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Belle II

$\mathbf{b} \to \mathbf{c}\tau\nu$ overview and Belle II prospects

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On behalf of the Belle II collaboration

Anomalies and Precision in the Belle II era

Vienna, 6-8.9. 2021

Introduction

- semi-tauonic $b \to c\tau\nu$ decays provide powerful probes of the Standard Model (SM)

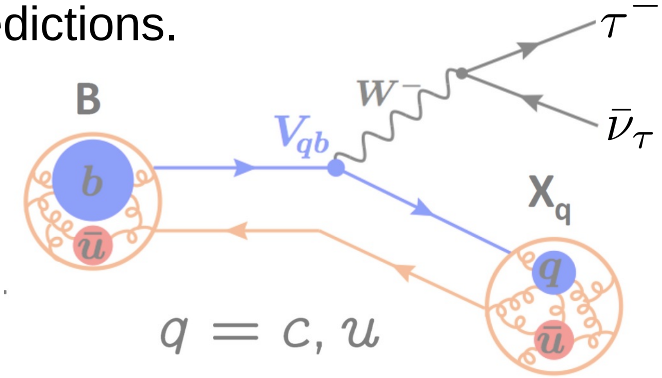
→ NP contributions typically less constrained than in $b \to c\ell\nu$ $(\ell = e, \mu)$

→ rich spectrum of kinematic observables accessible

→ complementary sensitivities of different modes to various SM extensions

→ far from fully explored, experimentally very challenging

→ in the last decade several measurements indicating enhanced rates of $b \to c\tau\nu$ compared with the SM predictions.



Observables

signal

Lepton flavor universality tests: $\mathcal{R}(H_c) = \frac{\mathcal{B}(B \to H_c\, \tau\bar{\nu}_\tau)}{\mathcal{B}(B \to H_c\, \ell\bar{\nu}_\ell)}$ $H_C = D^{(*)}, J/\psi$ $(\ell = e, \mu)$

normalization

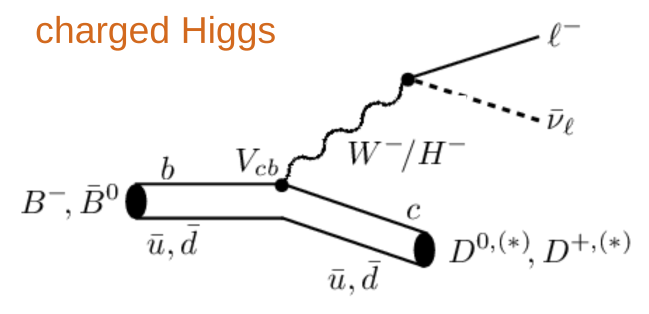
→ experimentally and theoretically convenient due to cancellation of several uncertainties in the ratio

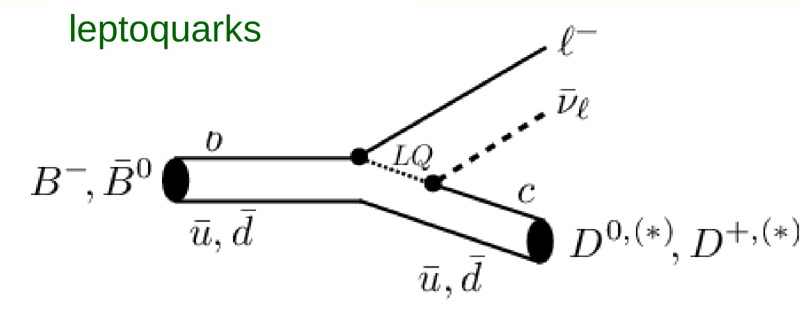
Kinematic variables: e.g. $q^2 = (p_B - p_{D^*})^2$ distributions

Polarization fractions: τ polarization, D^{*-} longitudinal polarization

Uncertainties of the SM predictions for $\mathcal{R}(H_c)$ range from 1% to 3%

→ sensitivity to NP contributions





Measurement basics

- relatively large branching fractions

- but multiple neutrinos in the final state → challenging decay reconstruction

→ determination of initial B momentum allows for evaluation of

$$q^2 = (p_B - p_{D^*})^2$$
momentum transfer to leptons

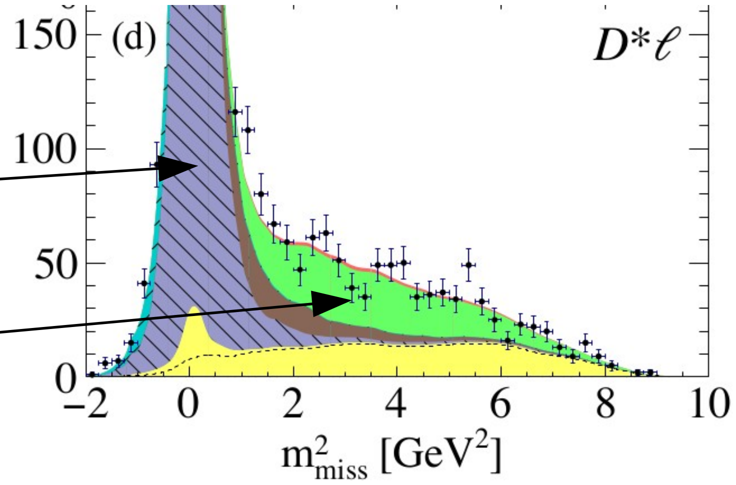
$$m^2_{\mathrm{miss}} = (p_B - p_{D^{(*)}} - p_\ell)^2$$
missing mass

