Belle II @ SuperKEKB

Livio Lanceri - INFN, Trieste - on behalf of the Belle II Collaboration
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A tale of two B factories

BaBar @ PEP-II (SLAC)

energy-asymmetric electron-positron colliders
mostly $E_{CM} = 10.580$ GeV: Y(4S)

1999 - 2008
> 560 fb$^{-1}$
470M $B\bar{B}$ pairs @ Y(4S)

Belle @ KEKB (KEK)

1999 - 2010
>1000 fb$^{-1}$
770M $B\bar{B}$ pairs @ Y(4S)
A tale of two B factories

since 2000:
KM mechanism of CPV validated
+ a lot of Flavour Physics

CP violation in $b \to c\bar{c}s$ decays

The Physics of the $B$ Factories

a must-have book, joint enterprise
The B factory approach

- CM energy = 10.580 GeV

- Asymmetric energy beams: boost the B pair to measure $\Delta t$

$$e^+e^- \rightarrow Y(4S) \rightarrow B^0\overline{B}^0$$

$$B^+B^-$$

$\Delta t \approx \frac{z(1) - z(2)}{c\gamma\beta}$

Effective cross sections:

<table>
<thead>
<tr>
<th>$e^+e^-$</th>
<th>$\sigma$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb$</td>
<td>1.05</td>
</tr>
<tr>
<td>$cc$</td>
<td>1.30</td>
</tr>
<tr>
<td>$ss$</td>
<td>0.35</td>
</tr>
<tr>
<td>$uu$</td>
<td>1.39</td>
</tr>
<tr>
<td>$dd$</td>
<td>0.35</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.94</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>1.16</td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>$\approx 40$</td>
</tr>
</tbody>
</table>

Favorable Signal / Background:

$$\frac{\sigma_{bb}}{\sigma_{had}} \equiv 0.28$$

Boost:

SuperKEKB
$E_{\text{HER}} = 7.0$ GeV
$E_{\text{LER}} = 4.0$ GeV

$\gamma\beta \approx 0.28$
Quest for the new Holy Grail

Physics Beyond the Standard Model at the intensity frontier

New CP violating phases in the quark sector?
Is Lepton Flavour universality conserved?
Is there a Left-Right symmetry in nature?
FCNC beyond the SM?
Sources of Lepton Flavour violation?
Dark sector of particle physics?

... and, still within SM: QCD, spectroscopy:
Nature of strong force in hadrons?

...
Challenges for a new B factory

Hunting for small BSM effects in many observed events:

\[ N_{\text{obs}} = L \cdot \sigma \cdot \epsilon \]

HF cross-sections: no game !?

\[ \sigma_{bb, \, LHC} \approx \text{mb} \]

\[ \sigma_{bb, \, Y(4S)} \approx \text{nb} \]

Need strong compensations:
accelerator luminosity \( L \)
detector/analysis efficiencies \( \epsilon \)
Luminosity at $e^+e^-$ colliders

KEKB peak-$L$ record:

$$L = 2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

SuperKEKB aim:

$$L = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$$

A factor 40 !!

Ingredients?

Present progress?
SuperKEKB vs KEKB

Lower emittance: new lattice, $e^- e^+$ sources, $e^+$ damping ring, LER bending magnets, beam pipe; new SC final focussing ($\beta^*_y$)

$\times 20$ smaller beams ($\epsilon, \beta^*_y$)

$\times 2$ larger currents

$\Rightarrow$ luminosity $\times 40$

---

**Machine parameters**

<table>
<thead>
<tr>
<th></th>
<th>SuperKEKB LER/HER</th>
<th>KEKB LER/HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$(GeV)</td>
<td>4.0/7.0</td>
<td>3.5/8.0</td>
</tr>
<tr>
<td>$\epsilon_x$(nm)</td>
<td>3.2/4.6</td>
<td>18/24</td>
</tr>
<tr>
<td>$\beta^*_y$ at IP(mm)</td>
<td>0.27/0.30</td>
<td>5.9/5.9</td>
</tr>
<tr>
<td>$\beta_x$ at IP(mm)</td>
<td>32/25</td>
<td>120/120</td>
</tr>
<tr>
<td>Half crossing angle(mrad)</td>
<td>41.5</td>
<td>11</td>
</tr>
<tr>
<td>$I$(A)</td>
<td>3.6/2.6</td>
<td>1.6/1.2</td>
</tr>
<tr>
<td>Lifetime</td>
<td>$\sim 10\text{min}$</td>
<td>130min/200min</td>
</tr>
<tr>
<td>$L$(cm$^{-2}$s$^{-1}$)</td>
<td>$80 \times 10^{34}$</td>
<td>$2.1 \times 10^{34}$</td>
</tr>
</tbody>
</table>
nano-beam & final focus

luminosity:  

\[ L = \frac{\gamma \pm }{2er_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{\pm} \xi_y \pm}{\beta_y^*} \right) \left( \frac{R_L}{R_{\xi y}} \right) \]

\( \beta_y^* \) function at the IP

“hourglass” requirement:

KEKB:  
\[ \beta_y^* \geq \sigma_z \simeq 6 \text{ mm} \]

SuperKEKB:  
\[ \beta_y^* \geq d = \frac{\sigma_x^*}{\phi} \simeq 300 \text{ \( \mu \)m} \]

\( \beta_y^* \) squeezed by a factor 20!
Insertion of QCS magnets
Continuous injection

The Japanese are very efficient in injecting large crowds at rush hours into fast, frequent and precisely timed trains.
Continuous injection

The Injector pushes particles into 4 rings simultaneously at 50 Hz, topping off the 1576 HER and LER bunches

$\Rightarrow$ HER, LER currents: constant at $< 1 \%$ level
SuperKEKB, past and present

Phase 1 (2016)
single beam commissioning

Phase 2 (2018)
pilot run (500 pb\(^{-1}\)) with collisions,
Belle II: without vertex detector

Phase 3 (2019 \ldots)
physics run (6.5 fb\(^{-1}\)), squeezing \(\beta_y^*\)
Belle II: complete detector

<table>
<thead>
<tr>
<th>parameter</th>
<th>achieved</th>
<th>design</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_{HER,max}) [A]</td>
<td>0.940</td>
<td>3.6</td>
</tr>
<tr>
<td>(I_{LER,max}) [A]</td>
<td>0.880</td>
<td>2.6</td>
</tr>
<tr>
<td>(\beta_y^*) [mm]</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>#bunches</td>
<td>1576</td>
<td>2364</td>
</tr>
<tr>
<td>(L_{peak}) [cm(^{-2}) s(^{-1})]</td>
<td>(6.1 \times 10^{33})</td>
<td>(8 \times 10^{35})</td>
</tr>
<tr>
<td>(L_{max}) (det.off)</td>
<td>(12 \times 10^{33})</td>
<td></td>
</tr>
</tbody>
</table>

progressively squeezing \(\beta_y^*\)
fighting beam blow-up, QCS quenches,
backgrounds in Belle II
beam backgrounds

e^{+}\text{e}^{-} \text{ colliders are “clean”, but... at high luminosity, beam-induced backgrounds become a challenge}

at the highest luminosities, QED backgrounds will dominate:
\[ e^{+}\text{e}^{-} \rightarrow e^{+}\text{e}^{-}\gamma \]
\[ e^{+}\text{e}^{-} \rightarrow e^{+}\text{e}^{-}e^{+}\text{e}^{-} \]

at present, single beam backgrounds are predominant, higher in LER:
- beam-gas (residual gas in beam pipe)
- Touschek (intra-bunch scattering)
- injection-induced
- “dust events”, occasional large losses
CDC HV trips with large bkgd
beam abort protection against radiation spikes
simulations & collimator studies
aggressive plan for monthly increase in peak luminosity: MD alternating with physics continue with $\beta_y^*$ squeeze (11 months), then increase beam currents design peak lumi in 2025…!

rough rule of thumb: $1 \text{ab}^{-1}(\text{Belle II}) \simeq 1 \text{fb}^{-1}(\text{LHCb})$

Integrated luminosity approximate targets:
1 ab$^{-1}$ (= Belle data sample) in 2021
5 ab$^{-1}$ in 2022
50 ab$^{-1}$ in 2027
Belle II assets

Observables & analysis methods

Belle II detector performance & first results from Phase 3
Time-dependent CP asymmetry

Y(4S) decays into a coherent, entangled, anti-symmetric B\Bbar state

B-flavor tagging efficiency and $\Delta t$ resolution function are obtained from data
(measurement of mixing, with exclusively reconstructed self-tagging B states)
Y(4S) decays into a coherent, entangled, anti-symmetric BB state

B-flavor tagging efficiency and $\Delta t$ resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging B states)
inclusive B-flavour tagging

Multi-variate analysis tagger
many sub-taggers with many variables
exploiting correlations with B flavour

Expected total effective efficiency
\[ \sum_i e_i (1 - 2w_i)^2 \simeq 37\% \]
(compare with Belle, BaBar 30, 33%)
dilution factor due to mis-tag \( w \):
\[ A_{CP}^{obs} = (1 - 2w)A_{CP} \]
“Back-of-the-envelope” sensitivity

Sensitivity for CP asymmetries

Observed asymmetry is diluted: \( A_{\text{obs}} = D A_{\text{CP}} \)

Uncertainty on \( A_{\text{CP}} = A_{\text{obs}} / D \):

\[
\delta A_{\text{CP}} \approx \frac{1}{D \sqrt{N_{\text{obs}}}} = \frac{1}{D \sqrt{\epsilon \cdot \text{BR} \cdot N_{\text{prod}}}}
\]

Figures of merit

Number of produced events

\( N_{\text{prod}} = \int L dt \times \sigma_{bb} \times 2f_0 \)

Efficiency

\( \epsilon = \epsilon_{\text{det}} \cdot \epsilon_{\text{CP}} \cdot \epsilon_{\text{tag}} \)

Dilution factors

\( D = d_{\text{mix}} \cdot d_{\text{mistag}} \cdot d_{\text{bkgd}} \)

\( d_{\text{mix}} \simeq 0.47 \) for integrated asymm.

B factory is strong here!
Full event reconstruction

• for signals with weak signature:
  • decays with missing momentum (many neutrinos in the final state)
  • inclusive analyses

• background rejection improved fully reconstructing the “tag” B

• tag with semileptonic decays
  • PRO: higher efficiency $\epsilon_{tag} \approx 1.5\%$
  • CON: more background, B momentum unmeasured

• tag with hadronic decays
  • PRO: cleaner events, B momentum OK
  • CON: smaller efficiency $\epsilon_{tag} \approx 0.3\%$

• New algorithm developed by Belle II: “Full Event Interpretation”:
  Comput. Softw. Big Sci. 3 (2019) no. 1, 6
single-photon trigger

- only possible at a B factory!
- special single-photon trigger
- not available in Belle, only 10% of BaBar data set
- allows searches for exotics such as:
  - dark photons $A'$
    $e^+e^- \rightarrow \gamma A', A' \rightarrow \text{invisible}$
The Belle II detector

Extensive upgrade: new/upgraded detectors 30 kHz trigger & DAQ

Performance in Phase 3 studied on a 2.6 fb⁻¹ data set, see next slides
examples of particle reconstruction

\[ D^{* \pm} \rightarrow D(K^- \pi^+)\pi^\pm \]

- charmed mesons (already shown, Phase 2)
  - ready for charm physics!

- charmonium: \( J/\psi \)
  - electrons and muons on almost equal footing

\[ J/\psi \rightarrow e^+e^- \quad J/\psi \rightarrow \mu^+\mu^- \]
Particle IDentification ($\pi, K, e, \mu, \ldots$) is crucial:

- particle reconstruction
- B-flavour tagging

Contributions from sub-detectors: here an example of K efficiency&mis-ID, from TOP only and combined with CDC, ARICH

- measured on a control sample: $D^{*+} \rightarrow D^0[K^-\pi^+]\pi^+$
- compared with MC expectations
photons

- Electromagnetic calorimeter: clustering works well
- good resolution in inclusive $\pi^0, \eta$ reconstruction from photon pairs

$\pi^0 \rightarrow \gamma\gamma$

$\eta \rightarrow \gamma\gamma$
$B \rightarrow J/\psi K_S$

“golden channel” for CPV, CKM angle $\sin 2\phi_2$ ($\sin 2\beta$)

kinematics:
- two variables

$\Delta E = E_B - E_{beam}$

$M_{bc} = \sqrt{E_{beam}^2 - p_E^2}$

beam-constrained invariant mass

signal yield:
$N_{B \rightarrow J/\psi K_S} = 26.9 \pm 5.2$
$B^\pm \rightarrow DK^\pm$

- an example: observation of one of the decay modes that will be essential for the measurement of the CKM unitarity angle $\phi_3 = \gamma$
- it demonstrates the relevance of PID at high momenta to improve the signal/bkgd ratio

![Graph showing the decay process](image)

Belle II
2019 (preliminary)

$\int L \, dt = 2.62 \text{ fb}^{-1}$

Candidates per 0.015 GeV

- Data
- Total fit
- $B^+ \rightarrow D\pi^+$ signal
- $B^+ \rightarrow DK^+$ signal
- Background

![Graph showing the decay process](image)
Searching for BSM contributions to the loops in \( b \rightarrow s\gamma \) radiative penguins will be an important part of the physics program.

- re-discovery of \( B \rightarrow K^*\gamma \) in the 2.6 fb\(^{-1}\) data sample.
Hadronic B decays

- Very important for the “full event reconstruction”

- A collection of B decays to hadrons “re-discovered” in Phase 3 data (2.6 fb⁻¹)

- $B^{+/0} \rightarrow D^{(*)}h$

- Distributions of candidates in the $(M_{bc}, \Delta E)$ variables
Semileptonic B decays

- Signals for $B \rightarrow D^{*+} \ell^- \bar{\nu}$, $D^{*+} \rightarrow D^0 \pi^+$
- Recoil mass technique: $M_{miss}^2$
- Analysis performed on small sub-samples of the available data:
  - 0.41 fb⁻¹ for $\ell = \text{electrons}$
  - 0.34 fb⁻¹ for $\ell = \text{muons}$
- Clear signals for both electrons and muons
time measurements

- VXD: 4 double-sided Si-strip layers + 1 pixel layer at 14mm from the beam

- Impact parameter resolution ≃ 14 μm, 2x better than Belle

- $\Delta t = \gamma \beta c \Delta z$, resolution is dominated by tag side

- Traditional beam-spot constrained $z$ measurement will be biased at smaller beam spots: study required

Demo exercise: $D^0$ lifetime on a small data set (0.34 fb$^{-1}$)

$\tau_{D^0} = (370 \pm 40)$ fs
time-dependent B mixing

unmixed (U) opposite-flavour tag

integrated: \[ \chi_d = \frac{N_M}{N_U + N_M} = (17.3 \pm 3.6)\% \]

WA 18.6 %

time-dependent:

\[ A(|\Delta t|) = \frac{N_U(|\Delta t|)}{N_U(|\Delta t|) + N_M(|\Delta t|)} \]

self-tagging signal: \[ B \rightarrow D^{*} \ell \nu \]

+other-side tag: opposite flavour or same flavour

mixed (M) same-flavour tag
dark sector: $Z' \rightarrow$ invisible

- search for $e^+e^- \rightarrow \mu^+\mu^-Z'$
  $Z' \rightarrow$ invisible

- $Z'$ poorly constrained at low mass, could explain the $(g - 2)_\mu$ anomaly

- recoil mass distribution compatible with backgrounds

- first physics from Belle II...
  the upper limit will improve with more data

- similar analysis completed for
  $e^+e^- \rightarrow \mu^\pm e^\mp Z'_{LFV}$
  $Z'_{LFV} \rightarrow$ invisible
Physics prospects

- Physics potential of Belle II: discussed in a series of “B2TIP” workshops (experiment + theory)
  - an executive summary: input to the European Particle Physics Strategy update (October 2018)
- general idea: complementary to LHCb, in particular for final states with photons, neutrinos, missing energy

- Physics program of Belle II:
  - CP Violation & CKM
  - Lepton universality
  - Lepton flavour violation
  - Dark sector
  - Hadron spectroscopy
<table>
<thead>
<tr>
<th>Process</th>
<th>Observable</th>
<th>Expected precision</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to \eta' K_s$</td>
<td>$\sigma(S_{CP})$</td>
<td>0.03 (0.015)</td>
<td>Similar precision for each, $K$ and $K^*$ final state</td>
</tr>
<tr>
<td>$B \to K(*)\nu\nu$</td>
<td>$\sigma(Br)/Br$</td>
<td>25% (10%)</td>
<td></td>
</tr>
<tr>
<td>$B \to X_{s+d}\gamma$</td>
<td>$\sigma(A_{CP})$</td>
<td>0.015 (0.005)</td>
<td></td>
</tr>
<tr>
<td>$B \to X_{d}\gamma$</td>
<td>$\sigma(A_{CP})$</td>
<td>0.14 (0.05)</td>
<td></td>
</tr>
<tr>
<td>$B \to K^*0\gamma$</td>
<td>$\sigma(S_{CP})$</td>
<td>0.09(0.03)</td>
<td></td>
</tr>
<tr>
<td>$B \to \rho\gamma$</td>
<td>$\sigma(S_{CP})$</td>
<td>0.19(0.06)</td>
<td></td>
</tr>
<tr>
<td>$B \to X_s\ell^+\ell^-$</td>
<td>$\sigma(R_{X_s})/R_{X_s}$</td>
<td>9%-12% (3%-4%)</td>
<td></td>
</tr>
<tr>
<td>$B \to X_s\gamma$</td>
<td>$\sigma(Br)/Br$</td>
<td>4% (3%)</td>
<td></td>
</tr>
<tr>
<td>$B \to D(*)\nu\nu$</td>
<td>$\sigma(R_{D(<em>)})/R_{D(</em>)}$</td>
<td>3%-6% (2%-3%)</td>
<td></td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
<td>limit on $Br$</td>
<td>$10^{-9}$ (50 ab$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>$\tau \to \mu\rho^0$</td>
<td>limit on $Br$</td>
<td>$2 \cdot 10^{-10}$ (50 ab$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>$A' \to invisible$</td>
<td>limit on $\epsilon$ (\gamma/A' mixing)</td>
<td>$3 \cdot 10^{-4}$ (20 fb$^{-1}$)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Expected precision for Belle II measurements of selected observables [5]. Unless stated otherwise the precision is given for integrated luminosity of 5 ab$^{-1}$ (50 ab$^{-1}$).
an optimistic roadmap

- $B \to \eta'K_s$ new CP
- Confirm $B \to D^*\tau\nu$ new physics
- Resolve $|V_{ub}|$ puzzle
- $e^+e^- \to A'(\chi\chi)\gamma$
- $e^+e^- \to \pi\pi(\gamma)$ precision for $(g-2)_\mu$
- $B \to \mu\nu$ discovery
- $W_R$ in $B \to \rho\gamma$
- $B \to K\nu\nu$ SM discovery
- $B \to K\text{ee} \text{ LFUV}$ new physics

All the details are in
“The Belle II Physics Book”
E. Kou, P. Urquijo et al.

https://inspirehep.net/record/1692393/
Summary

• B factories have unique features, that make them ideal tools to investigate flavour physics.

• Luminosity and beam backgrounds are the main challenges for a successful participation in the quest for BSM physics.

• SuperKEKB is progressing with an aggressive plan to step up from the KEKB peak luminosity by a factor 40.

• Belle II has been taking the first physics data with the complete detector, with very good performance. Our analysis tools are getting ready to deal with physics.

• The road ahead will certainly be bumpy and not easy, with strong competition from LHCb, but the journey will be exciting and rewarding: we may even glimpse at BSM physics, if it really is there!
back-up slides
25 SC magnets in QCS-L

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
16 SC correctors: a1, b1, a2, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
1 compensation solenoid

30 SC magnets in QCS-R

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid
Collision Scheme

KEKB head-on (crab crossing)

$\sigma_x^* \sim 100-150 \, \mu m$
$\sigma_z \sim 6-7 \, mm$

Nano-Beam Scheme SuperKEKB

$\sigma_z \sim 5-6 \, mm$
$\sigma_x^* \sim 10-12 \, \mu m$

$d = \frac{\sigma_x^*}{\phi}$

$2\phi = 83 \, mrad$

$\phi_{\text{pwinski}} \sim 20$

interaction region = bunch length

interaction region $<<$ bunch length

Hourglass requirement

$\beta_y^* \geq \sigma_z \sim 6 \, mm$

$\beta_y^* \geq \frac{\sigma_x^*}{\phi} \sim 300 \, \mu m$

Vertical beta function at IP can be squeezed to $\sim 300\mu m$. Need small horizontal beam size at IP.

$\rightarrow$ low emittance, small horizontal beta function at IP.

No crab waist scheme has been assumed at SuperKEKB
Some definitions

- **Key parameters**
  - $\beta_y^*$, chromatic effects
  - Piwinski angle $\frac{\sigma_z \theta_c}{\sigma_x^*}$: bunch length/overlap area
  - Hour glass effect $\frac{\sigma_x^*}{\theta_c \beta_y^*}$: ratio of overlap area and $\beta_y^*$

\[ \theta_c : \text{half crossing angle} \]
Luminosity projections

- Peak Luminosity in $10^{24}$ cm$^{-2}$s$^{-1}$
- Integrated Luminosity in $10^{3}$ ab$^{-1}$

- $\beta_y^*$ squeezing
- $\beta_y^*$ [mm]

- 2020-2023 timeline with projected luminosity milestones:
  - 1E35
  - 2E35
  - 1 ab$^{-1}$
tracking performance: as expected

- impact parameter $d_0$
distribution for 2-track events
- alignment and calibration are working well
- VXD resolution in impact parameter $\delta d_0 \simeq 14 \ \mu m$
A new implementation of the “full event reconstruction” concept at a B-factory

the “tag side” B is exclusively reconstructed in many hadronic and semileptonic final states

FEI = Full Event Interpretation: using a machine learning technique (BDT = Boosted Decision Trees) and a large number of decay modes

Example shown here: on a data subsample of 0.41 fb$^{-1}$

Example shown here: on a data subsample of 0.41 fb$^{-1}$
Full Event Interpretation

- More decay modes included in full reconstruction of tag side
- Fast Boosted Decision Tree (BDT) method
Belle II physics program

- Precision CKM
- CPV in $b \rightarrow s$ penguin decays
- Tauonic decays
- FCNC
- Charm decays
- LFV tau decays
- Hadron spectroscopy
- Dark sector
$B \rightarrow \eta' K_S$ projection

- BSM physics in penguin loops
- Measurement of $\sin 2\phi_1^{\text{eff}} (B \rightarrow \eta' K_S)$
- Projection to $50 \text{ ab}^{-1}$ Belle II data set
tests of LFU in semileptonic decays

\[ B \rightarrow D^{(*)} \tau \nu \]

Standard Model prediction theoretically clean
Yield and \( q^2 \) distribution from a form factor

Simplest case of new Physics from Charged Higgs

Measure a ratio \( R = \frac{B( B \rightarrow D^{(*)} \tau \nu )}{B( B \rightarrow D^{(*)} \ell \nu )} \)
Experimentally hard: signature is not a peak on a smooth background!

Data driven methods to control the backgrounds
(most dangerous \( D^{**} \) background)
test of LFU in leptonic decays

**LFU with leptonic decays**

Very clean theoretically, hard experimentally
SM is helicity suppressed
Sensitive to NP contribution (charged Higgs)

\[
B(B \rightarrow l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B
\]

\[
B(B \rightarrow l\nu) = B(B \rightarrow l\nu)_{SM} \times r_H
\]

\[
r_H = (1 - \tan^2 \beta \frac{m_B^2}{m_H^2})^2 \quad \text{in 2HDM type II}
\]

<table>
<thead>
<tr>
<th>Mode</th>
<th>SM BR</th>
<th>Current meas.</th>
<th>Belle II 5 ab-1</th>
<th>Belle II 50 ab-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau\nu)</td>
<td>(10^{-4})</td>
<td>20% uncertainty</td>
<td>15%</td>
<td>6%</td>
</tr>
<tr>
<td>(\mu\nu)</td>
<td>(10^{-6})</td>
<td>40% uncertainty*</td>
<td>20%</td>
<td>7%</td>
</tr>
<tr>
<td>(e\nu)</td>
<td>(10^{-11})</td>
<td>Beyond reach</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* PRL 121 031801 2.4\(\sigma\) excess [2.9,10.7]\(\times10^{-7}\) at 90\% C.L.

Belle II can test LFU also with

\[
R^{\tau\mu} = \frac{\Gamma(B \rightarrow \mu\nu)}{\Gamma(B \rightarrow \tau\nu)}
\]

\[
R^{\tau\nu} = \frac{\Gamma(B \rightarrow e\nu)}{\Gamma(B \rightarrow \tau\nu)}
\]

Belle II Full simulation with expected background conditions with hadronic tags only

Extrapolation of untagged Belle analysis
$B \rightarrow K^{(*)} \nu \bar{\nu}$

Suppressed in the SM: BRs $10^{-5} - 10^{-6}$ may be enhanced by NP

Constraints on new physics contributions to Wilson coefficients $C_L, C_R$

90% CL excluded by Belle and Babar

68% CL allowed by Belle II at 50 ab$^{-1}$

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle II 5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^+ \nu \bar{\nu})$</td>
<td>30%</td>
<td>11%</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow K^{*0} \nu \bar{\nu})$</td>
<td>26%</td>
<td>9.6%</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$</td>
<td>25%</td>
<td>9.3%</td>
</tr>
</tbody>
</table>
 Tau LFV decays: projections

- expect an improvement by more than an order of magnitude in tau LFV decay limits by Belle II