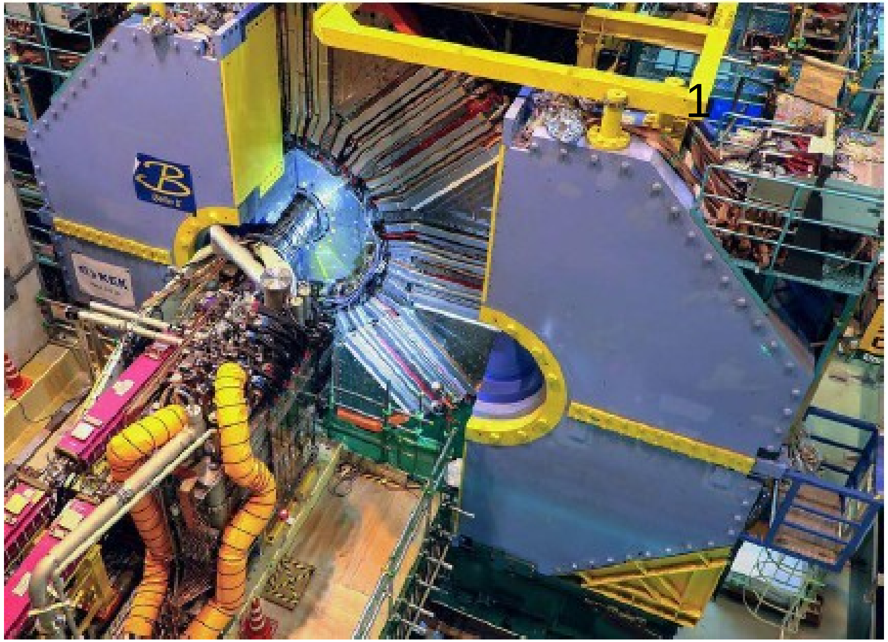
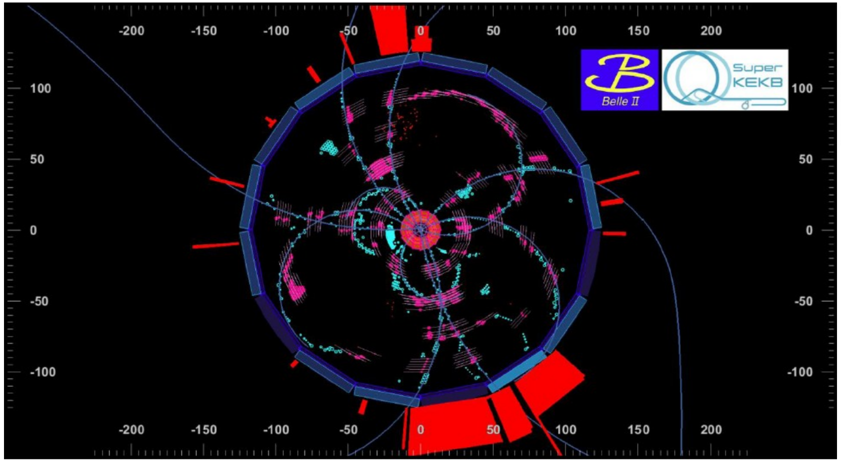




Studies of the X(3872) at Belle II

HADRON2021, Universidad Nacional Autónoma de México - 26-30.July.2021

Elisabetta Prencipe, JLU – University of Giessen (DE)

Outline

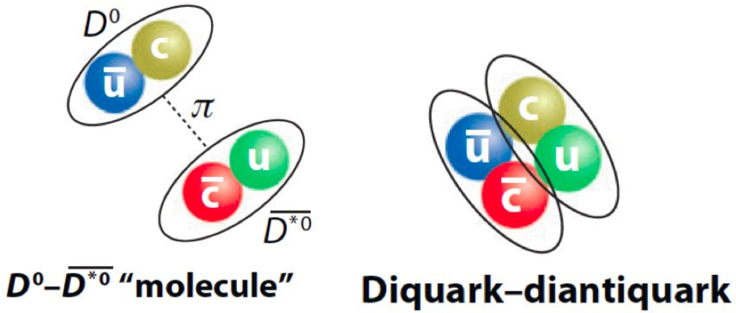
- Introduction
- Overview on the X(3872) results
- The Belle II detector
- Analysis of the $B^{\pm,0} \rightarrow J/\psi \pi^+ \pi^- K^{\pm,0}$ decays at Belle II
- Analysis of $B^{\pm} \rightarrow D^0 \overline{D}^0 \pi^0 K^{\pm}$
- Perspectives with 50 ab^{-1}
- Summary

Introduction

- X(3872): observed by Belle in $B^{\pm} \rightarrow J/\psi \pi^{+}\pi^{-}K^{\pm}$ decays in 2003
- Most cited Belle paper ever: PRL 91 (2003) 262001, 1096 citations
- Quantum numbers of the X(3872) do not fit into quark models
- Confirmed $J^{PC} = 1^{++}$ by LHCb in 2013 (10 years later!)
- Observed in B decays, $p\bar{p}$, pp, $e^{+}e^{-} \rightarrow \gamma X$

What is then the X(3872)?

