Belle Results on $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and $B^- \to \tau^-\bar{\nu}_\tau$

March 27, 2017

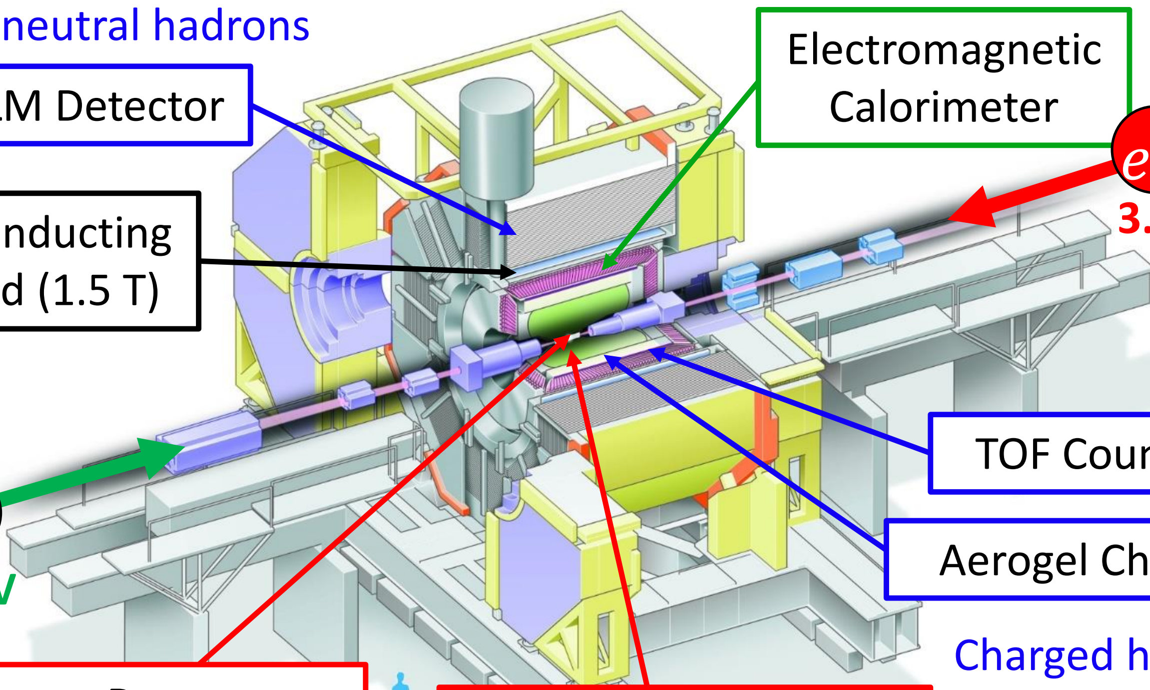
Mini-workshop on $D^{(*)}\tau^-\bar{\nu}_\tau$ and Related Topics

Shigeki Hirose

(Nagoya University)

Belle Experiment

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

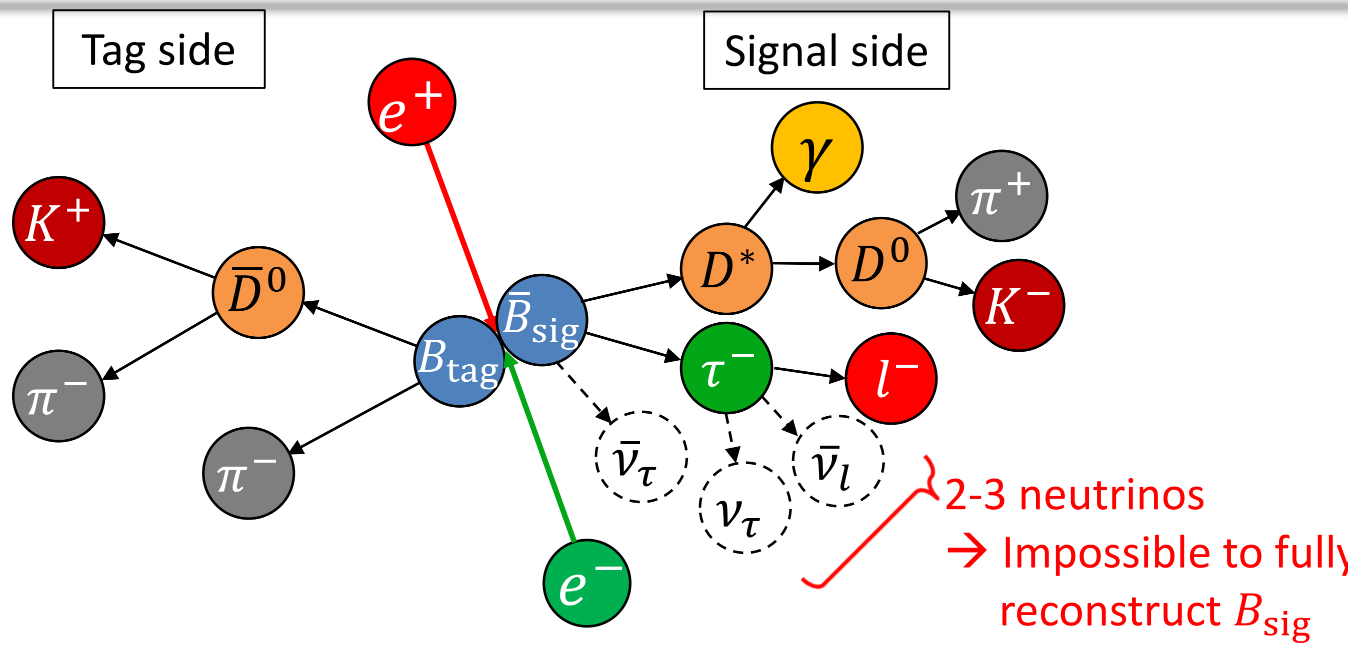


Silicon Vertex Detector
- 4 layers
- ~40 µm for impact parameter resolution

Charged hadron ID ($K^\pm$, $\pi^\pm$, p)
- π efficiency: ~90%
- Fake rate: ~10%

at 3 GeV/c

Analysis Method



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

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

- For $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$, we measure

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

(Semi-)Tauonic Studies at Belle

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

Tag method	τ decay	$N_{B\bar{B}}$	Reference
Inclusive	$\pi^-\nu_\tau, l^-\bar{\nu}_l\nu_\tau$	535 M	PRL 99, 191807 (2007)
Inclusive	$\pi^-\nu_\tau, l^-\bar{\nu}_l\nu_\tau$	657 M	PRD 82, 072005 (2010)
Hadronic	$l^-\bar{\nu}_l\nu_\tau$	772 M	PRD 92, 072014 (2015)
Semileptonic	$l^-\bar{\nu}_l\nu_\tau$	772 M	PRD 94, 072007 (2016)
Hadronic	$\pi^-\nu_\tau, \rho^-\nu_\tau$	772 M	arXiv:1612.00529

First Observation of $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$

First measurement of τ polariztaion

Inclusive reconstruction for hadronic B_{tag} decays

- $B^- \to \tau^-\bar{\nu}_\tau$

Tag method	τ decay	$N_{B\bar{B}}$	Reference
Hadronic	$\pi^-\nu_\tau, \rho^-\nu_\tau,$ $\pi^-\pi^+\pi^-\nu_\tau, l^-\bar{\nu}_l\nu_\tau$	449 M	PRL 97, 251802 (2006)
Semileptonic	$\pi^-\nu_\tau, l^-\bar{\nu}_l\nu_\tau$	657 M	PRD 82, 071101(R) (2010)
Hadronic	$\pi^-\nu_\tau, \rho^-\nu_\tau, l^-\bar{\nu}_l\nu_\tau$	772 M	PRL 110, 131801 (2013)
Semileptonic	$\pi^-\nu_\tau, \rho^-\nu_\tau, l^-\bar{\nu}_l\nu_\tau$	772 M	PRD 92, 051102(R) (2016)

