Exotic and Conventional Quarkonium Physics Prospects at Belle II

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On behalf of the Belle II Collaboration
The Belle II Experiment

Sensitivity for the total width of the $X(3872)$

Search for a partner state of the $X(3872)$ at the $D^*0 \bar{D}^*0$ threshold

$D^0$ reconstruction in early data sets

Outlook
The Belle II Experiment

Successor of Belle Experiment
Located at SuperKEKB
→ asymmetric collider at $\Upsilon(4S)$ energy 10.53 GeV
Nano beam scheme:
$\mathcal{L} = 8 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
The Belle II Experiment

Two data sets so far:
Phase 2 (2018), 504 pb$^{-1}$
Phase 3 (2019), 6.5 fb$^{-1}$
Phase 2 with 4 layers SVD and 4/32 PXD modules only
Phase 3 Full SVD 1/2 PXD other half in 2021

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Previous studies on sensitivity done in $X(3872) \rightarrow J/\psi \pi^{\pm} \pi^{\mp}$
(Phys. Rev. D 84, 05 2004 (2011))
Fit signal component with Breit Wigner convoluted with Gauss for signal component
$\Gamma_{tot} < 1.2$ MeV < mass resolution $\approx 1.86 \pm 0.01$ MeV/$c^2$
$\Rightarrow$ improvement of mass resolution essential

$\Rightarrow$ use channel with smaller $Q$ – value ($D^0 \bar{D}^0 \pi^0$) to increase mass resolution
Studies on the $X(3872)$

$Simulations$

Mass spectrum after reconstruction and selection

- Correct reconstructed signal
- Incorrect reconstruction of signal
- BG from general $B\bar{B}/q\bar{q}$ events

- Mass resolution: $684 \pm 8$ keV
- Signal yield with $1$ ab$^{-1}$: $64.5 \pm 23.9$

Comes from large error of:
$$\text{Br}(B^\pm \rightarrow K^\pm X(3872)) \times \text{Br}(X(3872) \rightarrow D^0 \bar{D}^0 \pi^0)$$

Belle II simulation
[Input] $\Gamma_{\text{tot}} = 0.0$ MeV

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Studies on the $X(3872)$

Simulations

Sensitivity to total width of $X(3872)$

- Sensitivity is estimated with toy-MC samples.

- With the full data sample of Belle II (50 ab$^{-1}$), total width with values up to
  - $[90\% \text{ C.L.}] \sim 180$ keV
  - $[3\sigma \text{ significance}] \sim 280$ keV
  - $[5\sigma \text{ significant}] \sim 570$ keV
  
  can be measured.

→ Poster of Yuji Kato
A new Charmonium-Like state at the $D^*0 \bar{D}^*0$ threshold

**Theoretical Models**


molecular interpretation : $J^{PC} = 2^{++}$, heavy quark spin symmetry to $X(3872)$ D-wave decay to $D^*0 \bar{D}^*0$ possible, implies $\Gamma \approx 10\text{MeV}$

molecular mixture with charmonium admixture


→ predicts narrow peak from triangle singularity $\approx 10$ MeV above $X(3872)\pi^0$ threshold

![Graph](image-url)
Simulation

new strategy $\rightarrow$ decay chain 2

\[ \Upsilon(4S) \rightarrow B^+B^- \]
\[ \rightarrow X(4014)K^+ \]
\[ \rightarrow D^0 \bar{D}^0 \pi^0\pi^0 \]
\[ \rightarrow K^-\pi^+ \]
\[ \rightarrow K^-\pi^+\pi^0 \]
\[ \rightarrow K^-\pi^+\pi^+\pi^- \]
\[ \rightarrow K^-K^+ \]
\[ \rightarrow K^0_S\pi^+\pi^- \]

- $D^0$ decays up to $\approx 30\%$ of the branching fraction
- 100’000 signal events with beam background simulated
- Final state reconstruction stays same, except for $\pi^0$.
  We now use the total $\pi^0$ energy to discriminate between $\pi^0$ from $D^{*0}$ and $D^0$
- Statistics goes down by about 50\% due to missing $\gamma$ channel

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Among the $B^\pm$ candidates which survived the $M_{bc}$-$\Delta E$ selection, the one with the lowest $\chi^2_{bcs}$ per event is used as "correct" $X(4014)$-mother.

\[ \chi^2_{bcs} = \left( \frac{\Delta M_{D_0}}{\sigma_{M_{D_0}}} \right)^2 + \left( \frac{\Delta M_{D^0}}{\sigma_{M_{D^0}}} \right)^2 + \left( \frac{\Delta E}{\sigma_{\Delta E}} \right)^2 + \left( \frac{\Delta M_{\pi^0}}{\sigma_{\pi^0}} \right)^2 + |d_0 K^\pm| + |d_{z K^\pm}| \]
X(4014) reconstruction in $\Delta E-M_{bc}$ signal-window

apply BCS

- Reconstructed mass before BCS, peak can already be seen but combinatorial BKG very high
- apply BCS $\rightarrow$ clear peak can be seen, reconstruction efficiency $\approx 1.3\%$
- purity $\approx 15\%$
Background estimation