Unluckily a charmonium, but….



Overview of the X(3872)

- X(3872) observed in different decay modes: $J/\psi\pi^+\pi^-$, $J/\psi\pi^+\pi^-\pi^0$, $D^0\overline{D}^{*0}$, $\gamma J/\psi$…

Well established!

- Identity card of the X(3872), from PDG averaged values:

M_X = 3861.75±0.06 MeV/c^2

Γ = 1.19±0.21 MeV

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

- Total width measurement can constrain theoretical models.

Can Belle II measure it?

Can Belle II distinguish between different parameterizations (BW, Flatté)?

A detailed analysis of the X(3872) line shape, using the Flatté parametrization, is more appropriate than the Breit-Wigner (BW) form for states near an S-wave strongly coupled threshold

Further studies about the X(3872)

- From B factories: X(3872) in B decays, and recently in $\gamma\gamma^*$
- FNAL, LHC: X(3872) also in prompt processes

Compact tetraquark
PRD71(2005)014028
PLB 662(2008)424

Hadronic Molecule
PLB590(2004)209
PRD77(2008)014029
PRD100(2019)0115029(R)

Hadrocharmonium
PLB666(2008)344
PLB671(2009)82

Further studies about the X(3872)

- From B factories: X(3872) in B decays, and recently in γγ*
- FNAL, LHC: X(3872) also in prompt processes

- production rate at the Tevatron too large by orders of magnitude for the X(3872) to be a weakly **bound charm-meson molecule**. New theoretical explanation: **re-scattering effects** → additional interactions between the D mesons in the final state could lead to significantly enhanced X(3872) production rates.

Artoisenet, Braaten, PRD 81 (2010) 114018

Bignamini et al, PRL 103 (2009) 162001

- re-scattering could be significant if the relative momenta of the D mesons are small, and at large transverse momenta (pT, no contribution is expected). Therefore, measuring the pt-dependence of the X(3872) production rate could give insights about the validity of the “charm-meson molecule” hypothesis.

- CMS studied X(3872) → $J/\psi\pi^+\pi^-$ and its properties with thousand yield

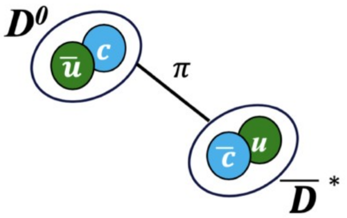
CMS, JHEP 04 (2013) 154

- X(3872) copiously produced in prompt processes rather than B mesons (only **26% in B decays**)
- X(3872) → $J/\psi\pi^+\pi^-$: the decay proceeds through a ρ meson ($\pi^+\pi^-$ pairs)
- the predicted pt-dependence of the X(3872) is actually larger than the measured rate, but fairly modeled

Further studies about the X(3872)

- From B factories: X(3872) in B decays, and recently in γγ*
- FNAL, LHC: X(3872) also in prompt processes

- LHCb recently scrutinized the nature of the X(3872) by studying its multiplicity dependent relative suppression compared to a conventional charmonium state, *i.e.* ψ(2S).