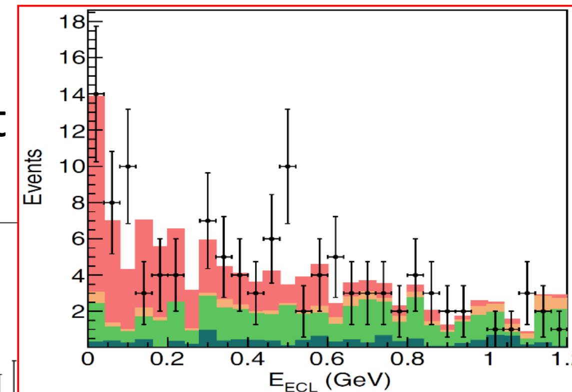
First evidence

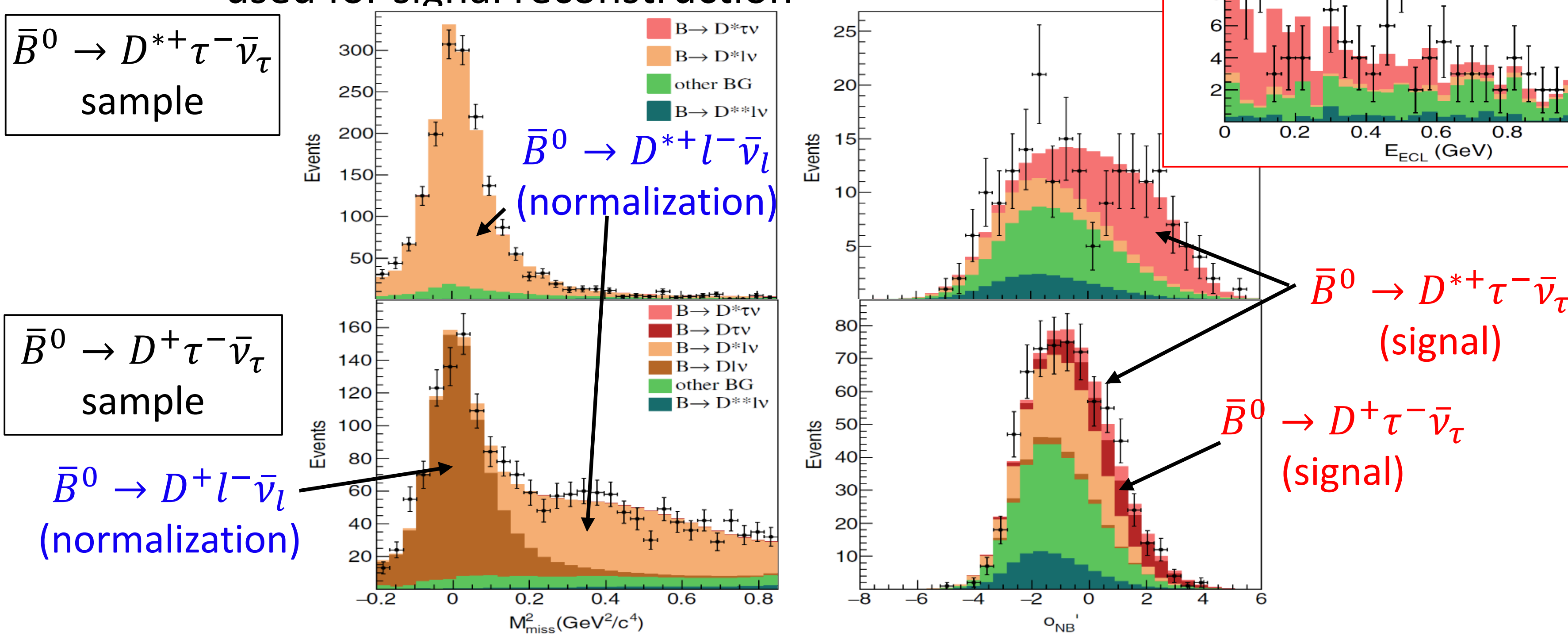
: Important contribution of Nagoya group

Belle Collaboration, Phys. Rev. D 92, 072014 (2015)

■ $R(D^{(*)})$ with Hadronic Tagging

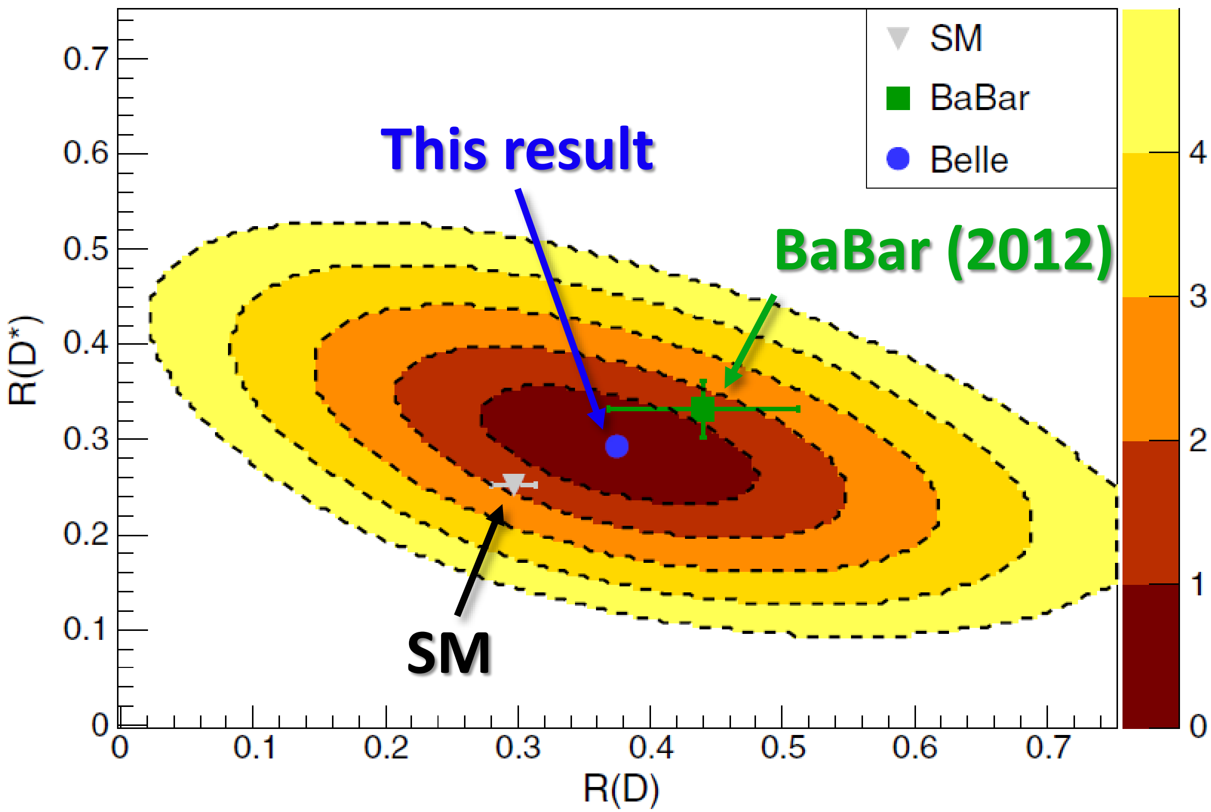
- $M^2_{\rm miss}$ to measure $\bar{B} \to D^{(*)} l^- \bar{\nu}_l$
  - $M^2_{\rm miss} = \left(p_{e^+e^-} - p_{B_{\rm tag}} - p_{D^{(*)}} - p_l\right)^2$ → 0 GeV²/c⁴
- (Transformed) neural network output ($O_{\rm NB}'$) to measure $\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau$
  - Powerful variable is $E_{\rm ECL}$: sum of ECL energy not used for signal reconstruction





Belle Collaboration, Phys. Rev. D 92, 072014 (2015)

■ $R(D^{(*)})$ Result



Strong correlation due to cross-feed between $\bar{B} \to D\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$

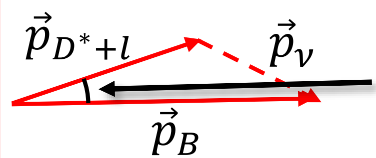
$$R(D) = 0.375 \pm 0.064(\mathrm{stat.}) \pm 0.026(\mathrm{syst.})$$
$$R(D^*) = 0.293 \pm 0.038(\mathrm{stat.}) \pm 0.015(\mathrm{syst.})$$

→Compatibility with the SM is 1.8σ

■ $R(D^*)$ with Semileptonic Tagging

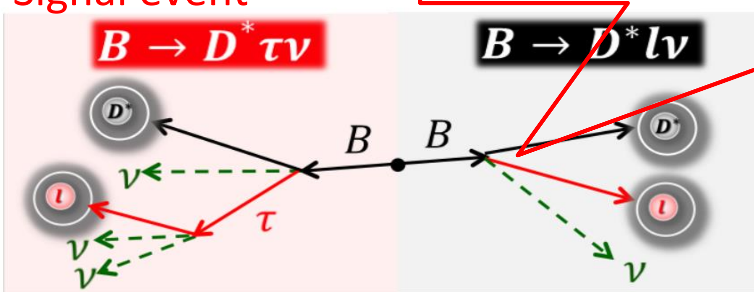
- Independent analysis of the previous $R(D^{(*)})$ measurement
- More background due to a ν in $\bar{B}_{\rm tag} \to D^{(*)} l^- \bar{\nu}_l$

