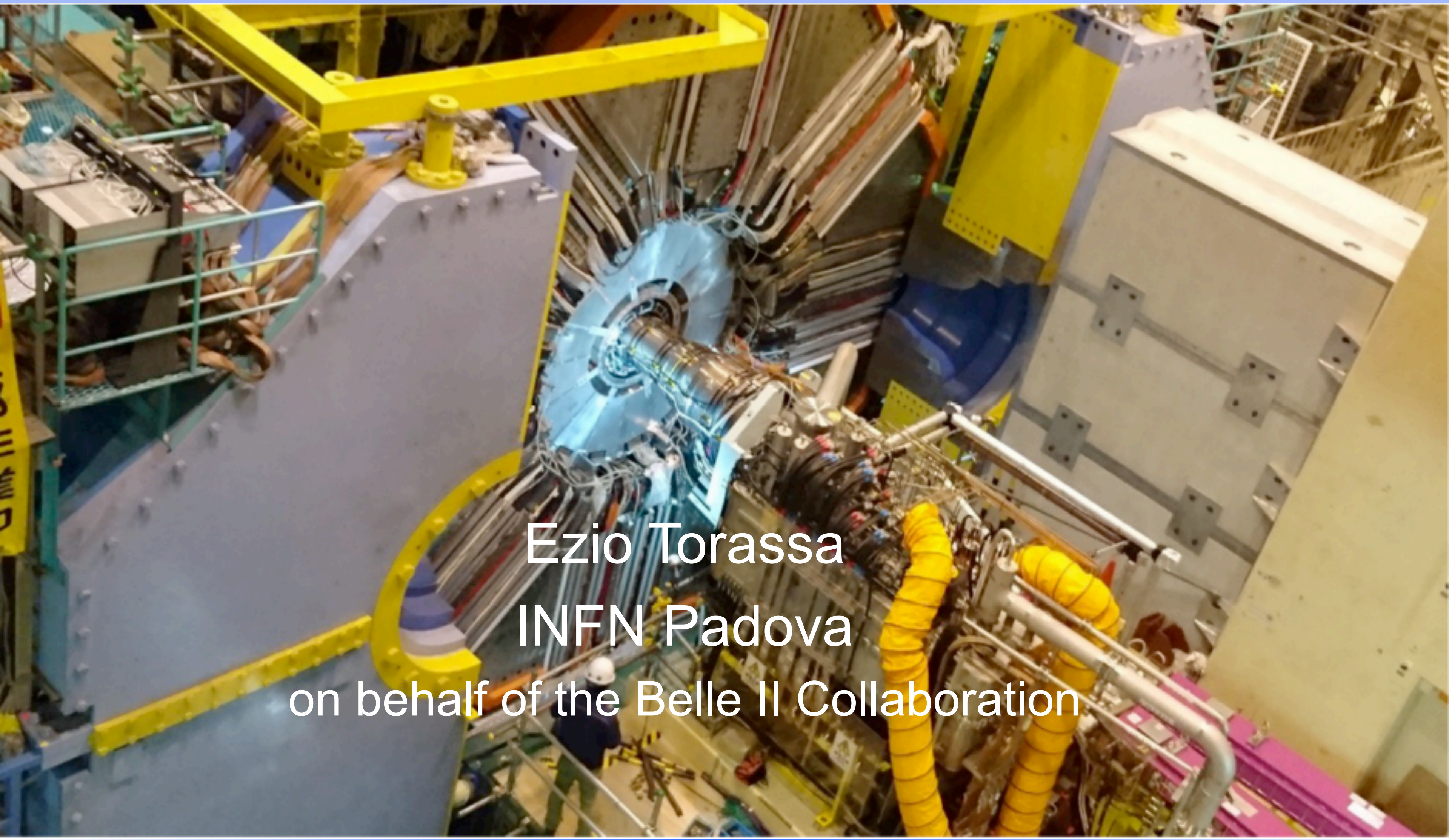
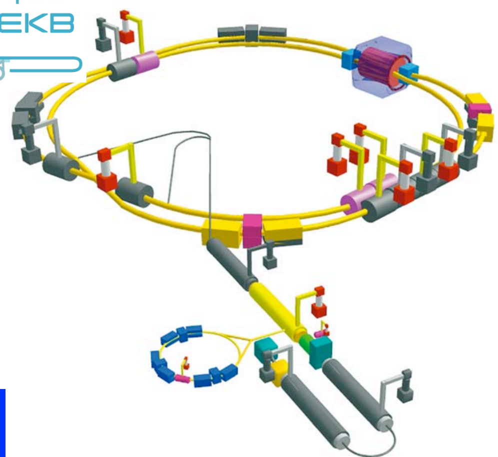
Latest results from Belle II



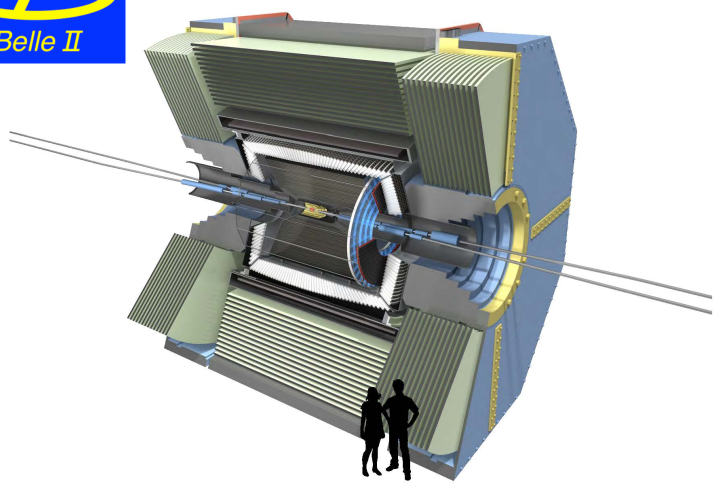
Ezio Torassa
INFN Padova
on behalf of the Belle II Collaboration

March 10th 2021 La Thuile 2021 Virtual mode

Outlook



- SuperKEKB collider
- Current integrated luminosity
- Luminosity plan

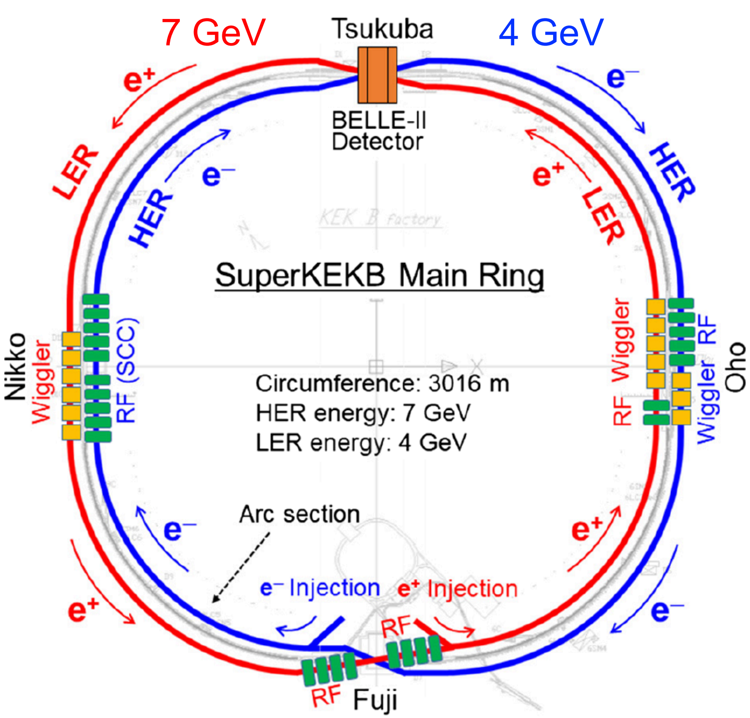


- Belle II Detector
- Detector performance
- Belle II Physics program
- Belle II Physics results:
  - Dark sector, $\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}_\ell$
  - $B\overline{B}$ mixing, TD CPV, τ mass
- Summary

SuperKEKB collider

SuperKEKB is a new e^+e^- collider located at KEK (Tsukuba, Japan), it operates in the **intensity frontier** region with a target instantaneous luminosity of 6×10^{35} cm^{-2} s^{-1} which is 30 times larger than that of the previous KEKB collider.

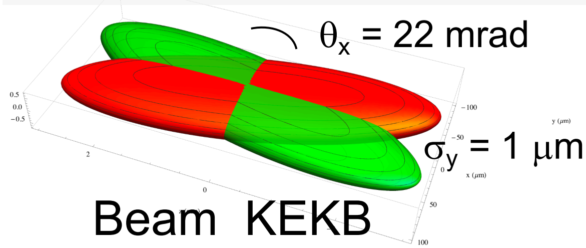
$\sqrt{s}$ = 10.58 GeV

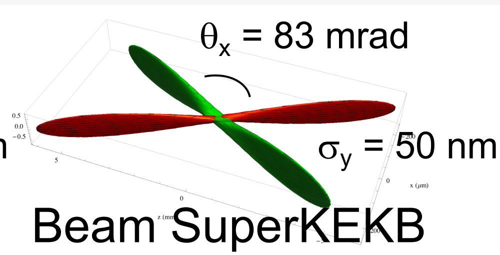


	Instantaneous luminosity (cm^{-2} s^{-1})	Integrated recorded luminosity (ab^{-1})
Babar PEP-II	1×10^{34} cm^{-2} s^{-1}	0.55 0.43 Y(4S)
Belle KEKB	2.11×10^{34} cm^{-2} s^{-1}	1 0.71 (Y4S)
Belle II SuperKEKB	6×10^{35} cm^{-2} s^{-1}	50

