# Overview of the recent status/results in the exotics sector at Belle

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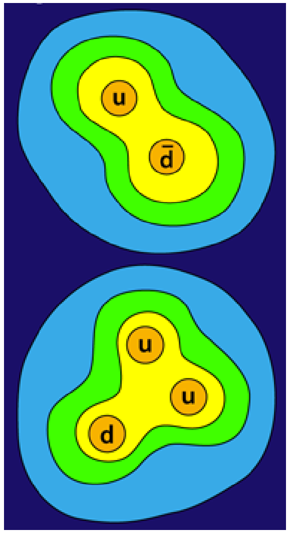
# Outline

- Introduction
- The X states
- The Y states
- The $Z_c$ and $Z_b$ states
- Other topics
- Summary & Outlook

# Hadrons: normal & exotic

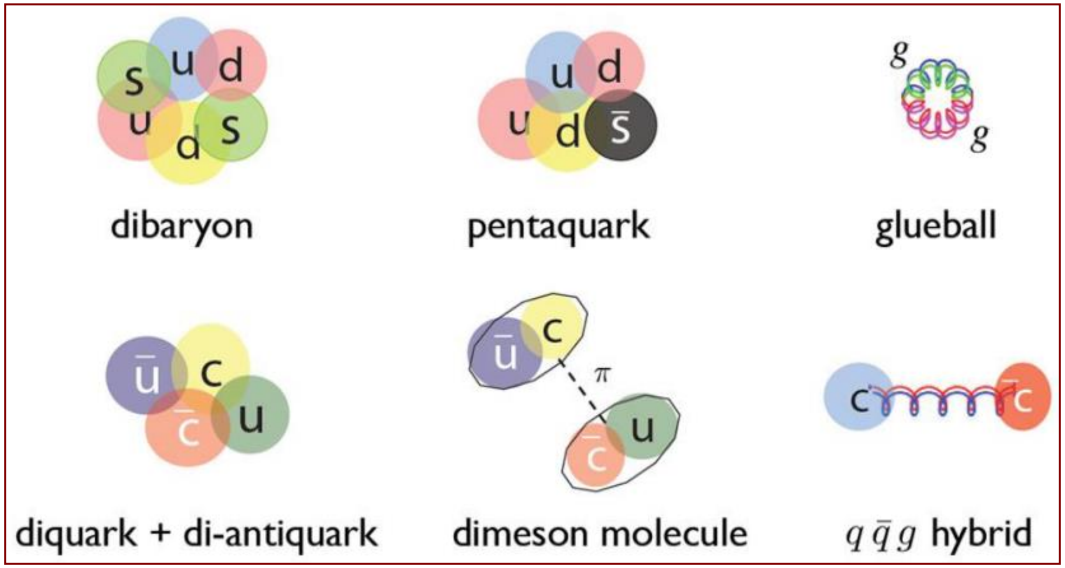
- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks




Normal

vs.

Exotic



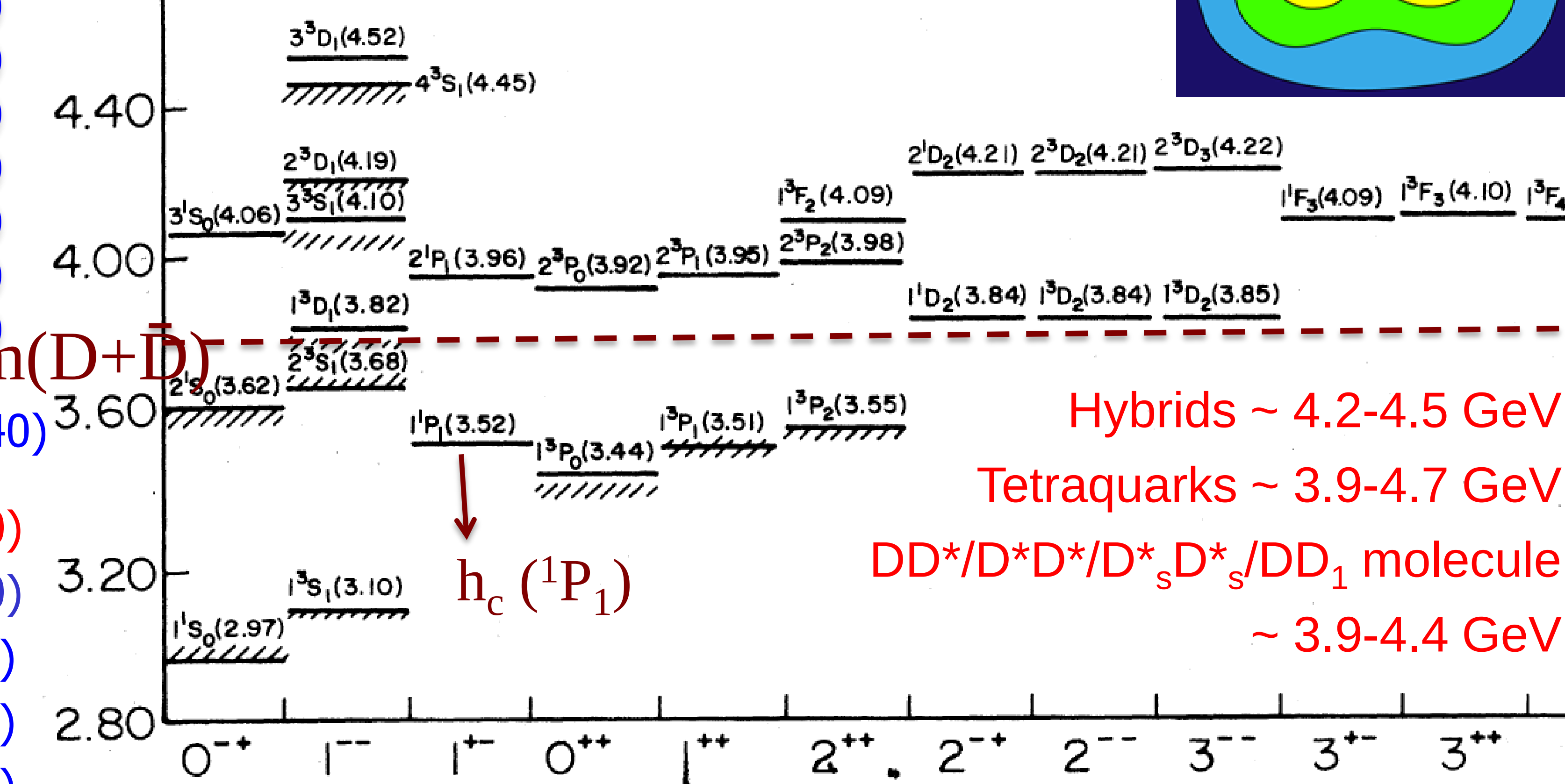

- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

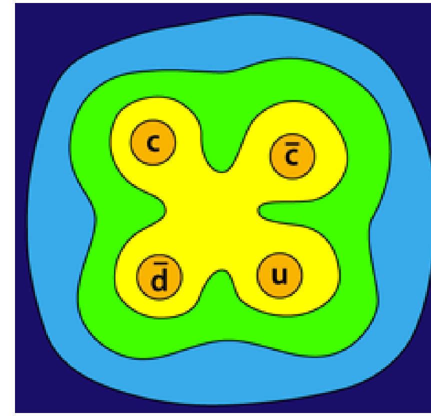
# XYZ particles

- XYZ or quarkonium-like particles
- Not an obvious quarkonium
- But quarkonium in the final state

X(3823)
X(3872)
X(3915)
X(4350)
Y(4008)
Y(4260)
Y(4140)
Y(4360)
Y(4660)
Y(4630)
...
XYZ(3940)

$Z_c(3900)$
$Z_c(4020)$
Z(4430)
Z(4250)
Z(4050)
...




Hybrids ~ 4.2-4.5 GeV

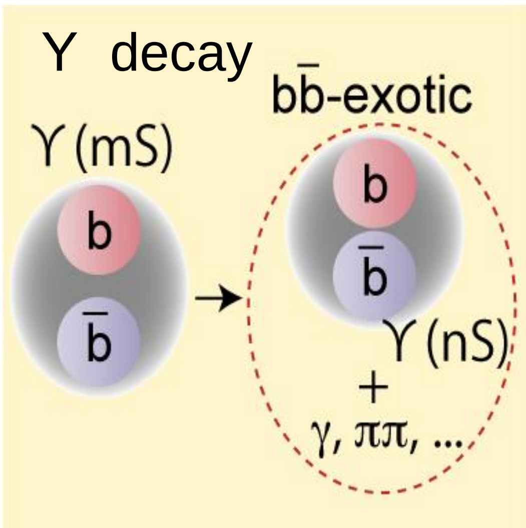
Tetraquarks ~ 3.9-4.7 GeV

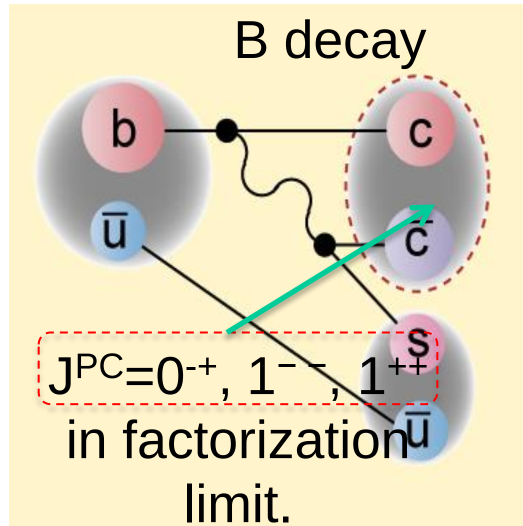
$DD^*/D^*D^*/D^*_sD^*_s/DD_1$ molecule

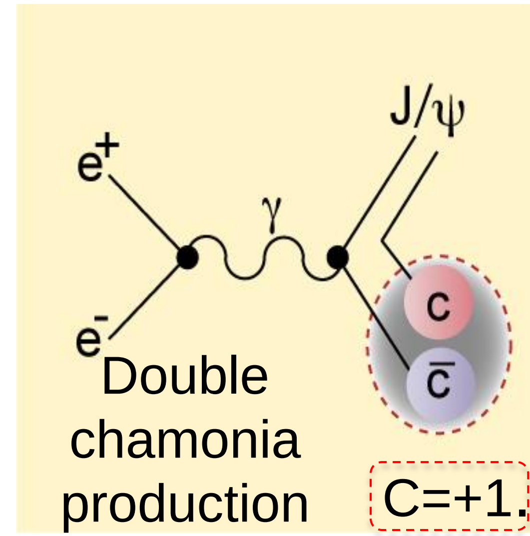
~ 3.9-4.4 GeV

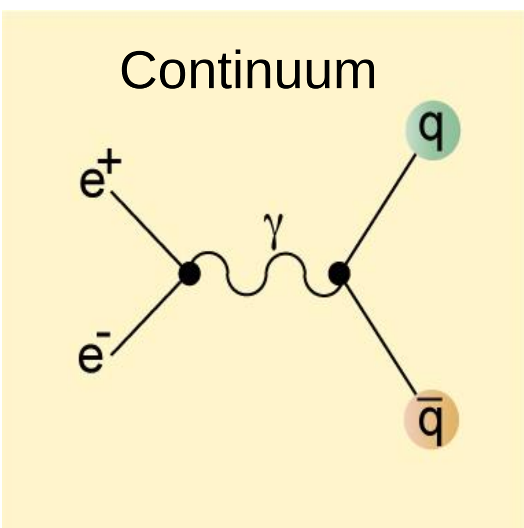
Godfrey & Isgur, PRD32, 189 (1985)

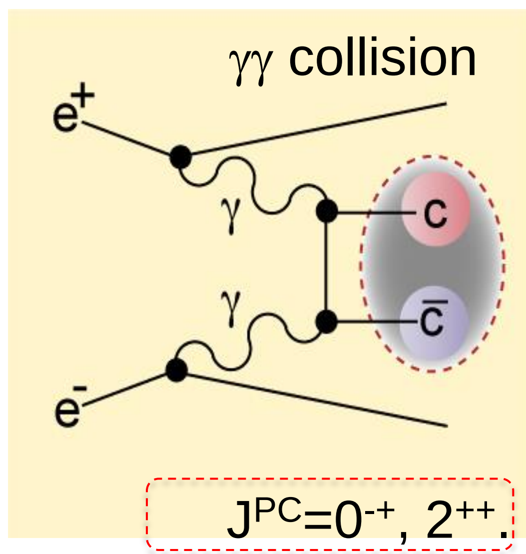
# Variety of recorded reactions

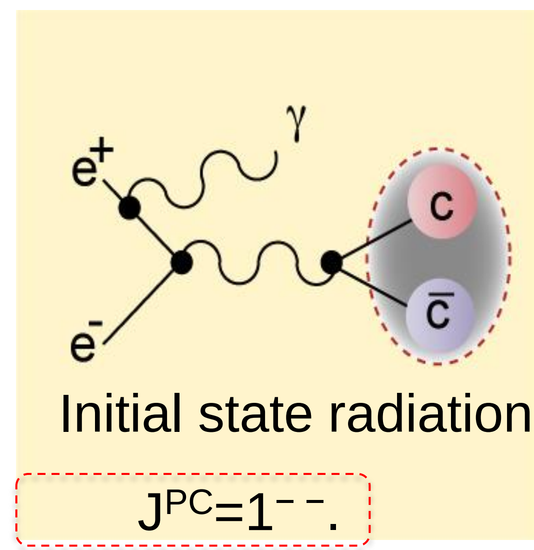


# Too many models !

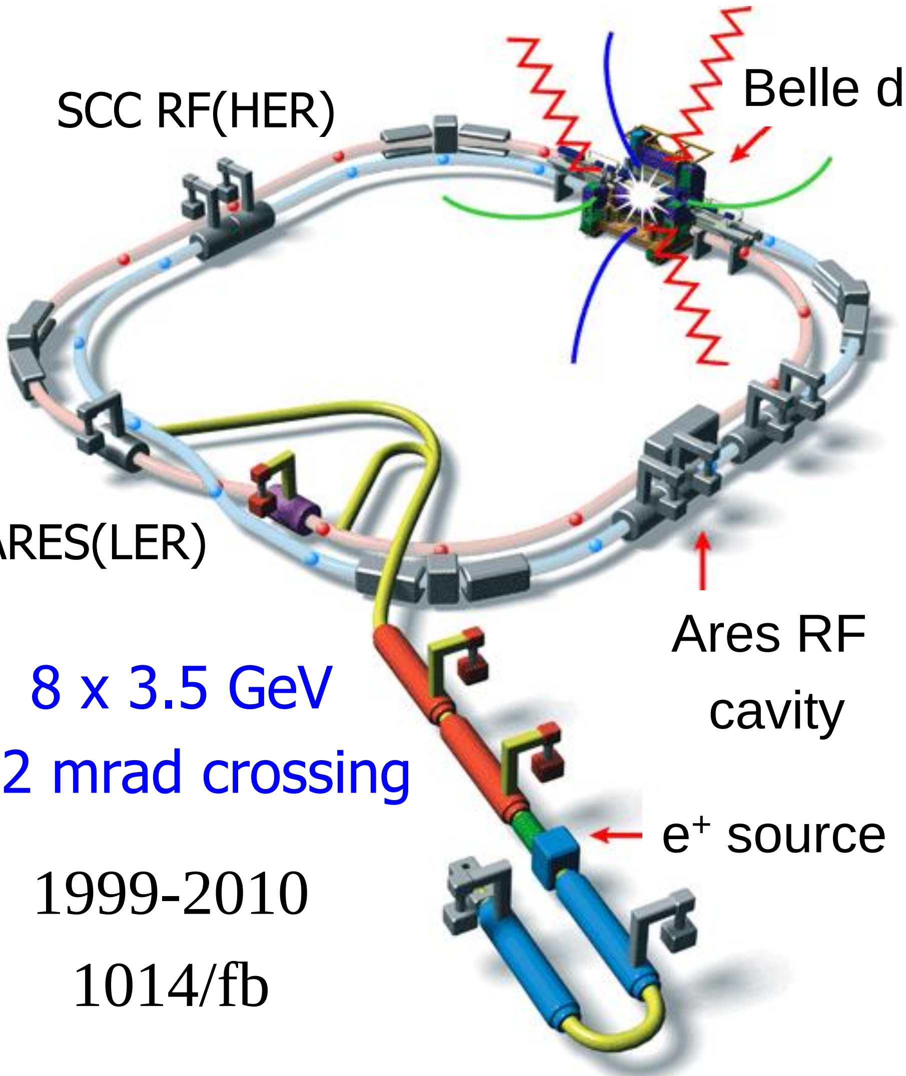
- Theory 1: screened potential
- Theory 2: hybrids with excited gluons
- Theory 3: tetraquark states
- Theory 4: meson molecules
- Theory 5: cusps effect
- Theory 6: final state interaction
- Theory 7: coupled-channel effect
- Theory 8: mixing of normal quarkonium and exotics
- Theory 9: mixture of all these effects
- Theories …

QCD is another least understood part of the SM.

