# Tree-level New Physics searches in Semileptonic B decays at Belle

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On behalf of Belle collaboration

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# Outline

- New physics searches in $B \to D^*\tau\nu$ decay.

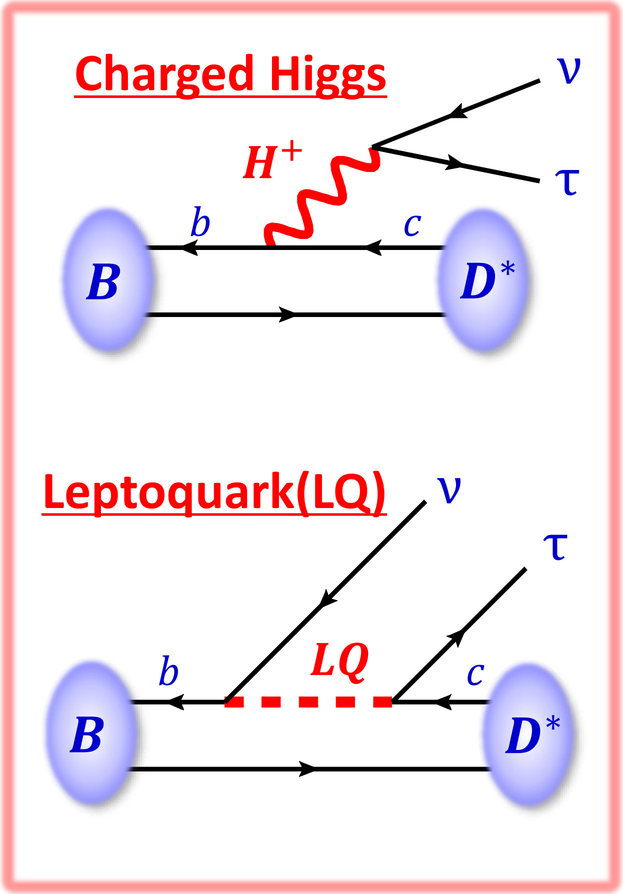
1. $\mathcal{R}(D^*)$ with **semileptonic tag**
    - Shown at Moriond 2016, submitted to PRD (arXiv:1607.07923)
    - Compatibility test in model-independent approach is newly done.
2. $\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ with **hadronic tag** and **τ hadronic decay** *New !*
    - Shown for the first time, preliminary
    - First measurement of $\tau$ polarization in $B \to D^*\tau\nu$ decay.

- Both analyses are based on complete $\Upsilon(4S)$ Belle data set of 711 $\text{fb}^{-1}$.

# Physics Motivation

## $B \to D^*\tau\nu$ decay

- New physics could change $\mathcal{B}$ and $\tau$ **polarization** $(\mathcal{P}_\tau)$.
  - $\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\ell\nu)} = \frac{\text{signal}}{\text{normalization}}$ $(\ell = e, \mu)$
    - Several uncertainties cancel in ratio.
    - $\mathcal{R}(D^*)^{\text{SM}} = 0.252 \pm 0.003$ *S. Fajfer, J.F. Kmaenik, I. Nisandzic PRD 85, 094025 (2012)*
    - Belle, BaBar, and LHCb measured.
  - $\mathcal{P}_\tau^{\text{SM}} = -0.497 \pm 0.014$ *M. Tanaka, R. Watanabe PRD 87, 034028 (2013)*
    - Not measured yet.



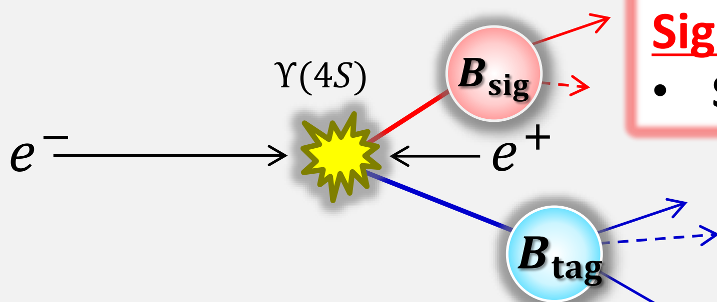

## Choice of $\tau$ decay

- **Leptonic decay ($\tau \to \ell\nu\nu$)**
  - Used in all $\mathcal{R}(D^*)$ measurements so far.
  - Advantageous for bkg suppression.
- **Two-body hadronic decay ($\tau \to h\nu$)**
  - Advantageous for $\mathcal{P}_\tau$ measurement.

# Tagging Techniques

## Hadronic/Semileptonic(SL) tag

- Unique and powerful tools at $B$ factories to analysis final states with multiple $\nu$.



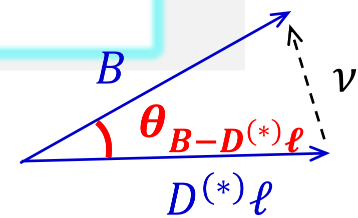

**Signal side**

- **Signal decay**

**Reconstruct $B_{tag}$ from know decays.**

**Tag side**

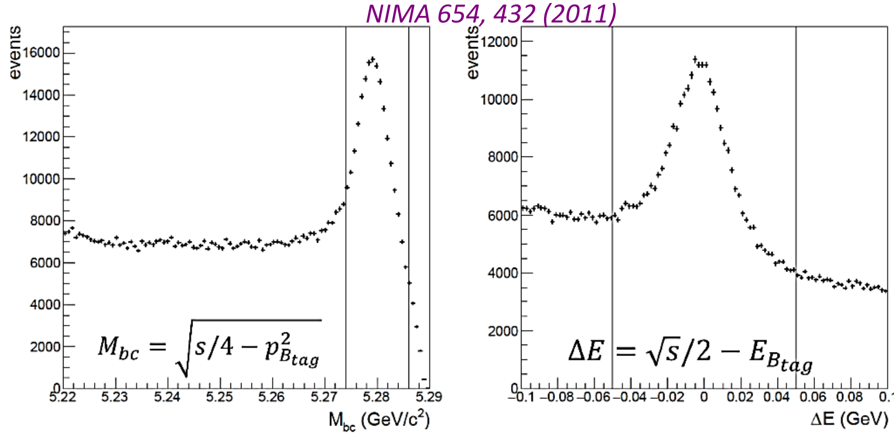
- **Hadronic decay :** $B \to D^{(*)}X,\ J/\psi X, \ldots$
- **Semileptonic decay :** $B \to D^{(*)}\ell\nu$




**Had-tag.**

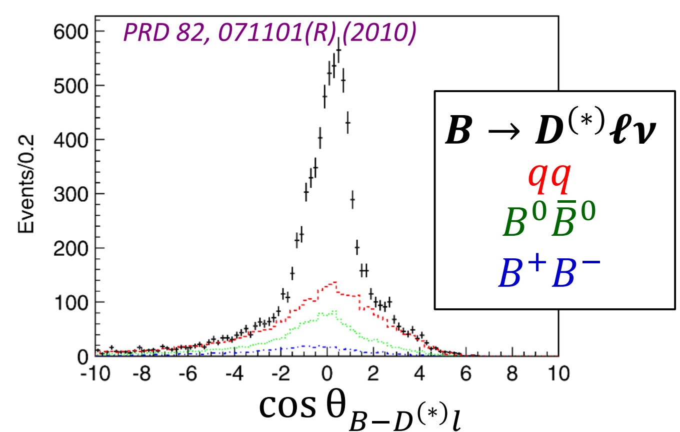
$$M_{bc} = \sqrt{E_{\text{beam}}^2 - \vec{p}_{B_{\text{tag}}}^{\,2}} \qquad \Delta E = E_{\text{beam}} - E_{B_{\text{tag}}}$$

NIMA 654, 432 (2011)




**SL-tag.**

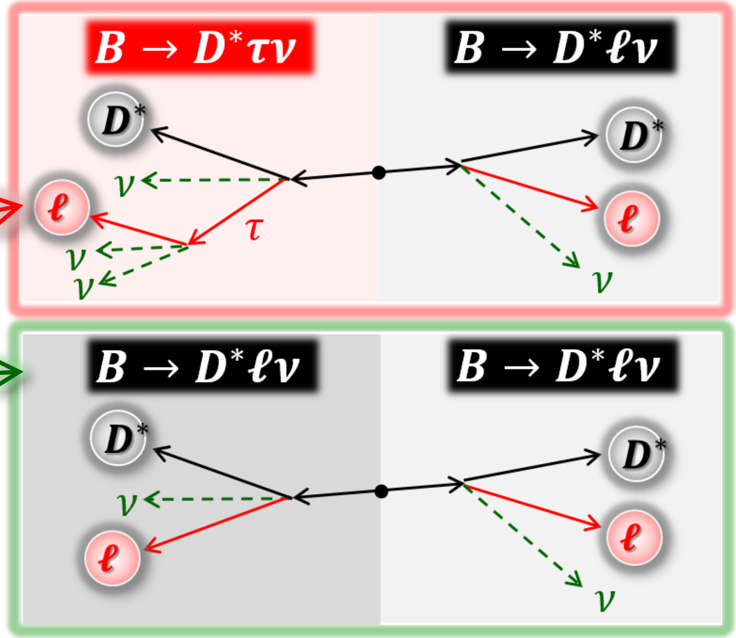
$$\cos\theta_{B-D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|\vec{p}_B|\cdot|\vec{p}_{D^{(*)}\ell}|}$$



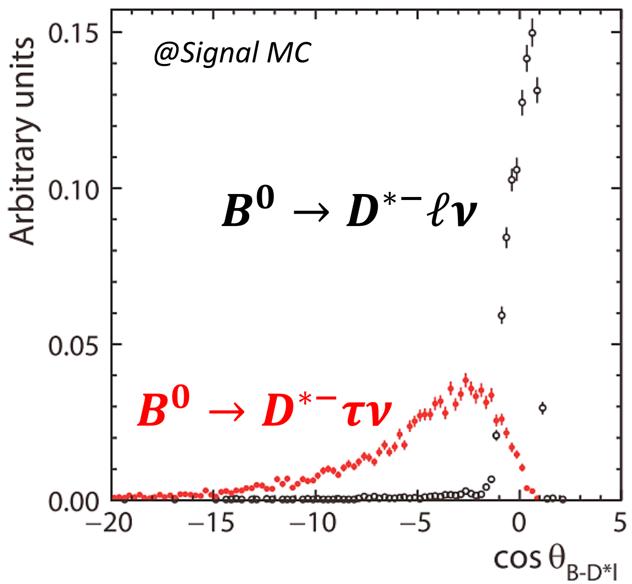
# $\mathcal{R}(D^*)$ with Semileptonic Tag

