$B \to D^{(*)}\tau\nu$ decays at Belle and prospects at Belle II

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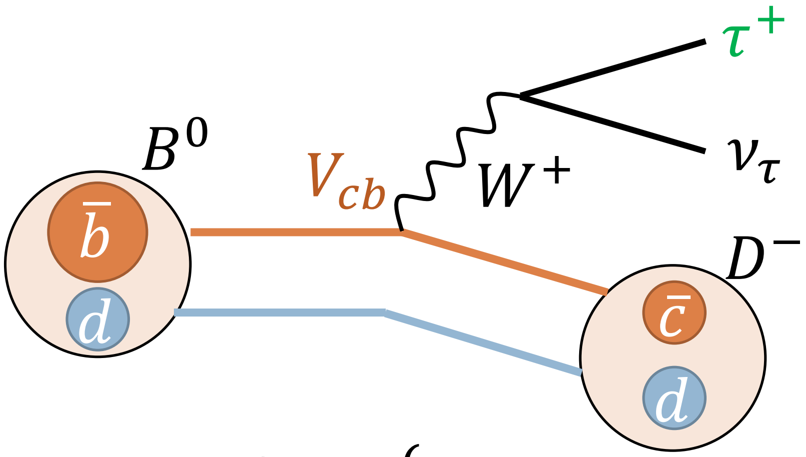
Anomalies 2019

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



Sensitive to New Physics because the massive 3rd generation b quark and τ lepton are involved.

$$\begin{aligned}\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \Big\{ & [\bar{c}\gamma^\mu(1-\gamma_5)b]\big[\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau\big] \quad \text{... SM } (W^\pm) \\ & - \frac{m_b m_\tau}{m_B^2} \bar{c}[g_S + g_P\gamma_5]b[\bar{\tau}(1-\gamma_5)\nu_\tau]\Big\} \quad \text{... New Physics } (H^\pm) \\ & + \mathrm{h.c.}\end{aligned}$$

Flavor-dependent coupling to the fermions

$$\frac{\mathrm{d}\Gamma(B^- \to D^0 \ell^- \bar{\nu})}{\mathrm{d}w} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2-1)^{3/2} |\eta_{\mathrm{EW}}|^2 |V_{cb}|^2 |\mathcal{G}(w)|^2$$

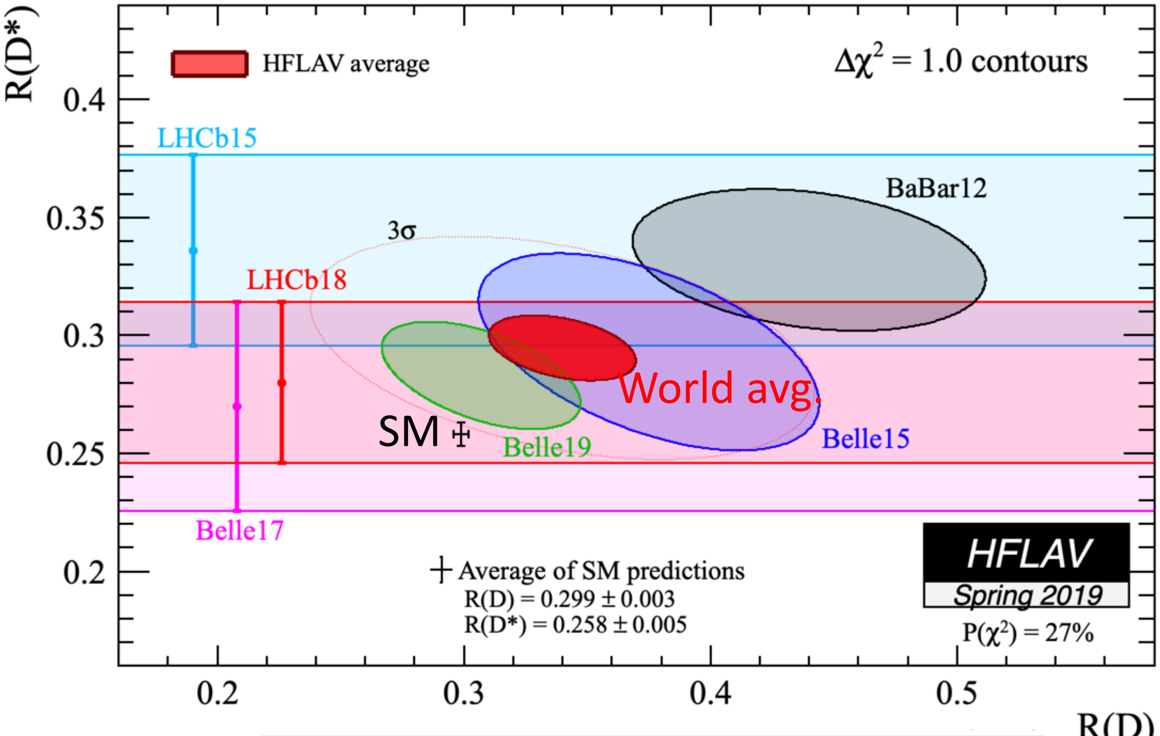
$$\frac{\mathrm{d}\Gamma(B^- \to D^{*0} \ell^- \bar{\nu})}{\mathrm{d}w} = \frac{G_F^2 m_{D^*}^3}{4\pi^3}(m_B - m_{D^*})^2 (w^2-1)^{1/2} |\eta_{\mathrm{EW}}|^2 |V_{cb}|^2 \chi(w) |\mathcal{F}(w)|^2$$

Sizable uncertainties on $|V_{cb}|$ and the form factors

Hint of new physics in $b \rightarrow c\ell\nu$ tree decays

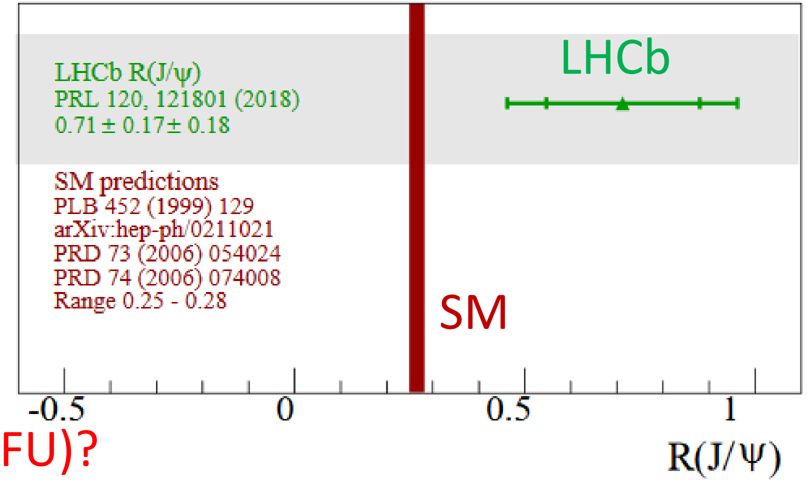
$$R(D^{(*)}) = \frac{\Gamma(B \rightarrow D^{(*)}\tau\nu)}{\Gamma(B \rightarrow D^{(*)}\ell\nu)}$$

Useful observable to probe new physics since the uncertainties on $|V_{cb}|$ and the form factors as well as the experimental systematic cancel out



Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005

$$R(J/\Psi) = \frac{\Gamma(B_c \rightarrow J/\Psi\tau\nu)}{\Gamma(B_c \rightarrow J/\Psi\mu\nu)}$$



LHCb R(J/ψ)
PRL 120, 121801 (2018)
0.71 ± 0.17± 0.18

SM predictions
PLB 452 (1999) 129
arXiv:hep-ph/0211021
PRD 73 (2006) 054024
PRD 74 (2006) 074008
Range 0.25 - 0.28

Deviation also in

$$R(K^{(*)}) = \frac{\Gamma(B \rightarrow K^{(*)}\mu\mu)}{\Gamma(B \rightarrow K^{(*)}ee)}$$

… $b \rightarrow s\ell\ell$ penguin decays

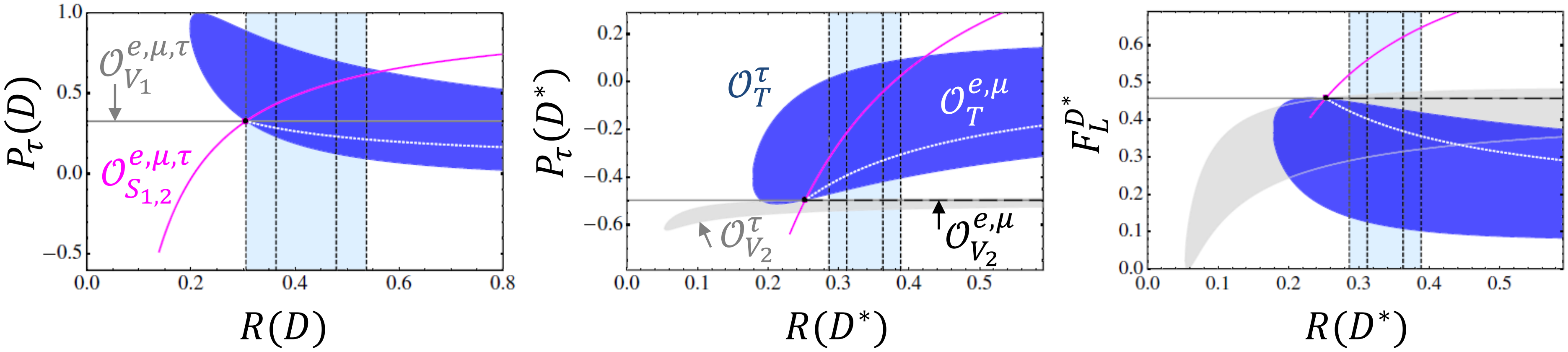
Violation of Lepton Flavor Universality (LFU)?

