# Lepton Flavour Universality in B Decays and Other Recent Results at Belle

BELLE

## $b \to c\tau\nu_\tau$

- Measurement of $R(D)$ and $R(D^*)$ with a semileptonic tagging method

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B\to D^{(*)}\tau\nu)}{\mathcal{B}(B\to D^{(*)}\ell\nu)}, \qquad \ell = e, \mu$$

Belle Collab., arXiv:1904.08794

- Measurement of the $D^{*-}$ polarization in the decay $B^0 \to D^{*-}\tau^+\nu_\tau$

Belle Collab., arXiv:1903.03102

## $b \to s\ell^+\ell^-$

- Test of lepton flavor universality in $B \to K^*\ell^+\ell^-$ decays at Belle

$$R(K^*) \equiv \frac{\mathcal{B}(B\to K^*\mu^+\mu^-)}{\mathcal{B}(B\to K^*e^+e^-)}$$

Belle Collab., arXiv:1904.02440

*Results (still preliminary), are based on the full data set recorded by the Belle detector at $\Upsilon(4S)$.*

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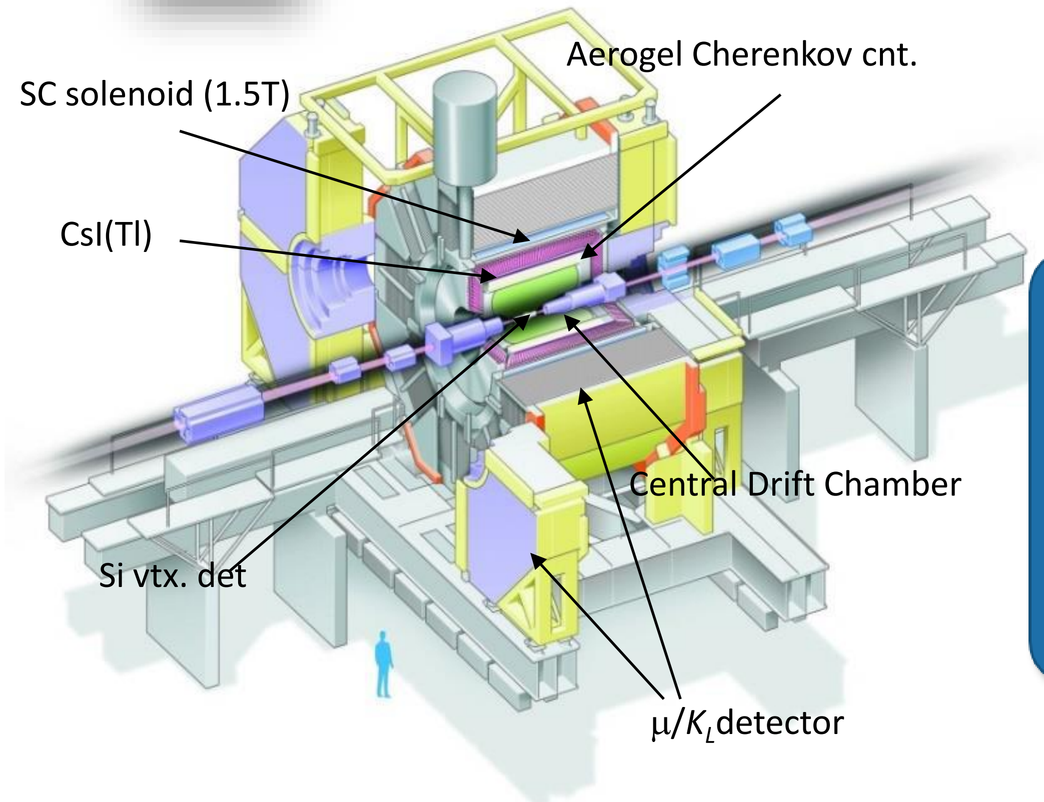
Maria Różańska, H. Niewodniczański Institute of Nuclear Physics, Kraków, on behalf of the Belle Collaboration

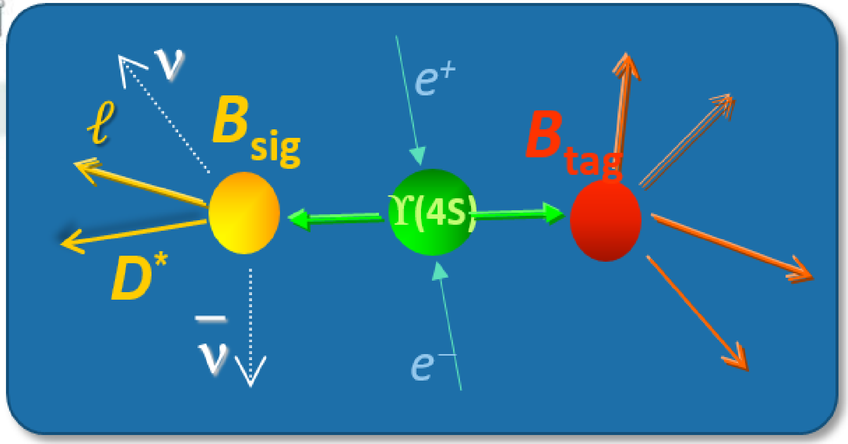
# Belle experiment

**Belle detector:** high-hermeticity (86% of solid angle), multi-purpose magnetic spectrometer operating (1999-2010) at KEKB collider, collected 772M $B\overline{B}$ pairs from

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



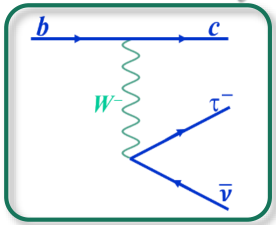

Unique tool to study experimentally challenging $B$- meson decays, e.g. to multiple neutrinos

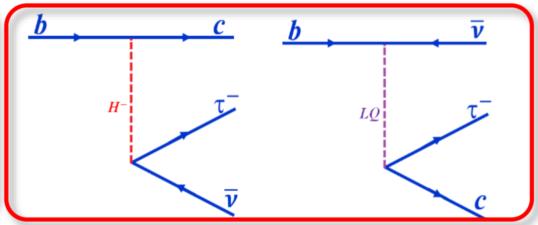



- employ $B_{tag}$- reconstruction techniques to infer more information on $B_{sig}$

# $B \to D^{(*)}\tau\nu_\tau$

- $b \to c\tau\nu_\tau$ transitions




SM and NP contribute at the tree level

- Theoretically well-controlled observables, with complementary sensitivity to NP:

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

Common uncertainties (partly) cancel out:

- Theoretical uncertainty of some form factors
- Uncertainty of $|V_{cb}|$
- Experimental uncertainty of efficiencies, partial *BF's…*

➢ Differential (*e.g.* $q^2$ ) distributions

➢ τ (and $D^*$) polarization

- Experimentally challenging!

➢ B-factories exploit $B_{\text{tag}}$- reconstruction techniques

➢ Measurements of $R(D^{(*)})$ achieved sensivity that challenges SM and some of it's extensions.

HFLAV Summer 2018

$R(D) = 0.407 \pm 0.039 \pm 0.024$ ~2.3σ above the SM ($0.299 \pm 0.003$)

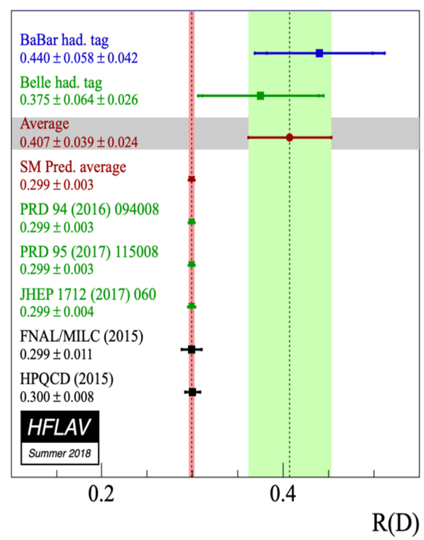
$R(D^*) = 0.306 \pm 0.013 \pm 0.007$ ~3.0σ above the SM ($0.258 \pm 0.05$)

