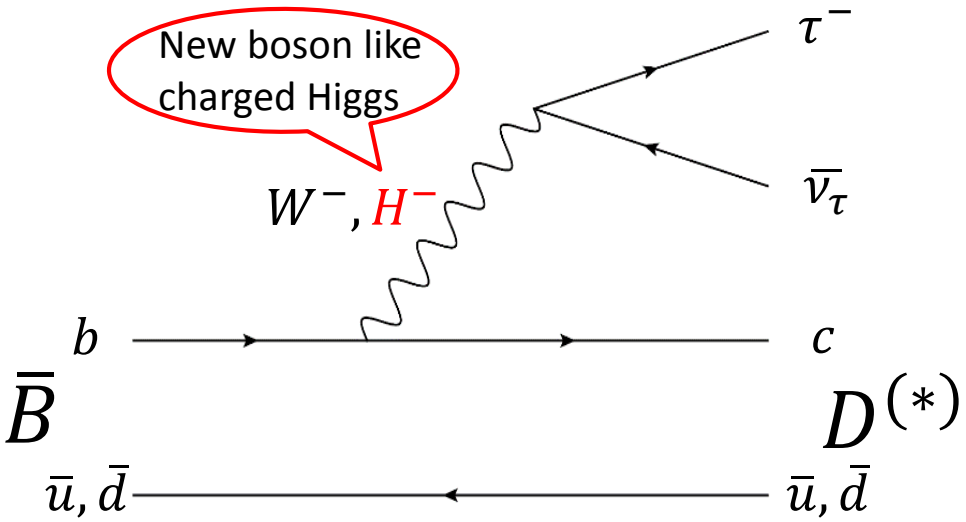
Measurement of $\bar{B} \to D^{(*)}\tau^{-}\bar{\nu_{\tau}}$ at Belle

September 20, 2016 at TAU 2016

Shigeki Hirose (Nagoya University)

For the Belle Collaboration

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



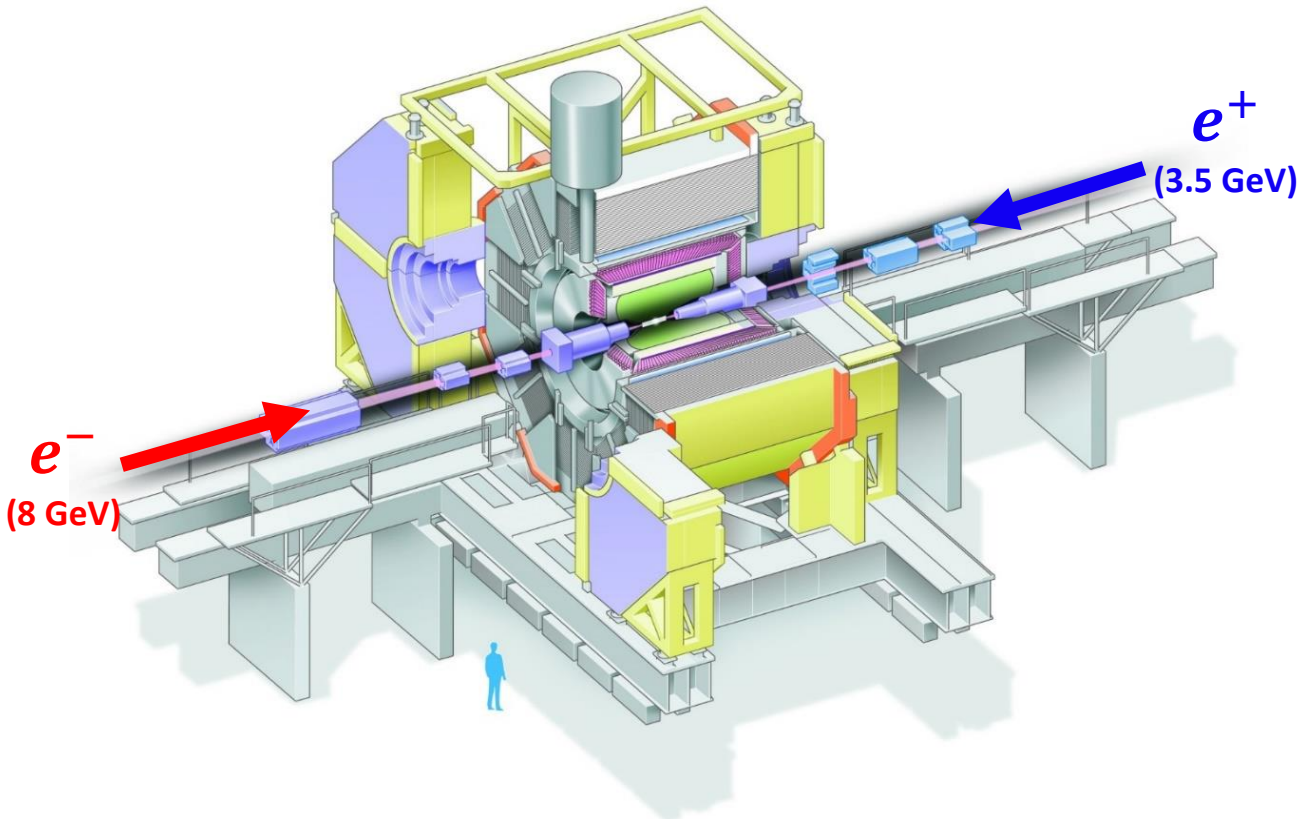
- Semileptonic decay with two massive fermions: b and τ
  - Sensitive to NP with non-universal coupling over three generation
- We typically measure

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

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

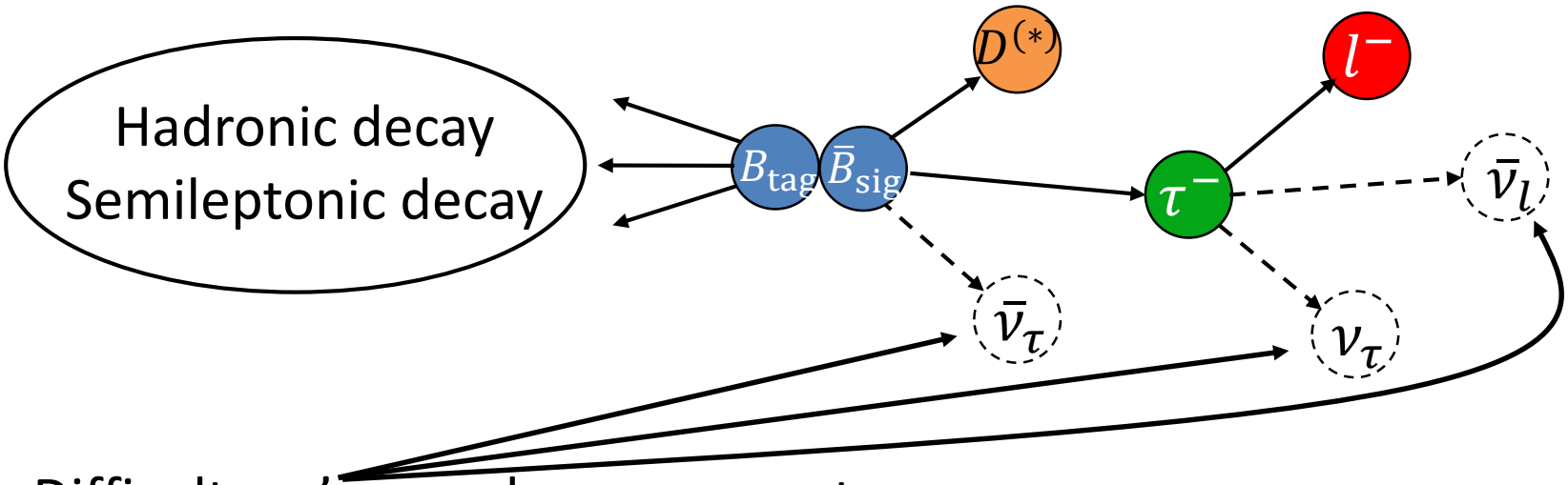
- BaBar reported a 3.4σ tension from the SM in 2012

