Recent results on baryons from Belle

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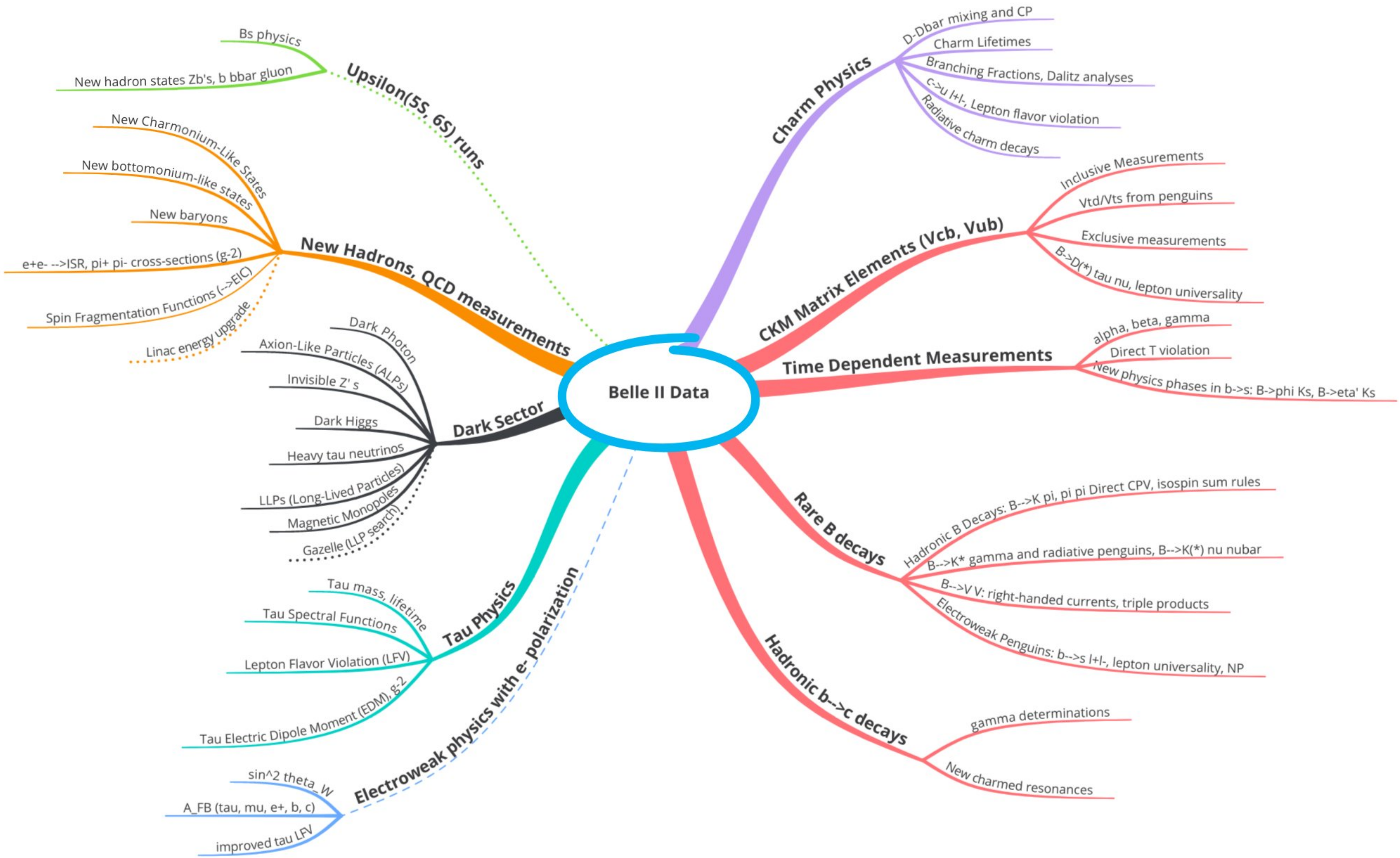
Yonsei University

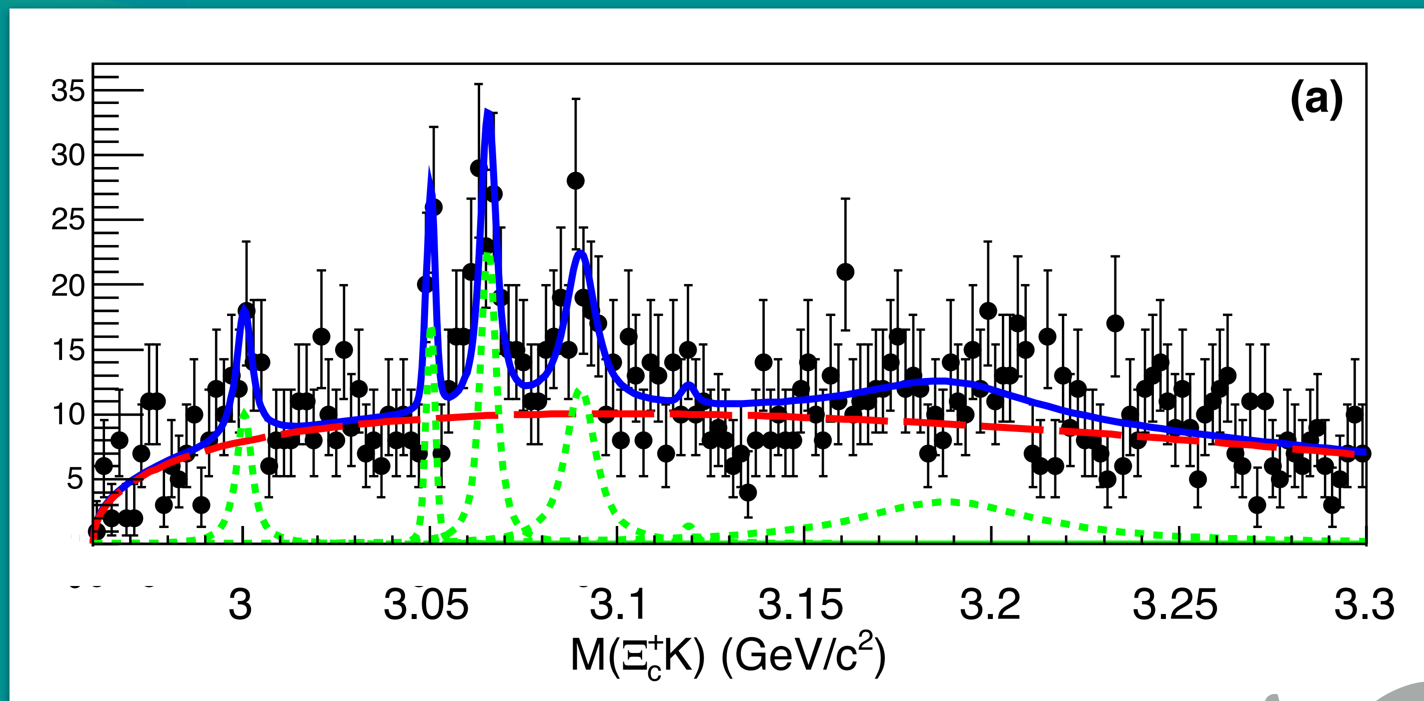
Inha HTG Workshop, July 8, 2022

Belle II Physics Mind-map




bottomonium-like states
New baryons
pi- cross-sections (g-2)
Functions (-->EIC)
Linac energy upgrade
New Hadrons, QCD measurements
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Monopoles
Dark Sector
Belle II

this talk



Baryon structures (Belle)

- Weak decays
  - $\Xi_c^0 \to \Lambda K_S^0,\ \Sigma^0 K_S^0,\ \Sigma^+ K^-$ arXiv:2111.08981
  - $\Xi_c^0 \to \Lambda \overline{K}^{*0},\ \Sigma^0 \overline{K}^{*0},\ \Sigma^+ K^{*-}$ JHEP 2106, 160 (2021)
  - $\Lambda_c^+ \to p\omega$ (BF) PRD 104, 072008 (2021)
  - ✓ $\Omega_c^0 \to \pi^+ \Omega(2012)^- \to \pi^+ (\bar{K}\Sigma)^-$ PRD 104, 052005 (2021)
  - $\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu)$ and asym. of $\Xi_c^0 \to \Xi^- \pi^+$ PRL 127, 121803 (2021)
  - $\Lambda_c^+ \to p\eta,\ p\pi^0$ PRD 103, 072004 (2021)
  - $\Xi_c^0 \to \Xi^0 K^+ K^-$ PRD 103, 112002 (2021)
  - ✓ $\Lambda_c^+ \to \eta\Lambda\pi^+,\ \eta\Sigma^0\pi^+,\ \Lambda(1670)\pi^+,\ \eta\Sigma(1385)^+$ PRD 103, 052005 (2021)

- Hadronic properties & radiative decays
  - ✓ mass, width of $\Sigma_c(2455)^+,\ \Sigma_c(2520)^+$ PRD 104, 052003 (2021)
  - ✓ $\Xi_c(2815)^0 \to \Xi_c^0\gamma,\ \Xi_c(2790)^0 \to \Xi_c^0\gamma,$ PRD 102, 071103 (2020)
  - ✓ Spin-parity of $\Xi_c(2970)^+$ PRD 103, L111101 (2021)
  - B baryonic decays, $B \to \Lambda_c \Xi_c$ PRD 100, 112010 (2019)
  - $\Xi(1620)^0$ & $\Xi(1690)^0$ in $\Xi_c^+ \to \Xi^- \pi^+ \pi^=$ PRL 122, 072501 (2019)
  - ...
  - Excited Ω^- observations PRL 121, 052003 (2018)
  - Excited Ω_c (obs. 4 states) PRD 97, 051102 (2018)

- Weak decays
  - $\Xi_c^0 \to \Lambda K_S^0,\ \Sigma^0 K_S^0,\ \Sigma^+ K^-$ — arXiv:2111.08981
  - $\Xi_c^0 \to \Lambda \overline{K}^{*0},\ \Sigma^0 \overline{K}^{*0},\ \Sigma^+ K^{*-}$ — JHEP 2106, 160 (2021)
  - $\Lambda_c^+ \to p\omega$ (BF) — PRD 104, 072008 (2021)
  - ✓ $\Omega_c^0 \to \pi^+ \Omega(2012)^- \to \pi^+(\bar{K}\Sigma)^-$ — PRD 104, 052005 (2021)
  - $\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu)$ and asym. of $\Xi_c^0 \to \Xi^- \pi^+$ — PRL 127, 121803 (2021)
  - $\Lambda_c^+ \to p\eta,\ p\pi^0$ — PRD 103, 072004 (2021)
  - $\Xi_c^0 \to \Xi^0 K^+ K^-$ — PRD 103, 112002 (2021)
  - ✓ $\Lambda_c^+ \to \eta\Lambda\pi^+,\ \eta\Sigma^0\pi^+,\ \Lambda(1670)\pi^+,\ \eta\Sigma(1385)^+$ — PRD 103, 052005 (2021)

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  - ✓ Spin-parity of $\Xi_c(2970)^+$ — PRD 103, L111101 (2021)
  - B baryonic decays, $B \to \Lambda_c \Xi_c$ — PRD 100, 112010 (2019)
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  - ...
  - Excited Ω^- observations — PRL 121, 052003 (2018)
  - Excited Ω_c (obs. 4 states) — PRD 97, 051102 (2018)

- Baryon papers in 2022
  - ★ Ξ_c^0 decays (W emission vs. W exchange) — PRD 105, L011102 (2022)
  - ★ $\Xi_c^0 \to \Lambda_c^+ \pi^-$ ($s \to uW^*$ vs. W exchange) — arXiv:2206.08527
  - ★ $\Lambda_c \to \Sigma\gamma$, $\Xi_c \to \Xi\gamma$ (radiative) — arXiv:2206.12517
  - $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ (semileptonic) — PRD 105, L091102 (2022)
  - $\Lambda_c^+ \to p\eta'$ (SCS) — JHEP 03 (2022) 090
  - new excited states decaying to $\Sigma_c(2455)\pi^\pm$ — arXiv:2206.08822

Outline

- Results on baryonic states
  - W-exchange contribution
  - radiative decay
  - semileptonic decay
- Baryonic dark matter searches
  - $B^0 \to \Lambda\psi_{\mathrm{DS}}$ search
- Studies of exotic hadrons
  - $X(3872) \to \pi^+\pi^-\pi^0$ search
  - Tetraquark ($T_{cc\bar{s}\bar{s}}$) search

Belle & Belle II

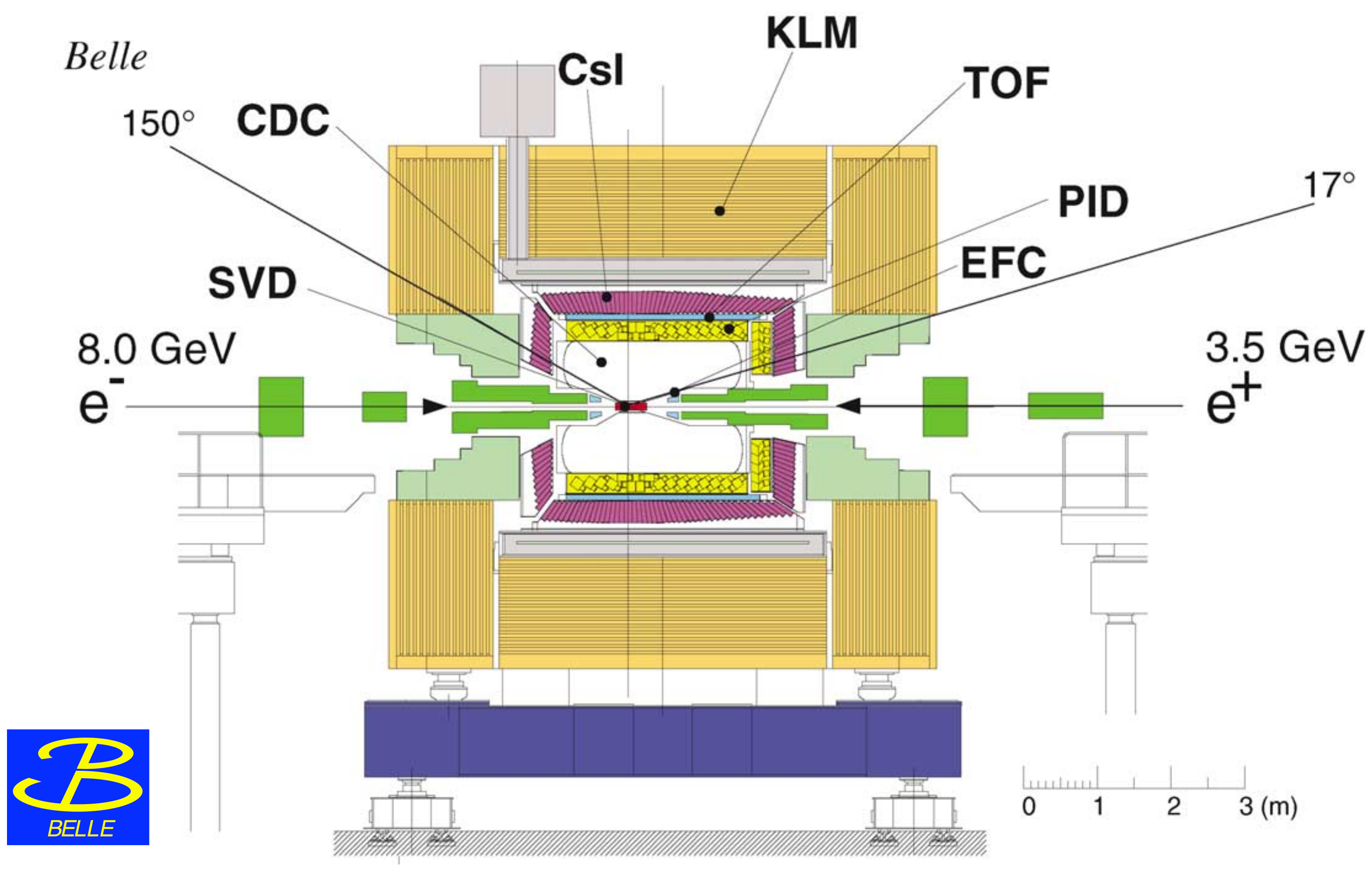
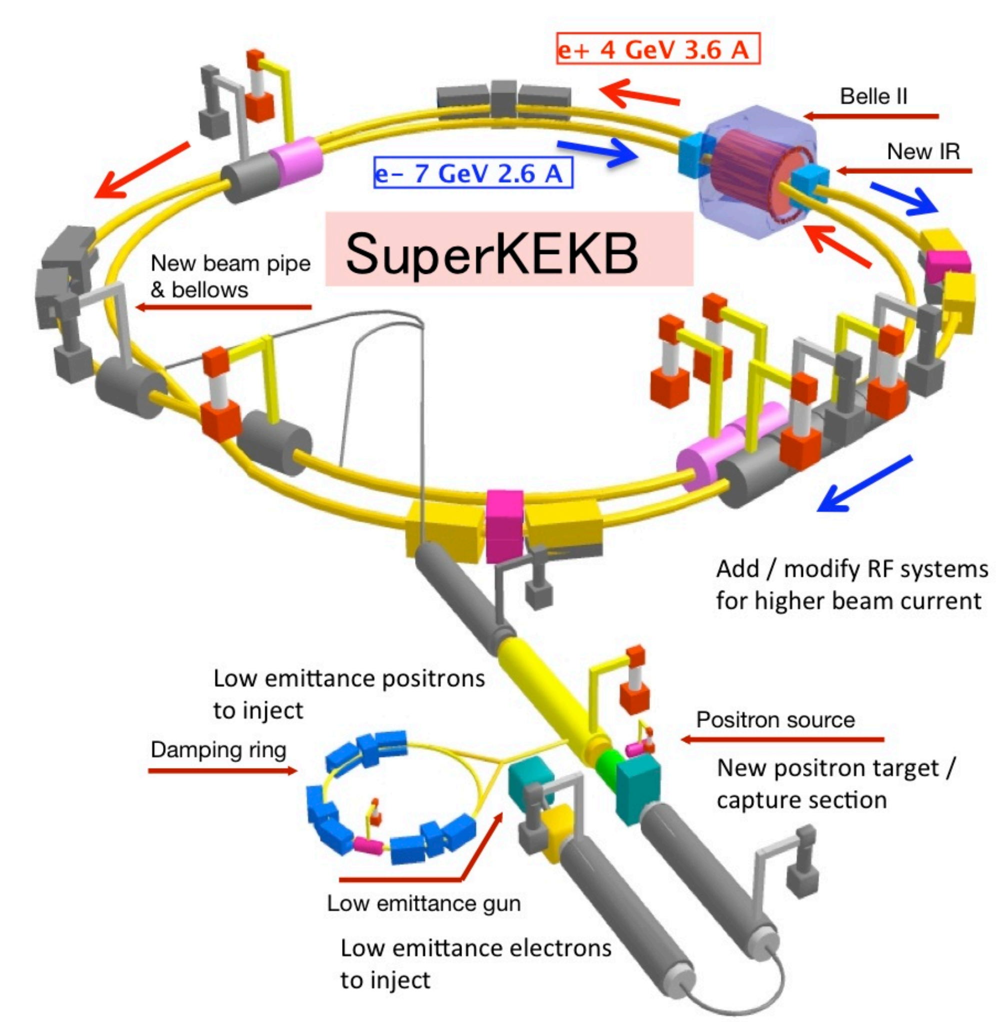
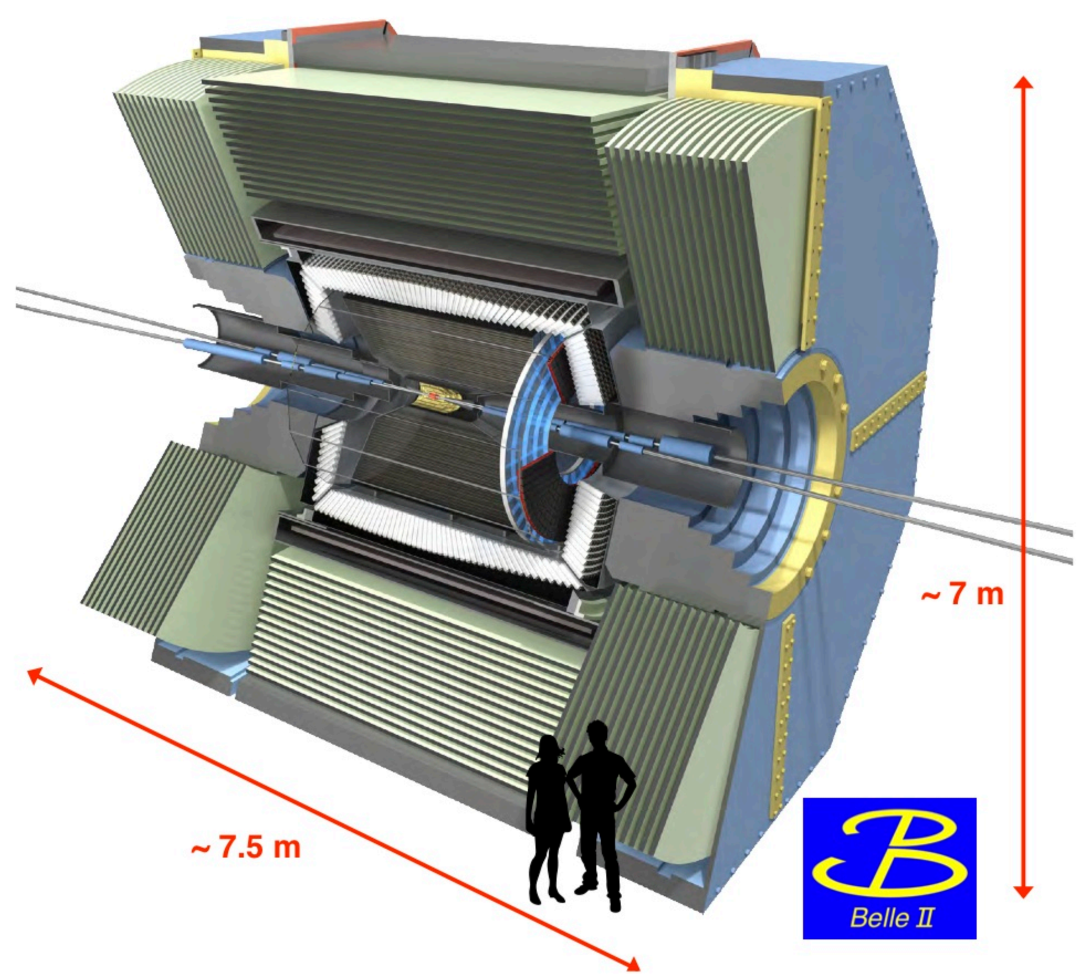


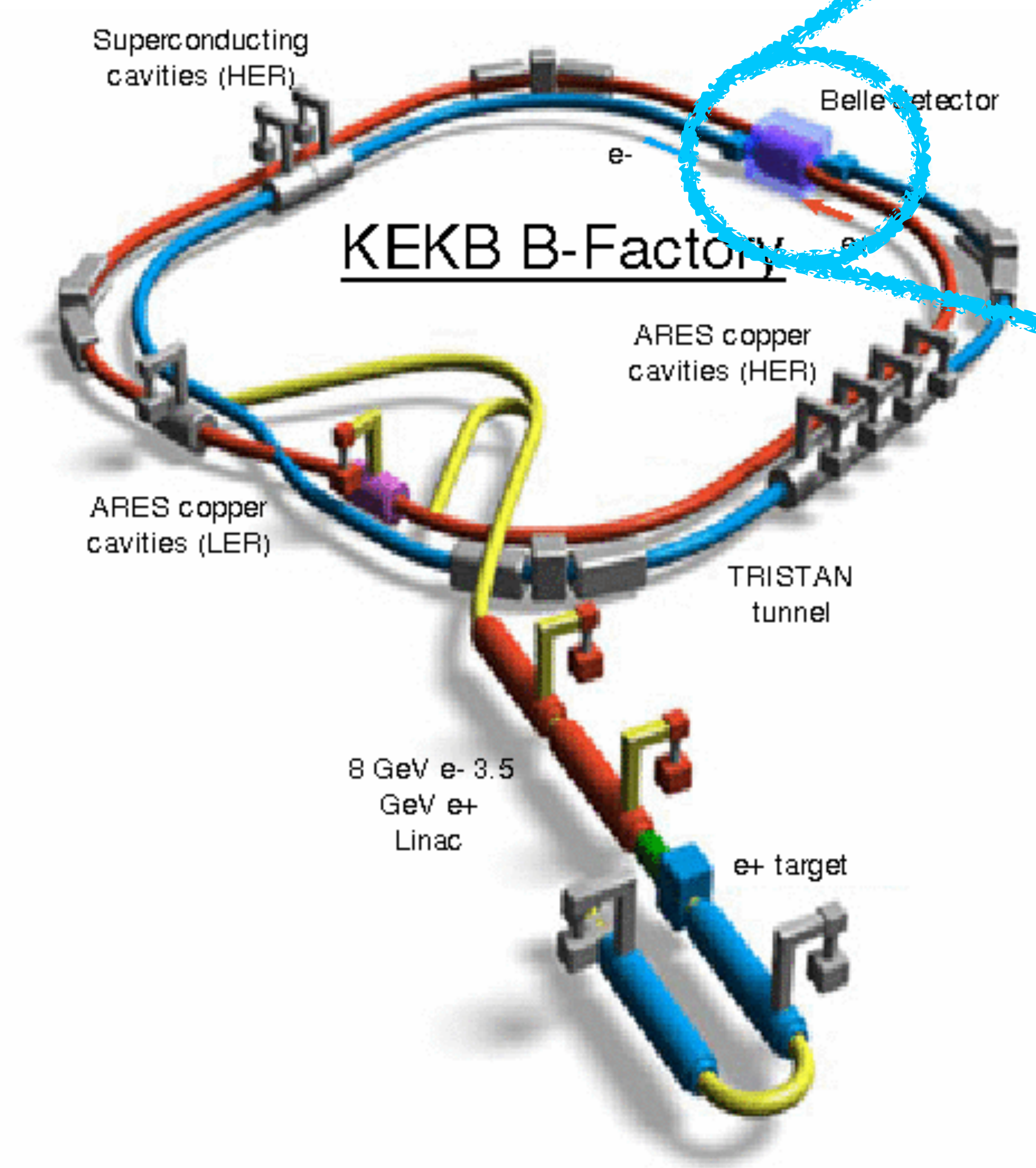
Fig. 1. Side view of the Belle detector.



