Probing the Standard Model with Electroweak Penguin B Decays

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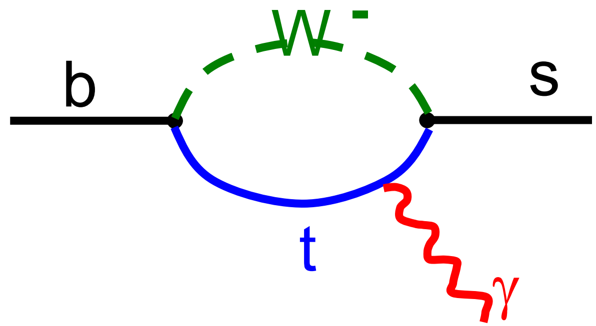
Outline:

- Branching fractions
- CP Asymmetry
- Isospin breaking
- Measurement of CKM parameters
- B Decays
  - $b \rightarrow s\gamma$: $B \rightarrow K^*\gamma$, $B \rightarrow \rho\gamma$, $B \rightarrow K^*(1430)\gamma$, etc.
  - $b \rightarrow s\, l^+ l^-$: $B \rightarrow K\, l^+ l^-$, $B \rightarrow K^*\, l^+ l^-$

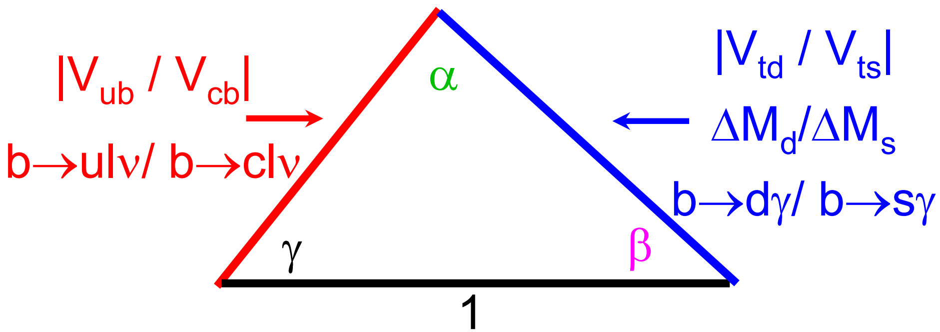
Electroweak Penguins : Sensitivity to New Physics

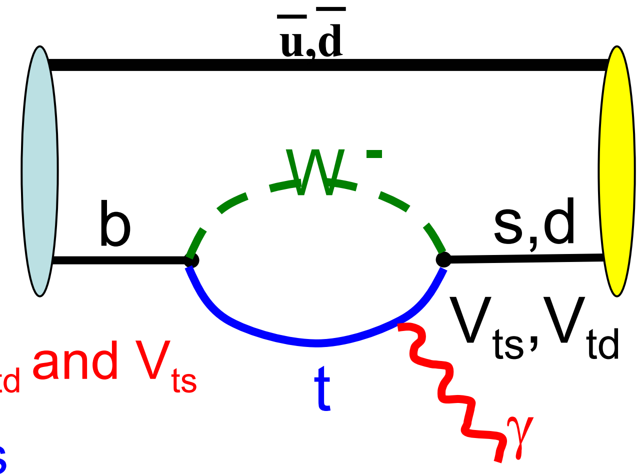


b→sγ penguin

- **Flavor changing neutral currents (b→s) are small**
- **At tree level FCNC is prohibited in the Standard Model**
- **Loop level contributions (radiative penguins: strong and EM)**
- **EM radiative penguins are a good indirect probe of new physics as non-Standard Model contributions ($H^{\pm}$, $\chi^{\pm}$, ..) can appear in the loop**
- **New Physics can effect the branching fraction and/or CP and isospin breaking asymmetries**

Measuring CKM Parameters



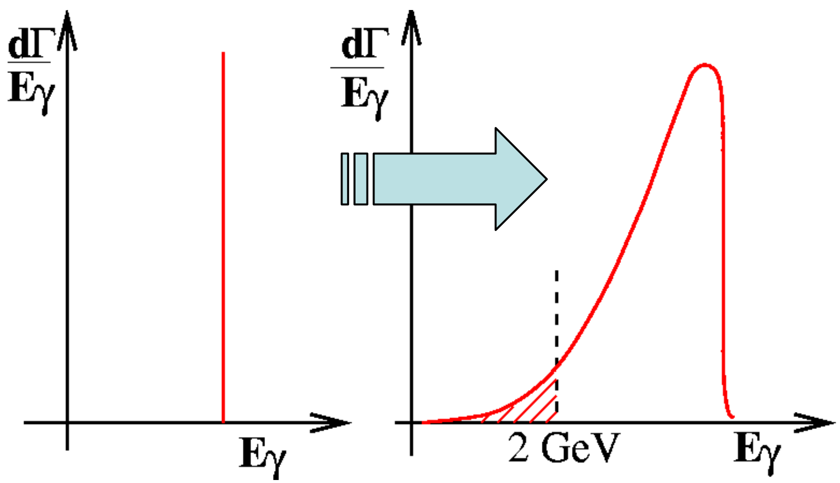


Measuring $b \rightarrow s\gamma$ and $b \rightarrow d\gamma \Rightarrow$ access to V_{td} and V_{ts}

- Theorists ideal: inclusive measurements
  - Avoid hadronic uncertainty
  - However, large experimental backgrounds
- Experimentally more accessible: exclusive measurements
  - Backgrounds much reduced
  - Must contend with large B-meson model dependence
  - Most theoretical and systematic effects cancel in the ratio of $B \rightarrow K^*\gamma$ and $B \rightarrow \rho\gamma$, $B \rightarrow \omega\gamma$

Understanding the B Meson

γ Energy Spectrum: No monochromatic γ spectrum because of b quark motion within the B meson



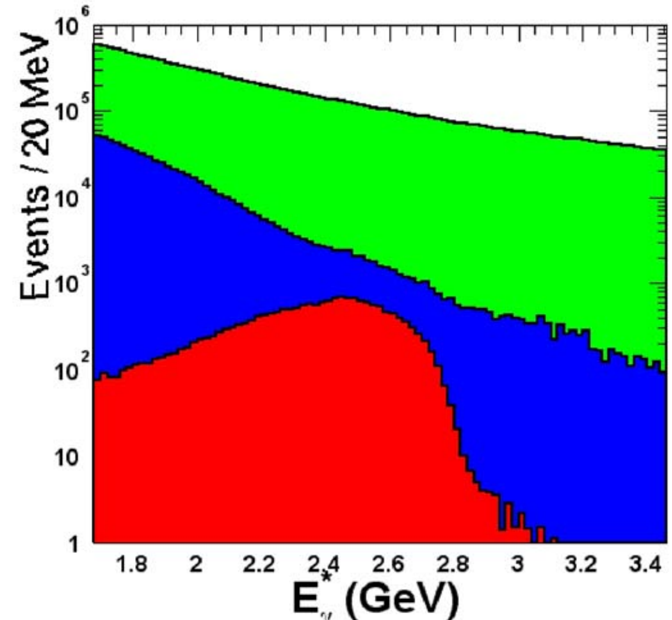
From moments analysis of γ energy spectrum → extraction of Heavy Quark Effective Theory (HQET) parameters:

- **$\bar{\Lambda}$ = energy of the light degrees of freedom in the B meson**
- **λ_1=average momentum squared of the b quark in the B meson**

Understanding the B meson model is important for reducing systematic uncertainty in measurement of V_{ub} from semileptonic decays.

Tackling b→sγ, b→dγ Backgrounds

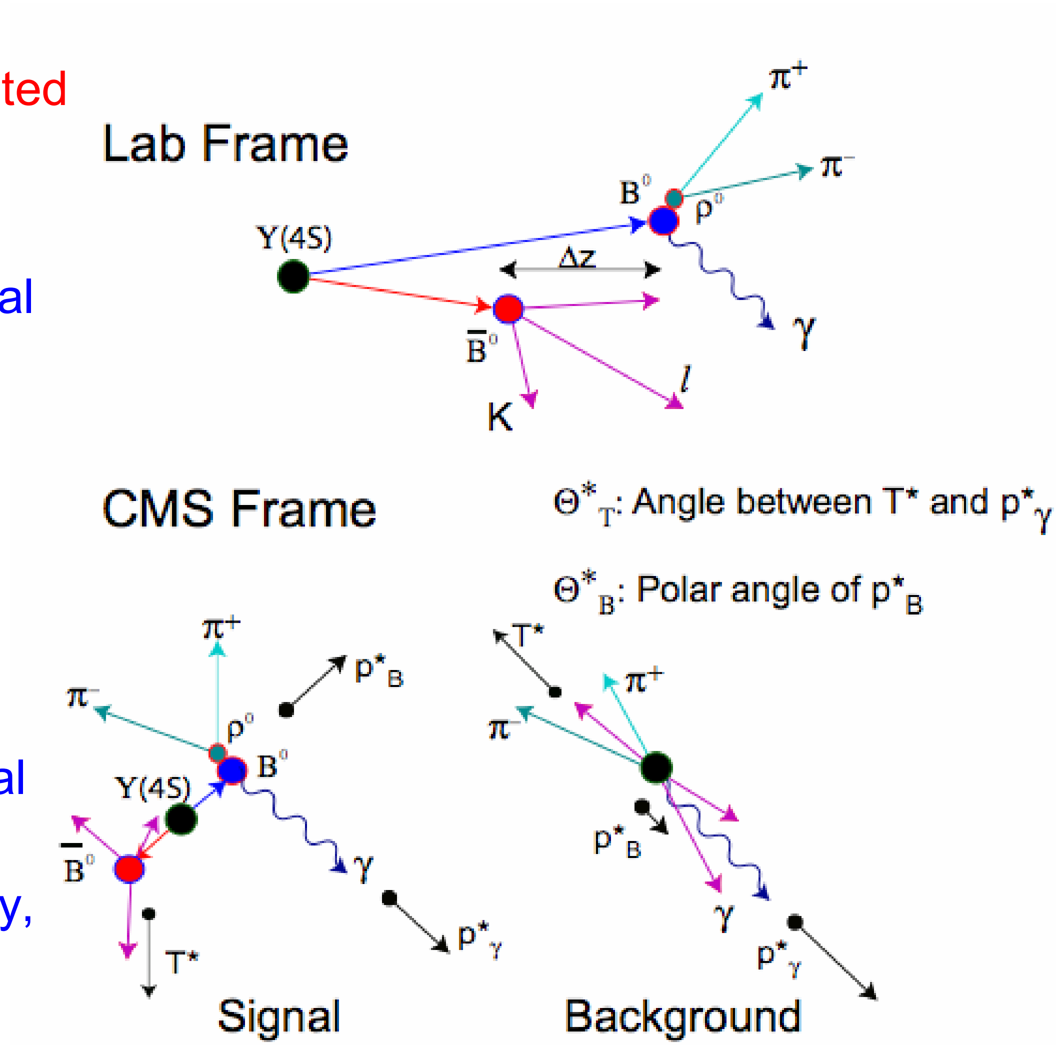
- Fully Inclusive Analysis
  - Large continuum background
    - Event shapes, B-Tagging
    - Statistical subtraction using off resonance data
  - B background (π^0 and η misidentification)
    - Strict vetos based on calorimeter energy profile
- Semi-Inclusive Analysis
  - Require hadronic system with a single kaon and up to 3 pions
  - B mass reconstruction
- Exclusive Analysis
  - Cuts down the background by explicitly reconstructing hadronic system and combining with g to make B candidates
    - K*, higher K resonances, ρ, ω



