Sensitivity to the X(3872) total width at the Belle II experiment

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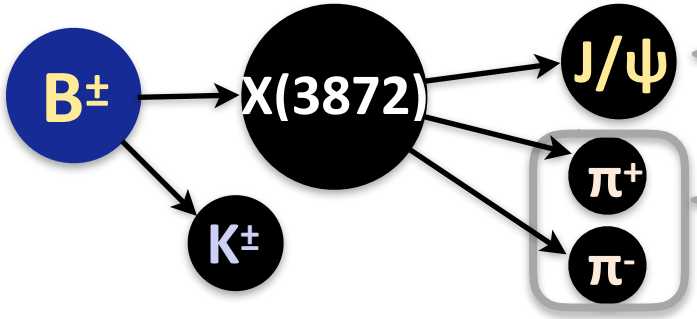
for the Belle II collaboration

HADRON2019
Guilin, Aug 17th 2019

X(3872)

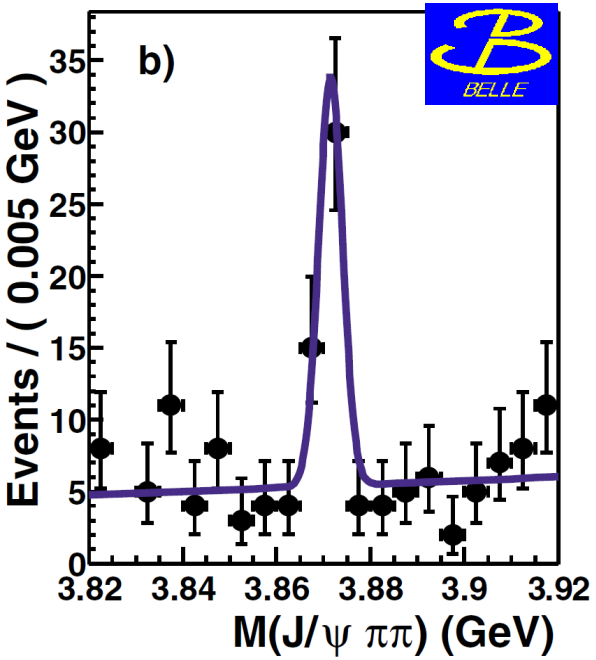
- One candidate of exotic hadrons.
  - It was discovered in **B decay** at Belle in 2003.



$c\bar{c}$ component is included.

ρ meson component is dominant.

Phys. Rev. Lett. 91, 262001



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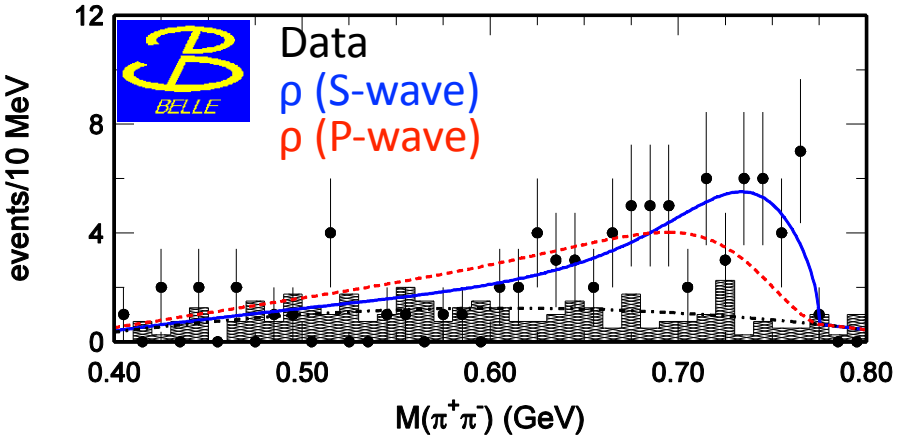
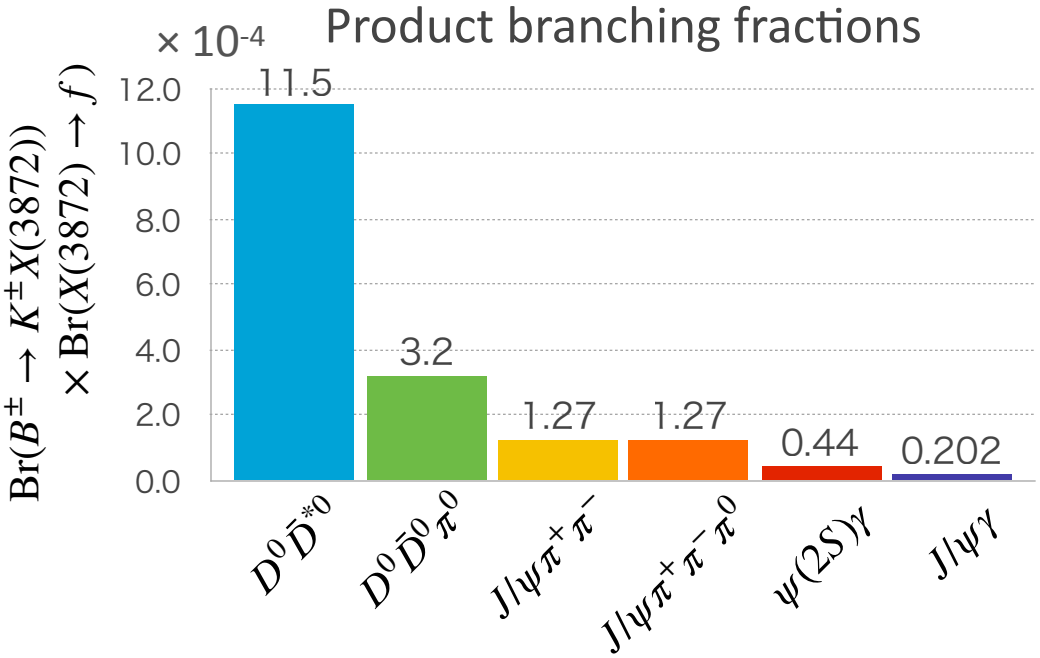


Is there exotic component?

X(3872)

- A lot of X(3872) characteristics have been observed.
  - Various decay modes have been observed.
    Product of two branching fractions are measured.

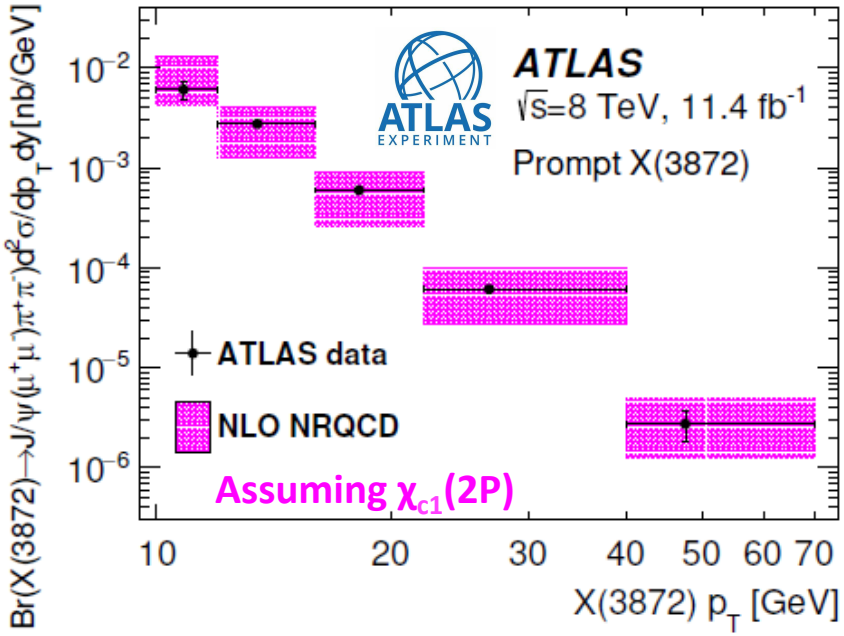


  - $M_{X(3872)}$ = 3871.69 ± 0.17 MeV/c² → Consistent with $D\bar{D}^*$ threshold
  - $J^{PC} = 1^{++}$

→ Support interpretation as pure $D\bar{D}^*$ molecule.