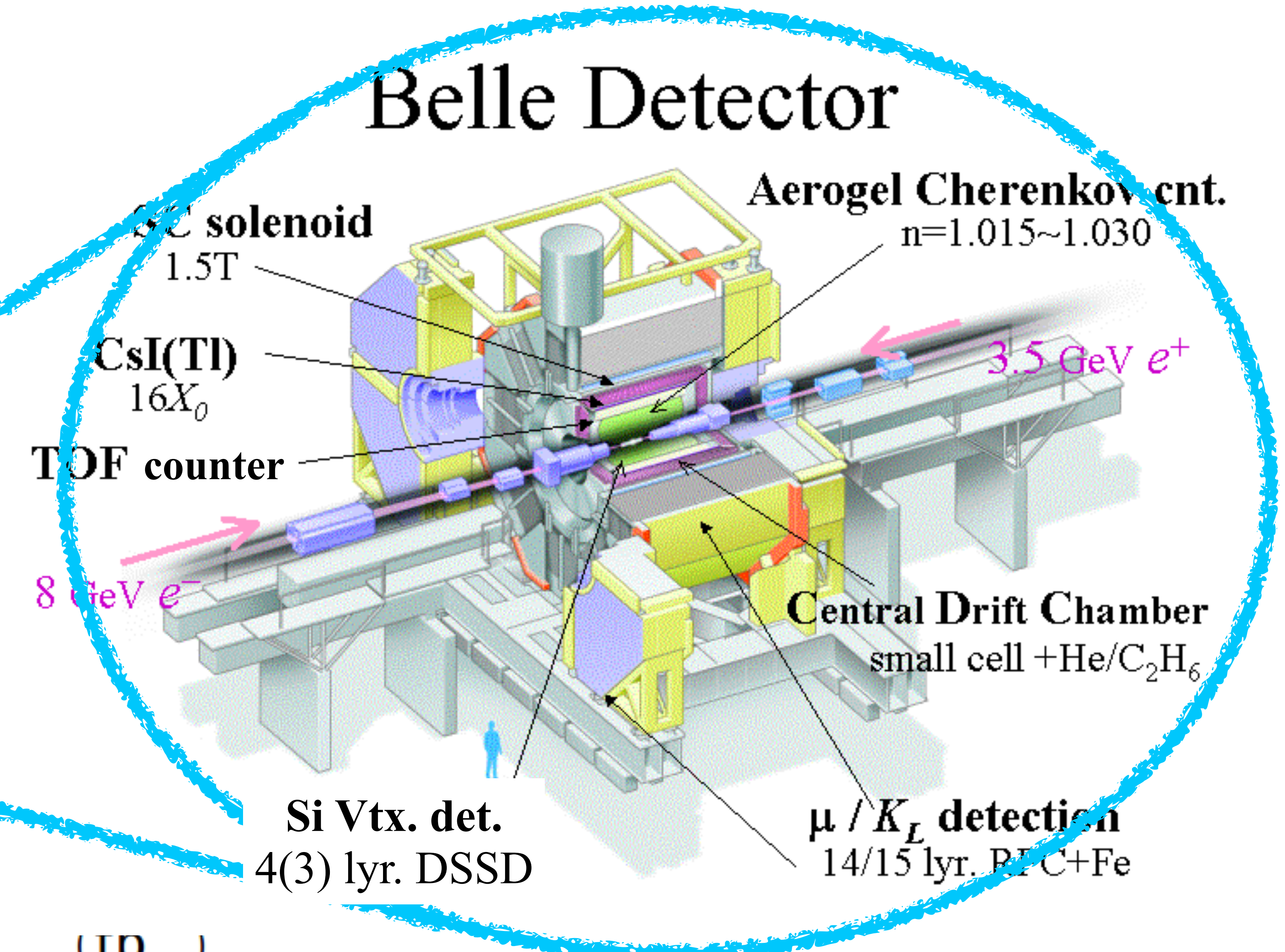


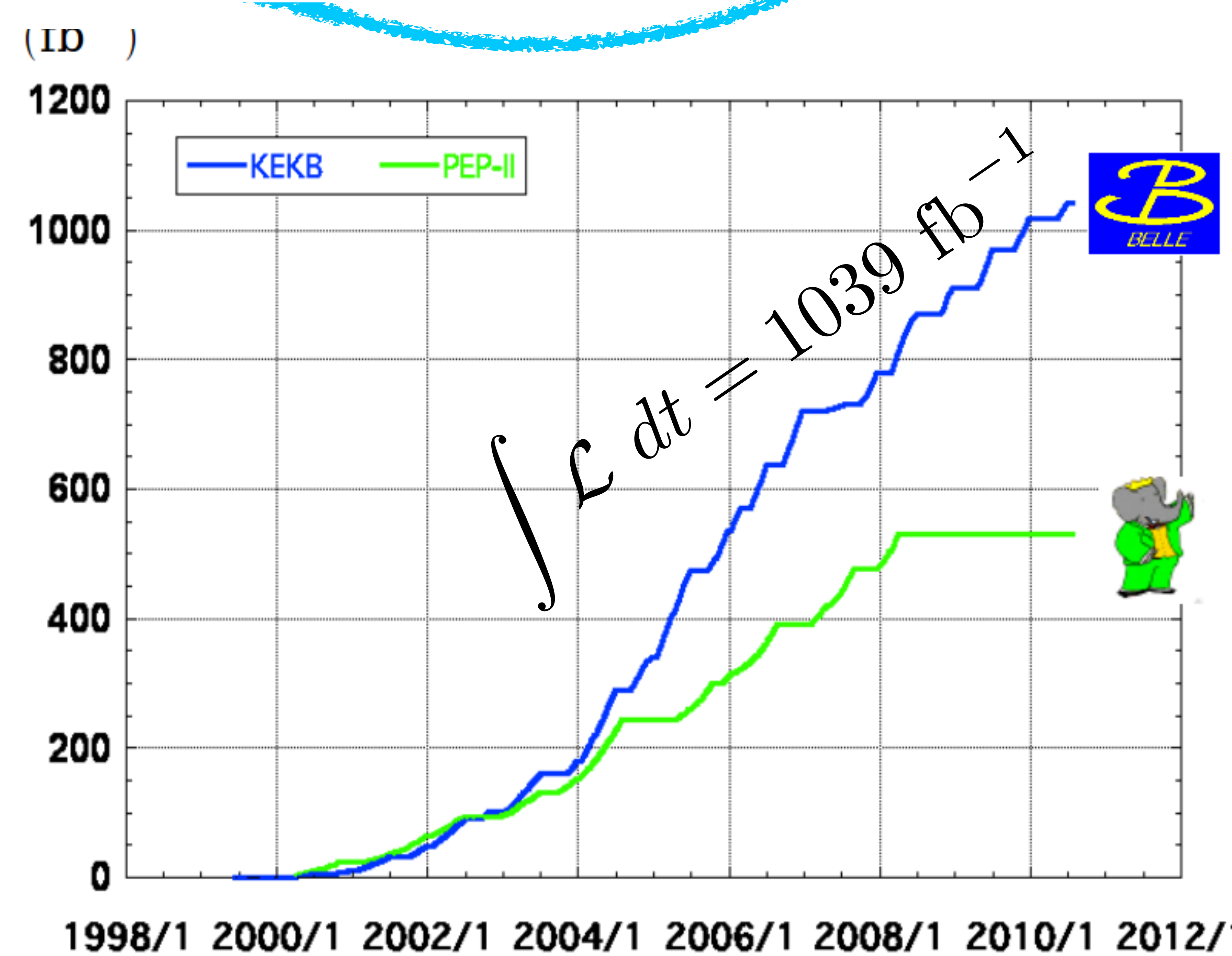
22 countries
100 institutions
~450 members

$$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$$



$$e^- \xrightarrow{8\ \text{GeV}} (\star) \xleftarrow{3.5\ \text{GeV}} e^+$$





> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

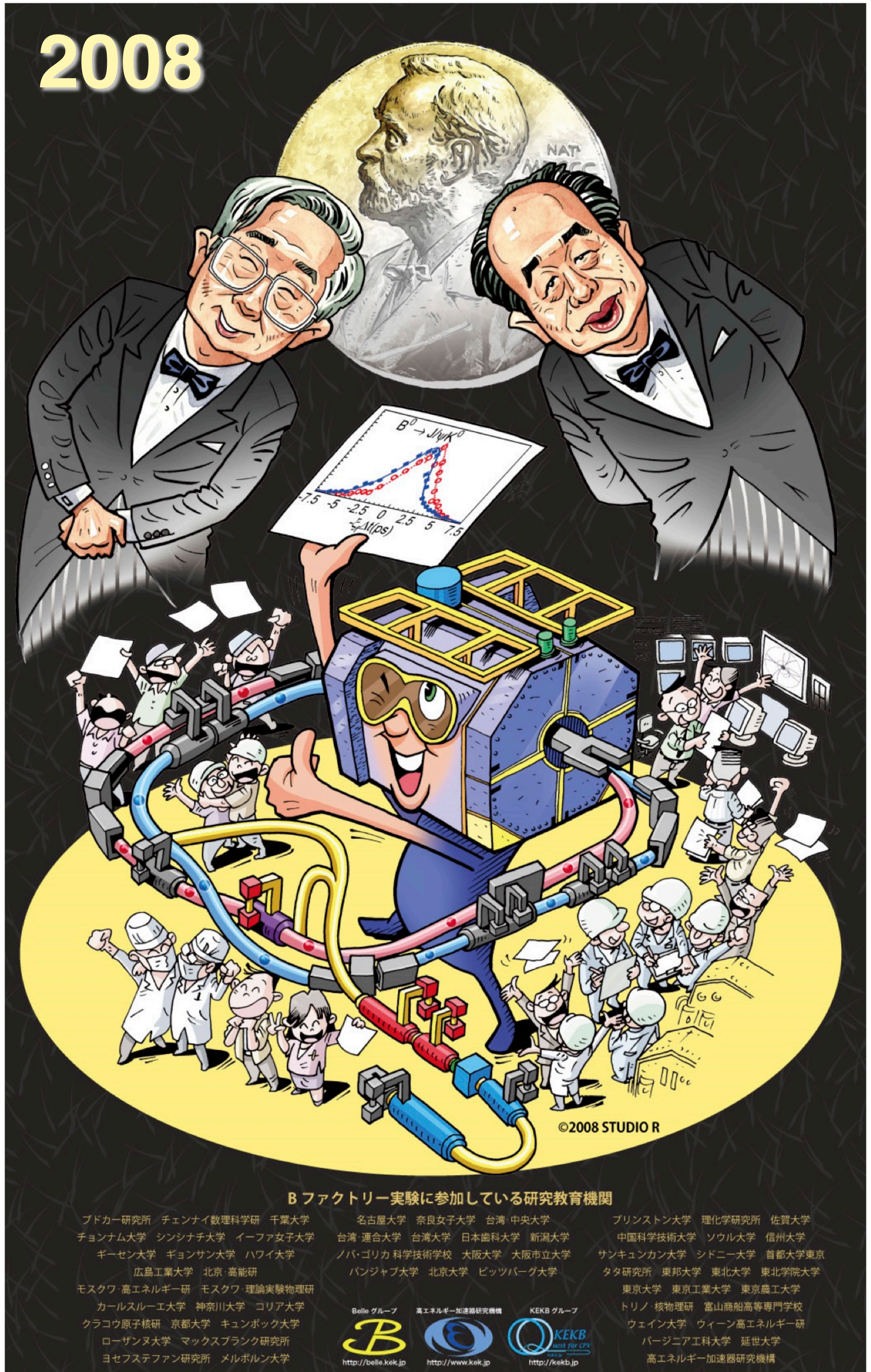
$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

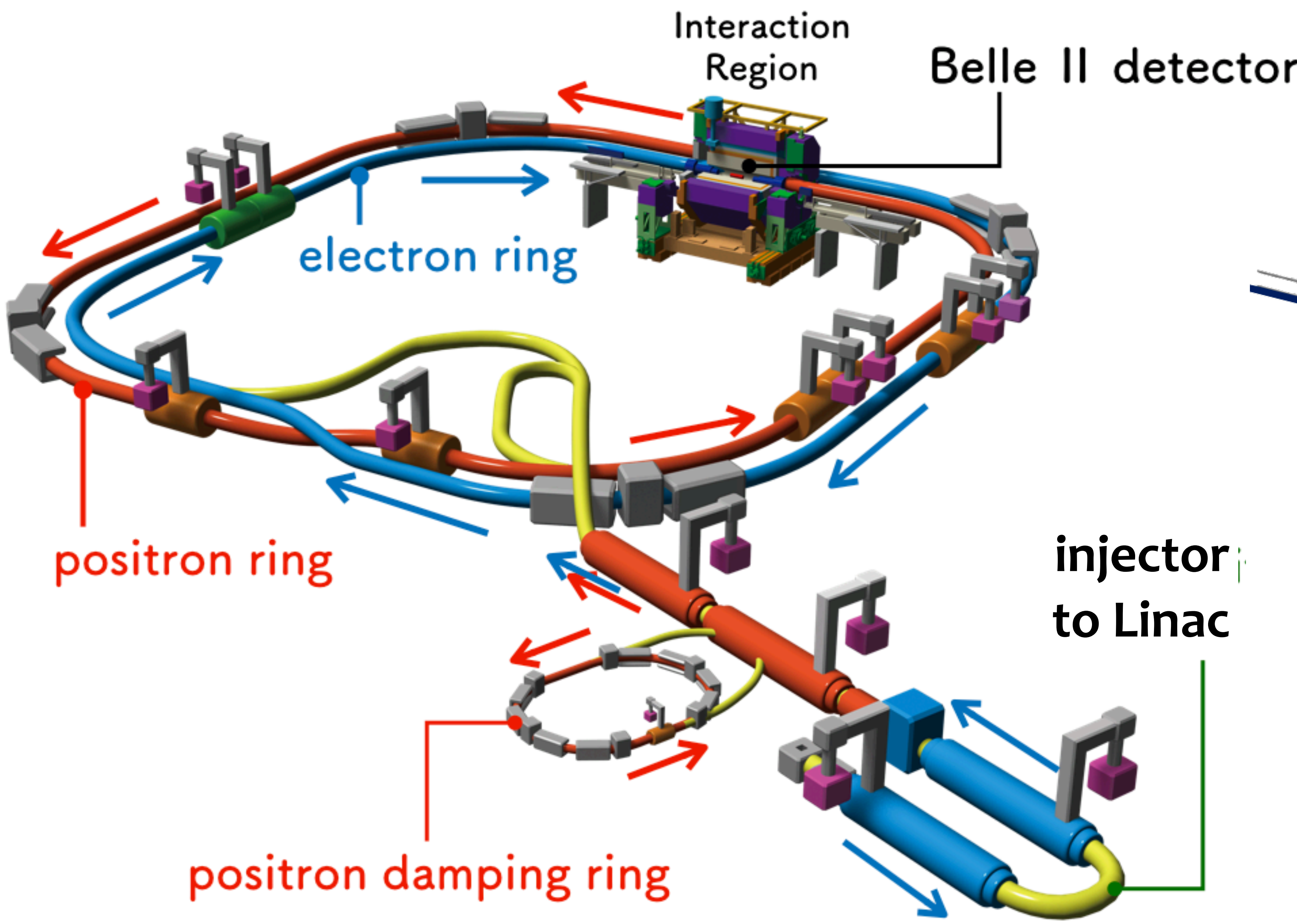
~ 54 fb^{-1}

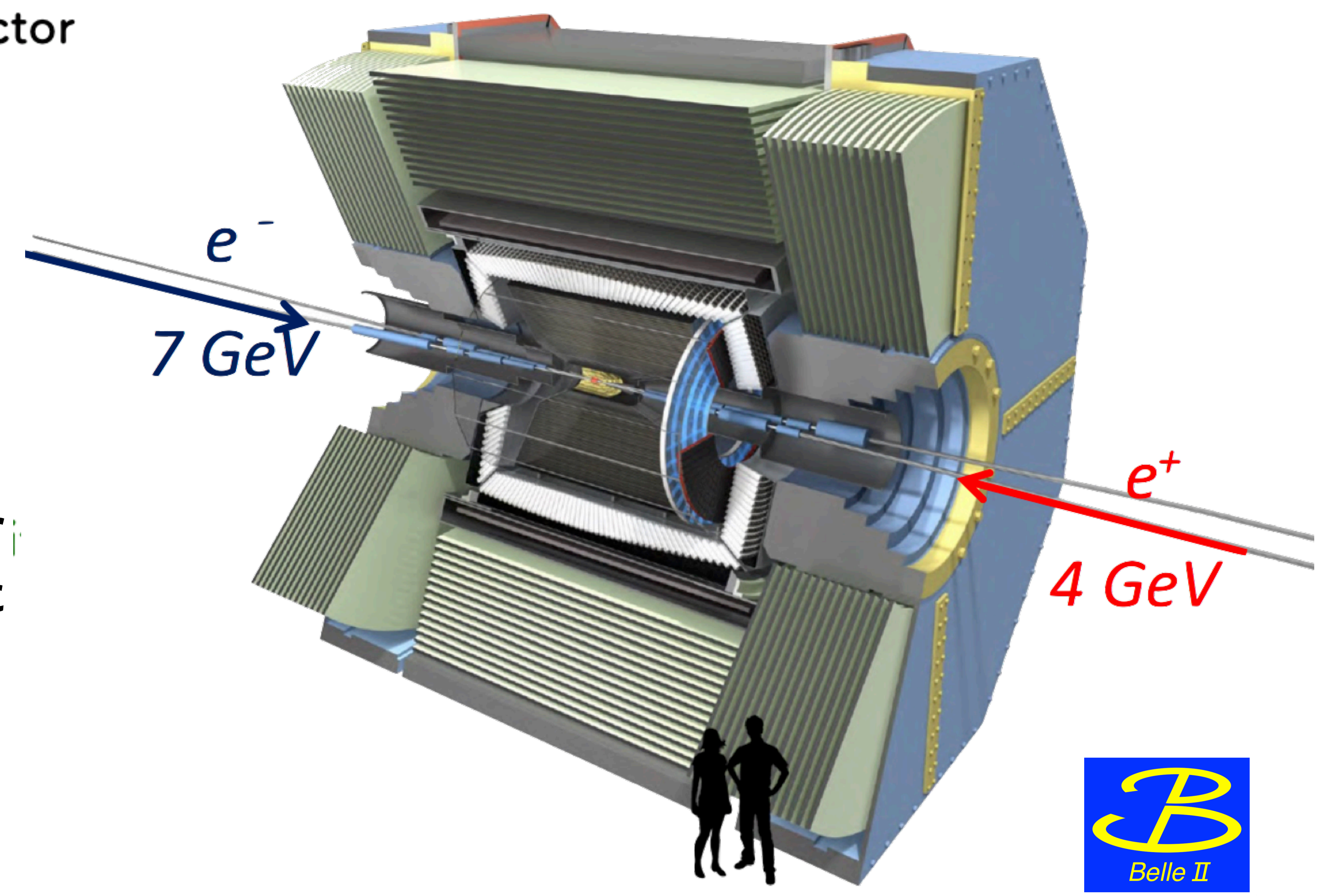


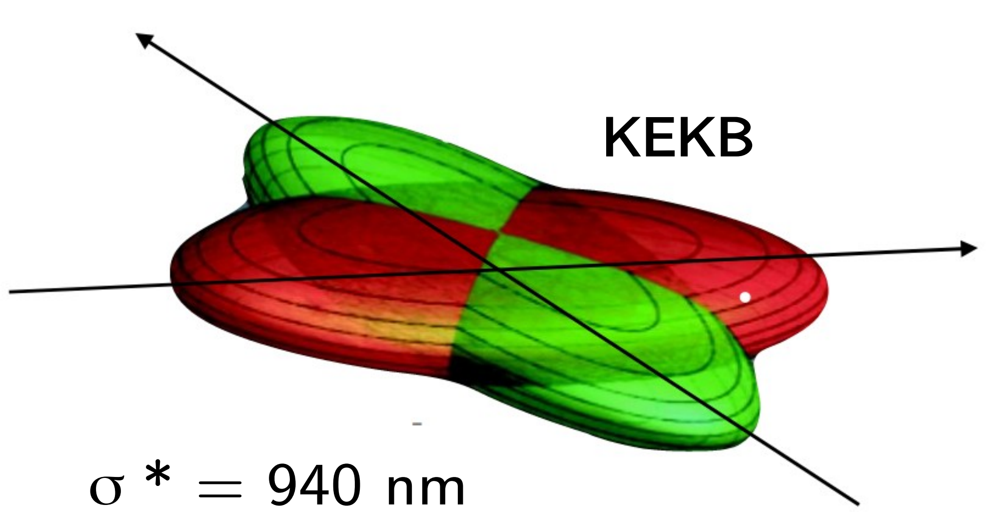
Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons, e.g. $D^*_{s0}(2317)^+$
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

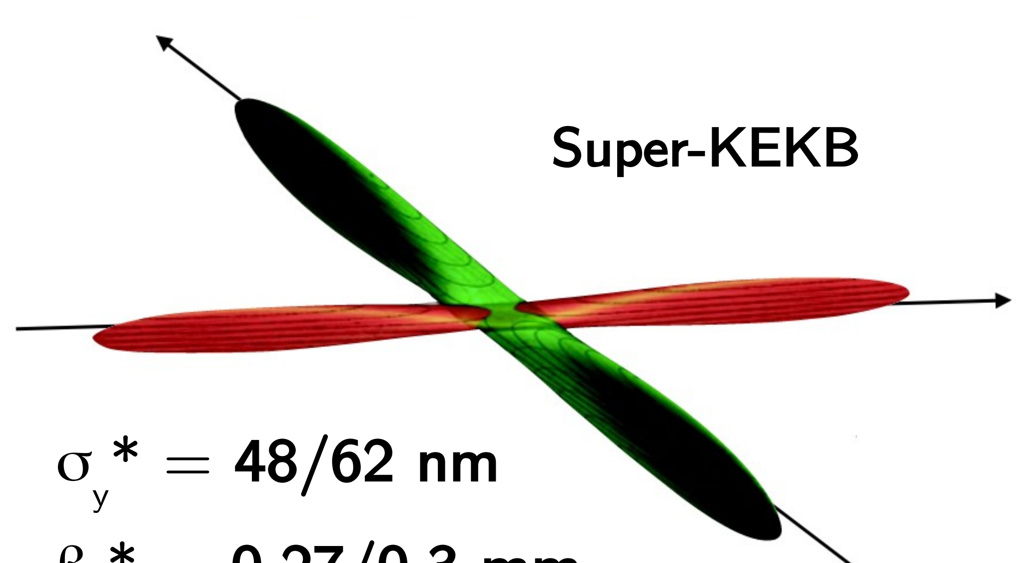
SuperKEKB $\quad e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+ \quad$ Belle II







$\sigma_y^* = 940$ nm
$\beta_y^* = 5.9$ mm
$\sigma_x^* = 147/170$ µm



$\sigma_y^* =$ **48/62 nm**
$\beta_y^* =$ **0.27/0.3 mm**
$\sigma_x^* =$ **10.1/10.7 µm**

$$\mathcal{L}_{\rm II}^{\rm peak} \approx 30 \times \mathcal{L}_{\rm I}^{\rm peak}$$

$$\int^{\rm goal} \mathcal{L}_{\rm II}\, dt = 50\ {\rm ab}^{-1} \approx 50 \int \mathcal{L}_{\rm I}\, dt$$

The Belle II Collaboration

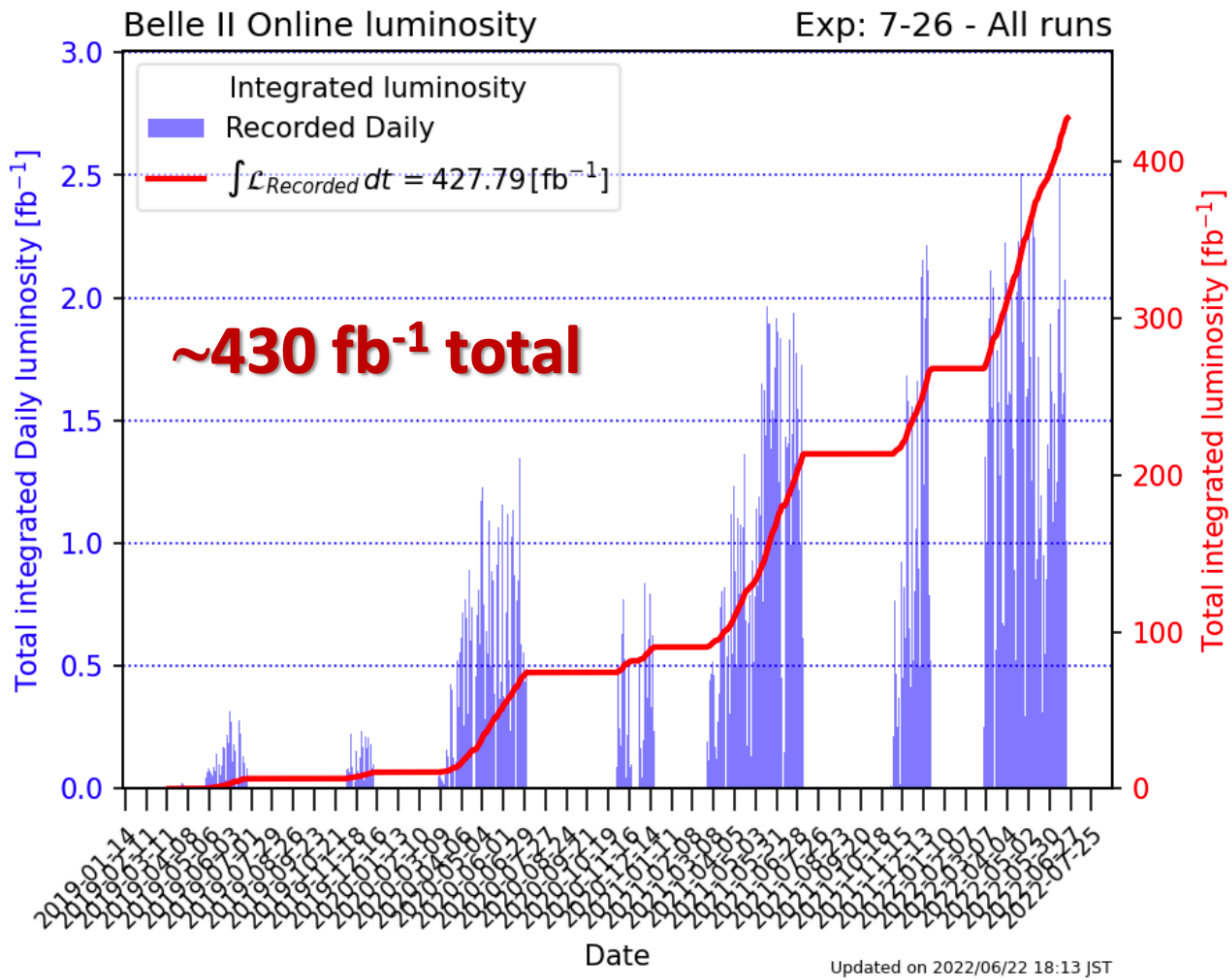
26 countries/regions, ~120 institutions, ~1000 collaborators

Belle II

Collected luminosity up to now: 2019-2022

Belle II has been in operation through the Pandemic era, with modified working mode in accordance with the anti-pandemic policy.
(*See back-up slide!*)

peak luminosity world record
$4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

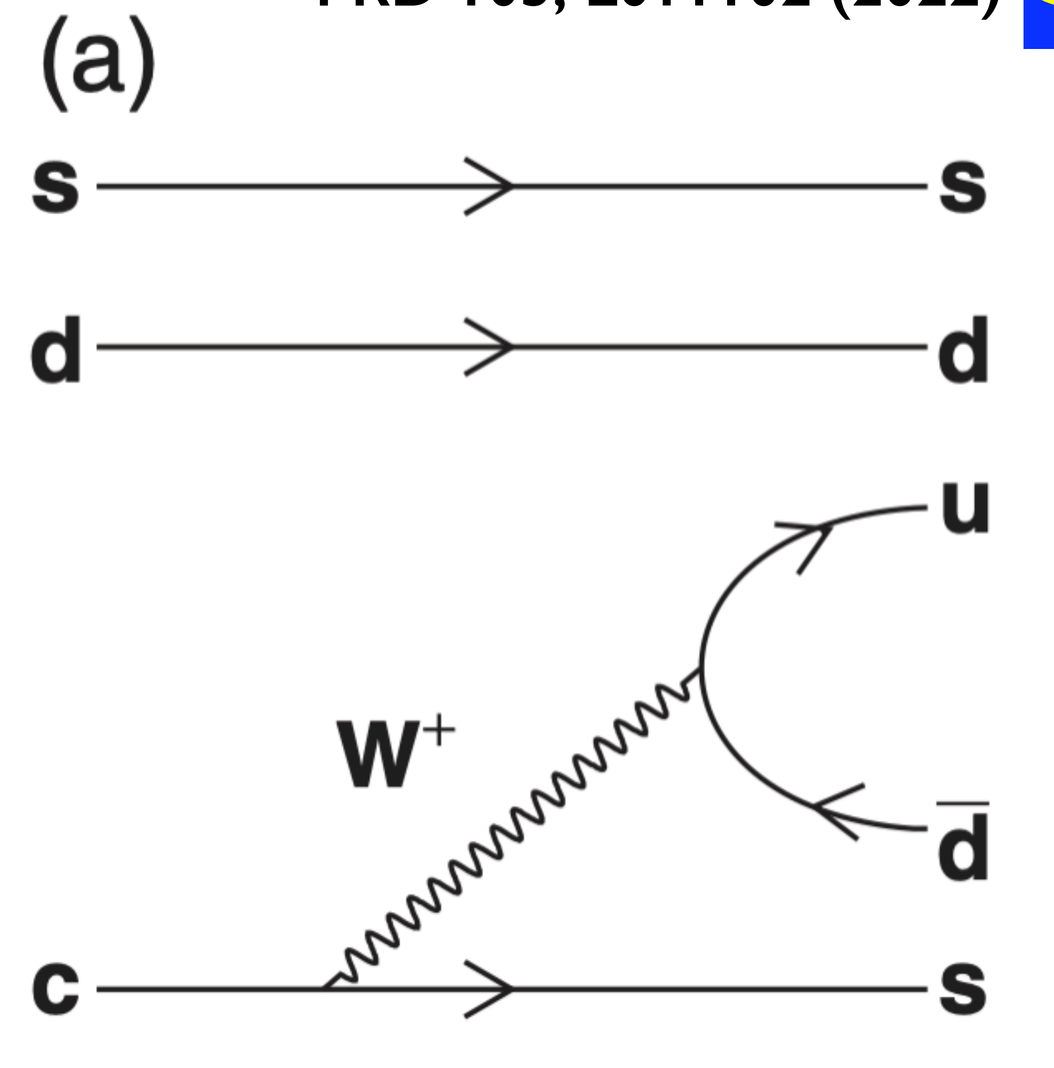


W-exchange processes

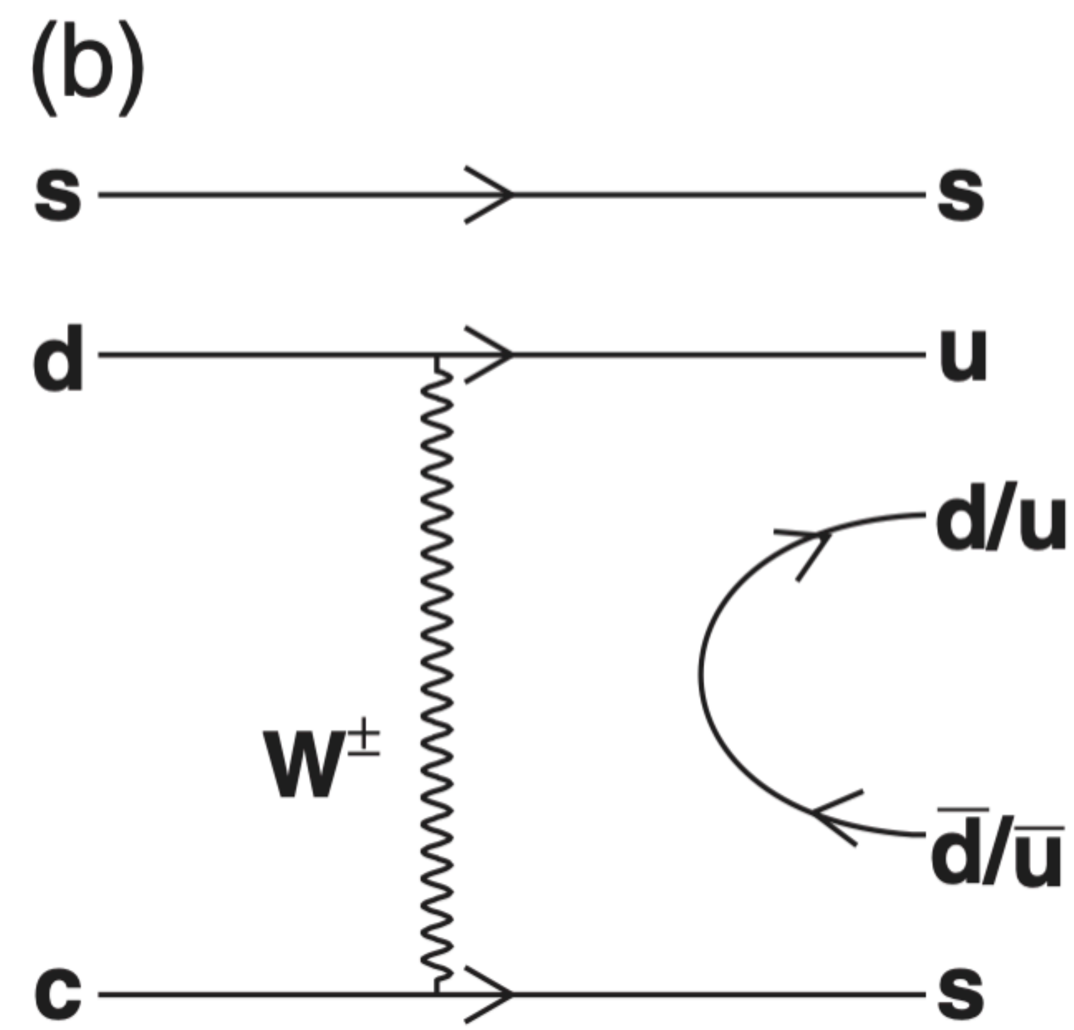
PRD 105, L011102 (2022)

