Status and outlook for R(D(*))

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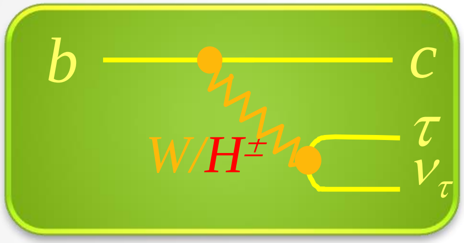
Sep. 12, 2020

Anomalies 2020

Semi-tauonic B decay: $B \to D^{(*)}\tau\nu$

- 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

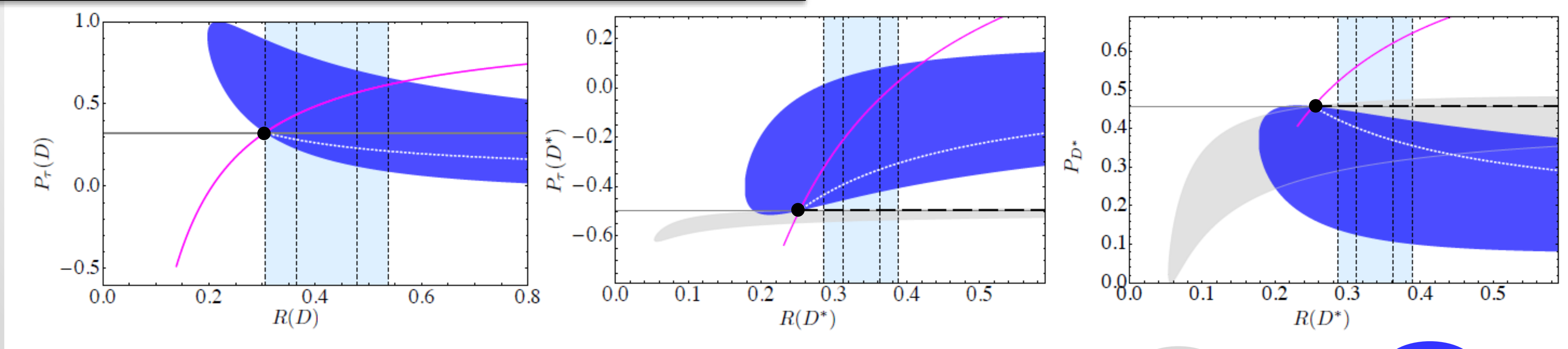
SM R(D) = 0.299±0.003, R(D*)=0.258±0.005 [HFLAV2019]

Polarizations of τ and D* can probe the NP model

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

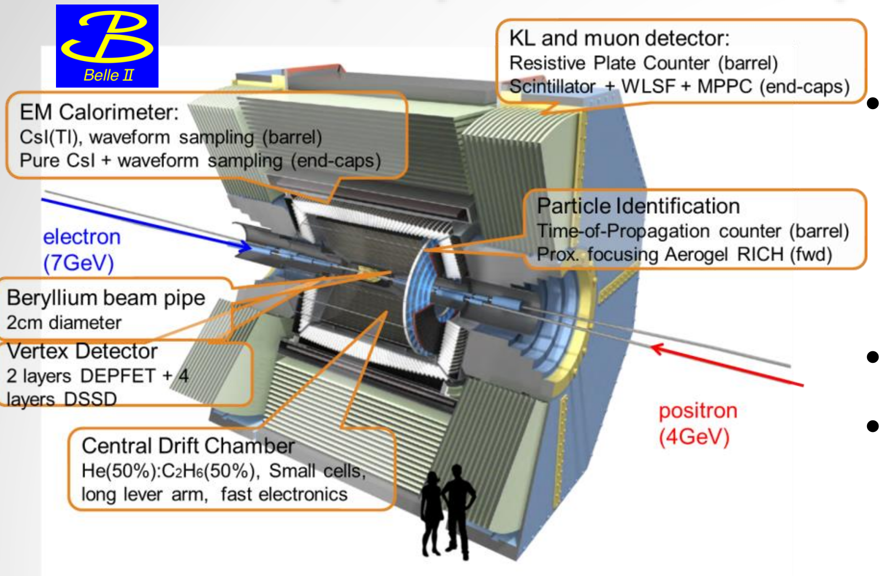
NP type (vector, scalar, tensor) dependence

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

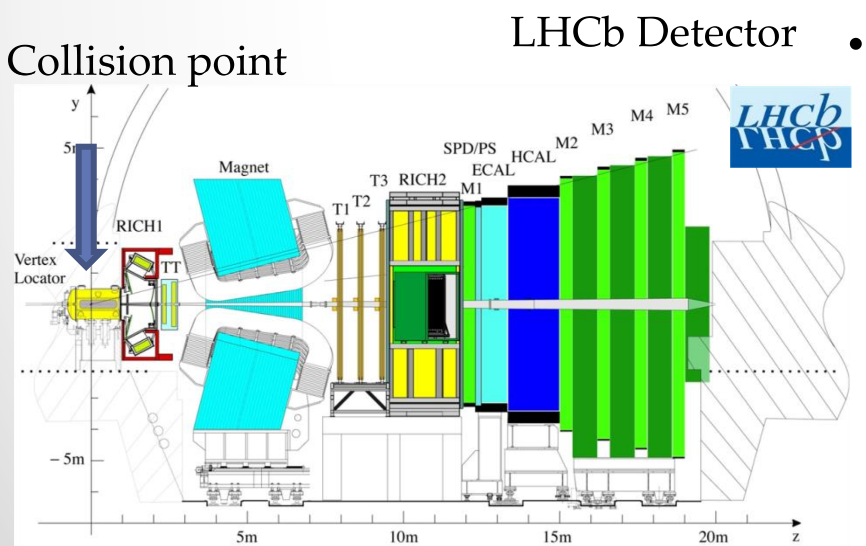


Meas.(2013) • SM — Scalar Vector Tensor

R(D) and R(D*) Experiments



- **B factory experiments**
  - Produce $B\bar{B}$ pairs via $e^+e^- \to \Upsilon(4s)$
  - **Only one $B\bar{B}$ pair in an event**
  - **4π detector surrounding the IP**
- **Belle** + **BaBar** have accumulated >~**1ab**$^{-1}$
- **Belle II** started physics data taking in 2019 and will accumulate **50 ab**$^{-1}$

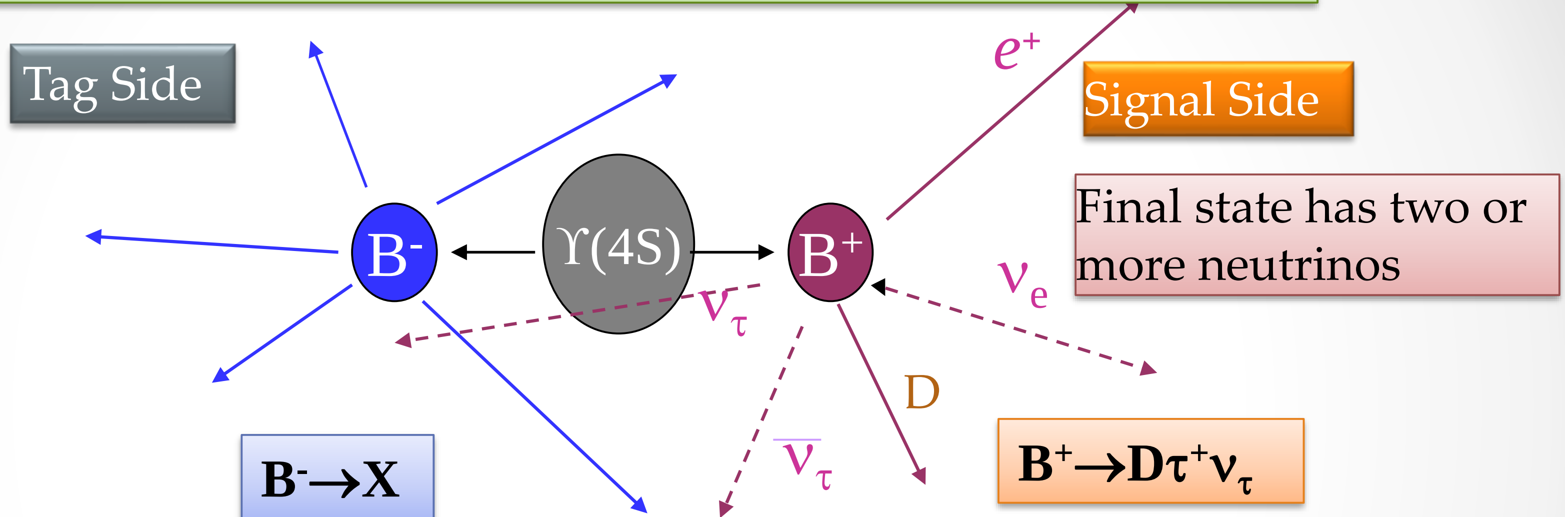


- **LHCb**
  - Experiment dedicated to B physics at LHC
  - **Many b hadrons produced in pp collisions**
  - Single arm detector covering the forward region
  - **Large boost → good separation of vertices: primary vertex, B, D, τ**
  - Collected Run 1 + Run 2 ~ 9fb^{-1}
  - Now in long shutdown for upgrade

These experiments are complementary

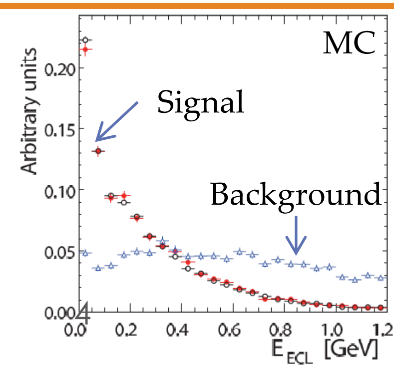
B→D$^{(*)}$τν Analysis at B factories

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 tagging B and signal B candidates
  → Remaining energy in the calorimeter (E_{ECL})
- Multiple missing neutrinos → (Missing mass)^2 > 0



