$\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and Related Tauonic Topics at Belle

Rencontres de Moriond EW 2017

March 23, 2017

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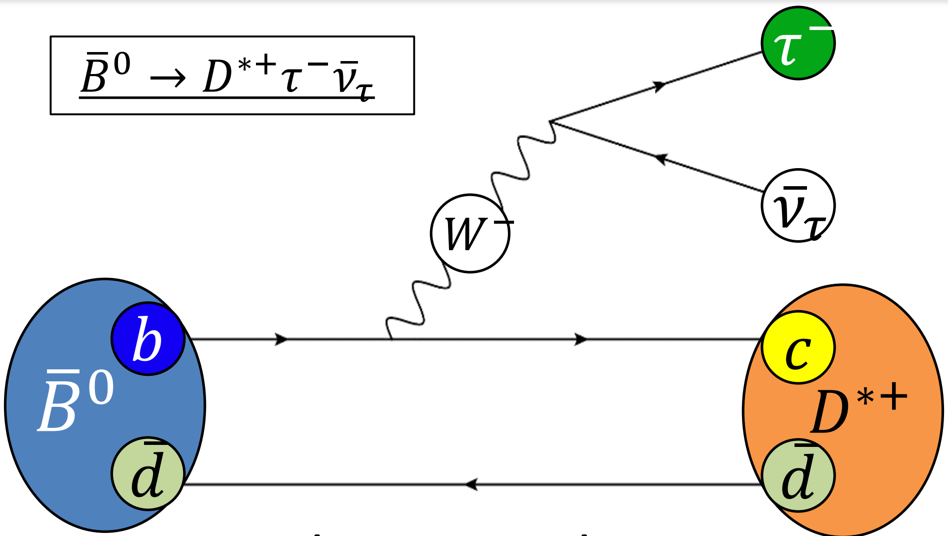
On behalf of the Belle Collaboration

■ $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$



- Test for lepton universality using the ratio:

$$R(D^{(*)}) \equiv \frac{BF(B \to D^{(*)}\tau^-\bar{\nu}_\tau)}{BF(B \to D^{(*)}l^-\bar{\nu}_l)} \ (l^- = e^-, \mu^-)$$

→Uncertainties are largely cancelled: V_{cb}, form factors, efficiency etc.

SM: $R(D) = 0.300 \pm 0.008$ — Fermilab Lattie and MILC Collaborations, Phys. Rev. D 92, 034506 (2015)

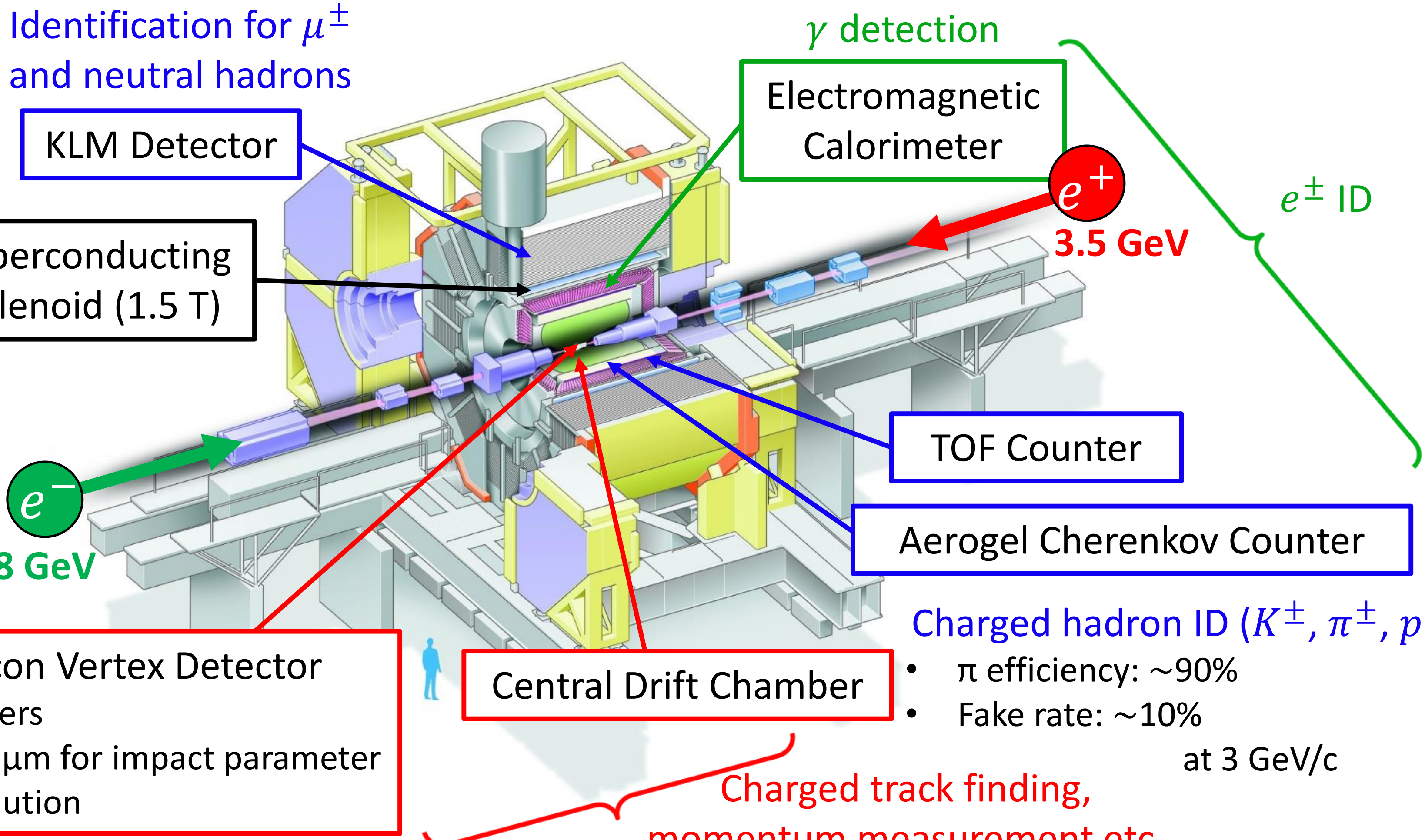
$R(D^*) = 0.252 \pm 0.003$ — S. Fajfer, et al., Phys. Rev. D 85, 094025 (2012)

