Experimental prospects for $b \to s \nu\nu$ and $B \to l \nu (\gamma)$

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Flavour in the Era of the LHC
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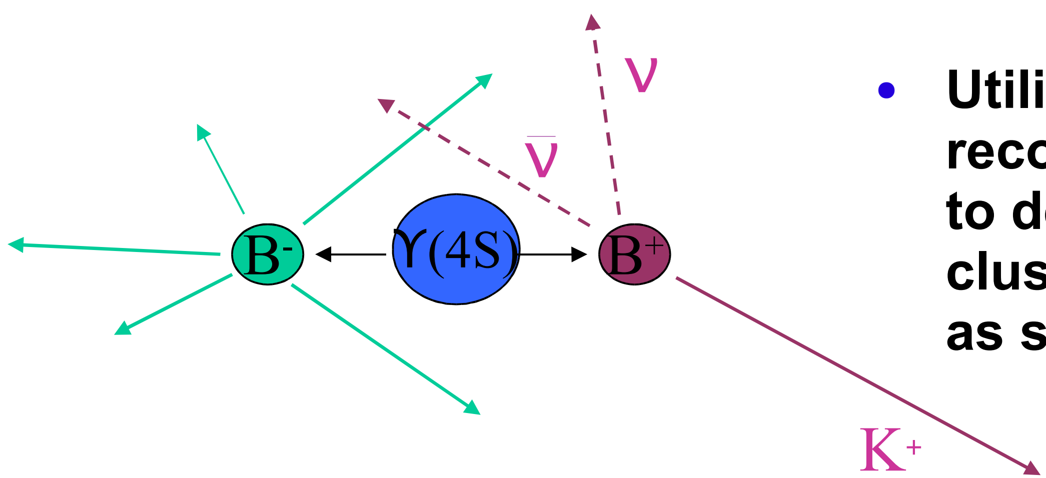
Methodology

Rare B decays with neutrinos are an area where B factories have a substantial advantage over hadronic machines

- If only one neutrino is present in an event, the 4-vector can be deduced from the missing energy/momentum
- If multiple neutrinos are present, there are insufficient kinematic contraints to uniquely determine the signal decay
  - rely heavily on event topology and total missing energy: requires ability to distinguish “signal B” particles from the “other B” decay daughters



- **Utilize full (or nearly full) reconstruction of the other B to deduce which tracks and clusters should be considered as signal candidates**

Tag B reconstruction

- **Signal candidate defined as whatever is left over after "tag B" reconstruction**
  - Effectively a tagged single-B beam (albeit with bad beam backgrounds...)
  - $\Upsilon(4S)$ equivalent of method used at CLEO-c
- **Two tagging method used by BABAR:**

$B^- \rightarrow D^{(*)0} X^-$
- $\rightarrow K^- \pi^+$
- $\rightarrow K^- \pi^+ \pi^0$
- $\rightarrow K^- \pi^+ \pi^- \pi^+$
- $\rightarrow K^0_s \pi^+ \pi^-$

$B^- \rightarrow D^0 \ell^- \nu\ (X^0)$
- $\rightarrow K^- \pi^+$
- $\rightarrow K^- \pi^+ \pi^0$
- $\rightarrow K^- \pi^+ \pi^- \pi^+$
- $\rightarrow K^0_s \pi^+ \pi^-$

X^- **system**: up to five charged tracks (K, π) and two additional π^0

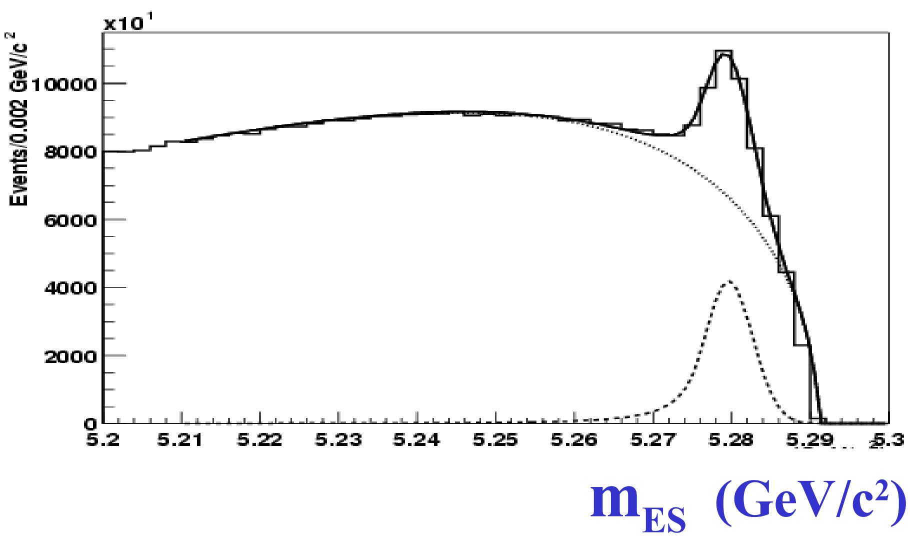
X^0 **system**: γ or π^0 candidates from possible $D^{(*)0} \rightarrow D^0 \gamma / \pi^0$ transitions

