Recent Belle II results on semileptonic B decays and tests of lepton-flavor universality

Kazuki Kojima (Nagoya University)
on behalf of the Belle II Collaboration

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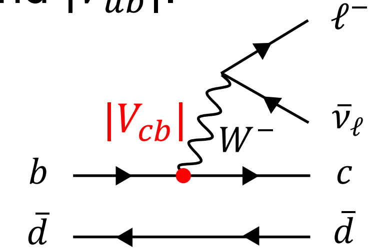
Semileptonic B Decays

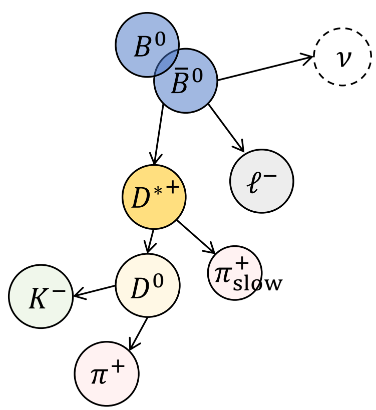
Semileptonic B decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$.

- $|V_{xb}|$ are limiting the global constraining power of unitarity triangle fits.
- Important inputs in predictions of the SM rates of ultrarare decays, such as $B_s \to \mu\nu$ and $K \to \pi\nu\nu$.



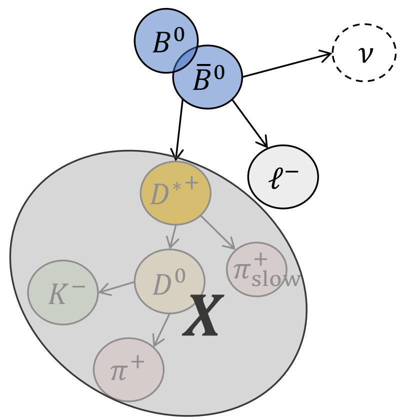
A longstanding discrepancy between inclusive and exclusive determinations is observed.

Exclusive

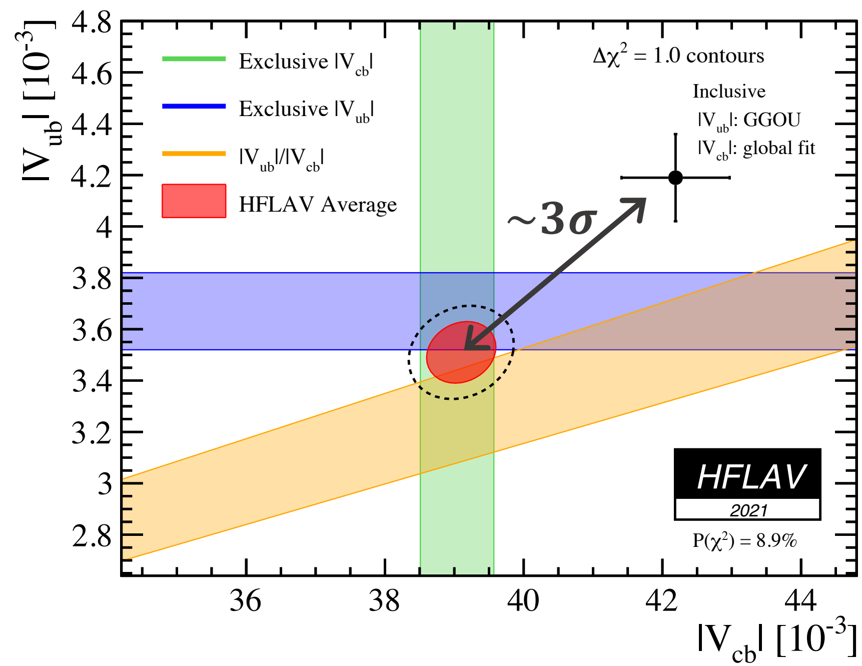


Reconstruct all daughters through specific channels exclusively.

Inclusive



Reconstruct a lepton and assign other tracks and clusters as an inclusive daughter X.



The current experimental focus is on understanding the origin of this discrepancy.

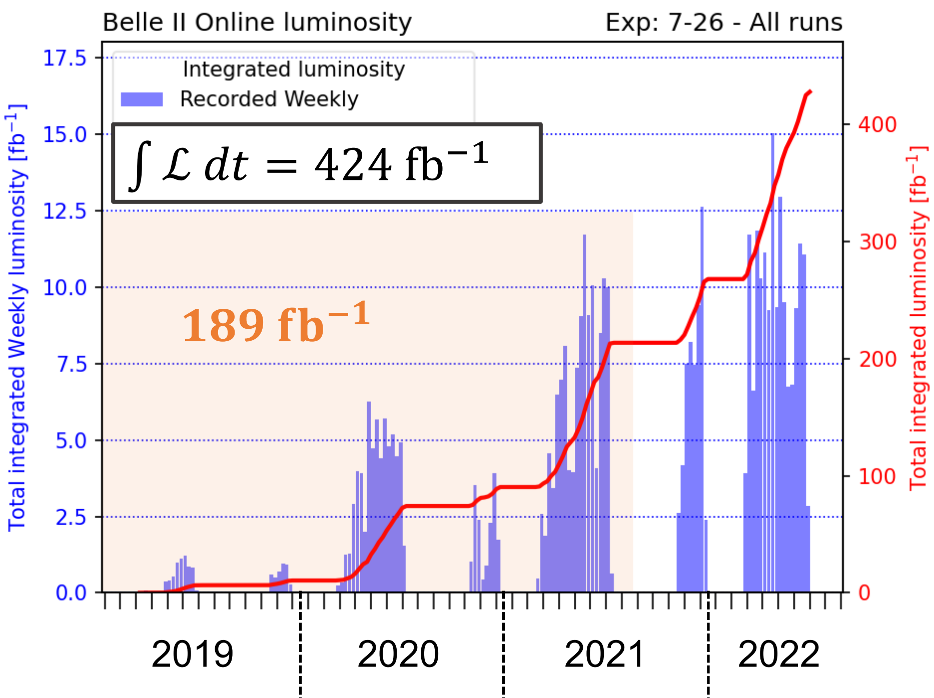
This inconsistency limits the power of precision in flavor physics.