Counter evidence of pure molecule model

Cross section of prompt X(3872) in pp-collision (LHC experiment)



(JHEP01(2017)117)

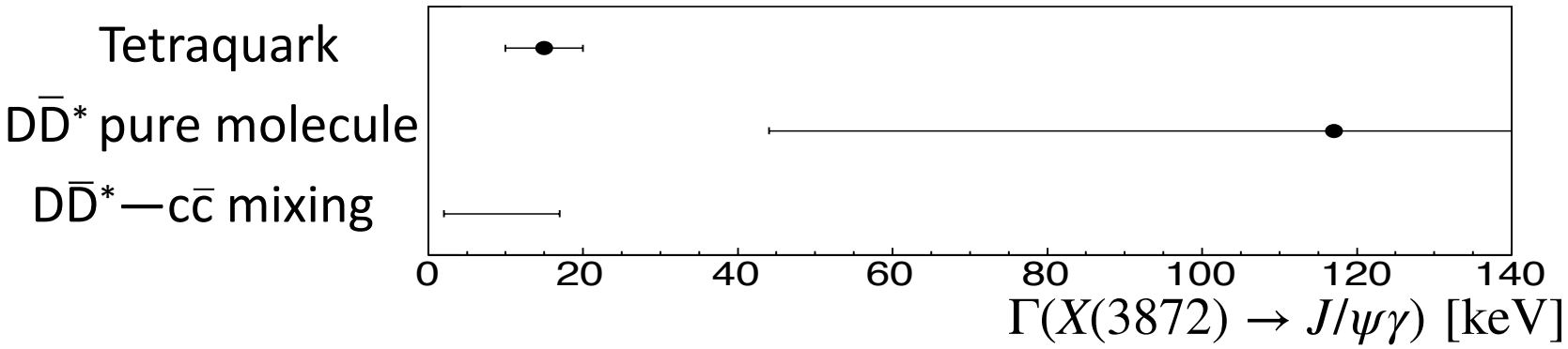
- Should be suppressed for a molecule.
  → Consistent with cross section for pure $\chi_{c1}(2P)$ state.
  → $D\bar{D}^* - \chi_{c1}(2P)$ mixture state?

- Need further information about production and decay.
  - X(3872) total width measurement
    Current X(3872) total width:
    $\Gamma_{\mathrm{tot}} < 1.2\ \mathrm{MeV}$

Why total width?

- **X(3872) total width** provides us partial widths for each decay.

$$\Gamma(X(3872) \to f) = \mathrm{Br}(X(3872) \to f) \times \Gamma_{\mathrm{tot}}$$



- In case of $X(3872) \to J/\psi\gamma$ decay, $\mathrm{Br}(X(3872) \to J/\psi\gamma) < \sim 0.02$

Comes from relative branching fractions for known decay modes

[1] S. Dubnicka, et. al., Phys. Rev. D **81**, 114007 (2010)
[2] F. Aceti, et. al., Phys. Rev. D **86**, 113007 (2012)
[3] Y. Dong, et. al, J. Phys. G: Null.Part. Pays. 38, 015001 (2011)

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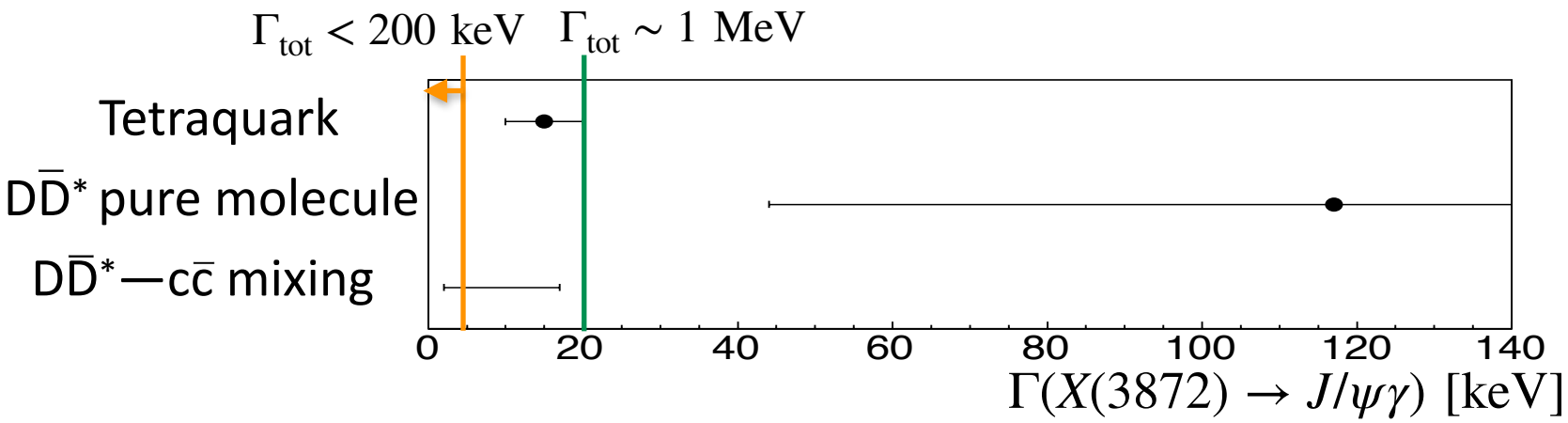
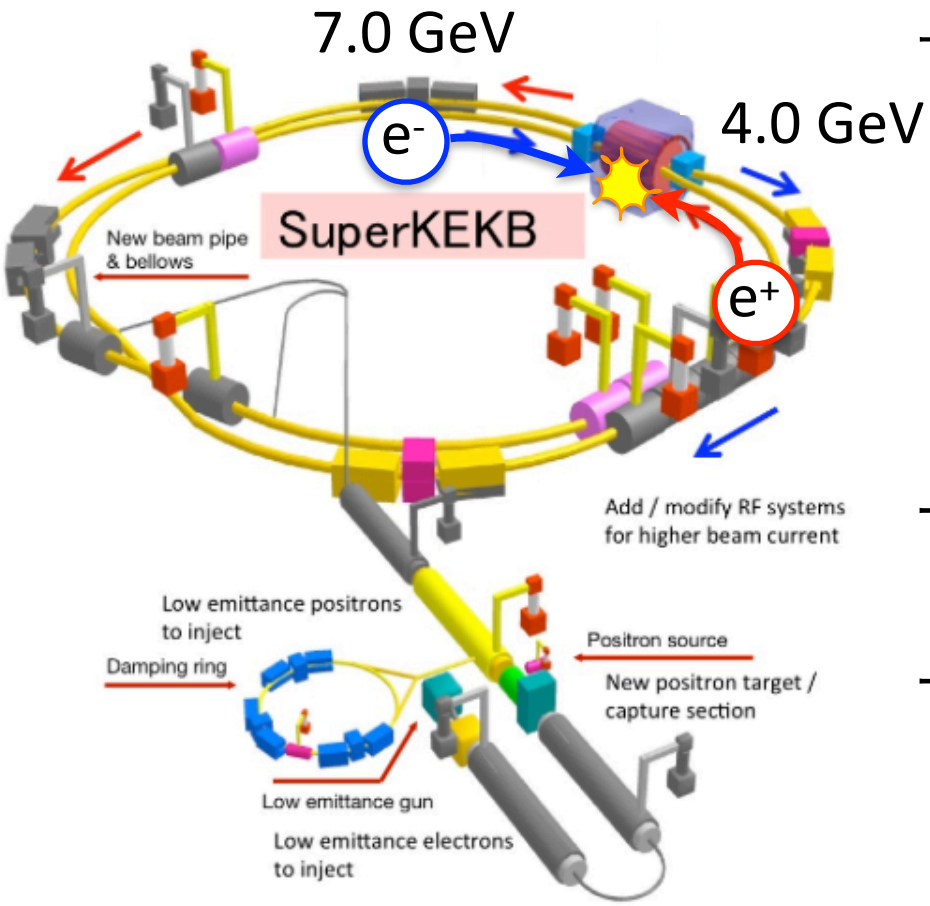


