Overview of Exotic hadrons at Belle

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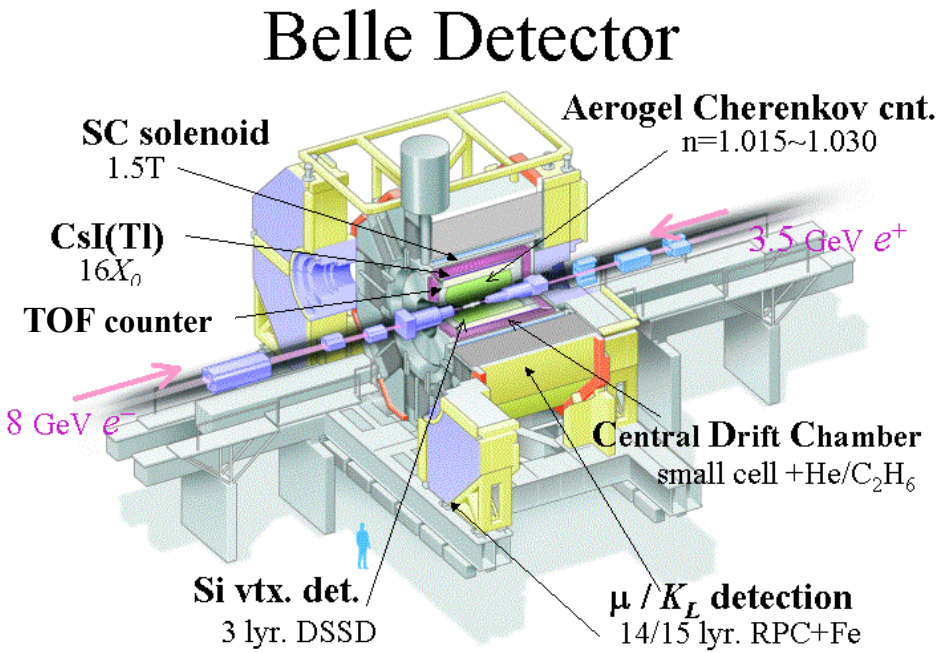
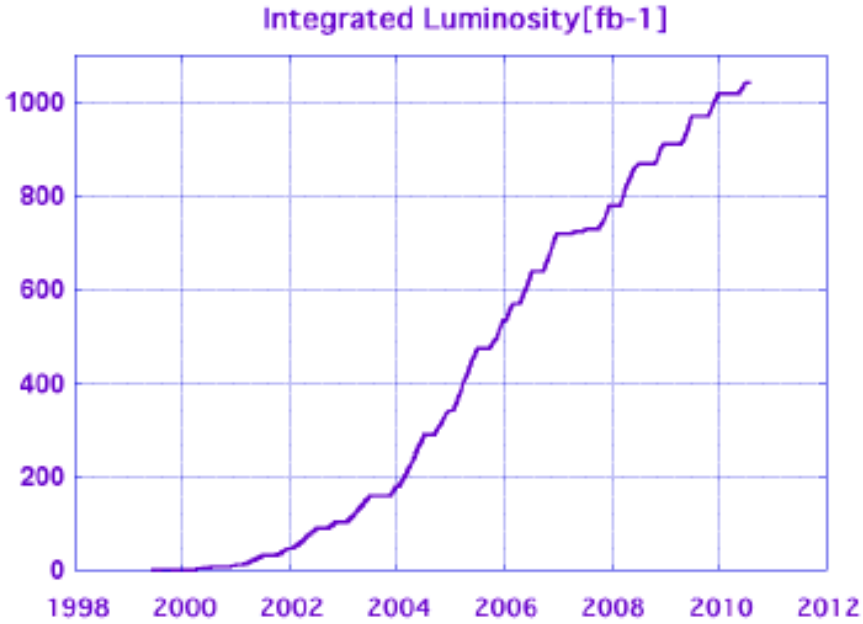
ICNFP, Crete, Greece, July 29 , 2014

The Belle experiment





Peak luminosity recorded at KEKB:
L=2.1 x 10^{34}/cm^2/sec with crab cavities

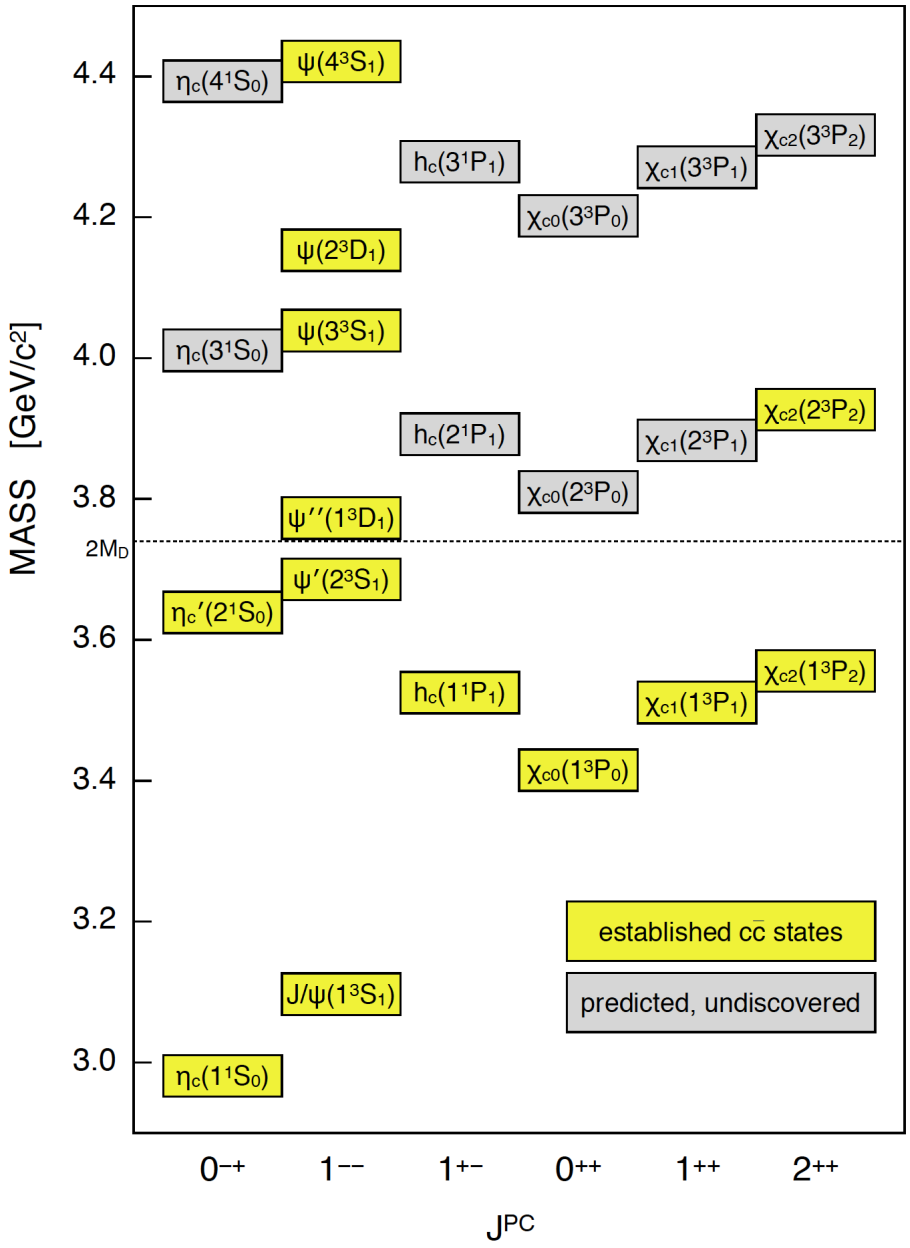
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

The XYZ Charmonium-like mesons

- Search for X-like states in decays with η_c
- $Z(4430)^+$: quantum number measurement
- New charged state $Z(4200)^+$ in $B \rightarrow J/\psi \pi K$
- Charged state $Z_c(3895)$

Charmonium spectrum

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



D(or higher)- wave states are not shown here
But evidence of $^3D_2$ (2^{--}) in $B \to \chi_{c1}\gamma K$ decay was already reported

XYZ charmoniumlike mesons

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (<2.2)	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$ $p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$ $B \to K(\omega J/\psi)$ $B \to K(D^{*0}\bar{D}^0)$ $B \to K(\gamma J/\psi)$
$Z_c(3900)^+$	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^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$

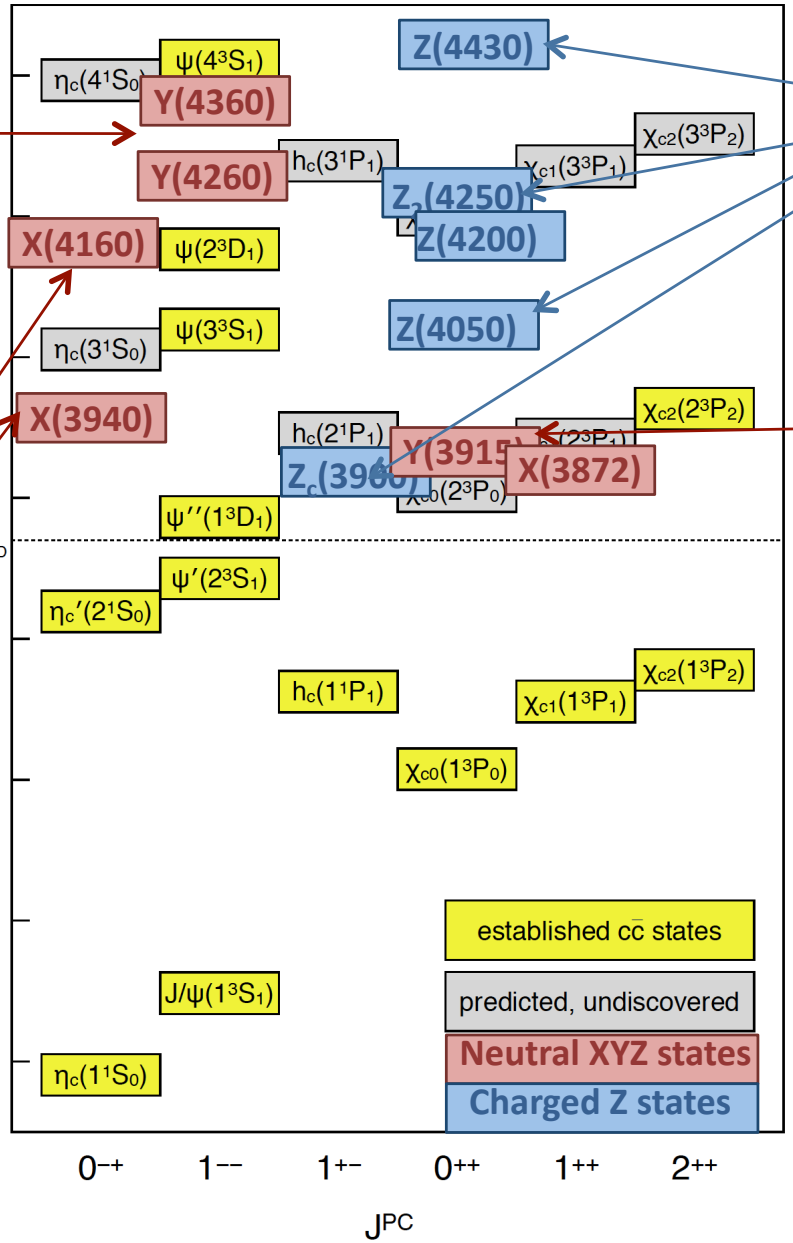
$Y(4260) \to \gamma\ X(3872)$

$Z(4200)^+$

$c\bar{c}$ 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 (5) charged Zs must have a minimal quark content of $c\bar{c}u\bar{d}$

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

X-like states decaying to η_c modes

Motivation:

- X(3872) was first observed by Belle in $B \to K(J/\psi\pi^+\pi^-)$. Angular analysis of this mode performed by LHCb determined all quantum numbers: 1^{++}.
- If X(3872) is a $D^0\overline{D}^{*0}$ molecule, there may other «X-like» particles with different quantum numbers, that are also bound states of $D^{(*)}$ mesons.
  - X(3872): $(D^0\overline{D}^{*0} - \overline{D}^0D^{*0})$ combination: $J^{PC}=1^{+-}$, decays $X\to\eta_c\omega$, $X\to\eta_c\rho$

    For $J^{PC}=2^{-+}$ charmonium, $X\to \eta_c \pi^+\pi^-$
  - X(3730): $(D^0\overline{D}^0 + \overline{D}^0D^0)$ combination: $J^{PC}=0^{++}$, decays $X\to\eta_c\eta$, $X\to\eta_c\pi^0$
  - X(4014): $(D^{*0}\overline{D}^{*0} + \overline{D}^{*0}D^{*0})$ combination: $J^{PC}=0^{++}$, decays $X\to\eta_c\eta$, $X\to\eta_c\pi^0$

Analysis features:

- X is produced in charged B decays: $B^\pm \to K^\pm X$
- $\eta_c \to K_S K\pi$, $K_S \to \pi^+\pi^-$
- combined fit of 2 decays modes of η ($\gamma\gamma$ and $\pi^+\pi^-\pi^0$)
- test mode $B^\pm \to K^\pm\psi(2S)$, $\psi(2S) \to J/\psi\pi^+\pi^-$ gives results consistent with PDG
- $B^\pm$ decays into the same final states, but without intermediate X are studied

X-like states decaying to η_c mode

$B^{\pm} \to K^{\pm} X$

X(3872)

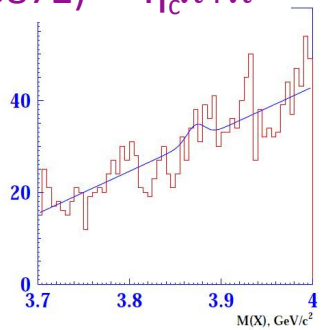
- $\to \eta_c \pi^+ \pi^-$
- $\to \eta_c \omega,\ \omega \to \pi^+\pi^-\pi^0,\ \pi^0 \to \gamma\gamma$

X(3730)

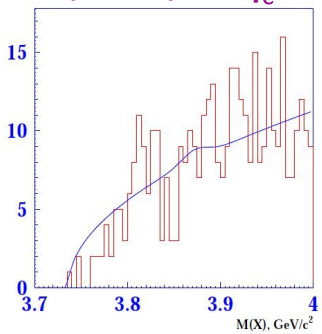
X(4014)

- $\to \eta_c \eta$
  - $\to \gamma\gamma$
  - $\to \pi^+\pi^-\pi^0,\ \pi^0 \to \gamma\gamma$
- $\to \eta_c \pi^0,\ \pi^0 \to \gamma\gamma$

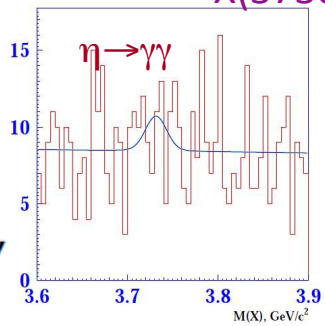
X(3872)→ $\eta_c\pi+\pi-$

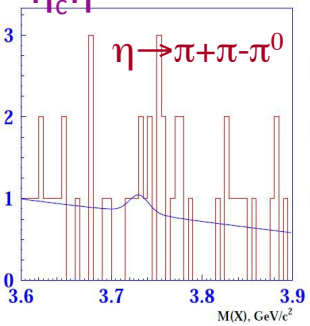


X(3872)→ $\eta_c\omega$

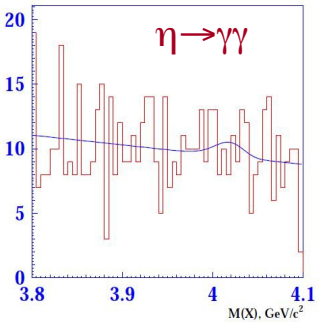


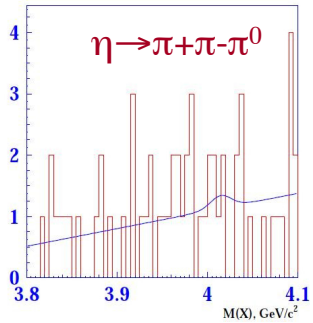
X(3730)→ $\eta_c\eta$



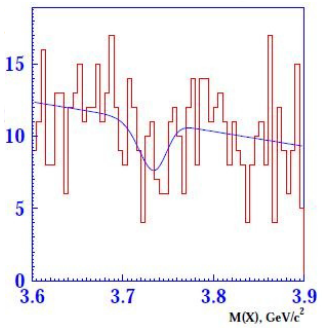


X(4014)→ $\eta_c\eta$

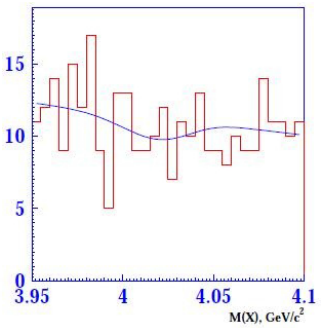




X(3730)→ $\eta_c\pi^0$



X(4014)→ $\eta_c\pi^0$



Anna Vinokurova
June, QCD2014

X-like states decaying to η_c mode

X mass, MeV/c^2	Decay mode $B^\pm \to K^\pm X$	Yield	U (90% C.L.)
3872	$X \to \eta_c \pi^+\pi^-$	17.9 ± 16.5	3.0×10^{-5}
	$X \to \eta_c \omega$	6.0 ± 12.5	6.9×10^{-5}
3730	$X \to \eta_c \eta$,		4.6×10^{-5}
	$\eta \to \gamma\gamma$	13.8 ± 9.9	
	$\eta \to \pi^+\pi^-\pi^0$	1.4 ± 1.0	
	$X \to \eta_c \pi^0$	-25.6 ± 10.4	5.7×10^{-6}
4014	$X \to \eta_c \eta$,		3.9×10^{-5}
	$\eta \to \gamma\gamma$	8.9 ± 11.0	
	$\eta \to \pi^+\pi^-\pi^0$	1.3 ± 1.6	
	$X \to \eta_c \pi^0$	-8.1 ± 13.2	1.2×10^{-5}

