ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Review of B_u leptonic decays

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Flavor Physics and CP Violation Conference
Bled, May 12-16, 2007

Summary

- $B \to \ell \nu_\ell$
  - Motivation
  - $B \to \tau \nu_\tau$
    - ➔ Belle's analysis
    - ➔ BaBar's analyses: semileptonic and hadronic tags
    - ➔ Constraints on charged Higgs
    - ➔ future prospects
  - $B \to e \nu_e$, $B \to \mu \nu_\mu$ at Belle and BaBar
- $B \to \ell \nu_\ell \gamma$
- Summary of results

HOT AT FPCP07

I will assume you all know what Belle, BaBar, CLEO, M_{bc}, m_{ES}, ΔE are...

$$B^+ \to \ell^+ \nu_\ell$$

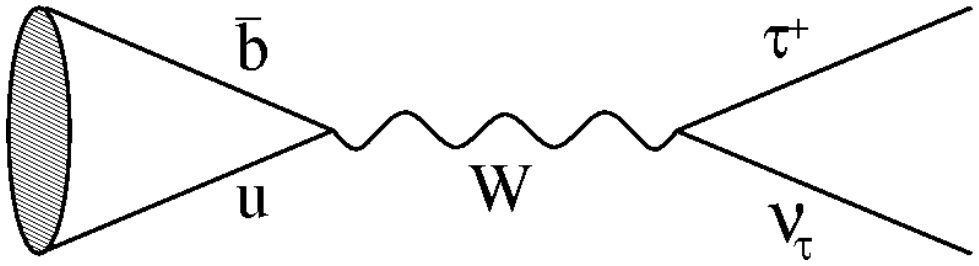
$B^+ \to \ell^+ \nu_\ell$: motivation

SM:

B lifetime

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

Direct Measurement of decay constant f_B!



- **BF($B \to \tau \nu_\tau$) ≃ 1.6 x 10^{-4} in SM**
- Other $\ell \nu_\ell$ modes are helicity suppressed ~$(m_\ell)^2$:

  BF($B \to \mu \nu_\mu$) ~ 4.7 x 10^{-7}

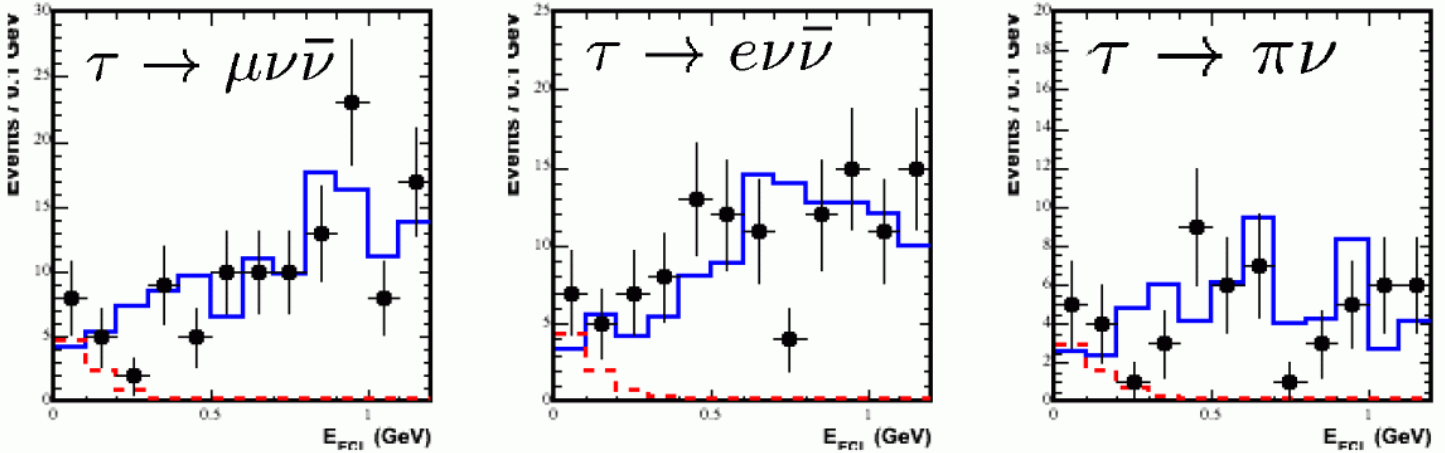
  BF($B \to e \nu_e$) ~ 1.1 x 10^{-11}

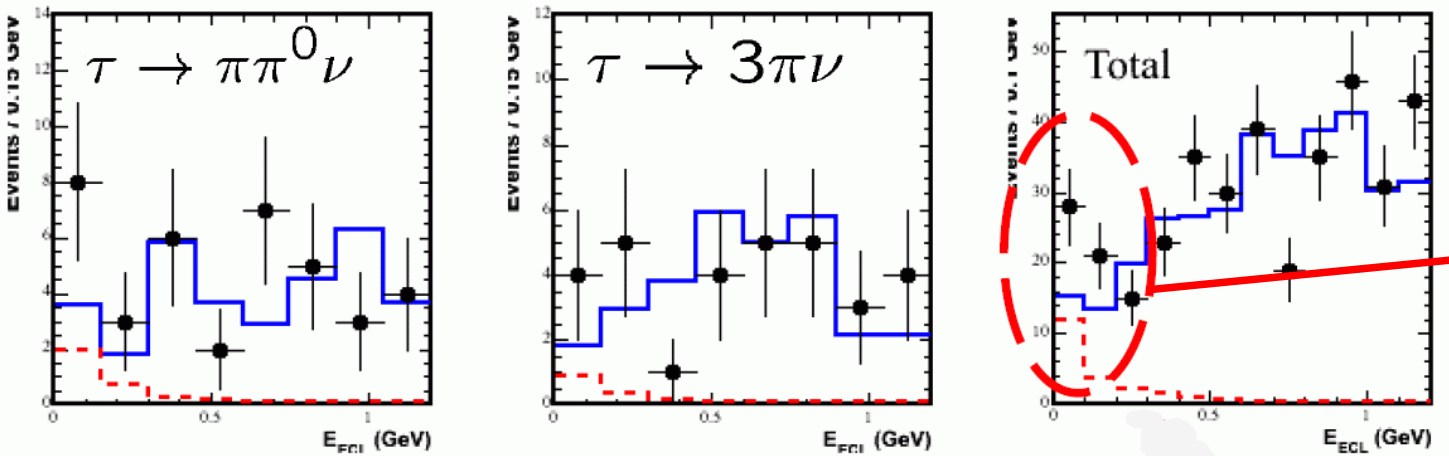
BSM: Possible enhancements of BF in New Physics:
- Charged Higgs models: can explore the (M_H, tanβ) plane.

Theoretically very clean, experimentally difficult: 1 neutrino for e, μ, 2 or more for τ mode: must reconstruct the other side B!

$B^+ \to \tau^+ \nu_\tau$ at Belle: analysis

- Reconstruct the companion B in exclusive $\bar{D}^{(*)0} h^+$ and $\bar{D}^{(*)0} D^{(*)+}_s$ channels to get a pure (55%) B^+B^- sample (6.8×10^5 evts)
- Reconstruct signal from remaining particles in the event
- τ lepton reconstructed in 5 decay modes (81% of all modes)
- Final selection based on remaining energy in ECL: $E_{ECL} \cong 0$ for signal





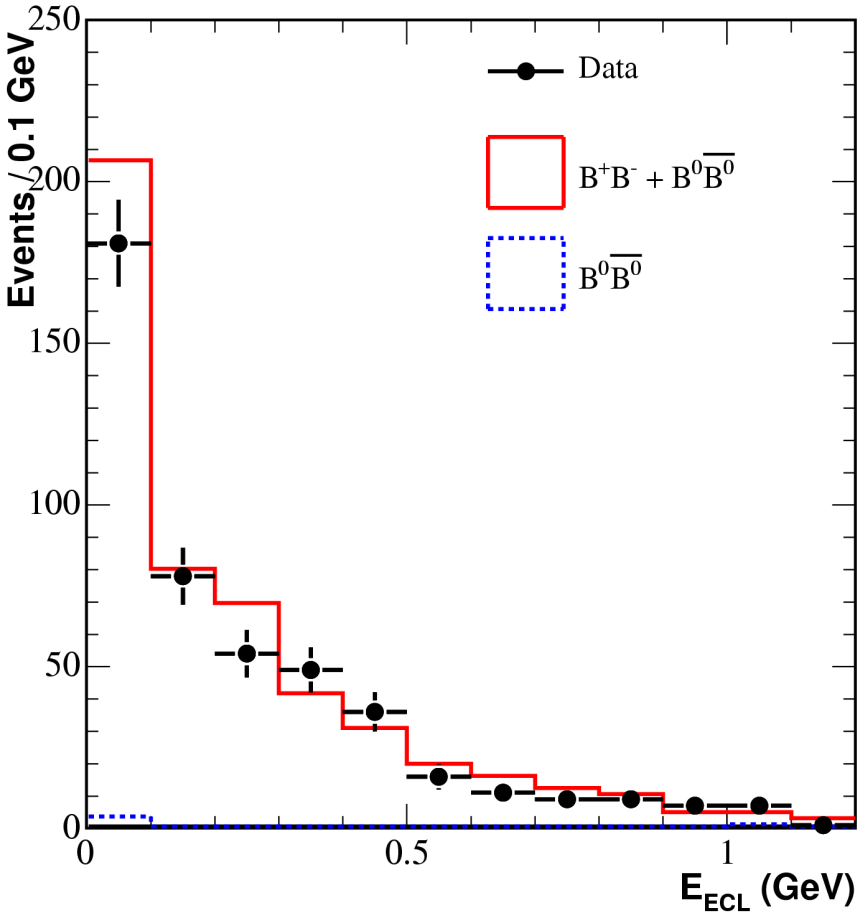
PRL 97, 251802 (2006)

Dataset: 414 fb^{-1}

Excess of events visible in the signal region!

