Searches for $b \to s,d\ \nu\bar{\nu}$

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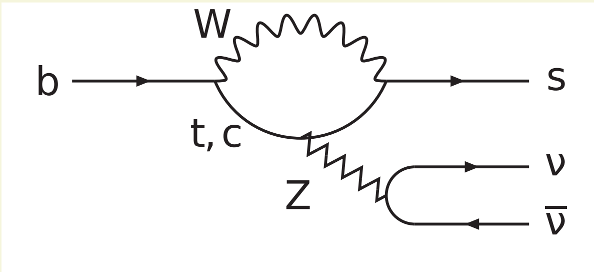
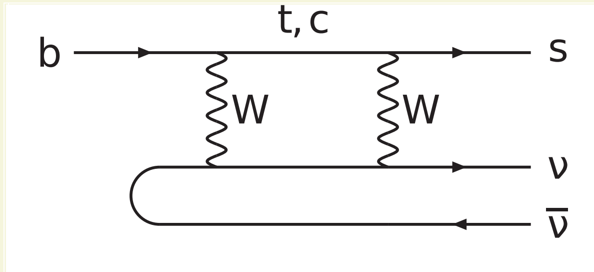
(on behalf of the *BABAR* collaboration)

Motivation for searches of $b \to s,d\ \nu\bar{\nu}$

- **suppressed modes in Standard Model (SM) which can be significantly enhanced by New Physics**
- **FCNC** processes, **forbidden at tree level**, allowed at one-loop or EW penguin diagrams





- SM predictions

  $B^+ \to K^{*+}\nu\bar{\nu} \simeq 6.8 \cdot 10^{-6}$ JHEP 0904, 022 (2009)

  $B^+ \to K^{+}\nu\bar{\nu} \simeq 4.4 \cdot 10^{-6}$ Nucl. Phys. B 209, 137-142 (2010)

  good accuracy since:

  - only one hadron in final state
  - no long-distance hadronic effects from EM penguin contributions as in $b \to s,d\ \ell^+\ell^-$

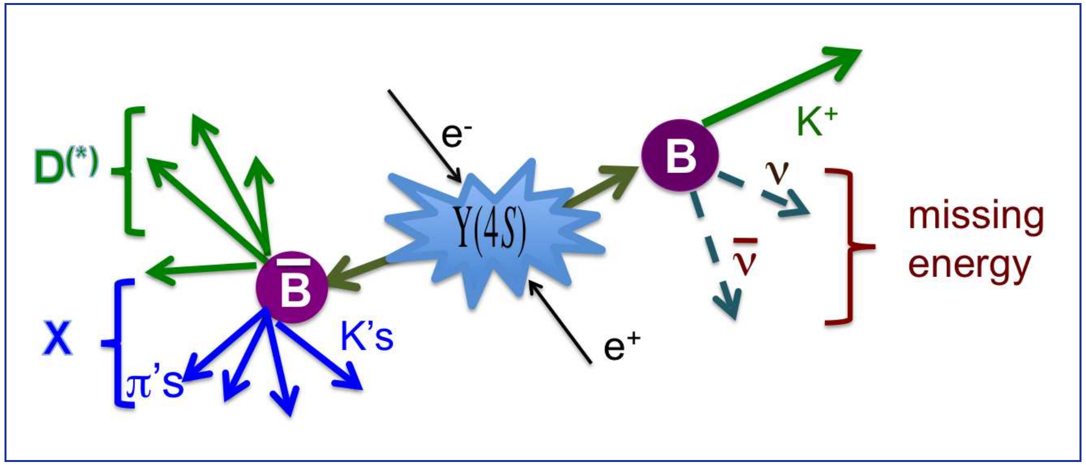
- **enhancements in New Physics models**: Nucl.Phys. B 209, 137-142 (2010), JHEP 0904, 022 (2009)

B-factories are most suited for experimental detection of these modes

Experimental results on $b \to s,d\ \nu\bar{\nu}$

- because of the two undetected neutrinos in the final state, searches rely on
  - either an esclusive (**hadronic B tag**) reconstruction of the other B in the event
  - or a partial (**semileptonic B tag**) reconstruction