Upper limits on the
$\mathcal{B}(B^\pm \to K^\pm X) \cdot \mathcal{B}(X \to \eta_c h)$
for $h = \pi^+\pi^-, \omega, \eta, \pi^0$

Belle preliminary

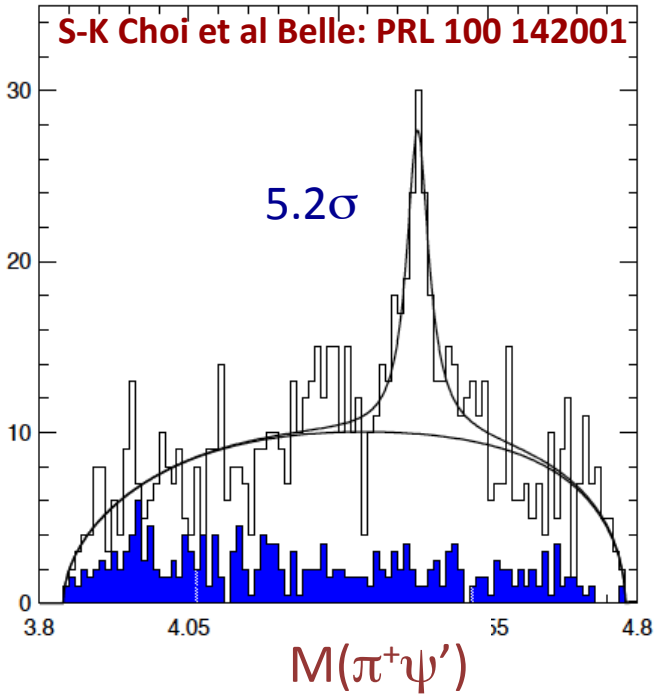
Upper limits on the
$\mathcal{B}(B^\pm \to K^\pm \eta_c h)$
for $h = \pi^+\pi^-, \omega, \eta, \pi^0$

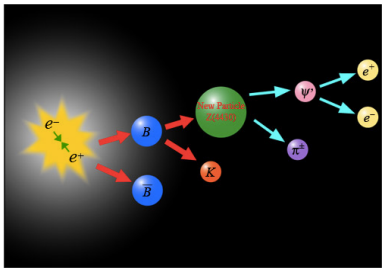
Decay mode	Yield	U (90% C.L.)
$B^\pm \to K^\pm \eta_c \pi^+\pi^-$	155 ± 72	3.9×10^{-4}
$B^\pm \to K^\pm \eta_c \omega$	-41 ± 27	5.3×10^{-4}
$B^\pm \to K^\pm \eta_c \eta$,		2.2×10^{-4}
$\eta \to \gamma\gamma$	-14.1 ± 26.1	
$\eta \to \pi^+\pi^-\pi^0$	-1.8 ± 3.4	
$B^\pm \to K^\pm \eta_c \pi^0$	-1.9 ± 12.1	6.2×10^{-5}

The Z(4430)

Found by Belle in 2007

Belle : 660M BB





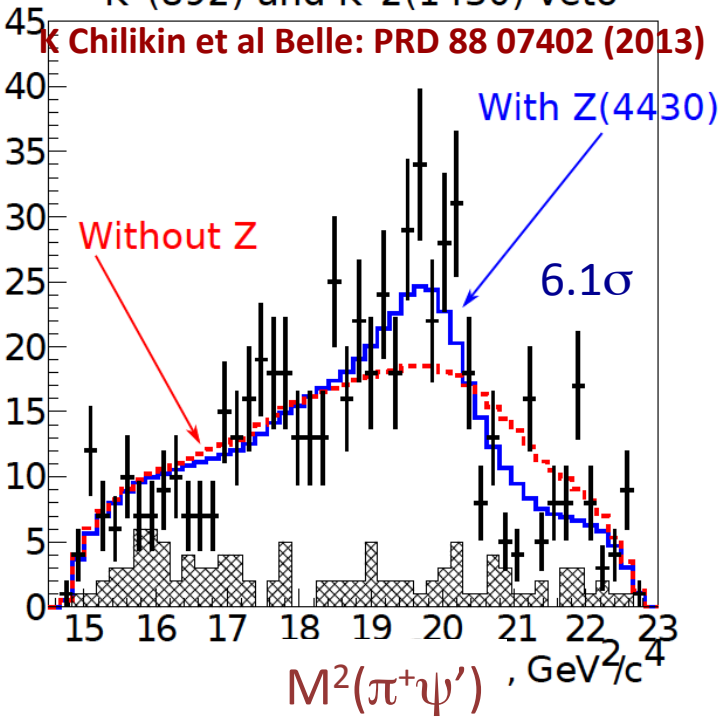
$$M = 4485^{+22+28}_{-22-11}\ \text{MeV}$$

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

Belle : 772 M BB

2013: 4-dim amplitude analysis

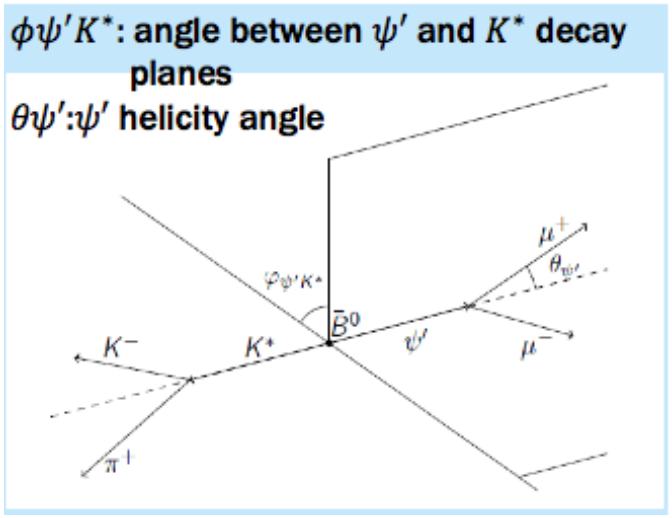
K*(892) and K*2(1430) veto



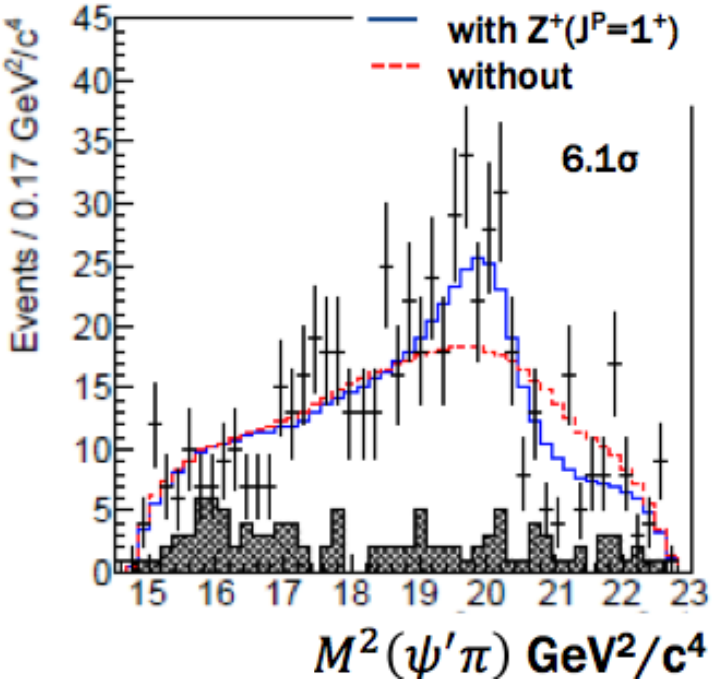
$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') = (6.0^{+1.7+2.5}_{-2.0-1.4}) \times 10^{-5}$$

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

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



$(M^2(K\pi),\ M^2(\psi'\pi),\ \phi\psi',\ \theta\psi')$



Results from 4D fit

(4-dimensional amplitude analysis of $B^0 \to \psi(2S)K^+\pi^-$)

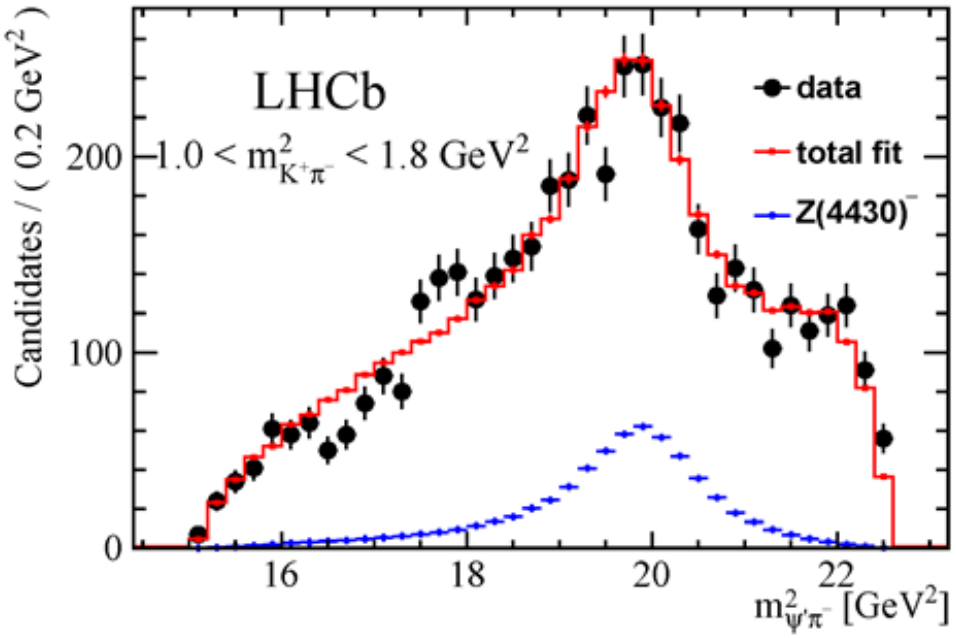
J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4479 ± 16	4477 ± 4	4485 ± 20	4478 ± 22	4384 ± 19
Width, MeV	110 ± 50	22 ± 14	200 ± 40	83 ± 25	52 ± 28
Significance	4.5σ	3.6σ	6.4σ	2.2σ	1.8σ

1^+ is favored over 0^- by 2.9 σ

Confirmed by LHCb

$B \rightarrow K\pi^+\psi'$

4-dim amplitude analysis



$$J^P = 1^+$$

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

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

Statistical significance : 13.9σ

PRL 112, 222002 (2014)

$$Bf(B^0 \rightarrow Z(4430)^- K^+) \times Bf(Z(4430)^- \rightarrow \pi^-\psi') = (0.059 \pm 0.009^{+0.015}_{-0.033}) Bf(B^0 \rightarrow K^+\pi^-\psi')$$

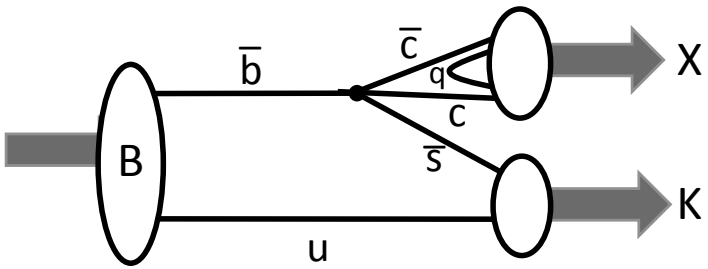
$$\Rightarrow Bf(B^0 \rightarrow Z(4430)^- K^+) \times Bf(Z(4430)^- \rightarrow \pi^-\psi') \approx (3.4^{-1.1}_{-2.3}) \times 10^{-5}$$

X(3872) – Z(4430) comparison

using PDG numbers:

$$Bf(X_{3872} \to \pi^+\pi^- J/\psi) = \frac{(0.86 \pm 0.08) \times 10^{-5}}{Bf(B^+ \to X_{3872} K^+)}$$

$Bf(B^+ \to X_{3872} K^+)$:



"factorizable" spectator diagram

$$\text{PDG}: Bf(B^+ \to X_{3872} K^+) < 3.2 \times 10^{-4}$$

$$\Rightarrow Bf(X_{3872} \to \pi^+\pi^- J/\psi) > 2.3\%$$

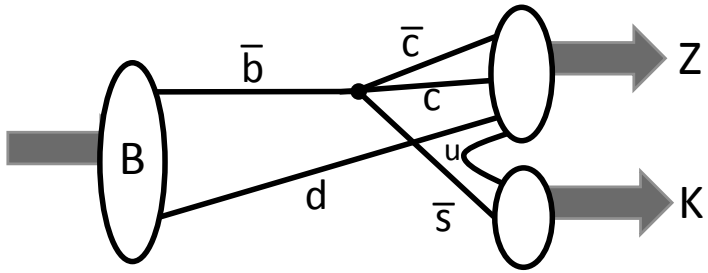
$$\Gamma^{tot}_{X(3872)} < 1.2 \text{ MeV} \Rightarrow$$

$$\Gamma(X_{3872} \to \pi^+\pi^- J/\psi) < 160 \text{ keV}$$

Using Belle – LHCb avgs:

$$Bf(Z^-_{4430} \to \pi^- \psi') \approx \frac{(4.4 \pm 1.7) \times 10^{-5}}{Bf(B^0 \to Z^-_{4430} K^+)}$$

$Bf(B^0 \to Z^-_{4430} K^+)$:



non-factorizable non-spectator diagram

$$\text{if}: Bf(B^0 \to Z^-_{4430} K^+) < Bf(B^+ \to X_{3872} K^+)$$

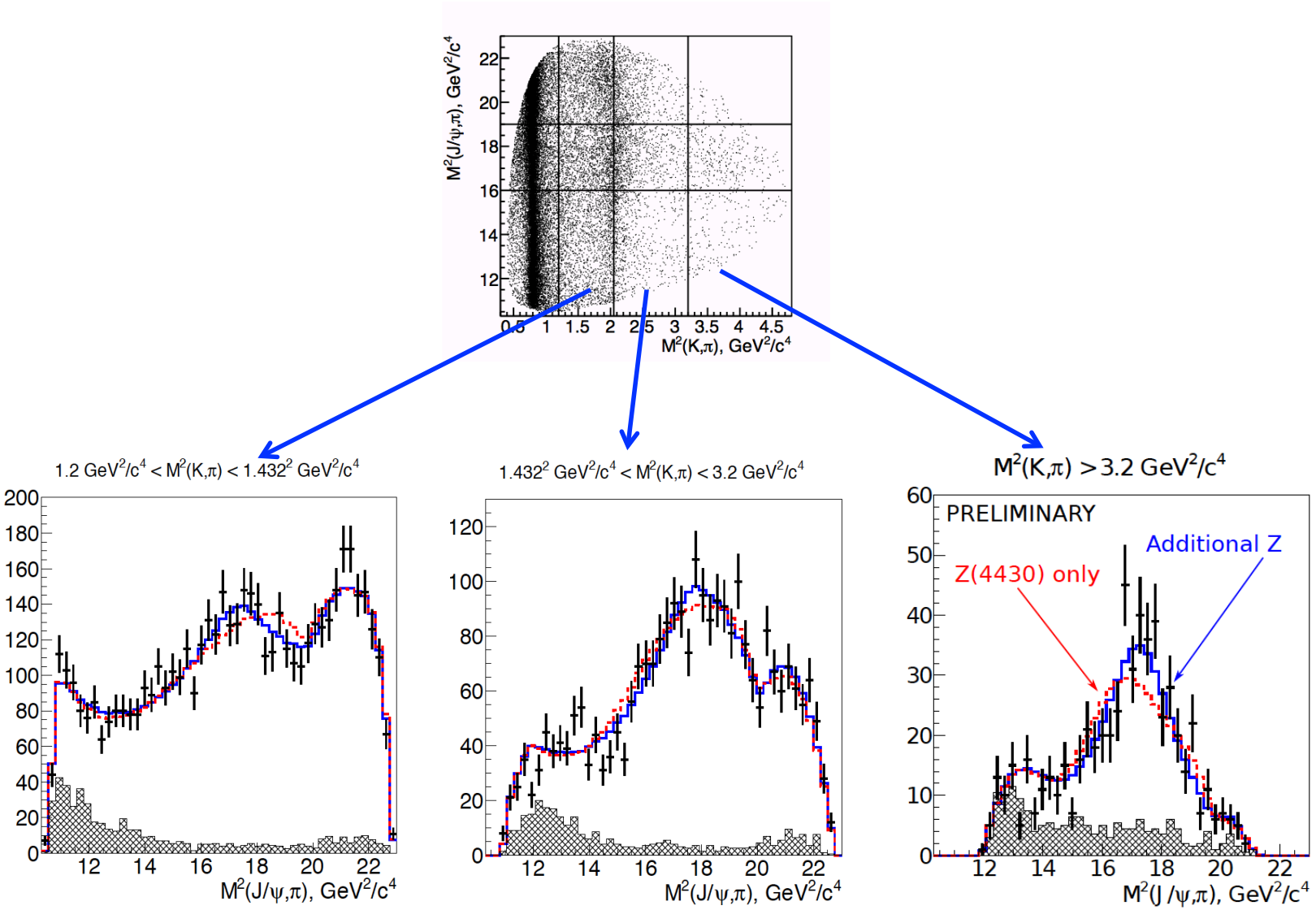
$$\Rightarrow Bf(Z^-_{4430} \to \pi^- \psi') > 5.3\%$$