D^* and τ polarizations in $B \to D^* \tau \nu$

Observable which could distinguish the type of new physics:
Longitudinal polarizations

- $P_\tau(D^*) = \dfrac{\Gamma^+(D^*) - \Gamma^-(D^*)}{\Gamma^+(D^*) + \Gamma^-(D^*)}$ $\Gamma^\pm(D^*)$: decay rate with τ helicity $\lambda_\tau = \pm\frac{1}{2}$
- $F_L^{D^*} = \dfrac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)}$ $\Gamma\left(D_{L(T)}^*\right)$: decay rate of longitudinally (transversely) polarized D^*

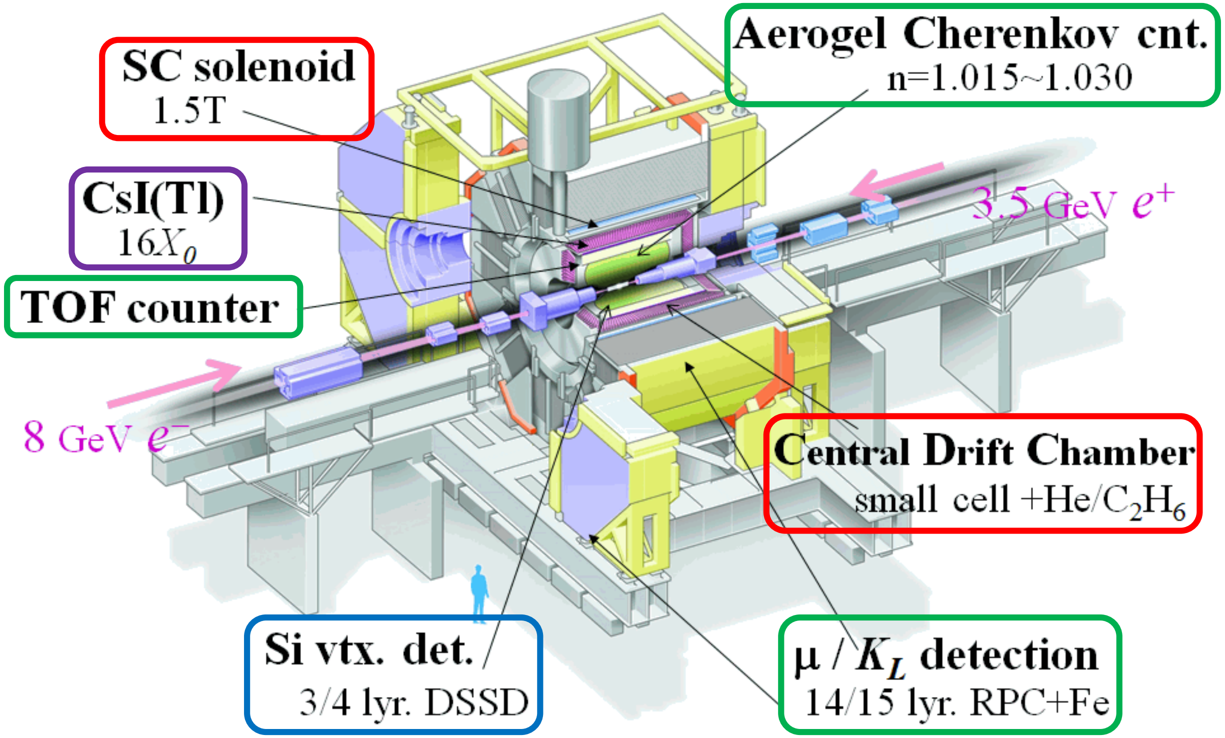
New physics scenarios [Phys. Rev. D 87, 034028 (2013)]



Belle measured $R(D)$, $R(D^*)$, $P_\tau(D^*)$, and $F_L^{D^*}$.

The Belle experiment

- Collected 772 x 10^6 $B\bar{B}$ events at KEKB factory (1999-2010), asymmetric e^+e^- collider at $\sqrt{s} = 10.58$ GeV, in Japan.
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ (very clean and well-known initial state)

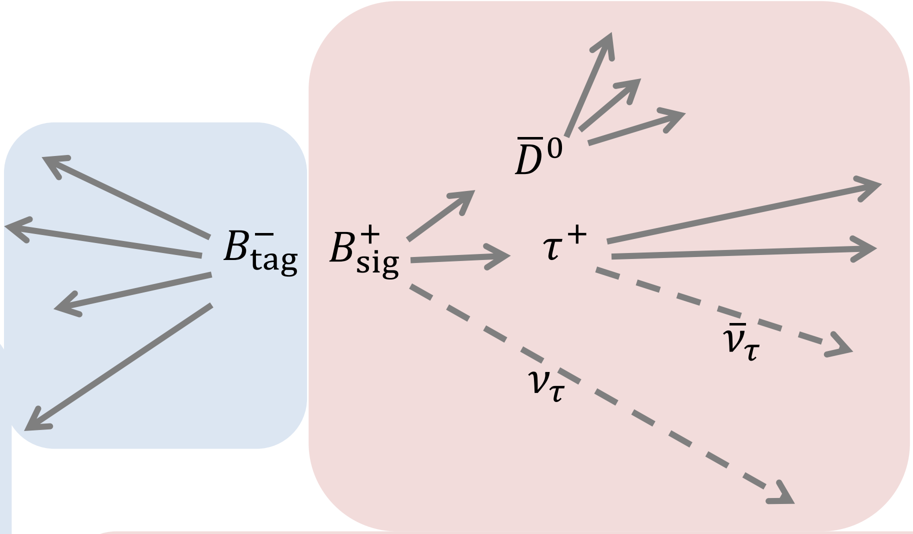


Hermetic spectrometer capable of

- Tracking and momentum meas. of charged tracks
- Vertex meas.
- Particle ID
- γ energy meas.

$B \to D^{(*)}\tau\nu$ reconstruction in Belle

- Not a rare decay
  - In SM, $\mathcal{B}(B^+ \to \bar{D}^0\tau^+\nu_\tau) = 0.66\%$ and $\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = 1.23\%$
- but reconstruction of τ is challenging due to multiple neutrinos.
  - → Need full reconstruction of the event
    - Suppress non-$B\bar{B}$ bkgd. and misreconstructed events
  - → quite low efficiency
  - → need a high statistics



Reconstruct one of the B's decaying

1. Hadronically ($\varepsilon_{\text{sig}} \approx 0.2\%$)
2. Semileptonically ($\varepsilon_{\text{sig}} \approx 0.5\%$)
3. Inclusively ($\varepsilon_{\text{sig}} \approx$ a few %)

↓ Efficiency

↑ Purity

Select the other B of the signal decay with

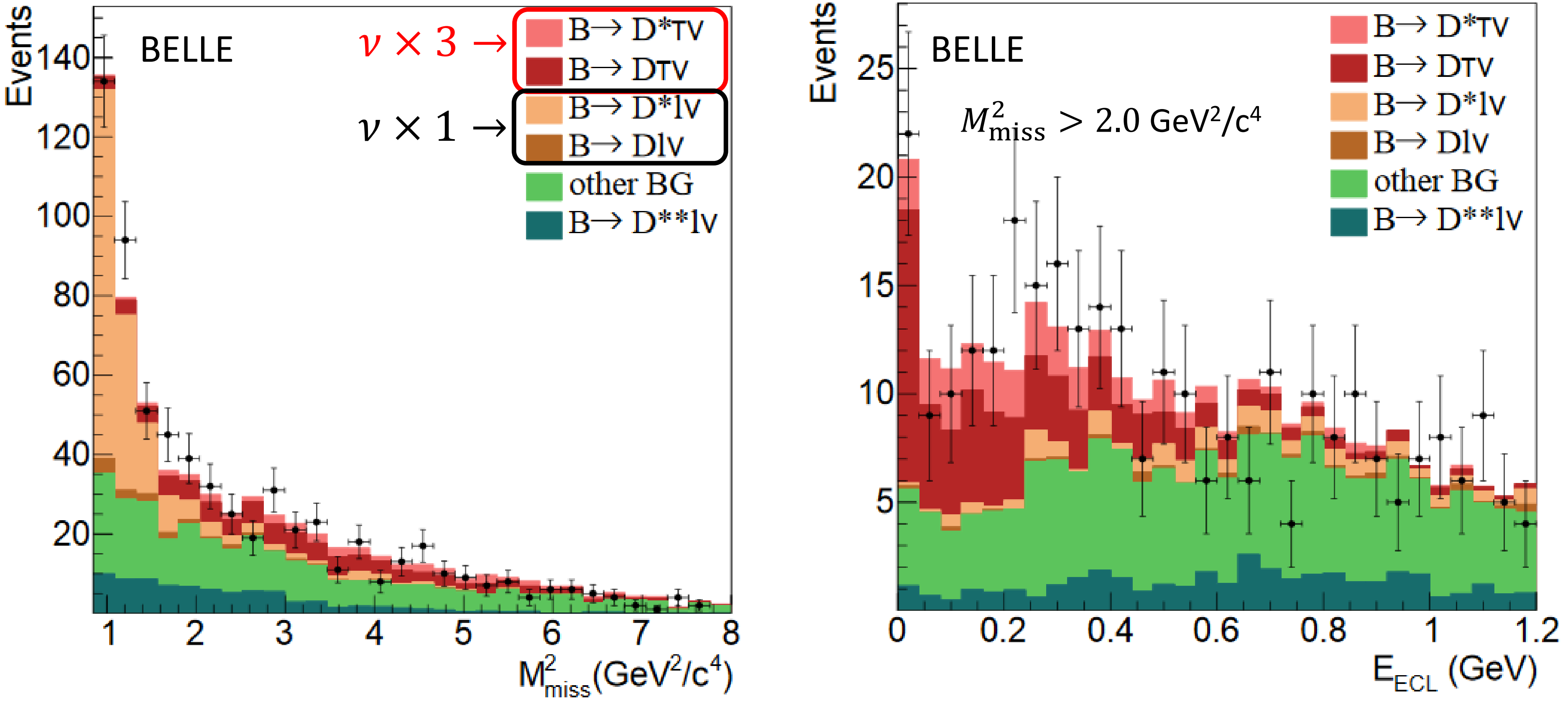
- a $D^{(*)}$
- a charged daughter of τ
  1. Leptonic τ decay
  2. Hadronic τ decay

