Belle II status and prospects for studies of charged currents

Sourav Dey
on behalf of the Belle II Collaboration

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• Exchange of $W$ bosons
• Verified mediators of neutrino absorption and emission
• Unambiguous signals of $W$ bosons first seen in UA1 and UA2 experiments at Super Proton Synchrotron in CERN (1983)
• $b \to c, d \to u$ etc. Change of flavor
• Belle II prospects (covered in this talk):
  • $b \to c$ anomalies
  • Light lepton Universality tests
  • $|V_{cb}|$ measurement
SuperKEKB

- 40 times larger luminosity than previous generation KEKB
- Using nano-beam scheme with a tiny beam spot:
  - 60 nm x 10 \(\mu\)m x few 100 \(\mu\)m in y, x, z
  - A few hundred atomic layers in y
• SuperKEKB collides electron and positrons

• $\sqrt{s} = 10.58$ GeV: mass of $\Upsilon(4S)$

• $B\bar{B}$ pair production with a boost of the center-of-mass system: asymmetric collider

• $B$ mesons can decay in a number of ways: prospect for studying a vast region of particle physics (Precision studies of $B$, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)
The Belle II Detector

- SuperKEKB collides electron and positrons
- $\sqrt{s} = 10.58$ GeV : mass of $\Upsilon(4S)$
- $B\bar{B}$ pair production with a boost of the center-of-mass system: asymmetric collider
- $B$ mesons can decay in a number of ways: prospect for studying a vast region of particle physics (Precision studies of $B$, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)
Luminosity

- Design integrated luminosity 50 ab$^{-1}$
- Regular data-taking since April 2019
- Current integrated luminosity 424 fb$^{-1}$
- Peak luminosity recorded: $4.7 \times 10^{34}$ cm$^{-1}$s$^{-1}$
- At present, we have a long shutdown for accelerator and detector upgrades, will resume data taking in late 2023
Light-Lepton Universality Test: $R(X_{e/\mu})$ Measurement
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- Excellent sensitivity to potential lepton-universality-violating (LUV) physics
- Previous direct searches
  - BR ratio in a single exclusive charmed hadron decay mode [Phys. Rev. D 100, 052007 (2019)].
  - the shapes of kinematic distributions of all decays to charmed hadrons [Phys. Rev. D 104, 112011 (2021)]
- First measurement of the inclusive branching fraction ratio.
- The most precise test of $e - \mu$ universality in semi-leptonic B-meson decays to date

\[
R(X_{e/\mu}) = \frac{\mathcal{B}(\bar{B} \to Xe^-\bar{\nu}_e)}{\mathcal{B}(\bar{B} \to Xm^-\bar{\nu}_\mu)}
\]

This analysis uses:
- Belle II collision data from 2019 and 2021 at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV,
- Integrated luminosity $189 \text{ fb}^{-1}$, ~ $198 \times 10^6$ BB pairs.
- Additional $18 \text{ fb}^{-1}$ off-resonance collision data below the $\Upsilon(4S)$ resonance, for backgrounds from continuum processes $e^+e^- \to q\bar{q}$, where $q = u, d, s, c$ quarks

arXiv:2301.08266
Light-Lepton Universality Test: $R(X_{e/\mu})$ Measurement

- $X$ the generic hadronic final state of the semi-leptonic decay of any flavor of B meson originating from $b \to c\ell\nu$ or $b \to u\ell\nu$ quark transitions

- Tag-side B mesons decay in fully hadronic modes (FEI)

- Lepton charge requirement:
  - corresponds to the charge of a primary lepton from the semi-leptonic decay of a signal B meson
  - that signal B meson has the opposite flavor to the tag B candidate

Inclusive signal modes

- MVA based approach
- reconstructs more than 100 explicit decay channels

https://doi.org/10.1007/s41781-019-0021-8
Simultaneous binned template fits to the $p_e^B$ and $p_\mu^B$ spectra

($p_e^B =$ momentum of $e$ in $B$ rest frame etc.)

Light-Lepton Universality Test : $R(X_{e/\mu})$ Measurement

$R(X_{e/\mu}) = 1.033 \pm 0.010{\text{(stat)}} \pm 0.019{\text{(syst)}}$

$R(X_{e/\mu} | p_l^B > 1.3 \text{ GeV/c}) = 1.031 \pm 0.010{\text{(stat)}} \pm 0.019{\text{(syst)}}$

Consistent with Standard Model $R(X_{e/\mu})_{SM}$ \cite[1] by 1.2$\sigma$ and the exclusive Belle $R(D^{*}_{e/\mu})$ \cite[2,3] measurement

Light-Lepton Universality Test: Angular Asymmetry
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- $B^0 \rightarrow D^* l^- \nu$ channel is used and reconstructed exclusively
- First dedicated light-lepton LU test using a complete set of angular asymmetry observables
  - designed to cancel most theoretical and experimental uncertainties
  - highly sensitive to LUV
- lepton universality is tested by comparing five angular asymmetries of $e$ and $\mu$

Belle II collision data from 2019 and 2021 at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV,
- Integrated luminosity $189 \text{ fb}^{-1}$, $\sim 198 \times 10^6$ BB pairs.

This analysis uses:
Due to the spin of the final-state $D^*$, much of the properties of the V –A coupling and the spin of the virtual $W$ are encoded in angular distributions of the final-state particles.

