Study of exotic hadrons at Belle

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(For the Belle Collaboration)

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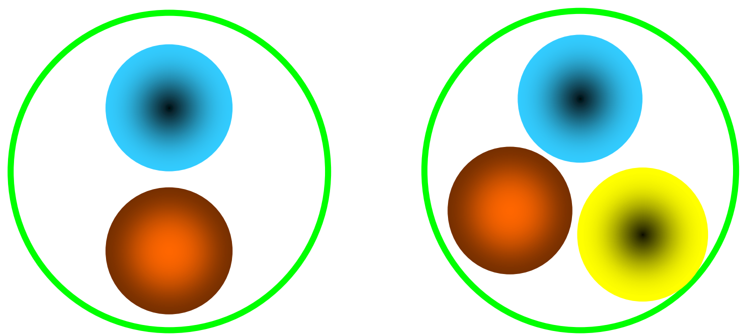
Hadrons：normal & exotic

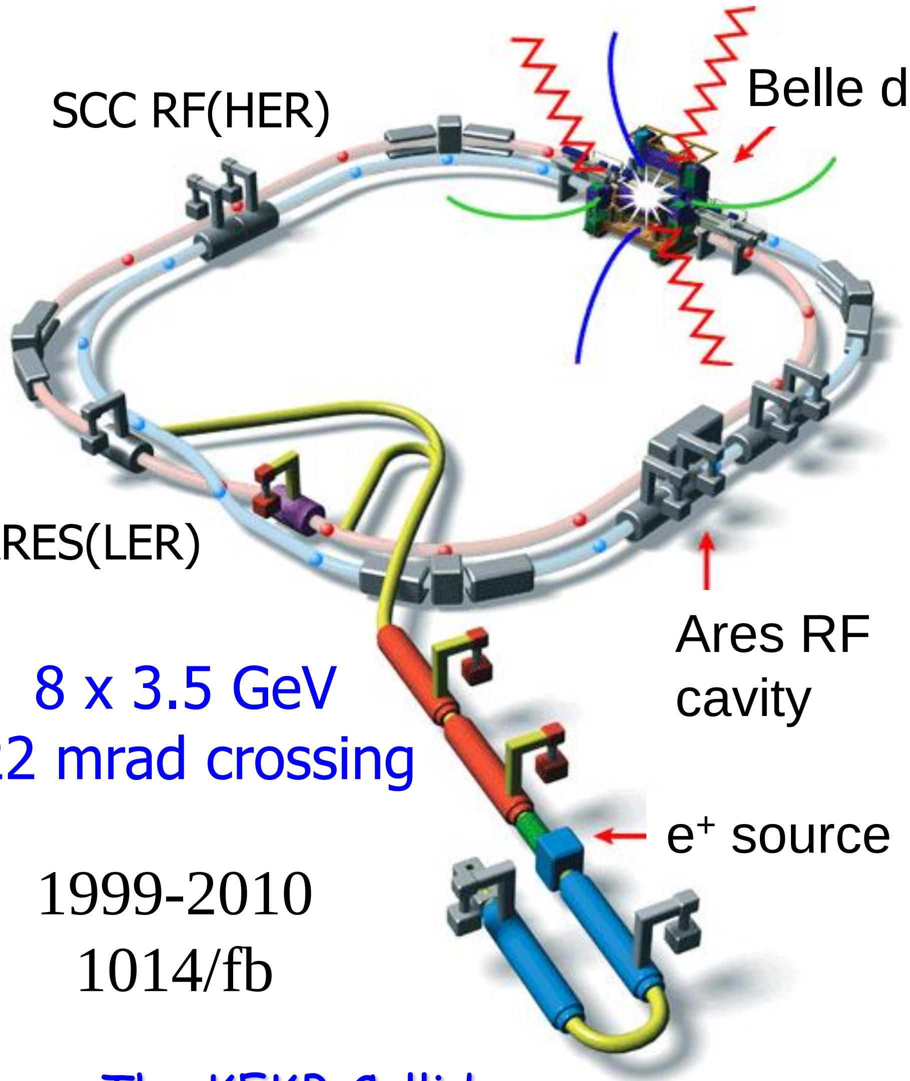
- Hadrons are composed from 2 (meson) quarks or
  3 (baryon) quarks

Quark model



- QCD doesnot 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

The Belle experiment



8 x 3.5 GeV
22 mrad crossing

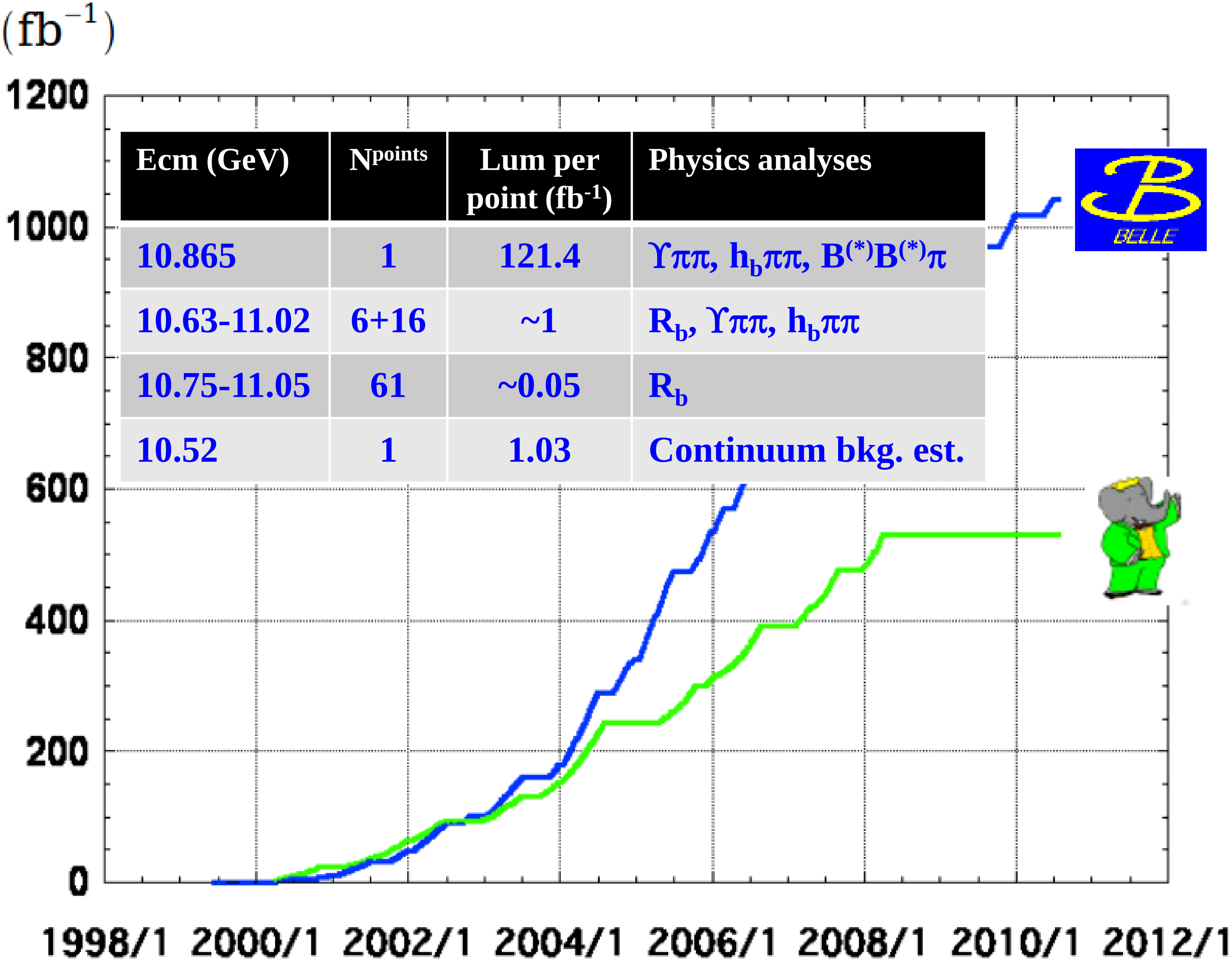
1999-2010
1014/fb

The KEKB Collider

World record:

$L = 2.1 \times 10^{34}/cm^2/sec$

Integrated luminosity of B factories



Ecm (GeV)	Npoints	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}

Outline

- $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$, $\pi^+\pi^- h_b(nP)$, $B^{(*)}B^{(*)}\pi$
  - $\Upsilon(5S)$, $\Upsilon(6S)$, Z_b
- $e^+e^- \rightarrow \pi^+\pi^-\psi(nS)$, $J/\psi\ \bar{D}D$
  - Y(4260), Y(4360), Y(4660), Z_c, X*(3860)
- JPC=0−− glueball, $P_s \rightarrow \phi p$ in Λ_c decays
- Summary and perspectives

$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

- tag $\Upsilon(nS)\to\mu^+\mu^-$ and select $\pi^+\pi^-$, fit to $|A_{5S}+e^{i\phi}A_{6S}|^2$

$\Upsilon(5S)$:

Mass = $(10891.9 \pm 3.2 \pm^{0.6}_{1.5})$ MeV

Width = $(53.7 \pm^{7.1}_{5.6} \pm^{0.9}_{5.4})$ MeV

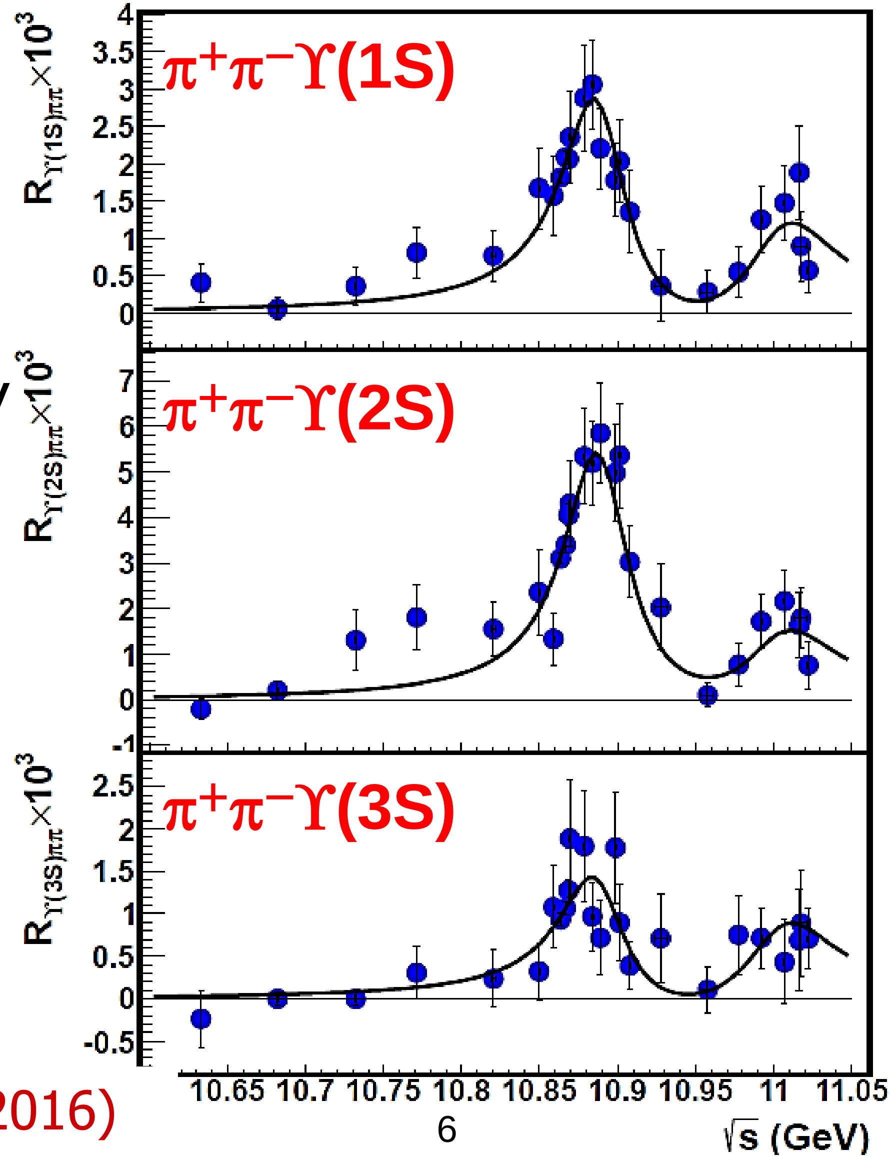
$\Upsilon(6S)$:

Mass = $(10987.5 \pm^{6.4}_{2.5} \pm^{2.2}_{2.1})$ MeV

Width = $(61 \pm^{9}_{19} \pm^{2}_{20})$ MeV

$\phi = -1.0 \pm 0.4 \pm^{1.0}_{0.1}$ rad

- Results agree with previous measurements
- Also agree with fit with Rb reasonably well
- Still room for improvement

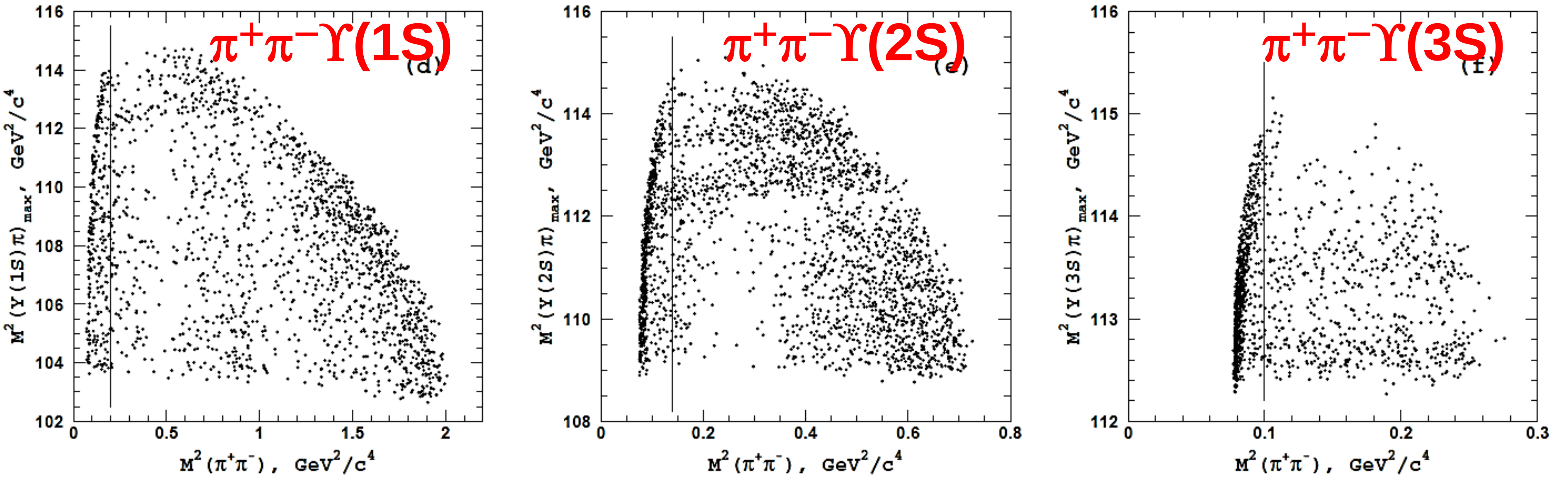


arXiv:1501.01137, PRD 93, 011101(R) (2016)

