LFU in charged-current *B* decays

Suzanne Klaver, on behalf of the LHCb collaboration,
also including material from Belle and BaBar

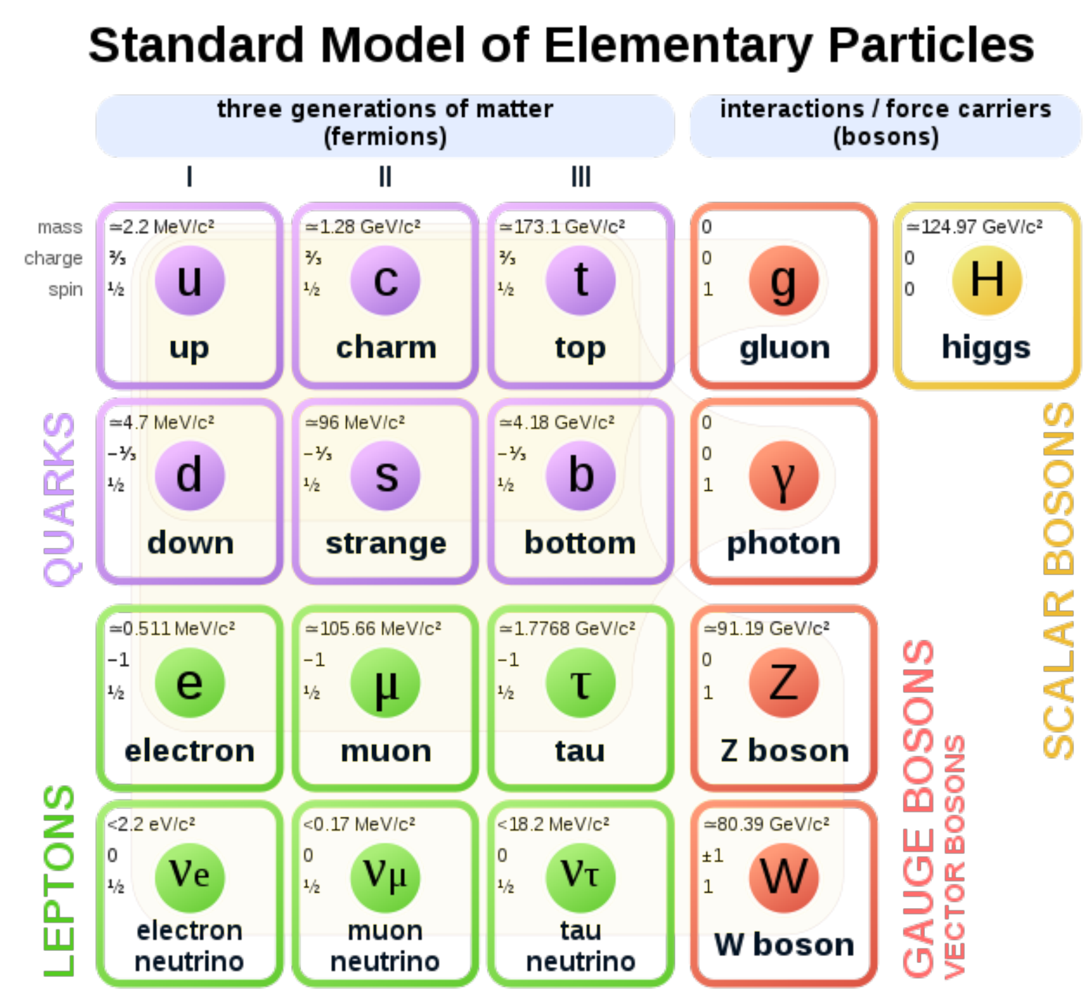
FPCP 2019

Victoria BC, 8 May 2019

Lepton flavour universality

In the SM there are three families of fermions:

- they have same gauge charge assignments
  → same coupling (**universality**)
- only difference between the families comes from the Yukawa couplings with the Higgs field, resulting in **CKM** and **PMNS** matrices and **different masses**
- measure lepton universality in **ratios**: CKM elements cancel, and only difference is in **lepton mass**



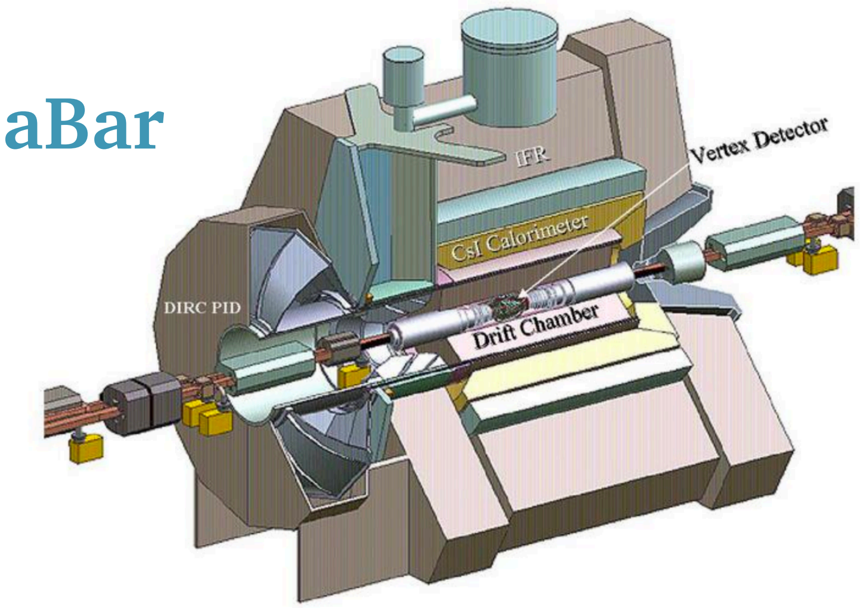
Experiments: B-factories

- e^+e^- colliders @ $\Upsilon(4S)$ resonance
- b quarks produced from $\Upsilon(4S) \rightarrow B^+B^-$ or $B^0\,\bar{B}^0$, → 4π detectors (asymmetric, boost of $\Upsilon(4S)$)
- very clean environment, little background
- well-constrained kinematics help reconstruct final states with neutrinos

BaBar: 1999–2008: 433 fb^{-1} @ $\Upsilon(4S)$

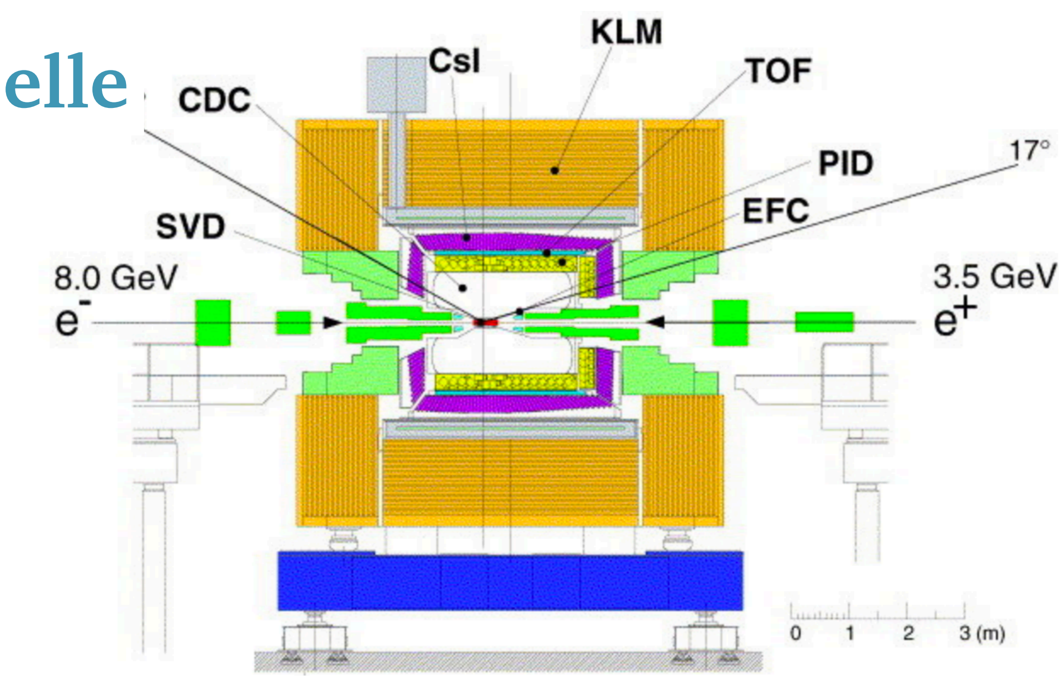
Belle: 1999–2010: 711 fb^{-1} @ $\Upsilon(4S)$