→An unknown boson (charged Higgs etc.) may modify $R(D^{(*)})$

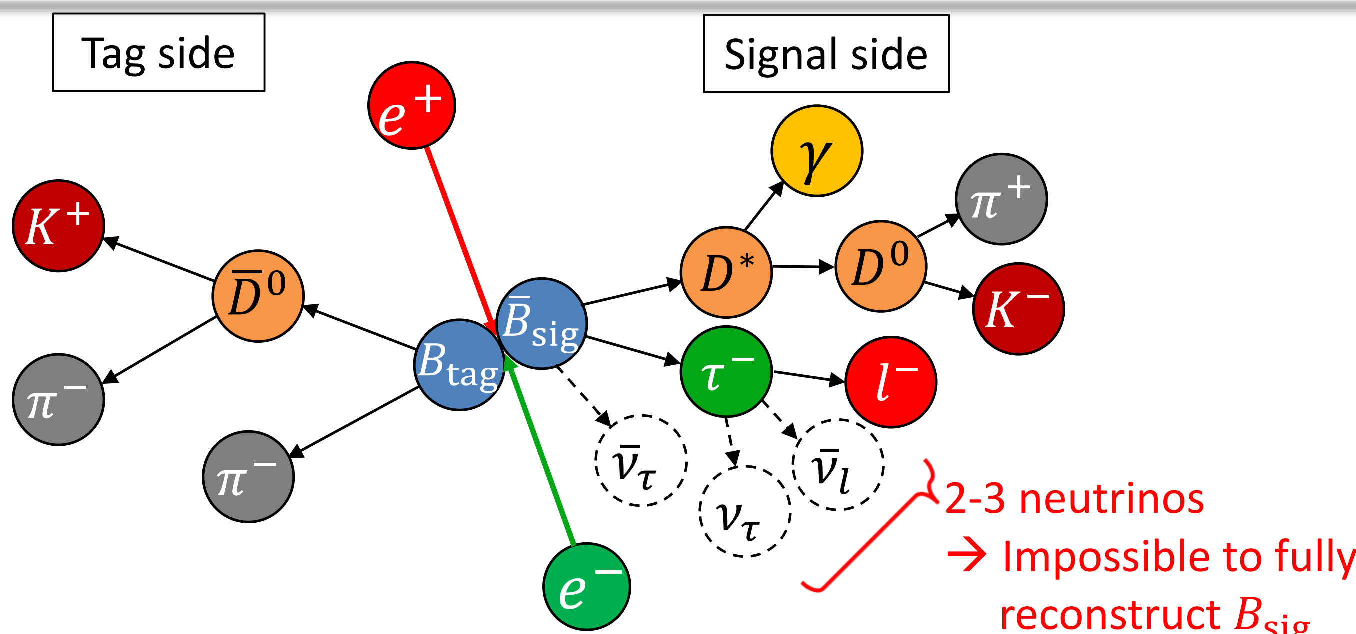
- First observation by Belle in 2007 Belle Collaboration, Phys. Rev. Lett. 99, 191807 (2007)
- 3.9σ discrepancy from the SM has been observed as of 2015
  - Average of the measurements at Belle, BaBar and LHCb
- Two new results from Belle in 2016

Belle Experiment

- KEKB: e^+e^- collider at $\sqrt{s}$ = 10.58 GeV, at KEK in Japan
  - Produce B mesons via $\Upsilon(4S) \rightarrow B\bar{B}$
- World record luminosity; Data contains 7.72×10^8 $B\bar{B}$



■ Tagging Method



- Tag a counterpart B meson ($B_{\rm tag}$) using <u>hadronic</u> or <u>semileptonic</u> decays

  →Obtain information of $B_{\rm sig}$ indirectly

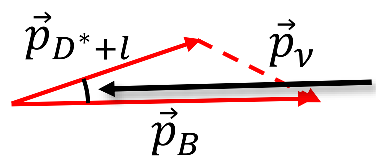
- Three results with full data sample
  - Hadronic tag + $\tau^- \to l^-\bar{\nu}_l\nu_\tau$ for $R(D)$ and $R(D^*)$ Belle Collaboration, Phys. Rev. D 92, 072014 (2015)
  - Semileptonic tag + $\tau^- \to l^-\bar{\nu}_l\nu_\tau$ for $R(D^*)$
  - Hadronic tag + $\tau^- \to h^-\nu_\tau$ for $R(D^*)$ and τ polarization

  } **Today's topic**

■ $R(D^*)$ with Semileptonic Tagging

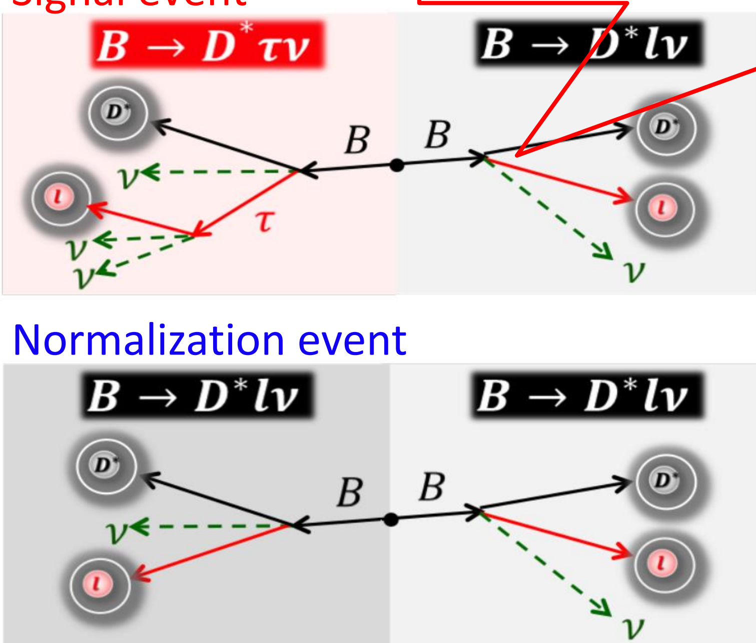
- Independent analysis of the previous $R(D^{(*)})$ measurement
- More background due to a ν in $\bar{B}_{\rm tag} \to D^{(*)} l^- \bar{\nu}_l$

