Recent results from Belle II

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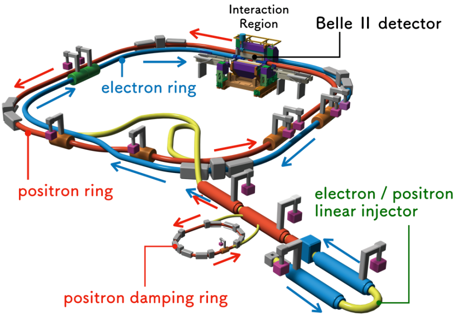
Outline

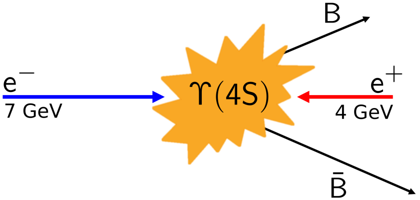
1. Introduction
   - Belle II experiment overview
   - Experimental techniques
2. Recent results from Belle II
   - tests of Lepton Flavour Universality in exclusive and inclusive semitauonic B decays
   - measurement of fully leptonic decay $B \to \tau\nu$
   - $B \to K\nu\nu$ status (missing energy decay, one of the highlights from Run 1)
3. Prospects, upgrade plans and summary

Belle II experiment

SuperKEKB: new Intensity Frontier machine

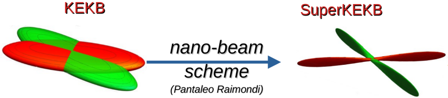


- **SuperKEKB + Belle II detector** $\equiv 2^{\mathrm{nd}}$ generation **super B-factory**
- **substantial upgrade** of the B factory facility located as KEK (Tsukuba, Japan)
- asymmetric $e^+ e^-$ collider operating **mainly** at energy of $\Upsilon(4S)$ (10.58 GeV)



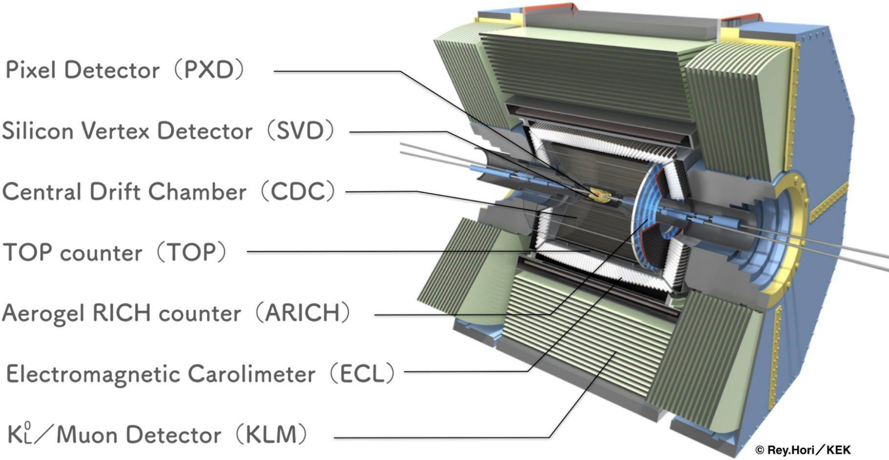
high luminosity achieved by:

- squeeze beams at IP (vertical 60 $\sim$nm)
- increase beam currents and smaller β_y^*
- larger crossing angle **(22 $\rightarrow$ 83 mrad)**



Belle II experiment

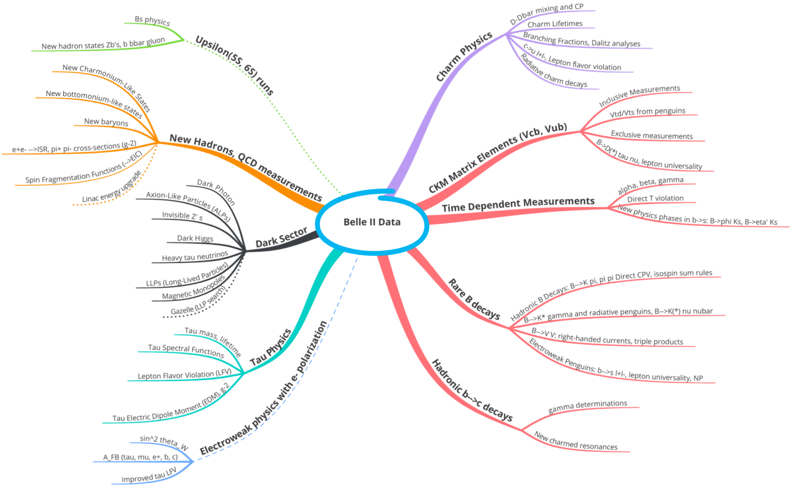
Belle II detector: multipurpose, $\sim 4\pi$ magnetic spectrometer



- hermetic detector: full event reconstruction to exploit kinematic constraints
- excellent tracking, PID, and vertex performance

Belle II physics program

unique capabilities of e^+e^- B factory



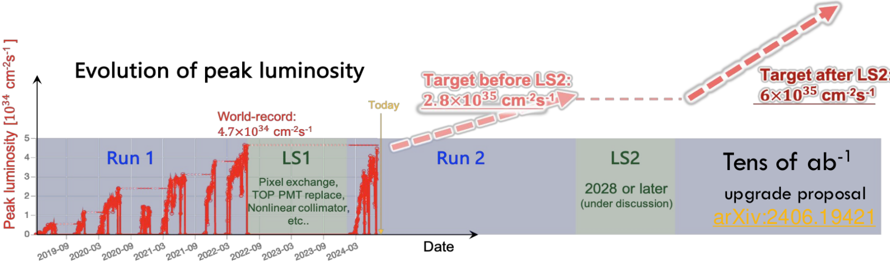
complementary to and competitive with the LHC and other flavour physics experiments

