Experimental mini-review on leptonic B decays

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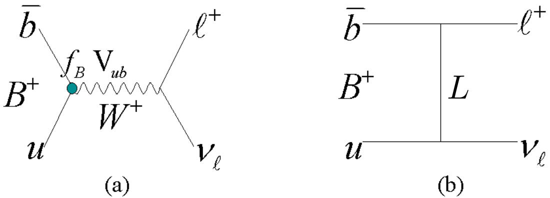
WG 2 @ CKM 2016, TFIR, Mumbai

Outline

- Motivations and features
  - To tag, or not to tag
- $B^+ \to \tau^+\nu$
- $B^+ \to \ell^+\nu(\gamma)$
- Prospects (Belle II)

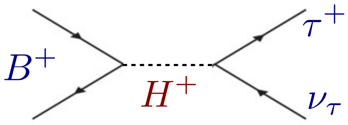
Motivations for $B^+ \to \ell^+ \nu$



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

- very clean place to measure $f_B |V_{ub}|$ and/or search for new physics (e.g. H^+, LQ)
- but, helicity-suppressed: $\Gamma \propto m_\ell^2$
  $\Gamma(B^+ \to e^+ \nu) \ll \Gamma(B^+ \to \mu^+ \nu) \ll \Gamma(B^+ \to \tau^+ \nu)$

$B^+ \to \tau^+\nu$ by new physics, e.g. H^+



- $B^+ \to \tau^+\nu$ can be affected by new physics effects
  For instance, H^+ of 2-Higgs doublet model (type II)

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

where $r_H = \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$ W.S. Hou, PRD 48, 2342 (1993)

- The ratio $\mathcal{B}(B^+ \to \tau^+\nu)/\mathcal{B}(B^+ \to \ell^+\nu)$ can be a very powerful test of lepton flavor universality.
  "*It's worth to look for LFU breaking effects in $B \to \tau\nu$ and $B \to K\tau\tau$*" by P. Paradisi @ CKM 2016

Features of $B^+ \to \ell^+\nu$

SM predictions

- $\mathcal{B}(B^+ \to \tau^+\nu) \sim 10^{-4}$
- $\mathcal{B}(B^+ \to \mu^+\nu) \sim \mathcal{B}(B^+ \to \tau^+\nu)/300$
- $\mathcal{B}(B^+ \to e^+\nu) \sim \mathcal{B}(B^+ \to \tau^+\nu)/10^7$

Experimental features

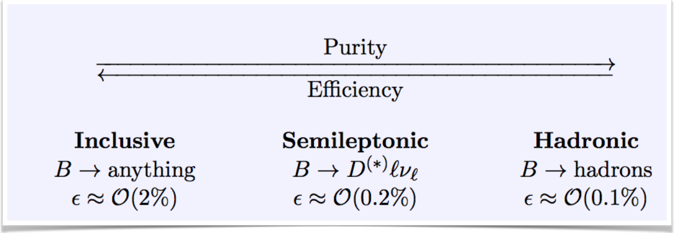
- $B^+ \to \tau^+\nu$ large BF, but multiple ν's
- $B^+ \to \ell^+\nu$ $(\ell \neq \tau)$ $E_\ell \sim M_B/2$, but small BF

To tag, or not to tag

- Why bother?
  - $B^+ \to \tau^+\nu$ has multiple ν's in the final state
  - need extra kinematic constraints to improve sensitivity
  - exploit $\Upsilon(4S)$ producing $B\bar{B}$ and nothing else

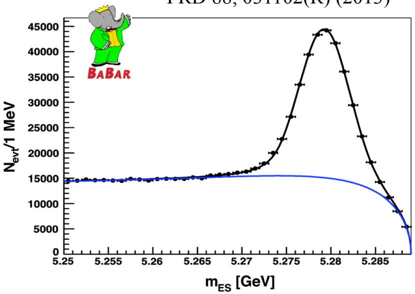
$$e^+e^- \to \Upsilon(4S) \to B_{\rm sig}\overline{B}_{\rm tag}$$

