Rediscovery of X(3872) at Belle II Experiment

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X(3872) Mini Review

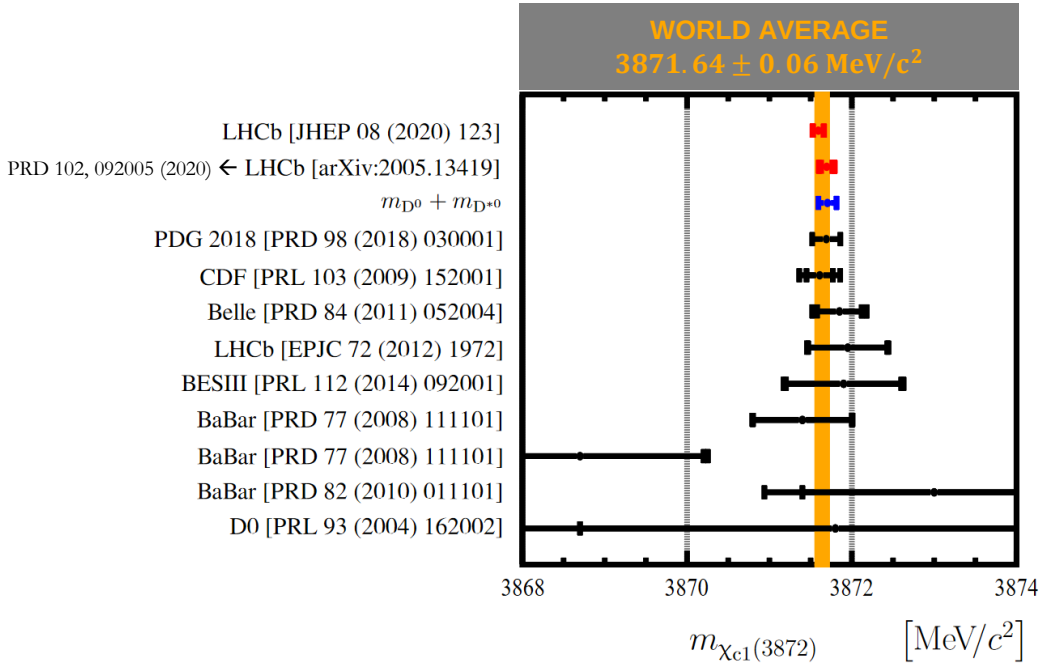
The notation was changed to $\chi_{c1}(3872)$
but just for the sake of convenience, I will stick to X in this talk.

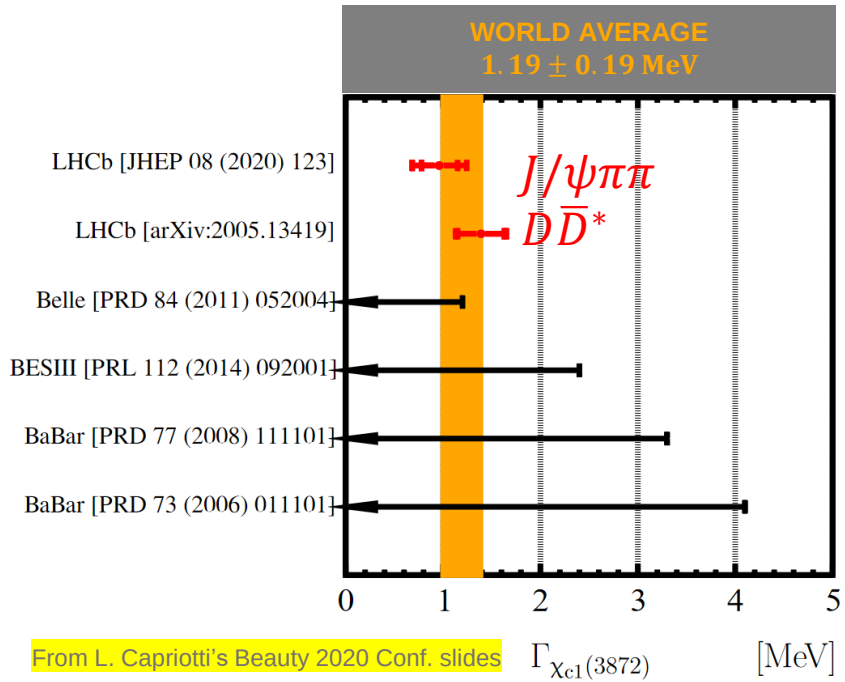
- The 2003 first discovery from Belle in $B \to K(J/\psi\pi^+\pi^-)$ channel PRL 91, 262001 (2003)
- Has been widely studied since then

Productions in	$B \to KX$,	$p\bar{p}$,	pp,	$e^+e^- \to \gamma X$			
Well established decay modes	$J/\psi\pi^+\pi^-$,	$J/\psi\pi^+\pi^-\pi^0$,	$J/\psi\gamma$,	$\psi(2S)\gamma$,	$D\bar{D}\pi$,	$D\bar{D}\gamma$,	$\pi^0\chi_{c1}$

- Yet the knowledge of the particle is not complete yet
  - Tetraquark / Molecule / Charmonium-Molecule mixture?
  - Full width measurement can pin down the partial width and provide a handle to constrain model predictions.
  - The most recent measurements are…

Great summaries by Dr. Skwarnicki and Dr. Guo
in the first day EXOTIC session!

