Rare B Decays at Belle II

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On Behalf of the Belle II Collaboration

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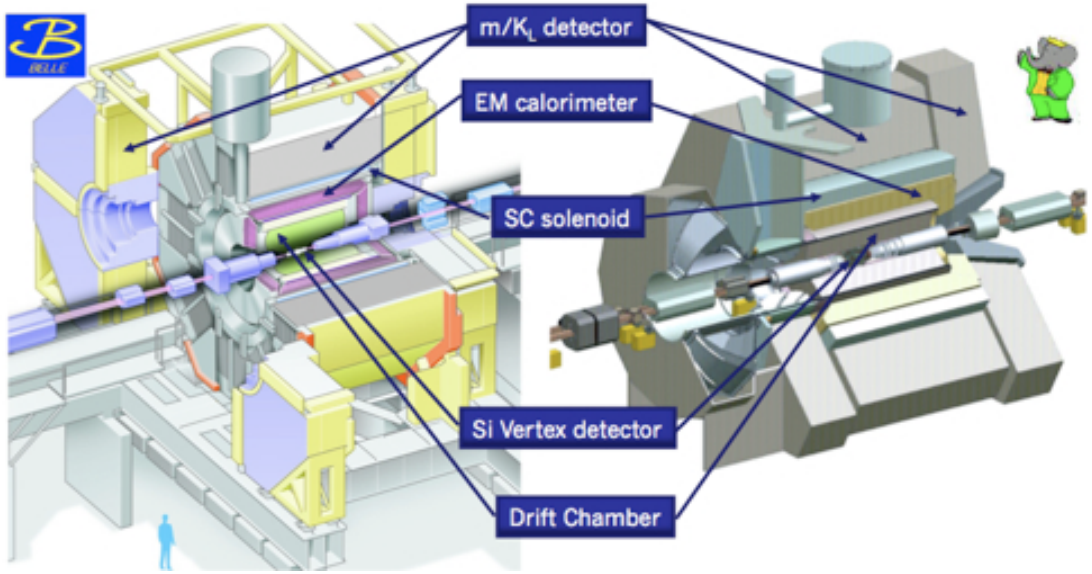
Outline

- Motivation for the e^+e^- B factory
- The **SuperKEKB** collider
- The **Belle II** detector
- The **Prospects** of **rare B decays at Belle II**

The 1st-generation *B* factories

"*B* factory": High-luminosity, asymmetric-energy e^+e^- collider operating at $\sqrt{s} = 10.59$ GeV to produce $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



https://www2.kek.jp/proffice/archives/feature/2010/BelleBaBarBook.html

Belle in Japan
1999-2010
~1000 fb^{-1}= 1 ab^{-1}

BaBar in the US
1999-2008
~500 fb^{-1}= 0.5 ab^{-1}

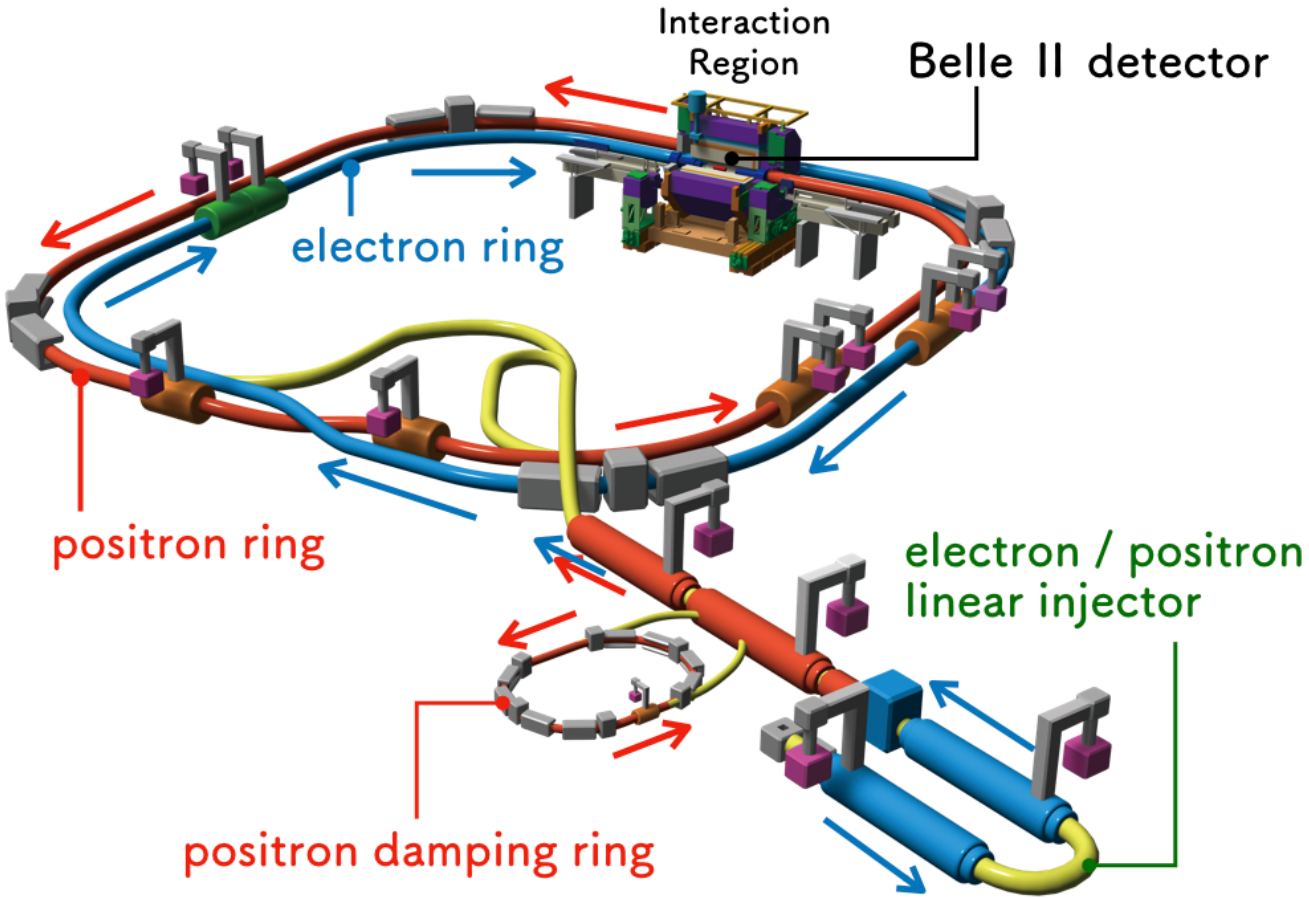
Initial goal: test the CP-violation mechanism of the SM

