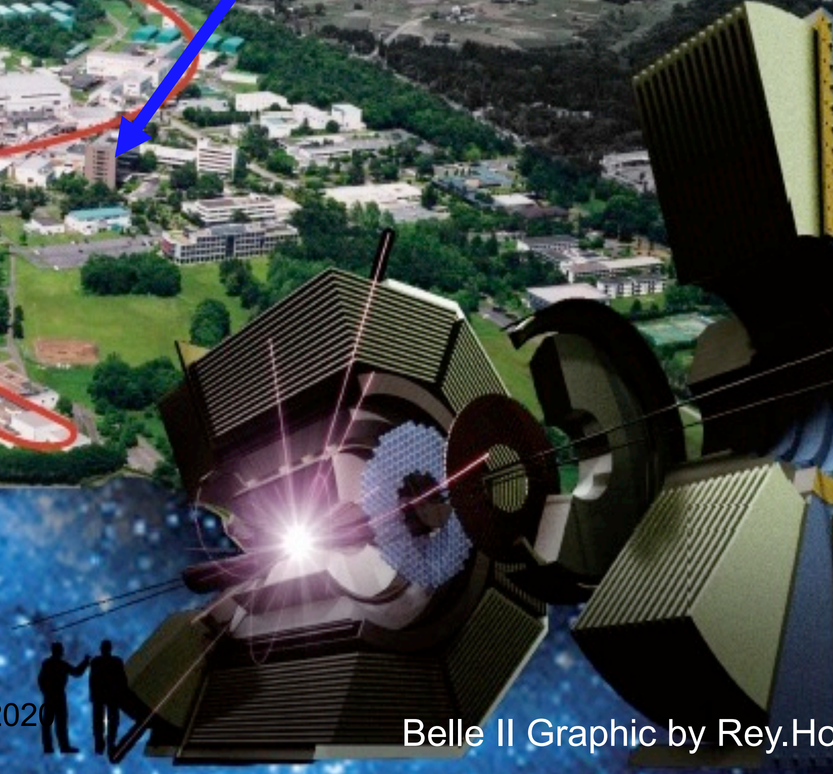
Belle II at SuperKEKB, Status and Prospects

Zdenek Dolezal
Charles University Prague
for Belle II

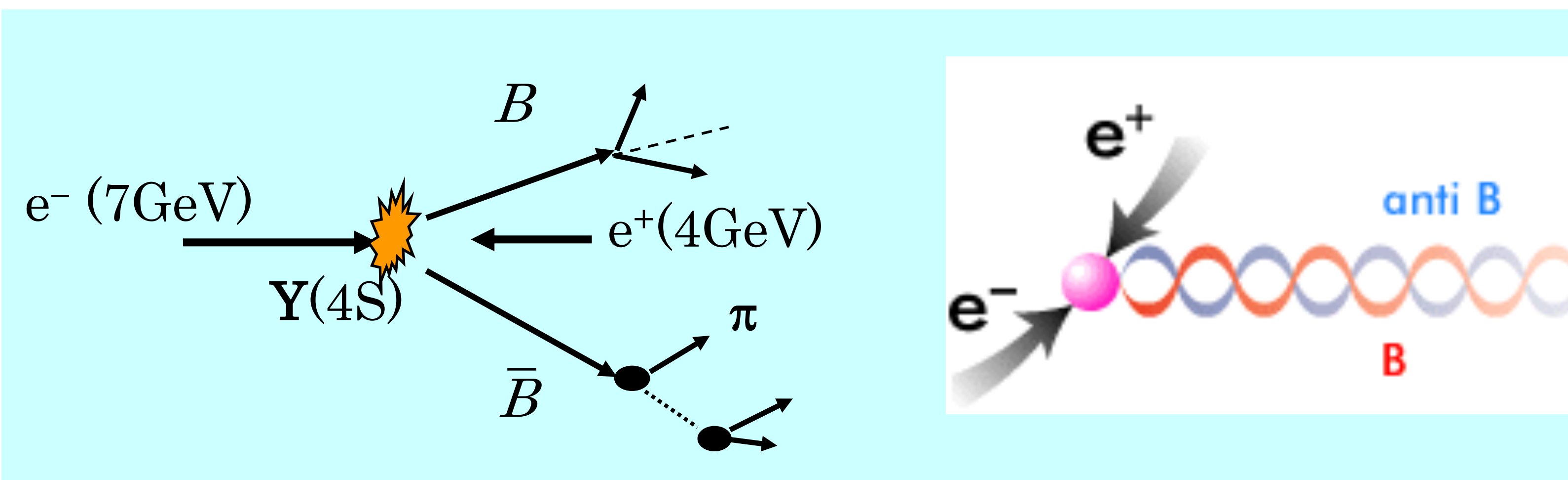


KEK
High Energy Accelerator Reseach Organization

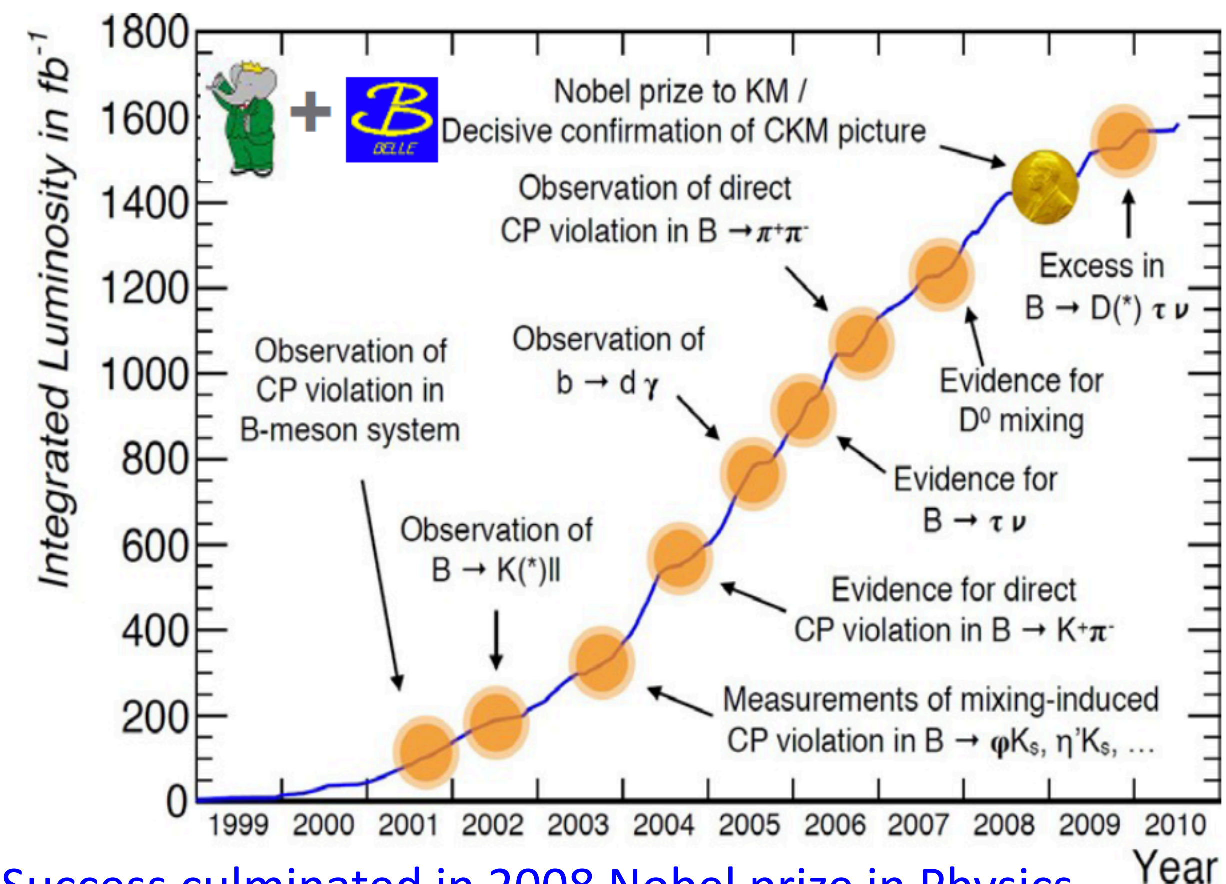
Belle II Graphic by Rey.Ho

Asymmetric energy Flavor factories

- e^+e^- beams tuned at Υ*(4S)* resonance 10.6 GeV
- 50% decays: coherent production $\boldsymbol{B^0\overline{B}^0}$
- Fully reconstruct one of the *B*'s
- Tag the flavor of the other B



First-generation Factories



- Success culminated in 2008 Nobel prize in Physics
- Rich legacy left for next generation experiments

