The First Evidence of B→τ ν from Belle & Future Prospect

As a contribution to WG2 (neutrino modes)
Ref: K.Ikado's talk at FPCP06
hep-ex/0604018

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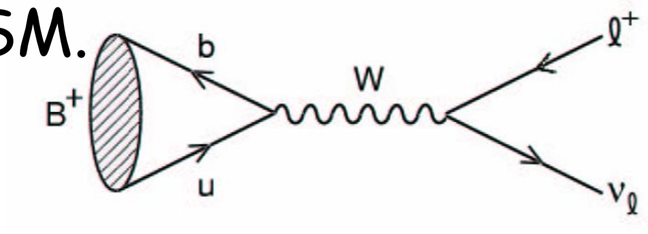
(Talk presented by T.I.)
Nagoya University

May 15, 2006
"Flavour in the LHC era" @ CERN

B→τ ν (within the SM)

- Proceed via W annihilation in the SM.



- Branching fraction is given by

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

- Provide information of $f_B|V_{ub}|$
  - $|V_{ub}|$ from $B \to X_u l \nu$ ➡ f_B ⟺ cf) Lattice (δ~10%)
  - $Br(B \to \tau\nu)/\Delta m_d$ ➡ $|V_{ub}| / |V_{td}|$

- Expected branching fraction

$$|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$$

HFAG [hep-ex/0603003]

$$f_B = (0.216 \pm 0.022)\ GeV$$

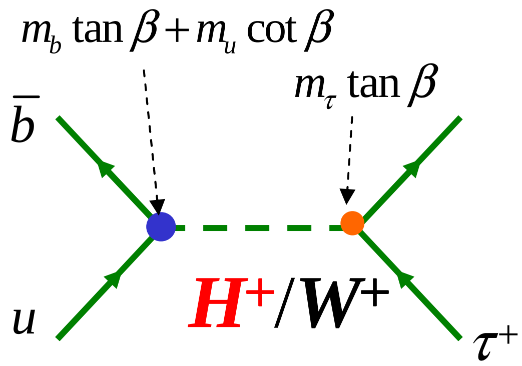
HPQCD [PRL95,212001(2005)]

$$Br(B \to \tau\nu) = (1.59 \pm 0.40) \times 10^{-5}$$

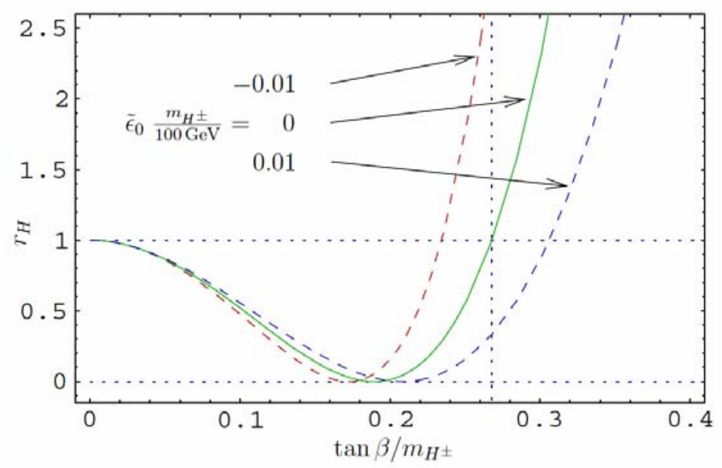
B→τ X as a Probe to Charged Higgs

Charged Higgs contribution to B decays

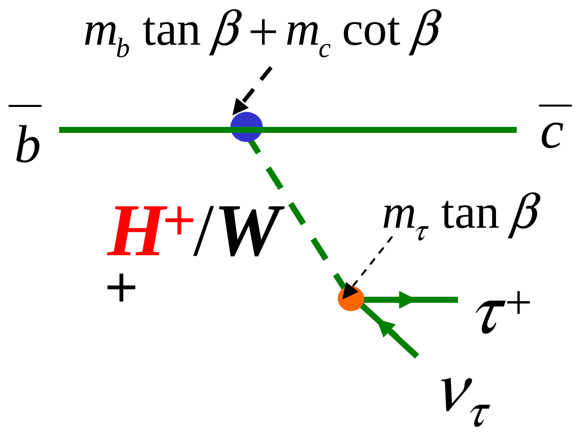
- Leptonic: B→τ ν



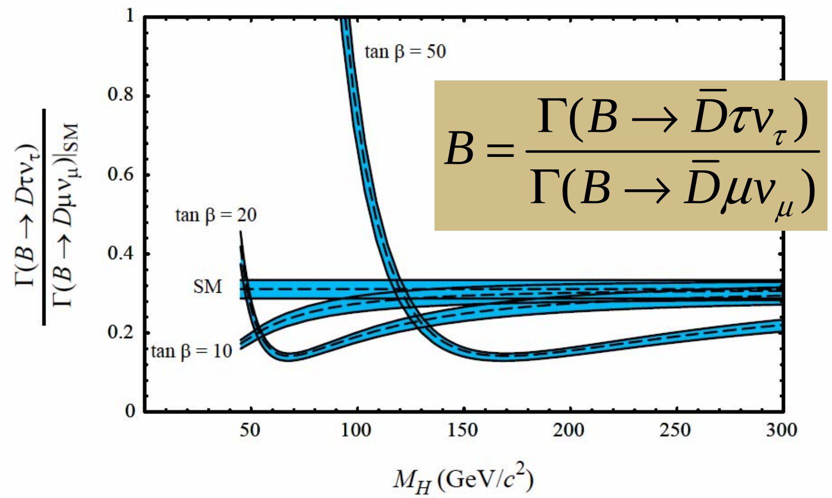
Br(SM)
~ 9 x 10^{-5}



- Semileptonic: B→D τ ν



Br(SM)
~ 8 x 10^{-3}

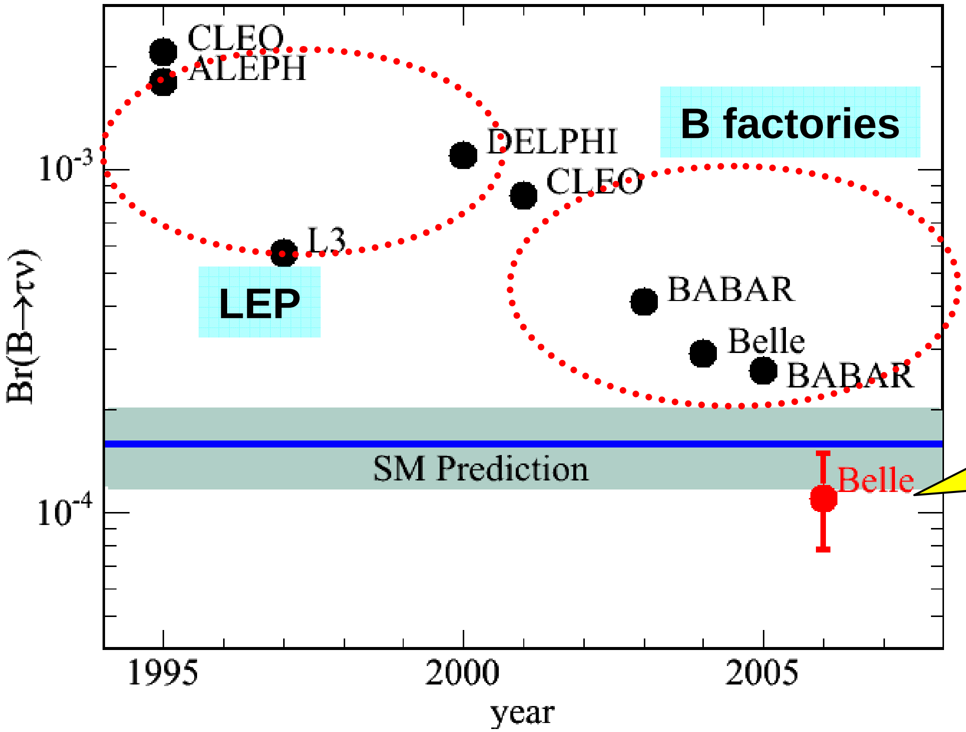


Decay amplitude $\propto m_b m_\tau \tan^2\beta$

Tauonic decay is the most sensitive !

Search for B→τν

- B→ τν is important for both SM and BSM.
- Purely leptonic → Theoretically very clean
- More than two ν's → Experimentally very challenging.
- Its detection is a milestone of B physics.



First Evidence !
April 2006

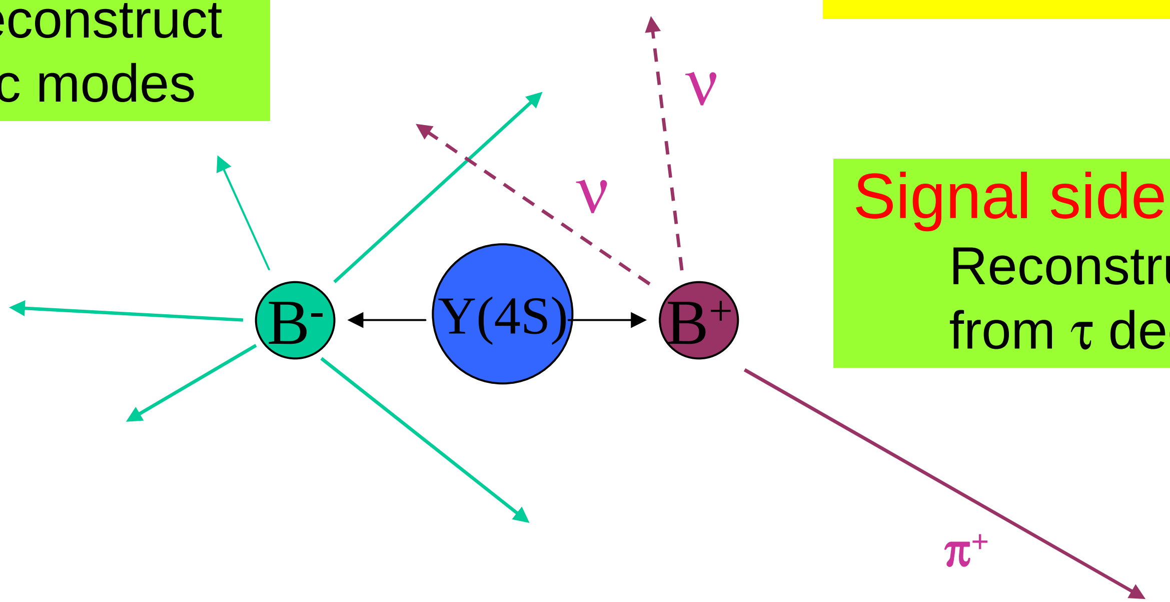
$B \to \tau\nu$ Analysis Concepts

- B decays with missing neutrinos lack the kinematic constraints which are used to separate signal events from backgrounds (M_{bc} and ΔE).
- Reconstruct the decay of the non-signal B (tagging), then look for the signal decay in whatever is left over

More than 2 neutrinos appear in $B \to \tau\nu$ decay

Tagging side : Fully reconstruct hadronic modes

Signal side : Reconstruct particles from τ decay



Features with Fully Reconstructed B Tag

- **Pros: Offline B meson Beam**
  - B momentum is known.

    → Resolution of M_{miss}^2 can be significantly improved.
  - B-flavor/charge is known.

