21 April 2010
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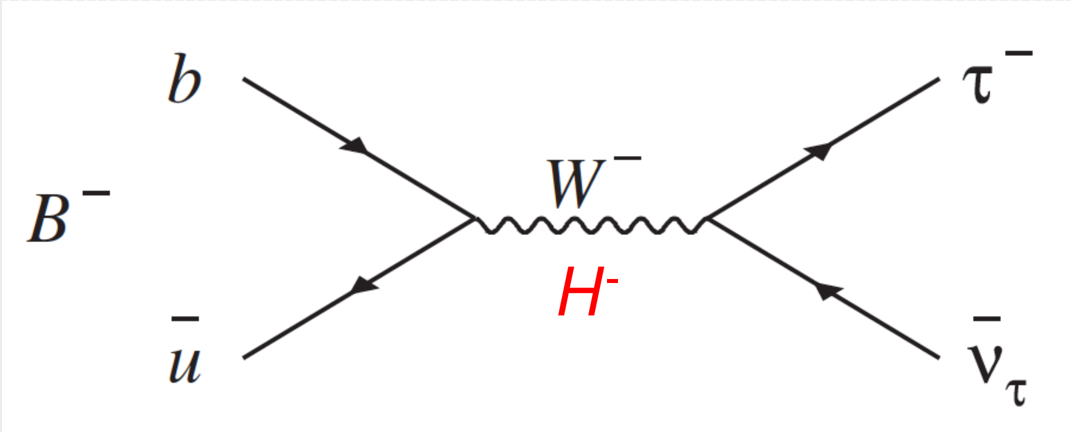
Evidence of the Purely Leptonic Decay $B^- \rightarrow \tau^- \bar{\nu}_\tau$

PRL 97, 251802 (2006)

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



- Standard model

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

  - Expected value = $(1.59 \pm 0.40) \times 10^{-4}$
- Supersymmetry or two-Higgs doublet models
  - $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ can be changed.

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

Two Higgs-doublets

- SUSY needs two Higgs-multiplets.
  - If there is one Higgs-multiplet, the electroweak gauge symmetry would suffer an anomalies (would be inconsistent as a quantum theory).
  - Another completely different reason is that a Y=1/2 (-1/2) Higgs-multiplet can give masses to charge +2/3 quarks (charge -1/3 quarks and charged leptons), because of the structure of SUSY theories.
- Two-Higgs-doublet SUSY models are minimal extensions of the standard model.

$$\tan\beta = \frac{\mathrm{VEV}_1}{\mathrm{VEV}_2}$$

Hep-ph/9709356 "A Supersymmetry Primer" Stephen P. Martin

Charged Higgs

- If there are two Higgs-doublets, five Higgs bosons appears.
  - One (complex) Higgs-doublet has 4 degrees of freedom (DOF). Subtracted 3 SU(2)-gauge DOF, 1 DOF (= 1 physical Higgs boson), remains.
  - Two (complex) Higgs-doublets have 8 DOF. Subtracted 3 SU(2)-gauge DOF, 5 Higgs appears.
- In the five Higgs bosons, one pair can have the same mass. Natural to define charged Higgs.

$$H^{\pm} \equiv \frac{1}{\sqrt{2}}(\varphi_1 + i\varphi_2)$$

(Text from Yamamoto-sensei, section 9.5)

$H^{\pm}$ contribution

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times r_H$$

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

[Wei-Shu Hou Phys. Rev. D48, 2342 (1993)]

$$(G_F/\sqrt{2})V_{ib}\{[\bar{u}_i\gamma_u(1-\gamma_5)b][\bar{l}\gamma_u(1-\gamma_5)\nu] - R_l[\bar{u}_i(1+\gamma_5)b][\bar{l}(1-\gamma_5)\nu]\} ,$$

