Searches for New Physics in Rare *B* Decays at BaBar

$b \to s\gamma$ inclusive/exclusive

$B \to Kll$ and $B \to K^*ll$

$B \to \tau\nu$ and $B \to \tau\tau$

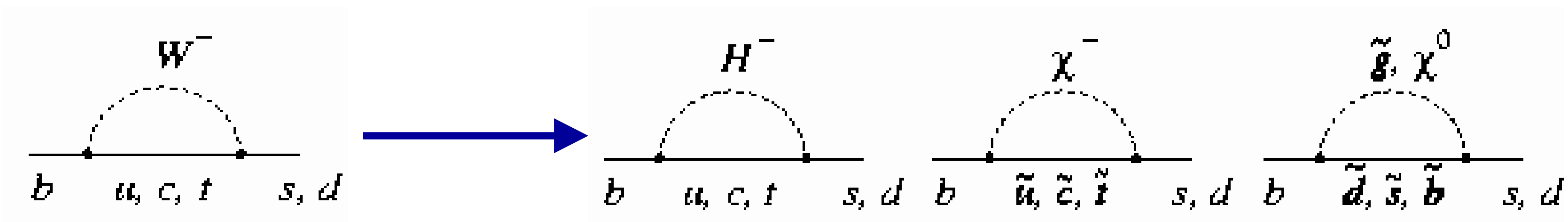
Jonathan Hollar
University of Wisconsin- Madison
For the BaBar collaboration

Pheno '06 Symposium

Searching for New Physics in *B* Decays

At tree-level, Standard Model usually dominates ⇒ focus on decays with no tree-level SM contribution

- Rare flavor-changing neutral currents proceeding through loop/box “penguin” diagrams
- Virtual *t, W* appear in the loop ⇒ indirect probes of much higher energy scales

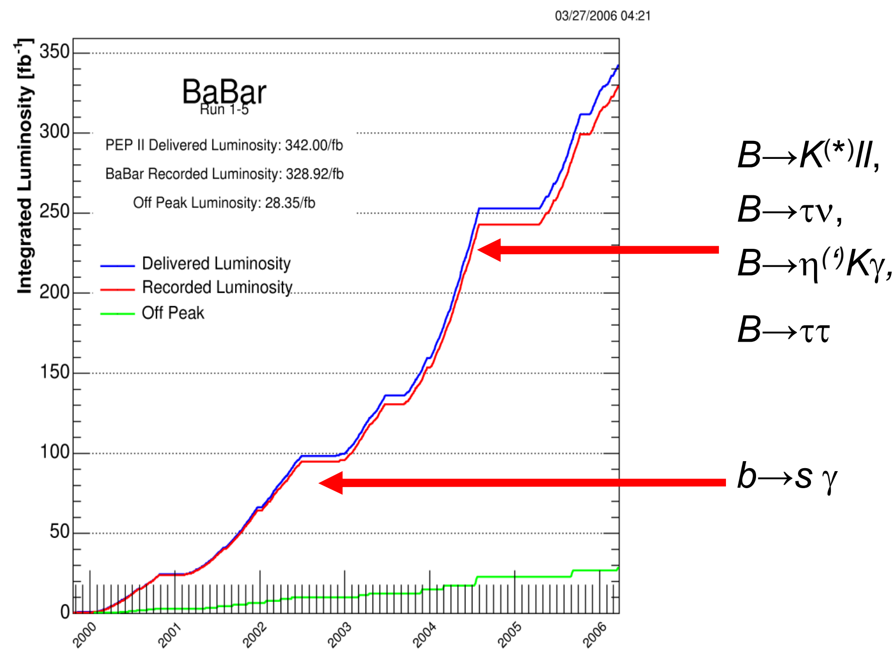


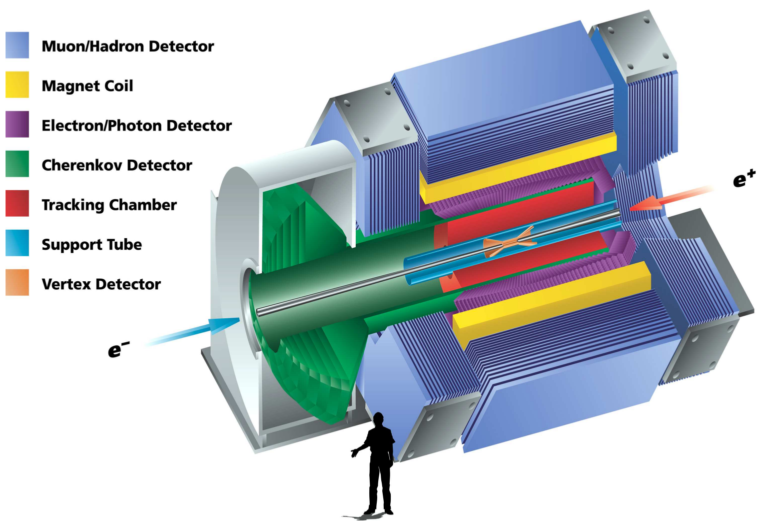
New Physics can enter at leading order!

BaBar detector & dataset

Need large data samples to study rare decays

- >350 fb^{-1} (**~370 million *B*-pairs**) delivered by PEPII
- Analyses shown here use 80 – 210 fb^{-1} samples

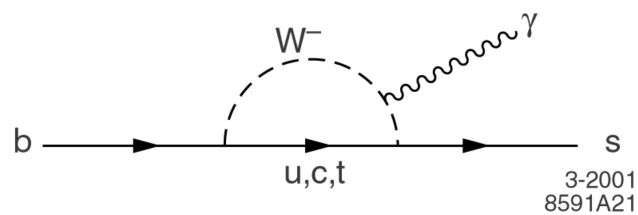




Analyses exploit BaBar's:

- Good neutral energy resolution
- Charged K/π separation, lepton ID
- Low multiplicity environment, coherent production of B-pairs

$b \to s\gamma$



$$H_{eff} \propto \sum_i C_i O_i$$

Short-distance /perturbative (C_i)

Long-distance /non-perturbative (O_i)

Rate depends on the C_7 "Wilson coefficient" in the Operator Product Expansion

- New physics can alter magnitude/sign of C_7
- Also sensitive to non-SM right-handed currents

Experimentally: large backgrounds of photons from light quarks (continuum), initial state radiation, π^0 from *B* decays

Analyses can be done:

- **Inclusively: theoretically clean**, more difficult experimentally
- **Exclusively: easier experimentally**, more theoretical uncertainties (form factors)