- "Clean" channels are only used to get high purity.
  - leptonic τ decay : $\tau \to \ell\nu\nu$
  - $B^0\bar{B}^0 \to (D^{*-}\ell^+)(D^{*+}\ell^-)$ channel

- $$\mathcal{R}(D^*) = \frac{\text{signal}}{\text{normalization}}$$



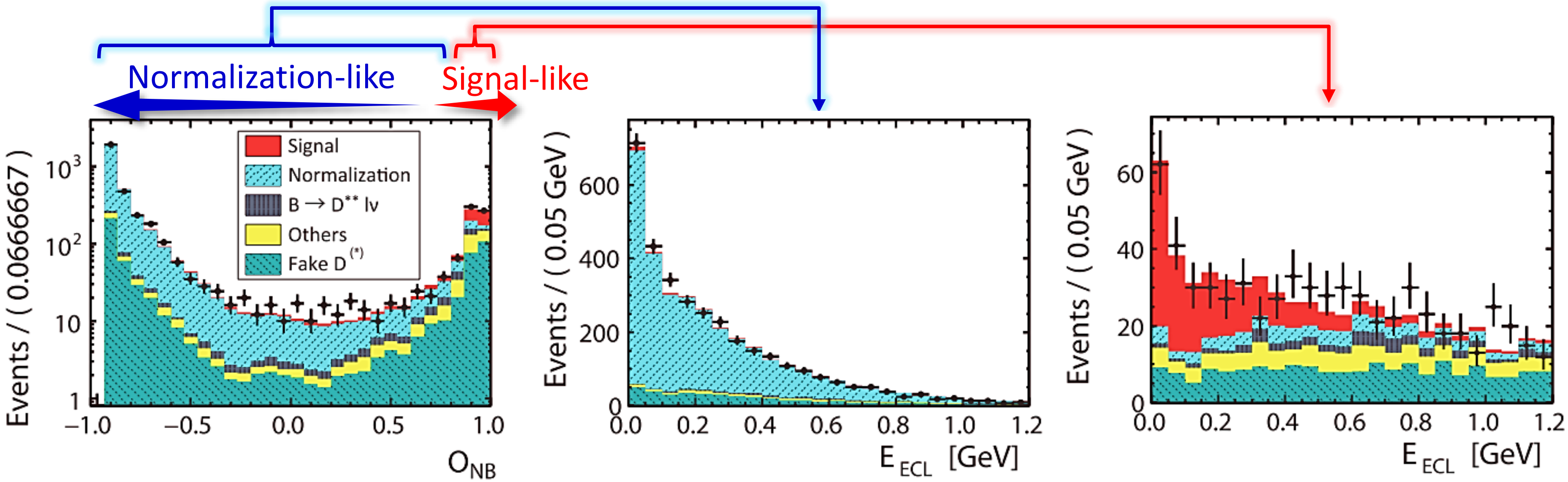

- Signal and normalization are tagged by double semileptonic tag.
- Candidates with the lower value of $\cos\theta_{B-D^*\ell}$ are assigned as $B_{\rm sig}$.



# Result of $\mathcal{R}(D^*)$ Measurement

$\mathcal{R}(D^*)$ with SL-tag

- Two-dimensional fit :
  1. $\mathcal{O}_{\mathbf{NB}}$ (Neural network output, mainly based on $\cos\theta^{\mathrm{low}}_{B-D^*\ell}$)
  2. $\boldsymbol{E}_{\mathbf{ECL}}$ (sum of residual energy in calorimeter)




- $\boldsymbol{\mathcal{R}(D^*) = 0.302 \pm 0.030(\mathrm{stat}) \pm 0.011(\mathrm{syst})}$
  - $13.8\sigma$ significance including syst. error.
  - $1.6\sigma$ larger than SM prediction
  - Consistent with other measurements.

# Compatibility Test in Model Independent Approach



$\mathcal{R}(D^*)$ with SL-tag

- Examine the impact of each operators in kinematics.
  - **Effective Hamiltonian for $b \to c\tau\nu_\tau$**

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[ \underbrace{\mathcal{O}_{V_1}}_{\text{SM}} + \underbrace{\sum_{X=S_1,S_2,V_1,V_2,T} C_X \mathcal{O}_X}_{\text{NP}} \right]$$

**Five operators**

$$\mathcal{O}_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_{\tau L}),$$ 2HDM (type-II)

$$\mathcal{O}_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{\tau L}),$$ 2HDM

$$\mathcal{O}_{V_1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}),$$ SM

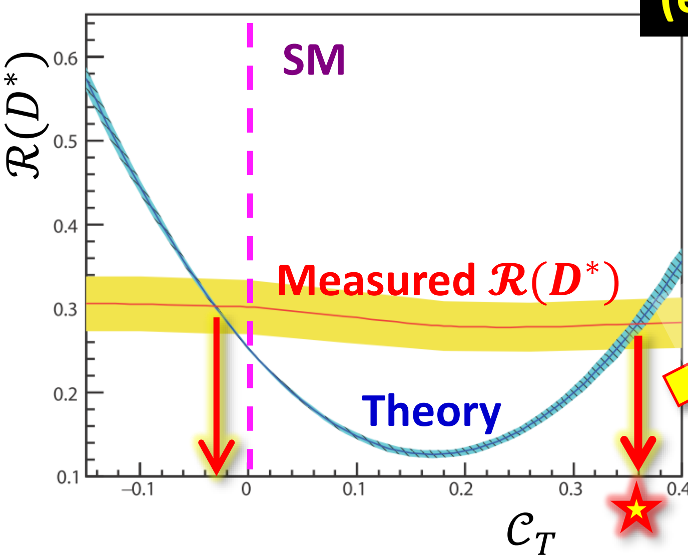
$$\mathcal{O}_{V_2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}),$$ RH-current

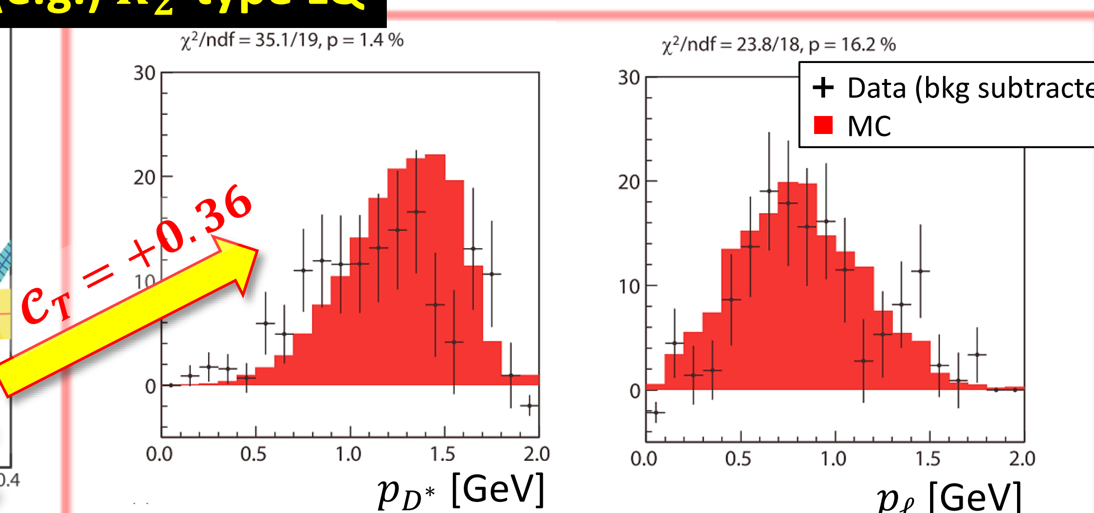
$$\mathcal{O}_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L}),$$ Tensor

- Two leptoquark(LQ) models are also studied.
  - $\mathcal{C}_{S_2} = +7.8\mathcal{C}_T$ : $(SU(3)_C, SU(2)_L)_Y = (3,2)_{7/6}$ → $R_2$**-type LQ**
  - $\mathcal{C}_{S_2} = -7.8\mathcal{C}_T$ : $(SU(3)_C, SU(2)_L)_Y = (3^*,2)_{1/3}$ → $S_1$**-type LQ**

(assuming no additional $\mathcal{O}_{V_1}$ contribution)

**(e.g.) $R_2$-type LQ**



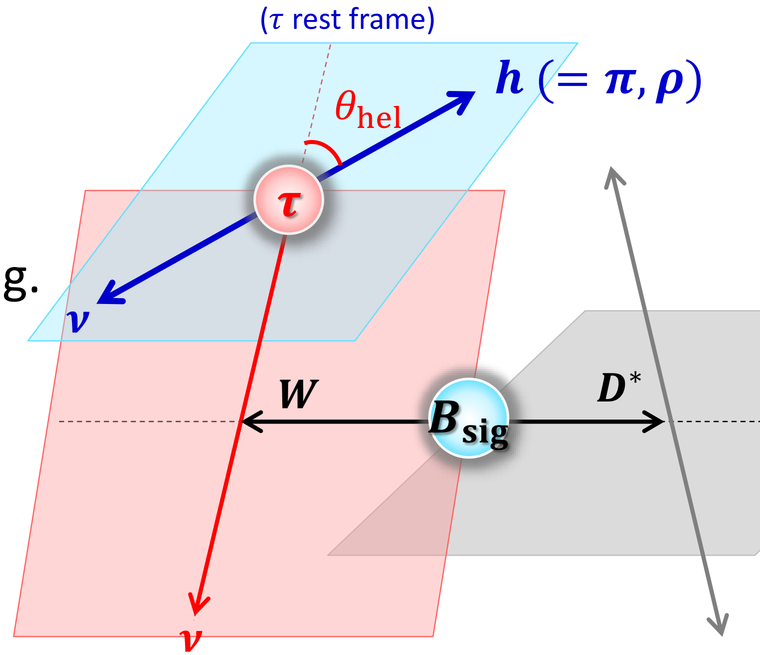

→ Large contributions from tensor are disfavored.

