Pulely leptonic and radiative leptonic decays from the e^+e^- B-factories

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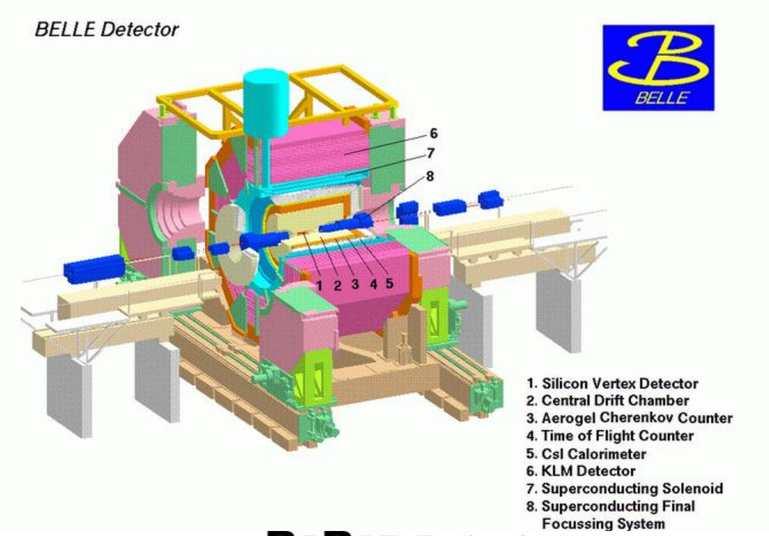
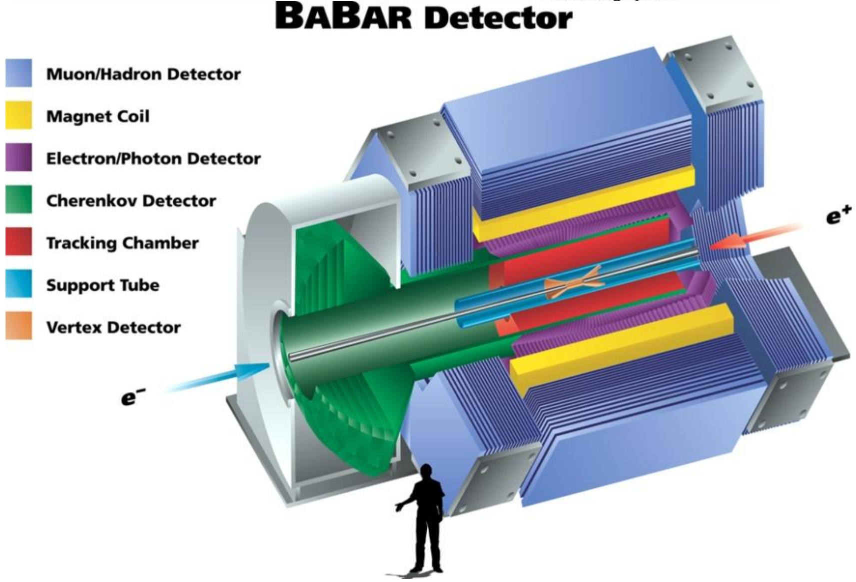
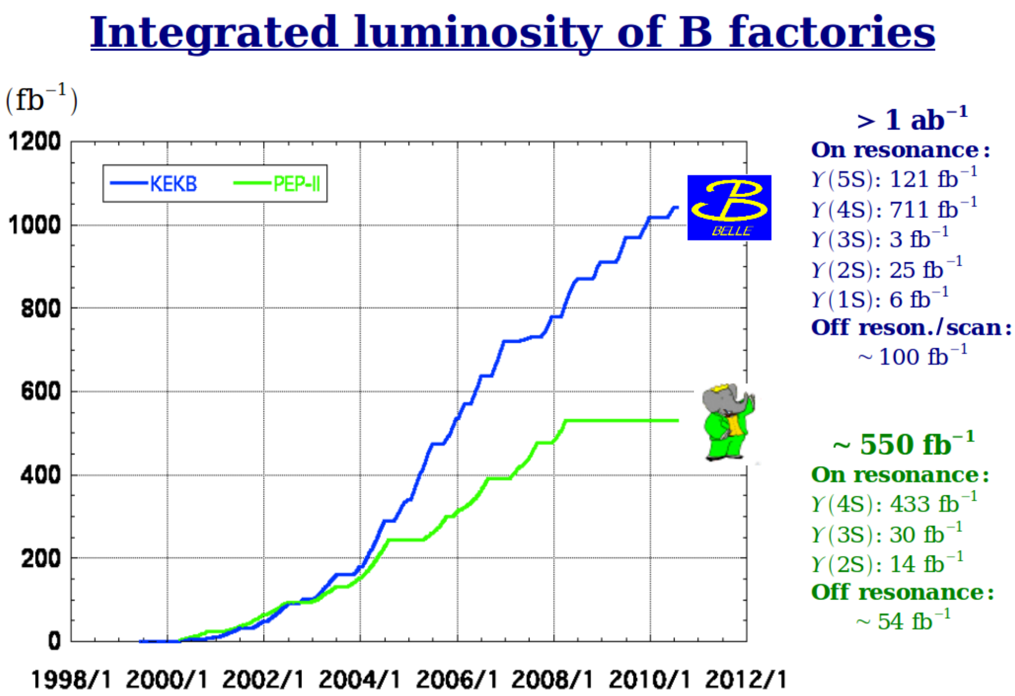
B-factories



BELLE Detector
BELLE
1 2 3 4 5
6
7
8
1. Silicon Vertex Detector
2. Central Drift Chamber
3. Aerogel Cherenkov Counter
4. Time of Flight Counter
5. CsI Calorimeter
6. KLM Detector
7. Superconducting Solenoid
8. Superconducting Final Focussing System

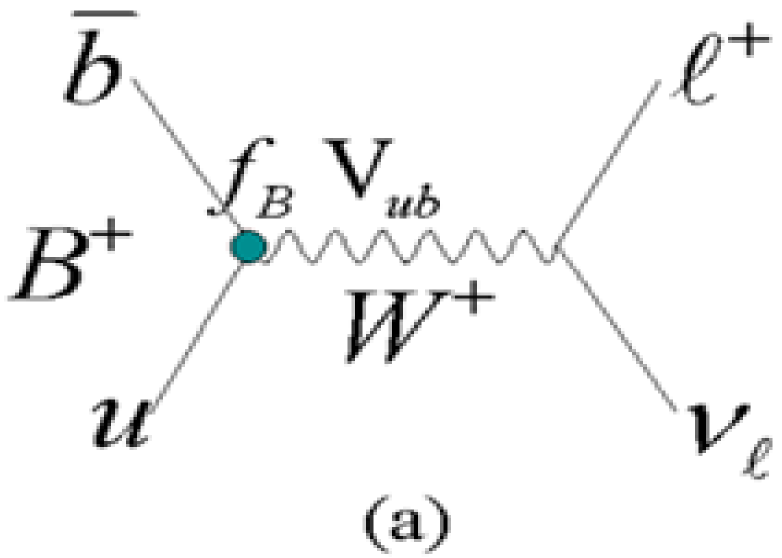


BABAR Detector
Muon/Hadron Detector
Magnet Coil
Electron/Photon Detector
Cherenkov Detector
Tracking Chamber
Support Tube
Vertex Detector
e+
e-



Integrated luminosity of B factories
(fb^{-1})
1200
1000
800
600
400
200
0
1998/1 2000/1 2002/1 2004/1 2006/1 2008/1 2010/1 2012/1
KEKB
PEP-II
BELLE
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}
~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Leptonic decay



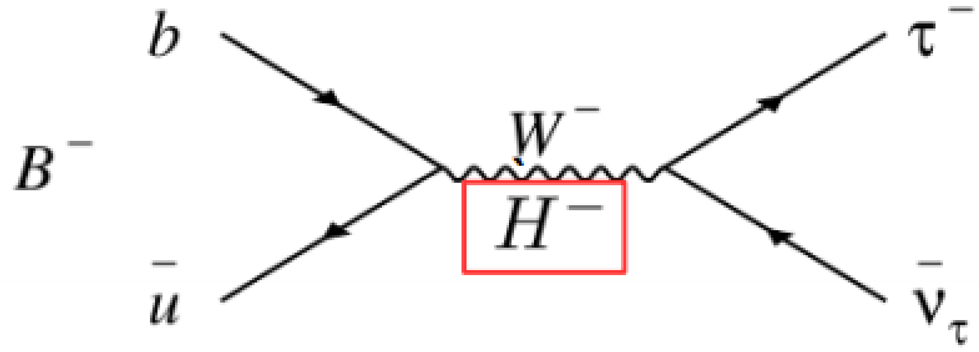
SM Predictions:

