XYZ results from Belle experiment

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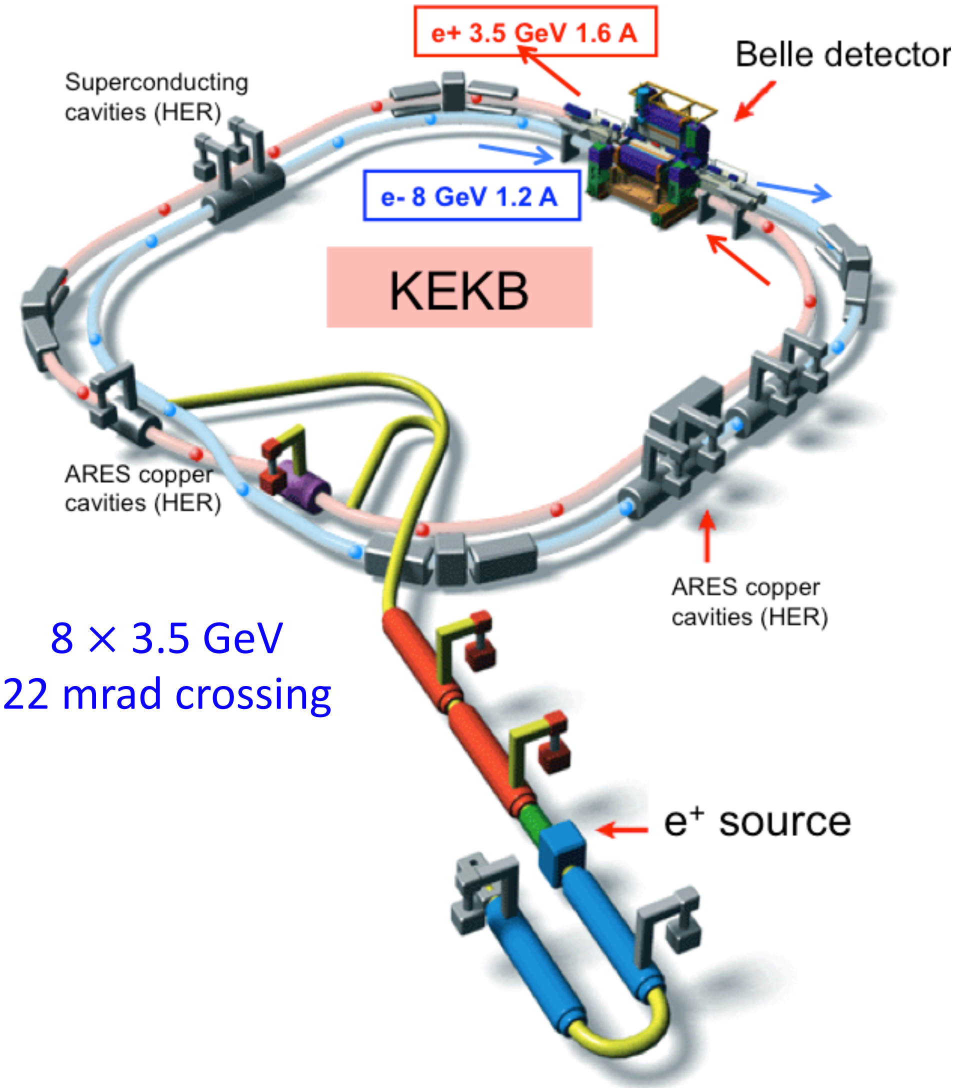
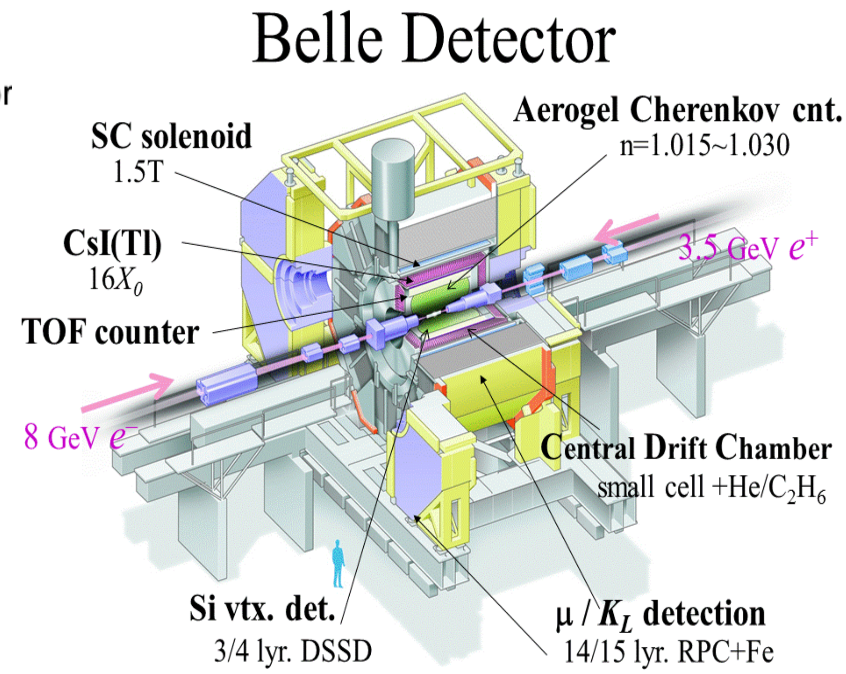
第二届强子与重味物理理论与实验联合研讨会
2021年3月25-39日
兰州大学

Belle experiment and data samples



8 × 3.5 GeV
22 mrad crossing



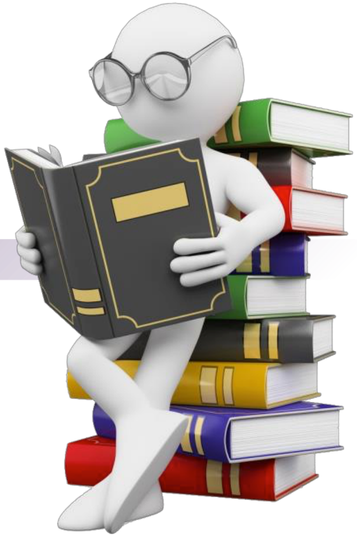
Data taking: 1999 – 2010

On/off/Scan Υ(nS) peaks

Total luminosity: 980 fb^{-1}

772M $B\bar{B}$ events @$\Upsilon(4S)$

Selected topics



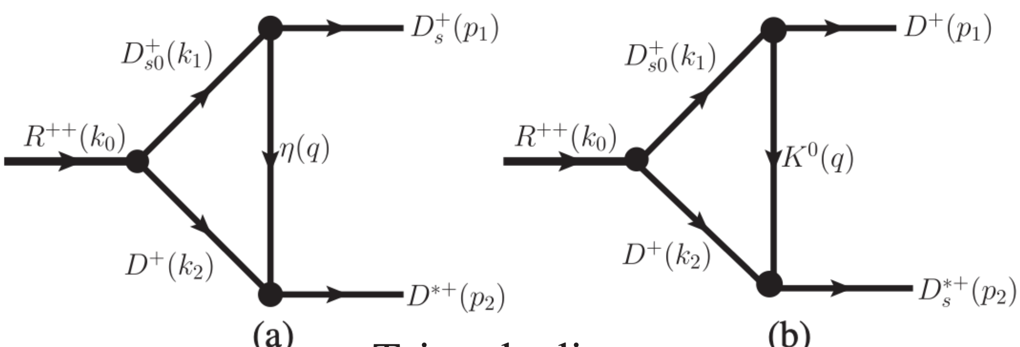
XYZ studies at Belle:

- ***Search for a doubly-charged DDK bound state R^{++}*** *[PRD 102, 112001 (2020)]*
- ***$X(3872) \to \pi^+\pi^- J/\psi$ in single-tag two-photon reactions*** *[PRL 126, 122001 (2021)]*
- ***Search for $B^0 \to X(3872)\gamma$*** *[PRD 100, 012002 (2019)]*

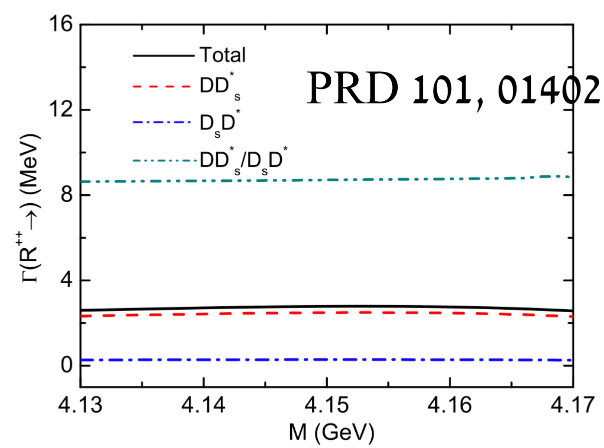
Search for $R^{++} \to D^+ D_s^{*+}$

[PRD 102, 112001 (2020)]

- The R^{++} can be interpreted as a $D^+ D_{s0}^*(2317)^+$ moleculelike state with exotic properties: doubly charged and doubly charmed in Refs. [PRD 99, 076017 (2019), PRD 100, 034029 (2019), PRD 101, 014022 (2020)].
- The alternative processes are via triangle diagrams into $R^{++} \to D^+ D_s^{*+}$ and $R^{++} \to D_s^+ D^{*+}$.
- The mass of R^{++} is predicted to be in the range of 4.13 to 4.17 GeV/c^2; the width is (2.30—2.49) MeV.



