# New physics in B decays with neutrinos

*January 19, 2004*
*Super B Factory Workshop*
*Hawaii*

**Steven Robertson**

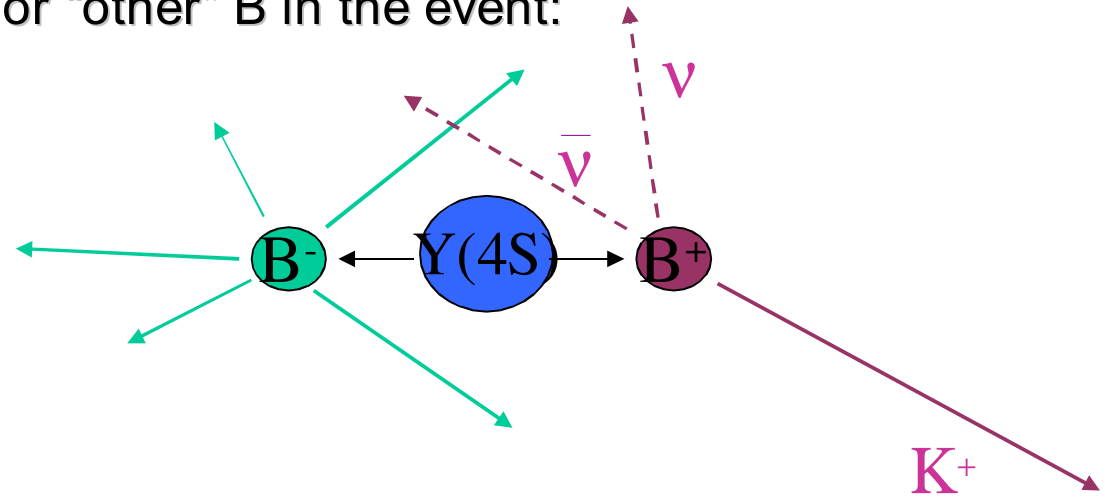
McGill

# Overview

- **B decay modes with (one or more) neutrinos generally lack "smoking-gun" signatures which allow easy signal identification**
  - unlikely that experiments at hadron machines will be able to study these modes
  - topological signature of low multiplicity and significant missing energy
    - **reconstruction (inclusive or exclusive) of the "companion" B**
- **Leptonic decays of B mesons**
  - $B^+ \rightarrow l^+\nu$ $(l = e, \mu \text{ or } \tau)$
- **Radiative leptonic decays**
  - $B^+ \rightarrow l^+\nu\gamma$ $(l = e, \mu)$
- **b–>s and b–>d FCNC processes:**
  - Exclusive $B^+ \rightarrow X_s^+ \nu\nu$ and $B^+ \rightarrow X_d^+ \nu\nu$
  - $B^0 \rightarrow \tau^+\tau^-$ and $B^0 \rightarrow \nu\nu(\gamma)$

# Method

- **If one neutrino is present in an event, the $p_{miss}$ 4-vector can be obtained (with poor resolution) by summing the observe particles**
- **When multiple neutrinos are present, there are insufficient kinematic contraints uniquely identify the decay**
  - rely heavily on event topology and large missing energy
  - "bookkeeping" requires that all particles be associated with either the signal or "other" B in the event:




- **Utilize full B reconstruction techniques to distinguish decay products of the two B's**

# Hadronic tag B reconstruction

- **Fully reconstruct the accompanying B in the event and search for evidence of the signal decay in the remainder**

**Energy substituted mass:** $m_{ES} = \sqrt{E_{beam}^{cm} - p_B^{cm}}$

**Energy difference:** $\Delta E = E_B^{cm} - E_{beam}^{cm}$

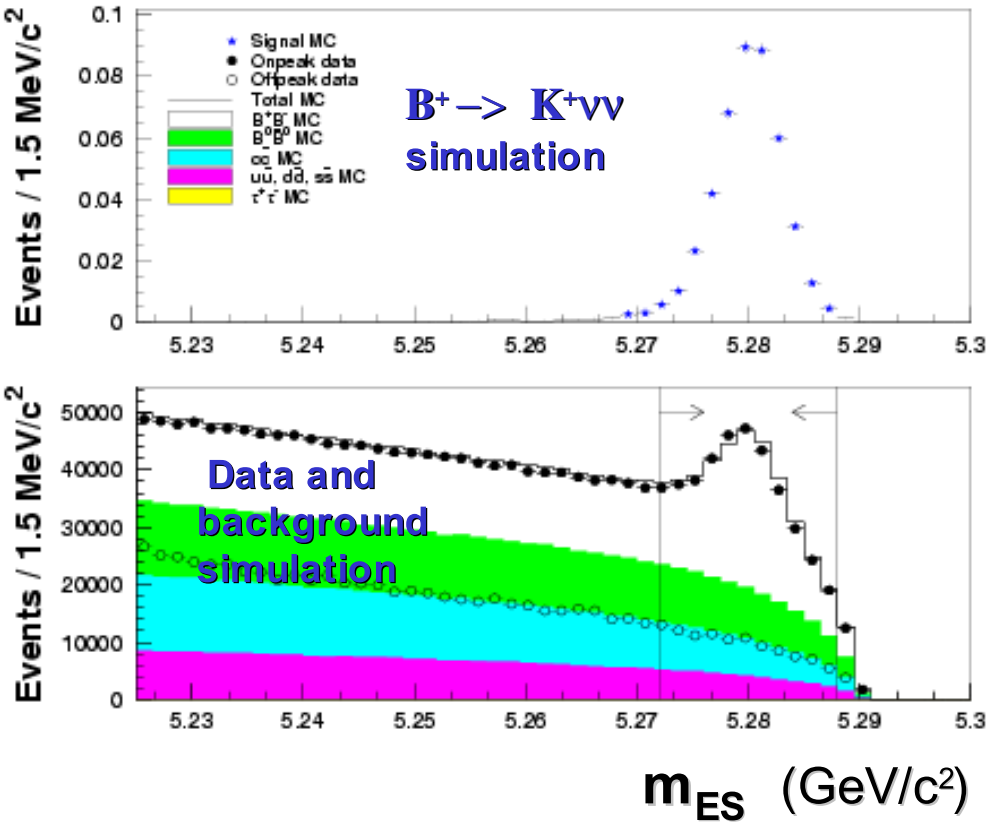
$B^- \rightarrow D^{(*)0} X^-$

- $K^- \pi^+$
- $K^- \pi^+ \pi^0$
- $K^- \pi^+ \pi^- \pi^+$
- $K^0_S \pi^+ \pi^-$