The 2nd-generation *B* factories: Belle II and LHCb

Property	LHCb	Belle II
$\sigma_{\bar{b}b}(nb)$	~150,000	~**1**
$\int Ldt\ (fb^{-1})\ by\ 2027$	~**25**	~50,000
Background level	**High**	Low
Typical efficiency	**Low**	High
π^0, K_S efficiency	**Low**	High
Initial state	**Not well known**	Well known
Decay-time resolution	Excellent	**Good**
Collision spot size	**Large**	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	**Partly B_s**
τ physics capability	**Limited**	Excellent
B-flavor tagging efficiency	**3.5-6%**	36%

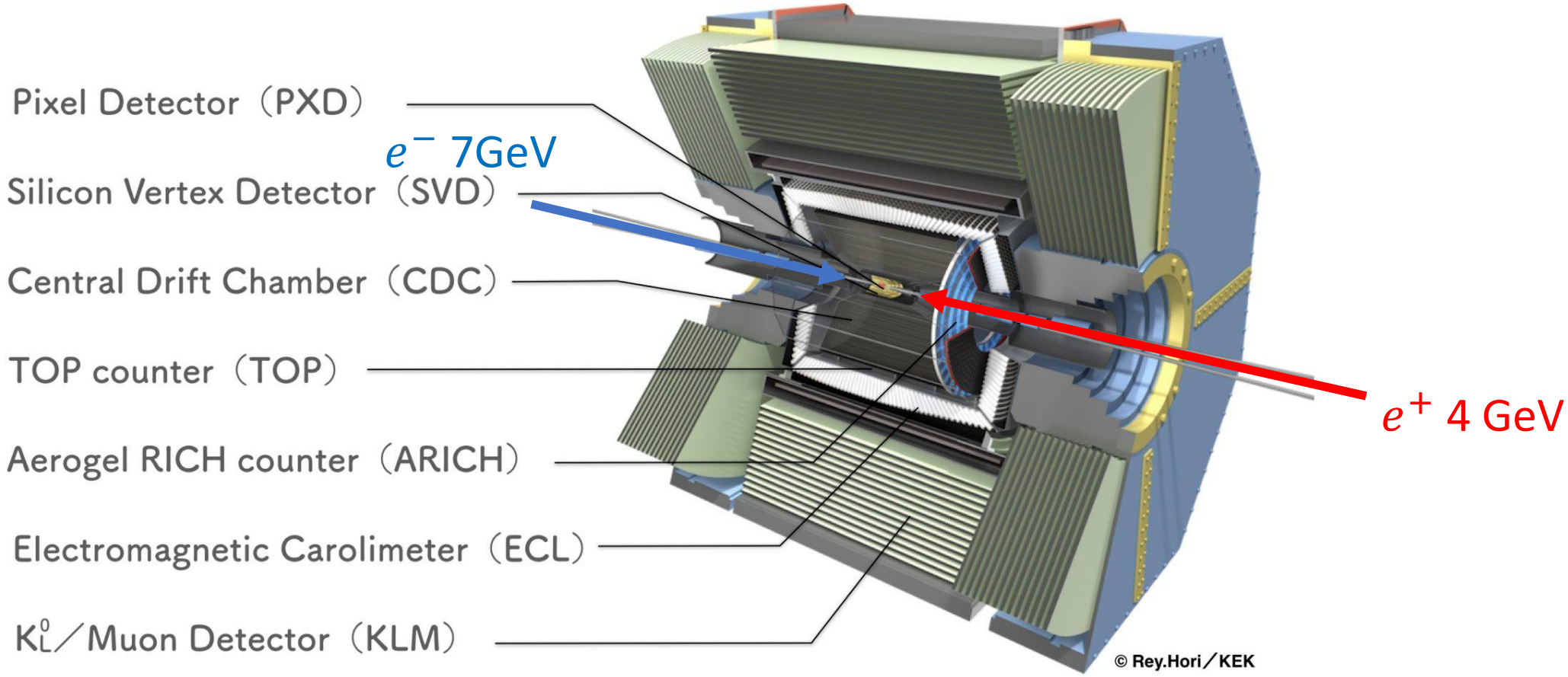
Reference: Abi Soffer, Intensity Frontier in Particle Physics, October 2019, Taipei