Current DATA status

+ luminosity projections

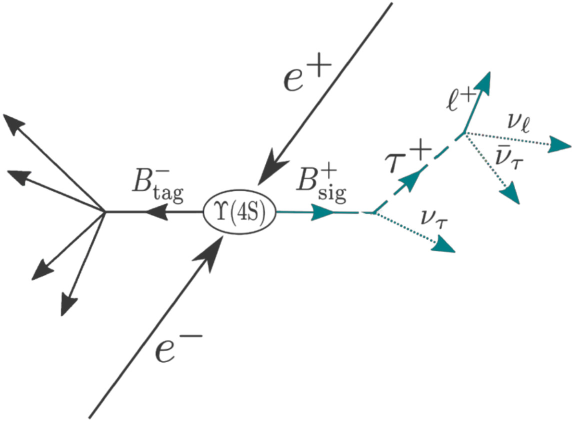
- Run 1 (2019-2022): $L_{\text{integrated}} \approx 400\ \text{fb}^{-1}$ ($\approx$ Babar dataset)
- Run 2 (2024-2028 or later): $\approx 150\ \text{fb}^{-1}$ so far; **goal: up to 10 ab^{-1}**

- **Dec 2024: World record of instantaneous L: $5.1 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$**
- **ultimate targets**:
  - peak luminosity: $6 \times 10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$ (30x KEKB)
  - integrate up to 50 ab^{-1} (50x Belle dataset) in next decade



Experimental techniques

tagging in B decays



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

tagging in B decays

efficiency

- Inclusive
  $B \to hadrons$ (inclusive modes)
  $\epsilon_{\mathrm{tag}} \approx O(100\%)$
  - + large statistics
  - – large backgroud
- Semileptonic (inclusive or exclusive)
  $B \to D^{(*)}\ell\nu_\ell$
  $\epsilon_{\mathrm{tag}} \approx O(10\%)$
  - + efficient reconstrucion
  - – less information about B_{tag} due to ν_ℓ
- Hadronic
  $B \to hadrons$ (exclusive modes)
  $\epsilon_{\mathrm{tag}} \approx O(1\%)$
  - + high purity
  - – low tagging efficiency

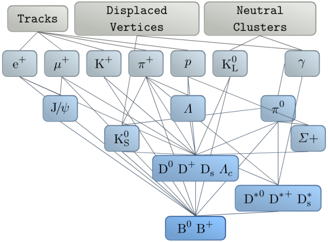
purity

$\Rightarrow$ optimal technique depends on what we have on signal side

$\Rightarrow$ total efficiency depends on final selection

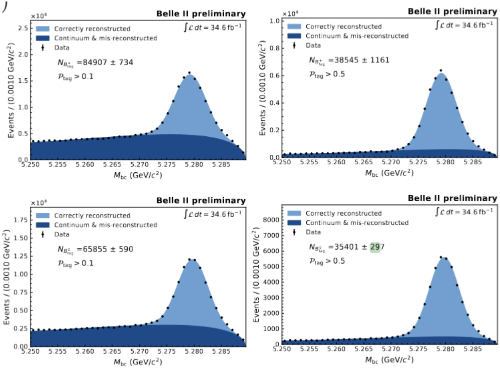
Experimental techniques

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: $D^{(*)}\ell\nu$, $D^{(*)}\pi\ell\nu$
- $\epsilon_{SL} \approx 2\%$, $\epsilon_{had} \approx 0.5\%$

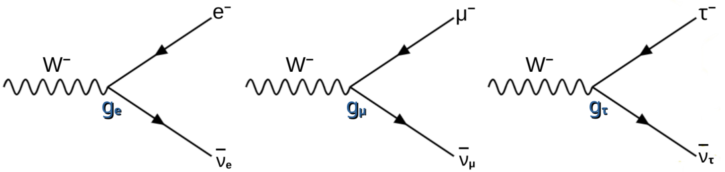


$$M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - (\vec{p}_{B_{tag}}^{\,\mathrm{CM}})^2}$$

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

Lepton Flavor Universality

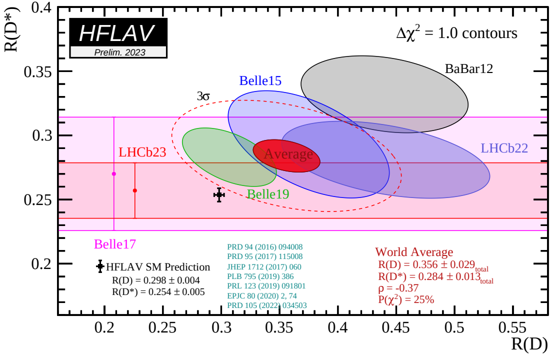
one of the assumption in SM



- 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 branching ratios driven by differences in masses: $m_e < m_\mu < m_\tau$, not by couplings
- test "laboratories": on shell W decays in ATLAS/CMS; off shell in B & τ decays at Belle/Belle II/LHCb; ...