- Favored regions and p-values for each scenarios are summarized in backup slide.

# $\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ with Hadronic Tag



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



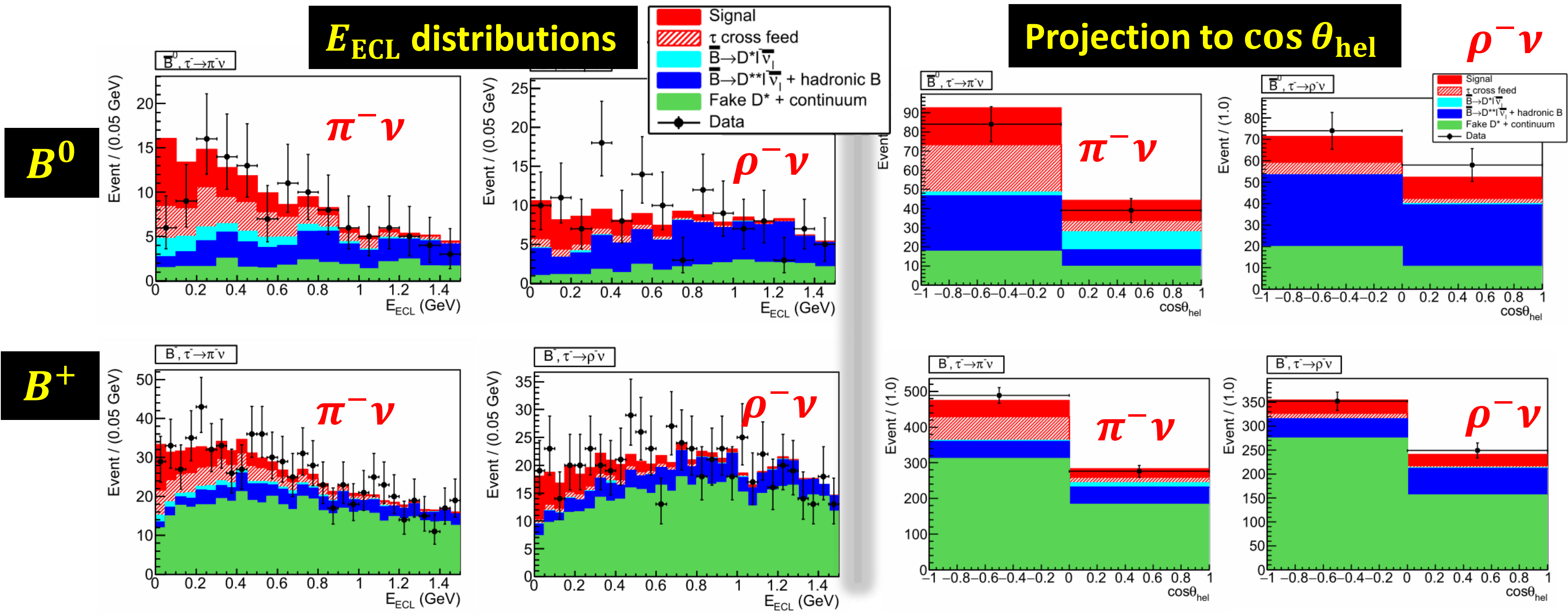

- Tau helicity angle ($\cos\theta_{\rm hel}$) is sensitive to $\mathcal{P}_\tau$.
  - 4-momentum of $B_{\rm sig}$ is determined by had-tag.
  - Two-body hadronic $\tau$ decays are used.
    - $\tau \to h\nu, \quad h = \pi^-, \rho^- \; (\to \pi^-\pi^0)$
    - $\alpha = \begin{cases} 1 & \text{for } \tau \to \pi^-\nu \text{ (pseudo scalar meson)} \\ 0.45 & \text{for } \tau \to \rho^-\nu \text{ (vector meson)} \end{cases}$, $\; 0.45 = \dfrac{m_\tau^2 - 2m_V^2}{m_\tau^2 + 2m_V^2}$

- Both $B^0/B^+$ channels are used.
  - $D^{*+} \to D^0\pi^+/D^+\pi^0, D^{*0} \to D^0\pi^0/D^0\gamma$
- $M_{\rm miss}^2$ is used for determination of $B \to D^*\ell\nu$ (denominator in $\mathcal{R}(D^*)$ )
- Correct $\mathcal{P}_\tau^{\rm raw}$ to $\mathcal{P}_\tau^{\rm true}$ in fitter, considering acceptance effect.
  - $\cos\theta_{\rm hel} < 0.8$ for $(\tau \to \pi^-\nu)$

# Fit for $\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ Measurements

$\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ with Had-tag

- Simultaneous fitting of eight $E_{\mathrm{ECL}}$ distributions:
  - $(B^0, B^+) \otimes (\pi\nu, \rho\nu) \otimes$(Forward/backward $\cos\theta_{\mathrm{hel}}$)



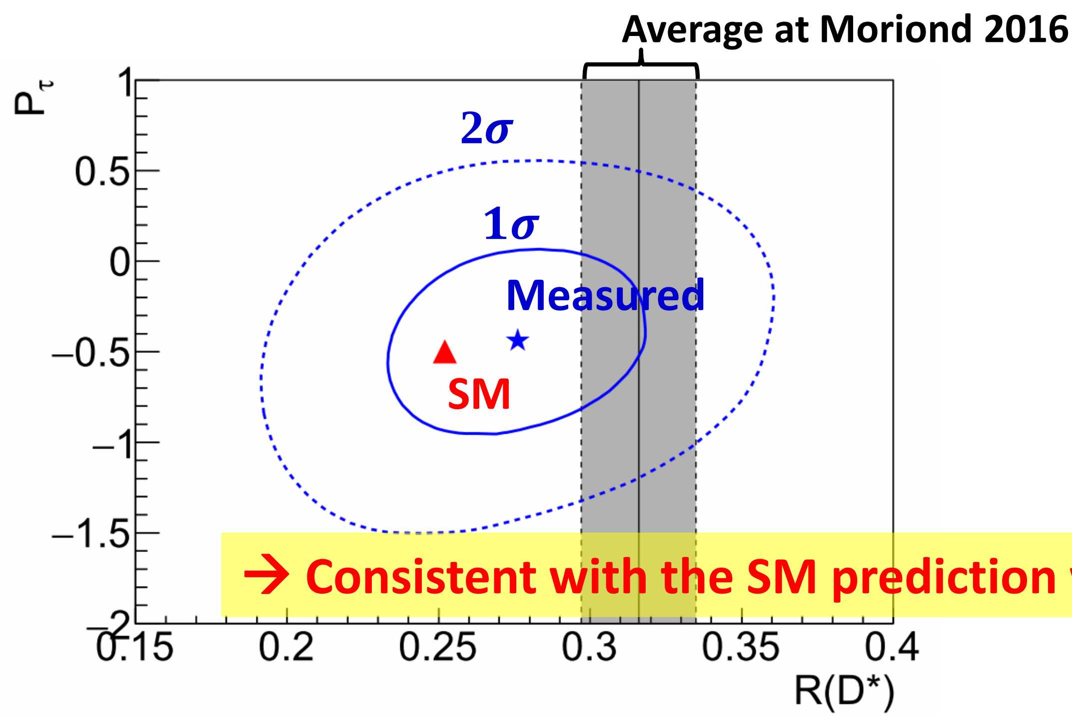

- Dominant Bkg (except fake $D^*$, which can be determined by sideband) arises from hadronic $B$ decay (e.g. $B \rightarrow D^*\ \mathrm{n}\pi$).
  - Calibrated by requiring additional particles and reconstructing these events.
  - Yield of hadronic $B$ decay is floated.

# Result of $\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ Measurements



$\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ with Had-tag

- $\mathcal{R}(D^*) = 0.276 \pm 0.034(\text{stat})^{+0.029}_{-0.026}(\text{syst})$ ***Preliminary***
  - $7.1\sigma$ significance including systematic uncertainty.
  - Consistent with SM prediction and other measurements.
- $\mathcal{P}_\tau = -0.44 \pm 0.47(\text{stat})^{+0.20}_{-0.17}(\text{syst})$ ***Preliminary***
  - **First $\mathcal{P}_\tau$ measurements !**
  - Consistent with SM prediction $(-0.497 \pm 0.014)$ within uncertainty. *M. Tanaka, R. Watanabe, PRD 87, 034028 (2013)*
- Systematics arises mainly from hadronic $B$ bkg, MC statistics.

