Measurements of semileptonic and leptonic *B* decays at Belle II

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on behalf of the Belle II collaboration

HELMHOLTZ

Introduction

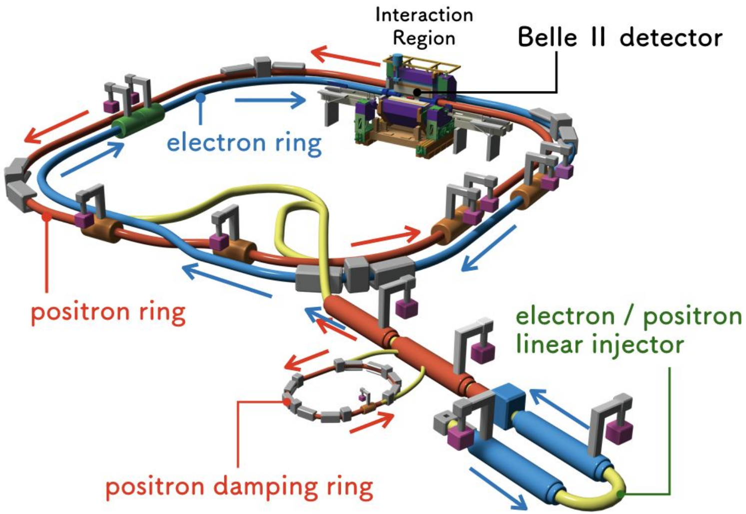
- New Belle II leptonic and semileptonic results using the **full Run 1 dataset of 365 fb^{-1}** or **390M $B\bar{B}$ pairs** collected at an e^+e^- centre-of-mass energy at the $Y(4S)$ resonance mass (10.58 GeV)

arXiv:2502.04885
Submitted to PRD

- **One new leptonic *B* decay result**
  - Measurement of the $B^+ \to \tau\,\nu$ branching fraction with a hadronic tagging method
    - See Giovanni Gaudino's YSF talk this evening for more details
- **Two new semileptonic *B* decay results** **New for Moriond !** **Preliminary**
  - Determination of $|V_{cb}|$ using $B \to D\,l\,\nu$ decays with an inclusive tagging method
  - Test of lepton flavour universality with measurements of $R(D^+)$ and $R(D^{*+})$ using semileptonic *B* tagging
    - First result using semileptonic *B* tagging !
    - First combined *R(D)* and *R(D*)* Belle II measurement !

Experimental setup

SuperKEKB



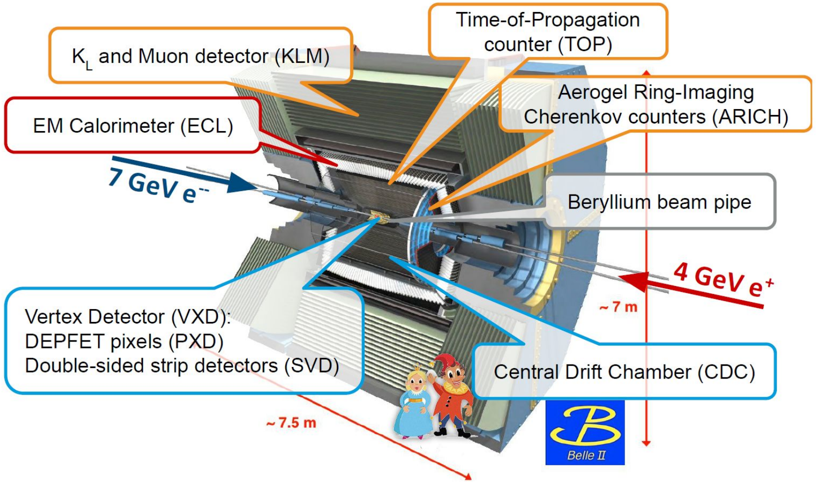
Asymmetric-energy $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$

Centre-of-mass energy = 10.58 GeV

World record instantaneous luminosity

5.1×10^{34} cm^{-2} s^{-1} (27/12/2024)

Belle II



~4π spatial coverage

Well known initial state

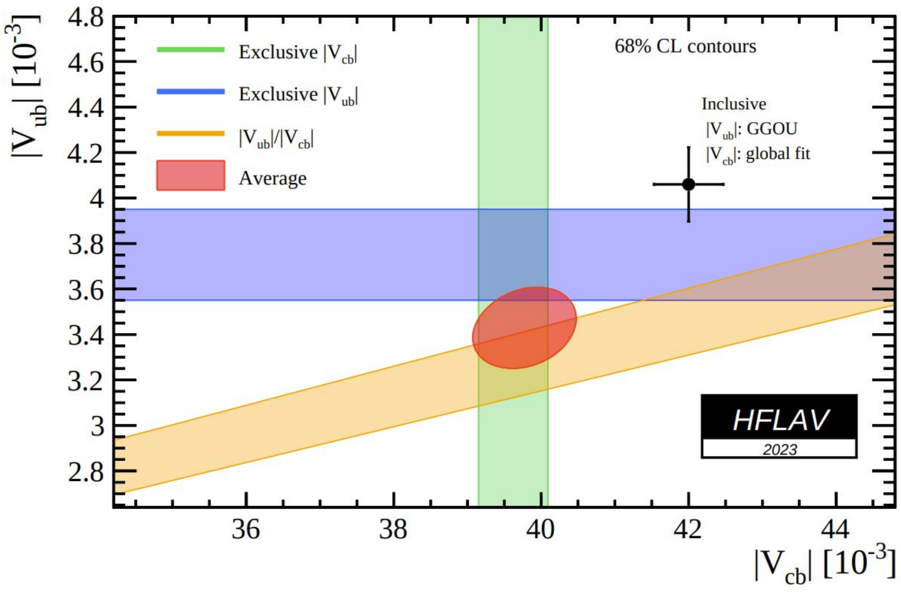
⇒ Measurements with missing energy

Run 1 luminosity: 365.37 ± 1.70 fb^{-1}

$|V_{qb}|$ measurements

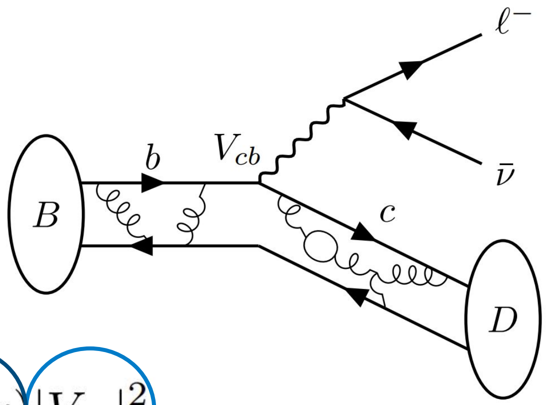
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Measurements of $|V_{qb}|$ are crucial to **constrain the CKM matrix**
- They are usually measured using semileptonic *B* decays
  - Via **exclusive decays**
    - $B \rightarrow \pi\, l\, \nu$, $B \rightarrow D\, l\, \nu$ …
  - Or via **inclusive decays** where no explicit requirements are applied on the hadronic system
- The two methods yield values which **differ by ~3σ** for both $|V_{ub}|$ and $|V_{cb}|$