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 $R(D^*)$

$\sim$ **3.2**$\boldsymbol{\sigma}$ **for** $\boldsymbol{R(D) \& R(D^*)}$

- 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

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

the first test of LFU via **exlusive** B decays at Belle II, with hadronic and semileptonic tagging

PRD **110** 072020 (2024)

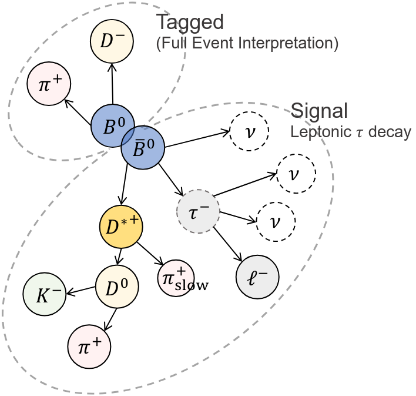
$R(D^*)$ with **hadronic tagging**

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:
  $B^0 \to \overline{D^*}\tau^+(\ell^+)\nu_\tau$, $B^+ \to \overline{D^{*0}}\tau^+(\ell^+)\nu_\tau$
- three D^* decay channels:
  $D^{*+} \to D^0\pi^+, D^+\pi^0$; $D^{*0} \to D^0\pi^0$



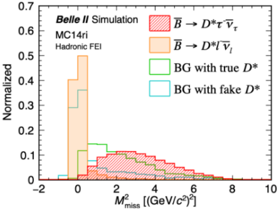
based on DATA sample: 189 fb^{-1}

$R(D^*)$ with **hadronic tagging**

signal extraction

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

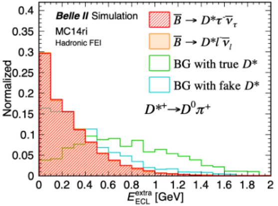
$$R(D^*) = \frac{N_{\bar{B}\to D^*\tau^-\bar{\nu}_\tau}}{N_{\bar{B}\to D^*\ell^-\bar{\nu}_\ell}/2} \cdot \frac{\varepsilon_{\bar{B}\to D^*\ell^-\bar{\nu}_\ell}}{\varepsilon_{\bar{B}\to D^*\tau^-\bar{\nu}_\tau}} \quad (\varepsilon\text{: reconstruction efficiency})$$



Missing mass

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

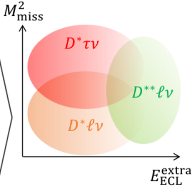
$\bar{B}\to D^*\ell^-\bar{\nu}_\ell$ ($\ell = e, \mu$) events peak at 0.
$\bar{B}\to D^*\tau^-\bar{\nu}_\tau$ events have a larger M^2_{miss} due to multiple-neutrino emission from the τ decay.



Extra energy in the calorimeter

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

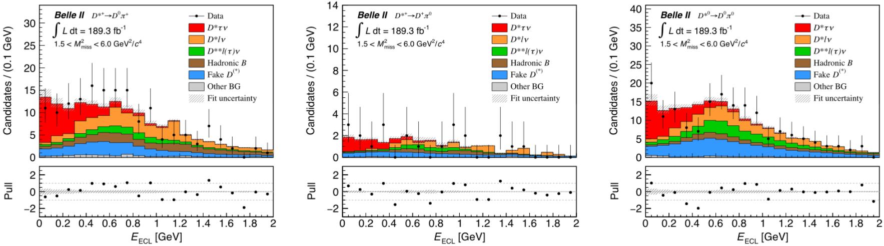
Signal candidates peak at 0.
Background candidates have a larger $E^{\text{extra}}_{\text{ECL}}$ due to additional clusters from missing particles.



$R(D^*)$ with **hadronic tagging**

Result + E_{ECL} in signal enriched region

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



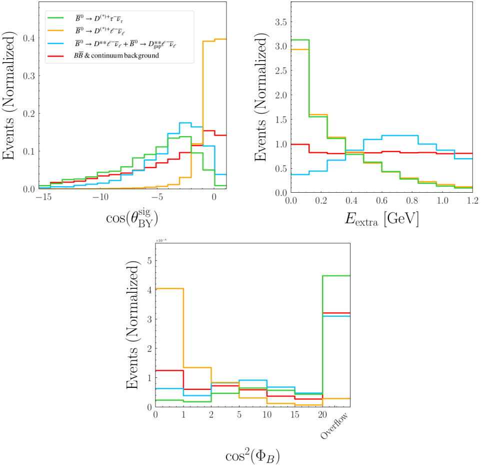
- result consistent with both the SM and the HFLAV average
- the leading systematics from pdfs shapes (O(10%)), simulated data statistics (O(7%))

$R(D^{(*)})$ with **semileptonic** tagging

preliminary

Reconstruction

- tag side B mesons with semileptonic exclusive modes (w/ FEI)
- on signal side: $B^0 \to D^{(*)-}\tau^+\nu$ and τ in leptonic decay channels
- D mesons on both sides reconstructed through various decays to K^+, K_s, π^+, π^0
- 4 components: signal, normalization, $B \to D^{**}\ell\nu$, $B\bar{B}$ + continuum



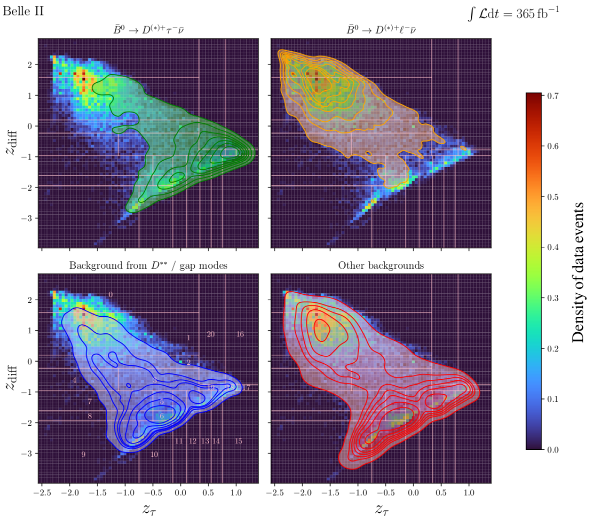
$\cos(\theta_{\rm BY}^{\rm sig})$ - cosine of the angle between B momentum and Y (momenta of visible decay products) in the c.m. frame

