$B \to \tau \nu / D \tau \nu$
B DECAYS TO τ LEPTONS

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Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

NAGOYA
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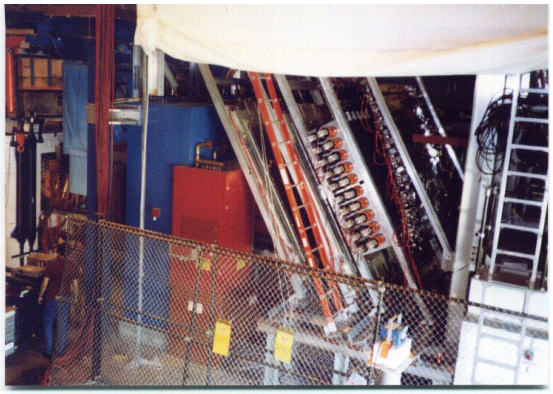
Talk Outline

- Introduction
- Purely leptonic decay $B \to \tau \nu$
- Semileptonic decay $B \to D^{(*)} \tau \nu$
- Future Prospect
- Summary



BNL-E813/836
Search for "H particle"
My PhD experiment

Special thanks to Dr. Y. Horii (cf. his talk at Beauty2013)

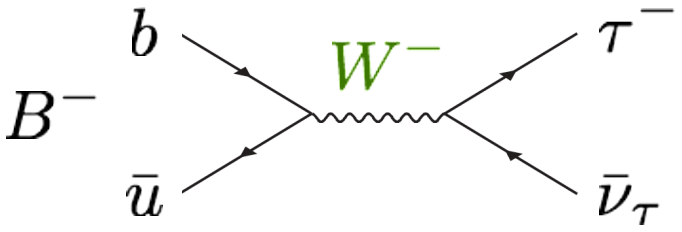
$$B \to \tau \nu \,/\, B \to D^{(*)} \tau \nu$$

Sensitive for NP (H^+,…)

Key flavor physics observables in the LHC era !

$B^- \to \tau^- \nu$ in SM

- Proceed via W-exchange, helicity suppressed.



$$Br(B \to e\nu) \quad 10^{-11}$$
$$Br(B \to \mu\nu) \quad 10^{-7}$$
$$Br(B \to \tau\nu) \quad 10^{-4}$$

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

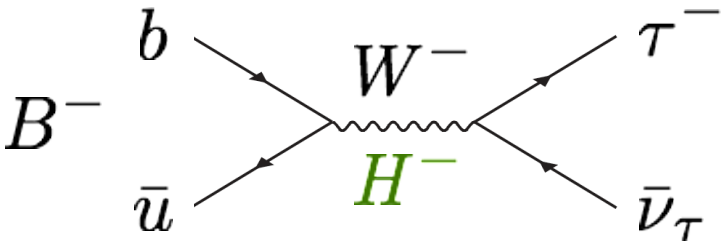
- Parameters
  - B decay constant: $f_B = 191 \pm 9$ MeV — HPQCD, PRD86
  - CKM matrix: $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ — *b→ulν*, PRD86

$$Br_{SM}(\tau\nu) = (1.20 \pm 0.25) \times 10^{-4}$$

Can be obtained also from a global CKM fit

Charged Higgs Effect in B→τ ν

- Charged Higgs exchange interferes with the helicity suppressed W-exchange.

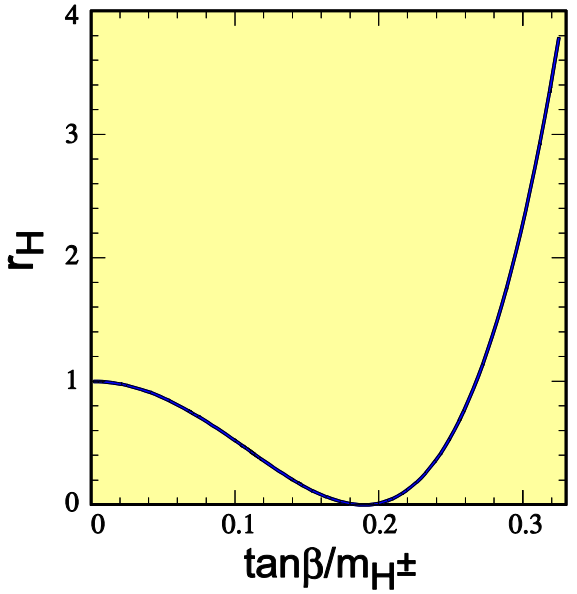


- Example of Br modification

$$Br = Br_{SM} \times r_H \qquad r_H = \left|1 - g_S\right|^2$$

Type II 2HDM, W. S. Hou, PRD 48, 2342 (1993),

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

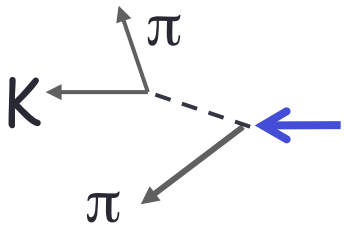


Analysis for $B \to \tau\nu$

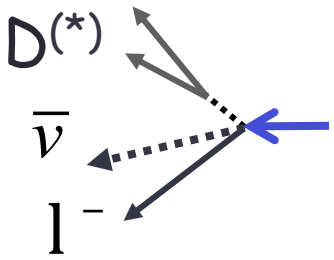
Tagging side:

S/N

Hadronic tags
$B_{tag} \to D^{(*)}\pi/\rho$ etc.

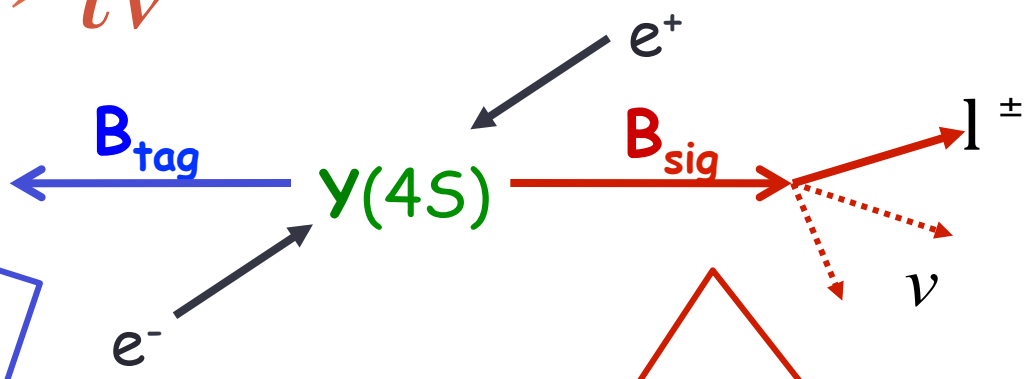


Semileptonic tags
$B_{tag} \to D^{(*)}l\nu$ etc.



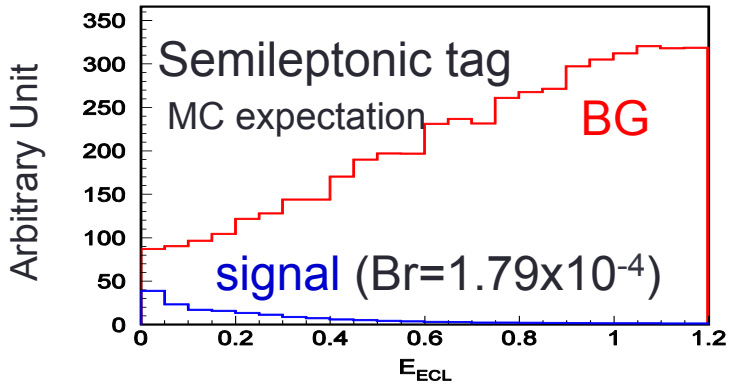
Inclusive tags
Used for Belle $B \to D^{*}\tau\nu$