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

$\varepsilon_{reco}$ = ~(0.13 – 0.18)%

**~1500-2000 reconstructed $B^\pm$ mesons per $fb^{-1}$**



# Semileptonic tag B reconstruction

- **Comparatively high statistics due to large b –> c $l$ ν branching ratio:**

  **~5500 events per fb$^{-1}$**

Paul Jackson, UVic

- **For low multiplicity signal modes, low combinatorics result in very clean B reconstruction**
- **Need to explicitly veto feeddown from $B^0$ –> $D^{*+}$(->$D^0$ $\pi^+$) $l^-$ ν**

$B^-$ –> $D^0$ $l^-$ ν ($X^0$)

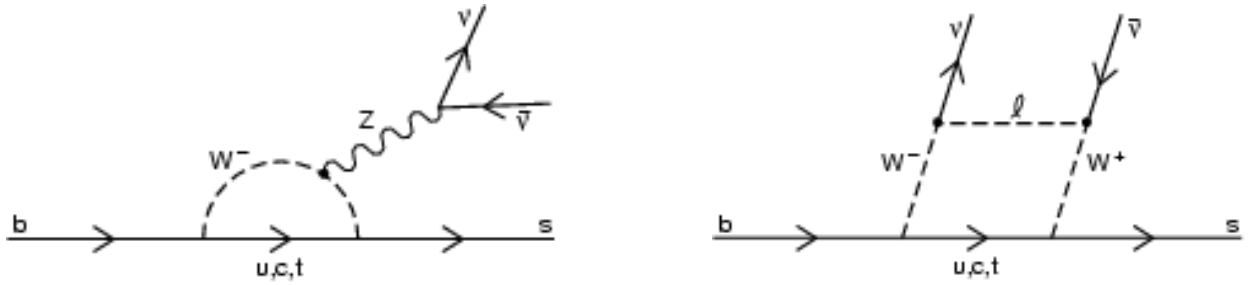
- $K^-$ $\pi^+$
- $K^-$ $\pi^+$ $\pi^0$
- $K^-$ $\pi^+$ $\pi^-\pi^+$
- $K^0_S$ $\pi^+$ $\pi^-$

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

- **Some issues arise in handling of higher mass charm states**
  - Un-reconstructed $D^{(*)0}$ –> $D^0$ γ / $\pi^0$ decays can contribute energy & multiplicity to "signal" reconstruction
- **Reconstruction doesn't have to be "perfect"**
  - It just has to correctly identify most of the non-signal B

# $B \to X_s \nu\bar{\nu}$ and $B \to X_d \nu\bar{\nu}$

- $B \to X_s \nu\nu$ proceeds in the SM via EW penguin and box diagrams:




- **Inclusive rate calculation theoretically very clean:**
  - $C^{\nu}_{10}$ only, no long distance contributions, QCD corrections small
- **Experimentally very challenging!**
  - search instead for exclusive decay modes:

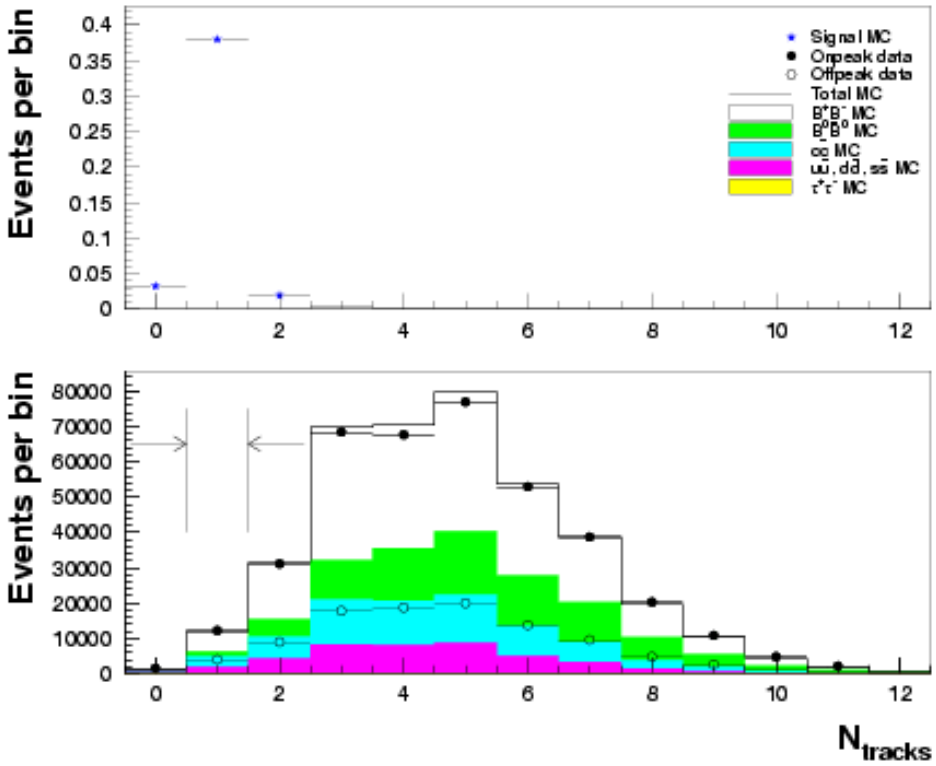
$$Br(B^+ \to K^+ \nu\bar{\nu})_{SM} \sim 4 \times 10^{-6}$$
$$Br(B^+ \to K^{*+} \nu\bar{\nu})_{SM} \sim 1.3 \times 10^{-5}$$