- How to tag?
  - "**hadronic tagging**" – full reconstruction of the decay chain of $B_{\rm tag}$
  - "**semileptonic tagging**" – use $B^+ \to \overline{D}^{(*)}\ell^+\nu$



$B^+ \to \tau^+\nu$ by hadronic B-tagging

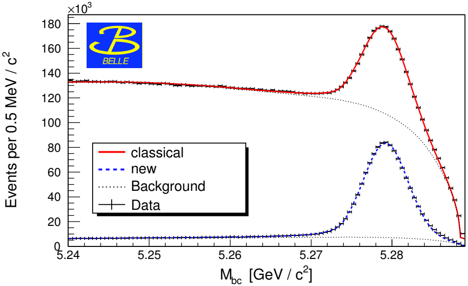
PRD 88, 031102(R) (2013)



Full-recon. B sample
for $B^+ \to \tau^+\nu$ analysis

"NeuroBayes"

M. Feindt, *et al.*, NIM A 654, 432 (2011)

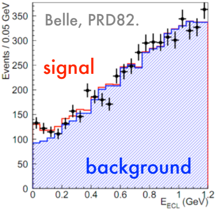


Full-recon. B^+ sample
Old vs. **New** @ same efficiency

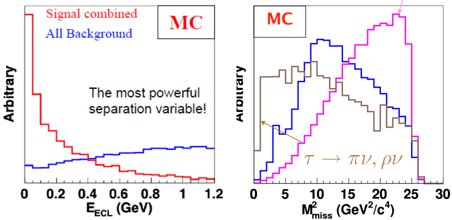
$B^+ \to \tau^+ \nu$ (Belle, had) – signal extraction

- Signal τ modes: $\tau^+ \to e^+ \nu_e \overline{\nu}_\tau,\ \mu^+ \nu_\mu \overline{\nu}_\tau,\ \pi^+ \overline{\nu}_\tau,\ \rho^+ \overline{\nu}_\tau$
- π^0, K_L^0 veto – demand no trace of π^0, K_L^0 after reconstructing $B_{\rm tag}$ and $B_{\rm sig}$
  - K_L^0 gives $\sim 5\%$ improvement in the expected sensitivity
- 2D fitting to $E_{\rm ECL}$ & $M^2_{\rm miss}$
  - improve sensitivity by $\sim 20\%$; more robust against peaking backgs. in $E_{\rm ECL}$

previous analyses
($E_{\rm ECL}$ only)



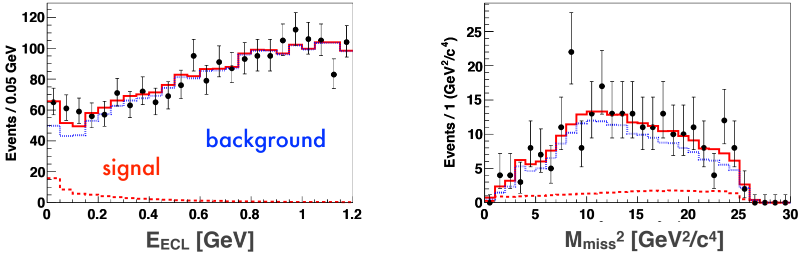
■ ***The fitting variables***



$E_{\rm ECL}$ = residual energy in the EM calorimeter (ECL) that has not been attributed to either $B_{\rm sig}$ or $B_{\rm tag}$

$B^+ \to \tau^+\nu$ (Belle, had) – Result

- Simultaneous fit to different τ decay modes
  Figures below shown for the sum of different τ decay modes

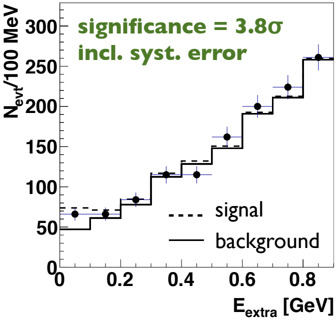


(Projection for all M_{miss}^2 region.) (Projection for E_{ECL} < 0.2 GeV)