■ Belle Experiment at KEK, Japan



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

■ Tagging Method



- Difficulty: ν's carry large momentum away

  →Use the advantage: no additional particle to two B's in $\Upsilon(4S) \rightarrow B\bar{B}$

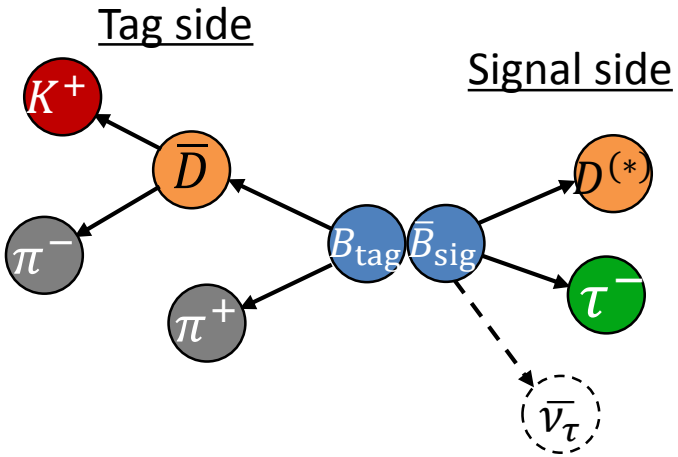
- Reconstruct one B meson (B_{tag})

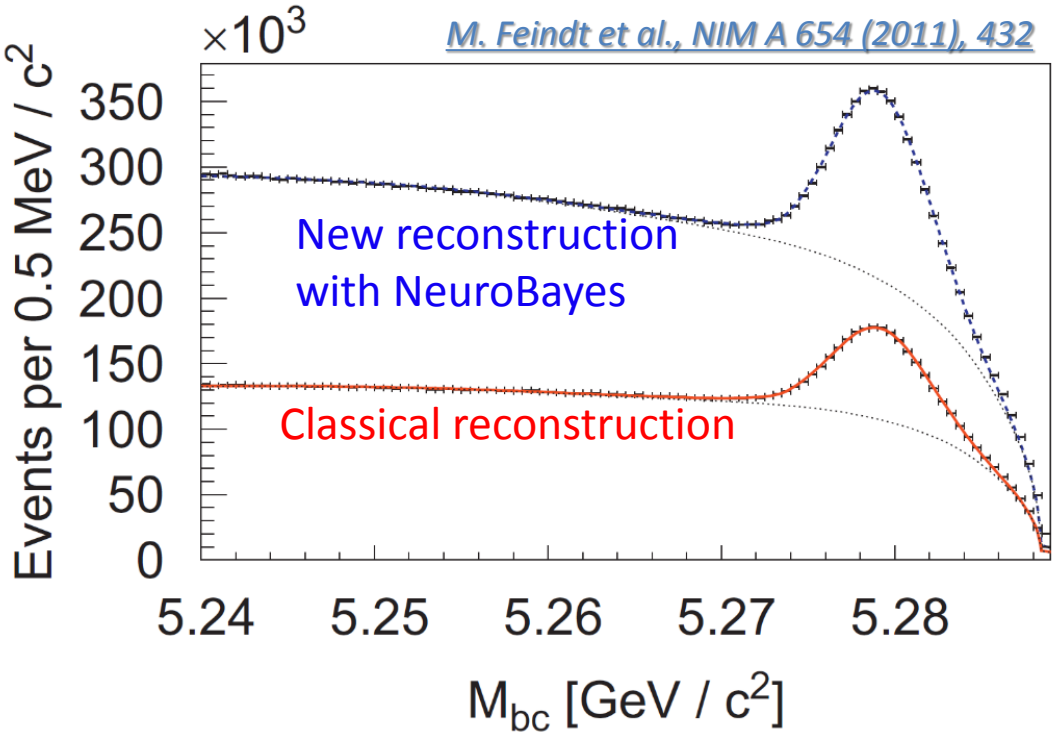
  →Obtain the signal B meson (B_{sig}) information indirectly

■ Hadronic Tagging

- B_{tag} reconstruction with hadronic decays
  - Full 4-momentum can be reconstructed
  - Low efficiency ($O(10^{-3})$) due to small BFs of exclusive hadronic decays