Separation of signal/normalization

$$M^2_{\mathrm{miss}} = \left|p_{e^+e^-} - p_{\mathrm{tag}} - p^{\mathrm{detected}}_{\mathrm{sig}}\right|^2$$

E_{ECL}: sum of ECL clusters which are not associated with reconstructed particles

$D^+\ell^-$ sample of $B \rightarrow D^{(*)}\tau\nu$ with hadronic tag



Phys. Rev. D 92 (2015) 072014

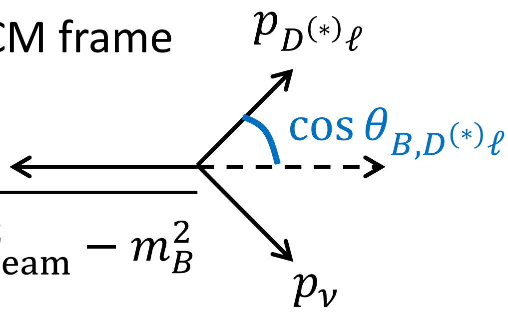
Separation of signal/normalization

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

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

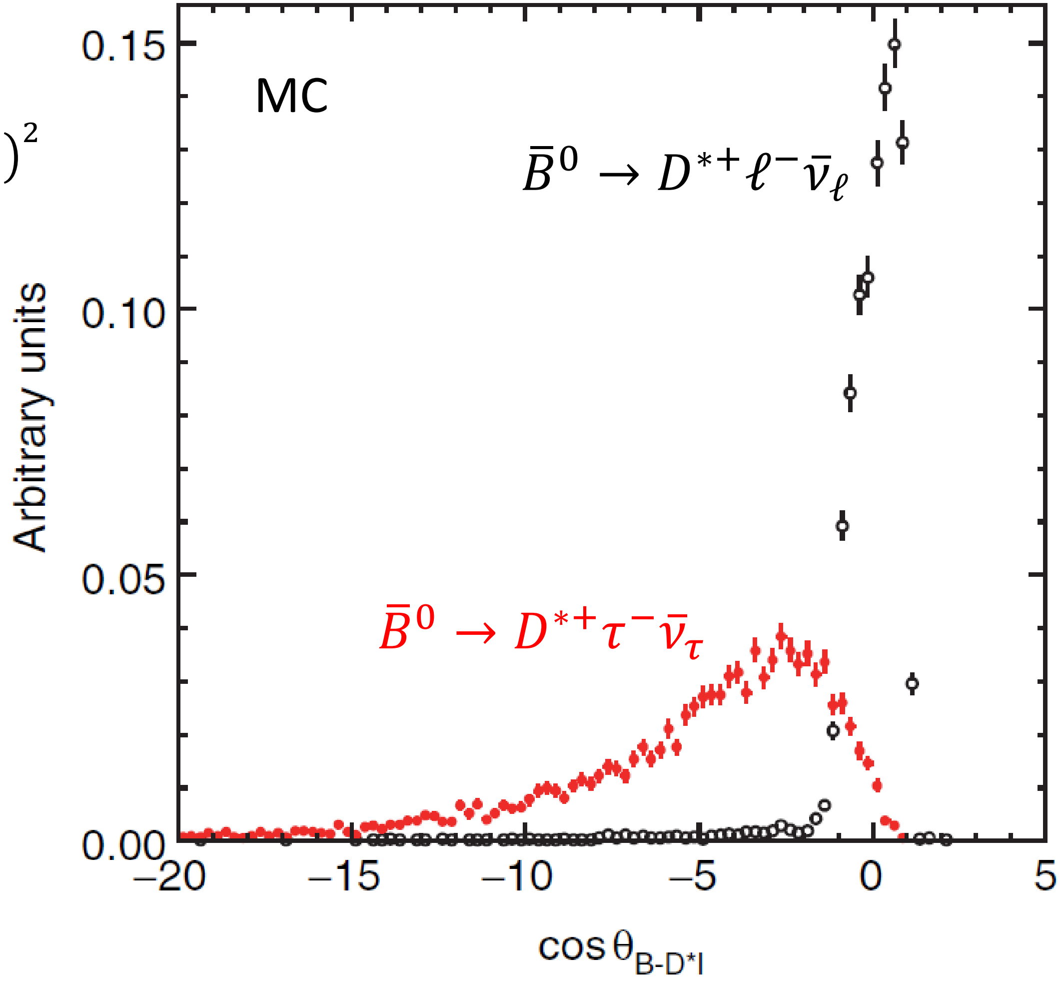
$$M_{\text{miss}}^2 = (E_{\text{beam}} - E_{D^{(*)}\ell})^2 - (p_B - p_{D^{(*)}\ell})^2 = 0$$

CM frame

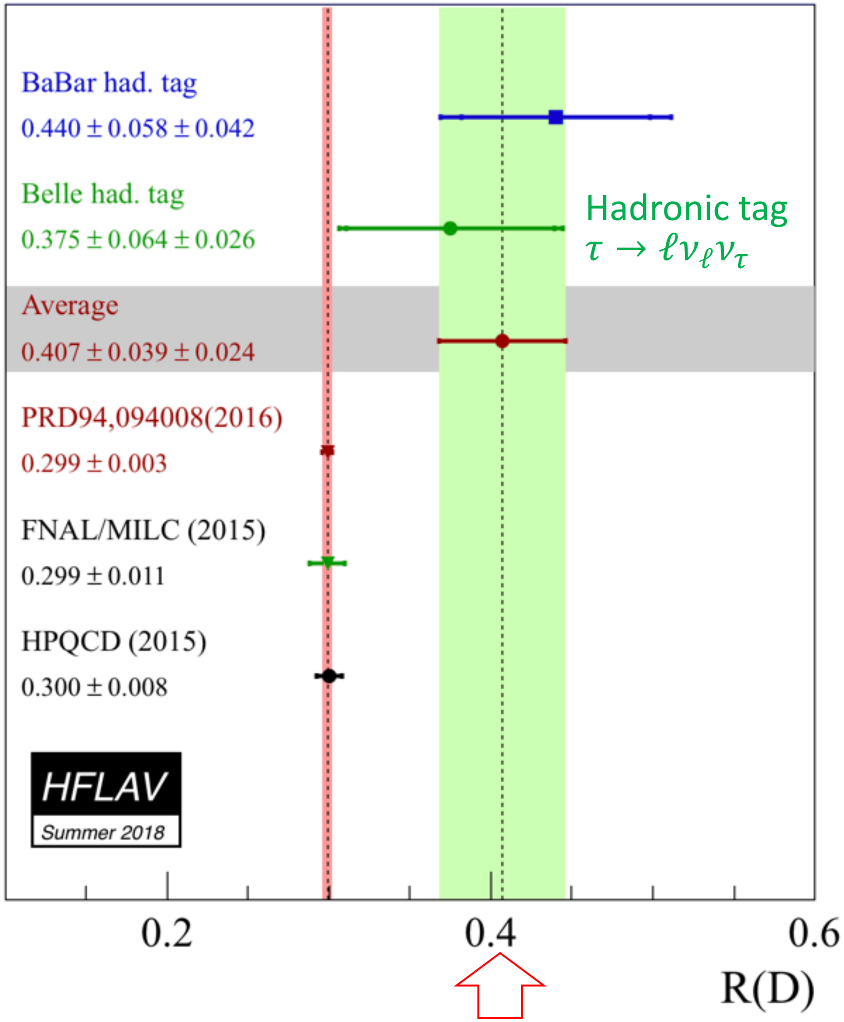


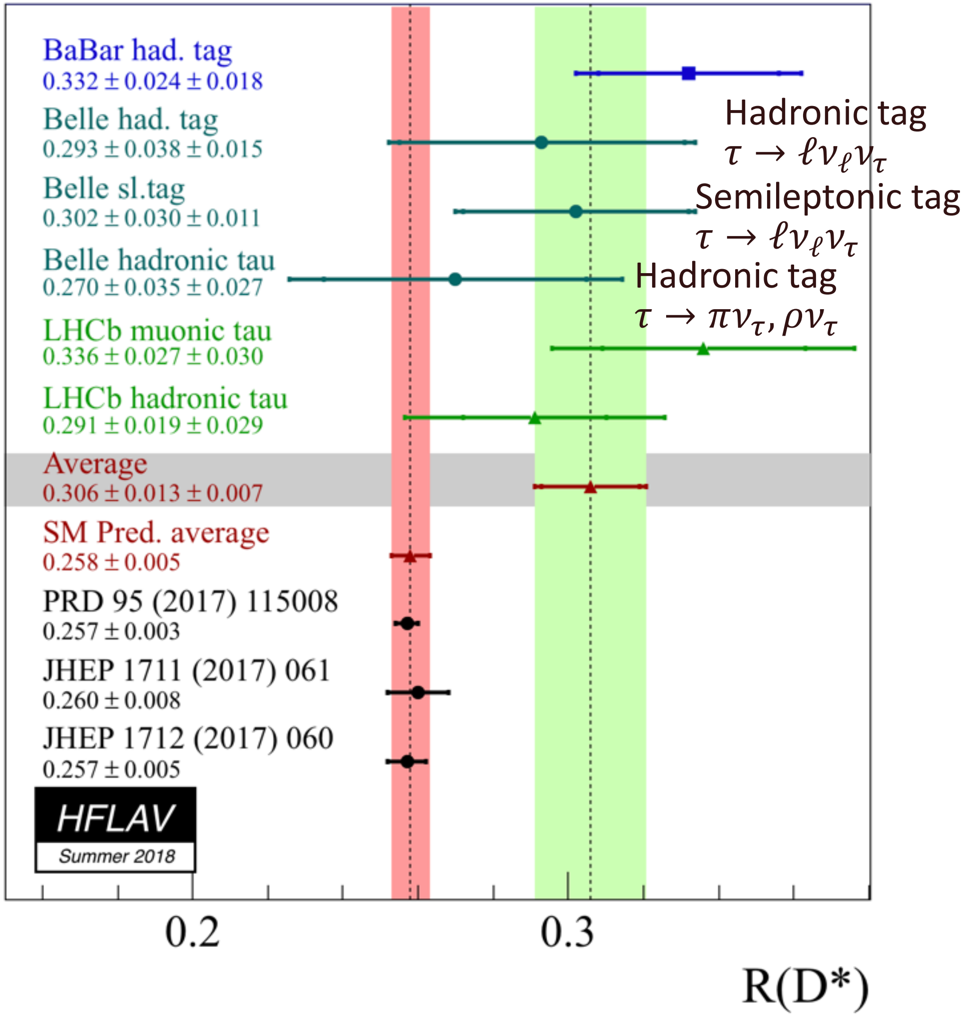
$$p_B = \sqrt{E_{\text{beam}}^2 - m_B^2}$$