Eff



Signal side: $B_{sig} \to \tau\,\nu$

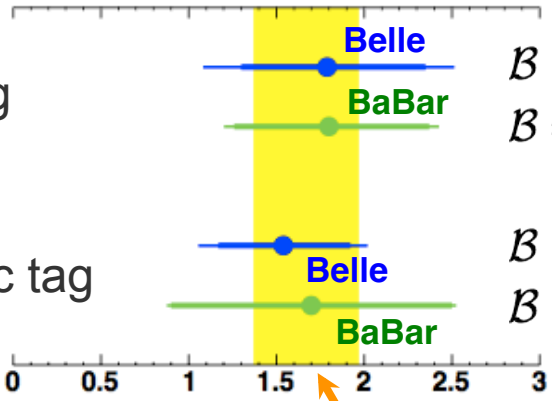
- Detect charged track(s)
- Missing energy due to ν's
- No extra activities in EM calorimeter
  ($E_{ECL(extra)}$)



Status for B→ τ ν before ICHEP 2012

Hadronic tag

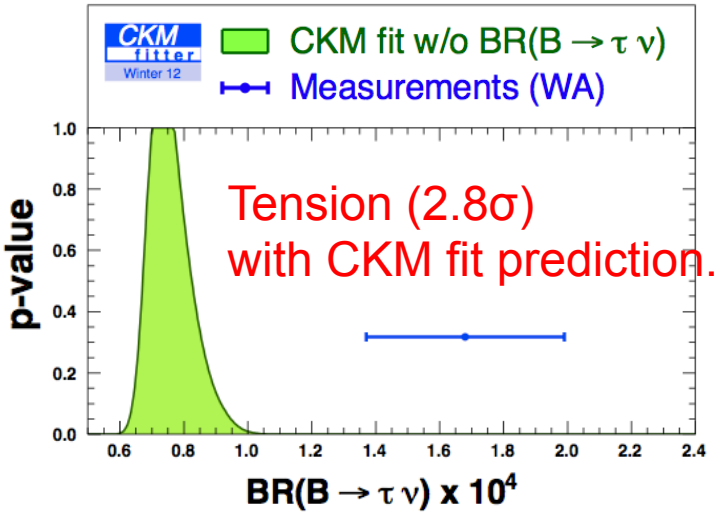
Semileptonic tag

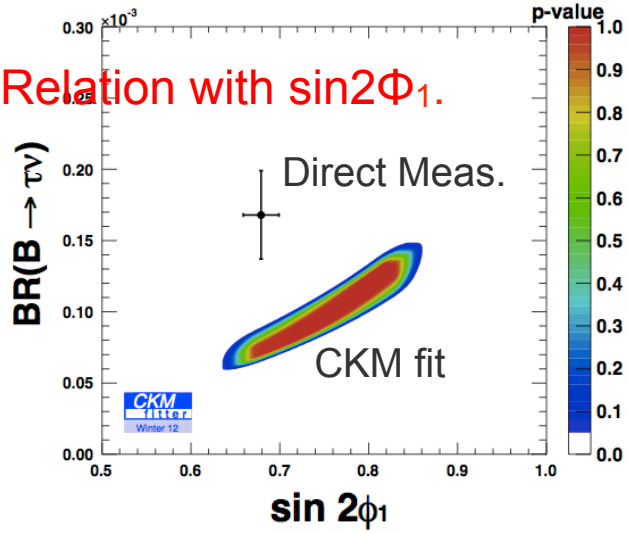


$$\mathcal{B} = [1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})] \times 10^{-4}$$
$$\mathcal{B} = [1.80^{+0.57}_{-0.54}(\text{stat}) \pm 0.26(\text{syst})] \times 10^{-4}$$

$$\mathcal{B} = [1.54^{+0.38}_{-0.37}(\text{stat})^{+0.29}_{-0.31}(\text{syst})] \times 10^{-4}$$
$$\mathcal{B} = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$$

WA (HFAG): $\mathcal{B}$ = (1.67 ± 0.30) x 10^{-4}

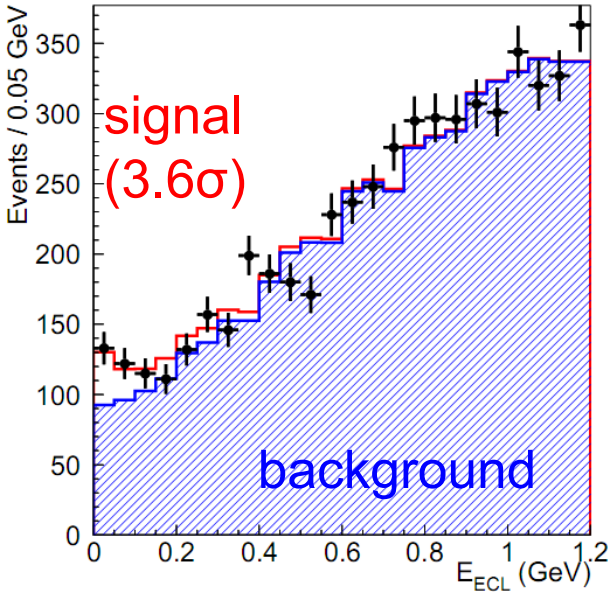




$B \to \tau\ \nu$ by Semileptonic Tag

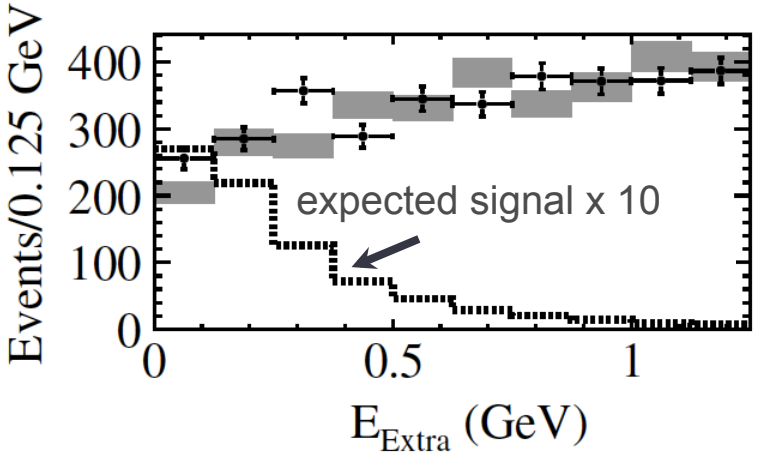
Belle

- PRD 82, 071101(R) (2010).
- Use 657 M BB.
- $B=[1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}]\times10^{-4}$.



BaBar

- PRD 81, 051101(R) (2010).
- Use 459 M BB.
- $B=[1.7\pm0.8\pm0.2]\times10^{-4}$.



(Counting method employed.)

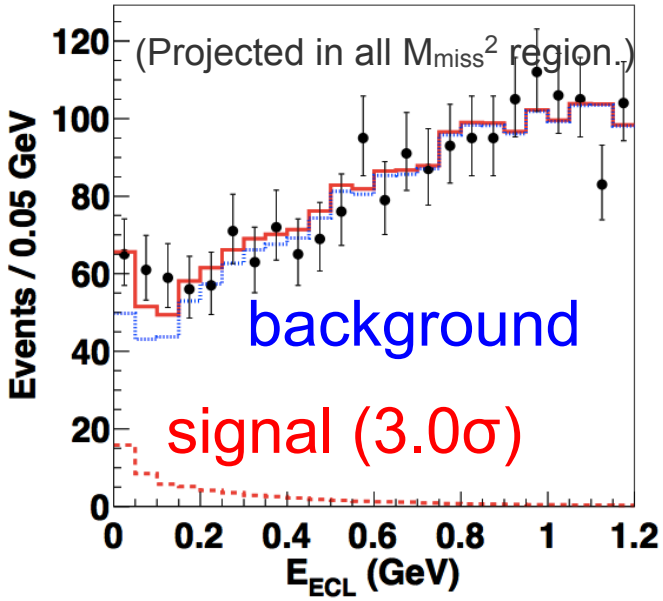
Belle at ICHEP2012

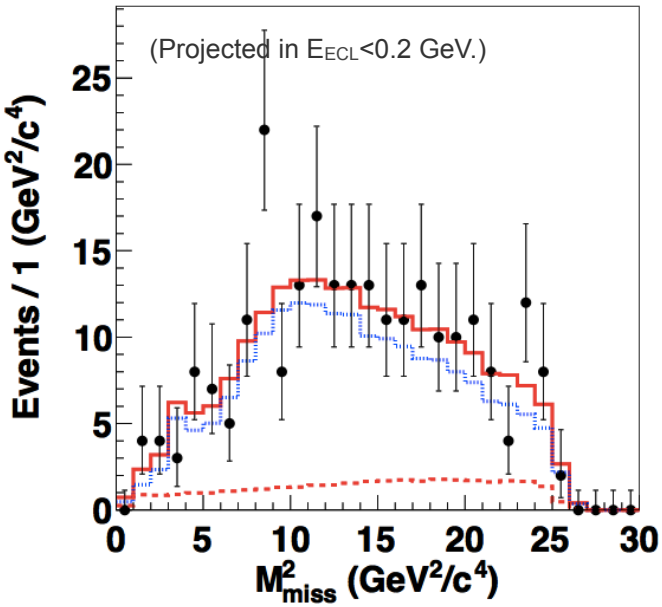
(w.r.t. Belle2006)

