Hadron and Quarkonium Exotica

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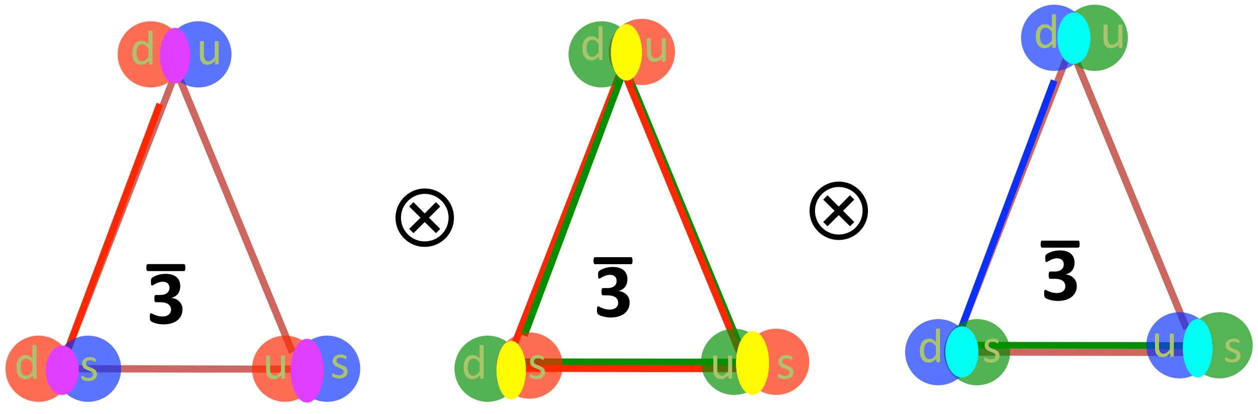
Physics in Collision, IHEP, Beijing, Sep 4-7, 2013

multiquark states from diquarks & diantiquarks

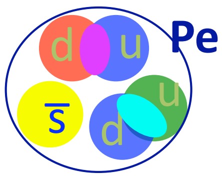
red-blue diquark | green-red diquark | blue-green diquark



magenta (anti-green)
anti-triplet

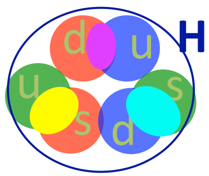
yellow (anti-blue)
anti-triplet

cyan (anti-red)
anti-triplet



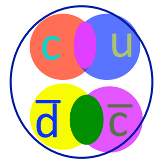
Pentaquark

magenta-cyan-yellow
color singlet 5-q state



H-dibaryon

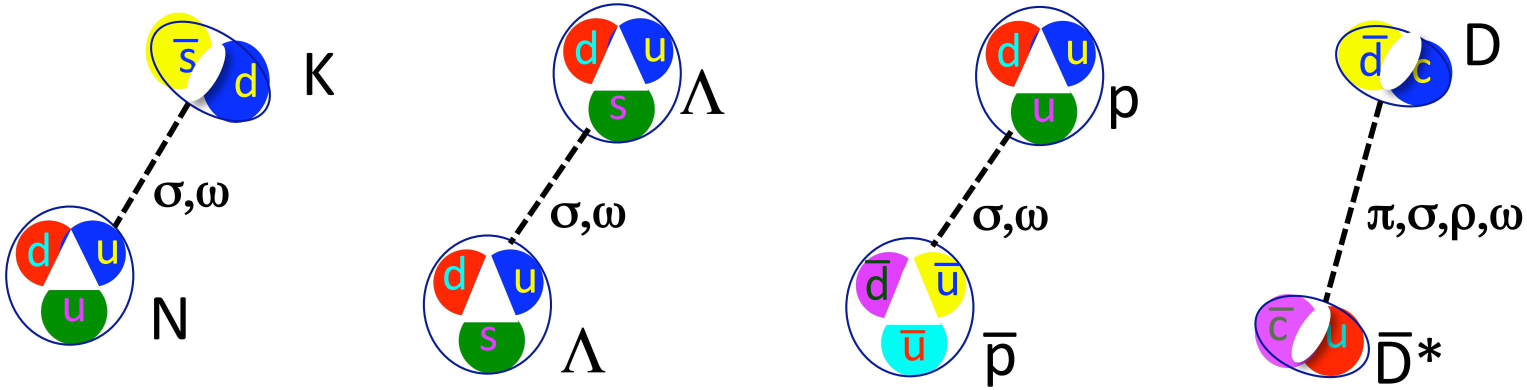
magenta-cyan-yellow
color singlet 6-q state



tetraquark meson

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

multiquark states from “molecules”



Pentaquark

H-dibaryon

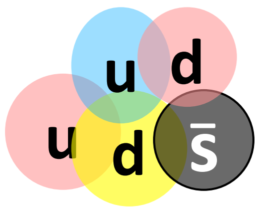
baryonium

tetraquark meson

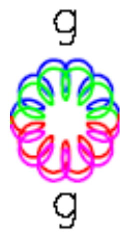
-new dimensions to Nuclear Physics-

Non-$q\bar{q}$ mesons or non-qqq baryons predicted by `QCD-motivated' models

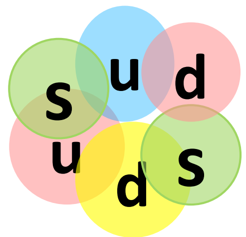
Where are they ??



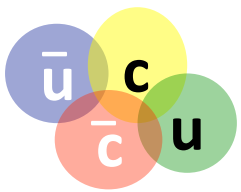
pentaquarks



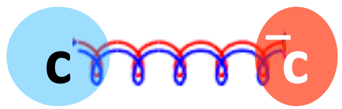
glueballs



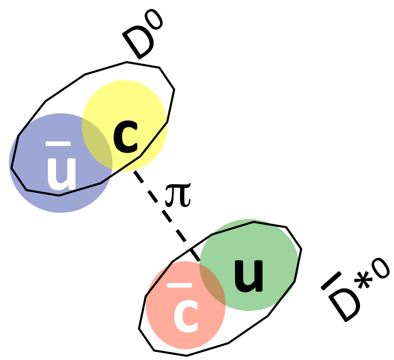
H-dibaryon



diquark-diantiquarks



hybrids



molecules

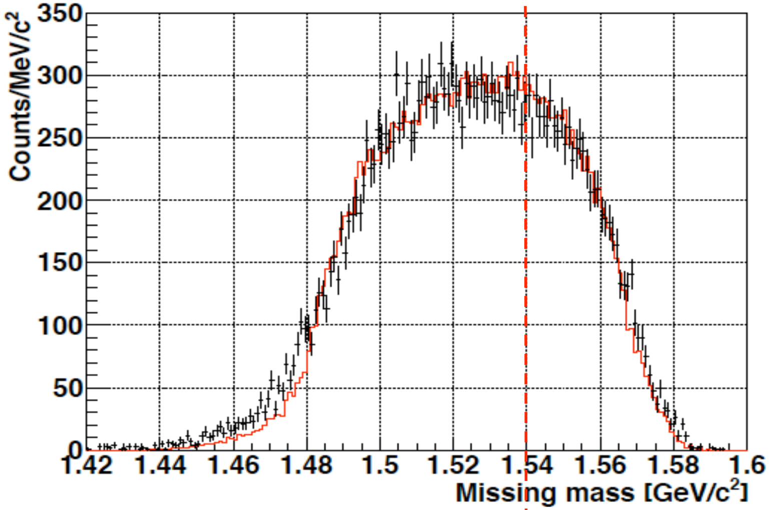
non-$q\bar{q}$ & non-qqq color-singlet combinations

- Pentaquark
- H-Dibaryon
- Baryonium
- Doubly charged state

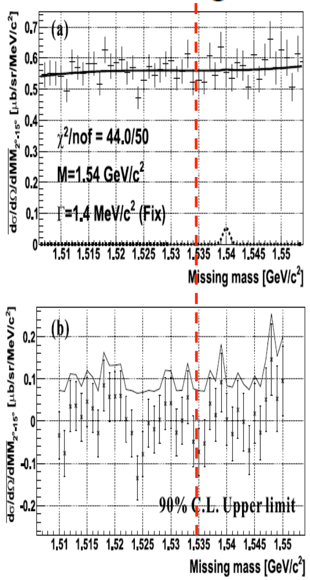
No Pentaquarks

J-PARC E19 - 2012 PRL 109, 132002

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

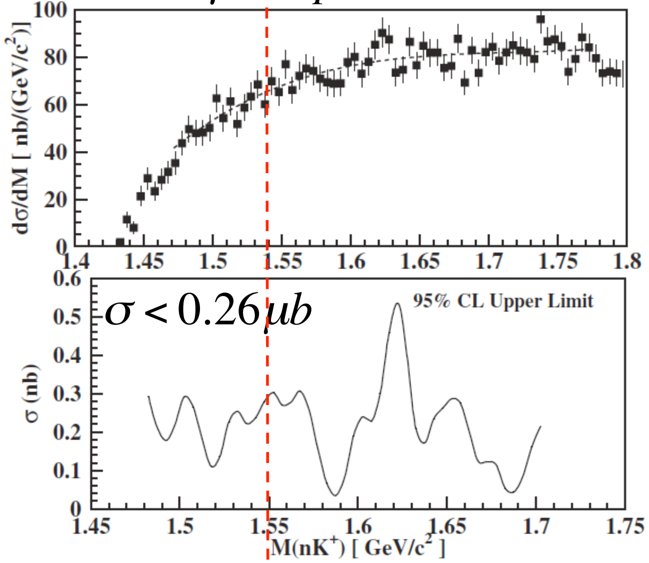


$$\frac{d\sigma}{d\Omega} < 0.26 \mu b / sr$$



JLab CLAS -2006 PRL 96, 212001

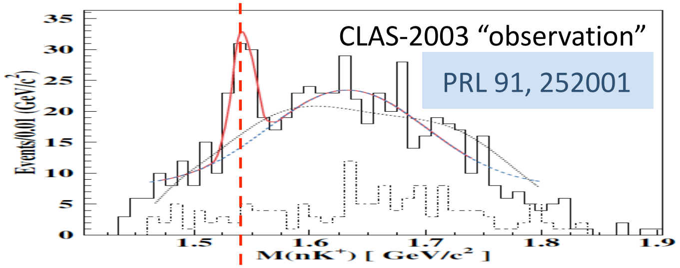
$\gamma d \rightarrow p K^- K^+ n$



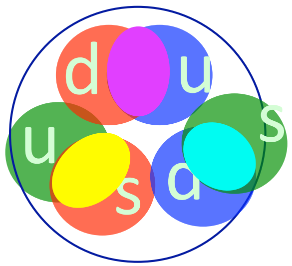
$\sigma < 0.26 \mu b$

CLAS-2003 "observation"

PRL 91, 252001

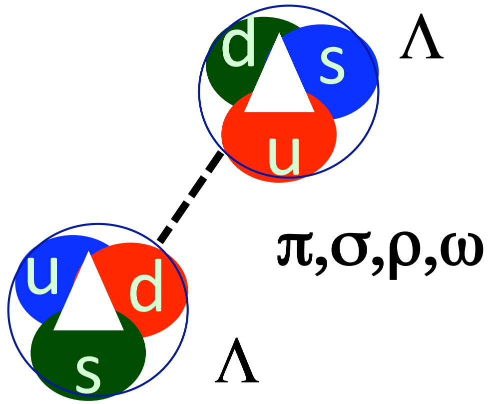


H dibaryon



Tightly bound
diquark triplet

or



Hyperon-hyperon
molecular state

R.L. Jaffee, PRL 38, 195 (1977): $J^P = 0^+$ di-hyperon with $M_H \approx 2m_\Lambda - 80$ MeV

models predict $M_H \approx 2m_\Lambda$

long-lived

$c\tau > 3$ cm!!

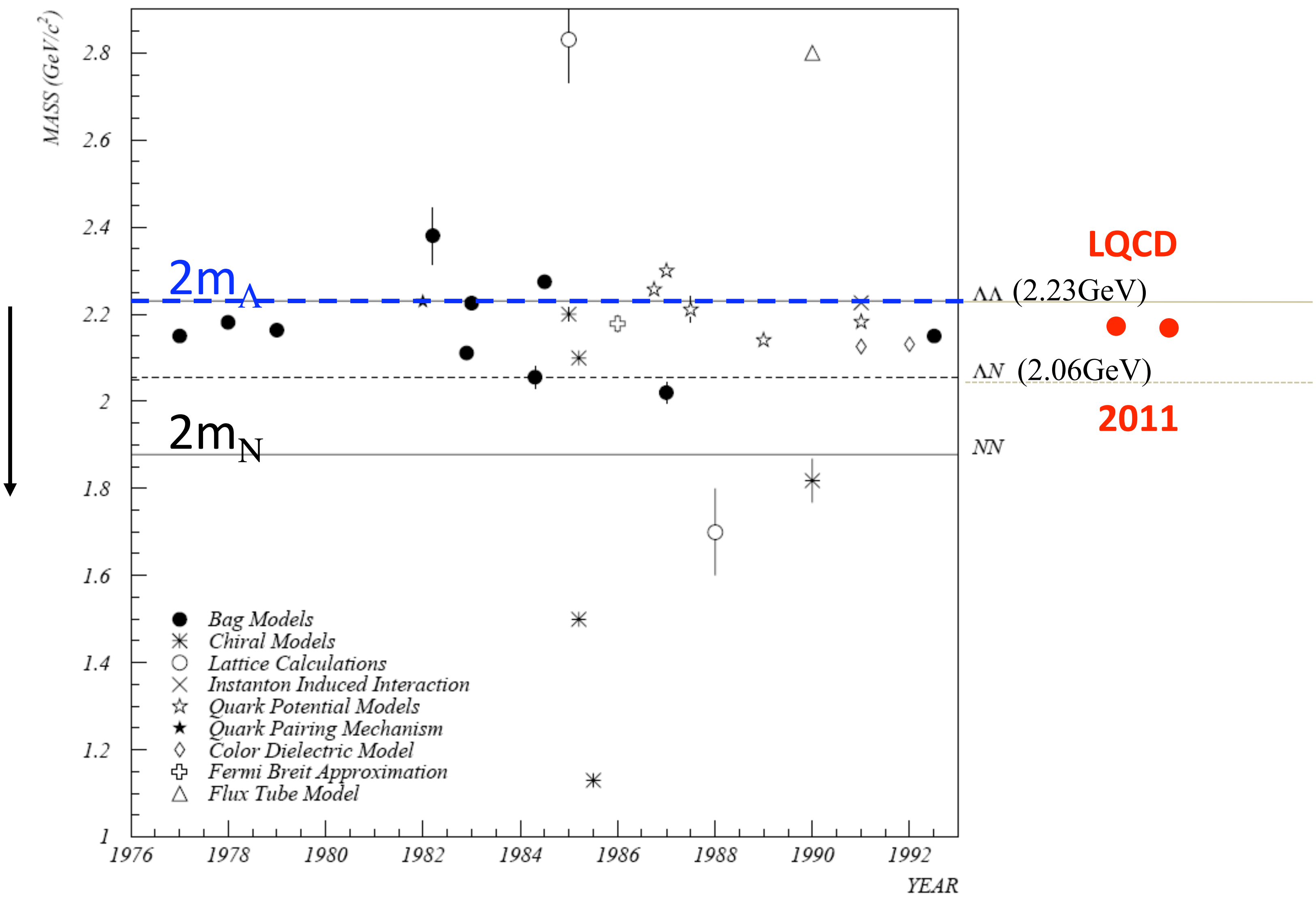


Figure 1: Theoretical predictions for the mass of the H-dibaryon as a function of year of prediction

Recent Lattice QCD calculations

S.R. Beane *et al* (NPLQCD) PRL 106, 062001 (2011)

T. Inoue *et al* (NPLQCD) PRL 106, 062002 (2011)

Evidence for a Bound H-dibaryon from Lattice QCD

S.R. Beane,[1,2] E. Chang,[3] W. Detmold,[4,5] B. Joo,[5] H.W. Lin,[6] T.C. Luu,[7]
K. Orginos,[4,5] A. Parreño,[3] M.J. Savage,[6] A. Torok,[8] and A. Walker-Loud[9]
(NPLQCD Collaboration)

[1]*Albert Einstein Zentrum für Fundamentale Physik, Institut für theoretische Physik, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[2]*Department of Physics, University of New Hampshire, Durham, NH 03824-3568, USA*
[3]*Dept. d'Estructura i Constituents de la Matèria. Institut de Ciències del Cosmos (ICC), Universitat de Barcelona, Martí Franquès 1, E08028-Spain*
[4]*Department of Physics, College of William and Mary, Williamsburg, VA 23187-8795, USA*
[5]*Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, VA 23606, USA*
[6]*Department of Physics, University of Washington, Box 351560, Seattle, WA 98195, USA*
[7]*N Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*
[8]*Department of Physics, Indiana University, Bloomington, IN 47405, USA*
[9]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
(Dated: December 20, 2010)

$M_H = 2m_\Lambda - 16.1 \pm 2.1 \pm 4.6$ MeV

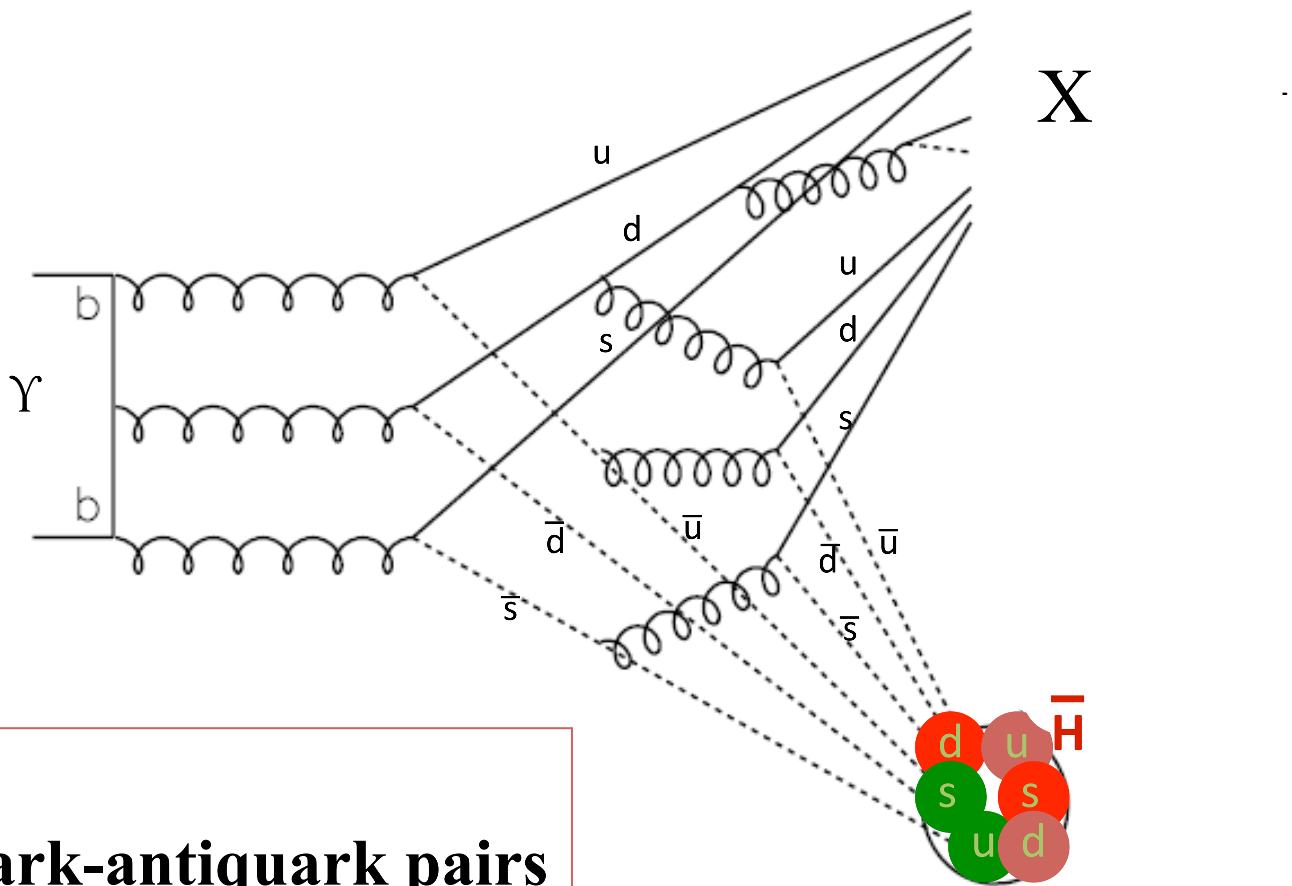
Bound H-dibaryon in Flavor SU(3) Limit of Lattice QCD

Takashi Inoue[1] Noriyoshi Ishii[2], Sinya Aoki[2,3], Takumi Doi[3], Tetsuo Hatsuda[4,5],
Yoichi Ikeda[6], Keiko Murano[7], Hidekatsu Nemura[8], Kenji Sasaki[3]
(HAL QCD Collaboration)

[1]*Nihon University, College of Bioresource Sciences, Fujisawa 252-0880, Japan*
[2]*Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan*
[3]*Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan*
[4]*Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan*
[5]*IPMU, The University of Tokyo, Kashiwa 277-8583, Japan*
[6]*Nishina Center for Accelerator-Based Science, Institute for Physical and Chemical Research (RIKEN), Wako 351-0198, Japan*
[7]*High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[8]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*

$M_H = 2m_\Lambda$ – "(30~40) MeV"

Production via gluons in $\Upsilon(1S)$ decays

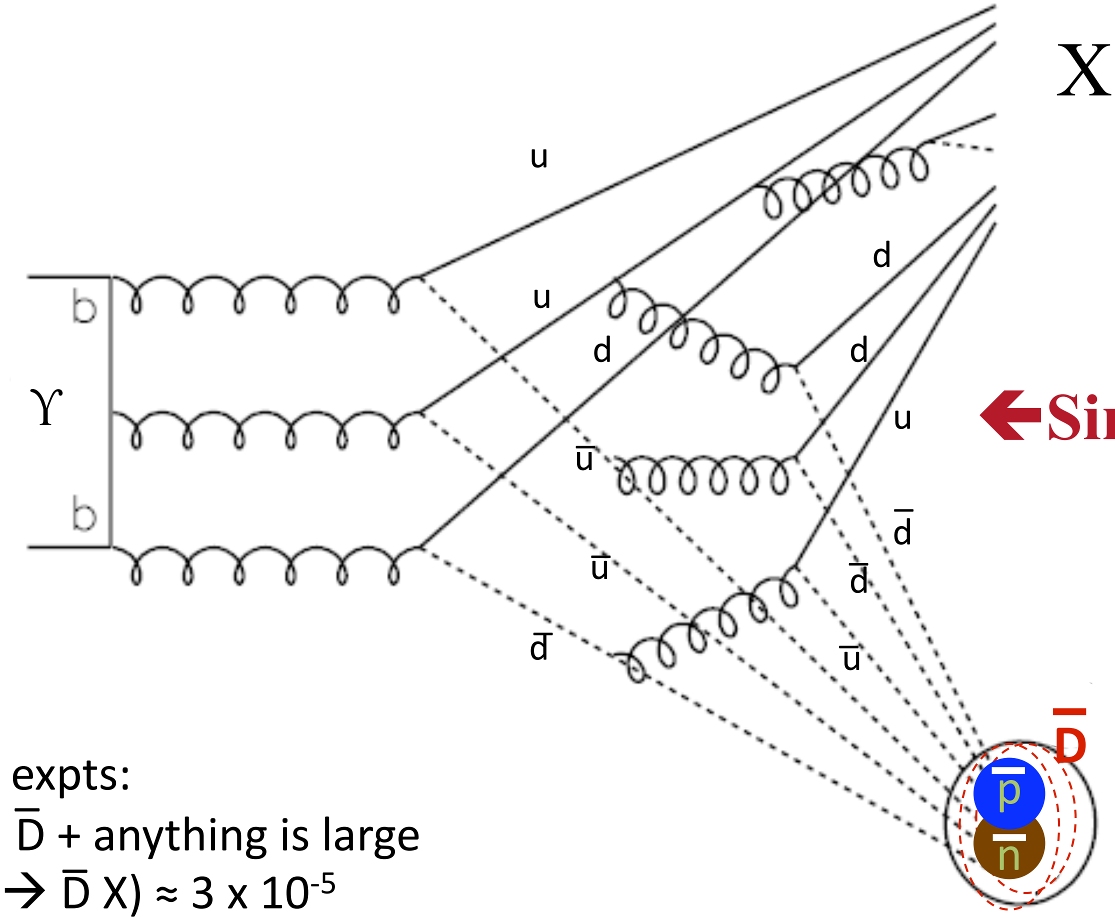


Need to:

produce 6 quark-antiquark pairs
(including two $s\bar{s}$ quark pairs)
very close in phase space

🡐Is this likely???