Inclusive EM cluster spectrum
(includes γ and misidentified hadrons)

Signal & Background Topology

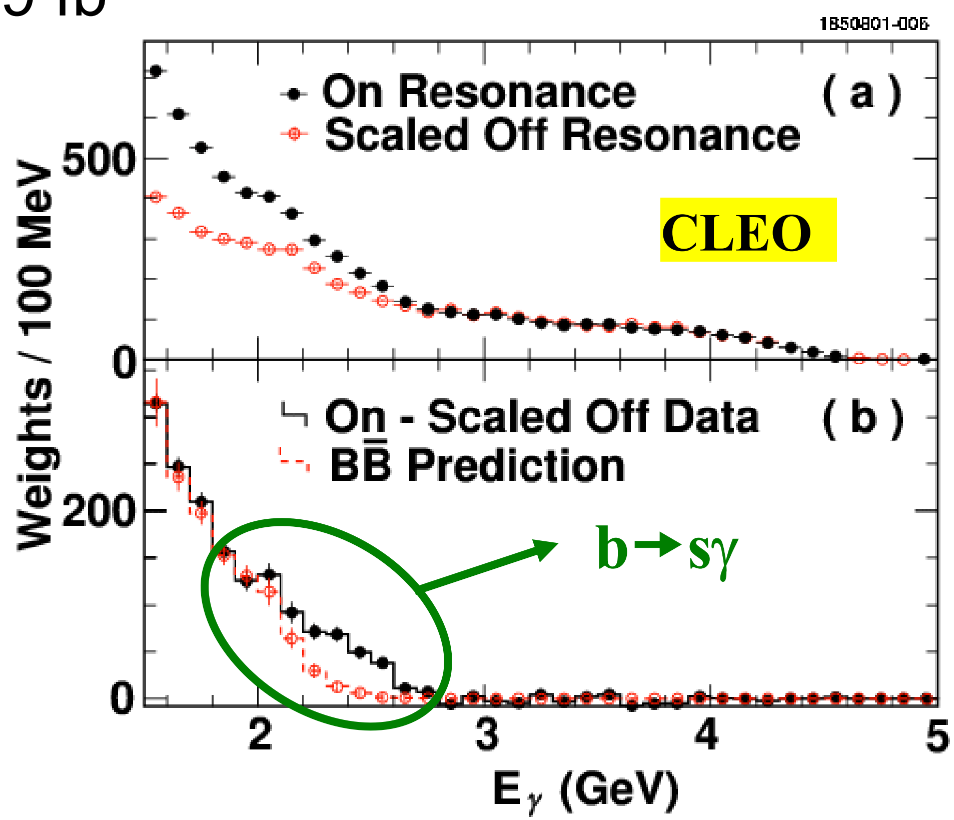
- At BaBar & Belle Bs are boosted
  - Large Δz identifies B
- In CMS frame
  - Signal events are spherical
  - Continuum is jet like
  - Thrust, sphericity,…
  - Angles about γ direction
  - Net flavor of the event
- Multivariate analysis
  - Individual variables offer limited separation of signal from background
  - Newer analysis, especially, $b \rightarrow d,\gamma$, use sophisticated techniques



Suppressing b→sγ background Using Off-resonance Data

Identify γ and suppress background exploiting large off-resonance data set + other techniques (CLEO)

~9 fb^{-1}



- Experimentally hard to suppress BB background at low γ energy
- Lower energy cut on the γ energy in all the experimental measurements ➔ model dependence
- Eg. E_γ>2 GeV corresponds to ~ 90% of the whole spectrum

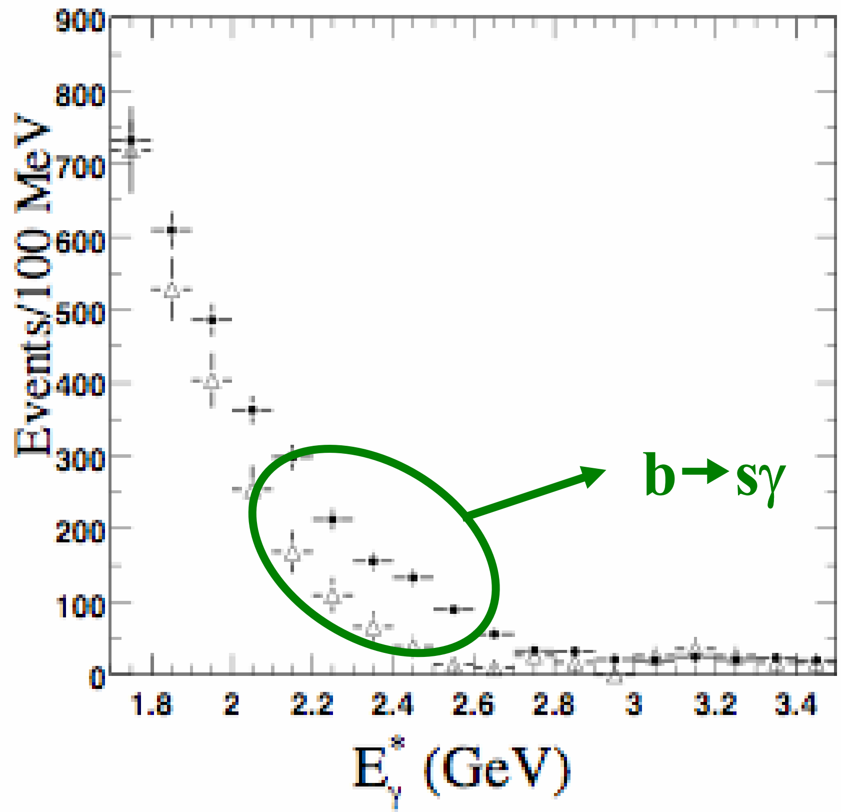
Suppressing $b \rightarrow s\gamma$ background by tagging lepton from the other B

Preliminary result presented at ICHEP 2002:

BABAR

$55\ \mathrm{fb}^{-1}$

Lepton tagged

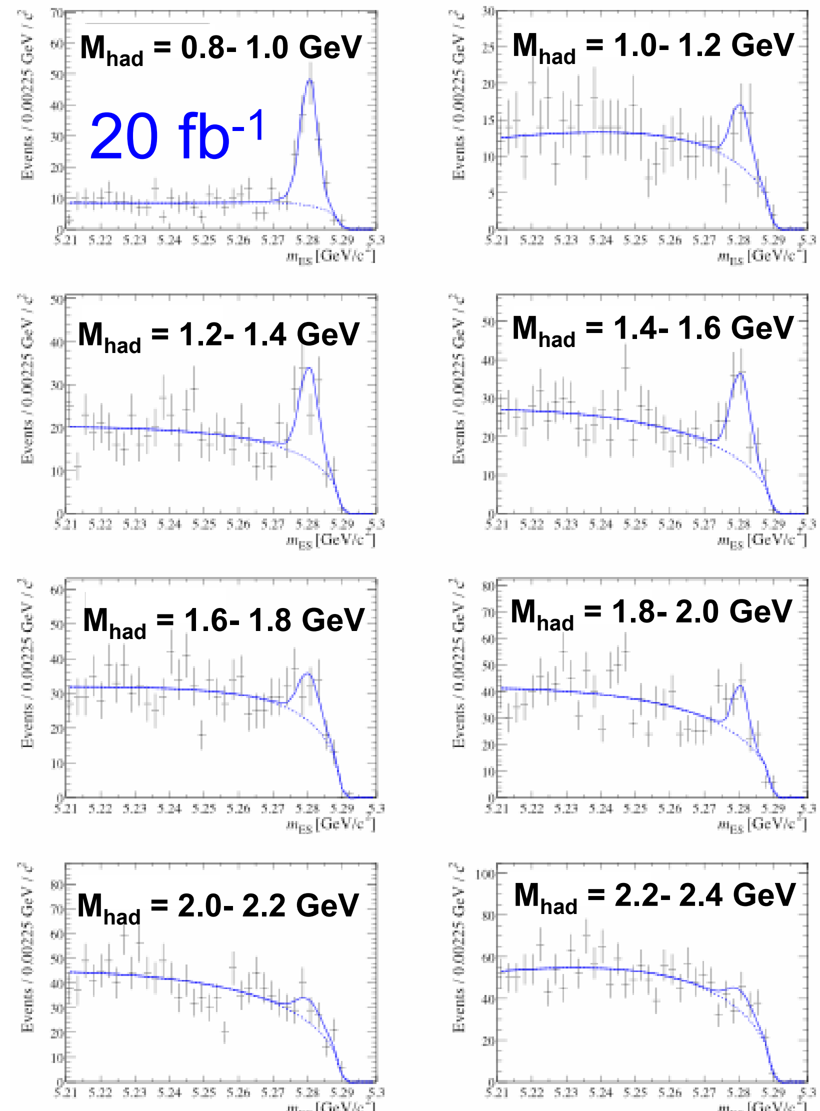


$\triangle = B\bar{B} +$ Continuum Backgrounds

Suppressing b→sγ background by summing up exclusively reconstructed B mesons

$$\text{Two body decay} \Rightarrow E_\gamma = \frac{M_b^2 - M_{had}^2}{2M_b}$$

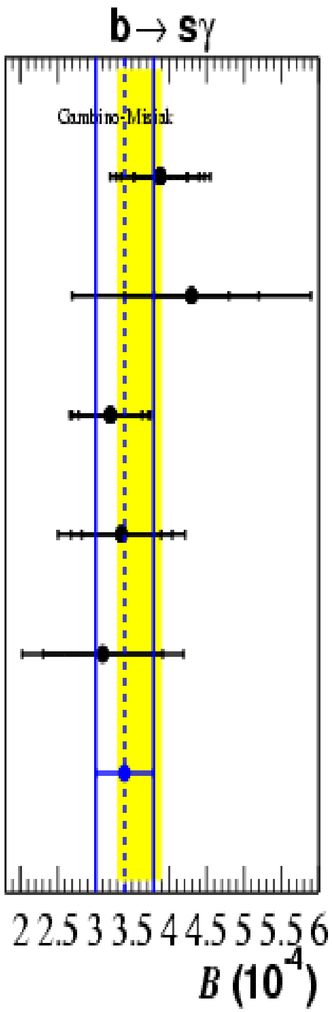
- Reconstruct 12 hadronic modes
  - Require $K^{\pm}$ or K_s and up to 3 pions ($n_{\pi 0} \leq 1$)
  - Extract signal from m_{es}, ΔE fits in bins of hadronic mass M_{had}
- Advantages
  - M_{had} has better resolution than E_γ
  - M_{had} spectrum can be used for improving V_{ub} measurement
- Difficulties
  - Multiple candidates
    - Selected best with least ΔE
  - Larger background for high multiplicty states
  - Missing mode correction model



Reconstructed B Mass

$b \to s\gamma$ Branching Fraction

	$B \pm stat \pm syst \pm theo$
BaBar hep-ex/0207076	$(3.88 \pm 0.36 \pm 0.37^{+0.43}_{-0.23})\ 10^{-4}$
BaBar hep-ex/0207074	$(4.3 \pm 0.5 \pm 0.8 \pm 1.3)\ 10^{-4}$
CLEO PRL 87, 251807, 2001	$(3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10})\ 10^{-4}$
BELLE PLB 511, 151, 2001	$(3.36 \pm 0.53 \pm 0.42^{+0.50}_{-0.54})\ 10^{-4}$
Aleph PLB 429, 169, 1998	$(3.11 \pm 0.80 \pm 0.72)\ 10^{-4}$
Average	$(3.40 \pm 0.39)\ 10^{-4}$



Aleph result scaled to expectation at Y(4S) in making the average

Unofficial averages made using L.Lyons *et al.*, NIM A270, 110, 1988

Theoretical prediction for $B(b \to s\gamma\ (E_\gamma > 1.6\ \text{GeV})) = (3.60 \pm 0.30) \cdot 10^{-4}$ Gambino, Misiak hep-ph/010434

No consistent treatment of the theoretical errors among the experiments

Average made assuming only theoretical errors correlated

Experimental results consistent with the SM ➔ limits on new physics contributions (Ellis et al., hep

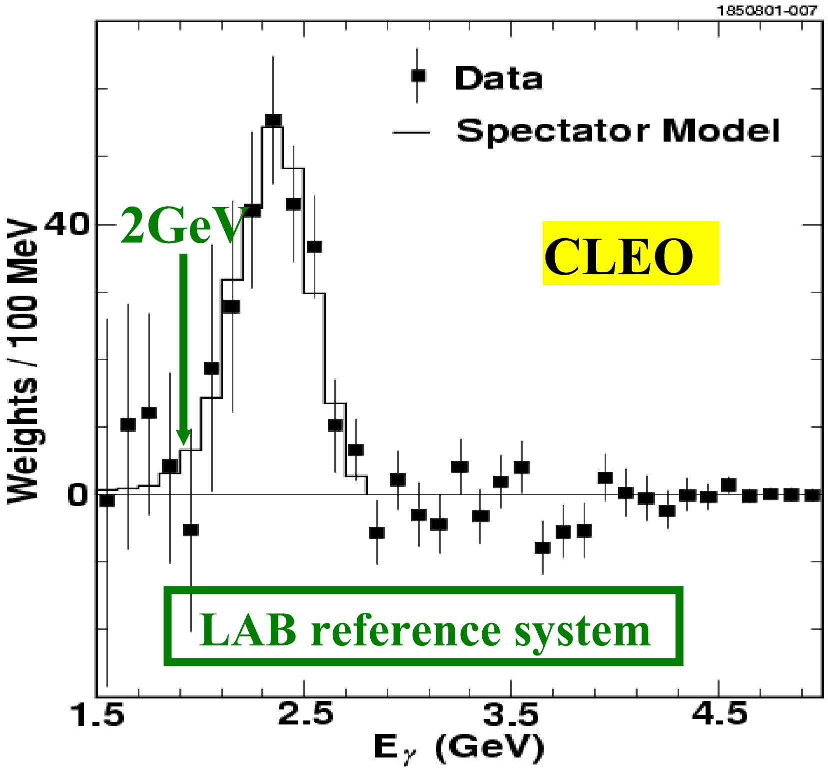
Direct CP asymmetry in $b \to s\gamma$

$$A_{CP} = \frac{B(b \to s\gamma) - B(\bar{b} \to \bar{s}\gamma)}{B(b \to s\gamma) + B(\bar{b} \to \bar{s}\gamma)}$$

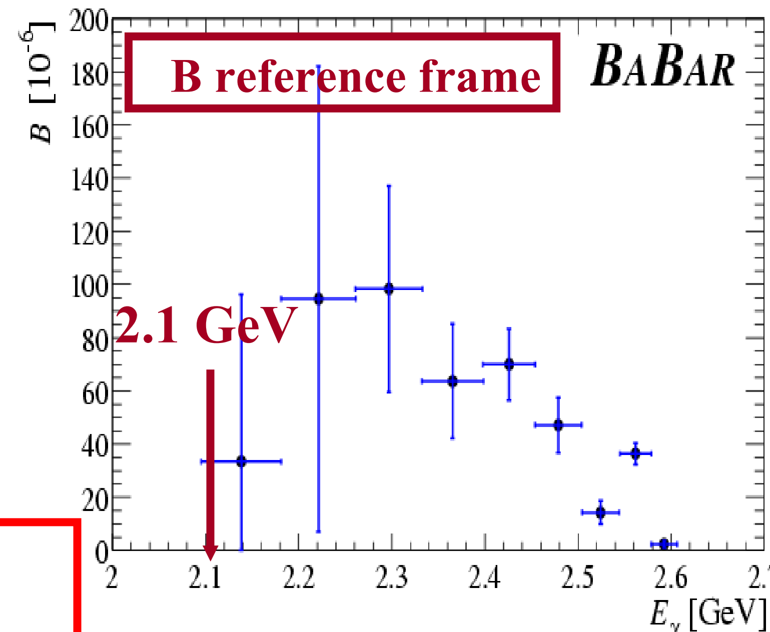
- Only a measurement from CLEO, using inclusive and exclusive final states (PRL 86, 5661, 2001), 9.1 fb^{-1}
- Inclusive final states: need to flavor tag the other B
- Exclusive final states: self-tagging
- No distinction between $b \to s\gamma$ and $b \to d\gamma$

  $A_{CP} = 0.965 * A_{CP}(b \to s\gamma) + 0.02 * A_{CP}(b \to d\gamma) = (-0.079 \pm 0.108 \pm 0.22) \cdot (1.0 \pm 0.030)$
- Asymmetry is consistent with zero within rather large errors.