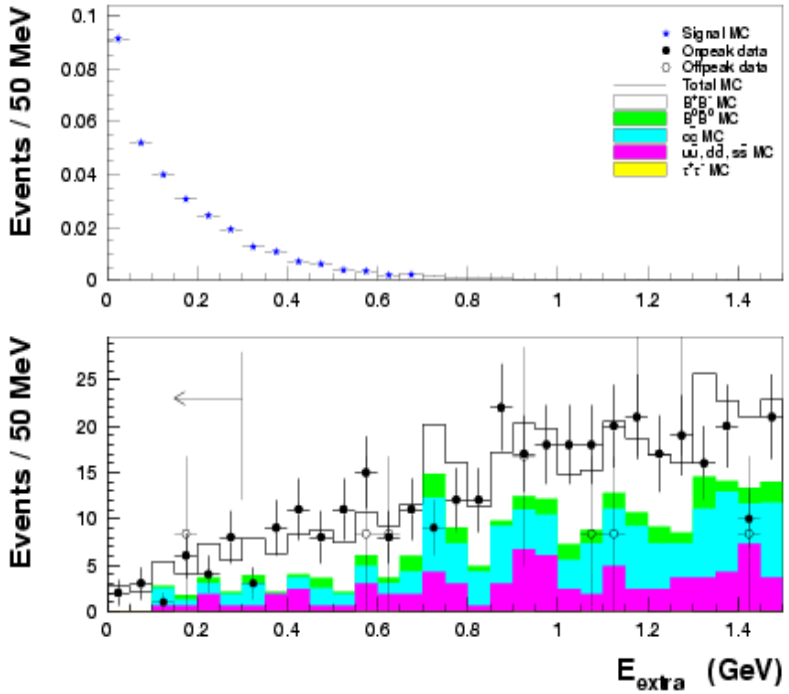
~30% of inclusive rate

  - Current limits more than an order of magnitude above SM rate

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

- **Use hadronic and/or SL tag samples then constrain remaining charged tracks and neutral clusters**
  - Essentially equivalent to imposing a "missing energy" constraint

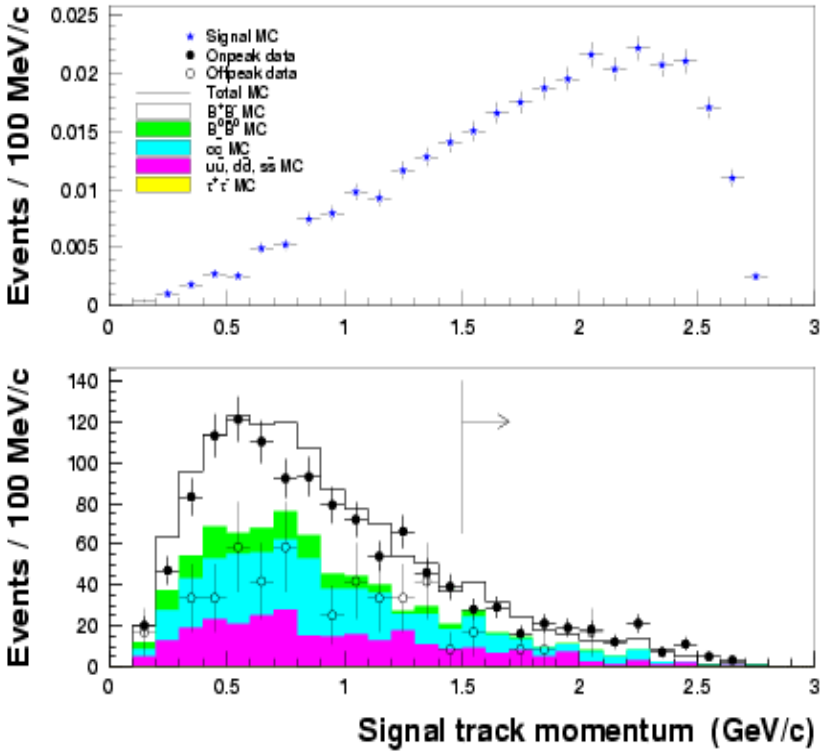



- **Backgrounds suppressed primarily by low multiplicity of signal channel**
  - "topological" selection

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

- **Exploit also the hard K momentum spectrum of signal events**
  - Some model dependence of limit due to form factor uncertainty
  - Selection re-optimization for high-lumi environment will result in harder momentum cut
    - **increased model dependence!**




- **BABAR analysis using ~80fb$^{-1}$ with a combination of hadronic and semileptonic tags:**

$$\mathrm{Br}(B^+ \to K^+ \nu\nu) < 7.0 \times 10^{-5} \quad 90\%\ \mathrm{CL}$$

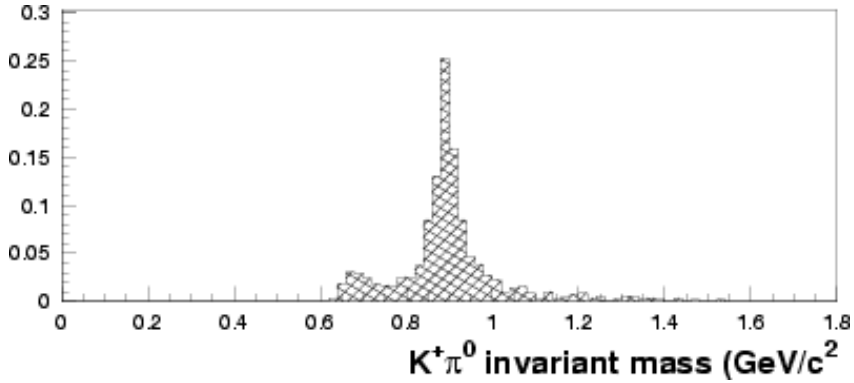
*BABAR* Prelim!