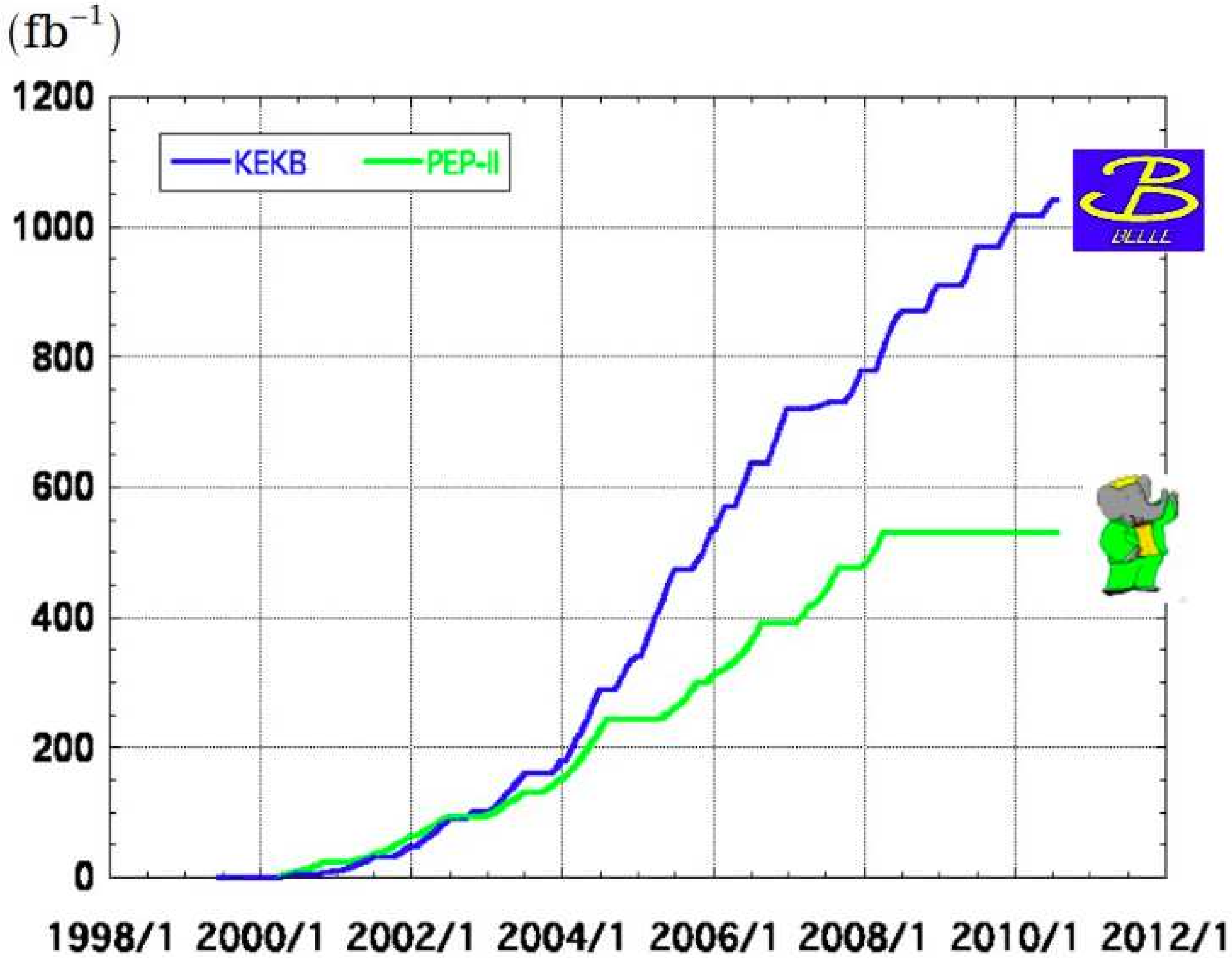
hadronic B tag analysis



- PRL 86, 2950 (2001) CLEO $9.7{\cdot}10^6$ B decays $B \to K^+\nu\bar{\nu} < 2.4{\cdot}10^{-4}$ at 90% CL
- PRD 87, 112005 (2013) BABAR $471{\cdot}10^6$ $B\bar{B}$ pairs $B \to K^{(*)}\nu\bar{\nu} < 1.6\text{–}12.0{\cdot}10^{-5}$ at 90% CL

  new B hadronic tag analysis, results from combination with B semileptonic tag results of two previous papers
  - PRD 82 112002 (2010) BABAR $459{\cdot}10^6$ $B\bar{B}$ pairs B semileptonic tag
  - PRD 78 072007 (2008) BABAR $454{\cdot}10^6$ $B\bar{B}$ pairs B hadronic & semileptonic tags
- PRD 87 111103(R) (2013) Belle $772{\cdot}10^6$ $B\bar{B}$ pairs $B \to h^{(*)}\nu\bar{\nu} < 4.0\text{–}21.3{\cdot}10^{-5}$ at 90% CL
  - B hadronic tag, improves on previous paper PRL 99, 221802 (2007)