Inclusive $b \to s\gamma$ analyses

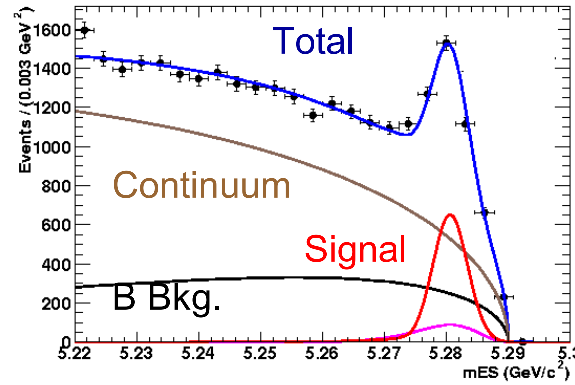
Sum-of-exclusive

Fully reconstruct the *B* in 38 distinct final states (~60% of total):

- $K\gamma$+nπ (n < 5), also states w. an η or 1-3 kaons
- Neural network to reject background
- Extract yield from fit to energy substituted mass:

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

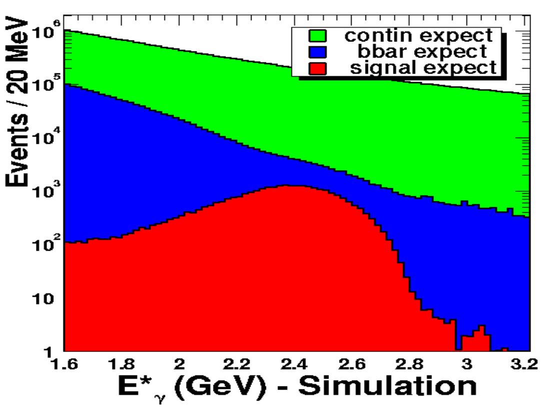
Eγ > 1.9 GeV



Phys. Rev. Lett 93, 021804 (2004)

Phys. Rev. D 72, 052004 (2005)

Fully Inclusive

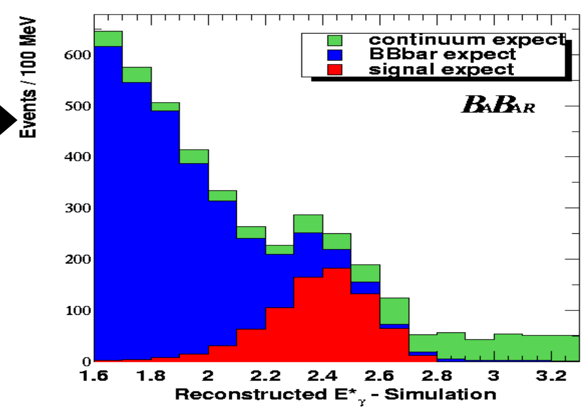


Use only the γ

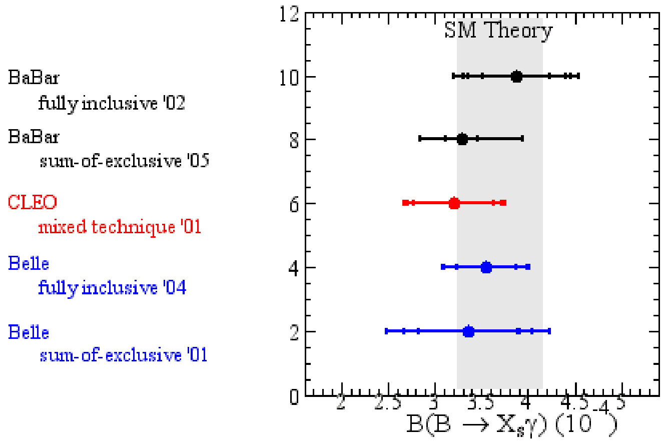
Lepton "tag" from the other B to reduce backgrounds

Subtract remaining backgrounds

Eγ > 1.9 GeV



b → *s*γ results



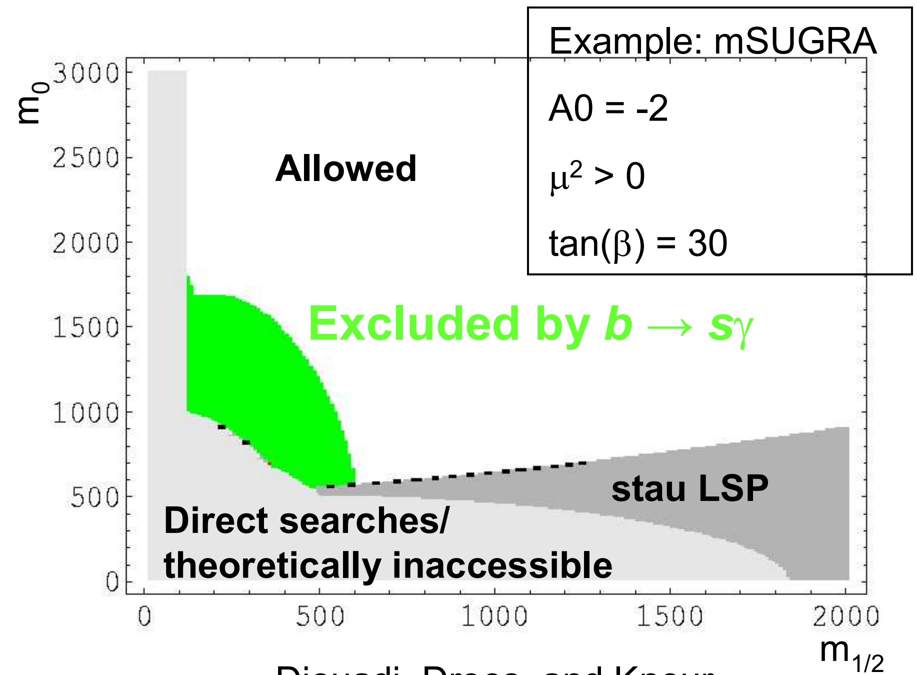
B(*B* → *s*γ) = (3.55 ± 0.26) x 10^{-4} Exp. world avg.
B(*B* → *s*γ) = $(3.61\ ^{+0.37}_{-0.49})$ x 10^{-4} SM (NLO)
(HFAG extrapolation to Eγ > 1.6 GeV)

Outstanding agreement between experiment and SM

- Strong constraints on many New Physics scenarios

Coming improvements

- More data (experiment)
- NNLO calculation (theory)