$$\Gamma_{avg} = (181 \pm 31) \text{ MeV}$$

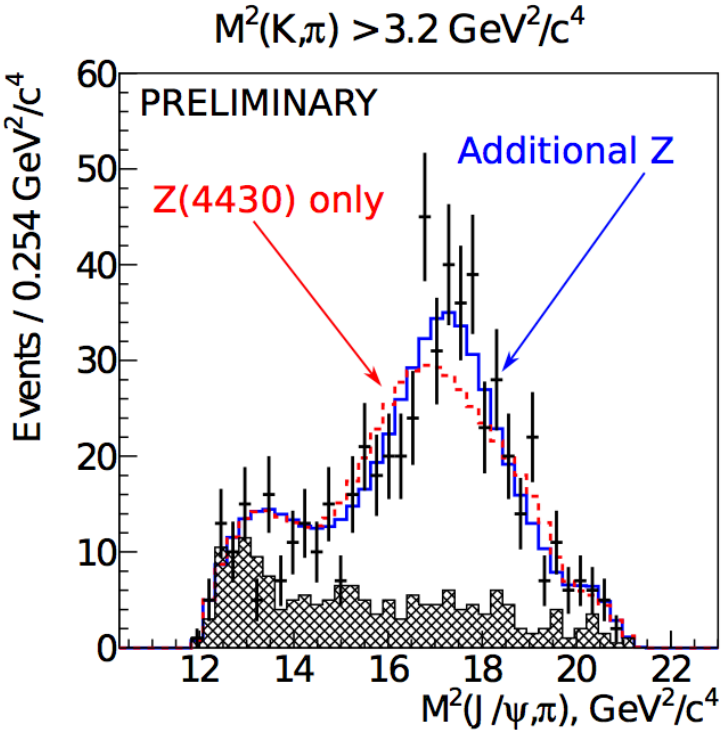
$$\Rightarrow \Gamma(Z^-_{4430} \to \pi^- \psi') > 7.5 \text{ MeV}$$

$$>> 7.5 \text{ MeV}??$$

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



New state $Z(4200)^+ \rightarrow \pi^- J/\psi$



7.2 σ

$$M = 4196^{+31+17}_{-29-6}\ \mathrm{MeV}/c^2$$

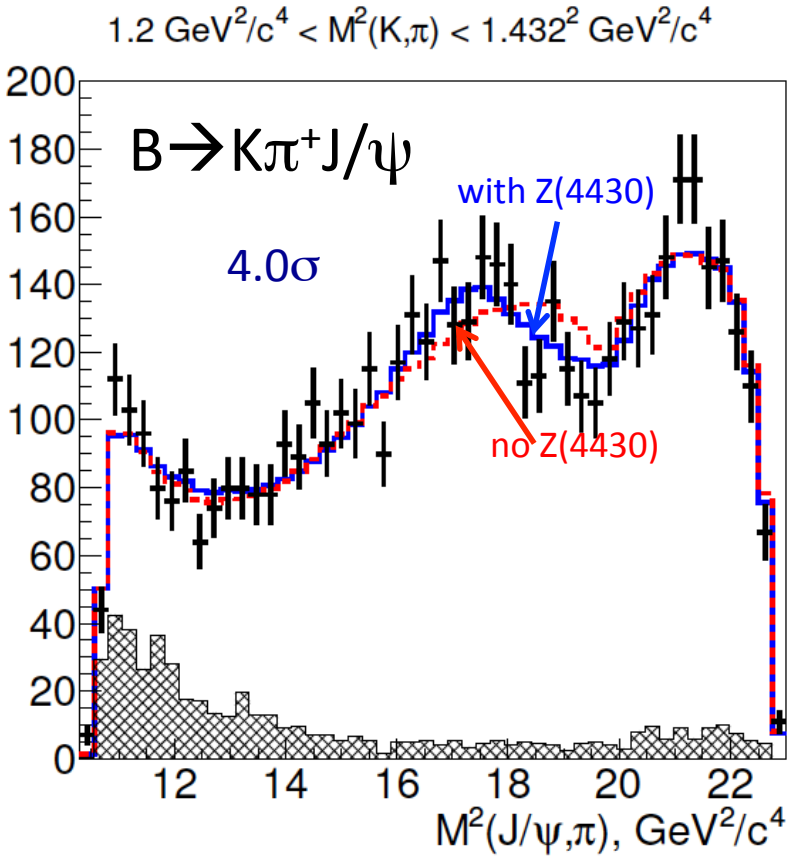
$$\Gamma = 370^{+70+70}_{-70-85}\ \mathrm{MeV}$$

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

Amplitude analysis of $B \to J/\psi K\pi$

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4220 ± 14	4315 ± 40	4196 ± 27	4209 ± 14	4203 ± 24
Width, MeV	71 ± 20	220 ± 80	370 ± 61	64 ± 18	121 ± 53
Significance	3.3σ	2.3σ	8.2σ	3.9σ	1.9σ

$Z(4430)^+ \rightarrow \pi^- J/\psi$



K. Chilikin, Moriond QCD March 24, 2014

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

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

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

$M(Z_c(4430))-M(Z_c(3900)) = 589 \pm 30$ MeV

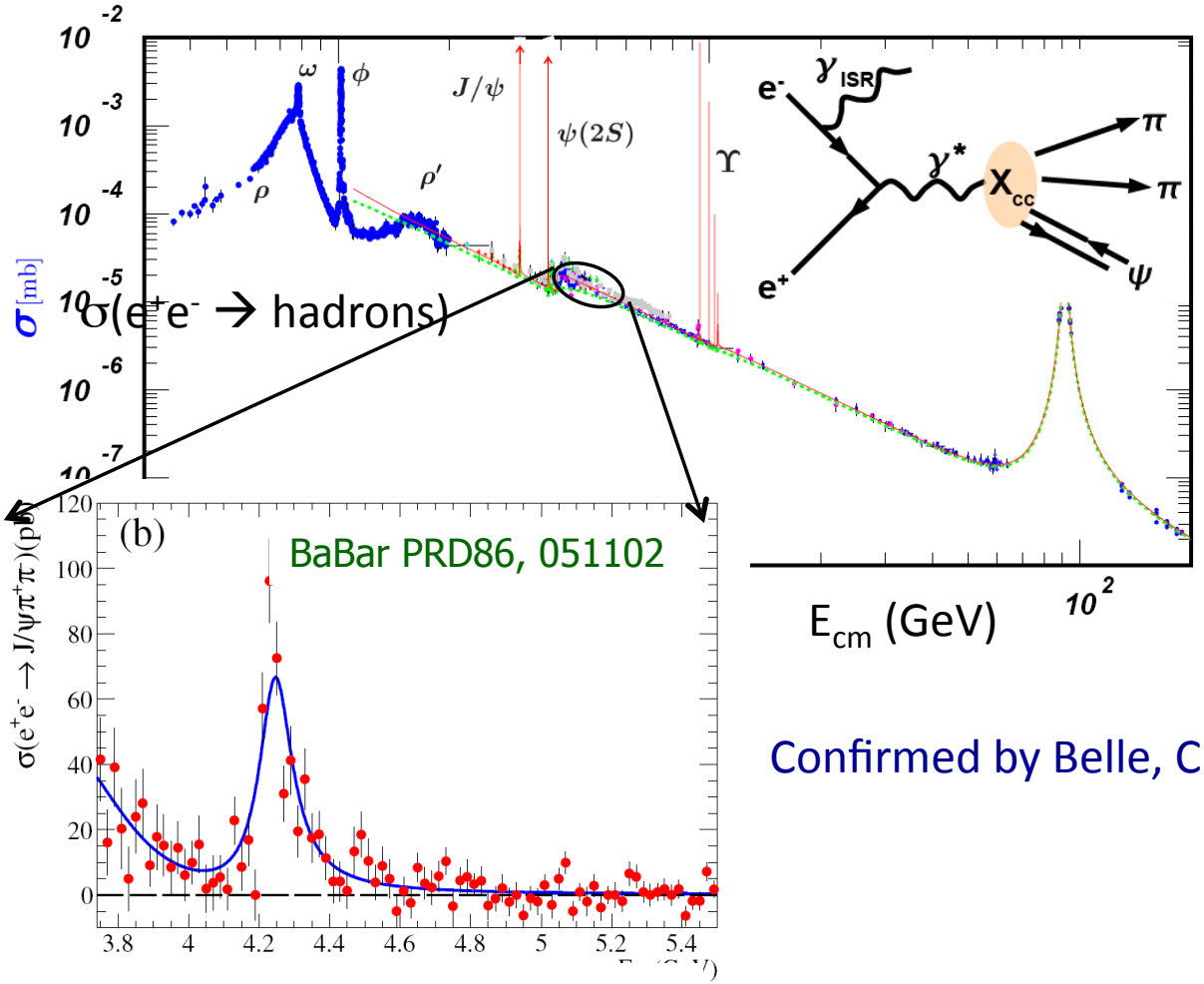
$M(\psi') - M(J/\psi) = 589$ MeV

Is Z(4430) a radial excitation of the ground state of $Z_c(3900)$?

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

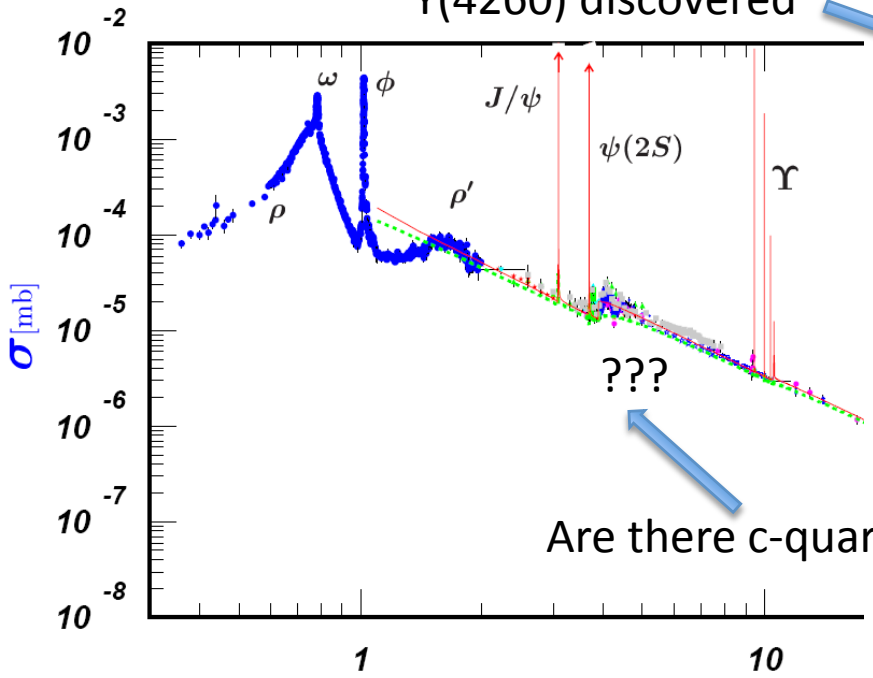
the Y(4260)

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



Confirmed by Belle, CLEO & BES etc

Are there c-quark versions of Z_b's



Y(4260) discovered

Is there a b-quark equivalent?

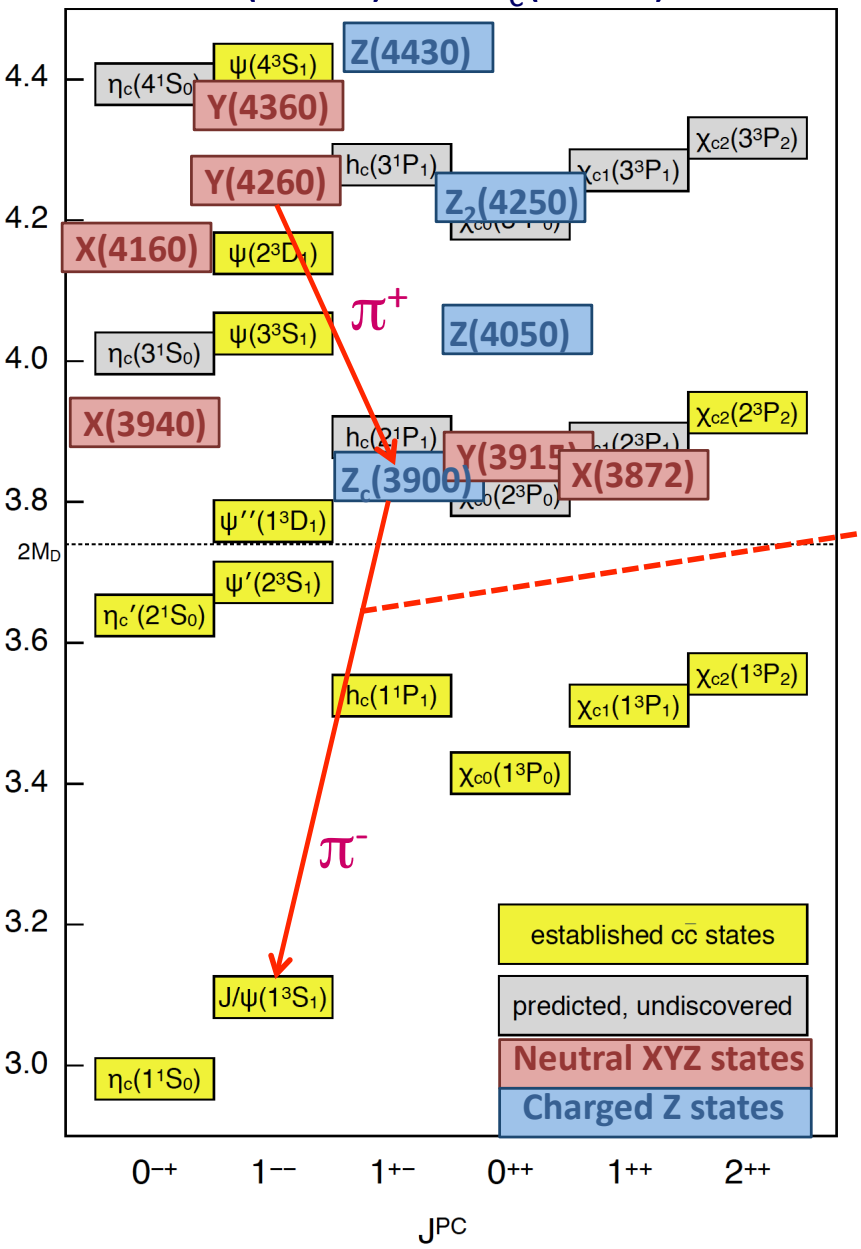
Yes, & it decays to Z_b states

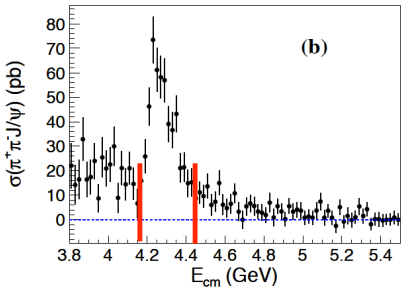
Are there c-quark versions of Z_b's?