Hadronic molecule ⇒ very weakly bound with a large radius ∼ 10 fm

$$M_{X(3872)} - M_{\bar{D}} - M_{D^*} = 0.1 \pm 0.27 \text{ MeV}$$

Compact tetraquark ⇒ tightly bound with small radius ∼ 1 fm

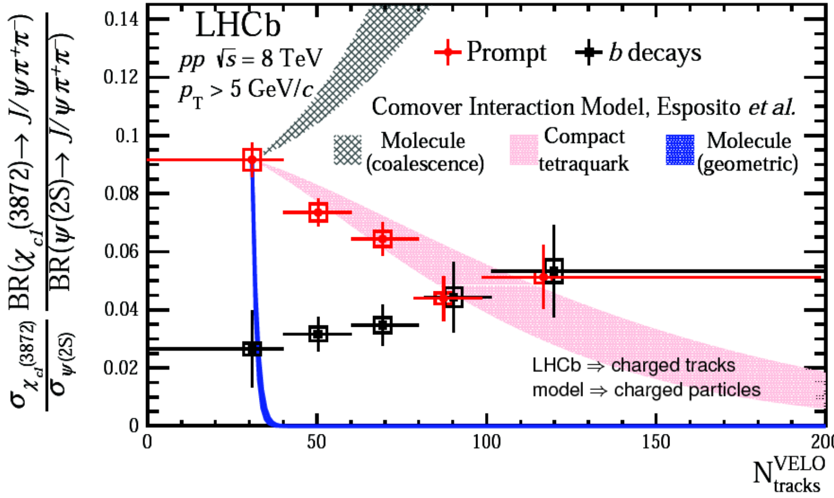
Further studies about the X(3872)

- From B factories: X(3872) in B decays, and recently in γγ*
- FNAL, LHC: X(3872) also in prompt processes

PRL 126 (2021), 092001

- LHCb:
  - the prompt ratio decreases with the multiplicity
    → stronger suppression of X(3872) over ψ(2S)

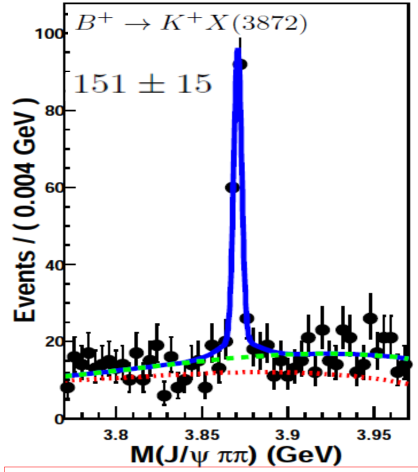
  - non-prompt ratio constant in multiplicity

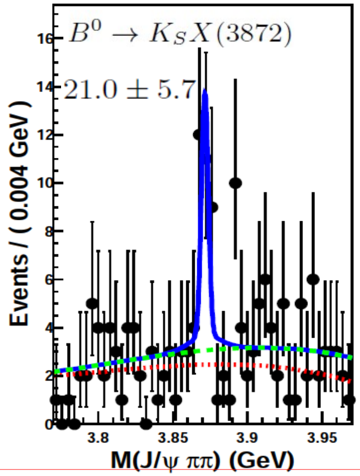


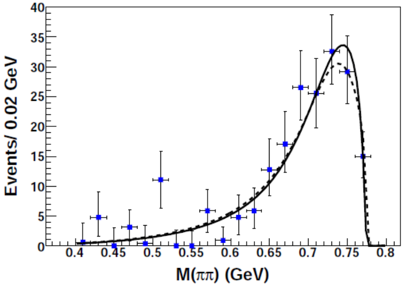
- Model by *Esposito et* al (arXiV: 2006.15044) favors the **compact tetraquark scenario**.
- *Braaten et al* (PRD 103 (2021) 071901) suggests it is a **charm-meson molecule**.

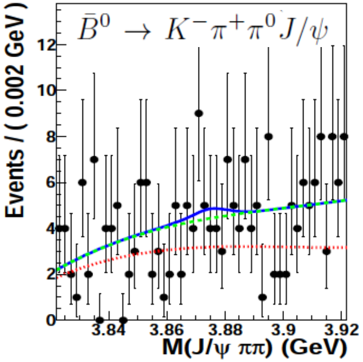
The X(3872) at Belle

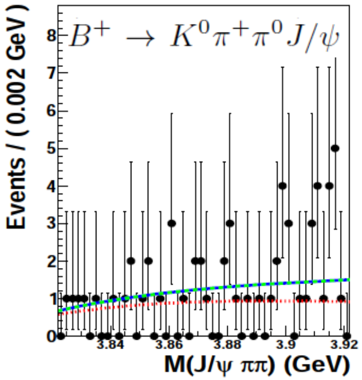
PRD 84 (2011) 052004, 772M $B\bar{B}$ pairs











Search for charged partners of X(3872)

↓

no evidence!

