R(D) & R(D*) measurements at Belle

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for the Belle Collaboration

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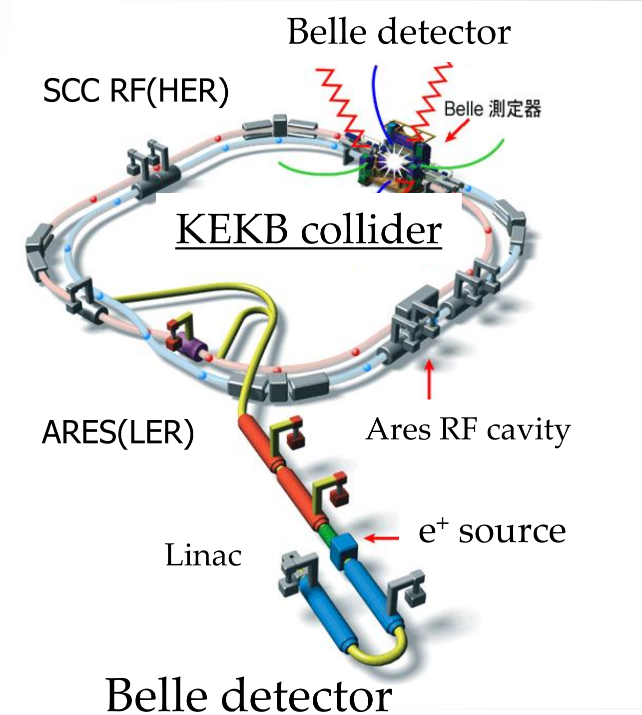
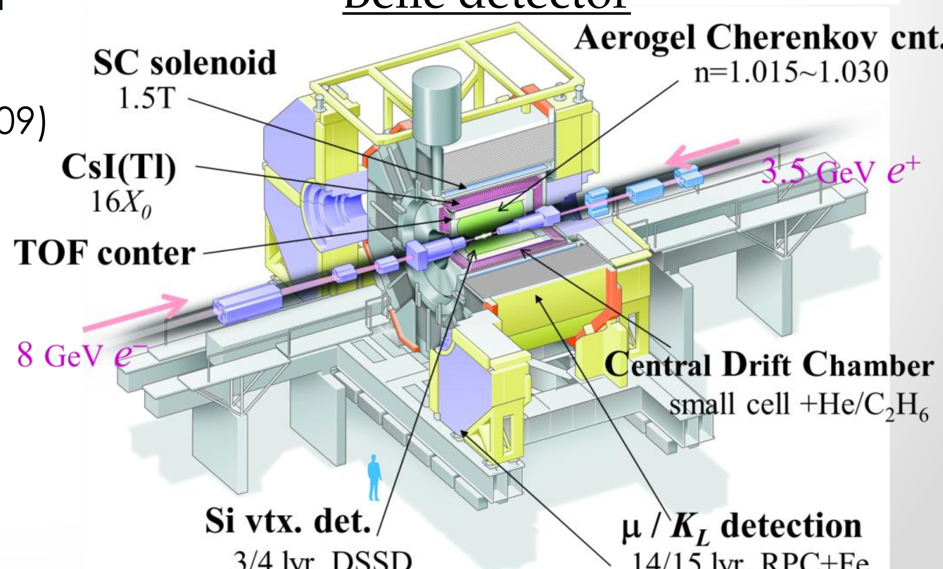
18th international conference on B-physics at frontier machines

Belle and KEKB



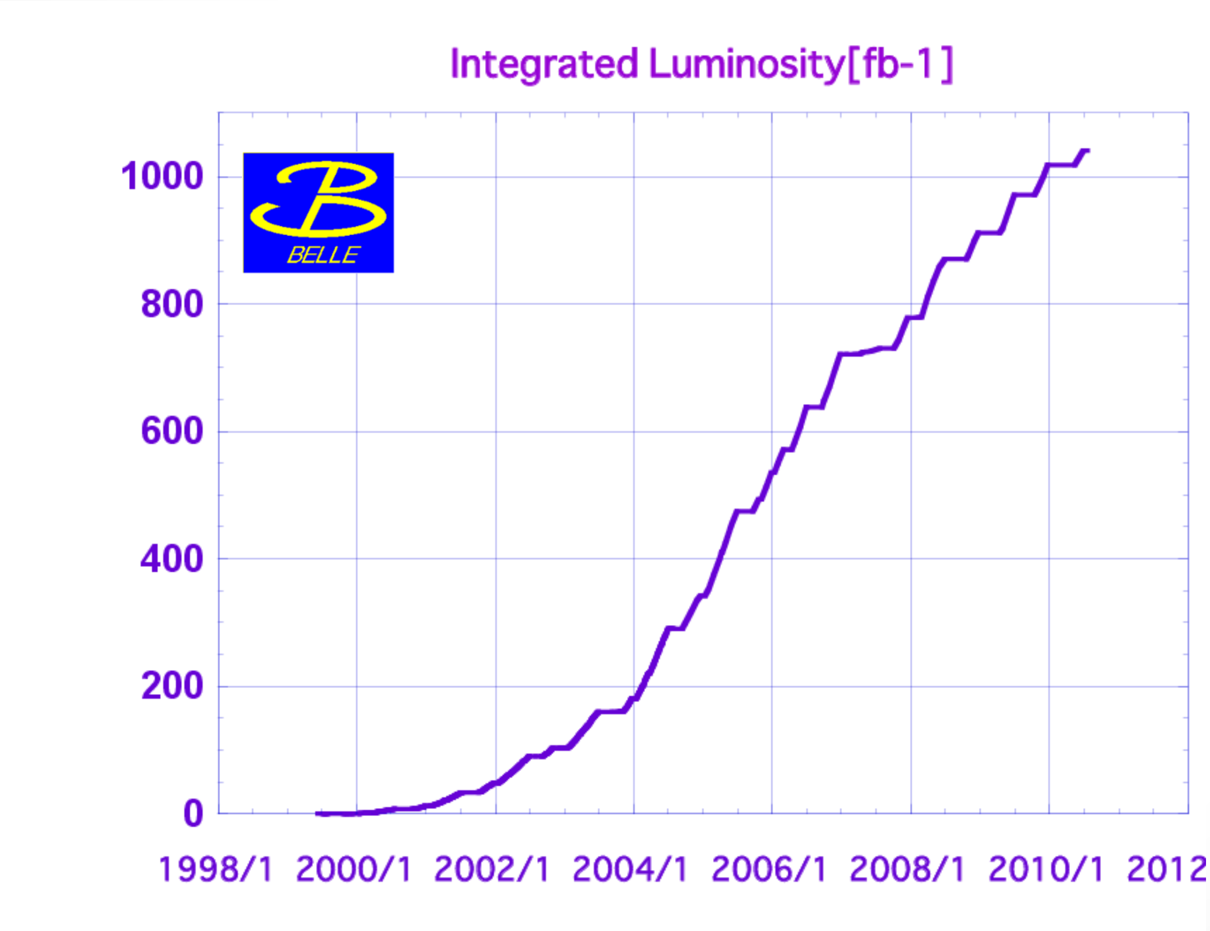
Belle detector



- KEKB
  - Achieved World Highest Luminosity (as of 2009)
    - $L = 2.1 * 10^{34}$ /cm^2/sec ~ 20 $B\bar{B}$ pairs / sec
  - Asymmetric energy to boost B mesons
    - 8.0GeV e^- × 3.5GeV e^+
- Belle
  - Multi-purpose 4π detector
  - Vertexing, tracking, EM calorimeter, PID
- Data taking for 1999-2010

Belle Integrated Luminosity

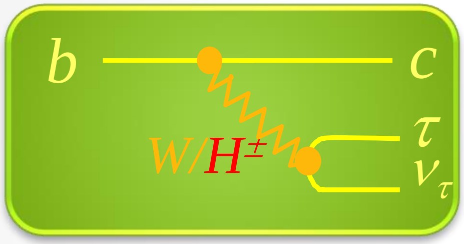
- The world largest integrated luminosity of > 1ab^{-1}
- 711 fb^{-1} on Υ(4S) resonance → **772×10^{6} $B\bar{B}$ pairs**



