Radiative B Decays
(an Experimental Overview)

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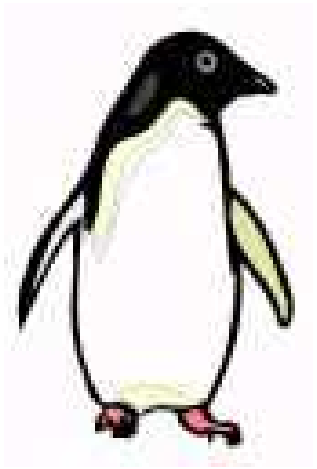
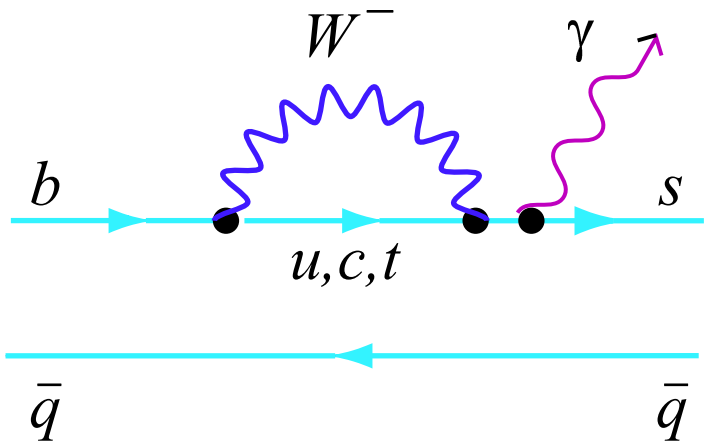
CLEO Collaboration





FPCP
May 18, 2002

The Observables

- Rates for exclusive decays. *eg,* $B \to K^*(892)\,\gamma$
- Rate for inclusive decay $b \to s\,\gamma$ (actually $B \to X_s\,\gamma$)
- CP asymmetry, inclusive decays

$$a_{cp} = \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)}$$

- CP asymmetry, exclusive decays
- Photon energy spectrum in inclusive decays $B \to X_s\,\gamma$
- Same observables for $b \to d\,\gamma$

What do you learn?

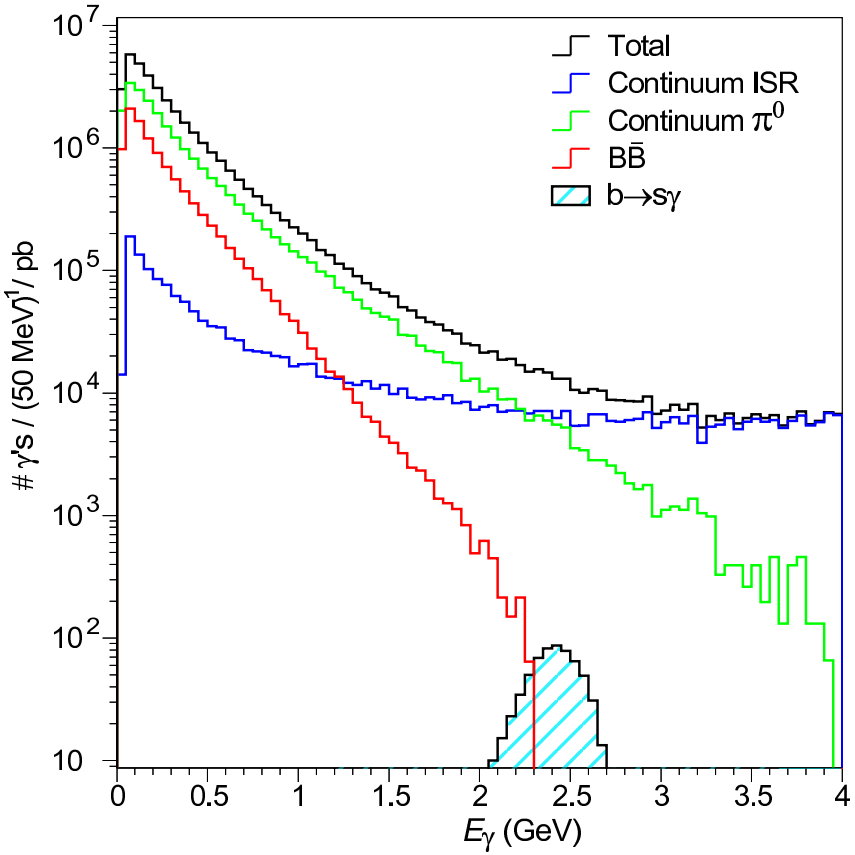
- Rate for exclusive decays
  - Experimentally easiest.
  - $B \to K^*(892)\,\gamma$ first penguin seen(1993).
  - Form factors not known, so not good for "New Physics".
- Rate for inclusive decays
  - Loops, w &t, so sensitive to other heavy things in loop (*i.e.* "New Physics")
  - Reliably calculated with SM and with "New Physics"
  - ⁂ excellent for revealing or limiting "New Physics".
- CP asymmetry
  - Expected to be very small in SM.
  - 10-20% in some "New Physics".
  - Inclusive more reliably calculated than exclusives, but if big in either, New Physics.