Motivation for another e^+e^- Flavor Factory

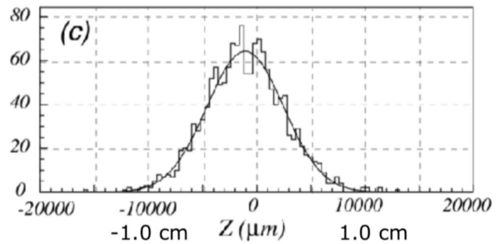
- Precision CKM metrology ➛ Standard Model (SM) candle
- New CP violating phases ➛ CP violation in B and D decays
- Any imprint of new physics in FCNC transitions? ➛ radiative and electroweak penguin decays
- How about charged Higgs boson? ➛ study tree-level decay $B \to \tau\nu$ or $B \to D^{(*)}\tau\nu$
- New physics in τ sector ➛ search for lepton flavor violating (LFV) τ-decays
- Can we probe dark matter? ➛ hidden dark sector

Belle II @ SuperKEKB will address these and other questions with almost two orders of magnitude larger dataset than Belle+BABAR

SuperKEKB

Ordinary collision (KEKB)

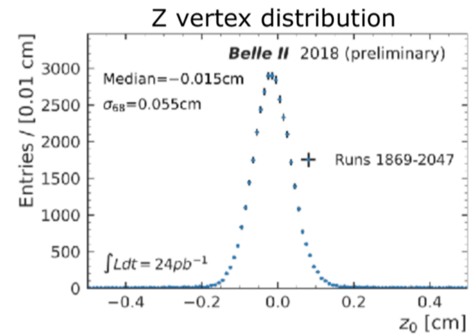
Belle case 1999 data



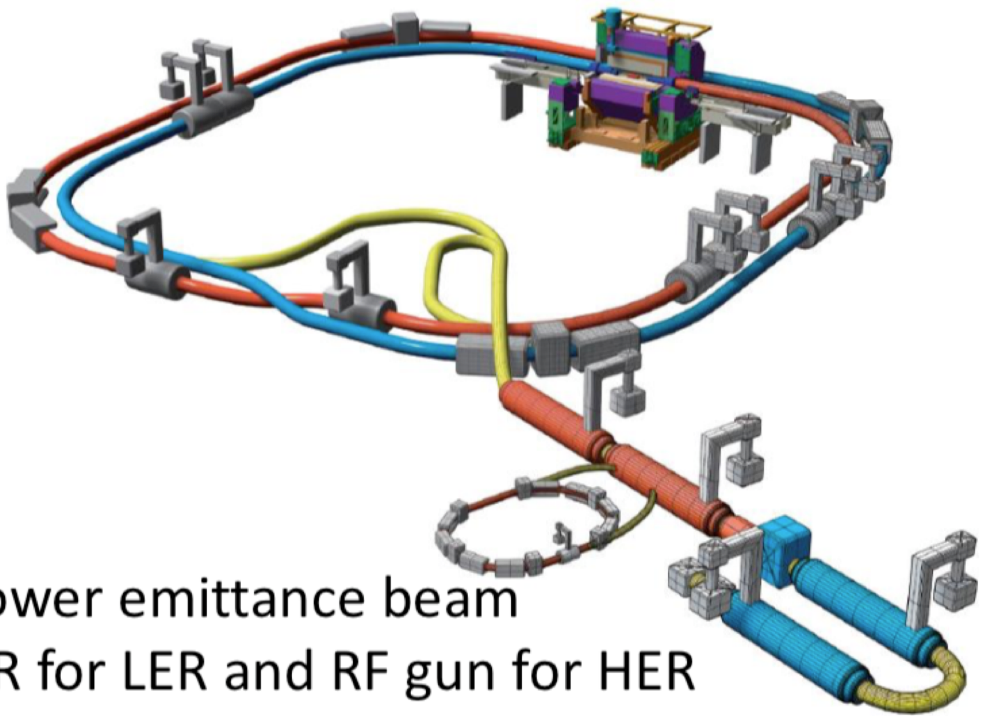
-1.0 cm　　1.0 cm

σ = 4.5 mm

Nano-Beam (SuperKEKB Phase2)



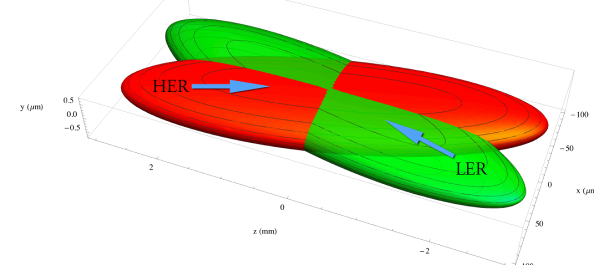
σ = 550 μm



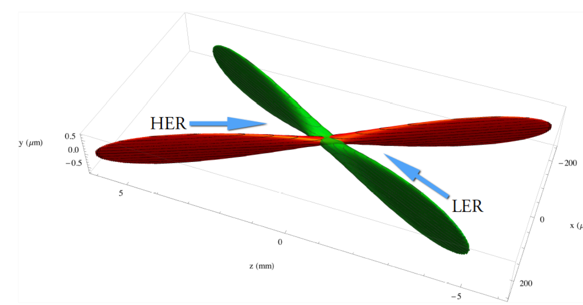
Lower emittance beam

DR for LER and RF gun for HER

Beams at KEKB



Nanobeams at SuperKEKB



Interaction-point size: $6 \times 0.06 \times 150\ \mu m^3$

Nanobeam Scheme

$$L = \frac{N^2 f_b}{4\pi\ \sigma_x \sigma_y} = \frac{\gamma_{e\pm}}{2e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-beam parameter

Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 ~ 1 (short bunch)

Classical electron radius

Beam size ratio@IP 1 ~ 2 % (flat beam)

Vertical beta function@IP

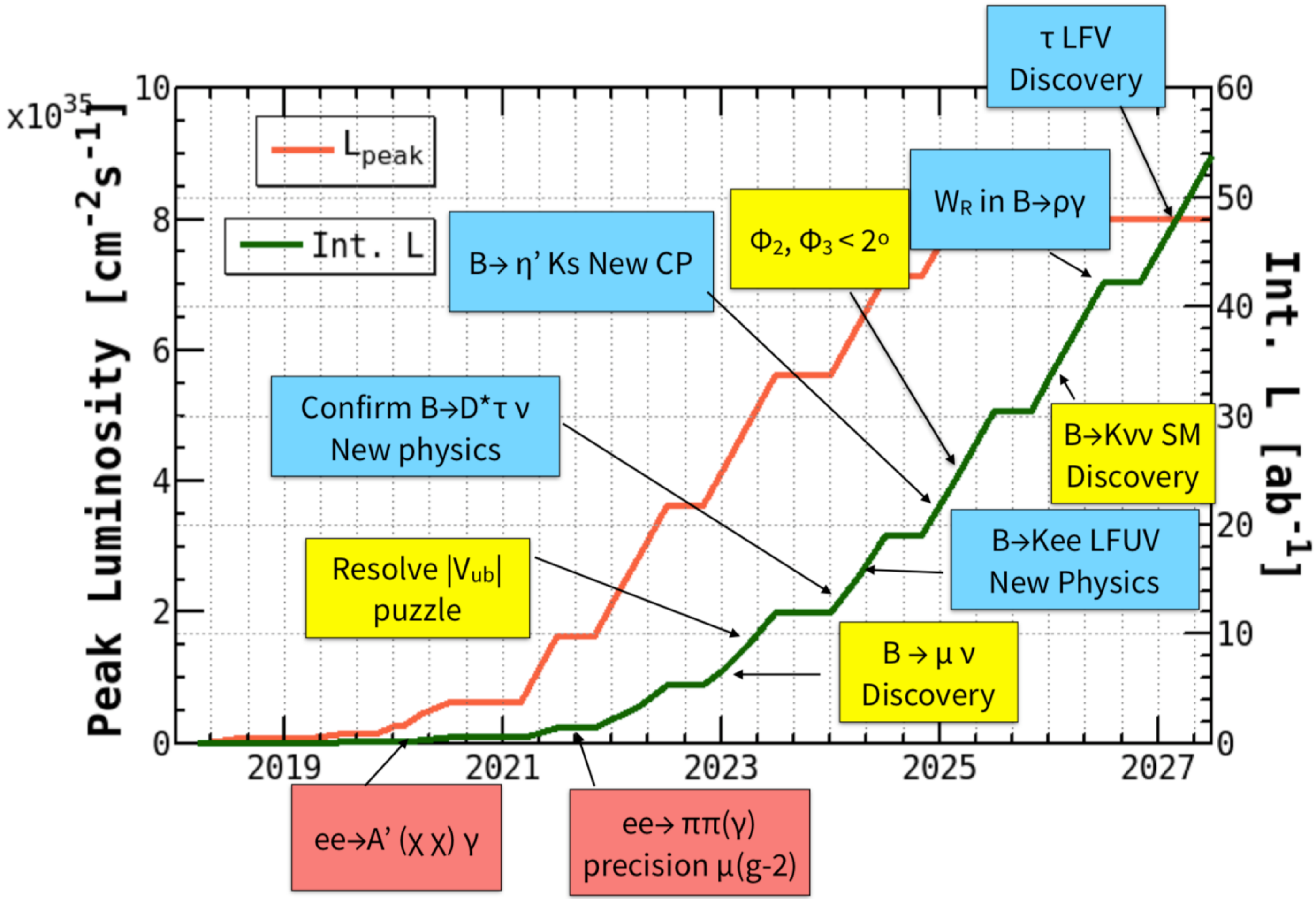
		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Beam crossing angle	φ	22		83		mrad
β function @ IP	β_x^*/β_y	1200/5.9		32/0.27	25/0.30	mm
Beam current	I_b	1.64	1.19	3.6	2.6	A
Luminosity	L	2.1 x 10^{34}		8 x 10^{35}		$cm^{-2}s^{-1}$