Triangle diagrams



PRD 101, 014022 (2020)]

- A state decaying to $D^+D_s^{*+}$ is also a good candidate for a doubly-charged tetraquark according to Ref. [PRL 119, 202002 (2017)].

State	J^P	$m(Q_iQ_jq_kq_l)$	Decay Channel	Q [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	3978	D^+D^{*0} (3876)	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	4156	$D^+D_s^{*+}$ (3977)	179
$\{cc\}[\bar{q}_k\bar{q}_l]$	$0^+,1^+,2^+$	4146,4167,4210	D^+D^0, D^+D^{*0}(3734,3876)	412,292,476
$[bc][\bar{u}\bar{d}]$	0^+	7229	B^-D^+/B^0D^0 (7146)	83
$[bc][\bar{q}_k\bar{s}]$	0^+	7406	B_SD (7236)	170
$[bc][\bar{q}_k\bar{q}_l]$	1^+	7439	B^*D/BD^* (7190/7290)	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	7272	B^*D/BD^* (7190/7290)	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	7445	DB_S^* (7282)	163
$\{bc\}[\bar{q}_k\bar{q}_l]$	$0^+,1^+,2^+$	7461,7472,7493	BD/B^*D (7146/7190)	317,282,349

Selections and datasets

$\boldsymbol{R^{++} \to D^+ D_s^{*+}}$

- $D^+ \to K^-\pi^+\pi^- / K_S^0(\to \pi^+\pi^-)\pi^+$
- $D_s^{*-} \to D_s^- \gamma$
- $D_s^- \to \phi\pi^- / \bar{K}^{*0} K^+$

- $\Upsilon(1S, 2S) \to \boldsymbol{R^{++}}$+anything
- $e^+e^- \to \boldsymbol{R^{++}}$+anything at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV; ISR correction is considered assuming a 1/s dependence.

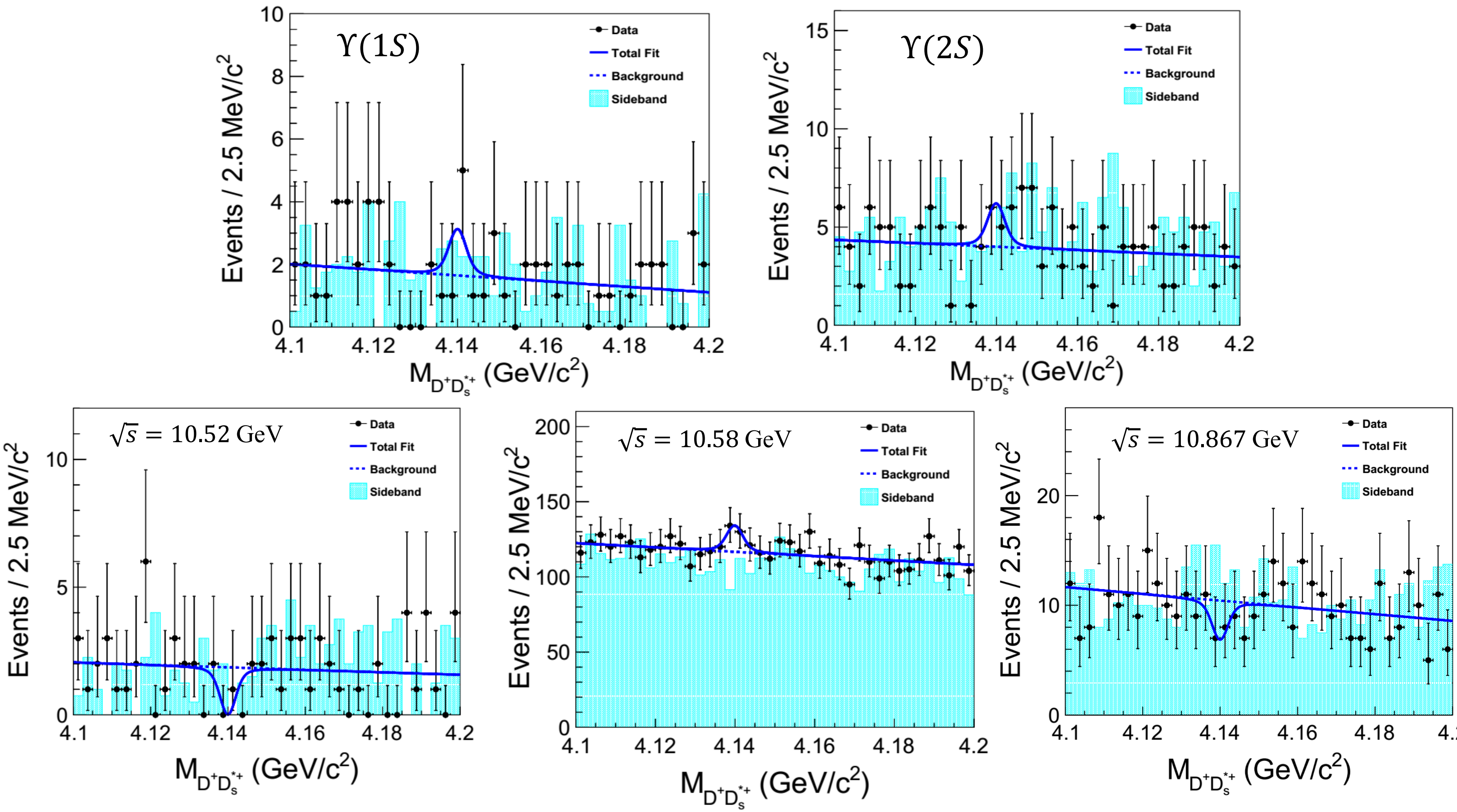
Selections have been optimized by maximizing the Punzi parameter $S/(\frac{3}{2} + \sqrt{B})$.

Data samples:

$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})	Events
9.46 [$\Upsilon(1S)$]	5.74±0.09	(102±3) million
10.023 [$\Upsilon(2S)$]	24.91±0.35	(158±4) million
10.52	89.5±1.3	-
10.58 [$\Upsilon(4S)$]	711±10	-
10.867 [$\Upsilon(5S)$]	121.4±1.7	-

Total luminosity: 952 fb^{-1}

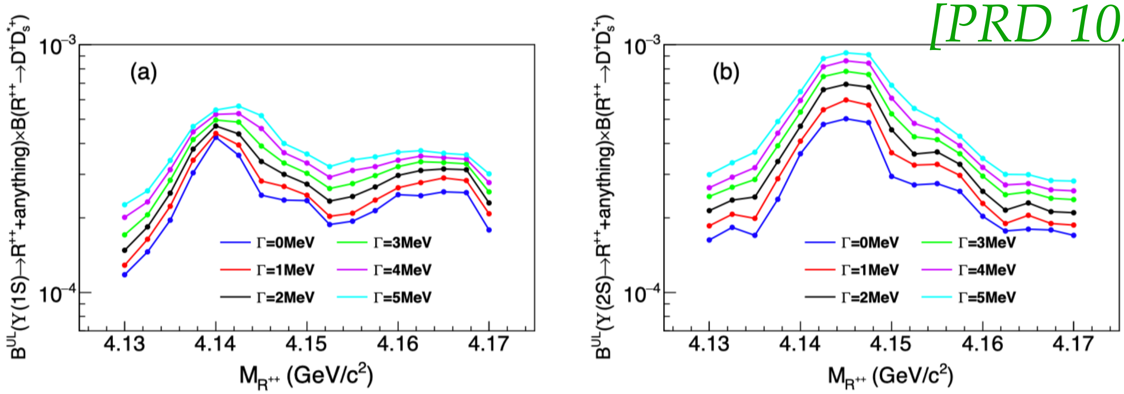
$M(D^+ D_s^{*+})$ distributions

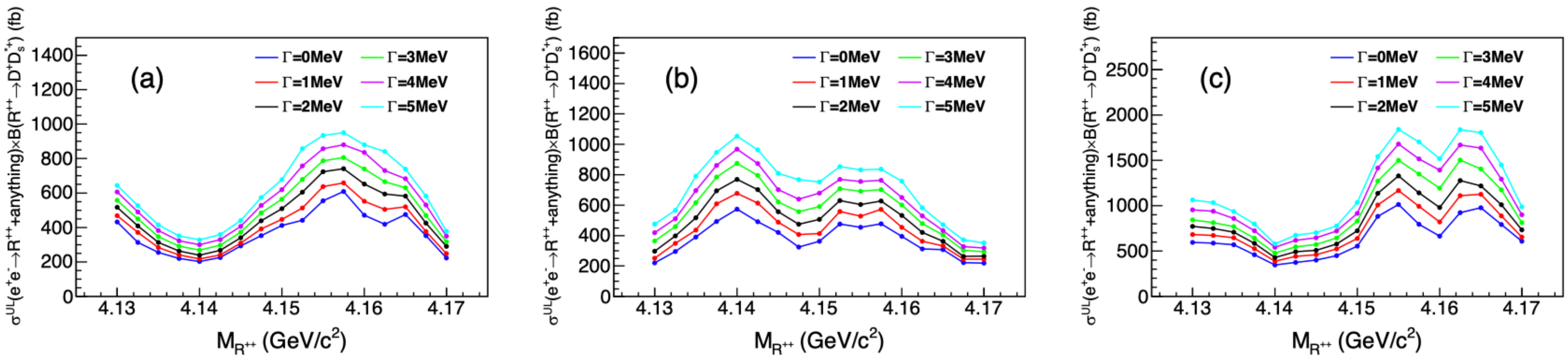


- The cyan shaded histograms are from normalized M(D^+) and M(D_s^{*+}) sideband events.
- The fitted results with the R^{++} mass fixed at 4.14 GeV/c^2 and width fixed at 2 MeV.
- No R^{++} signals are observed.