Tagging Methods

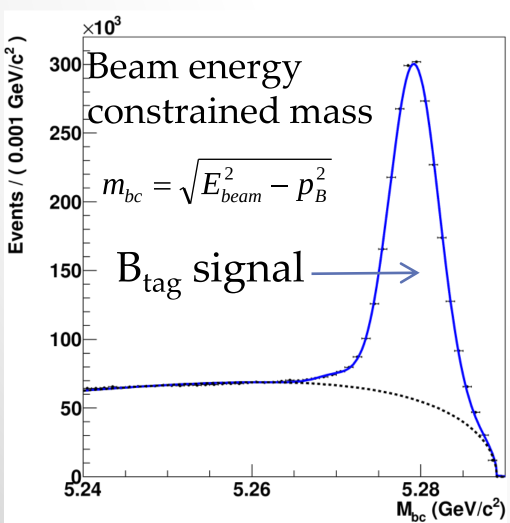
- ## Hadronic Tag

Exclusive tag

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

Inclusive tag

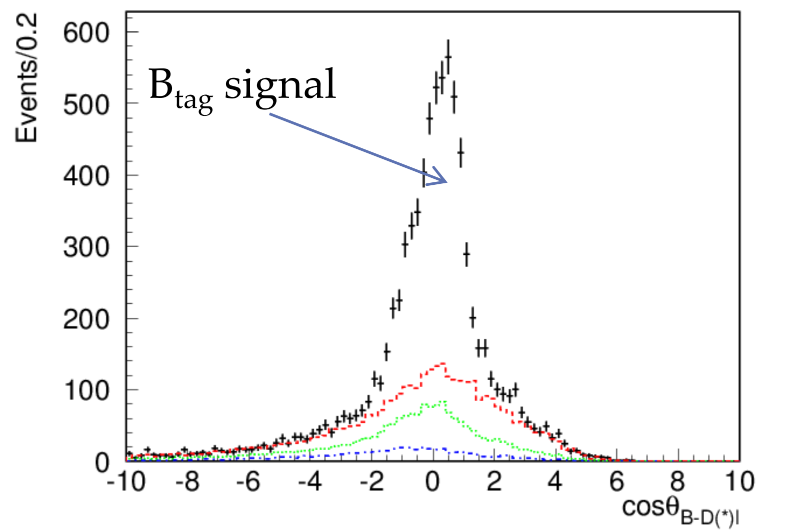
- Reconstruct tag-side B with all particles except signal-side
- Higher efficiency than exclusive tag
- Need clean signal-side final state
- **Used for first observation of B→D*τν by Belle [PRL99, 191807(2007)]**



- ## Semileptonic Tag

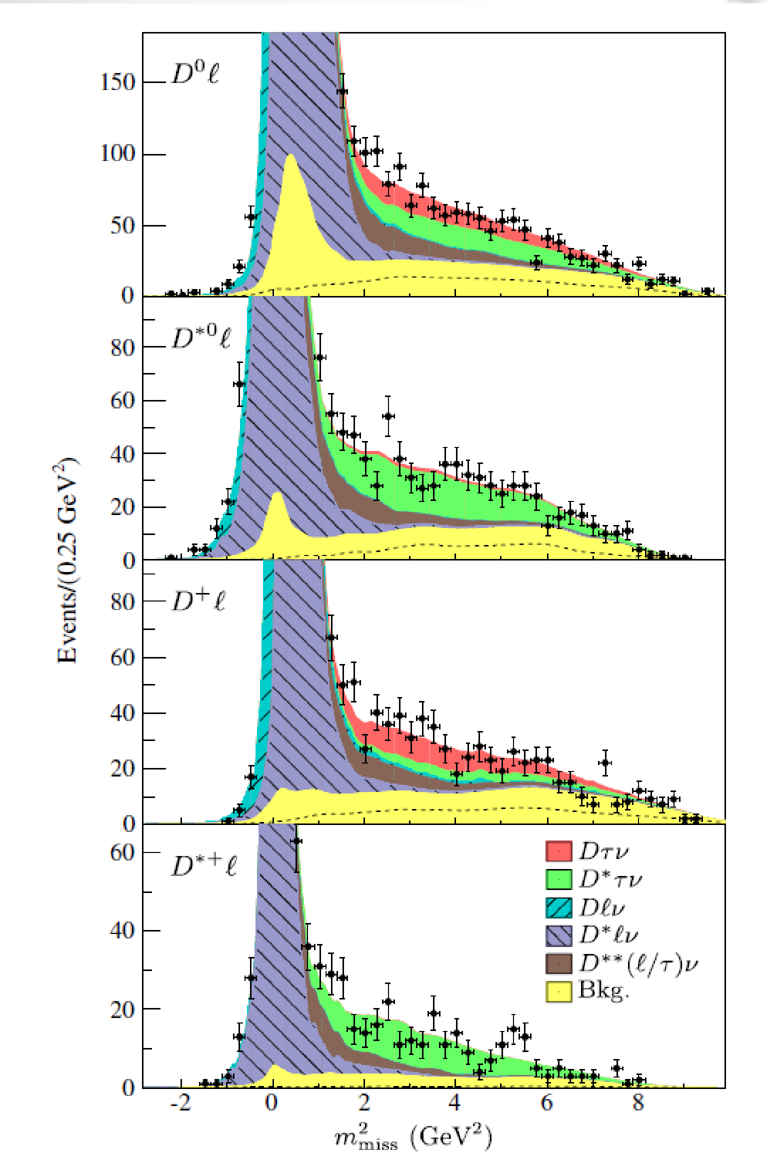
- Reconstruct $B \to D^{(*)} l \nu$
  - Partial reconstruction with
    - $E_B = E_{beam}$
    - Undetected neutrino mass ~ 0
- Tagging efficiency ~ 0.5%
- More background

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



$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\rm beam}^{\rm cms} E_{D^{(*)}\ell}^{\rm cms} - m_B^2 - M_{D^{(*)}\ell}^2}{2P_B^{\rm cms} \cdot P_{D^{(*)}\ell}^{\rm cms}}$$

Results with Hadronic Tag by BaBar



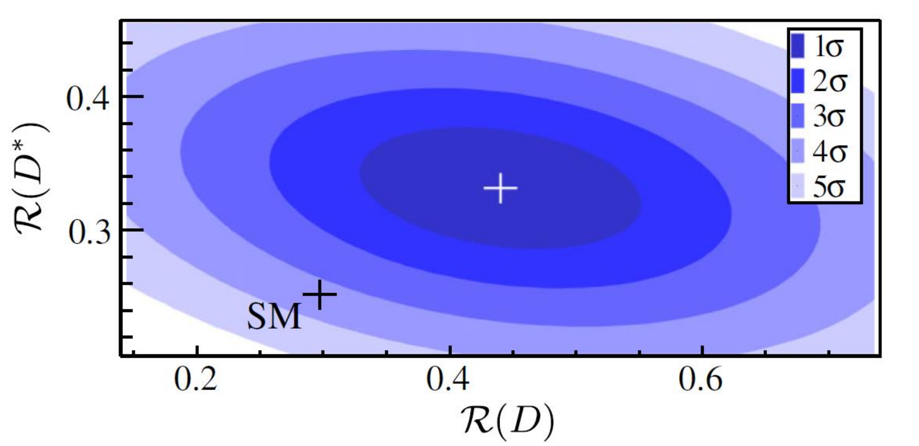
[PRL109, 101802 (2012)]
[PRD88, 072012 (2013)]

- 471 M $B\overline{B}$ sample
- Leptonic tau decays are used

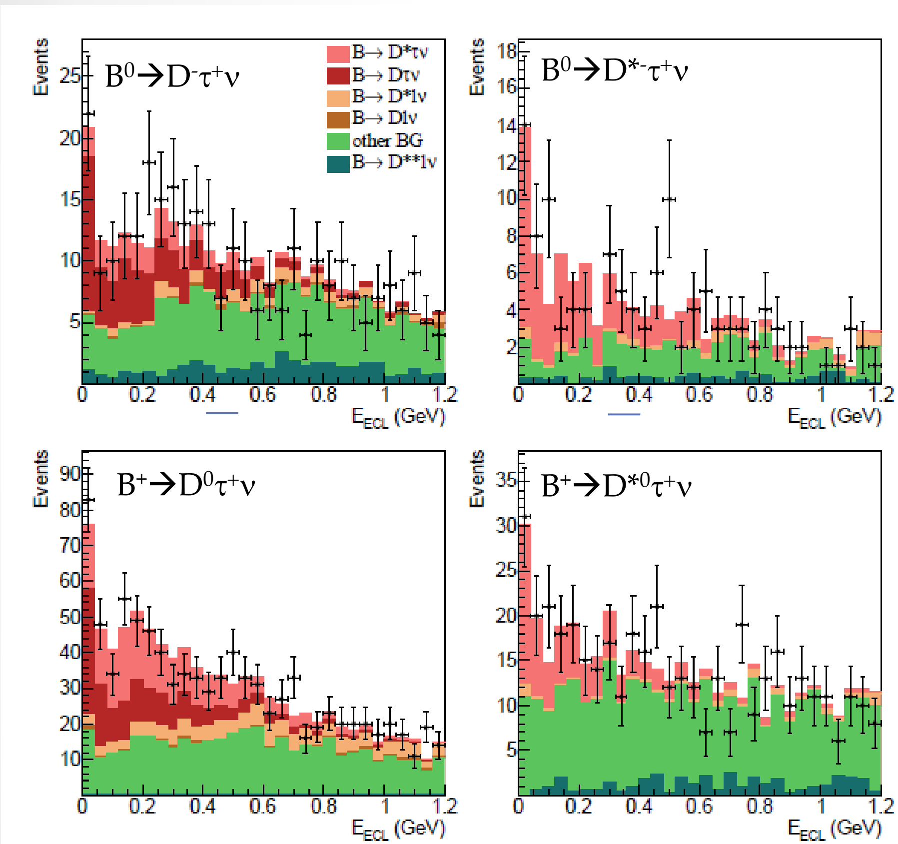
$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$$

$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$$

Both are larger than SM expectations



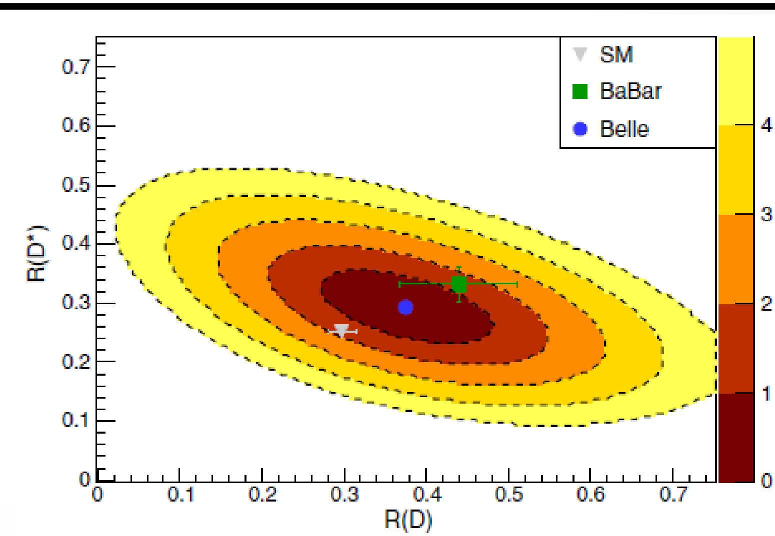
Results with Hadronic Tag by Belle (leptonic τ decays)



[PRD92,072014(2015)]

