Tests of Lepton Flavour Universality in B decays at Belle II

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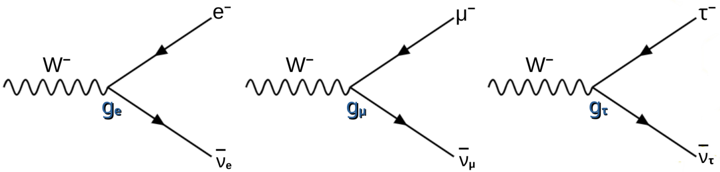
Outline

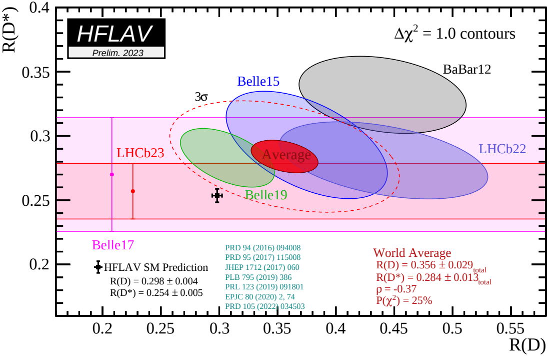
1. Introduction
   - LFU
   - Experimental techniques
2. First results from Belle II
   - $R(X_{\tau/\ell})$
   - $R(D^*)$
3. Ongoing analyses
   - $R(\pi)$
4. Prospects and summary



- in the SM all leptons share the same electroweak coupling, a symmetry known as Lepton Flavour Universality: $g_e = g_\mu = g_\tau$
- difference in dynamic driven by differences in masses: $m_e < m_\mu < m_\tau$
- Is this accidental (~~fundamental~~) symmetry of the Standard Model fully preserved?
- test "laboratories": on shell W decays in ATLAS/CMS; off shell in B & τ decays at Belle/Belle II; ...

LFU in B decays

tension with SM



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

$\ell = e, \mu$

deviation from SM:

$\sim 1.98\sigma$ for $R(D)$

$\sim 2.15\sigma$ for $R(D^*)$

$\sim$ **3.2σ for $R(D)$&$R(D^*)$**

- ongoing updates on $R(D^{(*)})$ @ Belle II
- measure other inclusive ($R(X_{\tau/\ell})$) and exclusive ($R(\pi)$, $R(\rho)$) ratios
- utilize additional complementary observables sensitive to interaction structures

  $\Rightarrow$ more in next talk by Mateusz Kaleta

MC generators

- $e^+e^- \to (\Upsilon(4S) \to B\overline{B})$ for measured B decays by EvtGen (ver. V00-10-07 / ver. R02-00-00)
- $e^+e^- \to q\overline{q}(q = u, d, s, c)$ by KKMC
- decay rates of B decays for which no measurements exist + hadronization of $e^+e^- \to q\overline{q}$ by PYTHIA (ver. 6 / ver. 8)
- τ decays by TAUOLA
- electromagnetic final-state radiation by PHOTOS

- detector response by GEANT (ver. 3 / ver. 4)
- remark: independent `DECAY.DEC` files and (some) EvtGen models in basf and basf2 (Belle and Belle II frameworks)

Experimental techniques

tagging in B decays

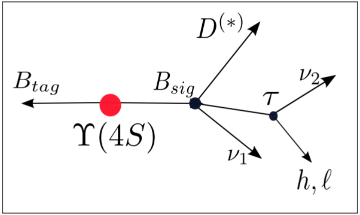
efficiency

purity

- Inclusive
  $B \to$ *hadrons* (inclusive modes)
  $\epsilon \approx O(1\%)$
  - \+ large statistics
  - – large backgroud
- Semileptonic
  $B \to D^{(*)}\ell\nu_\ell$
  $\epsilon \approx O(0.3\%)$
  - \+ efficient reconstrucion
  - – less information about $B_{\rm tag}$ due to ν_ℓ
- Hadronic
  $B \to$ *hadrons* (exclusive modes)
  $\epsilon \approx O(0.1\%)$
  - \+ high purity
  - – low tagging efficiency

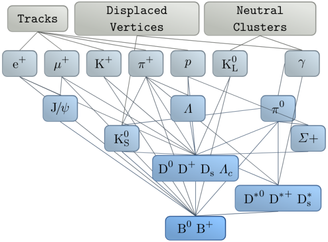
Modes with missing energy (i.e. multi ν) in final state:

- exclusive production of $B\overline{B}$ pairs at B factories
- kinematical constrains from beam energy
- $B_{\rm tag}$ kinematics, flavour/charge



