Rare B decays with neutrinos at the B-factories

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On behalf of the BaBar and Belle collaborations

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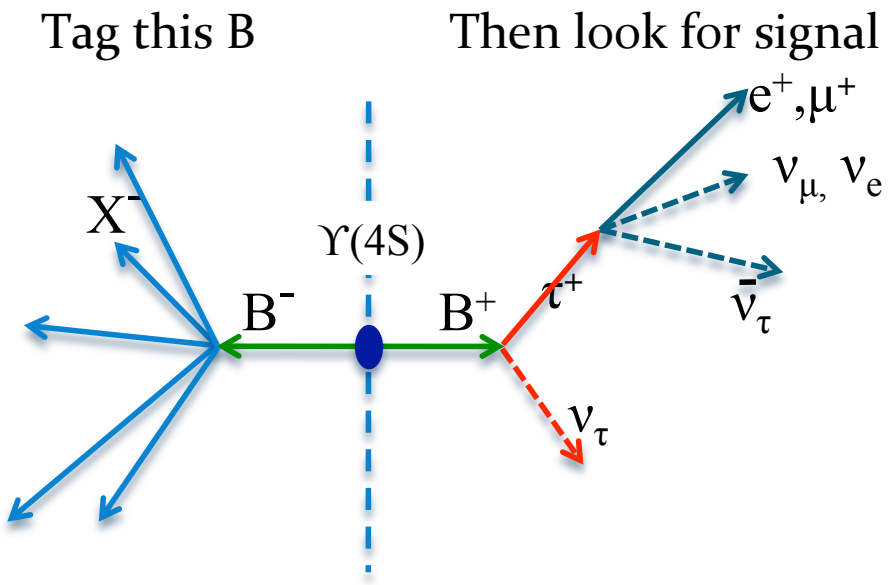
Maale Hachamisha, Israel, May 26th 2011

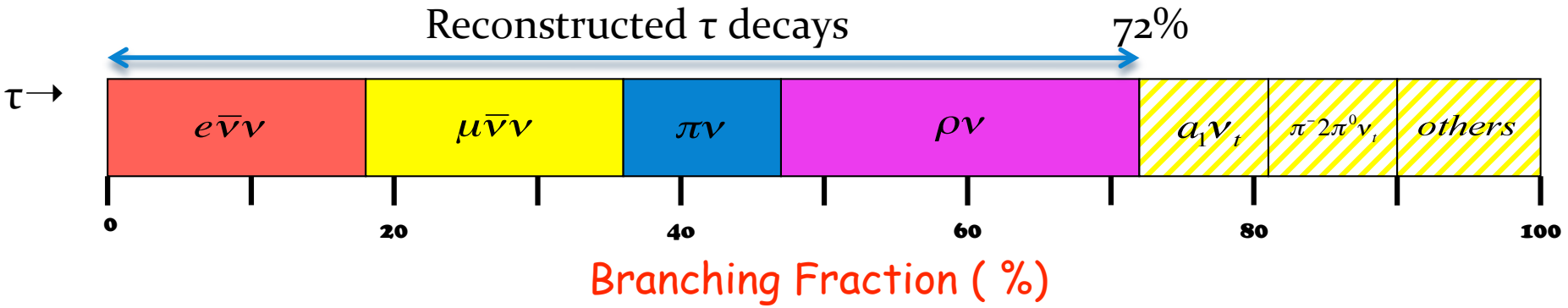
Outline

- Brief description of the "Recoil Method" tagging technique
- Leptonic B decays
  - $B \to \tau \nu$, $B \to e \nu, \mu \nu$ and $B \to \mu \nu \gamma$
- Rare $b \to s(d) \nu \nu$ decays
  - $B \to K^{(*)} \nu \nu$, and other $h \nu \nu$
  - $B \to K \tau \tau$

B tagging

- Weak signal signature
  - Decay with missing momentum (many neutrinos in the final state)
  - Lack of kinematics constraints in final state
- background rejection improved identifying the companion B (tag)
- Look for signal in the rest of the event
  - Expect to find nothing more than visible signal decay products and no activity in the calorimeter

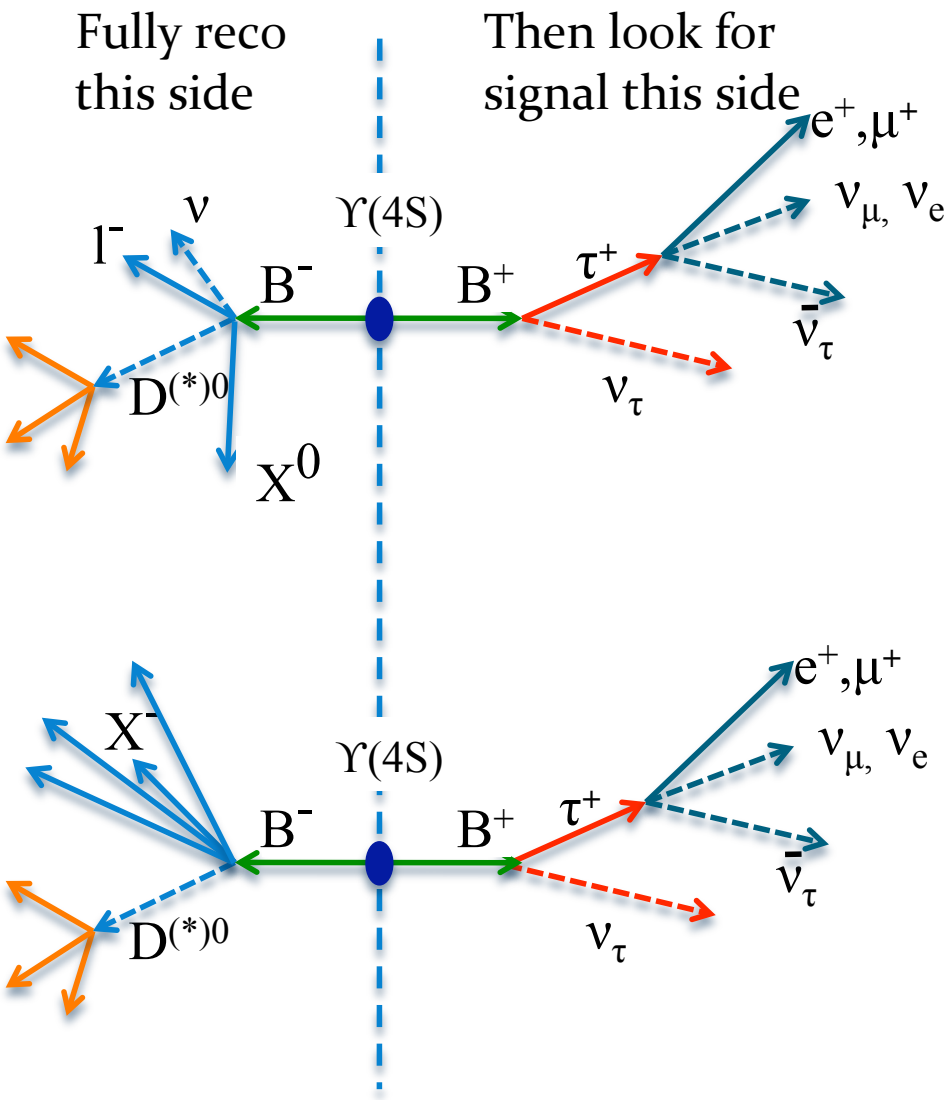




Two kinds of tag exploited

- Semileptonic B decays
  - $B \rightarrow D^* l \nu$
  - PRO: Higher efficiency ε_{tag} ~ 1.5%
    CON: more backgrounds, B momentum unmeasured

- Hadronic B decays with charm
  $B^+ \rightarrow D^{(*)0} X^+$ or $B^0 \rightarrow D^{(*)+} X^-$
  X is a charged system of hadrons among (π, K, π^0, K_s) up to 5 charged particles and 2 neutrals
  - PRO: cleaner events,
    B momentum reconstructed
    CON: smaller efficiency ε_{tag} ~ 0.15%



Tag reconstruction

Hadronic tags:

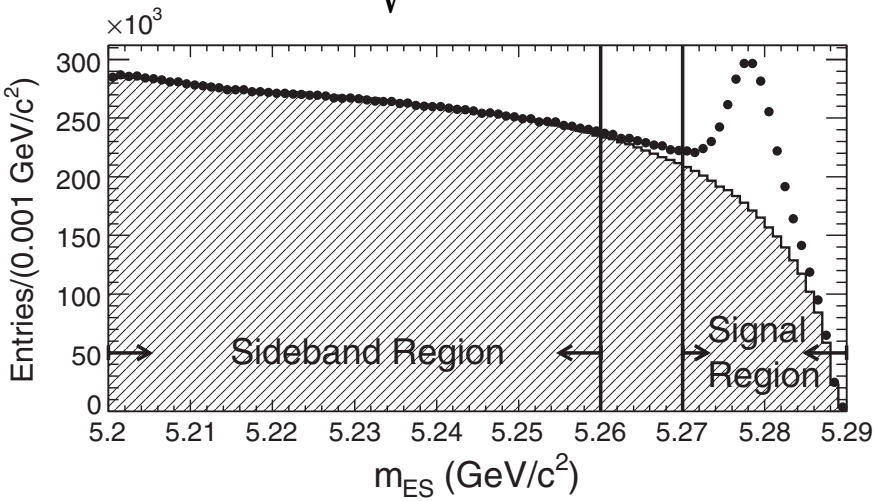
Full reconstruction of the B decay chain.