$B \rightarrow D \ell \nu$ MEASUREMENT AT BELLE II

$B \to D\, l\, \nu$ measurement at Belle II



$$w = \frac{M_B^2 + M_D^2 - q^2}{2 M_B M_D} \quad q^2 = (p_\ell + p_{\nu_\ell})^2$$

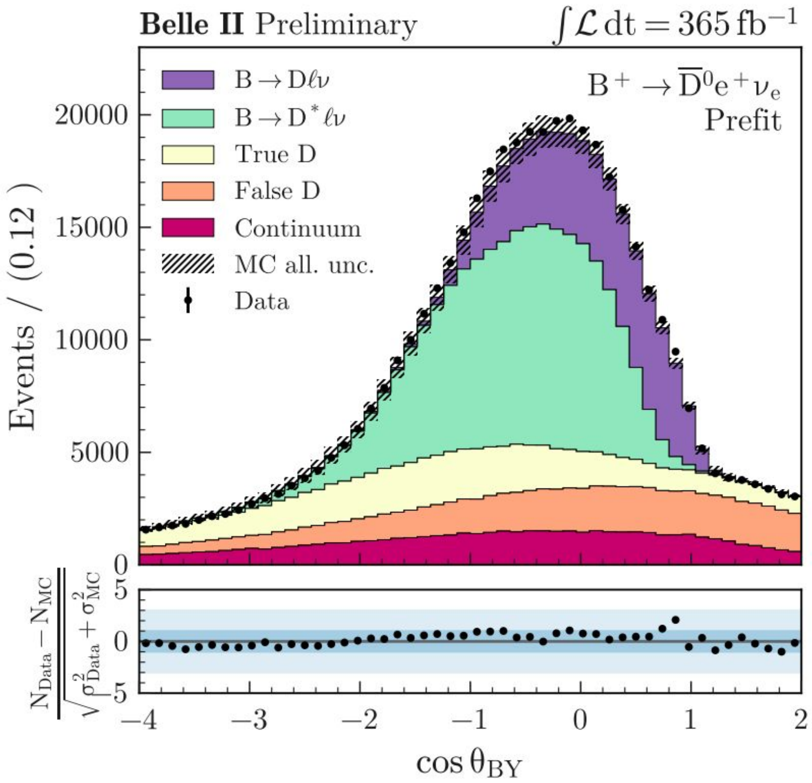
$$\frac{d\Gamma(B \to D\ell\nu)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(M_B + M_D)^2 (w^2 - 1)^{3/2} \eta_{EW}^2 \mathcal{G}^2(w) |V_{cb}|^2$$

- The differential decay rate as a function of the recoil parameter w is proportional to $|V_{cb}|^2$ and the $B \to D$ form factors
- Studying **$B \to D\, l\, \nu$ has 3 main advantages** compared to $B \to D^* (\to D^0 \pi^+)\, l\, \nu$
  - Both isospin states D^0/D^+ are accessed
  - The measurement doesn't depend on the reconstruction of a low-momentum π
    - Leading systematic uncertainty for $B \to D^*\, l\, \nu$ measurements
  - The form factor calculation is more precise
- Belle II has already measured $|V_{cb}|$ via $B \to D^*\, l\, \nu$ (PRD 108, 092013)
  - $|V_{cb}|_{BGL} = (40.57 \pm 1.16) \times 10^{-3}$

$B \to D\, l\, \nu$ measurement at Belle II

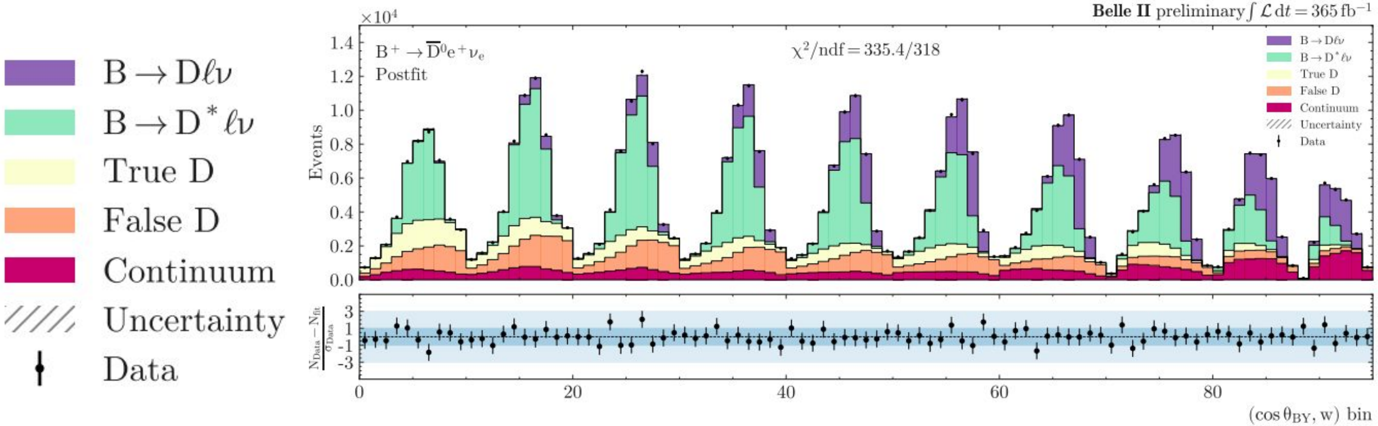
- The Belle II measurement is performed using B^0 and B^+ decays **without explicitly reconstructing the partner *B* meson** from the $Y(4S) \to B\bar{B}$ decay
  - $D^- \to K^+ \pi^- \pi^-$ and $D^0 \to K^- \pi^+$
- The signal is extracted using the **cosθ_{BY} variable** where *Y* represents the *Dl* system

$$\cos\theta_{BY} = \frac{2\,E_B^* E_Y^* - M_B^2 - M_Y^2}{2|p_B^*||p_Y^*|}$$



$B \to D\, l\, \nu$ measurement at Belle II

- The signal is **extracted from a 2D binned template fit of cosθ_{BY}:w** split in 10 bins each
- The fit is performed simultaneously on **4 separate channels D^0e^-, $D^0\mu^-$, D^+e^- and $D^+\mu^-$** to extract the individual **branching fractions** and a **lepton flavour universality test**