What do you learn? – cont'd

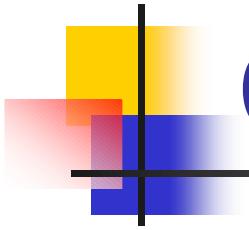
- Photon energy spectrum in $b \to s\gamma$
  - Insensitive to New Physics ($b \to s\gamma$ is 2-body, a line)
  - Depends on quark mass and Fermi momentum
    - Can give B light cone shape function (useful for obtaining $|V_{ub}|$ from $b \to u\ell\nu$ inclusive).
    - Can help determine HQET OPE expansion parameters (needed for obtaining $|V_{cb}|$ from $b \to c\ell\nu$ inclusive).
- $b \to d\gamma$
  - Initial interest will be in determing $|V_{td}|$

    (but watch out for long distance effects, and for additional CKM factors from c - and u - quark loops).

The Experimental Problems



- MUST suppress continuum.
- MUST subtract continuum.
- To push spectrum down below 2.2 GeV, must handle backgrounds from other *B* decay processes.



Outline for Rest of Talk

- Branching Fractions for Exclusive Decays
- Branching Fraction for Inclusive Decays
- CP Asymmetries
- Photon Energy Spectrum
- $b \to d\,\gamma$

Discovery of Penguins
CLEO -1993

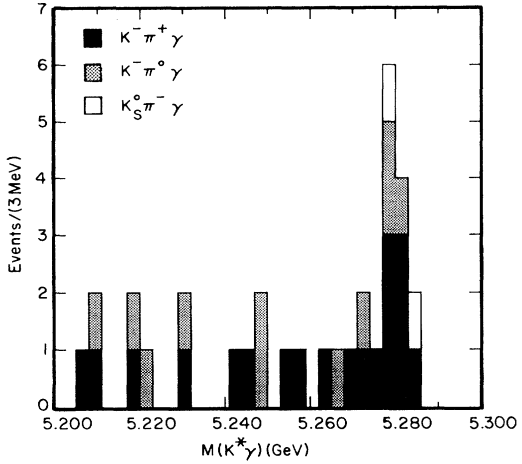


FIG. 2. The $K^*\gamma$ mass distributions for $B^0 \to K^{*0}\gamma$; $B^- \to K^{*-}\gamma$, $K^{*-} \to K^0_S\pi^-$; and $B^- \to K^{*-}\gamma$, $K^{*-} \to K^-\pi^0$ candidates.

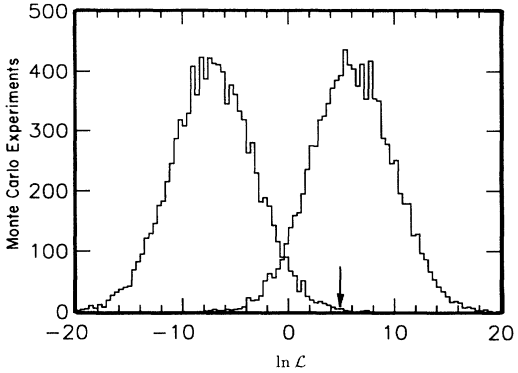
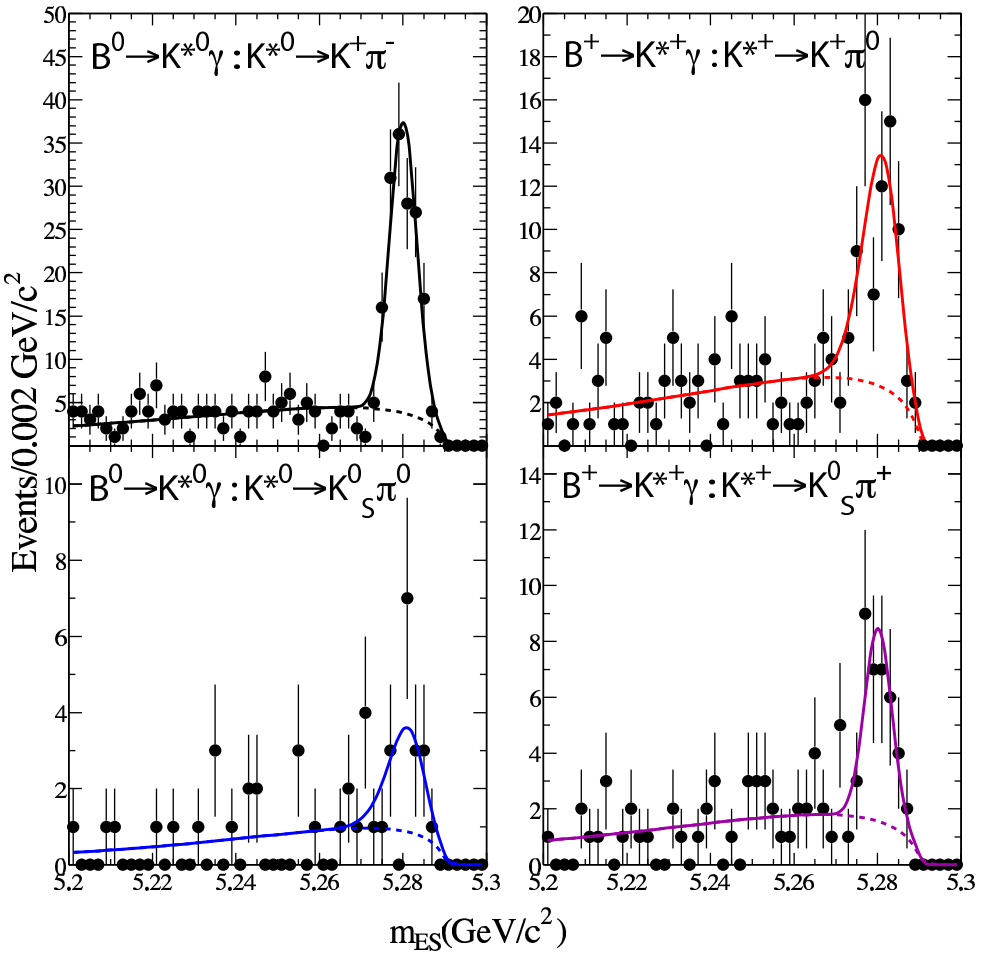