SuperKEKB collider



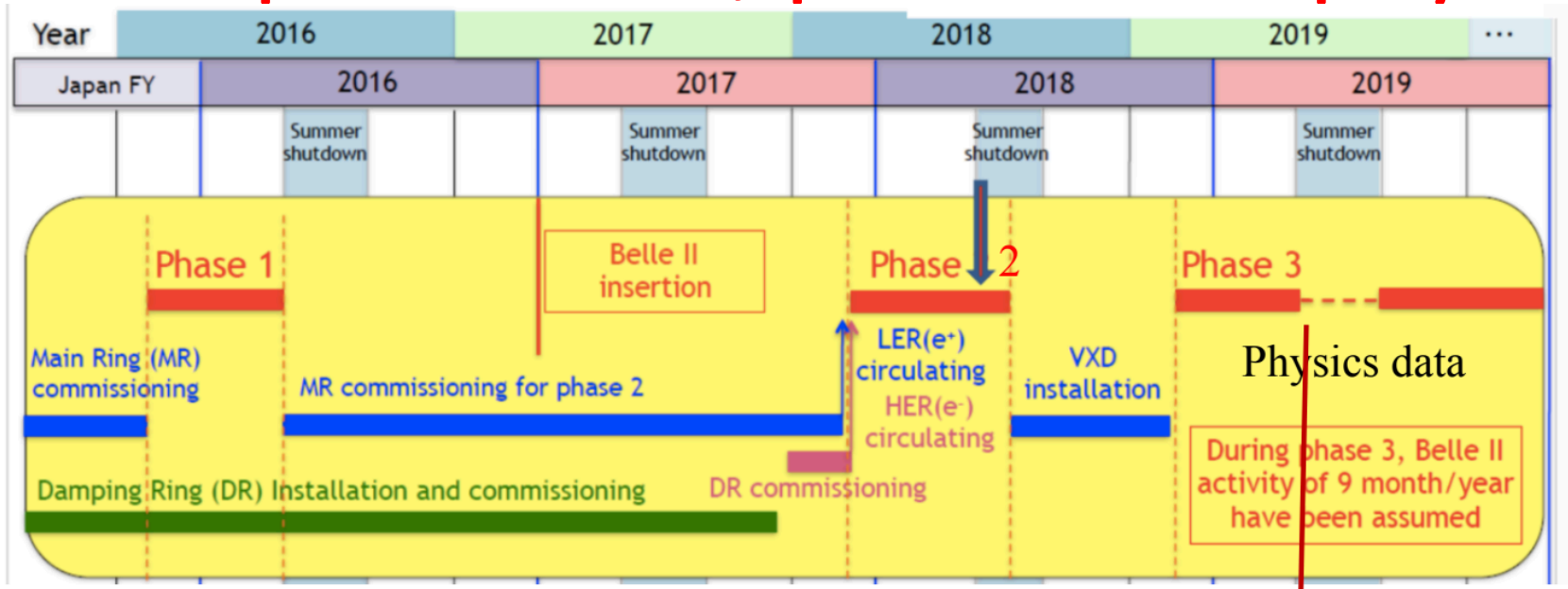
The electron and positron rings are about **3-km-long**. The tunnel used for SuperKEKB is the same as KEKB.

Belle II detector



PXD, TOP and ARICH are new designs; SVD, CDC, ECL and KLM are upgraded from original designs in Belle.