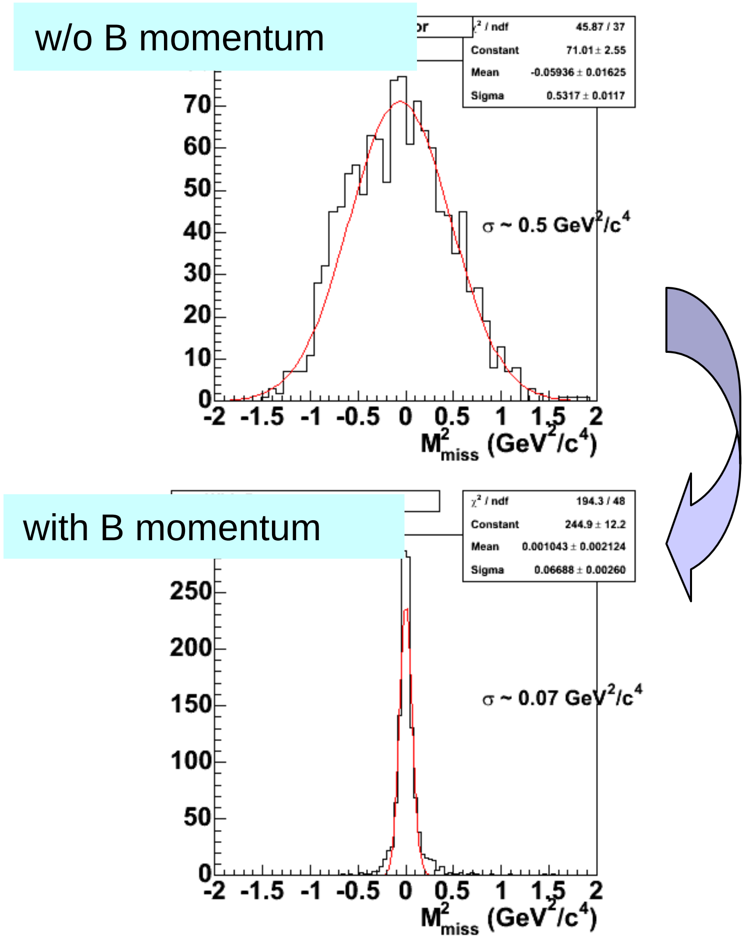
    → We can treat charged & neutral B separately

→ Large background reduction

- **Cons: Low statistics**
  - Tagging efficiency : 0.2 - 0.3%

→ Large lum. required !

M_{miss}^2 for $B^- \to D^0 \mu^- \nu$ (MC)



Fully Reconstructed Tag at Belle (447M $B\bar{B}$)

$B^+ \to \bar{D}^{(*)0} + \pi^+ / \rho^+ / a_1^+ / D_S^{(*)+}$

$\bar{D}^{*0} \to \bar{D}^0\pi^0 / \bar{D}^0\gamma$, $D_S^{*+} \to D_s^+\gamma$

$B^0 \to D^{(*)-} + \pi^+ / \rho^+ / a_1^+ / D_S^{(*)+}$

$D^{*-} \to \bar{D}^0\pi^- / D^-\pi^0$, $D_S^{*+} \to D_s^+\gamma$

$\bar{D}^0 \to$ 7 modes

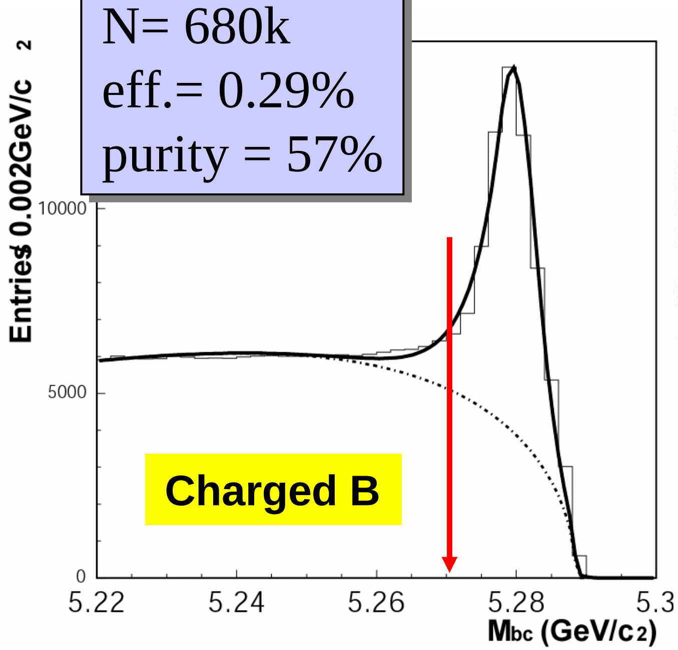
$D^- \to$ 6 modes

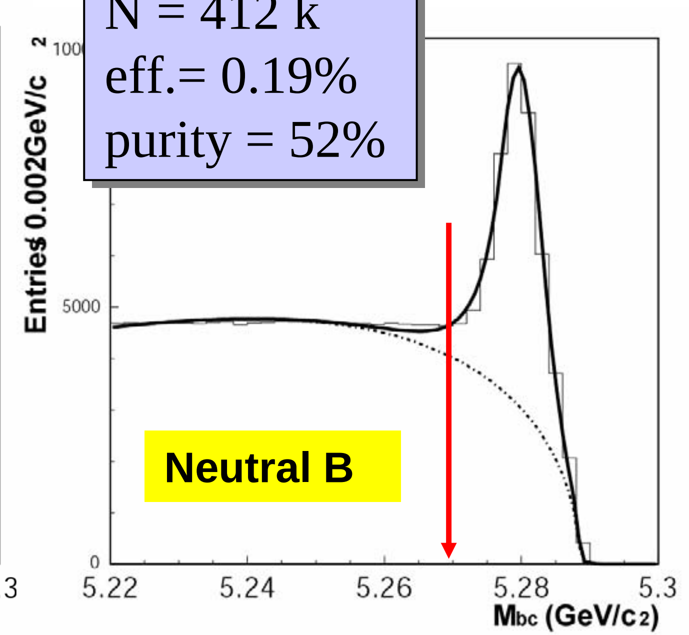
$D_s^+ \to$ 2 modes

~ 180 channels used

- Beam constrained mass

Charged B	Neutral B
N= 680k	N = 412 k
eff.= 0.29%	eff.= 0.19%
purity = 57%	purity = 52%





m ~ 5.28 GeV/c²

σ~ 3 MeV/c² due to σ(E_{beam})

~10% for feed-across between B^+ and B^0

Signal region : $-0.08 < \Delta E < 0.06$ GeV, $M_{bc} > 5.27$ GeV/c²

Signal Selection (1)

- τ lepton is identified in the 5 decay modes.

$$\tau^- \rightarrow \mu^-\nu\bar{\nu},\ e^-\nu\bar{\nu},\ \pi^-\nu,\ \pi^-\pi^0\nu,\ \pi^-\pi^+\pi^-\nu$$

81% of all τ decay modes

- Signal selection criteria.

$\tau^- \rightarrow \mu^-\nu\bar{\nu}$	$\tau^- \rightarrow e^-\nu\bar{\nu}$	$\tau^- \rightarrow \pi^-\nu$	$\tau^- \rightarrow \pi^-\pi^0\nu$	$\tau^- \rightarrow \pi^-\pi^+\pi^-\nu$
1 signal-side track				3 signal-side tracks
No signal-side π^0			1 signal-side π^0	No signal-side π^0
$E_{ECL} < 0.2$ GeV			$E_{ECL} < 0.3$ GeV	
$P^*_{\ell^-} > 0.3$ GeV		$P^*_{\pi^-} > 0.8$ GeV	$P^*_{\pi\pi^0} > 1.2$ GeV	$P^*_{3\pi} > 1.8$ GeV
$P^*_{miss} > 0.2$ GeV		$P^*_{miss} > 1.0$ GeV	$P^*_{miss} > 1.2$ GeV	$P^*_{miss} > 1.8$ GeV
			$\lvert M_{\rho^+} - M_{\pi\pi^0}\rvert < 0.15$ GeV	$\lvert M_{\rho^0} - M_{\pi^+\pi^-}\rvert < 0.15$ GeV
				$\lvert M_{a_1^+} - M_{3\pi}\rvert < 0.3$ GeV
$-0.86 < \cos\theta^*_{miss} < 0.95$				

- Signal-side efficiency including τ decay br.)

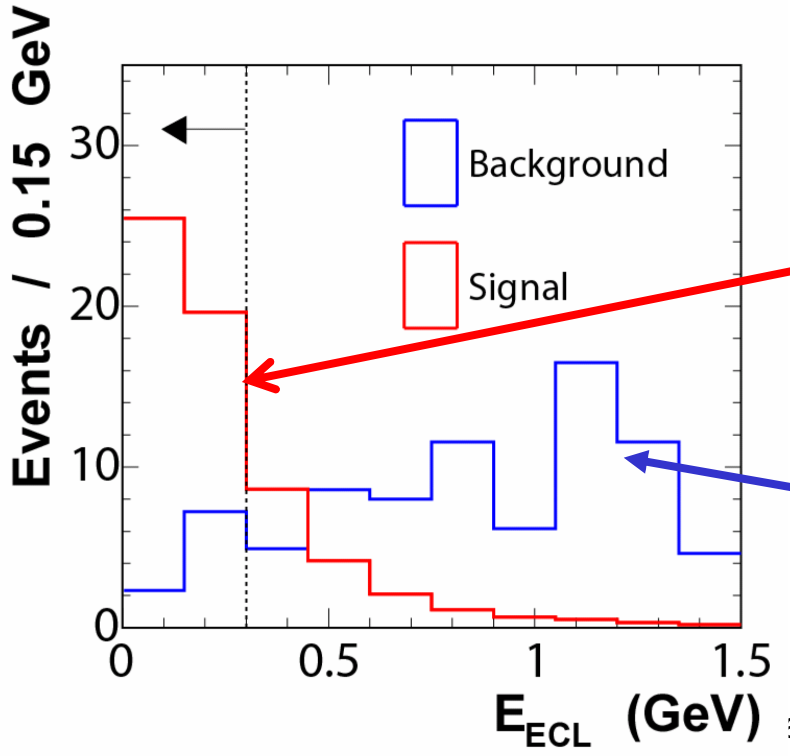
32.92 ±0.12%

- All selection criteria were optimized before examining the signal region (blind analysis).

Signal Selection (2)

- Extra neutral energy in calorimeter E_{ECL}
  - Most powerful variable for separating signal and background
  - Total calorimeter energy from the neutral clusters which are not associated with the tag B

$$E_{ECL} = E_{tot} - E_{rec.\ B} \quad (-E_{\pi^0} \text{ for } \pi^-\pi^0\nu)$$



Minimum energy threshold

- **Barrel : 50 MeV**
- **For(Back)ward endcap : 100(150) MeV**

Zero or small value of E_{ECL} arising only from beam background

Higher E_{ECL} due to additional neutral clusters

MC includes overlay of random trigger data to reproduce beam backgrounds.

Signal Selection (3)

- Extra neutral energy E_{ECL} Validation by double tagged sample (control sample);
  - B_{tag} is fully reconstructed
  - B_{sig} is semileptonic decays

$B^+ \to D^{(*)0} X^+$ (fully reconstruction)