BaBar



Nucl.Instrum.Meth.A479:1-116,2002

Belle



Nucl.Instrum.Meth. A479 (2002) 117-232

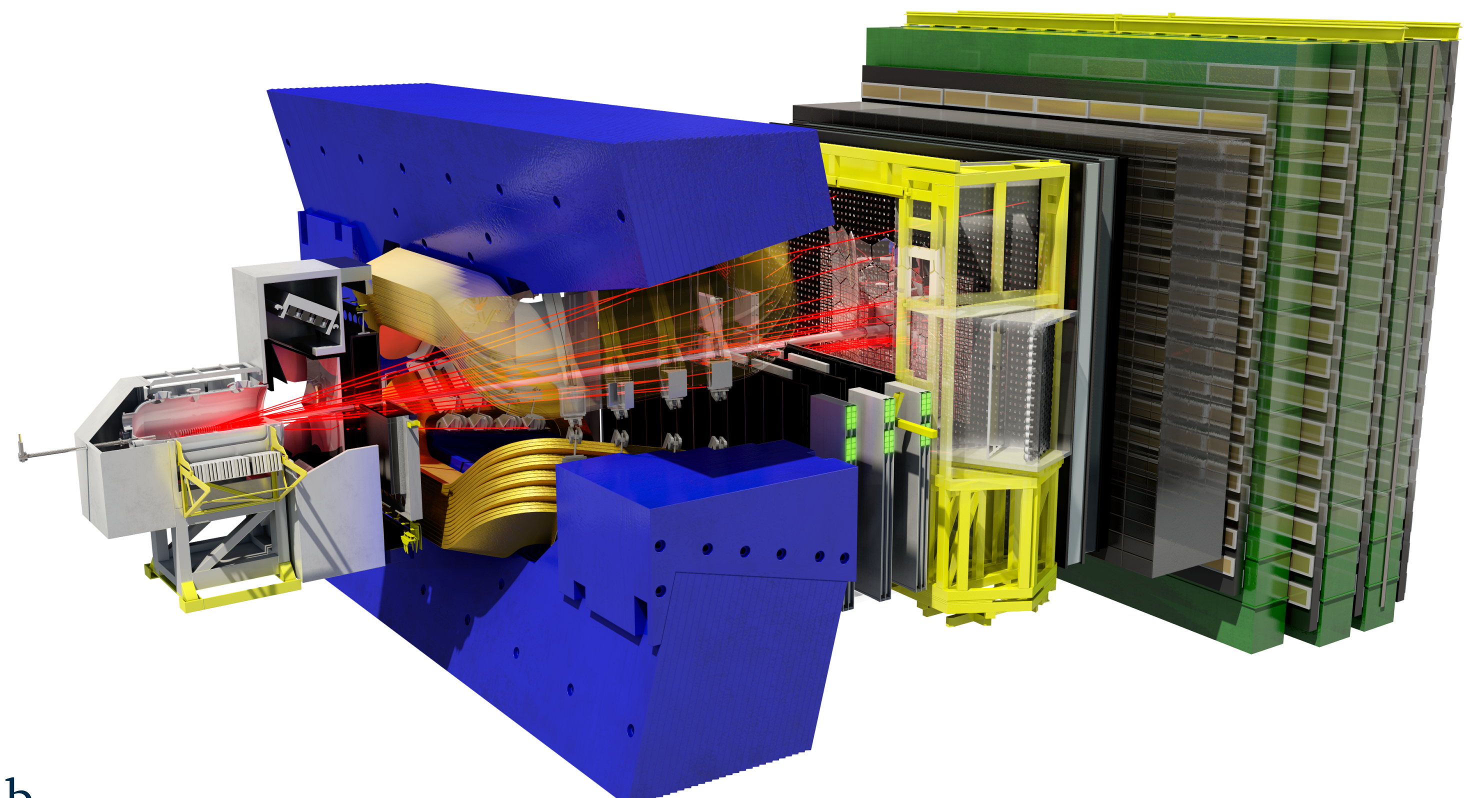
Experiments: LHCb

JINST 3 (2008) S08005

- *pp* collisions @ LHC
- *b* quarks produced by gluon fusion → forward direction
- boosted CM energy helps to reconstruct vertices
- many more *b*'s, but a lot more background
- all *b*-hadron species are produced: B^+, B^0, B_s, B_c, Λ_b

Run 1: 2011–2012: 3 fb^{-1} @ 7-8 TeV

Run 2: 2015–2018: 6 fb^{-1} @ 13 TeV



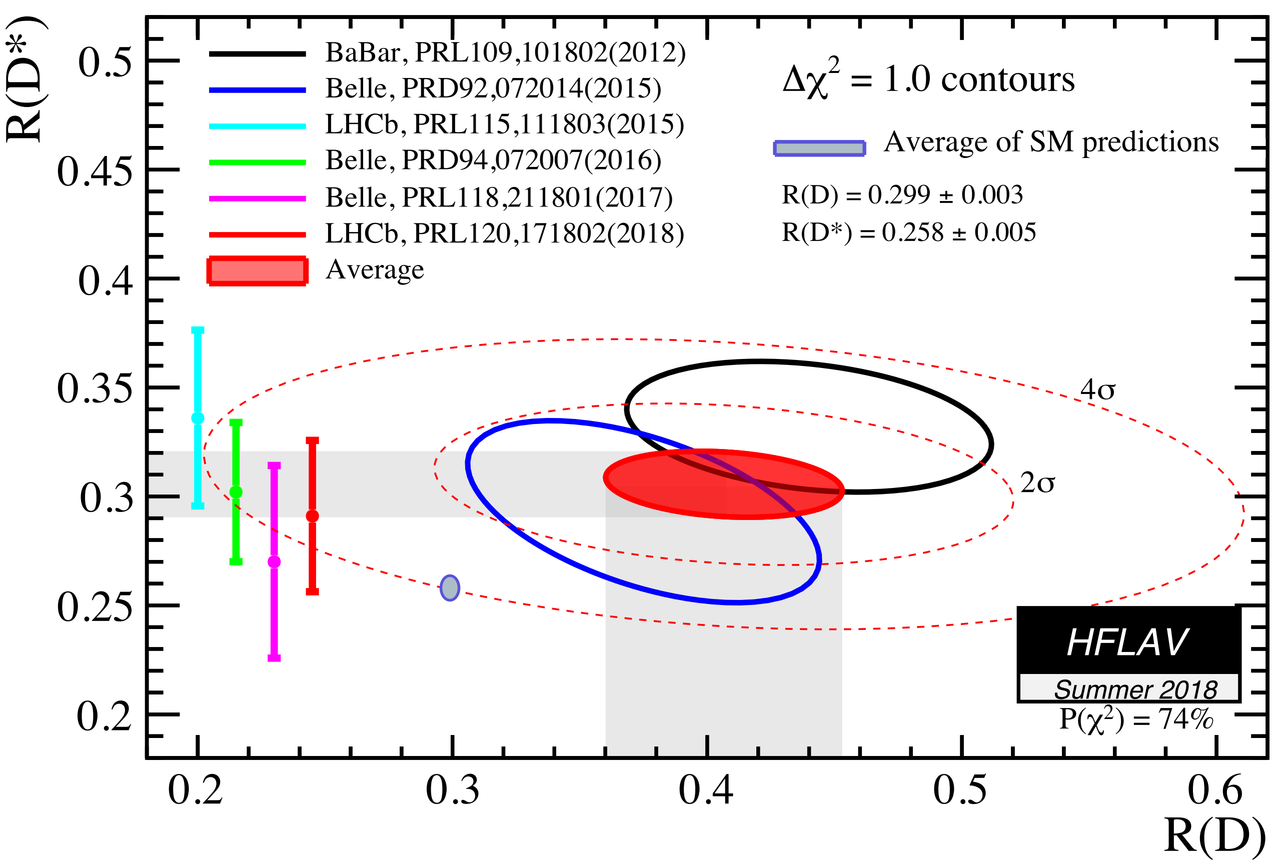
Overview *R(D)* and friends

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell' \overline{\nu}_{\ell'})}$$

ℓ' = μ (LHCb)

ℓ' = e/μ (B-factories)

- Tree-level processes are sensitive to new physics: charged Higgs, leptoquarks etc.
- Predictions are theoretically clean.
- Large data sets.
- Before Moriond EW 4σ tension with the SM for *R(D)-R(D*)*.