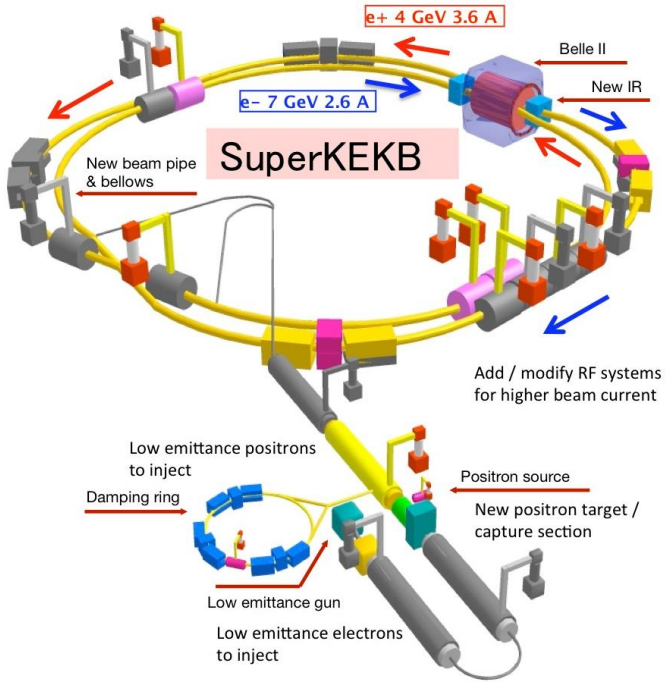


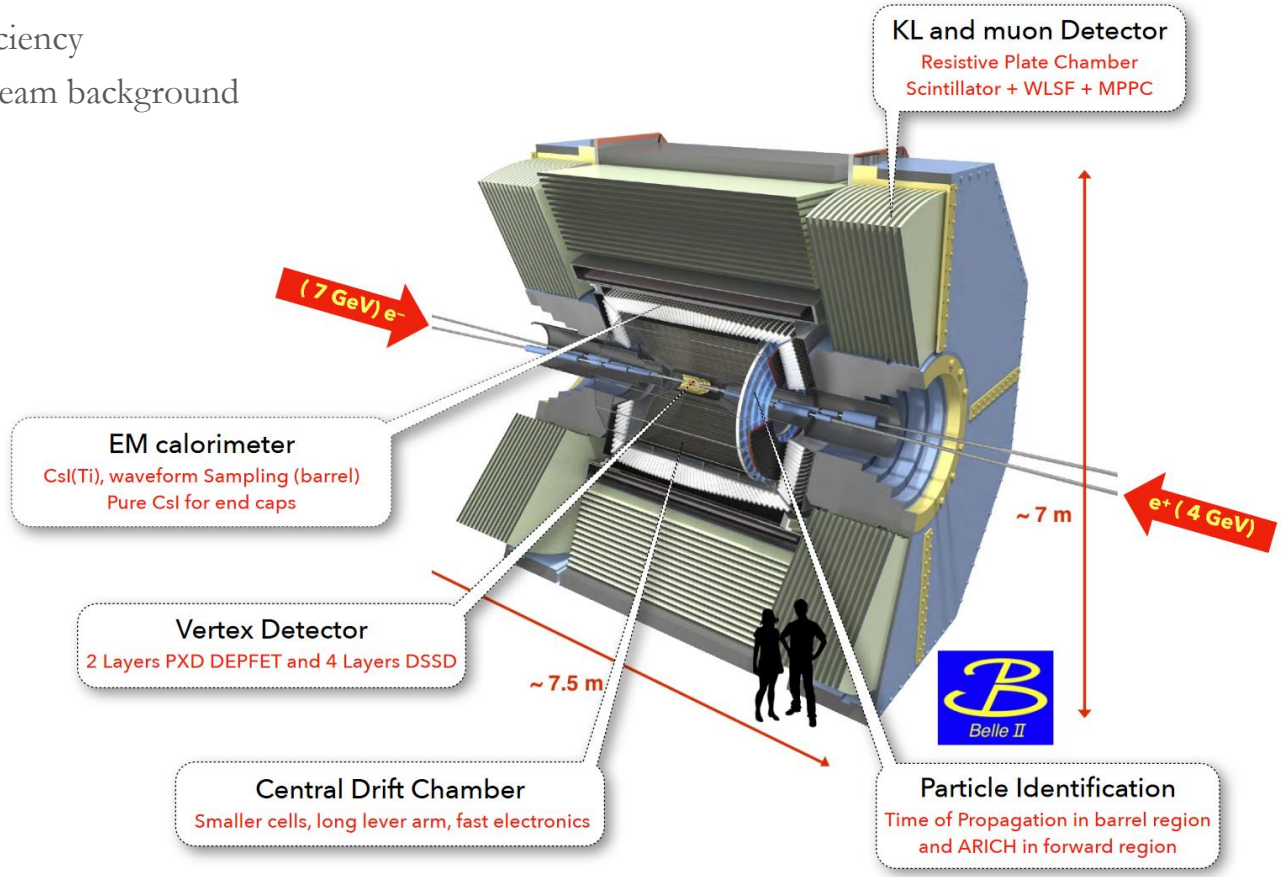


From L. Capriotti's Beauty 2020 Conf. slides

Belle II Detector

- A 4π detector with ability to detect $\pi, K, p, e, \mu, \gamma$ in wide momentum range
- $\sqrt{s} \sim 10.58$ GeV
- Operates on SuperKEKB accelerator designed to reach $\sim 30 - 40$ times ($6.5 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) the luminosity of the older KEKB
- Major differences to Belle:
  - Introduction of PXD for improved vertexing / better Ks efficiency
  - Upgrade in Particle Identification to cope with much higher beam background

