

Measurement of $R(D)$ and $R(D^*)$ with a semileptonic tag at Belle

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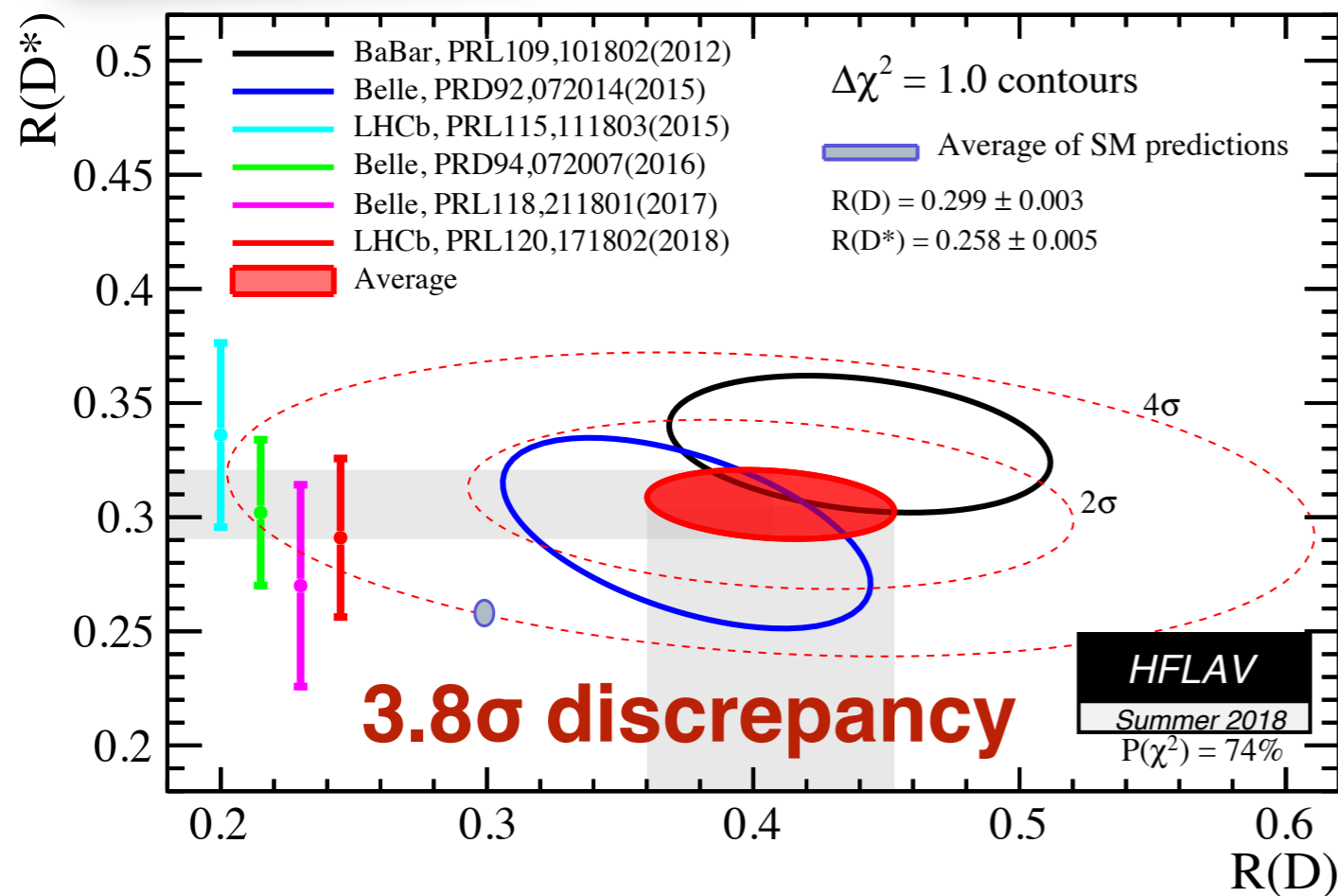
on behalf of the Belle collaboration

54th Rencontres de Moriond, EW

22/03/2019



The R(D) and R(D*) puzzles



$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \rightarrow D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^+ \ell^- \bar{\nu}_\ell)}$$

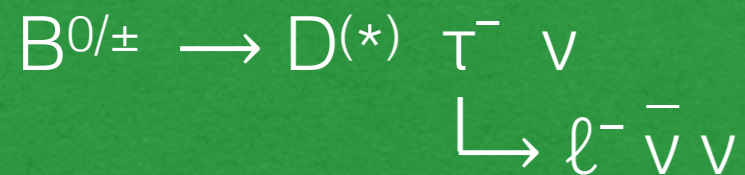
$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{*+} \ell^- \bar{\nu}_\ell)}$$

where $\ell = e, \mu$

Experiment	Tag method	τ mode	R(D)	R(D*)
Babar '12	Hadronic	$\ell \nu \nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle '15	Hadronic	$\ell \nu \nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
LHCb '15	-	$\ell \nu \nu$	-	$0.336 \pm 0.027 \pm 0.030$
Belle '16	Semileptonic	$\ell \nu \nu$	-	$0.302 \pm 0.030 \pm 0.011$
Belle '17	Hadronic	$\pi \nu, \rho \nu$	-	$0.270 \pm 0.035 \pm 0.027$
LHCb '18	-	$\pi \pi \pi$	-	$0.291 \pm 0.019 \pm 0.029$
Average	-	-	$0.407 \pm 0.039 \pm 0.024$	$0.306 \pm 0.013 \pm 0.007$
SM			0.299 ± 0.003	0.258 ± 0.005

This measurement

B-signal



signal mode



normalization mode

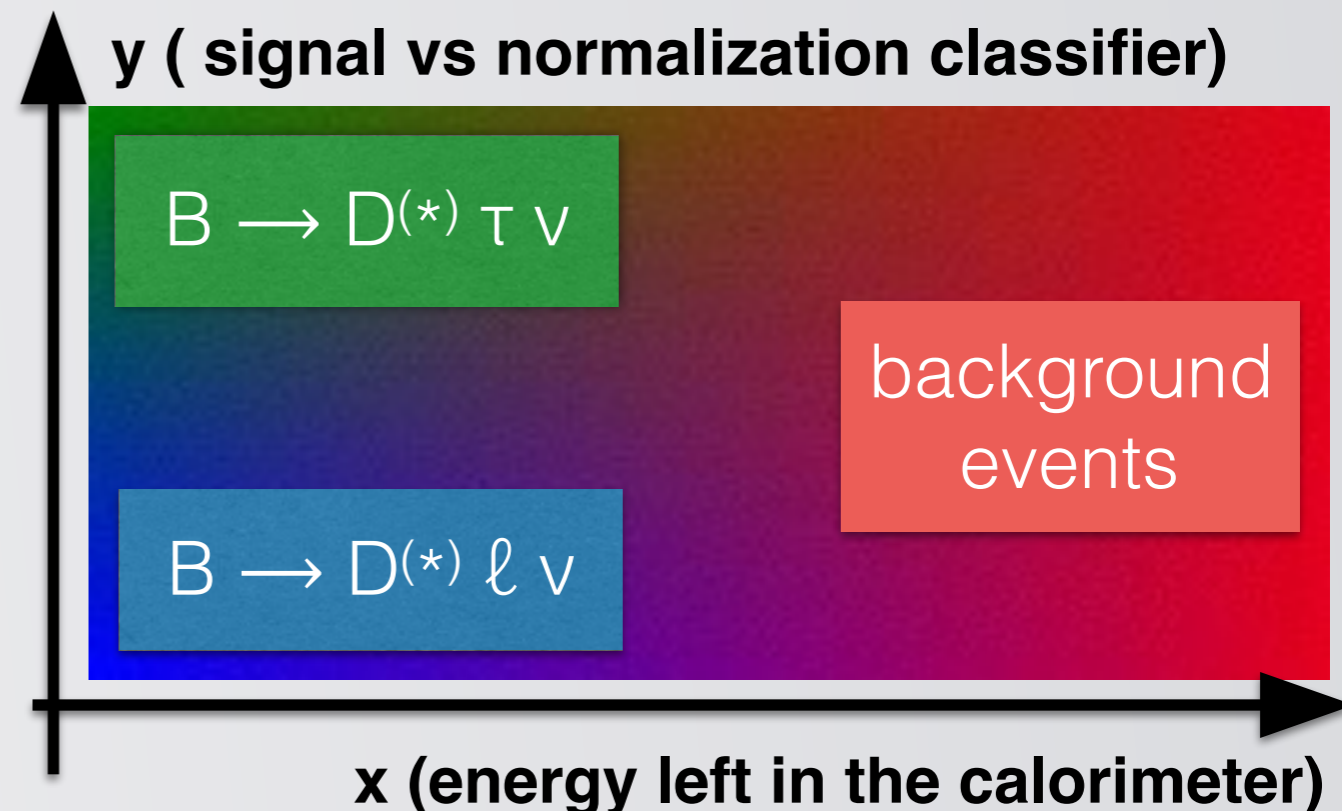
Y(4S)

