Belle II: Status and Prospects

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On behalf of Belle II

TeVPA 2021
25-29 October 2021
Exploring this Universe

Energy frontier
Direct production of new particles - limited by beam energy (LHC – ATLAS, CMS)

Intensity / precision frontier
New virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)

even if NP were not found in direct searches, NP effects could indirectly appear in high precision measurements

Numerous talks at this conference!
2001: large CP violation observed in transitions of b-quark from $e^+e^-$ colliders at the $\Upsilon(4S)$ mass energy (B factories) → success of standard model (SM) theory.
2001–: Use quark dynamics to probe indirectly beyond standard model (BSM) dynamics.

KEKB + Belle, PEP-II + BaBar, dedicated to searches for CP violation in B mesons, experimentally confirmed Kobayashi Maskawa mechanism.

First successful move on matter-antimatter asymmetry (not all accounted for).
SuperKEKB accelerator

Integrated luminosity expected $50 \text{ ab}^{-1}$.

$\times 40$ previous B factory.

Adopting beam squeezing and current increase as means to achieve higher luminosity, the project aims to a peak luminosity of $6 \times 10^{35}$ cm$^{-2}$s$^{-1}$, 30 times more than KEKB. On 22 June 2020, SuperKEKB set a new world record for peak luminosity: $3.1 \times 10^{34}$cm$^{-2}$s$^{-1}$. 

Nano-beam Scheme:
Belle II detector

Compared with Belle:
• Vertexing (decay time) resolution;
• Better momentum resolution;
• Slightly higher acceptance;
• More sophisticated trigger.

Compared with hadron colliders:
• low-background production of huge amounts of B/D/tau particles;
• kinematic constrains from $e^+e^-$ production offer unique precision in final states with multiple neutrinos or $\pi^0$. 

1100 members, 123 institutions, 26 countries
Belle II physics program

\[ e^+e^- \rightarrow B \bar{B} : 1.05 \text{ nb} \]
\[ e^+e^- \rightarrow \tau^+\tau^- : 0.92 \text{ nb} \]
\[ e^+e^- \rightarrow c \bar{c} : 1.3 \text{ nb} \]

Very rich topics

“The Belle II Physics Book”

PTEP 2019 (2019) 12, 123C01
D⁰/D⁺ lifetime

Motivation:
- Test of non-perturbative QCD
- Measured for the first time with sub-percent precision by FOCUS – 20 years ago
- No measurement from Belle/BaBar/LHCb
- D⁺ lifetime is used as reference (LHCb)

Analysis strategy:
2D fit of decay time and its uncertainty. All parameters extracted directly from the data.

Thanks to the good vertexing and high purity in the signal region.

<table>
<thead>
<tr>
<th>Our result</th>
<th>WA</th>
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<tbody>
<tr>
<td>( \tau(D^0) = (410.5 \pm 1.1 \pm 0.8) \text{ fs} )</td>
<td>( \tau(D^0) = (410.1 \pm 1.5) \text{ fs} )</td>
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<tr>
<td>( \tau(D^+) = (1030.4 \pm 4.7 \pm 3.1) \text{ fs} )</td>
<td>( \tau(D^+) = (1040 \pm 7) \text{ fs} )</td>
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Accepted by PRL, arXiv: 2108.03216
Time dependent CPV in B decays, $\beta(\phi_1)$

Measurement of CKM phase through the interference of B mixing amplitude with decay amplitude to a CP eigenstate.
(Flagship measurement of the B factories.)

$\Delta z = \beta \gamma c \Delta t$
$\Delta t = t_{CP} - t_{tag}$

$\langle \Delta z \rangle \sim 130 \mu m$ at Belle II

$A_f(\Delta t) = \frac{\Gamma(B^0(\Delta t) \to f) - \Gamma(B^{0*}(\Delta t) \to f)}{\Gamma(B^0(\Delta t) \to f) + \Gamma(B^{0*}(\Delta t) \to f)}$

$S_f = \sin 2\phi_1 = 0.55 \pm 0.21\text{(stat.)} \pm 0.04\text{(syst.)}$

Still very important at Belle II: $\phi_1$ (current precision $\sim 0.7^\circ$) is fundamental inputs of the CKM fit. We expect to improve by a factor of 5.
- Another fundamental input for the CKM fit, proceeding only through $B^- \to D^0 K^-$ tree level transitions;
- On this field, LHCb will have the upper hand, but Belle II will contribute in modes with neutrals in the final state;
- Good $K-\pi$ separation is important to suppress the favored $B \to D \pi$ decays.