- **Still a long way to go to reach the SM**

# Exclusive B –> $X_{s/d}\nu\nu$ modes

**Analysis can be expanded to include several other similar decay modes:**

- **$B^+$ –> $K^{*+}(892)\,\nu\nu$**
  - Can exploit K* mass for background reduction, but reduced efficiency due to neutral daughter reconstruction
  - Expect O(1) event with 1ab$^{-1}$ using hadronic tag sample for a SM BR of ~1.1x10$^{-5}$




- **$B^+$ –> $\pi^+\nu\nu$**
  - "trivial" extension to $K^+\nu\nu$ search (change PID) but with order of magnitude higher backgrounds
  - SM likely out of reach even with ~30ab$^{-1}$ but probably limits at level of ~10$^{-5}$ – 10$^{-6}$
- **$B^+$ –> $\rho^+\nu\nu$**
  - $\pi^+\pi^0$ mass constraint helps reduce backgrounds, but situation likely comparable to $\pi^+\nu\nu$

# Neutral B modes

- **Hadronic and semileptonic tag B reconstruction can also be used for exclusive $B^0 \to X_{s/d} \nu\nu$ searches**
  - Reduced tag B efficiency compared to charged B modes due to Br's of reconstructable modes
- **$B^0 \to K^0_s \nu\nu$, $B^0 \to K^{(*)0} \nu\nu$ both have reduced signal efficiencies compared with $B^+ \to K^+ \nu\nu$ but may ultimately have lower backgrounds**
- **Further study needed**

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

- **Helicity suppressed tree-level processes in the SM**

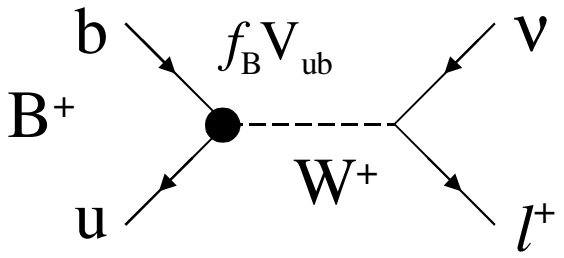
$$\mathrm{Br}(B^+ \to l^+\nu) = \frac{G_F^{\,2} m_B m_l^{\,2}}{8\pi}\left(1 - \frac{m_l^{\,2}}{m_B^{\,2}}\right) f_B^{\,2} |V_{ub}|^2 \tau_B$$

*SM Predictions*

$\mathrm{BR}(B^+ \to \tau^+\nu) \approx 9\times10^{-5}$

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

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

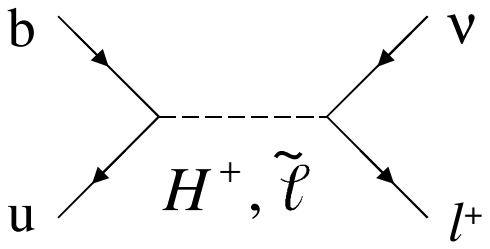



- **Could provide direct measurement of $f_B$ via product $f_B^{\,2}|V_{ub}|^2$**
- **Experimental limits currently a factor of five or more from SM predictions:**

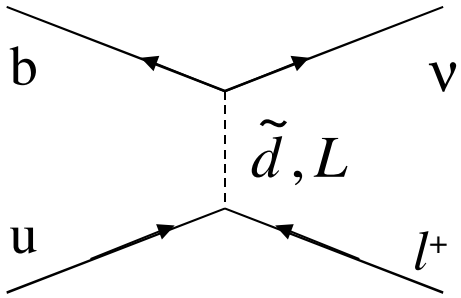
| | BaBar(81 fb$^{-1}$) | Belle (60 fb$^{-1}$) | CLEO |
|---|---|---|---|
| $\mathrm{BR}(B^+ \to \tau^+\nu)$ | $< 4.1\times10^{-4}$ | - | $< 8.4\times10^{-4}$ |
| $\mathrm{BR}(B^+ \to \mu^+\nu)$ | $< 6.6\times10^{-6}$ | $< 6.8\times10^{-6}$ | $< 2.1\times10^{-5}$ |
| $\mathrm{BR}(B^+ \to e^+\nu)$ | - | $< 5.4\times10^{-6}$ | $< 1.5\times10^{-5}$ |

# Non SM contributions

- **Lots of room for New Physics!**
- **Possible New Physics contributions to leptonic branching ratios include:**
  - Mediation by charged Higgs boson ($H^+$) in models with more than one Higgs doublet (e.g. MSSM)
    - **Possible enhancement up to observed experimental limits**
    - **Constraint on $\tan\beta/m_{H+}$ currently dominated by $B\to\tau\nu$**




  - Scalar sparticles in R-parity violating SUSY models
    - **Current branching ratio limits constrain R-parity violating couplings**
  - Pati-Salam Leptoquarks:



# $B^+ \to \tau^+\nu$

- **Comparitively large SM branching fraction and likely most sensitive to possible new physics**

  **SM:** $\mathbf{Br(B^+ \to \tau^+\nu) \sim 9 \times 10^{-5}}$

  - third-generation leptons potentially couple to new physics
- **Experimentally very challenging due to minimum of two neutrinos in final state**
- **Best limit from BABAR (~80fb$^{-1}$) using method similar to B–>Kνν**
  - Combination of fully reconstructed **hadronic** and **semileptonic** tags
  - τ decay final states: **eνν**, **μνν**, **πν**, **ρν** and **$a_1\nu$** (3π)

**$Br(B^+ \to \tau^+\nu) < 4.1 \times 10^{-4}$ 90% CL** *BABAR* Prelim!

- **Still a factor of ~5 above the SM!**
  - expect ~5 signal events at SM BF with current analysis

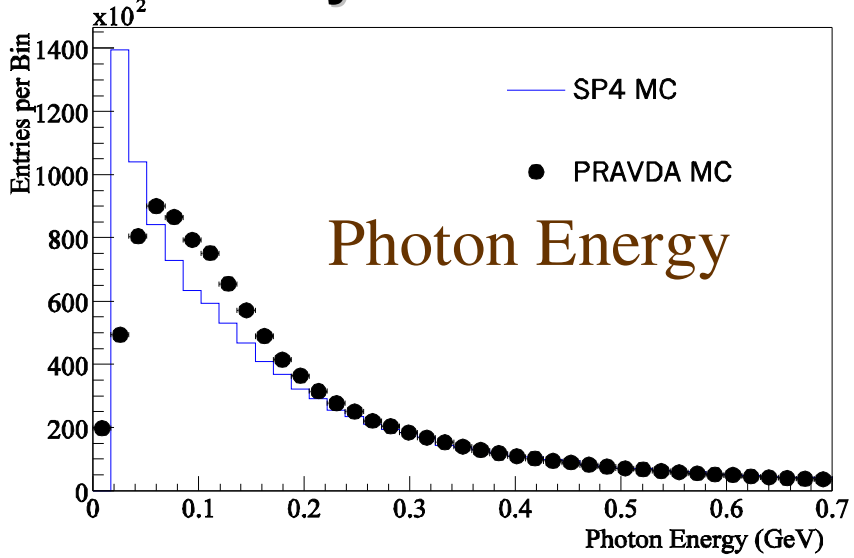
# $B^+ \to \tau^+\nu$ fast simulation

- **Studies performed using *BABAR* fast simulation ("Pravda") to evaluate Super B factory reach**