  →Focus on $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$
- Signal/normalization separation based on smaller $\cos\theta_{B-D^*l}$

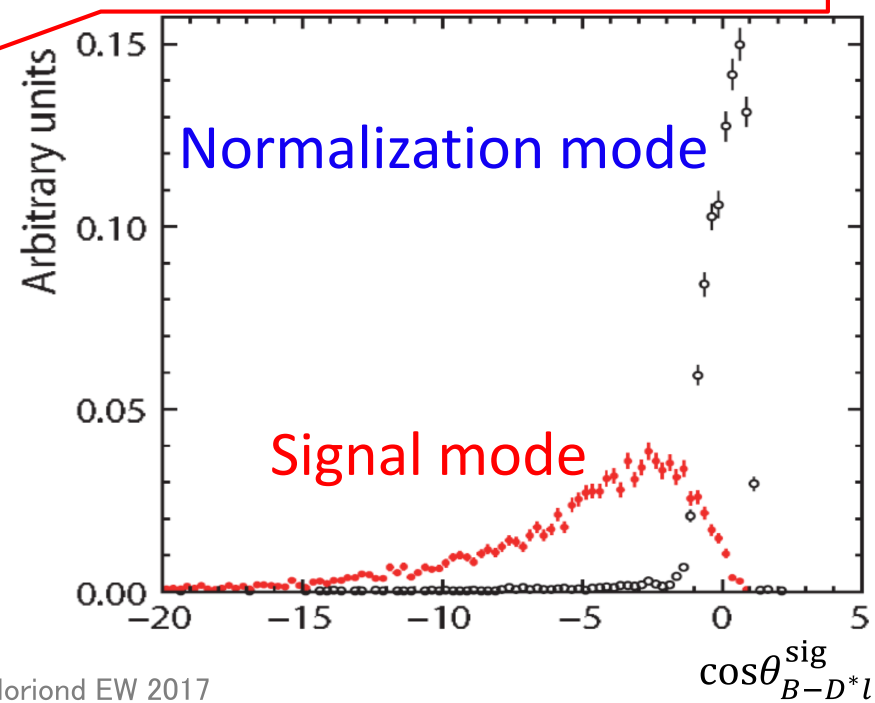


$$\cos\theta_{B-D^*l} = \frac{E^*_{\rm beam} E^*_{D^*l} - m_B^2 - m_{D^*l}^2}{2|p^*_{\rm beam}||p^*_{D^*l}|}$$

Signal event



Normalization event



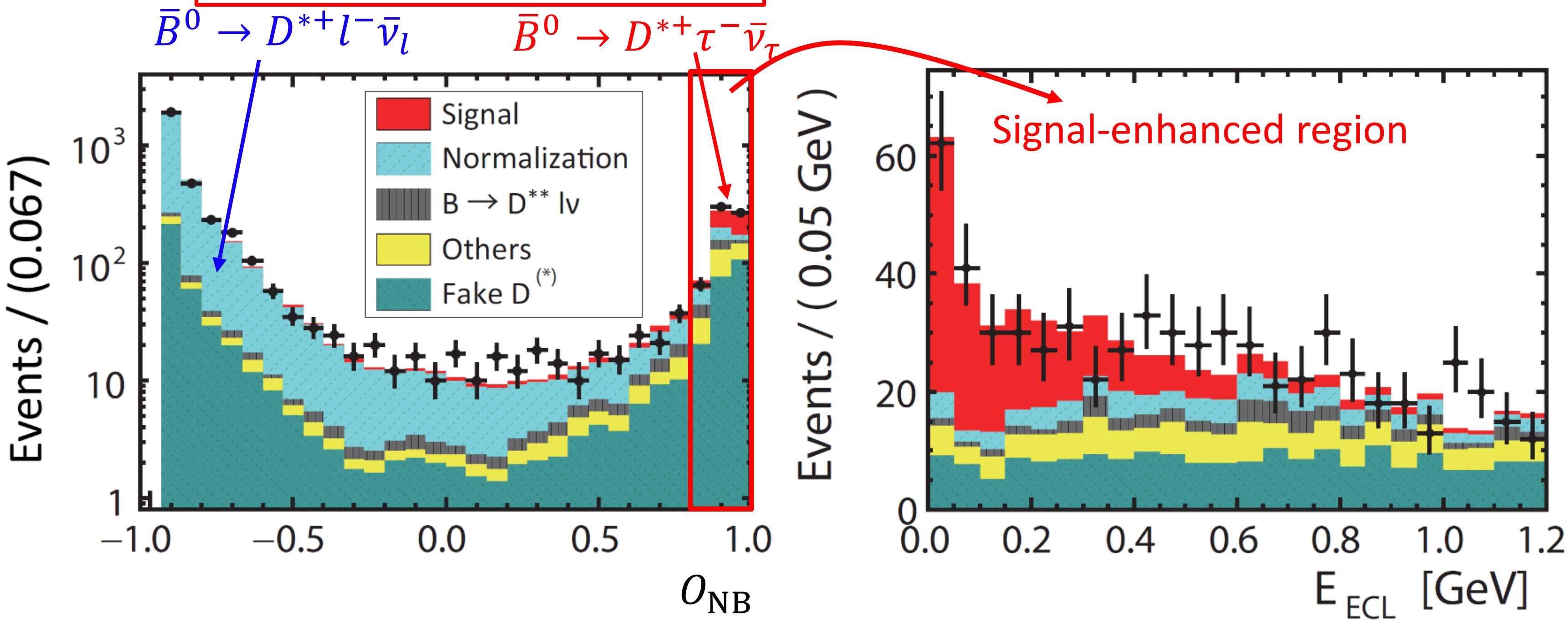
Belle Collaboration, Phys. Rev. D 94, 072007 (2016)