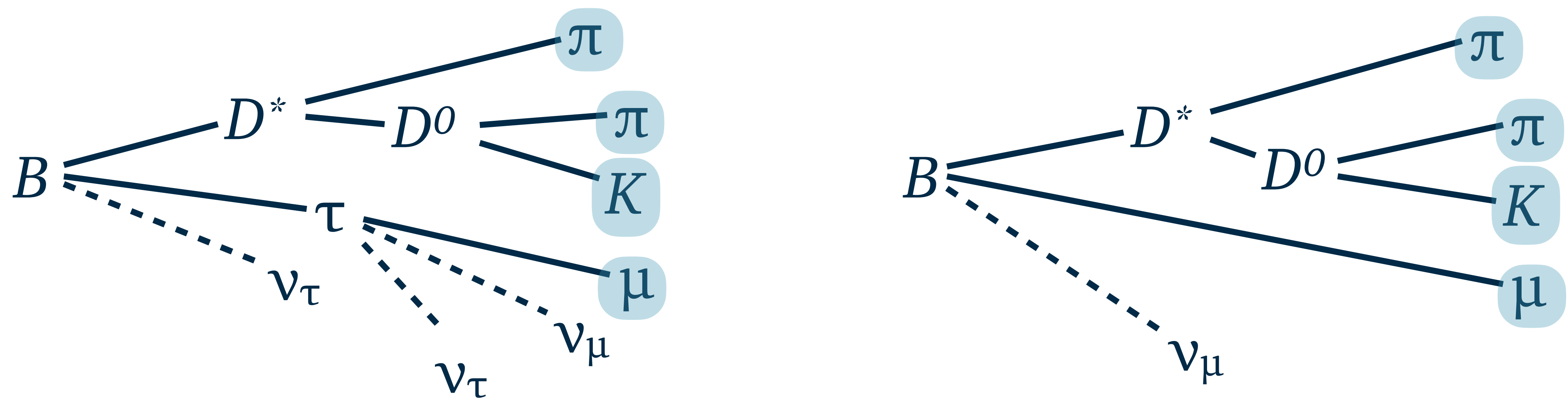
Leptonic τ decays

Reconstructing τ

- $\tau \to \mu\, \nu_\mu\, \nu_\tau$ $\qquad \mathscr{B}(\tau \to \mu\, \nu_\mu\, \nu_\tau) = 17.4\%$
- $\tau \to e\, \nu_e\, \nu_\tau$ $\qquad \mathscr{B}(\tau \to e\, \nu_e\, \nu_\tau) = 17.8\%$

Strategy:

- Signal and normalisation channels have same visible final state



- Part of systematics cancels in the ratio.
- Backgrounds from inclusive semileptonic decays, with many unknowns (form factors, decay rates etc).

Hadronic τ decays

Reconstructing τ

- Hadronic decays:

Decay	$\mathcal{B}$ (%)
$\tau^- \to \pi^-\pi^0\,\nu_\tau$	25.49 ± 0.09
$\tau^- \to \pi^-\,\nu_\tau$	10.82 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\,\nu_\tau$	9.02 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\pi^0\,\nu_\tau$	4.49 ± 0.05

First two: 1-prong decays, only at *B* factories

Last two: 3-prong decays, only at LHCb

Strategy:

- Final states are not the same.
- Systematics (at LHCb) do not cancel in the ratio between signal and normalisation channel.
  → measure with respect to another decay with similar final state

LHCb vs. B-factories

- LHCb:
  - use the B flight direction to measure transverse component of missing momentum
  - cannot measure longitudinal component, so use approximation to access rest frame kinematics:
    - $(\gamma\beta_z)_B = (\gamma\beta_z)_{D^*\mu}$
    - 18% resolution on B momentum
- B factories:
  - B momentum is known
  - tag algorithms use the other B in the event:
    - hadronic tag: 0.3% efficient, very pure: all backgrounds are fully reconstructed
    - SL tag: 1% efficient, less pure

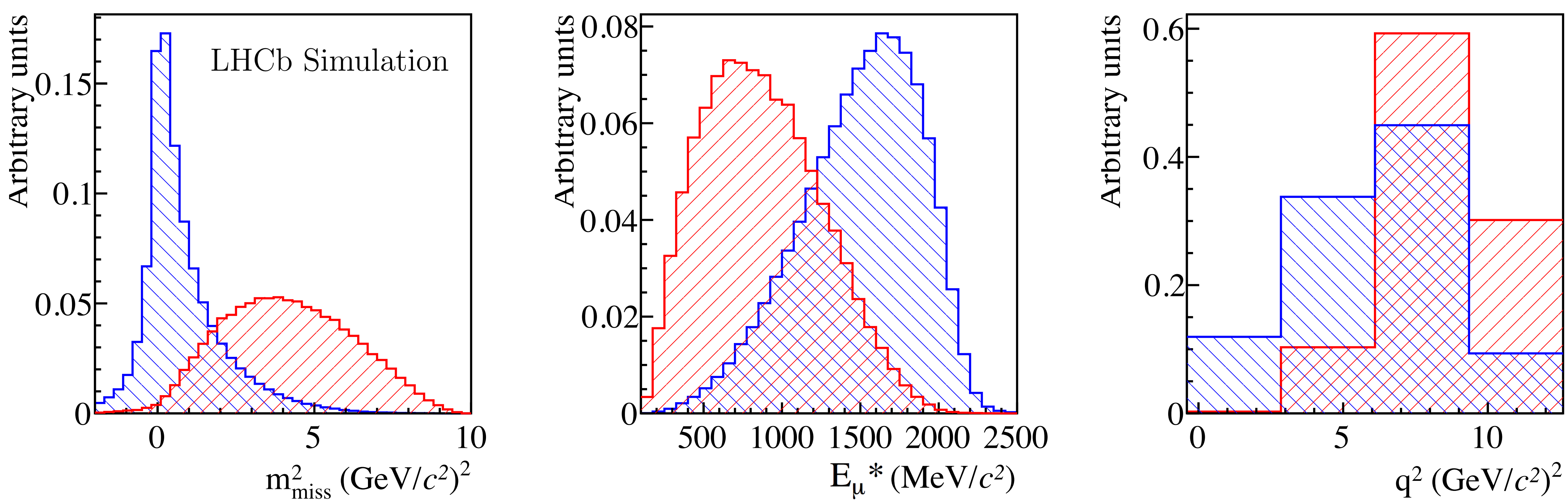
Discriminating variables for *R(D)*

- Make the fit templates from most discriminating variables: kinematic
- As an *example**, the muonic *R(D*)* analysis from LHCb: **PRL 115 (2015) 111803**
  - signal channel: $\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$
  - normalisation channel: $\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu$

