Exotic and Conventional Quarkonium Physics Prospects at Belle II

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On behalf of the Belle II Collaboration

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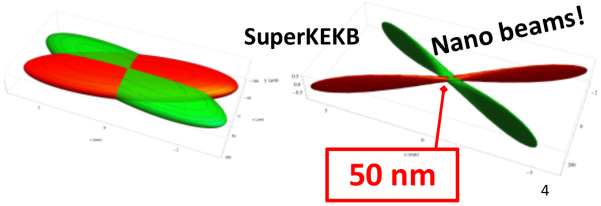
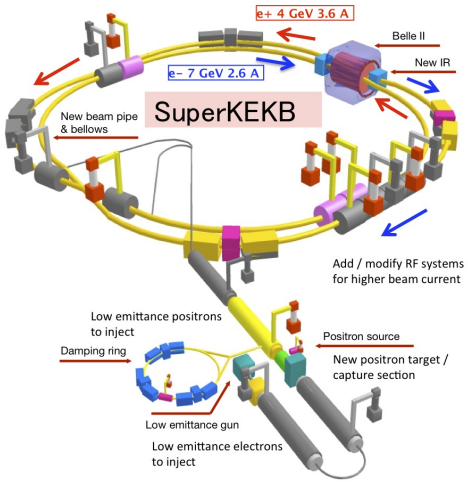
Outline

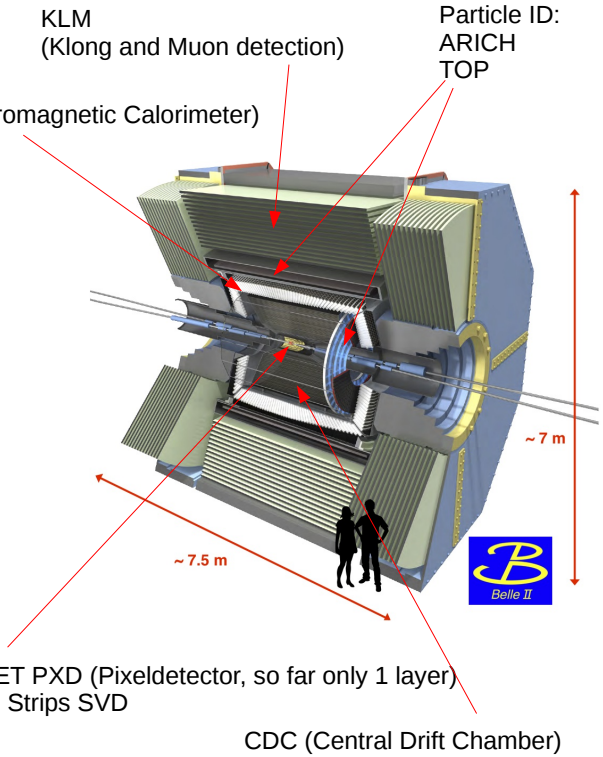
- The Belle II Experiment
- Sensitivity to the total width of the $X(3872)$
- Search for a partner state of the $X(3872)$ at the $D^{*0}\bar{D}^{*0}$ threshold
- D^0 reconstruction in early data sets
- Outlook

The Belle II Experiment

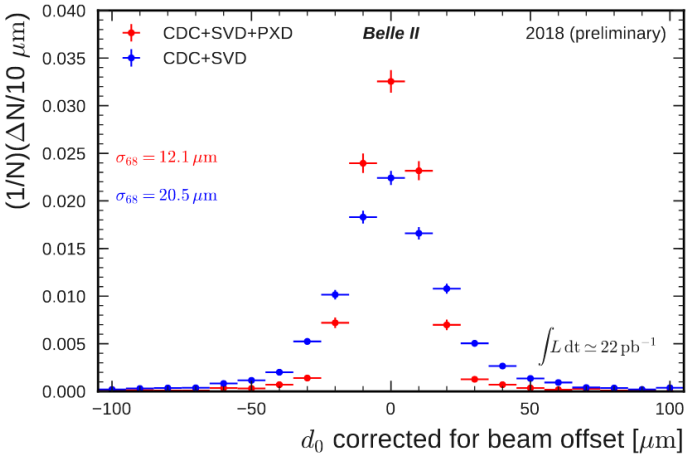
Successor of Belle Experiment
Located at SuperKEKB
$\rightarrow$ asymmetric collider at $\Upsilon(4S)$ energy 10.53 GeV
Nano beam scheme:
$\mathcal{L} = 8 \cdot 10^{35}\ cm^{-2}s^{-1}$