$\Xi_c^0 \to \Lambda K_S^0,\ \Sigma^0 K_S^0,\ \Sigma^+ K^-$

- Charmed baryons — unique lab to study subtle interplay of strong and weak int.
- *W*-exchange is non-negligible, unlike the case with mesons
- ∃ theoretical works for two-body hadronic weak decays: $\Xi_c^0 \to B + P$
  - see the Table (*next page*)



$\Xi_c^0 \to \Lambda \overline{K}^0, \Sigma^0 \overline{K}^0$

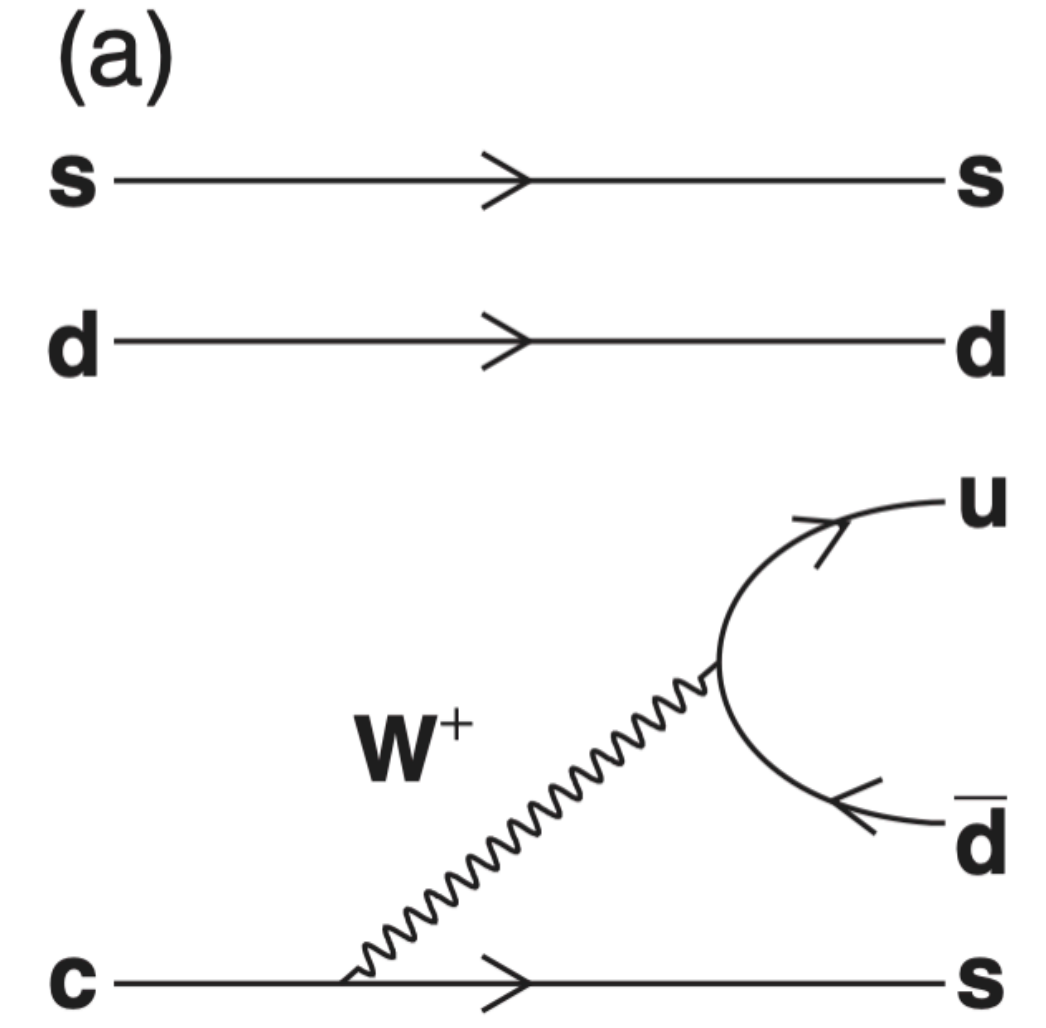


$\Xi_c^0 \to \Lambda \overline{K}^0, \Sigma^0 \overline{K}^0, \Sigma^+ K^-$

TABLE I. The predicted branching fractions in units of 10^{-3} for the CF decays $\Xi_c^0 \to \Lambda \bar{K}^0 / \Sigma^0 \bar{K}^0 / \Sigma^+ K^-$ based on dynamical model calculations and $SU(3)_F$ flavor symmetry approaches.

Modes	Zou *et al.* [4]	Geng *et al.* [5]	Zhao *et al.* [6]
$\Xi_c^0 \to \Lambda \bar{K}^0$	13.3	10.5 ± 0.6	8.3 ± 5.0
$\Xi_c^0 \to \Sigma^0 \bar{K}^0$	0.4	0.8 ± 0.8	7.9 ± 4.8
$\Xi_c^0 \to \Sigma^+ K^-$	7.8	5.9 ± 1.1	22.0 ± 5.7

purely non-factorizable



$\Xi_c^0 \to \Lambda \overline{K}^0, \Sigma^0 \overline{K}^0$

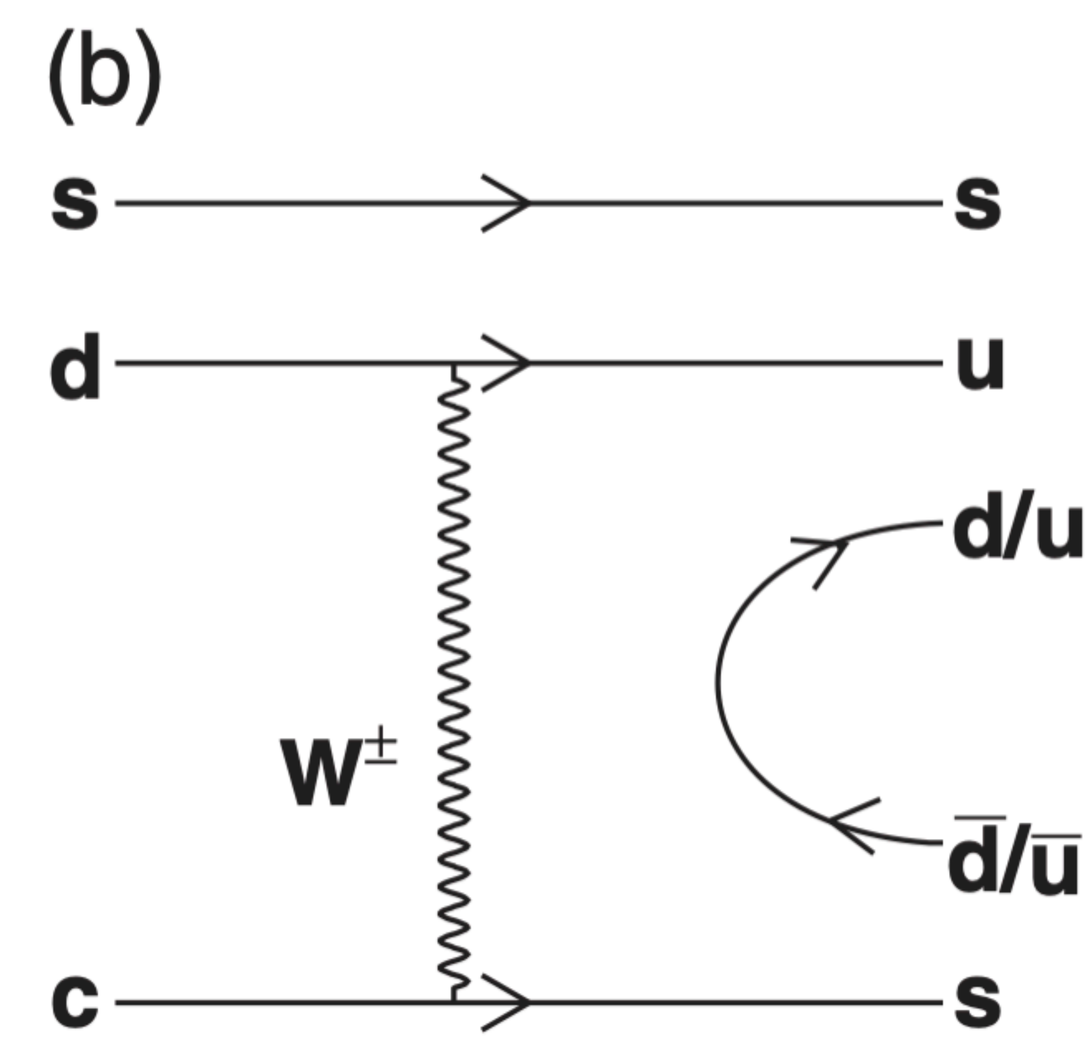
dynamical model calculations

[4] J. Zou, F. Xu, G. Meng, and H. Y. Cheng, Phys. Rev. D **101**, 014011 (2020).

$SU(3)_F$ symmetry approaches

[5] C. Q. Geng, C. W. Liu, and T. H. Tsai, Phys. Lett. B **794**, 19 (2019).

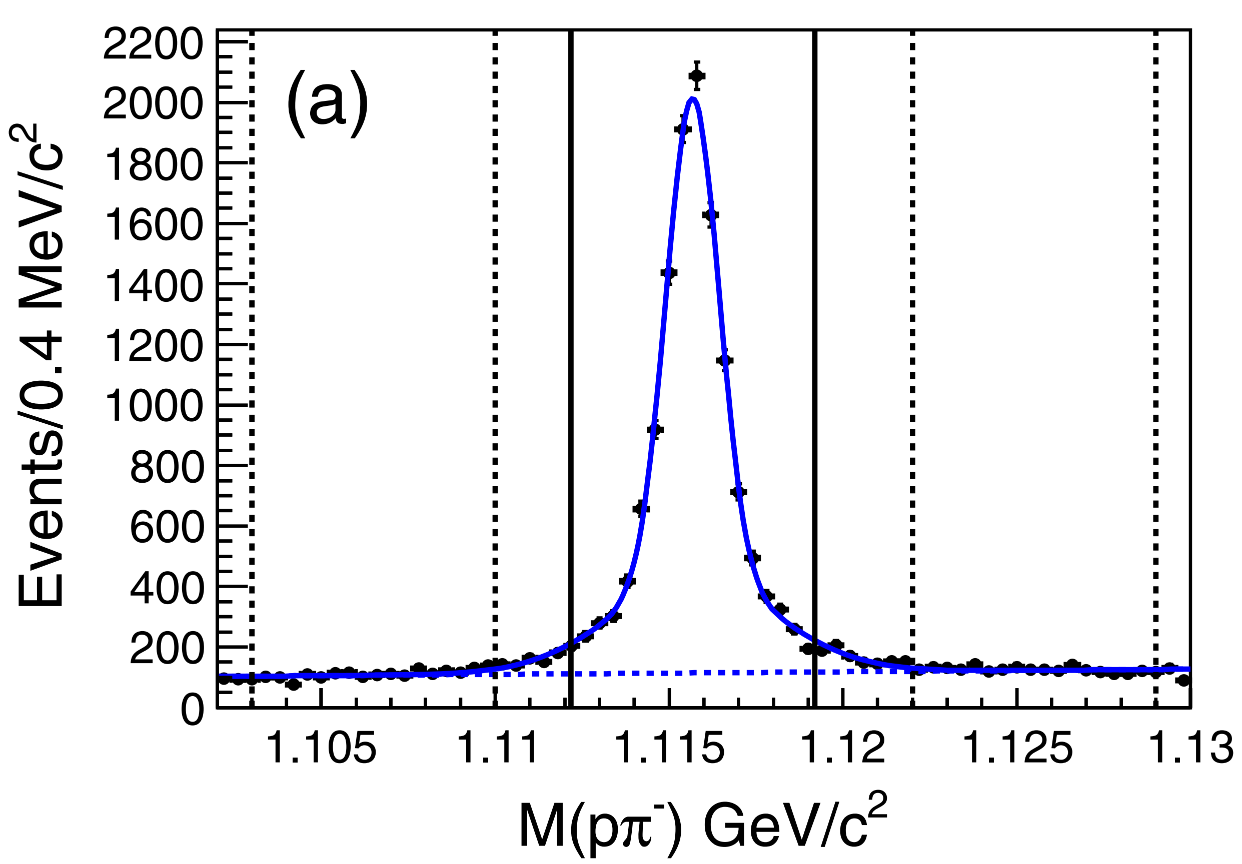
[6] H. J. Zhao, Y. L. Wang, Y. K. Hsiao, and Y. Yu, J. High Energy Phys. 02 (2020) 165.



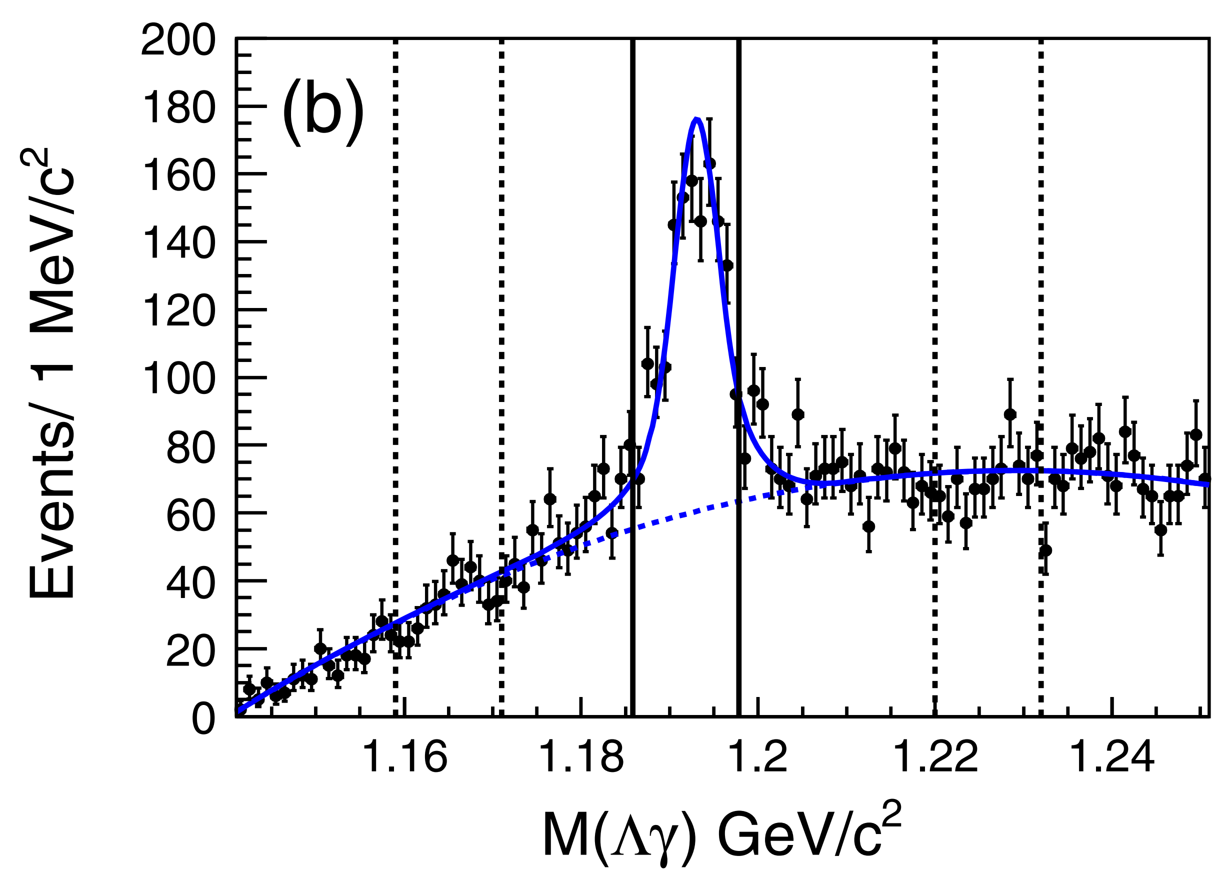
$\Xi_c^0 \to \Lambda \overline{K}^0, \Sigma^0 \overline{K}^0, \Sigma^+ K^-$

$\Xi_c^0 \to \Lambda K_S^0, \Sigma^0 K_S^0, \Sigma^+ K^-$

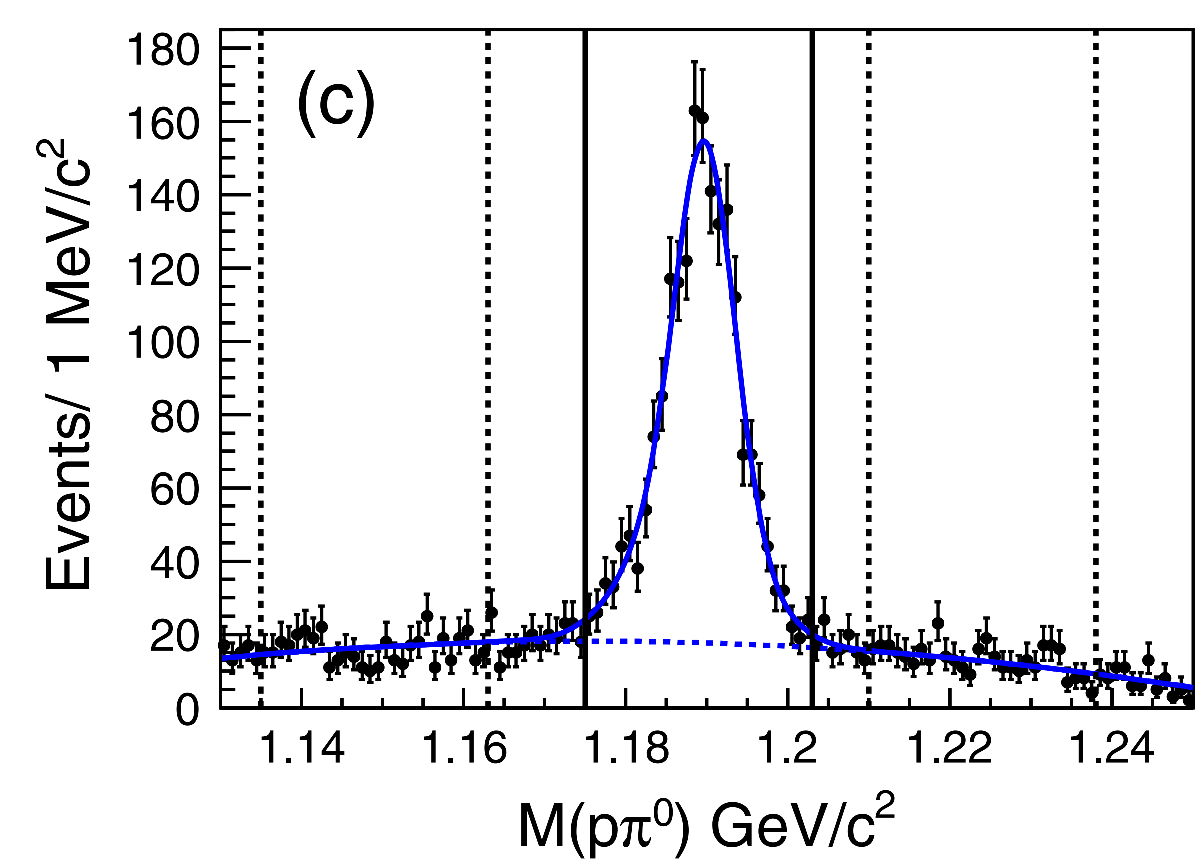
- existing measurements: ΛK_S^0 (Belle 2005)
- $\int \mathscr{L} dt = 980\ \mathrm{fb}^{-1}$ on or near $\Upsilon(nS)$ $(n = 1,\cdots,5)$



for $\Lambda \to p\pi^-$



$\Sigma^0 \to \Lambda\gamma$



$\Sigma^+ \to p\pi^0$

$\Xi_c^0 \to \Lambda K_S^0,\ \Sigma^0 K_S^0,\ \Sigma^+ K^-$

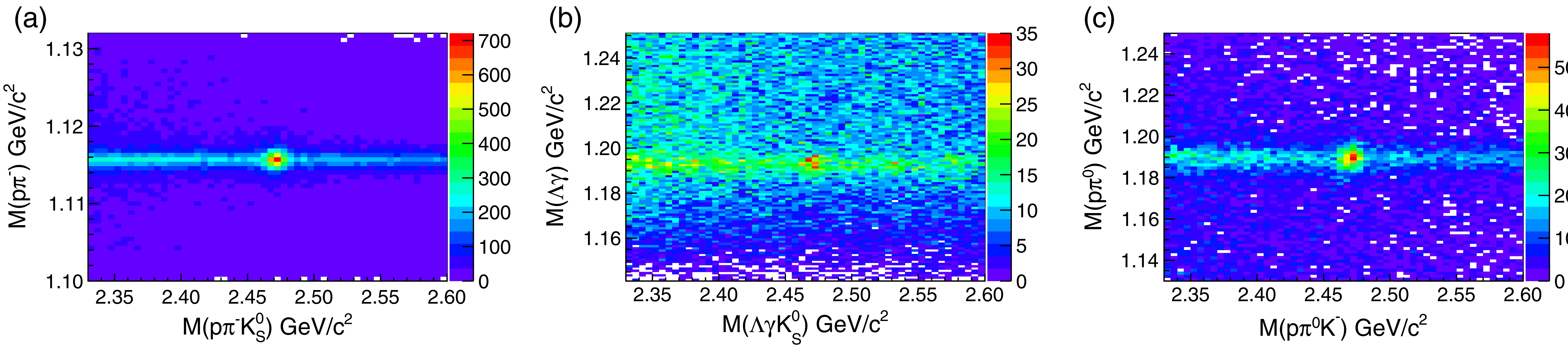
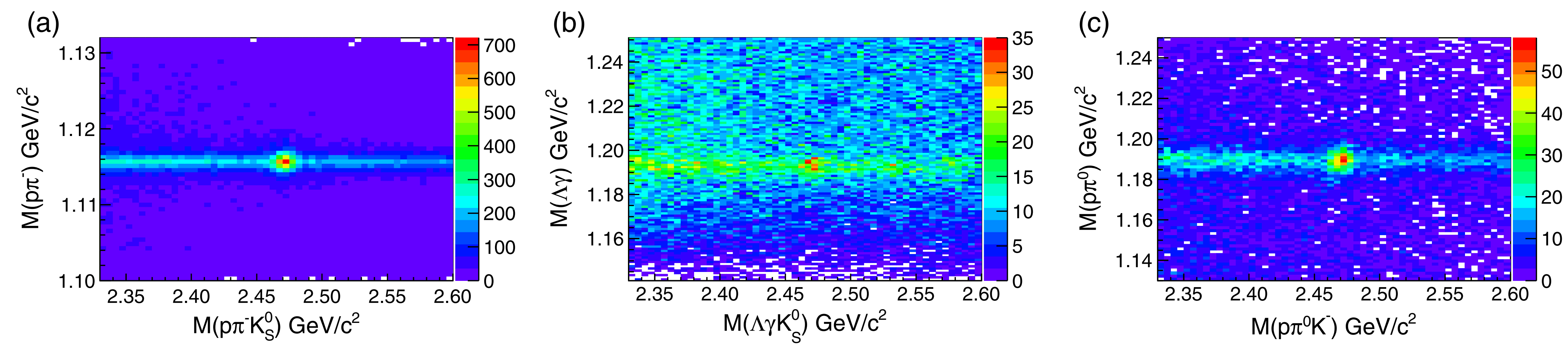


FIG. 4. The scatter plots of (a) $M(p\pi^-)$ versus $M(p\pi^- K_S^0)$, (b) $M(\Lambda\gamma)$ versus $M(\Lambda\gamma K_S^0)$, and (c) $M(p\pi^0)$ versus $M(p\pi^0 K^-)$ from the selected $\Xi_c^0 \to \Lambda K_S^0$, $\Xi_c^0 \to \Sigma^0 K_S^0$, and $\Xi_c^0 \to \Sigma^+ K^-$ candidates in data.