$$M_{X(3872)} = (3871.84 \pm 0.27\ (\text{stat}) \pm 0.19\ (\text{syst}))\ \text{MeV}$$

$$\Delta M_{X(3872)} = (-0.69 \pm 0.97\ (\text{stat}) \pm 0.19\ (\text{syst}))\ \text{MeV}$$

consistent with 0 ⇒ against diquark-antidiquark model

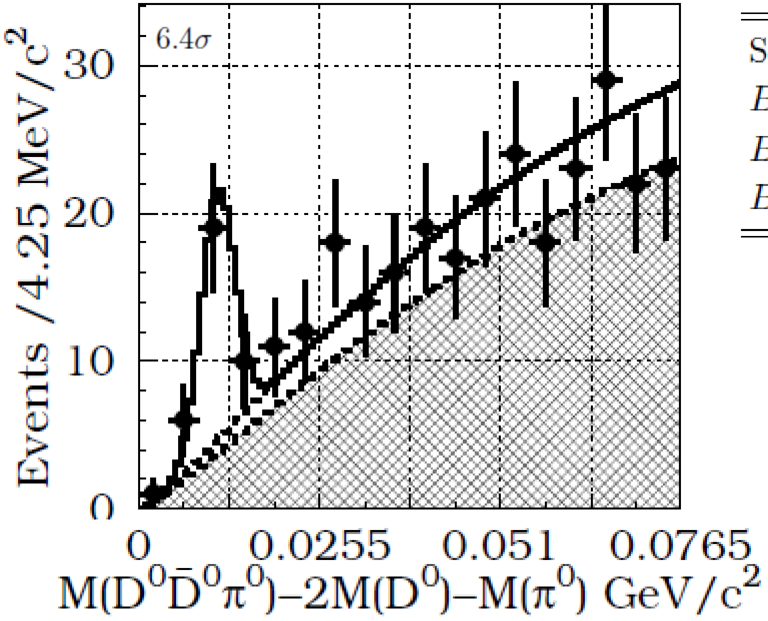
$$R(X) = \frac{\mathcal{B}(B^0 \to K^0 X(3872))}{\mathcal{B}(B^+ \to K^+ X(3872))} = 0.50 \pm 0.14\ (\text{stat}) \pm 0.04\ (\text{syst})$$

in molecular models: $0.06 \leq R(X) \leq 0.29$

$\Gamma_{X(3872)} < 1.2\ \text{MeV}$ @90% c.l.