Djouadi, Drees, and Kneur

JHEP 0603:033, 2006

$b \to s\gamma$ asymmetries

CP, isospin asymmetries are complementary probes of New Physics

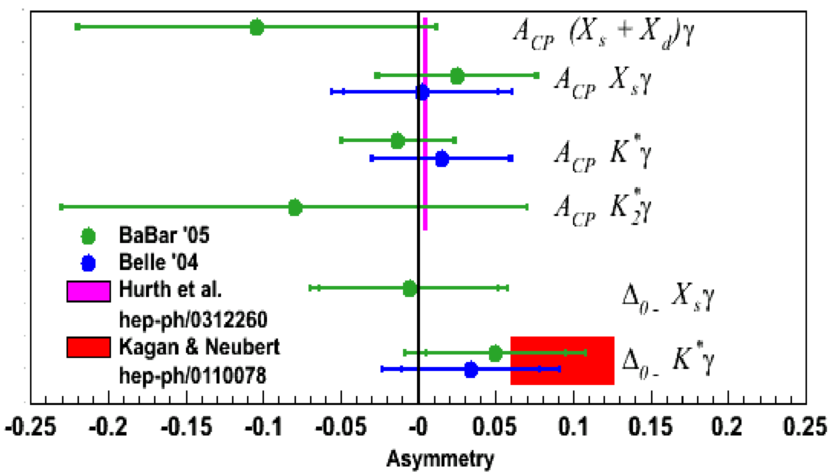
Null tests of SM predictions, e.g.

$A_{CP}(B \to X_s\gamma) \sim 10^{-4}$

$A_{CP}(B \to (X_s + X_d)\gamma) \sim 10^{-9}$

$$A_{CP} \equiv \frac{\Gamma(b \to x\gamma) - \Gamma(\bar{b} \to \bar{x}\gamma)}{\Gamma(b \to x\gamma) + \Gamma(\bar{b} \to \bar{x}\gamma)}$$

New Physics could lead to asymmetries of order 10^{-2} – 10^{-1}



Results are all consistent with the SM

- *CP* asymmetries measured with precision of 5-10%

Exclusive $B \to \eta(')K\gamma$

BF Results (x 10^{-6})

$B(B^+ \to \eta K^+\gamma) = 10.0 \pm 1.3 \pm 0.5$

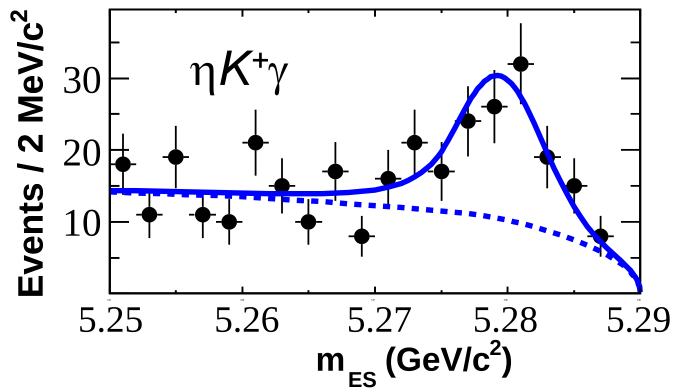
$B(B^0 \to \eta K^0\gamma) = 11.3\,^{+2.8}_{-2.6} \pm 0.6$

$B(B^+ \to \eta' K^+\gamma) < 4.2$

$B(B^0 \to \eta' K^0\gamma) < 6.6$

Submitted to PRL (hep-ex/0603054)

$A_{CP}(B \to \eta K^+\gamma) = -0.086 \pm 0.120 \pm 0.010$

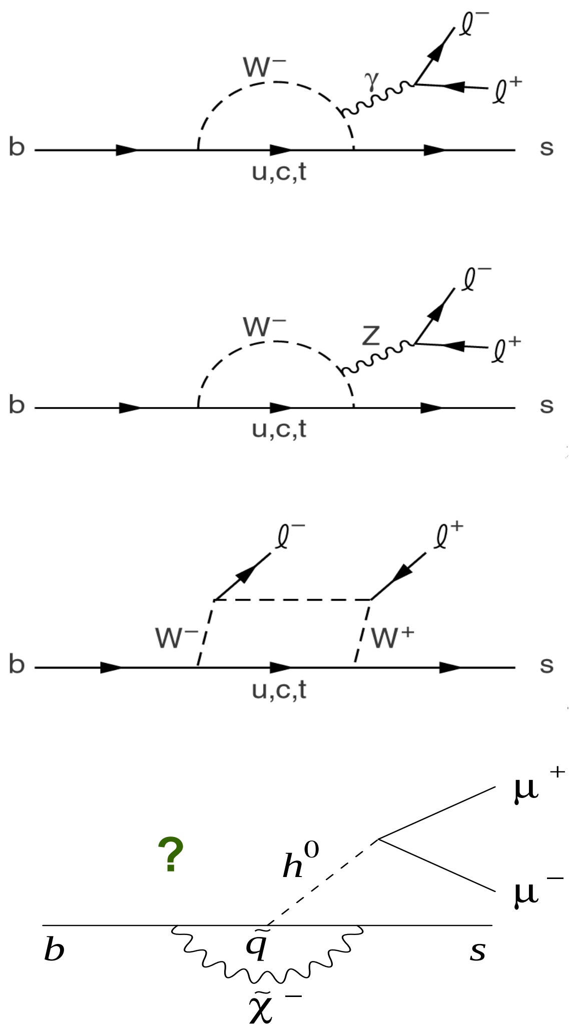


Improved measurement of $\eta K\gamma$ - First 5σ observation of neutral mode

First search for $\eta' K\gamma$ - No signal observed (suppressed relative to $\eta K\gamma$)

First measurement of direct *CP* asymmetry in $\eta K\gamma$ mode – consistent with 0, SM