γ energy spectrum in $b \rightarrow s\gamma$



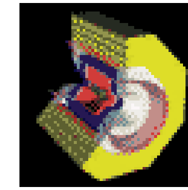
Inclusive analyses need to boost γ from LAB frame to B frame.
Exclusive analyses from M_{Xs}
➔ E_γ in B frame



CLEO (PRL 87, 251807, 2001)
E_γ > 2.0 GeV
$\langle E_\gamma \rangle$ = 2.346±0.032±0.011 GeV
$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2$ = 0.0226±0.0066±0.0020 GeV^2

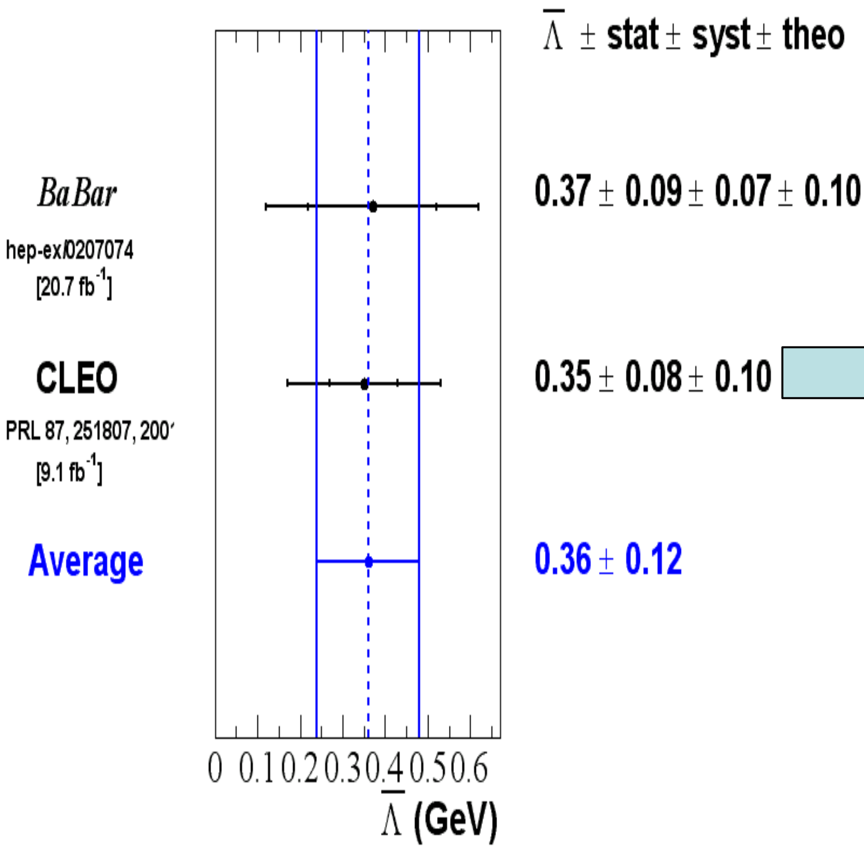
BaBar (hep-ex/0207074)
E_γ > 2.1 GeV
$\langle E_\gamma \rangle$=2.35±0.04±0.04 GeV

B Meson parameters from b→sγ



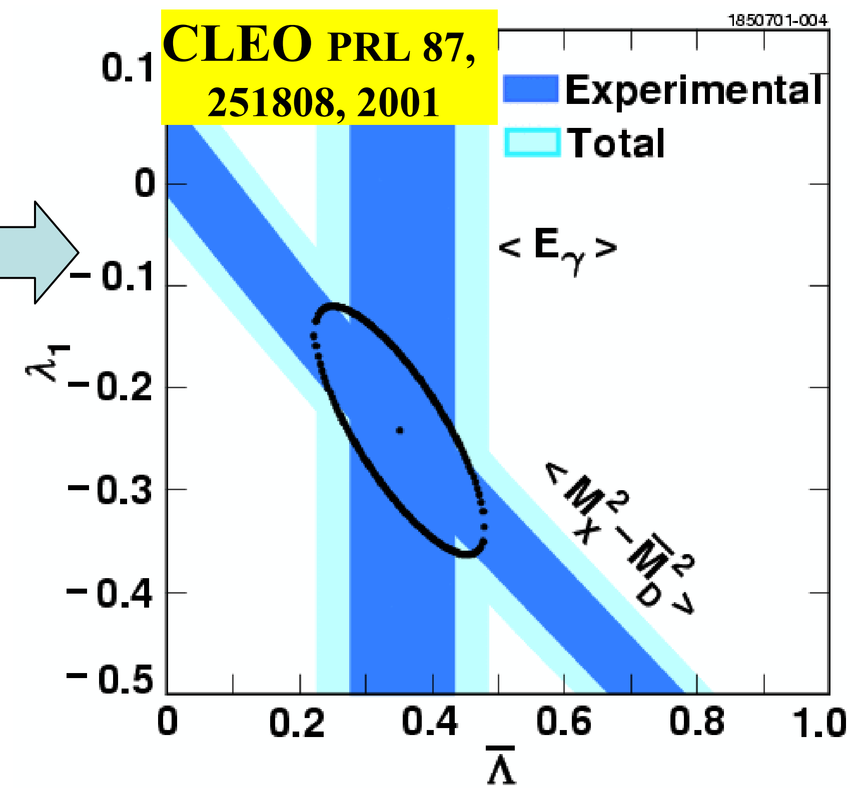
$\overline{\Lambda}$ from first E_γ moment

(Ligeti et al. PRD 60, 034019, 1999):



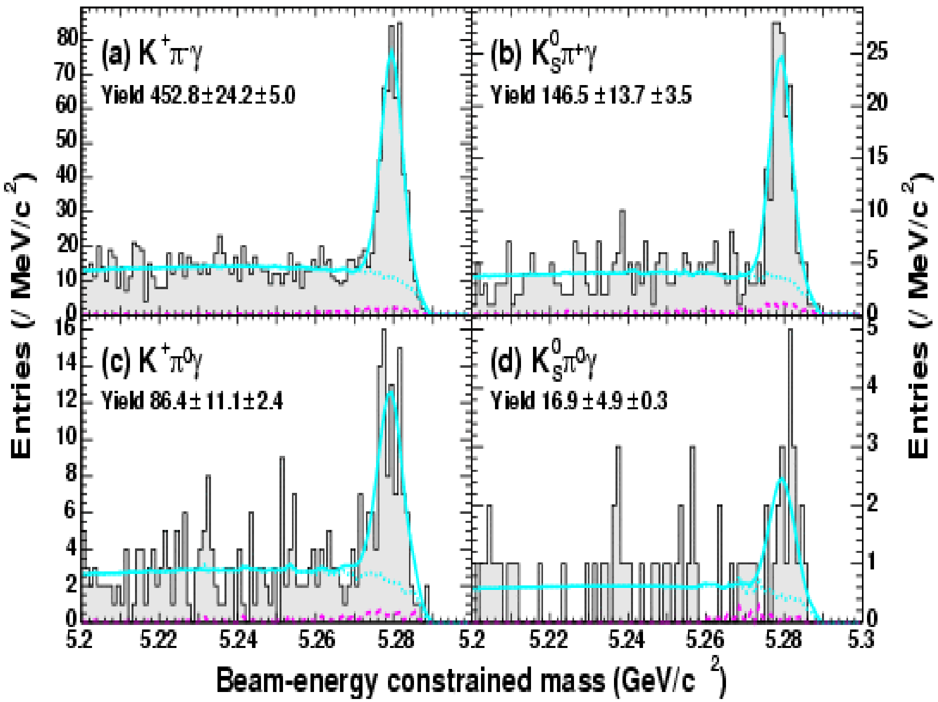
Using the hadronic mass moments in inclusive semileptonic B decays

$$\lambda_1 = -0.24 \pm 0.11 \text{ GeV}^2$$

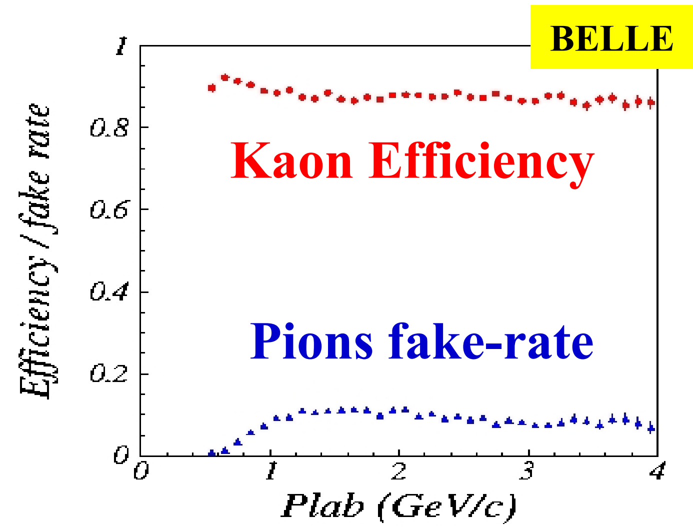


Exclusive Decay: $B \to K^*\gamma$

$B \to K^*(892)\gamma$ – BELLE

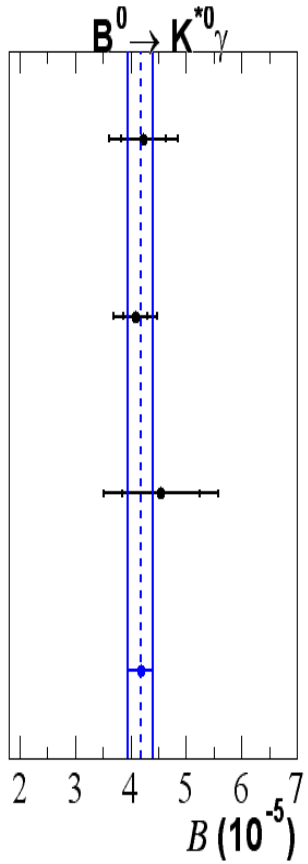


- First observation of $B \to K^*(892)\gamma$ and $B \to K^*_2(1430)\gamma$ by CLEO (1993 and 2000).
- Much higher statistics now. Results close to being systematics limited.
- Measurements of Branching Fractions, CP asymmetries and isospin asymmetry between B^0 and $B^\pm$ decay widths

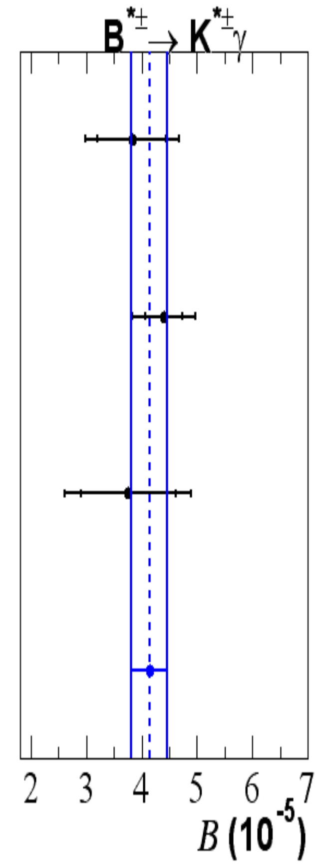


Kaon ID is important to reduce background

$B \to K^* \gamma$ results



	B ± stat ± syst
BaBar PRL 88, 101805, 2002 [20.7 fb^{-1}]	$(4.23 \pm 0.40 \pm 0.22)\ 10^{-5}$
BELLE BELLE-CONF-0239 [78 fb^{-1}]	$(4.09 \pm 0.21 \pm 0.19)\ 10^{-5}$ **New**
CLEO PRL 84, 5283, 2000 [9.2 fb^{-1}]	$(4.55 \pm 0.70 \pm 0.34)\ 10^{-5}$
Average	$(4.18 \pm 0.23)\ 10^{-5}$