■ Signal Extraction

- Two-dimensional fit to neural network output (O_{NB}) and E_{ECL}

- $\cos\theta^{\mathrm{sig}}_{B-D^{*}l}$
- M^2_{miss}
- Total energy of $B_{\mathrm{tag}} + B_{\mathrm{sig}}$

Summed energy, not used for the event reconstruction



$$R(D^*) = 0.302 \pm 0.030\,(\mathrm{stat.}) \pm 0.011(\mathrm{syst.})$$

First measurement of $\bar{B} \to D^{*}\tau^{-}\bar{\nu}_{\tau}$ using the semileptonic tagging

Compatibility with the SM is 1.6σ

Belle Collaboration, arXiv:1612.00529 (submitted to Phys. Rev. Lett.)

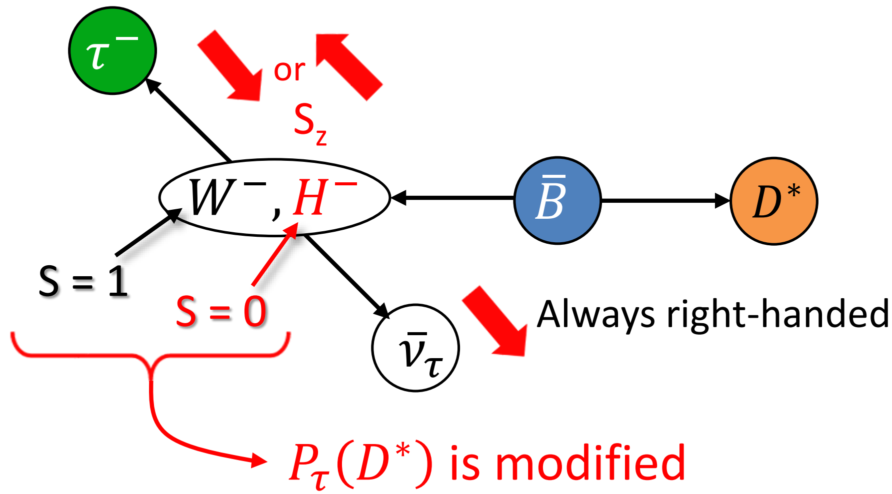
■ $R(D^*)$ and $P_\tau(D^*)$ with Hadronic τ Decays

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

$\Gamma^{+(-)}$ for right-(left-)handed τ

$$P_\tau(D^*)_{SM} = -0.497 \pm 0.013$$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)



- τ polarization is a variable sensitive to NP
  - It can be measured using two-body decays of τ

Target of this analysis

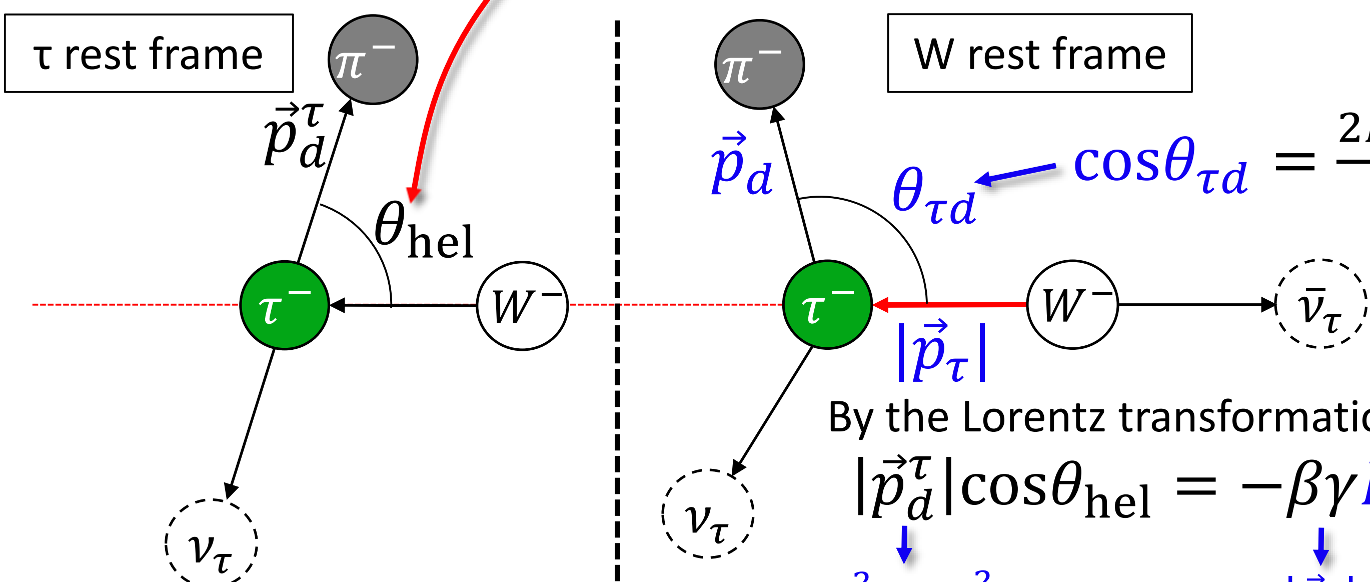
- First measurement of $P_\tau(D^*)$ using $\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau$
- New measurement of $R(D^*)$
  - Independent study of previous measurements using $\tau^- \to l^-\bar{\nu}_l\nu_\tau$