Phys. Rev. D 94 (2016) 072007



Previous results on $R(D)$ and $R(D^*)$





Only two (direct) measurements with hadronic tag

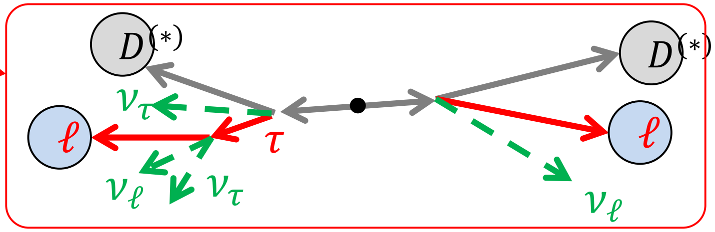
→ $R(D)$ with semileptonic tag has just been added by Belle.

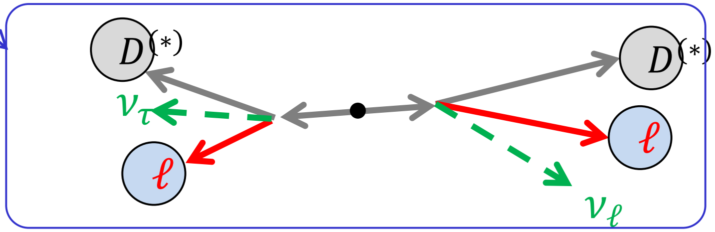
$B \to D^{(*)}\tau\nu$ with semileptonic tag

arXiv:1904.08794

- Simultaneous measurement of $R(D)$ and $R(D^*)$

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





  - In the previous result only $B^0\bar{B}^0 \to (D^{*-}\ell^+)(D^{*+}\ell^-)$
  - Add $B^0\bar{B}^0 \to (D^{(*)-}\ell^+)(D^{(*)+}\ell^-)$ and $B^+B^- \to (\bar{D}^{(*)0}\ell^+)(D^{(*)0}\ell^-)$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} = \frac{1}{2\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)} \cdot \underbrace{\boxed{\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}}}_{\text{MC}} \cdot \underbrace{\boxed{\frac{N_{\text{sig}}}{N_{\text{norm}}}}}_{\text{Fit PDFs to the data}}$$

- Analysis with the Belle II software framework
  - To reconstruct B_{tag} we can exploit FEI (Full Event Interpretation; Multivariate analysis with Boosted-Decision Tree classifier) → higher efficiency

Comput. Softw. Big. Sci. (2019) 3: 6

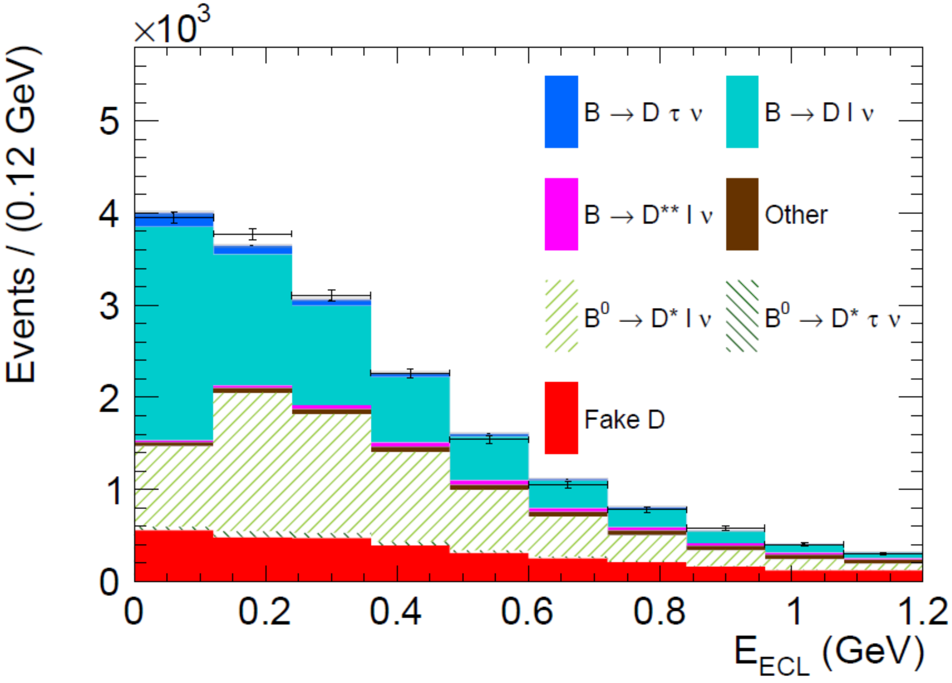
Signal extraction

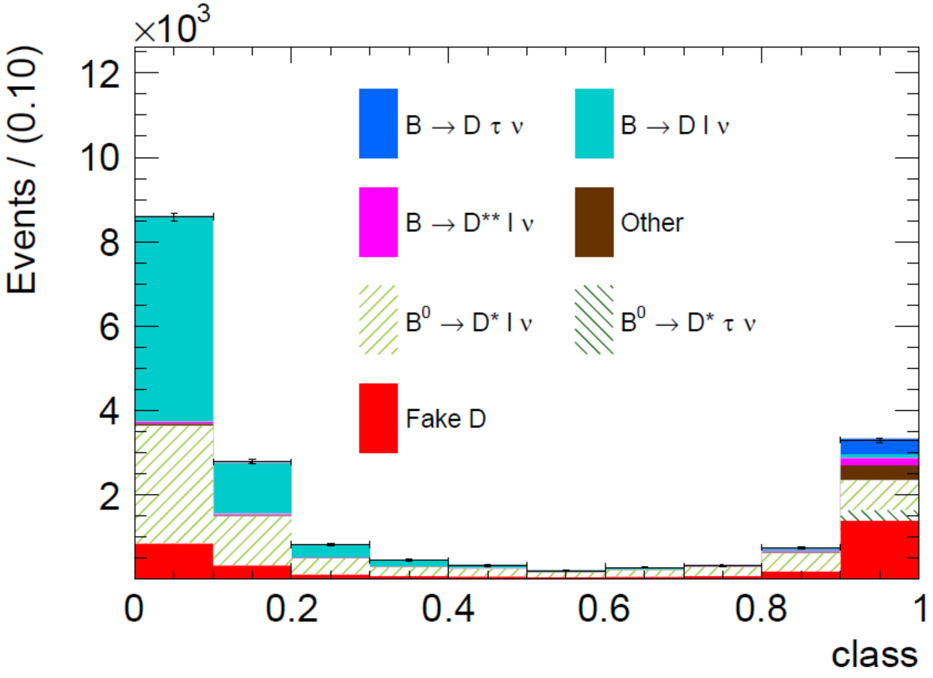
- Boosted-Decision Tree
  - Input variables: $\cos\theta_{B,D^{(*)}\ell}$, M_{miss}^2, E_{vis}
  - Classifier output: “class”
- 2D extended maximum-likelihood fit on “class” and E_{ECL}
  - PDF from MC; yield by fitting
    - Signal: Free
    - Normalization: Free
    - $B \to D^{**}\ell\nu$: Free
    - Fake $D^{(*)}$: Fixed (calibrated using the sidebands)
    - Feed-down for normalization: Free
      - $B^+ \to D^0\ell\nu \leftarrow B^+ \to (D^{*0} \to D^0\pi^0/\gamma)\ell\nu$, $B^0 \to (D^{*+} \to D^0\pi^+)\ell\nu$
      - $B^0 \to D^+\ell\nu \leftarrow B^0 \to (D^{*+} \to D^+\pi^0)\ell\nu$
    - Feed-down for signal: Constrained
      - $N_{\mathrm{feed-down}} = K \cdot N_{\mathrm{sig}}^{D^*\ell}$ (K: Fixed to MC)
    - Other backgrounds: Fixed to MC
      - Continuum, fake lepton, $B \to D_s^{(*)}D^{(*)}$, etc.