- Signal yield: $62^{+23}_{-22} \pm 6$ significance = 3.0σ incl. systematic error
  Major sources of systematic error are: background PDF (8.8%), K_L^0 efficiency (7.3%), and $B_{\rm tag}$ efficiency (7.1%).
- $\mathcal{B}(B^+ \to \tau^+\nu) = \left(0.72^{+0.27}_{-0.25} \pm 0.11\right) \times 10^{-4}$ PRL 110, 131801 (2013)

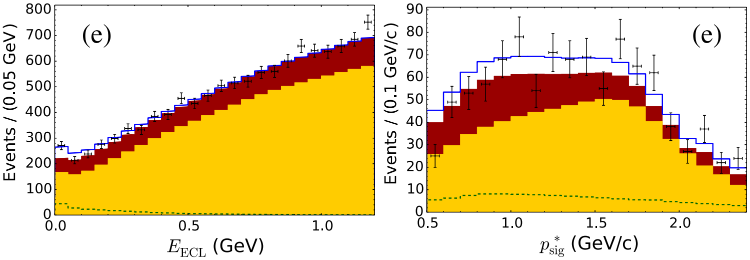
$B^+ \to \tau^+\nu$ (BaBar, had) – Result

- Hadronic B-tagging analysis with $N_{B\bar{B}} = 468 \times 10^6$
- Signal τ modes: $\tau^+ \to e^+\nu_e\overline{\nu}_\tau,\ \mu^+\nu_\mu\overline{\nu}_\tau,\ \pi^+\overline{\nu}_\tau,\ \rho^+\overline{\nu}_\tau$
- Signal extraction via $E_{\rm extra}$ $(= E_{\rm ECL})$ $N_{\rm sig} = 62.1 \pm 17.3$ from simultaneous fit to the four τ modes
- $\mathcal{B}(B^+ \to \tau^+\nu) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$
- Major systematic uncertainties are from background PDF's (10%), B-tag efficiency (5%), etc.



PRD 88, 031102(R) (2013)

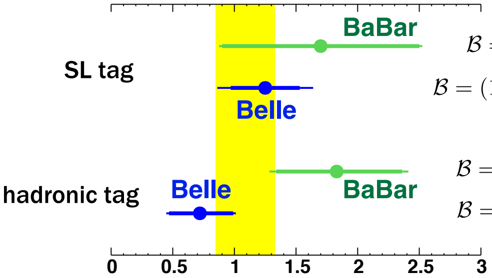
$B^+ \to \tau^+\nu$ (Belle, SL-tag)



- tagged by $B^- \to D^{(*)0}\ell^-\overline{\nu}$
- Signal extraction by 2D-fitting $(E_{\rm ECL}, p^*_{\rm sig})$
  $N_{\rm sig} = 222 \pm 50$ events
- $\mathcal{B}(B^+ \to \tau^+\nu) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$
  4.6σ significance by combining had-tag and SL-tag analyses of Belle

PRD 92, 051102(R) (2015)

$B^+ \to \tau^+\nu$ Summary



$\mathcal{B} = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$

$\mathcal{B} = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$

$\mathcal{B} = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$

$\mathcal{B} = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$

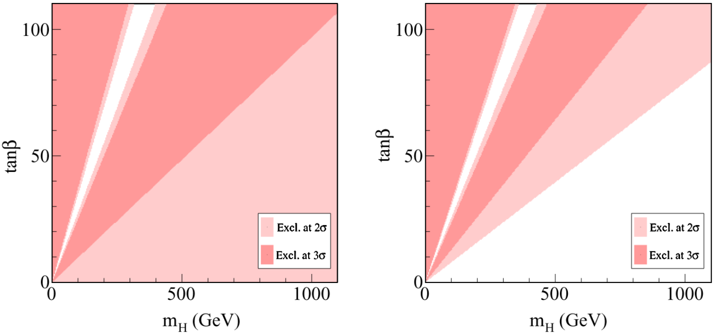
Belle combined: $\mathcal{B}(B^+ \to \tau^+\nu) = (0.91 \pm 0.22) \times 10^{-4}$
BaBar combined: $\mathcal{B}(B^+ \to \tau^+\nu) = (1.79 \pm 0.48) \times 10^{-4}$
World average: $\mathcal{B}(B^+ \to \tau^+\nu) = (1.09 \pm 0.24) \times 10^{-4}$