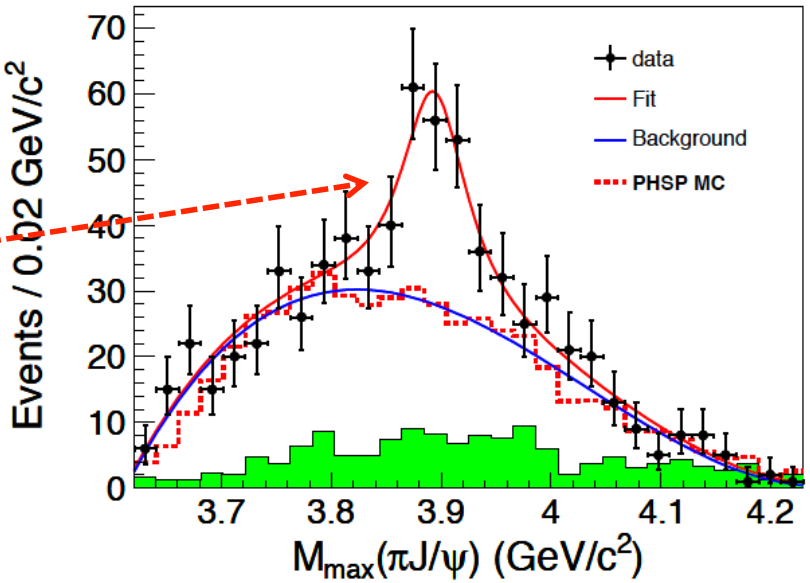
$Z_c(3895)$ by Belle

PRL 110, 252002 (2013)
arXiv:1304.0121

$e^+e^- \rightarrow Y(4260) \rightarrow \pi^- Z_c(3895)^+ \rightarrow \pi^+\pi^- J/\psi$





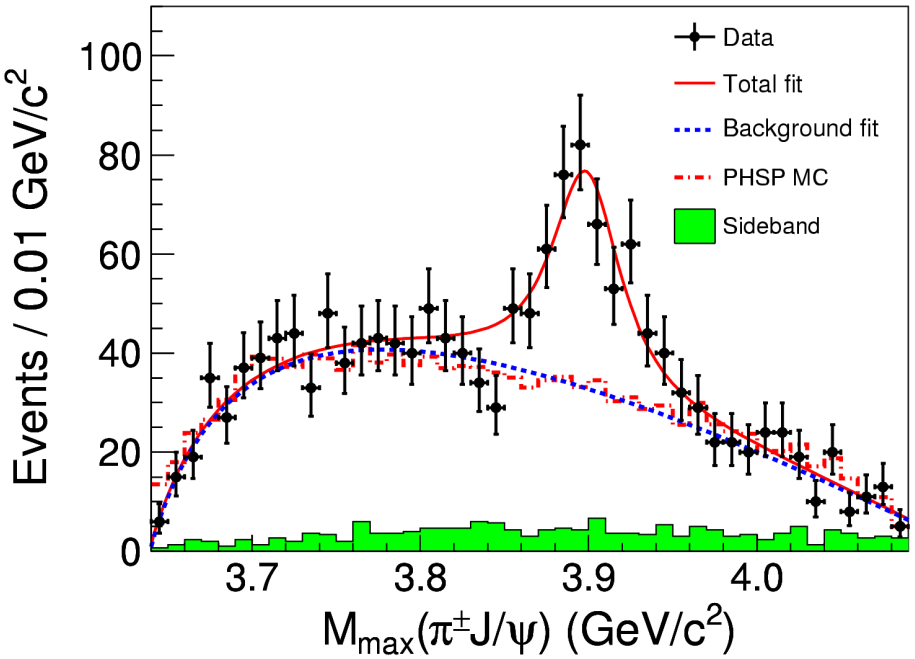


BESIII data clearly establish $J^P=1^+$ From DD*

- Mass = (3894.5 ± 6.6 ± 4.5) MeV
- Width = (63 ± 24 ± 26) MeV
- Fraction = (29.0 ± 8.9)% (stat. error only)
- Significance = 5.2 σ

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

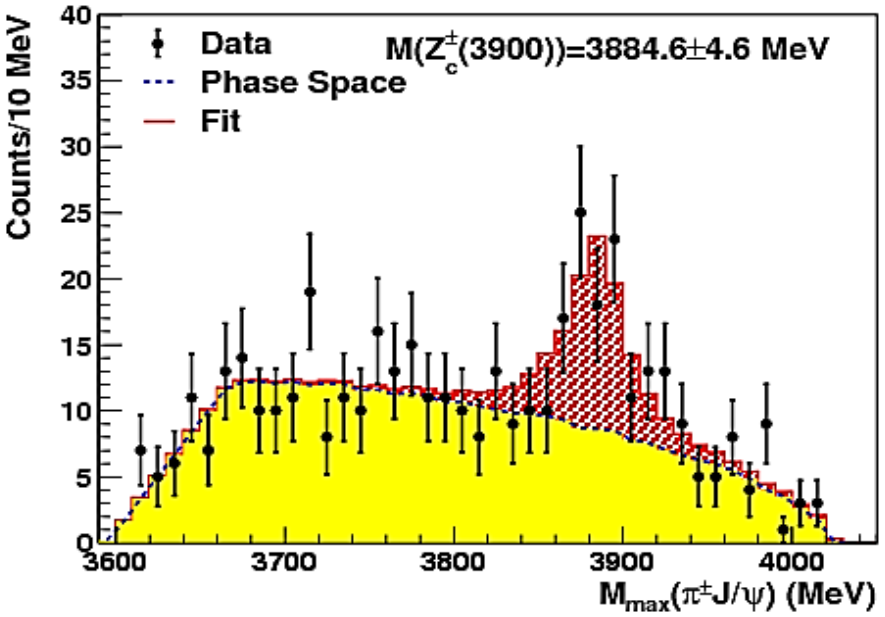
BESIII: PRL 110, 252001
arXiv:1303.5949



- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%
- Significance > 8 σ

CLEOc data

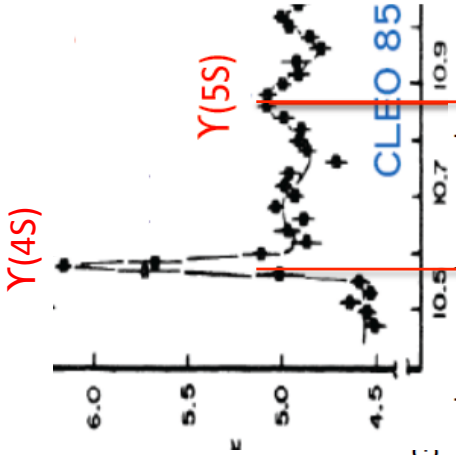
at 4.17 GeV: 1304.3036

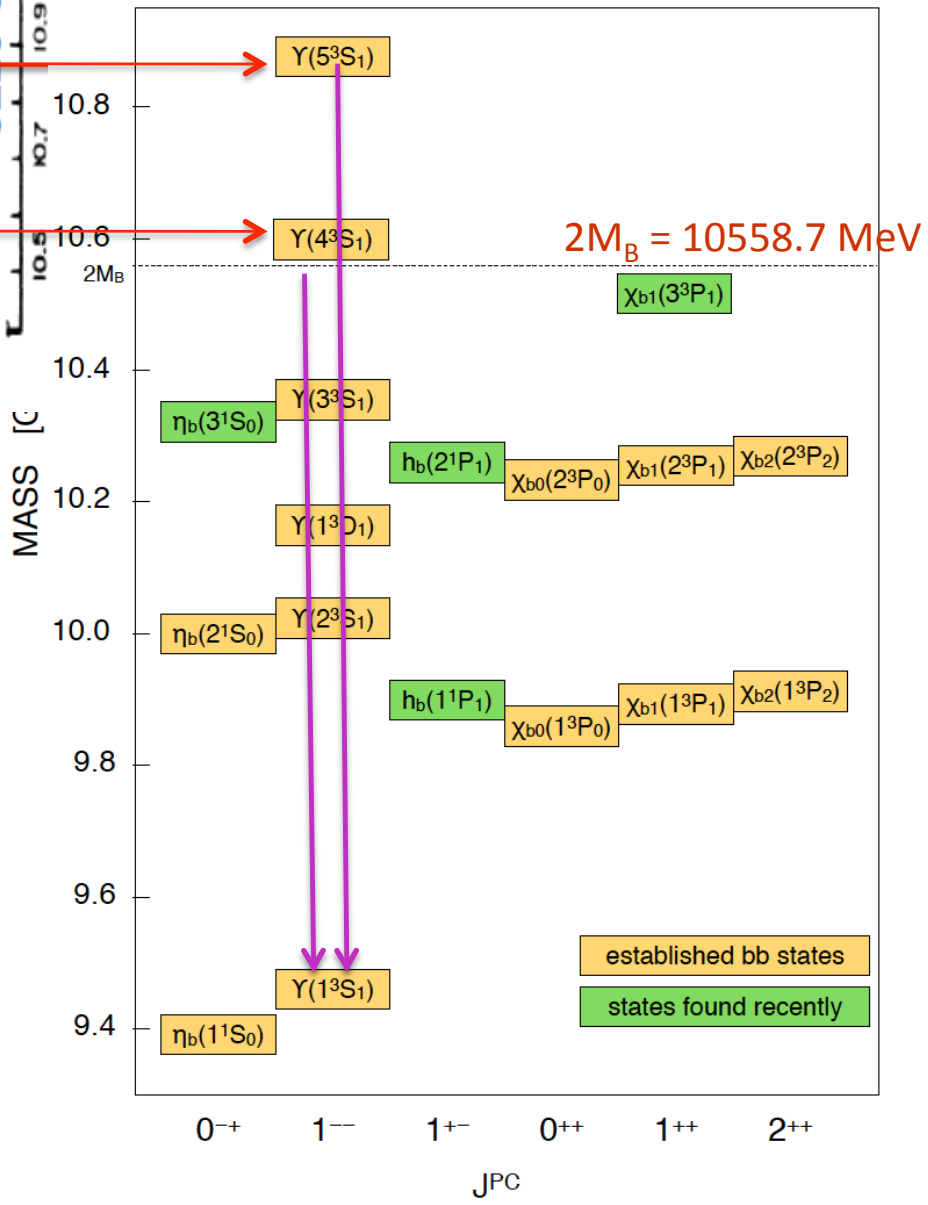


- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events
- 6.1σ

The Bottomonium-like mesons

“bottomonium” $b\bar{b}$ mesons



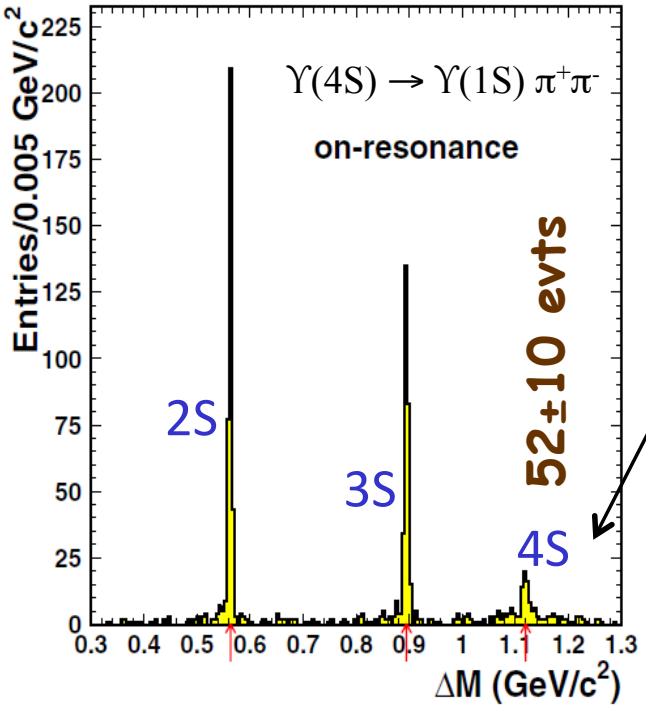


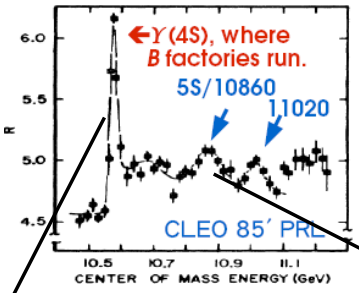
Is there any anomaly in $\Upsilon(4S,5S) \rightarrow \pi^+\pi^- \Upsilon(1S)$?

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

Belle: PRD 75 071103

477 fb^{-1}





Signal

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

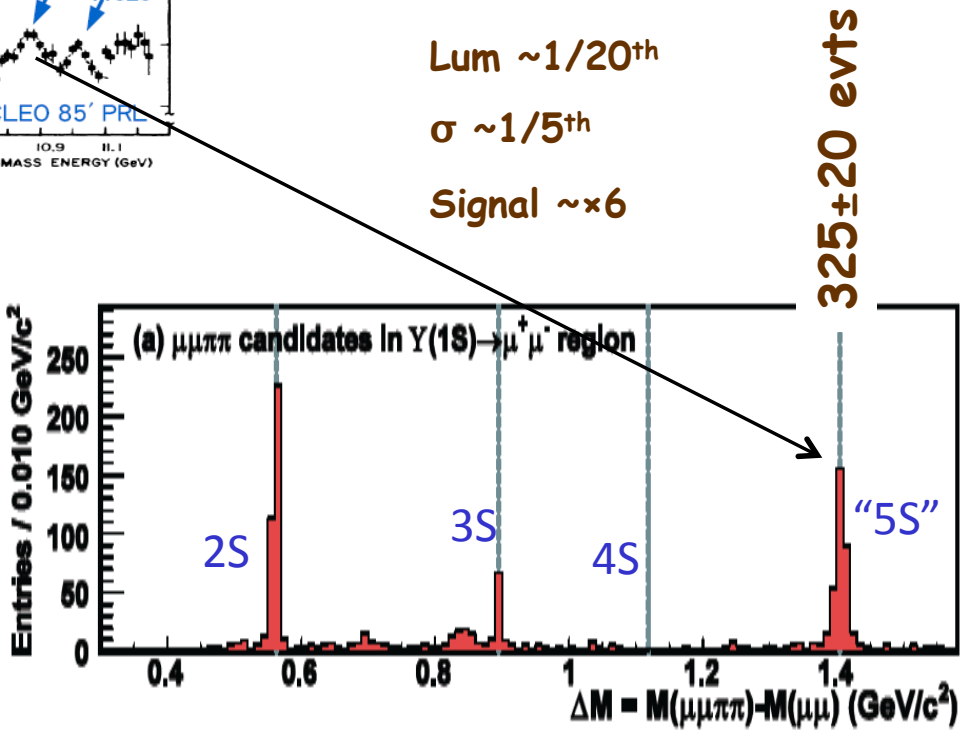
Belle: PRL 100 112001

23.6 fb^{-1}

Lum ~1/20th

σ ~1/5th

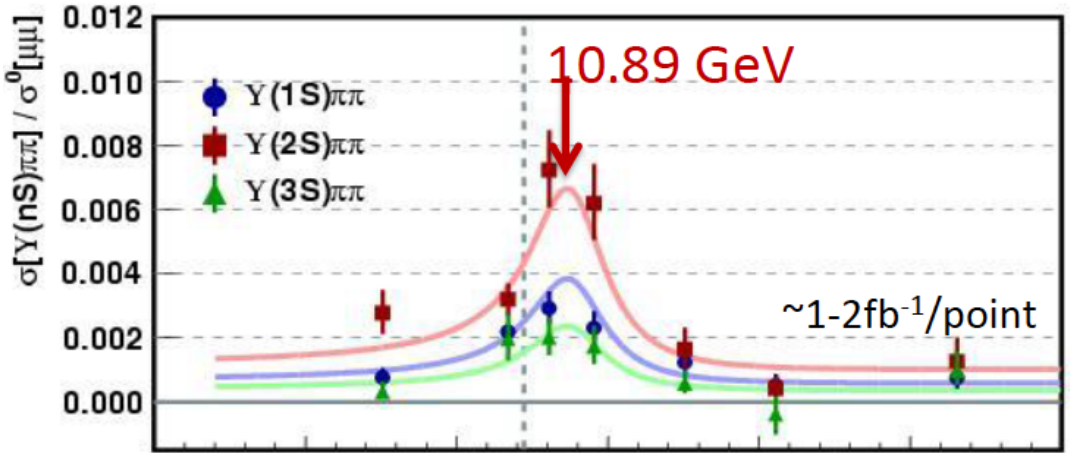
Signal ~×6



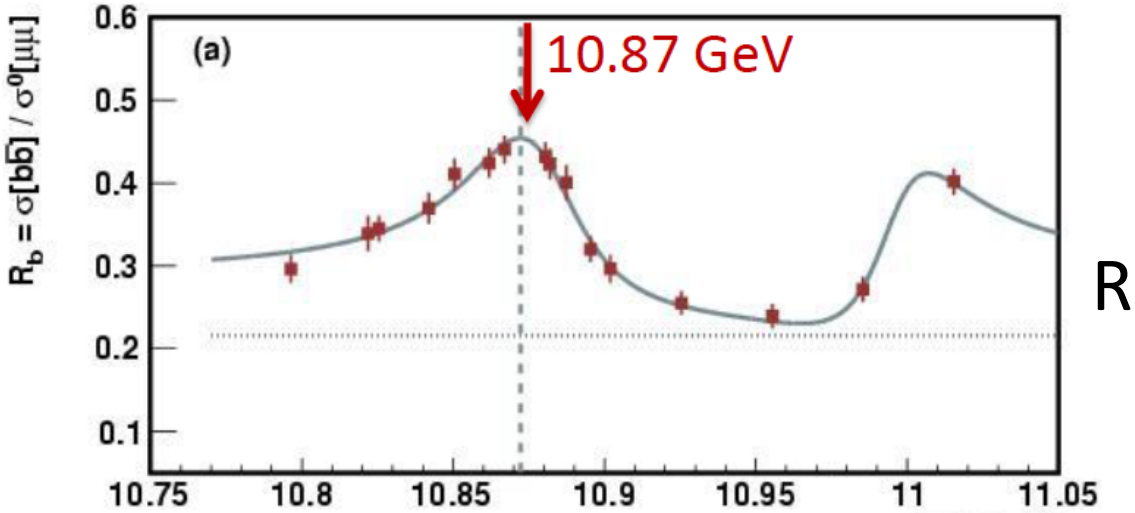
parent	N($\pi^+\pi^-\Upsilon$(1S))	$\Gamma(\Upsilon_{4S}\to\pi\pi\Upsilon_{1S})$	Γ_{theory}
Υ(4S)	52±10	1.75 ± 0.35 keV	1.47±0.03 keV
"Υ(5S)"	325±20	590 ± 110 keV	<1.5 keV