Requirements on the quality of the tag are analysis dependent

Possible to separate the "combinatorial" wrong tags from correct (peaking) tags in data

$$\Delta E = \sqrt{s}/2 - E_B$$

$$m_{ES} = \sqrt{s/4 - p_B^2}$$

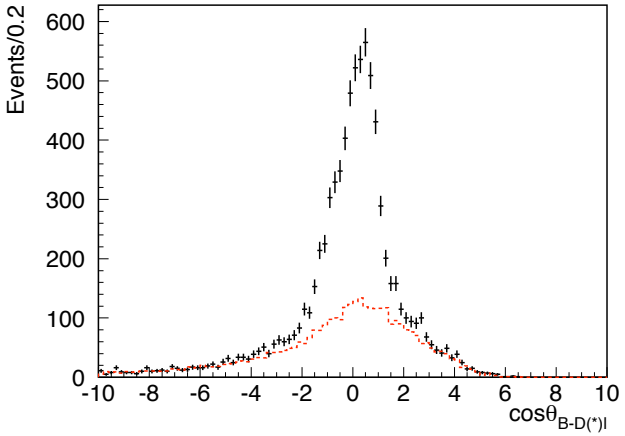


Semileptonic tags:

Recontruct Y = D-l pair.

Kinematics and known B meson energy determine the angle between B and Y.

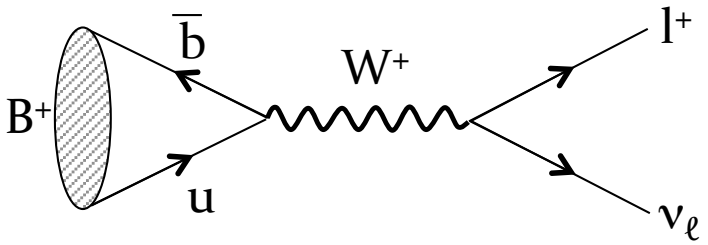
$$\cos\theta_{B,Y} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$



$B \rightarrow \tau\nu$

- Both tag reconstruction techniques used at B-factories
  - 4 independent measurements of the BF

B → l ν decays in the SM



$$\mathcal{B}(B \to l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

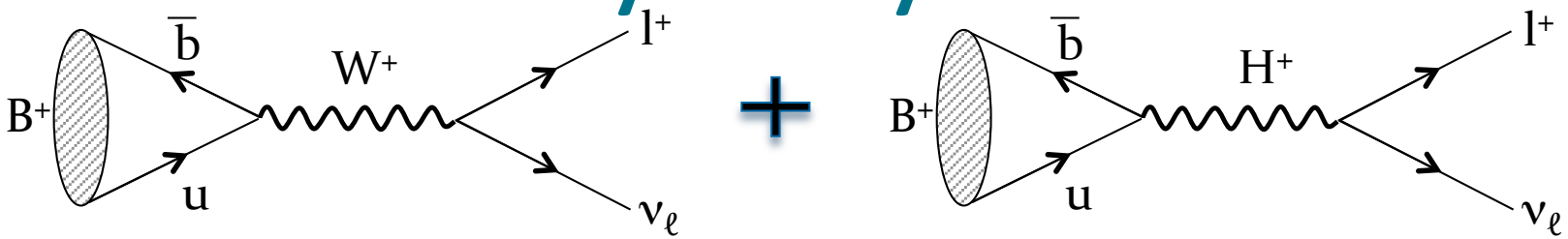
Helicity suppression

Experimental sensitivity to f_B assuming V_{ub}

- Can be used to measure the B meson decay constant f_B assuming V_{ub}
- Vub (exp.+theory) and f_B (theory) uncertainties dominate the SM expectation uncertainty:
  - Using $f_B = 190 \pm 13$ MeV * and $V_{ub} = (3.5 \pm 0.4) \times 10^{-3}$ **
    $BF_{SM}(B \to \tau\nu) = (0.80 \pm 0.20) \times 10^{-4}$

*HPQCD collaboration arXiv:0902.1815v2
** UTFit and CKM fitter collaborations

B → l ν decays beyond the SM



- Additional tree level contribution from a charged Higgs
  - Branching fraction theoretical expression depends on the NP model

$$\mathcal{B}(B \to l\nu)_{2HDM} = \mathcal{B}(B \to l\nu)_{SM} \times (1 - tan^2\beta \frac{m_B^2}{m_H^2})^2$$

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

$$\mathcal{B}(B \to l\nu)_{SUSY} = \mathcal{B}(B \to l\nu)_{SM} \times (1 - \frac{tan^2\beta}{1 + \epsilon_0 tan\beta} \frac{m_B^2}{m_H^2})^2$$

A.G. Akeroyd and S.Recksiegel J.Phys.G29, 2311 (2003)

- B → τν measurement used to set 90% exclusion regions in the plane of NP parameters $M_H \times \tan\beta$

Signal Selection

- Exploit kinematics and topology of in the signal side
  - Single charged tracks passing particle identification criteria
  - Requirement on CMS momentum for 1 prong modes
  - More constraints for $\tau \rightarrow \pi\pi^0\nu$

- Most discriminating variable residual energy in the calorimeter (E_{extra})
  - Defined as the total energy of clusters passing a minimum energy requirement
  - Used in a maximum likelihood fit to determine the branching fraction
- E_{extra} distribution validated with the use of double-tagged events
- Simultaneous fit of the BF to E_{extra}

$$\mathcal{L}_k = e^{-(n_{s,k}+n_{b,k})} \prod_{i=1}^{N_k} \left\{ n_{s,k}\mathcal{P}_k^s(E_{i,k}) + n_{b,k}\mathcal{P}_k^b(E_{i,k}) \right\}$$