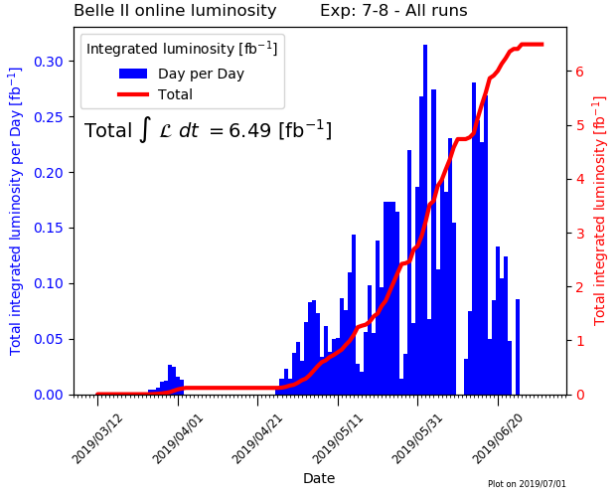






The Belle II Experiment



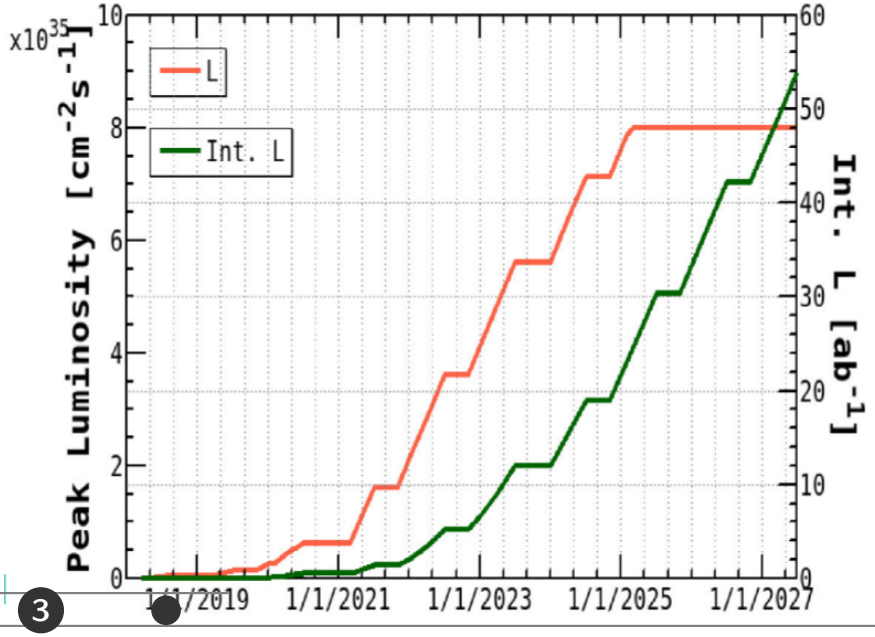


2019

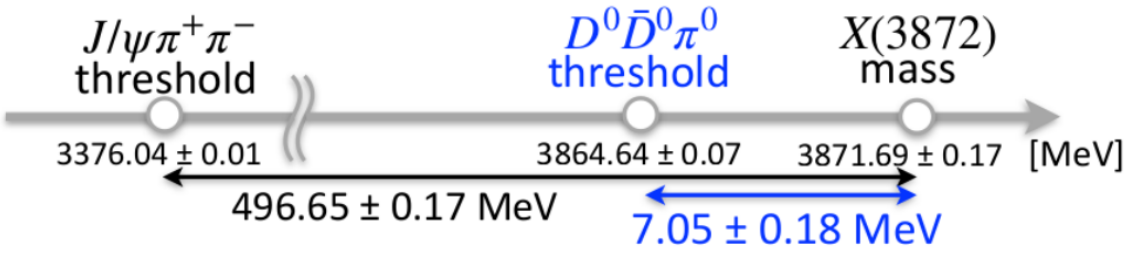
Two data sets so far:
Phase 2 (2018), 504 pb^{-1}
Phase 3 (2019), 6.5 fb^{-1}

→ only 410 pb^{-1} shown

Phase2 with a subset of SVD and PXD modules onlyPhase3 Full SVD, 1/2 PXD modules other half in 2021