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

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

# The Belle experiment




8 x 3.5 GeV
22 mrad crossing

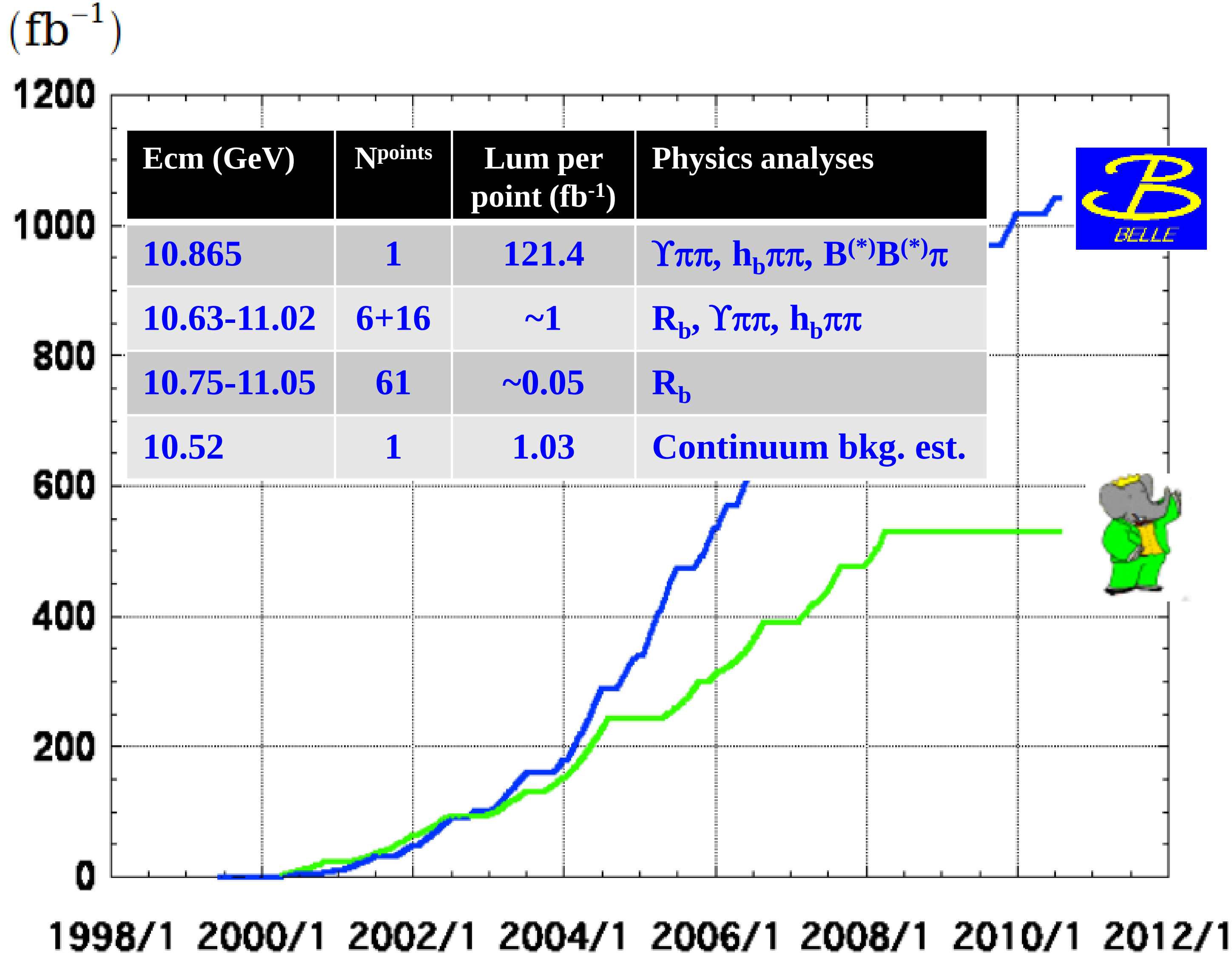
1999-2010
1014/fb

The KEKB Collider

World record:

**L = 2.1 x $10^{34}$/$cm^2$/sec**

# Integrated luminosity of B factories




| Ecm (GeV) | $N^{points}$ | Lum per point ($fb^{-1}$) | Physics analyses |
|---|---|---|---|
| 10.865 | 1 | 121.4 | $\Upsilon\pi\pi$, $h_b\pi\pi$, $B^{(*)}B^{(*)}\pi$ |
| 10.63-11.02 | 6+16 | ~1 | $R_b$, $\Upsilon\pi\pi$, $h_b\pi\pi$ |
| 10.75-11.05 | 61 | ~0.05 | $R_b$ |
| 10.52 | 1 | 1.03 | Continuum bkg. est. |

**> 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 $fb^{-1}$

**~ 550 $fb^{-1}$**

**On resonance:**

$\Upsilon(4S)$: 433 $fb^{-1}$

$\Upsilon(3S)$: 30 $fb^{-1}$

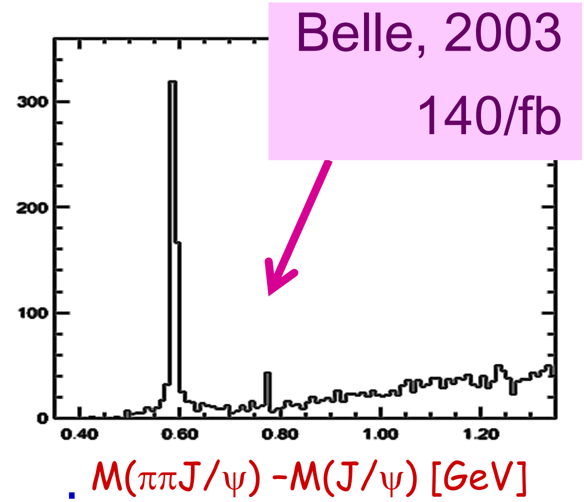
$\Upsilon(2S)$: 14 $fb^{-1}$

**Off resonance:**

~ 54 $fb^{-1}$

# The X states

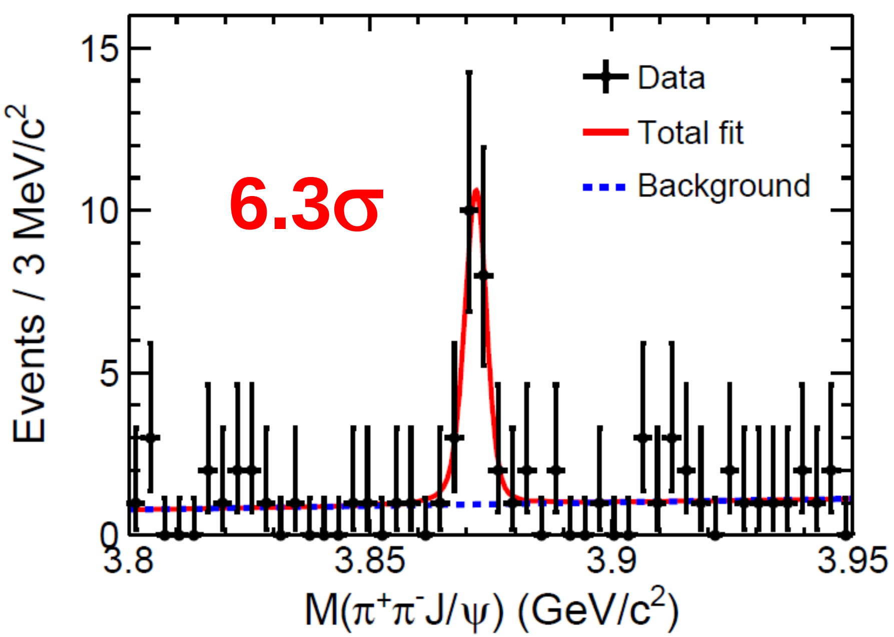
# What is the X(3872)?

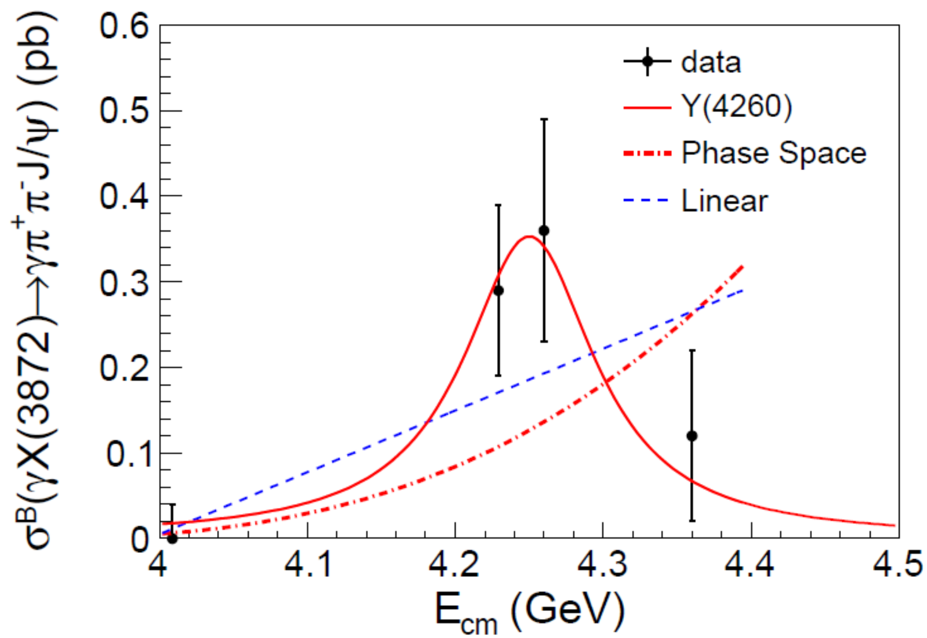



- Mass: Very close to $\bar{D}^0 D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$
- Production
  - in $\bar{p}p$/pp collison – rate similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - Y(4260)→γ+X(3872)
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature (very likely exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron?)?
  - Mixture of excited $\chi_{c1}$ and $\bar{D}^0 D^{*0}$ bound state?
  - Many other possibilities (if it is not $\chi'_{c1}$, where is $\chi'_{c1}$?)

# BESIII Observation of Y(4260)→γX(3872)

PRL 112, 092001 (2014)




N(X(3872)) = 20.1±4.5

M(X(3872)) = 3871.9±0.7±0.2 MeV

A new Y(4260) decay mode

A new X(3872) production mode

If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, ( >2.6% in PDG)

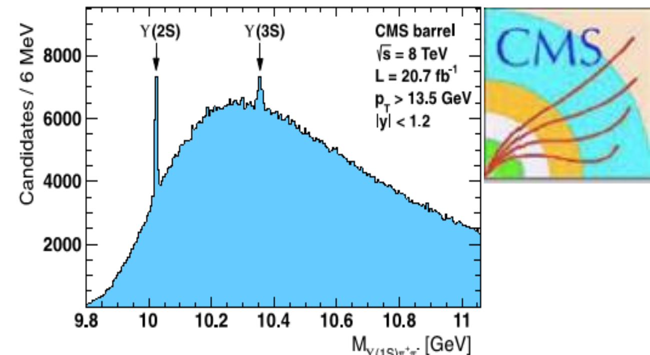
$$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 10\%$$

Large transition ratio !

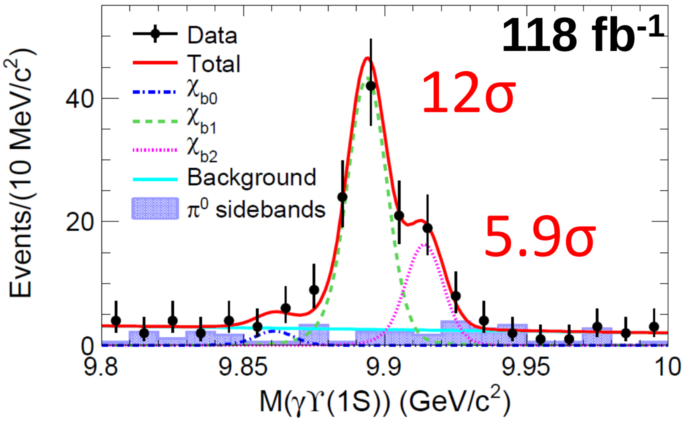
# Search for $X_b$ in $e^+e^- \to \gamma\pi^+\pi^-\pi^0\Upsilon(1S)$ at 10.867 GeV

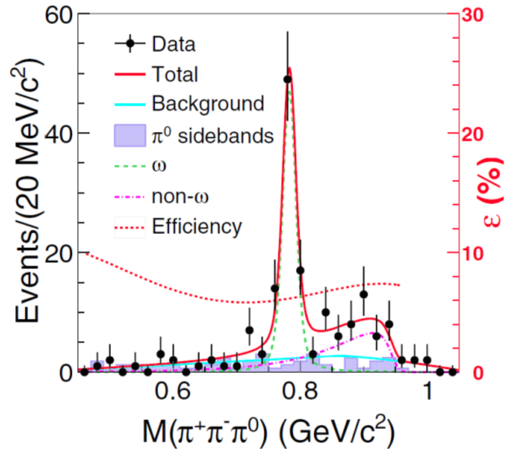
**PRL 113, 142001 (2014)**

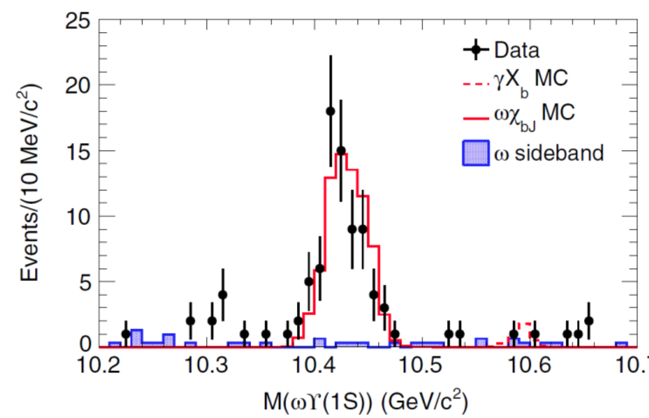
- The X(3872) counterpart in the bottomonium sector $X_b$, NOT observed decay channel $\pi^+\pi^-\Upsilon(1S)$.
- As $X_b$ is above $\omega\Upsilon(1S)$ threshold, this Isospin-conserving process should be a more promising decay mode. [PRD88, 054007].




PLB 727, 57 (2013) .



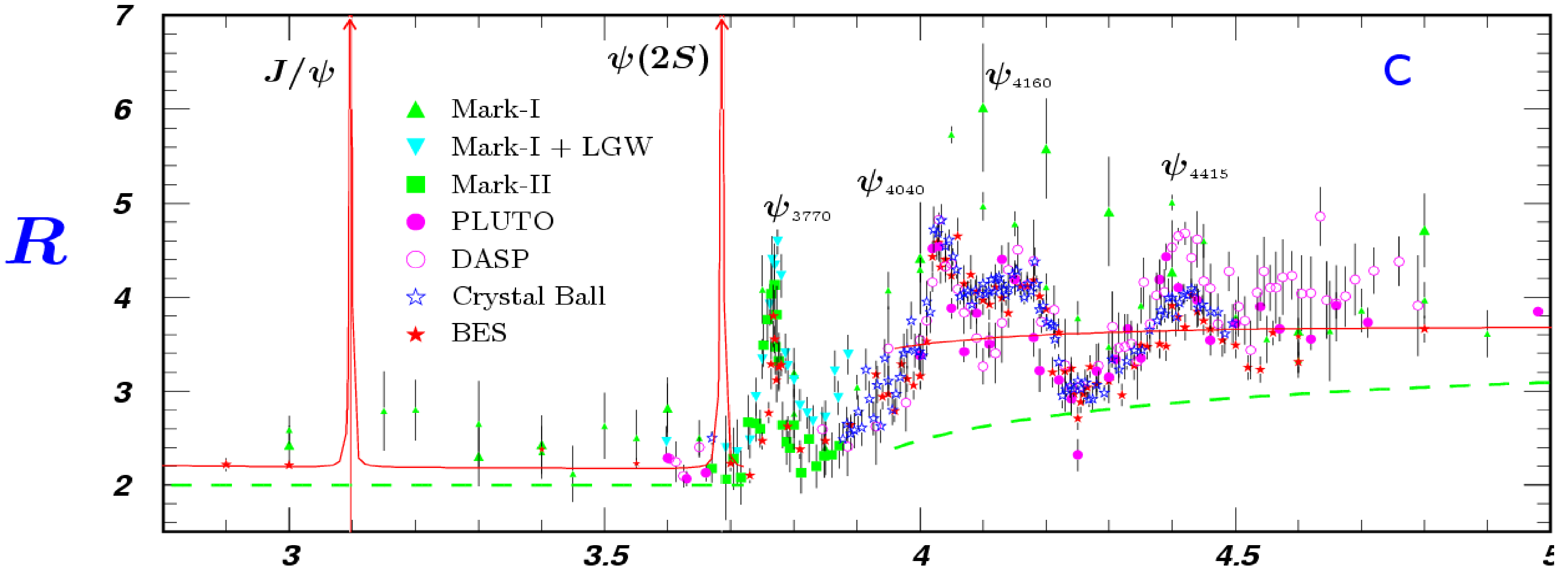

- Large Brs of Υ(5S) to $\pi^+\pi^-\pi^0\chi_{b1/b2}$, $\omega\chi_{b1/b2}$ are observed for the first time and their ratios are measured.

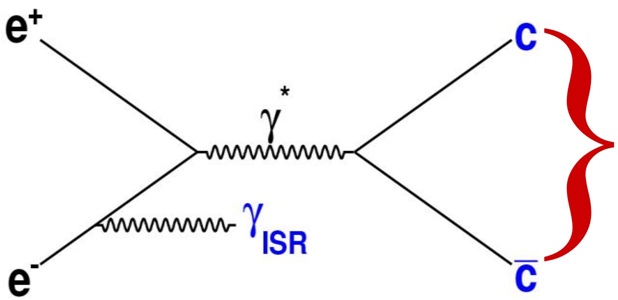
Assuming $X_b$ is narrow, the upper limit on the product branching fraction was given.

# The Υ states

(vectors)

