ψππ	$4247\pm12\ ^{+17}_{-32}$	$108\pm19\pm10$
Belle (548fb⁻¹)	Y(4010) ?	J/Ψππ	$4008\pm40\ ^{+114}_{-28}$	$226\pm44\pm87$

Also confirmed by CLEO-c and CLEOIII !

967 fb^{-1}

Revisit Y @ Belle

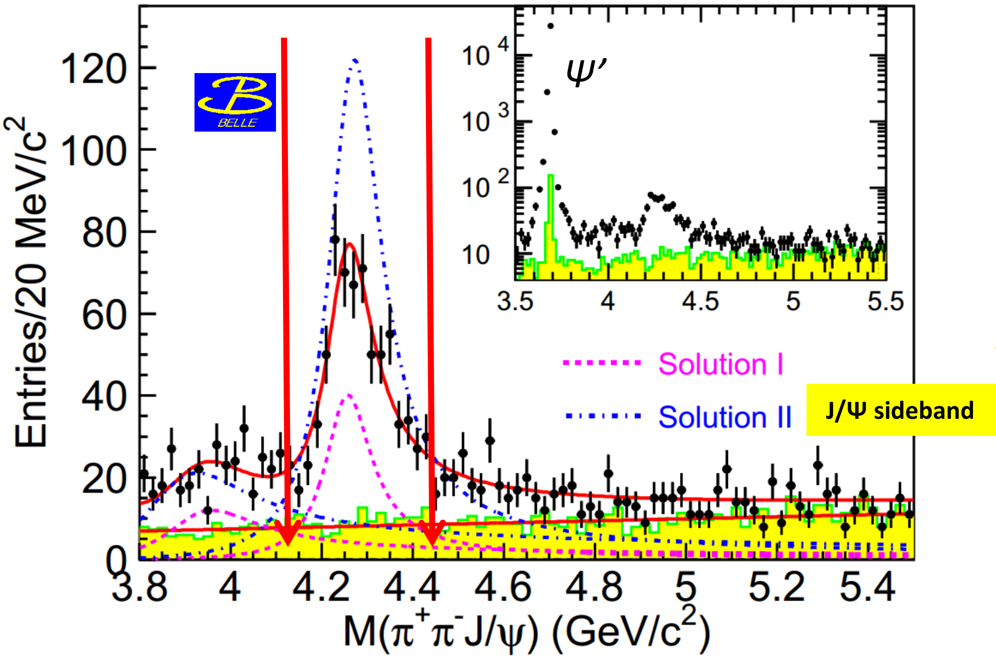


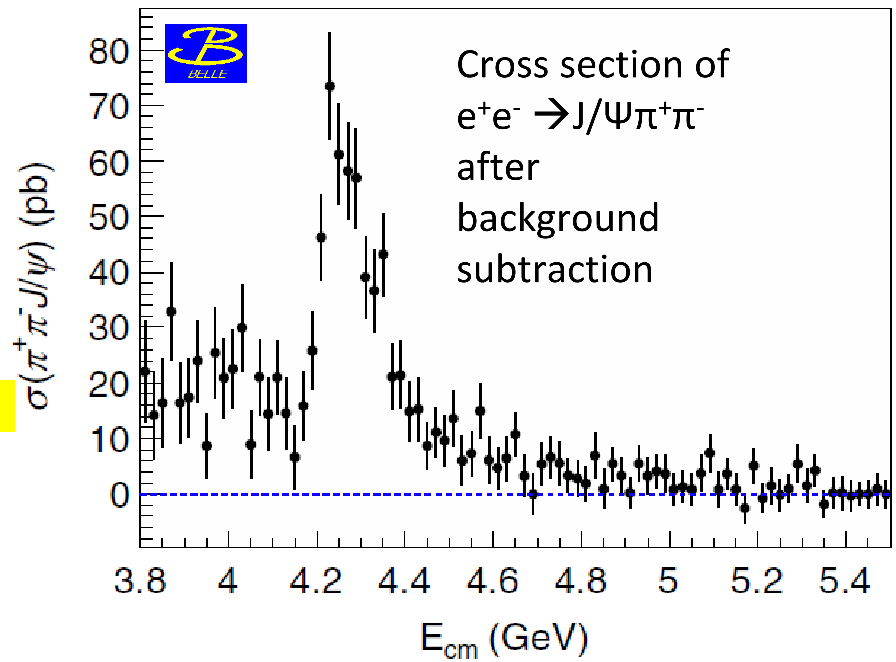


Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

967 fb^{-1}

Revisit Y @ Belle

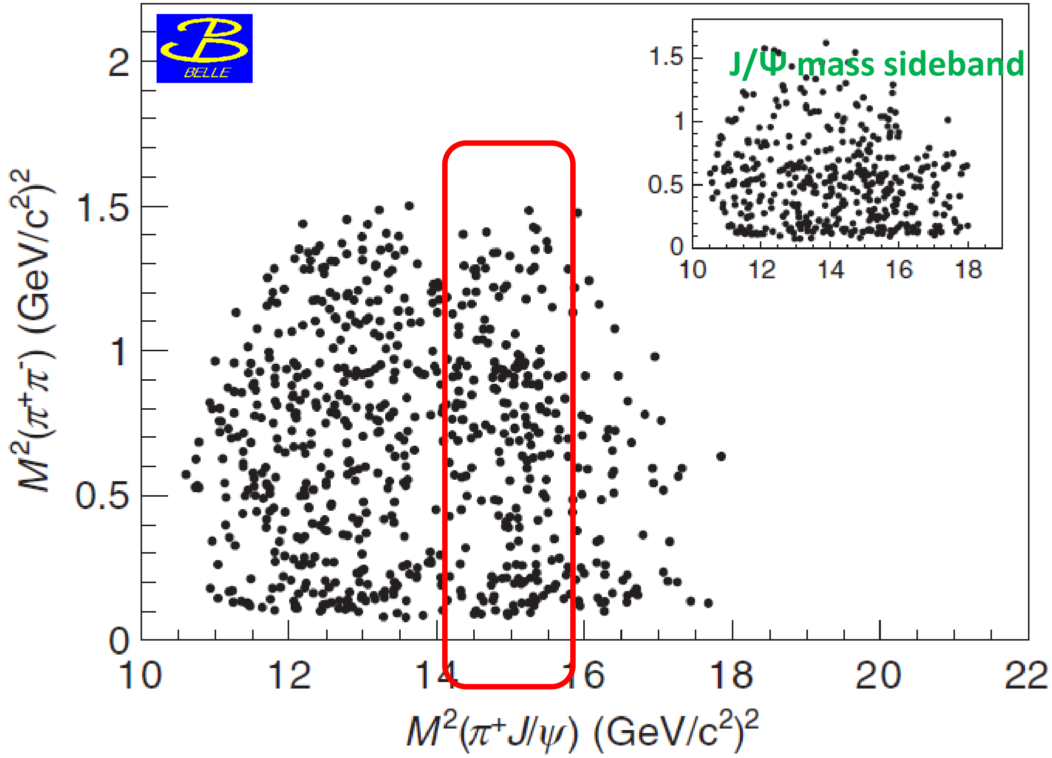




Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

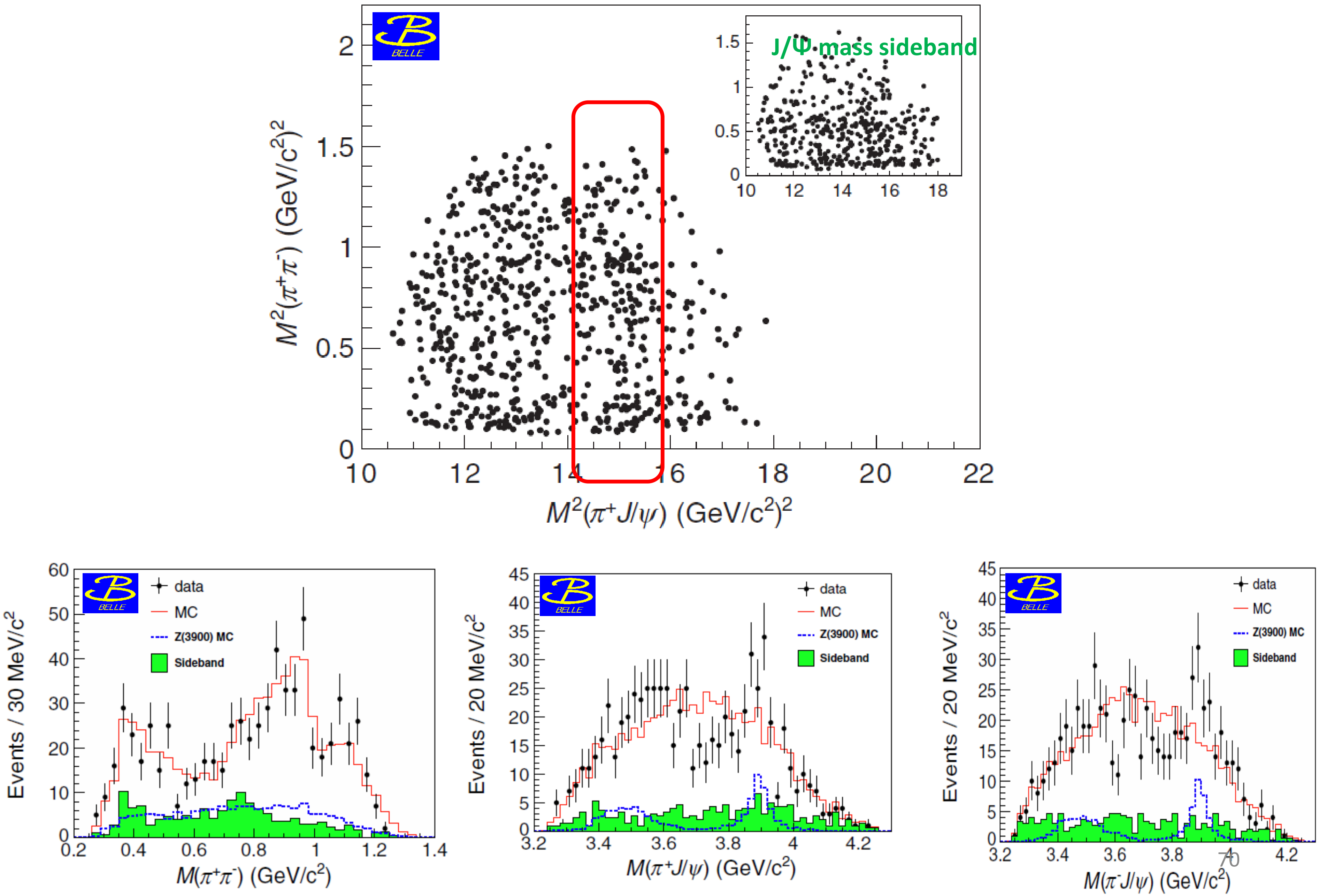
967 fb^{-1}

Intermediate state in Y(4260)→J/Ψππ



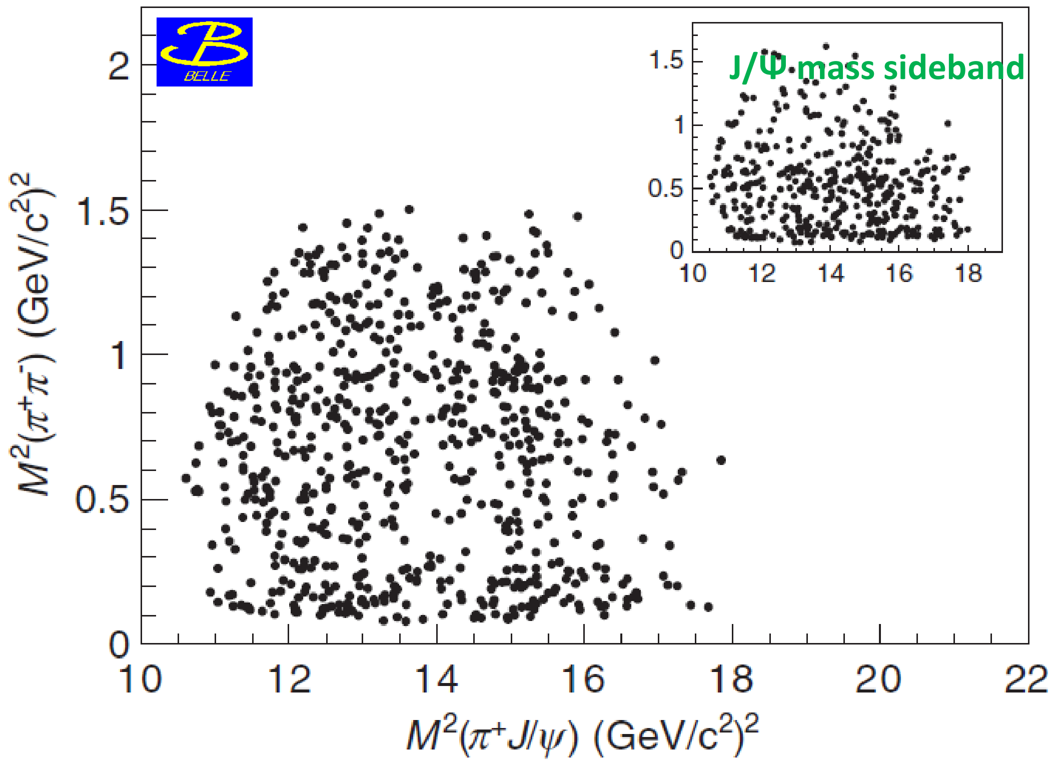
967 fb⁻¹

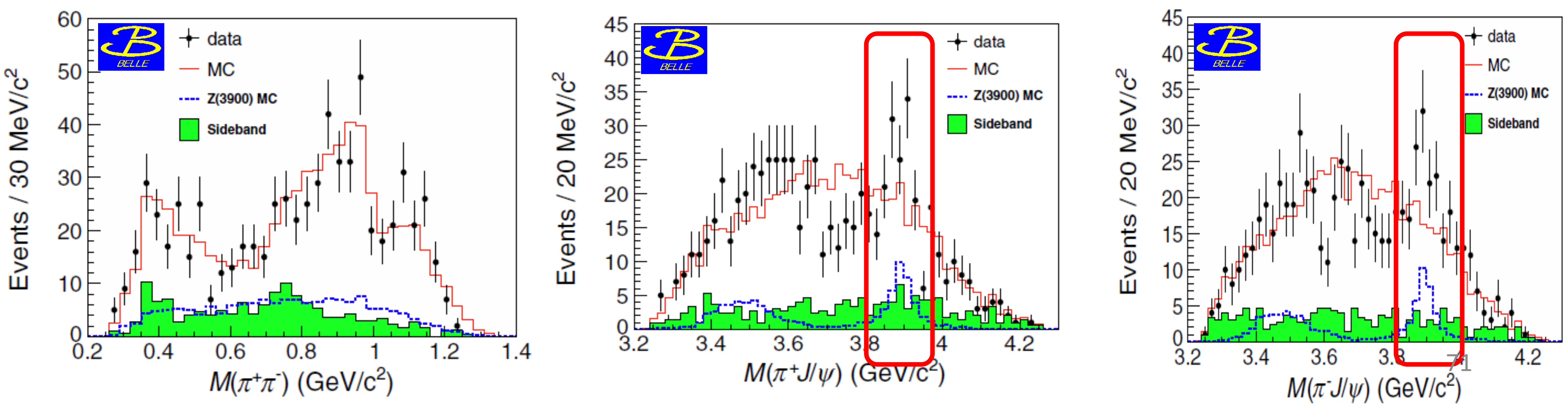
Intermediate state in Υ(4260)→J/Ψππ



