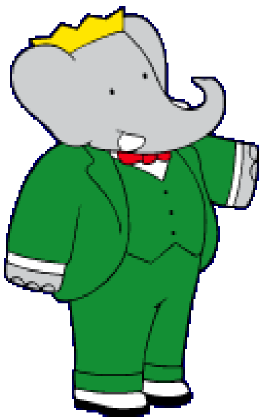
Measuring $b\to d\gamma$, $b\to s\gamma$ and $|V_{td}/V_{ts}|$ at BaBar



ICHEP 2010

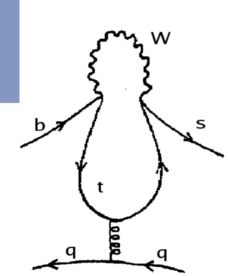
24th July 2010

Debbie Bard - SLAC

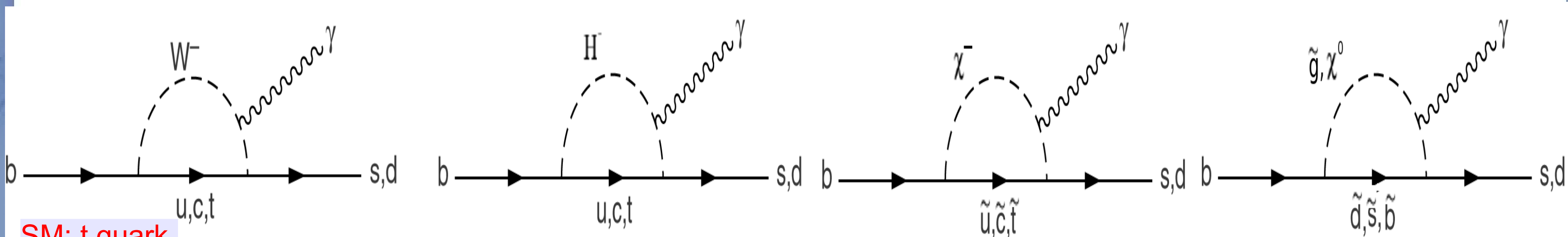
on behalf of the BaBar collaboration

SLAC NATIONAL ACCELERATOR LABORATORY

Motivation



- Radiative penguin transitions are flavour changing neutral currents (FCNC) forbidden at tree level in the Standard Model (SM)
  - proceed via one loop or high order processes.
- New Physics (NP) can appear in the loop with size comparable to leading SM contributions.



SM: t quark dominates

- $b\to d\gamma$ transition is CKM suppressed w.r.t $b\to s\gamma$ by a factor of ~20 in the SM.

Motivation

- Analysis of b→dγ with equivalent b→sγ decay can be used to measure ratio of CKM matrix elements:

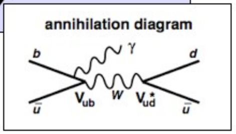
isopin factor: 1(.5) for $\rho^{\pm}(\rho^0)$

form factor ratio

$$\frac{\mathcal{B}(B\to\rho\gamma)}{\mathcal{B}(B\to K^*\gamma)} = S_\rho \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1-m_\rho^2/M_B^2}{1-m_{K^*}^2/M_B^2)}\right)^3 \zeta^2[1+\Delta R]$$

well measured

annihilation amplitude corrections



- Constraint on $|V_{td}/ V_{ts}|$ independent of measurement from B_s/B_d mixing frequencies
  - **discrepancies between two could indicate NP.**
- Measurement of $|V_{td}/ V_{ts}|$ using ratio of branching fractions of exclusive decays B→(ρ,ω)γ and B→K*γ is well established
  - no discrepancies seen w.r.t. B mixing results – where next?
  - theory error on exclusive ratio ~8% [1], on inclusive ratio ~1% [2]?

*[1] Ball, Jones + Zwicky, PRD **75**, 054004 (2007), [2] Ali et al., PRB **429**, 87 (1998)*

Analysis Overview

- **Measure** partial branching fractions (BFs) of sum of seven modes in four regions:
  - $B \rightarrow X_d \gamma$ and $B \rightarrow X_s \gamma$.
  - Low (0.5< m_{had} <1.0 Gev/c^2) hadronic mass dominated by $B \rightarrow (\rho,\omega)\gamma$ and $B \rightarrow K^*\gamma$ resonances.
  - High (1.0< m_{had} <2.0 GeV/c^2) hadronic mass containing non-resonant decays.
- **Extrapolate** from partial to inclusive BFs within each mass bin.
  - need to include un-reconstructed decay modes – requires knowledge of fragmentation of hadronic systems X_d and X_s.
- **Combine** mass ranges for inclusive BFs in m_{had} <2.0 GeV/c^2 and calculate $|V_{td}/ V_{ts}|$.
  - For $|V_{td} / V_{ts}|$, need to extrapolate to all masses. This is an extrapolation based on theoretical model of photon spectrum, not experimental information.

Analysis Overview

arXiv: 1005.4087 (2010), submitted to PRD-RC

- Semi-inclusive analysis: approximate inclusive decay with sum of final states.
- Reconstruct $B \to X_d \gamma$ in seven exclusive decay modes.
- Reconstruct $B \to X_s \gamma$ in same modes by reversing particle identification requirement on one charged particle to obtain a K^+.
- Significant background from continuum ($e^+e^- \to q\bar{q}$, q=u,d,s,c) background processes, which are jet-like compared to isotropic BB events. Use event topology to discriminate against them.