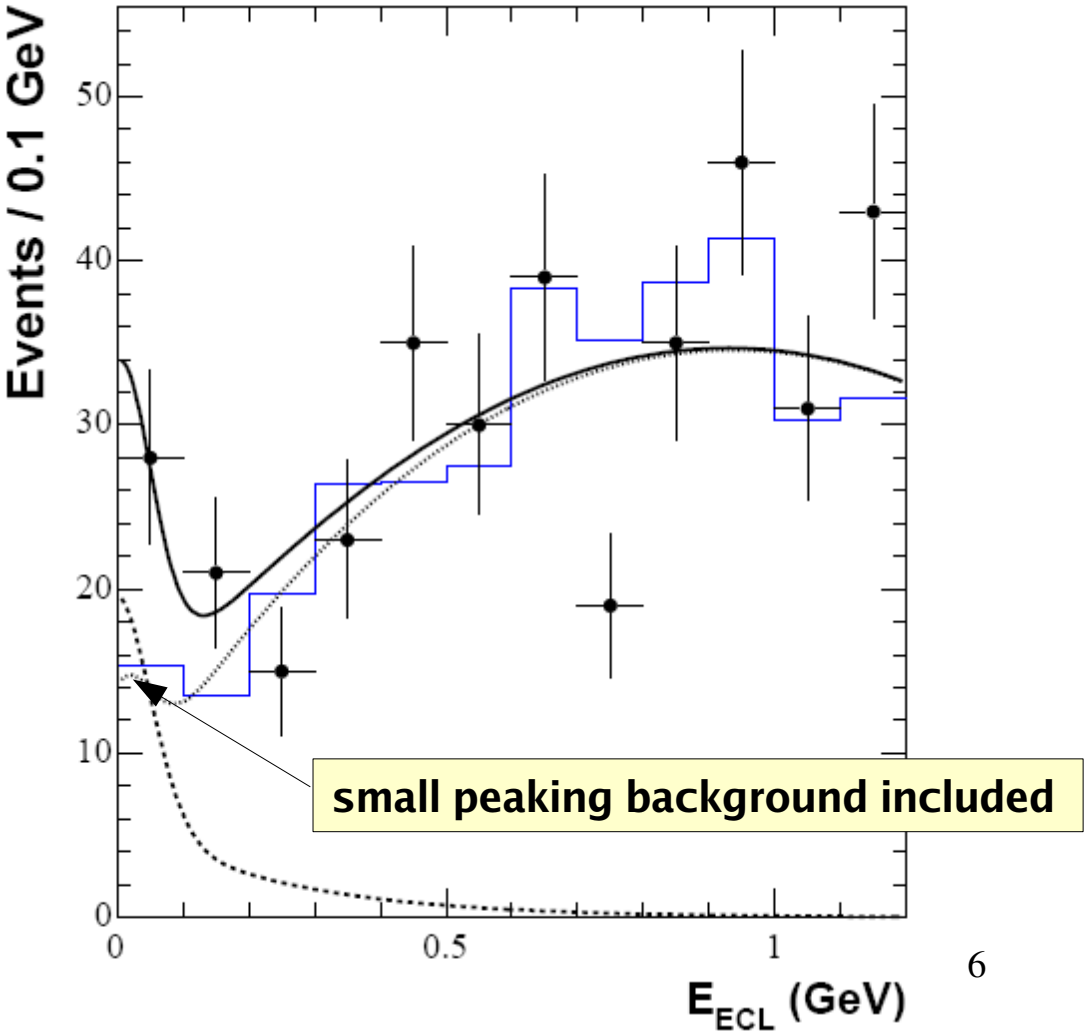
$B^+ \to \tau^+ \nu_\tau$ at Belle: the fit

To validate the E_{ECL} cut, use a control sample of double tagged events: B_{sig} substituted by $B \to D^{*0} \ell \nu$:



FIT RESULT:

signal
background
total



$B^+ \to \tau^+ \nu_\tau$ at Belle: results

	N_{obs}	N_s	N_b	Σ
$\mu^- \bar{\nu}_\mu \nu_\tau$	13	$5.6^{+3.1}_{-2.8}$	$8.8^{+1.1}_{-1.1}$	2.2σ
$e^- \bar{\nu}_e \nu_\tau$	12	$4.1^{+3.3}_{-2.6}$	$9.0^{+1.1}_{-1.1}$	1.4σ
$\pi^- \nu_\tau$	9	$3.8^{+2.7}_{-2.1}$	$3.9^{+0.8}_{-0.8}$	2.0σ
$\pi^- \pi^0 \nu_\tau$	11	$5.4^{+3.9}_{-3.3}$	$5.4^{+1.6}_{-1.6}$	1.5σ
$\pi^- \pi^+ \pi^- \nu_\tau$	9	$3.0^{+3.5}_{-2.5}$	$4.8^{+1.4}_{-1.4}$	1.0σ

Total significance:

3.5 σ

First evidence of a purely leptonic B decay

systematics included

***BELLE* result**

$BF(B \to \tau \nu_\tau) = (1.79^{+0.56}_{-0.49}\,(stat)^{+0.46}_{-0.51}\,(syst)) \times 10^{-4}$

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

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

SM:

$BF(B \to \tau \nu_\tau) = (1.59 \pm 0.40) \times 10^{-4}$

$f_B = 0.216 \pm 0.022$ GeV

from lattice QCD:
HPQCD, Phys. Rev. Lett. 95, 212001 (2005)

First direct determination of f_B

$B^+ \to \tau^+ \nu_\tau$: constraints on BSM

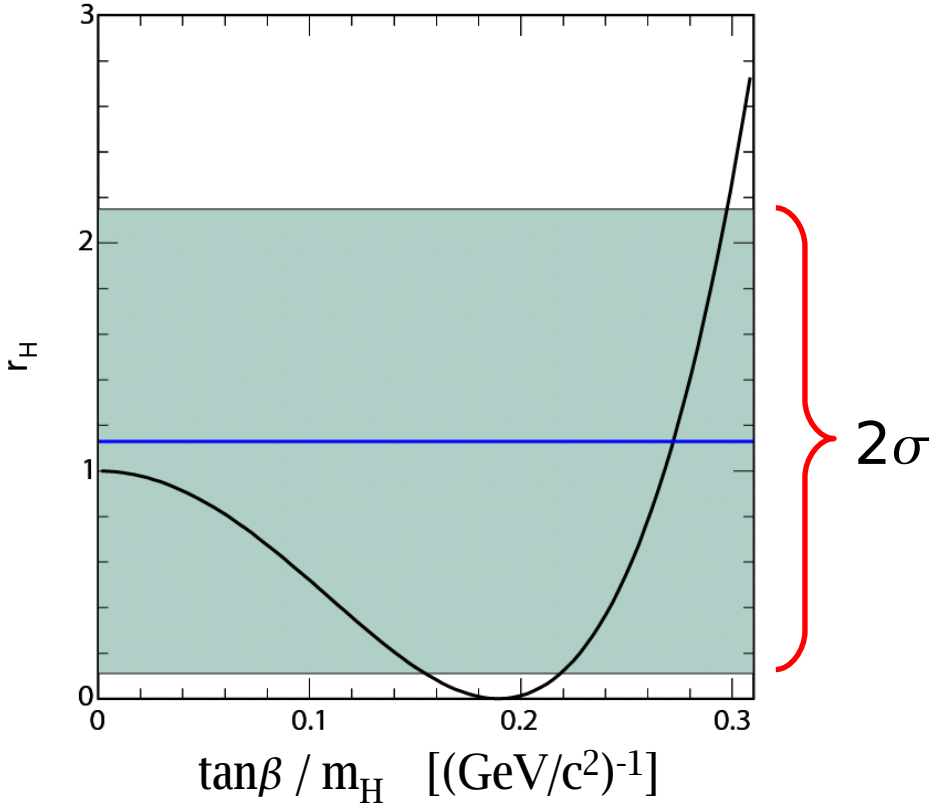
Constraint on Charged Higgs (two Higgs doublet model, type II):

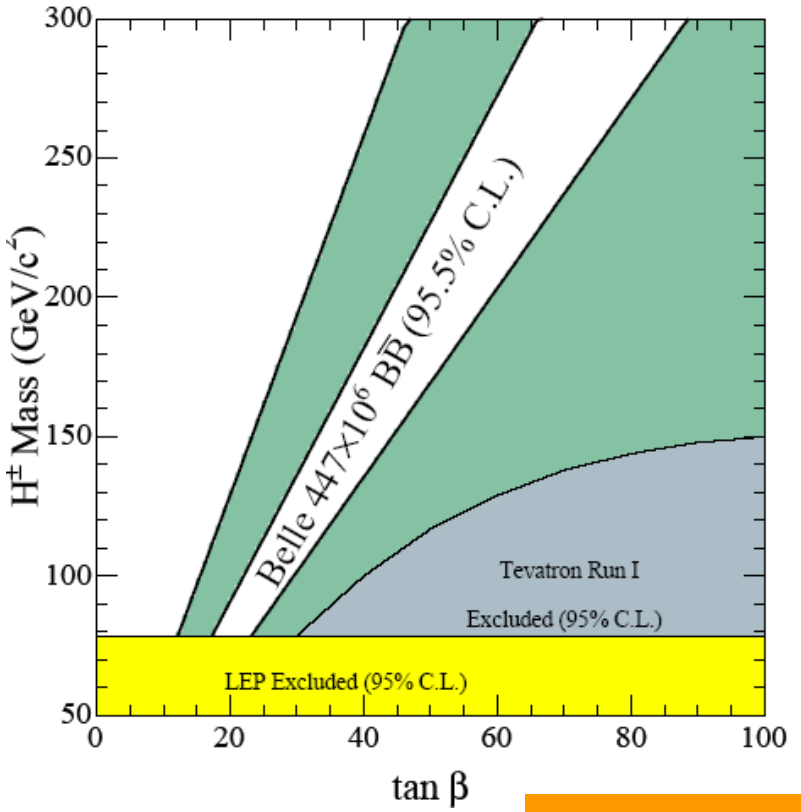
$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times r_H \qquad r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2\beta)^2$$