967 fb⁻¹

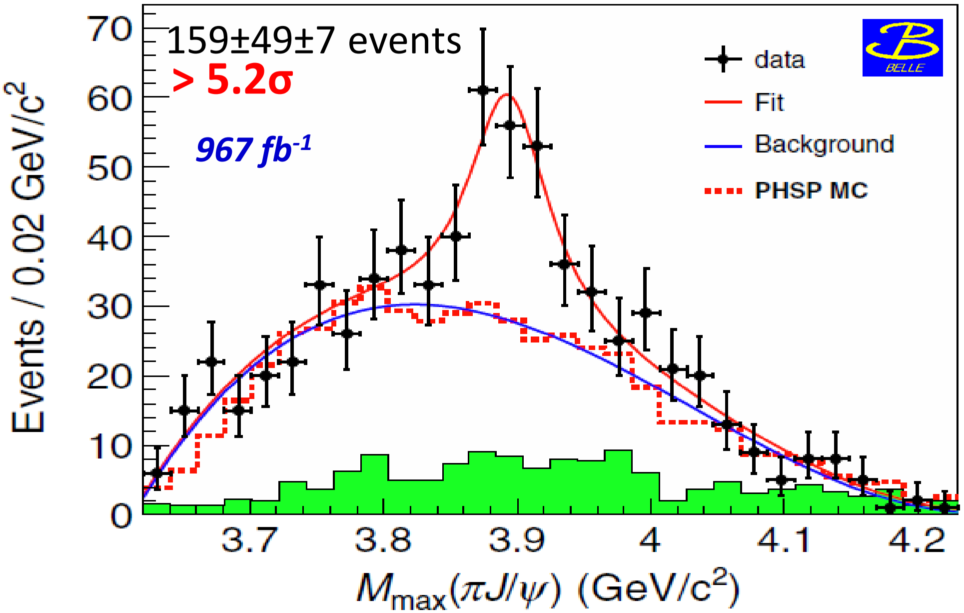
Intermediate state in Y(4260)→J/Ψππ





Observation of Z(3895)$^+$

Belle PRL110, 252002 (2013)



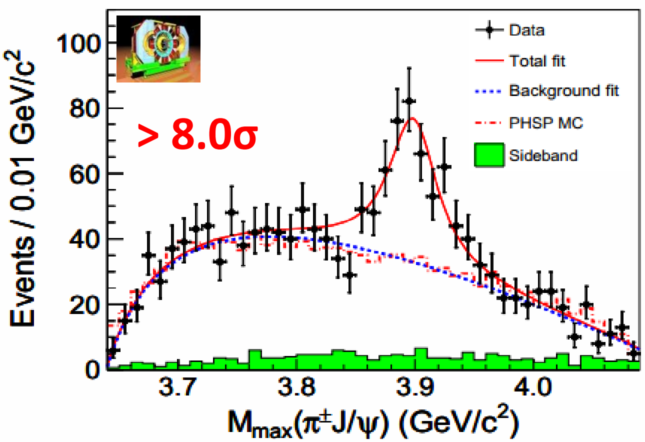
Measured properties

- Mass = (3894.5±6.6± 4.5) MeV
- Width = (63±24±26) MeV

$$\frac{BR[Y(4260) \to Z(3895)^{\pm}\pi^{\mp}]}{BR[Y(4260) \to J/\psi\pi^+\pi^-]} = (29.0 \pm 8.9)\%$$

Test hypothesis that interference between S and D waves in $\pi^+\pi^-$ system might produce structure similar to the enhancement.

➢ Partial waves alone cannot produce $J/\Psi\pi^{\pm}$ invariant mass peak near 3.9 GeV/c^2.



BESIII at 4.26 GeV PRL110, 252001 (2013)

Measured by BES III