$\Xi_c^0 \to \Lambda K_S^0,\ \Sigma^0 K_S^0,\ \Sigma^+ K^-$



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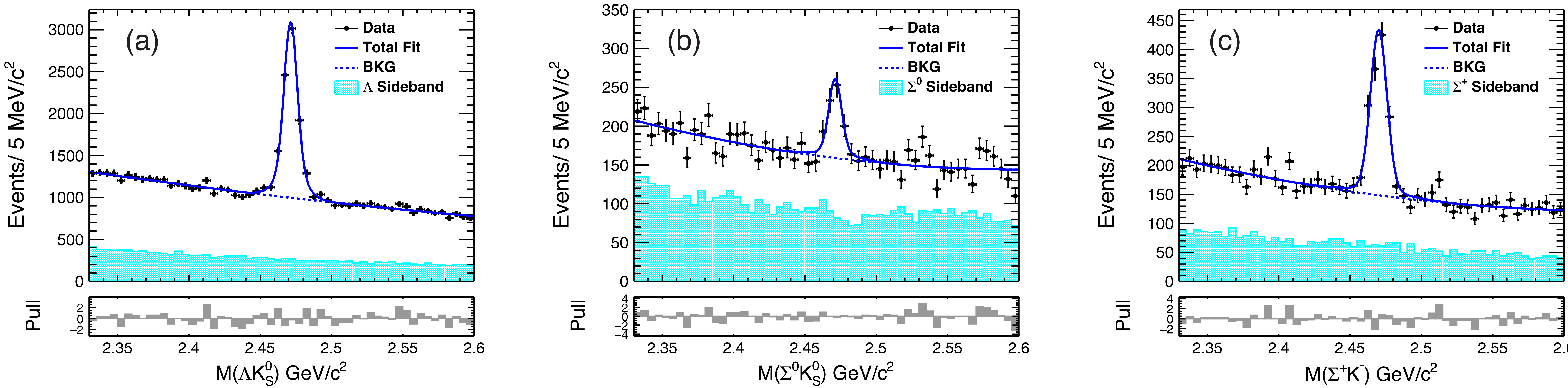
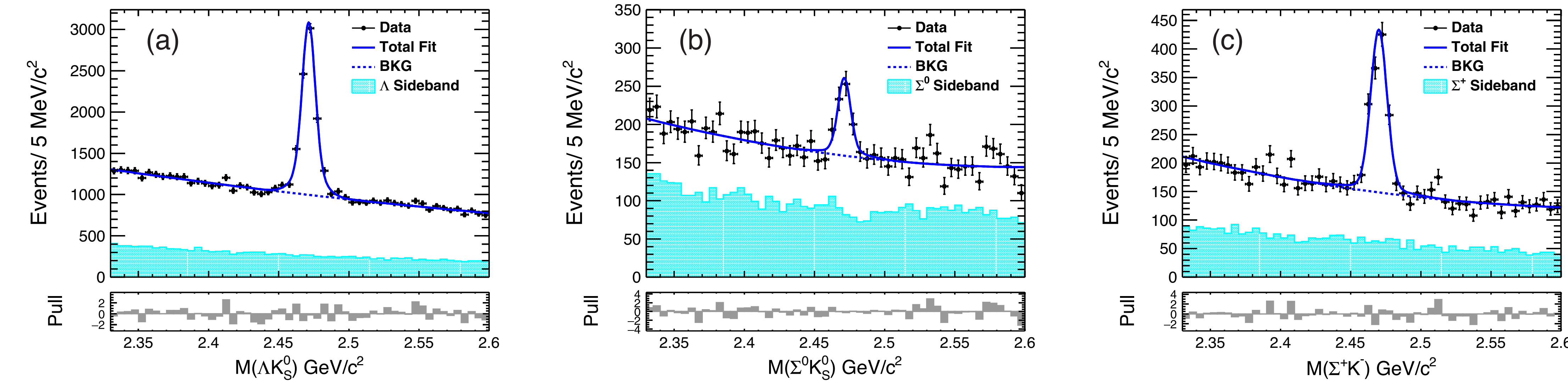


$\Xi_c^0 \to \Lambda K_S^0, \Sigma^0 K_S^0, \Sigma^+ K^-$

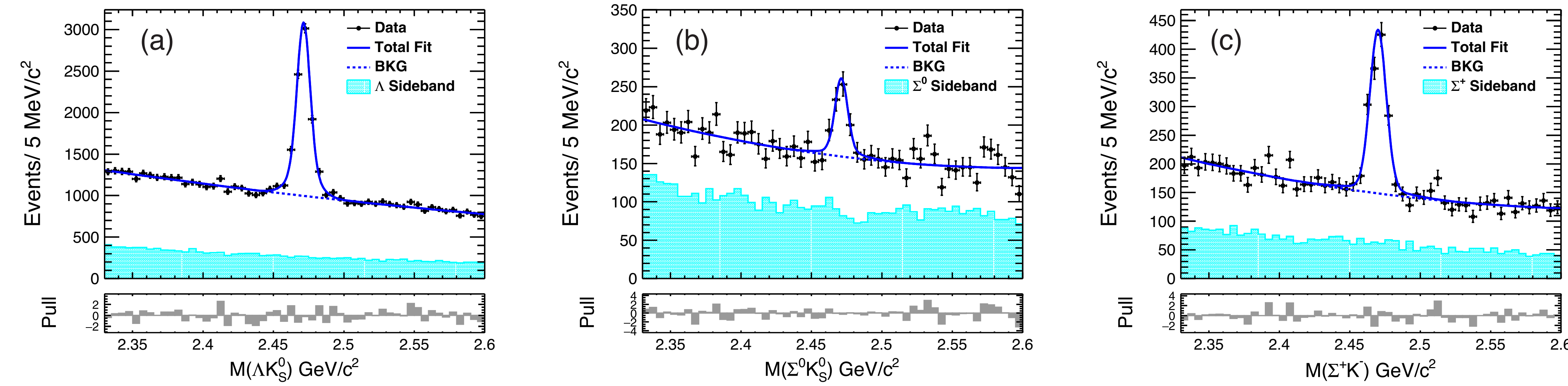


$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda K_S^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = \frac{N^{\rm obs}_{\Lambda K_S^0}\epsilon_{\Xi^-\pi^+}\mathcal{B}(\Xi^- \to \Lambda\pi^-)}{N^{\rm obs}_{\Xi^-\pi^+}\epsilon_{\Lambda K_S^0}\mathcal{B}(K_S^0 \to \pi^+\pi^-)}$$
$$= 0.229 \pm 0.008({\rm stat}) \pm 0.012({\rm syst}),$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = \frac{N^{\rm obs}_{\Sigma^+ K^-}\epsilon_{\Xi^-\pi^+}}{N^{\rm obs}_{\Xi^-\pi^+}\epsilon_{\Sigma^+ K^-}} \times \frac{\mathcal{B}(\Xi^- \to \Lambda\pi^-)\mathcal{B}(\Lambda \to p\pi^-)}{\mathcal{B}(\Sigma^+ \to p\pi^0)\mathcal{B}(\pi^0 \to \gamma\gamma)}$$
$$= 0.123 \pm 0.007({\rm stat}) \pm 0.010({\rm syst}).$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Sigma^0 K_S^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = \frac{N^{\rm obs}_{\Sigma^0 K_S^0}\epsilon_{\Xi^-\pi^+}}{N^{\rm obs}_{\Xi^-\pi^+}\epsilon_{\Sigma^0 K_S^0}} \times \frac{\mathcal{B}(\Xi^- \to \Lambda\pi^-)}{\mathcal{B}(\Sigma^0 \to \Lambda\gamma)\mathcal{B}(K_S^0 \to \pi^+\pi^-)}$$
$$= 0.038 \pm 0.006({\rm stat}) \pm 0.004({\rm syst}),$$

$\Xi_c^0 \to \Lambda K_S^0,\ \Sigma^0 K_S^0,\ \Sigma^+ K^-$



$$\mathcal{B}(\Xi_c^0 \to \Lambda K_S^0) = (3.27 \pm 0.11 \pm 0.17 \pm 0.73) \times 10^{-3},$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^0 K_S^0) = (0.54 \pm 0.09 \pm 0.06 \pm 0.12) \times 10^{-3},$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^-) = (1.76 \pm 0.10 \pm 0.14 \pm 0.39) \times 10^{-3},$$

Modes	Zou *et al.* [4]	Geng *et al.* [5]	Zhao *et al.* [6]
$\Xi_c^0 \to \Lambda \bar{K}^0$	13.3	10.5 ± 0.6	8.3 ± 5.0
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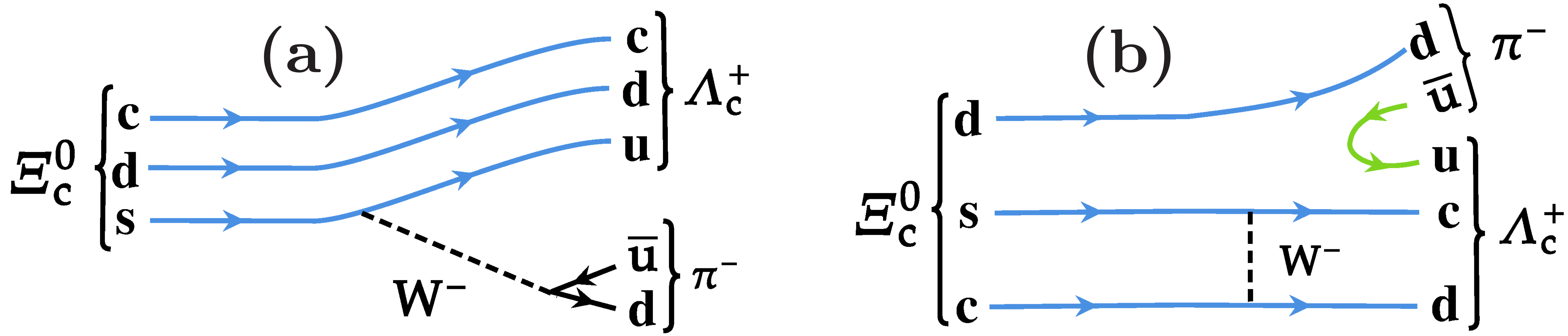
$\Xi_c^0 \to \Sigma^+ K^-$	7.8	5.9 ± 1.1	22.0 ± 5.7

in 10^{-3}

$\Xi_c^0 \to \Lambda_c^+ \pi^-$



W emission   *W* exchange

$(\mathrm{CLY})^2$('92) [1]	Voloshin [3]	Gronau [4]	Faller [5]	$(\mathrm{CLY})^2$('06) [6]
0.39	$> (0.25 \pm 0.15)$	1.34 ± 0.53	< 3.9	0.17

TABLE I: Theoretical predictions on the branching fraction of $\Xi_c^0 \to \Lambda_c^+ \pi^-$ before experimental measurement (10^{-3}). All the results have been normalized using the current world average lifetimes of the $SU(3)$ anti-triplets [8, 9].

[1] H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, T. M. Yan, and H. L. Yu, Phys. Rev. D **46**, 5060 (1992).

[3] M. B. Voloshin, Phys. Rev. D **100**, 114030 (2019).

[4] M. Gronau and J. L Rosner, Phys. Lett. B **757**, 330 (2016).

[5] S. Faller and T. Mannel, Phys. Lett. B **750**, 653 (2015).

[6] H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, T. M. Yan, and H. L. Yu, JHEP **03**, 028 (2016).

$\Gamma(\Lambda_c^+ \pi^-)/\Gamma_{total}$ **Γ_{21}/Γ**

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
5.5±0.2±1.8	6.3k	[1] AAIJ 20AH	LHCB	pp at 13 TeV

large syst error (model assumption)

$\Xi_c^0 \to \Lambda_c^+ \pi^-$

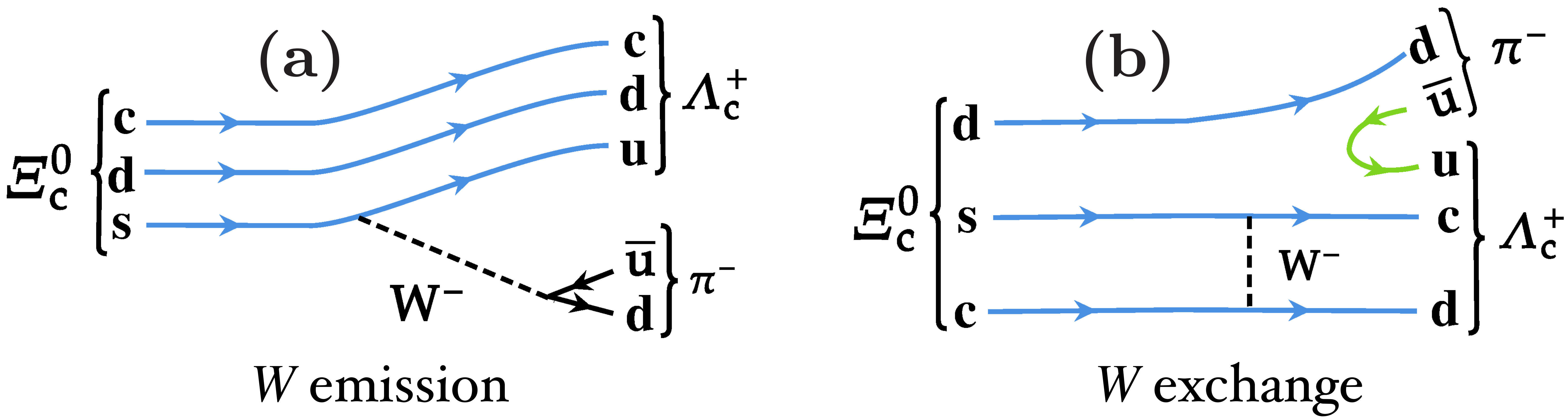


Table 9
Uncertainties of the branching ratios (in %) caused by the quark

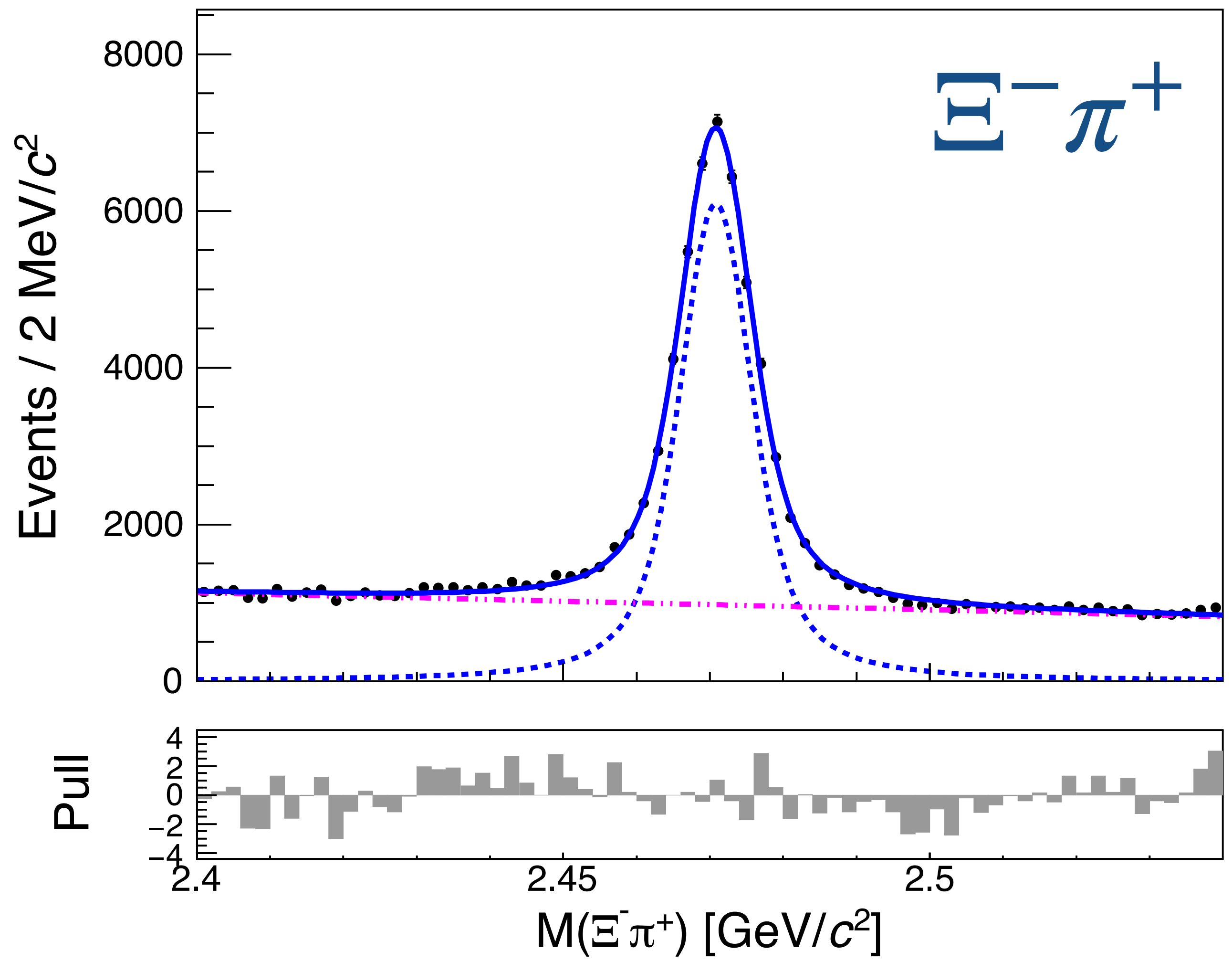
Input	$\Xi_c^+ \to \Lambda_c \pi^0$	$\Xi_c^0 \to \Lambda_c \pi^-$	Ξ_b^0 –
Exp. Data	···	0.55 ± 0.20 [1]	···
m_q	1.11 ± 0.10	0.58 ± 0.051	0.01
m_s	1.11 ± 0.17	0.58 ± 0.088	0.01
m_c	1.11 ± 0.053	0.58 ± 0.027	0.01
m_b	1.11 ± 0	0.58 ± 0	0.01
K	1.11 ± 0.34	0.58 ± 0.18	0.01
R	1.11 ± 0	0.58 ± 0.002	0.01
Combined	1.11 ± 0.40	0.58 ± 0.21	0.01

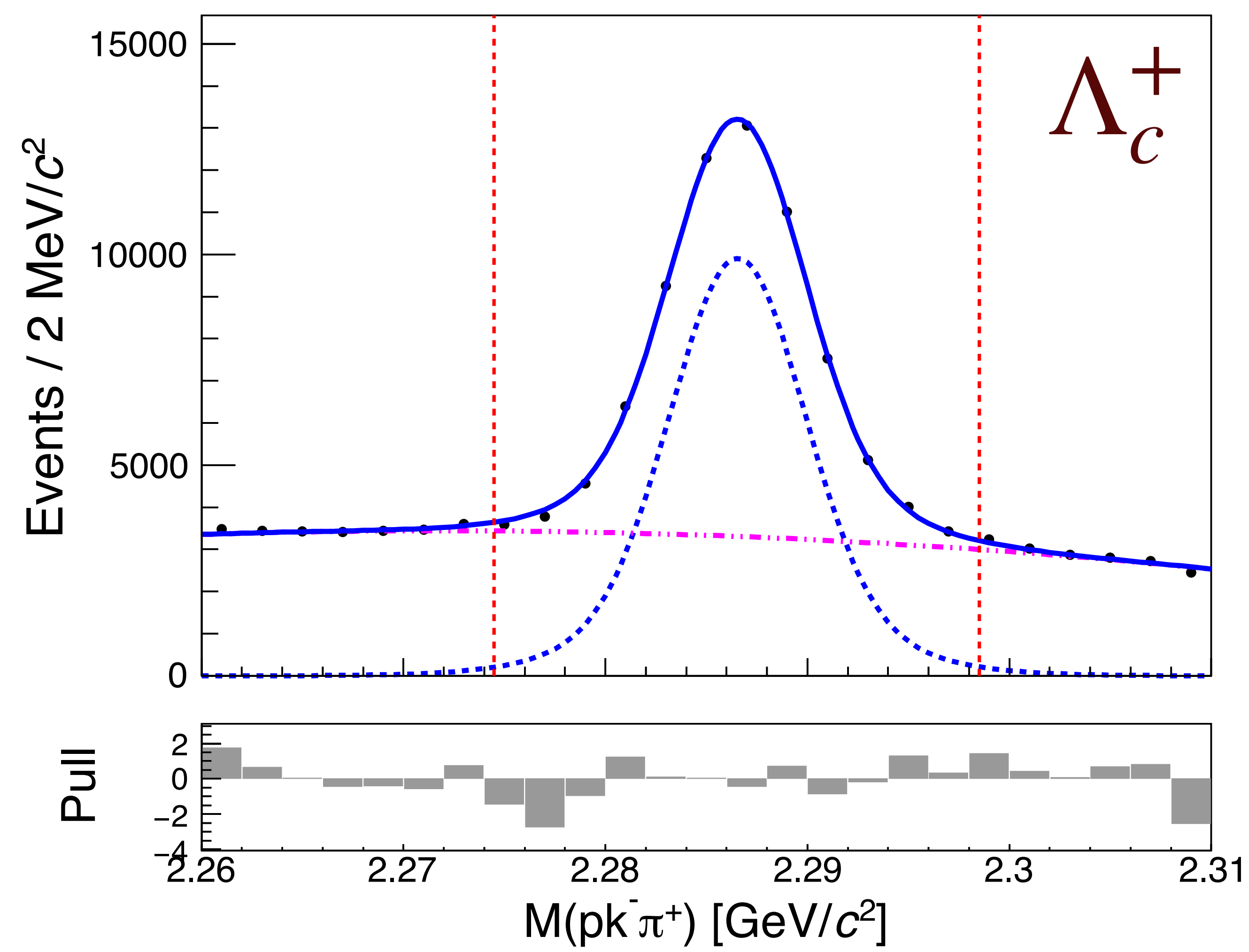
[10] P. Y. Niu, Q. Wang, and Q. Zhao, Phys. Lett. B **826**, 136916 (2022).

based on a constituent quark model

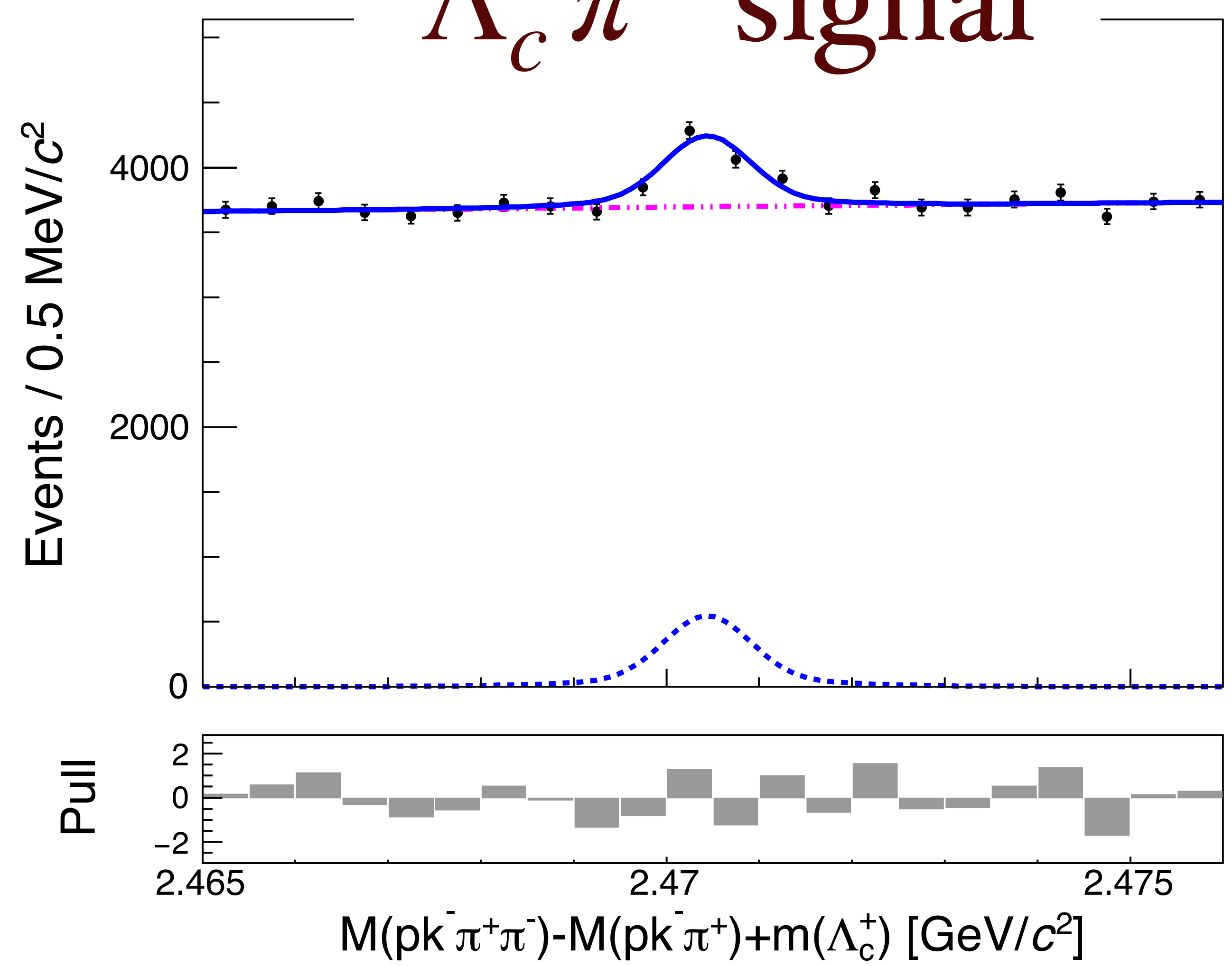
$\Xi_c^0 \to \Lambda_c^+ \pi^-$

- $\int \mathscr{L} dt = 983 \text{ fb}^{-1}$ on or near $\Upsilon(nS)$ $(n = 1,\cdots,5)$



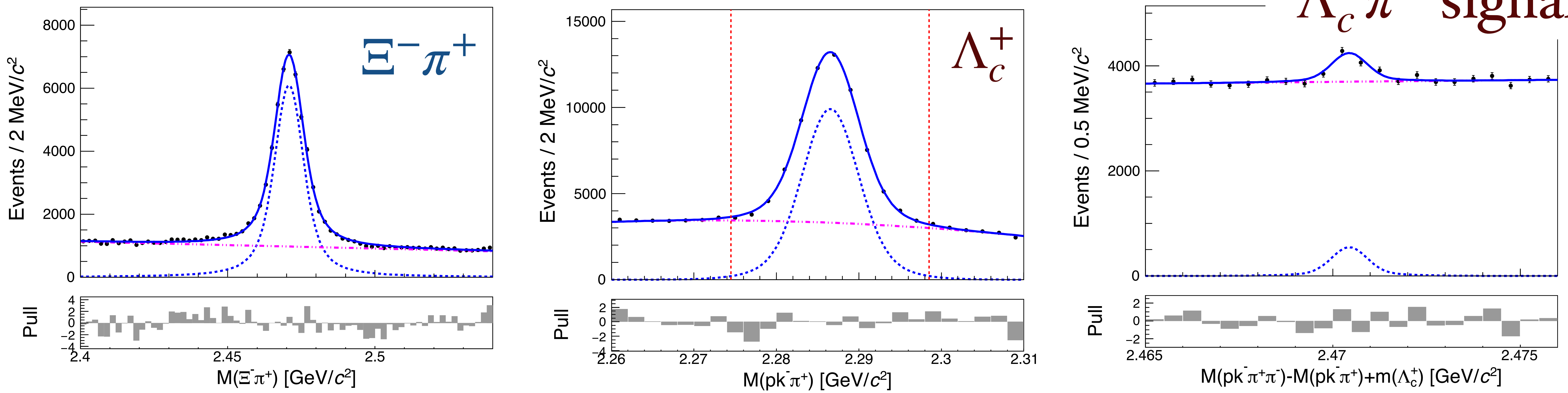


$\Lambda_c^+\pi^-$ signal



$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda_c^+ \pi^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = \frac{N_{\Lambda_c \pi} \times \epsilon_{\Xi\pi}^{\text{ref}} \times \mathcal{B}(\Xi^- \to \Lambda\pi^-) \times \mathcal{B}(\Lambda \to p\pi^-)}{N_{\Xi\pi} \times \epsilon_{\Lambda_c\pi}^{\text{sig}} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.38 \pm 0.04 \pm 0.04$$

$\Xi_c^0 \to \Lambda_c^+ \pi^-$



$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = \frac{N_{\Lambda_c\pi} \times \epsilon_{\Xi\pi}^{\rm ref} \times \mathcal{B}(\Xi^- \to \Lambda\pi^-) \times \mathcal{B}(\Lambda \to p\pi^-)}{N_{\Xi\pi} \times \epsilon_{\Lambda_c\pi}^{\rm sig} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.38 \pm 0.04 \pm 0.04$$

Using $\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.43 \pm 0.32)\,\%$, we measure

$$\mathscr{B}(\Xi_c^0 \to \Lambda_c^+\pi^-) = (0.54 \pm 0.05 \pm 0.05 \pm 0.12)\,\%$$

- consistent w/ LHCb, with slightly larger uncertainty
- BF larger than theory predictions