On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~100 fb^{-1}

Semi-tauonic B decay: B→D$^{(*)}$τν

- Sensitive to new physics



Ratio of τ to μ,e could be reduced/enhanced

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

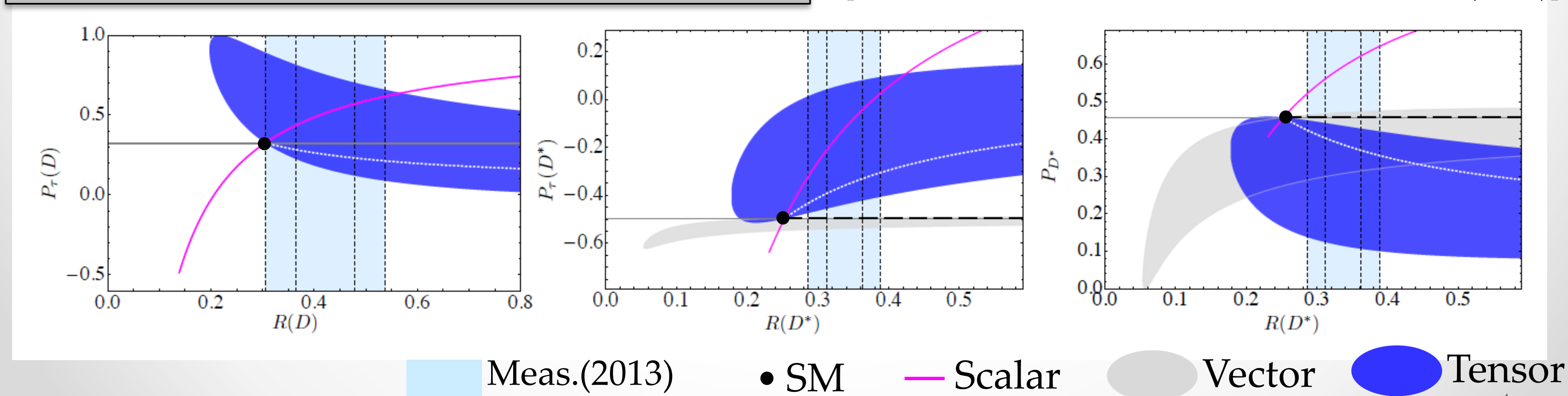
L=e,μ

Polarizations of τ and D* can probe the NP model

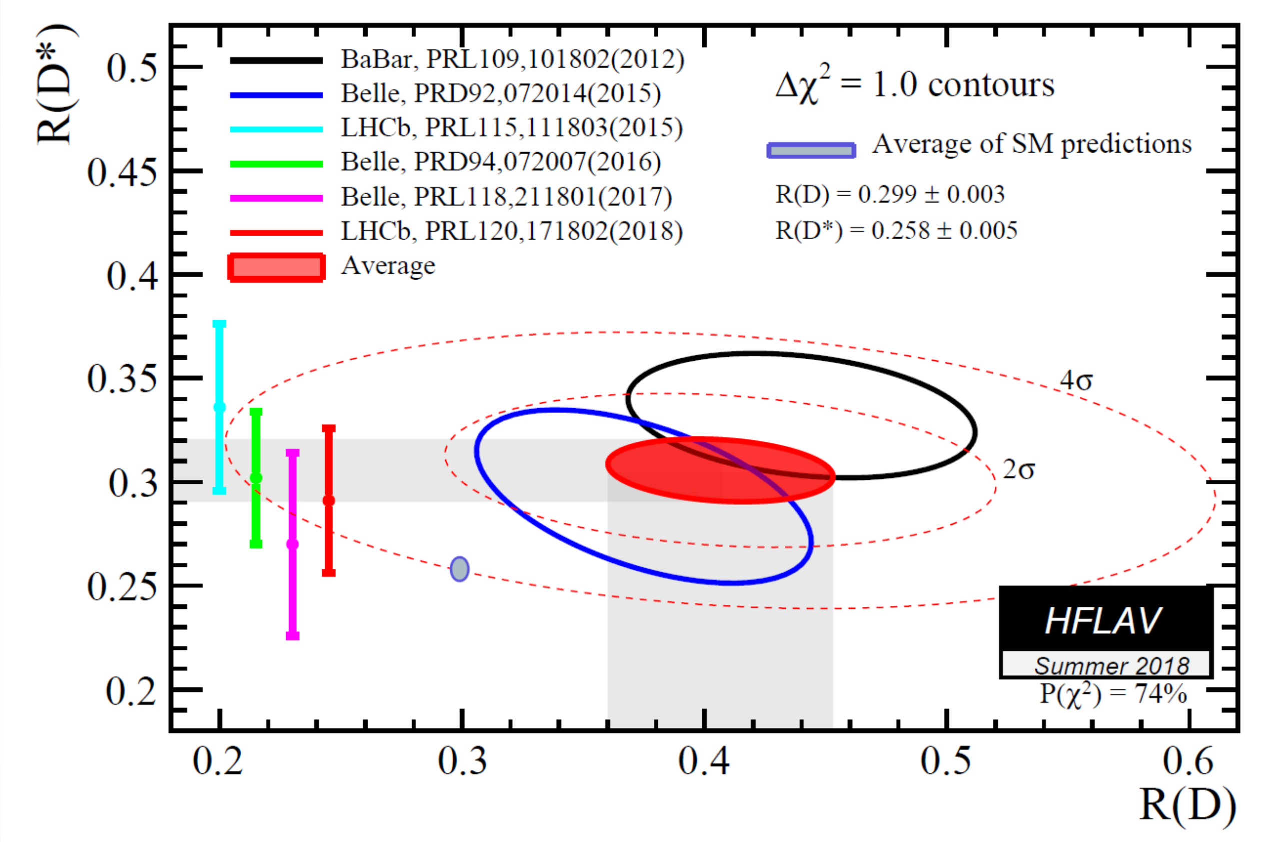
$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)}$$

NP type (vector, scalar, tensor) dependence

[M. Tanaka and R. Watanabe PRD 87, 034028 (2013)]



Previous R(D$^{(*)}$) Situation

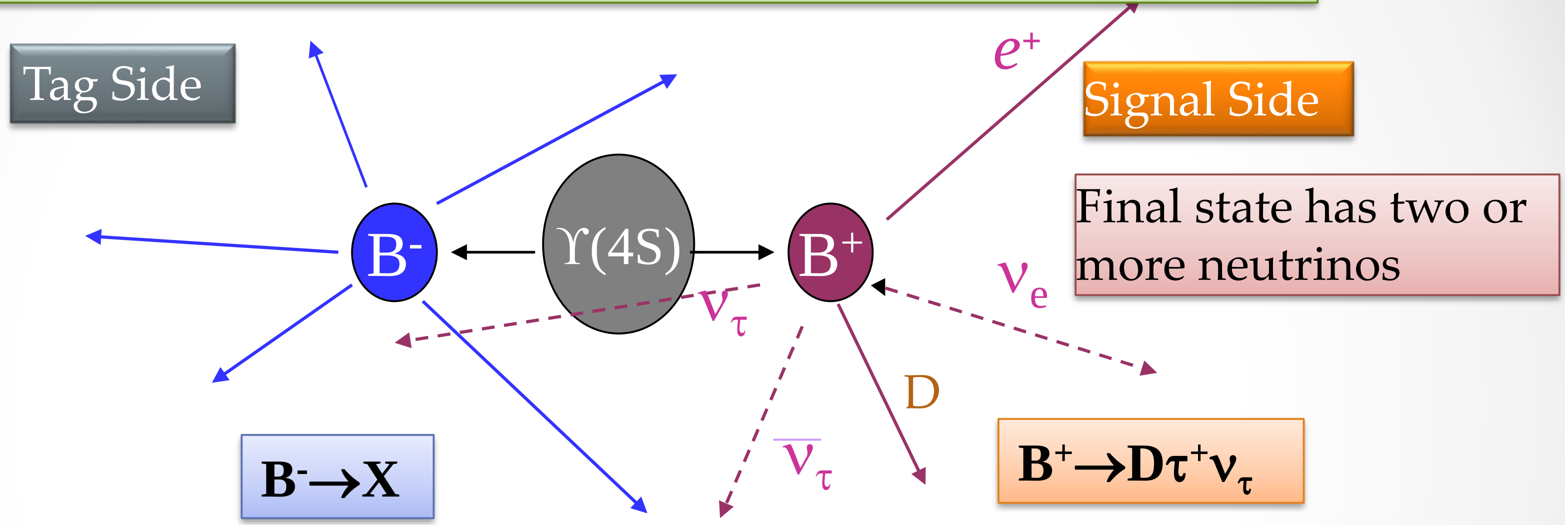


- **3.8 σ deviation from the SM expectation in 2018**

  → New Belle R(D) and R(D*) results in 2019

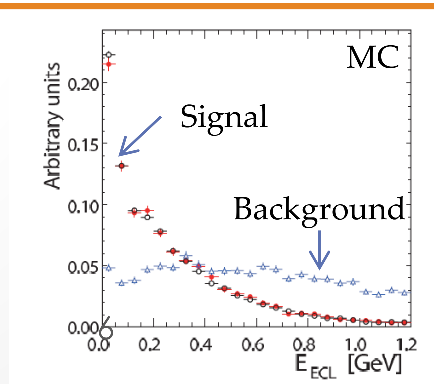
$B \rightarrow D^{(*)}\tau\nu$ Analysis at Belle