- 772 M $B\bar{B}$ sample
- Leptonic tau decays are used

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$



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

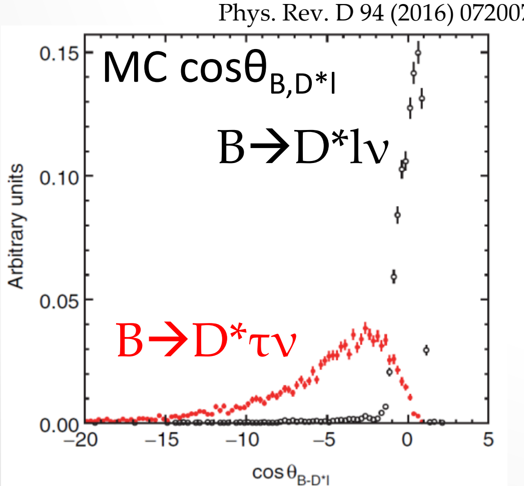
- Previous Analysis [PRD94,072007(2016)]

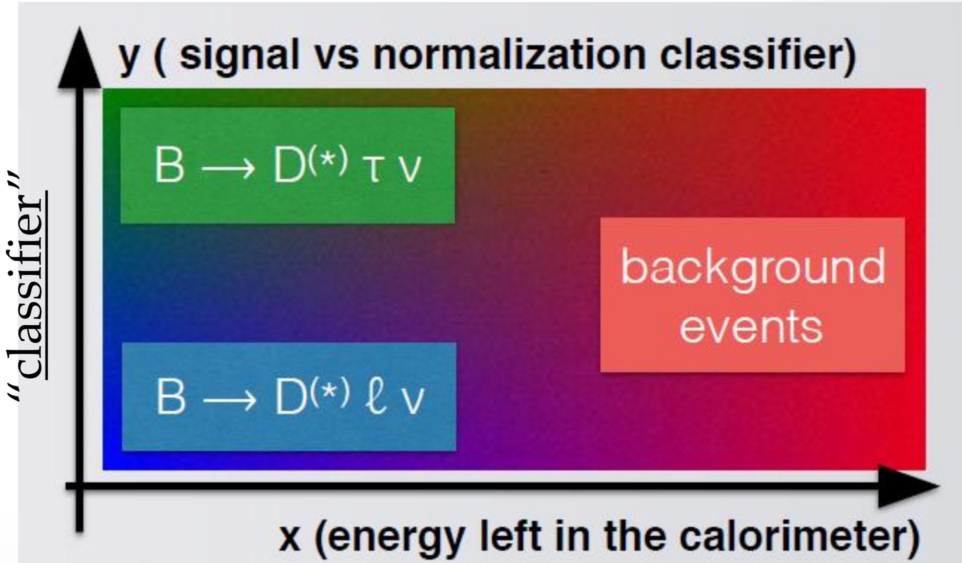
  Measure **R(D*) with $B^0 \to D^{*-}\tau^+\nu$** (and charge conjugate) decays
  - Good signal purity by using clean $D^{*-} \to D^0 \pi^-$ decays
- **Recent Update [PRL124,161803 (2020)]**
  - **Full Event Interpretation (FEI)** tool developed in **BelleII software framework** [Comput. Softw. Big. Sci. (2019) 3:6]
  - Multivariate analysis with Boosted-Decision Tree classifier

  → Better efficiency and enable to use more signal decay modes
  - **Both R(D) and R(D*)** with **both B^0 and $B^+ \to D^*\tau\nu$**
  - 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



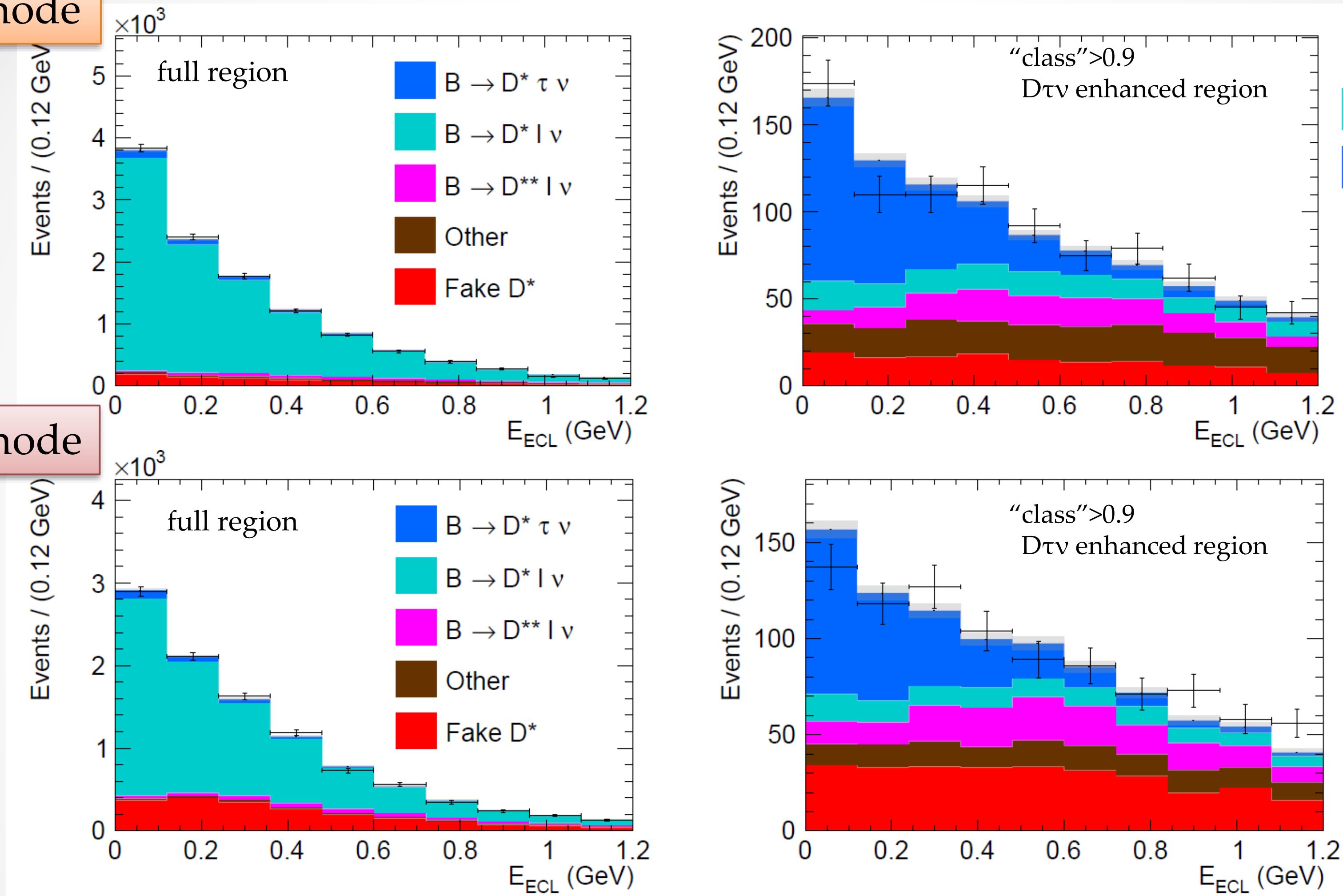


E_{ECL}

Belle R(D*) Semileptonic Tag Result

$D^{*+}l$ mode

$D^{*0}l$ mode



Signal

B→Dlν

B→Dτν

$D^{*+}\ell^-$	$B \to D^*\tau\nu$	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
	$B \to D^{**}\ell\nu$	406 ± 64
	Fake D^*	1993 ± 122 (Fixed)
	Other	187 ± 7 (Fixed)