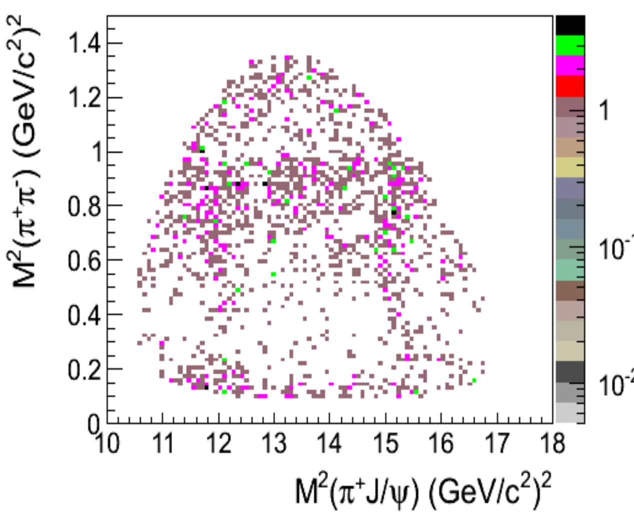
# ISR production of vector charmonia



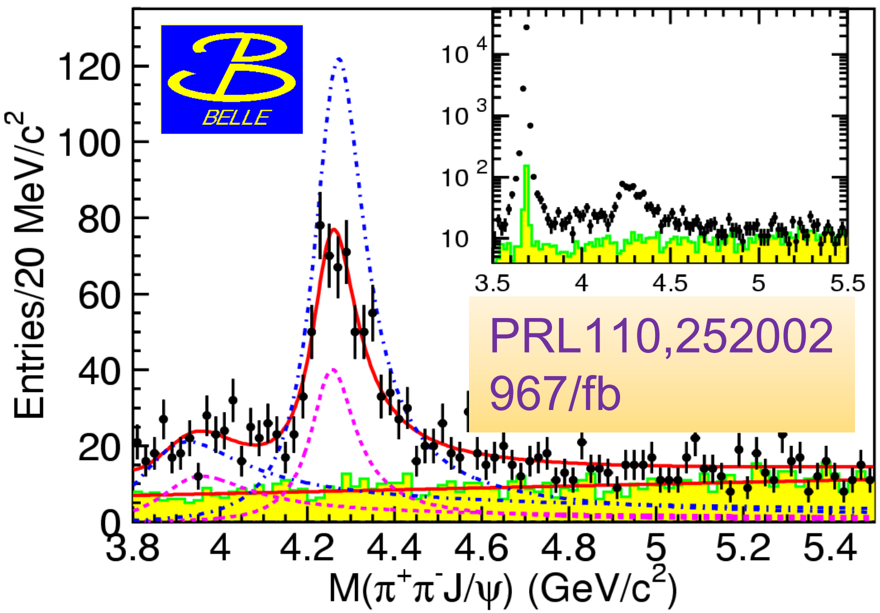

$J^{PC} = 1^{--}$

ψ', ψ'', Y…

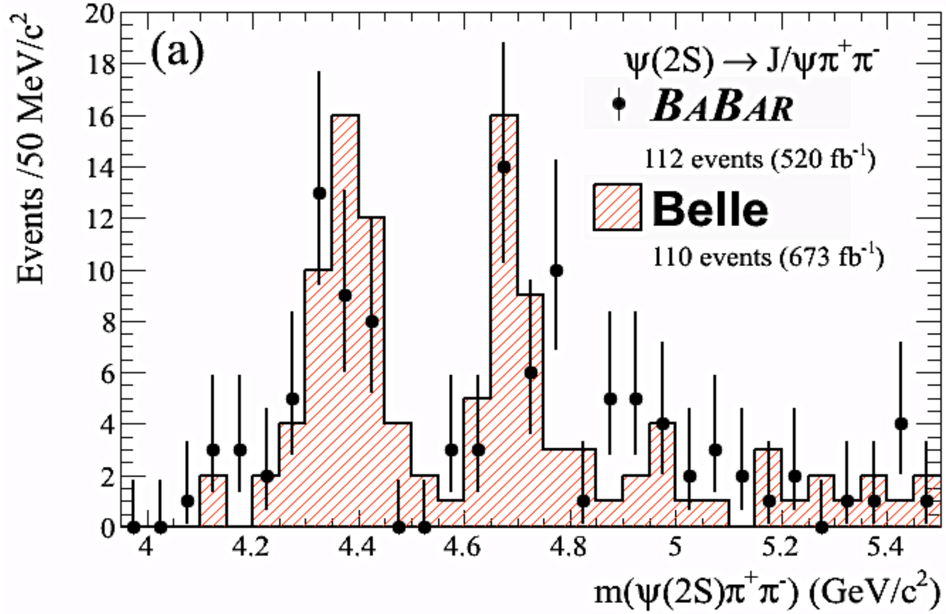


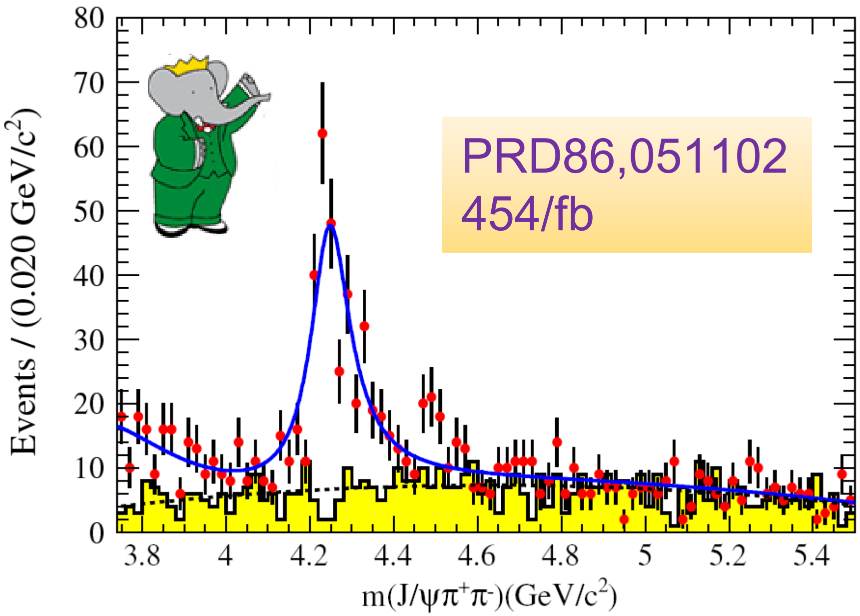
# The Y states

Belle: PRL99,142002, 670/fb
BaBar: PRD89, 111103, 520/fb

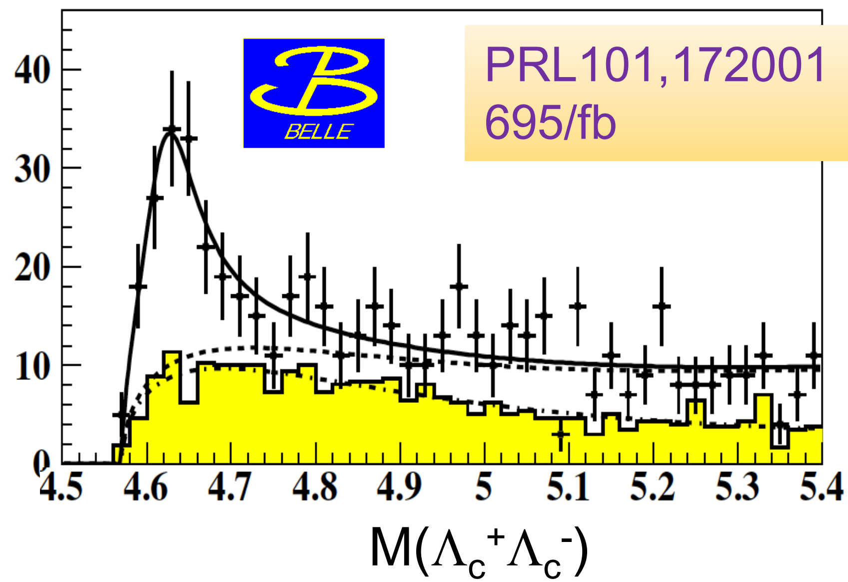



PRL110,252002
967/fb

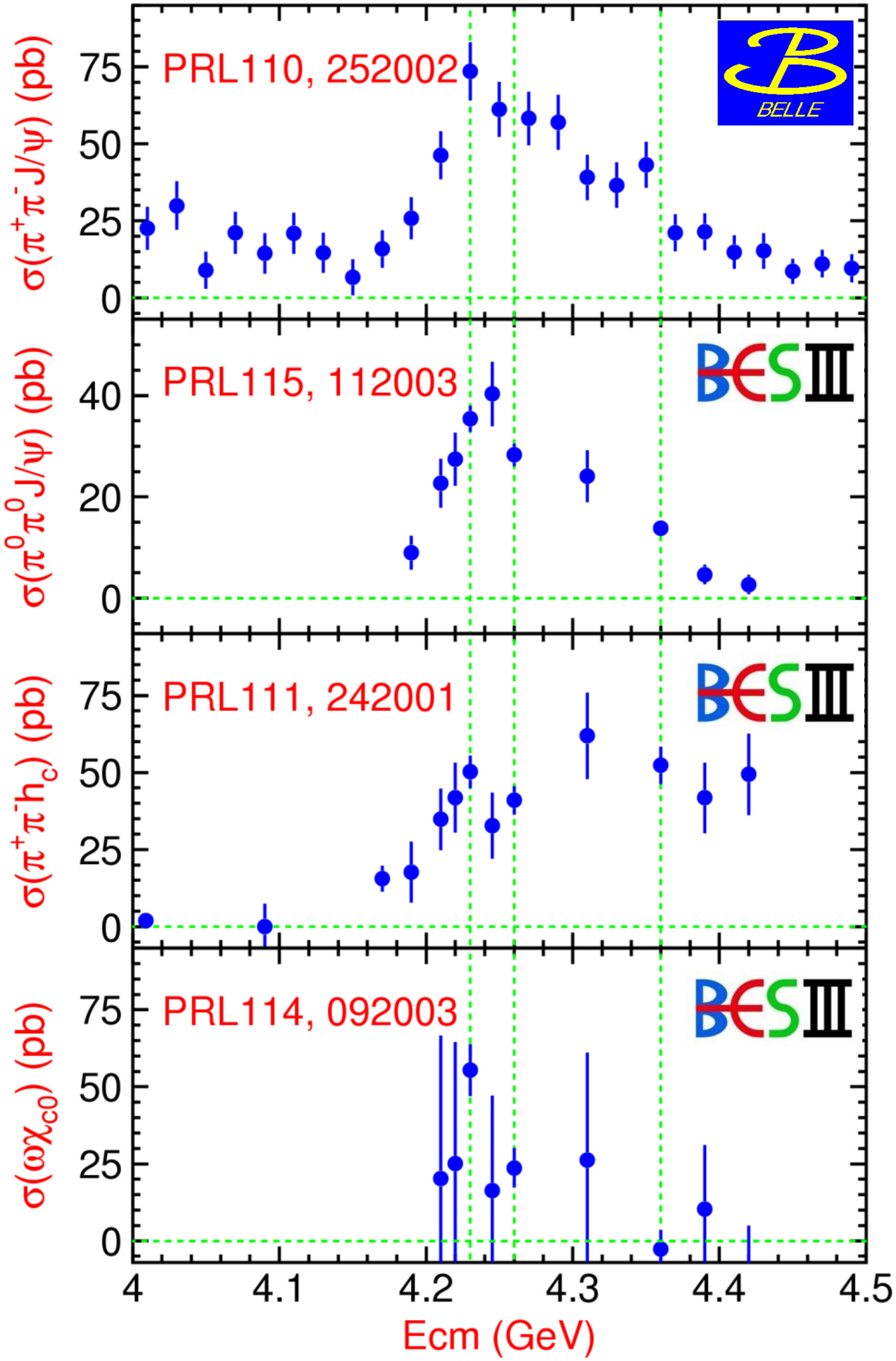



PRD86,051102
454/fb




PRL101,172001
695/fb



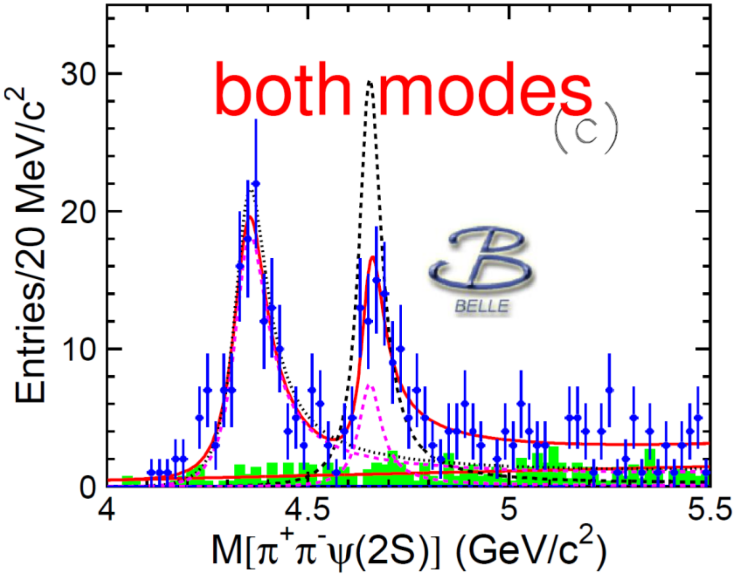

- In $\pi\pi J/\psi$, cross section peaks at lower than 4.26 GeV
- There is a narrow peak at 4.22 in $\pi\pi h_c$
- Possibly a narrow structure in $\omega\chi_{c0}$
- More updates from BESIII will come out very soon
  - ➢ simultaneous fit to all the modes?
  - ➢ Better model to parametrize the line shapes?

# Updated $e^+e^- \to \pi^+\pi^-\psi(2S)$

PRD 91, 112007 (2015)

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$.

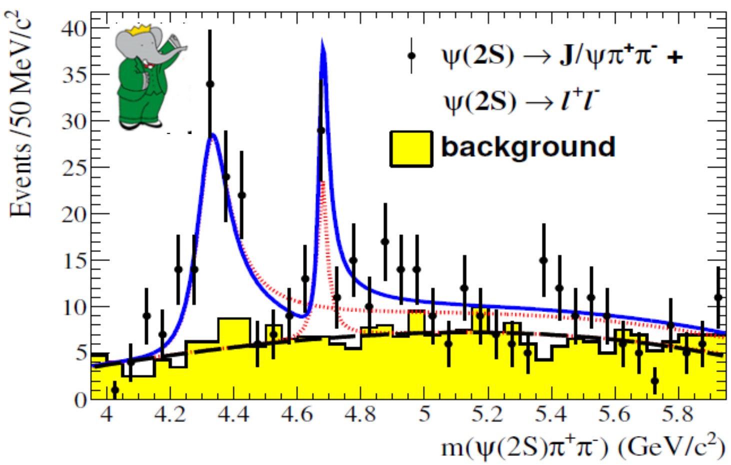
$Amp = BW_1 + e^{i\phi} \cdot BW_2$




| Parameters | Solution I | Solution II |
|---|---|---|
| $M_{Y(4360)}$ (MeV$/c^2$) | $4347 \pm 6 \pm 3$ | |
| $\Gamma_{Y(4360)}$ (MeV) | $103 \pm 9 \pm 5$ | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV) | $9.2 \pm 0.6 \pm 0.6$ | $10.9 \pm 0.6 \pm 0.7$ |
| $M_{Y(4660)}$ (MeV$/c^2$) | $4652 \pm 10 \pm 11$ | |
| $\Gamma_{Y(4660)}$ (MeV) | $68 \pm 11 \pm 5$ | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV) | $2.0 \pm 0.3 \pm 0.2$ | $8.1 \pm 1.1 \pm 1.0$ |
| $\phi$ (°) | $32 \pm 18 \pm 20$ | $272 \pm 8 \pm 7$ |

$\chi^2/ndf = 18.7/21$ .

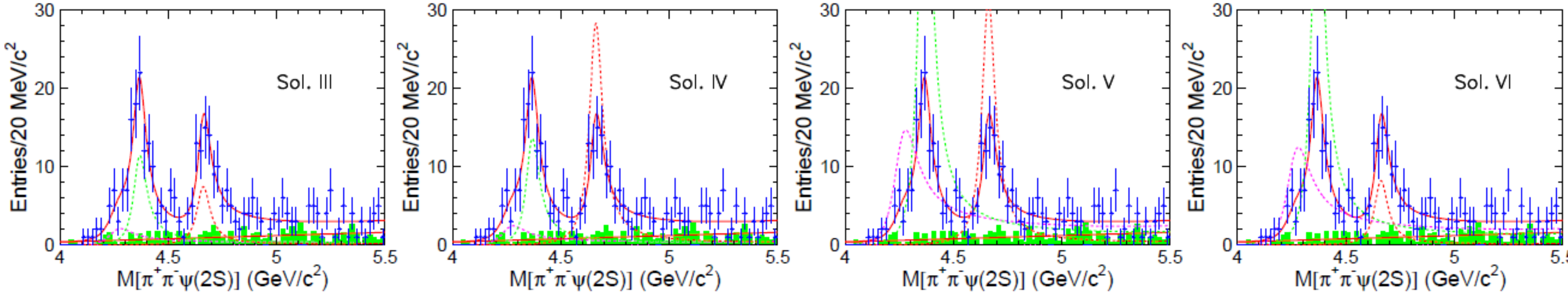
- Consistent with previous measurement
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.
- If $Y(4260)$ is included in the fit, ...




PRD89, 111103 (2014)

# M(π⁺π⁻ψ(2S)) with Y(4260,4360,4660)

Unbinned simultaneous maximum likelihood fit for $Y(4260)$, $Y(4360)$ and $Y(4660)$. $Amp = BW_1 + e^{i\phi_1} \cdot BW_2 + e^{i\phi_2} \cdot BW_3$.



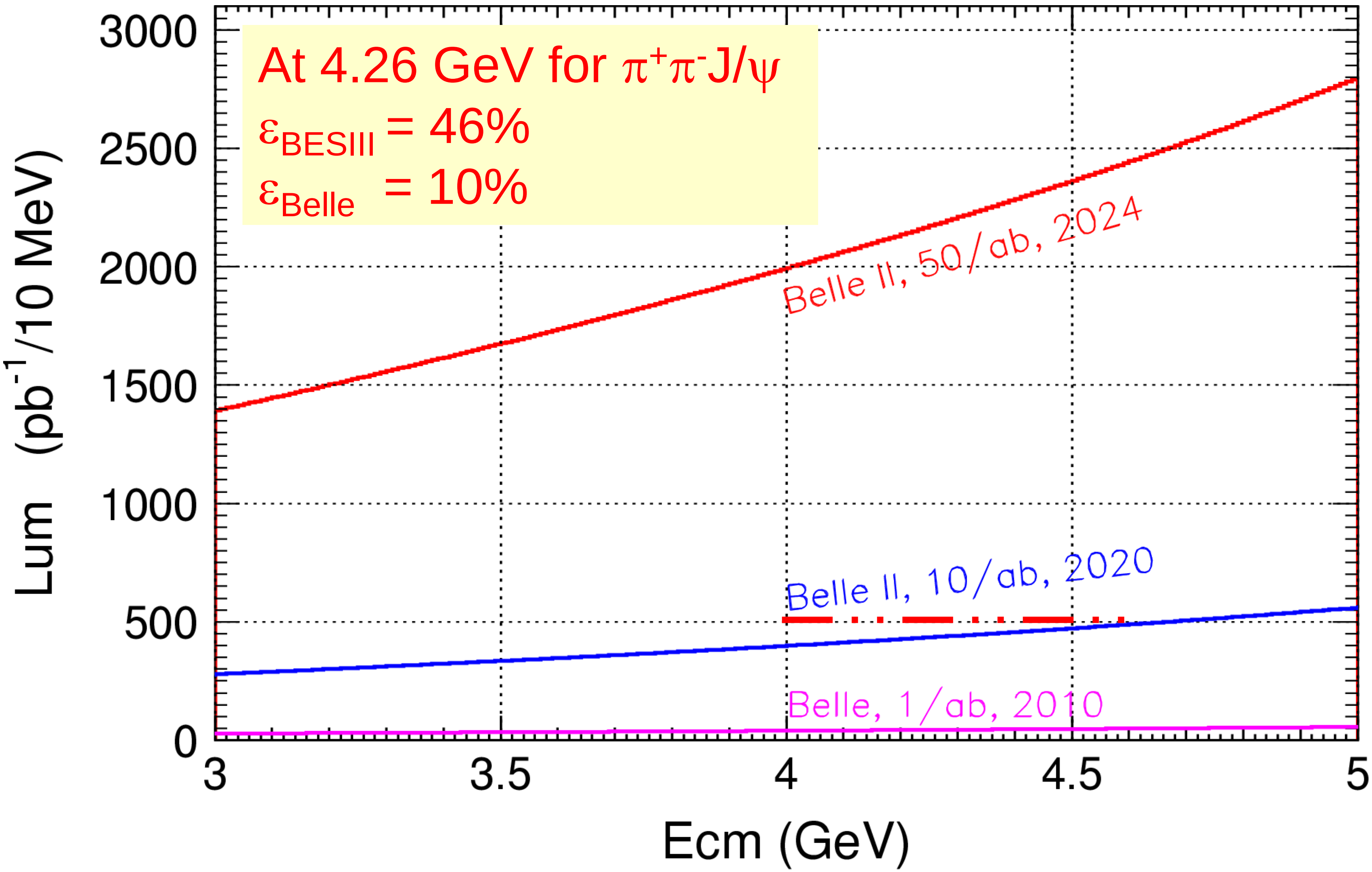

| Parameters | Solution I | Solution II | Solution III | Solution IV |
|---|---|---|---|---|
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4260)}$ (eV) | $1.5 \pm 0.6 \pm 0.4$ | $1.7 \pm 0.7 \pm 0.5$ | $10.4 \pm 1.3 \pm 0.8$ | $8.9 \pm 1.2 \pm 0.8$ |
| $M_{Y(4360)}$ (MeV$/c^2$) | $4365 \pm 7 \pm 4$ | | | |
| $\Gamma_{Y(4360)}$ (MeV) | $74 \pm 14 \pm 4$ | | | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV) | $4.1 \pm 1.0 \pm 0.6$ | $4.9 \pm 1.3 \pm 0.6$ | $21.1 \pm 3.5 \pm 1.4$ | $17.7 \pm 2.6 \pm 1.5$ |
| $M_{Y(4660)}$ (MeV$/c^2$) | $4660 \pm 9 \pm 12$ | | | |
| $\Gamma_{Y(4660)}$ (MeV) | $74 \pm 12 \pm 4$ | | | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV) | $2.2 \pm 0.4 \pm 0.2$ | $8.4 \pm 0.9 \pm 0.9$ | $9.3 \pm 1.2 \pm 1.0$ | $2.4 \pm 0.5 \pm 0.3$ |
| $\phi_1$ (°) | $304 \pm 24 \pm 21$ | $294 \pm 25 \pm 23$ | $130 \pm 4 \pm 2$ | $141 \pm 5 \pm 4$ |
| $\phi_2$ (°) | $26 \pm 19 \pm 10$ | $238 \pm 14 \pm 21$ | $329 \pm 8 \pm 5$ | $117 \pm 23 \pm 25$ |

Significance of $Y(4260)$ is $2.4\sigma$—low, but affects $Y(4360)$ and $Y(4660)$ masses and widths.