Utilize the B factory specific feature :
only one B-meson pair is produced



Tag B pair event by reconstructing one B meson in hadronic or semileptonic B Decay
→ Provide pure single B event

Require **no** particle remains after removing products of tagging B and the particle(s) from signal decays
← Remaining energy in the calorimeter (E_{ECL})



Tagging Methods

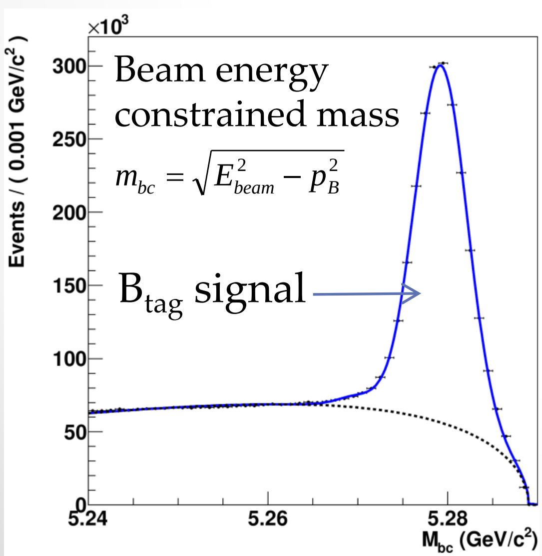
- ## Hadronic Tag

Exclusive tag

- Fully reconstruct in B→DX decays
  - ~1100 exclusive decay channels [NIM A 654, 432 (2011)]
- Tagging efficiency ~ 0.2 %
- Less background

Inclusive tag

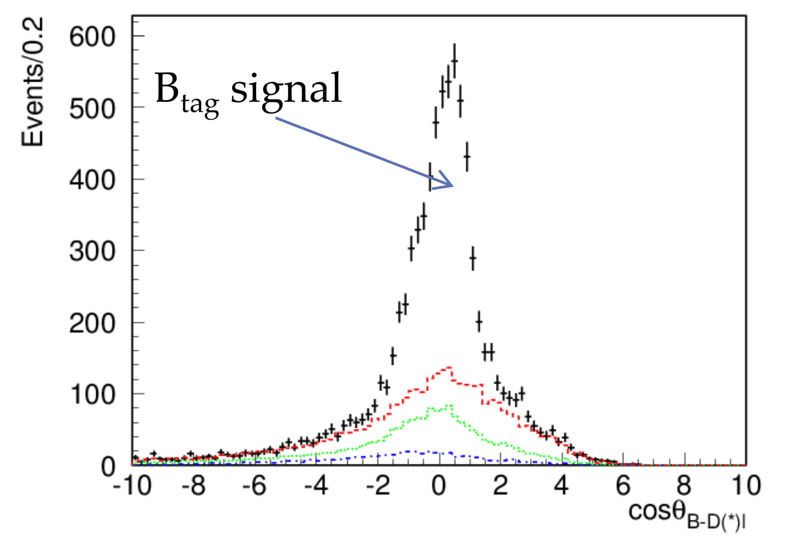
- Reconstruct tag-side B with all particles except signal-side
- Higher efficiency than exclusive tag
- Need clean signal-side final state



- ## Semileptonic Tag

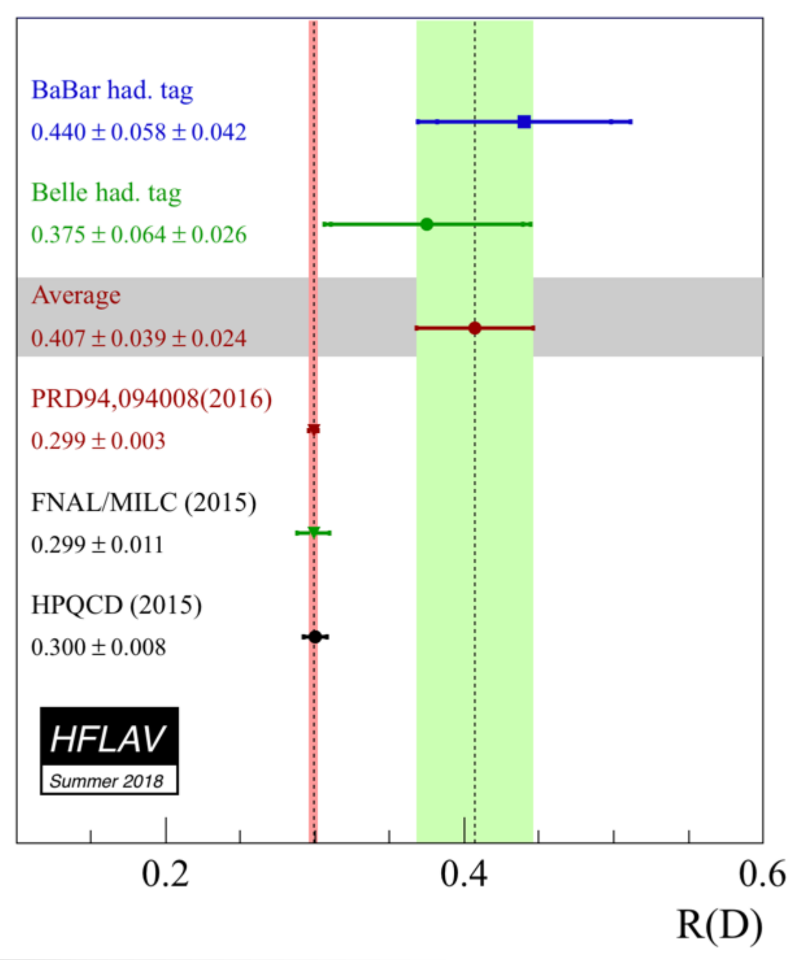
- Reconstruct $B \to D^{(*)} l \nu$
  - Partial reconstruction with
    - $E_B = E_{beam}$
    - Undetected neutrino mass ~ 0
- Tagging efficiency ~ 0.5%
- More background

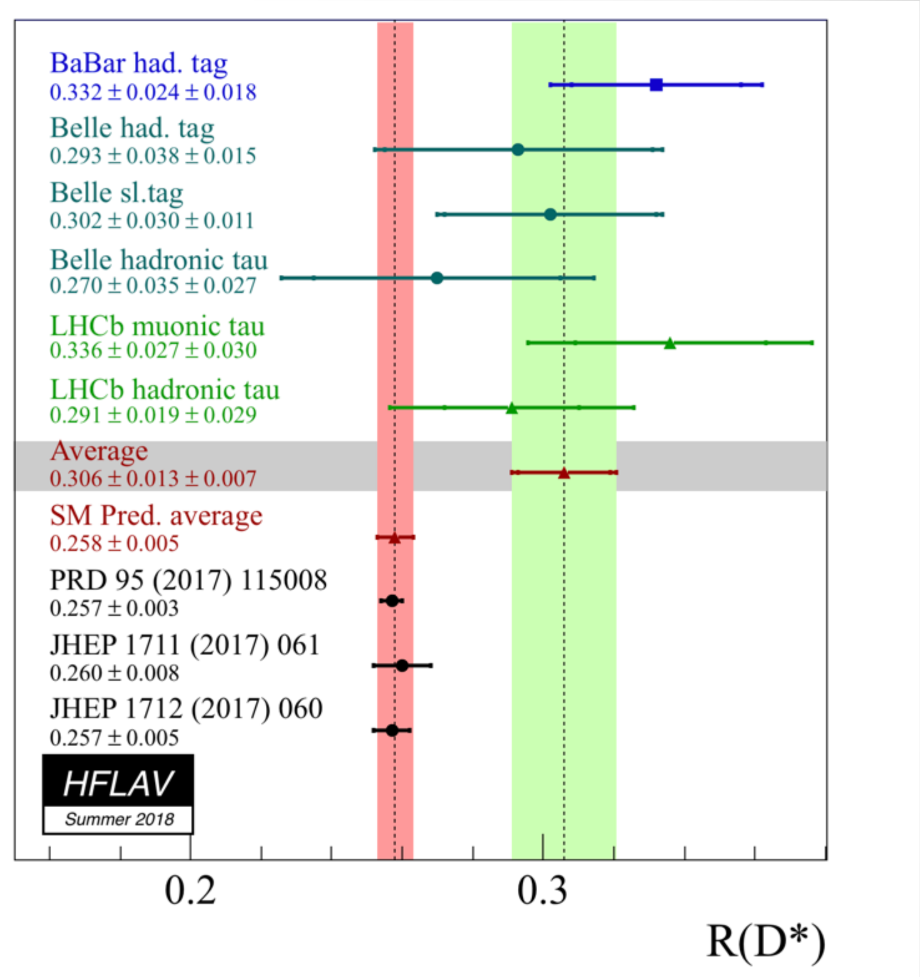
Belle B→τν analysis [PRD 82, 071101(R) (2010)]