→ Collect as many B_{tag} decay chains as possible + multivariate analysis

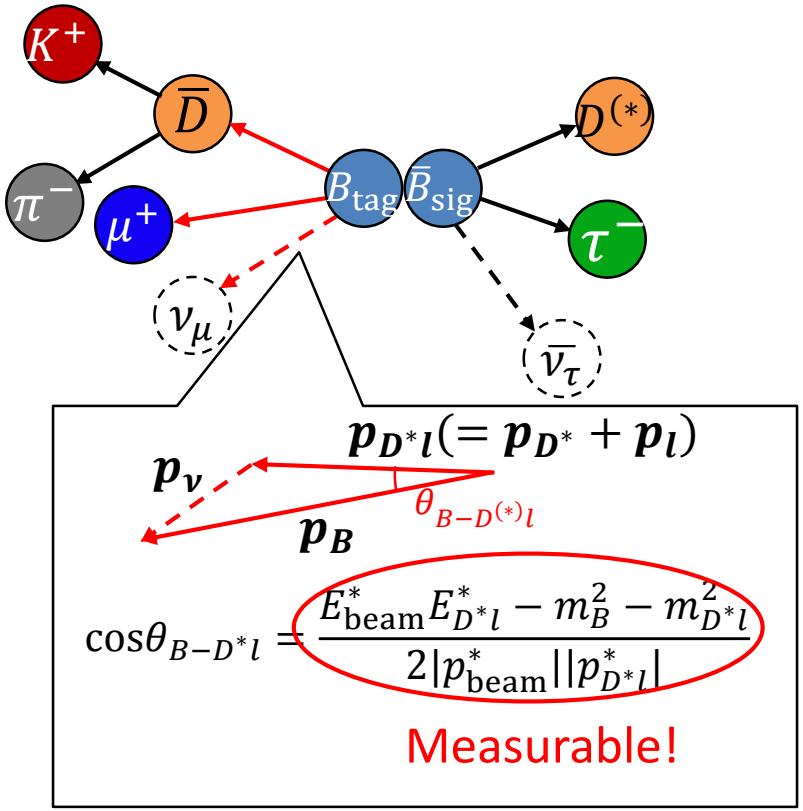


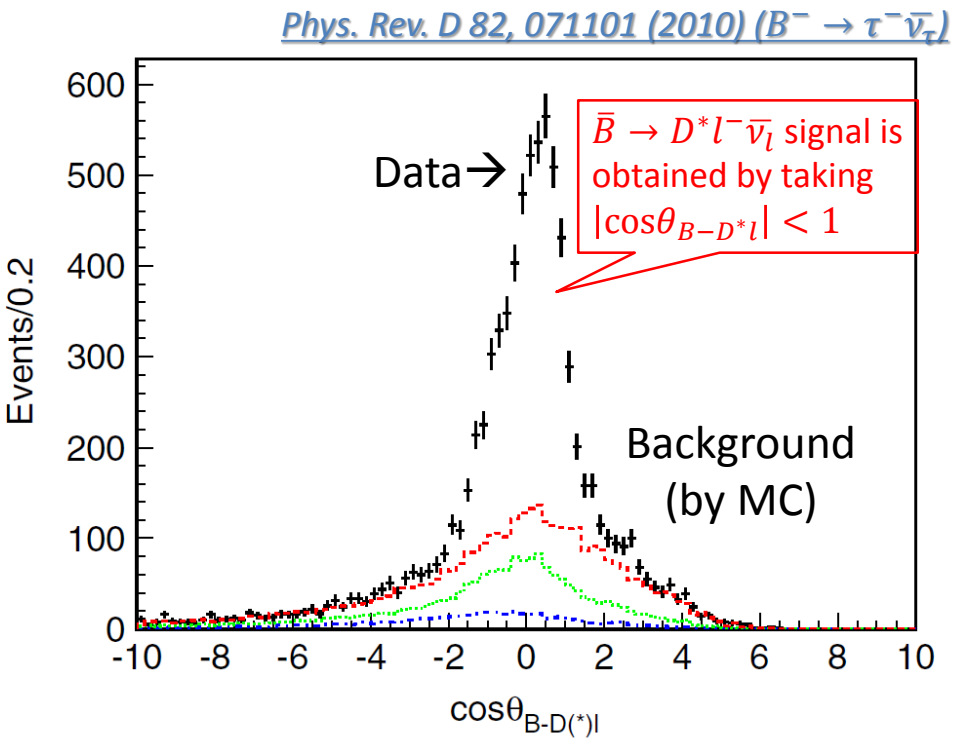


■ Semileptonic Tagging

- B_{tag} reconstruction with semileptonic decays
  - One ν in the tag side

    →Nevertheless B_{tag} can be selected with $\cos\theta_{B-D^*l}$
  - Better reconstruction efficiency: $O(10^{-2})$





Results from Belle

- Three results with the Belle full data sample
  - $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ with hadronic tagging *Phys. Rev. D 92, 072014 (2015)*
    - First analysis with the Belle full data sample
    - Both $R(D)$ and $R(D^*)$ are measured
  - $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with semileptonic tagging
    - First application of semileptonic tagging to the $R(D^*)$ measurement

      arXiv:1607.07923, submitted to PRD
  - $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ with hadronic tagging
    - First $R(D^*)$ measurement only with hadronic τ decays: $\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau$
    - First τ polarization measurement in the semitauonic decays

      arXiv:1608.06391, shown at ICHEP 2016

$\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau$ Measurement with Hadronic Tagging, $\tau^- \to l^- \bar{\nu}_l \nu_\tau$

Phys. Rev. D 92, 072014 (2015)

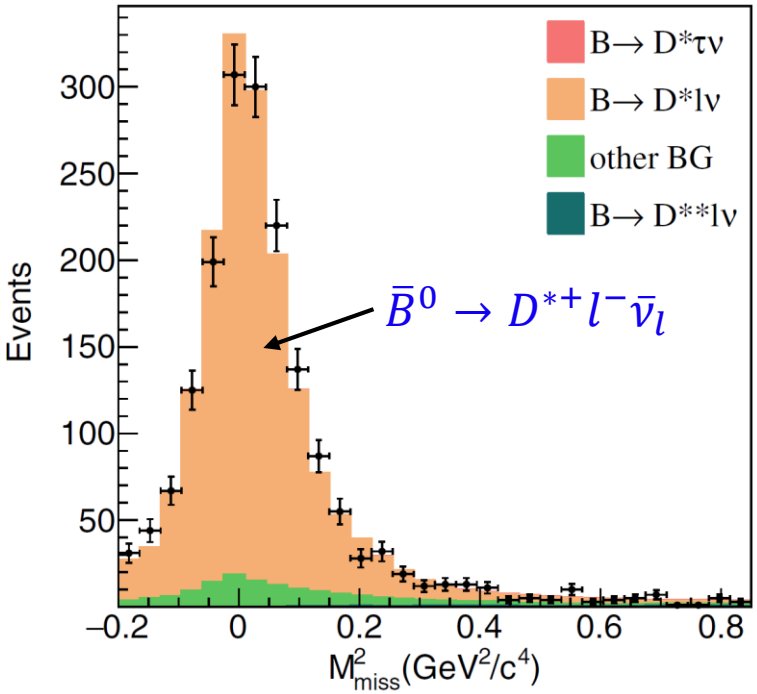
Normalization Extraction

- $\bar{B} \to D^{(*)} l^- \bar{\nu}_l$ is normalization mode for $R\left(D^{(*)}\right)$
- M^2_{miss} is used for the region -0.2 < M^2_{miss} < 0.85 GeV^2/c^4

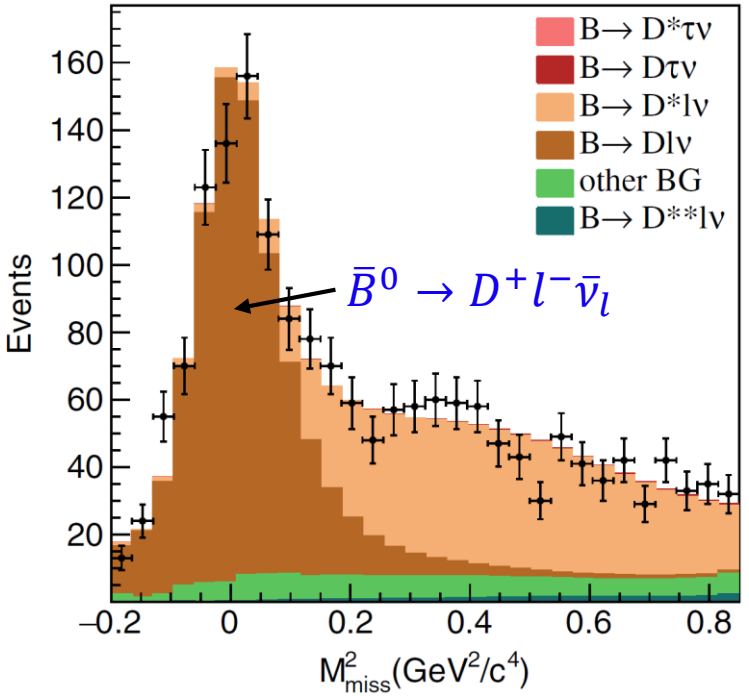
$$M^2_{\mathrm{miss}} = \left(p_{\mathrm{beam}} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_l\right)^2$$