Anti-deuteron production in Υ(1S) decays



← Similar process!!

ARGUS & CLEO expts:

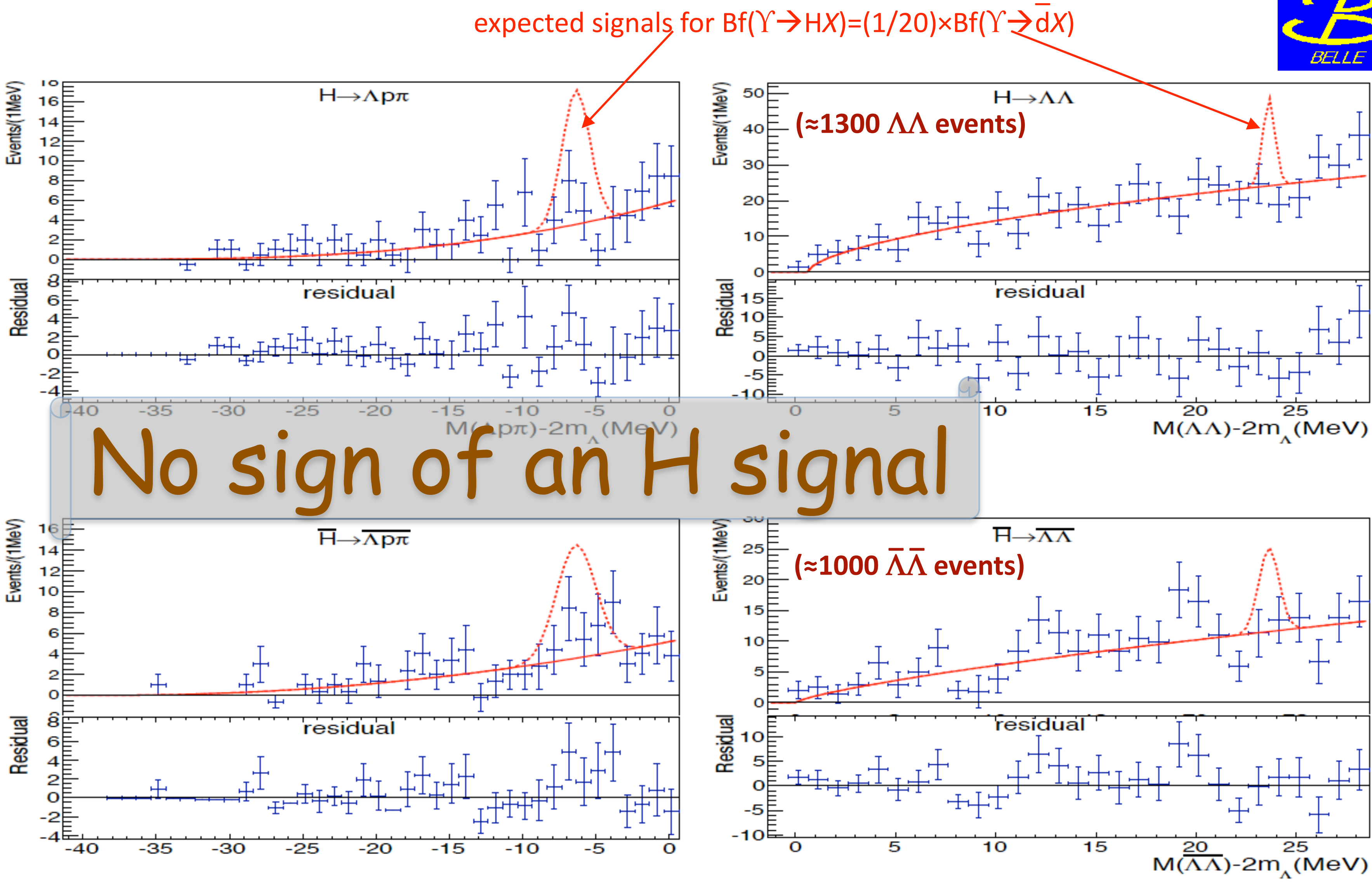
Υ (1,2S)→ $\bar{D}$ + anything is large

Bf(Υ(1,2S)→ $\bar{D}$ X) ≈ 3 x 10^{-5}

H. Albrecht *et al* (ARGUS) PRB 236, 102 (1990)
D.M. Asner *et al* (CLEO) PRD 75, 012009 (2007)

Belle data samples: 100×10^6 Υ(1S) decays + 160×10^6 Υ(2S) decays

$\Upsilon(1,2S) \rightarrow \Lambda p \pi^- X$ & $\Upsilon(1,2S) \rightarrow \Lambda\Lambda X$

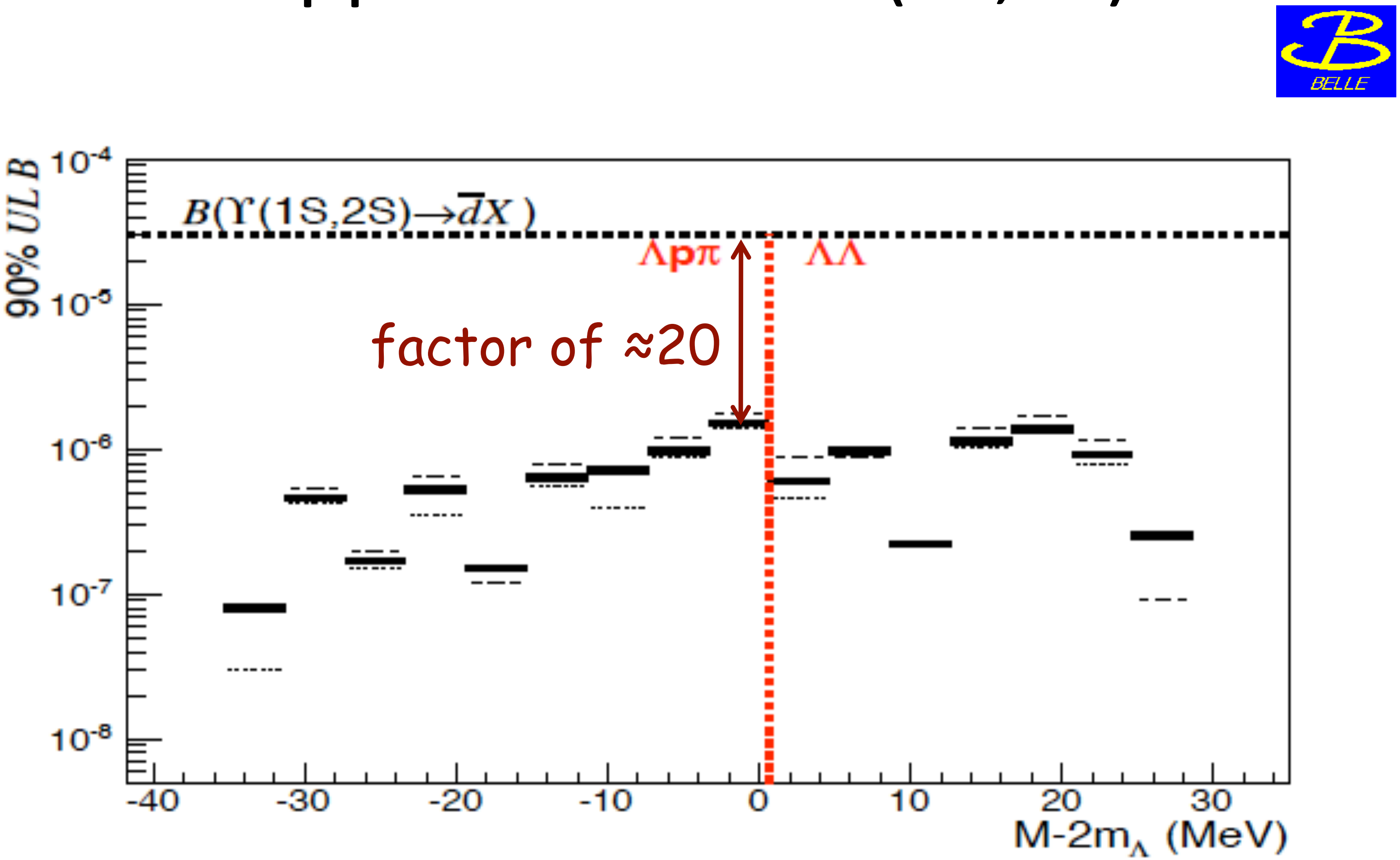


No sign of an H signal

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

Belle data samples: 100×10^6 $\Upsilon(1S)$ decays + 160×10^6 $\Upsilon(2S)$ decays

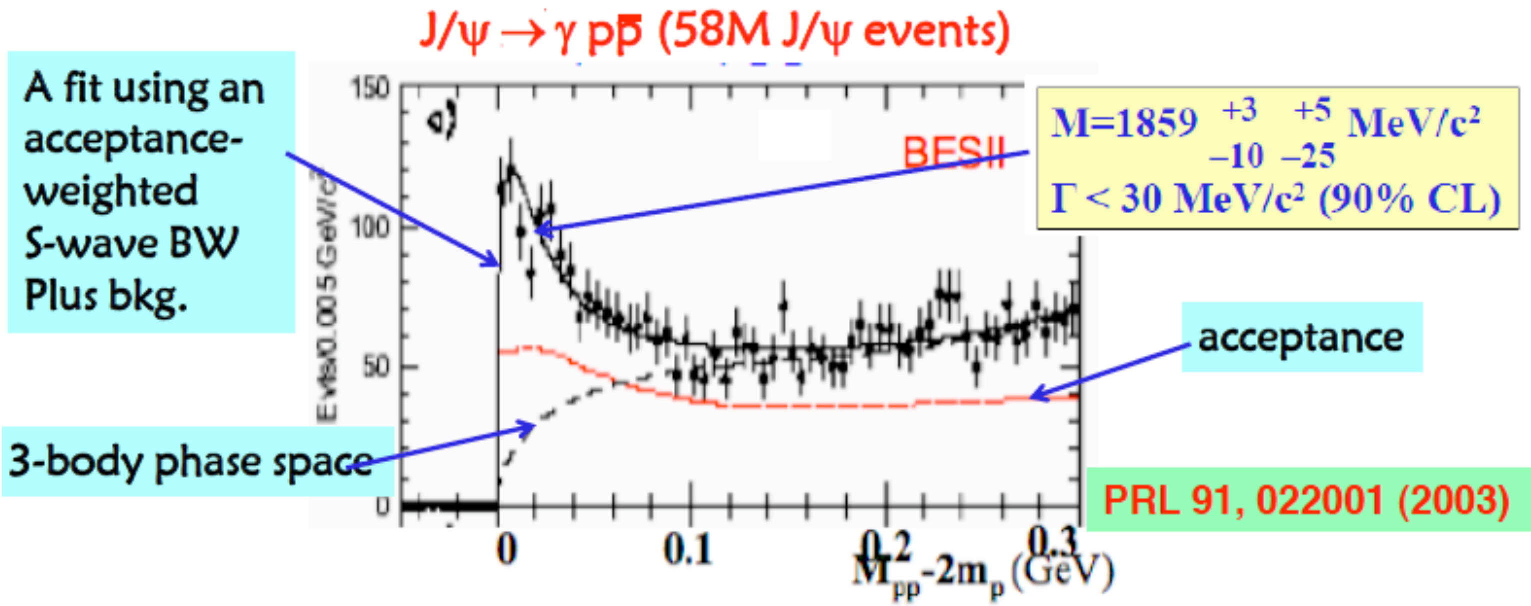
90% CL upper limits on $\Upsilon(1S,2S) \rightarrow H\ X$



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

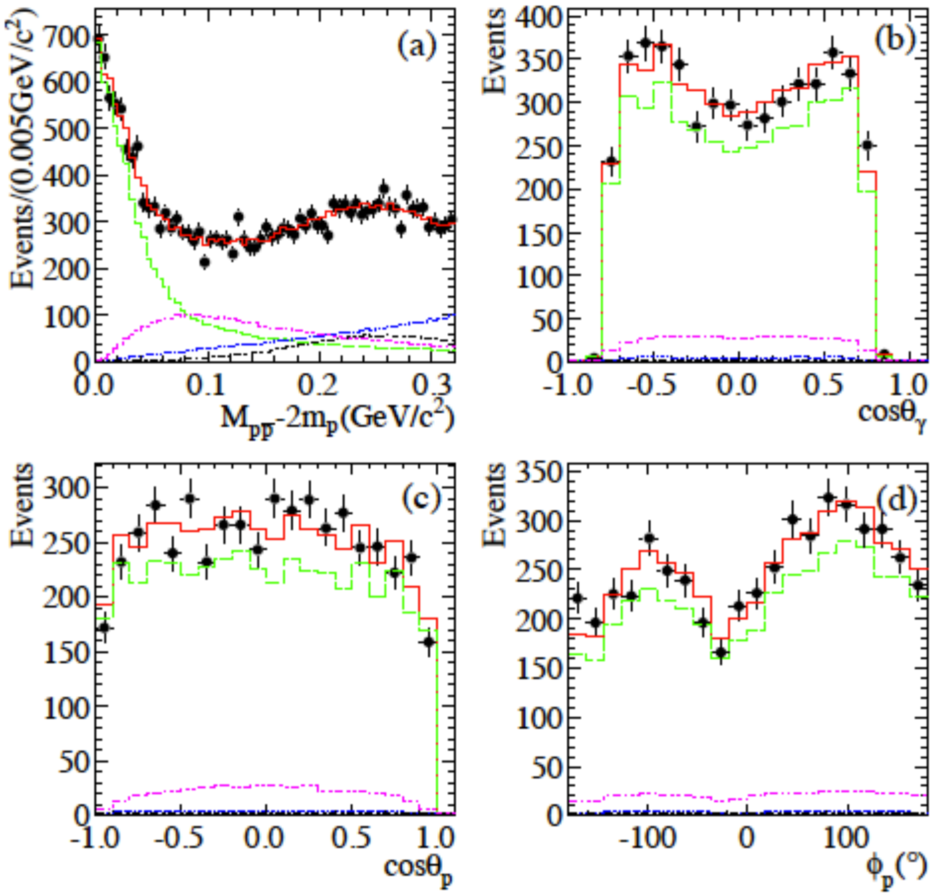
$p\bar{p}$ bound state in $J/\psi \rightarrow \gamma p\bar{p}$?

BESII -- 10 years ago --



2012, with 5x more data

$J/\psi \rightarrow \gamma p\bar{p}$



PRL 108, 112003 (2012)

Partial Wave Analysis:

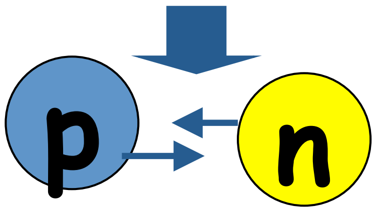
- $J^{PC} = 0^{-+}$ >6.8σ better than other assignments
- I=0 FSI improves the fit quality by ~7σ
- $M = 1832^{+19}_{-5}\,^{+18}_{-17} \pm 19_{model}$ MeV
  ($\approx 2m_p$-40 MeV)
- $\Gamma <$ 76 MeV
- $Bf(J/\psi \rightarrow \gamma X) \times Bf(X \rightarrow p\bar{p})$=
  $(9.0^{+0.4}_{-1.1}\,^{+1.5}_{-5.0} \pm 2.3_{model}) \times 10^{-5}$
  → suggests $Bf(X \rightarrow p\bar{p})$~large

A $p\bar{p}$ bound state (baryonium)?

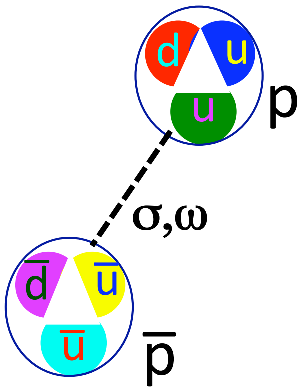
There are lots & lots of models about this possibility

deuteron:

attractive nuclear force

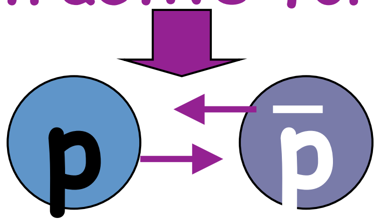


loosely bound
3-q 3-q color
singlets with
$M_d = 2m_p - \varepsilon$



baryonium:

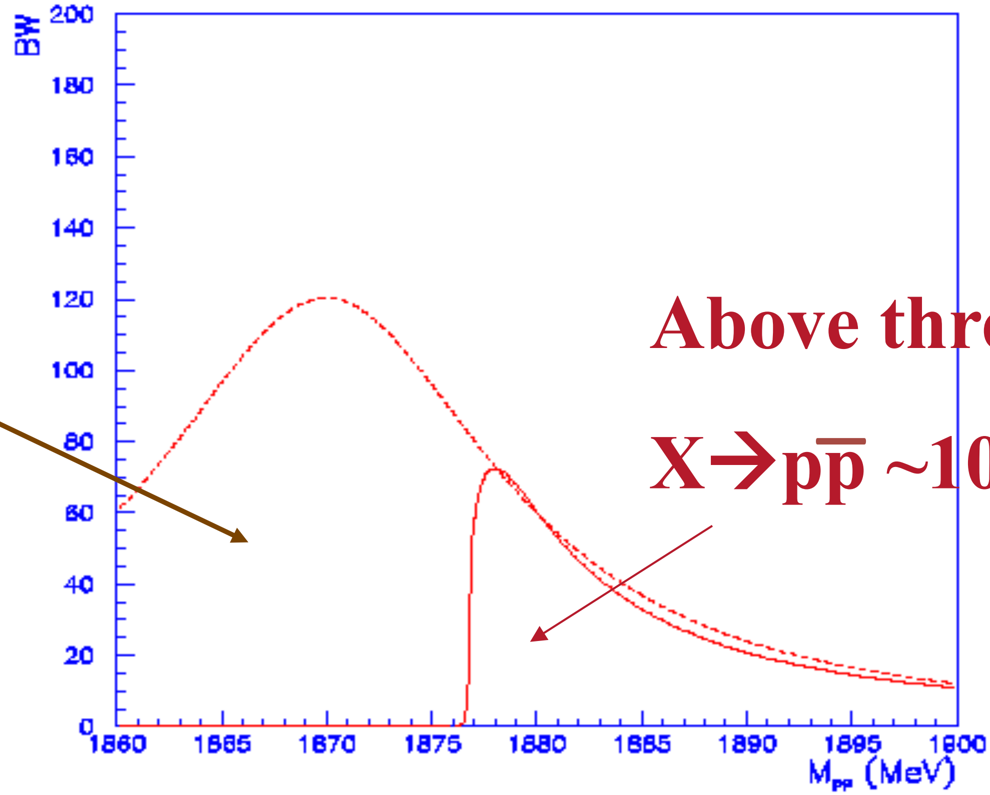
attractive force?



loosely bound
3-q 3-$\bar{q}$ color
singlets with
$M_b = 2m_p - \delta$?

Expectation for $p\bar{p}$ bound state

below-threshold
p and $\bar{p}$
annihilate to
mesons



Above threshold

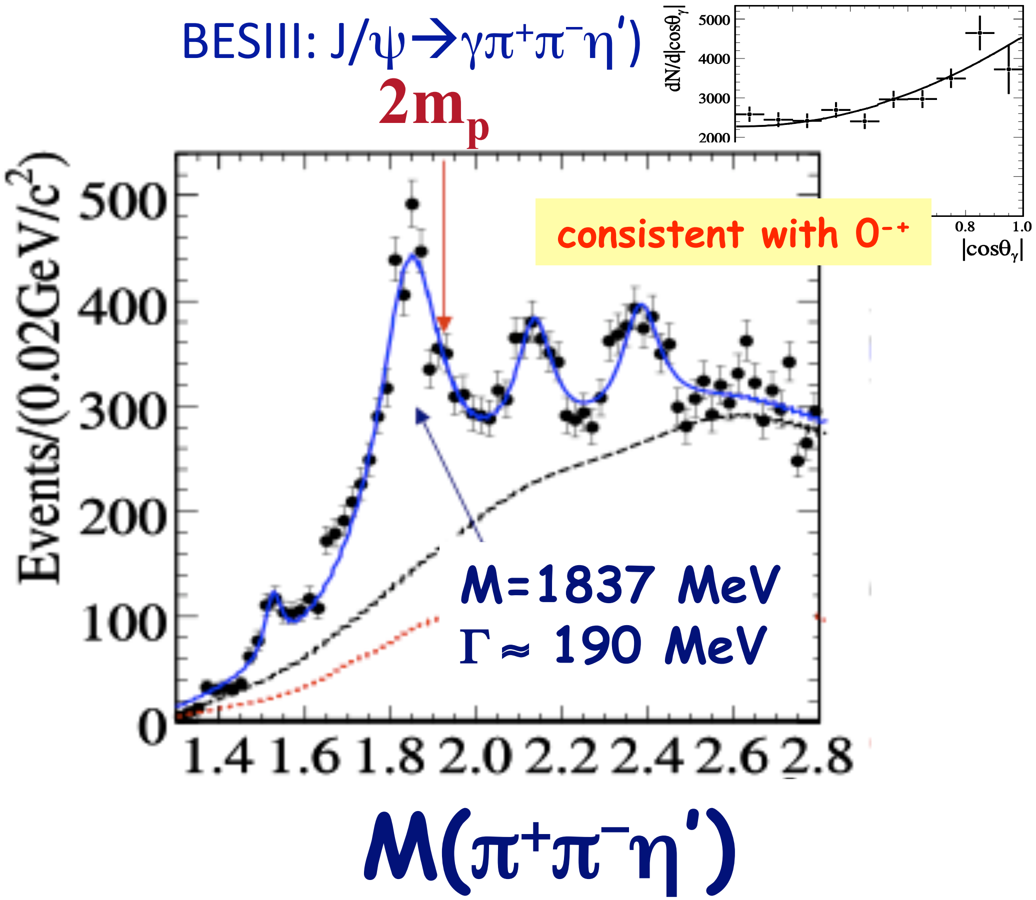
$X \rightarrow p\bar{p} \sim 100\%$

$m_p + m_p$

$I=0$, $J^{PC}=0^{-+}$ init. state:
$p\bar{p} \rightarrow \pi^+\pi^-\eta'$ and $3(\pi^+\pi^-)$
are common

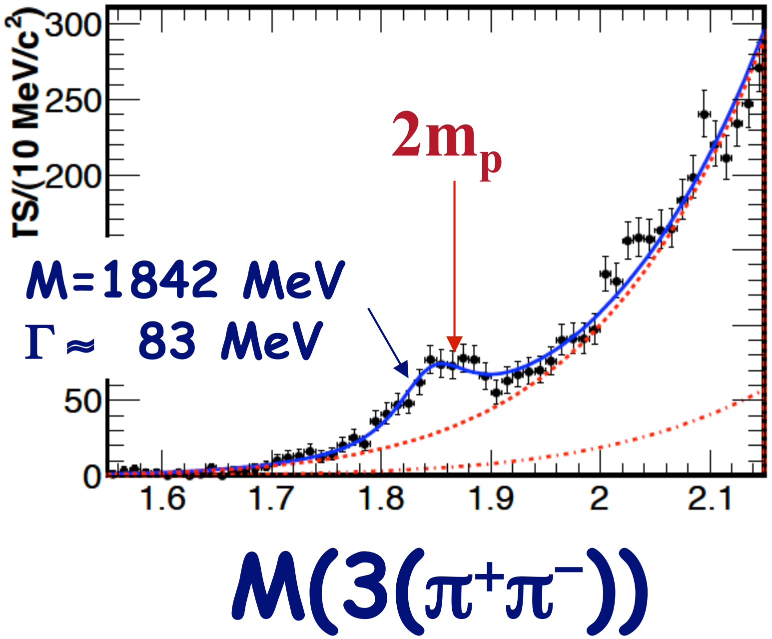
$J/\psi \rightarrow \gamma X(1835) \rightarrow \gamma (\pi^+\pi^-\eta')$?
$\rightarrow \gamma\, 3(\pi^+\pi^-)$?

