Exotic and Conventional Quarkonium Physics Prospects at Belle II

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On behalf of the Belle II Collaboration

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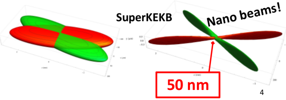
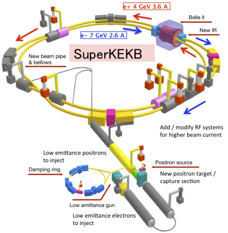
Outline

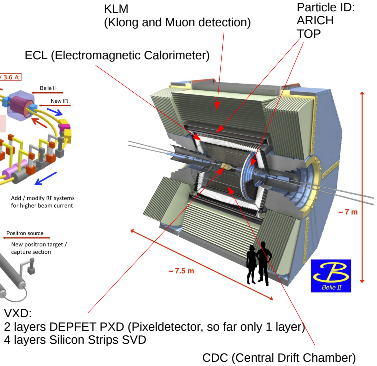
- The Belle II Experiment
- Sensitivity for the total width of the $X(3872)$
- Search for a partner state of the $X(3872)$ at the $D^{*0}\bar{D}^{*0}$ threshold
- D^0 reconstruction in early data sets
- Outlook

The Belle II Experiment

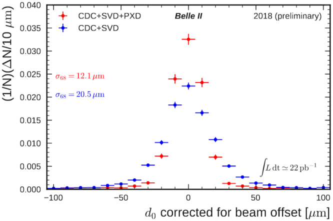
Succesor of Belle Experiment
Located at SuperKEKB
$\rightarrow$ assymetric collider at $\Upsilon(4S)$ energy 10.53 GeV
Nano beam scheme:
$\mathcal{L} = 8 \cdot 10^{35} cm^{-2} s^{-1}$

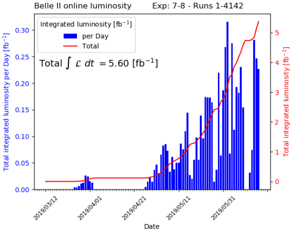






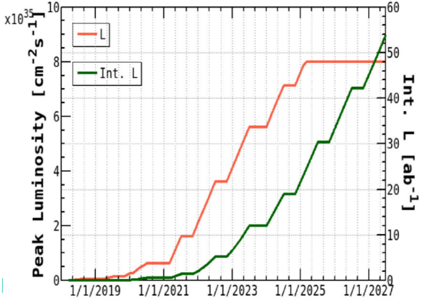
The Belle II Experiment



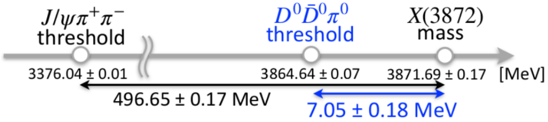


2019

Two data sets so far:
Phase 2 (2018), 504 pb^{-1}
Phase 3 (2019), 6.5 fb^{-1}
Phase2 with 4 layers SVD and 4/32 PXD modules only
Phase3 Full SVD 1/2 PXD other half in 2021

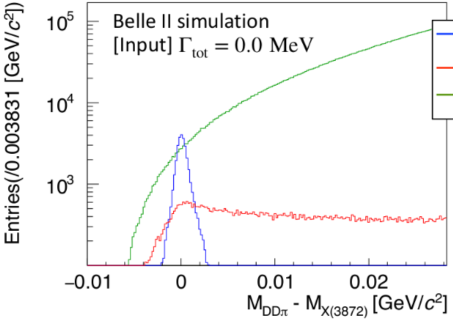


Previous studies on sensitivity done in $X(3872) \to J/\psi\pi^{\pm}\pi^{\mp}$ (Phys. Rev. D 84, 05 2004 (2011))
Fit signal component with Breit Wigner convoluted with Gauss for signal component
$\Gamma_{tot} < 1.2$ MeV $<$ mass resolution $\approx 1.86 \pm 0.01$ MeV$/c^2$
$\Rightarrow$ improvement of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