- Mass = (3899.0±3.6± 4.9) MeV
- Width = (46±10±20) MeV

$$\frac{BR[Y(4260) \to Z(3900)^{\pm}\pi^{\pm}]}{BR[Y(4260) \to J/\psi\pi^+\pi^-]} = (21.5 \pm 3.3)\%$$

T. Xiao, *et al.* PLB 727 (2013) 366

Using CLEO data, T. Xiao *et al.* has also confirmed Z$^+$ and claim for an evidence for neutral Z !

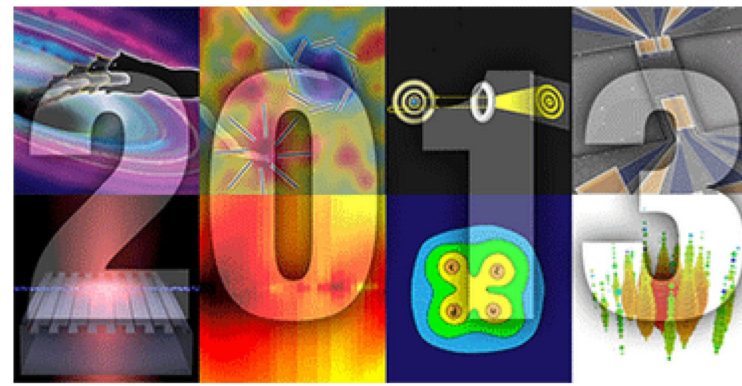
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

Physics looks back at the standout stories of 2013.

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

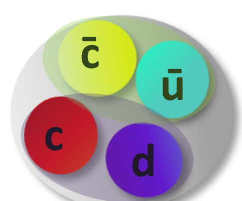
– Matteo Rini and Jessica Thomas



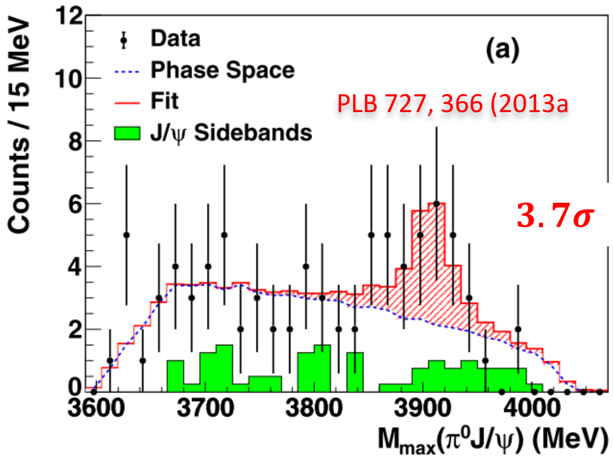
Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