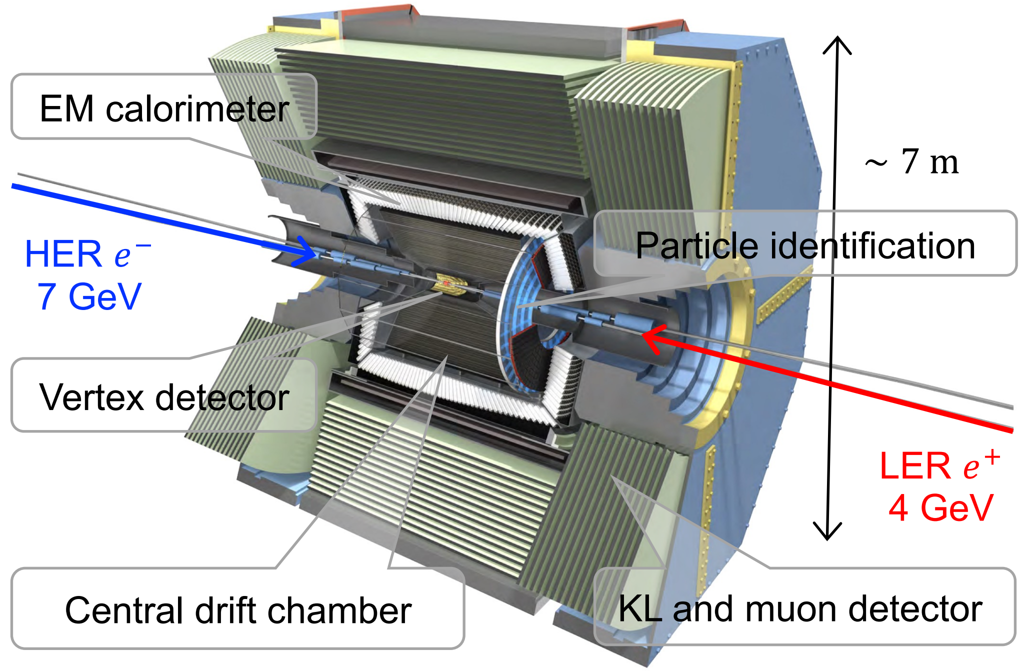
SuperKEKB/Belle II Experiment

Electron-positron collider at a center of mass energy of the $\Upsilon(4S)$ resonance or around.

The world's highest instantaneous luminosity: $4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

We can take advantage of the low multiplicity and the well-known initial state of the e^+e^- collisions.



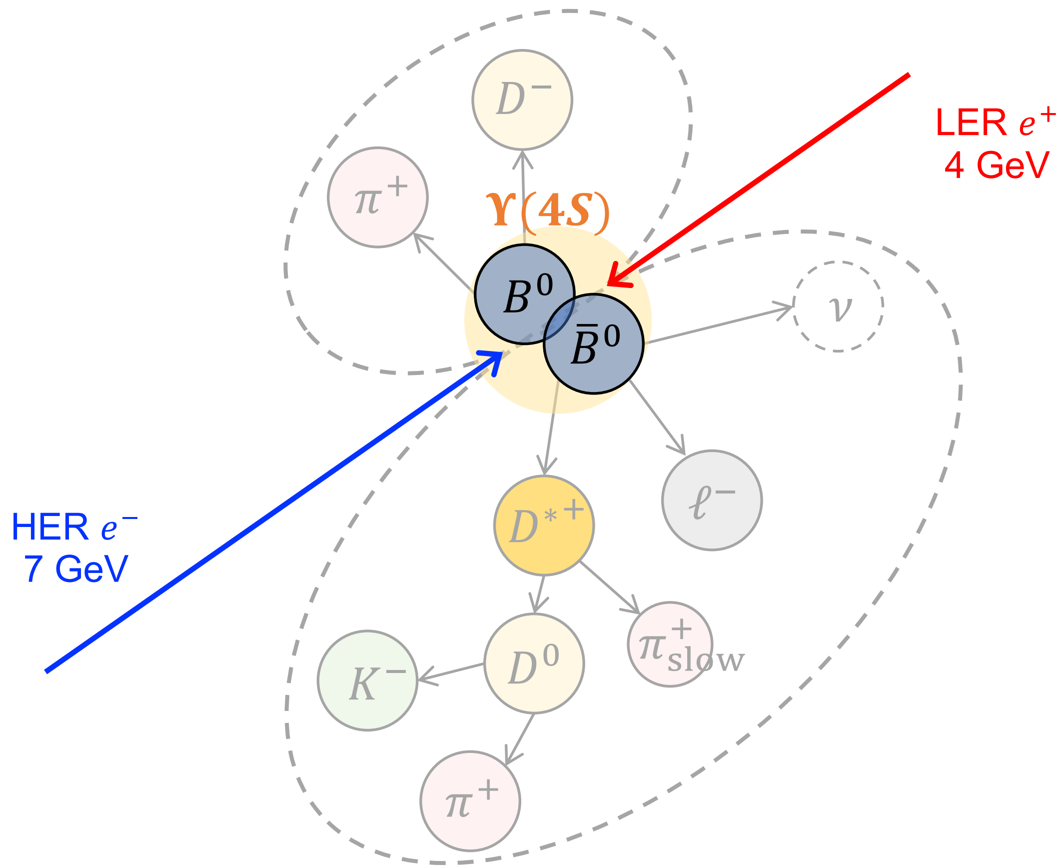


$\sigma(b\bar{b})$~1.1 nb, $\sigma(q\bar{q})$~3.7 nb ($q = u, d, s, c$) at $\sqrt{s} = 10.58$ GeV

Today's results based on $189\ \mathrm{fb^{-1}}$ recorded between 2019 and 2021.

Reconstruction

B mesons are generated in pairs from a $\Upsilon(4S)$ ($b\bar{b}$ resonance) decay.