$\Rightarrow$ use channel with smaller $Q - value$ $(D^0\bar{D}^0\pi^0)$ to increase mass resolution

Mass spectrum after reconstruction and selection



- Mass resolution: 684 ± 8 keV
- Signal yield with 1 ab^{-1}:

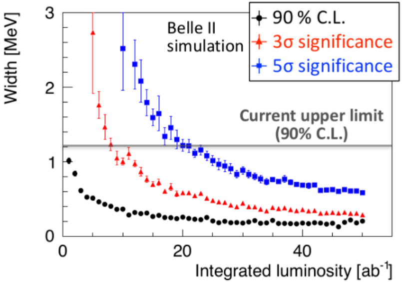
  64.5 ± 23.9

Comes from large error of

$$\mathrm{Br}(B^{\pm} \to K^{\pm}X(3872)) \times \mathrm{Br}(X(3872) \to D^0\bar{D}^0\pi^0)$$

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% C.L.] ~ 180 keV

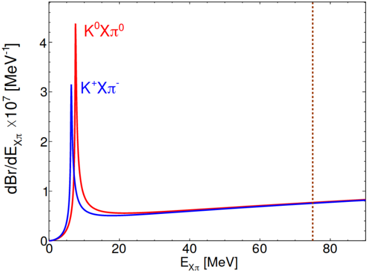
  [3σ significance] ~ 280 keV

  [5σ significant] ~ 570 keV

  can be measured.

→ Poster of Yuji Kato

Predicted by Törnqvist, Phys. Rev. Lett. 67(1991)556
Guo, Hidalgo-Duque, Nieves, Valderrama, Phys. Rev. D88(2013)054007
molecular interpretation : $J^{PC} = 2^{++}$, heavy quark spin symmetry to $X(3872)$ D-wave decay to $D^{*0}\overline{D}^{*0}$ possible, implies $\Gamma \approx 10 MeV$
molecular mixture with charmonium admixture
Recent interest: Braaten, He, Ingles, arXiv:1902.03259
$\rightarrow$ predicts narrow peak from triangle singularity $\approx$ 10 MeV above $X(3872)\pi^0$ threshold



Simulation

new strategy → decay chain 2

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

$\quad \hookrightarrow X(4014) K^+$

$\quad\quad \hookrightarrow D^0 \bar{D}^0 \pi^0 \pi^0$

$\quad\quad\quad \rightarrow K^- \pi^+$

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

$\quad\quad\quad \rightarrow K^- \pi^+ \pi^+ \pi^-$

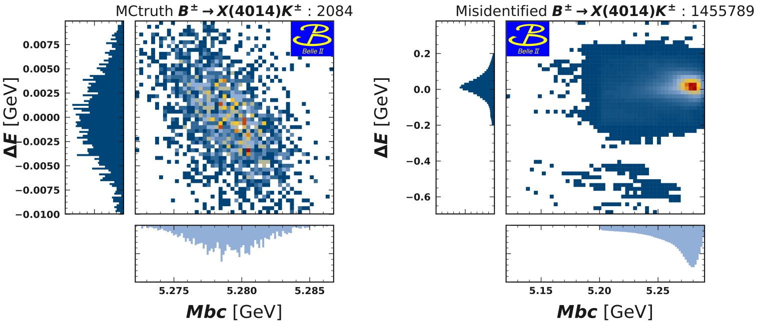
$\quad\quad\quad \rightarrow K^- K^+$

$\quad\quad\quad \rightarrow K^0_S \pi^+ \pi^-$

- 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 π^0.
  We now use the total π^0 energy to discriminate between π^0 from D^{*0} and D^0
- Statistics goes down by about 50% due to missing γ channel

$X(4014)$ reconstruction in ΔE-M_{bc} signal-window

best candidate selection



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

$$\chi^2_{bcs} = \left(\frac{\Delta M_{D^0_1}}{\sigma_{M_{D^0}}}\right)^2 + \left(\frac{\Delta M_{D^0_2}}{\sigma_{M_{D^0}}}\right)^2 + \left(\frac{\Delta E}{\sigma_{\Delta E}}\right)^2 + \left[\left(\frac{\Delta M_{\pi^0}}{\sigma_{\pi^0}}\right)^2\right] + |d0_{K^{\pm}}| + |dz_{K^{\pm}}|$$