- Use 772M BB (full) data x 1.7
- Improved tracking eff. by reprocessing data
- Improved hadronic tags x 2.2 (NueroBayes algorithm)
- Improved signal selection efficiency (in trade of S/N) x 1.8
- Newly added K_L veto
- Better understanding of peaking background
- 2D fit in (E_{ECL}, M_{miss}^2) for signal extraction

$$Br(B \to \tau\nu) = [0.72\ ^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$$

Published in PRL110, 131801 (2013)!

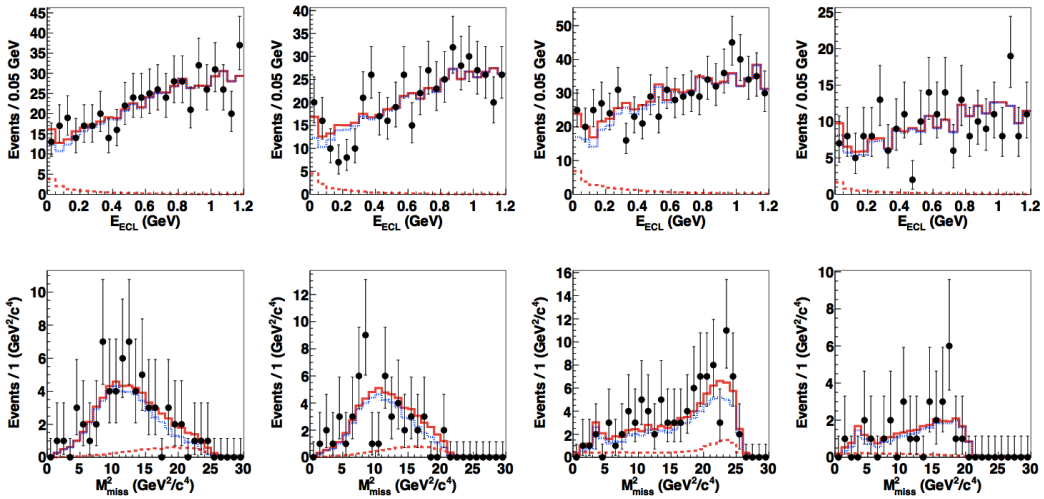




B→ τ ν by Hadronic Tag at Belle, Mode Independence

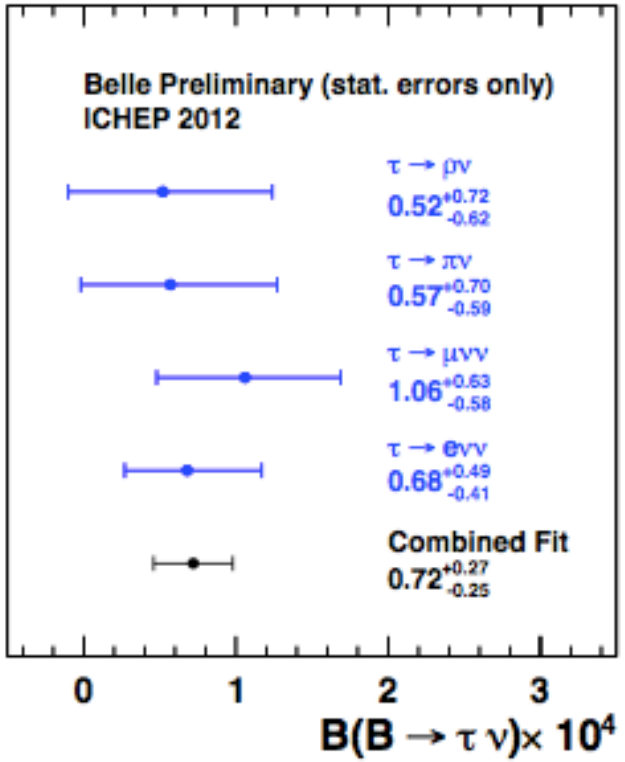
As a check, we fit by floating the yields for different τ modes.

τ→eνν τ→μνν τ→πν τ→ρν



Take τ→eνν, μνν, ρν cross-feeds in τ→πν candidates as signal.

Mode	Number of signal	Efficiency
$e^-\overline{\nu}_e\nu_\tau$	$15.5^{+11.2}_{-9.4}$	2.98×10^{-4}
$\mu^-\overline{\nu}_\mu\nu_\tau$	$25.6^{+15.1}_{-13.8}$	3.12×10^{-4}
$\pi^-\nu_\tau$	$7.8^{+9.5}_{-7.9}$	1.76×10^{-4}
$\rho^-\nu_\tau$	$13.6^{+18.7}_{-16.1}$	3.37×10^{-4}



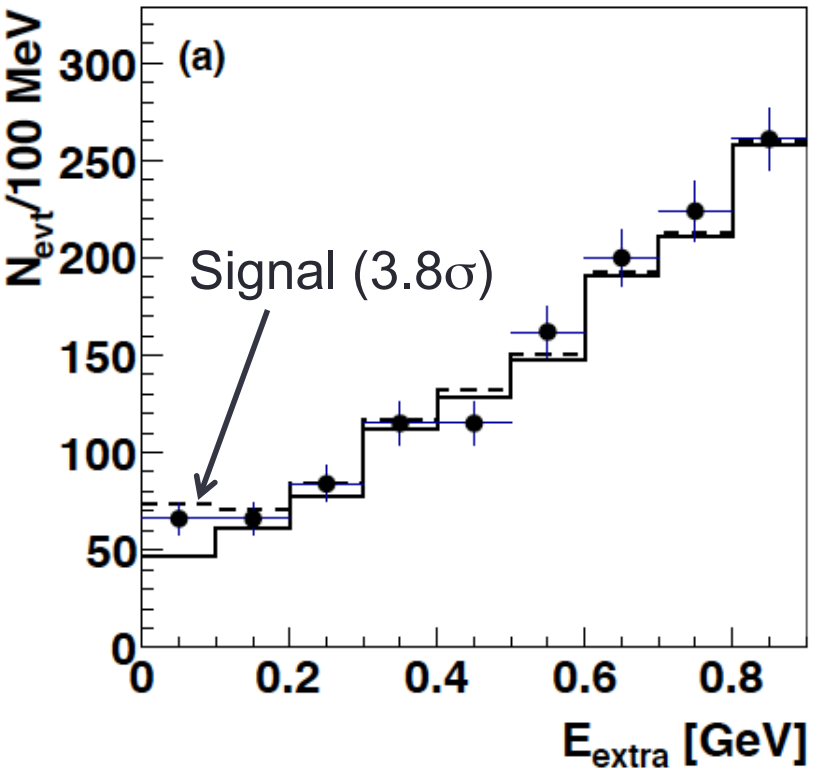
Consistent results.

Rare unobserved BG decays (e.g. B→μνγ) would show up in individual signal modes.

