Bottomonium decays and $e^+e^- \to \omega\chi_{bJ}$ scan at Belle

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On behalf of Belle Collaboration

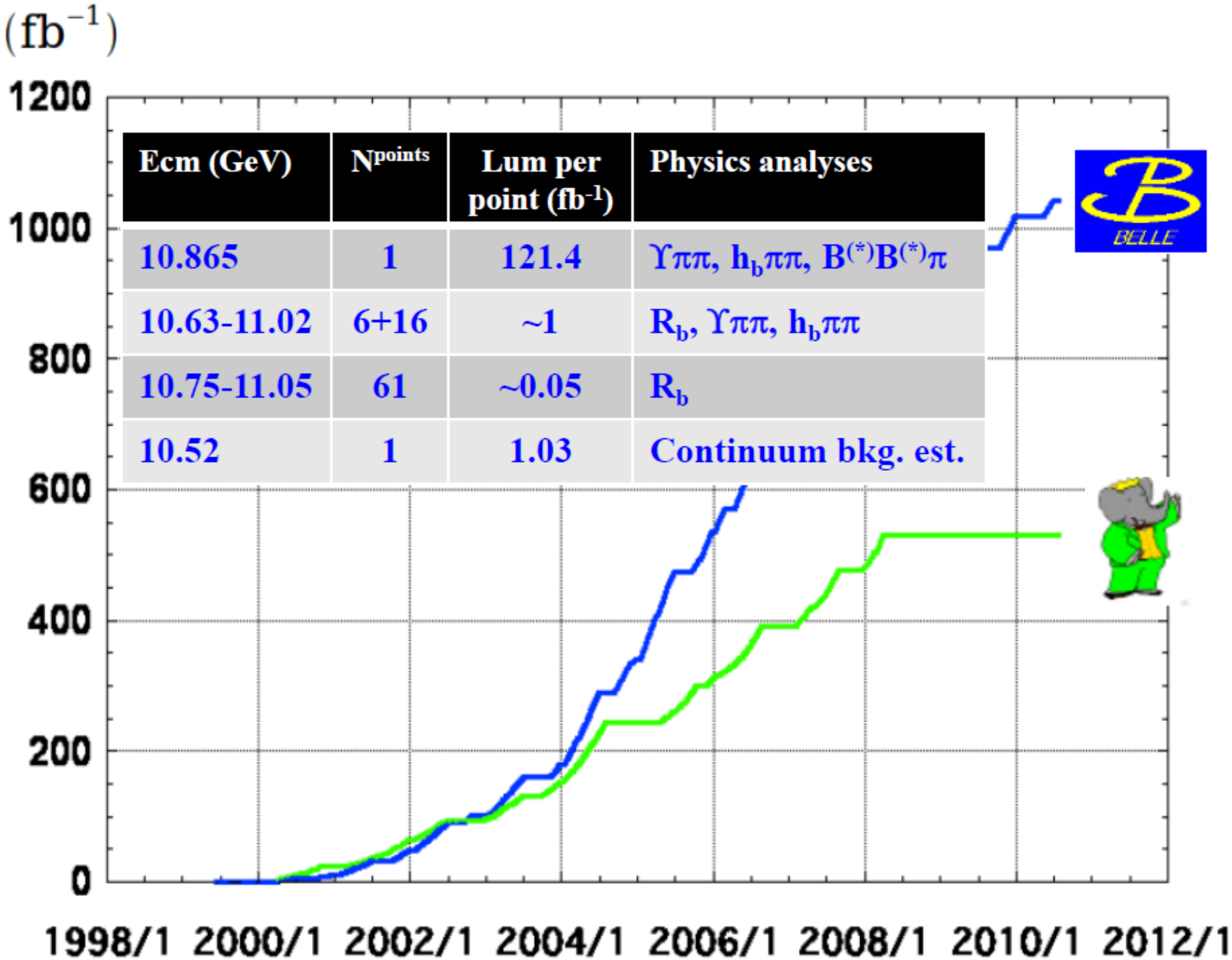
Outline

- $\Upsilon(nS) \to Z_c^{(\prime)} Z_c^{(\prime)}$

- $\Upsilon(1,2,3S) \to \Omega^- + X$

- $e^+e^- \to \omega\chi_{bJ}$ and $\phi\chi_{bJ}$

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.

Belle data

> 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}

$\Upsilon(1,2S)/e^+e^- \to Z_c^+ Z_c^{(\prime)-}$ PRD97, 112004 (2018)

- Double Z_c production provide experimental inputs

PLB 764,174(2017); PRD 91, 114025 (2015).