90% C.L. upper limits

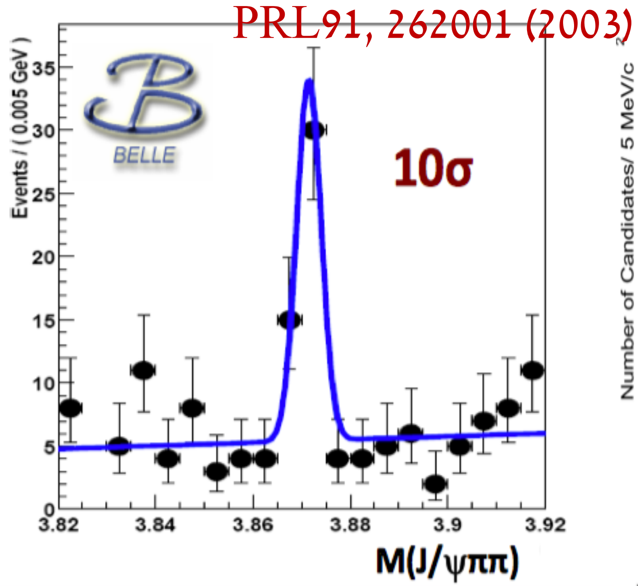
[PRD 102, 112001 (2020)]

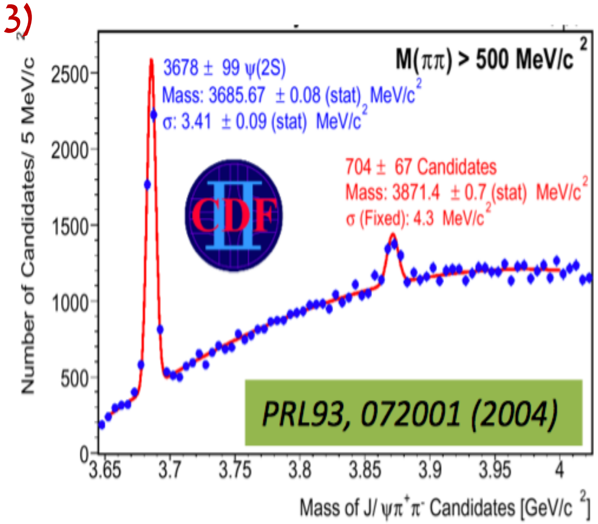


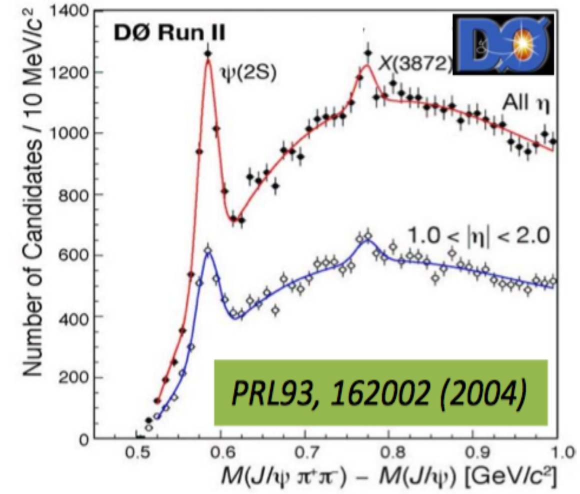


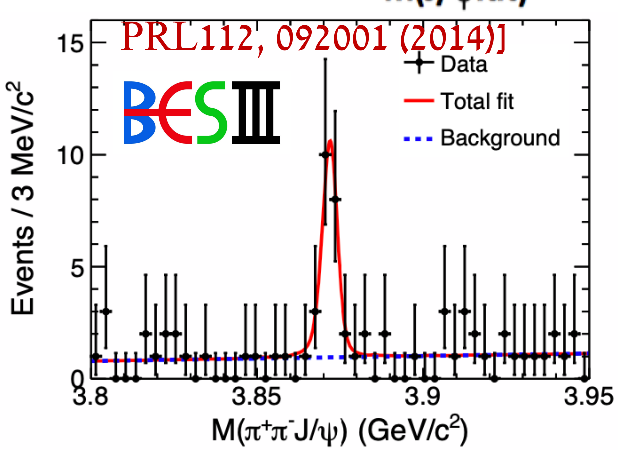
90% C. L. Upper limits [M(R^{++}) varying from 4.13 to 4.17 GeV/c^2, Γ(R^{++}) varying from 0 to 5 MeV]
$\mathcal{B}(\Upsilon(1S)\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) <$ (1.18 – 5.65)×10^{-4}
$\mathcal{B}(\Upsilon(2S)\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) <$ (1.63 - 9.27)×10^{-4}
$\sigma(e^+e^-\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) <$ (202.8 – 950.6) fb at $\sqrt{s}$ = 10.52 GeV
$\sigma(e^+e^-\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) <$ (218.9 – 1054.0) fb at $\sqrt{s}$ = 10.58 GeV
$\sigma(e^+e^-\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) <$ (346.6 – 1841.7) fb at $\sqrt{s}$ = 10.867 GeV

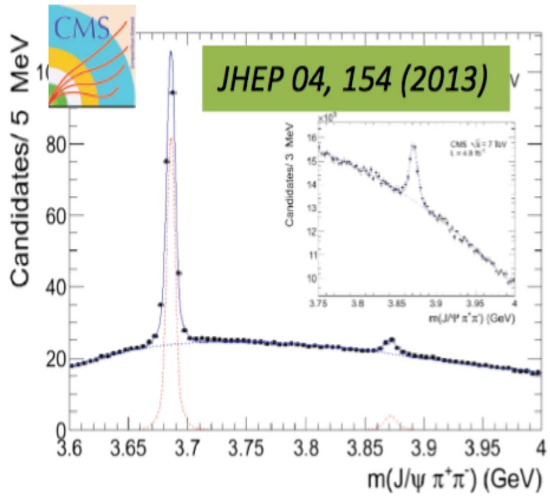
X(3872) productions

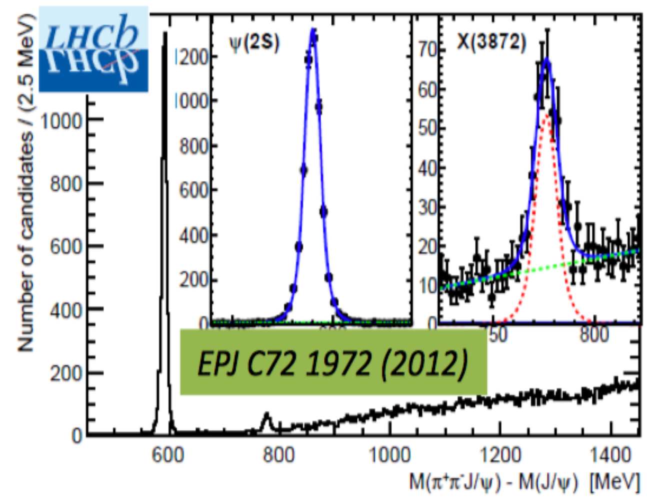












Various production ways:

$B \to X(3872)K, \Lambda_b^0 \to X(3872)pK^-$; e^+e^- radiative decay; pp and $p\bar{p}$ collisions

Evidence for X(3872)→ $\pi^+\pi^-J/\psi$ produced in single-tag two-photon interactions

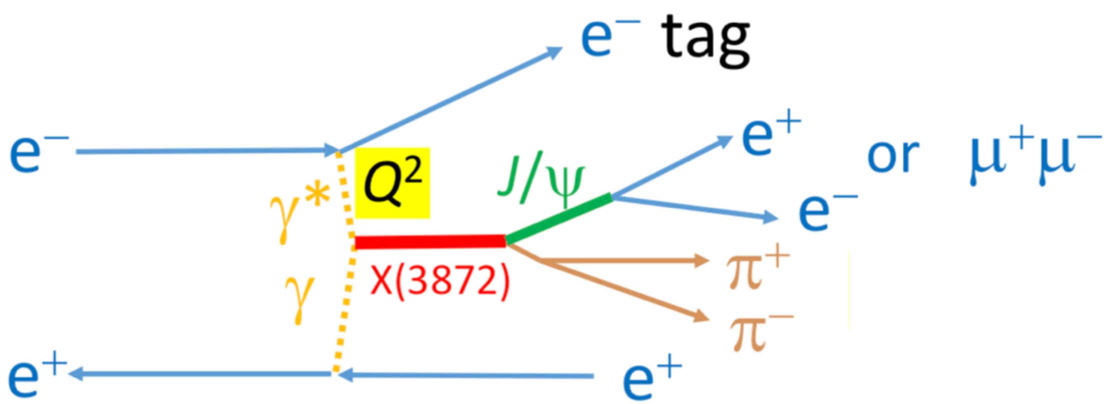
[PRL 126, 122001 (2021)]

- One of the final-state electrons, referred to as a tagging electron, is observed, and the other scatters at an extremely forward (backward) angle and is not detected [Nucl. Phys. B 523, 423 (1998)]. Such events are called single-tag events.
- The measurement of X(3872) in two-photon reactions help to understand its internal structure.