$\mathcal{L}$ x 30 : x1.5 current increase

x 20 β_y^* vertical beta function decrease





SuperKEKB startup

2016 Phase 1	2017	2018 Phase 2	2019 - 2021 Phase 3
1^{st} Feb 1^{st} July	Belle II installed except SVD & PXD	19^{th} Mar 7^{th} July	from 11^{th} Mar 2019 to now
TOP detector installation	Main Ring renovation Installation of QCS Dumping ring install.	SVD det. Installation	
Single Beam commissioning		**Beam collisions**	**Beam collisions**
Summer STOP	Winter STOP	$\mathcal{L}_{MAX} = 5.55 \times 10^{33}$ cm^{-2} s^{-1} $\int \mathcal{L} = 0.5$ fb^{-1}	$\mathcal{L}_{MAX} = 2.4 \times 10^{34}$ cm^{-2} s^{-1} $\int \mathcal{L} = 94.5$ fb^{-1}

Current integrated luminosity

We kept SuperKEKB and Belle II running in 2020 during the COVID-19 crisis, with extra effort from the local crew and the help of remote shifters

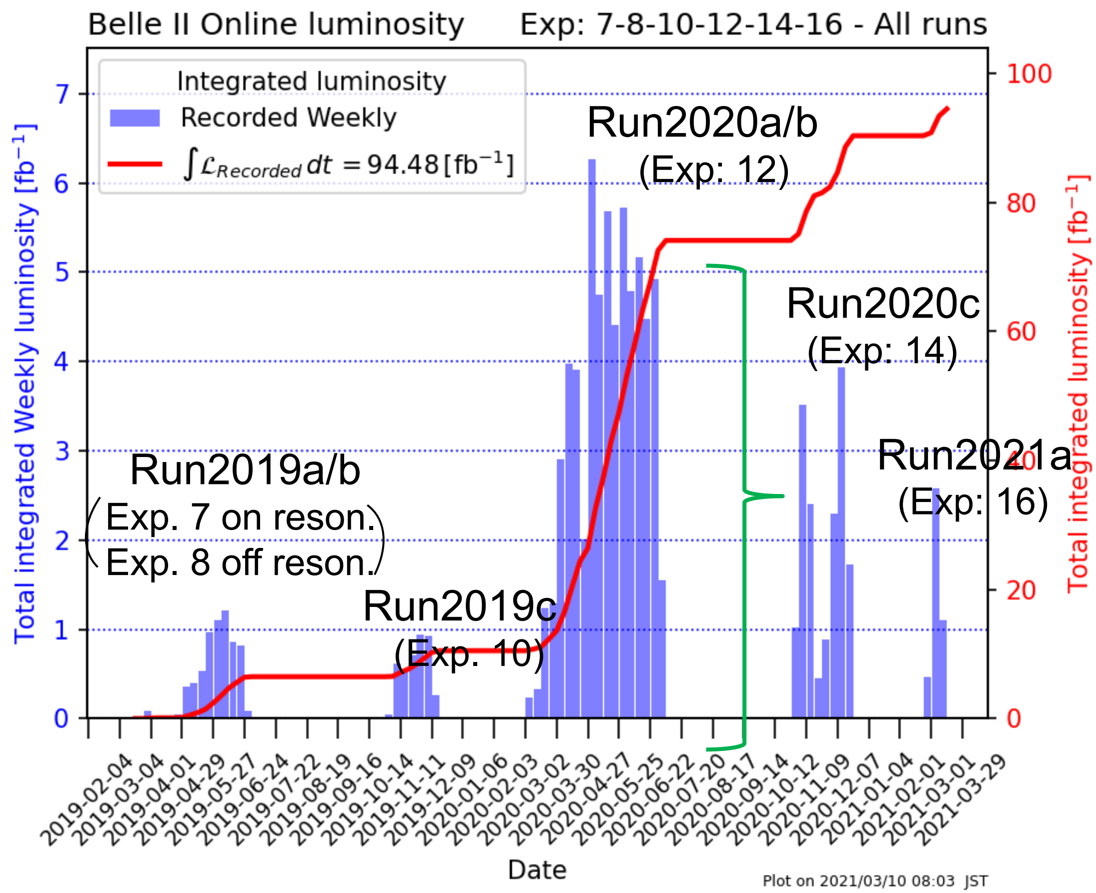
Luminosity world record

$2.11 \times 10^{34}\ cm^{-2}s^{-1}$
(KEK June 2009)

$2.14 \times 10^{34}\ cm^{-2}s^{-1}$
(LHC May 2018)

$2.4 \times 10^{34}\ cm^{-2}s^{-1}$
(SuperKEKB June 2020)

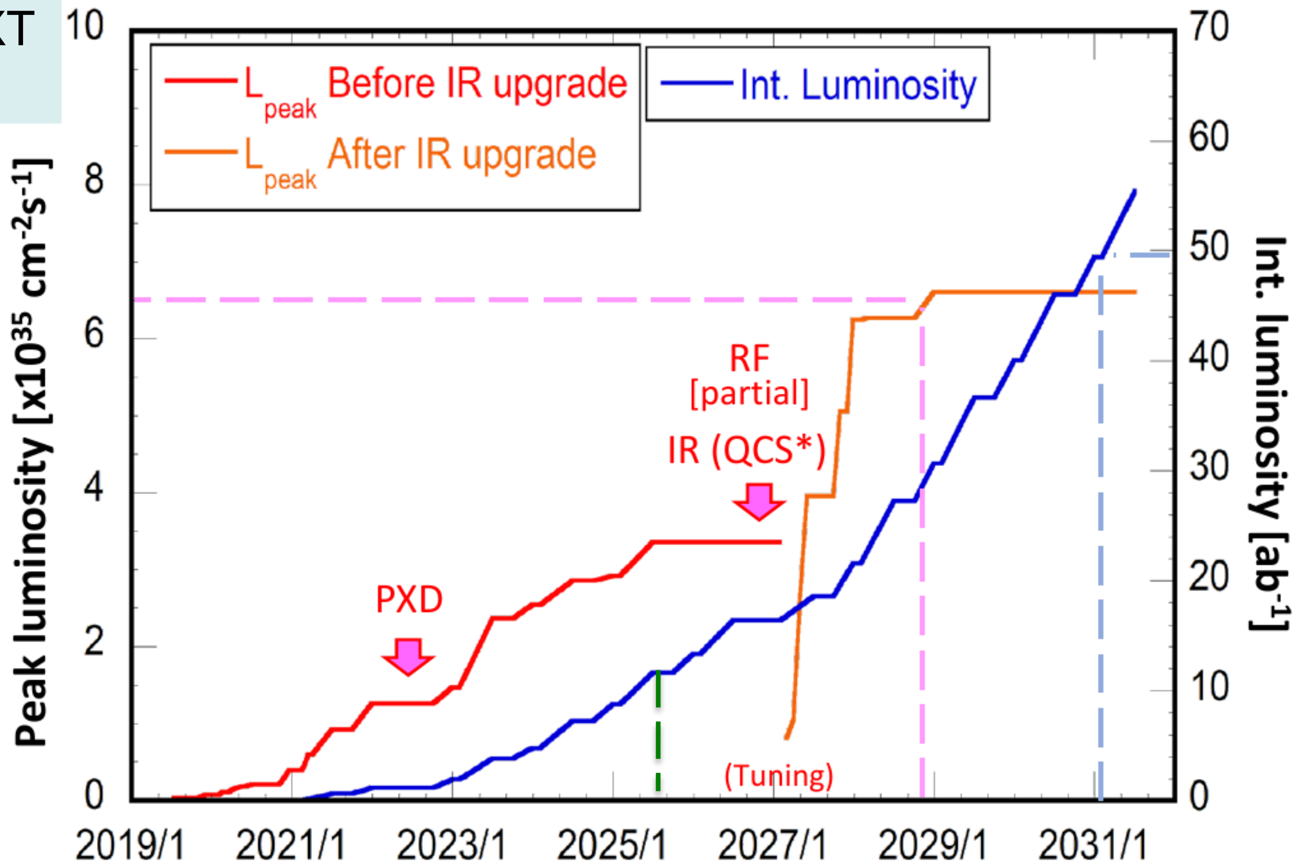
Current $\int \mathcal{L} = 94.5\ fb^{-1}$



Results presented here used Run2019 + ~40% Run2020a/b: $\int \mathcal{L} = 34.6\ fb^{-1}$
Next preliminary results will use Run2019 + 100% Run2020a/b: $\int \mathcal{L} = 62.8\ fb^{-1}$

Luminosity plan

Submitted to MEXT roadmap 2020



$\int \mathcal{L} = 0.5 \div 1\ ab^{-1}$ in 2022

$\int \mathcal{L} = 10\ ab^{-1}$ in 2026

$\mathcal{L}_{peak} = 6\ 10^{35}\ cm^{-2}\ s^{-1}$ in 2029

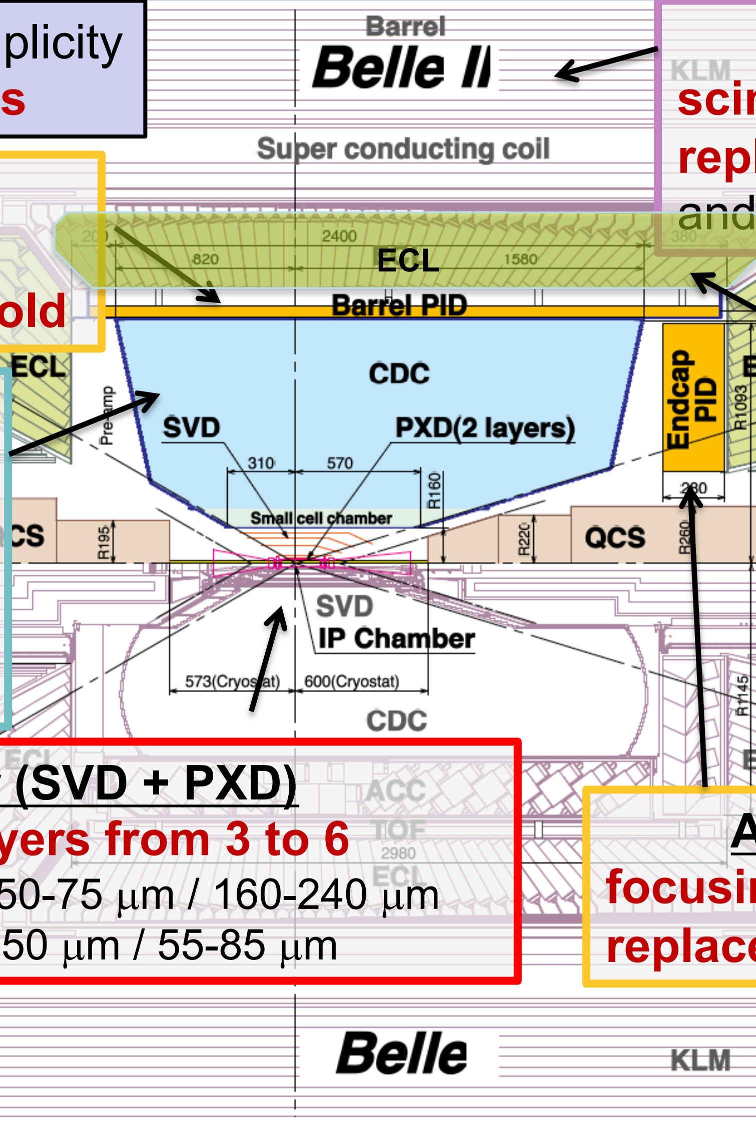
$\int \mathcal{L} = 50\ ab^{-1}$ in 2031