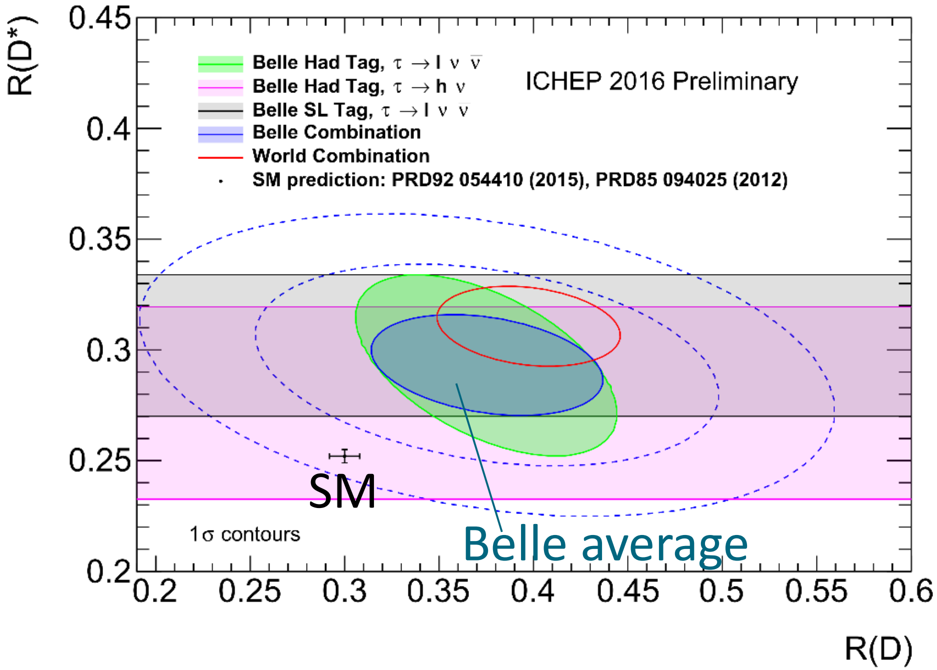



**→ Consistent with the SM prediction within $0.6\sigma$**

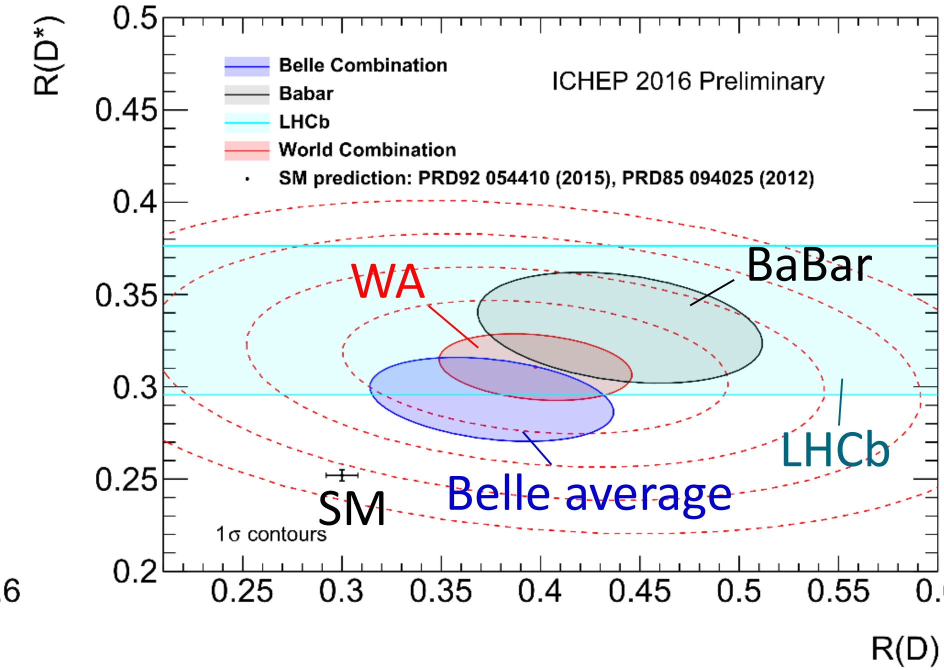
# Combined Plots

- Correlation of systematic uncertainties about semileptonic decay are considered.
  - Assumption : large correlation in measurements of the same observable and null correlation between $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$.

**Belle combination**




**Comparison among experiments**




→ Precision of $\mathcal{R}(D^*)$ is improved by combining three Belle results.

→ Belle average is slightly smaller than BaBar/LHCb results, but still larger than SM prediction.

# Summary

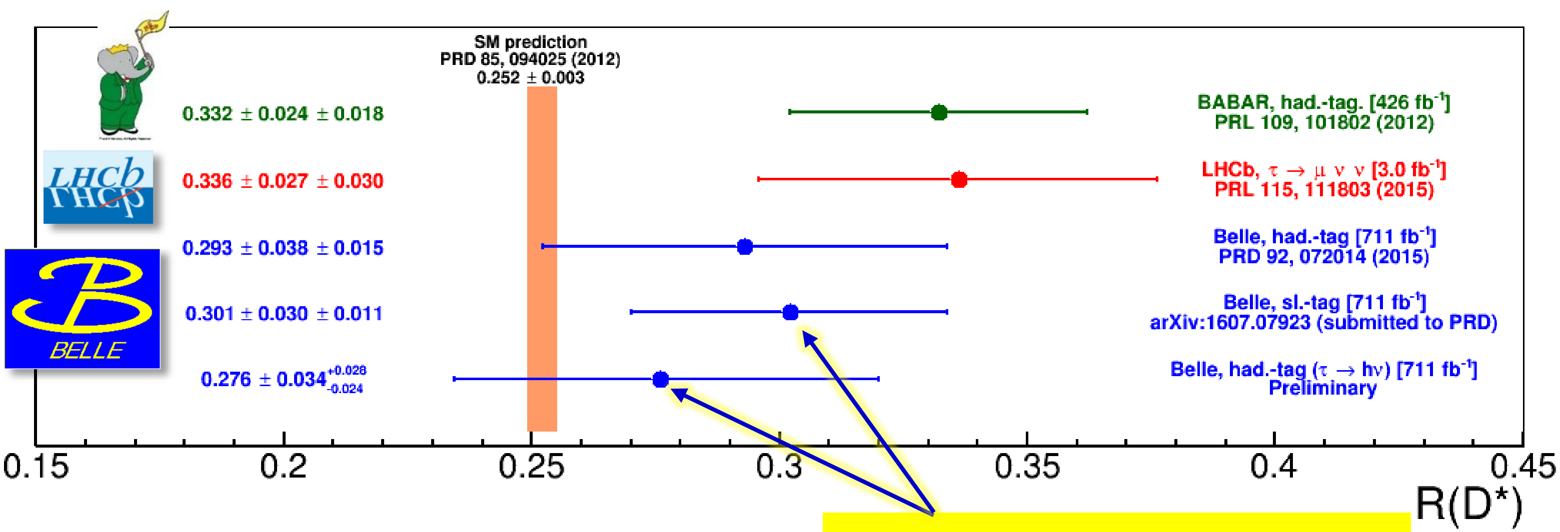
- $B \to D^*\tau\nu$ decay is sensitive to several new physics scenarios.
- Belle continues to contribute to $B \to D^*\tau\nu$ decay actively.
  - $\mathcal{R}(D^*) = 0.302 \pm 0.030(\text{stat}) \pm 0.011(\text{syst})$

    ***Submitted to PRD*** *(arXiv:1607.07923)*

    - First measurement of $\mathcal{R}(D^*)$ using semileptonic tag.
  - $\mathcal{R}(D^*) = 0.276 \pm 0.034(\text{stat})^{+0.029}_{-0.026}(\text{syst})$
  - $\mathcal{P}_\tau = -0.44 \pm 0.47(\text{stat})^{+0.20}_{-0.17}(\text{syst})$

    ***Preliminary***

    - First measurement of $\tau$ polarization in $B \to D^*\tau\nu$ decay.



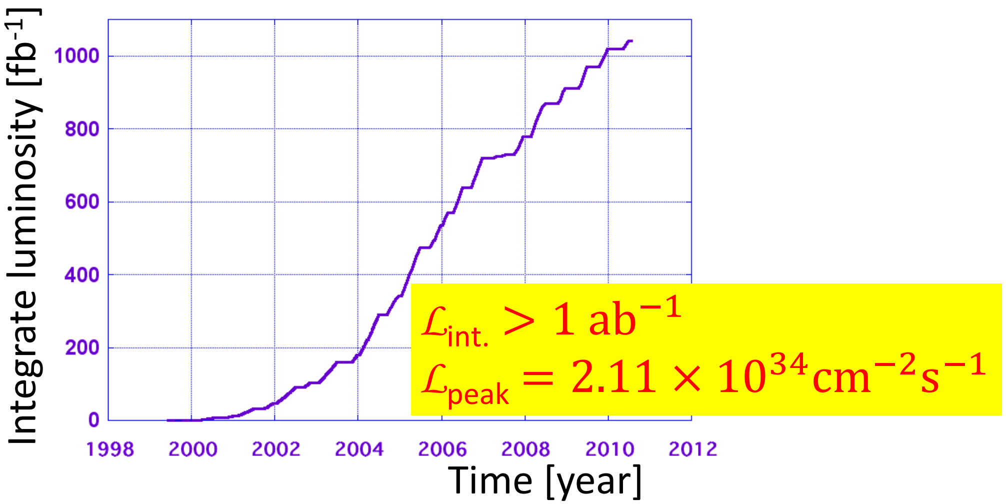

**Results presented here.**

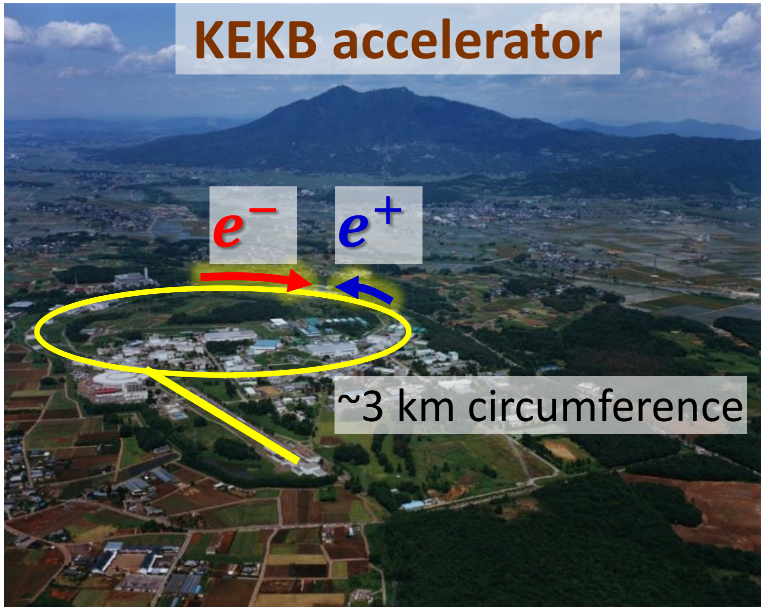
- More analyses about $b \to c\tau\nu$ are ongoing at Belle. Stay tuned.