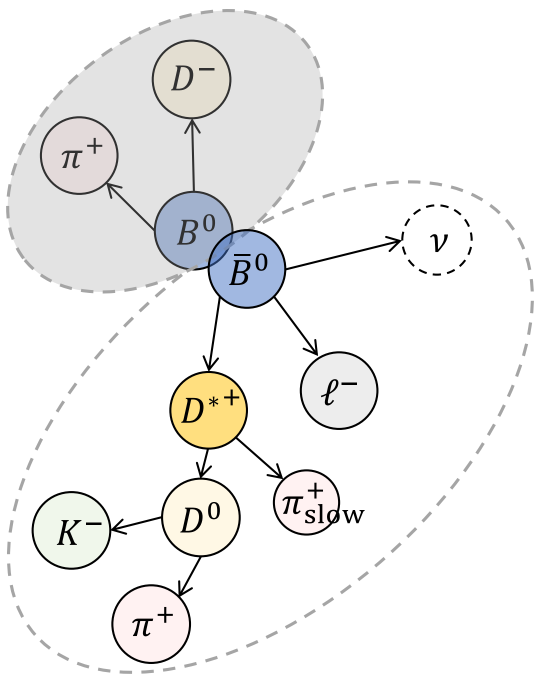


Reconstruction: Untagged vs Tagged

B mesons are generated in pairs from a $\Upsilon(4S)$ ($b\bar{b}$ resonance) decay.

Untagged

Partner B is not reconstructed explicitly.

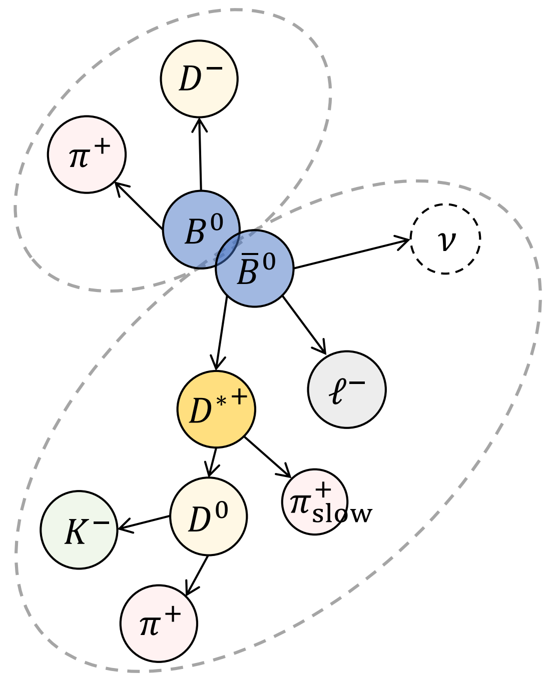


✓ Higher efficiency

△ Approximate B kinematics information

Tagged

Partner B is fully reconstructed
with hadronic decays to tag $B\bar{B}$ events.



△ Lower efficiency

✓ More precise B kinematics from the partner B

Partner B identification is unique to B-factories.

Recent $|V_{cb}|$ and $|V_{ub}|$ Results at Belle II

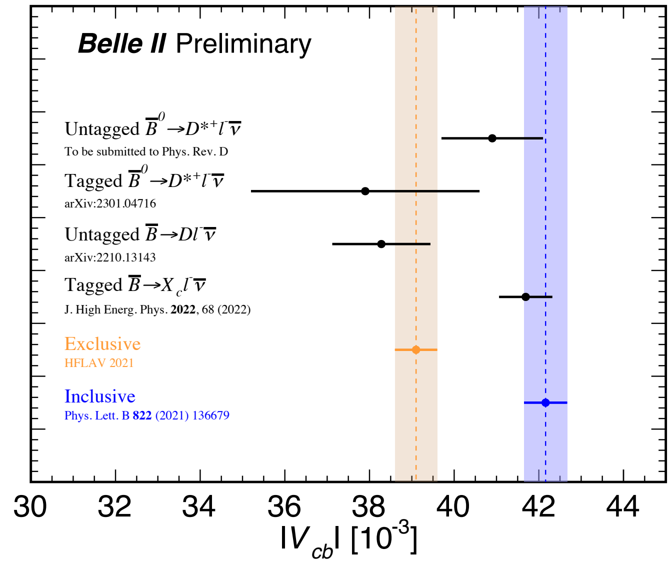
Belle II measures $|V_{cb}|$ and $|V_{ub}|$ using the following methods and decay modes.

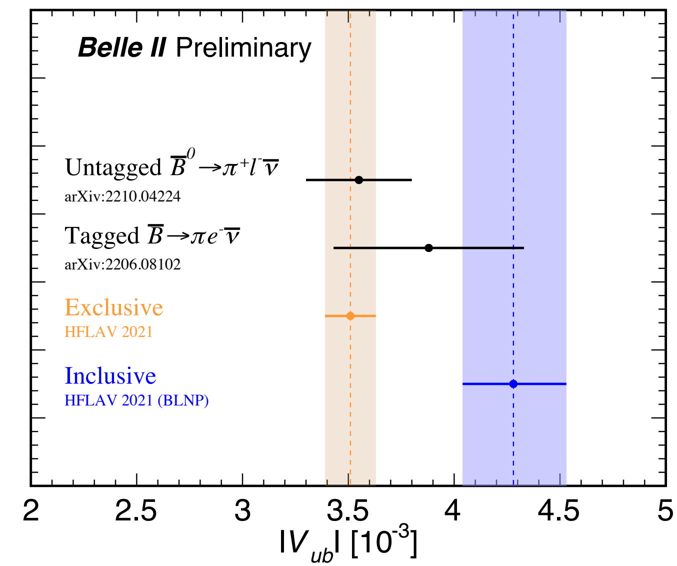
1. $|V_{cb}|$ measurement

Exclusive	Untagged	$\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$
	Tagged	$\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$
	Tagged	$\bar{B} \to D\ell^-\bar{\nu}_\ell$
Inclusive	Tagged	$\bar{B} \to X_c\ell^-\bar{\nu}_\ell$

2. $|V_{ub}|$ measurement

Exclusive	Untagged	$\bar{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell$
	Tagged	$\bar{B} \to \pi e^-\bar{\nu}_e$ (63 fb^{-1})





The exclusive and inclusive measurements prefer respective averages, although the uncertainties are large.