The X(3872) at Belle

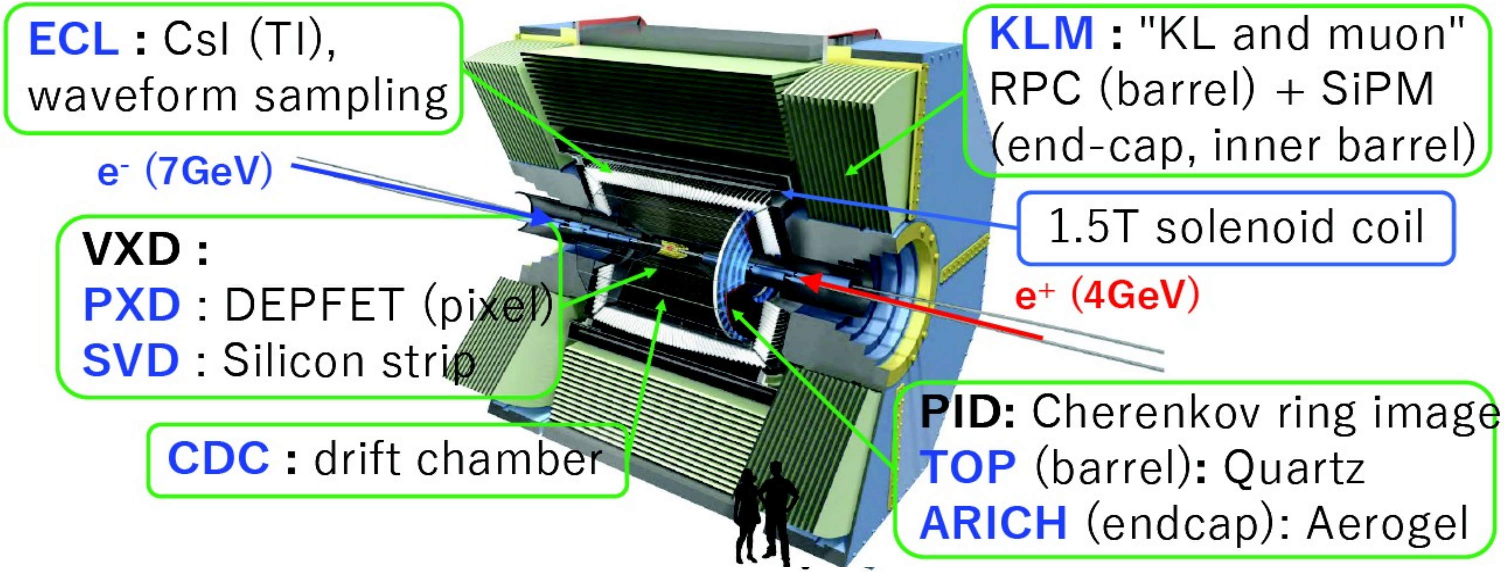
PRL 97 (2006) 162002 , 414 fb^{-1}



Signal	$\epsilon\mathcal{B} \times 10^4$	N_{obs}	sig, σ	$\mathcal{B} \times 10^4$
$B \to D^0\overline{D}^0\pi^0 K$	2.12±0.10	24.1±6.1	6.4	$1.27 \pm 0.31^{+0.22}_{-0.39}$
$B^+ \to D^0\overline{D}^0\pi^0 K^+$	3.62±0.14	17.4±5.2	5.0	$1.07 \pm 0.31^{+0.19}_{-0.33}$
$B^0 \to D^0\overline{D}^0\pi^0 K^0$	0.84±0.04	6.5±2.6	4.6	$1.73 \pm 0.70^{+0.31}_{-0.53}$

What is then the X(3872)?

The Belle II detector

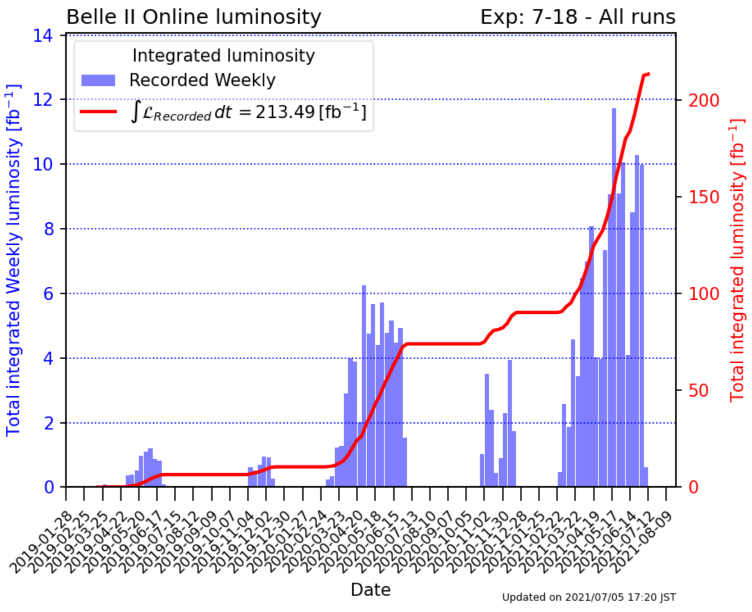


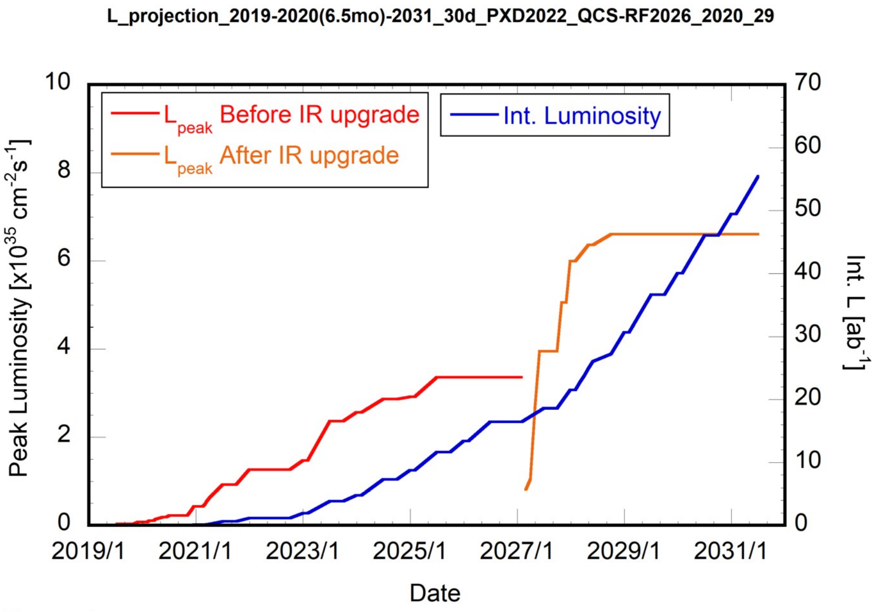
Issues to overcome
- Beam background
- High rate capability
- Boost ~ 2/3