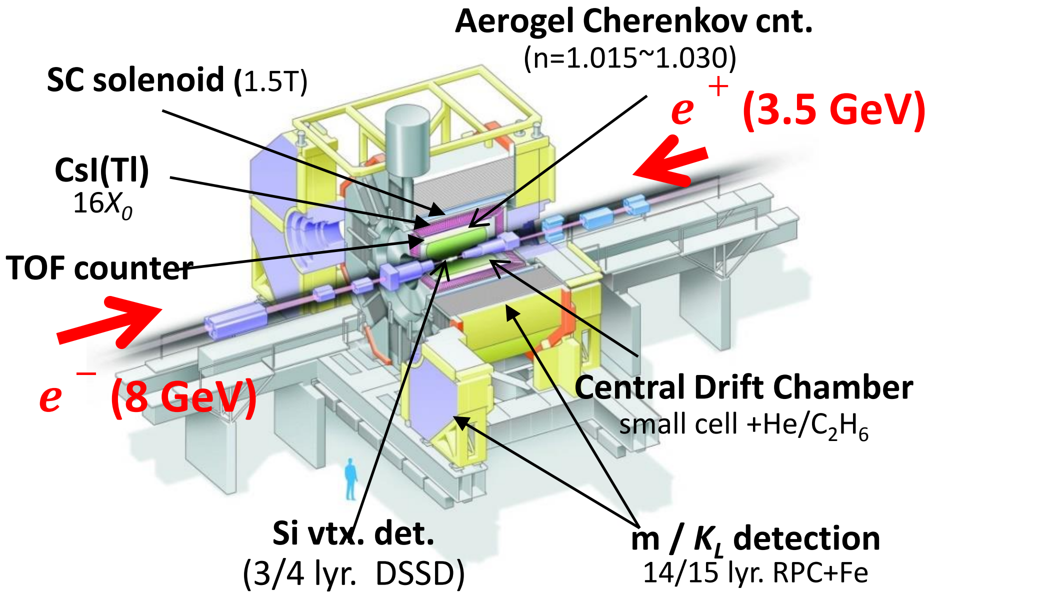
# Backup

# Belle Experiment

- KEKB accelerator and Belle detector at Tsukuba, Japan.
  - Asymmetric $e^+e^-$ energy to boost B mesons
  - Data taking for 1999-2010
  - Good particle ID capability
    - $(p, \pi^\pm, K^\pm, \gamma, e, \mu, K_L^0)$
  - Good momentum resolution
    - $\frac{\sigma_{P_t}}{P_t} = 0.19P_t \oplus \frac{0.30}{\beta}\%$



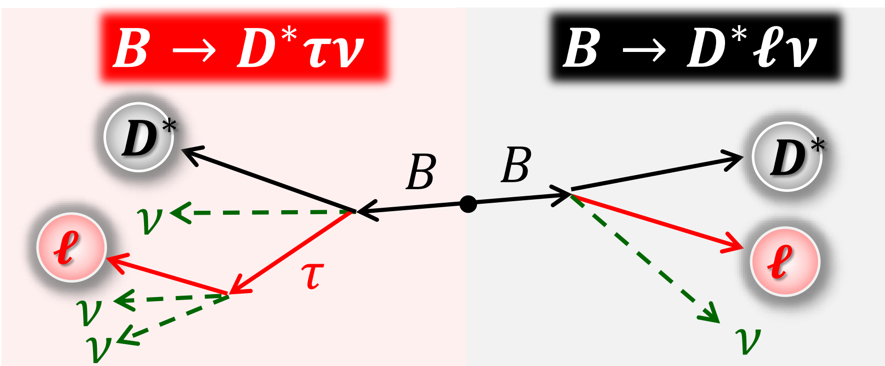



# Signal and Background

- Same background sources as analysis with hadronic tagging.

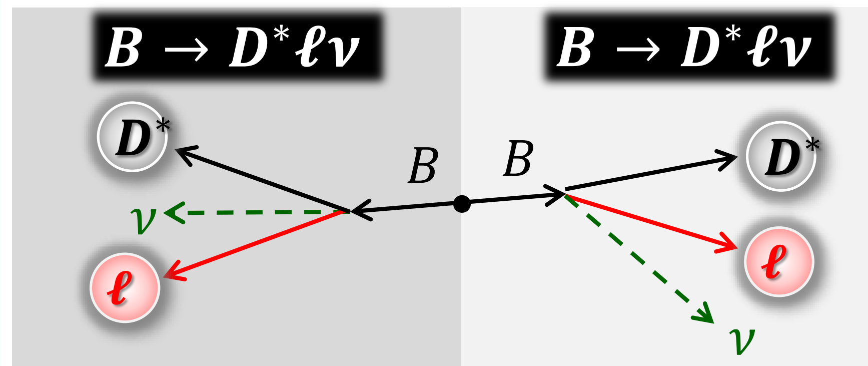
## Signal




4 neutrinos in final state

## Background

### 1. Normalization




2 neutrinos in final state

### 2. $B \to D^{**}\ell\nu$

- One of the dominant systematic source
- Mainly 2 neutrinos + more than one pion in final state.

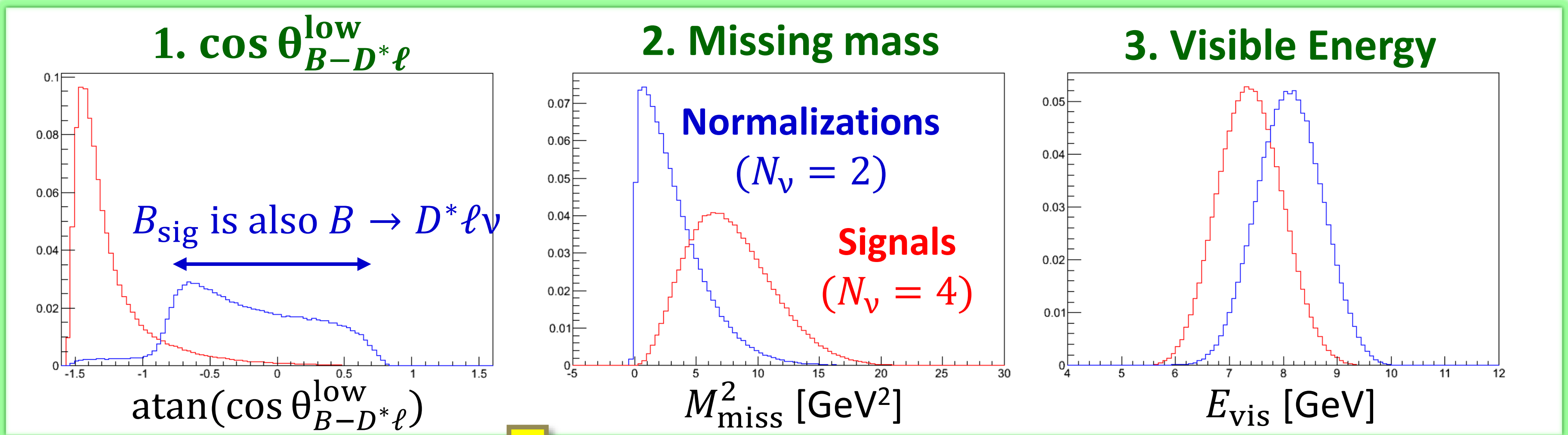
### 3. Others

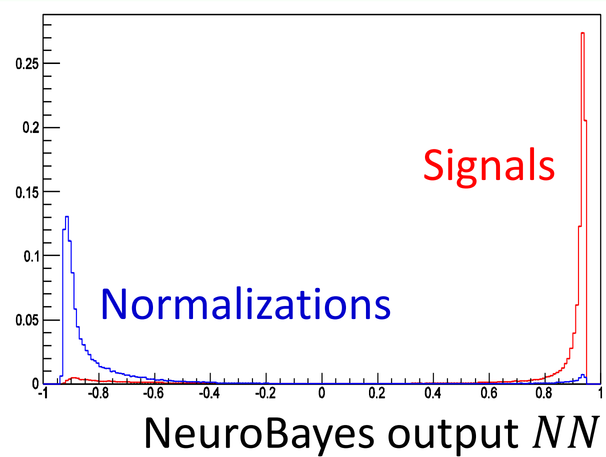
- $B \to X_c D^*$, combinatorial (fake $D^{(*)}$) background, continuum background, ….

→ Separation of signal and background using information on missing particles.

# Background Separation

- **Separate signal from normalizations using NeuroBayes.**
  - **Signals** : $B_{\rm sig}B_{\rm tag} \to (D^*\tau\nu)_{\rm sig}(D^*\ell\nu)_{\rm tag}$
  - **Normalizations** : $B_{\rm sig}B_{\rm tag} \to (D^*\ell\nu)_{\rm sig}(D^*\ell\nu)_{\rm tag}$
- Three input for NeuroBayes.



# Systematic Uncertainty and Prospect for Belle II

$\mathcal{R}(D^*)$ with SL-tag

| | $\mathcal{R}(D^*)$ [%] | | | |
|---|---|---|---|---|
| Sources | $\ell^{\rm sig} = e, \mu$ | $\ell^{\rm sig} = e$ | $\ell^{\rm sig} = \mu$ | |
| MC statistics for PDF shape | 2.2% | 2.5% | 3.9% | ☆ |
| PDF shape of the normalization | $^{+1.1}_{-0.0}$% | $^{+2.1}_{-0.0}$% | $^{+2.8}_{-0.0}$% | ☆ |
| PDF shape of $B \to D^{**}\ell\nu_\ell$ | $^{+1.0}_{-1.7}$% | $^{+0.7}_{-1.3}$% | $^{+2.2}_{-3.3}$% | ☆ |
| PDF shape and yields of fake $D^{(*)}$ | 1.4% | 1.6% | 1.6% | (☆) |
| PDF shape and yields of $B \to X_c D^*$ | 1.1% | 1.2% | 1.1% | ☆ |
| Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$ | 1.2% | 1.5% | 1.9% | ☆ |
| Modeling of semileptonic decay | 0.2% | 0.2% | 0.3% | |
| $\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$ | 0.2% | 0.2% | 0.2% | |
| Total systematic uncertainties | $^{+3.4}_{-3.5}$% | $^{+4.1}_{-3.7}$% | $^{+5.9}_{-5.8}$% | |

- Current statistical uncertainty ~ 10%.
  - 3.8 % at 5 ab$^{-1}$
  - 1.2 % at 50 ab$^{-1}$
- We must reduce systematic uncertainty at Belle II.