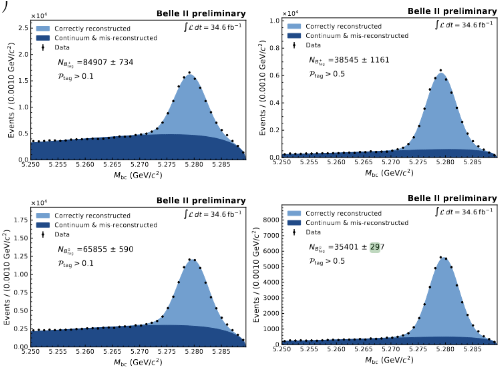
Experimental techniques

exclusive B_{tag} reconstruction algorithm



Full Event Interpretation (FEI)

- improved algorithm based on BDTs
- hierarchical approach to reconstruct $O(10^4)$ decay chains
- for hadronic tag: dominant tag-side decay mode categories: $D\pi$, $D^*\pi$, $Dn\pi$, $D^*n\pi$
- for semileptonic tag: $D^{(*)}\ell\nu$, $D^{(*)}\pi\ell\nu$
- $\epsilon_{SL} \approx 2\%$, $\epsilon_{had} \approx 0.5\%$

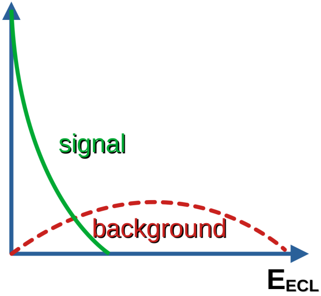


$$M_{bc} = \sqrt{E_{\text{beam}}^2 - (\vec{p}_{B_{tag}}^{\,CM})^2}$$

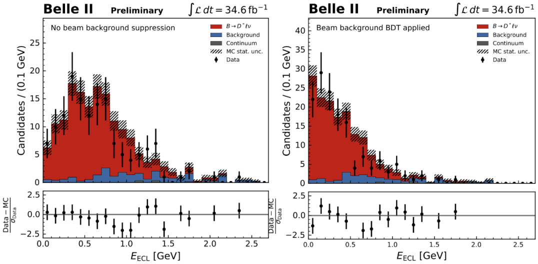
- E_{beam} is the beam energy in the CMS of $\Upsilon(4S)$
- $\vec{p}_B$ is the momentum of the reconstructed B_{tag}

Experimental techniques

@ B-factories: key variable



ideal vs. reconstructed



E_{ECL} (called also E_{extra})

- hermetic, with large acceptance detector (Electromagnetic CaLorimeter)
- sum energy of all neutral clusters in the event after reconstruction of signal and B_{tag}
- $E_{\mathrm{ECL}} \approx 0$ 0 for correctly reconstructed signal
- $E_{\mathrm{ECL}} > 0$ for bkg, extra energy due to additional energy deposition
- final shape depends on photons selection, which reduce beam bkg and hadronic split-off photons

$R(X_{\tau/\ell})$

the first test of LFU via **inclusive** B decays at Belle II

$R(X_{\tau/\ell})$: ratio explicitly or with B mesons only

PRL. **132**, 211804 (2024)

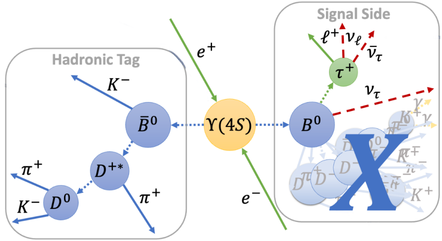
$$R(X) = \frac{\mathcal{B}(B \to X\tau^+\nu_\tau)}{\mathcal{B}(B \to X\ell^+\nu_\ell)}$$

Challenges

- large background from less constrained X (significant systematic uncertainties associated with background composition)
- difficult MC modeling of the $X = D, D^*, D^{**}$ (source of cross-feeds), non resonant hadronic decays ("gap") ≈ 1 %
- $\Rightarrow$ dedicated data driven templates reshaping

Selection

- hadronic FEI ($\epsilon_{had} \approx 0.1\%$) $+\ell$
- optimized lepton ID requirements and quality of tracks+clusters from X
- continuum suppressed by BDT