B-tag

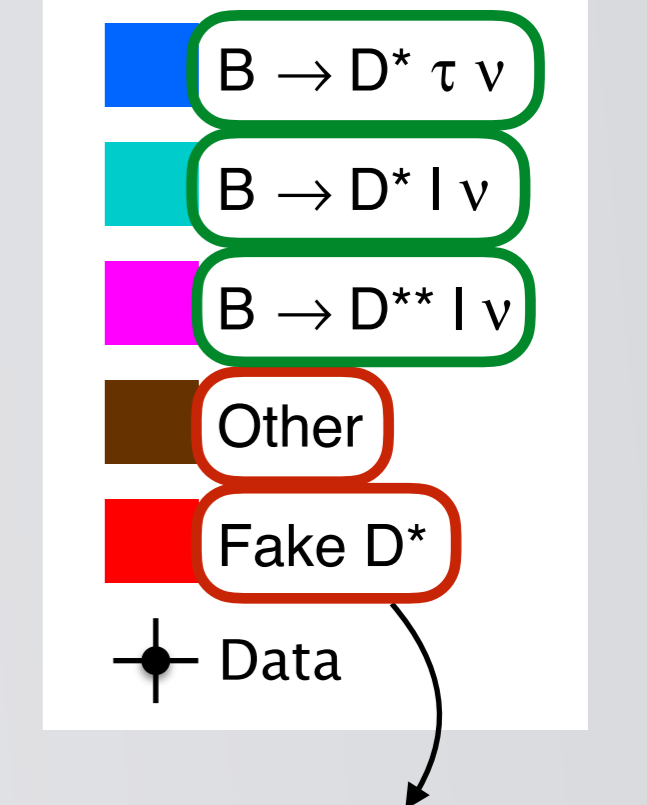
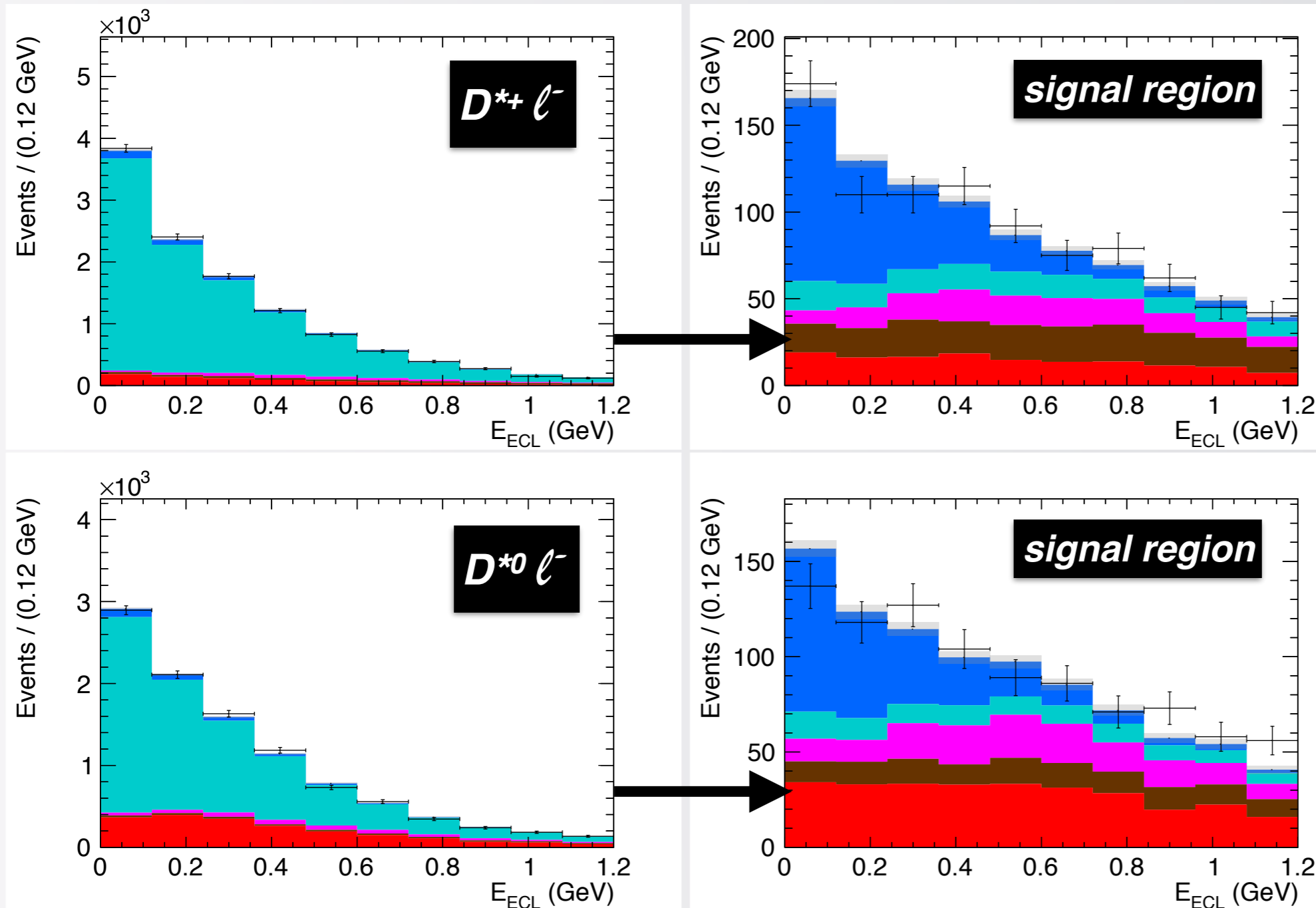


use BDT hierarchical algorithm

- Measure **R(D)** and **R(D*)** and their statistical and systematic correlations simultaneously
- Three main components can be identified for the reconstructed events. We use **a 2D fit** as signal extraction method