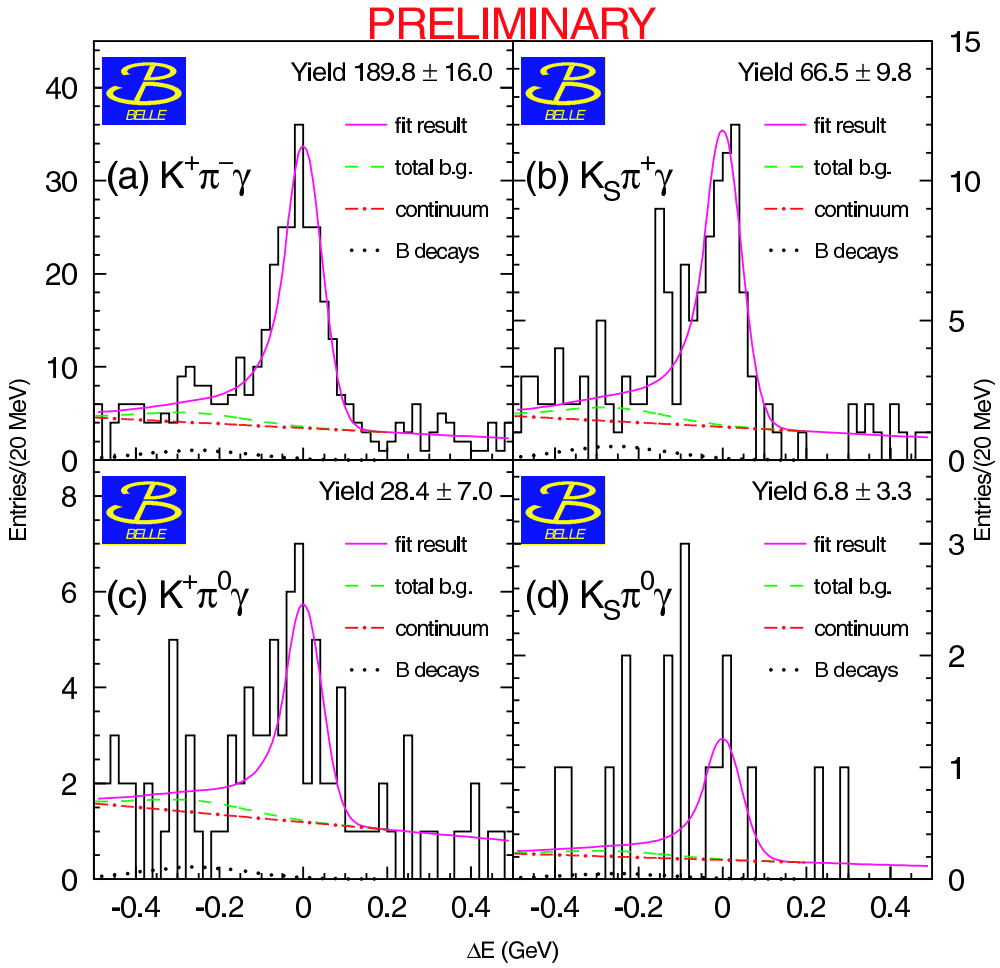
FIG. 3. The $\ln\mathcal{L}$ distributions for 10 000 "experiments" of 8 events each, drawn from $B^0 \to K^{*0}\gamma$ Monte Carlo (right curve) or continuum Monte Carlo (left curve) simulations. The value for the 8 $B^0 \to K^{*0}\gamma$ candidate events is indicated by an arrow.