	B ± stat ± syst
BaBar PRL 88, 101805, 2002 [20.7 fb^{-1}]	$(3.83 \pm 0.62 \pm 0.22)\ 10^{-5}$
BELLE BELLE-CONF-0239 [78 fb^{-1}]	$(4.40 \pm 0.33 \pm 0.24)\ 10^{-5}$ **New**
CLEO PRL 84, 5283, 2000 [9.2 fb^{-1}]	$(3.76 \pm 0.86 \pm 0.28)\ 10^{-5}$
Average	$(4.14 \pm 0.33)\ 10^{-5}$

BELLE isospin asymmetry:

$r = \tau_{B\pm}/\tau_{B0} = 1.083 \pm 0.017$

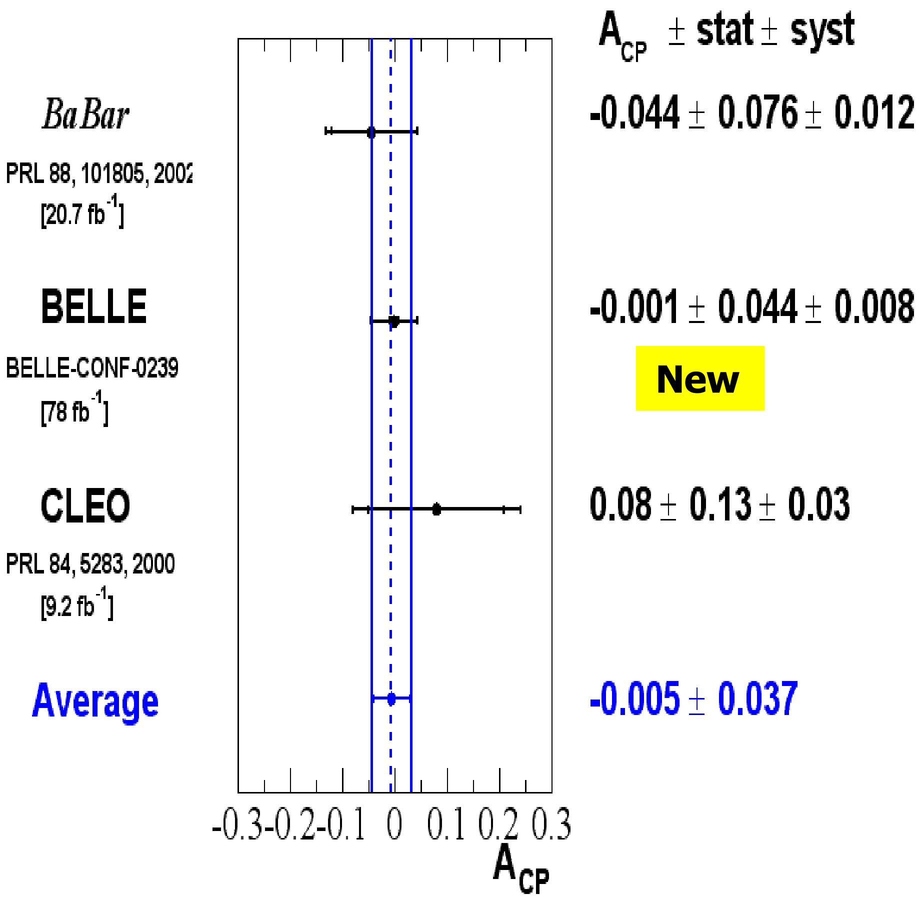
$$\Delta_{0\pm} = \frac{r\mathcal{B}(B^0 \to K^{*0}\gamma) - \mathcal{B}(B^\pm \to K^{*\pm}\gamma)}{r\mathcal{B}(B^0 \to K^{*0}\gamma) + \mathcal{B}(B^\pm \to K^{*\pm}\gamma)} = +0.003 \pm 0.045 \pm 0.018$$

New

Isospin breaking (Kagan & Neubert hep-ph/0110078) can test Wilson coefficients (C_6/C_7)

Direct CP asymmetry

$$A_{CP} = \frac{\mathcal{B}(\bar{B}\to\bar{K}^{*}\gamma)-\mathcal{B}(B\to K^{*}\gamma)}{\mathcal{B}(\bar{B}\to\bar{K}^{*}\gamma)+\mathcal{B}(B\to K^{*}\gamma)}$$



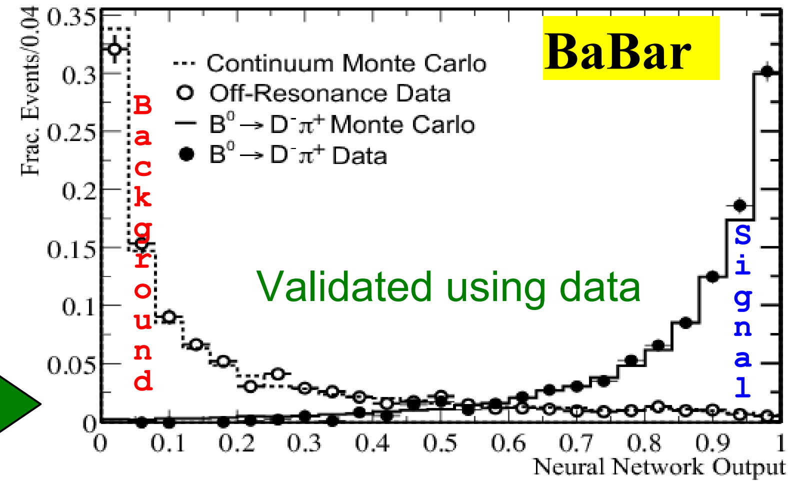
- Few percent accuracy!
- Statistics limited
- Systematic uncertainty
  - Mainly due to particle identification asymmetry
  - Background asymmetry.
  - Other systematic errors present in Branching Fraction cancel in A_{CP}

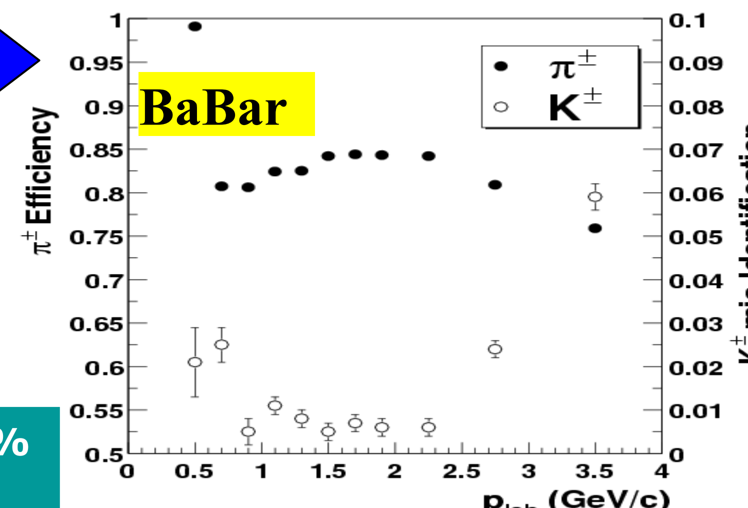
$-0.070 < A_{CP} < 0.053$ @ 90% CL

Improved BG reduction for B → ρ/ω γ

Challenges :

- **Lower branching fraction and higher background than for B→K*γ. Multivariate analysis techniques used for background subtraction.**
- **Feed-through from K*γ has to be removed. Use particle identification to reduce K→π fake rate to ~1%**
- **Irreducible background from B→ρπ^0**

