JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
JENNIFER 2
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ErUM-FSP T09 Belle II

Studies of the X(3872) at Belle and Belle II: measurements and perspectives

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Workshop on Hadron Spectroscopy: The Next Big Steps
MITP, Mainz, 17.03.2022

Outline

- Absolute branching fraction
- Decays to χ_{c1}
- Searches for partner states
- Production mechanism
  ($B \to K\pi X$ and $\gamma\gamma$)
- Width measurement (3-dim fit)

Belle

- Width measurement (small Q value)
- Production mechanism
  (B^+ vs. B^0)
- Search for molecule partner X(4014)

Belle II

ABSOLUTE BRANCHING FRACTION

PDG 2020

$\chi_{c1}(3872)$ $I^G(J^{PC}) = 0^+(1^{++})$

also known as $X(3872)$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{\chi_{c1}(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
Full width $\Gamma < 1.2$ MeV, CL = 90%

$\chi_{c1}(3872)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi^+\pi^- J/\psi(1S)$	> 3.2 %	650
$\omega J/\psi(1S)$	> 2.3 %	†
$D^0\overline{D}^0\pi^0$	>40 %	117
$\overline{D}^{*0} D^0$	>30 %	4
$\pi^0\chi_{c1}$	> 2.8 %	319
$\gamma J/\psi$	$> 7 \times 10^{-3}$	697
$\gamma\psi(2S)$	> 4 %	181
$\pi^+\pi^-\eta_c(1S)$	not seen	745
$\pi^+\pi^-\chi_{c1}$	not seen	218
$p\overline{p}$	not seen	1693

100% ?

PDG 2021

$\chi_{c1}(3872)$ $I^G(J^{PC}) = 0^+(1^{++})$

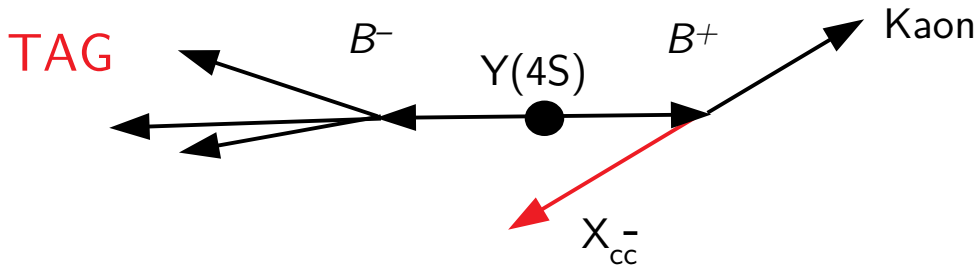
also known as $X(3872)$

Mass $m = 3871.65 \pm 0.06$ MeV
$m_{\chi_{c1}(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
Full width $\Gamma = 1.19 \pm 0.21$ MeV (S = 1.1)

$\chi_{c1}(3872)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-	$< 2.8 \times 10^{-6}$	90%	1936
$\pi^+\pi^- J/\psi(1S)$	(3.8 ± 1.2) %		650
$\pi^+\pi^-\pi^0 J/\psi(1S)$	not seen		588
$\omega\eta_c(1S)$	< 33 %	90%	368
$\omega J/\psi(1S)$	(4.3 ± 2.1) %		†
$\phi\phi$	not seen		1646
$D^0\overline{D}^0\pi^0$	$(49\ ^{+18}_{-20})$ %		116
$\overline{D}^{*0} D^0$	(37 ± 9) %		†
$\gamma\gamma$	< 11 %	90%	1936
$D^0\overline{D}^0$	< 29 %	90%	519
D^+D^-	< 19 %	90%	502
$\pi^0\chi_{c2}$	< 4 %	90%	273
$\pi^0\chi_{c1}$	(3.4 ± 1.6) %		319
$\pi^0\chi_{c0}$	< 70 %	90%	–
$\pi^+\pi^-\eta_c(1S)$	< 14 %	90%	745
$\pi^+\pi^-\chi_{c1}$	$< 7 \times 10^{-3}$	90%	218
$p\overline{p}$	$< 2.4 \times 10^{-5}$	95%	1693
Radiative decays			
γD^+D^-	< 4 %	90%	502
$\gamma\overline{D}^0 D^0$	< 6 %	90%	519
$\gamma J/\psi$	$(8 \pm 4) \times 10^{-3}$		697
$\gamma\chi_{c1}$	$< 9 \times 10^{-3}$	90%	344
$\gamma\chi_{c2}$	< 3.2 %	90%	303
$\gamma\psi(2S)$	(4.5 ± 2.0) %		181
***C*-violating decays**			
$\eta J/\psi$	< 1.8 %	90%	491

$B^+ \to K^+ X_{c\bar{c}}$

Particular situation at $\Upsilon(4S)$: $m(\Upsilon(4S))=m_B+m_{\overline{B}}$
$\to B$ mesons at rest in cms system



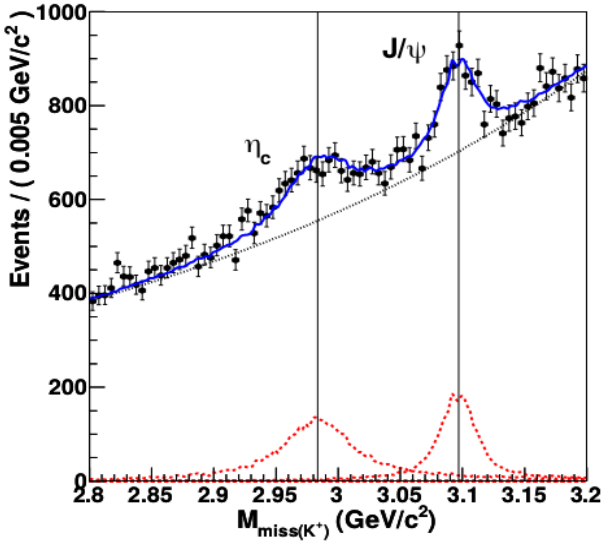
Hierarchical full reconstruction of 1104 hadronic decays
NeuroBayes neural-network package
M. Feindt, F. Keller, M. Kreps, T. Kuhr, S. Neubauer, D. Zander, A. Zupanc
Nucl. Instrum. Meth. A654 (2011) 432