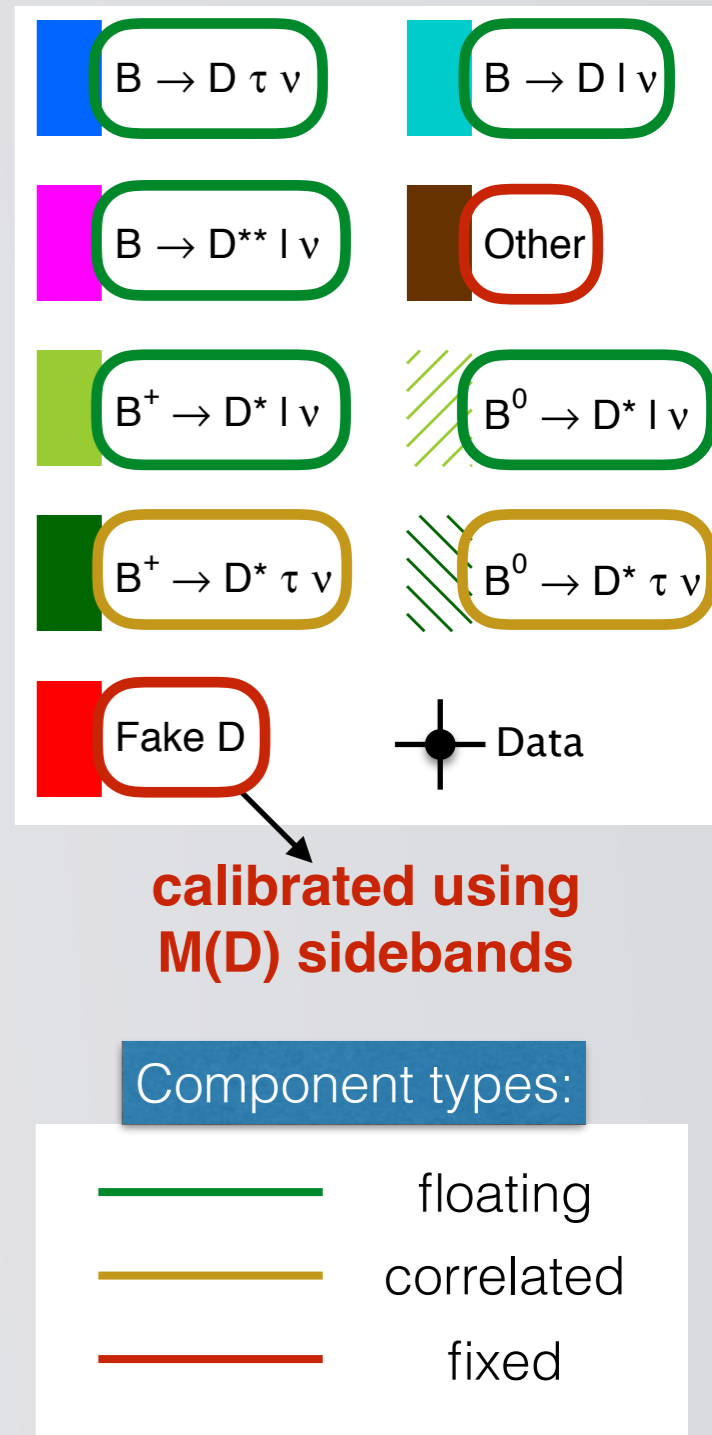
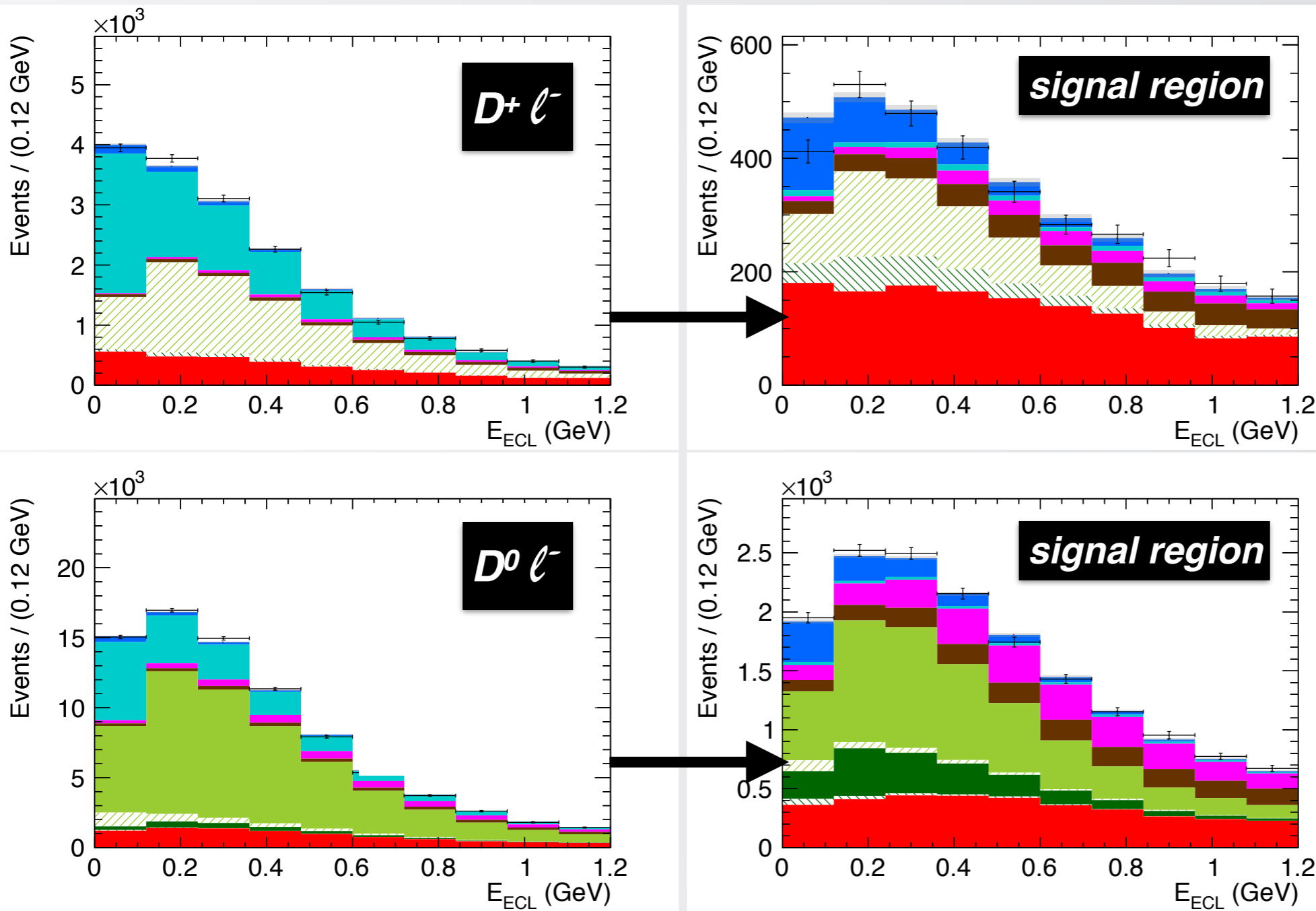
Preliminary fit results, $D^* \ell$ samples



Component types:



Preliminary fit results, D ℓ samples



Preliminary systematic uncertainties

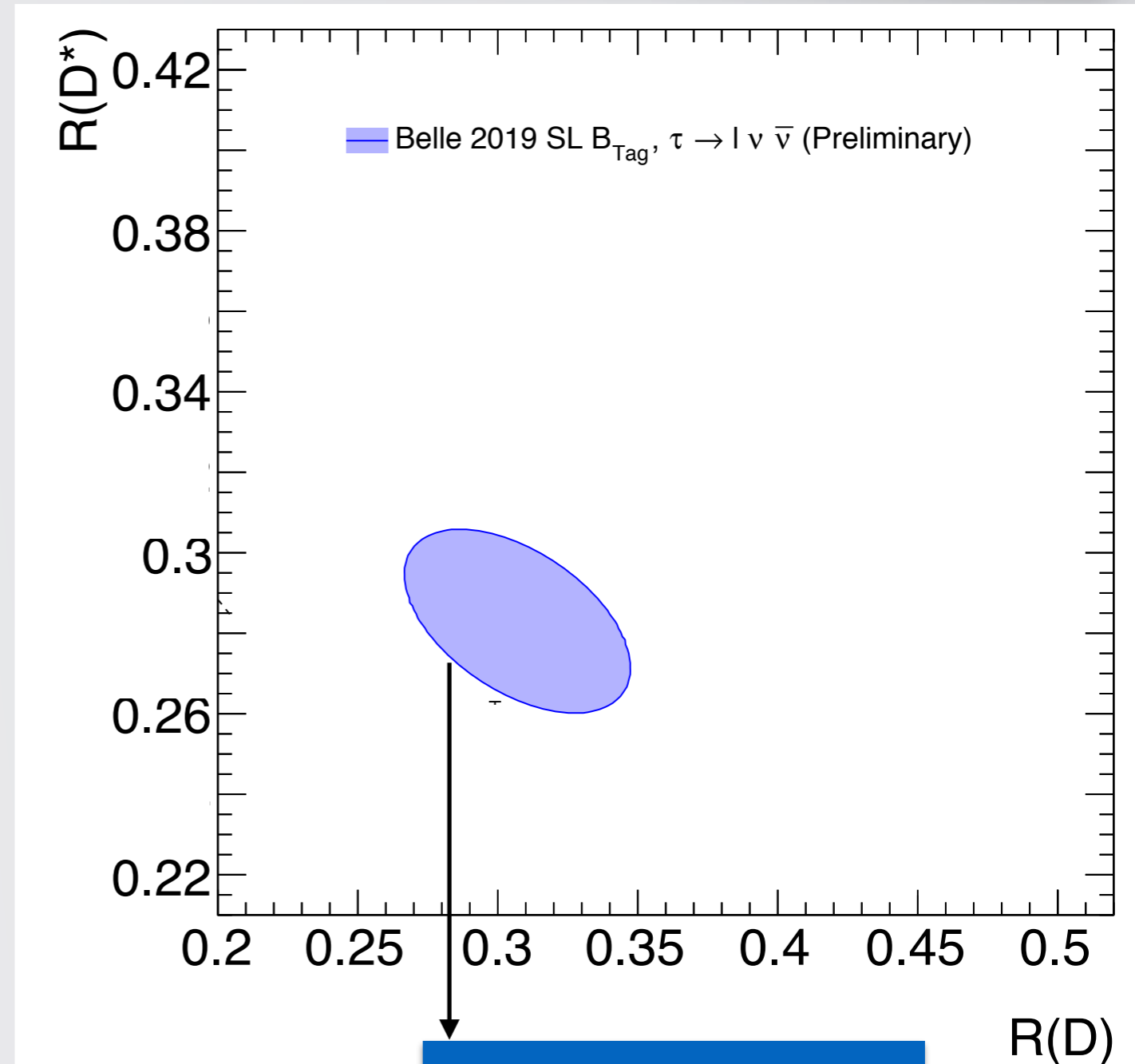
Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
D^{**} Composition	0.62	1.26
Fake $D^{(*)}$ Calibration	0.18	0.10
B_{tag} Calibration	0.06	0.04
Feed-down Factors	1.52	0.37
Efficiency Factors	1.73	3.60
Lepton Efficiency and Fake Rate	0.33	0.28
Slow π Efficiency	0.07	0.07
PDFs Statistics	3.94	1.92
B Decay Form Factors	0.50	0.24
Luminosity	0.09	0.04
$\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)$	0.05	0.02
$\mathcal{B}(D)$	0.31	0.12
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau)$	0.13	0.12
Sum	4.66	4.32

PDF	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
Signal	1.98	1.16
Normalization	0.96	0.63
$\bar{B} \rightarrow D^{**} \ell^- \bar{\nu}_\ell$	0.79	0.59
Other	0.93	0.65
Fake $D^{(*)}$ -mesons	1.83	0.82
Mixed Feed-down, ℓ	1.64	0.29
Charged Feed-down, ℓ	1.45	0.56
Mixed Feed-down, τ	0.68	0.20
Charged Feed-down, τ	0.78	0.28
Sum	3.94	1.92

- Results are still statistically dominated

Conclusion / Preliminary $R(D^{(*)})$ averages

- **Most precise measurement** of $R(D)$ and $R(D^*)$ to date
- First **$R(D)$** measurement performed with a **semileptonic tag**

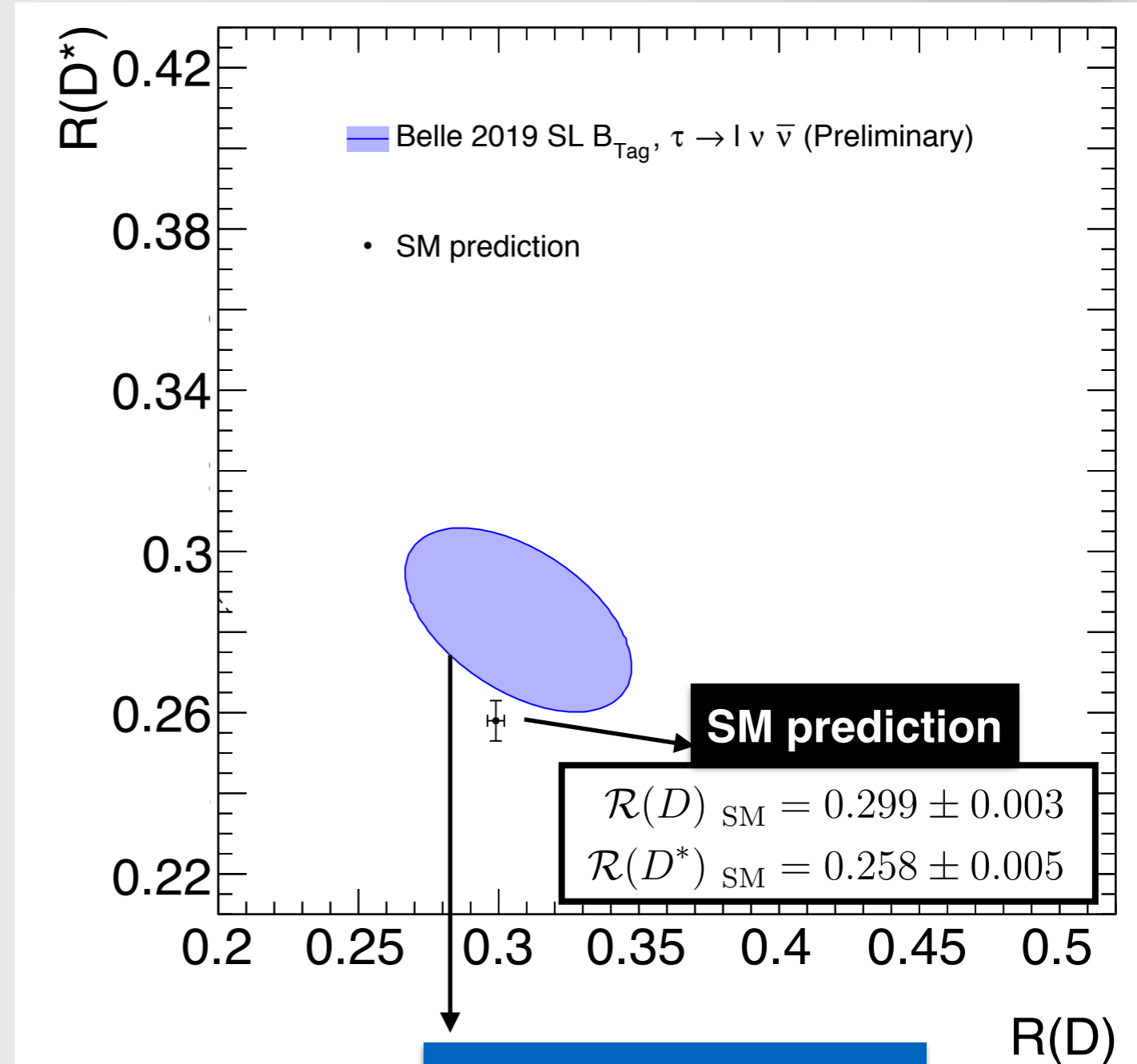


This result

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

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- Results **compatible with SM** expectation within **1.2σ**