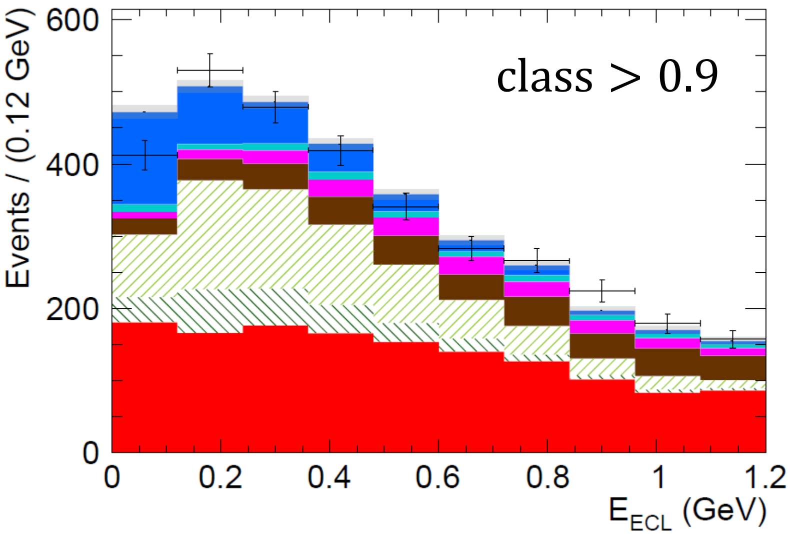
Exploit isospin symmetry:

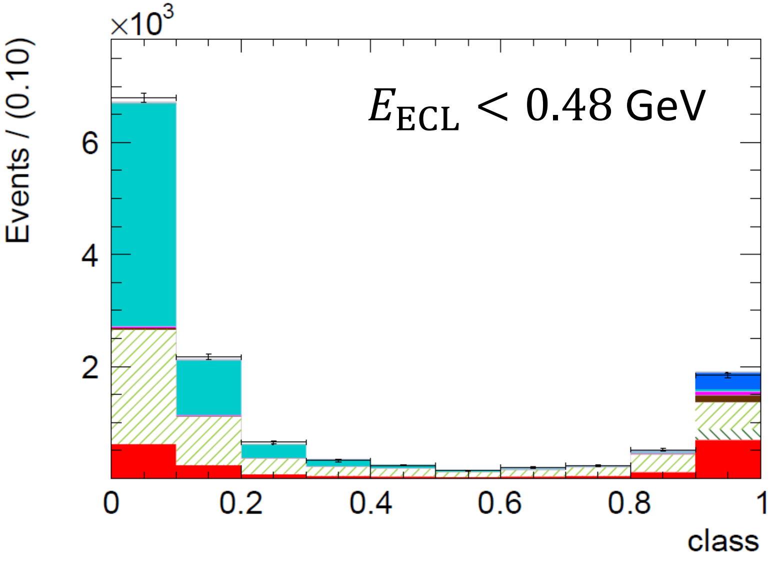
$$R(D^{(*)}) = R(D^{(*)+}) = R(D^{(*)0})$$

Fit results ($D^+\ell^-$ channel)





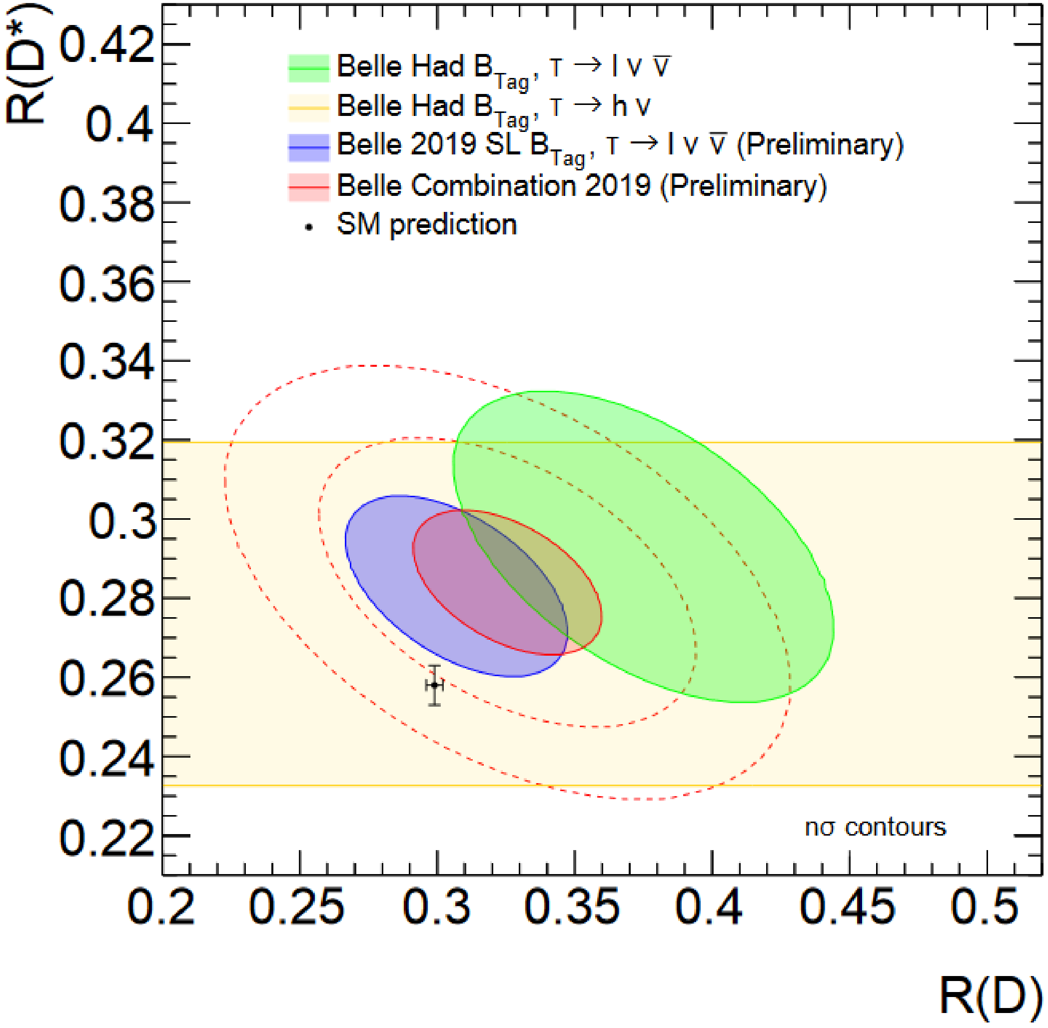




Result on $R(D)$ and $R(D^*)$

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

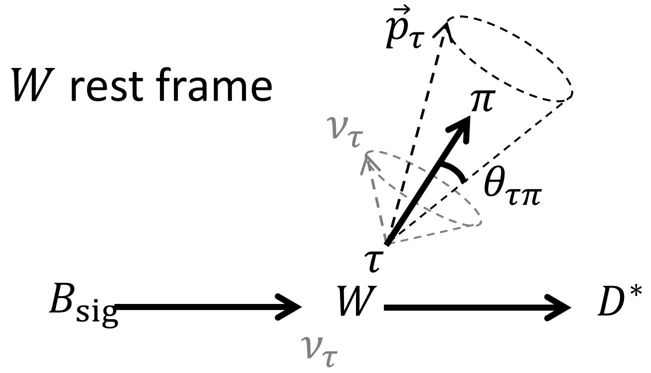
⇨ Agree with SM within 1.2s



τ polarization: $P_\tau(D^*)$

Angular distribution of τ decay

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{hel}}} = \frac{1}{2}\left[1 + \alpha P_\tau(D^*)\cos\theta_{\mathrm{hel}}\right] \qquad \alpha = \begin{cases} 1 & \text{for } \tau \to \pi\nu \\ 0.45 & \text{for } \tau \to \rho\nu \end{cases}$$



- $\vec{p}_\tau$ can be constrained to lie on the cone with a half apex angle $\theta_{\tau\pi}$:

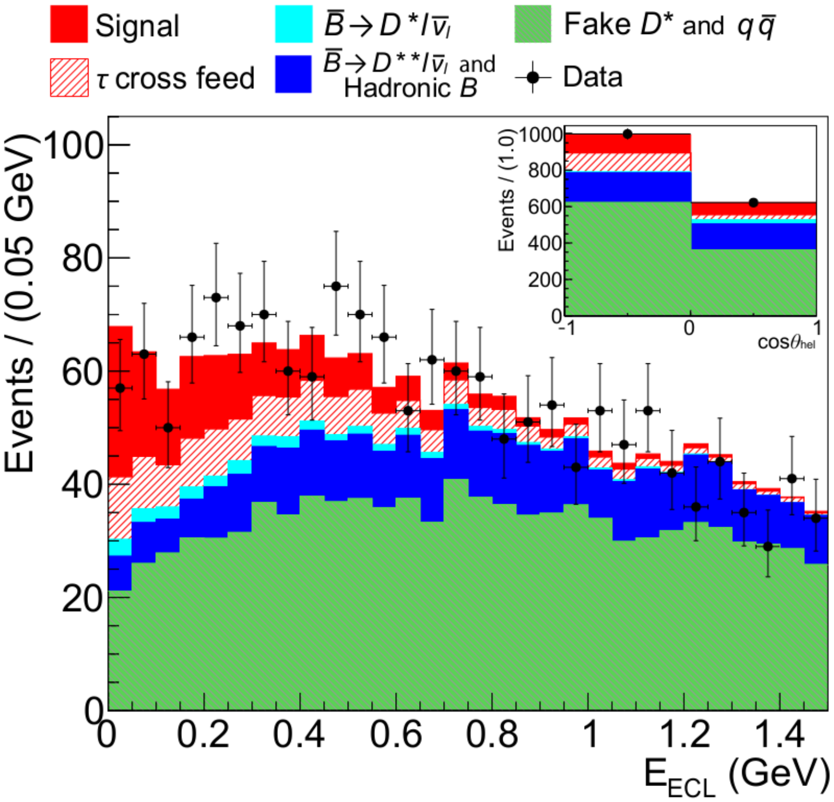
$$\cos\theta_{\tau\pi} = \frac{2E_\tau E_\pi - m_\tau^2 - m_\pi^2}{2|\vec{p}_\tau||\vec{p}_\pi|}$$

- Boost in an arbitrary direction on the cone to translate $\cos\theta_{\tau\pi}$ to $\cos\theta_{\mathrm{hel}}$ in the τ rest frame.