- In case of $X(3872) \to J/\psi\gamma$ decay, $\mathrm{Br}(X(3872) \to J/\psi\gamma) < \sim 0.02$
  → If Γ_{tot} is determined by ~O(100 keV) or the upper limit is improved, it has capability of testing the models.

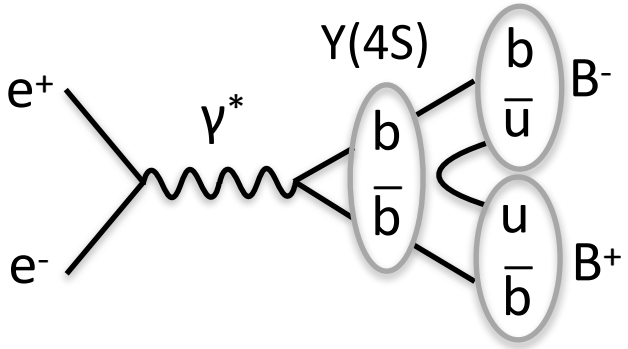
[1] S. Dubnicka, et. al., Phys. Rev. D **81**, 114007 (2010)
[2] F. Aceti, et. al., Phys. Rev. D **86**, 113007 (2012)
[3] Y. Dong, et. al, J. Phys. G: Null.Part. Pays. 38, 015001 (2011)

Belle II experiment

- Next-generation B factory experiment with an electron-positron collider, SuperKEKB



— $\sqrt{s} = 10.58$ GeV

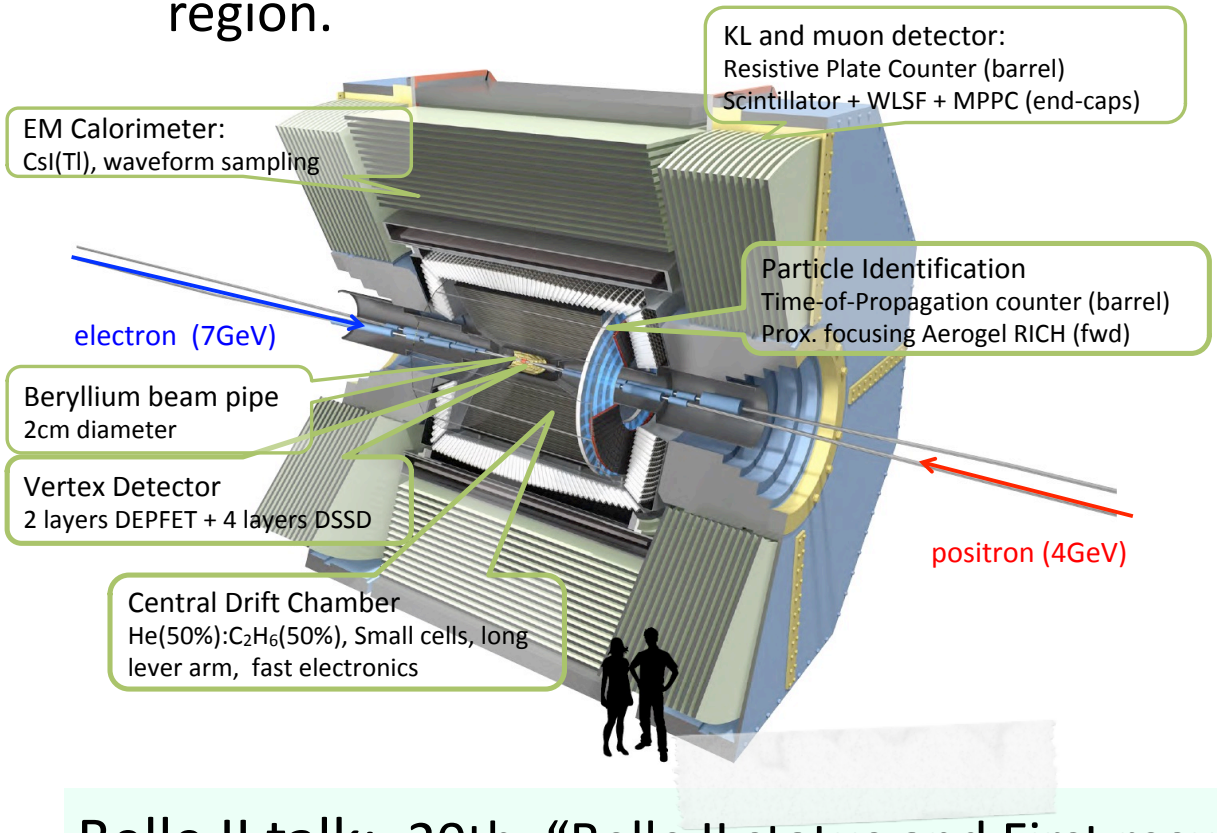


— Instantaneous design luminosity
$8.0 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$ (× 40 to Belle)

— Goal of integrated luminosity:
50 $\mathrm{ab^{-1}}$ (× 50 to Belle)
= ~5.5 × 10^{10} $B\bar{B}$ pairs

Belle II experiment

- Belle II detector: General purpose 4π detector
  → Capable of detecting $\pi^{\pm}$, $K^{\pm}$, p, e, μ and γ for wide momentum region.

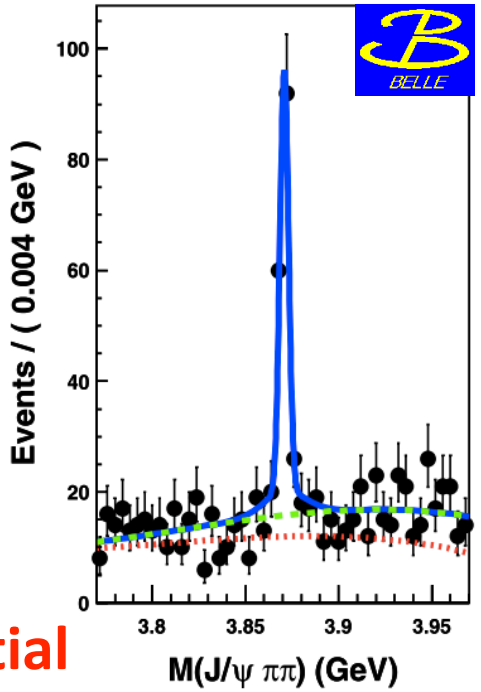


- Has better momentum/ vertex resolution
- Improve PID performance with technology of Cherenkov ring-imaging

Belle II talk: 20th, "Belle II status and First result" (L. Li)
21th, "Exotic and Conventional Quarkonium Physics Prospects at Belle II" (S. Jia)