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

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

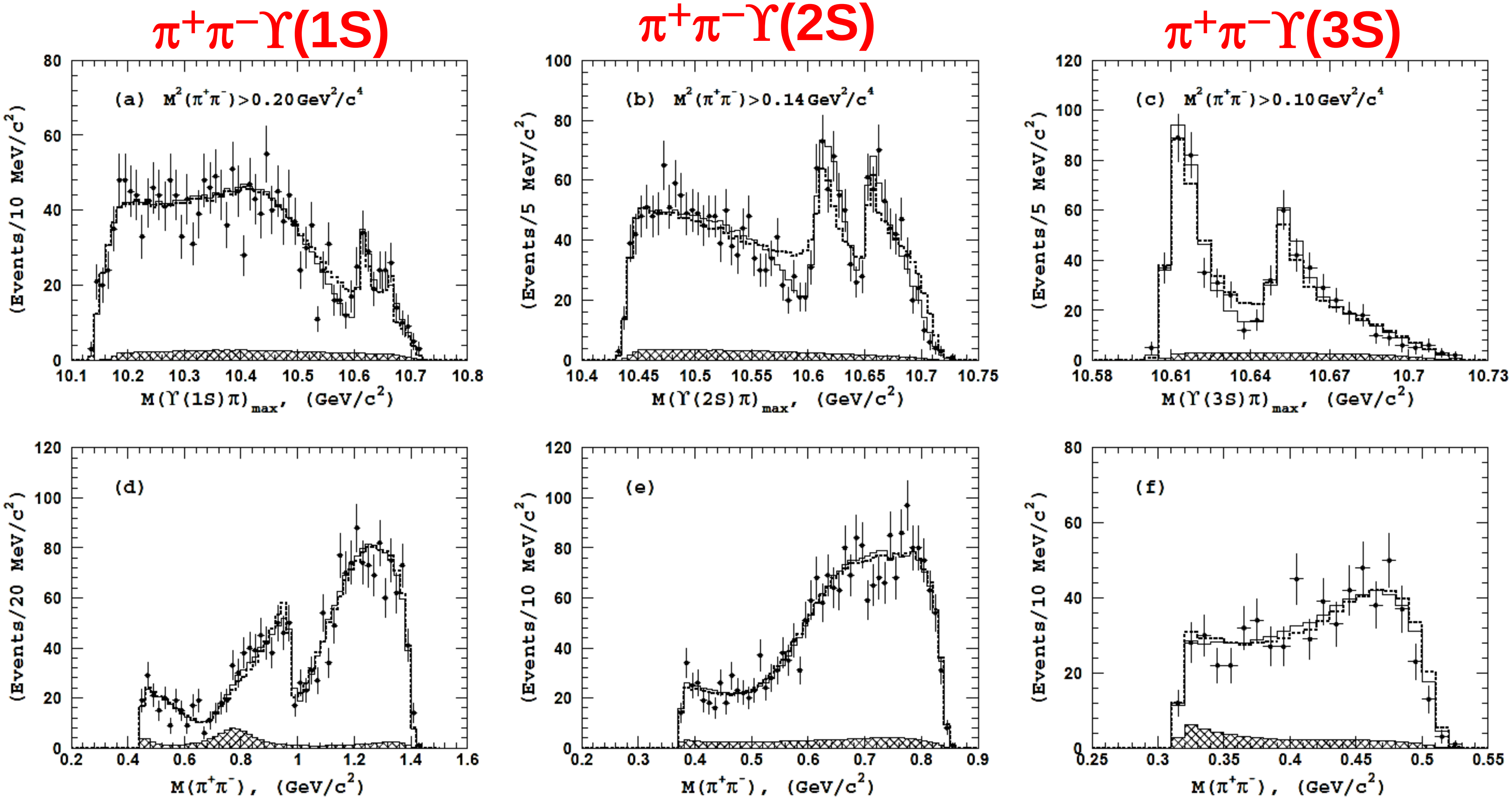
Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
Signal yield	2090 ± 115	2476 ± 97	628 ± 41
Efficiency, %	45.9	39.0	24.4
$\mathcal{B}_{\Upsilon(nS)\to\mu^+\mu^-}$, % [14]	2.48 ± 0.05	1.93 ± 0.17	2.18 ± 0.21
$\sigma^{\rm vis}_{e^+e^-\to\Upsilon(nS)\pi^+\pi^-}$, pb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



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 JP=1+ of Z_b states determined



PRD91, 072003 (2015)

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

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$/c^2$	$12.1^{+11.3+2.7}_{-4.8-0.6}$	$14.2 \pm 3.7^{+0.9}_{-0.4}$	$9.3 \pm 2.2^{+0.3}_{-0.5}$
ϕ_Z, degrees	$67 \pm 36^{+24}_{-52}$	$-10 \pm 13^{+34}_{-12}$	$-5 \pm 22^{+15}_{-33}$
$c_{Z_b(10650)}/c_{Z_b(10610)}$	$0.40 \pm 0.12^{+0.05}_{-0.11}$	$0.53 \pm 0.07^{+0.32}_{-0.11}$	$0.69 \pm 0.09^{+0.18}_{-0.07}$
$f_{\Upsilon(nS)f_2(1270)}$, %	$14.6 \pm 1.5^{+6.3}_{-0.7}$	$4.09 \pm 1.0^{+0.33}_{-1.0}$	$-$
$f_{\Upsilon(nS)(\pi^+\pi^-)_S}$, %	$86.5 \pm 3.2^{+3.3}_{-4.9}$	$101.0 \pm 4.2^{+6.5}_{-3.5}$	$44.0 \pm 6.2^{+1.8}_{-4.3}$
$f_{\Upsilon(nS)f_0(980)}$, %	$6.9 \pm 1.6^{+0.8}_{-2.8}$	$-$	$-$

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

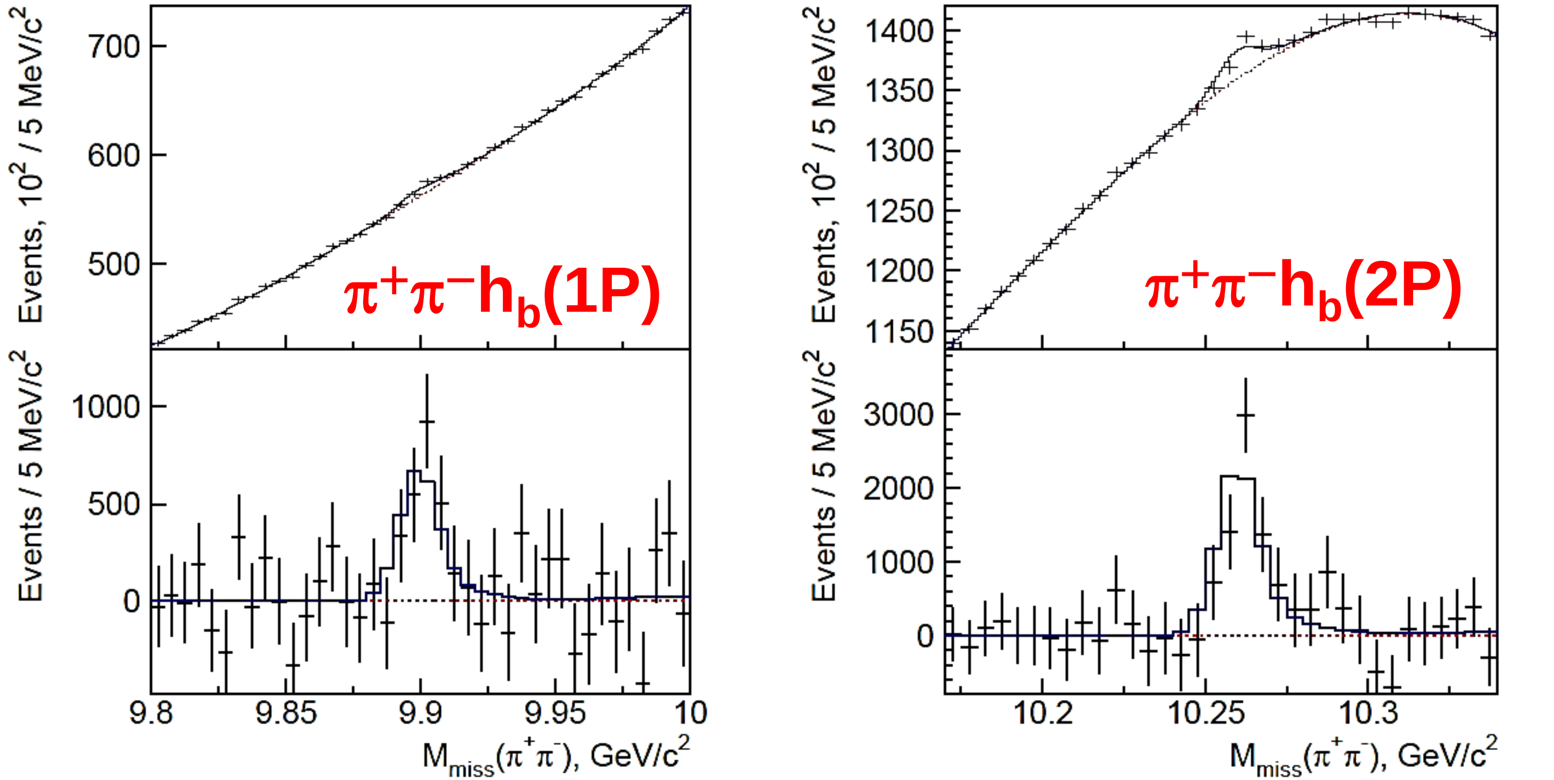
$$\sigma_{Z_b^\pm(10650)\pi^\mp} \times \mathcal{B}_{\Upsilon(1S)\pi^\mp} = 20 \pm 7^{+4}_{-3}\ \text{fb}$$
$$\sigma_{Z_b^\pm(10650)\pi^\mp} \times \mathcal{B}_{\Upsilon(2S)\pi^\mp} = 165 \pm 49^{+43}_{-20}\ \text{fb}$$
$$\sigma_{Z_b^\pm(10650)\pi^\mp} \times \mathcal{B}_{\Upsilon(3S)\pi^\mp} = 194 \pm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

- Relative BR of Z_b decays

PRD91, 072003 (2015)

$e^+e^- \to \pi^+\pi^- h_b(nP)$

- Reconstruct $\pi^+\pi^-$, require π^+/π^- recoil mass in Z_b region: $10.59 < M_{miss}(\pi) < 10.67$ GeV/c^2
- check the $\pi^+\pi^-$ recoil mass for $h_b(nP)$



arXiv:1508.06562, PRL117, 142001 (2016)

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

$\Upsilon(5S)$:

Mass = $(10884.7 \pm^{3.2}_{2.9} \pm^{8.6}_{0.6})$ MeV

Width = $(44.2 \pm^{11.9}_{7.8} \pm^{2.2}_{15.8})$ MeV

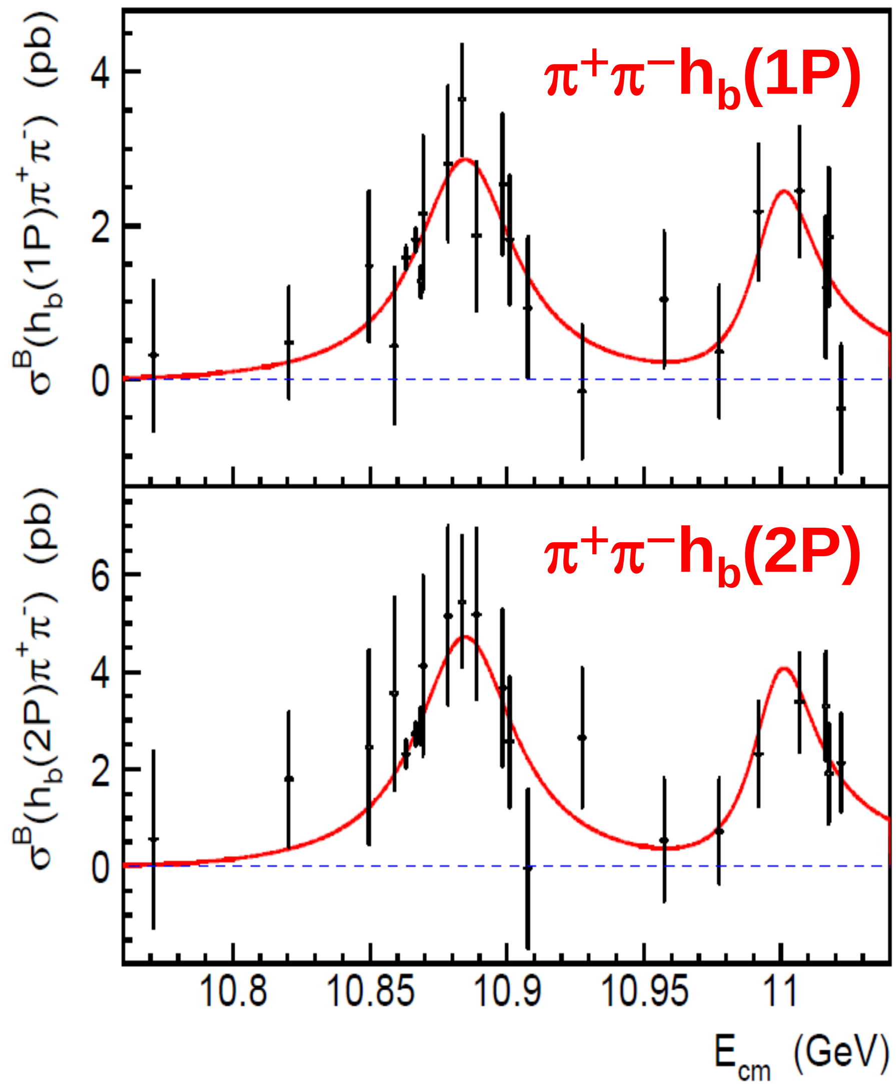
$\Upsilon(6S)$:

Mass = $(10998.6 \pm 6.1 \pm^{16.1}_{1.1})$ MeV

Width = $(29 \pm^{20}_{12} \pm^{2}_{7})$ MeV

$\phi = 0.64 \pm^{0.37}_{0.11} \pm^{0.13}_{0.0}$ rad

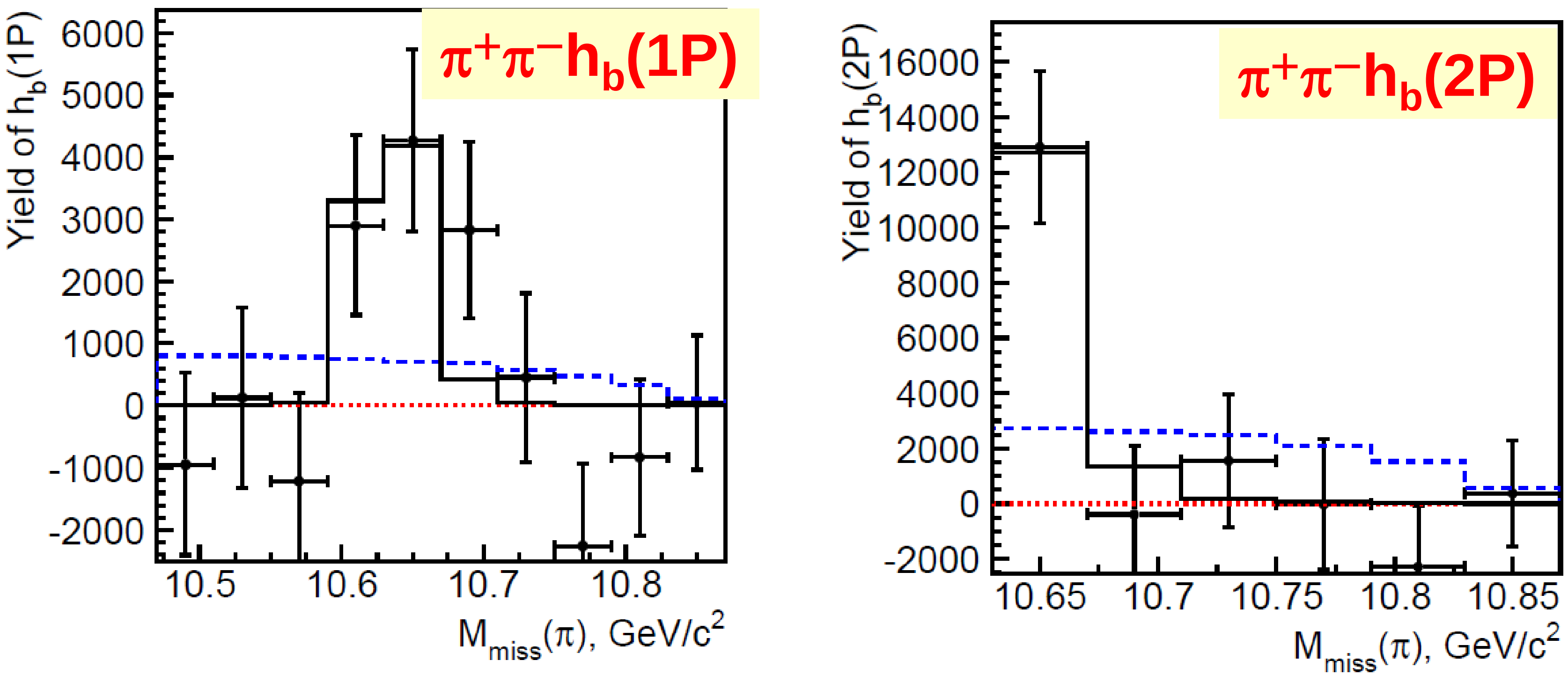
- Resonant parameters agree with from $e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)$
- $e^+e^- \rightarrow \pi^+\pi^- h_b(nP)$ at the same level as $e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)$
- 1st obs. of $\Upsilon(6S) \rightarrow \pi^+\pi^- h_b(nP)$



arXiv:1508.06562, PRL117, 142001 (2016)

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

- Events mainly from Z_b intermediate states
  not clear if only one Z_b or both.
- Belle II will tell us.