BaBar at ICHEP2012

arXiv: 1207.0698

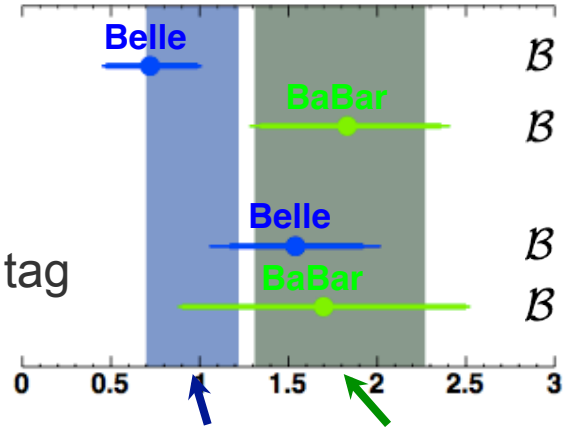
- Use 468M BB (full) data sample
- Use four τ decay channels
  - eνν, μνν, πν, ρν
- Expanded set of hadronic tag modes
  - including B→J/ψ X
  - ~x 2 w.r.t. BaBar2008



$$Br(B \to \tau\nu) = [1.83\ ^{+0.53}_{-0.49} \pm 0.24] \times 10^{-4}$$

Status for B→ τ ν after ICHEP 2012

Hadronic tag

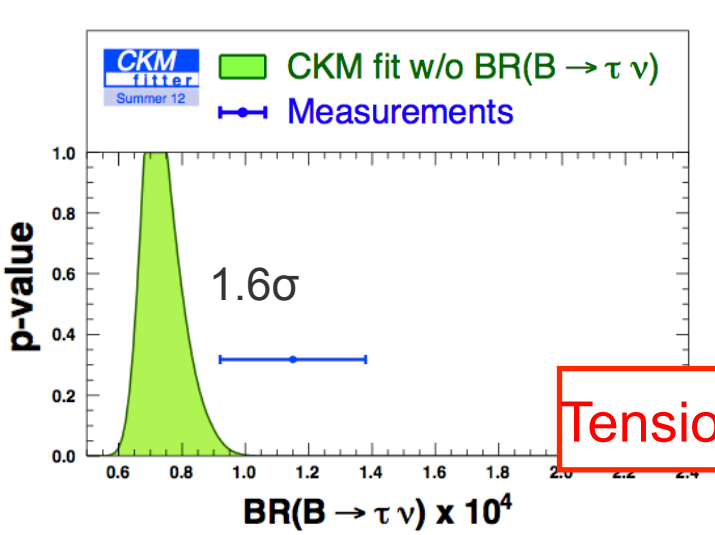


Semileptonic tag

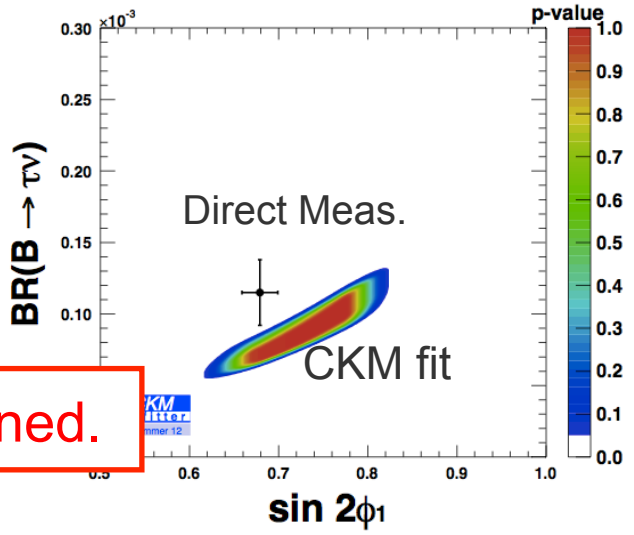
$$\mathcal{B} = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$$
$$\mathcal{B} = [1.83^{+0.53}_{-0.49}(\text{stat}) \pm 0.24(\text{syst})] \times 10^{-4}$$
$$\mathcal{B} = [1.54^{+0.38}_{-0.37}(\text{stat})^{+0.29}_{-0.31}(\text{syst})] \times 10^{-4}$$
$$\mathcal{B} = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$$

Belle combined: $\mathcal{B}$=(0.96±0.26)x10^{-4} BaBar combined: $\mathcal{B}$=(1.79±0.48)x10^{-4}

A naive world average: $\mathcal{B}$=(1.15±0.23)x10^{-4}



Tension weakened.



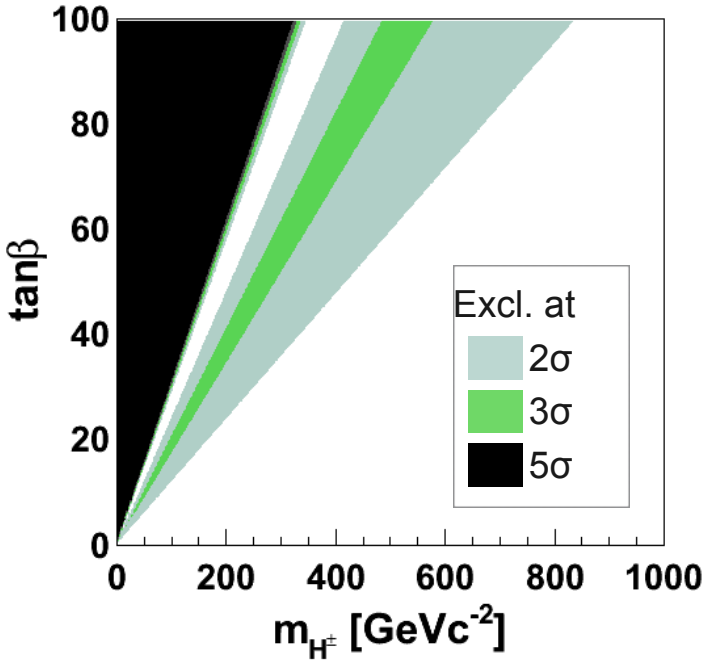
Constraint on Charged Higgs from B→ $\tau\ \nu$

- Assume Type-II 2HDM.

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\rm SM} \times r_H$$
$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

- Use
  - B(B→ $\tau\ \nu$) = (1.15±0.23)×10^{-4}
  - B(B→ $\tau\ \nu$)$_{SM}$ = (1.11±0.28)×10^{-4}

  where B(B→ $\tau\ \nu$)$_{SM}$ is obtained from
  - f_B = (191±9) MeV (HPQCD, PRD86)
  - $|V_{ub}|$ = (4.15±0.49)×10^{-3} (PDG, PRD86)



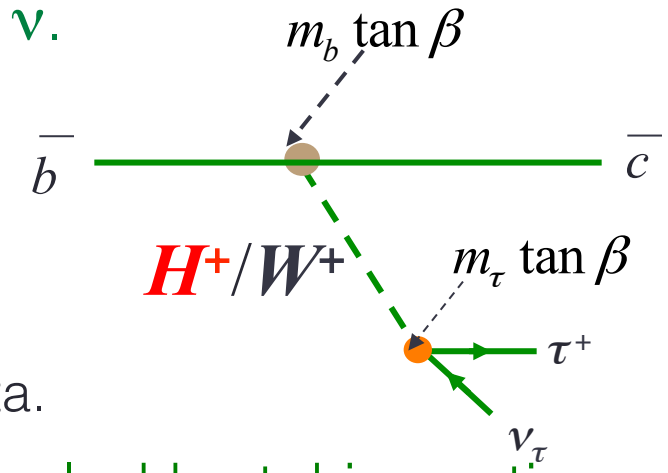
Personal figure by Y. Horii.

Stringent constraint on tanβ and m_H obtained.

Note: constraint strongly depends on f_B and $|V_{ub}|$.

B→D τ ν

- B→D τ ν is another process sensitive to the charged Higgs, and complementary to B→τ ν.
  - Relatively large Br ~0.8%
  - Different theory systematics:
    - free from V_{ub} and f_B ambiguity.
    - depends on the B→D form factors, which can be deduced from D l ν data.