Technical choice
- Finer segmentation, waveform sampling.
- Material change
- Larger angular coverage (CDC, SVD)
- Closer to the IP (PXD) 3 ->1.4cm
- Particle ID improve (K/π)(TOP, ARICH)

Data planning at Belle II

- Summer run 2021 concluded: 213.49 fb^{-1}
- Planned 50 ab^{-1}
- Monthly luminosity record in May 2021: 40.3 fb^{-1}
- Peak luminosity record: 3.1 x 10^{34} cm^{-2} s^{-1}





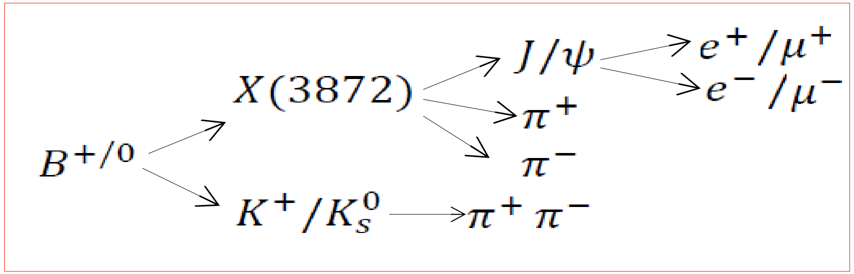
X(3872) at Belle II: analysis strategy

- With >30 fb^{-1}: analysis feasible! extrapolation from Belle
- Analysis conducted with 62.8 fb^{-1} @ $\Upsilon(4S)$, Belle II data
- Rigorously followed strategy of ‘veiled-data’ analysis
- Reconstructed: $B^{\pm,0} \rightarrow J/\psi \pi^+ \pi^- K^{\pm,0}$, $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
- Control channel: $B^{\pm,0} \rightarrow \psi(2S) K^{\pm,0}$

- Goal of this study:
  - rediscovery the X(3872)
  - Branching Fraction measurement

Rediscovery channel, yet!
Sample too small for new charmonium results

X(3872) at Belle II: event selection



Tracks:
  PID for leptons and pions
  POCA selection: d0<1.0 cm, z0<3.0cm

K^0_S:
  Vertex fit
  490< $m_{\pi+\pi-}$<506 MeV/c^2

J/ψ
  3.070<$m_{\mu\mu}$<3.117 GeV/c^2
  3.065<m_{ee}<3.117 GeV/c^2, with bremss. recovery
  → mass fit constraint is applied

$B^{\pm,0}$

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

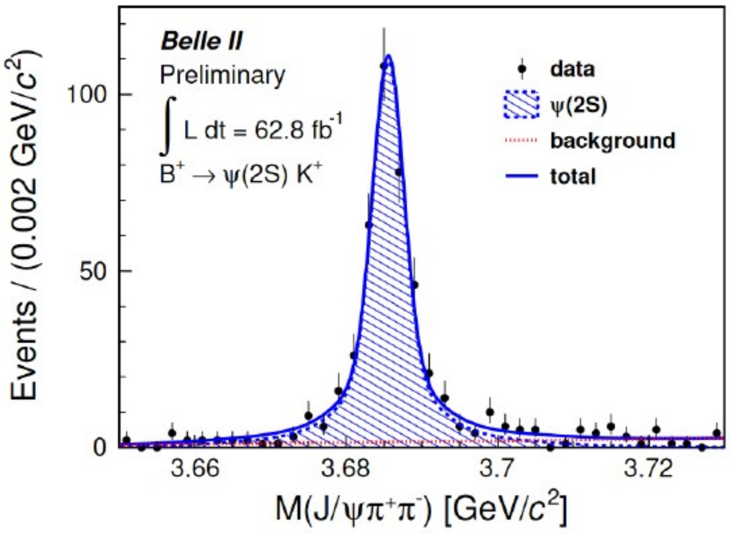
Continuum suppression: R_2<0.4

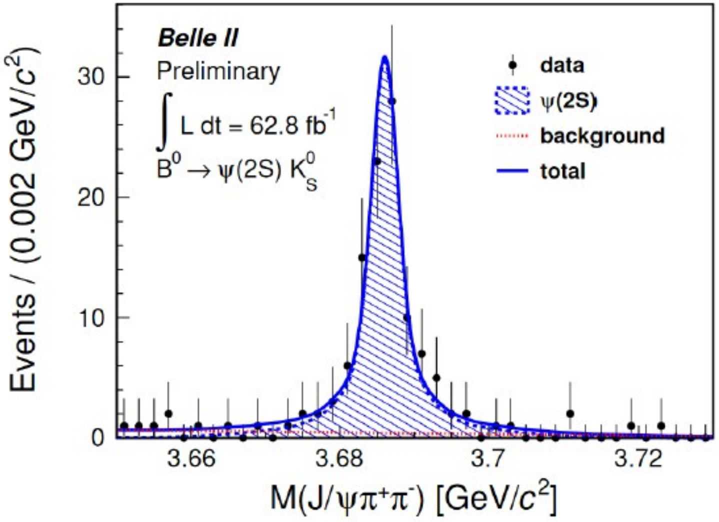
$$M^{meas}_{\pi+\pi-} - M^{meas}_{\ell+\ell-\pi+\pi-} + m_{J/\psi} > -0.150\ \mathrm{GeV/c^2}$$