More details will be in Chunhui's plenary talk on July 21st.
https://indico.cern.ch/event/1114856/contributions/5375782/

Tests of Lepton Flavor Universality

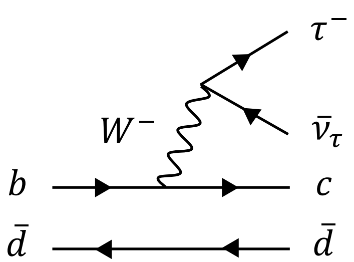
Anomalies in $b \to c$ Decays

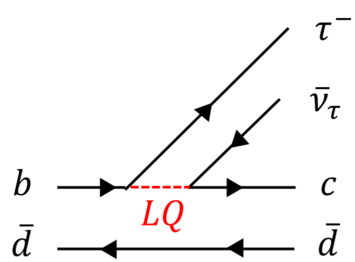
The SM postulates the universality of the lepton coupling to the electroweak gauge bosons.

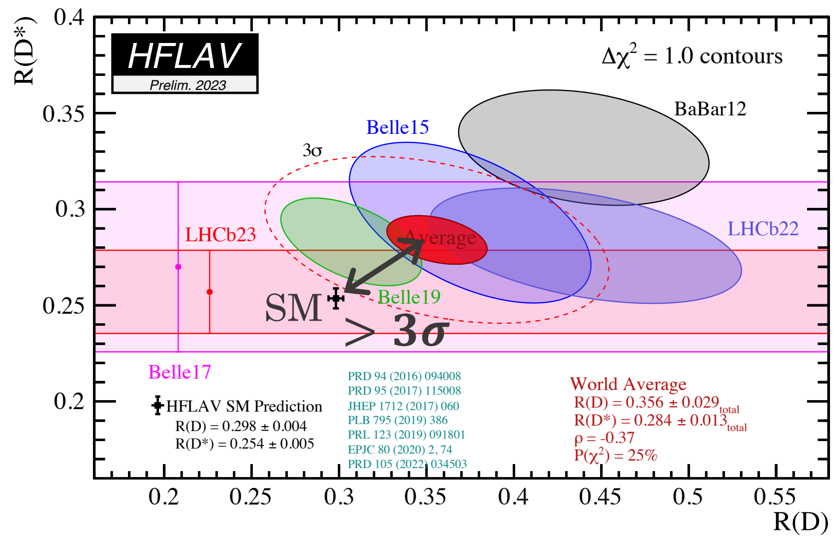
$$g_\ell \ (\ell = e, \mu, \tau)$$

The BaBar, Belle and LHCb experiments have observed excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays in $R\left(D^{(*)}\right)$ measurements by 3.2σ from the SM.

$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}, (\ell = e \text{ or } \mu)$$







The tension with the SM could be a sign of New Physics.

Light-Lepton Universality Test

Light-Lepton Universality Tests in $b \to c$ Decays

New Physics in $R(D^{(*)})$ could induce a violation of the lepton flavor universality in the following observables for the light-lepton side of e and μ.

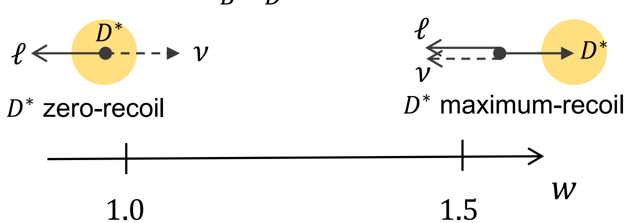
Angular asymmetries in $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$:

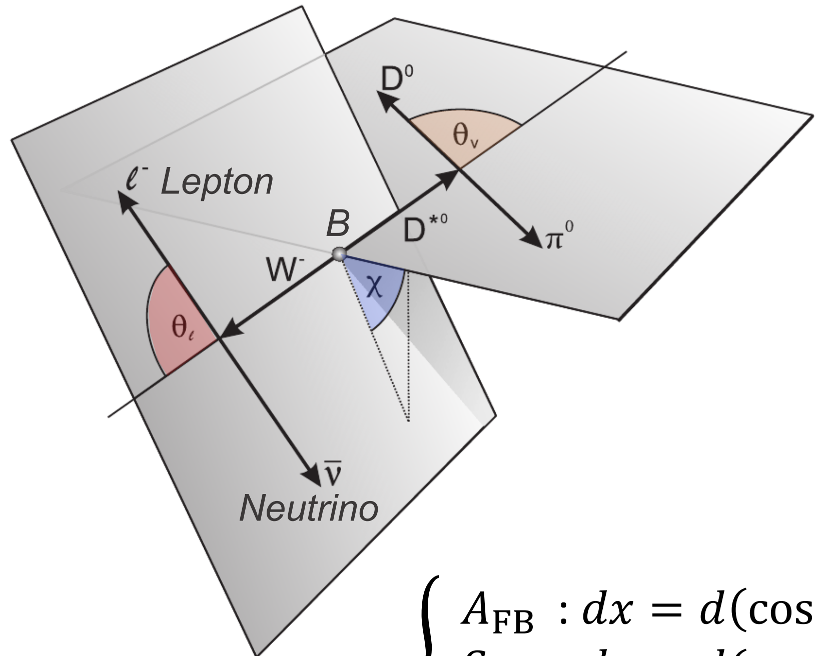
$$\Delta\mathcal{A}_x(w) = \mathcal{A}_x^e(w) - \mathcal{A}_x^\mu(w)$$

Angular observable

$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] dx \, \frac{d^2\Gamma}{dw\,dx}$$

$$w \equiv \frac{m_B^2 + m_D^2 - (p_B - p_{D^*})^2}{2 m_B m_{D^*}}$$: recoil parameter





$$\begin{cases} A_{\rm FB} : dx = d(\cos\theta_\ell) \\ S_3 : dx = d(\cos 2\chi) \\ \vdots \end{cases}$$