$B \to X_d \gamma$	$B \to X_s \gamma$
$B^0 \to \pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\gamma$
$B^+ \to \pi^+\pi^0\gamma$	$B^+ \to K^+\pi^0\gamma$
$B^+ \to \pi^+\pi^-\pi^+\gamma$	$B^+ \to K^+\pi^+\pi^-\gamma$
$B^0 \to \pi^+\pi^-\pi^0\gamma$	$B^0 \to K^+\pi^-\pi^0\gamma$
$B^0 \to \pi^+\pi^-\pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\pi^+\pi^-\gamma$
$B^+ \to \pi^+\pi^-\pi^+\pi^0\gamma$	$B^+ \to K^+\pi^-\pi^+\pi^0\gamma$
$B^+ \to \pi^+\eta\gamma$	$B^+ \to K^+\eta\gamma$

(Charge conjugate states implied throughout)

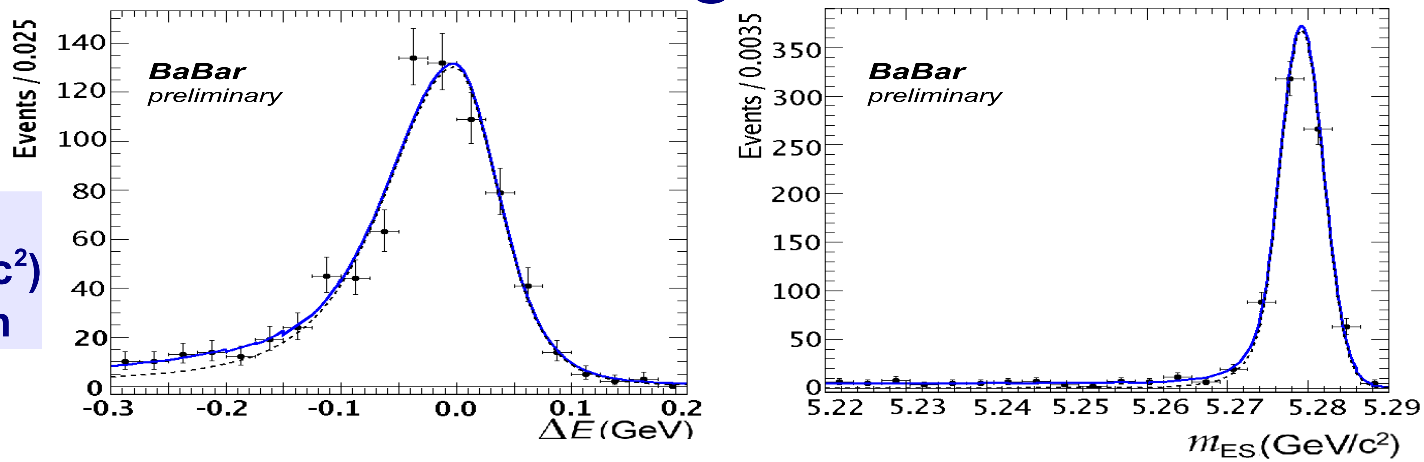
– Use full BaBar dataset of 423 fb^{-1} (471×10^6 $B\bar{B}$ pairs).

Maximum Likelihood fit

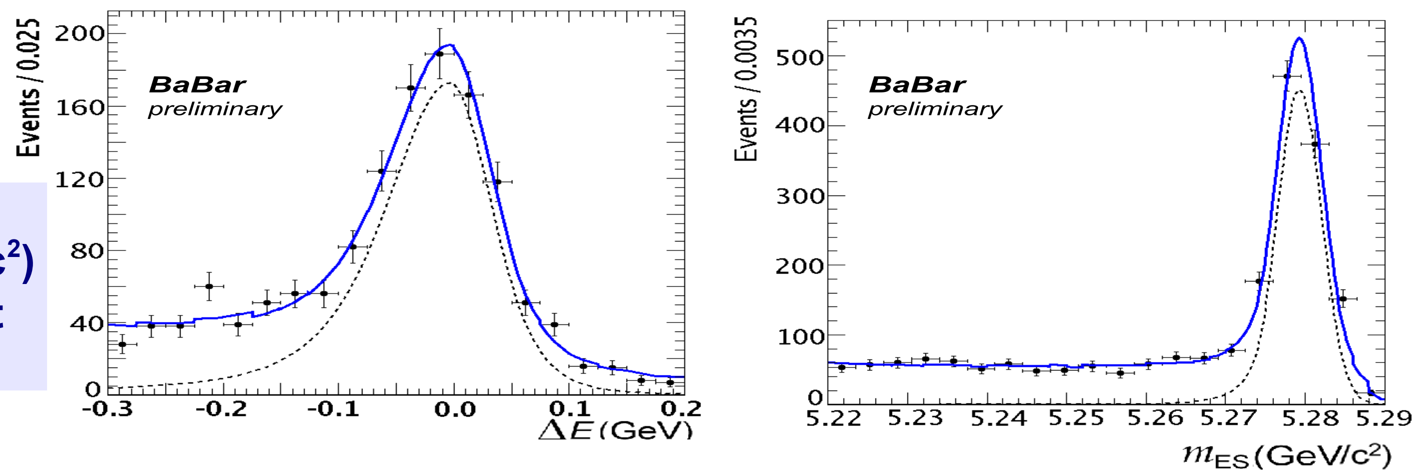
- We enhance sensitivity by performing multi-dimensional likelihood fits to signal and background in two variables:
  - $m_{ES} = \sqrt{(E^{*2}_{beam} - p^{*2}_{B})}$, $\Delta E = E^{*}_{B} - E^{*}_{beam}$
- Signal peaks around zero in ΔE, and around B mass in m_{ES}, backgrounds are smoothly varying.
- Fit contains components for signal, mis-reconstructed signal decays from the same and other mass regions, continuum and other B decays.
  - also component for significant $B \rightarrow X_s\gamma$ background in fit for $B \rightarrow X_d\gamma$.
- Signal, continuum and generic B yields and continuum shape parameters are obtained from the fit to data.
  - signal shape parameters are determined from fit to $B \rightarrow X_s\gamma$ data.