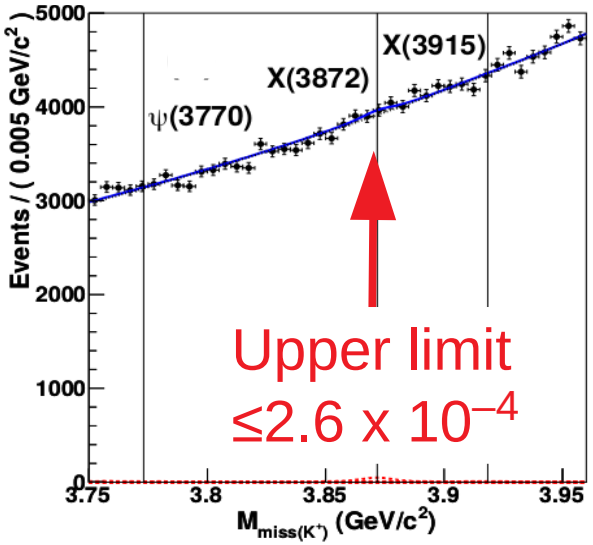
Disadvantage: reconstruction efficiency small (requires tag side)
$\varepsilon \leq 0.26\ \%$

$B^+ \to K^+ X_{c\bar{c}}$

Belle, Phys. Rev. D97 (2018) 012005

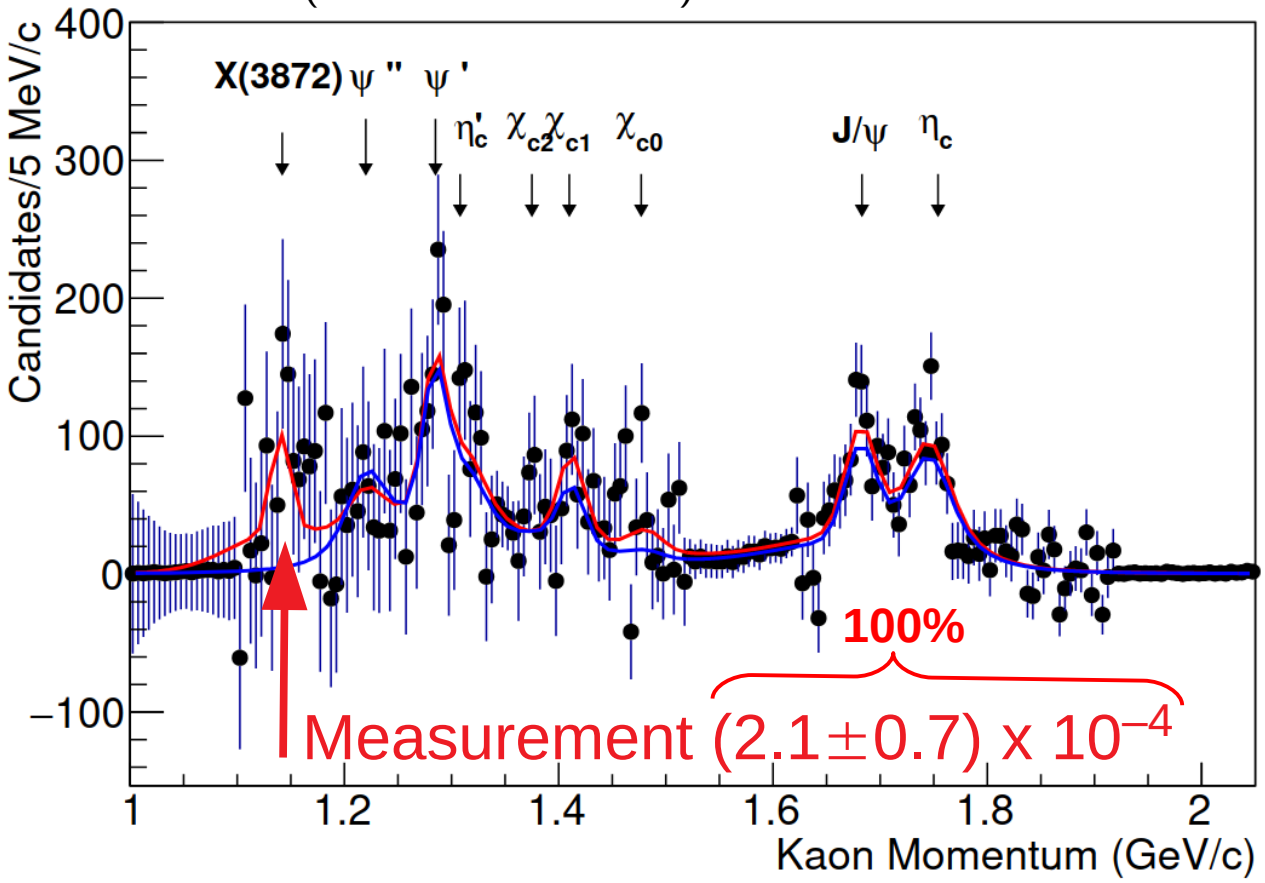
711 fb^{-1} (full Belle data set)





BaBar, Phys.Rev.Lett. 124 (2020) 152001

424 fb^{-1} (full BaBar data set)



p($K^\pm$) in the B meson rest frame

$$M_{\mathrm{miss(h)}} = \sqrt{(p^*_{\mathrm{e^+e^-}} - p^*_{\mathrm{tag}} - p^*_{\mathrm{h}})^2}/c$$

Belle II can improve error to ≤0.1 with 50 ab^{-1}

DECAYS

In the following, product branching fractions are given.

$$\underbrace{\mathcal{B}(B \to K X(3872))}_{\mathcal{B}_{absolute}} \times \mathcal{B}(X(3872) \to ...)$$

Decays to χ_{c1}

- $X(3872) \to \chi_{c1}\pi^+\pi^-$

  Belle, Phys. Rev. D 93 (2016) 052016 (711 fb^{-1})

  upper limit $\mathcal{B} \leq 1.5 \times 10^{-6}$
  (0.6% of all X(3872))

- $X(3872) \to \chi_{c1}\pi^0$

  Belle, Phys. Rev. D 99 (2019) 111101 (711 fb^{-1})