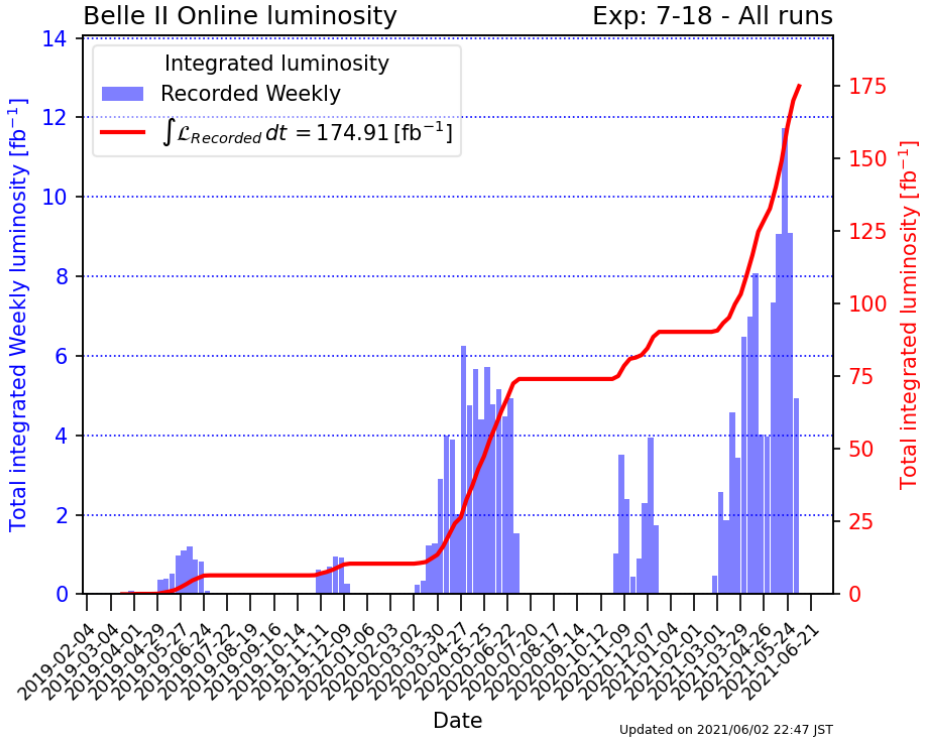


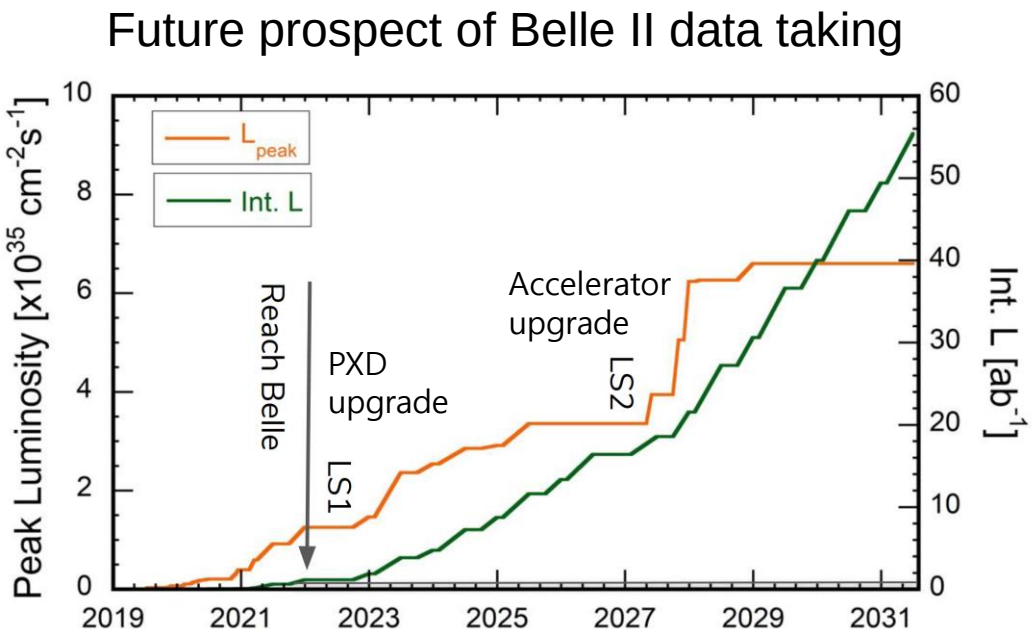


Belle II TDR: arXiv1011.0352

Belle II Dataset

- Aiming to collect 50ab^{-1} data mostly on $\Upsilon(4S)$ resonance (50 times of Belle)
- Current integrated luminosity $175\ \text{fb}^{-1}$ (peak instantaneous: $2.9 \times 10^{-34}\text{cm}^{-2}\text{s}^{-1}$)
- Increasing by $1 - 1.5\text{fb}^{-1}$ day by day

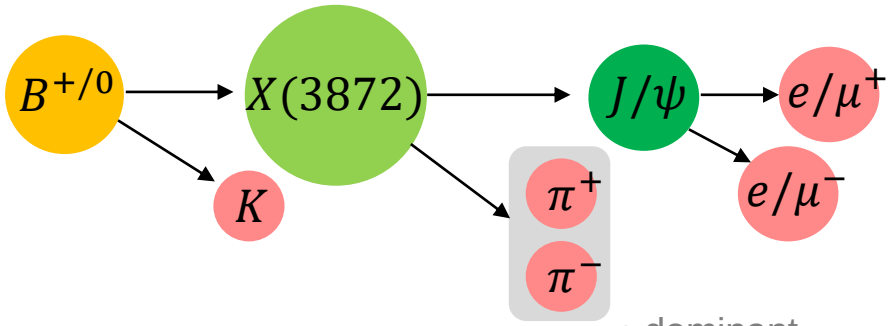




- Today, based on 62.8fb^{-1} $\Upsilon(4S)$ data: $B \to KX(3872): X(3872) \to J/\psi\pi^+\pi^-$ with high reconstruction rate

Analysis by Hikari Hirata, Kato Yuji, and Toru Iijima (Nagoya University.)

Reconstruction and Event Selection



ρ dominant

Track Selection

① PID for leptons and pions
② Point of closest approach to the interaction point in $r-\phi$ (along z direction) < 1.0 (3.0) cm

K_S^0

① Vertex fit with two oppositely charged pions
② $490 < M_{\pi^+\pi^-} < 506\ \mathrm{MeV}/c^2$

J/ψ

① $3.070\ (3.065) < M_{J/\psi\to\mu^+\mu^-(e^+e^-)} < 3.117\ \mathrm{GeV}/c^2$
(Bremsstrahlung photons are recollected)
② Mass-constrained fit after the first criterion

B

① $M_{bc}\left(\equiv\sqrt{(s/2)^2-(p_B^{cms})^2}\right) > 5.27\ \mathrm{GeV/c^2}$
② $|\Delta E(\equiv s/2-E_B^{cms})| < 0.02\ \mathrm{GeV/c^2}$