B → K^* γ (BaBar)

- Run I (22.7 M BB)
  H Tanaka
  Moriond 2002



B → $K^*\gamma$ (Belle)



$B \to K^* \gamma$ Branching Fractions

	$B \to K^{*0} \gamma$	$B^- \to K^{*-} \gamma$
CLEO '93	$4.0 \pm 1.7 \pm 0.8$	$5.7 \pm 3.1 \pm 1.1$
CLEO '00	$4.55 \pm 0.70 \pm 0.34$	$3.76 \pm 0.86 \pm 0.28$
BaBar '02	$4.23 \pm 0.40 \pm 0.22$	$3.83 \pm 0.62 \pm 0.22$
Belle (prelim)	$4.08 \pm 0.34 \pm 0.26$	$4.92 \pm 0.57 \pm 0.38$
average	$4.21 \pm 0.25 \pm 0.26$	$4.32 \pm 0.38 \pm 0.30$

(All numbers, X10 $^{-5}$)

$B \to K^*_2(1430)\,\gamma$ Branching Fractions

CLEO '00	$1.66 \pm 0.56 \pm 0.13 \times 10^{-5}$
Belle (prelim)	$1.50 \pm 0.56 \pm 0.12 \times 10^{-5}$

- Other Exclusives (Belle)

$B^+ \to K^+\pi^-\pi^+\gamma$	$2.4 \pm 0.5 \pm 0.3 \times 10^{-5}$
$K^{*o}\pi^+\gamma$	$2.0 \pm 0.65 \pm 0.2 \times 10^{-5}$
$K^+\rho^o\gamma$	$1.0 \pm 0.5 \pm 0.25 \times 10^{-5}$
$K^+\pi^-\pi^+\gamma$ (NR)	$< 0.9 \times 10^{-5}$

Continuum Suppression for Inclusives -CLEO

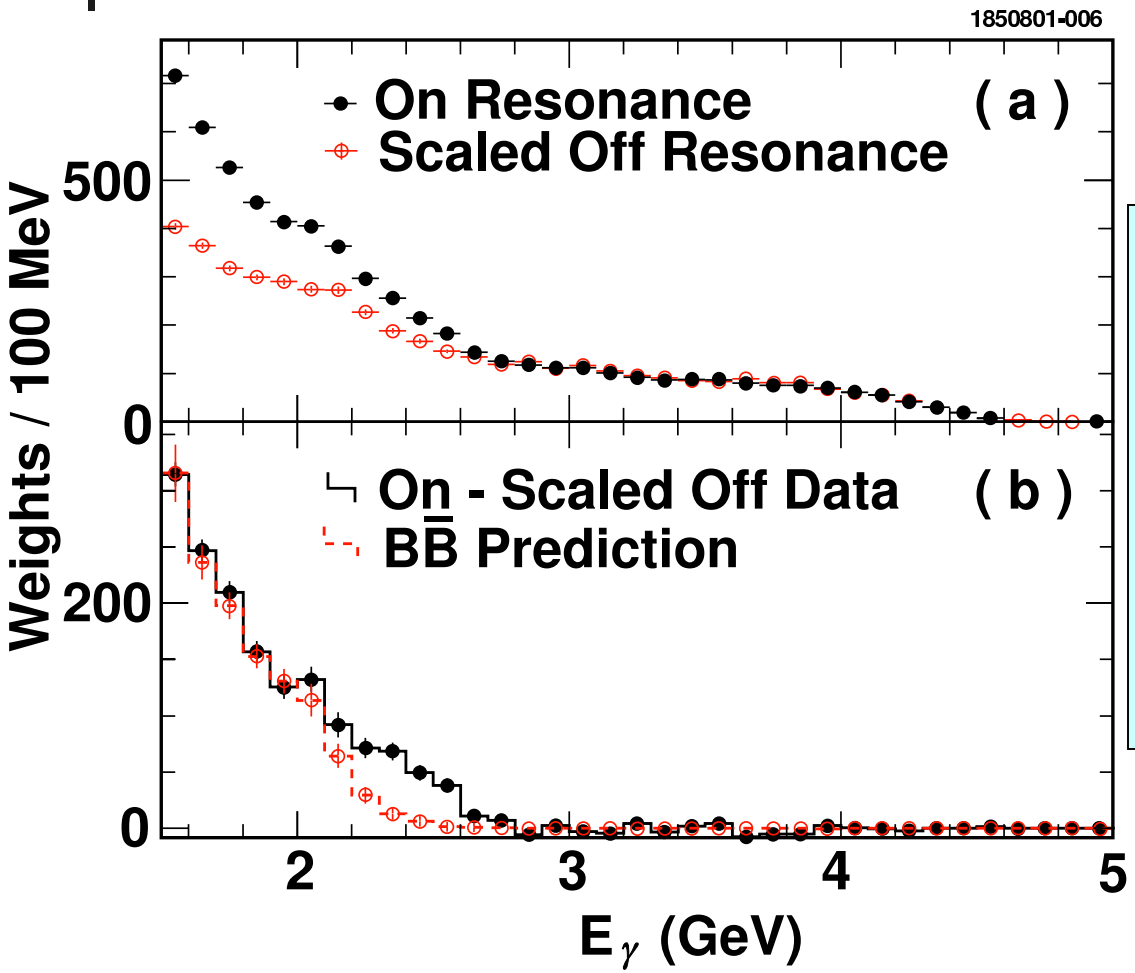
- **Event shape variables:**
  R_2, $S_\perp$, R'_2, $\cos\theta'$,
  cone energies within 20°, 30°
  of γ direction and -γ direction.
  Into neural net, 8 inputs, 1 output.
- **"Pseudoreconstruction":** Search events for combinations of particles that look like B->$X_s\gamma$. For X_s use $K^\pm$ or K^o_s, and 1-4 π (at most 1 π^o).
  - Calculate