Start-up schedule, phase 3 for physics data



First collisions, 26 April, 2018

- Collected ~ 5 fb^{-1}
  - 0.5% of Belle
- Mostly at $L \sim 0.5\times10^{34}\ cm^2s^{-1}$
  - 25% of KEKB
- Reached $L \sim 1.2\times10^{34}\ cm^2s^{-1}$
  - With high background
  - Ongoing work on background

Detector performance and rediscovery of known physics

- Current integrated luminosity, ~$5 fb^{-1}$ is similar to that of CLEO in mid-90's
- Used mostly for **validating detector performance and commissioning**
- Please check the talks:
  - **Belle II Status and prospects, Speaker**: Tadeas Bilka
  - **First results on DM searches at Belle II, Speaker**: Michael de Nuccio

Expected Luminosity in the Near Term

	Until 2020/7/1				Until 2021/3/31			
	Int. L [fb^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]	Int. L [fb^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]
Base (conservative) plan	100	2.2	0.8	1				
Possible (expected) plan	150	3.5	0.9	1				
Case N1: 6.5 months operation	150	3.5	0.9	1	500	9.5	1.1	0.5
Case N2: 5.4 months operation	150	3.5	0.9	1	320	8.1	1	0.5

Reference: Y. Suetsugu, B2GM, 2020.Feb.03

The Int. L will be **100 - 150 fb^{-1}** until 2020/7/1 (**10%~15%** of Belle), and **320 – 500 fb^{-1}** until 2021/3/31 (**32%~50%** of Belle).

Expected Luminosity in the Middle Term

	Until 2022/3/1				Until 2023/3/31			
	Int. L [ab^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]	Int. L [ab^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]
Case M1: FY2020 6.5 months PXD exc. 2022	1.5	19	1.3	0.3	3.4	26	1.7	0.3
Case M2: FY2020 5.4 months PXD exc. 2021	0.6	16	1.1	0.3	3.4	25	1.6	0.3
Case M3: FY2020 5.4 months PXD exc. 2022	1.2	17	1.2	0.3	2.7	24	1.6	0.3

Reference: Y. Suetsugu, B2GM, 2020.Feb.03

The Int. L will be **0.6 – 1.5 ab^{-1}** until 2022/3/1 (**60%~150%** of Belle), and **2.7 – 3.4 ab^{-1}** until 2023/3/31 (**270%~340%** of Belle).

The Belle II Physics Book

- The "Belle II Physics Book" has been recently accepted for publication by PTEP;
- This is the results of several years of collaboration between Belle II and the Theory Community;
- Sensititivity estimates on the golden (and silver) channels are given.

arXiv: 1808.10567
DOI: 10.1093/ptep/ptz106

200+ citations

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

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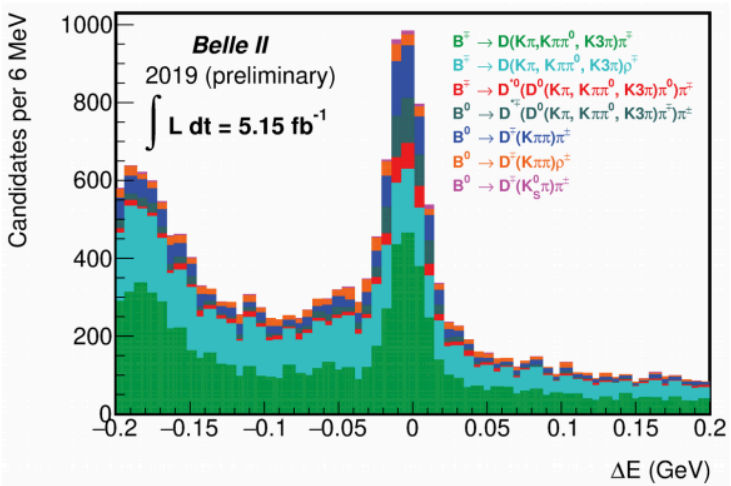
	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}] vs LHCb	vs Belle	Anomaly	NP
●	$B \to \pi\ell\nu_\ell$	$\lvert V_{ub}\rvert$	⋆⋆⋆	10-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆
●	$B \to X_u\ell\nu_\ell$	$\lvert V_{ub}\rvert$	⋆⋆	2-10	⋆⋆⋆	⋆⋆	⋆⋆⋆	⋆
●	$B \to \tau\nu$	$Br.$	⋆⋆⋆	>50 (2)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \mu\nu$	$Br.$	⋆⋆⋆	>50 (5)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to D^{(*)}\ell\nu_\ell$	$\lvert V_{cb}\rvert$	⋆⋆⋆	1-10	⋆⋆⋆	⋆⋆	⋆⋆	⋆
●	$B \to X_c\ell\nu_\ell$	$\lvert V_{cb}\rvert$	⋆⋆⋆	1-5	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆
●	$B \to D^{(*)}\tau\nu_\tau$	$R(D^{(*)})$	⋆⋆⋆	5-10	⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆
●	$B \to D^{(*)}\tau\nu_\tau$	P_τ	⋆⋆⋆	15-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆
●	$B \to D^{**}\ell\nu_\ell$	$Br.$	⋆	-	⋆⋆	⋆⋆⋆	⋆⋆	-