  Mousumi Datta, Wisconsin

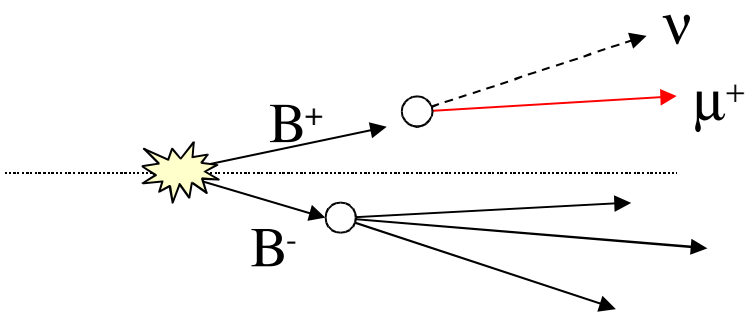
  - Tag B reconstruction efficiency depends on tracking/PID performance, and will most likely be similar to current performance
    - **if we can't reconstruct B's with it, then we won't build it...**
    - **no point simulating; can use "back of envelope" method**

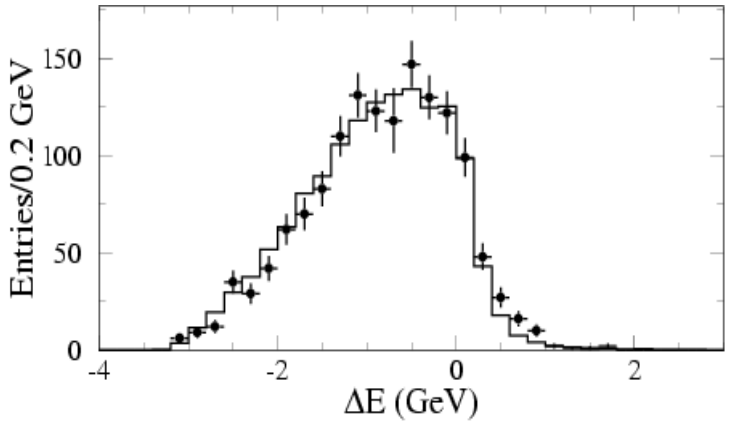
- **Signal $B^+ \to \tau^+\nu$ performance (cut optimization, efficiency and especially background levels) depends critically on details of tracking and calorimetry**
  - Dominant backgrounds are from $B^+B^-$ events with unreconstructed charged particles and/or unreconstructed $K_L$
  - Need FULL simulation with realistic neutrals reconstruction, hadronic shower simulation and beam backgrounds



# $B^+ \to \mu^+\nu$ current results

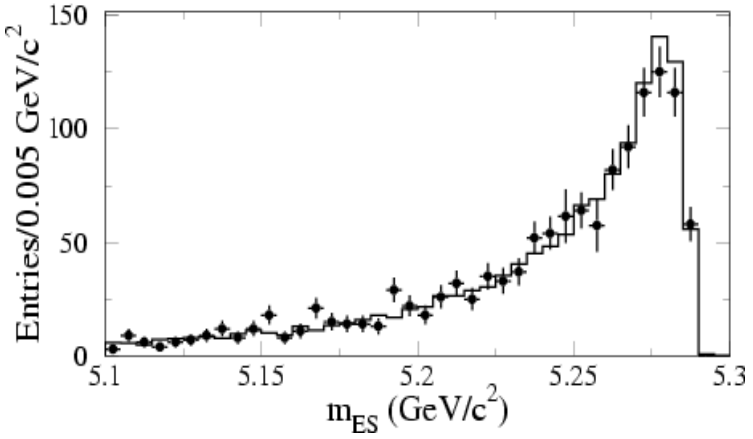
- **Identify high P muon, then "inclusively" reconstruct companion B from all remaining particles in the event**
  - background rejection mainly based on $m_{ES}$ and $\Delta E$ of companion B



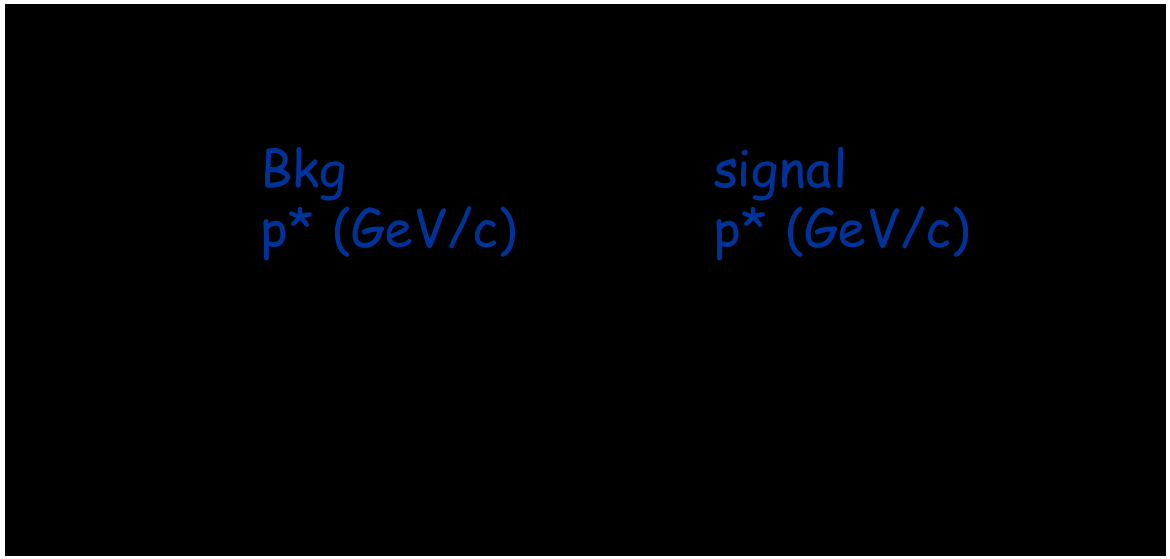




- **Recent BABAR analysis yielded**

  $BR(B^+ \to \mu^+ \nu_\mu) < 6.6 \times 10^{-6}$ (Submitted to PRL)
  - Comparable prelim result from Belle
- **Very poor resolution on $m_{ES}$ and $\Delta E$**
  - $\varepsilon$ ~ few % and O(10) background events for 81fb$^{-1}$ of data