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

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

$$r_H = 1.13 \pm 0.51$$





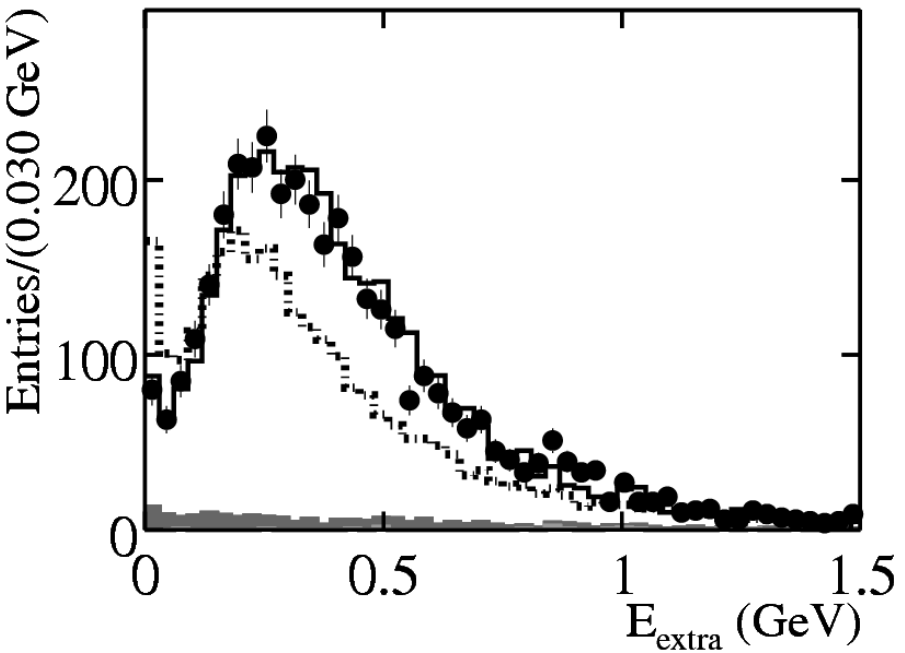
95.5% C.L. exclusion

W.S. Hou, Phys. Rev. D 48, 2342 (1993)

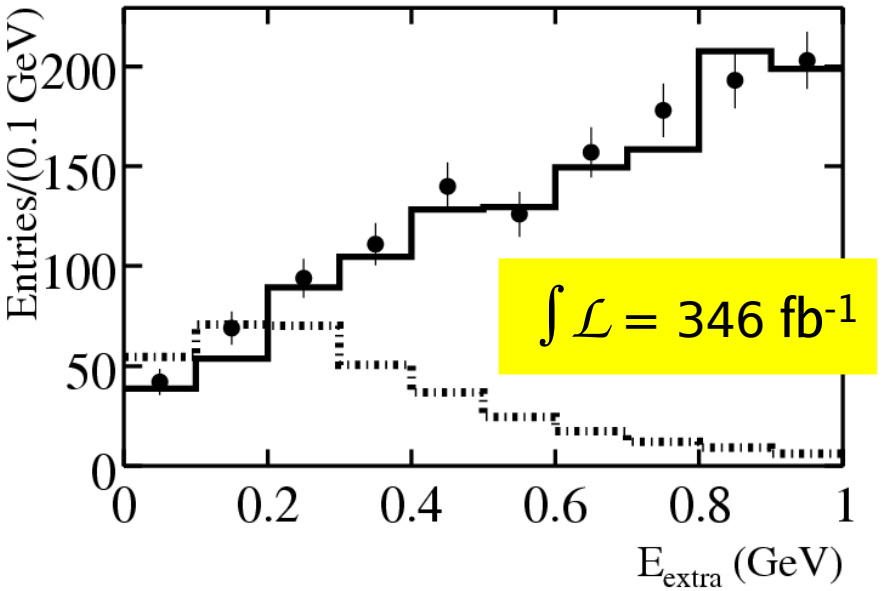
$B^+ \to \tau^+ \nu_\tau$: Babar's semileptonic tag analysis

UPDATED – HOT at FPCP07 - See talk by A. Gritsan on Sunday.

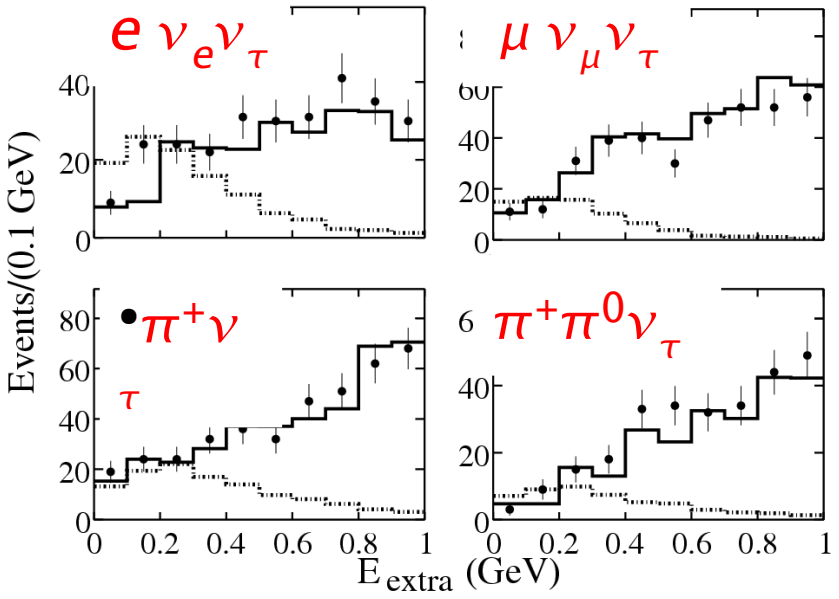
- Exclusive reconstruction of B_{tag} in $B^- \to D^0 \ell^- \bar{\nu}_\ell X$ ($X = \pi^0$ or γ) with $\ell = e, \mu$ and $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^0$, $K_s{}^0\pi^+\pi^-$.
- Higher efficiency, but lower purity than $D^{*0}\ell^-\nu_\ell$
- Signal: $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$, $\mu^+\nu_\mu\bar{\nu}_\tau$, $\pi^+\bar{\nu}_\tau$, $\pi^+\pi^0\bar{\nu}_\tau$, 71% of total
- Most powerful separation signal-background using E_{extra}: CM energy of neutrals and tracks not associated with either tag or signal.
- Mode dependent signal regions: $E_{extra} < 0.25 - 0.48$ GeV
- Tag B yield and E_{extra} validated with double tagged events
- Expected background evaluated by extrapolating data in sidebands in E_{extra} with same ratio as in MC.



$B^+ \to \tau^+ \nu_\tau$: Babar's semileptonic tag results



τ decay mode	Expected background events	Observed events in on-resonance data
$\tau^+ \to e^+ \nu\overline{\nu}$	44.3 ± 5.2	59
$\tau^+ \to \mu^+ \nu\overline{\nu}$	39.8 ± 4.4	43
$\tau^+ \to \pi^+ \overline{\nu}$	120.3 ± 10.2	125
$\tau^+ \to \pi^+ \pi^0 \overline{\nu}$	17.3 ± 3.3	18
All modes	221.7 ± 12.7	245



Signal above normalised to BF=10^{-3}

BaBar

$$\mathcal{B}(B^+ \to \tau^+ \nu) = (0.9 \pm 0.6(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-4}$$

$$\mathcal{B}(B^+ \to \tau^+ \nu) < 1.7 \times 10^{-4} \quad \text{90\% CL}$$

$$f_B \cdot |V_{ub}| = (7.2^{+2.0}_{-2.8}(\text{stat.}) \pm 0.2(\text{syst.})) \times 10^{-4}\ \text{GeV}$$

Central value extracted using a likelihood ratio computed from Poisson probabilities. Upper limit obtained with toy experiments and frequentist interpretation.