Fit to data for $B \to X_s \gamma$

Low mass
(0.5 - 1.0 GeV/c^2)
$B \to K^* \gamma$ region



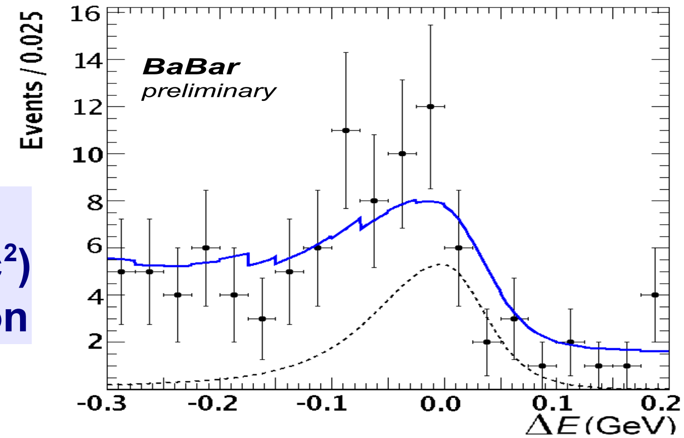
High mass
(1.0 - 2.0 GeV/c^2)
non-resonant region

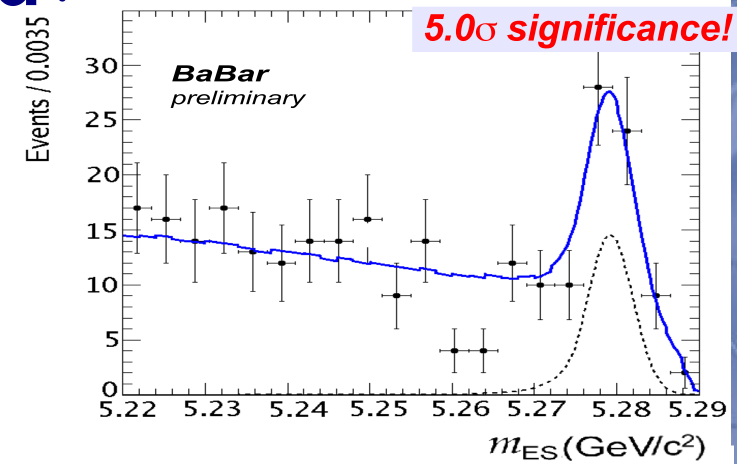


– Large signal yields allows us to study the fragmentation of the non-resonant $b \to s\gamma$ decays, and adjust our simulation accordingly.

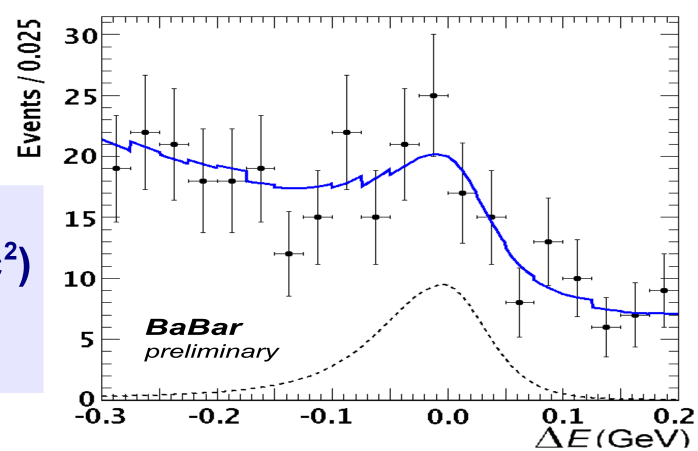
Fit to data for $B \to X_d \gamma$

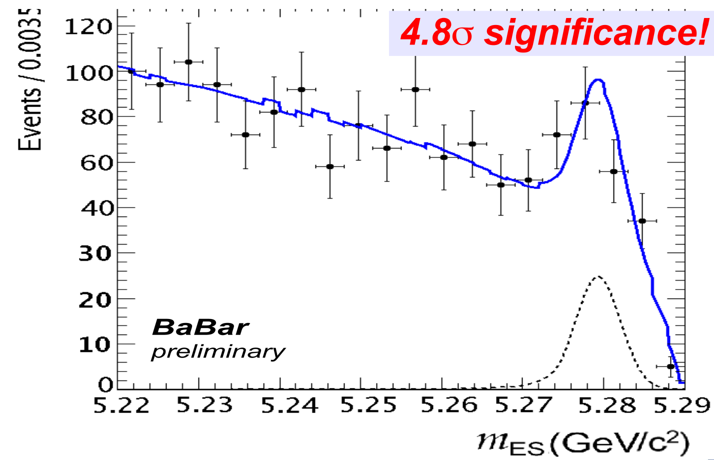
Low mass (0.5 - 1.0 GeV/c²) $B \to (\rho,\omega)\gamma$ region





High mass (1.0 - 2.0 GeV/c²) non-resonant region





- (Jagged lines artefact of combination of several binned histogram PDFs.)
- **First significant observation of $b \to d\gamma$ in non-resonant modes!**

Systematic Errors

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Track selection	0.3%	0.4%	0.3%	0.4%
Photon reconstruction	1.8%	1.8%	1.8%	1.8%
π^0/η reconstruction	0.9%	1.1%	1.4%	1.6%
Neural network	1.1%	4.9%	1.1%	4.9%
B counting	0.6%	0.6%	0.6%	0.6%
PID (*)	2.0%	2.0%	2.0%	2.0%
Fit bias (*)	0.1%	0.9%	4.9%	6.5%
PDF shapes (*)	2.3%	0.6%	3.7%	3.4%
Histogram binning (*)	0.8%	0.2%	1.8%	1.8%
Background (*)	0.8%	1.2%	5.9%	7.0%
Fragmentation (*)	-	3.3%	-	5.1%
Signal model	-	5.8%	-	6.0%
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%