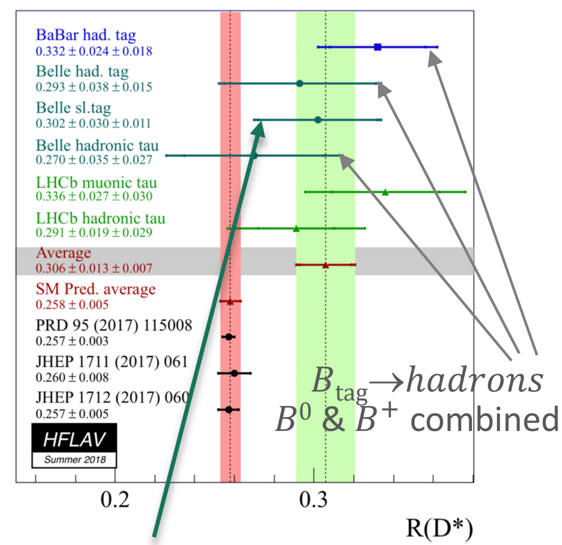
$R(D^*)$ & $R(D)$ ~3.8σ away from the SM

$$\frac{\mathcal{B}(B^0\to D^{*-}e^+\nu)}{\mathcal{B}(B^0\to D^{*-}\mu^+\nu)} = 1.01 \pm 0.01(stat) \pm 0.03(syst)$$

Belle, arXiv:1809.03290

➢ Experimental uncertainties larger than those of the SM predictions ⇒ call for improvements




➢ one of the most precise results is obtained with $B_{tag}\to D^*\ell\nu$, **only $B^0 \to D^{*-}\tau^+\nu$ measured** ⇒ very promissing approach

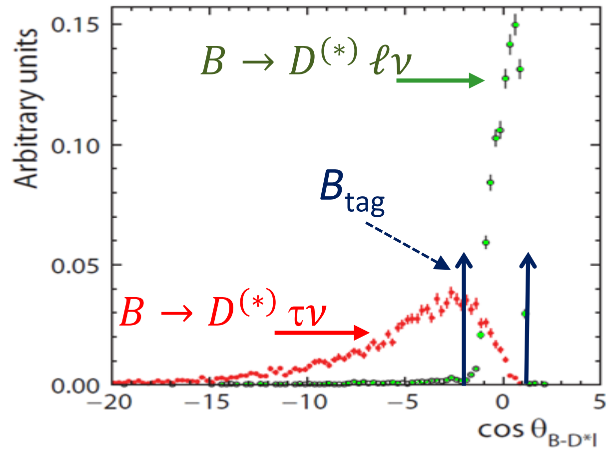
# Measurement of $R(D)$ and $R(D^*)$ with semileptonic tagging

Belle Collab., arXiv:1904.08794

## ➢ Reconstruct $B_{tag}$ decay: $B \to D^{(*)}\ell\nu$ (BDT-based hierarchical algorithm)

- BDT classifier output, $-2 < \cos\theta_{B,Y}^{tag} < 1$

$$\cos\theta_{B,Y} = \frac{2E_{beam}E_Y - m_B^2 - M_Y^2}{2|p_B||p_Y|} \quad Y = D^{(*)}\ell$$

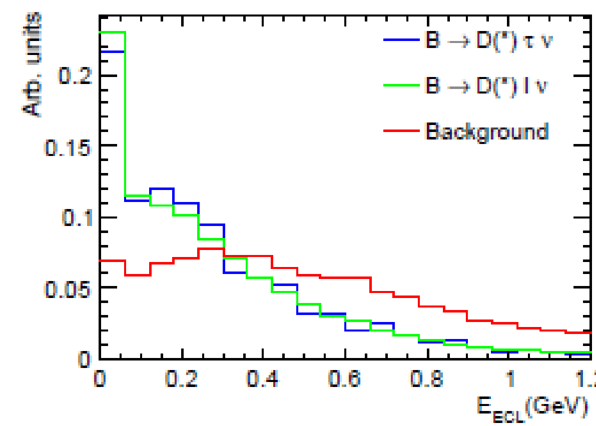



## ➢ Search for $D^{(*)}\ell$ among remaining tracks and clusters

- No extra charged tracks, or $\pi^0$'s…
- $\cos\theta_{B,Y}^{sig} < 1, \quad |p_{D^{(*)}}| < 2$ GeV
- 4 disjoint data samples: $D^{*+}\ell^-, D^{*0}\ell^-, D^+\ell^-, D^0\ell^-$

## ➢ Distinguish $B \to D^{(*)}\ell(\tau)\nu$ from background

- $E_{ECL}$ – sum of the energies of remaining neutral clusters, $E_{ECL} \approx 0$ for signal, tends to be higher for background




## ➢ Distinguish $B \to D^{(*)}\tau\nu$ from $B \to D^{(*)}\ell\nu$

- BDT classifier with input variables:

$$\cos\theta_{B,Y}^{sig}, E_{vis} = \Sigma E_i, M_{miss}^2 = (E_{beam} - E_{D^{(*)}\ell})^2 - (p_{D^{(*)}\ell})^2$$

## ➢ Extract $R(D)$ and $R(D^*)$

- Extended maximum likelihood 2-D fit to the BDT classifier output and $E_{ECL}$
- Fit simultaneously 4 $D^{(*)}\ell$ samples

# Measurement of $R(D)$ and $R(D^*)$ with sl tagging - fit

Belle Collab., arXiv:1904.08794

## Fit components

**floating**

- norm: $B \to D^{(*)}\ell\nu$
- signal: $B \to D^{(*)}\tau\nu$
- feed-down
  - $B^+ \to D^*\ell\nu \Longrightarrow D\ell\nu$
  - $B^0 \to D^*\ell\nu \Longrightarrow D\ell\nu$
- background
  - $B \to D^{**}\ell\nu$

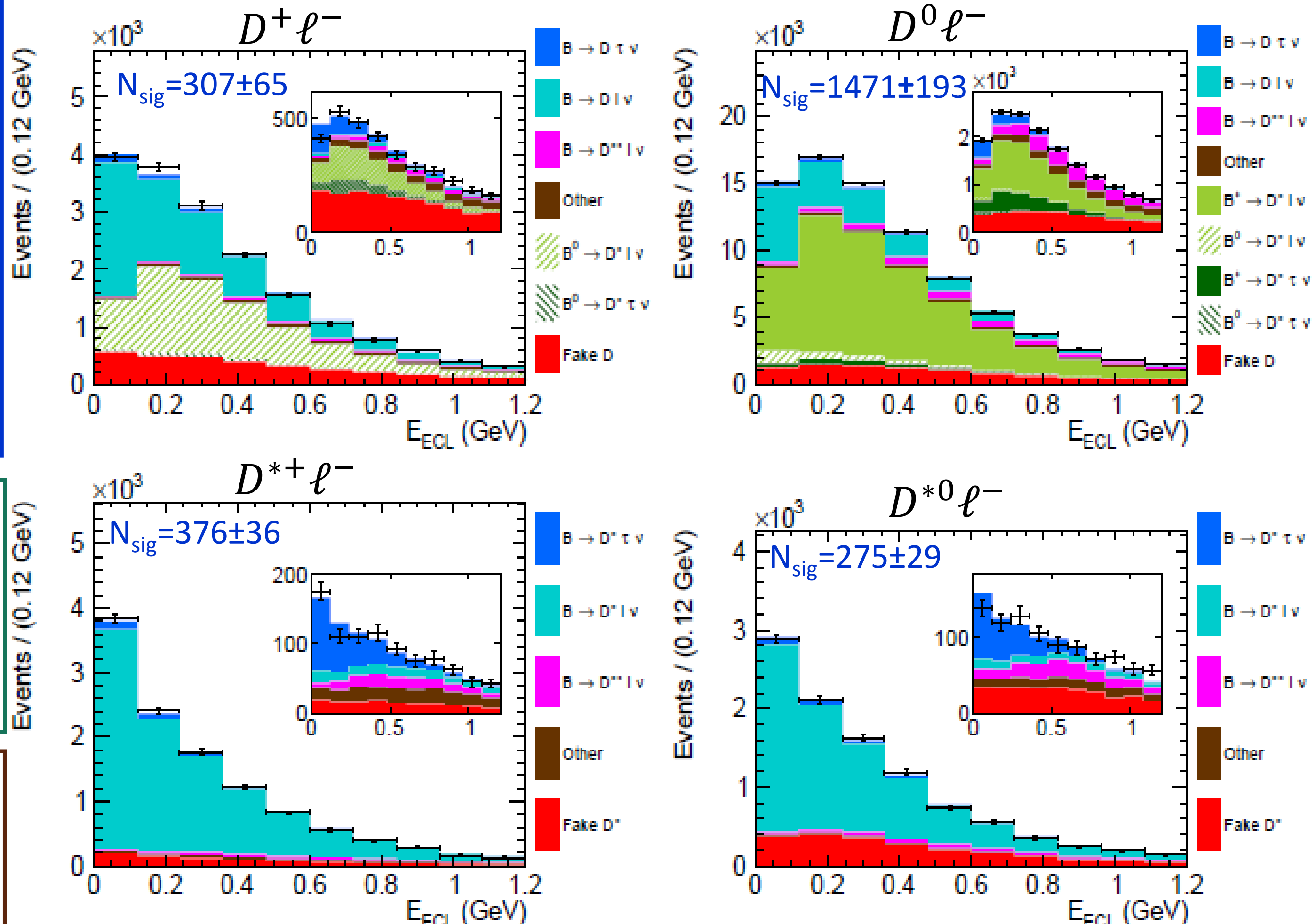
**correlated**

- feed-down
  - $B^+ \to D^*\tau\nu \Longrightarrow D\tau\nu$
  - $B^0 \to D^*\tau\nu \Longrightarrow D\tau\nu$