# B –> μν fast simulation studies



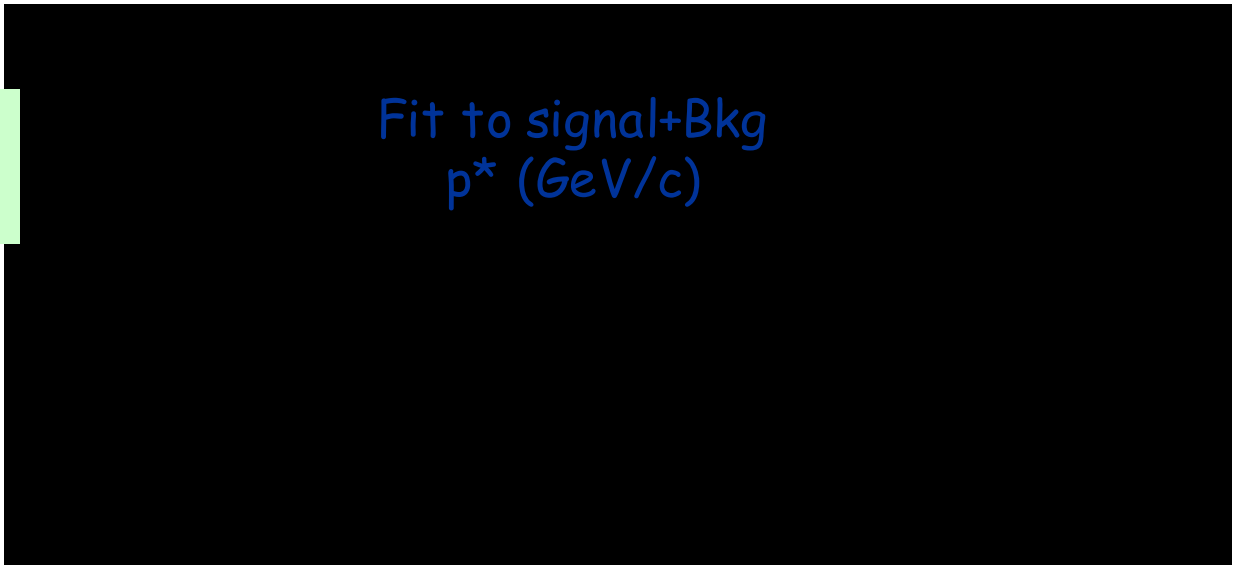

Thomas Moore, U.Mass

Background PDF:
Gaussian
Signal PDF:
2 Gaussian

In future, we could fit $\Delta E$, $m_{ES}$, p* simultaneously

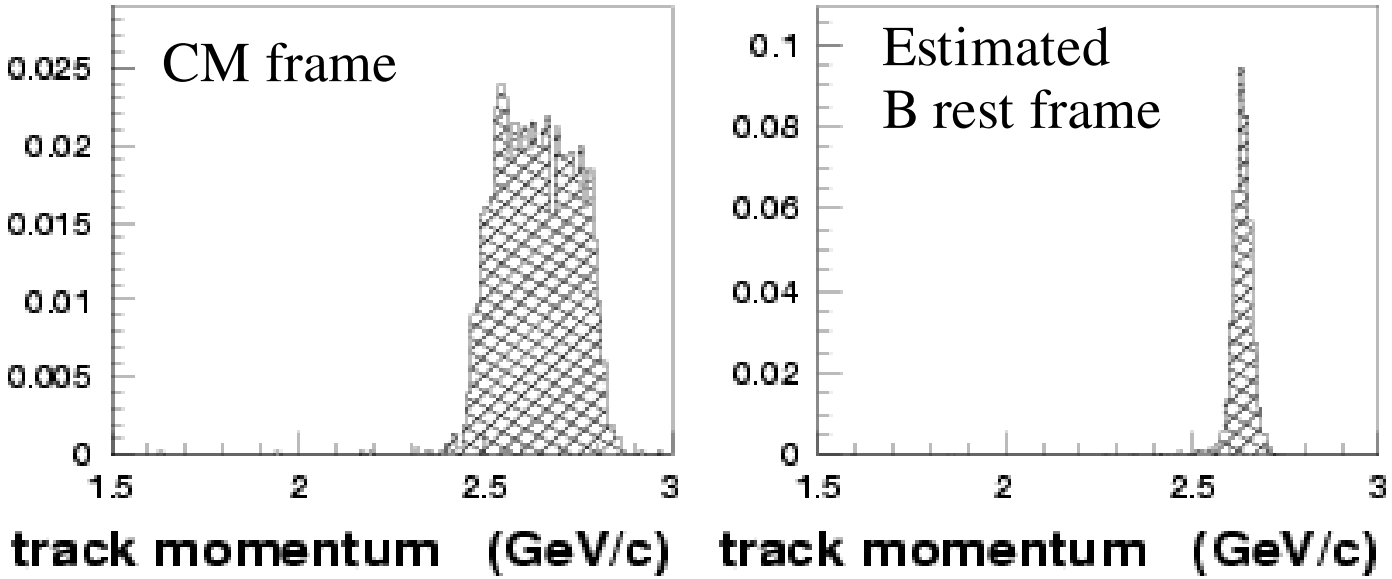
N(signal) = 106±16
σ ≈ 15%

For 2xBF (ε)
σ → 9%
For ½ BF (ε)
σ→ 27%



# $B^+ \to l^+\nu$ using "recoil" method

- **Reconstruct "tag B" using method of $B\to\tau\nu$ and $B\to K\nu\nu$**
  - Substantial efficiency "hit", but dramatic reduction in continuum background (dominant in untagged analysis)
  - Almost no "signal-side" cuts needed (not even PID?)
  - Hadronic reconstruction recovers lepton momentum $\delta$-function due to knowledge of the B rest frame:




- **"Sensitive" to SM rate for $B\to\mu\nu$ a at ~1ab$^{-1}$ with background <<1**

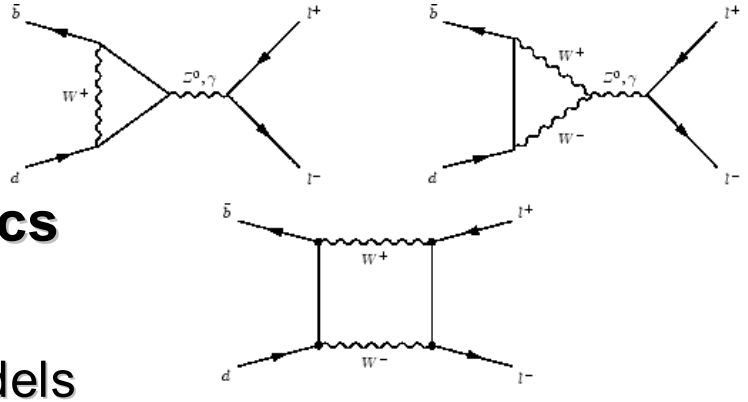
# $B^+ \to l^+ \nu \gamma$

- **SM rates are predicted to be ~1 x $10^{-6}$**
  - Published limits from CLEO:

    $B^+ \to \mu^+ \nu \gamma < 5.2 \times 10^{-5}$ and $B^+ \to \mu^+ \nu \gamma < 2.0 \times 10^{-4}$
- **Photon removes helicity supression**
  - $l$ = e, $\mu$ and $\tau$ modes are all (in principle) accessible
- **Analysis using "conventional" method suggests that backgrounds *may* preclude observation of SM rate**
- **In high lumi environment, could use exclusive B reconstruction**
  - Strongly suppress continuum/combinatoric backgrounds
  - Knowledge of signal B rest frame should help suppress combinatoric background from B decays
    - **Improved neutrino 4-vector resolution due to tag B kinematic constraints**
- **With 1ab$^{-1}$ of data, expect ~1 event at SM rate using only the hadronic tag sample**
- **No detailed simulation studies yet**

# $B^0 \to \tau^+\tau^-$ (and $B^0 \to \tau^+ l^-$ )

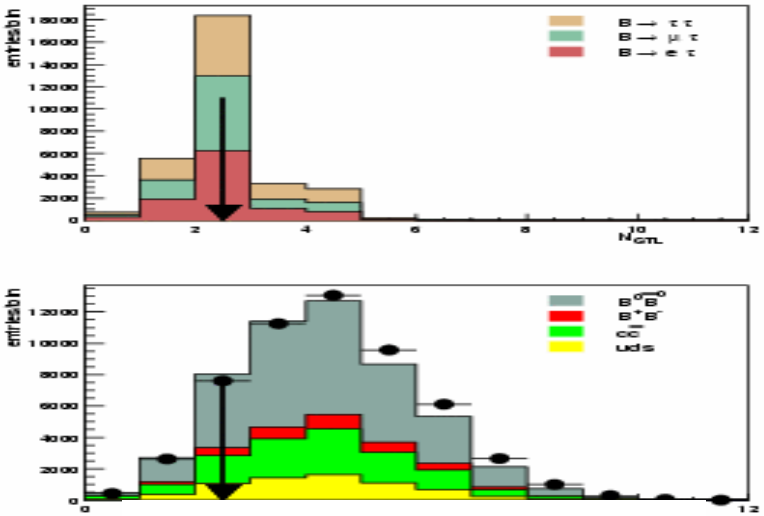
- **$B^0 \to \tau^+\tau^-$ proceeds in SM via EW penguin and box diagrams**
  - SM Br ($B^0 \to \tau^+ \tau^-$) ~ $10^{-8}$
  - Currently no published direct limits



- **Interesting due to potential New Physics coupling to 3rd generation**
  - LFV modes permitted in various BSM models

    **(e.g. SUSY seesaw model; Dedes et al. hep-ph/0209207)**

- **Experimentally challenging due to presence of multiple neutrinos and lack of clear signature(s)**
  - use (clean) hadronic tag sample and 1-prong tau decays (e, μ, π, ρ, $a_1$)
  - Exploit low multiplicity and large missing energy of signal events