FOUR solutions with equally good fit quality, which is $\chi^2/ndf = 14.8/19$.

# ISR at Belle II vs. BESIII

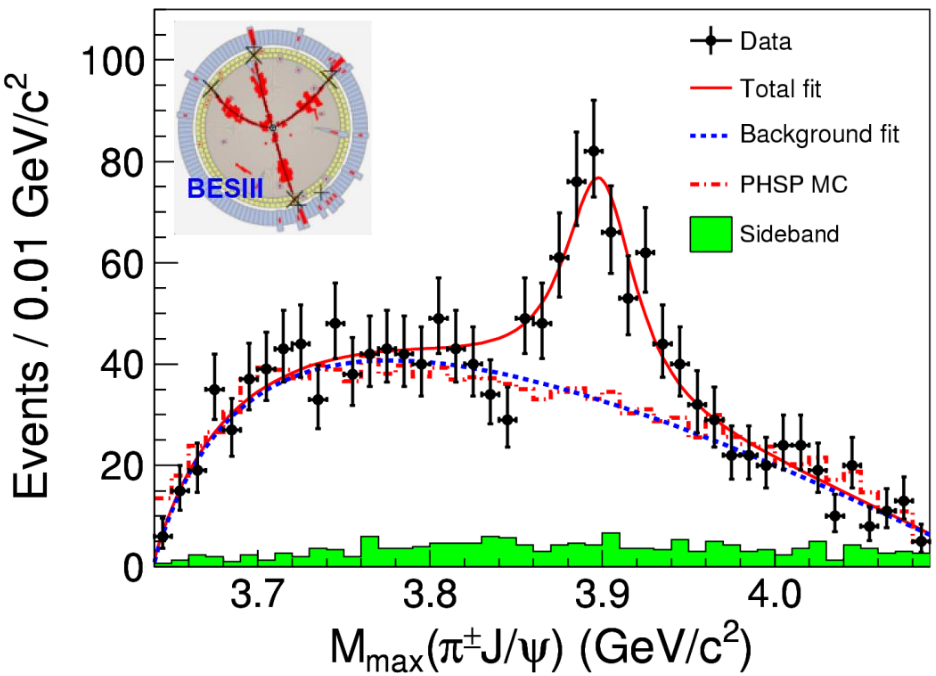
ISR produces events at all CM energies BESIII can reach



# The $Z_c$ and $Z_b$ states

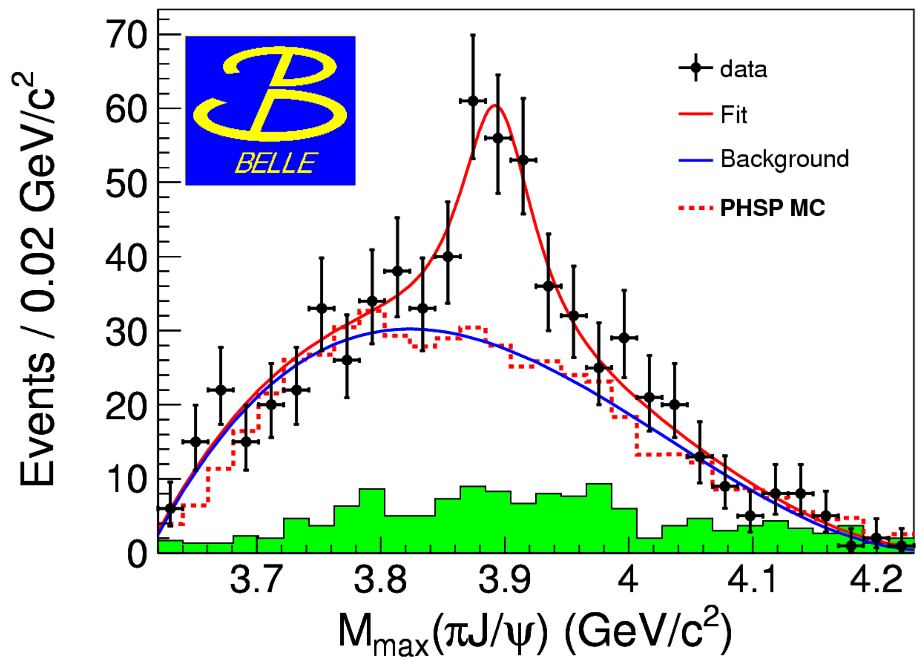
# $Z_c(3900)$ observed in two experiments!

BES3 at 4.26 GeV: PRL110,252001




- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events
- >8σ

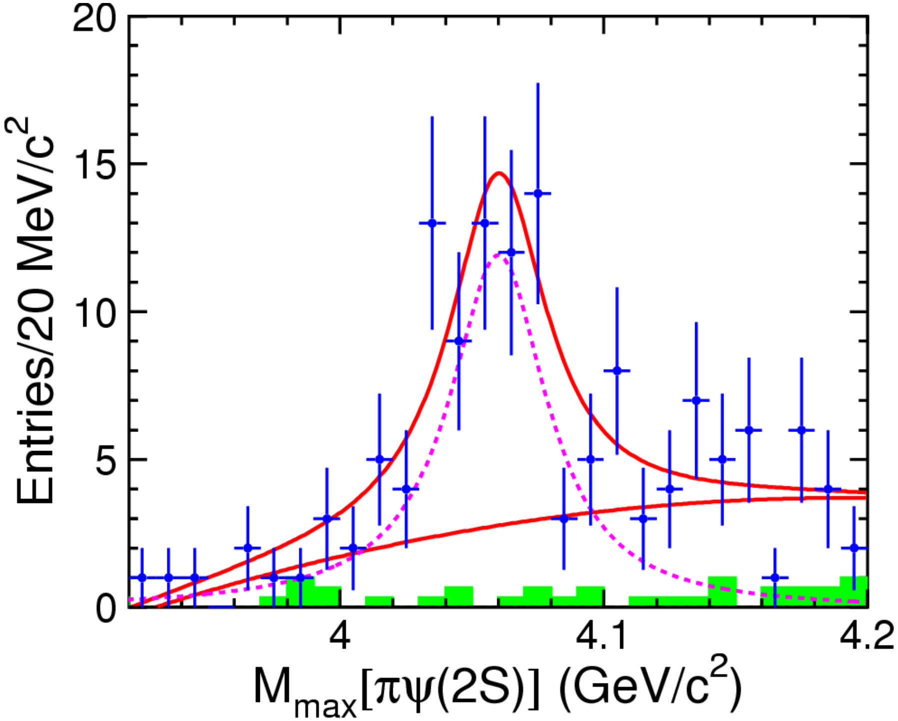
Belle with ISR: PRL110, 252002




- M = 3894.5±6.6±4.5 MeV
- Γ = 63±24±26 MeV
- 159 ± 49 events
- >5.2σ

# $Z_c(4050)^{\pm} \rightarrow \pi^{\pm}\psi'$

PRD91, 112007(2015)



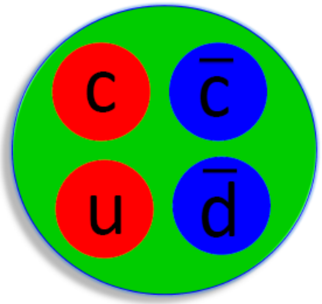

An unbinned maximum-likelihood fit is performed on the distribution of $M_{max}(\pi^{\pm}\psi(2S))$, the maximum of $M(\pi^{+}\psi(2S))$ and $M(\pi^{-}\psi(2S))$, simultaneously with both modes.

- Y(4360) signal region
- $M(Z_c) = 4054 \pm 3 \pm 1$ MeV/$c^2$
- $\Gamma = 45 \pm 11 \pm 6$ MeV
- Significance: >**3.5σ**

BESIII results on $e^{+}e^{-} \rightarrow \pi^{+}\pi^{-}\psi'$ will come out soon.

# What's the nature of these $Z_c$ states?

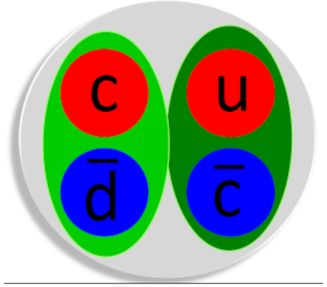
- At least 4 quarks, not a conventional meson
- Tetraquark state?




Phys. Rev. D87,125018(2013); Phys. Rev. D88, 074506(2013);

Phys. Rev. D89,054019(2014); Phys. Rev. D90,054009(2014); etc

- $D^{(*)}\bar{D}^{(*)}$ molecule state?



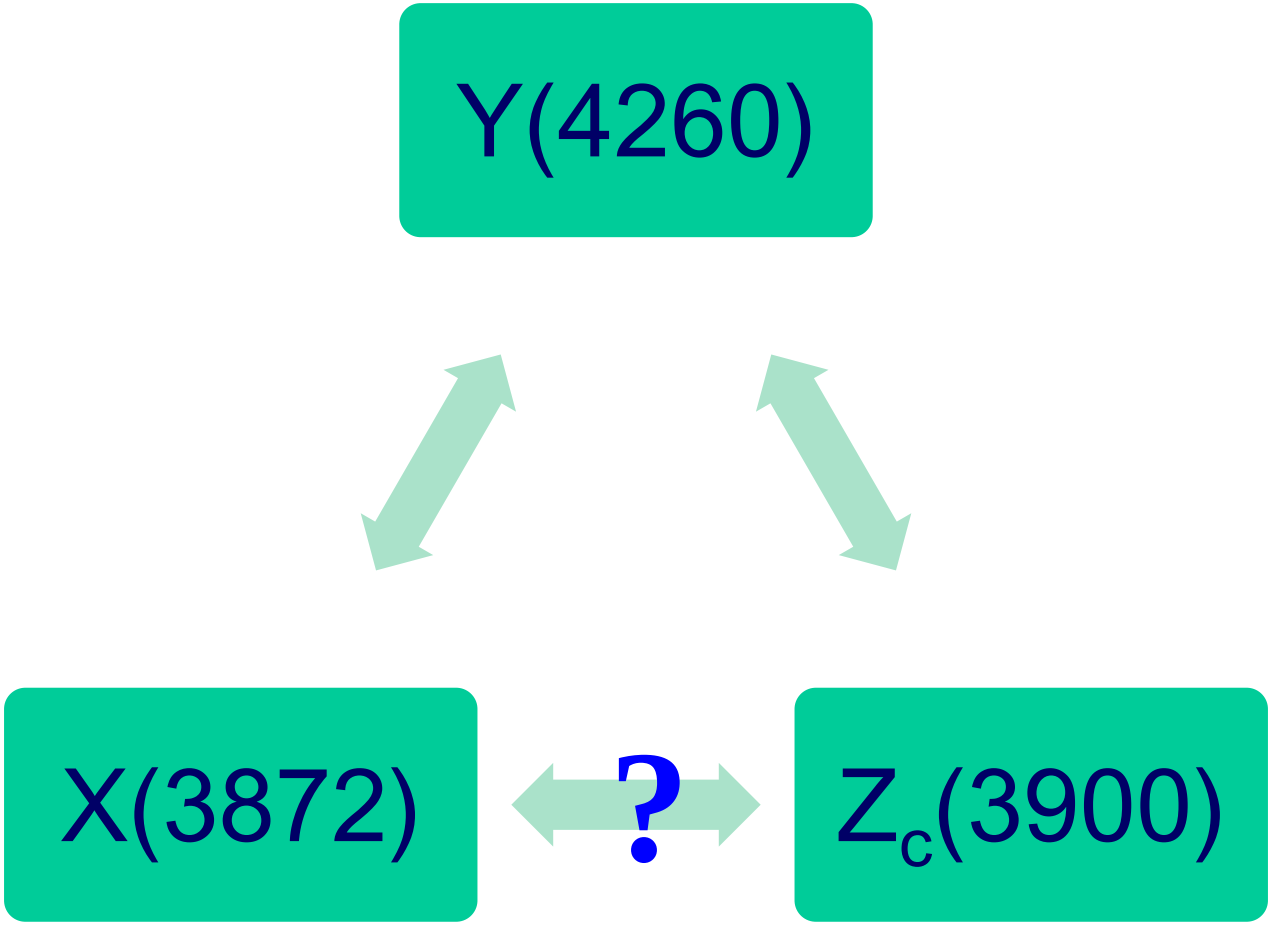

Phys. Rev. Lett. 111, 132003 (2013); Phys. Rev. D 89, 094026 (2014)

Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); etc

- FSI?
- Cusp?
- …

# X、Y、Z particles are correlated!

What are they? Are they all molecules/tetraquarks/…?

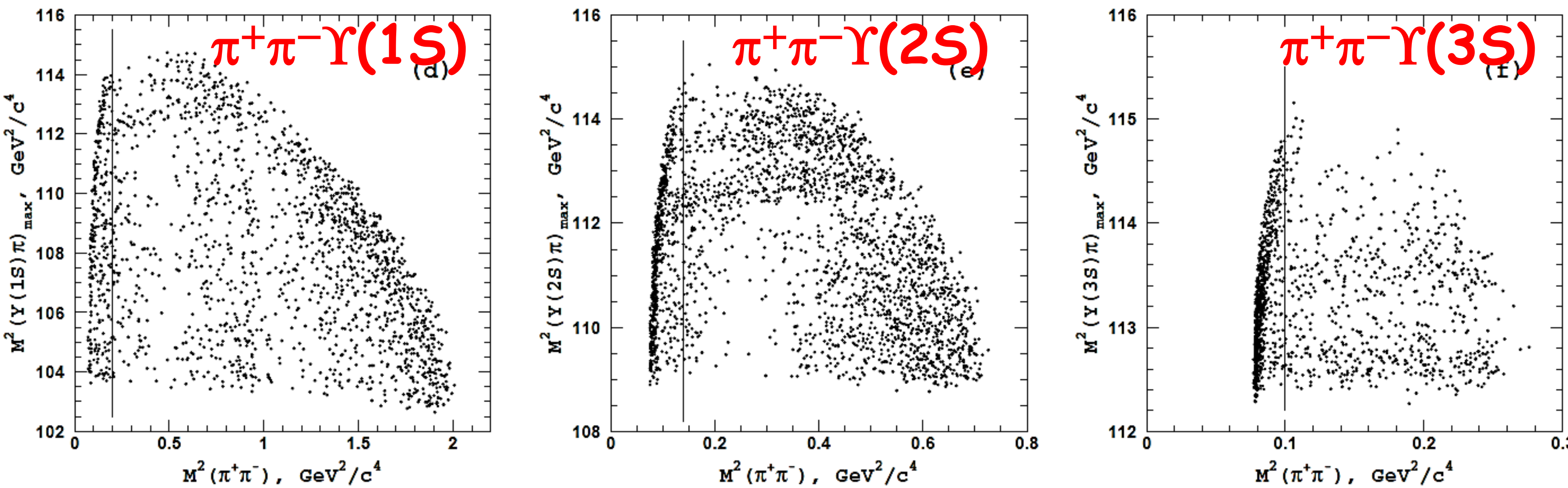


# $Z_b$ in $\Upsilon(5S)\to\pi^+\pi^-\Upsilon(nS)$

Born cross section

- 121 $fb^{-1}$ data, tag $\Upsilon(nS)\to\mu^+\mu^-$ and select $\pi^+\pi^-$

| Final state | $\Upsilon(1S)\pi^+\pi^-$ | $\Upsilon(2S)\pi^+\pi^-$ | $\Upsilon(3S)\pi^+\pi^-$ |
| --- | --- | --- | --- |
| Signal yield | $2090 \pm 115$ | $2476 \pm 97$ | $628 \pm 41$ |
| Efficiency, % | 45.9 | 39.0 | 24.4 |
| $\mathcal{B}_{\Upsilon(nS)\to\mu^+\mu^-}$, % [14] | $2.48 \pm 0.05$ | $1.93 \pm 0.17$ | $2.18 \pm 0.21$ |
| $\sigma^{\rm vis}_{e^+e^-\to\Upsilon(nS)\pi^+\pi^-}$, pb | $1.51 \pm 0.08 \pm 0.09$ | $2.71 \pm 0.11 \pm 0.30$ | $0.97 \pm 0.06 \pm 0.11$ |
| $\sigma_{e^+e^-\to\Upsilon(nS)\pi^+\pi^-}$, pb | $2.27 \pm 0.12 \pm 0.14$ | $4.07 \pm 0.16 \pm 0.45$ | $1.46 \pm 0.09 \pm 0.16$ |
| $\sigma^{\rm vis}_{e^+e^-\to\Upsilon(nS)\pi^+\pi^-}$, pb [1] | $1.61 \pm 0.10 \pm 0.12$ | $2.35 \pm 0.19 \pm 0.32$ | $1.44^{+0.55}_{-0.45} \pm 0.19$ |

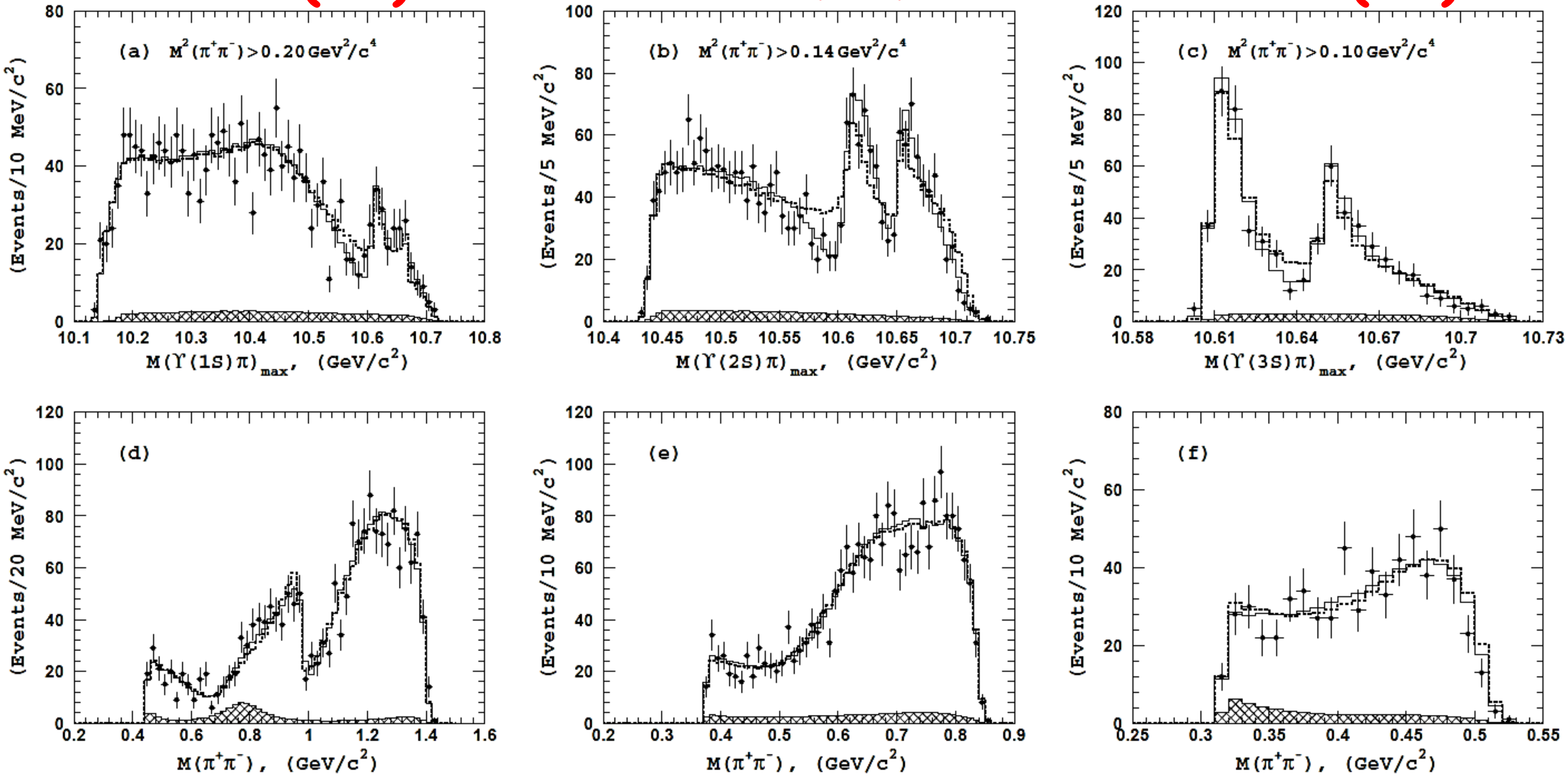



Belle: PRD91, 072003 (2015)