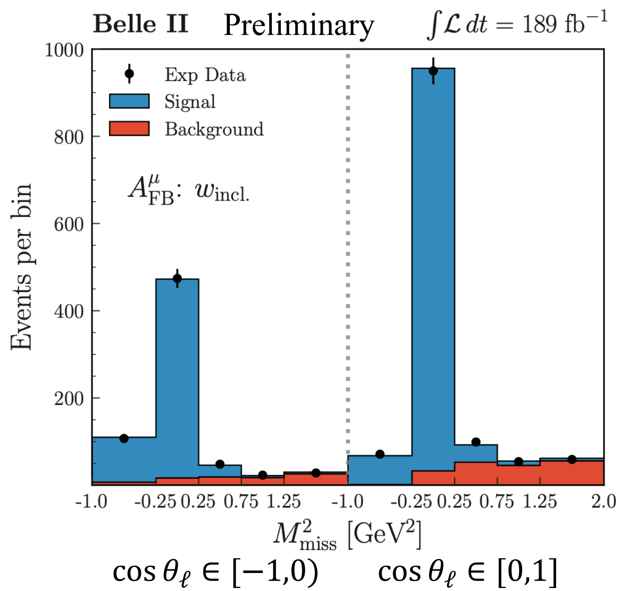
$\mathcal{A}_x(w)$ are theoretically and experimentally reliable probes of light-lepton universality unique to Belle II.

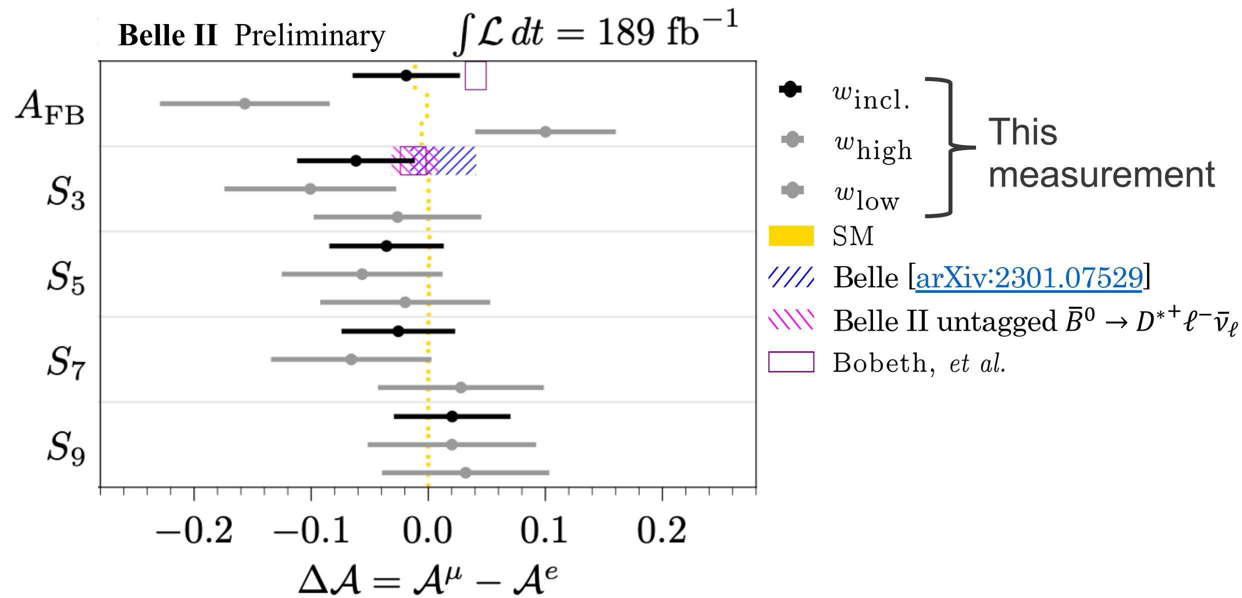
Major cancellation of theoretical and experimental uncertainties

Result

The first universality test by a complete set of angular observables as a function of recoil w

- Simultaneous determination of five angular asymmetries in three recoil ranges by fitting $M_{\text{miss}}^2 \equiv \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$.
- Comparing asymmetries between e and μ, $\Delta\mathcal{A}_x(w) = \mathcal{A}_x^\mu(w) - \mathcal{A}_x^e(w)$





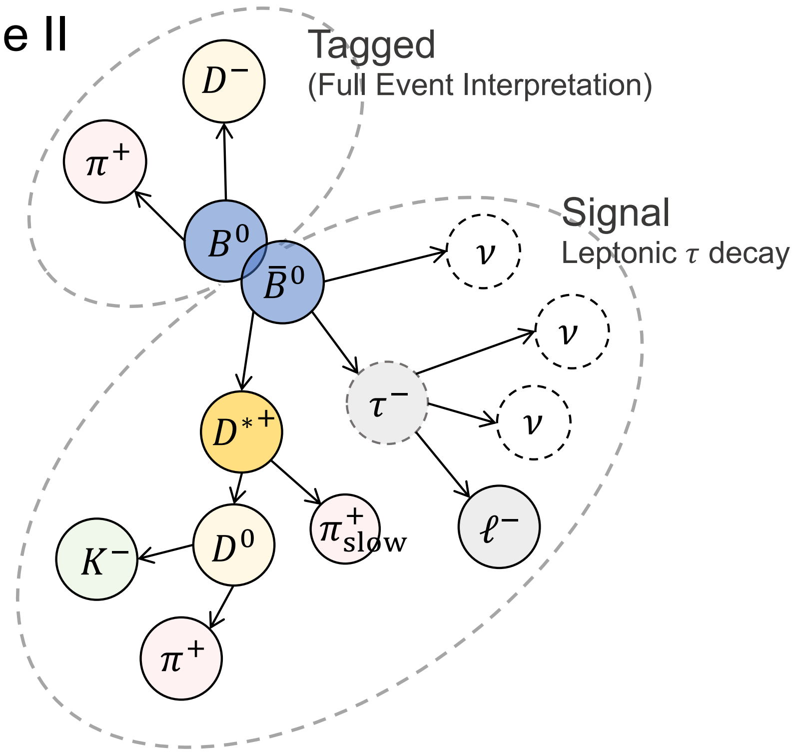
No evidence of lepton universality violation at the current level of statistics

We establish a basic measurement for a test of lepton flavor universality using semileptonic B decays at Belle II toward tests involving τ decays.