**fixed**

- fake $D^{(*)}$ calibrated from data
- other bkgds - fixed from MC

$E_{\mathrm{ECL}}$ fit projections; insets show signal enhanced region (class > 0.9)

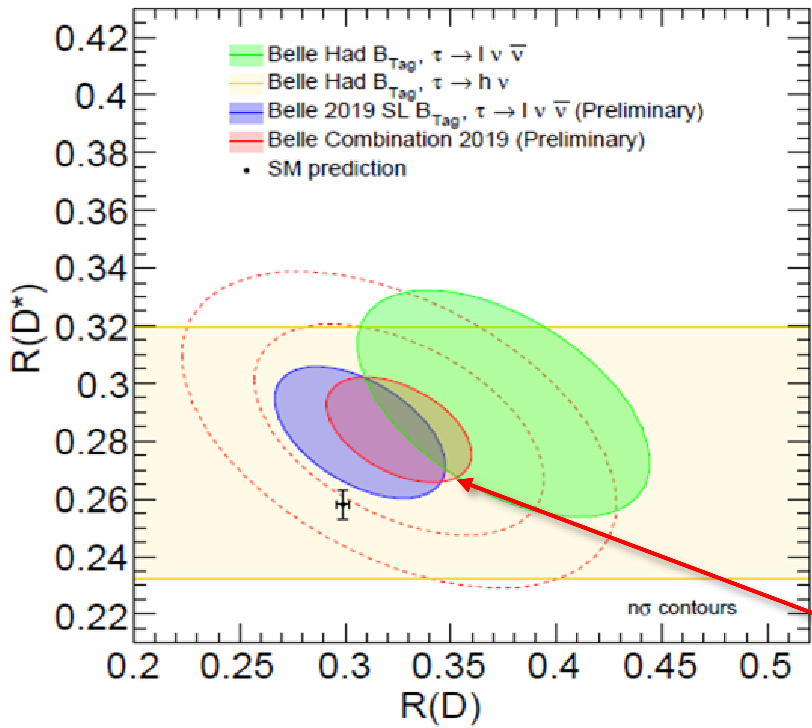


# Measurement of $R(D)$ and $R(D^*)$ with sl tagging - results

Belle Collab., arXiv:1904.08794

$$R(D^{(*)}) = \frac{1}{2\mathcal{B}(\tau \to \ell\nu\nu)} \times \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \times \frac{N_{\rm sig}}{N_{\rm norm}}$$

$R(D) = 0.307 \pm 0.037(stat) \pm 0.016(\text{syst})$
compatible within 0.2σ with SM
$R(D^*) = 0.283 \pm 0.018(\text{stat}) \pm 0.014(\text{syst})$
compatible within 1.1σ with SM*
Combined $R(D)$&$R(D^*)$ compatible within ~1.2σ with SM




Most precise measurement of $R(D^{(*)})$ to date

* New SM prediction: $R(D^*) = 0.253 \pm 0.006$ ~1.3σ
P. Gambino, M. Jung, S. Schacht, arXiv:1905.08209 [hep-ph]

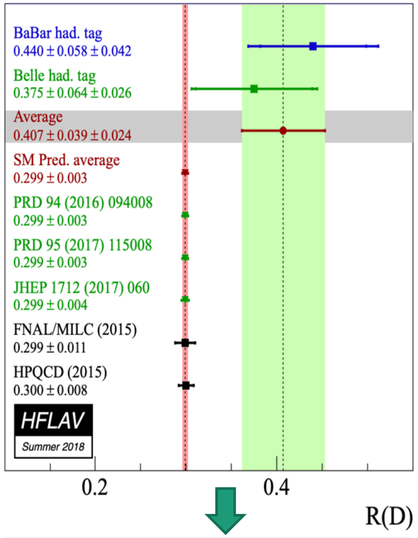
## Systematic uncertainties (%)

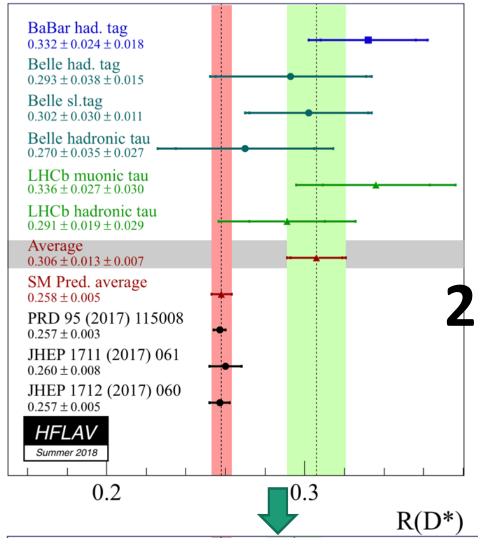
| source | $\Delta R(D)$ | $\Delta R(D^*)$ |
|---|---|---|
| $D^{**}$ composition | 0.76 | 1.41 |
| Fake $D^{(*)}$ calibr. | 0.19 | 0.11 |
| $B_{\rm tag}$ calibration | 0.07 | 0.05 |
| Feed-down factors | 1.69 | 0.44 |
| Efficiency factors | 1.93 | 4.12 |
| Lepton eff. & fake rate | 0.36 | 0.33 |
| Slow $\pi$ efficiency | 0.08 | 0.08 |
| PDF shapes | 4.39 | 2.25 |
| $B$ decay form fact. | 0.55 | 0.28 |
| $\mathcal{B}(B \to D^{(*)}\ell\nu)$ | 0.05 | 0.02 |
| $\mathcal{B}(D)$ | 0.35 | 0.13 |
| $\mathcal{B}(D^*)$ | 0.04 | 0.02 |
| $\mathcal{B}(\tau \to \ell\nu\nu)$ | 0.15 | 0.14 |
| $BF$s of $\Upsilon(4S)$ | 0.10 | 0.04 |
| Total | 5.21 | 4.94 |

**Preliminary Belle average**

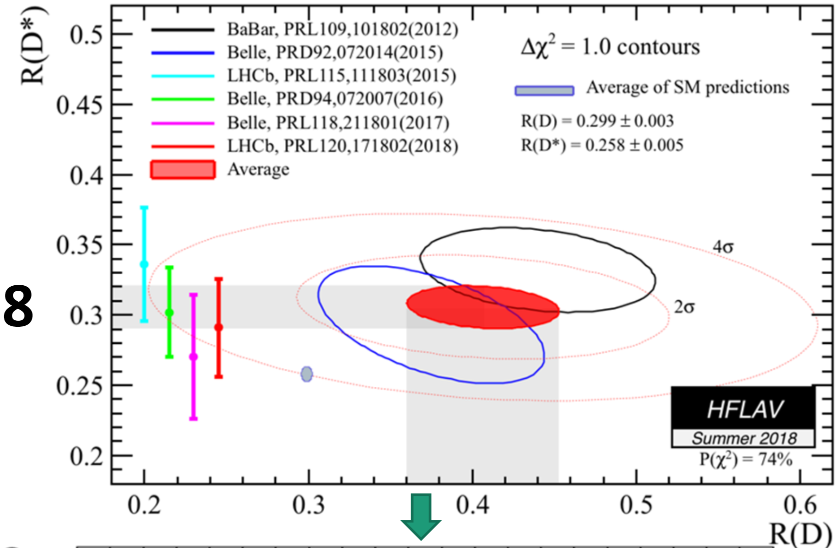
$R(D) = 0.326 \pm 0.034$
$R(D^*) = 0.284 \pm 0.018$
correlation: $\rho = -0.47$
compatible within ~2σ with SM