Belle II detector

New trigger: for low multiplicity and **dark sector searches**

TOP: barrel PID
quartz bars + MCP-PMT
replaced aerogel threshold

Central Drift Chamber
He (50%) C_2H_6 (50%)
smaller cell size
n. wires = 14336 from 8400
longer lever arm
r_{ext}-r_{int} = 0.97 m from 0.8 m



KLM: K_L and Muon
scintillator+WLS+SiPM
replaced all 14 endcap RPC and **2 innermost barrel RPC**

ECL: Calorimeter
CsI(TI) crystals + PIN-PD
electronics upgrade for waveform sampling

Vertex detector (SVD + PXD)
Increased number of layers from 3 to 6
4 layers SVD DSSD N-type 50-75 μm / 160-240 μm
2 layers PXD DEPFET 50 μm / 55-85 μm

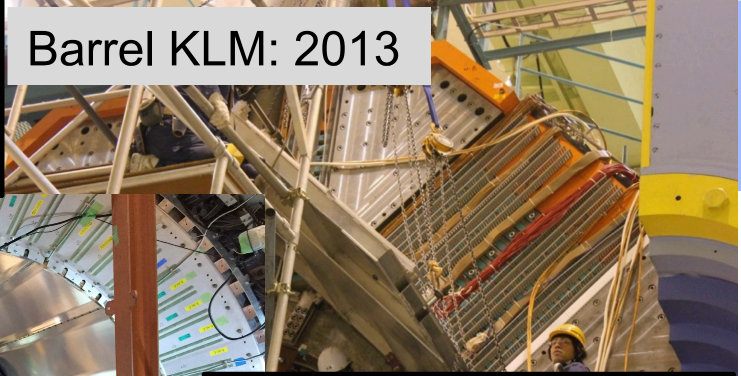
ARICH: endcap PID
focusing aerogel RICH + HAPD
replaced aerogel threshold

Magnet
1.5 Tesla

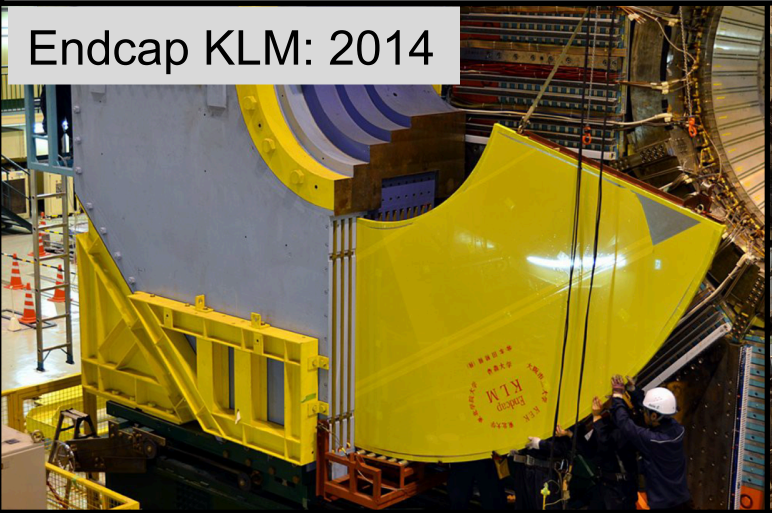
7 m height
7.5 m length

Subdetector installation

Barrel KLM: 2013

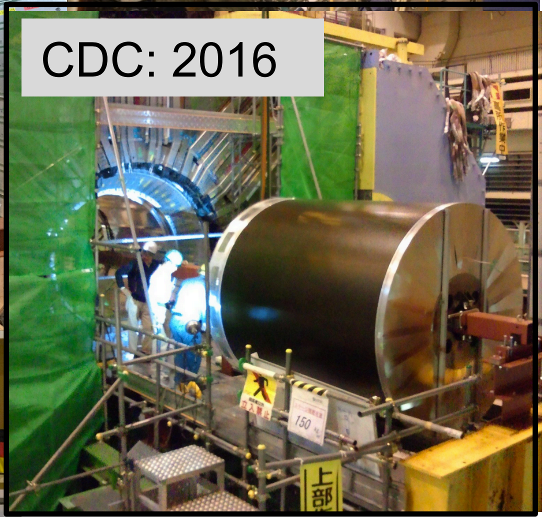


Endcap KLM: 2014



TOP: 2016

CDC: 2016



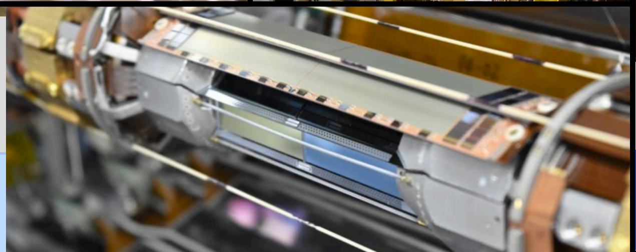
ARICH: 2017

ECL: 2017

SVD: 2018

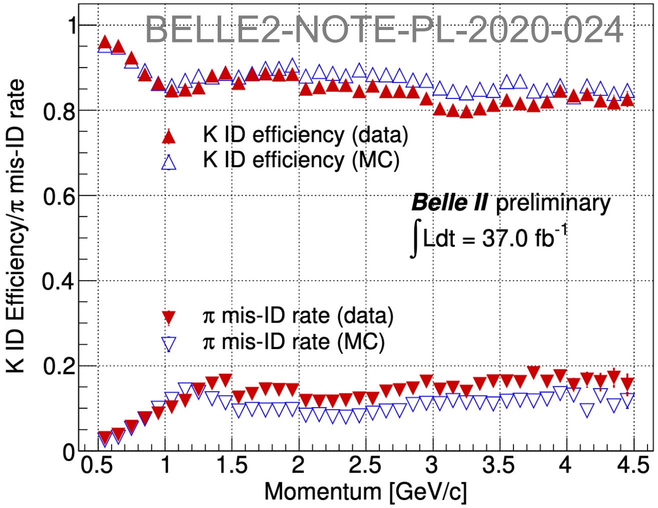
PXD: 2018 Inner layer
+ 2 outer ladders

PXD: 2022 Full detector

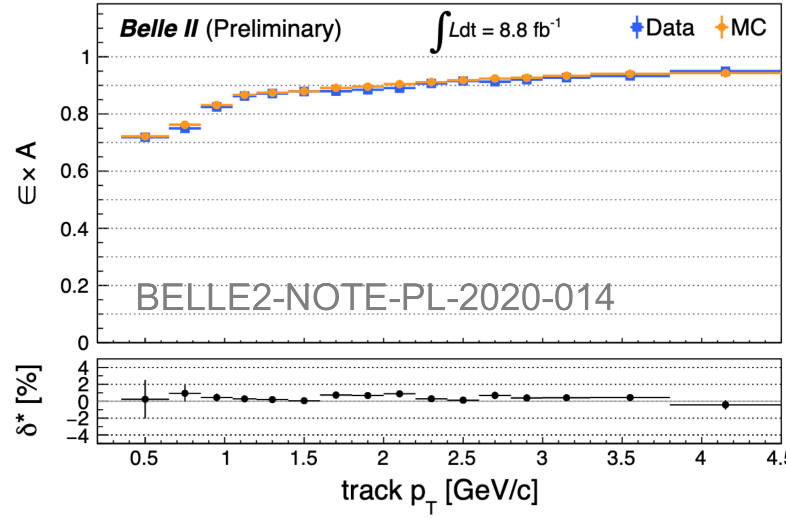


Detector performance

Particle Identification (K/π separation)



Tracking efficiency (with $\tau^+\tau^-$ events)