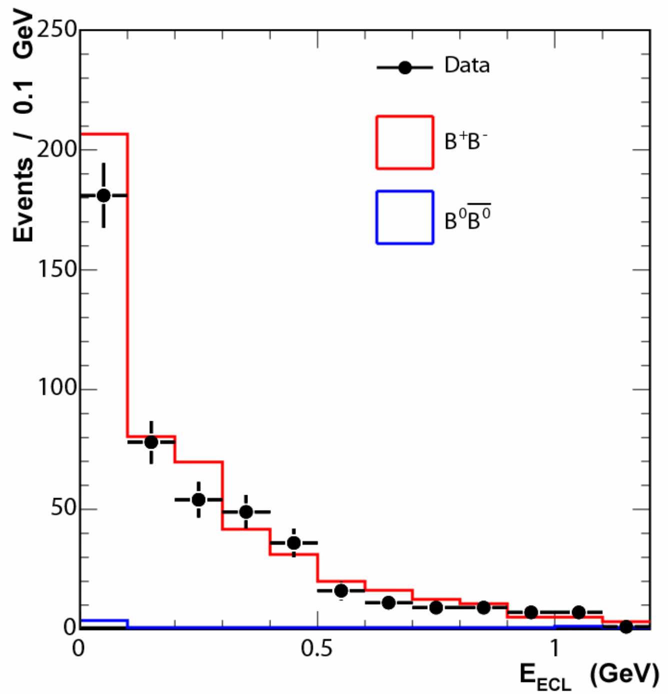
$B^- \to D^{*0} l^- \nu$

$\quad \hookrightarrow D^0 \pi^0$

$\quad\quad \hookrightarrow K^- \pi^+$

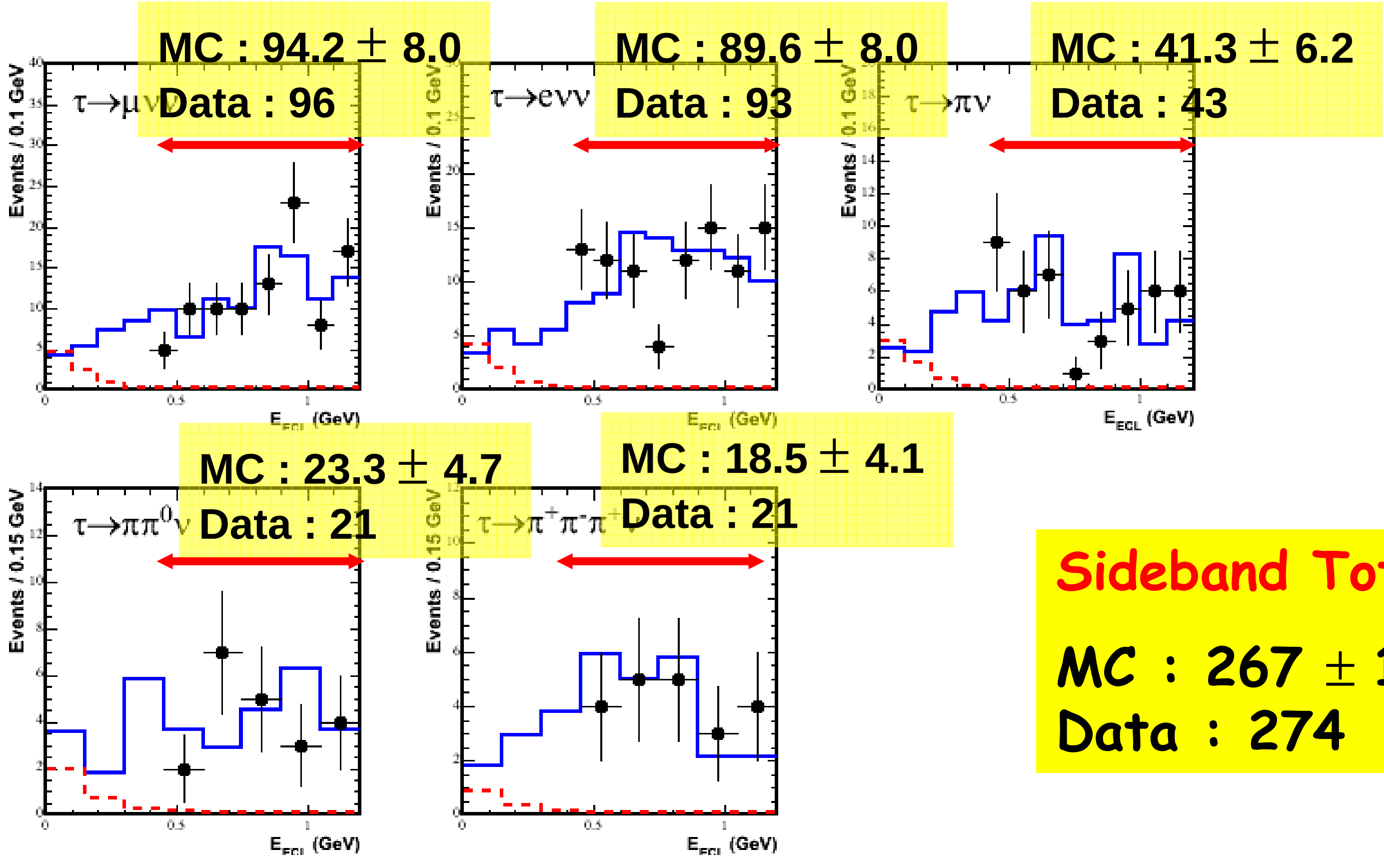
$\quad\quad\quad K^- \pi^+ \pi^- \pi^+$

B^+B^-	494 ± 18
B^0B^0	7.9 ± 2.2
Total	502 ± 18
Data	458



Purity ~ 90%

Background Estimation



Sideband Total

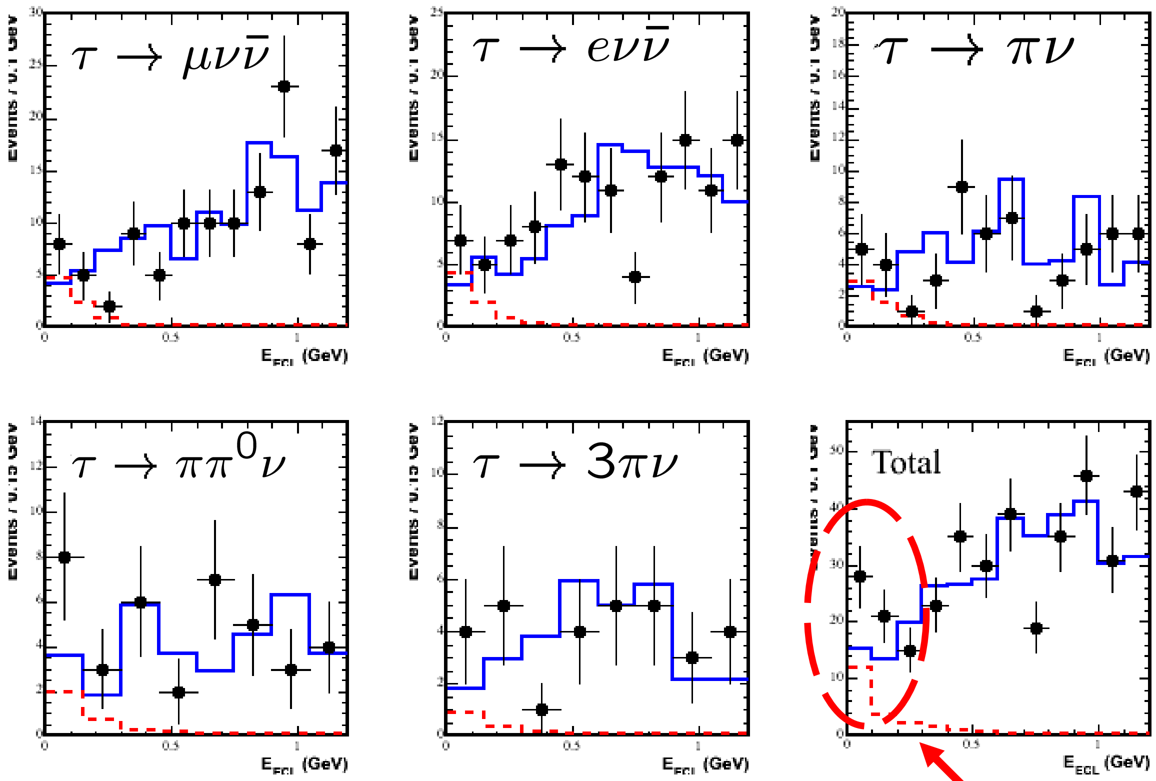
MC : 267 ± 14
Data : 274

Large MC samples for $e^+e^- \rightarrow BB$, qq, $X_u l\nu$, $X_u \tau\nu$, $\tau^+\tau^-$, and rare B decays are used (including beam-background).

Majority come from $B \rightarrow D^{(*)} X\, l\, \nu$ (~90%) + Xu l ν/rare (~10%).

Result: Opening the Box !

- The signal regions are examined after finalizing all of the selection criteria.



414 fb^{-1}

estimated background and observed events in the signal region

	BG	Data
$\mu^-\nu\bar{\nu}$	9.4 ± 2.6	13
$e^-\nu\bar{\nu}$	8.6 ± 2.3	12
$\pi^-\nu$	4.7 ± 1.7	9
$\pi^-\pi^0\nu$	5.9 ± 1.9	11
$\pi^-\pi^+\pi^-\nu$	4.2 ± 1.6	9
Total	32.8 ± 4.6	54

Observe excess in signal region !