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

Helicity suppressed in the SM

$$\Gamma_{SM}(B^+ \to l^+ \nu_l) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

New Physics in Leptonic decay



NP contributions might interfere and modify SM branching fraction

Most prominent : $H^{\pm}$ from 2-Higgs-Doublet-Models (2HDM) as in MSSM

2HDM Type II : $$\Gamma(B^{+} \to l^{+}\nu_{l}) = \Gamma_{SM} \times r_{H}$$

$$r_{H} = \left(1 - \frac{m_{B}^{2}}{m_{H}^{2}} \tan^{2}\beta\right)^{2}$$

Status

Babar Belle	Hadronic tagging	Semileptonic tagging	Non tagging (Inclusive)
B→τ ν	PRD88_031102(2013) PRL110_131801(2013)	PRD81_051101(2010) **Submitted to PRD(RC) arXiv:1503.05613**	
B→ l ν	PRD77_091104(2008) PRD91_052016(2015)	PRD81_051101(2010)	PRD79_091101(2009) PLB647_67-73(2007)
B→ l ν γ	PRD80_111105(2009) **Submitted to PRD arXiv:1504.05831**		

8 published Papers (+2 submitted)

Analysis methods

A B meson pair (and nothing else) is produced by $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$
Therefore if we measure one B, we can study missing neutrinos in the other B

Variables that help signal extraction

$E_{ECL}(=E_{extra})$: remaining energy of ECL clusters after subtraction energy from tag-side and signal-side.
→ For signal, 0 GeV peak is expected.

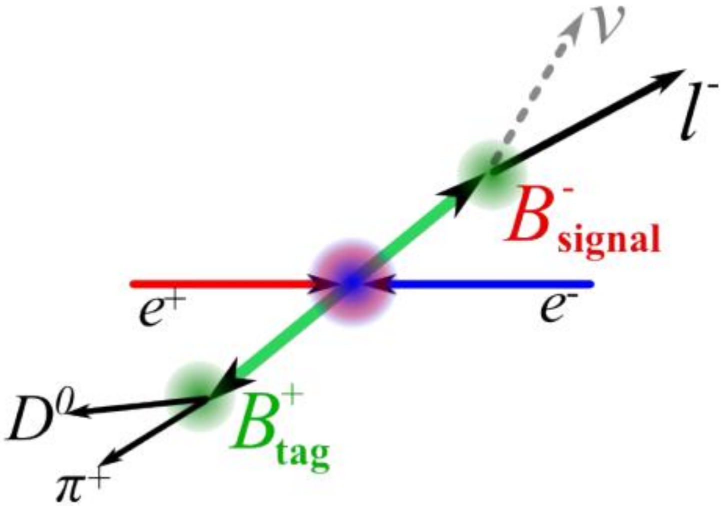
$M_{bc}(=m_{ES})=\mathrm{sqrt}(\ s/4 - p^2(B_{tag})\ )$: Use momentum of tagged B meson.

m^2_{miss} : missing mass squared
p_l^B : signal lepton momentum at signal B rest frame

Two independent tags are used.

- Hadronic tag
- Semileptonic tag

Hadronic tagging

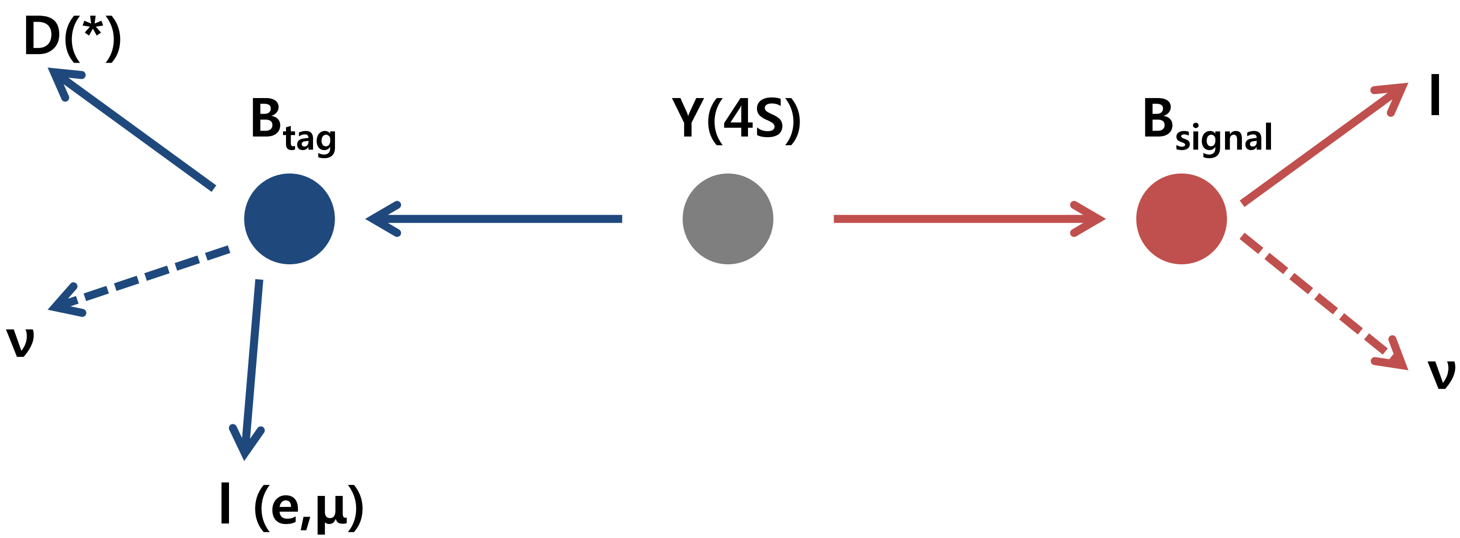


- **One B meson is completely reconstructed from known b→c decays without ν**
- **Low efficiency, High purity**
- **Good momentum resolution**

Belle : use 615 channels to reconstruct B^+ meson
use network output of the multivariate selection algorithm

Babar : reconstruction channel is different for each analysis
doesn’t use neural network,
different best B selection criteria

Semileptonic tagging



- Reconstruct B meson with D(*) meson and lepton (e,μ)
- Use large branching fraction of semileptonic decays
- Only one massless particle is missing in the reconstruction of the decay

$B^+ \rightarrow \tau^+ \nu_\tau$

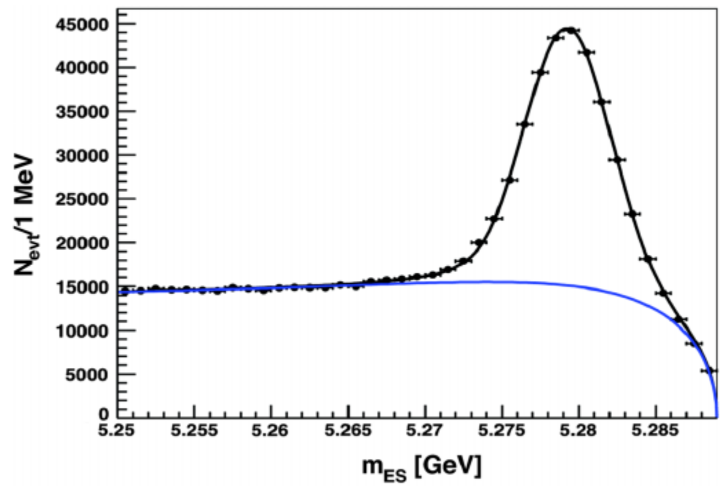
(1) $B^+ \rightarrow \tau^+ \nu_\tau$: hadronic

PRD88_031102(2013)

- Signal τ modes: $\tau \rightarrow e\,\nu\,\nu$, $\mu\,\nu\,\nu$, $\pi\,\nu$, $\rho(\pi\,\pi^0)\,\nu$
- Multiple B candidate

