Charmonium(like) and open charm production at Belle

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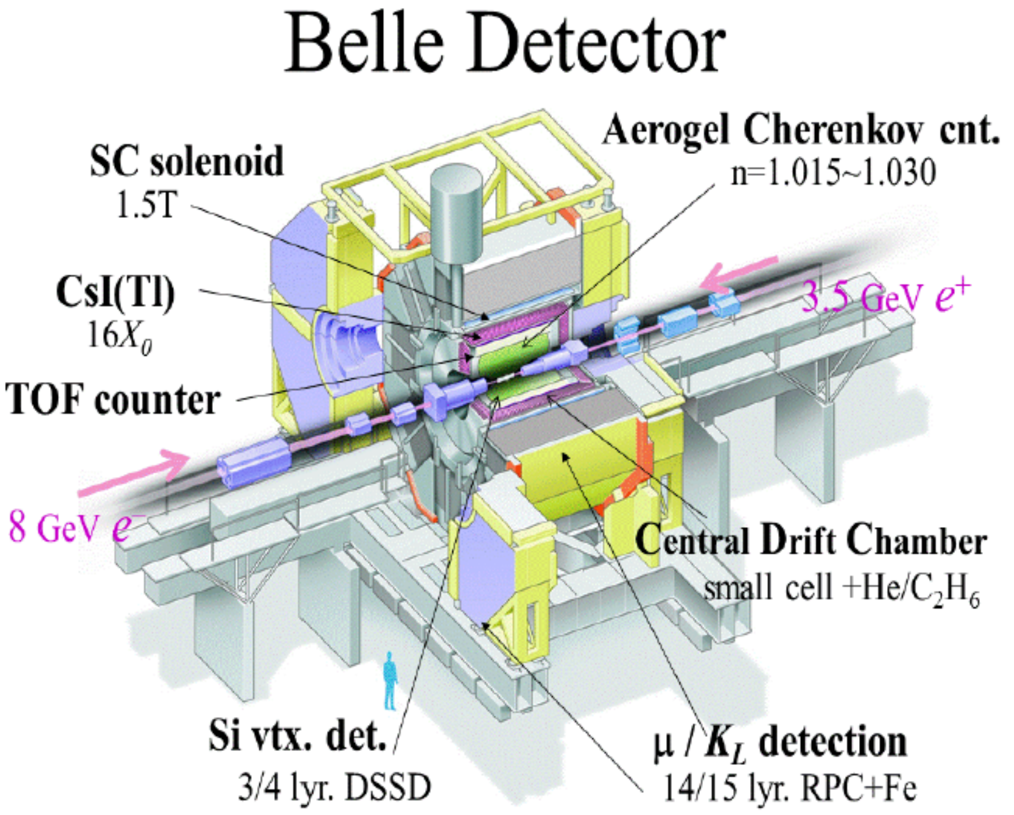
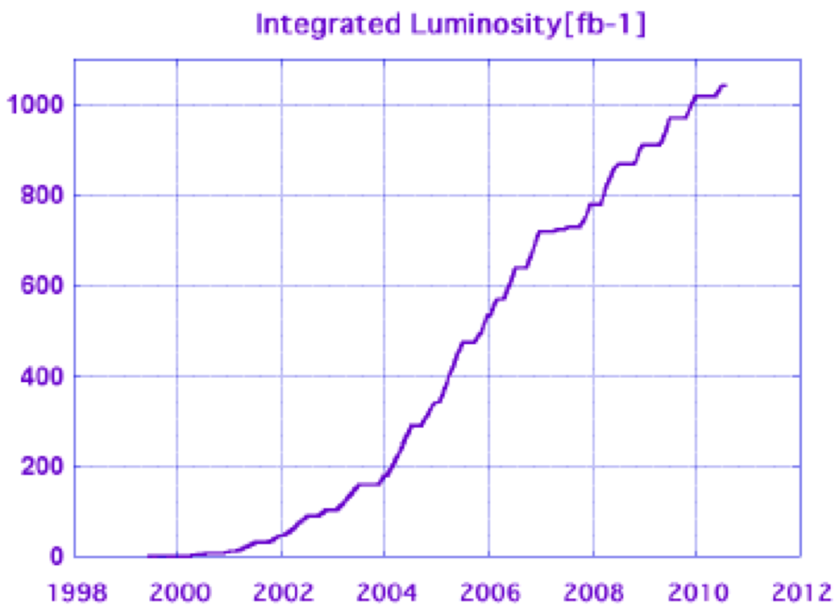
For the Belle Collaboration

XIIIth Quark Confinement and Hadron Spectrum, 2018 Aug 5, Maynooth University, Ireland

The Belle Experiment





$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow \bar{B}_{sig} B_{tag}$$

$> 1\ ab^{-1}$

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}

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

(Target Luminosity 10^{34})

Outline

- Absolute branching fraction measurement for $B \rightarrow X_{c\bar{c}}K^+$

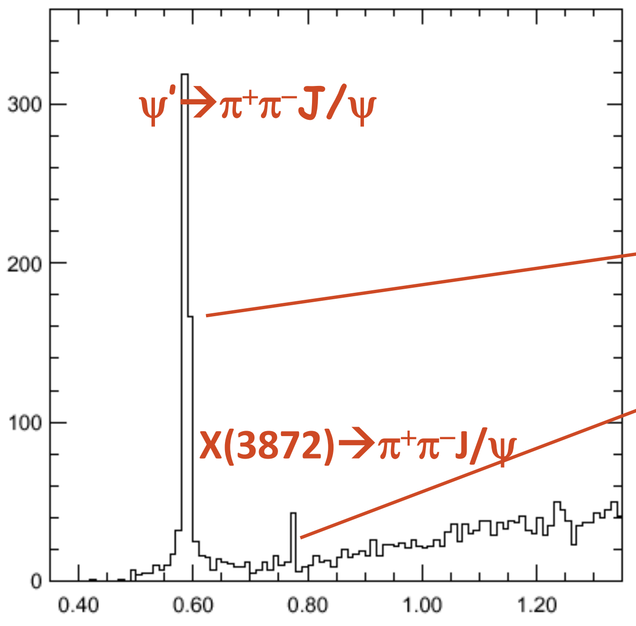
- Observation of χ_{c0}' in $e^+e^- \rightarrow J/\psi\ D\bar{D}$

- Search for $\Upsilon(1S,2S)\rightarrow Z^+Z^{(\prime)-}$ and $e^+e^-\rightarrow Z^+Z^{(\prime)-}$ at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV

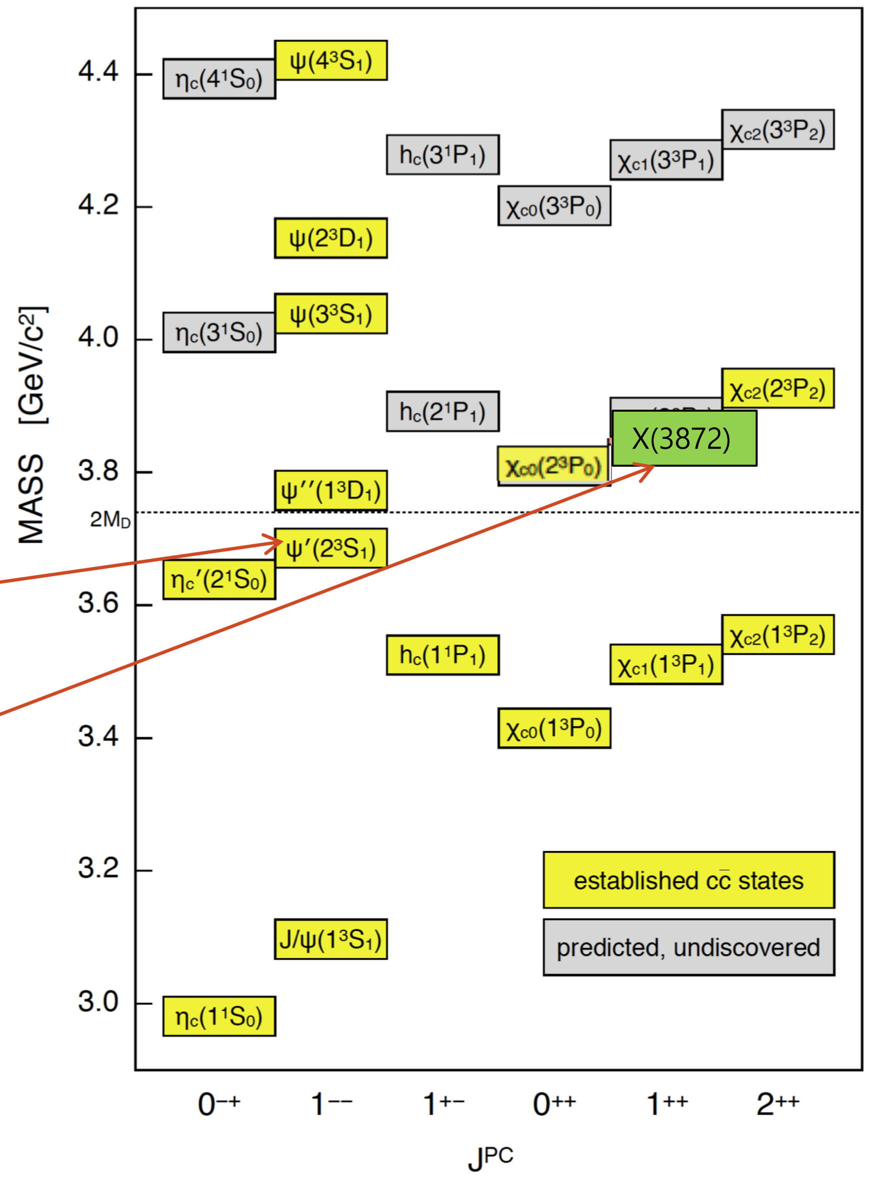
- $\gamma\gamma \rightarrow \eta_c(1S,2S)$: First observation of $\eta_c(2S)\rightarrow\eta'\pi\pi$

Absolute BF measurement for $B^+ \to X_{c\bar{c}} K^+$

Belle PRL 91, 262001 (2003)