  upper limit $\mathcal{B} \leq 8.1 \times 10^{-6}$

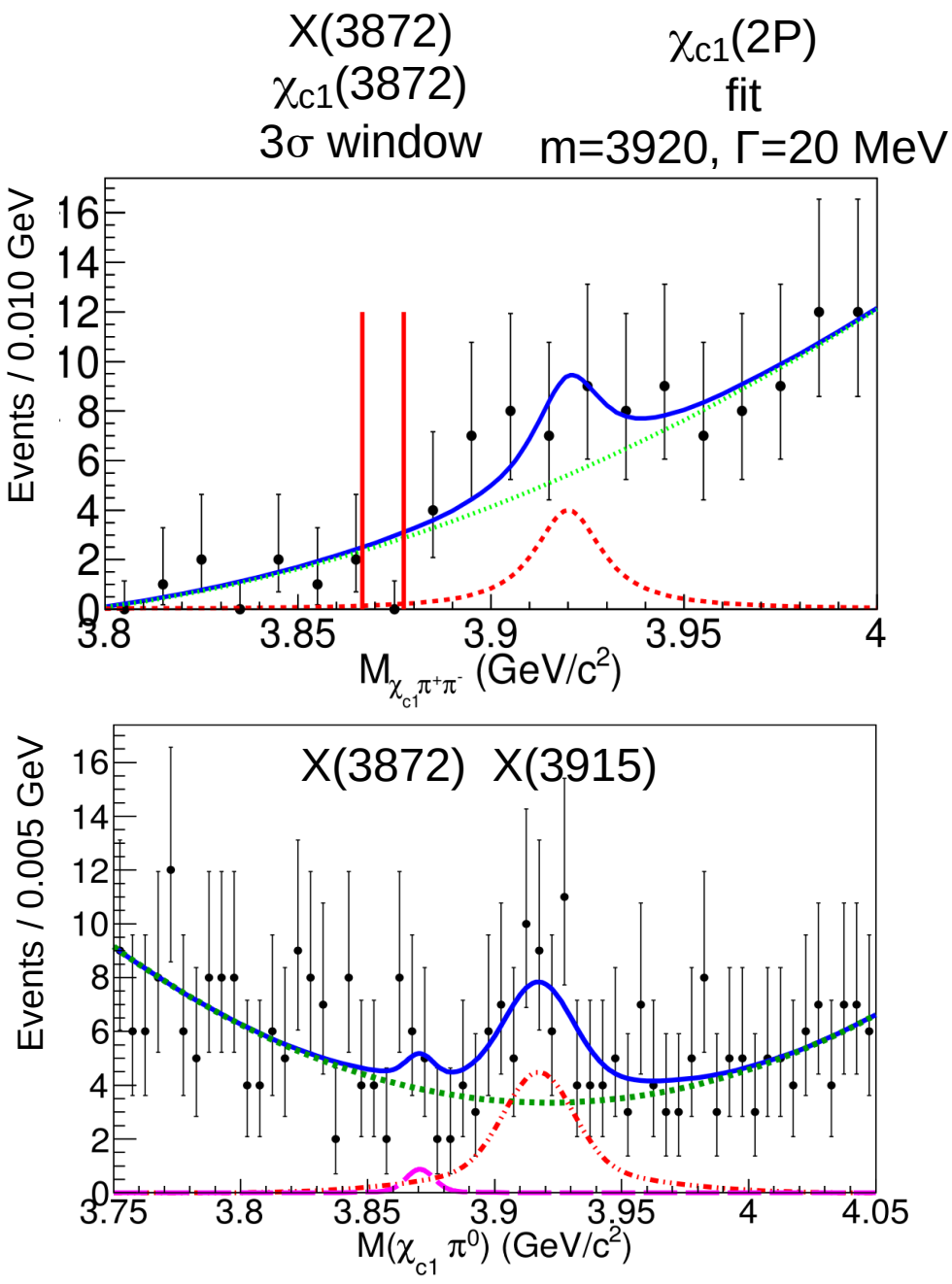
  (3.2% of all X(3872))

  observed by BESIII,

  Phys. Rev. Lett. 122 (2019) 202001

  $\mathcal{B} = 3.4 \pm 1.6$ %

  isospin violating decay
  for charmonium small branching fraction
  e.g. $\psi' \to J/\psi\pi^0$, $\mathcal{B} = (1.268 \pm 0.032) \times 10^{-3}$



Searches for partner states

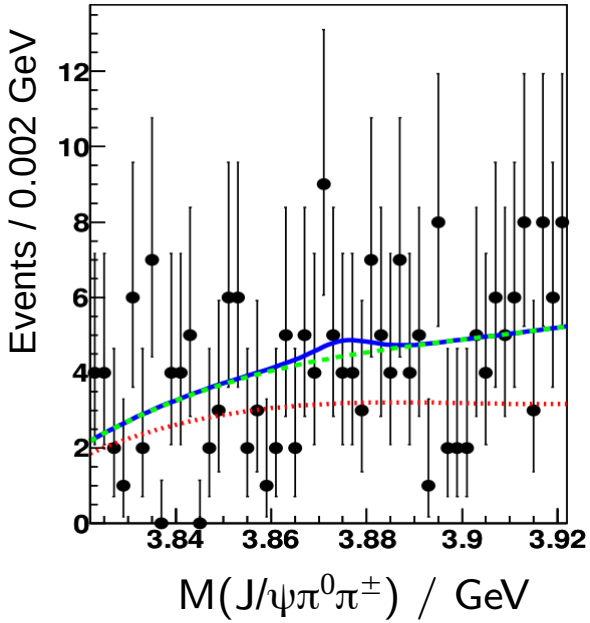
- Charged partner (I_3 partner), $X^{\pm} \to J/\psi\rho^{\pm}$

  PRD 84 (2011) 052004 (711 fb^{-1})

  upper limit $\mathcal{B} \leq 5.4 \times 10^{-6}$

  (2.4% of all X(3872), if $\mathcal{B}(X^{\pm}) = \mathcal{B}(X^0)$)

  Reminder: $Z^{\pm,0}(3900)$ cannot be the isospin partner (wrong G-parity)



- C=–1 partner*, $X^{C-odd} \to J/\psi\eta$

  PTEP 2014 (2014) 4, 043C01 (711 fb^{-1})

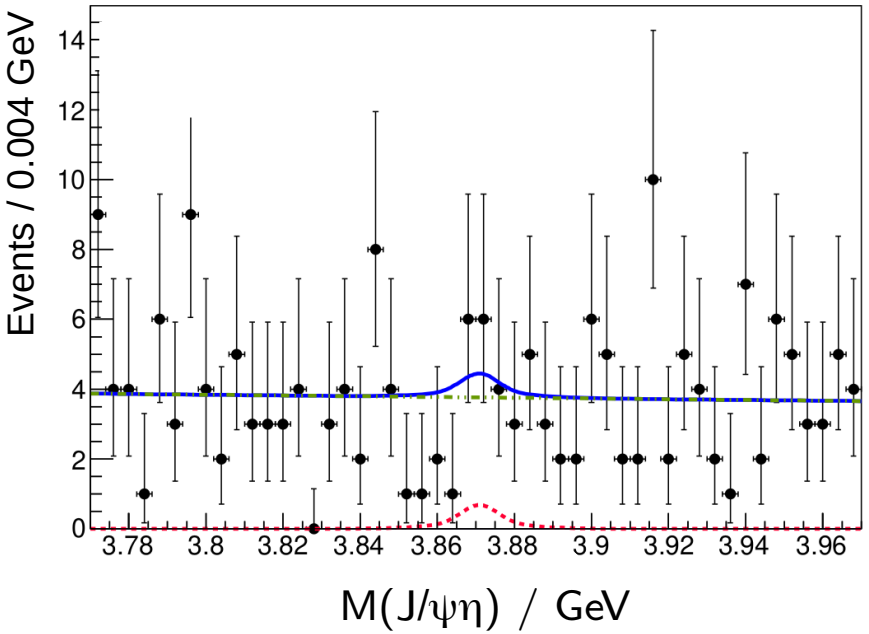
  upper limit $\mathcal{B} \leq 3.8 \times 10^{-6}$