BESIII: $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$



BESIII PRL 106, 072002 (2011)

BESIII: $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$



BESIII **arXiv:1305.5333**

$M=1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV

$\Gamma=83 \pm 14.2 \pm 11$MeV

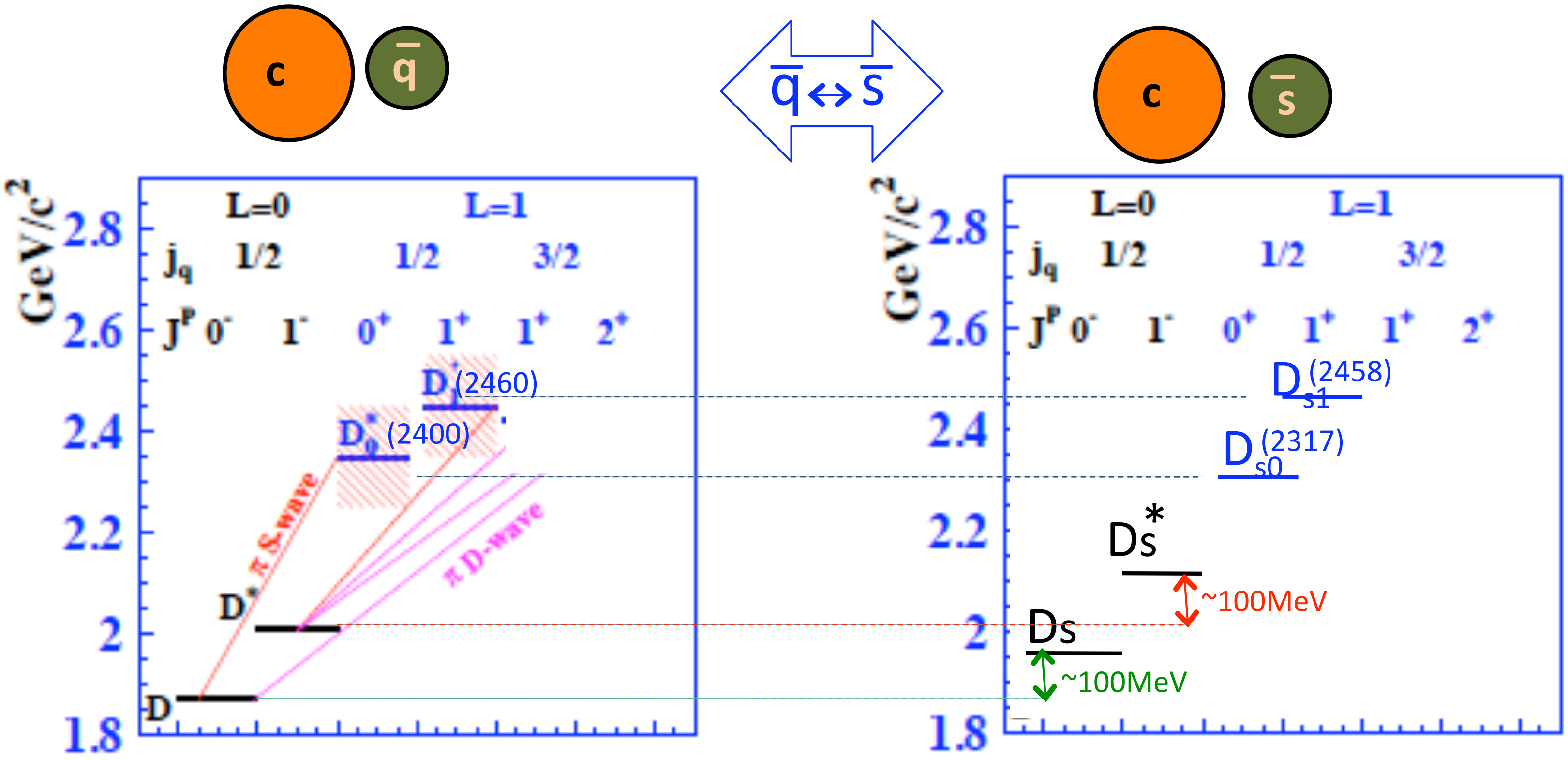
Are the $p\bar{p}$, $\pi^+\pi^-\eta'$ & $3(\pi^+\pi^-)$ peaks all from the same state?

channel	M (Mev)	Γ (MeV)	J^{PC}	$Bf(J/\psi\to\gamma X)xBf(X\to f\,i)$
$p\bar{p}$	1832^{+32}_{-38}	13^{+25}_{-13}	0^{-+}	$(0.9^{+0.3}_{-0.5})x10^{-4}$
$\pi^+\pi^-\eta'$	1837^{+7}_{-4}	190^{+39}_{-37}	0^{-+}(?)	$(2.9\pm0.1)x10^{-4}$
$3(\pi^+\pi^-)$	1842^{+8}_{-5}	83 ± 17	$?^{?+}$	$(0.24\pm0.08)x10^{-4}$

Need: J^{PC} measurement for the $X(1842)\to3(\pi^+\pi^-)$ signal
better measurements of widths & line shapes
other decay modes

Some of this will be done soon with BESIII's 1.2B J/ψ event data sample,

Charmed Meson Spectrum Puzzle



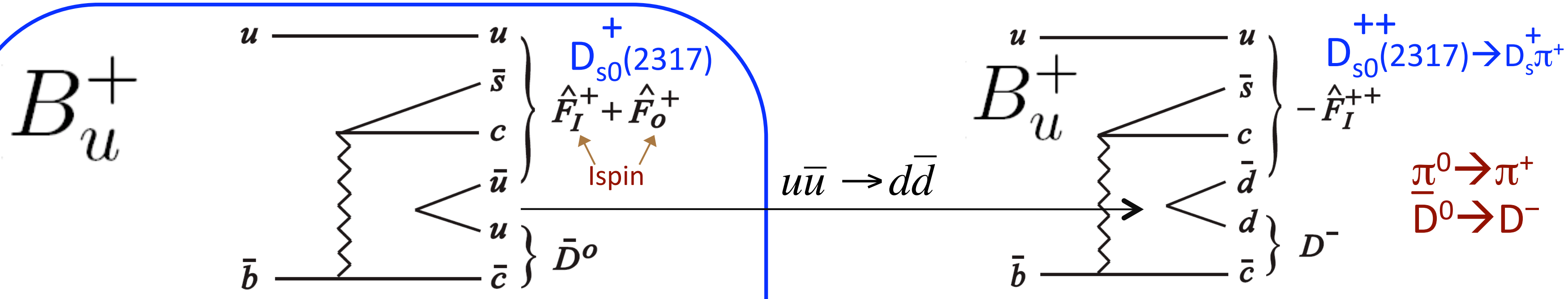
The D_s & D_s* masses are heavier than the D & D* masses, consistent with m_s-m_q~100MeV.

Why aren't the D_{s0}(2317) and D_{s1}(2458) masses higher than their non-strange partners?

Search for Z^{++} (= $D_{sJ}^{++}(2317)$)

Some theorists (e.g. Terasaki, PTP 116, 435 (2006)) interpret D_{sJ} mesons as tetraquarks

$D_{s0}^{+}(2317)$ production

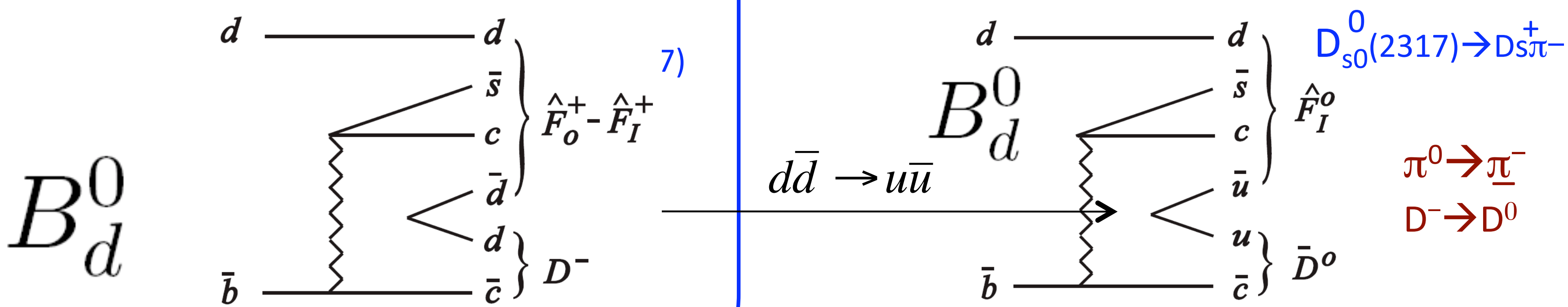


$$B_u^+ \to \bar{D}^0(\text{or } \bar{D}^{*0})\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$$

predict:

$$B(B_u^+ \to D^-\hat{F}_I^{++}) \sim B(B_u^+ \to \bar{D}^0\tilde{D}_{s0}^+(2317)[D_s^+\pi^0])$$

PDG: $(0.73^{+0.22}_{-0.17}) \times 10^{-3}$



$$B_d^0 \to D^-\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$$

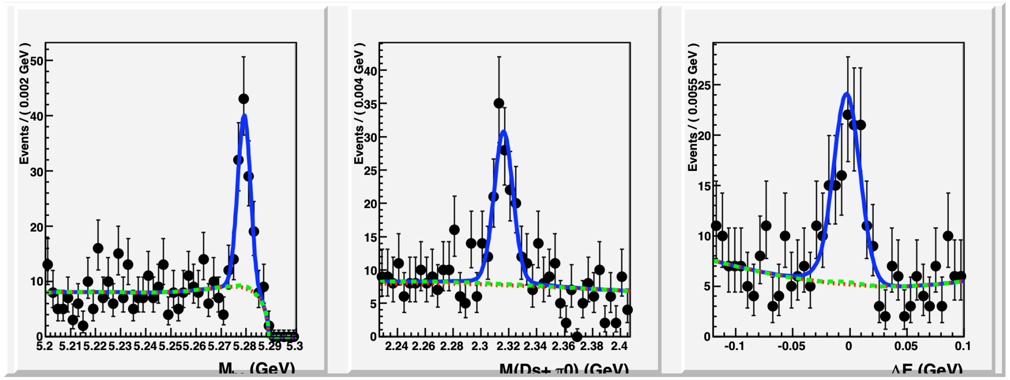
predict:

$$B(B_d^0 \to \bar{D}^0\hat{F}_I^0) \sim B(B_d^0 \to D^-\tilde{D}_{s0}^+(2317)[D_s^+\pi^0])$$

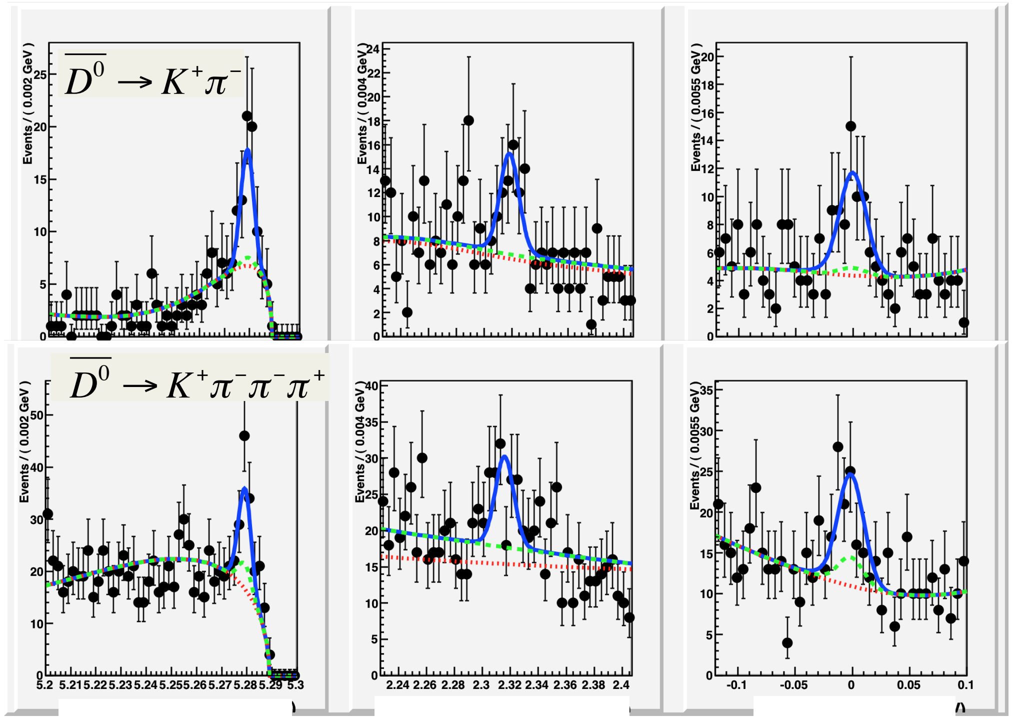
PDG: $(0.97^{+0.40}_{-0.33}) \times 10^{-3}$

Improved BF for B $\rightarrow D_{s0}^{+}D$: $D_{s0}^{+}\rightarrow K^{+}K^{-}\pi^{+}$

$B^{0}\rightarrow D^{-}D_{s0}^{+}(2317)$ $D^{-}\rightarrow K^{+}\pi^{-}\pi^{-}$



$B^{+}\rightarrow \overline{D^{0}}D_{s0}^{+}(2317)$;



Mbc (GeV) MD$_s\pi$ (GeV) ΔE (GeV)

$$Bf(B^{0}\rightarrow D^{-}D_{S0}^{+}(2317))Bf(D_{S0}^{+}\rightarrow D_{s}^{+}\pi^{0})$$
$$=(1.00\pm 0.12\pm 0.10\pm 0.05)\times 10^{-3}$$

PDG(B^0): $(0.97^{+0.40}{-0.33})\times 10^{-3}$

weighted average

$$Bf(B^{+}\rightarrow \overline{D^{0}}D_{S0}^{+}(2317))Bf(D_{S0}^{+}\rightarrow D_{s}^{+}\pi^{0})$$
$$=(0.78^{+0.13}_{-0.12}\pm 0.10\pm 0.05)\times 10^{-3}$$

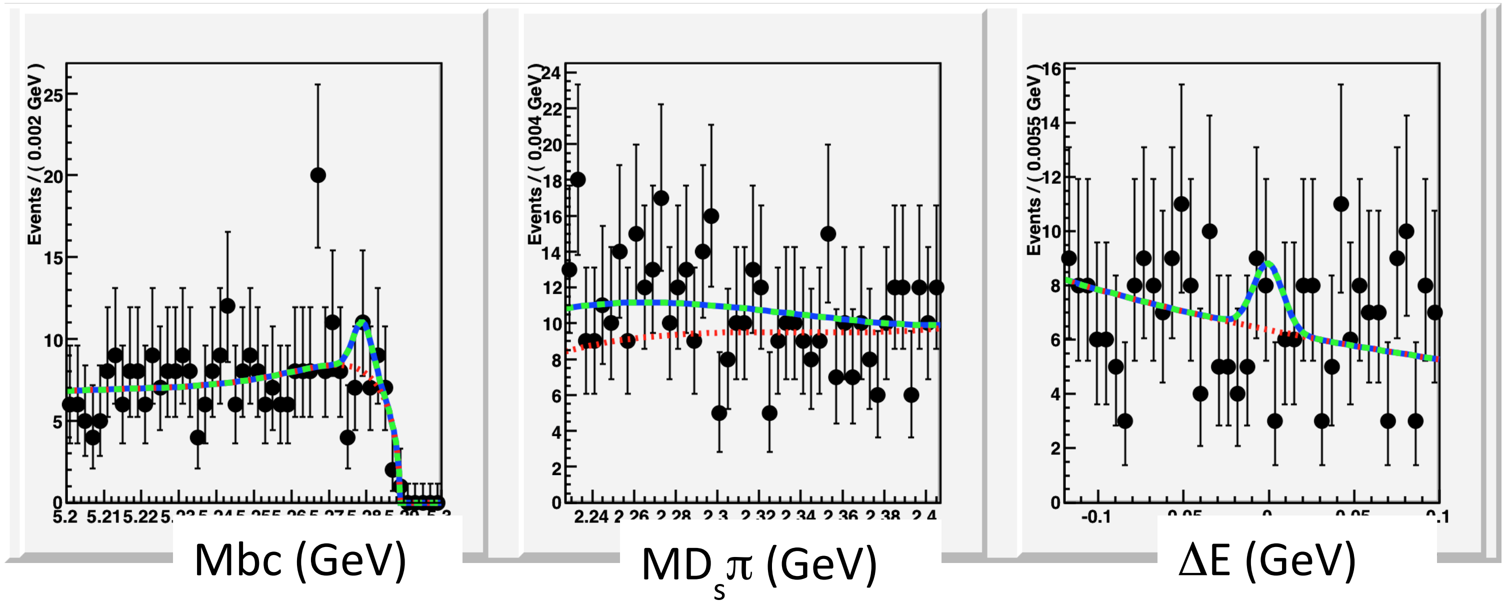
PDG(B^+): $(0.73^{+0.22}{-0.17})\times 10^{-3}$

Agrees with PDG avgs
& improves on the errors

Belle Preliminary

Search for Z^{++} in $B^+ \to D^- Z^{++}$; $Z^{++} \to D_{s0}^{+}\pi^+$

Belle Preliminary



$$Bf(B^+ \to D^- Z^{++}(2317))Bf(Z^{++} \to D_s^+\pi^+) < 0.28 \times 10^{-4} \ (90\% \ CL)$$

No indication of signal

Factor of ~30 below predicted level

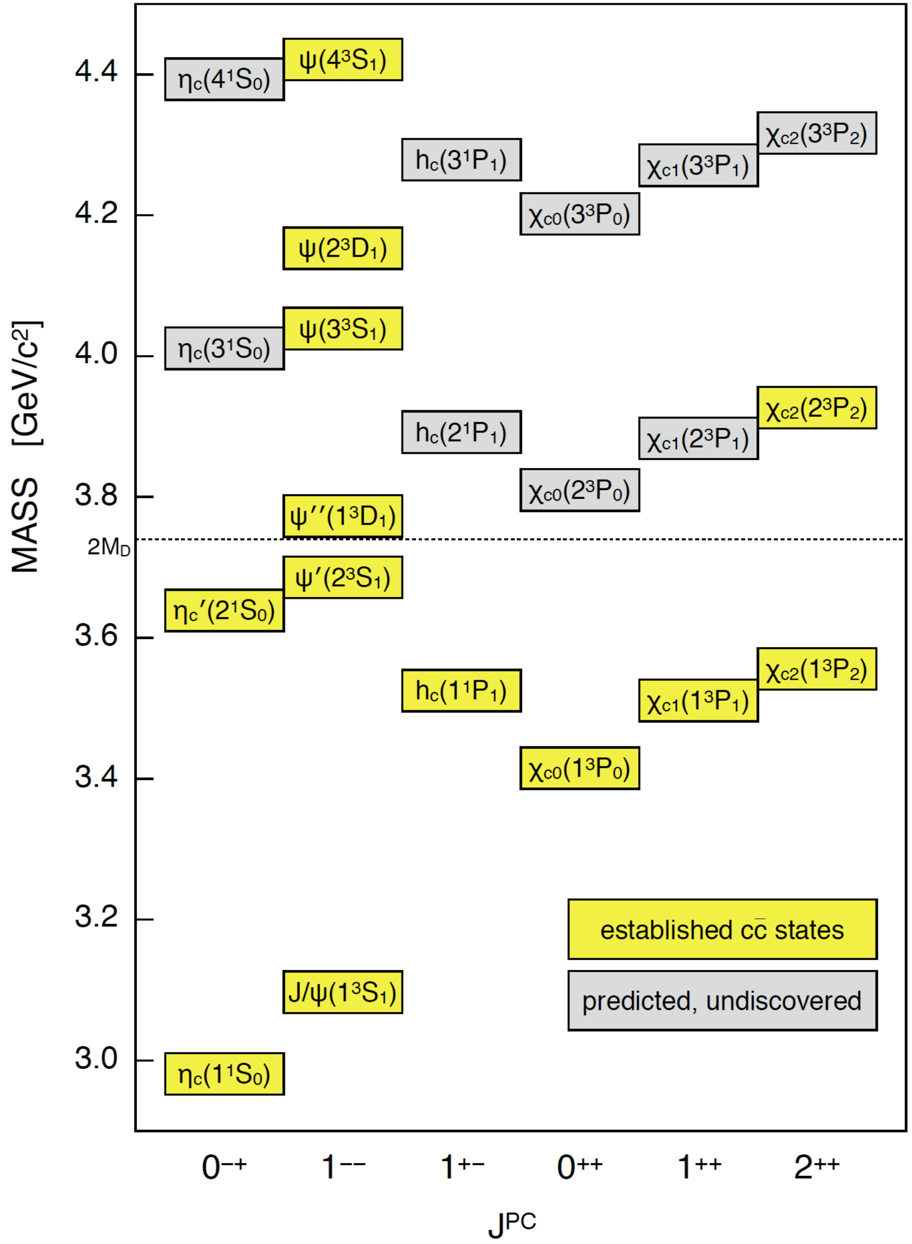
BaBar search in e+e- annihilation

$$\frac{\sigma(e^+e^- \to D_{sJ}^{++}X)}{\sigma(e^+e^- \to D_{sJ}(2317)^+X)} < 1.7\times10^{-2} \ @95\%CL$$

$$\frac{\sigma(e^+e^- \to D_{sJ}^{0}X)}{\sigma(e^+e^- \to D_{sJ}(2317)^+X)} < 1.3\times10^{-2} \ @95\%CL$$

The XYZ quarkonium-like mesons

Charmonium spectrum



Any meson that decays to a c and $\bar{c}$ quark should fit in one of the (gray) unassigned states.