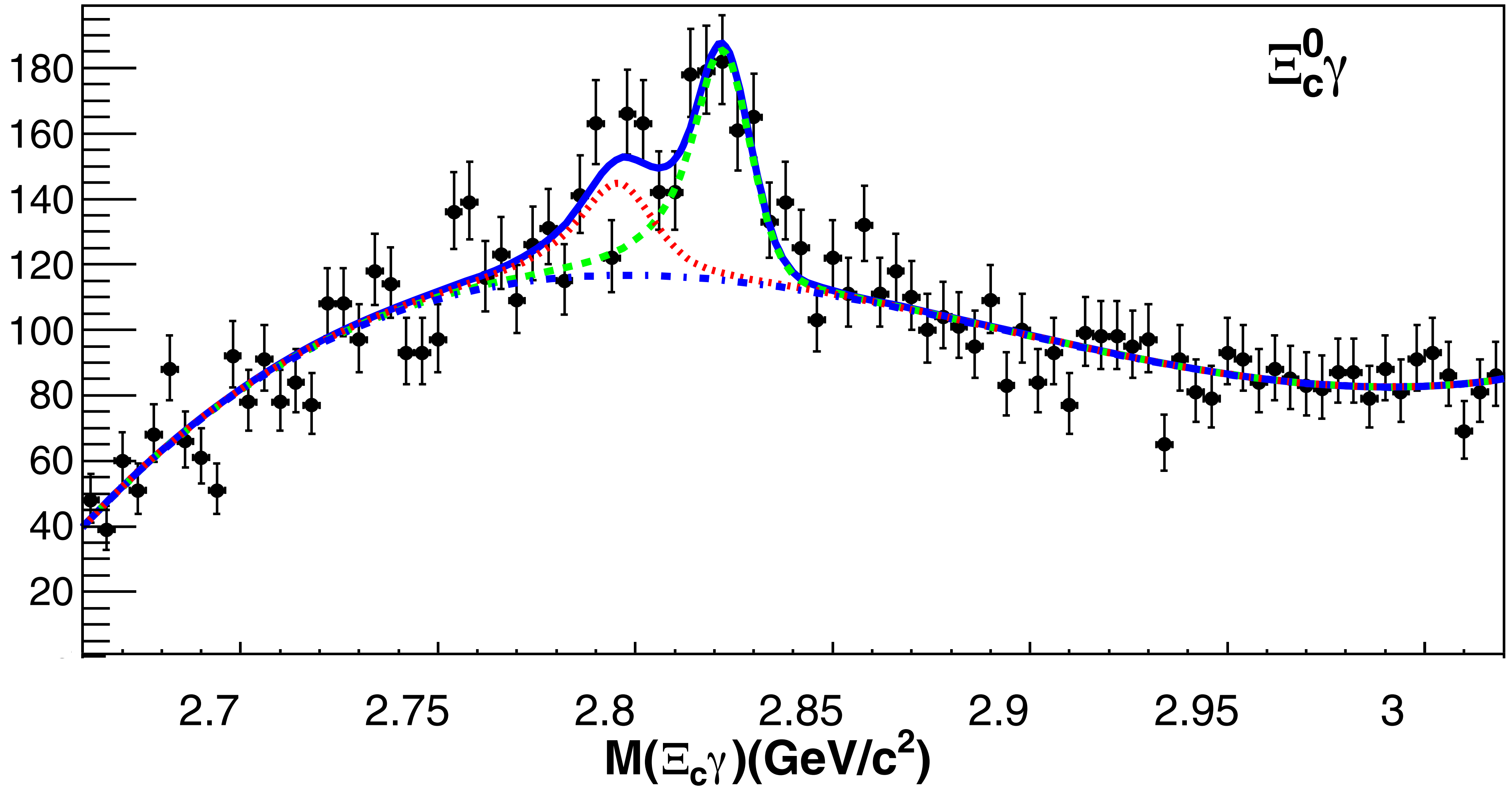
Radiative decays

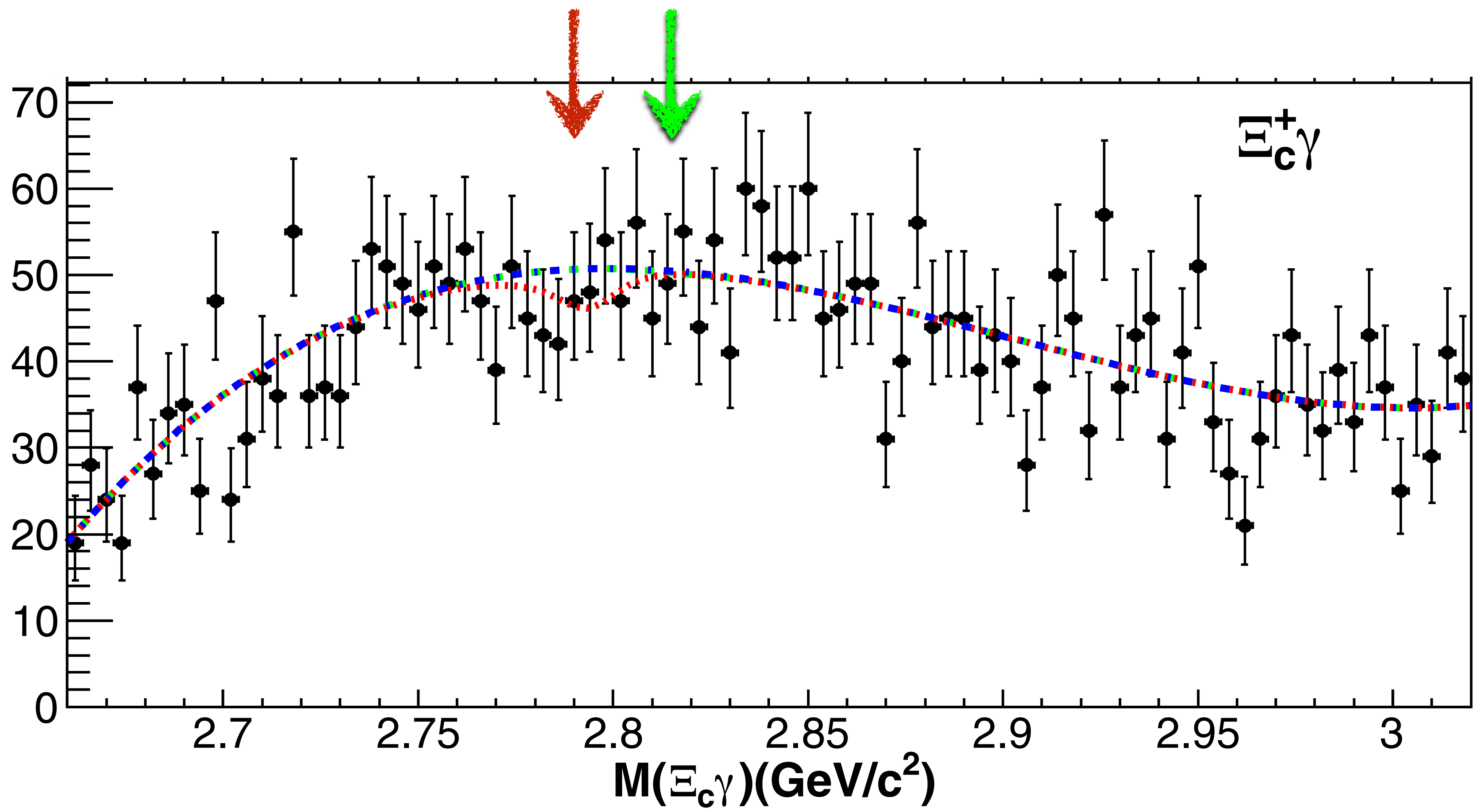
$\Xi_c(2790/2815) \to \Xi_c\gamma$

- Recently measured $\Xi_c(2790)^{+/0}$ & $\Xi_c(2815)^{+/0}$ masses and widths
  - In the picture of $(c + ud, us)$, these are typically interpreted as $L = 1$ orbital excitations ("λ").
  - The nature of these states are identified by mass spectra and decay modes.
- Excited charmed baryons mostly decay via strong interactions.
  - the only observed EM decays : $\Xi_c' \to \Xi_c\gamma,\ \Omega_c(2770) \to \Omega_c\gamma$
- Wang, Yao, Zhong, Zhao (PRD 96, 116016 (2017)) predicts
  - assuming λ excitations, large widths of $\Xi_c(2790)^0 \to \Xi_c^0\gamma,\ \Xi_c(2815)^0 \to \Xi_c^0\gamma$ $(\Gamma \gtrsim 200\ \text{keV})$
  - assuming ρ excitations (between the two light quarks), much smaller widths $(< 10\ \text{keV})$ for the Ξ_c^+ baryons

PRD 102, 071103 (2021)

$\Xi_c(2790/2815) \rightarrow \Xi_c\gamma$





$$R^0_{2790} = \frac{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-]} = 0.13 \pm 0.03 \pm 0.02$$

$$R^+_{2790} = \frac{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c'^0\pi^+ \to \Xi_c^0\gamma\pi^+]} < 0.06 \text{ @ } 90\% \text{ C.L.}$$

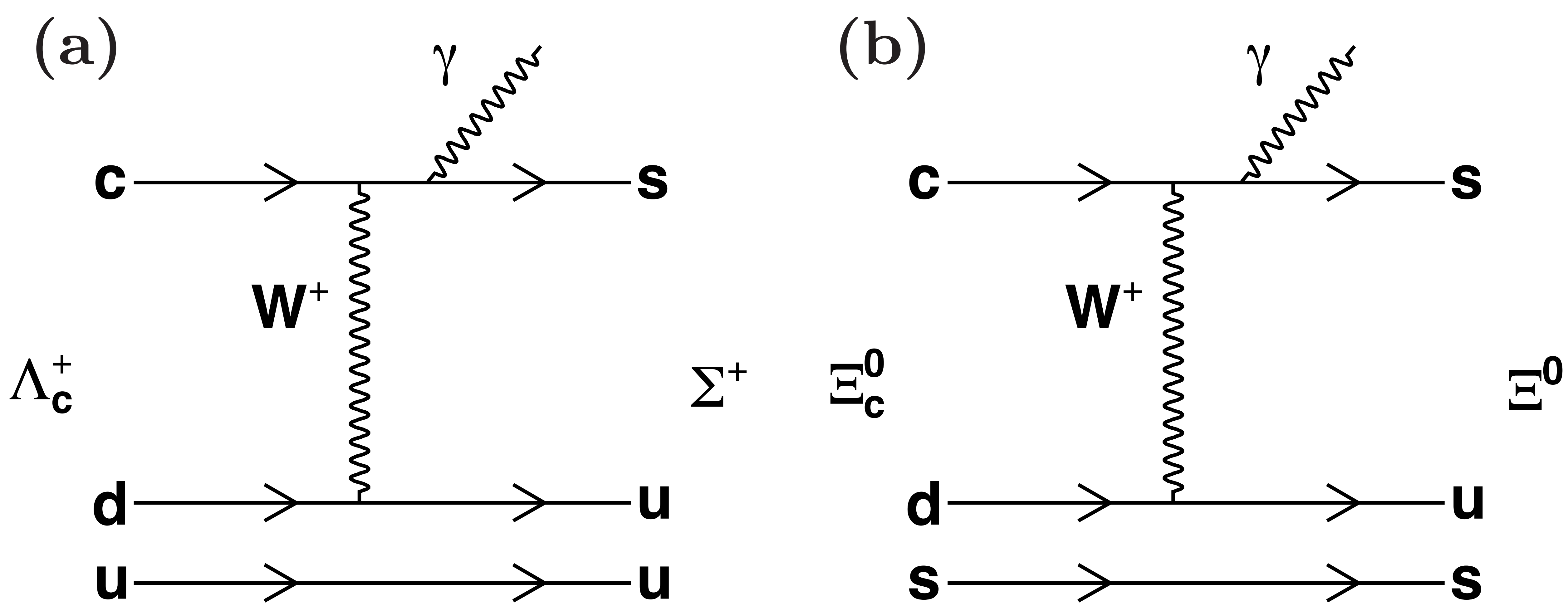
$$R^0_{2815} = \frac{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-]} = 0.41 \pm 0.05 \pm 0.03$$

$$R^+_{2815} = \frac{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^+\pi^-]} < 0.09 \text{ @ } 90\% \text{ C.L.}$$

- First observation of radiative decays of orbitally excited Ξ_c
- Confirm the theoretical prediction [WYZZ, PRD (2017)]

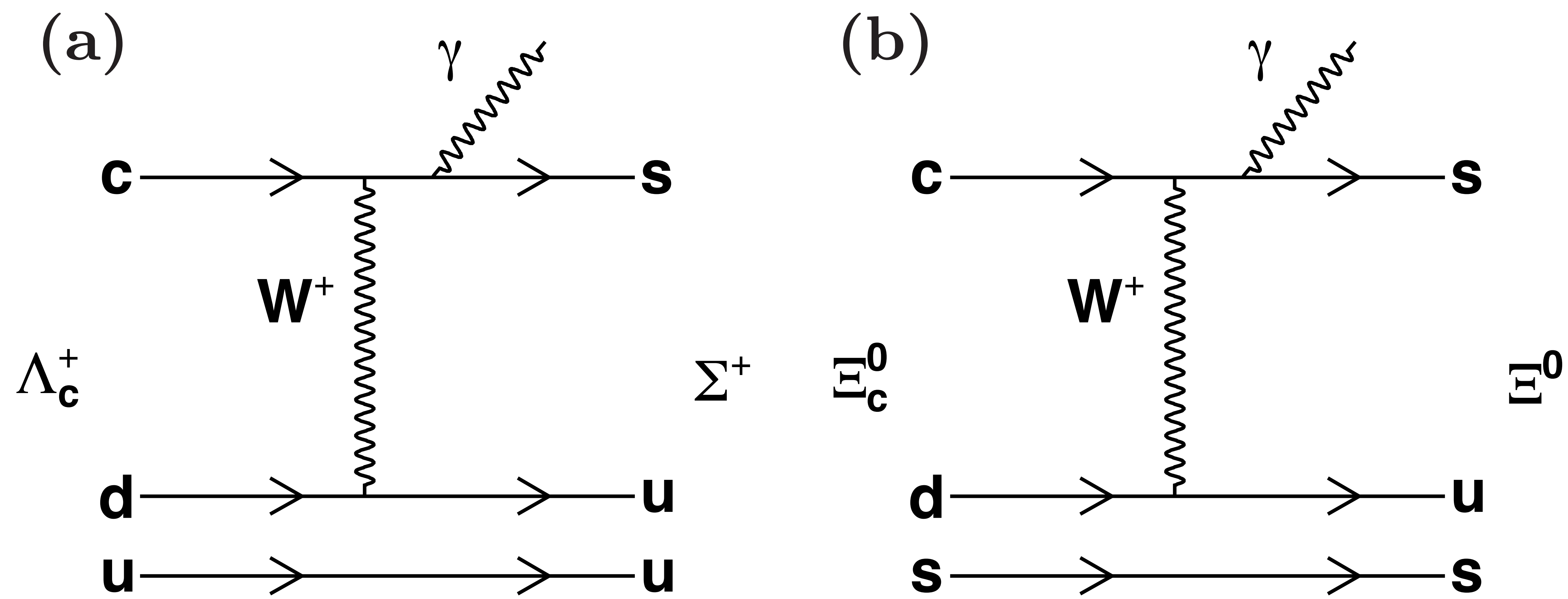
$\Lambda_c^+ \to \Sigma^+\gamma, \;\; \Xi_c^0 \to \Xi^0\gamma$

- **weak radiative** decays, via W exchange



- not been observed in charmed baryons
- $\exists$ (+) signals for charm mesons: $D^0 \to \phi\gamma, \overline{K}^{*0}\gamma$ https://doi.org/10.1103/PhysRevLett.118.051801
- $\exists\ \Lambda_b \to \Lambda\gamma$ by LHCb (2019) $\Leftarrow b \to s\gamma$

$\Lambda_c^+ \to \Sigma^+\gamma, \;\; \Xi_c^0 \to \Xi^0\gamma$



Modes	Kamal [4]	Uppal [5] (I)	Uppal [5] (II)	Cheng [6]
$\Lambda_c^+ \to \Sigma^+\gamma$	6.0	4.5	29.1	4.9
$\Xi_c^0 \to \Xi^0\gamma$	...	3.0	19.5	4.8

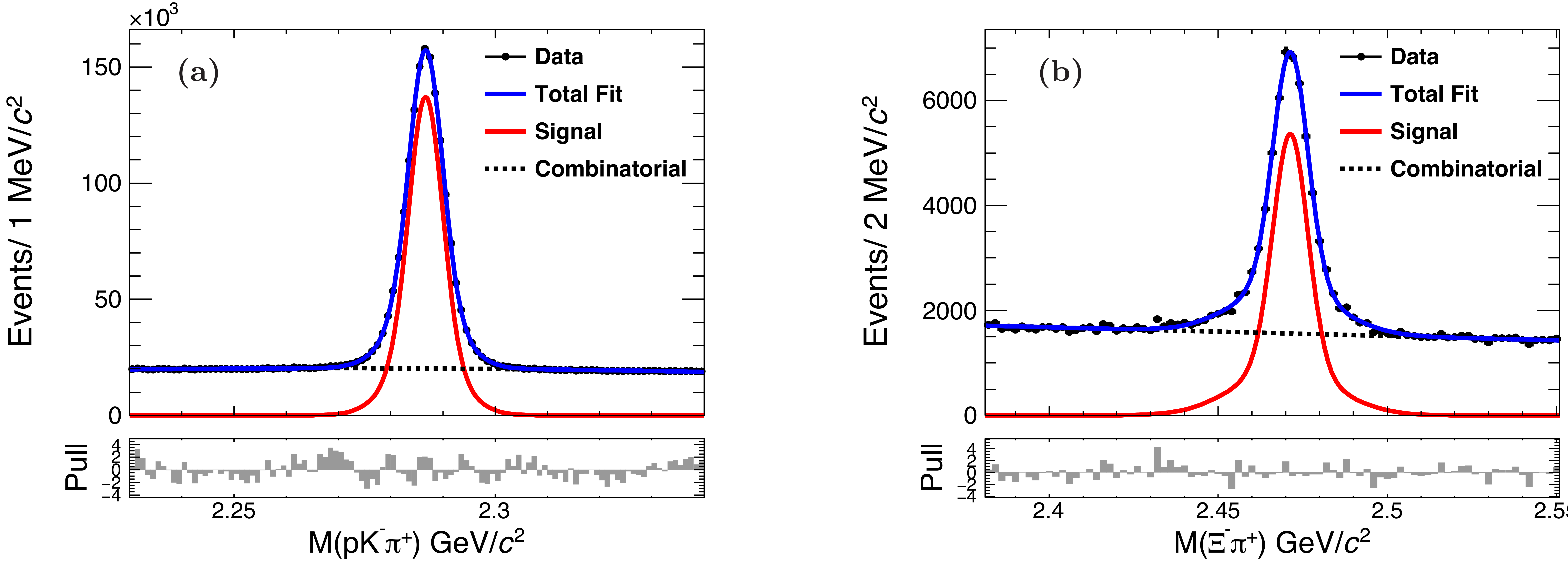
- theory predictions of BF in units of 10^{-5}
- two cases for [5] depeding on $|\psi(0)|^2$

[4] A. N. Kamal, Phys. Rev. D **28**, 2176 (1983).
[5] T. Uppal and R. C. Verma, Phys. Rev. D **47**, 2858 (1993).
[6] H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, T. M. Yan, and H. L. Yu, Phys. Rev. D **51**, 1199 (1995).

arXiv:2206.12517

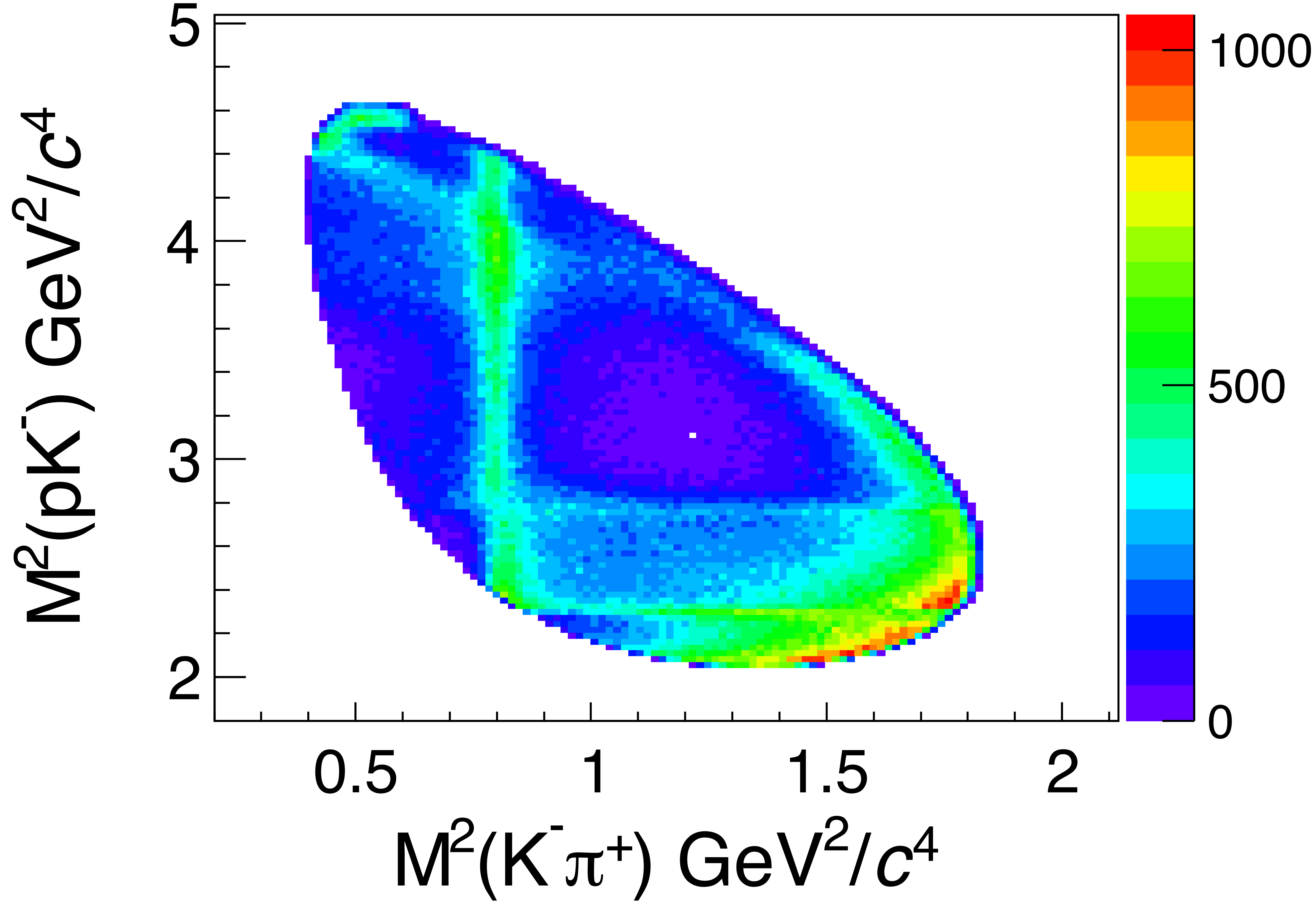
$\Lambda_c^+ \to \Sigma^+\gamma$, $\Xi_c^0 \to \Xi^0\gamma$

- 980 fb^{-1} Belle data
- use $\Xi^0 \to \Lambda\pi^0$, $\Sigma^+ \to p\pi^0$
- each mode, ***normalized*** to $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+$



$\Lambda_c^+ \to \Sigma^+\gamma$, $\Xi_c^0 \to \Xi^0\gamma$

- Efficiencies of the reference modes



$\Lambda_c^+ \to pK^-\pi^+$ signal efficiency is weighted over the Dalitz distribution

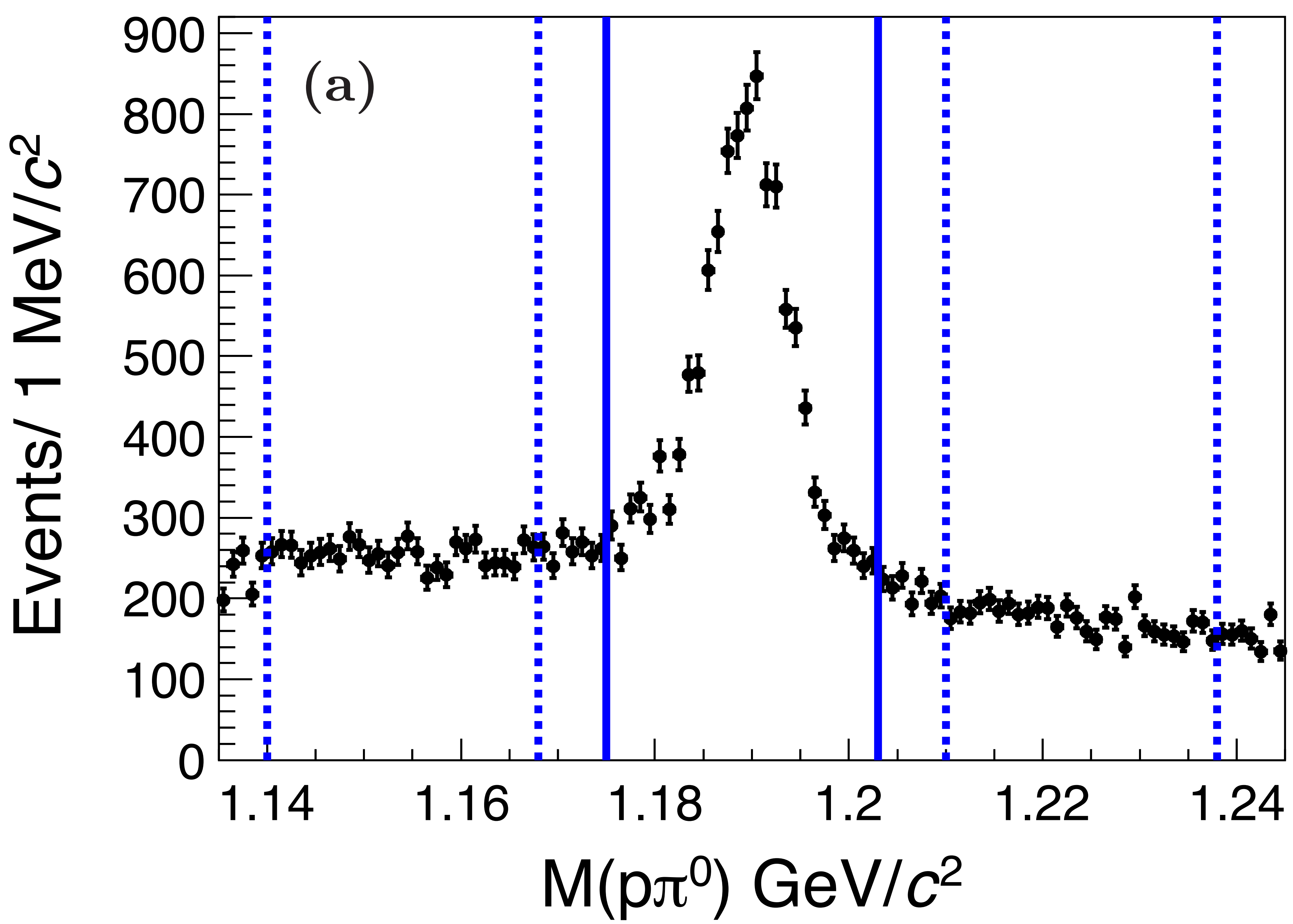
$$\epsilon = \frac{\sum_i s_i}{\sum_j s_j/\epsilon_j}$$