  (1.7% all X(3872), if $\mathcal{B}(X^{\text{C-odd}}) = \mathcal{B}(X^0)$)

  *In tetraquark models

  $\frac{1}{\sqrt{2}}(S\overline{A} \pm \overline{S}A)$

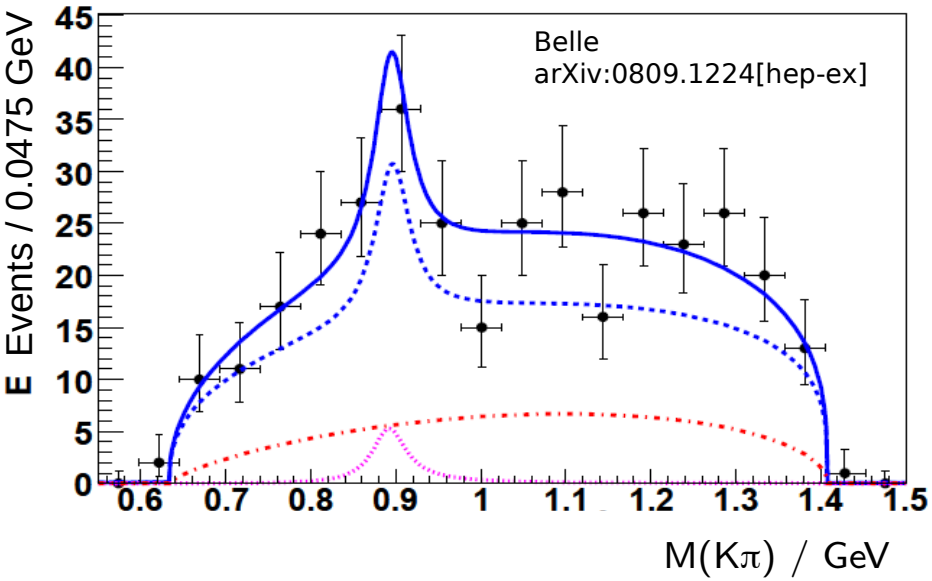
  with S scalar diquark, A axialvector diquark



PRODUCTION MECHANISM

Production mechanism $B \to K\pi X(3872)$

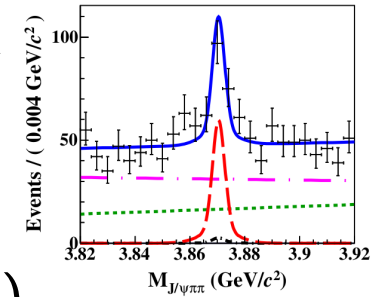
KπX(3872)



- $\mathcal{B} = 10.6 \times 10^{-6}$ for $B \to K\pi X$ same order of magnitude as $\mathcal{B} = 8.6 \times 10^{-6}$ for $B \to KX$ (although different phasespace)

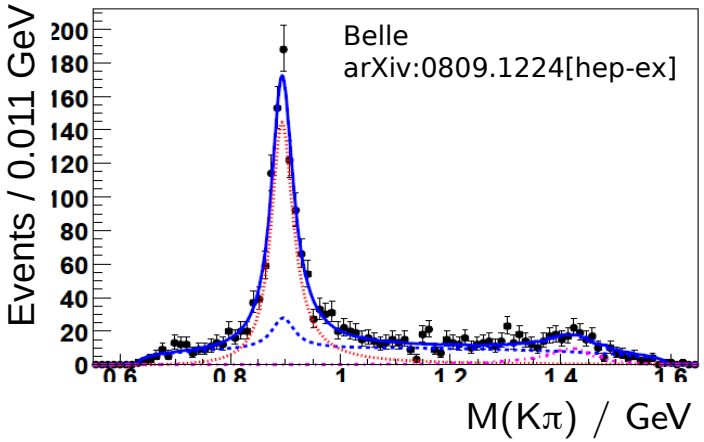
  Phys. Rev. D 84 (2011) 052004 (711 fb–1)

  1st observation for B^0, evidence for B^+

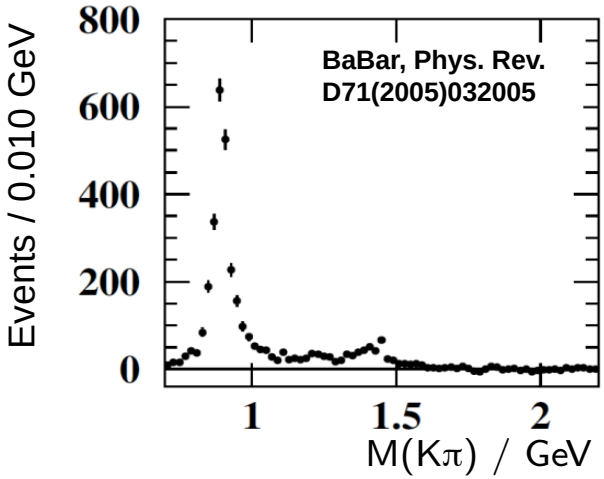


- Resonant K* component is only 34% (but 68% for $B \to K\pi\psi'$)

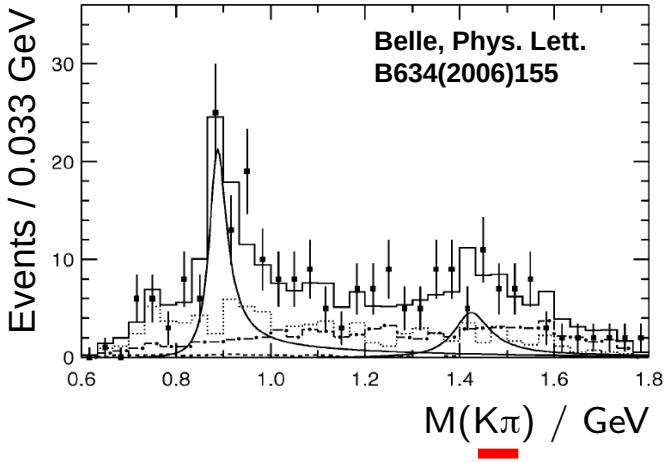
Kπψ′



KπJ/ψ

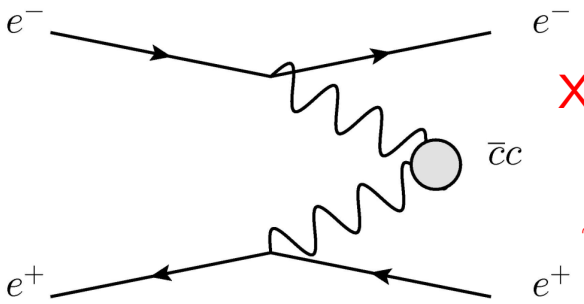


Kπχc1



B→KπX(3872) is very different from B→ Kπ[cc]