→Because of only one ν, $M^2_{\mathrm{miss}} = m^2_\nu = 0$

$(\bar{B}^0, D^{*+})$ sample



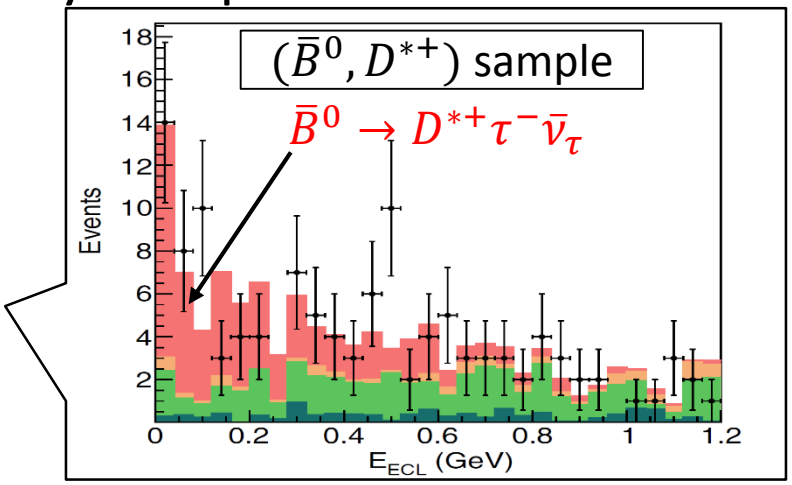
$(\bar{B}^0, D^{+})$ sample

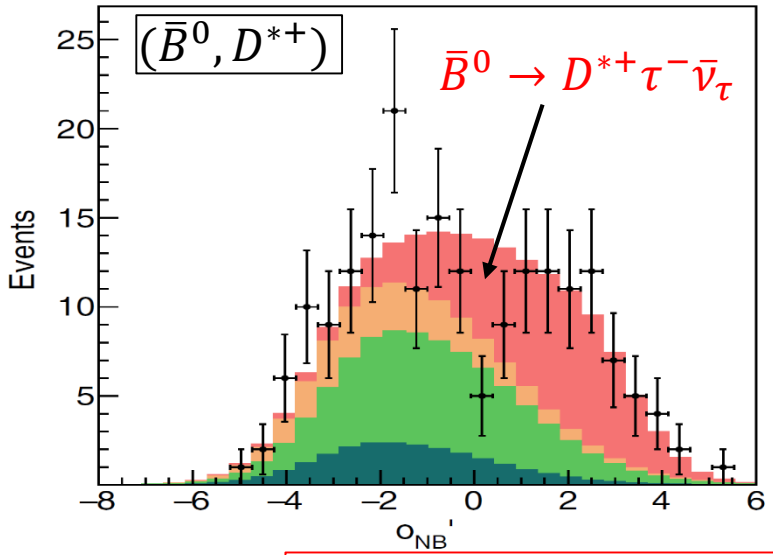


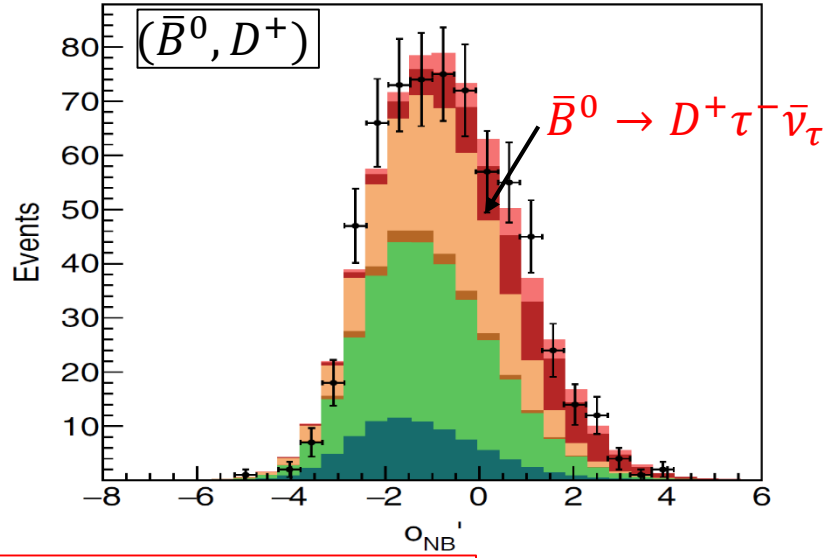
Signal Fit

- To extract signal, multivariate analysis is performed in the region $M^2_{\mathrm{miss}} > 0.85\ \mathrm{GeV}^2/c^4$

  → Signal extraction with transformed NeuroBayes output ($O_{\mathrm{NB}}{}'$) with
  - E_{ECL} (remaining energy in ECL)
  - M^2_{miss}
  - lepton momentum etc.







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

→ About half are related to $\bar{B} \to D^{**} l^- \bar{\nu}_l$

$\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$ Measurement

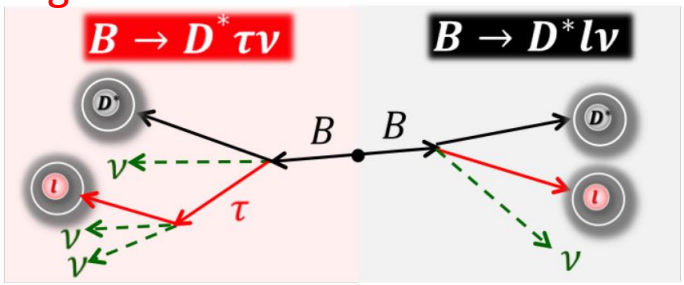
with Semileptonic Tagging, $\tau^- \to l^- \bar{\nu}_l \nu_\tau$

arXiv:1607.07923, submitted to PRD

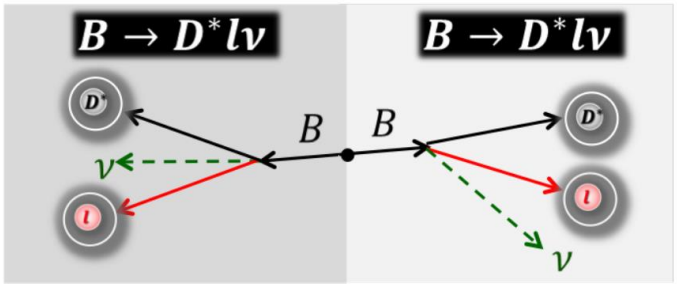
$R(D^*)$ with Semileptonic Tagging

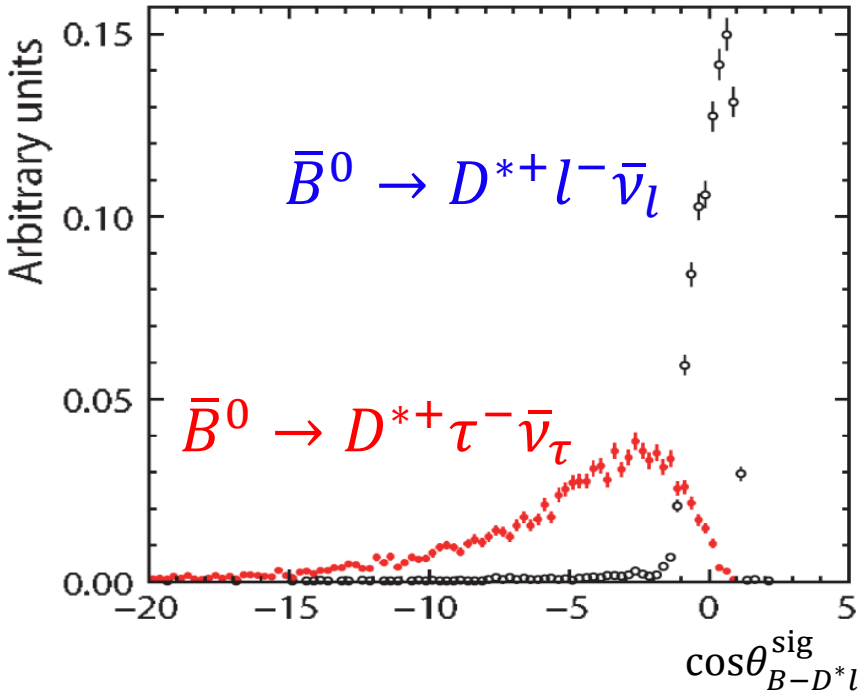
- Motivation
  - Different tag mode → Independent data sample from the previous result
- Less kinematic constraint causes more background
  - The cleanest mode $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ was measured in this analysis
- Signal can be separated from normalization with $\cos\theta^{\mathrm{sig}}_{B-D^*l}$
  - Multivariate analysis with two more variables: M^2_{miss} and the total energy of B_{tag} and B_{sig}