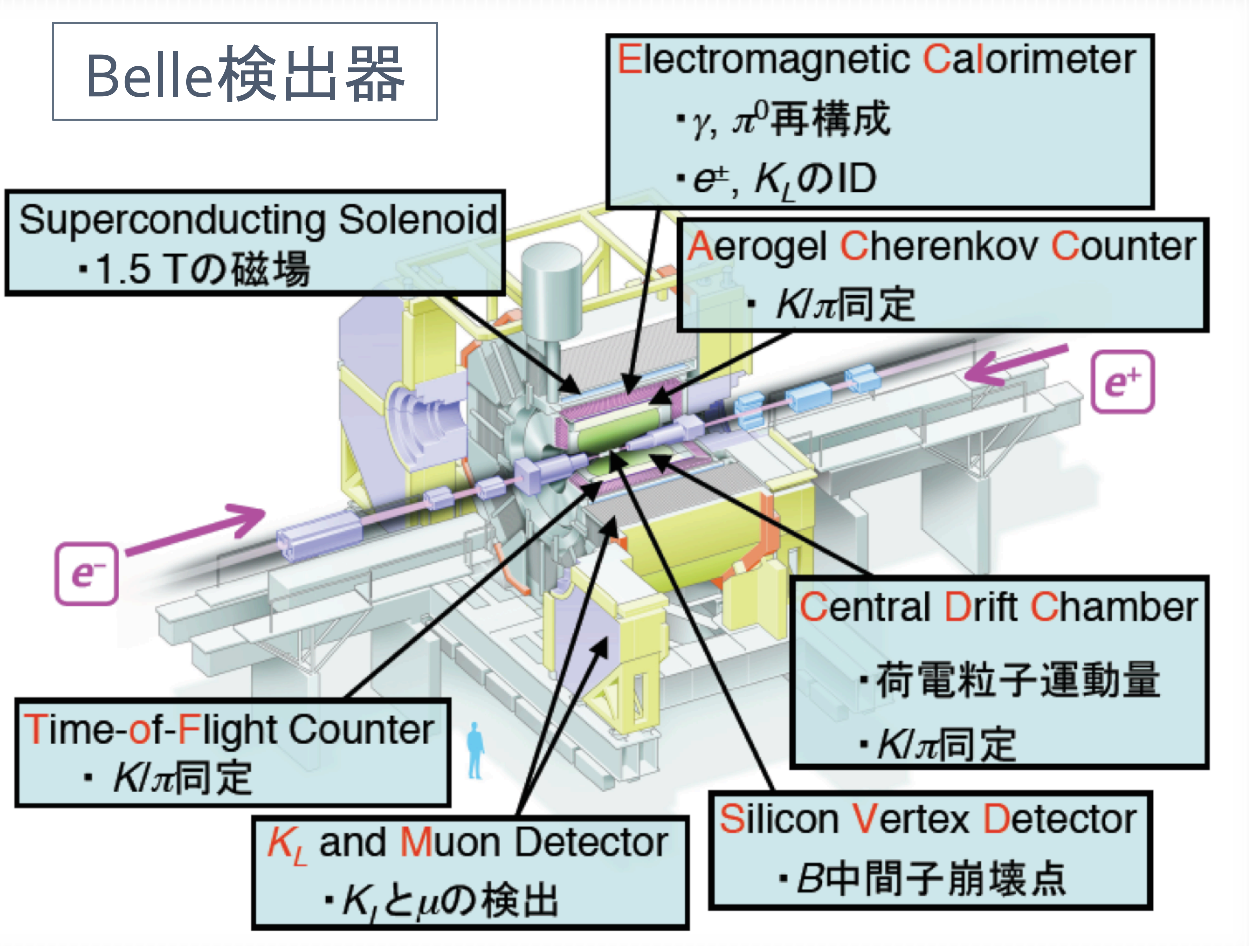
where

$$R_l = \tan^2\beta(m_b m_l / m_{H^-}^2) .$$

Here we consider $l = \tau$.

- From the measurement of $\mathcal{B}$(B→τν), we can constrain the region in $m_{H\pm}$-tanβ plane.