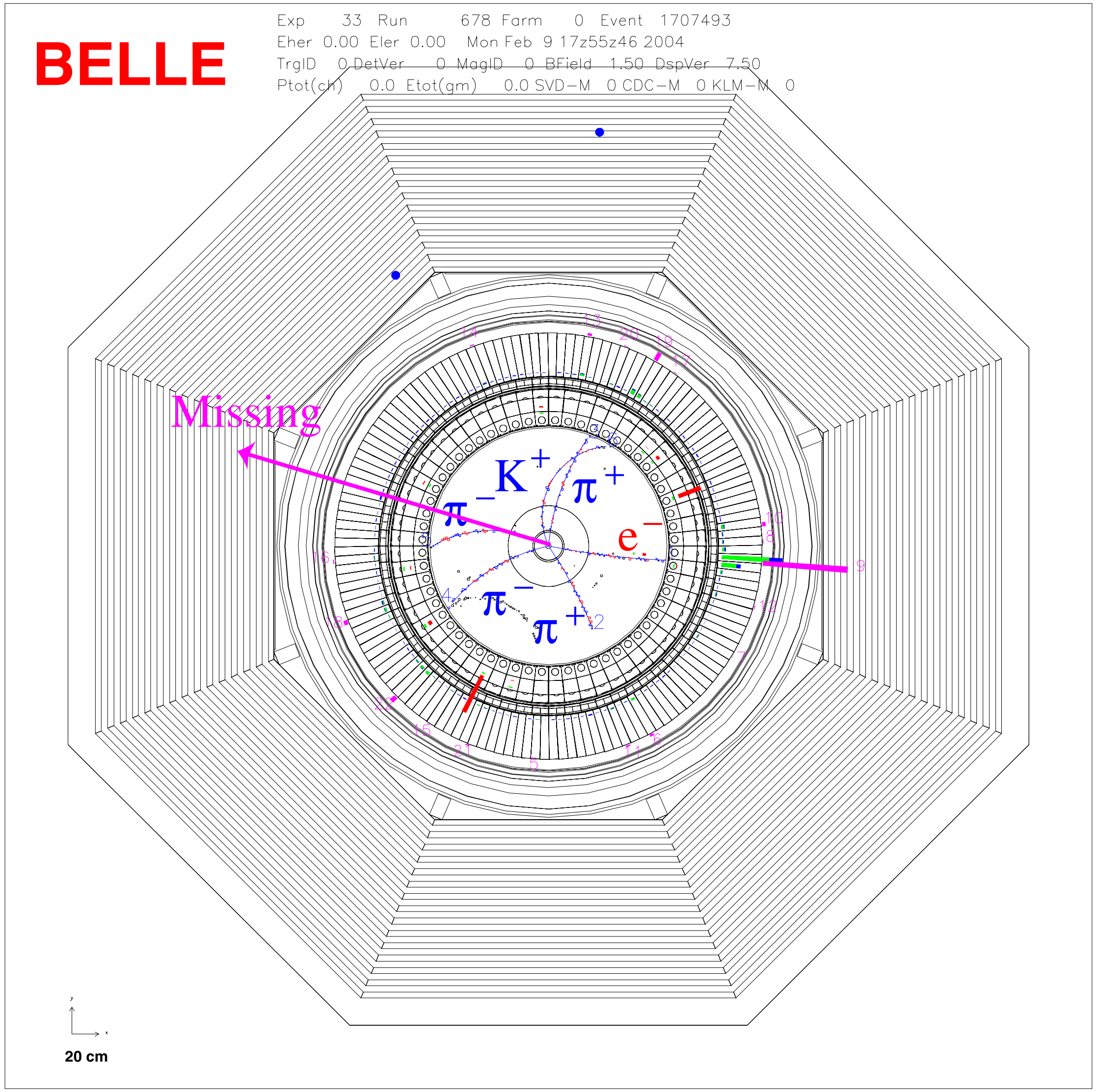
$B \to \tau\nu$ Candidate Event

$B^+ \to \overline{D^0}\pi^+$

└→ $K^+ \pi^- \pi^+ \pi^-$

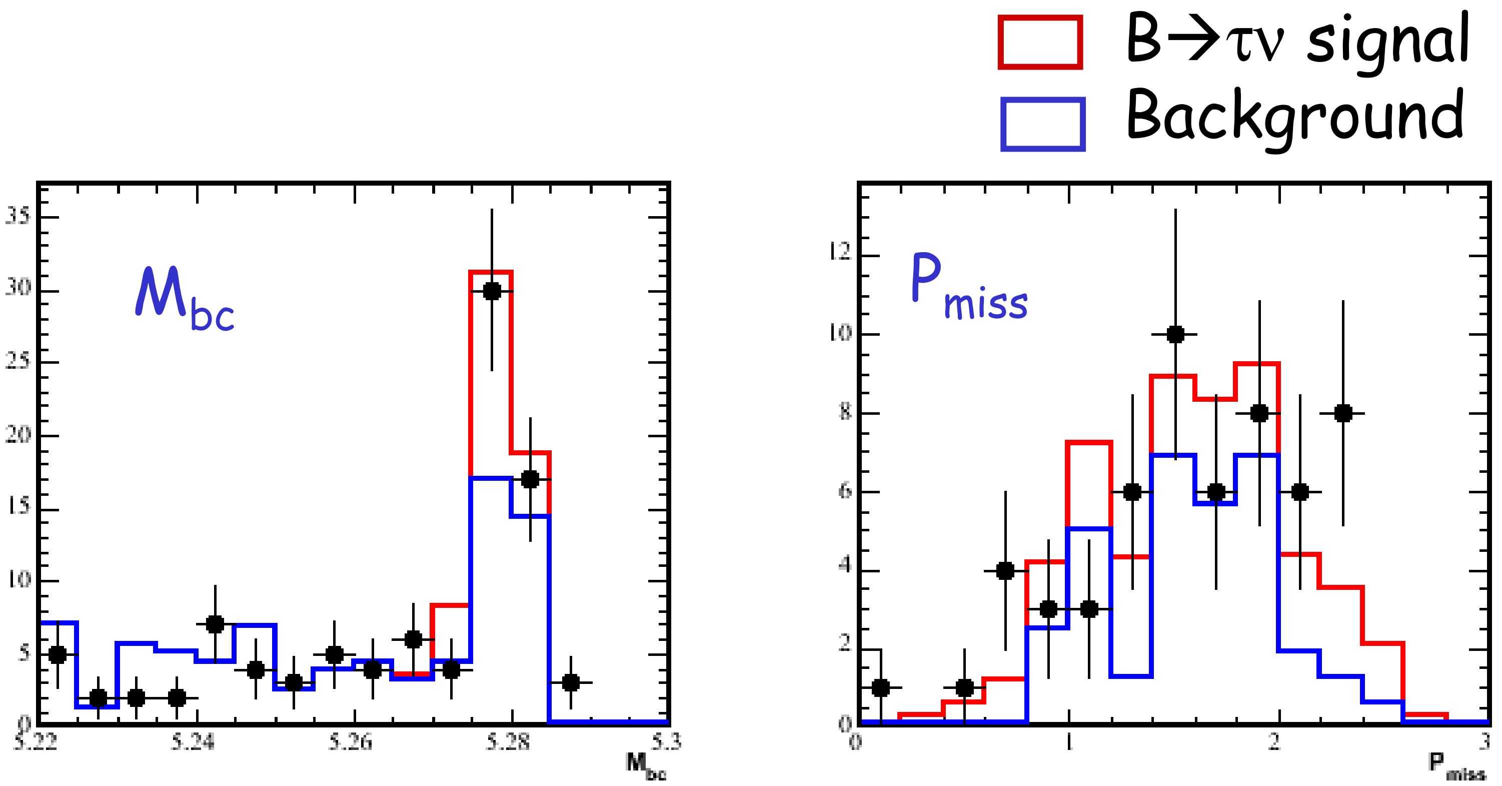
$B^- \to \tau^- \nu$

└→ $e^- \nu\nu$



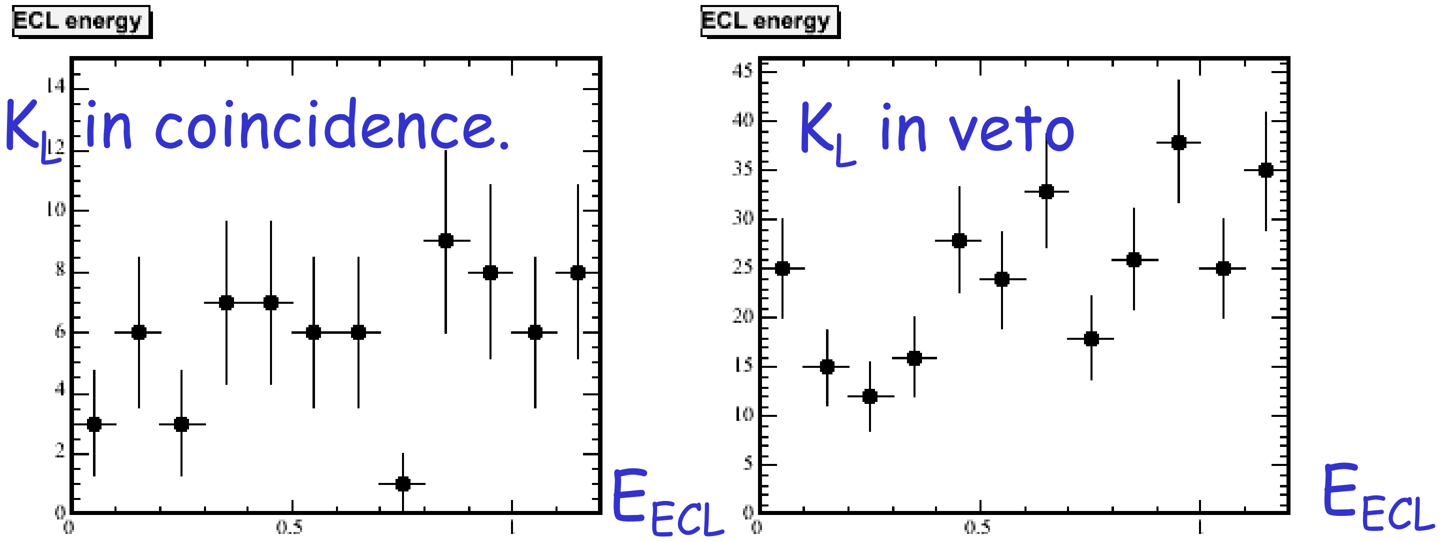
Verification of the Signal (1)

- For events in the E_{ECL} signal region, distribution of event selection variables other than E_{ECL} are verified.
- They are consistent with MC expectation for $B \to \tau\nu$ signal + background.



Verification of the Signal(2)

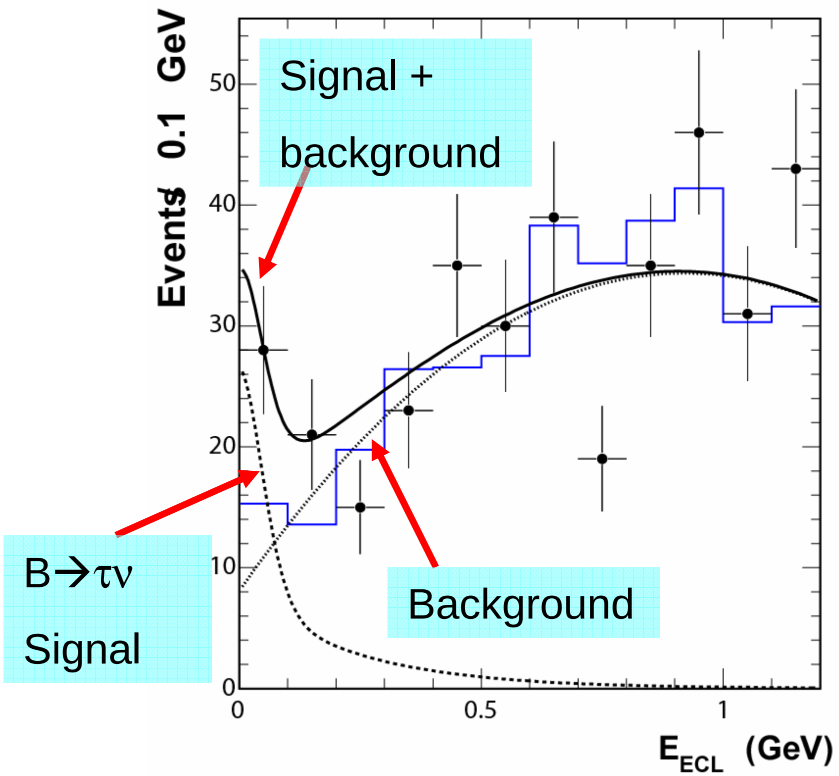
- About 30% of background have neutral cluster in the KLM detector (K_L candidates).
- The excess remains after requiring K_L veto.



- We do not use this cut in the result, to avoid introducing large systematic error due to K_L detection efficiency uncertainty.

Fit Results

- The final results are deduced by unbinned likelihood fit to the obtained E_{ECL} distributions.



Signal shape : Gauss + exponential
Background shape : second-order polynomial

	N_{obs}	N_s	N_b	Σ
$\mu^-\bar{\nu}_\mu\nu_\tau$	13	$5.4^{+3.2}_{-2.2}$	$9.1^{+0.2}_{-0.1}$	2.3σ
$e^-\bar{\nu}_e\nu_\tau$	12	$3.9^{+3.5}_{-2.5}$	$9.2^{+0.2}_{-0.2}$	1.5σ
$\pi^-\nu_\tau$	9	$3.4^{+2.6}_{-1.6}$	$4.0^{+0.2}_{-0.1}$	1.9σ
$\pi^-\pi^0\nu_\tau$	11	$6.2^{+3.9}_{-2.7}$	$4.2^{+0.3}_{-0.3}$	2.6σ
$\pi^-\pi^+\pi^-\nu_\tau$	9	$3.1^{+3.1}_{-2.6}$	$3.7^{+0.3}_{-0.2}$	1.2σ
Combined	54	$21.2^{+6.7}_{-5.7}$	$30.2^{+0.5}_{-0.4}$	4.2σ

Σ : Significance with systematics

Observe $21.2^{+6.7}_{-5.7}$ events with a significance of 4.2σ

Systematic Uncertainty

- Signal selection efficiencies

Source	$\mu^-\nu\bar{\nu}(\%)$	$e^-\nu\bar{\nu}(\%)$	$\pi^-\nu(\%)$	$\pi^-\pi^0\nu(\%)$	$\pi^+\pi^-\pi^+\nu(\%)$
Tracking	1.0	1.0	1.0	1.0	3.0
τ decay BR	0.3	0.3	1.0	0.6	1.1
MC statistics	0.6	0.6	0.7	1.0	2.0
Lepton ID	2.1	2.1	-	-	-
π^0 reconstruction	-	-	-	3	-
$\pi^\pm$ ID	-	-	2.0	2.0	6.0

- Tag reconstruction efficiency : 10.5%

  Difference of yields between data and MC in the $B^- \to D^{*0} l^- \nu$ control sample

- Number of BB : 1%
- Signal yield : $^{+12\%}_{-10\%}$
  - signal shape ambiguity estimated by varying the signal PDF parameters
  - BG shape : changing PDF
- Total systematic uncertainty $^{+17\%}_{-15\%}$

B→τν Branching Fraction

- Branching fractions are calculated by

$$\mathcal{B} = \frac{N_s}{2 \cdot \varepsilon^{\mathrm{sel}} \cdot \varepsilon^{\mathrm{tag}} \cdot N_{BB}}$$

