Search for Baryon Number Violation in Two-Body B Decays to Charmed Baryons

Tianping Gu, Vladimir Savinov (University of Pittsburgh)
On behalf of the Belle Collaboration

May 9th, 2021

Baryon Asymmetry of the Universe

Sakharov's Three Conditions for Baryogenesis

- Baryon number violation
- C and CP violation
- Departure from thermal/chemical equilibrium

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

Ways to search for baryon number violation (BNV):

decays of tau lepton, Decays of B mesons, Proton decay, Oscillations…

Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe -Sakharov, A.D. Pisma Zh.Eksp.Teor.Fiz. 5 (1967) 32-35, JETP Lett. 5 (1967) 24-27, Sov.Phys.Usp. 34 (1991) no.5, 392-393, Usp.Fiz.Nauk 161 (1991) no.5, 61-64

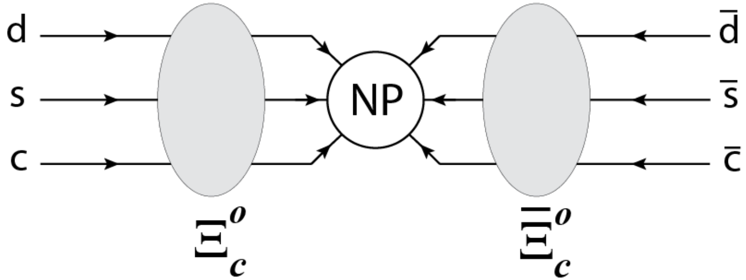
Baryon Number Violation via Baryon-Antibaryon Oscillations

(1). Neutron-antineutron oscillations

(2). Charmed and bottom baryon oscillations (proposed by D. McKeen and A. Nelson)

LHCb searched for Ξ_b^0 oscillations in 2017 and set an upper limit on oscillation rate of $\omega < 0.08\ ps^{-1}$ at the 95% confidence level

In this analysis, we search for Ξ_c^0 oscillations

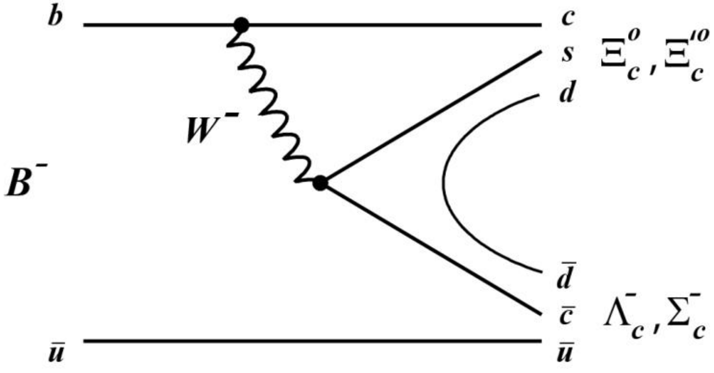


1. Phillips II, D. G., W. M. Snow, K. Babu, S. Banerjee, D. V. Baxter, Z. Berezhiani, M. Bergevin et al., Physics Reports, 612 (2016)
2. McKeen, David, Ann E. Nelson., Physical Review D, 94, 076002 (2016).
3. Aitken, Kyle, David McKeen, Thomas Neder, Ann E. Nelson., Physical Review D, 96, 075009 (2017).
4. LHCb: Aaij, R., et. al., Physical review letters, 119, 181807 (2017).

$B^{-} \to \Xi_c^0 \Lambda_c^-$

Discovered by Belle: Chistov, R., et. al., Physical Review D, 74, 111105 (2006)

In this analysis we search for baryon number violation either due to direct non-SM process or via charmed baryon-antibaryon oscillations using two-body decay $B^{-} \to \Xi_c^0 \Lambda_c^-$.



Mode1	$B^{-} \to \Xi_c^0 \Lambda_c^-$	SM
Mode2	$B^{-} \to \overline{\Xi}_c^0 \Lambda_c^-$	BNV
Mode3	$B^{+} \to \overline{\Xi}_c^0 \overline{\Lambda}_c^+$	SM
Mode4	$B^{+} \to \Xi_c^0 \overline{\Lambda}_c^+$	BNV

For oscillations hypothesis, charge of Λ_c^- tags the flavor of B meson at production time, so we know the flavor of the other charmed baryon (i.e., Ξ_c^0 is expected, but we may detect $\overline{\Xi}_c^0$).

Decay Channels Used in the Analysis

	Channel		Product of all relevant branching fractions (10^-7)
1	$\Xi_c^0 \to \Xi^- \pi^+$	$\Lambda_c^- \to \bar{p} K_S^0$	2.80
2	$\Xi_c^0 \to \Xi^- \pi^+$	$\Lambda_c^- \to \bar{p} K^+ \pi^-$	11.1
3	$\Xi_c^0 \to \Lambda K^- \pi^+$	$\Lambda_c^- \to \bar{p} K_S^0$	1.81
4	$\Xi_c^0 \to \Lambda K^- \pi^+$	$\Lambda_c^- \to \bar{p} K^+ \pi^-$	7.16
5	$\Xi_c^0 \to \bar{p} K^- K^- \pi^+$	$\Lambda_c^- \to \bar{p} K_S^0$	0.875
6	$\Xi_c^0 \to \bar{p} K^- K^- \pi^+$	$\Lambda_c^- \to \bar{p} K^+ \pi^-$	3.45

Branching fractions for

$$\Xi_c^0 \to \Xi^- \pi^+ / \Lambda K^- \pi^+ / \bar{p} K^- K^- \pi^+$$

are from recent Belle measurement

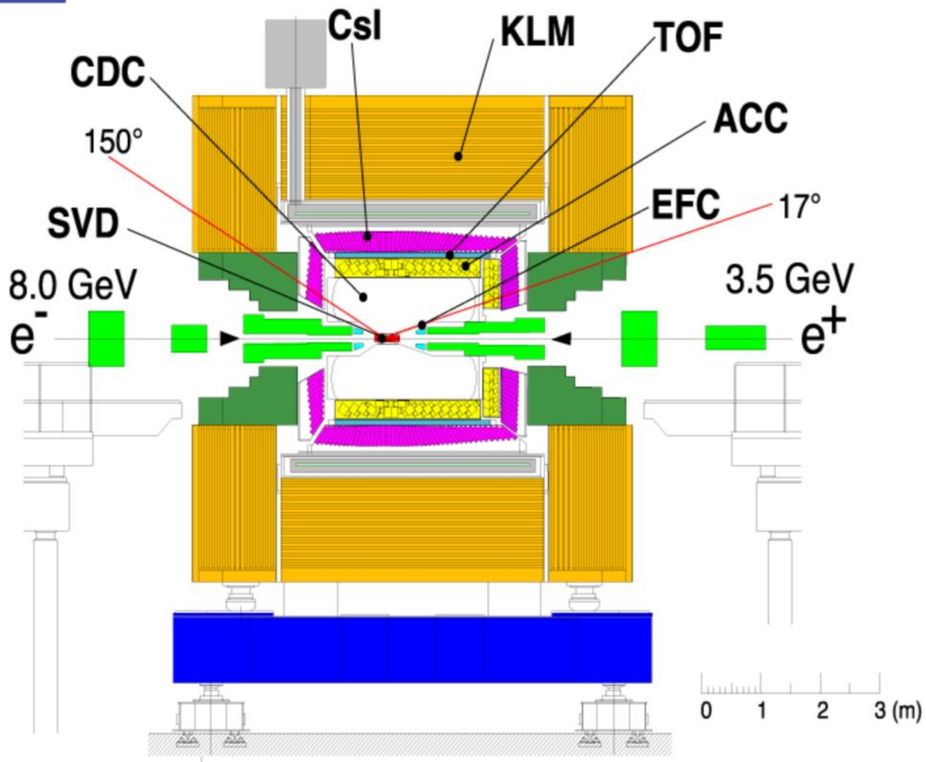
In our analysis we use 3x2=6 channels:

$$\Xi_c^0 \to \Xi^- \pi^+ / \Lambda K^- \pi^+ / \bar{p} K^- K^- \pi^+$$

$$\Lambda_c^- \to \bar{p} K_S^0 / \bar{p} K^+ \pi^-$$

Belle Collaboration: Li, Y. B., Shen, C. P., Yuan, Physical Review Letters, 122, 082001 (2019).

Belle Detector @ KEKB e^+e^- collider



Operated between 1999 and 2010

Integrated luminosity collected at Υ(4S): 711 fb^{-1}
(771 million $B\overline{B}$ meson pairs)

Charged particle tracking : SVD, CDC
Particle identification: CDC, TOF, ACC, KLM and ECL
EM Calorimetry: Csl (ECL)

Excellent tracking performance:

$$\sigma_{r\phi} = 130\ \mu\text{m}$$
$$\sigma_z = 200\text{–}1400\ \mu\text{m}$$
$$\sigma_{p_t}/p_t = 0.3\%\sqrt{p_t^2 + 1}$$
$$\sigma_{\text{d}E/\text{d}x} = 6\%$$

1. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res. Sect. A 479, 117 (2002);
2. also see Section 2 in J. Brodzicka et al., Prog. Theor. Exp. Phys. 2012, 04D001 (2012).

Selection Criteria

Particle candidates	Selection criteria
$\pi^{\pm}$	$R_{\pi,K} > 0.6,\ R_{e,hadron} < 0.95$
$K^{\pm}$	$R_{\pi,K} < 0.6,\ R_{e,hadron} < 0.95$
$p/\overline{p}$	$R_{p/\overline{p},\pi} > 0.6, R_{p/\overline{p},K} > 0.6$
Λ	Vertex reconstruction, $\|M_{\Lambda} - m_{\Lambda}\| < 10MeV/c^2$
K_s^0	Vertex reconstruction with additional selection based on neutral network
Ξ^-	$\|M_{\Xi^-} - m_{\Xi^-}\| < 10MeV/c^2$
Ξ_c^0	$\|M_{\Xi_c^0} - m_{\Xi_c^0}\| < 20MeV/c^2$
Λ_c^-	$\|M_{\Lambda_c^-} - m_{\Lambda_c^-}\| < 10MeV/c^2$
B^-	$M_{bc} > 5.2GeV/c^2, \|\Delta E\| < 0.25GeV$

M_{bc}: beam-constrained B mass:

$$M_{bc} = \sqrt{{E_{beam}}^2 - {p_B}^2}$$

ΔE: energy difference:

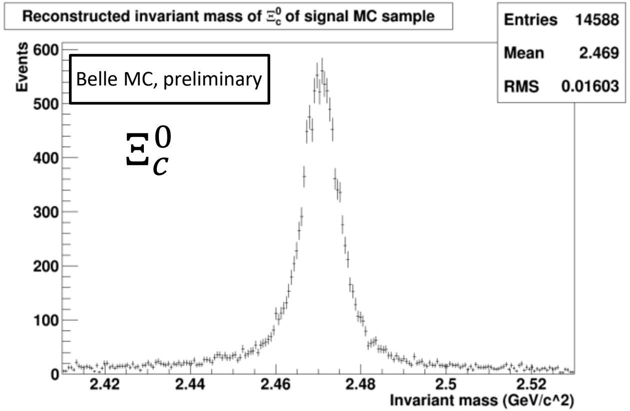
$$\Delta E = E_B - E_{beam}$$

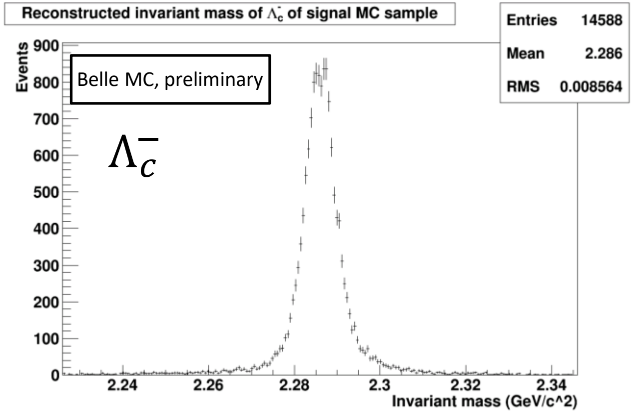
- Best candidate selection using χ^2 obtained from vertex fits to Λ_c^-, Ξ_c^0, Ξ^- candidates
- Likelihood-based Particle Identification (PID) is used:

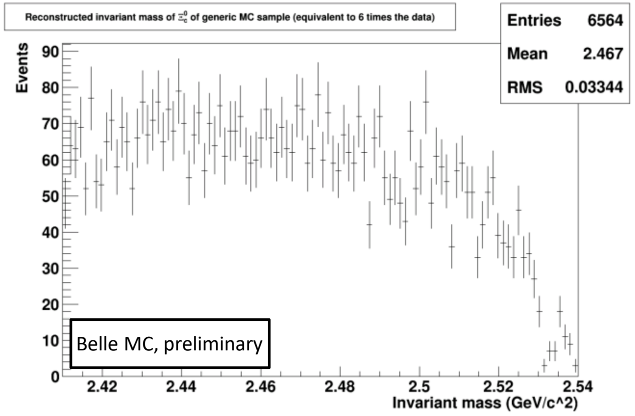
$$R_{i,j} = L_i/(L_i + L_i)\ , i,j \in \{\pi, K, p, e\}$$