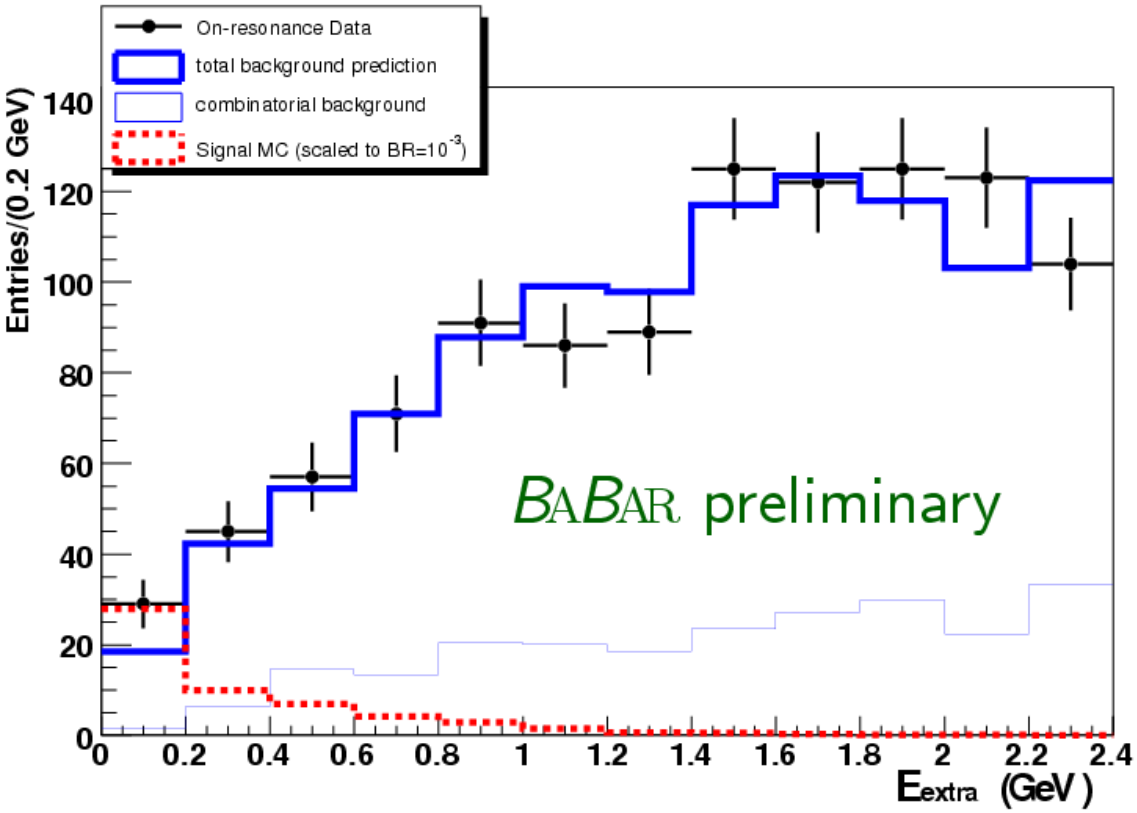
$B^+ \to \tau^+ \nu_\tau$: Babar's hadronic tag

NEW – HOT at FPCP07 - See talk by A. Gritsan on Sunday

- Same luminosity, same τ modes and general strategy as semileptonic tag.
- Exclusive reconstruction of B_{tag} in $B^- \to D^{(*)0} X^-$:
  - $D^{*0} \to D^0\pi^0$, $D^0\gamma$
  - $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^0$, $K_s^0\pi^+\pi^-$
  - $X^- = n_1\pi^\pm\ n_2K^\pm\ n_3K_s^0\ n_4\pi^0$ $(n_1+n_2 \le 5,\ n_3 \le 2,\ n_4 \le 2)$
- Signal window mode dependent: $E_{extra} < 0.10 - 0.29$ GeV

5.92×10^5 tags
$\epsilon_{tag} = 0.15\%$

τ decay mode	Expected background	Observed
$\tau^+ \to e^+\nu\overline{\nu}$	1.47 ± 1.37	4
$\tau^+ \to \mu^+\nu\overline{\nu}$	1.78 ± 0.97	5
$\tau^+ \to \pi^+\overline{\nu}$	6.79 ± 2.11	10
$\tau^+ \to \pi^+\pi^0\overline{\nu}$	4.23 ± 1.39	5
All modes	14.27 ± 3.03	24



$B^+ \to \tau^+ \nu_\tau$: Babar's hadronic & combination

BaBar : hadronic tag results

$$\mathcal{B}(B^+ \to \tau^+ \nu) = 1.8^{+1.0}_{-0.9}(\text{stat.+bkg}) \pm 0.3(\text{syst.})) \times 10^{-4}$$

$$f_B \cdot |V_{ub}| = (10.1^{+2.8}_{-2.5}(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{-4}\ \text{GeV}$$

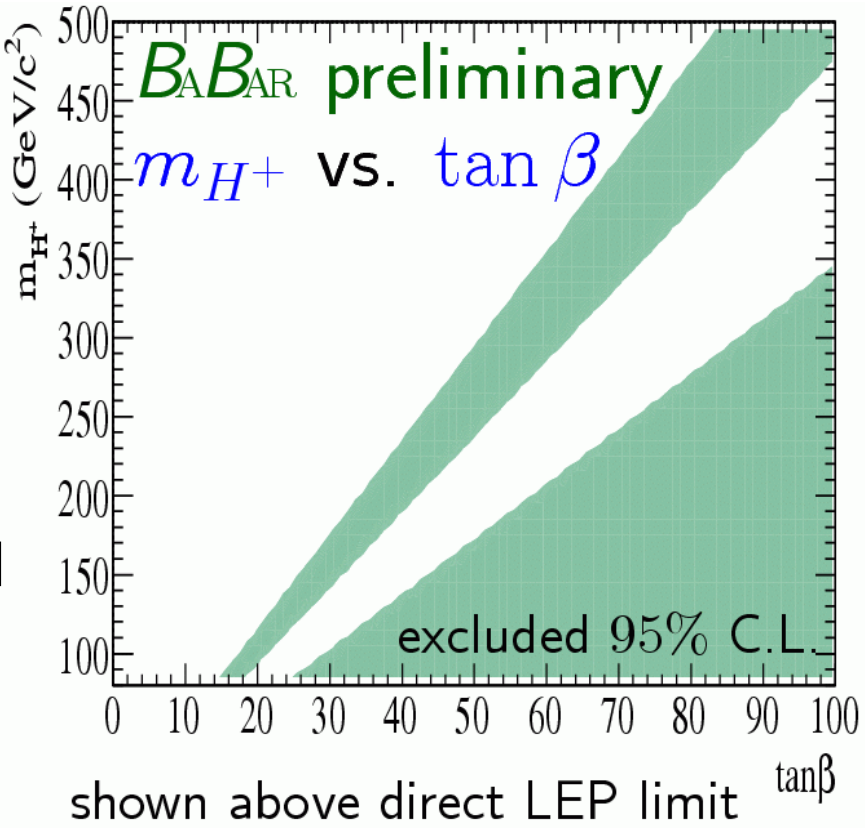
Significance: 2.2σ (2.7σ without bkg. uncertitude)

Combine likelihoods of semileptonic and hadronic **BaBar's** analyses:

$$\mathcal{B} = (1.20^{+0.40+0.29}_{-0.38-0.30} \pm 0.22) \times 10^{-4}$$

(stat.) (bkg.) (eff.)

Significance: 2.6σ (3.2σ stat.)



MY **quick BOTE** combination of Belle and BaBar (just Gaussian weighted average):

BF($B \to \tau \nu_\tau$) = (1.41 ± 0.43)x10^{-4}

See talk by H. Lacker on Monday for constraints on ρ, η plane

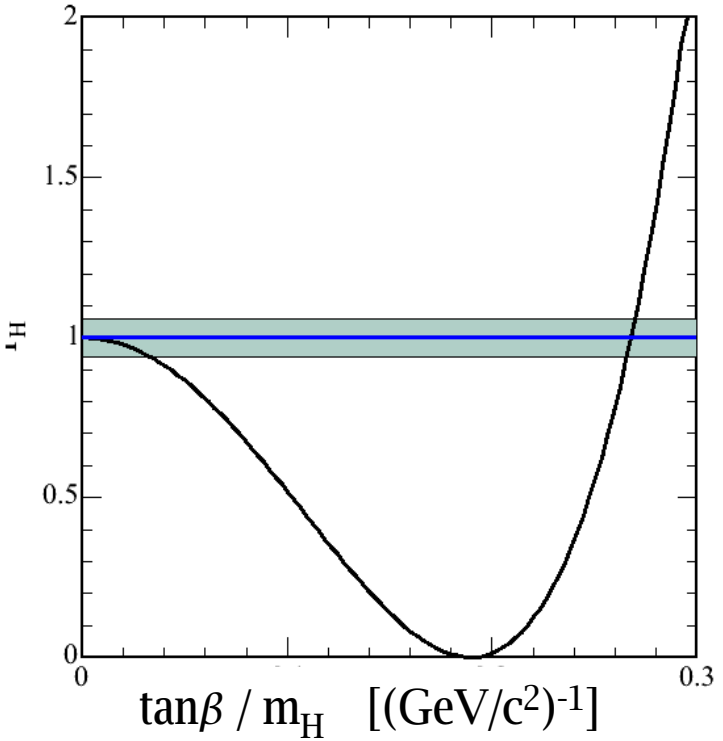
Future prospects for $B^+ \to \tau^+ \nu_\tau$