X(3872): $J^{PC} = 1^{++}$

$\gamma\gamma \rightarrow X(3872)$ ➡ Not allowed

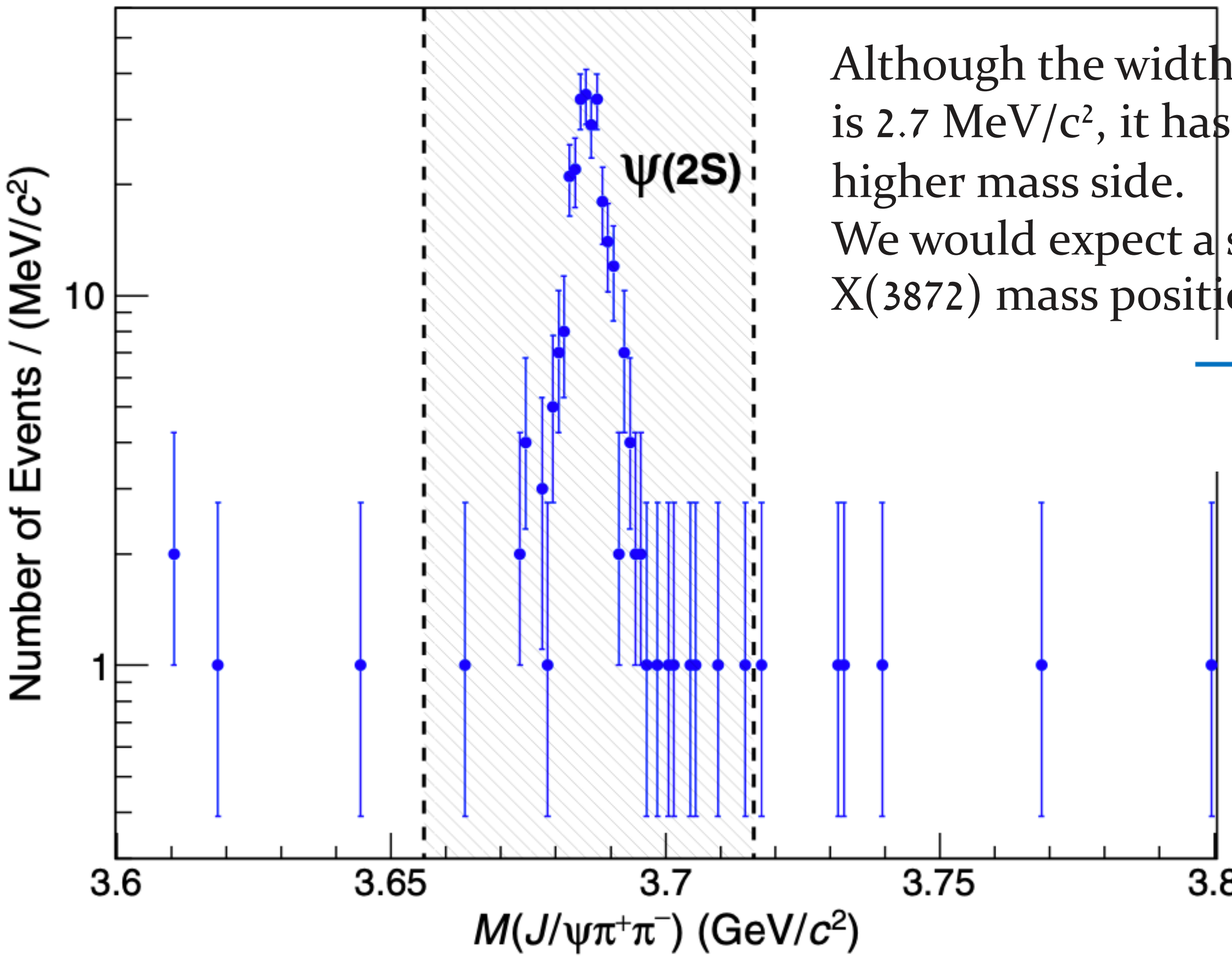
But, $\gamma^*\gamma \rightarrow X(3872)$ ➡ Allowed



Data sample:
825 fb^{-1} in e^+e^- collisions near 10.6 GeV

$-Q^2$ is the invariant mass-squared of the virtual photon.

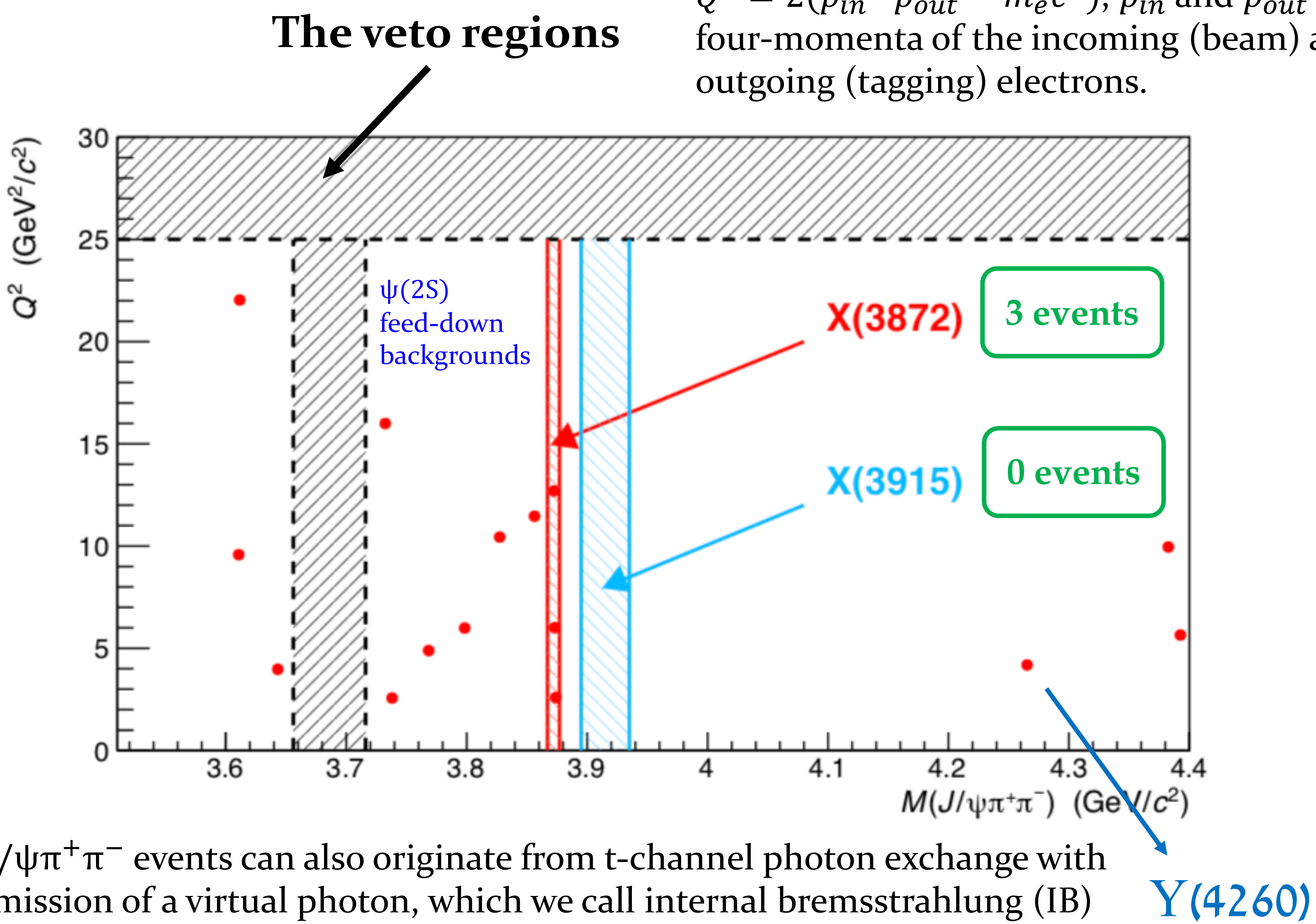
Background: $e^+e^- \to e^+e^-\psi(2S)$



Although the width of the ψ(2S) peak is 2.7 MeV/c², it has a tail on the higher mass side.
We would expect a step around X(3872) mass position.

The whole spectrum of M($J/\psi\pi^+\pi^-$)

$Q^2 = 2(p_{in} \cdot p_{out} - m_e^2 c^2)$, p_{in} and p_{out} are the four-momenta of the incoming (beam) and outgoing (tagging) electrons.