XYZ charmoniumlike mesons

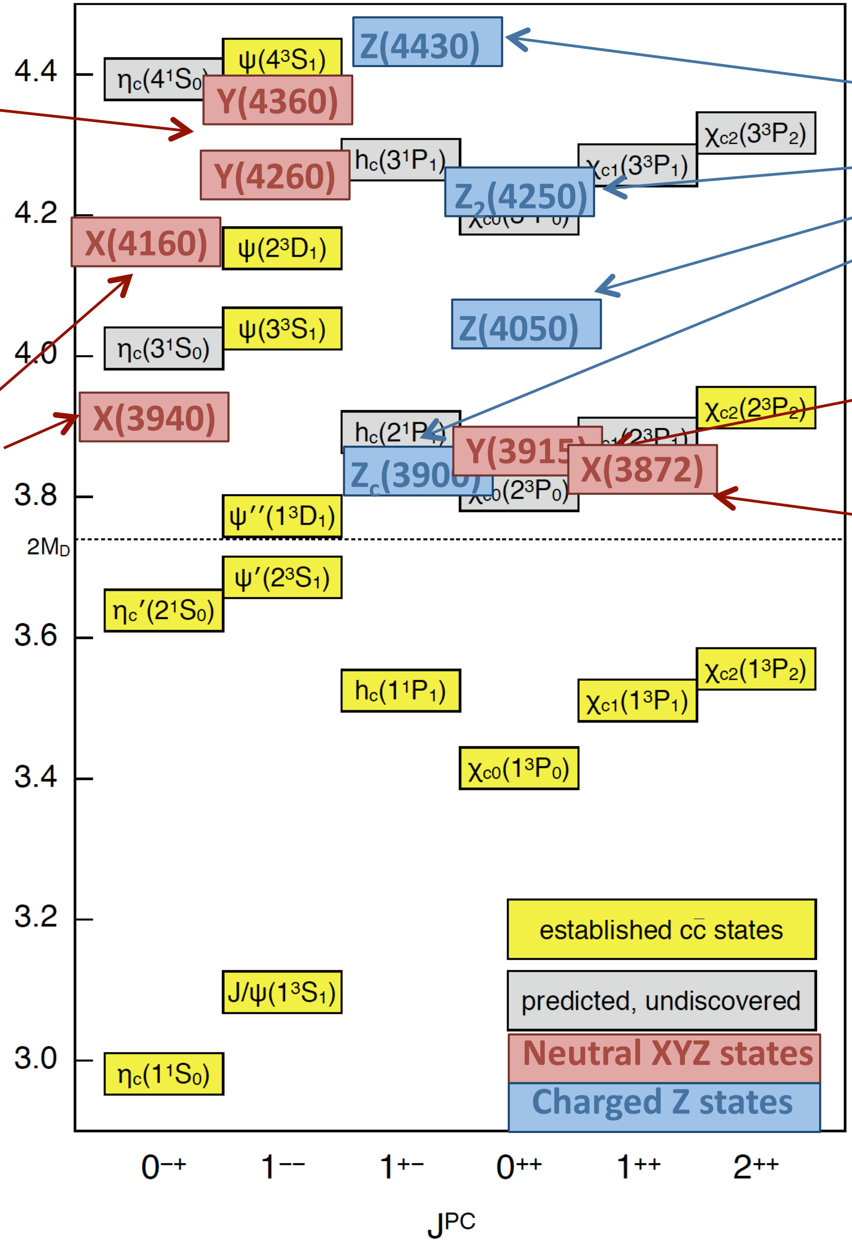
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0}\bar{D}^0)$
				$B \to K(\gamma J/\psi)$
$Z_c(3900)^+$	3899 ± 6	46 ± 22	$1^{+(-)}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$
$X(3915)$	3915.6 ± 3.1	28 ± 10	0^{++}	$B \to K(\omega J/\psi)$
				$e^+e^- \to e^+e^-(\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	0^{-+}	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (\ldots)$
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$0^{+(+)}/1^{-(+)}$	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	0^{-+}	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$0^{+(+)}/1^{-(+)}$	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	$1^{+(-)}$	$B \to K(\pi^+\psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$

$Y(4260) \to_\gamma X(3872)$

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

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

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



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

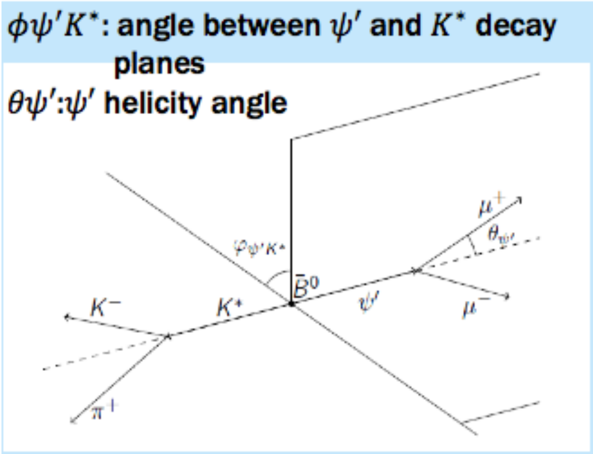
the Y(3915) mass and $\Gamma(Y \rightarrow \omega J/\psi)$ are too high for the $\chi_{c0}(2P)$

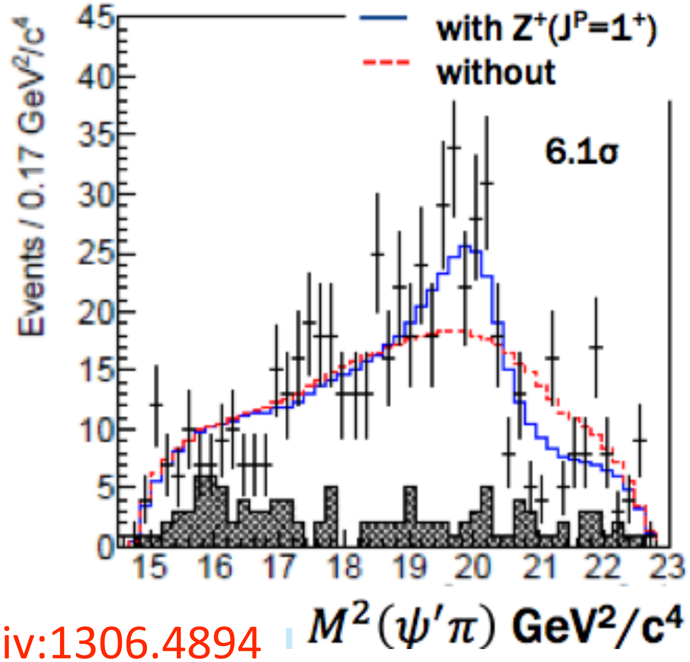
the X(3872) is a long complex story.

Latest news observing Y(4260) $\rightarrow \gamma$ X(3872) !! see Shen Chengping' talk

Quantum numbers of the $Z(4430)^+$

$Z(4430)^+ \rightarrow \pi^+\psi'$ in $B \rightarrow K^-\pi^+\psi'$





Results from 4D fit
$(M^2(K\pi),\ M^2(\psi'\pi),\ \phi\psi',\ \theta\psi')$

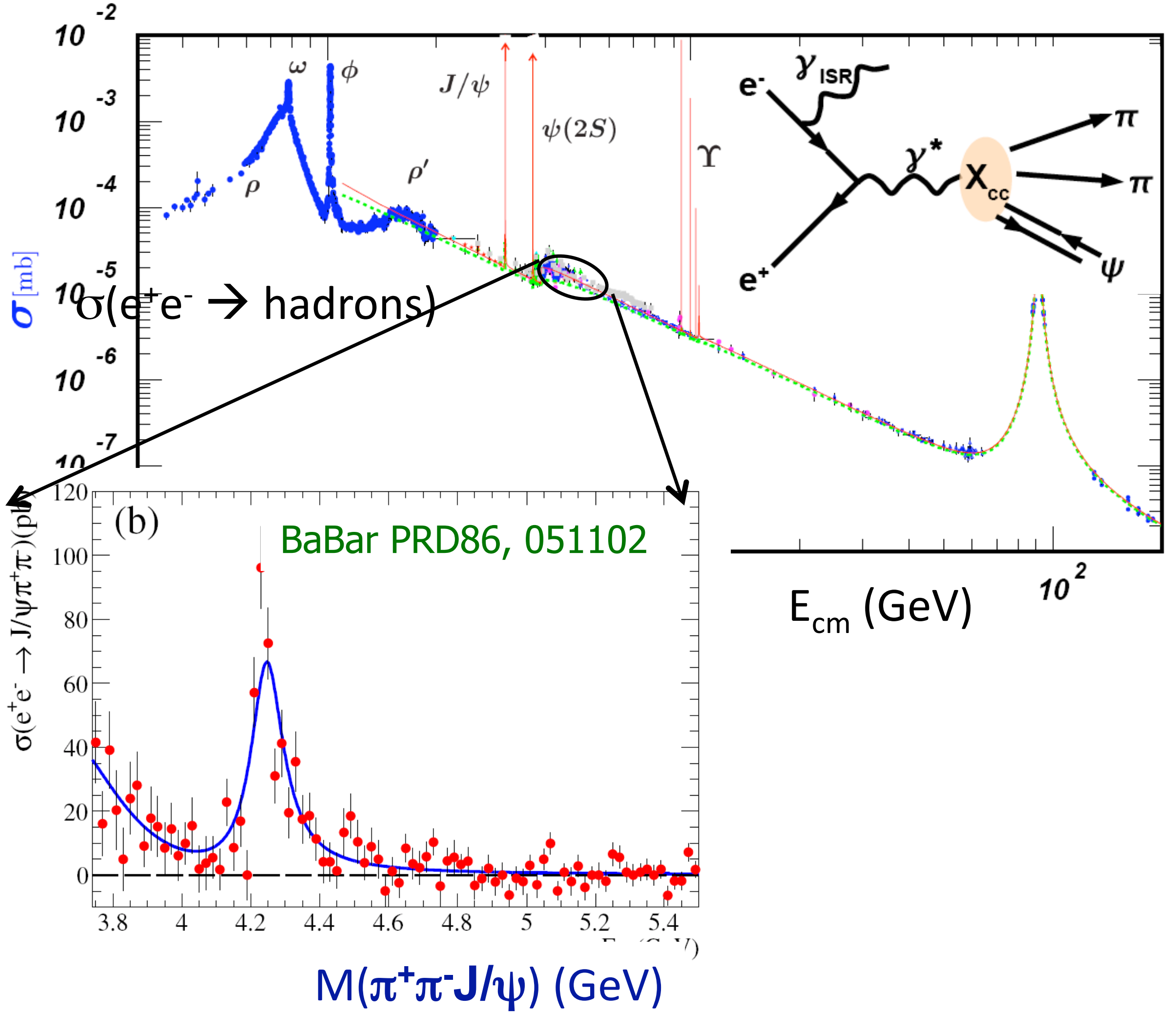
arXiv:1306.4894

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4470 ± 20	4482 ± 4	4500 ± 12	4545 ± 2	4367 ± 2
Width, MeV	139 ± 36	10.9 ± 0.3	126 ± 20	11.2 ± 0.6	9.1 ± 0.6
Significance	4.4σ	1.2σ	6.1σ	2.3σ	2.6σ

1^+ is favored over 0^- by 2.9 σ

the Y(4260)

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



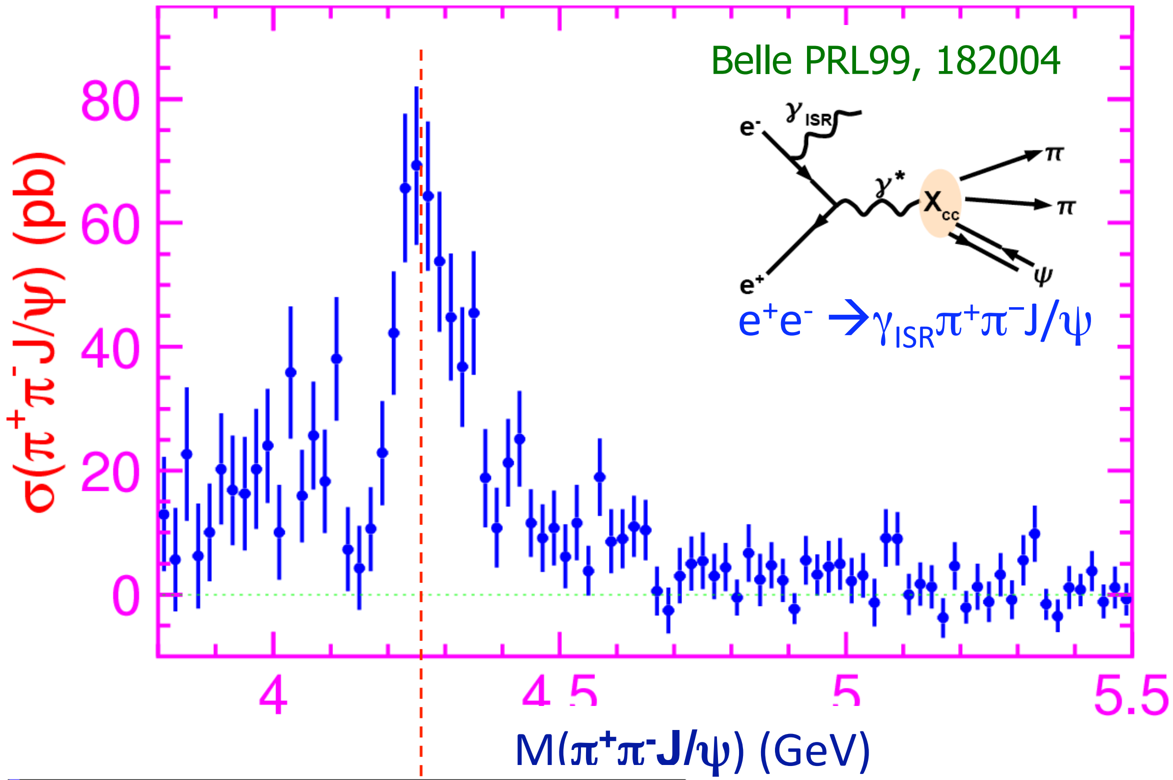
Y(4260) → $\pi^+\pi^- J/\psi$ confirmed by Belle

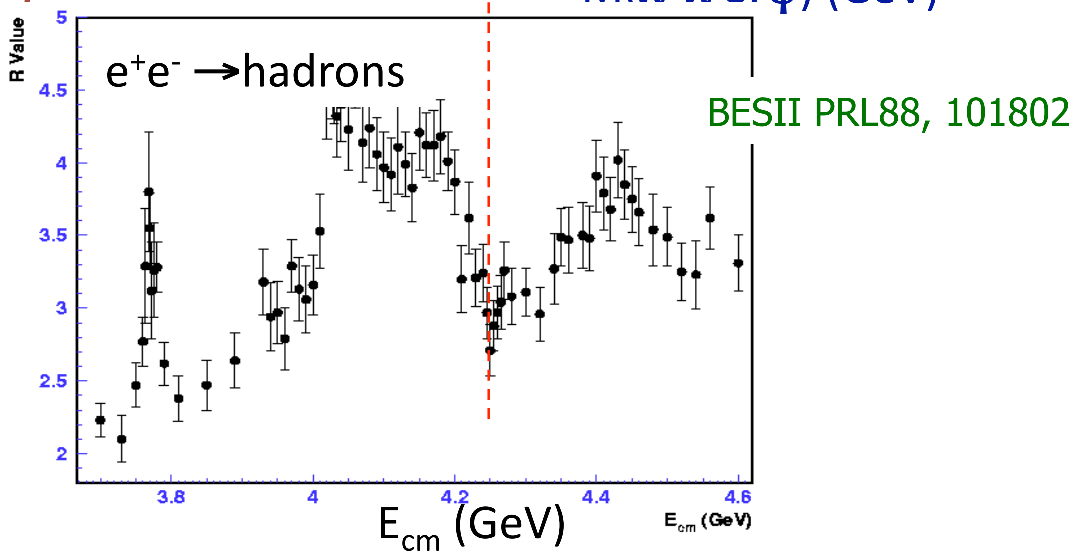
No sign of Y(4260) → $D^{(*)}D^{(*)}$

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

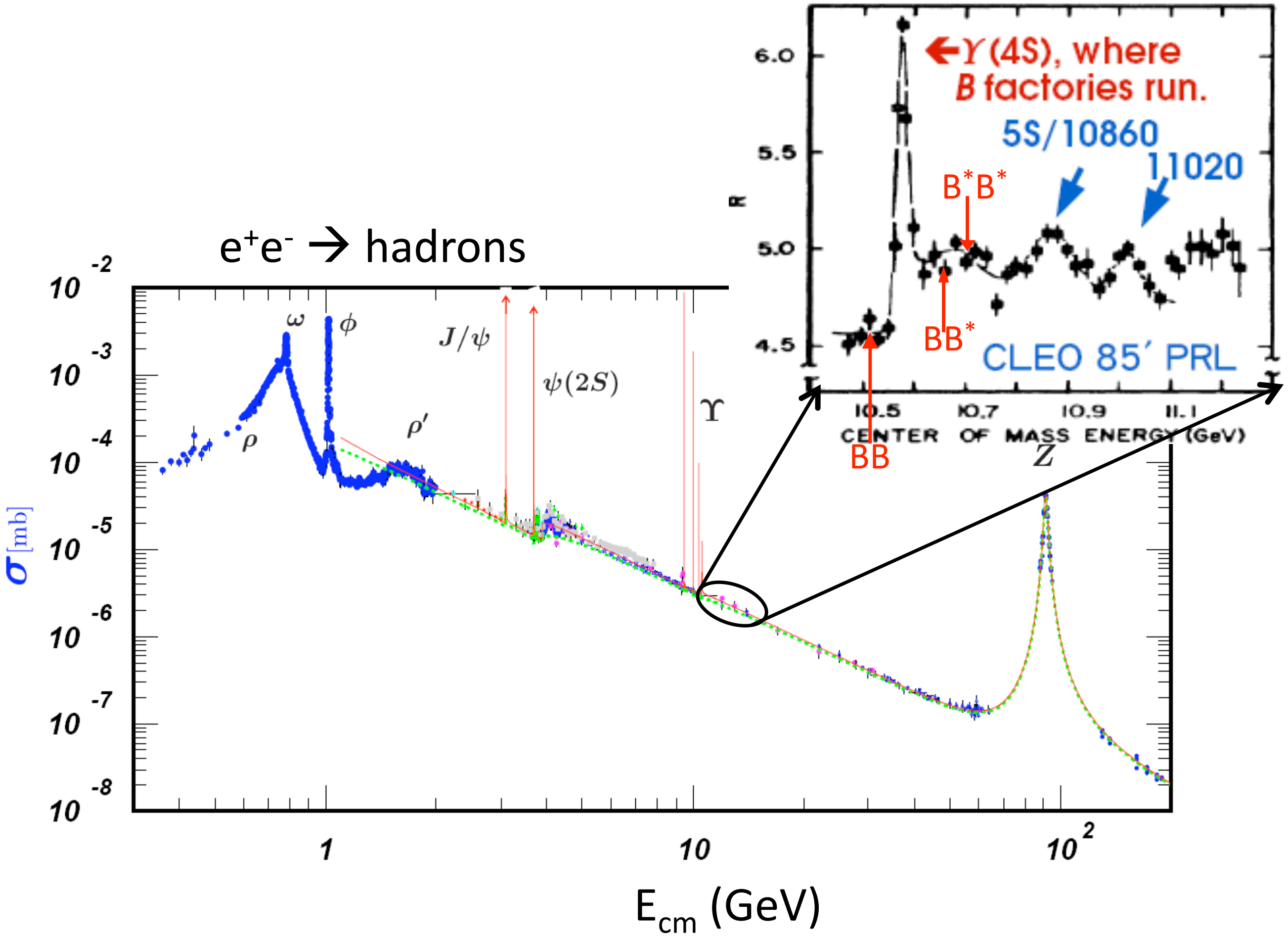
→ $\Gamma(\pi^+\pi^- J/\psi)$ is large, 10~100 × charmonium

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





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



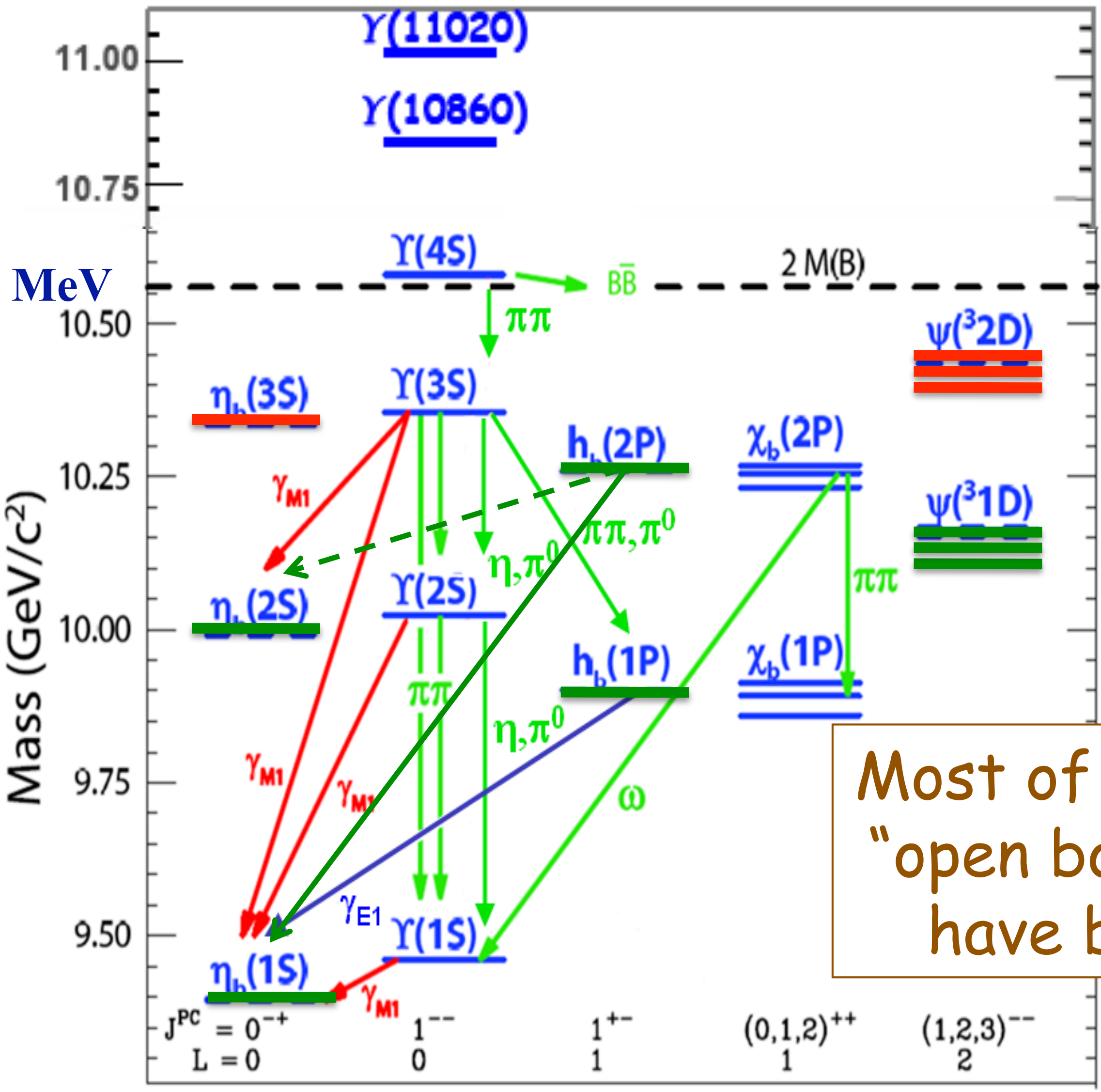
Bottomonium spectrum 2013

established

recently discovered

still not discovered

$2M_B = 10.56$ MeV

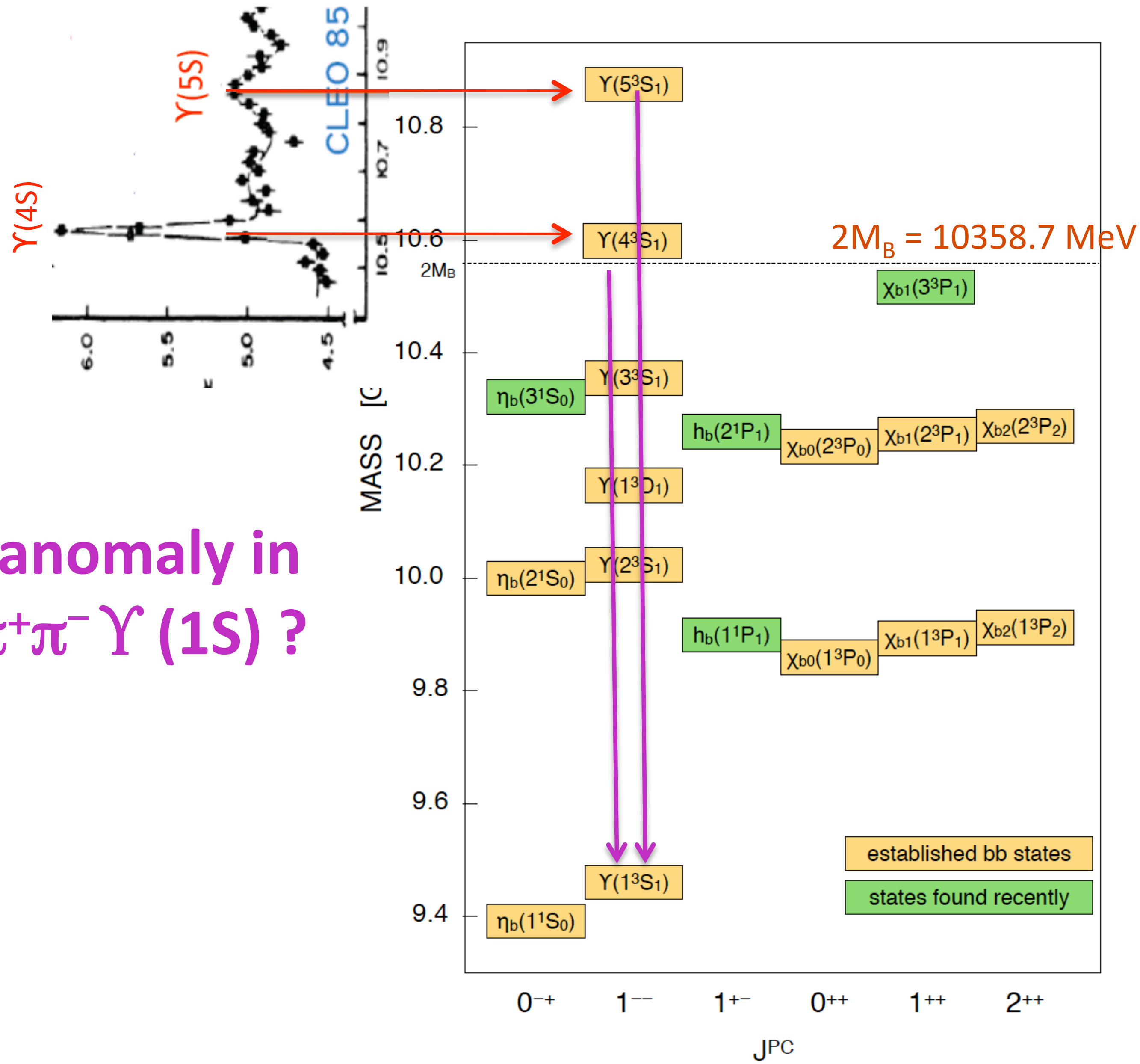


Belle: PRL109, 232002

$h_b(1,2P) \to \gamma \eta_b(1,2S)$

Most of the states below "open bottom" threshold have been identified

“bottomonium” $b\bar{b}$ mesons



Is there any anomaly in $\Upsilon(4S,5S) \rightarrow \pi^+\pi^-\Upsilon(1S)$?