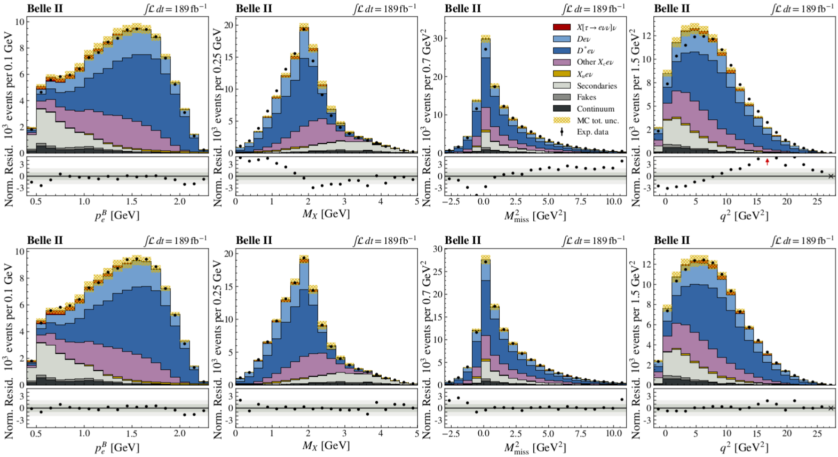
based on DATA sample: 189 fb^{-1}

Control samples

- "high-p_ℓ^B" ($p_\ell^B > 1.4$ GeV$/c^2$) composed of 95%$B \to X\ell\nu$
- "same charge" enriched with fakes, secondaries, continuum, $B \to X\tau(\ell)\nu$ from neutral B meson oscillations

$R(X_{\tau/\ell})$

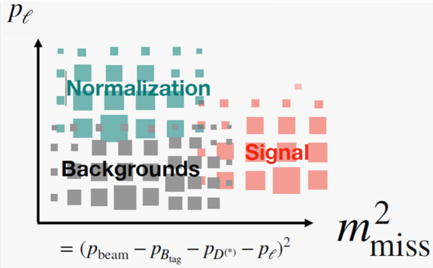
simulation reweighting



- four key kinematic quantities
- electron channel before (top) and after (bottom) template shape calibration
- mismodeling in M_X due to significant deficit/excess for low/high region due to relative abundance od D decays with K_L^0

Strategy

- 2D binned likelihood template fit in the lepton momentum $p_\ell^{B_{\rm sig}}$ in signal B rest frame and squared missing mass $M^2_{\rm miss} = ((\sqrt{s}, \vec{0}) - P_{B_{\rm sig}} - P_{B_{\rm tag}})$
- 4 components: signal, normalization, $B\overline{B}$ bkg, continuum
- continuum with constraint on yield derived from off-resonance data

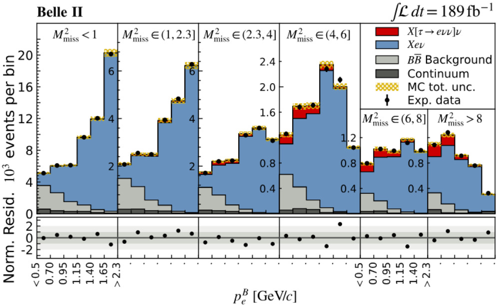


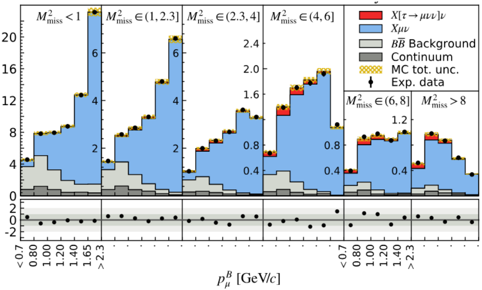
Signal yield

- $X\tau\nu$: $N_e^{\rm meas} = 2590 \pm 450$
  $N_\mu^{\rm meas} = 1810 \pm 460$
- $X\ell\nu$: $N_e^{\rm meas} = 95690 \pm 770$
  $N_\mu^{\rm meas} = 89970 \pm 810$
- $R(X_{\tau/\ell}) = \frac{N_\tau^{\rm meas}}{N_\ell^{\rm meas}} \times \frac{N_\tau^{\rm sel}}{N_\ell^{\rm sel}} \times \frac{N_\tau^{\rm gen}}{N_\ell^{\rm gen}}$
- **meas**ured, **sel**ected, **gen**erated

$R(X_{\tau/\ell})$

Fit results



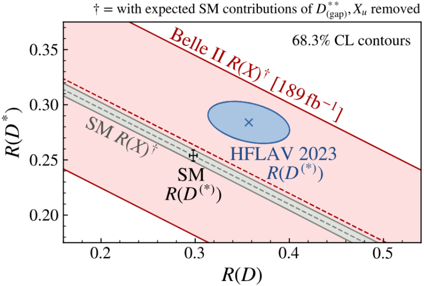


- 1D template fit projections of lepton spectra in missing mass bins
- SM prediction:
  $R(X_{\tau/\ell}) = 0.223 \pm 0.005$
- specific modes:
  $R(X_{\tau/e}) = 0.232 \pm 0.020(stat) \pm 0.037(syst)$
  $R(X_{\tau/\mu}) = 0.222 \pm 0.027(stat) \pm 0.050(syst)$
- combined:
  $R(X_{\tau/\ell}) = 0.228 \pm 0.016 \pm 0.036$