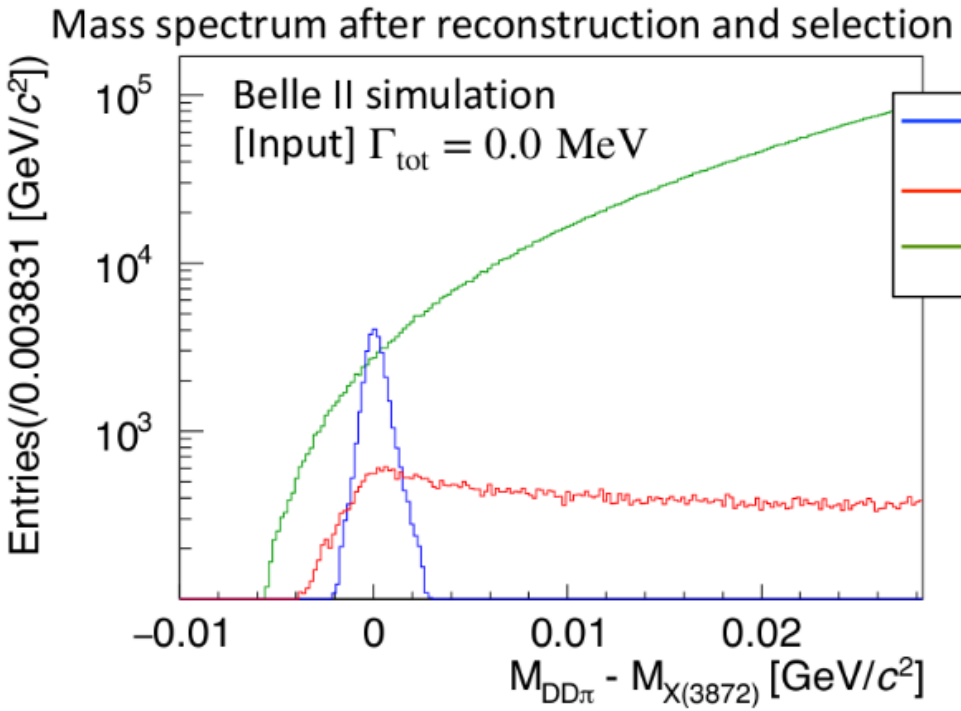
Previous studies on sensitivity done in $X(3872) \to J/\psi\pi^{\pm}\pi^{\mp}$ (Phys. Rev. D 84(2011)052004)
Fit signal component with Breit Wigner convoluted with Gaussian for signal component
$\Gamma_{tot} < 1.2$ MeV $<$ mass resolution $\approx 1.86 \pm 0.01$ MeV$/c^2$
$\Rightarrow$ improvement of 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



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

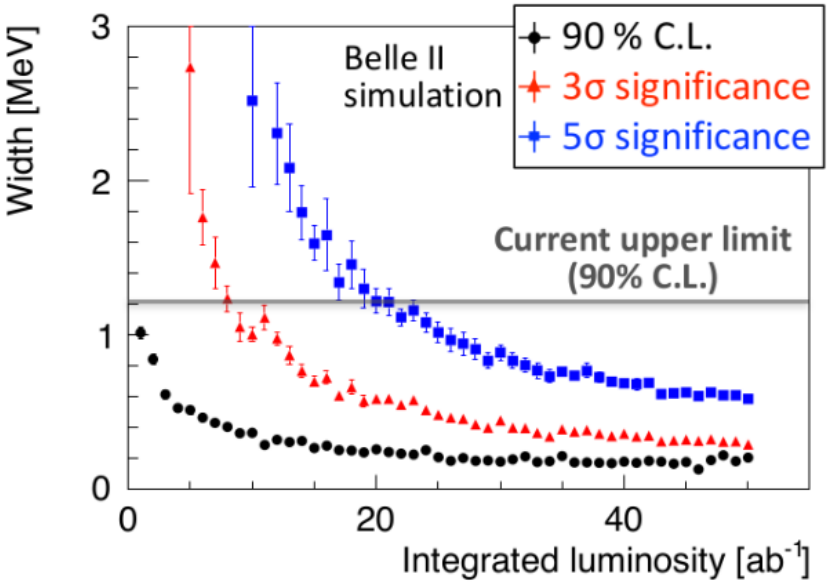
- Mass resolution: 684 ± 8 keV
- Signal yield with 1 ab^{-1}:

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

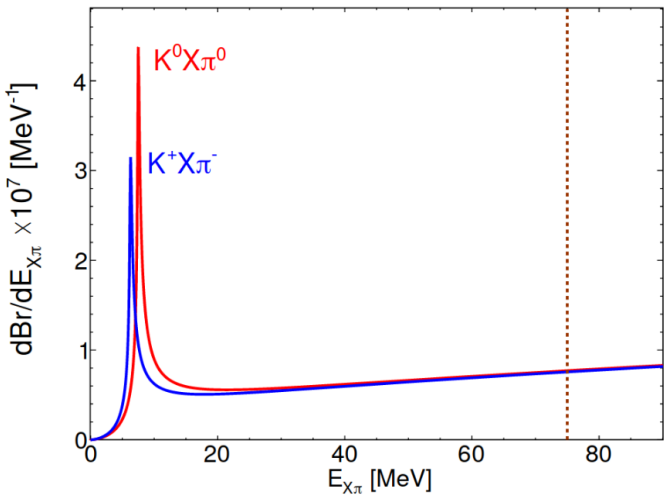
  can be measured.