- Fully characterized by four parameters.
Light-Lepton Universality Test: Angular Asymmetry

- Angular Observable:

\[ A_x(w) = \left( \frac{d\Gamma}{dw} \right)^{-1} \left[ \int_0^1 - \int_{-1}^0 \right] dx \frac{d^2\Gamma}{dw dx} \]

- theoretically and experimentally clean probes of LUV

\[ \Delta A_x(w) = A^\mu_x(w) - A^e_x(w) \]

- Most uncertainties cancel
  - experimental uncertainties cancel in the asymmetries \( A \)
  - hadronic uncertainties in the form factors, largely cancel in \( \Delta A \)

\[
\begin{align*}
A_{FB} : x &= \cos \theta_I \\
S_3 : x &= \cos 2\chi \\
S_5 : x &= \cos \chi \cos \theta_V \\
S_7 : x &= \sin \chi \cos \theta_V \\
S_9 : x &= \sin 2\chi
\end{align*}
\]

Three w regions

- \( D^* \) zero-recoil
- \( D^* \) maximum-recoil

\[
\begin{align*}
W_{low} &\quad W_{incl.} &\quad W_{high} \\
1.0 &\quad 1.275 &\quad 1.5
\end{align*}
\]
Light-Lepton Universality Test: Angular Asymmetry: Results

No evidence of deviation from the standard model has been observed up to P values of 0.12.

For each asymmetry $A_X$ and $w$ range, signal candidates separated into + and − categories based on the measured value of $x$.

Numbers of signal events determined with binned maximum-likelihood fit of $M_{miss}^2$.

$M_{miss}^2 \equiv \left( p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell \right)^2$

For $B \rightarrow D^{**}l\nu$
Determination of $|V_{cb}|$ using $\bar{B}_0 \to D^*+l-\bar{\nu}_l$
Determination of $|V_{cb}|$ using $\bar{B}_0 \to D^{*+} l^- \bar{\nu}_l$

- The non-perturbative physics:

$$\frac{d^4T}{dw \ d\cos \theta_l \ d\cos \theta_V \ d\chi} \propto |V_{cb}|^2 \times |F(w, \cos \theta_l, \cos \theta_V, \chi)|^2$$

- is parametrized by three form factors as a function of

$$w = \frac{p_B \cdot p_{D^*}}{m_Bm_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_Bm_{D^*}}$$

- The neutrino direction is reconstructed inclusively using the known angle $\cos \theta_{BY}$ between the $B$ and the $Y = D^* + l$ direction

$$\cos \theta_{BY} = \frac{2E_B^{CM}E_Y^{CM} - m_{Bc}^2 - m_{Yc}^2}{2 |\vec{p}_B^{CM}| \ |\vec{p}_Y^{CM}| c^2}$$

- Signal yields in bins of kinematic variables $w$, $\cos \theta_l$, $\cos \theta_V$ and $\chi$ are determined bin by bin independently by 2D fits of $\cos \theta_{BY}$ and $\Delta M = M(D^*) - M(D^0)$

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Determination of $|V_{cb}|$ using $\bar{B}_0 \to D^*+l^-\bar{\nu}_l$

- The non-perturbative physics:
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\frac{d^3\Gamma}{dw \ d\cos\theta_l \ d\cos\theta_V d\chi} \propto |V_{cb}|^2 \times |F(w, \cos\theta_l, \cos\theta_V, \chi)|^2
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\[
\cos\theta_{BY} = \frac{2E_B^{CM} E_Y^{CM} - m_B^2 c^4 - m_Y^2 c^4}{2|\vec{p}_B^{CM}||\vec{p}_Y^{CM}| c^2}
\]

- Signal yields in bins of kinematic variables $w, \cos\theta_l, \cos\theta_V$ and $\chi$ are determined bin by bin independently by 2D fits of $\cos\theta_{BY}$ and $\Delta M = M(D^*) - M(D^0)$

An example only: done for all the bins, for all the kinematic variables

Belle II

$\int \mathcal{L} dt = 189.3 \text{ fb}^{-1}$

$\bar{B}^0 \to D^* e^- \bar{\nu}_e$

$10^3$ entries/Bin
Determination of $|V_{cb}|$ using $\bar{B}_0 \rightarrow D^{*+} l^- \bar{\nu}_l$

- Bin-to-bin migration is corrected with SVD (Singular Value Decomposition) unfolding method [arXiv:hep-ph/9509307]

$\mathcal{M}_{ij} = P(\text{measured value in bin } i \mid \text{true value in bin } j)$
Determination of $|V_{cb}|$ using $\bar{B}_0 \to D^{*+} l^- \bar{\nu}_l$

- $|V_{cb}|$ value is determined from measured partial rates $\Delta \Gamma$

Boyd-Grinstein-Lebed parameterization

$$|V_{cb}|_{BGL} = (40.9 \pm 0.3_{\text{stat}} \pm 1.0_{\text{sys}} \pm 0.6_{\text{theo}}) \times 10^{-3}$$

Caprini-Lellouch-Neubert parameterization

$$|V_{cb}|_{BGL} = (40.4 \pm 0.3_{\text{stat}} \pm 1.0_{\text{sys}} \pm 0.6_{\text{theo}}) \times 10^{-3}$$

results agree well with the standard-model expectations, give no evidence for LUV

To be submitted to PRD
To sum up...

- The results shown in this presentation agree with SM
- No evidence of LUV(yet)

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