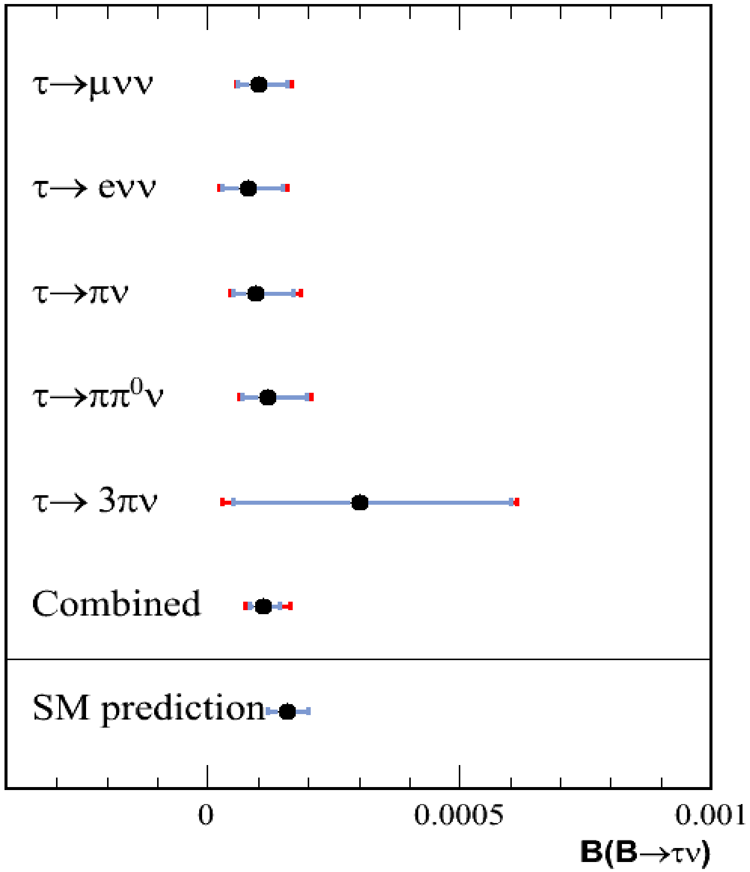
- All τ decay modes combined

$$\mathcal{B}(B \to \tau\nu) = (1.06^{+0.34}_{-0.28}(\mathrm{stat})^{+0.18}_{-0.16}(\mathrm{syst})) \times 10^{-4}$$

⇔ SM : $B(B \to \tau\nu) = (1.59 \pm 0.40) \times 10^{-4}$

Result is consistent with SM prediction within error

Extracted branching fraction for each τ decay mode



f_B Extraction

- Product of B meson decay constant f_B and CKM matrix element $|V_{ub}|$

$$f_B \cdot |V_{ub}| = (7.73^{+1.24}_{-1.02}(\mathrm{stat})^{+0.66}_{-0.58}(\mathrm{syst})) \times 10^{-4}\ \mathrm{GeV}$$

G_F	1.16639×10^{-5}	GeV^{-2}
τ_B	$(1.643 \pm 0.010) \times 10^{-12}$	s
m_B	5.279	GeV
m_τ	1.77699	GeV

- Using $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$ from HFAG

$$f_B = 0.176^{+0.028}_{-0.023}(\mathrm{stat})^{+0.020}_{-0.018}(\mathrm{syst})\ \mathrm{GeV}$$

14% 11% = 8%(exp.) + 8%(V_{ub})

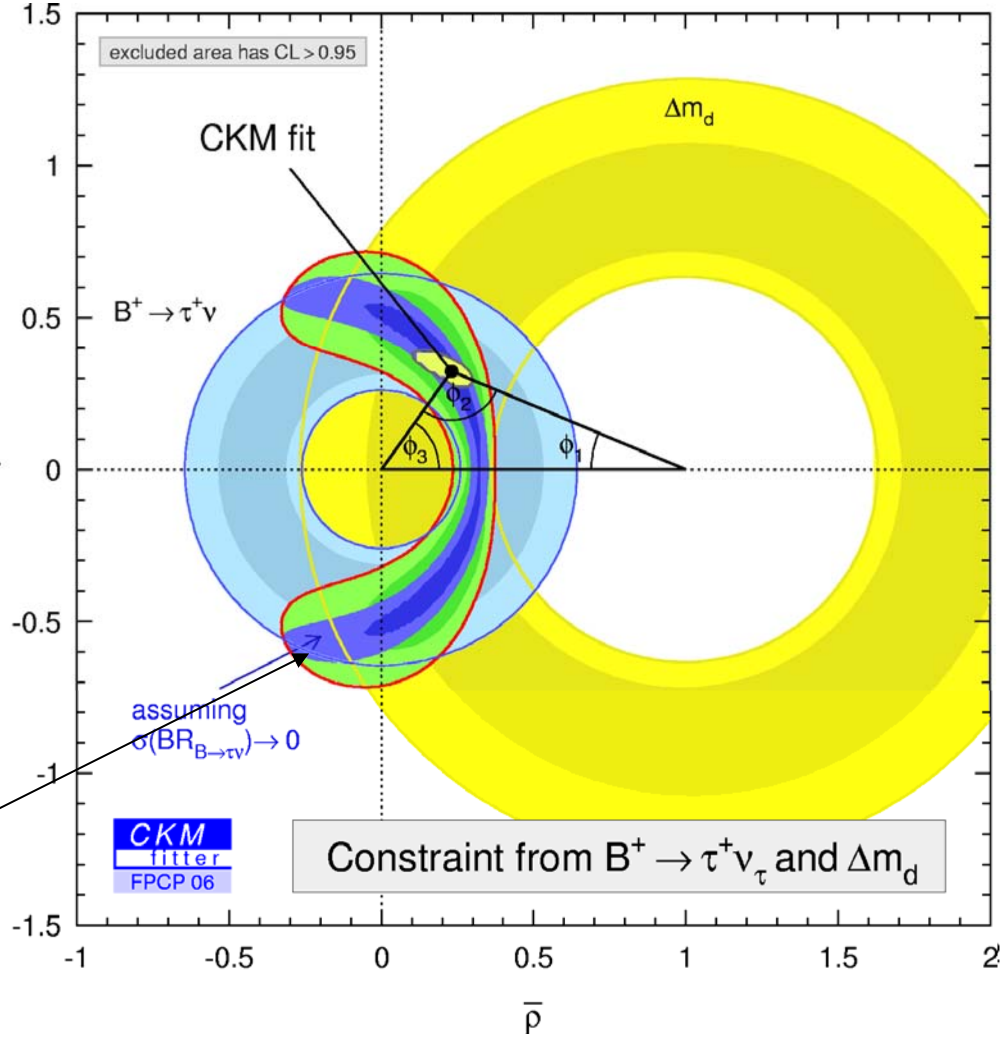
$f_B = 0.216 \pm 0.022$ GeV

[HPQCD, Phys. Rev. Lett. 95, 212001 (2005)]

Constraints on $|V_{ub}|/|V_{td}|$

- Constraint in the $(\bar{\rho},\bar{\eta})$ plane from the **B→τν** branching fraction and Δm_d

$$\frac{\mathcal{B}(B \to \tau\nu)}{\Delta m_d} = \frac{|V_{ub}|^2}{|V_{td}|^2}$$
$$= \frac{1}{[1-(\lambda^2/2)^2]} \frac{\bar{\rho}^2+\bar{\eta}^2}{(1-\bar{\rho})^2+\bar{\eta}^2}$$



Constraint for
$\Delta Br(B \to \tau\nu) \to 0$
Improved measurement will help.

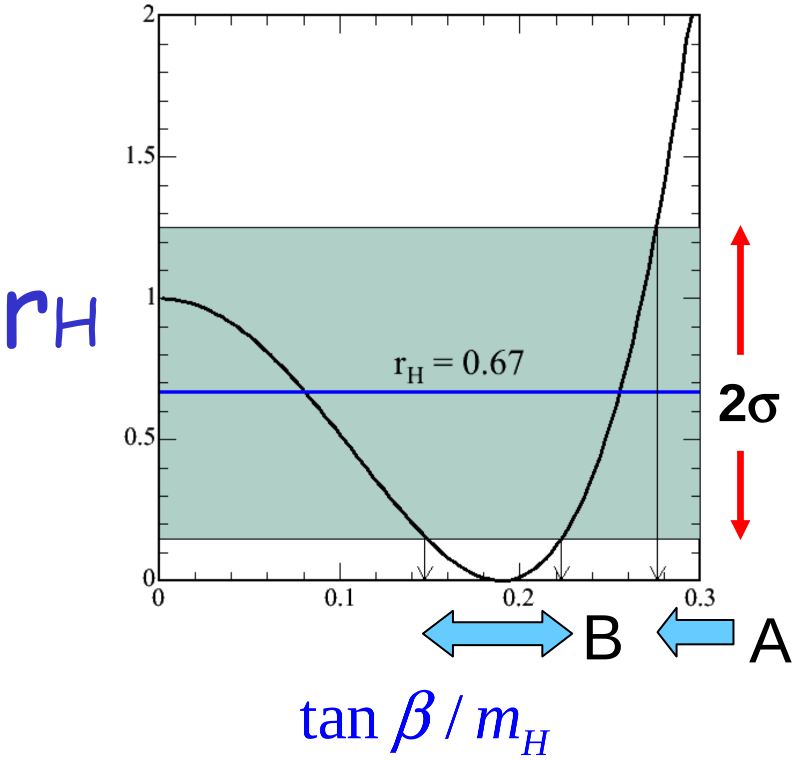
Constraints on Charged Higgs

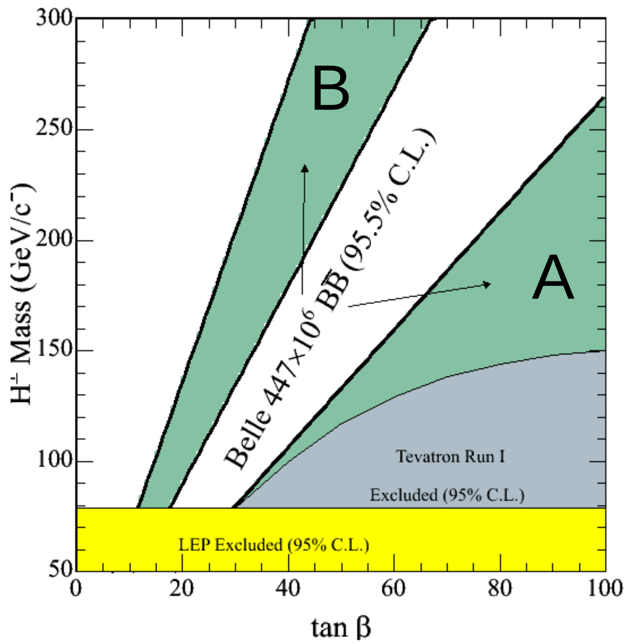
$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times r_H \qquad r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

$$\mathcal{B}(B \to \tau\nu) = (1.06^{+0.34}_{-0.28}(\mathrm{stat})^{+0.18}_{-0.16}(\mathrm{syst})) \times 10^{-4}$$

$$B(B \to \tau\nu)_{SM} = (1.59 \pm 0.40) \times 10^{-4}$$

$$r_H = 0.67^{+0.29}_{-0.26}$$





95.5%C.L. exclusion boundaries

Future Prospect (1)

- $Br(B \to \tau\, \nu)$ measurement:

  Further accumulation of luminosity help to reduce both statistical and systematic errors errors.

  - Some of the major systematic errors come from limited statistics of the control sample.

- $|V_{ub}|$ measurement:

  < 5% in future is an realistic goal.

Note:

$$Br \propto |V_{ub}|^2 \ f_B^2$$

- f_B from theory

  ~10% now → 5% ?