→ Poster of Yuji Kato

A new Charmonium-Like state at the $D^{*0}\bar{D}^{*0}$ threshold

Theoretical Models

- Predicted by Törnqvist, Phys. Rev. Lett. 67(1991)556
- Guo, Hidalgo-Duque, Nieves, Valderrama, Phys. Rev. D88(2013)054007molecular 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



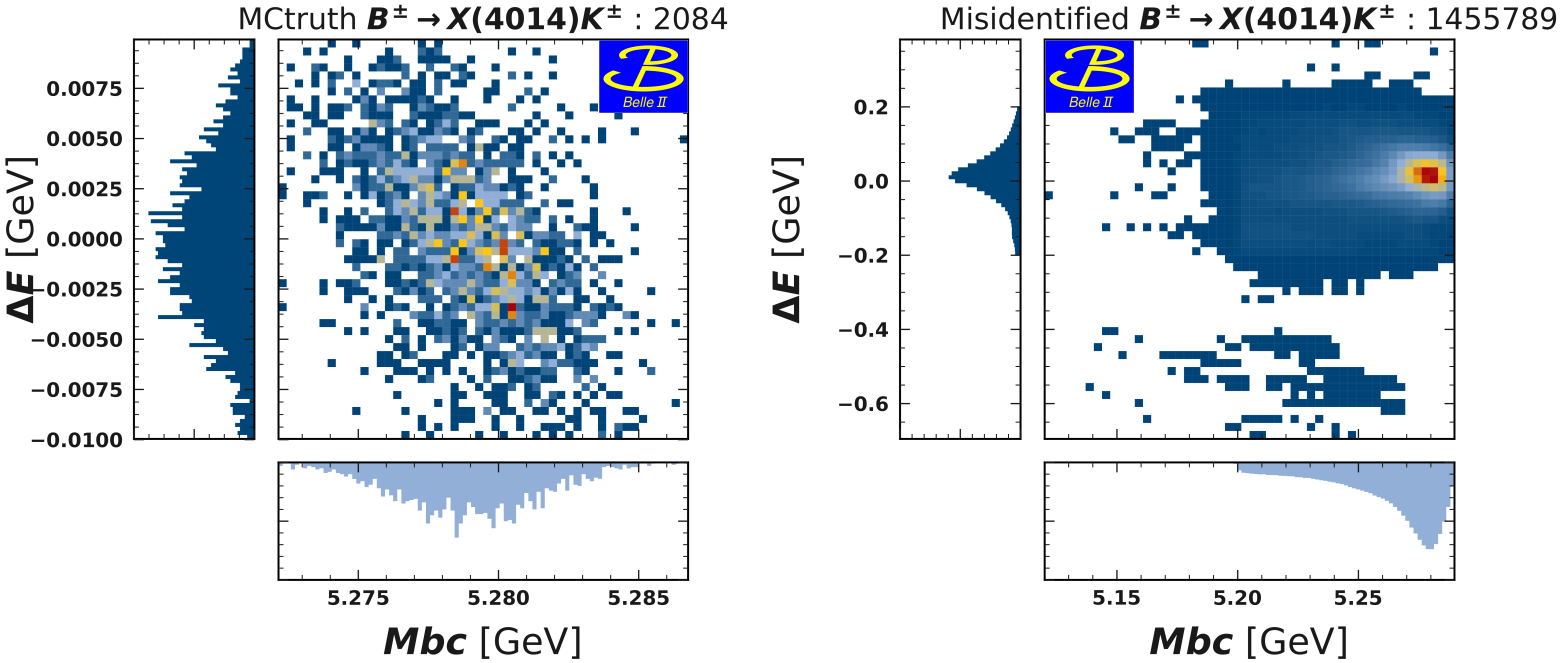
Simulation study of the $X(4014)$

$$\Upsilon(4S) \to B^+B^-$$
$$\hookrightarrow X(4014)K^+$$
$$\hookrightarrow D^0\bar{D}^0\pi^0\pi^0$$
$$\to K^-\pi^+$$
$$\to K^-\pi^+\pi^0$$
$$\to K^-\pi^+\pi^+\pi^-$$
$$\to K^-K^+$$
$$\to K^0_S\pi^+\pi^-$$

- D^0 decays up to $\approx 30\%$ of the branching fraction
- 100'000 signal events with beam background simulated
- Final state reconstruction same as we use for reconstruction on 2019 data set (shown later)
- Statistics goes down by about 50% due to missing γ channel