10 cosθ_{BY} distributions in 10 w bins

arXiv:2411.18639

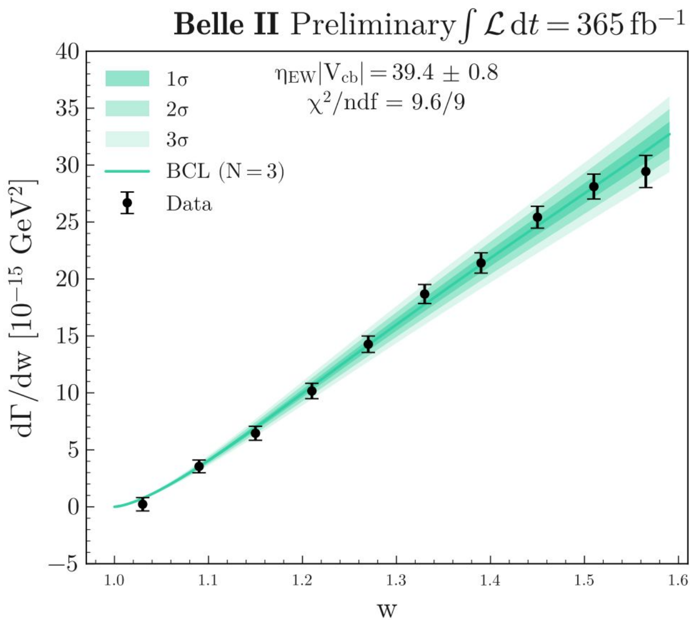
	Belle II	HFLAV
$\mathcal{B}(B \to D^-\ell^+\nu)$	$2.06 \pm 0.12\%$	$2.12 \pm 0.06\%$
$\mathcal{B}(B \to \bar{D}^0\ell^+\nu)$	$2.31 \pm 0.10\%$	$2.21 \pm 0.06\%$

$$\frac{\mathcal{B}(B \to De\nu)}{\mathcal{B}(B \to D\mu\nu)} = 1.02 \pm 0.03$$

$B \to D \, l \, \nu$ measurement at Belle II

Results

- The differential decay rate ***ΔΓ/Δw*** in 10 *w* bins is obtained from the **same fit**
- The obtained values of ***ΔΓ/Δw*** **are fitted** to the differential rate expressed using the Bourrely, Caprini, Lellouch (BCL) form factor parametrisation with a χ^2 fit with lattice QCD constraints → **extraction of $|V_{cb}|$ and BCL form factor parameters**



Measured values — Predicted values

$$\chi^2 = \sum_{i,j}^{10} \left(\frac{\Delta\Gamma_i}{\Delta w} - \frac{\Delta\Gamma_{i,\mathrm{BCL}}}{\Delta w} \right) \mathbf{C}_{ij}^{-1} \left(\frac{\Delta\Gamma_j}{\Delta w} - \frac{\Delta\Gamma_{j,\mathrm{BCL}}}{\Delta w} \right) + \sum_{k,l}^{5} (c_k - c_{k,\mathrm{FLAG}}) \mathbf{D}_{kl}^{-1} (c_l - c_{l,\mathrm{FLAG}})$$

LQCD constraints (FNAL/MILC + HPQCD)

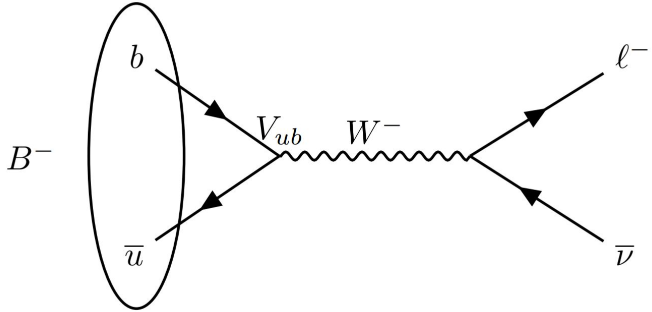
$$|V_{cb}|_{BCL} = (39.2 \pm 0.8) \times 10^{-3}$$

$|V_{cb}|_{\mathrm{excl.}} = (39.77 \pm 0.46) \times 10^{-3}$ $|V_{cb}|_{\mathrm{incl.}} = (41.97 \pm 0.48) \times 10^{-3}$

$B \to \tau\nu$ MEASUREMENT AT BELLE II

Leptonic *B* decays

Introduction



- Purely leptonic *B* decays are the cleanest channels to measure $|V_{ub}|$
- Their branching ratio depends on the *B* meson decay constant which can be extracted precisely from lattice QCD
- However, they are strongly helicity suppressed and therefore hard to study
- All individual measurements are below the 5σ discovery threshold

$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

f_B = 190.0 ± 1.3 MeV
[FLAG]

$B \to \tau\nu$

Experiment	Tag	$\mathcal{B}(10^{-4})$
Belle	Hadronic	$0.72^{+0.27}_{-0.25} \pm 0.11$
BABAR	Hadronic	$1.83^{+0.53}_{-0.49} \pm 0.24$
Belle	Semileptonic	$1.25 \pm 0.28 \pm 0.27$
BABAR	Semileptonic	$1.8 \pm 0.8 \pm 0.2$
PDG		1.09 ± 0.24

$B \to \tau\nu$ measurement at Belle II

arXiv:2502.04885
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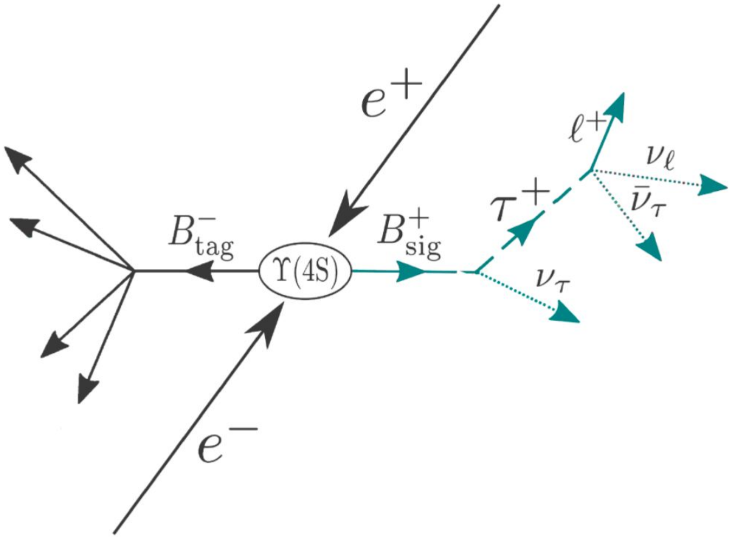
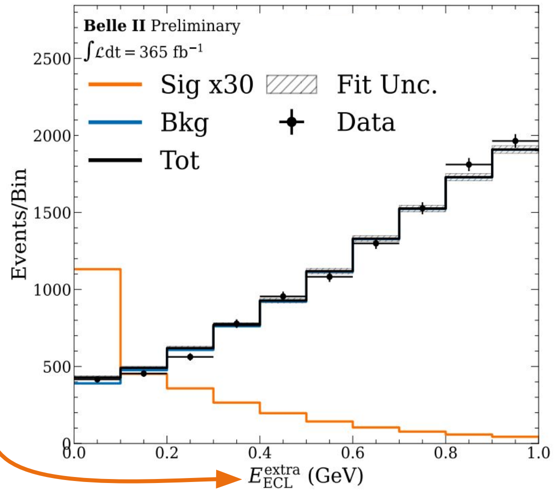
- The Belle II measurement is performed by reconstructing **tag-side *B* mesons** in their **hadronic decay channels**
  - This is necessary to constrain the event kinematics despite the presence of multiple undetected neutrinos
- The **signal-side τ is reconstructed in 4 channels** to maximise the reconstruction efficiency
  - BR($\tau \to e\nu\nu$) = 17.8%
  - BR($\tau \to \mu\nu\nu$) = 17.4%
  - BR($\tau \to \pi\nu$) = 10.8%
  - BR($\tau \to \rho\nu$) = 25.5%
  - Total = 71.5%