(*) indicates error does not cancel in ratio of BFs

- Systematic errors calculated from data/MC comparisons.
- Largest contributions from ML fit bias, uncertainties in background estimation, fragmentation of hadronic system and choice of photon spectral model.
- Partial BF given as sum of seven modes, within each mass range:

	efficiency	Partial branching fraction
$B \to X_s\gamma$ low mass	4.52%	$(1.89 \pm 0.08 \pm 0.08) \times 10^{-5}$
$B \to X_s\gamma$ high mass	1.60%	$(6.57 \pm 0.28 \pm 0.59) \times 10^{-5}$
$B \to X_d\gamma$ low mass	3.09%	$(1.20 \pm 0.31 \pm 0.11) \times 10^{-6}$
$B \to X_d\gamma$ high mass	1.85%	$(3.21 \pm 0.81 \pm 0.46) \times 10^{-6}$

Systematic Errors

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Track selection	0.3%	0.4%	0.3%	0.4%
Photon reconstruction	1.8%	1.8%	1.8%	1.8%
π^0/η reconstruction	0.9%	1.1%	1.4%	1.6%
Neural network	1.1%	4.9%	1.1%	4.9%
B counting	0.6%	0.6%	0.6%	0.6%
PID (*)	2.0%	2.0%	2.0%	2.0%
Fit bias (*)	0.1%	0.9%	4.9%	6.5%
PDF shapes (*)	2.3%	0.6%	3.7%	3.4%
Histogram binning (*)	0.8%	0.2%	1.8%	1.8%
Background (*)	0.8%	1.2%	5.9%	7.0%
Fragmentation (*)	-	3.3%	-	5.1%
Signal model	-	5.8%	-	6.0%
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%

(*) indicates error does not cancel in ratio of BFs

- Systematic errors calculated from data/MC comparisons.
- Largest contributions from ML fit bias, uncertainties in background estimation, fragmentation of hadronic system and choice of photon spectral model.
- Partial BF given as sum of seven modes, within each mass range:

	efficiency	Partial branching fraction
$B \to X_s\gamma$ low mass	4.52%	$(1.89 \pm 0.08 \pm 0.08) \times 10^{-5}$
$B \to X_s\gamma$ high mass	1.60%	$(6.57 \pm 0.28 \pm 0.59) \times 10^{-5}$
$B \to X_d\gamma$ low mass	3.09%	$(1.20 \pm 0.31 \pm 0.11) \times 10^{-6}$
$B \to X_d\gamma$ high mass	1.85%	$(3.21 \pm 0.81 \pm 0.46) \times 10^{-6}$

Systematic Errors

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Track selection	0.3%	0.4%	0.3%	0.4%
Photon reconstruction	1.8%	1.8%	1.8%	1.8%
π^0/η reconstruction	0.9%	1.1%	1.4%	1.6%
Neural network	1.1%	4.9%	1.1%	4.9%
B counting	0.6%	0.6%	0.6%	0.6%
PID (*)	2.0%	2.0%	2.0%	2.0%
Fit bias (*)	0.1%	0.9%	4.9%	6.5%
PDF shapes (*)	2.3%	0.6%	3.7%	3.4%
Histogram binning (*)	0.8%	0.2%	1.8%	1.8%
Background (*)	0.8%	1.2%	5.9%	7.0%
Fragmentation (*)	-	3.3%	-	5.1%
Signal model	-	5.8%	-	6.0%
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%

(*) indicates error does not cancel in ratio of BFs

- Systematic errors calculated from data/MC comparisons.
- Largest contributions from ML fit bias, uncertainties in background estimation, fragmentation of hadronic system and choice of photon spectral model.
- Partial BF given as sum of seven modes, within each mass range:

	efficiency	Partial branching fraction
$B \to X_s\gamma$ low mass	4.52%	$(1.89 \pm 0.08 \pm 0.08) \times 10^{-5}$
$B \to X_s\gamma$ high mass	1.60%	$(6.57 \pm 0.28 \pm 0.59) \times 10^{-5}$
$B \to X_d\gamma$ low mass	3.09%	$(1.20 \pm 0.31 \pm 0.11) \times 10^{-6}$
$B \to X_d\gamma$ high mass	1.85%	$(3.21 \pm 0.81 \pm 0.46) \times 10^{-6}$

Systematic Errors

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Track selection	0.3%	0.4%	0.3%	0.4%
Photon reconstruction	1.8%	1.8%	1.8%	1.8%
π^0/η reconstruction	0.9%	1.1%	1.4%	1.6%
Neural network	1.1%	4.9%	1.1%	4.9%
B counting	0.6%	0.6%	0.6%	0.6%
PID (*)	2.0%	2.0%	2.0%	2.0%
Fit bias (*)	0.1%	0.9%	4.9%	6.5%
PDF shapes (*)	2.3%	0.6%	3.7%	3.4%
Histogram binning (*)	0.8%	0.2%	1.8%	1.8%
Background (*)	0.8%	1.2%	5.9%	7.0%
Fragmentation (*)	-	3.3%	-	5.1%
Signal model	-	5.8%	-	6.0%
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%

(*) indicates error does not cancel in ratio of BFs

- Systematic errors calculated from data/MC comparisons.
- Largest contributions from ML fit bias, uncertainties in background estimation, fragmentation of hadronic system and choice of photon spectral model.
- Partial BF given as sum of seven modes, within each mass range:

	efficiency	Partial branching fraction
$B \to X_s\gamma$ low mass	4.52%	$(1.89 \pm 0.08 \pm 0.08) \times 10^{-5}$
$B \to X_s\gamma$ high mass	1.60%	$(6.57 \pm 0.28 \pm 0.59) \times 10^{-5}$
$B \to X_d\gamma$ low mass	3.09%	$(1.20 \pm 0.31 \pm 0.11) \times 10^{-6}$
$B \to X_d\gamma$ high mass	1.85%	$(3.21 \pm 0.81 \pm 0.46) \times 10^{-6}$