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

best candidate selection, MC

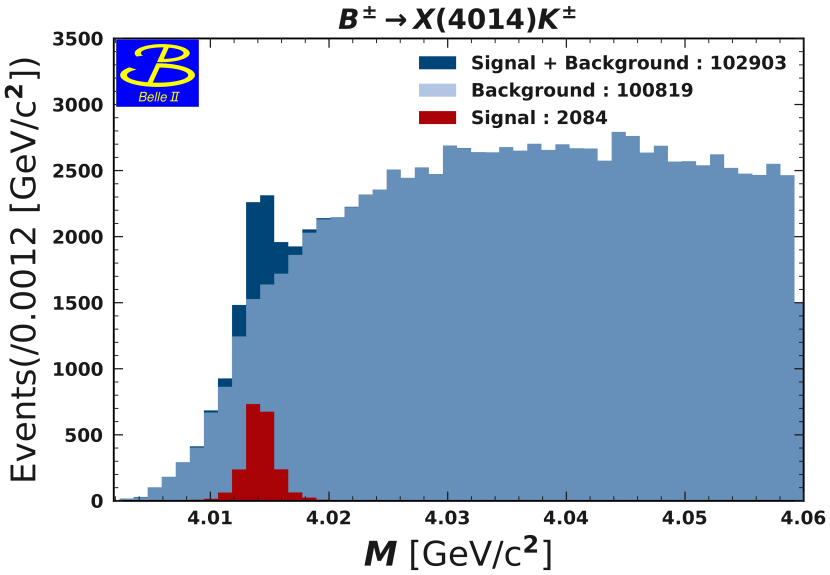


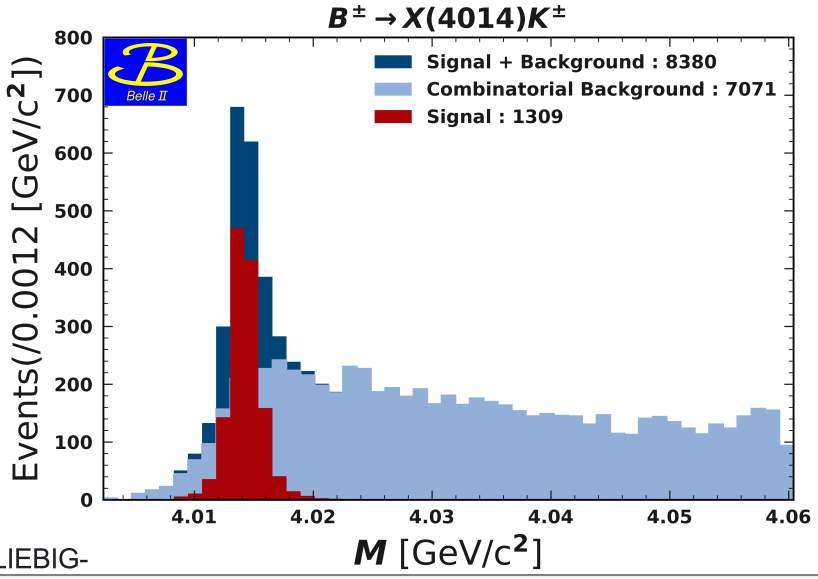
Among the $B^{\pm}$ candidates which survived the Mbc-ΔE selection, the one with the lowest χ^2_{bcs} per event is used as "correct" $X(4014)$-mother.

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

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

apply BCS, MC





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

Background estimation

Signal:

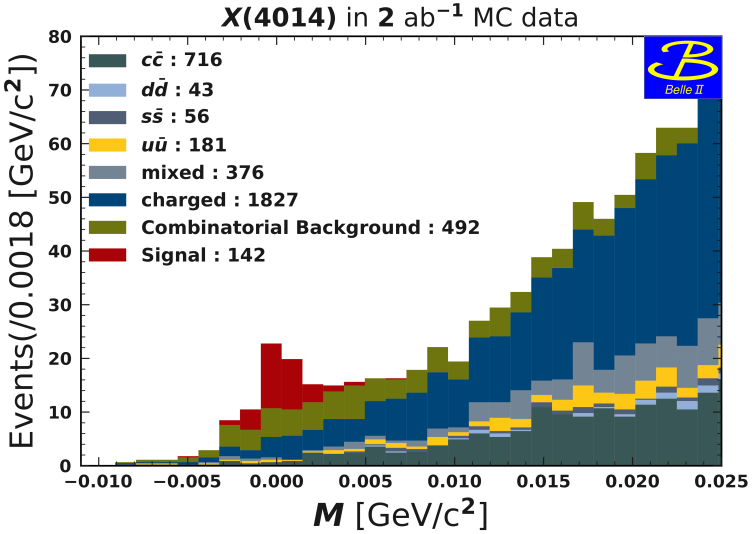
- signal branching fraction assumed as $1 \cdot 10^{-4}$
- identical to $X(3872)$ at $D^0 \bar{D}^{*0}$
- only $B^{\pm}$ decays taken into account
- $B(e^+ + e^- \to \Upsilon(4S) \to B\bar{B}) = 1.1$ nb
- ≈ 15.000 signal events expected in $\int Ldt = 2$ ab^{-1} (about 2x the data set of Belle and BaBar)

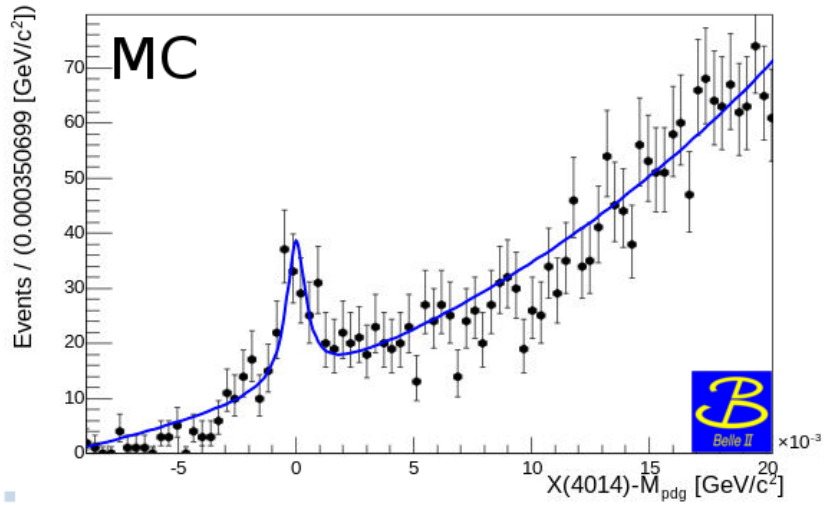
Background:

- $\int Ldt = 2$ ab^{-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

$X(4014)$ with Background

MC





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

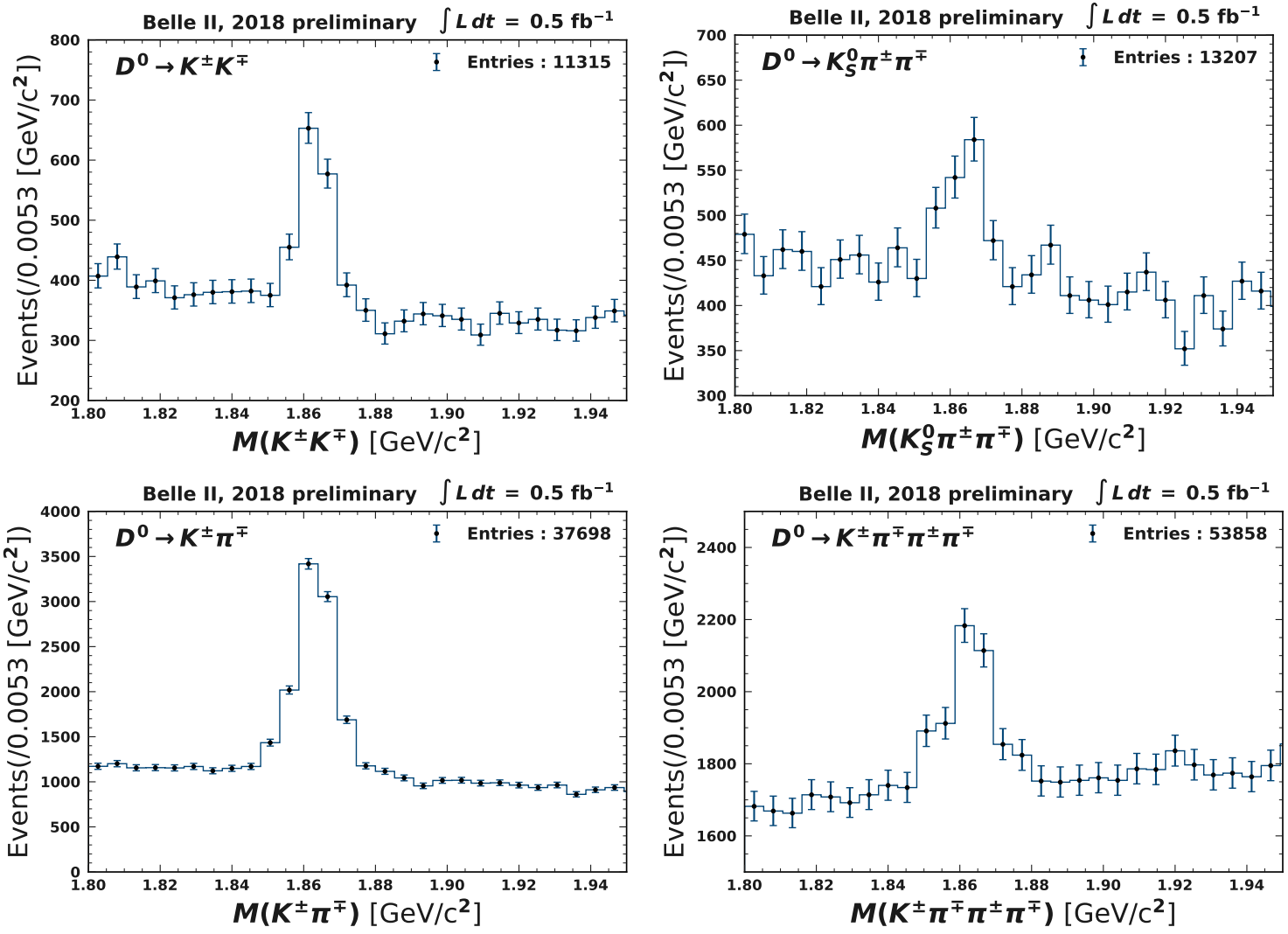
D^0 reconstruction in early data sets

Cuts on final state particles

- 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
- Impact parameters radial and along beam pipe direction 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$/c^2$
- Particle ID applied