Evidence for $\gamma\gamma \to X(3872)$



X(3872) or ψ(2S)

- X(3872) has $J^{PC} = 1^{++}$
  Landau–Yang theorem:
  coupling to two real photons is forbidden

- Here: at least one photon is virtual

$$\Gamma^{X(3872)}_{\gamma\gamma} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8} \pm 0.7\ eV$$

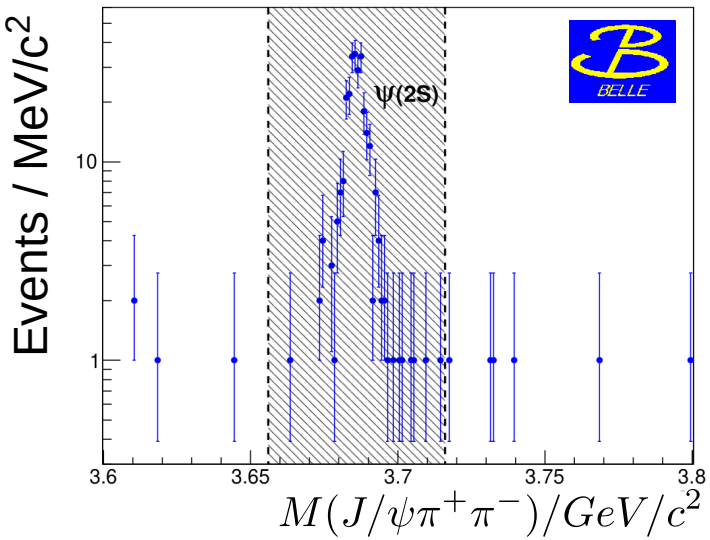
Belle, Phys. Rev. Lett. 126 (2021) 122001 (825 fb^{-1})

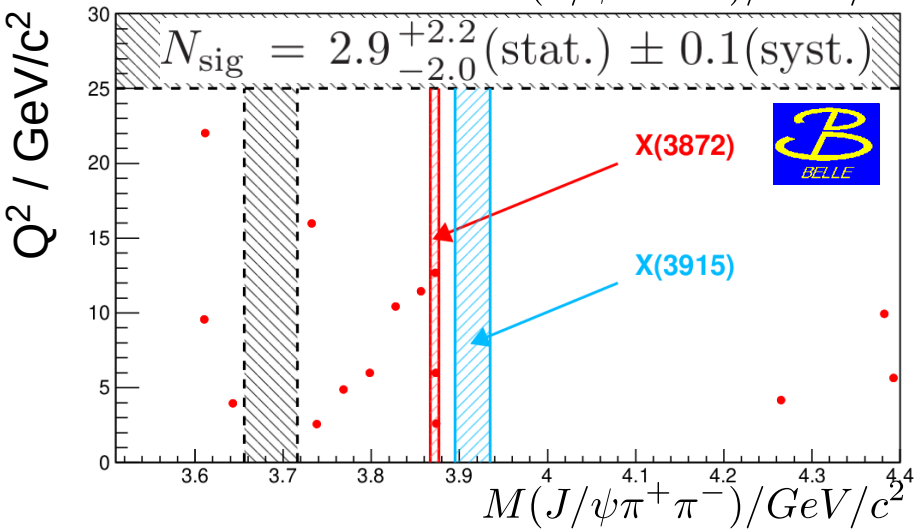
$$\underbrace{\Gamma^{X(3872)}_{ee} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}_{<0.13\ eV} \cdot \underbrace{\frac{1}{4\pi\alpha_{em}}}_{vertex} \leq 1.4\ eV$$

BESIII, Phys. Lett. B749 (2015) 414

- compatible with prediction for charmonium
  J. Kühn et al., Nucl. Phys. B 157 (1979) 125

Reference signal ($J^{PC}=1^{--}$)





Significance 3.2σ
(background
0.11 ± 0.10 events)

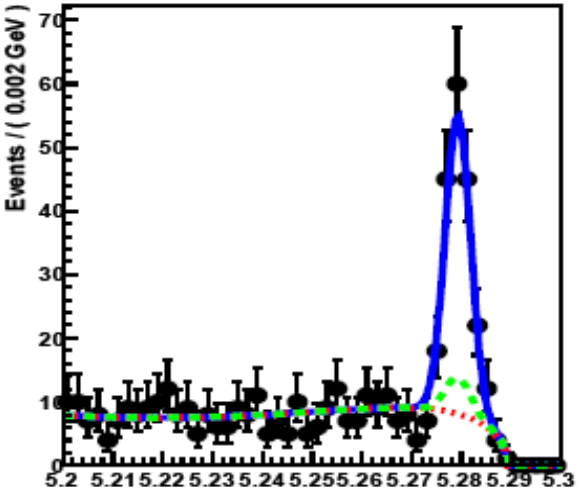
Q^2 calculated from momentum of single tagging electron

WIDTH

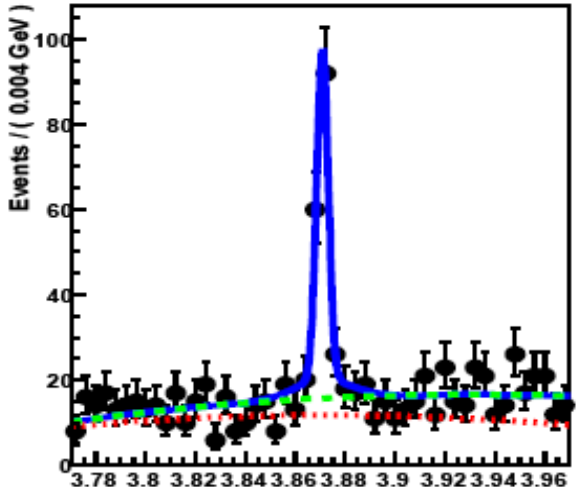
X(3872) width measurement at Belle

$$M_{\rm bc} \equiv \sqrt{(E^{\rm cms}_{\rm beam})^2 - (p^{\rm cms}_B)^2}$$

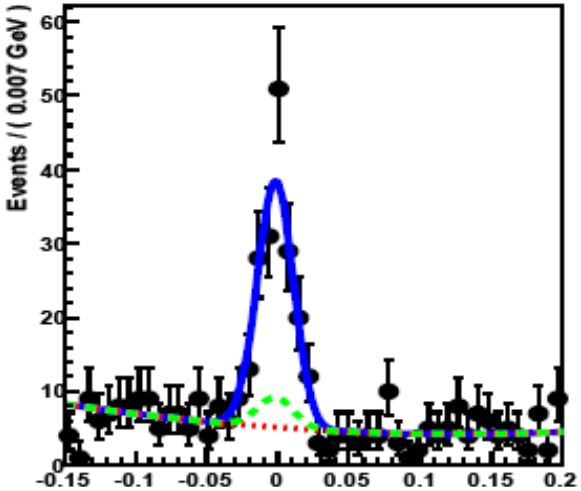
$$\Delta E \equiv E^{\rm cms}_B - E^{\rm cms}_{\rm beam}$$