Systematic Errors

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Track selection	0.3%	0.4%	0.3%	0.4%
Photon reconstruction	1.8%	1.8%	1.8%	1.8%
π^0/η reconstruction	0.9%	1.1%	1.4%	1.6%
Neural network	1.1%	4.9%	1.1%	4.9%
B counting	0.6%	0.6%	0.6%	0.6%
PID (*)	2.0%	2.0%	2.0%	2.0%
Fit bias (*)	0.1%	0.9%	4.9%	6.5%
PDF shapes (*)	2.3%	0.6%	3.7%	3.4%
Histogram binning (*)	0.8%	0.2%	1.8%	1.8%
Background (*)	0.8%	1.2%	5.9%	7.0%
Fragmentation (*)	-	3.3%	-	5.1%
Signal model	-	5.8%	-	6.0%
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%

(*) indicates error does not cancel in ratio of BFs

- Systematic errors calculated from data/MC comparisons.
- Largest contributions from ML fit bias, uncertainties in background estimation, fragmentation of hadronic system and choice of photon spectral model.
- Partial BF given as sum of seven modes, within each mass range:

	efficiency	Partial branching fraction
$B \to X_s\gamma$ low mass	4.52%	$(1.89 \pm 0.08 \pm 0.08) \times 10^{-5}$
$B \to X_s\gamma$ high mass	1.60%	$(6.57 \pm 0.28 \pm 0.59) \times 10^{-5}$
$B \to X_d\gamma$ low mass	3.09%	$(1.20 \pm 0.31 \pm 0.11) \times 10^{-6}$
$B \to X_d\gamma$ high mass	1.85%	$(3.21 \pm 0.81 \pm 0.46) \times 10^{-6}$

Systematic Errors

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Track selection	0.3%	0.4%	0.3%	0.4%
Photon reconstruction	1.8%	1.8%	1.8%	1.8%
π^0/η reconstruction	0.9%	1.1%	1.4%	1.6%
Neural network	1.1%	4.9%	1.1%	4.9%
B counting	0.6%	0.6%	0.6%	0.6%
PID (*)	2.0%	2.0%	2.0%	2.0%
Fit bias (*)	0.1%	0.9%	4.9%	6.5%
PDF shapes (*)	2.3%	0.6%	3.7%	3.4%
Histogram binning (*)	0.8%	0.2%	1.8%	1.8%
Background (*)	0.8%	1.2%	5.9%	7.0%
Fragmentation (*)	-	3.3%	-	5.1%
Signal model	-	5.8%	-	6.0%
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%

- Systematic errors calculated from data/MC comparisons.
- Largest contributions from ML fit bias, uncertainties in background estimation, fragmentation of hadronic system and choice of photon spectral model.
- Partial BF given as sum of seven modes, within each mass range:

	efficiency	Partial branching fraction
$B \to X_s\gamma$ low mass	4.52%	$(1.89 \pm 0.08 \pm 0.08) \times 10^{-5}$
$B \to X_s\gamma$ high mass	1.60%	$(6.57 \pm 0.28 \pm 0.59) \times 10^{-5}$
$B \to X_d\gamma$ low mass	3.09%	$(1.20 \pm 0.31 \pm 0.11) \times 10^{-6}$
$B \to X_d\gamma$ high mass	1.85%	$(3.21 \pm 0.81 \pm 0.46) \times 10^{-6}$

(*) indicates error does not cancel in ratio of BFs

Inclusive branching fractions

- To extrapolate to inclusive BF, must correct for un-reconstructed decay modes within measured mass range.
- Low mass regions contain no non-resonant component – simply correct for unreconstructed K*/ω decays.
- High mass region extrapolation based on MC fragmentation model (corrected for measured b→sγ decay modes).
- Vary fragmentation within physically-motivated bounds to obtain uncertainty on fragmentation correction
  - large systematic errors!

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%
Missing ≥ 5 body		9.6%		18.2%
Other missing states		7.5%		15.3%
Spectrum Model		1.8%		1.6%
Error on inclusive $\mathcal{B}$	4.0%	15.2%	9.3%	27.7%

	Branching Fraction
$b \to s\gamma$ low mass	$3.83 \pm 0.16 \pm 0.15 \times 10^{-5}$
$b \to s\gamma$ high mass	$19.2 \pm 0.8 \pm 1.7 \pm 2.3 \times 10^{-5}$
$b \to s\gamma$ $(m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$23.0 \pm 0.8 \pm 1.9 \pm 2.3 \times 10^{-5}$
$b \to d\gamma$ low mass	$1.25 \pm 0.32 \pm 0.12 \times 10^{-6}$
$b \to d\gamma$ high mass	$7.90 \pm 1.98 \pm 1.12 \pm 1.88 \times 10^{-6}$
$b \to d\gamma$ $(m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$9.15 \pm 2.01 \pm 1.24 \pm 1.88 \times 10^{-6}$
$\frac{B\to(\rho,\omega)\gamma}{B\to K^*\gamma}$	$0.033 \pm 0.009 \pm 0.003$
$\frac{b\to d\gamma}{b\to s\gamma}$ $(m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$0.040 \pm 0.009 \pm 0.005 \pm 0.010$

Inclusive branching fractions

- To extrapolate to inclusive BF, must correct for un-reconstructed decay modes within measured mass range.

- Low mass regions contain no non-resonant component – simply correct for unreconstructed K*/ω

World average BF(B→K*γ) = (4.21 ±0.18) x10^{-5} [1]

- High mass region extrapolation based on MC fragmentation [illegible] $b \to s\gamma$ decay modes).