* *Other analyses use different variables*

$m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$

$q^2 = (p_\ell + p_\nu)^= (p_B - p_{D^*})^2$



Measurements from LHCb

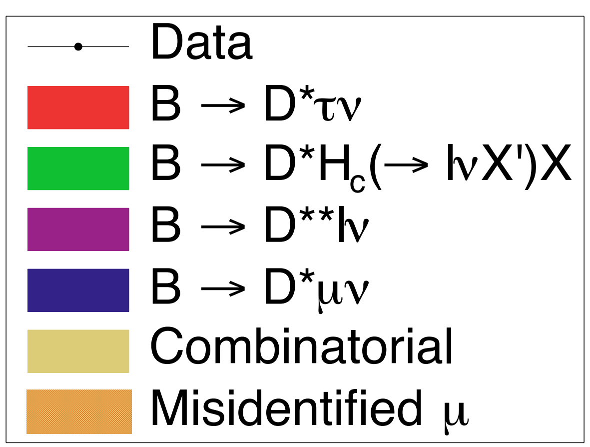
$R(D^*)$ leptonic

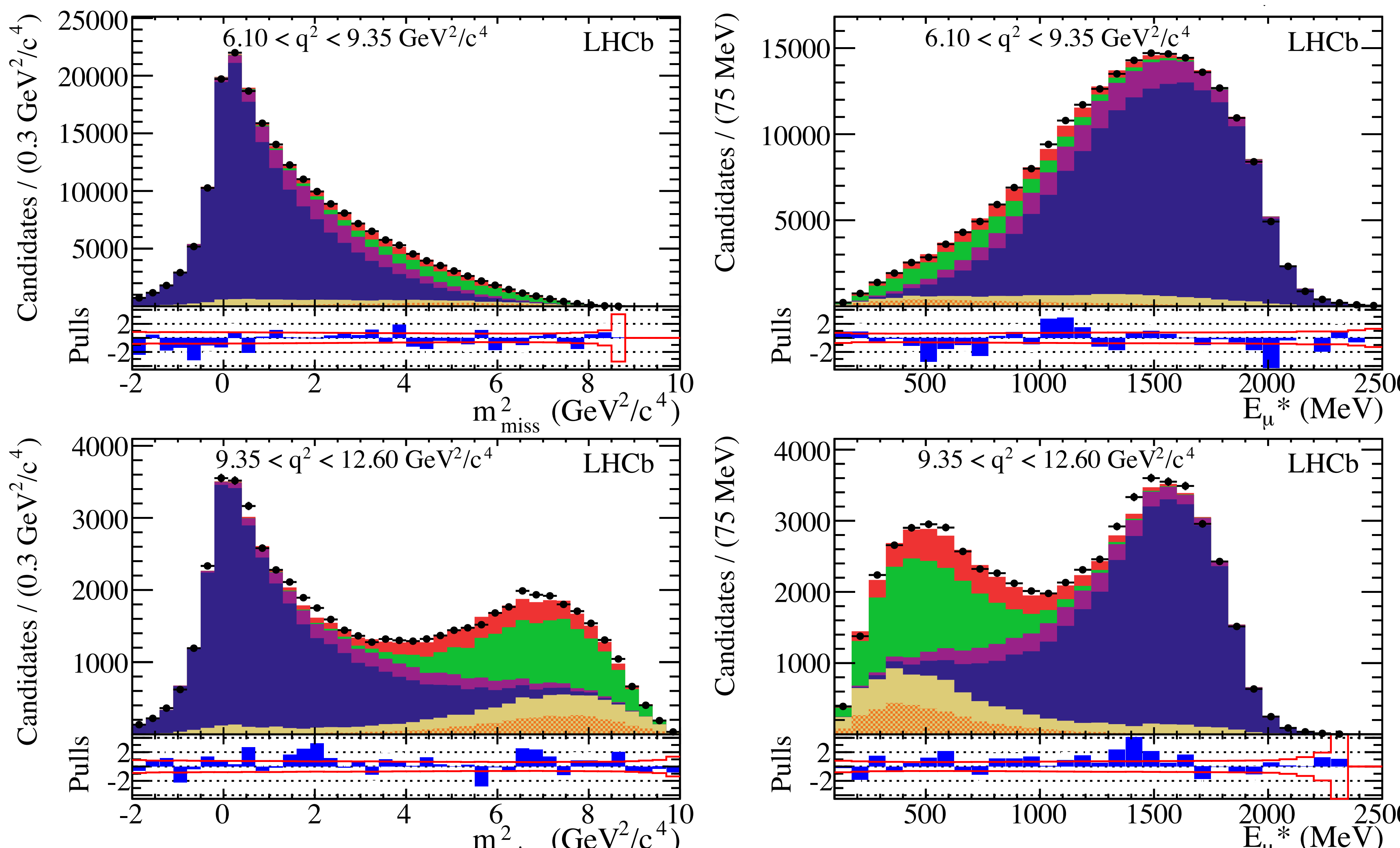
PRL 115 (2015) 111803

$$\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst}) \qquad \mathcal{R}(D^*) = \frac{\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau}{\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu}$$

- Compatible with SM within 2.1σ

Run 1



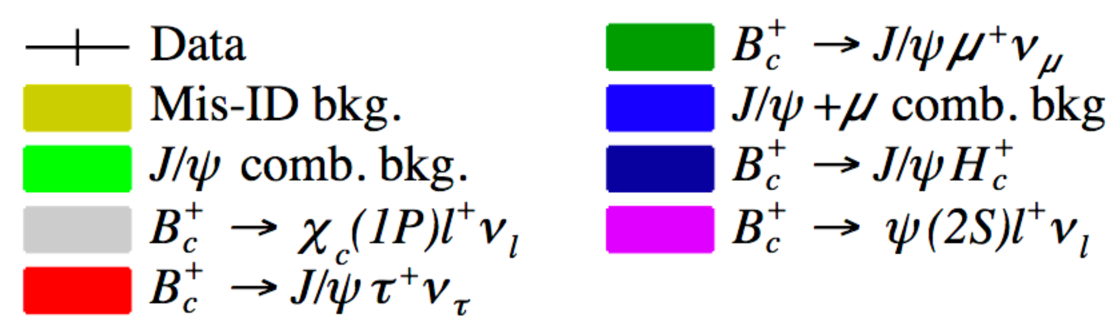


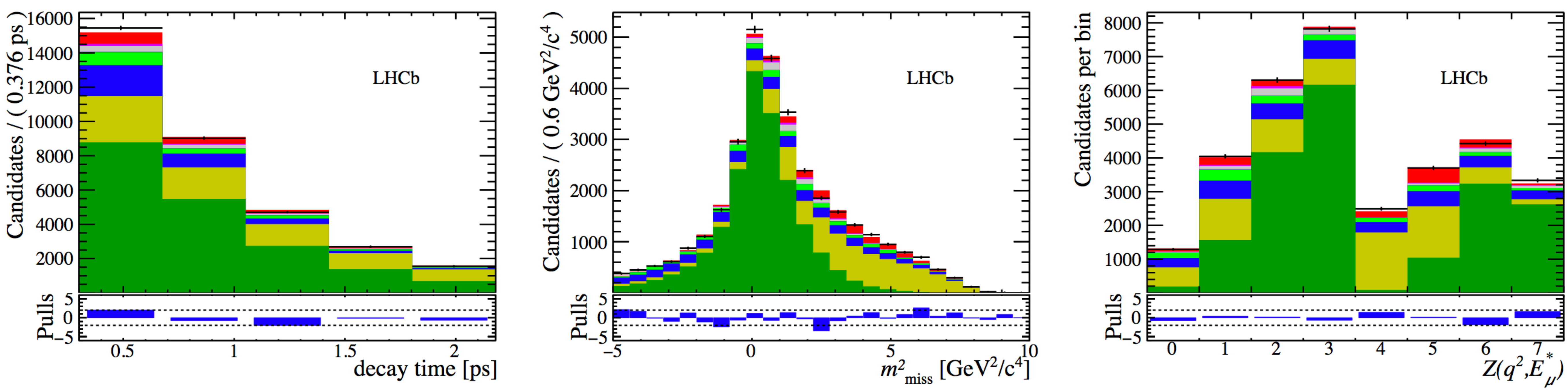
$R(J/\Psi)$ muonic

PRL 120, 121801 (2018)

- $\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\mathrm{stat}) \pm 0.18(\mathrm{syst})$ Run 1
- Compatible with SM within 2σ
- Systematics come from limited sample simulations, but largest from **uncertainty on form factors** (fit from data). Will improve with lattice calculations.

$$\mathcal{R}(J/\psi) = \frac{B_c^+ \to J/\psi \tau^+ \nu_\tau}{B_c^+ \to J/\psi \mu^+ \nu_\mu}$$





$R(D^*)$ hadronic

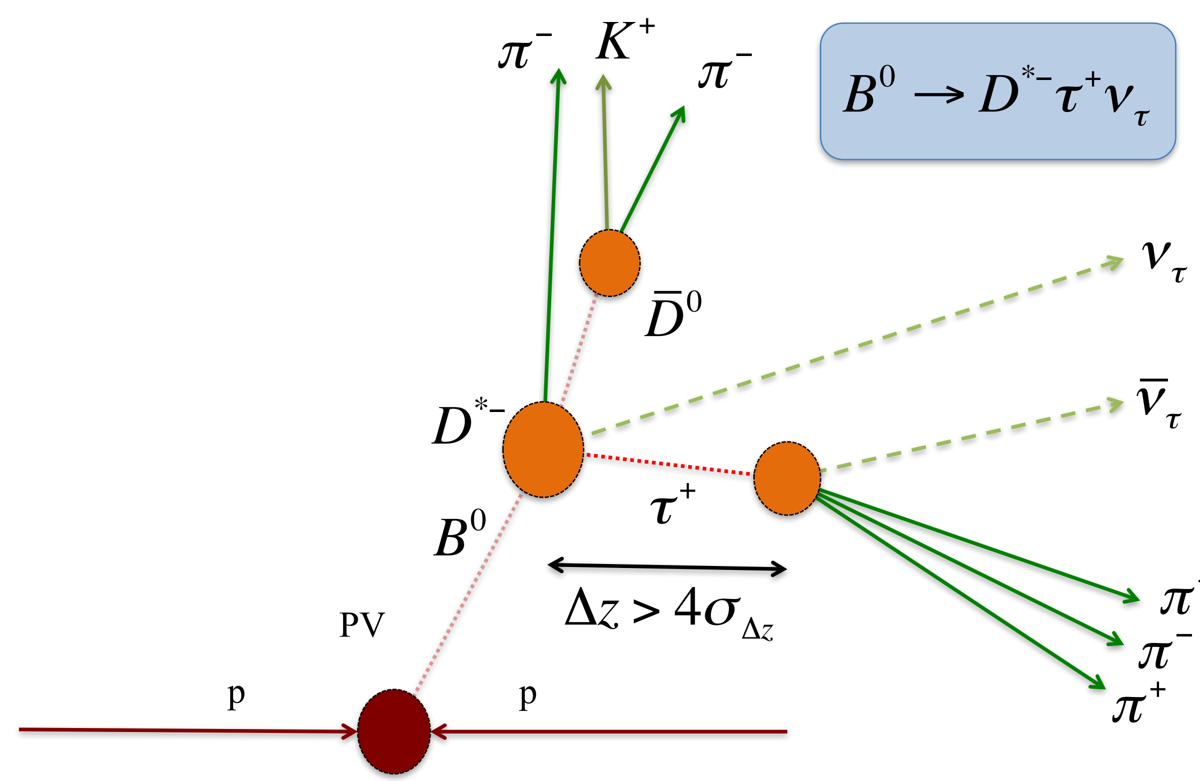
PRD 97, 072013 (2018)

PRL 120, 171802 (2018)

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}}_{\mathcal{K}(D^*)} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

Run 1

- Signal and normalisation channels have the same final state, such that many systematics cancel in the ratio.
- Use topology of the decay to suppress backgrounds.