# $Z_b$ in $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$

- Full partial wave analysis of $\Upsilon(5S) \rightarrow \pi^+\pi^-\mu^+\mu^-$
- Mass, width, fraction, and $J^P=1^+$ of $Z_b$ states determined

$\pi^+\pi^-\Upsilon(1S)$ $\pi^+\pi^-\Upsilon(2S)$ $\pi^+\pi^-\Upsilon(3S)$




Belle: PRD91, 072003 (2015)

# $Z_b$ in $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$

| Parameter | $\Upsilon(1S)\pi^+\pi^-$ | $\Upsilon(2S)\pi^+\pi^-$ | $\Upsilon(3S)\pi^+\pi^-$ |
|---|---|---|---|
| $f_{Z_b^{\mp}(10610)\pi^{\pm}}$, % | $4.8 \pm 1.2^{+1.5}_{-0.3}$ | $18.1 \pm 3.1^{+4.2}_{-0.3}$ | $30.0 \pm 6.3^{+5.4}_{-7.1}$ |
| $Z_b(10610)$ mass, MeV/$c^2$ | $10608.5 \pm 3.4^{+3.7}_{-1.4}$ | $10608.1 \pm 1.2^{+1.5}_{-0.2}$ | $10607.4 \pm 1.5^{+0.8}_{-0.2}$ |
| $Z_b(10610)$ width, MeV/$c^2$ | $18.5 \pm 5.3^{+6.1}_{-2.3}$ | $20.8 \pm 2.5^{+0.3}_{-2.1}$ | $18.7 \pm 3.4^{+2.5}_{-1.3}$ |
| $f_{Z_b^{\mp}(10650)\pi^{\pm}}$, % | $0.87 \pm 0.32^{+0.16}_{-0.12}$ | $4.05 \pm 1.2^{+0.95}_{-0.15}$ | $13.3 \pm 3.6^{+2.6}_{-1.4}$ |
| $Z_b(10650)$ mass, MeV/$c^2$ | $10656.7 \pm 5.0^{+1.1}_{-3.1}$ | $10650.7 \pm 1.5^{+0.5}_{-0.2}$ | $10651.2 \pm 1.0^{+0.4}_{-0.3}$ |
| $Z_b(10650)$ width, MeV/$c^2$ | $12.1^{+11.3+2.7}_{-4.8-0.6}$ | $14.2 \pm 3.7^{+0.9}_{-0.4}$ | $9.3 \pm 2.2^{+0.3}_{-0.5}$ |
| $\phi_Z$, degrees | $67 \pm 36^{+24}_{-52}$ | $-10 \pm 13^{+34}_{-12}$ | $-5 \pm 22^{+15}_{-33}$ |
| $c_{Z_b(10650)}/c_{Z_b(10610)}$ | $0.40 \pm 0.12^{+0.05}_{-0.11}$ | $0.53 \pm 0.07^{+0.32}_{-0.11}$ | $0.69 \pm 0.09^{+0.18}_{-0.07}$ |
| $f_{\Upsilon(nS)f_2(1270)}$, % | $14.6 \pm 1.5^{+6.3}_{-0.7}$ | $4.09 \pm 1.0^{+0.33}_{-1.0}$ | – |
| $f_{\Upsilon(nS)(\pi^+\pi^-)_S}$, % | $86.5 \pm 3.2^{+3.3}_{-4.9}$ | $101.0 \pm 4.2^{+6.5}_{-3.5}$ | $44.0 \pm 6.2^{+1.8}_{-4.3}$ |
| $f_{\Upsilon(nS)f_0(980)}$, % | $6.9 \pm 1.6^{+0.8}_{-2.8}$ | – | – |

$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(1S)\pi^{\mp}} = 109 \pm 27^{+35}_{-10} \text{ fb}$$
$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(2S)\pi^{\mp}} = 737 \pm 126^{+188}_{-85} \text{ fb}$$
$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(3S)\pi^{\mp}} = 438 \pm 92^{+92}_{-114} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(1S)\pi^{\mp}} = 20 \pm 7^{+4}_{-3} \text{ fb}$$
$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(2S)\pi^{\mp}} = 165 \pm 49^{+43}_{-20} \text{ fb}$$
$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(3S)\pi^{\mp}} = 194 \pm 53^{+43}_{-25} \text{ fb}$$

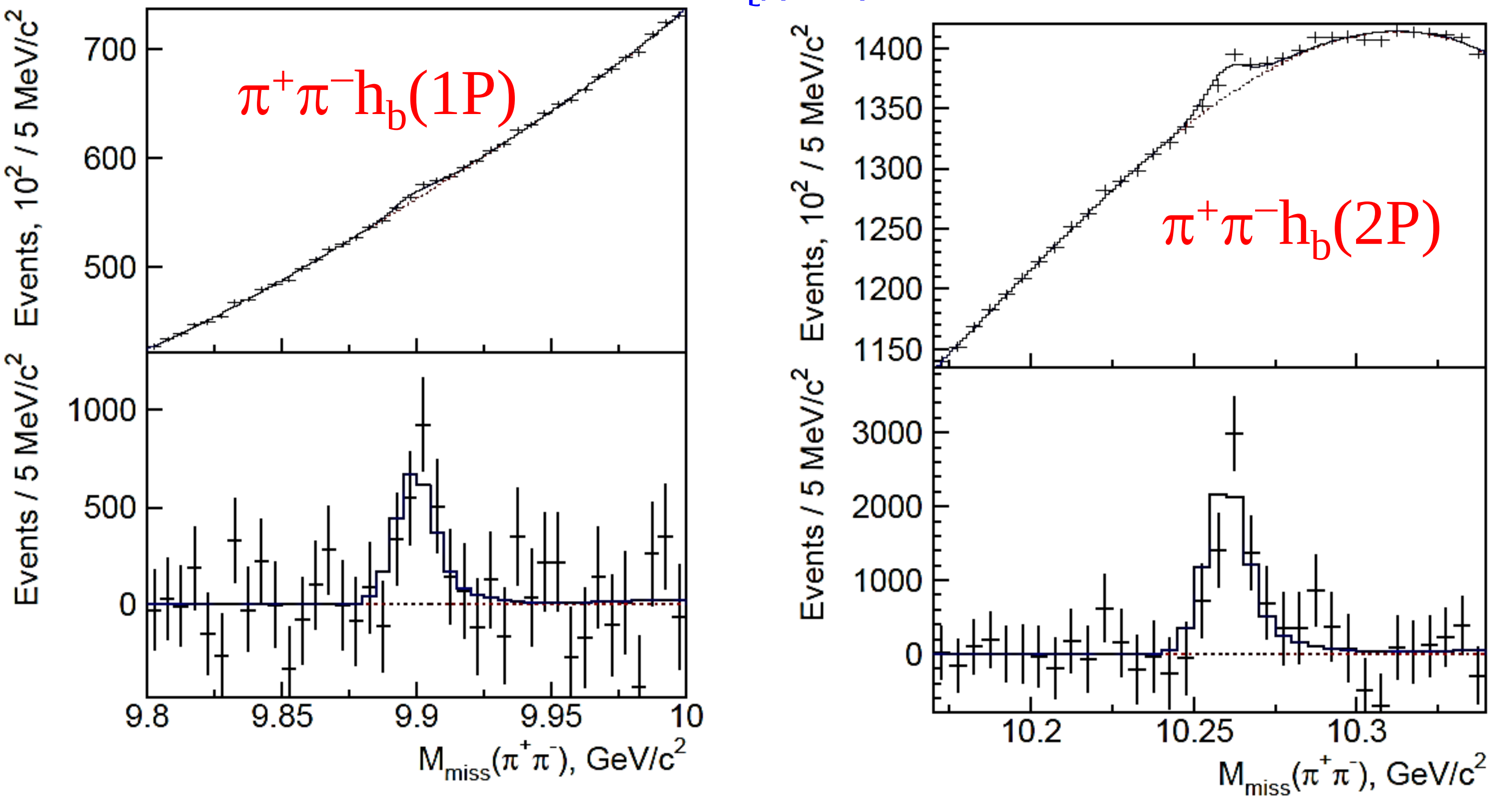
◆ Relative BR of $Z_b$ decays

Belle: PRD91, 072003 (2015)

# $e^+e^- \rightarrow \pi^+\pi^- h_b(nP)$

arXiv:1508.06562

- Using scan data between Y(5S) and Y(6S)
- Reconstruct $\pi^+\pi^-$, require $\pi^+/\pi^-$ recoil mass in $Z_b$ region: $10.59 < M_{miss}(\pi) < 10.67$ GeV/$c^2$
- check the $\pi^+\pi^-$ recoil mass for $h_b(nP)$



# $e^+e^- \rightarrow \pi^+\pi^- h_b(nP)$

Simultaneous fit:

$\Upsilon(5S)$:

Mass = $(10884.7 \pm^{3.6}_{3.4} \pm^{8.9}_{1.0})$ MeV

Width = $(40.6 \pm^{12.7}_{8.0} \pm^{1.1}_{19.1})$ MeV

$\Upsilon(6S)$:

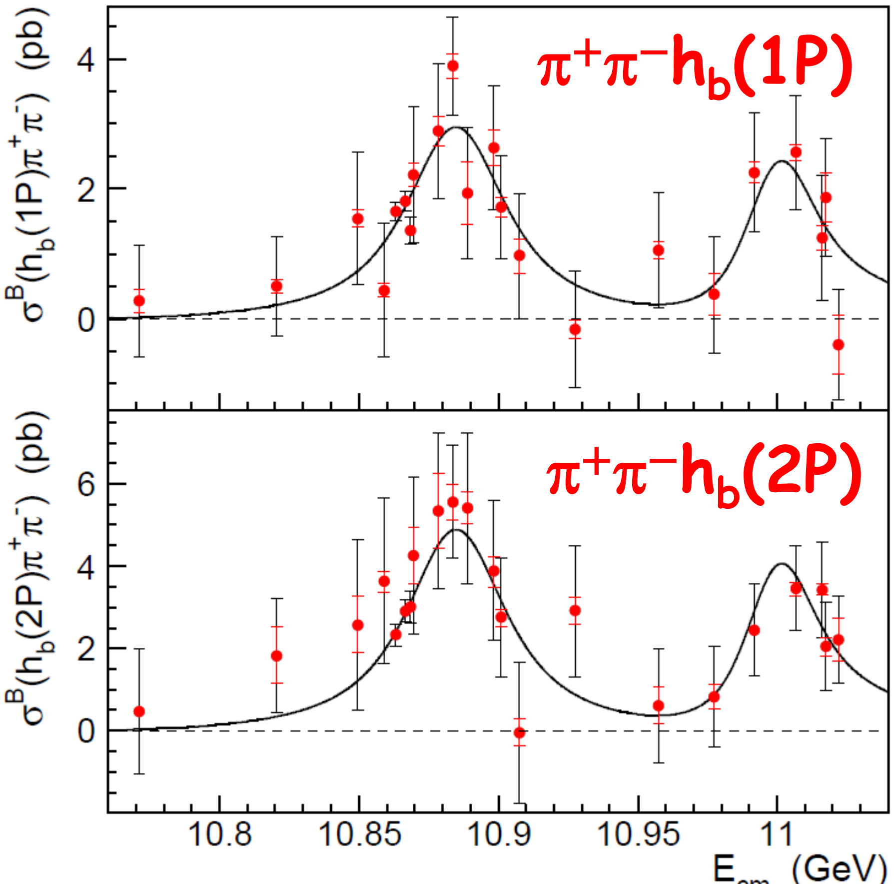
Mass = $(10999.0 \pm^{7.3}_{7.8} \pm^{16.7}_{1.0})$ MeV

Width = $(27 \pm^{27}_{11} \pm^{1}_{12})$ MeV

$\Delta\phi = 0.1 \pm^{0.4}_{0.8} \pm^{0.1}_{0.3}$ rad

- Resonant parameters agree with from $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$
- $e^+e^- \rightarrow \pi^+\pi^- h_b(nP)$ at the same level as $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$; similar shape.
- 1st obs. of $\Upsilon(6S) \rightarrow \pi^+\pi^- h_b(nP)$

3.6σ for 1P, 5.4σ for 2P.




Ecm=10865.6 ±2.0 MeV

$$\sigma^B(e^+e^- \to h_b(1P)\pi^+\pi^-) = 1.66 \pm 0.09 \pm 0.10\,\text{pb},$$

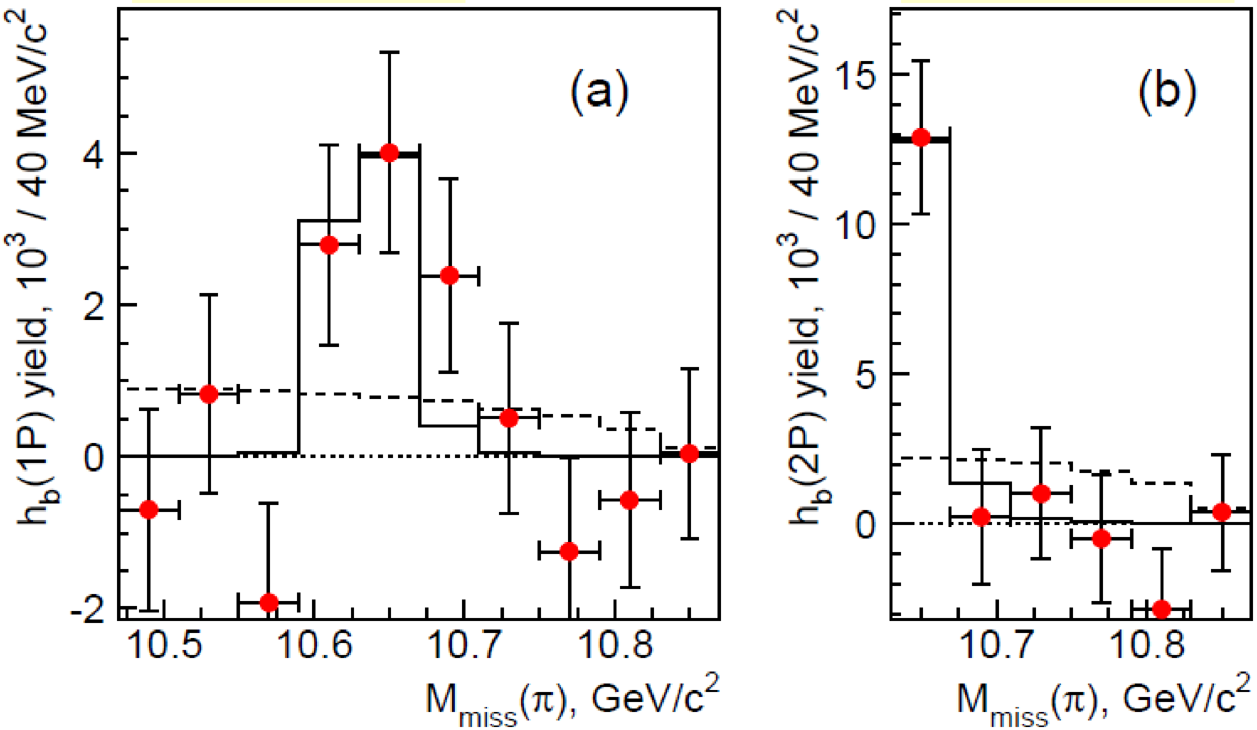
$$\sigma^B(e^+e^- \to h_b(2P)\pi^+\pi^-) = 2.70 \pm 0.17 \pm 0.19\,\text{pb}.$$

arXiv:1508.06562

# $Z_b$ in $\Upsilon(6S) \rightarrow \pi^+\pi^- h_b(nP)$

- Fit $\pi^+\pi^-$ missing in each $\pi$ missing mass spectra
- Events mainly from $Z_b$ intermediate states: not clear if only one $Z_b$ or both. Single $Z_b(10610)$ hypothesis is excluded at 3.4σ in $\pi^+\pi^- h_b(1P)$; Single $Z_b(10650)$ hypothesis cannot excluded.

**$\pi^+\pi^- h_b(1P)$** **$\pi^+\pi^- h_b(2P)$**





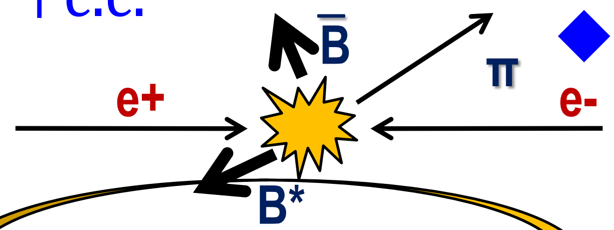

arXiv:1508.06562

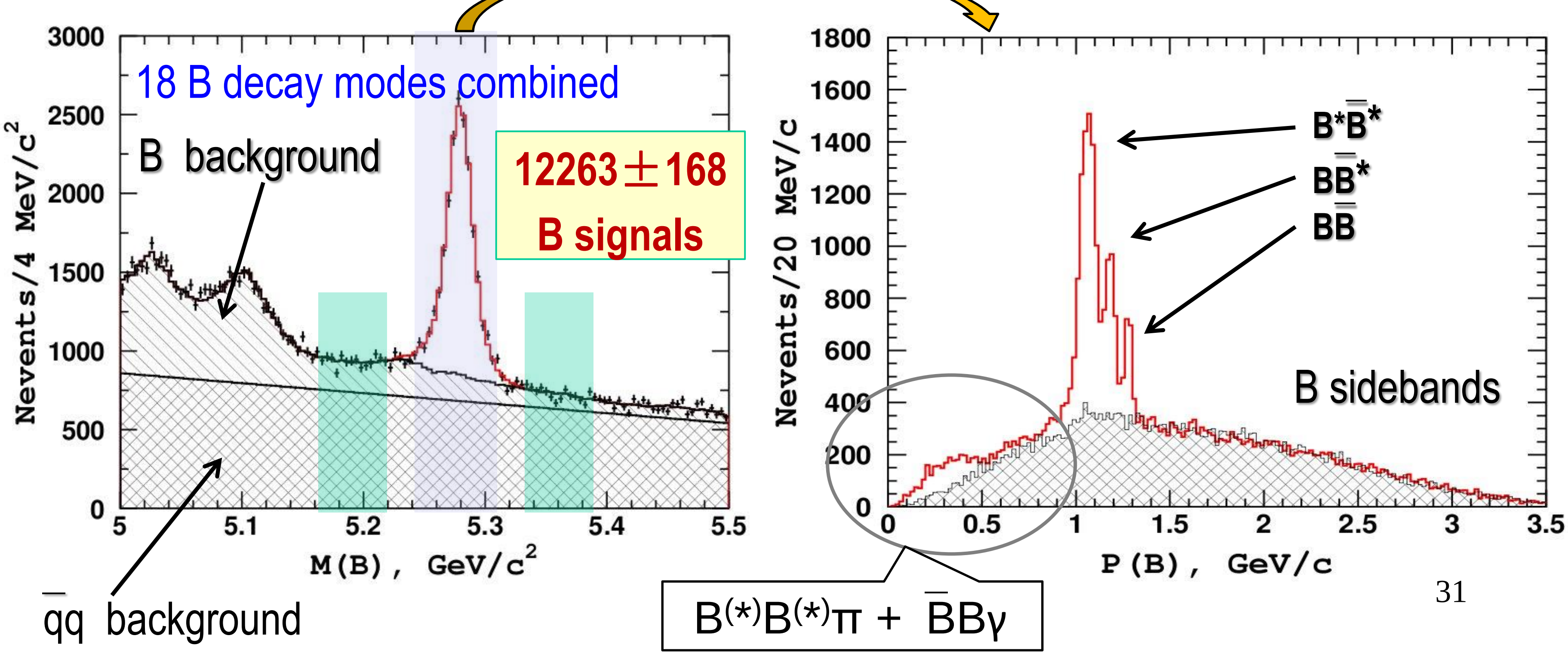
# $Z_b$ in $\Upsilon(5S) \rightarrow [B^{(*)}B^{(*)}]^{+}\pi^{-}$+c.c.