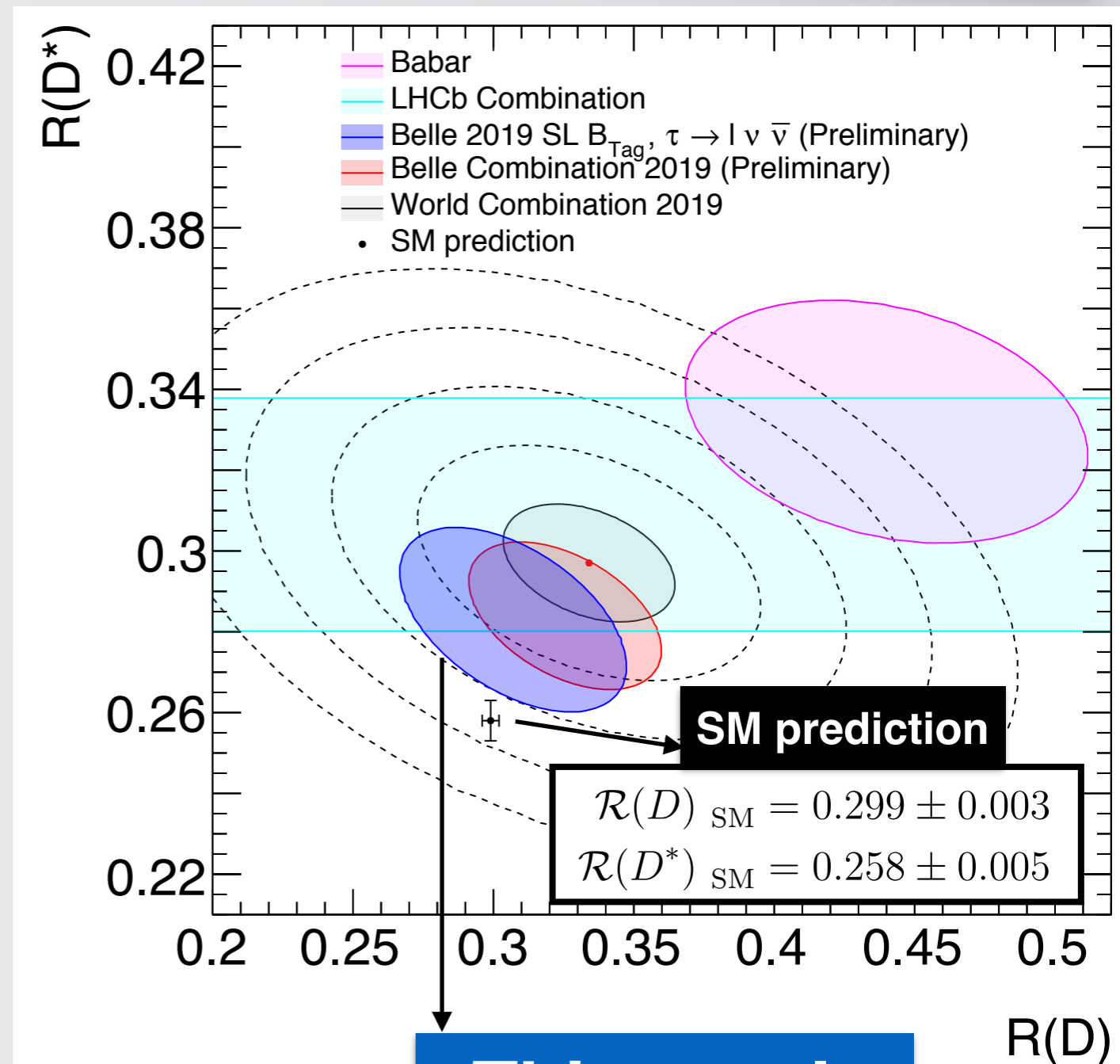


This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
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Conclusion / Preliminary $R(D^{(*)})$ averages

- **Most precise measurement** of $R(D)$ and $R(D^*)$ to date
- First **$R(D)$** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **$R(D) - R(D^*)$ Belle average** is now within **2σ** of the SM prediction
- **$R(D) - R(D^*)$ exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



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



**Thanks for
your
attention !**

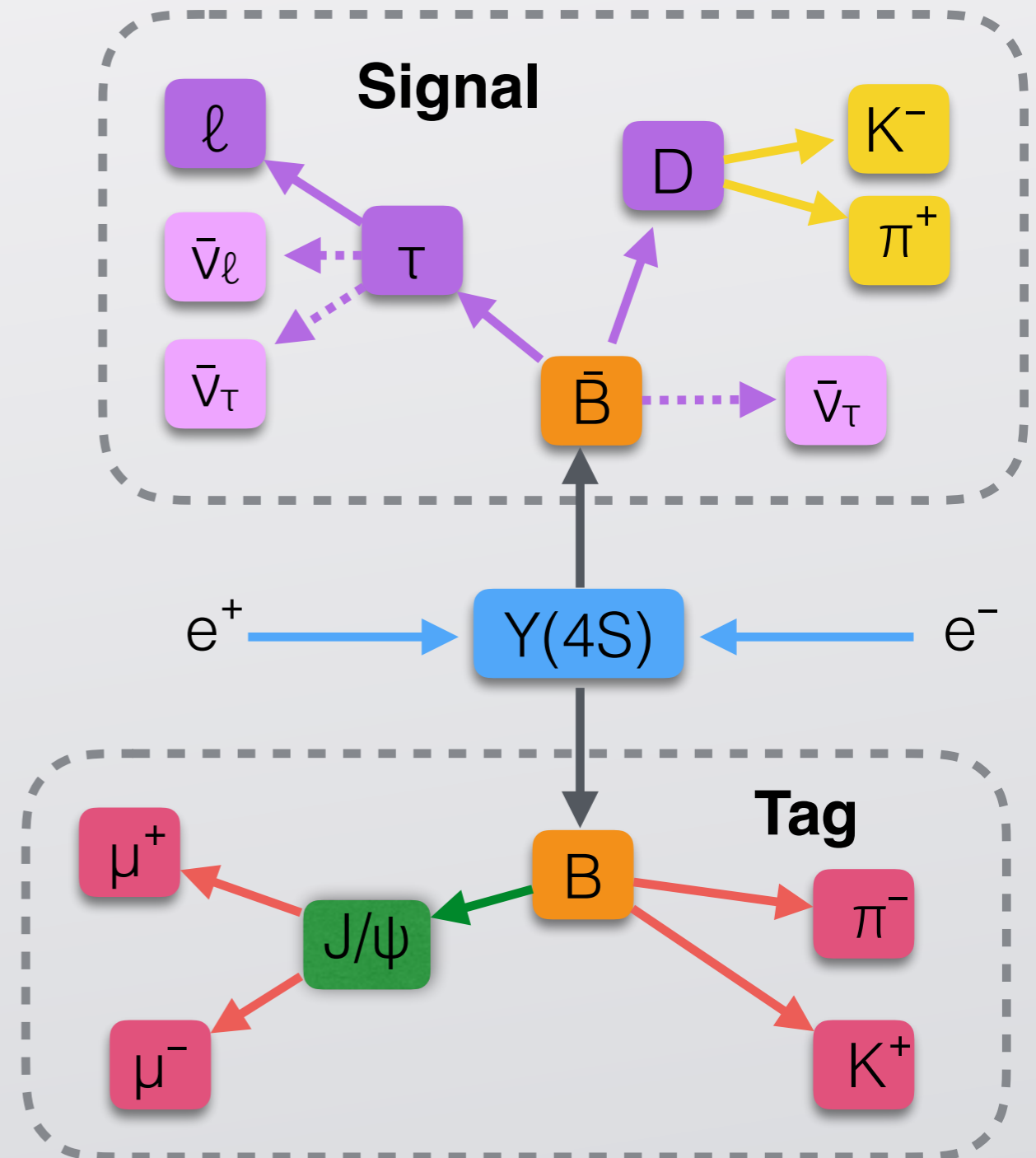
Back-up slides

Comparison to previous Belle semileptonic $R(D^*)$ result

	Phys. Rev. D94, 072007 (2016)	This analysis
Observables	$R(D^*)$	$R(D), R(D^*)$
B signal flavours	B^0	B^0, B^+
B tag channels	$D^{*-} \ell^+ \nu$	$D^- \ell^+ \nu, D^{*-} \ell^+ \nu,$
Tag reconstruction method	Same as normalization	Fast BDT
Tag selection	$\cos\theta_{B-D(*)\ell}$	$\cos\theta_{B-D(*)\ell},$ Fast BDT output