$\Gamma_{\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)}$

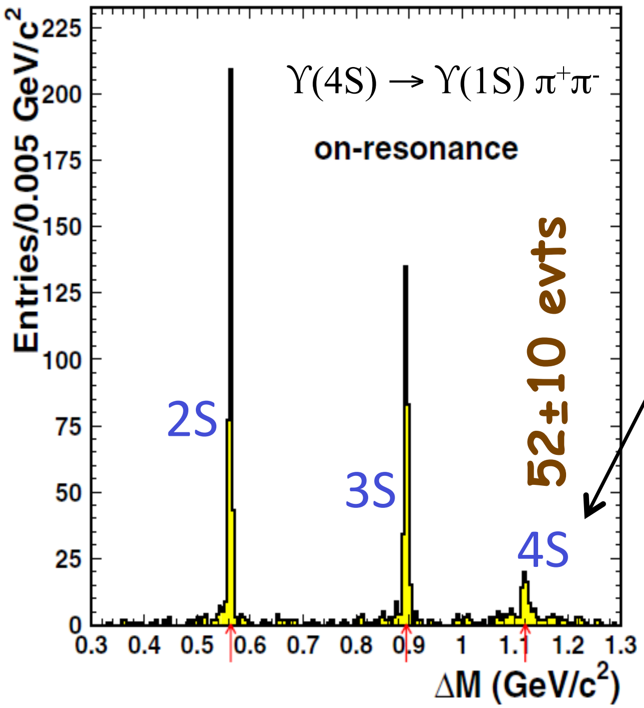
Belle: PRD 75 071103

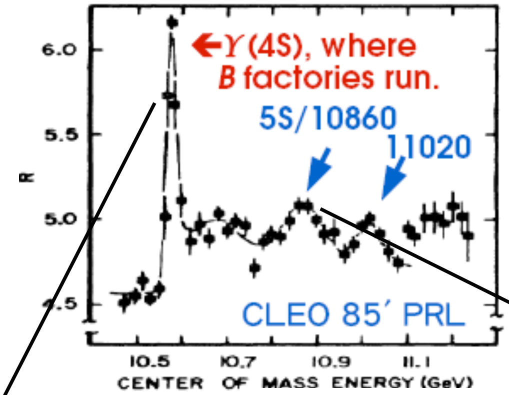
477 fb^{-1}

$\Gamma_{"\Upsilon(5S)"\to\pi^+\pi^-\Upsilon(1S)}$

Belle: PRL 100 112001

23.6 fb^{-1}



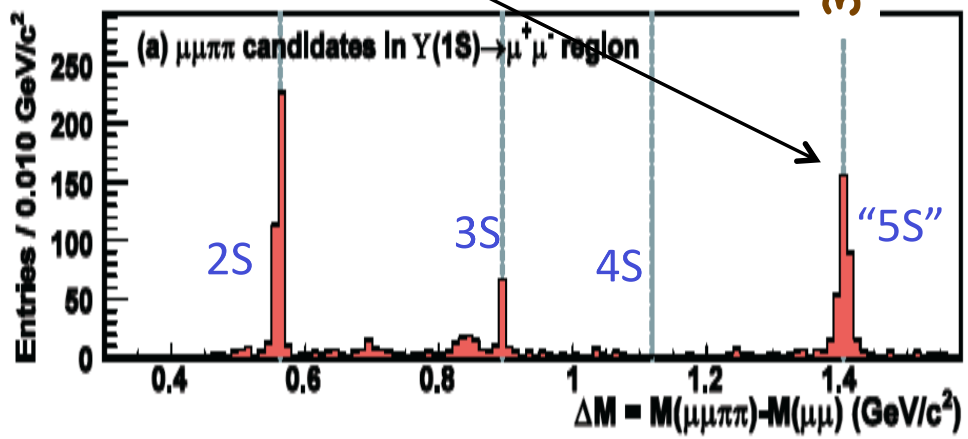


Signal

Lum ~1/20th

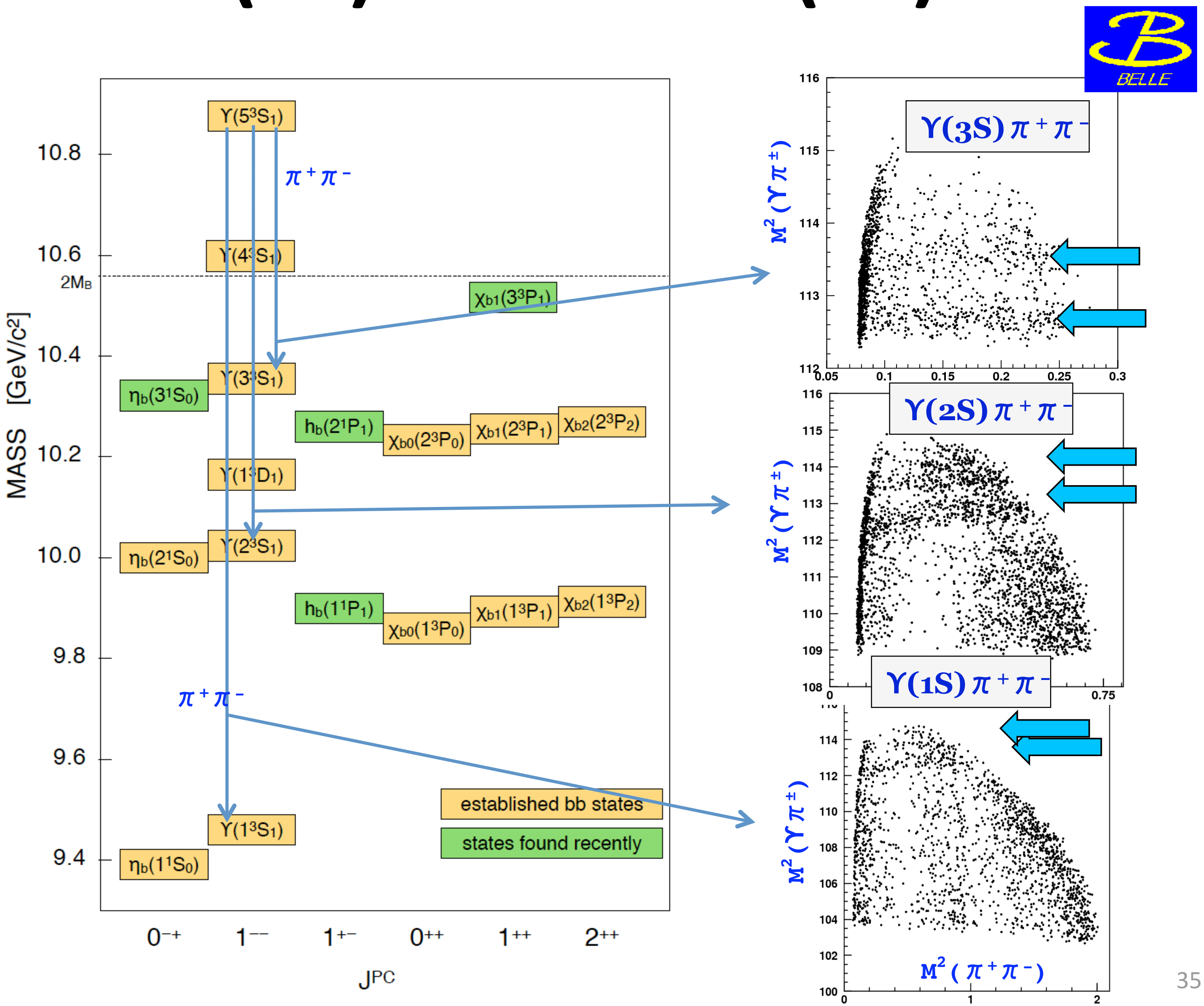
σ ~1/5th

Signal ~×6



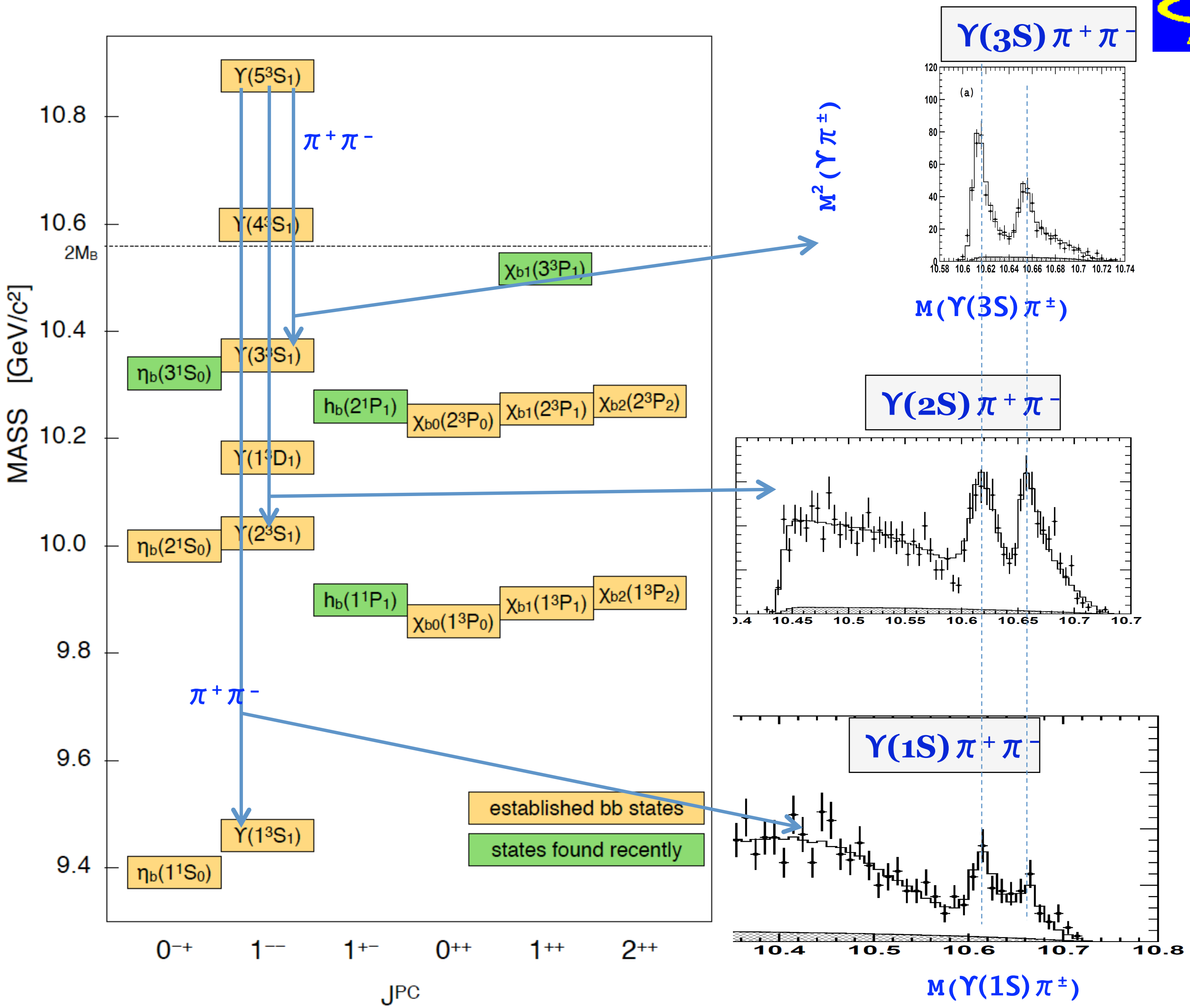
parent	$N(\pi^+\pi^-\Upsilon(1S))$	$\Gamma(Y_{4S}\to\pi\pi\Upsilon_{1S})$	Γ_{theory}
Υ(4S)	52±10	1.75 ± 0.35 keV	1.47±0.03 keV
"Υ(5S)"	325±20	590 ± 110 keV	<1.5 keV

"ϒ(5S)" → $\pi^+\pi^-$ ϒ (1S) ?



BELLE
MASS [GeV/c²]
10.8
10.6
2MB
10.4
10.2
10.0
9.8
9.6
9.4
ϒ(5³S₁)
ϒ(4³S₁)
χb1(3³P₁)
ϒ(3³S₁)
ηb(3¹S₀)
hb(2¹P₁)
χb0(2³P₀)
χb1(2³P₁)
χb2(2³P₂)
ϒ(1³D₁)
ϒ(2³S₁)
ηb(2¹S₀)
hb(1¹P₁)
χb0(1³P₀)
χb1(1³P₁)
χb2(1³P₂)
ϒ(1³S₁)
ηb(1¹S₀)
π⁺π⁻
π⁺π⁻
established bb states
states found recently
0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺
J^PC
ϒ(3S) π⁺π⁻
ϒ(2S) π⁺π⁻
ϒ(1S) π⁺π⁻
M²(ϒπ±)
M²(π⁺π⁻)

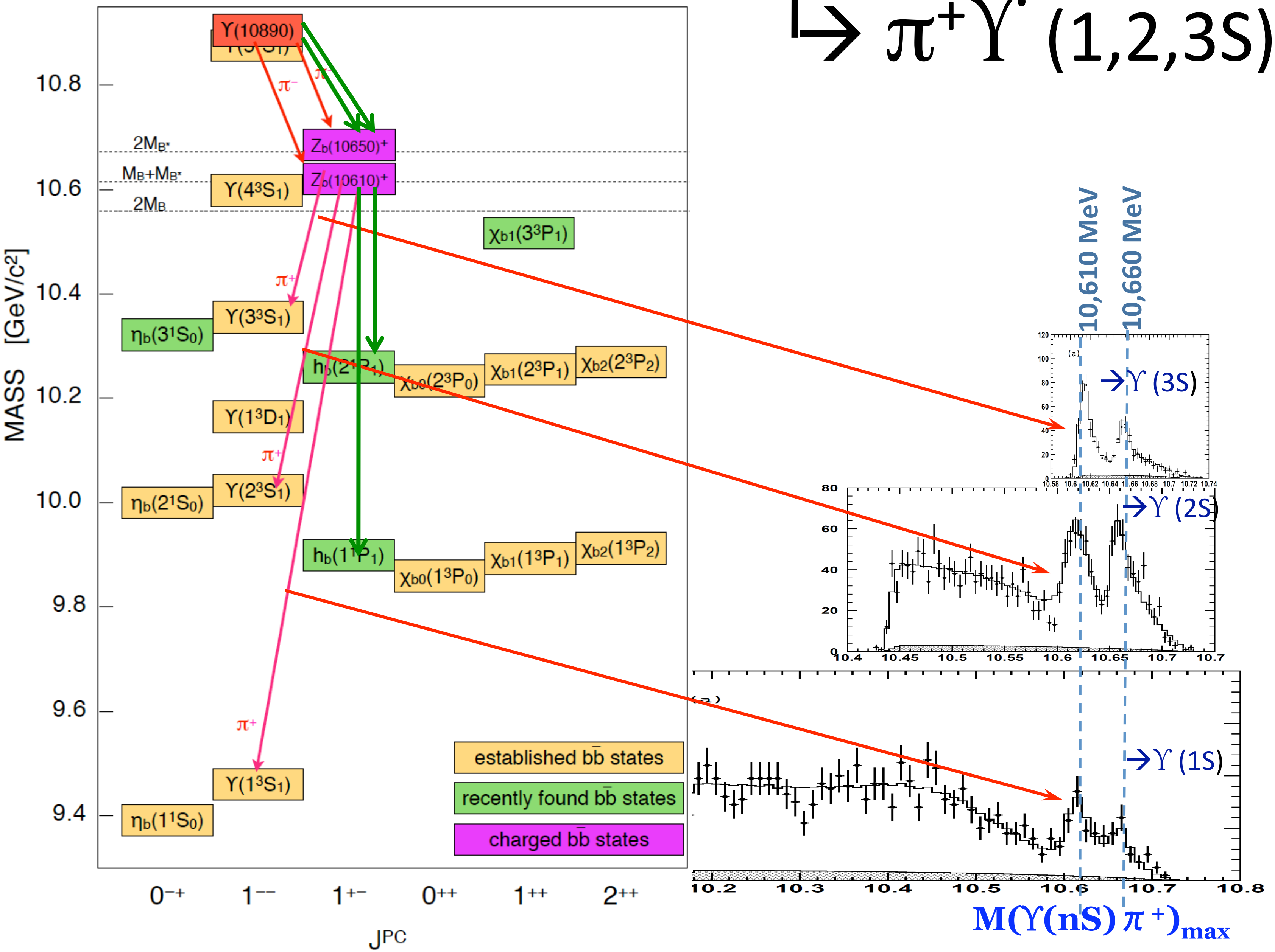
"Υ(5S)" → $\pi^+\pi^-$ Υ (1S) ?



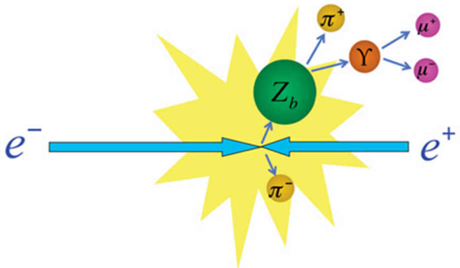
MASS [GeV/c²]
10.8
10.6
2MB
10.4
10.2
10.0
9.8
9.6
9.4
Υ(5³S₁)
Υ(4³S₁)
Υ(3³S₁)
Υ(1³D₁)
Υ(2³S₁)
Υ(1³S₁)
ηb(3¹S₀)
ηb(2¹S₀)
ηb(1¹S₀)
χb1(3³P₁)
hb(2¹P₁)
χb0(2³P₀)
χb1(2³P₁)
χb2(2³P₂)
hb(1¹P₁)
χb0(1³P₀)
χb1(1³P₁)
χb2(1³P₂)
π⁺π⁻
π⁺π⁻
established bb states
states found recently
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
JPC
Υ(3S)π⁺π⁻
M²(Υπ±)
M(Υ(3S)π±)
Υ(2S)π⁺π⁻
Υ(1S)π⁺π⁻
M(Υ(1S)π±)

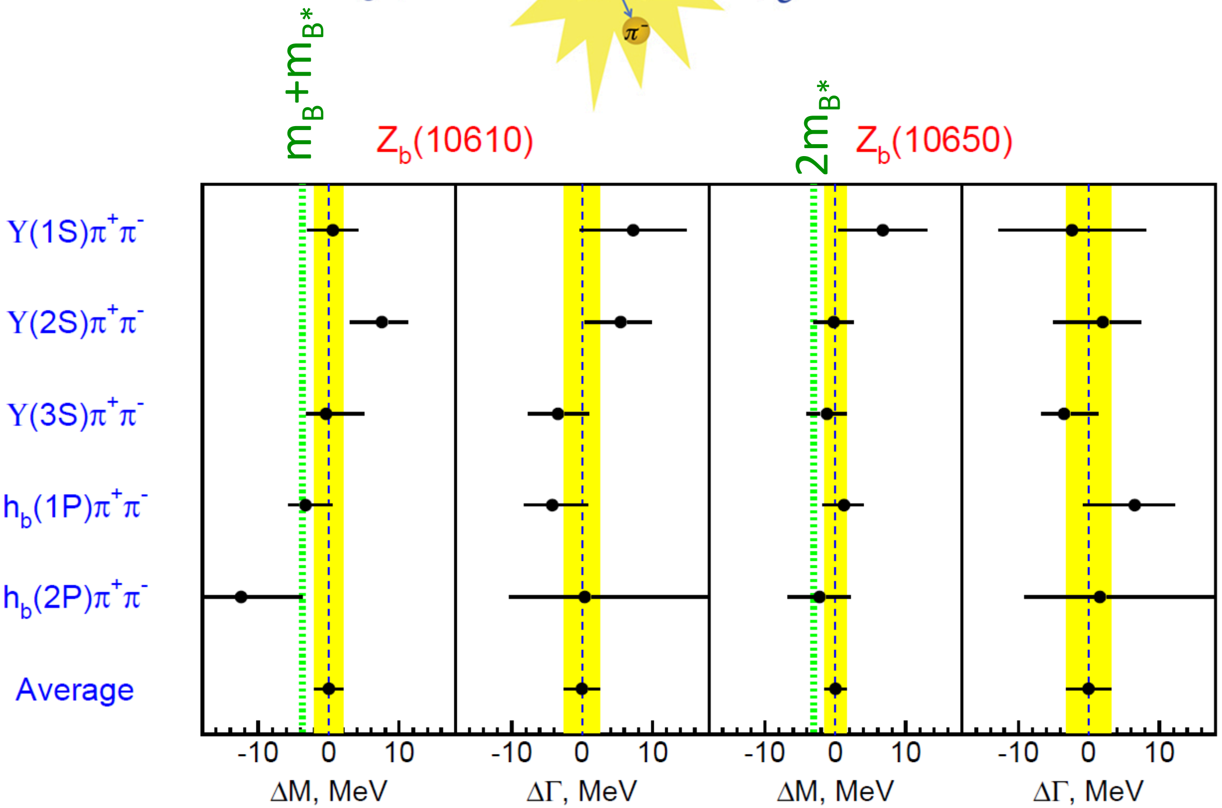
"Υ(5S)" → $\pi^- Z^+_{b1,2}$ ↳ $\pi^+\Upsilon$ (1,2,3S)

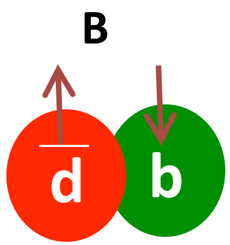
Belle PRL 108, 122001 (2012)
121.4 fb^{-1}

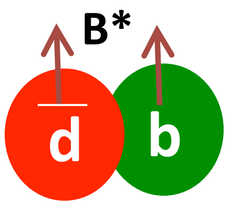


Summary of parameter measurements







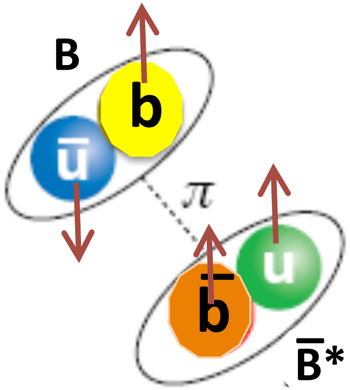


$Z_b(10610)$	$Z_b(10650)$
M=10607.2±2.0 MeV	M=10652.2±1.5 MeV
Γ=18.4±2.4 MeV	Γ=11.5±2.2 MeV

Belle PRL 108, 122001 ← March 2012

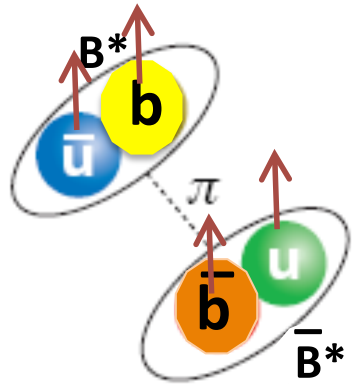
B-B̄* & B*-B̄* molecules??