Belle PRD 82, 091106R (2010)

Energy scan to search for anomalous structure



$R_{\Upsilon(nS)\pi\pi} = \sigma(\Upsilon(nS)\pi^+\pi^-)/\sigma^0(\mu\mu)$



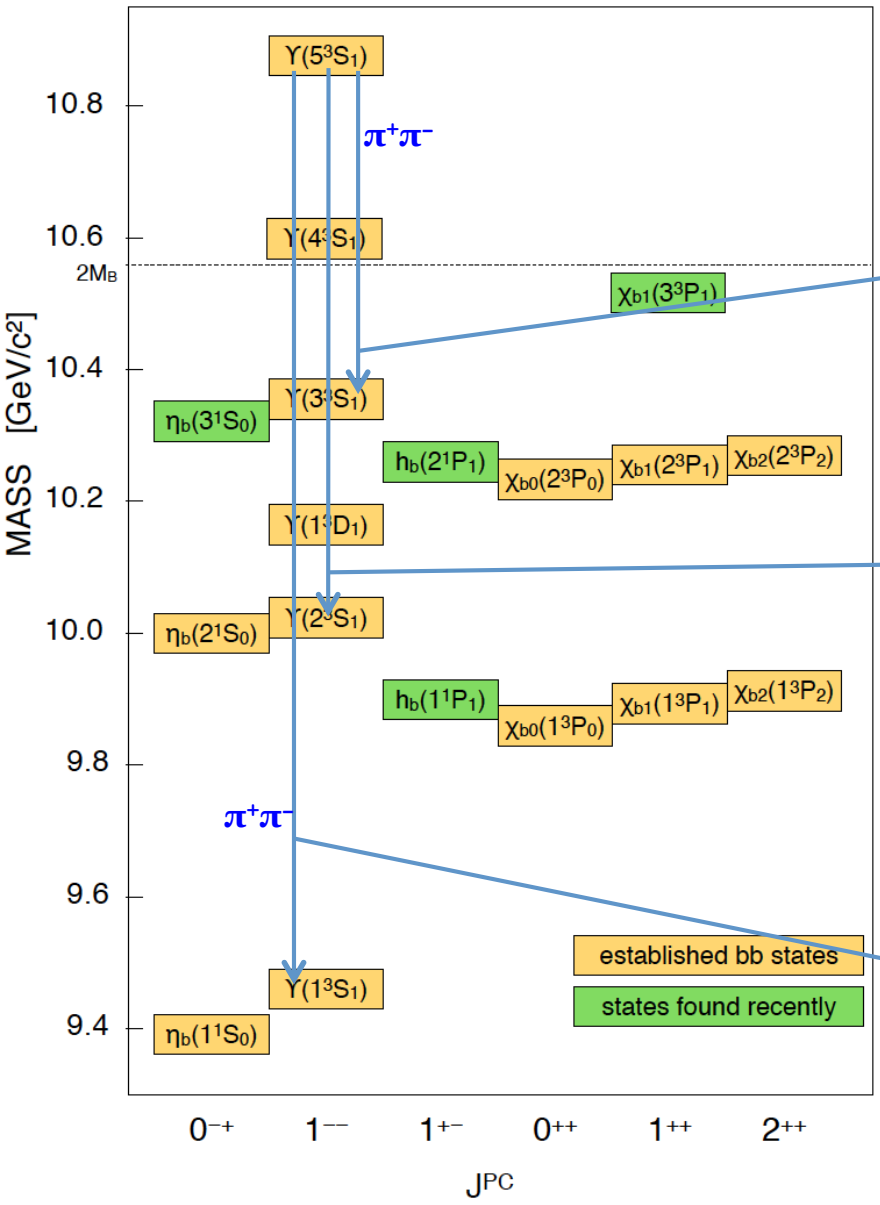
$R_b = \sigma(b\bar{b})/\sigma^0(\mu\mu)$

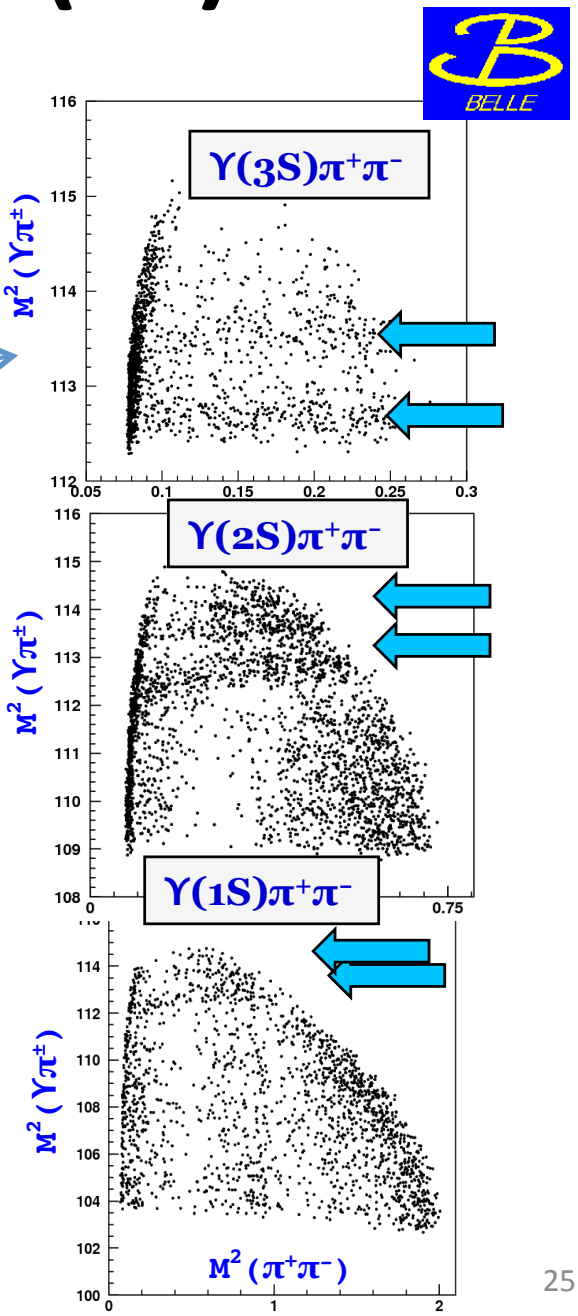
Peak location differs by 20 MeV

$\Delta M = M_{5S}(\Upsilon\pi\pi) - M_{5S}(bb) = 9\pm4$ MeV

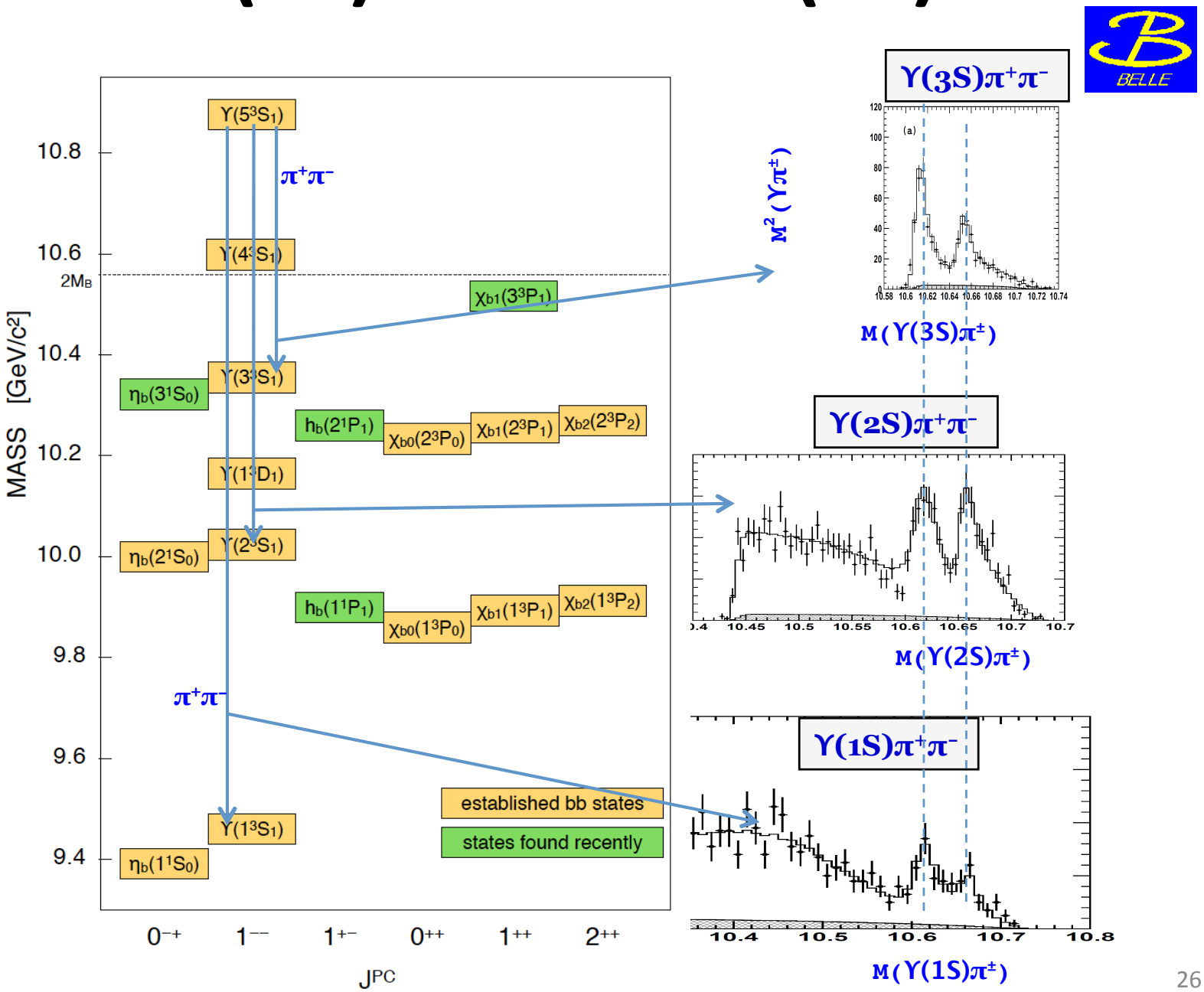
Recall Y(4260) with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$ $\Rightarrow$ Is there a Υ_b equivalent close to $\Upsilon(5S)$

"Υ(5S)" →π⁺π⁻Υ(1S) ?


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


BELLE
Υ(3S)π⁺π⁻
Υ(2S)π⁺π⁻
Υ(1S)π⁺π⁻
M²(Υπ±)
M²(π⁺π⁻)

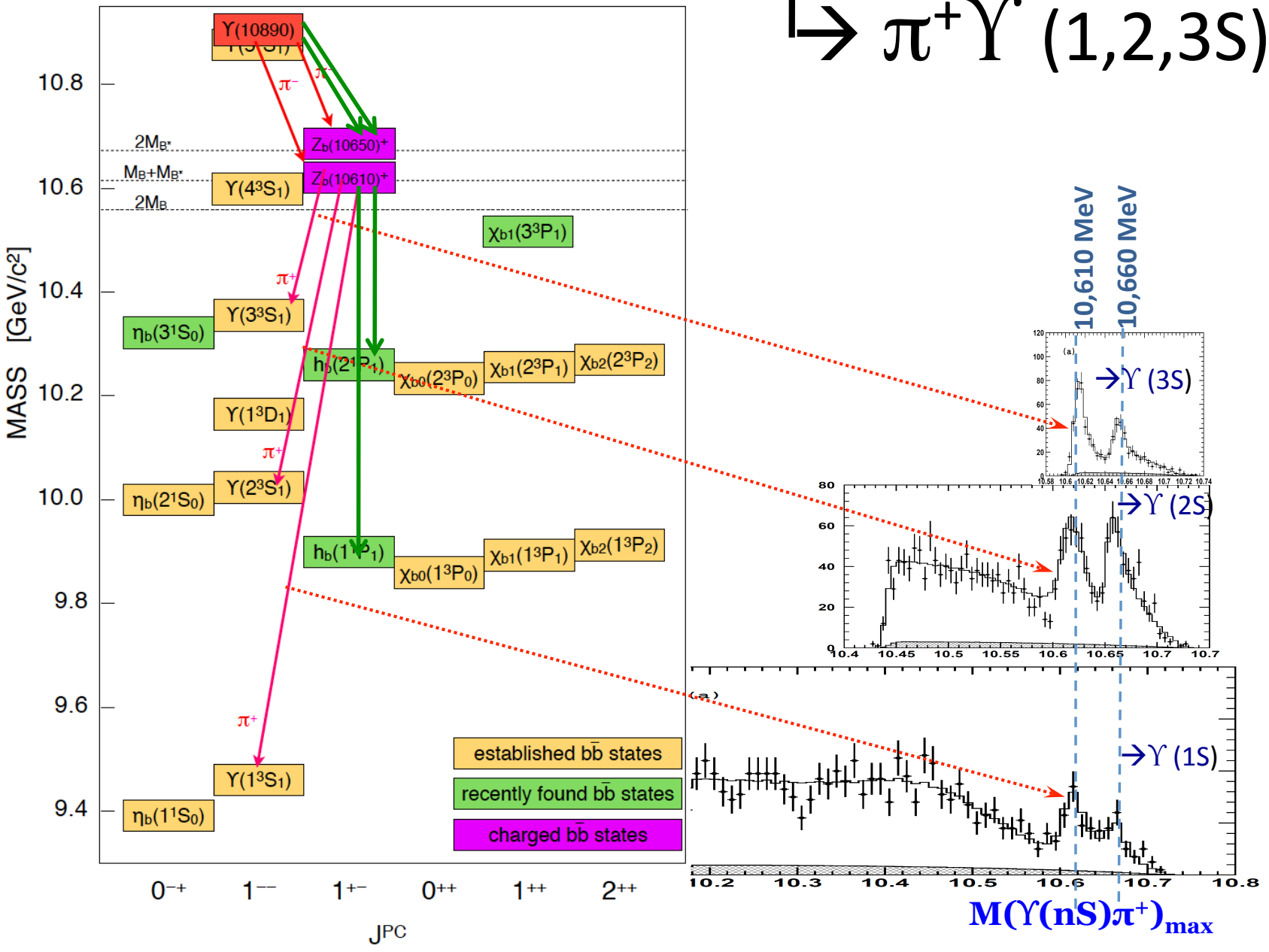
"Υ(5S)" →π⁺π⁻Υ(1S) ?


