Rare Decays at the *B* Factories

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Outline

Rare B Decays

Rare B decays, in general, proceed through

- Higher order (loop) diagrams such as penguin or box diagrams
- Tree or other diagrams suppressed by CKM matrix elements

Therefore, they are useful to

- search for new physics by looking at the contribution of non-SM particles
- obtain information on the CKM matrix
- test theoretical calculations for higher order diagrams

What does "rare" really mean in 2007?

The power of statistics

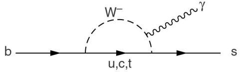
- *BABAR* and BELLE combined integrated luminosity $> 1000\,\text{fb}^{-1}$
- $\mathcal{B} \sim 10^{-4}$ now means quite decent statistics

Discussed today

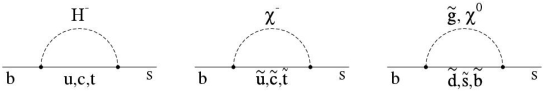
- Electroweak FCNC processes: $b \to s\gamma$, $b \to d\gamma$, $b \to s\ell^+\ell^-$
- Leptonic B decays: $B \to \tau\nu$

$b \longrightarrow s\gamma$ Transitions in the Standard Model

- FCNC processes only possible through loop diagrams in SM



- Loop-mediated processes can have large non-SM contributions



- Low-energy effective Hamiltonian for $b \longrightarrow s(d)$ transitions:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i(m_b) O_i(m_b)$$

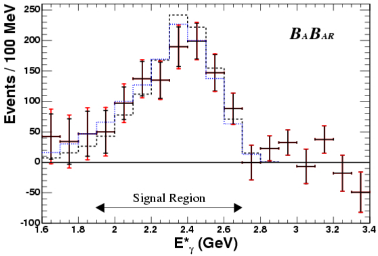
C_i: Wilson coefficients (calculated perturbatively)

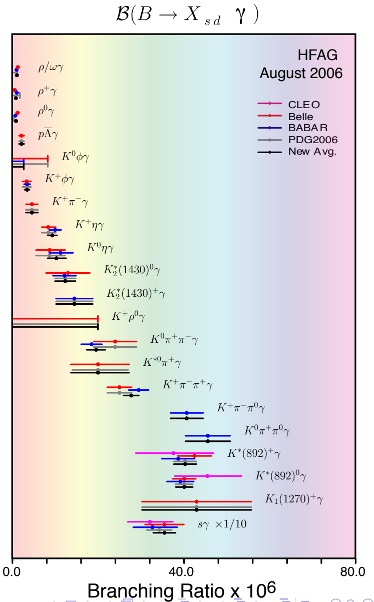
O_i: Products of field operators (nonperturbative; HQE inverse powers of m_b)

- New Physics can enter via non-SM values of Wilson Coefficients

Studies of radiative FCNC modes a major industry at *B*-Factories

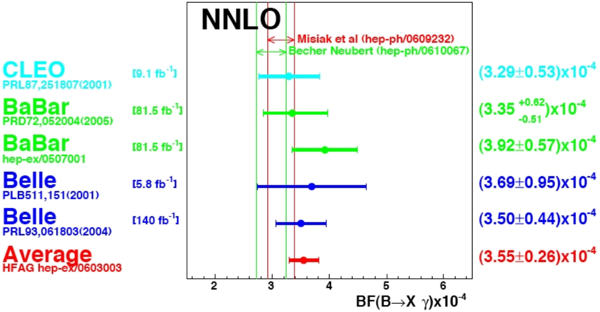
- precise determination of $b \to s\gamma$ in inclusive and exclusive modes
  - *BABAR* PRL 97:171803 (2006)
  - *BABAR* PRD 72:052004 (2005)
  - BELLE PRL 93:061803 (2004)
  - BELLE PLB 511:151 (2001)
- extraction of HQE parameters from γ energy spectrum



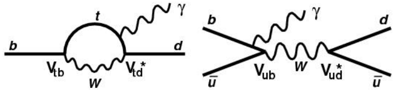


$b \to s\gamma$ Branching Fractions

- Inclusive $b \to s\gamma$ measurement is one of the most sensitive indirect probes of BSM physics
- Recent NNLO calculations suggest SM range for $\mathcal{B}(B \to X_s\gamma)$ slightly lower than experimental average



- Compare rates for exclusive $b \to d\gamma$ and $b \to s\gamma$ to extract off-diagonal CKM elements