- $|V_{cb}|$ and a part of QCD effects canceled by taking ratios.

$$\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B} \to D\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell^-\overline{\nu}_\ell)}, \quad \mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^*\ell^-\overline{\nu}_\ell)}$$

B→Dlν decay is measured precisely; $Br(B^- \to D^0 l\nu) = (2.26 \pm 0.11)\%$

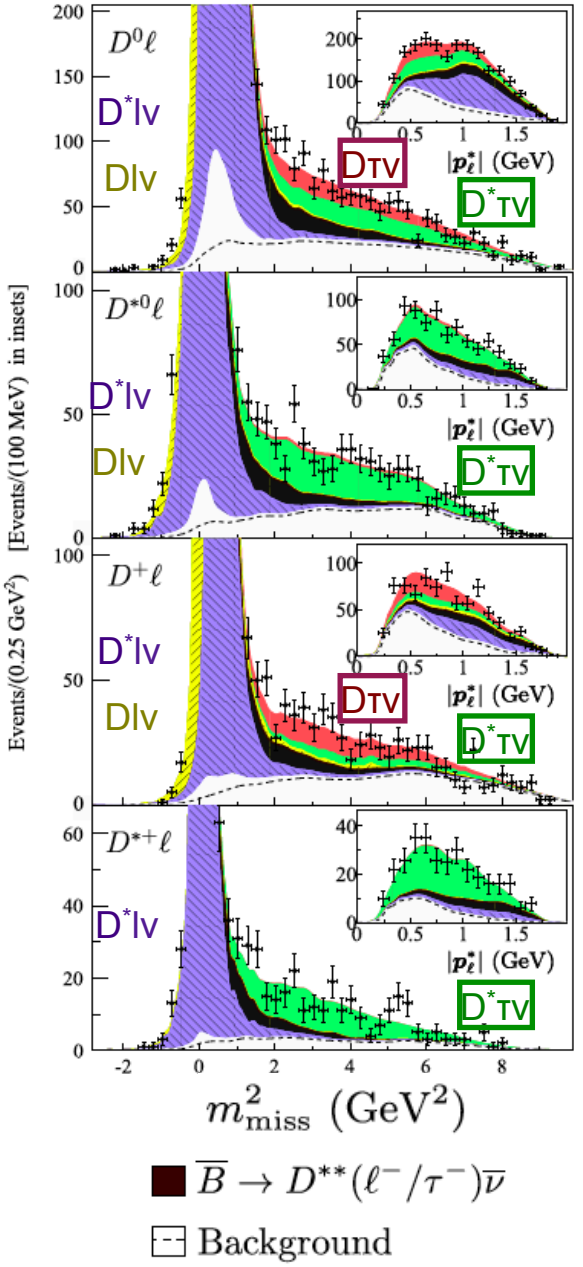
- Possible observables additional to the ratios:
  - τ polarization, D^* polarization, q^2 distribution, ...

M. Tanaka, R. Watanabe, PRD87, 034028 (2013)

$B \to D^{(*)} \tau \nu$ from BaBar

- PRL 109, 101802 (2012).
- arXiv:1303.0571, submitted to PRD.
- Use 471 M BB (full data).
- Improved hadronic tag by more modes.
- Boosted decision tree for event selection.

- $R(D) = B(D \tau \nu) / B(Dl \nu) =$ $0.440 \pm 0.058 \pm 0.042$
- $R(D^*) = B(D^* \tau \nu) / B(D^* l \nu) =$ $0.332 \pm 0.024 \pm 0.018$
- Systematic uncertainties from D^{**} BG, BG PDFs, BG yields, etc.



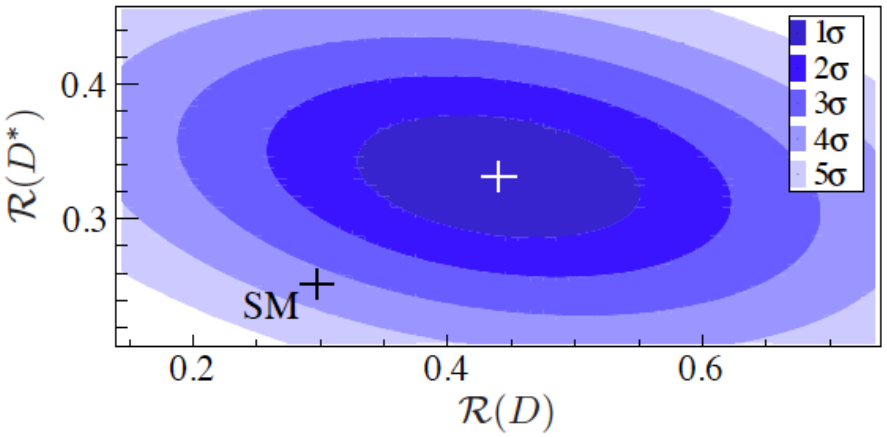
$B \to D^{(*)} \tau \nu$ from BaBar and SM

$$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072 \qquad \mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030$$

$\updownarrow$ 2.0σ $\qquad\qquad$ $\updownarrow$ 2.7σ

$$\mathcal{R}(D)_{\rm SM} = 0.297 \pm 0.017 \qquad \mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003$$

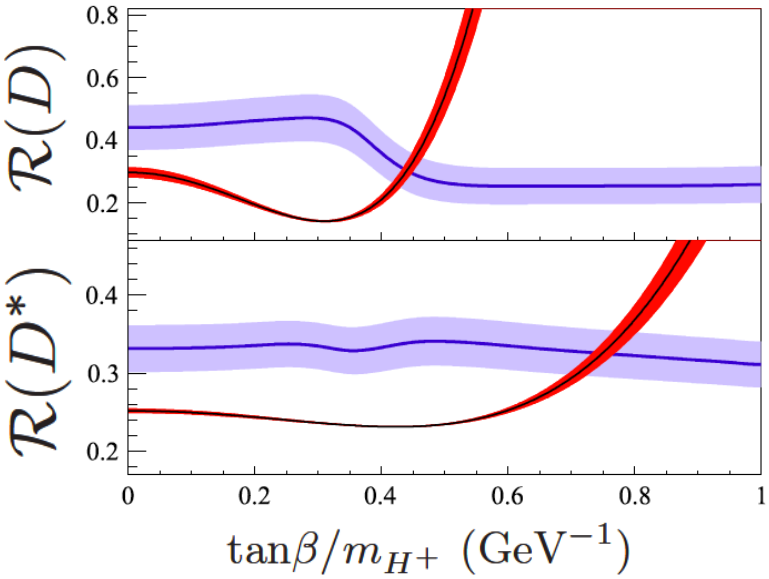
SM expectations in S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012).



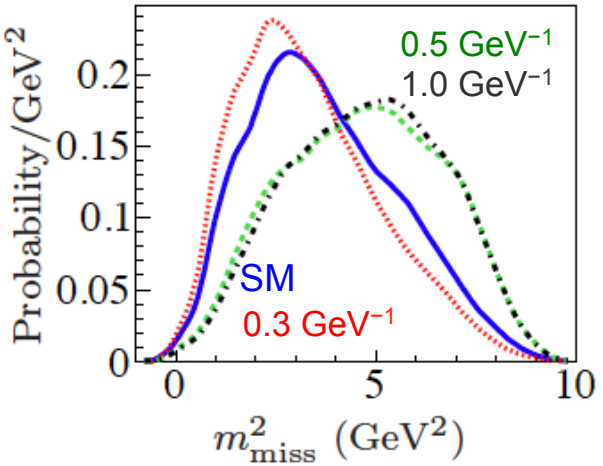
The possibility that the measured R(D) and R(D*) both agree with the SM predictions is excluded at the 3.4 σ level.

(σ for 1-D Gaussian function)

$B \to D^{(*)} \tau \nu$ from BaBar and Type-II 2HDM

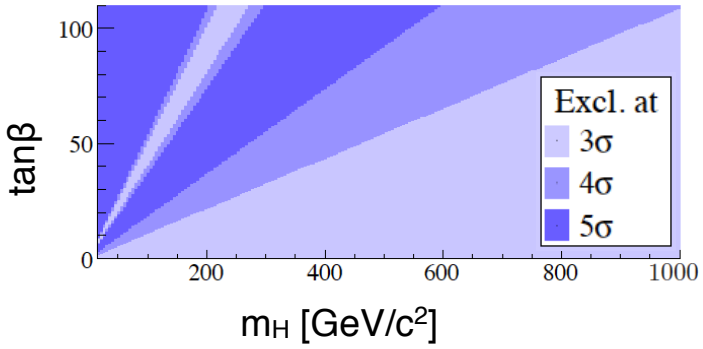


Blue: this result, red: Type-II 2HDM.



(The values indicated for tan β /m_H.)