$B \longrightarrow \tau\nu$ measurement at Belle II

- The total energy from neutral clusters not associated with either B mesons is **calibrated using 3 separate control samples** to correct $B\overline{B}$ backgrounds, signal with τ leptonic modes and signal with τ hadronic modes



$B \to \tau\nu$ measurement at Belle II

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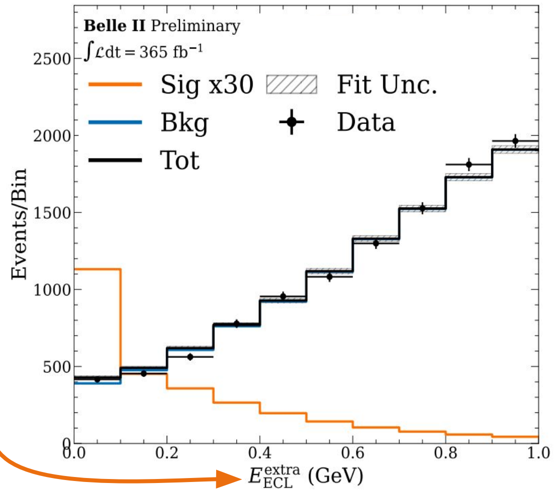
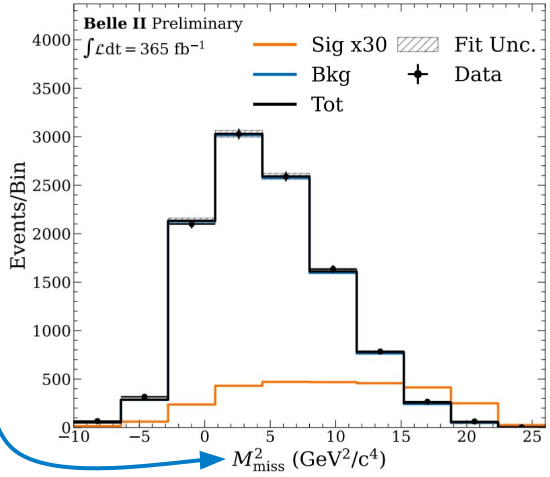


- The branching fraction is extracted from **2D fit** of the cluster energy and the event squared missing mass
- Simultaneous binned maximum likelihood fit of all 4 signal τ decay channels



$B \to \tau\nu$ measurement at Belle II

arXiv:2502.04885
Submitted to PRD

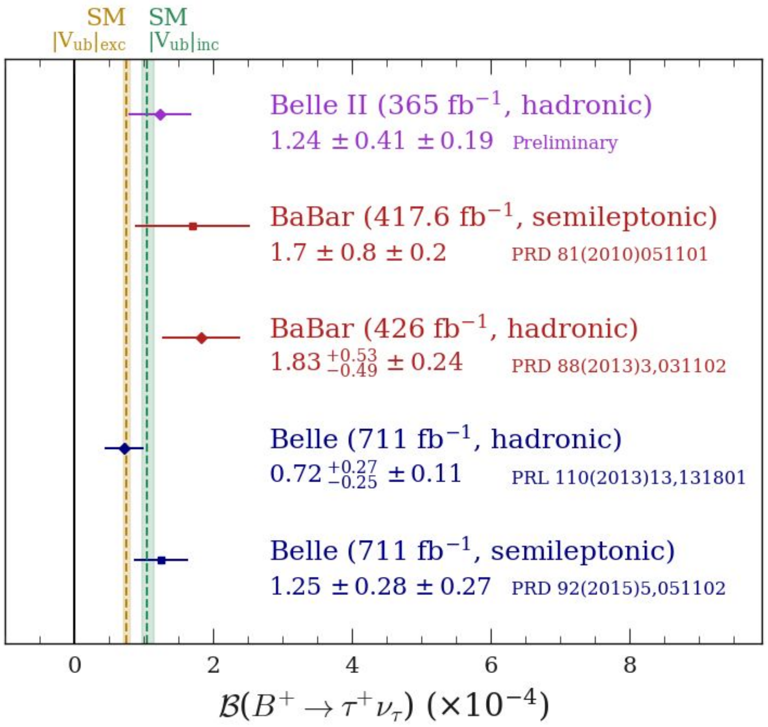
Results

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = [1.24 \pm 0.41(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-4}$$

- **Significance → 3.0σ**
  - Expected significance → 2.7σ
- The measurement is limited by statistics
- The leading systematic uncertainties come from
  - The finite size of the simulated samples
  - The neutral cluster calibration
- The extracted value of $|V_{ub}|$ is compatible with the exclusive and inclusive averages

$$|V_{ub}|_{B^+ \to \tau^+ \nu_\tau} = [4.41^{+0.74}_{-0.89}] \times 10^{-3}$$

$|V_{ub}|_{\text{excl.}} = (3.43 \pm 0.12) \times 10^{-3}$ $|V_{ub}|_{\text{incl.}} = (4.06 \pm 0.16) \times 10^{-3}$