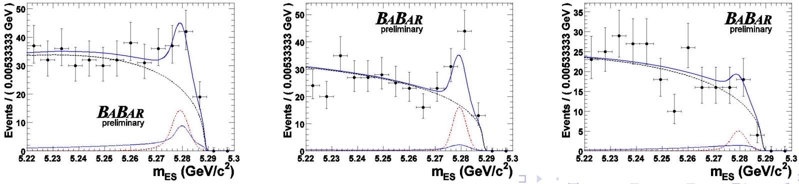
$$\frac{\mathcal{B}(B \to (\rho/\omega)\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/m_B^2}{1 - m_{K^*}^2/m_B^2}\right)^3 \zeta^2(1 + \Delta R)$$

$\Delta R = 0.1 \pm 0.1$: corrects for different decay dynamics [Ali et al., PLB 595,323 (2004)];

$\zeta = 1.17 \pm 0.09$: ρ/K^* FF ratio [Ball and Zwicky, hep-ph/0603232]

- Experimentally challenging: small $\mathcal{B}$ and large backgrounds, in particular due to photons from π^0, η, and $b \to s\gamma$ decays

ρ^+ ρ^0 ω



Isospin-normalized average:

$$\mathcal{B}(B \to (\rho/\omega)\gamma) = \frac{1}{2}\left(\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}\left[\mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma)\right]\right)$$

BABAR 316 fb^{-1} [PRL 98:151802 (2007)]

Mode	$\mathcal{B}\times 10^{-6}$	σ
$B^+ \to \rho^+\gamma$	$1.10^{+0.37}_{-0.33} \pm 0.09$	3.8
$B^0 \to \rho^0\gamma$	$0.79^{+0.22}_{-0.20} \pm 0.06$	4.9
$B^0 \to \omega\gamma$	$0.40^{+0.24}_{-0.20} \pm 0.03$	2.3
$B \to (\rho/\omega)\gamma$	$1.25^{+0.25}_{-0.24} \pm 0.09$	6.4

BELLE 386 fb^{-1} [PRL 96:221601 (2006)]

Mode	$\mathcal{B}\times 10^{-6}$	σ
$B^+ \to \rho^+\gamma$	$0.55^{+0.42}_{-0.36}{}^{+0.09}_{-0.08}$	1.6
$B^0 \to \rho^0\gamma$	$1.25^{+0.37}_{-0.33}{}^{+0.07}_{-0.06}$	5.2
$B^0 \to \omega\gamma$	$0.56^{+0.34}_{-0.27}{}^{+0.05}_{-0.10}$	2.3
$B \to (\rho/\omega)\gamma$	$1.32^{+0.34}_{-0.31}{}^{+0.10}_{-0.09}$	5.1

***B*-Factories combined**

$$\mathcal{B}(B \to (\rho/\omega)\gamma) = (1.28^{+0.20}_{-0.20} \pm 0.06) \times 10^{-6}$$

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

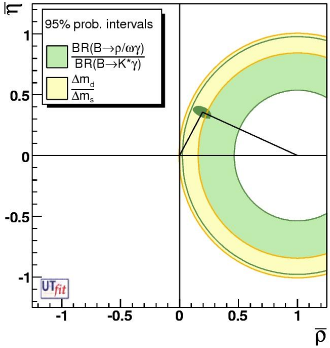
BELLE and *BABAR* combined

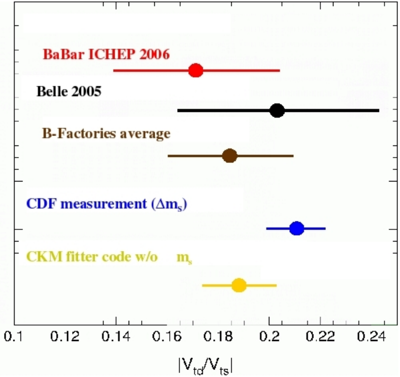
$$|V_{td}/V_{ts}| = 0.202^{+0.017}_{-0.016}(exp) \pm 0.015(th)$$

CDF [PRL 97:242003 (2006)]:

$\Delta m_s = 17.77 \pm 0.10(stat) \pm 0.07(sys)$

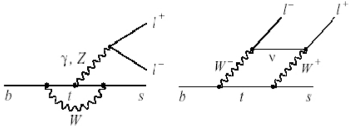
$|V_{td}/V_{ts}| = 0.2060 \pm 0.0007(exp)^{+0.0081}_{-0.0060}(theor)$

