Study of B decays with missing-E at B-factories (Belle & BABAR)

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Outline

- Introduction: **how to do missing-E**

- B decay modes with missing-E (Belle & BABAR)*

  - * $B^+ \to \tau^+\nu_\tau$
  - * $B \to D^{(*)}\tau^+\nu_\tau$
  - * $B^+ \to \ell^+\nu_\ell$

  - * search for heavy-ν
  - * invisible B decays, e.g. $B^0 \to \nu\bar{\nu}(\gamma)$
  - * semi-invisible B decays, e.g. $B \to h^{(*)}\nu\bar{\nu}$

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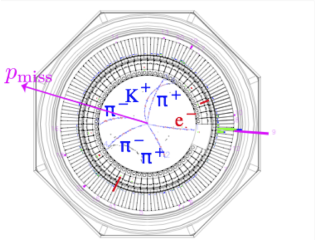
*For semileptonic decays, $B \to X\ell^+\nu_\ell$, see Bill Gary talk.

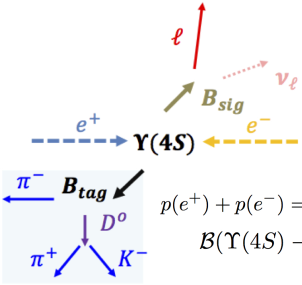
How to study B decays with missing-E

- (Ex) $B \to X_u \ell^+ \nu_\ell$, $B^+ \to \tau^+ \nu_\tau$ and other exotic kinds (e.g. $B^0 \to \nu\bar{\nu}$)
- **hadronic tagging method**
  - * full reconstruction of B_{tag} in $\Upsilon(4S) \to B_{\text{sig}} B_{\text{tag}}$
    $\Rightarrow$ measure B_{tag}, hence constraining the charge, flavor, & $(E, \vec{p})$ of B_{sig}
    $\Rightarrow$ very high-purity, but with low-efficiency ($\sim \mathcal{O}(0.1\%)$)
  - * need an algorithm for improved full-reconstruction of B mesons



$B^+_{tag} \to \bar{D}^0 \pi^+ \pi^+ \pi^-$
↳ $K^+\pi^-$

$B^-_{sig} \to \tau^- \bar{\nu}_\tau$
↳ $e^- \bar{\nu}_e \nu_\tau$



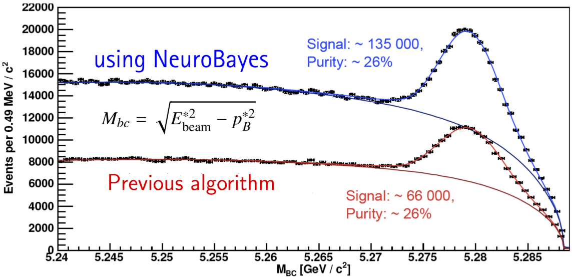
$$p(e^+) + p(e^-) = p(B_{\text{tag}}) + p(B_{\text{sig}})$$

$$\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$$

Hadronic *B*-tagging, *improved*

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

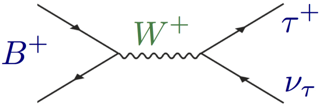
- using a **neural** network
- the NN output can be interpreted as **Bayesian** probability
- provides a well-discriminating variable for intermediate cuts, *whose behaviors are under control*

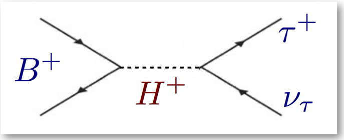


* $\times(2 \sim 3)$ statistical gain over previous hadron-tagged analyses!

$B^+ \to \tau^+ \nu_\tau$

$B^+ \to \tau^+\nu_\tau$ **SM vs. new physics**, e.g. H^+





$$\Gamma_{\mathrm{SM}}(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \quad (\ell = e, \mu, \tau)$$

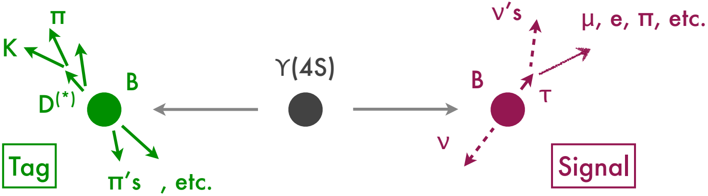
- $\Gamma(B^+ \to \tau^+\nu_\tau)$ can be affected by new physics effects. For instance, with H^+ of 2-Higgs doublet model (type II)

$$\Gamma(B^+ \to \tau^+\nu_\tau) = \Gamma_{\mathrm{SM}}(B^+ \to \tau^+\nu_\tau) \times r_H$$

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

- First evidence for $B^+ \to \tau^+\nu_\tau$ by Belle PRL 97, 251802 (2006)
  using hadronic tagging (“Full reconstruction”)

$B^+ \to \tau^+\nu_\tau$ **analysis by tagging**



- Two different methods of tagging
  - * hadronic tag: use fully-reconstructed hadronic B_{tag} decays
  - * semileptonic tag: use $B \to D^{(*)}\ell^+\nu_\ell$

    missing one ν_ℓ, but clean and plentiful enough to compensate for it

$B^+ \to \tau^+ \nu_\tau$ **(Belle)** *hadronic tagging*

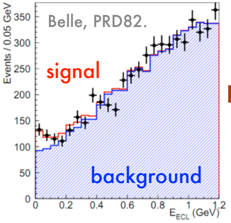
What's new from the previous hadronic-tag analysis (PRL, 2006)