Continuum Suppression

Normalized Fox-Wolfram moment $R2 < 0.4$

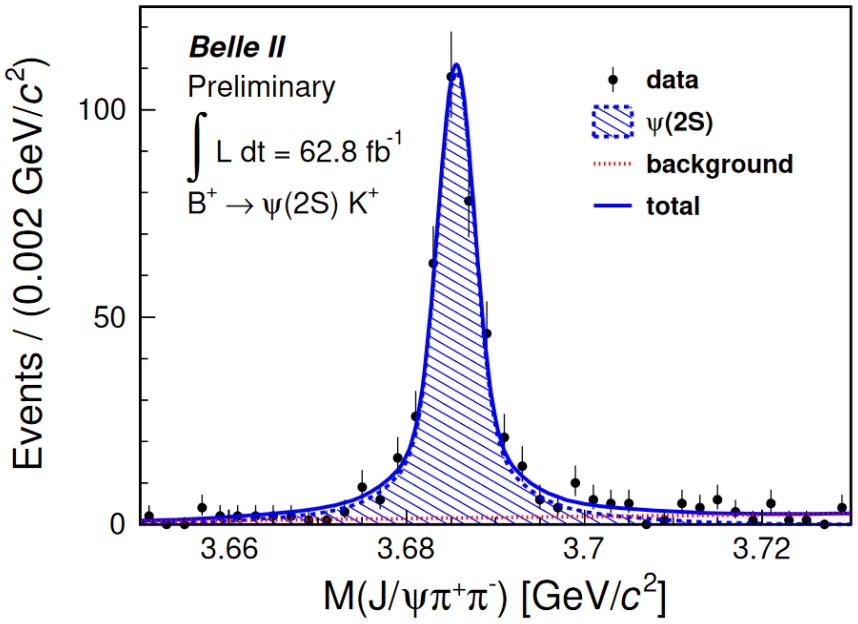
$M_{\pi^+\pi^-}$

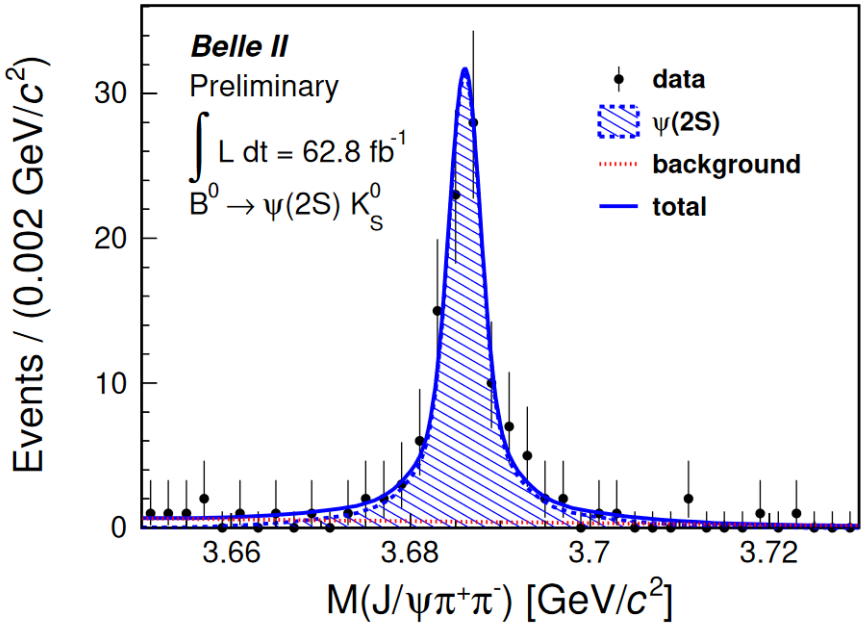
$M_{\pi^+\pi^-}^{meas} - M_{\ell^+\ell^-\pi^+\pi^-}^{meas} + m_{J/\psi} > -0.150\ \mathrm{GeV/c^2}$

- Retains ~90% of signal / suppresses background by ~75%
- Reduction in mis-identified pions

Control Sample Study with $B \to K\psi(2S): \psi(2S) \to J/\psi\pi^+\pi^-$

- $BF(B \to \psi(2S)K)$ from the Belle II data vs. World Average





- Same conditions for the X(3872) analysis applied: except for the $X(3872)$ specific $M_{\pi^+\pi^-}$ criterion
- Signal modeled in triple Gaussian with a common mean, Background in 1st order Chebyshev Polynomial
- Signal PDF width floated
- Unbinned maximum likelihood fit to the Data in $M_{J/\psi\pi^+\pi^-}$

Control Sample Study with $B \to K\psi(2S): \psi(2S) \to J/\psi\pi^+\pi^-$

$$BF = \frac{N_{signal}^{Observed}}{N_B \cdot \epsilon \cdot \Pi BF(\text{sub} - \text{decays})}$$