X 20

X 2

X 40

Luminosity vs Physics



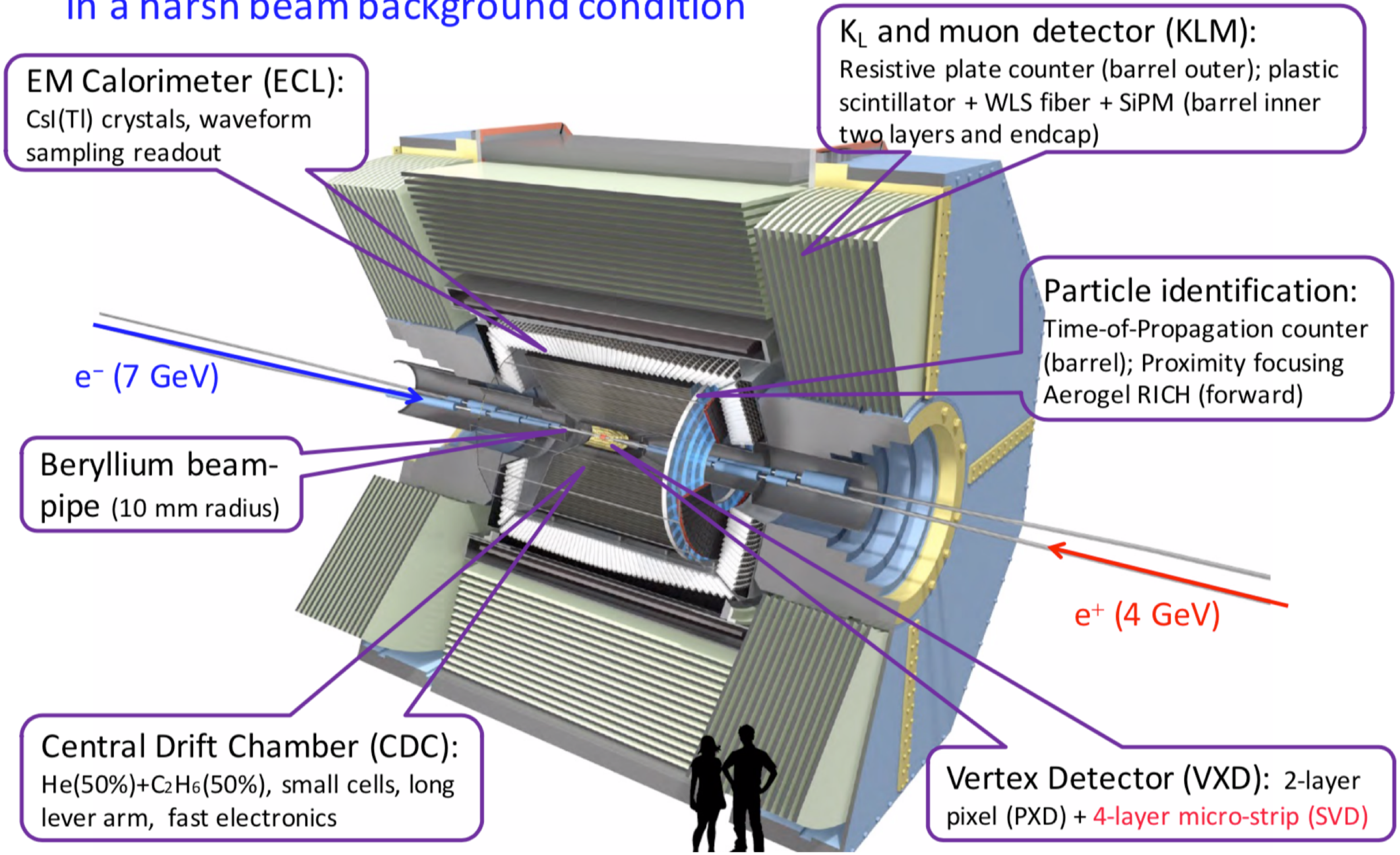
E. Kou et al. PTEP 2019(123C01)

Belle II Collaboration

26 countries, 113 institutions, close to 1000 collaborators

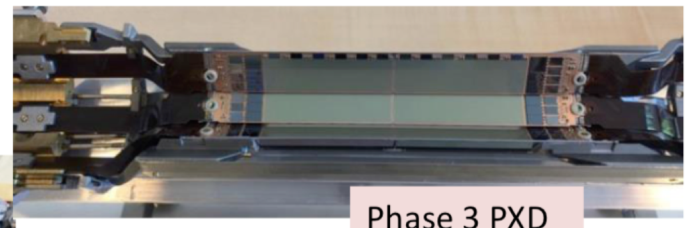
Belle II Detector

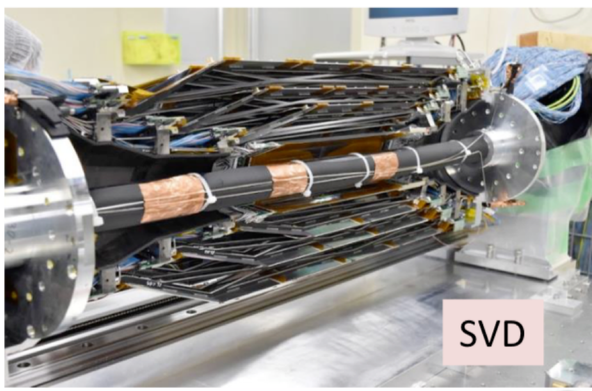
- Designed to operate with a performance similar or better than Belle, but in a harsh beam background condition

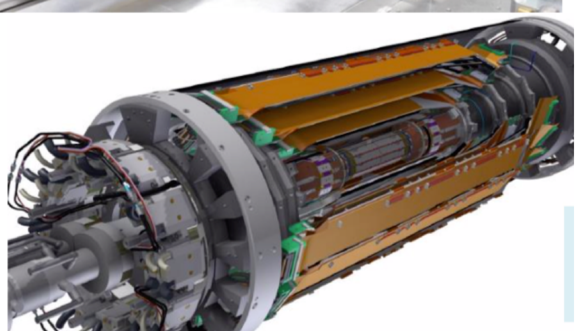


Vertex Detector (VXD)

Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 39mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**





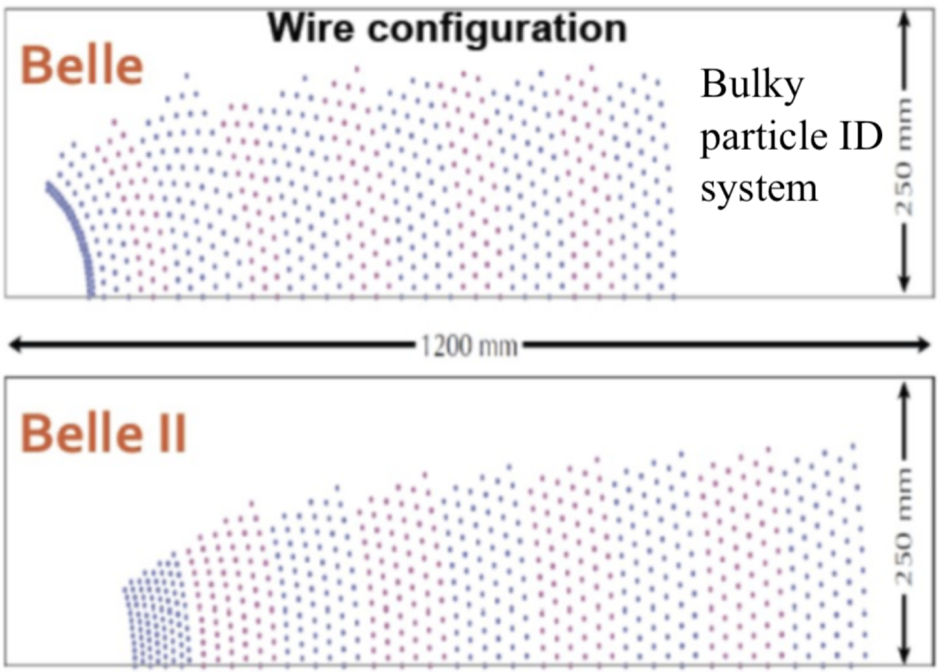


2 layers of DEPFET active pixels 75 μm thick (currently 2 modules in L2 only)