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

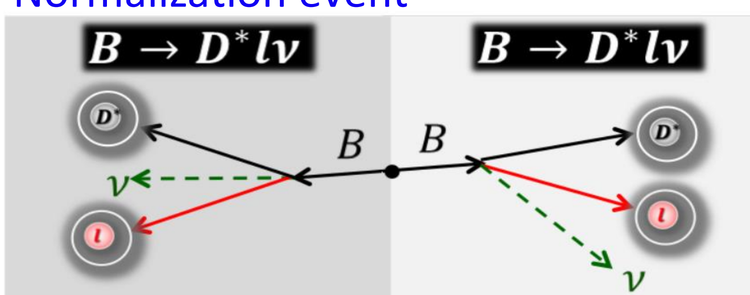


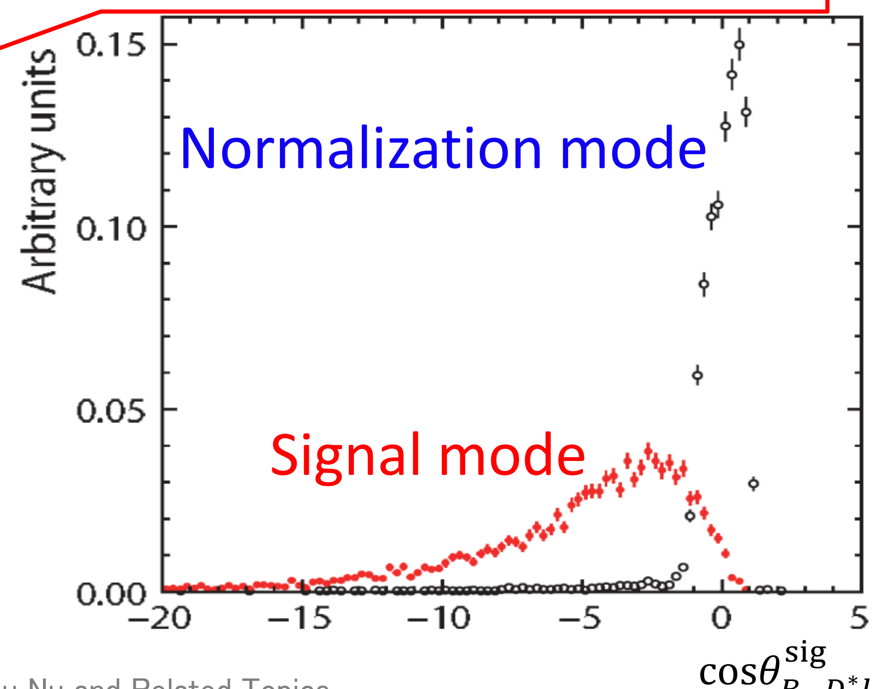
$$\cos\theta_{B-D^*l} = \frac{E^*_{\rm beam} E^*_{D^*l} - m_B^2 - m_{D^*l}^2}{2|p^*_{\rm beam}||p^*_{D^*l}|}$$

Signal event



Normalization event



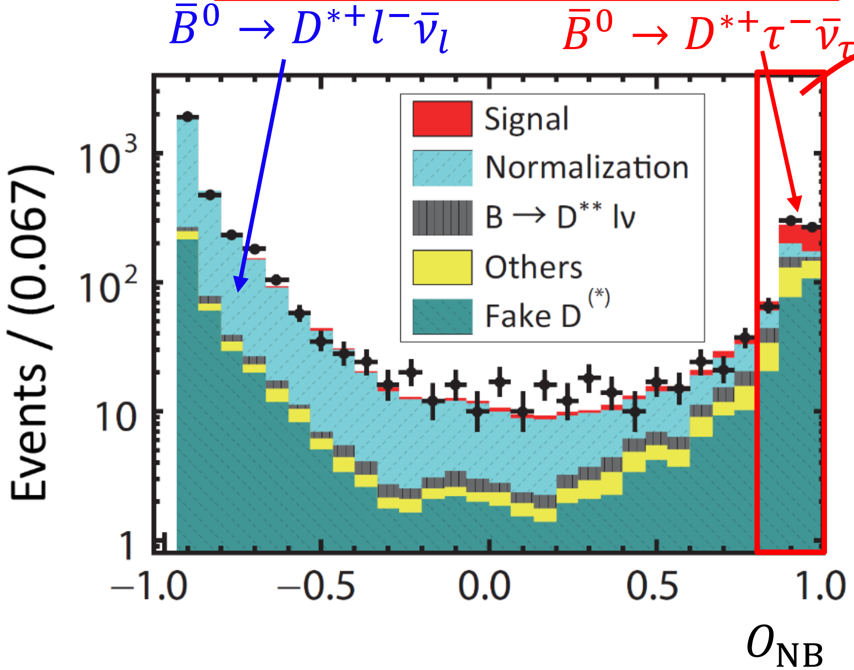


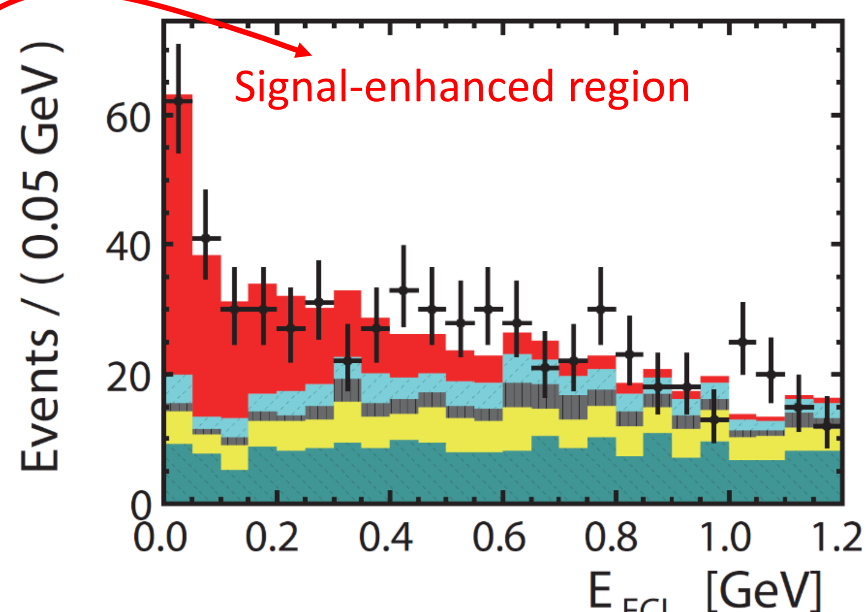
Signal Extraction

- 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

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

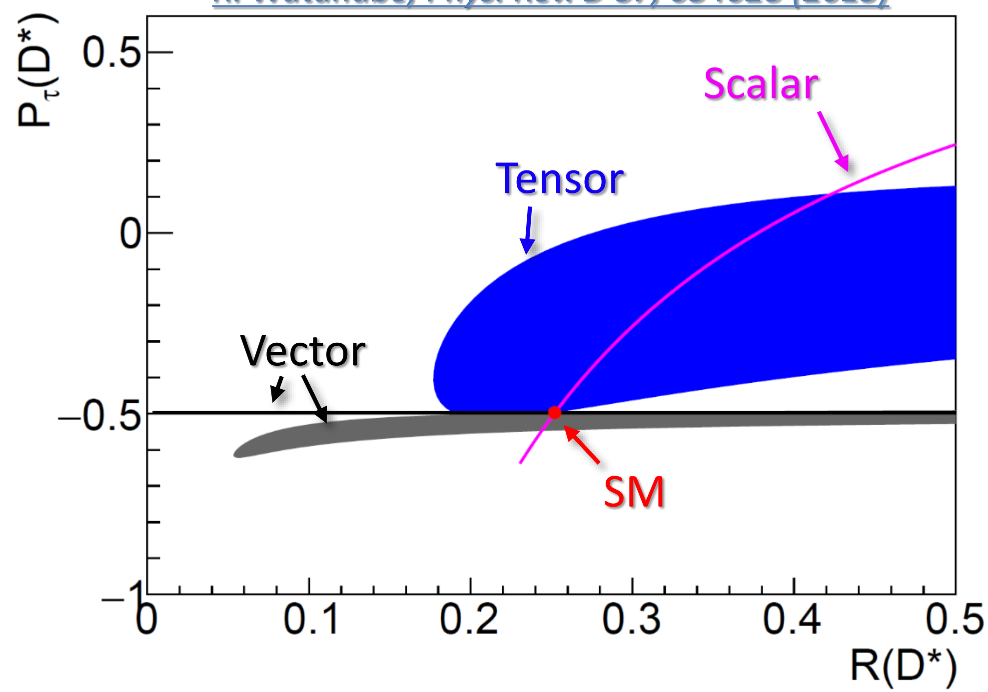
$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^{+(-)}$ 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)

Theoretical calculation based on M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)



- τ polarization is a variable sensitive to NP

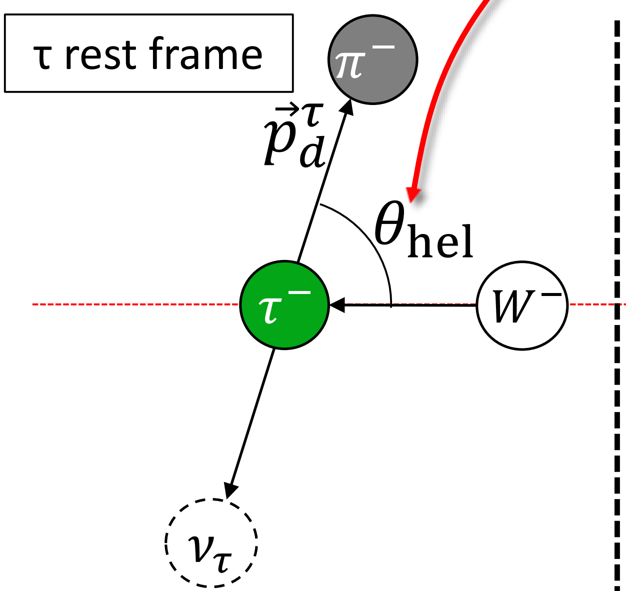
Target of this analysis

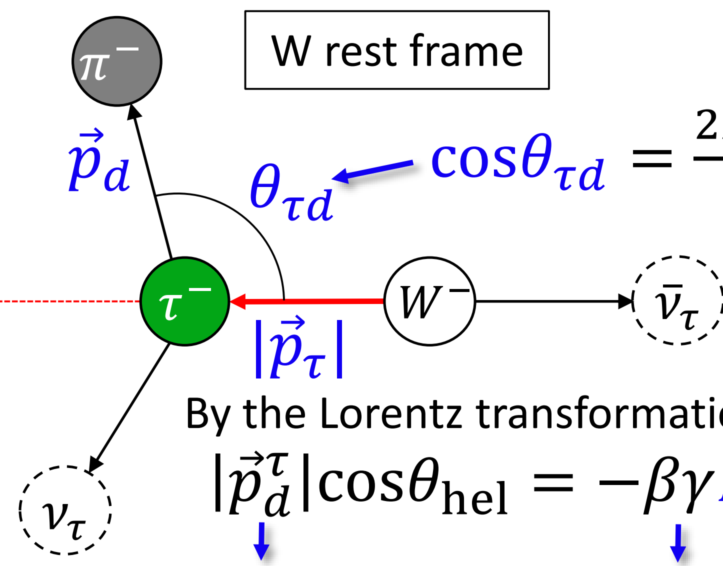
- First measurement of $P_\tau(D^*)$ using $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$
- New measurement of $R(D^*)$
  - Independent study of previous measurements using $\tau^- \to l^- \bar{\nu}_l \nu_\tau$