- Tag one Z_c with $\pi^{\pm}J/\psi, \pi^{\pm}\chi_{c1}, \pi^{\pm}\psi(2S)$

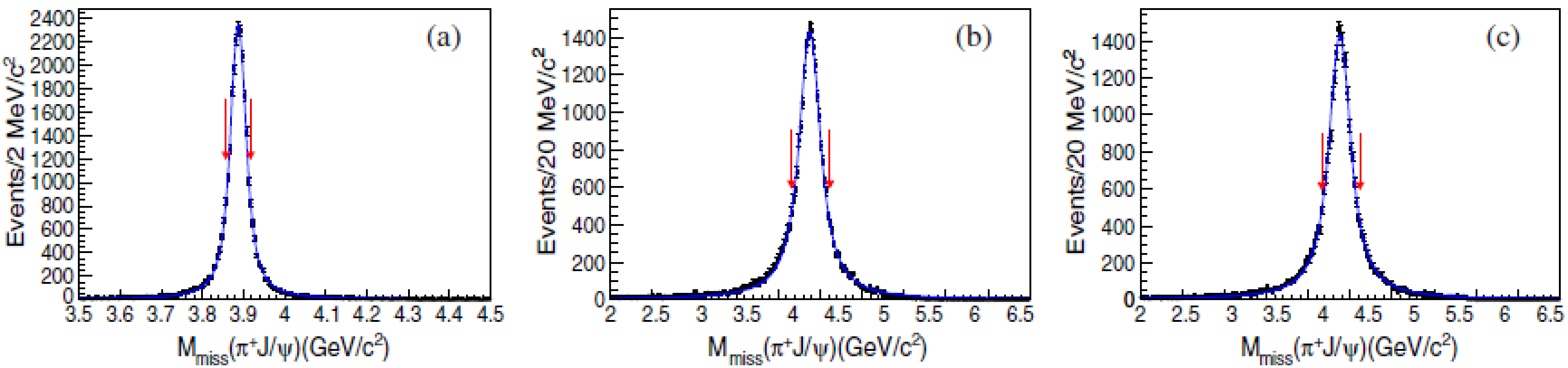
Z_c states	Z_c labels in Ref. [23]	Mass	Width
$Z_c^+(3900)$	$X^+(3900)$	3886.6 ± 2.4	28.1 ± 2.6
$Z_c^+(4200)$	$X^+(4200)$	4196^{+35}_{-32}	370^{+100}_{-150}
$Z_{c1}^+(4050)$	$X^+(4050)$	4051^{+24}_{-40}	82^{+50}_{-28}
$Z_{c2}^+(4250)$	$X^+(4250)$	4248^{+190}_{-50}	177^{+320}_{-70}
$Z_c^+(4050)$	$X^+(4055)$	4054 ± 3.2	45 ± 13
$Z_c^+(4430)$	$X^+(4430)$	4478^{+15}_{-18}	181 ± 31

Ref. [23] cited PDG here

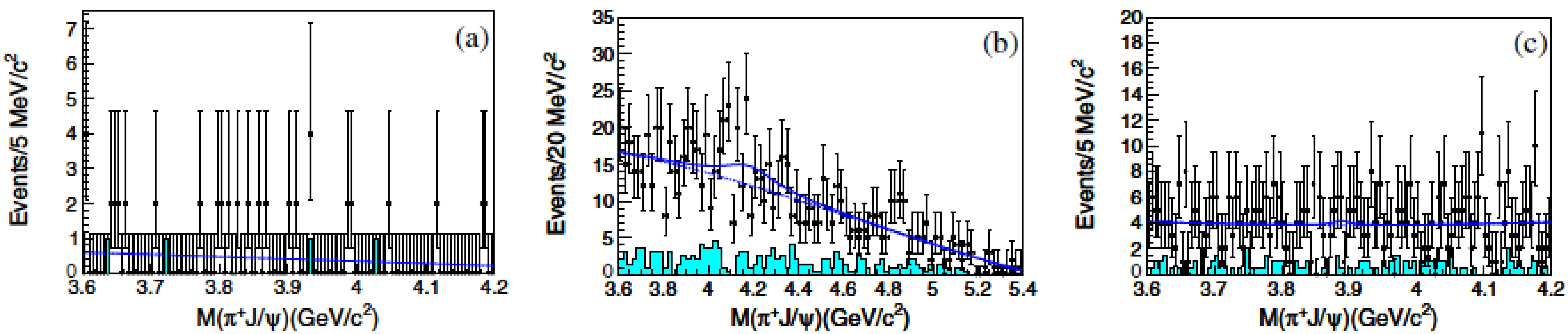
- The missing mass should be within the mass window of $Z_c^{(\prime)}$

- Use $\Upsilon(1S) \to Z_c + X, Z_c \to \pi^{\pm} J/\psi$ as an example
- The recoiling mass should be satisfy
  - $|M_{miss} - m_{Z_c(3900)}| < 0.03\ \mathrm{GeV/c^2}$
  - or $|M_{miss} - m_{Z_c(4200)}| < 0.21\ \mathrm{GeV/c^2}$

MC simulation for (a)$Z_c(3900)Z_c(3900)$ (b) $Z_c(4200)Z_c(4200)$ (c) $Z_c(3900)Z_c(4200)$