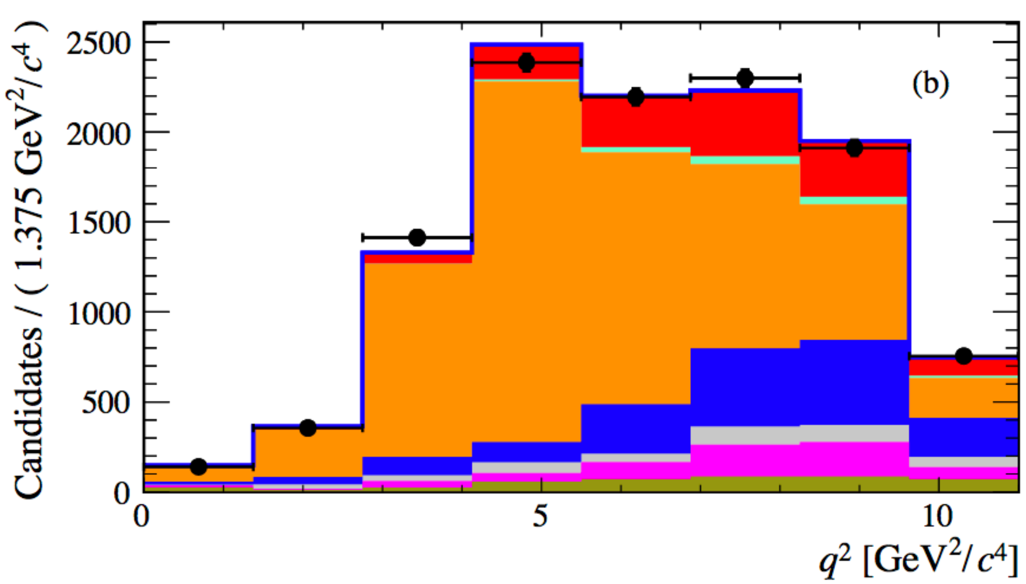
$R(D^*)$ hadronic

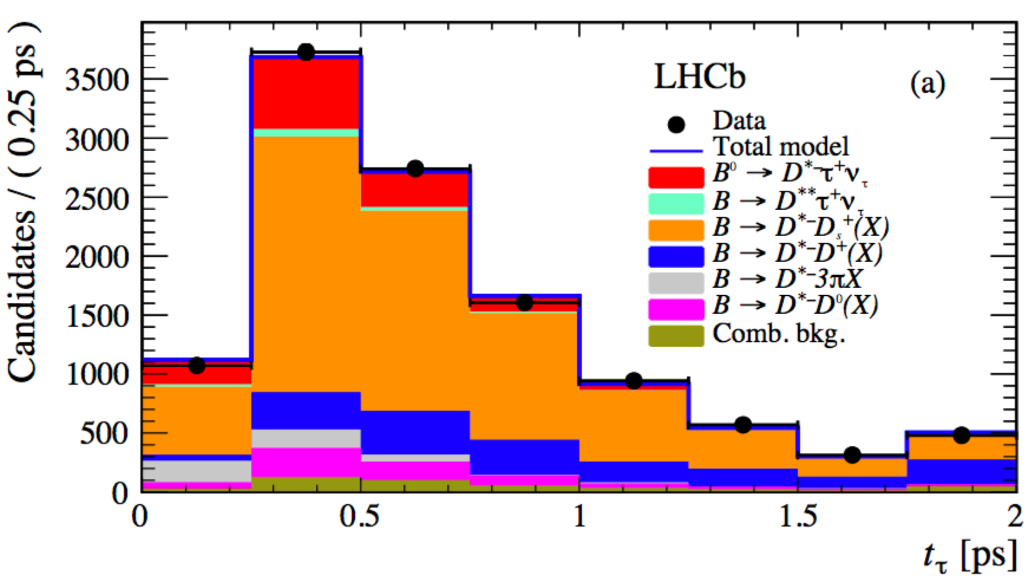
PRD 97, 072013 (2018)

PRL 120, 171802 (2018)

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}}_{\mathcal{K}(D^*)} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

- $\mathcal{K}(D^*) = 1.93 \pm 0.12(\text{stat}) \pm 0.17(\text{syst})$
- $\mathcal{R}(D^*) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{BR})$
- Compatible with SM within 1σ.





$R(D^*)$ hadronic

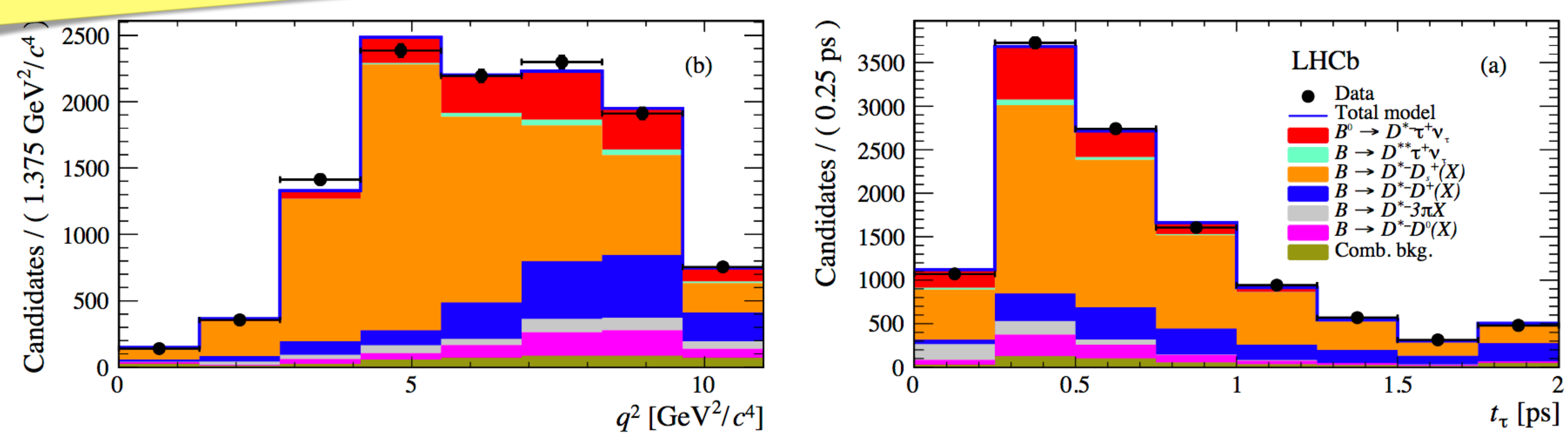
PRD 97, 072013 (2018)

PRL 120, 171802 (2018)

$$\mathcal{R}(D^*) = \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

external inputs have recently been updated by HFLAV!

- $\mathcal{K}(D^*$ … syst)
- $\mathcal{R}(D^*$ … 26(syst) $\pm\, 0.013$(BR)
- Comp…



BR($B^0 \to D^{*+}\mu\nu_\mu$)

HFLAV

- Since this year, D^{*+} and D^{*0} decays are not combined in this average, excluding inputs from measurements that combined these.