$$n_{s,k} = N_{B\overline{B}} \times \epsilon_k \times BF$$

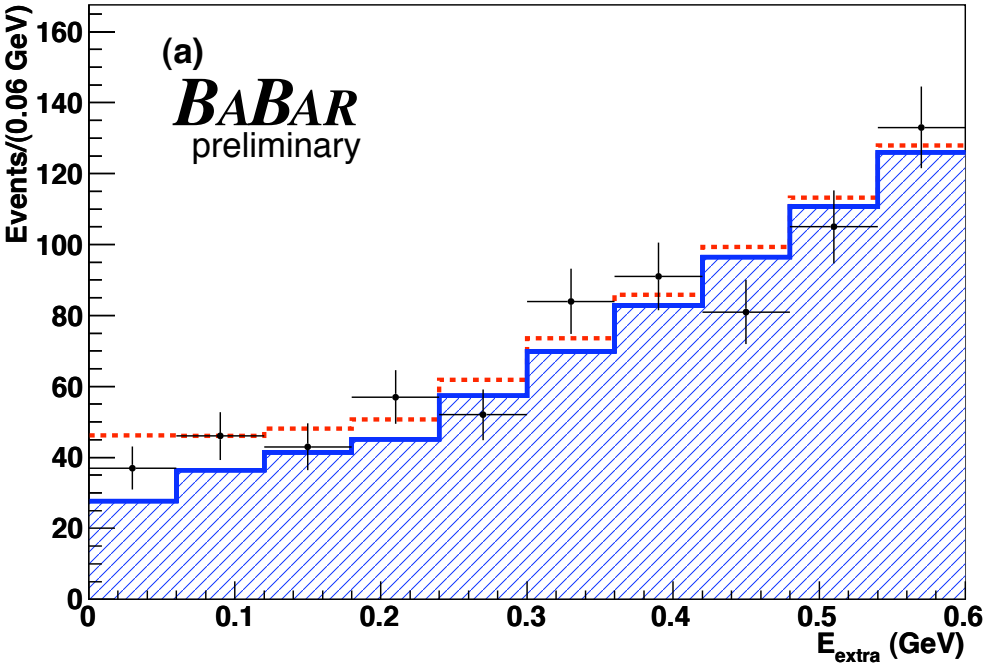
BaBar Hadronic tags

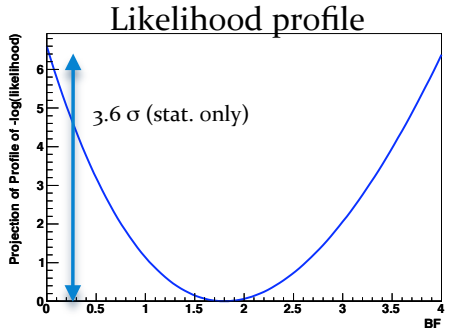
arXiv:1008.0104[hep-ex]
468 M B pairs

Combinatorial background estimated from data, B^+ background shape from MC

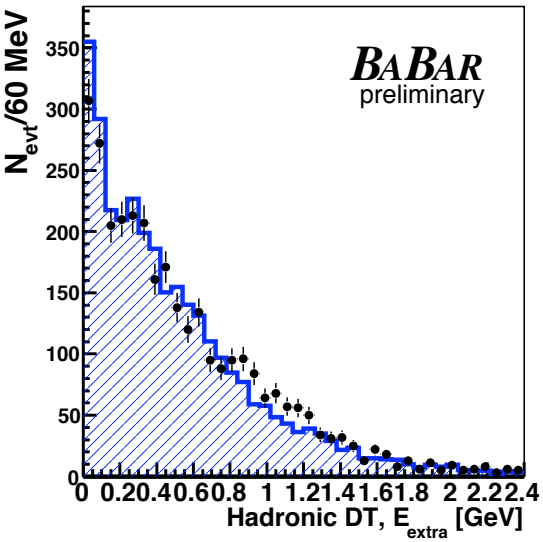
Fit to E_{extra} distribution show an excess of events excluding null hypothesis at 3.3 σ

$$\mathcal{B}(B \to \tau\nu) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$$ PRELIMINARY





MC modelling of signal E_{extra} PDF checked with double tags



Belle Hadronic tags

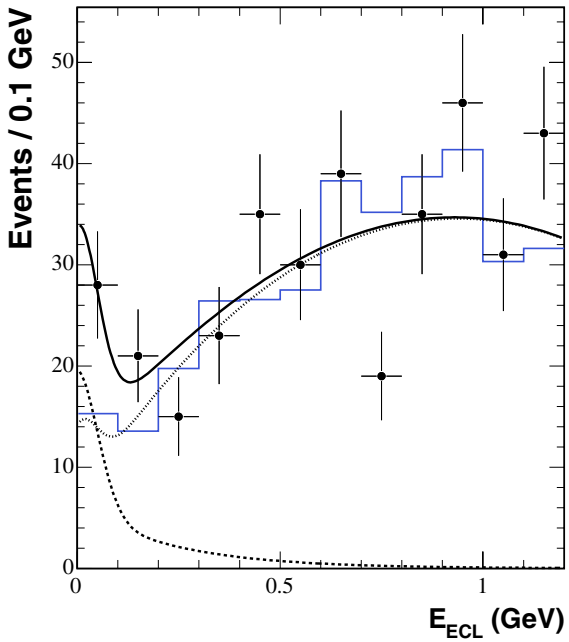
Phys. Rev. Lett. 97, 251802 (2006)
449 M B pairs

Combinatorial background estimated from data

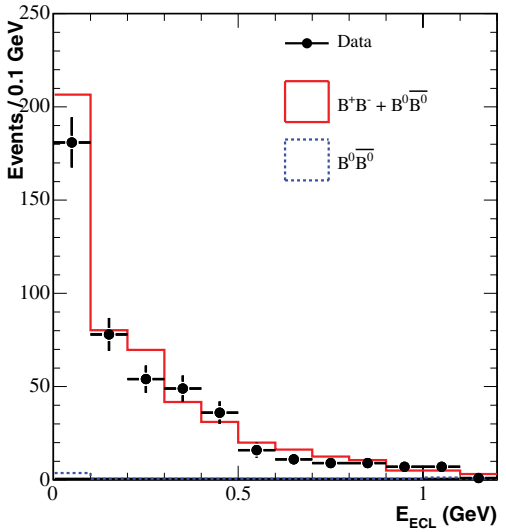
polynomial PDF for background, plus a peaking background form MC. Gaussian PDF for signal

Excess of events excludes null hypothesis at 3.3 σ

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



MC modelling of E_{extra} checked with double tags

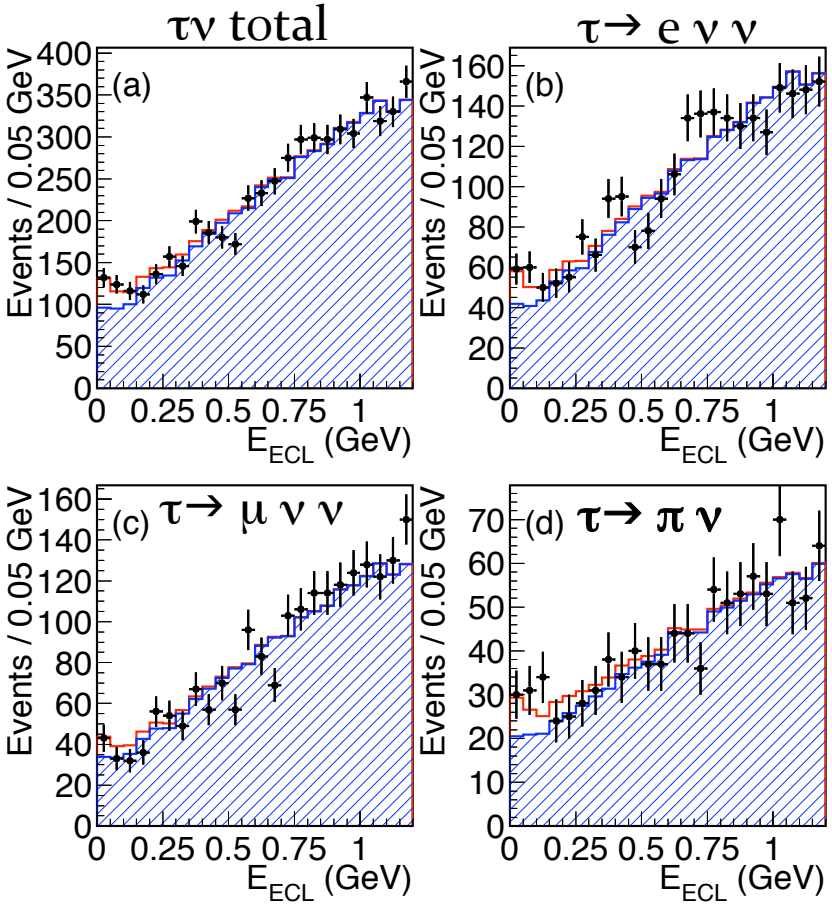


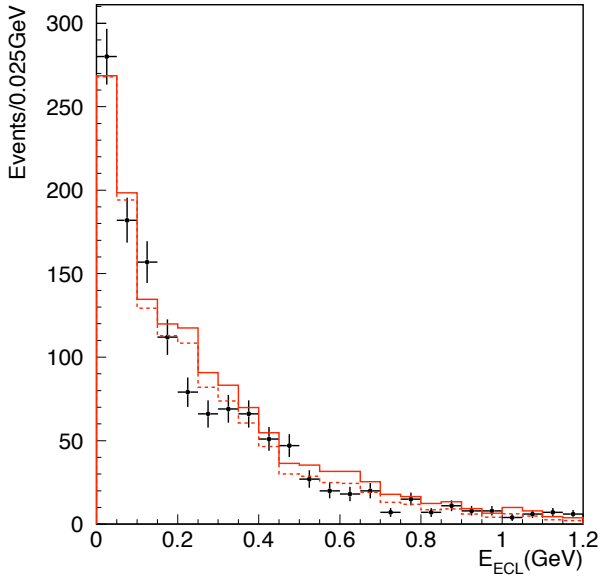
Belle SL tags

Phys. Rev. D 82,071101(R) (2010)
657 M B pairs

- Excluding null hypothesis at 3.6 σ

$$\mathcal{B}(B \to \tau\nu) = (1.54^{+0.38}_{-0.37}(\text{stat.})^{+0.29}_{-0.31}) \times 10^{-4}$$