- $B B\pi$ = $\bar{B}^0 B^+ \pi^-$+c.c.
- $B B^*\pi$ = $\bar{B}^{*0} B^+ \pi^-$+c.c./ $\bar{B}^0 B^{*+} \pi^-$+c.c.
- $B^* B^*\pi$ = $\bar{B}^{*0} B^{*+} \pi^-$+c.c.

- One B is reconstructed
- Select a bachelor $\pi^{\pm}$
- Check $B\pi$ recoil mass

arXiv:1512.07419

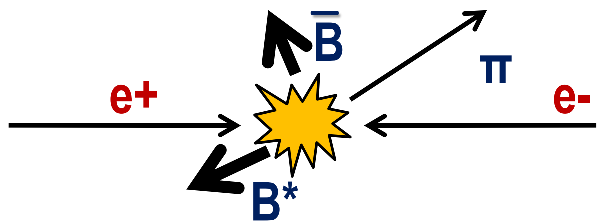


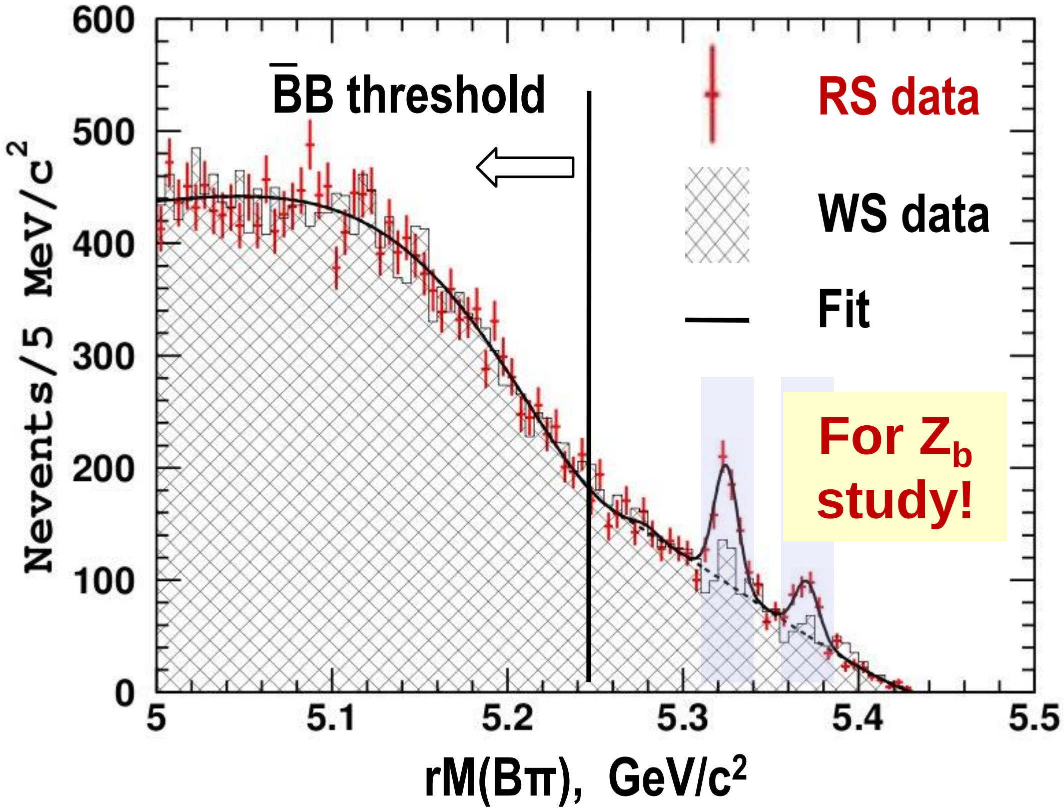



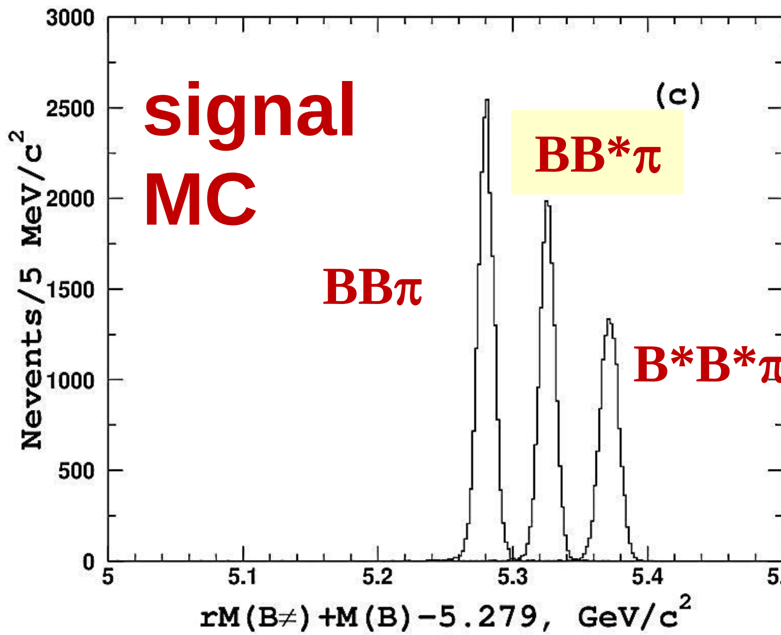
# $Z_b$ in $\Upsilon(5S) \rightarrow [B^{(*)}B^{(*)}]^{+}\pi^{-}$+c.c.

Combine the B with a charged pion

➔ calculate recoil mass of $B\pi$




$N(BB\pi) = 13 \pm 25$ $N(BB^*\pi) = 357 \pm 30$ $N(B^*B^*\pi) = 161 \pm 21$

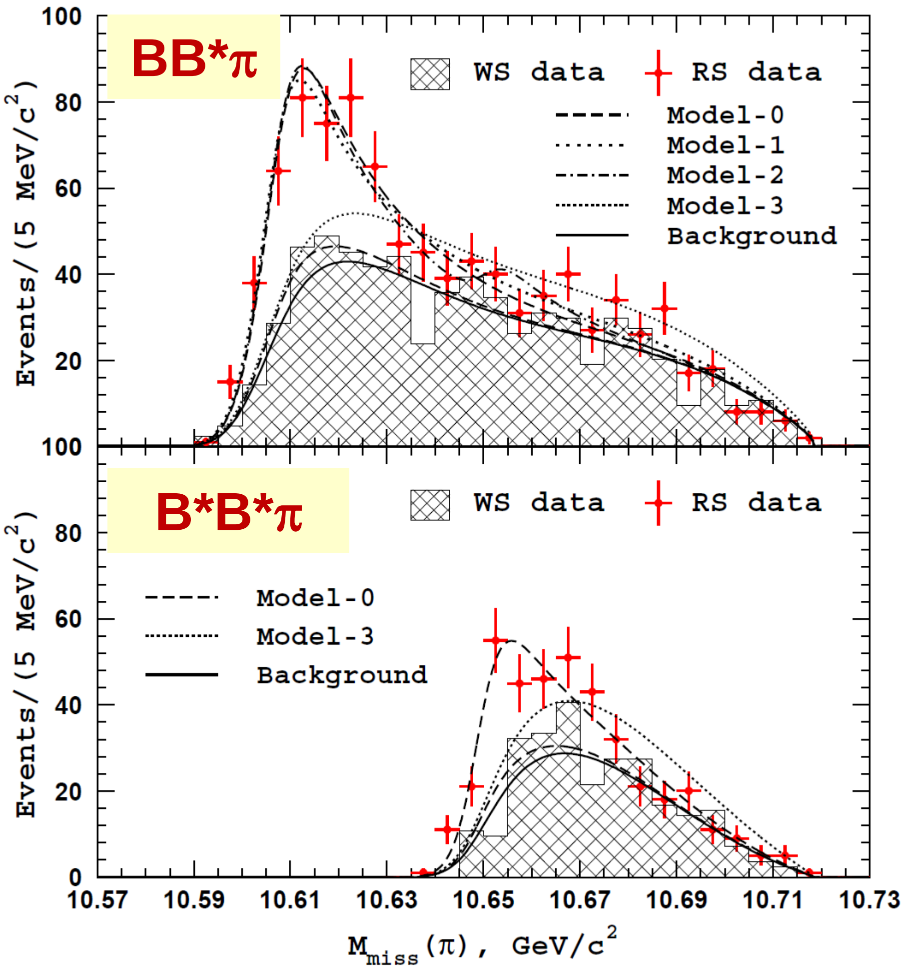
arXiv:1512.07419

# $Z_b$ in $\Upsilon(5S) \rightarrow [B^{(*)}B^{(*)}]^+\pi^- + c.c.$

Submitted to PRL - arXiv:1512.07419

Check recoil mass of bachelor $\pi^\pm$

- Simultaneous fit of right-sign (RS) and wrong-sign (WS) samples
- Contribution of signal events to the WS sample due to $B_0$ mixing (at 10% level)




Model-0 : $Z_b(10650)$ only

Model-1: $Z_b(10610)$ + Non-res.

Model-2: $Z_b(10610)$ + $Z_b(10650)$ with interference

Model-3: Non-resonance

$Z_b(10610)$ saturates $BB^*\pi$ and $Z_b(10650)$ saturates $B^*B^*\pi$

# $Z_b$ in $\Upsilon(5S) \to [B^{(*)}B^{(*)}]^+\pi^- + c.c.$

Submitted to PRL - arXiv:1512.07419

- Simultaneous fit of right-sign (RS) and wrong-sign (WS) samples
- Contribution of signal events to the WS sample due to $B_0$ mixing (at 10% level)

Summary of fit results to the $M_{\rm miss}(\pi)$ distributions for the three-body $BB^*\pi$ and $B^*B^*\pi$ final states.

| Mode | Parameter | Mod-0 | Mod-1 | | Mod-2 | | Mod-3 |
|---|---|---|---|---|---|---|---|
| | | | Sol 1 | Sol 2 | Sol 1 | Sol 2 | |
| $BB^*\pi$ | $f_{Z_b(10610)}$ | 1.0 | $1.45 \pm 0.24$ | $0.64 \pm 0.15$ | $1.01 \pm 0.13$ | $1.18 \pm 0.15$ | — |
| | $f_{Z_b(10650)}$ | — | — | — | $0.05 \pm 0.04$ | $0.24 \pm 0.11$ | — |
| | $\phi_{Z_b(10650)}$, rad. | — | — | — | $-0.26 \pm 0.68$ | $-1.63 \pm 0.14$ | — |
| | $f_{\rm nr}$ | — | $0.48 \pm 0.23$ | $0.41 \pm 0.17$ | — | — | 1.0 |
| | $\phi_{\rm nr}$, rad. | — | $-1.21 \pm 0.19$ | $0.95 \pm 0.32$ | — | — | — |
| | $-2\log\mathcal{L}$ | $-304.7$ | $-300.6$ | $-300.5$ | $-301.4$ | $-301.4$ | $-344.5$ |
| $B^*B^*\pi$ | $f_{Z_b(10650)}$ | 1.0 | $1.04 \pm 0.15$ | $0.77 \pm 0.22$ | | | — |
| | $f_{\rm nr}$ | — | $0.02 \pm 0.04$ | $0.24 \pm 0.18$ | | | 1.0 |
| | $\phi_{\rm nr}$, rad. | — | $0.29 \pm 1.01$ | $1.10 \pm 0.44$ | | | — |
| | $-2\log\mathcal{L}$ | $-182.4$ | $-182.4$ | $-182.4$ | | | $-209.7$ |

- Intermediate $Z_b(10610)$ dominates in the $BB^*\pi$ final state, while intermediate $Z_b(10650)$ dominates in the $B^*B^*\pi$ final state

$Z_b(10610)$ saturates $BB^*\pi$

and $Z_b(10650)$ saturates $B^*B^*\pi$

# $Z_b$ in $\Upsilon(5S) \rightarrow [B^{(*)}B^{(*)}]^+\pi^- + c.c.$

arXiv:1512.07419

Decay table of the $Z_b$ states

- Assuming that the known decays saturate $Z_b$ decay table =>

$B$ branching fractions for the $Z_b^+(10610)$ and $Z_b^+(10650)$ decays. The first quoted uncertainty is statistical; the second is systematic.

BRs of $Z_b$ decays

| Channel | Fraction, % | |
|---|---|---|
| | $Z_b(10610)$ | $Z_b(10650)$ |
| $\Upsilon(1S)\pi^+$ | $0.60 \pm 0.17 \pm 0.07$ | $0.17 \pm 0.06 \pm 0.02$ |
| $\Upsilon(2S)\pi^+$ | $4.05 \pm 0.81 \pm 0.58$ | $1.38 \pm 0.45 \pm 0.21$ |
| $\Upsilon(3S)\pi^+$ | $2.40 \pm 0.58 \pm 0.36$ | $1.62 \pm 0.50 \pm 0.24$ |
| $h_b(1P)\pi^+$ | $4.26 \pm 1.28 \pm 1.10$ | $9.23 \pm 2.88 \pm 2.28$ |
| $h_b(2P)\pi^+$ | $6.08 \pm 2.15 \pm 1.63$ | $17.0 \pm 3.74 \pm 4.1$ |
| $B^+\bar{B}^{*0} + \bar{B}^0B^{*+}$ | $82.6 \pm 2.9 \pm 2.3$ | – |
| $B^{*+}\bar{B}^{*0}$ | – | $70.6 \pm 4.9 \pm 4.4$ |

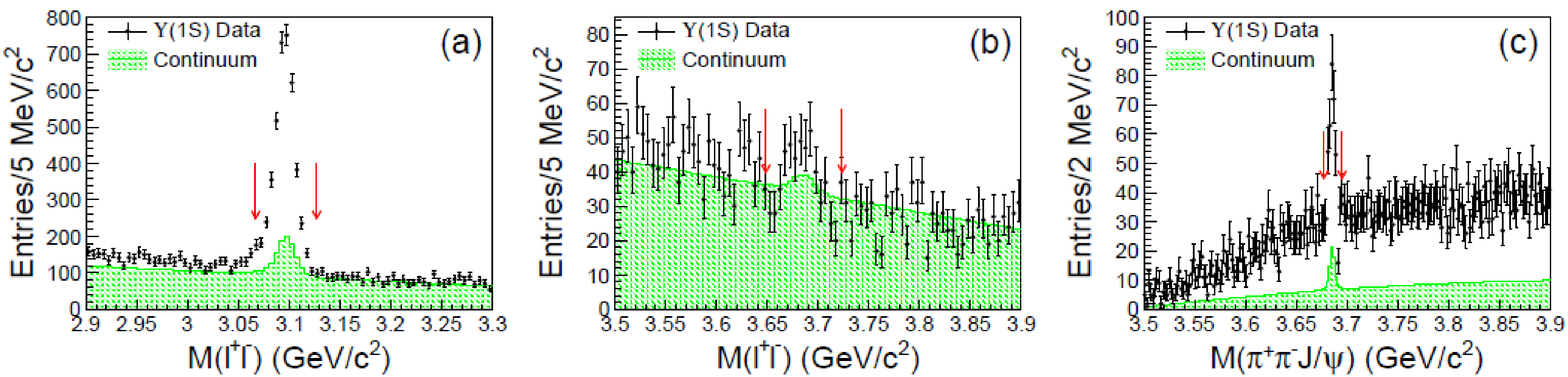
- $Z_b^+(10610)$ and $Z_b^+(10650)$ decays to $BB^*$ and $B^*B^*$ dominate
- Smoking gun of molecular structure

# Other topics

# Search for XYZ in Υ(1S) inclusive decays

- Very little available information on XYZ production in the decays of narrow Υ states
- Υ (1S) inclusive to J/Ψ and Ψ(2S) with large Brs [$(6.5\pm0.7)\times10^{-4}$ and $(2.7\pm0.9)\times10^{-4}$], some of the XYZ might have been produced

- Tag channels: Υ (1S) →J/Ψ + anything and Ψ(2S)+anything




$J/\Psi \to l^+l^-$ | $\Psi(2S) \to l^+l^-$ | $\Psi(2S) \to \pi^+\pi^- J/\Psi$

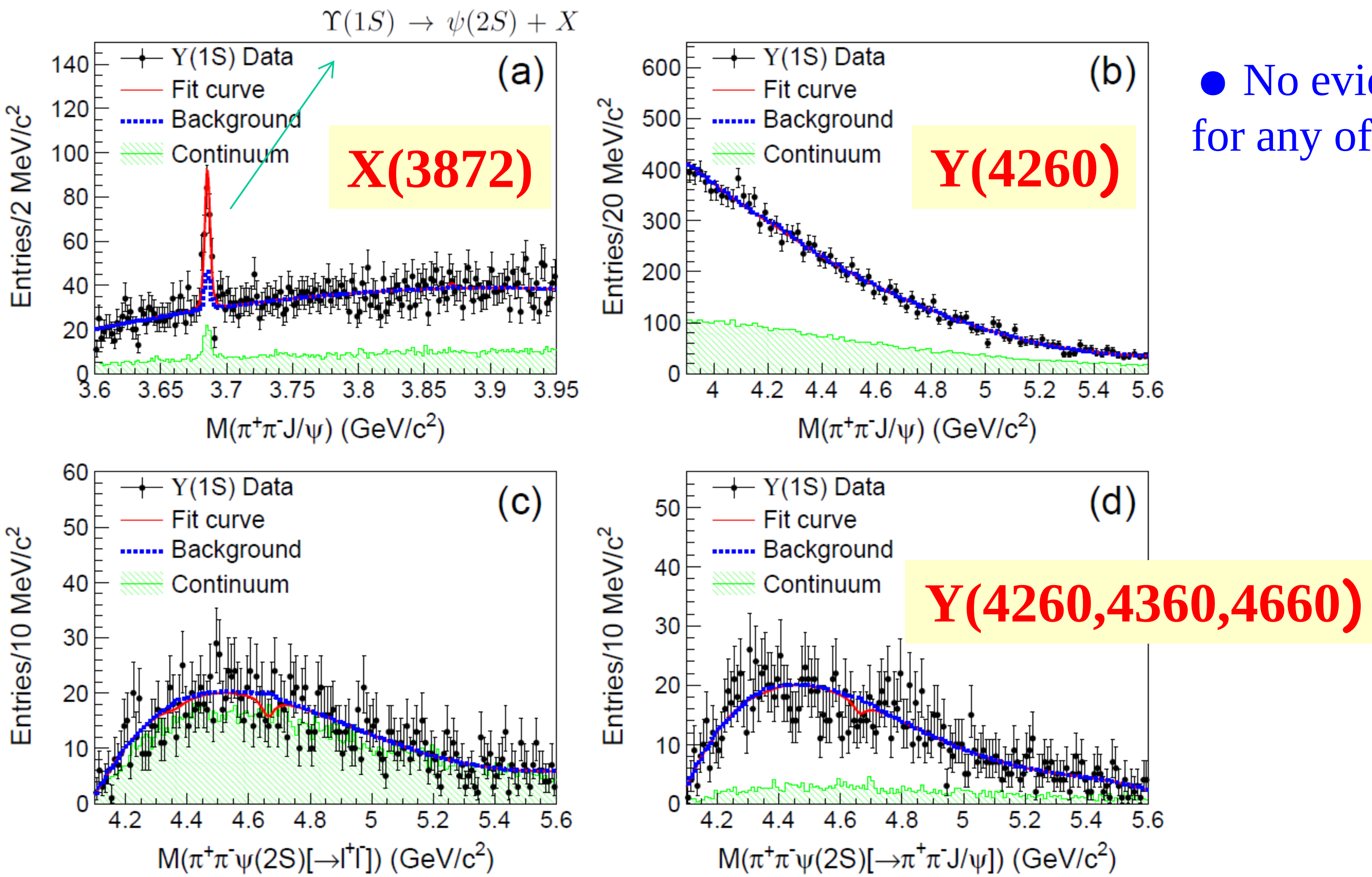
- Dots with error bars: data
- Shaded histogram: normalized continuum

arXiv:1605.00990

# Search for XYZ in Υ(1S) inclusive decays

Search for XYZ states by combining the J/Ψ or Ψ(2S) with one or two $K^{\pm}/\pi^{\pm}$