- Belle vs. BaBar – consistent within $\sim 1.7\sigma$
- The average is consistent with SM

$B^+ \to \tau^+\nu$ constraints on charged Higgs

- With 2-Higgs doublet model (type II),

  $\mathcal{B}(B^+ \to \tau^+\nu) = \mathcal{B}_{\mathrm{SM}}(B^+ \to \tau^+\nu) \times \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$



Plots are from PRD 88, 031102(R) (2013), by BaBar, based on BaBar's combined $\mathcal{B}(B^+ \to \tau^+\nu)$.

Search for $B^+ \to \ell^+\nu$

- (*experimental*) very clean
  - just a mono-energetic charged lepton and nothing else
- (*theoretical*) very small branching fraction compared to $B^+ \to \tau^+\nu$
  - helicity suppression: $\Gamma \propto m_\ell^2$
- Tagged vs. Untagged for $B^+ \to \ell^+\nu$,
  - tagging is not really necessary $\because$ mono-energetic ℓ^+ in the final state
  - Nonetheless, analyses with tagging have also been tried

$\Gamma(B^+ \to e^+\nu_e)/\Gamma_{total}$

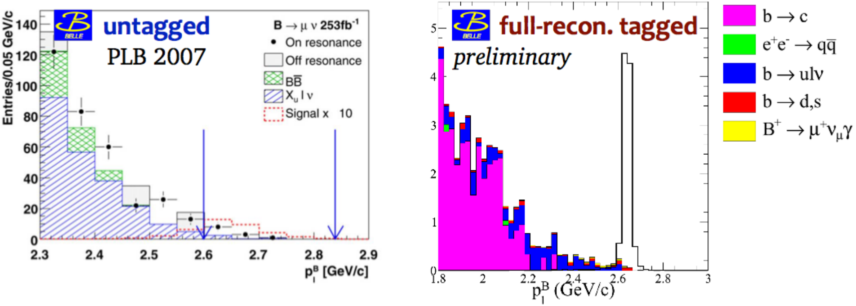
VALUE (10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT	
< 0.98	90	[1] SATOYAMA 2007	BELL	$e^+ e^- \to \Upsilon(4S)$	untagged
*** We do not use the following data for averages, fits, limits, etc ***					
<3.5	90	[2] YOOK 2015	BELL	$e^+ e^- \to \Upsilon(4S)$	had tag
<8	90	[1] AUBERT 2010E	BABR	$e^+ e^- \to \Upsilon(4S)$	SL tag
<1.9	90	[1] AUBERT 2009V	BABR	$e^+ e^- \to \Upsilon(4S)$	untagged
<5.2	90	[1] AUBERT 2008AD	BABR	$e^+ e^- \to \Upsilon(4S)$	had tag

$\Gamma(B^+ \to \mu^+\nu_\mu)/\Gamma_{total}$

	VALUE (10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
untagged	**< 1.0**	90	[1] AUBERT 2009V	BABR	$e^+ e^- \to \Upsilon(4S)$
	*** We do not use the following data for averages, fits, limits, etc ***				
had tag	<2.7	90	[2] YOOK 2015	BELL	$e^+ e^- \to \Upsilon(4S)$
SL tag	<11	90	[1] AUBERT 2010E	BABR	$e^+ e^- \to \Upsilon(4S)$
had tag	<5.6	90	[1] AUBERT 2008AD	BABR	$e^+ e^- \to \Upsilon(4S)$
untagged	<1.7	90	[1] SATOYAMA 2007	BELL	$e^+ e^- \to \Upsilon(4S)$

Why then bother with 'tagged' for $B^+ \to \ell^+\nu$?