M_{BC} /GeV



M(J/ψ π^+ π^-)/GeV



ΔE/GeV

- 3-dim fit for $X \to J/\psi\pi^+\pi^- \to$ kinematical over-constraint
  access to observables smaller than detector resolution

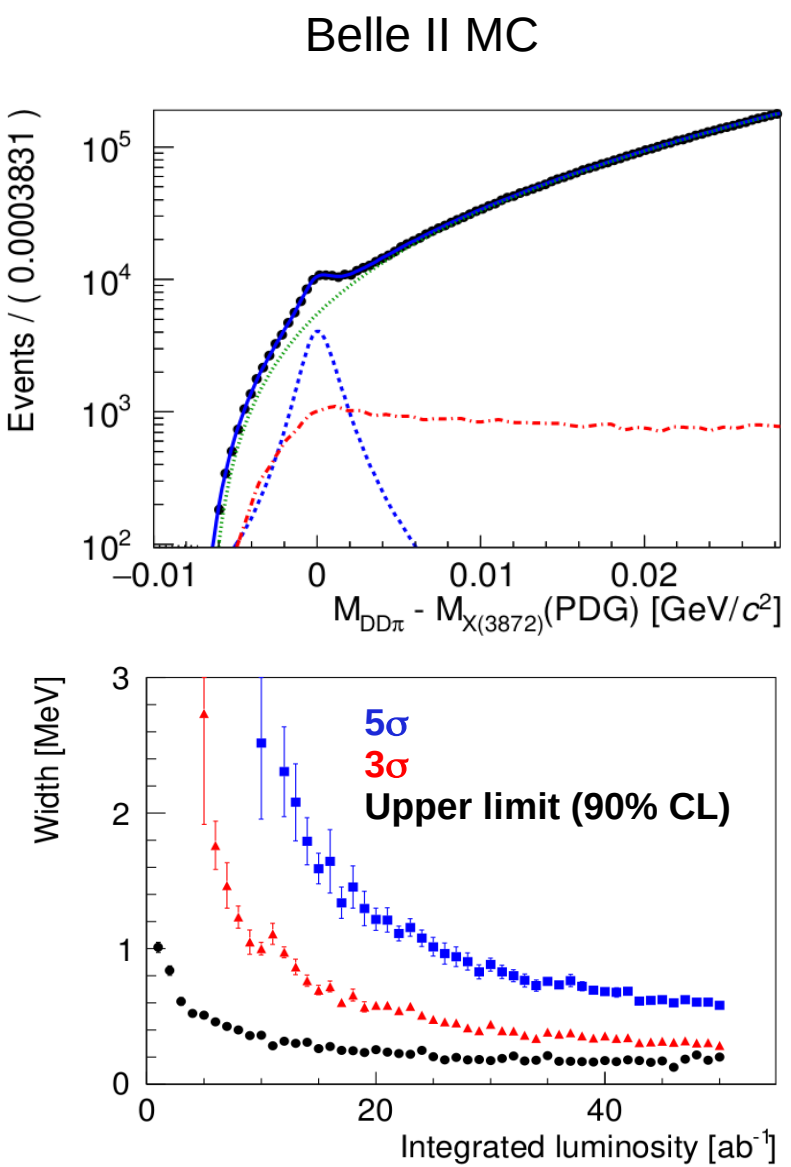
- Upper limit was determined, $\Gamma_X < 1.2\ MeV$ (90% C.L.)
  Belle, Phys. Rev. D84 (2011) 052004
  close to later world average (1.19±0.21 MeV, Breit-Wigner fit, PDG 2021)

- Fit was validated with ψ' (as control signal), factor ≃4 narrower width
  $\Gamma_{\psi'}$=0.52±0.11 MeV (0.304±0.009 MeV, PDG 2011)
  → offset bias 230 keV, systematic error 110 keV

From Belle to Belle II

Width of the X(3872) at Belle II, plan

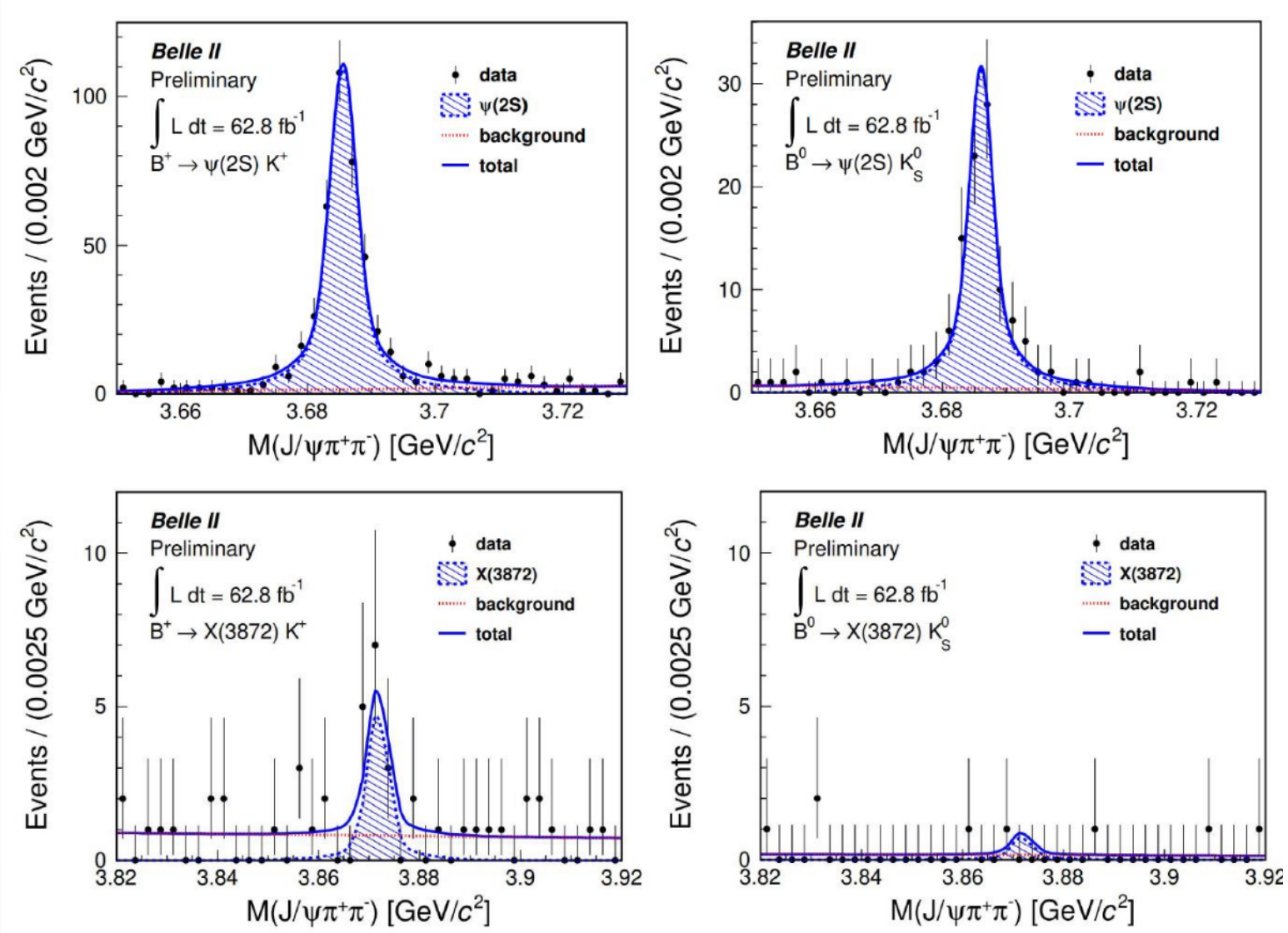
- New approach: use X(3872) $\rightarrow D^0 \overline{D}^0 \pi^0$ decay only seen at BaBar and Belle
  small Q value of 7 MeV
  (469 MeV for $J/\psi\pi\pi$)
- mass resolution 684±8 keV
  (1.93±0.04 MeV for $J/\psi\pi\pi$)
- width can be measured down to 280 keV
  (3σ significance for 50 ab^{-1})
  Reminder: Flatté fit
  $220^{+70+110}_{-60-130}$ keV (FWHM)
  LHCb, Phys. Rev. D102 (2020) 092005
- systematics still to be evaluated
- Future option: combined fit of
  $D^0 \overline{D}^0 \pi^0$ *and* $J/\psi\pi\pi$