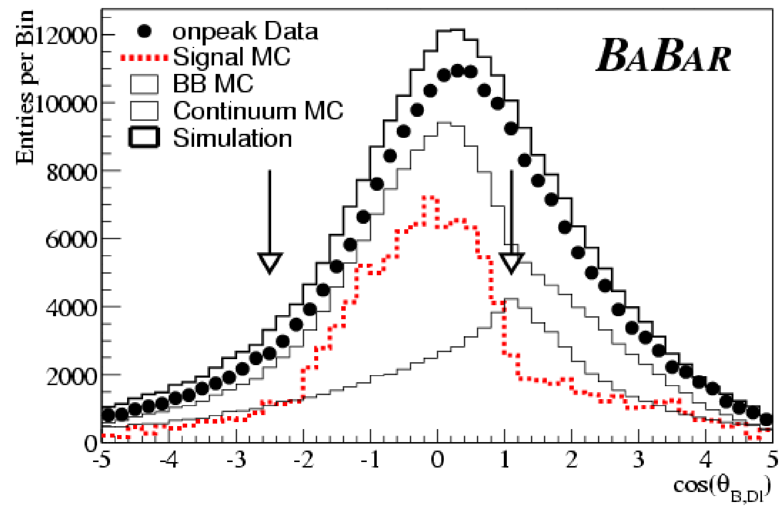
  - Also corresponding neutral B versions of these algorithms

- **Additional neutrino in SL tags does not significantly impact performance in analyses (e.g. $B^+ \rightarrow \tau^+ \nu$) in which there are already at least two others**

Hadronic and Semileptonic tags

- **Several variants of the SL tag method have been used by BABAR, e.g.:**
  - First $B^+ \rightarrow \tau^+ \nu$ result used both **$D^{*0}\ \ell\ \nu$** and **$D^0\ \ell\ \nu$** reconstructed events, resulting in problems with misreconstructed **$D^0\ \ell\ \nu$** candidates in which photons from $D^{(*)0} \rightarrow D^0\ \gamma / \pi^0$ transitions were missed (and hence polluted the "signal-side")
  - Second $B^+ \rightarrow \tau^+ \nu$ paper used only exclusively reconstructed **$D^{*0}\ \ell\ \nu$** tags
- **Semileptonic tag sample yields ~5.k events per fb^{-1}, while hadronic tag sample yields about half as much**
  - m_{ES} distribution used to estimate yield and combinatorial background





$$\cos_{BD\ell} \quad \frac{(2E_B E_{D\ell} \quad m_B^2 \quad m_{D\ell}^2)}{2|\vec{p}_B||\vec{p}_{D\ell}|}$$

$B^+ \to l^+\nu$

- **Leptonic B decays have very clean theoretical predictions, relation to CKM element $|V_{ub}|$ and decay constant f_B**

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

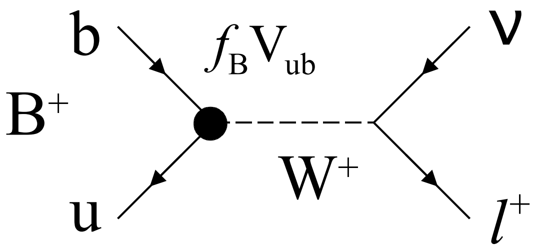
- **Helicity suppression results in SM predictions with an inverted hierarchy relative to experimentalist's preferences:**