	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}] vs LHCb	vs Belle	Anomaly	NP
●	$B \to J/\psi K^0_S$	ϕ_1	⋆⋆⋆	5-10	⋆⋆	⋆⋆	⋆	⋆
●	$B \to \phi K^0_S$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \eta' K^0_S$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \rho^\pm\rho^0$	ϕ_2	⋆⋆⋆	>50	⋆	⋆⋆⋆	⋆	⋆
●	$B \to J/\psi\pi^0$	ϕ_1	⋆⋆⋆	>50	⋆	⋆⋆⋆	-	-
●	$B \to \pi^0\pi^0$	ϕ_2	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆
●	$B \to \pi^0 K^0_S$	S_{CP}	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆

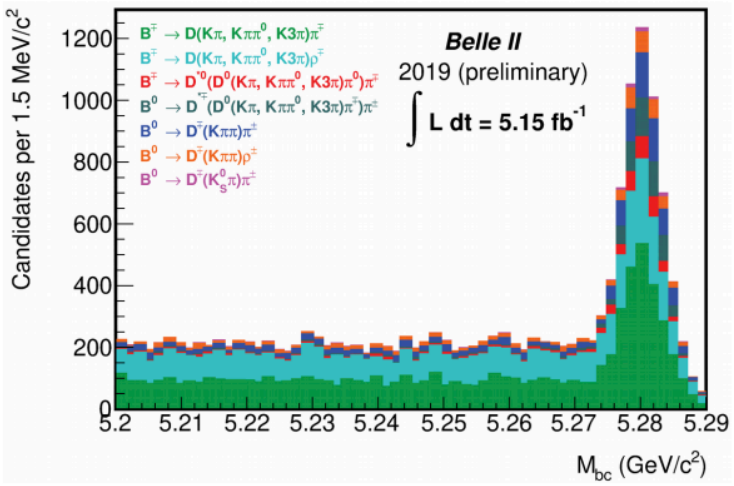
B-factory jargon

Two variables are extremely useful to discriminate against background for fully reconstructed final states:

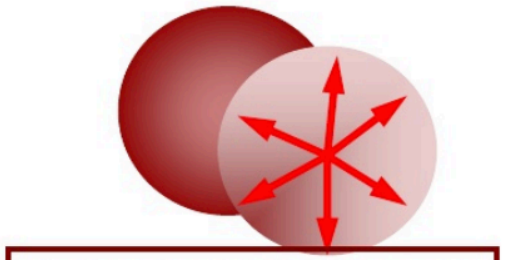
$$\Delta E = E_B^* - \frac{\sqrt{s}}{2}$$



$$M_{bc} = \sqrt{\frac{s}{4} - p_B^{*2}}$$



For many final states, the dominant source of background is the 'continuum', which is suppressed based on the different topology with respect to $B\overline{B}$ events:

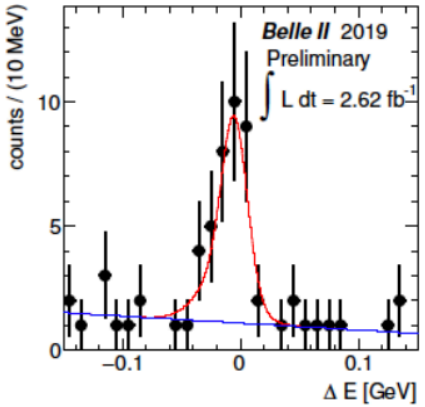


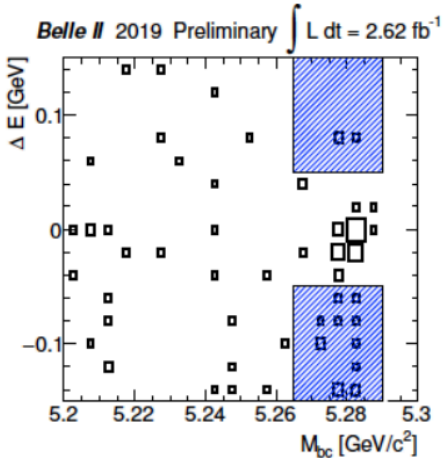
Spherical BB events

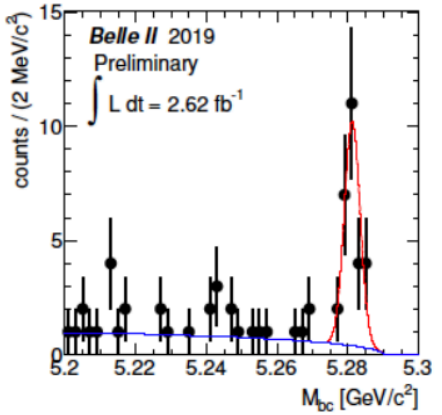
Jet-like qq events

Rediscovery of $B^0 \to J/\psi\, K^{(*)}$

$B^\circ \to J/\psi\, K^\circ_S,\ K^\circ_S \to \pi^+\pi^-$

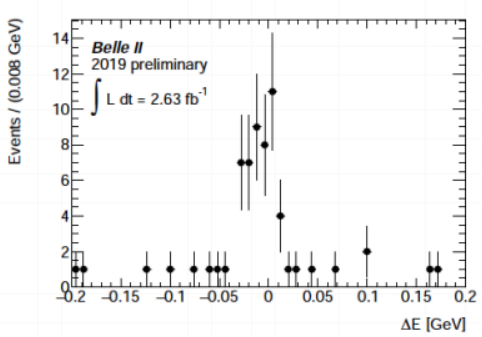


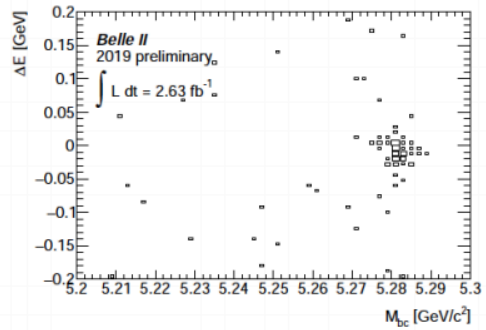




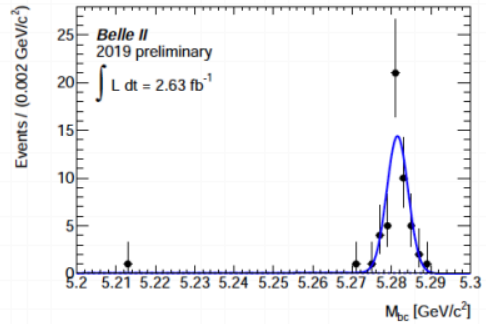
$N_{sig} = 26.9 \pm 5.2$

$B^\circ \to J/\psi\, K^{*\circ},\ K^{*\circ} \to K^-\pi^+$





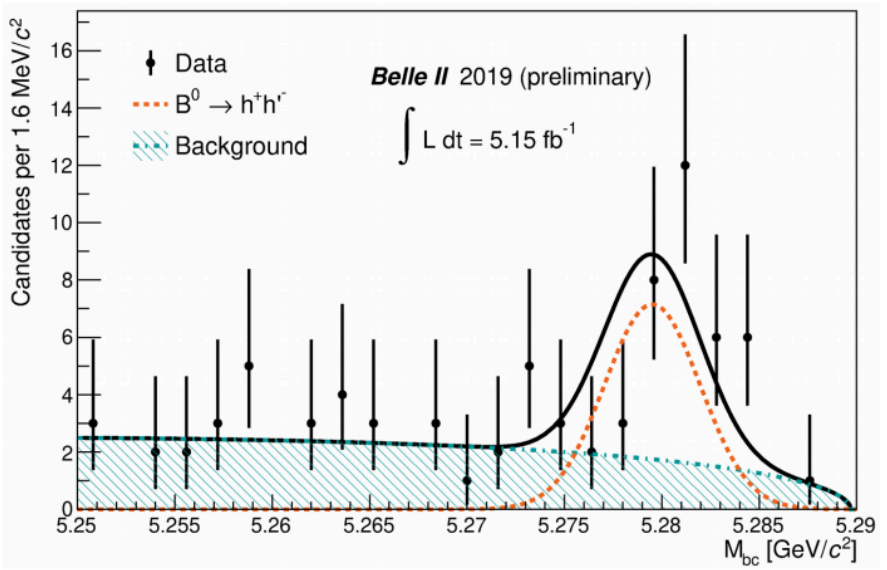
$N_{sig} = 48.6 \pm 7.0$

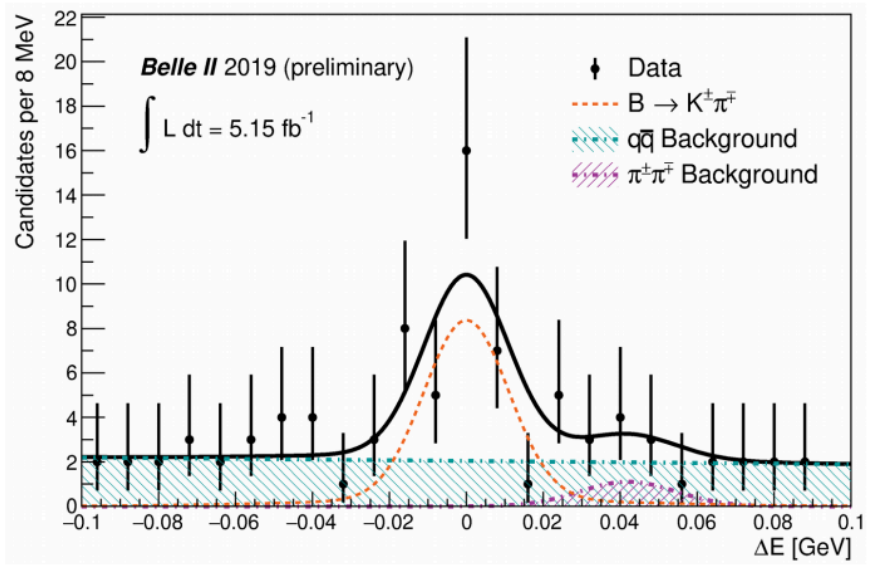


Not useful for measuring CP violation, but very useful to study vertexing resolution (comparing the J/ψ and the K* vertices)

Rediscovery of $B \to h^+h'^-$

- First milestone for the measurement of ϕ_2: rediscovery of the charmless $B \to h^+h'^-$ decays;