$$\chi^2_B = \left(\frac{E - E_{beam}}{\sigma_E}\right)^2 + \left(\frac{M - M_B}{\sigma_M}\right)^2$$

  - If event has χ^2_B<20, use χ^2_B , $|\cos\theta_{tt}|$ for additional suppression.

- **Leptons:** If event has lepton (e or μ), use $\theta_{\gamma\ell}$, E_ℓ for additional continuum suppression.
- **Weight:** For each event with a high energy γ, determine probability that it is $b \to s\,\gamma$, rather than continuum background. Weight each such event, according to probability.

CLEO, PRL 87, 251807 (2001)

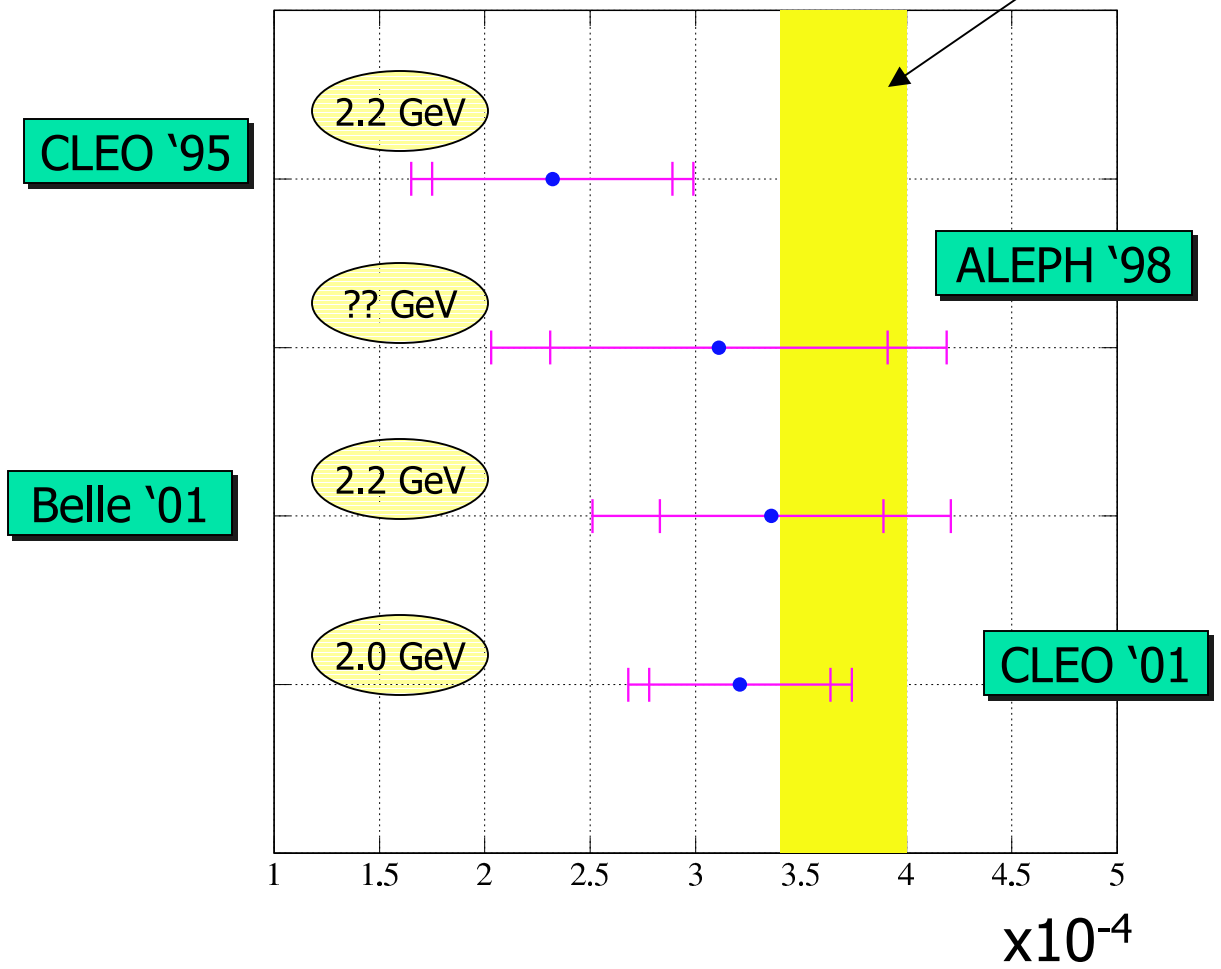


Photon energy spectra (weights per 100 MeV)

- Top shows the On Y(4S) and the scaled Off-resonance spectra.
- Bottom shows the difference and the spectrum estimated from B decay processes other than $b \to s\gamma$ and $b \to d\gamma$.