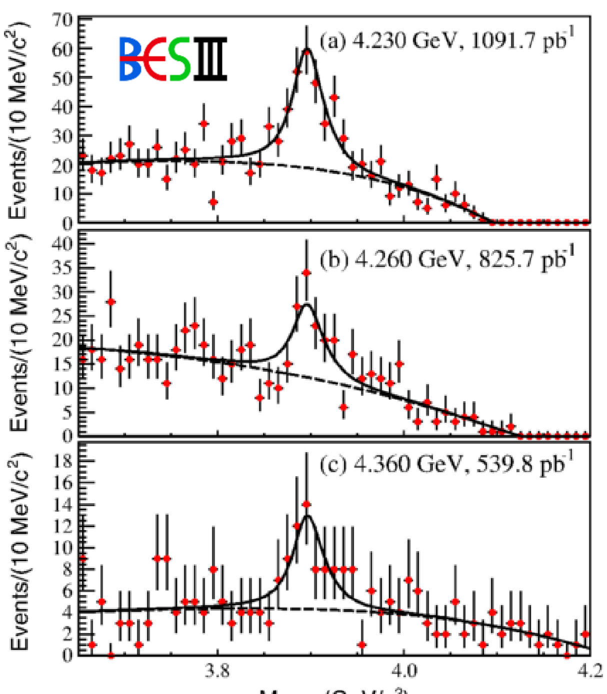


$Z_c^0(3900)$ in $e^+e^- \to \pi^0\pi^0 J/\psi$



Evidence of neutral isospin partner of $Z_c^{\pm}(3900)$ is observed in $e^+e^- \to \pi^0\pi^0 J/\psi$

$$M = (3886 \pm 6 \pm 4)\ \text{MeV}$$
$$\Gamma = (33 \pm 6 \pm 7)\ \text{MeV}$$



PRL 115, 112003(2013)

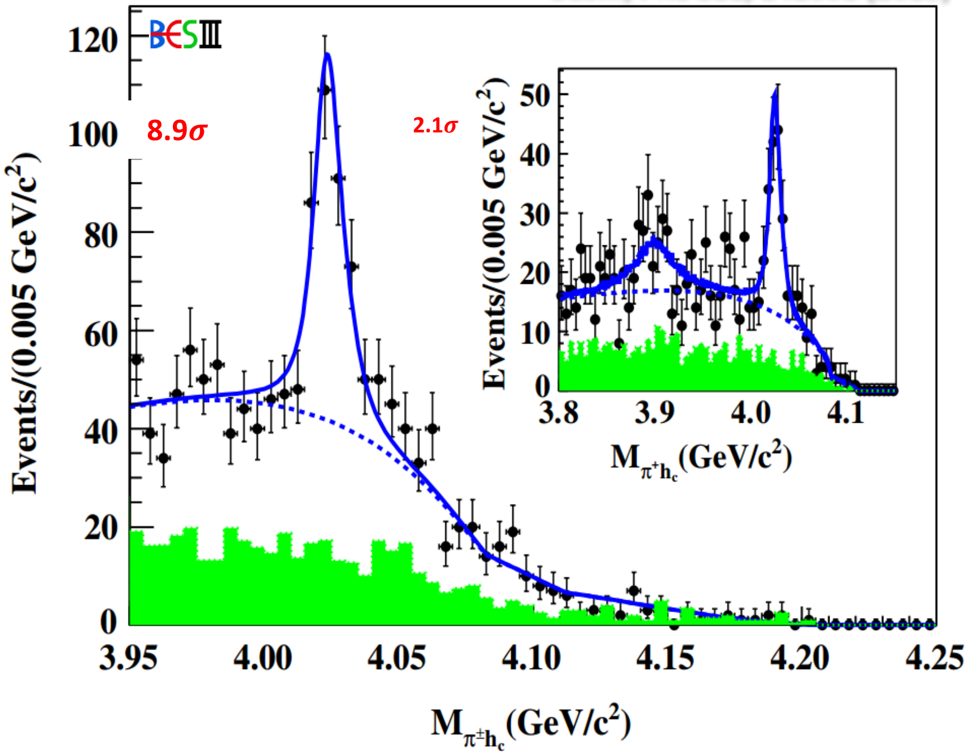
$$M = (3894.8 \pm 2.3 \pm 3.2)\ \text{MeV}$$
$$\Gamma = (29.6 \pm 8.2 \pm 8.2)\ \text{MeV}$$

Isospin triplet of Zc(3900)+ estalished

$Z_c^{\pm}(4020)$ in $e^+e^- \to \pi^+\pi^-h_c$

- No sharp structure in $\pi^+\pi^-h_c$ section, correlation with Y(4260) or Y(4360) unclear
- Narrow $\pi^{\pm}h_c$ structure observed
- No significance for $Z_c(3900) \to \pi^{\pm}h_c$

BESIII, PRL 111, 242001 (2013)



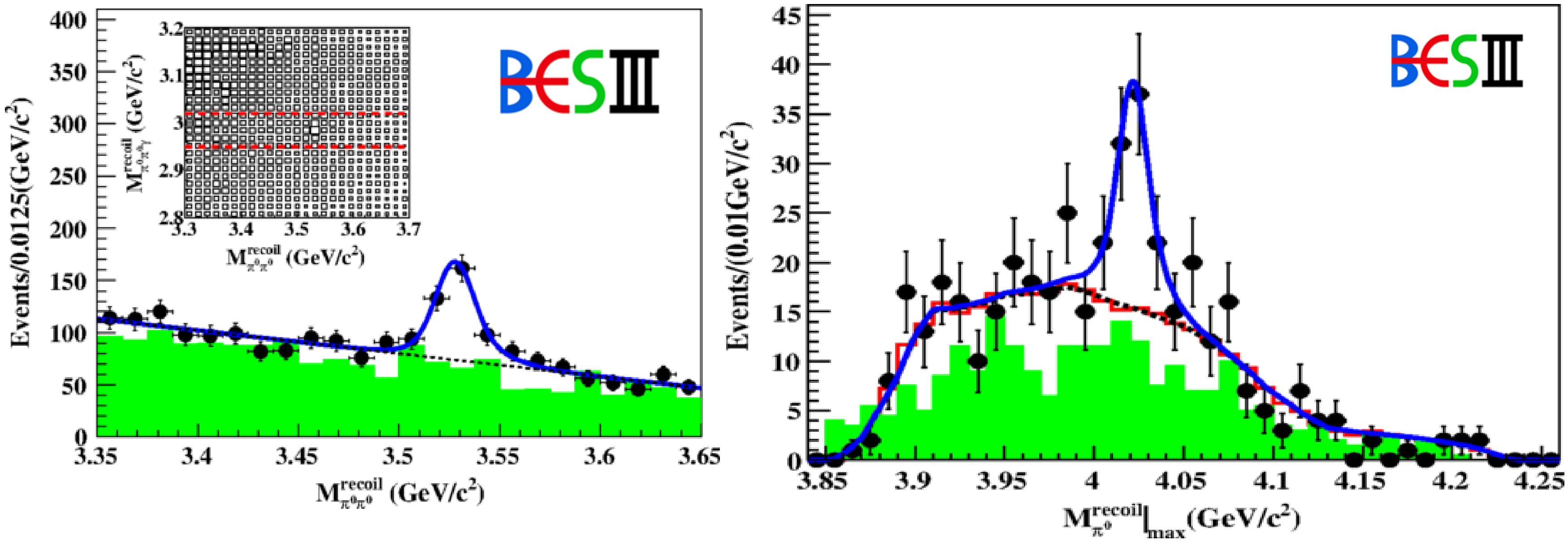
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$n_{h_c}^{obs}$	$\sigma(e^+e^- \to \pi^+\pi^-h_c)$ (pb)
3.900	52.8	<2.3	<8.3
4.009	482.0	<13	<5.0
4.090	51.0	<6.0	<13
4.190	43.0	8.8 ± 4.9	$17.7 \pm 9.8 \pm 1.6 \pm 2.8$
4.210	54.7	21.7 ± 5.9	$34.8 \pm 9.5 \pm 3.2 \pm 5.5$
4.220	54.6	26.6 ± 6.8	$41.9 \pm 10.7 \pm 3.8 \pm 6.6$
4.230	1090.0	646 ± 33	$50.2 \pm 2.7 \pm 4.6 \pm 7.9$
4.245	56.0	22.6 ± 7.1	$32.7 \pm 10.3 \pm 3.0 \pm 5.1$
4.260	826.8	416 ± 28	$41.0 \pm 2.8 \pm 3.7 \pm 6.4$
4.310	44.9	34.6 ± 7.2	$61.9 \pm 12.9 \pm 5.6 \pm 9.7$
4.360	544.5	357 ± 25	$52.3 \pm 3.7 \pm 4.8 \pm 8.2$
4.390	55.1	30.0 ± 7.8	$41.8 \pm 10.8 \pm 3.8 \pm 6.6$
4.420	44.7	29.1 ± 7.3	$49.4 \pm 12.4 \pm 4.5 \pm 7.6$