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

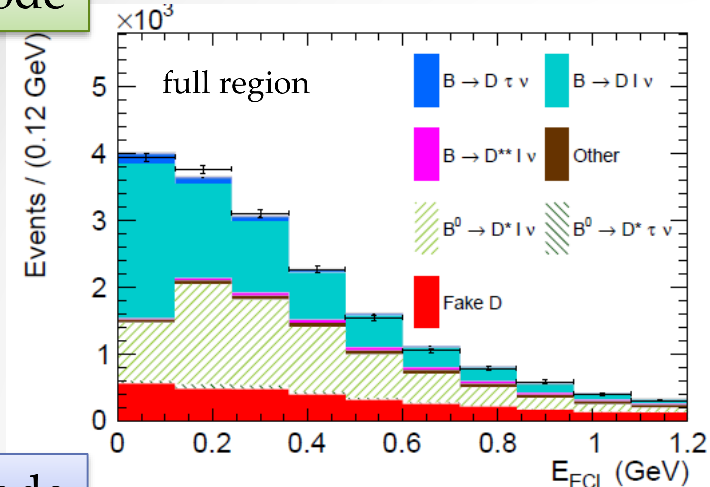
Belle R(D) Semileptonic Tag Result

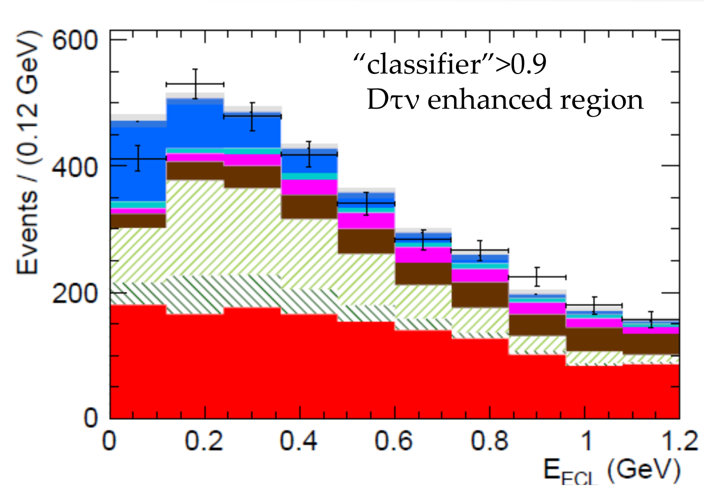
Signal

B→Dlν

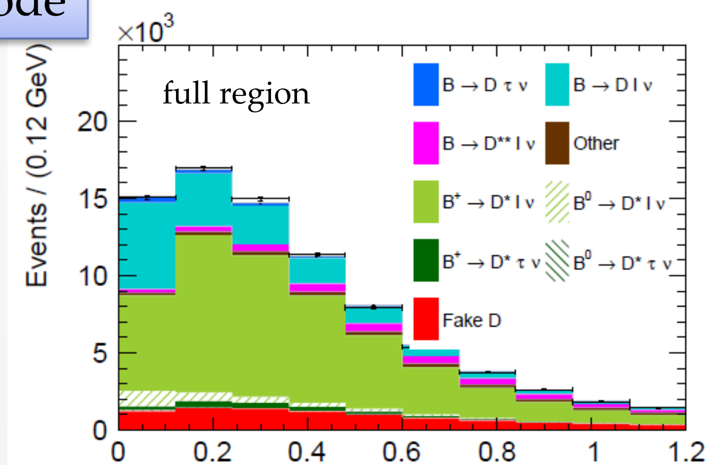
B→Dτν

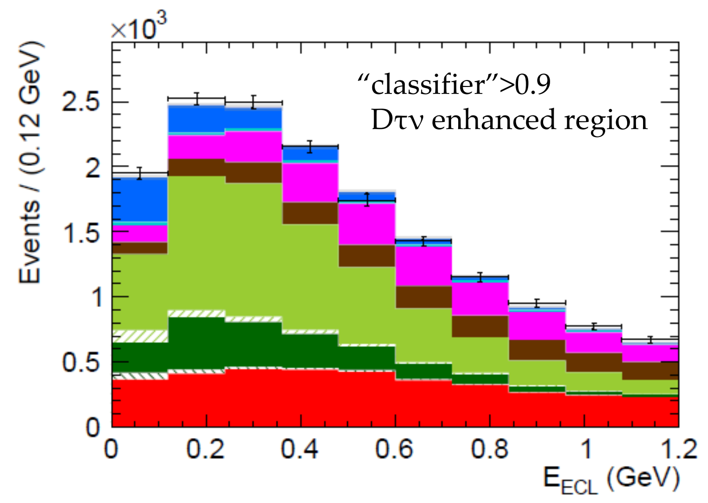
$D^{+}l$ mode





$D^{0}l$ mode





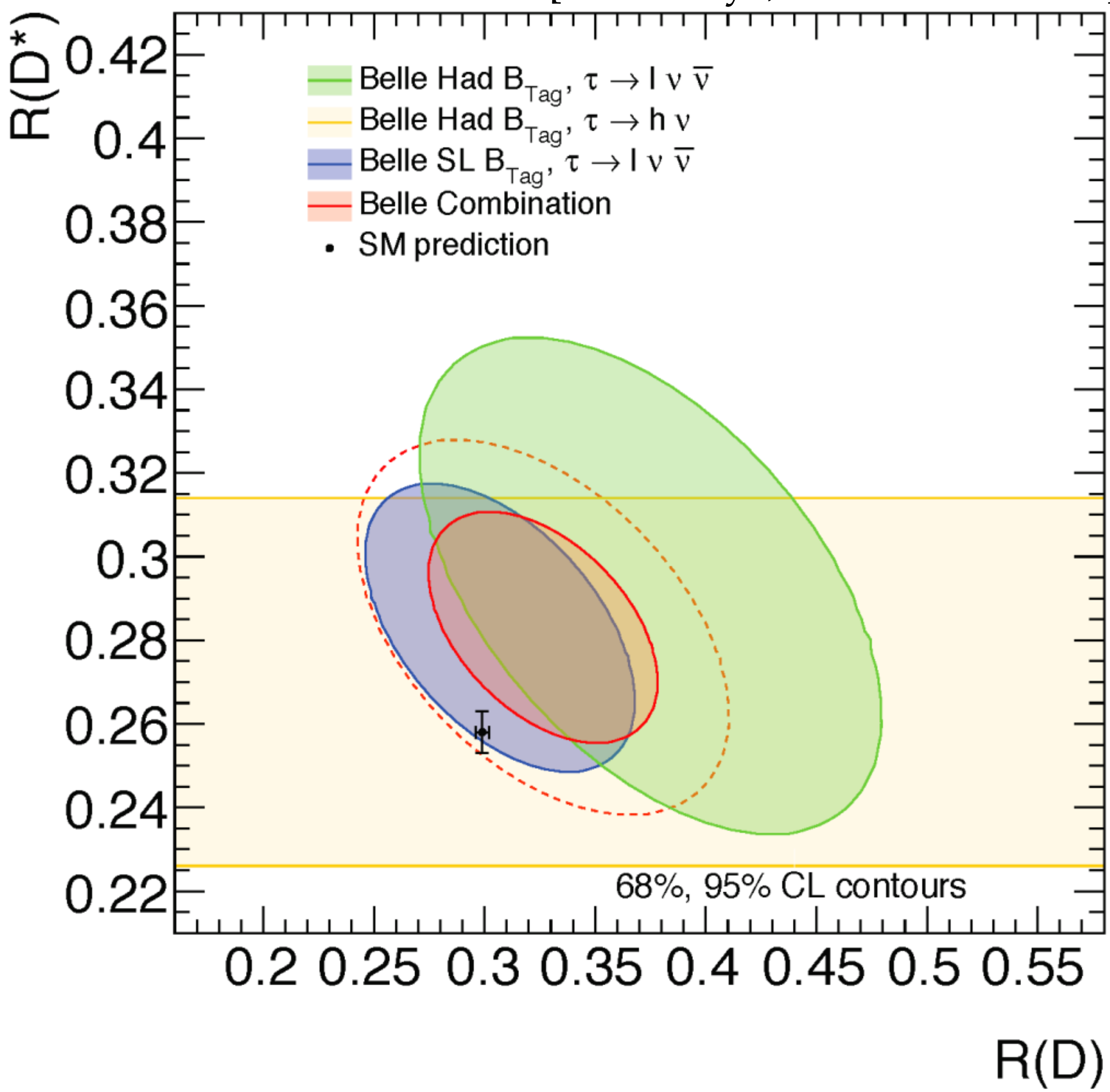
Channel	Component	Yield
$D^{+}\ell^{-}$	$B \to D\tau\nu$	307 ± 65
	$B \to D\ell\nu$	6800 ± 179
	$B^0 \to D^{*}\ell\nu$	6370 ± 225
	$B^0 \to D^{*}\tau\nu$	269 ± 24
	$B \to D^{**}\ell\nu$	413 ± 110
	Fake D	3072 ± 129 (Fixed)
	Other	506 ± 23 (Fixed)
$D^{0}\ell^{-}$	$B \to D\tau\nu$	1471 ± 193
	$B \to D\ell\nu$	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)

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

First R(D) measurement with Semileptonic tag

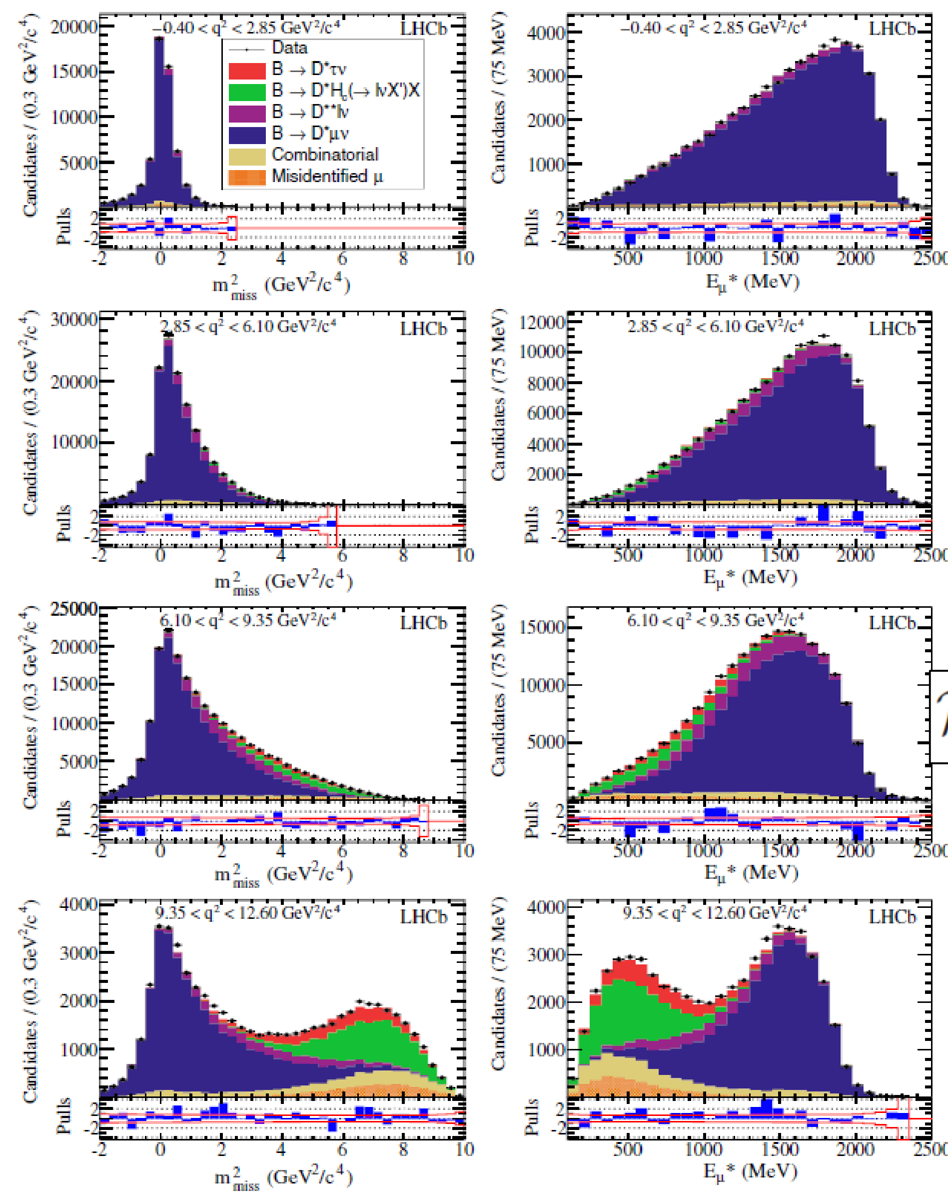
Belle R(D(*)) Results

[S. Sandilya, talk at FPCP2020]



Belle combined result at about 1.6 σ from SM

R(D*) with τ→μνν by LHCb



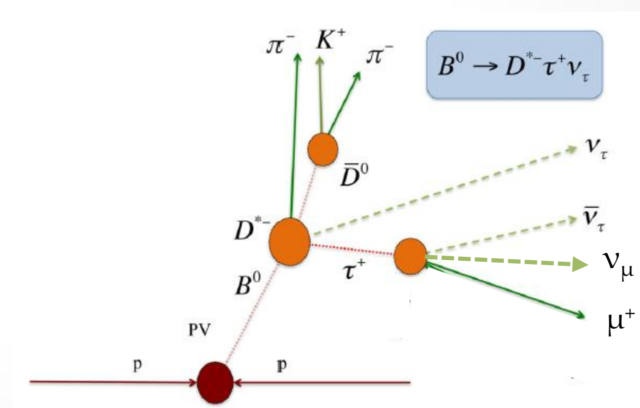
[PRL 115, 111803 (2015)]

- $3.0\ fb^{-1}$ Data
- $B^0 \to D^* \tau \nu$, $\tau \to \mu \nu \nu$
- 3D Fit to (Missing mass)^2, E_μ^*, q^2
- Primary and B vertices