Assumption in the following plots →

Lum.	$\Delta B(B \to \tau\nu)_{exp}$	$\Delta\|V_{ub}\|$
414 fb^{-1}	36%	7.5%
5 ab^{-1}	10%	5.8%
50 ab^{-1}	3%	4.4%

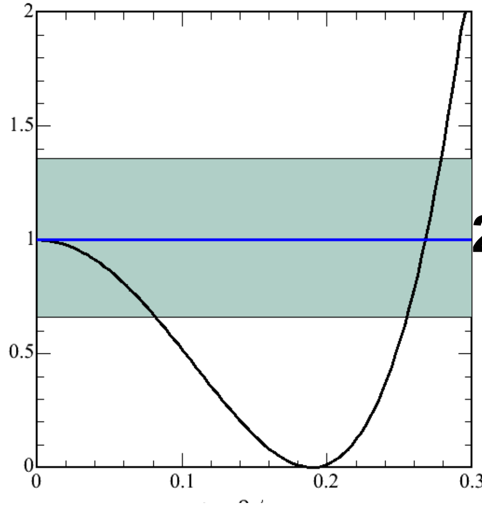
Future Prospect (2)

95.5%C.L. exclusion boundaries

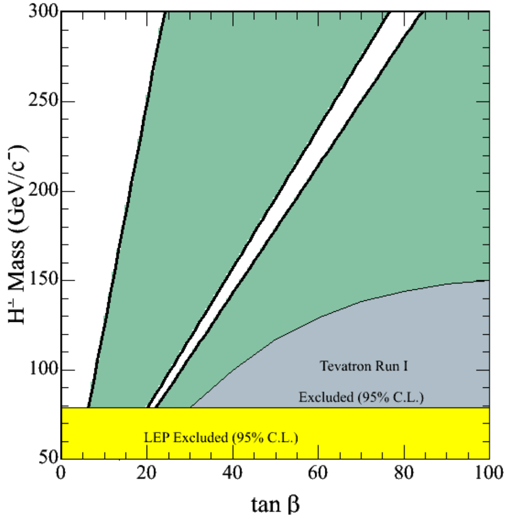
Δf_B(LQCD) = 5%

5ab $^{-1}$

r_H



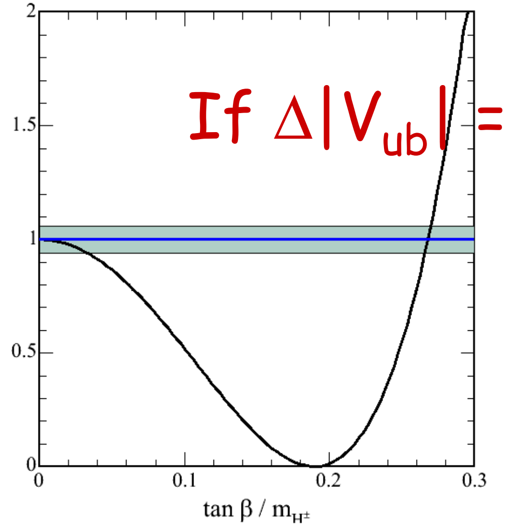
2σ

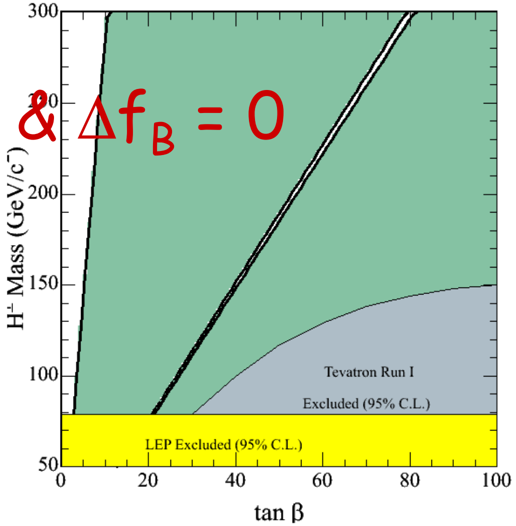


50ab $^{-1}$

If $\Delta|V_{ub}|$ = 0 & Δf_B = 0

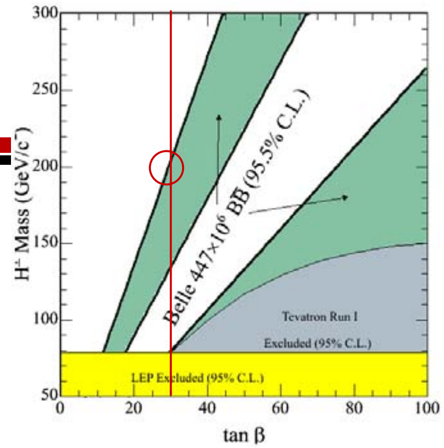
r_H



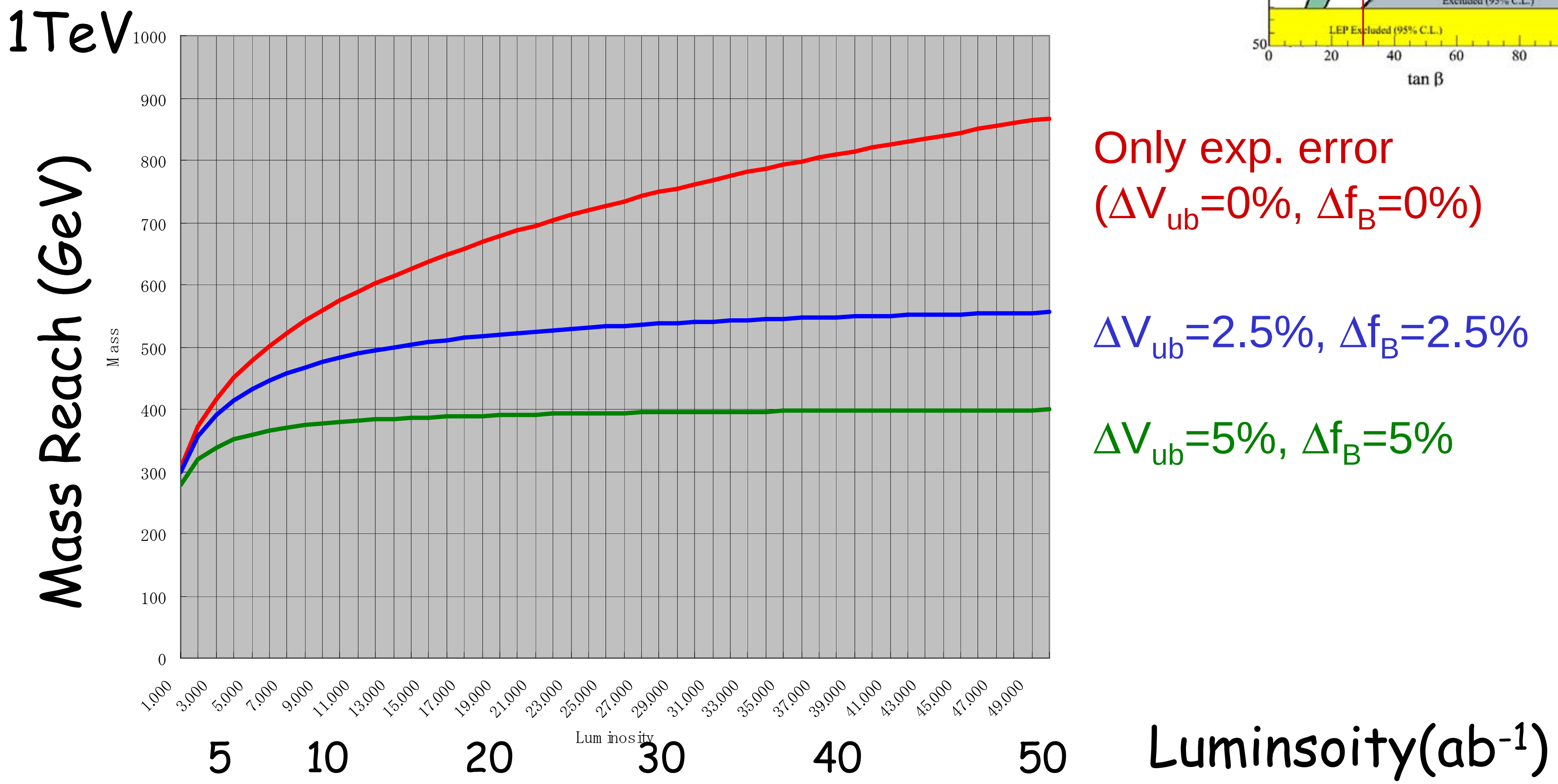


$\tan\beta / m_H$

Future Prospect (3)



Charged Higgs Mass Reach
(95%CL @ tanβ=30)



Only exp. error
(ΔV_{ub}=0%, Δf_B=0%)

ΔV_{ub}=2.5%, Δf_B=2.5%

ΔV_{ub}=5%, Δf_B=5%

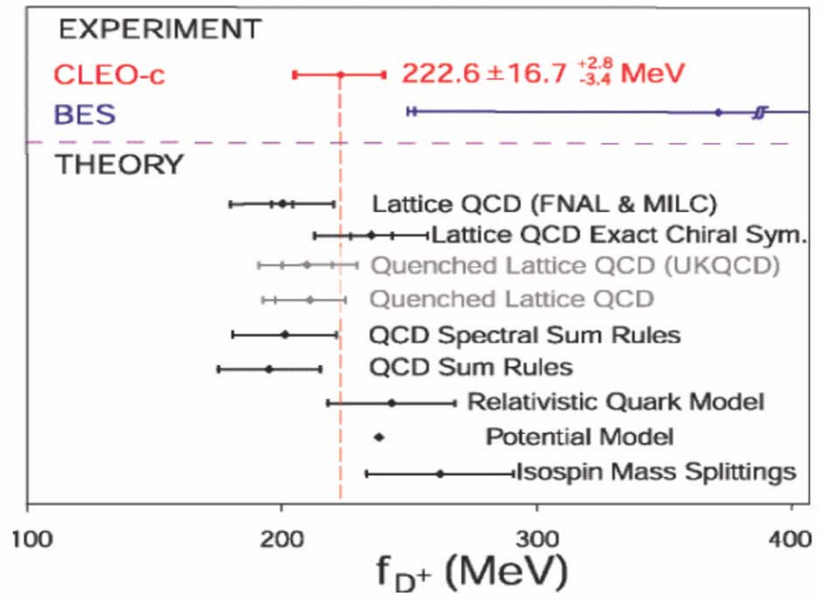
f_D measurements

Purely leptonic D decay by CLEO

$$D^+ \to \mu^+ \nu_\mu \quad \text{and} \quad f_{D^+}$$

$$\Gamma(D^+ \to l^+ \nu) = \frac{G_F^2}{8\pi} f_{D^+}^2 m_l^2 M_{D^+} \left(1 - \frac{m_l^2}{M_{D^+}^2}\right)^2 |V_{cd}|^2$$

$$Br(D^+ \to \mu^+ \nu_\mu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$$



Summary

- We have seen the evidence of B→ τ ν with 414fb^{-1} data at Belle.
  - The first evidence of purely leptonic B decays.
  - Branching fraction

$$\mathcal{B}(B \to \tau\nu) = (1.06^{+0.34}_{-0.28}(\mathrm{stat})^{+0.18}_{-0.16}(\mathrm{syst})) \times 10^{-4}$$

  - B decay constant

$$f_B = 0.176^{+0.028}_{-0.023}(\mathrm{stat})^{+0.020}_{-0.018}(\mathrm{syst})\ \mathrm{GeV}$$

  - Constraint on charged Higgs.