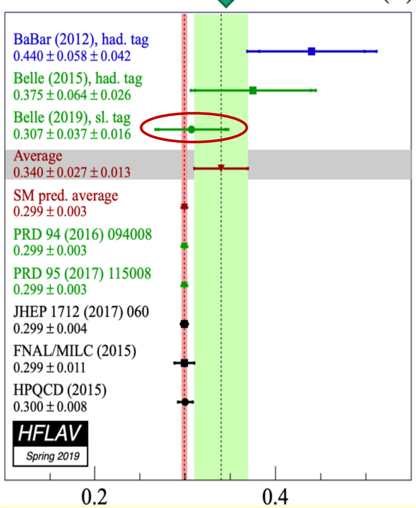
# $R(D)$ and $R(D^*)$ – 2019

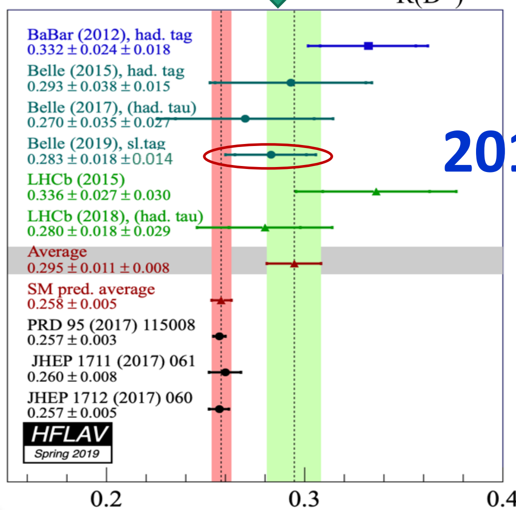


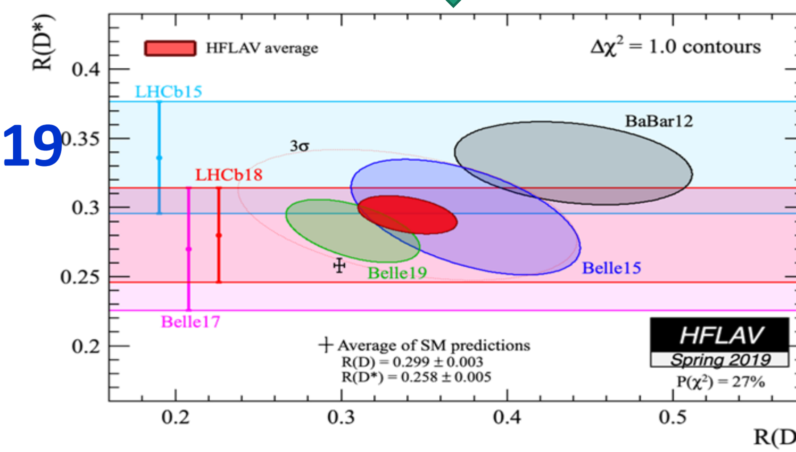

**2018**




**2019**




$R(D) = 0.340 \pm 0.027 \pm 0.013$
~1.4σ above the SM

$R(D^*) = 0.295 \pm 0.011 \pm 0.008$
~2.5σ above the SM

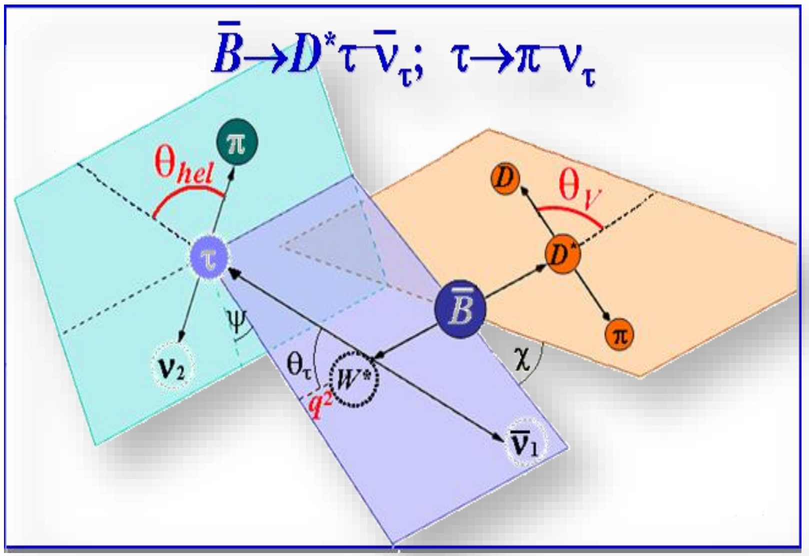
**$R(D^*)$ & $R(D)$ ~3.1σ away from the SM**

**Tension reduced to 3.1σ, but central values consistently above the SM predictions**

# Other observables in $B \to D^{(*)}\tau\nu$ decays

- (Inconclusive) hints of a deviation from the Standard Model in $b \to c\tau\nu_\tau$ transitions

- $\boldsymbol{R(D^{(*)})}$ systematically above the SM expectations, surprisingly larger effect for $R(D^{*})$;
- Measured distributions of $\boldsymbol{q^2}$ [BaBar PRD **88**,072012(2013), Belle PRD **92**,072014(2015)], $\boldsymbol{p_{D^*}}$ and $\boldsymbol{p_l}$ [Belle PRD **94**,072007(2016)] consistent with SM, but statistically limited;
- Angular observables in $B \to D^{(*)}\tau\nu$ decays, basically, not explored yet




**$\cos\theta_{hel}$** and **$\cos\theta_V$** can be reconstructed at B-factories using hadronic decays of $B_{\text{tag}}$

$$\vec{p}_{\text{sig}} = -\vec{p}_{\text{tag}}$$

**$\cos\theta_{hel}$** $\Rightarrow$ τ polarization ($P_\tau^{D^{(*)}}$)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1}{2}\left[1 + \alpha P_\tau \cos\theta_{hel}\right]$$

only $\tau \to M\,\nu_\tau$ decays

$$\text{SM:}\ \ P_\tau^{D^*} = -0.497 \pm 0.013$$

SM: M. Tanaka, R. Watanabe, PRD **87**, 034028(2013)

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

$\tau \to \pi\,\nu_\tau$ (α=1), $\tau \to \rho\,\nu_\tau$ (α=0.45)

Belle PRL **118**,211801(2017), PRD **97**, 012004 (2018)

**$\cos\theta_V$** $\Rightarrow$ $D^*$ polarization ($F_L^{D^*}$)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_V} = \frac{3}{4}\left[2\,F_L^{D^*}\cos^2\theta_V + F_T^{D^*}\sin^2\theta_V\right]$$

all τ decays

$$F_L^{D^*} + F_T^{D^*} = 1$$

$$\text{SM:}\ \ F_L^{D^*} = 0.47 \pm 0.01$$

SM: P. Gambino, M. Jung, S. Schacht, arXiv:1905.08209 [hep-ph]

# Measurement of the $D^{*-}$ polarization in the decay $B^0 \to D^{*-}\tau^+\nu_\tau$

Belle Collab., arXiv:1903.03102

- ❑ **Need efficient reconstruction of $B_{\rm tag}$ in hadronic modes**
  **$\Rightarrow$ do it inclusively** Belle PRL **99**, 191807 (2007), PRD **82**, 072005 (2010)

➢ Find $B_{\rm sig}$ candidates $D^{*-}\, d_\tau^+$ $\quad \tau^+ \to d_\tau^+ \nu_\tau(\bar{\nu}_\ell)$, $d_\tau = \ell, \pi$

➢ Reconstruct $B_{\rm tag}$ from remaining tracks and clusters

- $M_{\rm tag} = \sqrt{E_{\rm beam}^2 - |\boldsymbol{p}_{\bf tag}|^2}$; $\Delta E_{\rm tag} = E_{\rm tag} - E_{\rm beam}$; $E_{\rm tag} = \Sigma_i E_i$, $\boldsymbol{p}_{\rm tag} = \Sigma_i \boldsymbol{p}_i$
  $M_{\rm tag} > 5.2$ GeV , $-0.30 < \Delta E_{\rm tag} < 0.05$ GeV
- Suppress incorrectly reconstructed $B_{\rm tag}$'s:
  total charge=0, no extra $\ell^\pm$, $N_{\pi^0} + N_\gamma < 5$, $N_{K_L^0} = 0$ $(d_\tau = \pi)$