Signal event



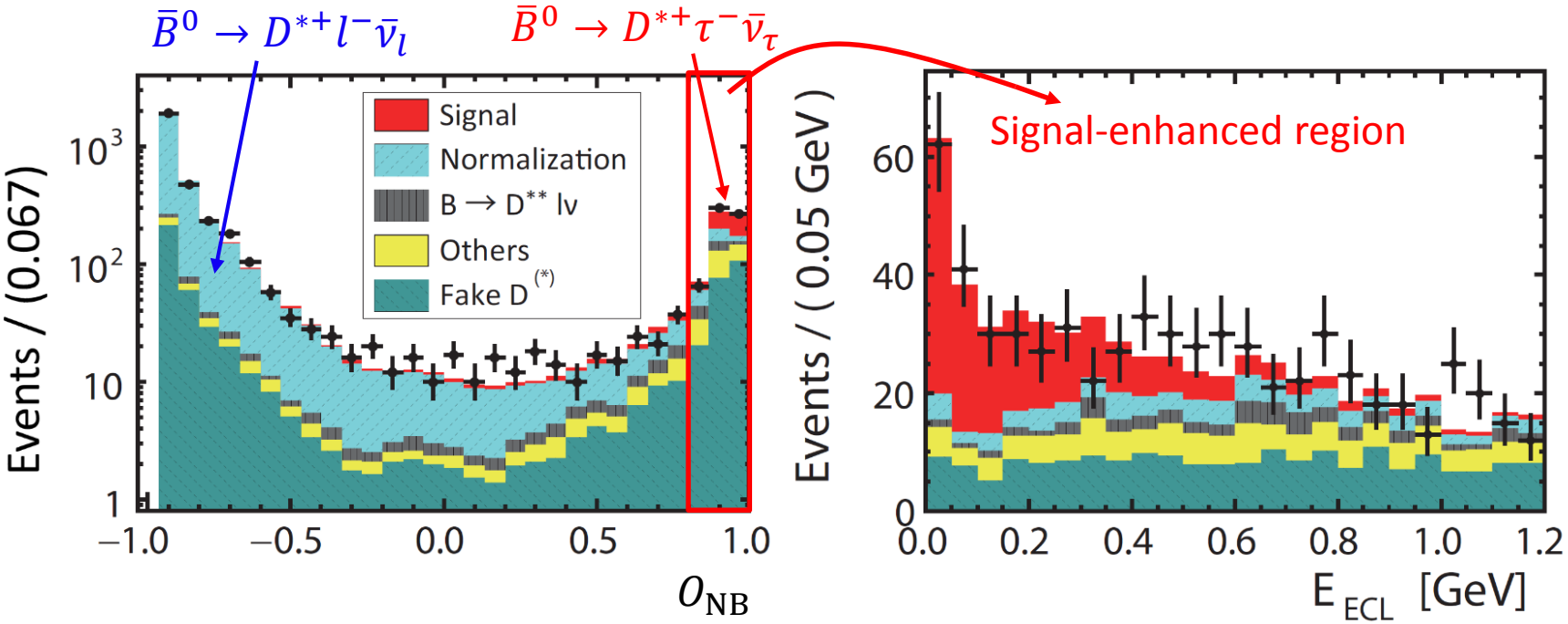
Normalization event





Signal Extraction

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



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

MC stat. for PDF shape
PDF shape of $\bar{B} \to D^{**} l^- \bar{\nu}_l$
etc.

$\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ Measurement with Hadronic tagging,

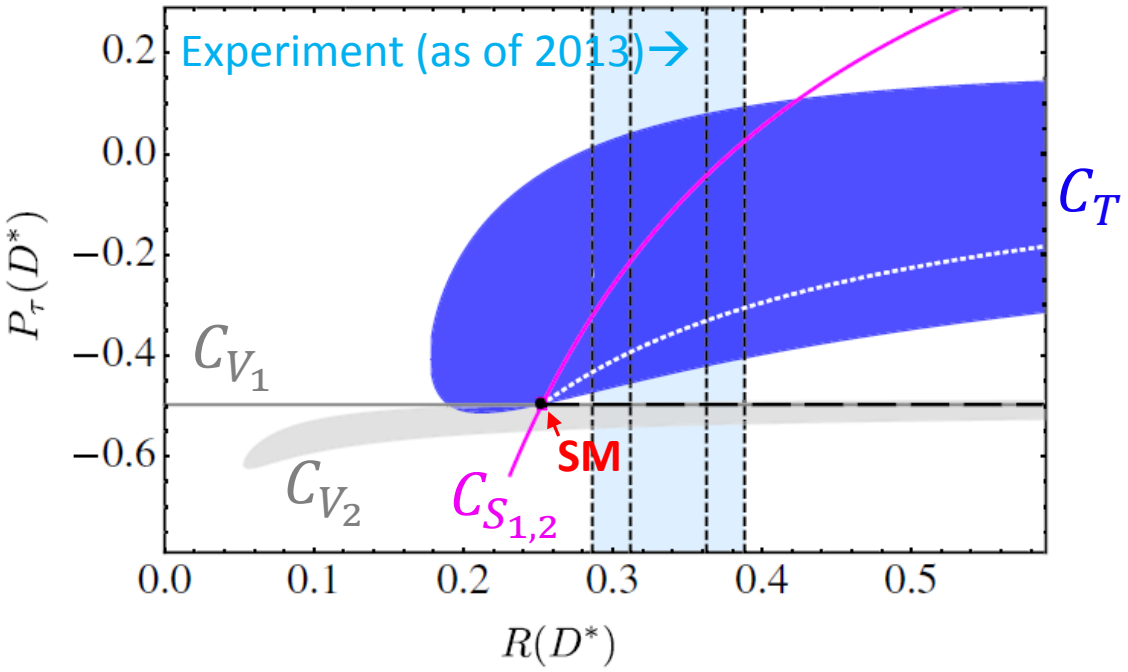
$$\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$$

arXiv:1608.06391, shown at ICHEP 2016

Measurement with Hadronic τ Decays

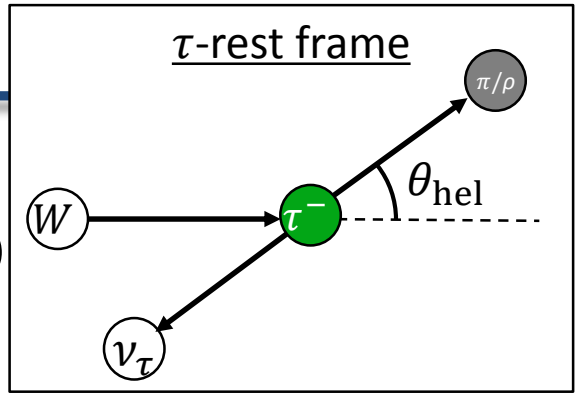
- $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$ can be used for measurement of $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$
- Advantage
  - Independent data sample from $\tau^- \to l^- \bar{\nu}_l \nu_\tau$ with almost the same τ BFs
  - Smaller effect from $\bar{B} \to D^{**} l^- \bar{\nu}_l$ while hadronic B bkgd. is significant
  - We can measure τ polarization thanks to two-body τ decays

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2} G_F V_{cb} \left[\delta_{\text{SM}} O_{V_1} + \Sigma_{i=V_1,V_2,S_1,S_2,T} C_i O_i \right]$$



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

Analysis Procedure for P_τ



- P_τ is extracted by

α = 1 for $\pi^-\nu_\tau$, 0.45 for $\rho^-\nu_\tau$

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

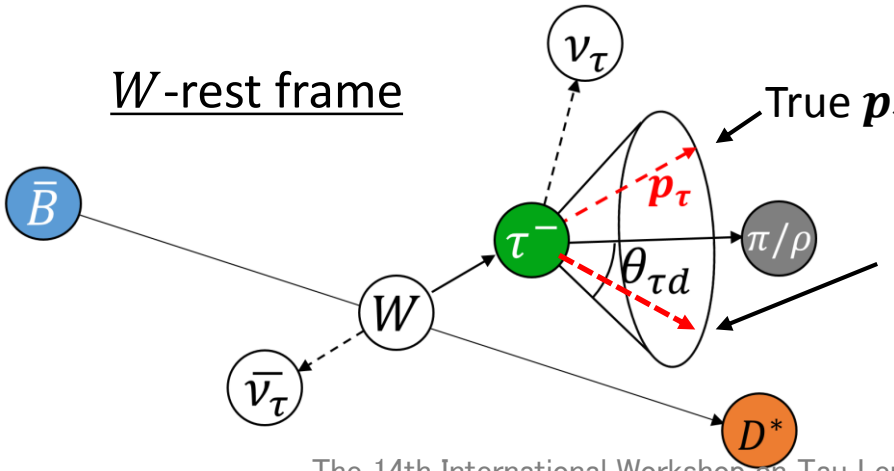
Because of low statistics, we use two $\cos\theta_{\rm hel}$ bins

$$P_\tau = \frac{2}{\alpha}\frac{\Gamma_{\cos\theta_{\rm hel}>0} - \Gamma_{\cos\theta_{\rm hel}<0}}{\Gamma_{\cos\theta_{\rm hel}>0} + \Gamma_{\cos\theta_{\rm hel}<0}}$$