- The signal lepton candidate's momentum in B_{sig} rest frame. -

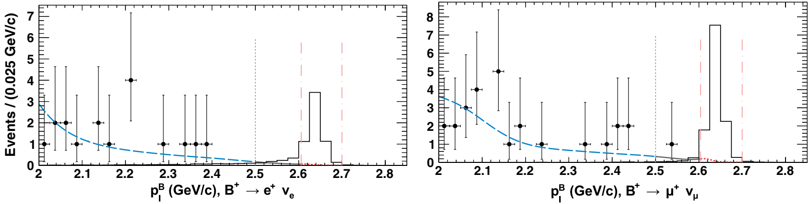


- much better resolution of p_ℓ^B with the full-recon. tagging
- But, does it make a case for 'full-recon-tagged' analysis of $B^+ \to \ell^+\nu$?

Why then bother with 'tagged' for $B^+ \to \ell^+\nu$?

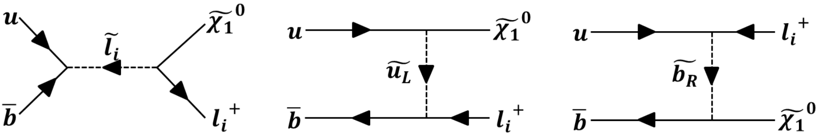
- Note: $\mathcal{B}_{\rm SM}(B^+ \to e^+\nu) \sim 10^{-11}$ and $\mathcal{B}_{\rm SM}(B^+ \to \mu^+\nu) \sim 3 \times 10^{-7}$
  $\Rightarrow$ Any signal for $B^+ \to e^+\nu$ at the Belle sensitivity is way beyond the SM
- In that case, are we *sure* what we see is *really* $B^+ \to e^+\nu$?
  What about $B^0 \to e^+\tau^-$? How about $B^+ \to e^+X^0$ where X^0 is any unknown particle from NP?
- With full-recon., we can use p_ℓ^B to discern many such cases
- Belle analysis with hadronic B-tagging

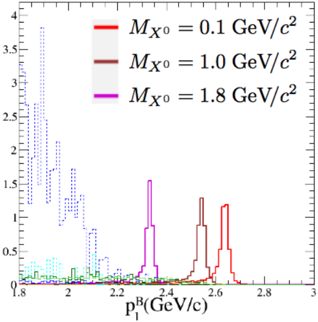
PRD 91, 052016 (2015)



Mode	ϵ_s [%]	$N_{\rm obs}$	$N_{\rm exp}^{\rm bkg}$	$\mathcal{B}$ (in 10^{-6})
$B^+ \to e^+\nu_e$	0.086 ± 0.007	0	0.10 ± 0.04	**< 3.5**
$B^+ \to \mu^+\nu_\mu$	0.102 ± 0.008	0	$0.26^{+0.09}_{-0.08}$	**< 2.7**

$B^+ \to \ell^+ X^0$ (Belle)



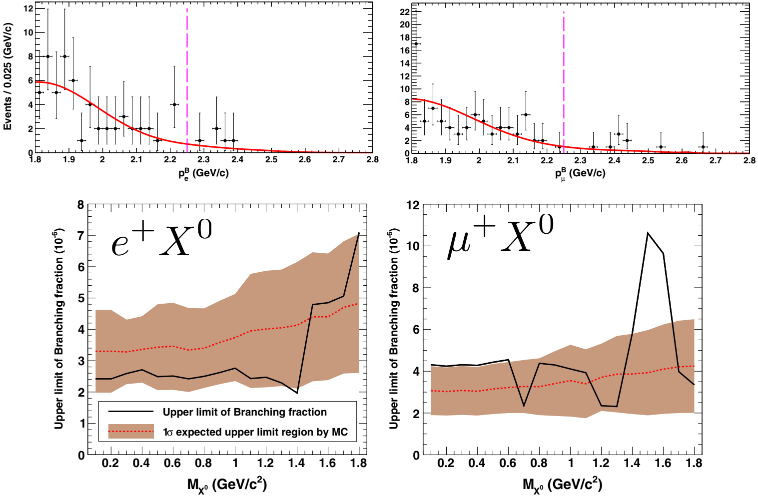


- Search for massive neutral invisible fermion “X^0”

  a heavy neutrino, or an LSP in RPV models, or whatever

- Very similar experimental signature to $B^+ \to \ell^+ \nu$
- But, p_ℓ^B gives a handle on M_X