$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E^{\rm cms}_{\rm beam}E^{\rm cms}_{D^{(*)}\ell} - m_B^2 - M^2_{D^{(*)}\ell}}{2P^{\rm cms}_B \cdot P^{\rm cms}_{D^{(*)}\ell}}$$

Preivous R(D) and R(D*)





- Only two R(D) measurements with hadronic tag

→ New Belle analysis of R(D) with semileptonic tag

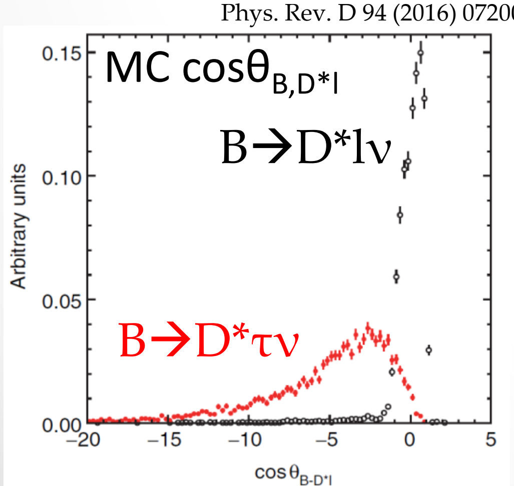
New R(D$^{(*)}$) Measurement with Semileptonic Tag

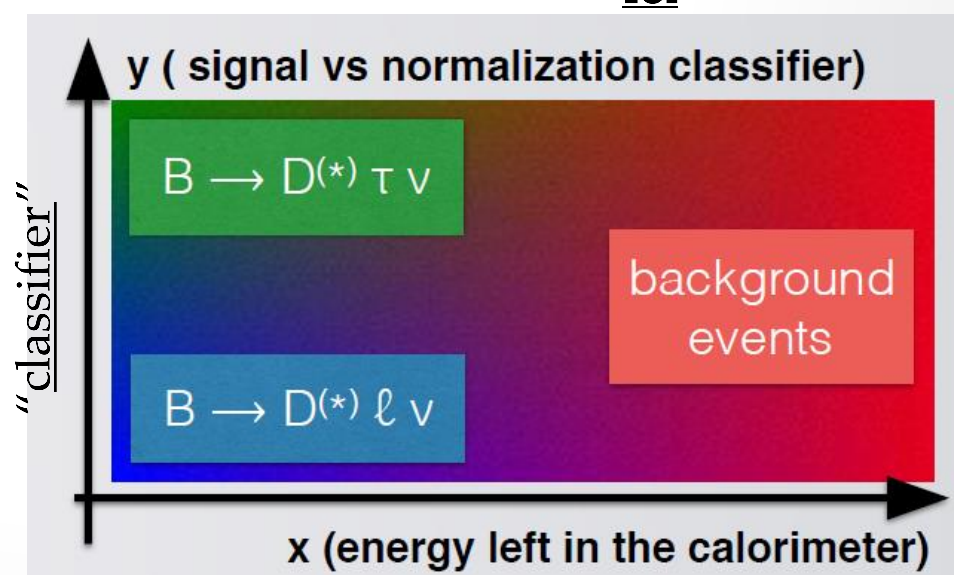
- **Previous Belle Semileptonic tag** [PRD94,072007(2016)]

  Measure **R(D*) with $B^0 \rightarrow D^{*-}\tau^+\nu$** (and charge conjugate) decays
  - o Good signal purity by using clean $D^{*-} \rightarrow D^0 \pi^-$ decays
- **New Semileptonic Analysis** [arXiv:1904.08794] preliminary
  - o **Full Event Interpretation (FEI)** tool developed in BelleII software framework [Comput. Softw. Big. Sci. (2019) 3:6]
  - o Multivariate analysis with Boosted-Decision Tree classifier
  - → Better efficiency and enable to use more signal decay modes
  - o **Both R(D) and R(D*)** with **both B^0 and $B^+ \rightarrow D^*\tau\nu$**
  - o 2D extended maximum-likelihood fit on **"classifier"** and **E_{ECL}**

Classifier: Boosted decision tree output of $\cos\theta_{B,D(*)l}$, M_{miss2} , E_{vis}