✓ >80%(60%) signal events for $d_\tau = \ell(\pi)$ contained at $M_{\rm tag}$>5.26 GeV

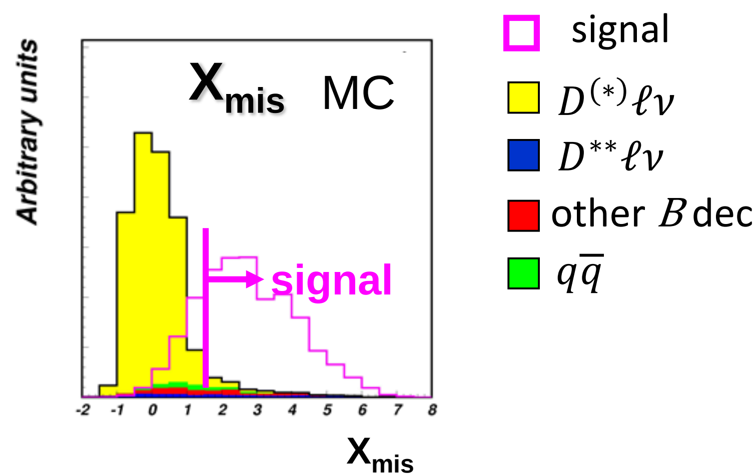
➢ Calibrate background using side-bands

- $M_{\rm tag} < 5.26$ GeV, $X_{\rm mis} < 0.75$ $(0.5)$ $d_\tau = \ell(\pi)$,
  $$X_{\rm mis} = \frac{E_{\rm beam} - E_{D^* d_\tau} - |\boldsymbol{p}_{D^* d_\tau}|.}{|\boldsymbol{p}_B|}$$

➢ Suppress background

- $X_{\rm mis} > 1.5$ $(1.0)$, $E_{\rm vis} < 8.7$ $(8.8)$ GeV , $d_\tau = \ell(\pi)$

✓ $M_{\rm tag}$ distributions flat for most bkgd
– can be used to extract signal yields



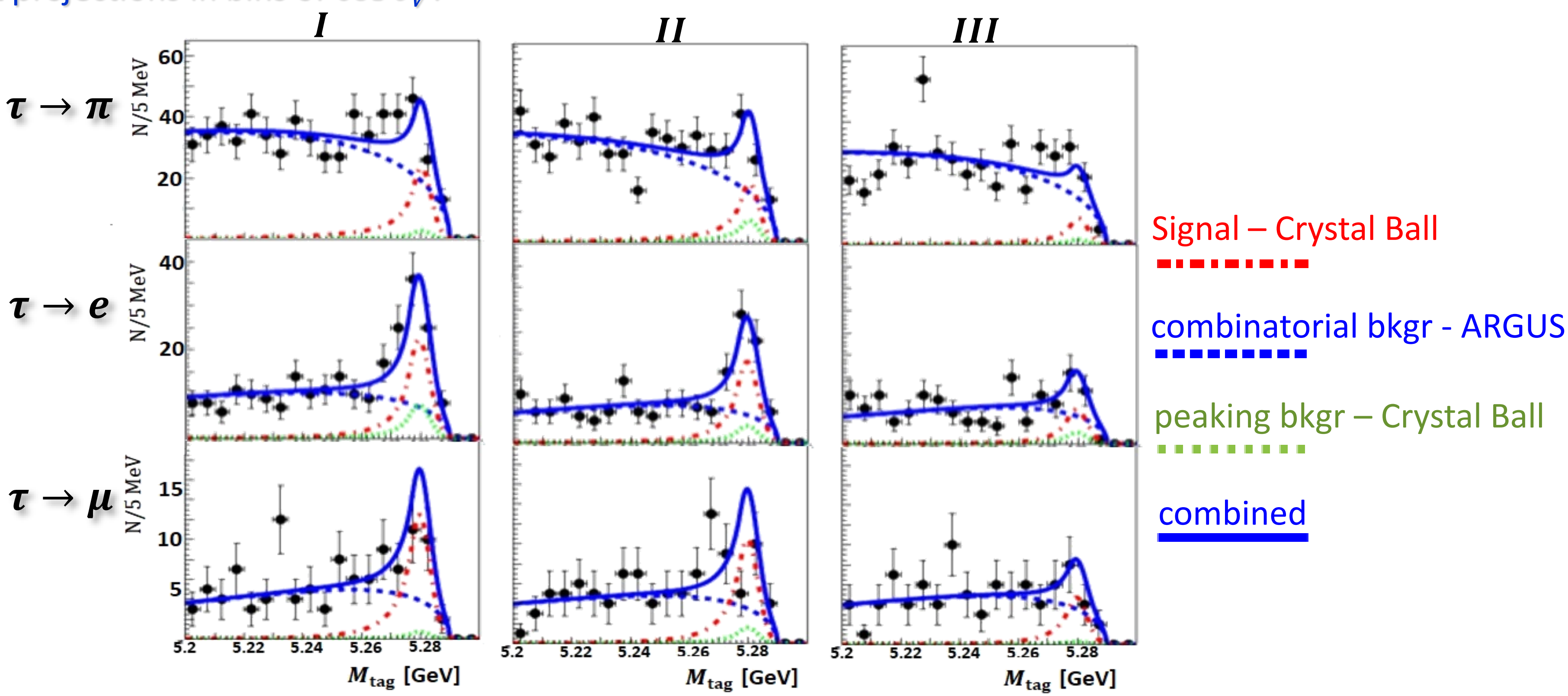
# Measurement of the $D^{*-}$ polarization in the decay $B^0 \to D^{*-}\tau^+\nu_\tau$

Belle Collab., arXiv:1903.03102

## ❑ Measure $\cos\theta_V$ distribution

- Extract signal yields in 3 equidistant bins of $\cos\theta_V$: $\boldsymbol{I}[-1,-0.67), \boldsymbol{II}\,[-0.67,-0.33), \boldsymbol{III}\,[-0.33,0)$
  - $\cos\theta_V > 0$ excluded because of low reconstruction efficiency of slow $\pi$ from $D^*$decay
  - signal yields ectracted from UEML fit to $M_{\rm tag}$ distributions ; simultanoeous fit to all decay chains

Fit projections in bins of $\cos\theta_V$:




$N^{I}_{\rm sig} = 151 \pm 21$ $\quad N^{II}_{\rm sig} = 125 \pm 19$ $\quad N^{III}_{\rm sig} = 55 \pm 15$

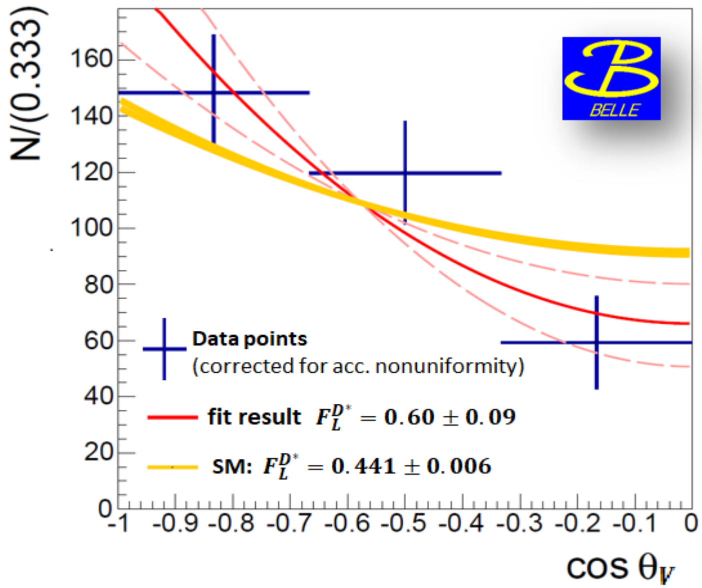
Acceptance correction factors: $s_I = 0.98$, $\quad s_{II} = 0.96$, $\quad s_{III} = 1.08$ $\quad$ *(SM dynamics assumed)*

# Measurement of the $D^{*-}$ polarization in the decay $B^0 \to D^{*-}\tau^+\nu_\tau$

Belle Collab., arXiv:1903.03102

- Extract fraction of the longitudinal $D^{*-}$ polarization from the angular distribution:

$$\frac{dN_{sig}}{d\cos\theta_V} = N_{sig}\frac{3}{4}\left[2F_L^{D^*}\cos^2\theta_V + (1-F_L^{D^*})\sin^2\theta_V\right]$$