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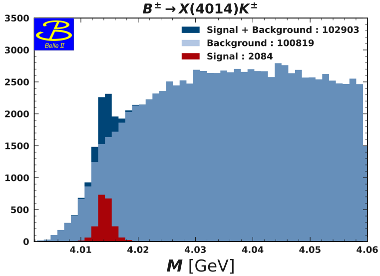
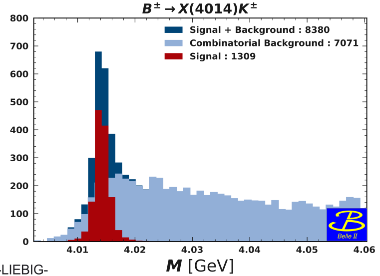
$X(4014)$ reconstruction in ΔE-M_{bc} signal-window

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
- $B(e^+ + e^- \to \Upsilon(4S) \to B\bar{B}) = 1.1nb$
- $\approx$ 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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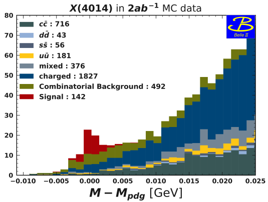

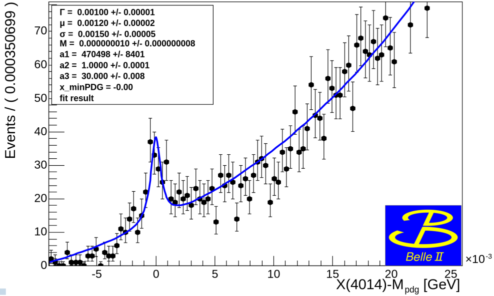

Background from generic B decays is huge but good suppression via $\Delta E - M_{bc}$ cut and best candidate selection.
With $2ab^{-1}$ we expect a significance of about 5σ

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- Cuts where pre-optimized in MC simulation:
- $E_\gamma > 0.25$ GeV, θ 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
- π^0 are selected with a photon energy larger 0.12 GeV$/c^2$
- *pionID* > 0.5, *kaonID* > 0.8

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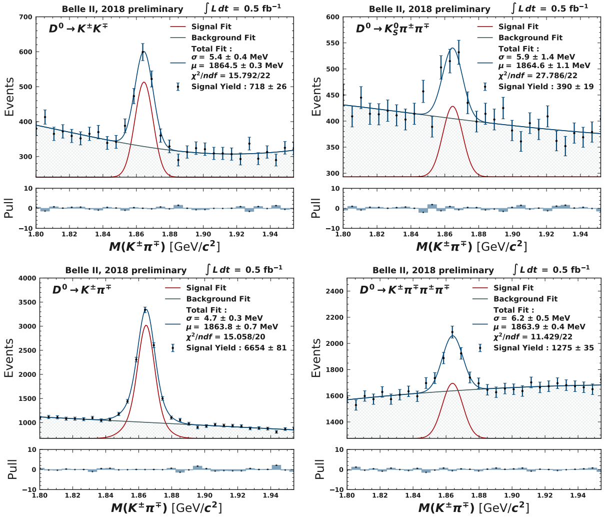
D^0 reconstruction in early data sets