Phys. Rev. D 94 (2016) 072007



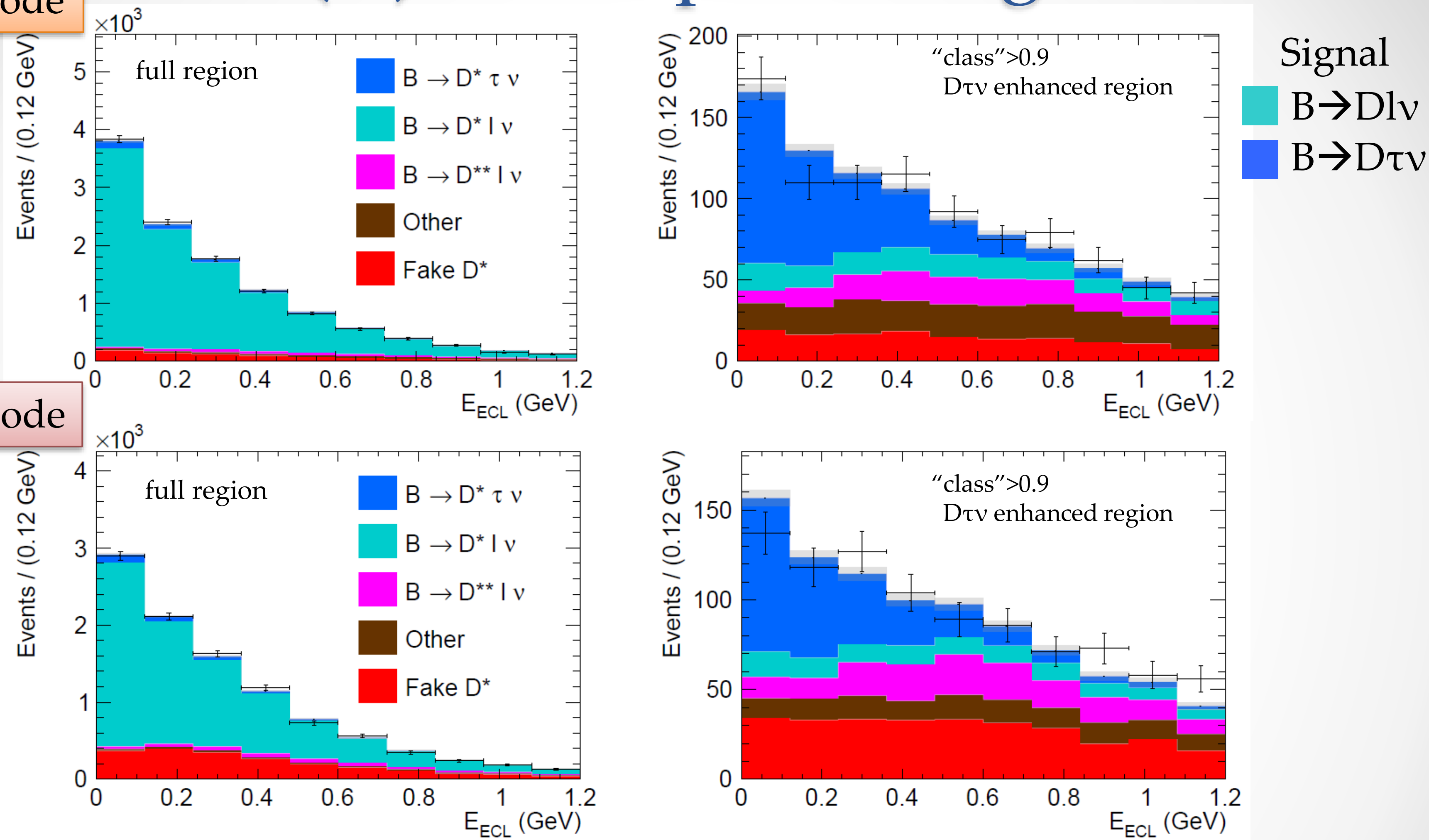


E_{ECL}

NewR(D) Semileptonic Tag Result

D*+l mode

D*0l mode



$D^{*+}\ell^-$	$B \to D^*\tau\nu$	376 ± 36
	$B \to D^*\ell\nu$	9794 ± 109
	$B \to D^{**}\ell\nu$	314 ± 65
	Fake D^*	754 ± 39 (Fixed)
	Other	287 ± 13 (Fixed)
$D^{*0}\ell^-$	$B \to D^*\tau\nu$	275 ± 29
	$B \to D^*\ell\nu$	7148 ± 100
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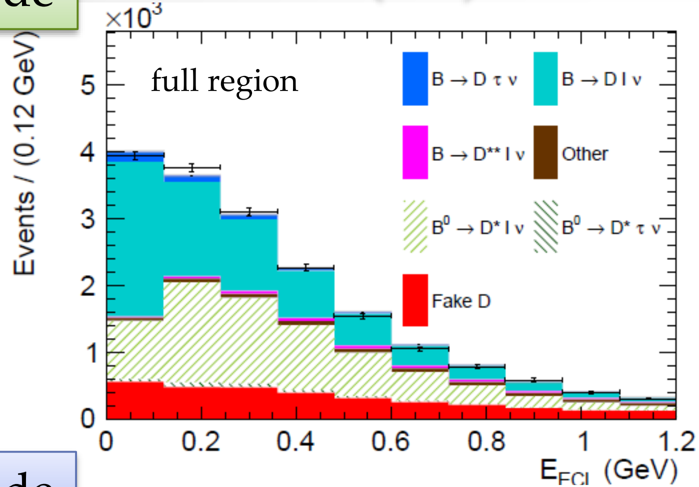
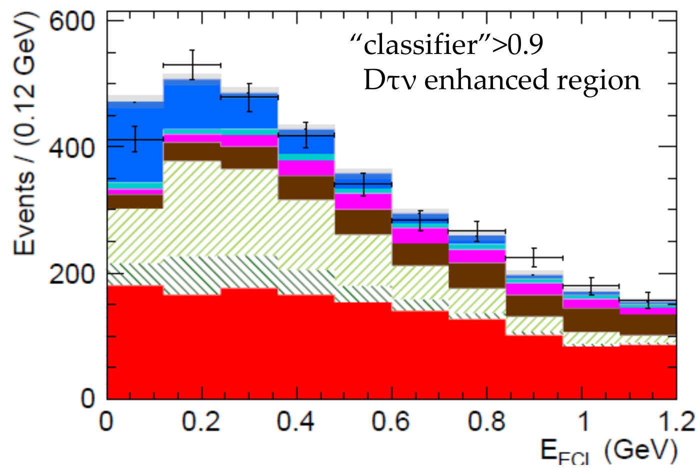
preliminary

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

NewR(D) Semileptonic Tag Result

$D^{+}l$ mode

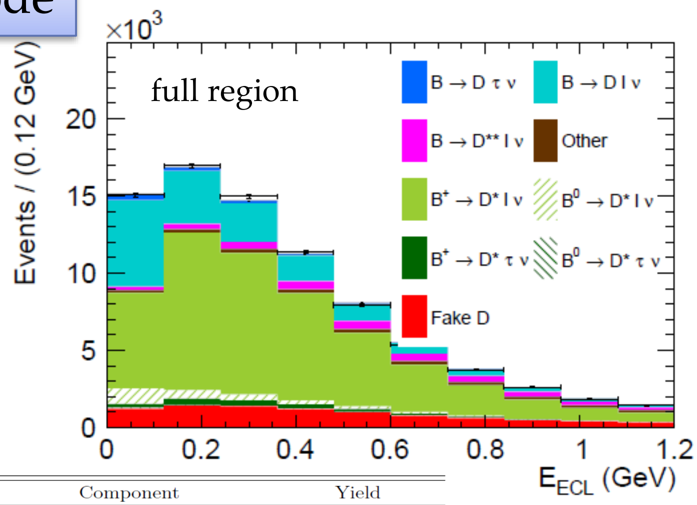


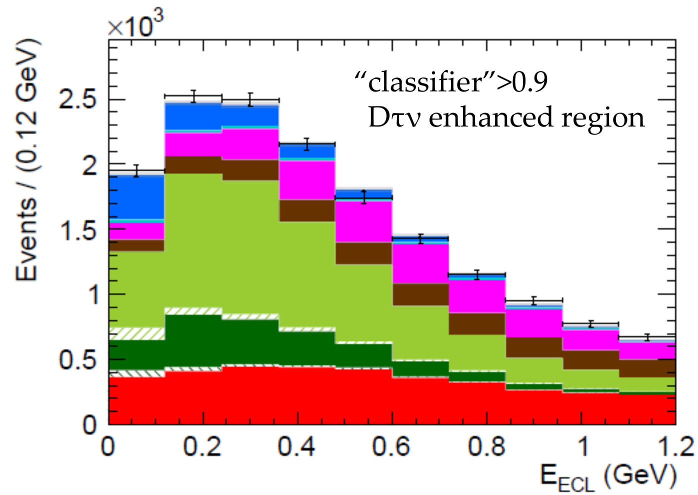


Signal

- $B \to D l \nu$
- $B \to D \tau \nu$

$D^{0}l$ mode





Channel	Component	Yield
$D^{+}\ell^{-}$	$B \to D\tau\nu$	307 ± 65
	$B \to D\ell\nu$	6800 ± 179
	$B^{0} \to D^{*}\ell\nu$	6370 ± 225
	$B^{0} \to D^{*}\tau\nu$	269 ± 24
	$B \to D^{**}\ell\nu$	413 ± 110
	Fake D	3072 ± 129 (Fixed)
	Other	506 ± 23 (Fixed)
$D^{0}\ell^{-}$	$B \to D\tau\nu$	1471 ± 193
	$B \to D\ell\nu$	16096 ± 436
	$B^{+} \to D^{*}\ell\nu$	45042 ± 563
	$B^{0} \to D^{*}\ell\nu$	2302 ± 531
	$B^{+} \to D^{*}\tau\nu$	1704 ± 177
	$B^{0} \to D^{*}\tau\nu$	123 ± 11
	$B \to D^{**}\ell\nu$	3595 ± 252
	Fake D	8708 ± 418 (Fixed)
	Other	2131 ± 83 (Fixed)