$R(X_{\tau/\ell})$

Systematics + reinterpretation

Source	Uncertainty [%] e	μ	ℓ
Experimental sample size	8.8	12.0	7.1
Simulation sample size	6.7	10.6	5.7
Tracking efficiency	2.9	3.3	3.0
Lepton identification	2.8	5.2	2.4
$X_c\ell\nu$ reweighting	7.3	6.8	7.1
$B\bar{B}$ background reweighting	5.8	11.5	5.7
$X\ell\nu$ branching fractions	7.0	10.0	7.7
$X\tau\nu$ branching fractions	1.0	1.0	1.0
$X_c\tau(\ell)\nu$ form factors	7.4	8.9	7.8
Total	18.1	25.6	17.3



- dominant systematics for shape reweighting for bkg templates, $X\ell\nu$ composition and form factors
- result in agreement with SM prediction as well consistent with enhanced semitauonic BF

$R(D^*)$

the first test of LFU via **exlusive** B decays at Belle II

$R(D^*)$

PRD **110** 072020 (2024)

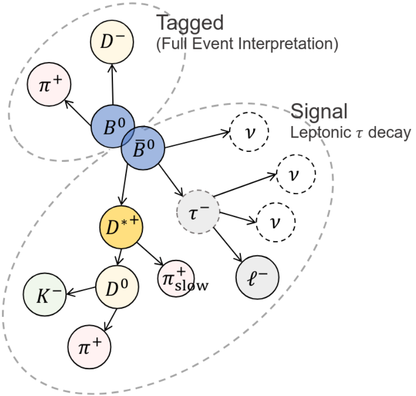
$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau^+ \nu_\tau)}{\mathcal{B}(B \to D^* \ell^+ \nu_\ell)}$$

Challenges

- multiple missing neutrinos in the final state $\Rightarrow$ no clear peak in observables
- modeling of leading bkg: $B \to D^{**} \ell \nu$
- calibrations + corrections (fake D^*, efficiency of FEI, . . .)

Reconstruction

- tag side by hadronic FEI
  signal side by leptonic τ decays
- decay chains:
  $B^0 \to \overline{D^*} \ell^+ \nu$, $B^+ \to \overline{D^{*0}} \ell^+ \nu$
- three D^* decay channels:
  $D^{*+} \to D^0 \pi^+$, $D^+ \pi^0$; $D^{*0} \to D^0 \pi^0$



based on DATA sample: 189 fb^{-1}

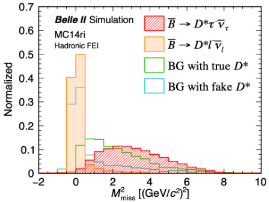
$R(D^*)$

signal extraction

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

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

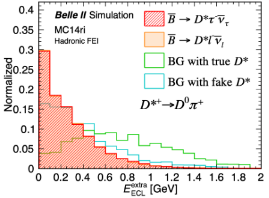
(ε: reconstruction efficiency)



Missing mass

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

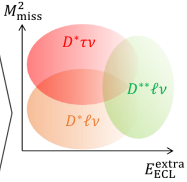
$\bar{B} \to D^*\ell^-\bar{\nu}_\ell$ ($\ell = e, \mu$) events peak at 0.
$\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ events have a larger $M^2_{\rm miss}$ due to multiple-neutrino emission from the τ decay.



Extra energy in the calorimeter

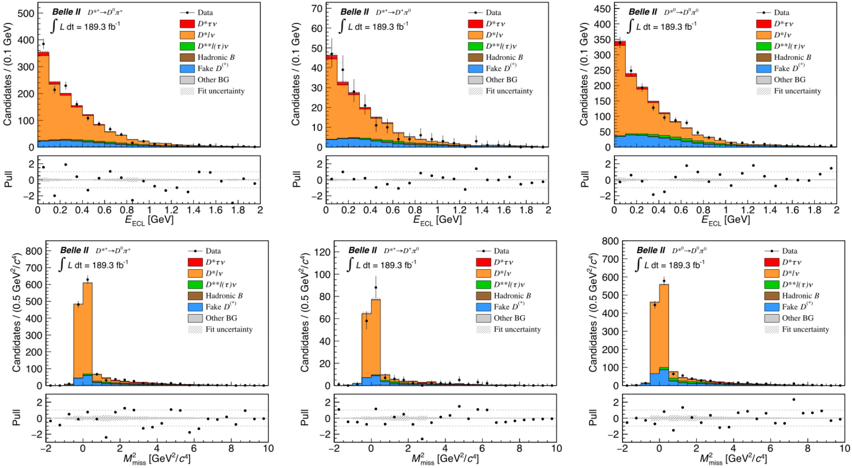
$E^{\rm extra}_{\rm ECL}$ Sum of the energy of clusters in the calorimeter not used for the $B\bar{B}$ reconstruction