- Reprocessing of full Belle data set (2011)
  ⇒ improved detection efficiencies of low p_T tracks and neutral particles
- $N_{B\bar{B}} = 771\text{M}$ (c.f. 449M for PRL, 2006; $+72\% \uparrow$)
- New algorithm for hadronic tagging NIMA 654, 432 (2011)
  ⇒ effectively, $\times 3$ B_{tag} sample size
- Signal extraction by 2D fit to $(E_{\text{ECL}}, M^2_{\text{miss}})$
  c.f. just a 1D fit to E_{ECL} for previous result (2006)
  - $E_{\text{ECL}} = \sum$ (energies of neutral clusters, not belonging to either B_{tag} or π^0 in B_{sig})
  - $M^2_{\text{miss}} = (E_{\text{CM}} - E_{B_{\text{tag}}} - E_{B_{\text{sig}}})^2 - |\vec{p}_{B_{\text{tag}}} + \vec{p}_{B_{\text{sig}}}|^2$

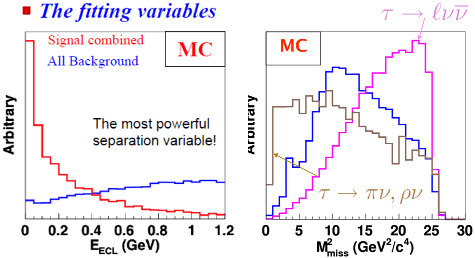
$B^+ \to \tau^+ \nu_\tau$ (Belle) – signal extraction

- 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 π^0, K_L^0 after reconstructing B_{tag} and B_{sig}
- 2D fitting to E_{ECL} & M^2_{miss}
  - improve sensitivity by $\sim 20\%$; more robust against peaking backgs. in E_{ECL}

previous analyses
(E_{ECL} only)

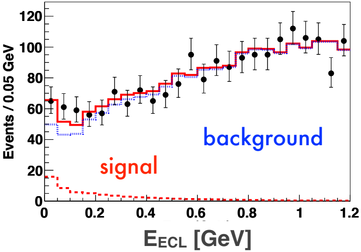


■ ***The fitting variables***

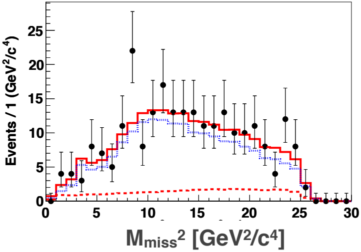


$B^+ \to \tau^+\nu_\tau$ (Belle) – Result

- 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.)

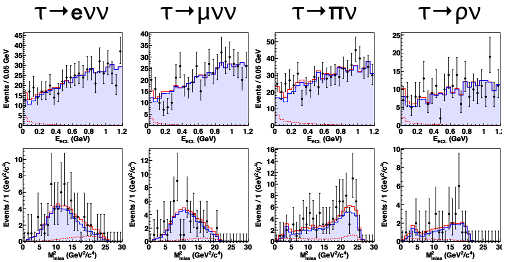


(Projection for E_{ECL} < 0.2 GeV)

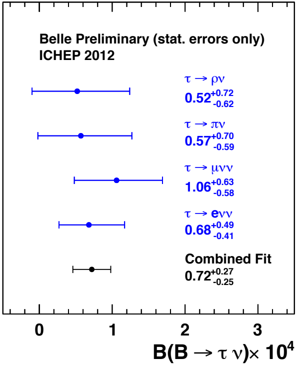
- Signal yield: $62^{+23}_{-22} \pm 6$ significance = 3.0σ incl. systematic error
  Major sources of systematic error are: background PDF (8.8%), K_L^0 efficiency (7.3%), and $B_{\rm tag}$ efficiency (7.1%).
- $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \left(0.72^{+0.27}_{-0.25} \pm 0.11\right) \times 10^{-4}$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

$B^+ \to \tau^+\nu_\tau$ (Belle) – Result

- A consistency check by fitting separately for different τ modes



Take τ→eνν, μνν, ρν cross-feeds in τ→πν candidates as signal.



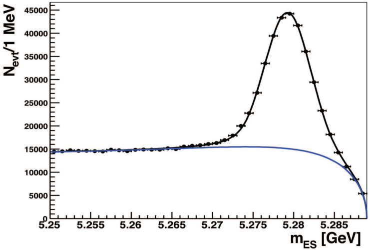
Sub-mode	$N_{\rm sig}$	ϵ (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$	16^{+11}_{-9}	3.0	$0.68^{+0.49}_{-0.41}$
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	26^{+15}_{-14}	3.1	$1.06^{+0.63}_{-0.58}$
$\tau^- \to \pi^-\nu_\tau$	8^{+10}_{-8}	1.8	$0.57^{+0.70}_{-0.59}$
$\tau^- \to \pi^-\pi^0\nu_\tau$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

Consistent results over different τ modes!