Exclusive Branching Fraction: B^0 -> D^{*-}lnu (using both isospin states)

Experiment	BF (rescaled) [%]
ALEPH	5.26 +/- 0.25 +/- 0.30
CLEO	5.55 +/- 0.17 +/- 0.24
OPAL excl	4.93 +/- 0.18 +/- 0.43
OPAL partial reco	5.42 +/- 0.25 +/- 0.52
DELPHI partial reco	4.85 +/- 0.13 +/- 0.72
DELPHI excl	5.27 +/- 0.20 +/- 0.37
BELLE	4.51 +/- 0.03 +/- 0.26
BABAR excl	4.45 +/- 0.04 +/- 0.26
BABAR D*0	4.90 +/- 0.07 +/- 0.34
BABAR global fit	4.90 +/- 0.02 +/- 0.19
Average	**4.88 +/- 0.01 +/- 0.10**

https://hflav-eos.web.cern.ch/hflav-eos/semi/summer16/html/ExclusiveVcb/exclBtoDstar.html

Exclusive Branching Fraction: B^0 -> D^{*-}lnu

Experiment	BF (rescaled) [%]
ALEPH	5.56 +/- 0.27 +/- 0.33
OPAL incl	6.13 +/- 0.28 +/- 0.57
OPAL excl	5.17 +/- 0.20 +/- 0.36
DELPHI incl	4.96 +/- 0.14 +/- 0.35
DELPHI excl	5.23 +/- 0.20 +/- 0.42
CLEO	6.17 +/- 0.19 +/- 0.37
BELLE	4.58 +/- 0.03 +/- 0.26
BABAR untagged	4.52 +/- 0.04 +/- 0.33
BABAR tagged	5.26 +/- 0.16 +/- 0.31
Average	**5.05 +/- 0.02 +/- 0.14**

https://hflav-eos.web.cern.ch/hflav-eos/semi/pdg19/html/ExclusiveVcb/exclBtoDstar.html

- Also, new Belle measurement is included arXiv:1809.03290v3 (not yet in table), see talk by Eiasha Waheed, new average: BR($B^0 \to D^{*+}\mu\nu_\mu$) $= (5.08 \pm 0.02 \pm 0.12)\%$

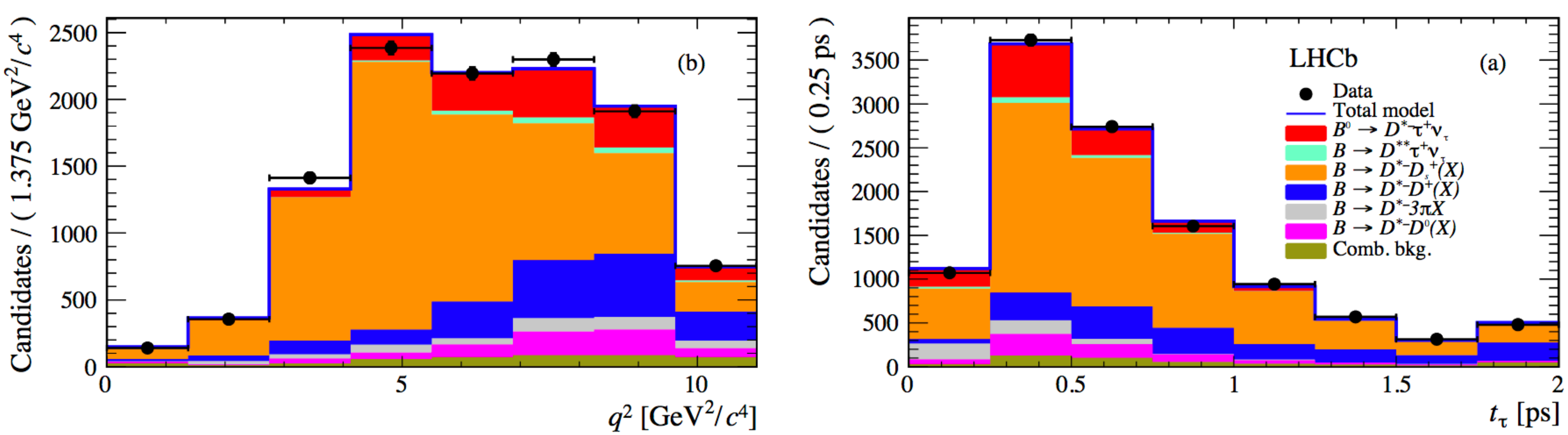
$R(D^*)$ hadronic

PRD 97, 072013 (2018)

PRL 120, 171802 (2018)

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}}_{\mathcal{K}(D^*)} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

- $\mathcal{K}(D^*) = 1.93 \pm 0.12(\text{stat}) \pm 0.17(\text{syst})$
- $\mathcal{R}(D^*) = 0.280 \pm 0.018(\text{stat}) \pm 0.029(\text{syst})$ Updated by HFLAV
- Compatible with SM within 1σ



Belle's SL-tagged $R(D^{(*)})$

SL-tagged $R(D^{(*)})$ by Belle

- At Moriond EW, **new** results were presented by Belle, followed by a conference note: arXiv:1904.08794
- Update of the SL-tagged analysis: from measuring $R(D^*)$ to a simultaneous measurement of $R(D)$-$R(D^*)$.
- Using the full $\Upsilon(4S)$ data set with 772×10^6 $B\bar{B}$ events.
- First SL-tagged $R(D)$: B_{tag} reconstructed using BDT and $B\to D^{(*)}\ell\nu$ decays, where $\ell = e, \mu$.
- On tag side: $\ell = \tau(\to\mu/e\ \nu\nu)$ vetoed by applying a cut on $\cos\theta_{B,D^{(*)}\ell}$: angle between B and $D^{(*)}\ell$ in $\Upsilon(4S)$ rest frame.

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|p_B||p_{D^{(*)}\ell}|}$$

Data samples and selection

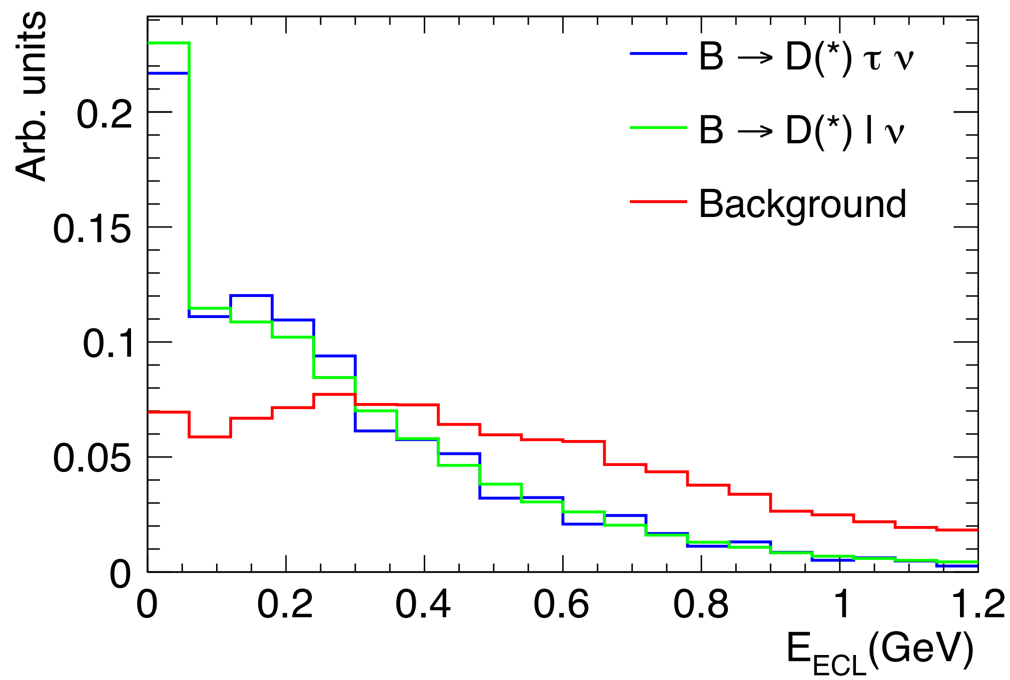
arXiv:1904.08794

- 4 data samples: $D^+\ell^-$, $D^0\ell^-$, $D^{*+}\ell^-$, $D^{*0}\ell^-$
  - D^0 reconstructed as $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+$, $K_S^0\pi^+\pi^-$, $K_S^0\pi^0$, $K_S^0K^+K^-$, K^+K^-, $\pi^-\pi^+$
    30% of D^0 BRs
  - D^+ reconstructed as $K^-\pi^+\pi^-$, $K_S^0\pi^+\pi^0$, $K_S^0\pi^+\pi^+\pi^-$, $K_S^0\pi^+$, $K^-K^+\pi^+$, $K_S^0K^+$
    22% of D^+ BRs
  - D^{*+} reconstructed as $D^0\pi^+$ or $D^+\pi^0$
  - D^{*0} reconstructed as $D^0\pi^0$
- D candidates are required to be within a mass window around their nominal mass.
- B mesons are required to have opposite flavour to suppress combinatorial background.

Fit parameters and components

- Use a 2D fit for these 4 samples
  - one parameter is E_{ECL}: energy deposited in ECL not associated with reconstructed particles
  - other parameter is `class`: outcome of a BDT based on E_{vis}, m^2_{miss}, $\cos\theta_{B,D^{(*)}\ell}$

arXiv:1904.08794



- Fit is performed simultaneously on the 4 samples, components are:
  - $D^{(*)}\tau\nu$
  - $D^{(*)}\ell\nu$
  - $D^{**}\ell\nu$, where $D^{**} = D_1, D_2^*, D_1', D_0^*$
  - feed-down from $D^*\ell\nu$ to $D\ell\nu$ decays

result from $D^*\ell$ ($D^*\tau$) samples is used to estimate contribution in $D\ell$ ($D\tau$)

Fit templates

arXiv:1904.08794

- Shapes of the templates are based on MC samples with a luminosity of 10× the total $B\bar{B}$ luminosity. For the D^{**} backgrounds this was 5× the total luminosity.
- MC samples have corrections applied from measurements on control samples:
  - lepton identification: corrected separately for *e* and μ using $e^+e^- \to e^+e^-\ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ decays.
- Backgrounds are fixed in fits, yields are based in m_{D^*}-m_D sidebands for fake *D*'s, and others from MC.
- Yields of signal, normalisation, D^{**} and feed-down are free in the fit.