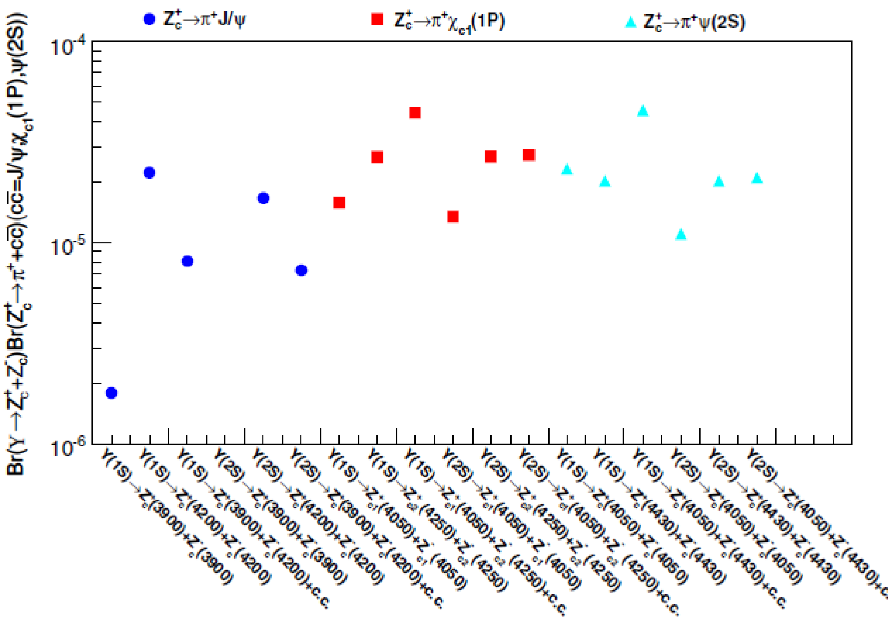


Fit to $M(\pi^{\pm} J/\psi)$ after missing mass requirement

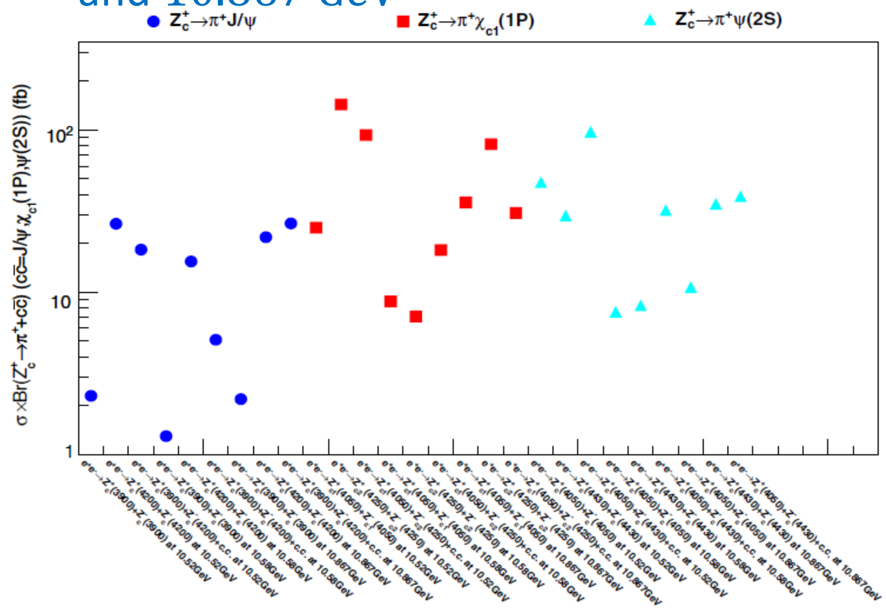


- No evident signal is found in every signal channel.
- Upper limits are obtained at 90% C.L.

$B(\Upsilon(1,2S) \to Z_c Z_c)$



Born cross section at $\sqrt{s} = 10.52, 10.58$ and 10.867 GeV



- Didn't deny the expectation, which is much lower than the measured production cross section.

Observation of an excited Ω^- in $\Upsilon(1,2,3S)$ decays

PRL 121, 052003 (2018)

Decay chain:

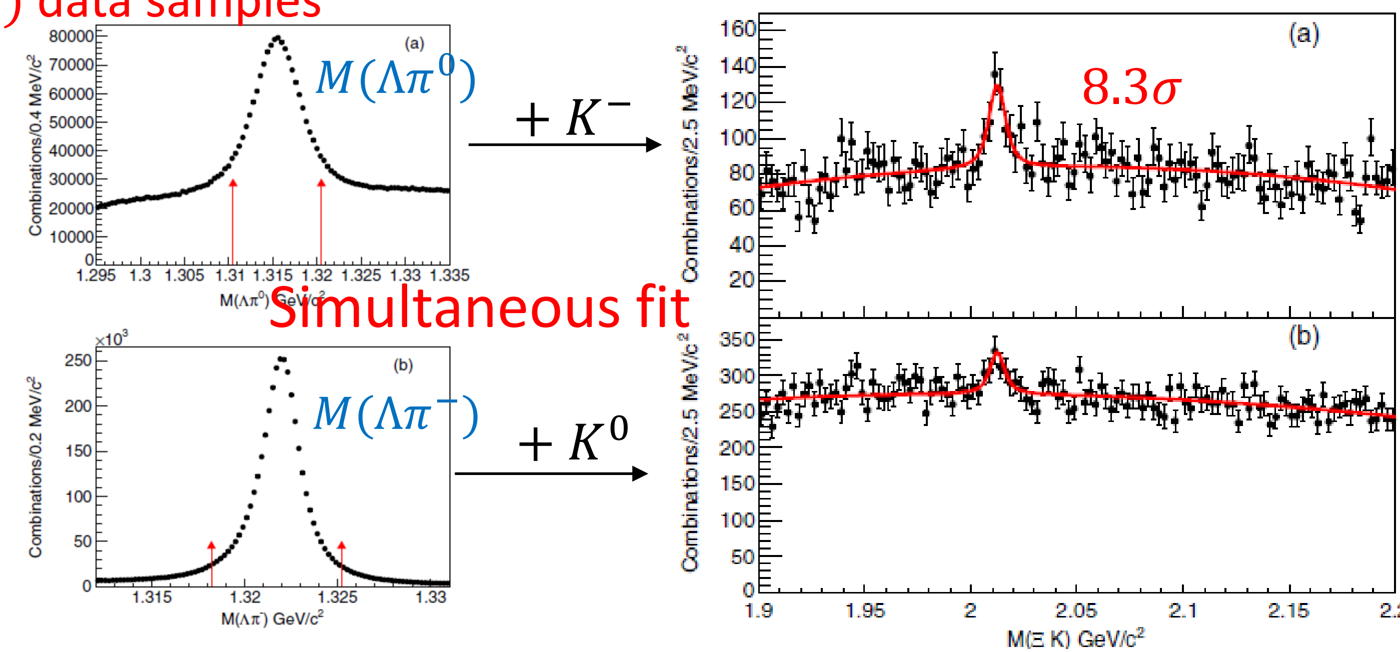
$\Omega^- \rightarrow \Xi^0 K^-$ and $\Xi^- \overline{K}^0$

$\Xi^- \rightarrow \Lambda\pi^-$

$\Xi^0 \rightarrow \Lambda\pi^0$

$\Lambda \rightarrow p\pi^-, K^0 \rightarrow \pi^+\pi^-, \pi^0 \rightarrow \gamma\gamma$

$\Upsilon(1,2,3S)$ data samples

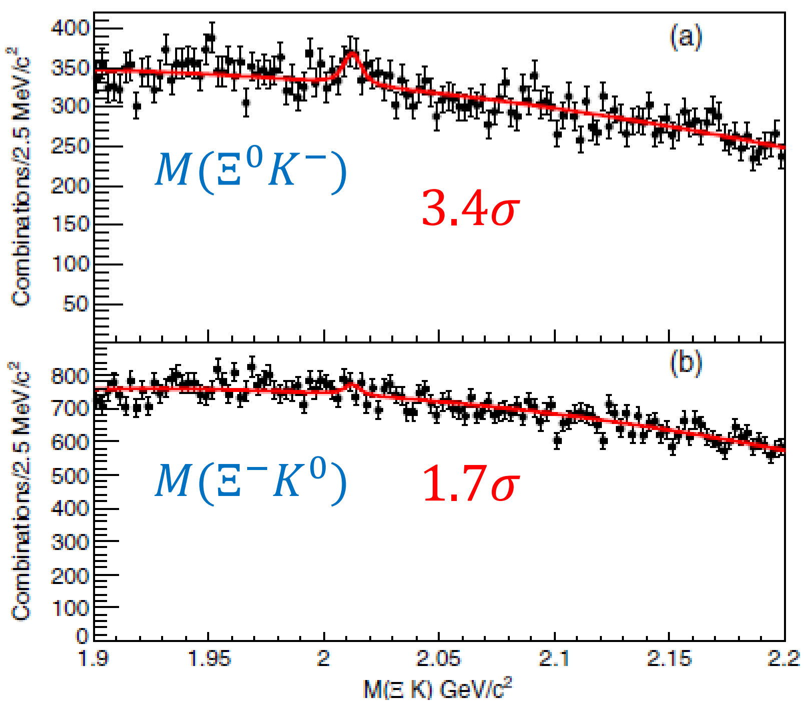


$M = 2012.4 \pm 0.7 \pm 0.6\ \mathrm{MeV/c^2}, \Gamma = 6.4^{+2.5}_{-2.0} \pm 1.6\ \mathrm{MeV}$

Independent fit result shows good agreement with that from simultaneous fit.