$\mathcal{B}(b \to s\gamma)$

Theory
Buras,Misiak, et al
Hep-ph/0203135



CP Asymmetry

$$a_{cp} = \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)}$$

- NOTE sign convention
- FOLLOW sign convention
  (so far, everyone seems to have.)

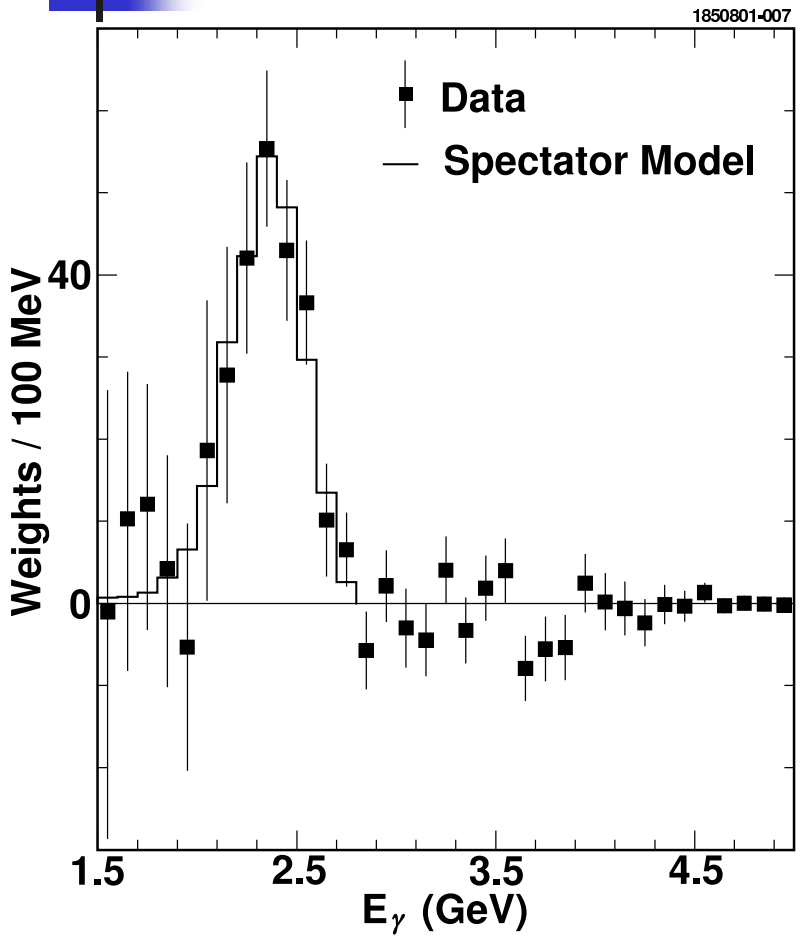
	B→K*(892)γ
CLEO, '00	$+0.08^{\pm}0.13^{\pm}0.03$
BaBar, '02	$-0.044^{\pm}0.076^{\pm}0.012$
Belle, new	$+0.032^{\pm}0.069^{\pm}0.020$
Average	$+0.009^{\pm}0.048^{\pm}0.018$

CLEO, '01 Inclusive -0.079+0.108+0.022
$(0.965\mathcal{A}(b\to s\gamma)+0.02\mathcal{A}(b\to d\gamma))$

Photon Energy Spectrum- the B Backgrounds

- γ's from $\pi^o \to \gamma\gamma$, $\eta \to \gamma\gamma$, that have escaped the π^o/η veto.
  - The big one (90% of total).
  - Measure π^o, η yields, treating π^o (η) as if it were a γ, all cuts as for $b \to s\gamma$ analysis. Use Monte Carlo to determine π^o/η veto efficiency.
- γ's from other sources
  - $\omega \to \pi^o\gamma$, $\eta' \to \rho^o\gamma$, radiative ψ decay, $\rho \to \pi\gamma$, $a_1 \to \pi\gamma$, final state radiation. $b \to u$ processes, $b \to s$g processes.
  - They're small, and with modest effort to have Monte Carlo event generator ok, one can trust the Monte Carlo.
- $K_{long,}\bar{n}$ interactions in calorimeter.
  - Determine contribution from lateral distribution in calorimeter (E9/E25).

CLEO (PRL 87, 251807 (2001))



Observed laboratory frame photon energy spectrum (weights/100 MeV) for ON minus scaled OFF minus B backgrounds, the putative $b \to s\gamma$ plus $b \to d\gamma$ signal.