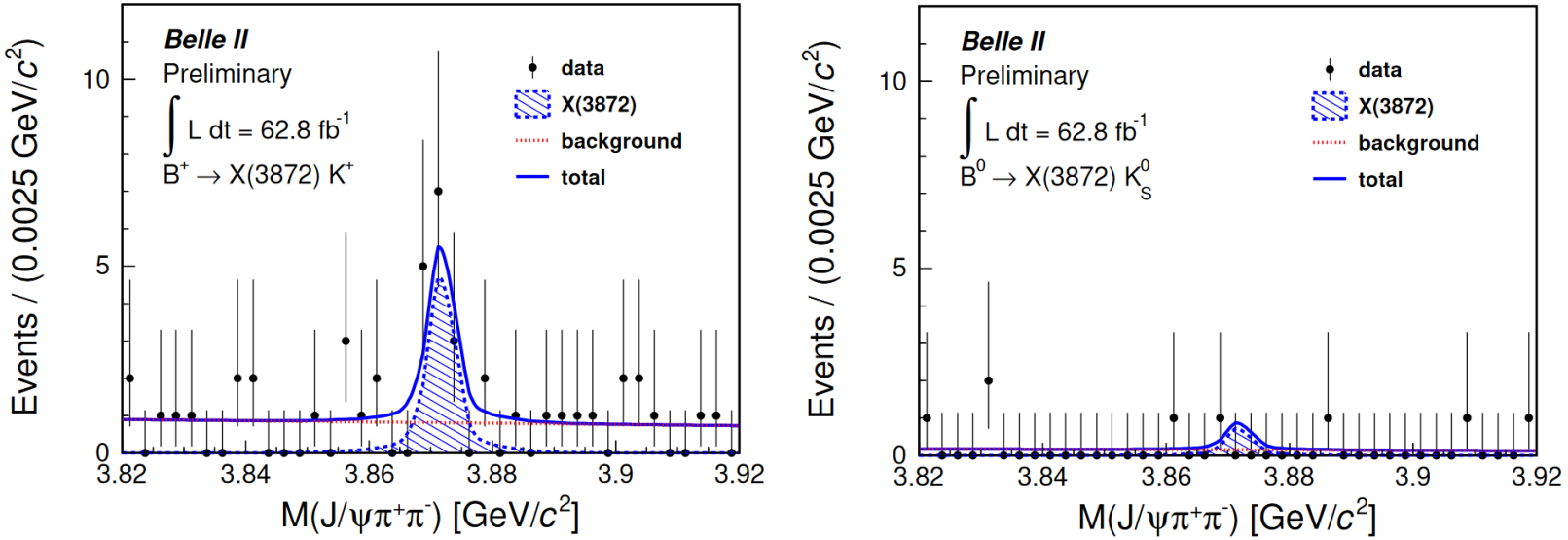
ϵ: acceptance x selection efficiency of the signal events with PID correction
N_B: Number of B mesons obtained

	$B^+ \to K^+\psi(2S)$	$B^0 \to K_S^0\psi(2S)$
Signal efficiency [%]	22.69 ± 0.16	17.40 ± 0.17
Obtained Branching Fraction (World average) [$\times 10^{-4}$]	6.08 ± 0.37 (6.19 ± 0.22)	6.18 ± 0.69 (5.8 ± 0.5)
Obtained / World Average	0.982 ± 0.069	1.07 ± 0.15

PDG2020: PTEP 2020, 083C01 (2020)

- Statistical uncertainty only
- In a good agreement with the world average branching fraction of $B \to K\psi(2S)$
- We see increased discrepancy with K/π Identification.
- Possible major systematic sources are: Tracking, K_S reconstruction, Number of B mesons (2.1%)