Tagging in Belle

- $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$: very clean and well-known initial state
- Reconstruct one of the B mesons in the $Y(4S)$ event (**B tag**) to gather information about the B decay of interest
- **Hadronic B decays:**
PRO: full B reconstruction, high purity
CON: low efficiency
~5000 channels
- **Semileptonic B decays:**
PRO: high efficiency
CON: one missing neutrino, low purity
~100 channels



Event selection and D(*) channels

K^\pm	Particle ID	KID > 0.1
e^\pm	Particle ID	eID > 0.3
	Kinematics	$p_{\text{lab}} > 0.200 \text{ GeV}/c$
μ^\pm	Particle ID	muID > 0.5
all charged	Track parameter	$\Delta r < 2.0 \text{ cm}$
	Track parameter	$ \Delta z < 5.0 \text{ cm}$
π^0	Invariant mass	$0.120 < M(\text{GeV}/c^2) < 0.150$
	E_γ	> 50/100/150 MeV (barrel/fwd/back)
	$\cos\theta_{\gamma\gamma}$	> 0
	Kinematics	$p_{\text{lab}} > 0.200 \text{ GeV}/c$
π_{slow}^0	Invariant mass	$ M_{\gamma\gamma} - M_{\pi^0}^{\text{PDG}} < 0.010 \text{ GeV}/c^2$
	E_γ , high	> 50 MeV
	E_γ , low	> 20 MeV
K_S^0	Invariant mass	$0.483 < M(\text{GeV}/c^2) < 0.513$
	K_S^0 Optimizer	$nb_{\text{vlike}} > 0.5$ and $nb_{\text{nolam}} > -0.4$
D^+	with π^0	Invariant Mass $-36 \text{ MeV}/c^2 < M_D^{\text{reco}} - M_D^{\text{PDG}} < 24 \text{ MeV}/c^2$
D^+	without π^0	Invariant Mass $-15 \text{ MeV}/c^2 < M_D^{\text{reco}} - M_D^{\text{PDG}} < 15 \text{ MeV}/c^2$
	Vertex fit	pValue > 0 (successful fit)
D^0	with π^0	Invariant Mass $-45 \text{ MeV}/c^2 < M_D^{\text{reco}} - M_D^{\text{PDG}} < 30 \text{ MeV}/c^2$
D^0	without π^0	Invariant Mass $-15 \text{ MeV}/c^2 < M_D^{\text{reco}} - M_D^{\text{PDG}} < 15 \text{ MeV}/c^2$
	Vertex fit	pValue > 0 (successful fit)
D^{*0}	$D^0 \pi^0$	$ M_{D^{*0}}^{\text{reco}} - M_{D^{*0}}^{\text{PDG}} < 2.0 \text{ MeV}/c^2$
D^{*+}	$D^0 \pi^+$	$ M_{D^{*+}}^{\text{reco}} - M_{D^{*+}}^{\text{PDG}} < 2.5 \text{ MeV}/c^2$
	$D^+ \pi^0$	$ M_{D^{*+}}^{\text{reco}} - M_{D^{*+}}^{\text{PDG}} < 2.0 \text{ MeV}/c^2$

D^0 channels	D^+ channels
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$K^- \pi^+ \pi^0$	$K^- \pi^+ \pi^+$
$K^- \pi^+ \pi^+ \pi^-$	$K_S^0 \pi^+ \pi^0$
$K^- \pi^+$	$K_S^0 \pi^+ \pi^+ \pi^-$
$K_S^0 \pi^+ \pi^-$	$K_S^0 \pi^+$
$K_S^0 \pi^0$	$K^- K^+ \pi^+$
$K^- K^+$	$K_S^0 K^+$
$\pi^- \pi^+$	
$K_S^0 K^+ K^-$	

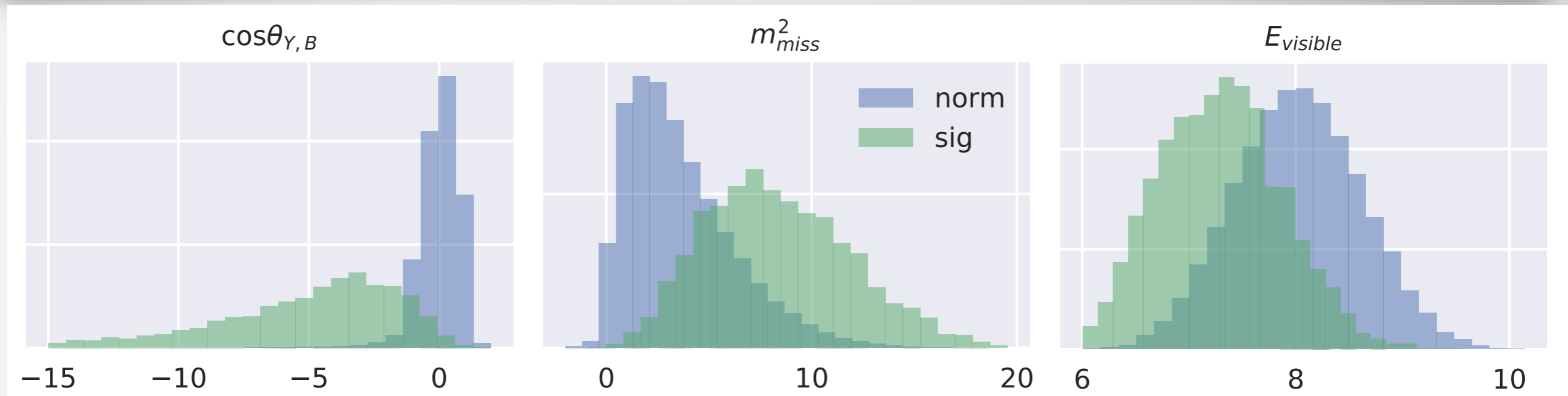
~ 30% of total

~ 22% of total

D* channels

$D^{*+} \rightarrow D^0 \pi^+$
 $D^{*+} \rightarrow D^+ \pi^0$
 $D^{*0} \rightarrow D^0 \pi^0$