B flavor tagger

$\varepsilon_{effective} = \sum_i \varepsilon_i \cdot (1-2w_i)^2$

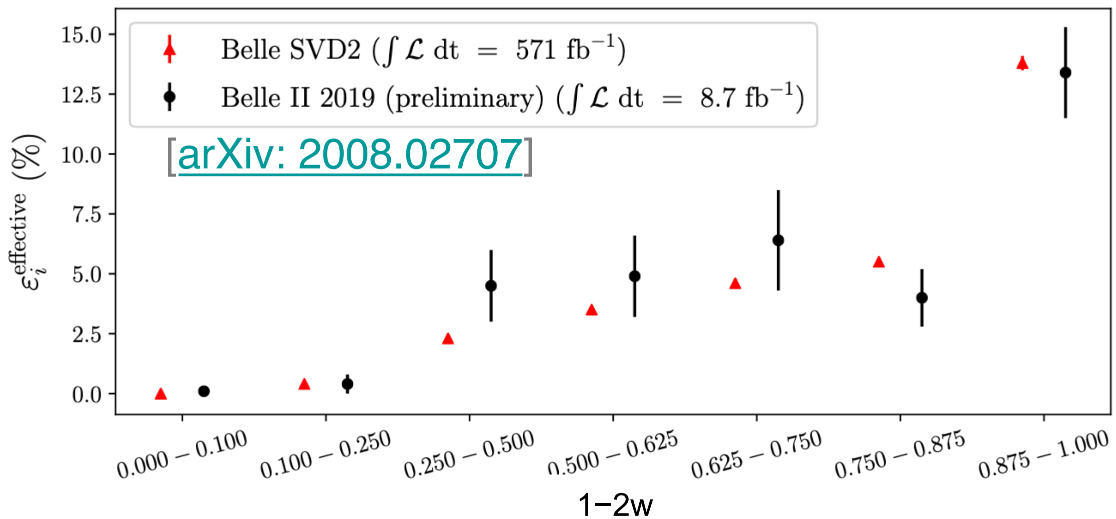
w_i = wrong-tag fractions

ε_i = tag efficiency

$\varepsilon_{effective}$ (Belle II MC) = ~37%

$\varepsilon_{effective}$ (Belle II) = $(33.8 \pm 3.9)\%$

$\varepsilon_{effective}$ (Belle) = $(30.1 \pm 0.4)\%$



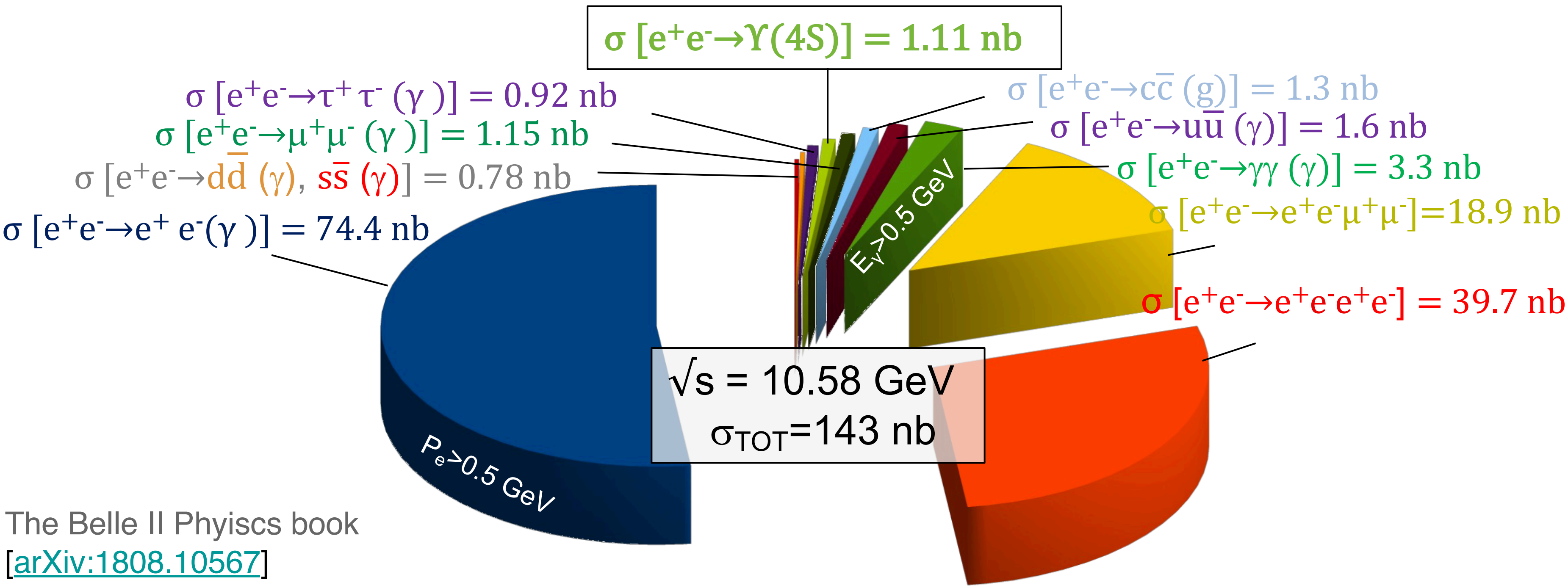
Belle II physics program

Energy scan

Υ(1s)	Υ(2s)	Υ(3s)	**Υ(4s)**	Υ(5s)	Υ(6s)
9.46 GeV	10.02 GeV	10.35 GeV	**10.58 GeV**	10.86 GeV	11.02 GeV

B^+B^- $(51.4\pm0.6)\%$

$B^0\bar{B}^0$ $(48.6\pm0.6)\%$



The Belle II Phyiscs book [arXiv:1808.10567]

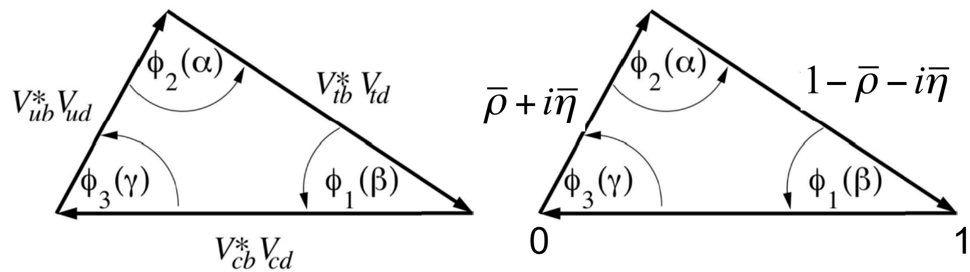
Belle II physics program

- Precise measurement of the CKM parameters

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d^{\text{mass}} \\ s^{\text{mass}} \\ b^{\text{mass}} \end{pmatrix}$$

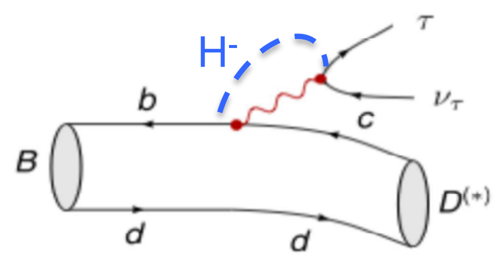
$$V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0$$

$$\frac{V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}} + 1 + \frac{V_{tb}^{*}V_{td}}{V_{cb}^{*}V_{cd}} = 0$$



- Search of new physics with precise measurements of B, charm and τ decays

$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \to D^{*}\tau\nu)}{\mathcal{B}(B \to D^{*}\ell\nu)} \qquad \mathcal{R}_{D} \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$



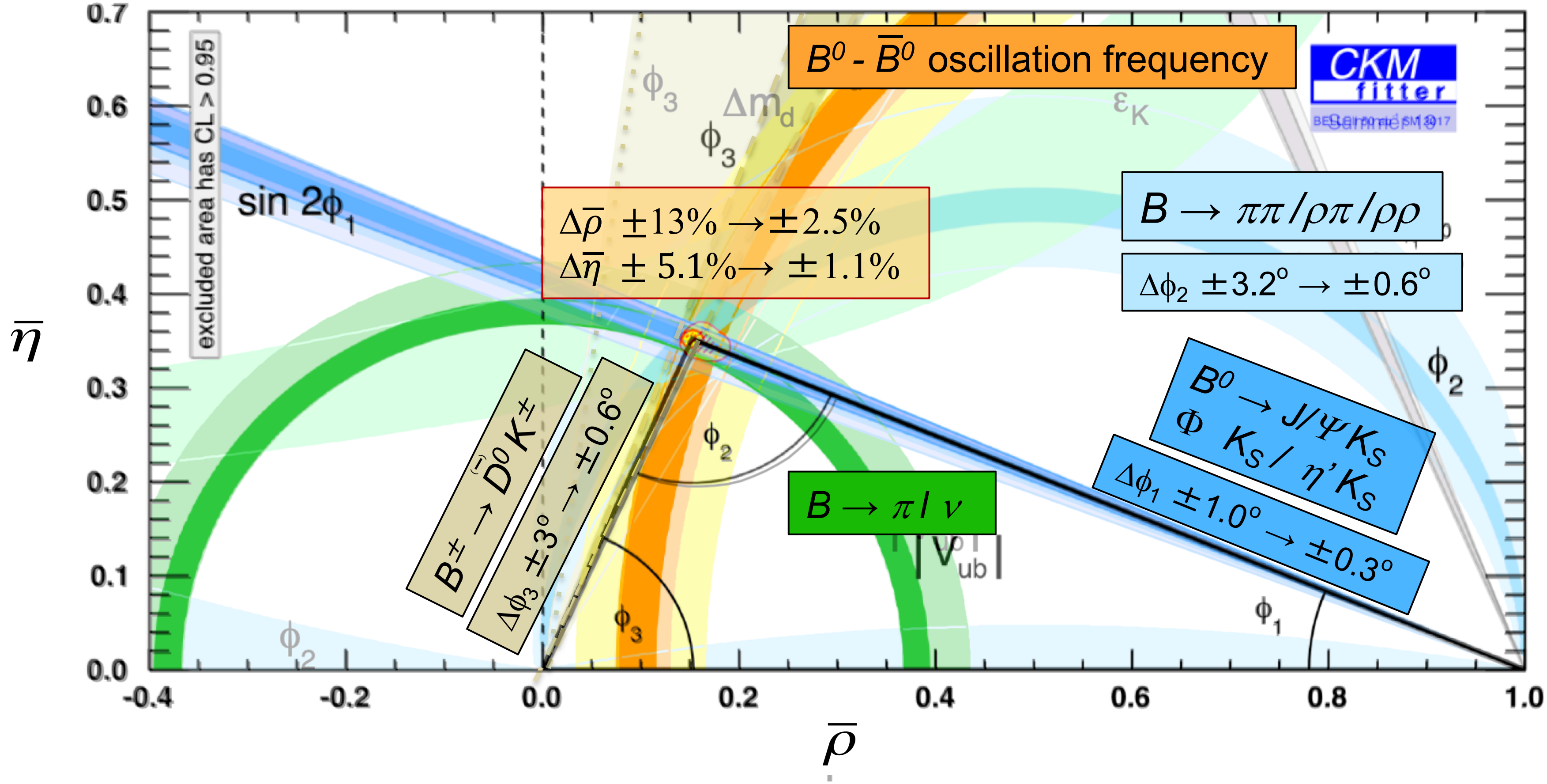
- Hadron spectroscopy and dark sector

Belle II physics program

CKM fitter Summer19 — $1.0\ ab^{-1}$ Belle + $0.5\ ab^{-1}$ Babar

BELLE2-PUB-PH-2018-001 — $50\ ab^{-1}$ Belle II

2σ errors
(mean values when asymmetric)