$\cos^2(\Phi_{\rm B}) = \frac{\cos^2\theta_{\rm BY}^{\rm sig} + \cos^2\theta_{\rm BY}^{\rm tag} + 2\cos\theta_{\rm BY}^{\rm sig}\cos\theta_{\rm BY}^{\rm tag}\cos\gamma}{\sin^2\gamma}$, where γ is angle between $\rm Y_{sig}$ and $\rm Y_{tag}$

$R(D^{(*)})$ with **semileptonic** tagging

Multivariate classification + fitting procedure

- BDT used to separate the events in 3 classes:
  - semitauonic signal
  - semileptonic signal
  - background events
- each event is assigned BDT score: z_τ, z_ℓ, z_{bkg}
- signal extracted in a 2D binned template fit of z_τ and $z_{\mathrm{diff}} = z_\ell$ - z_{bkg}



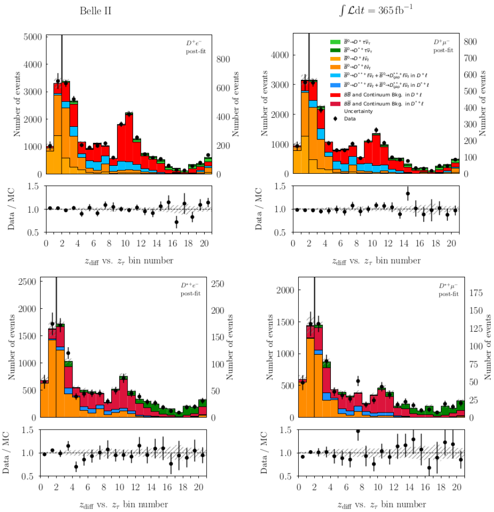
$R(D^*)$ with **semileptonic** tagging

Results based on full Run 1 dataset: 364.4 fb^{-1}

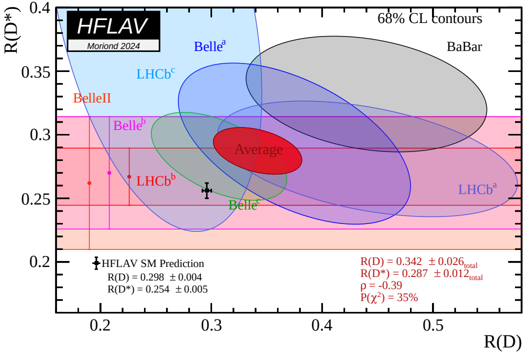
- fit performed over 4 separate channels: D^0e^-, $D^0\mu^-$, D^+e^-, $D^+\mu^-$
- preliminary results:

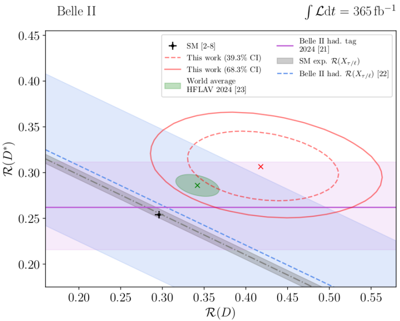
$$R(D) = 0.418 \pm 0.074(\text{stat}) \pm 0.051(\text{syst})$$
$$R(D^*) = 0.306 \pm 0.034(\text{stat}) \pm 0.018(\text{syst})$$

- measurement is statistically limited
- leading systematic uncertainties from the finite size of simulated samples, lepton identification efficiency and fake rate corrections



$R(D^{(*)})$
status 2025



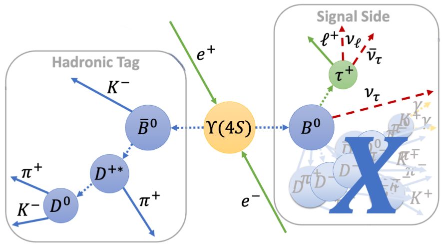


$$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X \tau^+ \nu_\tau)}{\mathcal{B}(B \to X \ell^+ \nu_\ell)}$$

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

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

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



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

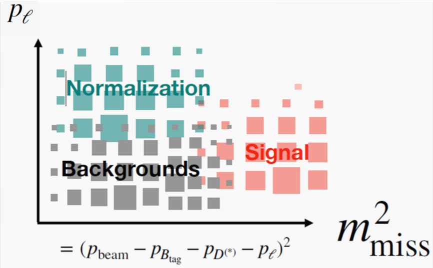
- "high-p_ℓ^B" ($p_\ell^B > 1.4$ GeV$/c^2$) composed of 95%$B \to X\ell\nu$
- "same charge" enriched with fakes, secondaries, continuum, $B \to X\tau(\ell)\nu$ from neutral B meson oscillations

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

Signal extraction

Strategy

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

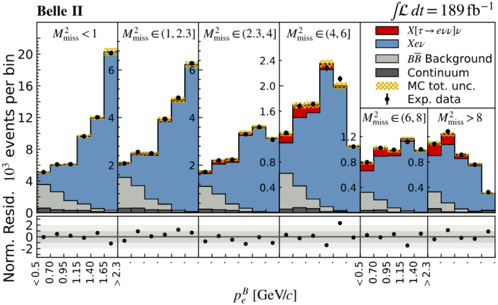


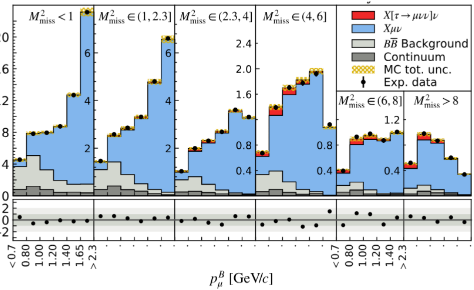
Signal yield

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

$R(X_{\tau/\ell})$: Fit results

1D template fit projections of lepton momenta in M^2_{miss} 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:
  $R(X_{\tau/\ell}) = 0.228 \pm 0.016 \pm 0.036$