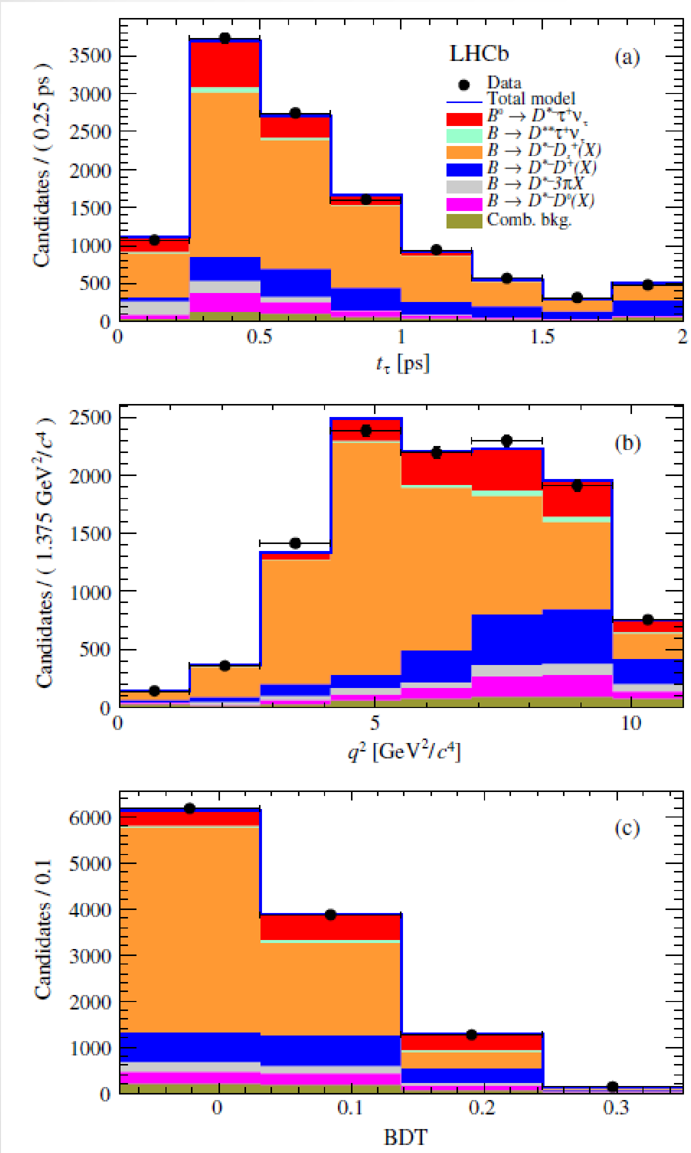
  → P_B direction
- $|P_B|$ is approximated by

  $(P_B)_z = m_B/m_{D^*\mu}\ (P_{D^*\mu})_z$

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



R(D*) with τ→3πν by LHCb

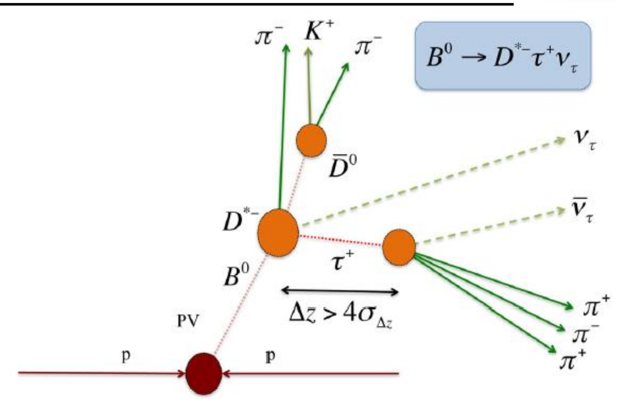


[PRD97, 072013 (2018)]

- 3.0 fb^{-1} Data
- Obtain Ratio

K(D*) = Br(B⁰→D*τν)/Br(B⁰→D*3π)

- **<u>Reconstruct Pτ Direction</u>**



- 3D fit to τ decay time, q^2, BDT output

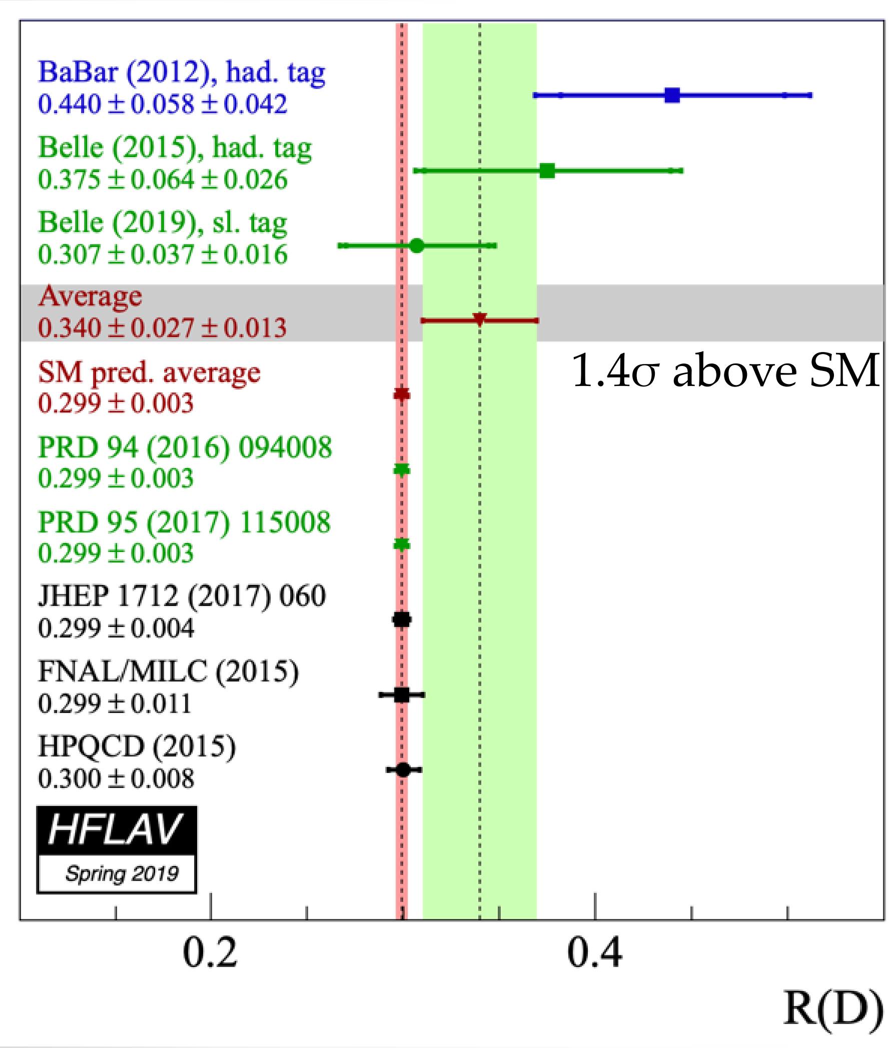
$$\mathcal{K}(D^{*-}) = 1.97 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})$$

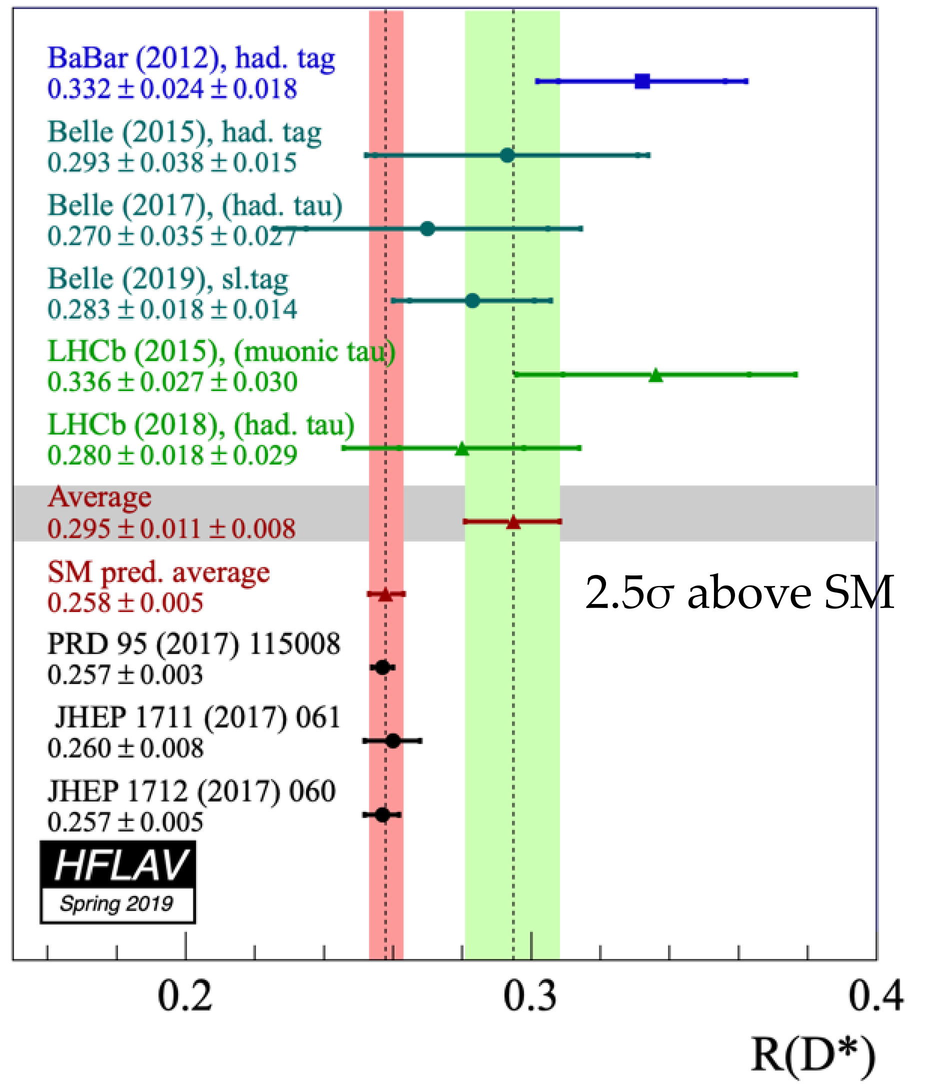
Multiply
Br(B→D*3π)/Br(B→D*lν)

R(D*) = 0.280 ± 0.018(stat) ± 0.029(syst)