Strategy for improvement of sensitivity

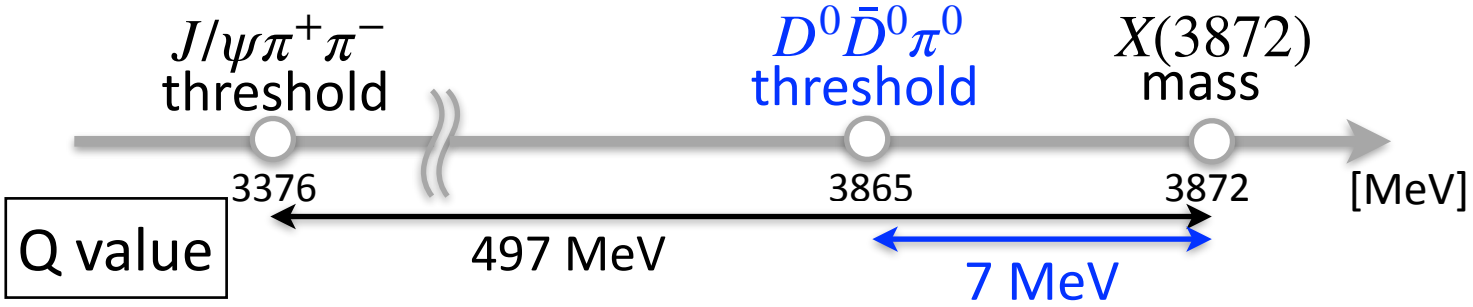
- Previous Study (Phys. Rev. D 84, 052004 (2011))
  - Use $X(3872) \to J/\psi\pi^+\pi^-$ mode.
  - Fit signal component of mass spectrum with Breit-Wigner convoluted with mass resolution.



Γ_{tot} < 1.2 MeV (90% C.L.) < Mass resolution 1.86 ± 0.01 MeV/c²

✴ **Improvement of mass resolution is more essential than that of statistics.**

- We propose to use decay mode with good mass resolution.



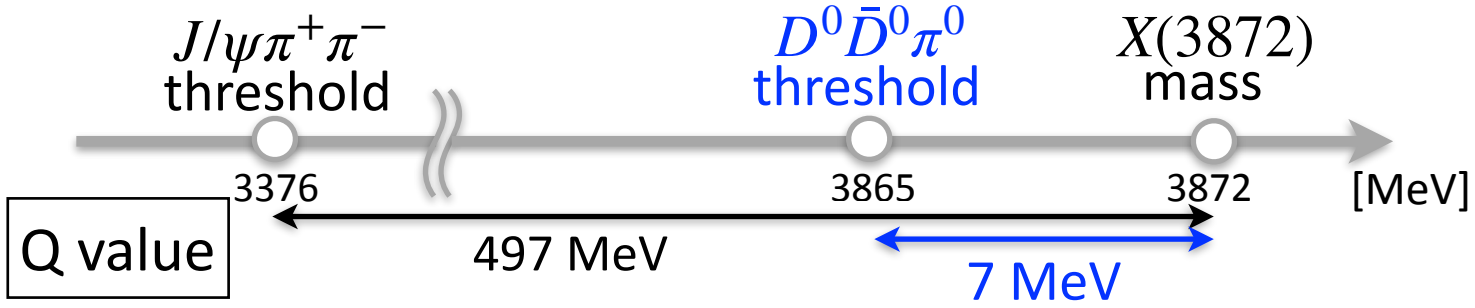
Strategy for improvement of sensitivity

- $D^0\bar{D}^0\pi^0$ mode should have good resolution
- However, $D^0\bar{D}^0\pi^0$ mode has too low signal yield to measure total width so far (Belle).

✴ **Belle II** is suitable for this measurement thanks to huge data sample.

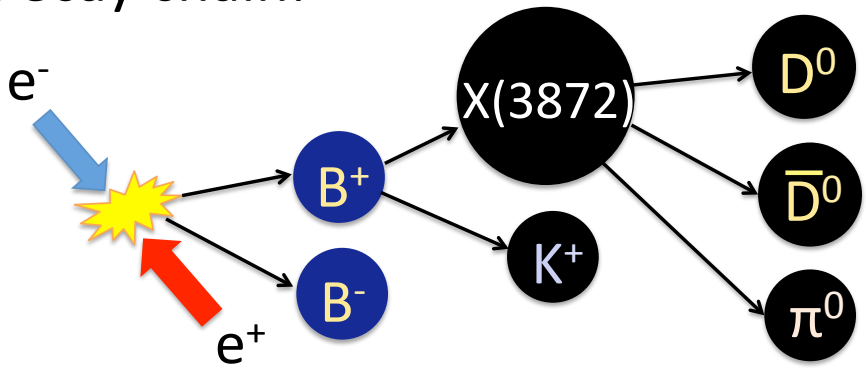
→ In this presentation, analysis overview and sensitivity to total width with simulation will be shown.

- We propose to use decay mode with good mass resolution.



Reconstruction and selection

Decay chain:



- D^0 mode

$$\begin{cases} D^0 \to K^+\pi^- \\ D^0 \to K^+\pi^-\pi^0 \\ D^0 \to K^+\pi^-\pi^-\pi^+ \end{cases}$$

~ 26% D^0 modes

- π^0 mode

$$\pi^0 \to \gamma\gamma$$

~ 99% π^0 modes

Event selection

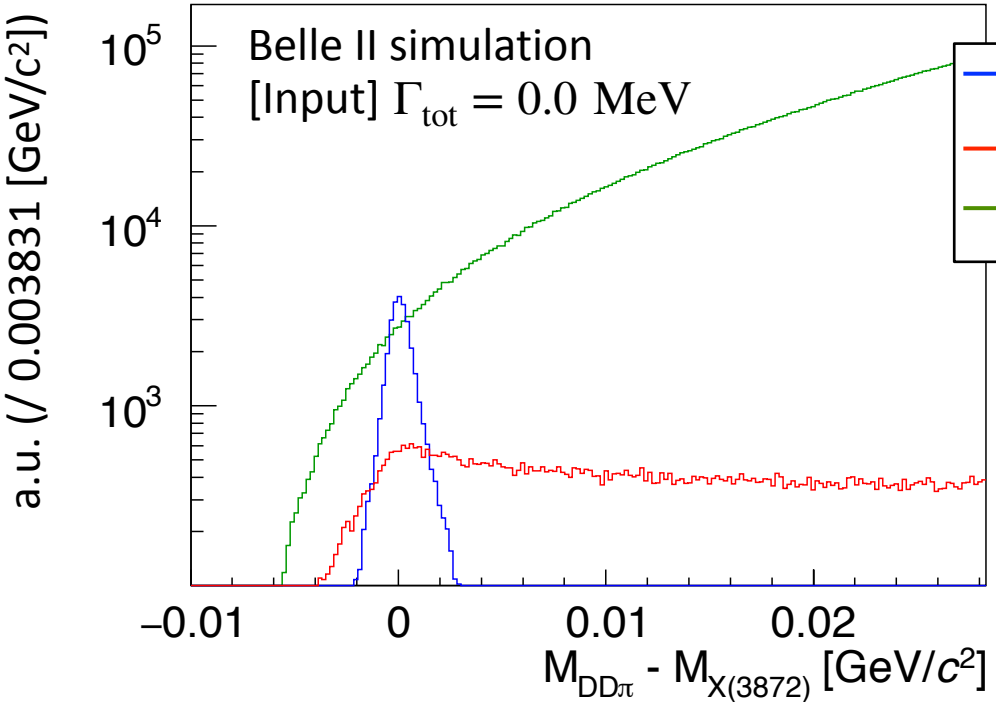
- For final state particle, PID, tracking ($K^{\pm}$, $\pi^{\pm}$) and cluster information (γ).
- For D^0 and π^0 mesons, signal regions are selected, and mass-constrained fits are used.
- For B mesons, beam-energy-constrained mass and CMS energy difference.