■ $P_\tau(D^*)$ Measurement Method

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

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





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

By the Lorentz transformation,

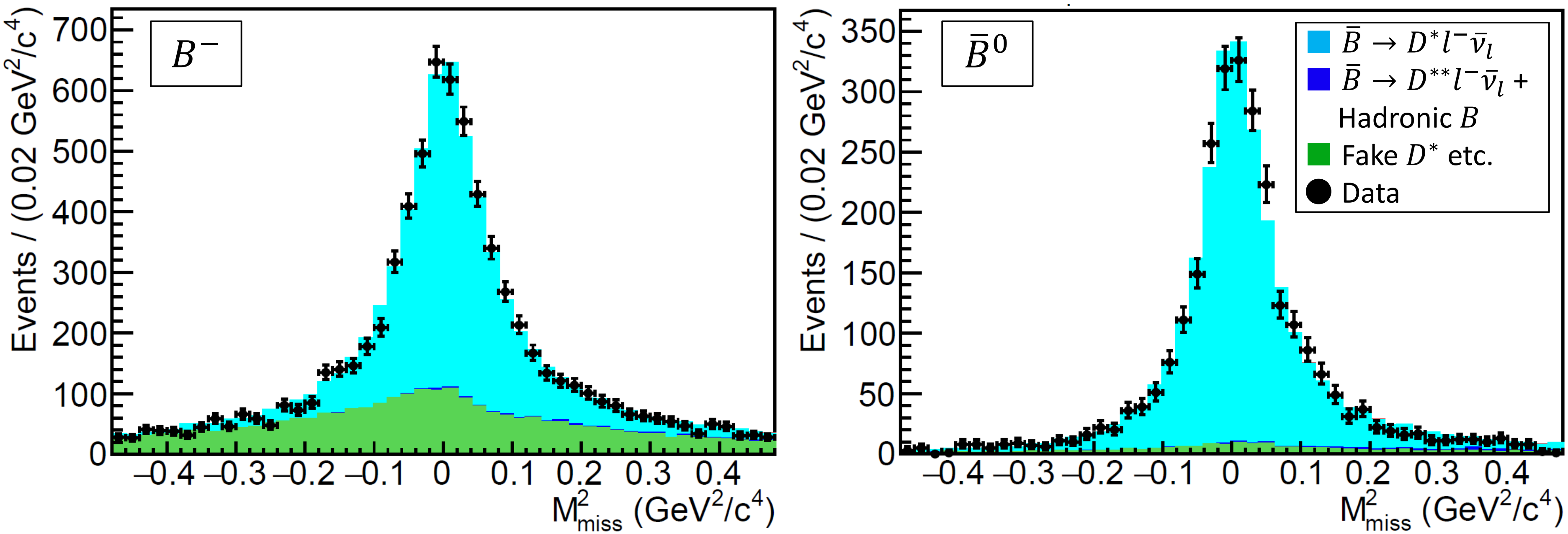
$$|\vec{p}_d^{\,\tau}|\cos\theta_{\mathrm{hel}} = -\beta\gamma E_d + \gamma|\vec{p}_d|\cos\theta_{\tau d}$$

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

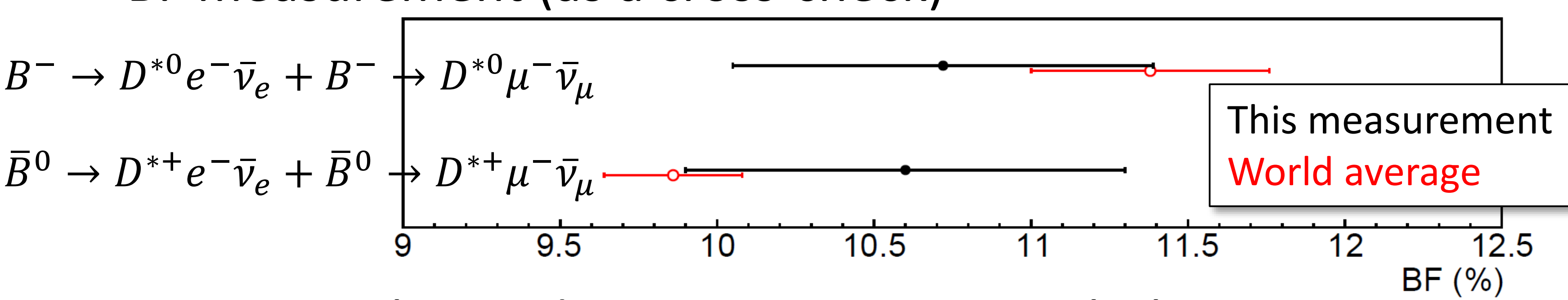
Solving the equation, $\cos\theta_{\mathrm{hel}}$ is obtained!

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

Fit to Normalization Mode

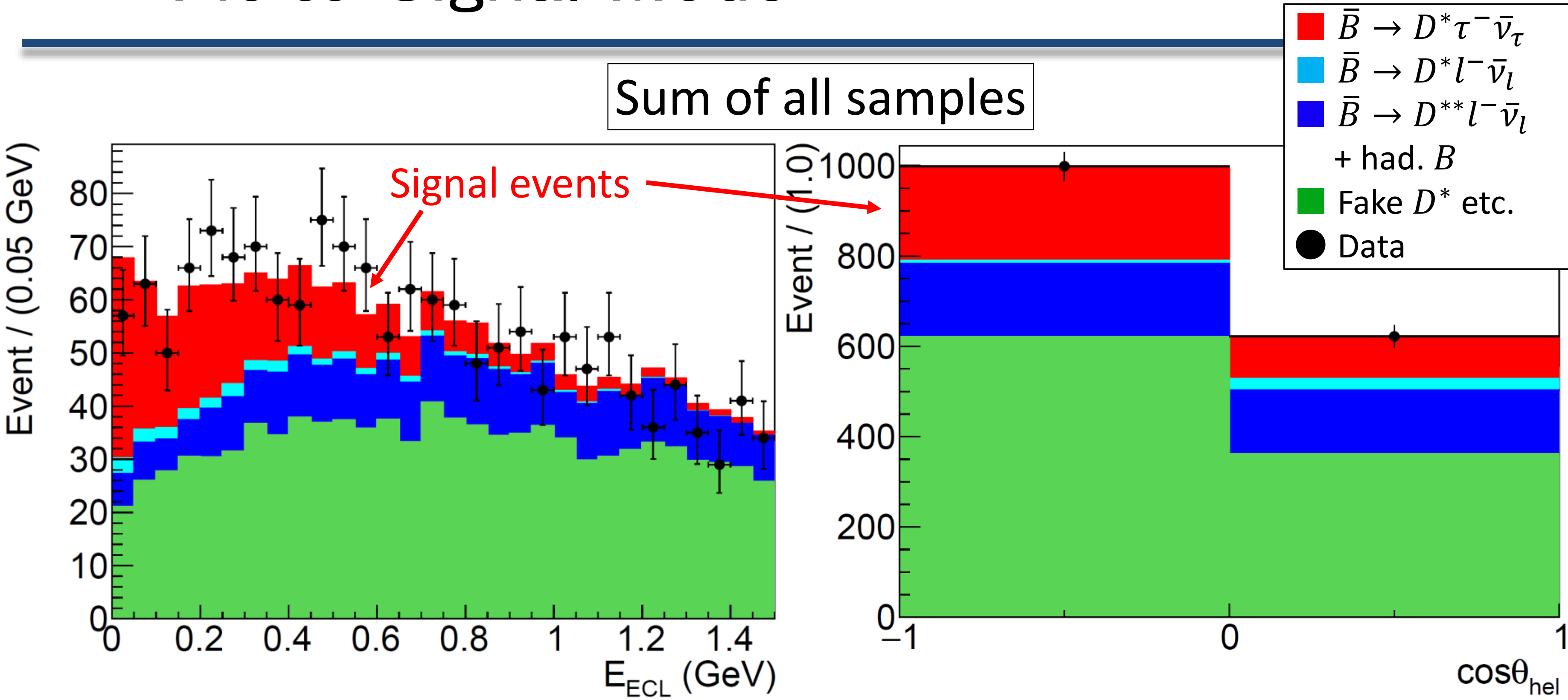


- Use $M^2_{\mathrm{miss}} = \left(p_{e^+e^-} - p_{\mathrm{tag}} - p_{D^*} - p_l\right)^2$
- BF measurement (as a cross-check)