Belle II physics results

2 published PRL dark-sector searches:

- Search for an invisibly decaying Z' boson [PRL 124(2020)141801] (published 6 April 2020)
- Search for axion-like particles [PRL 125(2020)161806] (published 14 October 2020)

12 conference papers posted to arXiv:

- Calibration of the hadronic full-event interpretation. [arXiv:2008.06096] (17 Aug. 2020)
- $B0 \rightarrow D^{*+} \ell\nu$ ((1) first result, (2) untagged, (3) using FEI). (12 June, 18 Aug., 16 Sep. 2020)
- Hadronic mass moments of $B \rightarrow X_c \ell\nu$ decays. [arXiv:2009.04493] (9 Sep. 2020)
- Rediscovery of $B \rightarrow \pi\ell\nu$. [arXiv:2008.08819] (20 Aug. 2020)
- B lifetime in hadronic decays. [arXiv:2005.07507] (15 May 2020)
- Calibration of the flavour tagger, [arXiv:2008.02707] (6 Aug 2020)
  used to make "rediscovery" of CPV in $B \rightarrow J/\psi K_S$. [BELLE2-NOTE-PL-2020-11-1]
- Rediscovery of $B \rightarrow \varphi K^*$. [arXiv:2008.03873] (10 Aug 2020)
- $B \rightarrow$ charmless ((1) first result, (2) CP asymmetries). (27 May, 20 Sep. 2020)
- Tau lepton mass measurement. [arXiv:2008.04665] (10 Aug 2020)

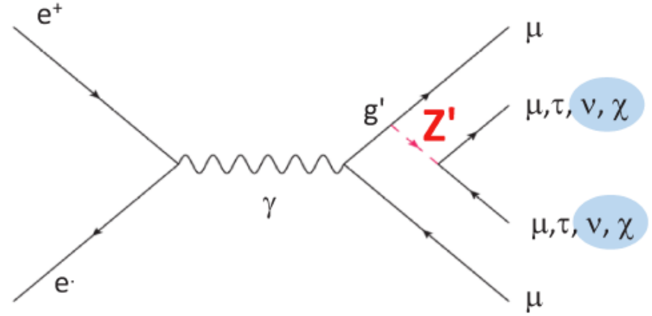
Charmless B decays → Riccardo Manfredi talk

Dark sector: Z' → invisible

Simple extensions of the SM: Z' boson originated for extra U(1)' symmetry that couples both to SM and NP invisible particles. [PRL 124(2020)141801]

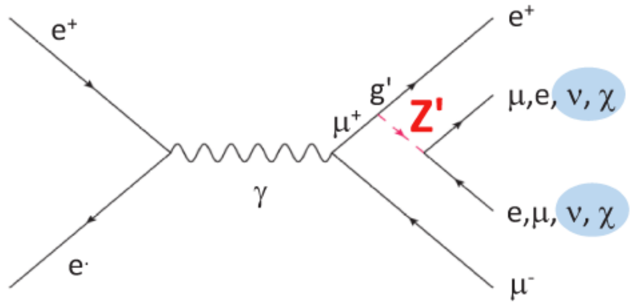
$L_\mu - L_\tau$ model

$e^+e^- \rightarrow \mu^+\mu^- Z'$, ($Z' \rightarrow$ invis.)

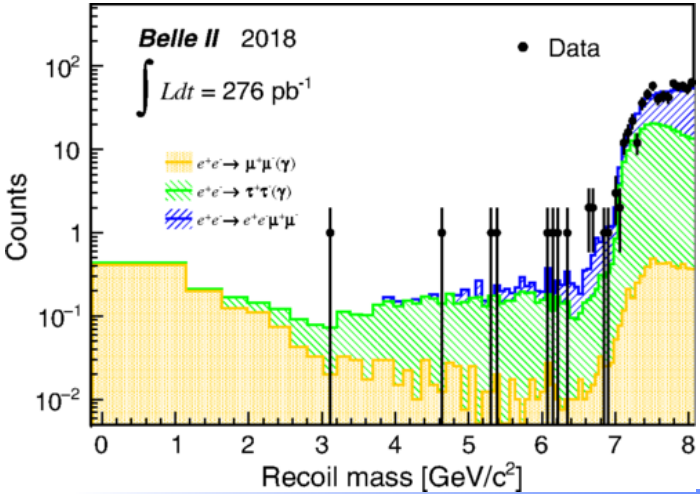


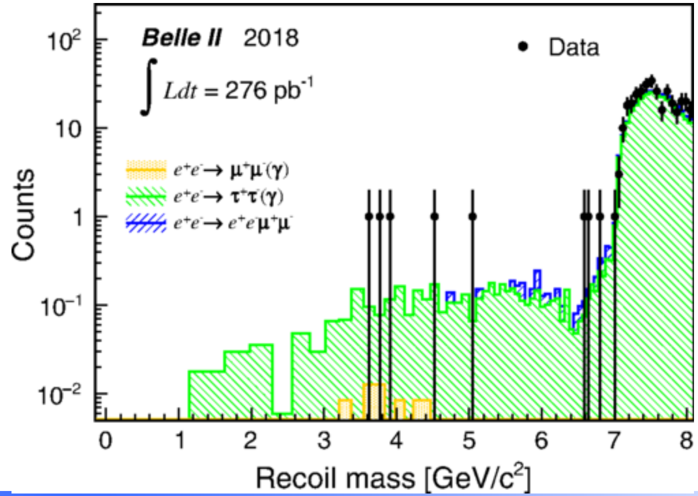
LFV scenario (e - μ coupling)

$e^+e^- \rightarrow e^\pm\mu^\mp Z'$, ($Z' \rightarrow$ invis.)



The signature is a bump in the recoil mass distribution of the $\ell^+\ell^-$ system

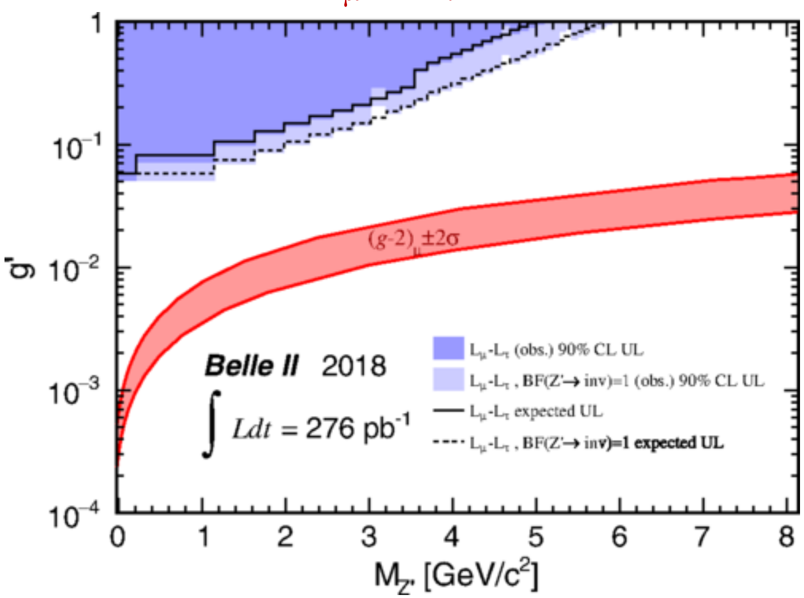




Dark sector: Z’ → invisible

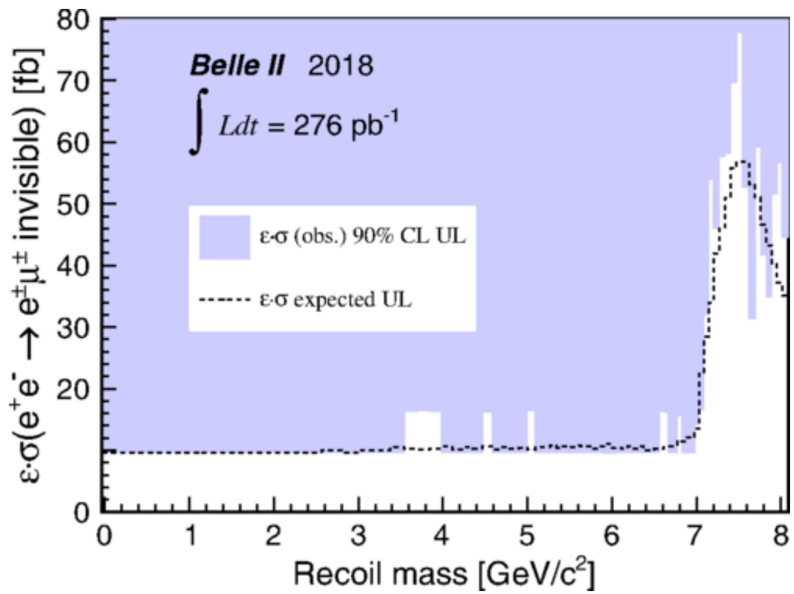
We used 0.276 fb^{-1} of good-quality data with full PID information taken in Phase2.
No anomalies were observed above 3σ local significance
We placed nontrivial exclusion limits:

$L_\mu - L_\tau$ model



90% C.L. upper limits on coupling constant g’

LFV scenario



90% C.L. upper limits on signal efficiency times cross section

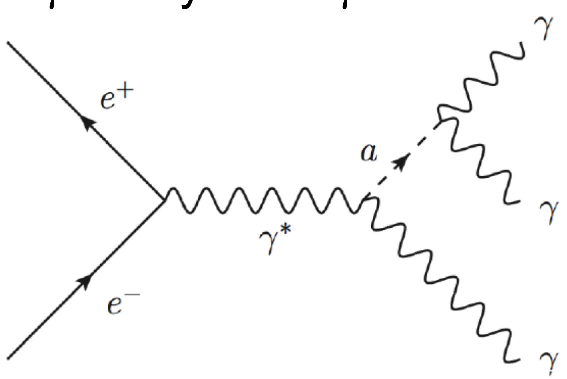
The red band shows the region that could explain the anomalous muon magnetic moment