Moments of the Spectrum

- CLEO obtains moments in the B rest frame, for Eγ(rest frame) > 2.0 GeV:

$$\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011 \ GeV$$

$$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.0226 \pm 0.0066 \pm 0.0020 \ GeV^2$$

- HQET plus OPE allows inclusive observables to be written as double expansions in powers of α_s and $1/M_B$ to order $\beta_0\alpha_s^2$ and $1/M_B^3$

$$\langle E_\gamma \rangle = \frac{M_B}{2}\left(1 - 0.385\frac{\alpha_s}{\pi} - 0.620\beta_0\left(\frac{\alpha_s}{\pi}\right)^2 - \frac{\bar{\Lambda}}{M_B}\left(1 - 0.954\frac{\alpha_s}{\pi} - 1.175\beta_0\left(\frac{\alpha_s}{\pi}\right)^2\right) - \frac{13\rho_1 - 33\rho_2}{12M_B^3} - \frac{\tau_1 + 3\tau_2 + \tau_3 + 3\tau_4}{4M_B^3} - \frac{\rho_2 C_2}{9M_D^2 M_B C_7} + O\left(\frac{1}{M_B^4}\right)\right)$$

$$\left\langle \left(E_\gamma - \langle E_\gamma \rangle\right)^2 \right\rangle = M_B^2\left(\frac{-\lambda_1}{12M_B^2} + 0.00815\frac{\alpha_s}{\pi} + 0.01024\beta_0\left(\frac{\alpha_s}{\pi}\right)^2 - \frac{\bar{\Lambda}}{M_B}\left(0.05083\frac{\alpha_s}{\pi} + 0.05412\beta_0\left(\frac{\alpha_s}{\pi}\right)^2\right) - \frac{2\rho_1 - 3\rho_2}{12M_B^3} - \frac{\tau_1 + 3\tau_2}{12M_B^3} + O\left(\frac{1}{M_B^4}\right)\right)$$

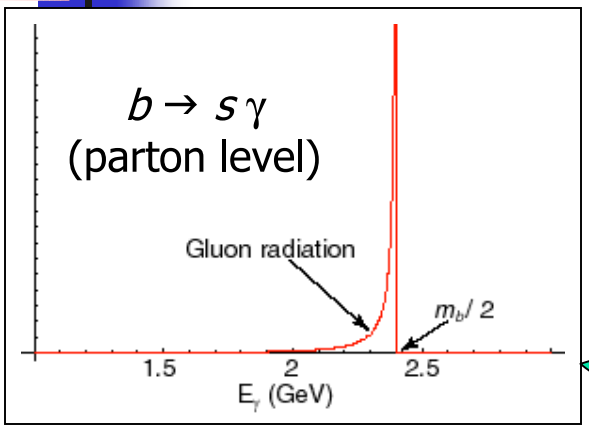
C_2 and C_7 are Wilson coefficients and β_0 is the one-loop QCD β function. The $1/M_B^3$ parameters are estimated from dimensional considerations to be $(0.5\text{GeV})^3$.

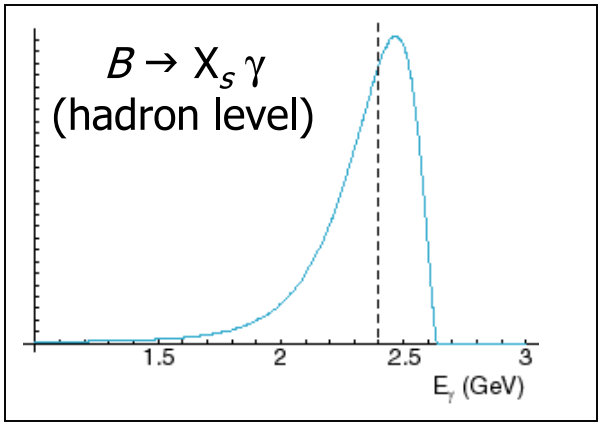
- Using the first CLEO obtains $\bar{\Lambda} = 0.35 \pm 0.08 \pm 0.10 GeV$

- The expression for the second moment converges slowly in 1/MB, and so CLEO made no attempt to extract parameters from it.