SM Predictions

$BR(B^+ \to \tau^+\nu) \sim 1\times10^{-4}$

$BR(B^+ \to \mu^+\nu) \sim 4\times10^{-7}$

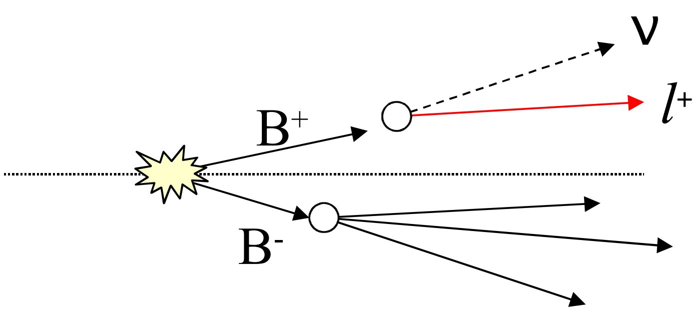
$BR(B^+ \to e^+\nu) \sim 10^{-12}$

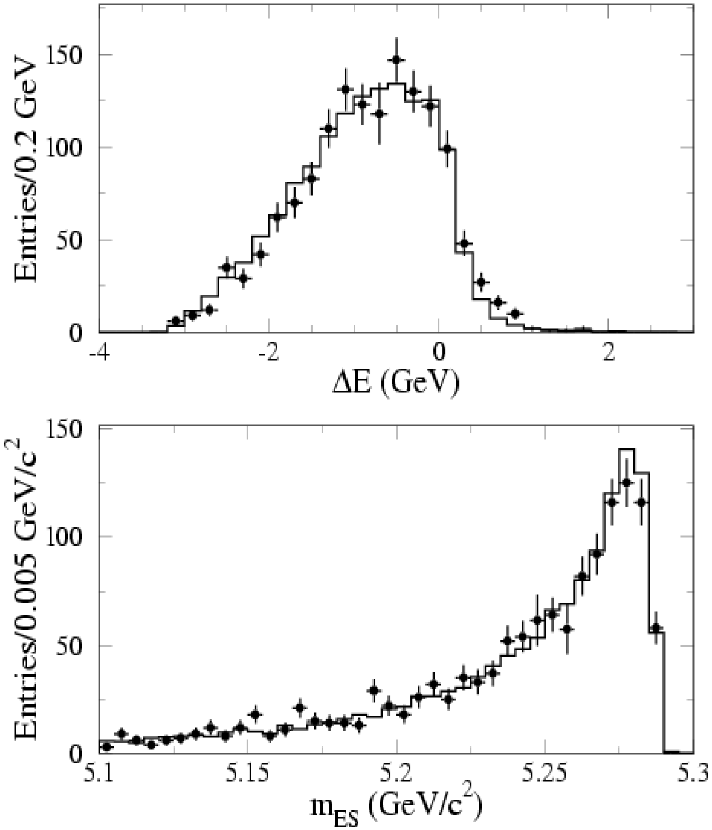


	BABAR	Belle	CLEO
$BR(B^+ \to \tau^+\nu)$	$< 2.6 \times 10^{-4}$	**1.06×10^{-4} (4.2σ)**	$< 8.4 \times 10^{-4}$
$BR(B^+ \to \mu^+\nu)$	$< 6.6 \times 10^{-6}$	$< 2 \times 10^{-6}$	$< 2.1 \times 10^{-5}$
$BR(B^+ \to e^+\nu)$	-	$< 5.4 \times 10^{-6}$	$< 1.5 \times 10^{-5}$

$B^+ \to l^+\nu$ (inclusive)

- **Conventional method is to look for a single high momentum lepton, then "inclusively" reconstruct the accompanying B via a 4-vector sum of everything else in the event**
  - lepton momentum is "smeared" in CM frame due to B momentum to give a box with width ~several hundred MeV/c