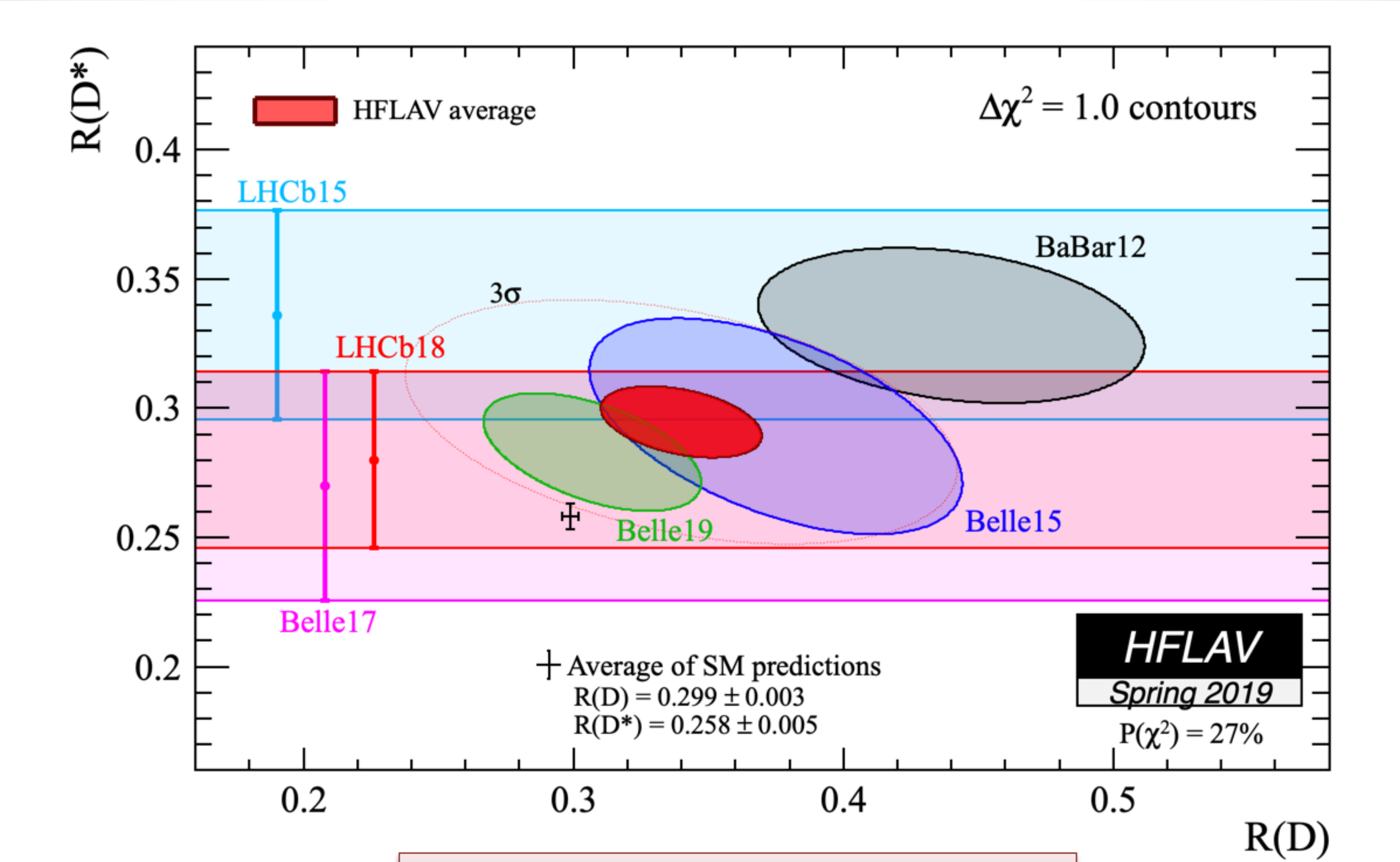
(Update of Br(B→D*lν) by HFLAV2019)

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





Latest R(D)-R(D*) vs SM



Deviation from SM is 3.1 σ

More measurements in Addition to R(D(*))

- Polarizations
- Other b→c hadrons

τ Polarization Measurement at Belle

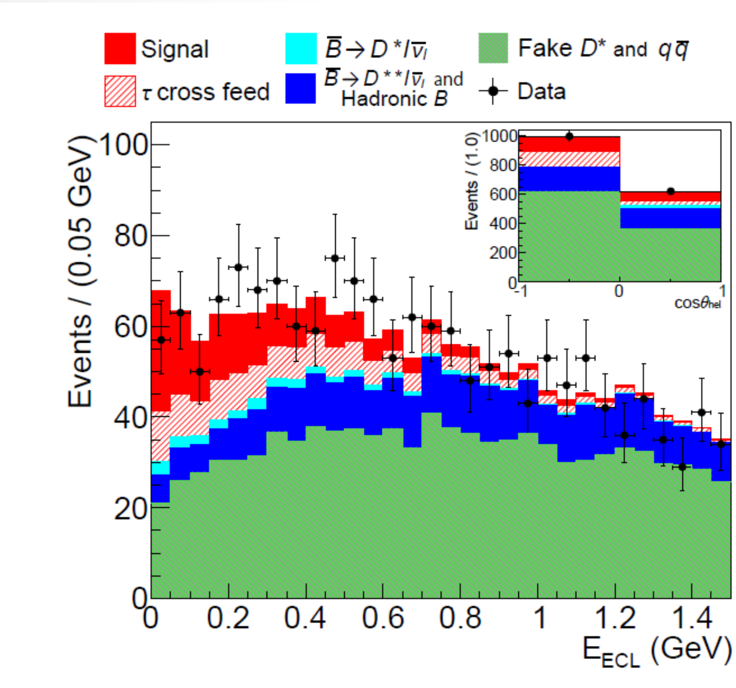
[PRL118, 211801 (2017) PRD97, 012004 (2018)]

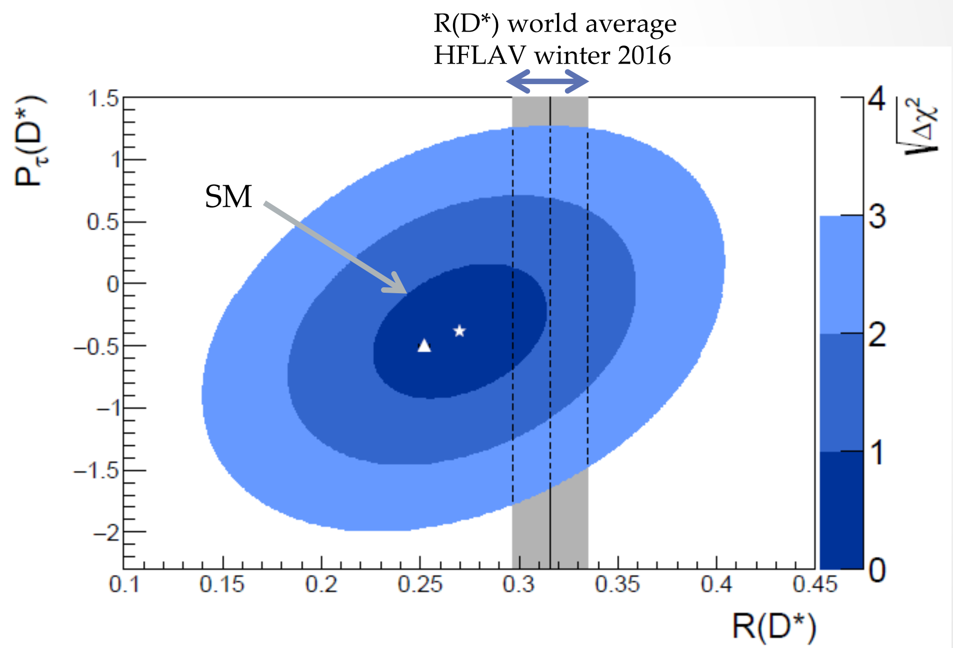
- Hadronic tag
- Two body tau decays : $\tau \rightarrow \pi\nu, \rho\nu$
  - Helicity angle sensitive to the tau polarization
- $P_\tau(D^*)_{SM} = -0.497 \pm 0.013$

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

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

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





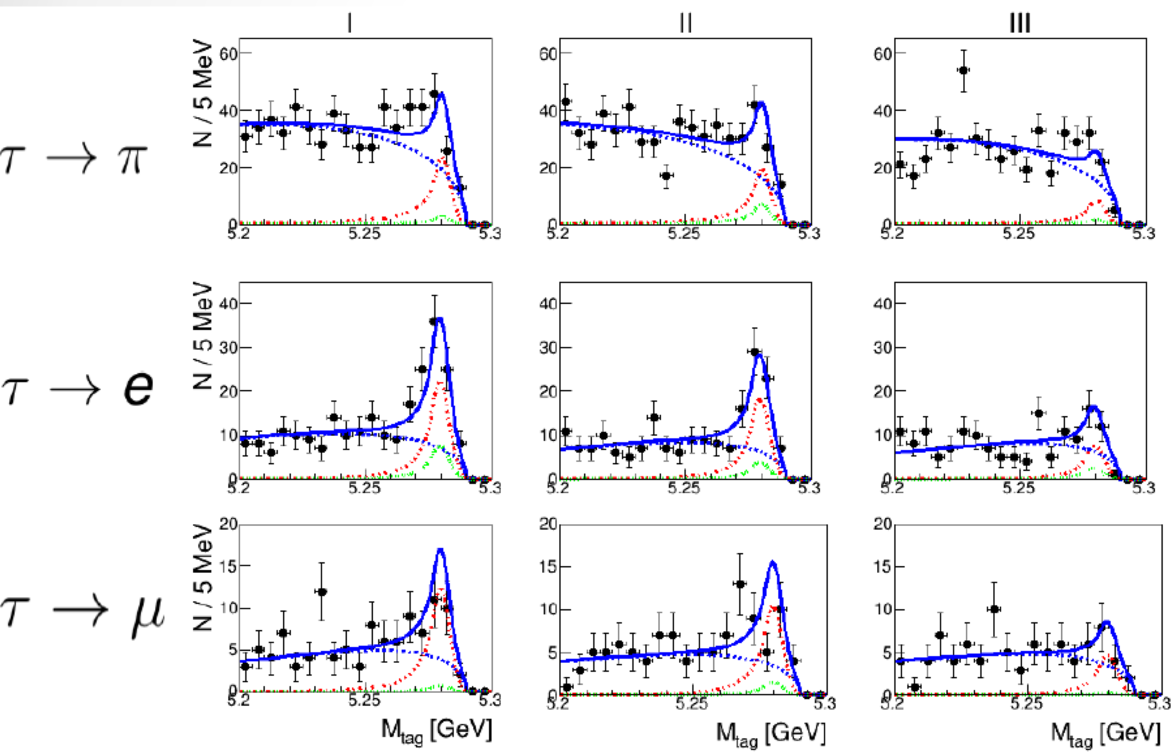
$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),$$

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

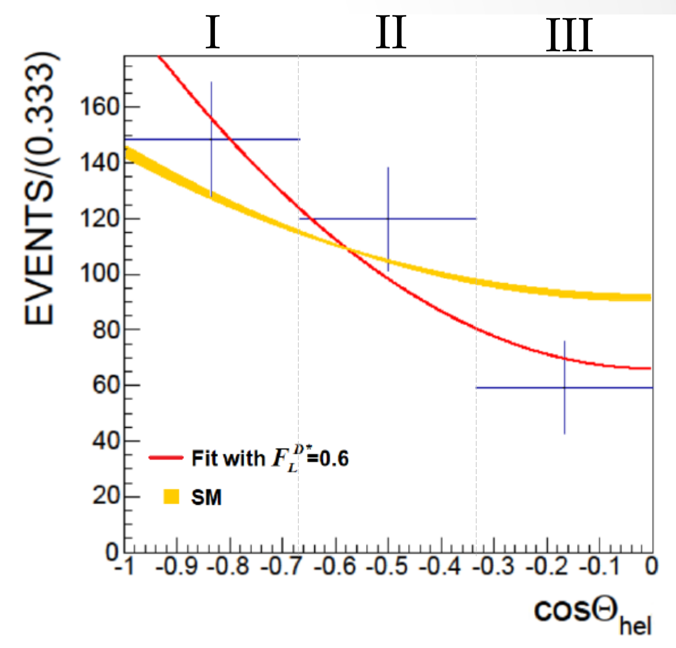
(R(D*) included in the HFLAV avg)