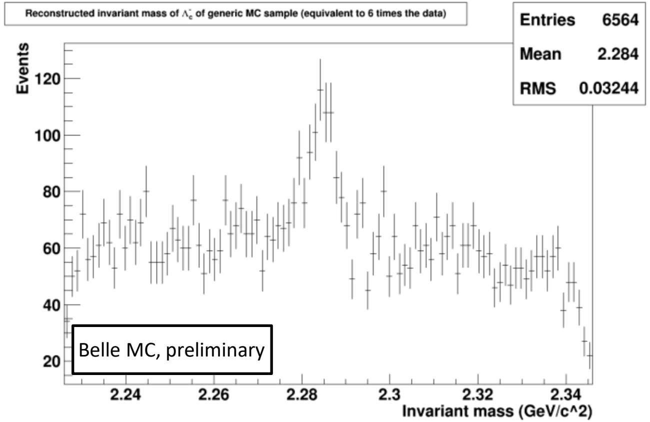
	Reconstruction efficiency
Channel 1	9.22%
Channel 2	7.56%
Channel 3	9.83%
Channel 4	8.12%
Channel 5	8.15%
Channel 6	6.90%

Reconstructed Invariant Masses of Signal Particle Candidates in MC

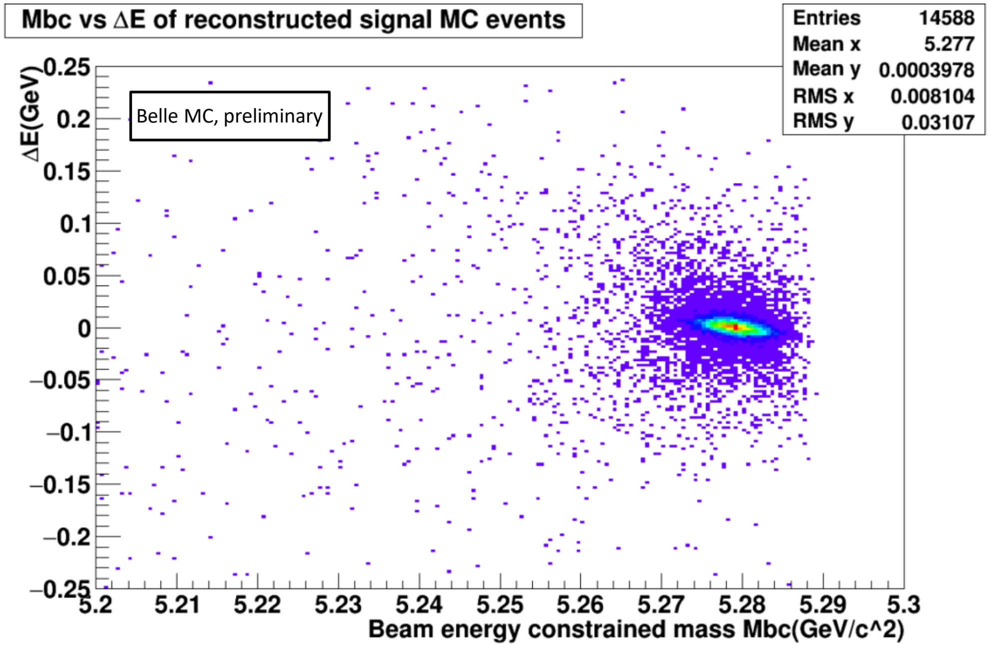


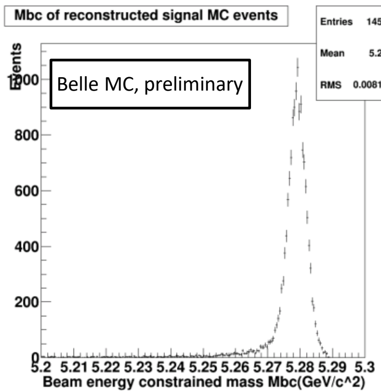


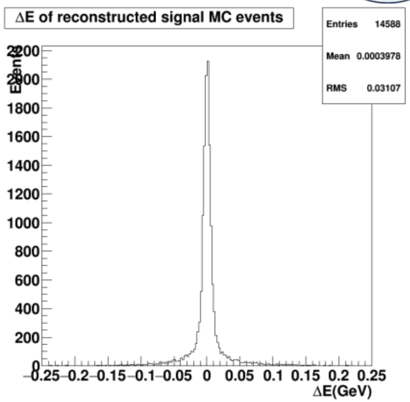




Signal Variables for 2D Maximum Likelihood Fit







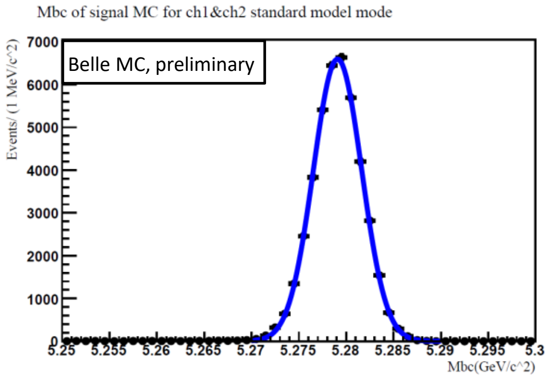
M_{bc}: beam-constrained B mass:

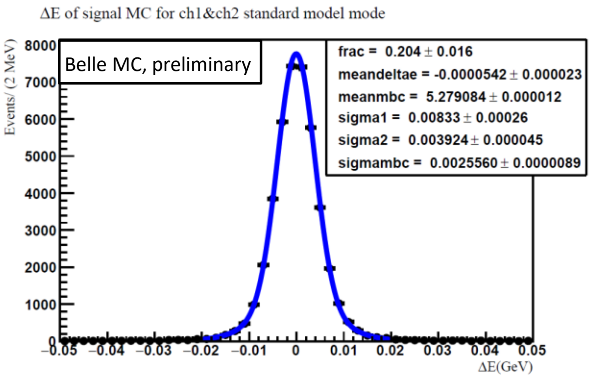
$$M_{bc} = \sqrt{E_{beam}{}^2 - p_B{}^2}$$

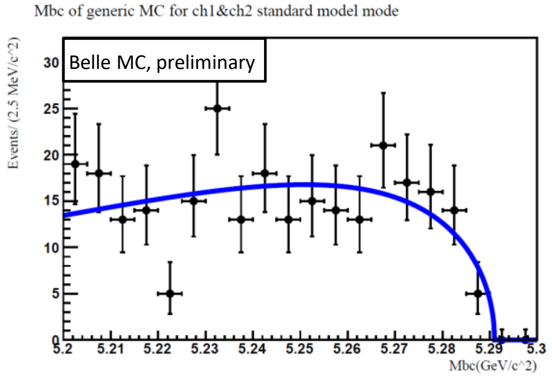
ΔE: energy difference:

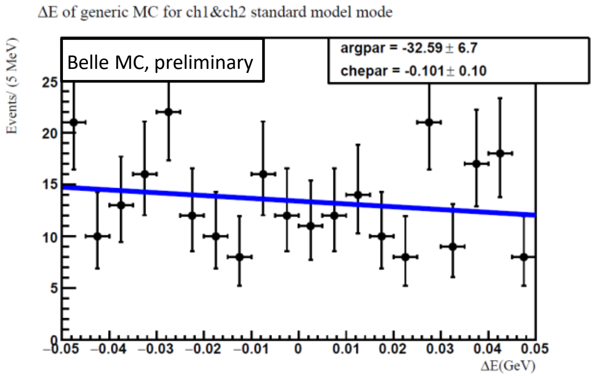
$$\Delta E = E_B - E_{beam}$$

2D Maximum Likelihood Fit is Used to Extract Signal







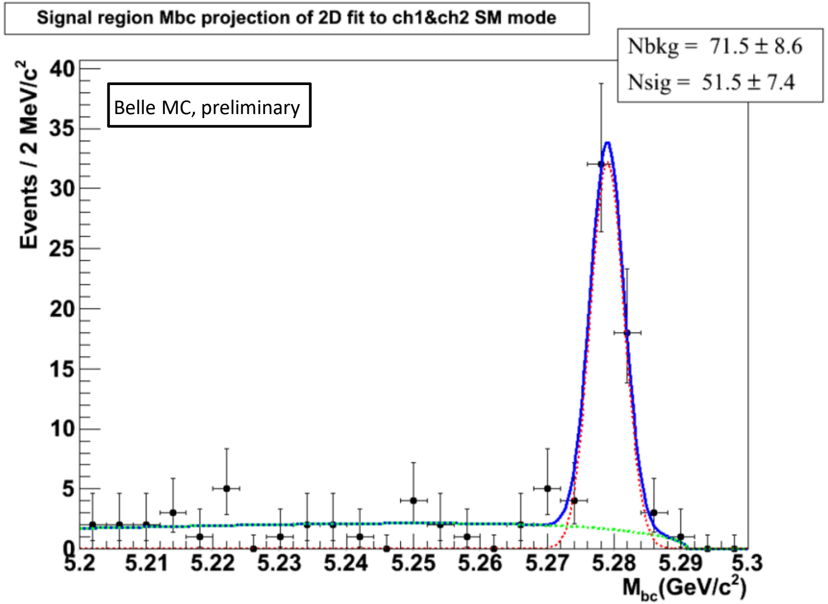


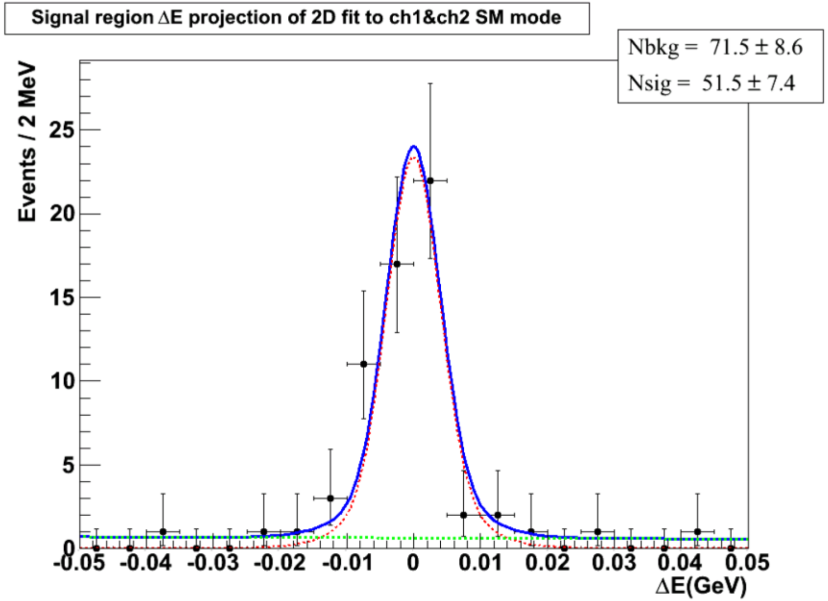
PDF	M_{bc}	ΔE
Signal	Gaussian	Double-Gaussian
Background	ARGUS	1st-order Chebychev

Background PDF: a product of two 1D PDFs

Signal PDF: strong correlation between signal variables, however, signal region is very narrow, so a product of 1D PDFs is tentatively used also

Toy MC experiment for Ch1 & Ch2 SM mode

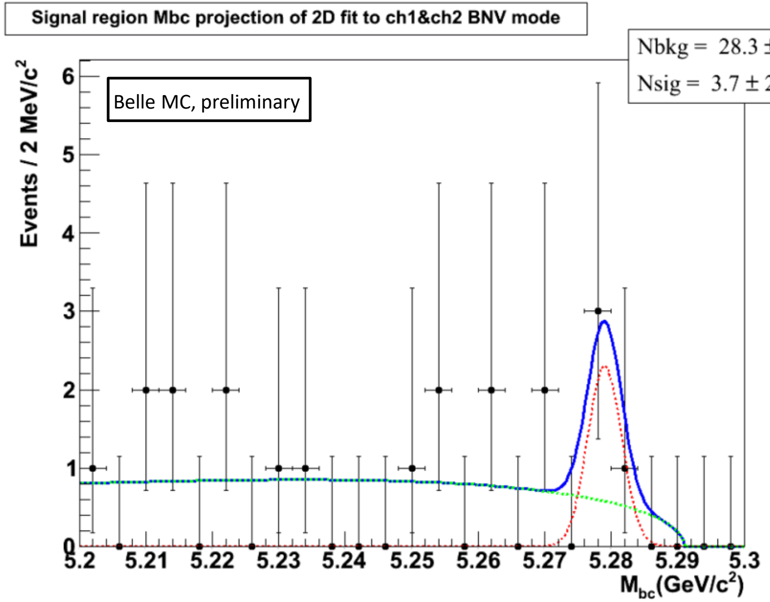


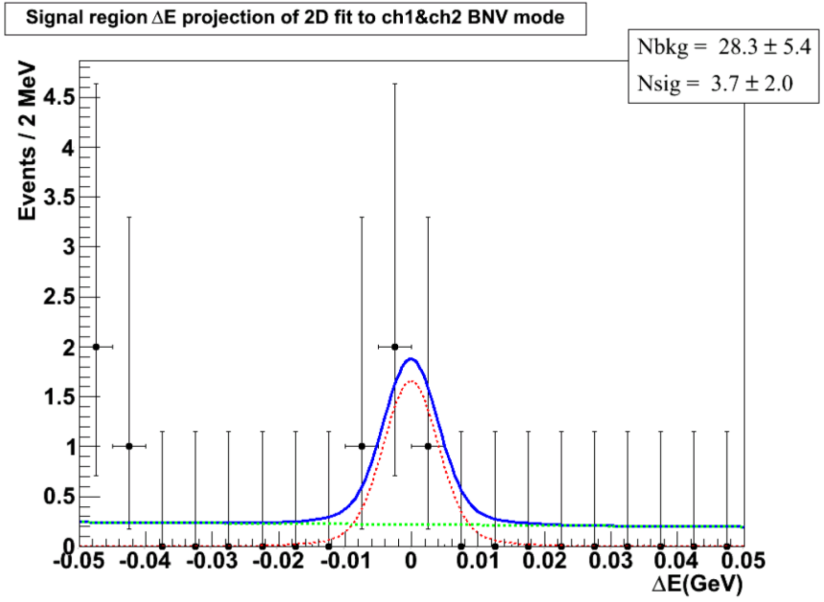


Toy MC experiment for Ch1 & Ch2 Standard Model mode:

- 50 signal events, predicted based on branching fraction measured in previous analysis
- 73 background events, predicted by generic MC and sideband of real data

Toy MC experiment for Ch1 & Ch2 BNV mode

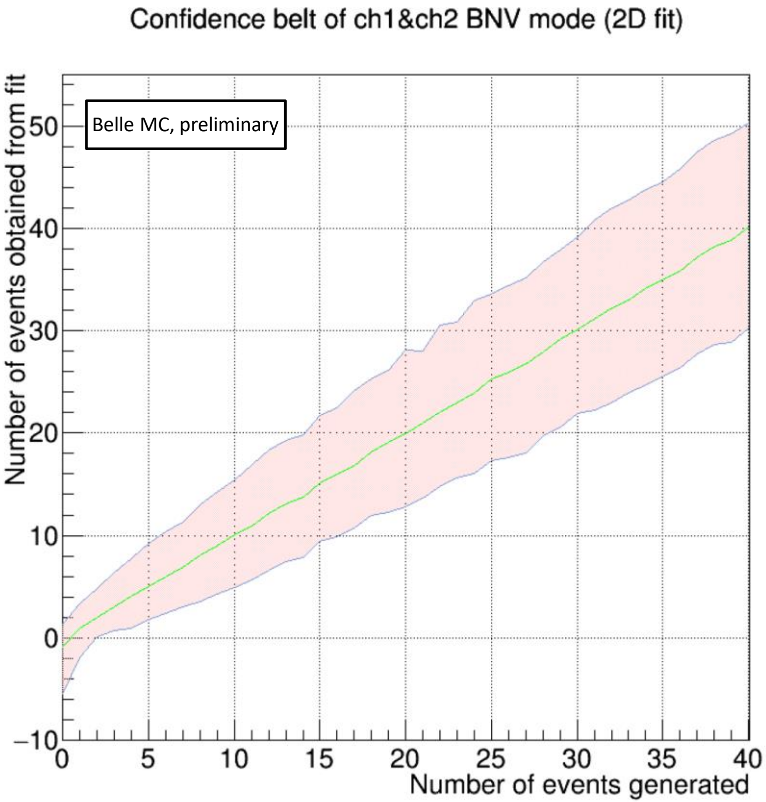




Toy MC experiment for Ch1 & Ch2 Baryon-number-violating mode:

- 5 signal events (10% of Standard Model mode)
- 27 background events, predicted by generic MC and sideband of real data

90% Confidence Belt for Ch1 & Ch2

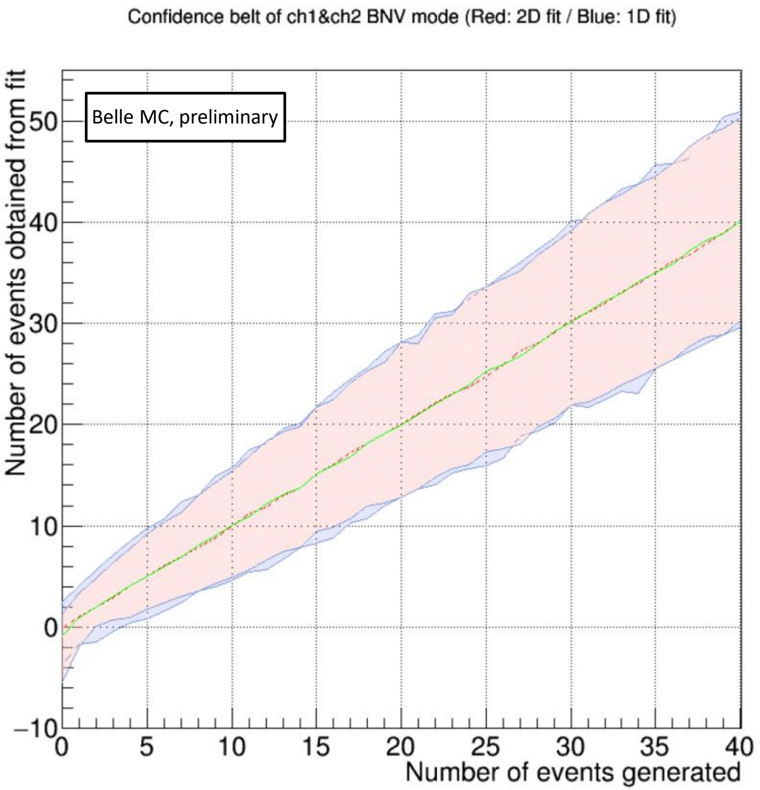


Upper limit on the branching fraction is estimated from a set a confidence belt obtained using frequentist method

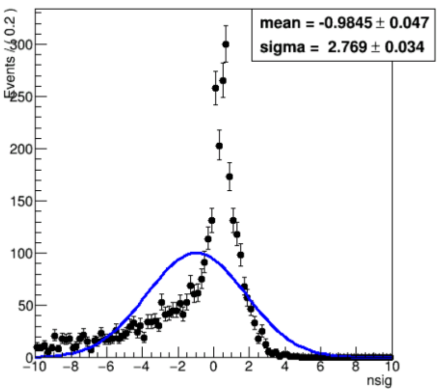
90% confidence belt:

The lower bounds are given by N_{sig}^{fit} which 5% of the results are below this value.
The upper bounds are given by N_{sig}^{fit} which 5% of the results are above this value.