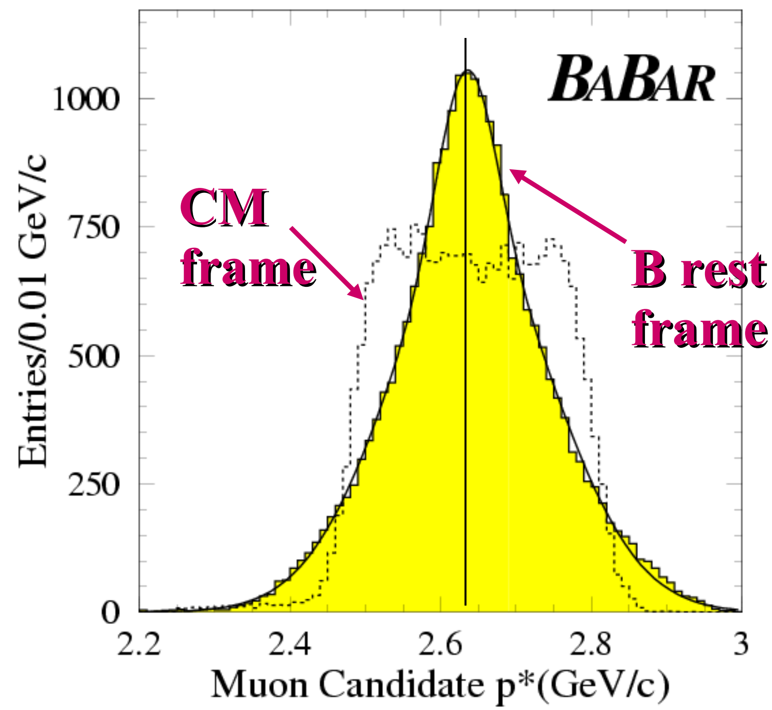


  - continuum suppression via event shape variables
  - B background suppression from hard ΔE and m_{ES} cuts

- **Efficiencies in the range 2-10%**

$B^+ \to l^+\nu$ (inclusive)

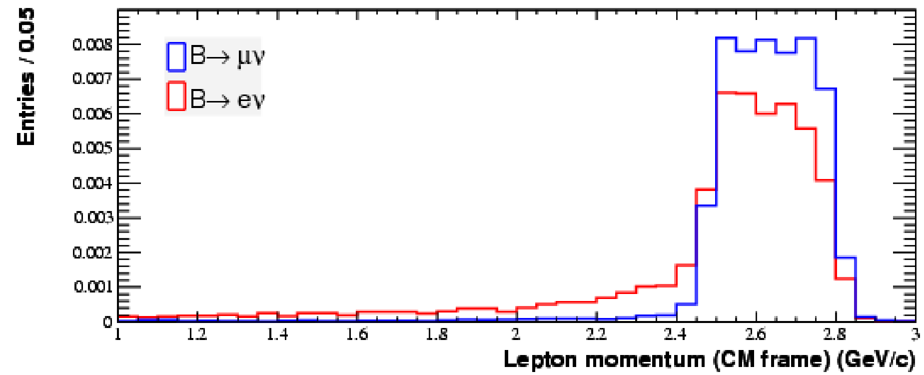
- **Possible to improve constraint on lepton p via knowledge of the signal B rest frame**
  - 2-body decay, hence lepton is monoenergetic
- **In the inclusive approach, improvement in p* resolution limited by degree to which accompanying B is correctly reconstructed**
  - in inclusive method, improvement is fairly small
  - extract signal from fit to (broad) p* peak on a ~flat background

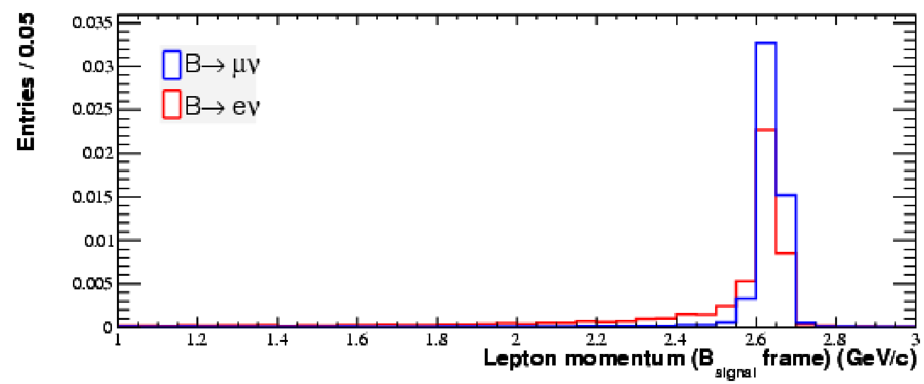


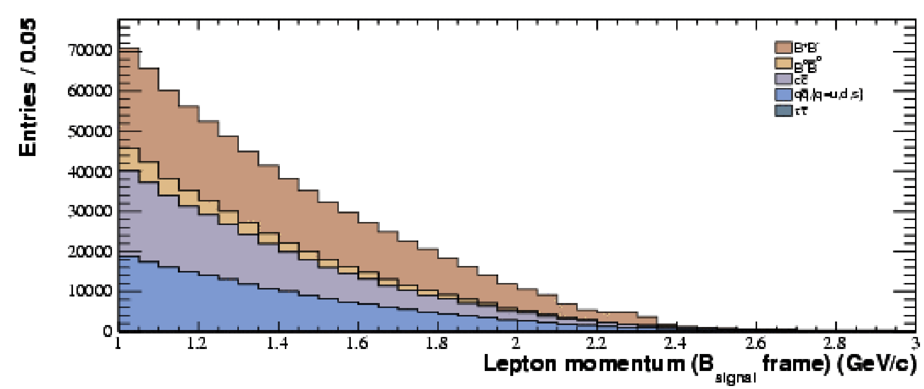
- **In case of perfect reconstruction of accompanying B, recover a δ-function, limited by tracking/beam energy resolution**
  - Hadronic tag B reconstruction