$Z_b(10610)^{\pm}$



B-B̄* "molecule"

$Z_b(10650)^{\pm}$



B*-B̄* "molecule"

$M_{Z_b(10610)} - (M_B + M_{B^*}) = +\,2.7 \pm 2.1$ MeV

$M_{Z_b(10650)} - 2M_{B^*} = +\,2.0 \pm 1.8$ MeV

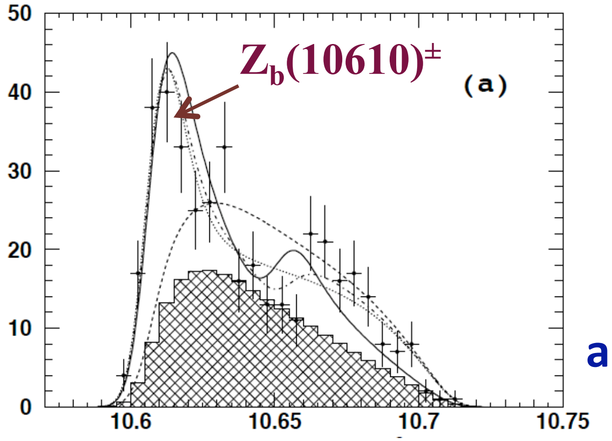
Slightly unbound threshold resonances??

Belle: M=10607.2±2.0 MeV, Γ=18.4±2.4 MeV; M=10652.2±1.5 MeV, Γ=11.5±2.2 MeV

PDG: $M_B + M_{B^*} = 10604.5 \pm 0.6$ MeV; $M_{B^*} + M_{B^*} = 10650.2 \pm 1.0$ MeV

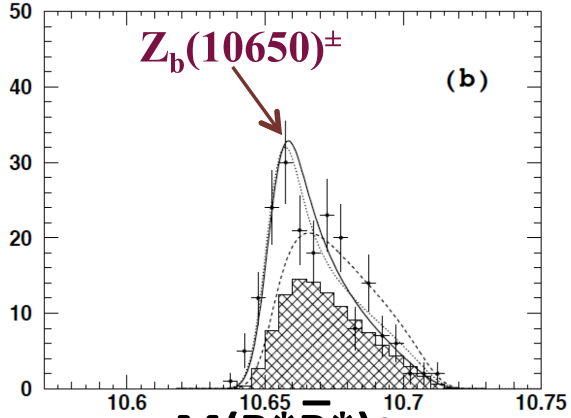
$Z_b(10610) \rightarrow B\bar{B}^*$ & $Z_b(10650) \rightarrow B^*\bar{B}^*$

"$\Upsilon(5S)$" $\rightarrow \pi^-(B\bar{B}^*)^+$



$M(B\bar{B}^*)$

"$\Upsilon(5S)$" $\rightarrow \pi^-(B^*\bar{B}^*)^+$



$M(B^*\bar{B}^*)$

arXiv:1308.2646

arXiv:1209.6450

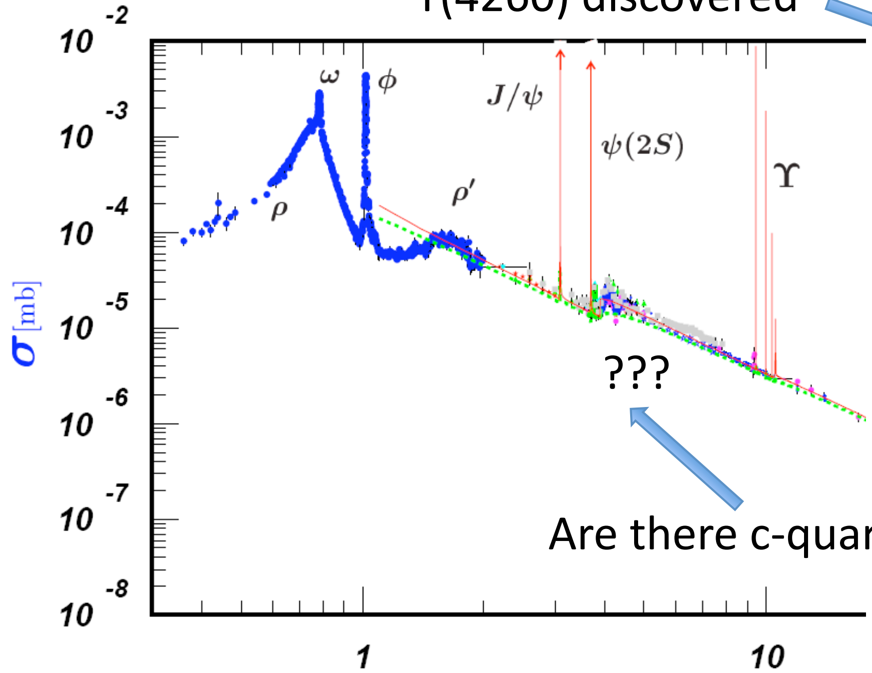
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

$$\frac{Bf(Z_b(10610) \rightarrow B\bar{B}^*)}{Bf(Z_b(10610) \rightarrow \pi^+(b\bar{b}))} = 6.2 \pm 0.7$$

$$\frac{Bf(Z_b(10650) \rightarrow B^*\bar{B}^*)}{Bf(Z_b(10650) \rightarrow \pi^+(b\bar{b}))} = 2.8 \pm 0.4$$

Are there c-quark versions of Z_b's

Y(4260) discovered



Is there a b-quark equivalent?

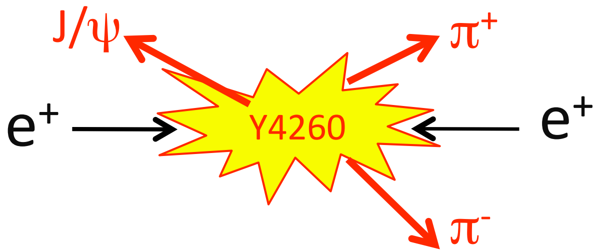
Yes, & it decays to Z_b states

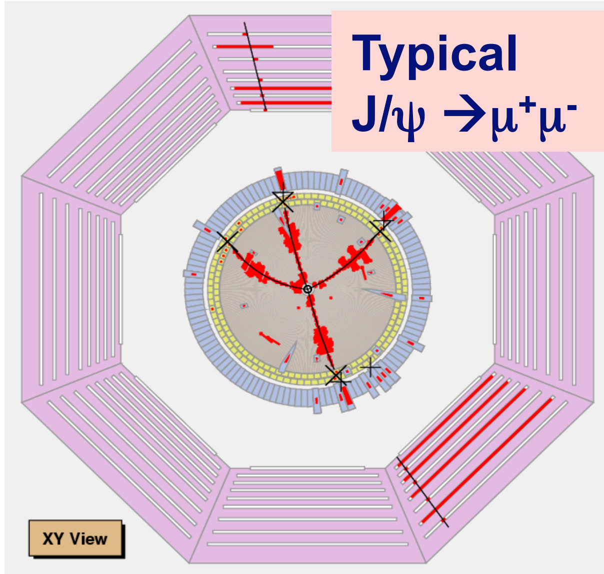
Are there c-quark versions of Z_b's?

run BEPCII/BESIII as a Y(4260) factory

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

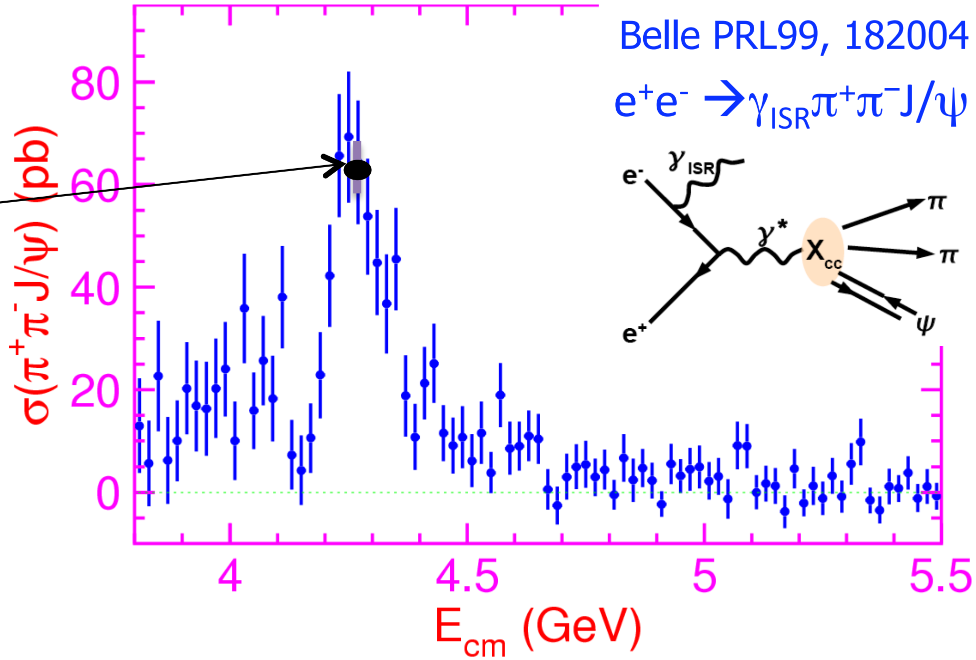
$@E_{cm}=4260$ MeV





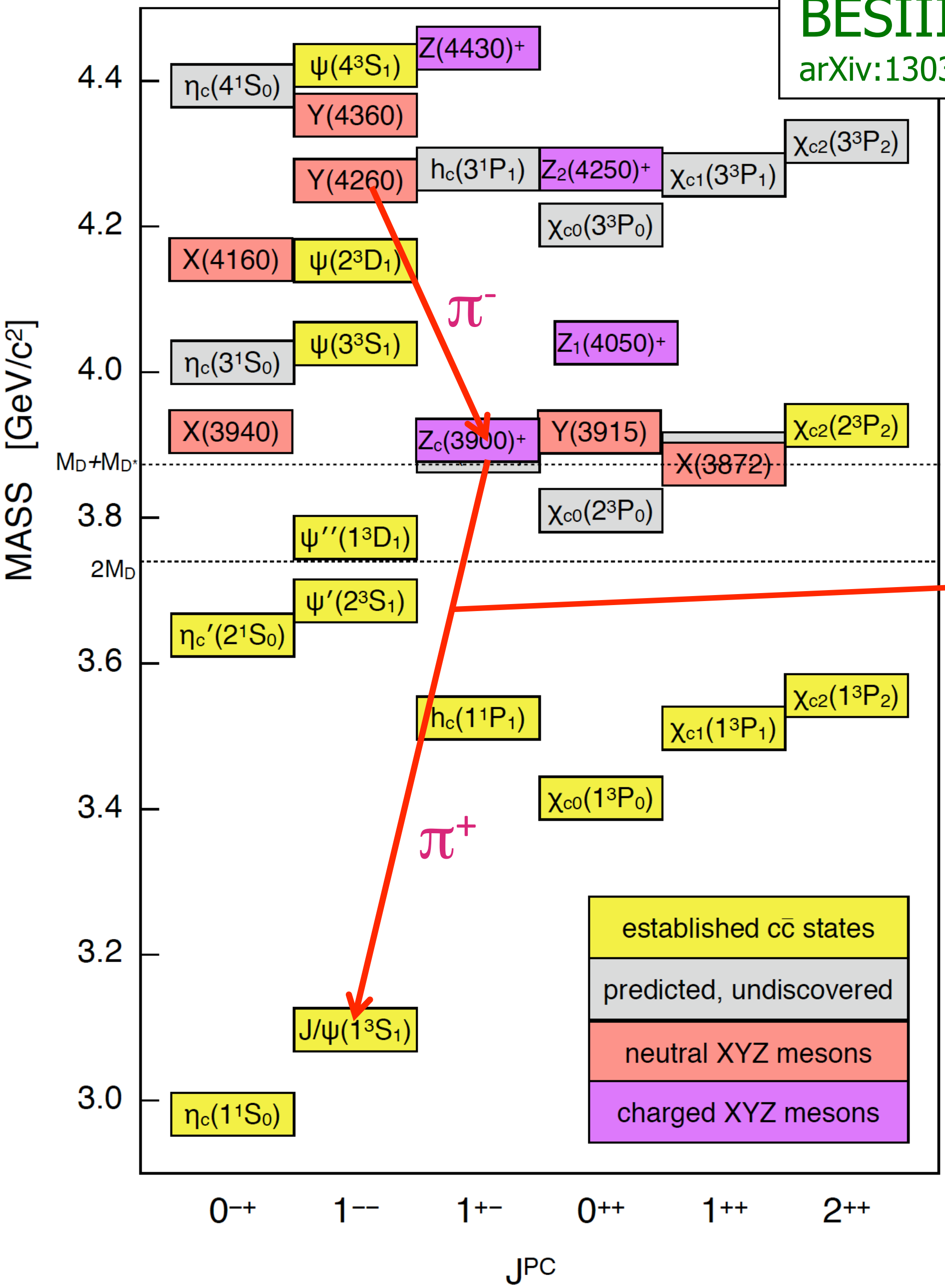
BESIII: arXiv:1303.5949

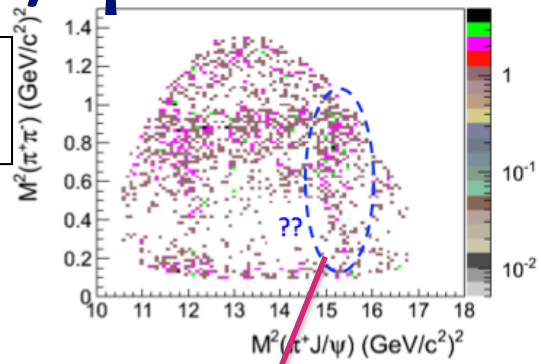
$\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9\pm1.9\pm3.7)$ pb

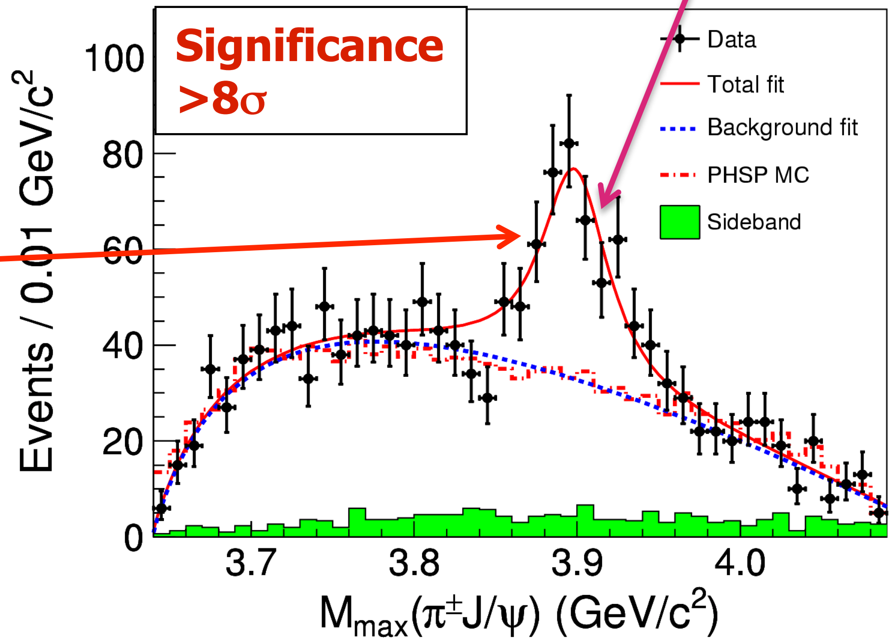


$Y(4260) \rightarrow \pi^- Z_c(3900)^+ \rightarrow \pi^-\pi^+ J/\psi$

BESIII: PRL 110, 252001
arXiv:1303.5949





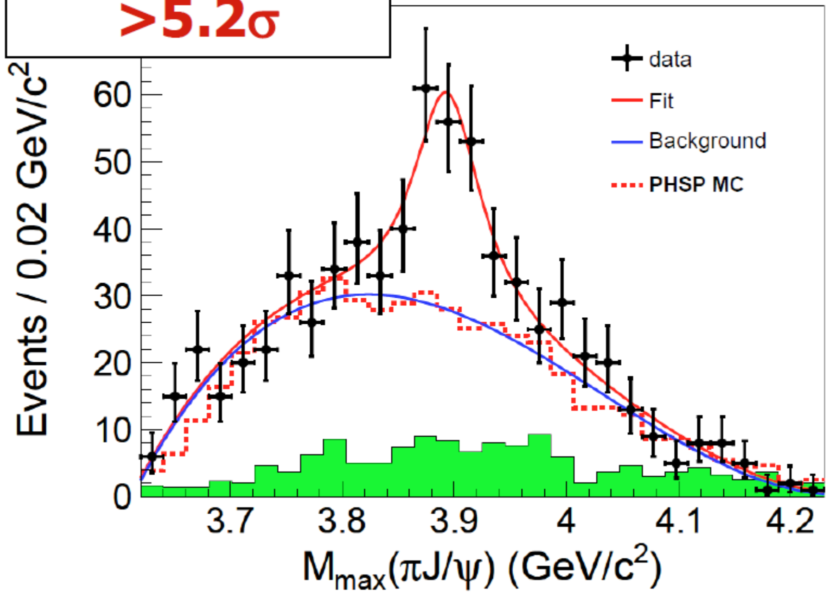


- **Mass = (3899.0±3.6±4.9) MeV**
- **Width = (46±10±20) MeV**
- **Fraction = (21.5±3.3±7.5)%**

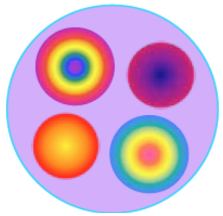
$Z_c(3895)^+$ by Belle

Significance $>5.2\sigma$

Belle: PRL 110, 252002
arXiv:1304.0121

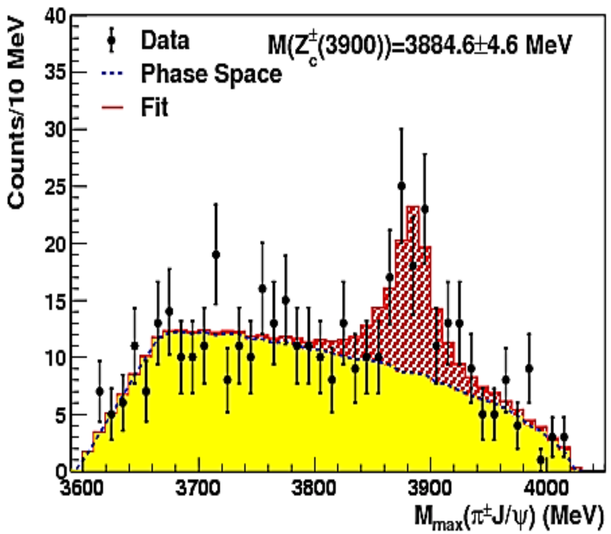


- **Mass = (3894.5 ± 6.6 ± 4.5) MeV**
- **Width = (63 ± 24 ± 26) MeV**
- **Fraction = (29.0 ± 8.9)% (stat. error only)**



Couples to $c\bar{c}$
Has electric charge
At least 4-quarks

Confirmed with CLEOc data!



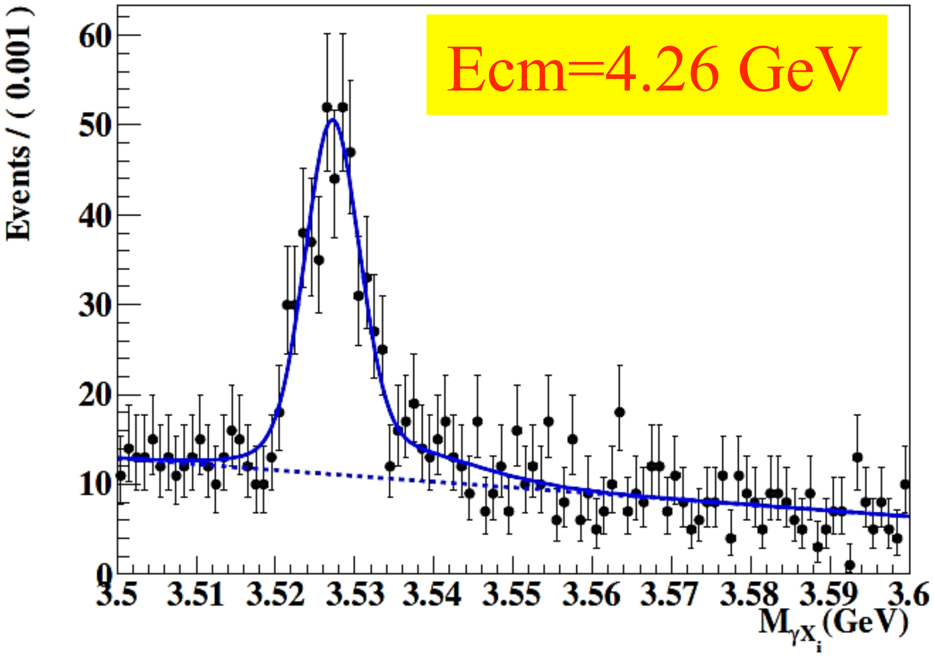
CLEOc data at 4.17 GeV: 1304.3036

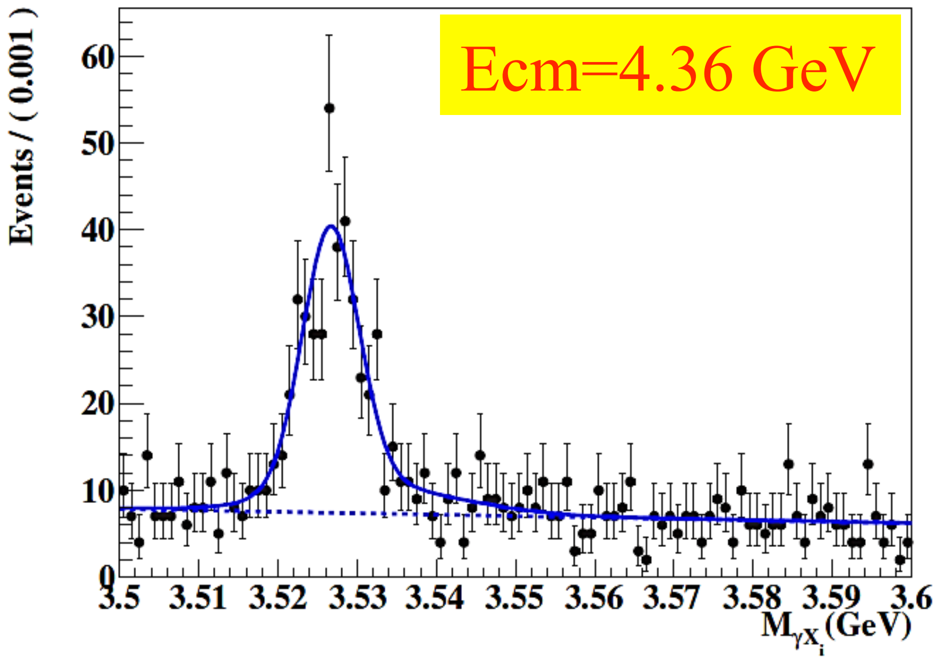
- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events
- 6.1σ