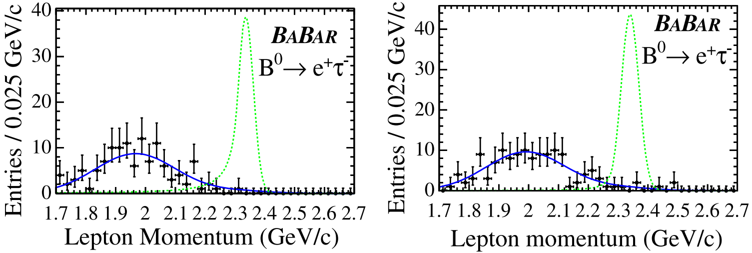
$B^+ \to \ell^+ X^0$ (Belle)



PRD 94, 012003 (2016)

$B^0 \to \ell^\pm \tau^\mp$ (BaBar)

PRD 77, 091104(R) (2008)



- In a hadronic B-tagging analysis very similar to $B^+ \to \ell^+\nu$, BaBar also searched for $B^0 \to \ell^\pm\tau^\mp$.
- Background suppression using $m_{\rm ES}$ and $E_{\rm extra}$
- Signal extraction by unbinned max. likelihood fit to p_ℓ^B

$$\mathcal{B}(B^0 \to e^\pm\tau^\mp) < 2.8 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \mu^\pm\tau^\mp) < 2.2 \times 10^{-5}$$

$B^+ \to \ell^+ \nu \gamma$

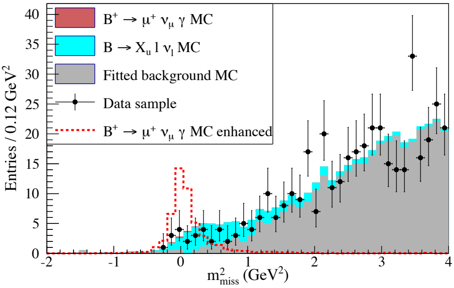
- Helicity suppression (of $B^+ \to \ell^+ \nu$) is avoided by γ.

$$\Gamma(B^+ \to \ell^+ \nu \gamma) \propto \frac{\alpha_{\rm EM}(G_{\rm F} m_B^2 |V_{ub}| f_B)^2}{\lambda_B^2}$$

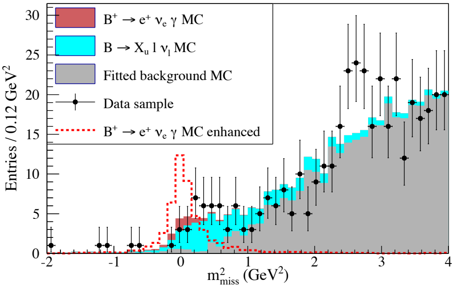
- λ_B is needed for QCDF to calculate, e.g., charmless hadronic B decays
- SM expectation: $\mathcal{B}(B^+ \to \ell^+ \nu \gamma) \sim \mathcal{O}(10^{-6})$
  - Calculation is reliable only for $E_\gamma > 1$ GeV
- Most stringent limits from Belle (2015) with hadronic B-tagging
  - using neural net to suppress the most significant background $B^+ \to \pi^0 \ell^+ \nu$

$B^+ \to \ell^+\nu\gamma$ (Belle)

PRD 91, 112009 (2015)



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



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

Enhanced signal MC portions in the figures correspond to $\mathcal{B} = 30 \times 10^{-6}$.