$B^+ \rightarrow l^+\nu$ (tagged)

- **Hadronic tag reconstruction efficiency is ~0.2%**
  - factor of >10 down from inclusive method
- **Signal candidate selection very highly efficient!**
  - require a single high-p* lepton plus "nothing" else
- **Several advantages:**
  - non-B background effectively removed by tag reconstruction
  - known B rest frame yields excellent p* resolution
  - main B background ($b \rightarrow u\, l\, \nu$) effectively removed by kinematics







$B^+ \rightarrow l^+\nu$ tagged or untagged?

Currently, inclusive method yields significantly better experimental limits, however:

- **Limits from inclusive analyses (BABAR, Belle) driven by background event statistics --expect future limits to scale according to 1/sqrt(Lumi)**
  - O(10) events in both analyses
- **Tagged analysis can be made essentially background-free, but limited by tag statistics --expect limits to scale as 1/(Lumi)**

Anticipate that tagged method will yield ~ comparable sensitivity for data samples of a few ab^{-1}

- Hope to have some "realistic" efficiency and background estimates by end of this workshop series

Radiative leptonic modes

Radiative decays, $B^+ \to l^+ \nu\gamma$, do not exhibit helicity suppression of non-radiative modes

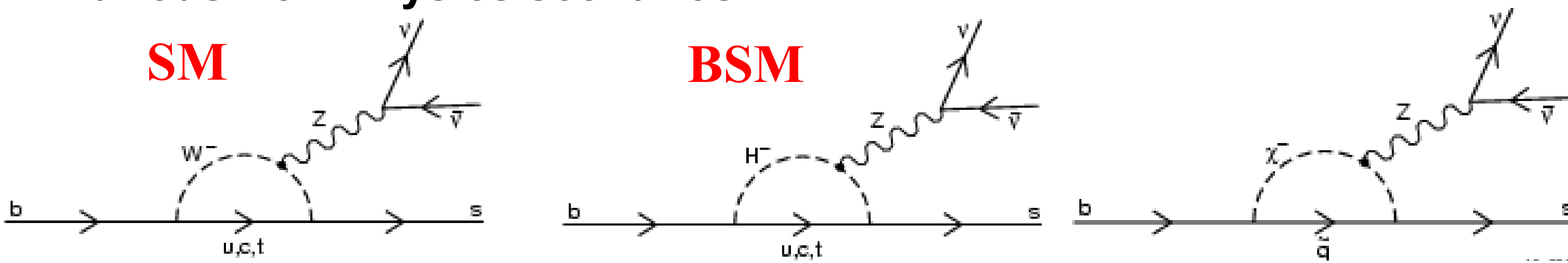
- Some additional suppression from factor of α in SM predictions, but rates are ~10^{-6} , well within reach (in principle) of existing B factories...
- so far, "inclusive" measurements have not kept pace with integrated lumi

	BABAR	Belle	CLEO
$BR(B^+ \to e^+ \nu \gamma)$	-	$< 2.2 \times 10^{-5}$	$<2.0 \times 10^{-5}$
$BR(B^+ \to \mu^+ \nu \gamma)$	-	$< 2.3 \times 10^{-5}$	$<5.2 \times 10^{-5}$

- **Why not? Two problems...**
  - Backgrounds from (poorly measured) exclusive $b \to u\, l\, \nu$ processes
  - Backgrounds from (poorly modeled) QED processes: radiative bhabha and two-photon
- **Both problems can be solved by using hadronic tag reconstruction**
  - control over signal B kinematics gives tight constraint on neutrino 4-vector
  - tag reconstruction suppresses non-B backgrounds; any residual background is well estimated from m_{ES} sideband

$b \to s\nu\nu$

- **Inclusive $b \to s\nu\nu$ claimed by theorists to be the "theoretically cleanest" rare B decay, with potentially interesting sensitivity to various New Physics scenarios**