    → Different final state = different background

■ $P_\tau(D^*)$ Measurement Method

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1}{2}(1 + \alpha P_\tau(D^*)\cos\theta_{\rm hel})$$

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



$$\cos\theta_{\tau d} = \frac{2E_\tau E_d - m_\tau^2 - m_d^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_d|}$$

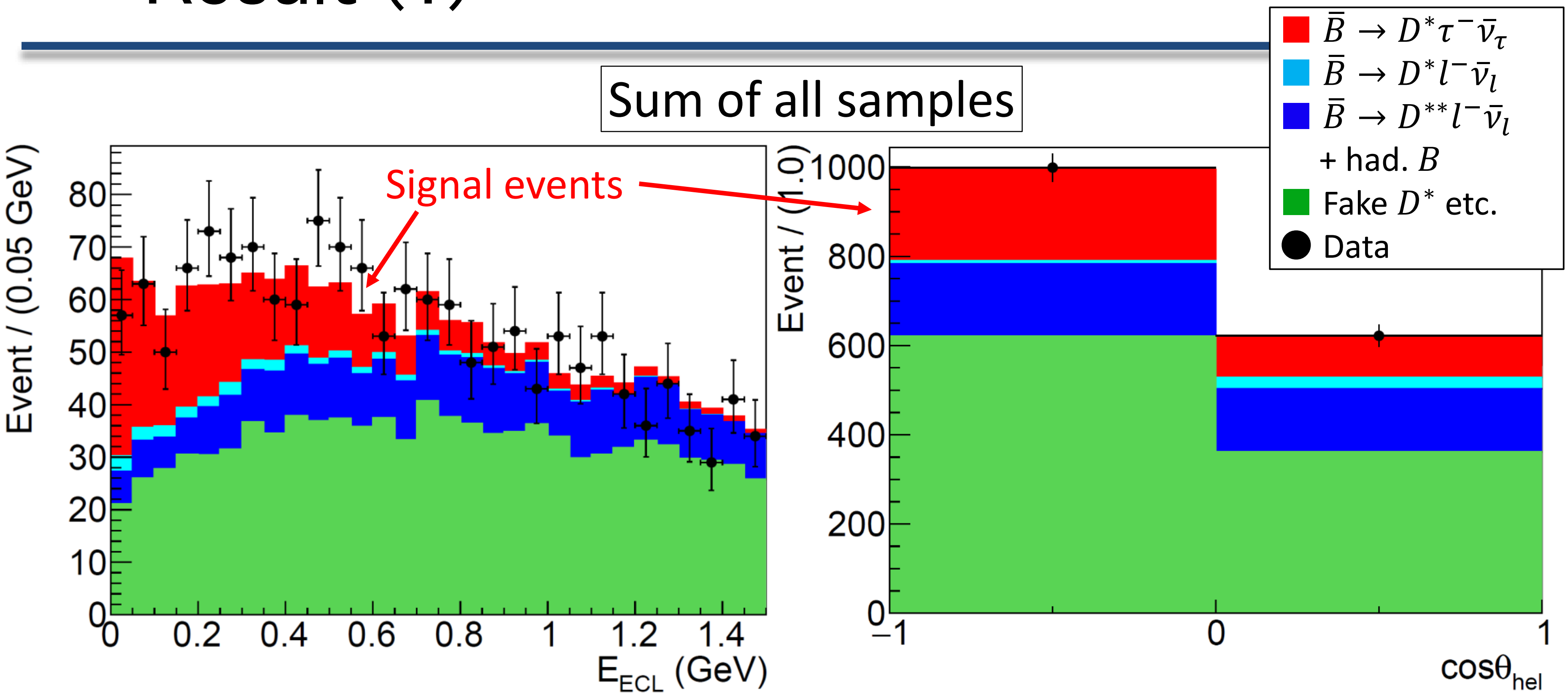
By the Lorentz transformation,

$$|\vec{p}_d^{\,\tau}|\cos\theta_{\rm hel} = -\beta\gamma E_d + \gamma|\vec{p}_d|\cos\theta_{\tau d}$$

$$|\vec{p}_d^{\,\tau}| \to \frac{m_\tau^2 - m_d^2}{m_\tau^2}, \quad \beta\gamma \to \frac{|\vec{p}_\tau|}{m_\tau}, \quad \gamma \to \frac{E_\tau}{m_\tau}$$

Solving the equation, $\cos\theta_{\rm hel}$ is obtained!

■ Result (1)