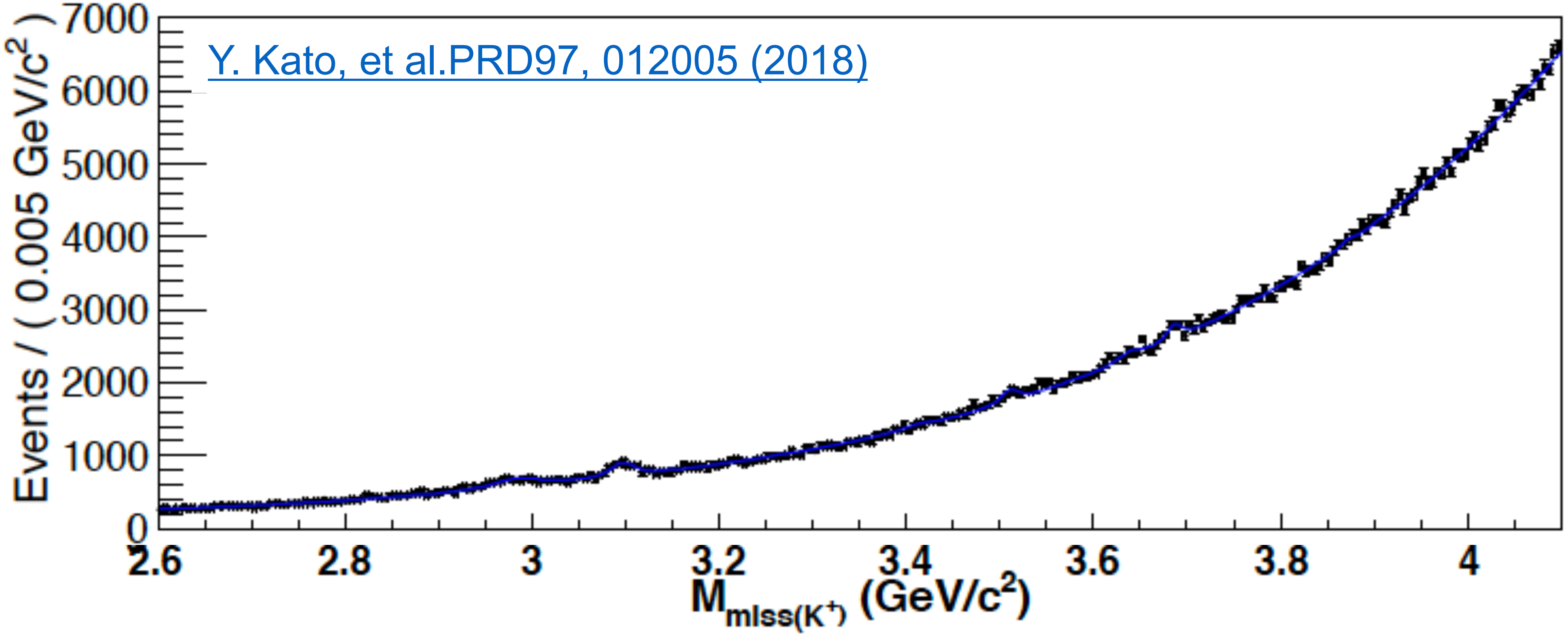


$M(\pi^+\pi^- J/\psi)$



Absolute BF measurement for $B^+ \to X_{c\bar{c}} K^+$

Not dependent on decay modes



Decaying hadronically

Missing mass : technique

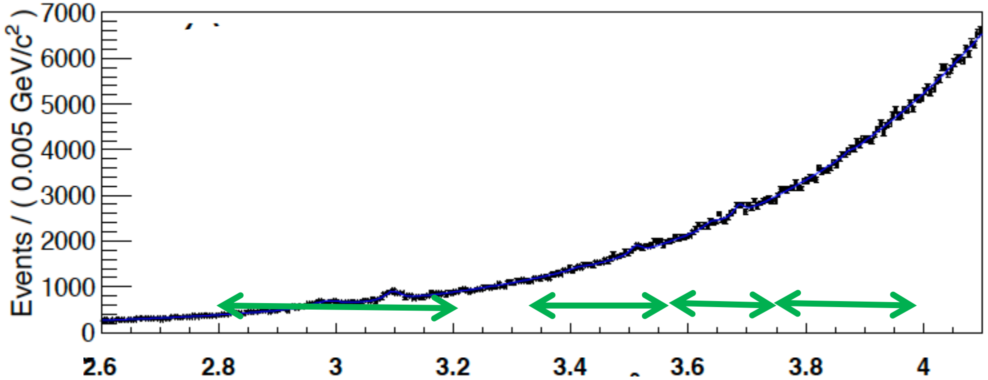
$$M_{\mathrm{miss(h)}} = \sqrt{(p^*_{\mathrm{e^+e^-}} - p^*_{\mathrm{tag}} - p^*_{\mathrm{h}})^2}/c$$

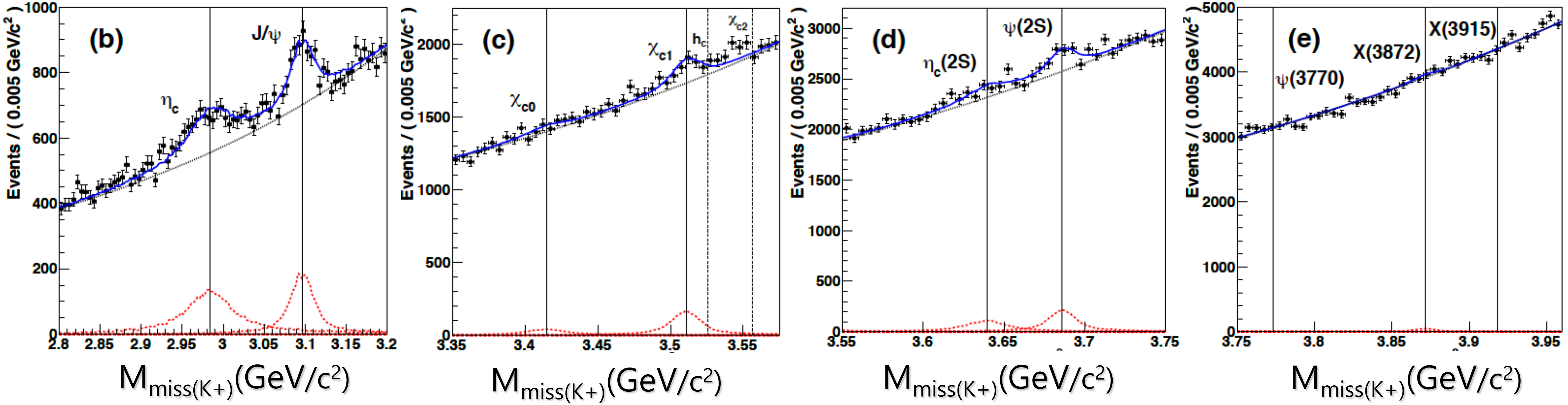
k

$e^+e^- \to \Upsilon(4S) \to \bar{B}_{sig} B_{tag}$

K only

Absolute BF measurement for $B^+ \to X_{c\bar{c}} K^+$





Summary of BF measurements for $B^+ \to X_{c\bar{c}}K^+$

TABLE II: Summary of the branching fraction measurements for $B^+ \to X_{c\bar{c}}K^+$ decay. For the branching fractions, the first uncertainties are statistical and the second are systematic. Values in brackets for $\mathcal{B}$ represent the 90% C.L. upper limits.

	Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]	
(b)	η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1	(b)
	J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031	
(c)	χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$	(c)
	χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23	
(d)	$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8	(d)
	$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24	
(e)	$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3	(e)
	$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)	
	$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-	

- Improved BF measurements for η_c and $\eta_c(2S)$.
- Results for J/ψ, χ_{c0}, χ_{c1} and $\psi(2S)$ are consistent with world average.
- No significant signals for $\psi(3770)$, $X(3872)$, $X(3915)$ and set ULs with 90% CL.

Improved M & Γ measurements of the X(3872)?

- Mass : Is $M_{X(3872)} > (m_{D0} + m_{D^*0})$ or $< (m_{D0} + m_{D^*0})$?
  -need more precise M_X and m_{D0} measurements

- Width : Is $\Gamma_{X(3872)} \approx \Gamma_{\chi c1}$ or $<< \Gamma_{\chi c1}$? ($\Gamma_{\chi c1}$ = 0.84+0.04 MeV)

$$\text{Belle (187 events)}: M_{X(3872)} = 3871.85 \pm 0.27 \pm 0.19 \text{ MeV}$$

Mass:

50 times of data

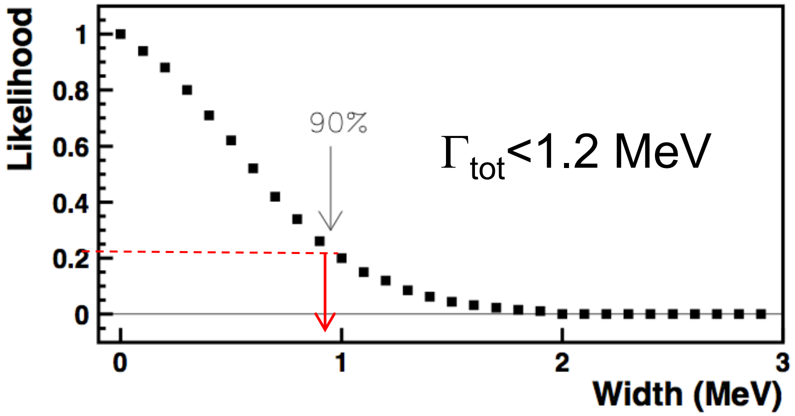
BelleII	statistical error:	0.27 → ~0.04
	systematic error:	0.19 → ~0.10 ← More work
		0.33 → ~0.11

BelleII will probably reduce $M_{X(3872)}$ error to the $m_{D0}+m_{D^*0}$ (3871.693±0.090 MeV) error Level. But, by the time BelleII runs, LHCb will probably have done much better.

Width:

Belle: X(3872) width limit (187 events): $\Gamma_{X(3872)} < 1.2$ MeV

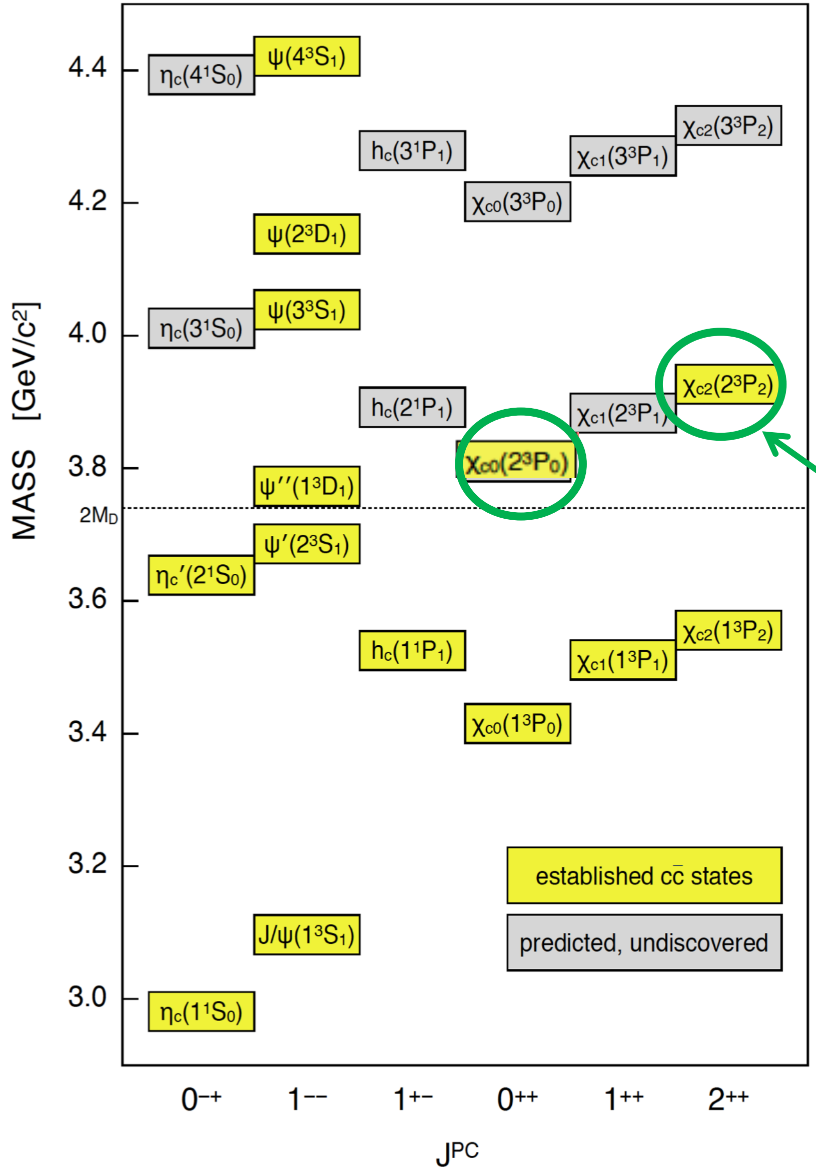
ψ' width measurement (4.4K events): $\Gamma_{\psi'} \approx 280 \pm 90$ keV   PDG: $\Gamma_{\psi'} = 299 \pm 8$ keV



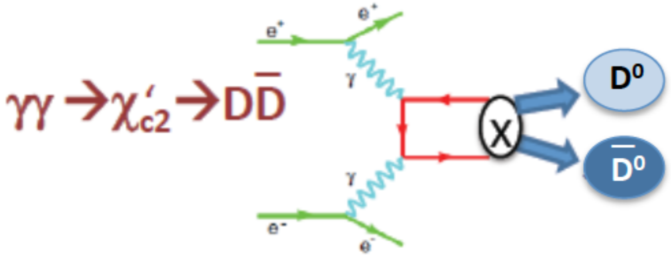
BelleII will be able to: make a >3σ measurement of $\Gamma_{X(3872)}$ if it is > 300keV
or set an upper-limit at this level if it is <300keV

No experiment will be able to do better than this until PANDA runs.