BABAR and Belle collected luminosity



$> 1\ \mathrm{ab}^{-1}$

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:

$\sim 100\ \mathrm{fb}^{-1}$

$\sim 550\ \mathrm{fb}^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

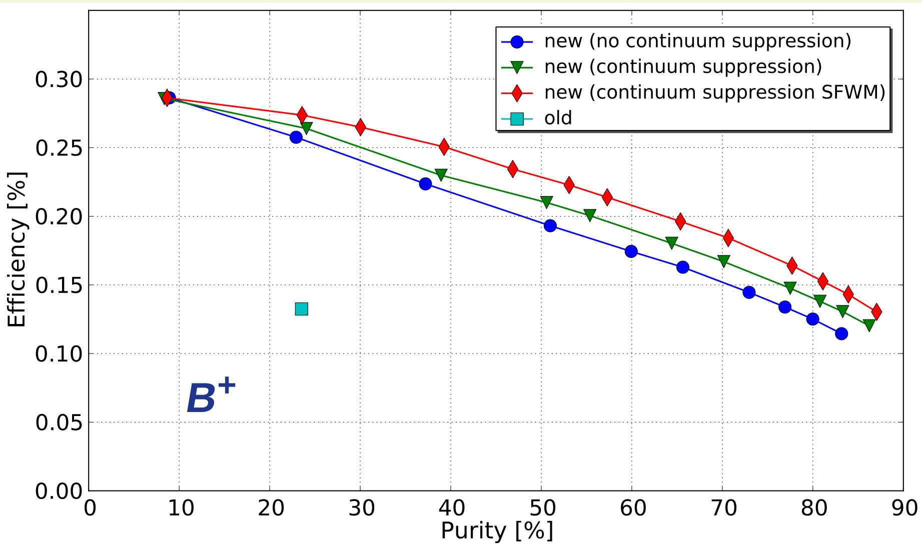
Off resonance:

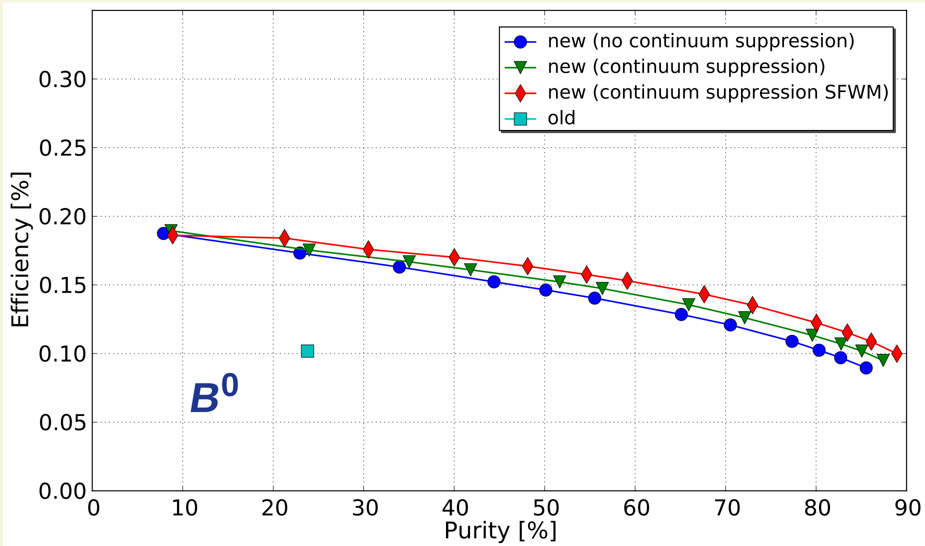
$\sim 54\ \mathrm{fb}^{-1}$

Belle search for $B \to h^{(*)}\nu\bar{\nu}$, analysis

PRD RC 87, 111103 (2013)