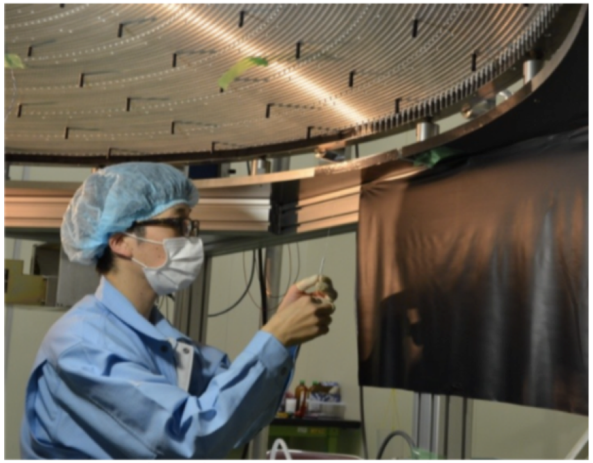
4 layers of double-sided strip sensors

Factor 2 or better impact parameter resolution in spite of the lowered Lorentz boost

Central Drift Chamber (CDC)



Outer radius almost ~20% larger than at BABAR/Belle:
Improved momentum resolution

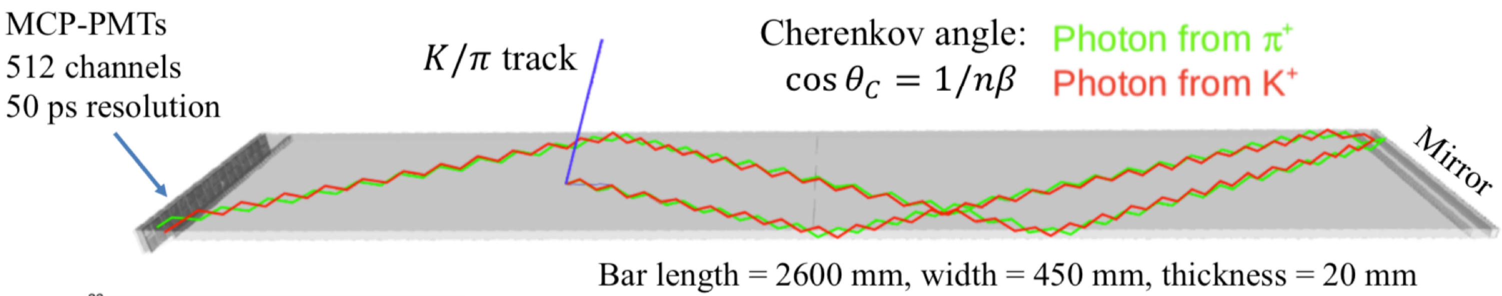


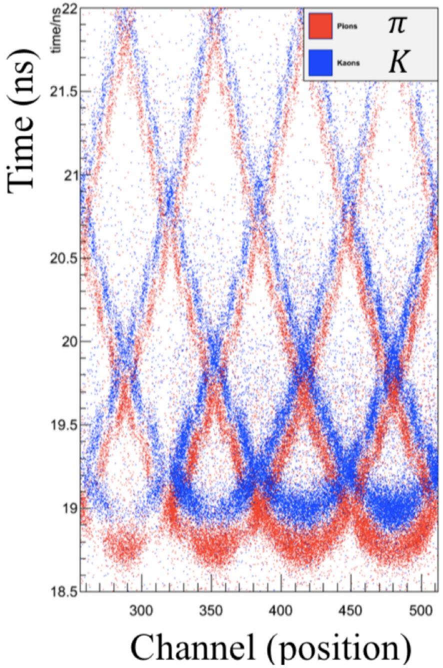
Stringing 51456 wires

	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C_2H_6	He:C_2H_6
Sense wire	W(Φ30μm)	W(Φ30μm)
Field wire	Al(Φ120μm)	Al(Φ120μm)

A. Soffer, Taipei 2019

Particle ID (Time of Propagation)

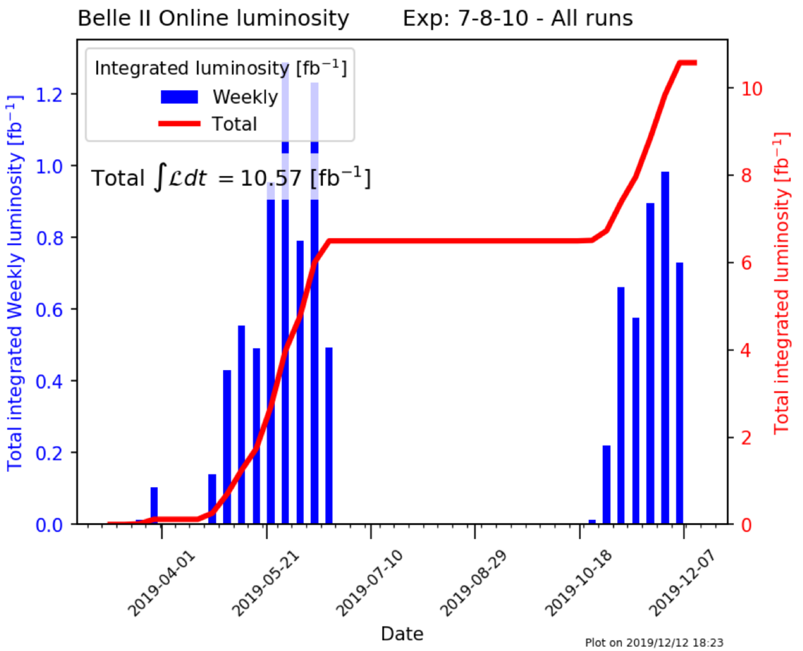




16 quartz-bar modules:

Quartz Property	Requirement
Flatness	<6.3µm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

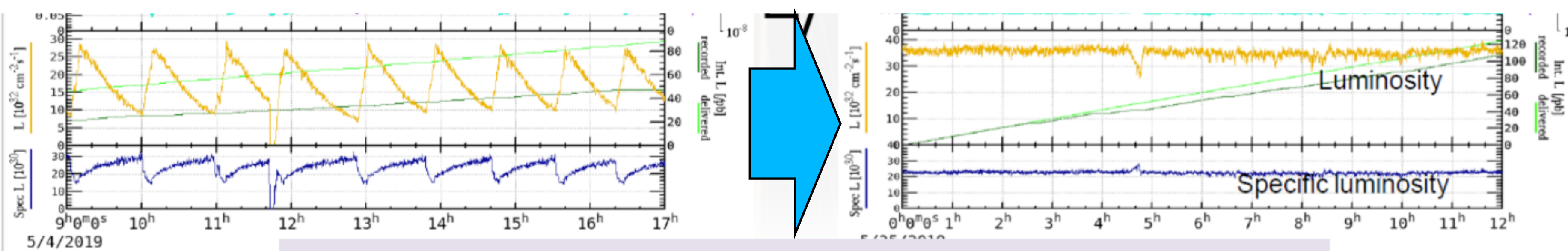
How far have we gone?



Full Belle II detector: Mar 2019

$L_{peak} = 1.2 \times 10^{34}\ cm^{-2}\ s^{-1}$

$L_{int} = 10.57\ fb^{-1}$



Continuous beam injection started from 14th, May.