$$M = (4023 \pm 3)\ \text{MeV}$$
$$\Gamma = (8 \pm 4)\ \text{MeV}$$

$Z_c^0(4020)$ in $e^+e^- \to \pi^0\pi^0 h_c$

BESIII, PRL 113, 212002(2013)

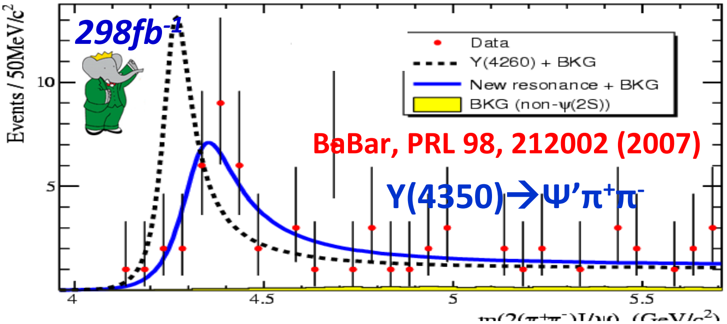
- Using data collected @4.23, 4.26 and 4.36 GeV to study $e^+e^- \to \pi^0\pi^0 h_c$
- Evidence of neutral isospin partner of $Z_c^{\pm}(4020)$

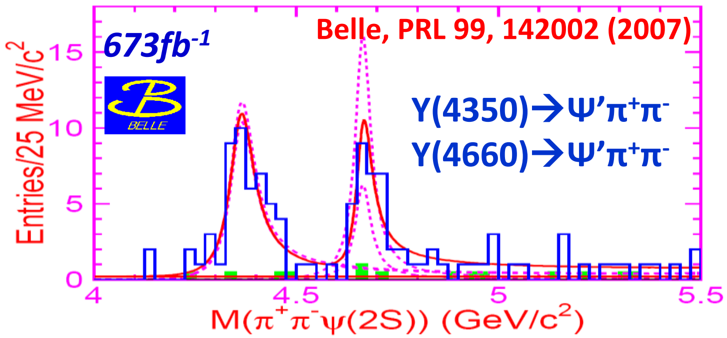


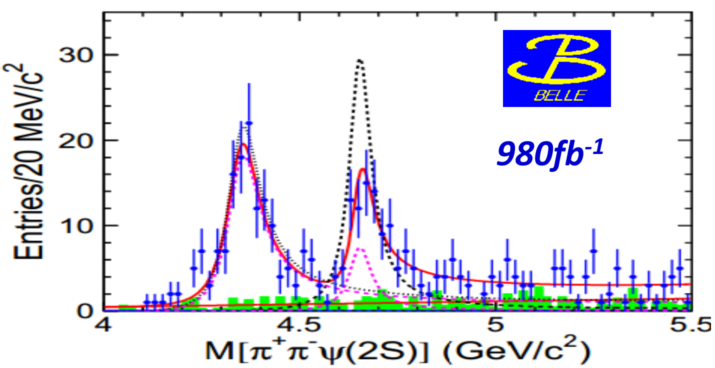
Width is fixed to that of $Z_c(4020)^{\pm}$

$\mathbf{M = (4023.6 \pm 2.2 \pm 3.9)}$ MeV

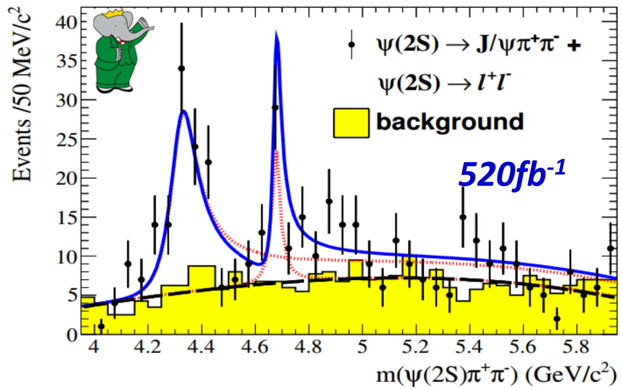
$e^+e^- \rightarrow \Psi'\pi^+\pi^-$ study







Belle PRD91, 112007 (2015)

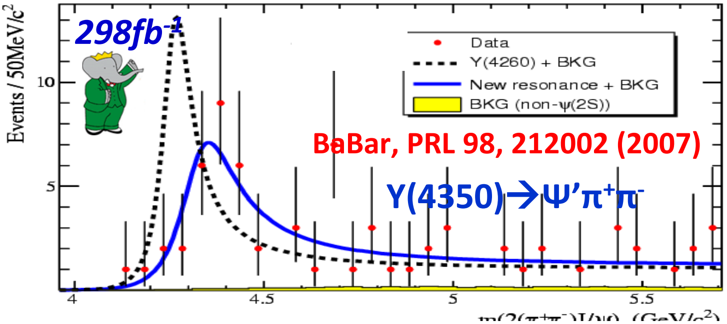


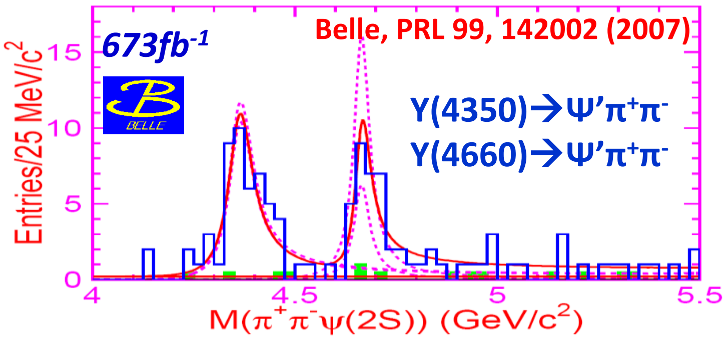
BaBar, PRD 89, 111103 (2014)

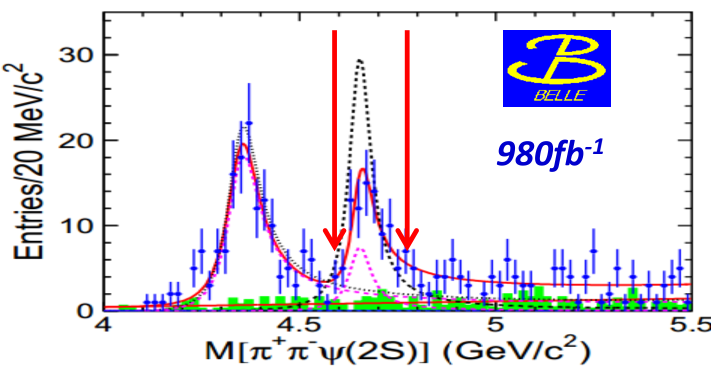
Y(4660) confirmed by BaBar !