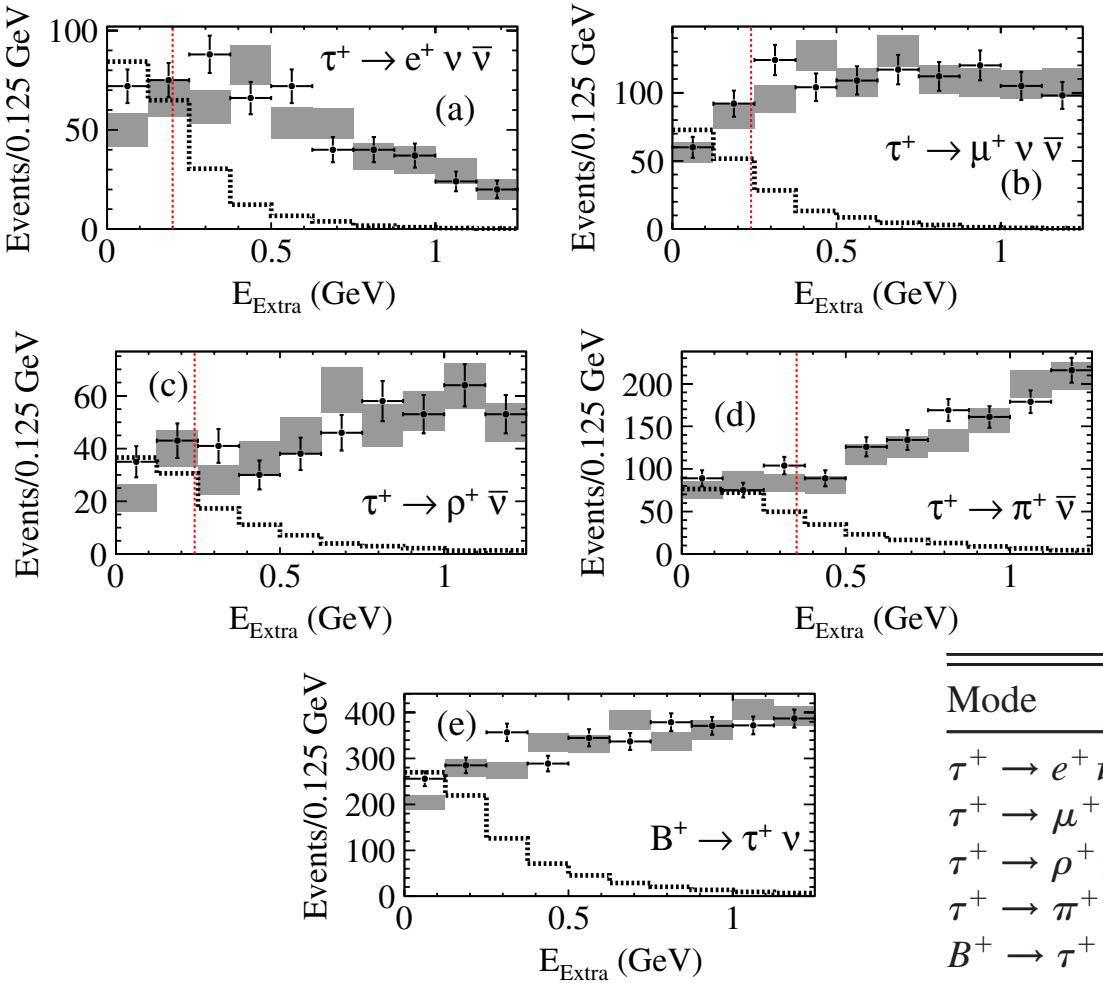




Decay Mode	Signal Yield	ε, 10^{-4}	$\mathcal{B}$, 10^{-4}
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$	73^{+23}_{-22}	5.9	$1.90^{+0.59}_{-0.57}{}^{+0.33}_{-0.35}$
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$	12^{+18}_{-17}	3.7	$0.50^{+0.76}_{-0.72}{}^{+0.18}_{-0.21}$
$\tau^- \to \pi^- \nu_\tau$	55^{+21}_{-20}	4.7	$1.80^{+0.69}_{-0.66}{}^{+0.36}_{-0.37}$
Combined	143^{+36}_{-35}	14.3	$1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}$

Phys. Rev. D 81,051101(R) (2010)
459 M B pairs

BaBar SL tags



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

Consistent with null hypothesis at 2.3 σ

Mode	$\mathcal{N}_{bg}^{data}$	N_{obs}	Branching fraction ($\times 10^{-4}$)
$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$	81 ± 12	121	(3.6 ± 1.4)
$\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$	135 ± 13	148	$(1.3^{+1.8}_{-1.6})$
$\tau^+ \to \rho^+ \bar{\nu}_\tau$	59 ± 9	71	$(2.1^{+2.0}_{-1.8})$
$\tau^+ \to \pi^+ \bar{\nu}_\tau$	234 ± 19	243	$(0.6^{+1.4}_{-1.2})$
$B^+ \to \tau^+ \nu_\tau$	509 ± 30	583	$(1.7 \pm 0.8 \pm 0.2)$
$B^+ \to \mu^+ \nu_\mu$	13 ± 8	12	<0.11 (90% C.L.)
$B^+ \to e^+ \nu_e$	24 ± 11	17	<0.08 (90% C.L.)

BF summary

BABAR Hadronic tags (468 M B-pairs)

$\mathcal{B}(B \to \tau\nu) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$

arXiv:1008.0104[hep-ex]

BABAR Semi-leptonic tags (459 M B-pairs)

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

Phys. Rev. D 81, 051101(R) (2010)

BABAR combined

$\mathcal{B}(B \to \tau\nu) = (1.76 \pm 0.49) \times 10^{-4}$

BELLE Hadronic tags (449 M B-pairs)

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

Phys. Rev. Lett. 97, 251802 (2006)

BELLE Semi-leptonic tags (657 M B-pairs)

$\mathcal{B}(B \to \tau\nu) = (1.54^{+0.38}_{-0.37}(\text{stat.})^{+0.29}_{-0.31}) \times 10^{-4}$

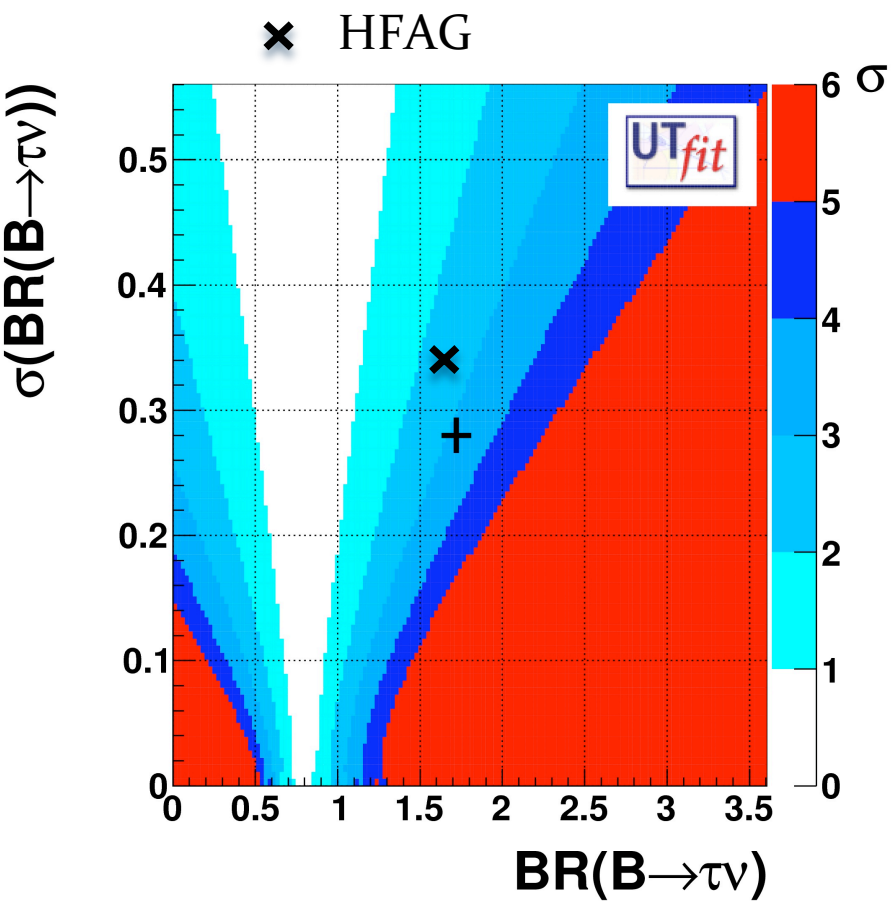
Phys. Rev. D 82, 071101(R) (2010)