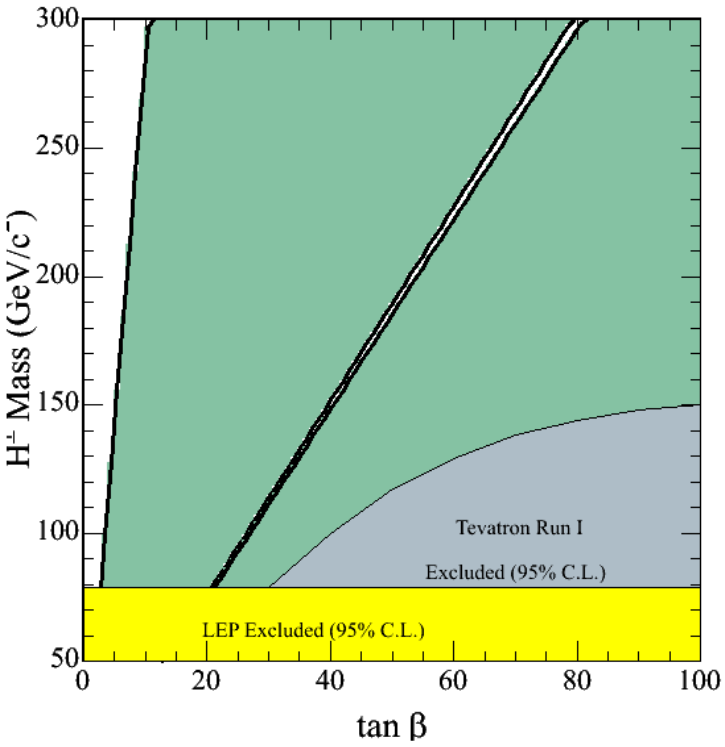
Extrapolating the current results to super-B factory luminosities:
(assuming Δf_B(LQCD) = 5%)

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%

With 50 ab^{-1}:

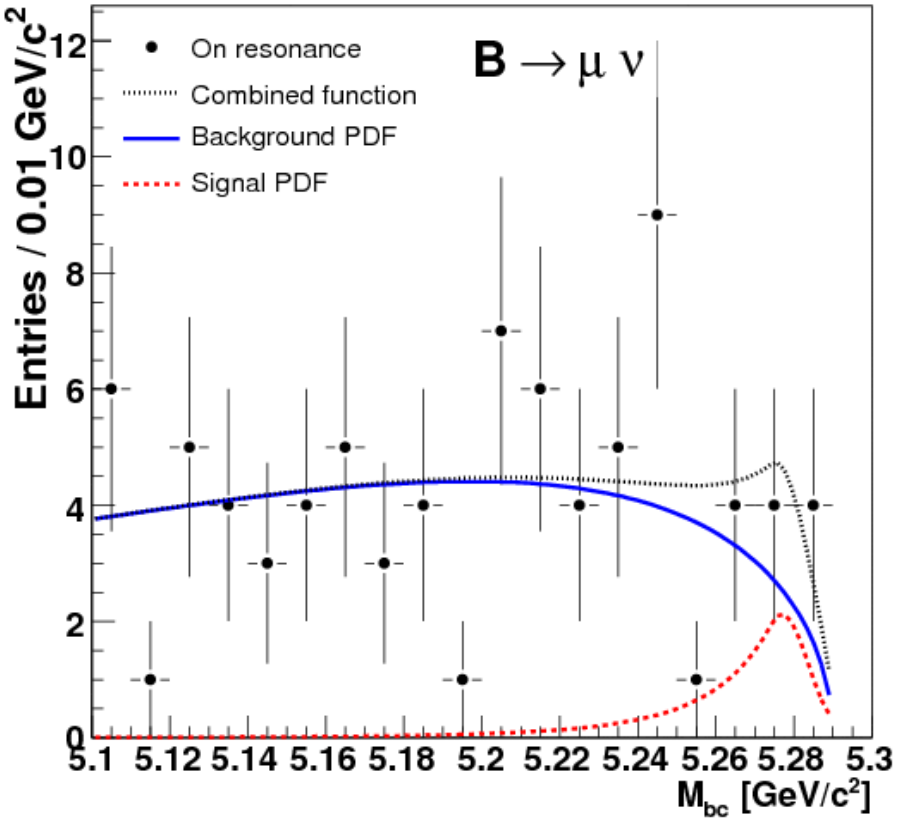
(optimistic:
assuming $\Delta|V_{ub}| = 0$
and $\Delta f_B = 0$)

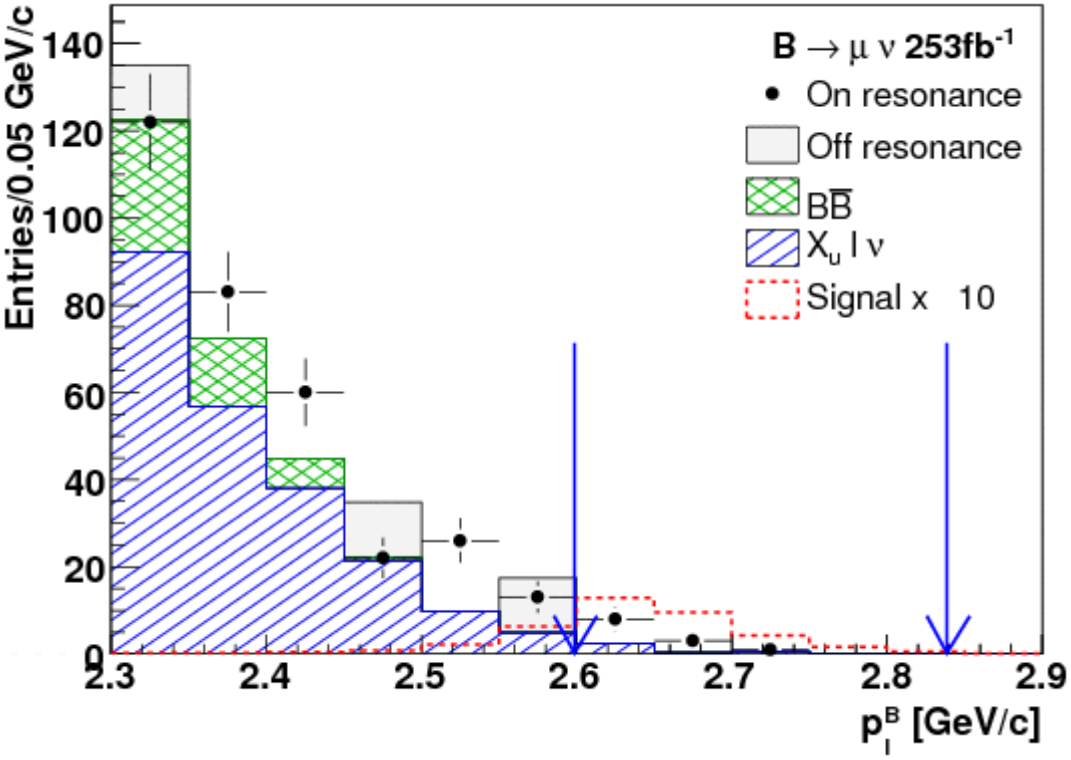




$B^+ \to e^+ \nu_e$ and $B^+ \to \mu^+ \nu_\mu$ at Belle

- Inclusive reconstruction of tag B
- One highly energetic lepton
- Large missing E and p
- Signal window defined on ΔE and M_{bc} of the companion B
- Cut on lepton momentum in B rest frame