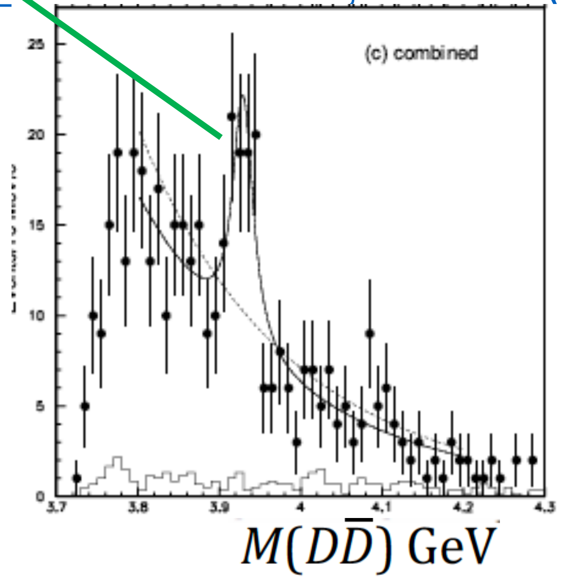
Observation of $\chi_{c0}(2^3P_0)$ in $e^+e^- \rightarrow J/\psi\ D\bar{D}$

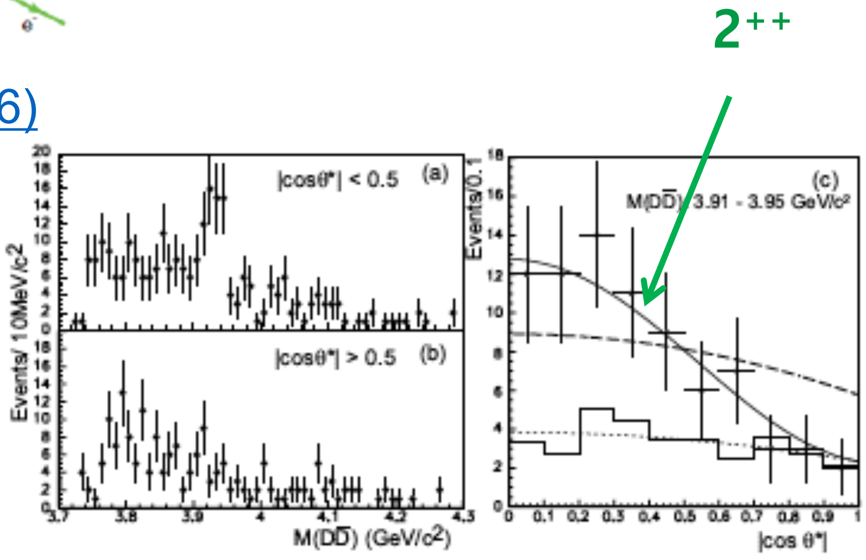


The χ_{c0}' and χ_{c2}' are expected to decay into $D\bar{D}$ in S-wave with a large width



S. Uehara:PRL 96, 082003 (2006)





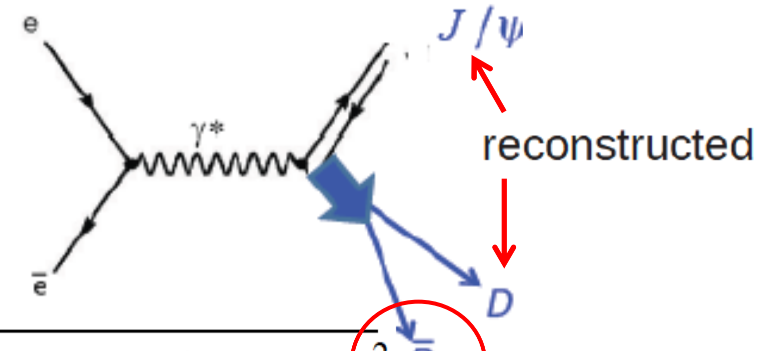
M=3927.2 ± 2.6MeV

Γ= 24 ± 6MeV

χ_{c0}' candidate

in $e^+e^- \rightarrow J/\psi D\bar{D}$

[K. Chilikin et al.: PRD95, 112003 (2017)]

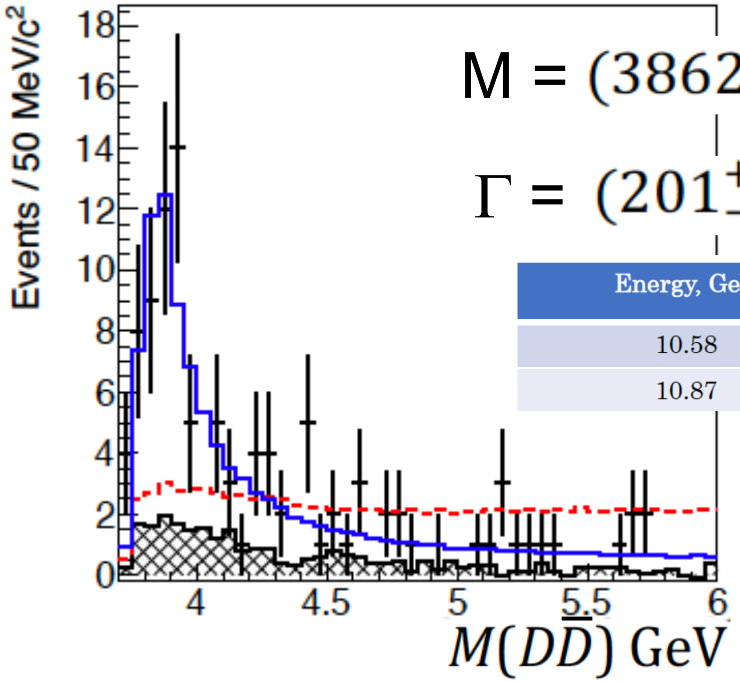


$$M_{rec} = \sqrt{[p(e^+e^-) - p(J/\psi) - p(D)]^2}$$

Reconstructed channels:

- $D^+ \rightarrow K^0_S\pi^+$, $K^-\pi^+\pi^+$, $K^0_S\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^0$, and $K^0_S\pi^+\pi^+\pi^-$.
- $D^0 \rightarrow K^-\pi^+$, $K^0_S\pi^+\pi^-$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$.

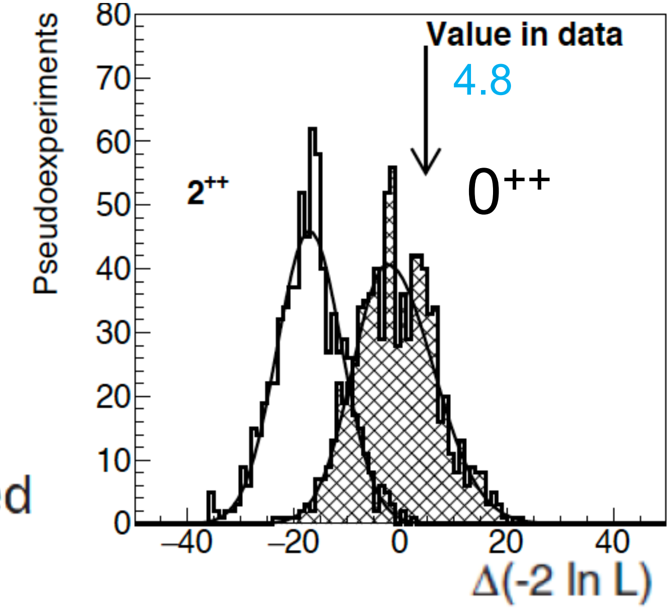
J/ψ and one of the D mesons are reconstructed



$M = (3862^{+26}_{-32}{}^{+40}_{-13})$ MeV/c²

$\Gamma = (201^{+154}_{-67}{}^{+88}_{-82})$ MeV

Energy, GeV	$\sigma^{(Born)}_{e^+e^-\rightarrow J/\psi X^*(3860)(\rightarrow D\bar{D})}$, (fb)
10.58	$21.7^{+3.9}_{-4.3}{}^{+2.9}_{-2.1}$
10.87	$17.9^{+7.2}_{-7.3}{}^{+2.4}_{-1.8}$



The measured mass & width are close to the potential model expectation of χ_{c0}'.

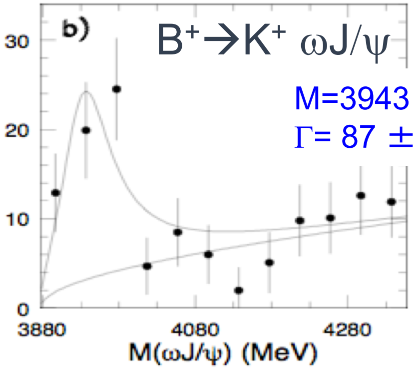
$J^{PC} = 0^{++}$ is favored over 2^{++} at the level of 2.5 σ.

Consistent with χ_{c0}' hypotheses

X(3915) (←Y(3940)) (ex - χ_{c0}' candidate)

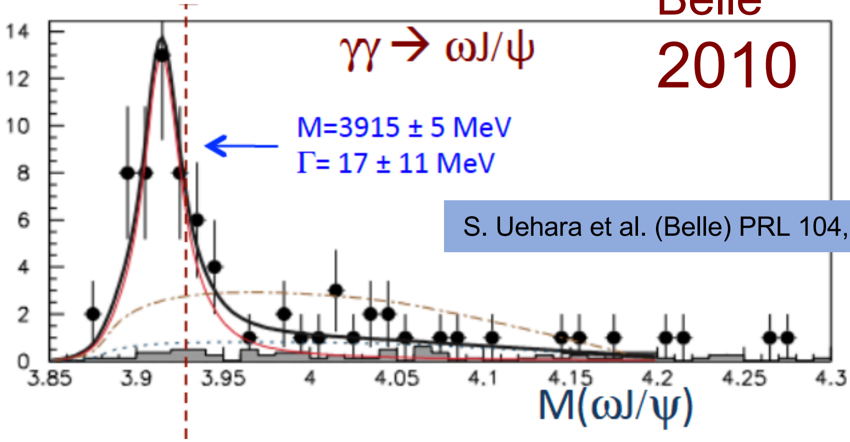
Belle
2005

S.-K. Choi et al. (Belle) PRL 94, 182002



M=3943 ± 17 MeV
Γ= 87 ± 34 MeV

Belle
2010

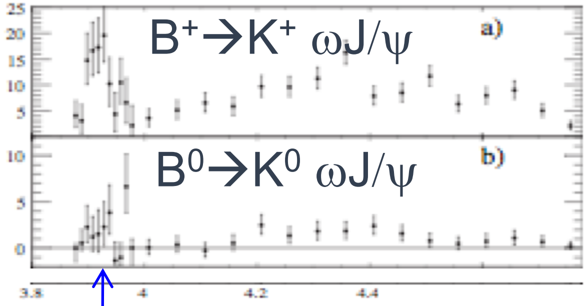


M=3915 ± 5 MeV
Γ= 17 ± 11 MeV

S. Uehara et al. (Belle) PRL 104, 092001

BaBar
2008

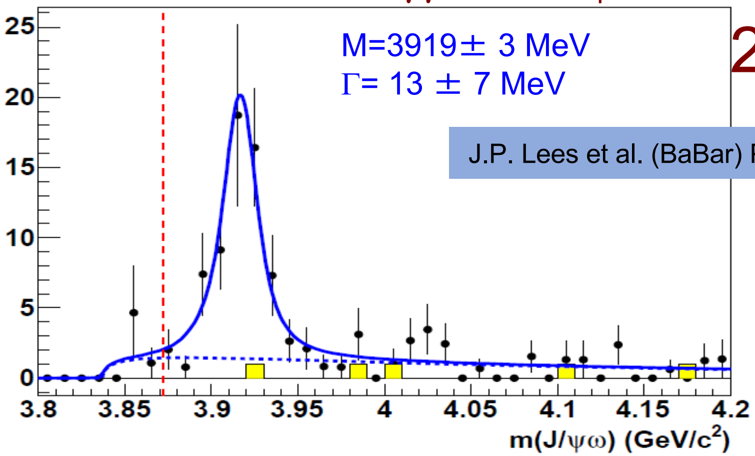
B. Aubert et al. (BaBar) PRL101, 182001



M=3915 ± 5 MeV
Γ= 34 ± 13 MeV

γγ → ωJ/ψ

BaBar
2012



M=3919± 3 MeV
Γ= 13 ± 7 MeV

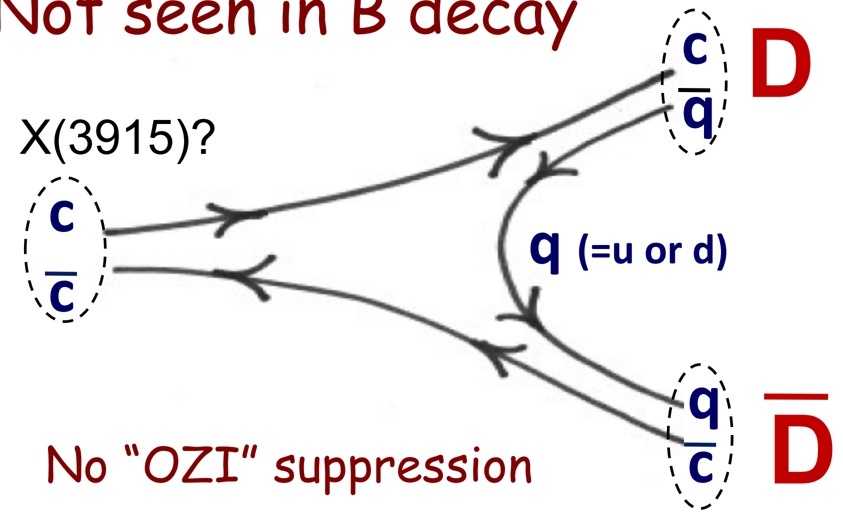
J.P. Lees et al. (BaBar) PRD 86, 072002

BaBar: $J^P = 0^+ \Rightarrow \chi_{c0}(2P)$ candidate

Then, what is the X(3915)?