$B^+ \to \tau^+ \nu_\tau$ (BABAR)

- Hadronic tagging analysis is updated with $N_{B\overline{B}} = 468 \times 10^6$
- Signal τ modes: $\tau^+ \to e^+ \nu_e \overline{\nu}_\tau,\ \mu^+ \nu_\mu \overline{\nu}_\tau,\ \pi^+ \overline{\nu}_\tau,\ \rho^+ \overline{\nu}_\tau$
- Mode-dependent, optimized selection criteria

Variable	e^+	μ^+	π^+	ρ^+
$\mathcal{P}$	$> 10\%$			
Cluster energy (MeV)	> 60			
$\mathcal{R}2$	< 0.57	< 0.56	< 0.56	< 0.51
$\lvert\cos\theta_{TB}\rvert$	< 0.95	< 0.90	< 0.65	< 0.8
L_P			> 0.30	> 0.45



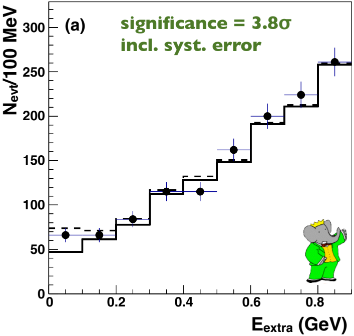
$B^+ \to \tau^+\nu_\tau$ (BABAR) – Result

- Signal extraction via $E_{\rm extra}$ $(= E_{\rm ECL})$
  $N_{\rm signal} = 62.1 \pm 17.3$ events
  from simultaneous fit to the four τ modes
- $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$
- Major systematic uncertainties are from
  background PDF's (10%), B-tag efficiency (5%), etc.

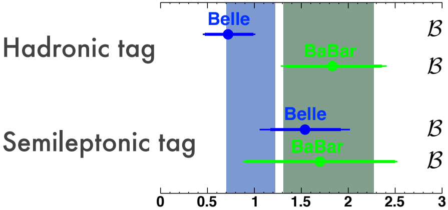
- Consistent results over different τ decay modes, within $\sim 2\sigma$

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	$1.83^{+0.53}_{-0.49}$

PRD 88, 031102(R) (2013)



$B^+ \to \tau^+\nu_\tau$ Belle/BABAR comparison



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

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

$$\mathcal{B} = [1.54^{+0.38}_{-0.37}(\text{stat})^{+0.29}_{-0.31}(\text{syst})] \times 10^{-4}$$

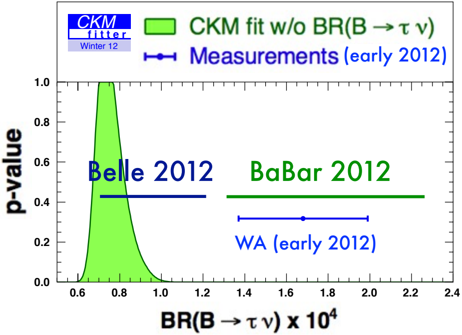
$$\mathcal{B} = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$$

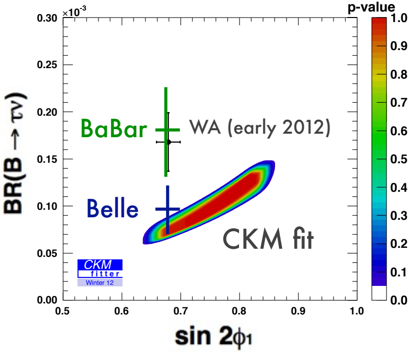
Belle combined: $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (0.96 \pm 0.26) \times 10^{-4}$

BaBar combined: $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.79 \pm 0.48) \times 10^{-4}$

- Belle vs. BaBar – consistent within $\sim 1.5\sigma$
- The results are consistent with $\mathcal{B}_{\text{SM}} = (1.10 \pm 0.30) \times 10^{-4}$, which is based on
  - * $f_B = (190 \pm 13)$ MeV from HPQCD, PRD 80, 014503 (2009)
  - * $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ from PDG 2012 (via $B \to X_u\ell\nu$, incl.+excl.)

$B^+ \to \tau^+ \nu_\tau$ Belle/BABAR comparison

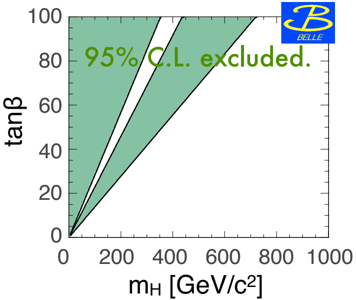




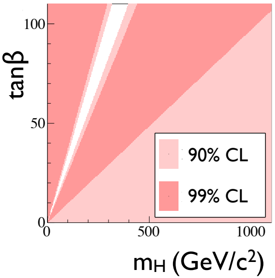
$B^+ \to \tau^+\nu_\tau$ constraints on charged Higgs

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

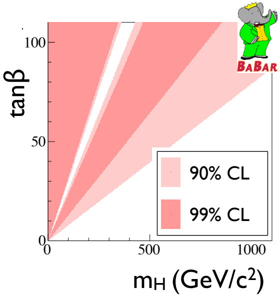
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu_\tau) \times \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$$