$$E^*_l = (p_\ell \cdot p_B)/m_B$$
charged lepton energy in B frame

→ basis for signal / normalization mode separation

single neutrino
$B \to D^* \, \ell \bar{\nu}_\ell$

multiple neutrinos
$B \to D^* \, \tau \bar{\nu}_\tau$

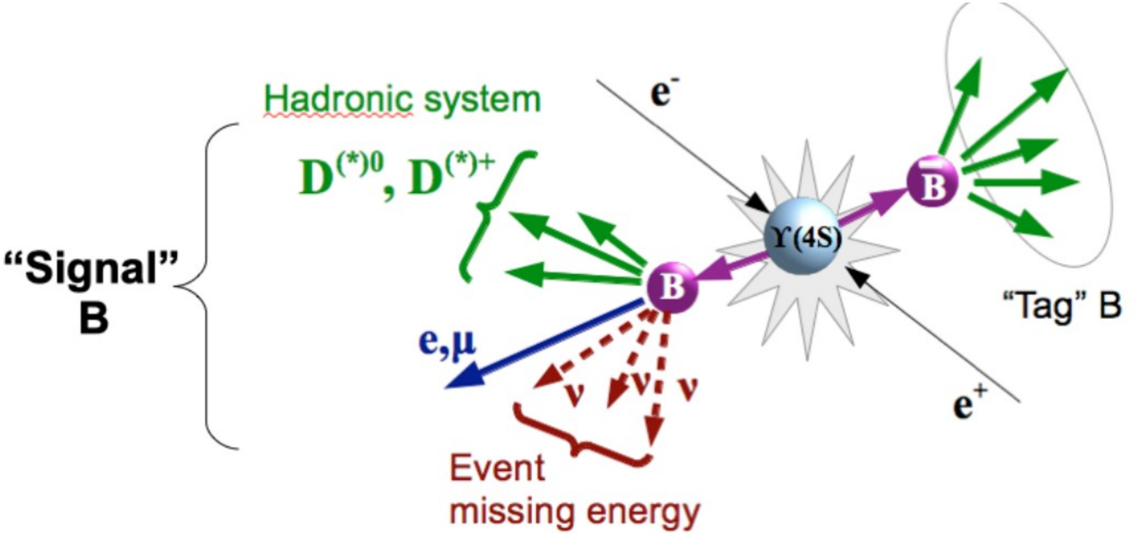


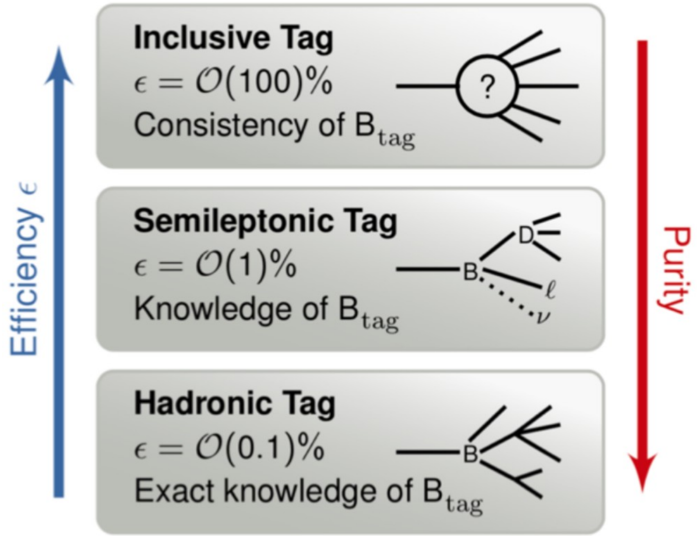
- accessible to **B factories** and **LHCb**