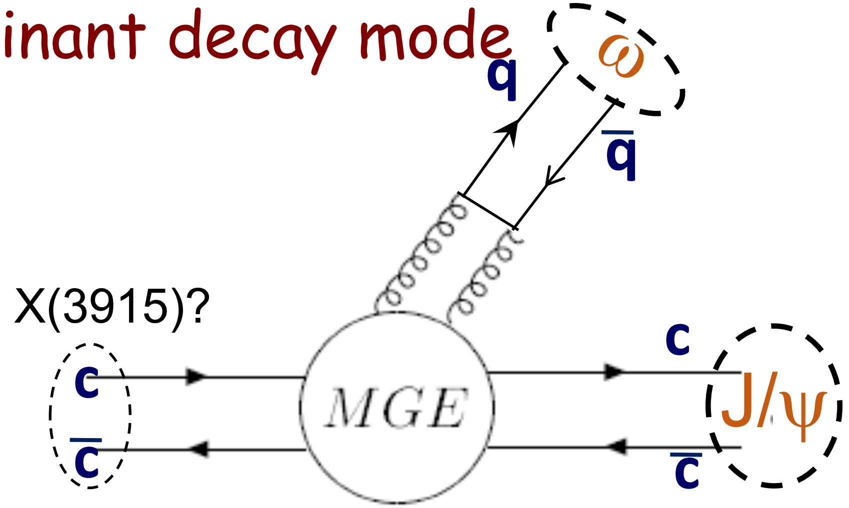
❖ χ_{c0}' is not OZI suppressed mode, but X(3915) is: $Bf(X_{3915}\to D^0\bar{D}^0) < 1.2\times Bf(X_{3915}\to \omega J/\psi)$

Not seen in B decay



No "OZI" suppression

Dominant decay mode



"OZI" suppression mode

❖ Measured width: 20 MeV is too small, expect > 100 MeV (190MeV) above S-wave threshold

❖ χ_{c0}' → DD should be dominant, but not seen in $\gamma\gamma$ either : $\Gamma(J/\psi\ \omega) > 0.6\ \Gamma(DD)$ [Olsen PRD91, 057501(2015)]

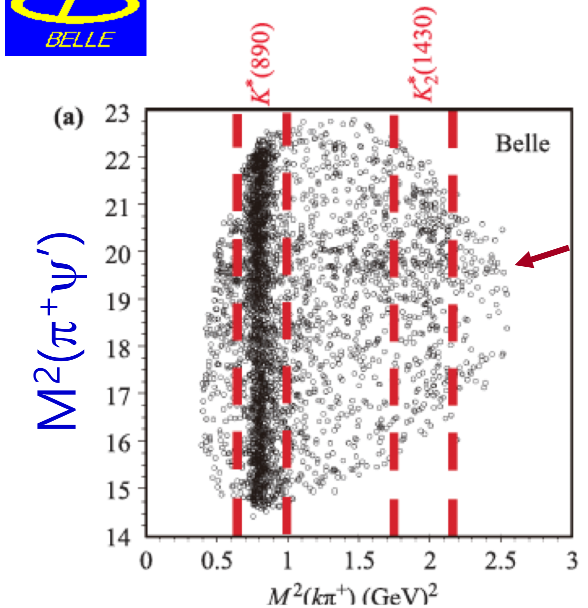
❖ No other 0^{++} charmonia nearby for the X(3915). [Zhou, et al. PRL115, 022001(2015)]

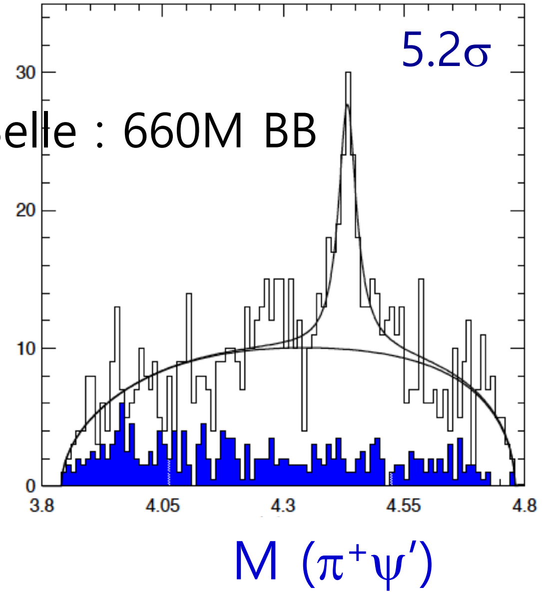
❖ Expect exotics : QCD diquark-diantiquark?

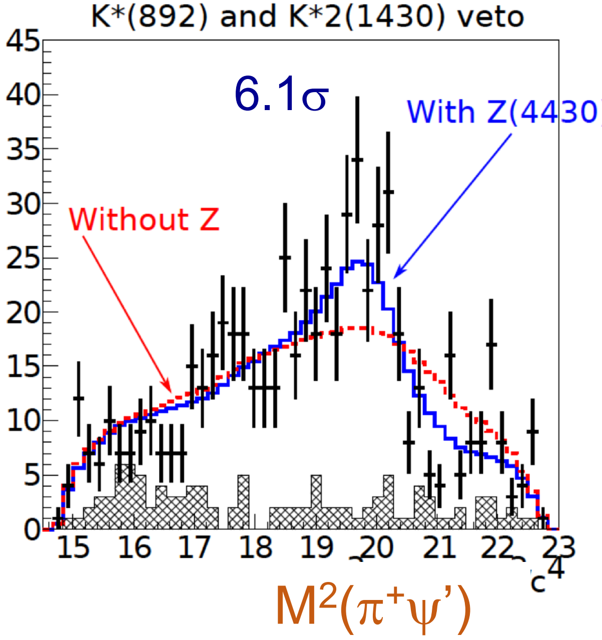
Search for $\Upsilon(1S,2S)\rightarrow Z^+Z^{(\prime)-}$ and $e^+e^-\rightarrow Z^+Z^{(\prime)-}$

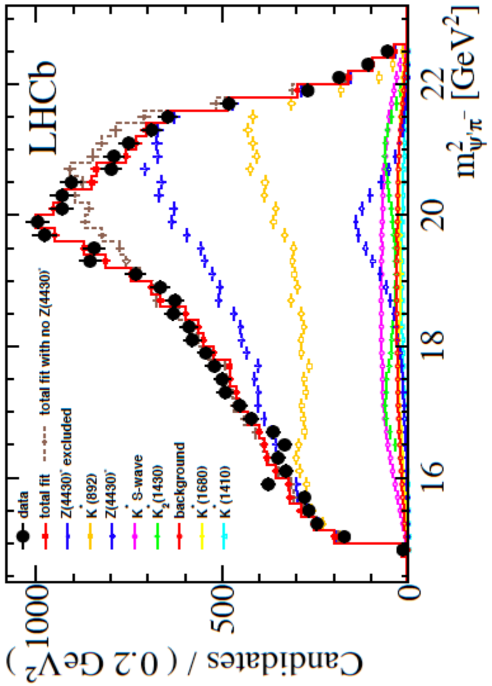
at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV

Z(4430) in $B \rightarrow \psi(2S)\pi^-K^+$

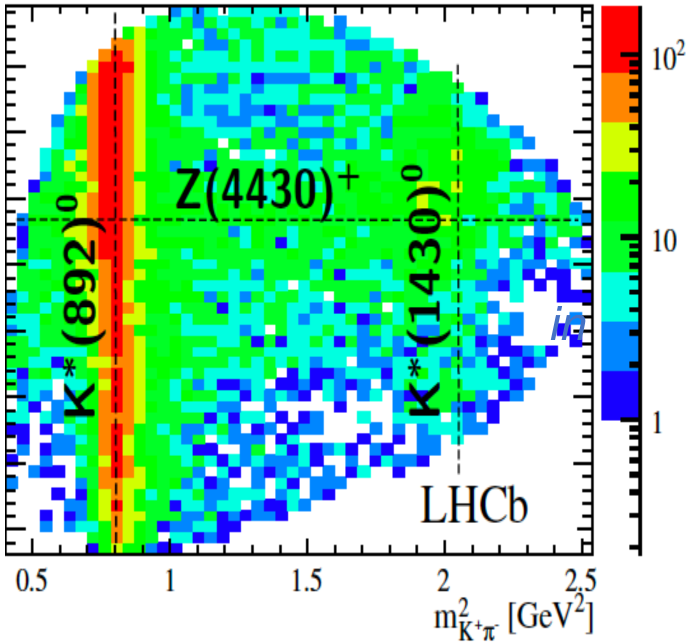








[PRL 112, 222002 (2014)]



2008 1-dim fit

$$M = 4433 \pm 4 \pm 2\ \text{MeV}$$
$$\Gamma = 45^{+18+30}_{-13-13}\ \text{MeV}$$

2013 4-dim fit

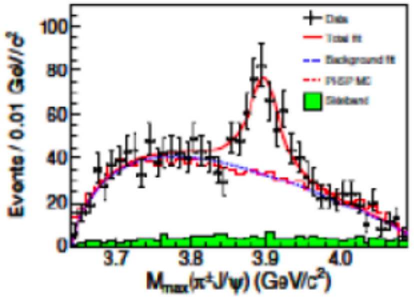
$$M = 4485^{+22+28}_{-22-11}\ \text{MeV}$$
$$\Gamma = 200^{+41+26}_{-46-35}\ \text{MeV}$$

2014 LHCb

$$M = 4475 \pm 7^{+15}_{-25} MeV$$
$$G = 172 \pm 13^{+27}_{-34} MeV$$

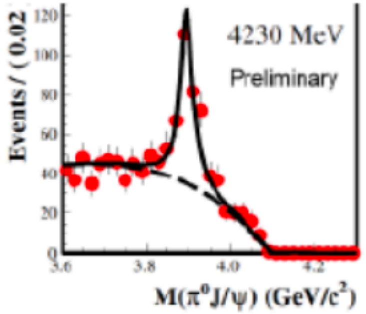
The Z_c states from BESIII (from ICHEP2018)

PRL 110, 252001 (2013)



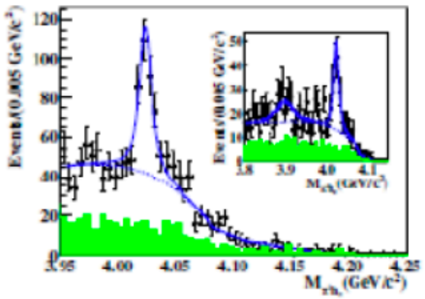
$e^+e^- \to \pi^-\pi^+J/\psi$

PRL 115, 112003 (2015)



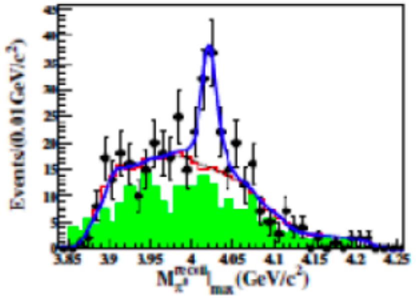
$e^+e^- \to \pi^0\pi^0J/\psi$

PRL 111, 242001(2013)



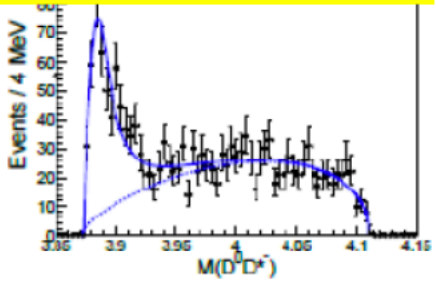
$e^+e^- \to \pi^-\pi^+h_c$

PRL113,212002 (2014)



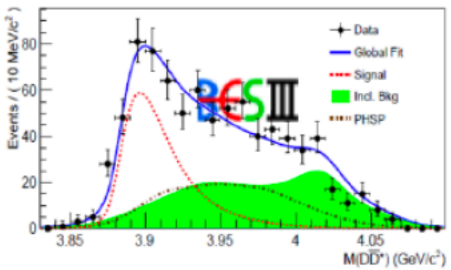
$e^+e^- \to \pi^0\pi^0h_c$

ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



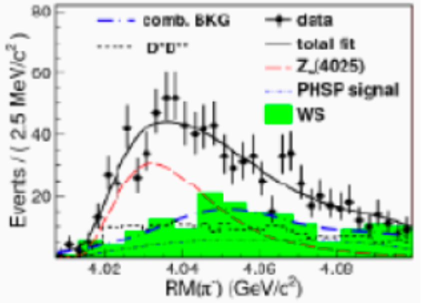
$e^+e^- \to \pi^-(D\bar{D}^*)^+$

PRL 115, 222002 (2015)