Obtained BFs are consistent with the WA

■ Fit to Signal Mode



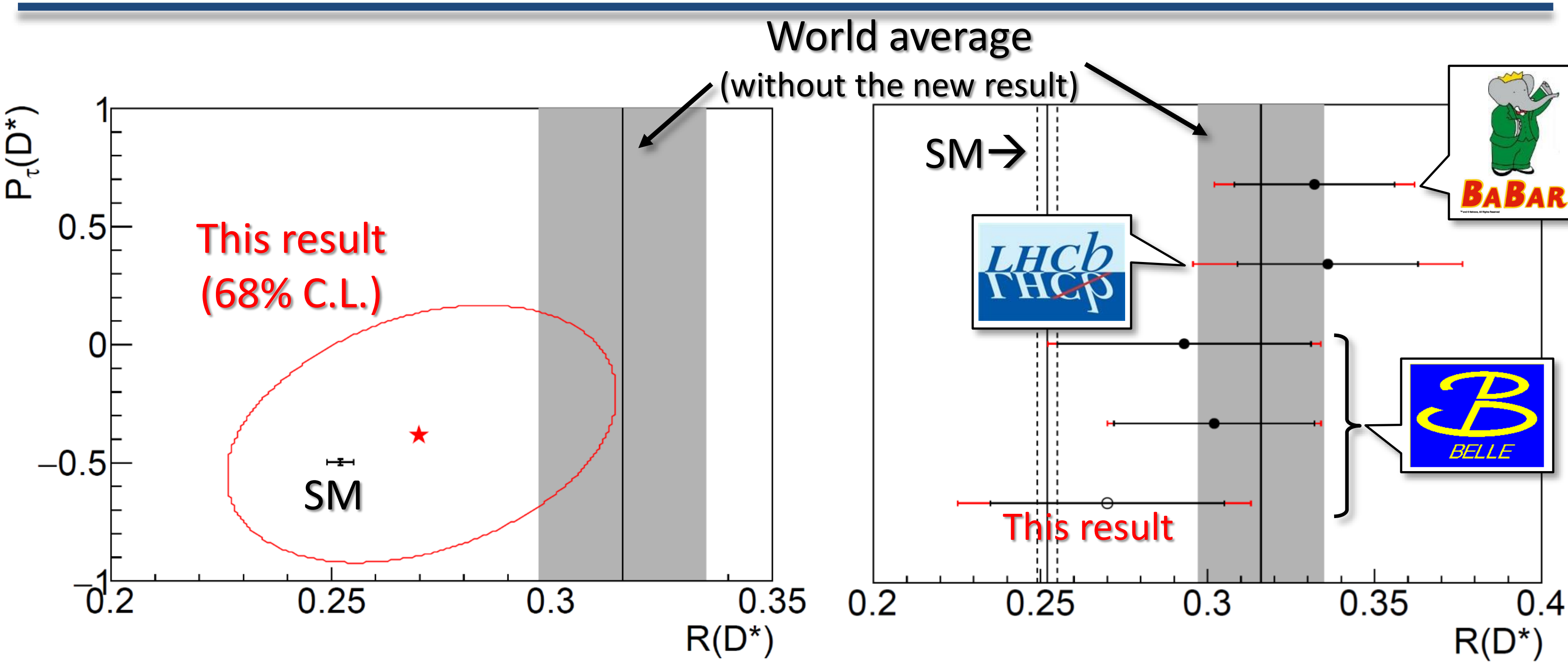
- Signal significance of about 7σ
  - First observation of the $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ signal using only hadronic τ decays

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

Compatibility with the SM within 0.4σ

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

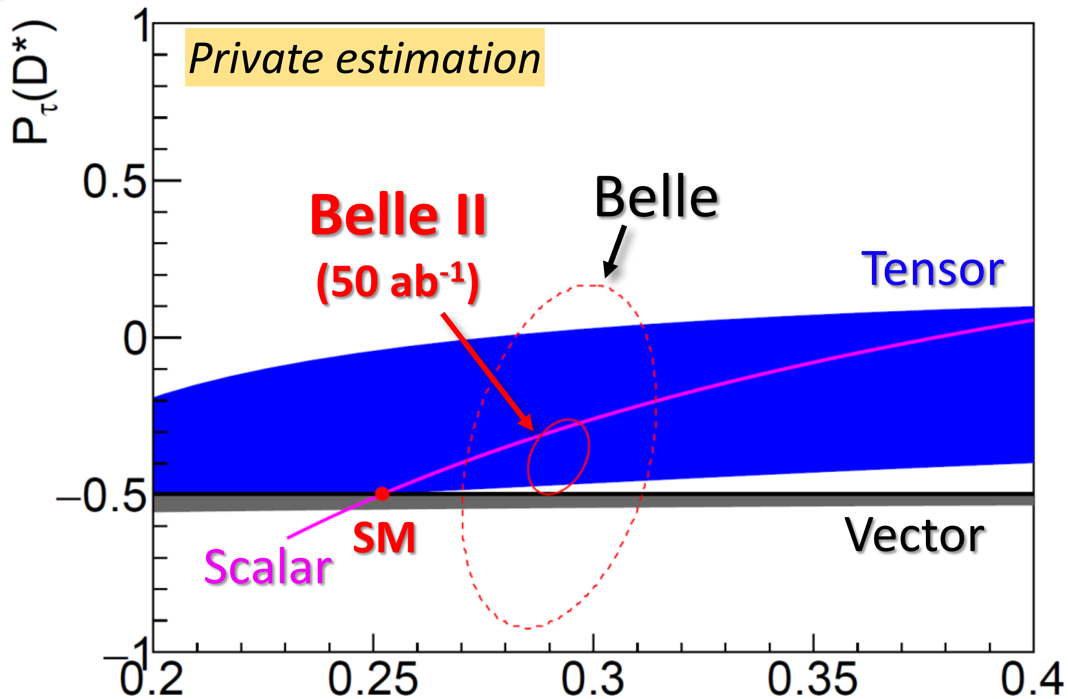
Result (2)



- 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
  - Comparable precision to the previous measurements is achieved

  → ~4σ discrepancy from the SM by combination of $R(D^{(*)})$

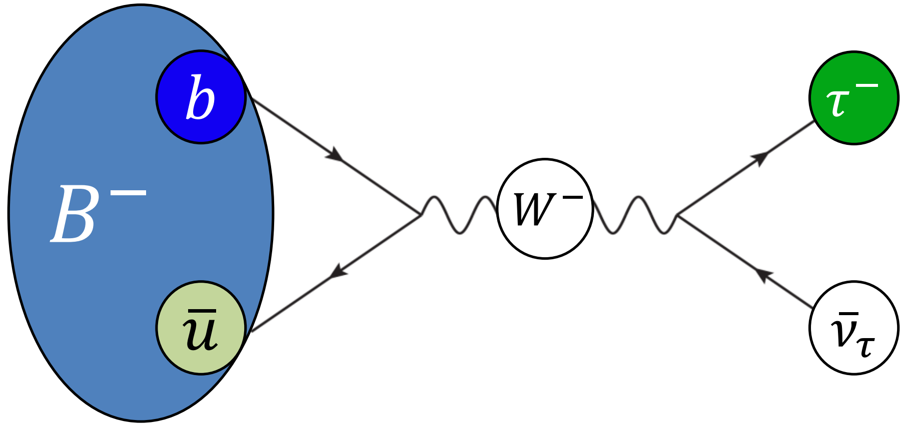
■ Extrapolation to Belle II ($P_\tau(D^*)$)



Theoretical calculation based on M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)

- Extrapolated precision at Belle II (x50 stat. + improved tag eff.)
  - $\delta P_\tau(D^*)$: 0.55 (Belle) → 0.11 (Belle II)
    → There is parameter space accessible by $P_\tau(D^*)$
  - High multiplicity hadronic B background will cause main systematics
- More Belle II prospects including $R\left(D^{(*)}\right)$ in Phill's talk

■ $B^- \to \tau^- \bar{\nu}_\tau$



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

  } Good probe for NP coupling to τ

- Branching fraction

Correction by NP
$r_{\rm NP} = 1$ for the SM

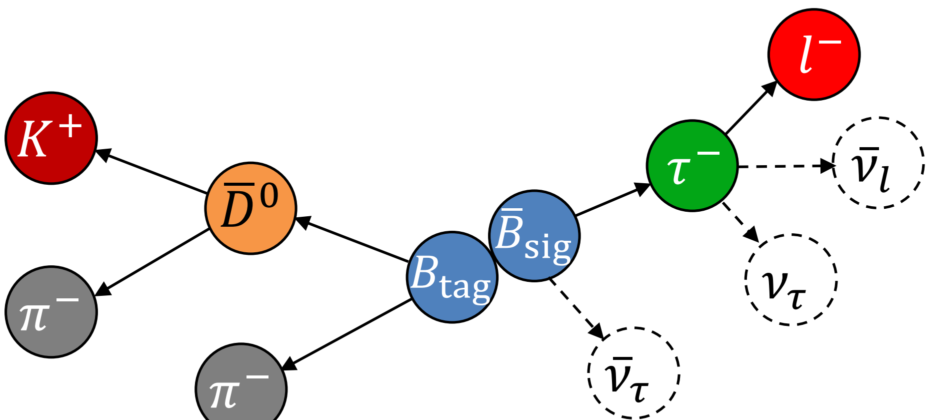
$$BF(B^- \to \tau^- \bar{\nu}_\tau)_{\rm SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \times r_{\rm NP}$$