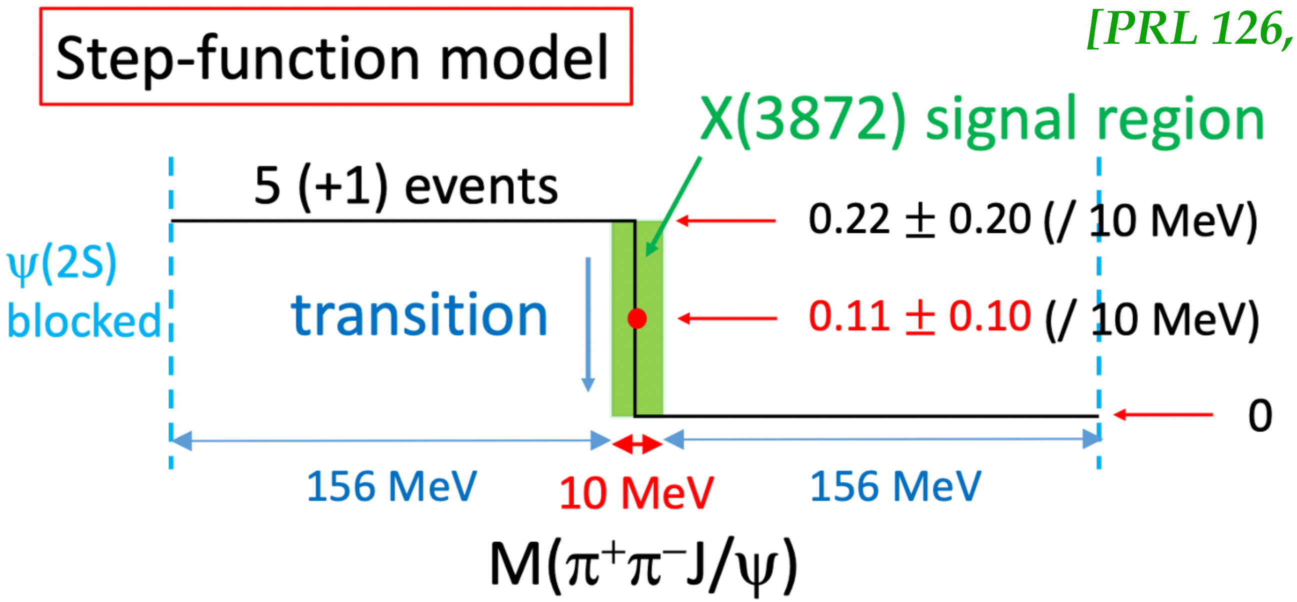
The $J/\psi\pi^+\pi^-$ events can also originate from t-channel photon exchange with the emission of a virtual photon, which we call internal bremsstrahlung (IB) [PRD 81, 117501 (2010)]. Both processes produce C-odd $J/\psi\pi^+\pi^-$, like ψ(2S), Y(4260), ...

Background Estimation:

We fit a linear function

$$\max(0, a[M(J/\psi\pi^+\pi^-) - 3.872\ \text{GeV}/c^2] + b)$$

[PRL 126, 122001 (2021)]

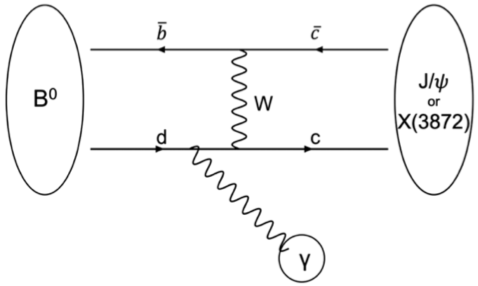


- M(X(3872)) = (3.8723±0.0012) GeV/c^2
- With 0.11±0.10 background events, the number of signal events is $N_{sig} = 2.9^{+2.2}_{-2.0}(\text{stat.}) \pm 0.1(\text{syst.})$ with a significance of 3.2σ (Feldman-Cousins method applied [Phys. Rev. D 57, 3873 (1998)]).
- With $0.032 < \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 0.061$ at 90% C.L., $\tilde{\Gamma}_{\gamma\gamma}$ = 20 – 500 eV. This is consistent with values predicted for $c\bar{c}$ model [NPB 523, 423 (1998), PRD 83, 114015 (2011)].

Search for $B^0 \to X(3872)\gamma$

[PRD 100, 012002 (2019)]

- In the SM, the decay $B^0 \to c\bar{c}\gamma$ proceeds dominantly through an exchange of a W boson and the radiation of a photon from the *d* quark of the B meson.
- Currently, the upper limit for $B^0 \to J/\psi\gamma$ is 1.5×10^{-6} at 90% confidence level.
- Considering X(3872) may be not a pure $c\bar{c}$ state the branching fraction of $B^0 \to J/\psi\gamma$ is larger?



To suppress generic BB spherical events and the jetlike $q\bar{q}$ continuum events, we do

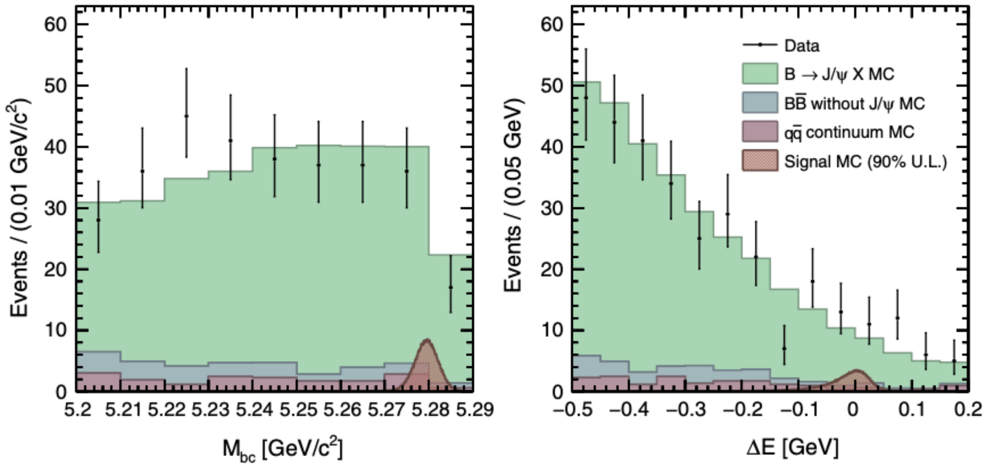
(1) multivariate analysis based on the neural network package named NEUROBAYES [Nucl. Instrum. Methods Phys. Res., Sect. A 559, 190 (2006)] to distinguish the signal and background with 33 input variables;

(2) optimize a figure of merit (FOM).

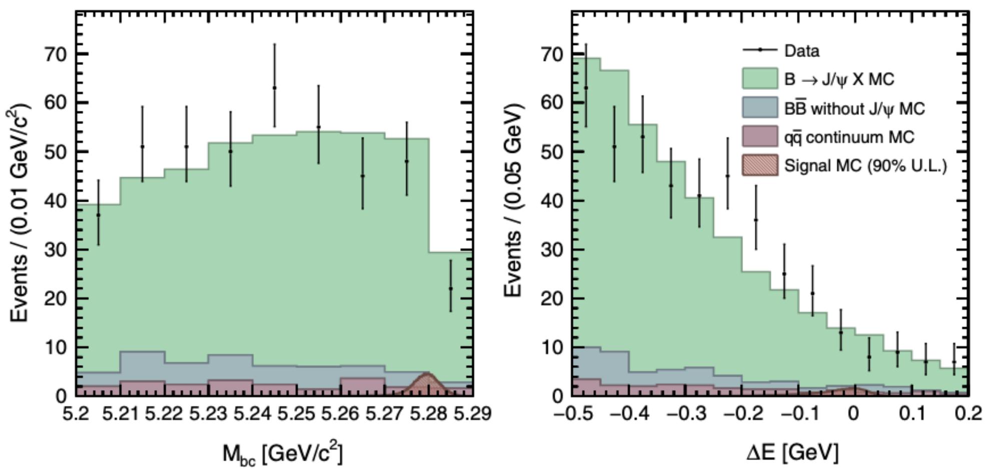
$$\mathrm{FOM} = \frac{\text{efficiency}}{0.5n + \sqrt{N_{\mathrm{bkg}}}}$$

Total luminosity:
711 fb^{-1}; 772×10^6 $B\bar{B}$ pairs

X(3872) decays to $J/\psi\pi^+\pi^-$ entirely via $J/\psi\rho$.



(a) Dimuon channel.



(b) Dielectron channel.

[PRD 100, 012002 (2019)]

$$\Delta E = E^*_{\rm recon} - E^*_{\rm beam}$$

$$M_{\rm bc} = \sqrt{E^2_{\rm beam} - (\sum_i p_i)^2}$$

We count the numbers of signal and backgrounds in regions of $M_{bc} >$ 5.27 GeV/c^2 and -0.15 < ΔE < 0.1 GeV.

The upper limit on $\mathcal{B}(B^0 \to X(3872)\gamma) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ is obtained with the Feldman-Cousins counting method [PRD 57, 3873 (1998)].

Channel	Dimuon	Dielectron	Total
N_{sig}	9	9	18
N_{bkg}	9.3	12.1	21.4
90% U.L.	9.2×10^{-7}	6.8×10^{-7}	5.1×10^{-7}

Measurements of branching fractions and asymmetry parameters of $\Xi_c^0 \to \Lambda \bar{K}^{*0}$, $\Xi_c^0 \to \Sigma^0 \bar{K}^{*0}$, and $\Xi_c^0 \to \Sigma^+ K^{*-}$

Motivation (I)

■ **Several resent experimental efforts from Belle and LHCb to study the properties of Ξ_c^0.**

- LHCb obtained the antitriplet charmed baryon lifetimes, where the decay lifetime of Ξ_c^0 is 3σ above the averaged value in PDG 2018.

$$(\tau_{\Lambda_c^+}, \tau_{\Xi_c^+}, \tau_{\Xi_c^0}) = (203.5 \pm 2.2, 456.8 \pm 5.5, 154.5 \pm 2.5)\ \text{fs}.$$

PRD 100, 032001 (2019)

- Belle obtained the absolute branching ratios in Ξ_c from the decay chains of B mesons, which can help to determine branching ratios of other relative channels.

$$\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.80 \pm 0.52)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (2.86 \pm 1.27)\%,$$

PRL 122, 082001 (2019)

- Belle measured resonant and non-resonant branching ratios in $\Xi_c^0 \to \Xi^0 K^+ K^-$.