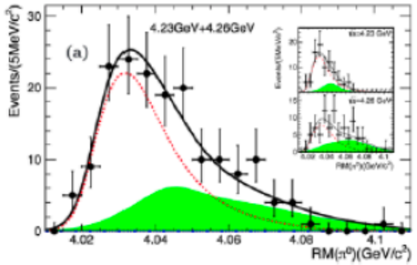
$e^+e^- \to \pi^0(D^*\bar{D})^0$

PRL 112, 132001 (2014)



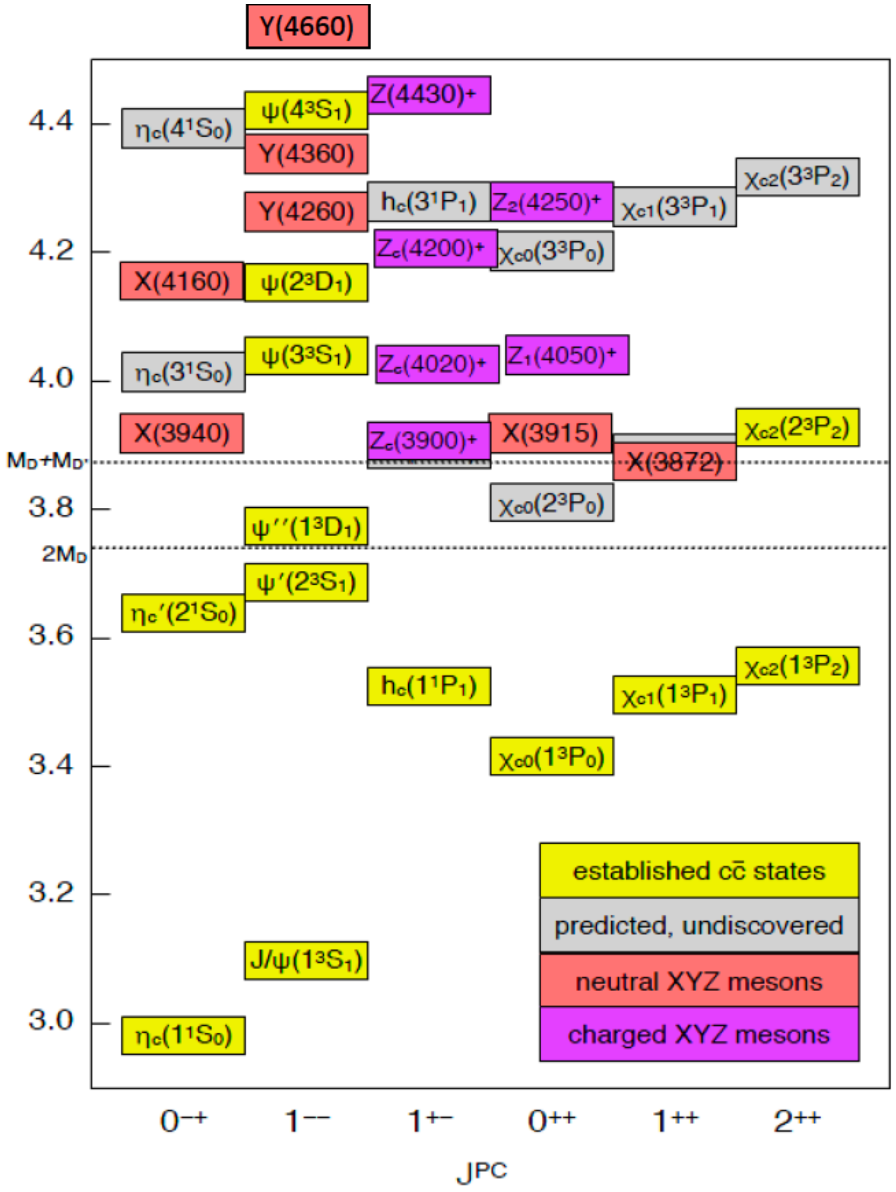
$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

PRL115, 182002 (2015)



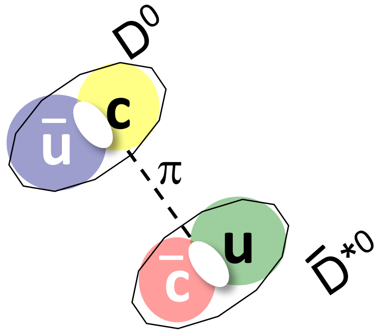
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

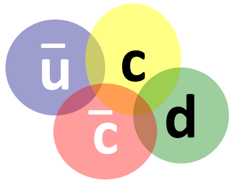
The Z_c states



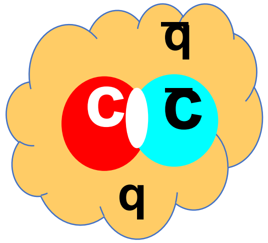
What's their nature?

loosely bound meson-antimeson "molecule"





tightly bound diquark-diantiquark



Hadro-charmonium

Search for $\Upsilon(1S,2S)\to Z^+Z^{(\prime)-}$ and $e^+e^-\to Z^+Z^{(\prime)-}$ at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV

S.Jia et al. PRD97, 112004 (2018)

The nature of Z states are not identified.
The electromagnetic FF are dependent on the model by S. J. Brodsky, et al. ***PLB 764, 174 (2017)*** ***PRD 91, 114025(2015)***

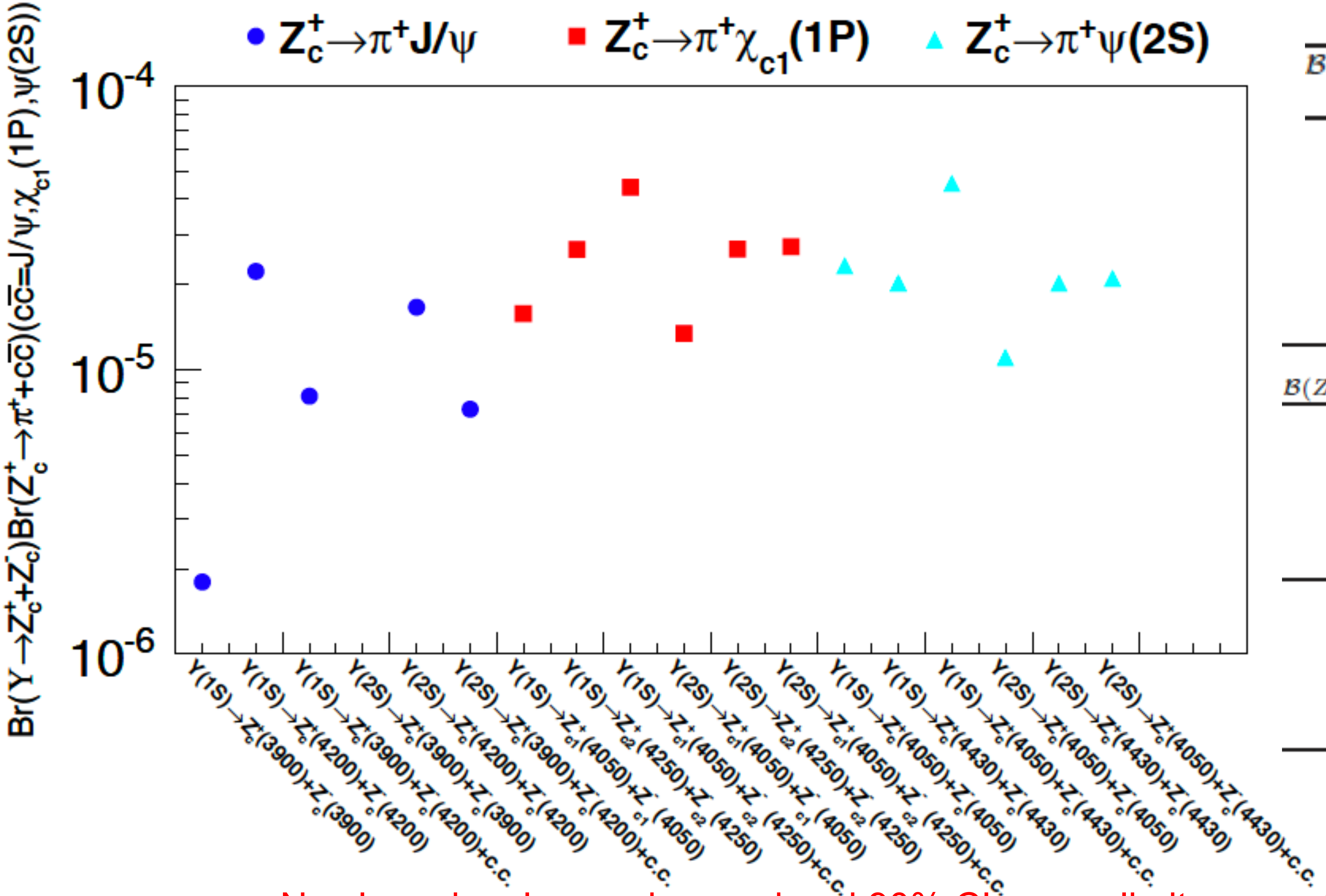
$$F_{Z_c^+ Z_c'^-} \sim \frac{1}{s^3}$$ *for tetraquark model*

$$F_{Z_c^+ Z_c'^-} \sim \frac{1}{s}$$ *for two tightly bound diquarks*

States	**Studied channels**
$Z_c(3900)/Z_c(4200) \to \pi^+ J/\psi$	$\Upsilon(1S,2S)$ /$e^+e^- \to Z_c(3900)+Z_c(3900)$, $Z_c(4200)/Z_c(4200)$, $Z_c(3900)/Z_c(4200)$
$Z_{c1}(4050)/Z_{c2}(4250) \to \pi^+\chi_{c1}$	$\Upsilon(1S,2S)$ /$e^+e^- \to Z_{c1}(4050)+Z_{c2}(4250)$, $Z_{c1}(4250)+Z_{c2}(4250)$, $Z_{c1}(4050)+Z_{c2}(4250)$
$Z_c(4050)/Z_c(4430) \to \pi^+\psi(2S)$	$\Upsilon(1S,2S)$ /$e^+e^- \to Z_c(4050)+Z_c(4430)$, $Z_c(4050)+Z_c(4430)$, $Z_c(4050)+Z_c(4430)$

Only one Z_c is fully reconstructed, the other is missing mass: $\sqrt{(p_{e^+e^-} - p_{\pi^+J/\psi})^2}$

$\Upsilon(1S,2S)\to Z^+Z^{(\prime)-}$



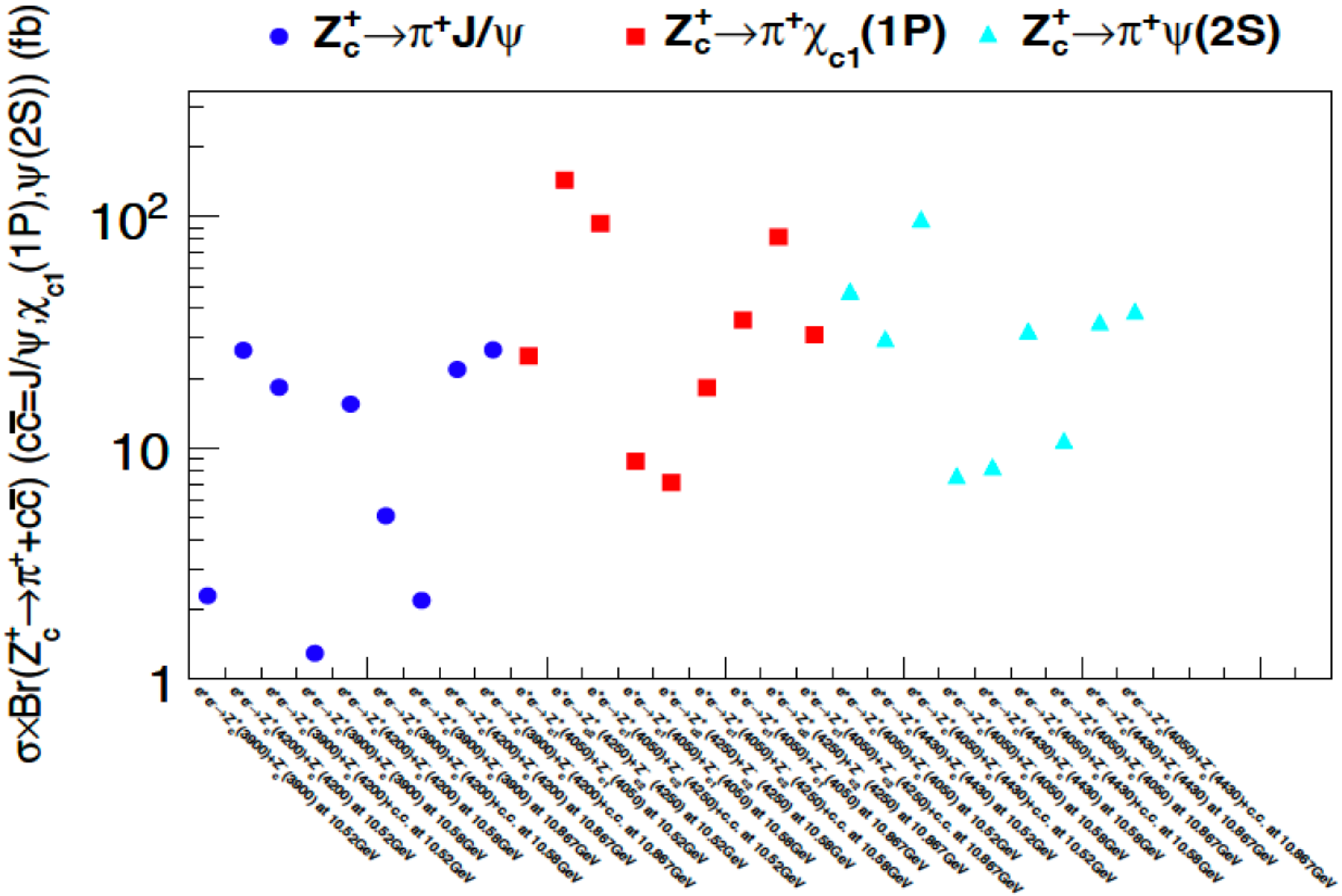
UL ($\times 10^{-6}$)