PRODUCTION MECHANISM

$X(3872)$ at Belle II, data

BELLE2-NOTE-PL-2021-002



Efficiency
22.9%

Efficiency
17.5%

Unbinned maximum likelihood fit with triple Gaussian and 1st order Chebyshev polynomial

By now, already factor 4 more data on tape (287.9 fb^{-1}, ~1/4 of Belle)

$X(3872)$ in neutral and charged B meson decays

- If $X(3872)$ is a $D\overline{D}^*$ molecule, ratio should be small (<0.1)

  B^0, K^0 contain d quarks, B^+, K^+ contain u quarks

  D^0, $\overline{D}^{*0}$ contain u quarks

  Braaten, Lu, Phys. Rev. D77 (2008) 014029
- If $X(3872)$ is charmonium, hybrid, glueball, ratio should be large ($=1$)
- Exotic nature of *X(3872)* is already seen in present Belle II data

  but: simultaneous fit of B^0 and B^+, and ratio was fixed

$$\frac{\mathcal{B}(B^0 \to K^0_s \psi')}{\mathcal{B}(B^+ \to K^+ \psi')} = \frac{(5.8 \pm 0.5) \times 10^{-4}}{(6.24 \pm 0.20) \times 10^{-4}} \simeq 0.93$$

PDG 2021

$$\frac{\mathcal{B}(B^0 \to K^0_s X(3872))}{\mathcal{B}(B^+ \to K^+ X(3872))} = \frac{(1.1 \pm 0.4) \times 10^{-4}}{(2.1 \pm 0.7) \times 10^{-4}} \simeq 0.52$$

X(4014)

X(4014) at Belle II, plan

- $D^{*0}\overline{D}^{*0}$ molecule, predicted by Törnqvist, Phys. Rev. Lett. 67 (1991) 556
- $J^{PC} = 2^{++}$

  pure (charmonium, tetraquark) or mixture (molecule)
- Mass prediction 4012 MeV (threshold 4017 MeV)

  heavy quark spin symmetry to X(3872)

  Guo, Hidalgo-Duque, Nieves, Valderrama,
  Phys. Rev. D88 (2013) 054007
- D-wave decay to $D^0\ \overline{D}^0$ possible, implies $\Gamma \simeq 10$ MeV

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

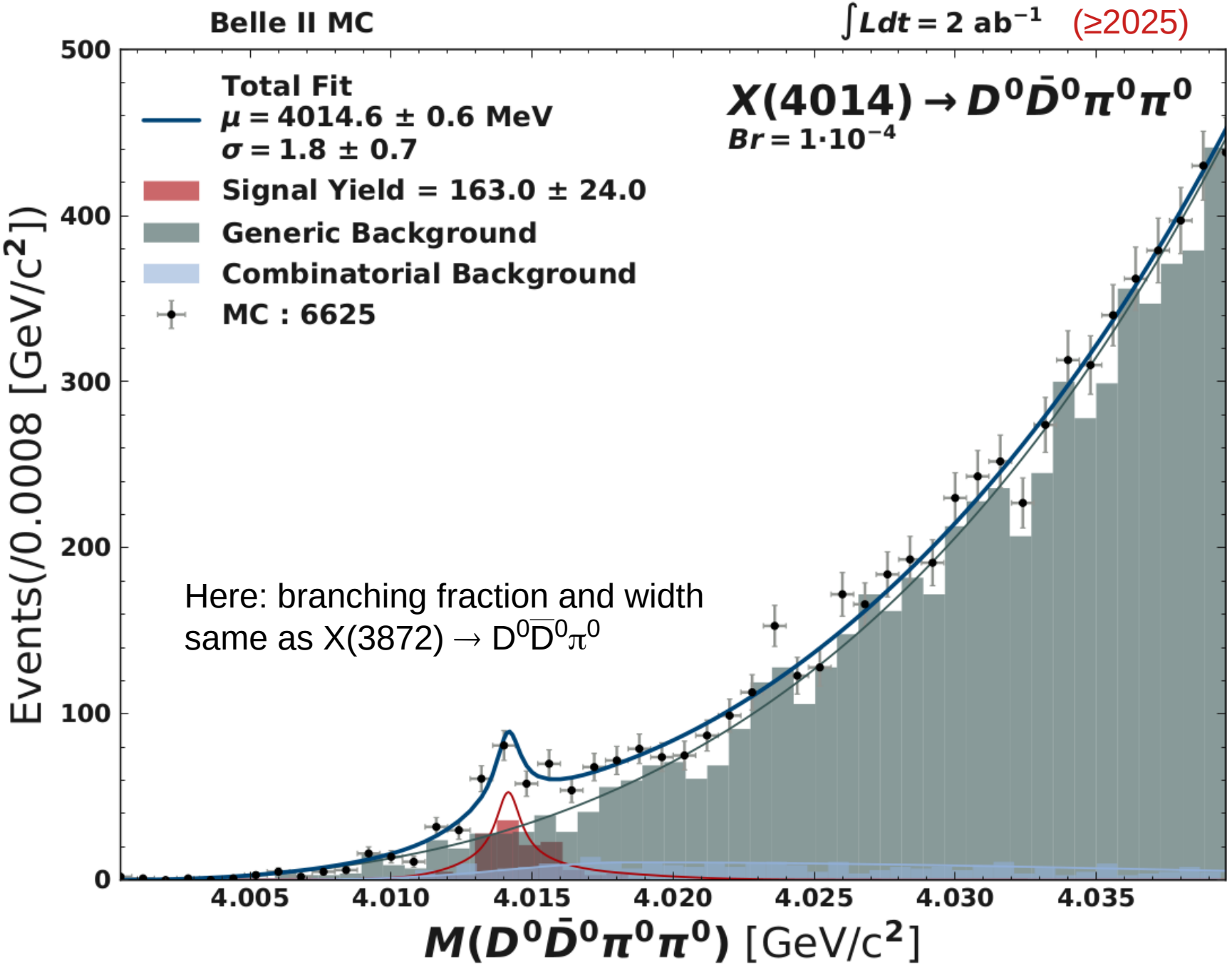
$$\left.\begin{array}{l} \longrightarrow K^-\pi^+ \\ \longrightarrow K^-\pi^+\pi^0 \\ \longrightarrow K^-\pi^+\pi^+\pi^- \\ \longrightarrow K^-K^+ \\ \longrightarrow K^0_S\pi^+\pi^- \end{array}\right\}$$