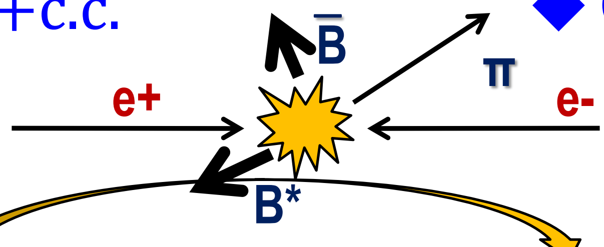
arXiv:1508.06562, PRL 117, 142001 (2016)

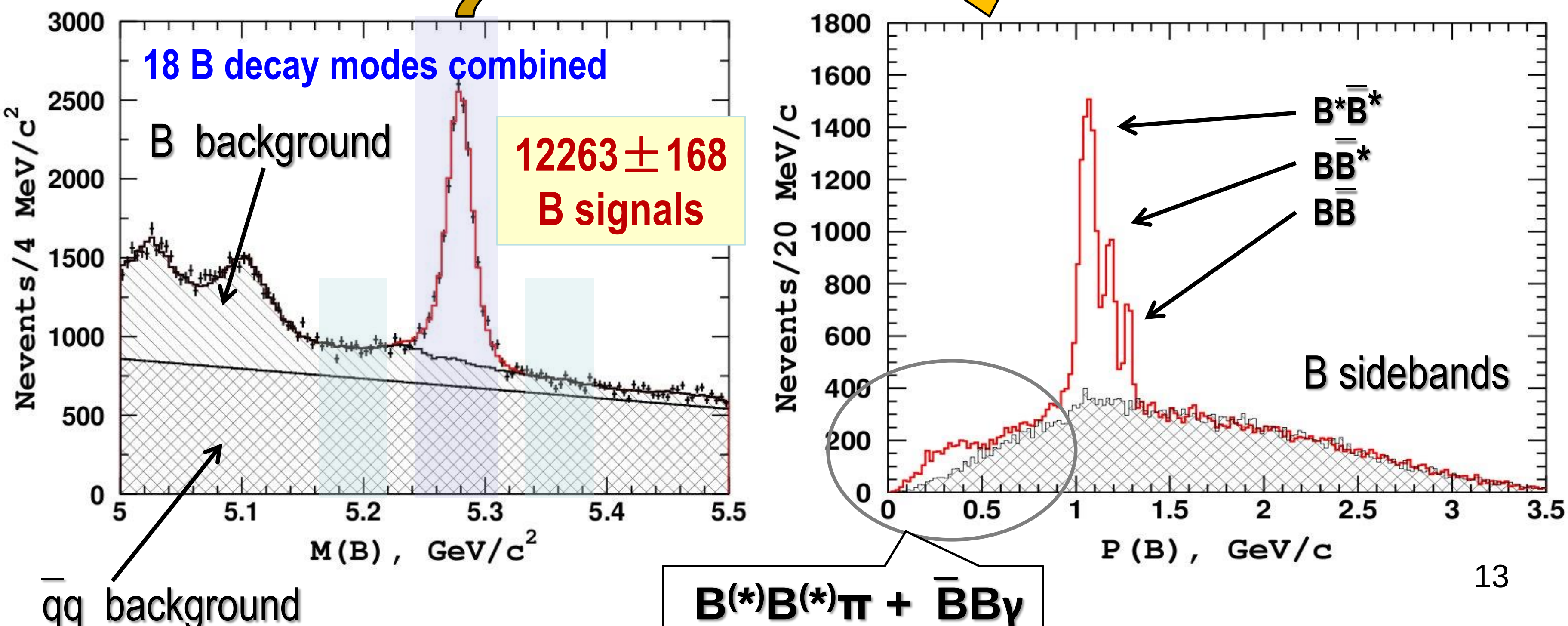
Z_b in $\Upsilon(5S)\to[B^{(*)}B^{(*)}]^+\pi^-+c.c.$

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

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

arXiv:1512.07419, PRL 116, 212001 (2016)

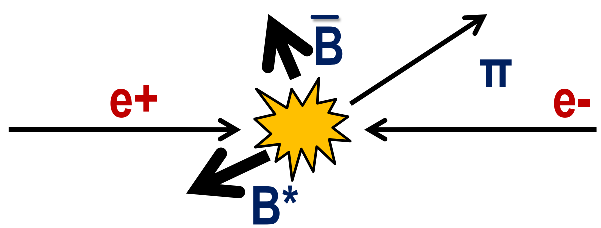


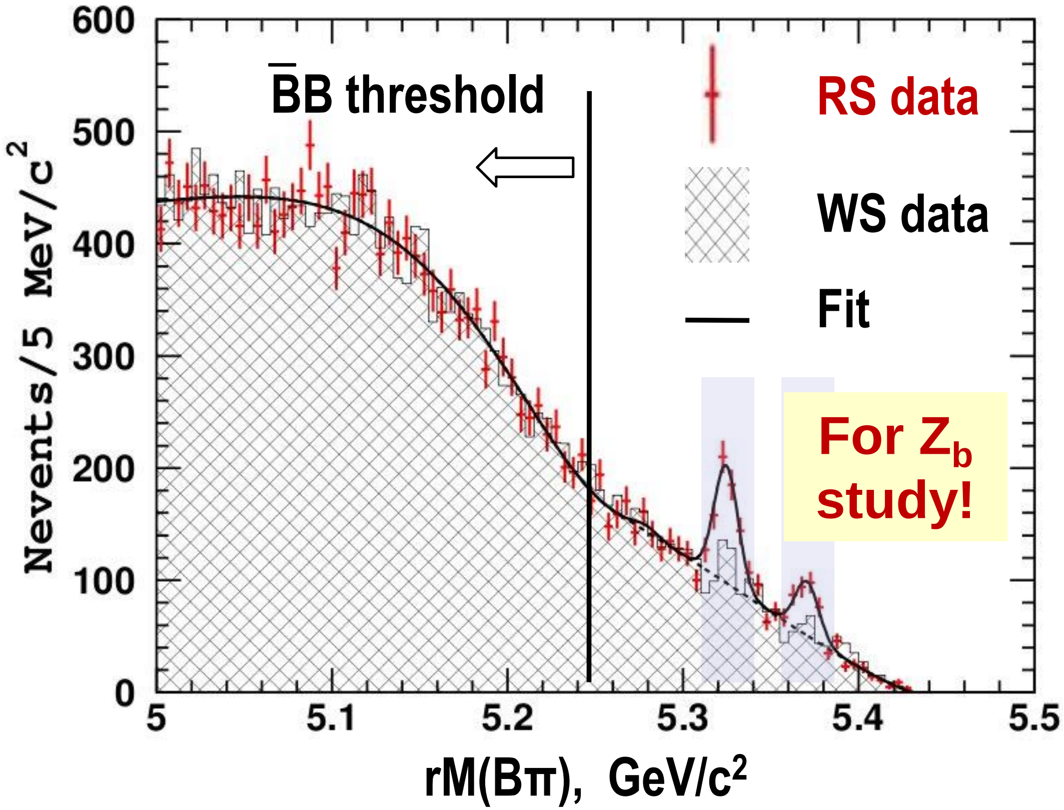


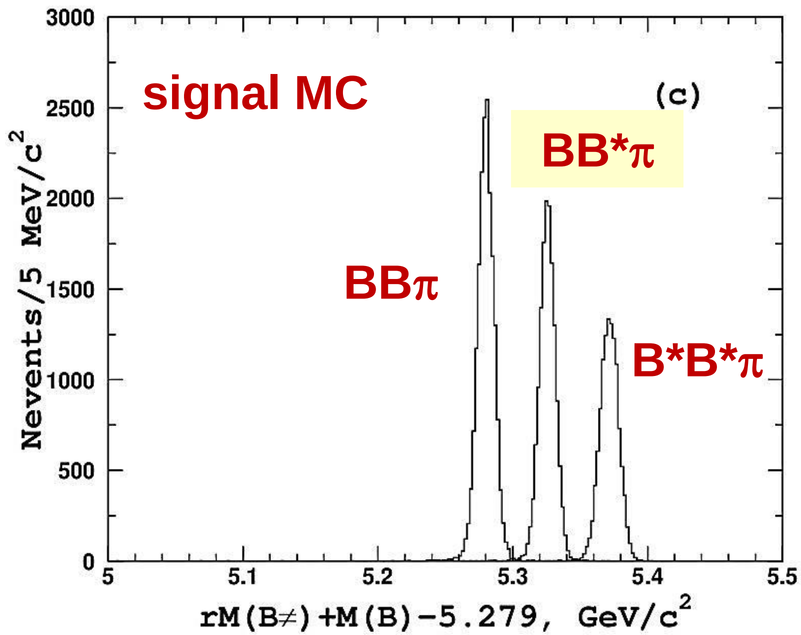
Z_b in $\Upsilon(5S) \to [B^{(*)}B^{(*)}]^+\pi^- + c.c.$

Combine the B with a charged pion

→ calculate recoil mass of $B\pi$







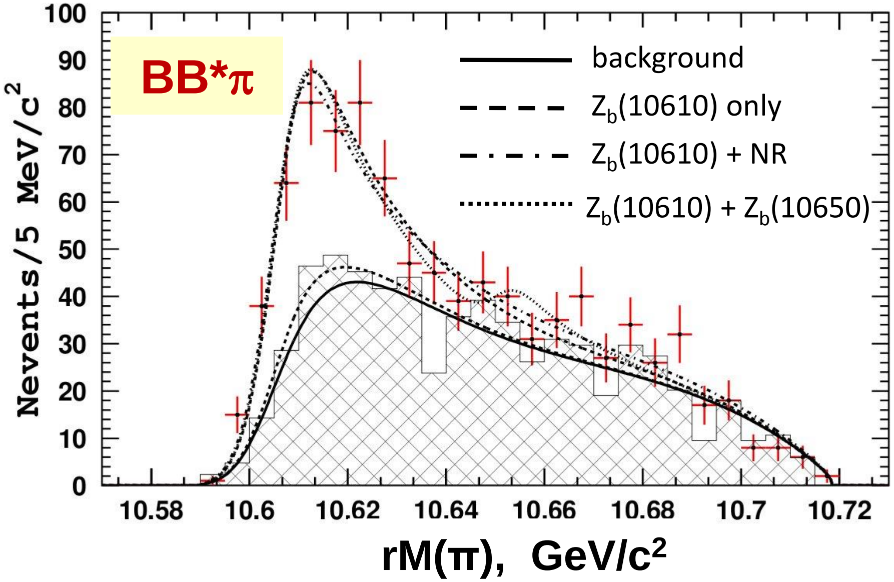
$N(BB\pi) = 13 \pm 25$ $N(BB^*\pi) = 357 \pm 30$ $N(B^*B^*\pi) = 161 \pm 21$

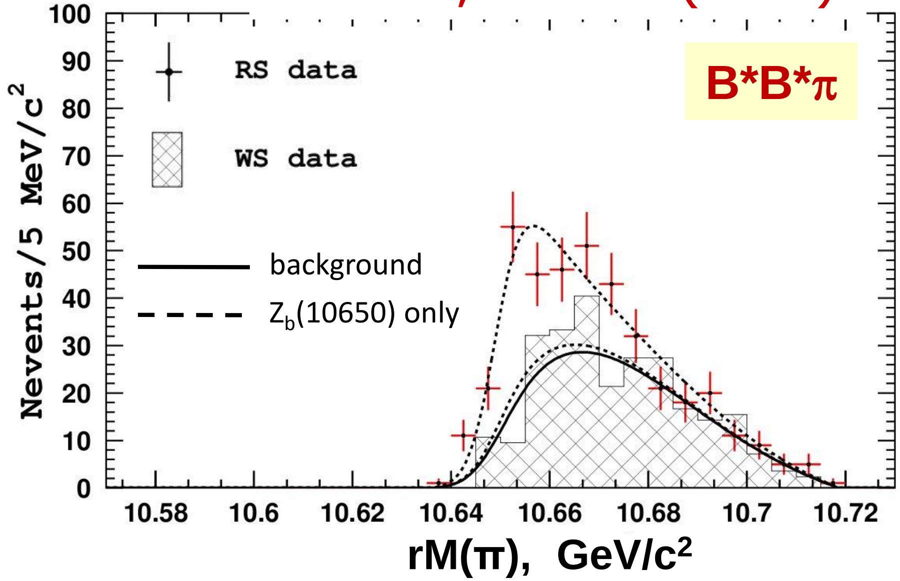
arXiv:1512.07419, PRL116, 212001 (2016)

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

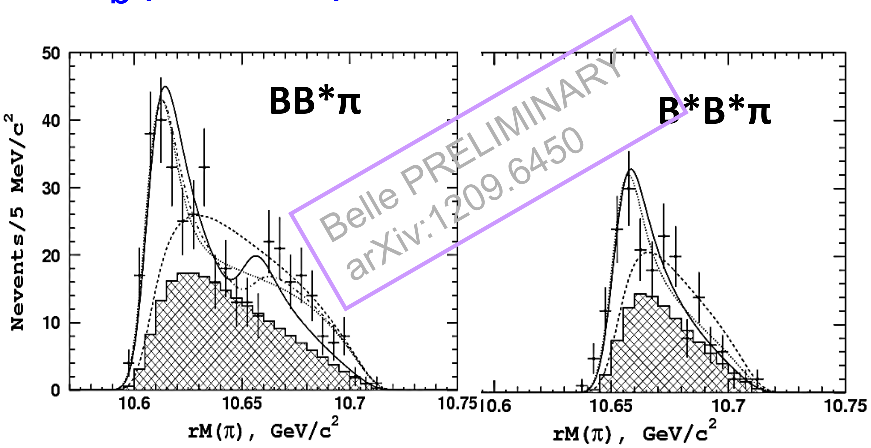
Check recoil mass of bachelor $\pi^{\pm}$

arXiv:1512.07419, PRL116, 212001 (2016)





Z_b(10610) saturates BB*π and Z_b(10650) saturates B*B*π



Assuming Z_b decays are saturated by observed channels, $B^{(*)}B^{*}$ channels dominate the Z_b decays

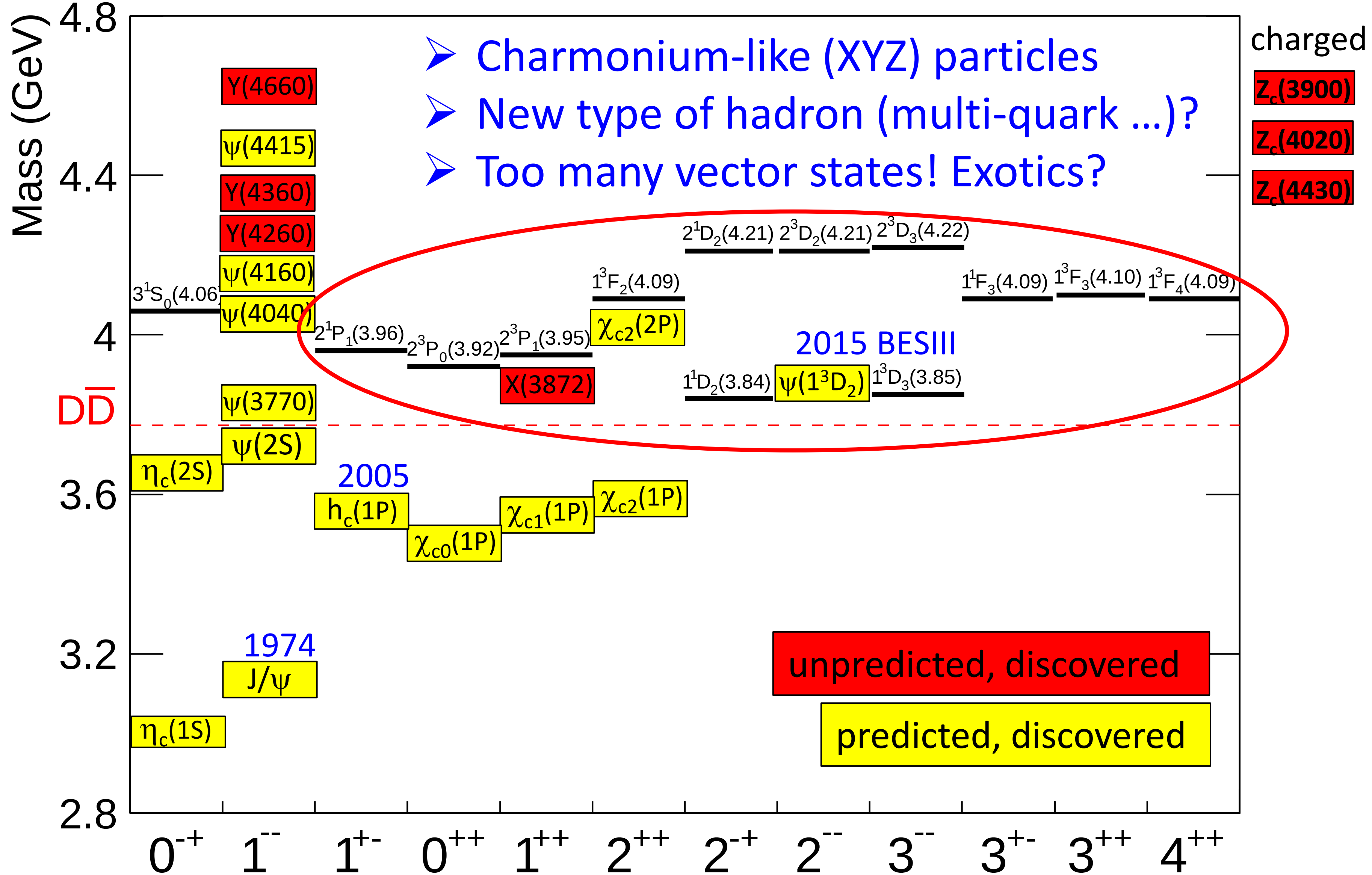
BRs of Z_b decays

Assuming these modes saturate Z_b decays

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	$\cdots$
$B^{*+}\bar{B}^{*0}$	$\cdots$	$73.7^{+3.4+2.7}_{-4.4-3.5}$

arXiv:1512.07419, , PRL116, 212001 (2016)

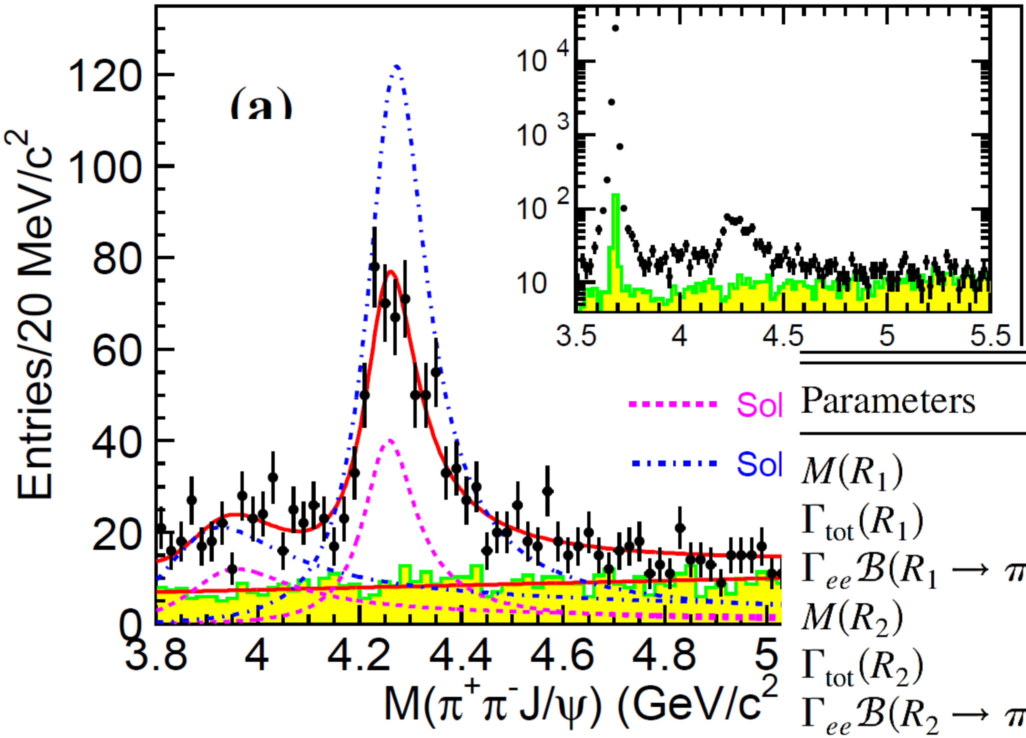
Charmonium(like) spectroscopy



Godfrey & Isgur, PRD32, 189 (1985)

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

PRL110, 252002 (2013)



Nature of evts at ~ 4 GeV is still not clear.