Experimental apparatus

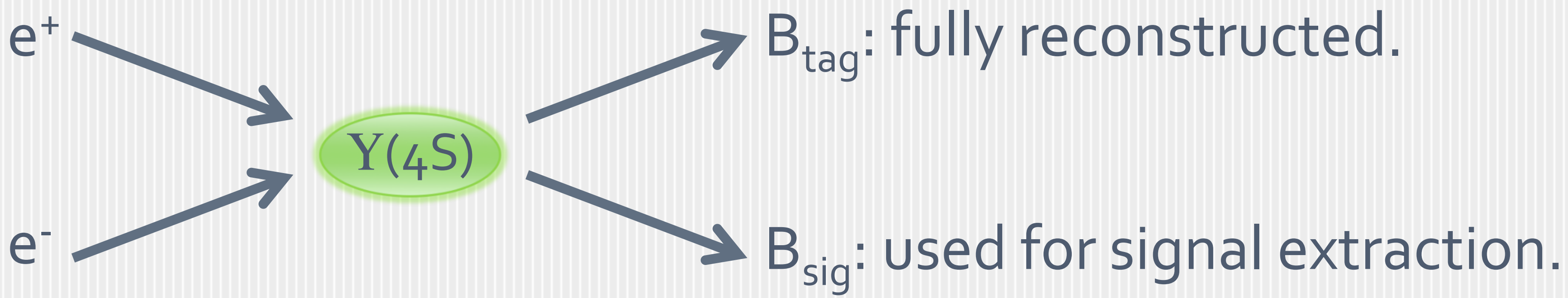


Use 414 fb^{-1} (449 x 10^6 BB).

Monte Carlo (MC) simulation

- GEANT-based simulation to estimate the detection efficiency and study the background. (Beam backgrounds are overlaid on events.)
  - Signal MC
  - BB and qq (q=u,d,s,c) MC
    - Twice the data sample.
  - Rare B decay MC
    - Charmless, radiative, electroweak decays and b→u semi-leptonic decays.

Basic strategy



- This method allows us to suppress strongly the combinatorial background from BB and qq.
- Blind-analysis for avoiding experimental bias.

B_{tag} reconstruction

- $B^+ \to \bar{D}^{(*)0}\pi^+$, $\bar{D}^{(*)0}\rho^+$, $\bar{D}^{(*)0}a_1^+$, $D^{(*)0}\bar{D}_s^{(*)+}$
  - $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K_S^0\pi^0$, $K_S^0\pi^+\pi^-$, $K_S^0\pi^-\pi^+\pi^0$, K^+K^-
  - $D_s^+ \to K_S^0K^+$, $K^+K^-\pi^+$
  - $\bar{D}^{*0} \to D^0\pi^0$, $D^0\gamma$
  - $D_s^{*+} \to D_s^+\gamma$
- $M_{bc} > 5.27$ GeV, -80 MeV $< \Delta E < 60$ MeV
- Best candidate selection: χ^2 $(\Delta E, M_D, M_{D*}-M_D)$
- Number of $B_{tag} = 6.80 \times 10^5$, purity $= 0.55$

B_{sig} ($B^- \rightarrow \tau^- \bar{\nu}_\tau$) reconstruction

- $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, $e^- \bar{\nu}_e \nu_\tau$, $\pi^- \nu_\tau$, $\pi^- \pi^0 \nu_\tau$, $\pi^- \pi^+ \pi^- \nu_\tau$ ($\mathcal{B}$=81%)
  - μ^-, e^-, $\pi^\pm$: PID, K-rejection
  - π^0: $|M_{\gamma\gamma} - m_{\pi^0}| < 20$ MeV
  - π^0 veto for the modes other than $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$
  - Lower limits for mode-by-mode momenta
  - Lower limits for missing momentum of the event p_{miss}
  - $-0.86 < \cos\theta^*_{miss} < 0.95$ (reject escaped particles)
  - $|M_{\pi\pi} - m_\rho| < 0.15$ GeV, $|M_{\pi\pi\pi} - m_{a1\text{-}}| < 0.3$ GeV ???

E_{ECL}

- E_{ECL}: remaining energy in the ECL.
  - Minimum energy threshold of 50 MeV (barrel), 100 MeV (forward), and 150 MeV (backward). (Beam background is more severe for endcaps.)

- Signal events peak at low E_{ECL}.
- Background events are distributed toward higher E_{ECL} due to additional neutral clusters.

Amount of background events

- Define the signal and sideband regions for E_{ECL}.
- Obtain N of events for sideband region of data.
- Obtain N of BG events for sideband region of MC, and check the consistency to data.
- Extrapolate N of BG events in signal region for data.