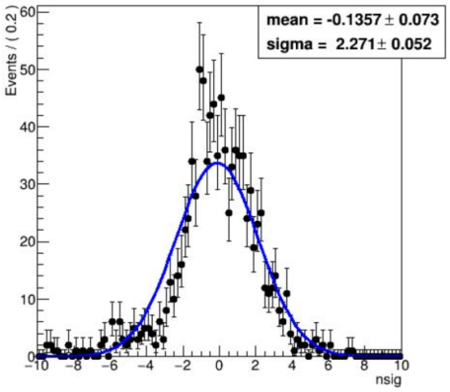
90% Confidence belt for Ch1 & Ch2



0 signal event ensemble test (2D fit)



0 signal event ensemble test (1D fit)

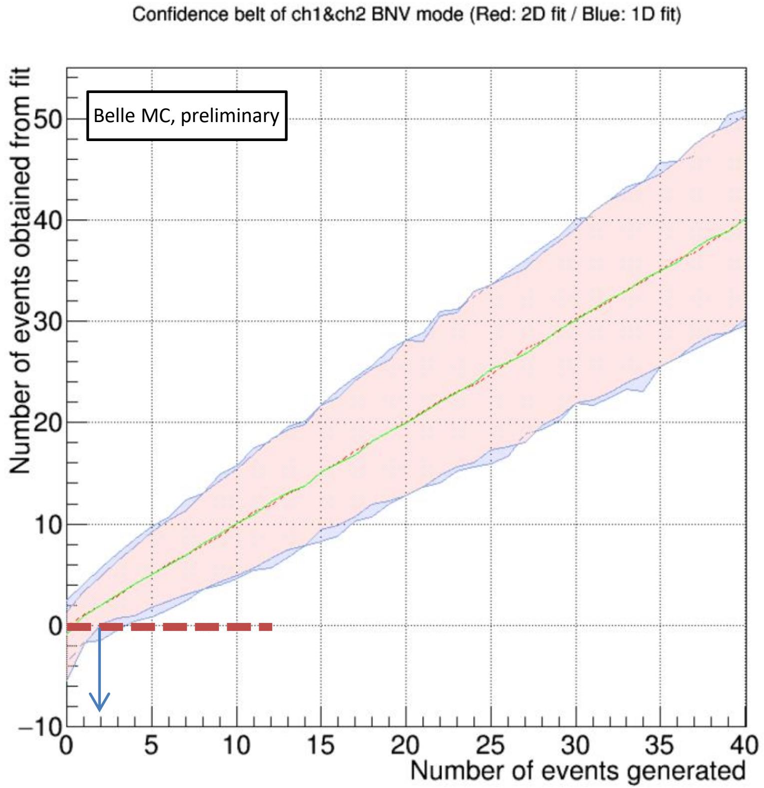


Small statistics in signal region make 2D fits fail often

Data analysis strategy: start with a 1D fit

If 1D fit shows a hint of signal, perform a 2D fit

Estimate of Upper Limit Using Ch1 & Ch2



Fit result example: 0 signal events -> the upper limit of 2 events

The branching fraction of BNV mode for ch1&ch2 would be

$$\mathcal{B}(B^- \to \Xi_c^0 \Lambda_c^-) = \frac{N_{sig}}{N_{B^-/B^+}(\epsilon_1 \mathcal{B}_1 + \epsilon_2 \mathcal{B}_2)}$$

where $\mathcal{B}_1 = \mathcal{B}(\Lambda_c^- \to \overline{p} K_S^0)\mathcal{B}(K_S^0 \to \pi^+\pi^-)\mathcal{B}(\overline{\Xi}_c^0 \to \Xi^+\pi^-)\mathcal{B}(\Xi^+ \to \overline{\Lambda}\pi^+)\mathcal{B}(\overline{\Lambda} \to \overline{p}\pi^+)$,
$\mathcal{B}_2 = \mathcal{B}(\Lambda_c^- \to \overline{p} K^+\pi^-)\mathcal{B}(\overline{\Xi}_c^0 \to \Xi^+\pi^-)\mathcal{B}(\Xi^+ \to \overline{\Lambda}\pi^+)\mathcal{B}(\overline{\Lambda} \to \overline{p}\pi^+)$,
ϵ_1 and ϵ_2 are reconstruction efficiencies for ch1 and ch2,
N_{sig} is the number of signal events obtained from fitting,
N_{B^-/B^+} is the number of B^-/B^+ mesons, 771×10^6 is used for this estimate.

Estimate of upper limit for Ch1 & Ch2

	Parameter	Factor
1	$\mathcal{B}(\Xi_c^0 \to \Xi^+\pi^-)$	1.43%
2	$\mathcal{B}(\Xi_c^0 \to \overline{\Lambda}K^+\pi^-)$	1.45%
3	$\mathcal{B}(\Xi_c^0 \to pK^+K^+\pi^-)$	0.48%
4	$\mathcal{B}(\Lambda_c^- \to \overline{p}K_s^0)$	1.59%
5	$\mathcal{B}(\Lambda_c^- \to \overline{p}K^+\pi^-)$	6.28%
6	$\mathcal{B}(K_s^0 \to \pi^+\pi^-)$	69.2%
7	$\mathcal{B}(\overline{\Lambda} \to \overline{p}\pi^+)$	63.9%
8	$\mathcal{B}(\Xi^+ \to \overline{\Lambda}\pi^+)$	99.9%

	Reconstruction efficiency
Channel 1	9.22%
Channel 2	7.56%
Channel 3	9.83%
Channel 4	8.12%
Channel 5	8.15%
Channel 6	6.90%

Fit result example: 0 signal events -> the upper limit of 2 events

The branching fraction of BNV mode estimated using ch1&ch2 would be

$$\mathcal{B}(B^- \to \overline{\Xi}_c^0\Lambda_c^-) = \frac{N_{sig}}{N_{B^-/B^+}(\epsilon_1\mathcal{B}_1 + \epsilon_2\mathcal{B}_2)}$$

where $\mathcal{B}_1 = \mathcal{B}(\Lambda_c^- \to \overline{p}K_S^0)\mathcal{B}(K_S^0 \to \pi^+\pi^-)\mathcal{B}(\overline{\Xi}_c^0 \to \Xi^+\pi^-)\mathcal{B}(\Xi^+ \to \overline{\Lambda}\pi^+)\mathcal{B}(\overline{\Lambda} \to \overline{p}\pi^+)$,
$\mathcal{B}_2 = \mathcal{B}(\Lambda_c^- \to \overline{p}K^+\pi^-)\mathcal{B}(\overline{\Xi}_c^0 \to \Xi^+\pi^-)\mathcal{B}(\Xi^+ \to \overline{\Lambda}\pi^+)\mathcal{B}(\overline{\Lambda} \to \overline{p}\pi^+)$,
ϵ_1 and ϵ_2 are reconstruction efficiencies for ch1 and ch2,
N_{sig} is the number of signal events obtained from fitting,
N_{B^-/B^+} is the number of B^-/B^+ mesons, 771×10^6 is used for this estimate.

$$\mathcal{B}(B^- \to \Xi_c^0\Lambda_c^-) = \frac{2}{(771.6 \times 10^6) \times (0.0143) \times (0.999) \times (0.639) \times \{9.22\% \times (0.0159) \times (0.692) + 7.56\% \times (0.0628)\}}$$
$$= 4.93 \times 10^{-5}$$

The upper limit on BNV mode's branching fraction will be re-interpreted as the upper limit on oscillation rate.