Extraction of signal for $B \to KX(3872)$

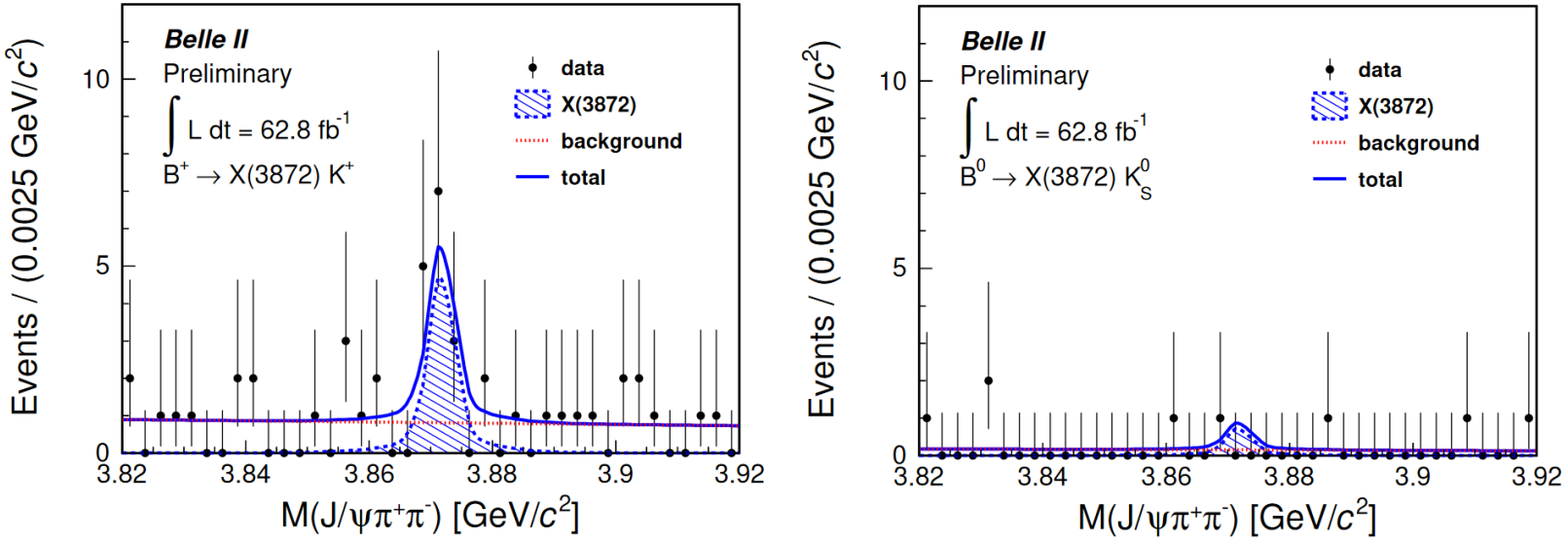


	B^+	B^0
$BF\big(B \to KX(3872)\big) \cdot BF(X(3872) \to J/\psi\pi^+\pi^-)$	8.6×10^{-6}	4.3×10^{-6}
ϵ	22.9%	17.5%
Expected signal yield / [1fb^{-1}]	0.267	0.0484

- Unbinned simultaneous extended maximum likelihood fit performed
- The ratio of signals yields to the expected signal yield per $1\ \text{fb}^{-1}$
  - $BF(B^0 \to X(3872)K^0)/BF(B^+ \to X(3872)K^+) = 0.50$ Belle, PRD 84, 052004 (2011).
  - Signal PDF: Histogram PDF assuming World Average Mass and Width from LHCb measurements.
  - Background PDF: 1st order Chebyshev Polynomial

Systematic study (Tracking, K_s reconstruction rate…) are currently being investigated!

Extraction of signal for $B \to KX(3872)$



	With signal hypothesis	Without signal hypothesis
Signal Yield	14.4 ± 4.6	-
Background in B^+ channel	31.6 ± 6.1	45.0 ± 6.7
Background in B^0 channel	7.0 ± 2.8	8.0 ± 2.8
Log likelihood	-231.01	-220.33

Statistical significance estimated to be:

$$-2\ln(L_0/L) = 4.6\sigma$$

	Belle		Belle II (This analysis)	
	Signal Yield / $\int Ldt$ [fb]	Signal Efficiency [%]	Signal Yield / $\int Ldt$ [fb]	Signal Efficiency [%]
$B^+ \to K^+\psi(2S)$	5.027 ± 0.090	17.8 ± 0.2	6.51 ± 0.37	22.7 ± 0.2
$B^0 \to K_s^0\psi(2S)$	1.145 ± 0.042	14.1 ± 0.2	1.66 ± 0.18	17.4 ± 0.2
$B \to KX(3872)$	0.212 ± 0.021	19.1 ± 0.2	0.194 ± 0.062	22.9

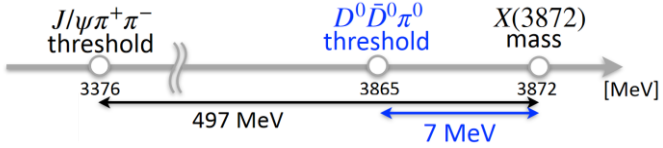
Note:

$K\psi(2S)$ at Belle II tends to higher efficiency due to looser criteria compared to Belle analysis as it was being used as a control sample for this analysis.

π-ID correction is not applied for the Belle II $KX(3872)$ analysis.

What next?: $X(3872)$ Width measurement

- Mass resolution of signal PDF (1.86 ± 0.01 MeV/c^2) > $\Gamma_{total}^{X(3872)}$ in $J/\psi\pi^+\pi^-$
- In order to improved the mass resolution $D^0\bar{D}^0\pi^0$ decay modes are preferred.