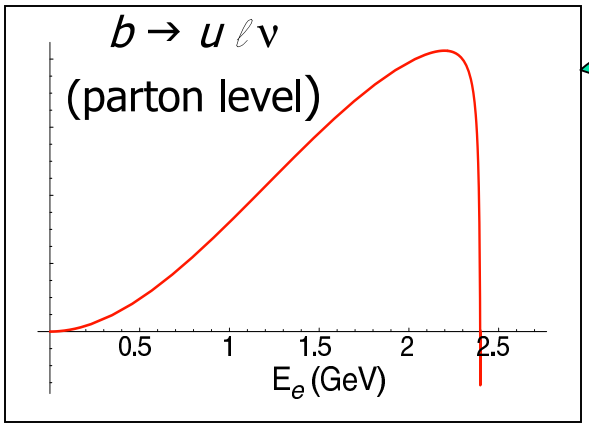
- $$\Gamma_{sl} = \frac{(0.3689)G_F^2 |V_{cb}|^2 M_B^2}{192\pi^3}\left[1 - 1.54\frac{\alpha_s}{\pi} - 1.43\left(\frac{\alpha_s}{\pi}\right)^2\beta_0 - 1.648\frac{\bar{\Lambda}}{M_B}\left(1 - 0.87\frac{\alpha_s}{\pi}\right) - 0.946\frac{\bar{\Lambda}^2}{M_B^2}\right.$$
$$- 3.185\frac{\lambda_1}{M_B^2} - 7.474\frac{\lambda_2}{M_B^2} - 0.298\frac{\bar{\Lambda}^3}{M_B^3} - 3.28\frac{\bar{\Lambda}\lambda_1}{M_B^3} + 7.997\frac{\bar{\Lambda}\lambda_2}{M_B^3} - 6.153\frac{\rho_1}{M_B^3}$$
$$\left. + 7.482\frac{\rho_2}{M_B^3} - 7.4\frac{\tau_1}{M_B^3} + 1.491\frac{\tau_2}{M_B^3} - 10.41\frac{\tau_3}{M_B^3} - 7.482\frac{\tau_3}{M_B^3} + O(1/M_B^4)\right]$$

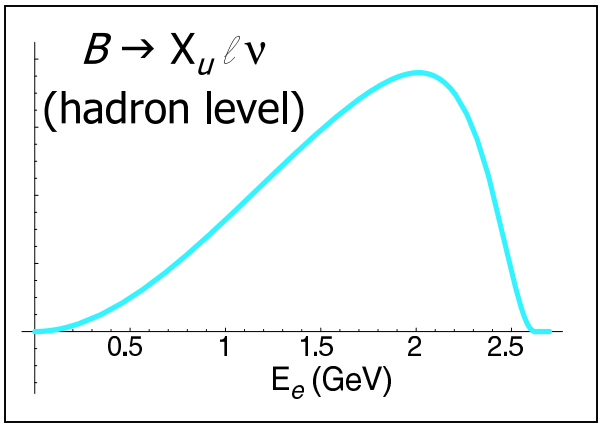
B → lightquark shape function, SAME (to lowest order in Λ_{QCD}/m_b) for $b \to s\gamma$ ⇨ $B \to X_s\gamma$ and $b \to u\ell\nu$ ⇨ $B \to X_u\ell\nu$.





Convolute with light cone shape function.





$b \to d\gamma$

- So far nothing on inclusive. Only upper limits on exclusives.
- Expect $\mathcal{B}(B \to \rho^+ \gamma) = 2 \times \mathcal{B}(B \to \rho^o \gamma) = 2 \times \mathcal{B}(B \to \omega \gamma)$

	B Pairs (Million)	Branching Fraction Upper Limits (10^{-6})		
		$\mathcal{B}(B \to \rho^+ \gamma)$	**2 x** $\mathcal{B}(B \to \rho^o \gamma)$	**2 x** $\mathcal{B}(B \to \omega \gamma)$
CLEO '00	9.7	13	34	18
Belle '01	11	10	21	---
BaBar **prelim**	63	2.8	3.0	---

BaBar limit by far the best ⇨ $[(1-\rho)^2+\eta^2]^{1/2} < 1.6$ (Tanaka, Moriond '02)

Still, not an improvement in limit on $|V_{td}|$ over that from B_s- $\bar{B}_s$ mixing.

Summary and Conclusions I

- $b \to s\gamma$ Exclusive branching fractions.
  - Not of great fundamental interest, but by identifying a larger fraction of the makeup of $B \to X_s \gamma$ decays, one will reduce some systematic errors on the branching fraction for the inclusive process $b \to s\gamma$. Belle progress on this front.
- $b \to s\gamma$ inclusive branching fraction.
  - Experiment agrees with SM theory, places strong restrictions on New Physics.
  - But really only one good measurement. Babar and Belle should get to work! They will need to:
    1. Accept photons down to 2.0 GeV, or lower. (2.2 GeV is no longer good enough)
    2. Take a reasonable amount of data below the Y(4S) resonance. (continuum subtraction MUST be done with DATA.)

Summary and Conclusions II

- CP asymmetry
  - No hint of a non-zero value.
  - Limits place weak restrictions on New Physics.
  - Plenty of room for improvement.
  - Asymmetry for inclusive wanted (Babar, Belle??)
- $b \to s\gamma$ photon energy spectrum
  - Has helped provide precise determination of $|V_{cb}|$ from the inclusive semileptonic decay branching fractions, and (more important) a good determination of $|V_{ub}|$ from the lepton endpoint yield in $b \to u\ell\nu$, with DEFENSIBLE ERRORS. Will be key for future determinations of $|V_{ub}|$ from inclusive $b \to u\ell\nu$.
  - Improvements in spectrum very desirable.
- $b \to d\gamma$
  - So far, nothing on inclusive, only upper limits on exclusives.
  - Not yet an improvement in limit on $|V_{td}|$ over that from B_s–$\overline{B}_s$ mixing.
  - Stay tuned.