Measurement basics - B factories

- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

- fully known initial state + hermetic detector (4π) → **tagging techniques**





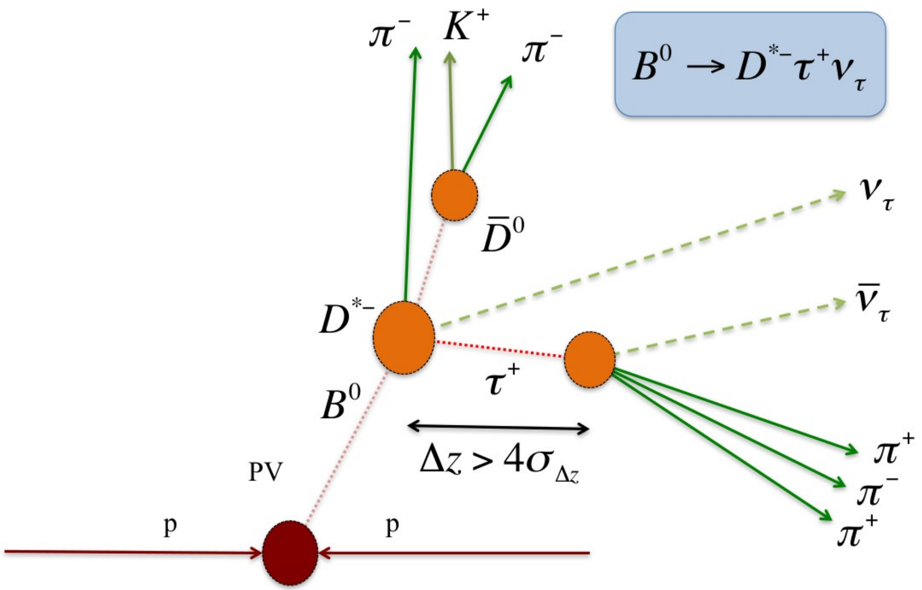
→ in signal/normalization events all particles in an event assigned (to B_{sig} or B_{tag})

background events: larger E_{ECL}

extra energy in EM calorimeter

signal vs. normalization: m^2_{miss} + kinematics

Measurement basics - LHCb



- tagging not available

- but very large sample of b-hadrons +
  large Lorentz boost +
  excellent vertexing

→ well separated vertices in the decay chain

- if τ decay vertex can be reconstructed (e.g $\tau \to (3\pi)\nu$)

  → B momentum determined up to discrete ambiguity

- for $\tau \to \mu\nu\bar{\nu}$ vertex not available

  → rest frame approximation: $$(p_B)_z = \frac{m_B}{m_{reco}}(p_{reco})_z$$

  $D^*\mu$

Summary of existing B-factory measurements

Hadronic tag with $\tau \to \ell\nu\bar{\nu}$

BaBar: Phys. Rev. Lett. 109, 101802, arXiv:1205.5442

Belle: Phys. Rev. D 92, 072014, arXiv:1507.03233

Result	BABAR	Belle
$\mathcal{R}(D)$	$0.440 \pm 0.058 \pm 0.042$	$0.375 \pm 0.064 \pm 0.026$
$\mathcal{R}(D^*)$	$0.332 \pm 0.024 \pm 0.018$	$0.293 \pm 0.038 \pm 0.015$

Semi-leptonic tag with $\tau \to \ell\nu\bar{\nu}$

Belle: Phys. Rev. Lett. 124, 161803, arXiv:1910.05864

$$\mathcal{R}(D) = 0.307 \pm 0.037\,(\mathrm{stat}) \pm 0.016\,(\mathrm{syst})$$

$$\mathcal{R}(D^*) = 0.283 \pm 0.018\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$$

Hadronic tag with $\tau \to \pi\nu, \tau \to \rho\nu$
Belle τ polarization measurement

Phys. Rev. D 97 (1), 012004, arXiv:1709.00129

$$R(D^*) = 0.270 \pm 0.035(\mathrm{stat})^{+0.028}_{-0.025}(\mathrm{syst})$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat})^{+0.21}_{-0.16}(\mathrm{syst})$$

Inclusive tag with $\tau \to \pi\nu, \tau \to \ell\nu\bar{\nu}$
Belle D^{*-} polarization measurement

arXiv:1903.03102

$$F_{L,\tau}(D^*) = 0.60 \pm 0.08(\mathrm{stat}) \pm 0.04(\mathrm{sys})$$

Example: Latest $\mathcal{R}(D^{(*)})$ from Belle – Semi-leptonic tag

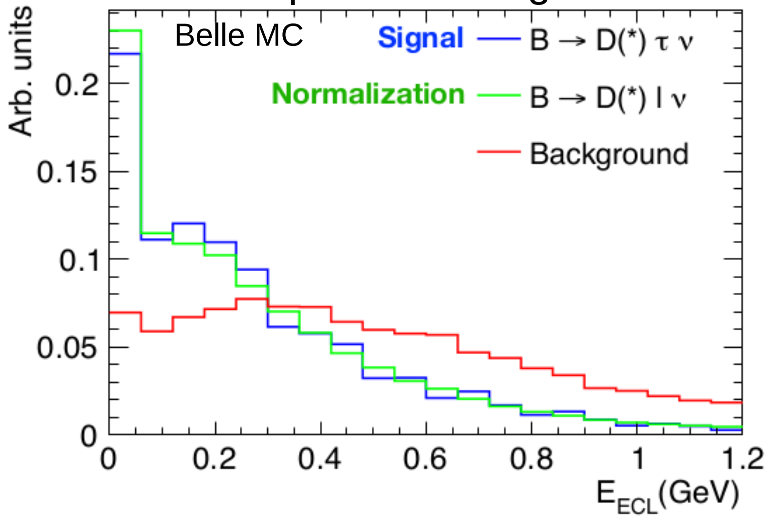
Phys. Rev. Lett. 124, 161803, arXiv:1910.05864