  - unfortunately, it appears to be intractable even in clean B factory environment, hence exclusive $B^+ \to K^+ \nu\nu$ has been main target of experimentalists to date*

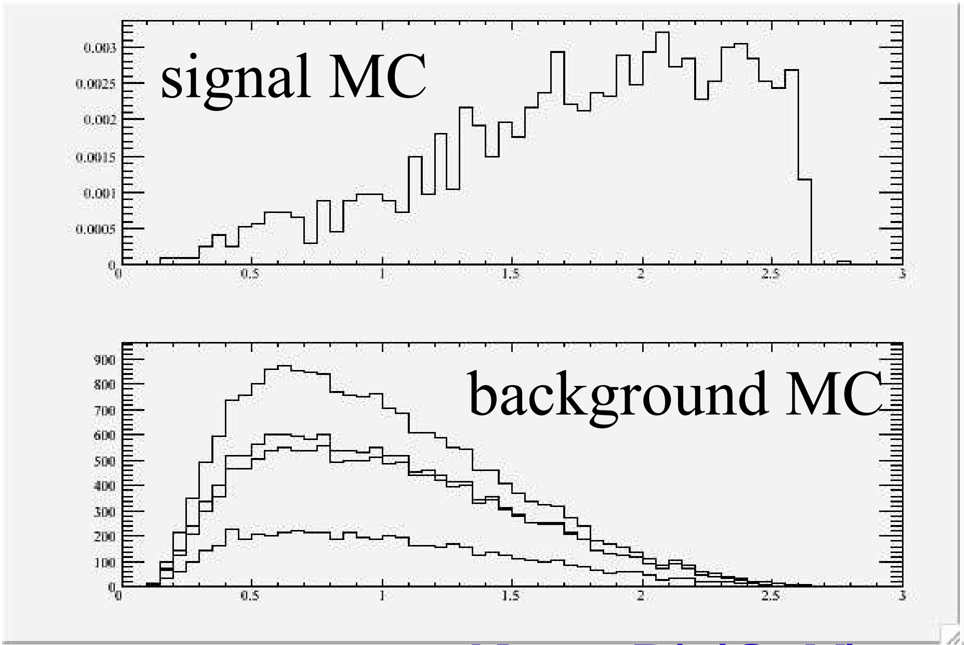
- **SM rate of 3.8×10^{-6} hence experiment is within an order of magnitude** (note that neither BABAR nor Belle results use full current dataset)

	BABAR	Belle	CLEO
$BR(B^+ \to K^+ \nu\nu)$	$< 5.2 \times 10^{-5}$	$< 3.6 \times 10^{-5}$	$< 2.4 \times 10^{-4}$

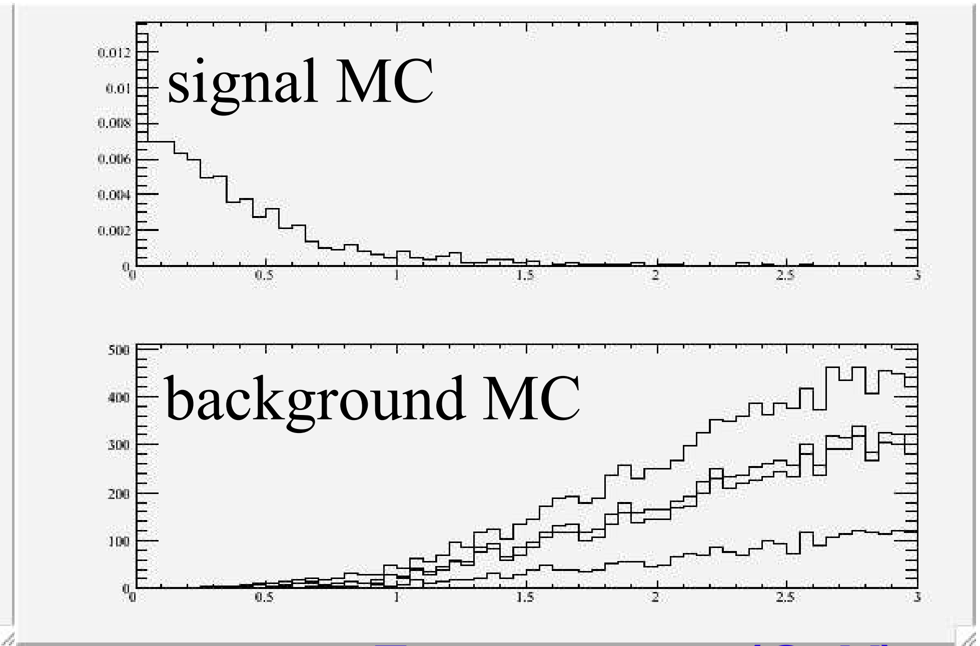
* there is an earlier paper from LEP, but limit is let stringent than current exclusive limits