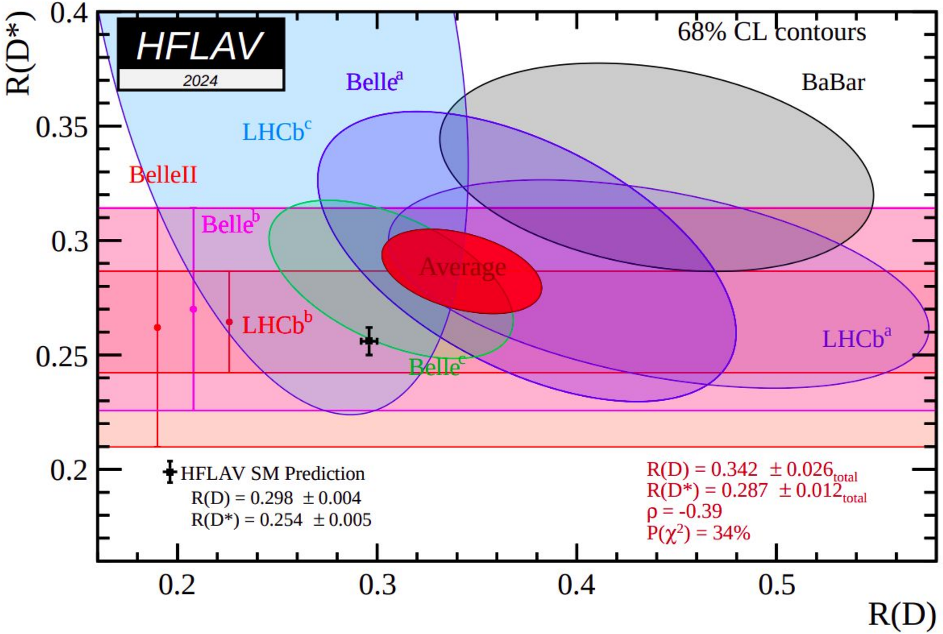


$R(D^{(*)})$ MEASUREMENT AT BELLE II

$R(D^{(*)})$ measurement at Belle II

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

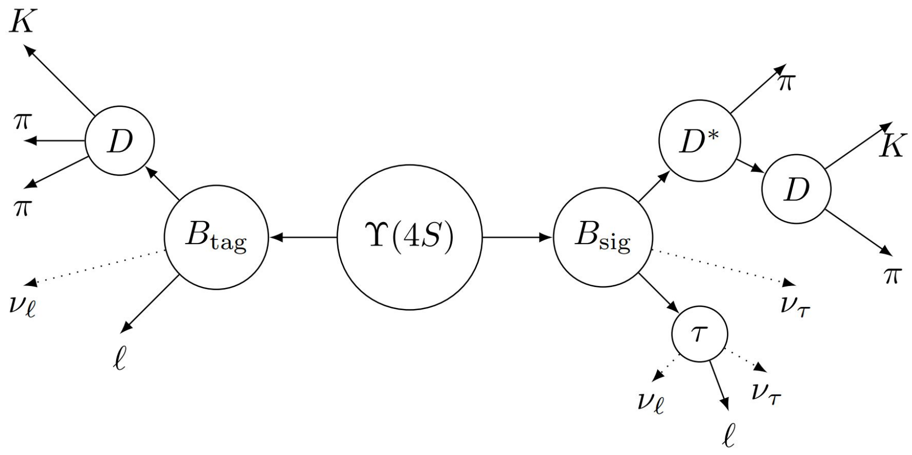
- Test **lepton flavour universality** by studying decays to heavy τ leptons versus light e, μ leptons
  - An observation of lepton flavour universality violation would be a clear signature of non-SM couplings with the 3rd fermion generation
- Such ratios have been measured by BaBar, Belle, LHCb and now Belle II
- Long standing **discrepancy** currently standing at **3.1σ** for the combined value of $R(D^{(*)})$



$R(D^{(*)})$ measurement at Belle II

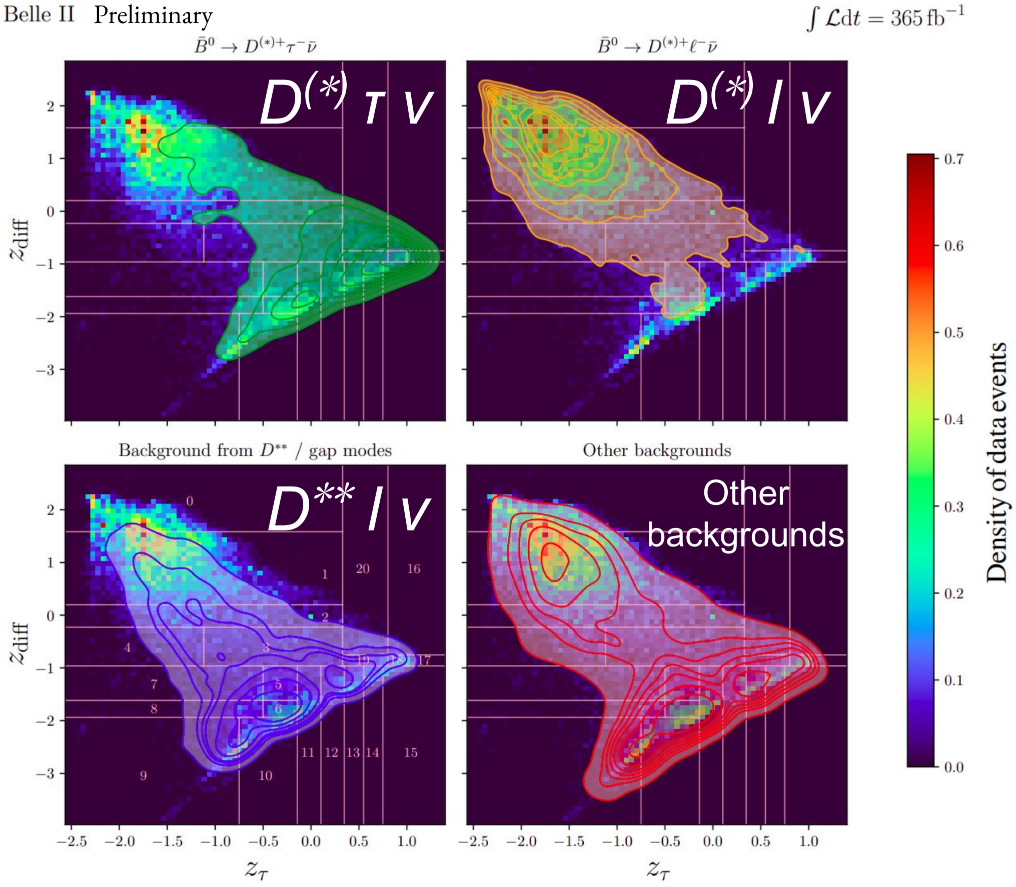
Reconstruction

- The Belle II measurement is performed with B^0 decays
- The Belle II measurement is performed by reconstructing **tag-side *B* mesons** in their **semileptonic decay channels**
  - $B_{tag} \rightarrow D/D^* \, l \, \nu$
- ***τ*** are reconstructed in their **leptonic decay channels**
  - $\tau \rightarrow l \, \nu \, \nu$
- ***D*** mesons on both sides are reconstructed through **various decays to *K*⁺, *K_S*, *π*⁺, *π⁰***
  - Tag side: 26 decay modes
  - Signal side: 13 decays modes



$R(D^{(*)})$ measurement at Belle II

- A **BDT** algorithm is used to separate the **events in 3 classes**
  - Semitauonic signal events
  - Semileptonic signal events
  - Background events
- Most **discriminating** input feature is **cosθ_{BY}**
- Each event is assigned a BDT score z_τ, z_l, z_{bkg}
- The signal is extracted in a **2D binned template fit** of z_τ and $z_{diff} = z_l - z_{bkg}$