Retains ~90% of signal while suppressing bkg by ~75%

Reduction in mis-ID pions

X(3872) at Belle II: control sample study





Unbinned maximum likelihood fit with triple-Gaussian + 1st order Chebyshev polynomial

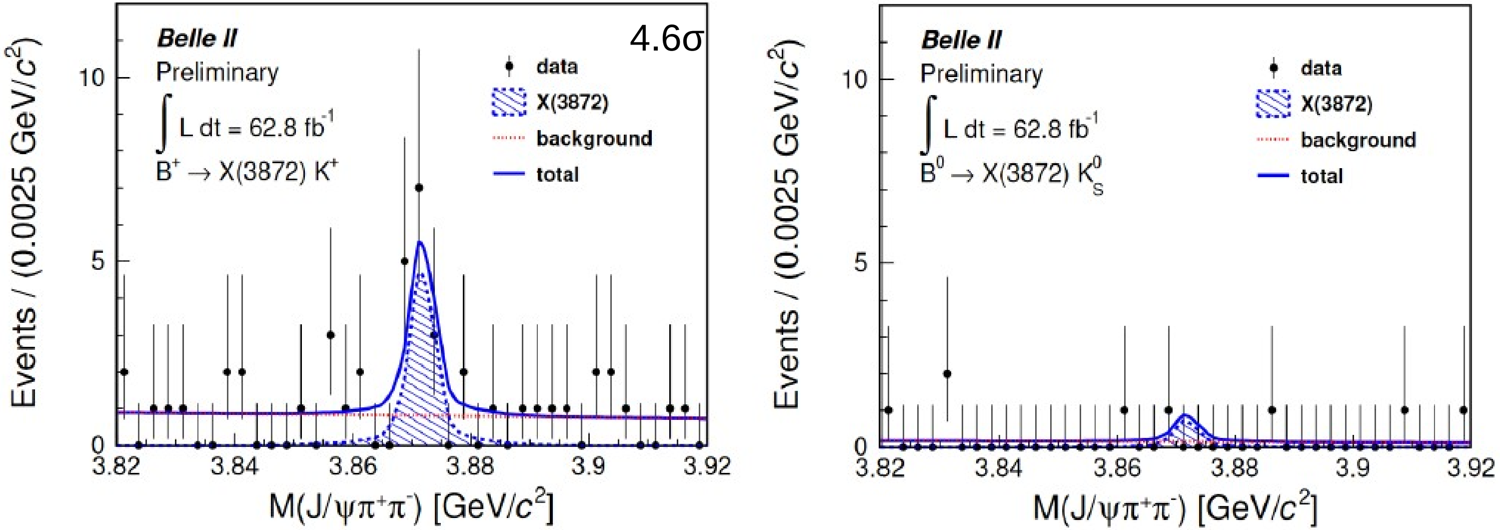
X(3872) at Belle II: control sample study

	$B^+ \to K^+\psi(2S)$	$B^0 \to K^0_s\psi(2S)$
Integrated Luminosity [fb^{-1}]	62.7947 ± 0.0051	62.7947 ± 0.0051
Signal yield /$\int Ldt$ [fb]	6.51 ± 0.37	1.66 ± 0.18
Signal efficiency [%]	22.69 ± 0.16	17.40 ± 0.17
Obtained Branching Fraction [$\times 10^{-4}$]	6.08 ± 0.37	6.18 ± 0.69
Obtained / World Average	0.982 ± 0.069	1.07 ± 0.15

World averages: $BF\left(B^+ \to K^+\psi(2s)\right) = (6.19 \pm 0.22) \times 10^{-4}, BF\left(B^0 \to K^0\psi(2s)\right) = (5.8 \pm 0.5) \times 10^{-4}$

- Statistics uncertainties, only
- Main systematic effects: tracking, K^0_S reconstruction, $n_{B\bar{B}}$ (2.1%)