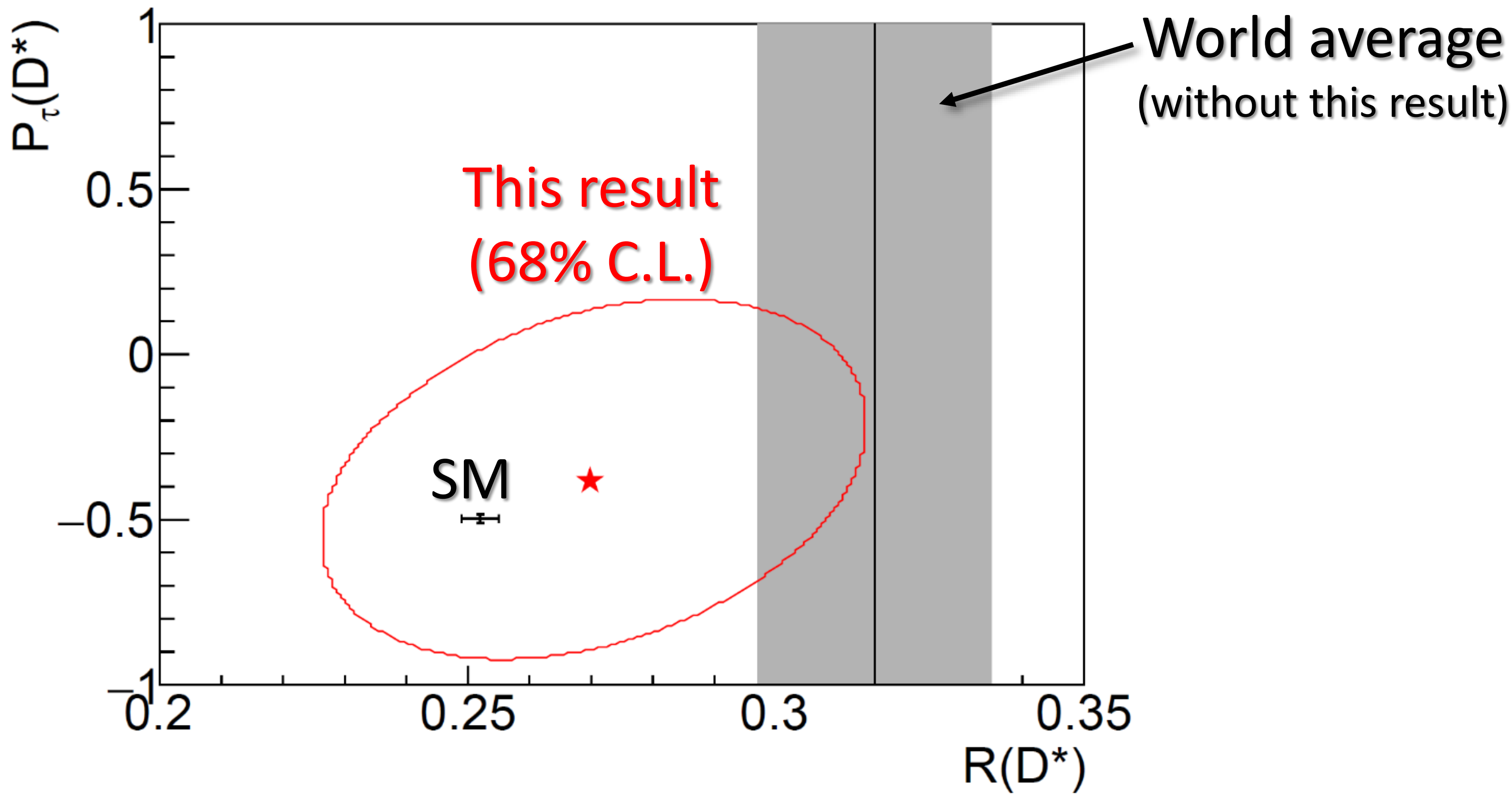


- Signal significance of about 7σ
  - First observation of the $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ signal using only hadronic τ decays

$$R(D^*) = 0.270 \pm 0.035(\text{stat.})\,^{+0.028}_{-0.025}(\text{syst.})$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})\,^{+0.21}_{-0.16}(\text{syst.})$$

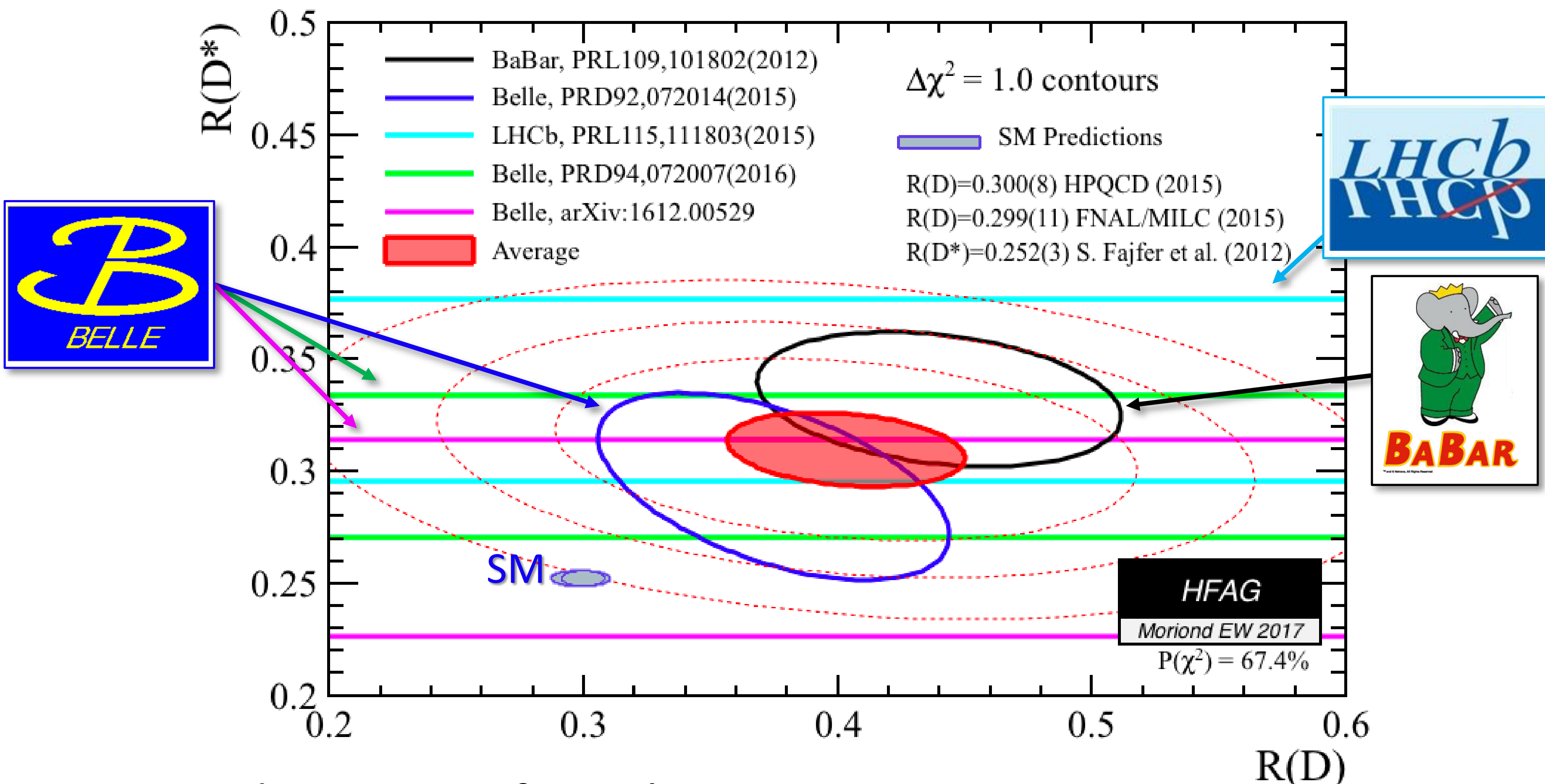
Compatibility with the SM within 0.4σ

■ Result (2)