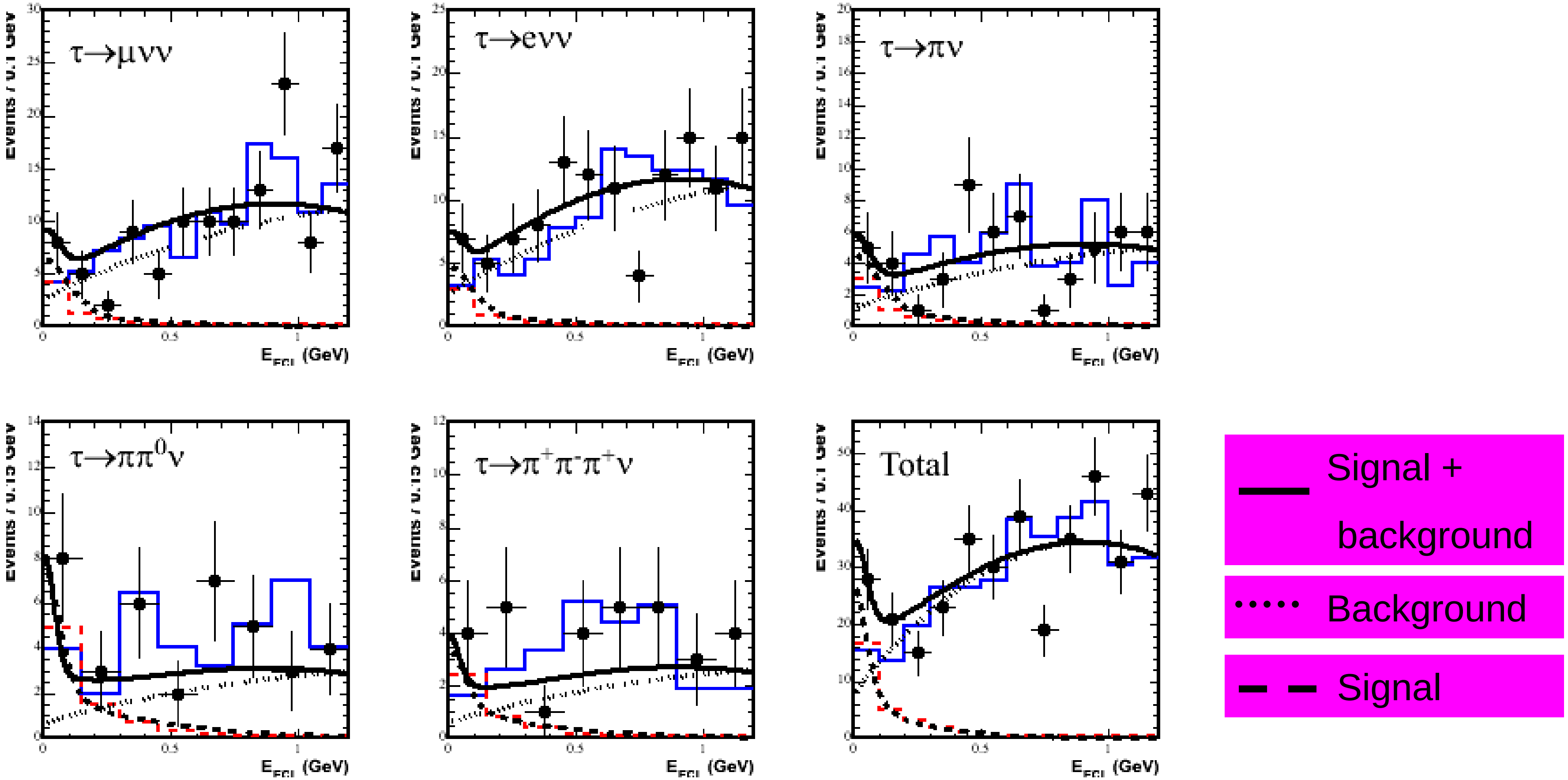
Probe up to ~200GeV at tanβ=30

- O(ab^{-1}) data, together with improved f_B and $|V_{ub}|$, will allow us to probe large tanb-mass space of charged Higgs.

Backup Slides

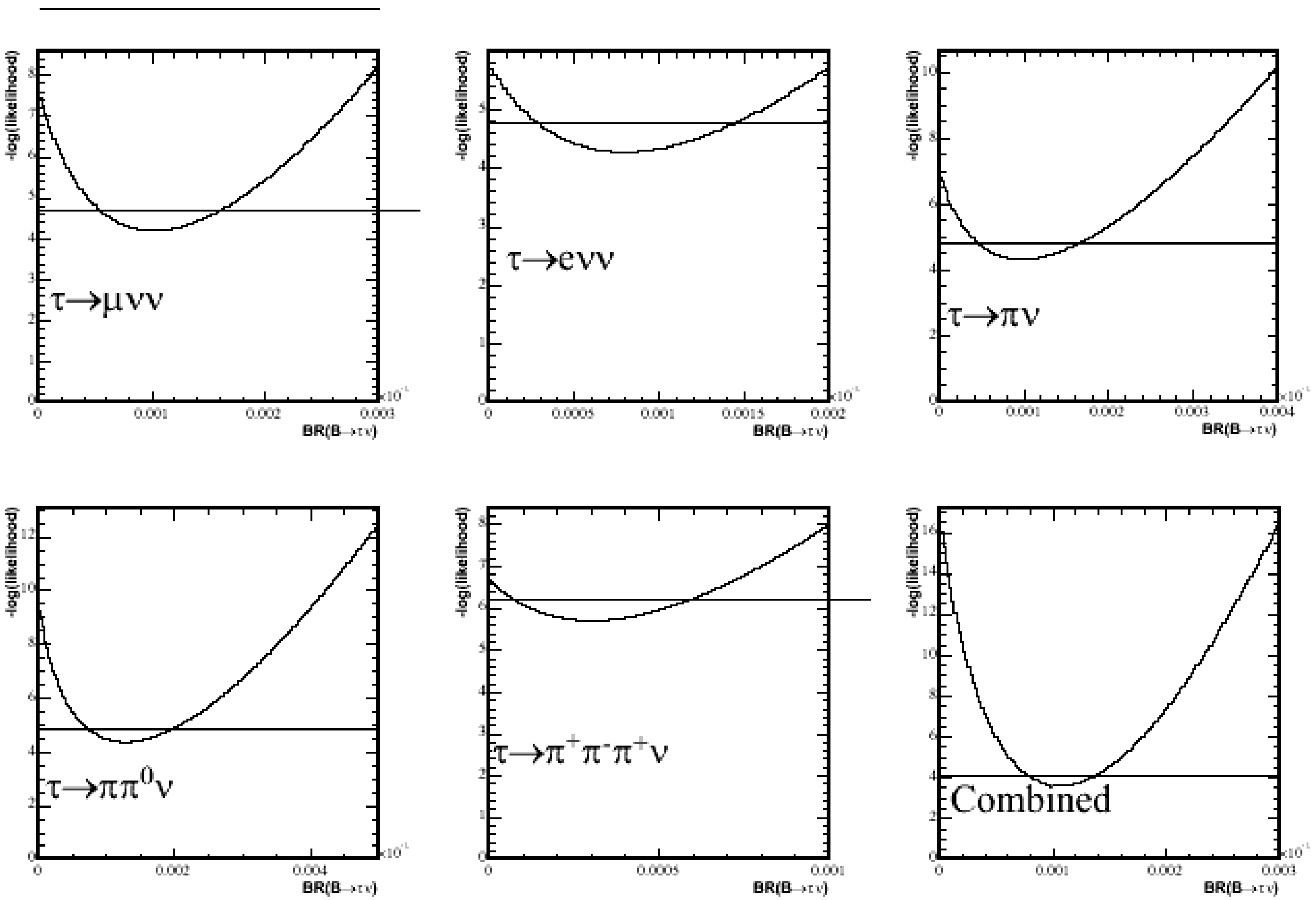
Fit Result (2)

- Likelihood fit results for each τ decay mode.



Fit Results (3)

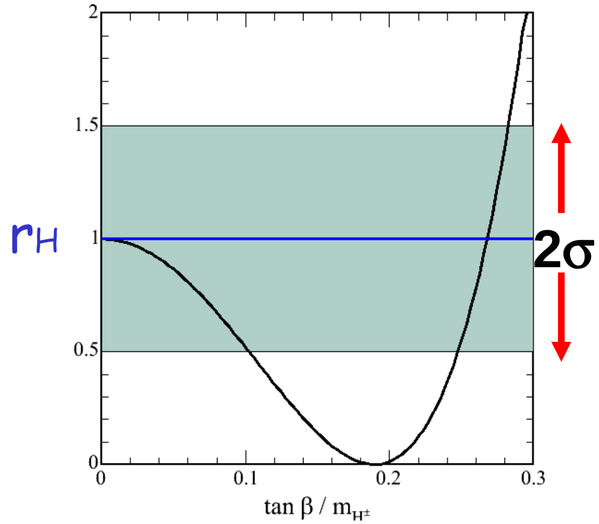
- Likelihood distributions for each τ decay mode.

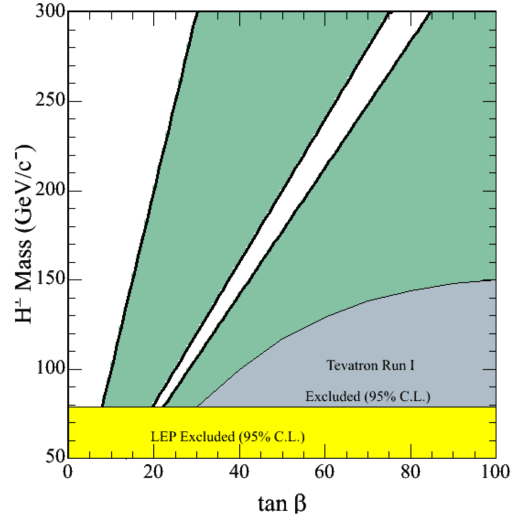


Future Prospect ($5ab^{-1}$)

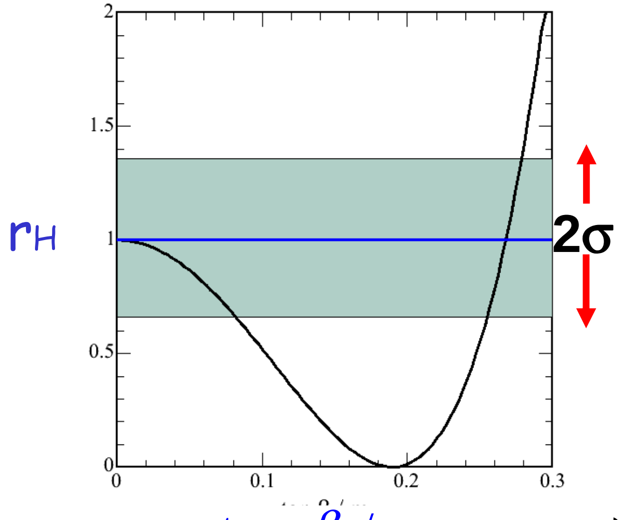
95.5%C.L. exclusion boundaries

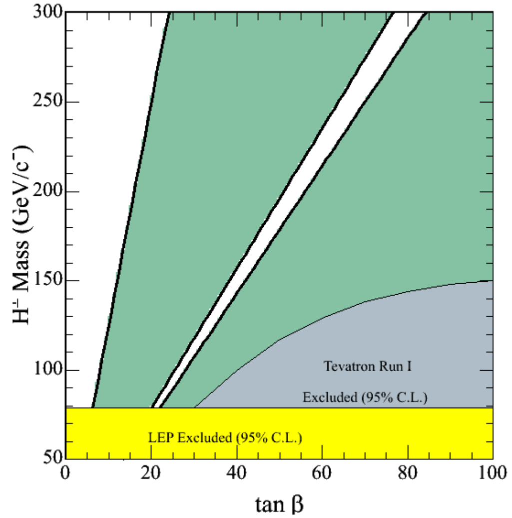
Δf_B(LQCD) = 10%





Δf_B(LQCD) = 5%

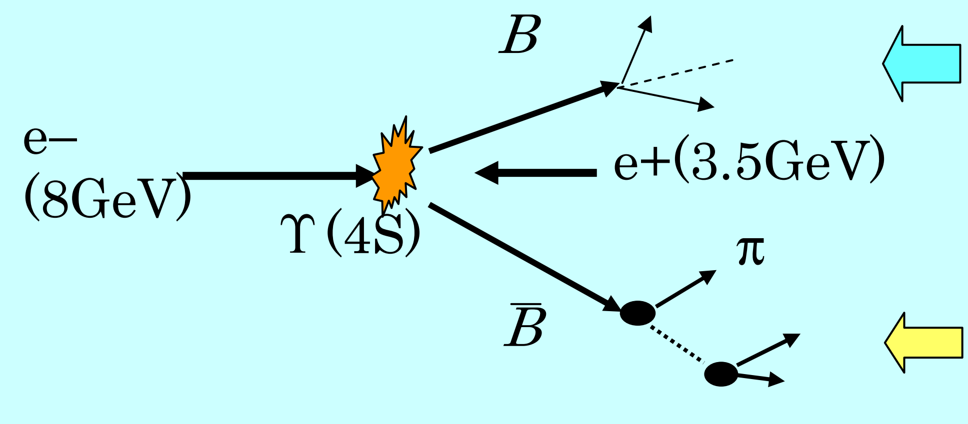




$\tan\beta / m_H$

Full Reconstruction Method

- Fully reconstruct one of the B's to tag
  - B production
  - B flavor/charge
  - B momentum



Decays of interests
B→Xu l ν,
B→K ν ν
B→Dτν, τν

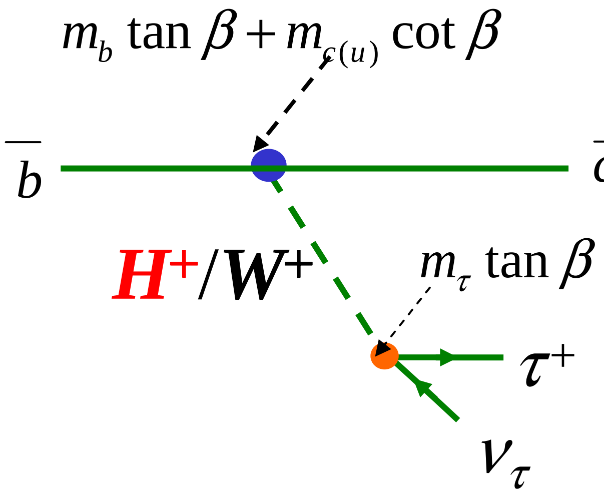
full (0.1~0.3%) reconstruction
B→Dπ etc.