HFAG average: $\mathcal{B}(B \to \tau\nu) = (1.64 \pm 0.34) \times 10^{-4}$

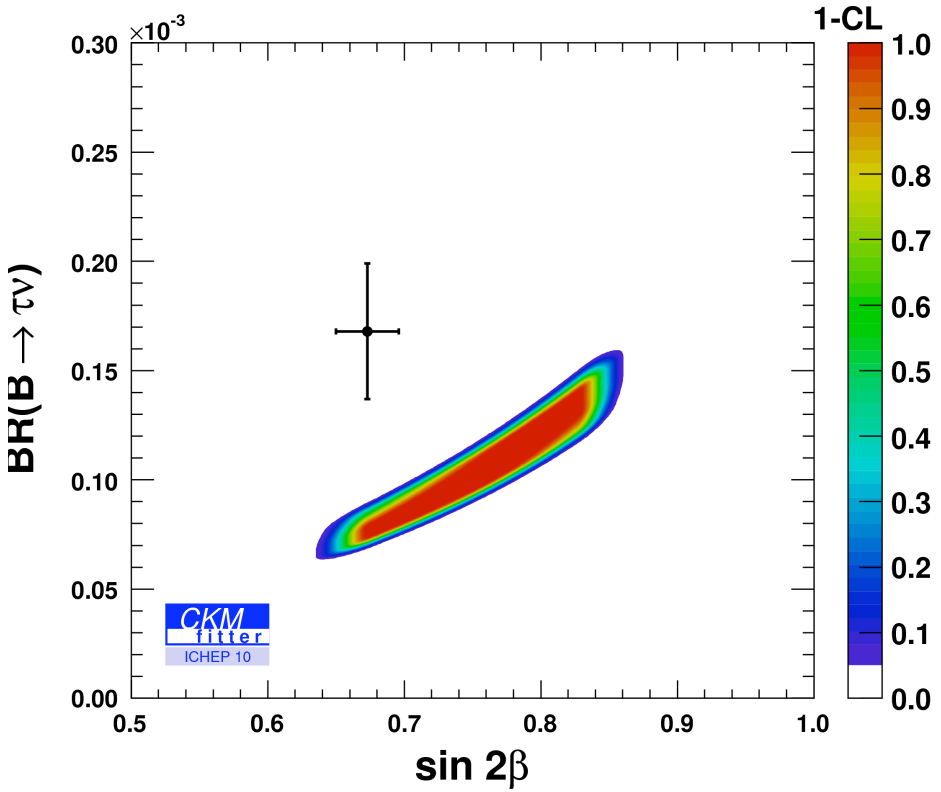
HFAG does not use the 2006 Belle hadronic tag result (www.slac.stanford.edu/xorg/hfag)

CKM fits compatibility

www.utfit.org



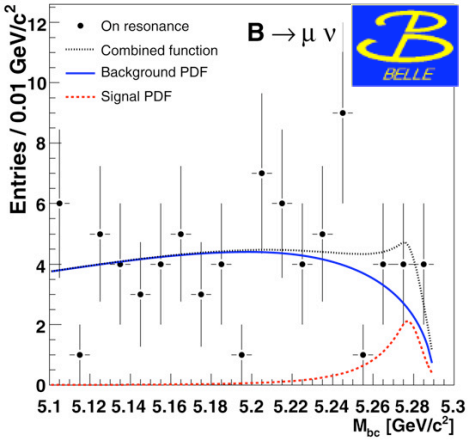
ckmfitter.in2p3.fr

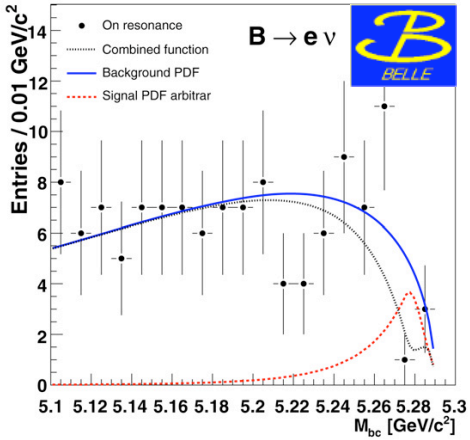


Phys. Rev. D 79,091101 (2009) 468 M B-pairs
Phys. Lett. B 647 (2007) 67

B → eν, μν untagged

- Monochromatic e or μ in B rest frame
  - Exploit kinematics and and topology of the rest of the event (no tag)
- No significant signal seen

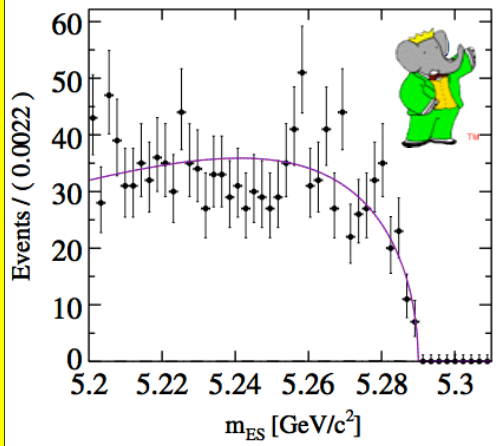


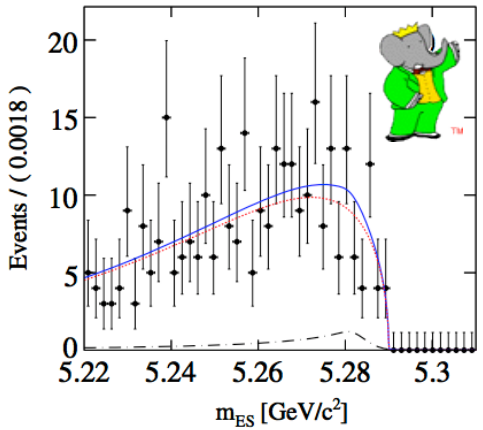


90% C.L. limits:

BF(B → eν) < 1.9 × 10^{-6} BABAR
BF(B → eν) < 0.98 × 10^{-6} BELLE

BF(B → μν) < 1.0 × 10^{-6} BABAR
BF(B → μν) < 1.7 × 10^{-6} BELLE





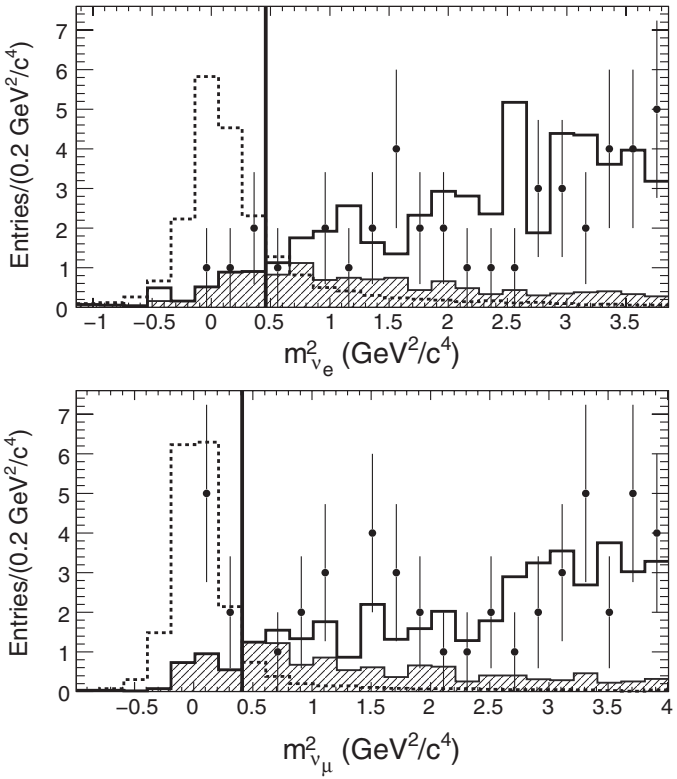
B → lνγ, hadronic tags

- Small excess for muon channel consistent with a 2.1 σ background fluctuation

Phys. Rev. D 80, 111105 (2009)
465 M B-pairs

	B→eνγ	B→μνγ
Expected bkg	2.7 ± 0.3 ±0.4	3.4 ± 0.7 ±0.7
Observed events	4	7
Signal efficiency	(7.8 ± 0.1 ±0.3) %	(8.1 ± 0.1 ±0.3)%
FC confidence limit	$<17 \times 10^{-6}$	$<26 \times 10^{-6}$
	$<15 \times 10^{-6}$	