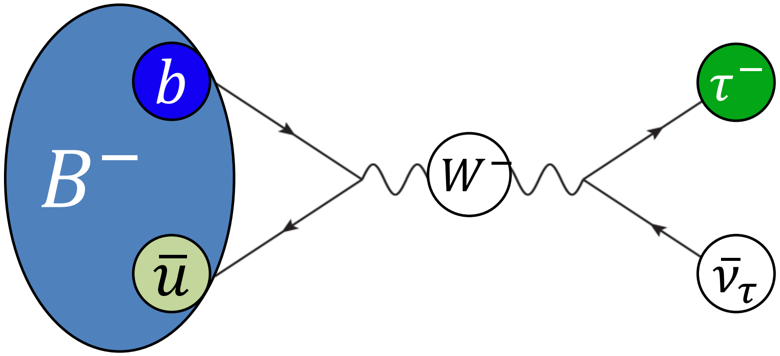
- Result is consistent with the SM within 0.4σ
- Excludes $P_\tau(D^*)$ > +0.5 at 90% C.L.→First result of $P_\tau(D^*)$
- First $R(D^*)$ measurement only with hadronic τ decays
  - Precision of 16%; comparable to the previous measurements (9-14%)

■ $R\left(D^{(*)}\right)$ by HFAG



- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R\left(D^{(*)}\right)$ than the SM
- More precise measurements at Belle II and LHCb are essential

■ $B^- \to \tau^- \bar{\nu}_\tau$



$$BF(B^- \to \tau^- \bar{\nu}_\tau)_{\rm SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Contains a τ lepton
- Rare decay at O(10^{-4})

} Good probe for NP coupling to τ

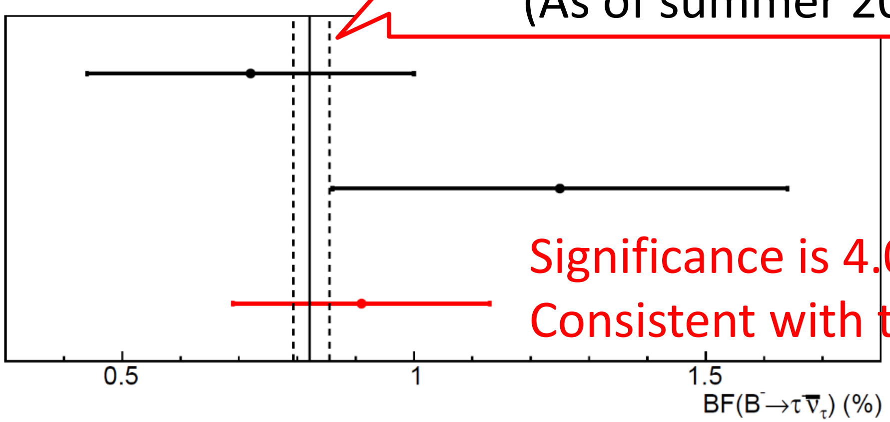
- Two measurements with full data

SM prediction by the CKM fitter (As of summer 2016)

Phys. Rev. Lett. 110, 131801 (2013)
(Hadronic tagging)

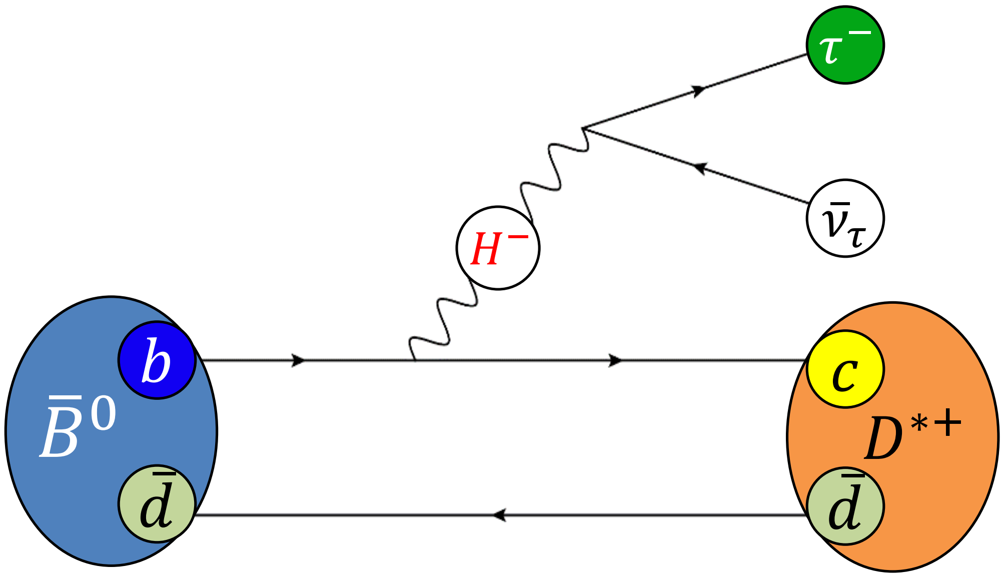
Phys. Rev. D 92, 051102 (R) (2015)
(Semileptonic tagging)