- using FEI (full event interpretation) for the tag-side $B \to D^{(*)} l \bar{\nu}_l$ reconstruction

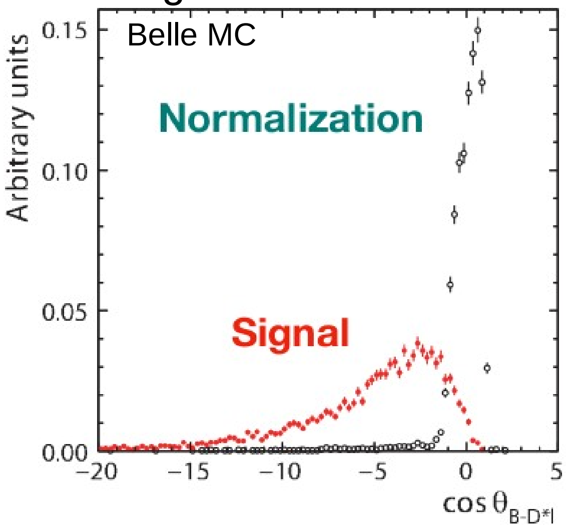
- reconstructed signal modes: $D^+\ell^-,\, D^0\ell^-,\, D^{*+}\ell^-,\, D^{*0}\ell^-\;\; (\ell = e, \mu)$

- combine kinematic variables using BDT: $(\cos\theta_{B,D^{(*)}l},\; m^2_{\mathrm{miss}},\; E_{\mathrm{vis}}) \to \mathcal{O}_{\mathrm{sig}}$

semi-leptonic / background



signal / normalization



- $E_{\rm ECL} - \mathcal{O}_{\rm sig}$ distributions of all samples are fit simultaneously, constraining $\mathcal{R}(D^{(*)0}) = \mathcal{R}(D^{(*)+})$

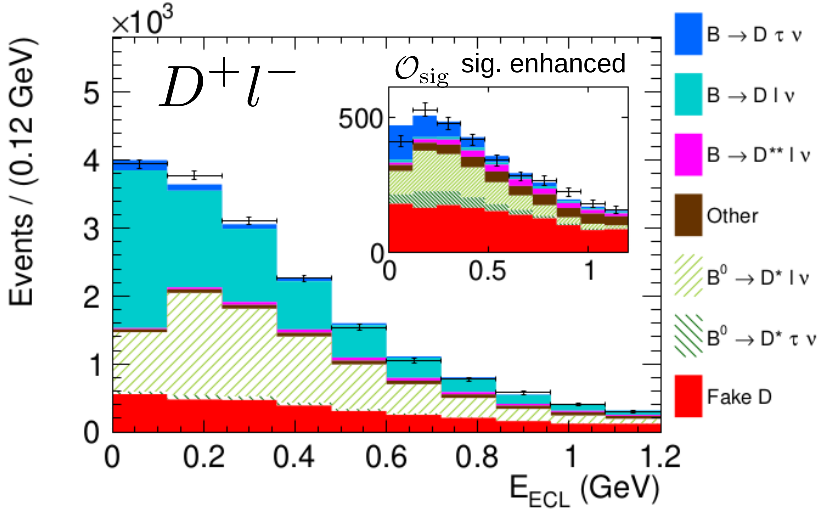
- free parameters: signal yields, normalization yields, $B \to D^{**} l\nu$ yield, feed-down $D^{(*)}$

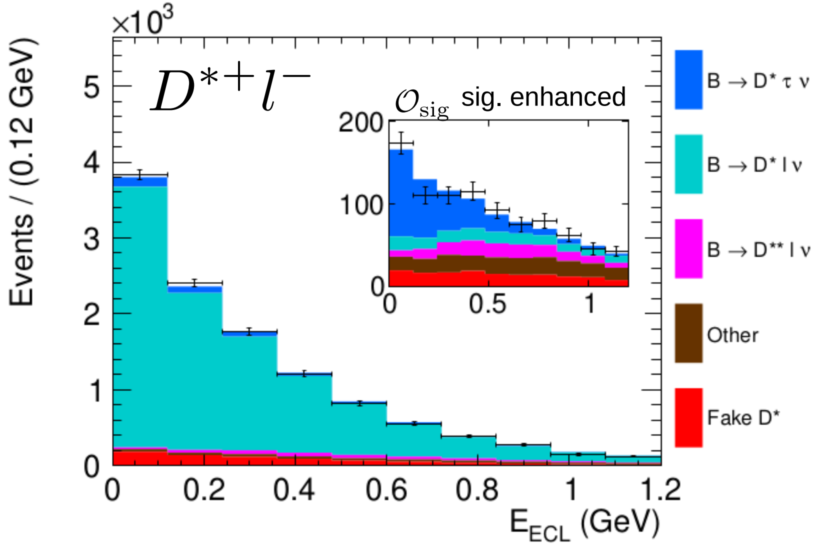
$$\mathcal{R}(D) = 0.307 \pm 0.037\,({\rm stat}) \pm 0.016\,({\rm syst})$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018\,({\rm stat}) \pm 0.014\,({\rm syst})$$

Most precise values to date!