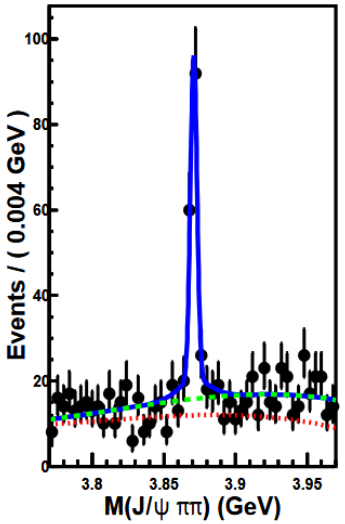


- Previous related search @ Belle: $X(3872) \to D^{*0}\bar{D}^0$

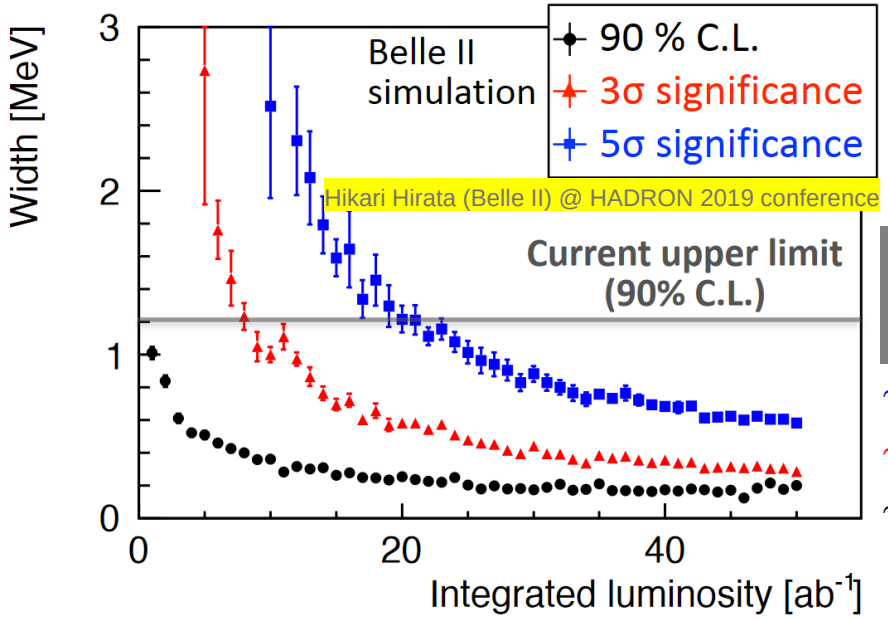
  $BF(B \to KX(3872)) \cdot BF(X(3872) \to D^{*0}\bar{D}^0) = (0.80 \pm 0.20 \pm 0.10) \times 10^{-4}$: $\Gamma_{total} = 3.9^{+2.8+0.2(syst)}_{-1.4-1.1(syst)}$

  Majority of systematics from fit bias, statistical limitation PRD 81, 031103 (2010).

Belle: PRD 84, 052004 (2011).



- **Looking forward to full width measurement at Belle II with $B \to KX(3872)$: $X(3872) \to DD\pi$!**
  - Toy MC study has already been performed with strategy of extracting signal in $M_{D^0\bar{D}^0\pi^0}$



Current WORLD AVERAGE from LHCb

$\Gamma = 1.19 \pm 0.19$ MeV

JHEP08(2020)123 / PRD102,092005(2020)

~570 keV

~280 keV

~180 keV

Summary

- The first study of exotic Charmonia at Belle II
- $X(3872)$ revisited at 4.6σ statistical significance!
- $62.8\ \mathrm{fb}^{-1}$ $\Upsilon(4S)$ data analyzed for $B \to KX(3872): X(3872) \to J/\psi\pi^+\pi^-$
- Belle II aims to reach $50\mathrm{ab}^{-1}$ data (5.5×10^{10} $B\bar{B}$s) and…

Provide total width of $X(3872)$ in $X \to D^0\bar{D}^0\pi^0$ or inclusively

Provide inputs on the properties of $X(3872)$ in its quantum numbers J^{PC}

Revisit more subchannels and improve measurements of the $X(3872)$ decays
e.g. $X(3872) \to J/\psi\gamma$ as low energy photon reconstruction is no problem @ Belle 2

BACKUP

PDG2020 summary

State	M [MeV]	Γ [MeV]	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [1049,1137] (>10), BaBar [1138] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi) \ldots$	CDF [1139–1141] (11.6), D0 [1142] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi) \ldots$	LHCb [1143–1145] (np), CMS [1146] (np)	2012	Ok
				$Y(4260) \to \gamma\,(\pi^+\pi^- J/\psi)$	BESIII [1147] (6.3)	2013	NC!
				$B \to K(\omega J/\psi)$	Belle [1148] (4.3), BaBar [1149] (4.0)	2005	NC!
				$B \to K(\gamma\, J/\psi)$	Belle [1148,1150] (5.5), BaBar [1151,1152] (3.6), LHCb [1153] (> 10)	2005	Ok
				$B \to K(\gamma\, \psi(2S))$	BaBar [1152] (3.5), Belle [1150] (0.2), LHCb [1153] (4.4)	2008	NC!
				$B \to K(D^0 \bar{D}^{*0})$	Belle [1154,1155] (6.4), BaBar [1156] (4.9)	2006	NC!

Control Sample Study with $B \to K\psi(2S): \psi(2S) \to J/\psi\pi^+\pi^-$ 34.2fb-1 w/ Systematics

Source	$B^+ \to K^+\psi(2S)$	$B^0 \to K_S^0\psi(2S)$
Tracking	8.5%	9.3%
K_S reconstruction efficiency	-	6.0%
Number of B mesons	2.1%	2.1%
Total	8.8%	11%