preliminary

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$

First R(D) measurement with Semileptonic tag

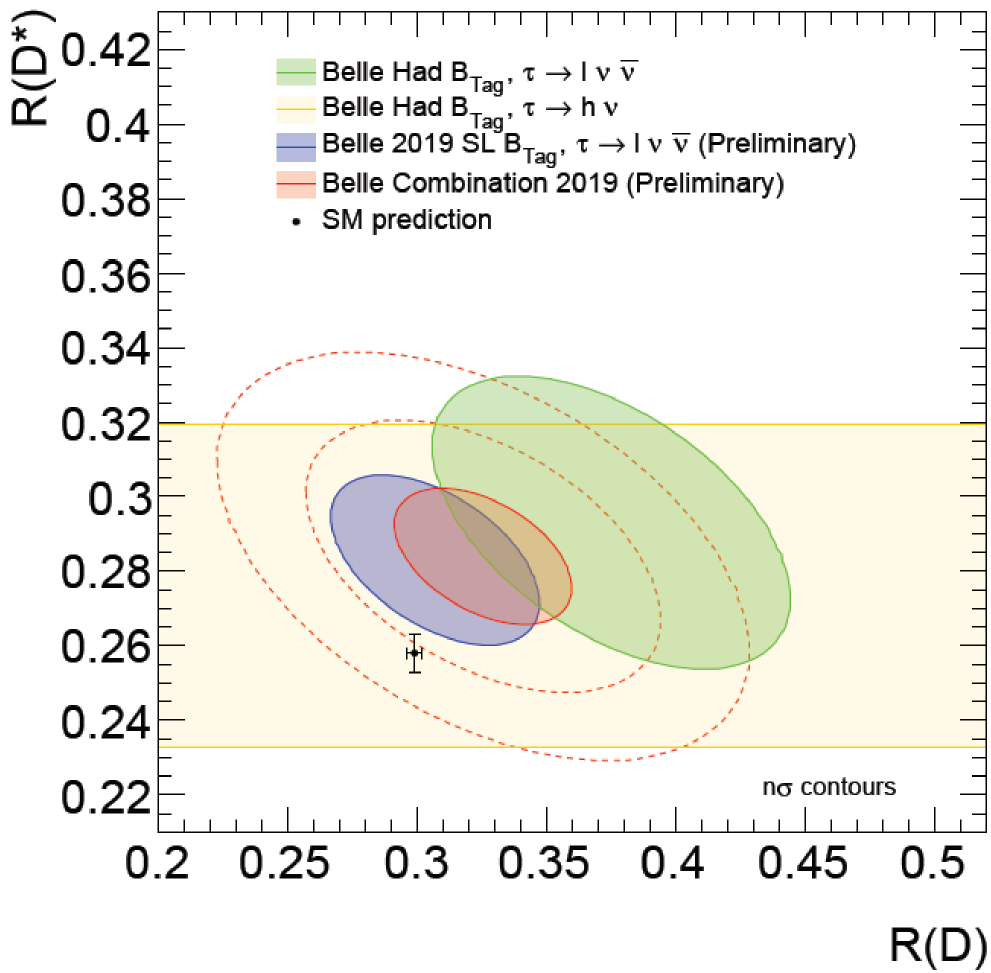
Belle R(D(*)) Results

New semileptonic tag (preliminary, [arXiv:1904.08794])

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$

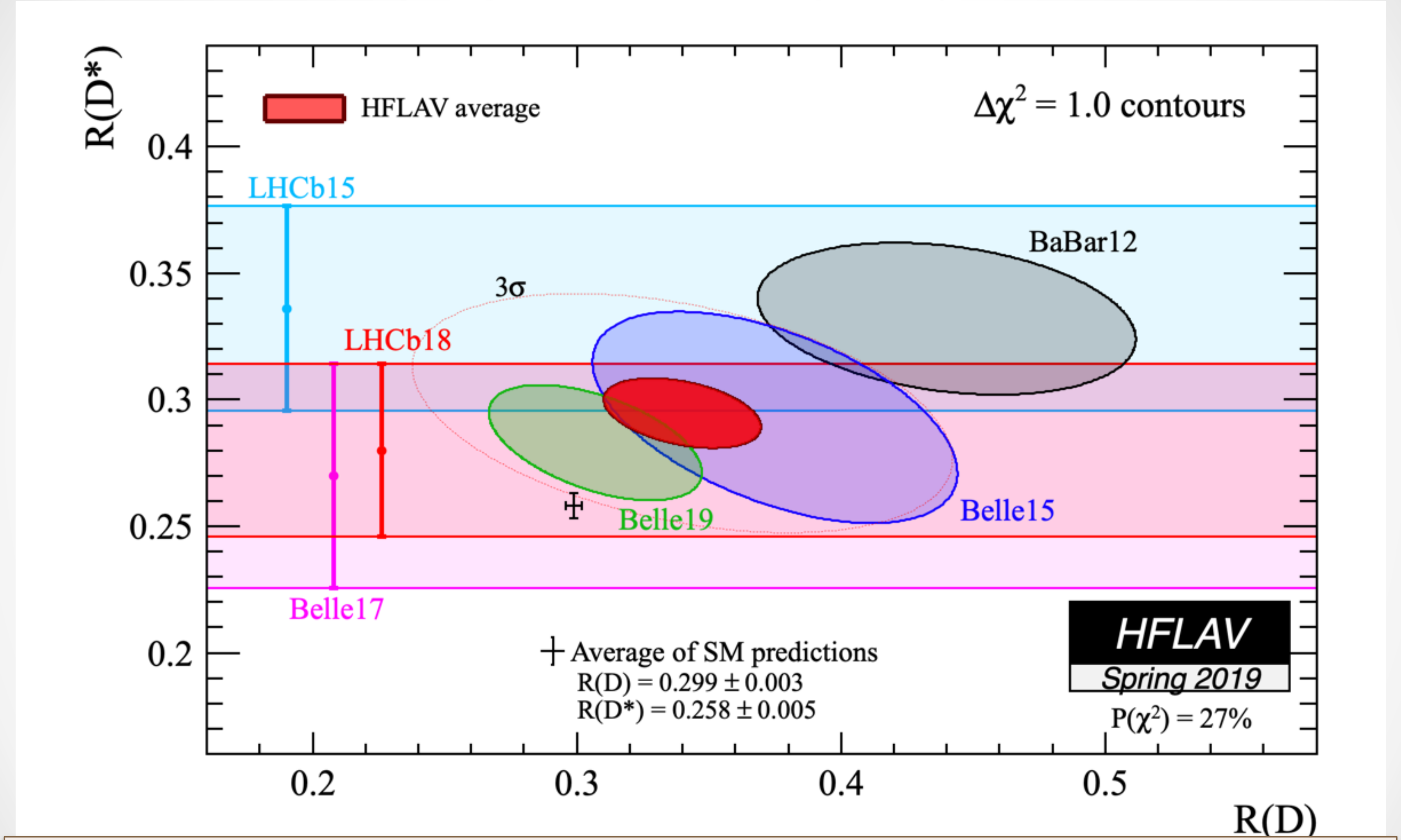
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

New semileptonic tag results consistent with SM in 1.2 σ



Belle combined result at about 2 σ from SM

Latest R(D) and R(D*) Situation



Belle new semileptonic tag results are the most precise R(D(*)) measurements

Deviation from SM reduced to 3.1 σ

τ Polarization Measurement

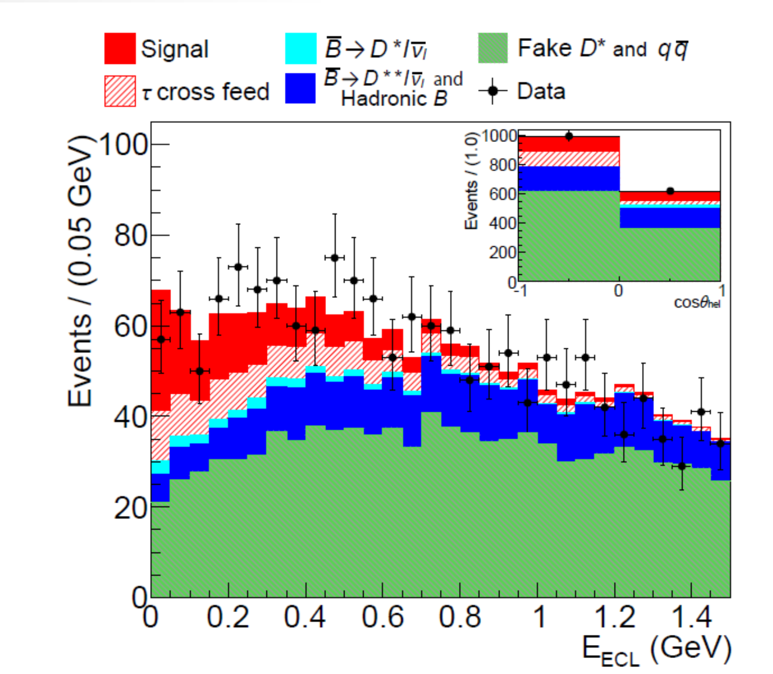
[PRL118, 211801 (2017) PRD97, 012004 (2018)]