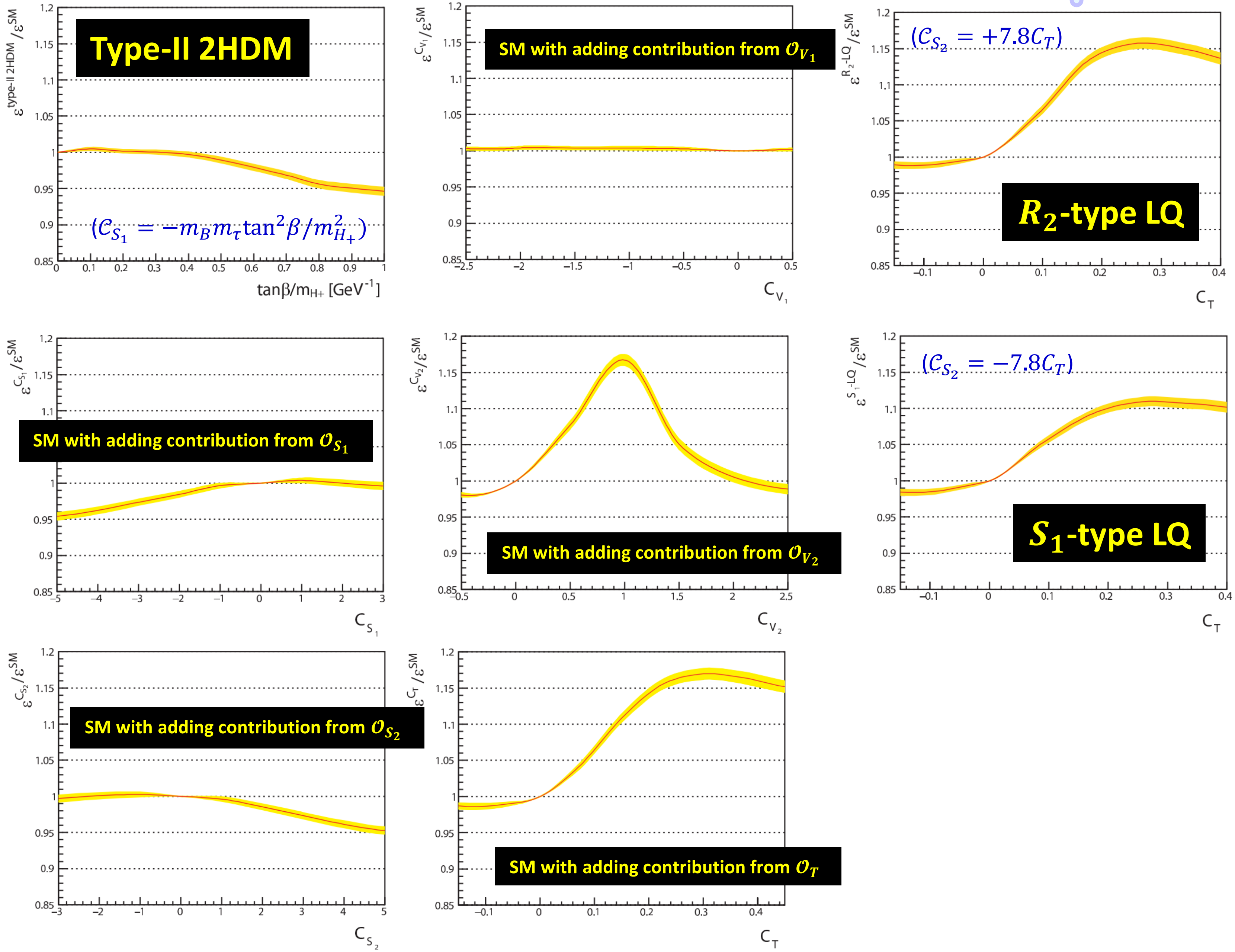
☆ Systematic uncertainties related to limited amount of MC samples

☆ Need to understand $B \to D^{**}\ell\nu$ and $B \to X_c D^*$ background

☆ Difference between data and MC is conservatively assigned as systematic uncertainty in this estimation.