→ Choose least |ΔE| B meson
- R2 : ratio between 2nd and 0th of Fox-Wolfram moments
- θ_{TB} : angle between thrust axis of B_{tag} and remaining
- L_P : likelihood ratio from reconstructed track momentum and missing momentum angle

$$L_P = \frac{L_S(p^*_{\mathrm{trk}}, \cos\theta_{\mathrm{miss}})}{(L_S(p^*_{\mathrm{trk}}, \cos\theta_{\mathrm{miss}}) + L_B(p^*_{\mathrm{trk}}, \cos\theta_{\mathrm{miss}}))}$$



Purity is estimated from the ratio of peaking events over total

(1) $B^+ \to \tau^+ \nu_\tau$: hadronic

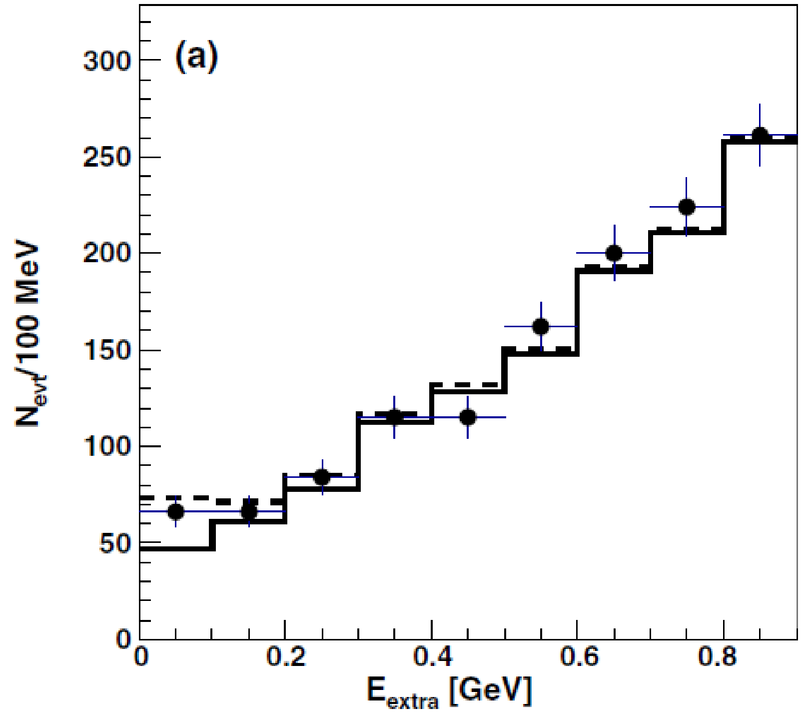
Uses 467.8M BB pairs

1D signal extraction in excess calorimeter energy(E_{extra})

$$\mathcal{B}(B^+ \to \tau^+ \nu) = (1.83^{+0.53}_{-0.49}(\text{stat}) \pm 0.24(\text{syst})) \times 10^{-4}$$

Significance : 3.8 σ

Decay mode	$\epsilon_k(\times 10^{-4})$	Signal yield	$\mathcal{B}(\times 10^{-4})$
$\tau^+ \to e^+ \nu \bar{\nu}$	2.47 ± 0.14	4.1 ± 9.1	$0.35^{+0.84}_{-0.73}$
$\tau^+ \to \mu^+ \nu \bar{\nu}$	2.45 ± 0.14	12.9 ± 9.7	$1.12^{+0.90}_{-0.78}$
$\tau^+ \to \pi^+ \nu$	0.98 ± 0.14	17.1 ± 6.2	$3.69^{+1.42}_{-1.22}$
$\tau^+ \to \rho^+ \nu$	1.35 ± 0.11	24.0 ± 10.0	$3.78^{+1.65}_{-1.45}$
Combined		62.1 ± 17.3	$1.83^{+0.53}_{-0.49}$



E_{extra} distribution for subdecay modes can see in backup slides

(2) $B^+ \to \tau^+ \nu_\tau$: hadronic

Signal τ modes: $\tau \to e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho(\pi\pi^0)\nu$

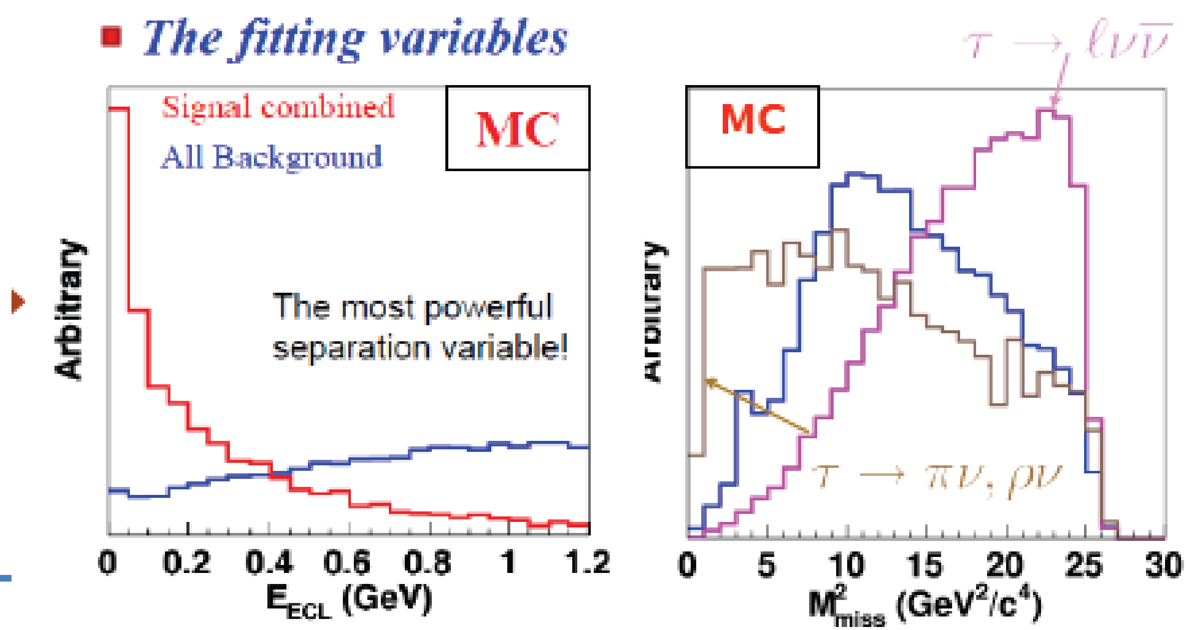
PRL 110, 131801(2013)

π^0 K_L veto

- K_L efficiency calibration by $D^0 \to \varphi K_S$, $\varphi \to K_L K_S$
- K_L gives ~ 5% improvement in the expected sensitivity

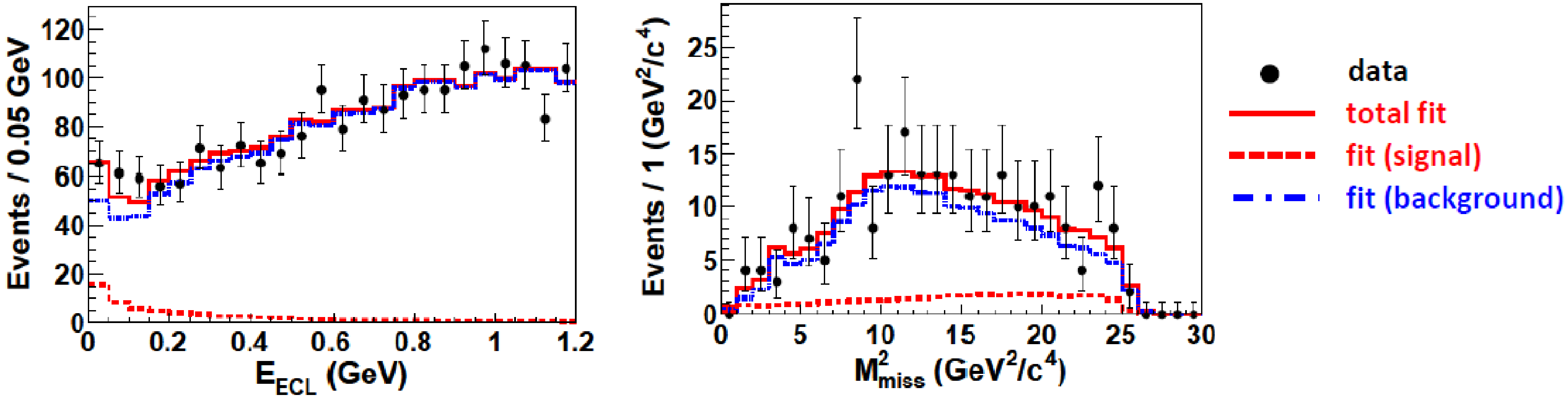
2D fitting on EECL and M2miss

$$E_{\rm ECL} = \sum \text{(energies of neutral clusters, not belonging to either } B_{\rm tag} \text{ or } \pi^0 \text{ in } B_{\rm sig})$$
$$M^2_{\rm miss} = (E_{\rm CM} - E_{B_{\rm tag}} - E_{B_{\rm sig}})^2 - |\vec{p}_{B_{\rm tag}} + \vec{p}_{B_{\rm sig}}|^2$$