Result (preliminary):

$F_L^{D^*} = 0.60 \pm 0.08(stat) \pm 0.04(syst)$

Can be reduced by adding $B^+ \to D^{*0}\tau^+\nu_\tau$

**Systematic uncertainties**

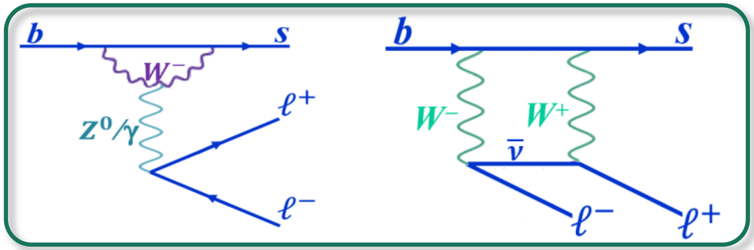
evaluated assuming SM dynamics

| source | | $\Delta F_L^{D^*}$ |
|---|---|---|
| MC statistics | bkgd combinatorial and peaking | $\pm 0.032$ |
| | signal shape | $\pm 0.010$ |
| | bkgd calibr. | $\pm 0.001$ |
| Background modelling | $D^{**}$ composition | $\pm 0.003$ |
| | $B \to D^{**}\tau\nu$ | $\pm 0.011$ |
| | $B \to$ hadrons | $\pm 0.005$ |
| | 2-body $B \to D^* M$ | $\pm 0.004$ |
| Signal modelling | Form factors | $\pm 0.002$ |
| | $\cos\theta_V$ resol. | $\pm 0.003$ |
| | Acceptance non-uniformity | $^{+0.015}_{-0.005}$ |
| Total | | $^{+0.039}_{-0.037}$ |

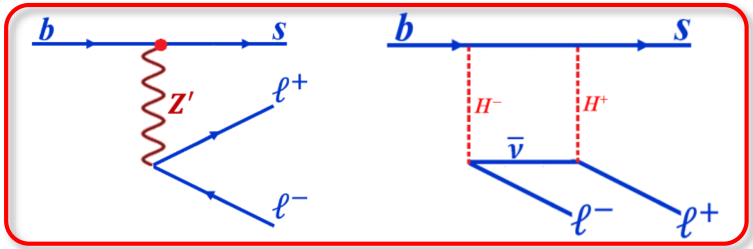

[1] A.K. Alok, D. Kumar, S. Kumbahar, S.U. Sankar, PRD **95**,115038(2017)
[2] Z.-R. Huang, Y. Li, M.A. Paracha, C. Wang, PRD **98**,095018(2018)
[3] S. Bhattacharya, S. Nandu, S.K. Patra Eur.Phys.J. C**79**,268 (2019)
[4] P. Gambino, M. Jung, S. Schacht, arXiv:1905.08209 [hep-ph]
[5] R.-X. Shi, L.-S. Geng, B. Grinstein, S. Jäger, J. M. Camalich, arXiv:1905.08498 [hep-ph]


| SM predictions | | Exp vs SM |
|---|---|---|
| $F_L^{D^*} = 0.46 \pm 0.04$ | [1] | 1.42σ |
| $F_L^{D^*} = 0.441 \pm 0.006$ | [2] | 1.76σ |
| $F_L^{D^*} = 0.457 \pm 0.010$ | [3] | 1.58σ |
| $F_L^{D^*} = 0.47 \pm 0.01$ | [4] | 1.44σ |
| $F_L^{D^*} = 0.455 \pm 0.009$ | [5] | 1.60σ |

# LFU in $b \to s\ell^+\ell^-$




Suppressed in the SM, $\mathcal{B}F's \sim 10^{-6}$




Many NP amplitudes can contribute causing complex phenomenology.

Several tensions (~3σ from SM) in $b \to s\ell^+\ell^-$ transitions (angular observables in $\to K^*\mu^+\mu^-$, $BF$'s of some $b \to s\ell^+\ell^-$ decays - theoretical uncertainties are still subject of debate) can be fit with NP models that predict $R(K^*) < 1$. e.g. B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, J. Virto, JHEP **01**, 093 (2018)

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \cong 1 \pm \mathcal{O}(10^{-4}(10^{-3}))$$ *robust SM prediction*

Precise test of LFU in FCNC

- $R(K) \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 0.846^{+0.060+0.016}_{-0.054-0.014}$ $\quad 1.1 < q^2 < 6\ \text{GeV}^2$ $\qquad q^2 = (M_{\ell^+\ell^-})^2$

  compatibility with SM: **2.5σ** LHCb Collab., PRL **122**,191801(2019)

- $R(K^{*0}) = 0.66^{+0.11}_{-0.07} \pm 0.03 \quad 0.45 < q^2 < 1.1\ \text{GeV}^2$

  $R(K^{*0}) = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad 1.10 < q^2 < 6\ \text{GeV}^2$

  compatibility with SM: **2.2–2.3σ** (low $q^2$), **2.4–2.5σ** (central $q^2$) LHCb Collab., JHEP **08**,055(2017)

**Belle**: ☹ lower statistics, ☺ good performance for $e^{\pm}$ modes

# Measurement of $R(K^*)$

Belle Collab., arXiv:1904.02440

## ➢ Reconstruction & selection of $B \to K^* \ell^+\ell^-$

$$B^0 \to K^{*0}\,\ell^+\ell^-, \quad K^{*0} \to K^+\pi^-, K_S^0\pi^0$$
$$B^+ \to K^{*+}\,\ell^+\ell^-, \quad K^{*+} \to K^+\pi^0, K_S^0\pi^+$$

- hierarchical NN reconstruction
- $\mathcal{P}_{e/\mu} \equiv \frac{\mathcal{L}_{e/\mu}}{\mathcal{L}_{e/\mu}+\mathcal{L}_\pi} > 0.9$

## ➢ Background suppression

- Multivariate method utilizing event topology and NN outputs
- Irreducible background from $B \to J/\psi K^*$ and $B \to \psi(2S)K^*$ reduced by rejecting events in the relevant $M_{\ell^+\ell^-}$ windows

## ➢ Signal extraction

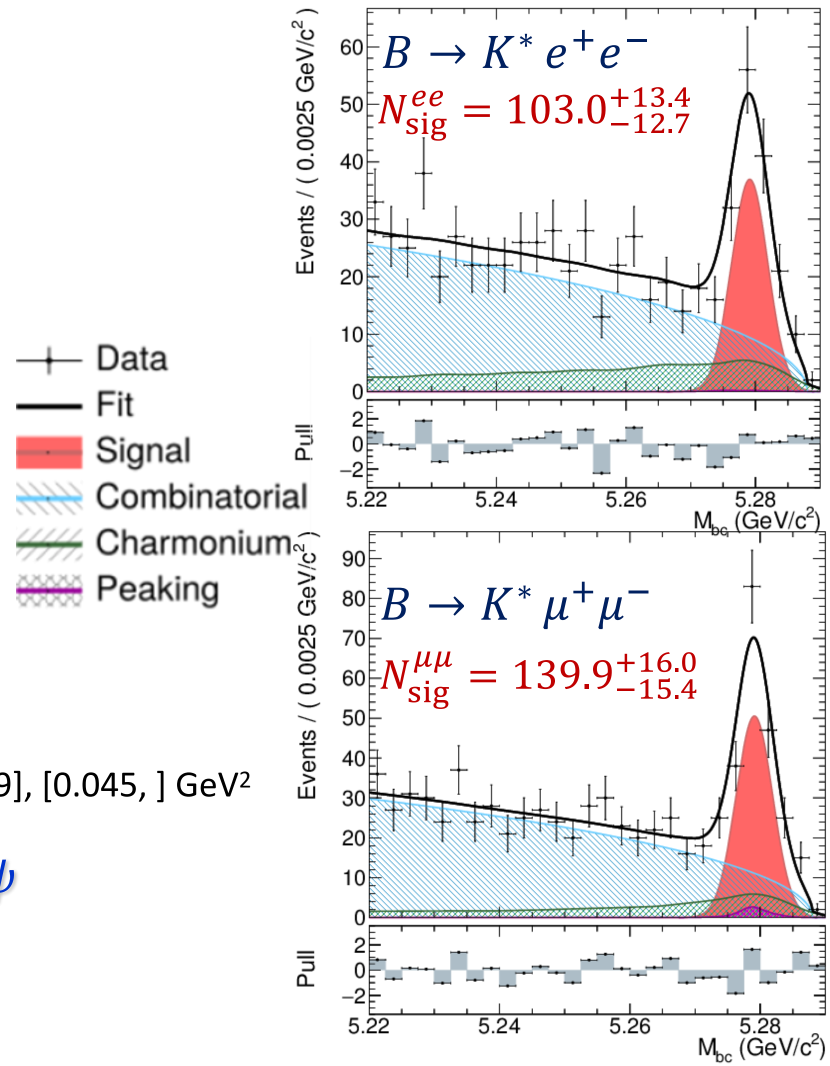
- UEML fit to $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - |\boldsymbol{p}_B|^2}$

  in several bins of $q^2$: [0.045, 1.1], [1.1, 6], [0.1, 8], [15, 19], [0.045, ] GeV²