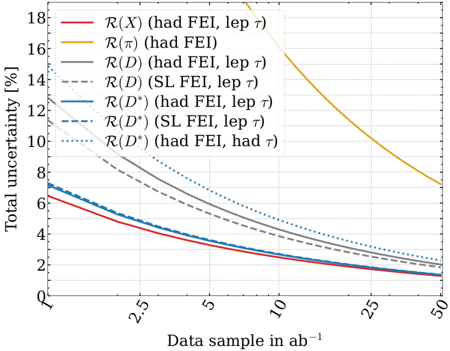
Main systematics:

- from poorly known modeling of $B \to D^{**}\ell\nu$, shape corrections

Prospects

expected Belle II sensitivity as fucntion of $\mathcal{L}_{\rm int}$

$$R(X) = \frac{\mathcal{B}(B \to X \tau^+ \nu_\tau)}{\mathcal{B}(B \to X \ell^+ \nu_\ell)};\ X = \pi, D, D^*;\ \ell = e, \mu$$



- extrapolation from Snowmass report: arXiv:2207.06307

The Belle II Experiment at SuperKEKB

– Input to the European Particle Physics Strategy,

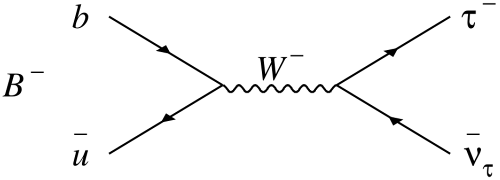
ArXiv: 2503.24155

measurements with 10 ab^{-1} (Run2):

- allow for accurate tagged measurement of $B \to D^{**}\ell\nu$, the most significant and poorly known background, whose feed-down may bias results
- exclude SM prediction on $R(D^{(*)})$ if the current central value persist
- give relative precisions: 1.8% for $R(D^*)$, 3.0% for $R(D)$

Measurement of $B \to \tau\nu$

rare, fully leptonic B decay, sensitive to BSM due to τ



ArXiv: 2502.04885, submitted to PRD

Measurement of $B \to \tau\nu$

Motivation and experimental status

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

- strongly helicity and CKM matrix $|V_{ub}|$ suppressed $\Rightarrow$ challenging to study
- very precise SM prediction: $\mathcal{B}(B^+\tau\nu_\tau) = (0.79 \pm 0.05) \times 10^{-4}$ depends on B meson decay constant (f_B = 190.0 $\pm$ 1.3 MeV, from lattice QCD)
- the cleanest channel to determine $|V_{ub}|$
- decay sensitive to BSM contributions (models with charged Higgs (2HDM), super-symmetric extension of SM), which can either suppress or enhance branching ratio
- PDG average: $\mathcal{BR} = (1.09 \pm 0.24) \times 10^{-4}$; consistent with SM prediction at 2 σ level, assuming $|V_{ub}|$ obtained with only exclusive decays

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

- all individual measurements below 5σ discovery threshold

Measurement of $B \to \tau\nu$

Reconstruction and experimental challenges

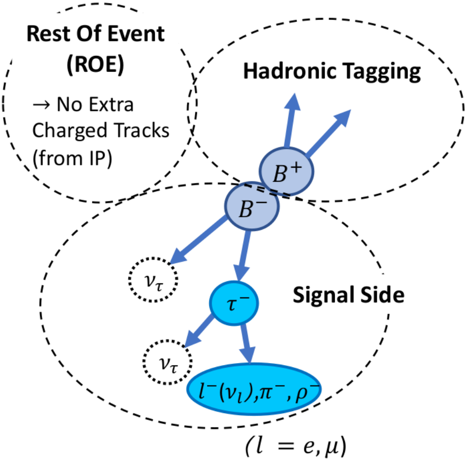
Reconstruction

- tag side (B_{tag}) with hadronic FEI (sum of exclusive modes)
- on signal side: τ reconstructed in 4 channels to maximise the reconstruction efficiency

  $\mathcal{B}(\tau \to e\nu\bar{\nu}) = 17.8\%$
  $\mathcal{B}(\tau \to \mu\nu\bar{\nu}) = 17.4\%$
  $\mathcal{B}(\tau \to \pi\nu) = 10.8\%$
  $\mathcal{B}(\tau \to \rho\nu) = 25.5\%$
  in total $\sim 70\%$

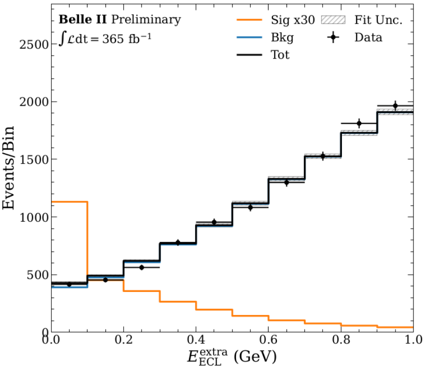
Experimental challenges

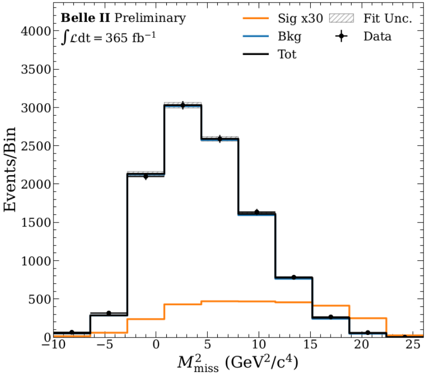
- low signal on huge bkg $\Rightarrow$ correct description of background: continuum and $B\bar{B}$
- validation with usage of many control channels $\Rightarrow$ correction of simulated data



