Belle II: Status and Prospects

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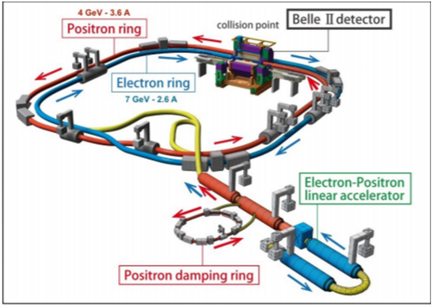
Outline

Introduction to Belle II — Experiment

- Belle II operates at SuperKEKB at KEK in Tsukuba, Japan



- Plan to take 50 ab^{-1} (50 $\times$ Belle) data
  $\sigma(e^+e^- \to B\bar{B}/c\bar{c}/\tau\bar{\tau}) \approx 1.05/1.3/0.92$ nb
- Designed $\mathscr{L}$: 6.5 $\times$ 10^{35} cm^{-2}s^{-1}
- Achieved $\mathscr{L}$: 3.1 $\times$ 10^{34} cm^{-2}s^{-1} (*New world record on 22/6/2021!*)

Belle II at high intensity frontier:

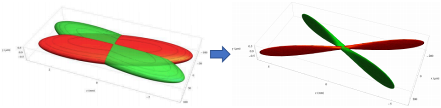
- Search for BSM physics
- Precisely measure SM parameters
- Reveal more properties of the strong interaction

Very rich physics topics:

- Semileptonic & Missing Energy B Decays
- Radiative & Electroweak Penguin B Decays
- Time Dependent CP Violation
- Hadronic B Decays to Charmless
- Hadronic B Decays to Charm
- Bottomonium & Charmonium
- Charm Physics & τ Physics
- Low Multiplicity Physics & Dark Sector Physics

For details, please see
The Belle II Physics Book

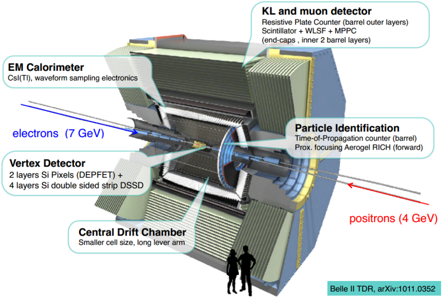
Introduction to Belle II — Collider & Dectector



KEKB SuperKEKB

Increase the luminosity:

- Squeeze beam size ($\times$ 20, to 50 nm at the IP)
- Increase the beam currents ($\times$ 1.5)



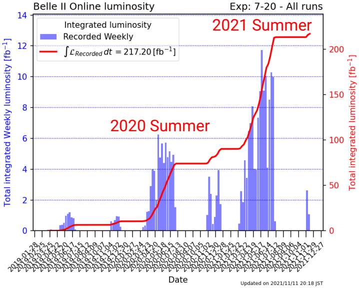
Compared with Belle:

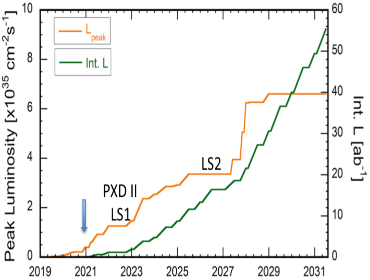
- Better vertexing (decay time) resolution
- Better momentum resolution
- More sophisticated trigger

Compared with experiments at hadron colliders:

- Low-background production of huge amounts of B/D/τ particles.
- Kinematic constrains from e^+e^- initial state offer unique precision in final states with multiple neutrinos or π^0s.

Introduction to Belle II — Data taking





- To date, Belle II has accumulated ~ 220 fb^{-1} data.
- Most of the results shown in this talk are extracted from the data collected before and in 2020 Summer ($\sim$ 72 fb^{-1}).
- The dark sector results only use the Phase 2 data ($\sim$ 0.5 fb^{-1}) accumulated in 2018 Summer.

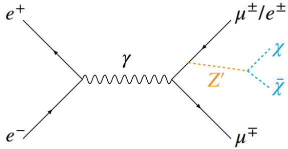
- Belle II Collaboration: 26 countries, 123 institutions, 1126 members.
- Belle II China Group: 12 + 1 institutions, 67 members, ranking 5th in the collaboration (高能所、中科大、北大、北航、复旦、辽师、山大、苏大、南京师大、郑大、湖南师大、河南师大 + 南开).

Outline

Published results — Search for invisibly decaying Z'

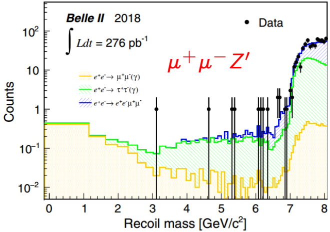
- Z': massive gauge boson
- Originate from the $L_\mu - L_\tau$ extension of the SM
- potentially address anomalies in $b \to s l^+ l^-$ and $(g-2)_\mu$

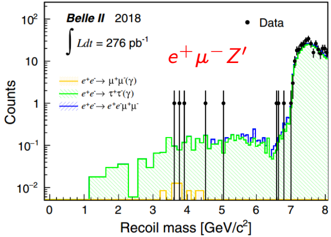
Signal: $e^+e^- \to \mu^+\mu^-(e^+\mu^-)$ + missing energy



No evidence for Z'
$g_{Z'\ell\ell} < 5\times10^{-2}...1$ for $m_{Z'} \leq 6$ GeV/c^2

[PRL.124.141801(2020)](PRL.124.141801(2020))

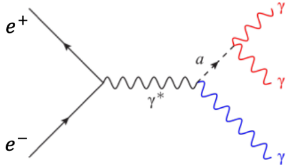




Published results — Search for axionlike particles

- Predicted by many extensions of the SM.
- Occur in most solutions of the strong CP problem.
- Can connect the SM particles to yet undiscovered DM particles.

Signal: $e^+e^- \rightarrow \gamma_{recoil} + a(\rightarrow \gamma\gamma)$

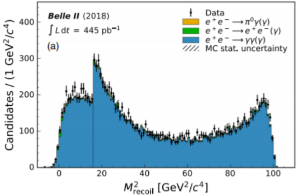


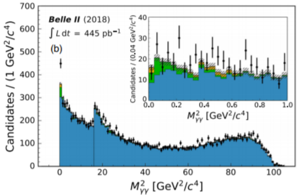
No evidence for ALP

$$g_{a\gamma\gamma} \lesssim 10^{-3}\,(\mathrm{GeV}/c^2)^{-1}$$
$$\text{for } 0.2 < m_a \leq 1\ \mathrm{GeV}/c^2$$

Most restrictive to date for $0.2 < m_a < 1\ \mathrm{GeV}/c^2$.

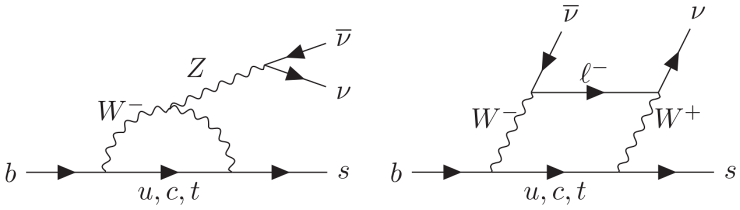
PRL.125.161806(2020)





Published results — Search for $B^+ \to K^+\nu\bar{\nu}$ (I)

- The decay $B^+ \to K^+\nu\bar{\nu}$ involves the FCNC transition $b \to s\nu\bar{\nu}$.

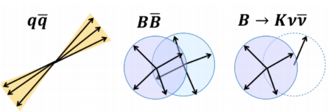


(a) Penguin diagram (b) Box diagram

- Its BF is predicted to be $(4.6 \pm 0.5) \times 10^{-6}$ by the SM, and could be potentially enhanced by the BSM.
- offers a complementary probe into the BSM scenarios that are proposed to explain the tensions observed in $b \to sl^+l^-$.
- helps constrain models that predict new particles, such as leptoquarks, axions, or dark matter particles.

Published results — Search for $B^+ \to K^+\nu\bar{\nu}$ (II)

- Previous analyses: explicit tagging approach with limited signal efficiency.
  - Semi-leptonic tag (0.2% @ Belle and BaBar)
  - Hadronic tag (0.04% @ BaBar)
- Belle II analysis: inclusive tagging approach with higher signal efficiency.
  - Employ event shape, vertexing, and kinematical variables.
  - Higher signal efficiency (4.3%), thus higher sensitivity at given luminosity.

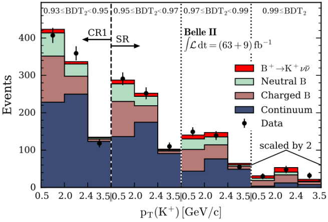


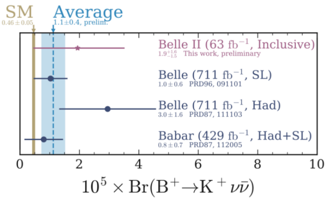
PRL.127.181802(2021)

Competitive result with 63 fb^{-1}!

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (1.9^{+1.3+0.8}_{-1.3-0.7}) \times 10^{-5}$$

4.1×10^{-5} @90% CL



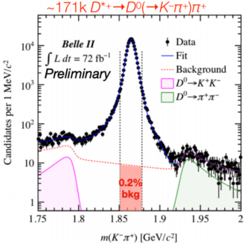


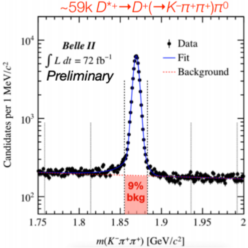
Published results — Measurement of D^0 and D^+ lifetimes (I)

- Test non-pertubative QCD effective models, such as the heavy-quark expansion.
- Needed to compare measured decay branching fractions to predicted decay partial widths.
- Input to LHCb measurements, to get the abosolute limetimes of the D_s^+ meson and charmed baryons.

- Measured for the first time with the sub-percent precision by FOCUS — almost 20 years ago.
- No measurement from Belle, BaBar, and LHCb.

- Excellent Belle II vertexing performance enables the high precision measurement of D^0 and D^+ lifetimes with early data.
  - Decay-time resolution 2 times better than BaBar and Belle.



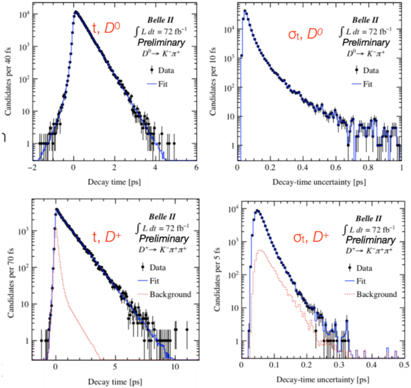


Signal D^0/D^+ candidates from D^{*+} in $e^+e^- \to c\bar{c}$

Published results — Measurement of D^0 and D^+ lifetimes (II)

arXiv:2108.03216 (Accepted by PRL)

Lifetimes are extracted by 2D fits to the decay times and their respective uncertainties.



World leading result:

	Our result	WA
$\tau(D^0)$ =	$(410.5 \pm 1.1 \pm 0.8)$ fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	$(1030.4 \pm 4.7 \pm 3.1)$ fs	(1040 ± 7) fs

Much room to reduce statistical uncertainty and systematic uncertainty on detector alignment.

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Statistical	1.1	4.7
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Input charm masses	0.01	0.03
Total systematic	0.8	3.1

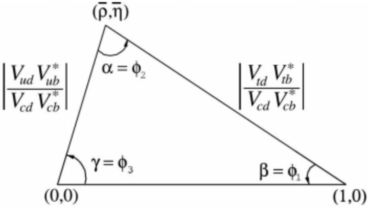
Outline

Measurements of CKM parameters

Complex phase cause CP violation

$$V=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A^2\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$V^\dagger V = 1 \Rightarrow \underset{\lambda^3\cdot 1}{V_{ub}^* V_{ud}} + \underset{\lambda^2\cdot\lambda}{V_{cb}^* V_{cd}} + \underset{1\cdot\lambda^3}{V_{tb}^* V_{td}} = 0$$



- Precision measurements of CKM parameters are keystones of Belle II experiment.

The Belle II Physics Book

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

- Precise angles and sides of the unitarity triangle are crucial to test the SM and investigate the BSM physcis.
- Intensive activities ongoing over early data ($\sim$ 30-70 fb^{-1}) to prepare measurements of UT angles and sides.

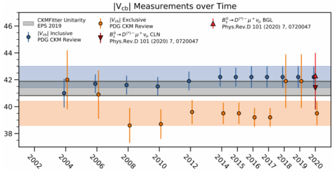
Preliminary measurements on CKM parameters
Measurements of $|V_{cb}|$ and $|V_{ub}|$

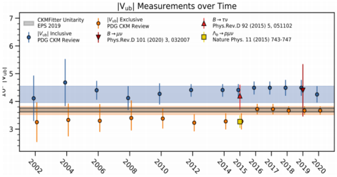
Both inclusive and exclusive approaches are used to measure $|V_{cb}|$ and $|V_{ub}|$:

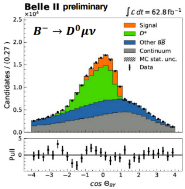
$|V_{ub}|$: $B \to X_u \ell \nu$, $B \to \pi(\rho,\eta)\ell\nu$ $(\ell = e, \mu)$

$|V_{cb}|$: $B \to X_c \ell \nu$, $B \to D^{(*)}\ell\nu$ $(\ell = e, \mu)$

Persistent tension between two approaches.

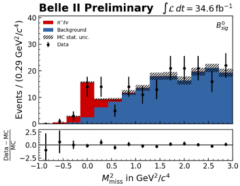






$\mathcal{B}(B^- \to D^0 \ell^- \overline{\nu}_l) = (2.293 \pm 0.053_{\text{stat}} \pm 0.084_{\text{syst}})\%$

arXiv:2110.02648

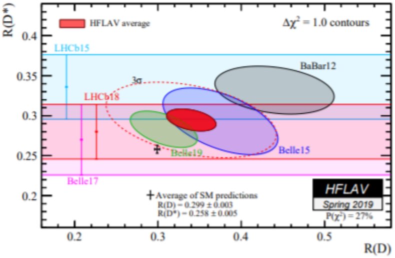


$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell)$ $(1.58 \pm 0.43_{\text{stat}} \pm 0.07_{\text{sys}}) \times 10^{-4}$

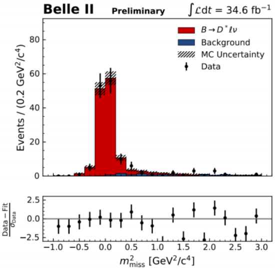
arXiv:2008.08819

Preliminary measurements on CKM parameters
Measurement of $R(D^{(*)})$

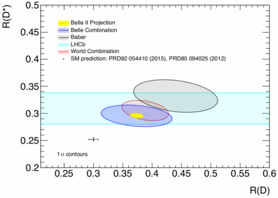
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \quad (\ell = e, \mu)$$



- Combined result of $R(D^{(*)}) \sim 3.1\sigma$ tension with the SM
- New physics can contribute at tree level
  - e.g. charged Higgs, leptoquark



$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = (4.51 \pm 0.41_{\rm stat} \pm 0.27_{\rm syst} \pm 0.45_{\pi_s})\,\%$
$\ell = e, \mu$



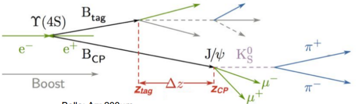
Belle II will be world-leading

Preliminary measurements on CKM parameters
Toward the measurement of $\sin(2\phi_1)$

- Flagship measurement of B factories.
- Still very important input to CKM fit.
- Golden mode: $B^0 \to J/\psi K^0_S$

$$A_f(\Delta t) = \frac{\Gamma(\bar{B}^0 \to J/\psi K^0_S) - \Gamma(B^0 \to J/\psi K^0_S)}{\Gamma(\bar{B}^0 \to J/\psi K^0_S) - \Gamma(B^0 \to J/\psi K^0_S)} = S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t)$$

Assume no direct CPV: Af ~ 0

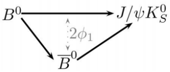


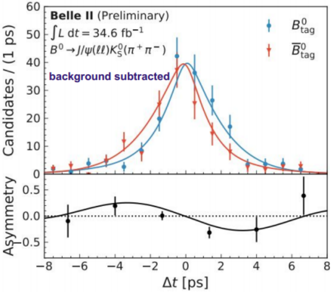
Belle: Δz≈200μm
Belle II: Δz≈130μm
with better Δz resolution

distance measurement

Δt = Δz / (βγc)

time measurement





$\sin(2\phi_1) \approx S_f = 0.55 \pm 0.21_{stat} \pm 0.04_{sys}$

world average: 0.699 ± 0.017

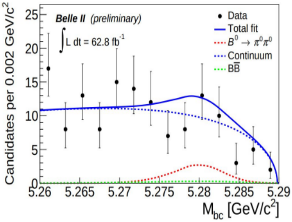
- The precision will be improved by a factor of 5 with full Belle II data.

Preliminary measurements on CKM parameters
Toward the measurement of ϕ_2

Unique Belle II capability to study all the B→ππ, ρρ partner decays to determine ϕ_2

$B^0 \to \pi^0\pi^0$: very challenging because four γ's.
Train BDT to suppress background photons.
3D fit of ΔE-Mbc-continuum suppression BDT.
Unique Belle II reach.
$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.98^{+0.48}_{-0.39}(\text{stat}) \pm 0.27(\text{syst})) \times 10^{-6}$

arXiv:2107.02373

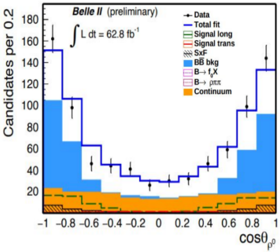


$B^+ \to \rho^+\rho^0$: π-only final state, large background because of ρ mass width. Additional challenge of angular analysis→6D fit including helicity angles.

longitudinal polarization fraction

$f_L(B^+ \to \rho^+\rho^0) = (0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst}))$
$\mathcal{B}(B^+ \to \rho^+\rho^0) = (20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})) \times 10^{-6}$

arXiv:2109.11456

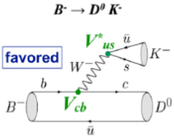


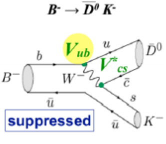
20% precision improvement wrt Belle on the same lumi!

On track to measure the CKM angle ϕ_2 at Belle II

Preliminary measurements on CKM parameters
Toward the measurement of ϕ_3

- LHCb will have the upper hand.
- Belle II will contribute in modes with neutral particles in the final state.
- Using both Belle data (711 fb^{-1}) + Belle II data (128 fb^{-1})
- A model-independent Dalitz plot analysis of $B^+ \to D(K_S h^+ h^-)K^+$





$$\frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D^0}K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0K^-)} = r_B e^{i(\delta_B + \phi_3)}$$

arXiv:2110.12125 (Submitted to JHEP)

$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,.$$

(Thanks to BESIII strong phase measurement, the third uncertainty reduces from 4° to 1°)

- Current precision worse than world average value ($\sim 3.3^\circ$).
- Will achieve a precision of $\sim 4^\circ$ with 10 ab^{-1} data, using $B^+ \to D(K_S h^+ h^-)h^+$ alone.
- The use of other modes will significantly reduce the uncertainty.

Summary and prospects

- Belle II, as a new-generation B-factory experiment, has set sail to accumulate a huge data sample of 50 ab^{-1} over the upcoming decade.
- Thanks to the excellent detector performance and the noval analysis approach, with the limited early data ($<$ 100 fb^{-1}), Belle II has produced a batch of world-leading physics results (Z', ALPs, $B^+ \to K^+ \nu\bar{\nu}$, D^0/D^+ lifetimes, etc.), as well as many preliminary results.
- Many interesting analyses, not mentioned here, are on the way to final measurements with more data.
- With the upcoming big data, Belle II will offer many unique precision probes into BSM physics, thus contributing to the progress of particle physics from the intensity frontier.

Thanks for your attention!

Toward the measurement of ϕ_3

The measurement is also performed on the Belle data sample alone and the results are reported in App. B. The statistical uncertainty in ϕ_3 is 11°, which is significantly improved from the 15° reported in the previous Belle analysis with the same data set [20]. The improvements are primarily due to the improved background rejection and K^0_S reconstruction, as well as the addition of $B^+ \to D(K^0_S K^+ K^-)h^+$ decays. The inclusion of Belle II data improves the precision of $x^{DK}_{\pm}$ and $y^{DK}_{\pm}$ parameters. However, the ϕ_3 statistical uncertainty does not improve despite introducing 17% more data. The reason is that the Belle II data favours a much smaller value of r^{DK}_B, which results in a central value of 0.129 for the combined fit compared to 0.144 for the Belle data alone. The uncertainty in ϕ_3 is inversely proportional to r_B, which explains the lack of improvement in ϕ_3 sensitivity when including the Belle II data. The world average value of r_B is 0.0996 ± 0.0026 [5] so it is not unexpected the value of r_B will regress towards this value as additional data is included.

The statistical precision on ϕ_3 is worse than the current world-average value [5]. However, the precision is limited by the size of the data sample, so a future analysis with a Belle II data set corresponding to $10\,\mathrm{ab}^{-1}$ will provide measurements with a precision of approximately 4° from the $B^+ \to D\left(K^0_S\pi^+\pi^-\right)h^+$ mode alone.[6] The use of other modes will give additional sensitivity to ϕ_3 [54].