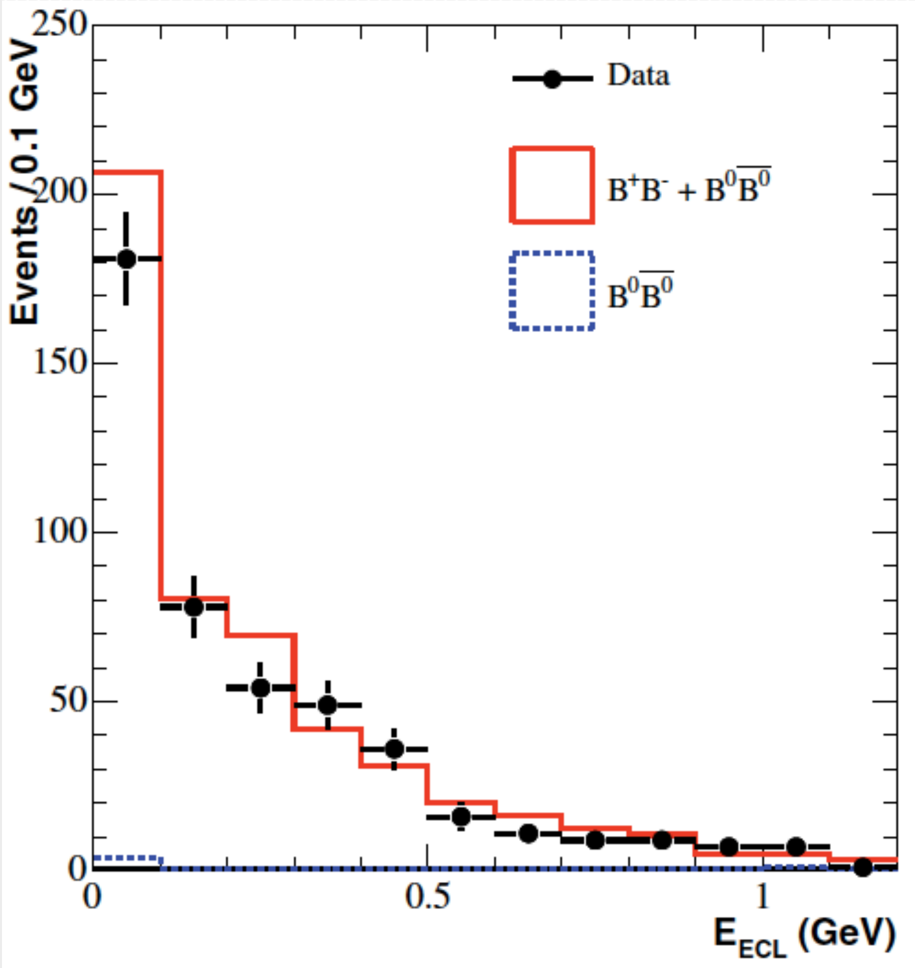
	N_{side}^{obs}	N_{side}^{MC}	N_{sig}^{MC}
$\mu^- \bar{\nu}_\mu \nu_\tau$	96	94.2 ± 8.0	9.4 ± 2.6
$e^- \bar{\nu}_e \nu_\tau$	93	89.6 ± 8.0	8.6 ± 2.3
$\pi^- \nu_\tau$	43	41.3 ± 6.2	4.7 ± 1.7
$\pi^- \pi^0 \nu_\tau$	21	23.3 ± 4.7	5.9 ± 1.9
$\pi^- \pi^+ \pi^- \nu_\tau$	21	18.5 ± 4.1	4.2 ± 1.6