Main systematic uncertainties

Source	$\Delta\mathcal{R}(D)$ (%)	$\Delta\mathcal{R}(D^*)$ (%)
D^{**} composition	0.76	1.41
PDF shapes	4.39	2.25
Feed-down factors	1.69	0.44
Efficiency factors	1.93	4.12



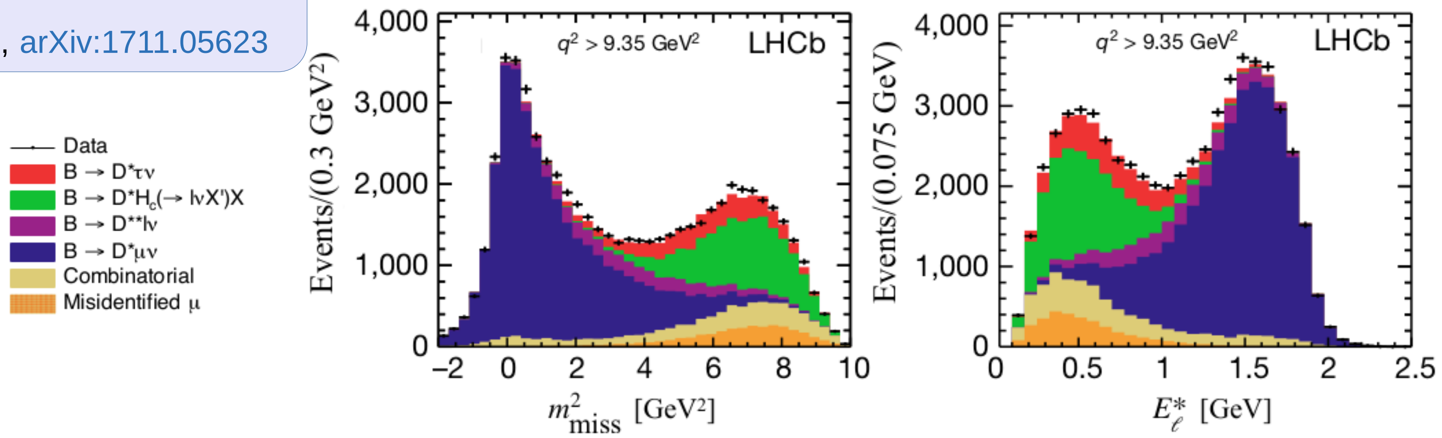


Summary of existing LHCb measurements

$\mathcal{R}(D^{*+})$ with $\tau \to \mu\nu\bar{\nu}$

Phys. Rev. Lett. 120 (12), 121801, arXiv:1711.05623

$$\mathcal{R}(D^{*+}) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$$



$\mathcal{R}(D^{*+})$ with $\tau \to \pi^-\pi^+\pi^-\nu$

Phys. Rev. D 97 (7), 072013, arXiv:1711.02505

$$\mathcal{R}(D^{*+}) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi\ \tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi\ l\bar{\nu}_l)}$$