D* Polarization Measurement at Belle

- 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



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



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

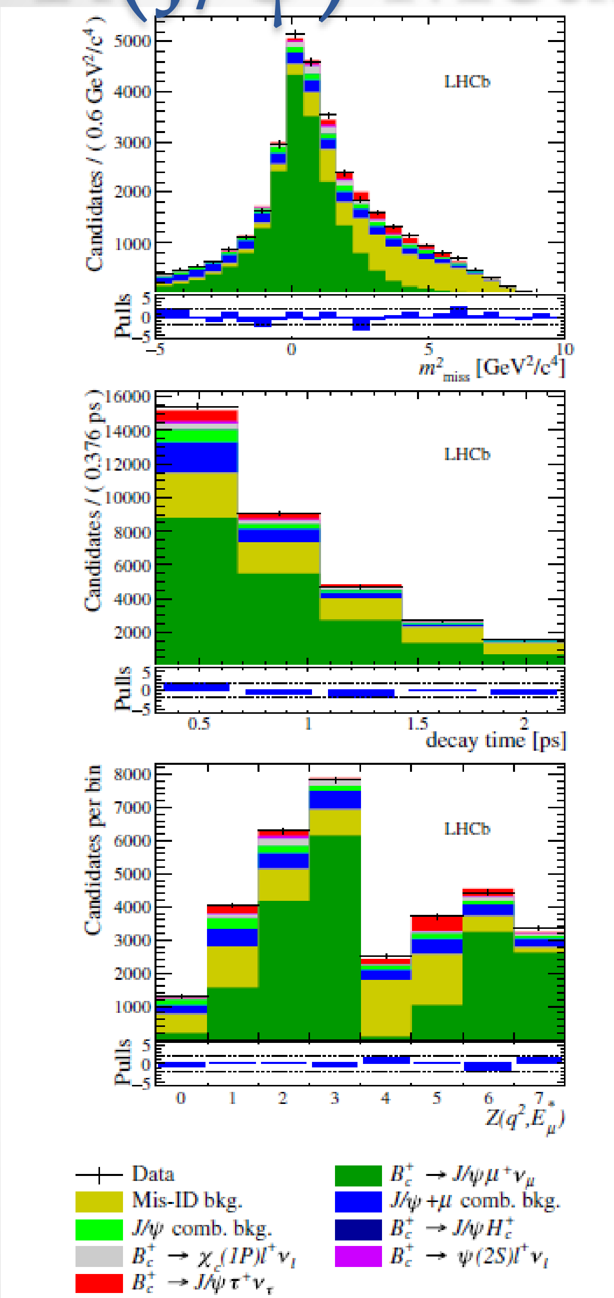
cf. in SM

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

preliminary
[arXiv:1903.03102]

within 2 σ of SM

R(J/ψ) Measurement at LHCb



[PRL120, 121801(2018)]

- 3.0 fb^{-1} Data
- Measure

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

- Same method as muonic R(D*) to estimate P_{Bc}
- 3D fit to (missing mass)^2, B_c decay time, category index Z for (q^2, E_{μ^*})bins

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

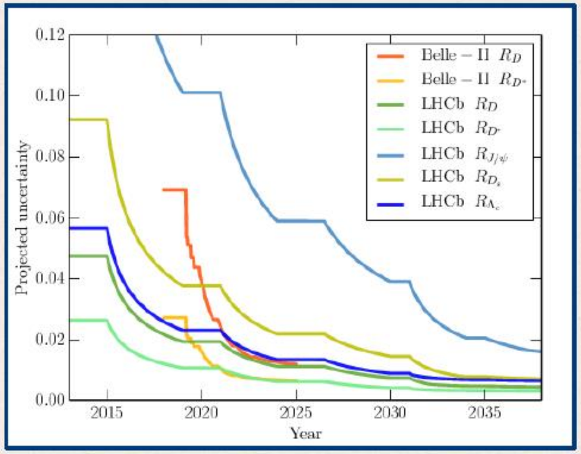
$$= 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst}).$$

2σ from SM expectation 0.25-0.28

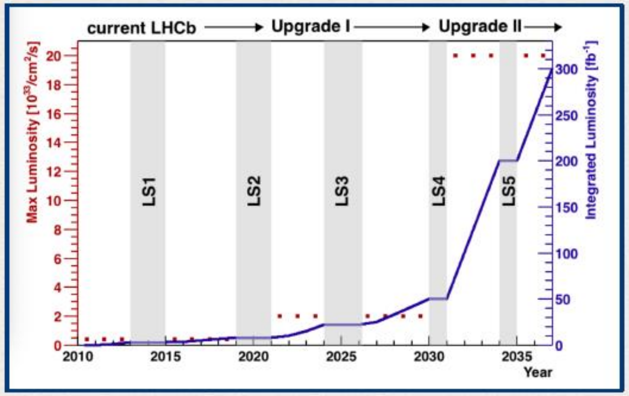
LHCb Future Prospect

[Beatriz Garcia Plana, talk at ICHEP2020]

Future prospects



[arXiv:1809.06229]



[arXiv:1808.08865]

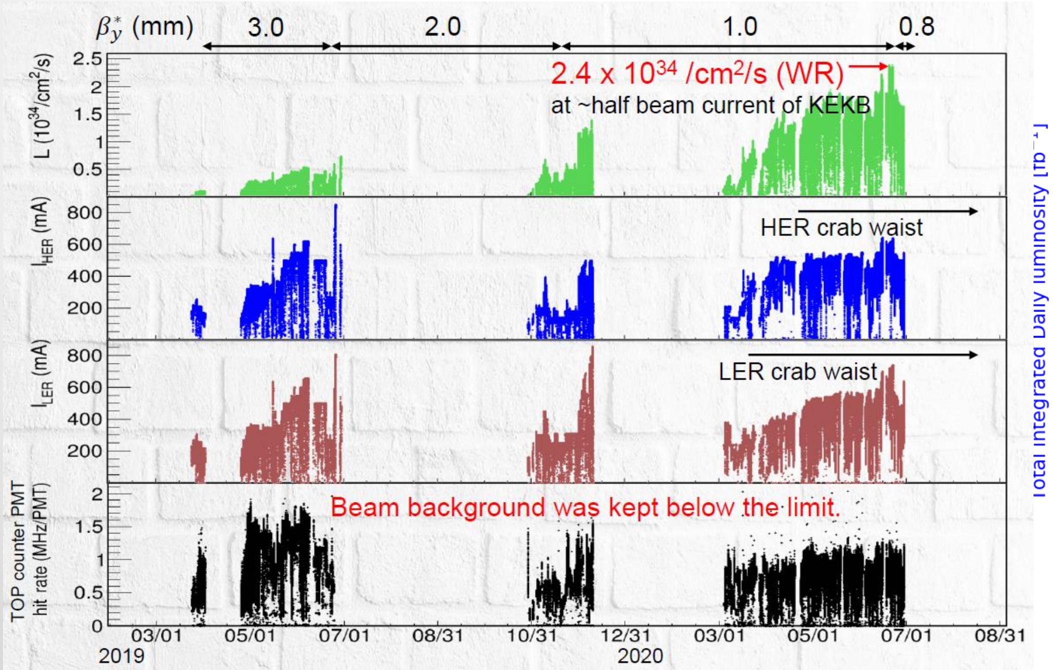
- ❖ **New results** are expected from:
  - Run 2 updates with a total uncertainty reduction
  - Ongoing analyses:
    - R(D^0): $B^+ \to D^0\tau\nu$
    - R(D^+): $\bar{B}^0 \to D^+\tau\nu$
    - $\mathrm{R}\left(D_s^{(*)}\right)$: $B_s \to D_s^{(*)}\tau\nu$
    - R(D^{**}): $B^+ \to D^{**}(2420)^0\tau\nu$
    - $\mathrm{R}\left(\Lambda_c{}^{(*)}\right)$: $\Lambda_b \to \Lambda_c{}^{(*)}\tau\nu$
    - R(J/ψ): $B_c^+ \to J/\psi\,\tau\nu$
    - R(p): $\Lambda_b \to p\tau\nu$
    - Combined measurement of R(D) and R(D^*)
  - Form factor measurements
    - $\Lambda_b \to \Lambda_c\, l\nu$
    - $\Lambda_b \to \Lambda_c{}^* l\nu$
    - $B_s \to D_s{}^{(*)} l\nu$ [arXiv:2003.08453]
  - Angular analyses
- ❖ In the **Upgrade I**, LHCb will collect ~50fb⁻¹ (luminosity ×5)

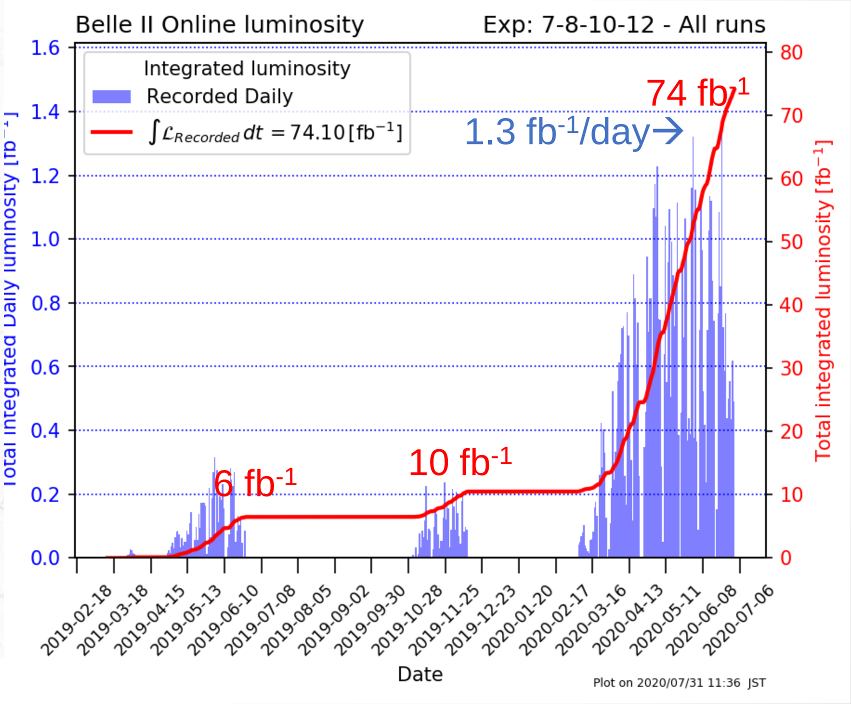
Beatriz García Plana (IGFAE-USC) ICHEP 2020 11

Belle II Accumulating Physics Data

- Belle II / SuperKEKB started physics data taking with full detectors in 2019
- Peak luminosity 2.4 x 10^{34} /cm^2/s (WR) exceeded KEKB
  - About half beam currents of KEKB, with β_y* squeezed to 1.0 mm (β_y*=0.3mm is the final target)
  - good achievement as a start up