$\mathcal{B}^{UL}(\Upsilon\to Z_c^+Z_c^{(\prime)-})\times$ $\mathcal{B}(Z_c^+\to\pi^+J/\psi)$
1.8
22.3
8.1
1.0
16.7
7.3

$\mathcal{B}^{UL}(\Upsilon\to Z_c^+Z_c^{(\prime)-})\times$ $\mathcal{B}(Z_c^+\to\pi^+\chi_{c1}(1P)/\pi^+\psi(2S))$
15.8
26.6
44.2
13.5
26.7
27.2
23.3
20.3
45.5
11.1
20.3
21.1

No clear signals are observed and 90% CL upper limits are set

$e^+e^- \to Z^+Z^{(\prime)-}$



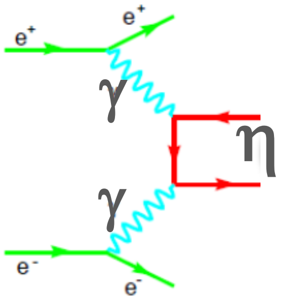
No clear signals are observed and 90% CL upper limits are set

UL ($\times 10^{-6}$)

$\sigma^{UL} \times \mathcal{B}(Z_c^+ \to \pi^+ J/\psi)$	$\sqrt{s}$ (GeV)
2.3	10.52
26.5	10.52
18.3	10.52
1.3	10.58
15.5	10.58
5.1	10.58
2.2	10.867
21.9	10.867
26.6	10.867

$\sigma^{UL} \times \mathcal{B}(Z_c^+ \to \pi^+ \chi_{c1}(1P)/\pi^+ \psi(2S))$	$\sqrt{s}$ (GeV)
25.0	10.52
143.9	10.52
93.2	10.52
8.8	10.58
7.1	10.58
18.2	10.58
35.7	10.867
82.0	10.867
30.8	10.867
47.7	10.52
29.7	10.52
97.9	10.52
7.6	10.58
8.3	10.58
32.2	10.58
10.8	10.867
35.2	10.867
39.1	10.867

$\eta_c(1S,2S) \rightarrow \eta'\pi\pi$ production in $\gamma\gamma$ collisions



$\eta_c, \eta_c' \rightarrow \eta' \pi^+\pi^-$

$\hookrightarrow \eta\pi^+\pi^-$ or $\gamma\rho$

Motivations:

- Playing an important role in QCD test

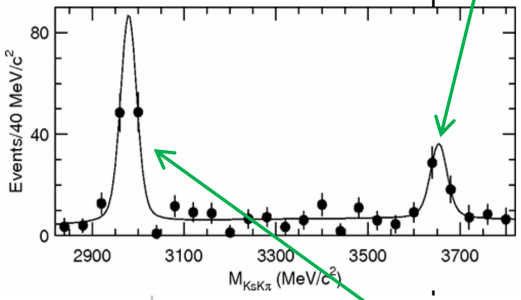
  N. Brambilla *et al.*, Eur. Phys. C **71**, 1534 (2011).

- Precise measurement of $\Gamma_{\gamma\gamma\rightarrow\eta c(1S,\,2S)}$ could give sensitive tests for QCD models

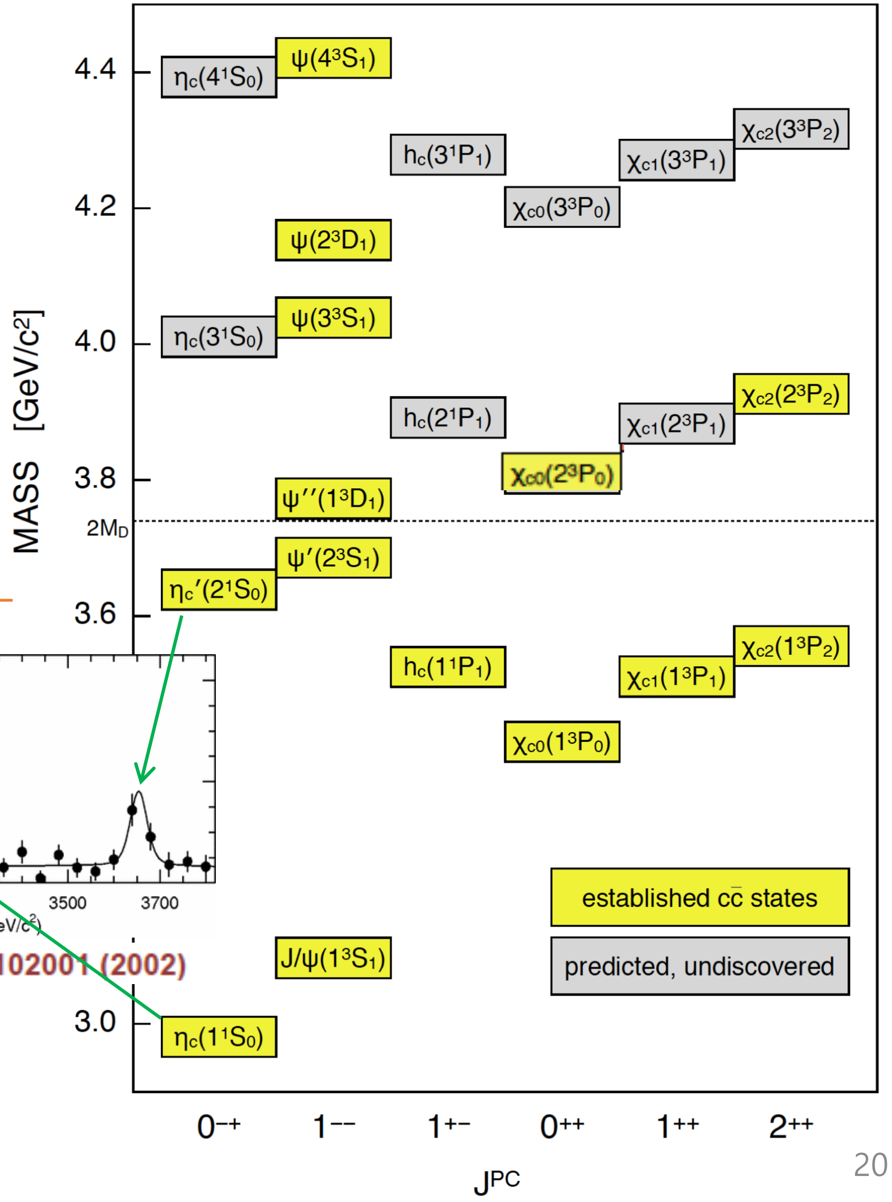
  J. P. Lansberg and T. N. Pham, Phys. Rev. D **74**, 034001 (2006).

- Poor measurement for $\eta_c \rightarrow \eta'\pi\pi$, other than $\eta_c \rightarrow K_sK\pi$
- Can be a discovery mode like as X(1835) seen in two photon process by Belle

$\eta_c' \rightarrow K_sK^+\pi^-$



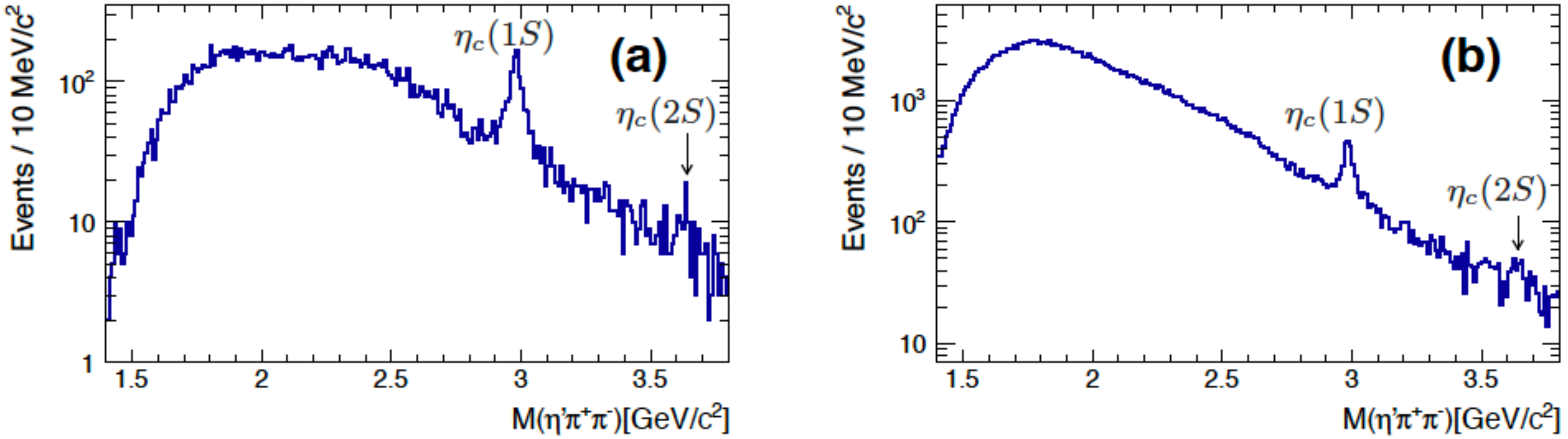
Belle PRL 89, 102001 (2002)



$\gamma\gamma \rightarrow \eta_c(1S,2S)$ at Belle

Xu et al. arXiv: 1805.03044 (2018)

792 fb^{-1} at $\sqrt{s}$=10.58 GeV (Υ(4S)) and 60 MeV below it.
149 fb^{-1} at $\sqrt{s}$=10.88 GeV (Υ(5S)) and scan data around this energy point.