World average BF(B→(ρ,ω)γ) = (1.30 ±0.19) x10^{-6} [1]

- Vary fragmentation within physically-motivated bounds to obtain uncertainty on fragmentation correction
  - large systematic errors!

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%
Missing ≥ 5 body		9.6%		18.2%
Other missing states		7.5%		15.3%
Spectrum Model		1.8%		1.6%
Error on inclusive $\mathcal{B}$	4.0%	15.2%	9.3%	27.7%

	Branching Fraction
$b \to s\gamma$ low mass	$3.83 \pm 0.16 \pm 0.15 \times 10^{-5}$
$b \to s\gamma$ high mass	$19.2 \pm 0.8 \pm 1.7 \pm 2.3 \times 10^{-5}$
[illegible] $2.0\,\mathrm{GeV}/c^2)$	$23.0 \pm 0.8 \pm 1.9 \pm 2.3 \times 10^{-5}$
$b \to d\gamma$ low mass	$1.25 \pm 0.32 \pm 0.12 \times 10^{-6}$
$b \to d\gamma$ high mass	$7.90 \pm 1.98 \pm 1.12 \pm 1.88 \times 10^{-6}$
$b \to d\gamma\ (m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$9.15 \pm 2.01 \pm 1.24 \pm 1.88 \times 10^{-6}$
$\frac{B \to (\rho,\omega)\gamma}{B \to K^*\gamma}$	$0.033 \pm 0.009 \pm 0.003$
$\frac{b \to d\gamma}{b \to s\gamma}\ (m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$0.040 \pm 0.009 \pm 0.005 \pm 0.010$

[1] HFAG April 2010

Fully inclusive branching fractions

- Theoretical formula for $|V_{td}/V_{ts}|$ is based on fully inclusive BF: need to extrapolate to all masses for calculation.
- Our mass range covers (60.2 $\pm$1.6)% of total spectrum in $b \rightarrow s\gamma$, (60.2 $\pm$1.9)% in $b \rightarrow d\gamma$ (based on Kagan-Neubert photon spectrum model [1] assuming b-quark mass of 4.65 GeV/c^2).
  - Error on extrapolation: compare difference in KN spectra for b-quarks masses of 4.60 GeV/c^2, 4.65 GeV/c^2, 4.70 GeV/c^2.
  - Error cancels in ratio.
- **BF($b \rightarrow s\gamma$) = (38.2 $\pm$1.3(stat.) $\pm$3.2(syst.) $\pm$3.8(extrap) $\pm$0.6(model))x10^{-5}**
- **BF($b \rightarrow d\gamma$) = (15.3 $\pm$3.4(stat) $\pm$2.1(syst) $\pm$3.2(extrap) $\pm$0.3(model))x10^{-6}**
- Spectra for $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$ are identical in theoretical models.
- Ratio is unchanged! = **0.040 $\pm$0.009(stat.) $\pm$0.005(syst.) $\pm$0.010(extrap.)**.

*[1] Kagan+Neubert, PRD **58**, 094012 (1998)*

Fully inclusive branching fractions

- Theoretical formula for $|V_{td}/V_{ts}|$ is based on fully inclusive BF: need to extrapolate to all masses for calculation.
- Our mass range covers (60.2 ±1.6)% of total spectrum in $b \to s\gamma$, (60.2 ±1.9)% in $b \to d\gamma$ (based on Kagan-Neubert photon spectrum models [1] assuming b-quark mass of 4.65 GeV/c^2).
  - Error on extrapolation: compare difference in KN spectra for b-quarks masses of 4.60 GeV/c^2, 4.65 GeV/c^2, 4.70 GeV/c^2
  - Error cancels in ratio

World average BF($b \to s\gamma$) = (35.5 ±2.4 ±0.9) x10^{-5} [2]

- **BF($b \to s\gamma$) = (38.2 ±1.3(stat.) ±3.2(syst.) ±3.8(extrap) ±0.6(model))x10^{-5}**
- **BF($b \to d\gamma$) = (15.3 ±3.4(stat) ±2.1(syst) ±3.2(extrap) ±0.3(model))x10^{-6}**
- Spectra for $b \to s\gamma$ and $b \to d\gamma$ are identical in theoretical models.
- Ratio is unchanged! = **0.040 ±0.009(stat.) ±0.005(syst.) ±0.010(extrap.)**.

[2] HFAG April 2010 results.

Calculating $|V_{td}/V_{ts}|$

- How to get from ratio of BFs to $|V_{td}/V_{ts}|$?

$$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} = \zeta^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 (1 + \Delta R)$$

- ζ and ΔR often calculated using parameters in terms of $\bar{\rho}$ and $\bar{\eta}$.

- However, these values for $\bar{\rho}$ and $\bar{\eta}$ are calculated with global fitters using previous measurements of $|V_{td}/V_{ts}|$ as an input. To make a truly independent calculation, we need to express the ratio of BFs as a function of $|V_{td}/V_{ts}|$ and an orthogonal coordinate, i.e. well-known CKM angle β.

- Full mass region [1]:
  - **$|V_{td}/V_{ts}|$ = 0.199 $\pm$0.022(*stat.*) $\pm$0.012(*syst.*) $\pm$0.027(*extrap.*) $\pm$0.002(*th.*)**

- Cross-check: low mass region only [2]:
  - **$|V_{td}/V_{ts}|$ = 0.197 $\pm$0.026(*stat.*) $\pm$0.009(*syst.*) $\pm$0.010(*th.*)**

*[1] Ali et al., PRB **429**, 87 (1998), [2] Ball, Jones + Zwicky, PRD **75**, 054004 (2007).*

Calculating $|V_{td}/V_{ts}|$

- How to get from ratio of BFs to $|V_{td}/V_{ts}|$?

$$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} = \zeta^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 (1 + \Delta R)$$

- ζ and ΔR often calculated using parameters in terms of ρ and η.
- However, these values for ρ and η are calculated with global fitters using previous measurements of $|V_{td}/V_{ts}|$ as an input. To make a truly independent calculation, we need to express the ratio of BFs as a function of $|V_{td}/V_{ts}|$ and an orthogonal coordinate, i.e. well-known CKM angle β.