V_{ub} from excl.+incl. b→ulν



V_{ub} from exclusive b→ulν



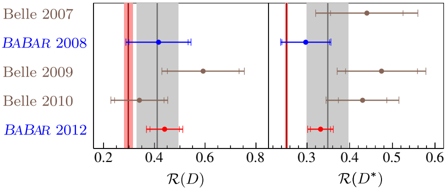
V_{ub} from inclusive b→ulν

$B \to D^{(*)}\tau^+\nu_\tau$

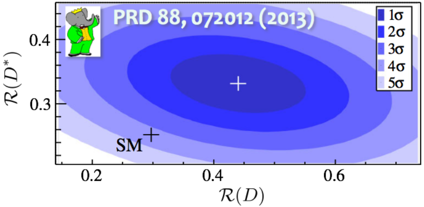
- $B \to D^{(*)}\tau^+\nu_\tau$ addresses similar NP issues with $B^+ \to \tau^+\nu_\tau$.
- $\exists$ a tendency:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell^+\nu_\ell)}$$

$$> R_{\text{SM}}(D^{(*)})$$



- PRL 109, 101802 (2012) BaBar $(R(D), R(D^*)) \neq (R(D), R(D^*))_{\text{SM}}$ by 3.4σ.
- Existing Belle results (PRL 2007, PRD 2010) show similar tendency, but not as significant.
- Belle is finalizing the measurement of $B \to \overline{D}^{(*)}\tau^+\nu_\tau$ with hadronic B-tagging, but not ready yet. *Please stay tuned!*



$B \to D^{(*)}\tau^+\nu_\tau$

- BaBar obtains signal yield by fitting $(M^2_{\rm miss}, p^*_\ell)$.

PHYSICAL REVIEW D **88,** 072012 (2013)

🟥 $D\tau\nu$
🟩 $D^*\tau\nu$
▨ $D\ell\nu$
▨ $D^*\ell\nu$
🟫 $D^{**}(\ell/\tau)\nu$
🟨 Bkg.

$m^2_{\rm miss} < 1\ {\rm GeV}^2$

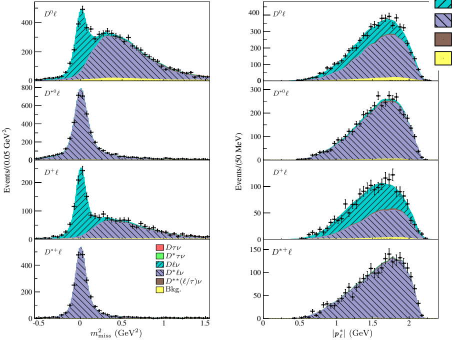


FIG. 7 (color online). Comparison of the $m^2_{\rm miss}$ and $|\boldsymbol{p}^*_\ell|$ distributions of the $D^{(*)}\ell$ samples (data points) with the projections of the results of the isospin-unconstrained fit (stacked colored distributions). The $|\boldsymbol{p}^*_\ell|$ distributions show the normalization-enriched region with $m^2_{\rm miss} < 1$ GeV^2, thus excluding most of the signal events in these samples.

$m^2_{\rm miss} \geq 1\ {\rm GeV}^2$

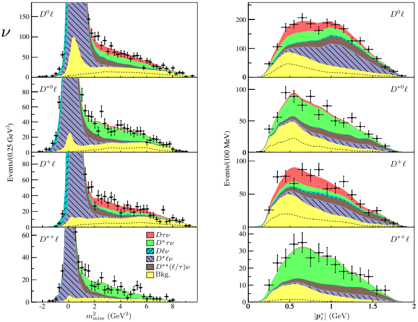
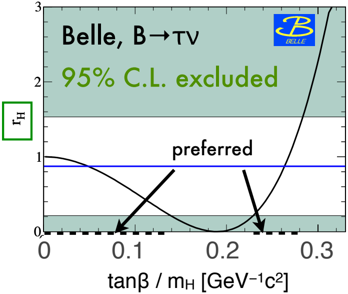
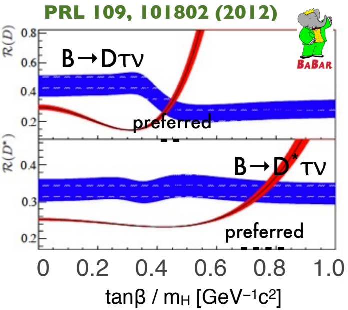
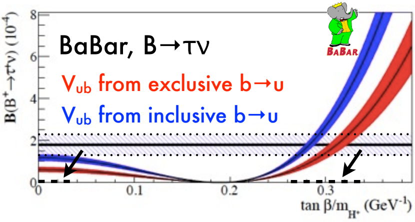


FIG. 8 (color online). Comparison of the $m^2_{\rm miss}$ and $|\boldsymbol{p}^*_\ell|$ distributions of the $D^{(*)}\ell$ samples (data points) with the projections of the results of the isospin-unconstrained fit (stacked colored distributions). The region above the dashed line of the background component corresponds to $B\bar{B}$ background and the region below corresponds to continuum. The peak at $m^2_{\rm miss} = 0$ in the background component is due to charge cross-feed events. The $|\boldsymbol{p}^*_\ell|$ distributions show the signal-enriched region with $m^2_{\rm miss} \geq 1$ GeV^2, thus excluding most of the normalization events in these samples.

$B^+ \to \tau^+\nu_\tau$ compared with $B \to D^{(*)}\tau^+\nu_\tau$







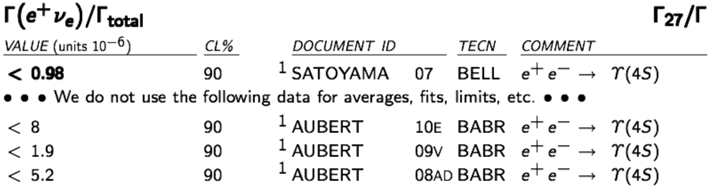
- $B^+ \to \tau^+\nu_\tau$, $D\,\tau^+\nu_\tau$, & $D^*\,\tau^+\nu_\tau$ prefer different regions of $\tan\beta/m_H$
  $\Rightarrow$ *stay tuned for Belle's update on $B \to D^{(*)}\tau\nu$*
- Is Type-II disfavored? ...
  We'll need further studies.