Parameters	Solution I	Solution II
$M_{Y(4360)}$	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$	$103 \pm 9 \pm 5$	
$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$	$68 \pm 11 \pm 5$	
$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

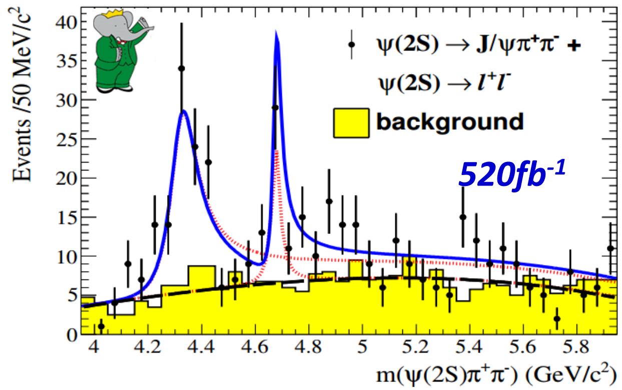
$e^+e^- \to \Psi'\pi^+\pi^-$ study







Belle PRD91, 112007 (2015)

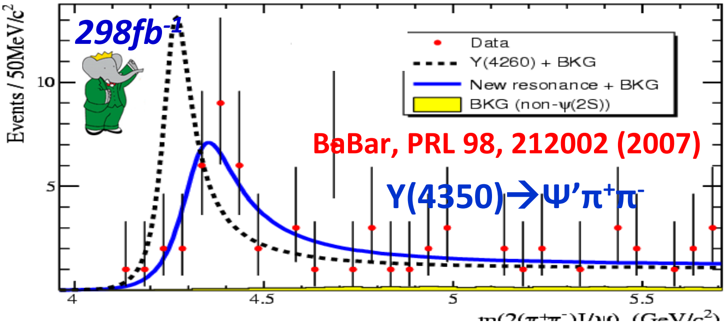


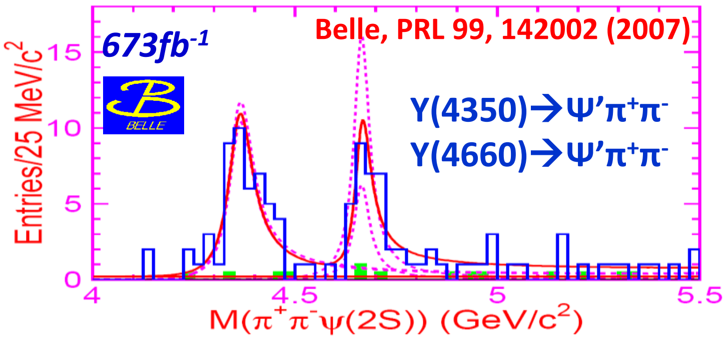
BaBar, PRD 89, 111103 (2014)

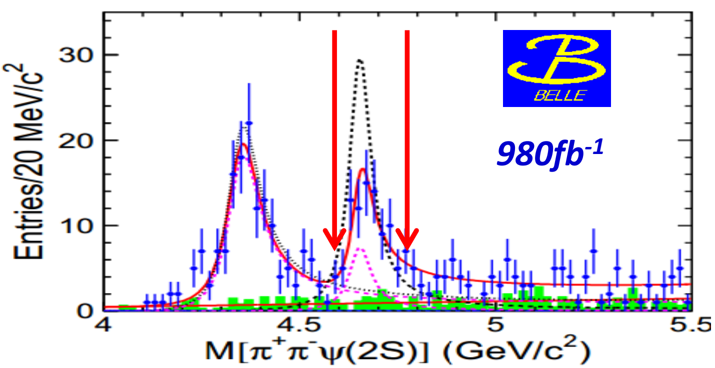
Y(4660) confirmed by BaBar !

Parameters	Solution I	Solution II
$M_{Y(4360)}$	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$	$103 \pm 9 \pm 5$	
$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$	$68 \pm 11 \pm 5$	
$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

$e^+e^- \to \Psi'\pi^+\pi^-$ study

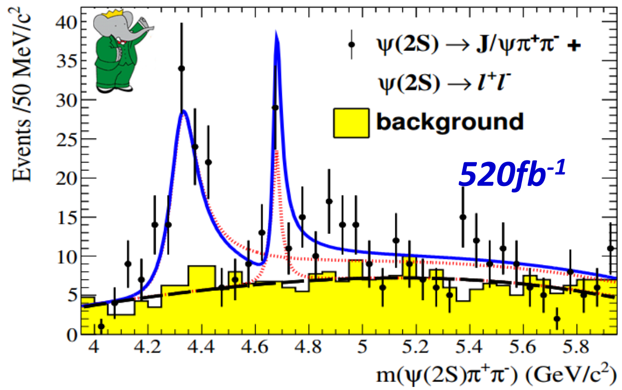






Belle PRD91, 112007 (2015)

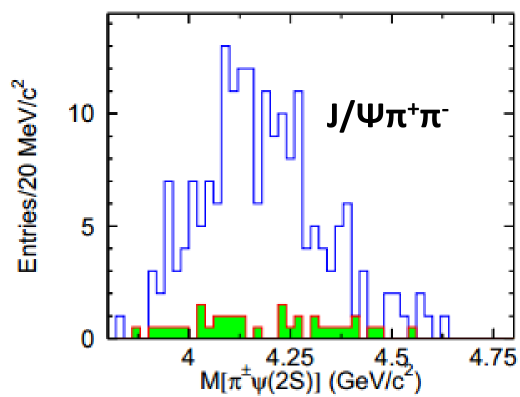
No significant result for charged state.

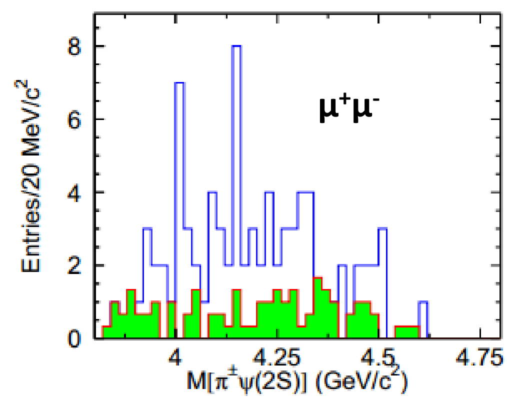


BaBar, PRD 89, 111103 (2014)

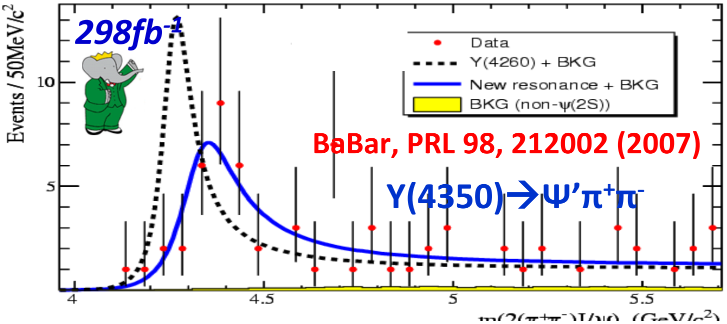
Y(4660) confirmed by BaBar !