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

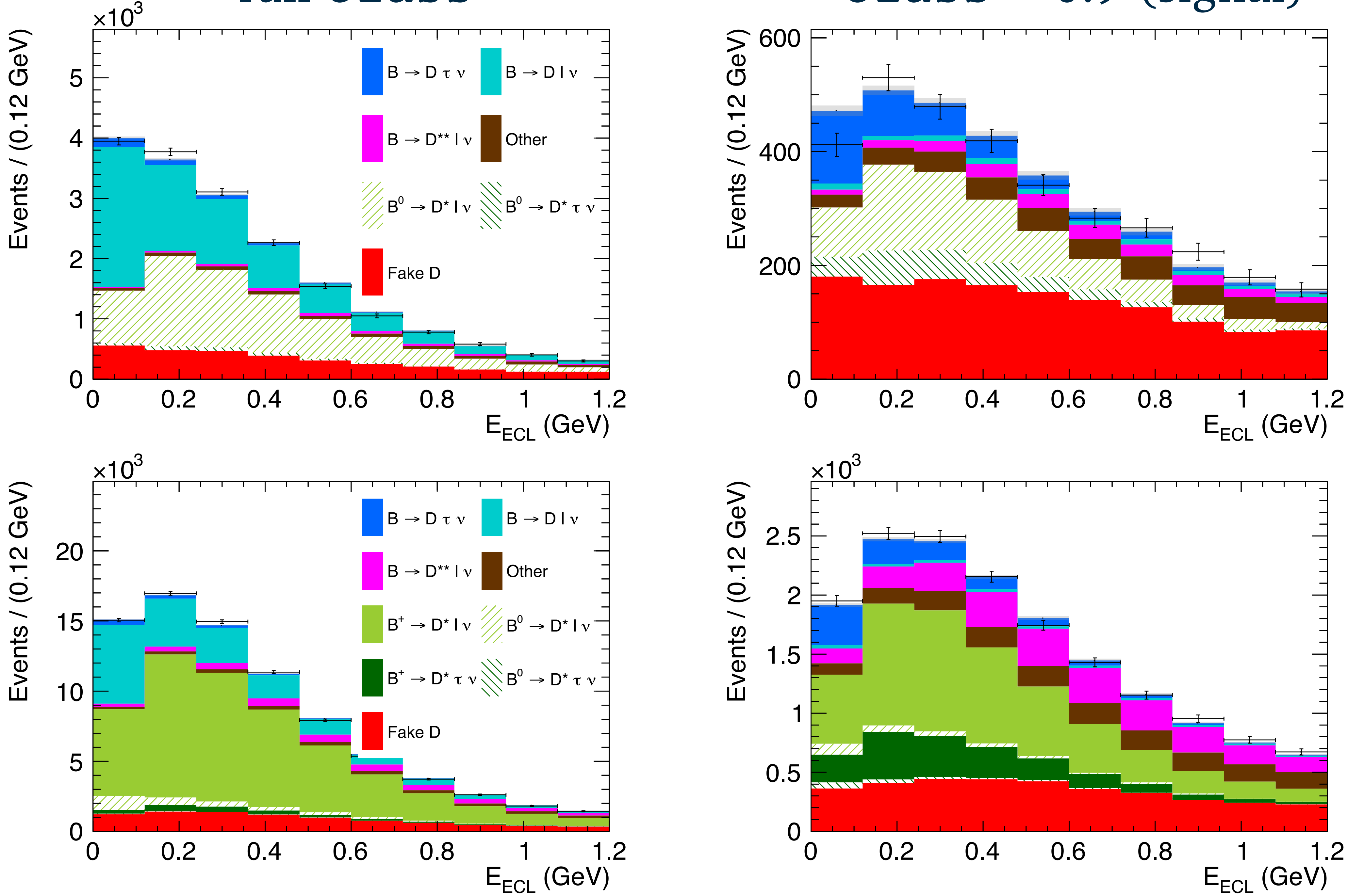
Fit results $D^{+}l$ and $D^{0}l$

arXiv:1904.08794

full `class` | `class` > 0.9 (signal)

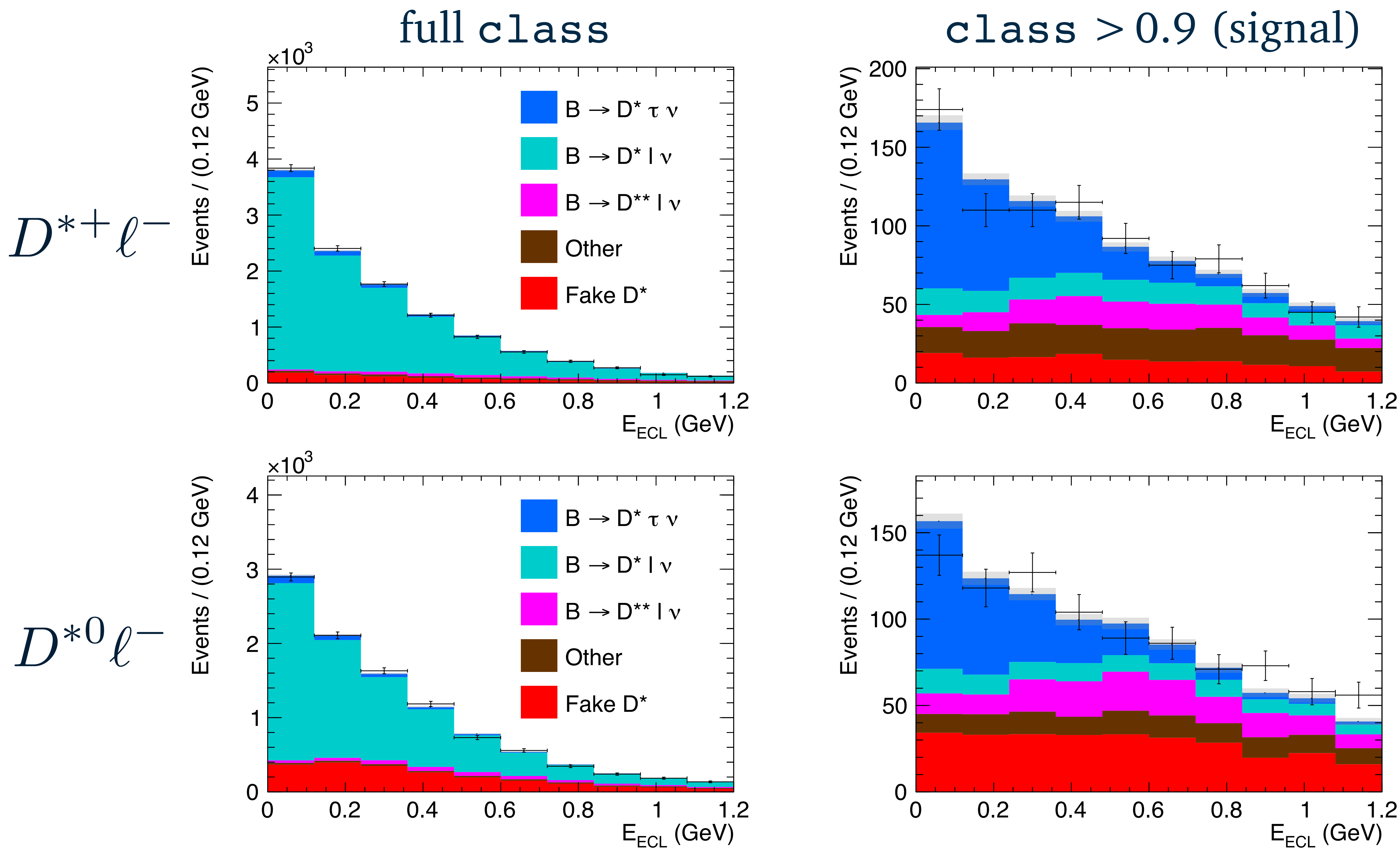
$D^{+}\ell^{-}$

$D^{0}\ell^{-}$



Fit results $D^{*+}l$ and $D^{*0}l$

arXiv:1904.08794



Systematic uncertainties

arXiv:1904.08794

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

Results SL-tagged *R*($D^{(*)}$)

arXiv:1904.08794

- This analysis finds:

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016 \qquad \rho = -0.53\,(\text{stat})$$