- $B \to h^{(*)}\nu\bar{\nu}$, $h^{(*)} = K^+, K^0_S, K^{*+}, K^{*0}, \pi^+, \pi^0, \rho^+, \rho^0, \phi$
- 711 fb^{-1} data sample, $772 \times 10^6 B\bar{B}$ pairs
- require **one *B* meson fully reconstructed in hadronic modes** (B_{tag})
  - 1104 decay channels exclusively reconstructed, documented in NIM A 654, 432-440 (2011)
  - hierarchical reconstruction procedure
  - multivariate approach (neural net package NeuroBayes) instead of cuts
  - efficiency improved by a factor ~2 at constant purity w.r.t. previous procedure
  - ***B* recostruction efficiency 0.28% B^+ and 0.18% B^0 per $B\bar{B}$ event**

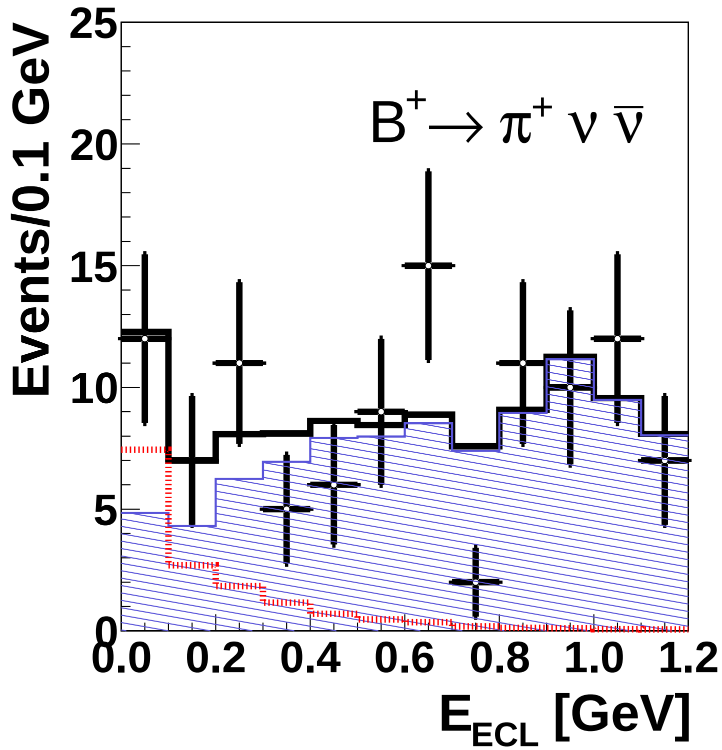




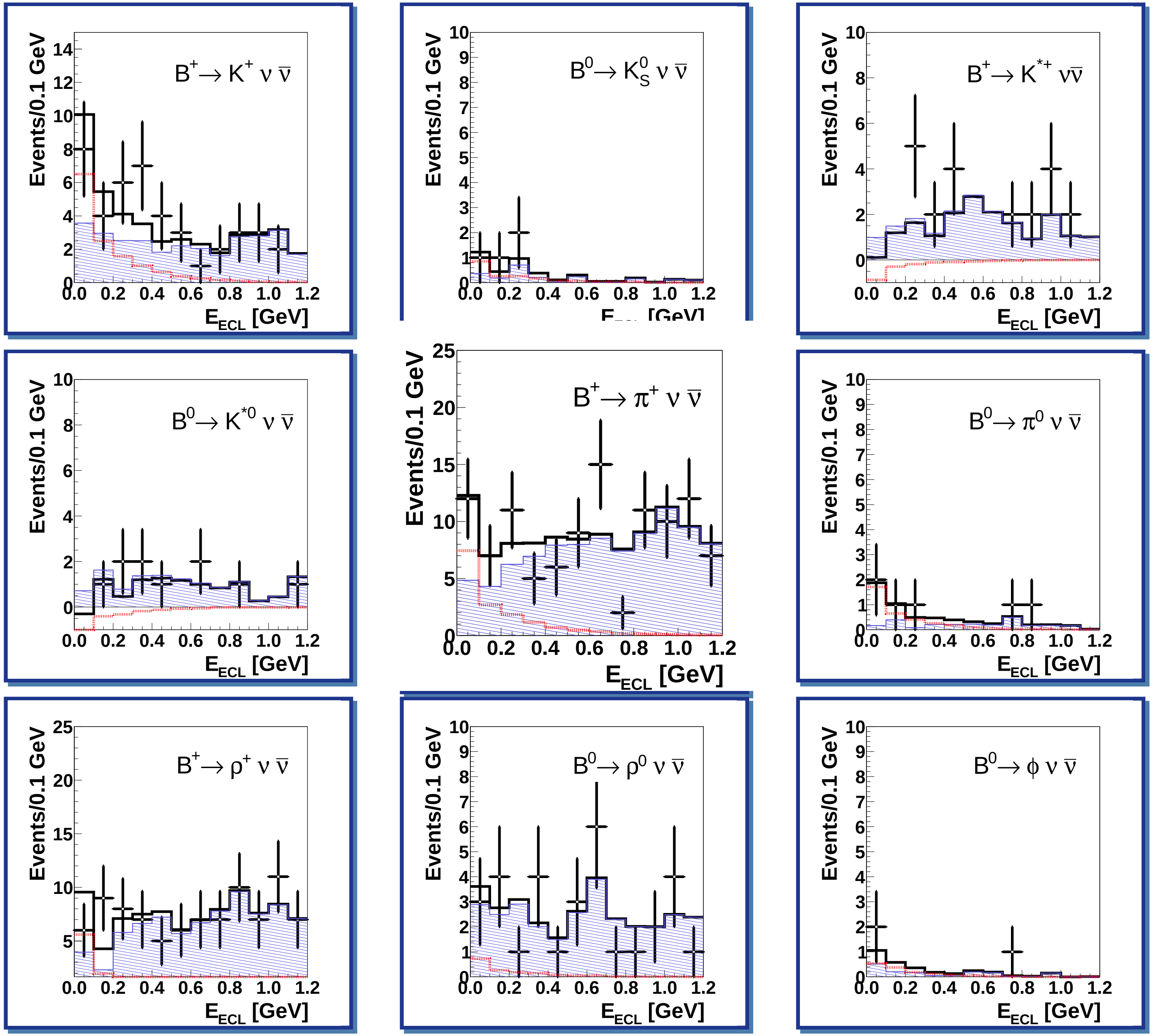
Belle search for $B \to h^{(*)}\nu\bar{\nu}$, analysis

PRD RC 87, 111103 (2013)

- find one light meson $h^{(*)} = K^+, K^0_S, K^{*+}, K^{*0}, \pi^+, \pi^0, \rho^+, \rho^0, \phi$
- no additional charged tracks or π^0 left in the event
- dominant continuum background suppressed with
  - cutting on modified Fox-Wolfram moments ($B\bar{B}$ more spherical)
  - require $-0.8 < \cos\theta_{CM}(\text{thrust} - h^{(*)}) < 0.7$ (angle between $h^{(*)}$ and the thrust axis in the CM frame)
- most effective variable to suppress remaining bkg is **E_{ECL}, sum of energy of non-associated ECL clusters** ($E_{cluster} > 50, 100, 150$ MeV in barrel, forw. endcap, backw. endcap)
- signal yield extracted from **ext. binned M.L. fit to E_{ECL}** distribution (signal peaks at zero, obtained with MC simulation)



Belle $B \to h^{(*)}\nu\bar{\nu}$, fits to E_{ECL} distributions for all $h^{(*)}$ searches: no significant signal



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

- significances and upper limits by evaluating the likelihood profile
- significance from ratio of likelihood values at maximum and at zero signal yield $S = \sqrt{2 \log \left(\frac{\mathcal{L}_{max}}{\mathcal{L}_0}\right)}$
- likelihood function convolved with a Gaussian corresponding to total systematic uncertainty
- expected upper limits by averaging obtained upper limits on simulated experiments with zero signal