- In order to reduce multiplicity of B candidates, best candidate selection is performed by selecting a candidate with minimum χ^2_{BCS} .

$$\chi^2_{BCS} = \left(\frac{\Delta M_{D^0}}{\sigma M_{D^0}}\right)^2 + \left(\frac{\Delta M_{\bar{D}^0}}{\sigma M_{\bar{D}^0}}\right)^2 + \left(\frac{\Delta M_{\pi^0}}{\sigma M_{\pi^0}}\right)^2 + \left(\frac{E_B - E_{\text{beam}}}{\sigma_{(E_B - E_{\text{beam}})}}\right)^2$$

$D^0\bar{D}^0\pi^0$ invariant mass

Mass spectrum after reconstruction and selection



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

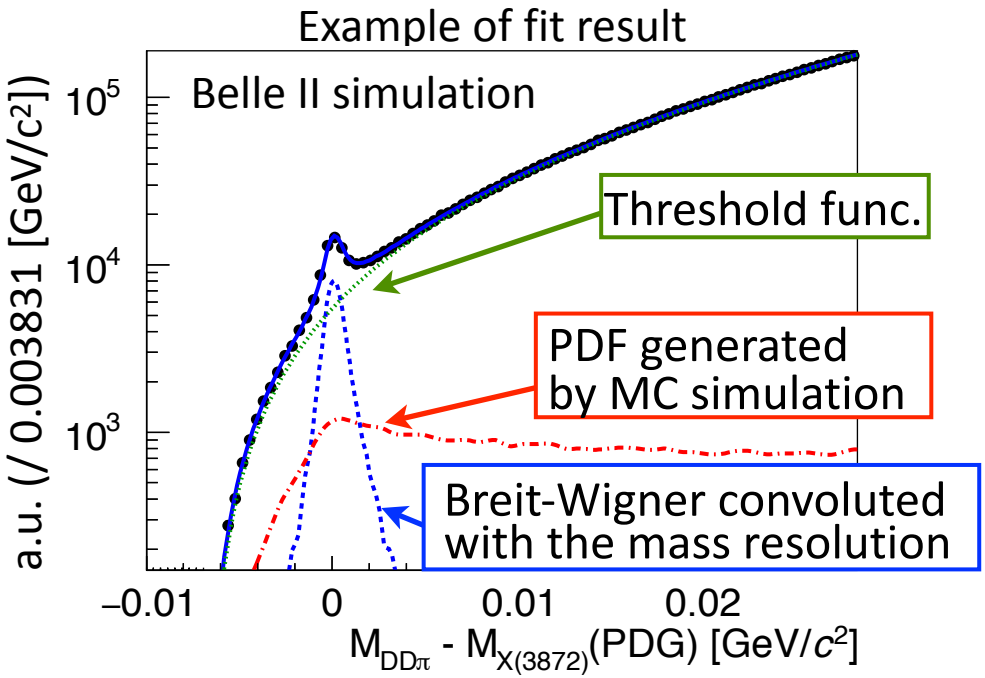
⟶ Compared with previous study ($J/\psi\pi^+\pi^-$mode),
Signal yields is around half, but the mass resolution is 3 times better.

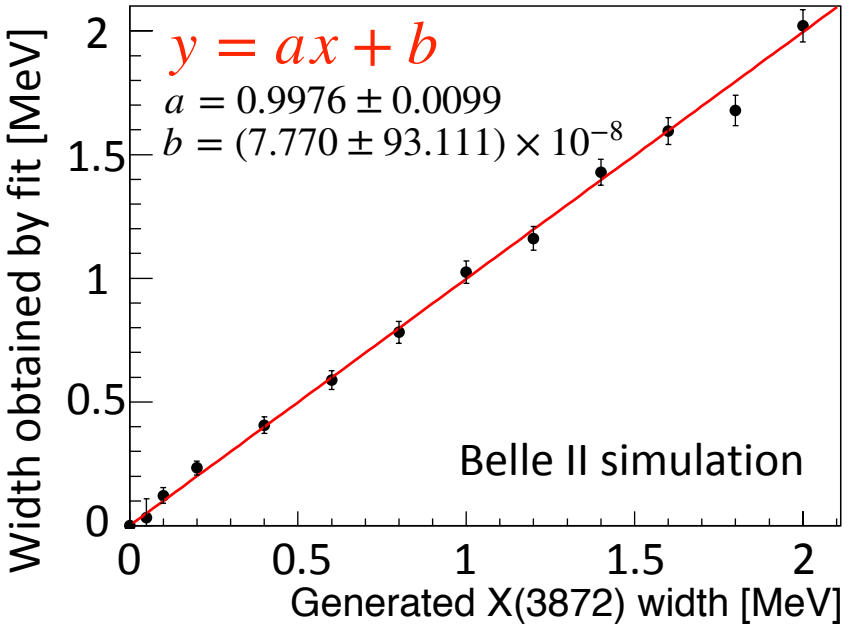
$D^0\bar{D}^0\pi^0$ mode provides a sample with the good mass resolution.

Total width extraction

- Total width is extracted by fitting the mass spectrum.
- Check if the total width is obtained by the fit correctly.
  → Linear relation between the total width generated in the simulation and that obtained by fit.

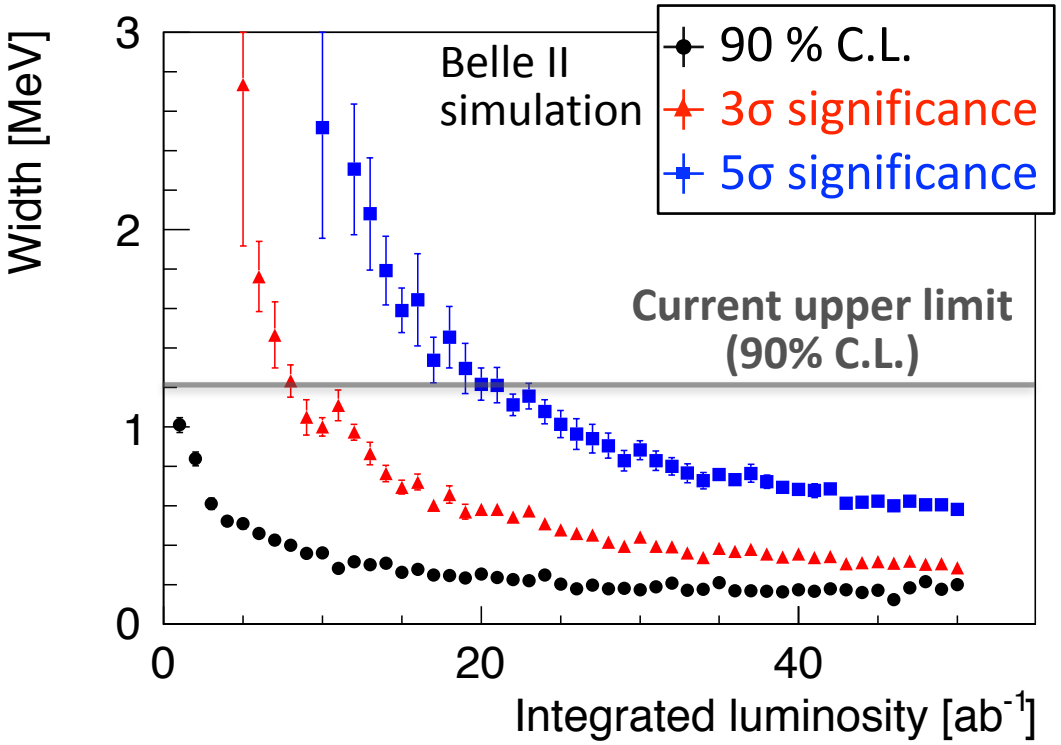
"Confirmed that there is no bias in the fit."