X(3872) at Belle II: results



Systematics not included, yet

	B^+	B^0
$BF(B \rightarrow KX(3872)) \cdot BF(X(3872) \rightarrow J/\psi\pi^+\pi^-)$	8.6×10^{-6}	4.6×10^{-6}
ϵ	22.9%	17.5%
Expected signal yield / $[1fb^{-1}]$	0.267	0.0484

X(3872): Belle II vs Belle

	Belle		Belle2 (This analysis)	
	Signal Yield / $\int Ldt$[fb^{-1}]	Signal Efficiency [%]	Signal Yield / $\int Ldt$ [fb^{-1}]	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^*

*still reduced statistics

Improvement!

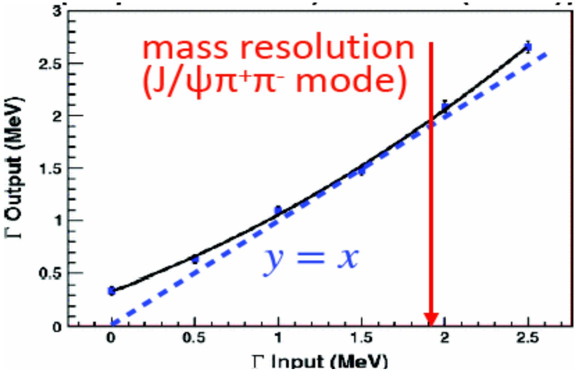
X(3872) total width

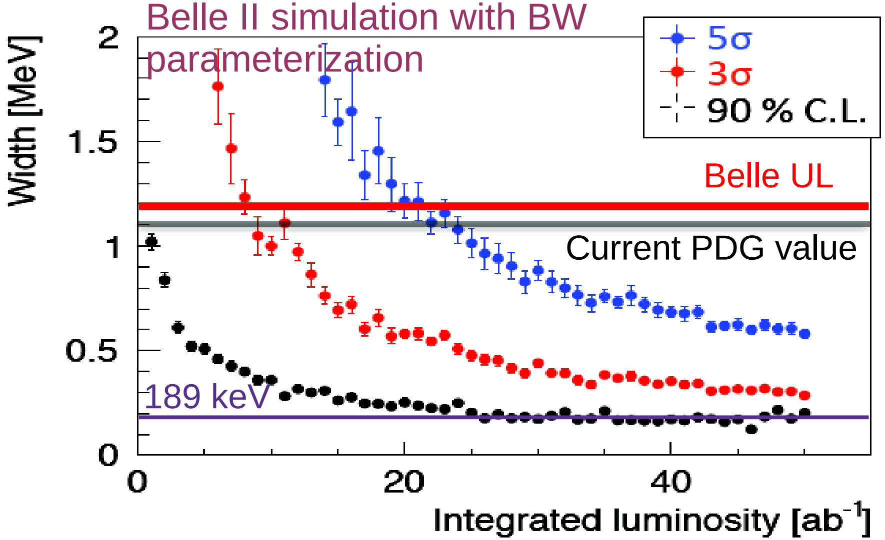
- Known upper limit: Γ < 1.2 MeV
  estimated from X(3872)$\rightarrow J/\psi\pi^+\pi^-$ on full Belle data sample
- Very promising: X(3872) $\rightarrow D^0\overline{D}^{*0}$

mode	Q value [MeV]
$J/\psi\pi^+\pi^-$	495.65±0.17
$D^0\overline{D}^0\pi^0$	7.05±0.18
$D^0\overline{D}^{0*}$	0.01±0.18

- Very low Q value $\rightarrow$ the mass resolution is extremely good.
- Expected great improvement in the width measurement with 50 ab^{-1}

Belle, PRD 84 (2011) 052004





Summary

- Belle II collected ~213 fb^{-1} integrated luminosity data
- Peak luminosity: 3.1 x 10^{34} cm^{-2} s^{-1}
- Interesting results in charmonium spectroscopy expected in the next years
- Rediscovery channels confirm good status of the detector
- X(3872): with 62 fb^{-1} data, close to the observation of X(3872) in $B^{\pm} \rightarrow J/\psi\pi^{+}\pi^{-}K^{\pm}$; 4.6 σ
- Very promising channel for the width measurement: X(3872) $\rightarrow D^{0}\overline{D}^{0}\pi^{0}$
  - precision measurement possible at Belle II;
  - we might be able to compare different parameterizations.
- Next step: X(3872) $\rightarrow \psi(2S)\gamma$. Photon detection not a problem at Belle II!

B2GM June 2019