- Impossible to retrieve the complete τ momentum
  - Utilize the W-rest frame by taking $\boldsymbol{p}_W = \boldsymbol{p}_{B_{\rm sig}} - \boldsymbol{p}_{D^*} = 0$

→Obtain $\cos\theta_{\tau d} = \frac{2E_\tau E_\pi - m_\tau^2 - m_\pi^2}{2|\boldsymbol{p_\tau}||\boldsymbol{p_\pi}|}$

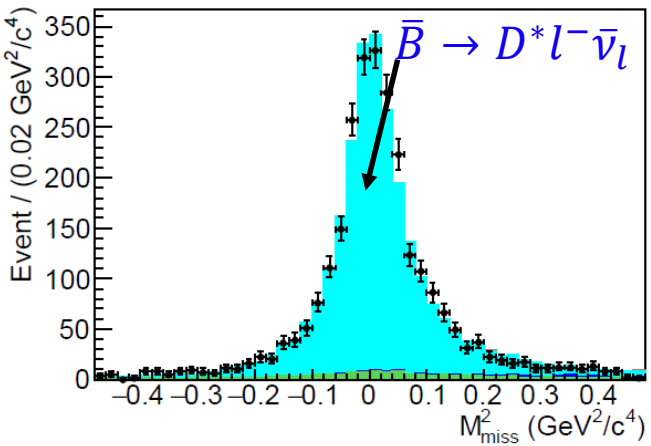
- Utilize rotation symmetry of the cone with $\theta_{\tau d}$

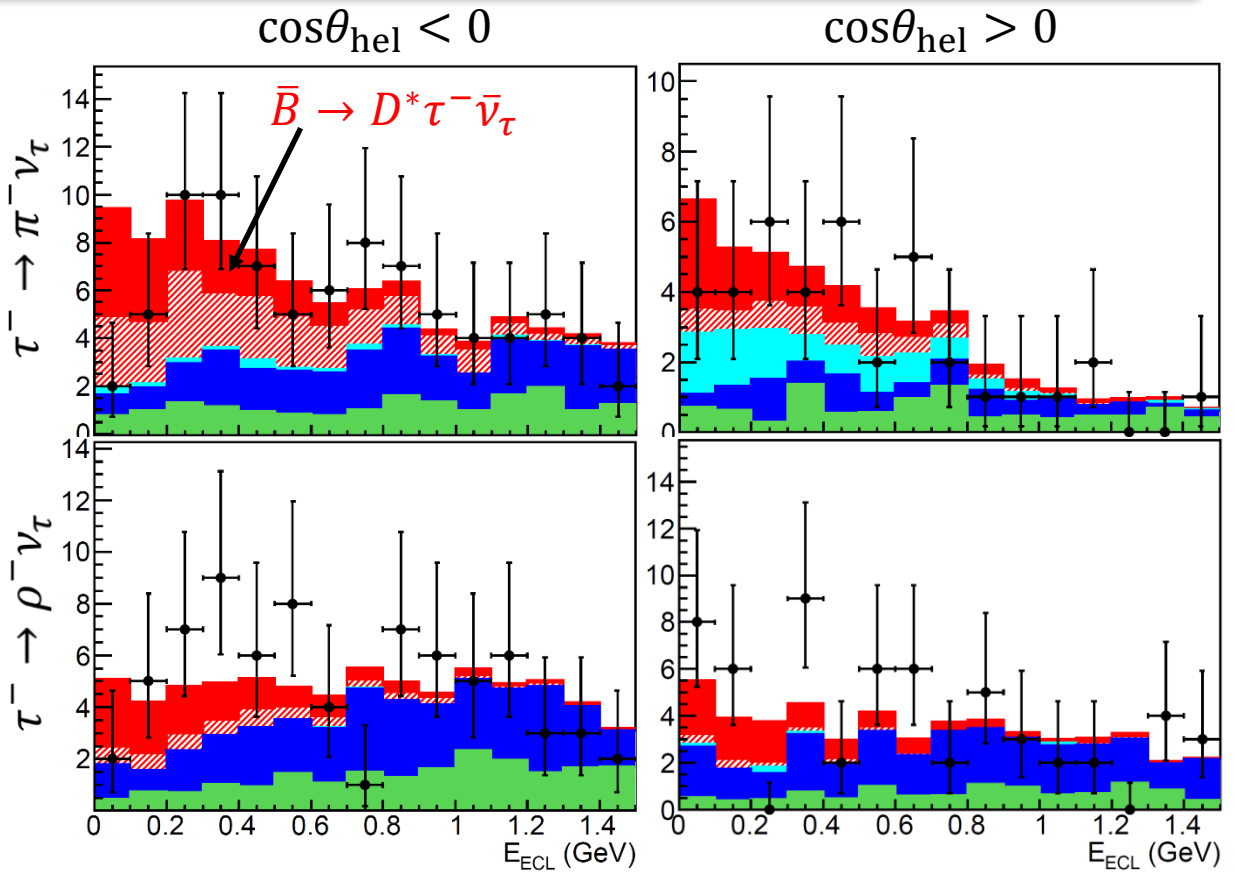


No special direction on the cone
→ We can obtain the correct $\theta_{\rm hel}$ even if we boost the different direction