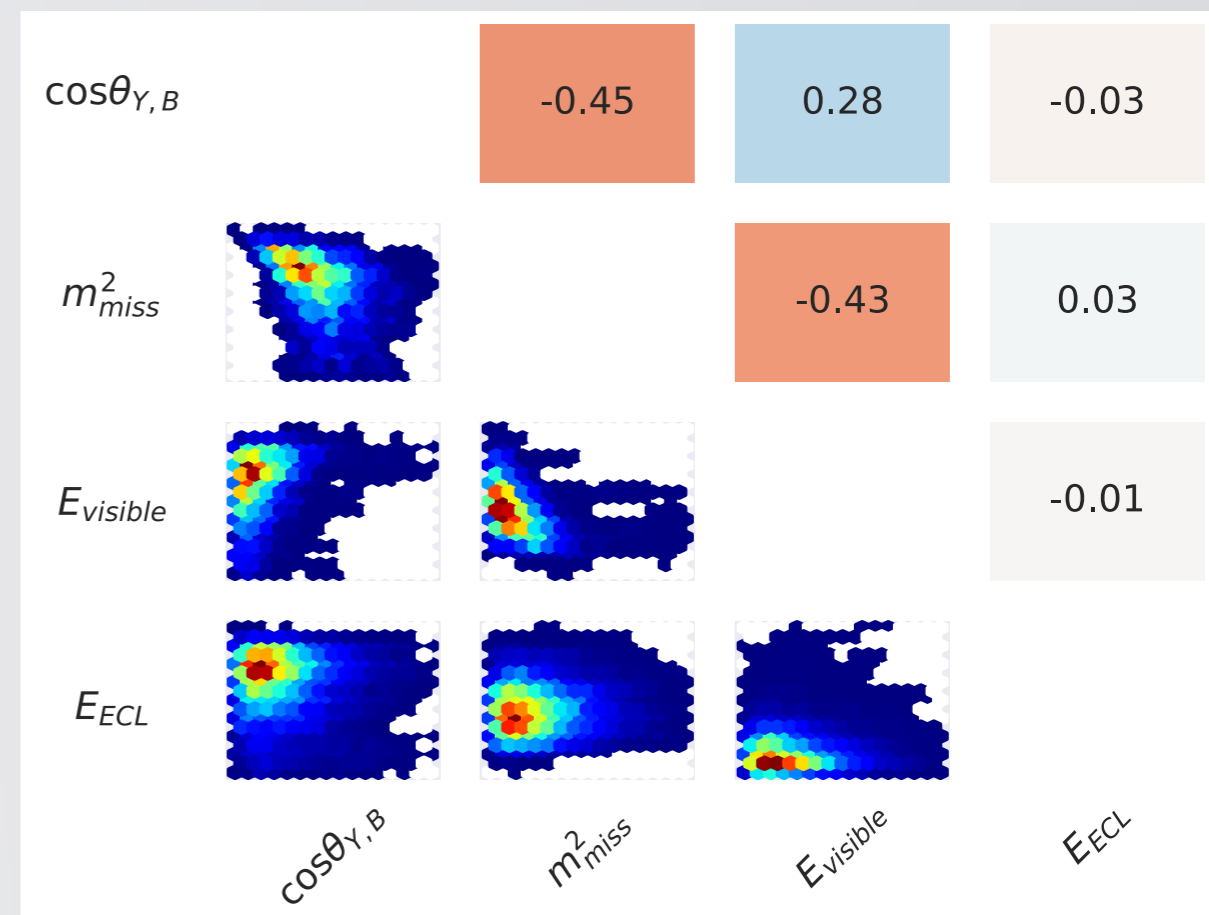
Signal vs normalisation classifier



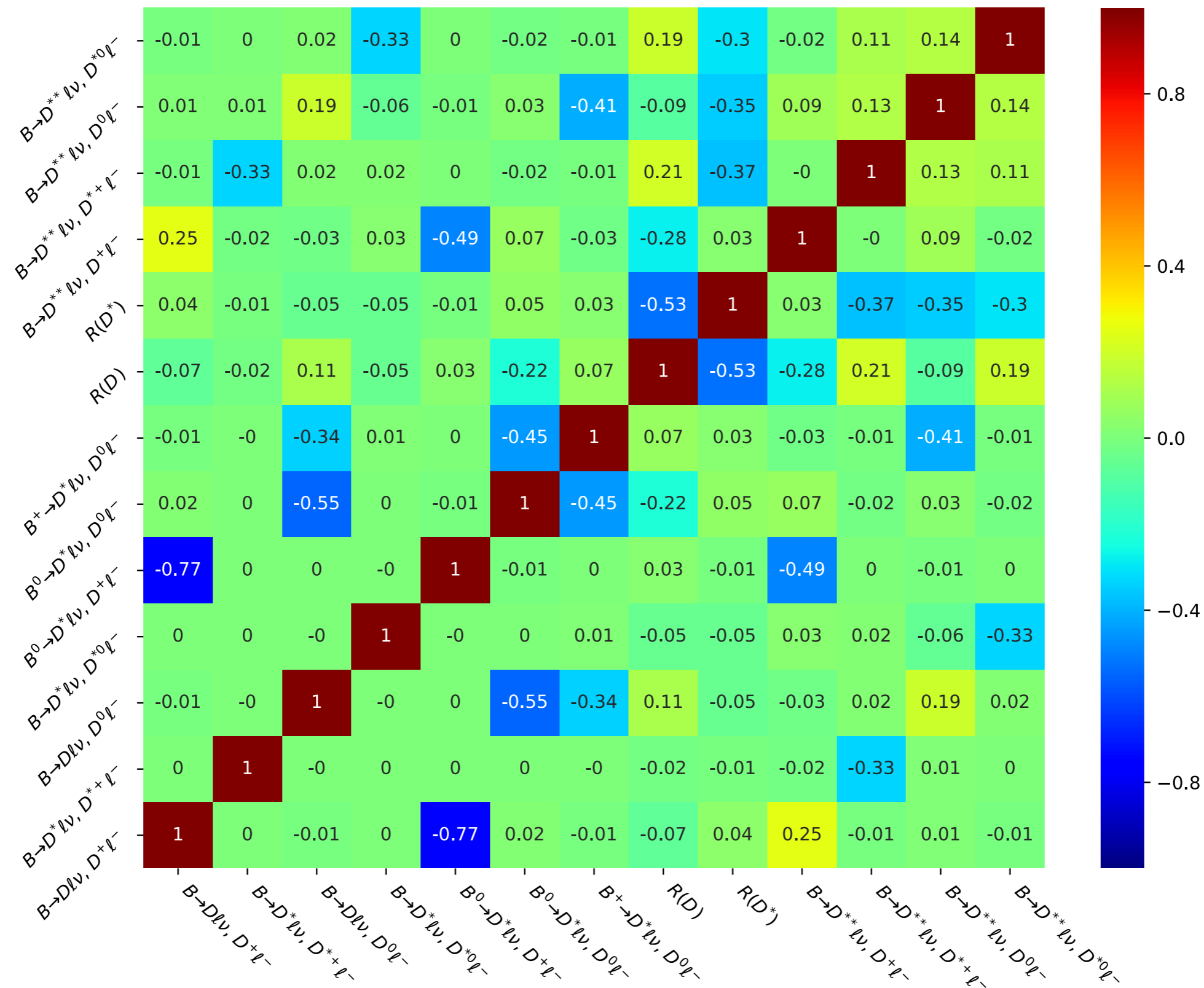
BDT classifier used to distinguish **signal** from **normalization** events.

The input variables used are:

- **squared missing mass**
- **$\cos\theta_{D^{(*)} \ell - B}$**
- **$E_{visible}$** (sum of all particles' energies)