Missing mass



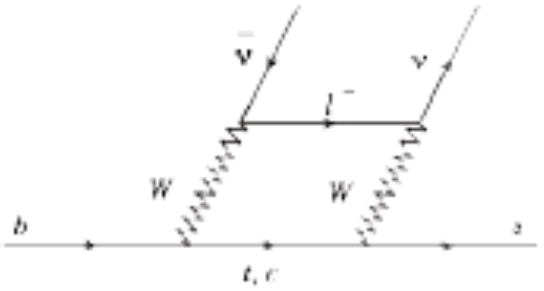
$B \to K^{(*)} \nu\nu$

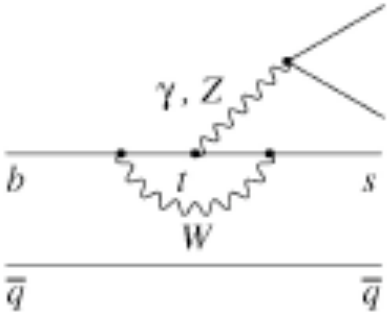
Mode	BaBar Had tag	BaBar SL tag	Belle Had tag	Belle SL tag
$K^+ \nu\,\nu$	✓	✓	✓	
$K_S \nu\,\nu$		✓	✓	
$K^{*+} \nu\,\nu$	✓	✓	✓	
$K^{*0} \nu\,\nu$	✓	✓	✓	
$\pi^+ \nu\,\nu$			✓	
$\pi^0 \nu\,\nu$			✓	
$\rho^+ \nu\,\nu$			✓	
$\rho^0 \nu\,\nu$			✓	
$\phi \nu\,\nu$			✓	

- Babar uses SL and had tags – Belle hadronic tags only
- Belle searched also for other non-kaonic modes

Motivation

- FCNC b to s transition in the SM by W box or Z penguin

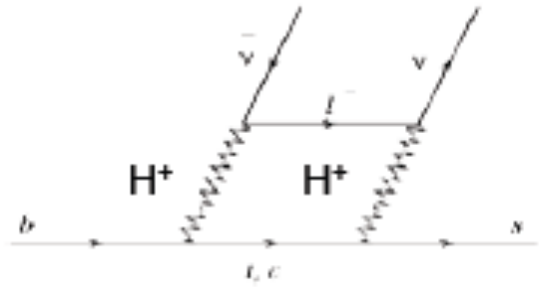


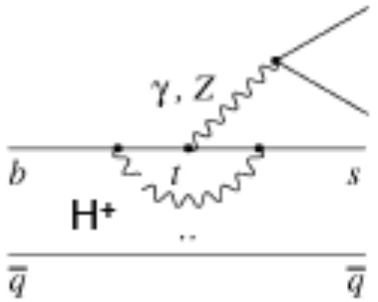


- Small SM branching fraction and final state with no hadronic uncertainties

BF ~ 4 times 10^{-6}

- Many new physics models may enhance the BF
  - Light scalars, MSSM, charged Higgs,…

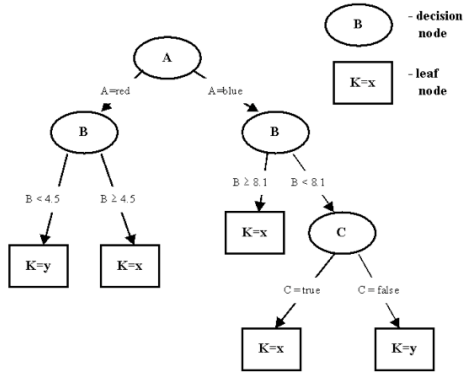


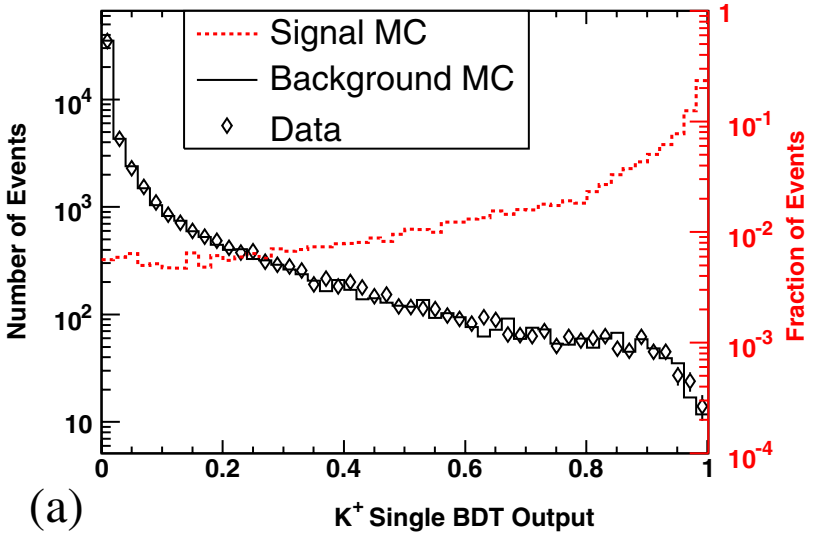


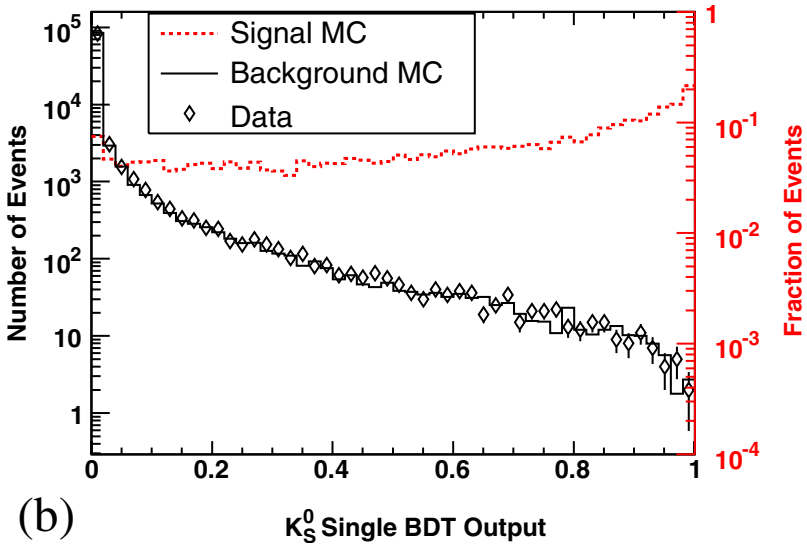
Phys. Rev. D 82, 112002 (2010)
459 M B pairs

BaBar $B^+ \to K^+ \nu \nu$ and $B^0 \to K_S \nu \nu$

- Semileptonic tags
- Multivariate analysis using bagged decision trees
  - Trained on MC simulated signal and background events
  - 26 (K^+) and 38(K_S) variables exploiting missing energy, event shape, kinematics and quality of the tag reconstruction