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



$R(D^*)$

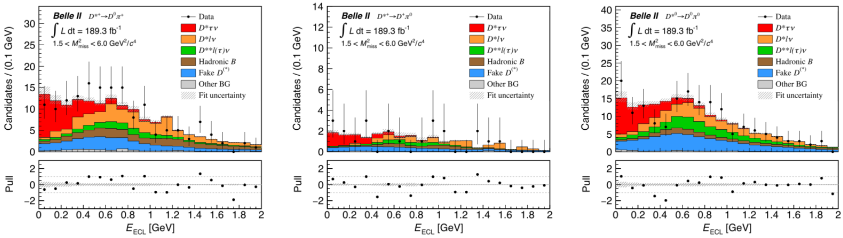
Fit results



$R(D^*)$

Result + E_{ECL} in signal enriched region

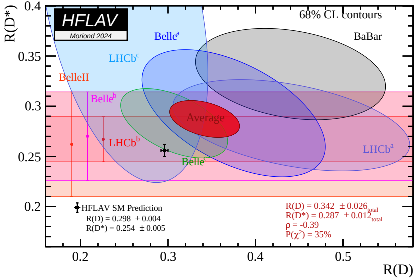
$$R(D^*) = 0.262^{+0.041}_{-0.039}(\mathrm{stat})^{+0.035}_{-0.032}(\mathrm{syst})$$



R(D*)

Systematics + update from HFLAV (Moriond 2024)

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$



- **updated deviation from SM** with new Belle II and LHCb results:
  $\sim$ 1.6σ for $R(D)$
  $\sim$ 2.5σ for $R(D^*)$
  $\sim$ **3.31σ for $R(D)\&R(D^*)$**

LFU tests in $b \to u\ell\nu$

$R(\pi), R(\rho)$

test of LFU in rare semitauonic B decays

$$R(\pi) = \frac{\mathcal{B}(B \to \pi\tau\nu)}{\mathcal{B}(B \to \pi\ell\nu)},$$

$$R(\rho) = \frac{\mathcal{B}(B \to \rho\tau\nu)}{\mathcal{B}(B \to \rho\ell\nu)}, \ell = e, \mu$$

Motivation:

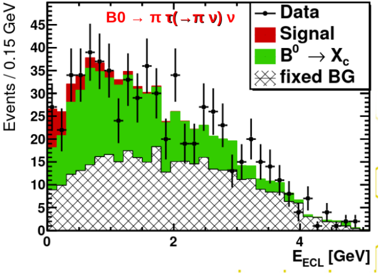
- R(π) similar to R(D) ➛ sensitive to scalar mediators
  - e.g. modification of q2 in 2HDM type-II
- R(ρ) similar to R(D*) ➛ sensitive to tensor mediators
  - larger set of angular observables that may probe NP effects

Challenges:

- **SM:** BF ($B^0 \to D^- \tau\nu$) = 1.05 ± 0.23 **x10^{-2}**
- **SM:** BF ($B^+ \to D^{*0} \tau\nu$) = 1.88 ± 0.20 **x10^{-2}**
- **SM:** BF ($B^0 \to \pi^- \tau\nu$) = 0.94 ± 0.04 **x10^{-4}**
- **SM:** BF ($B^+ \to \rho^0 \tau\nu$) = 0.85 ± 0.04 **x10^{-4}**

Experimental status:

- **UL:** BF (B0➛π τ ν) < 2.5 x10^{-4}; PRD 93, 032007 (2016)
- BF (B0➛π τ ν) = (1.52 ± 0.72 ± 0.13) x 10-4 @ 2.4 σ
- **SM**: R(π) = 0.641 ± 0.016; PRD 92 (11), 115019 (2015)
  - exp test of LFU: **R(π) = 1.05 ± 0.51**



$R(\pi)$

towards measurement

Modes:

- **signal**: $B^0 \to \pi^- \tau \nu$; $B^+ \to \rho^0 \tau \nu$
- **normalization**: $B^0 \to \pi^- l \nu$; $B^+ \to \rho^0 l \nu$; $l = e, \mu$

Reconstruction:

- B_{tag}: hadronic FEI
- B_{sig}: require 2 tracks: $\pi + e/\mu$
- cross check: hadronic τ decays ($\tau \to \pi/\rho\, \nu$)