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



Three diagrams (at least) at leading order

- γ penguin, Z penguin, W-box

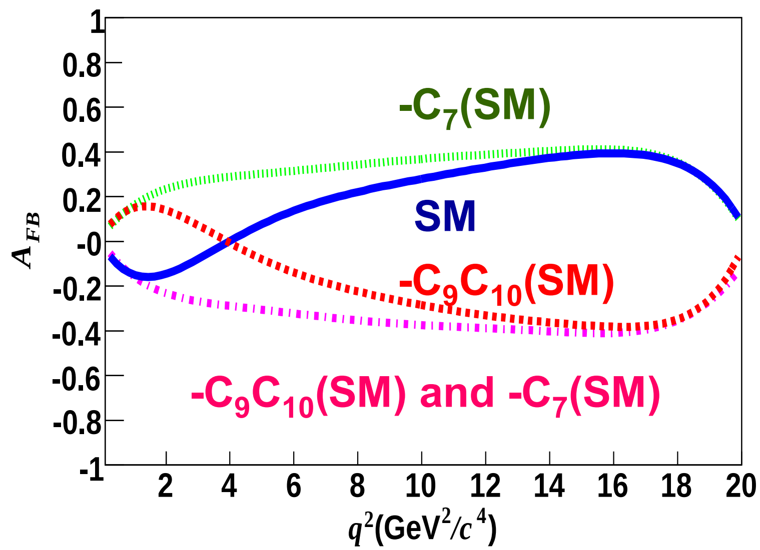
C_7 (EM), C_9(vector), C_{10}(axial vector) Wilson coefficients

- Magnitude of C_7 fixed by $b \to s\gamma$, sign not yet determined
- Magnitude and sign of C_9,C_{10} weakly constrained
- Additional operators/C_i also possible: scalar/Higgs penguins, etc.

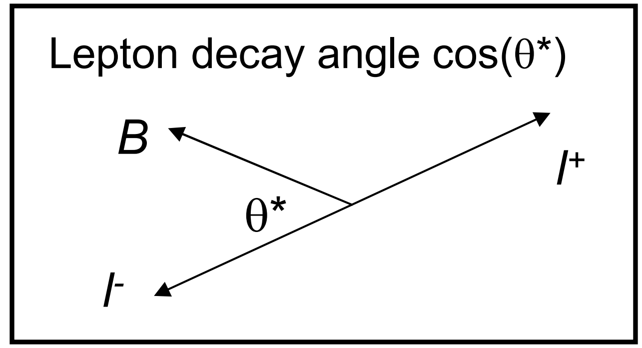
3-body decays ⇒ disentangle magnitude and sign of different operators

$B(B \to Kll) = (0.34 \pm 0.07 \pm 0.02) \times 10^{-6}$
$B(B \to K^*ll) = (0.78 \pm 0.18 \pm 0.11) \times 10^{-6}$

Angular variables



Predictions using NNLO Wilson coefficients + LCSR form factors



Forward-backward **asymmetric in *K**ll*** vs. q^2

- ~sign of Wilson coefficients

Forward-backward **symmetric in *Kll***

- If no new scalar operators

Kaon decay angle cos(θ_K) gives longitudinal *K** polarization

- Sensitive to sign(C_7) or new right-handed currents at low q^2

$B \to K^{(*)}ll$ Analysis and $B \to Kll$ Results

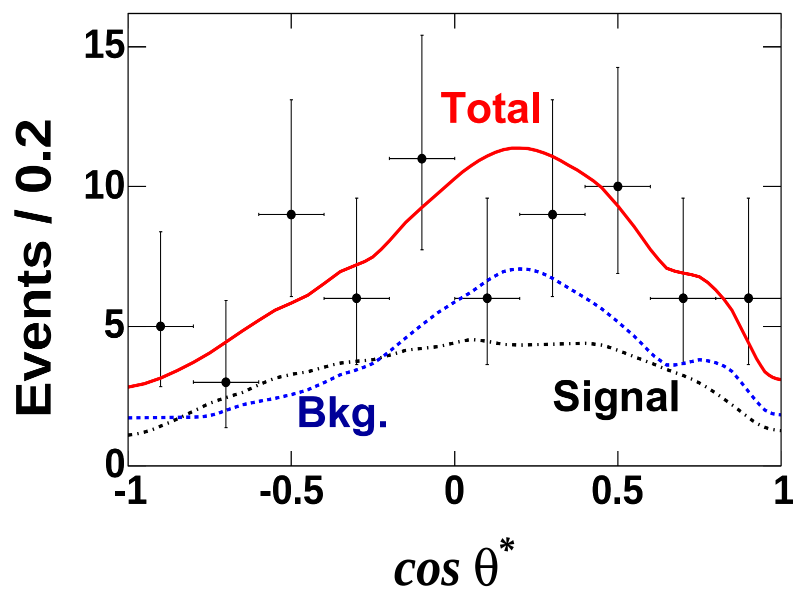
Fits to $\cos(\theta^*)$, $\cos(\theta_K)$ to extract A_{FB}, K^* polarization in 2 bins of q^2

- Background angular distributions modeled from sideband control samples
- Correct for angular efficiency/acceptance
- Procedure validated on $J/\psi K^{(*)}$, $\psi' K^{(*)}$ control samples

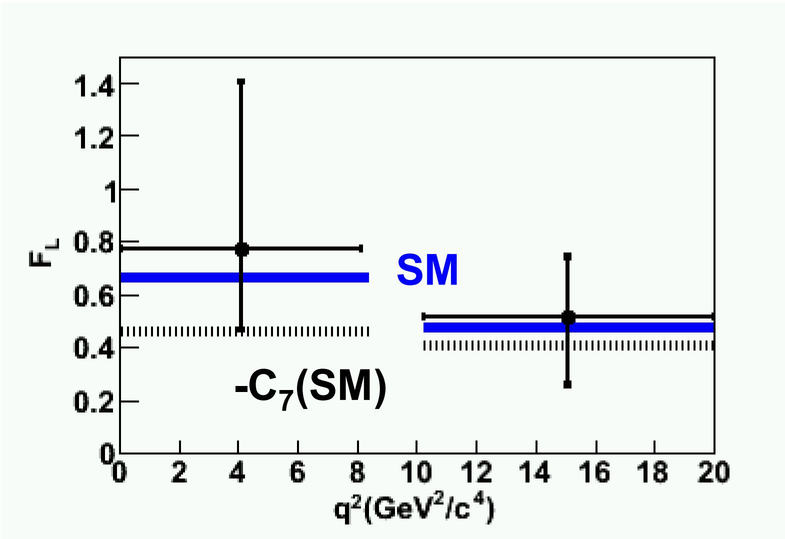
FB asymmetry, scalar contribution in $B^+ \to K^+ll$ is consistent with 0, SM