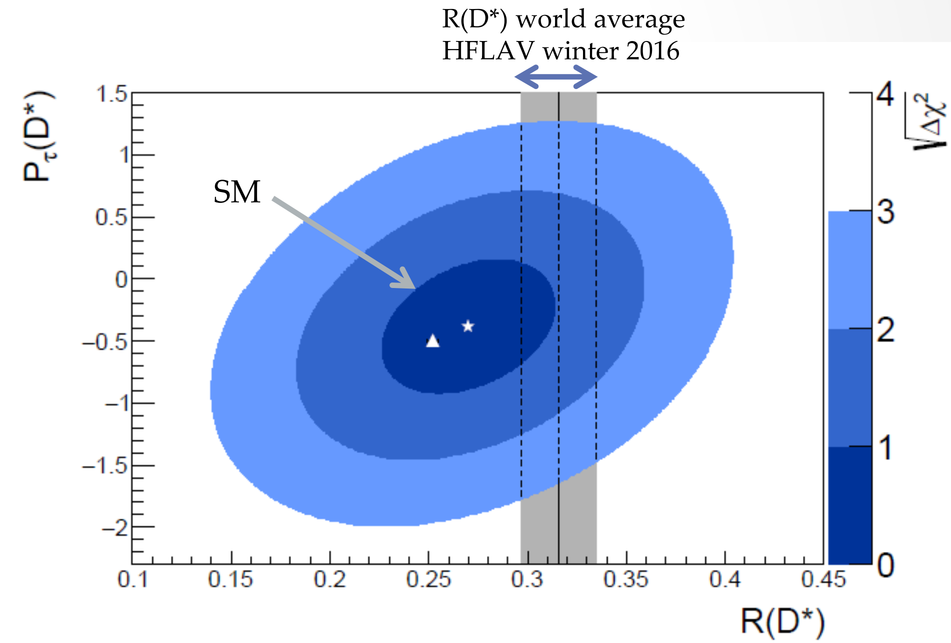
- Hadronic tag
- Two body tau decays : $\tau \to \pi\nu, \rho\nu$
  - Helicity angle sensitive to the tau polarization
- $P_\tau(D^*)_{SM} = -0.497 \pm 0.013$

[Tanaka,Watanabe, PRD 87, 034028 (2013)]

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1}{2}(1 + \alpha \cdot \mathcal{P}_\tau \cos\theta_{hel})$$

$$\alpha = \begin{cases} 1 & \text{for } \tau \to \pi^-\nu \\ 0.45 & \text{for } \tau \to \rho^-\nu \end{cases}$$



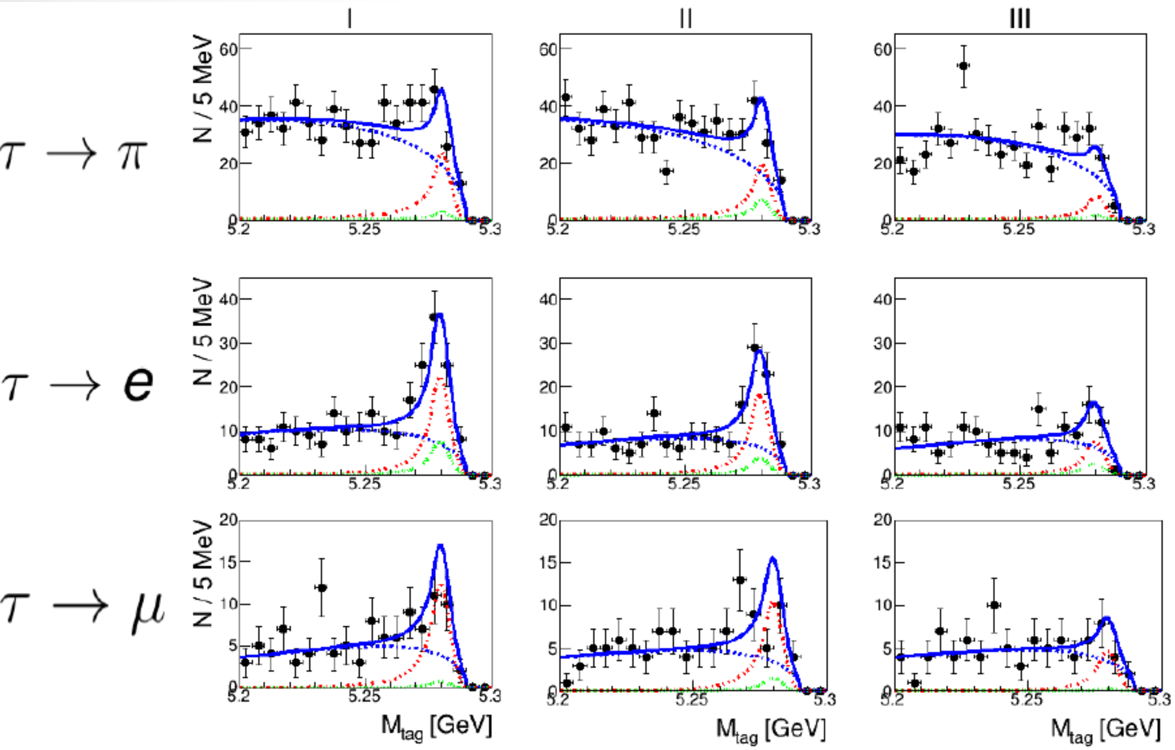


$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),$$

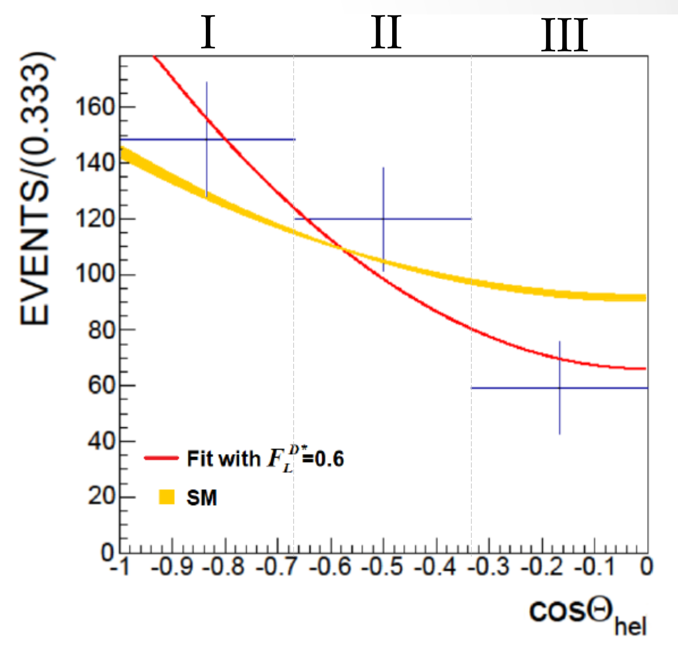
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst}),$$

D* Polarization Measurement

- Reconstruct $B^0 \rightarrow D^* \tau \nu$
- Utilized **inclusive tag** method
- Extract signal yield in three $D^* \rightarrow D\pi$ helicity angle regions
- Fit the helicity angle distribution



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



preliminary

[arXiv:1903.03102]

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

cf. in SM

- $F_L^{D^*} = 0.46 \pm 0.03$ [PRD95, 115038(2017)]
- $F_L^{D^*} = 0.441 \pm 0.006$ [arXiv: 1808: 03565]

within 2 σ of SM

Summary

- $B \to D^{(*)}\tau\nu$ decays are good probes for New Physics
- Tension exists between measurements and SM

- New Belle Semileptonic tag R(D) and R(D*) results:

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

(preliminary)
within 1.2 σ from SM

  - First R(D) measurement with Semileptonic tag
  - Most precise R(D) and R(D*) measurement
- τ and D* polarizations are also measured at Belle
  - First D* polarization measurement in $B^0 \to D^*\tau\nu$ decays