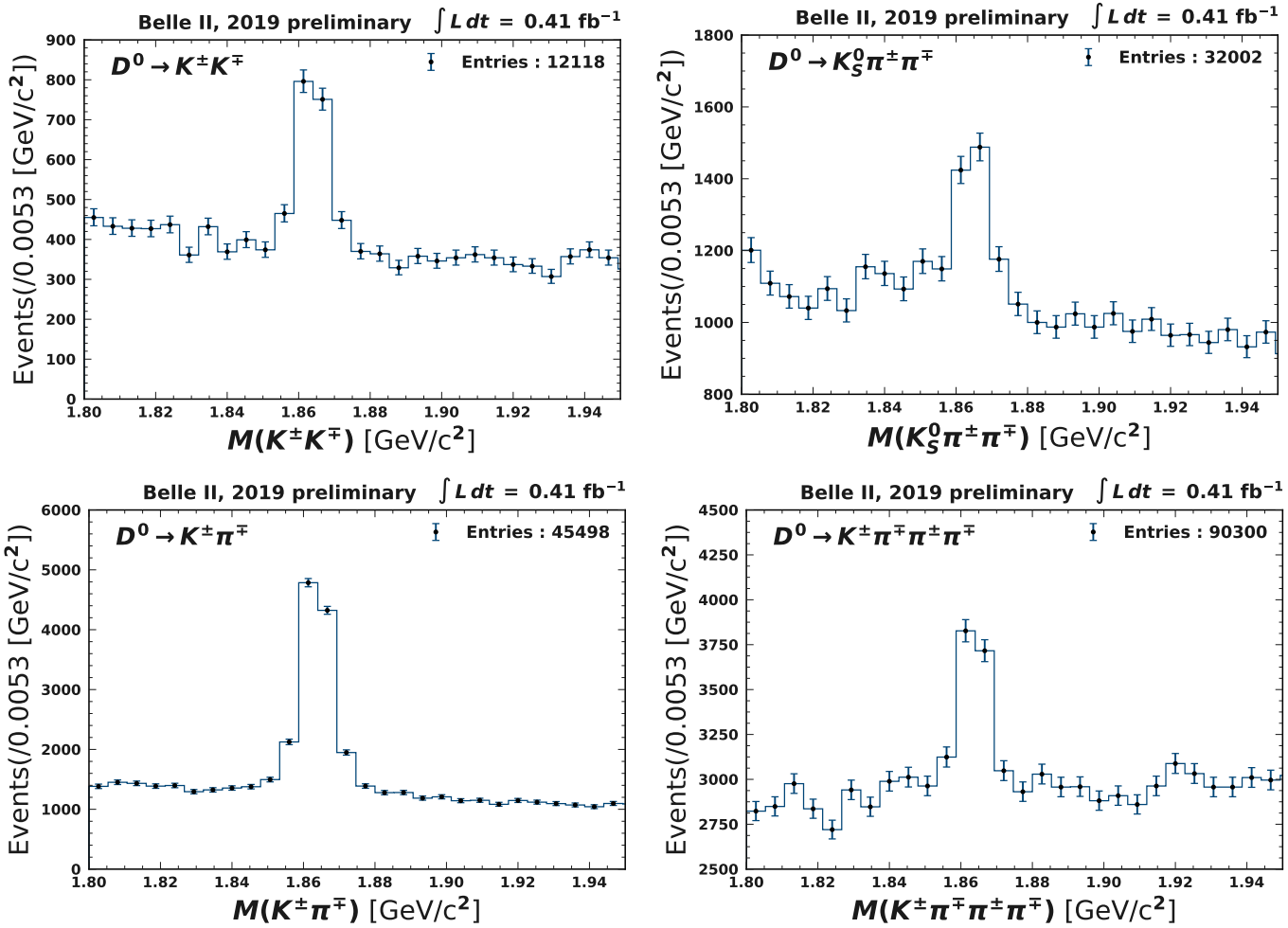
D^0 reconstruction in early data sets

on 2018 data, 504 pb^{-1}



D^0 reconstruction in early data sets

on 2019 data , 449 pb^{-1}



Resolution and Yield improved compared to 2018

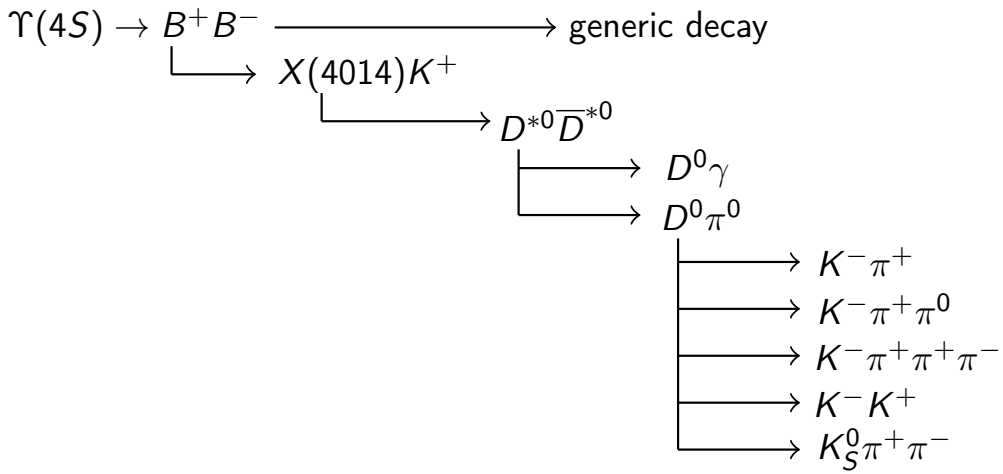
Summary and Outlook

- Belle II can reach sub-MeV sensitity 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 σ significance with 1.3% reconstruction efficiency
- reconstruction of neutral B decay to $X(4014)K_S^0$ will be added
  $\rightarrow$ improves statistics, needed for small Belle data set
- search on Belle data (using Belle II framework) is under investigation
- D^0 reconstruction works on data, improvement of resolution and yield from 2018 to 2019 data set