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0 \phi(\to K^+K^-))}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = 0.036 \pm 0.004\ (\text{stat.}) \pm 0.002\ (\text{syst.})$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0 K^+K^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = 0.039 \pm 0.004\ (\text{stat.}) \pm 0.002\ (\text{syst.})$$

arXiv: 2012.05607 (2020)

- The first branching fraction of the decay of the Ξ_c^0 to a charmed baryon has been measured by LHCb to be Br($\Xi_c^0 \to \Lambda_c^+\pi^-$) = (1.135$\pm$0.002$\pm$0.387)%. PRD 102, 071101 (R) (2020)

- Measurements of Br($\Xi_c^0 \to \Xi^- l^+ \upsilon_l$) and asymmetry parameter of $\Xi_c^0 \to \Xi^-\pi^+$ from Belle. See Y. B. Li's slides in details.

arXiv: 2103.06496 (2021)

Motivation (II)

- There are some difficulties for the theoretical study in the non-leptonic decays of charmed baryons due to the failure of the factorization approach.
- Branching fraction measurements help to distinguish different theoretical models.
- The asymmetry parameters of Ξ_c^0 are still not well measured, which is important to test parity violation in charmed-baryon sectors.

Decay branching fractions (%) and asymmetry parameters of the Cabibbo favored $B_c \to B_n + V$ decays in QCD and $SU(3)_F$ approach.

Branching fractions	KK [1]	Zen [2]	HYZ [3]	GLT [4]
$\Xi_c^0 \to \Lambda^0 \overline{K}^{*0}$	1.55	1.15	0.46±0.21	1.37±0.26
$\Xi_c^0 \to \Sigma^0 \overline{K}^{*0}$	0.85	0.77	0.27±0.22	0.42±0.23
$\Xi_c^0 \to \Sigma^+ K^{*-}$	0.54	0.37	0.93±0.29	0.24±0.17

Asymmetry parameters	KK [1]	Zen [2]	GLT [4]
$\Xi_c^0 \to \Lambda^0 \overline{K}^{*0}$	0.58	+0.49	-0.67±0.24
$\Xi_c^0 \to \Sigma^0 \overline{K}^{*0}$	-0.87	+0.25	-0.42±0.62
$\Xi_c^0 \to \Sigma^+ K^{*-}$	-0.60	+0.51	$-0.76^{+0.64}_{-0.24}$

[1] Z. Phys. C 55, 659 (1992) [2] Phys. Rev. D 50, 5787 (1994) [3] Phys. Lett. B 792, 35 (2019)
[4] Phys. Rev. D 101, 053002 (2020)

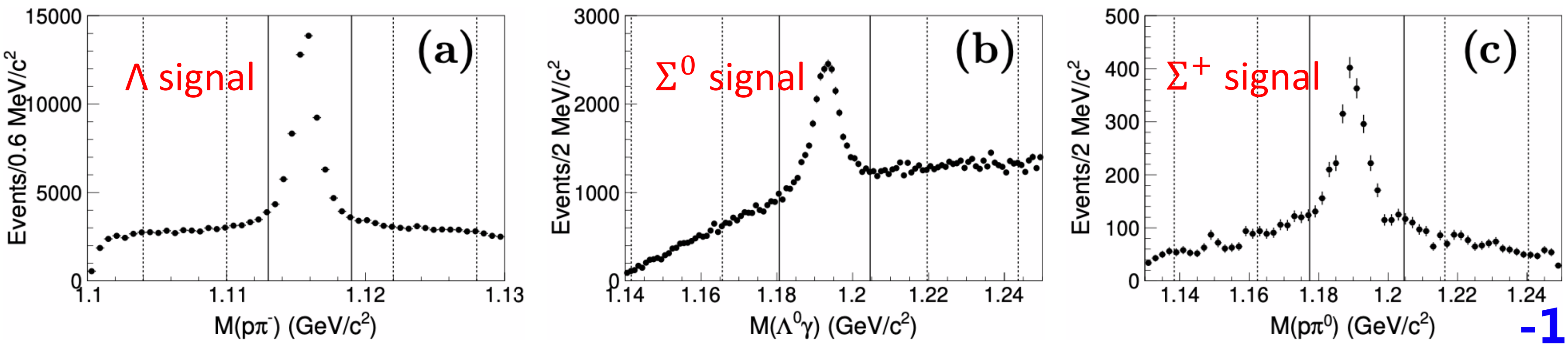
Selections and Datasets

Selections:

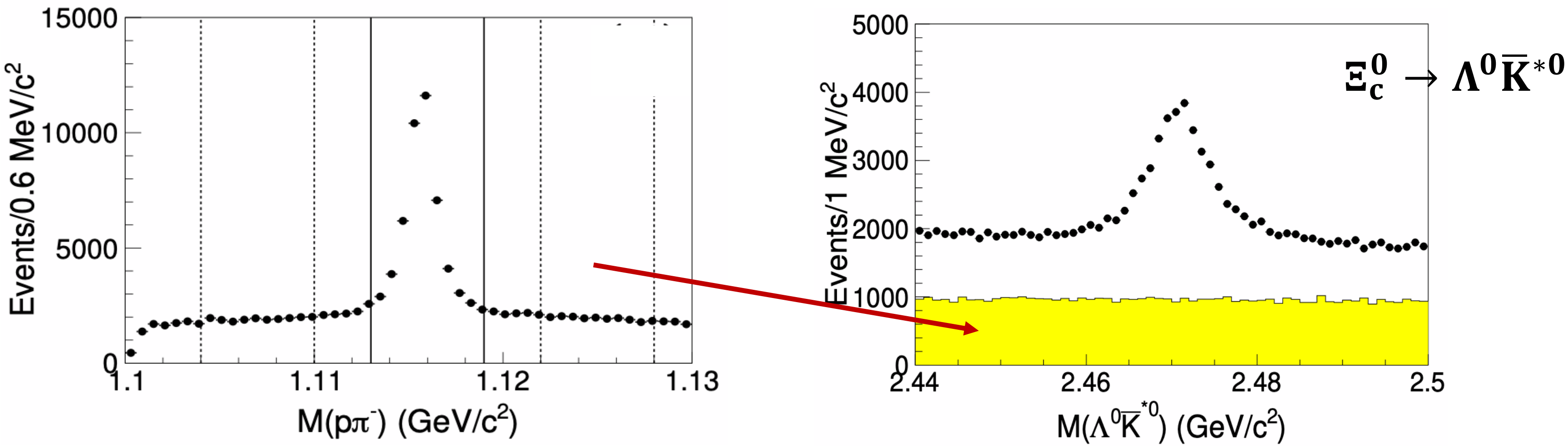
- Using a multivariate analysis with a neural network based on sets of input variables, the K_S^0 and Λ candidates are reconstructed from $\pi^+\pi^-$ and pπ^-.
- The flight directions of Σ^+ candidates, which are reconstructed from their fitted production and decay vertices, are required to be consistent with their momentum directions.
- $x_p > 0.5$; $x_p \propto [0,1]$ is scaled momentum of $\boldsymbol{\Xi_c^0}$, which can remove all backgrounds from B decays.

Data samples: 980 fb^{-1} e^+e^- collisions data samples

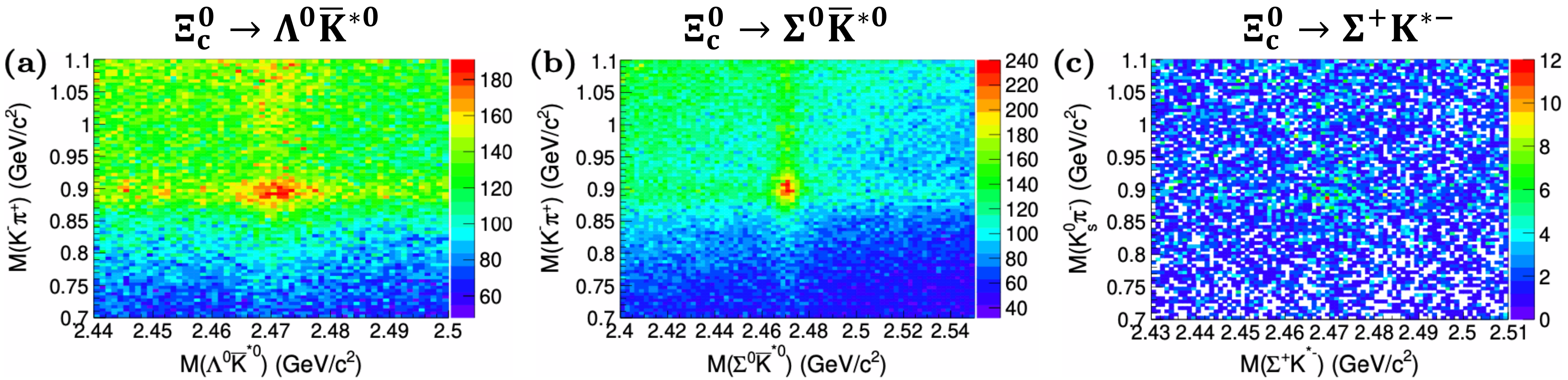
Inclusive MC samples: $\mathrm{B} = \mathrm{B}^+, \mathrm{B}^0$, or $\mathrm{B}_s^{(*)}$ decays and $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{q}\bar{\mathrm{q}}\ (\mathrm{q} = \mathrm{u}, \mathrm{d}, \mathrm{s}, \mathrm{c})$ at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV



Peaking backgrounds from K*



No peaking background is found from non-resonance contributions of Λ candidates.