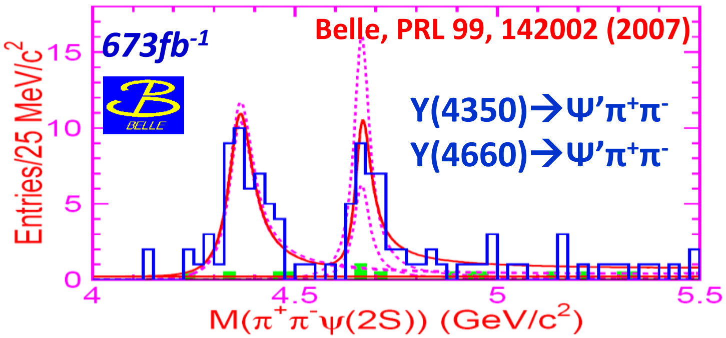
Parameters	Solution I	Solution II
$M_{Y(4360)}$	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$	$103 \pm 9 \pm 5$	
$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$	$68 \pm 11 \pm 5$	
$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

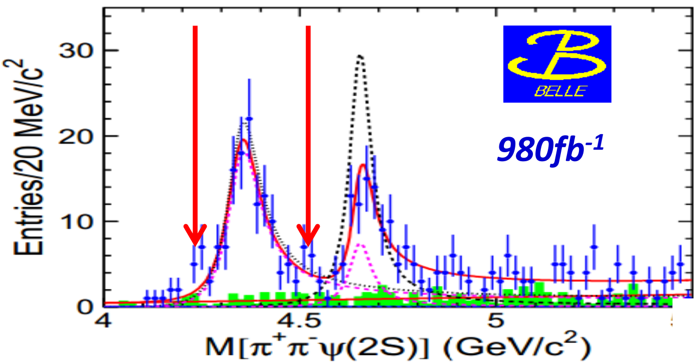




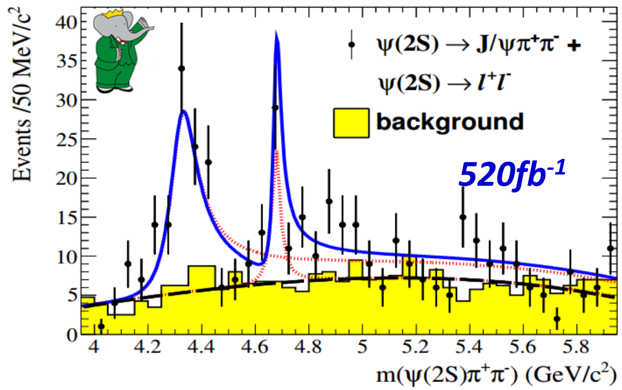
$e^+e^- \to \Psi'\pi^+\pi^-$ study







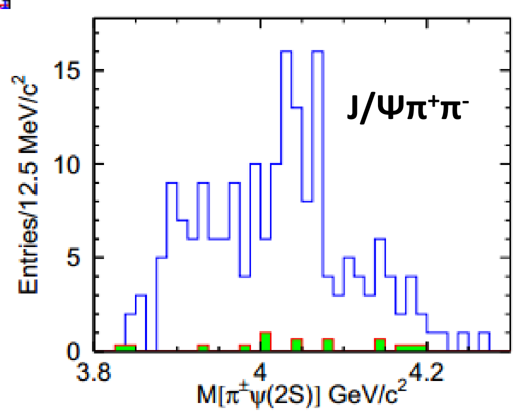
Belle PRD91, 112007 (2015)

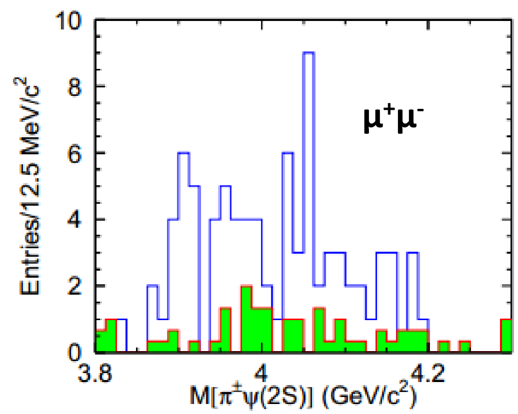


BaBar, PRD 89, 111103 (2014)

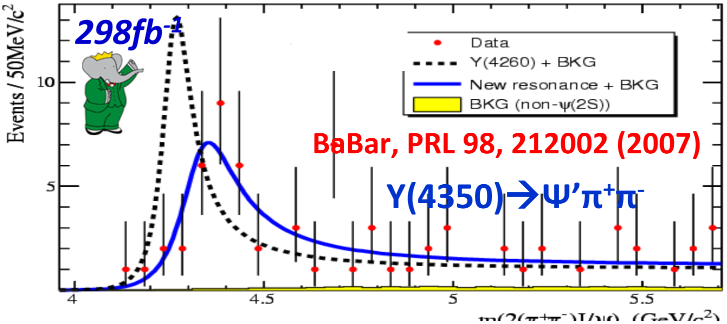
Y(4660) confirmed by BaBar !

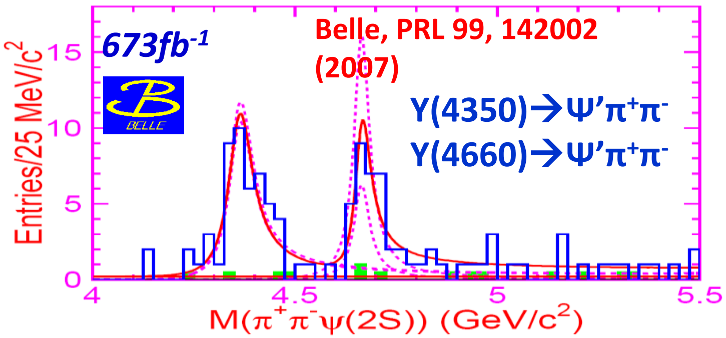
Parameters	Solution I	Solution II
$M_{Y(4360)}$	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$	$103 \pm 9 \pm 5$	
$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$	$68 \pm 11 \pm 5$	
$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

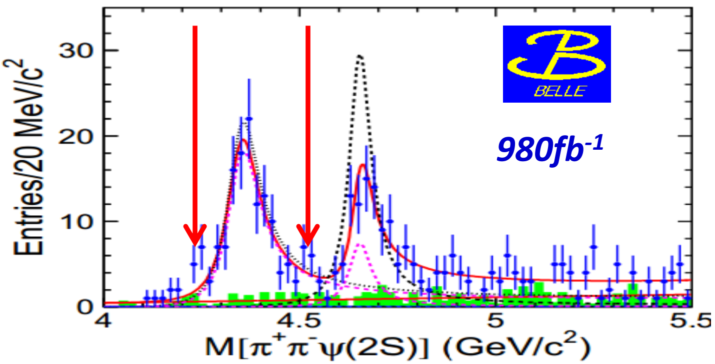




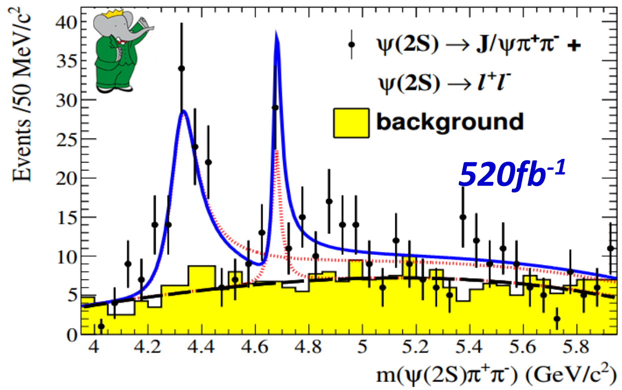
$e^+e^- \to \Psi'\pi^+\pi^-$ study







Belle PRD91, 112007 (2015)