- Two measurements with the full data sample of Belle

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

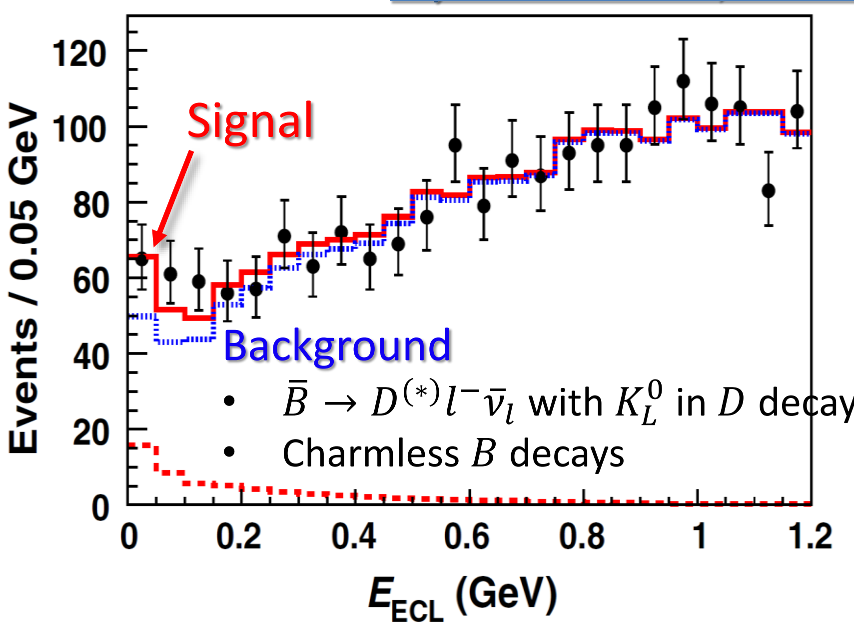
  Phys. Rev. D 92, 051102(R) (2015) (Semileptonic tagging)

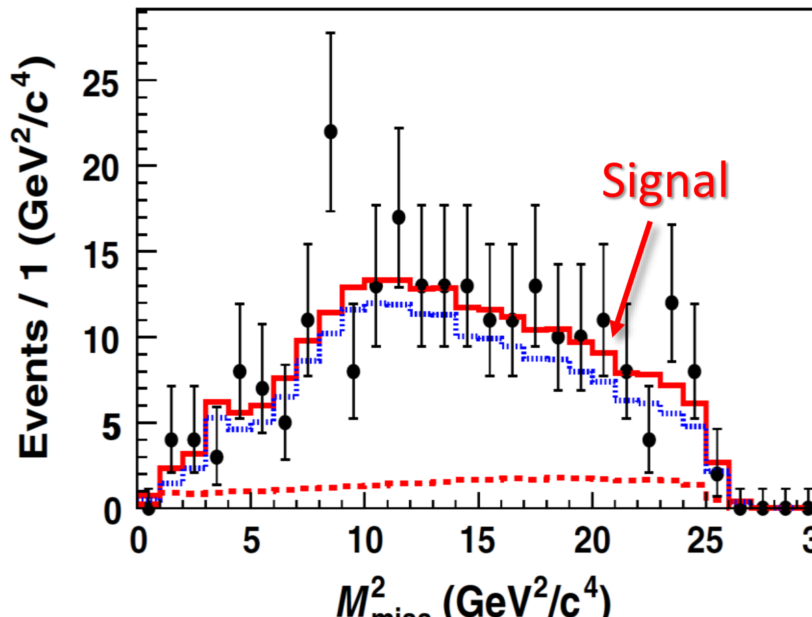
■ $B^- \to \tau^- \bar{\nu}_\tau$ Measurements at Belle



- Both analyses use $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau, l^- \bar{\nu}_l \nu_\tau$
- Signature: only one charged particle (+ π^0 for $\rho^- \nu_\tau$ mode) in the signal side
- 2-D fit for signal extraction

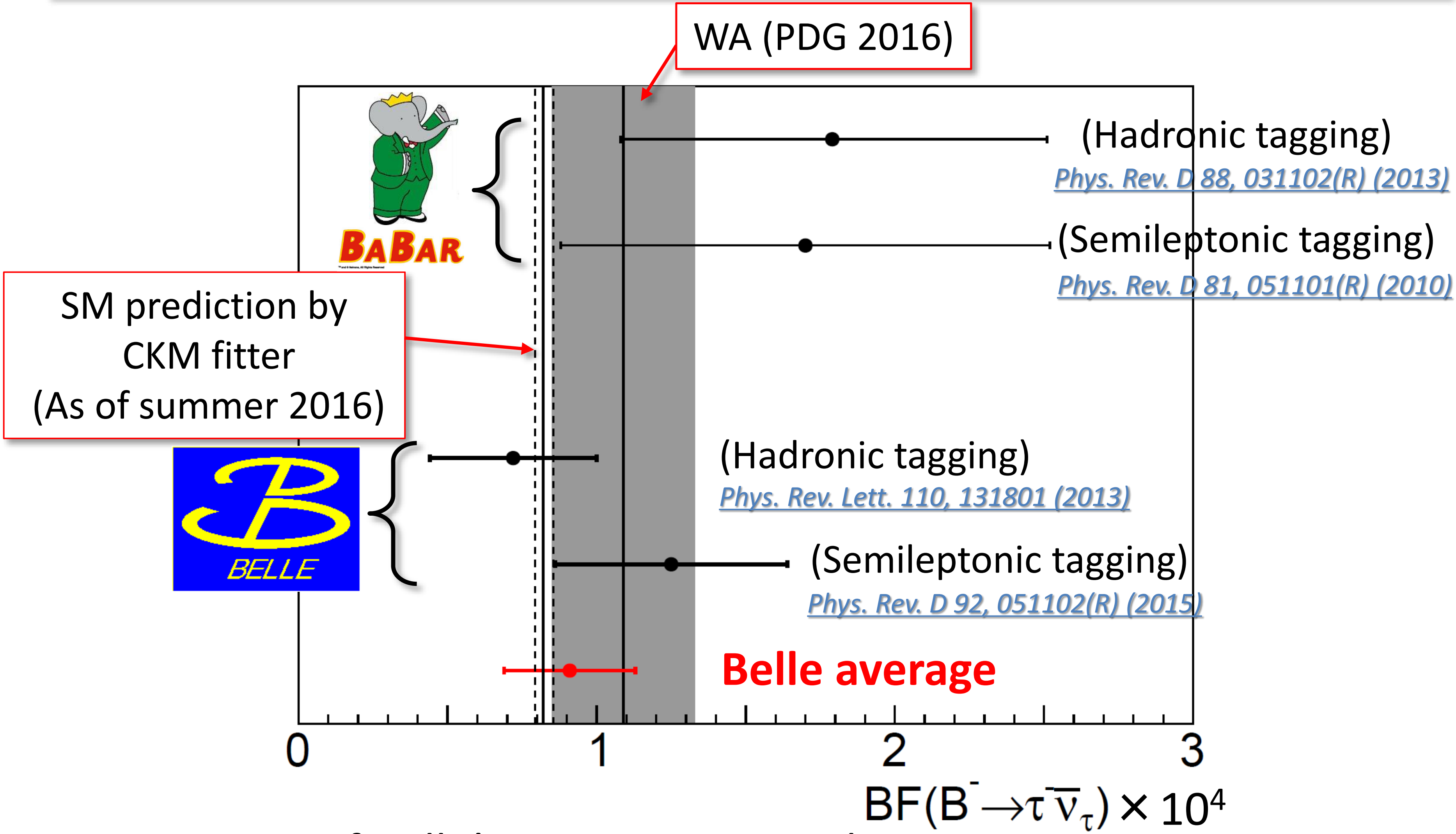
Phys. Rev. Lett. 110, 131801 (2013) (Hadronic tagging)





In the SL tagging analysis, p_l is used instead

■ $B^- \to \tau^- \bar{\nu}_\tau$ Results from Belle

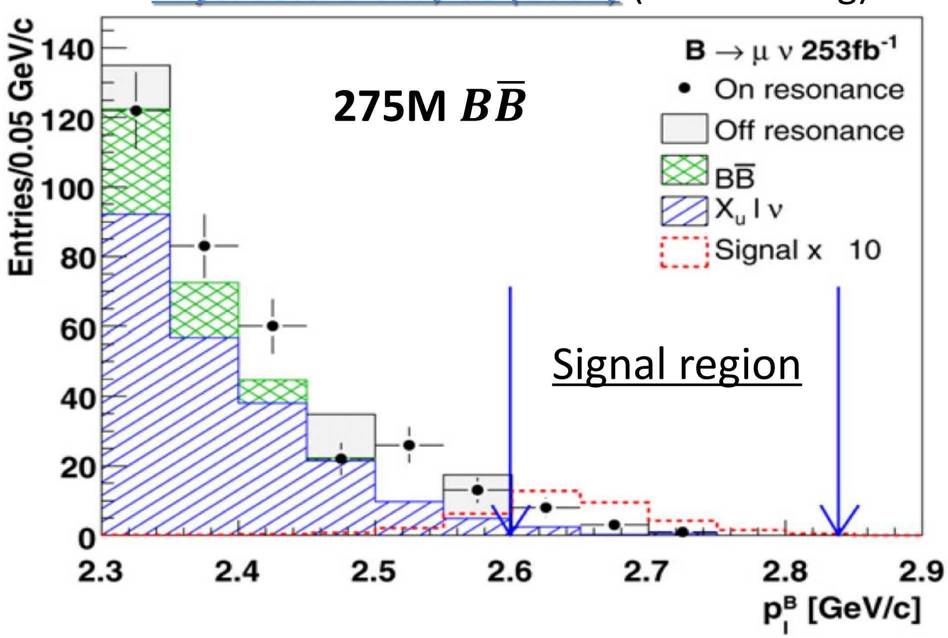


- Average of Belle's measurements shows 4.0σ significance
- Consistent with the SM

■ How about $B^- \to \mu^- \bar{\nu}_\mu$?