95% = BB, 5% = qq

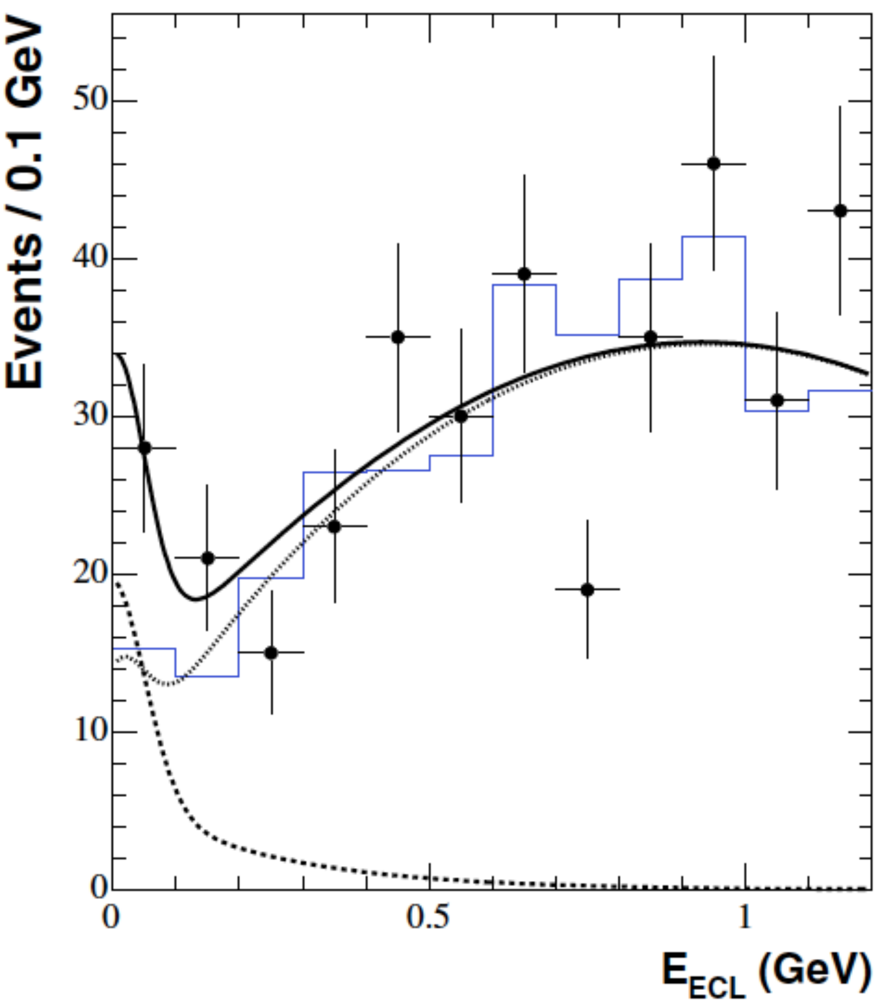
90% = $B^- \to D^{(*)0} l^- \bar{\nu}$
10% = rare B decay

Validation of E_{ECL} simulation

- $B^- \rightarrow D^{*0} l^- \bar{\nu}$ ($l = \mu$, e) control sample.
  - $D^{*0} \rightarrow D^0 \pi^0$
  - $D^0 \rightarrow K^- \pi^+$, $K^- \pi^- \pi^+ \pi^+$
  - The sources affecting E_{ECL} are similar to those for signal, while the number of events is larger compared to signal.
- Figure shows the distributions for data and MC.
  - The good agreement is seen.