More details in Gagan's talk

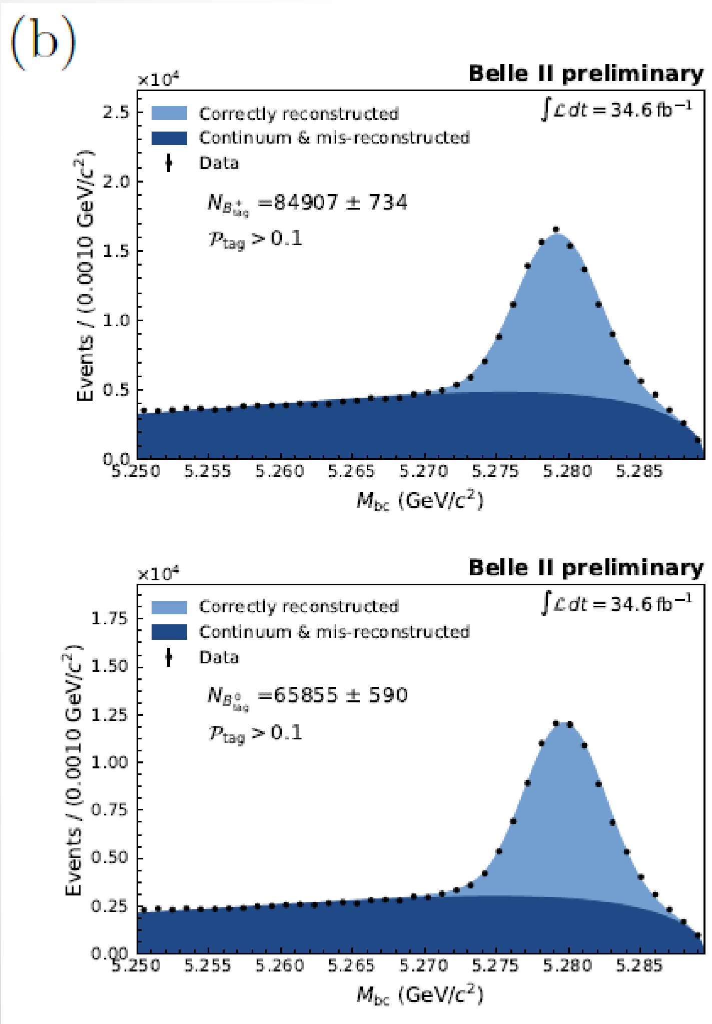




Hadronic Tag in Early BelleII Data

- Belle II analysis software works very well.
- Hadronic tag (Full Event Interpretation) performance calibrated with data

[BELLE2-CONF-PH-2020-005, arXiv: 2008.06096]

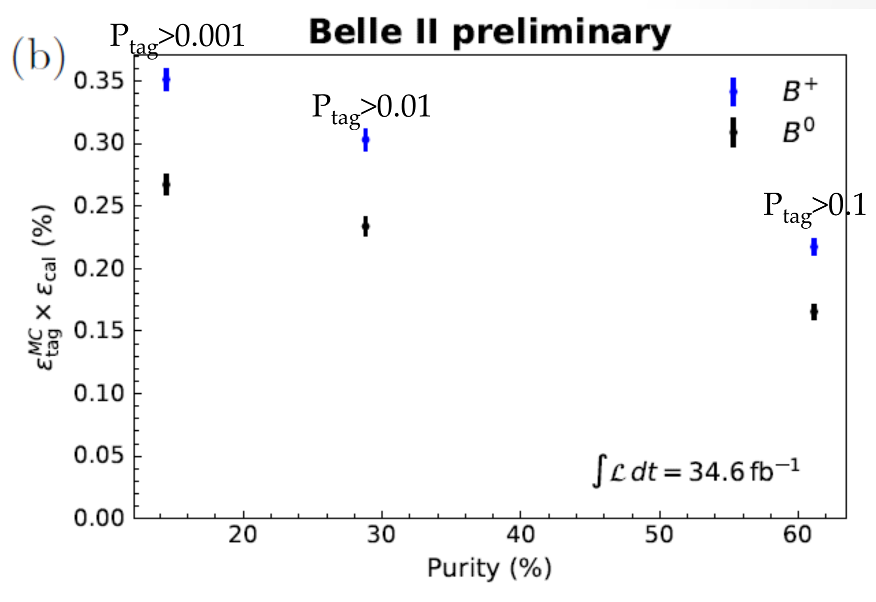


Reconstructed variables:

Mbc = $\sqrt{(E_{beam}^2 - p_B^2)}$

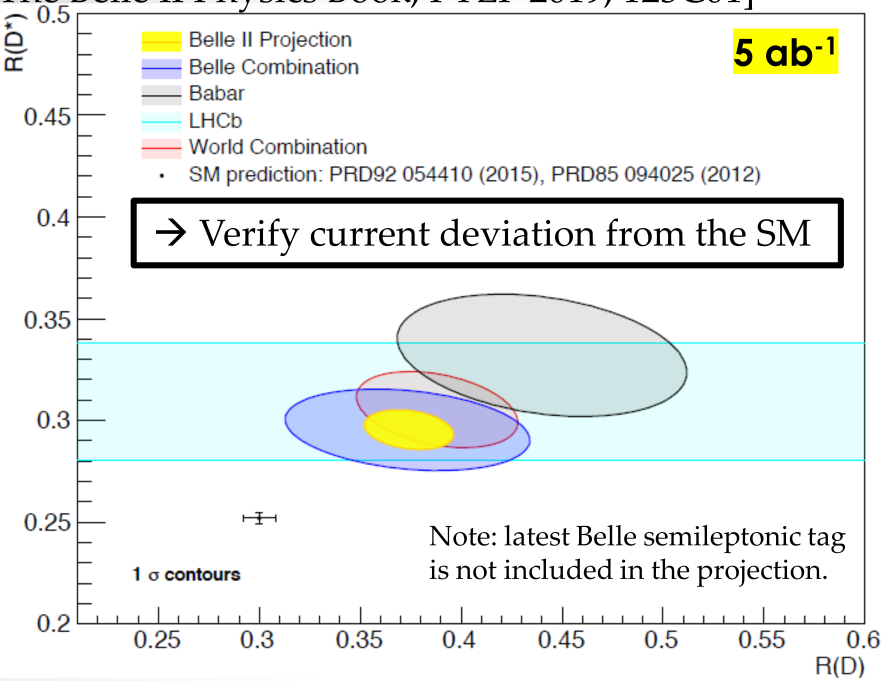
P_{tag} : classifier of purity

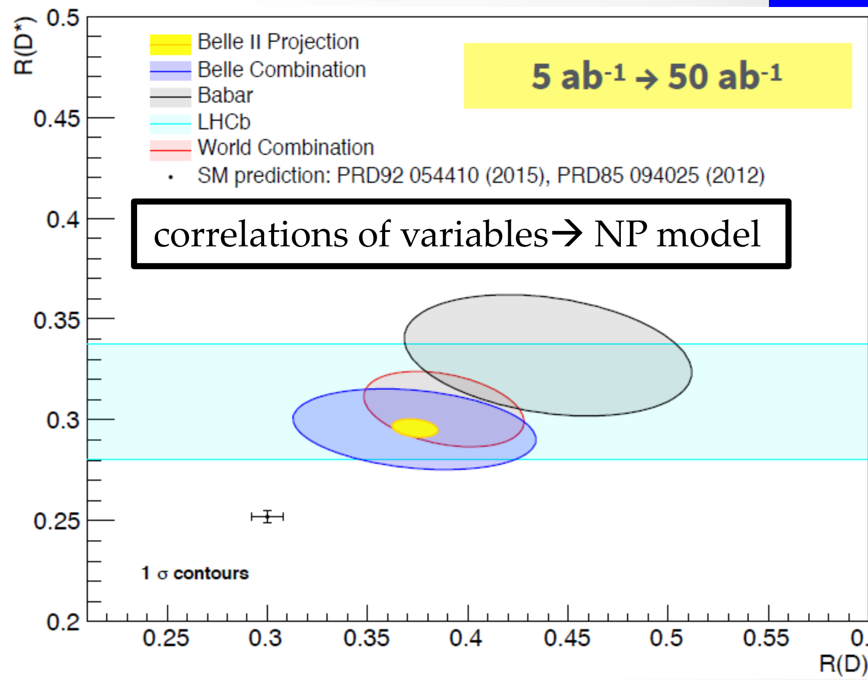
Purity dependent efficiency is calibrated



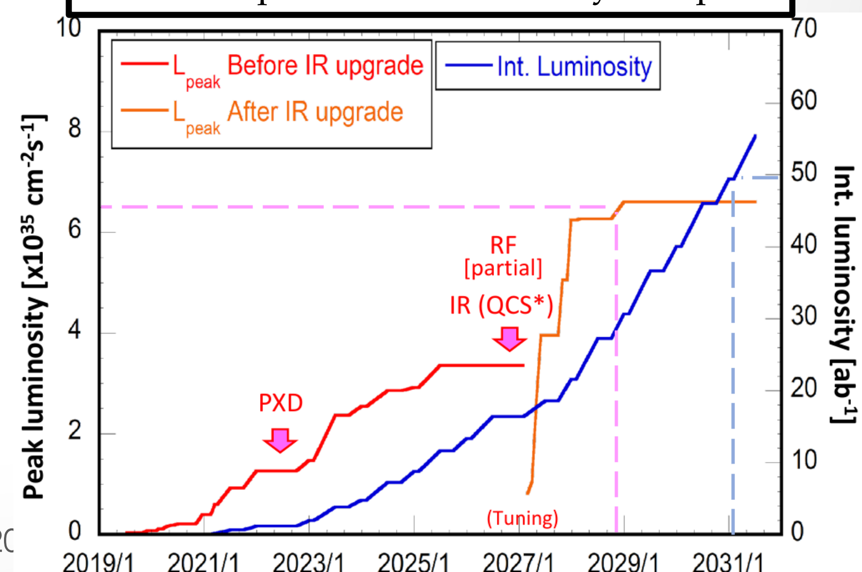
R(D(*)) Belle II Prospect

[The Belle II Physics Book, PTEP 2019, 123C01]





Belle II/SuperKEKB Luminosity Prospect



Expected Precision at Belle II for R(D(*)), τ polarization

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

Summary

- $B \rightarrow D^{(*)}\tau\nu$ decays are good probes for New Physics
- Belle, BaBar, LHCb have measured R(D(*)) with various methods and sub-decay modes
  - In addition to R(D(*)), other variables have been also measured
    - τ, D* Polarizations
    - R(J/ψ)
- 'Anomaly' exists between measurements and SM
  - Little bit reduced but still there is 3.1 σ difference
- LHCb and Belle II will provide more interesting results in future
  - Verify or reject the current 'anomaly'
  - Determine the new physics model, if exists

Belle Systematic Errors

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%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

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		${}^{+0.039}_{-0.037}$