Simplified fit with 2 BWs.

R_1=Y(4008)
R_2=Y(4260)

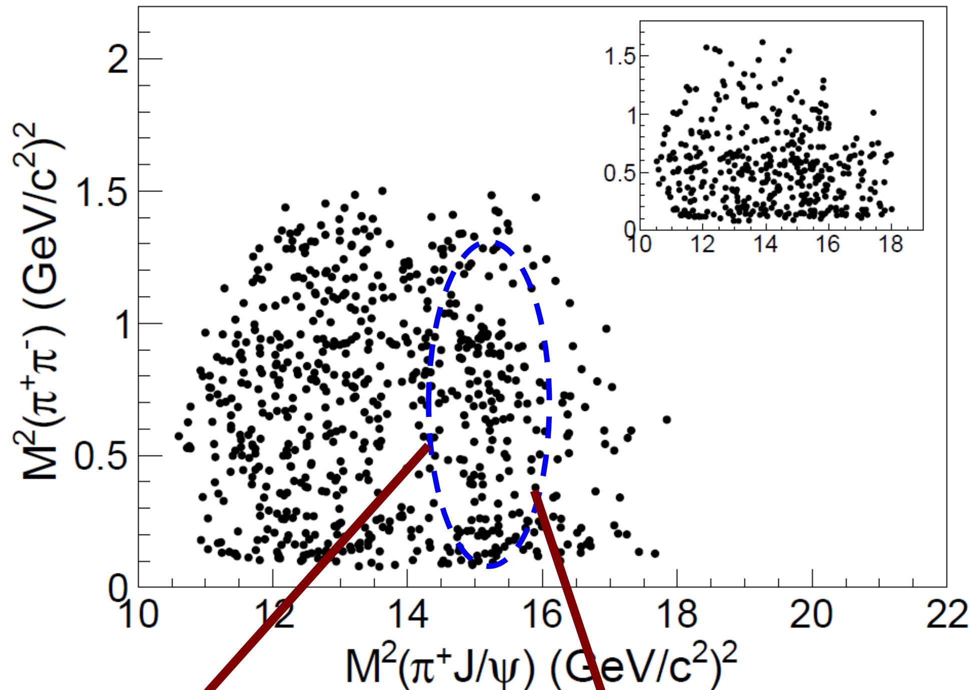
Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{\rm tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{\rm tot}(R_2)$	$134.1 \pm 16.4 \pm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

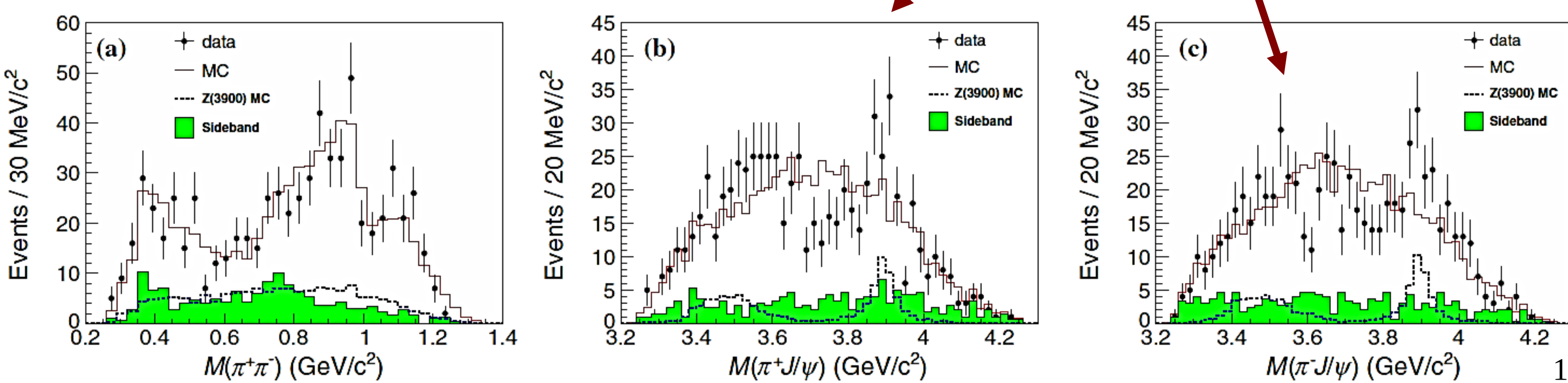
1. Fit with two coherent resonances $|BW_1+e^{i\phi}*BW_2|^2$+bkg.
2. Mass of Y(4008) is lower than before
3. Fit quality: χ^2/ndf=101/84, confidence level is 9.3%

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

PRL110, 252002 (2013)

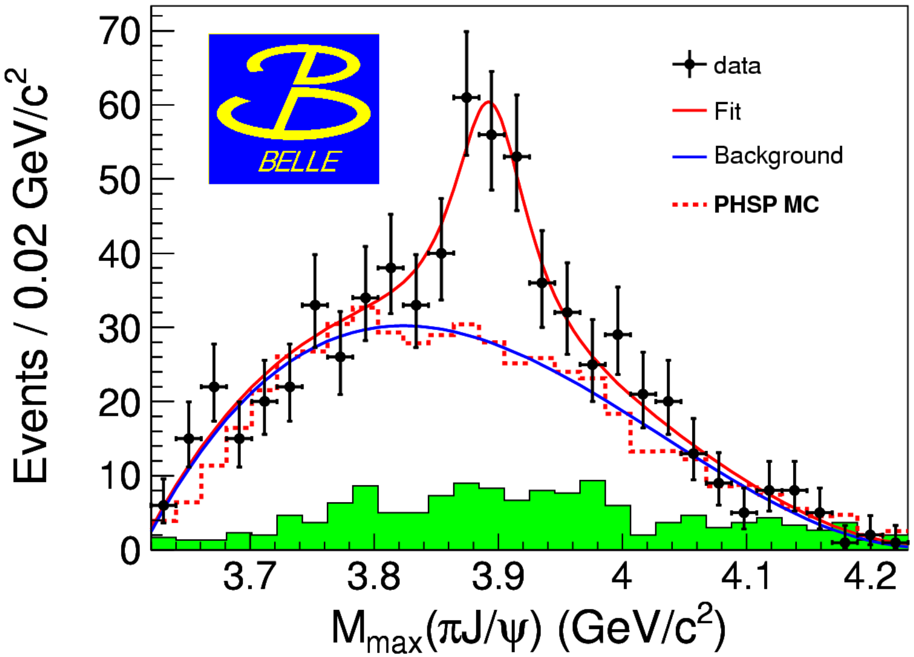
- $M^2(\pi\pi)$ vs. $M^2(\pi J/\psi)$ for $4.15 < M(\pi\pi J/\psi) < 4.45$ GeV
- (inset) Background events in J/ψ-mass sidebands
- Structures both in $\pi\pi$ and $\pi J/\psi$ systems
- 689 events in J/ψ signal region, purity~80%



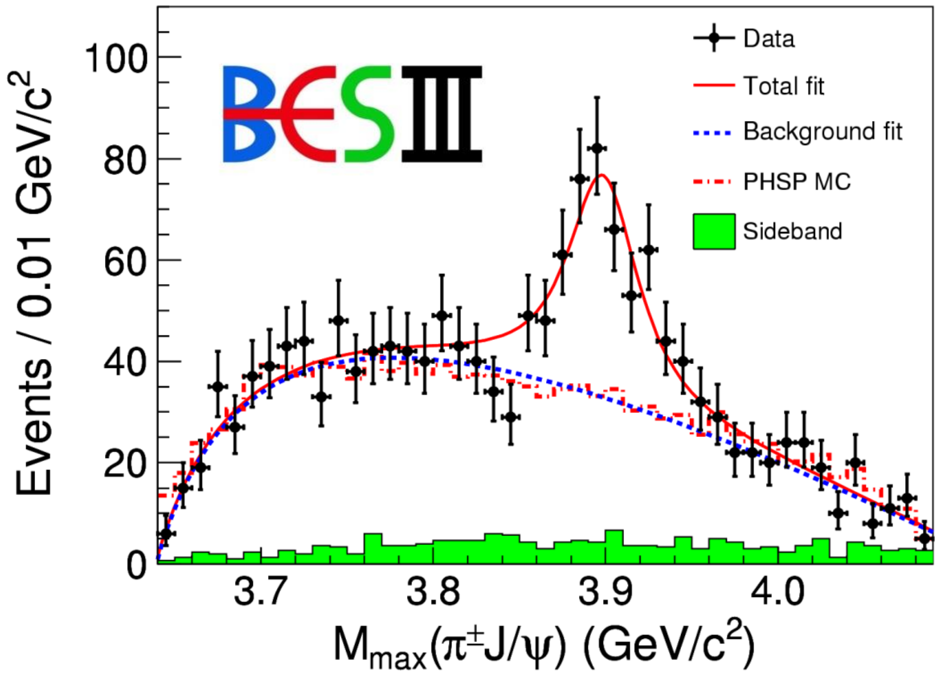


Z(3900)$^+$ observed in two experiments!

Belle with ISR: PRL110, 252002	BESIII at 4.260 GeV: PRL110, 252001



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



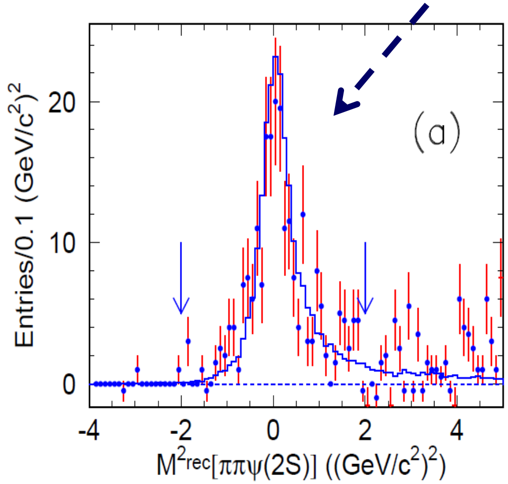
- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events
- >8σ

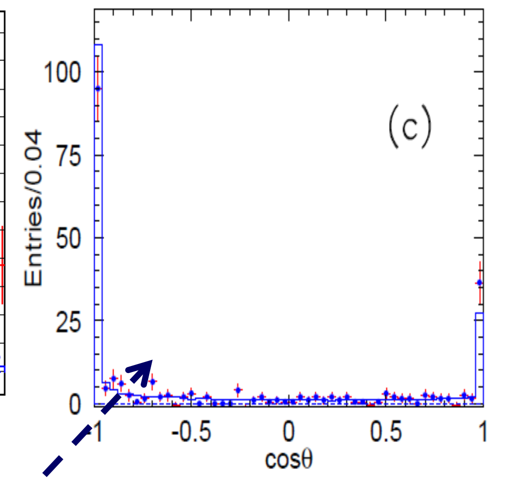
$e^+e^- \to \pi^+\pi^-\psi(2S)$ via ISR

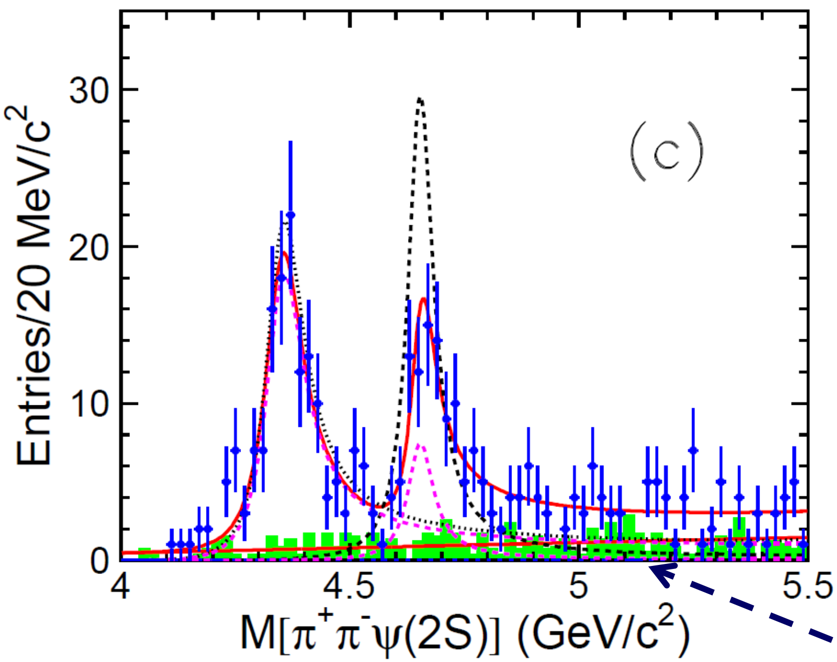
980 fb^{-1}

$\psi'(\to J/\psi\ \pi\pi$ or $\mu\mu) + \pi\pi$
no extra tracks
detection of γ_{ISR} is not required

- **Clear signal of missed massless particle ($M_{rec}^2(\psi'\pi\pi)\sim 0$)**







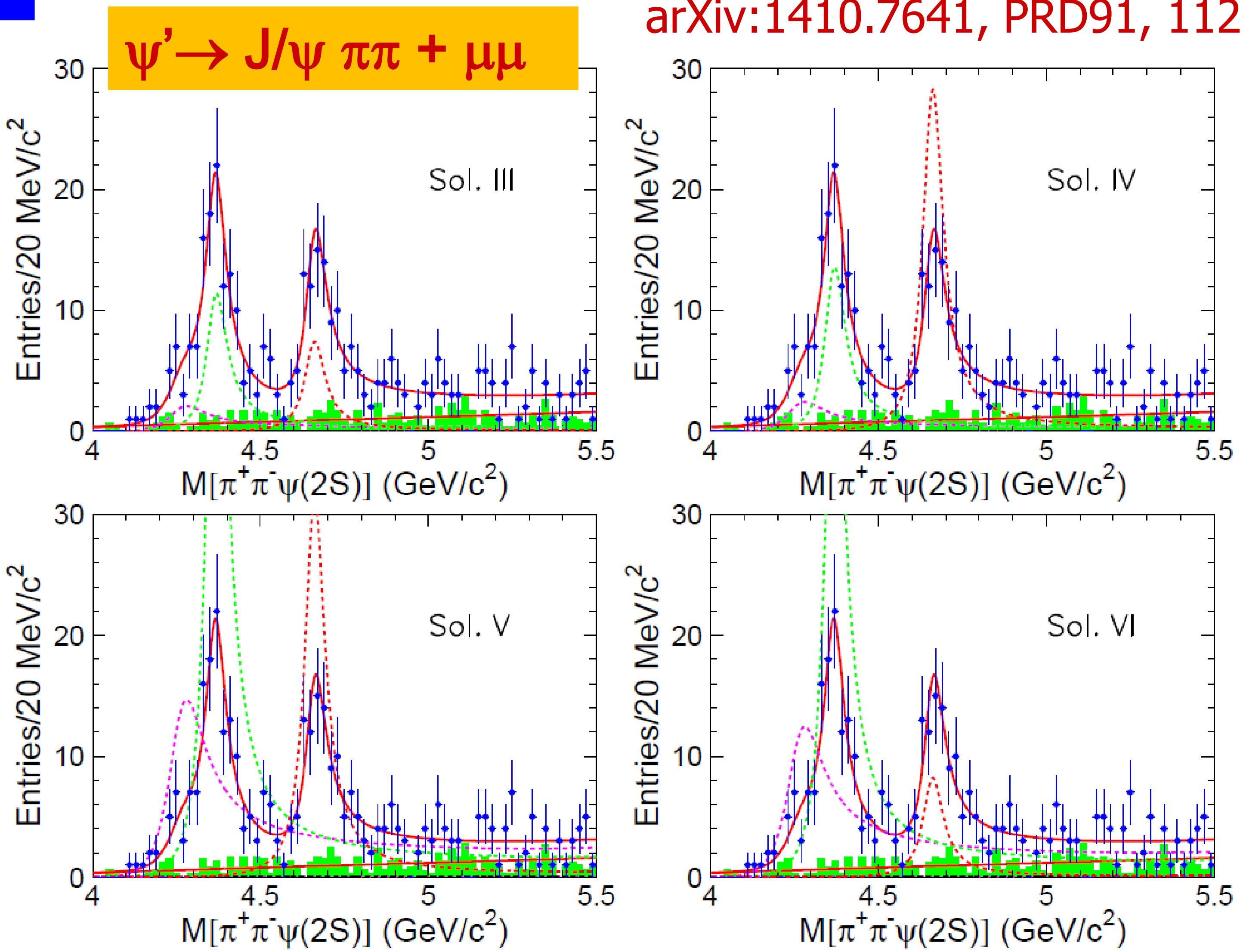
- **Polar angle distribution agrees well with ISR expectation**
- **Combinatorial background estimated by ψ' sidebands**
- **Bkgs from real $(\psi'\pi\pi)_{non\ ISR}$ or $\psi'\ X_{non\ \pi\pi}$ are negligibly small**