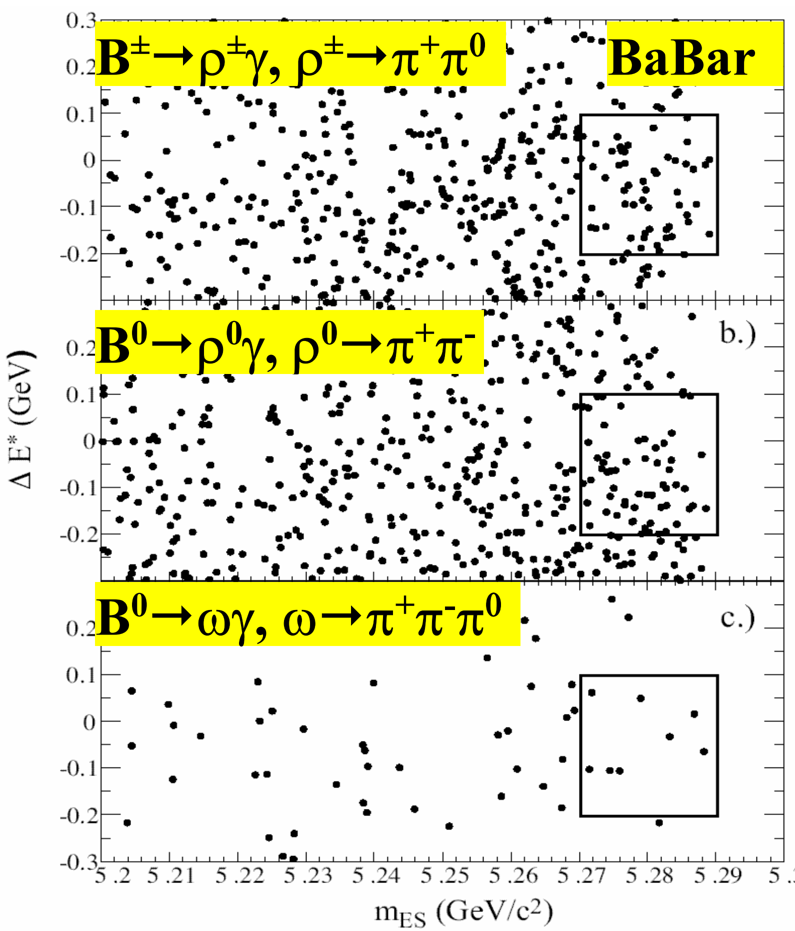


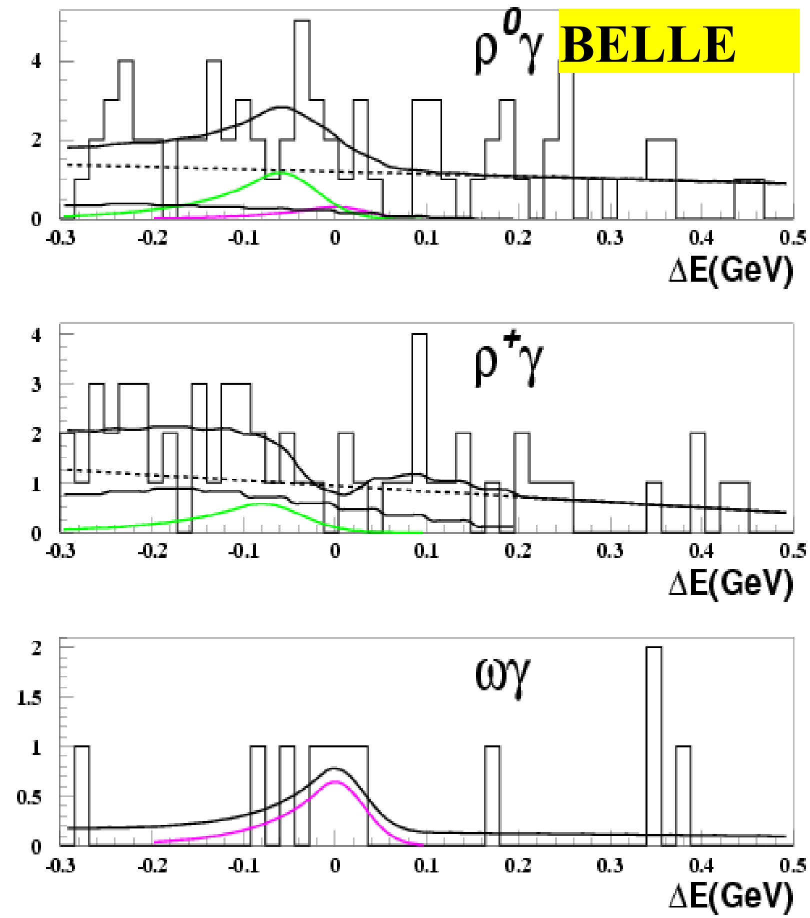


~80% π efficiency with ~1-2% K mis-ID up to ~3 GeV

B → ρ/ω γ

There is no evidence for signal yet:





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

Upper limits at 90% CL on *branching ratio* are set:

	BaBar (Moriond '03)	BELLE (Moriond '03)	CLEO (PRL 84, 5283, 00)	Theory (Ali & Parkhomenko) hep-ph/0105203
	78 fb^{-1}	78 fb^{-1}	9.2 fb^{-1}	
$\mathcal{B}(B^0 \to \rho^0\gamma)$	$< 1.2 \cdot 10^{-6}$	$< 2.6 \cdot 10^{-6}$	$< 17 \cdot 10^{-6}$	$(0.49 \pm 0.18) \cdot 10^{-6}$
$\mathcal{B}(B^\pm \to \rho^\pm\gamma)$	$< 2.1 \cdot 10^{-6}$	$< 2.7 \cdot 10^{-6}$	$< 13 \cdot 10^{-6}$	$(0.90 \pm 0.34) \cdot 10^{-6}$
$\mathcal{B}(B^0 \to \omega\gamma)$	$< 1.0 \cdot 10^{-6}$	$< 4.4 \cdot 10^{-6}$	$< 9.2 \cdot 10^{-6}$	$(0.49 \pm 0.18) \cdot 10^{-6}$

CKM Parameters: $|V_{td} / V_{ts}|$

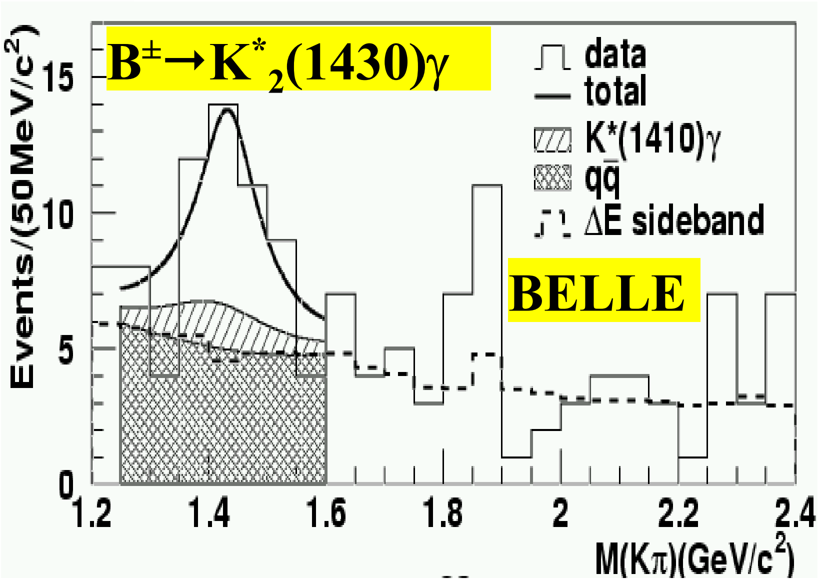
- Theoretical errors on hadronic effects mostly cancel in the ratio of exclusive modes
  - Left with ~15% residual uncertainty: Ali and Parmachenko
- Measurement complementary to $B_{d,s}$ mixing $\Delta M_d/\Delta M_s$
- Must first discover $b \rightarrow d\ \gamma$!

$$\frac{\mathrm{BF}(B \rightarrow \rho\gamma)}{\mathrm{BF}(B \rightarrow k^{*}\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1-\dfrac{m_\rho^2}{m_B^2}}{1-\dfrac{m_{k^*}^2}{m_B^2}}\right) \varsigma^2 \left[1+\Delta R\right]$$

$$\varsigma = 0.7 \text{ and } \Delta R = -0.25 \text{ (from Ali et al.)} \Rightarrow$$

$$\left|\frac{V_{td}}{V_{ts}}\right| < 0.36 \text{ at 90\% confidence level}$$

Understanding the hadronic spectrum: Higher K^* resonances



Ultimate goal is to track down all the resonances which contribute to the $b \to s\gamma$ spectrum!

$\mathcal{B}(B \to K^*_2(1430)\gamma)$

BELLE $(1.5^{+0.6}_{-0.5} \pm 0.1) \cdot 10^{-5}$

CLEO $(1.66^{+0.59}_{-0.53} \pm 0.13) \cdot 10^{-5}$

Average $(1.58 \pm 0.39) \cdot 10^{-5}$

90% CL limits on other resonances

- $\mathcal{B}(B \to K_1(1270)\gamma) < 8.7 \cdot 10^{-5}$
- $\mathcal{B}(B \to K_1(1400)\gamma) < 4.6 \cdot 10^{-5}$
- $\mathcal{B}(B \to K^*(1410)\gamma) < 6.2 \cdot 10^{-5}$

Helicity distributions used to distinguish the resonances

Results from BELLE (PRL 89, 231801, 2002), 29.4 fb^{-1} and CLEO (PRL 84, 5283, 2000), 9.2 fb^{-1}

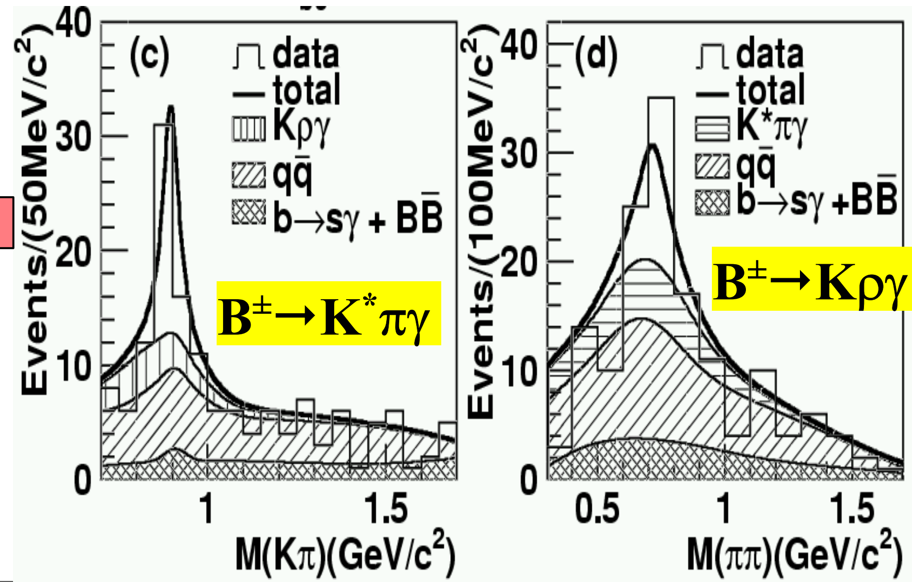
Understanding the hadronic spectrum: Higher mass systems