First $R(D^*)$ Result from Belle II

$R(D^*)$ Measurement

The first measurement of $R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)}$ at Belle II



- Reconstruct $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ and $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$ ($\ell = e, \mu$) with the same selections.
  - Hadronic B-tagging
  - Leptonic τ decays: $\tau \to e \bar{\nu}_e \nu_\tau / \mu \bar{\nu}_\mu \nu_\tau$
  - Three D^* decay channels: $D^{*+} \to D^0 \pi^+ / D^+ \pi^0$, $D^{*0} \to D^0 \pi^0$

- Extract yields of both signal $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ and normalization $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$ modes with two observables unique to a tagged analysis, $M^2_{\rm miss}$ and $E^{\rm extra}_{\rm ECL}$, as discriminating variables through a simultaneous fit among three D^* decay channels.

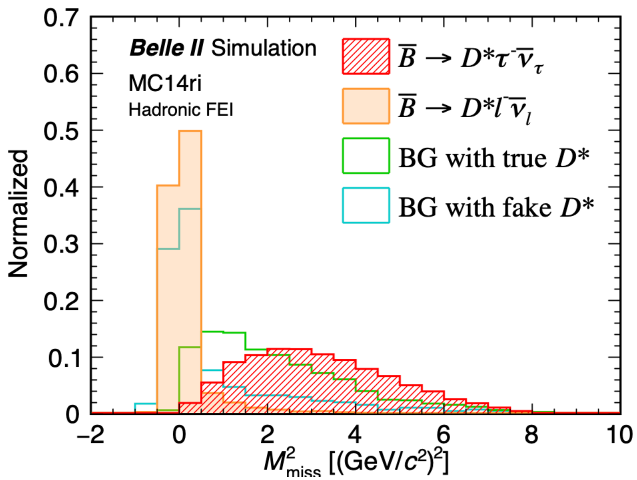
Challenge: Multiple missing neutrinos in the final state of $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$

$\to$ No clear peak in observables

$R(D^*)$ Signal Extraction

We determine $R(D^*)$ from a two-dimensional fit by extracting both $N_{\bar{B}\to D^*\tau^-\bar{\nu}_\tau}$ and $N_{\bar{B}\to D^*\ell^-\bar{\nu}_\ell}$.

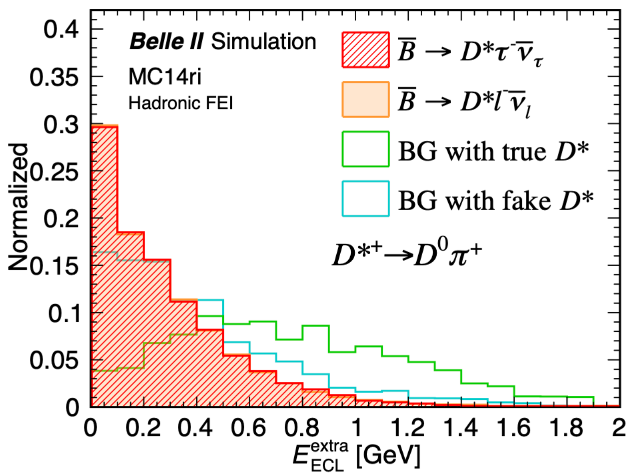
$$R(D^*) = \frac{N_{\bar{B}\to D^*\tau^-\bar{\nu}_\tau}}{N_{\bar{B}\to D^*\ell^-\bar{\nu}_\ell}/2} \cdot \frac{\varepsilon_{\bar{B}\to D^*\ell^-\bar{\nu}_\ell}}{\varepsilon_{\bar{B}\to D^*\tau^-\bar{\nu}_\tau}}$$ (ε: reconstruction efficiency)



Missing mass

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

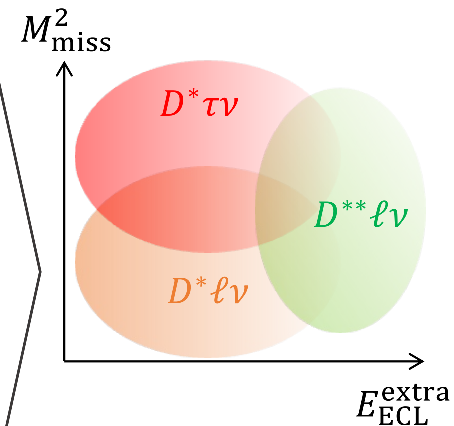
$\bar{B} \to D^*\ell^-\bar{\nu}_\ell$ ($\ell = e, \mu$) events peak at 0.
$\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ events have a larger $M^2_{\rm miss}$ due to multiple-neutrino emission from the τ decay.



Extra cluster energy in the calorimeter

$E^{\rm extra}_{\rm ECL}$ Sum of the cluster energy in the calorimeter not used for the $B\bar{B}$ reconstruction

Signal candidates peak at 0.
Background candidates have a larger $E^{\rm extra}_{\rm ECL}$ due to additional clusters from missing particles.