- Continuum background is suppressed using a BDT classifier utilizing variables sensitive to the event topology;
- Only very loose PID requirements on the final state particles;
- A clear signal (~25 events) is observed for the $K^+\pi^-$ mode;
- More statistics will be needed to observe the more elusive $\pi^+\pi^-$ signal.





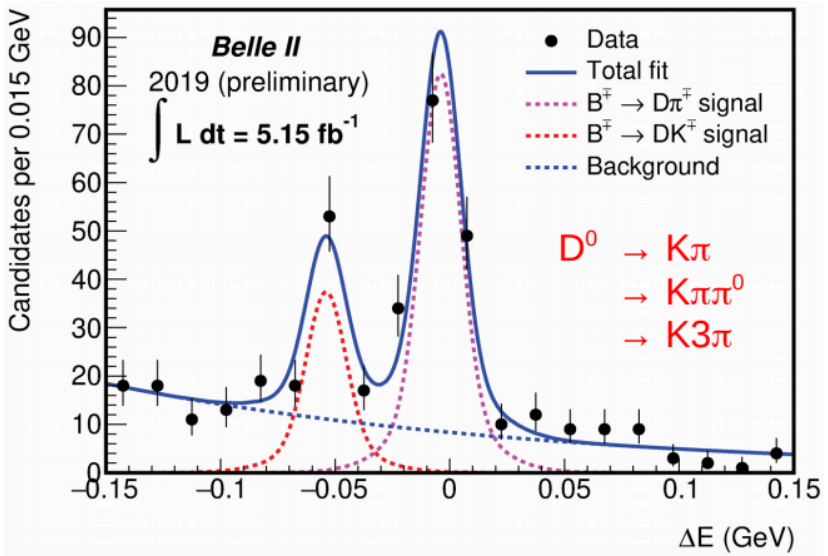
Rediscovery of B → DK at Belle II

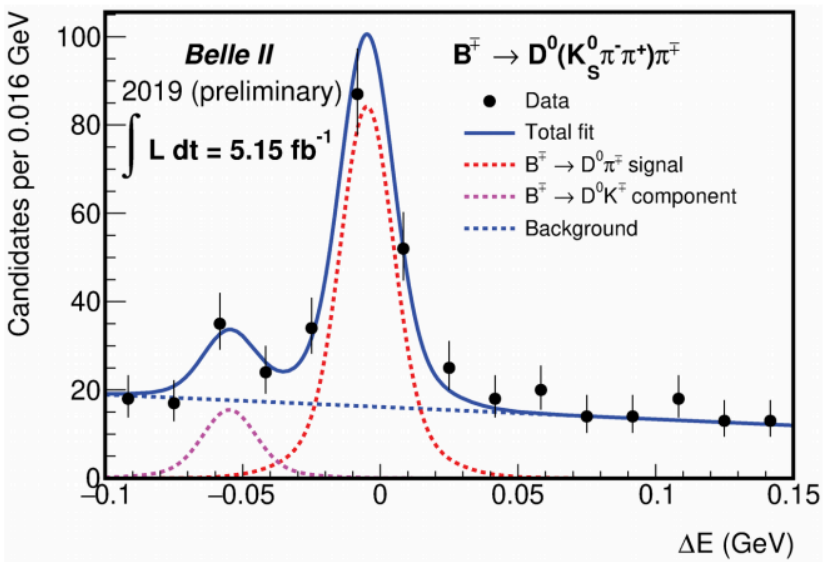
- Major milestone: rediscover the $B^+ \to D^\circ K^+$ signal, next to the higher branching fraction mode $B^+ \to D^\circ \pi^+$;
- Multivariate discriminator suppresses continuum background;
- Tight PID criteria for the $D^\circ \to K\pi$, $K\pi\pi^\circ$, $K3\pi$ modes:

  pionID (bachelor hadron) < 0.4

  (53 ± 9 B → DK signal events)

- Also the golden mode for the GGSZ analysis ($D^\circ \to K_S\pi^+\pi^-$) is starting to show up (new since Lepton Photon!).