efficiency small

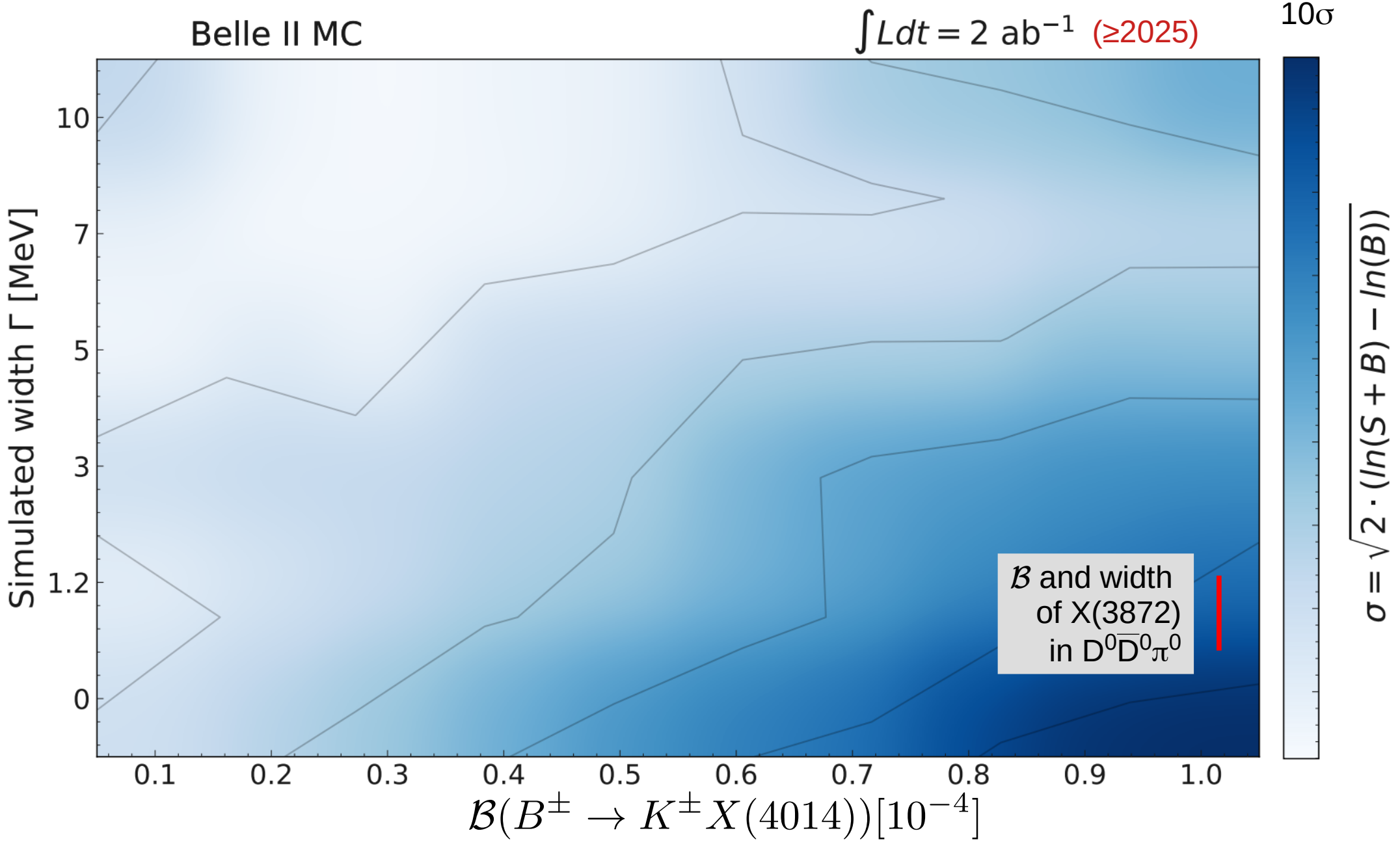
$\simeq$1.0 % for Belle

$\simeq$1.5 % for Belle II

($\simeq$15% for X$\to$J/$\psi\pi\pi$)


Belle II MC
$\int Ldt = 2\ ab^{-1}$ (≥2025)
$X(4014) \to D^0\bar{D}^0\pi^0\pi^0$
$Br = 1{\cdot}10^{-4}$
Total Fit
$\mu = 4014.6 \pm 0.6$ MeV
$\sigma = 1.8 \pm 0.7$
Signal Yield = 163.0 ± 24.0
Generic Background
Combinatorial Background
MC : 6625
Here: branching fraction and width same as X(3872) → $D^0\bar{D}^0\pi^0$
Events(/0.0008 [GeV/c^2])
$M(D^0\bar{D}^0\pi^0\pi^0)$ [GeV/c^2]
0
100
200
300
400
500
4.005
4.010
4.015
4.020
4.025
4.030
4.035

X(4014) discovery map



Conclusion

- Absolute branching fraction was measured
- Width measurements can reach sub-MeV sensitivity (3-dim fit, small Q value)
- Where are the partner states?