$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014 \qquad \rho = -0.52\,(\text{syst})$$

- Most precise measurements of $R(D)$ and $R(D^*)$ to date!
- Breakdown between muon and electron modes:

electron:

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

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

muon:

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

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

- Different measurement from Belle shows LFU between *e* and μ:

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

→ see talk by Eiasha Waheed

arXiv: 1809.03290v3

Outlook and conclusions

New HFLAV averages

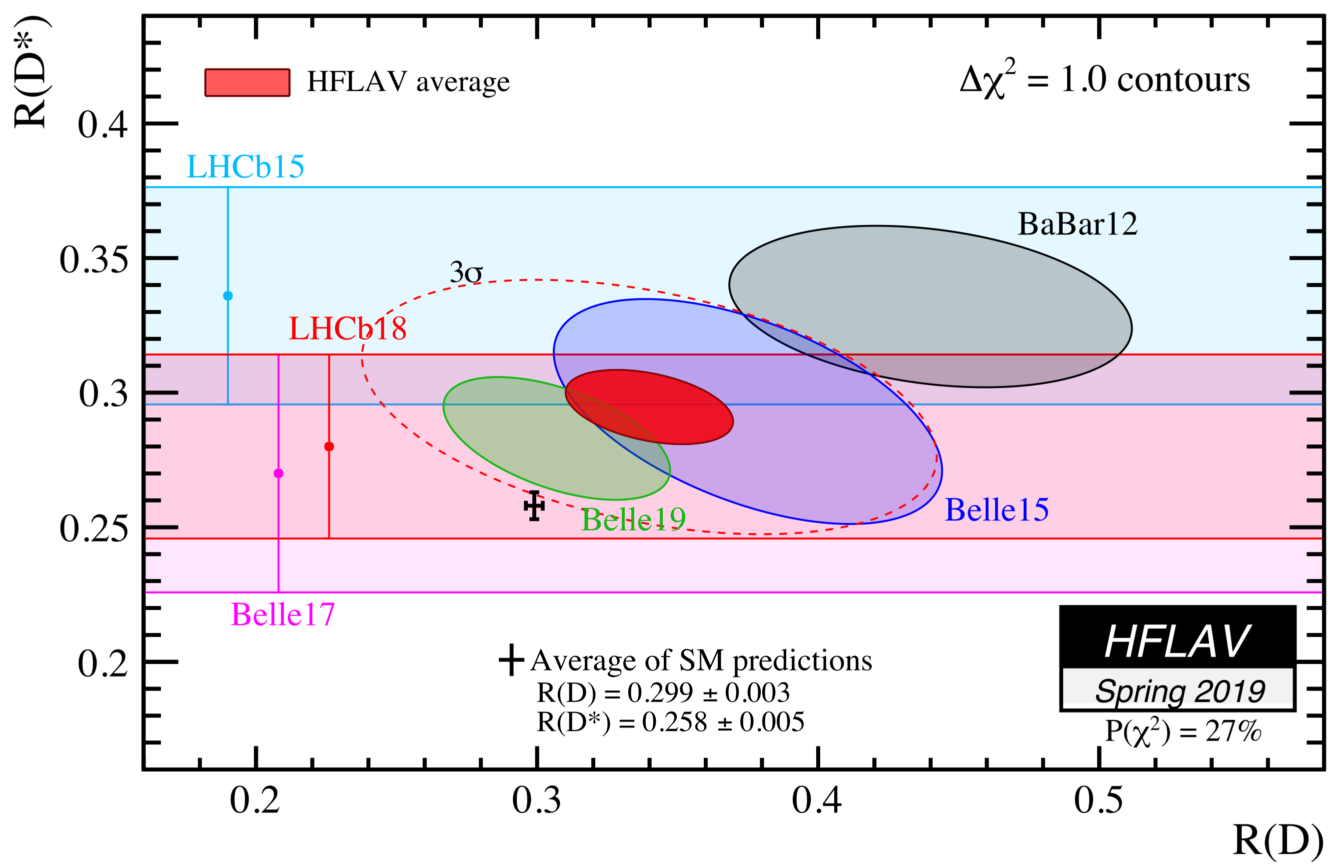
https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

- After the updates from the external inputs from LHCb's hadronic $R(D^{*})$ and the new Belle result, the new HFLAV averages are:

$$\mathcal{R}(D^{*}) = 0.298 \pm 0.011 \pm 0.007$$

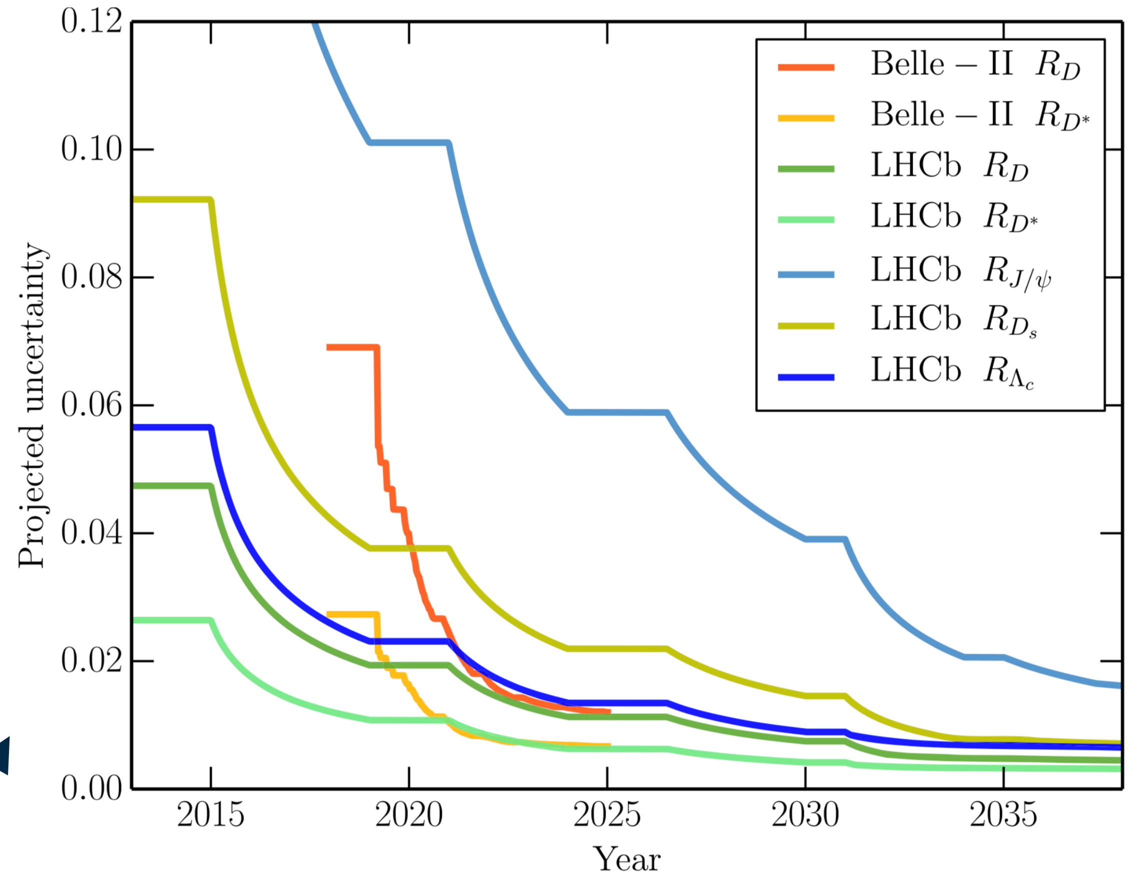
$$\mathcal{R}(D) = 0.349 \pm 0.027 \pm 0.015$$

- 3.1σ difference with the Standard Model.



Prospects for LFU measurements

- So far, all LHCb's measurements are only on Run 1 data. Run 2 is analysed as we speak and new results can be expected, including an extension of the muonic $R(D^*) \rightarrow R(D)$-$R(D^*)$.
- Other channels are also being studied: $R(D^+)$, $R(\Lambda_c)$, $R(D_s^{(*)})$, $R(pp)$, …
- Of course Belle II and LHCb upgrades are on their way (see talks Friday by Hulya Atmacan and Silvia Gambetta).
- Prospects of various decays modes in the coming years.



J. Phys. G: Nucl. Part. Phys. 46 (2019) 023001

Conclusions

- A lot of things happening in field of LFU!
- Updated $R(D)$-$R(D^*)$ discrepancy with SM is 3.1σ.
- There's a lot more data to be analysed, different decay channels to study, and new experiments on the way.
- Many other interesting variables to study, in particular angular distributions which also constrain the nature of possible new physics.
- Upgraded experiments (both LHCb and Belle II) will allow us to finally confirm or rule out LU breaking.

Backup

LHCb recorded luminosity