## ➢ Control sample: data in the veto region of $J/\psi$

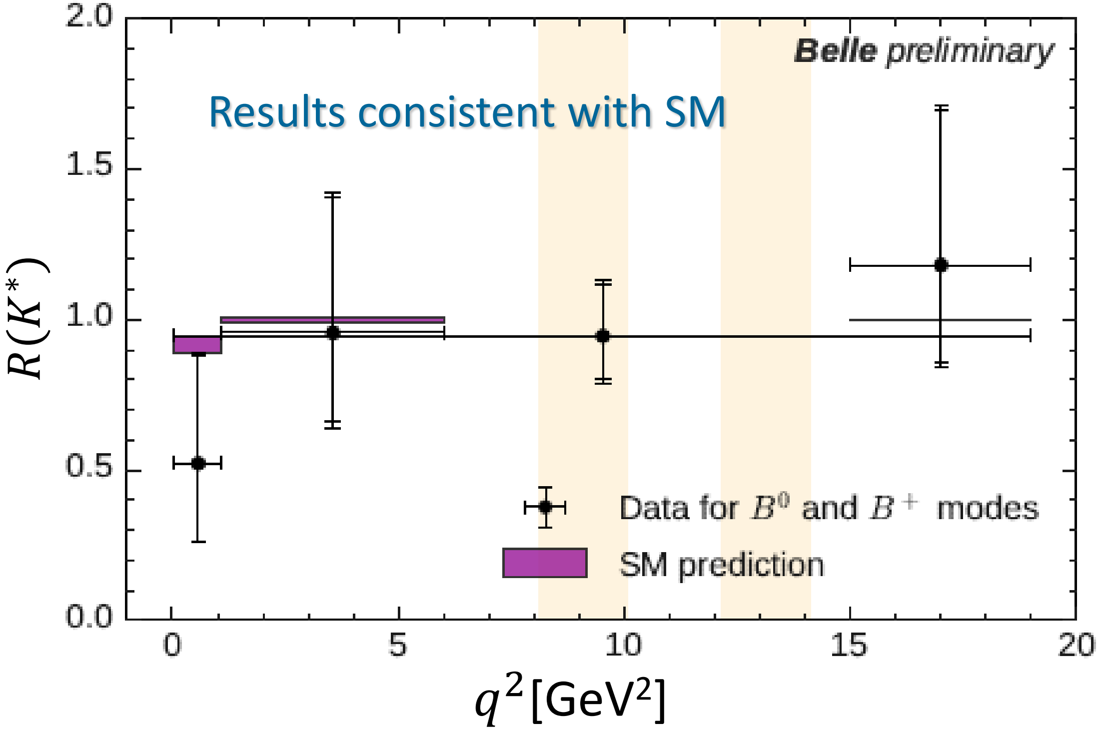
$$\frac{\mathcal{B}(B\to J/\psi(\to\mu^+\mu^-)K^*)}{\mathcal{B}(B\to J/\psi(\to e^+e^-)K^*)} = 1.015 \pm 0.025 \pm 0.038$$

Example fit for $q^2 > 0.045$ GeV²



# Measurement of $R(K^*)$

Belle Collab., arXiv:1904.02440




**Systematic uncertainties**
**for $B^{+/0}$ modes and $q^2$ > 0.045 GeV²**

| source | $\Delta R(K^*)$ |
|---|---|
| $e, \mu$ efficiency | 0.061 |
| MC size | 0.004 |
| Classifier | 0.013 |
| Signal shape | 0.008 |
| Tracking eff. | 0.016 |
| Peaking bkgr. | 0.031 |
| Charmonia bkgr. | 0.023 |
| total | 0.075 |

| $q^2$ in GeV$^2$/c$^4$ | All modes | $B^0$ modes | $B^+$ modes |
|---|---|---|---|
| [0.045, 1.1] | $0.52^{+0.36}_{-0.26} \pm 0.05$ | $0.46^{+0.55}_{-0.27} \pm 0.07$ | $0.62^{+0.60}_{-0.36} \pm 0.10$ |
| [1.1, 6] | $0.96^{+0.45}_{-0.29} \pm 0.11$ | $1.06^{+0.63}_{-0.38} \pm 0.13$ | $0.72^{+0.99}_{-0.44} \pm 0.18$ |
| [0.1, 8] | $0.90^{+0.27}_{-0.21} \pm 0.10$ | $0.86^{+0.33}_{-0.24} \pm 0.08$ | $0.96^{+0.56}_{-0.35} \pm 0.14$ |
| [15, 19] | $1.18^{+0.52}_{-0.32} \pm 0.10$ | $1.12^{+0.61}_{-0.36} \pm 0.10$ | $1.40^{+1.99}_{-0.68} \pm 0.11$ |
| [0.045, ] | $0.94^{+0.17}_{-0.14} \pm 0.08$ | $1.12^{+0.27}_{-0.21} \pm 0.09$ | $0.70^{+0.24}_{-0.19} \pm 0.07$ |

⇐ first measurements

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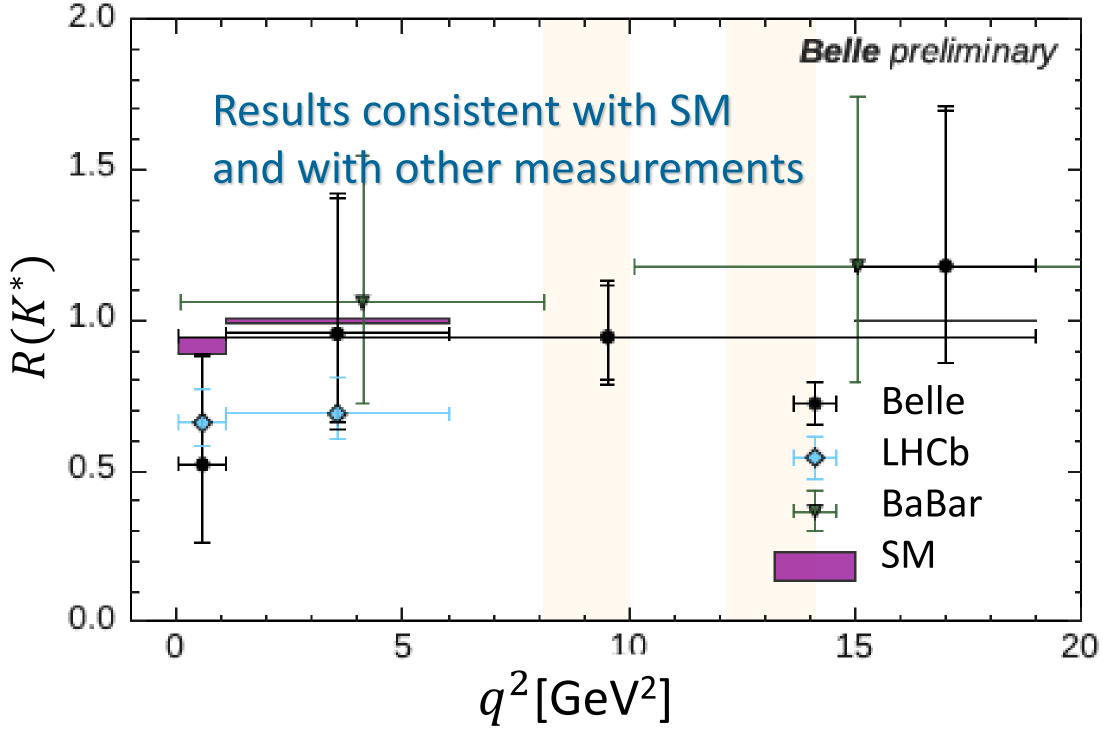
Belle Collab., arXiv:1904.02440