$A_{FB}(B^+ \to K^+ll) = 0.15\,^{+0.21}_{-0.23} \pm 0.08$

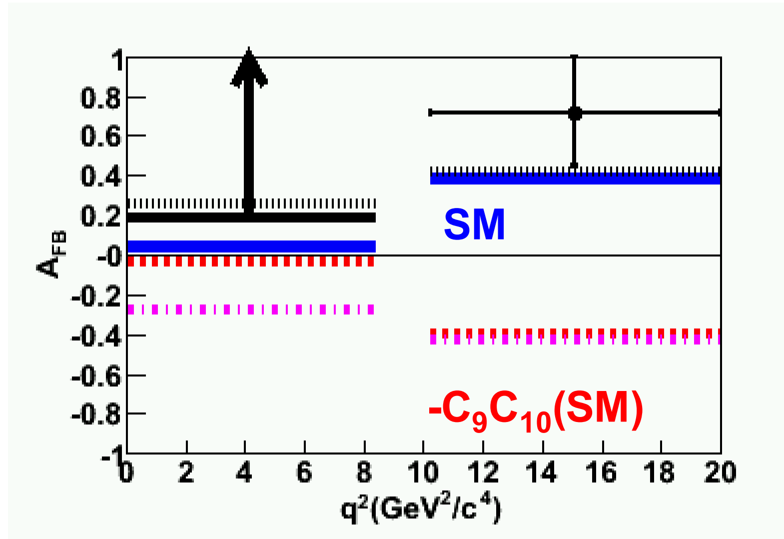
$F_S\,(B^+ \to K^+ll) = 0.81\,^{+0.58}_{-0.61} \pm 0.46$



$B \to K^* ll$ Results



- First measurement of *K** polarization in this mode
- **Consistent with SM**
- With more data, can determine sign of C_7



- High q^2 A_{FB} agrees with SM, **excludes wrong sign C_9C_{10}** at >3σ (agrees with Belle results)
- Low q^2 limit is consistent with SM at 2% (2.05 σ)

Phys. Rev. D 73 092001 (2006)

Rare B decays with τ's

New Physics could couple strongly to heavy/3rd generation leptons

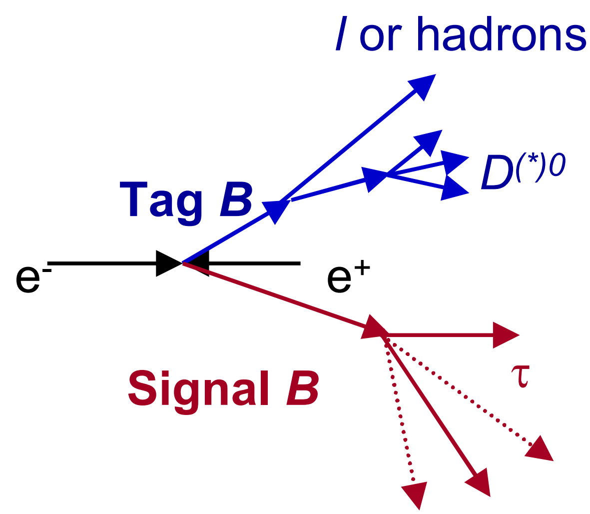
- Higgs, leptoquarks, etc.

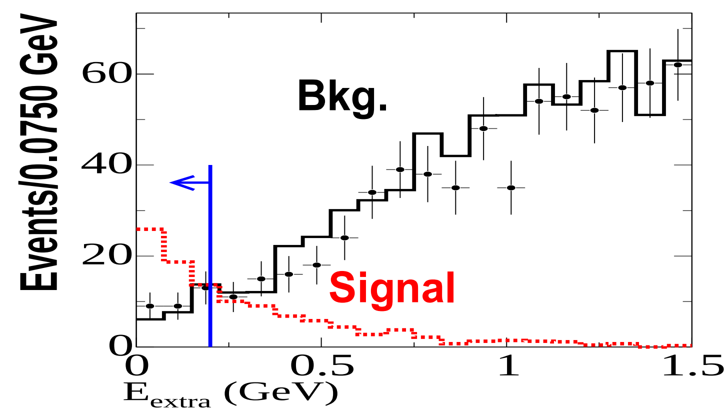
Extremely challenging analyses

- The τ decays, with undetectable neutrinos in the final state

Reconstruct the other ("Tag") B as $B \rightarrow D^{(*)}$ + hadrons or $B \rightarrow D^{(*)} l \nu$

- Anything left is (ideally) from the other B
- Partially reconstruct τ candidates in several decay modes (typically 30-50% of the total rate)
- True signal has little residual energy ("E_{extra}" or "E_{res}") in the calorimeter

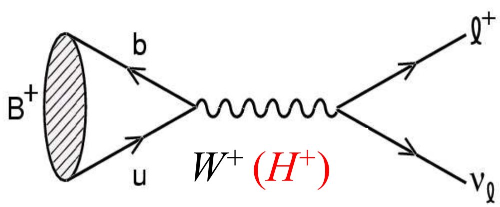




Decay modes

$B \to \tau\nu$

W annihilation diagram in SM



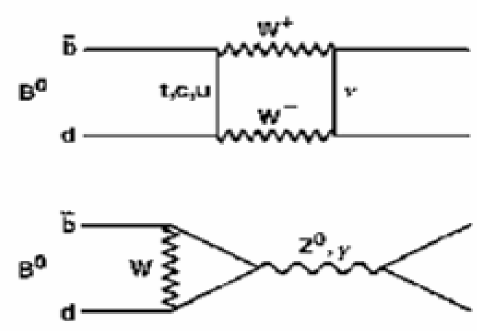
- SM B($B \to \tau\nu$) ~ 1.6 x 10^{-4}
- **Sensitive to charged Higgs at tree level**

Two statistically independent analyses

- Semileptonic tag (211 fb^{-1})
- Hadronic tag (82 fb^{-1})

$B \to \tau\tau$

Leading order loop/box diagrams



- SM B($B \to \tau\tau$) ~ 1 x 10^{-7}
- **No previous experimental results for this mode**

Hadronic tag analysis (210 fb^{-1})

- Neural network to suppress remaining backgrounds

$B \to \tau\nu$ results

No signals observed ⇒ set upper limits from combined hadronic/semileptonic tag analyses