$B^+ \to K^+\nu\nu$

- **All B factory results are based on methods utilizing hadronic-tag reconstruction**
  - BABAR paper quotes a combined result from SL and hadronic tag methods
    - very little impact on analysis performance from using SL tag sample in spite of additional neutrino
  - Signal selection relies on high momentum Kaon and presence of little or no additional energy not associated with the tag B:



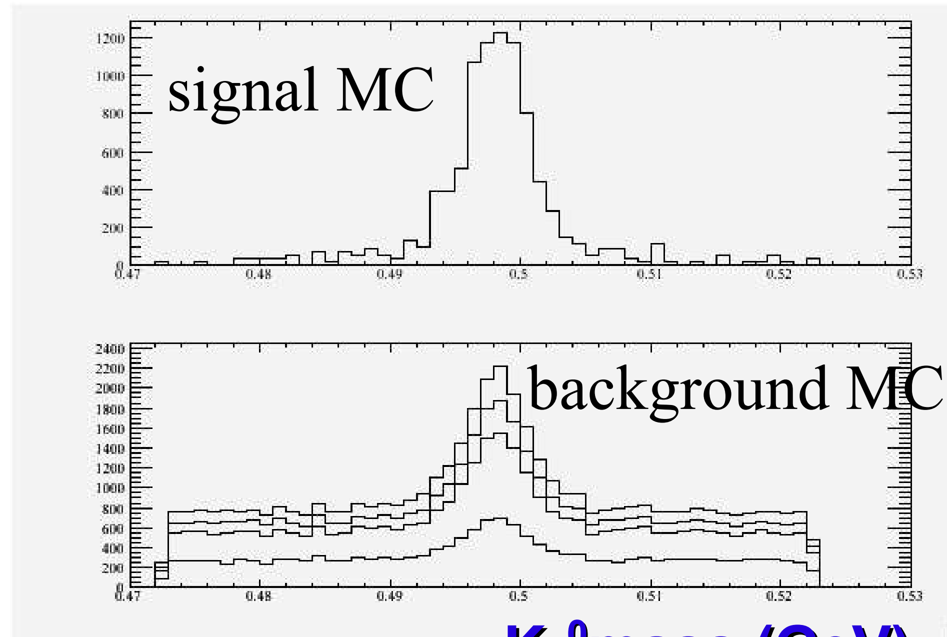
Kaon P* (GeV)



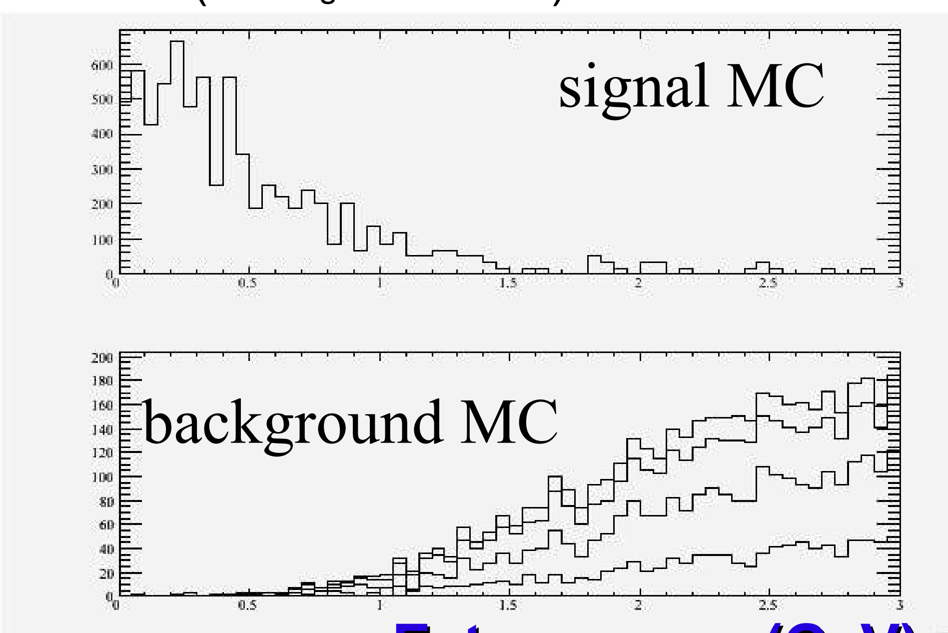
Extra energy (GeV)