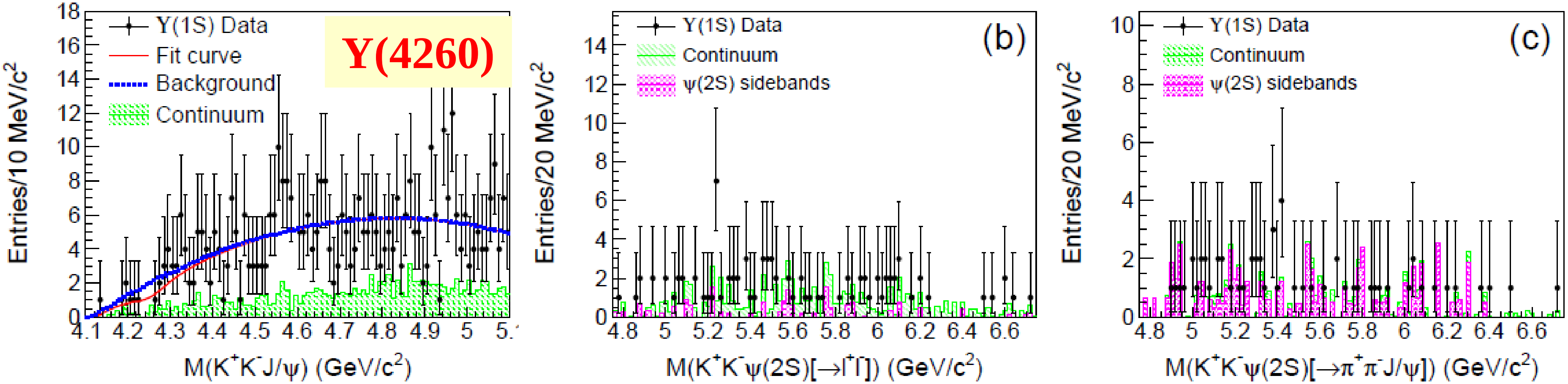
arXiv:1605.00990



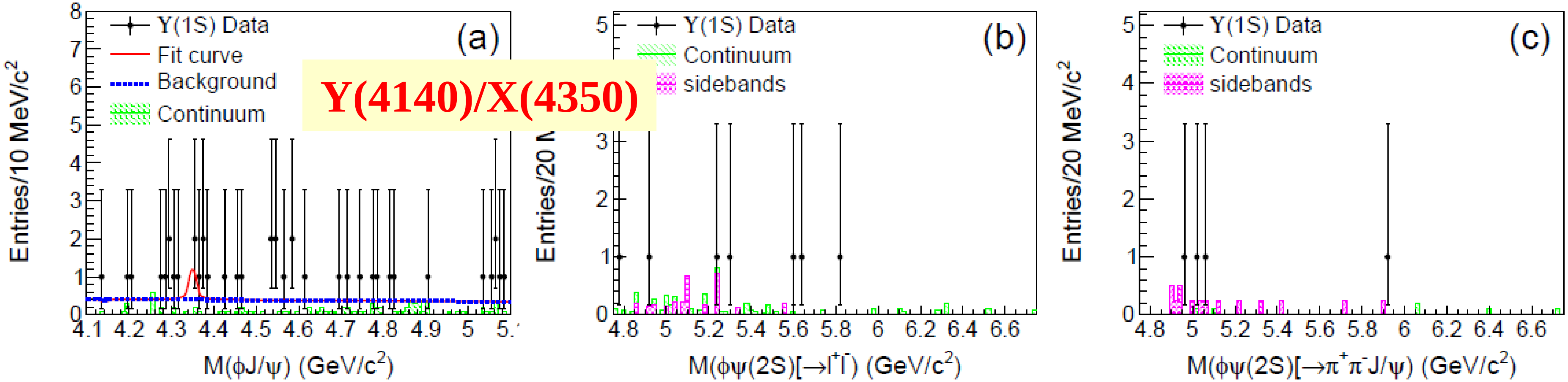

- No evident signals for any of these states

# Search for XYZ in Υ(1S) inclusive decays

arXiv:1605.00990



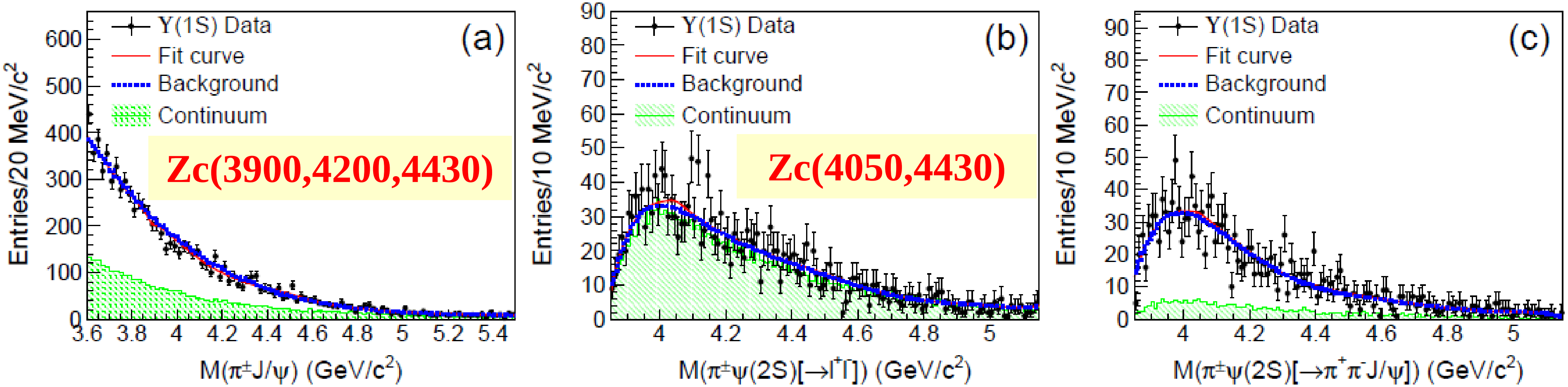

- No evidence is found for new structures or any of the known XYZ states.



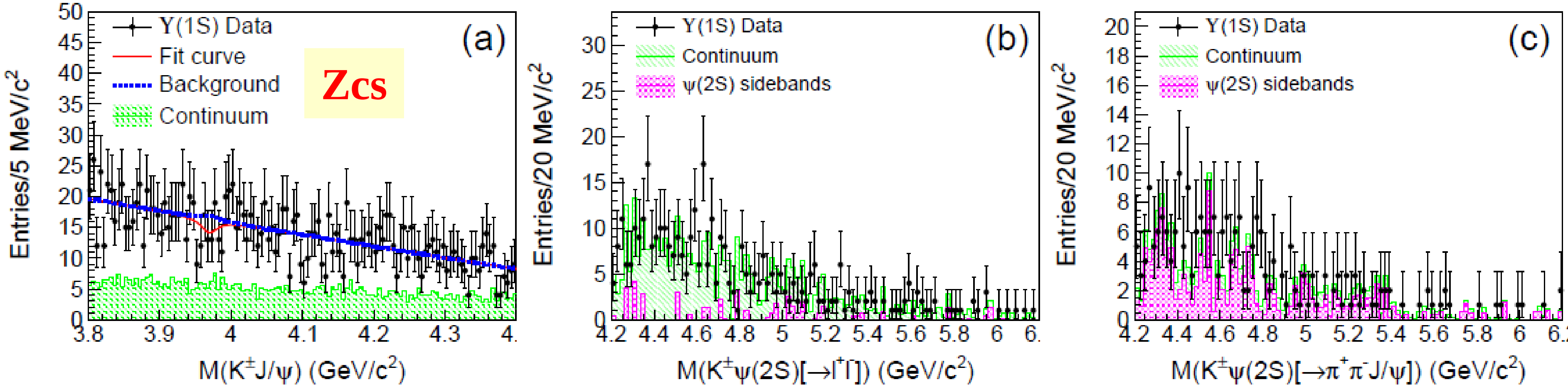

- No structures can be identified.

# Search for XYZ in Υ(1S) inclusive decays

arXiv:1605.00990




Zcs: M=(3.97±0.08) GeV/c2, Γ=(24.9±12.6) MeV [J Korean Phys. Soc. 55, 424(2009); PRD88,096014(2013)]




- No structures can be identified.

# Search for XYZ in Υ(1S) inclusive decays

arXiv:1605.00990

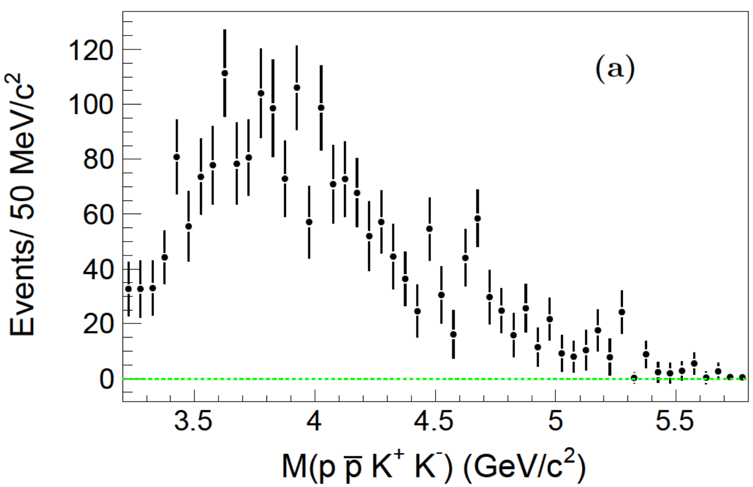
| State | $N_{\rm fit}$ | $N_{\rm up}$ | $\varepsilon(\%)$ | $\sigma_{\rm syst}(\%)$ | $\Sigma(\sigma)$ | $\mathcal{B}_R$ |
|---|---|---|---|---|---|---|
| $X(3872) \to \pi^+\pi^- J/\psi$ | 4.8±15.4 | 31.4 | 3.26 | 18.7 | 0.3 | $< 9.5 \times 10^{-6}$ |
| $Y(4260) \to \pi^+\pi^- J/\psi$ | −31.1±88.9 | 134.6 | 3.50 | 35.6 | – | $< 3.8 \times 10^{-5}$ |
| $Y(4260) \to \pi^+\pi^- \psi(2S)$ | 6.7±29.4 | 56.9 | 0.71 | 35.0 | 0.2 | $< 7.9 \times 10^{-5}$ |
| $Y(4360) \to \pi^+\pi^- \psi(2S)$ | −25.4±30.1 | 45.6 | 0.86 | 50.0 | – | $< 5.2 \times 10^{-5}$ |
| $Y(4660) \to \pi^+\pi^- \psi(2S)$ | −55.0±26.2 | 23.1 | 1.06 | 40.7 | – | $< 2.2 \times 10^{-5}$ |
| $Y(4260) \to K^+K^- J/\psi$ | −13.7±10.9 | 14.5 | 1.91 | 45.8 | – | $< 7.5 \times 10^{-6}$ |
| $Y(4140) \to \phi J/\psi$ | −0.1±1.2 | 3.6 | 0.69 | 11.0 | – | $< 5.2 \times 10^{-6}$ |
| $X(4350) \to \phi J/\psi$ | 2.3±2.5 | 7.6 | 0.92 | 10.4 | 1.2 | $< 8.1 \times 10^{-6}$ |
| $Z_c(3900)^\pm \to \pi^\pm J/\psi$ | −26.5±39.1 | 57.5 | 4.39 | 47.3 | – | $< 1.3 \times 10^{-5}$ |
| $Z_c(4200)^\pm \to \pi^\pm J/\psi$ | −238.6±154.2 | 235.1 | 3.87 | 48.4 | – | $< 6.0 \times 10^{-5}$ |
| $Z_c(4430)^\pm \to \pi^\pm J/\psi$ | 94.2±71.4 | 195.8 | 3.97 | 34.4 | 1.2 | $< 4.9 \times 10^{-5}$ |
| $Z_c(4050)^\pm \to \pi^\pm \psi(2S)$ | 37.0±47.7 | 112.7 | 1.27 | 46.2 | 0.4 | $< 8.8 \times 10^{-5}$ |
| $Z_c(4430)^\pm \to \pi^\pm \psi(2S)$ | 23.2±42.4 | 92.0 | 1.35 | 47.1 | 0.1 | $< 6.7 \times 10^{-5}$ |
| $Z_{cs}^\pm \to K^\pm J/\psi$ | −22.2±17.4 | 22.4 | 3.88 | 48.7 | – | $< 5.7 \times 10^{-6}$ |

We searched for a variety of XYZ states in Υ(1S) inclusive decays for the first Time. No evident signal is found for any of them and 90% C.L. upper limits are set on the product branching fractions .

# Search for exotic baryons in $\gamma\gamma \to p\bar{p}K^+K^-$

arXiv:1604.02525

- LHCb reported $P_c(4380)^+$ and $P_c(4450)^+$ in $J/\Psi$ p system
- The first strong experimental evidence for a pentaquark state, $\Theta(1540)^+$, was reported in $\gamma n \to n K^+ K^-$ in the LEPS experiment
- The possibility of observing additional hypothetical exotic baryons in $\gamma\gamma$ collisions is discussed in [J. Phys. G30,1801 (2004)]
- We search for novel exotic baryons, denoted as $\Theta(1540)^0 \to pK^-$ and $\Theta(1540)^{++} \to p K^+$ which are similar to $\Theta(1540)^+$, in $\gamma\gamma \to p\bar{p}K^+K^-$.

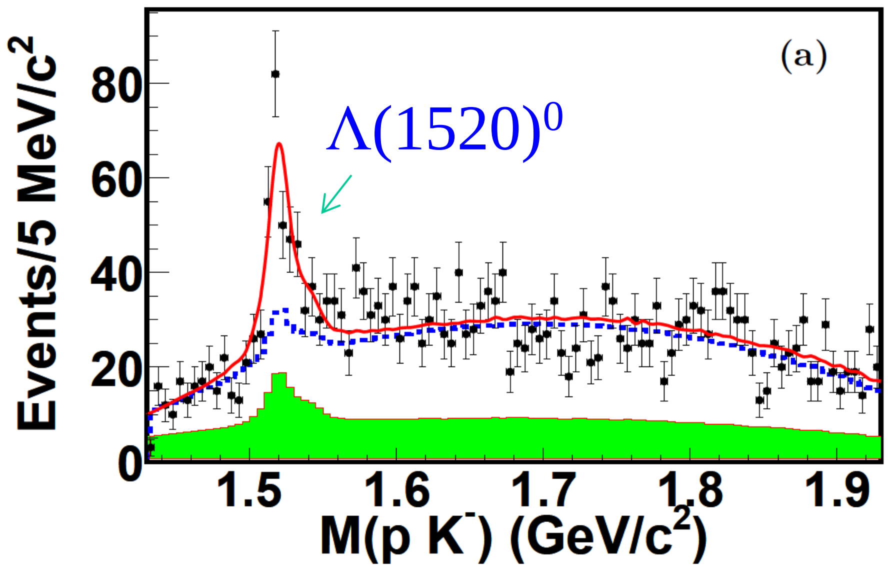



$$\sigma_{\gamma\gamma\to p\bar{p}K^+K^-}(W_{\gamma\gamma}) = \frac{n^{\rm fit}}{\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}\epsilon(W_{\gamma\gamma})\Delta W_{\gamma\gamma}}$$

$\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}$ is the differential luminosity

# Search for exotic baryons in pK systems

arXiv:1604.02525




Simultaneous fit: $\Lambda(1520)^0$ and $\Theta(1540)^0$ signal are included.