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

Mode	N_{tot}	N_{sig}	Significance	ϵ, 10^{-4}	**Upper limit**	Expected limit
$B^+ \to K^+\nu\bar{\nu}$	43	$13.3^{+7.4}_{-6.6}(stat) \pm 2.3(syst)$	2.0σ	5.68	$< \mathbf{5.5 \times 10^{-5}}$	2.2×10^{-5}
$B^0 \to K^0_s\nu\bar{\nu}$	4	$1.8^{+3.3}_{-2.4}(stat) \pm 1.0(syst)$	0.7σ	0.84	$< \mathbf{9.7 \times 10^{-5}}$	7.3×10^{-5}
$B^+ \to K^{*+}\nu\bar{\nu}$	21	$-1.7^{+1.7}_{-1.1}(stat) \pm 1.5(syst)$	–	1.47	$< \mathbf{4.0 \times 10^{-5}}$	5.8×10^{-5}
$B^0 \to K^{*0}\nu\bar{\nu}$	10	$-2.3^{+10.2}_{-3.5}(stat) \pm 0.9(syst)$	–	1.44	$< \mathbf{5.5 \times 10^{-5}}$	4.6×10^{-5}
$B^+ \to \pi^+\nu\bar{\nu}$	107	$15.2^{+7.1}_{-6.2}(stat) \pm 1.4(syst)$	2.6σ	3.39	$< \mathbf{9.8 \times 10^{-5}}$	3.8×10^{-5}
$B^0 \to \pi^0\nu\bar{\nu}$	6	$3.5^{+2.6}_{-1.9}(stat) \pm 0.6(syst)$	1.9σ	1.66	$< \mathbf{6.9 \times 10^{-5}}$	3.6×10^{-5}
$B^+ \to \rho^+\nu\bar{\nu}$	90	$11.3^{+6.3}_{-5.4}(stat) \pm 4.1(syst)$	1.7σ	1.35	$< \mathbf{21.3 \times 10^{-5}}$	10.2×10^{-5}
$B^0 \to \rho^0\nu\bar{\nu}$	31	$1.6^{+5.0}_{-4.1}(stat) \pm 0.4(syst)$	0.4σ	0.64	$< \mathbf{20.8 \times 10^{-5}}$	15.7×10^{-5}
$B^0 \to \phi\nu\bar{\nu}$	3	$1.4^{+2.9}_{-0.9}(stat) \pm 0.8(syst)$	0.5σ	0.58	$< \mathbf{12.7 \times 10^{-5}}$	8.7×10^{-5}

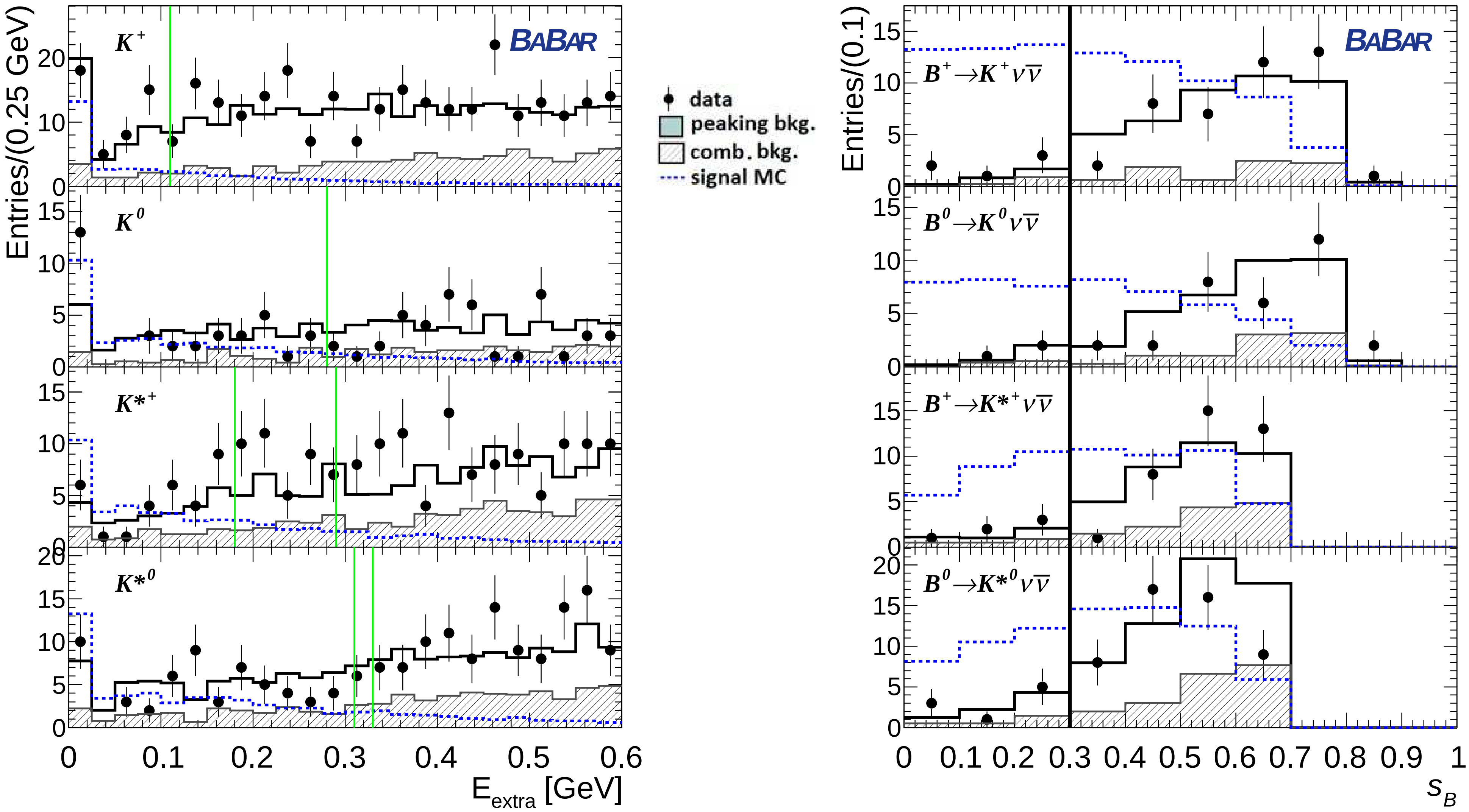
BABAR $B \to K^{(*)}\nu\bar{\nu}$ search, analysis