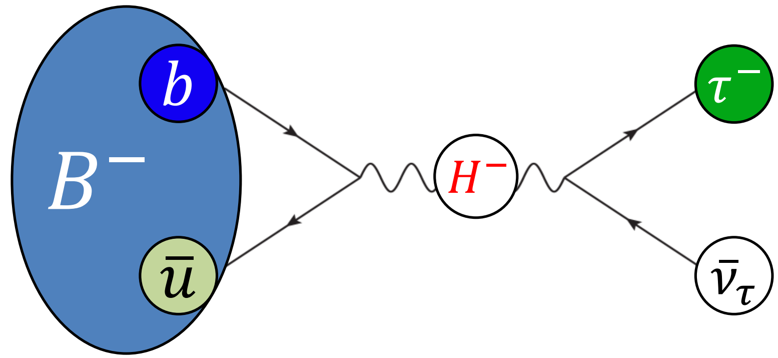
Belle average



Significance is 4.0σ
Consistent with the SM

Charged Higgs in Type-II 2HDM (1)





- Charged Higgs appears in the Two Higgs Doublet Model
  - Large coupling to the τ lepton
- Contribution from Type-II 2HDM

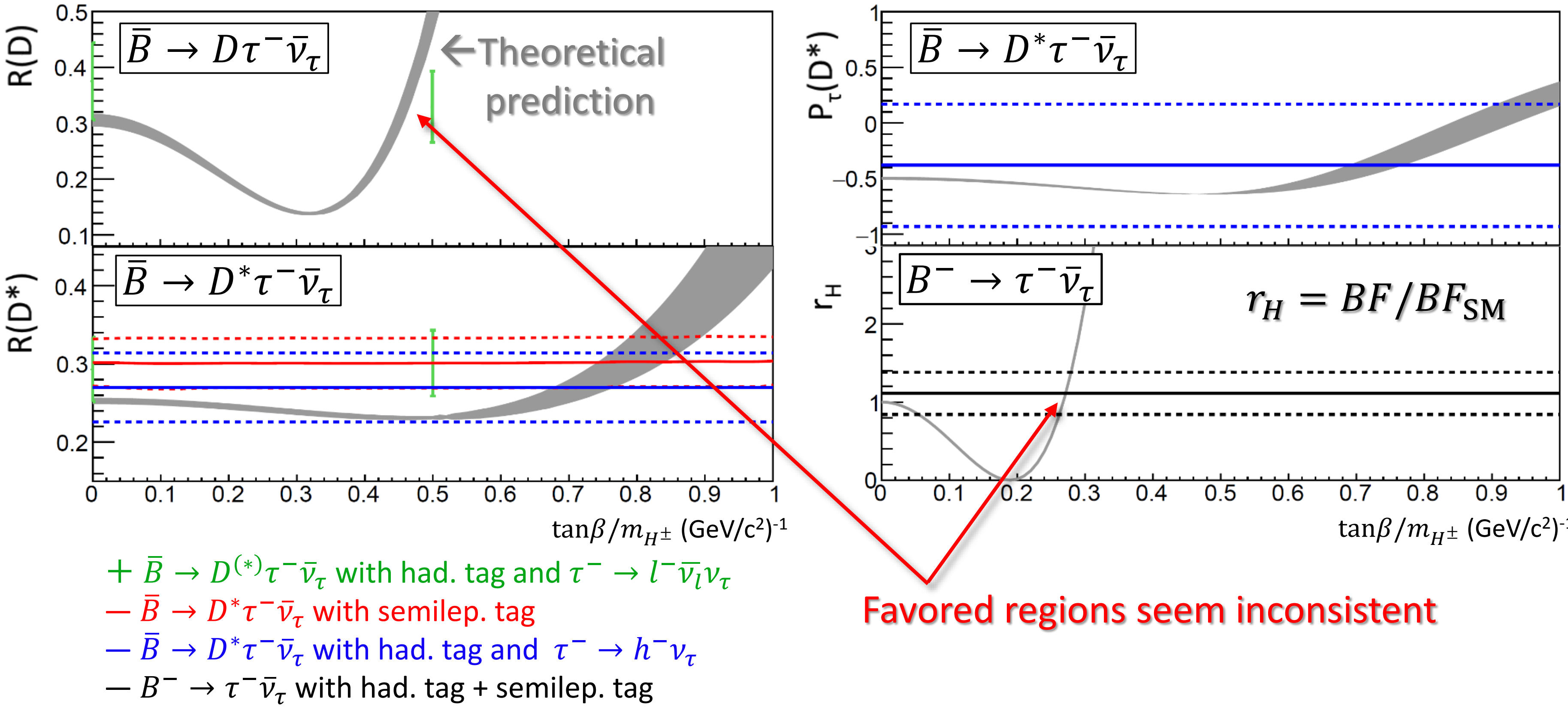
Ratio of VEV in two Higgs doublets

$$\mathcal{L}_{\mathrm{eff}} = -2\sqrt{2} G_F V_{ib} \left[O_{\mathrm{SM}} - m_b m_\tau \frac{\tan^2\beta}{m_{H^\pm}^2} O_S \right] \begin{cases} i = c \text{ for } \bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau \\ i = u \text{ for } B^- \to \tau^- \bar{\nu}_\tau \end{cases}$$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)
W.-S. Hou, Phys. Rev. D 48, 2342 (1993)

Both modes have negative interference of charged Higgs with the SM

■ Charged Higgs in Type-II 2HDM (2)



- All the results are consistent with, but always larger than the SM
- Large value of $\tan\beta/m_{H^\pm}$ seems disfavored

Summary

- $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and $B^- \to \tau^-\bar{\nu}_\tau$ are interesting modes in terms of sensitivity to NP such as charged Higgs

- Belle released two new measurements for $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ in 2016
  - First application of semileptonic tagging to the $R(D^*)$ measurement
  - First measurement of $P_\tau(D^*)$ by hadronic tag + $\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau$

- The results for (semi-)tauonic decays at Belle are close to the SM
  - However, world-average $R\left(D^{(*)}\right)$ including results from BaBar and LHCb shows ~4σ deviation from the SM

Important to improve precision at Belle II