(2) $B^+ \to \tau^+ \nu_\tau$: hadronic

$$E_{\mathrm{ECL}} = \sum \text{(energies of neutral clusters, not belonging to either } B_{\mathrm{tag}} \text{ or } \pi^0 \text{ in } B_{\mathrm{sig}}\text{)}$$
$$M^2_{\mathrm{miss}} = (E_{\mathrm{CM}} - E_{B_{\mathrm{tag}}} - E_{B_{\mathrm{sig}}})^2 - |\vec{p}_{B_{\mathrm{tag}}} + \vec{p}_{B_{\mathrm{sig}}}|^2$$



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

Significance: 3.0 σ.

Sub-mode	N_{sig}	ϵ (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	16^{+11}_{-9}	3.0	$0.68^{+0.49}_{-0.41}$
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	26^{+15}_{-14}	3.1	$1.06^{+0.63}_{-0.58}$
$\tau^- \to \pi^- \nu_\tau$	8^{+10}_{-8}	1.8	$0.57^{+0.70}_{-0.59}$
$\tau^- \to \pi^- \pi^0 \nu_\tau$	14^{+19}_{-16}	3.4	$0.52^{+0.72}_{-0.62}$
Combined	62^{+23}_{-22}	11.2	$0.72^{+0.27}_{-0.25}$

Uses full belle data sample

449M → 772M BB pairs

2D signal extraction in E_{ecl} and M^2_{miss}

(3) $B^+ \rightarrow \tau^+ \nu_\tau$: semileptonic

- Loose selection criteria are applied to maximize the efficiency.
- Multivariate selection (MVS) method based on NeuroBayes package.
- Multiple B candidate

arXiv:1503.05613

→ choose with maximal value of tag-side MVS output.

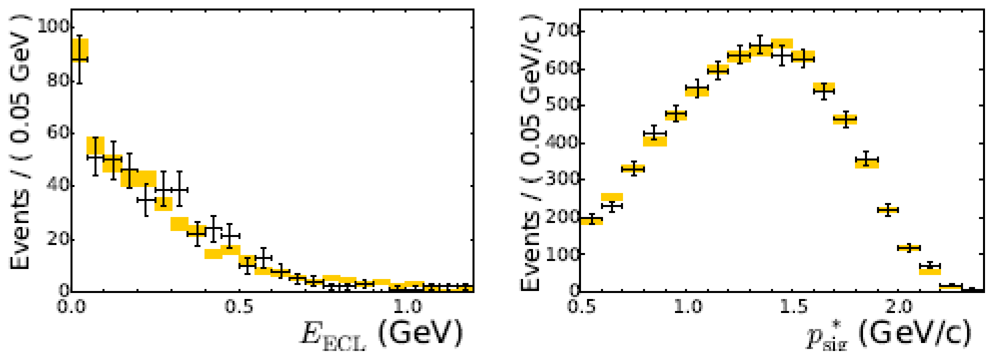
$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2c^4 - m_{D^{(*)}\ell}^2c^4}{2p_B^* p_{D^{(*)}\ell}^* c^2}$$

Cosine of the angle between the momentum of the B meson and the $D^{(*)}l$ system.

(3) $B^+ \rightarrow \tau^+ \nu_\tau$: semileptonic

- Use $B \rightarrow D^{*0} l \nu$, $B \rightarrow D^0 \pi^+$ double tagged sample to check Data MC difference.
  - → Use E_{ECL} and p_{sig}^*
  - → Reconstruction efficiency is corrected by the ratio

p_{sig}^* : momentum of signal-side particle in the CM



- Veto backgrounds from converted photons in the electron modes.
- 23.1×10^{-4} total efficiency (For details, see backup slides p.33)

(3) $B^+ \rightarrow \tau^+ \nu_\tau$: semileptonic

BELLE

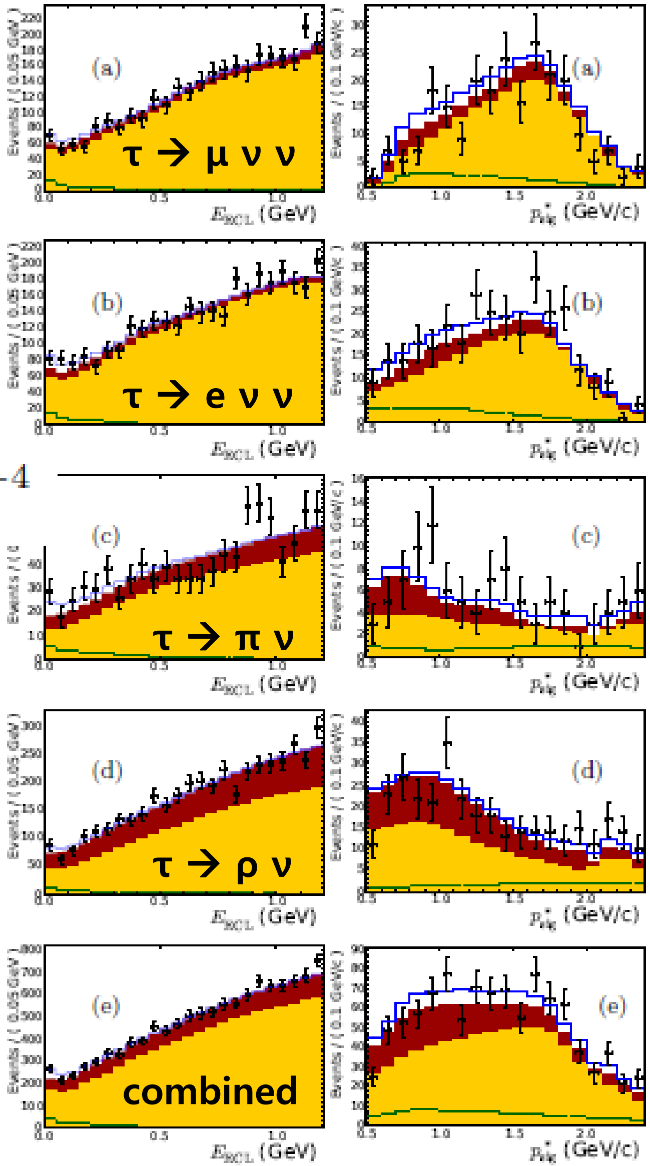
Uses 772M BB pairs

2D unbinned Maximum-likelihood fit for signal extraction (E_{ECL} and p^*_{sig})