Examination of signal region



Points: data
Solid histogram: BG MC
Curves: result of the fit

- Sum of the number of observed events in signal region = N_{obs}

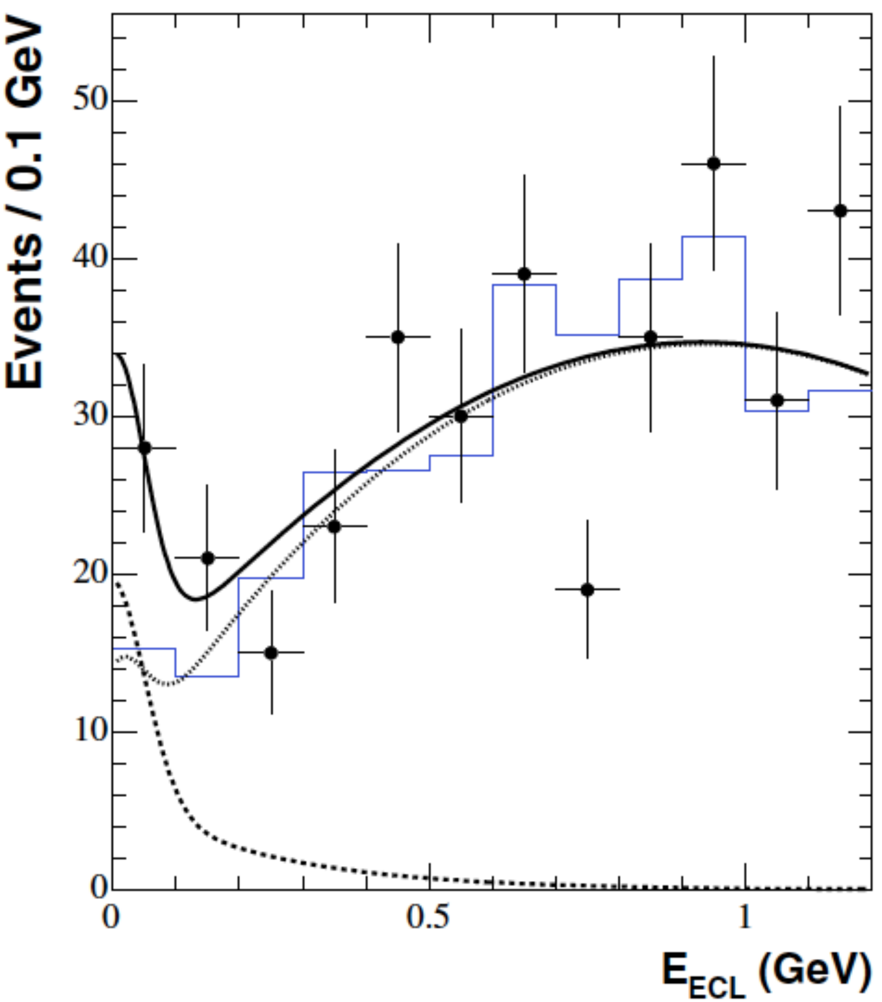
	N_{obs}
$\mu^- \bar{\nu}_\mu \nu_\tau$	13
$e^- \bar{\nu}_e \nu_\tau$	12
$\pi^- \nu_\tau$	9
$\pi^- \pi^0 \nu_\tau$	11
$\pi^- \pi^+ \pi^- \nu_\tau$	9

- The significant excess is seen.
- Checks are performed using M_{bc} and p_{miss} distributions and K_L^o veto.

- Number of signal events is estimated by fitting E_{ECL} distribution.
  - PDFs are constructed from MC.
    - f_s: sum of a Gaussian and an exponential.
    - f_b: sum of a Gaussian (for peaking BG) and a second-order polynomial.
  - Extended likelihood method is used.

$$\mathcal{L} = \frac{e^{-(n_s+n_b)}}{N!} \prod_{i=1}^{N} (n_s f_s(E_i) + n_b f_b(E_i))$$

  - Obtained Numbers are listed below.



Points: data
Solid histogram: BG MC
Curves: result of the fit

	N_s	N_b
$\mu^-\bar{\nu}_\mu\nu_\tau$	$5.6^{+3.1}_{-2.8}$	$8.8^{+1.1}_{-1.1}$
$e^-\bar{\nu}_e\nu_\tau$	$4.1^{+3.3}_{-2.6}$	$9.0^{+1.1}_{-1.1}$
$\pi^-\nu_\tau$	$3.8^{+2.7}_{-2.1}$	$3.9^{+0.8}_{-0.8}$
$\pi^-\pi^0\nu_\tau$	$5.4^{+3.9}_{-3.3}$	$5.4^{+1.6}_{-1.6}$
$\pi^-\pi^+\pi^-\nu_\tau$	$3.0^{+3.5}_{-2.5}$	$4.8^{+1.4}_{-1.4}$

Branching fractions

- Branching fraction $\mathcal{B} = N_s / (2\ \varepsilon\ N_{B+B-})$
  - N_s = number of signal events
  - ε = detection efficiency = $\varepsilon_{tag} \times \varepsilon_{sel}$
  - N_{B+B-} = number of B meson pairs

	$\varepsilon^{sel}(\%)$	$\mathcal{B}(10^{-4})$
$\mu^-\bar{\nu}_\mu\nu_\tau$	3.64 ± 0.02	$2.57^{+1.38}_{-1.27}$
$e^-\bar{\nu}_e\nu_\tau$	4.57 ± 0.03	$1.50^{+1.20}_{-0.95}$
$\pi^-\nu_\tau$	4.87 ± 0.03	$1.30^{+0.89}_{-0.70}$
$\pi^-\pi^0\nu_\tau$	1.97 ± 0.02	$4.54^{+3.26}_{-2.74}$
$\pi^-\pi^+\pi^-\nu_\tau$	0.77 ± 0.02	$6.42^{+7.58}_{-5.42}$

- $\mathcal{B}(B^- \rightarrow \tau^-\bar{\nu}_\tau) = (1.79^{+0.56}_{-0.49}) \times 10^{-4}$
  - Obtained by a simultaneous fit to the five modes constraining the five signal components by $\mathcal{B}$.