$340\ \mathrm{MeV}/\mathrm{c}^2$ higher than the ground state

Data	Mode	Mass (MeV/c^2)	Yield	Γ(MeV)	χ^2/d.o.f.	n_σ
$\Upsilon(1S,2S,3S)$	$\Xi^0 K^-$, $\Xi^- K_S^0$ (simultaneous)	2012.4 ± 0.7	242 ± 48, 279 ± 71	$6.4^{+2.5}_{-2.0}$	227/230	8.3
$\Upsilon(1S,2S,3S)$	$\Xi^0 K^-$	2012.6 ± 0.8	239 ± 53	6.1 ± 2.6	115/114	6.9
$\Upsilon(1S,2S,3S)$	$\Xi^- K_S^0$	2012.0 ± 1.1	286 ± 87	6.8 ± 3.3	101/114	4.4
Other	$\Xi^0 K^-$	2012.4 (fixed)	209 ± 63	6.4 (fixed)	102/116	3.4
Other	$\Xi^- K_S^0$	2012.4 (fixed)	153 ± 89	6.4 (fixed)	133/116	1.7



Check with other datasets.

More data, less signal.

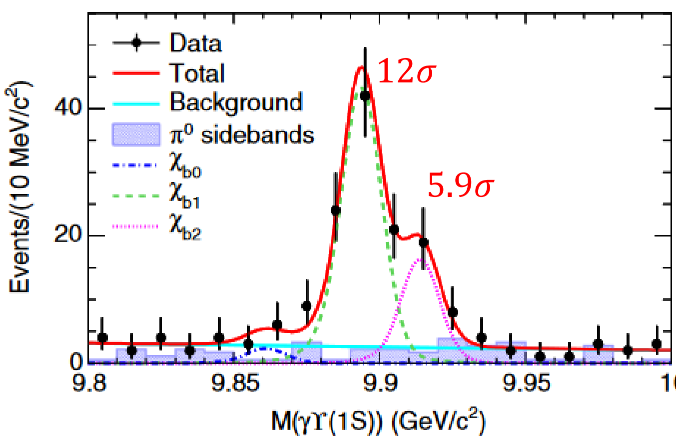
Primarily in the decay of $\Upsilon(1,2,3S)$

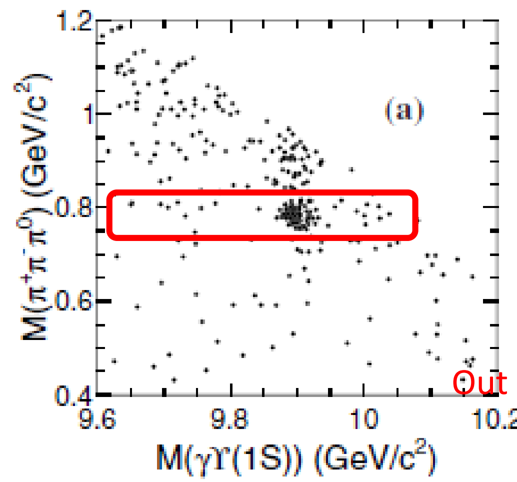
PRL 121, 052003 (2018)

$\Upsilon(5S) \to \omega\chi_{bJ}$

PRL **113**, 142001(2014)

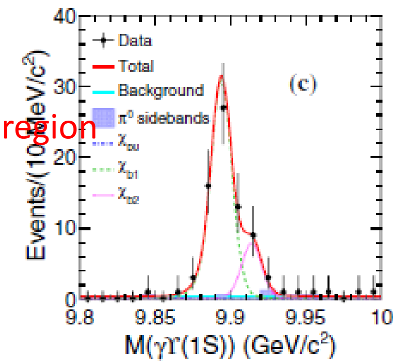
- Use $\Upsilon(5S)$ on-resonance data.
- Fully construction, $\chi_{bJ} \to \Upsilon(1S)\gamma$, $\Upsilon(1S) \to l^+l^-$
- $\omega\chi_{b1/b2}$ are observed for the first time in e^+e^- annihilation.
- Also, very clear signal of $\pi^+\pi^-\pi^0\chi_{b1,2}$



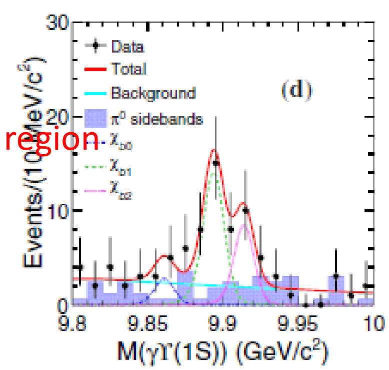


Previous result

Within signal region



Out of signal region

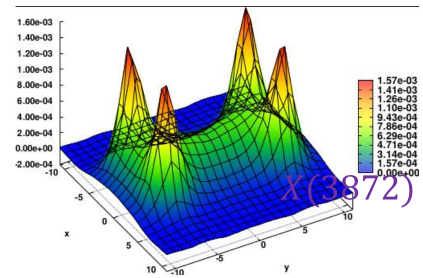


From the 2D fit of the $M(\pi^+\pi^-\pi^0)$ vs $M(\gamma\Upsilon(1S))$:

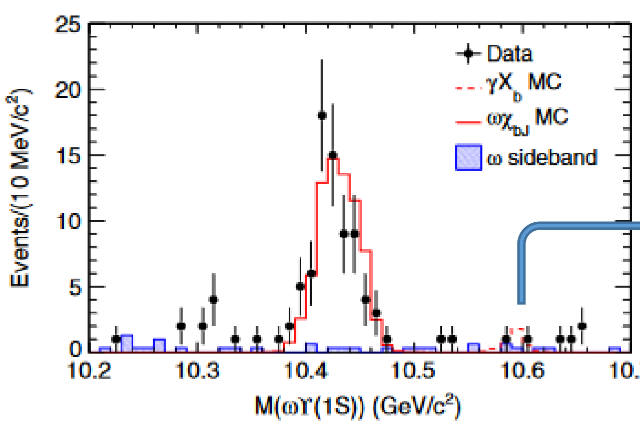
PRL **113**, 142001(2014)

Mode	Yield	Σ (σ)	ε (%)	$\sigma_{\mathcal{B}}$ (pb)	$\mathcal{B}$ (10^{-3})	$\sigma_{\rm sys}^{(1)}$ (%)	$\sigma_{\rm sys}^{(2)}$ (%)
$\pi^+\pi^-\pi^0\chi_{b0}$	< 13.6	1.0	6.43	< 3.1	< 6.3	25	24
$\pi^+\pi^-\pi^0\chi_{b1}$	80.1 ± 9.9	12	6.61	$0.90 \pm 0.11 \pm 0.13$	$1.85 \pm 0.23 \pm 0.23$	14	12
$\pi^+\pi^-\pi^0\chi_{b2}$	28.6 ± 6.5	5.9	6.65	$0.57 \pm 0.13 \pm 0.08$	$1.17 \pm 0.27 \pm 0.14$	14	12
$\omega\chi_{b0}$	< 7.5	0.5	6.35	< 1.9	< 3.9	29	28
$\omega\chi_{b1}$	59.9 ± 8.3	12	6.53	$0.76 \pm 0.11 \pm 0.11$	$1.57 \pm 0.22 \pm 0.21$	14	13
$\omega\chi_{b2}$	12.9 ± 4.8	3.5	6.56	$0.29 \pm 0.11 \pm 0.08$	$0.60 \pm 0.23 \pm 0.15$	26	25
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b0}$	< 10.7	0.4	6.68	< 2.3	< 4.8	41	41
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b1}$	23.6 ± 6.4	4.9	6.88	$0.25 \pm 0.07 \pm 0.06$	$0.52 \pm 0.15 \pm 0.11$	21	20
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b2}$	15.6 ± 5.4	3.1	6.91	$0.30 \pm 0.11 \pm 0.14$	$0.61 \pm 0.22 \pm 0.28$	45	45

$\frac{\sigma(e^+e^-\to\omega\chi_{b2})}{\sigma(e^+e^-\to\omega\chi_{b1})} = 0.38 \pm 0.16 \pm 0.09$, where the common systematic uncertainties cancel.



- X_b, $X(3872)$ counterpart in the bottomonium sector.
- X_b is above $\omega\Upsilon(1S)$ threshold, should be a more promising (PRD **88**, 054007(2013)).



No significant signal of X_b is observed.

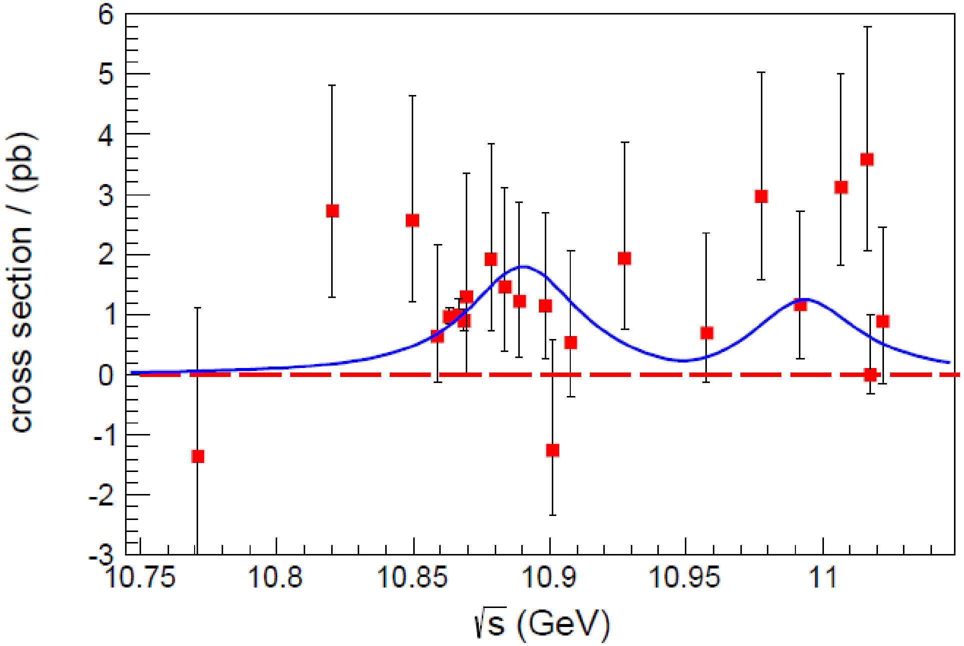
-0.4 ± 2.0 X_b from the fit.