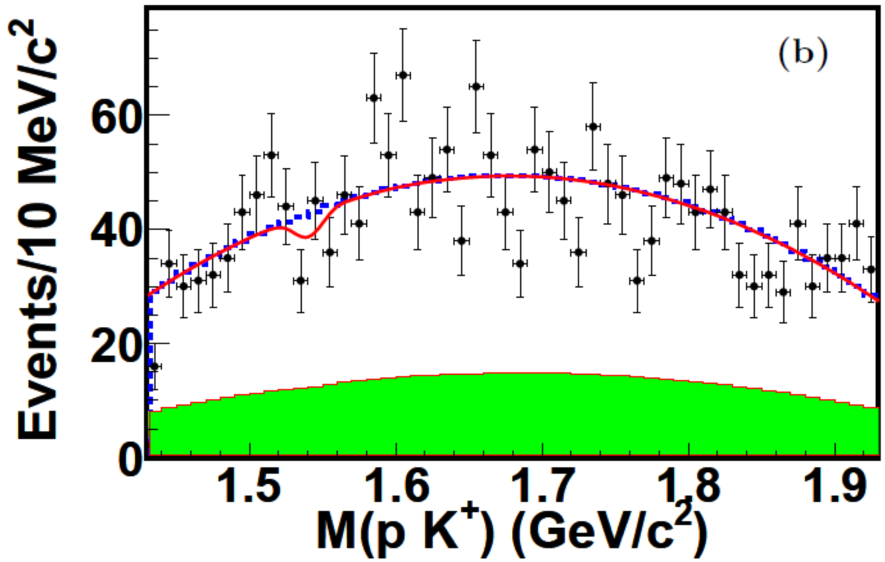
Solid line: the simultaneous fit

The dotted curve: background estimate

The shaded histogram: $\sum Pt^*$ sideband

$288 \pm 48$ $\Lambda(1520)^0$events, 8.6σ

$22 \pm 34$ $\Theta(1540)^0$ events, 1.4σ

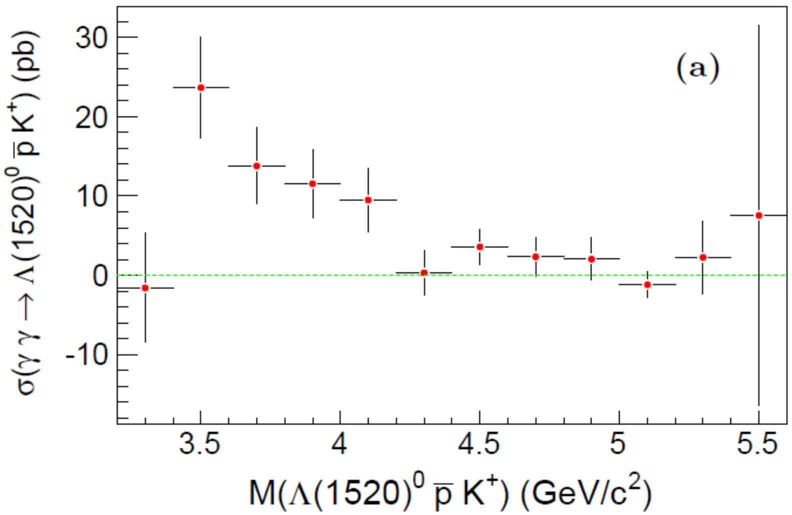


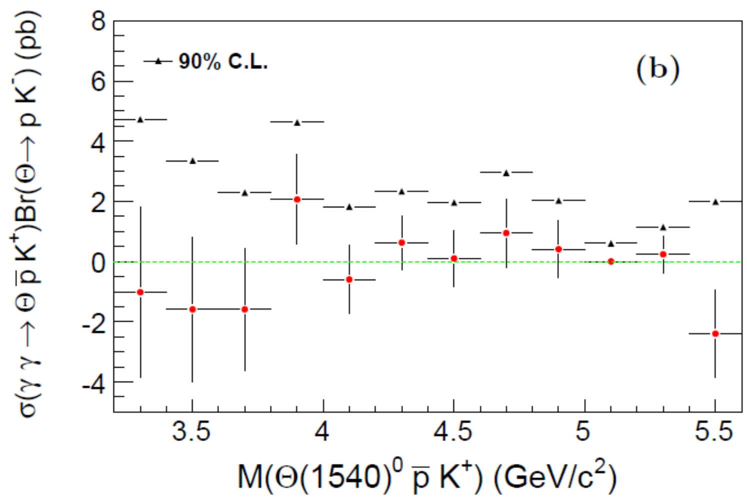

$-16 \pm 34$ $\Theta(1540)^{++}$ events

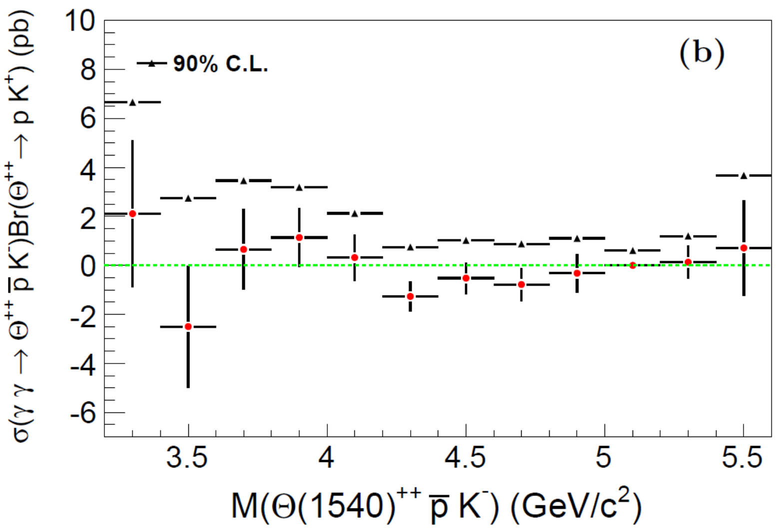
No evidence of $\Theta(1540)^0$ or $\Theta(1540)^{++}$ is seen in M(p $K^-$) or M(p$K^+$) .

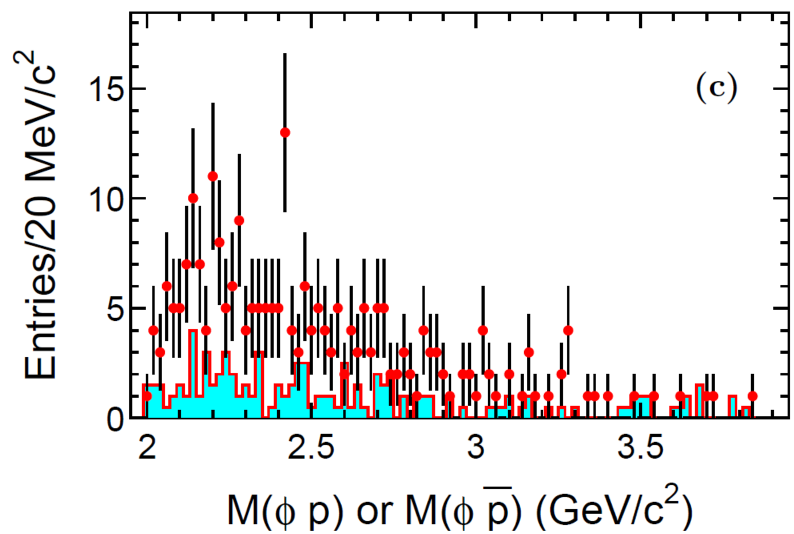
# Search for exotic baryons in pK systems

arXiv:1604.02525




No evidence of an $s\bar{s}$ partner of the Pc(4380,4450) is observed.

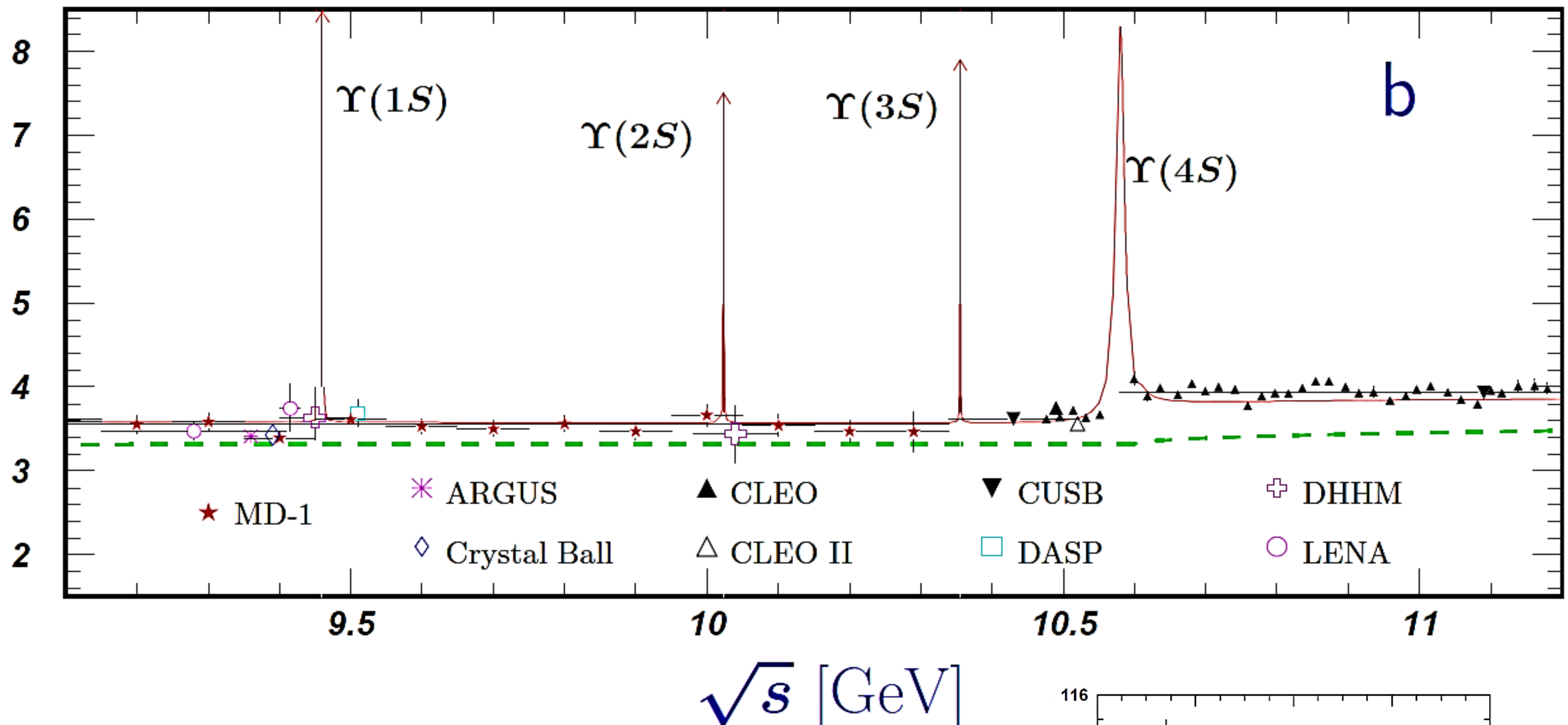
# Summary & outlooks

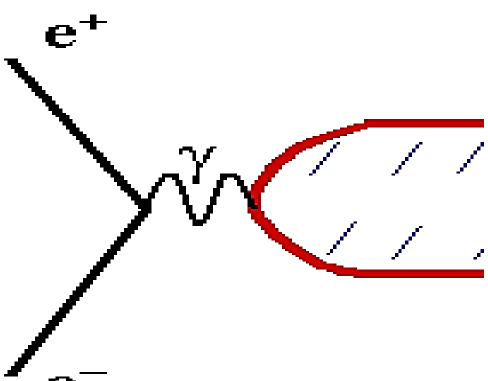
- More studies on X(3872) and search for $X_b$
- Updates on some Y states
- Observation of some $Z_c$ and $Z_b$ states
- Searches for XYZ states in Y(1S) decays
- Searches for exotic states in pK systems in two-photon process
- Very exciting time ahead for BelleII with lots of (new) exotic states to follow from 2018 !

Thanks a lot!

谢谢！

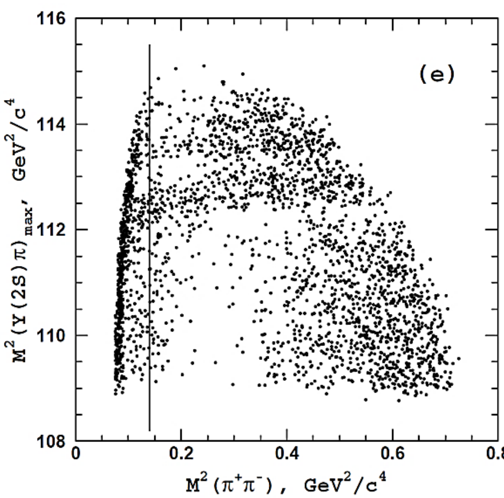
# $e^+e^-$ annihilation to vector bottomonia




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

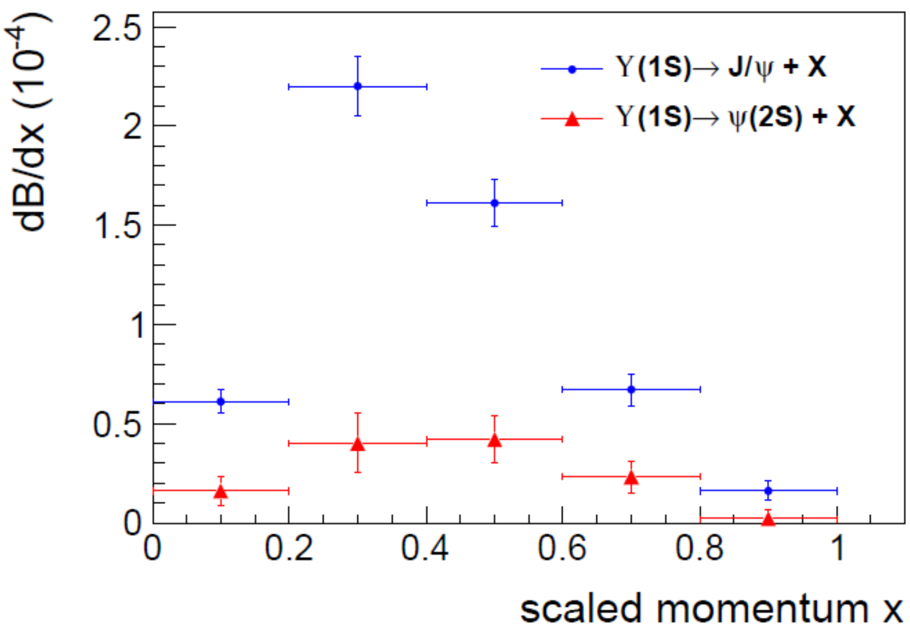
$\Upsilon(nS)$, $Y_b$…



# Search for XYZ in $\Upsilon(1S)$ inclusive decays

Define the scaled momentum $x = p^*_\psi / (\frac{1}{2\sqrt{s}} \times (s - m^2_\psi))$ arXiv:1605.00990

| $x$ | $\Upsilon(1S) \to J/\psi + X$ $N_{\rm fit}$ | $\varepsilon$ | $\sigma_{\rm syst}$ | $\mathcal{B}(\times 10^{-4})$ | $\Upsilon(1S) \to \psi(2S) + X$ $N_{\rm fit}$ | $\varepsilon$ | $\sigma_{\rm syst}$ | $\mathcal{B}(\times 10^{-4})$ |
|---|---|---|---|---|---|---|---|---|
| (0.0, 0.2) | 379.28±28.05 | 6.06 | 4.3 | $0.61 \pm 0.05 \pm 0.03$ | 30.14±10.52 | 1.81 | 21.8 | $0.16 \pm 0.06 \pm 0.04$ |
| (0.2, 0.4) | 1297.60±48.60 | 5.78 | 5.4 | $2.20 \pm 0.08 \pm 0.12$ | 71.25±18.31 | 1.76 | 26.5 | $0.40 \pm 0.10 \pm 0.11$ |
| (0.4, 0.6) | 904.56±41.55 | 5.51 | 5.6 | $1.61 \pm 0.07 \pm 0.09$ | 71.45±15.37 | 1.68 | 18.6 | $0.42 \pm 0.09 \pm 0.08$ |
| (0.6, 0.8) | 353.95±29.27 | 5.15 | 6.8 | $0.67 \pm 0.06 \pm 0.05$ | 39.52±12.04 | 1.65 | 16.6 | $0.23 \pm 0.07 \pm 0.04$ |
| (0.8, 1.0) | 54.23±13.36 | 3.36 | 7.6 | $0.16 \pm 0.04 \pm 0.02$ | 2.53±5.65 | 1.40 | 78.4 | $0.02 \pm 0.04 \pm 0.02$ |
| sum | 2989.62±75.03 | 5.62 | 4.7 | $5.25 \pm 0.13 \pm 0.25$ | 214.89±29.31 | 1.71 | 8.9 | $1.23 \pm 0.17 \pm 0.11$ |




- The use of x removes the beam-energy dependence from the comparison of the continuum data to that taken at the $\Upsilon(1S)$ resonance.
- An unbinned extended simultaneous likelihood fit is applied to the x-dependent $\Psi$ spectra to extract the signal yields in the $\Upsilon(1S)$ and continuum data samples.

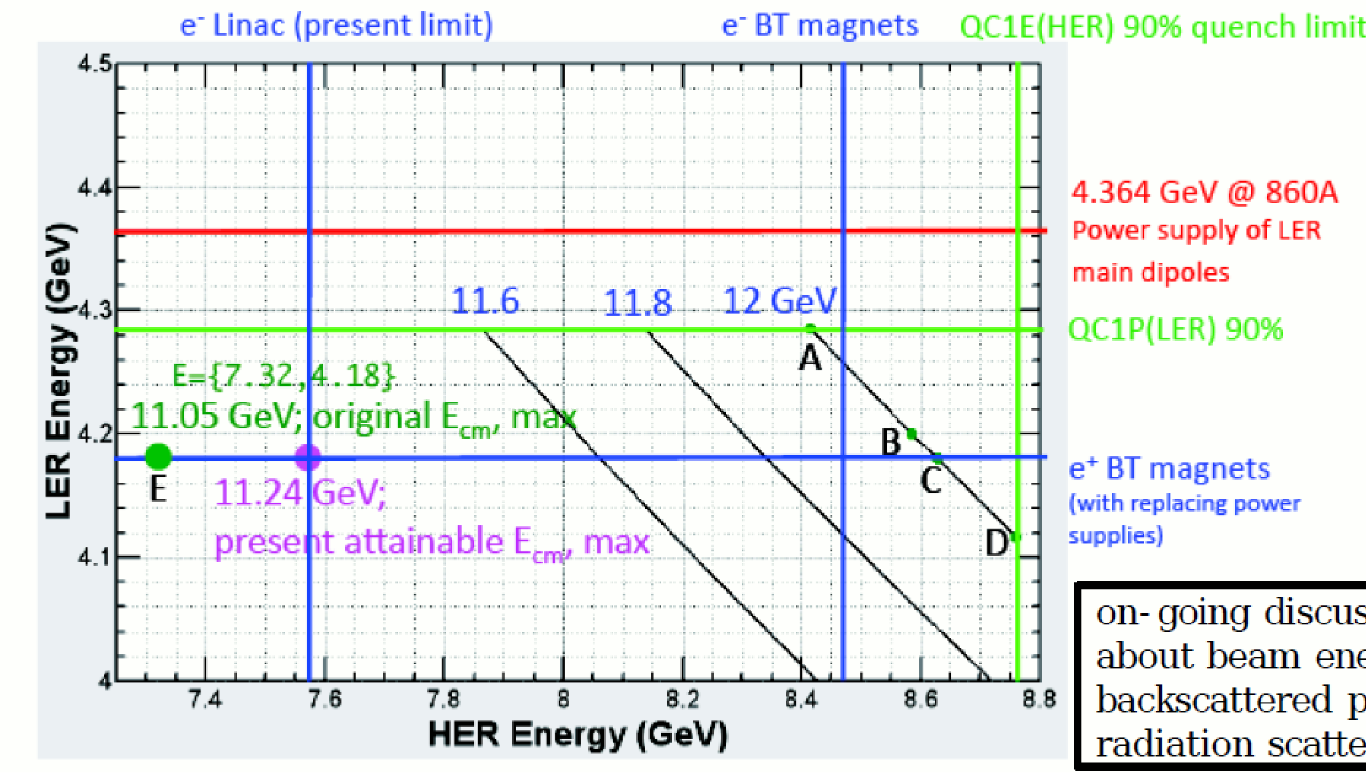
Ours have smaller central values and much better precision than the PDG averages

# Higher energy run

from K. Akai, BPAC Feb 2012

- Design: original design maximum energy is 11.05 GeV at $\Upsilon(6S)$
- Possible higher energy run (11.5 GeV – 12 GeV) ?
  - If any, higher energy run will be after several years running at $\Upsilon(4S) \sim \Upsilon(6S)$
  - **present max $E_{cm}$ is 11.24 GeV**, limited by $e^-$ Linac and $e^+$ BT magnets
  - In order to inject the electron beam to HER at the required energy for 12 GeV operation, there must be huge reinforcement of Linac (replacement of S-band with C-band, 7.571 → 8.6 GeV

11.24 GeV region: $\Lambda_b \overline{\Lambda}_b$ threshold




e.g. [arXiv:1211.0103]

on-going discussion with SuperKEKB people about beam energy measurement using backscattered photons produced by laser radiation scattered head-on the beams