Phys. Rev. Lett. 120 (12), 121801, arXiv:1711.05623

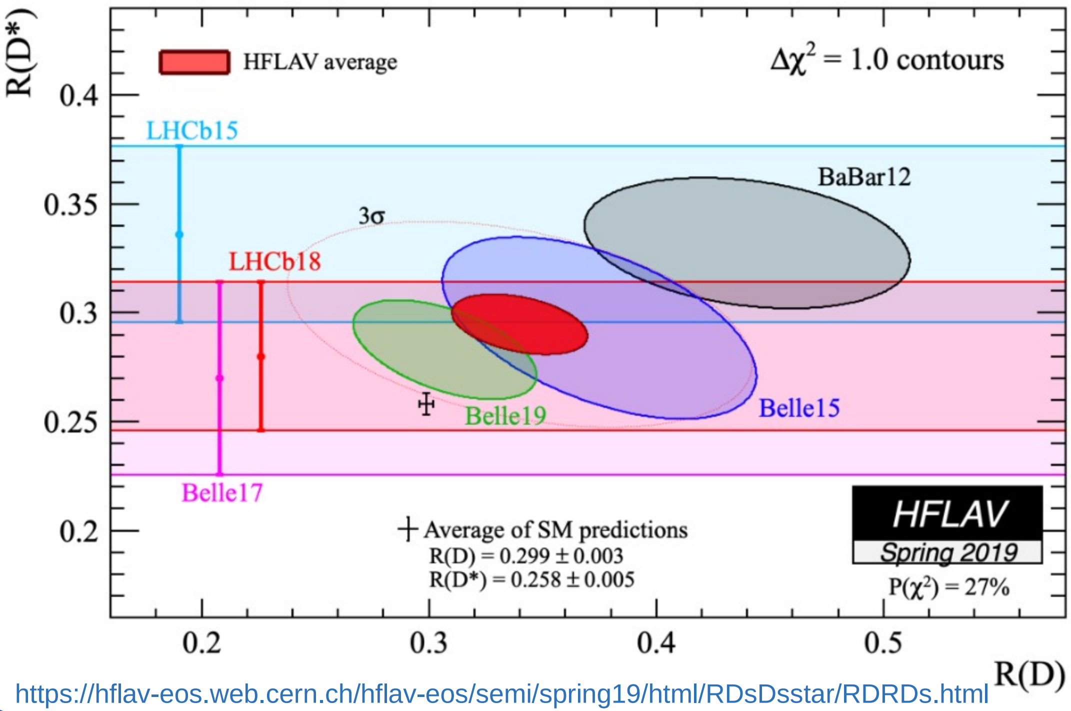
$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

$\mathcal{R}(J/\psi)^{SM} = 0.2582 \pm 0.0038$ ⟹ $\sim 2\sigma$ deviation

- so far $\mathcal{R}(D)$ not measured: lower $\mathcal{B}$, no D* mass constraint, significant D^* feed-down

Consistency with the SM predictions

$\mathcal{R}(D) - \mathcal{R}(D^*)$



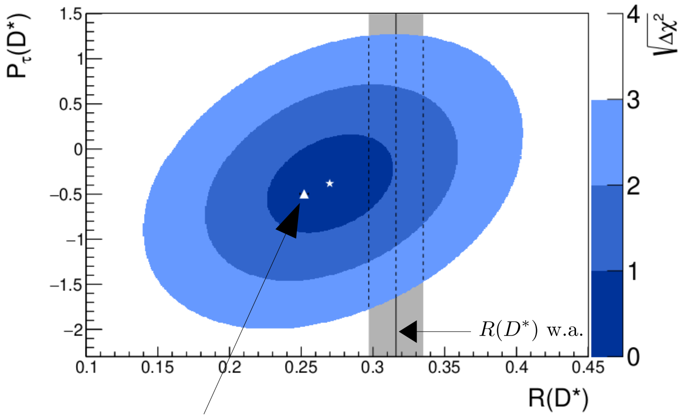
https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

→ present world average of $\mathcal{R}(D) - \mathcal{R}(D^*)$ deviates from the SM with significance of $\sim 3.1\sigma$

Belle τ polarization measurement

Phys. Rev. D 97 (1), 012004, arXiv:1709.00129

$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \qquad \Gamma^{\pm} - \tau \text{ helicity}$$