Two significant clusters:
Y(4360)+Y(4660);
a few events at Y(4260)

arXiv:1410.7641, PRD 91, 112007 (2015)

Fit with 3 BWs [4 solutions]

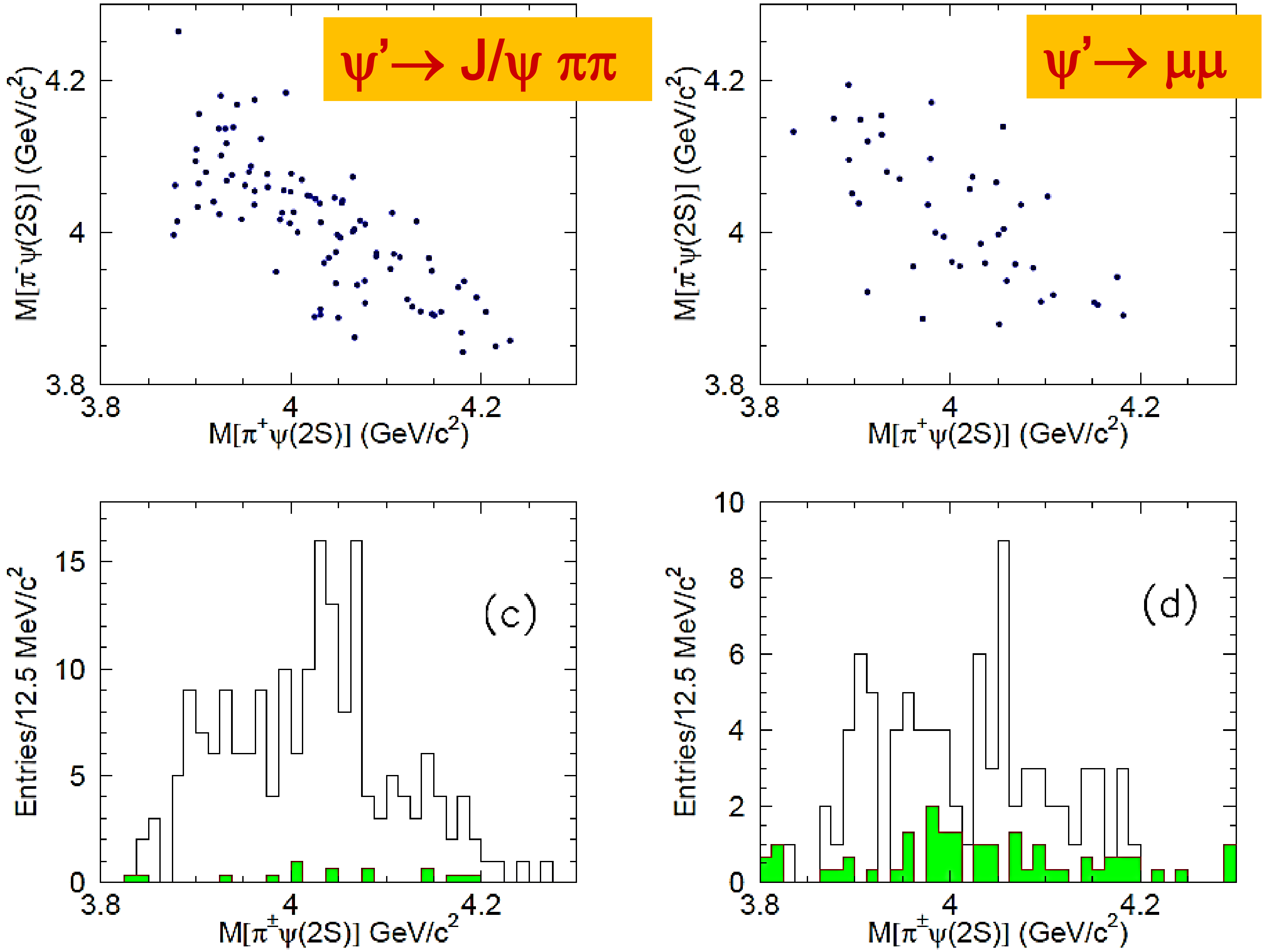
arXiv:1410.7641, PRD91, 112007



Significance of Y(4260) is 2.4σ [significant at BESIII!]

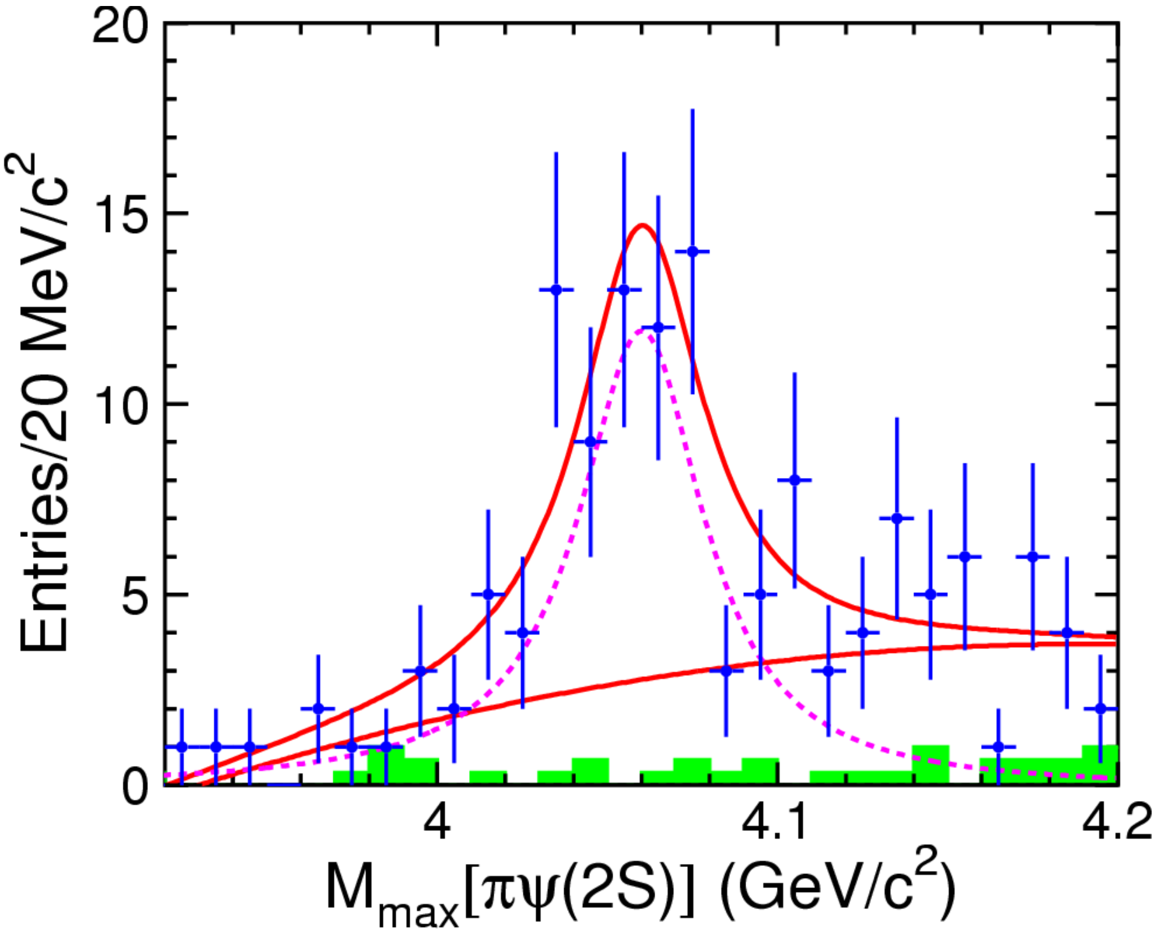
Affect the parameters of Y(4360) and Y(4660) significantly!

Z_c states from Y(4360) decays?



arXiv:1410.7641, PRD91, 112007

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



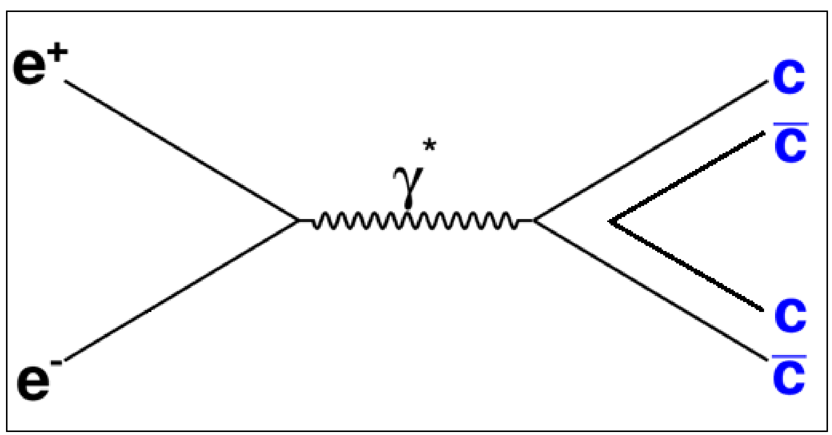
arXiv:1410.7641
PRD91, 112007

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.

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

The X state as $\chi_{c0}(2P)$

X*(3860) in double charmonium production



States in $e^+e^- \rightarrow J/\psi\ [\psi'] + X$

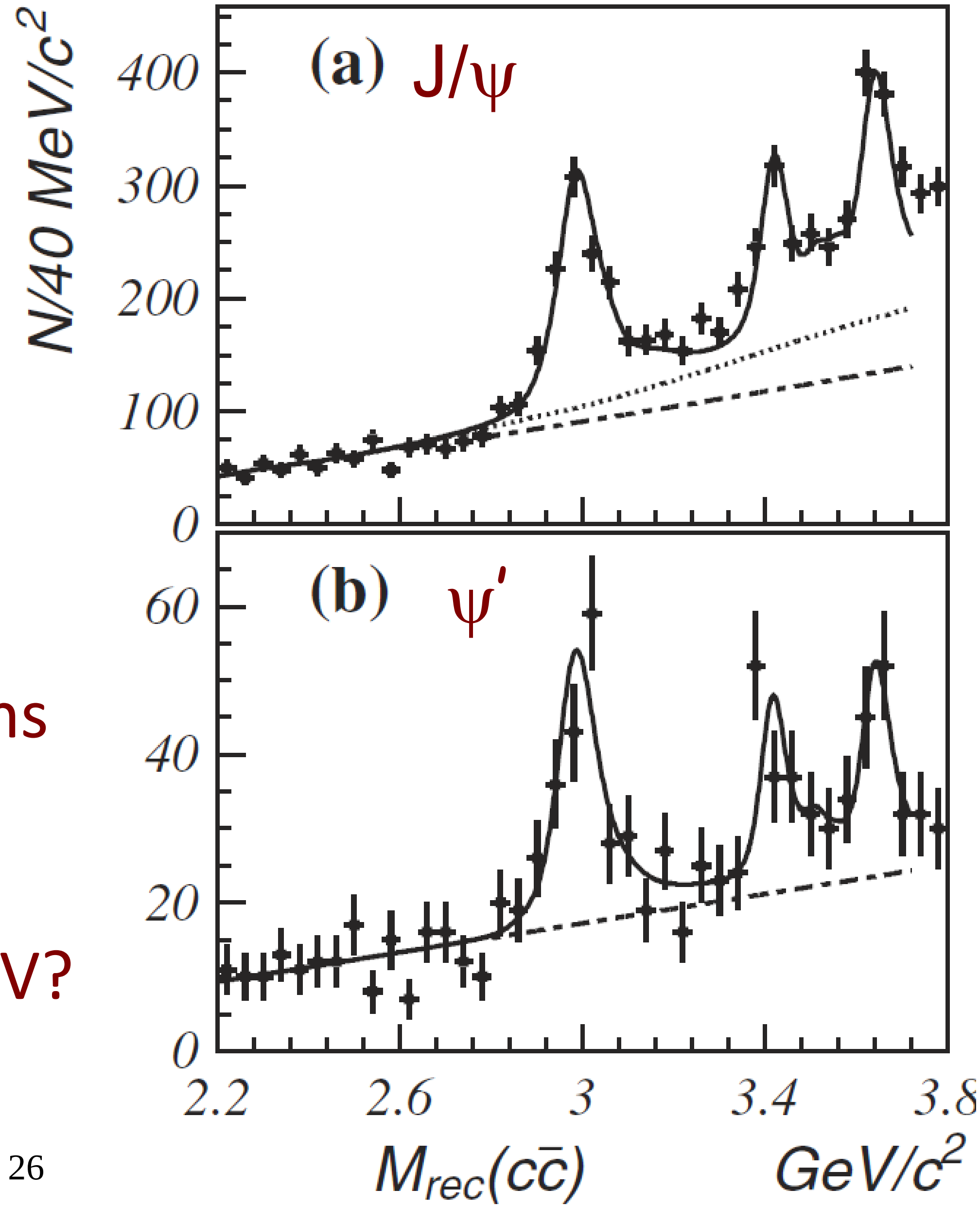
PRD79, 071101 (2009)

Full Belle $\Upsilon(4S)$ data

1. Significant spin-0 charmonium states: $\eta_c(1S)$, χ_{c0}, $\eta_c(2S)$
2. No states with other spins

What happens at M>3.8 GeV?

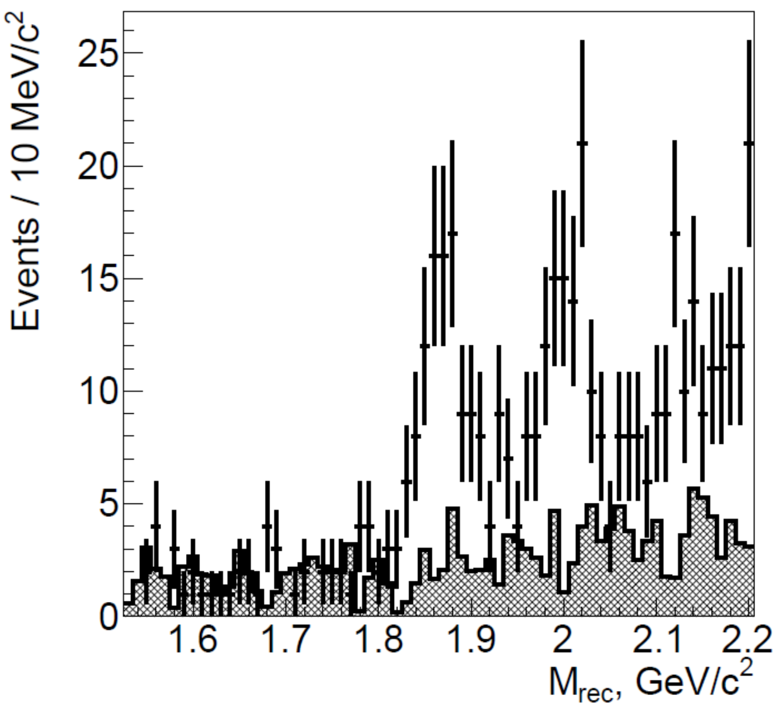
➔suppress background!

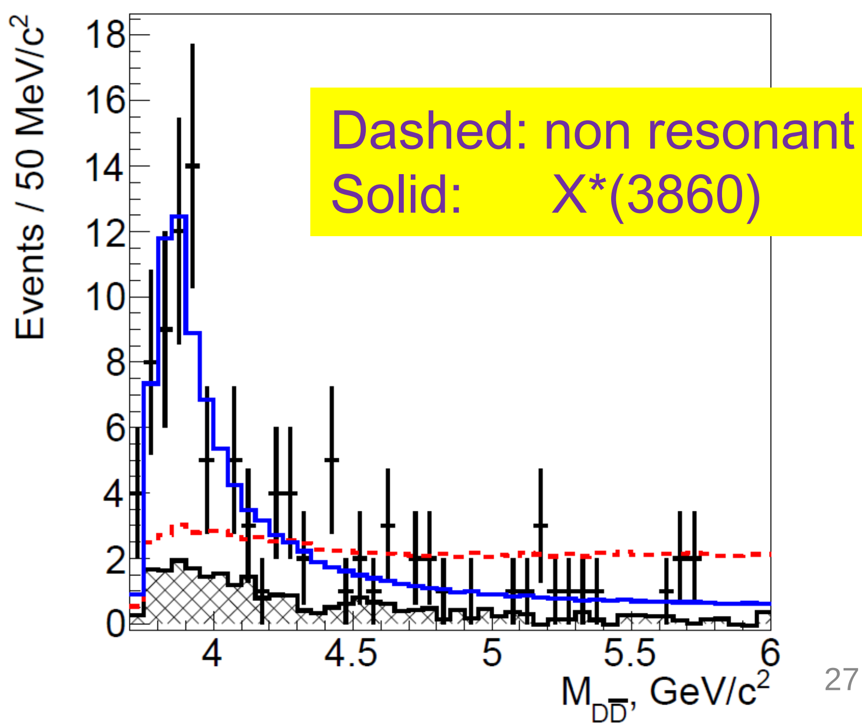


$X^*(3860)$ in $e^+e^- \rightarrow J/\psi + \bar{D}D$

arXiv: 1704.01872， PRD95,112003 (2017)

1. Reconstruct $J/\psi \rightarrow ee/\mu\,\mu$
2. Reconstruct D+ in 5 decay modes, D0 in 4 decay modes
3. Require $J/\psi D$ recoil mass in D mass region
4. Mass constraints for J/ψ, D and $\bar{D}$ to improve mass resolutions.