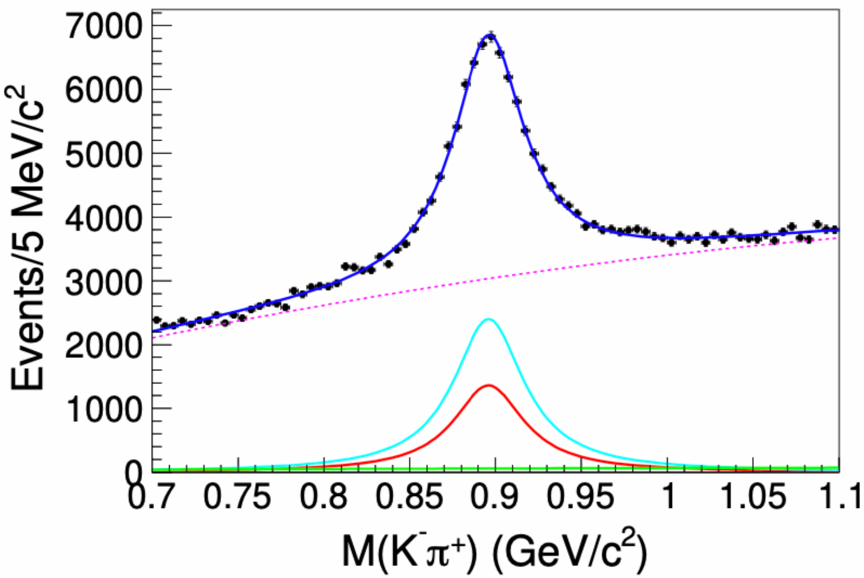
But we found a part of Ξ_c^0 signal events are from the events outside of $\overline{K}^{*0}$ and K^{*-} signal regions, especially in the higher sides of $M(K^-\pi^+)$ and $M(K_S^0\pi^-)$.

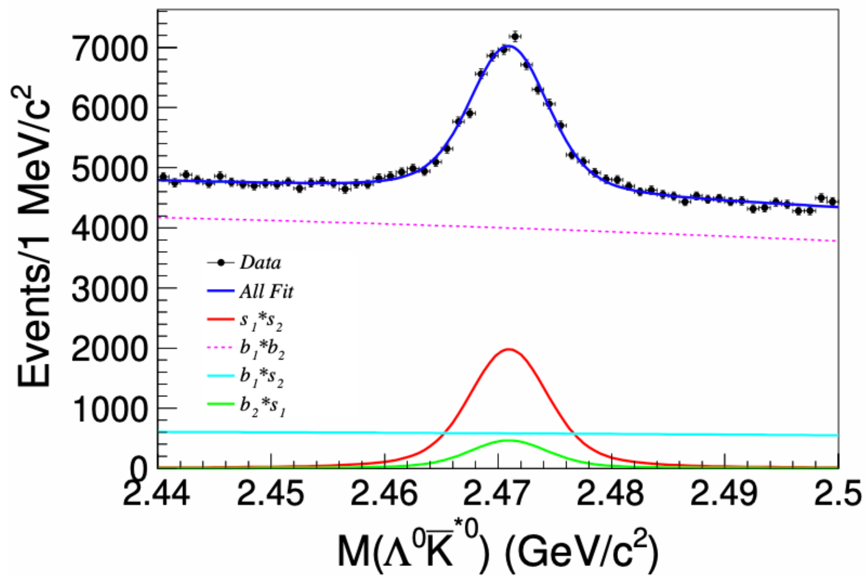
A two-dimentional (2D) fit to extract signal yields

$$f(M_1, M_2) = N^{\rm sig} s_1(M_1)s_2(M_2) + N^{\rm bg}_{\rm sb} s_1(M_1)b_2(M_2) + N^{\rm bg}_{\rm bs} b_1(M_1)s_2(M_2) + N^{\rm bg}_{\rm bb} b_1(M_1)b_2(M_2)$$

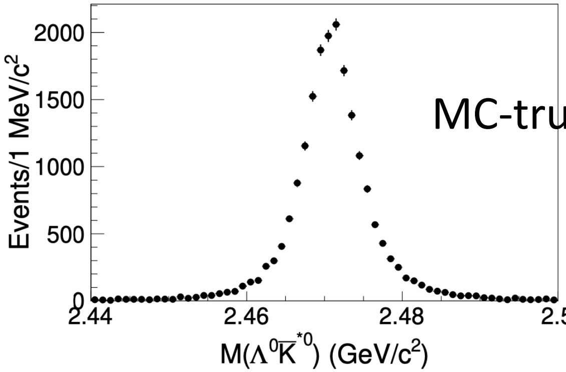
We use inclusive MC samples to do input/output check:

$\Xi_c^0 \to \Lambda \bar{K}^{*0}(\to K^- \pi^+)$





Signal Yields	
2D fit (output)	19734±340
MC-truth Matching (input)	19836

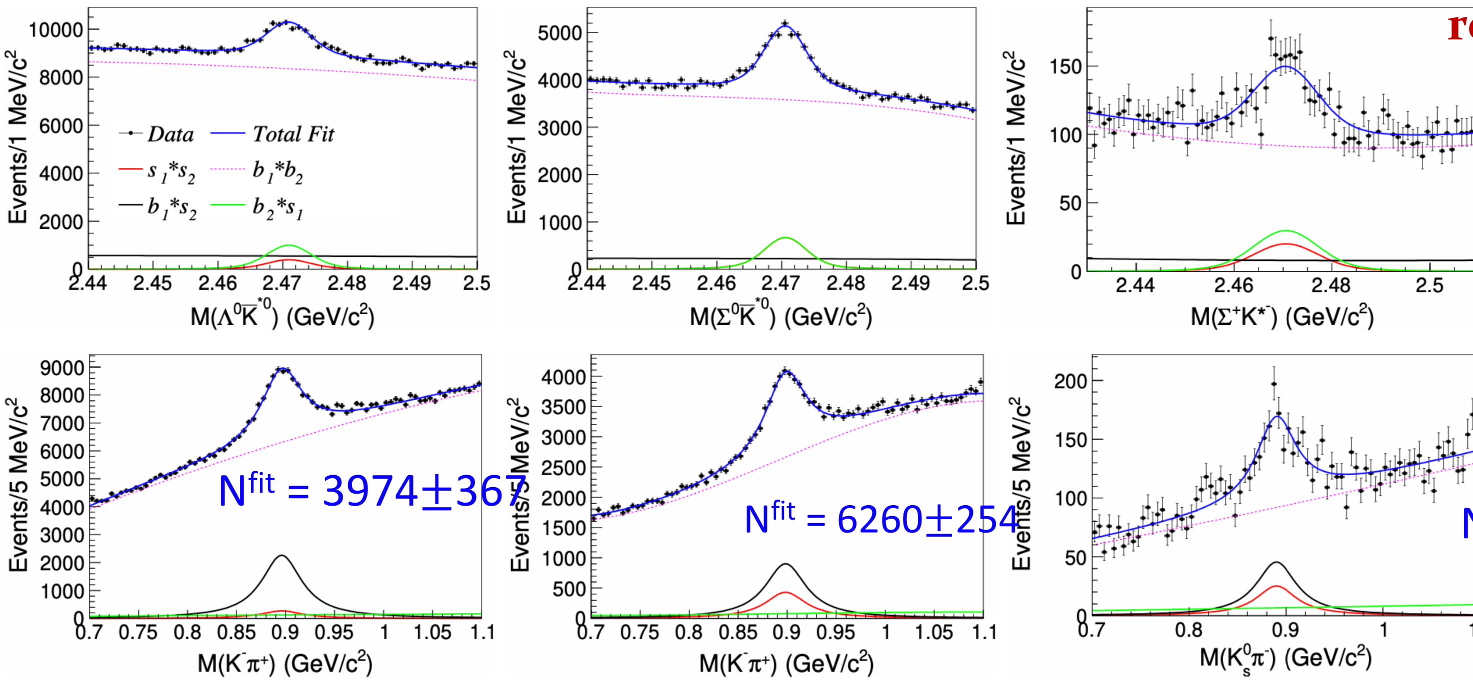


MC-truth Matching

Branching fractions

$\Xi_c^0 \to \Lambda^0 \overline{K}^{*0}$ $\Xi_c^0 \to \Sigma^0 \overline{K}^{*0}$ $\Xi_c^0 \to \Sigma^+ K^{*-}$

Preliminary results



$\mathcal{B}(\Xi_c^0 \to \Lambda \bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$0.18 \pm 0.02(\text{stat.}) \pm 0.01(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$0.69 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^{*-})/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$0.34 \pm 0.06(\text{stat.}) \pm 0.02(\text{syst.})$

$\mathcal{B}(\Xi_c^0 \to \Lambda \bar{K}^{*0})$	$(3.3 \pm 0.3(\text{stat.}) \pm 0.2(\text{syst.}) \pm 1.0(\text{ref.})) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})$	$(12.4 \pm 0.5(\text{stat.}) \pm 0.5(\text{syst.}) \pm 3.6(\text{ref.})) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^{*-})$	$(6.1 \pm 1.0(\text{stat.}) \pm 0.4(\text{syst.}) \pm 1.8(\text{ref.})) \times 10^{-3}$

By using the reference mode $\Xi_c^0 \to \Xi^- \pi^+$ [arXiv: 2103.06496 (2021)], we calculate the absolute branching fractions with signal yields between reference and signal channels after efficiency corrections.