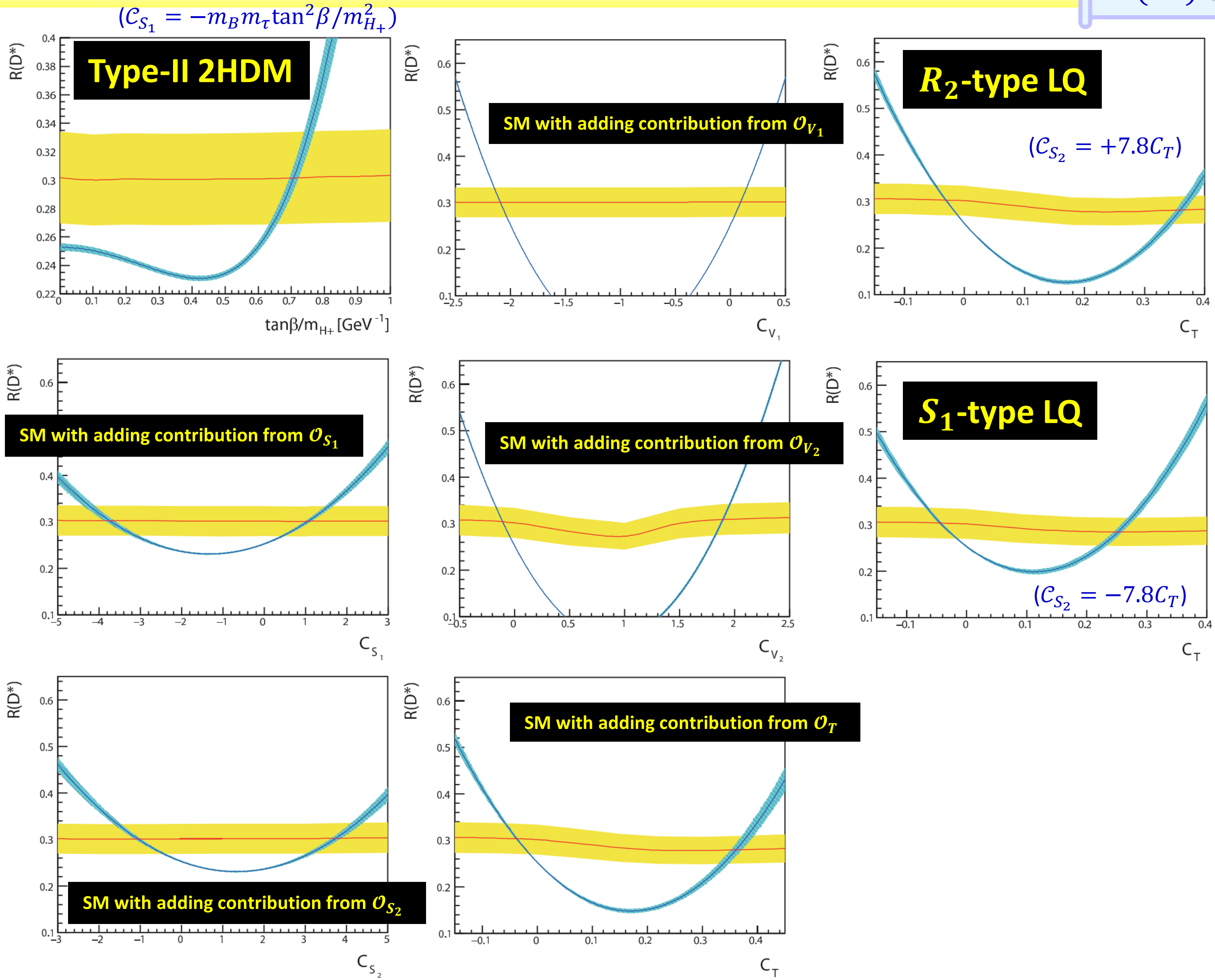
# Efficiency Variation

$\mathcal{R}(D^*)$ with SL-tag



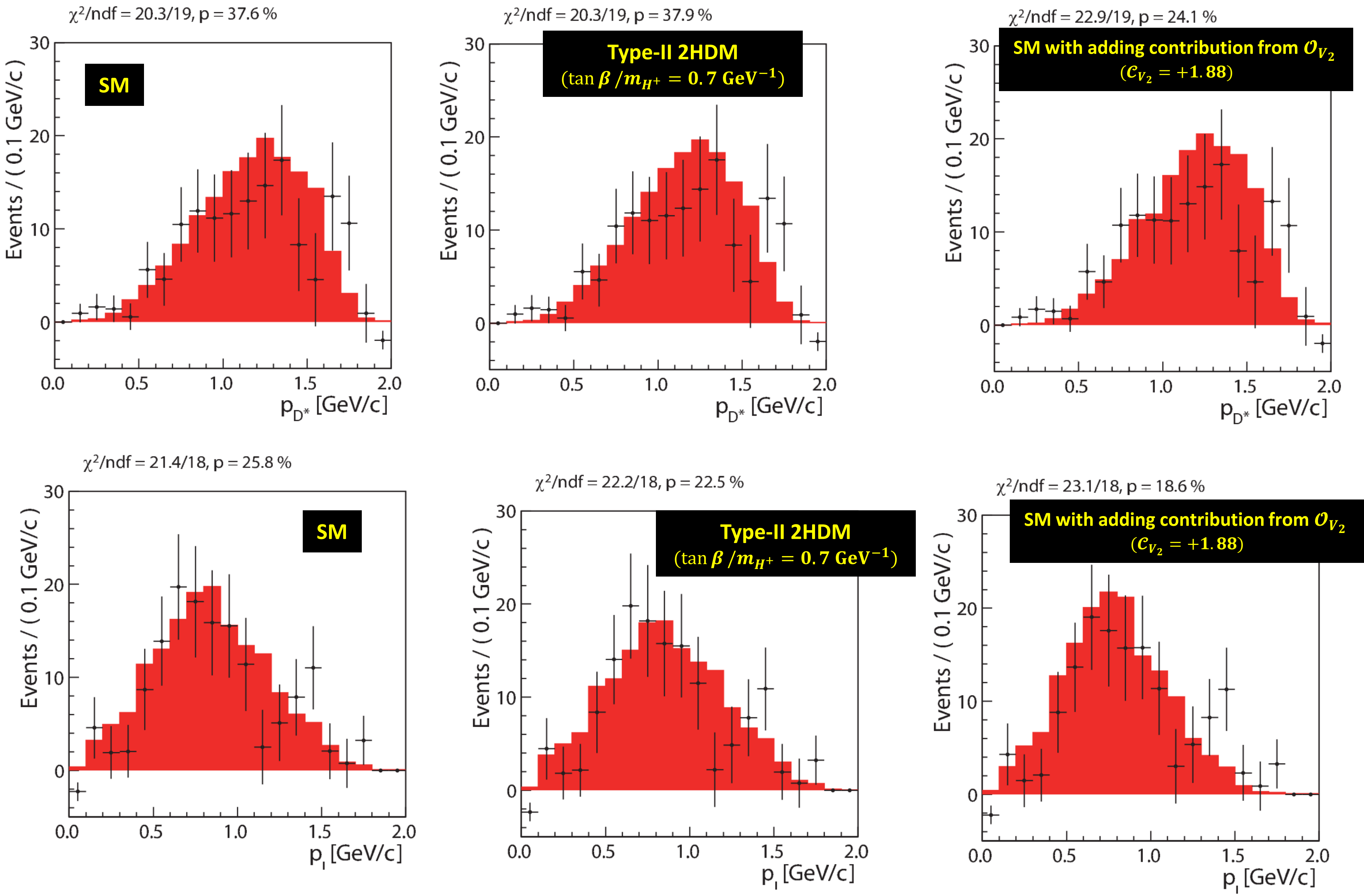
# Measured $\mathcal{R}(D^*)$

$\mathcal{R}(D^*)$ with SL-tag



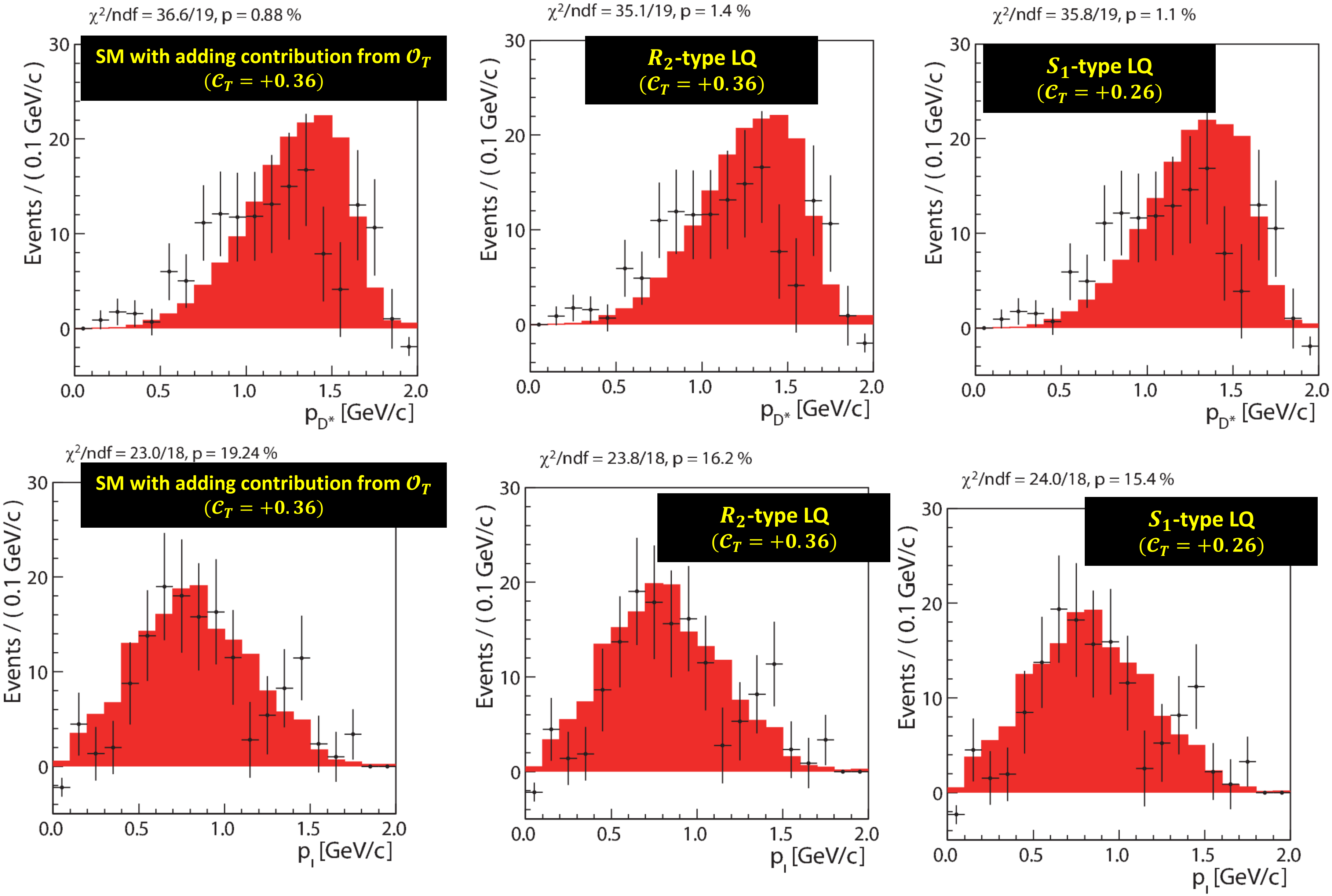
# Kinematic Distributions

$\mathcal{R}(D^*)$ with SL-tag



# Kinematic Distributions

$\mathcal{R}(D^*)$ with SL-tag



# Summary Table of Compatibility Tests

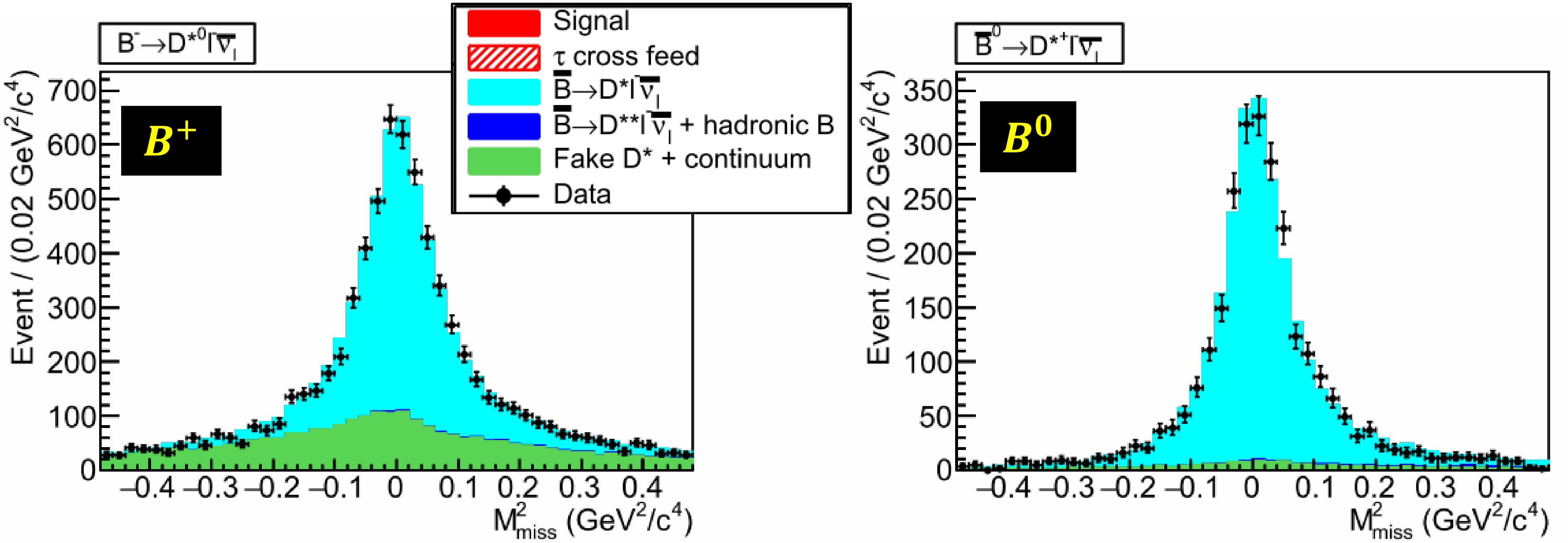
$\mathcal{R}(D^*)$ with SL-tag

| Models or operators | Parameters | Allowed regions (68% C.L.) |
|---|---|---|
| $\mathcal{O}_{S_1}$ | $C_{S_1}$ | $[-4.25, -3.09]$, $[+0.44, +1.57]$ |
| $\mathcal{O}_{S_2}$ | $C_{S_2}$ | $[-1.56, -0.43]$, $[+3.12, +4.28]$ |
| $\mathcal{O}_{V_1}$ | $C_{V_1}$ | $[-2.15, -2.03]$, $[+0.05, +0.15]$ |
| $\mathcal{O}_{V_2}$ | $C_{V_2}$ | $[-0.17, 0.00]$, $[+1.83, +1.96]$ |
| $\mathcal{O}_T$ | $C_T$ | $[-0.06, -0.01]$, $[+0.34, +0.39]$ |
| $R_2$-type leptoquark | $C_T(= +C_{S_2}/7.8)$ | $[-0.05, -0.01]$, $[+0.34, +0.38]$ |
| $S_1$-type leptoquark | $C_T(= -C_{S_2}/7.8)$ | $[-0.07, -0.01]$, $[+0.22, +0.28]$ |

| Model or operator | Parameter | $p$ values [%] | |
|---|---|---|---|
| | | $p_{D^*}$ | $p_\ell$ |
| SM | | 37.6 | 25.8 |
| Type-II 2HDM | $\frac{\tan\beta}{m_{H^+}} = 0.7\ \mathrm{GeV}^{-1}$ | 37.9 | 22.5 |
| $\mathcal{O}_{V_2}$ | $C_{V_2} = +1.88$ | 24.1 | 18.6 |
| $\mathcal{O}_T$ | $C_T = +0.36$ | 0.9 | 19.2 |
| $R_2$-type leptoquark model | $C_T = +0.36$ | 1.4 | 16.2 |
| $S_1$-type leptoquark model | $C_T = +0.26$ | 1.1 | 15.4 |