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

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

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

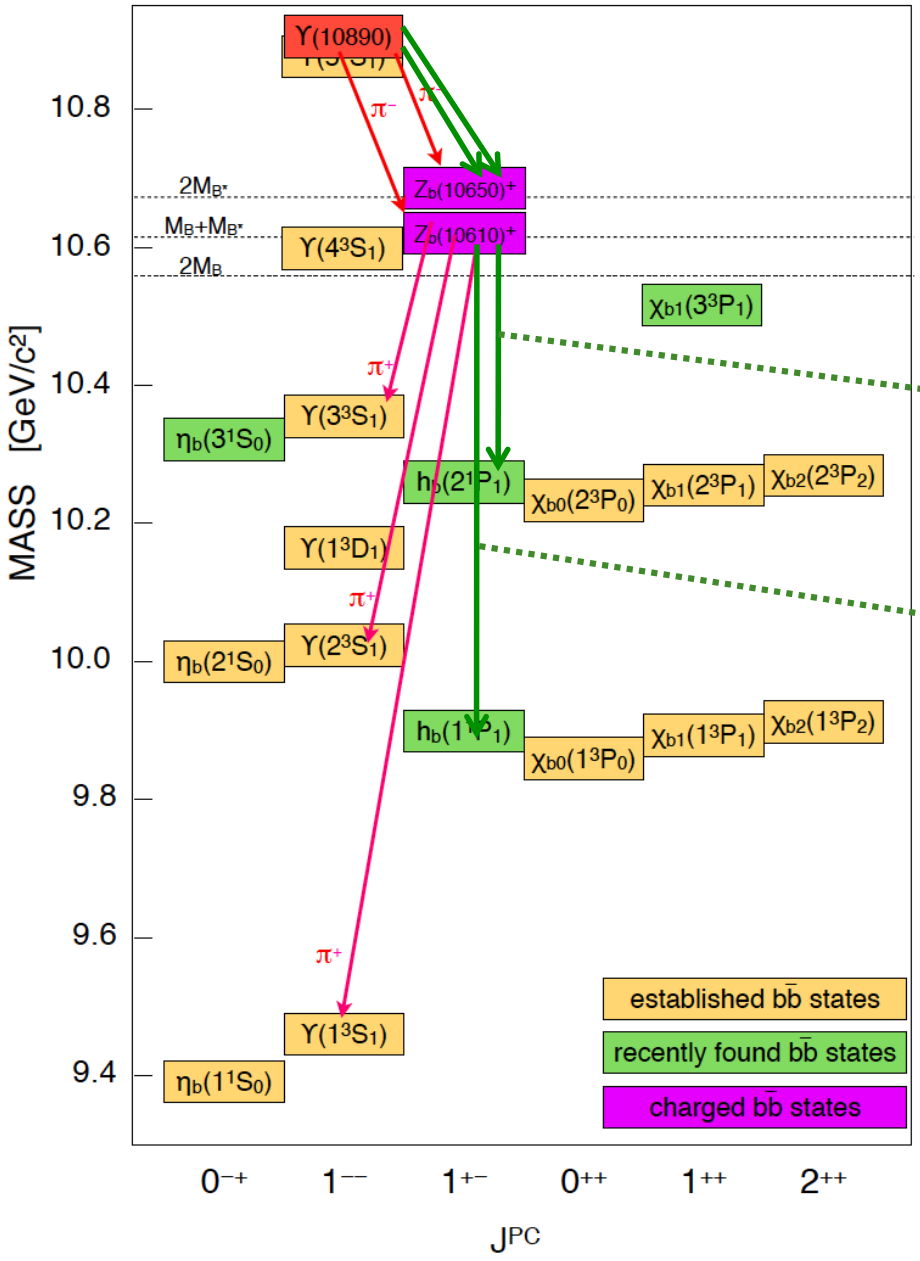
Bottomonium spectrum

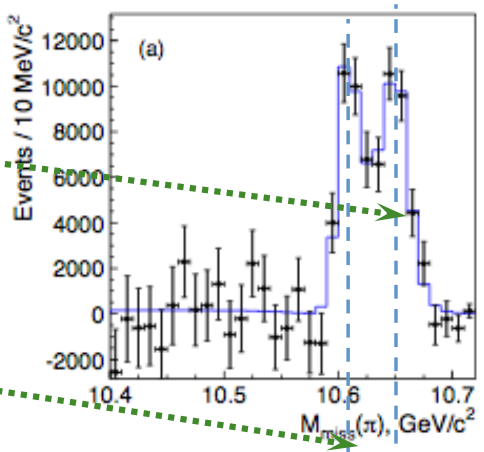


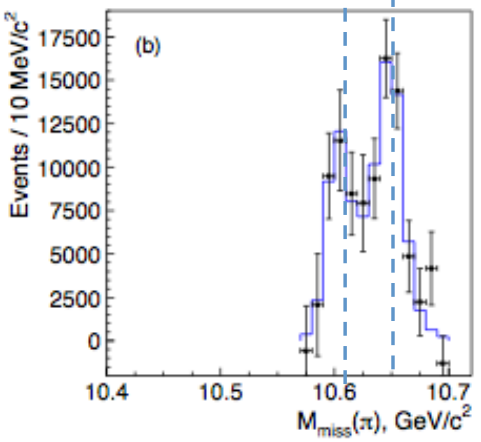
"Υ(5S)" → $\pi^- Z_{b1,2}^+$ → $\pi^+ h_b(1P, 2P)$

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

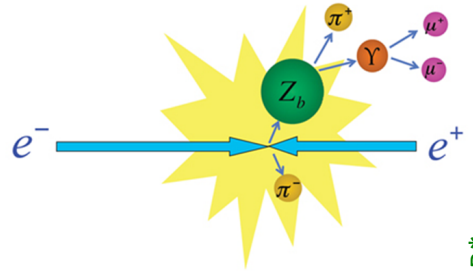
Bottomonium spectrum

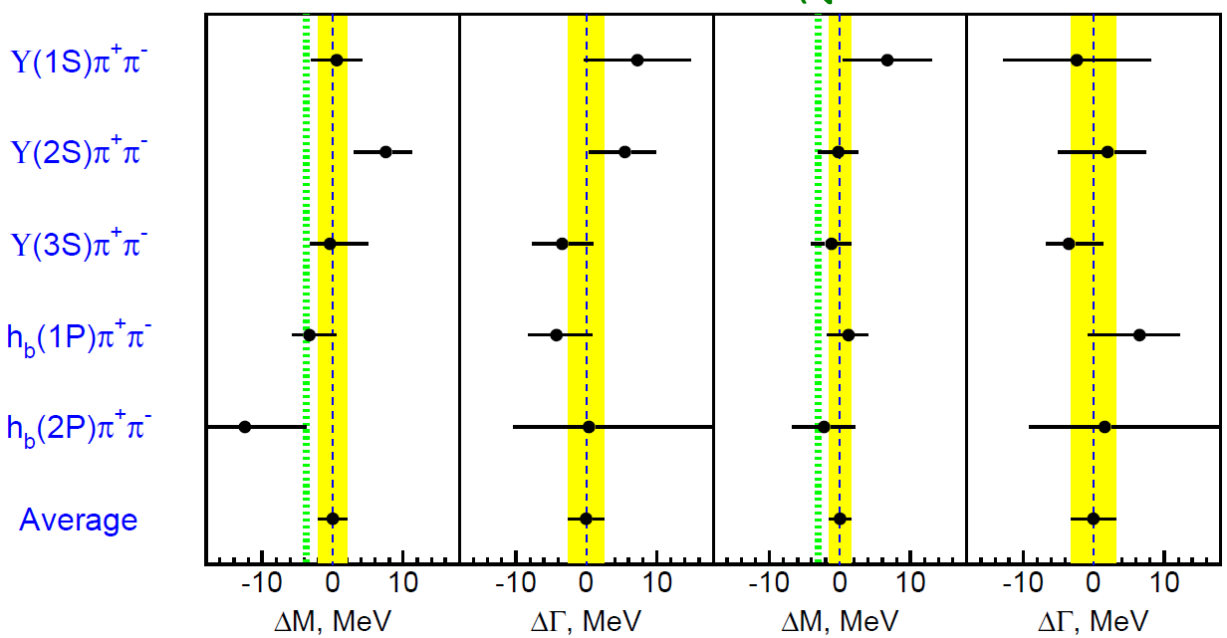


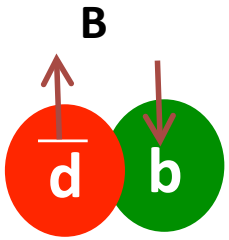


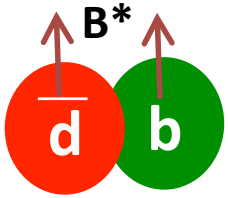


Summary of parameter measurements









$Z_b(10610)$

M=10607.2±2.0 MeV

Γ=18.4±2.4 MeV

$Z_b(10650)$

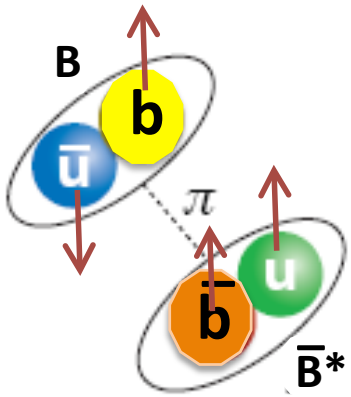
M=10652.2±1.5 MeV

Γ=11.5±2.2 MeV

Belle PRL 108, 122001 ← March 2012

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

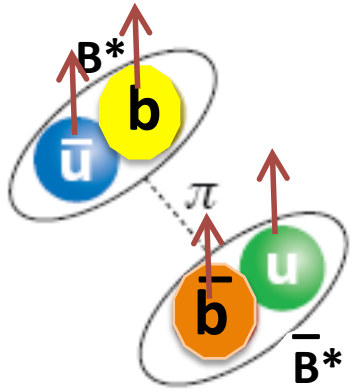
$Z_b(10610)^{\pm}$



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

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

$Z_b(10650)^{\pm}$



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

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

Slightly unbound threshold resonances??

Belle: M=10607.2±2.0 MeV, Γ=18.4±2.4 MeV

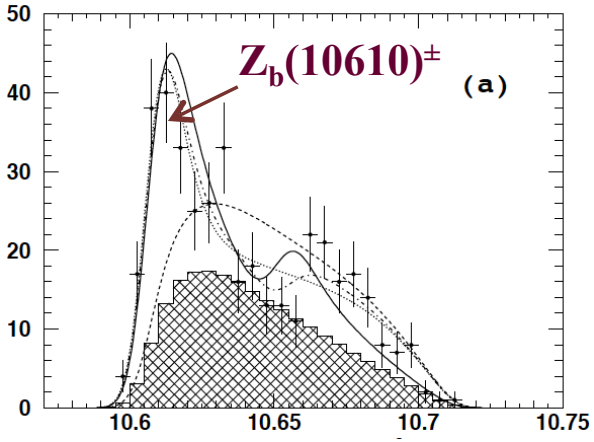
M=10652.2±1.5 MeV, Γ=11.5±2.2 MeV

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

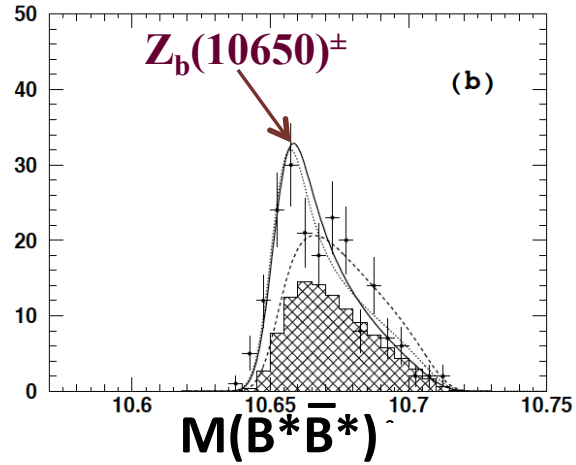
$M_{B^*} + M_{B^*} = 10650.2 \pm 1.0$ MeV

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

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



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



[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

$$\frac{Bf(Z_b(10610)\to B\bar{B}^*}{Bf(Z_b(10610)\to \pi^+(b\bar{b})} = 6.2\pm0.7$$

$$\frac{Bf(Z_b(10650)\to B^*\bar{B}^*}{Bf(Z_b(10650)\to \pi^+(b\bar{b})} = 2.8\pm0.4$$

New Measurement of R_b , $R_{\Upsilon(nS)\pi\pi}$ and $\Upsilon(6S)$

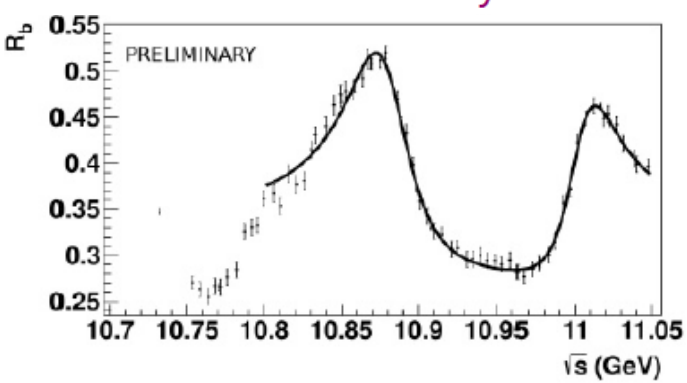
$$R_X = \sigma_{e^+e^-\to X}/\sigma_{e^+e^-\to\mu^+\mu^-}$$

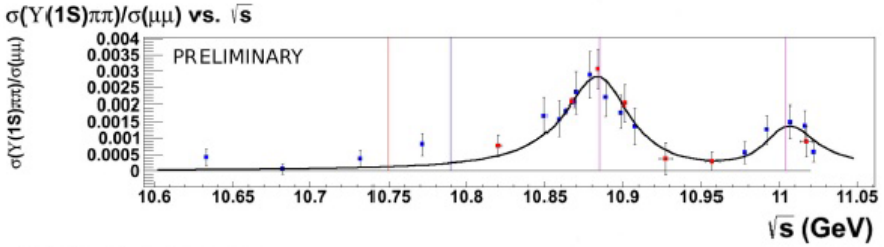
- Mass of $\Upsilon(5S)$:
  $b\bar{b}$: $10880.4 \pm 0.9 \pm 1.4$,
  $\Upsilon\pi^+\pi^-$:
  $10884.6 \pm 1.4 \pm 1.1$.
- Observed:
  $\Upsilon(6S) \to \Upsilon\pi^+\pi^-$.

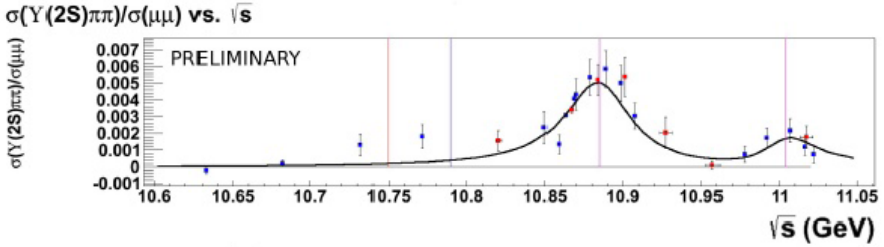
At 10.865 GeV:

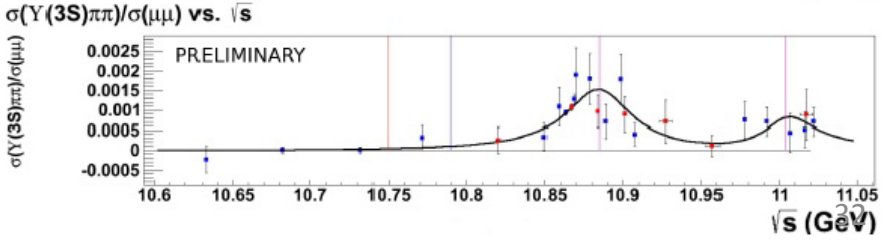
Contribution	$R_X \times 10^3$
$\Upsilon(1S)\pi^+\pi^-$	$2.4 \pm 0.1 \pm 0.7$
$\Upsilon(2S)\pi^+\pi^-$	$4.2 \pm 0.2 \pm 1.1$
$\Upsilon(3S)\pi^+\pi^-$	$1.3 \pm 0.1 \pm 0.5$

Preliminary results









Summary

◆ NEW charged state $Z(4200)^+$ is observed in $B \rightarrow J/\psi\, \pi^+ K^-$ decay. The quantum number is 1^+.

◆ Preferred quantum number of $Z(4430)^+$ is 1^+ in $B \rightarrow \psi'\, \pi^+ K^-$ decay and New evidence of the $Z(4430)^+ \rightarrow \pi^+ J/\psi$ is found.

◆ No X-like states are observed in decays to $\eta_c \pi^+ \pi^-$, $\eta_c \omega$, $\eta_c \eta$, and $\eta_c \pi^0$. Upper limits for the corresponding product BF's were set.

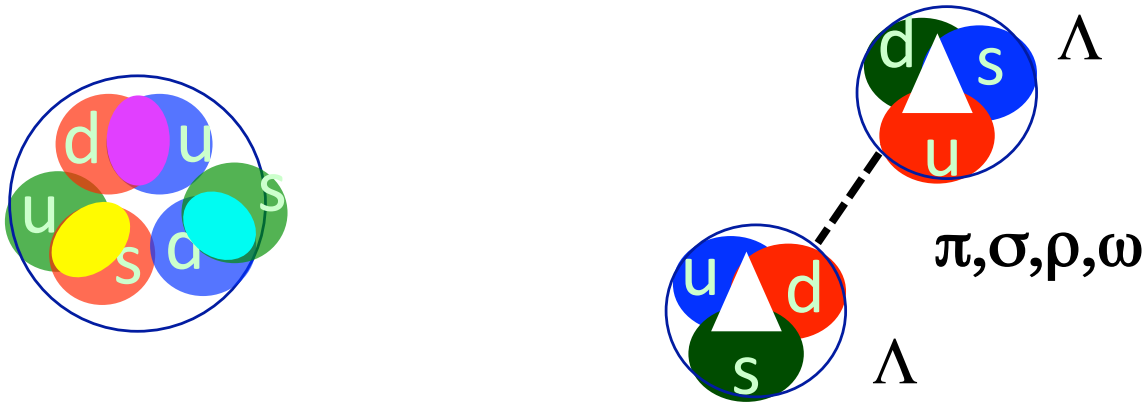
◆ Review of charged Z_b

◆ The $J^{PC}=1^{--}$ Y(4260) and "Υ(5S)" have no compelling interpretation : huge couplings to $\pi^+\pi^- J/\psi$ ($\pi^+\pi^- \Upsilon(nS)$) and strong sources of charged Z_c (Z_b) states with M near $m_{D(*)}+m_{D^*}$ ($m_{B(*)}+m_{B^*}$).