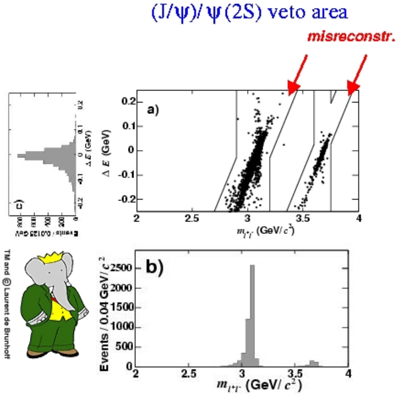




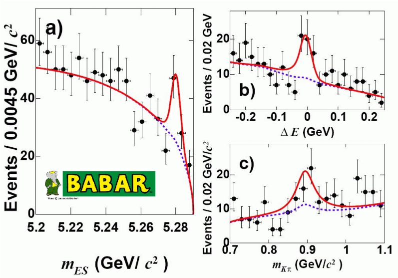
$B \to K^{(*)}\ell^+\ell^-$

$B \to X_s\ell^+\ell^-$ receives contributions from C_7 (photon penguin), C_9 (vector EW) and C_{10} (axial-vector EW)





- Interference between contributing amplitudes produces asymmetric angular $\ell^+\ell^-$ distribution
- $\mathcal{A}_{\rm FB}$ sensitive to non-SM values of Wilson coefficients



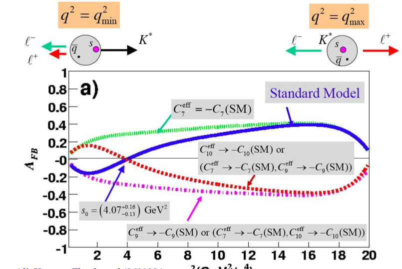
$B \to K^{(*)}\ell^+\ell^-$ Results

Smallest branching fractions of any observed B decay

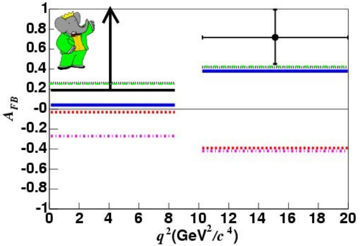
BaBar (208 fb^{-1})	$\mathcal{B}(B \to K\ell^+\ell^-) =$	$(0.34 \pm 0.07 \pm 0.02)$	$(6.6)\ \sigma$
[PRD 73:092001 (2006)]	$\mathcal{B}(B \to K^*\ell^+\ell^-) =$	$(0.78^{+0.19}_{-0.17} \pm 0.11)$	$(6.7)\ \sigma$
BELLE (253 fb^{-1})	$\mathcal{B}(B \to K\ell^+\ell^-)$	$(0.55^{+0.08}_{-0.07} \pm 0.03)$	
[hep-ex/0410006]	$\mathcal{B}(B \to K^*\ell^+\ell^-)$	$(1.65^{+0.23}_{-0.22} \pm 0.09)$	

$B \to K^*\ell^+\ell^-$ Forward-Backward Asymmetry

BELLE (357 fb^{-1})	$\mathcal{A}_{FB} = 0.50 \pm 0.15 \pm 0.02$	$(3.4\ \sigma)$	[PRL 96:251801 (2006)]
BaBar (208 fb^{-1})	$\mathcal{A}_{FB} > 0.55\ (q^2 > 0.1)$	(95% C.L.)	[PRD 73:092001 (2006)]

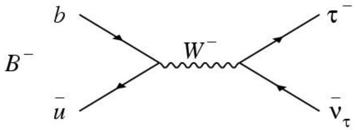


s_0: Ali, Kramer, Zhu, hep-ph/0601034



Leptonic B Decays

- In the SM: helicity-suppressed EW tree processes

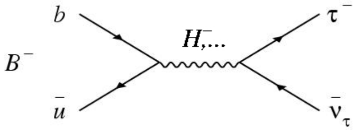


SM Rates

$\mathcal{B}(B \to \tau\nu) \sim 10^{-4}$
$\mathcal{B}(B \to \mu\nu) \sim 10^{-7}$
$\mathcal{B}(B \to e\nu) \sim 10^{-11}$