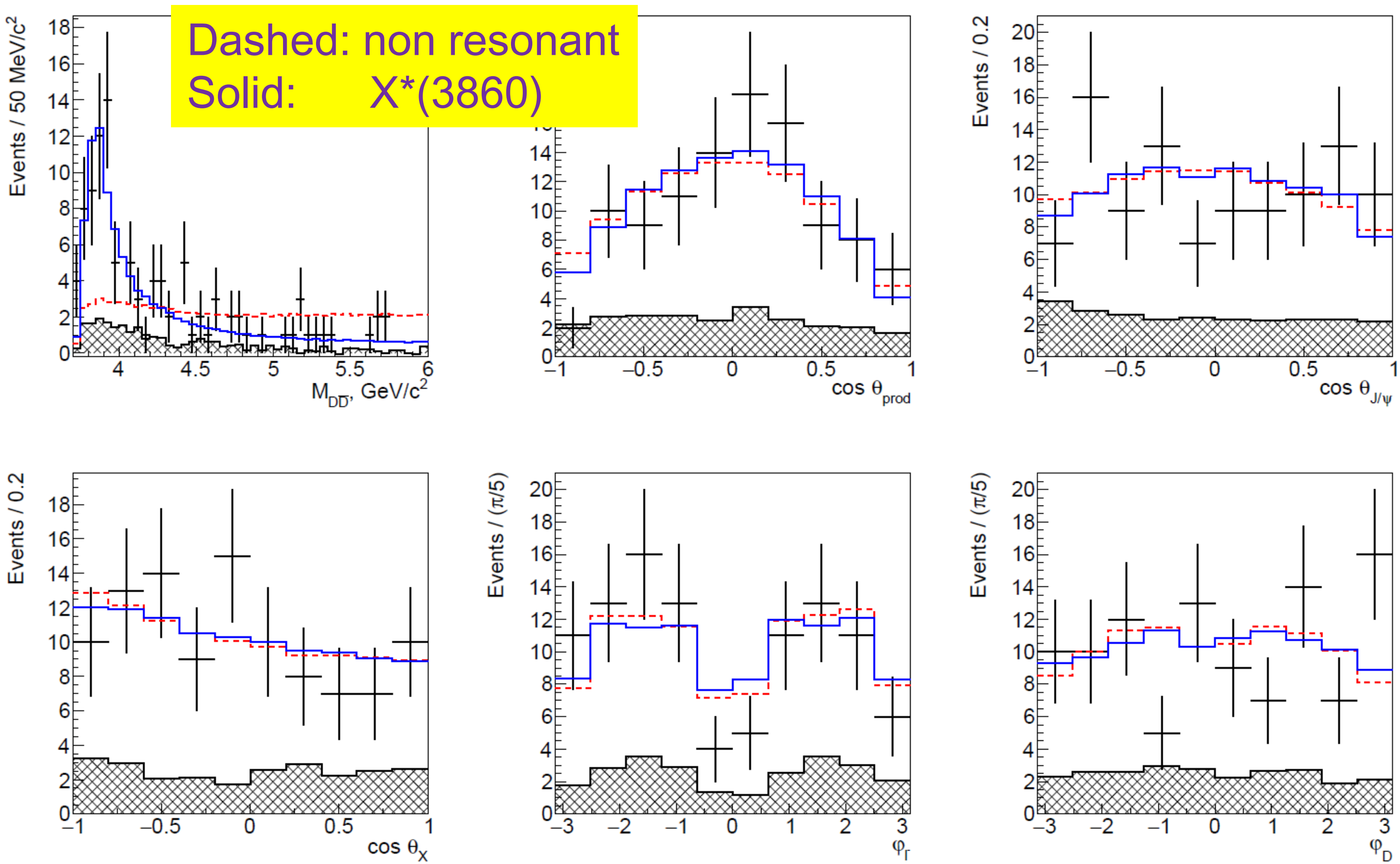




X*(3860) in $e^+e^- \rightarrow J/\psi + \bar{D}D$

arXiv: 1704.01872， PRD95,112003 (2017)

PWA of the data, blue lines are fit with X*



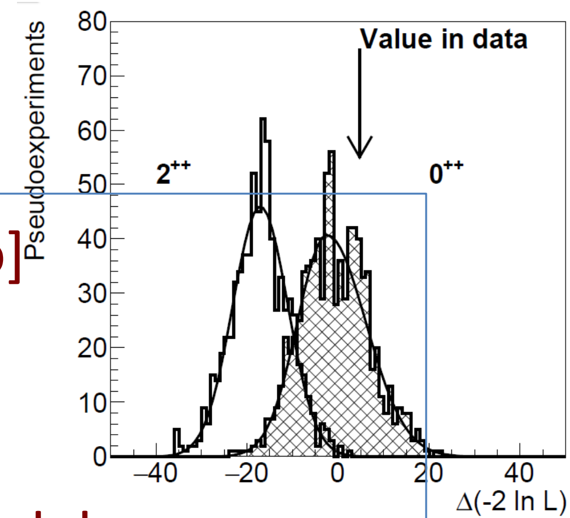
X*(3860) in $e^+e^- \to J/\psi + \bar{D}D$

$Mass$: 3862^{+26+40}_{-32-13} MeV

$width$: $201^{+154+88}_{-67-82}$ MeV

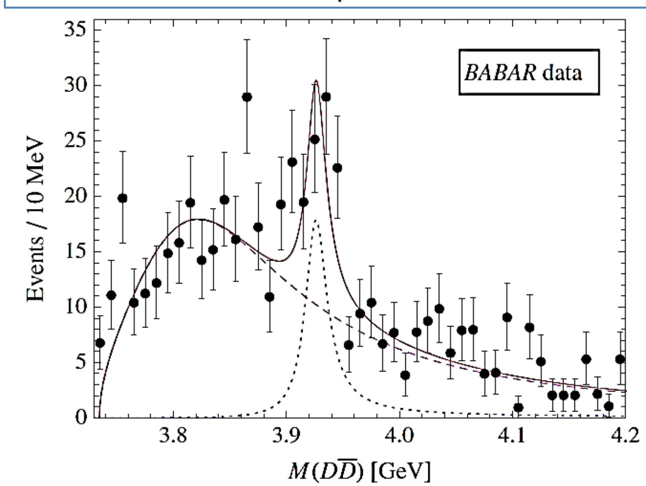
JPC=0++ (2++ not excluded)

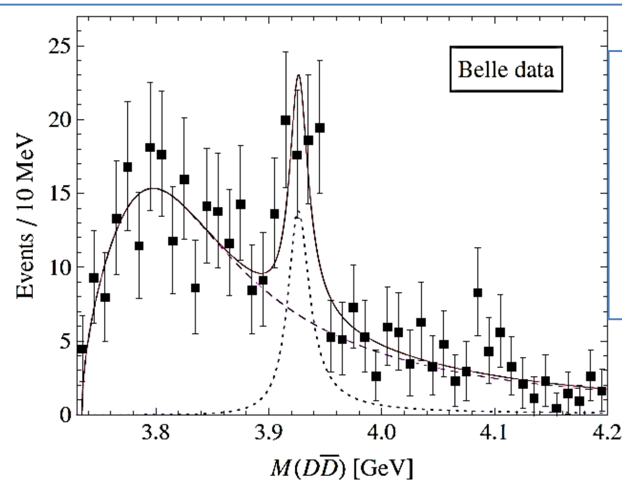
arXiv: 1704.01872, PRD95,112003



Good candidate for $\chi_{c0}(2P)$ [PLB661, KTChao]

- With $\chi_{c2}(2P)$=Z(3930), $\chi_{c1}(2P)$=X(3872)?
- J/ψ recoil with spin-zero dominant
- Mass/width reasonable agree with potential models
- Observed in $\gamma\gamma$ fusion? [BaBar, Belle, FKGuo-PRD86]





Mass=3838±12 MeV

Width=221±19 MeV

Light Hadrons

Search for 0^{--} oddball

- QCD allows the existences of glueballs.
- No definite conclusions from experimental results.
- Mixing with quarkonium states makes the search very hard.
- The $J^{PC}=0^{--}$ could not be quarkonia (exotic numbers).
- Proposed production channel:

$\Upsilon(1S,2S) \to \chi_{c1} + G_0^{--}$, $f_1(1285) + G_0^{--}$; $\chi_{b1} \to J/\psi + G_0^{--}$, $\omega + G_0^{--}$.

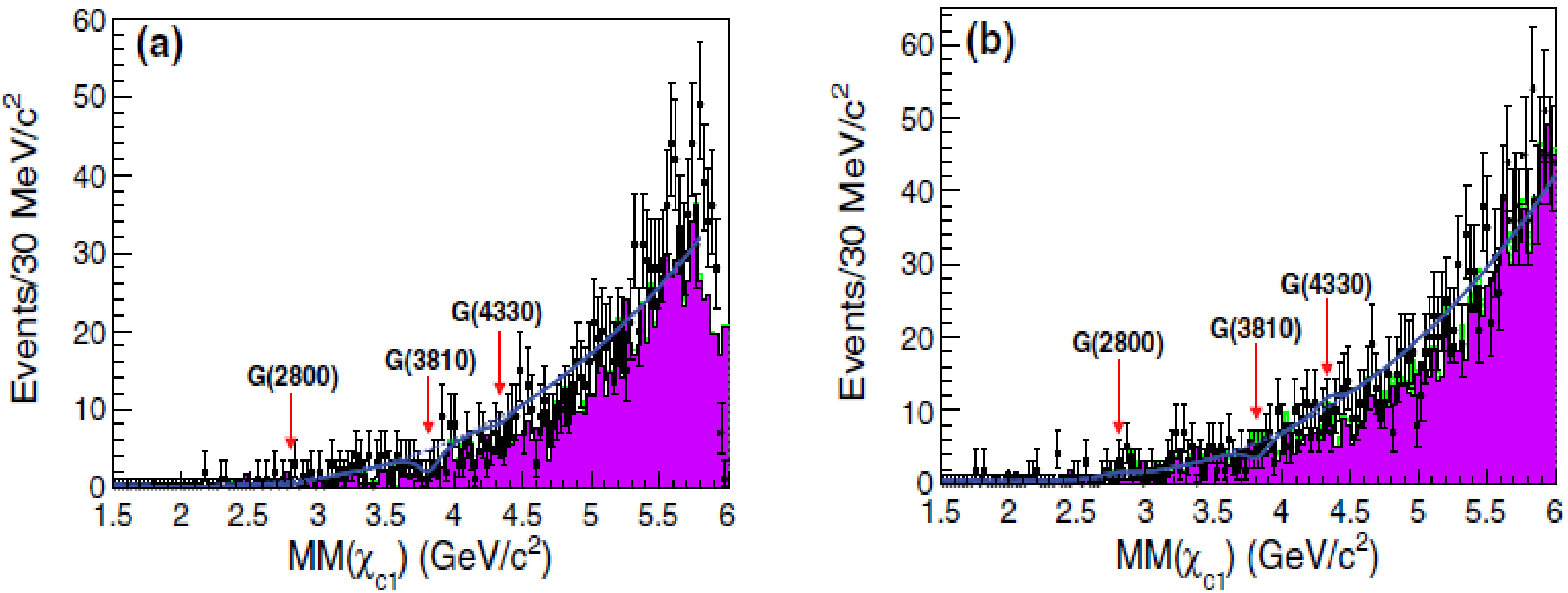
The predicted G_0^{--} masses are 2.80, 3.81 and 4.33 GeV/c^2.

[PRL113, 221601 (2014)]、[JHEP 1510 (2015) 137]

Measurements of $\Upsilon(1S,2S) \to \chi_{c1} + G_0^{--}$

arXiv: 1611.07131, PRD 95, 012001 (2017)

The χ_{c1} recoil mass spectra in the (a) $\Upsilon(1S)$ and (b) $\Upsilon(2S)$ data samples.



N_{signal}=−3.8±3.9 (6.2± 6.4), −20.4±7.8 (−18.5±9.2), −5.7±11.3 (12.5±14.9)

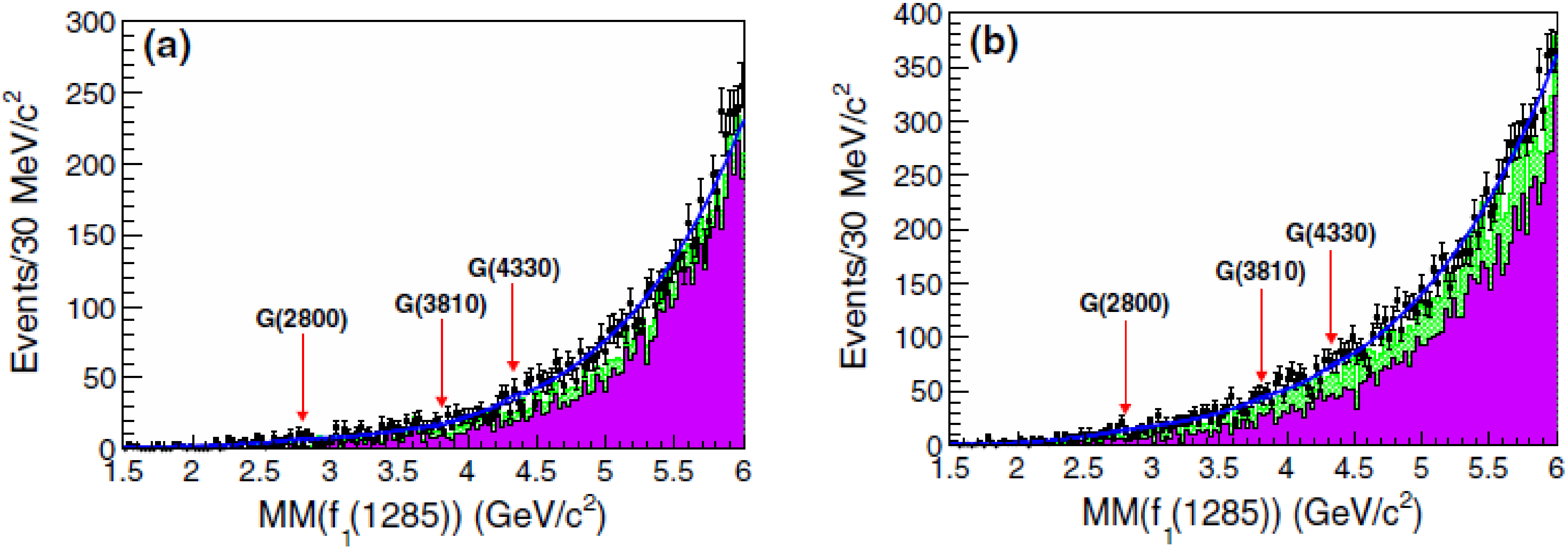
for the G(2800), G(3810), G(4330)

in the $\Upsilon(1S)$ ($\Upsilon(2S)$) data samples.

Measurements of $\Upsilon(1S,2S) \to f_1(1285) + G_0^{--}$

arXiv: 1611.07131, PRD 95, 012001 (2017)

$f_1(1285)$ recoil mass spectra in (a) $\Upsilon(1S)$ and (b) $\Upsilon(2S)$ data samples.