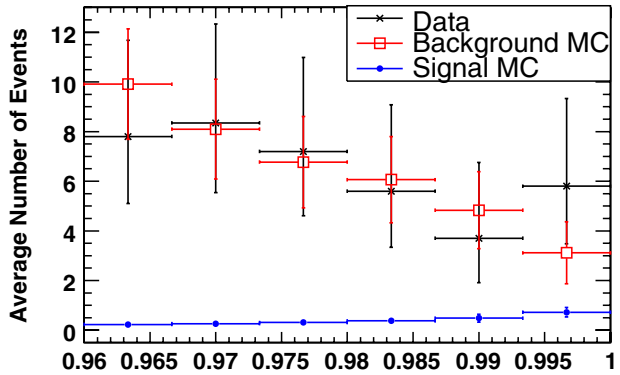


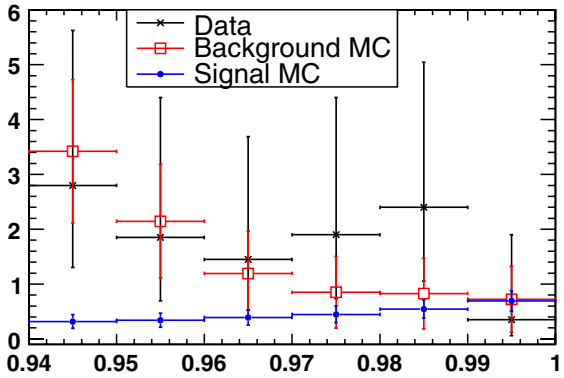


BaBar $B^+ \to K^+ \nu\nu$ and $B^0 \to K_S \nu\nu$

- No significant signal seen

Zoom in the signal region





Expected background

Mode	ϵ (in %)	N_{sgnl}	N_{bkgd}
K^+	0.16	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$
K^0_S	0.06	0.5 ± 0.1	$3.9 \pm 1.3 \pm 0.4$
low-q^2 K^+	0.24	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$
high-q^2 K^+	0.28	2.1 ± 0.3	$187 \pm 10 \pm 46$

Observed events

Mode	N_{obs}	N_{excess}	Prob.
K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$	38%
K^0	$6.1^{+4.0}_{-2.2}$	$2.2^{+4.1}_{-2.8}$	23%
low-q^2 K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$	38%
high-q^2 K^+	164^{+13}_{-13}	-23^{+49}_{-48}	33%

BF Upper limit

Mode	BF	90% CL	95% CL
	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$
K^+	$0.2^{+0.8}_{-0.7}$	1.3	1.6
K^0	$1.7^{+3.1}_{-2.1}$	5.6	6.7
Comb. K^+, K^0	$0.5^{+0.7}_{-0.7}$	1.4	1.7
Low-q^2 K^+	$0.2^{+0.6}_{-0.5}$	0.9	1.1
High-q^2 K^+	$-1.8^{+3.8}_{-3.8}$	3.1	4.6

460 M B pairs

BABAR $B^+ \to K^+ \tau^+ \tau^-$

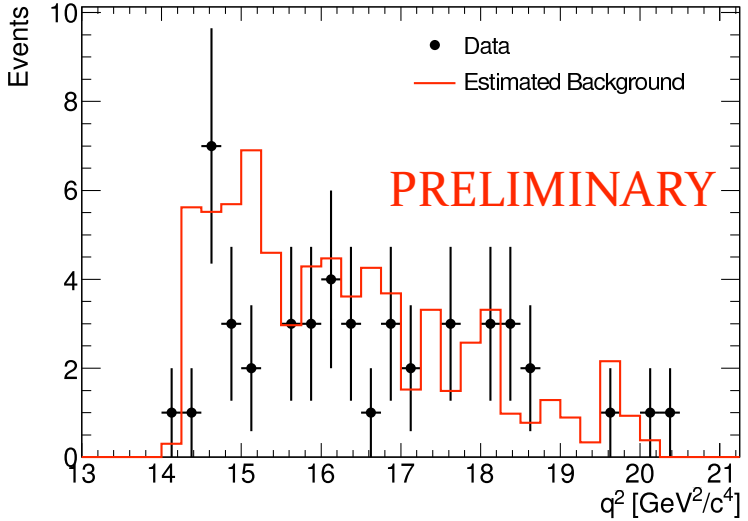
PRELIMINARY

- Hadronic tag
- 1 prong τ decays, exactly three tracks, particle ID
- Requirements on q^2, track momentum, event shape, missing momentum, residual energy in calorimeter

- Expected background events: 65 ± 7
- Observed events: 47
- Signal efficiency 4.4 x 10^{-4}

- No excess of events seen
- 90% CL upper limit set to BF < 3.3 10^{-3}

Momentum transfer to lepton pair q^2

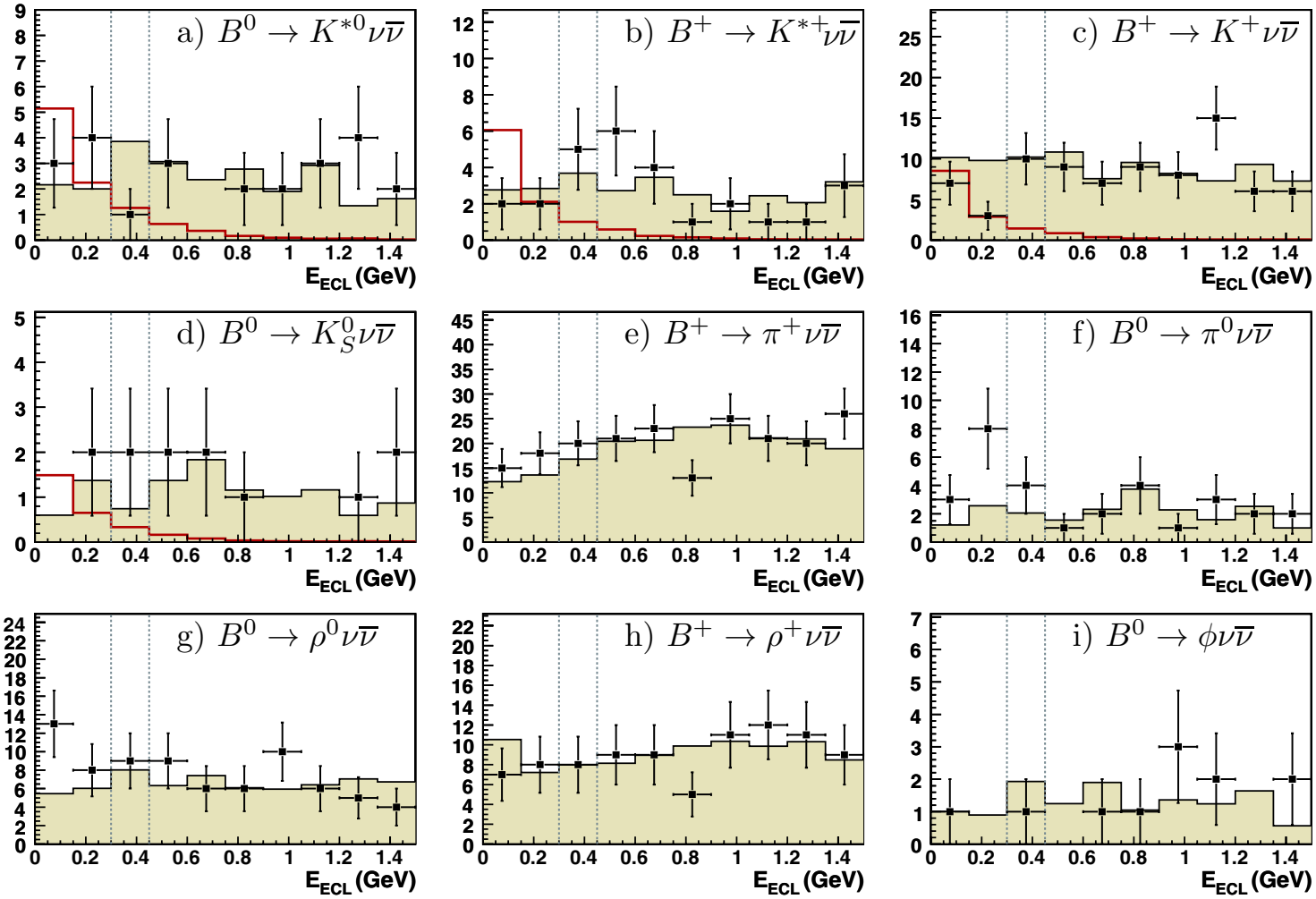


Phys. Rev. Lett. 99, 221802 (2007)
535 M B pairs

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

- Hadronic tags
- Reconstruction of many final states in the rest of the event
  - K^+, π^+, $K^{*+}(K\pi)$, $K^{*0}(K\pi)$, K_S $(\pi^+\pi^-)$, ρ^+, ρ^0, ϕ (KK)
- Selection requirements on signal-like kinematics and veto of extra charged particles or π^0.
- Requirement on the momentum of the hadron
- Extra energy in the calorimeter defines the signal region
  - Signal region is Eextra < 300 MeV
  - Sideband region 450 MeV < Eextra < 1.5 GeV
- Cut and count analysis
  - Background yield measured on the sideband and scaled using MC