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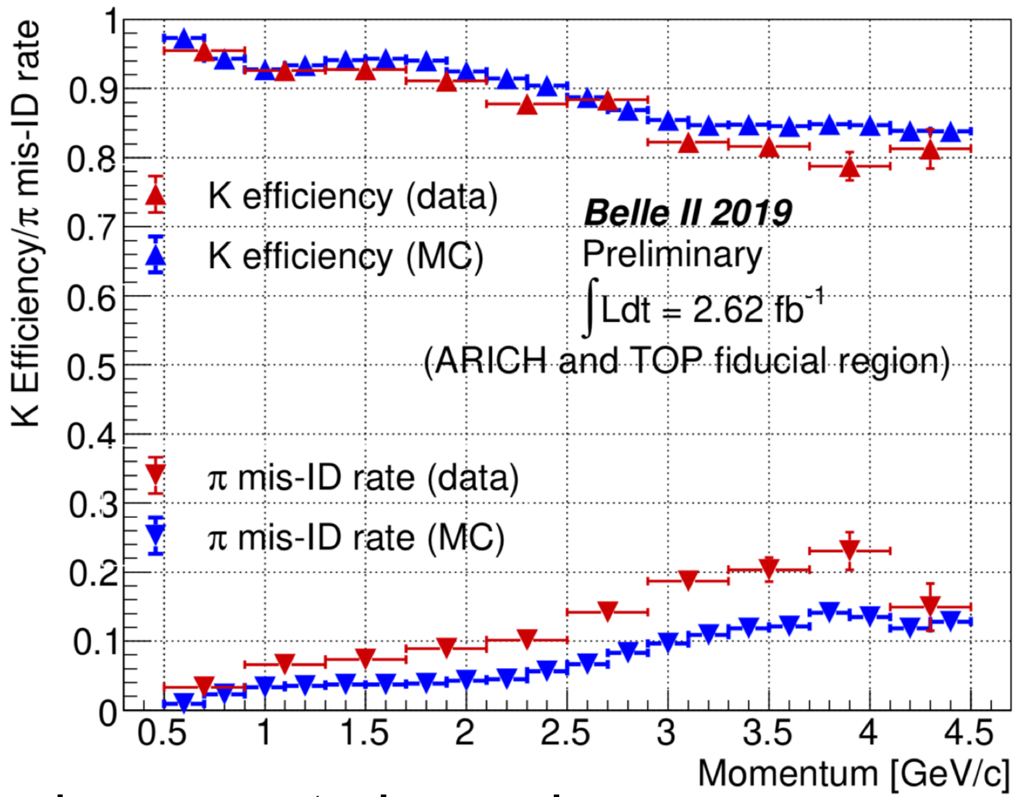
K/π Particle Identification

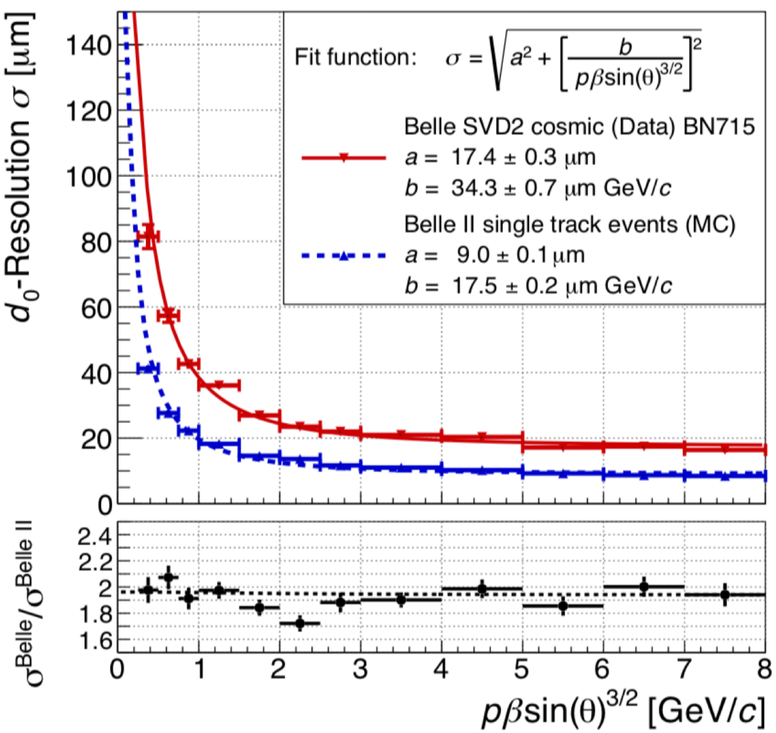
BELLE2-NOTE-PL-2019-022

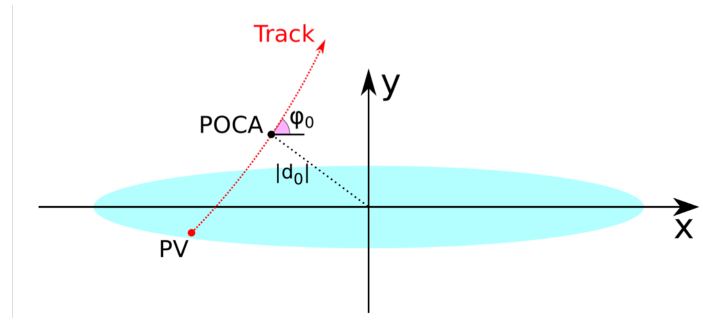


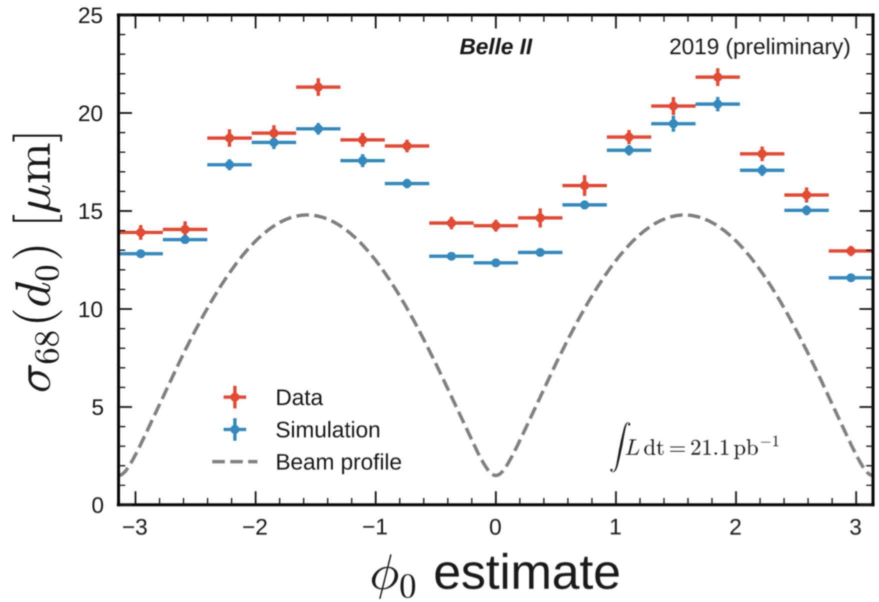
Measured on a control sample
$D^{*+} \rightarrow D^0[K^- \pi^+_s]\pi+$