Exp. R(D$^{(*)}$) dependency mainly from m_{miss}^2 dependency (reflection of q^2 dependence).

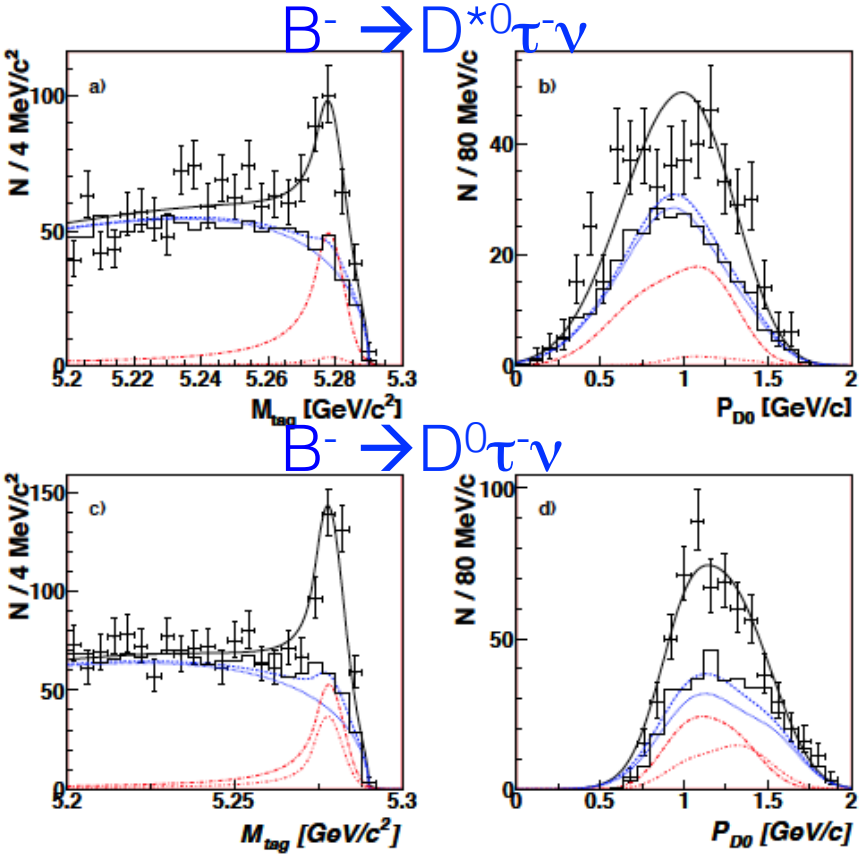


The combination of R(D) and R(D*) excludes the Type-II 2HDM at 99.8% C.L. for any value of tan β /m_H.

Note: Type III and q^2 spectra in arXiv:1303.0571.

$B \to D^{(*)} \tau \nu$ from Belle

- Inclusive tags
  - B_{tag}'s are reconstructed by the four-vector sum of the tracks w/o recon. of the intermediate mesons.
  - PRL99, 191807 (2007), 535M BB
    - First observation of $B^0 \to D^{*-} \tau^+ \nu$ (5.2σ)
  - PRD82, 072005(2010), 657M BB
- Hadronic tags
  - Hep-ex/0910.4301, 657M BB, Preliminary



$B \to D^{(*)} \tau \nu$ from Belle

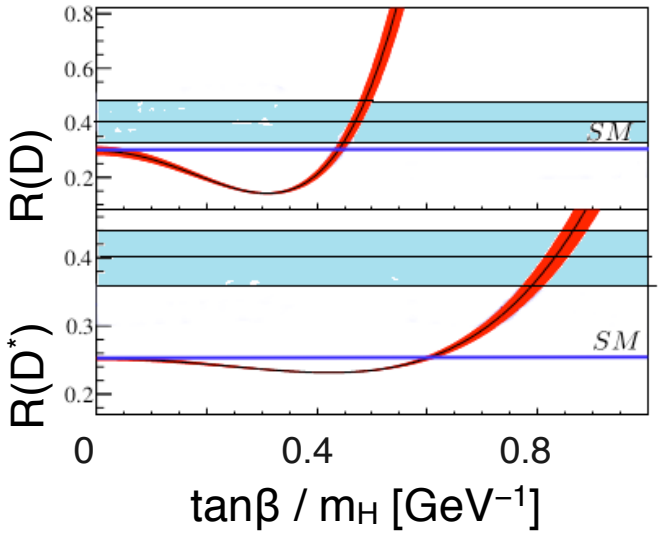
A. Bozek's averages (KEK-FF 2013):

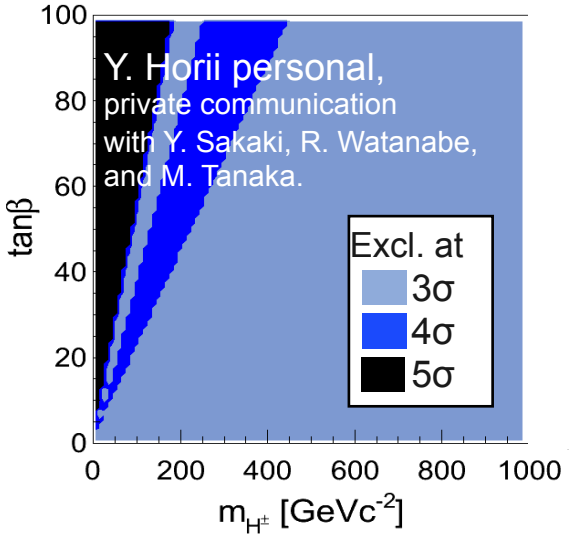
(naive averages for inclusive and exclusive hadronic tags)

	Deviation from SM
$R(D) = 0.430 \pm 0.091$	$1.4\ \sigma$
$R(D^*) = 0.405 \pm 0.047$	$3.0\ \sigma$
Combined	$3.3\ \sigma$

Correlation btw R(D) and R(D*) neglected conservatively.

Constraint on Type-II 2HDM:





Experimental $R(D^{(*)})$ dependence on $\tan\beta / m_H$ not considered.
Experimental correlation between R(D) and R(D*) not considered.

Prospect at Belle II

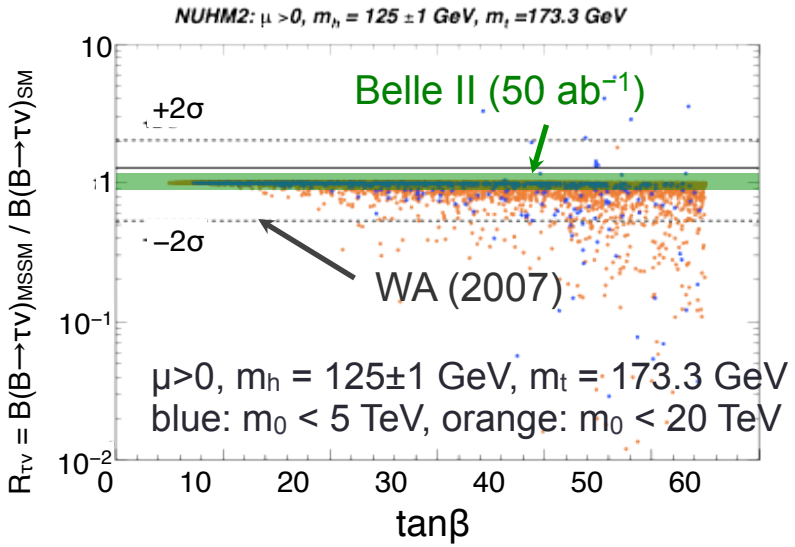
- 7GeV e^- ×4GeV e^+,
- $L_{peak} = 8 \times 10^{35} cm^{-2} s^{-1}$,
- $L_{int} = 50 ab^{-1}$

- $B \rightarrow \tau\nu$
  - Precision ~ a few %
  - Need better precision for $f_B |V_{ub}|$.