$B^0 \rightarrow K_s^0 \nu\nu$

- **Somewhat lower overall experimental sensitivity due to reconstruction efficiency:**
  - Neutral hadronic B tag has ~40% smaller yield than charged B tag
  - Another factor of ~4 loss of efficiency due to K^0 reconstruction (via $K_s^0 \rightarrow \pi^+\pi^-$)



K_s^0mass (GeV)



Extra energy (GeV)

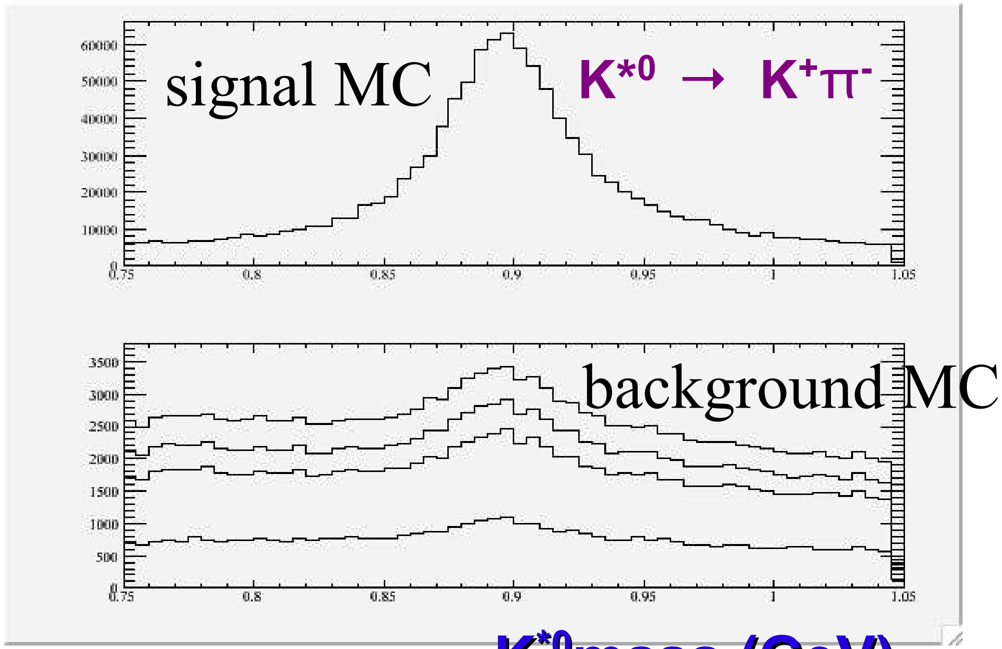
- **However, for comparable cuts to $B^+ \rightarrow K^+ \nu \nu$, the overall background rate looks similar**

$B^+ \to K^{*+}\nu\nu$ and $B^0 \to K^{*0}\nu\nu$

- $B \to K^*\nu\nu$ modes are expected to have roughly twice the branching fractions of the $B \to K\nu\nu$ modes, but potentially somewhat lower selection efficiencies due to K^0 daughter decays:

  $K^{*0} \to K^+\pi^-, K^0\pi^0$ $\quad\quad$ $K^{*+} \to K^+\pi^0, K^0\pi^+$

- Available kinematic constraints from K0, K* reconstruction give additional handles on backgrounds (e.g. from sideband studies or cut tuning
  - Initial "realistic" simulation studies suggest that backgrounds are roughly comparable to $B^+ \to K^+\nu\nu$ and $B^0 \to K^0\nu\nu$, but sensitivity studies are still in progress



K^{*0} mass (GeV)

Summary

- Although $B^+ \to \tau^+ \nu$ currently the best measured of the leptonic modes, $B^+ \to \mu^+ \nu$ or the radiative modes have the potential to ultimately give the most precise results.
- In the limit of very large data statistics, the hadronic tag reconstruction method can provide competitive results with the conventional "inclusive" methods for these leptonic decays
- Prospects for substantial improvements in current $b \to s\nu\nu$ limits by exploiting charged and neutral K* modes
- Hope to have realistic estimates of efficiencies and background in these modes over next several months