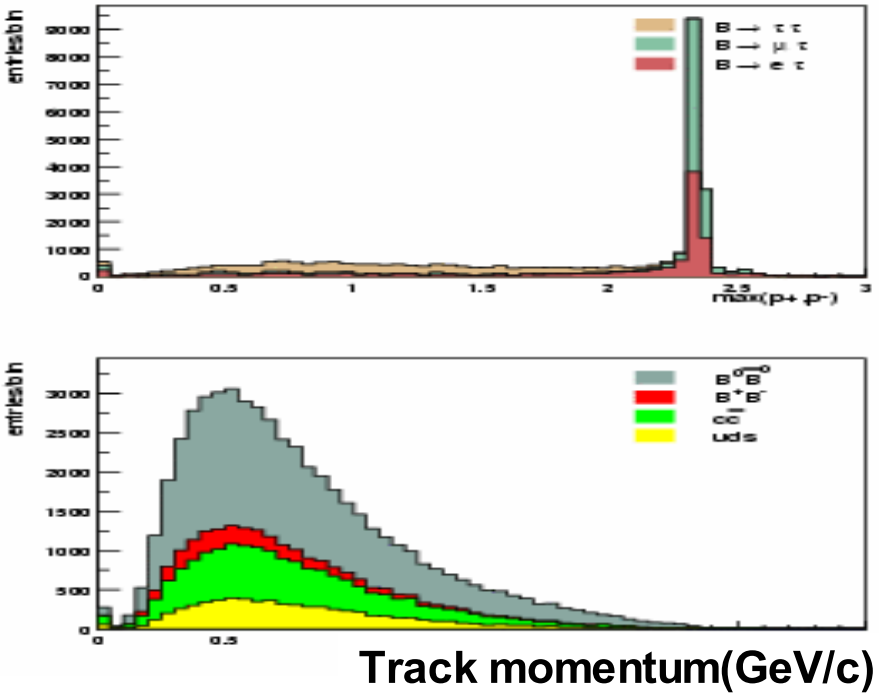


**Number of tracks**

# $B^0 \to \tau^+\tau^-$ (and $B^0 \to \tau^+ l^-$)

Chris Potter, Oregon

- **Unfortunately, $B^0 \to \tau^+\tau^-$ final states possesses irreducible(?) physics backgrounds from $b \to c \to s$ cascade decays with an unobserved $K_L$ in the final state**
  - BABAR full simulation studies
    - **Approximately 2/3 of background events contain one or more unidentified $K_L$**
    - **~1/3 or background events have two or more charged tracks passing outside of the detector acceptance**
- **Very challenging to push limit below ~$10^{-4}$ - $10^{-5}$ level**
- **LFV $B^0 \to \tau^+ l^-$ ($l$=e,μ) modes have distinctive mono-energetic leptor**
  - Don't need tag B reconstruction; use method similar to $B^0 \to \mu^+\nu$
    - **flag hard and soft leptons, and inclusively reconstruct second B using all remaining particles**

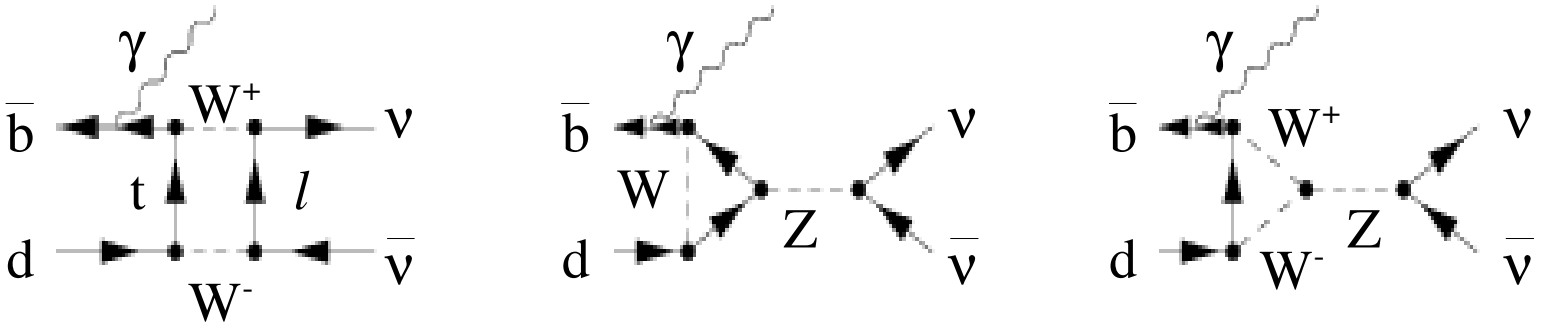


# $B^0 \to \nu\bar{\nu}(\gamma)$ (a.k.a. $B^0 \to$ invisible)

- **Standard Model $B^0 \to \nu\bar{\nu}$ process is helicity suppressed to (effectively) zero**

Justin Albert, Caltech

- **$B^0 \to \nu\bar{\nu}\gamma$ can occur at one loop level with BF ~$10^{-9}$**




  - Can be "faked" by various phenomenological models e.g. SUSY with a neutralino LSP which couples to B decays (Dedes et al. hep-ph/0106199) leading to enhancement by two orders of magnitude
- **Experimental signature is multiplicity (zero!) and missing energy**
- **Search can use both hadronic and SL reconstructed tags**
  - No physics backgrounds, but potentially sensitive to detector performance
    - **acceptance, tracking efficiency, spurious and/or unreconstructed neutrals**
    - **Need detailed simulation studies to estimate physics reach**

# Expected sensitivities

| Mode | "Current" analysis (~80fb$^{-1}$) | 1 ab$^{-1}$ | 10 ab$^{-1}$ |
|---|---|---|---|
| $B^+ \to K^+ \nu\nu$ | < 7.0x10$^{-5}$ | 3-10 events | 30-100 evts |
| $B^+ \to K^{*+} \nu\nu$ | ~ (1x10$^{-4}$) | 1-3 events | 10-30 evts |
| $B^0 \to K^0_S \nu\nu$ | ? | | |
| $B^0 \to K^{*0} \nu\nu$ | ? | | |
| $B^+ \to \tau^+\nu$ | < 4.1x10$^{-4}$ | O(10) evts | ? |
| $B^0 \to \tau^+\tau^-$ | ~ O(10$^{-3}$) | Br ~ O(10$^{-4}$) | hard |
| $B^0 \to \tau^+ l^-$ | ~ (1x10$^{-4}$) | Br ~ (1x10$^{-5}$) | Br ~ O(10$^{-6}$) ? |
| $B^0 \to \nu\nu$ | ~ O(10$^{-5}$) | Br ~ O(10$^{-6}$) | Br ~ O(10$^{-7}$) |

- $B^+ \to \mu^+\nu$ **and** $B^+ \to l^+\nu\gamma$ **limits will likely approach SM rates using "untagged" analysis with ~1ab$^{-1}$ of data**
  - precision measurements possible with >10ab$^{-1}$
  - "tagged" analysis to control backgrounds?

# Conclusions

- **"Recoil method" using hadronic and/or semileptonic tag B reconstruction is potentially a major selling point for a Super B factory:**
  - O(10M) reconstructed tags (H+SL) with 1ab$^{-1}$ of data!
  - Permits searches to be performed for modes which are otherwise inaccessible
  - Constrained kinematics will potentially be of benefit to background- or systematics-limited modes which do not currently use this method
    - **B–>μν, B–>μνγ, b–>dγ , b–>u*l*ν**
- **Modes such as $B^0$–>ττ and $B^0$–>νν(γ) will yield interesting limits in near future and perhaps also in Super B era**
- **Expect to have sensitivity to SM rates for B–>*l*ν (in μ and τ modes) and b–>sνν with ~1 ab$^{-1}$ of data**