N_{signal}=20.2±14.2 (25.0± 22.3), −23.0±25.2 (31.7±39.0), 31.8±30.0 (68.3±47.2)

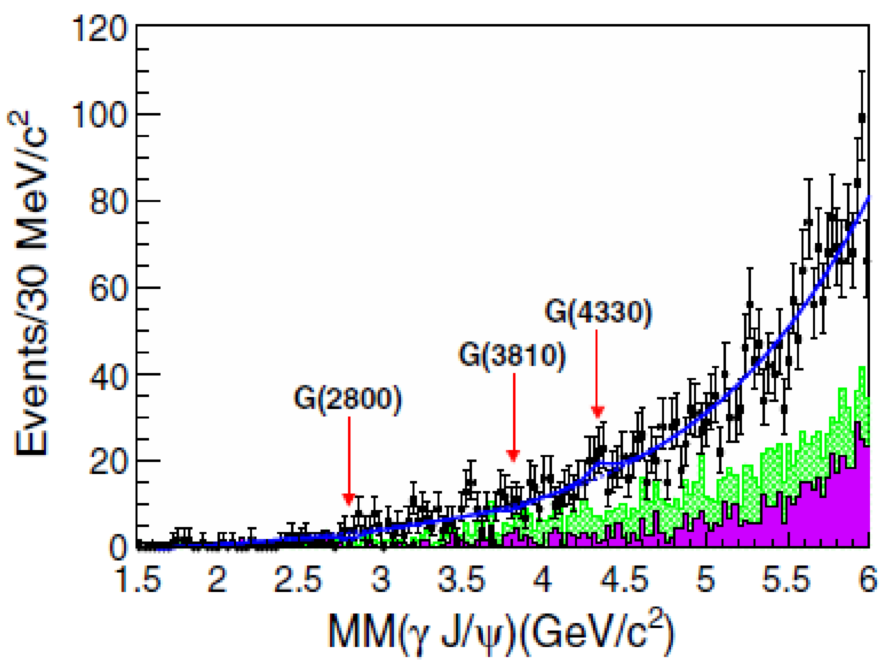
for the G(2800), G(3810), G(4330)

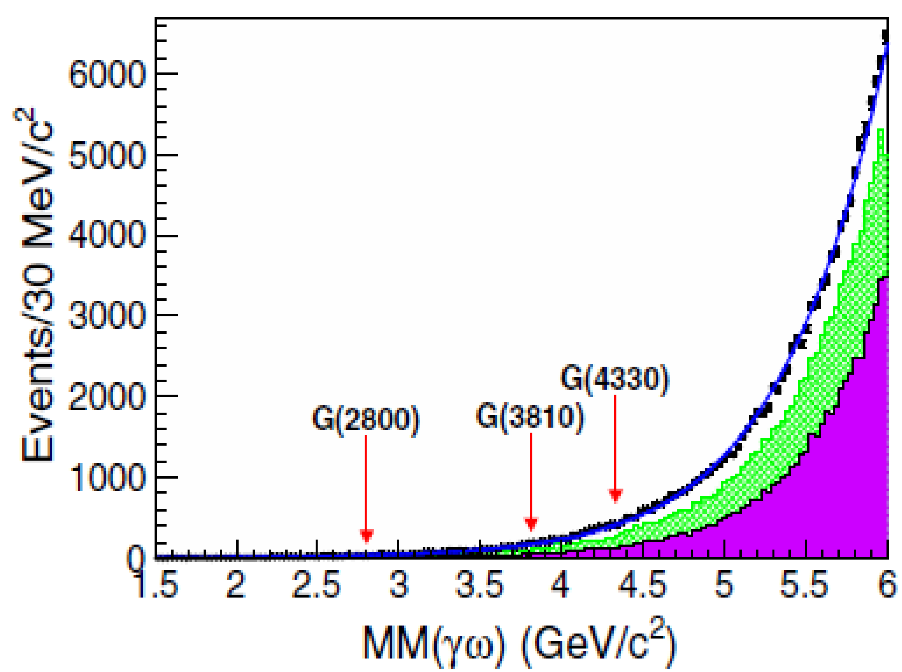
in the $\Upsilon(1S)$ ($\Upsilon(2S)$) data samples.

Measurements of $\chi_{b1} \to J/\psi(\omega) + G_0^{--}$

arXiv: 1611.07131, PRD 95, 012001 (2017)

The χ_{b1} is identified through the decay $\Upsilon(2S) \to \gamma\chi_{b1}$.





N_{signal}=-11.4±6.8 (22.0±34.1), −7.1±13.5 (129.6±75.2), 27.0±19.5 (133±365)

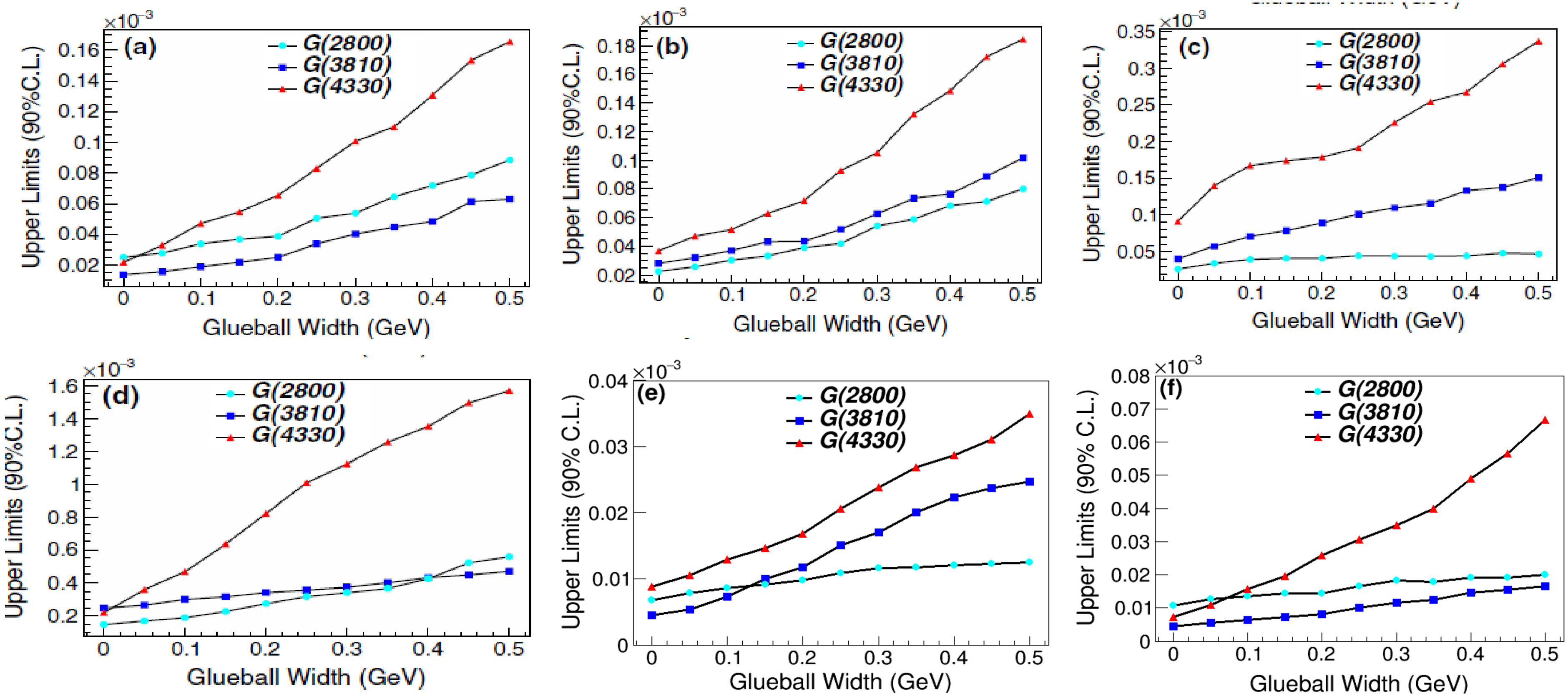
for the G(2800), G(3810), G(4330)

in the $\chi_{b1} \to J/\psi(\omega)$+G modes.

No 0^{--} oddballs observed

Upper limits on BR ~ 10^{-5}–10^{-3} level @ 90% C.L.

The upper limits on the branching fractions for $\Upsilon(1S) \to f_1(1285) + G_0^{--}$ (a), $\Upsilon(2S) \to f_1(1285) + G_0^{--}$ (b), $\chi_{b1} \to J/\psi$+Glueball (c), $\chi_{b1} \to \omega + G_0^{--}$ (d), $\Upsilon(1S) \to \chi_{c1} + G_0^{--}$ (e) and $\Upsilon(2S) \to \chi_{c1} + G_0^{--}$ (f) as a function of the assumed G_0^{--} decay width.



arXiv: 1611.07131, PRD 95, 012001 (2017)

Observation of P_c states at LHCb

LHCb: PRL115, 072001 (2015)

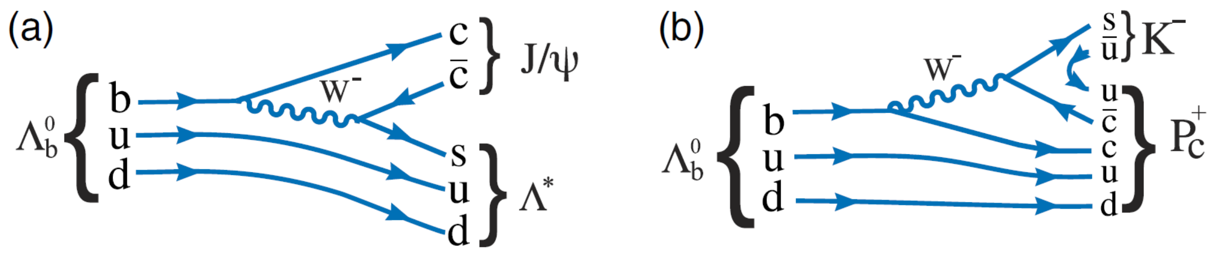
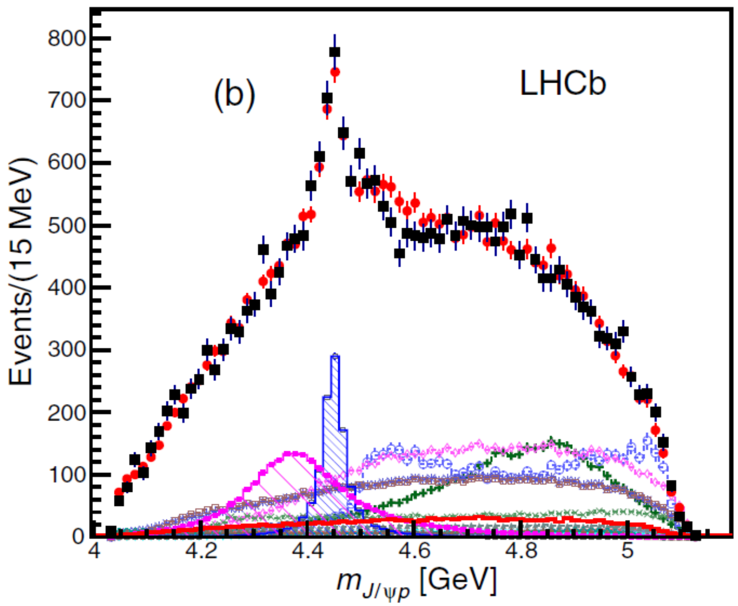
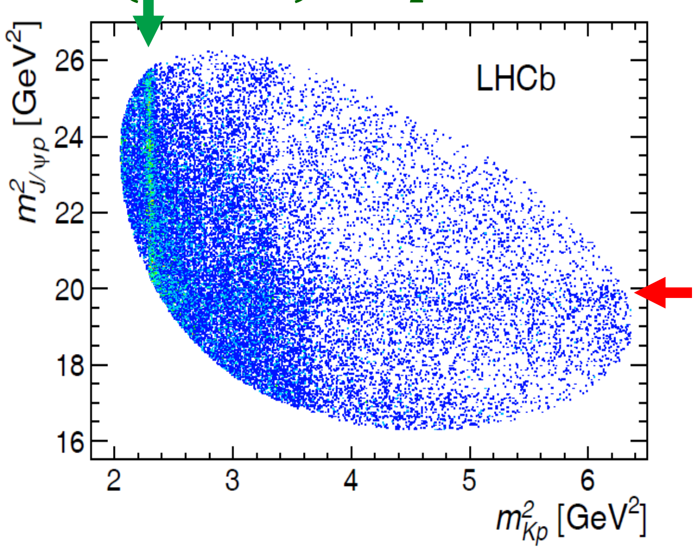


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.





Search for P_s at Belle

Belle: arXiv: 1707.00089, PRD (in press), 915 fb^{-1} data

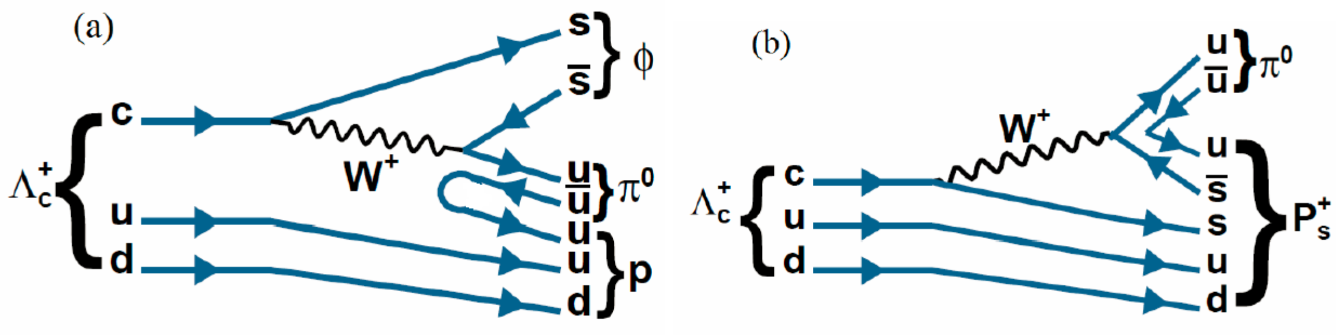


FIG. 1. Feynman diagram for the decay (a) $\Lambda_c^+ \to \phi p \pi^0$ and (b) $\Lambda_c^+ \to P_s^+ \pi^0$.

Just replace $\bar{c}c$ with $\bar{s}s$ in LHCb case

Phase space is limited

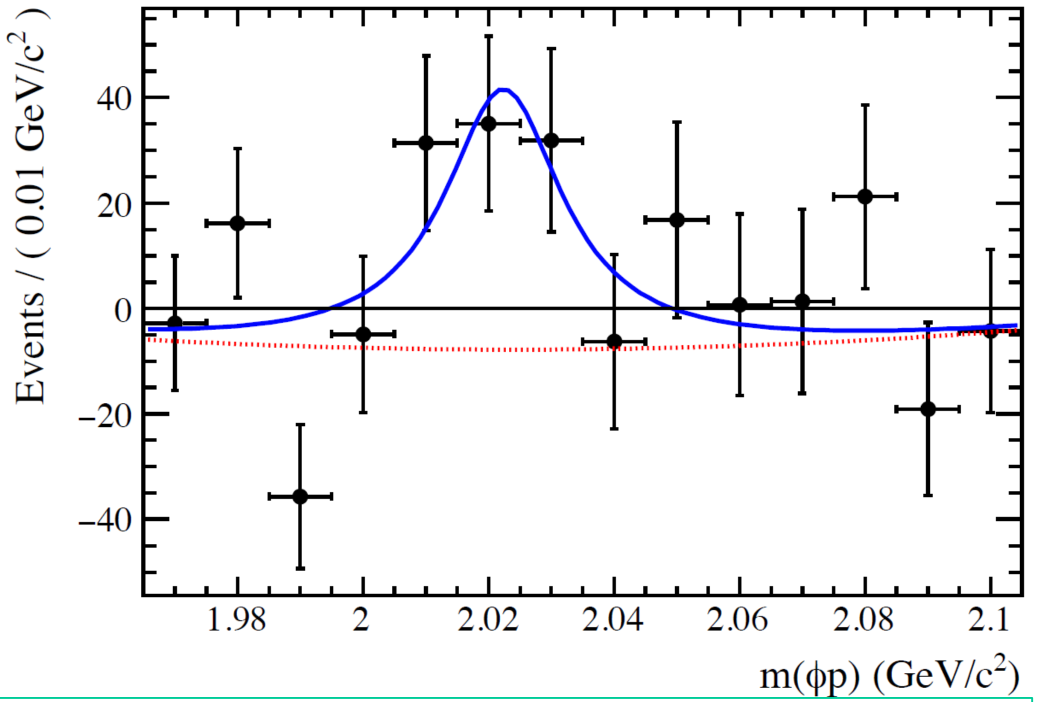
Select high momentum Λ_c

$\Sigma^+ \rightarrow p\pi^0$ vetoed

No significant P_s at Belle

Belle: arXiv: 1707.00089, PRD (in press), 915 fb^{-1} data

No significant P_s signal. Best fit yields a peak at (2025±5) MeV with a width (22±12) MeV



Number of candidate $\Lambda_c \rightarrow P_s\pi^0 \rightarrow \phi p \pi^0$ events: 77.6±28.1

$B(\Lambda_c \rightarrow P_s\pi^0) \times B(P_s \rightarrow \phi p) < 8.3 \times 10^{-5}$ @90% C.L.