B-mixing average $|V_{td}/V_{ts}|$ = 0.2059 ±0.001(*exp.*) ±0.008(*th.*) [1]

- Full mass region [1]:
  - **$|V_{td}/V_{ts}|$ = 0.199 ±0.022(*stat.*) ±0.012(*syst.*) ±0.027(*extrap.*) ±0.002(*th.*)**
- Cross-check: low mass region only [2]:
  - **$|V_{td}/V_{ts}|$ = 0.197 ±0.026(*stat.*) ±0.009(*syst.*) ±0.010(*th.*)**

Agrees with previous measurements!

[1] HFAG winter 2006 results

Calculating $|V_{td}/V_{ts}|$

- How to get from ratio of BFs to $|V_{td}/V_{ts}|$?

$$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} = \zeta^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 (1 + \Delta R)$$

- ζ and ΔR often calculated using parameters in terms of ρ and η.
- However, these values for ρ and η are calculated with global fitters using previous measurements of $|V_{td}/V_{ts}|$ as an input. To make a truly independent calculation, we need to express the ratio of BFs as a function of $|V_{td}/V_{ts}|$ and an orthogonal coordinate, i.e. well-known CKM angle β.
- Full mass region [1]:
  - $|V_{td}/V_{ts}|$ = 0.199 ±0.022

BaBar $|V_{td}/V_{ts}|$ = 0.233 ±0.025(*exp.*) ±0.023(*th.*) [1]
Belle $|V_{td}/V_{ts}|$ = 0.195 ±0.020(*exp.*) ±0.015(*th.*) [2]

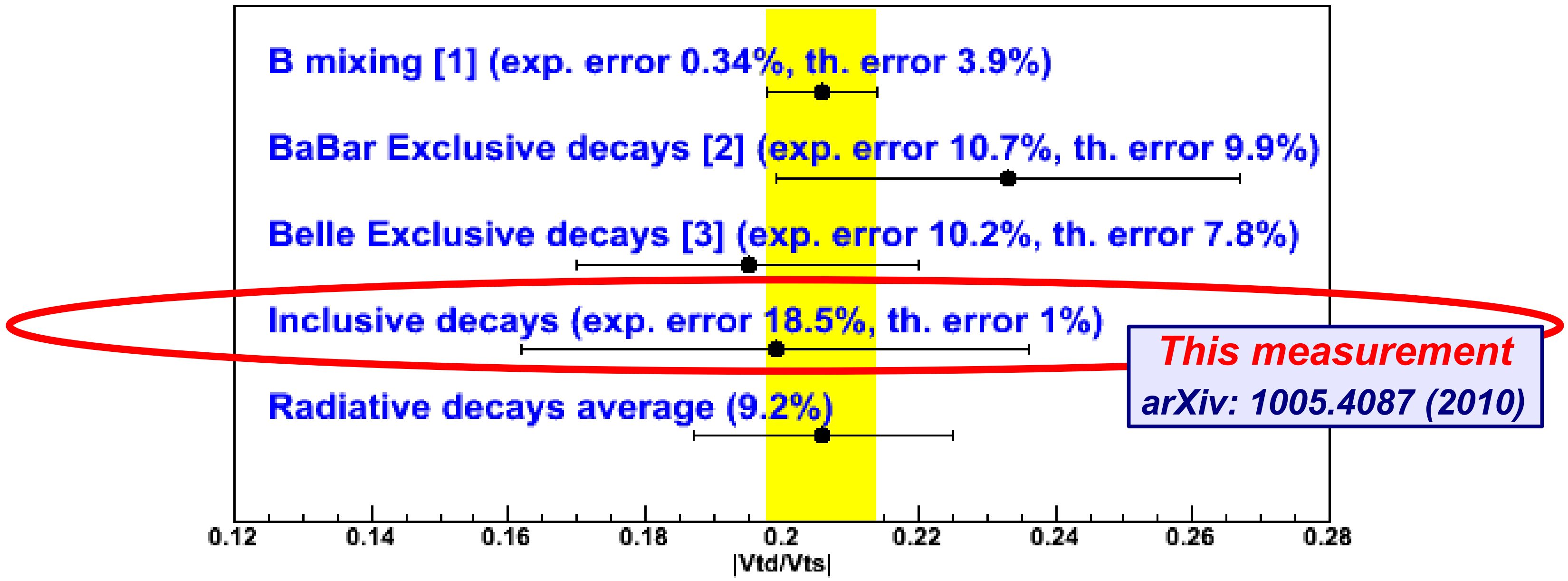
- Cross-check: low mass region only [2]:
  - **$|V_{td}/V_{ts}|$ = 0.197 ±0.026(*stat.*) ±0.009(*syst.*) ±0.010(*th.*)**

Agrees with previous measurements!

*[1] BaBar collab. PRL **98**, 151802 (2007), [2] Belle collab. PRL **101**, 111801 (2008.)*

Conclusions

- First significant measurement of non-resonant $b \to d\gamma$ decays!
- Measurements of $B \to K^*\gamma$, $b \to s\gamma$ and $B \to (\rho,\omega)\gamma$ all compatible with previous results.
- Measurement of $|V_{td}/V_{ts}|$ compatible with, and competitive with previous results, with significantly smaller theoretical uncertainty!