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

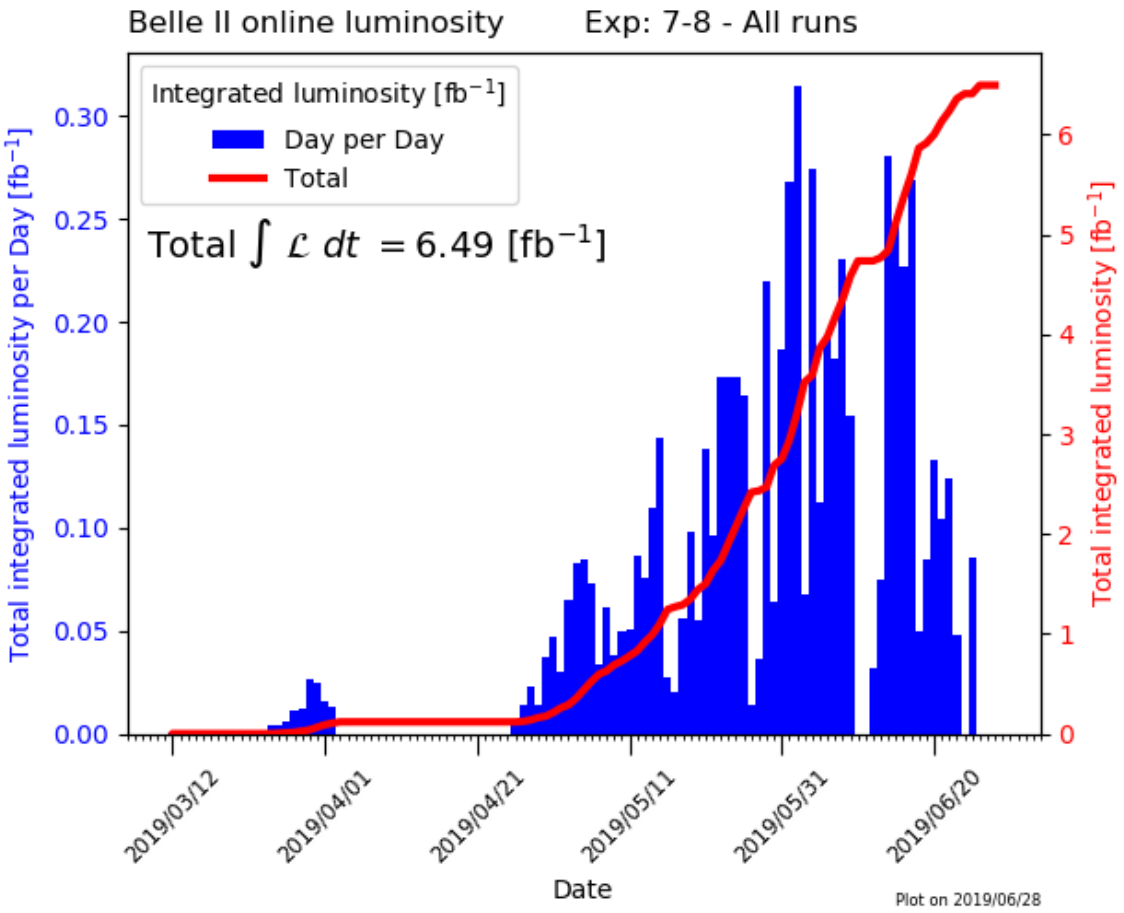
[5σ significance] ~ 570 keV

can be measured.

- Belle II is capable of measuring total widths.
- Next, we need detailed study of mass resolution and background with data.

Belle II status

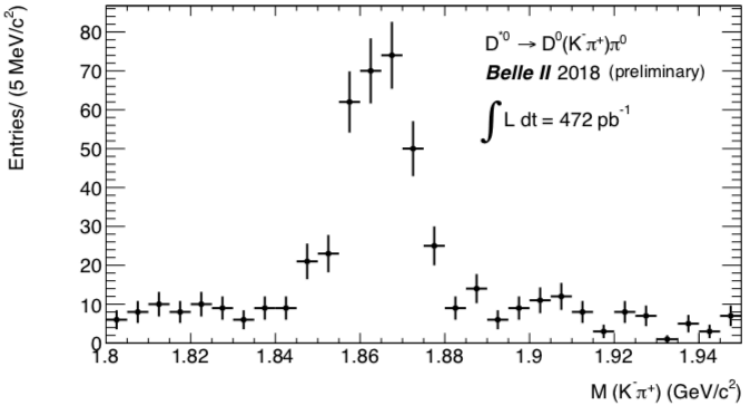
- ~6.5 fb^{-1} data was collected from March. 25 to July 1st.



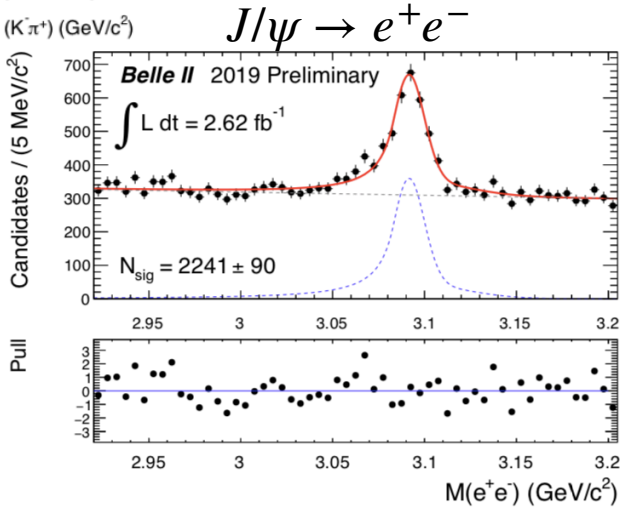
Belle II status

- ~6.5 fb^{-1} data was collected from March. 25 to July 1st.
- We rediscovered open-charm mesons and charmonia.
- Mass resolution study is on-going with inclusive hadron sample.