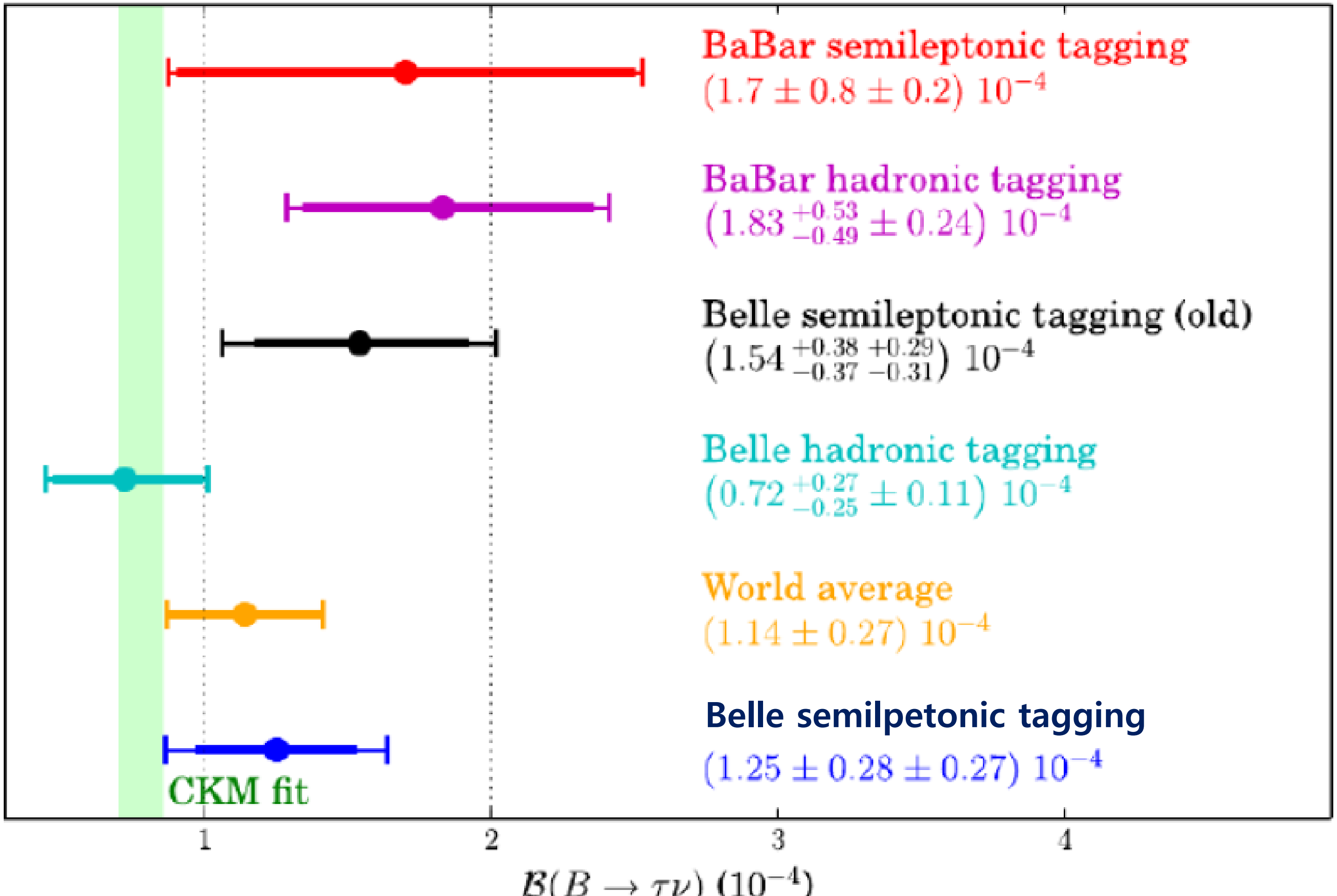
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = [1.25 \pm 0.28(\text{stat.}) \pm 0.27(\text{syst.})] \times 10^{-4}$$

Significance : 3.8 σ

Decay Mode	N_{sig}	$\mathcal{B}(10^{-4})$
$\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu$	13±21	0.34±0.55
$\tau^+ \to e^+\bar{\nu}_\tau\nu_e$	47±25	0.90±0.47
$\tau^+ \to \pi^+\bar{\nu}_\tau$	57±21	1.82±0.68
$\tau^+ \to \rho^+\bar{\nu}_\tau$	119±33	2.16±0.60
Combined	222±50	1.25±0.28



$B^+ \rightarrow \tau^+ \nu_\tau$ summary



Belle combined branching fraction $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) = [0.91 \pm 0.19(\text{stat.}) \pm 0.11(\text{syst.})] \times 10^{-4}$

4.6 σ significance

$$B^{+} \rightarrow l^{+}\ \nu_{l}$$

(4) $B^+ \rightarrow l^+ \nu_l$ untagged

PLB647_67-73(2007)

PRD79_091101(2009)

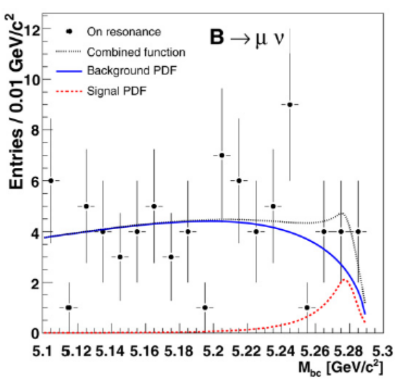
Uses 276.6M BB pairs

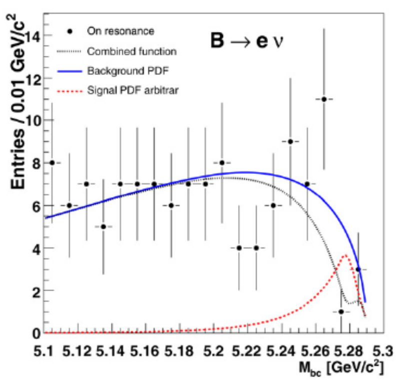
1D signal extraction using M_{bc}

Best upper limits for $B^+ \rightarrow e^+ \nu_e$

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 1.7 \times 10^{-6} \quad (90\%\ \text{C.L.})$$

$$\mathcal{B}(B^+ \to e^+ \nu_e) < 9.8 \times 10^{-7} \quad (90\%\ \text{C.L.})$$





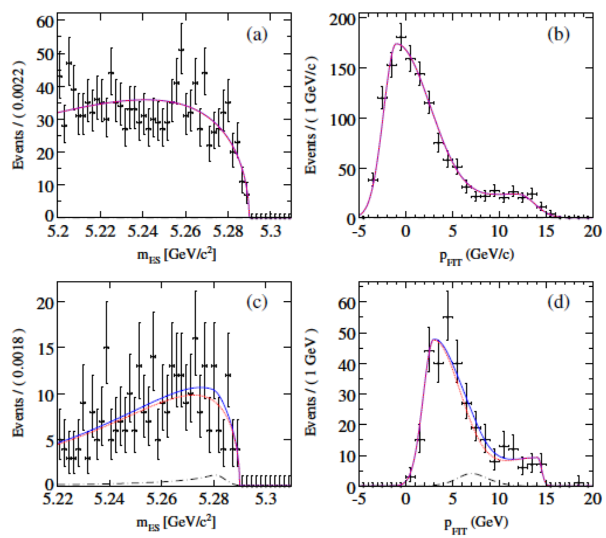
Uses 468M BB pairs

2D signal extraction using m_{ES} p_{FIT}

Best upper limits for $B^+ \rightarrow \mu^+ \nu_\mu$

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 1.0 \times 10^{-6}$$

$$\mathcal{B}(B^+ \to e^+ \nu_e) < 1.9 \times 10^{-6}$$



(5) $B^+ \rightarrow l^+ \nu_l$ tagged

PRD77_091104(2008)

PRD81_051101(2010)

Hadronic tagging

Uses 378M BB pairs

1D signal extraction using signal lepton momentum at signal B frame

$$\mathcal{B}(B^+ \to e^+ \nu) < 5.2 \times 10^{-6}$$

$$\mathcal{B}(B^+ \to \mu^+ \nu) < 5.6 \times 10^{-6}$$

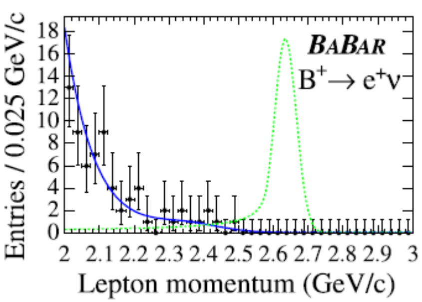
Semileptonic tagging

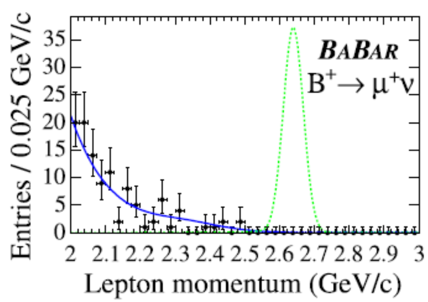
Uses 458.9M BB pairs

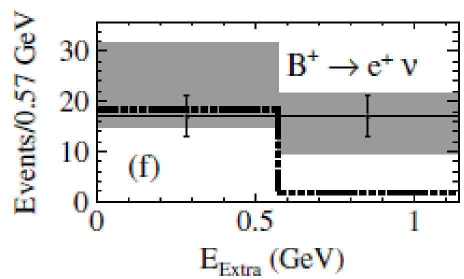
1D signal extraction using E_{Extra}

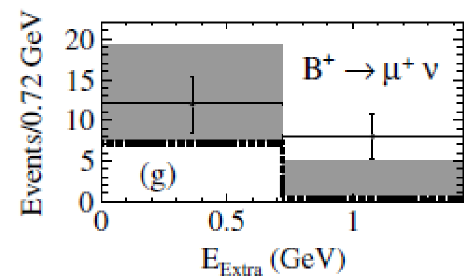
$$\mathcal{B}(B^+ \to e^+ \nu_e) < 0.8 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 1.1 \times 10^{-5}$$