Track Impact Parameter Resolution

Belle vs Belle II
Factor 2 better



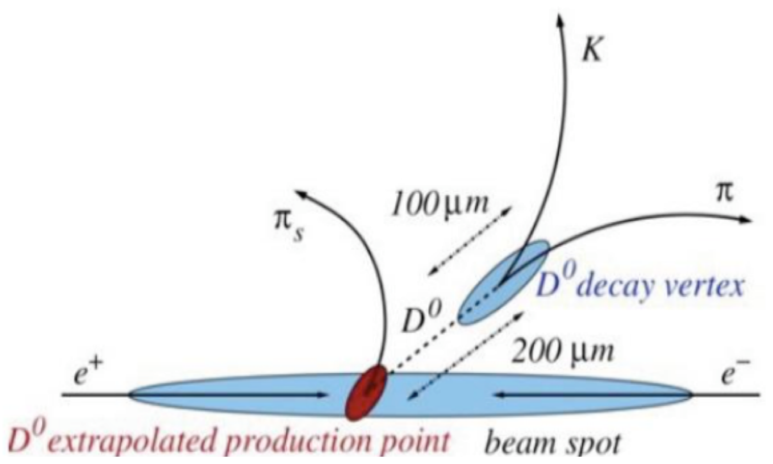


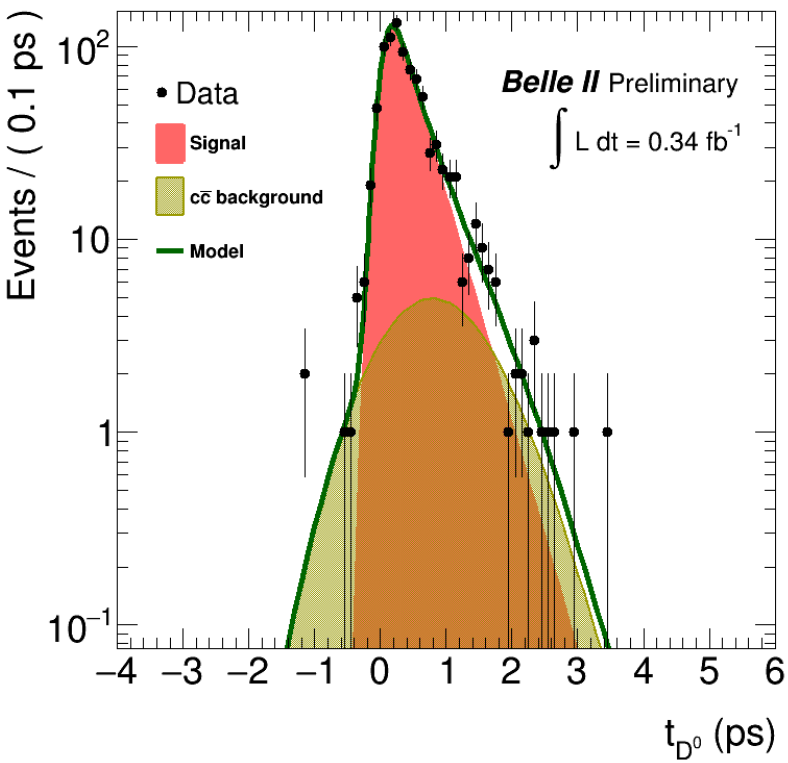


Impact parameter resolution: 14 μm

D^0 Lifetime

BELLE2-NOTE-PL-2019-003





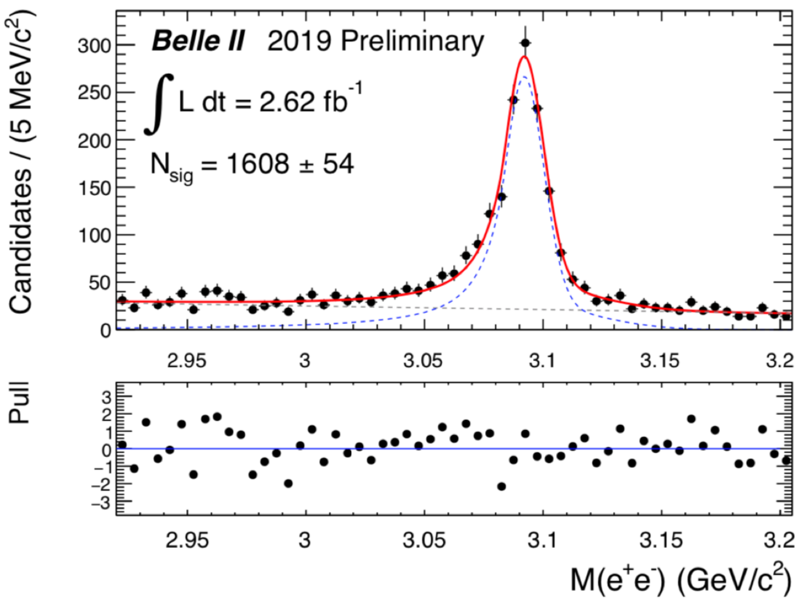
Good position resolution/alignment crucial!

Result with a small dataset
τ_{D0} = $(370 \pm 40_{stat})$ fs
Accepted value 410 fs

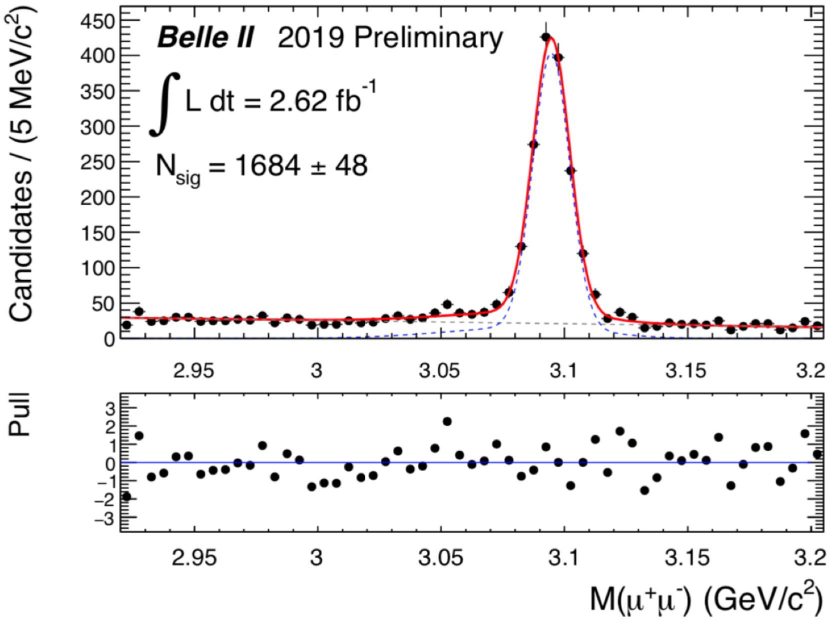
J/Ψ Reconstruction

BELLE2-NOTE-PL-2019-018

e^+e^-



$\mu^+\mu^-$

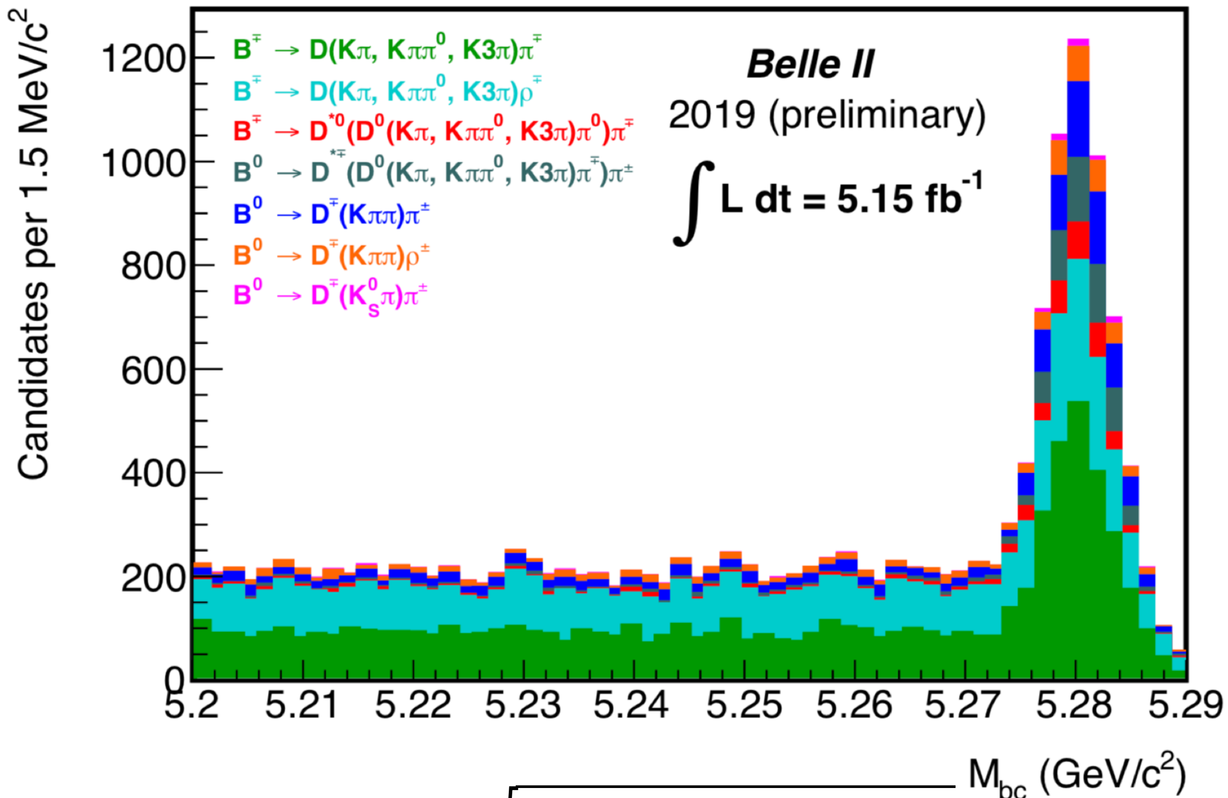


Dilepton invariant mass

Rediscovery of B Mesons

BELLE2-NOTE-PL-2019-028

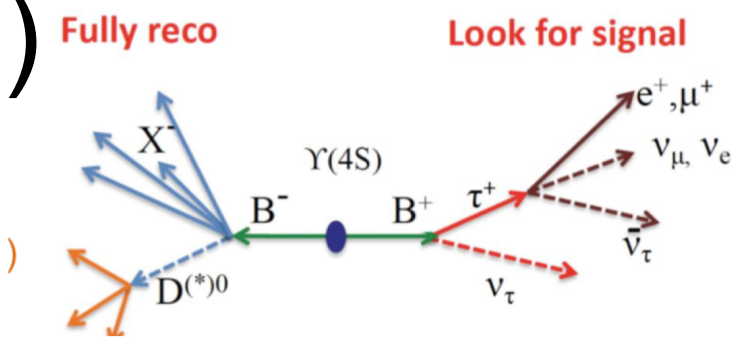
Demonstration of Belle II's B Physics Capabilities:
Modes with neutrals, and K mesons are efficiently reconstructed along with all-charged final states containing kaons and pions.