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

- (experimental) very clean
  - just a charged lepton and nothing else
- (theoretical) suppressed
  - helicity suppression: $\mathcal{B} \propto m_\ell^2$

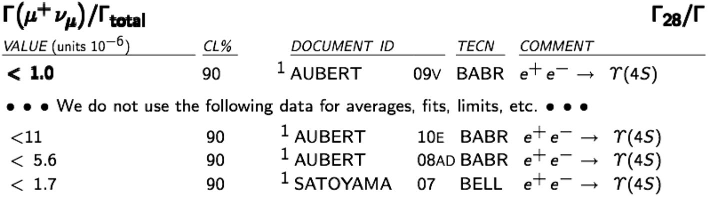
$$\Gamma(B^+ \to e^+\nu) \ll \Gamma(B^+ \to \mu^+\nu) \ll \Gamma(B^+ \to \tau^+\nu)$$

$B^+ \to \ell^+ \nu_\ell$ tagged vs. untagged



$\Gamma(e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*	
< 0.98	90	[1] SATOYAMA	07	BELL	$e^+ e^- \to \Upsilon(4S)$	untagged
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 8	90	[1] AUBERT	10E	BABR	$e^+ e^- \to \Upsilon(4S)$	
< 1.9	90	[1] AUBERT	09V	BABR	$e^+ e^- \to \Upsilon(4S)$	untagged
< 5.2	90	[1] AUBERT	08AD	BABR	$e^+ e^- \to \Upsilon(4S)$	full-recon.

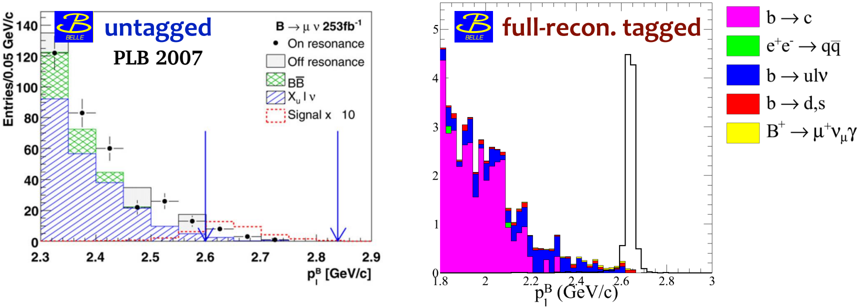


$\Gamma(\mu^+ \nu_\mu)/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*	
< 1.0	90	[1] AUBERT	09V	BABR	$e^+ e^- \to \Upsilon(4S)$	untagged
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<11	90	[1] AUBERT	10E	BABR	$e^+ e^- \to \Upsilon(4S)$	
< 5.6	90	[1] AUBERT	08AD	BABR	$e^+ e^- \to \Upsilon(4S)$	full-recon.
< 1.7	90	[1] SATOYAMA	07	BELL	$e^+ e^- \to \Upsilon(4S)$	untagged

Why 'tagged' for $B^+ \to \ell^+\nu_\ell$?

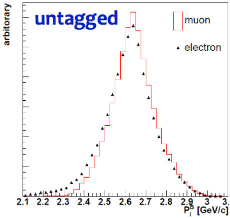
- The signal lepton candidate's momentum in B_{sig} rest frame. -



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

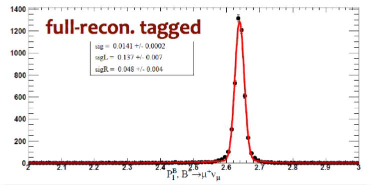
Why ‘tagged’ for $B^+ \to \ell^+\nu_\ell$?

- Note: $\mathcal{B}_{\rm SM}(B^+ \to e^+\nu_e) \sim 10^{-11}$ and $\mathcal{B}_{\rm SM}(B^+ \to \mu^+\nu_\mu) \sim 3 \times 10^{-7}$
  $\Rightarrow$ Any signal for $B^+ \to e^+\nu_e$ at the Belle (or Belle II) sensitivity is way beyond the SM
- In that case, are we *sure* what we see is *really* $B^+ \to e^+\nu_e$?
- What about $B^0 \to e^+\tau^-$? How about $B^+ \to e^+X^0$ where X^0 is any exotic neutral particle that just behaves like a neutrino?



$\epsilon_{sig} = 2.18\%$

$N_{bkg} = 7.4 \pm 1.0$



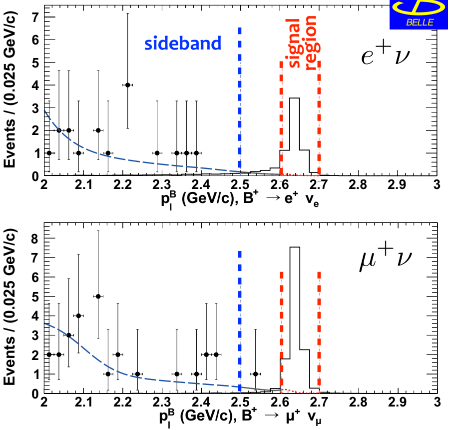
$\epsilon_{sig} = 0.104\%$

$N_{bkg} = 0.26^{+0.10}_{-0.08}$

- With full-recon., p_ℓ^B resolution is sharp enough to discern many such cases

$B^+ \to \ell^+ \nu_\ell$ results (Belle)