◆ Cross sections $e^+e^- \rightarrow b\bar{b}$ and $\Upsilon(nS)\pi^+\pi^-$ are measured again in the energy range of 10.63 – 11.03 GeV : Υ(6S) is observed in the $\Upsilon(6S) \rightarrow \Upsilon(1,2,3S)\, \pi^+\pi^-$.

Back-up slides

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!!

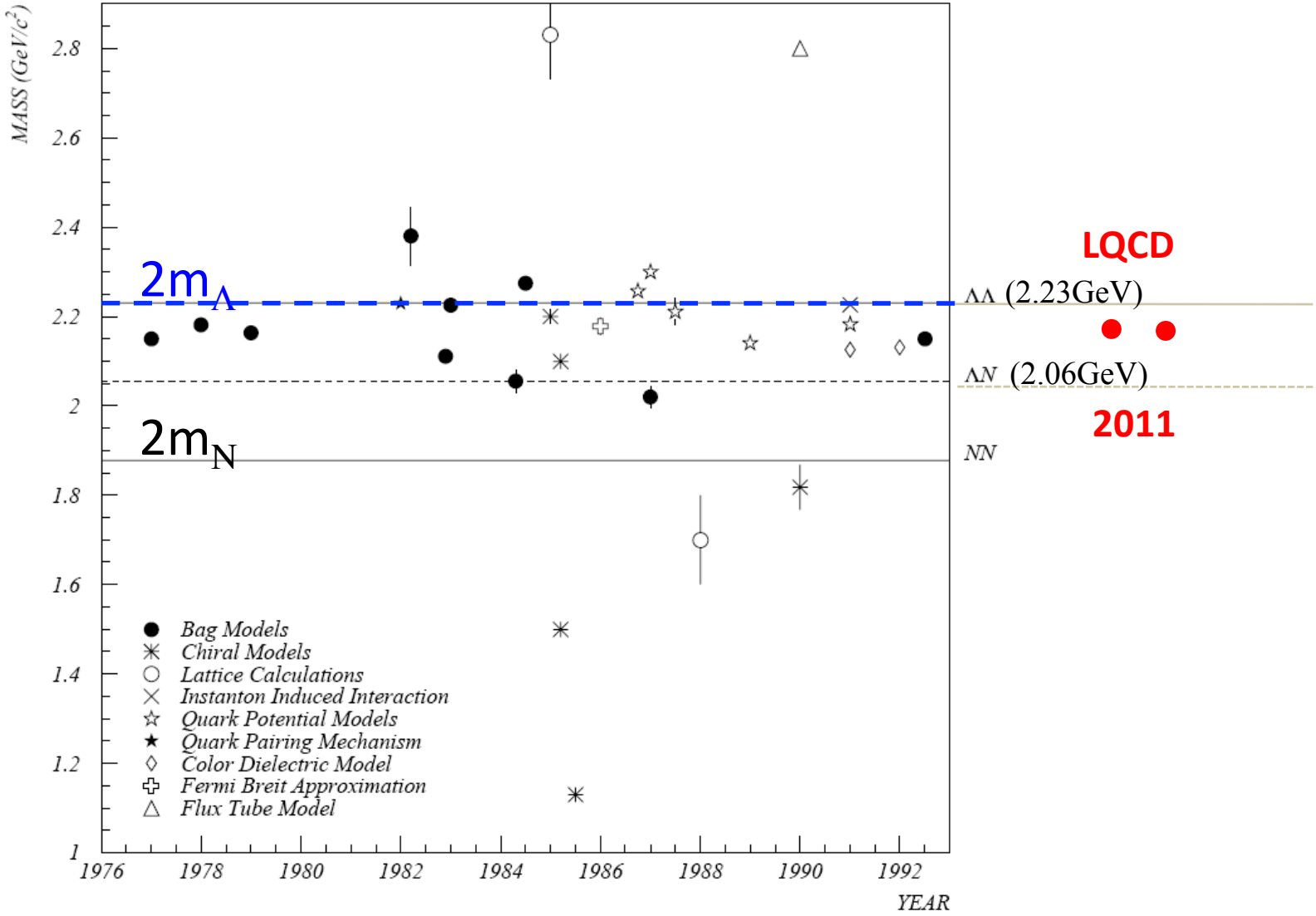


Figure 1: Theoretical predictions for the mass of the H-dibaryon as a function of year of prediction

Recent Lattice QCD calculations

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

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)

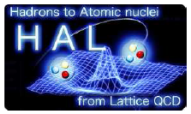
[1] *Albert Einstein Zentrum für Fundamentale Physik, Institut für theoretische Physik, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[2] *Department of Physics, University of New Hampshire, Durham, NH 03824-3568, USA*
[3] *Dept. d'Estructura i Constituents de la Matèria. Institut de Ciències del Cosmos (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

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

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)



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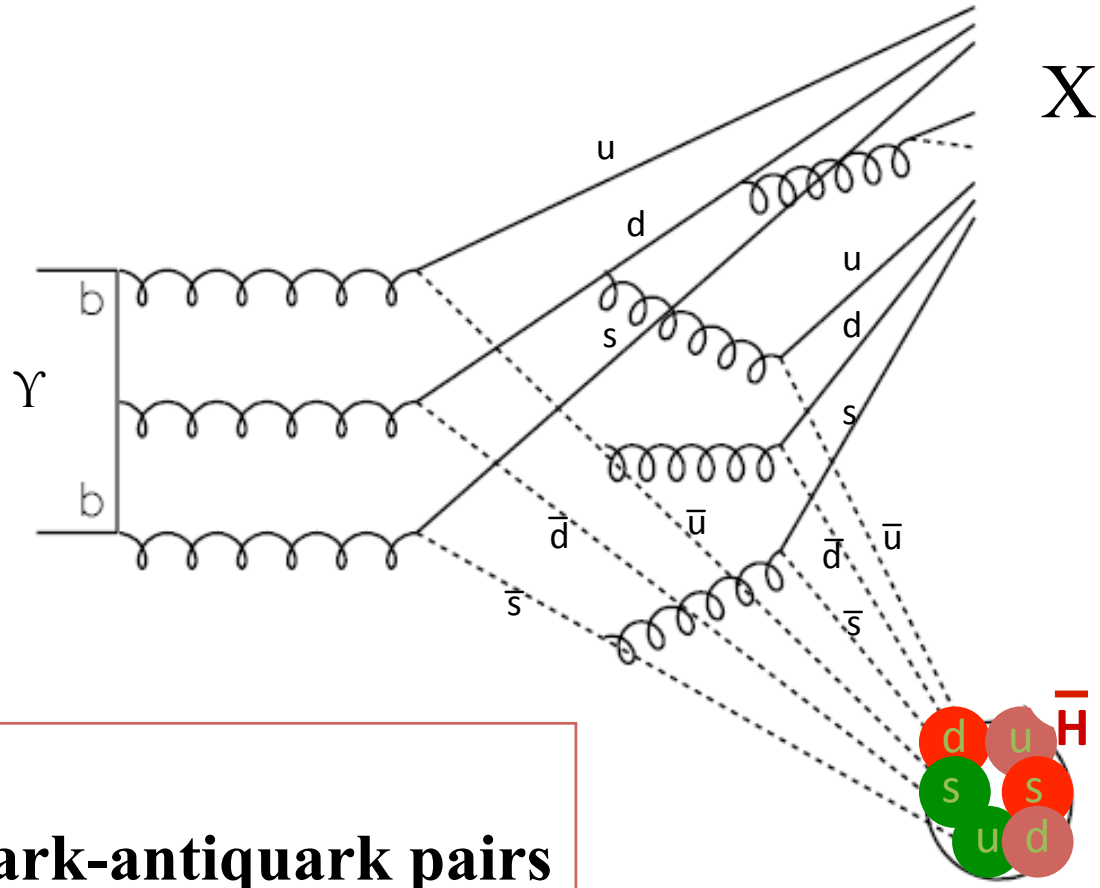
$M_H = 2m_\Lambda -$ "(30~40) MeV"

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



Need to:

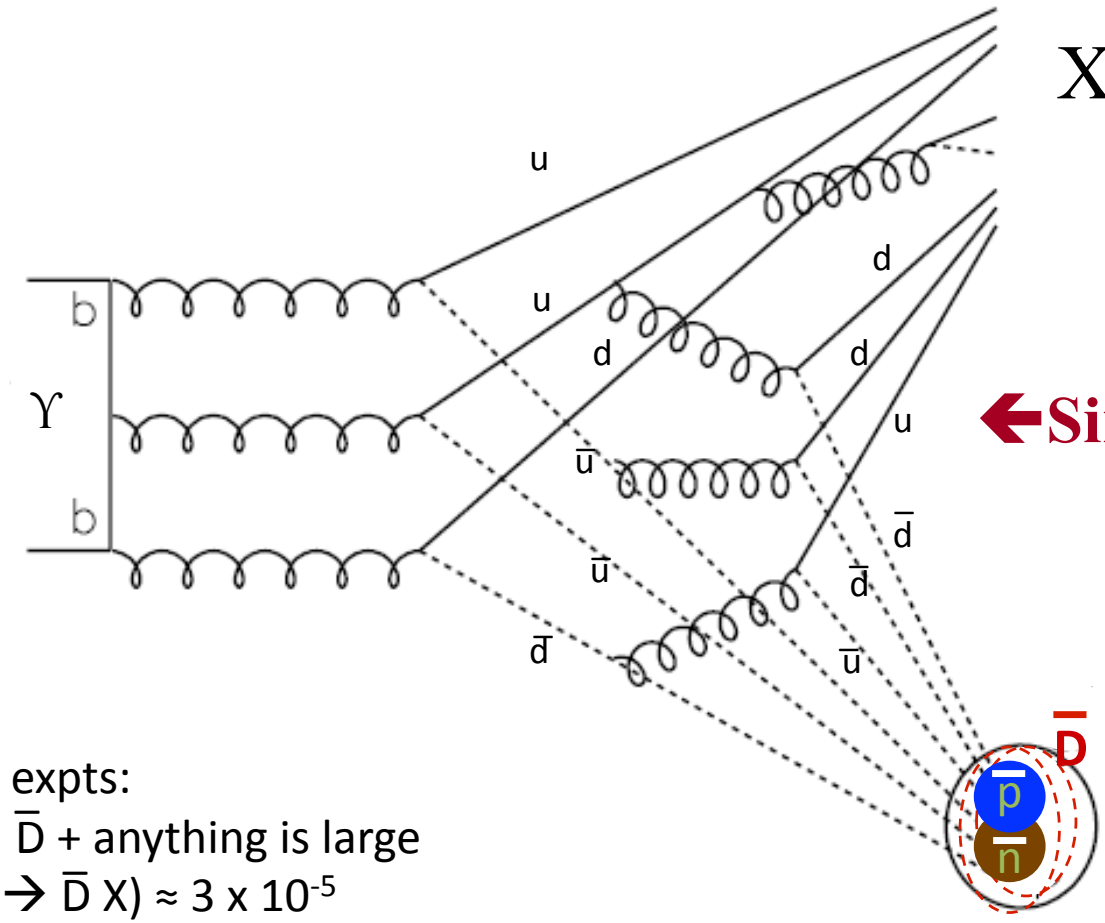
produce 6 quark-antiquark pairs

(including two $s\bar{s}$ quark pairs)

very close in phase space

←Is this likely???

Anti-deuteron production in $\Upsilon(1S)$ decays



←Similar process!!

ARGUS & CLEO expts:

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

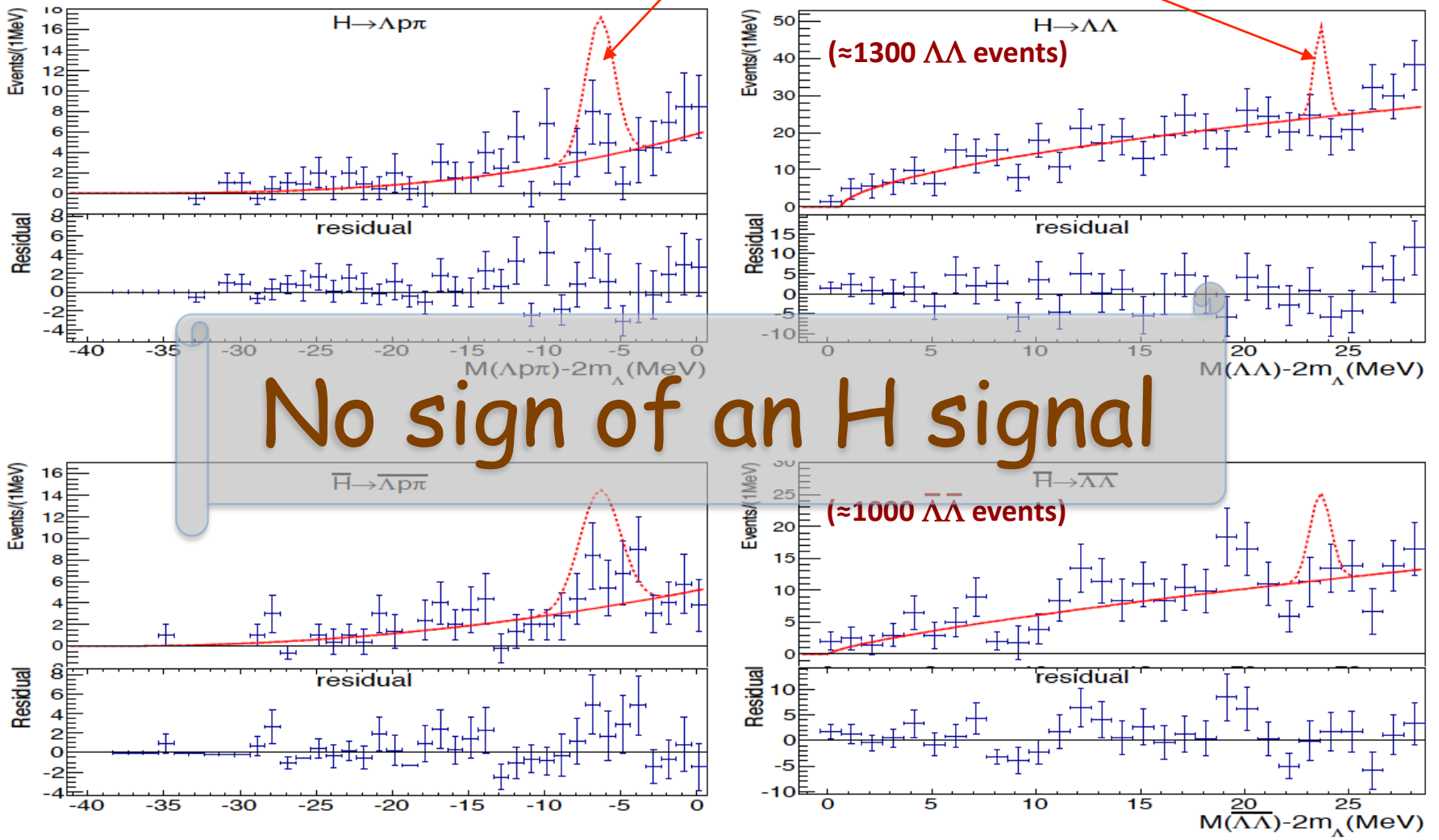
$Bf(\Upsilon(1,2S) \rightarrow \bar{D} X) \approx 3 \times 10^{-5}$

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 $\Upsilon(1S)$ decays + 160×10^6 $\Upsilon(2S)$ decays

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

expected signals for Bf($\Upsilon\rightarrow HX$)=(1/20)×Bf($\Upsilon\rightarrow\bar{d}X$)