BELLE results at 90% CL

$BF(B \to \mu \nu_\mu) < 1.7 \times 10^{-6}$

$BF(B \to e \nu_e) < 9.8 \times 10^{-7}$

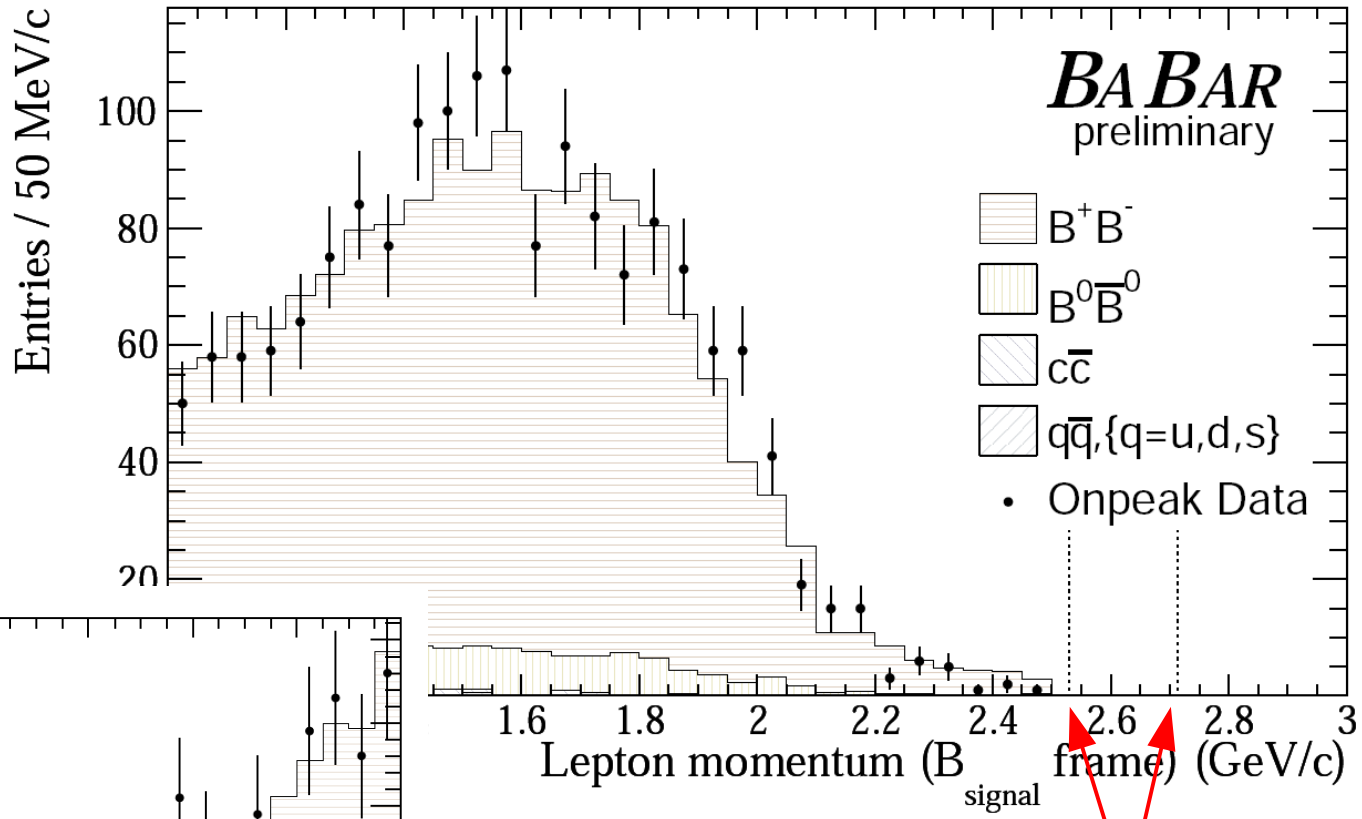
Based on 253 fb^{-1} of data

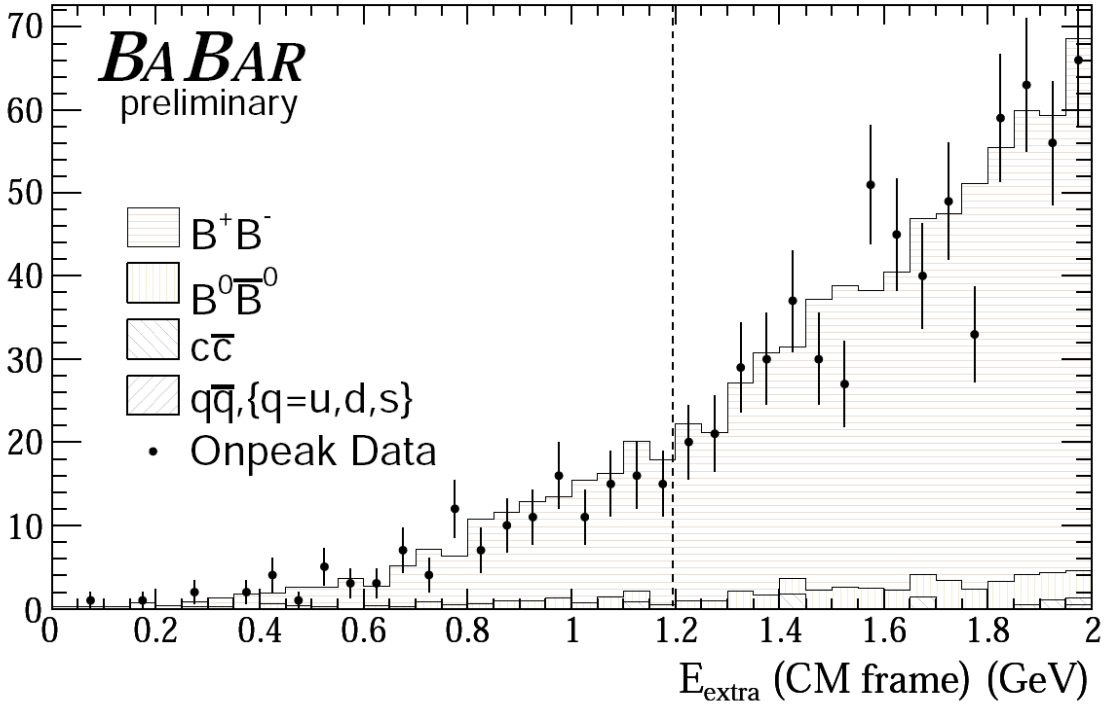
N.Satoyama et al. (Belle collab.)
Phys. Lett. B 647, 67 (2007)

$B^+ \to e^+ \nu_e$ and $B^+ \to \mu^+ \nu_\mu$ at BaBar

hep-ex/0607110

- 209 fb^{-1} dataset
- Exclusive reconstruction of tag B in $B^+ \to D^{(*)0} + X^+$
- Select B_{tag} in ΔE, m_{ES}
- Total efficiency ~0.1%
- Frequentist extraction of BF limits





No events in the signal window

at 90% CL

$BF(B \to \mu \nu_\mu) < 6.2 \times 10^{-6}$

$BF(B \to e \nu_e) < 7.9 \times 10^{-6}$

BaBar

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

$B^+ \to \ell^+ \nu_\ell \gamma$: motivation & "old" limits

PRO: The presence of the photon can lift helicity suppression; BFs are enhanced and independent of lepton flavour up to $(m_\ell / m_B)^2$

CON: it is not as theoretically "clean" as purely leptonic modes

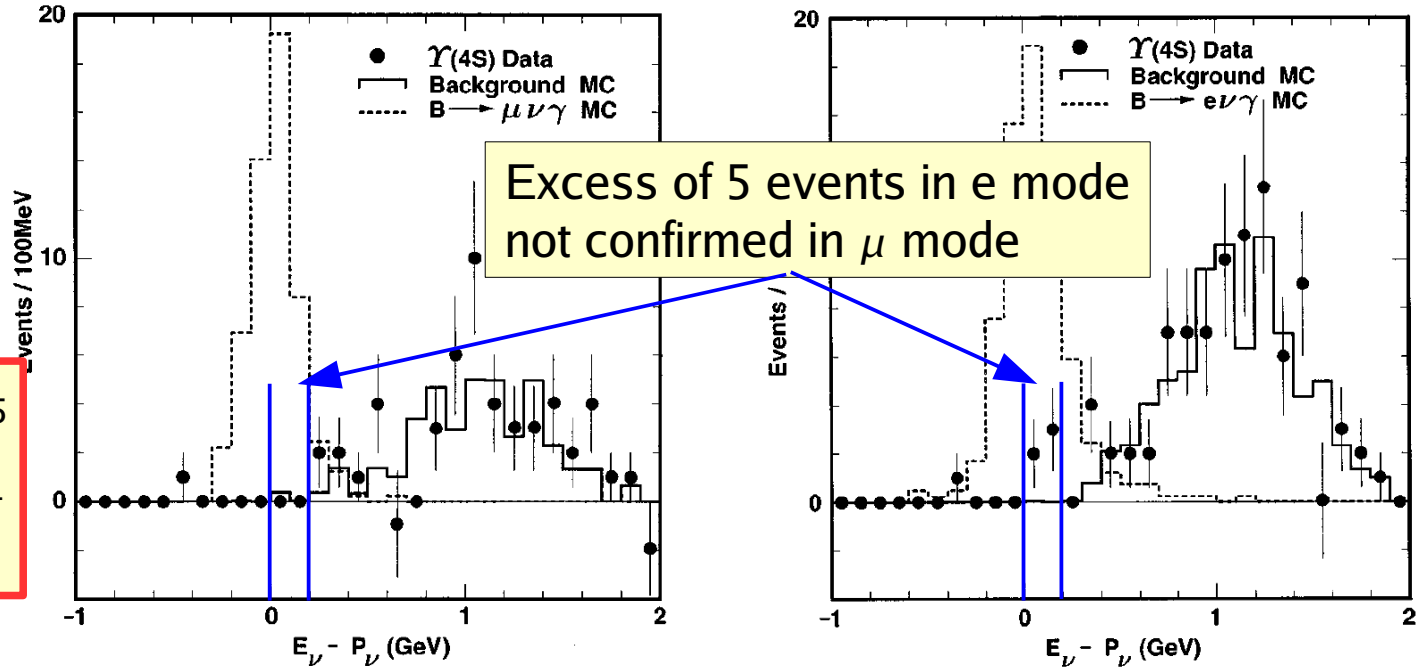
CLEO limits: based on 2.5 fb^{-1} T.E. Browder *et al.*, Phys.Rev. D56, 11 (1997)

- Signal modeled as in Burdman, Goldman, Wyler, Phys.Rev. D51, 111 (1995)
- expect BF$\cong$1-4x10^{-6}

at 90% CL

$BF(B \to \mu \nu_\mu \gamma) < 5.2 \times 10^{-5}$

$BF(B \to e \nu_e \gamma) < 2.0 \times 10^{-4}$



BELLE results presented at ICHEP04, unpublished: hep-ex/0408132

$BF(B \to \mu \nu_\mu \gamma) < 2.2 \times 10^{-5}$ $BF(B \to e \nu_e \gamma) < 2.3 \times 10^{-5}$

based on 140 fb^{-1}

$B^+ \to \ell^+ \nu_\ell \gamma$: *BaBar* analysis

- Use different theoretical framework.
- Measure some partial BF, in a restricted region of phase space:

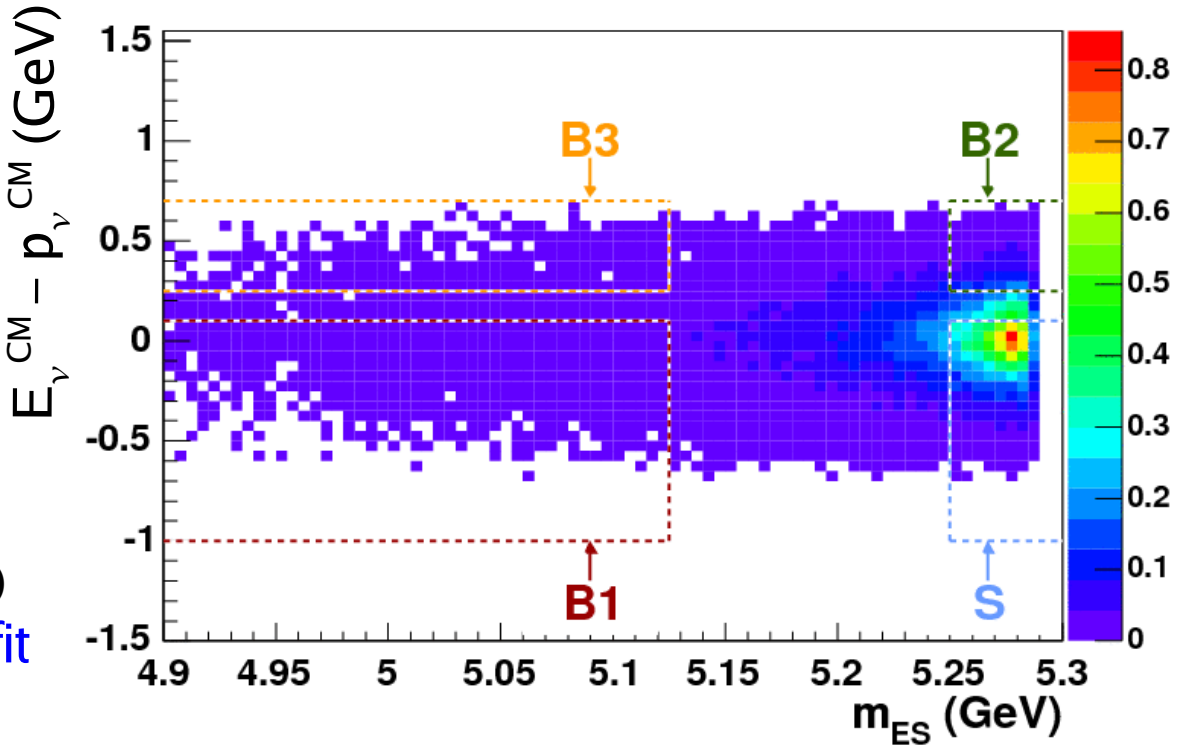
$1.875 < E_\ell^{CM} < 2.850\,GeV$, $0.45 < E_\gamma^{CM} < 2.35\,GeV$, $\cos\theta_{\ell\gamma} < -0.36$

- Lumi: 210.5 fb^{-1}, reconstruct inclusively the recoiling B, extract signal from 2D ML fit based on event counts in signal window and sidebands:
- Can fit separate modes or joint e-μ assuming equal BF (90% CL):

$$\Delta B(B \to \gamma \mu \nu_\mu) < 2.1 \times 10^{-6}$$
$$\Delta B(B \to \gamma e \nu_e) < 2.8 \times 10^{-6}$$
$$\Delta B(B \to \gamma \ell \nu_\ell) < 2.3 \times 10^{-6}$$

(Bayesian limits with flat prior in BF)

With some input from theory, joint fit translates to:



$$BF(B \to \gamma \ell \nu_\ell) < 5.0 \times 10^{-6} \quad (90\%\ CL)$$

arXiv:0704.1478

Summary

Heavy Flavor Averaging Group
March 2007

Compilation of B Leptonic Branching Fractions
All branching fractions are in units of 10^{-6}

In PDG2006 New since PDG2006 (preliminary) New since PDG2006 (published)

RPP#	Mode	PDG2006 Avg.	BABAR	Belle	CLEO	CDF	D0	New Avg.
15	$e^+\nu$	< 15	< 7.9	< 1.0	< 15			< 1.0
16	$\mu^+\nu$	< 6.6	< 6.2	< 1.7	< 21			< 1.7
17	$\tau^+\nu$	< 260	$88 \pm 68 \pm 11$	179^{+56+46}_{-49-51}	< 840			132 ± 49
18	$e^+\nu_e\gamma$	< 200			< 200			< 200
19	$\mu^+\nu_\mu\gamma$	< 52			< 52			< 52

Status as of March 2007

Summary

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17	$\tau^+\nu$	< 260	$120 \pm 49 \pm 22$	179^{+56+46}_{-49-51}	< 840			132 ± 49
18	$e^+\nu_e\gamma$	< 200			< 200			< 200
19	$\mu^+\nu_\mu\gamma$	< 52	< 5.0		< 52			< 52

published!

Preliminary!

new!

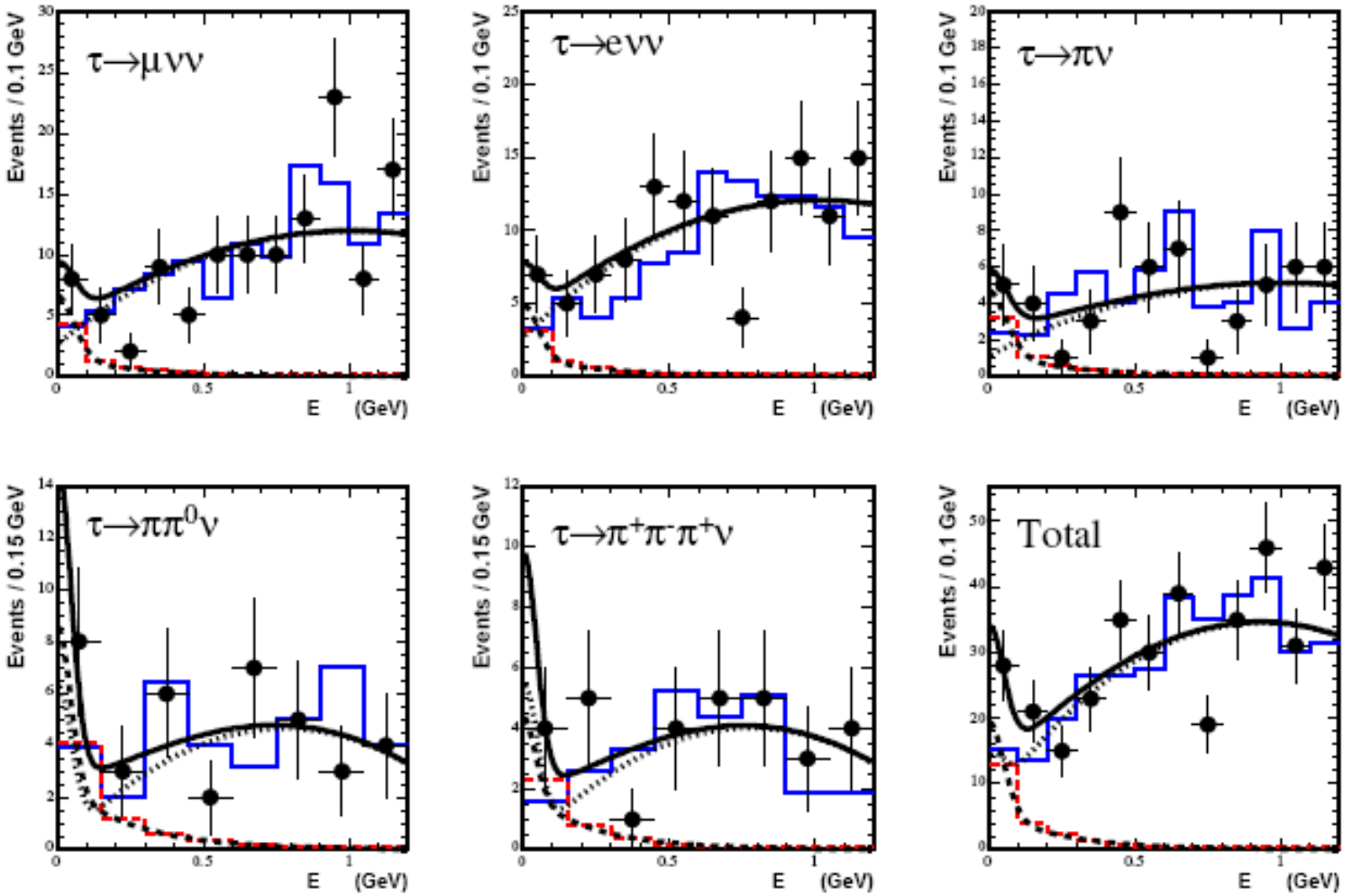
Status at FPCP 2007 (12-16 May 07)

Conclusions

- $B \to \tau \nu_\tau$: first evidence of a purely leptonic B decay
  - → Measured branching fraction consistent with SM prediction
  - → First direct determination of the B decay constant
  - → Set constraints on M_H–tanβ in MSSM
- $B \to e \nu_e$, $B \to \mu \nu_\mu$: limits start to get close (factor 3-4) to SM for the muon mode
- $B^+ \to \ell^+ \nu_\ell \gamma$: also getting close to SM predictions... but comparisons are more difficult due to model dependence
- Still a lot to come from existing experiments and hopefully a Super-B factory!

BACKUP SLIDES

Belle $B^+ \to \tau^+ \nu_\tau$, fits to individual modes



Belle $B^+ \to \tau^+ \nu_\tau$, syst. unc.