Measurement of $B \to \tau\nu$

signal signature and fitting strategy





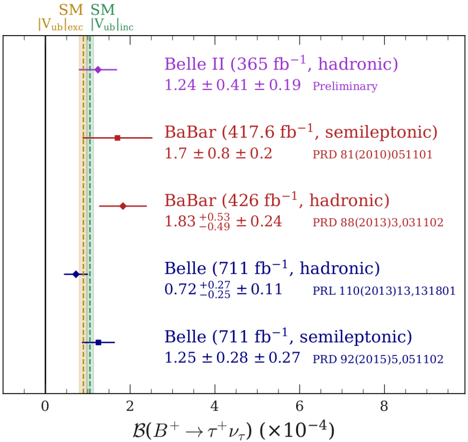
- the most discriminating variables: residual energy and missing mass
  $M^2_{miss} = (p^*_{\mathrm{beam}} - p^*_{\mathrm{tag}} - p^*_{\mathrm{sig}} - p^*_{\mathrm{ROE}})$
- **signal signature:** low E^{extra}_{ECL} and high M^2_{miss}
- signal extracted by simultaneous binned ML 2D fit to M^2_{miss} and E^{extra}_{ECL}

Measurement of $B \to \tau\nu$

Results based on full Run 1 dataset: 365 fb^{-1}

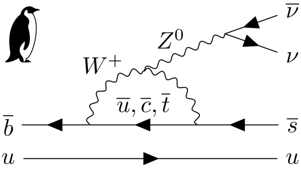
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = [1.24 \pm 0.41\,(\text{stat.}) \pm 0.19\,(\text{syst.})] \times 10^{-4}$$

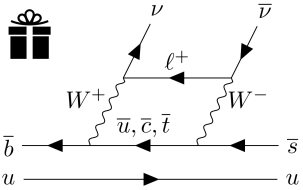
- total significance $\to 3.0\ \sigma$
- measurement limited by statistics
- the leading systematic uncertainties come from finite size of the simulated samples and neutral cluster calibration
- extracted value of $|V_{ub}|$ compatible with the exclusive and inclusive averages $|V_{ub}|_{B^+\to\tau^+\nu_\tau} = [4.41^{+0.74}_{-0.89}] \times 10^{-3}$

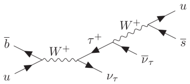


First evidence for $B^+ \to K^+ \nu\bar{\nu}$

missing energy decay $\Rightarrow$ golden channel of e^+e^- B-factories







PRD **109**, 112006 (2024)

Exclusive $b \to s\nu\nu$ processes

observables, SM predictions and current Upper Limits

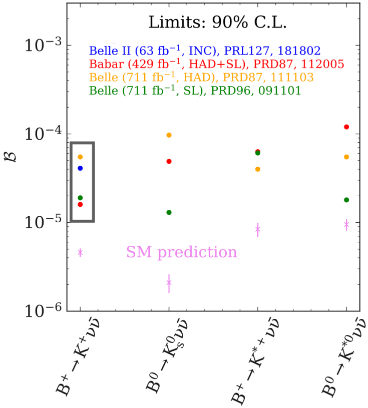
- complementary probes of non SM physics scenarios proposed to explain anomalies observed in $b \to s\ell^+\ell^-$
- (differential) branching fraction: $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$, $\frac{d\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{dq^2}$,
  where q^2 - squared mass of neutrinos
- polarization fraction $F_L(q^2)$ for K*

[EPJC 83 (2023) 3, 252]

Decay	SM total	LD contribution	SD contribution
$B^+ \to K^+\nu\bar{\nu}$	5.06 ± 0.31	0.63 ± 0.06	4.44 ± 0.30
$B^0 \to K^0_S\nu\bar{\nu}$	2.05 ± 0.14	—	2.05 ± 0.14
$B^+ \to K^{*+}\nu\bar{\nu}$	10.86 ± 1.43	1.07 ± 0.10	9.79 ± 1.42
$B^0 \to K^{*0}\nu\bar{\nu}$	9.05 ± 1.37	—	9.05 ± 1.37

$\times 10^{-6}$

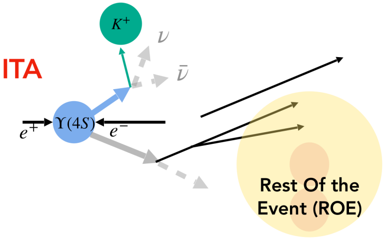
- pre-summer 2023 status



$B^+ \to K^+ \nu\bar{\nu}$

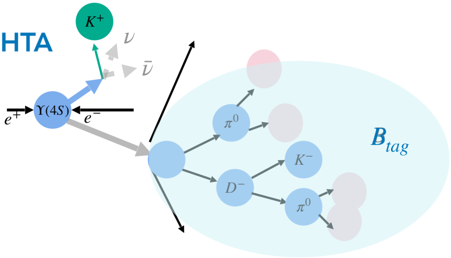
2 methods of reconstruction

common approach to reconstruct charged tracks and neutral clusters



Inclusive TAgging

- select candidates for signal track: kaon
- build $B_{\rm tag}$ out of Rest Of Event
- use the lowest value of $q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^*$ to select best candidate $\to$ resolution $\sim$ 1 GeV