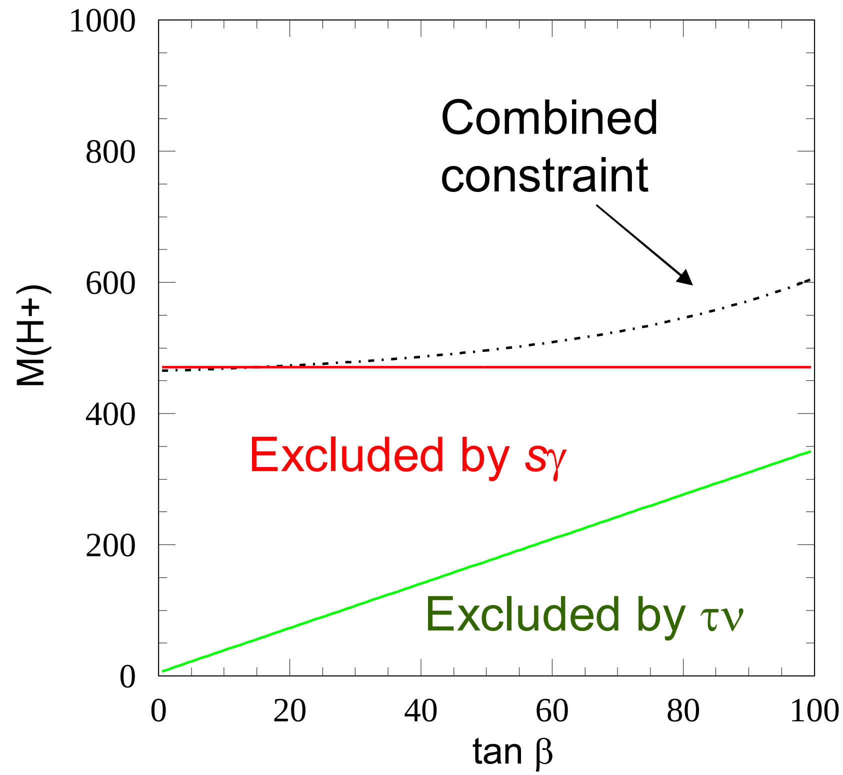
$B(B \to \tau\nu) < 2.6 \times 10^{-4}$ (90% CL)

Phys. Rev. D 73, 057101 (2006)

Limits within a factor ~2 of SM prediction

Constraints on charged Higgs mass/tanβ in Type II 2HDM

- Complementary to limits from $b \to s\gamma$ at high tanβ



Update: Evidence for $B \to \tau\nu$ reported by Belle at FPCP 2006 (414 fb^{-1}):

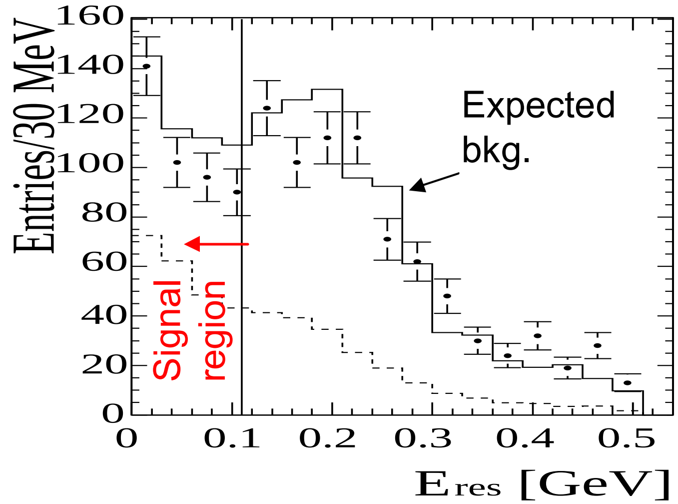
$B(B \to \tau\nu) = (1.06^{+0.34}_{-0.28}{}^{+0.18}_{-0.16}) \times 10^{-4}$

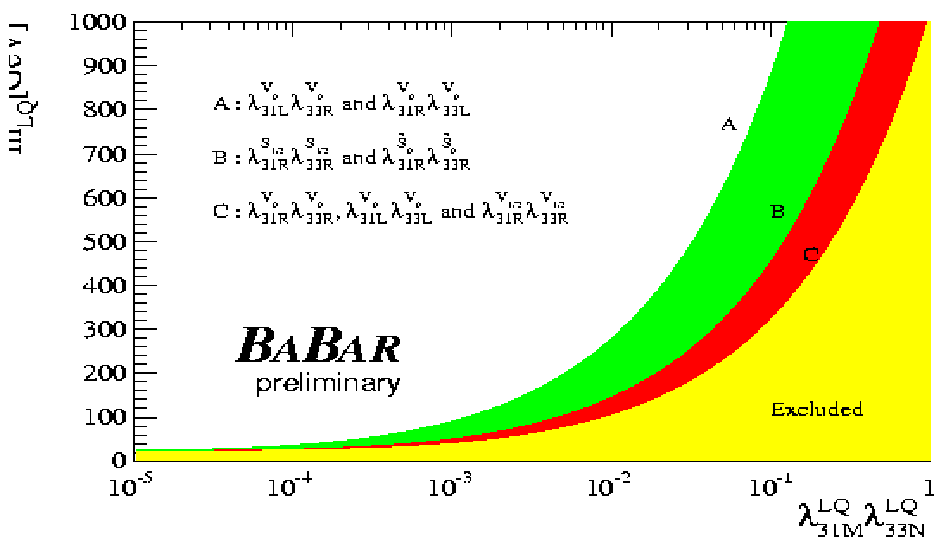
$B \to \tau\tau$ results

No evidence of signal:

N (expected background) = 281 ± 40
N (observed) = 263 ± 19

$B(B \to \tau\tau) < 3.4 \times 10^{-3}$ (90% CL)





First ever limits on this decay mode!

New limits on 3rd generation leptoquark masses/couplings

Submitted to PRL (hep-ex/0511015)

Conclusions

Rare *B* decays are an excellent place to find/constrain New Physics

$b \rightarrow s\gamma$ rates, *CP* asymmetries are now precision measurements

- Strong constraints on many models

$A_{FB}(B \rightarrow K^*ll)$ disfavors new physics with wrong sign C_9C_{10}

- Determination of sign of C_7 with more data

$B \rightarrow \tau\nu$ approaching SM sensitivity (evidence from Belle)

First limits on $B \rightarrow \tau\tau$

Analyses shown here use only 8 - 20% of the final BaBar dataset

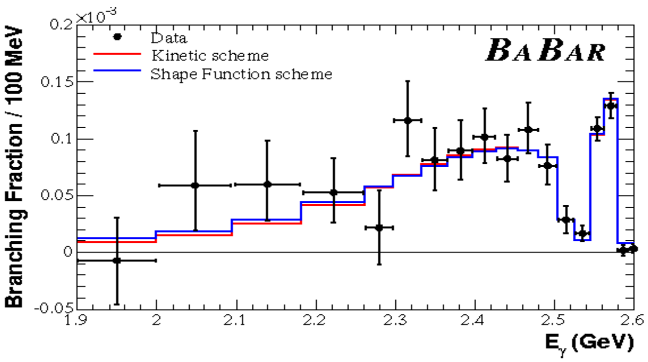
Most measurements are statistics limited – stay tuned for new results!