arXiv:1406.6356 ***submitted to PRD***



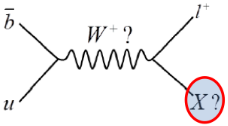
Mode	ϵ_s [%]	N_{obs}	N_{exp}^{bkg}
$B^+ \to e^+\nu$	0.086	0	0.10 ± 0.04
$B^+ \to \mu^+\nu$	0.102	0	$0.26^{+0.09}_{-0.08}$

$$\mathcal{B}(B^+ \to e^+\nu_e) < 3.4 \times 10^{-6}$$

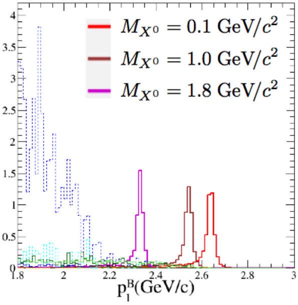
$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 2.7 \times 10^{-6}$$

both @ 90% CL w/ Feldman-Cousins method

$B^+ \to \ell^+ X^0$



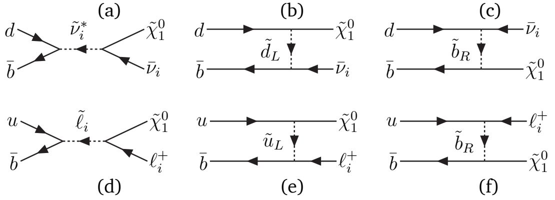
not seen in the detector



- Search for massive neutral invisible fermion X^0

  Dedes, Dreiner, Richardson, PRD 65, 015001 (2001)

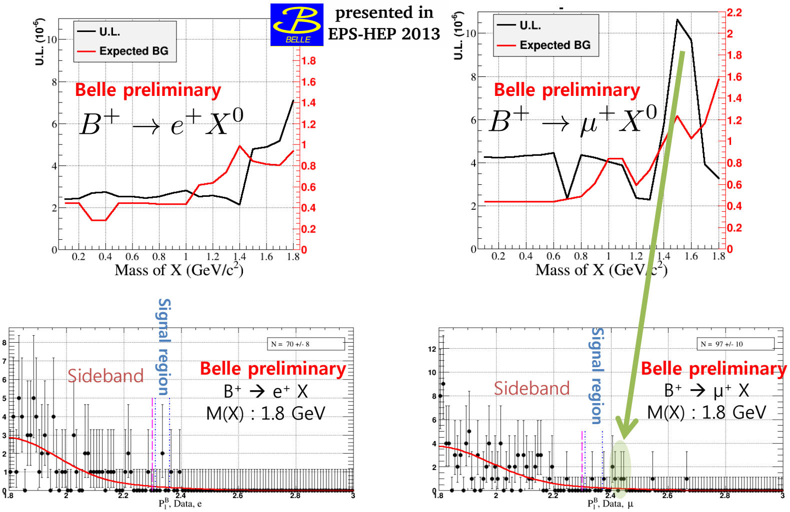
  $\mathcal{B}_{\mathrm{RPV}} \sim \mathcal{O}(10^{-7})$



Neutralino production in B-meson decays : (a-c) $B_d^0 \longrightarrow \bar{\nu}_i \tilde{\chi}_1^0$, and (d-f) $B^+ \longrightarrow \ell_i^+ \tilde{\chi}_1^0$

- Experimentally, very similar to $B^+ \to \ell^+ \nu_\ell$
- But, p_ℓ^B gives a handle on M_X

$B^+ \to \ell^+ X^0$ Results

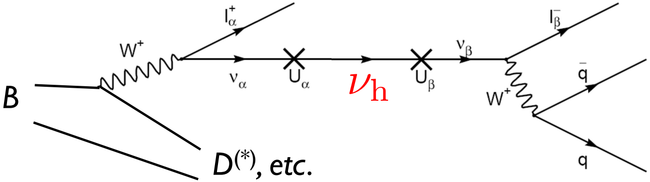


presented in EPS-HEP 2013

Heavy ν search (Belle)

See back-up slides for this!

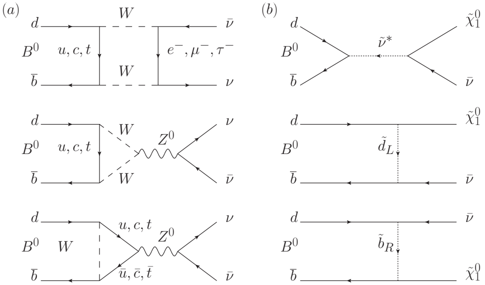
- Search for $B \to (X)\ell_2^+\nu_\mathrm{h}$ with $\nu_\mathrm{h} \to \ell_1^\pm\pi^\mp$.
  If ν_h is of Dirac type, $\nu_\mathrm{h} \to \ell_1^-\pi^+$.



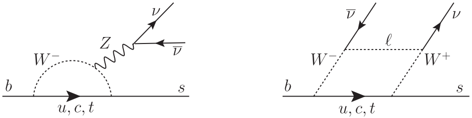
(semi-)invisible B modes (BABAR/Belle)

See back-up slides for these modes!

- $B^0 \to \nu\bar{\nu}(\gamma)$



- $B^0 \to h^{(*)}\nu\bar{\nu}$



Closing words

- The production mechanism of B mesons in the e^+e^- B-factories make it possible to study B decay modes with large missing energies.
  - * Techniques of tagging hadronic or semi-leptonic B decay modes has been greatly improved and exploited. They will become even more powerful tools for Belle II.