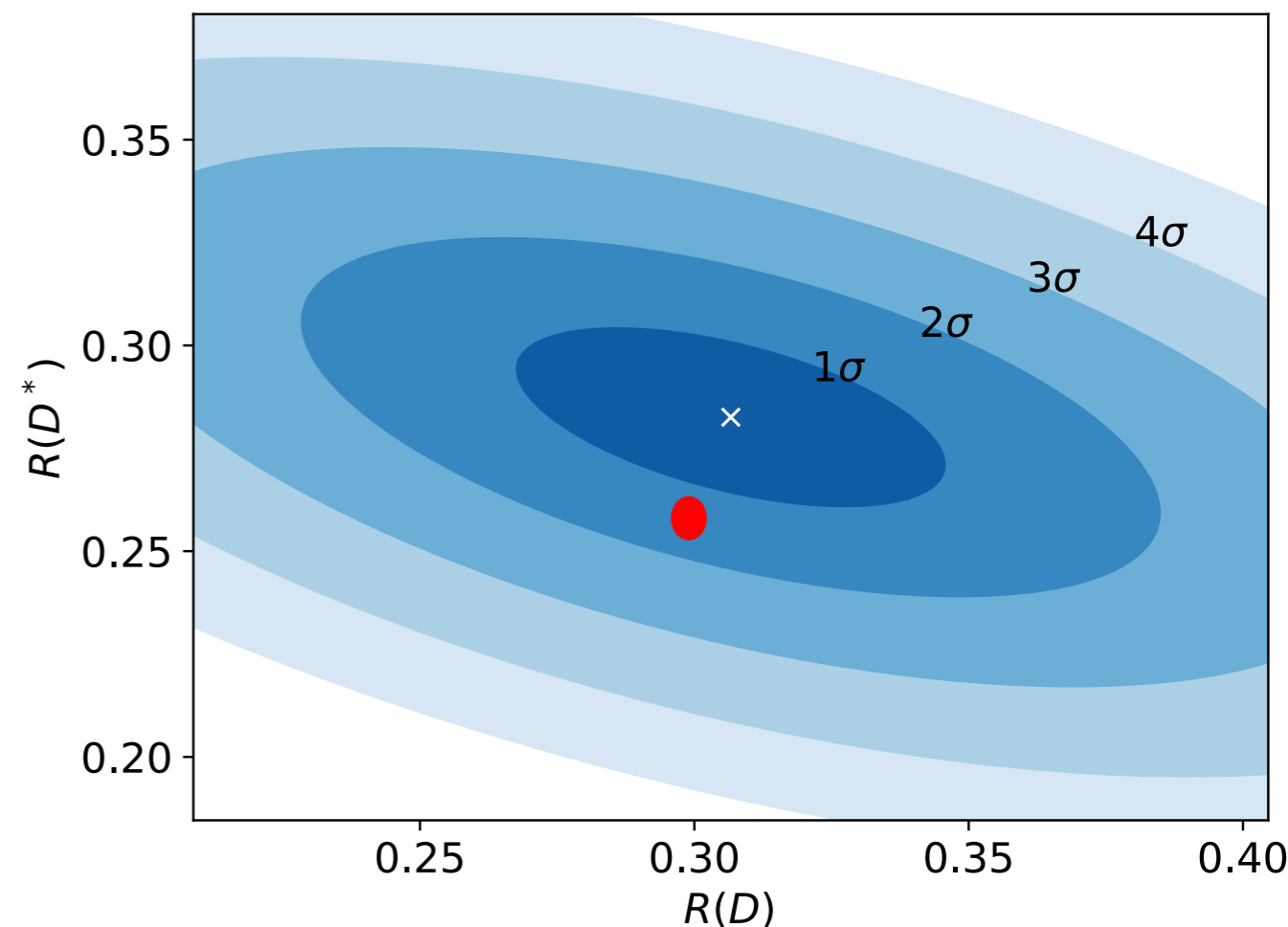
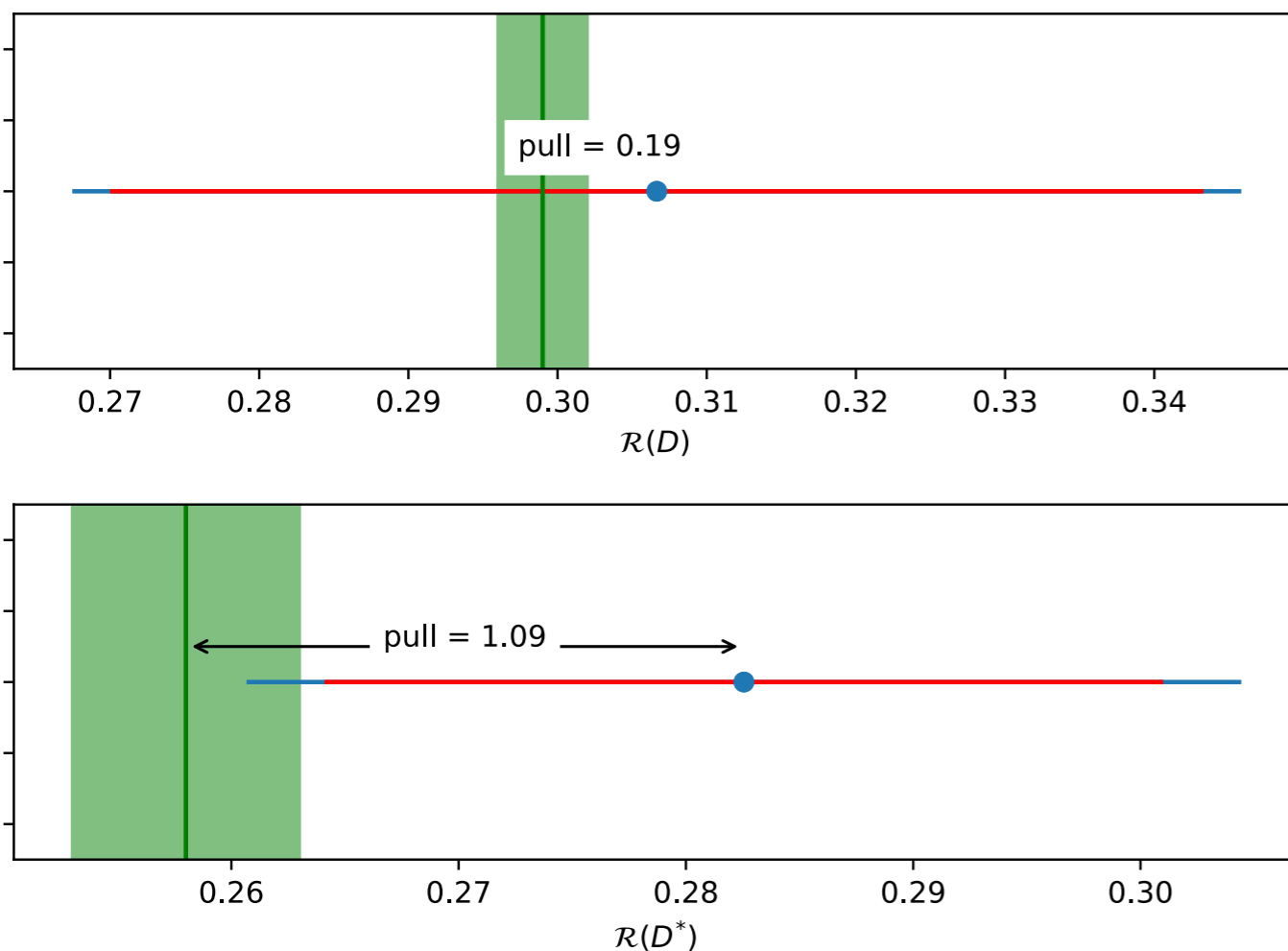
Fit correlation matrix



$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ preliminary results

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

$$\begin{aligned}\mathcal{R}(D)_{\text{SM}} &= 0.299 \pm 0.003 \\ \mathcal{R}(D^*)_{\text{SM}} &= 0.258 \pm 0.005.\end{aligned}$$



$B \rightarrow D(^*) \tau \nu$ @ Belle II

- Current measurements are statistically limited
- Dominant systematics from:
 - MC statistics \rightarrow larger at Belle II
 - limited knowledge of $B \rightarrow D^{**} l \nu$ and $B \rightarrow D(^*) X c$ bkg \rightarrow dedicated studies with large data sample at Belle II
- Study kinematic distributions, polarization

Errors @ Belle II

	5 ab^{-1}	50 ab^{-1}
$R(D)$	$(6.0 \pm 3.9)\%$	$(2.0 \pm 2.5)\%$
$R(D^*)$	$(3.0 \pm 2.5)\%$	$(1.0 \pm 2.0)\%$
$P_T(D^*)$	0.18 ± 0.08	0.06 ± 0.04