*[1] HFAG winter 2006 results, [2] BaBar collab. PRL **98**, 151802 (2007), [3] Belle collab. PRL **101**, 111801 (2008).*

Extra Slides

Fragmentation of hadronic system

- Fragmentation of hadronic system in MC not the same in data – need to correct what we can.
- $B \to X_s \gamma$ has high signal yield – can measure fragmentation of hadronic system here and correct the MC.
- We measure 7 modes, also take advantage of data/MC differences found in previous sum-of-inclusive $b \to s\gamma$ analysis.

Decay mode	Efficiency-corrected fraction in MC	Efficiency-corrected fraction in data	Ratio data/MC	Ratio data/MC in previous analysis
$B \to K^+\pi^-\gamma$	0.193	0.098	0.51 ±0.04	0.65 ±0.04
$B \to K^+\pi^0\gamma$	0.118	0.033	0.28 ±0.05	0.36 ±0.06
$B \to K^+\pi^-\pi^+\gamma$	0.206	0.230	1.21 ±0.08	1.34 ±0.11
$B \to K^+\pi^-\pi^0\gamma$	0.250	0.370	1.48 ±0.08	1.35 ±0.11
$B \to K^+\pi^-\pi^+\pi^-\gamma$	0.058	0.079	1.36 ±0.30	0.75 ±0.27
$B \to K^+\pi^-\pi^+\pi^0\gamma$	0.158	0.182	1.15 ±0.25	1.00 ±0.23
$B \to K^+\eta\gamma$	0.017	0.009	0.50 ±0.25	1.05 ±0.41

Fragmentation of hadronic system

- Low mass regions easy – correct for unreconstructed K*/ ω decays.
- High mass regions – how much width do our 7 decay modes cover?
  - Use weighted MC for b→sγ, unweighted MC for b→dγ.
- For systematic error, vary each category of missing modes (high and low multiplicity) by some amount, then renormalise to retain total BF in mass region, and see how proportion of our reconstructed modes changes.
  - Known b→sγ data/MC corrections are varied within their errors.
  - What about unknown missing fractions? Consider alternative fragmentation models e.g. applying b→sγ corrections to b→dγ, "hybrid" mix of resonances + non-res MC.

Proportion in $b \to s\gamma$ 1.0-2.0 GeV/c^2	Default model	Hybrid model
7 reconstructed modes	35.6%	40.0%
"known" 2/3/4 body modes	35.8%	40.2%
unreconstructed 2/3/4 body modes	12.6%	11.5%
unreconstructed 5+ body modes	16.1%	8.3%

Proportion in $b \to d\gamma$ 1.0-2.0 GeV/c^2	Default model	$b \to s\gamma$ weights applied	Hybrid model
7 reconstructed modes	42.3%	39.5%	46.9%
unreconstructed 2/3/4 body modes	27.0%	34.5%	34.9%
unreconstructed 5+ body modes	30.7%	26.0%	18.3%

Calculating $|V_{td}/V_{ts}|$

- Extract $X=|V_{td}/V_{ts}|$ from ratio of inclusive BFs
  - Use NLO calculation of Ali, *et al.* [Phys. Lett. B429 87]

$$R = \lambda^2[1+\lambda^2(1-2\bar{\rho})]\left[(1-\bar{\rho})^2+\bar{\eta}^2+\frac{D_u}{D_t}(\bar{\rho}^2+\bar{\eta}^2)+\frac{D_r}{D_t}(\bar{\rho}(1-\bar{\rho})-\bar{\eta}^2)\right]$$

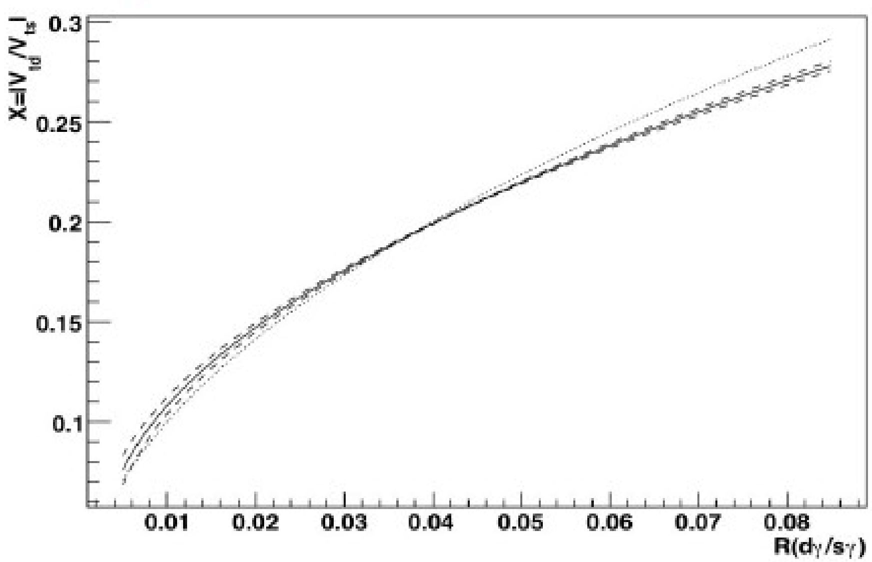
  - Rewrite in terms of X and UT angle β

$$R = \kappa_1 X^2 + \kappa_2 X + \kappa_3,$$

$$\kappa_1 = 1+\frac{D_u}{D_t}\left(1-2\lambda^2\cos^2\beta\right)-\frac{D_r}{D_t}\left(\lambda^2\cos^2\beta+1\right),$$

$$\kappa_2 = \lambda\cos\beta\left[\frac{D_u}{D_t}\left(3\lambda^2-2\right)+\frac{D_r}{D_t}\left(1+\frac{\lambda^2}{2}\right)\right],$$

$$\kappa_3 = \lambda^2\frac{D_u}{D_t}\left(1-\lambda^2\right).$$



  - Uncertainties from PDG and numerical calculations of D factors