Hadronic TAgging

- reconstruct hadronic tag ($B_{\rm tag}$)
- out of remaining tracks select signal track consistent with kaon
- use the lowest value of q^2_{rec} to select best candidate $\to$ resolution $\sim$ 250 GeV

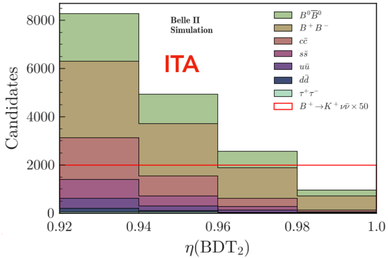
$B^+ \to K^+ \nu\bar{\nu}$

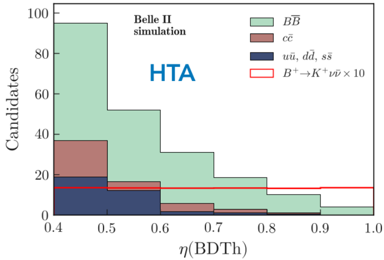
background suppression and fitting strategy

ITA: 2 consecutive BDTs to suppress continuum and $B\bar{B}$
signal eff. = 8%; purity = 0.9%
HTA: one BDT to suppress $B\bar{B}$ and continuum
signal eff. = 0.8%; purity = 3.5%

fitting strategy: binned maximum likelihood fit to extract parameter of interest: signal strength μ
$\mu = \frac{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})}{\mathcal{B}_{\mathrm{SM}}(B^+ \to K^+ \nu\bar{\nu})}$, with $\mathcal{B}_{\mathrm{SM}} = 4.97 \times 10^{-6}$
remark: measuring short-distance contribution only

ITA fit variable:
transformed classifier output $\eta(BDT_2)$ and q^2_{rec}
HTA fit variable:
transformed classifier output $\eta(BDTh)$

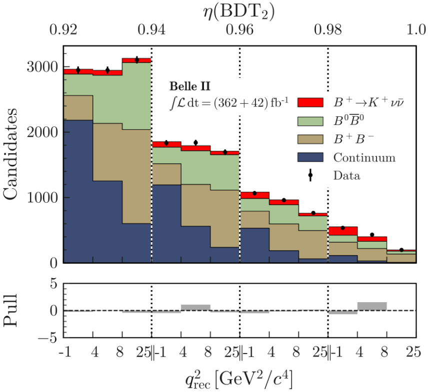




$B^+ \to K^+ \nu \bar{\nu}$

Results based on full Run1 dataset: 362 fb^{-1}

ITA



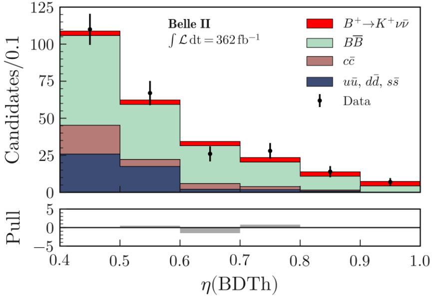
$\mu = 5.4 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})$

$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) =$

$2.7 \pm 0.5(\text{stat}) \pm 0.5(\text{syst}) \times 10^{-5}$

- 3.5σ wrt bkg only
- 2.9σ wrt to the SM

HTA



$\mu = 2.2^{+1.8}_{-1.7}(\text{stat})^{+1.6}_{-1.1}(\text{syst})$

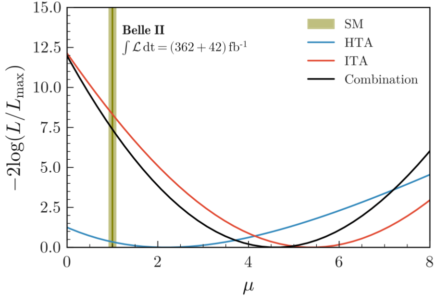
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) =$

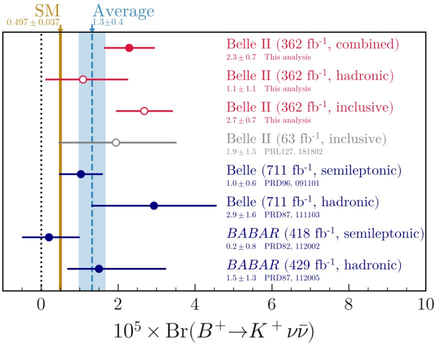
$1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst}) \times 10^{-5}$

- 1.1σ wrt bkg only
- 0.6σ wrt to the SM

$B^+ \to K^+ \nu \bar{\nu}$

Results and current experimental status





$$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$$
$$\mathcal{B}(B^+ \to K^+ \nu \bar{\nu}) =$$
$$2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst}) \times 10^{-5}$$

- 3.5σ **wrt bkg only**
- 2.7σ wrt to the SM

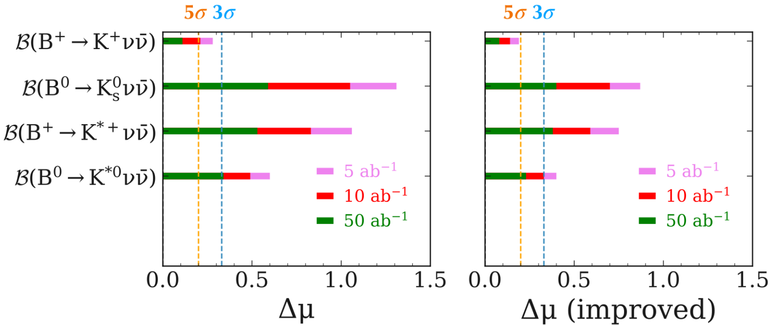
combination improves the ITA precision by 10%