$B^+ \to \ell^+\nu\gamma$ (Belle)

PRD 91, 112009 (2015)

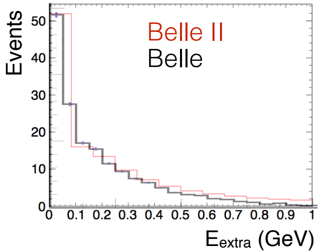
- Signal yields and partial $\mathcal{B}$ for $E_\gamma > 1$ GeV

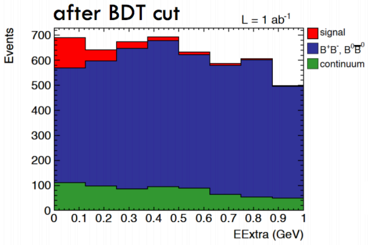
Mode	Signal yield	$\mathcal{B}$ (10^{-6})	Significance (σ)	$\mathcal{B}$ limit (10^{-6})
$B^+ \to e^+\nu_e\gamma$	$6.1\,^{+4.9}_{-3.9}\,^{+1.0}_{-1.3}$	$3.8\,^{+3.0}_{-2.4}\,^{+0.7}_{-0.9}$	1.7	< 6.1
$B^+ \to \mu^+\nu_\mu\gamma$	$0.9\,^{+3.6}_{-2.6}\,^{+1.0}_{-1.5}$	$0.6\,^{+2.1}_{-1.5}\,^{+0.7}_{-1.1}$	0.4	< 3.4
$B^+ \to \ell^+\nu_\ell\gamma$	$6.6\,^{+5.7}_{-4.7}\,^{+1.6}_{-2.2}$	$2.0\,^{+1.7}_{-1.4}\,^{+0.6}_{-0.7}$	1.4	< 3.5

- From the partial $\mathcal{B}$, we set $\lambda_B(E_\gamma > 1\text{ GeV}) > 238$ MeV
  By varying input parameters, we obtain $\lambda_B > (172, 410)$ MeV
- 2nd analysis with looser cut ($E_\gamma > 0.4$ GeV) also gives no signal and consistent results

BaBar result: $\mathcal{B}(B^+ \to \ell^+\nu\gamma) < 15.6 \times 10^{-6}$, PRD 80, 111105(R) (2009)

$B^+ \to \tau^+\nu$ Prospects for Belle II



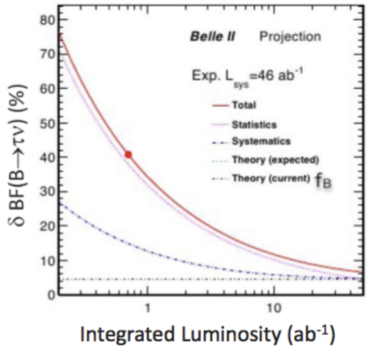


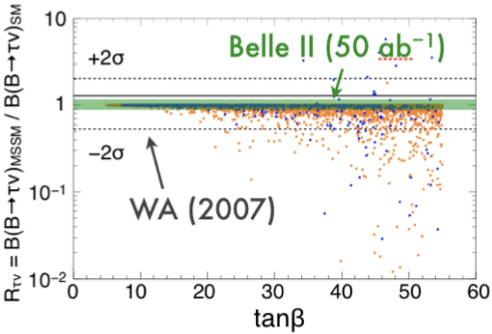
Plots & tables by A. Zupanc (Belle II)

- Eextra is crucial for B ➔ τν study
  - In Belle II, beam background is much higher
  - But these can be rejected by selection based on ECL cluster's energy, timing, shape, etc.
- Expected precision at 1 ab^{-1} ~ 27%
- Major systematic sources (bkg. PDF, K_L veto eff., B_{tag} eff.) can be improved with more data

Eextra < 1	BaBar had. (2013)	Belle had. (2013)	Belle II MC study
signal effic. (%)	0.72	1.1	1.6