$R(D^{(*)})$ measurement at Belle II

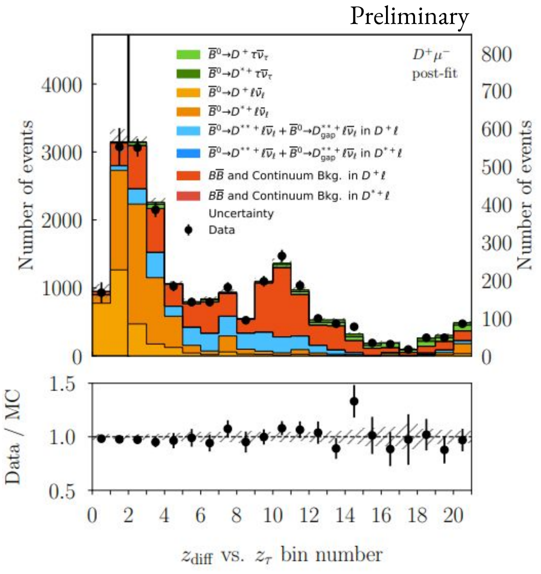
Results

$D^{(*)}$ τ ν

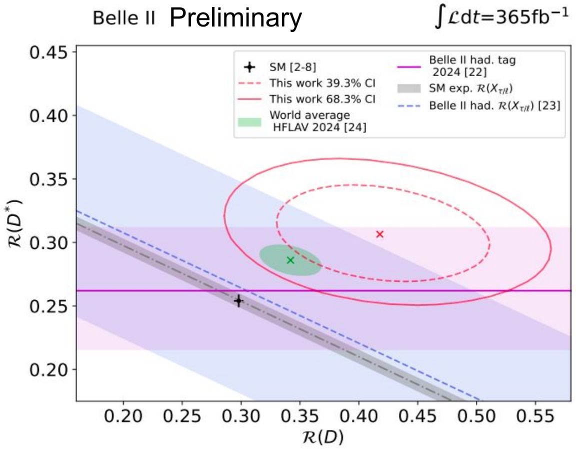
$D^{(*)}$ l ν

D^{**} l ν

Backgrounds



- The fit is performed over **4 separate channels**: ***D^+e^-*, *$D^+\mu^-$*, *$D^{*+}e^-$*, *$D^{*+}\mu^-$*** and The measurement is statistically limited
- The leading systematic uncertainties are coming from
  - The finite size of the simulated samples
  - The lepton identification efficiency and fake rate corrections
- The addition of B^+ modes will improve the precision



$$\mathcal{R}(D^+) = 0.418 \pm 0.074\ (\text{stat}) \pm 0.051\ (\text{syst})$$

$$\mathcal{R}(D^{*+}) = 0.306 \pm 0.034\ (\text{stat}) \pm 0.018\ (\text{syst})$$

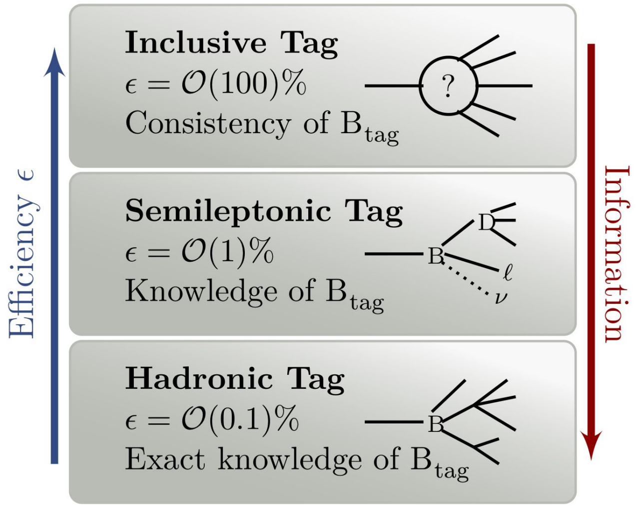
Summary

- **3 very recent high-profile Belle II analyses** were presented here
  - Measurement of $|V_{cb}|$ via $B \to D\, l\, \nu$ decays
    - Competitive with previous measurements of $|V_{cb}|$ via $B \to D^*\, l\, \nu$ decays which are usually preferred because of a branching fraction about twice higher
  - $B^+ \to \tau\, \nu$ branching fraction measurement
    - Competitive with previous measurements
    - Measurements of $|V_{ub}|$ with negligible theoretical uncertainty
  - Combined $R(D^+)$ and $R(D^{*+})$ measurement
    - First Belle II result with semileptonic tagging method
    - First Belle II combined $R(D)$-$R(D^*)$ measurement

BACKUP

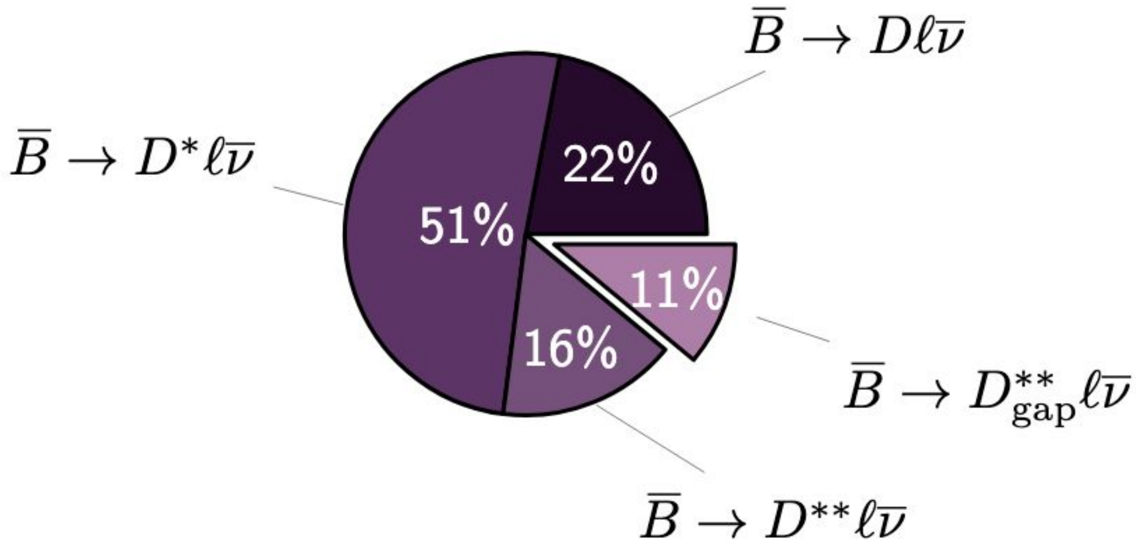
Tagging methods

- At B-factories it is possible to reconstruct both *B* mesons coming from the $Y(4S) \rightarrow B_{sig}\overline{B}_{tag}$ decay
- Three possible tagging strategies
  - Inclusive tagging (untagged)
    - Only simple consistency selections are applied on the B_{tag}
    - Offers high efficiency for statistically limited measurements
  - Semileptonic tagging
    - Reconstruct the B_{tag} in its $B \rightarrow D/D^* \, l \, \nu$ decays
    - Relatively low efficiency but more kinematically constrained events
  - Hadronic tagging
    - Reconstruct the B_{tag} in its hadronic decays in a total of O(10,000) channels
    - Very low efficiency but precise reconstruction of the full event
    - Particularly useful for measurements with undetected particles and/or inclusive systems



$B \to X_c\, l\, \nu$ decays

- The sum of branching fractions of semileptonic B decays to D, D^* and D^{**} doesn't match the measured inclusive $B \to X_c\, l\, \nu$ branching fraction
- To fill the gap, unmeasured decays are added referred to as gap modes
  - $B \to D^{(*)}\, \eta\, l\, \nu$