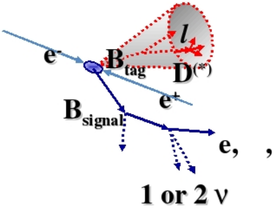
$$\mathcal{B}(B^+ \to \ell^+\nu_\ell) = \frac{G_f^2}{8\pi}|V_{ub}|^2 f_B^2 m_B m_\ell^2 \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2$$

- New physics contributions can arise from diagrams with internal lines containing non-SM particles:



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

- Large SM branching fraction, however..
- Experimentally challenging: several final states with multiple neutrinos
- Typical experimental signature: one charged track + nothing



BABAR Method

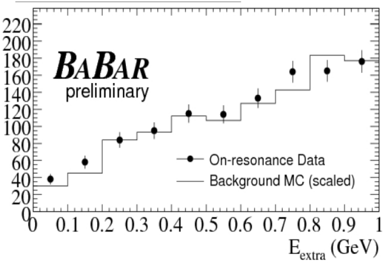
- Tag with semileptonic decay (e.g. $B \to D^*\ell\nu$ etc.)
- higher efficiency, lower purity

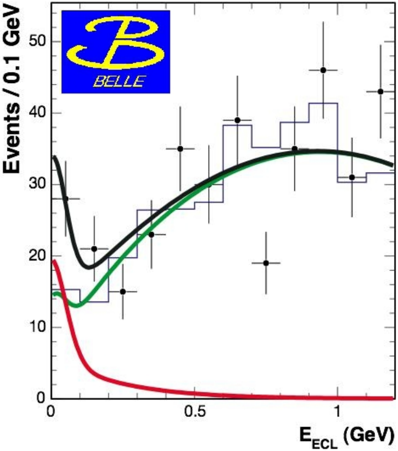
Belle Method

- Fully reconstruct B (using $B \to Dn\pi$ etc.)
- lower efficiency, higher purity

- Signal side: $\tau^+ \to e^+\nu_e\bar{\nu}_\tau,\ \mu^+\nu_e\bar{\nu}_\tau,\ \pi^+\bar{\nu}_\tau,\ \pi^+\pi^0\bar{\nu}_\tau,\ \pi^+\pi^-\pi^+\bar{\nu}_\tau.$
- Then look at extra energy in calorimeter
- Signal peaks at ~ 0.

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





BABAR [hep-ex/0608019]

$\mathcal{B} = (0.88^{+0.68}_{-0.67} \pm 0.11) \times 10^{-4}$

$< 1.80 \times 10^{-4}$ (90% CL)

320 M $B\bar{B}$

Belle [PRL 97, 251802 (2006)]

$\mathcal{B} = (1.79^{+0.56}_{-0.49}\ {}^{+0.39}_{-0.46}) \times 10^{-4}$

Significance 3.5 σ

449 M $B\bar{B}$

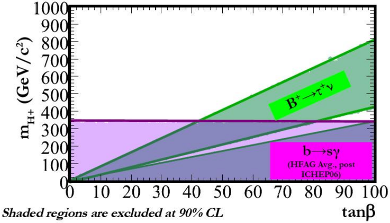
$B^+ \to \tau^+\nu$ Combined Results

Combined *BABAR*/BELLE

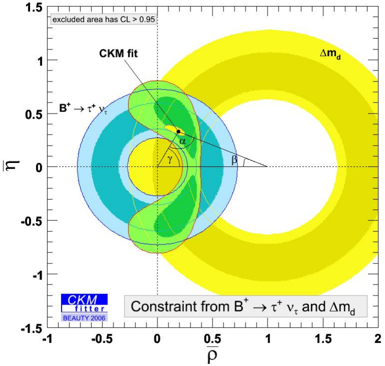
$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.31 \pm 0.48) \times 10^{-4} \ (2.5\ \sigma)$$

Comparison with SM can be interpreted either

- as constraint on New Physics (with $|V_{ub}| f_B$ from UT fit)
  $$R_{B\tau\nu} = \frac{\mathcal{B}^{\mathrm{SUSY}}(B_u \to \tau\nu)}{\mathcal{B}^{\mathrm{SM}}(B_u \to \tau\nu)} = \left[1 - \frac{m_B^2}{m_{H\pm}^2} \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta}\right]^2$$
- using UTFit 'SM' value for $|V_{ub}|$:
  $$\mathcal{B}(B^+ \to \tau^+\nu) = (0.85 \pm 0.13) \times 10^{-4}$$