$\mathcal{B}(\Upsilon(10860) \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S)) < 2.9 \times 10^{-5}$ at 90% C.L.

Update of $\Upsilon(5S) \to \omega\chi_{bJ}$

Full energy scan data

PRD **98**, 091102(R) (2018)

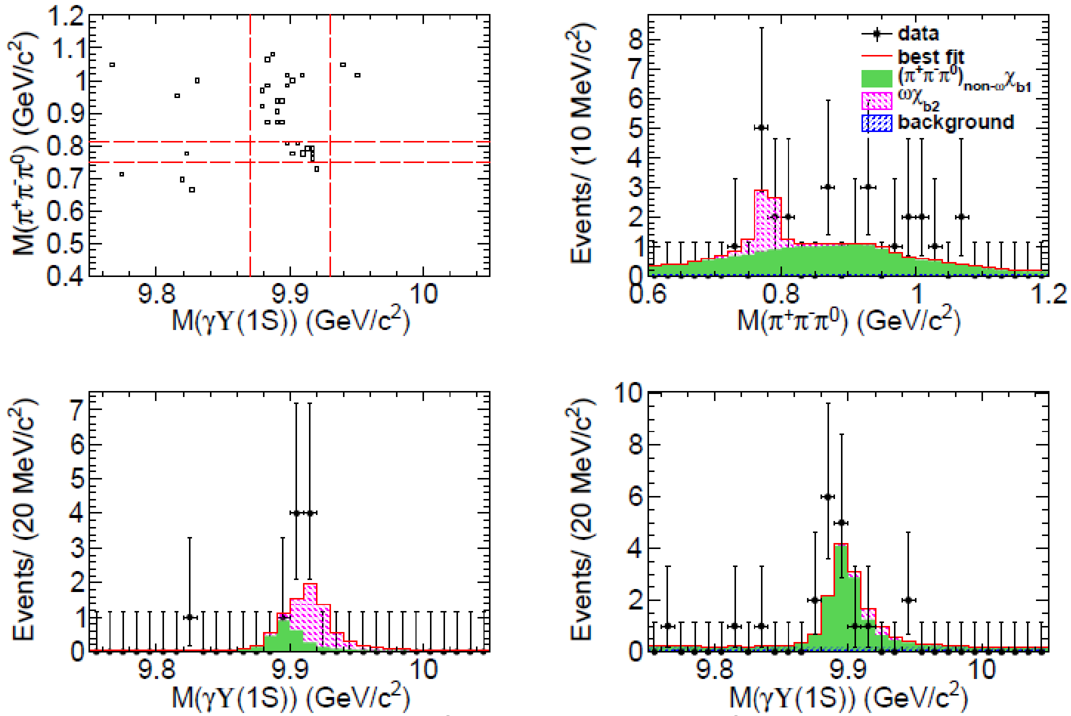


Do not separate ω and $\pi^+\pi^-\pi^0$, nor χ_{b1} and χ_{b2}

- Assume the transition is from $\Upsilon(5S)$ and $\Upsilon(6S)$
  - $B[\Upsilon(5S) \to \pi^+\pi^-\pi^0\chi_{bJ}] = (2.5 \pm 0.6 \pm 2.1 \pm 0.7) \times 10^{-3}$
  - $B[\Upsilon(6S) \to \pi^+\pi^-\pi^0\chi_{bJ}] = (8.7 \pm 4.3 \pm 6.1^{+4.5}_{-2.5}) \times 10^{-3}$
  - Main systematic uncertainty rises from the assumption. Consistent with previous work.

$\Upsilon(6S) \to \pi^+\pi^-\pi^0\chi_{bJ}$

For data in
$10.96 - 11.05$ GeV



- 2D fit with $\omega\chi_{b1}, \omega\chi_{b2}, \pi^+\pi^-\pi^0\chi_{b1}, \pi^+\pi^-\pi^0\chi_{b2}$. The significances are $0.0\sigma, 5.3\sigma, 2.5\sigma, 0.0\sigma$.
- 2D fit $\omega\chi_{b2}$ and $\pi^+\pi^-\pi^0\chi_{b1}$. The significances are 6.1σ and 4.0σ.
- Observation for $\Upsilon(6S) \to \pi^+\pi^-\pi^0\chi_{b1}$ and evidence for $\Upsilon(6S) \to \omega\chi_{bJ}$

$$R_{21} \equiv \frac{B[\Upsilon(6S)\to\omega\chi_{b2}]}{B[\Upsilon(6S)\to\omega\chi_{b1}]} = 0.4 \pm 0.2,\ (\sim 1.7\Sigma \text{ from the prediction})$$