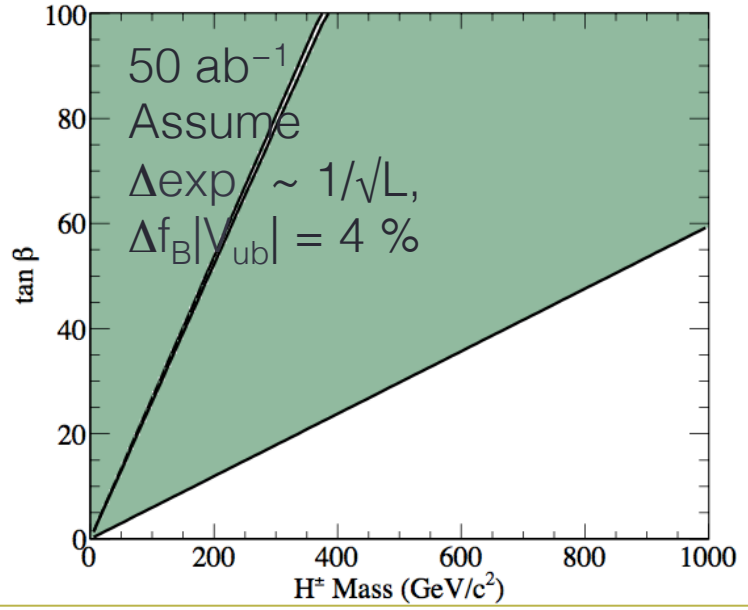
- $B \rightarrow \mu\nu$, $e\nu$
  - 5σ observation expected for $B(B \rightarrow \mu \nu)_{SM}$ at ~10 ab^{-1}.
  - $O(10^{-8})$ sensitivity at 50 ab^{-1}.
  - Interesting to compare w/ $B \rightarrow \tau\nu$

2-parameter nonuniversal Higgs model

H. Baer, V. Barger, and A. Mustafayev,PRD85, 075010



Charged Higgs constraint (Type-II 2HDM)



Request for theory

- It is of great importance to improve precision for the SM prediction;
  - $f_B\,|V_{ub}|$ for $B \to \tau\nu$

    Present error
    $\Delta f_B \sim 5\%$
    $\Delta|V_{ub}| \sim 10\%$ + incl. vs excl. saga
  - Form factors for $B \to D\tau\nu$

    Recent Lattice QCD (FNAL/MILC)
    Predicts R(D)=0.316(12)(7)
    ~1s higher than the previous estimates

Summary

- $B \to \tau\ \nu$ and $B \to D^{(*)}\ \tau\ \nu$ are powerful tools for both testing the SM and searching for NP (charged Higgs,…).

  Key flavor physics observables in the LHC era !

- Recent $B \to \tau\ \nu$ results have weakened the tension with CKM fit.
- Recent $B \to D^{(*)}\ \tau\ \nu$ results disfavor SM and type-II two Higgs doublet model at a level of $>3\,\sigma$.
  - Final result from Belle using full data coming soon.
- It is very important to measure $B \to \tau\nu$ /$D^{*}\tau\nu$ with a few % precision.

Belle II will start physics run in 2016 !

Backup

Charged Higgs in b → τ

- Extensions of the SM, which require >2 Higgs doublets, generate new flavor-changing interactions at tree-level via exchange of a charged Higgs.
- The H^+ coupling is proportional to the fermion mass, and it is natural to look at (semi-)leptonic B decays into a τ in the final state.

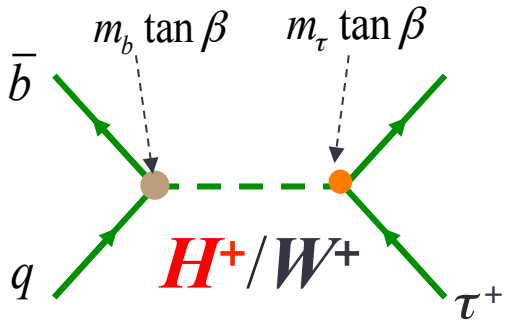
B → τ transition (MSSM)

$$\mathcal{H}^{\text{eff}} = 2\sqrt{2}\, G_F\, V_{qb} \{ (\bar{b}_L\, \gamma^\mu\, q_L)\, (\bar{\nu}_L\, \gamma_\mu\, \tau_L) - \frac{m_b m_\tau}{m_B^2} g_S\, (\bar{b}_R\, q_L)\, (\bar{\nu}_L\, \tau_R) \};$$

Effective scalar coupling;

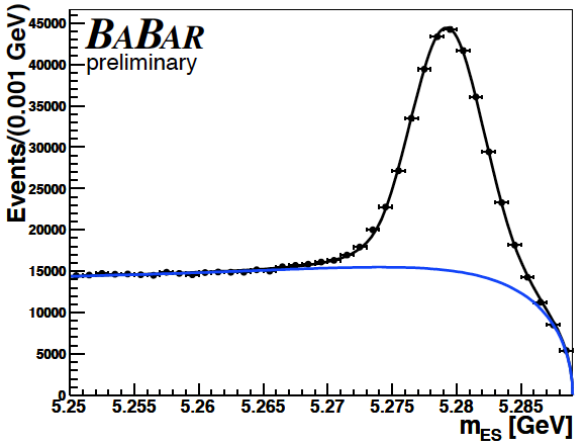
$$g_S = \frac{M_B^2 \tan^2\beta}{M_H^2} \frac{1}{(1+\varepsilon_0 \tan\beta)(1+\varepsilon_\tau \tan\beta)},$$

SUSY Loop correction
$\varepsilon_0=\varepsilon_t=0$ in Type-II 2HDM



Tag for $B \to \tau\ \nu$

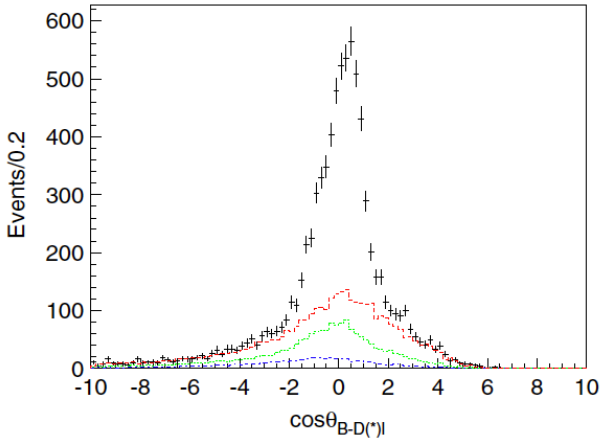
Hadronic tag for B→τν by BaBar



$$m_{\mathrm{ES}} = \sqrt{s/4 - p_B^2}$$

- Modes: $B \to D^{(*)}\pi$, etc.
- Efficiency = ~0.2%.
- Less background.
- p_{Bsig} determined.

Semileptonic tag for B→τν by Belle



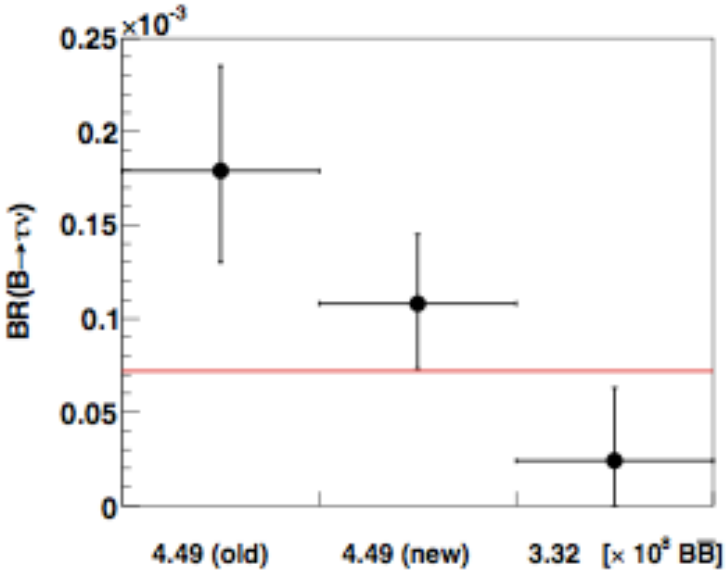
$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\mathrm{beam}}^{\mathrm{cms}} E_{D^{(*)}\ell}^{\mathrm{cms}} - m_B^2 - M_{D^{(*)}\ell}^2}{2P_B^{\mathrm{cms}} \cdot P_{D^{(*)}\ell}^{\mathrm{cms}}}$$

- Modes: $B \to D^{(*)}l\nu$.
- Efficiency = ~1%.
- More background.
- p_{Bsig} not determined.