Systematic errors

- N_{B+B-}: ±1%
- Signal yields: $^{+23\%}_{-26\%}$
  - Signal shape: data/MC difference on control sample.
  - Background shape: BR uncertainty of peaking BG.
- Efficiencies
  - E_{tag}: ±10.5% (obtained from control sample)
  - E_{sel}: ±5.6% (tracking, π^0 reconstruction, PID, BR of τ decays, MC statistics)

BR and the significance

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = (1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})) \times 10^{-4}$$

- The significance is defined as the following.

$$\Sigma = \sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$$

  - L_o = likelihood value obtained assuming zero signal events.
  - L_{max} = maximum likelihood value.
  - The systematic error is included as a Gaussian function, which is convoluted to the likelihood function.
- The obtained significance is 3.5σ.

Conclusion

- The first evidence of the decay $B^- \rightarrow \tau^- \nu_\tau$ is found.

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = (1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})) \times 10^{-4}$$

  - The significance is 3.5σ.
- The result is consistent with the SM prediction.
- Using the known values of G_F, m_B, m_τ, and τ_B,

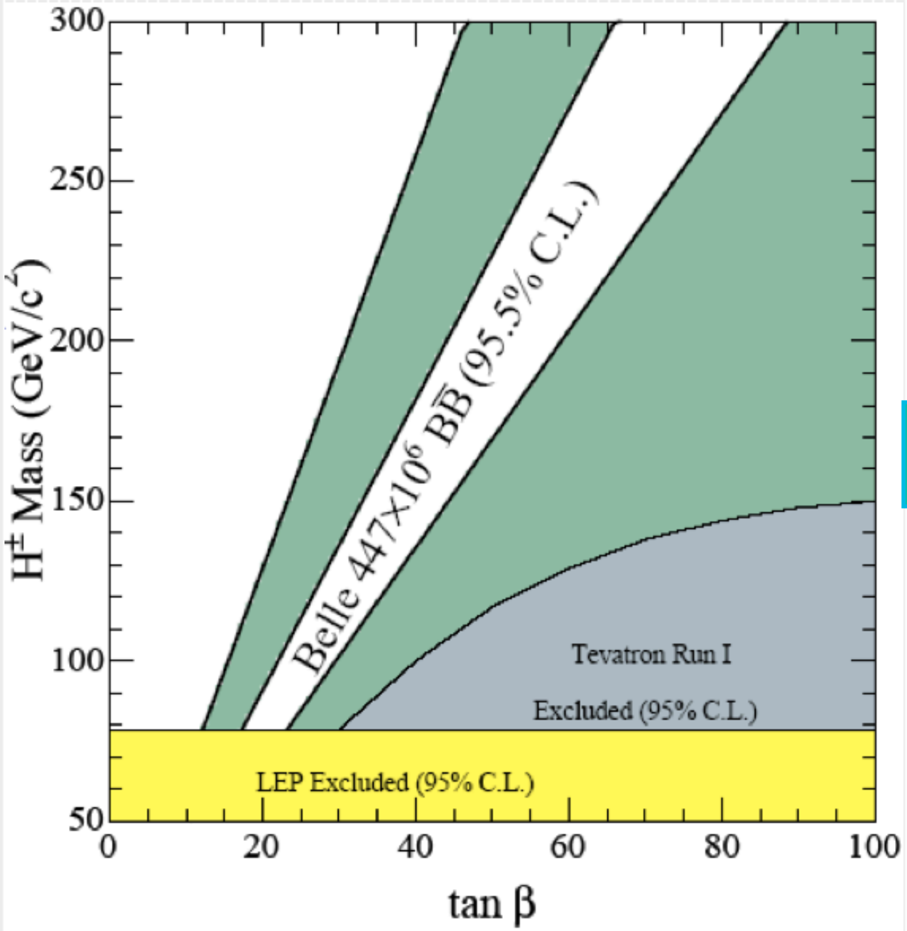
$$f_B|V_{ub}| = (10.1^{+1.6}_{-1.4}(\text{stat})^{+1.3}_{-1.4}(\text{syst})) \times 10^{-4}\ \text{GeV}$$

$$f_B = 0.229^{+0.036}_{-0.031}(\text{stat})^{+0.034}_{-0.037}(\text{syst})\ \text{GeV}$$