- 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 $B \to D^{*0}\ell\nu$ control sample
- Number of BB : 1%
- Signal yield : +22.5% -25.7%

  - signal shape ambiguity estimated by varying the signal PDF parameters

  - BG shape : changing PDF
- **Total systematic uncertainty: +25.5% -28.4%**

BaBar $B^+ \to \tau^+ \nu_\tau$, hadronic tag

Summary of signal selection:

Variable	$\tau^+ \to e^+ \nu \overline{\nu}$	$\tau^+ \to \mu^+ \nu \overline{\nu}$	$\tau^+ \to \pi^+ \overline{\nu}$	$\tau^+ \to \pi^+ \pi^0 \overline{\nu}$
$E_{\rm extra}$ (GeV)	< 0.160	< 0.100	< 0.230	< 0.290
π^0 multiplicity	0	0	≤ 2	n.a.
Track multiplicity	1	1	≤ 2	1
$\lvert cos\theta^*_{TB} \rvert$	≤ 0.9	≤ 0.9	≤ 0.7	≤ 0.7
$p^*_{\rm trk}$ (GeV/c)	< 1.25	< 1.85	> 1.5	n.a.
$cos\theta^*_{\rm miss}$	< 0.9	n.a	< 0.5	< 0.55
$p^*_{\pi^+\pi^0}$ (GeV/c)	n.a.	n.a.	n.a.	> 1.5
ρ quality	n.a.	n.a.	n.a.	< 2.0
E_{π^0} (GeV)	n.a.	n.a.	n.a.	> 0.250

$B^+ \to e^+ \nu_e$ and $B^+ \to \mu^+ \nu_\mu$ at Belle

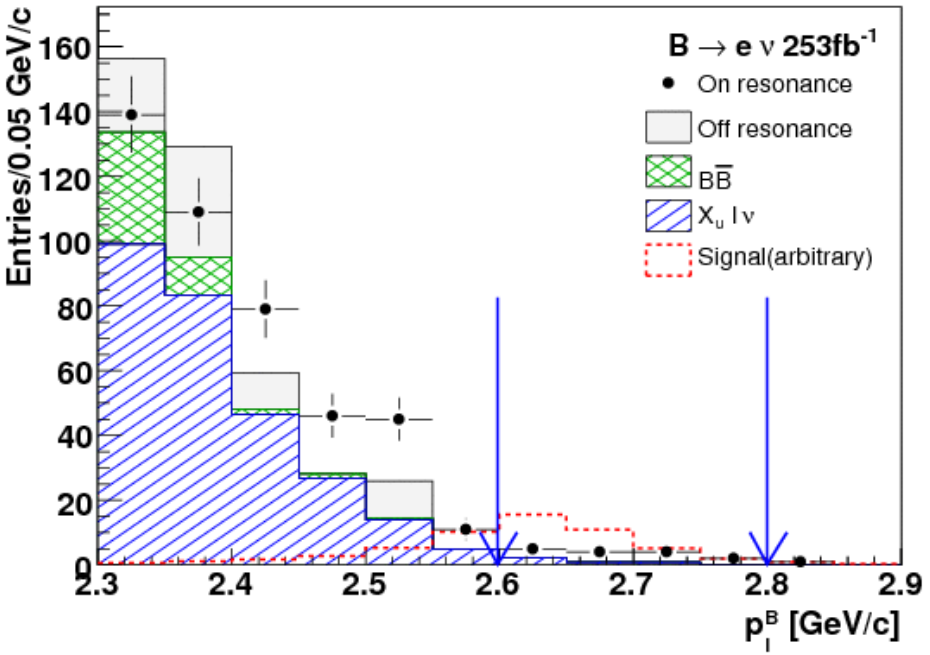
Systematic uncertainties:

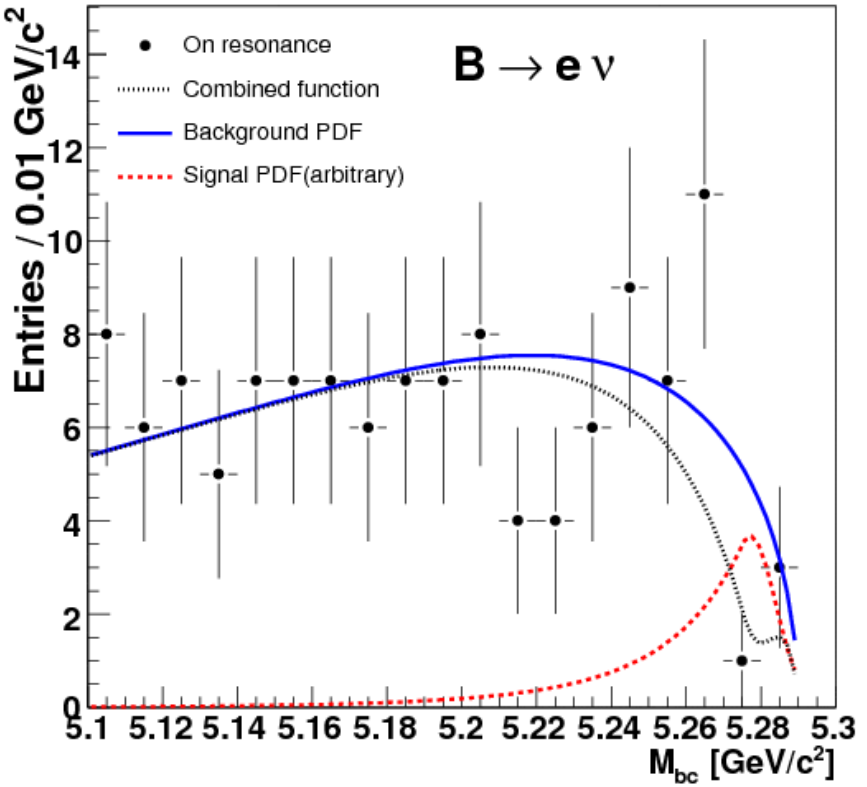
Sources		Muon Mode	Electron Mode
$N_{B\bar{B}}$		1.1%	1.1%
Signal Efficiency	Lepton ID	4.4%	1.1%
	Tracking	1.0%	1.0%
	MC statistics	2.3%	2.1%
	$B^+ \to D^0 \pi^+$	3.6%	3.6%
$M_{\rm bc}$ Shape	Signal	6.5%	3.2%
	Background	8.1%	15.7%
Total		12.2%	16.7%

Details of selection and fit results:

	Muon Mode	Electron Mode
Signal Efficiency (fit region)	3.15 ± 0.07 %	3.86 ± 0.08 %
Signal Efficiency (signal region)	2.18 ± 0.06 %	2.39 ± 0.06 %
Observed in Signal region [events]	12	15
Expected background [events]	7.4 ± 1.0	13.4 ± 1.4
Signal yield [events]	4.1 ± 3.1	-1.8 ± 3.3
Significance	1.3	–
SM Prediction [events]	2.8 ± 0.2	$(7.3 \pm 1.4) \times 10^{-5}$

Plots for the electron mode:





$B^+ \to \ell^+ \nu_\ell \gamma$: more theory

TWO CONTRIBUTIONS:

1. Structure-Dependent (SD) model: photon produced in transition from scalar B to off-shell vector (B*) or axial-vector (B') meson.
2. Internal bremsstrahlung (IB), (emission in initial or final state particle) is suppressed by helicity conservation

$$\mathcal{B}(B^+ \to \gamma \ell^+ \nu_\ell) = \alpha \frac{G_F^2 |V_{ub}|^2}{288\pi^2} f_B^2 \tau_B m_B^5 \left(\frac{Q_u}{\lambda_B} - \frac{Q_b}{m_b} \right)^2$$

Q_i : charge of quark i

λ_B : first inverse moment of B light cone distribution amplitude (enters calculations of BF of hadronic *B* decays) $\sim \Lambda_{QCD}$

$$\Delta\mathcal{B} = \alpha \frac{G_F^2 |V_{ub}|^2}{32\pi^4} f_B^2 \tau_B m_B^3 \left[a + bL + cL^2 \right]$$

$$L = (m_B/3)(1/\lambda_B + 1/(2m_b))$$

a, *b*, *c*: (model independent) computable constants

$B^+ \to \ell^+ \nu_\ell \gamma$ at BaBar: details

Fit results:

Muon channel				
	S	B1	B2	B3
Fit cont.	20.0±11.8	116.3±14.7	42.6±12.8	213.2±42.1
Off-peak	23.0±16.2	158.1±40.8	17.4±12.3	219.7±45.8
Fit $B\overline{B}$	59.1± 8.5	61.0± 9.9	61.7± 9.8	286.6±46.6
Fit signal	−5.2±13.8	−1.3± 3.4	−0.4± 1.0	−0.2± 0.5
Total fit	74.0± 8.1	176.0±12.4	103.9± 9.8	500.0±22.1
On-peak	73.0± 8.5	170.0±13.0	111.0±10.5	498.0±22.3

Electron channel				
	S	B1	B2	B3
Fit cont.	55.4±20.5	181.1±16.2	48.9±14.1	356.7±54.4
Off-peak	41.4±20.7	239.7±48.9	79.0±27.9	294.5±52.9
Fit $B\overline{B}$	69.2± 8.5	59.2± 8.5	140.1±15.5	393.8±57.2
Fit signal	−8.4±22.3	−1.5± 3.9	−1.2± 3.3	−0.4± 1.0
Total fit	116.2±10.3	238.7±14.5	187.7±12.5	750.2±26.5
On-peak	119.0±10.9	231.0±15.2	176.0±13.3	764.0±27.6

Systematics:

Multiplicative	Muon	Electron	Joint
Tracking efficiency	1.3%	1.3%	1.3%
Particle ID	3.5%	2.2%	2.1%
Neutral reconstruction	1.6%	1.6%	1.6%
Selection efficiency	6.0%	5.0%	6.0%
B counting	1.1%	1.1%	1.1%
Charged to neutral B ratio	9.4%	9.4%	9.4%
Additive			
Shape of Δ_{EP} vs. $m_{\rm ES}$	0.3	0.2	0.3
η mode BF	0.3	0.1	0.2
π,ρ mode BF, ff	0.3	0.4	0.4
$B \to X_u \ell^+ \nu_\ell$ BF	0.4	0.2	0.3