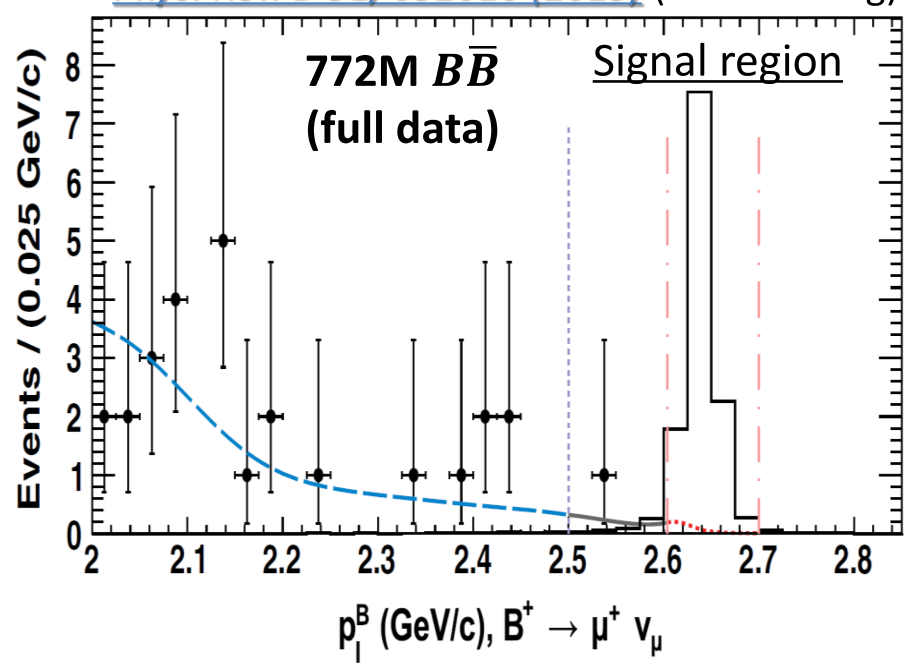
- Purely leptonic decay with a muon
  - SM predicts $BF = (3.78\ ^{+0.18}_{-0.17}) \times 10^{-6}$ (CKM fitter as of summer 2016)
  - Ratio with $\tau^-\bar{\nu}_\tau$ is a good probe for NP having $r_{\mathrm{NP}}(\tau^-\bar{\nu}_\tau) \neq r_{\mathrm{NP}}(\mu^-\bar{\nu}_\mu)$
- Two body decay → p_μ is monochromatic in the B-rest frame

Phys. Lett. B 647, 88 (2007) (Inclusive tag)



Advantage: better efficiency (~3%)

Phys. Rev. D 91, 052016 (2015) (Hadronic tag)



Advantage: better resolution

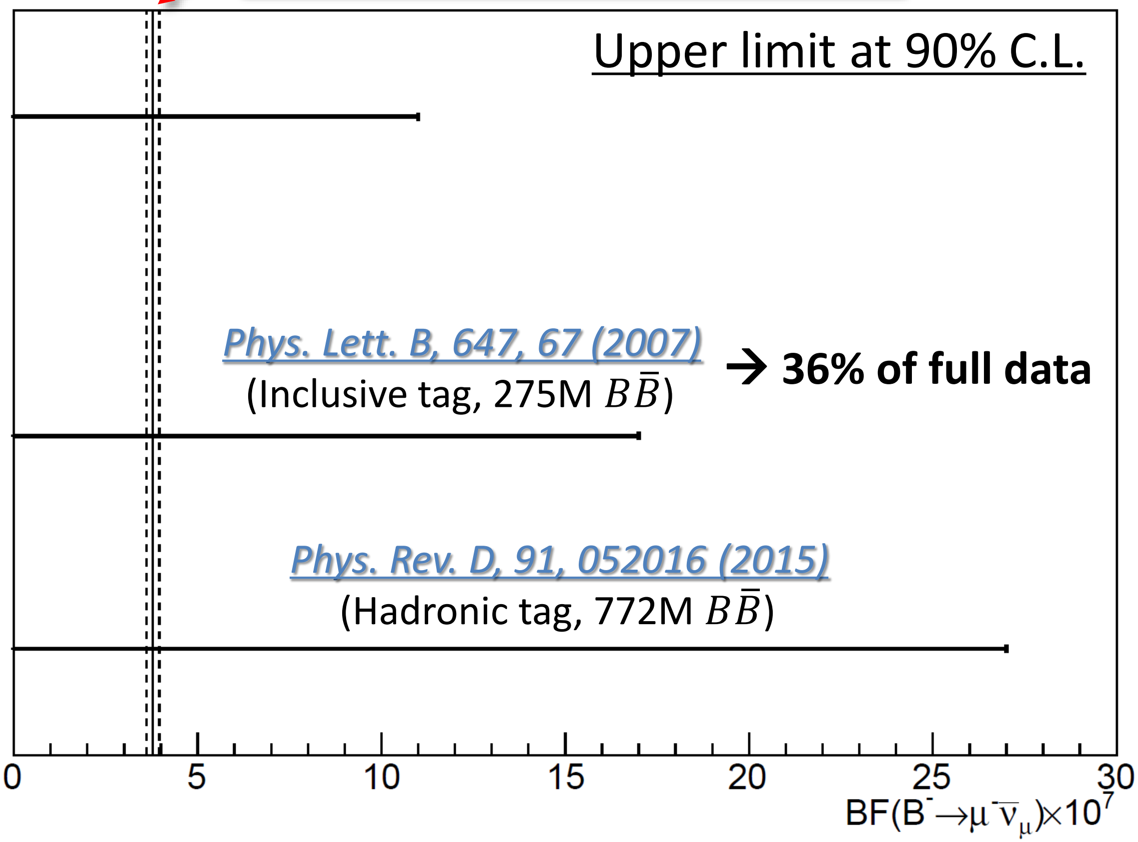
■ $B^- \to \mu^- \bar{\nu}_\mu$ Results from Belle

SM prediction by CKM fitter
(As of summer 2016)

Current best limit by BaBar
Phys. Rev. D 79, 091101 (2009)
(Inclusive tag, 468M $B\bar{B}$)

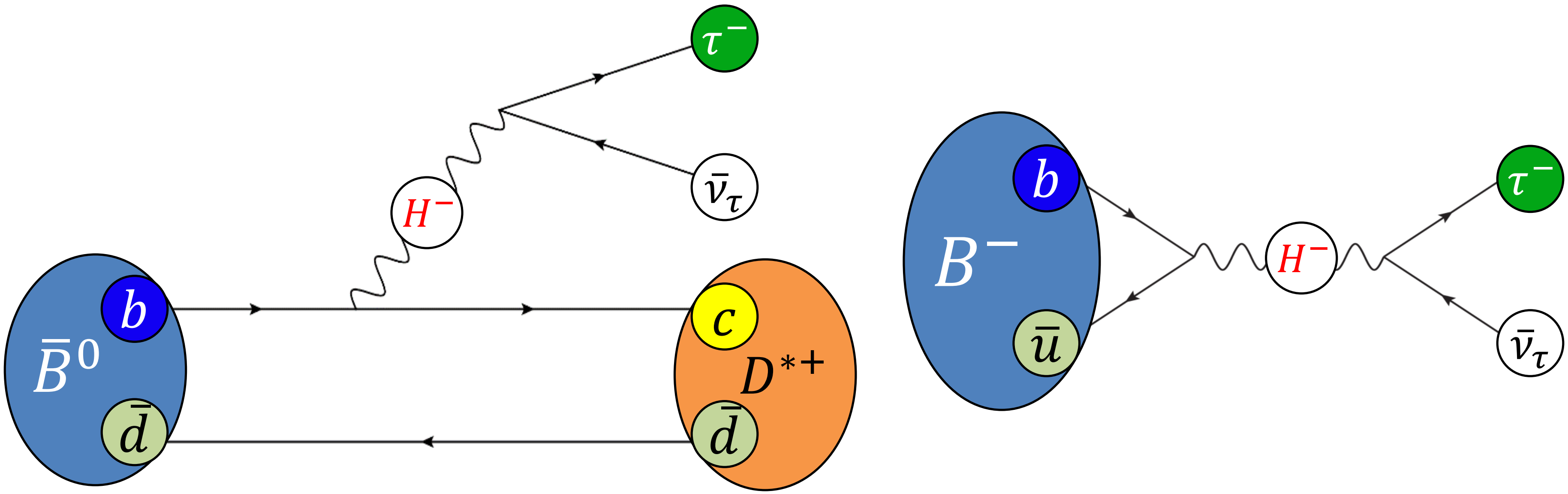
Phys. Lett. B, 647, 67 (2007)
(Inclusive tag, 275M $B\bar{B}$) → **36% of full data**