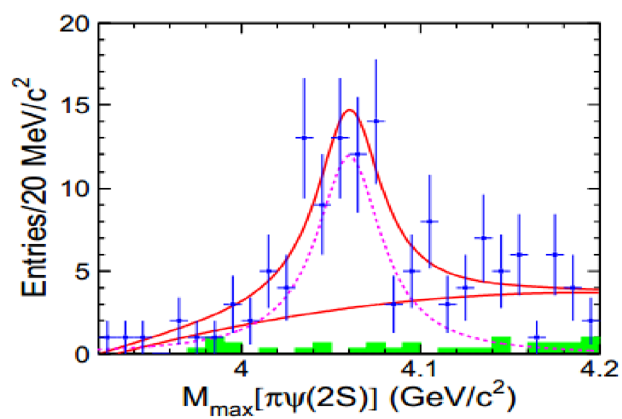


BaBar, PRD 89, 111103 (2014)

Y(4660) confirmed by BaBar !

Parameters	Solution I	Solution II
$M_{Y(4360)}$	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$	$103 \pm 9 \pm 5$	
$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$	$68 \pm 11 \pm 5$	
$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

Significance : 3.5 σ

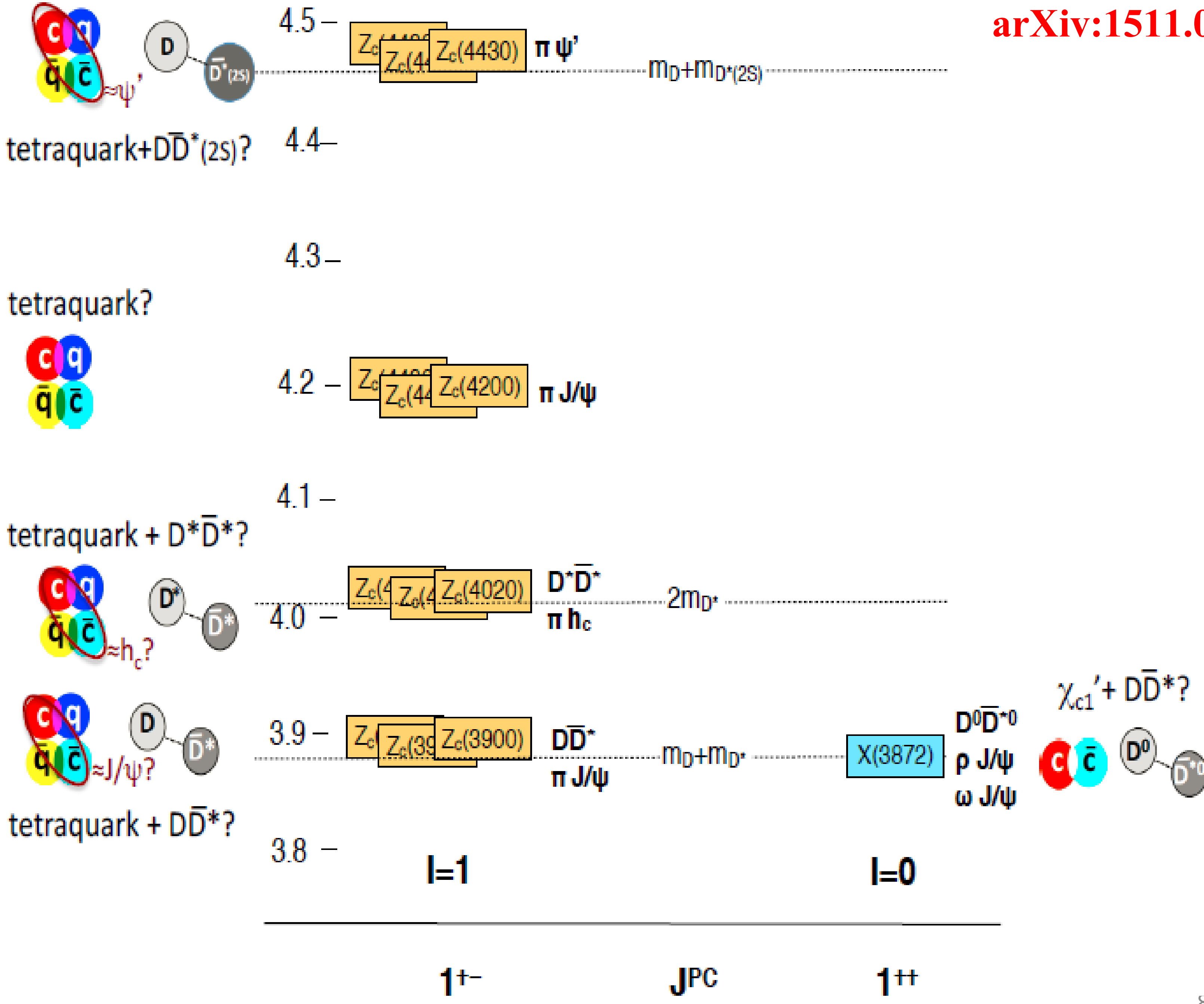


Measured properties

- Mass = (4054±3± 1) MeV
- Width = (45±11±6) MeV

Does it have any relation to $Z(4050)^+ \to \chi_{c1}\pi^+$?
Also, no hint of $Z(4430)^+ \to \Psi'\pi^+$ as in $B^0 \to \Psi'\pi^+K^-$

arXiv:1511.01589

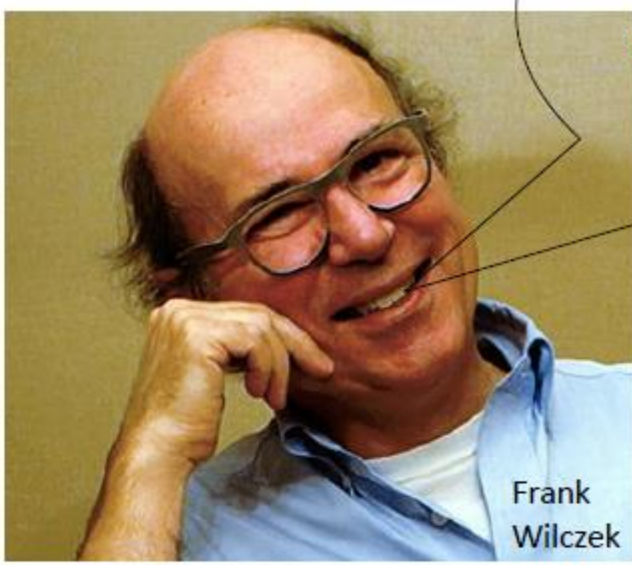


Summary

Frank Wilczek (on long-distance QCD)

https://www.edge.org/conversation/frank_wilczek-power-over-nature

We have something called a standard model, but its foundations are kind of scandalous. We have not known how to define an important part of it mathematically rigorously,...



From Olsen’s talk at Vietnam 2016

Thank you

धन्यवाद

ਧੰਨਵਾਦ

ধন্যবাদ

આભાર

ಧನ್ಯವಾದಗಳು

നന്ദി

நன்றி

شکریہ

ଧନ୍ୟବାଦ୍