Belle B → $h^{(*)}\nu\nu$



Belle B → $h^{(*)}\nu\nu$

- No evidence of signal in any mode
- Assessed 90% U.L. with Feldman-Cousins prescriptions

Mode	$N_{\rm obs}$	$N_{\rm side}$	N_b	$\epsilon(\times 10^{-5})$	U.L.
$K^{*0}\nu\bar{\nu}$	7	16	4.2 ± 1.4	5.1 ± 0.3	$<3.4 \times 10^{-4}$
$K^{*+}\nu\bar{\nu}$	4	18	5.6 ± 1.8	5.8 ± 0.7	$<1.4 \times 10^{-4}$
$\rightarrow K^0_S\pi^+$	1	7	2.3 ± 1.2	2.8 ± 0.3	
$\rightarrow K^+\pi^0$	3	11	3.3 ± 1.4	3.0 ± 0.4	
$K^+\nu\bar{\nu}$	10	60	20.0 ± 4.0	26.7 ± 2.9	$<1.4 \times 10^{-5}$
$K^0\nu\bar{\nu}$	2	8	2.0 ± 0.9	5.0 ± 0.3	$<1.6 \times 10^{-4}$
$\pi^+\nu\bar{\nu}$	33	149	25.9 ± 3.9	24.2 ± 2.6	$<1.7 \times 10^{-4}$
$\pi^0\nu\bar{\nu}$	11	15	3.8 ± 1.3	12.8 ± 0.8	$<2.2 \times 10^{-4}$
$\rho^0\nu\bar{\nu}$	21	46	11.5 ± 2.3	8.4 ± 0.5	$<4.4 \times 10^{-4}$
$\rho^+\nu\bar{\nu}$	15	66	17.8 ± 3.2	8.5 ± 1.1	$<1.5 \times 10^{-4}$
$\phi\nu\bar{\nu}$	1	9	1.9 ± 0.9	9.6 ± 1.4	$<5.8 \times 10^{-5}$

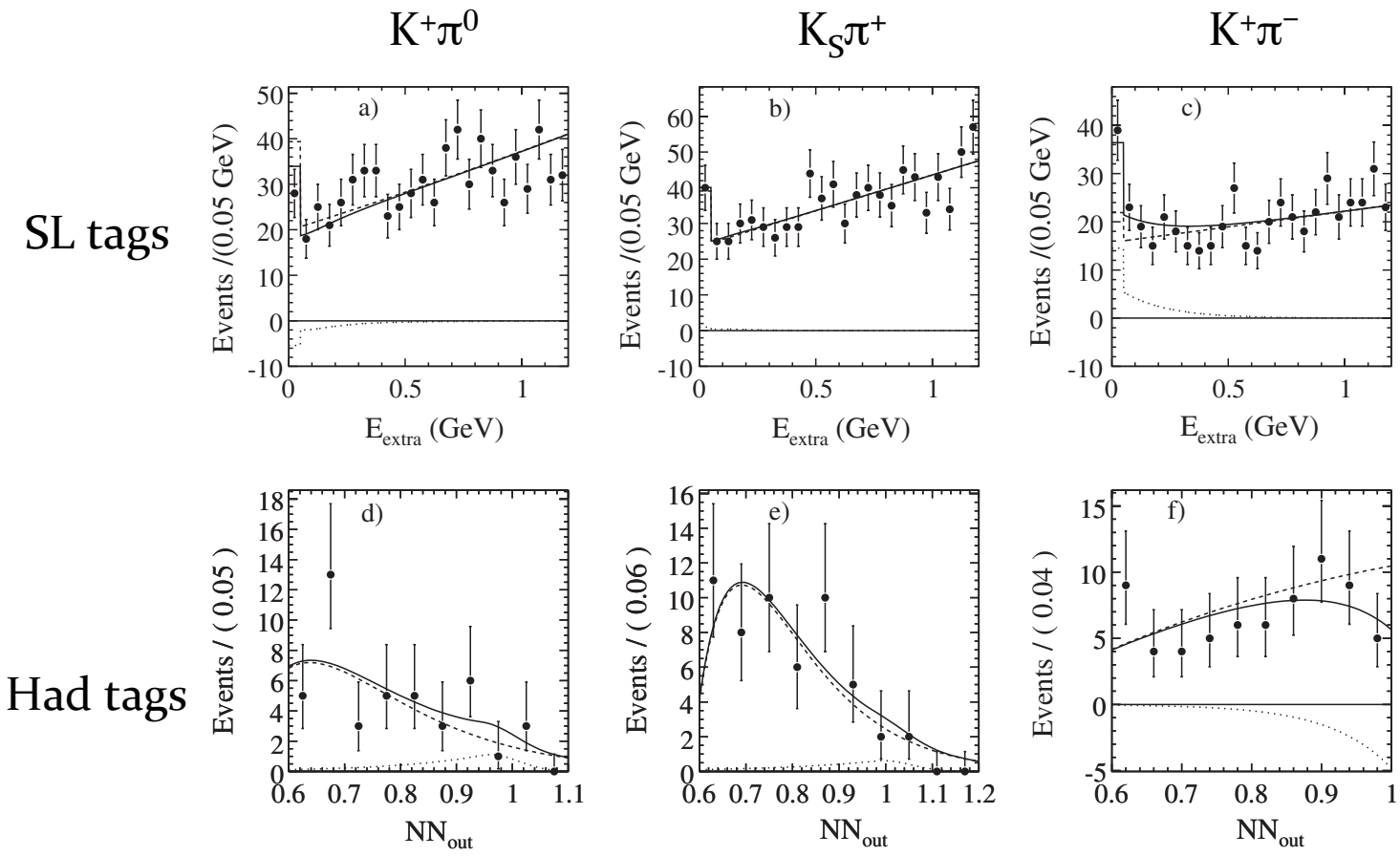
Phys. Rev. D 78, 072007 (2008)
454 M B pairs

BaBar $B \rightarrow K^{(*)} \nu \nu$

- Both hadronic and semileptonic tagging
- Final state K^{*+} ($K^+\pi^0$, $K_s\pi^+$) and $K^{*0}(K\pi)$
- Signal selection based on event shape, tag reconstruction quality, missing momentum
- Hadronic tag analysis combines the variables in a Neural net

- Signal yield extracted by a maximum likelihood fit to
  - Residual energy in the calorimeter (SL tag analysis)
  - NN distribution (hadronic tags)

BaBar B → K(*) ν ν



B($B^+ \to K^{*+} \nu$) < 8 ×10^{-5}

B($B^0 \to K^{*0} \nu$) < 12 ×10^{-5}

Conclusions

- $B \to \tau\nu$ measurement well-established
  - 4 independent measurements consistent among one another
  - HFAG average (no Belle with had tag) is $BF(B \to \tau\nu) = (1.63 \pm 0.34) \times 10^{-4}$
    - My naïve average of all mesurements is $BF(B \to \tau\nu) = (1.67 \pm 0.31) \times 10^{-4}$
  - Intriguing disagreement with rest of CKM according to UTFit and CKMFitter collaborations
- No signal seen in the other leptonic B decay modes and $B \to K(*)\nu\nu$ searches
  - Most stringent upper limit is on $B^+ \to K^+\nu\nu$ at 3-4 times the SM prediction

Future prospects

- Leptonic B decays and b → s ν ν are clean modes to look for evidence of new physics
- Experimentally challenging. Feasible only at e^+e^- machines
- Results may be refined at current B-factories exploiting the full dataset (Belle) or working hard to improve the tagging
- Golden modes for the next generation of B-factories that will take data at unprecedented luminosity
  - See tomorrow talks from B. Ratcliff on SuperB and T. Browder on Belle II