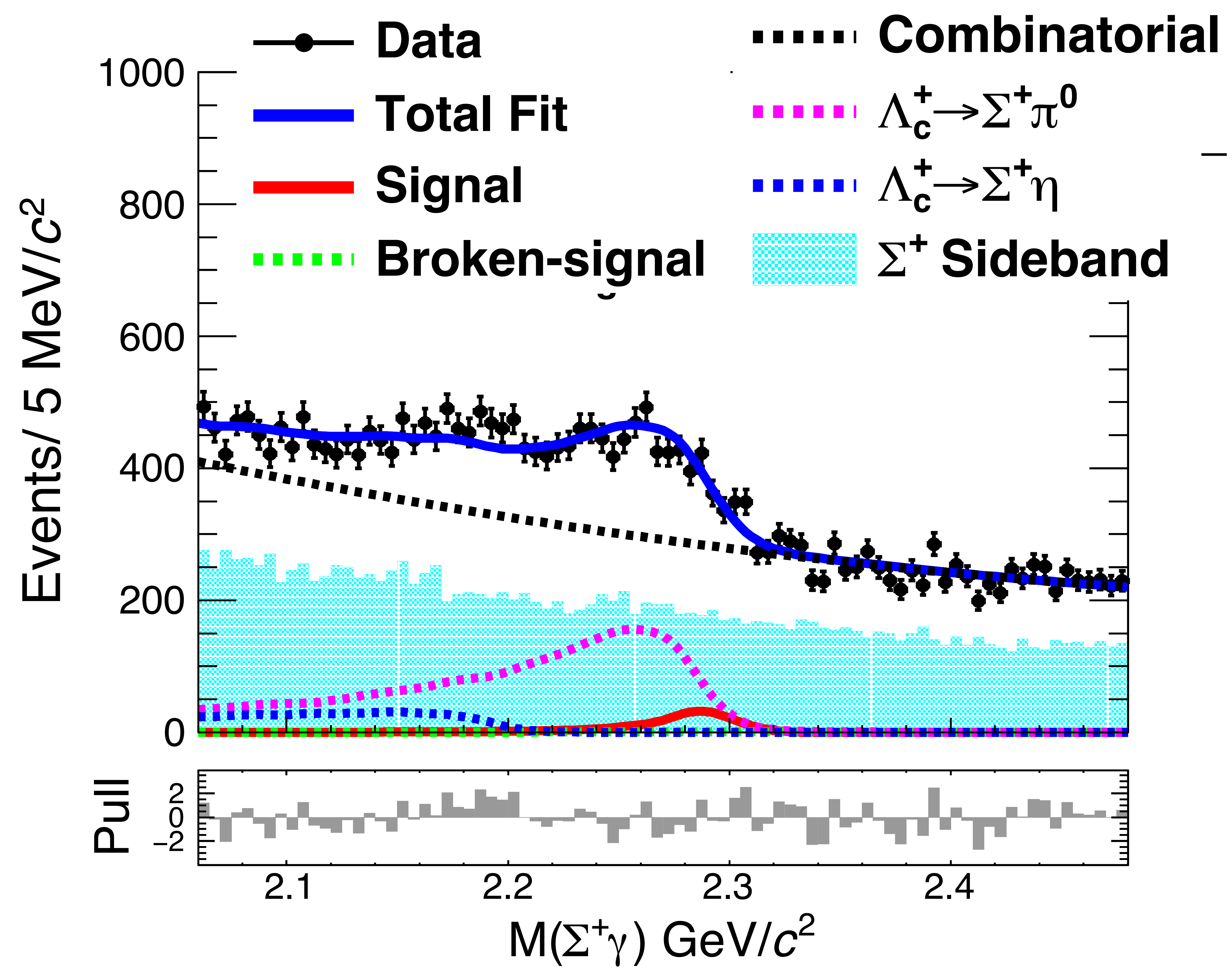
$$= (12.79 \pm 0.02)\,\%$$

For $\Xi_c^0 \to \Xi^-\pi^+$, the efficiency is

$$\epsilon = (16.96 \pm 0.05)\%$$

$\Lambda_c^+ \to \Sigma^+\gamma$, $\Xi_c^0 \to \Xi^0\gamma$

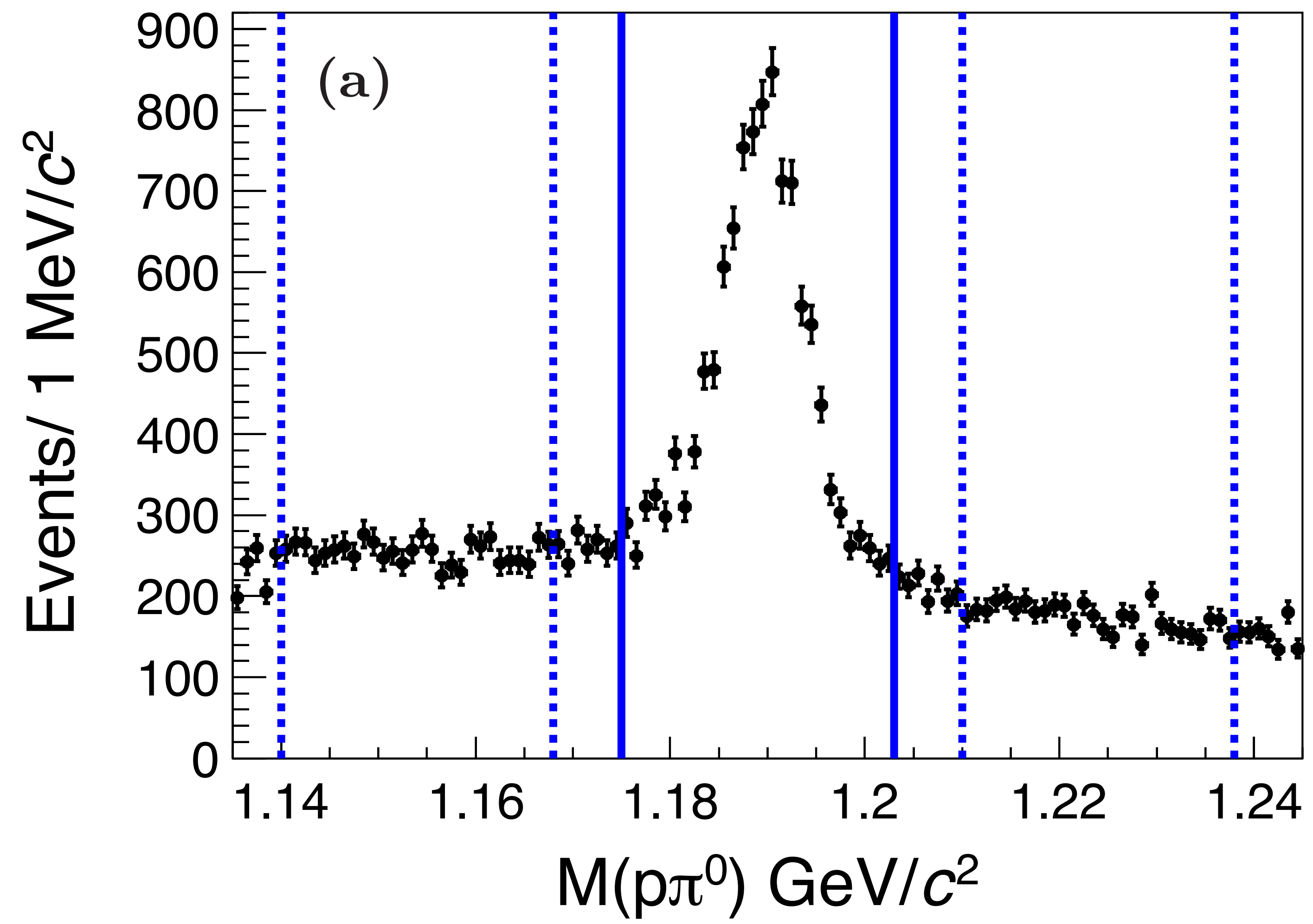


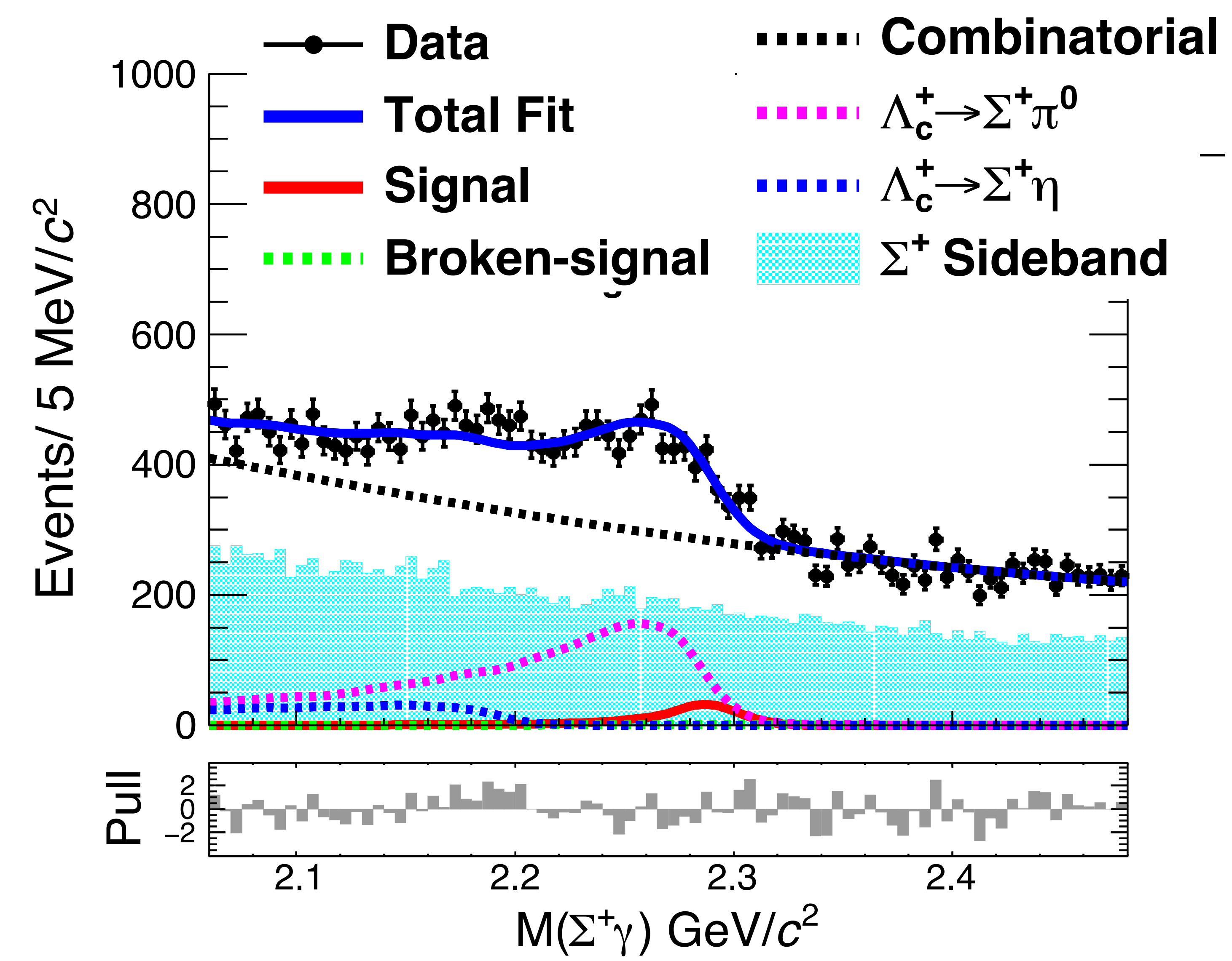


Modes	$N^{\rm obs}$	$N^{\rm UL}$	$\epsilon(\%)$
$\Lambda_c^+ \to \Sigma^+\gamma$	340±110	608	2.98±0.01
$\Lambda_c^+ \to pK^-\pi^+$	1281910±2040	...	12.79±0.02

$S = 2.2\sigma\ (3.2\sigma)$

$\Lambda_c^+ \to \Sigma^+\gamma$, $\Xi_c^0 \to \Xi^0\gamma$





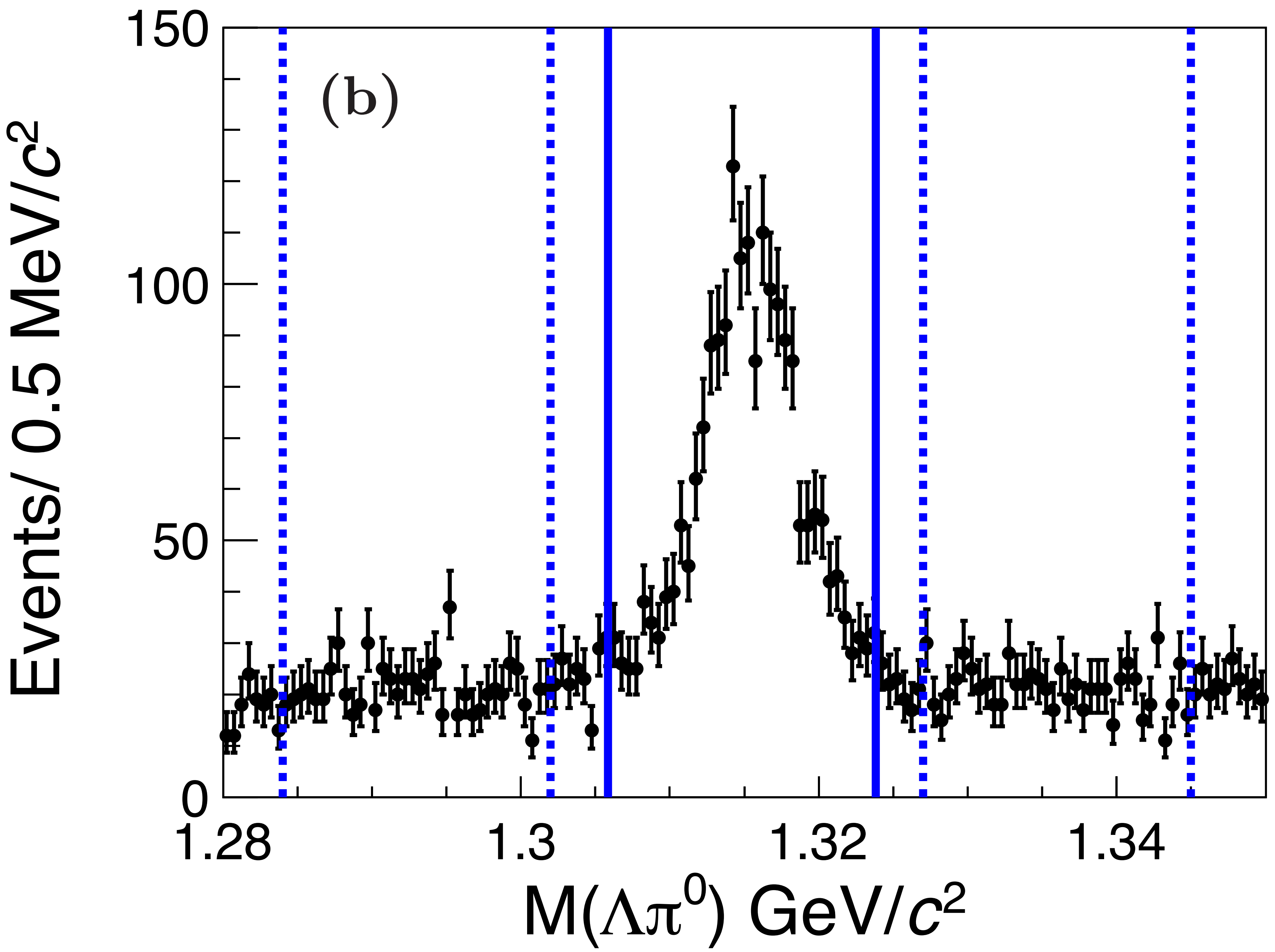
$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\gamma)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} < \frac{N^{\rm UL}_{\Sigma^+\gamma}\epsilon_{pK^-\pi^+}}{N^{\rm obs}_{pK^-\pi^+}\epsilon_{\Sigma^+\gamma}} \times \frac{1}{\mathcal{B}(\Sigma^+ \to p\pi^0)\mathcal{B}(\pi^0 \to \gamma\gamma)}$$

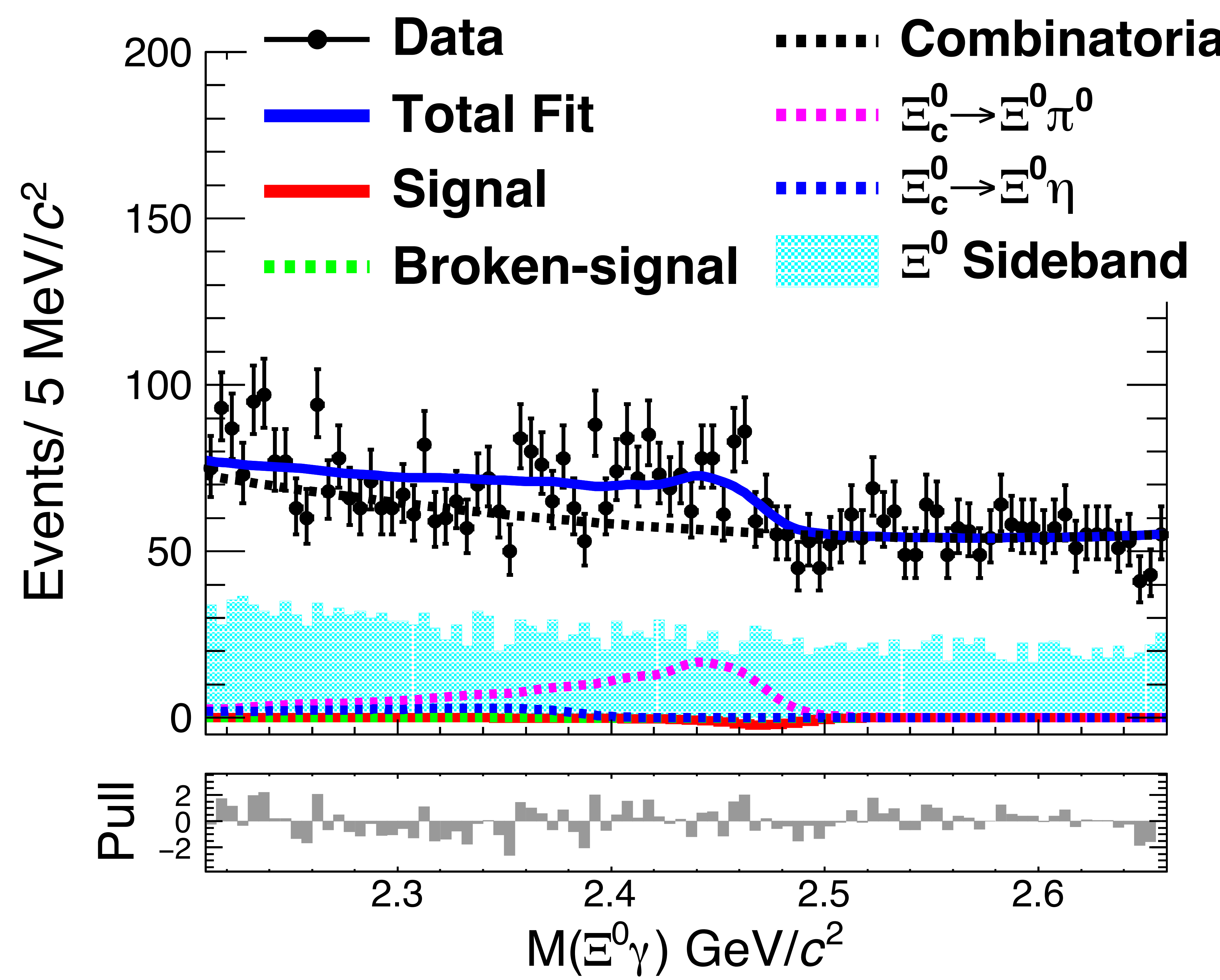
$$= 4.0 \times 10^{-3}$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.6 \times 10^{-4}$$

The UL is slightly smaller than case (ii) prediction of Ref.[5]

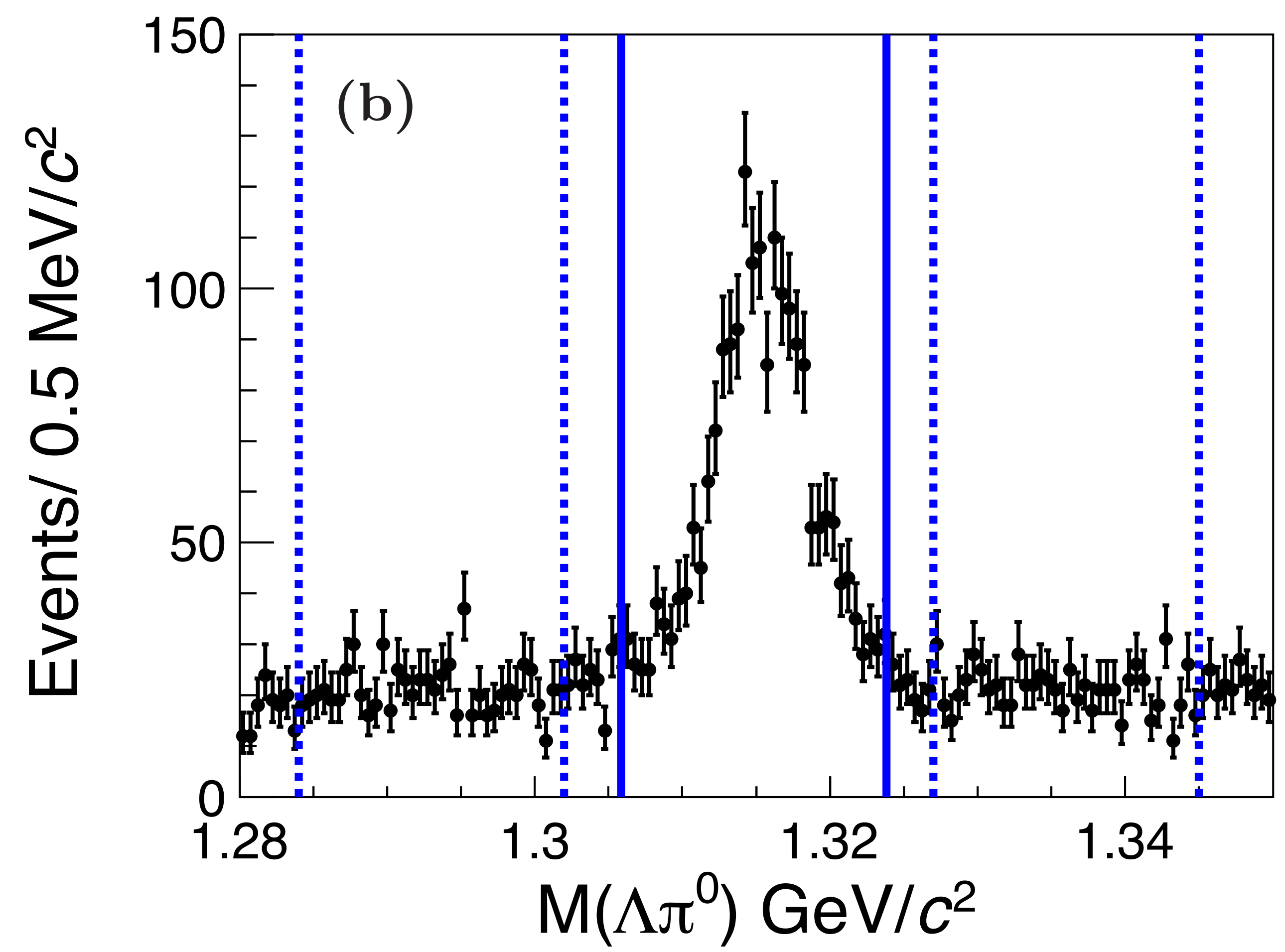
$\Lambda_c^+ \to \Sigma^+\gamma$, $\Xi_c^0 \to \Xi^0\gamma$

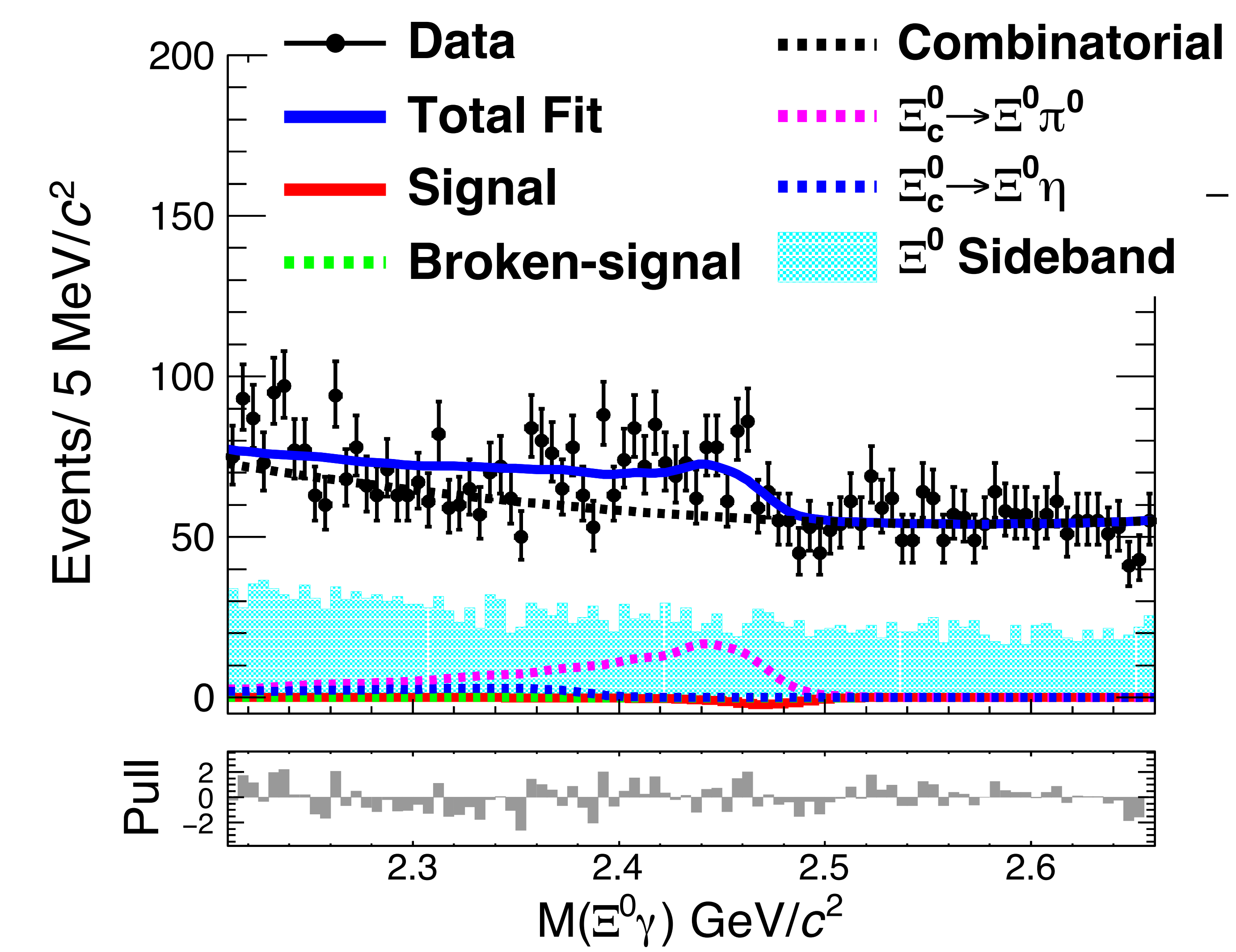




Modes	N^{obs}	N^{UL}	$\epsilon(\%)$
$\Xi_c^0 \to \Xi^0\gamma$	-18 ± 48	91	3.03 ± 0.01
$\Xi_c^0 \to \Xi^-\pi^+$	45063 ± 445	...	16.96 ± 0.05

$\Lambda_c^+ \to \Sigma^+\gamma$, $\Xi_c^0 \to \Xi^0\gamma$





$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\gamma)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} < \frac{N^{\rm UL}_{\Xi^0\gamma}\epsilon_{\Xi^-\pi^+}}{N^{\rm obs}_{\Xi^-\pi^+}\epsilon_{\Xi^0\gamma}} \times \frac{\mathcal{B}(\Xi^- \to \Lambda\pi^-)}{\mathcal{B}(\Xi^0 \to \Lambda\pi^0)\mathcal{B}(\pi^0 \to \gamma\gamma)}$$

$$= 1.2 \times 10^{-2}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\gamma) < 1.7 \times 10^{-4}$$

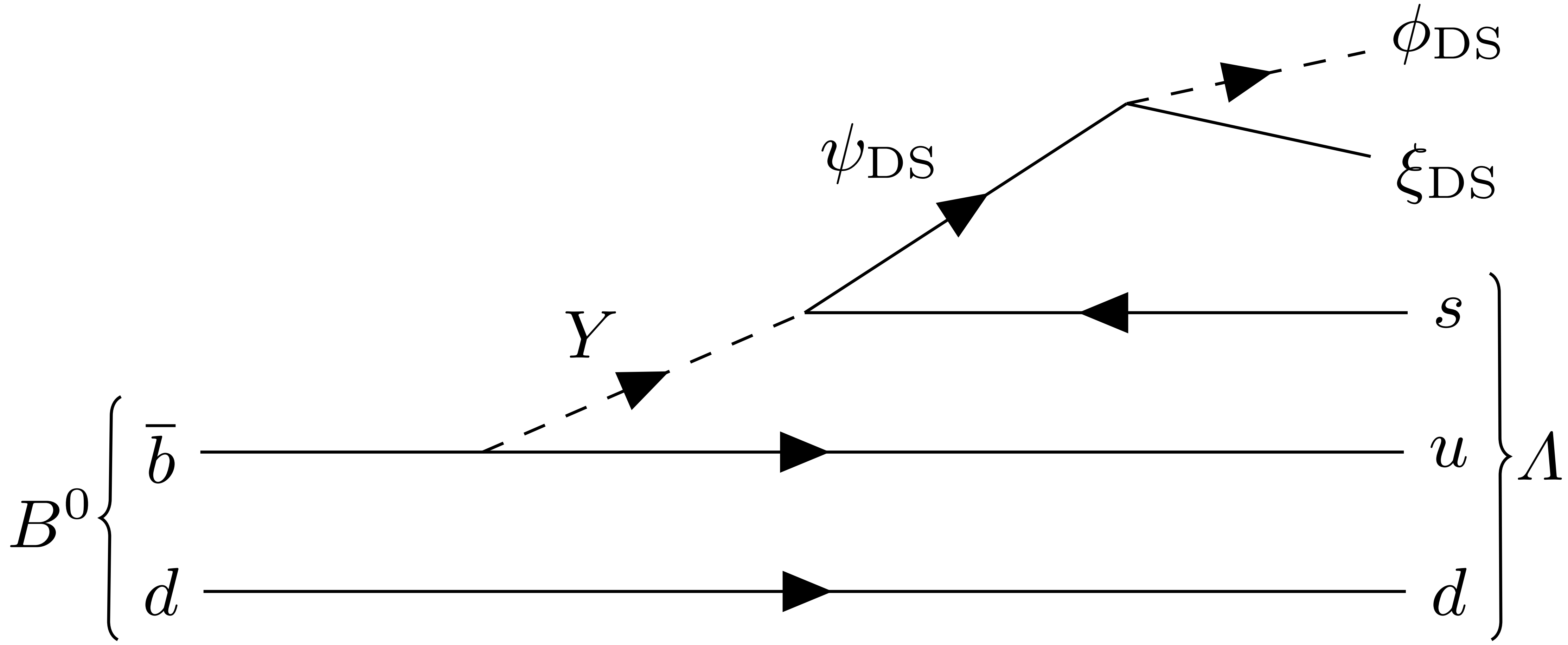
The UL is slightly smaller
than case (ii) prediction of Ref.[5]