Result on $P_\tau(D^*)$

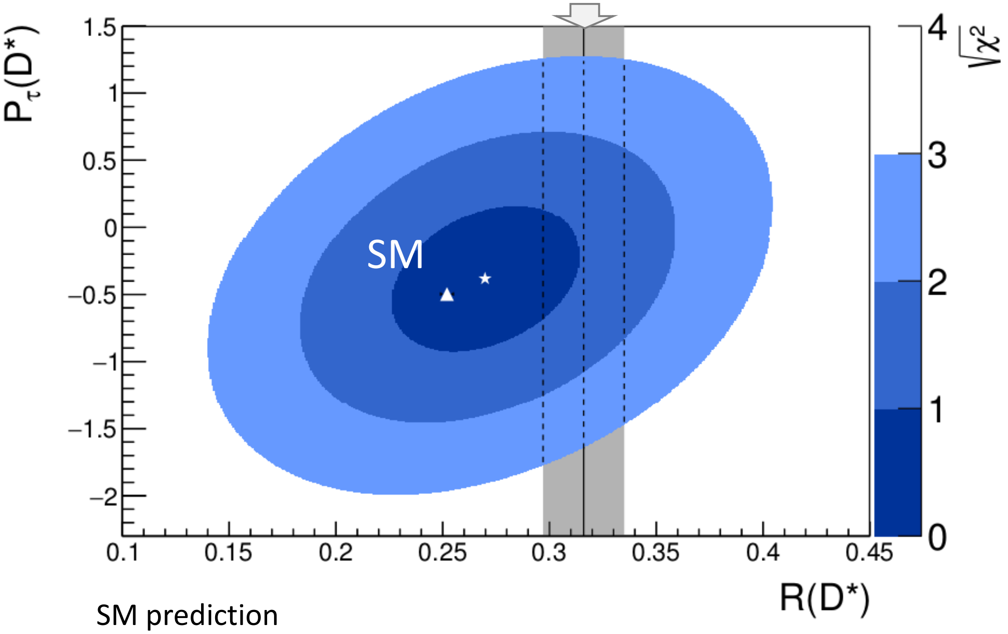
PRL 118, 211801 (2017)

- Hadronic tag
- Two-body τ decays ($\tau \to \pi\nu_\tau, \rho\nu_\tau$)



World average

HFLAV arXiv:1412.7515



SM prediction
PRD 85, 094025 (2012); PRD 87, 034028 (2013)

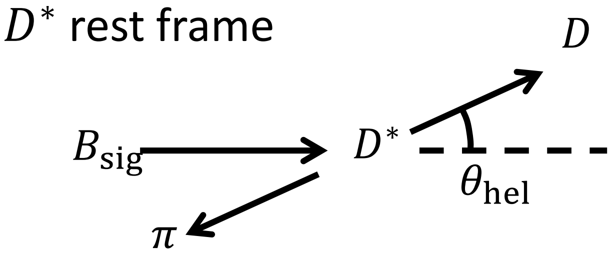
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst})$$

SM: $P_\tau(D^*) = -0.497 \pm 0.013$

D^* polarization: $F_L^{D^*}$

Angular distribution of D^* decay

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{hel}}} = \frac{3}{4}\left[2F_L^{D^*}\cos^2\theta_{\mathrm{hel}} + F_T^{D^*}\sin^2\theta_{\mathrm{hel}}\right] \qquad (F_L^{D^*} + F_T^{D^*} = 1)$$



D^* rest frame

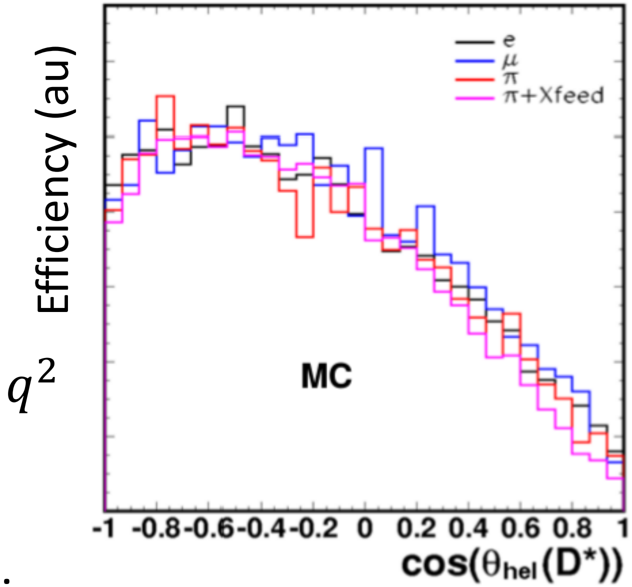
[Pros]

- All τ decays are useful.
- Not affected by cross-feeds of τ decays.

[Cons]

- Strong dependence of acceptance on $\cos\theta_{\mathrm{hel}}$ and q^2 due to the slow π from D^*, which is softer at a larger $\cos\theta_{\mathrm{hel}}$.

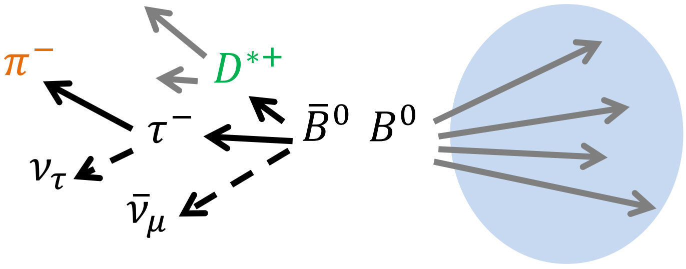
  → Used only $\cos\theta_{\mathrm{hel}} < 0$ in the Belle $F_L^{D^*}$ analysis.



$F_L^{D^*}$ with inclusive tag

arXiv:1903.03102

- Select candidates for B_{sig} daughters; D^{*+} + (ℓ^- or π^-).
  - $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
    - $D^{*+} \to D^0\pi^+$
      - $D^0 \to K^-\pi^+,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^-\pi^+$
    - $\tau^- \to \ell^-\nu_\tau\bar{\nu}_\tau,\ \pi^-\bar{\nu}_\tau$



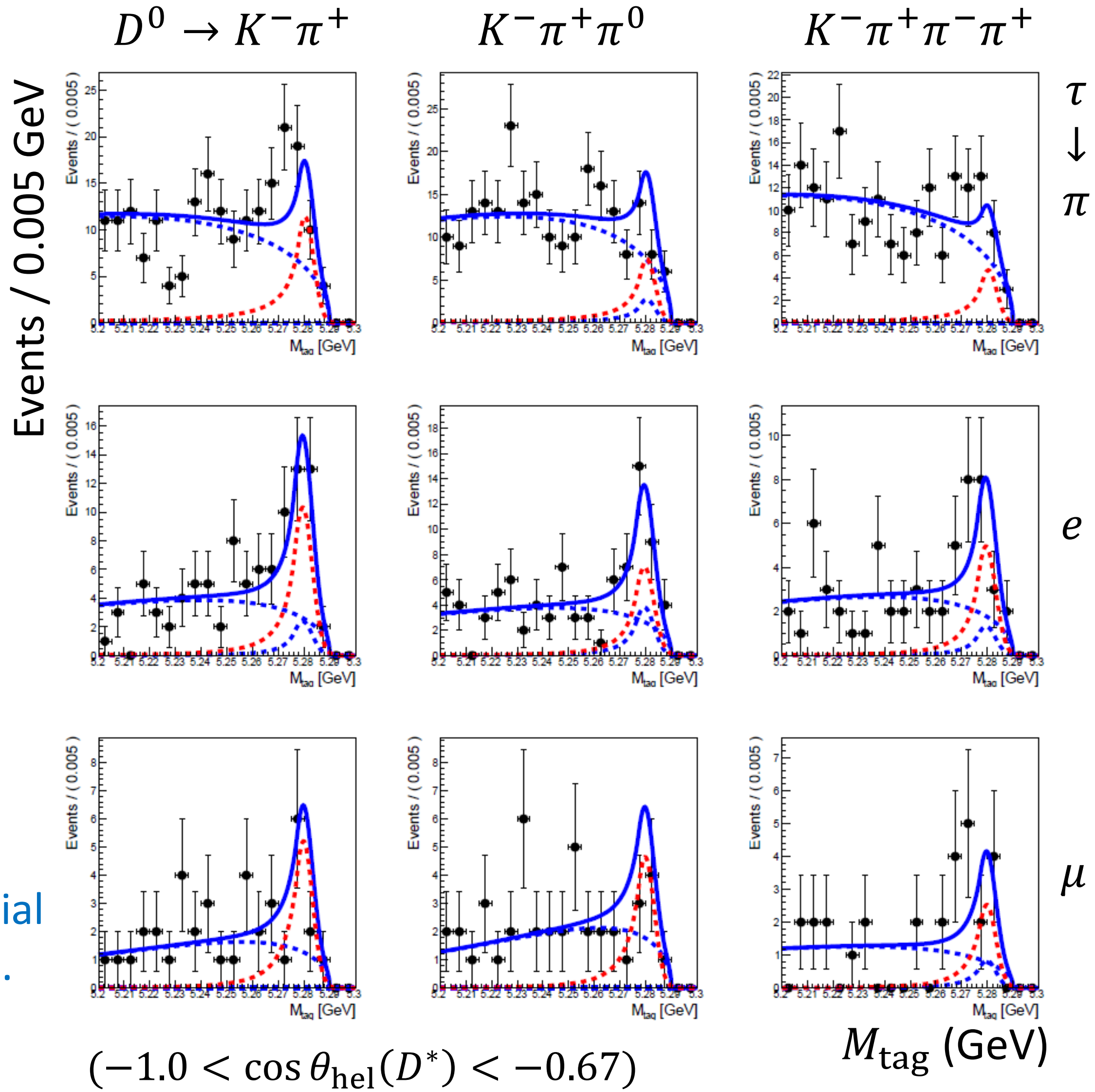
- Reconstruct B_{tag} inclusively from all the remaining particles.
  - Proper assignment of the particles without missing should lead to

$$M_{\mathrm{tag}} \equiv \sqrt{E_{\mathrm{beam}}^2 - \left|\vec{p}_{\mathrm{tag}}\right|^2} \approx M_B$$

$$\Delta E_{\mathrm{tag}} \equiv E_{\mathrm{tag}} - E_{\mathrm{beam}} \approx 0$$

Signal extraction for $F_L^{D^*}$ measurement

Simultaneous extended unbinned max likelihood fit to all 9 sub-channels in the M_{tag} distrbutions for each of 3 bins of $\cos\theta_{\text{hel}}$



Signal

Combinatorial

Peaking bkg.