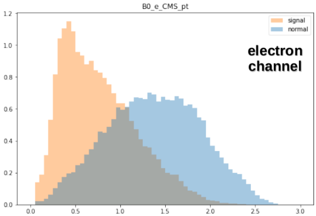
Bkg:

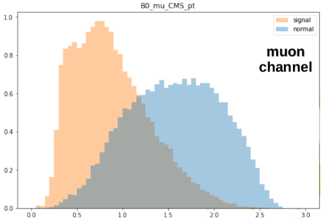
- dominated by $B \to X_c\, (e\backslash\mu\backslash\tau)\, \nu$
- continuum ($c\bar{c}$, $s\bar{s}$, $u\bar{u}$, $d\bar{d}$)

Experimental challenges:

- low momentum leptons from $\tau \Rightarrow$ require improvement of PID, corrections of acceptance effects, better background suppression
- optimization purity of $E_{ECL} \Rightarrow$ higher S/N

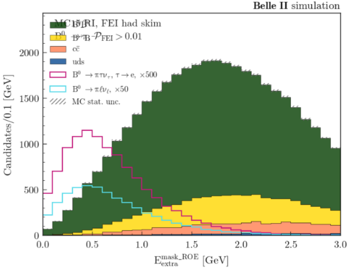
reconstructed transverse momentum of leptons from **signal** and **normalization** modes

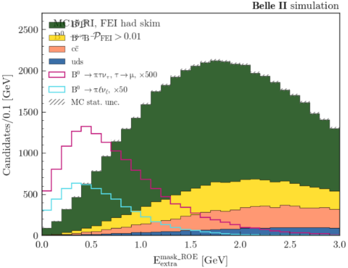


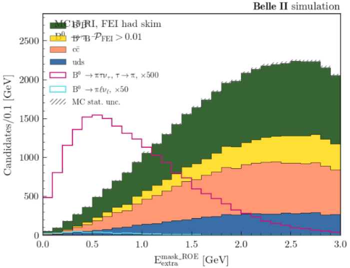


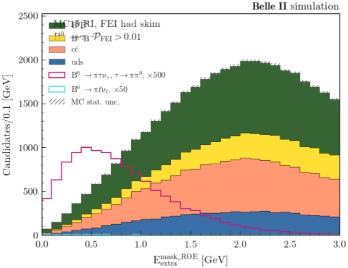
$R(\pi)$

signal extraction from E_{extra} (from AN)



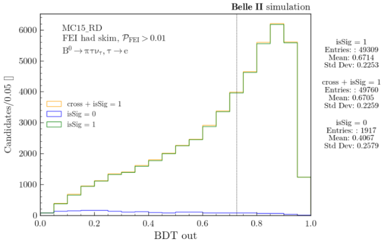


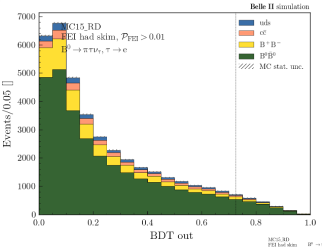




$R(\pi)$

bkg suppressed by BDT in electron mode (from AN)





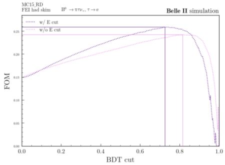
$$\text{FOM} = \frac{S}{\sqrt{S+B}}$$

S and B are scaled to data lumi

FOM is calculated with the cut on cut on $E_{extra} < 1.5$ GeV.

BDT out > 0.73	Signal efficiency [%]	Bkg retention [%]
BDT cut	51.27 ± 0.23	4.58 ± 0.05
All selection	0.1436 ± 0.0009	6.28 ± 0.04

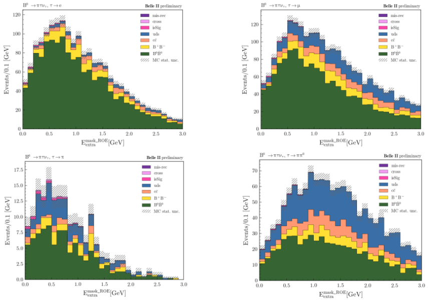
Signal efficiency also includes FEI reconstruction efficiency (#TM signal events/# generated MC events).



Comparing BDTs trained w/ and w/o cut on Eextra.