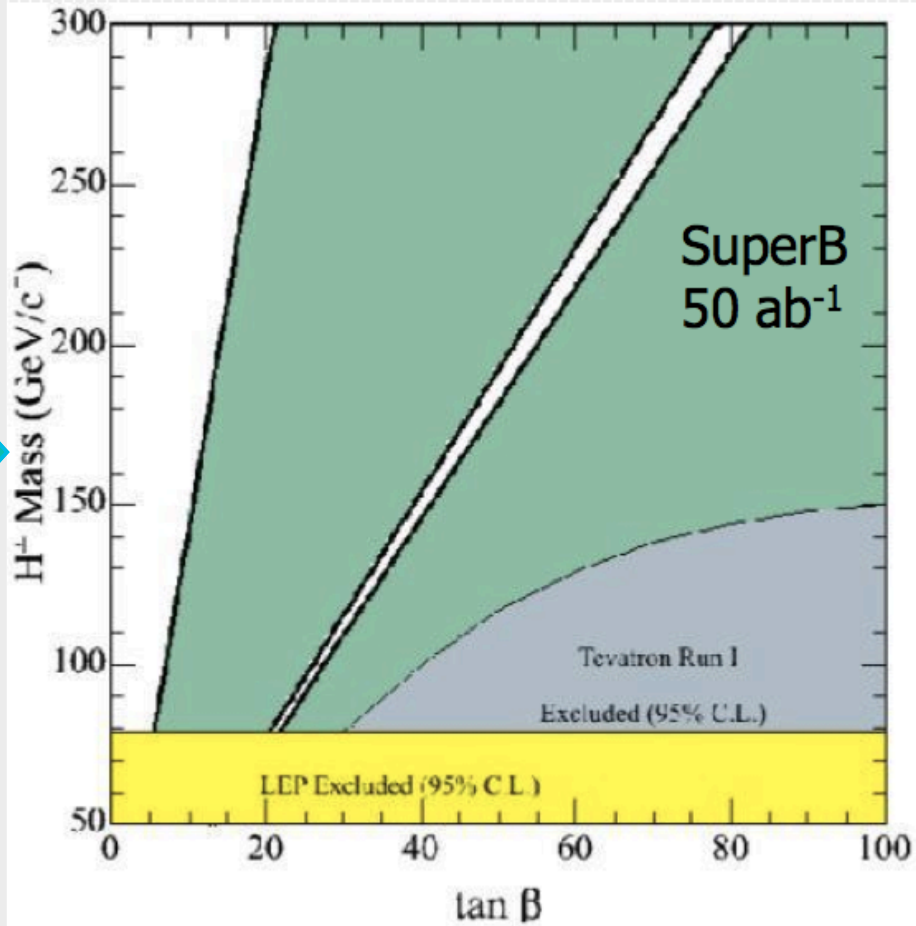
(First direct determination of the B meson decay constant f_B)

Constraint on $M_{H\pm}$-tanβ plane

Belle



Belle II (50 ab⁻¹)



Memo (status at Belle)

- B→τν with Hadronic (Fullrecon) tag

  Previous analysis:

  3.5 sigma evidence (447M $B\bar{B}$) [PRL 97, 251802 (2006)]

  - No significant signal observed in 657M $B\bar{B}$ sample after fixing bug in fullrecon module..
  - **analysis using full data (772M $B\bar{B}$) with improvements added toward this summer.**
    - E_{ECL} - MM^2 2 dimensional fit
    - Tagging efficiency improvement
      - By new tracking (caseB data)
      - New fullrecon module if it is effective.
    - Background suppression by K_L veto
- 3.6σ significance from semileptonic tagging.
  - Will be published soon.