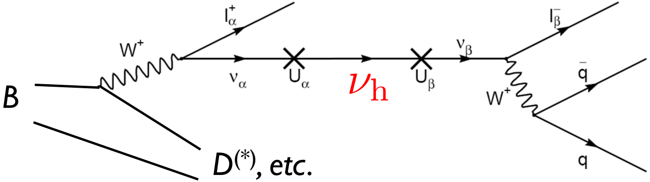
- Many interesting results on leptonic B decays (including $B \to D^{(*)}\tau^+\nu_\tau$), with a large missing energy due to missing neutrino(s), are available from Belle and *BABAR*.
  - * Great sensitivity to NP (*complementary to LHC*), especially for H^+
  - * Stay tuned for updated $B \to D^{(*)}\tau^+\nu_\tau$ from Belle!

Back-up materials

Heavy ν search

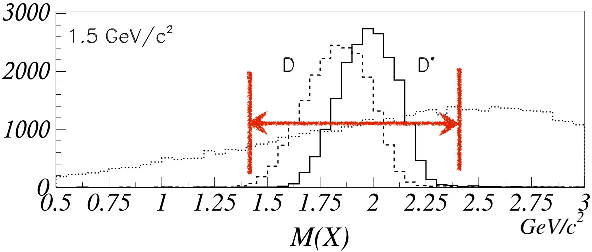
- Motivation
  - Within the minimal SM, ∃ no place for ν_R.
    But with ν oscillations, we need ν_R for $m_\nu \neq 0$. In what capacity do we have it?
  - Heavy neutrinos ("ν_h") appear in many BSM hypotheses.
    The ν_h's might even be of Majorana type.

- Search for $B \to (X)\ell_2^+ \nu_h$ with $\nu_h \to \ell_1^\pm \pi^\mp$.
  If ν_h is of Dirac type, $\nu_h \to \ell_1^- \pi^+$.



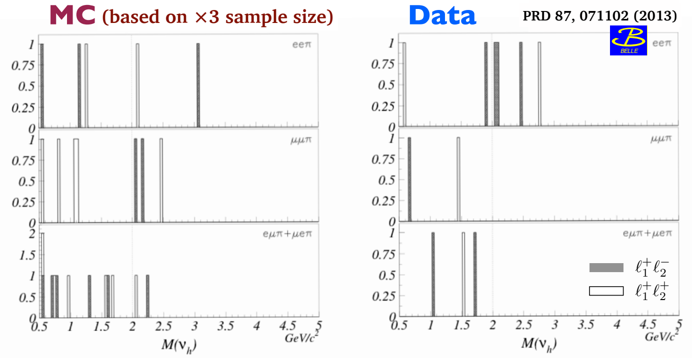
Heavy ν search (Belle)

- Separately for large and small $M(\nu_h)$
  - * "small" $M(\nu_h) < 2.0$ GeV/c^2: $X = D,\ D^*$ only
    $D^{(*)}$ is identified by "missing mass": $M_X^2 \equiv (E_{CM} - E_{\ell_1\ell_2\pi})^2 - P^2_{\ell_1\ell_2\pi} - P_B^2$
  - * "large" $M(\nu_h) \geq 2.0$ GeV/c^2: $X = D^{(*)}$, light meson, "nothing"



Heavy ν search (Belle) *Results*

mode	MC expected	Data
$ee\pi$	1.7 ± 0.7	6 ± 2.4
$\mu\mu\pi$	2.3 ± 0.9	2 ± 1.4
$e\mu\pi + \mu e\pi$	4.0 ± 1.2	3 ± 1.7

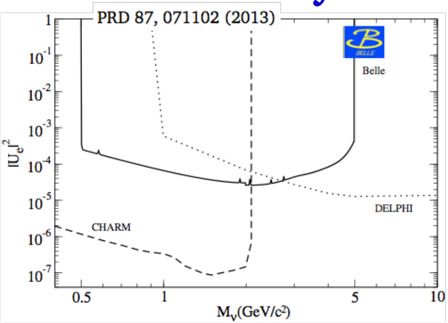


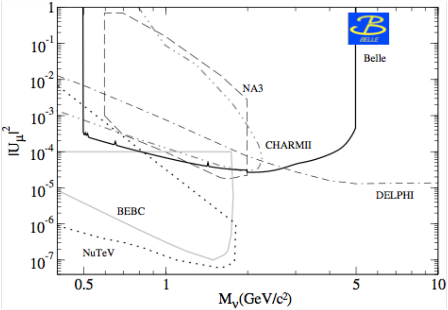
MC (based on ×3 sample size)

Data

PRD 87, 071102 (2013)

Heavy ν search *Results*


PRD 87, 071102 (2013)



- Upper limits on $\nu_\mathrm{h} - \nu_\ell$ mixing ($|U_\ell|^2$) are obtained, in the range $0.5 < M(\nu_\mathrm{h}) < 5$ GeV/c^2.

  Maximum sensitivity is reached at $M(\nu_\mathrm{h}) \sim 2$ GeV/c^2.