Summary & Outlook

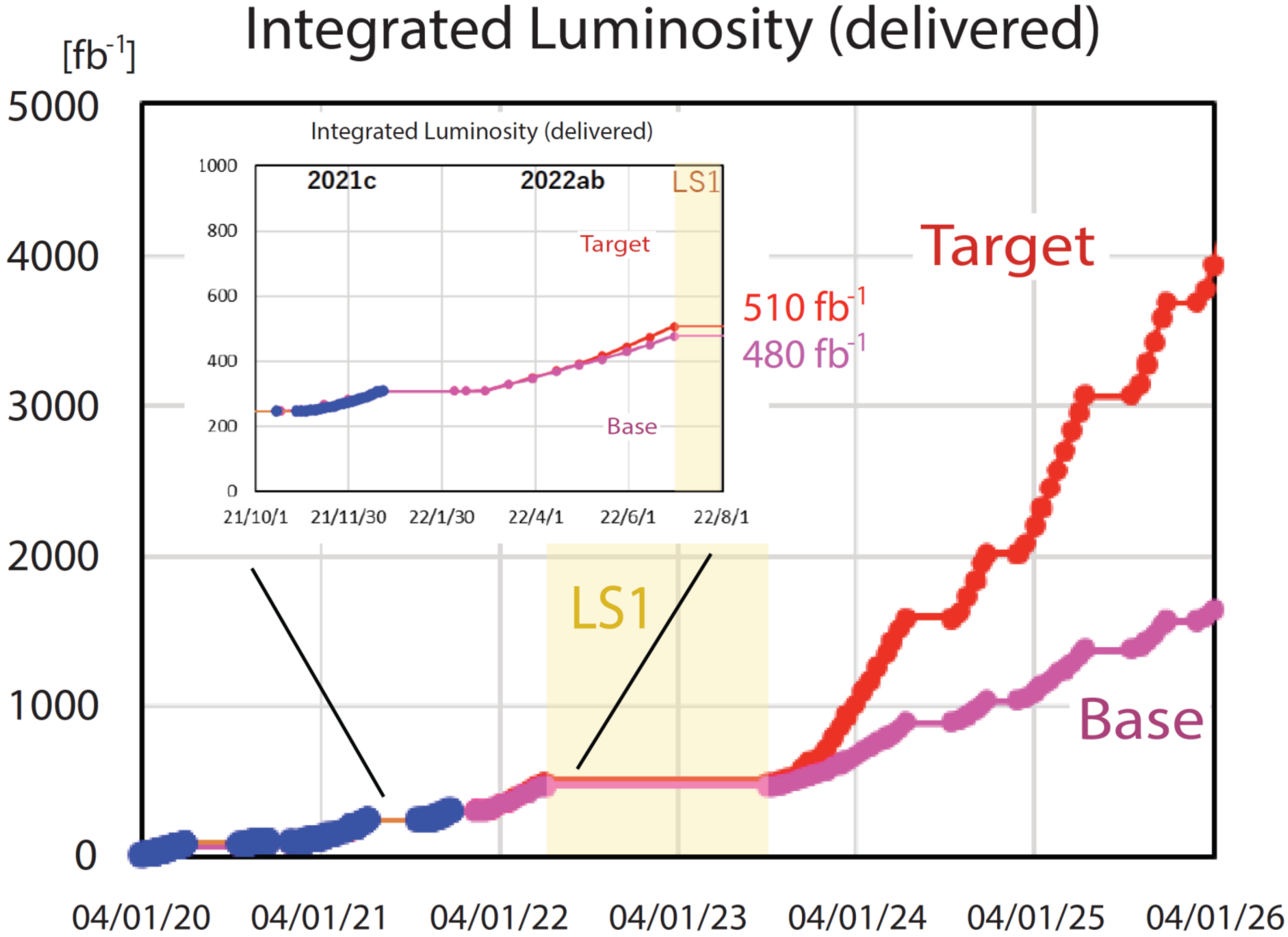
Summary

- Presented a search for baryon number violation in B decay $B^{-} \rightarrow \Xi_c^0 \Lambda_c^-$
- With MC study, we expect to have a 5×10^{-5} sensitivity with Belle data

Outlook

- For Belle II, with better vertex resolution, time-dependent oscillation measurement should be possible, 10 times larger statistics would improve sensitivity by the factor of at least 3

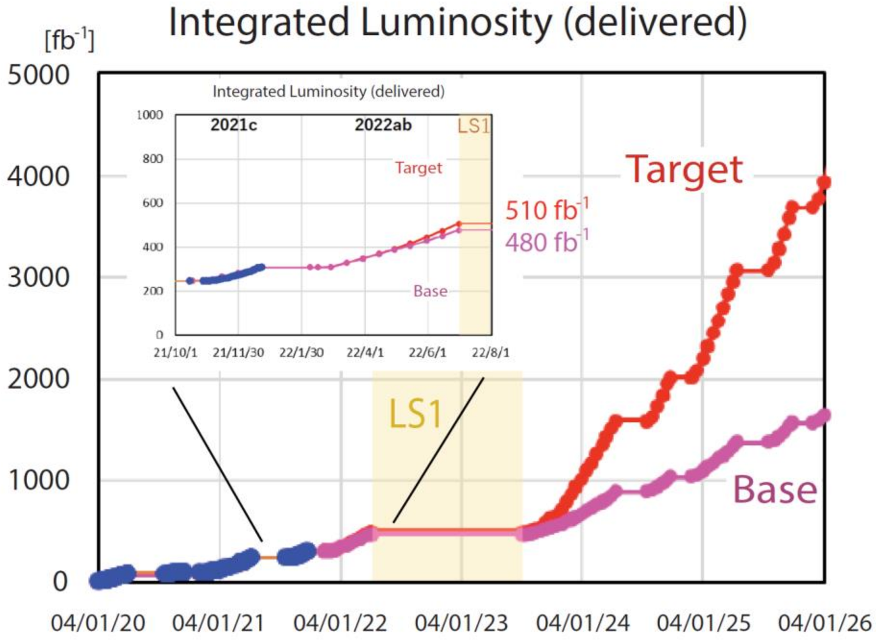
Backup


Integrated Luminosity (delivered)
[fb-1]
5000
4000
3000
2000
1000
0
04/01/20
04/01/21
04/01/22
04/01/23
04/01/24
04/01/25
04/01/26
Target
Base
LS1
510 fb-1
480 fb-1
Integrated Luminosity (delivered)
1000
800
600
400
200
0
2021c
2022ab
LS1
Target
Base
21/10/1
21/11/30
22/1/30
22/4/1
22/6/1
22/8/1