PRD 87, 112005 (2013)

- most recent fully reconstructed $B_{\rm tag}$ sample, twice the efficiency of the previous one
  - 1680 B decay modes, efficiency for this analysis $\sim$0.3%
- select events with one fully reco $B_{\rm tag}$ and up to three tracks
- retain only the $B_{\rm tag}$ modes that have at least 68% purity → 448 modes
- continuum bkg suppressed with multivariate likelihood selector based on six event-shape variables
- reconstruct remaining tracks in six B decay channels:
  $B^+ \to K^+\nu\bar{\nu}$, $K^0_S\nu\bar{\nu}$, $K^{*+}\nu\bar{\nu}$ ($K^{*+} \to K^+\pi^0$, $K^{*+} \to K^0_S\pi^+$), $K^{*0}\nu\bar{\nu}$ ($K^{*0} \to K^+\pi^-$, $K^{*0} \to K^0_S\pi^0$)
- cut on E_{extra}, sum of unassociated neutral calorimeter deposits > 50 MeV
- cut on $s_B < 0.3$, where $s_B = \dfrac{(p_{B_{\rm sig}} - p_{K^{(*)}})^2}{m_B^2} = \dfrac{q^2}{m_B^2} = \dfrac{m^2_{\nu\bar{\nu}}}{m_B^2}$
- peaking bkg subtracted using MC simulations
- 90% CL limits computed from the yields using mixed frequentist-Bayesian approach
  (R. Barlow, Comput. Phys. Commun. 149, 97 (2002)
  assume Gaussian uncertainties for signal efficiency and estimated BKG, convolve Poisson 90% CL limits

BaBar $B \to K^{(*)}\nu\bar{\nu}$ search, results

PRD 87, 112005 (2013)



BABAR $B \to K^{(*)}\nu\bar{\nu}$ search, E_{extra} and s_B distributions and cuts

PRD 87, 112005 (2013)