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⇐ first measurements

# Summary and outlook

- New measurement of $R(D^{(*)})$ using semileptonic $B_{\text{tag}}$ decays

$$R(D) = 0.307 \pm 0.037(stat) \pm 0.016(syst)$$
$$R(D^*) = 0.283 \pm 0.018(stat) \pm 0.014(syst)$$

  - first measurement of $R(D)$ with semileptonic tagging
  - most precise $R(D^{(*)})$ measurements to date
  - results consistent with SM within ~1.3σ
  - tension between SM and experimental world averages reduced 3.8σ ⇒ ~3.1σ

- Measurement of $D^{*-}$ polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$

$$F_L^{D^*} = 0.60 \pm 0.08(stat) \pm 0.04(syst)$$

  - first measurement of $D^*$ polarization in semitauonic decay
  - the measured value consistent with SM within ~1.5σ
  - experimental accuracy can be further improved with Belle data by including $B^+ \to D^*\tau\nu_\tau$
  - $\frac{d^2\Gamma}{dq^2 d\cos\theta_V}$ feasible at Belle II (enhanced sensitivity to NP, reduced acceptance effects)

- New measurements of $R(K^*)$ in several bins of $q^2$: [0.045, 1.1], [1.1, 6], [0.1, 8], [15, 19], [0.045, ] GeV²

$$R(K^*) = 0.94^{+0.17}_{-0.14}(stat) \pm 0.08(syst), \quad \text{for } q^2 > 0.045\ \text{GeV}^2$$

  - first measurement of $R(K^{*+})$
  - all results compatible with SM and other measurements

- Experimental accuracy limited by statistics ⇒ good prospects for Belle II, with expected 50× larger data sample.

# Backup slides

| | | |
|---|---|---|
| $D^+\ell^-$ | $B \to D\tau\nu$ | $307 \pm 65$ |
| | $B \to D\ell\nu$ | $6800 \pm 179$ |
| | $B^0 \to D^*\ell\nu$ | $6370 \pm 225$ |
| | $B^0 \to D^*\tau\nu$ | $269 \pm 24$ |
| | $B \to D^{**}\ell\nu$ | $413 \pm 110$ |
| | Fake $D$ | $3072 \pm 129$ (Fixed) |
| | Other | $506 \pm 23$ (Fixed) |
| $D^0\ell^-$ | $B \to D\tau\nu$ | $1471 \pm 193$ |
| | $B \to D\ell\nu$ | $16096 \pm 436$ |
| | $B^+ \to D^*\ell\nu$ | $45042 \pm 563$ |
| | $B^0 \to D^*\ell\nu$ | $2302 \pm 531$ |
| | $B^+ \to D^*\tau\nu$ | $1704 \pm 177$ |
| | $B^0 \to D^*\tau\nu$ | $123 \pm 11$ |
| | $B \to D^{**}\ell\nu$ | $3595 \pm 252$ |
| | Fake $D$ | $8708 \pm 418$ (Fixed) |
| | Other | $2131 \pm 83$ (Fixed) |
| $D^{*+}\ell^-$ | $B \to D^*\tau\nu$ | $376 \pm 36$ |
| | $B \to D^*\ell\nu$ | $9794 \pm 109$ |
| | $B \to D^{**}\ell\nu$ | $314 \pm 65$ |
| | Fake $D^*$ | $754 \pm 39$ (Fixed) |
| | Other | $287 \pm 13$ (Fixed) |
| $D^{*0}\ell^-$ | $B \to D^*\tau\nu$ | $275 \pm 29$ |
| | $B \to D^*\ell\nu$ | $7148 \pm 100$ |
| | $B \to D^{**}\ell\nu$ | $406 \pm 64$ |
| | Fake $D^*$ | $1993 \pm 122$ (Fixed) |
| | Other | $187 \pm 7$ (Fixed) |

TABLE I. Systematic uncertainties contributing to the $\mathcal{R}(D^{(*)})$results.

| Source | $\Delta R(D)$ (%) | $\Delta R(D^*)$ (%) | Correlation |
|---|---|---|---|
| $D^{**}$ composition | 0.76 | 1.41 | -0.41 |
| Fake $D^{(*)}$ calibration | 0.19 | 0.11 | -0.76 |
| $B_{\text{tag}}$ calibration | 0.07 | 0.05 | -0.76 |
| Feed-down factors | 1.69 | 0.44 | 0.53 |
| Efficiency factors | 1.93 | 4.12 | -0.57 |
| Lepton efficiency and fake rate | 0.36 | 0.33 | -0.83 |
| Slow pion efficiency | 0.08 | 0.08 | -0.98 |
| MC statistics | 4.39 | 2.25 | -0.55 |
| $B$ decay form factors | 0.55 | 0.28 | -0.60 |
| Luminosity | 0.10 | 0.04 | -0.58 |
| $\mathcal{B}(B \to D^{(*)}\ell\nu)$ | 0.05 | 0.02 | -0.69 |
| $\mathcal{B}(D)$ | 0.35 | 0.13 | -0.65 |
| $\mathcal{B}(D^*)$ | 0.04 | 0.02 | -0.51 |
| $\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$ | 0.15 | 0.14 | -0.11 |
| Total | 5.21 | 4.94 | -0.52 |

## electron:

$$\mathcal{R}(D) = 0.281 \pm 0.042 \pm 0.017$$

$$\mathcal{R}(D^*) = 0.304 \pm 0.022 \pm 0.016$$

## muon:

$$\mathcal{R}(D) = 0.373 \pm 0.068 \pm 0.030$$

$$\mathcal{R}(D^*) = 0.245 \pm 0.035 \pm 0.020$$

# $R(K^*)$: Systematics

| $q^2$ in GeV$^2$ / c$^4$ | $e, \mu$ eff. | MC size | classifier | sig. shape | tracking | peaking bkg. | $c\bar{c}$ bkg. | total |
|---|---|---|---|---|---|---|---|---|
| all modes | | | | | | | | |
| - [0.045, None] - | 0.061 | 0.004 | 0.013 | 0.008 | 0.016 | 0.031 | 0.023 | 0.075 |
| - [0.1, 8] - | 0.058 | 0.005 | 0.029 | 0.002 | 0.016 | 0.054 | 0.051 | 0.100 |
| - [15, 19] - | 0.090 | 0.012 | 0.012 | 0.014 | 0.020 | 0.003 | 0.003 | 0.095 |
| - [0.045, 1.1] - | 0.027 | 0.006 | 0.008 | 0.025 | 0.009 | 0.026 | 0.001 | 0.047 |
| - [1.1, 6] - | 0.065 | 0.008 | 0.048 | 0.033 | 0.017 | 0.070 | 0.013 | 0.114 |
| $B^0$ modes | | | | | | | | |
| - [0.045, None] - | 0.073 | 0.006 | 0.030 | 0.018 | 0.022 | 0.031 | 0.021 | 0.092 |
| - [0.1, 8] - | 0.058 | 0.006 | 0.040 | 0.019 | 0.017 | 0.033 | 0.018 | 0.084 |
| - [15, 19] - | 0.091 | 0.013 | 0.007 | 0.012 | 0.022 | 0.007 | 0.001 | 0.096 |
| - [0.045, 1.1] - | 0.024 | 0.007 | 0.044 | 0.005 | 0.009 | 0.049 | 0.001 | 0.071 |
| - [1.1, 6] - | 0.082 | 0.010 | 0.040 | 0.062 | 0.021 | 0.070 | 0.012 | 0.133 |
| $B^+$ modes | | | | | | | | |
| - [0.045, None] - | 0.044 | 0.005 | 0.032 | 0.018 | 0.010 | 0.025 | 0.023 | 0.068 |
| - [0.1, 8] - | 0.060 | 0.010 | 0.039 | 0.040 | 0.014 | 0.048 | 0.107 | 0.144 |
| - [15, 19] - | 0.089 | 0.028 | 0.016 | 0.041 | 0.021 | 0.008 | 0.002 | 0.106 |
| - [0.045, 1.1] - | 0.033 | 0.013 | 0.067 | 0.060 | 0.009 | 0.006 | 0.000 | 0.097 |
| - [1.1, 6] - | 0.045 | 0.010 | 0.137 | 0.060 | 0.011 | 0.086 | 0.009 | 0.179 |

Acceptance effects in $B \to D^* \tau \nu$

$\theta_{hel}(D^*) \equiv \theta_V$