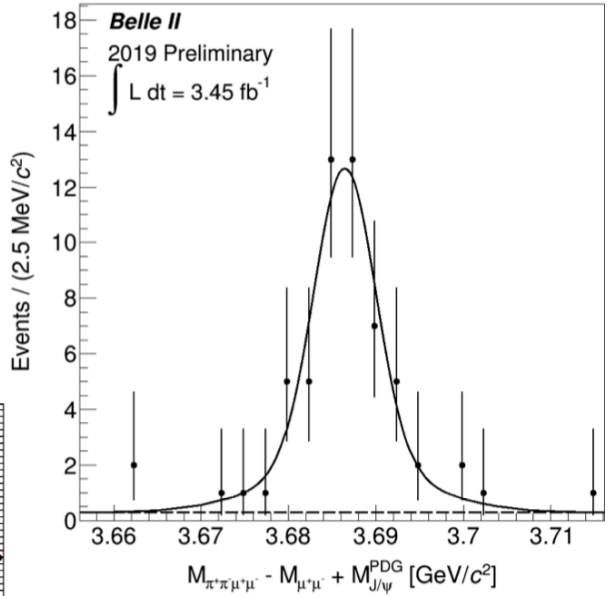
$D^{*0} \to D^0\pi^0$



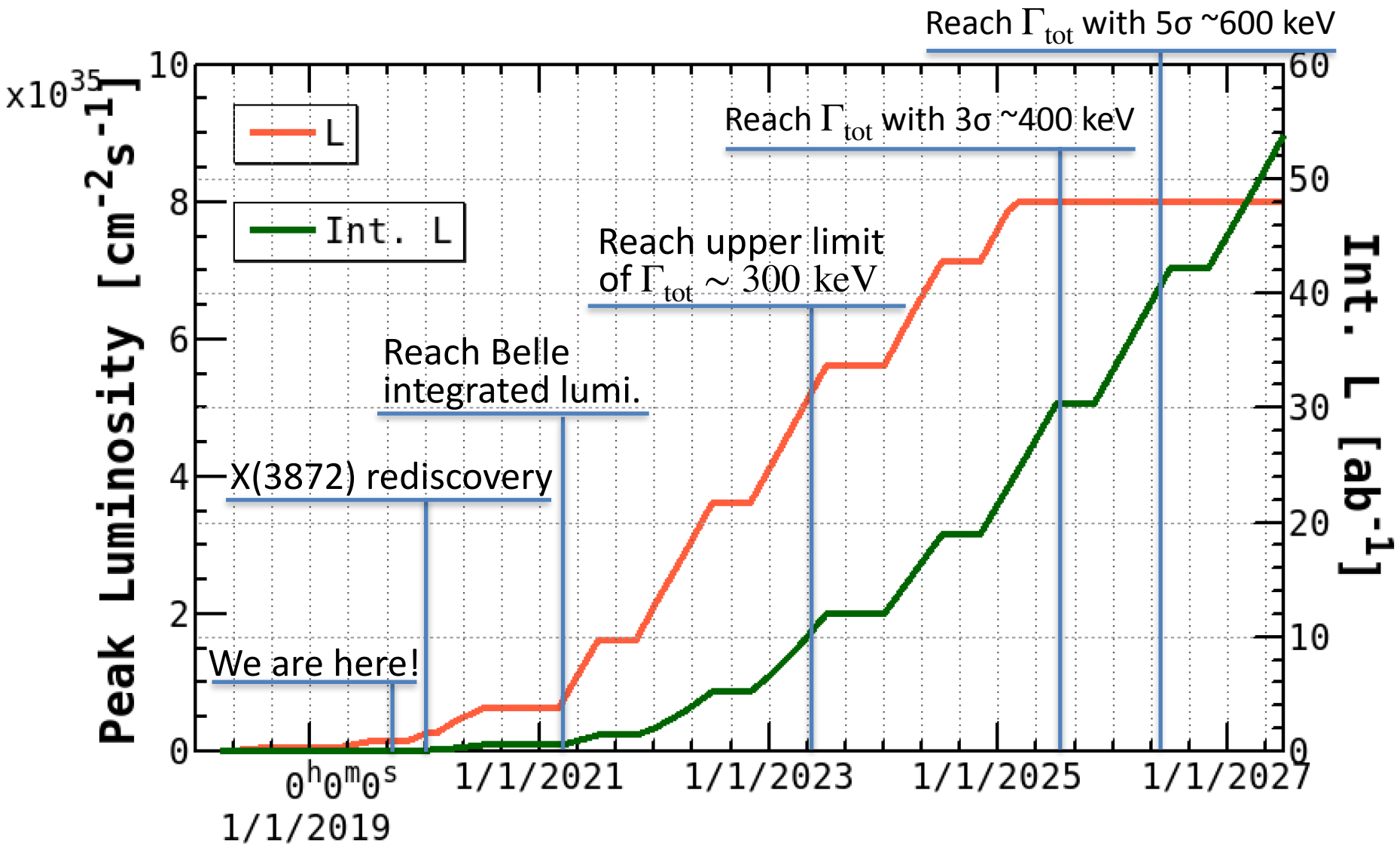
$J/\psi \to e^+e^-$



$\psi(2S) \to J/\psi\pi^+\pi^-$



Prospect


Reach Γ_{tot} with 5σ ~600 keV
Reach Γ_{tot} with 3σ ~400 keV
Reach upper limit of Γ_{tot} ~ 300 keV
Reach Belle integrated lumi.
X(3872) rediscovery
We are here!
L
Int. L
Peak Luminosity [cm^{-2}s^{-1}] x10^{35}
Int. L [ab^{-1}]
0
2
4
6
8
10
0
10
20
30
40
50
60
0^{h}0^{m}0^s
1/1/2019
1/1/2021
1/1/2023
1/1/2025
1/1/2027

Conclusion

- In order to derive X(3872) partial widths for each decay mode, we aim at significant measurement of X(3872) total width.
- Sensitivity to the total width at Belle II is estimated by simulation
  - We used a sample with good mass resolution, $D^0\bar{D}^0\pi^0$ decay mode.

    → There is no bias in total width extraction.
  - With the full data sample of Belle II, it is possible to measure total width with 3σ(5σ) significance with values up to 280(570) keV.
- Now, ~6.5 fb^{-1} data was collected in Belle II, and many hadrons have been rediscovered. We are studying mass resolution and background with data.
- We also plan measure precise mass spectrum to test possibility of cusp.

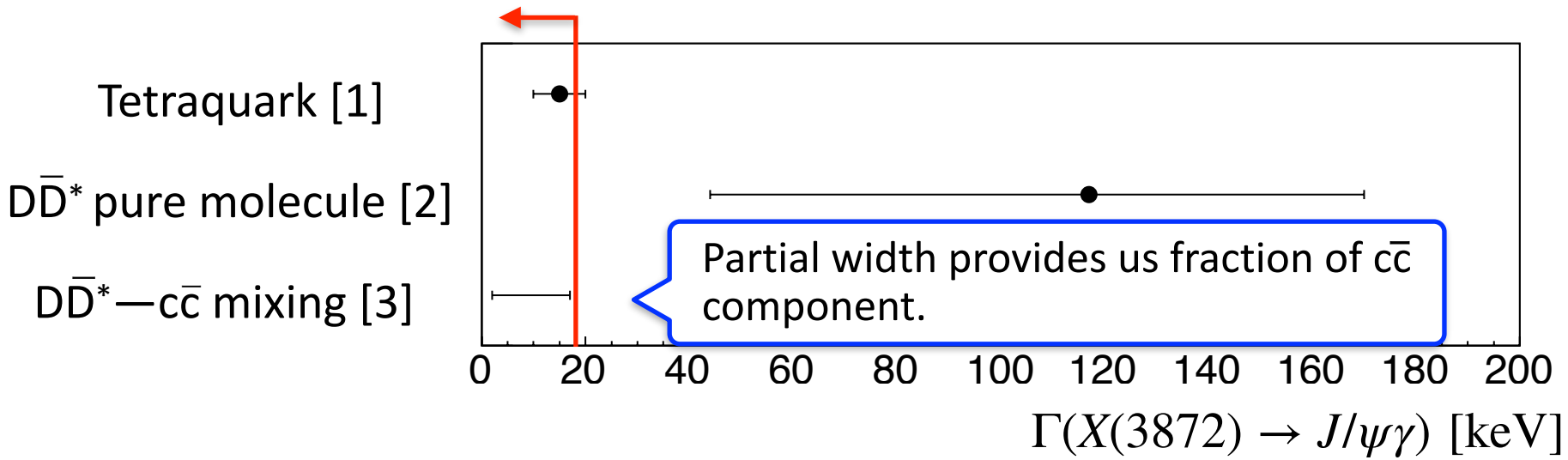
Stay tuned!