	$B^+ \to [K^+\pi^0]\nu\bar{\nu}$	$B^+ \to [K^0_S\pi^+]\nu\bar{\nu}$	$B^0 \to [K^+\pi^-]\nu\bar{\nu}$	$B^0 \to [K^0_S\pi^0]\nu\bar{\nu}$
N_i^{peak}	$1.2 \pm 0.4 \pm 0.1$	$1.3 \pm 0.4 \pm 0.1$	$5.0 \pm 0.8 \pm 0.5$	$0.2 \pm 0.2 \pm 0.0$
N_i^{comb}	$1.1 \pm 0.4 \pm 0.0$	$0.8 \pm 0.3 \pm 0.0$	$2.0 \pm 0.5 \pm 0.1$	$0.5 \pm 0.3 \pm 0.0$
N_i^{bkg}	$2.3 \pm 0.5 \pm 0.1$	$2.0 \pm 0.5 \pm 0.1$	$7.0 \pm 0.9 \pm 0.5$	$0.7 \pm 0.3 \pm 0.0$
ε_i^{sig} ($\times 10^{-5}$)	$4.9 \pm 0.2 \pm 0.4$	$6.0 \pm 0.2 \pm 0.5$	$12.2 \pm 0.3 \pm 1.4$	$1.2 \pm 0.1 \pm 0.1$
N_i^{obs}	3	3	7	2
Limit	$< 19.4 \times 10^{-5}$	$< 17.0 \times 10^{-5}$	$< 8.9 \times 10^{-5}$	$< 86 \times 10^{-5}$
BF($B^{+/0} \to K^{*+/0}\nu\bar{\nu}$)	$(3.3^{+6.2+1.7}_{-3.6-1.3}) \times 10^{-5}$		$(2.0^{+5.2+2.0}_{-4.3-1.7}) \times 10^{-5}$	
Limit	$< 11.6 \times 10^{-5}$		$< 9.3 \times 10^{-5}$	
BF($B \to K^*\nu\bar{\nu}$)	$(2.7^{+3.8+1.2}_{-2.9-1.0}) \times 10^{-5}$			
Limit	$< 7.9 \times 10^{-5}$			

	$B^+ \to K^+\nu\bar{\nu}$	$B^0 \to K^0\nu\bar{\nu}$
N_i^{peak}	$1.8 \pm 0.4 \pm 0.1$	$2.0 \pm 0.5 \pm 0.2$
N_i^{comb}	$1.1 \pm 0.4 \pm 0.0$	$0.9 \pm 0.4 \pm 0.1$
N_i^{bkg}	$2.9 \pm 0.6 \pm 0.1$	$2.9 \pm 0.6 \pm 0.2$
ε_i^{sig} ($\times 10^{-5}$)	$43.8 \pm 0.7 \pm 3.0$	$10.3 \pm 0.2 \pm 1.2$
N_i^{obs}	6	3
BF_i	$(1.5^{+1.7+0.4}_{-0.8-0.2}) \times 10^{-5}$	$(0.14^{+6.0+1.7}_{-1.9-0.9}) \times 10^{-5}$
Limits	$(> 0.4, < 3.7) \times 10^{-5}$	$< 8.1 \times 10^{-5}$
BF($B \to K\nu\bar{\nu}$)	$(1.4^{+1.4+0.3}_{-0.9-0.2}) \times 10^{-5}$	
Limits	$(> 0.2, < 3.2) \times 10^{-5}$	

BaBar $B \to K^{(*)}\nu\bar{\nu}$ search, combination with previous analyses

PRD 87, 112005 (2013)

- yields from previous analyses and using semi-leptonic tags combined with latest hadronic tag analysis
  - improved s_B simulation, which decreased signal efficiency, used to update former yields

$$
\begin{aligned}
\mathrm{BF}(B^+ \to K^+\nu\bar{\nu}) &< 1.6 \times 10^{-5} \\
\mathrm{BF}(B^0 \to K^0\nu\bar{\nu}) &< 4.9 \times 10^{-5} \\
\mathrm{BF}(B \to K\nu\bar{\nu}) &< 1.7 \times 10^{-5} \\
\mathrm{BF}(B^+ \to K^{*+}\nu\bar{\nu}) &< 6.4 \times 10^{-5} \\
\mathrm{BF}(B^0 \to K^{*0}\nu\bar{\nu}) &< 12.0 \times 10^{-5} \\
\mathrm{BF}(B \to K^{*}\nu\bar{\nu}) &< 7.6 \times 10^{-5}
\end{aligned}
$$

Conclusions

- CLEO and later BABAR and Belle searched for $b \to s,d\ \nu\bar{\nu}$ processes and set 90% CL upper limits

process	best 90% CL exp. limits	SM predictions
$B^+ \to K^{*+}\nu\bar{\nu}$	$40{\cdot}10^{-6}$	$\simeq 6.8{\cdot}10^{-6}$
$B^+ \to K^+\nu\bar{\nu}$	$16{\cdot}10^{-6}$	$\simeq 4.4{\cdot}10^{-6}$

- there is still some space to see New Physics enhancements over the SM predictions
- BelleII will be able to probe about up to the range of the SM predictions