- as constraint on $|V_{ub}|$ (with f_B from lattice)

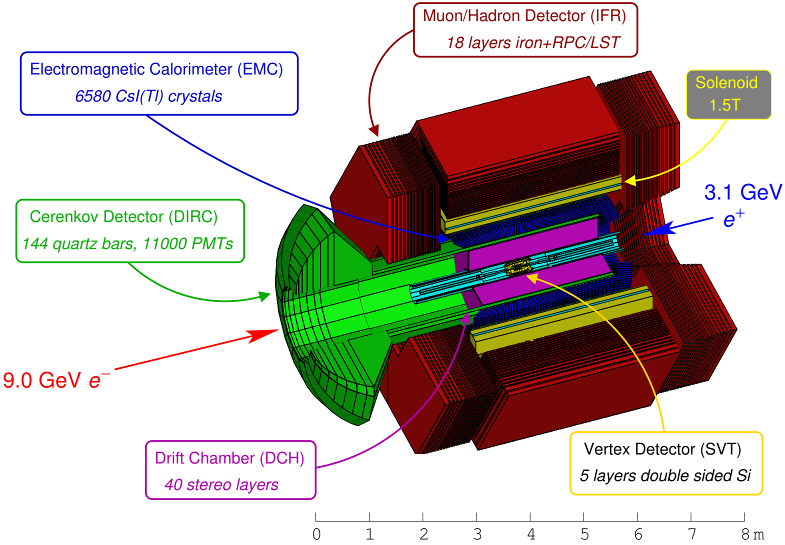


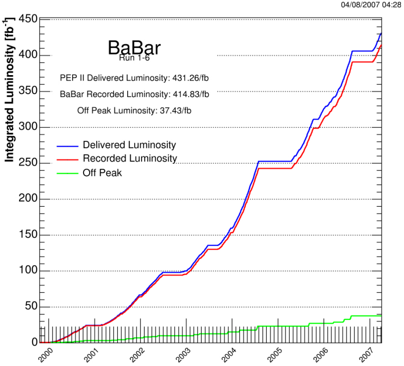
Conclusions

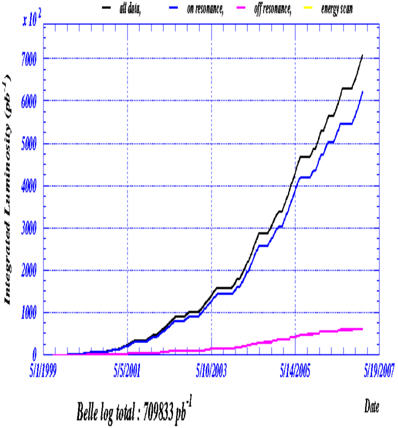
- With over 1 billion $B\bar{B}$ events recorded by the B-Factories together, study of many 'rare' decay modes is now possible
- Branching fractions as small as $\times 10^{-6}$can be measured
- The achievable precision opens up windows to look for physics beyond the SM
- Presented today: radiative penguin and leptonic B-decays
- But there are many more results (charmless,..)
- Current B-Factory statistics expected to double by 2008.

Backup Slides

The *BABAR* Detector







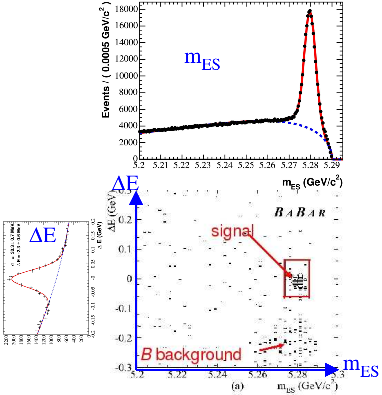
Latest Numbers

Total recorded luminosity: *BABAR* 420 fb^{-1}, Belle 715 fb^{-1}

Basics of *B*-Decay Analysis

Event selection:

- Quality cuts for tracks and showers
- Continuum rejection using event shape variables
- *B*-background estimated by modeling
- Kinematic signal identification
  - $m_{\mathrm{ES}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}}$
  - $\Delta E = E^{*}_{B} - E^{*}_{\mathrm{beam}}$
- Yields, asymmetries determined by maximum likelihood fit over m_{ES}, ΔE, etc.



$\sigma(m_{\mathrm{ES}}) = 2.7\,\mathrm{MeV}$

$\sigma(\Delta E) = 10..50\,\mathrm{MeV}$