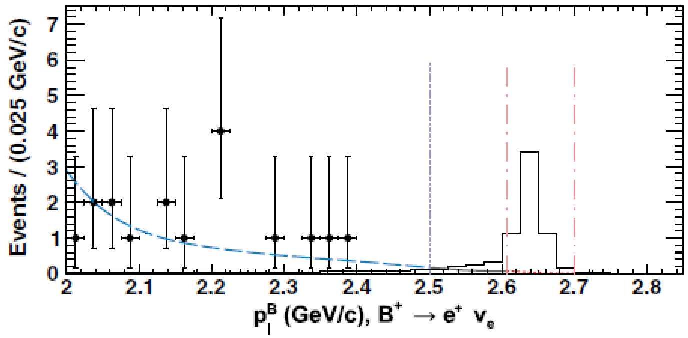
(5) $B^+ \to l^+ \nu_l$ tagged

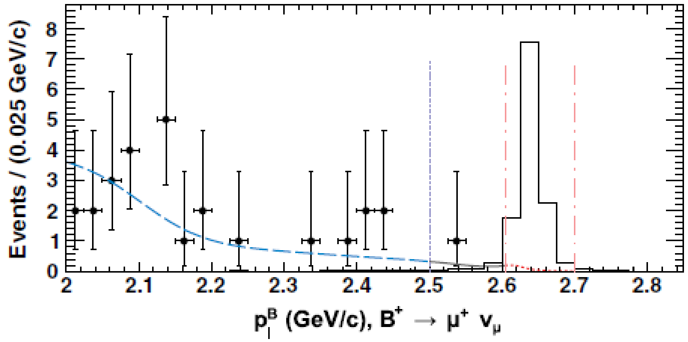
- **p_l^B : Signal lepton momentum in B_{sig} rest frame**
- Signal extraction by p_l^B (counting)
- U.L. calculated using Feldman-Cousins method
- most stringent limits obtained with the hadronic tagging method

PRD91_052016(2015)

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 2.7 \times 10^{-6}$$
$$\mathcal{B}(B^+ \to e^+ \nu_e) < 3.5 \times 10^{-6}$$

Mode	ϵ_s [%]	N_{obs}	N_{exp}^{bkg}
$B^+ \to e^+ \nu_e$	0.086 ± 0.007	0	0.10 ± 0.04
$B^+ \to \mu^+ \nu_\mu$	0.102 ± 0.008	0	$0.26^{+0.09}_{-0.08}$





$B^+ \rightarrow l^+ \nu_l \gamma$

Radiative leptonic decay ($B^+ \rightarrow l^+ \nu_l \gamma$)

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{em} G_F^2 |V_{ub}|^2}{48\pi^2} m_B^4 (1 - x_\gamma) x_\gamma^3 \left[F_A^2 + F_V^2\right]$$

$$x_\gamma = 2E_\gamma / m_B$$

$$\begin{aligned} F_V(E_\gamma) &= \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) \\ &+ \left[\xi(E_\gamma) + \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_b m_B f_B}{2E_\gamma m_b}\right], \\ F_A(E_\gamma) &= \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) \\ &+ \left[\xi(E_\gamma) - \frac{Q_u m_B f_B}{(2E_\gamma)^2} - \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_\ell f_B}{E_\gamma}\right] \end{aligned}$$

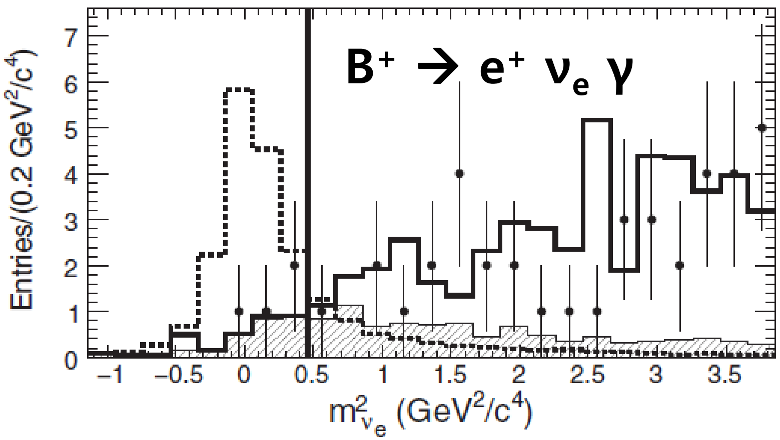
- The branching fraction determines λ_B, a parameter describing the quark momentum distribution in the B meson.
- photon removes helicity suppression → can increase branching fraction

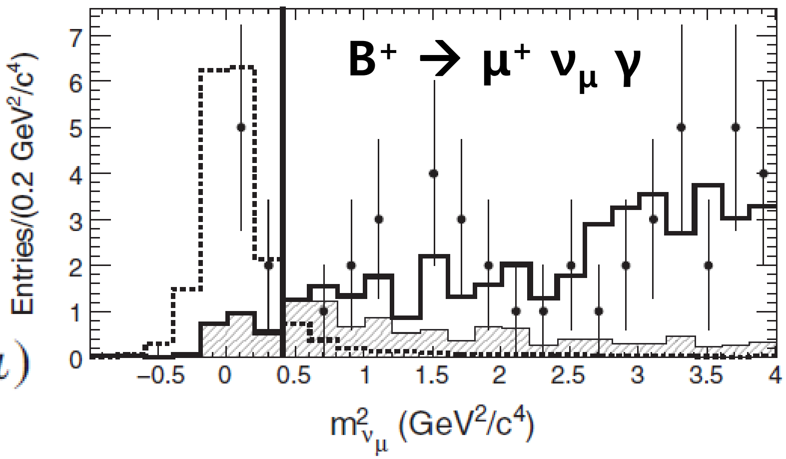
(6) $B^+ \rightarrow l^+ \nu_l \gamma$

PRD80_111105(2009)

- **Signal counting using m^2_ν**
- **Uses 465M BB pairs**

- Obtain model-independent upper limit and U.L. for each form factor limits





$$\mathcal{B}(B^+ \rightarrow e^+ \nu_e \gamma) < 17 \times 10^{-6}$$

$$\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu \gamma) < 24 \times 10^{-6}$$

$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell \gamma) < 15.6 \times 10^{-6} \ (\ell = e \text{ or } \mu)$$