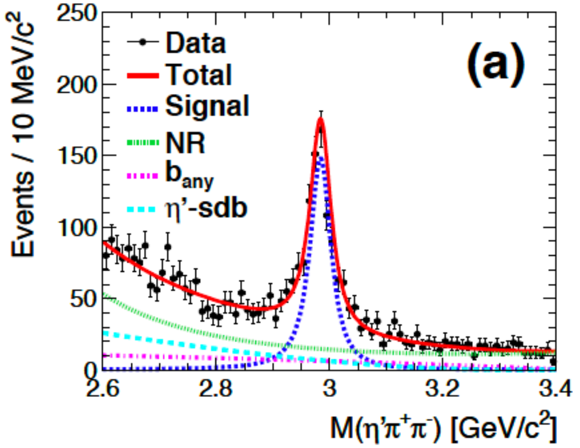


$\eta_c(1S,2S) \rightarrow \eta'(\rightarrow \eta\pi\pi)\pi\pi$

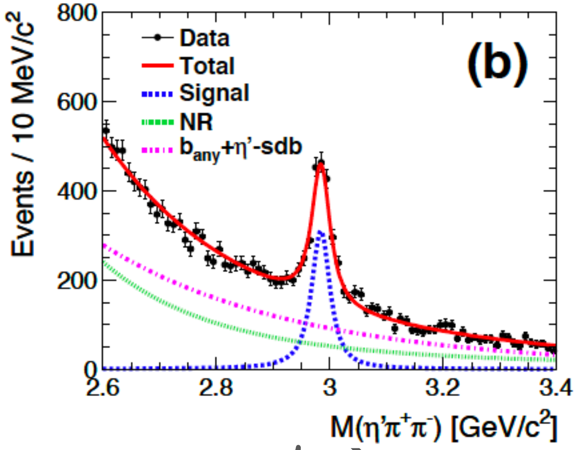
$\eta_c(1S,2S) \rightarrow \eta'(\rightarrow \rho\gamma)\pi\pi$

Clear η_c(1S) signal for both η' decay modes
Huge background by the low energy photons for $\eta' \rightarrow \rho\gamma$ mode

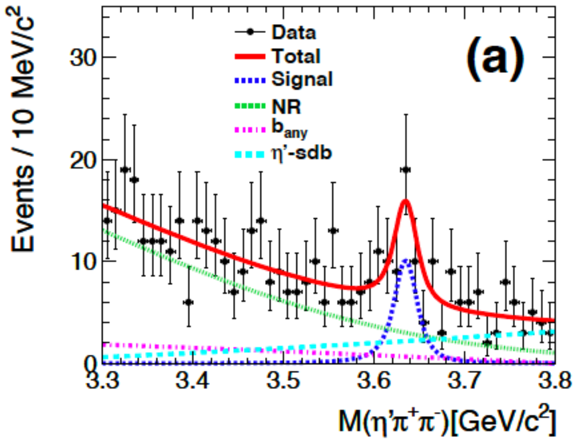
Simultaneous Fit to $\eta_c(1S)$ and $\eta_c(2S)$



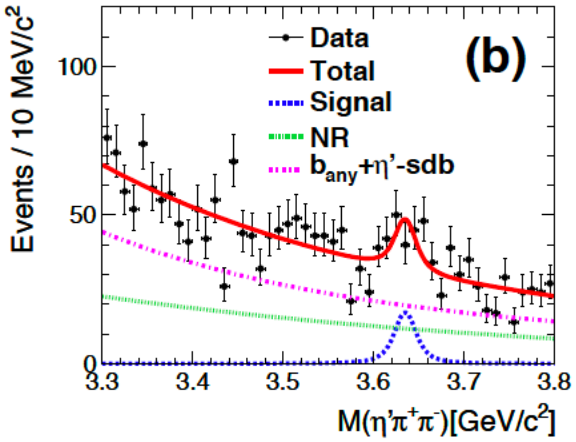
$\eta_c(1S) \to \eta'(\to \eta\pi\pi)\pi\pi$



$\eta_c(1S) \to \eta'(\to \rho\gamma)\pi\pi$



$\eta_c(2S) \to \eta'(\to \eta\pi\pi)\pi\pi$



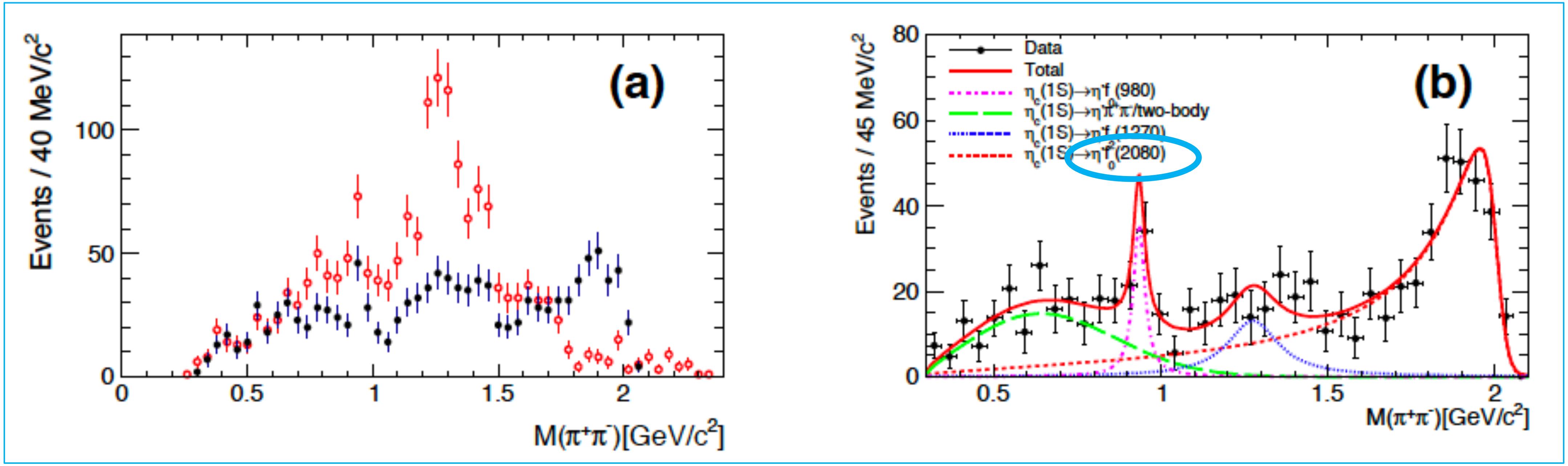
$\eta_c(2S) \to \eta'(\to \rho\gamma)\pi\pi$

	$\eta_c(1S)$		$\eta_c(2S)$	
	$\gamma\rho$	$\eta\pi^+\pi^-$	$\gamma\rho$	$\eta\pi^+\pi^-$
n_s	1728^{+69}_{-68}	945^{+38}_{-37}	65^{+14}_{-13}	41^{+9}_{-8}
M (MeV/c^2)	$2984.6 \pm 0.7 \pm 2.2$		$3635.1 \pm 3.7 \pm 2.9$	
Γ (MeV)	$30.8^{+2.3}_{-2.2} \pm 2.5$		11.3[fixed]	
$\Gamma_{\gamma\gamma}\mathcal{B}$ (eV)	$65.4 \pm 2.6 \pm 6.9$		$5.6^{+1.2}_{-1.1} \pm 1.1$	

First observation of η_c**(2S)**→ $\eta'\pi\pi$

with a significance of **5.5** σ

$M_{\pi\pi}$ distribution in $\eta_c(1S) \rightarrow \eta'(\rightarrow \eta\pi\pi)\ \pi\pi$



$M_{\pi\pi}$ distribution within signal region
$2.9 < M(\eta_c(1S)) < 3.06$ GeV
$M_{\pi\pi}$ within sideband region of
2.6–2.81GeV or 3.15–3.36GeV

N_s (signal yields fitted in each bin) distribution

$\eta_c(1S) \rightarrow \eta' f_0(2080)$ observation is evident

Summary

- Recent studies on charmonium(like) states were reported

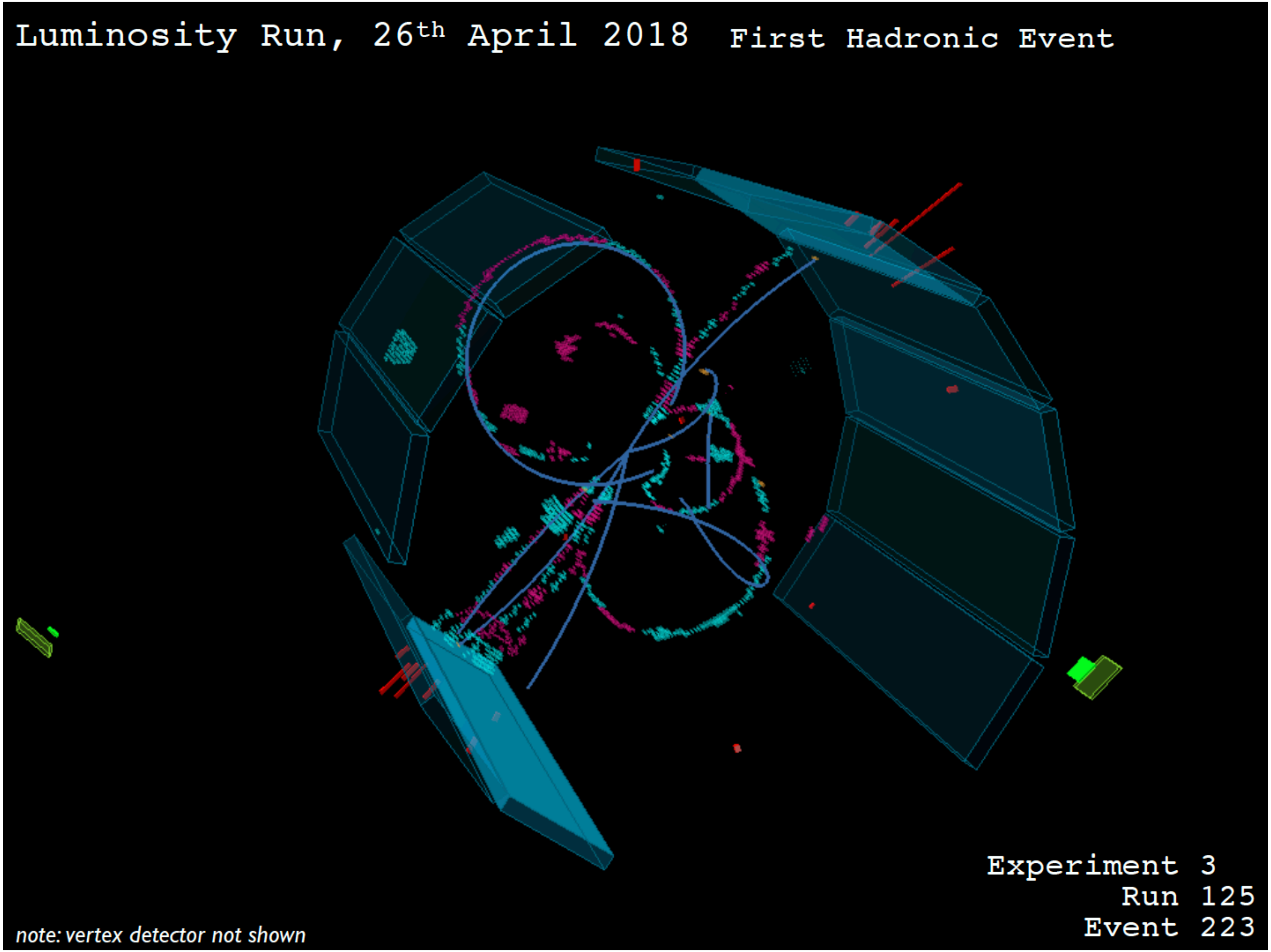
- The absolute branching fractions of $B^+ \rightarrow X_{cc}K^+$ have been measured, but statistics is not enough to measure BFs for $B \rightarrow \{\psi(3770), X(3872), X(3915)\}K$, etc, and set ULs.

- A new χ_{c0}' (canididate) in $D\bar{D}$ was found with the mass of $M = (3862^{+26}_{-32}{}^{+40}_{-13})\ \mathrm{MeV}/c^2$ and width $\Gamma = (201^{+154}_{-67}{}^{+88}_{-82})\ \mathrm{MeV}$. Then, the X(3915) is Not $\chi_{c0}(2P)$. What is it?

- Double $Z_c^+ Z_c^-$ production in Y(1S and 2S) decays and in e+e- annihilation at the $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV have been studied. No significant signals are observed in any of studied modes and 90% CL Uls are set.

- First observation of $\eta_c(2S) \rightarrow \eta'\pi\pi$ with a significance of 5.5σ in $\eta_c(1S,2S)$ production in two photon collision.