$B \to D\,l\,\nu$ measurement at Belle II

BCL expansion

BCL expansion: PRD 79, 013008 (2009)

$$r = M_D/M_B \qquad \mathcal{G}^2(w) = \frac{4r}{(1+r)^2} f_+^2(w) \qquad f_0(w_{\max}) = f_+(w_{\max})$$

$$f_+(q^2) = \frac{1}{1-q^2/M_+^2} \sum_{k=0}^{N-1} a_k \left[z^k - (-1)^{k-N} \frac{k}{N} z^N \right] \qquad f_0\left(q^2\right) = \frac{1}{1-q^2/M_0^2} \sum_{k=0}^{N-1} b_k z^k$$

	Values	Correlation coefficients				
a_0^+	0.8959(92)	1	0.26	-0.38	0.95	0.51
a_1^+	-8.03(15)		1	0.17	0.33	0.86
a_2^+	49.3(31)			1	-0.31	0.16
a_0^0	0.7813(73)				1	0.47
a_1^0	-3.38(15)					1

Measured parameters of the N = 3 BCL expansion

$B \to D\, l\, \nu$ measurement at Belle II

Systematics budget

Fractional contributions to the total relative uncertainty of $|V_{cb}|$

$|V_{cb}| = (39.2 \pm 0.4\ (\text{stat.}) \pm 0.6\ (\text{syst.}) \pm 0.5\ (\text{theo.})) \times 10^{-3}$

	Uncertainty [%]
Statistical uncertainty	0.9
MC Stat. Error	0.5
N_{bb}	0.5
f_{00}/f_{+-}	0.1
$f_{\not{B}}$	0.3
$\mathcal{B}(D \to K\pi(\pi))$	0.3
Selection	0.5
$\mathcal{B}(B \to X_c \ell \nu)$	0.3
Lepton identification	0.2
Kaon identification	0.5
Tracking efficiency	0.3
Signal PDF	0.4
$B \to D^* \ell \nu$ form factor	0.1
w background modelling	0.5
Background reweighing	0.3
$\tau_{B^{0/\pm}}$	0.1
Total Systematic	1.5
Lattice QCD inputs	1.2
Long-distance QED	0.4
Total theory	1.3
Total	2.1

$B \to D\, l\, \nu$ measurement at Belle II

Electroweak and QED corrections

- Short-distance electroweak corrections are well understood
  - $\eta_{EW} = (1.0066 \pm 0.0002)$ [Nucl. Phys. B 196, 83 (1982)]

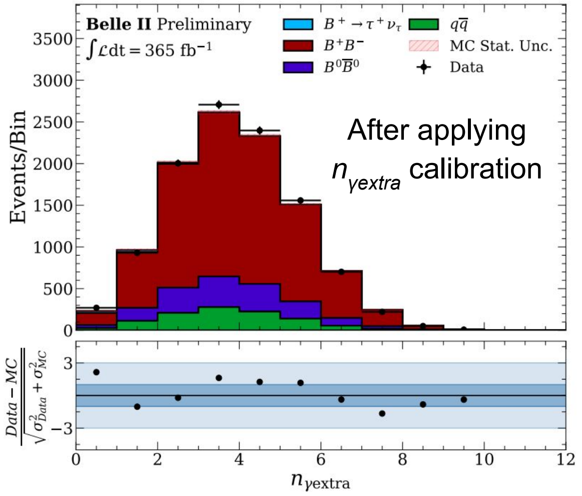
- Long-distance QED corrections arise from photon exchange between the *D* meson and the charged lepton (Coulomb correction)
  - $\delta_{Coulomb} = (1 + \alpha\pi) = 1.023$ [Phys. Rev. D 41, 1736 (1990)]
  - A nuisance parameter θ is introduced to take into account the isospin-breaking effect of the Coulomb correction which modifies the *B* lifetime ratio
    - $\tau_{0+} \to \tau_{0+}(1 + \alpha\pi\theta)$
  - This is an important information that cannot be accessed in $B \to D^*\, l\, \nu$ measurements where the D^* is usually reconstructed via $D^*\,(\to D^0\,\pi^+)$

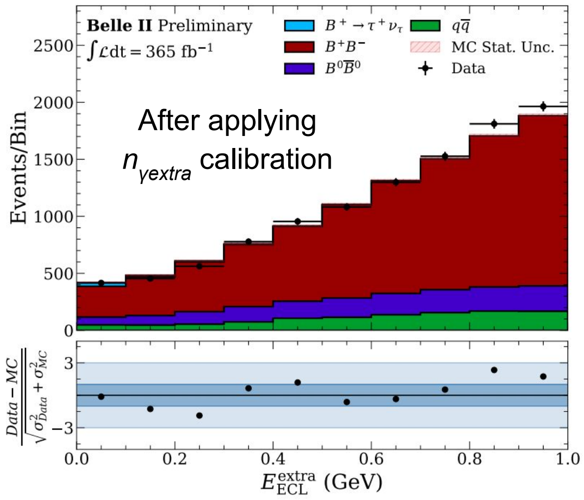
$B \to \tau\nu$ measurement at Belle II

Calibration and validation

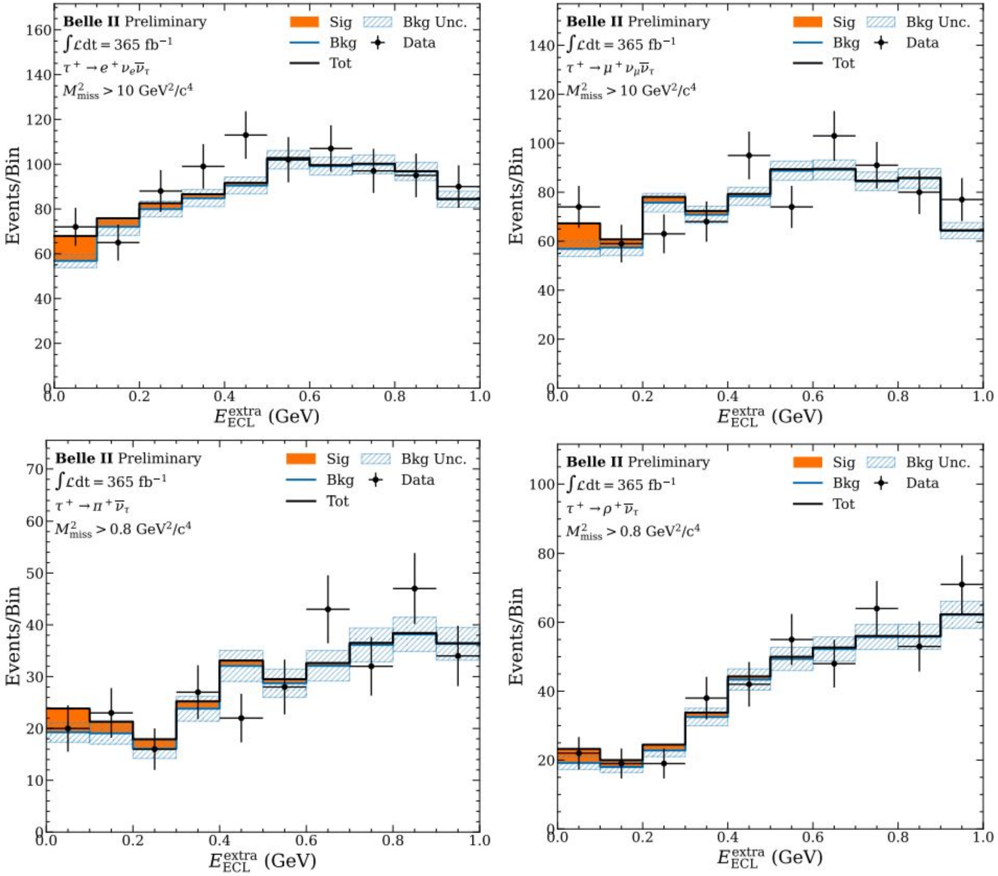
$$w_{\text{cont.}} = \frac{\mathcal{S}_{\text{cont.}}}{1 - \mathcal{S}_{\text{cont.}}}$$