Signal Extraction *Preliminary*

$\bar{B}^0$ sample

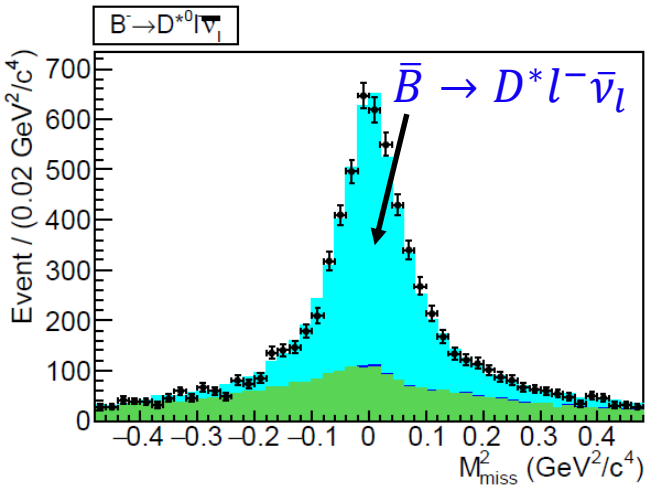


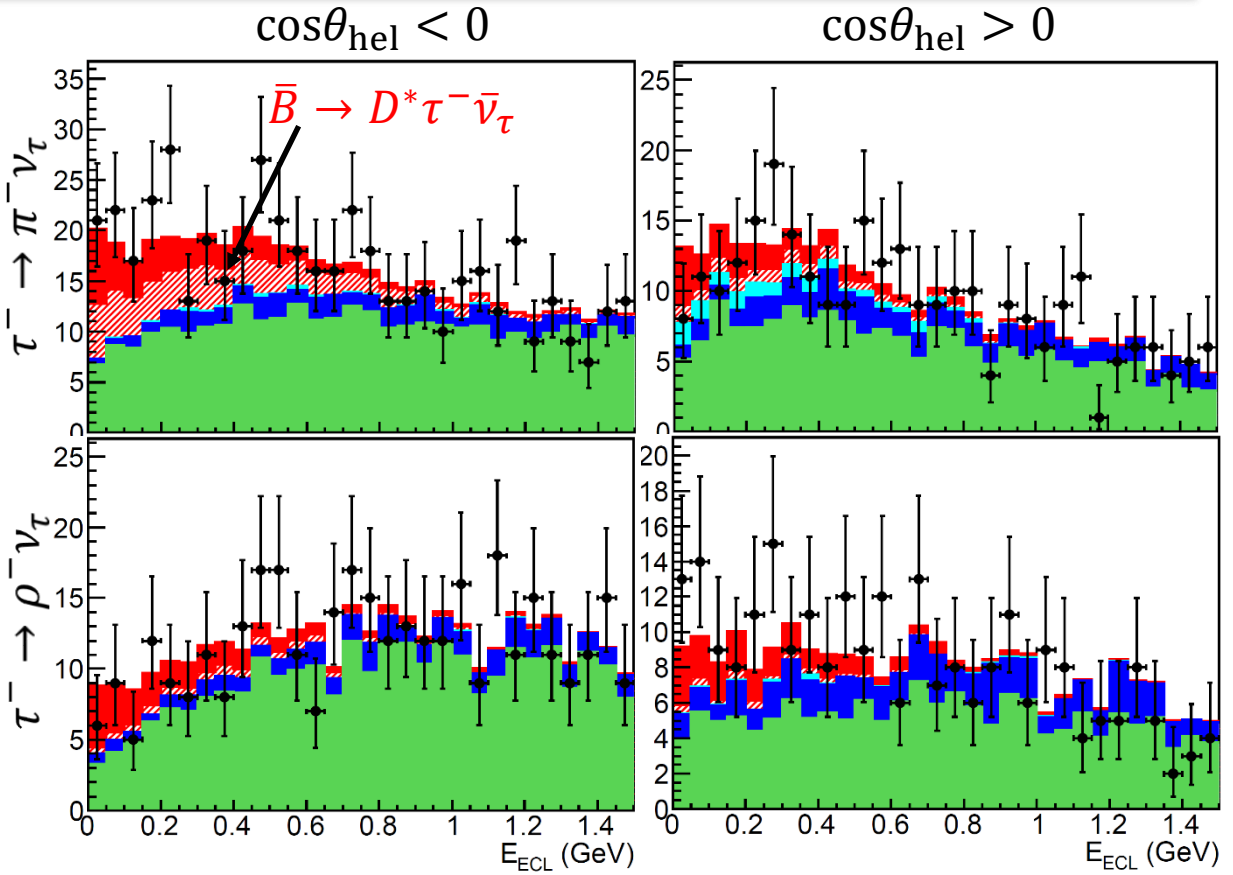


- Similar method to the had. tag + $\tau^- \to l^- \bar{\nu}_l \nu_\tau$ analysis
  - M^2_{miss} for $\bar{B} \to D^* l^- \bar{\nu}_l$
  - E_{ECL} for $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$

Signal Extraction *Preliminary*

B^- sample





Hadronic B background, MC statistics etc.

$$R(D^*) = 0.276 \pm 0.034(\text{stat.})\ ^{+0.029}_{-0.026}(\text{syst.})$$
$$P_\tau = -0.44 \pm 0.47(\text{stat.})\ ^{+0.20}_{-0.17}(\text{syst.})$$

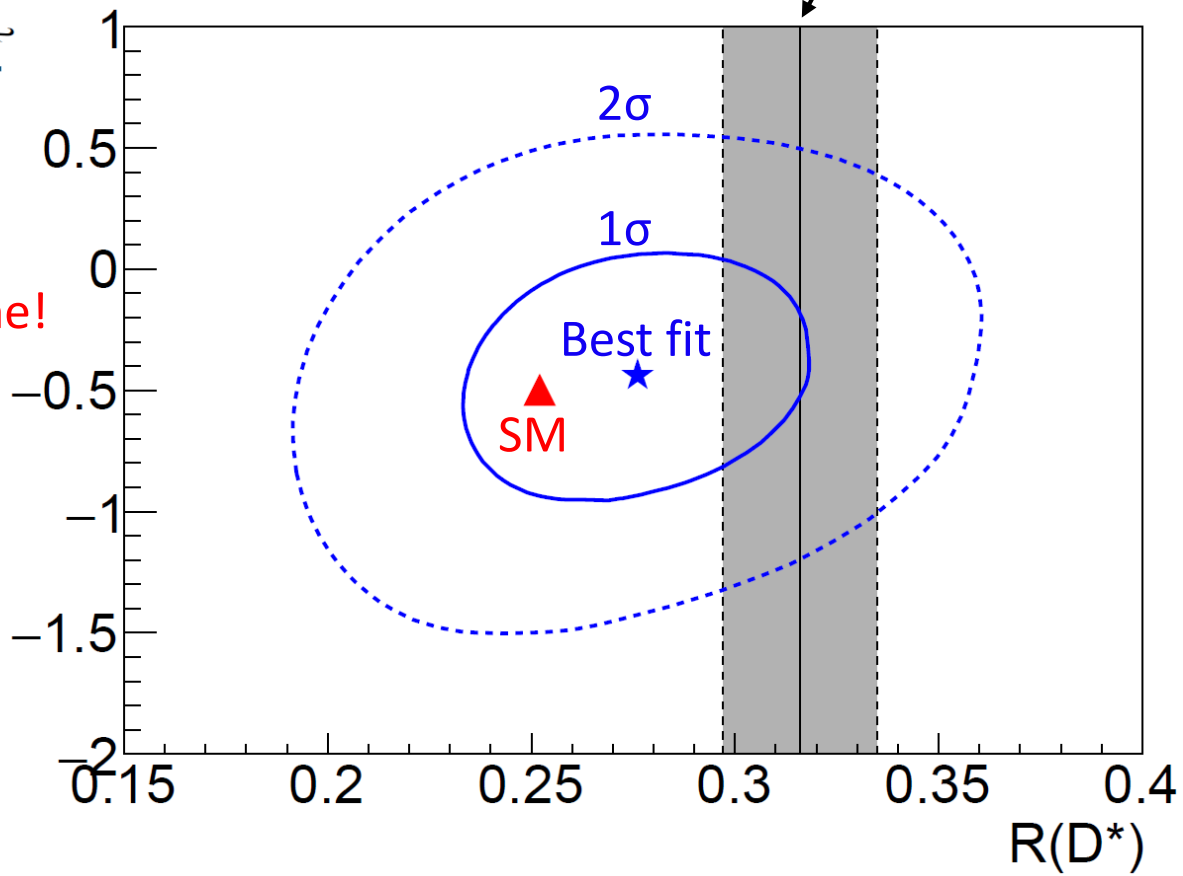
First $R(D^*)$ measurement only with hadronic τ decays!

■ Comparison with SM and Prev. Results

Preliminary

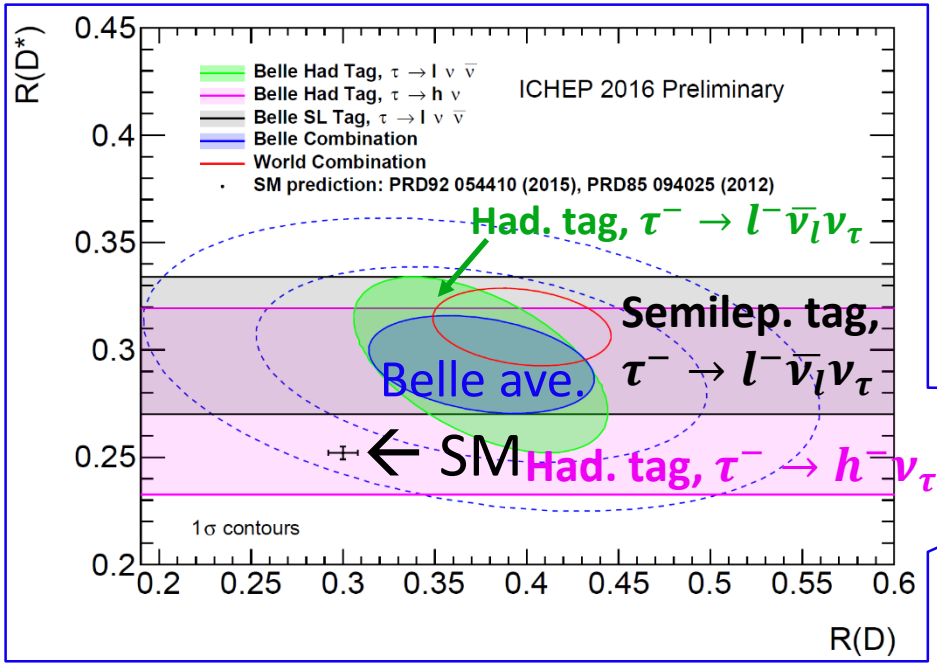
Experimental average without the new result