Comparison for B→ τ ν Using Hadronic Tag at Belle

	PRL 97 (2006)	This analysis	
Tag	Hadronic tag	Hadronic tag (new)	
Number of $B\overline{B}$ events ($\times 10^8$)	4.49	4.49	3.22
Efficiency ($\times 10^{-4}$)	3.0	11.2	11.2
Signal yield	$24.1^{+7.6}_{-6.6}$	$54.1^{+18.8}_{-17.4}$	$8.6^{+14.0}_{-12.4}$
$\mathcal{B}(B^- \to \tau^- \overline{\nu}_\tau)$ ($\times 10^{-4}$)	$1.79^{+0.56}_{-0.49}$	$1.08^{+0.37}_{-0.35}$	$0.24^{+0.39}_{-0.34}$

- New analysis is based on improved tag, loose event selection, and reprocessed data.
- Most of the data after the selection are independent from old analysis.
- Assuming that all events in old analysis are included in new analysis, the remaining data sample in N_{BB} = 4.49 × 10^8 provides BR ~ (0.6±0.4) × 10^{-4} (1.9σ from old result).



$B^{\pm} \to D^{(*)} \tau \nu$ by Hadronic Tag from Belle

- Using 657 M BB.
- Simultaneous fit to both subsets.
- $D^{(*)}lv$ as control sample and normalization.
- Evidence for signals.

$$R(D^0\tau^-\bar{\nu}_\tau/D^0l^-\bar{\nu}_\tau) = 0.70^{+0.19}_{-0.18}(\text{stat})^{+0.11}_{-0.09}(\text{syst})$$

3.8σ

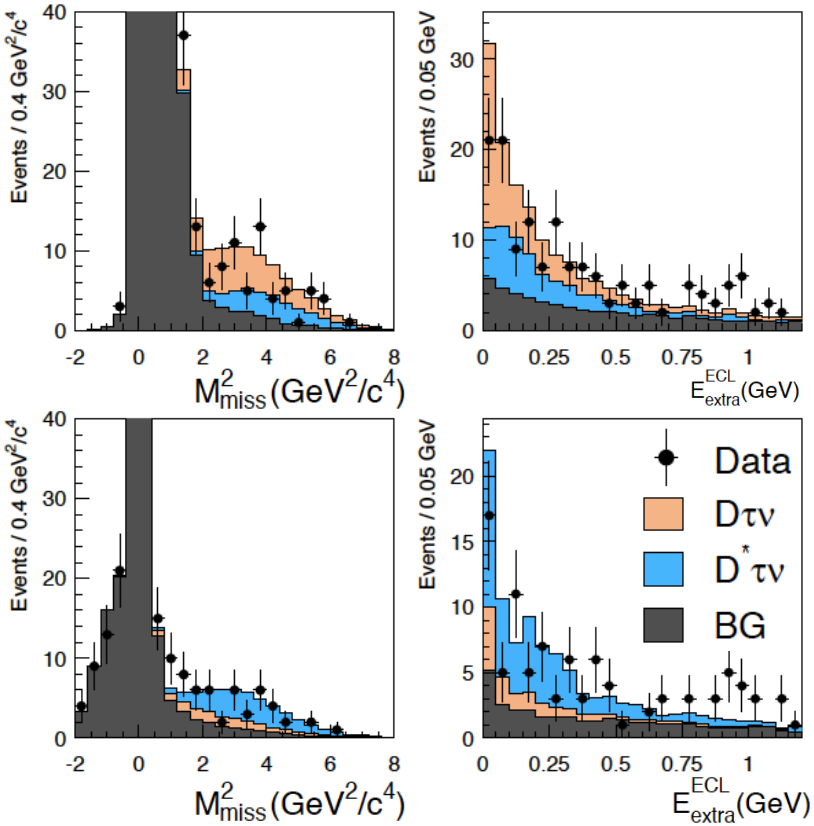
$$R(D^{*0}\tau^-\bar{\nu}_\tau/D^{*0}l^-\bar{\nu}_\tau) = 0.47^{+0.11}_{-0.10}(\text{stat})^{+0.06}_{-0.07}(\text{syst})$$

3.9σ

$$\mathcal{B}(D^0\tau^-\bar{\nu}_\tau) = [1.51^{+0.41}_{-0.39}(\text{stat})^{+0.24}_{-0.19}(\text{syst}) \pm 0.15(\text{norm})]\%$$

$$\mathcal{B}(D^{*0}\tau^-\bar{\nu}_\tau) = [3.04^{+0.69}_{-0.66}(\text{stat})^{+0.40}_{-0.47}(\text{syst}) \pm 0.22(\text{norm})]\%$$

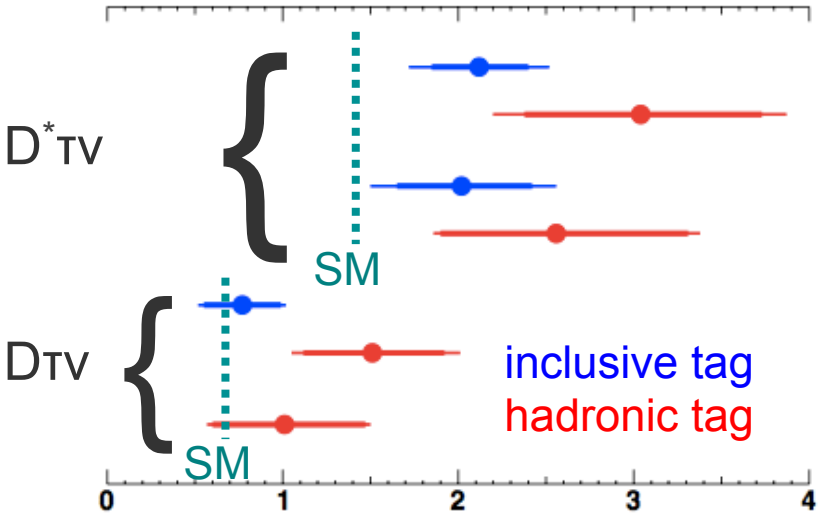
Syst. from PDFs and cross-feeds.



BG: Dlv, D*lv, D**lv, DX, ...

arXiv:0910.4301

Summary for $B \to D^{(*)} \tau \nu$ from Belle



$$\mathcal{B}(D^{*0}\tau^-\bar{\nu}_\tau) = [2.12^{+0.28}_{-0.27}(\text{stat}) \pm 0.29(\text{syst})]\%$$
$$\mathcal{B}(D^{*0}\tau^-\bar{\nu}_\tau) = [3.04^{+0.69}_{-0.66}(\text{stat})^{+0.40}_{-0.47}(\text{syst}) \pm 0.22(\text{norm})]\%$$

$$\mathcal{B}(D^{*+}\tau^-\bar{\nu}_\tau) = [2.02^{+0.40}_{-0.37}(\text{stat}) \pm 0.37(\text{syst})]\%$$
$$\mathcal{B}(D^{*+}\tau^-\bar{\nu}_\tau) = [2.56^{+0.75}_{-0.66}(\text{stat})^{+0.31}_{-0.22}(\text{syst}) \pm 0.10(\text{norm})]\%$$

$$\mathcal{B}(D^{0}\tau^-\bar{\nu}_\tau) = [0.77 \pm 0.22(\text{stat}) \pm 0.12(\text{syst})]\%$$
$$\mathcal{B}(D^{0}\tau^-\bar{\nu}_\tau) = [1.51^{+0.41}_{-0.39}(\text{stat})^{+0.24}_{-0.19}(\text{syst}) \pm 0.15(\text{norm})]\%$$

$$\mathcal{B}(D^{+}\tau^-\bar{\nu}_\tau) = [1.01^{+0.46}_{-0.41}(\text{stat})^{+0.13}_{-0.11}(\text{syst}) \pm 0.10(\text{norm})]\%$$

inclusive tag: PRL 99 (535M BB), PRD 82 (657M BB).
hadronic tag: arXiv:0910.4301 (657M BB).

- Good agreement btw the results for inclusive and hadronic tags.
- Not significant but slightly larger than SM expectations.