Dark matter

in baryonic *B* decays

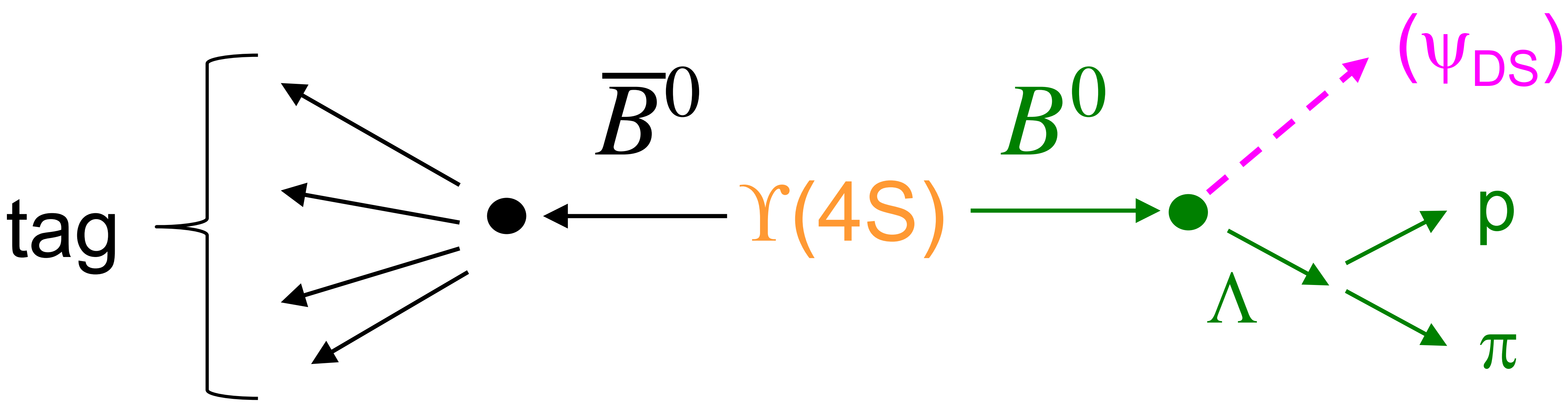
Search for $B^0 \to \Lambda\psi_{\mathrm{DS}}$

- B-mesogenesis — explains Baryogenesis and DM with B decays
  - ✓ Elor, Escudero, Nelson [PRD 99, 035031 (2019)]
  - ✓ predicts $\mathscr{B}(B^0 \to \Lambda\psi_{\mathrm{DS}} + \text{meson}) > 10^{-4}$
- Existing limits
  - ✓ $\mathscr{B}(B^0 \to \Lambda\psi_{\mathrm{DS}}) \lesssim 2 \times 10^{-4}$ by ALEPH (EPJC 2001)
  - ✓ $m(\psi_{\mathrm{DS}}) \lesssim 3.5$ GeV, indirectly constrained by CMS, ATLAS (from searches for TeV-scale color triplet scalars)

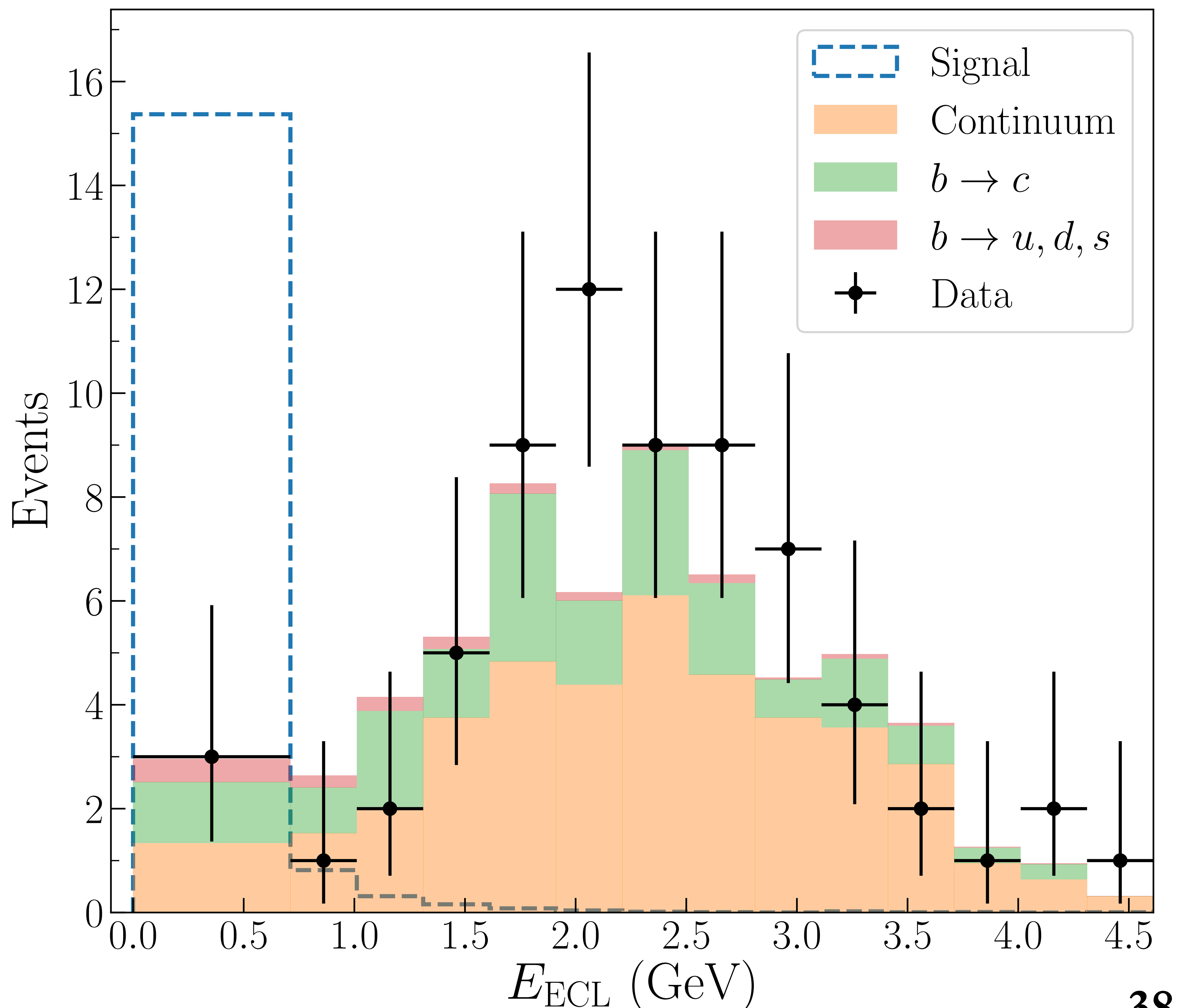


Search for $B^0 \to \Lambda\psi_{DS}$

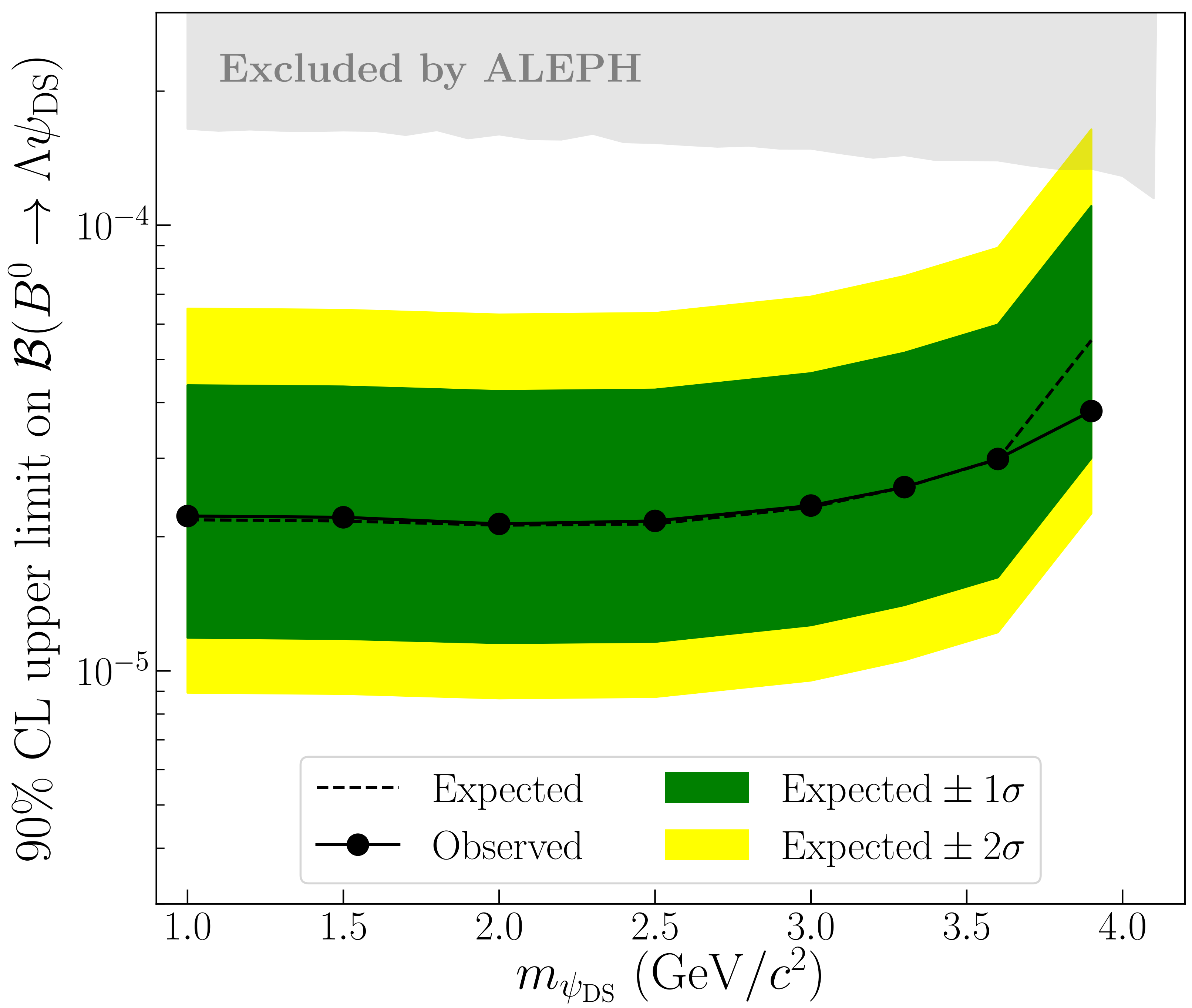
- B-mesogenesis — explains Baryogenesis and DM with B decays
  - ✓ Elor, Escudero, Nelson [PRD 99, 035031 (2019)]
  - ✓ predicts $\mathscr{B}(B^0 \to \Lambda\psi_{DS} + \text{meson}) > 10^{-4}$
- Belle strategy
  - ✓ Hadronic B-tagging, and look for Λ + *nothing* in the signal-B
  - ✓ use E_{ECL} for background suppression
    $E_{ECL} < 0.57 \sim 0.74$ depending on $m_{\psi_{DS}}$

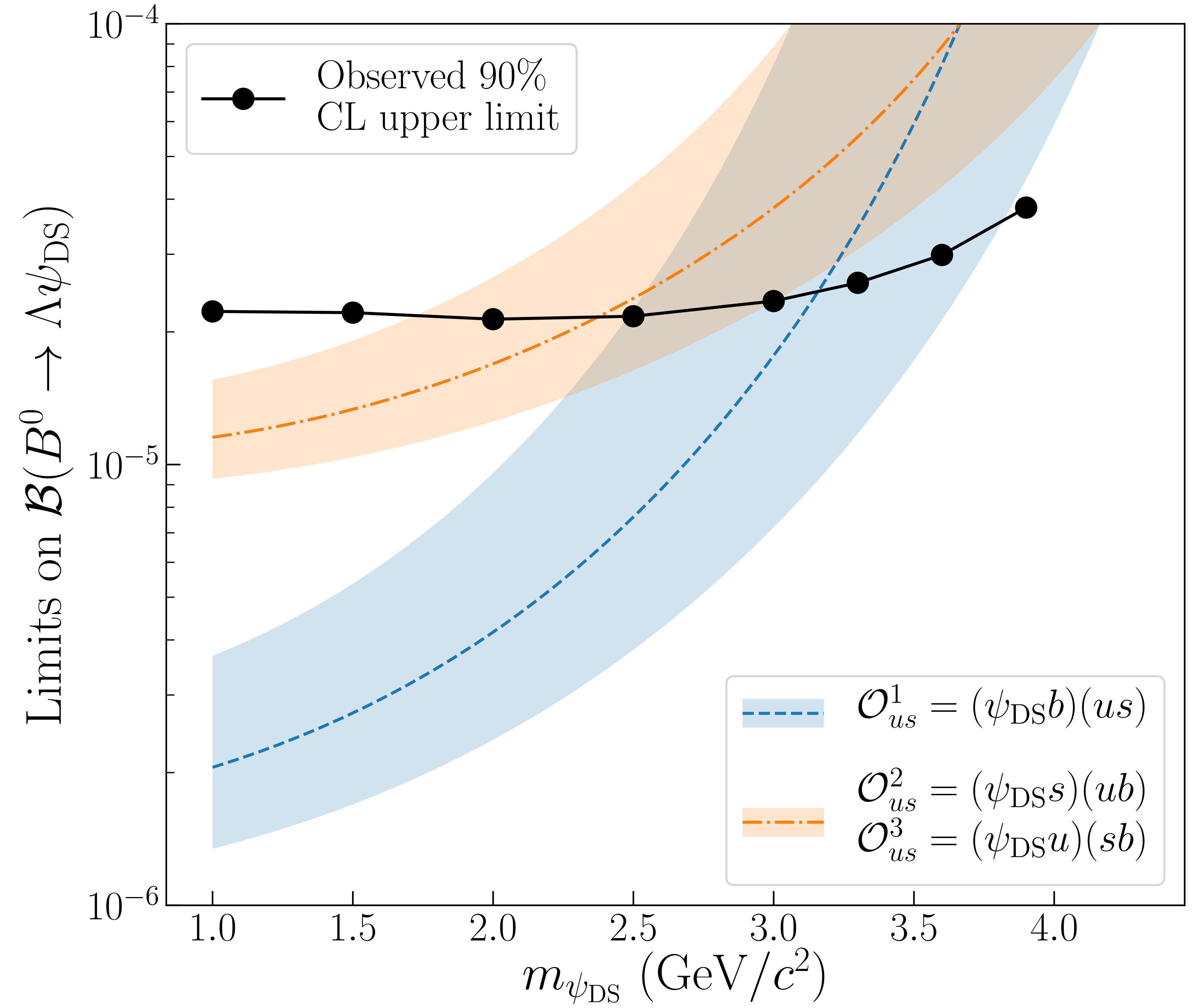


E_{ECL} distribution for
- $m_{\psi_{DS}} = 2.5$ GeV
- $\mathscr{B}(B^0 \to \Lambda\psi_{DS}) = 8 \times 10^{-5}$



Search for $B^0 \to \Lambda\psi_{\mathrm{DS}}$





- No signal; $\mathscr{B}(B^0 \to \Lambda\psi_{\mathrm{DS}}) < (2.1 \sim 3.8) \times 10^{-5}$
- Excludes $m_{\psi_{\mathrm{DS}}} \gtrsim 3.0$ GeV for "type-2" and "type-3" hypotheses†

† Alonso-Alvarez, Elor, Escudero, PRD 104, 035028 (2021)

other subjects from Belle

Exotic hadrons

$X(3872)$, $T_{cc\bar{s}\bar{s}}$

arXiv:2206.08592
submitted to PRD

Search for $X(3872) \to \pi^+\pi^-\pi^0$

- $X(3872)$ the trailblazer for the new wave of exotic hadrons [Belle (2003)]
  - ✓ $m(X(3872)) \simeq M(D^0\overline{D}^{*0})$
  - ✓ a molecule or a tetraquark?
- $X(3872)$ abs. branching fractions
  - ✓ could be crucial to better understand the nature of the particle
  - ✓ a global analysis[1]
    - nothing much known of BF's to final states w/o heavy flavors
  - ✓ ∃ prediction[2] of BF($X(3872) \to \pi^+\pi^-\pi^0$) $\lesssim 10^{-3}$
  - ✓ so, why not search for it?

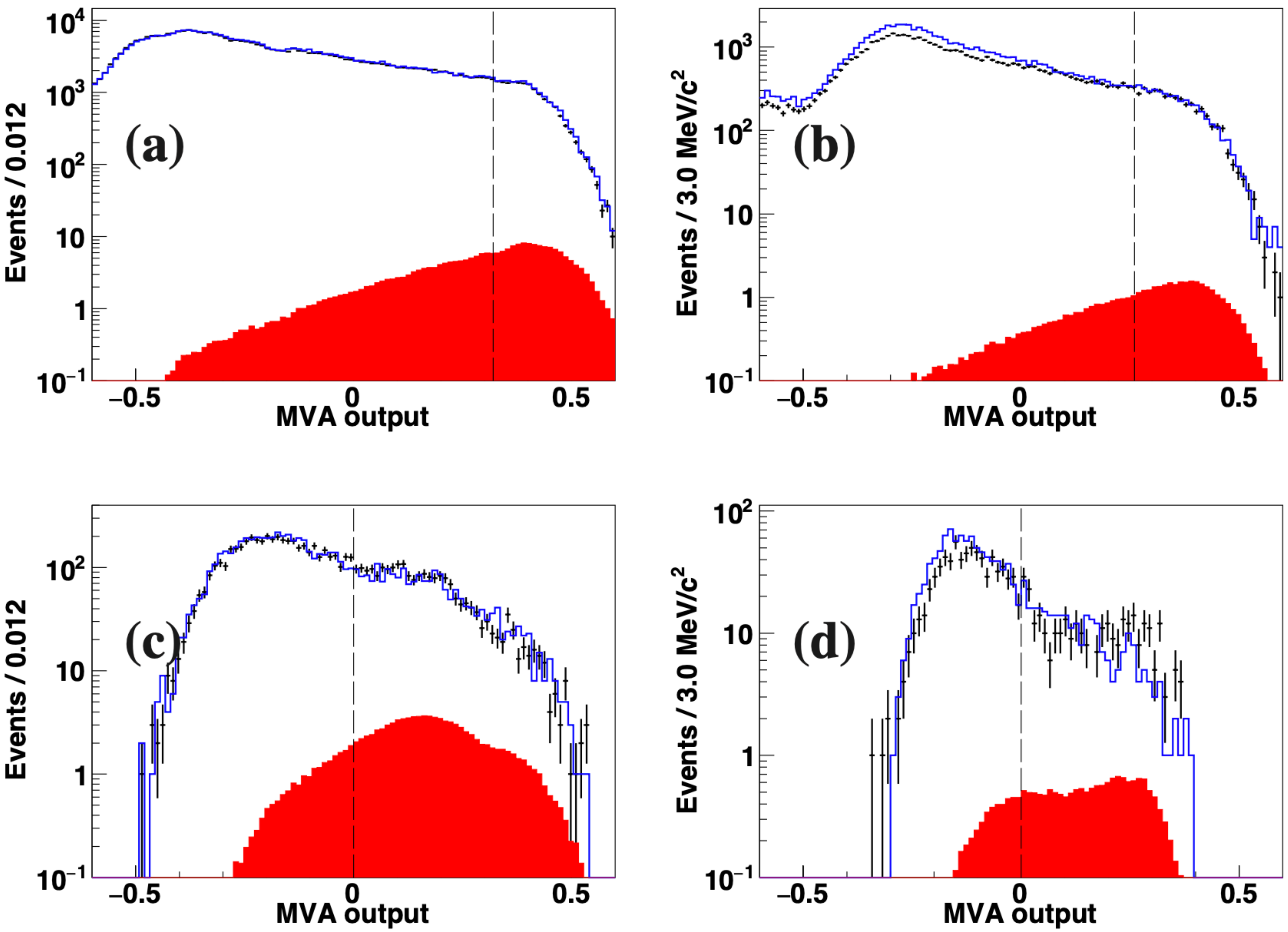
Decay mode	Branching fraction
$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
$X(3872) \to D^{*0}\bar{D}^0 + \text{c.c.}$	$(52.4^{+25.3}_{-14.3})\%$
$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
$X(3872) \to \text{unknown}$	$(31.9^{+18.1}_{-31.5})\%$

[1] Li & Yuan, PRD 100, 094003 (2019)
[2] Achasov & Shestakov, PRD 99, 116023 (2019)

arXiv:2206.08592
submitted to PRD

Search for $X(3872) \to \pi^+\pi^-\pi^0$

$B^+ \to K^+\pi^+\pi^-\pi^0$ $\quad$ $B^0 \to K_S^0\pi^+\pi^-\pi^0$



3-body phase space for $X(3872) \to \pi^+\pi^-\pi^0$

"Case 1"

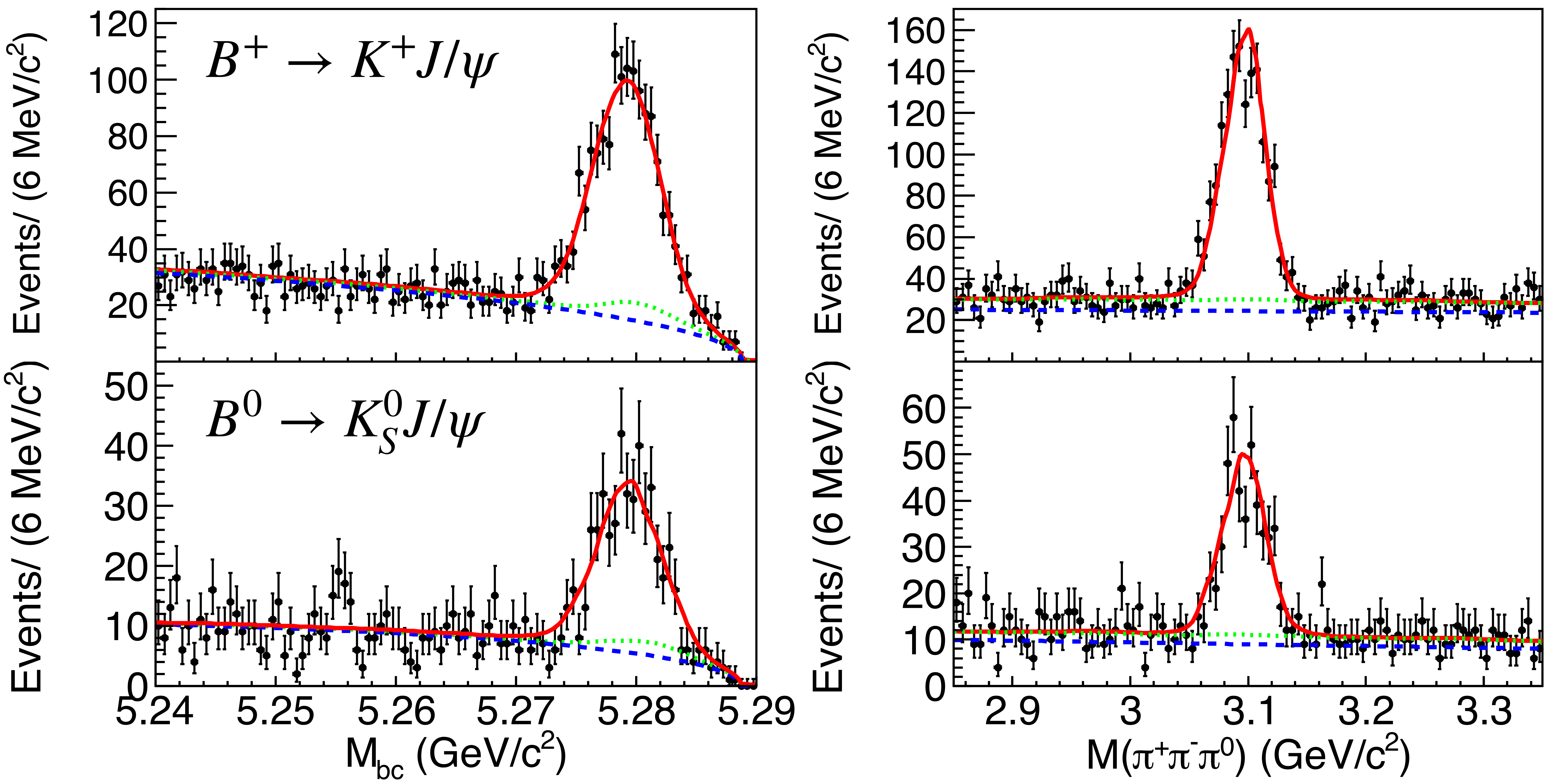
$X(3872) \to \pi^+\pi^-\pi^0$ by Achasov & Shestakov

"Case 2"

MVA to suppress continuum bkgd.