$B^+ \to \tau^+\nu$ Prospects for Belle II



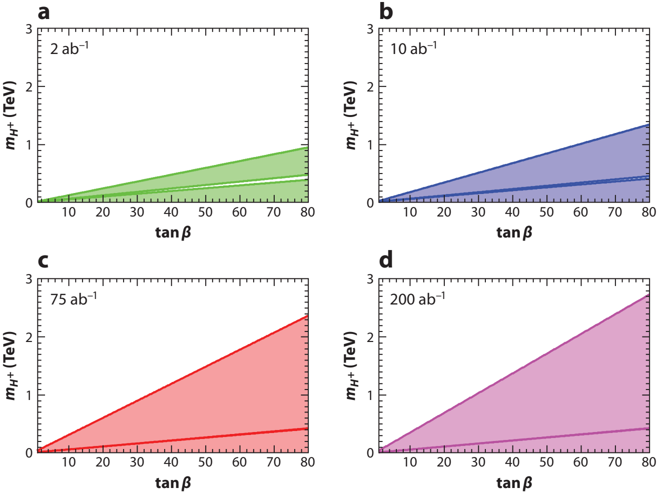


Expected precision with $\int \mathcal{L}\, dt = 50\ (5)\ \mathrm{ab}^{-1}$

- $\mathcal{B}(B^+ \to \tau^+\nu)$: 5% (10%)
- $\mathcal{B}(B^+ \to \mu^+\nu)$: 7% (20%)

$B^+ \to \tau^+\nu$ Prospects for Belle II

from Ciuchini & Stocchi, Ann. Rev. Nucl. Part. Sci. 61 (2011) 491

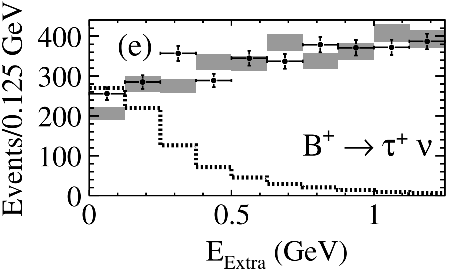


Concluding Remarks

- Leptonic B decays, in particular $B^+ \to \ell^+ \nu$ $(\ell = e, \mu, \tau)$, provide powerful probe for new physics beyond the SM.
- $B^+ \to \tau^+ \nu$ decays have been measured at nearly 5σ significance, and new physics models such as 2HDM (II) have been tested.
- With hadronic B-tagging, Belle has searched for *invisible, massive, lepton-like neutral* particle X^0 in $B^+ \to \ell^+ X^0$ for the first time.
- Belle II with $\int \mathcal{L}\, dt = 50\ \mathrm{ab}^{-1}$ branching fractions for $B^+ \to \tau^+ \nu$ $(B^+ \to \mu^+ \nu)$ are expected to be measured with precision of $5\ (7)\%$.

Back-up slides

$B^+ \to \tau^+\nu$ (BaBar, SL-tag)

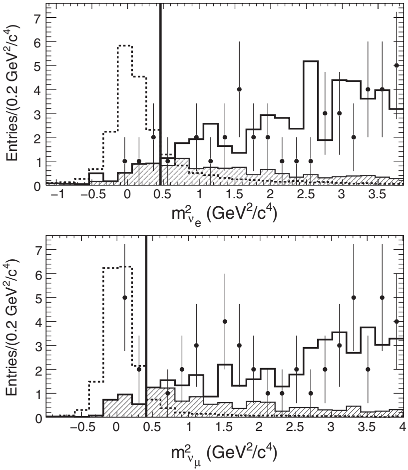


- tagged by $D^0\ell^-\nu X$ (X, not explicitly reconstructed)
- Count events in E_{extra} signal region
  $N_{\text{obs}} = 583$ events, with $N_{\text{bg}} = 509 \pm 30$ events
- $\mathcal{B}(B^+ \to \tau^+\nu) = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$

PRD 81, 051101(R) (2010)

$B^+ \to \ell^+\nu\gamma$ (BaBar)

PRD 80, 111105(R) (2009)



- hadronic B-tagging
- $N_{BB} = 465 \times 10^6$
- Signal counting in M^2_{miss} for $e\nu\gamma$ $(\mu\nu\gamma)$
  - $-1 < M^2_{\text{miss}} < 0.46$ (0.41) GeV$^2/c^4$
  - 4 (7) events observed
  - with 2.7 ± 0.6 (3.4 ± 1.0) background events
- Results

  $\mathcal{B}(B^+ \to \ell^+\nu\gamma) < 15.6 \times 10^{-6}$

  $\Rightarrow \lambda_B > 0.3$GeV @ 90% CL