$(-1.0 < \cos\theta_{\text{hel}}(D^*) < -0.67)$

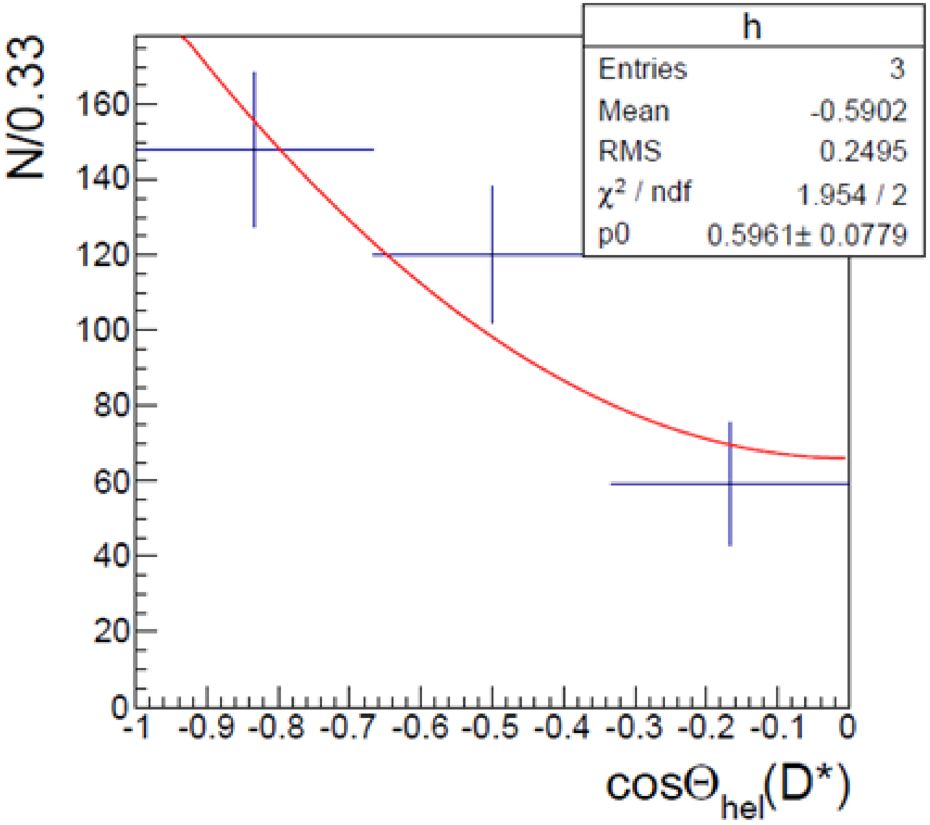
Result on $F_L^{D^*}$

$F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.035(\text{syst})$

cf. in SM

- $F_L^{D^*} = 0.46 \pm 0.03$ [Phys. Rev. D 95, 115038 (2017)]
- $F_L^{D^*} = 0.441 \pm 0.006$ [arXiv:1808.03565]

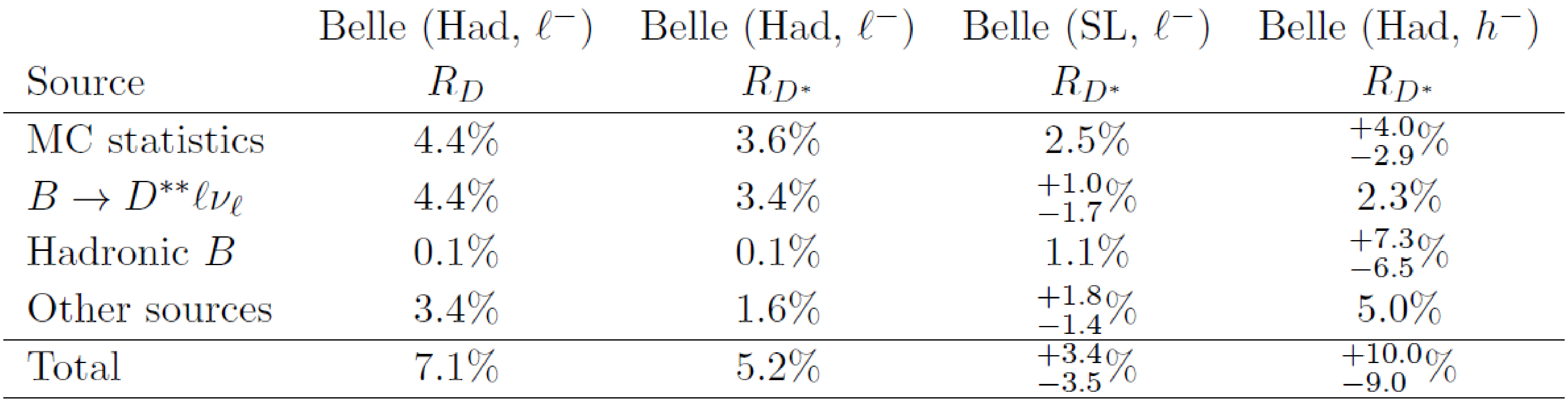
Consistent with SM within 2σ



Prospects for $B \to D^{(*)}\tau\nu$ at Belle II

- Belle 0.772 x 109 $B\bar{B}$ → Belle II ~50 x 109 $B\bar{B}$ (50 ab^{-1} in 7 years)

Composition of the systematic uncertainties in each Belle analysis

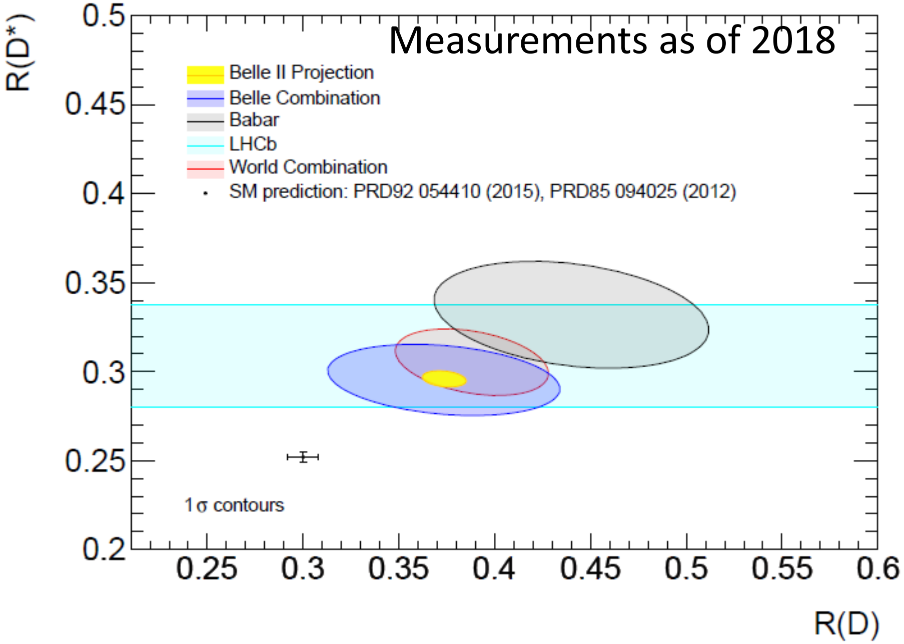


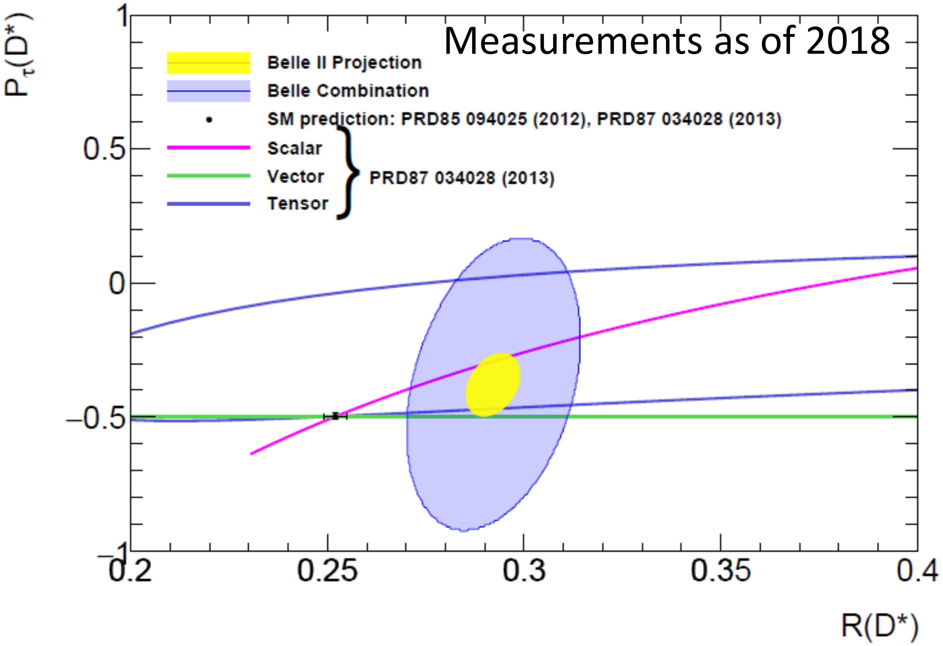
	Belle (Had, ℓ^-)	Belle (Had, ℓ^-)	Belle (SL, ℓ^-)	Belle (Had, h^-)
Source	R_D	R_{D^*}	R_{D^*}	R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}\%$
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}\%$	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}\%$
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}\%$	5.0%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

"The Belle II Physics Book", arXiv:1808.10567

- The uncertainty due to the MC statistics is reducible.
  - MC stat affects the estimation of the reconstruction efficiency, understanding of small cross-feed components and PDFs for the fit.
- The uncertainties from $\mathcal{B}(B \to D^{**}\ell\nu_\ell)$, D^{**} decays and hadronic B decays have to be reduced.
  - Need dedicated measurements of $B \to D^{**}\ell\nu_\ell$ and hadronic B decays with a large data sample.