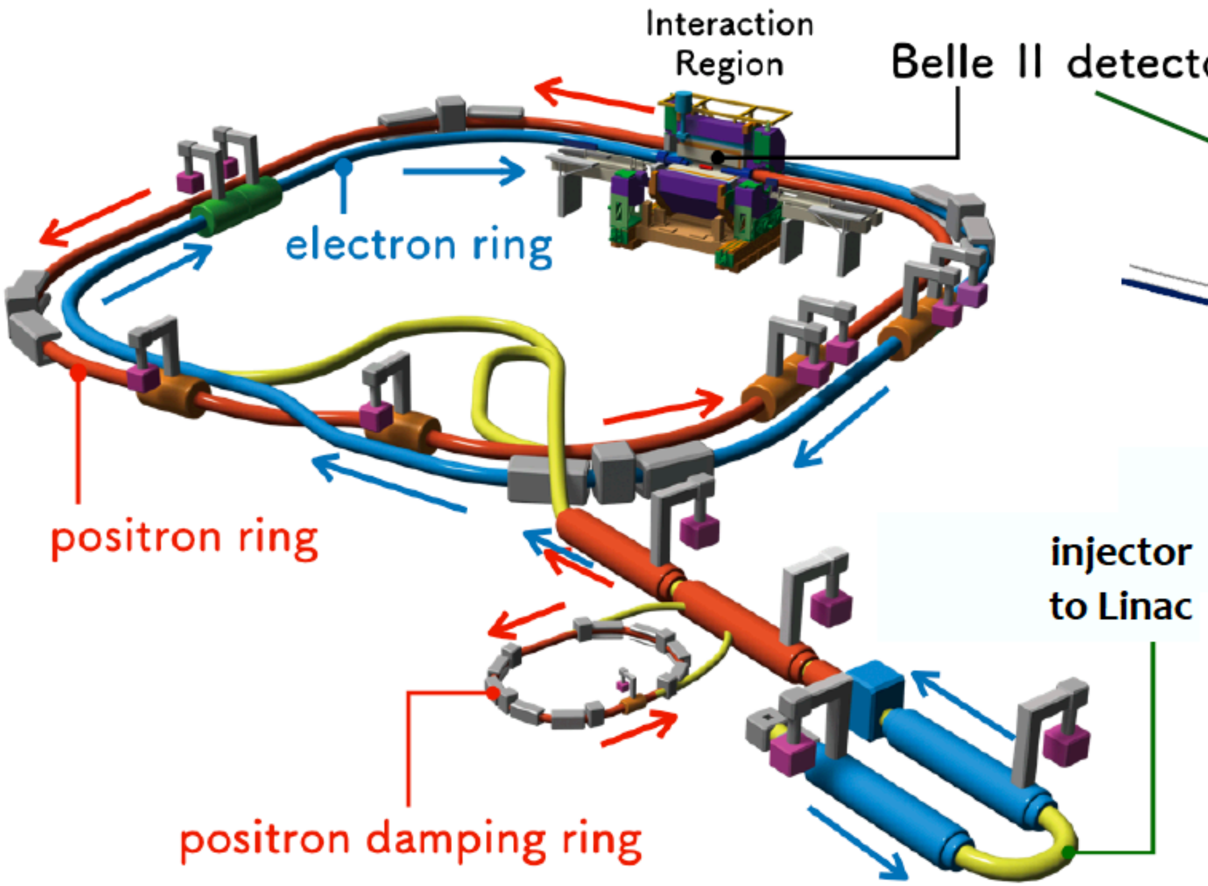
- More exciting results are going to come out from BelleII.

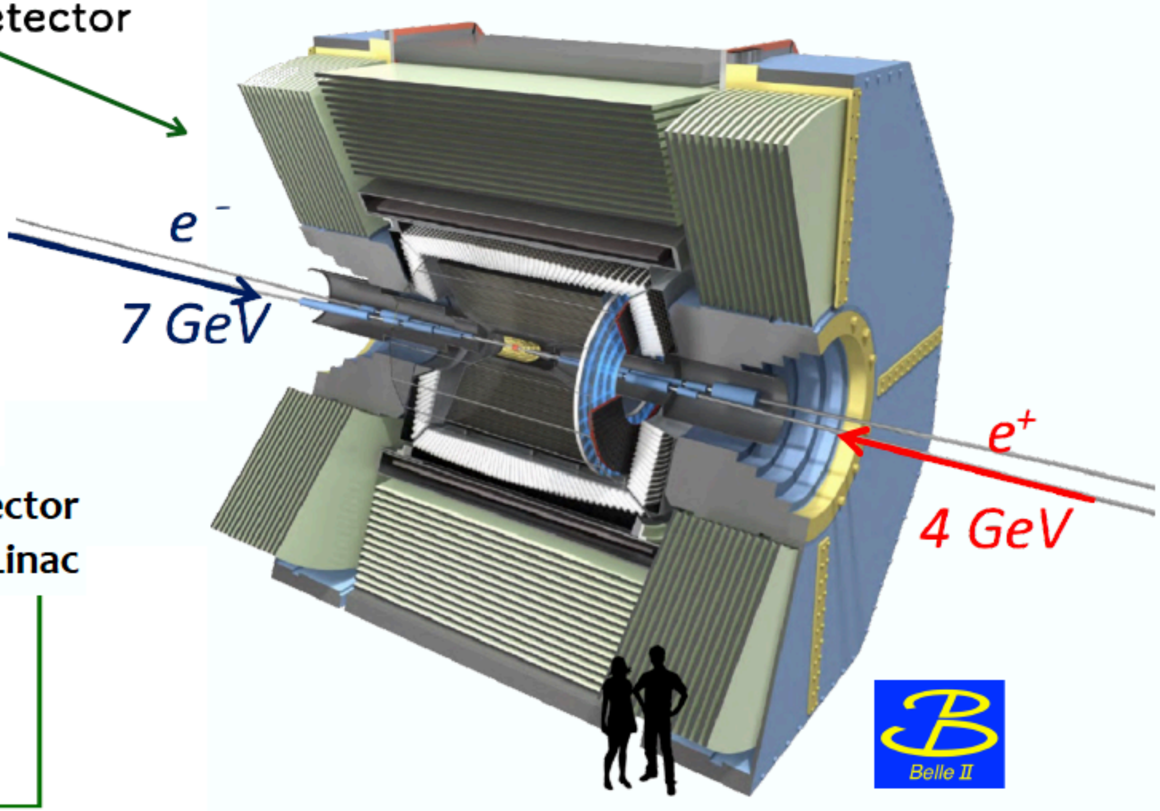

Luminosity Run, 26th April 2018
First Hadronic Event
Experiment 3
Run 125
Event 223
note: vertex detector not shown

Thank You

SuperKEKB

Belle II



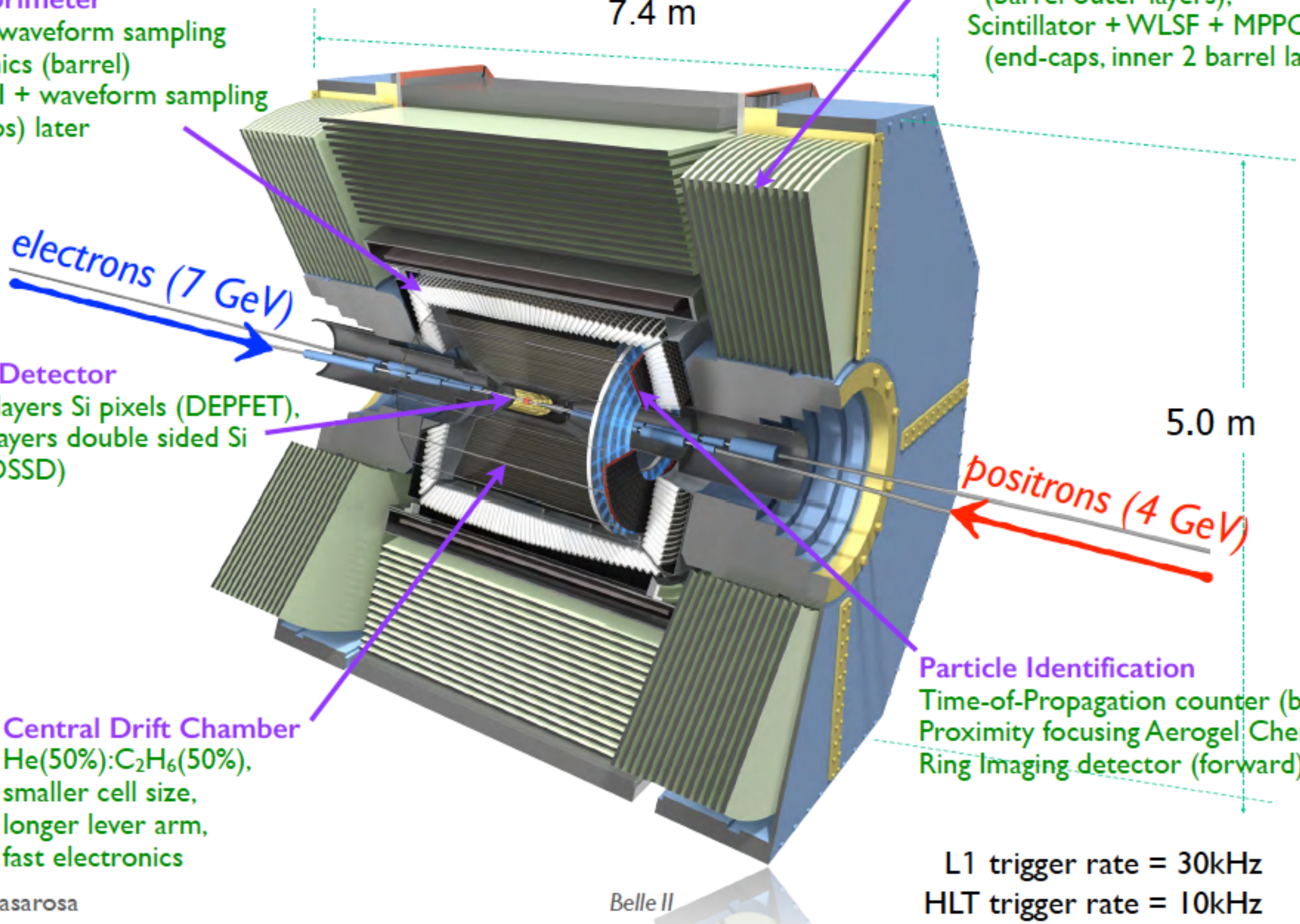


$$\mathcal{L}^{\rm peak} = 40 \times \mathcal{L}^{\rm peak}_{\rm Belle}$$

$$e^- \xrightarrow{7\ \mathrm{GeV}} (\star) \xleftarrow{4\ \mathrm{GeV}} e^+$$

$$\int^{\rm goal} \mathcal{L}\, dt = 50\ {\rm ab}^{-1} = 50 \times \mathcal{L}^{\rm int}_{\rm Belle}$$

The *Belle II* Detector



K_L & μ Detector
Resistive Plate Counter (barrel outer layers),
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM calorimeter
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later

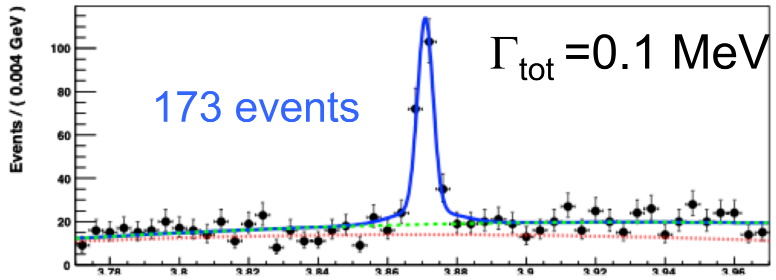
Vertex Detector
PXD: 2 layers Si pixels (DEPFET),
SVD: 4 layers double sided Si strips (DSSD)

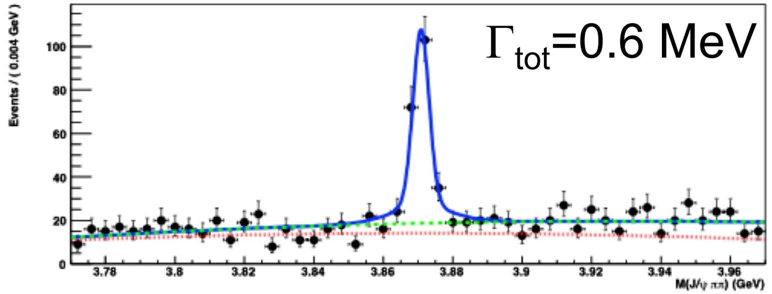
Particle Identification
Time-of-Propagation counter (barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)

Central Drift Chamber
He(50%):C_2H_6(50%),
smaller cell size,
longer lever arm,
fast electronics

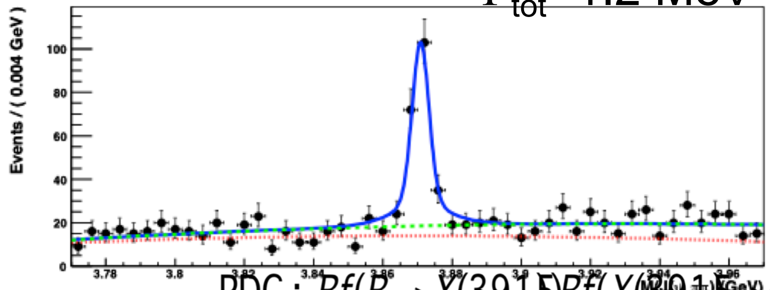
L1 trigger rate = 30kHz
HLT trigger rate = 10kHz

Width :





Γ_{tot}=1.2 MeV



PDG : $Bf(B \to X(3915))Bf(X(3915) \to \omega J/\psi) = (3.0^{+0.9}_{-0.7}) \times 10^{-5}$

PDG : $\Gamma(X(3915) \to \gamma\gamma)Bf(X(3915) \to \omega J/\psi) = (54 \pm 9)$eV