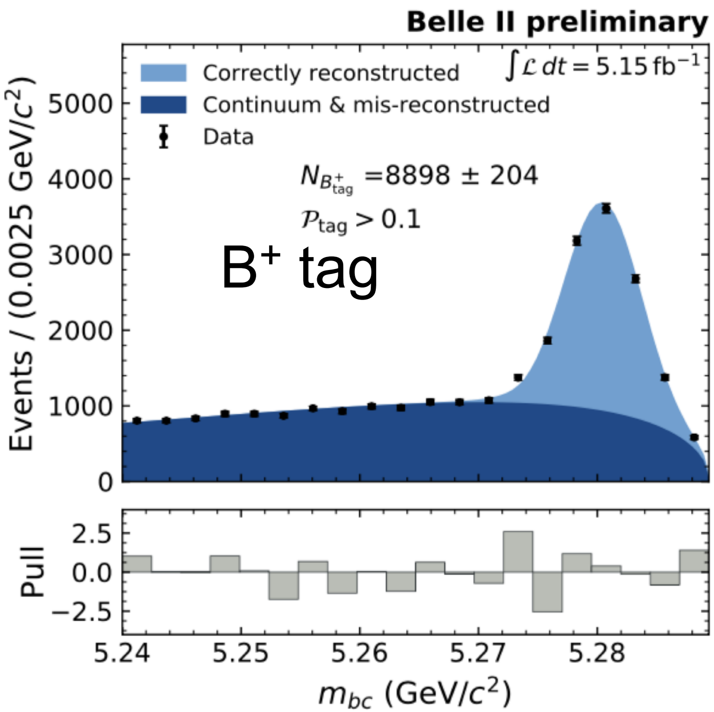


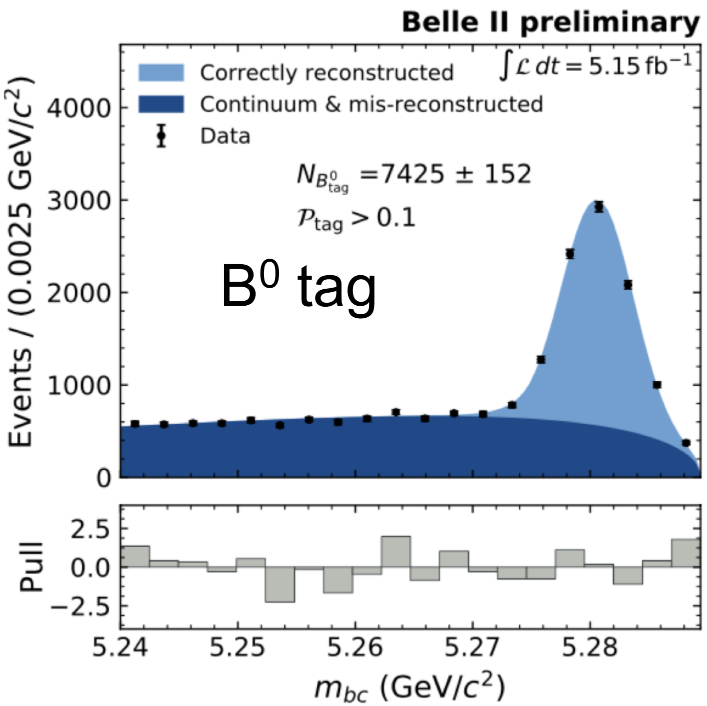
$$M_{bc} = \sqrt{\left(\frac{E_{cm}}{2}\right)^2 - p_{recon}^2}$$

Full Event Interpretation Reconstruction (FEI)

This machine-learning technique (BDT) brings higher reconstruction efficiency



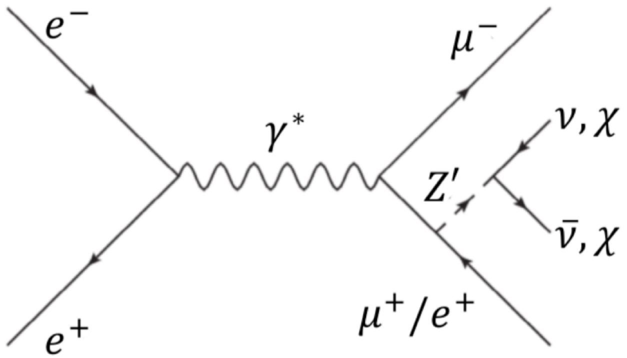




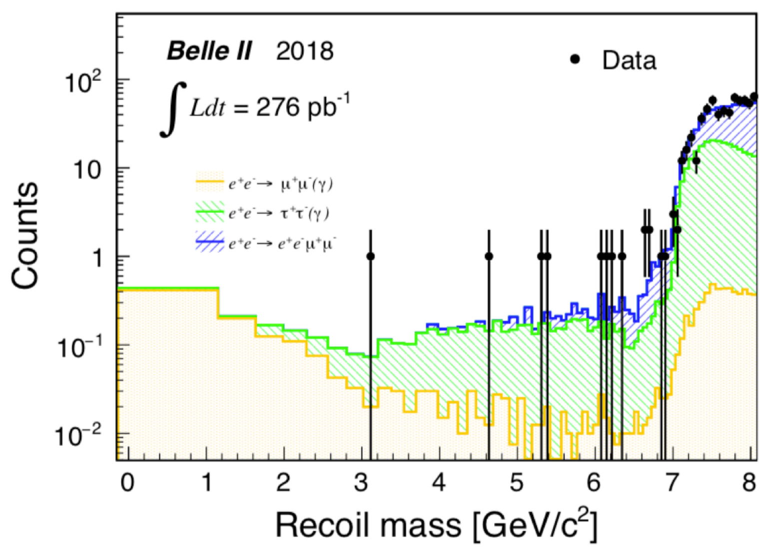
BELLE2-NOTE-PL-2019-009

First Belle II NP Search

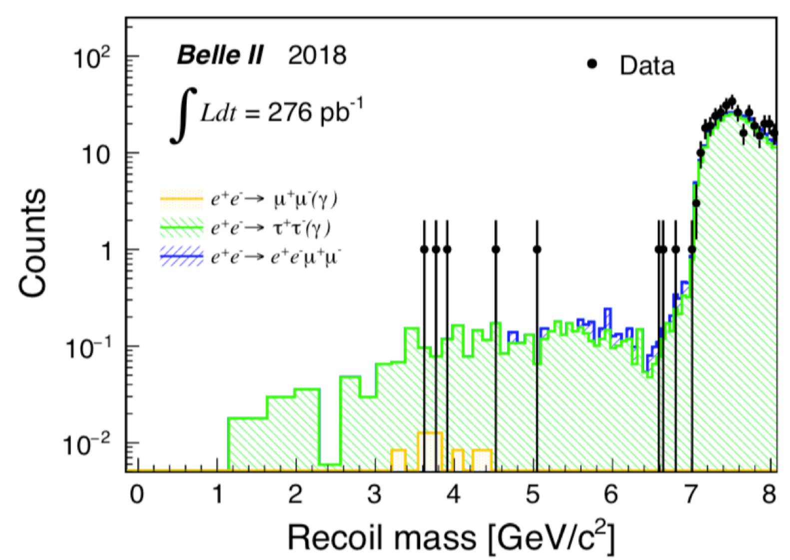
A low-mass Z' that couples to a $\mu\mu$ or μe vertex is poorly constrained in the $Z' \to$ invisible channel. Could be responsible for the $g_\mu - 2$ anomaly.



$e^+e^- \to \mu^+\mu^-$ +inv.



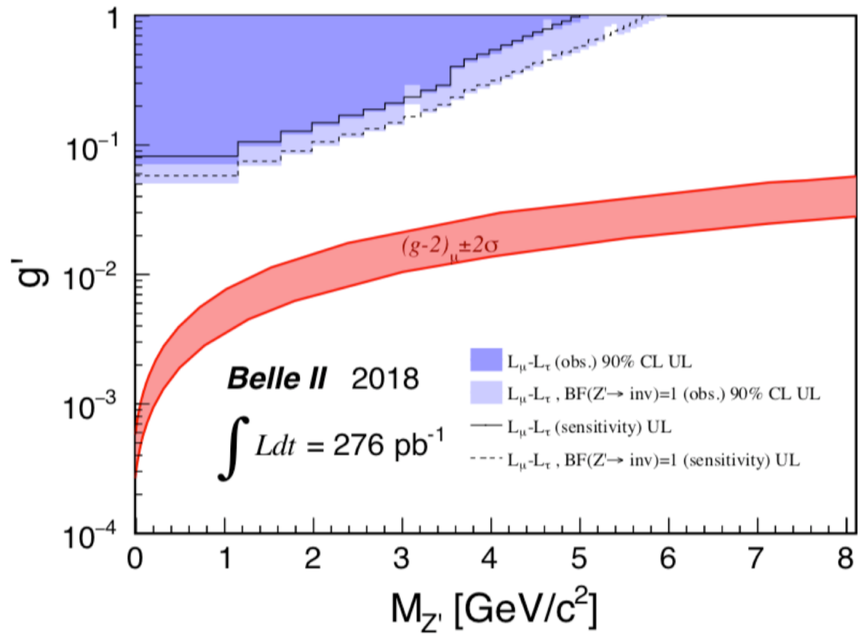
$e^+e^- \to \mu^\pm e^\mp$ +inv.