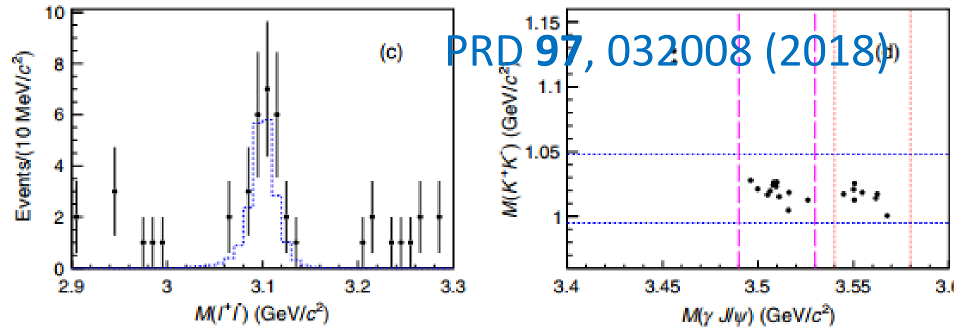
EPJC 77, 165(2017)

$\Upsilon(6S) \to \phi\chi_{bJ}$

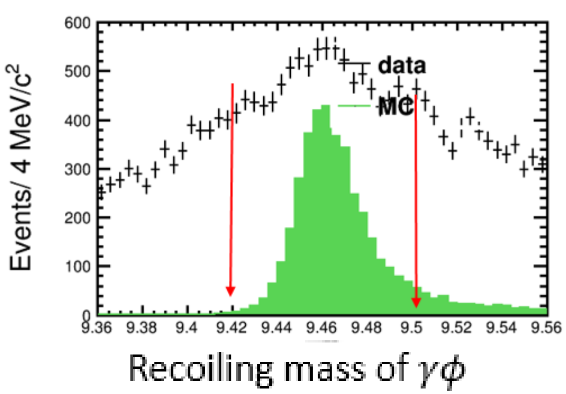
- BESIII observed the process $e^+e^- \to \phi\chi_{cJ}$ [PRD **97**, 032008 (2018)], which might be $\psi(4415,4660) \to \phi\chi_{cJ}$.
- The hadronic loop effect theory gives the prediction

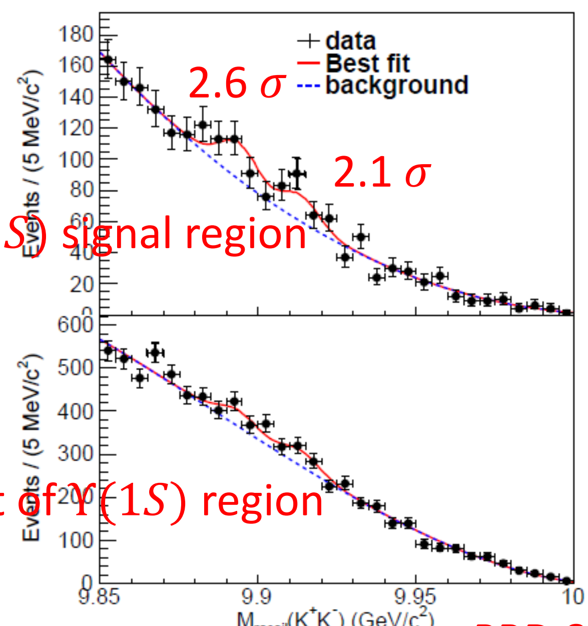
$$B[\Upsilon(6S) \to \phi\chi_{bJ}] \sim 10^{-6}$$

$$R_{21} \equiv \frac{B[\Upsilon(6S) \to \phi\chi_{b2}]}{B[\Upsilon(6S) \to \phi\chi_{b1}]} \sim 4.43$$



PRD **97**, 032008 (2018)





Average Born cross section: < 0.7 pb and < 1.0 pb for $e^+e^- \to \phi\chi_{b1}$ and $\phi\chi_{b2}$, respectively.

PRD **98**, 091102(R) (2018)

Summary

- A new excited Ω baryon state is observed
  - $M = 2012.4 \pm 0.7 \pm 0.6\ \mathrm{MeV/c^2}, \Gamma = 6.4^{+2.5}_{-2.0} \pm 1.6\ \mathrm{MeV}$
  - More likely to be a $\frac{3}{2}^-$ state described in Ref.[PRD 34, 2809 (1986)]
- Double exotic states search is performed
  - Not in contradiction with the expectation
- $\pi^+\pi^-\pi^0\chi_{bJ}$ is observed in $\Upsilon(6S)$ energy region
  - Make Analogy between $\Upsilon(5,6S)$ and $\psi(4660)$. Will there be more interesting physics?