Asymmetry parameter extractions

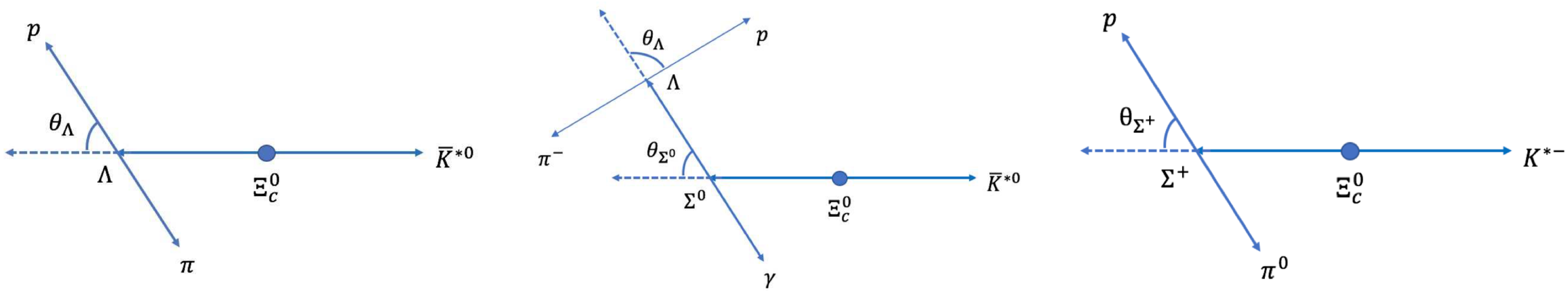
For $\Xi_c^0 \to \Lambda^0\overline{K}^{*0}$, $\Xi_c^0 \to \Sigma^0\overline{K}^{*0}$, and $\Xi_c^0 \to \Sigma^+K^{*-}$, the differential decay rates [PRD 101, 053002 (2020)] are given by:

$$\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha(\Xi_c^0 \to \Lambda\overline{K}^{*0})\alpha(\Lambda \to p\pi^-)\cos\theta_\Lambda,$$

$$\frac{dN}{d\cos\theta_{\Sigma^0}} \propto 1 + \alpha(\Xi_c^0 \to \Sigma^0\overline{K}^{*0})\alpha(\Sigma^0 \to \Lambda\gamma)\cos\theta_{\Sigma^0}, \text{ and}$$

$$\frac{dN}{d\cos\theta_{\Sigma^+}} \propto 1 + \alpha(\Xi_c^0 \to \Sigma^+K^{*-})\alpha(\Sigma^+ \to p\pi^0)\cos\theta_{\Sigma^+}.$$

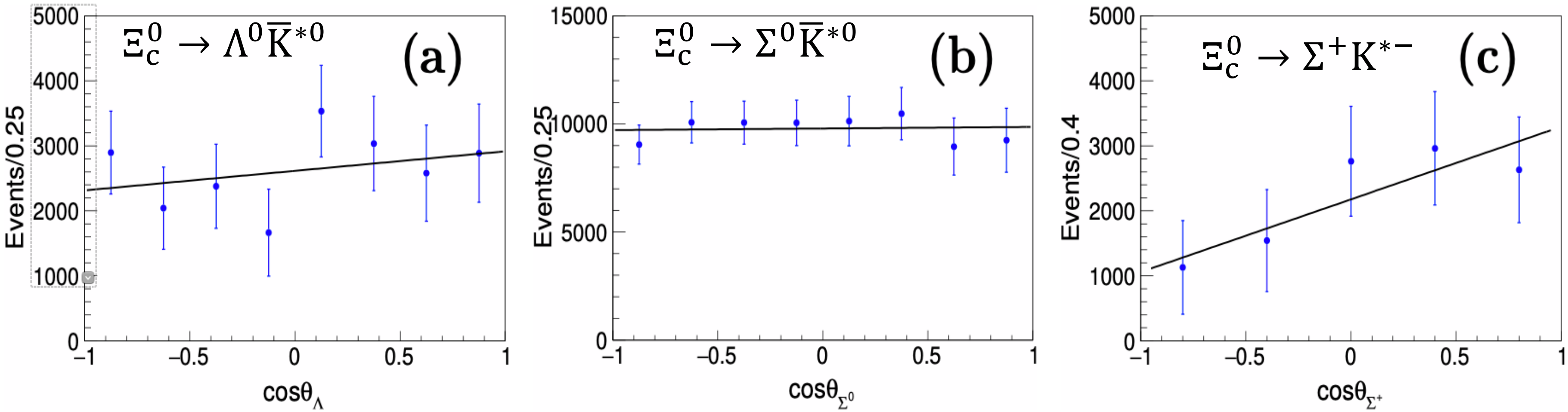
Definitions of θ_Λ, θ_{Σ^0}, and θ_{Σ^+}:



- This measurement is insensitive to production polarization of Ξ_c^0 in B-factory [PRD 63, 111102 (2001)].
- The asymmetry parameter $\alpha(\Sigma^0 \to \Lambda\gamma)$ is expected to be zero due to the case of parity conservation for an electromagnetic decay of $\Sigma^0 \to \Lambda\gamma$.

Asymmetry parameters

Preliminary results



Note that $\alpha(\Lambda \to p\pi^-) = 0.747 \pm 0.010$ and $\alpha(\Sigma^+ \to p\pi^0) = -0.980 \pm 0.017$ from PDG.

$\alpha(\Xi_c^0 \to \Lambda \bar{K}^{*0})\alpha(\Lambda \to p\pi^-)$	$0.115 \pm 0.164(\text{stat.}) \pm 0.038(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})\alpha(\Sigma^0 \to \gamma\Lambda)$	$0.008 \pm 0.072(\text{stat.}) \pm 0.008(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+ K^{*-})\alpha(\Sigma^+ \to p\pi^0)$	$0.514 \pm 0.295(\text{stat.}) \pm 0.012(\text{syst.})$
$\alpha(\Xi_c^0 \to \Lambda \bar{K}^{*0})$	$0.15 \pm 0.22(\text{stat.}) \pm 0.05(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+ K^{*-})$	$-0.52 \pm 0.30(\text{stat.}) \pm 0.02(\text{syst.})$

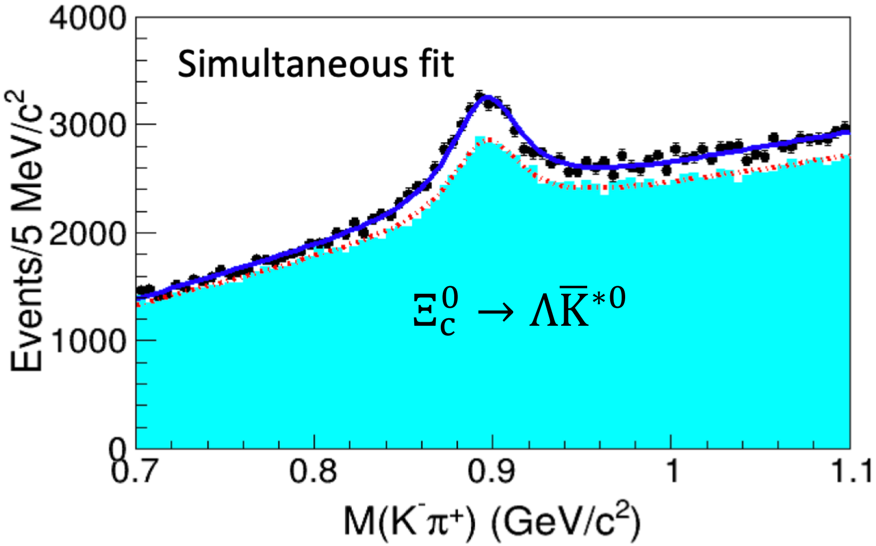
Summary

- Although Belle has stopped data taking for ~10 years ago, we are still producing exciting results.
- We reported the first search for a doubly-charged DDK bound state R^{++}, the evidence of X(3872) in single-tag two-photon reactions, and the first search for X(3872) in B radiative decays.
- Branching fractions and asymmetry parameters of $\Xi_c^0 \to \Lambda\overline{K}^{*0}$, $\Xi_c^0 \to \Sigma^0\overline{K}^{*0}$, and $\Xi_c^0 \to \Sigma^+K^{*-}$ have been measured for the first time.
- We always expect the results from much larger Belle II data samples. Belle II will reach 50 ab^{-1} by 2027, which will provide greater sensitivity and precise measurements in hadron physics.

Thanks for your attentions!

Backup

The dots with error bars show the invariant mass distributions for $\overline{K}^{*0}$ candidates within Ξ_c^0 signal region. The cyan histogram is from Ξ_c^0 mass sidebands.



The dots with error bars show the invariant mass distributions for $\overline{K}^{*0}$ candidates within Ξ_c^0 signal region. The cyan histogram is from Ξ_c^0 mass sidebands.