Limits on Z‘ → invisible

$e^+e^- \rightarrow \mu^+\mu^- + \text{inv.}$

Limit on $Z'\mu\mu$ coupling for $Br(Z' \rightarrow \text{inv}) = 1$

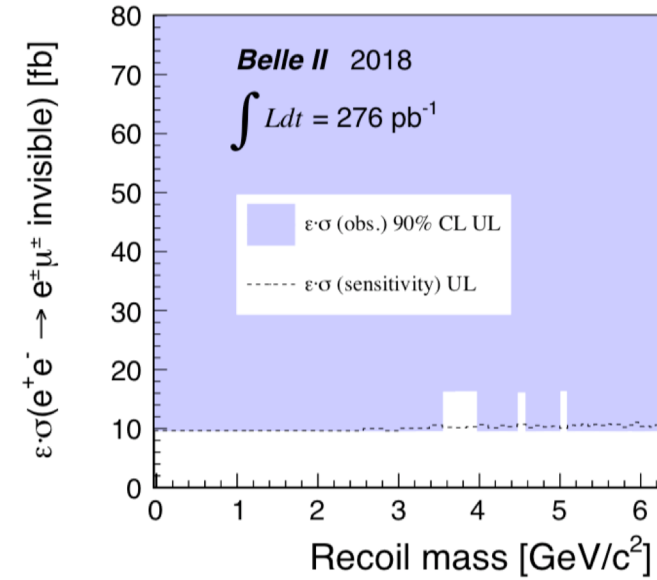


References:

- Shuve & Yavin, PRD 89 (2014) 113004
- Galon & Zupan, JHEP 2017 (2017) 83
- Galon, Kwa, Tanedo, JHEP 2017 (2017) 64
- BABAR limits in $Z' \rightarrow \mu^+\mu^-$ case: PRD 94 (2016) 011102

$e^+e^- \rightarrow \mu^{\pm}e^{\mp} + \text{inv.}$

Limit on efficiency times cross section

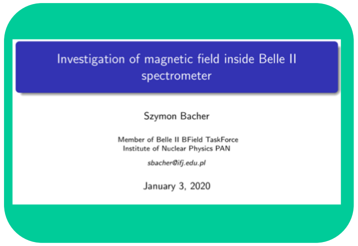


Some theory work on the MC needed in order to extract cross-section limits

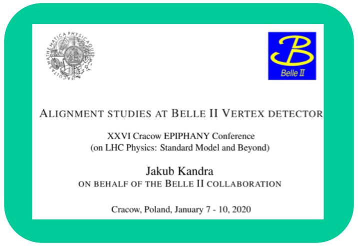
arXiv:1912.11276
Submitted to PRL

Summary

- The Belle II experiment is a powerful tool to find signs of new physics by precision measurement of huge statistics of heavy flavor decays
- From 2018, Belle II physics run has started
- First physics results: re-discovery of B meson, Z', B mixing,
- Full event interpretation
- From February 2020 beam operation restarts
- More info at student talks:

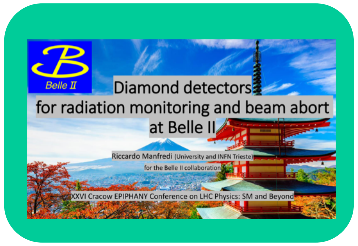


S. Bacher



J. Kandra

B. Knysh



R. Manfredi

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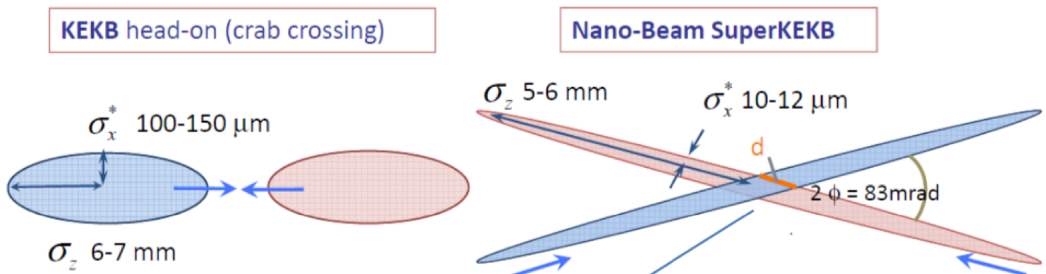
Backup

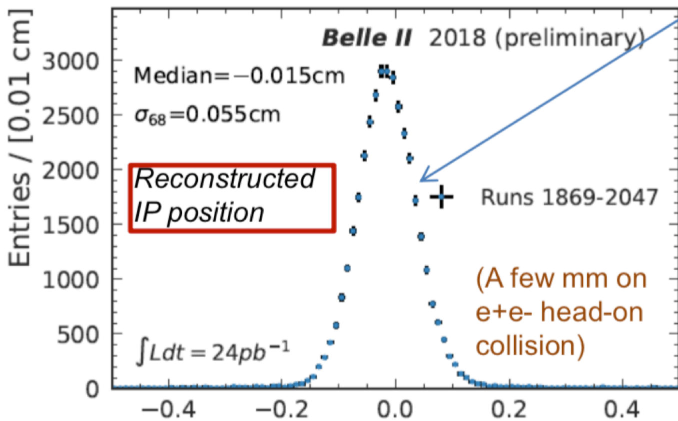
New Constraints by the nano-beam scheme

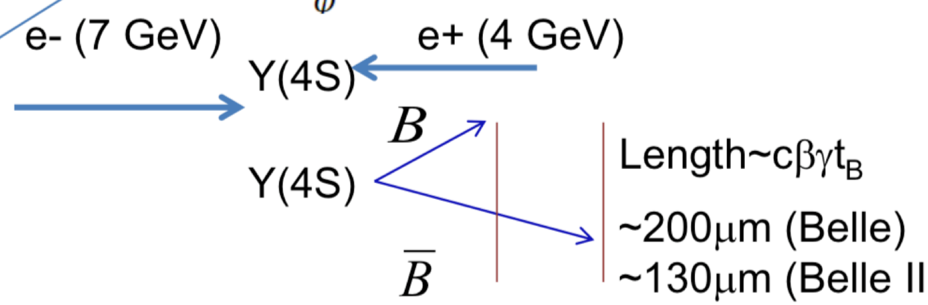


Hourglass requirement

$\beta_y^* \geq \sigma_z$ ~ 6 mm

$\beta_y^* \geq \frac{\sigma_x^*}{\phi}$ ~ 300 μm





SuperKEKB $\beta\gamma$=0.28 : e$^-$(7GeV), e+ (4GeV)
KEKB $\beta\gamma$=0.42: e$^-$(8GeV), e+ (3.5GeV)

LER (3.5 GeV -> 4GeV):
- for longer Touschek lifetime ∝ E ^{3}

HER (8 GeV -> 7GeV):
- Lower emittance beam ∝ 1/E ^{2}
- Lower Synchrotron radiation loss

●To realize nano-beam, Lorentz boost factor is decreased down to 2/3.

○Thanks to Nano-beam scheme: diameter of IP beam pipe is reduced from 3cm to 2cm

Comparison with the LHCb

e^+e^- has advantages in…	LHCb has advantages in…
CPV in $B\to\phi K_S$, $\eta' K_S$,…	CPV in $B\to J/\psi K_S$
CPV in $B\to K_S\pi^0\gamma$	Most of B decays not including ν or γ
$B\to K\nu\nu$, $\tau\nu$, $D^{(*)}\tau\nu$	Time dependent measurements of B_S
Inclusive $b\to s\mu\mu$, *see*	$B_{(s,d)}\to\mu\mu$
$\tau\to\mu\gamma$ and other LFV	B_c and bottomed baryons
$D^0\overline{D^0}$ mixing	

Complementary!!

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$A_{CP}(D^+ \to \pi^+\pi^0)$ $[10^{-2}]$	**	0.17	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

☞ From Belle II physics book

arXiv:1808.10567
(to appear in PTEP)

Precision CKM metrology

Direct and mixing-induced CP violation in B decays

(Semi-)leptonic B decays

Radiative & electroweak penguins

Vibrant charm program

Search of LFV tau decays

Sub-detector installation