Single B meson beam in offline !

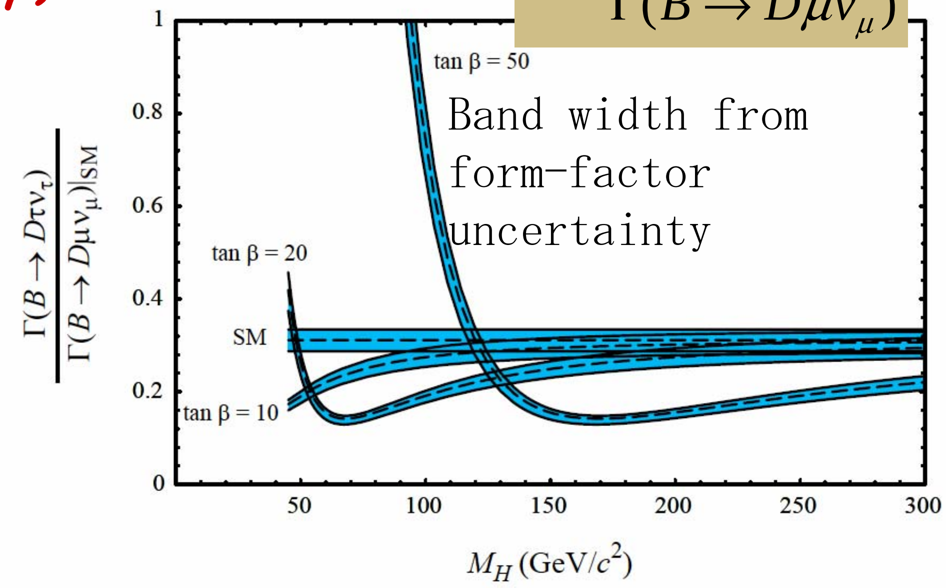
Powerful tools for B decays w/ neutrinos

Search for Charged Higgs

- $B \to D\tau\nu$ (semileptonic decay)

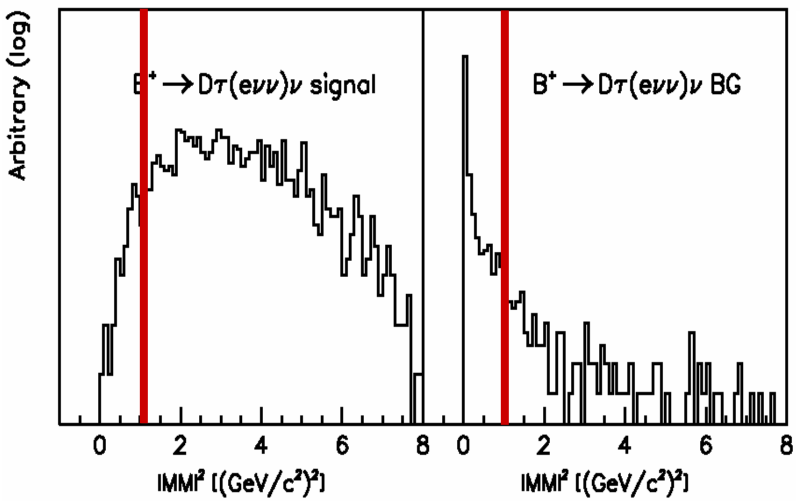


$$B = \frac{\Gamma(B \to \bar{D}\tau\nu_\tau)}{\Gamma(B \to \bar{D}\mu\nu_\mu)}$$



- Full reconstruction tag
- Signal → large missing mass
- Expected at $5ab^{-1}$

Mode	Nsig	Nbkg	dB/B
$D^0\tau^+(\ell^+\bar{\nu}_\tau\nu_\ell)\nu_\tau$	280	550	7.9%
$D^0\tau^+(h^+\bar{\nu}_\tau)\nu_\tau$	620	3600	

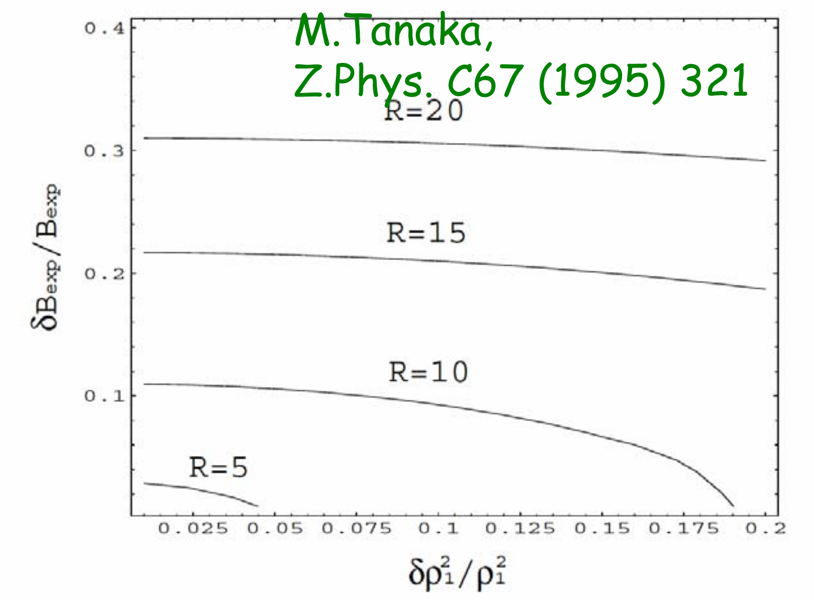


Constraint to Charged Higgs

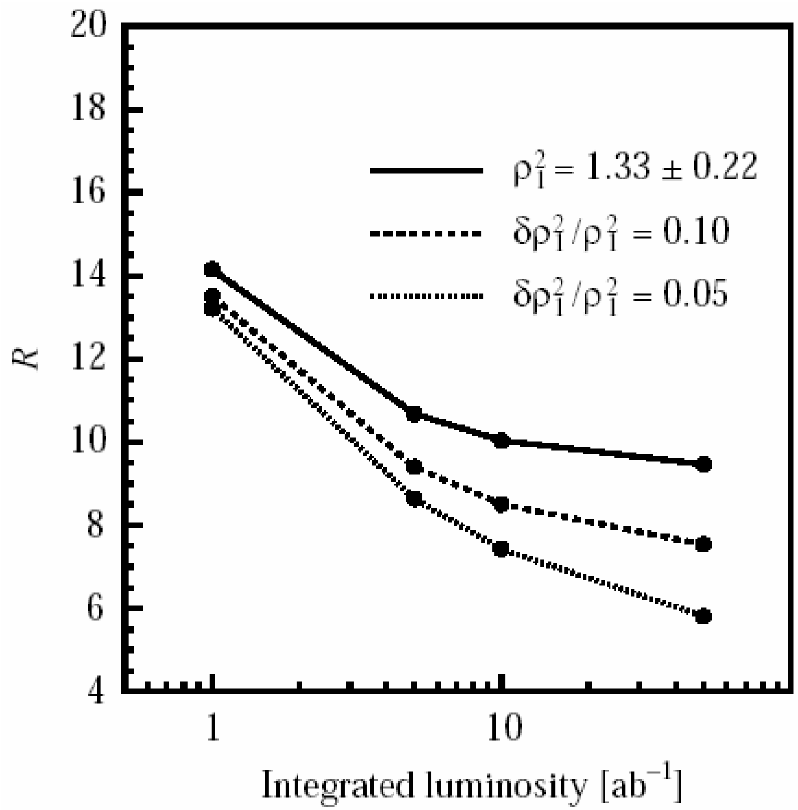
- Once branching fraction is measured, we can constrain R.

$$R \equiv \frac{M_W}{M_H} \tan\beta$$

M.Tanaka,
Z.Phys. C67 (1995) 321



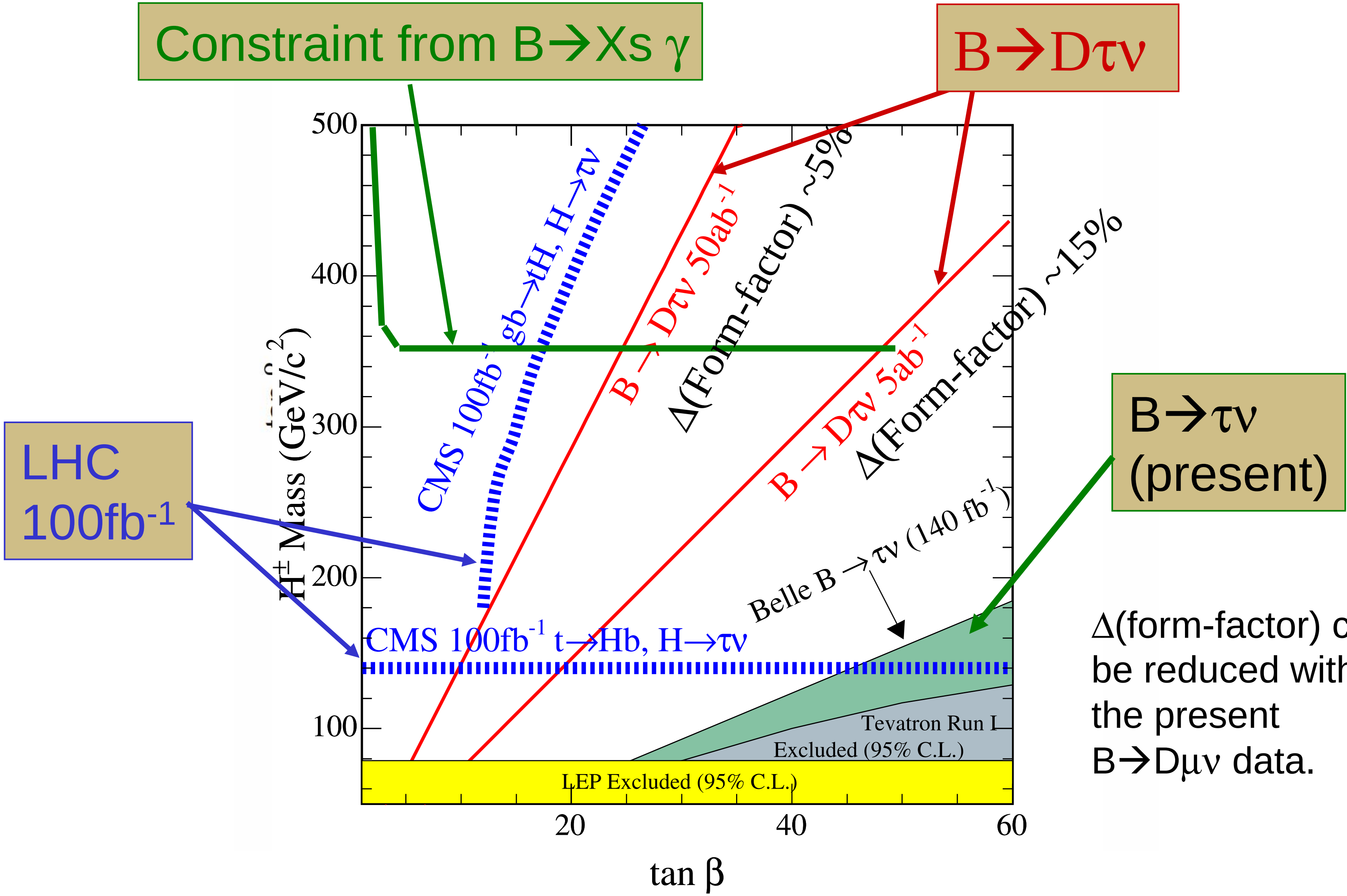
Form factor error



ρ can be determined experimentally
by B semiletonic decays

$R < 11$ at 5ab^{-1}

Sensitivity for Charged Higgs



Δ(form-factor) can be reduced with the present B→Dμν data.