Studies of the X(3872) at Belle II


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Outline

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

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

What is then the $\chi(3872)$?

Unluckily a charmonium, but….
Overview of the X(3872)

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

- Identity card of the X(3872), from PDG averaged values:
  
  $M_X = 3861.75 \pm 0.06 \text{ MeV/c}^2$
  $\Gamma = 1.19 \pm 0.21 \text{ MeV}$
  $J^{PC} = 1^{++}$

- 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 $\gamma\gamma^*$
- 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 ($p_T$, no contribution is expected). Therefore, measuring the $p_T$-dependence of the $X(3872)$ production rate could give insights about the validity of the “charm-meson molecule” hypothesis.

- CMS studied $X(3872) \rightarrow J/\psi\pi^+\pi^-$ 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)
  - $X(3872) \rightarrow J/\psi\pi^+\pi^-$: the decay proceeds through a $\rho$ meson ($\pi^+\pi^-$ pairs)
  - the predicted $p_T$-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 $\sim 10$ fm

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

**Compact tetraquark** ⇒ tightly bound with small radius $\sim 1$ fm
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

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

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

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

What is then the X(3872)?

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

<table>
<thead>
<tr>
<th>Signal</th>
<th>$\epsilon B \times 10^4$</th>
<th>$N_{obs}$</th>
<th>sig, $\sigma$</th>
<th>$B \times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow D^0 \bar{D}^0 \pi^0 K$</td>
<td>2.12±0.10</td>
<td>24.1±6.1</td>
<td>6.4</td>
<td>1.27±0.31</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^0 \bar{D}^0 \pi^0 K^+$</td>
<td>3.62±0.14</td>
<td>17.4±5.2</td>
<td>5.0</td>
<td>1.07±0.31</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^0 \bar{D}^0 \pi^0 K^0$</td>
<td>0.84±0.04</td>
<td>6.5±2.6</td>
<td>4.6</td>
<td>1.73±0.70</td>
</tr>
</tbody>
</table>
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 $\rightarrow$ 1.4cm
- Particle ID improve ($K/\pi$) (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: \(3.1 \times 10^{34}\) 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$^{-1}$ @ Y(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**

![Diagram](image)

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

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass Constraints</th>
</tr>
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<tbody>
<tr>
<td>$K^0_s$</td>
<td>$490 &lt; m_{\pi^+\pi^-} &lt; 506$ MeV/c²</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$3.070 &lt; m_{\mu^+\mu^-} &lt; 3.117$ GeV/c², with bremsstrahlung recovery</td>
</tr>
<tr>
<td></td>
<td>$3.065 &lt; m_{ee} &lt; 3.117$ GeV/c²</td>
</tr>
</tbody>
</table>

$B^\pm,0$

$$M_{bc} (\equiv \sqrt{(s/2)^2 - (p_B^{\text{CMS}})^2}) > 5.27 \text{ GeV/c}^2$$

$$|\Delta E (\equiv s/2 - E_B^{\text{CMS}})| < 0.02 \text{ GeV/c}^2$$

Continuum suppression: $R_2 < 0.4$

Reduction in mis-ID pions

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

Retains ~90% of signal while suppressing bkg by ~75%
**X(3872) at Belle II: control sample study**

Unbinned maximum likelihood fit with triple-Gaussian + 1\textsuperscript{st} order Chebyshev polynomial
X(3872) at Belle II: control sample study

<table>
<thead>
<tr>
<th></th>
<th>$B^+ \to K^+\psi(2S)$</th>
<th>$B^0 \to K_s^0\psi(2S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Luminosity [fb$^{-1}$]</td>
<td>$62.7947 \pm 0.0051$</td>
<td>$62.7947 \pm 0.0051$</td>
</tr>
<tr>
<td>Signal yield /$\int L dt$ [fb]</td>
<td>$6.51 \pm 0.37$</td>
<td>$1.66 \pm 0.18$</td>
</tr>
<tr>
<td>Signal efficiency [%]</td>
<td>$22.69 \pm 0.16$</td>
<td>$17.40 \pm 0.17$</td>
</tr>
<tr>
<td>Obtained Branching Fraction [$\times 10^{-4}$]</td>
<td>$6.08 \pm 0.37$</td>
<td>$6.18 \pm 0.69$</td>
</tr>
<tr>
<td>Obtained / World Average</td>
<td>$0.982 \pm 0.069$</td>
<td>$1.07 \pm 0.15$</td>
</tr>
</tbody>
</table>

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

- 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

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<tr>
<th></th>
<th>$B^+$</th>
<th>$B^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BF(B \to KX(3872)) \cdot BF(X(3872) \to J/\psi\pi^+\pi^-)$</td>
<td>$8.6 \times 10^{-6}$</td>
<td>$4.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>22.9%</td>
<td>17.5%</td>
</tr>
<tr>
<td>Expected signal yield / [1fb$^{-1}$]</td>
<td>0.267</td>
<td>0.0484</td>
</tr>
</tbody>
</table>
X(3872): Belle II vs Belle

<table>
<thead>
<tr>
<th></th>
<th><strong>Belle</strong></th>
<th><strong>Belle2 (This analysis)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal Yield / $\int L dt$ [fb$^{-1}$]</td>
<td>Signal Efficiency [%]</td>
</tr>
<tr>
<td>$B^+ \to K^+\psi(2S)$</td>
<td>5.027 ± 0.090</td>
<td>17.8 ± 0.2</td>
</tr>
<tr>
<td>$B^0 \to K_S^0\psi(2S)$</td>
<td>1.145 ± 0.042</td>
<td>14.1 ± 0.2</td>
</tr>
<tr>
<td>$B \to KX(3872)$</td>
<td>0.212 ± 0.021</td>
<td>19.1 ± 0.2</td>
</tr>
</tbody>
</table>

*still reduced statistics

**Improvement!**
X(3872) total width

- Known upper limit: $\Gamma < 1.2$ MeV
  estimated from $X(3872) \to J/\psi \pi^+ \pi^-$ on full Belle data sample

- Very promising: $X(3872) \to D^0 D^{*0}$

<table>
<thead>
<tr>
<th>mode</th>
<th>Q value [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>495.65±0.17</td>
</tr>
<tr>
<td>$D^0 D^0 \pi^0$</td>
<td>7.05±0.18</td>
</tr>
<tr>
<td>$D^0 D^{0*}$</td>
<td>0.01±0.18</td>
</tr>
</tbody>
</table>

- Very low Q value $\rightarrow$ the mass resolution is extremely good.

- Expected great improvement in the width measurement with 50 ab$^{-1}$
Summary

- Belle II collected ~213 fb\(^{-1}\) integrated luminosity data
- Peak luminosity: 3.1 \(\times 10^{34}\) 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 \(\sigma\)
- Very promising channel for the width measurement: \(X(3872) \rightarrow D^0\bar{D}^0\pi^0\)
  - 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!