$B \to K^{(*)}\nu\bar{\nu}$

Future prospects

- measure other modes: $B^+ \to K^{*+}\nu\bar{\nu}$, $B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K^0_S\nu\bar{\nu}$
- exploit further Belle dataset
- measure other observables: polarization fraction $F_L(q^2)$ for K* (target for $\sim$50ab^{-1})

2 scenarios: baseline and improved (Snowmass White Paper ArXiv: 2207.06307)



$\Delta\mu$ - uncertainty on signal strength assuming SM

improved scenario (better bkg suppression, more tagging approaches, improved systematics) assumes 50% increase in signal efficiency

Prospects

Detector and accelerator upgrades based on input to European Strategy for Particle Physics

- main challenge for full Luminosity related to beam bkgs from various sources
- ongoing detector R&D for upgrades to enhance BSM physics sensitivity $\Rightarrow$ focus on reducing occupancy, improving radiation tolerance
- detector upgrades (after Run 2): replacement of VXD with monolithic CMOS sensors, study for CDC inner layer replacement with silicon, staged replacement of TOP PMTs, new readout for ECL, mitigation of degradation in KLM
- SuperKEKB upgrades: Aiming for a peak luminosity of 10^{35} cm^{-2}s^{-1} by 2026 and eventually 50 ab^{-1} integrated luminosity.
  Plans include optics squeezing, increased stored currents, and addressing the specific luminosity discrepancy.
  Further upgrades planned for LS2, including injector, RF systems, and the interaction region (IR) with superconducting final focusing magnets using Nb_3Sn cables.
- consideration for Polarization Upgrade: Exploring a modest upgrade of SuperKEKB for precision electroweak physics with longitudinally polarized electrons ("Chiral Belle")

Summary

main results based on Run1 dataset

- Belle II provides many precise tests of Lepton Flavour Universality in semileptonic B decays with missing energy
- Presented results:
  - the new measurements of $R(D^*)$ with hadronic tagging and combined $R(D)$ + $R(D^*)$ with semileptonic tagging via **exclusive** B decays
  - the first measurement of $R(X_{\tau/\ell})$ via **inclusive** B decays
  - measurement of purely leptonic $B^+ \to \tau\nu_\tau$ with competitive accuracy
  - the first evidence of FCNC process $B^+ \to K^+\nu\bar{\nu}$ with $\sim$3.5σ
- ongoing efforts are focused on updating measurements with the full Run 1 dataset and preparing for the follow-up of Run 2, starting in October 2025

BACKUP

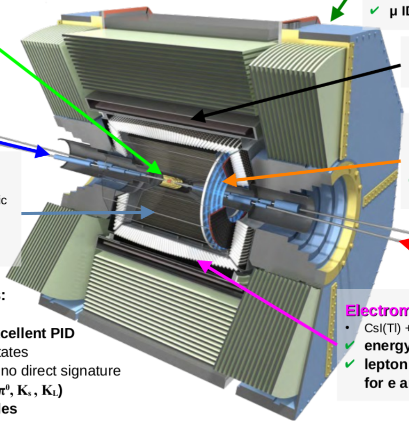
Belle II detector

+ performance

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

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

Magnetic field
- **1.5 T superconducting magnet**



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

Tracking detector
- central drift chamber (He + C_2H_6)
- small cells, long lever arm, fast electronic
- ✔ **spatial resolution: 100 μm**
- ✔ **p_T resolution ~ 0.4%/p_T**
- ✔ **dE/dx resolution: 5%**

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, π^0, K_s , K_L) nearly as well as charged particles**

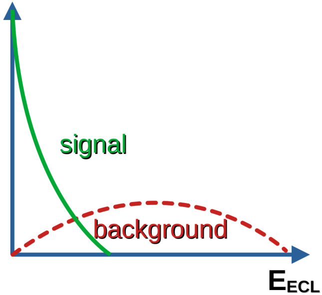
Electromagnetic Calorimeter
- CsI(Tl) + waveform sampling (barrel + end-caps)
- ✔ **energy resolution ~1.6-4%**
- ✔ **lepton ID efficiency 90% at fakes: 0.5% for e and 7% for μ**

Experimental techniques

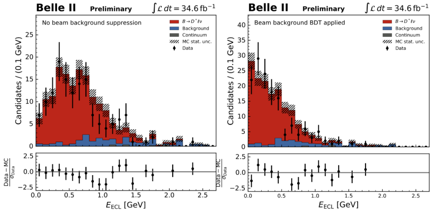
@ B-factories: key variable

residual energy in ECL (called E_{ECL} or 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



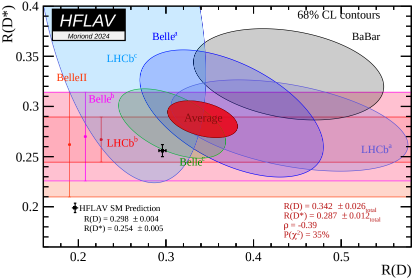
ideal vs. reconstructed



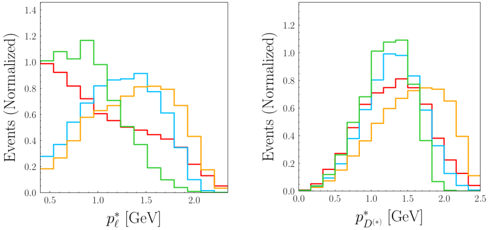
R(D*)

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:
  $\sim 1.6\sigma$ for $R(D)$
  $\sim 2.5\sigma$ for $R(D^*)$
  $\sim 3.31\sigma$ for $R(D)\&R(D^*)$



Events (Normalized)
p^*_ℓ [GeV]
$p^*_{D^{(*)}}$ [GeV]