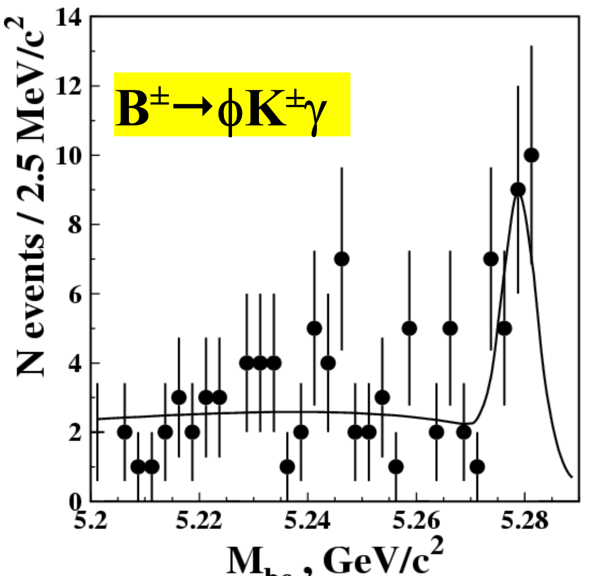
BELLE (PRL 89, 231801, 2002), 29.4 fb^{-1}

$\mathcal{B}(B \to K^*\pi\gamma) = (3.1 \pm 1.0) \cdot 10^{-5}$

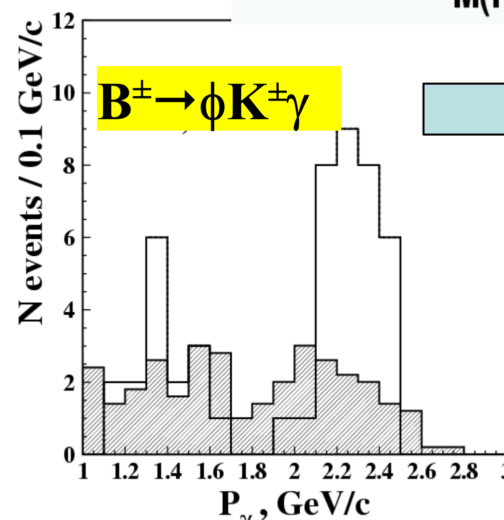
$\mathcal{B}(B \to K\rho\gamma) = (3.0 \pm 1.6) \cdot 10^{-5}$

~ 1/3 $\mathcal{B}(B \to X_s\gamma)$ **due to**
$K^*\gamma + K^*_2(1430)\gamma + K^*\pi\gamma + K\rho\gamma$





Beam-constrained mass



Photon momentum

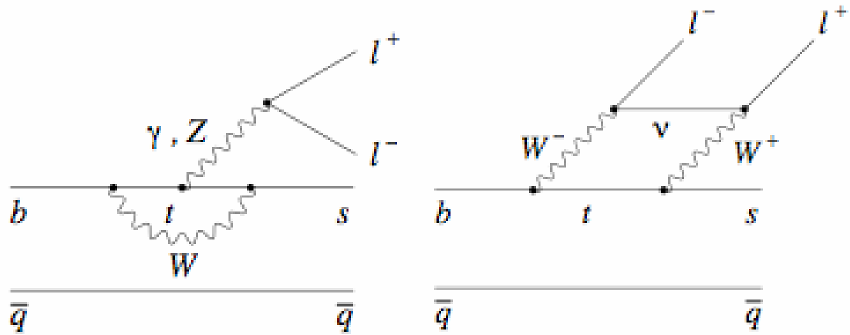
NEW result from BELLE , 90 fb^{-1}

$\mathcal{B}(B^\pm \to K^\pm\phi\gamma) = (3.4 \pm 0.9 \pm 0.4) \cdot 10^{-6}$

(5.5σ significance)

$\mathcal{B}(B^0 \to K^0\phi\gamma) < 8.3 \cdot 10^{-6}$ **@ 90%CL**

New physics sensitivity is higher for $b \to s\, l^+ l^-$



Exclusive decays:

$$\mathcal{B}(B \to K\ell^+\ell^-) = (0.35 \pm 0.12) \times 10^{-6}$$

$$\mathcal{B}(B \to K^* e^+ e^-) = (1.58 \pm 0.49) \times 10^{-6}$$

$$\mathcal{B}(B \to K^* \mu^+ \mu^-) = (1.19 \pm 0.39) \times 10^{-6}$$

Inclusive rate:

$$\mathcal{B}(b \to s e^+ e^-) = (6.9 \pm 1.0) \times 10^{-6}$$

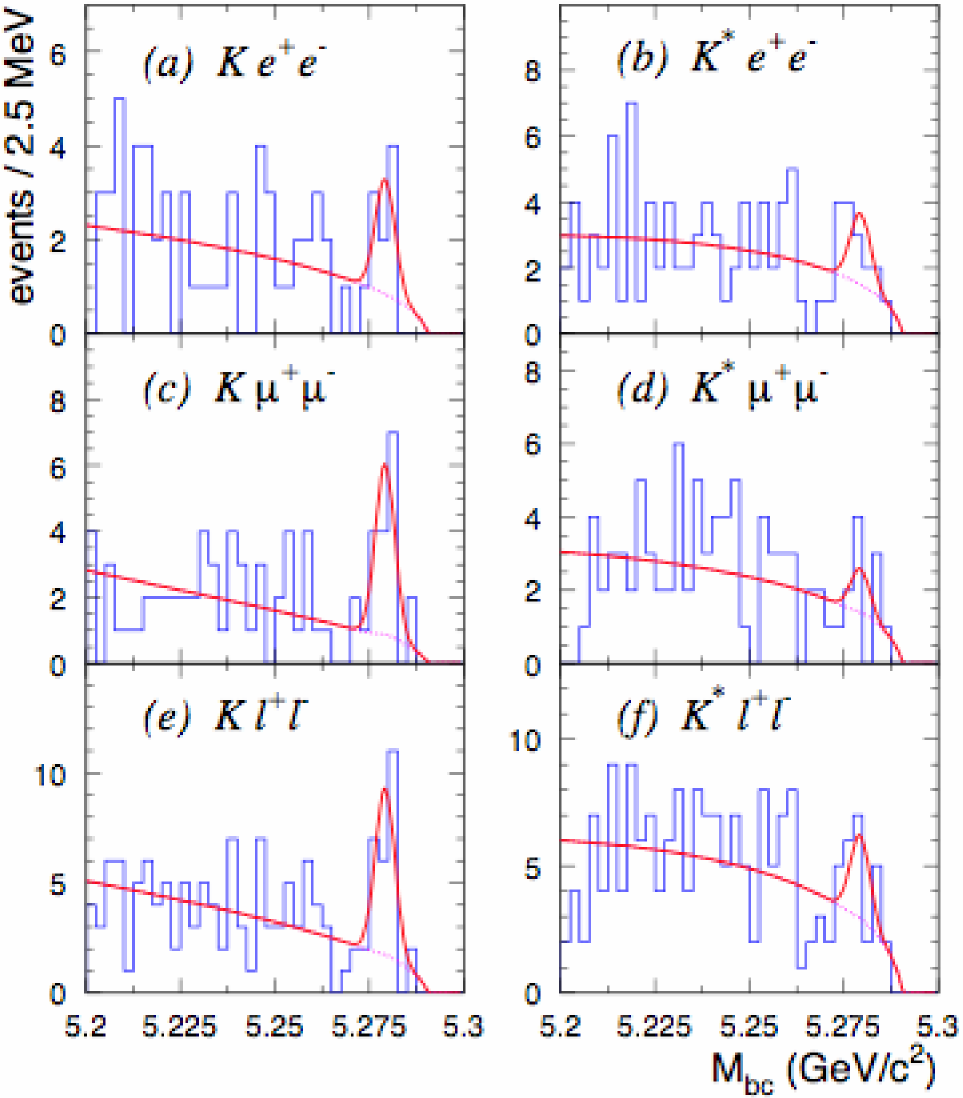
$$\mathcal{B}(b \to s \mu^+ \mu^-) = (4.2 \pm 0.7) \times 10^{-6}$$

Ali, Lunghi, Greub & Hiller, hep-ph/0112300

- Lepton forward-backward asymmetry and rate dependence on $s=(q^2/m_b)^2$ can be checked.
- Scope for new physics!
- Hurth hep-ph/0212304

Exclusive decays $B \rightarrow K^{(*)} l^+ l^-$

- Belle first established signal with 29 fb^{-1}
- Has newly updated result with 60 fb^{-1} ⇒