$R(\pi)$

sensitivity study (from AN)



		# signal events		# bkg events	
		isSig	isSig + cross	!isSig	!isSig + !cross
w/o E_{extra} cut	$\tau \to e$	10	10	1787	1787
	$\tau \to \mu$	8	9	2332	2329
	$\tau \to \pi$	3	5	165	164
	$\tau \to \pi\pi^0$	3	3	1347	1347
	All	24	27	5631	5627
w/ E_{extra} cut $E_{extra} < 1.5$ GeV	$\tau \to e$	9	9	1297	1297
	$\tau \to \mu$	8	9	1452	1448
	$\tau \to \pi$	3	4	149	144
	$\tau \to \pi\pi^0$	3	3	760	760
	All	23	25	3658	3649

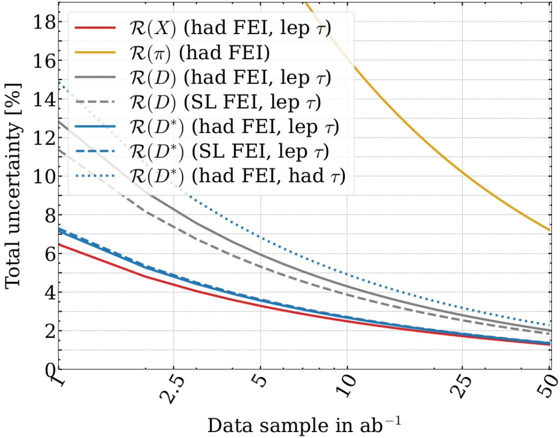
Expected number of events for signal and background for 365 fb^{-1}.
Number of signal events is estimated from signal MC samples.

Further reduction of bkg is needed:

- Improve BDT
- Veto extra neutral particles from ROE - needs to be added to the reconstruction script

Prospects

extrapolation from Snowmass report



$$R(X) = \frac{\mathcal{B}(B \to X \tau^+ \nu_\tau)}{\mathcal{B}(B \to X \ell^+ \nu_\ell)}$$

$X = \pi, D, D^*$; $\ell = e, \mu$

- expected Belle II sensitivity for various R measurements as a function of luminosity based on existing Belle and Belle II studies

Summary

+ prospects

- Belle II provide precise experimental information to resolve the puzzle with $R(D^{(*)})$ anomalies
- the first measurement of $R(X_{\tau/\ell})$, test of LFU via **inclusive** B decays
- the first measurement of $R(D^*)$ on Belle II dataset
- ongoing study on $R(\pi)$

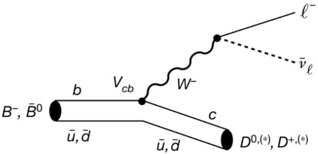
- important to carry out other complementary measurements in semitauonic B decays (differential distributions, angular observables, . . .)
- still untapped potential from combining the Belle and Belle II datasets
- indication of possible violation of LFU, often accompanied by LFV $\Rightarrow$ more in talk by Junaid Ur Rehman

BACKUP

Credits to :
Anja Novosel (IJS), Henrik J. (Bonn), Kazuki Kojima (Nagoya), Florian Bernlochner (Bonn)
for plots, slides or figures

Semitauonic B decays

SM predictions + New Physics scenarios

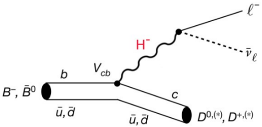


Arithmetic average of SM predictions from HFLAV:

$$R(D^*)^{\rm SM} = \frac{\mathcal{B}(B \to \bar{D}^* \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D}^* \ell^+ \nu_\ell)} = 0.258 \pm 0.005$$

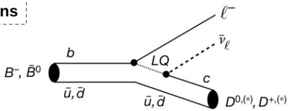
$$R(D)^{\rm SM} = \frac{\mathcal{B}(B \to \bar{D} \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D} \ell^+ \nu_\ell)} = 0.299 \pm 0.003$$