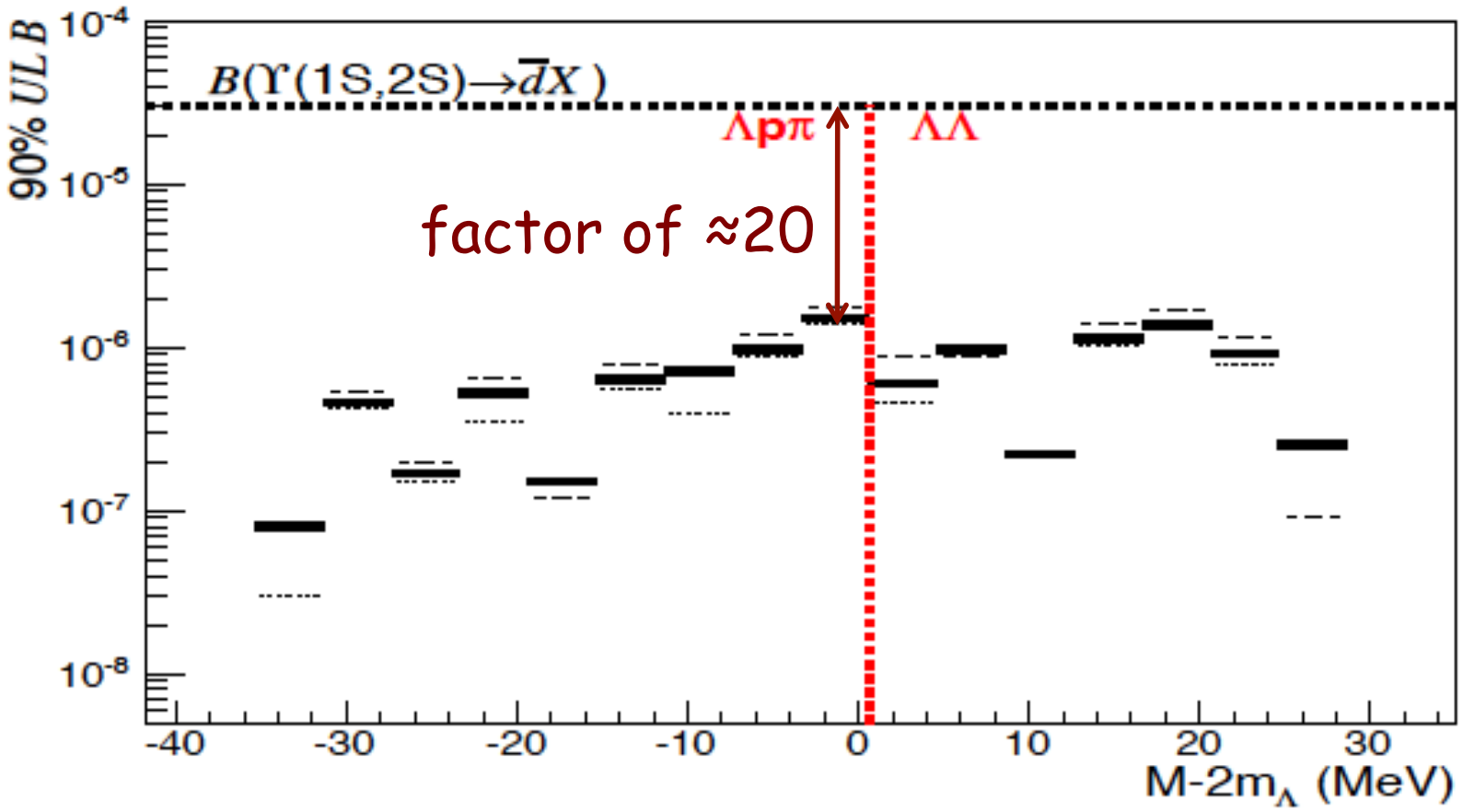


No sign of an H signal

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

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)

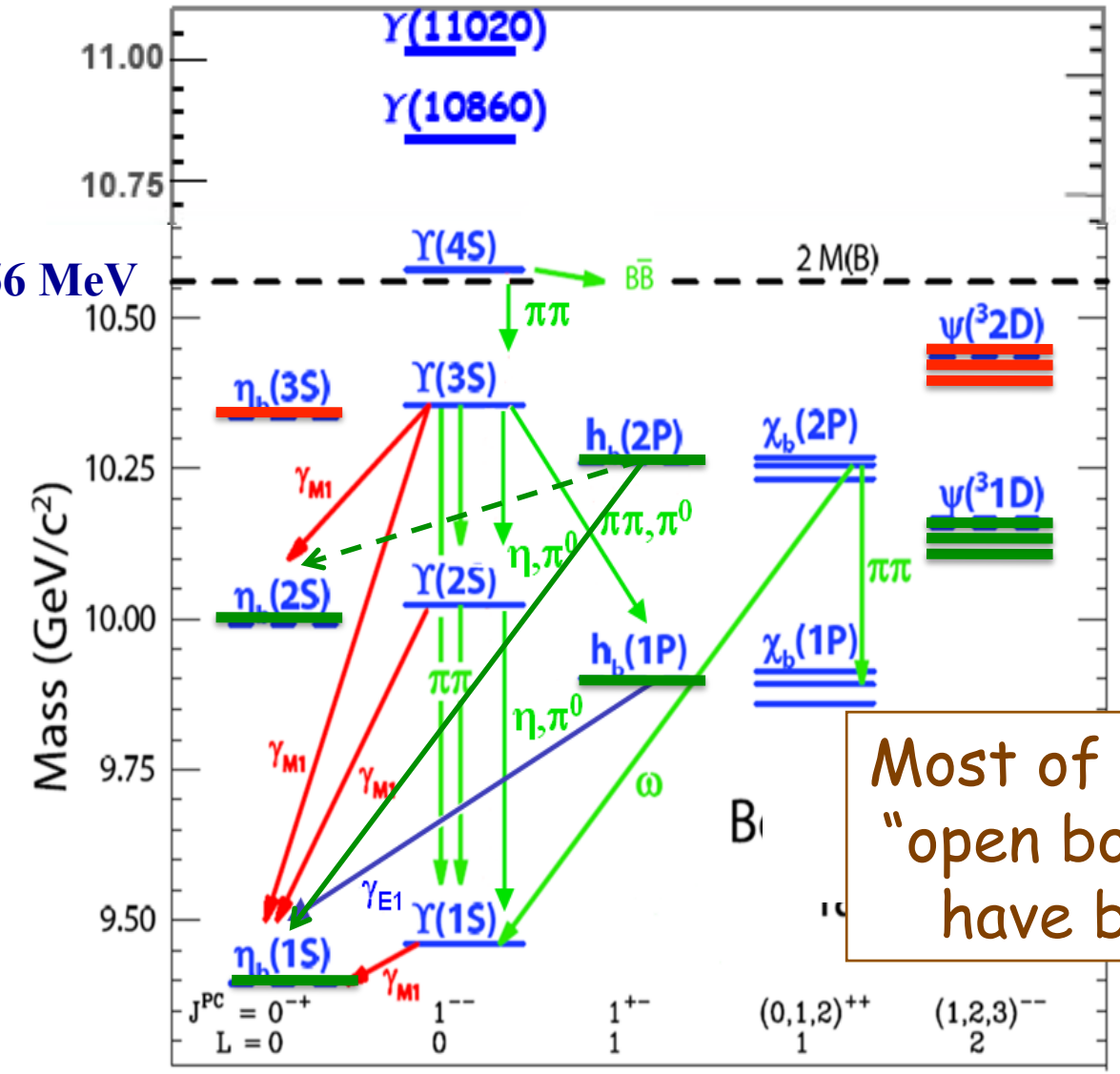
Bottomonium spectrum

established

recently discovered

still not discovered

$2M_B = 10.56$ MeV



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

"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}

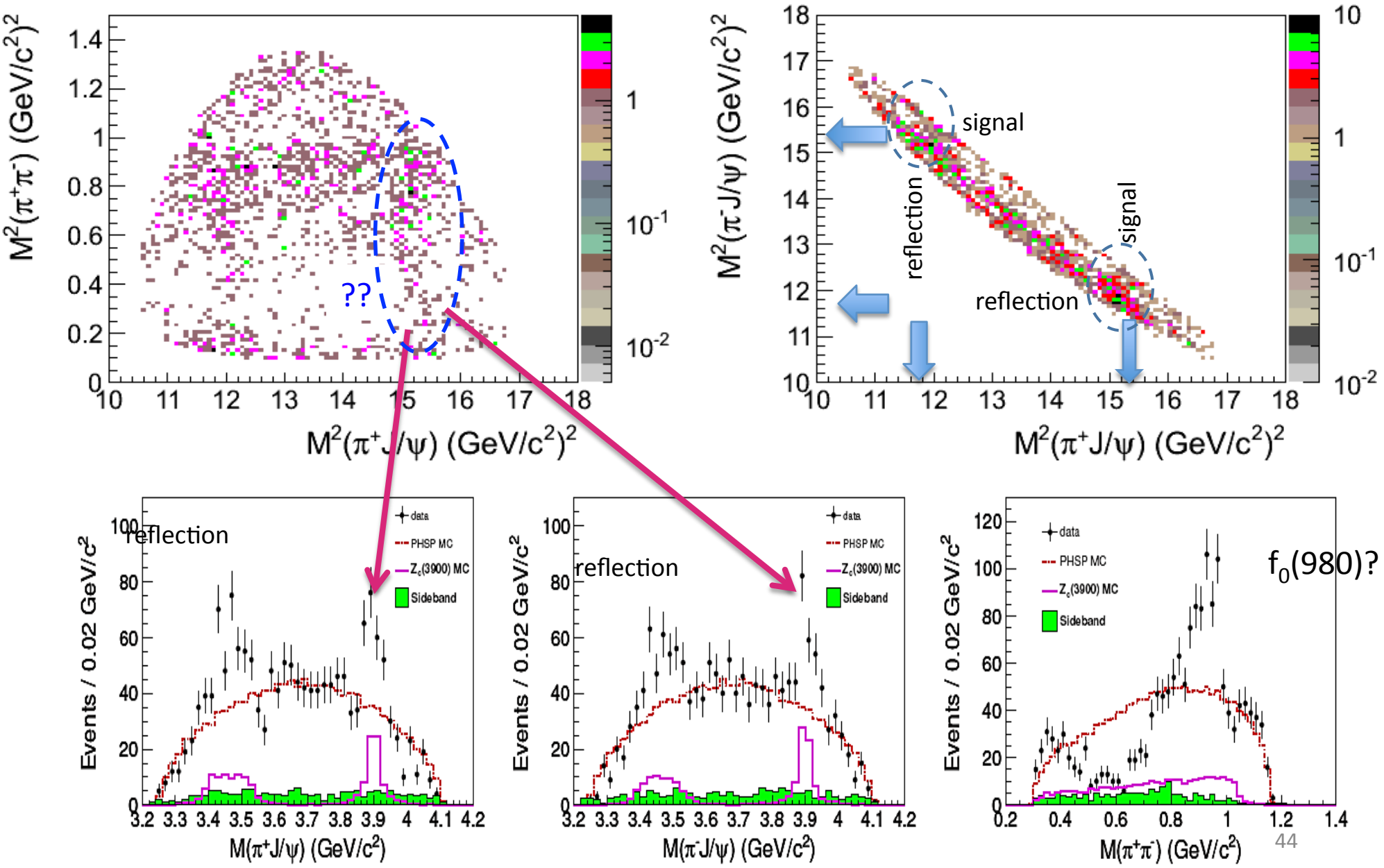
$$Bf(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = (0.008 \pm 0.0003)\%$$

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

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

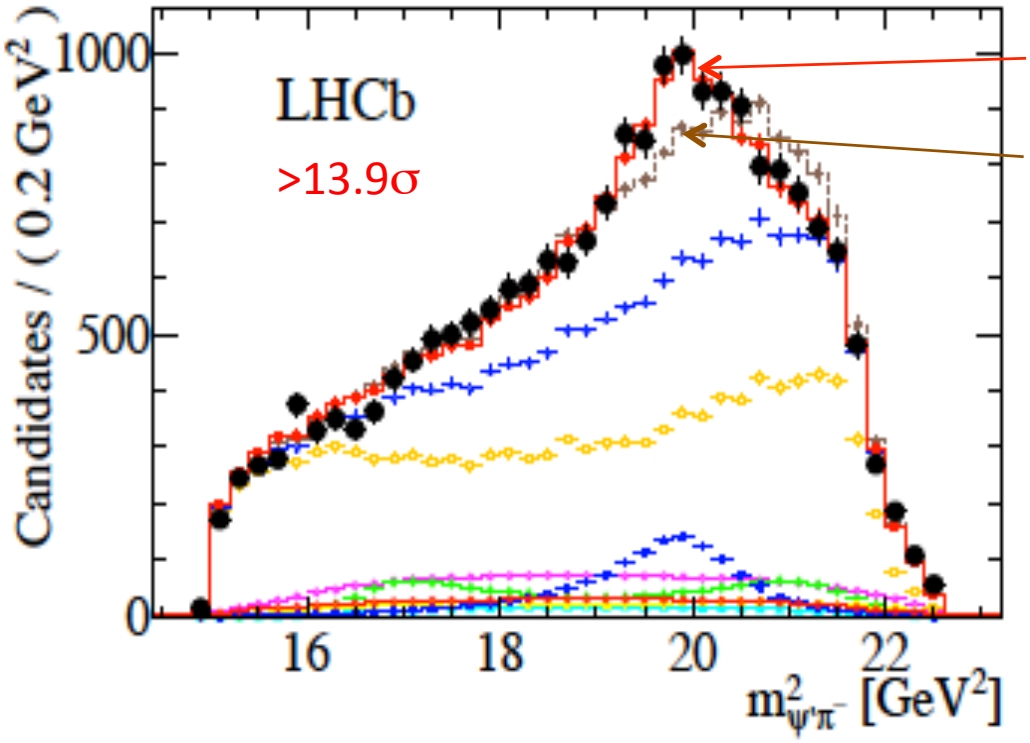
⇒ Is there a Y_b equivalent close to Υ(5S)

Dalitz plots & 1D projections in Y(4260)→$\pi^-\pi^+J/\psi$



Confirmed by LHCb

4-dim amplitude analysis



Fit with $Z(4430)^+$

Fit without $Z(4430)^+$

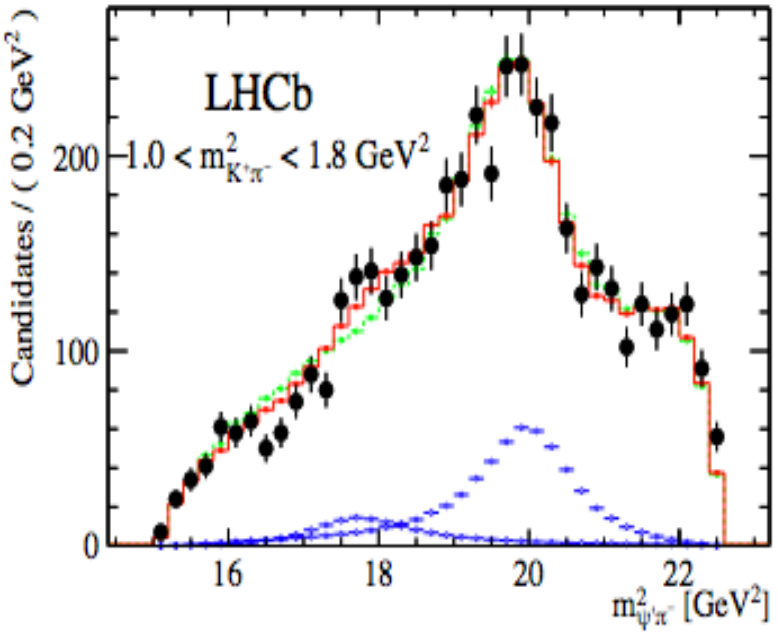
Statistical significance : 13.9σ

arXiv:1404.1903, submitted to PRL

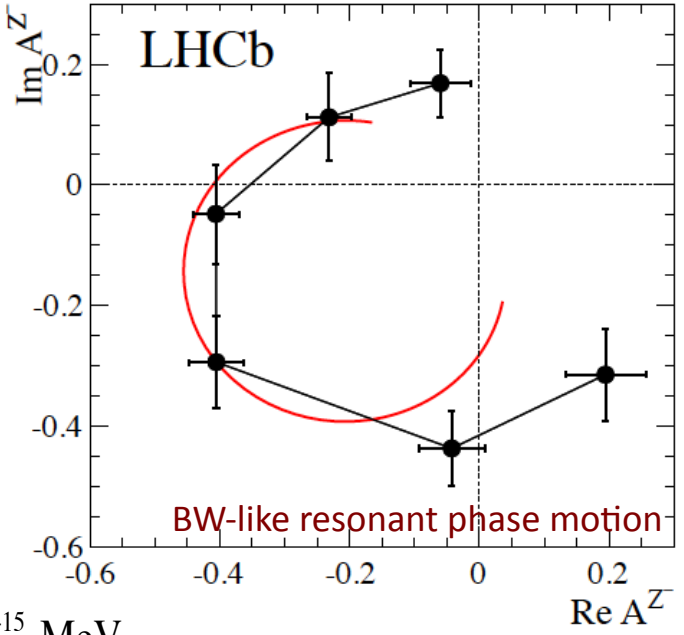
Confirmed by LHCb (continued)

$B \to K\pi^+\psi'$

4-dim amplitude analysis



Model-ind. Argand plot



$J^P = 1^+$

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

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

$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') = (0.059 \pm 0.009^{+0.015}_{-0.033}) Bf(B^0 \to K^+ \pi^- \psi')$$

$$\Rightarrow Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') \approx (3.4^{-1.1}_{-2.3}) \times 10^{-5}$$