(6) $B^+ \rightarrow l^+ \nu_l \gamma$

arXiv:1504.05831

- **Uses 772M BB pairs**
- **2 cases are considered ($E_\gamma^B > 1.0$ GeV , $E_\gamma^B > 0.4$ GeV)**
- Signal extraction by using 2 variables

$$m^2_{\rm miss} = (p_{B_{\rm sig}} - p_\ell - p_\gamma)^2/c^4$$

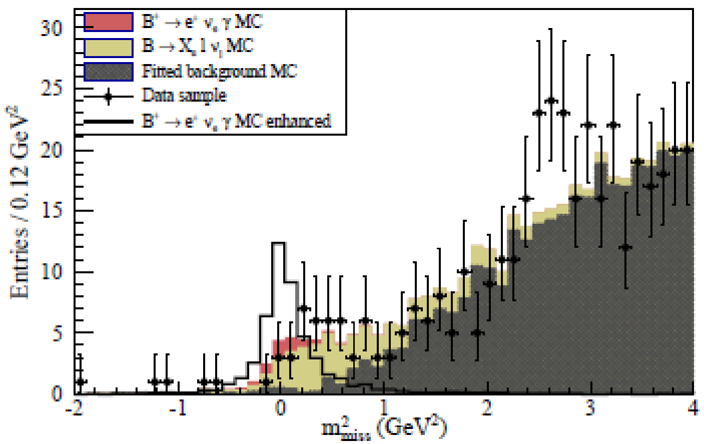
Neural Network output

Extra energy in EM calorimeter
Angle between signal γ and ν
$m(\pi^0)$ with $E(\gamma_{back}) > 40$ MeV
$m(\pi^0)$ without cut on $E(\gamma_{back})$
$m(\eta)$ with $E(\gamma_{back}) > 300$ MeV
Angle between signal γ and l
$m(\eta)$ with $E(\gamma_{back}) > 100$ MeV
$m(\pi^0)$ with $E(\gamma_{back}) > 60$ MeV
$m(\pi^0)$ with ECL cuts scaled by 0.6

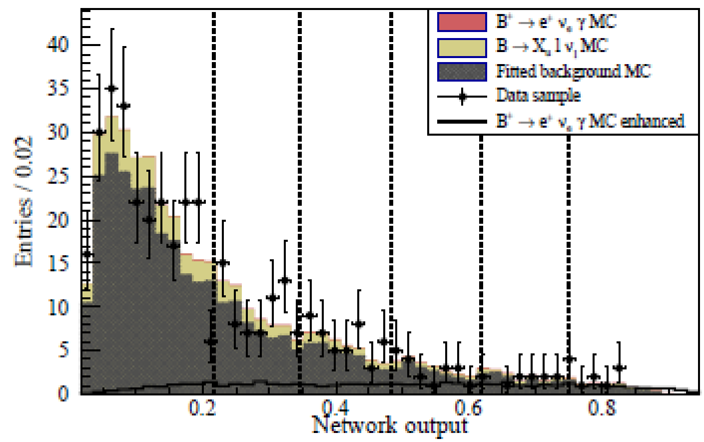
※ $m(\pi^0)$ and $m(\eta)$ are included in Neural network to suppress the main background ($B^+ \rightarrow l^+ \nu_l \pi^0$, $B^+ \rightarrow l^+ \nu_l \eta$)

(6) $B^+ \rightarrow l^+ \nu_l \gamma$

signal extraction by extended unbinned 1D max. likelihood fit to the m^2_{miss} distribution in six bins of the neural net output.



(a) Electron channel

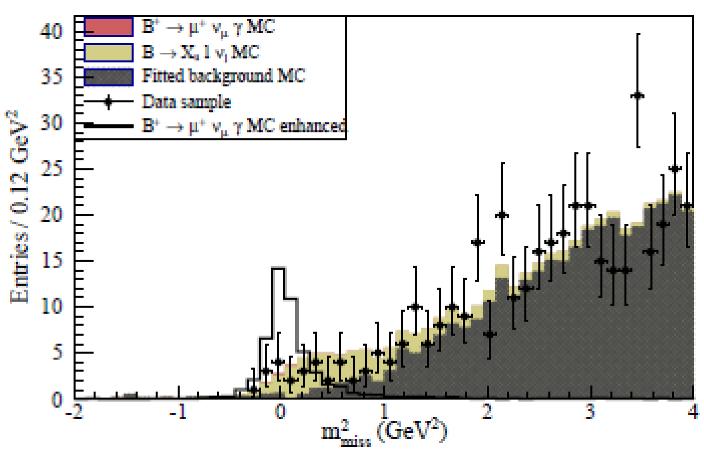


(a) Electron channel

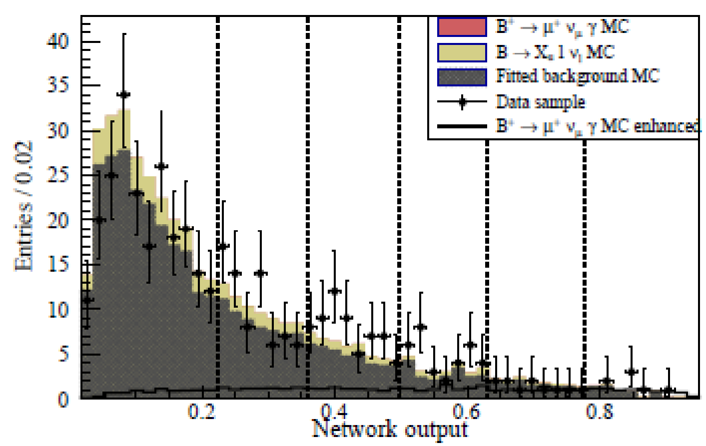
$B^+ \rightarrow e^+ \nu_e \gamma$

m^2_{miss}

Neural net output



(b) Muon channel



(b) Muon channel

$B^+ \rightarrow \mu^+ \nu_\mu \gamma$

(6) $B^+ \rightarrow l^+ \nu_l \gamma$

- **No hint of signals, and we set upper limits**
- **Most stringent upper limits in all modes!**

$$\mathcal{B}(B^+ \to e^+\nu_e\gamma) < 6.1 \times 10^{-6}$$
$$\mathcal{B}(B^+ \to \mu^+\nu_\mu\gamma) < 3.4 \times 10^{-6}$$
$$\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) < 3.5 \times 10^{-6}$$

Summary

- B-factories have studied purely leptonic and radiative leptonic decay with a goal of searching for new physics beyond SM.
- Semileptonic tagging $B^+ \rightarrow \tau^+ \nu_\tau$ searches at Belle has 3.8 σ significance
- Radiative leptonic decay searches at Belle gives most stringent upper limit of branching fraction.
- e^+e^- B-factory experiments has an advantage for these studies and these will remain important subjects in the Belle-II.

BACKUP

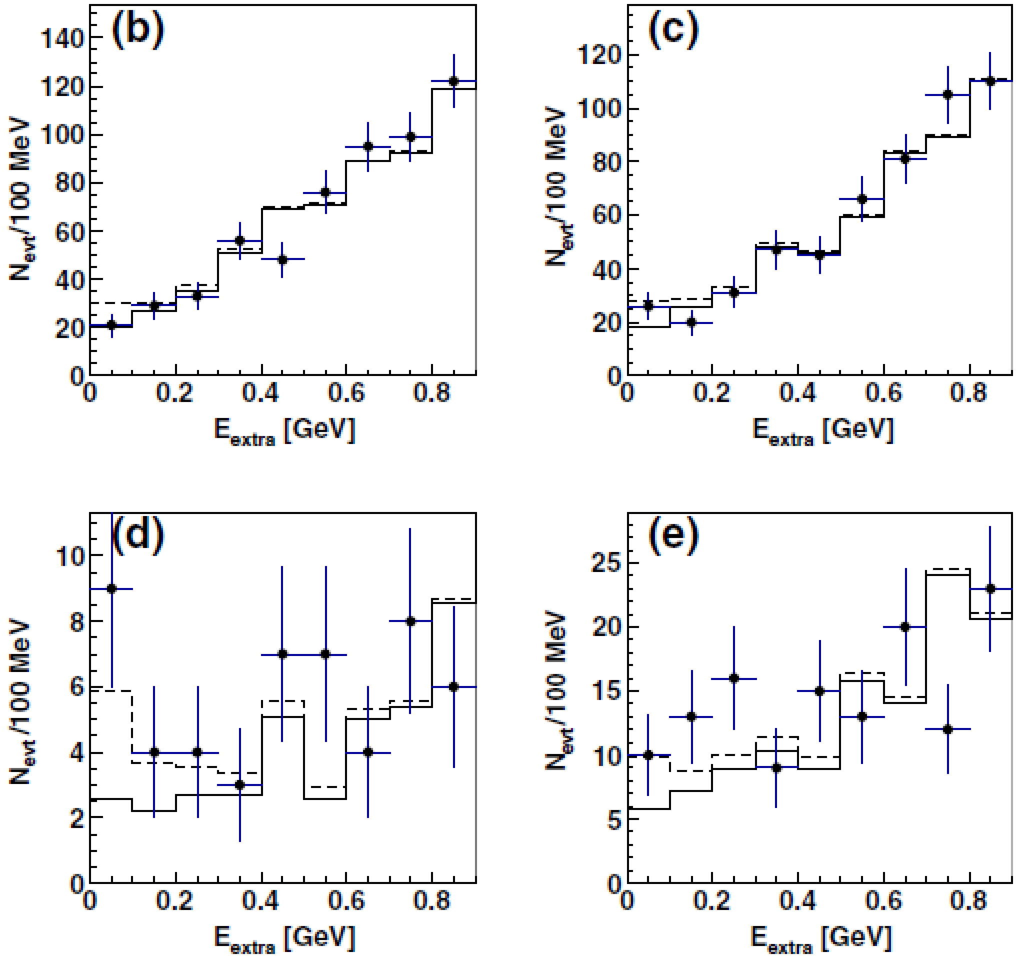
(1) $B^+ \rightarrow \tau^+ \nu_\tau$: hadronic