Extra Slides

$b \to s\gamma$ spectrum/moments

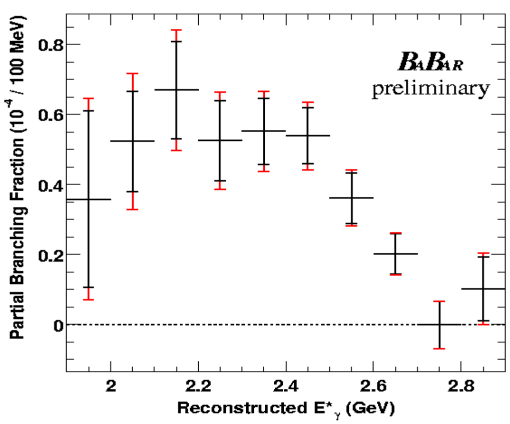
$b \to s\gamma$ photon spectrum, moments not sensitive to new physics (2-body decay)

- Can study parameters of the Heavy Quark Expansion (HQE)
- **Determination of m_b to < 1%**



From combination of $b \to s\gamma$ (BaBar, Belle + CLEO) with $b \to cl\nu$ (BaBar):

	m_b (GeV)	μ_π (GeV^2)
Kinetic scheme	4.590 ± 0.039	0.401 ± 0.040
Shape function scheme	4.604 ± 0.038	0.189 ± 0.038



More $B \to K^{(*)}ll$

$A_{CP}(K^+ll) = -0.07 \pm 0.22 \pm 0.02$

$A_{CP}(K^*ll) = 0.03 \pm 0.23 \pm 0.03$

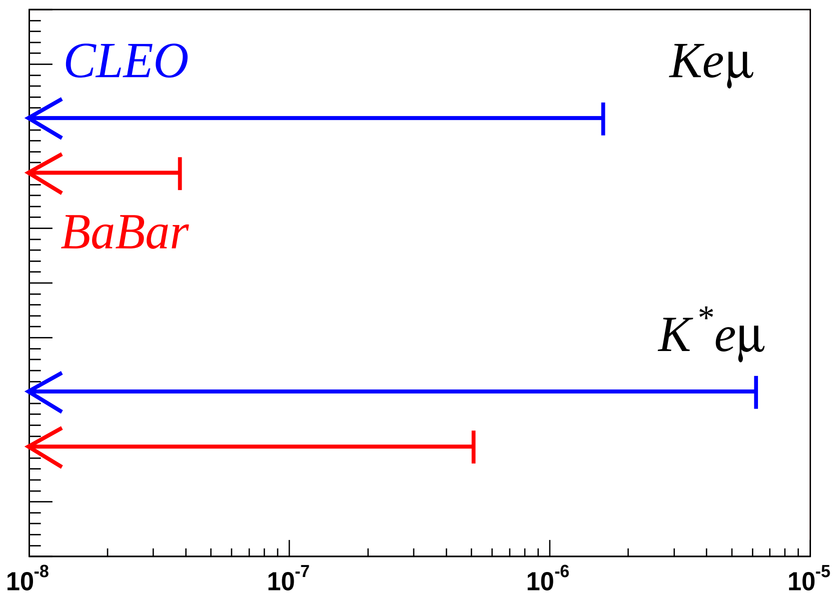
$A_{CP}(SM) \sim 0$

Muon/electron ratios

$R_K = 1.06 \pm 0.48 \pm 0.08$

$R_{K^*} = 1.40 \pm 0.78 \pm 0.10$

$R_K(SM) = 1.0000 \pm 0.0001$



Improved limits on LFV modes

$B(B \to Ke\mu) < 3.8 \times 10^{-8}$ (90% CL)

$B(B \to K^*e\mu) < 51 \times 10^{-8}$ (90% CL)

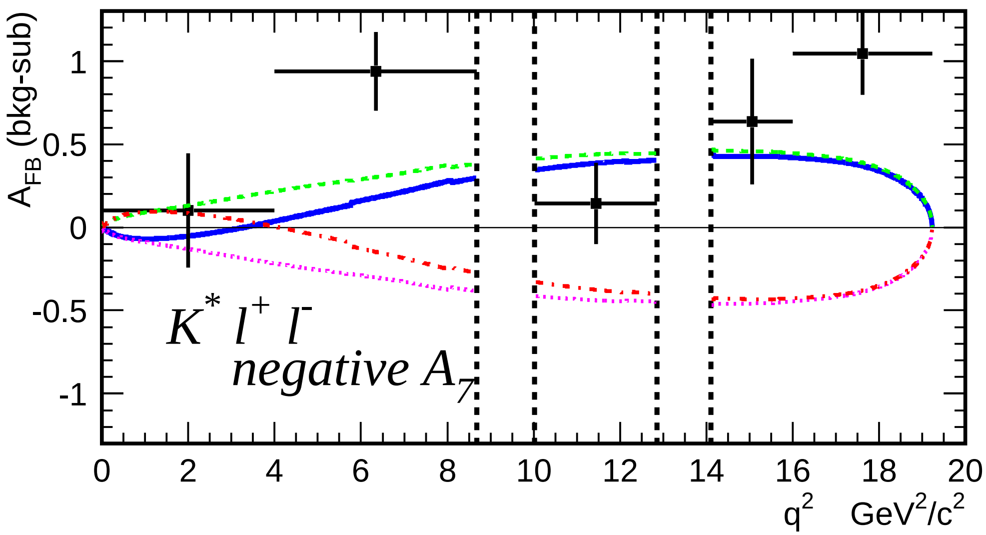
All results are consistent with SM predictions

Belle $B \rightarrow K^{(*)}ll$

Analysis based on 414 fb-1

Fit directly for Wilson coefficients from q^2, $\cos(\theta^*)$

- Fix C_7 to +/- SM value
- Wrong-sign C_9C_{10} excluded at 98.2% CL
- Consistent with SM or wrong-sign C_7