Thank you for your attention.

Partial width for $X(3872) \rightarrow J/\psi\gamma$

$$\Gamma(X(3872) \rightarrow J/\psi\gamma) = \Gamma_{tot} \times \underbrace{BR(X(3872) \rightarrow J/\psi\gamma)}_{< \sim 1\ \%} < 0.01 \times \Gamma_{tot}$$

If Γ_{tot} upper limit = 180 keV, $\Gamma(X(3872) \rightarrow J/\psi\gamma) < 18$ keV



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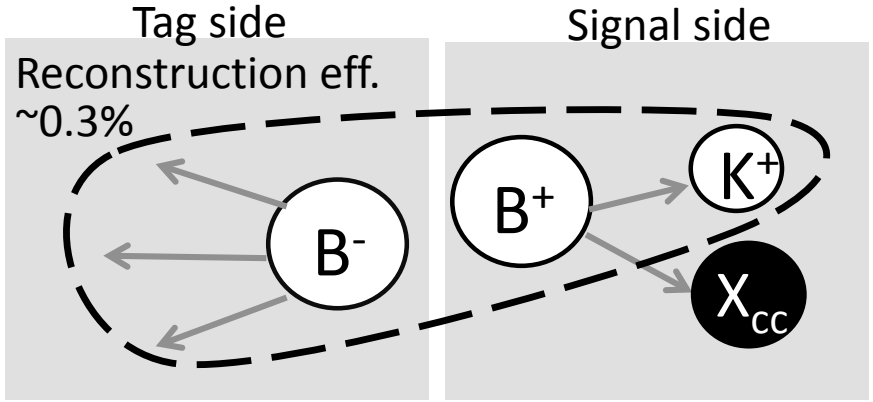
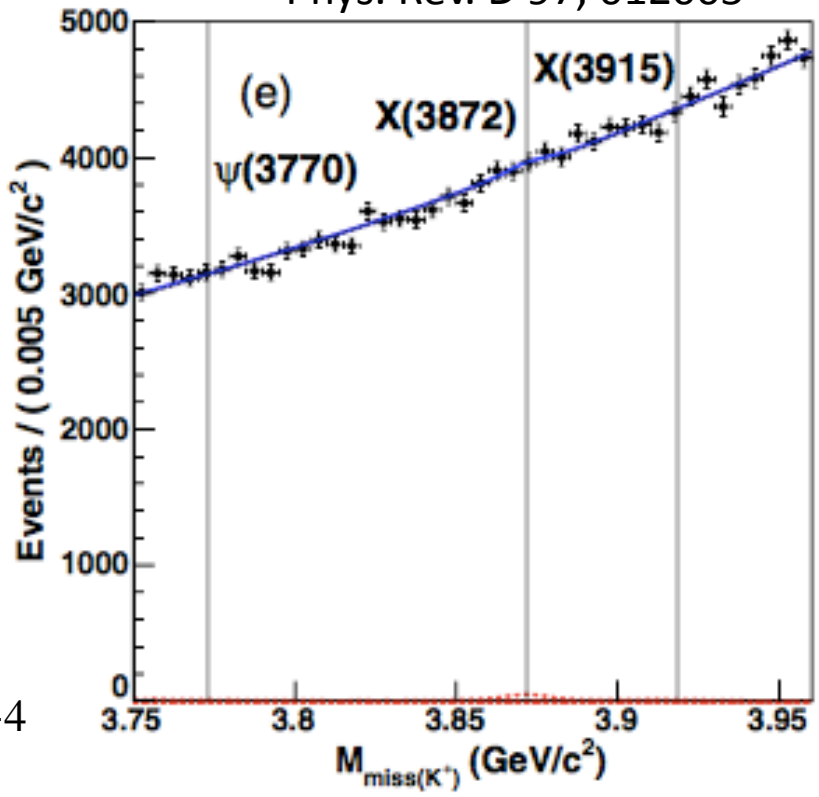
$\mathrm{Br}(B^{\pm} \to K^{\pm}X(3872))$ measurement



Phys. Rev. D 97, 012005



X_{cc} is reconstructed by missing mass

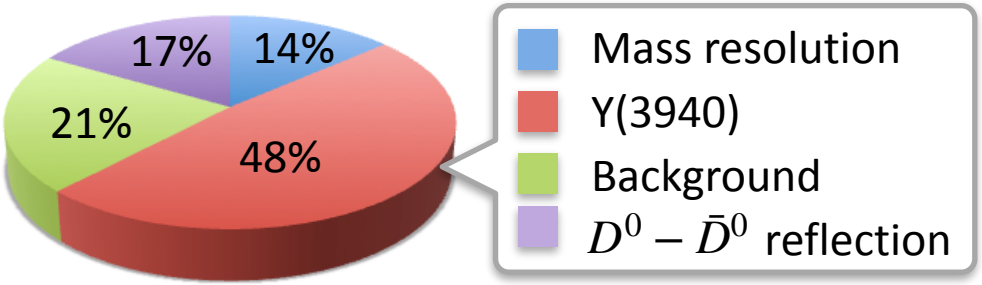
$$M^2_{X_{cc}} = (P_{\mathrm{beam}} - P_{B\mathrm{tag}} - P_{K^+})^2$$

$$\to \mathrm{Br}(B^{\pm} \to K^{\pm}X(3872)) < 2.6 \times 10^{-4}$$

- With the full data sample of Belle II, it is possible to measure with 7σ significance (naive expectation).
- More realistic simulation is on going.

Statistical and systematic uncertainty

- Systematics ~ +200/-660 keV (Phys. Rev. D **96**, 074014 (2017))
  - ✴ Naive expectation from previous study of $D^0\bar{D}^{*0}$ mode



- Statistical uncertainty

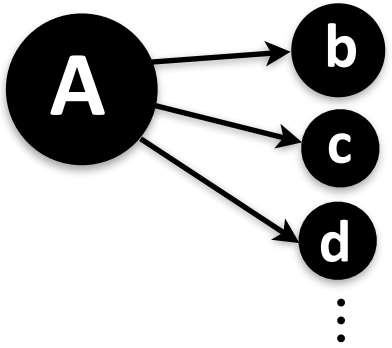
Summary table of total width sensitivity and statical error obtained by fit

Integrated lumi. [ab^{-1}]	3σ significance [keV]	Statistical error [keV]
10	1000	± 550
20	580	± 140
30	440	± 150
40	360	± 90
50	280	± 80

- With >20 ab^{-1}, systematic error become dominant
  → Make it suppress

Relation between mass resolution and Q value

- Consider a decay mode of particle A, $A \rightarrow bcd\cdots$
- Reconstructed mass M



$$M = \sqrt{\left(\sum_{i=bcd\cdots} E_i\right)^2 - \left(\sum_i \vec{P}_i\right)^2}$$

→ Mass resolution σM can be derived as follows

$$\sigma M = \sqrt{\sum_i \left(\frac{\partial M}{\partial E_i}\right)^2 (\sigma E_i)^2 + \sum_i \left(\frac{\partial M}{\partial Px_i}\right)^2 (\sigma Px_i)^2 + \cdots}$$

$$\begin{cases} \dfrac{\partial M}{\partial E_i} = \dfrac{E_i}{M} \\ \dfrac{\partial M}{\partial Px_i} = \dfrac{Px_i}{M} \\ \vdots \end{cases}$$

For the smaller Q-value mode, E, Px_i, Py_i, Pz_i are smaller.
→ Therefore, the mass resolution are small.