# $M^2_{\text{miss}}$ Fit

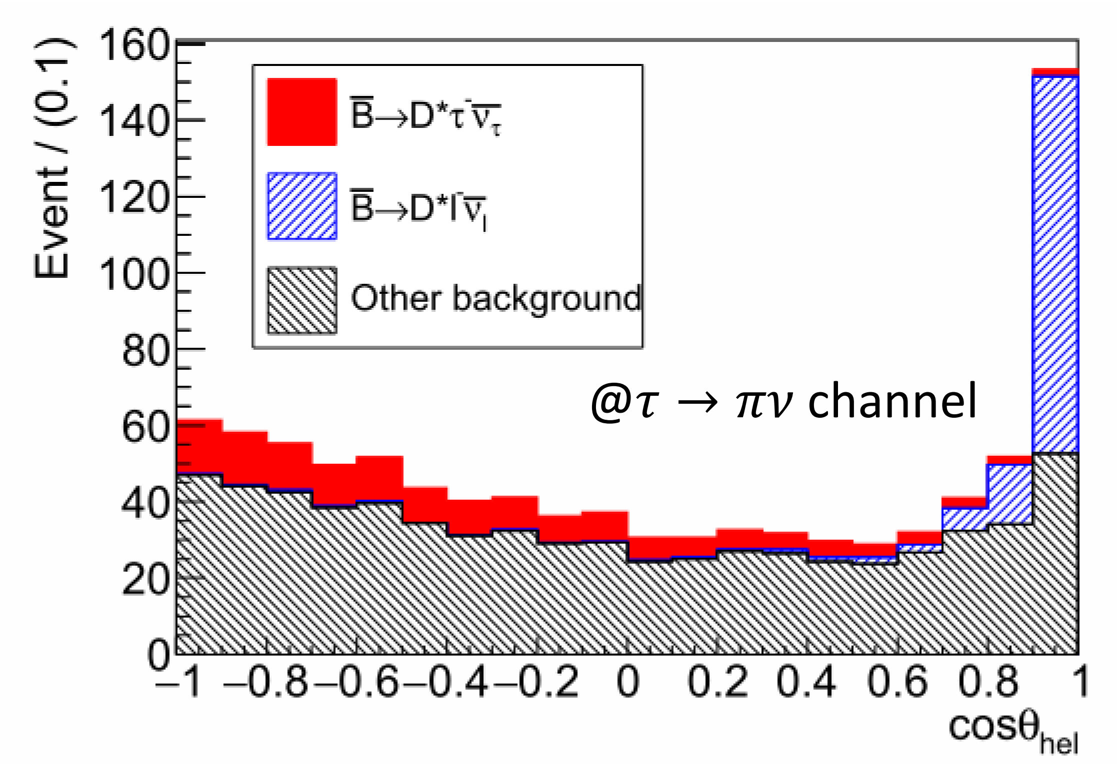
$\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ with Had-tag



# $\cos\theta_{\rm hel}$ Distributions



- $\cos\theta_{\rm hel} < 0.8$ in $\tau \to \pi\nu$ channel to mitigate $B \to D^*\ell\nu$.
- Correlation between $\cos\theta_{\rm hel}$ and $M^2_{\rm miss}$.

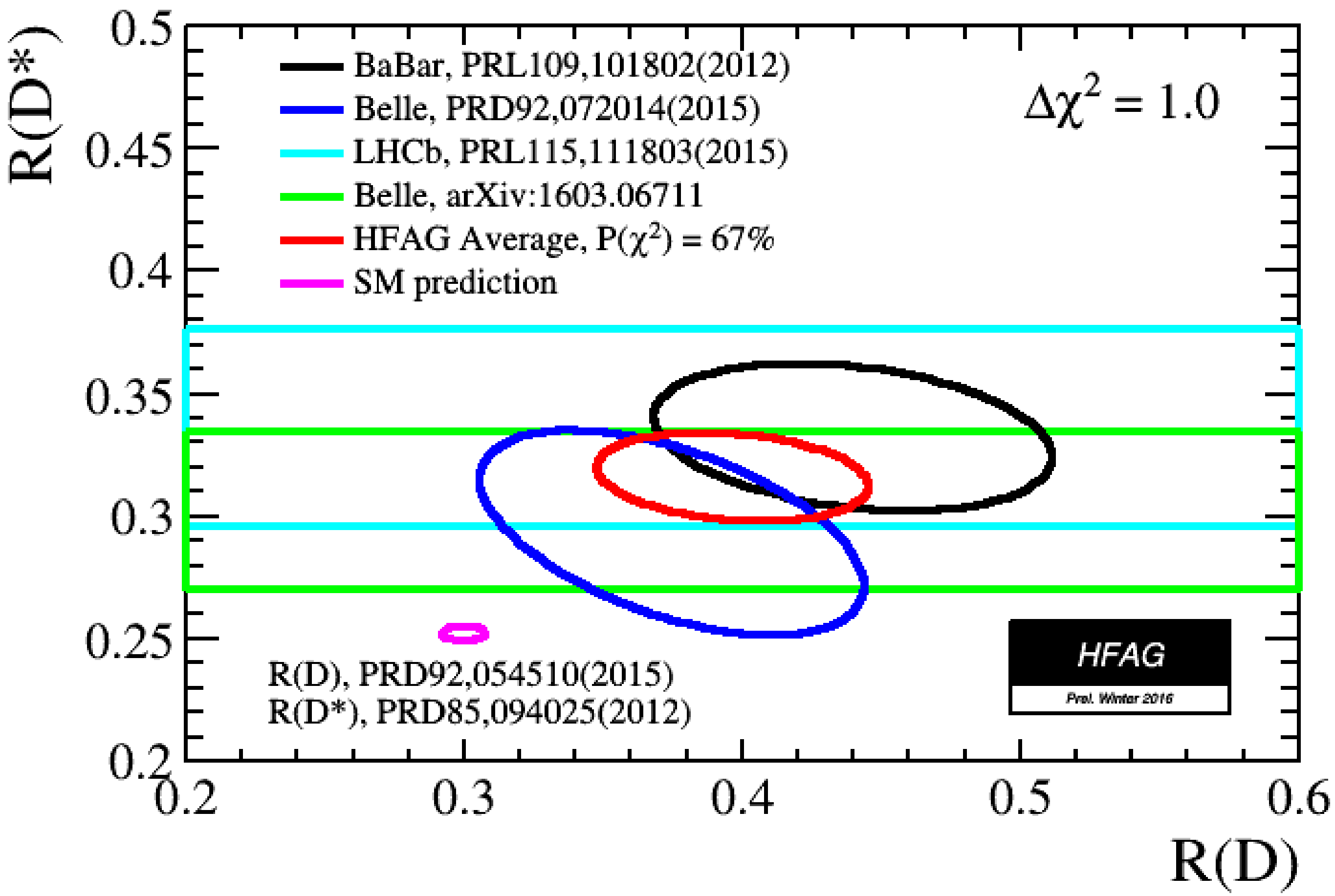


# Systematic Uncertainty

$\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ with Had-tag

| Source | $R(D^*)$ | $P_\tau$ |
|---|---|---|
| Hadronic $B$ composition | $^{+7.8\%}_{-6.9\%}$ | $^{+0.14}_{-0.11}$ |
| MC statistics for each PDF shape | $^{+3.5\%}_{-2.8\%}$ | $^{+0.13}_{-0.11}$ |
| Fake $D^*$ PDF shape | 3.0% | 0.010 |
| Fake $D^*$ yield | 1.7% | 0.016 |
| $\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$ | 2.1% | 0.051 |
| $\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$ | 1.1% | 0.003 |
| $\bar{B} \to D^{*}\ell^-\bar{\nu}_\ell$ | 2.4% | 0.008 |
| $\tau$ daughter and $\ell^-$ efficiency | 2.1% | 0.018 |
| MC statistics for efficiency calculation | 1.0% | 0.018 |
| EvtGen decay model | $^{+0.8\%}_{-0.0\%}$ | $^{+0.016}_{-0.000}$ |
| Fit bias | 0.3% | 0.008 |
| $\mathcal{B}(\tau^- \to \pi^-\nu_\tau)$ and $\mathcal{B}(\tau^- \to \rho^-\nu_\tau)$ | 0.3% | 0.002 |
| $P_\tau$ correction function | 0.1% | 0.018 |
| Common sources | | |
| Tagging efficiency correction | 1.4% | 0.014 |
| $D^*$ reconstruction | 1.3% | 0.007 |
| $D$ sub-decay branching fractions | 0.7% | 0.005 |
| Number of $B\bar{B}$ | 0.4% | 0.005 |
| Total systematic uncertainties | $^{+10.4\%}_{-9.5\%}$ | $^{+0.20}_{-0.17}$ |

# HFAG plot



R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, arXiv:1603.06711
HFAG Average, P(χ²) = 67%
SM prediction
Δχ² = 1.0
R(D), PRD92,054510(2015)
R(D*), PRD85,094025(2012)
HFAG
Prel. Winter 2016
0.2
0.3
0.4
0.5
0.6
R(D)