$B(\Lambda_b \rightarrow P_c(4450)K) \times B(P_c \rightarrow J/\psi p) = (1.3 \pm 0.4) \times 10^{-5}$

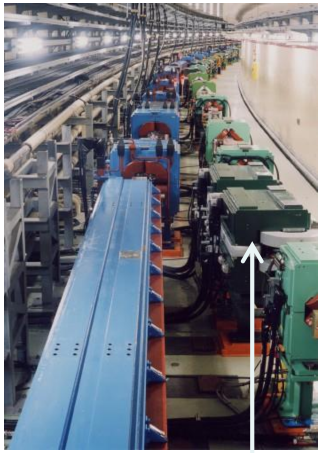
[LHCb, CPC40, 011001 (2016)]

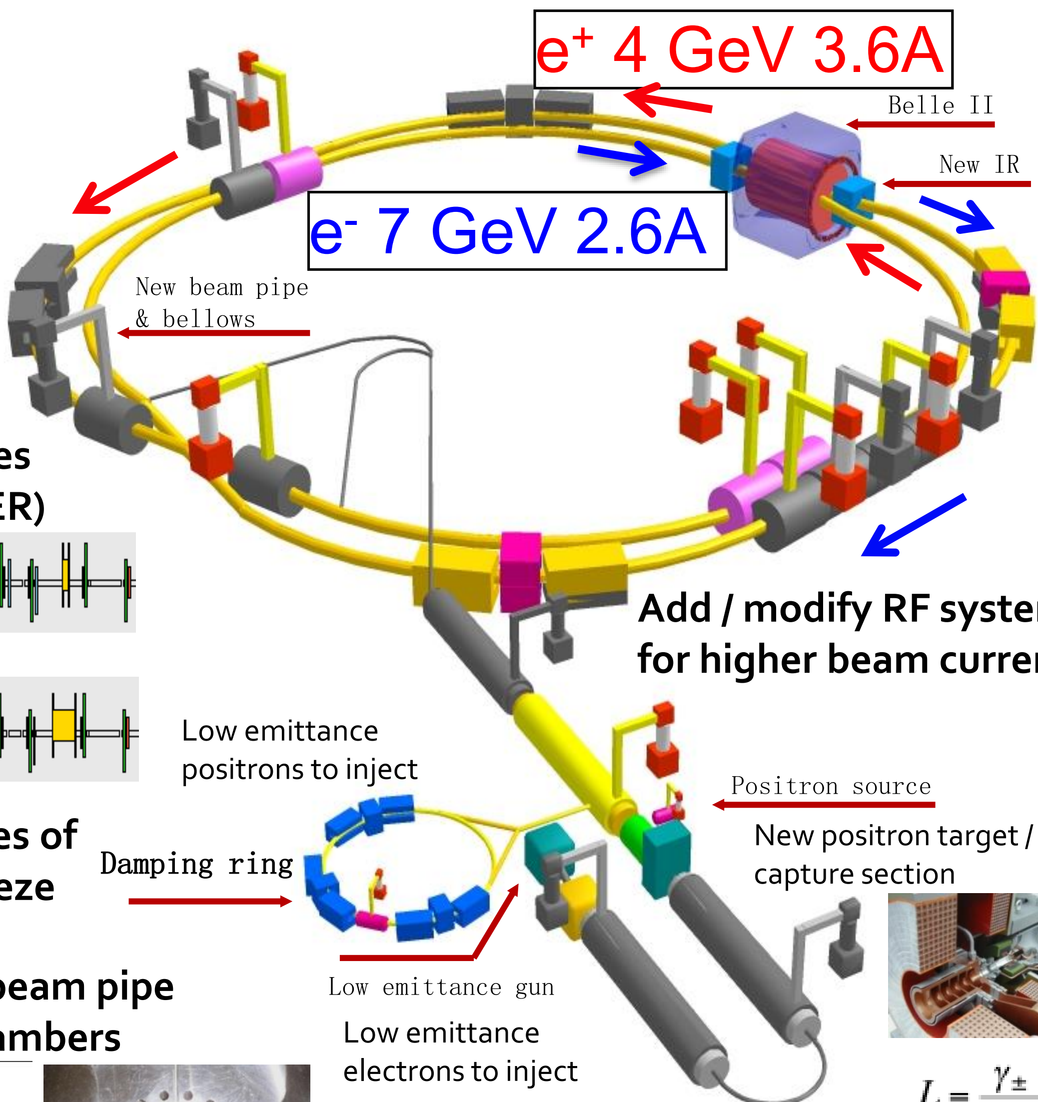
Summary

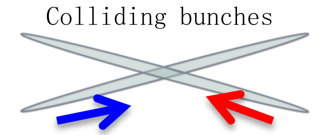
- With the world's largest data samples in bottomonium energy region Belle achieved a lot
  - improved knowledge on $\Upsilon(5S)$, $\Upsilon(6S)$, Z_b states
- With ISR events, Belle studied charmoniumlike states
  - Improved measurement of Y(4260), Y(4360) & Y(4660)
  - Observation of $Z_c(3900)$; evidence for $Z_c(4050) \rightarrow \pi\psi'$
- Observation of X*(3860) as a $\chi_{c0}(2P)$ candidate
- Neither 0^{--} oddball, nor pentaquark P_s is observed
- Belle II is coming ……

From KEKB to SuperKEKB

Grey is recycled, colored is new

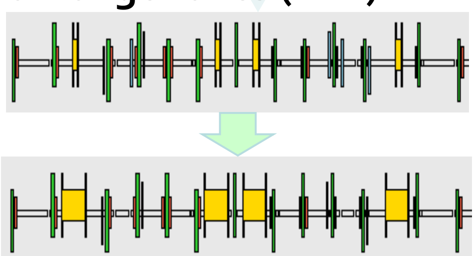






New superconducting / permanent final focusing quads near the IP

Replace short dipoles with longer ones (LER)

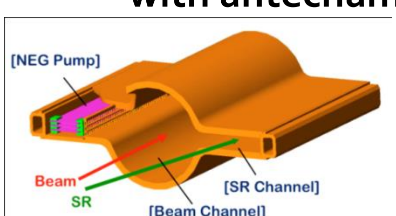


Add / modify RF systems for higher beam current

Redesign the lattices of HER & LER to squeeze the emittance

New positron target / capture section

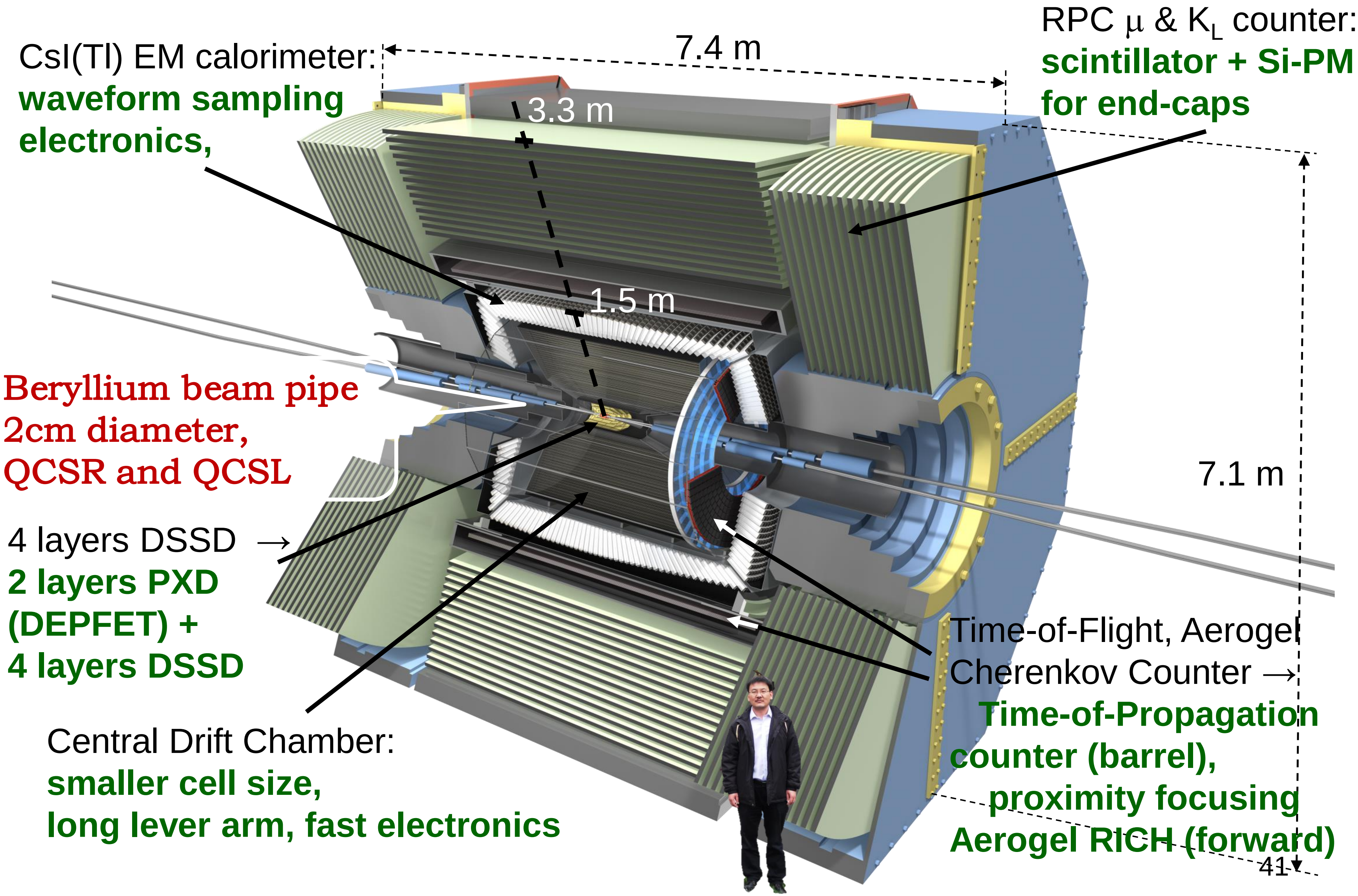
TiN-coated beam pipe with antechambers



$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Target: L = $8\times10^{35}/\mathrm{cm}^2/\mathrm{s}$

Belle II detector upgrade



Belle II Roll In

April 11th, 2017, Belle II Milestone!

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

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The Belle II detector is now in place at the SuperKEKB facility in Japan.

FACILITIES

Belle II rolls in

On 11 April, the Belle II detector at the KEK laboratory in Japan was successfully "rolled-in" to the collision point of the upgraded SuperKEKB accelerator, marking an important milestone for the international B-physics community. The Belle II experiment is an international collaboration hosted by KEK in Tsukuba, Japan, with related physics goals to those of the LHCb experiment at CERN but in the pristine environment of electron–positron collisions. It will analyse copious quantities of B mesons to study CP violation and signs of physics beyond the Standard Model (*CERN Courier* September 2016 p32).

"Roll-in" involves moving the entire 8 m-tall, 1400 tonne Belle II detector system from its assembly area to the beam-collision point 13 m away. The detector is now integrated with SuperKEKB and all its seven subdetectors, except for the innermost vertex detector, are in place. The next step is to

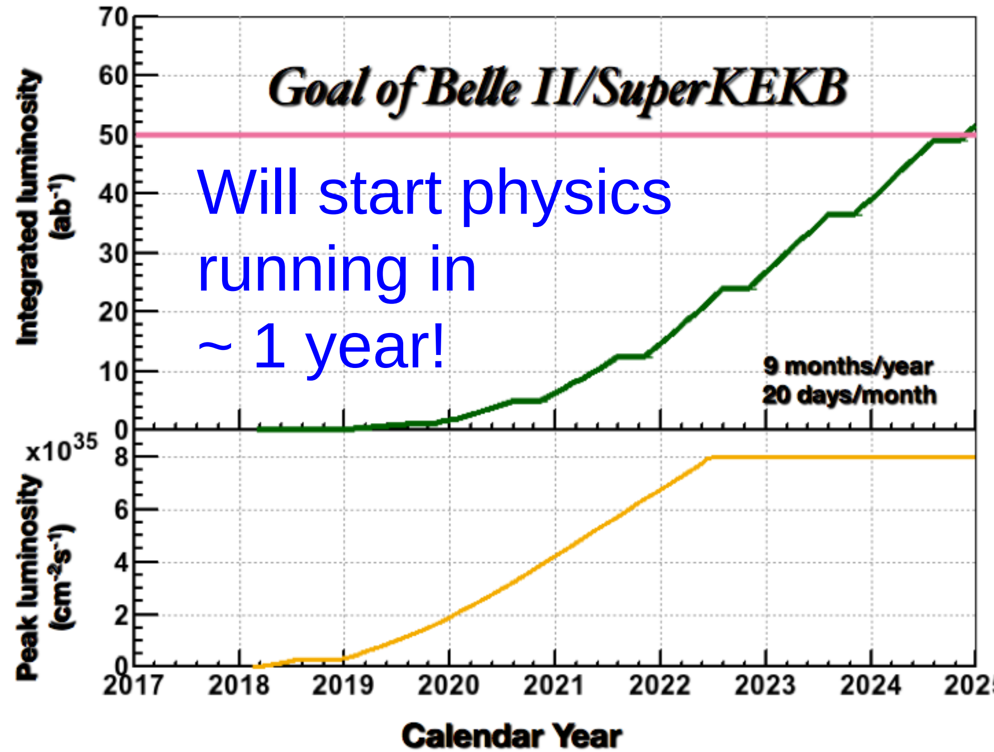
collected with much improved precision.

Luminosity profile of SuperKEKB

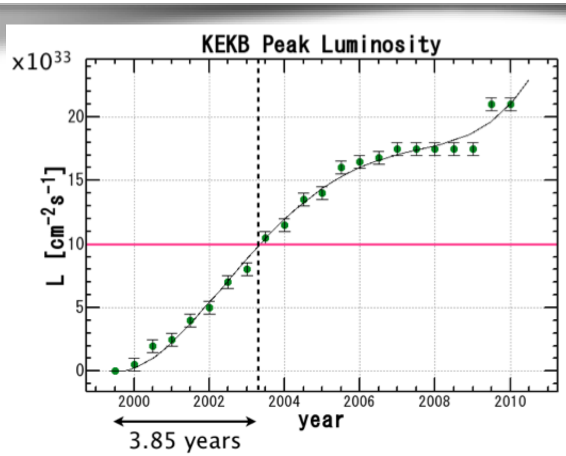
Expected data sample @ full luminosity

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

* assuming 100% running at each energy



Will start physics running in ~ 1 year!



- Assumptions:
  - same commission time to reach design lum. as KEKB
  - 9 months/year running
  - 20 days/month

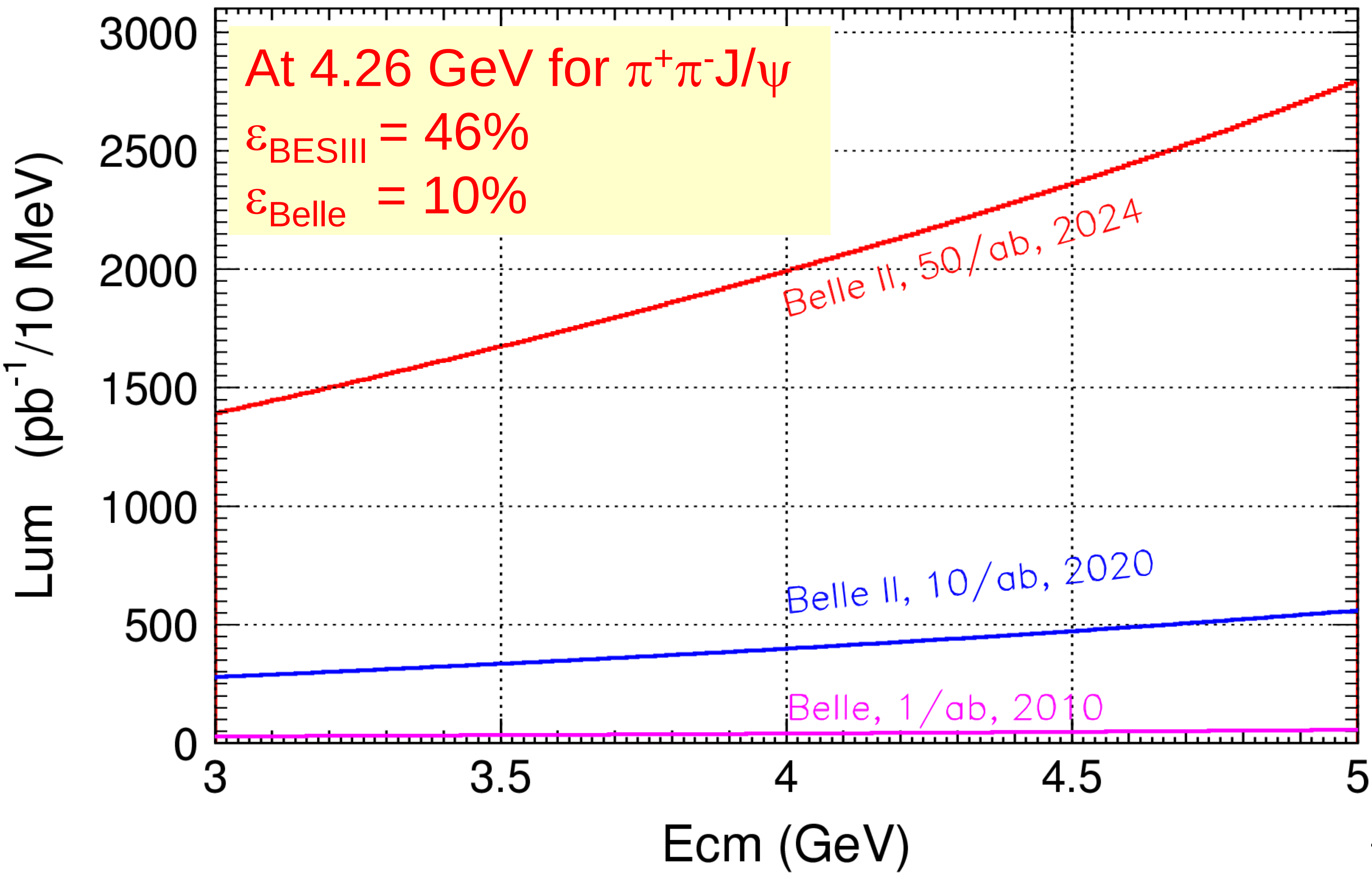
With 50 times more data, we expect a bright future of hadron physics at Belle II!

Thanks a lot!

The end

Charmonium region at Belle II

ISR produces events at all CM energies BESIII can reach



$M(\pi^+\pi^-)$ distributions

PRD91, 112007