Model independent measurement (Dalitz plot analysis) of $\phi_3$ by $B^+ \to D \left(K_S^0 \, h^+ \, h^-\right) h^+$ using Belle + Belle II data.

$$A_{B^+} \left(m_-^2, m_+^2\right) \propto A_D \left(m_-^2, m_+^2\right) + r_B^{DK} e^{i(\delta_B^{DK} - \phi_3)} A_D \left(m_-^2, m_+^2\right)$$

$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ.$$
CKM elements $|V_{cb}|$ and $|V_{ub}|$

Tree level nature of semi-leptonic $B$ decays $\rightarrow$ SM gauges $\rightarrow$ key roles for $|V_{cb}|$ and $|V_{ub}|$.

Inclusive and exclusive determinations offer independent and complementary results $\rightarrow$ persistent tension between two approaches.

- $|V_{cb}|$ from $B \rightarrow X_c l \nu$, $B \rightarrow D^{(*)} l \nu$ ($l = e, \mu$)
- $|V_{ub}|$ from $B \rightarrow X_u l \nu$, $B \rightarrow \pi(\rho, \eta) l \nu$ ($l = e, \mu$)

Inclusive:

**Observed $b \rightarrow u \ell \nu_\ell$ excess in data ($> 3\sigma$).**

Exclusive:

$$\mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu_\ell) = [1.58 \pm 0.43 \pm 0.07] \times 10^{-4}$$

Preliminary, arXiv: 2103.02629
\[ |V_{cb}| \text{ cont'd} \]

\[ R_{D^*}(\tau) \equiv \frac{\text{Br}(B \to D^{(*)}\tau \bar{\nu}_\tau)}{\text{Br}(B \to D^{(*)}\ell \bar{\nu}_\ell)_{\ell=e,\mu}} \]

Lepton flavour universality (LFU) violated?

\[ R_D = 0.340 \pm 0.027 \pm 0.013 \quad +1.4\sigma \text{ from SM} \]
\[ R_{D^*} = 0.295 \pm 0.011 \pm 0.008 \quad +2.5\sigma \text{ from SM} \]
\[ R_D/R_{D^*} \text{ combined} \quad +3.08\sigma \text{ from SM} \]

Full Event Interpretation algorithm exploited, tagging B using over 100 hadronic decay modes.

\[ \mathcal{B}(\bar{B}^0 \to D^{*+}\ell^- \bar{\nu}_\ell) = (4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s})\% \]

BELLE2-CONF-PH-2020-023
Unique Belle II capability to study all the $B \to \pi \pi, \rho \rho$ partner decays to determine $\alpha$.

$B^0 \to \pi^0 \pi^0$: very challenging because four $\gamma$'s.
Train BDT to suppress background photons.
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

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

$f_L(B^+ \to \rho^+ \rho^0) = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst})$

$\mathcal{B}(B^+ \to \rho^+ \rho^0) = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$

BELLE2-TALK-CONF-2021-013

20% precision improvement wrt Belle at the same lumi!
Wrt BaBar's best (scaled): better on BF, same on $f_L$. 
\[ B^+ \to K^+ \nu \bar{\nu} \]

Flavor changing neutral-current. The SM prediction of its Br is \((4.6 \pm 0.5) \times 10^{-6}\). Unobserved, but BSM could potentially enhance its Br. Complementary probe to BSM from \(b \to s \ell \ell\)

Previous analyses: tagged approach with limited signal efficiency:
- semileptonic tag (0.2% @ Belle, BaBar)
- hadronic tag (0.04% @ BaBar)
Belle II approach: novel inclusive tagging technique - signal efficiency 4.3%

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

\[ 4.1 \times 10^{-5} \text{ @90\% CL} \]

Accepted by PRL, arXiv:2104.12624
$\tau$ mass

Two methods for measuring $m_\tau$:

- Measurement in the production thresholds (DELCO, BES, KEDR, BES III).
- Pseudo-mass ($M_{\min}$) distribution (ARGUS, OPAL, Babar, Belle).

\[ M_{\min} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau \]

Belle II (Preliminary)

\[ \int dt = 8.8 \text{ fb}^{-1} \]

$\mu = 1777.28 \pm 0.75 \text{ MeV/c}^2$

τ lifetime

Important SM parameter. Its precision has implications in LFU, α_s (m_t), etc.

Previous measurements:

- Z-peak: LEP (DELPHI, L3, ALEPH, OPAL).
- Y-peak: CLEO, BaBar, Belle ¹.


Strategy at Belle II:

1. Reconstruct vertex for 3-prong τ. Only one 3-prong = higher statistics.
2. Estimate the τ momentum \( \vec{p}_\tau \). Hadronic decays in both sides.
3. Find the production vertex. Intersection of \( \vec{p}_\tau \) with the plane IP_y.

Proper decay time distribution

\[
\tau = \ell_{3\text{-prong}} \frac{m_\tau}{|\vec{p}_{3\text{-prong}}| c}
\]

Belle II 2020 (Simulation)
Lepton flavor violation in $\tau$

Super rare processes. With huger statistic (50 ab$^{-1}$), one more step approaching them.
Dark sector

**Search for an axion like particle (ALP)**
Signal: $e^+ e^- \rightarrow \gamma_{\text{recoil}} + a (\rightarrow \gamma \gamma)$

![Diagram of ALP signal](image1)

*No evidence for ALP*

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

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

**Search for an Invisibly Decaying Z'**
Signal: $e^+ e^- \rightarrow \mu^+ \mu^- (e^+ \mu^-) + \text{missing E}$

![Diagram of Z' signal](image2)

*No evidence for Z'*

$$g_{Z'\ell\ell} < 5 \times 10^{-2} \ldots 1 \text{ for } m_{Z'} \leq 6 \text{ GeV/c}^2$$

More details at Rajesh Maiti’s talk, Dark sector physics at Belle II.
Summary

• A new-generation B-factory has set sail to produce billions of B, D, and tau decays over the next decade. A collaboration of 1100 members from 126 institutions over 26 countries built and operates Belle II, a dedicated state-of-the-art instrument to explore them.

• A rich program is ahead and early harvesting offers already impactful results: D lifetimes, $B^+ \rightarrow K^+ \nu \bar{\nu}$, ALP, $Z'$, etc.

• Belle II will soon offer unique precision probes for BSM physics.
Thank you for your attention!
Back up
Data-taking so far

SuperKEKB raises the bar

22 August 2021

A new world record!
Performance overview

Strong charged particle identification.

Good momentum resolution.

High γ efficiency.

Flavor tagging efficiency comparable to Belle.

Greatly improved time resolution compared to previous B-factories.
Belle II luminosity prospect

![Graph showing peak luminosity and integration luminosity over time]

- $L_{\text{peak}}$ Before IR upgrade
- $L_{\text{peak}}$ After IR upgrade

- 6.5 x $10^{35}$ cm$^{-2}$ s$^{-1}$

**Date**

**Peak Luminosity [x$10^{35}$ cm$^{-2}$ s$^{-1}$]**

**Int. L [ab$^{-1}$]**

YOU ARE HERE

2019/1 2021/1 2023/1 2025/1 2027/1 2029/1 2031/1
SM predictions for $R_D(*)$

<table>
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<th>Reference</th>
<th>R(D)</th>
<th>R(Di*)</th>
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<tr>
<td>D.Bigi, P.Gambino, Phys.Rev. D94 (2016) no.9, 094008 [arXiv:1606.08030 [hep-ph]]</td>
<td>0.299 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>F.Bernlochner, Z.Ligeti, M.Papucci, D.Robinson, Phys.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ph]]</td>
<td>0.299 ± 0.003</td>
<td>0.257 ± 0.003</td>
</tr>
<tr>
<td>S.Jaiswal, S.Nandi, S.K.Patra, JHEP 1712 (2017) 060 [arXiv:1707.09977 [hep-ph]]</td>
<td>0.299 ± 0.004</td>
<td>0.257 ± 0.005</td>
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<tr>
<td>Arithmetic average</td>
<td>0.299 ± 0.003</td>
<td>0.258 ± 0.005</td>
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</tbody>
</table>

CKM

$$
\begin{bmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{bmatrix}
$$