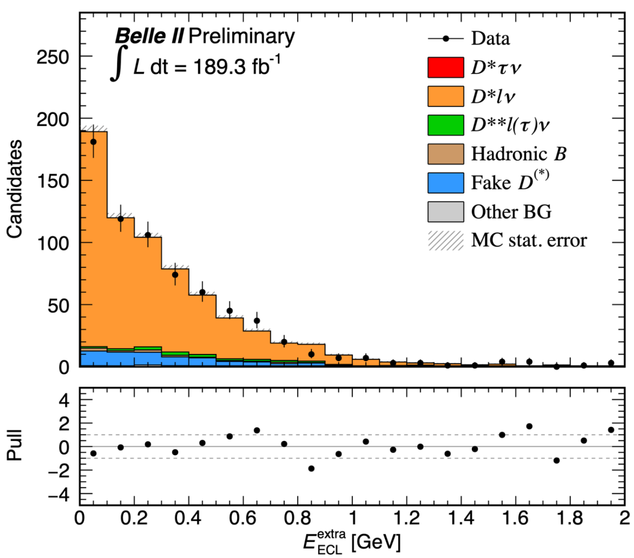


Data-driven Validation at Side-band Regions

We evaluate $\bar{B} \to D^{*}\ell^{-}\bar{\nu}_{\ell}$ and major background contributions from $\bar{B} \to D^{**}\ell^{-}\bar{\nu}_{\ell}$ and fake D^{*} in three side-band regions.

q^2 side band for $\bar{B} \to D^{*}\ell^{-}\bar{\nu}_{\ell}$

$q^2 \equiv (p_\ell + p_\nu)^2 < 3.5\ \mathrm{GeV}/c$
below m_τ^2 threshold

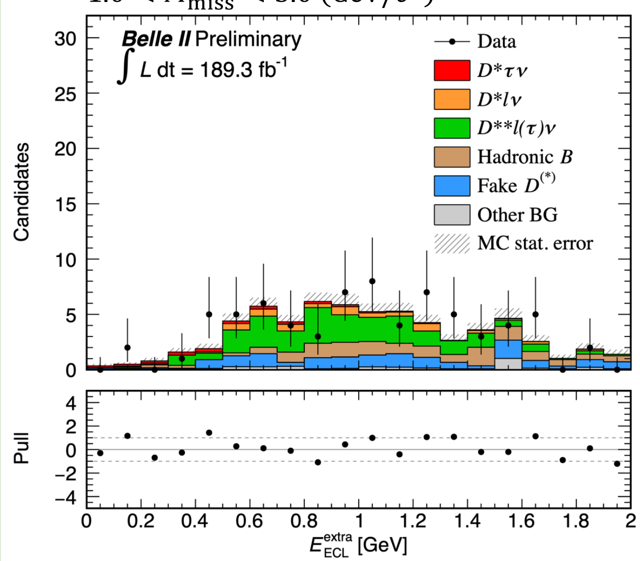


$\bar{B} \to D^{**}\ell^{-}\bar{\nu}_{\ell}$-enhanced side band

An additional π^0 is require to $B\bar{B}$.

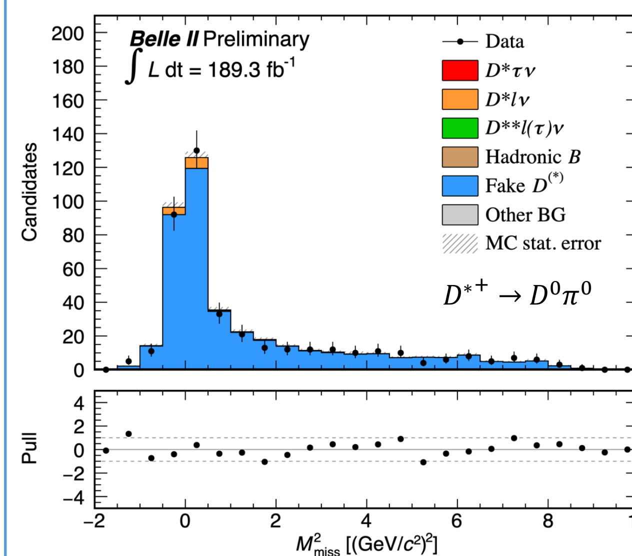
$\bar{B} \to D^{**}\ell^{-}\bar{\nu}_{\ell}$ have unknown rates and can mimic $\bar{B} \to D^{*}\tau^{-}\bar{\nu}_{\tau}$.

$1.0 < M_{\mathrm{miss}}^2 < 5.0\ (\mathrm{GeV}/c^2)^2$



$\Delta M_{D^*} (\equiv M_{D^*} - M_D)$ side bands for fake D^*

Constrain the fake D^* yields in the signal regions with calibration factors at the ΔM_{D^*} side bands.



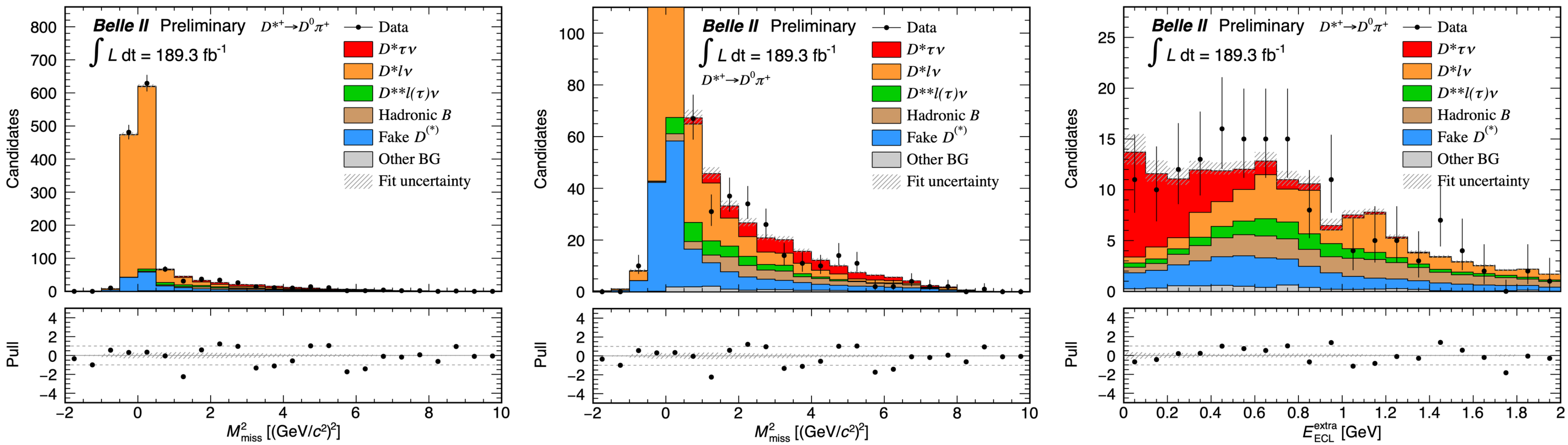
All side-band regions agree with the data.