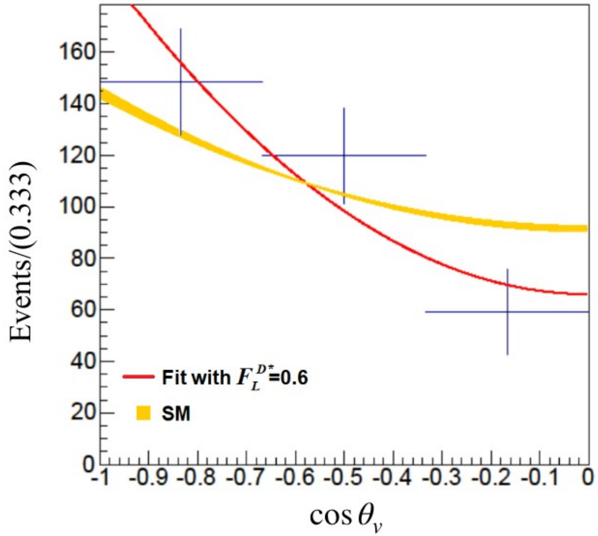


SM expectation

Phys. Rev. D 88, 094012 (2013) arXiv:1309.0301

Belle D^{*-} longitudinal polarization fraction

arXiv:1903.03102



Phys. Rev. D 98, 095018 (2018) arXiv:1808.03565

consistent with the SM at 1.6σ

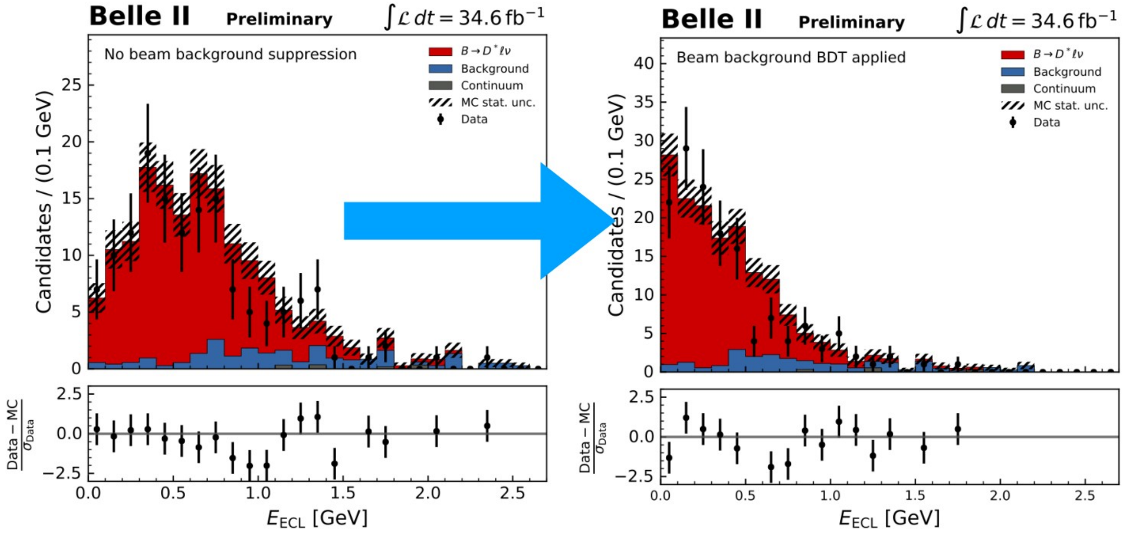
Prospects @ Belle II

- uncertainty in existing B-factory measurements largely statistically dominated

- but increased luminosity at Belle II with higher beam background levels will provide very challenging environment $\rightarrow$ novel methods

- relevant input to $\mathcal{R}(D^{(*)})$ anomaly already with $\sim 0.5\ \mathrm{ab}^{-1}$ (summer 2022)

fight beam backgrounds with ML methods



expected sensitivity $(\pm \mathrm{stat} \pm \mathrm{syst})$

	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$

PTEP 2019 (12), 123C01, arXiv:1808.10567

$\mathcal{R}(D^{(*)})$ systematic uncertainty considerations

Main systematics in existing Belle measurements

Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}\%$
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}\%$	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}\%$
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}\%$	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}\%$	$^{+10.0}_{-9.0}\%$

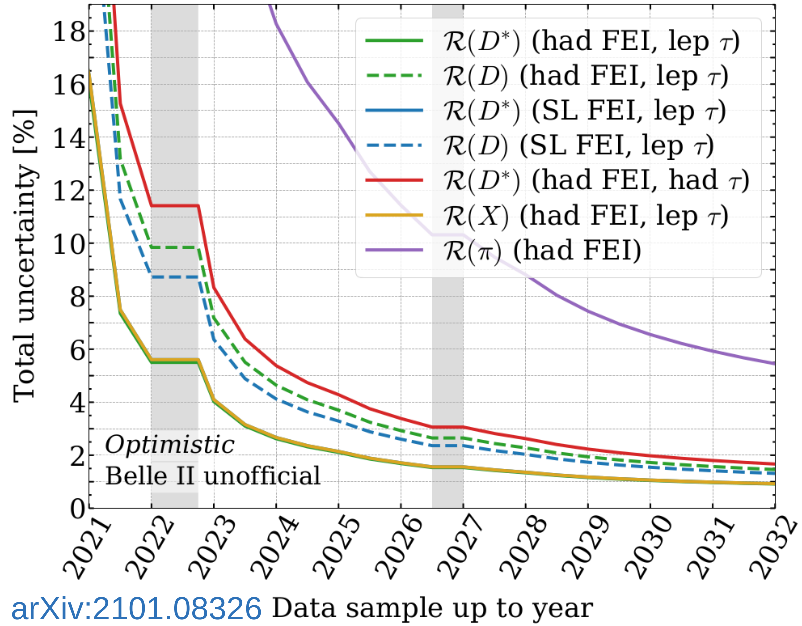
- PDF templates, efficiencies → reducible with larger MC samples
- dedicated measurements of $B \to D^{**}\ell\nu_\ell$ and exclusive hadronic B decays (e.g. $B \to D^*\pi^+X$)
- improved modeling of $B \to D^{(*)}\ell/\tau\nu$ form factors, lepton id. efficiencies, etc.