- Continuum calibration
  - Use a sample of data collected 60 MeV below the *Y(4S)* resonance
  - Train a BDT to distinguish simulated and data events
  - The classifier response $S_{cont.}$ is used to reweight continuum events
- The data-simulation disagreement in E^{extra} variable is known to originate from an incorrect modelling of the extra neutral cluster multiplicity $n_{\gamma extra}$
- 3 control samples are used to extract calibration factors in bins of $n_{\gamma extra}$
  - Extra track sample → $B\bar{B}$ background
  - $B \to D^* l \nu$ sample → signal $\tau \to l \nu \nu$
  - Double tag sample → signal $\tau \to h \nu$





$B \to \tau\nu$ measurement at Belle II



Fit results in signal enriched regions

- M^2_{miss} > 10 GeV^2 for leptonic τ channels
- M^2_{miss} > 0.8 GeV^2 for hadronic τ channels

$B \to \tau\nu$ measurement at Belle II

Systematics budget

Source	Syst.
Simulation statistics	13.3%
Fit variables PDF corrections	5.5%
Decays branching fractions in MC	4.1%
Tag B^- reconstruction efficiency	2.2%
Continuum reweighting	1.9%
π^0 reconstruction efficiency	0.9%
Continuum normalization	0.7%
Particle identification	0.6%
Number of produced $\Upsilon(4S)$	1.5%
Fraction of B^+B^- pairs	2.1%
Tracking efficiency	0.2%
Total	15.5%

Fractional contributions to the total relative systematic uncertainty of the $B \to \tau\nu$ branching fraction

$R(D^{(*)})$ measurement at Belle II

D decay modes

Decay mode	tag side	signal side
$D^0 \to K^-\pi^+\pi^0$	✓	✓
$D^0 \to K^-\pi^+\pi^+\pi^-$	✓	✓
$D^0 \to K^-K^+K^0_S$	✓	✓
$D^0 \to K^-K^+$	✓	✓
$D^0 \to K^-\pi^+$	✓	✓
$D^0 \to K^0_S\pi^+\pi^-$	✓	✓
$D^0 \to \pi^-\pi^+$	✓	✓
$D^0 \to K^-\pi^+\pi^0\pi^0$	✓	-
$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$	✓	-
$D^0 \to \pi^-\pi^+\pi^0$	✓	-
$D^0 \to \pi^-\pi^-\pi^+\pi^0$	✓	-
$D^0 \to \pi^-\pi^+\pi^+\pi^-$	✓	-
$D^0 \to K^0_S\pi^0$	✓	-
$D^0 \to K^0_S\pi^+\pi^-\pi^0$	✓	-
$D^0 \to K^-K^+\pi^0$	✓	-
$D^+ \to K^-\pi^+\pi^+$	✓	✓
$D^+ \to K^0_S\pi^+\pi^0$	✓	✓
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	✓	✓
$D^+ \to K^0_S\pi^+$	✓	✓
$D^+ \to K^-K^+\pi^+$	✓	✓
$D^+ \to K^0_S K^+$	-	✓
$D^+ \to \pi^+\pi^0$	✓	-
$D^+ \to K^-\pi^+\pi^+\pi^0$	✓	-
$D^+ \to \pi^+\pi^+\pi^-$	✓	-
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	✓	-
$D^+ \to K^+K^0_S K^0_S$	✓	-
$D^0 \to K^-K^+\pi^+\pi^0$	✓	-

$R(D^{(*)})$ measurement at Belle II

Systematics budget

Fractional contributions to the total (relative) uncertainty of *R(D)* and *R(D*)*

Systematic Uncertainty	$\Delta\mathcal{R}(D^{+})$	$\Delta\mathcal{R}(D^{*+})$
Additive		
MC sample size	0.033 (8.0%)	0.014 (4.7%)
Gap $\mathcal{B}$	0.027 (6.4%)	0.001 (0.1%)
LID efficiency (μ)	0.022 (5.1%)	0.001 (0.1%)
Fake rates (e)	0.012 (2.9%)	0.003 (0.9%)
Continuum fraction	0.002 (0.6%)	0.001 (0.2%)
Gap FFs	0.002 (0.5%)	0.001 (0.2%)
$\overline{B} \to D^{(*)}\ell\bar{\nu}_\ell$ / $\tau\bar{\nu}_\tau$ FFs	0.002 (0.5%)	0.002 (0.7%)
$\mathcal{B}(\overline{B} \to D^{**}\ell\bar{\nu}_\ell)$	0.002 (0.5%)	0.001 (0.1%)
$\overline{B} \to D^{**}\ell\bar{\nu}_\ell$ FFs	0.001 (0.3%)	0.001 (0.2%)
BDT modeling	0.001 (0.3%)	0.001 (0.2%)
LID efficiency (e)	0.001 (0.1%)	0.001 (0.2%)
Fake rates (μ)	0.001 (0.1%)	0.001 (0.1%)
$\pi^{\pm}$ from $D^* \to D\pi$	0.003 (0.7%)	0.001 (0.1%)
Total Additive Uncertainty	0.050 (12%)	0.015 (4.8%)
Multiplicative		
$\overline{B} \to D^{(*)}\ell\bar{\nu}_\ell$ / $\tau\bar{\nu}_\tau$ FFs	0.009 (2.1%)	0.011 (3.5%)
MC sample size	0.007 (1.7%)	0.004 (1.2%)
LID efficiency (e)	0.001 (0.2%)	0.001 (0.2%)
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.001 (0.2%)	0.001 (0.2%)
LID efficiency (μ)	0.001 (0.1%)	0.001 (0.1%)
Tracking efficiency	0.001 (0.1%)	0.001 (0.1%)
$\pi^{\pm}$ from $D^* \to D\pi$	– (–)	0.001 (0.2%)
Total Multiplicative Uncertainty	0.012 (2.8%)	0.011 (3.7%)
Total Syst. Uncertainty	0.051 (12%)	0.018 (6.2%)
Total Stat. Uncertainty	0.074 (18%)	0.034 (11%)
Total Uncertainty	0.090 (22%)	0.039 (13%)