Backup

A new Charmonium-Like state at the $D^{*0}\bar{D}^{*0}$ threshold

decay chain

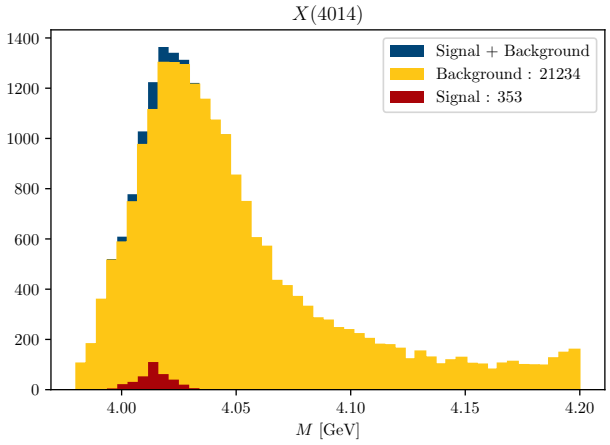


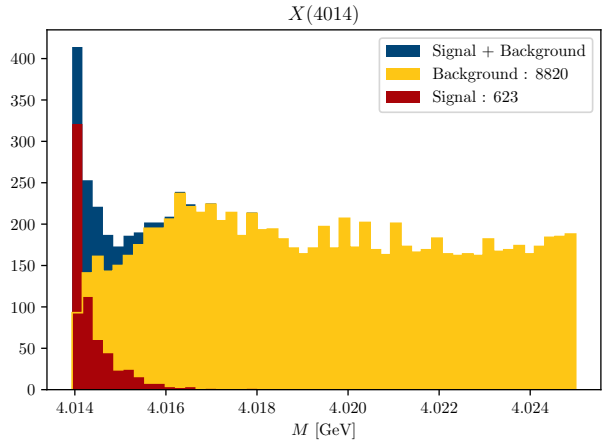
D^0 decays up to $\approx 30\%$ of the branching fraction

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

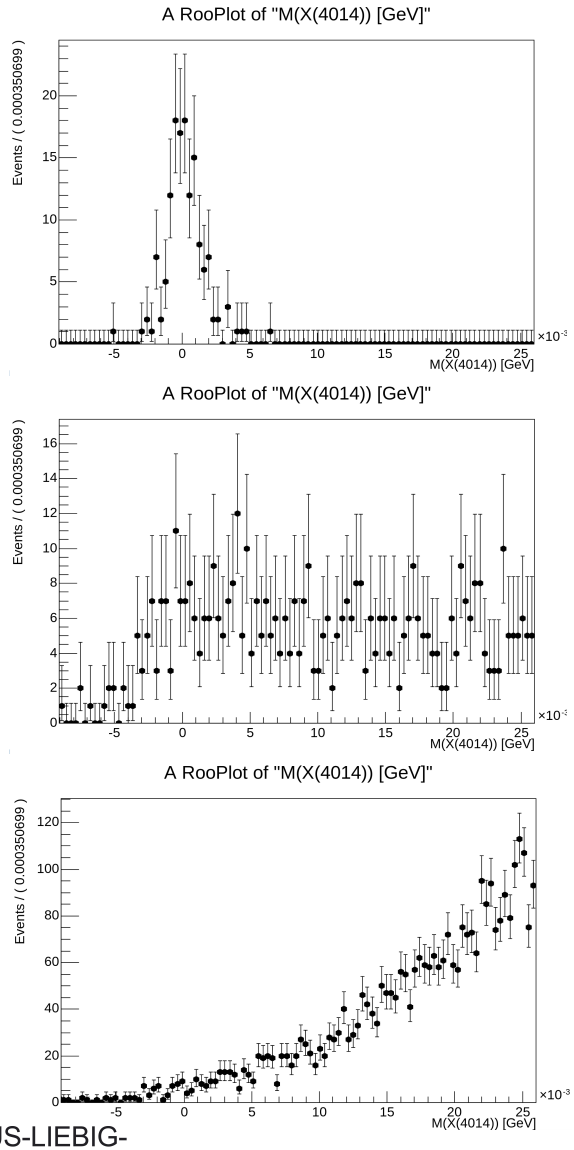
D^{*0} mass fitted $\rightarrow$ peak can be seen but any entry below 4014 MeV cut off

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!

$X(4014)$ with Background

Fits



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