Observation of $e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

BESIII preliminary

Charm, Changzheng Yuan





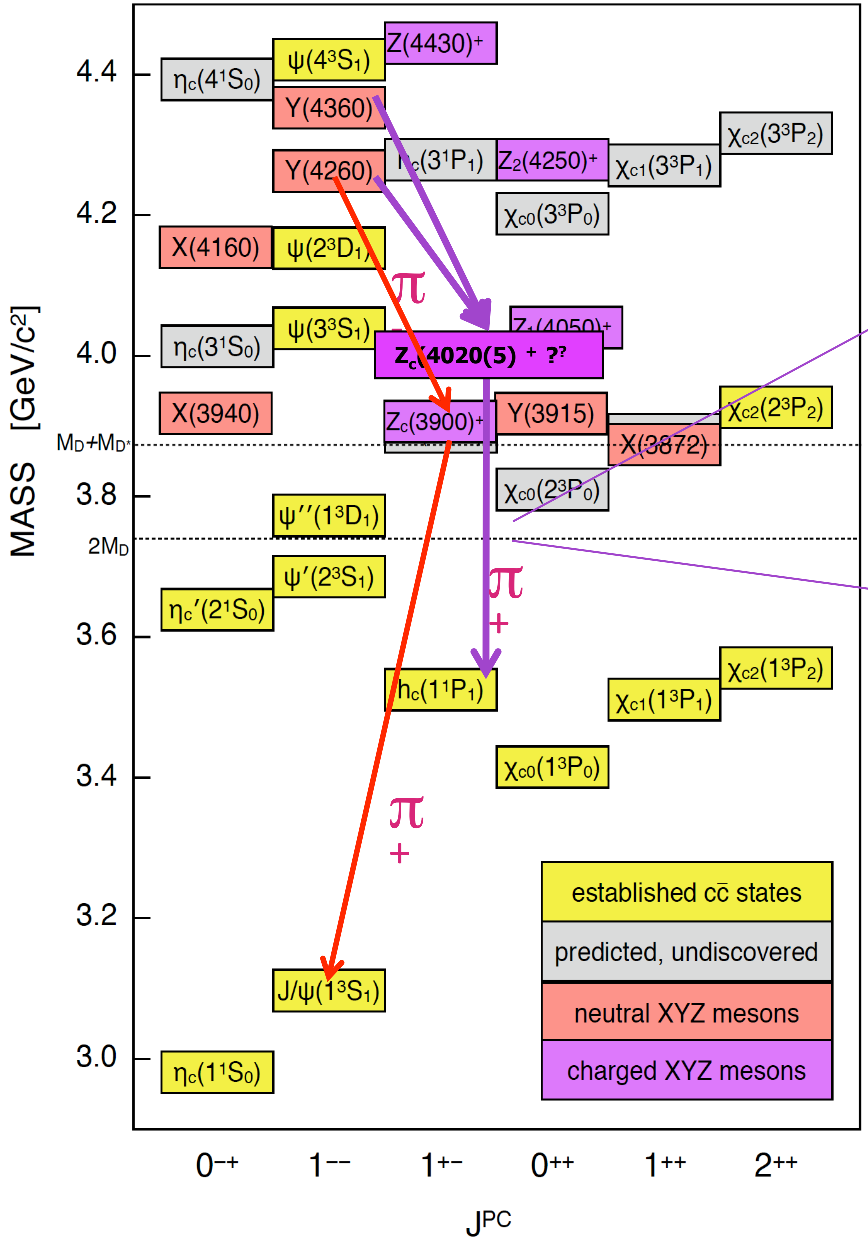
$N(h_c)=416\pm28$
Lum=827/pb
$\sigma^B= 41.0\pm2.8\pm7.4$ pb

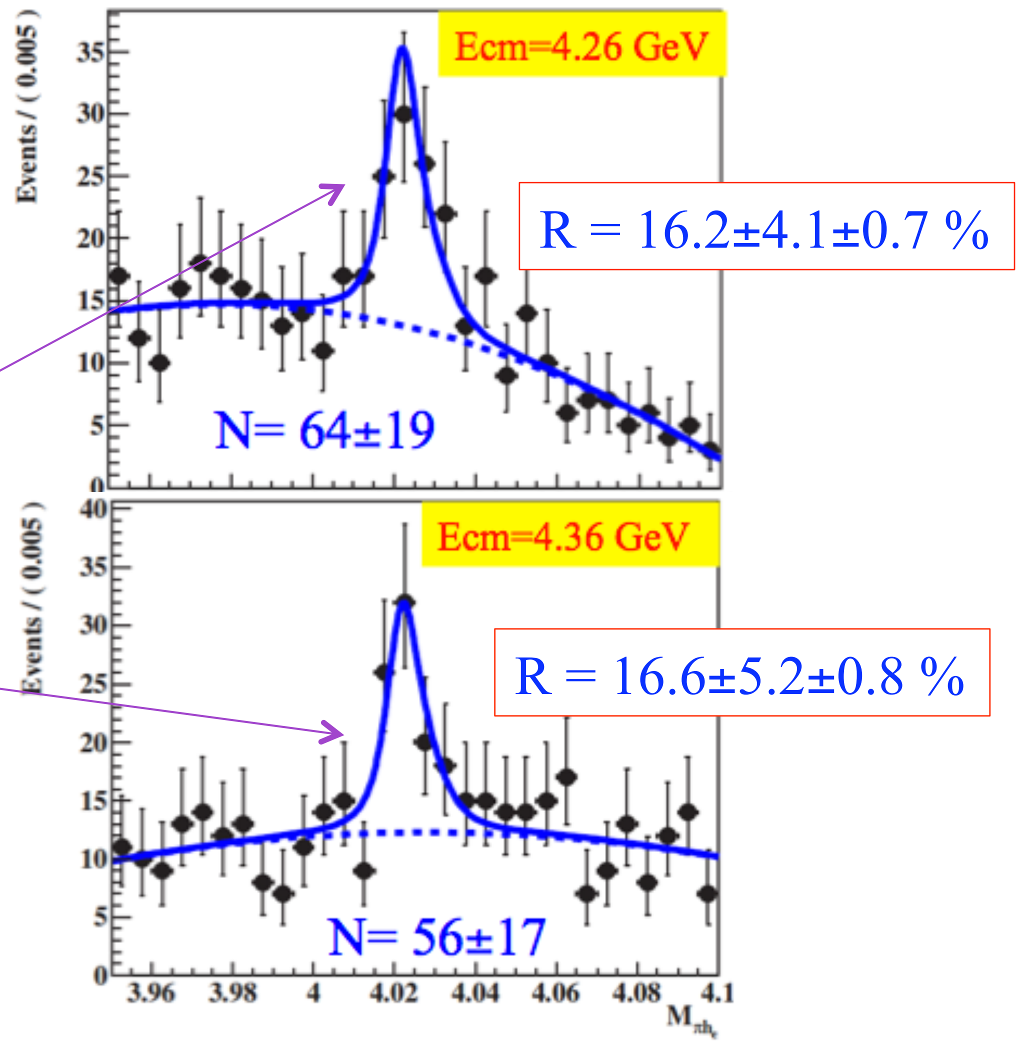
$N(h_c)=357\pm25$
Lum=544/pb
$\sigma^B= 52.3\pm3.7\pm9.2$ pb

$h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ hadrons [16 exclusive decay modes added]

$e^+e^- \to \pi^+ Z_c(4020)^- \to \pi^+\pi^- h_c(1P)$

BESIII preliminary





$$R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp \to \pi^+\pi^- h_c(1P))}{\sigma(e^+e^- \to \pi^+\pi^- h_c(1P))}$$

Simultaneous fit to 4.26/4.36 GeV data: 6.4σ

$M(Z_c(4020)) = 4021.8\pm1.0\pm2.5$ MeV;

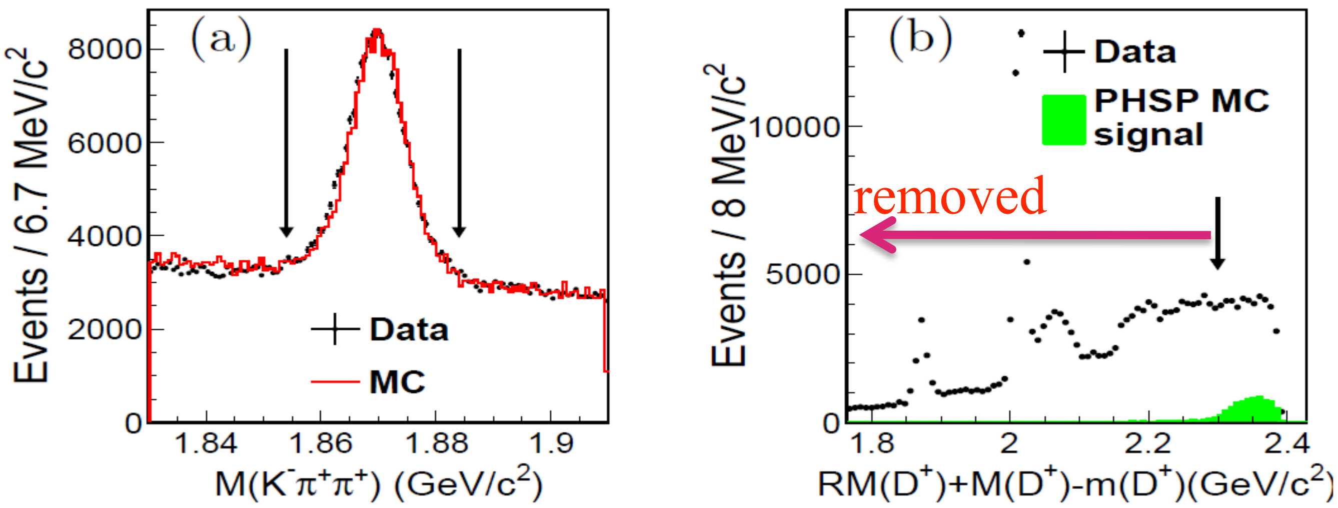
$\Gamma(Z_c(4020)) = 5.7\pm3.4\pm1.1$ MeV

$e^+e^- \to \pi^- (D^*\bar{D}^*)^+$ + c.c. at BESIII

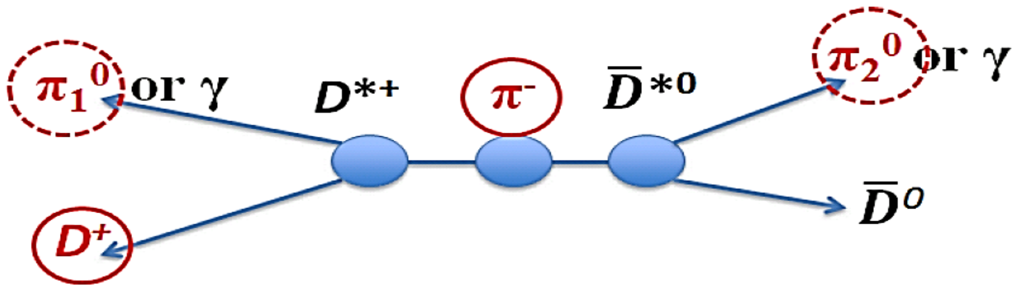
Charm, Changzheng Yuan

827 pb^{-1} data at Ecm=4.26 GeV

Tag a D^+ and a bachelor π^-, reconstruct one π^0 to suppress the background.



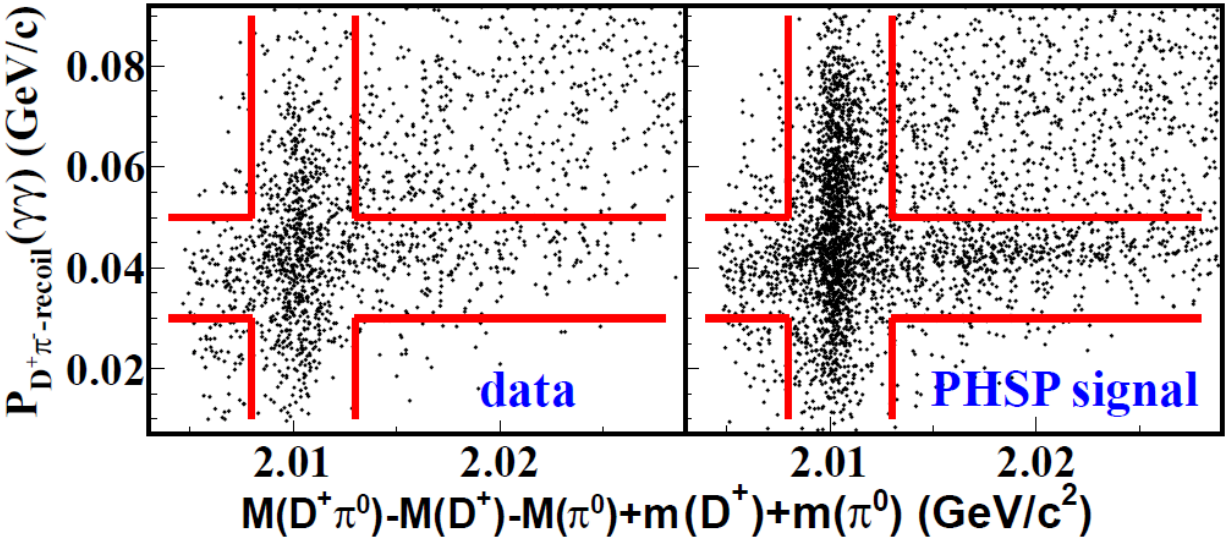
Remove
DD,
DD*,
D*D*,
DsDs, …

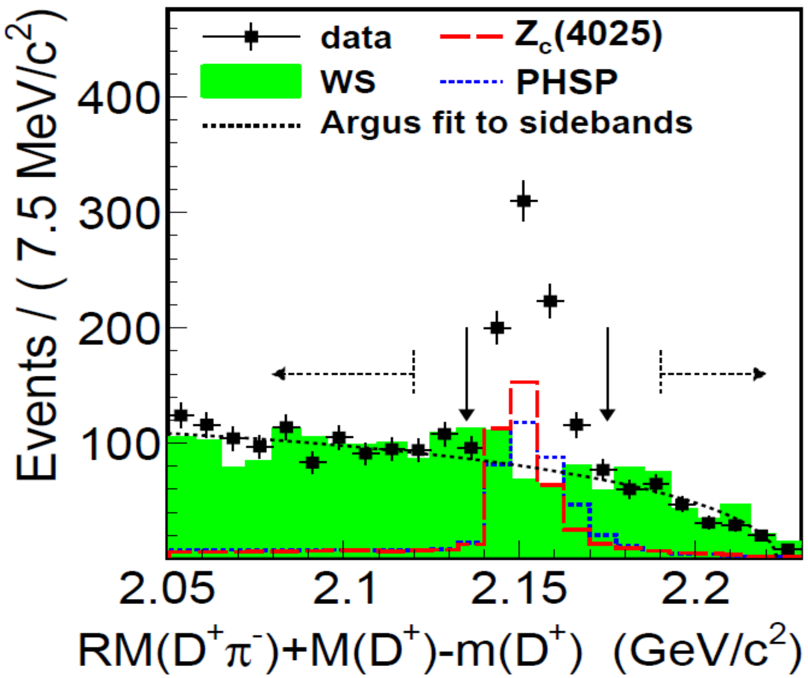


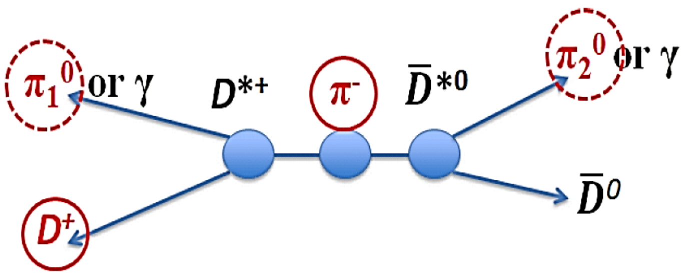
BESIII
1308.2760

Topology of the decays of the signal process. Thick line circled D^+ and π^- are detected in the final states and at least one of the dashed line circled π^0_1 or π^0_2 is tagged.

$e^+e^- \to \pi^- Z_c(4025)^+ \to \pi^- (D^*\bar{D}^*)^+ + c.c.$



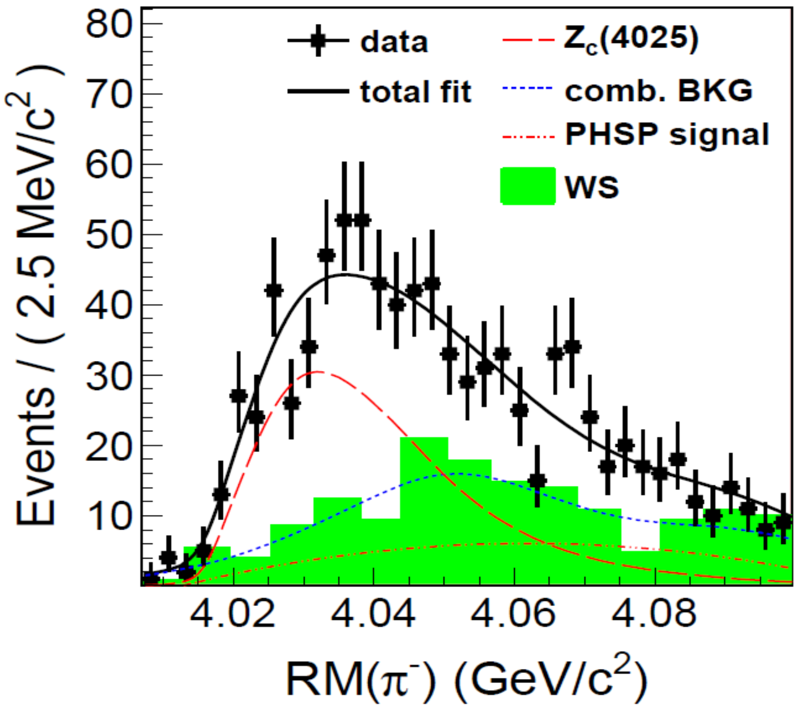




Topology of the decays of the signal process. Thick line circled D^+ and π^- are detected in the final states and at least one of the dashed line circled π_1^0 or π_2^0 is tagged.

$e^+e^- \rightarrow \pi^- Z_c(4025)^+ \rightarrow \pi^- (D^*\bar{D}^*)^+ + c.c.$

BESIII: 1308.2760, submitted to PRL



Fit to $\pi^{\pm}$ recoil mass **>10σ**

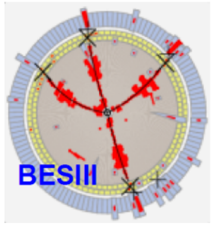
Yields : 401±47 $Z_c(4025)$ events.

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV

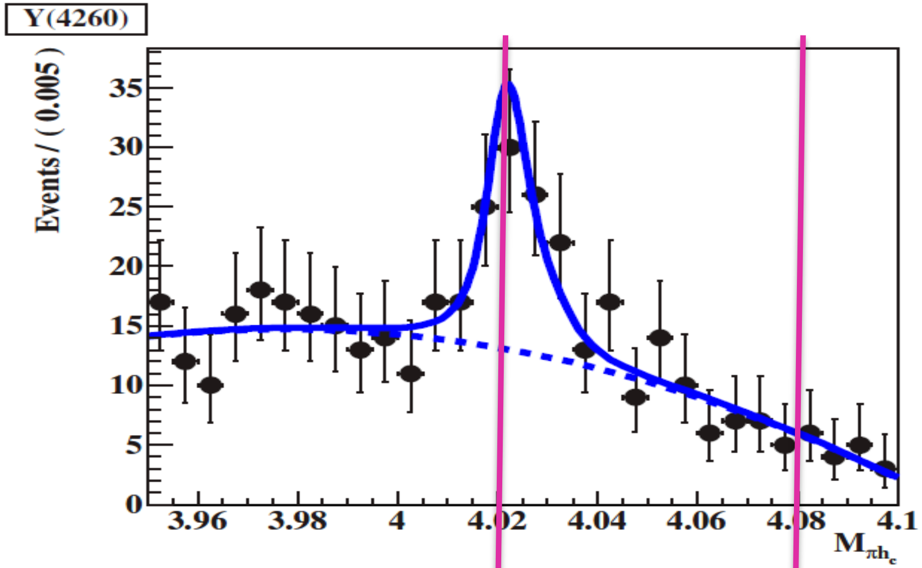
$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

$$\sigma(e^+e^- \rightarrow (D^*\overline{D^*})^{\pm}\pi^{\mp}) = (137 \pm 9 \pm 15)\,pb$$

$$R = \frac{\sigma(e^+e^- \rightarrow Z_c^{\pm}\pi^{\mp} \rightarrow \pi^{\pm}(D^*\overline{D^*})^{\mp}}{\sigma(e^+e^- \rightarrow (D^*\overline{D^*})^{\pm}\pi^{\mp})} = (65 \pm 9 \pm 6)\%$$



$Z_c(4020)=Z_c(4025)$?



- M(4020) = 4021.8±1.0±2.5 MeV
- M(4025) = 4026.3±2.6±3.7 MeV
- Γ(4020) = 5.7±3.4±1.1 MeV
- Γ(4025) = 24.8±5.7±7.7 MeV

PDG2012: $M_{D^{*+}} + M_{D^{*0}}$ = 4017.3±0.2 MeV

Close to D*D* threshold=4017 MeV

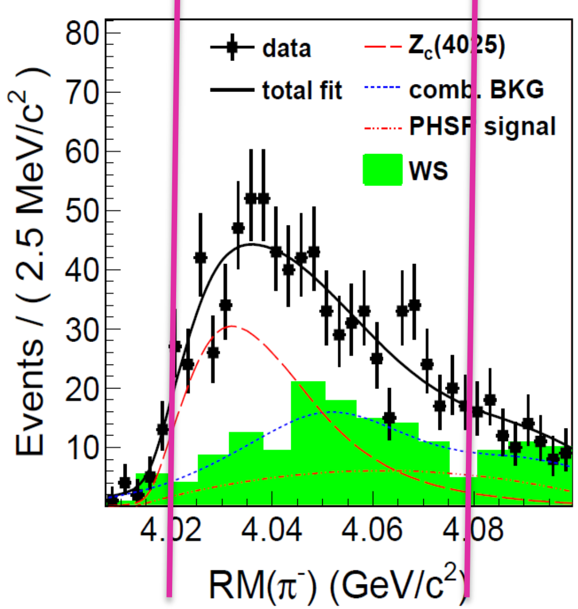
Mass consistent with each other but width ~2σ difference

Interference with other amplitudes may change the results

Coupling to πD*D* is much larger than to πh_c if they are the same state

Will fit with Flatte formula

BESIII preliminary
The Zc' is found!