Search for $X(3872) \to \pi^+\pi^-\pi^0$

Validation by using $B \to K\, J/\psi(\to \pi^+\pi^-\pi^0)$



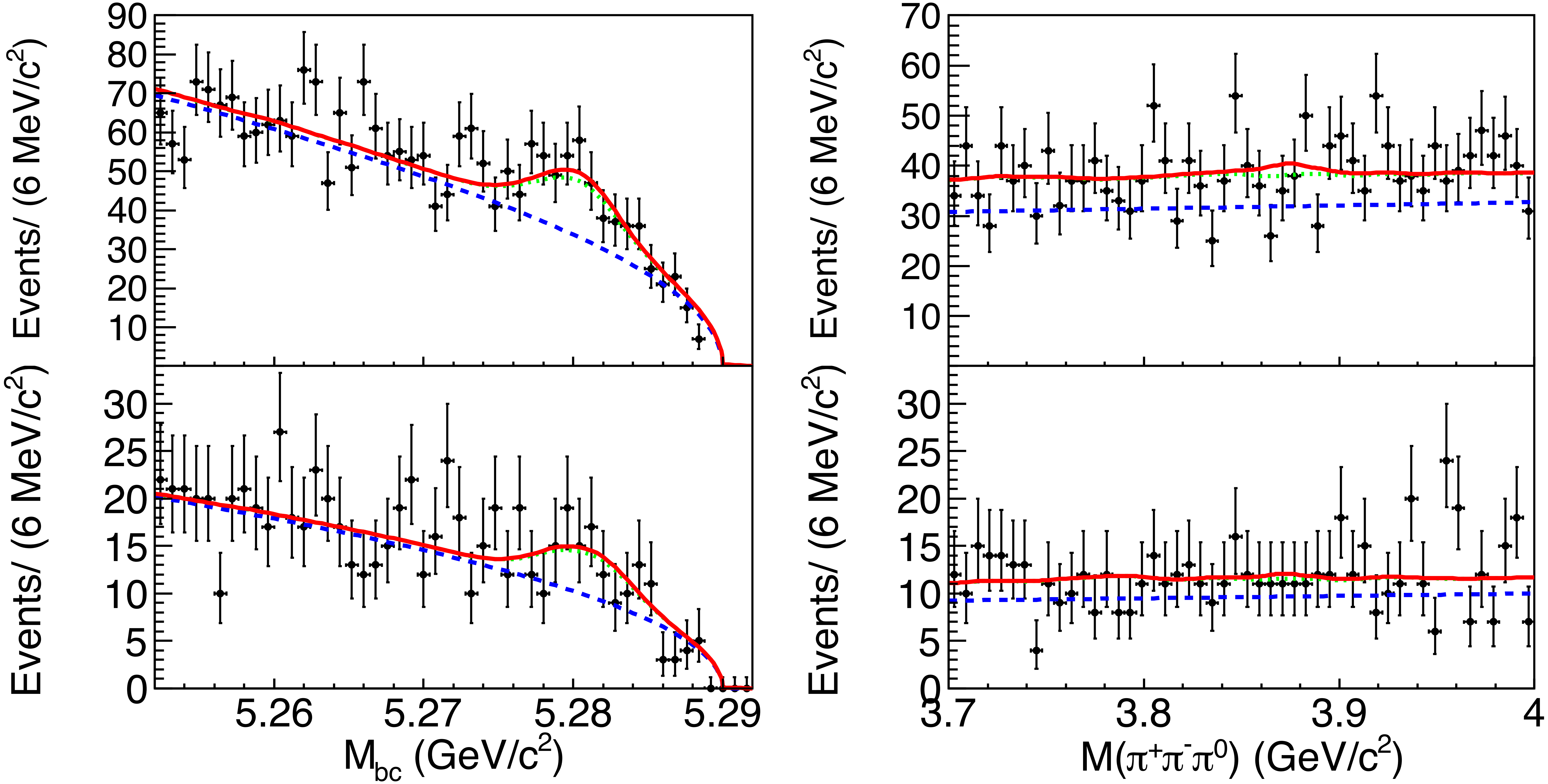
- measured $\mathscr{B}(J/\psi \to \pi^+\pi^-\pi^0) = (2.00 \pm 0.06)\,\%$; consistent w/ world avg.

arXiv:2206.08592
submitted to PRD

Search for $X(3872) \to \pi^+\pi^-\pi^0$

Fit for signal extraction: $B \to K\ J/\psi(\to \pi^+\pi^-\pi^0)$

Case 1

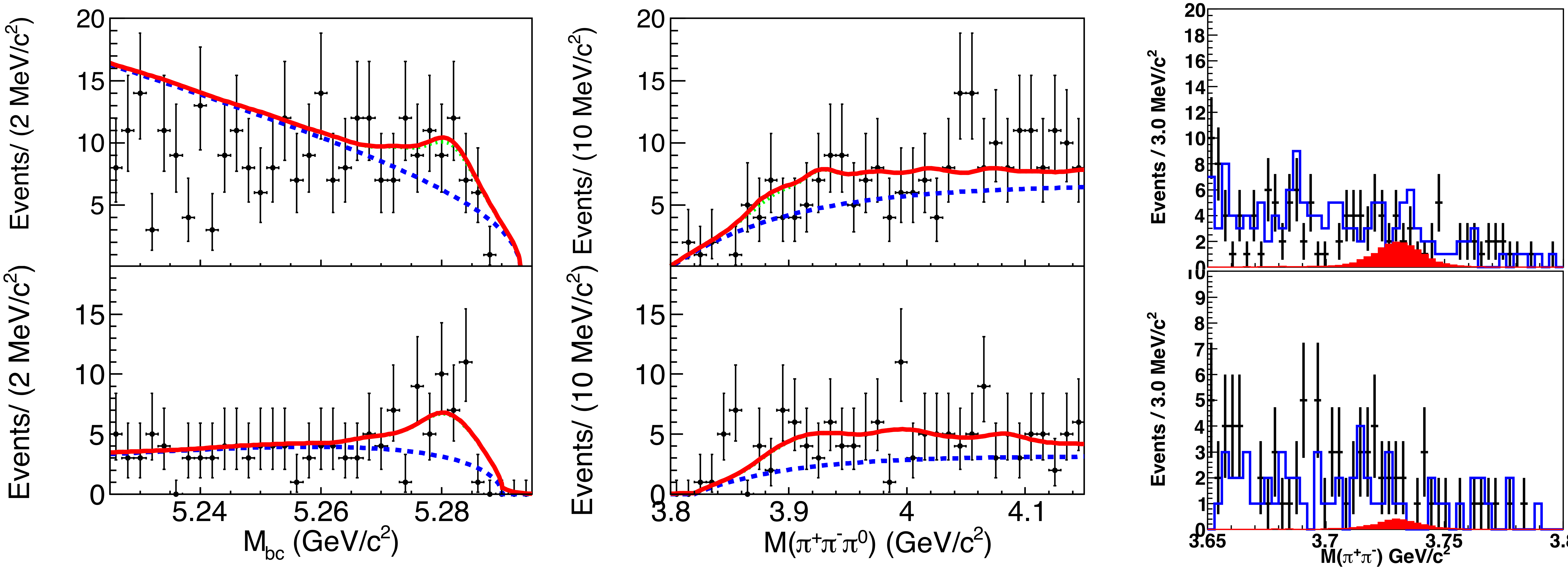


arXiv:2206.08592
submitted to PRD

Search for $X(3872) \to \pi^+\pi^-\pi^0$

Fit for signal extraction: $B \to K\, J/\psi(\to \pi^+\pi^-\pi^0)$

Case 2

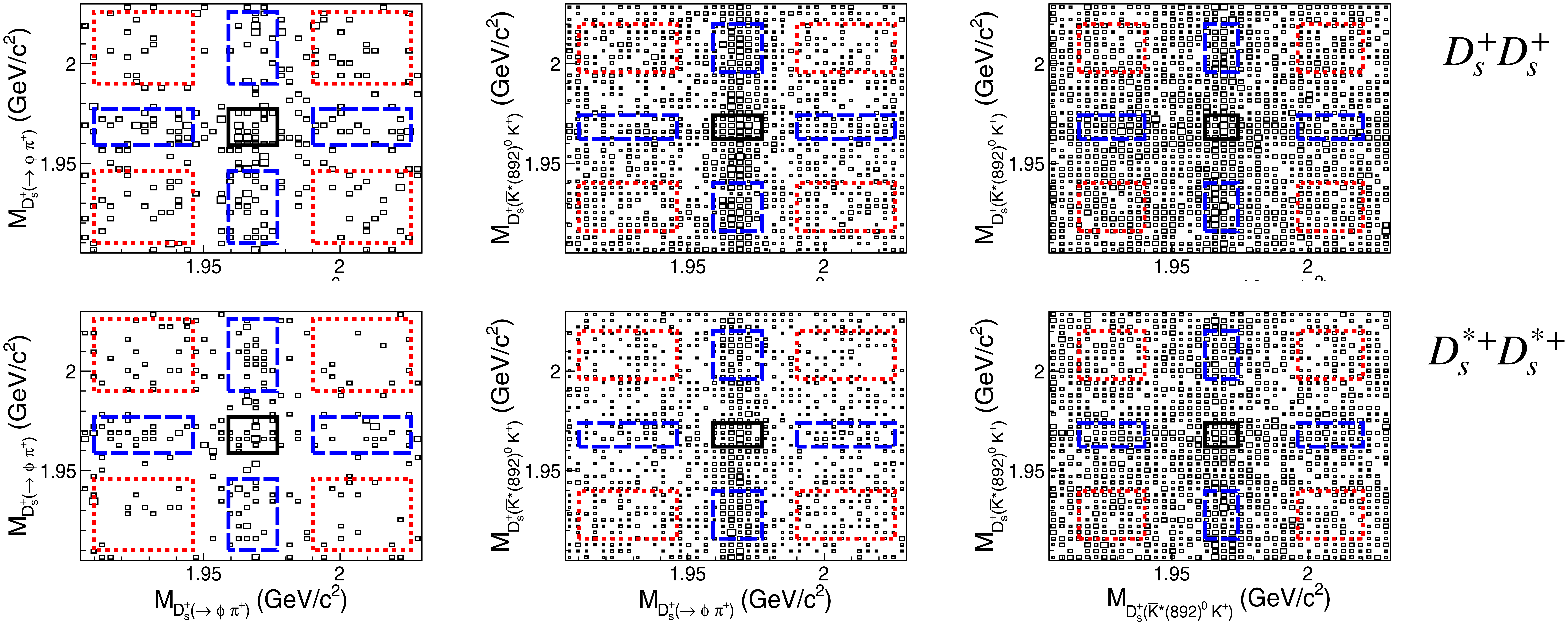


channel	case I	case II
$B^\pm \to K^\pm X(3872),\ X(3872) \to \pi^+\pi^-\pi^0$	$< 1.9 \times 10^{-6}$	$< 1.5 \times 10^{-7}$
$B^0 \to K^0 X(3872),\ X(3872) \to \pi^+\pi^-\pi^0$	$< 1.5 \times 10^{-6}$	$< 1.8 \times 10^{-7}$
$X(3872) \to \pi^+\pi^-\pi^0$	$< 1.3\%$	$< 1.2 \times 10^{-3}$

arXiv:2206.08592
submitted to PRD

Search for $X_{cc\bar{s}\bar{s}}$

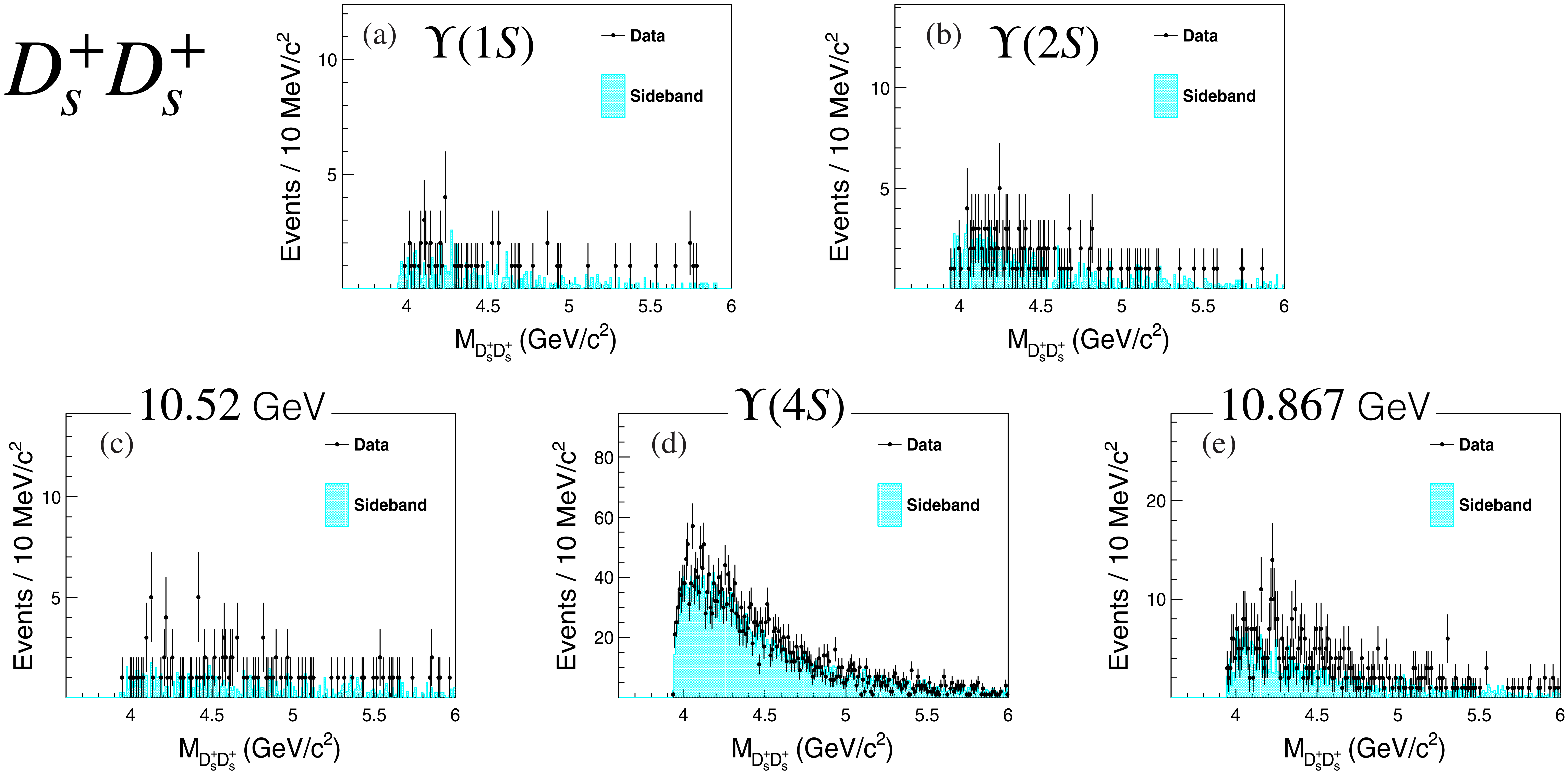
- Search for doubly-heavy tetraquark states in $D_s^+ D_s^+$ and in $D_s^{*+} D_s^{*+}$
  - ✓ in 5 energy regions: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(4S)$, 10.52 GeV, and 10.867 GeV
  - ✓ use $D_s^{*+} \to D_s^+ \gamma$ with $D_s^+ \to \phi(\to K^+K^-)\pi^+$, and $D_s^+ \to \overline{K}^{*0}(\to K^-\pi^+)K^+$



arXiv:2206.08592
submitted to PRD

Search for $X_{cc\bar{s}\bar{s}}$

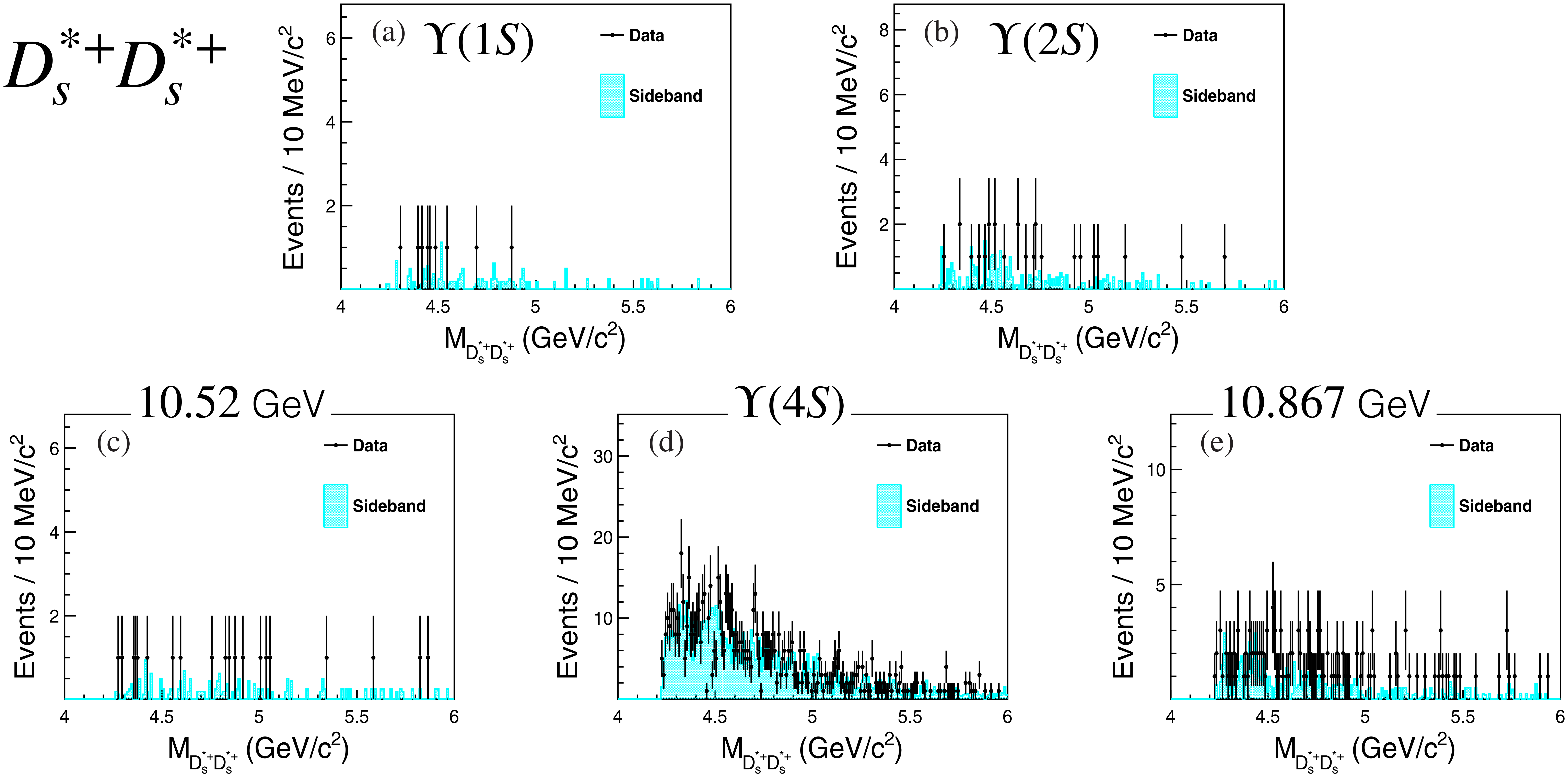
$D_s^+ D_s^+$



- no signals found in any mode, any energy point ⇒ set upper limits!

Search for $X_{cc\bar{s}\bar{s}}$

$D_s^{*+} D_s^{*+}$



- no signals found in any mode, any energy point ⇒ set upper limits!

Closing remarks

- We have presented recent results from Belle experiment, focusing on studies of baryons and exotic hadrons.
- Belle has achieved great things in CP violations, CKM unitarity, rare decays, quarkonia, etc., but at the same time an excellent place to study baryons, exotic hadrons as well as dark sector searches.
- And, the effort goes on with the upgraded facility, Super-KEKB collider and Belle II detector.

"We shall not cease from exploration"†

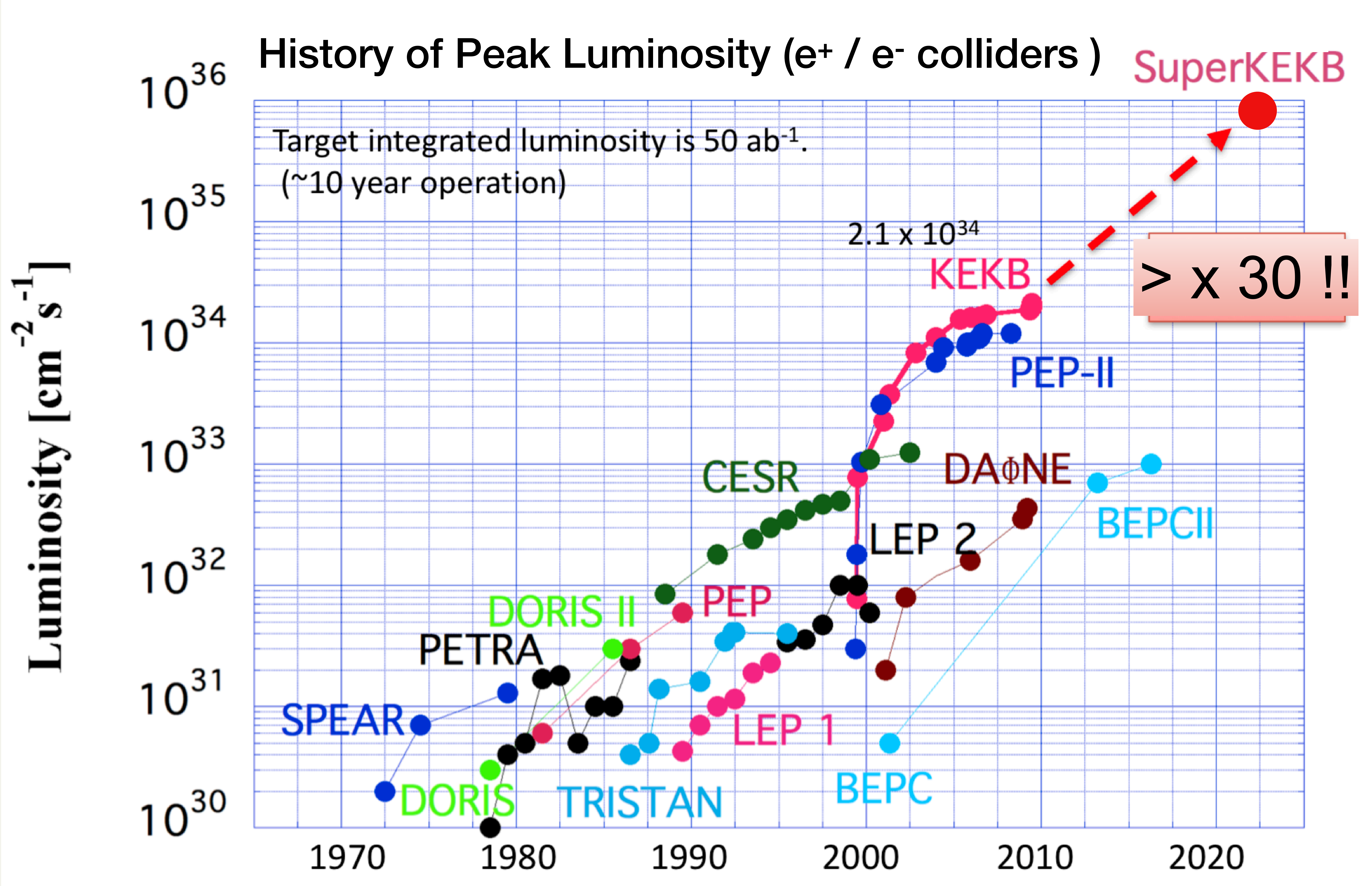
---

† T. S. Eliot

Thank you!

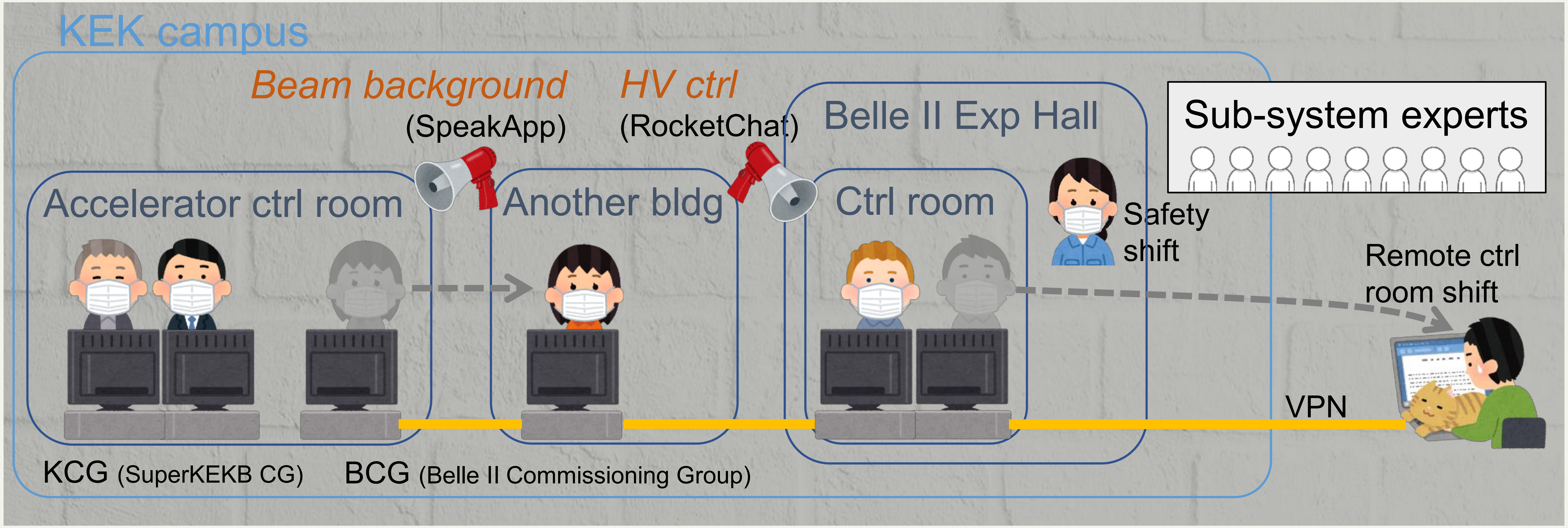
Back-up materials

The Luminosity Frontier



Belle II operations under Pandemic

- Minimize person-to-person contact and avoid 3C
  - Remote control room shifts and expert shifts
  - Travel restrictions (~40 Belle II colleagues on-site)
  - Online meetings



from ICHEP2020 talk by K. Matsuoka

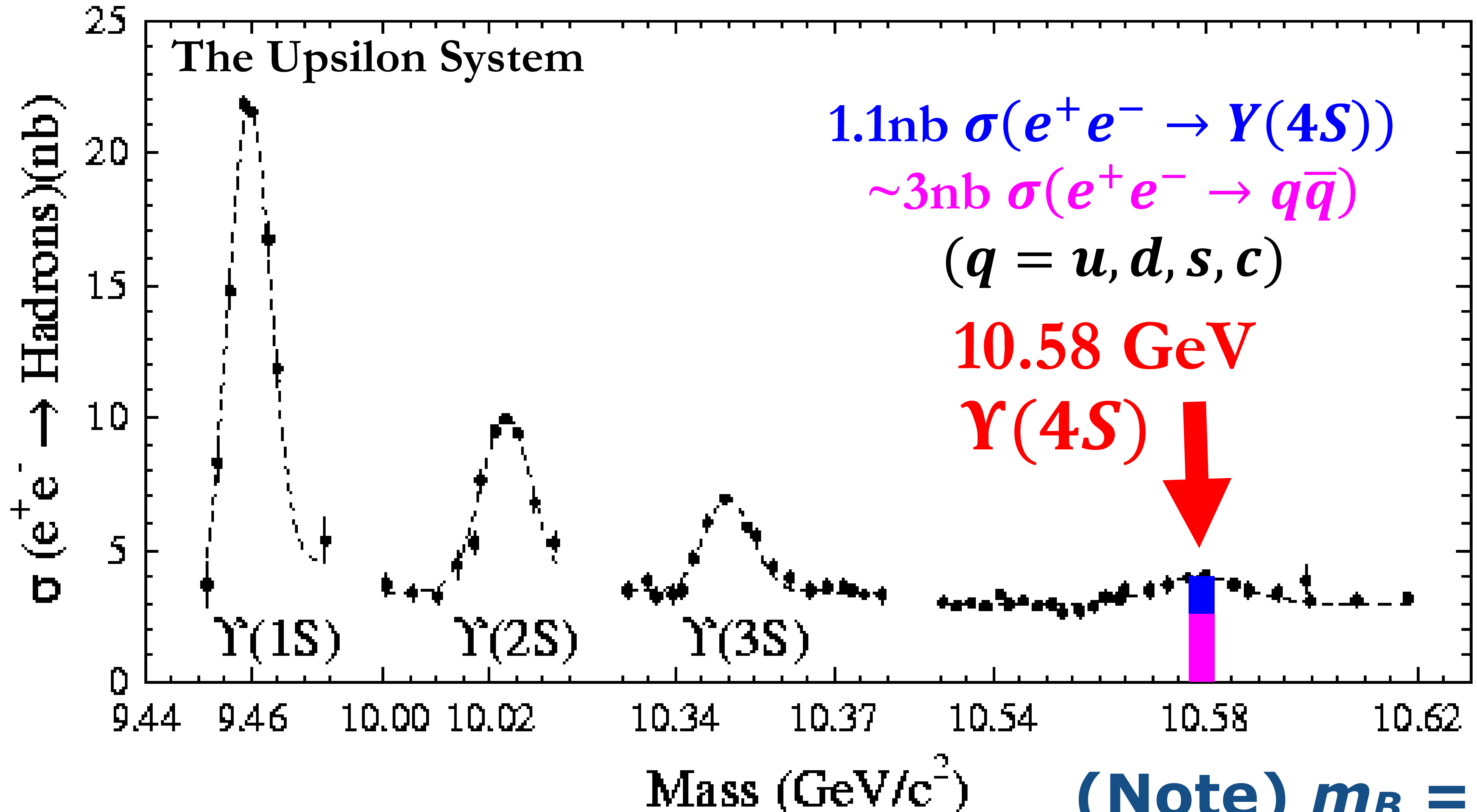
Search for $X(3872) \to \pi^+\pi^-\pi^0$

Systematic uncertainties

TABLE III. Summary of systematic uncertainties on the $B(X(3872) \to \pi^+\pi^-\pi^0)$ measurement (in unit of %).

Source	$B^+ \to K^+ X(3872)$	$B^0 \to K^0_S X(3872)$
Tracking	1.1	0.7
PID	2.9	1.8
K^0_S selection	0.0	2.2
π^0 selection	2.3	2.3
Signal MC model	0.7	0.7
$\mathcal{B}(B \to K X(3872))$	31.6	$^{+45.4}_{-36.4}$
Total	31.8	$^{+45.6}_{-36.6}$
Number of $B\bar{B}$	1.4	
B^+B^- Fraction	1.2	
MVA requirements	3.0	
Weighted total	$^{+35.7}_{-34.1}$	

$e^+e^- \rightarrow \Upsilon(4S)$ as a B-factory



(Note) m_B = 5.28 GeV

- $\mathcal{B}(\Upsilon(4S) \rightarrow B\overline{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\overline{B}$ in the final state
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained