Recent results from Belle II

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on behalf of Belle II Collaboration

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Belle II physics program

Study of rare decays of B, D and $\tau$

**GOAL**
uncover New Physics beyond the Standard Model

Belle II will pursue NP in many ways:

* improving precision of CKM matrix elements and phases
* testing violations of lepton conservation and universality
* probing the existence of dark-sector particles
* and many more …
SuperKEKB
new Intensity Frontier machine

\[ \text{cc}, \text{ss}, \bar{u}u, \bar{d}d, \bar{l}l, \tau^+\tau^- \rightarrow e^+e^- \rightarrow Y(nS) \rightarrow B^(*)\bar{B}^(*) \]

- **SuperKEKB + Belle II detector** ≡ 2nd generation super B-factory
- **substantial upgrade** of the B factory facility located at KEK (Tsukuba, Japan)
- **SuperKEKB**: asymmetric \(e^+e^-\) collider operating **mainly** at \(m_{Y(4S)} = 10.58\text{ GeV}\)
- high luminosity achieved by
  - squeeze beams at IP (vertical ~60 nm)
  - increase beam currents + make smaller \(\beta^*\)
  - larger crossing angle (22 → 83 mrad)

TARGETS

- peak luminosity: \(6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\) (30x KEKB)
- integrate up to 50 ab\(^{-1}\) (50x Belle) in a decade!
**SuperKEKB**

**new Intensity Frontier machine**

- SuperKEKB + Belle II detector ≡ 2nd generation super B-factory located at KEK (Tsukuba, Japan)
- asymmetric e⁺e⁻ collider operating **mainly** at 10.58 GeV: Υ(4S)

**Current status**

- complete detector started taking data in spring 2019
- total **integrated luminosity** collected before summer 2022: **424 fb⁻¹** (good runs)
  - at the Υ(4S) resonance: **363 fb⁻¹**
  - similar DATA as BaBar, ~0.5 Belle DATA
- new **World Record of peak luminosity**: 4.7 x 10^{34} cm⁻² s⁻¹ ( > 2 x KEKB record)
- Long Shutdown 1 (LS1) from summer 2022 for 15 months
  - improvements of machine and detector (beam pipe, Pixel Vertex Detector, Time-Of-Propagation PMT)

**Luminosity projection**

- We are here

**Belle II luminosity page**
**Belle II detector**

**multipurpose ~ 4π magnetic spectrometer**

**Silicon vertex detectors**
- 2 layers DEPFET (pixel)
- 4 outer layers DSSD
  ✔ vertexing resolution ~ 15 μm

**Tracking detector**
- central drift chamber (He + C₂H₆)
- small cells, long lever arm, fast electronic
  ✔ spatial resolution: 100 μm
  ✔ p_T resolution ~ 0.4%/p_T
  ✔ dE/dx resolution: 5%

**Electromagnetic Calorimeter**
- CsI(Tl) + waveform sampling (barrel + end-caps)
  ✔ energy resolution ~1.6-4%
  ✔ lepton ID efficiency 90% at fakes: 0.5% for e and 7% for μ

**Particle ID detectors**
- Time-of-Propagation counter (barrel)
- Aerogel RICH (forward end-cap)
  ✔ hadron ID efficiency ~90% at 10% fakes

- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLS fiber + MPPC (end-caps & inner 2 barrel layers)
  ✔ μ ID efficiency: 90 %

**Magnetic field**
- 1.5 T superconducting magnet

**Key factors:**
- known initial state + nearly hermetic detector with excellent PID
  ► reconstruct fully-inclusive final states
  ► broadly search for particles with no direct signature
- reconstruct neutral particles (γ, π⁰, Kᵢ, K_L) nearly as well as charged particles

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**Particles**
- electrons (7 GeV)
- positrons (4 GeV)
Experimental techniques
@ B-factories

B-TAGGING

- exclusive production of $B\bar{B}$ pairs at B-factories
- kinematical constraints from beam energy in CM of $\Upsilon(4S)$
- in channels with missing energy (i.e. multi $\nu$ final state)
  - reconstruct partner of signal $B$ meson: $B_{\text{TAG}}$
    - using well measured channels
  - $B_{\text{TAG}}$ kinematics, flavor, charge

Different tagging approaches:

- **Inclusive:**
  - $B \rightarrow $ anything (hadrons + photons)
  - high $\epsilon \approx O(10\%)$ but lower purity

- **Semileptonic:**
  - $B \rightarrow \sum$ of $B \rightarrow D^{(*)} l \nu$
  - $BF \sim 20\%$; $\epsilon \approx O(1\%)$ with optimal purity

- **Hadronic:**
  - $B \rightarrow \sum$ of exclusive hadron modes
  - low $\epsilon \approx O(0.1\%)$ but high purity

Full Event Interpretation (FEI)

- improved B-tagging algorithm based on Boosted Decision Trees
- hierarchical approach to reconstruct $O(10^4)$ decay chains
  - $\epsilon_{\text{SL}} \approx 2\%$
  - $\epsilon_{\text{had}} \approx 0.5\%$

Dark sector

direct searches for light non-SM physics
Dark Sector

portals between DM and SM

→ identify particles and properties of Dark Matter through production at colliders

→ constraints on weakly coupled DM

▸ light dark mediator X as portal

Belle II has unique capability to search for dark matter and mediators at MeV-GeV scale

✔ dedicated low-multiplicity triggers

✔ e.g. single photon; single/two/three track(s); $E_{\text{ECL}} > 1\text{GeV}$

✔ hermetic detector + clean events

✔ high intensity collisions at ~10.6 GeV

Vector
Dark Photon, Z'

Scalar
Dark Higgs, Dark Scalar

Neutrino
Sterile neutrinos

X

Pseudoscalar
Axion-Like Particles

Standard Model
Motivation:
- U(1)’ vector portal extension of SM
  - Dark photon A’: coupled to SM photon via kinetic mixing parameter $\epsilon$
    - mass generated via spontaneous symmetry breaking
  - Dark Higgs h’: couples with $\alpha_D$ to A’

Signature:
- $M_{h'} < M_A' \rightarrow h'$ is long-lived (invisible)
  - $\Rightarrow$ 2 charged tracks + missing energy
- A’: $M_{\mu\mu}$ and h’: $M_{\text{recoil}}$

Selection:
- two reconstructed muons, $p_{T\mu\mu} > 0.1$ GeV/c
- recoil momentum in ECL barrel, no nearby photon
- cut on helicity angle of muon

Strategy:
- scan for excess in 2D plane of $M_{\text{recoil}}$ vs. $M_{\mu\mu}$
- ~9000 rotated elliptical mass windows to test signal hypotheses
Dark sector
Dark Higgsstrahlung: $e^+e^- \rightarrow A' h'$

Results:
- no significant excess above bkg was observed
  - 90% CL upper limits on $\sigma$ and $\varepsilon^2 \alpha_D$
- world leading limit: $1.65 < M_{A'} < 10.51 \text{ GeV/c}^2$

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Dark sector

**Z' → invisible**

**Motivation:**
- $L_\mu - L_\tau$ model can provide solution for $R(K^*)$ and $(g-2)_\mu$
- $Z'$ – new massive gauge boson coupled only to $\mu$ and $\tau$

**Searched signatures:**
- $\mu^+\mu^-$ final state with
  - $Z'$ – invisible (neutrinos/dark matter)
  - final states with missing energy $\Rightarrow M_{\text{recoil}}$

**Bkg:**
- $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$, $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$, $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$

**Selection:**
- two reconstructed muons, $p_{T\mu\mu} > 0.4$ GeV/c
- recoil momentum in ECL barrel, no nearby photon
- neural network trained to optimize Punzi FOM

**Strategy:**
- template fit in 2D plane of $\theta_{\text{recoil}}$ vs. $M_{\text{recoil}}^2$
Results:

- no excess found
  - 90% CL upper limits on $\sigma$ and coupling
- excluded fully invisible $Z'$ as explanation for $(g-2)_\mu$ in range $0.8 < M_{Z'} < 5.0$ GeV/c$^2$
Motivation:
- probe three different models: $Z'$, $L_\mu$, $L_\tau$, leptophilic dark scalar $S$, ALP

Signature:
- $\tau\tau$ resonance in $\mu^+\mu^-\tau^+\tau^-$ final states

Selection:
- 4 tracks: $2\mu + 2\ e/\mu/\pi$ (1-prong $\tau$ decay)
- $M(4\text{-track}) < 9.5 \text{ GeV/c}^2$

Bkg:
- $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ (1x3 prong)
- $e^+e^- \rightarrow q\bar{q}$ ($q=u,d,s,c$)
- $e^+e^- \rightarrow l^+l^-l^+l^-,\mu^+\mu^-\tau^+\tau^-,e^+e^-X_{\text{hadronic}}$

Bkg suppression:
- 8 neural networks trained for different ranges in $M_{\text{recoil}}(\mu\mu)$

Strategy:
- extract signal from fit to $M_{\text{recoil}}$ above floating bkg
Results:

- no significant excess above bkg has been found
  - 90% CL upper limits on $\sigma$ and couplings
- first constraints for S in range $M_S > 6.5$ GeV/c$^2$
- first direct constraints for ALP $\rightarrow \tau \tau$
Lepton Flavour Universality

$g_e = g_\mu = g_\tau$? accidental symmetry of SM?
LFU

experimental puzzles

Several measurements show tension with SM

\[ R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu)}{\mathcal{B}(B \to D^{(*)} \ell \nu)}, \ell = e, \mu \quad \sim 3.3 \sigma \]

\[ R(K) = \frac{\mathcal{B}(B \to K \mu^+ \mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \quad \sim 3.1 \sigma \]

Tension in \( B \to K^* \mu^+ \mu^- \) angular observables

- global discrepancy unlikely to be fluctuation
- exploit more complementary observables
\[
R(X_{\mu/e}) = \frac{\mathcal{B}(B \to X_{\mu/e})}{\mathcal{B}(B \to X_{\mu/e})}
\]

Challenges:
- larger background from less constrained X
- difficult MC modeling of the X = D, D*, D**, non resonant hadronic decays ('gap')
  - probe inclusive B → X l ν modeling in data-driven way

Selection:
- hadronic B-tagging with FEI (ε_{had} ≈ 0.1%)
- \(p_{t}^* > 1.3 \text{ GeV/c} \Rightarrow \) reject most of B → X τ ν
  - suppress fake and secondary leptons
- optimized lepton ID requirements
$R(X_{\mu/e})$

test of LFU via inclusive B decays

Strategy:
- binned likelihood template fit with 3 components:
  - signal, continuum ($c\bar{c}$, $s\bar{s}$, $u\bar{u}$, $d\bar{d}$), “fake leptons + secondaries”
  - $e$ and $\mu$ templates are fitted simultaneously in 10 $p_t^*$ bins

Results:
- $R(X_{\mu/e}) = 1.031 \pm 0.010 \pm 0.020$ for $p_t^* > 1.3$ GeV/c
- SM: $R(X_{\mu/e}) = 1.006 \pm 0.001$ » arXiv:2207.03432
- agrees with SM expectation within 1.4σ
- most precise single test of $e - \mu$ FU in semileptonic B decays
- precursor to measurement of $R(X_{\tau/l})$
- dominated systematics: lepton ID efficiency (~2%)
Motivation:
- test on control mode in preparation to first Belle II R(K) measurement
- demonstrate capability of detector performance on ‘SM candle’ process: \( B \rightarrow J/\psi(\ell\ell) K \)

Selection:
- pure selection: simple mass cuts on \( J/\psi, K_s \), and particle ID criteria on leptons and charged K

Strategy:
- extract branching fractions and \( r(K)_{J/\psi} \) from 2D unbinned fit to \( \Delta E \) and \( M_{bc} \) distributions

Results:
- precision limited by statistics
- in agreements with SM and other measurements (Belle, LHCb)
- lepton ID uncertainties decreased with respect to Belle by factor \(~2\)

\[
\Delta E = E_B^* - \sqrt{s}/2
\]

\[
m_{bc} = \sqrt{s/4 - \vec{p}_B^*}^2
\]

<table>
<thead>
<tr>
<th></th>
<th>Belle II (2022)</th>
<th>Belle (2021)</th>
<th>LHCb (2022)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r(K^+)_{J/\psi} )</td>
<td>1.009±0.022±0.008</td>
<td>0.994±0.011±0.010</td>
<td>0.981±0.020</td>
</tr>
<tr>
<td>( r(K_s)_{J/\psi} )</td>
<td>1.042±0.042±0.008</td>
<td>0.993±0.015±0.010</td>
<td>0.977±0.028</td>
</tr>
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</table>

\[ * \text{arXiv:2207.11275} \]
Belle II provide most precise experimental information to resolve the R(D^(0)) anomalies
Charged Lepton Flavour Violation

powerful tool to search for physics beyond SM

SM case with neutrino oscillation
BR ~ $10^{-54}$

NP case
BR ~ $10^{-10}$ - $10^{-7}$
τ physics @ Belle II

**Overview**

\[ e^+e^- \rightarrow \gamma(4S) \] = 1.05 nb
\[ e^+e^- \rightarrow \tau^+\tau^- \] = 0.92 nb

**τ features:**

- due to large mass
  - only lepton that can decay into hadrons, thus providing a clean laboratory to study QCD effects in the 1 GeV energy region
  - BSM contributions coupled more strongly to the third generation
  - direct observation of forbidden decays violating flavour conservation and/or universality ⇒ unambiguous signature of New Physics

**Challenges:**

- presence of neutrinos requires good reconstruction of missing energy, hermetic detector, minimal combinatorial and machine backgrounds
- low multiplicity channels require appropriate triggers
- lifetime measurements require excellent vertexing capabilities
### Current status
observed limits and projections

- 52 benchmark LFV $\tau$ decays have been searched
- modes can be classified as neutrinoless 2-body/3-body decays
- critical to probe all possible LFV modes of $\tau$
  \[ \Rightarrow \text{any excess in single channel not provide sufficient information on underlying mechanism} \]

<table>
<thead>
<tr>
<th>$\ell\gamma$</th>
<th>$IP^0$</th>
<th>$IS^0$</th>
<th>$IV^0$</th>
<th>III</th>
<th>lh$\bar{h}$</th>
<th>BNV</th>
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<tr>
<td>10$^{-3}$</td>
<td>10$^{-7}$</td>
<td>10$^{-6}$</td>
<td>10$^{-5}$</td>
<td>10$^{-9}$</td>
<td>10$^{-7}$</td>
<td>10$^{-5}$</td>
</tr>
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</table>

- Belle II detector sensitivity close to NP scenarios limits
  \[ \Rightarrow \text{expected to improve the results of previous B-factories by a factor } \sim 100 \text{ with statistics only} \]
- there are additional LFV search channels with extra non-SM particles
**LFV with light ALP production**

\( \tau \rightarrow l + \alpha \) (invisible)

**Motivation:**
- NP models: **light** Axion-Like Particle
- best UL on BF(\(\tau \rightarrow l \alpha\))/BF(\(\tau \rightarrow l \nu \nu\)) from ARGUS (476 pb\(^{-1}\), 1995)
- Belle II can set more stringent limits

**Reconstruction:**
- split event in two hemispheres across thrust axis: \( \vec{T} = \max(\sum_i \frac{\vec{p}_i \cdot \vec{T}}{|p_i|}) \)
- require 4 tracks:
  - **signal with 1 lepton track**
  - **tag with \(\tau \rightarrow 3\pi\nu + \) vertex**
  - Veto neutrals (\(\pi^0, \gamma\)) to suppress hadronic bkg

**Bkg:**
- irreducible: \(\tau \rightarrow l \nu \nu\)
- reducible: \(q\bar{q}, l^+l^-, l^+l^+l^-, l^+h+h^-\), correctly tagged \(\tau^+\tau^-\) with misidentified signal (suppressed by PID cut)

**Bkg suppression:**
- unknown mass of \(\alpha \rightarrow \) optimise selection using \(\tau \rightarrow l \nu \nu\)
- use ‘safe’ variables (**thrust**, \(M(3\pi)\), \(E_{cm}(3\pi)\)) which cannot distinguish between \(\tau \rightarrow l \nu \nu\) and \(\tau \rightarrow l \alpha\)
**LFV with light ALP production**

**Signature:**
- search for excess above SM spectrum after bkg suppression
- in two-body decay we have monochromatic peak in $\tau$ rest frame
- undetected $\nu$ in both $\tau$ ⇒ use approximated pseudo-rest frame

**Strategy:**
- extract signal using template fit to $x_\ell \equiv E_\ell/(m_\tau/2)$
- estimate $R = B(\tau \rightarrow \ell\alpha)/B(\tau \rightarrow \ell\nu\bar{\nu})$
- signal and SM systematics partially cancel out in ratio ⇒ different kinematic regime

\[ \hat{p}_\tau \approx -\frac{\vec{p}_{\text{tag}}}{|\vec{p}_{\text{tag}}|} \, , \quad E_\tau \approx \sqrt{s}/2 \]
LFV with light ALP production
\( \tau \to l + \alpha \) (invisible)

Results:
- we observe no signal and set 95% confidence level ULs on
  \[ R = \frac{\mathcal{B}(\tau \to \ell\alpha)}{\mathcal{B}(\tau \to \ell\nu\bar{\nu})} \]
- most stringent measurements in these channels to date

**ICHEP 2022**

\(62.8 \text{ fb}^{-1}\)
New results in a wide range of $B$, $\tau$ decays and dark matter searches on limited data sample show promising capabilities of next-generation $B$-factory

Until summer 2022 Belle II collected 424 fb$^{-1}$ ⇒ soon more new and updated results on the full sample

SnowMass reports for Belle II provide a lot of details on the machine, detector, analysis tools, and planned physics analyses

Belle II will contribute substantially to flavor physics throughout the next decade
BACKUP
**Belle II detector**

lepton ID performance

On-resonance: 190 fb\(^{-1}\)
Off-resonance: 18 fb\(^{-1}\)
(2019 – mid 2021)

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**eID > 0.9 selection.**

likelihood-based ID; mid\_ID rate is multiplied \(x10\) for illustration purposes

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**μID > 0.9 selection.**

likelihood-based ID; mid\_ID rate is multiplied \(x3\) for illustration purposes
Belle II detector

SVD performance + trigger

**TRIGGER**

- L1 Trigger: CDC+ECL+TOP+KLM
- Max. L1 DAQ: 30 kHz
- DAQ: pipeline readout

+ hit-time resolution ~ 3 ns ⇒ suppress beam-related background
The masses of mediator and of the DM candidates lead to different type of searches

arXiv: 1707.04591
Luminosity

2022

Belle II Online luminosity
Exp: 7-26 - All runs

Integrated luminosity
Recorded Weekly
\[ \int \mathcal{L}_{\text{Recorded}} \, dt = 427.79\,\text{fb}^{-1} \]
\[ L = \frac{\gamma_+}{2er_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} I_{\pm,\xi_y,\pm} \frac{R_L}{R_{\xi_y}} \beta_{y_\pm} \right) \times 2 \times 1 \times \frac{1}{20} \times 40 \text{ luminosity} \]
\( \tau \rightarrow l + \alpha \) (invisible)

UL on ratio