Integrated discrete asymmetry

A_{FB} (K^*ll) = 0.50 ± 0.15 ± 0.02

A_{FB} (Kll) = 0.10 ± 0.14 ± 0.01

$B \to (\rho/\omega)\gamma$

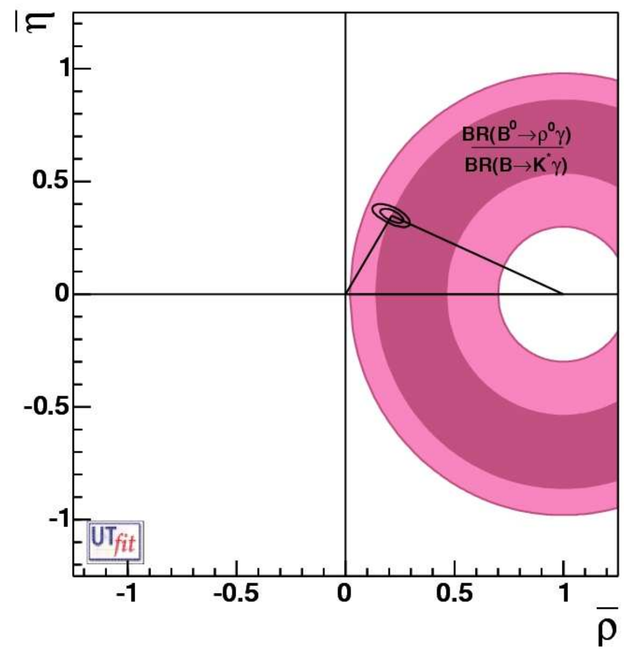
If no new physics in loops, ratio $(B\to(\rho/\omega)\gamma)/(B\to K^*\gamma)$ gives ratio of CKM matrix elements V_{td}/V_{ts}

BaBar 192 fb^{-1} result:

$B(B \to \rho(\omega)\gamma) = (0.6 \pm 0.3 \pm 0.1) \times 10^{-6}$
(2.1σ significance)

$|V_{td}/V_{ts}| < 0.19$ (90% CL)

If SM, should be consistent with values extracted from B_s mixing (CDF/D0)



Combined BaBar/Belle constraint from ρ^0 mode (UTfit)

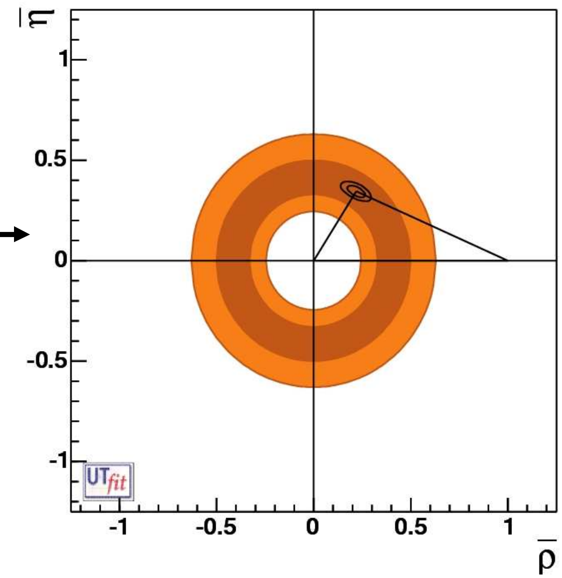
$B \to \tau\nu$ in the SM

$B \to \tau\nu$ depends on *B*-meson decay constant f_B and CKM element V_{ub}

If no new physics, rate can constrain V_{ub}

OR

assume V_{ub} and extract f_B for comparison with lattice QCD prediction



Combined BaBar/Belle constraint (UTfit)

$f_B = 0.180 \pm 0.031$ GeV	Experiment
$f_B = 0.192 \pm 0.026 \pm 0.009$ GeV	Lattice QCD

$B \rightarrow \tau\tau$ Leptoquark limits

$$\lambda_L\lambda_R, \lambda_R\lambda_L < 1.3 \times 10^{-3} \left[\frac{m_{V_0}}{100\,GeV}\right]^2$$

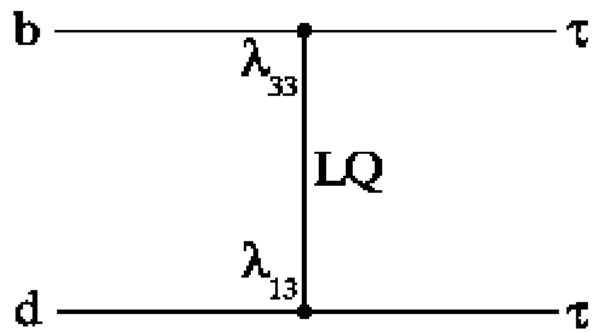
$$\lambda_L\lambda_L, \lambda_R\lambda_R < 9.8 \times 10^{-3} \left[\frac{m_{V_0}}{100\,GeV}\right]^2$$

$$\lambda_R\lambda_R < 9.8 \times 10^{-3} \left[\frac{m_{V_{1/2}}}{100\,GeV}\right]^2$$

$$\lambda_R\lambda_R < 4.9 \times 10^{-3} \left[\frac{m_{S_{1/2}}}{100\,GeV}\right]^2$$

$$\lambda_R\lambda_R < 4.9 \times 10^{-3} \left[\frac{m_{S_0}}{100\,GeV}\right]^2$$

Fermion subscripts are omitted. Subscripts L or R indicate quark chirality.



BF is enhanced by $\lambda_{31}\lambda_{33}$, suppressed by $1/m_{(LQ)}^4$

Grossman, Ligeti, and Nardi Phys. Rev. D 55, 2768 (1997)

Even more rare leptonic decays

Decay Mode	SM Prediction	BaBar UL (90% CL)
$B^0 \to e^+e^-$ $B^0 \to \mu^+\mu^-$ $B^0 \to e^\pm\mu^+$	2.4×10^{-15} 1.0×10^{-10} Negligible	6.1×10^{-8} 8.3×10^{-8} 18×10^{-8} PRL **94**, 221803 (2005)
$B^+ \to K^+\nu\nu$ $B^+ \to \pi^+\nu\nu$	4×10^{-6}	5.2×10^{-5} 1.0×10^{-4} PRL **94**, 101801 (2005)
$B \to \nu\nu$ ("Invisible")	$\propto (m_\nu/m_{B^\circ})^2$	2.2×10^{-4} PRL **93**, 091802 (2004)
$B^+ \to \mu^+\nu$	4.2×10^{-7}	6.6×10^{-6} PRL. **92**, 221803 (2004)