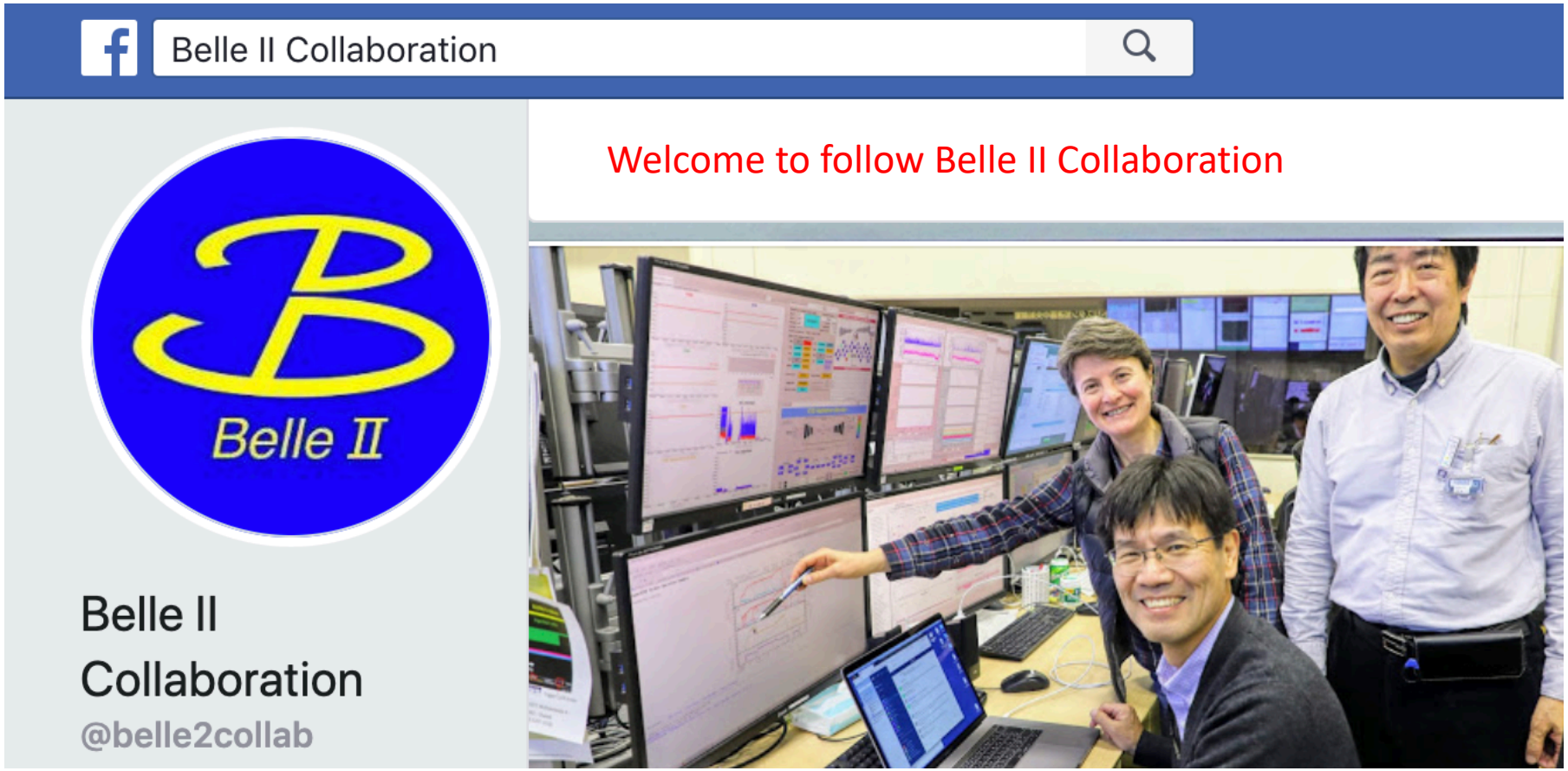


Summary

- Belle II began taking physics data in 2019
- Integrated luminosity ~5 fb^{-1} used for commissioning and some unique measurements
- Will reach Belle's integrated luminosity in 2022
- Belle II will be competitive/complementary to LHCb on many other areas soon
- The experiment is on its way to groundbreaking measurements

Backup

The new record of the peak luminosity



The photograph indicates the peak luminosity of Belle II experiment reached $\mathbf{105.43 \times 10^{32} / cm^2 / sec}$ in the evening of December 3, 2019. Credit: KEK Outreach Committee.