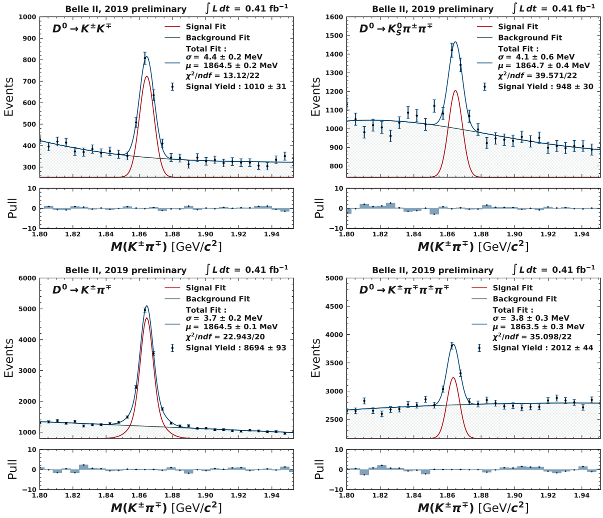
on 2018 data, $504pb^{-1}$



- 4.7 MeV $< \sigma <$ 6.2 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

Summary and Outlook

- Belle II can reach sub-MeV sensitivity for the total width of the $X(3872)$ 180 keV (90% C.L.) estimated for $50ab^{-1}$
- Belle II will search for the partner state of the $X(3872)$ at the $D^{*0}\bar{D}^{*0}$ threshold
- 15000 events expected in $2ab^{-1}$ of data
  $\rightarrow$ about 5 sigma significance with 1.3% reconstruction efficiency
- reconstruction of neutral B decay to $X(4014)K_S^0$ will be added
- search on Belle data (using Belle II framework) is under investigation

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Backup

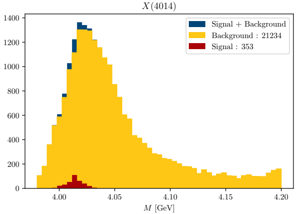
$\Upsilon(4S) \rightarrow B^+B^- \longrightarrow$ generic decay
- $\longrightarrow X(4014)K^+$
  - $\longrightarrow D^{*0}\overline{D}^{*0}$
    - $\longrightarrow D^0\gamma$
    - $\longrightarrow D^0\pi^0$
      - $\longrightarrow K^-\pi^+$
      - $\longrightarrow K^-\pi^+\pi^0$
      - $\longrightarrow K^-\pi^+\pi^+\pi^-$
      - $\longrightarrow K^-K^+$
      - $\longrightarrow K^0_S\pi^+\pi^-$

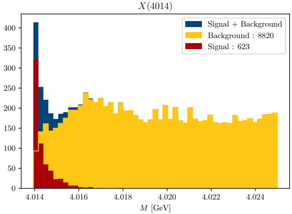
D^0 decays up to $\approx 30\%$ of the branching fraction

100'000 signal events with beam backgrounds simulated

$X(4014)$ reconstruction in signal window

after best candidate selection



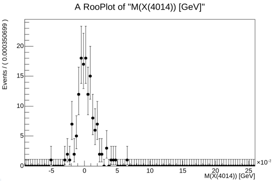


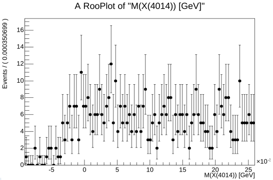
D^{*0} are reconstructed without mass fit $\rightarrow$ nothing to see here

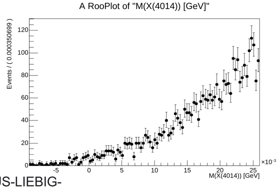
D^{*0} mass fitted $\rightarrow$ peak can be seen but any entry below 4014 MeV cut off

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^{*0} mass-fitted case

$\rightarrow$ new strategy is necessary!







Unbinned maximum likelihood fit:

- Signal (top):
  - Breit-Wigner convoluted with a Gaussian resolution
  - $F_{sig}(x) = \int BW(x-t) \cdot g(t, \sigma_X(x-t))dt$
- Combinatorial Background (middle):
  - Threshold function convoluted with Gaussian resolution
  - $F_{comb}(x) = \int tr(x-t) \cdot g(t, \sigma_X(x-t))dt$
  - $tr = (x - x_0)^{a_1} e^{a_2(x-x_0)+a_3(x-x_0)^2}$
- Generic Background (bottomm):
  - $tr = (x - x_0)^{a_1} e^{a_2(x-x_0)+a_3(x-x_0)^2}$

Global fit = sum of the separate fits