Exclusive Decays: $B \to K^{(*)} l^+ l^-$

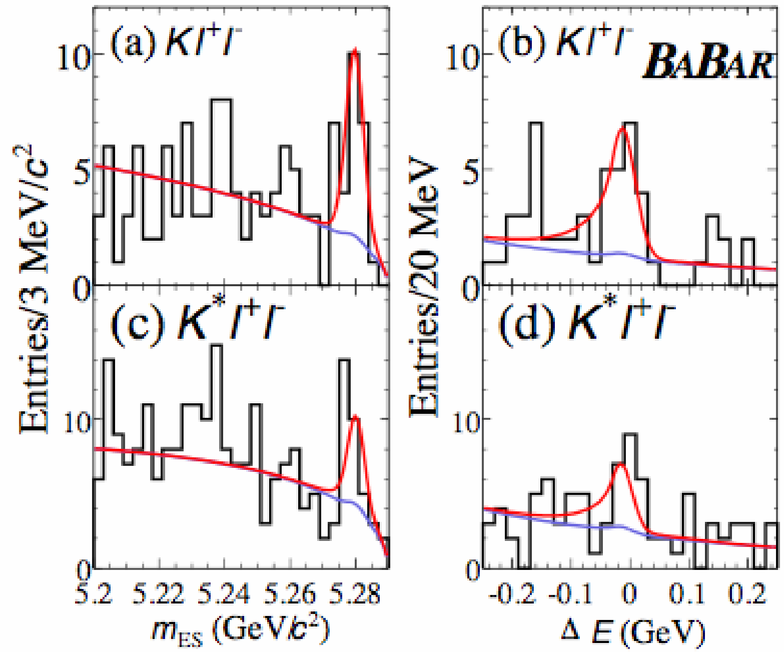
BABAR

Preliminary

78 fb^{-1}

$K\ell^+\ell^-$

4.4σ

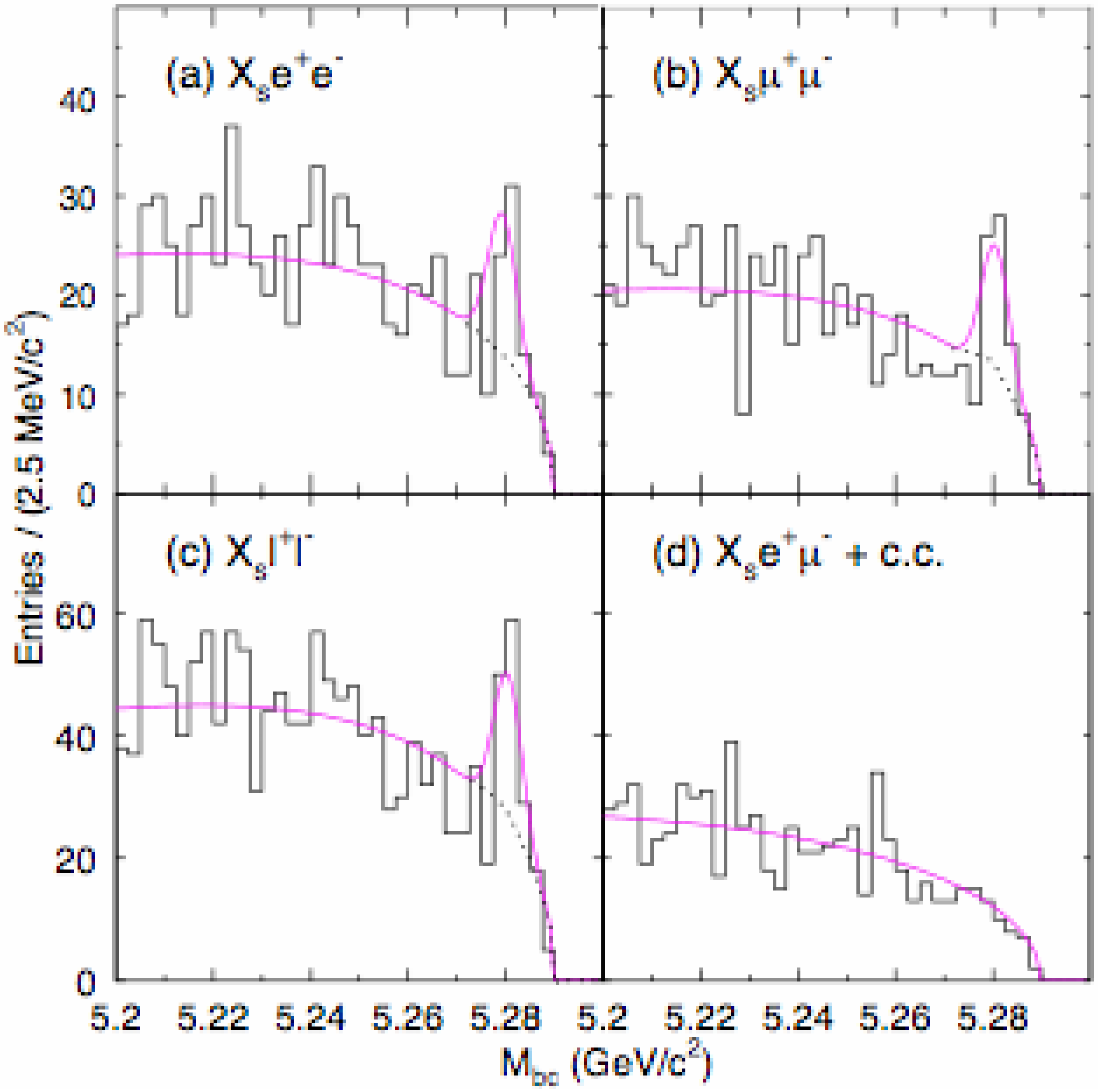


Averages of exclusive modes:

	$B \to K\ell^+\ell^- / 10^{-6}$	$B \to K^*\ell^+\ell^- / 10^{-6}$
BABAR	$0.78^{+0.24}_{-0.20} \pm 0.15$	< 3.0 (90% CL)
BELLE	$0.58^{+0.17}_{-0.15} \pm 0.06$	< 1.4 (90% CL)
Average	$0.66^{+0.15}_{-0.13} \pm 0.06$	

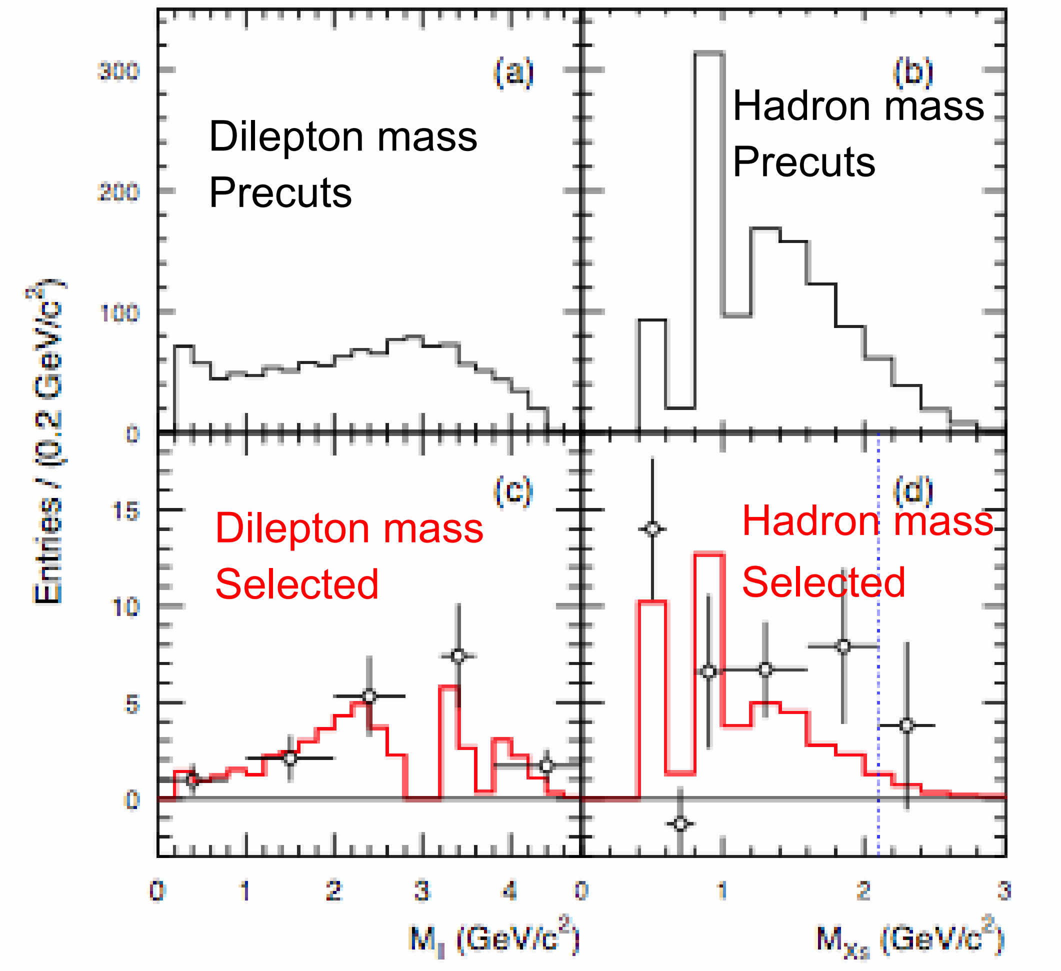
Inclusive decay: $b \rightarrow s\ l^+ l^-$

- Semi-inclusive
  - Use sum of exclusive modes techniques a la $b \rightarrow s\ \gamma$ analysis
  - Hadronic component, X_s, has one $K^\pm$ and up to 3 π



Inclusive b → s $l^+ l^-$ branching ratio

$$\mathcal{B}(B \to X_s l^+ l^-) = \left[6.1 \pm 1.4(\text{stat})^{+1.4}_{-1.1}(\text{syst})\right] \times 10^{-6}$$



Prediction:

$$\mathcal{B}(b \to s e^+ e^-) = (6.9 \pm 1.0) \times 10^{-6}$$

$$\mathcal{B}(b \to s \mu^+ \mu^-) = (4.2 \pm 0.7) \times 10^{-6}$$

- Signal: 57.4 events, 5.5σ
- Average of e^+e^- and $\mu^+\mu^-$
- Model dependence included in systematic uncertainty

Summary

- Precise measurements in $b \rightarrow s\gamma$
  - Branching Fractions (➔allows limits on new physics):
    - High precision results for $K^*\gamma$
    - Limits on other resonances and higher mass systems ➔ narrowing down all the $b \rightarrow s\gamma$ resonant spectrum
  - CP asymmetries (➔allows limits on new physics):
    - Best Direct CP limit in B system thus far
    - Indirect probe of new physics - will remain of interest for a while
  - Moments of X_s spectrum to understand B meson:
    - Measuring universal parameters important for measuring Vub
- Still awaiting $b \rightarrow d\gamma$ discovery!
  – *Allows measurement of V_{td}/V_{ts} complementary to $\Delta M_d/\Delta M_s$*
- Discovered $B \rightarrow K\, l^+ l^-$ (even better probe of new physics)
  - $K^*\, l^+ l^-$ and inclusive $B \rightarrow X_s\, l^+ l^-$ work in progress
- Integrated Luminosity: ~ 130-150 fb^{-1} by summer and
  ~ 500 fb^{-1} by 2006!