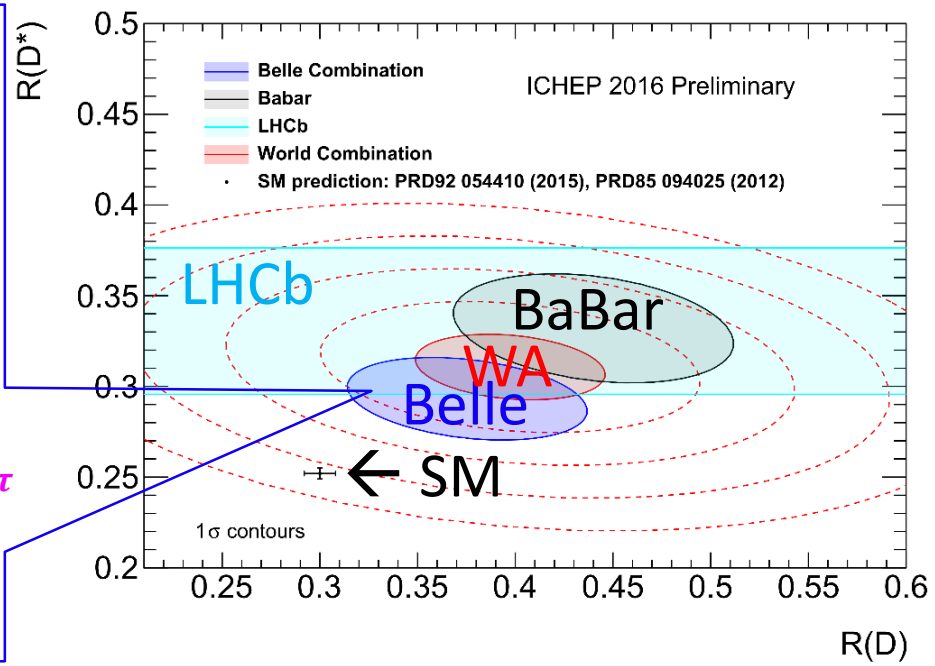
Constraint on P_τ is given for the first time!



- By combining $R(D^*)$ and P_τ, our result is consistent with the SM within 0.6σ

$R(D^{(*)})$ World Average

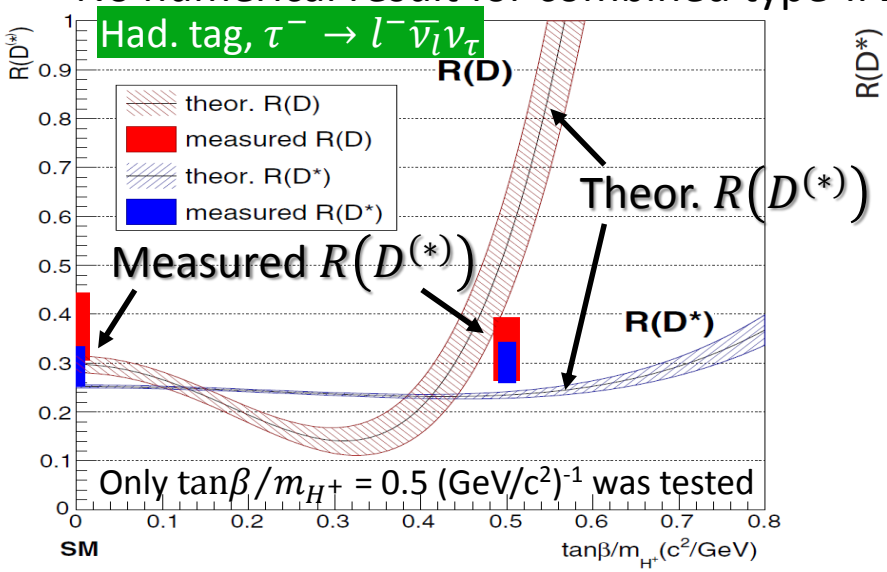


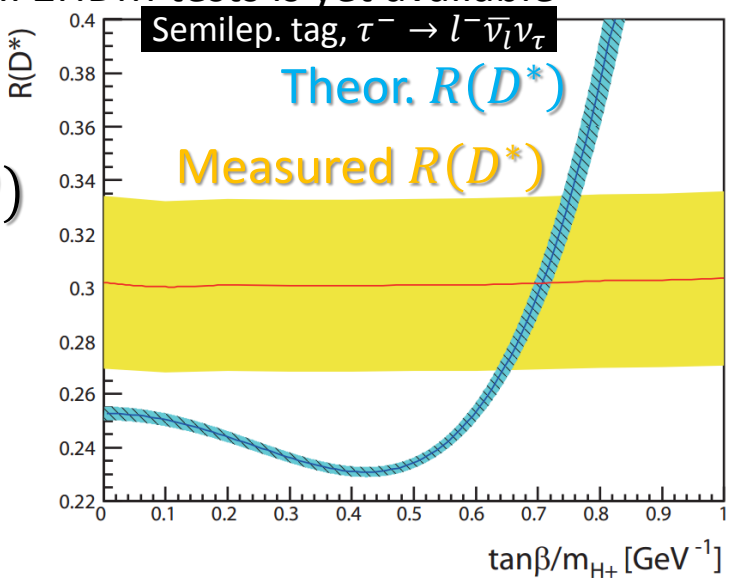


- Combination of $R(D^{(*)})$ results
  - Uncertainties arising from semileptonic background are assumed to have 100% correlation
- Belle's average is about 2σ away from the SM
  - Combining results from BaBar and LHCb, tension is about 4σ

■ Test of type-II 2HDM

- One benchmark model: type-II 2HDM
  - Parameter = $\tan\beta/m_{H^+}$
    - $\tan\beta$ = ratio of VEV of two Higgs doublets
    - m_{H^+} = charged Higgs mass
  - BaBar excluded it at 99.8% C.L. *BaBar, Phys. Rev. Lett. 109, 101802 (2012)*
- Belle: favored regions seem discrepant between $R(D)$ and $R(D^*)$
  - No numerical result for combined type-II 2HDM tests is yet available





- Many other models were tested in the semileptonic-tag analysis
- Similar NP tests will be done soon in the $\tau^- \to h^- \nu_\tau$ analysis

Summary

- $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ is an interesting mode as a probe for NP
- Three results from Belle
  - $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ with hadronic tagging, $\tau^- \to l^-\bar{\nu}_l\nu_\tau$
  - $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with semileptonic tagging, $\tau^- \to l^-\bar{\nu}_l\nu_\tau$
  - $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ with hadronic tagging, $\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau$

  → Combined $R(D^{(*)})$ by Belle shows about 2σ tension from the SM
  - The total discrepancy including BaBar and LHCb is about 4σ

<u>The tension still exists, important topic at Belle II</u>

- Prospects for near future: other ongoing analyses at Belle...
  - D^* polarization measurement
  - Inclusive $\bar{B} \to X\tau^-\bar{\nu}_\tau$ measurement