Summary

◆ QCD-motivated spectroscopies predicted by theorists do not seem to exist

- evidence for Pentaquarks has disappeared
- H-dibaryon with mass near $2m_\Lambda$ is excluded at stringent levels
- No hint on D_{s0}^{++} isospin partner state of $D_{s0}^{+}(2317)$
-

◆ Numerous non-$q\bar{q}$ mesons not specific to QCD have been found

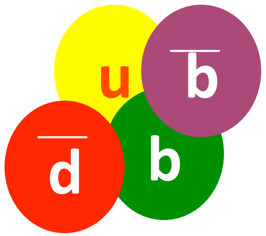
- Baryonium in $J/\psi \rightarrow \gamma p\bar{p}$ at BESII and BESIII ??
- XYZ mesons containing $c\bar{c}$ and $b\bar{b}$ pairs

◆ The $J^{PC}=1^{--}$ Y(4260) and "Υ(5S)" have no compelling interpretation

- huge couplings to $\pi^+\pi^- J/\psi$ ($\pi^+\pi^- \Upsilon(nS)$) ← *not predicted in any model!!*
- strong sources of charged Z_c (Z_b) states with M near $m_{D(*)}+m_{D*}$ ($m_{B(*)}+m_{B*}$)

Back-up slides

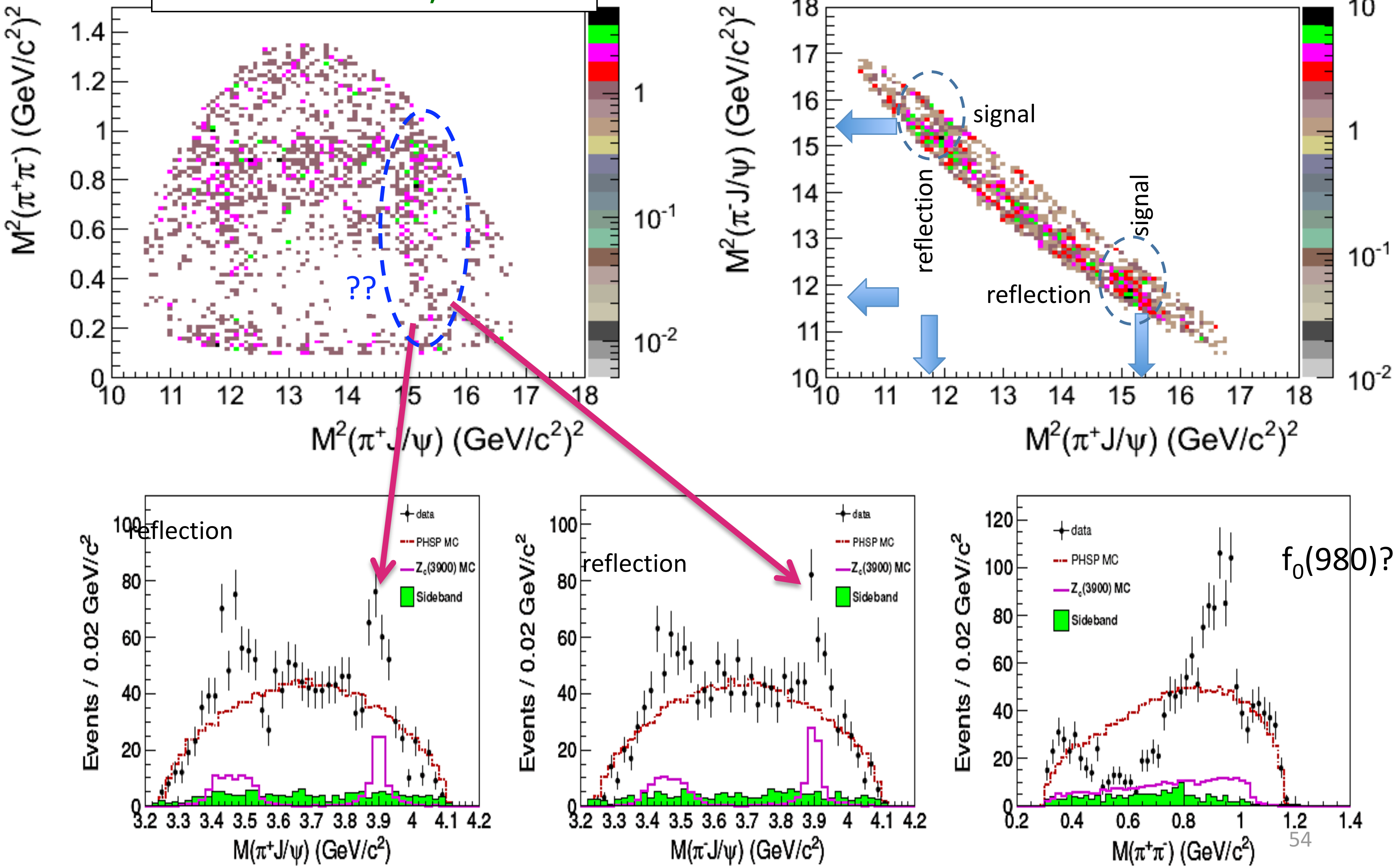
Z_{b1} & Z_{b2}, "smoking guns" for non-$q\bar{q}$ mesons



- decays to Υ(nS) & h_b(nP) ➔ must contain $b\bar{b}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at Ecm=4.26 GeV

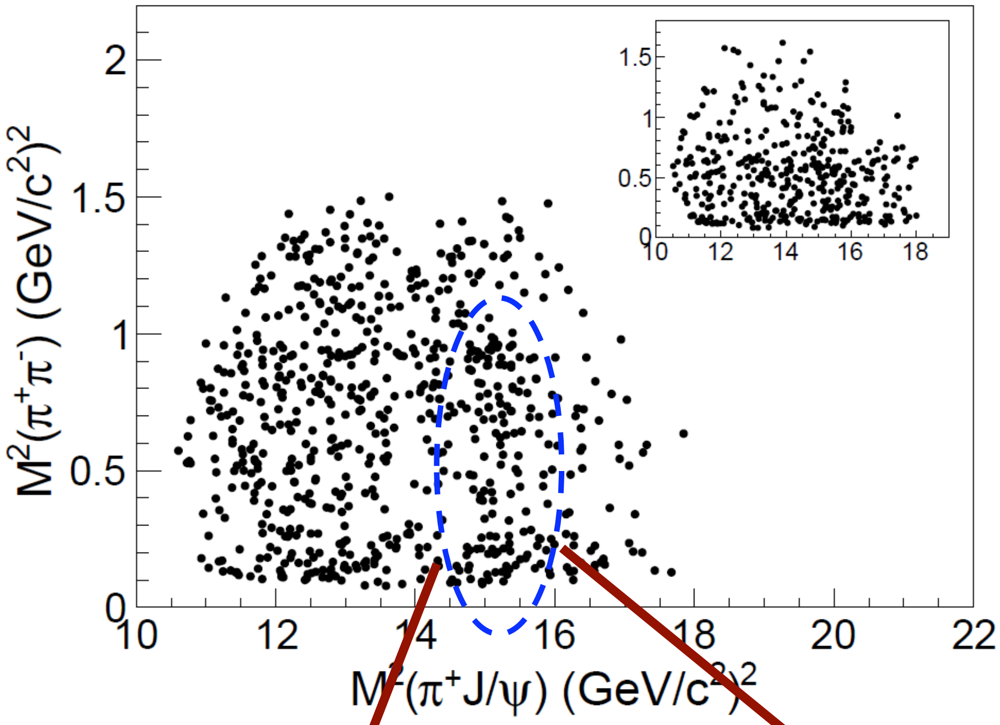
BESIII: PRL110, 252001

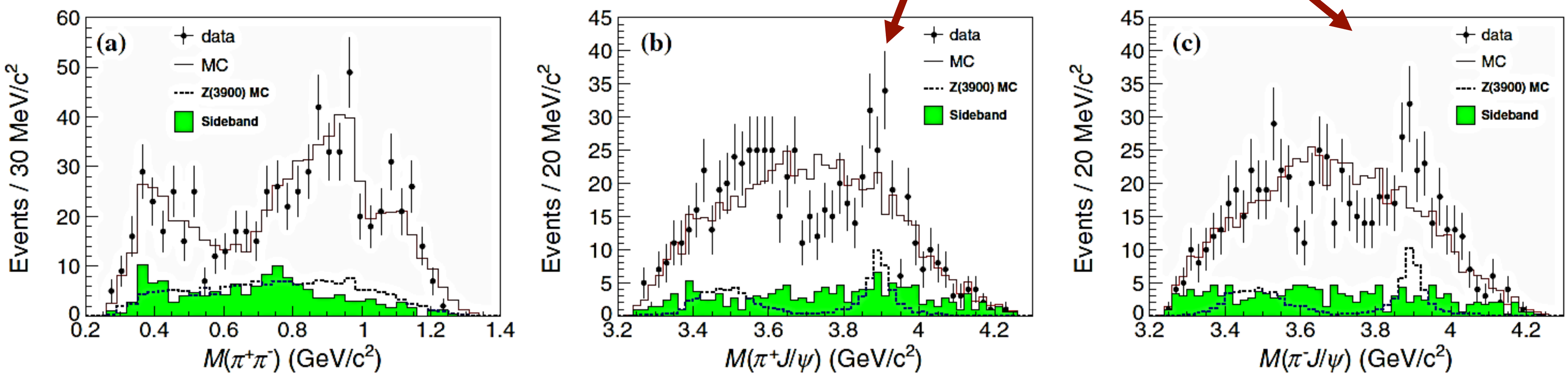


$e^+e^- \to \pi^+\pi^- J/\psi$ from ISR

Belle: PRL110, 252002

1. $M^2(\pi\pi)$ vs. $M^2(\pi J/\psi)$ for $4.15<M(\pi\pi J/\psi)<4.45$ GeV
2. (inset) Background events in J/ψ-mass sidebands
3. Structures both in $\pi\pi$ and $\pi J/\psi$ systems
4. 689 evts in J/ψ signal region, purity~80%



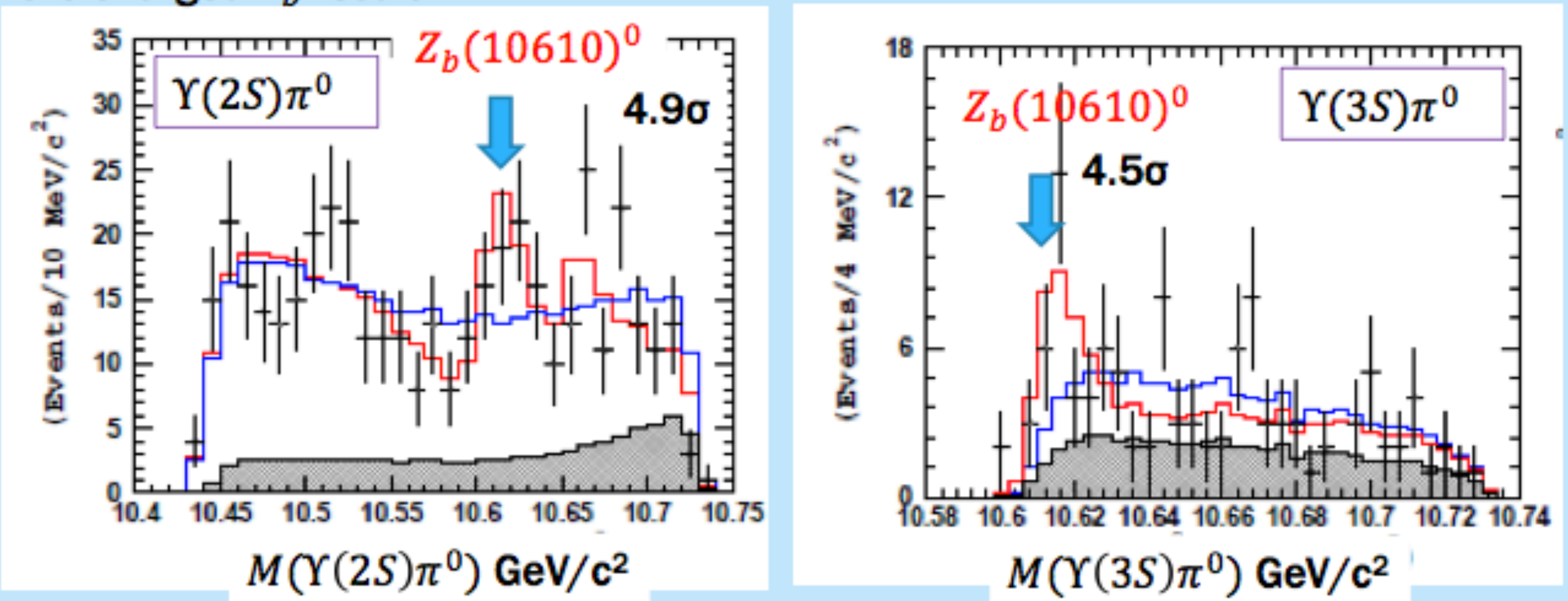


Neutral Z_b^0 in $\Upsilon(5S) \to Z_b^0\pi^0 \to \Upsilon(nS)\pi^0\pi^0$

- $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ **decay**

In this fit mass and width are fixed from the charged Z_b result.

fit result with Z_b (red)
fit result without Z_b (blue)

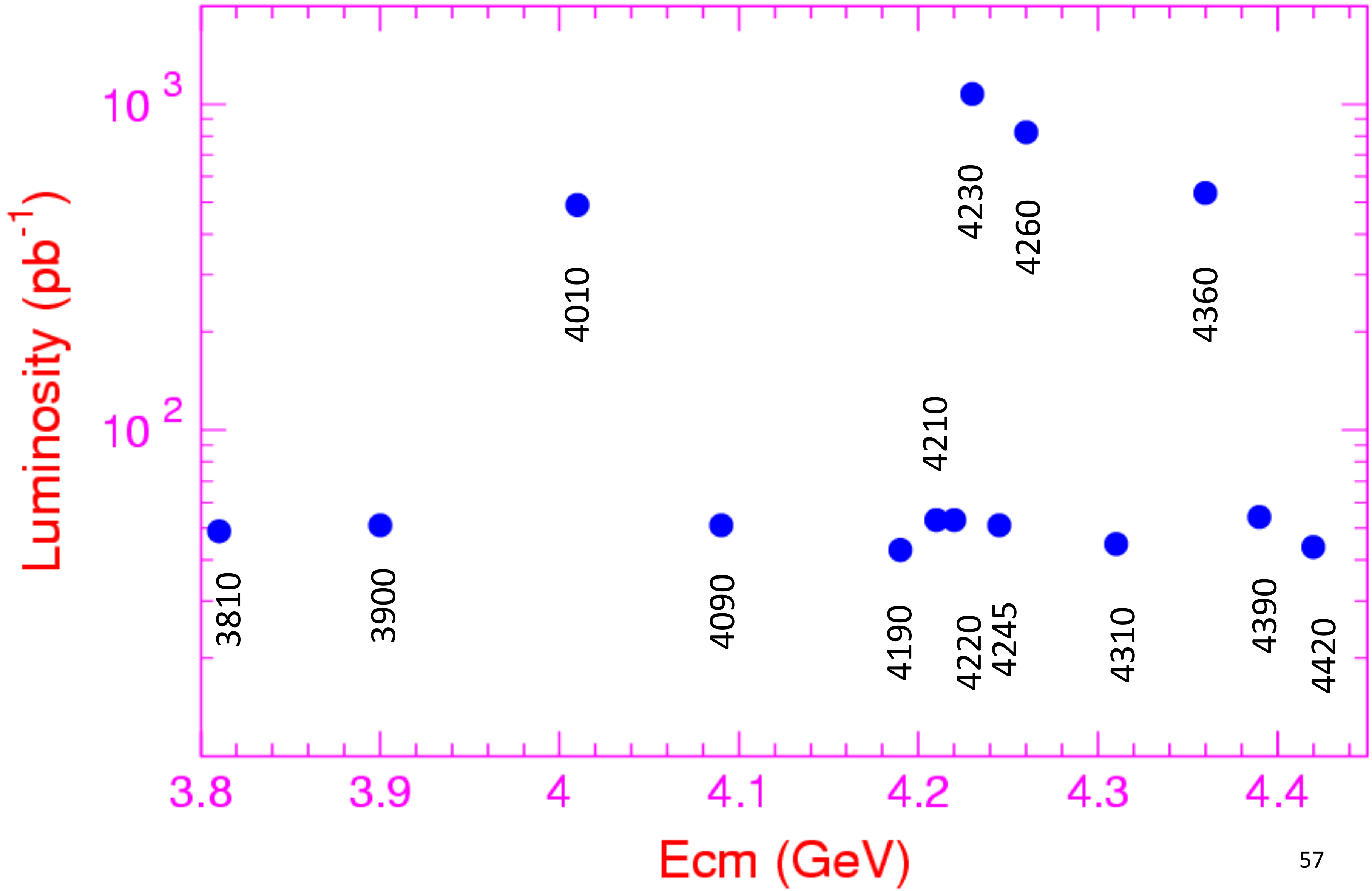


Simultaneous fit gives 6.3 σ for $Z_b(10610)^0$

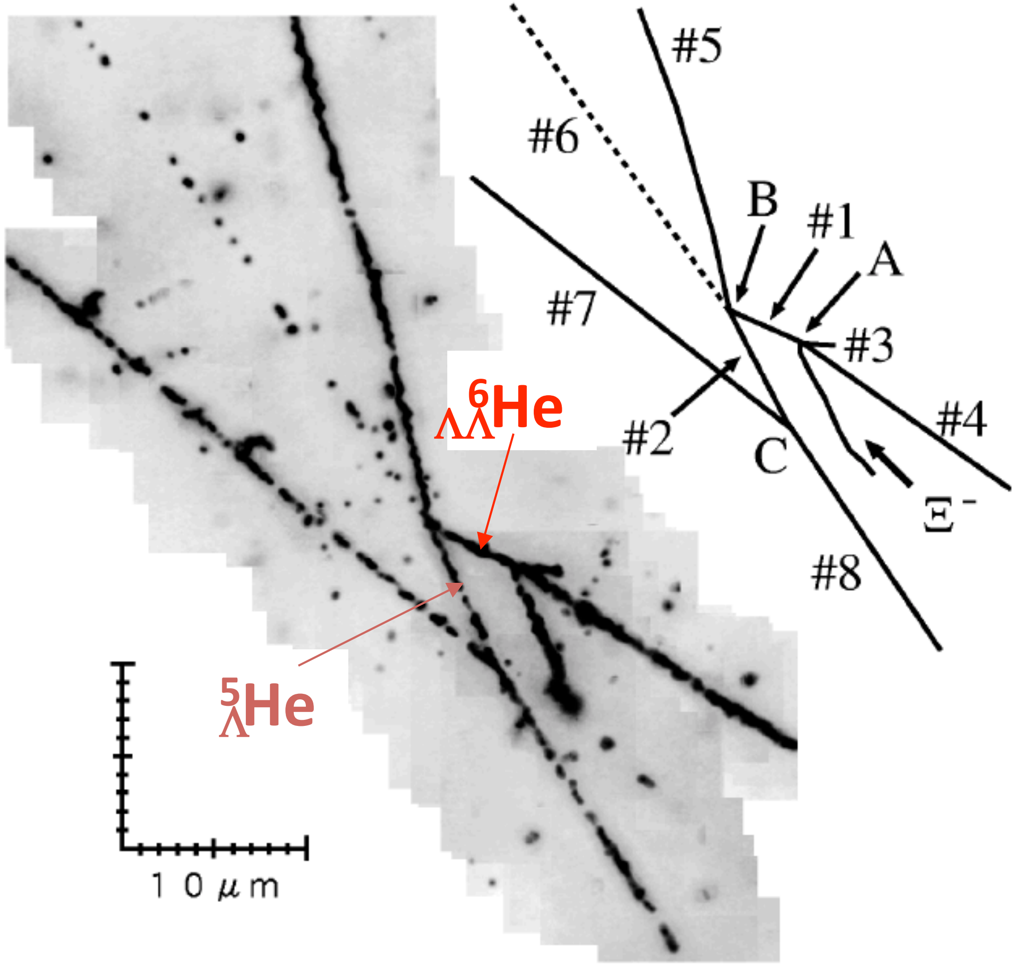
arXiv:1207.4345

BELLE

BESIII collected 3.3/fb for XYZ study



The "Nagara" $^{6}_{\Lambda\Lambda}$He event



H. Takahashi *et al*, PRL 87, 215502 (1977): $M_H > 2m_\Lambda$-7.7 MeV

2^{-+} $c\bar{c}$ assignment? η_{c2}?

pinned to:
$M\psi''$=3770 MeV
&$M\psi_2$=3823 MeV

- Mass is too high?:
  - 3872 *vs* 3837 MeV

- Expt: $\dfrac{\Gamma(\eta_{c2} \to \rho^0 J/\psi)}{\Gamma\eta_{c2} \to \gamma J/\psi)} = 3.4 \pm 1.2$

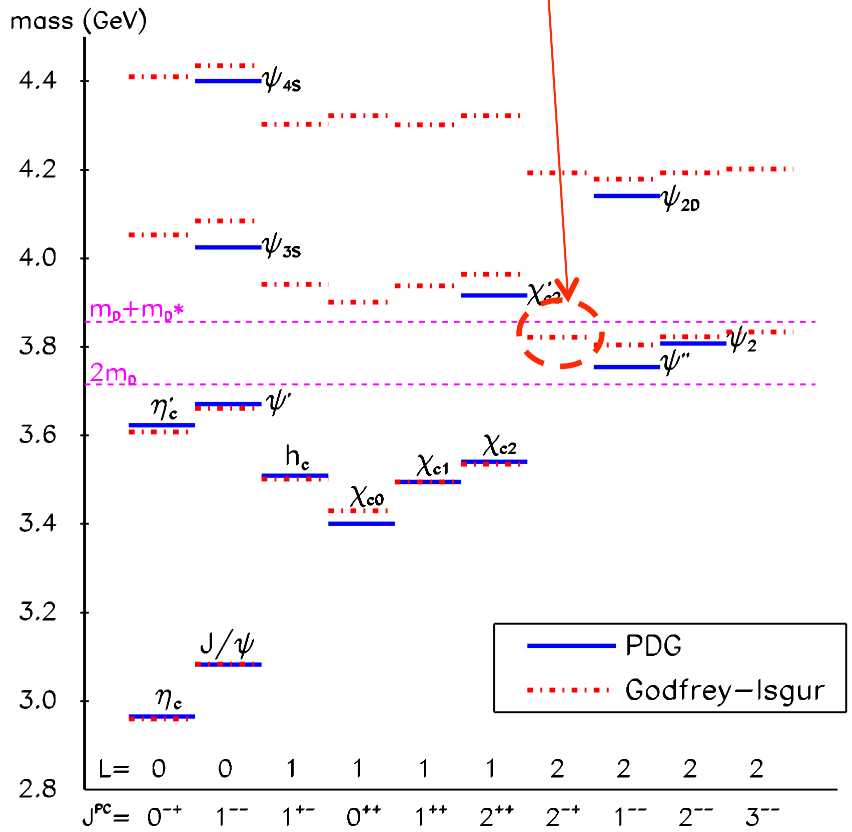
  use theory: $\Gamma(\eta_{c2} \to \gamma J/\psi) \approx 9\mathrm{keV}$
  Y. Jiaet *al* arXiv:0107.4541

  $\Rightarrow \Gamma(\eta_{c2} \to \rho^0 J/\psi) \approx 30\mathrm{keV}$

  ***c.f.*: $\Gamma(\psi' \to \pi^0 J/\psi) \approx 0.4$ keV**

- Theor: B→Kη_{c2} violates factorization
  - B→Kh_c not seen
  - B→Kχ_{c2} barely seen

- Theor: η_{c2}→ $D\bar{D}^*$ expected to be tiny
  Y. Kalasnikovaet *al* arXiv:1008.2895
  - Belle & BaBar::
  $\Gamma(X \to D\bar{D}^*)/\Gamma(X \to \pi^+\pi^- J/\psi)=9.5\pm3.1$



η_{c2}→γh_c(1S) & $\pi\pi\eta_c$ modes expected to dominate

“Υ(5S)” is very different from other Υ states

Anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$

Belle PRL 100, 112001 (2008)
23.6 fb^{-1}

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

X10^{-2}

$$Bf\,(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = (0.008 \pm 0.0003)\%$$

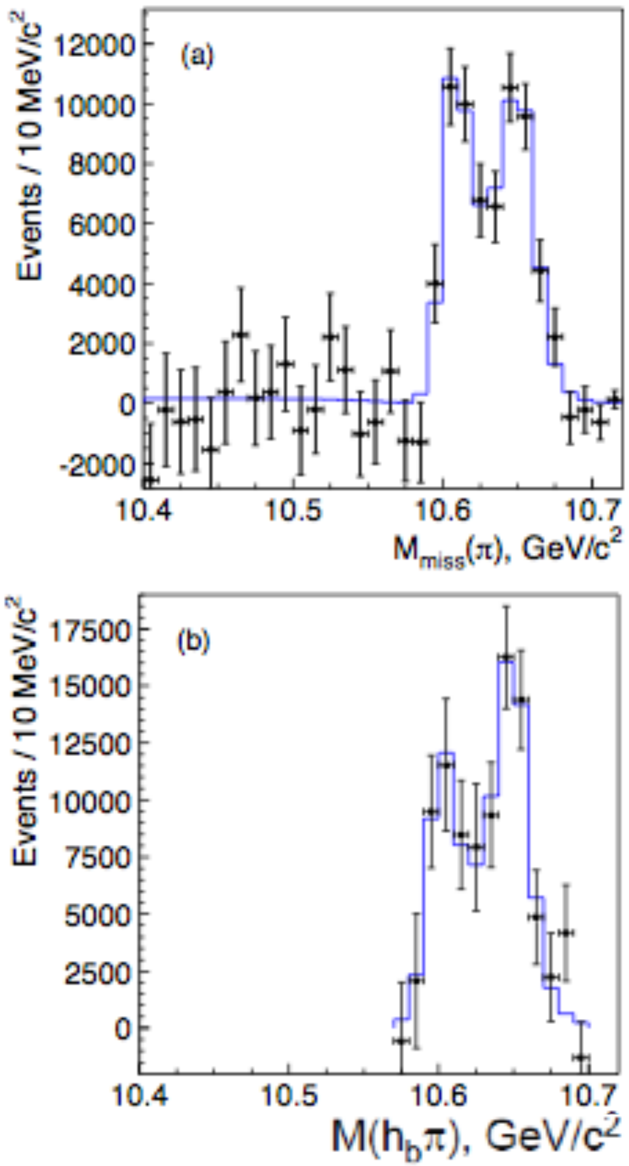
$$Bf\,(\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S)) = (0.53 \pm 0.06)\%$$

Recall Y(4260) with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$

$\Rightarrow$ Is there a Y_b equivalent close to Υ(5S)

The “XYZ” mesons

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$
$Z_{b1}(10610)$	10,607±2	18±2	1^-	$\pi^\pm\Upsilon(1,2,3S)/h_b(1,2S)$; BB*	`$\Upsilon(5S)$'$\to\pi^\pm Z_{b1}$
$Z_{b2}(10650)$	10,653±2	12±2	1^-	$\pi^\pm\Upsilon(1,2,3S)/h_b(1,2S)$;B*B*	`$\Upsilon(5S)$'$\to\pi^\pm Z_{b2}$


(a)
Events / 10 MeV/c^2
12000
10000
8000
6000
4000
2000
0
-2000
10.4
10.5
10.6
10.7
$M_{miss}(\pi)$, GeV/c^2
(b)
Events / 10 MeV/c^2
17500
15000
12500
10000
7500
5000
2500
0
10.4
10.5
10.6
10.7
$M(h_b\pi)$, GeV/c^2