- Upper limit for product branching fraction (for $M(\nu_\mathrm{h}) = 2$ GeV/c^2):

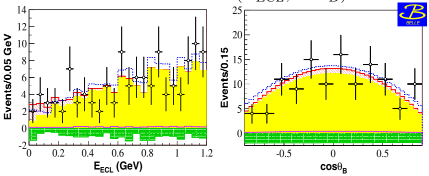
  $\mathcal{B}(B \to \ell_2 \nu_\mathrm{h}(X)) \times \mathcal{B}(\nu_\mathrm{h} \to \ell_1 \pi) < 7.2 \times 10^{-7}$ for $\ell = e,\ \mu$.

$B^0 \to \nu\bar{\nu}(\gamma)$

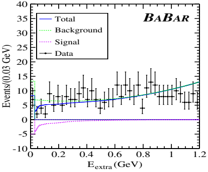
- (SM) strongly helicity-suppressed by $\mathcal{O}(m_\nu^2/m_B^2)$ Buchalla, Buras, NPB 400, 225 (1993)
  $\mathcal{B}_{\text{SM}}(B^0 \to \nu\bar{\nu}) \sim \mathcal{O}(10^{-20})$
- NP models predict significant branching fractions, e.g.
  $10^{-7} < \mathcal{B}(B^0 \to \bar{\nu}\tilde{\chi}_1^0) < 10^{-6}$ Dedes, Dreiner, Richardson, PRD 65, 015001 (2001)
- Results (upper limits @ 90% CL)

mode	$\mathcal{B}$ (in 10^{-5})	note	ref.
$B^0 \to \nu\bar{\nu}$	< 13	Belle, hadronic B-tag	PRD 86, 032002 (2012)
	< 2.4	BaBar, $B^0 \to D^{(*)-}\ell^+\nu$ tag	PRD 86, 051105 (2012)
$B^0 \to \nu\bar{\nu}\gamma$	< 1.7	BaBar, $B^0 \to D^{(*)-}\ell^+\nu$ tag	PRD 86, 051105 (2012)

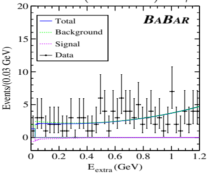
$B^0 \to \nu\bar{\nu}$ 2D fit to $(E_{\text{ECL}}, \cos\theta_B)$



$B^0 \to$ (invisible)



$B^0 \to$ (invisible) $+\gamma$



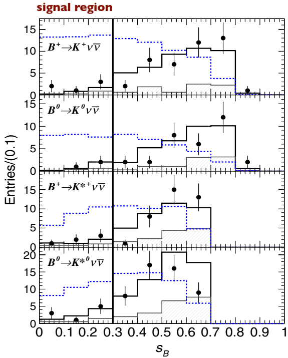
$B^0 \to h^{(*)}\nu\bar{\nu}$

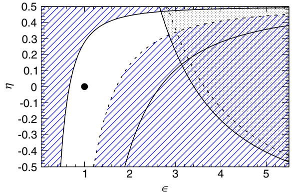
Expected theory

- (SM) $\mathcal{B}(B \to K\nu\bar{\nu}) = (4.5 \pm 0.7) \times 10^{-6}$ Altmannshofer, et al., JHEP 0904:022 (2009)
  $\mathcal{B}(B \to K^*\nu\bar{\nu}) = (3.8^{+1.2}_{-0.6}) \times 10^{-6}$
- many NP models (e.g. unparticle, SUSY at large tan β, models with scalar WIMP, etc.) predict $\mathcal{B} \sim \mathcal{O}(10) \times \mathcal{B}_{\rm SM}$

BaBar PRD 87, 112005 (2013)

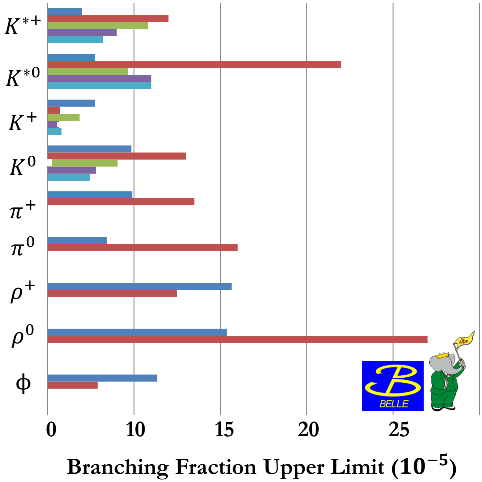
- ○ hadronic B-tagging
- ○ counting in signal regions of $E_{\rm extra}$ and $s_B (= q^2/m_B^2)$
- $\ast$ $\Delta\mathcal{B}(s_B)$, too
- $\ast$ constraints on $|C_L^\nu|$, $|C_R^\nu|$





$$\epsilon \equiv \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\rm SM}^\nu|}, \qquad \eta \equiv \frac{-{\rm Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

$B^0 \to h^{(*)}\nu\bar{\nu}$



Belle 2013, 772M $B\bar{B}$, Had.
Belle 2007, 535M $B\bar{B}$, Had.

Babar 2013, 471M $B\bar{B}$, Had.
Babar, 08' 10', ~460M $B\bar{B}$, SL.
Babar, Combined.

Had. : Hadronic Tagging Method
SL. : Semi-leptonic Tagging Method

Belle 2007 : PRL 99, 221802 (2007).
Babar 08' : PRD 78, 072007 (2008).
Babar 10' : PRD 82, 112002 (2010).

Belle 2013 : PRD 87, 111103
BaBar 2013 : PRD 87, 112005

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* Belle 2013 supersede Belle 2007

Summary plot from Y. Yook talk @FPCP 2013.