$\tau \rightarrow e\,\nu\,\nu$

$\tau \rightarrow \mu\,\nu\,\nu$

$\tau \rightarrow \pi\,\nu$

$\tau \rightarrow \rho\,\nu$



(3) $B^+ \rightarrow \tau^+ \nu_\tau$: semileptonic

	$\tau^+ \to \mu^+ \nu_\tau \bar{\nu}_\mu$	$\tau^+ \to e^+ \nu_\tau \bar{\nu}_e$	$\tau^+ \to \pi^+ \nu_\tau$	$\tau^+ \to \rho^+ \nu_\tau$
$p^*_{\ell_{\rm tag}}$	$p^*_{\ell_{\rm tag}} > 0.3$ GeV			
$p^*_{\rm sig}$	$p^*_{\ell_{\rm sig}} > 0.3$ GeV			
$p^*_{D^{(*)}_{\rm tag}}$	$p^*_{D^{(*)}_{\rm tag}} < 2.5$ GeV			
$dr_{\rm sig}$	$dr < 2$ cm			
$dz_{\rm sig}$	$dz < 4$ cm			
$\mathcal{N}_{\rm tag}$	$\mathcal{N}_{\rm tag} > 0.0066$	$\mathcal{N}_{\rm tag} > 0.0075$	$\mathcal{N}_{\rm tag} > 0.02$	$\mathcal{N}_{\rm tag} > 0.009$
$\cos\theta_{B,D^{(*)}\ell}$	$-1.7 < \cos\theta_{B,D^{(*)}\ell} < 1$	$-1.9 < \cos\theta_{B,D^{(*)}\ell} < 1$	$-1.3 < \cos\theta_{B,D^{(*)}\ell} < 1$	$-2.6 < \cos\theta_{B,D^{(*)}\ell} < 1$
$\mathrm{PID}_{\pi/K,\rm sig}$			$\mathrm{PID}_{\pi/K,\rm sig} > 0.2$	$\mathrm{PID}_{\pi/K,\rm sig} > 0.6$
$M_{\pi^+\pi^0}$				$\lvert M_{\pi^+\pi^0} - m_{\rho^+}\rvert < 0.195$ GeV
$\mathcal{N}_{\rm cs}$	$\mathcal{N}_{\rm cs} > -0.5$	$\mathcal{N}_{\rm cs} > -0.5$	$\mathcal{N}_{\rm cs} > 0.75$	$\mathcal{N}_{\rm cs} > 0$
$M_{\ell_{\rm sig}X}$	$M_{\ell_{\rm sig}X} > 0.2$ GeV			
$M_{\ell_{\rm tag}X}$	$M_{\ell_{\rm tag}X} > 0.2$ GeV			

(3) $B^+ \rightarrow \tau^+ \nu_\tau$: semileptonic

Final State	$e^+\nu_e\bar{\nu}_\tau$	$\mu^+\nu_\mu\bar{\nu}_\tau$	$\pi^+\bar{\nu}_\tau$	$\pi^+\pi^0\bar{\nu}_\tau$
$e^+\nu_e\bar{\nu}_\tau$	6.6 ± 0.1	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0
$\mu^+\nu_\mu\bar{\nu}_\tau$	0.1 ± 0.0	4.7 ± 0.1	0.6 ± 0.0	0.2 ± 0.0
$\pi^+\bar{\nu}_\tau$	0	0.1 ± 0.0	1.6 ± 0.0	0.5 ± 0.0
$\pi^+\pi^0\bar{\nu}_\tau$	0	0.1 ± 0.0	1.4 ± 0.0	4.9 ± 0.1
$\pi^+\pi^0\pi^0\bar{\nu}_\tau$	0	0	0.2 ± 0.0	1.3 ± 0.0
Other	0	0	0.1 ± 0.0	0.2 ± 0.0
All	6.8 ± 0.1	5.1 ± 0.1	4.0 ± 0.0	7.2 ± 0.1
Total	23.1 ± 0.1			

Row : Generated
Column : Reconstructed
Off-diagonal : cross-feeds

(3) $B^+ \to \tau^+ \nu_\tau$: semileptonic

TABLE III. List of systematic uncertainties.

Source	Relative Uncertainty (%)
Continuum description	14.1
Signal reconstruction efficiency	0.6
Background branching fractions	3.1
Efficiency calibration	12.6
τ decay branching fractions	0.2
Histogram PDF shapes	8.5
Best candidate selection	0.4
Charged track reconstruction	0.4
π^0 reconstruction	1.1
Particle identification	0.5
Charged track veto	1.9
Number of $B\bar{B}$ pairs	1.4
Total	21.2

(6) $B^+ \to l^+ \nu_l \gamma$

Most stringent upper limits !!

	Nominal analysis with $E_\gamma^{sig} > 1\,\mathrm{GeV}$						
	MC expectation			Data measurement			
Mode	Yield	Significance (σ)	$\mathcal{B}$ limit (10^{-6})	Yield	$\mathcal{B}$ (10^{-6})	Significance (σ)	$\mathcal{B}$ limit (10^{-6})
$B^+ \to e^+\nu_e\gamma$	$8.0 \pm 4.5\ ^{+1.0}_{-1.3}$	2.1	< 7.5	$6.1^{+4.9}_{-3.9}{}^{+1.0}_{-1.3}$	$3.8^{+3.0}_{-2.4}{}^{+0.7}_{-0.9}$	1.7	< 6.1
$B^+ \to \mu^+\nu_\mu\gamma$	$8.7 \pm 4.6\ ^{+1.0}_{-1.5}$	2.2	< 6.9	$0.9^{+3.6}_{-2.6}{}^{+1.0}_{-1.5}$	$0.6^{+2.1}_{-1.5}{}^{+0.7}_{-1.1}$	0.4	< 3.4
$B^+ \to \ell^+\nu_\ell\gamma$	$16.5 \pm 6.5\ ^{+1.6}_{-2.2}$	2.9	< 4.8	$6.6^{+5.7}_{-4.7}{}^{+1.6}_{-2.2}$	$2.0^{+1.7}_{-1.4}{}^{+0.6}_{-0.7}$	1.4	< 3.5

	Secondary analysis with $E_\gamma^{sig} > 400\,\mathrm{MeV}$						
	MC expectation			Data measurement			
Mode	Yield	Significance (σ)	$\mathcal{B}$ limit (10^{-6})	Yield	$\mathcal{B}$ (10^{-6})	Significance (σ)	$\mathcal{B}$ limit (10^{-6})
$B^+ \to e^+\nu_e\gamma$	$12.4 \pm 6.2\ ^{+1.8}_{-2.3}$	2.1	< 6.8	$11.9^{+7.0}_{-6.0}{}^{+1.8}_{-2.3}$	$4.9^{+2.9}_{-2.5}{}^{+0.8}_{-1.0}$	2.0	< 9.3
$B^+ \to \mu^+\nu_\mu\gamma$	$11.9 \pm 6.0\ ^{+1.7}_{-2.1}$	2.2	< 6.2	$-0.1^{+5.2}_{-4.1}{}^{+1.7}_{-2.1}$	-	-	< 4.3
$B^+ \to \ell^+\nu_\ell\gamma$	$24.9 \pm 8.7\ ^{+3.0}_{-3.5}$	2.9	< 4.3	$11.3^{+8.4}_{-7.4}{}^{+3.0}_{-3.5}$	$2.3^{+1.7}_{-1.5}{}^{+0.7}_{-0.8}$	1.4	< 5.1