Prospects for $B \to D^{(*)}\tau\nu$ at Belle II





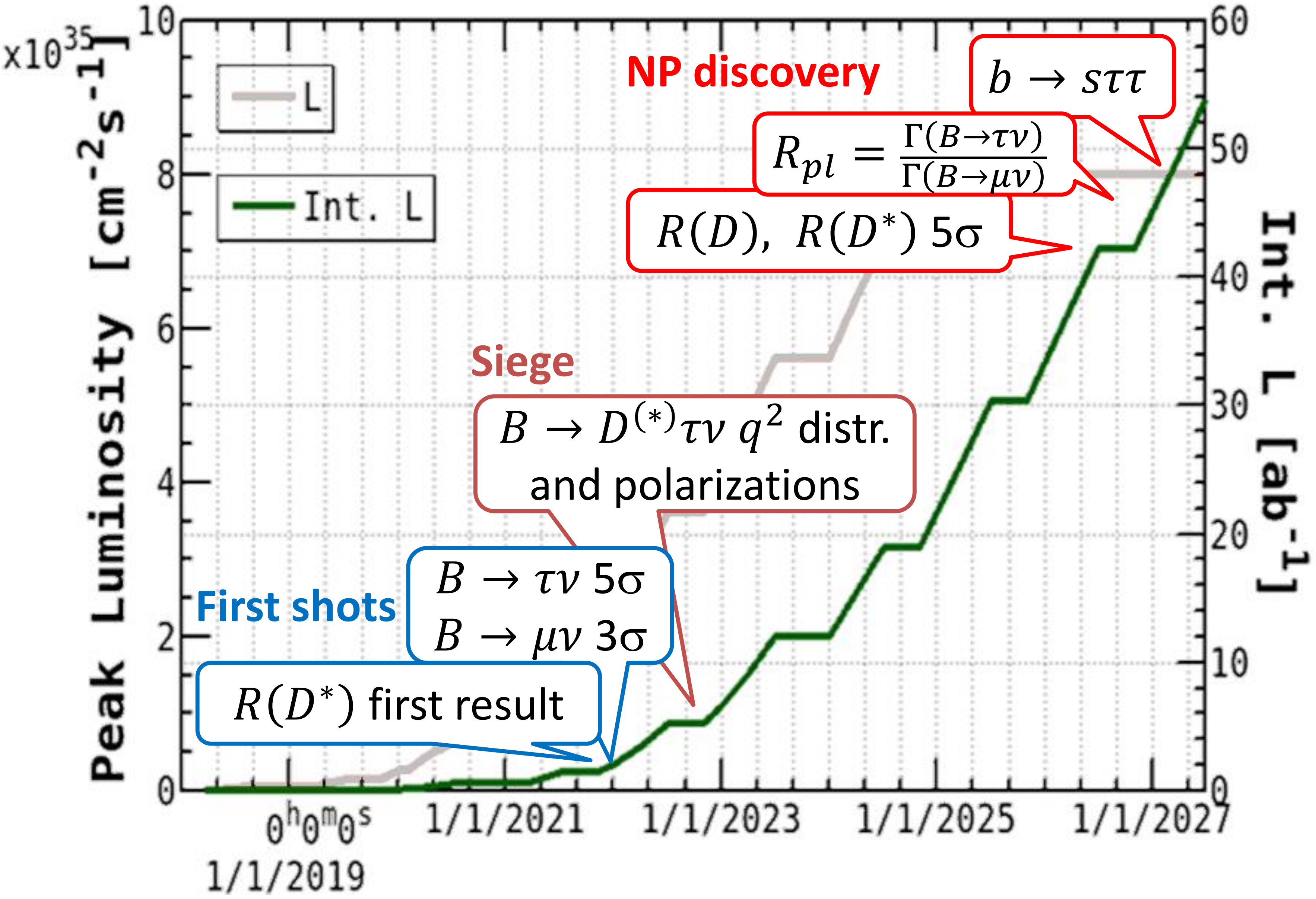
Expected precision (stat and syst)

	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

In addition, q^2 and other distributions of kinematic observables to discriminate the new physics scenarios.

“The Belle II Physics Book”, arXiv:1808.10567

Prospects on LFU



NP discovery

$b \rightarrow s\tau\tau$

$R_{pl} = \frac{\Gamma(B\rightarrow\tau\nu)}{\Gamma(B\rightarrow\mu\nu)}$

$R(D),\ R(D^*)$ 5σ

Siege

$B \rightarrow D^{(*)}\tau\nu\ q^2$ distr.
and polarizations

First shots

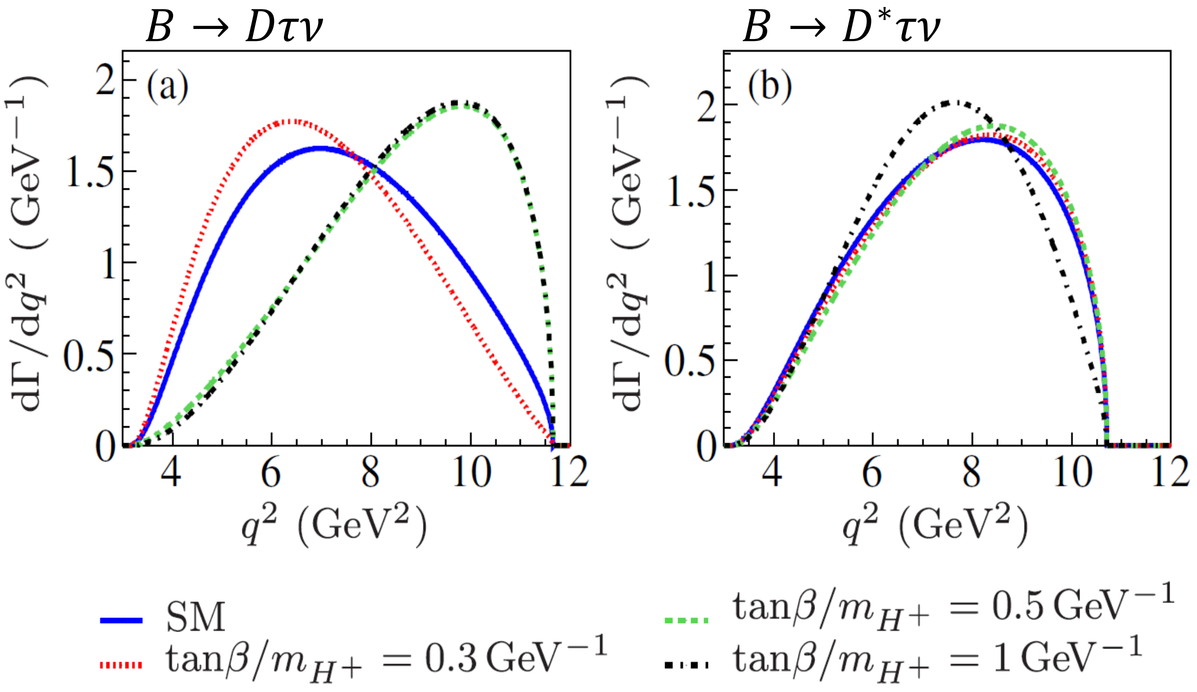
$B \rightarrow \tau\nu$ 5σ
$B \rightarrow \mu\nu$ 3σ

$R(D^*)$ first result

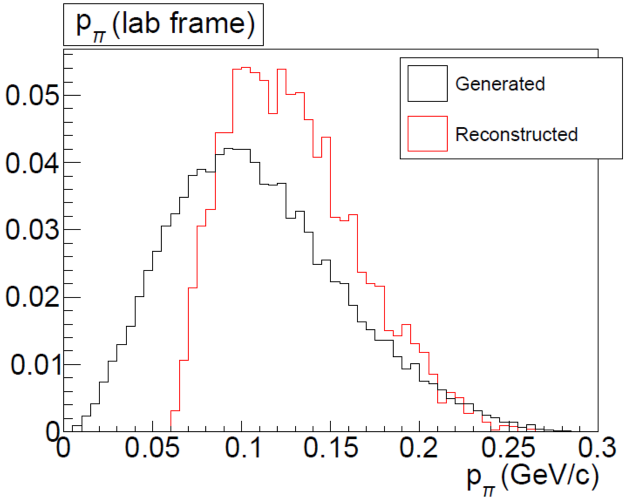
Caveat

- New Physics could change the distributions and thus the reconstruction efficiencies significantly.

→ To verify which New Physics model could explain the anomaly, one has to run the detector simulation for each model.



Phys. Rev. D 88 (2013) 072012



$D^{*+} \to D^0\pi^+$ sample

S. Hirose, doctor thesis (2017)

Summary

- The anomalies in the semileptonic B decays could indicate violation of lepton flavor universality.
- $R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$ and the polarizations of D^* and τ in $B \to D^{(*)}\tau\nu$ are useful observable to probe new physics.
- Belle measured those observables with different tagging methods. They are still limited by the statistics.
- Belle II will also play an important role on the $B \to D^{(*)}\tau\nu$ measurements with x50 data.