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

(preliminary)
within 2 σ from SM

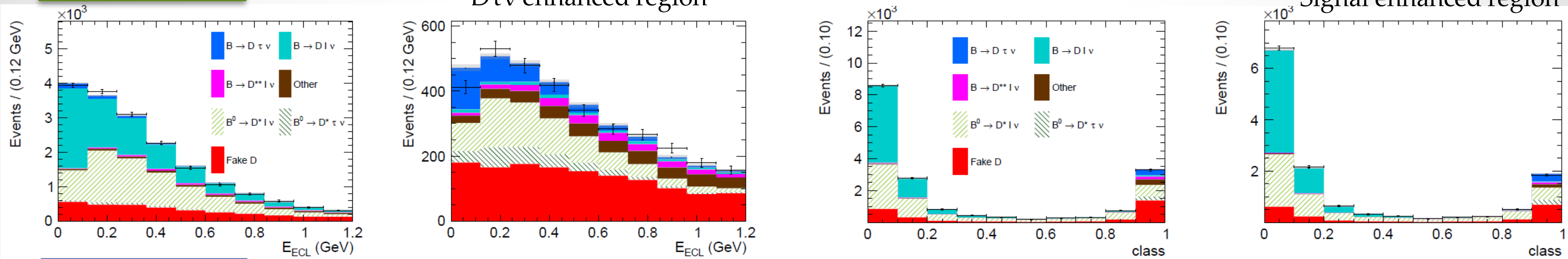
- Still there is large tension in R(D)-R(D*)
- Belle II has started → More interesting results in future

New R(D) Semileptonic Tag Result

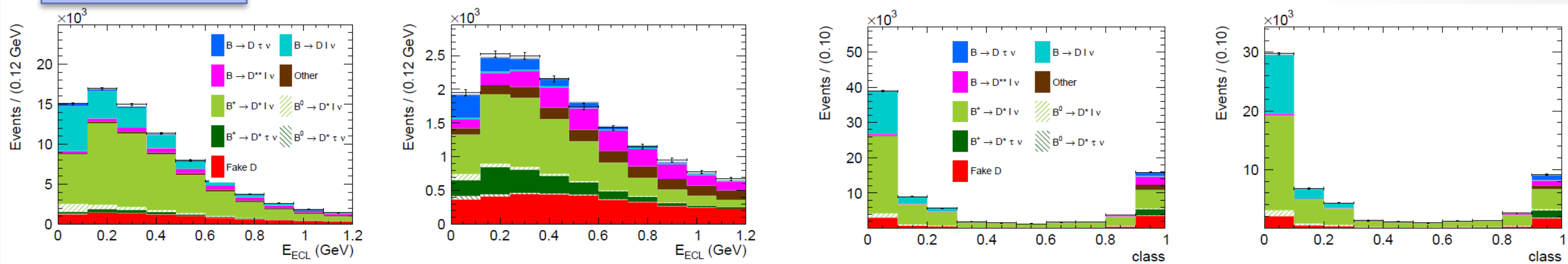
$D^{+}l$ mode

"class">0.9
$D\tau\nu$ enhanced region

E_{ECL}<0.48 GeV
Signal enhanced region



$D^{0}l$ mode



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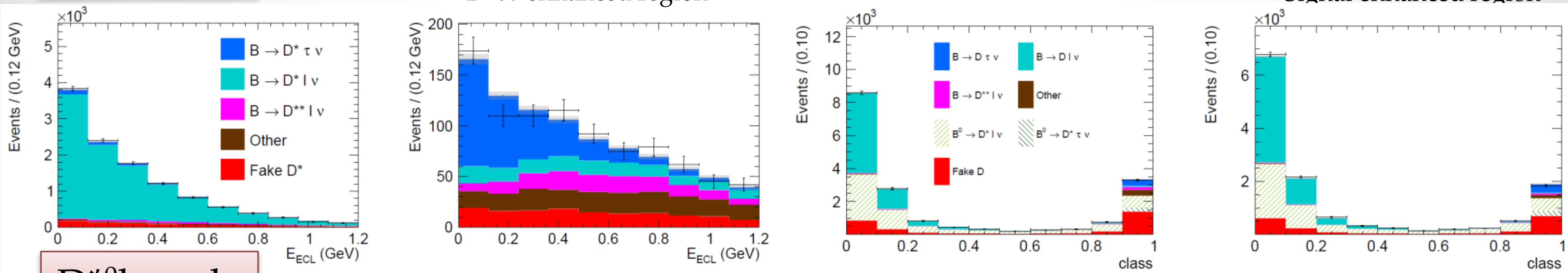

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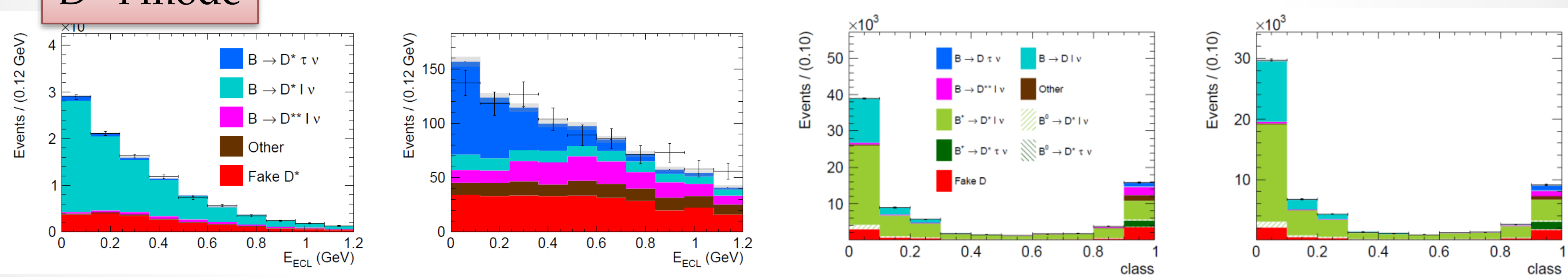

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preliminary

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$R(D^{(*)})$ Systematic Errors

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

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
D^{**} composition	0.62	1.26
Fake $D^{(*)}$ calibration	0.18	0.10
$B_{\rm tag}$ calibration	0.06	0.04
Feed-down factors	1.52	0.37
Efficiency factors	1.73	3.60
Lepton efficiency and fake rate	0.33	0.28
Slow pion efficiency	0.07	0.07
MC statistics	3.94	1.92
B decay form factors	0.50	0.24
Luminosity	0.09	0.04
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02
$\mathcal{B}(D)$	0.31	0.12
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.13	0.12
Total	4.66	4.32

τ Hadronic decay: R(D*), τ Polarization Systematic Errors

TABLE II. The systematic uncertainties in $R(D^*)$ and $P_\tau(D^*)$, where the values for $R(D^*)$ are relative errors. The group "common sources" identifies the common systematic uncertainty sources in the signal and the normalization modes, which cancel to a good extent in the ratio of these samples. The reason for the incomplete cancellation is described in the text.

Source	$R(D^*)$	$P_\tau(D^*)$
Hadronic B composition	$^{+7.7\%}_{-6.9\%}$	$^{+0.134}_{-0.103}$
MC statistics for PDF shape	$^{+4.0\%}_{-2.8\%}$	$^{+0.146}_{-0.108}$
Fake D^*	3.4%	0.018
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.4%	0.048
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.001
$\bar{B} \to D^*\ell^-\bar{\nu}_\ell$	2.3%	0.007
τ daughter and ℓ^- efficiency	1.9%	0.019
MC statistics for efficiency estimation	1.0%	0.019
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau)$	0.3%	0.002
$P_\tau(D^*)$ correction function	0.0%	0.010
Common sources		
Tagging efficiency correction	1.6%	0.018
D^* reconstruction	1.4%	0.006
Branching fractions of the D meson	0.8%	0.007
Number of $B\bar{B}$ and $\mathcal{B}(\Upsilon(4S) \to B^+B^-$ or $B^0\bar{B}^0)$	0.5%	0.006
Total systematic uncertainty	$^{+10.4\%}_{-9.4\%}$	$^{+0.21}_{-0.16}$

D* Polarization Systematic Errors

TABLE I. Summary of systematic uncertainties

Source		$\Delta F_L^{D^*}$
Monte Carlo statistics	AR shape and peaking background	± 0.032
	CB shape	± 0.010
	Background scale factors	± 0.001
Background modeling	$B \to D^{**} \ell \nu$	± 0.003
	$B \to D^{**} \tau \nu$	± 0.011
	$B \to$ hadrons	± 0.005
	$B \to \bar{D}^* M$	± 0.004
Signal modeling	Form factors	± 0.002
	$\cos \theta_{\mathrm{hel}}$ resolution	± 0.003
	Acceptance non-uniformity	$^{+0.015}_{-0.005}$
Total		$^{+0.039}_{-0.037}$