- with hadronic tagging Belle II will also have access to $\mathcal{R}(X_c)$

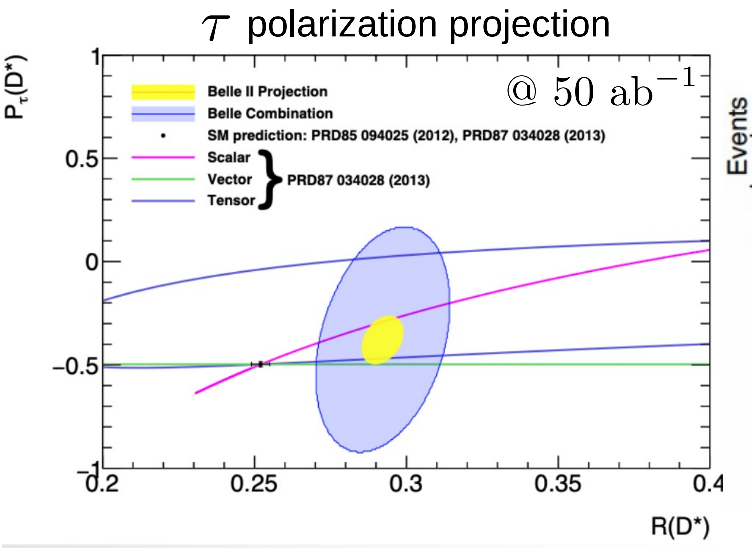
  → hadronic model independent test of LFU

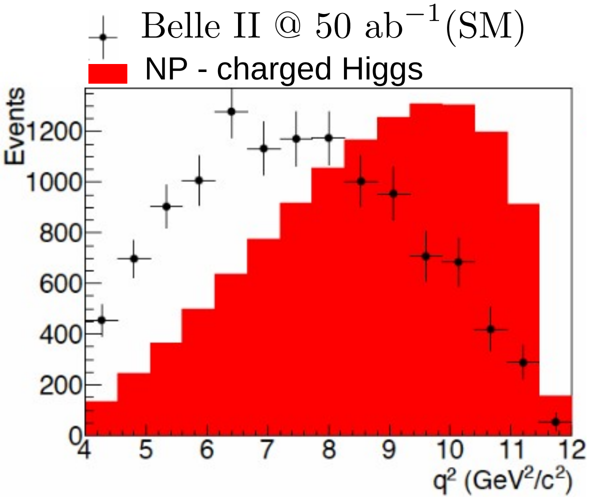
- with more data other observables will become increasingly important

  → angular correlations, polarizations, asymmetries
  → many of these much easier accessible at Belle II w.r.t LHCb



arXiv:2101.08326





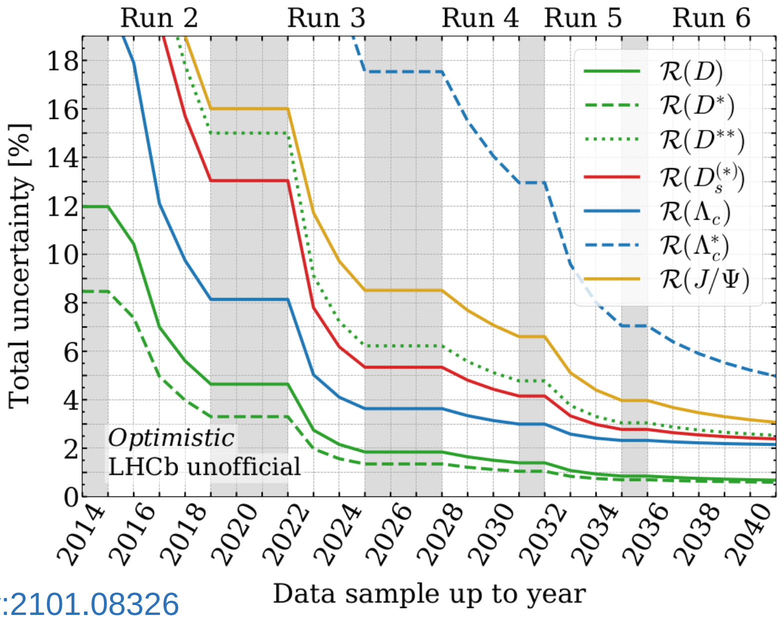
Prospects @ LHCb

- all existing LHCb measurements use Run 1 data only (3 fb-1)

- statistical uncertainties already at the level of systematic uncertainties
→ many contributions will get reduced with larger data samples

- many updates (+ 6 fb-1 of Run 2 data) + new analyses in progress

- $\mathcal{R}(D^+)$
- $\mathcal{R}(D^*)$ - (electron - muon)
- Combined measurement $\mathcal{R}(D^*)$ - $\mathcal{R}(D^0)$
- $\mathcal{R}(D^{**})$
- $\mathcal{R}(D_s^*)$
- $\mathcal{R}(J/\Psi)$
- $\mathcal{R}(\Lambda_c^*)$



arXiv:2101.08326

Summary

- semi-tauonic $b \to c\tau\nu$ decays provide powerful probes of the Standard Model (SM)

- many possible observable → but experimentally challenging

- in the last decade several measurements indicating enhanced rates of $b \to c\tau\nu$ compared with the SM predictions.

- complementary contributions from B factories and LHCb

- Belle II will provide important contributions to resolution of present anomalies already with $\sim 0.5\ \mathrm{ab}^{-1}$ of collected data (summer 2022)