Signal:

- signal branching fraction assumed as $1 \cdot 10^{-4}$
- identical to $X(3872)$ at $D^0 \bar{D}^{*0}$
- only $B^\pm$ decays taken into account
- $B(e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}) = 1.1\,nb$
- $\approx 15.000$ signal events expected in $\int Ldt = 2ab^{-1}$ (about 2x the data set of Belle and BaBar)

Background:

- $\int Ldt = 2ab^{-1}$
- beam background
- combinatorial background, from both $B$ and $\bar{B}$ (generic decays, all known branching fractions)
- non-resonant decay, same final state but without $X(4014)$ assumed as phase space decay

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Background from generic $B$ decays is huge but good suppression via $\Delta E - M_{bc}$ cut and best candidate selection. With $2ab^{-1}$ we expect a significance of about $5\sigma$. 

\[\gamma = 0.00100 \pm 0.00001\]
\[\mu = 0.00120 \pm 0.00002\]
\[\sigma = 0.00150 \pm 0.00005\]
\[M = 0.0000000010 \pm 0.0000000008\]
\[a_1 = 470498 \pm 8401\]
\[a_2 = 1.0000 \pm 0.0001\]
\[a_3 = 30.000 \pm 0.008\]
\[x_{\text{minPDG}} = -0.00\]

fit result
D$^0$ reconstruction in early data sets

Cuts on final state particles

- Cuts where pre-optimized in MC simulation:
  - $E_\gamma > 0.25$ GeV, $\theta$ in acceptance of ECL, ECL cluster Ratio $> 0.9$
  - $K^\pm, \pi^\pm$ with a $\chi^2 > 0.002$ on the track, no pID!
  - Impact parameters $d0$ and $z0$ smaller 0.5 cm and 3 cm respectively
  - $K_S^0$ selection on impact parameters, $\pi^\pm$ decay angle, displaced vertex
  - $\pi^0$ are selected with a photon energy larger 0.12 GeV/$c^2$
  - $\text{pionID} > 0.5$, $\text{kaonID} > 0.8$

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$D^0$ reconstruction in early data sets on 2018 data, 504\,pb$^{-1}$

- $4.7 \text{ MeV} < \sigma < 6.2 \text{ MeV}$
- combined signal yield $\approx 9100$
- Mass in agreement with PDG in $KK$ and $K_S\pi\pi$
$D^0$ reconstruction in early data sets on 2019 data, 449 pb$^{-1}$

- 3.7 MeV $< \sigma < 4.4$ MeV
- Combined signal yield $\approx 12650$
- Mass in agreement with PDG (except $K\pi\pi\pi$ slightly lower)
  $\rightarrow$ improvement compared to 2018 data
Belle II can reach sub-MeV sensitivity for the total width of the $X(3872)$ 180 keV (90% C.L.) estimated for $50 ab^{-1}$

Belle II will search for the partner state of the $X(3872)$ at the $D^{*0} \bar{D}^{*0}$ threshold

15000 events expected in $2 ab^{-1}$ of data
$\rightarrow$ about 5 sigma significance with 1.3% reconstruction efficiency

reconstruction of neutral $B$ decay to $X(4014)K^0_S$ will be added

search on Belle data (using Belle II framework) is under investigation
Backup
A new Charmonium-Like state at the $D^{*0}\bar{D}^{*0}$ threshold
decay chain

$\Upsilon(4S) \rightarrow B^+B^-$ generic decay

$\chi(4014)K^+ \rightarrow D^{*0}\bar{D}^{*0}$

$D^{0}\gamma \rightarrow D^0\pi^0$

$K^-\pi^+$

$K^-\pi^+\pi^0$

$K^-\pi^+\pi^+\pi^-$

$K^-K^+$

$K_S^0\pi^+\pi^-$

$D^0$ decays up to $\approx 30\%$ of the branching fraction
100’000 signal events with beam backgrounds simulated
$D^*$ are reconstructed without mass fit $\rightarrow$ nothing to see here

$D^*$ mass fitted $\rightarrow$ peak can be seen but any entry below 4014 MeV cut off

Like explained in Phys. Rev. D88(2013)054007, the pole of the $X(4014)$ is likely to be 2 MeV below the threshold $\rightarrow$ can not be seen in $D^*$ mass-fitted case

$\rightarrow$ new strategy is necessary!
Unbinned maximum likelihood fit:

- **Signal (top):**
  - Breit-Wigner convoluted with a Gaussian resolution
  - \( F_{\text{sig}}(x) = \int BW(x - t) \cdot g(t, \sigma_X(x - t))dt \)

- **Combinatorial Background (middle):**
  - Threshold function convoluted with Gaussian resolution
  - \( F_{\text{comb}}(x) = \int tr(x - t) \cdot g(t, \sigma_X(x - t))dt \)
  - \( tr = (x - x_0)^{a_1} e^{a_2(x - x_0)^2} + a_3(x - x_0)^2 \)

- **Generic Background (bottom):**
  - \( tr = (x - x_0)^{a_1} e^{a_2(x - x_0)^2} + a_3(x - x_0)^2 \)

Global fit = sum of the separate fits