Phys. Rev. D, 91, 052016 (2015)
(Hadronic tag, 772M $B\bar{B}$)



- Upper limit on BF is reaching the SM prediction
- Inclusive tag analysis with the full data sample is ongoing

■ Comparison with Type-II 2HDM (1)



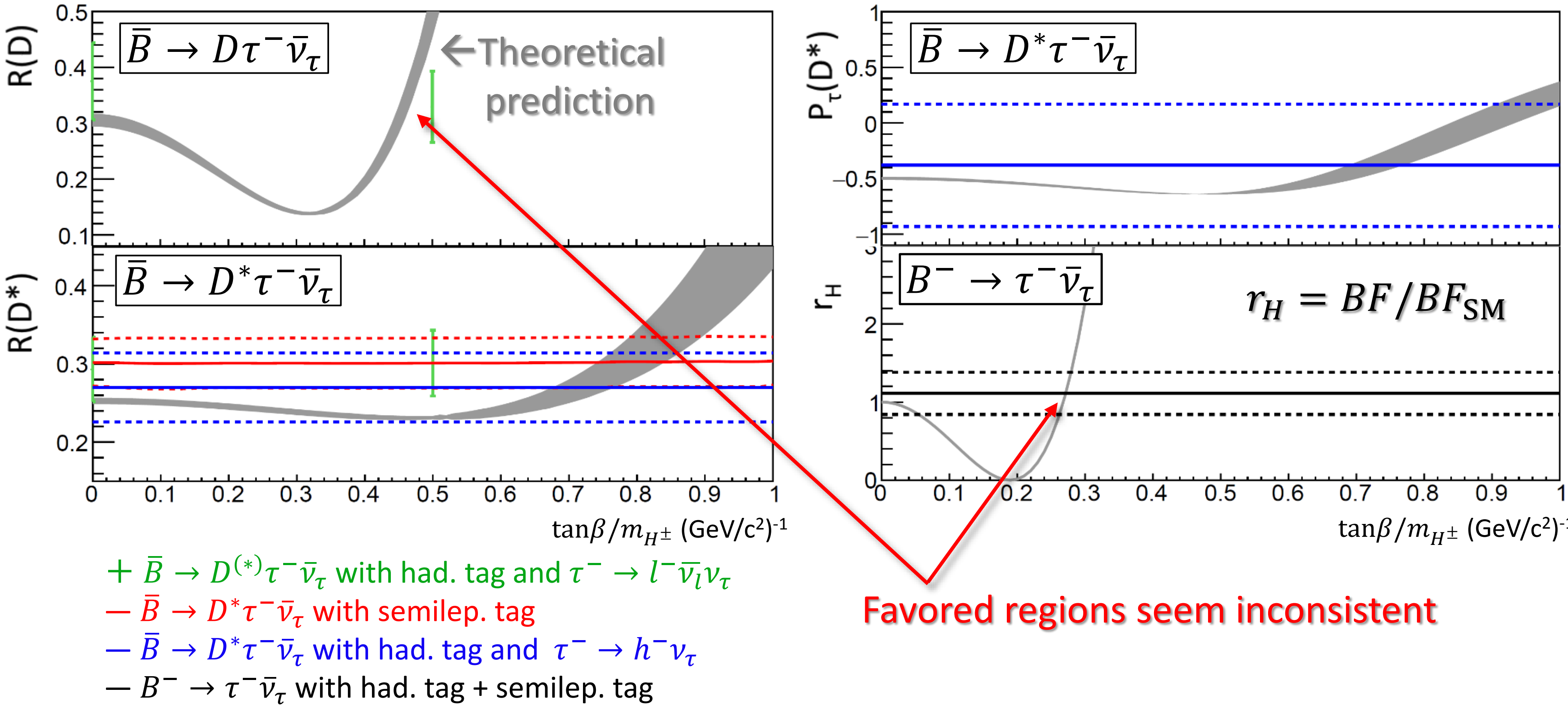
- Charged Higgs appears in the Two Higgs Doublet Model
  - Large coupling to the τ lepton
- Contribution from Type-II 2HDM

Ratio of VEV in two Higgs doublets

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

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

Comparison with Type-II 2HDM (2)



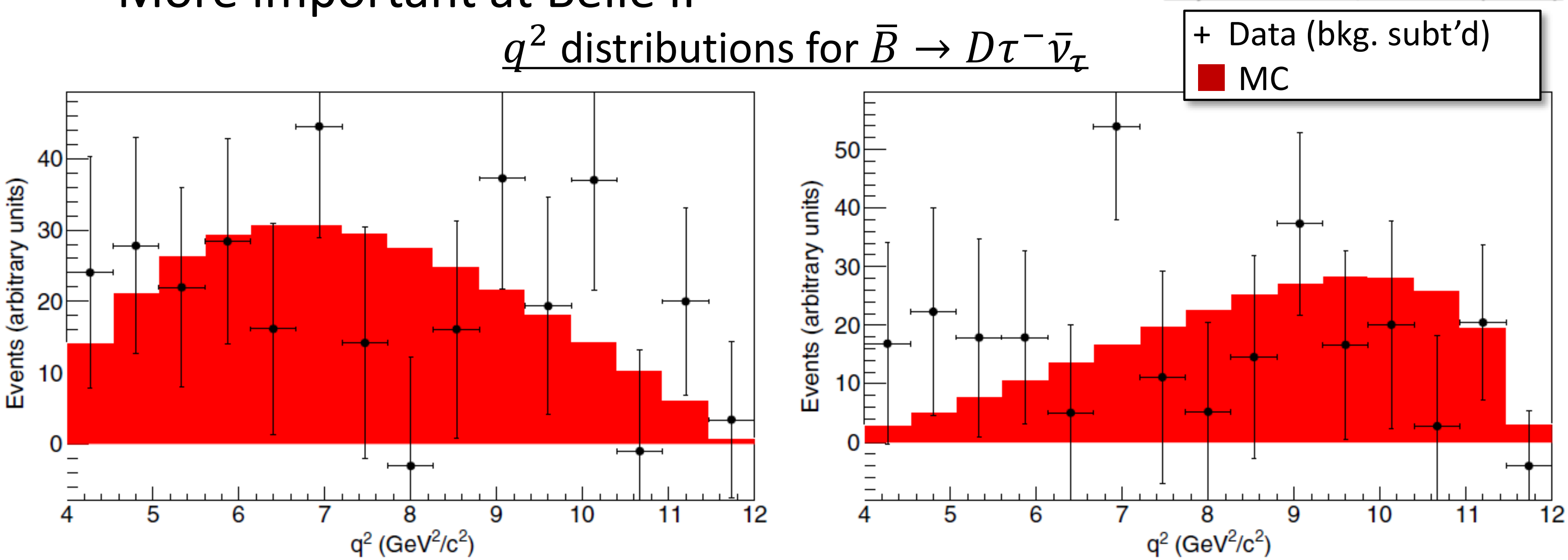
- All the results are consistent with, but always larger than the SM
  - Compatibility with the SM is about 80% C.L. *Private estimation*
- Large value of $\tan\beta/m_{H^\pm}$ seems disfavored

Type–II 2HDM Test using q^2

- $q^2 = \left(p_{B_{\rm sig}} - p_{D^{(*)}}\right)^2$ is sensitive to NP effects
  - Many theoretical studies e.g. *Y. Sakaki et al., Phys. Rev. D 91, 114028 (2015)*
- No significant favor is observed in the Belle's study
  - In the SL tag analysis, similar study has been performed using p_l and p_{D^*} → *Phys. Rev. D 94, 072007 (2016)*
- More important at Belle II

Phys. Rev. D 92, 072014 (2015)

q^2 distributions for $\bar{B} \to D\tau^-\bar{\nu}_\tau$



SM

$\tan\beta / m_{H^\pm}$ = 0.5(GeV/c²)⁻¹

Summary

- $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and $B^- \to \tau^-\bar{\nu}_\tau$ are interesting modes in terms of indirect NP search
  - Sensitivity to NP coupling to τ lepton

- Using full data, Belle performed three measurements for $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$, two measurements for $B^- \to \tau^-\bar{\nu}_\tau$

- The results for (semi-)tauonic decays at Belle are close to the SM: C.L. for compatibility with the SM is about 80%
  - On the other hand, world-average $R\left(D^{(*)}\right)$ including results from BaBar and LHCb shows ~4σ deviation from the SM

- <u>Important to investigate with improved precision at Belle II</u>
  - Not only $R\left(D^{(*)}\right)$ but also kinematics such as polarizations and q^2