Charged Higgs

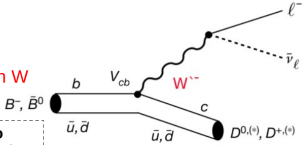


impact on R, q2, angular distributions

Leptoquarks



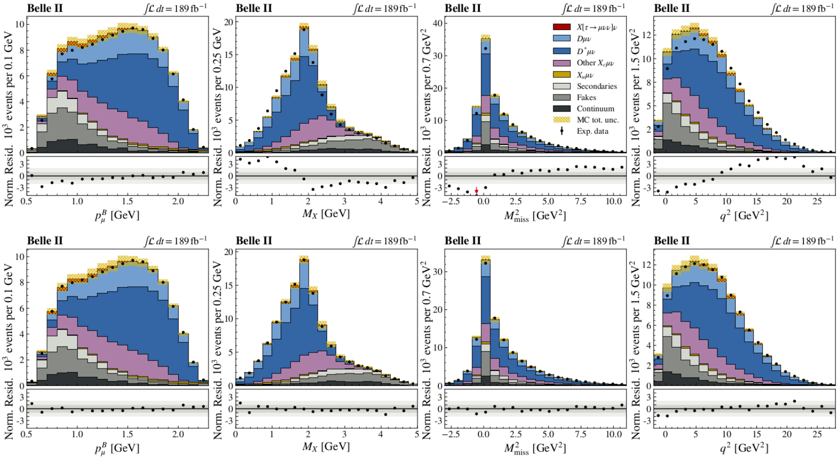
RH vector boson W



modify only R, no impact on kinematics

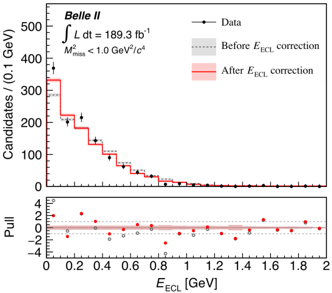
$R(X_{\tau/\ell})$

simulation reweighting



- four key kinematic quantities
- muon channel before (top) and after (bottom) template shape calibration
- mismodeling in M_X due to significant deficit/excess for low/high region due to relative abundance od D decays with K^0_L

$R(D^*)$



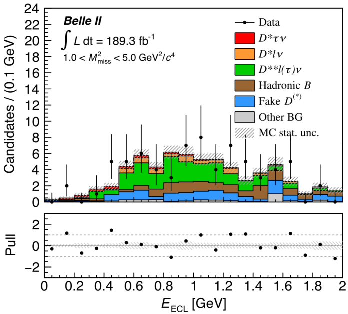


TABLE I. Simulated branching fractions of $\bar{B} \to D^{**}\ell^-\bar{\nu}$ decays used for modeling the leading background. The branching fractions used for the evaluation of the systematic uncertainty due to nonresonant $\bar{B} \to D^{(*)}\pi\ell^-\bar{\nu}_\ell$ are shown in parentheses.

	Branching fraction $[10^{-3}]$	
Decay	$\mathcal{B}(B^0)$	$\mathcal{B}(B^+)$
$\bar{B} \to D_1\ell^-\bar{\nu}_\ell$	6.16 ± 1.01	6.63 ± 1.09
$\bar{B} \to D_0^*\ell^-\bar{\nu}_\ell$	3.90 ± 0.70	4.20 ± 0.75
$\bar{B} \to D_1'\ell^-\bar{\nu}_\ell$	3.90 ± 0.84	4.20 ± 0.90
$\bar{B} \to D_2^*\ell^-\bar{\nu}_\ell$	2.73 ± 0.30	2.93 ± 0.32
$\bar{B} \to D_sK\ell^-\bar{\nu}_\ell$	$\cdots$	0.30 ± 0.14
$\bar{B} \to D_s^*K\ell^-\bar{\nu}_\ell$	$\cdots$	0.29 ± 0.19
$\bar{B} \to D\pi\ell^-\bar{\nu}_\ell$	$0\ (0.3 \pm 0.9)$	$0\ (0.3 \pm 0.9)$
$\bar{B} \to D^*\pi\ell^-\bar{\nu}_\ell$	$0\ (-1.1 \pm 1.1)$	$0\ (-1.1 \pm 1.1)$
$\bar{B} \to D\pi\pi\ell^-\bar{\nu}_\ell$	0.58 ± 0.82	0.62 ± 0.89
$\bar{B} \to D^*\pi\pi\ell^-\bar{\nu}_\ell$	2.01 ± 0.95	2.16 ± 1.02
$\bar{B} \to D\eta\ell^-\bar{\nu}_\ell$	4.09 ± 4.09	3.77 ± 3.77
$\bar{B} \to D^*\eta\ell^-\bar{\nu}_\ell$	4.09 ± 4.09	3.77 ± 3.77
$\bar{B} \to D_1\tau^-\bar{\nu}_\tau$	0.52 ± 0.52	0.56 ± 0.56
$\bar{B} \to D_0^*\tau^-\bar{\nu}_\tau$	0.33 ± 0.33	0.36 ± 0.36
$\bar{B} \to D_1'\tau^-\bar{\nu}_\tau$	0.33 ± 0.33	0.36 ± 0.36
$\bar{B} \to D_2^*\tau^-\bar{\nu}_\tau$	0.23 ± 0.23	0.25 ± 0.25
$\bar{B} \to D\pi\pi\tau^-\bar{\nu}_\tau$	0.05 ± 0.05	0.05 ± 0.05
$\bar{B} \to D^*\pi\pi\tau^-\bar{\nu}_\tau$	0.17 ± 0.17	0.18 ± 0.18
$\bar{B} \to D\eta\tau^-\bar{\nu}_\tau$	0.35 ± 0.35	0.32 ± 0.32
$\bar{B} \to D^*\eta\tau^-\bar{\nu}_\tau$	0.35 ± 0.35	0.32 ± 0.32