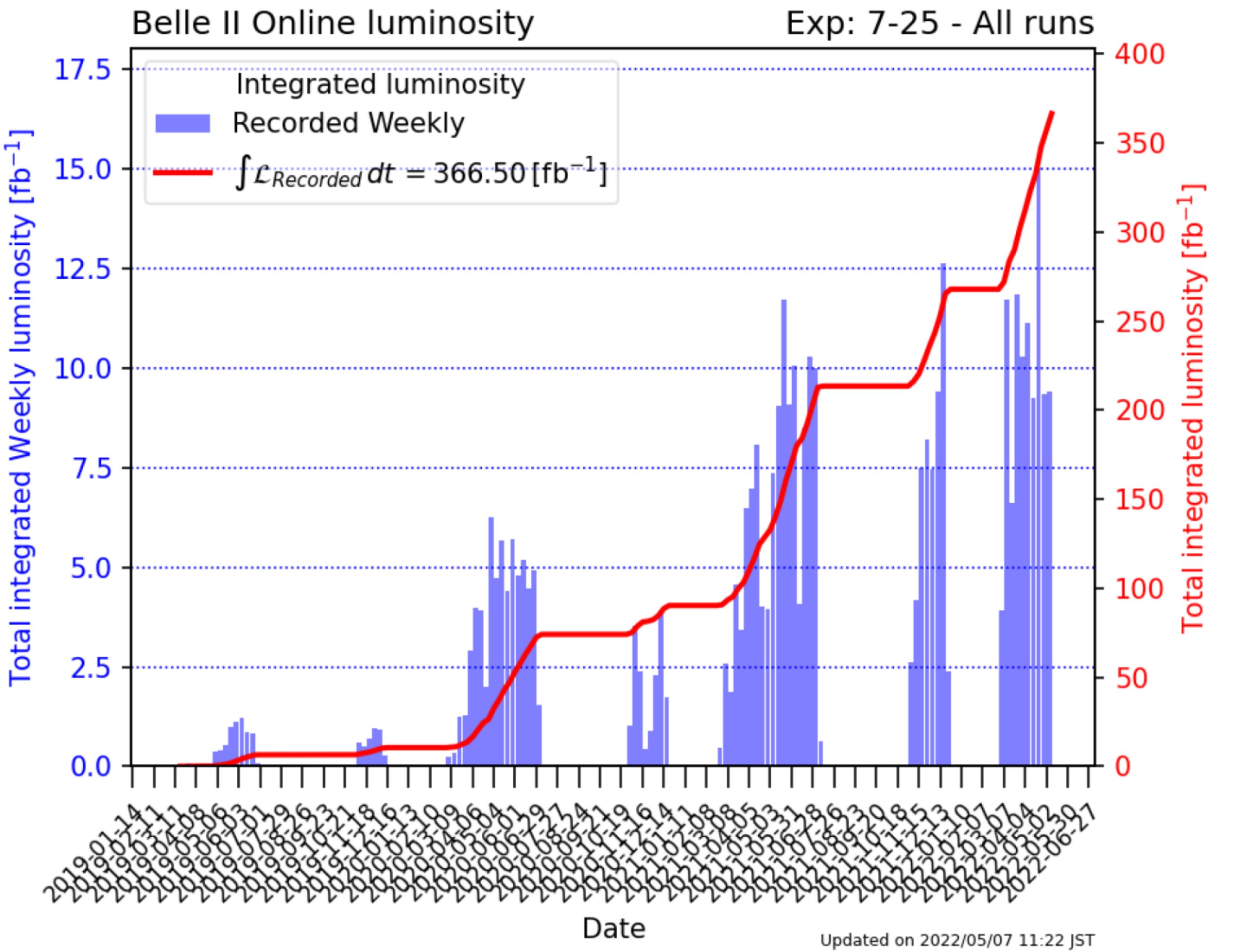
Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector
- We resume physics running from Fall 2023
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements
- An LS2 for machine improvements could happen on the time frame of 2026-2027



Belle II Online luminosity
Exp: 7-25 - All runs
Integrated luminosity
Recorded Weekly
$\int \mathcal{L}_{Recorded}\, dt = 366.50\, [fb^{-1}]$
Total integrated Weekly luminosity [fb⁻¹]
Total integrated luminosity [fb⁻¹]
Date
Updated on 2022/05/07 11:22 JST

THE UNIVERSITY OF MELBOURNE

Belle II - LHCb Comparison

+ Important contributions on B and D flavour physics from ATLAS, CMS, BESIII.

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B\rightarrow K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).
LHCb scheduled major upgrades during LS3 and LS4.
Belle II formulating a 250 ab^{-1} upgrade program post 2028.

Observable	Current Belle/ Babar	2019 LHCb	Belle II ($5\ ab^{-1}$)	Belle II ($50\ ab^{-1}$)	LHCb ($23\ fb^{-1}$)	Belle II Upgrade ($250\ ab^{-1}$)	LHCb upgrade II ($300\ fb^{-1}$)
CKM precision, new physics in CP Violation							
$\sin 2\beta/\varphi_1$ ($B\rightarrow J/\psi K_S$)	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/φ_3	13°	5.4°	4.7°	1.5°	1.5°	0.4°	0.4°
α/φ_2	4°	–	2	0.6°	–	0.3°	–
$\|V_{ub}\|$ (Belle) or $\|V_{ub}\|/\|V_{cb}\|$ (LHCb)	4.5%	6%	2%	1%	3%	<1%	1%
φ_s	–	49 mrad	–	–	14 mrad	–	4 mrad
S_{CP}($B\rightarrow\eta' K_S$, gluonic penguin)	0.08	○	0.03	0.015	○	0.007	○
A_{CP}($B\rightarrow K_S\pi^0$)	0.15	–	0.07	0.04	–	0.02	–
New physics in radiative & EW Penguins, LFUV							
S_{CP}($B_d\rightarrow K^*\gamma$)	0.32	○	0.11	0.035	○	0.015	○
R($B\rightarrow K^* l^+ l^-$) ($1<q^2<6\ GeV^2/c^2$)	0.24	0.1	0.09	0.03	0.03	0.01	0.01
R($B\rightarrow D^*\tau\nu$)	6%	10%	3%	1.5%	3%	<1%	1%
Br($B\rightarrow\tau\nu$), Br($B\rightarrow K^*\nu\nu$)	24%, –	–	9%, 25%	4%, 9%	–	1.7%, 4%	–
Br($B_d\rightarrow\mu\mu$)	–	90%	–	–	34%	–	10%
Charm and τ							
ΔA_{CP}($KK-\pi\pi$)	–	8.5×10^{-4}	–	5.4×10^{-4}	1.7×10^{-4}	2×10^{-4}	0.3×10^{-4}
A_{CP}($D\rightarrow\pi^+\pi^0$)	1.2%	–	0.5%	0.2%	–	0.1%	–
Br($\tau\rightarrow e\gamma$)	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
Br($\tau\rightarrow\mu\mu\mu$)	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

Results on other D & τ modes expected

○ *Possible in similar channels, lower precision*
– *Not competitive.*

arXiv:1808.08865 (Physics case for LHCb upgrade II), PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)