Result

New for LP2023

Post-fit distributions for $D^{*+} \rightarrow D^0\pi^+$

$1.5 < M^2_{\text{miss}} < 6.0\ (\text{GeV}/c^2)^2$



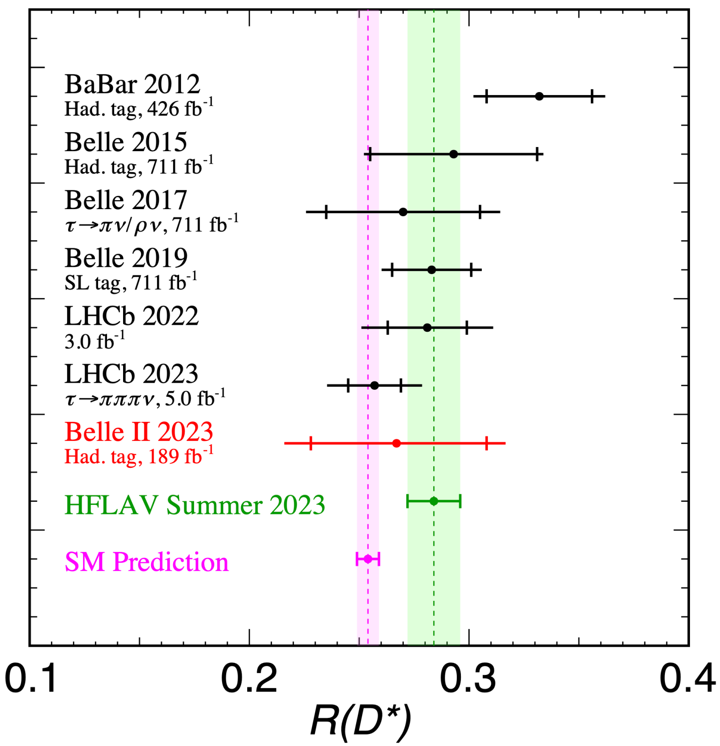
$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$

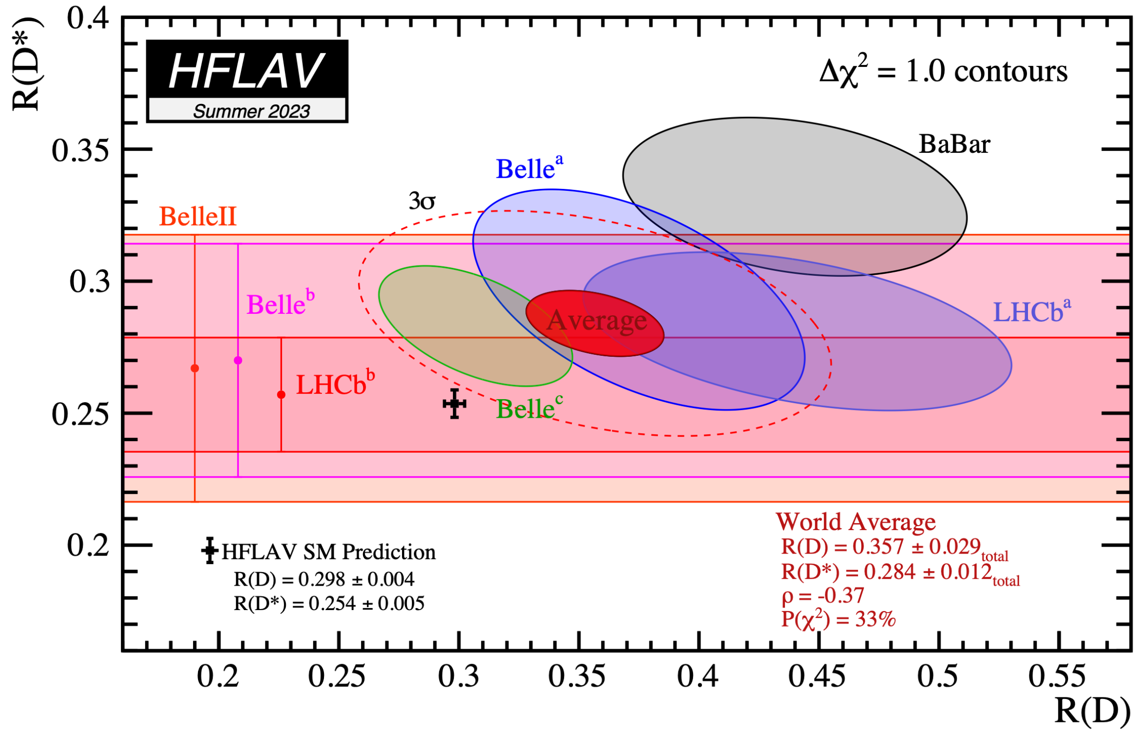
40% improvement in statistical precision over Belle at the same sample size

Systematics dominated by PDF uncertainties and simulated sample size.

Summary of $R(D^*)$ Measurements

New for LP2023





Our result is consistent with both the SM prediction and the HFLAV average.

The new HFLAV average increases the tension with the SM from 3.2σ to 3.3σ.

Summary

- Semileptonic B decays allow to determine the CKM matrix elements, $|V_{cb}|$ and $|V_{ub}|$.

$\sim 3\sigma$ discrepancy between the exclusive and inclusive determination limits our understanding of these fundamental parameters.

Belle II probes the discrepancy on independent data sets with improved experimental tools. We reported $|V_{cb}|$ and $|V_{ub}|$ with six channels.

- $> 3\sigma$ excess from the SM is observed in lepton universality tests in semileptonic B decays.

Belle II performed two measurements for tests of the lepton flavor universality.

A new unique measurement of a complementary set of angular asymmetries: $\Delta A_{FB}, S_3, S_5, S_7, S_9$

Consistent with the SM expectation

New for LP2023

New $R(D^*)$ result from the Belle II data

$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$

Consistent with both the HFLAV average and the SM expectation

$3.2\sigma \rightarrow 3.3\sigma$ excess