Dark sector: Axion-like particles

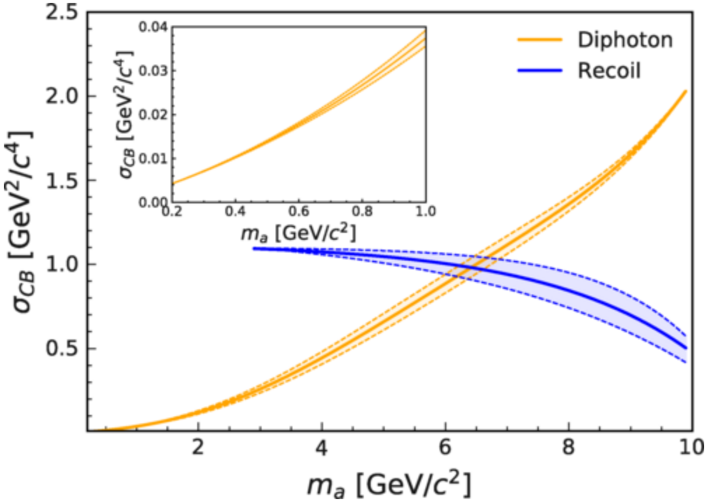
Axion/Axion-like: singlet neutral scalar or pseudoscalar

[PRL 125(2020)161806]

2γ decay and 3γ final state



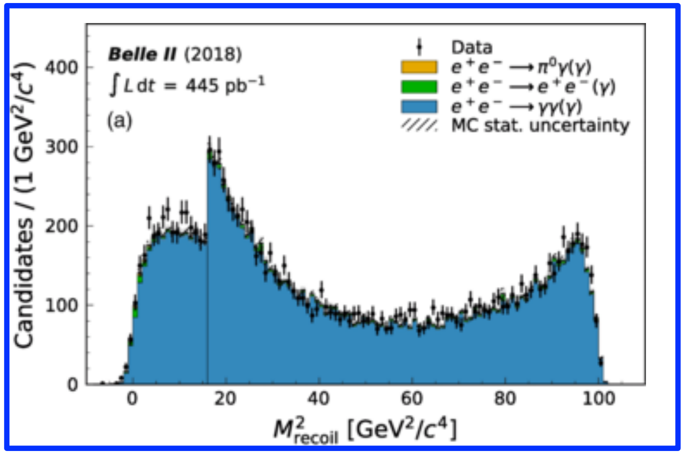
Signal can be identified by a peak in the 2γ invariant mass or in the recoil invariant mass

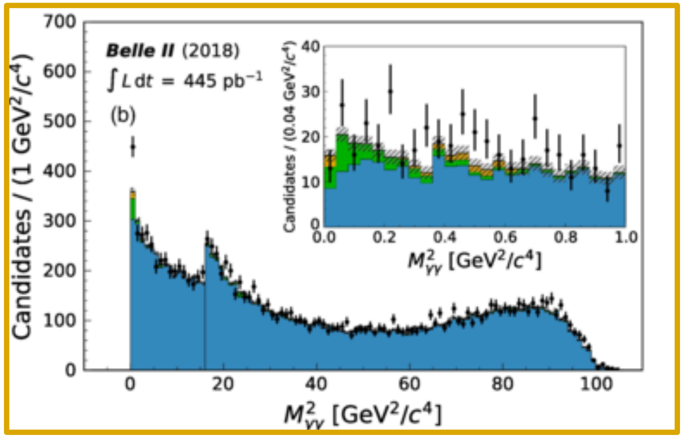


$\sigma(M^2_{\gamma\gamma})$ and $\sigma(M^2_{recoil})$ with uncertainties as a function of the ALP mass

Diphoton better if m_a < 6.5 GeV

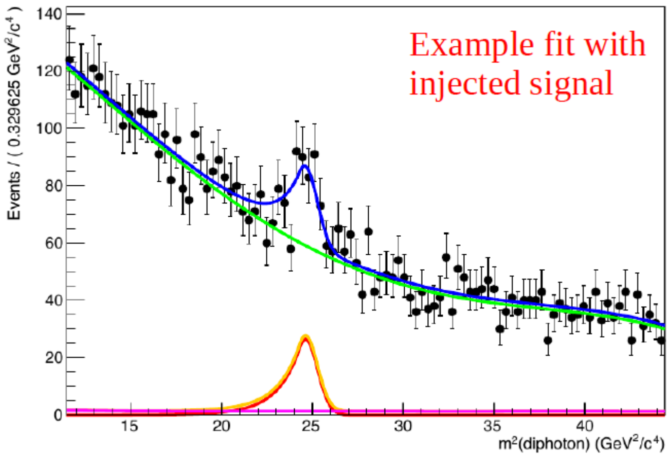
Recoil better if m_a > 6.5 GeV





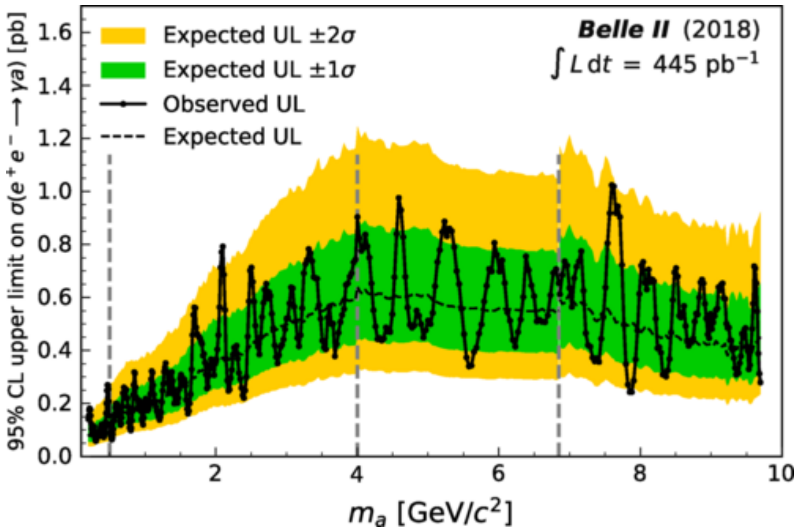
Dark sector: Axion-like particles

We used 0.445 fb^{-1} of good-quality data taken in Phase2.

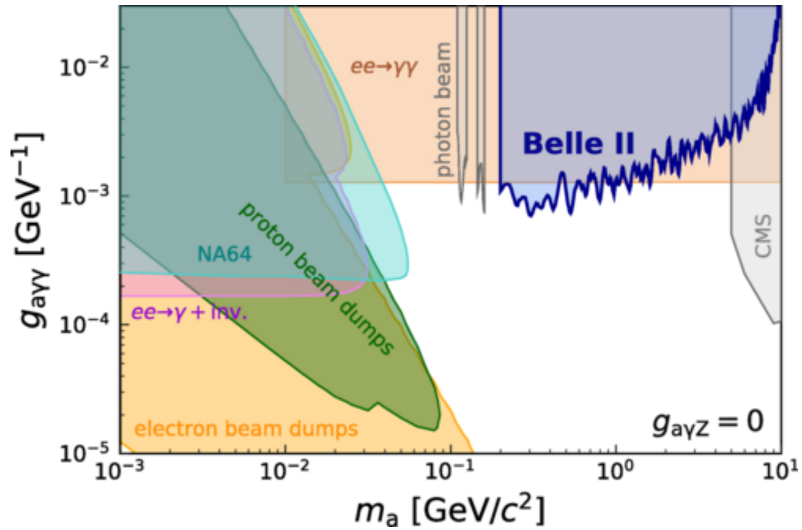


We model the peaking contribution using a Crystal Ball function. The mass-dependent CB parameters used in the real data are fixed by fitting simulated events.

No significant excess seen, the highest local significance is 2.8σ



Extension of the exclusion region in the ($g_{a\gamma\gamma}$,m_a) param. space already with ~0.5 fb^{-1}



$\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$

Measurements of semileptonic $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$ decay ($D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, ℓ=e or μ)

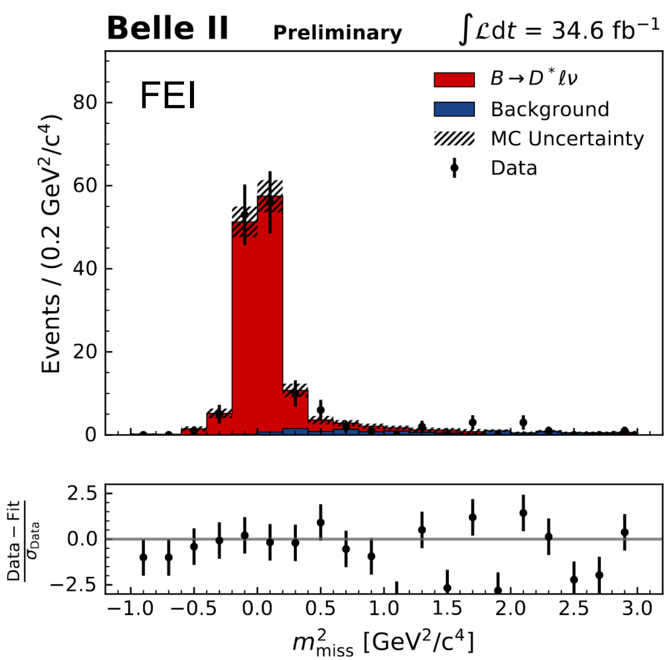
[arXiv:2008.10299] Full Event Interpretation (FEI algorithm)
[arXiv:2008.07198] Untagged

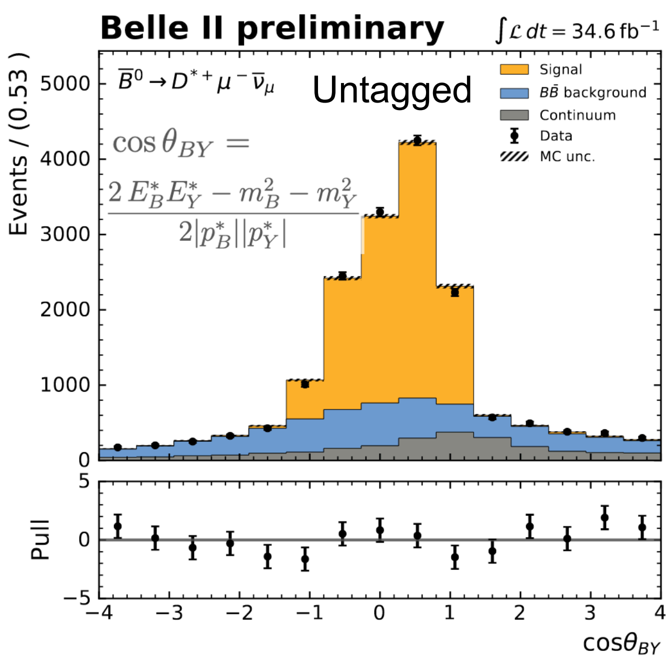
} 34.6 fb^{-1} of events

FEI: one of the B mesons produced in the collision event with hadronic decay channels (B_{tag}) is reconstructed and used to extract the signal of the other B meson (B_{sig})

$$m^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_l)^2 \qquad m^2_{miss} \approx m^2_\nu \sim 0$$

Untagged: B meson direction constrained on a cone around Y = $D^{*+} \ell^-$ direction





$\mathcal{B}$ [$B^0 \to D^*\ell\nu$]

FEI: **4.51** %
± 0.41(stat) %
±(0.27(syst) ± 0.45(π_s)) %

Unt.: **4.60** %
± 0.05(stat) %
±(0.17(syst) ± 0.45(π_s)) %

PDG: **5.05** %
±0.14 %

$\overline{B}^0 \rightarrow D^{*+} \ell^- \overline{\nu}_\ell$

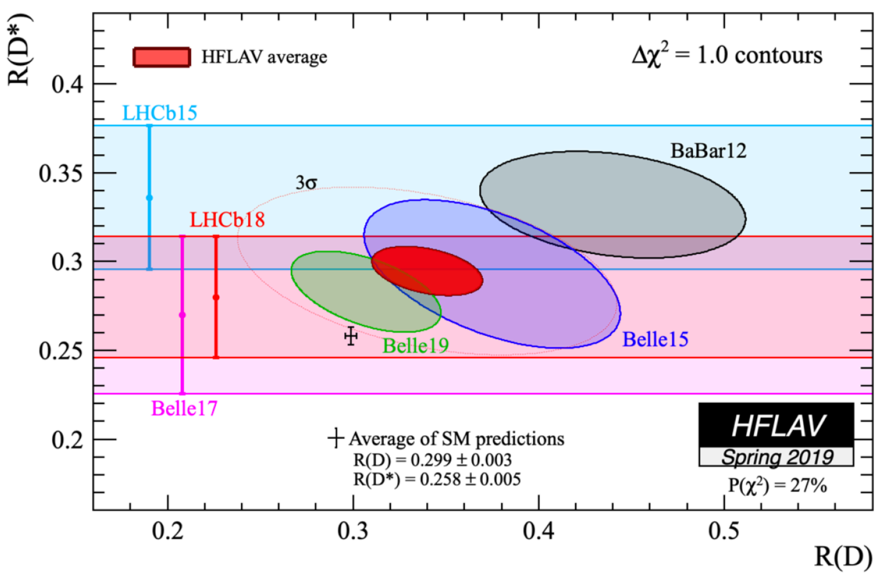
LFV test: $$R_{e\mu} = \frac{\mathcal{B}(\overline{B}^0 \rightarrow D^{*+} e^- \overline{\nu}_e)}{\mathcal{B}(\overline{B}^0 \rightarrow D^{*+} \mu^- \overline{\nu}_\mu)} = 0.99 \pm 0.03$$

Electron and muon semileptonic B decays are a background for the τ decay, Their understanding is also important for a precise measurement of $R_{\tau l}$ where we have a discrepancy with respect to SM expectation:

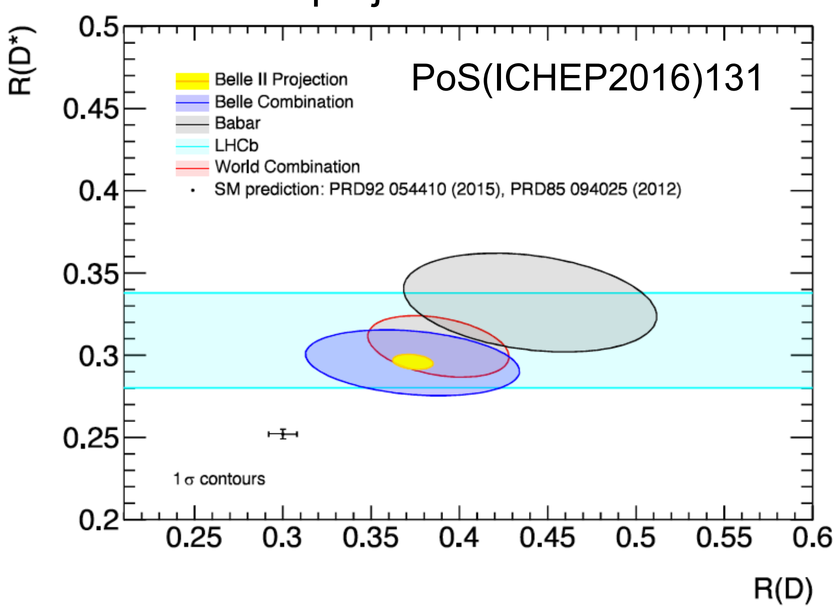
$(R_D, R_{D^*})_{measured}$ vs $(R_D, R_{D^*})_{SM}$

3.9 σ discrepancy in 2015

3.0 σ discrepancy in 2019



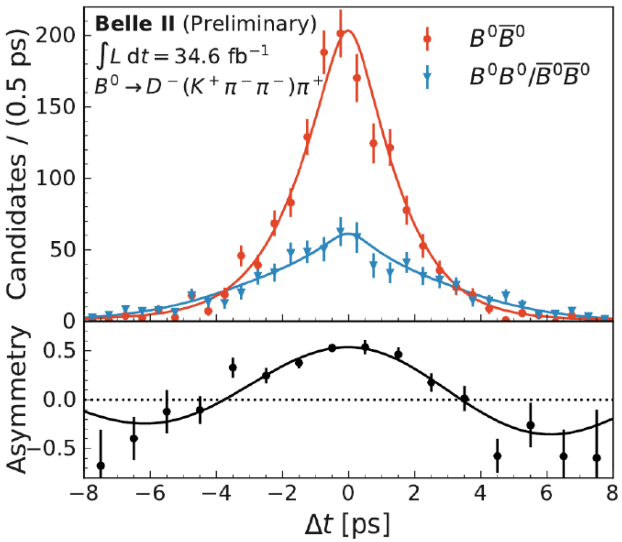
Belle II projection with 50 ab^{-1}



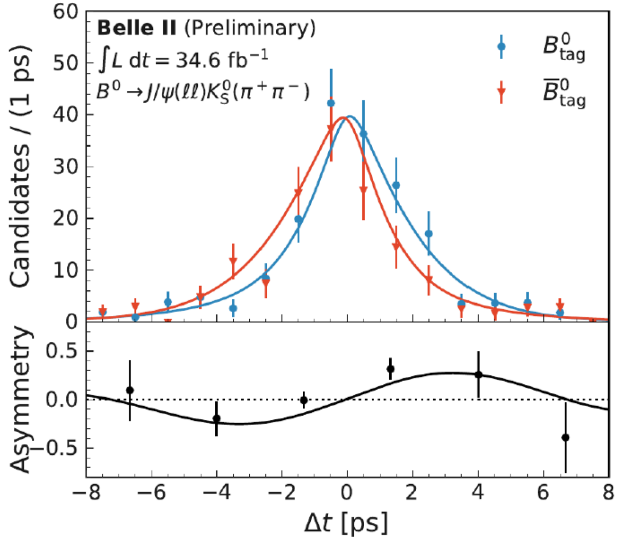
$B\bar{B}$ mixing and time-dependent CPV

[BELLE2-NOTE-PL-2020-11-1] We used 34.6 fb^{-1} of events

$B\bar{B}$ mixing on a sample of $B^0 \rightarrow D^-\pi^+$



Time-dependent CP violation on $B^0 \rightarrow J/\psi\ K_S$



$$A_{mixing}(t) = \frac{N^{unmix}(t) - Nmix(t)}{N^{unmix}(t) + Nmix(t)} = D\cos(\Delta m\ t)$$

$$A_{CP}(t) = D \sin 2\beta\ S \sin(\Delta m\ t)$$

(D = (1-2w) w = wrong tag fraction)

$\Delta m = (0.531 \pm 0.046 \pm 0.013)\ ps^{-1}$

$S = 0.55 \pm 0.21 \pm 0.04$

World Average: $\Delta m = (0.5065 \pm 0.0019)\ ps^{-1}$

$S = 0.691 \pm 0.017$

Current results will not have a large impact on the WA but the channel is essential to prove the readiness of the experiment to perform complex and precise measurements

τ mass measurement

We used 8.8 fb^{-1} of data accumulated during 2019 at Υ(4S) [arXiv:2008.04665]

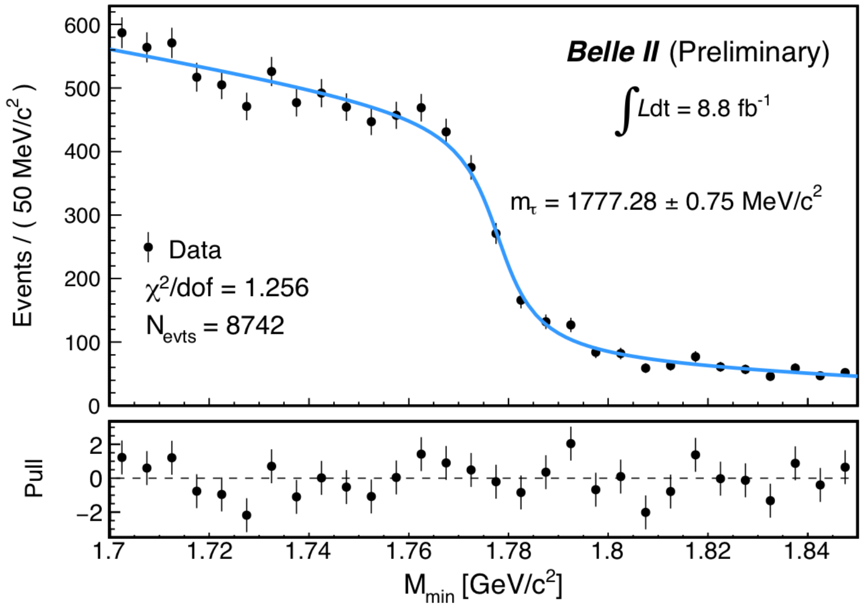
Three-prong τ decay: $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$

Identification of charged particles is based on the selection $E_{ECL}/P_{lab} < 0.8$

Mass of τ lepton measured from the threshold in "pseudomass" variable:

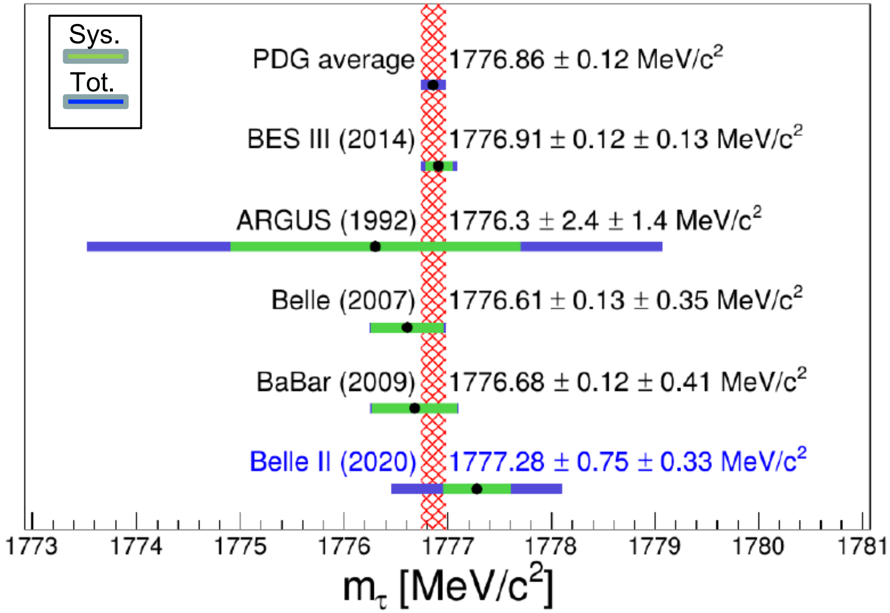
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$

$M_{min} \leq m_\tau$ without ISR and FSR



This measurement is in good agreement with the current world average.

Stat. error will dominate up to 50 fb^{-1}



Summary

- The SuperKEKB collider and the Belle II detector allowed to have stable data collection in 2019 and 2020. The max. luminosity now at 2.4×10^{34} cm^{-2} s^{-1} will be increased and will reach 6×10^{35} cm^{-2} s^{-1} in 2029.
- The data collected in the 2018 commissioning run allowed us to publish two PRL papers adding new exclusion limits in the Dark Sector.
- Belle II started Phase 3 operations in March 2019, up to now a total of 94.5 fb^{-1} integrated luminosity have been recorded.
- Several analysis are ongoing, we are already competitive with BaBar and Belle in the Dark Sector, we plan to get a similar statistics within 2022 and to become competitive with them for all the analysis.

Backup

SuperKEKB parameters

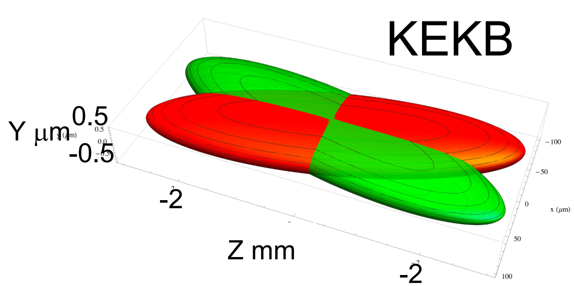
$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

$I_\pm$ beam current
β_y^* vertical beta function
$\zeta_{y\pm}$ beam-beam parameter
R_L , R_ζ reduction factors

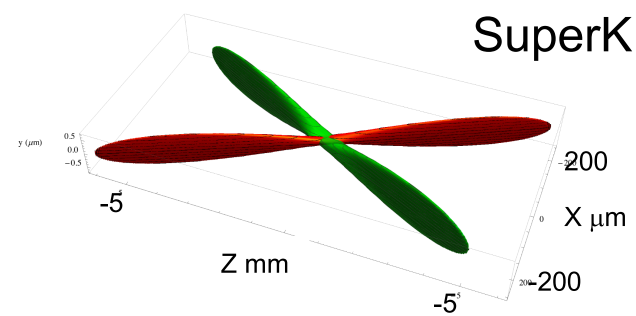
Machine parameters

	E (GeV) LER HER	I (A) LER HER	β^*_y (mm) LER HER	$\zeta_{y\pm}$ LER HER	Crossing angle (mrad)
KEKB	3.5 8.0	1.64 1.19	5.9 5.9	0.129 0.090	22
SuperKEKB	4.0 7.0	2.80 2.00	0.30 0.30	0.088 0.081	83
		x 1.5	x 20		

The factor 30 of instantaneous luminosity increase can be obtained with a factor 1.5 of beam currents increase and a factor 20 of β_y^* decrease.
β_y^* = distance were $\sigma_y = 2\ \sigma_y$ (IP)



θ_x = 22 mrad
σ_x = 150 μm
σ_y = 940 nm



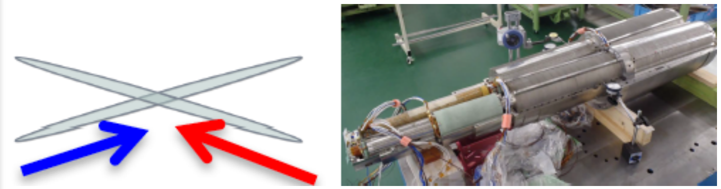
θ_x = 83 mrad
σ_x = 10 μm
σ_y = 50 nm

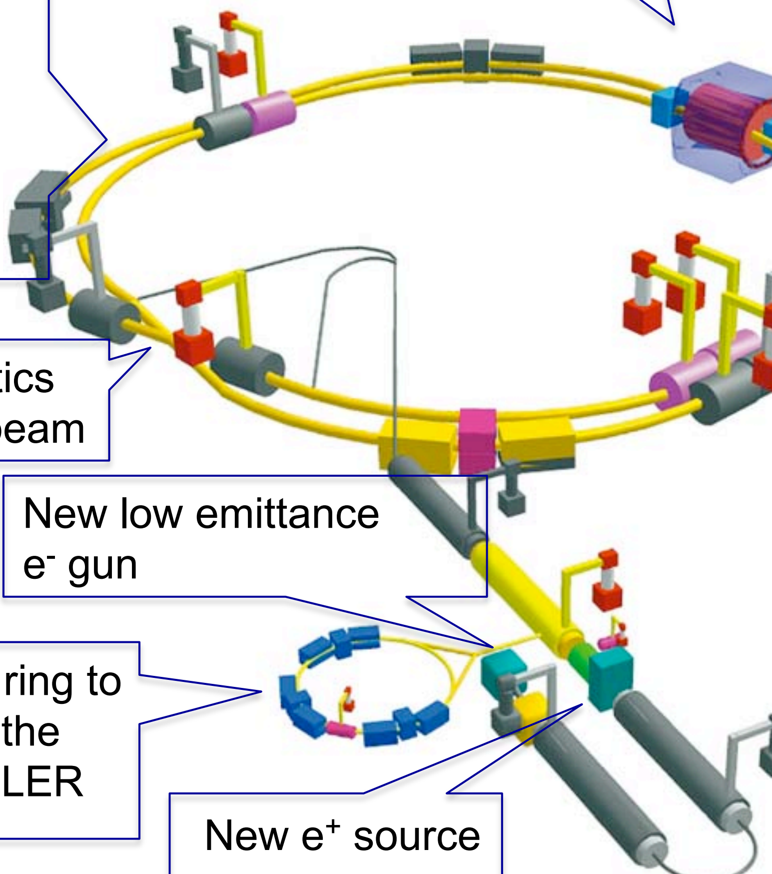
From KEKB to SuperKEKB

New Titanium-Nitride coated beam-pipe with antechambers to suppress electron cloud effect

Belle detector upgraded to Belle II

New QCS final focus magnets for nano-beam scheme





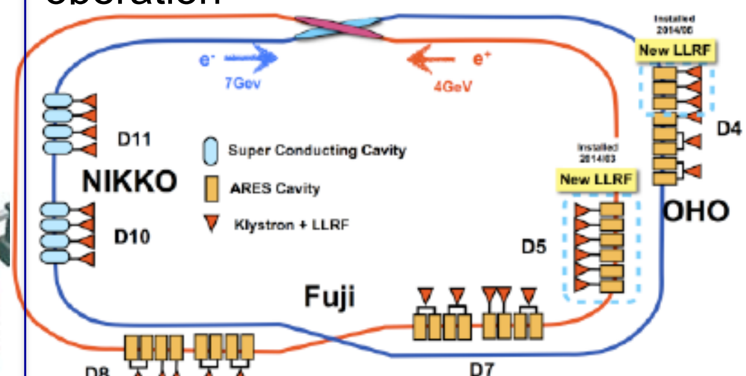
Optimize beam optics for low emittance beam

New low emittance e^- gun

Positron damping ring to inject positrons in the small acceptance LER

New e^+ source

New RF cavities and modified RF system for high beam current operation



Belle II Collaboration

- 1050 active collaborators (15% are women)
- 120 institutions
- 26 countries/regions