

CP Violation studies with Rare B Physics at CLEO

Adam Lyon
(University of Rochester)
for the CLEO Collaboration

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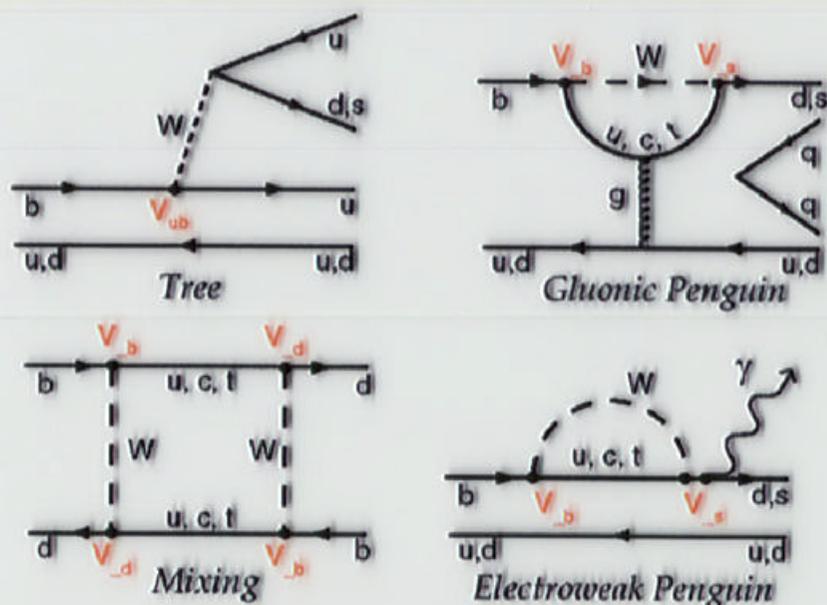
4th International Workshop on B Physics and CP violation Ise-Shima, Japan

Outline

- ◆ Charmless Hadronic Decays
 - ❖ $B \rightarrow \phi K, B \rightarrow \phi K^*$
 - ❖ Summarize $B \rightarrow K\pi, \pi\pi; B \rightarrow \eta' h$; Asymmetry
- ◆ Radiative Decays
 - ❖ $b \rightarrow s \gamma$ inclusive (**Asymmetry**), exclusive
 - ❖ $b \rightarrow d \gamma$ exclusive

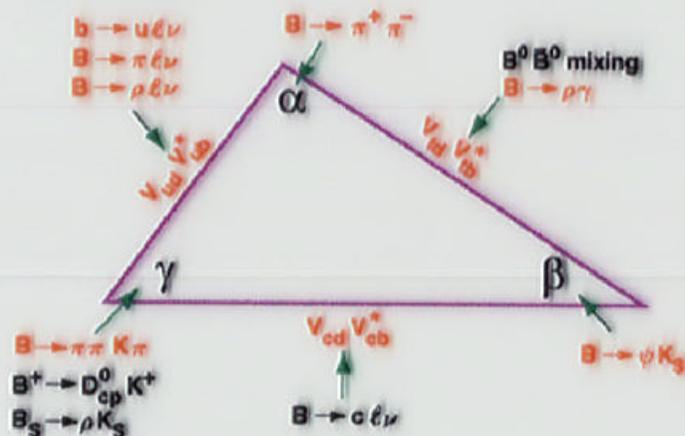
Rare B Physics

- ◆ Involving loops and boxes



Rates from loops and boxes are non-negligible because Top is so heavy (incomplete GIM)

- ◆ Learn about Unitarity Triangle:

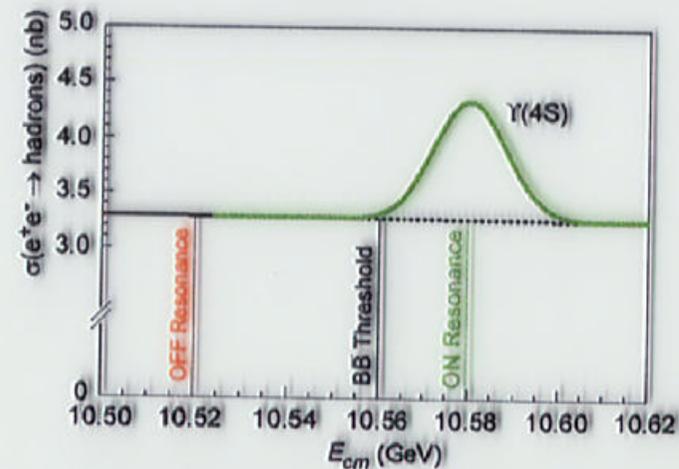
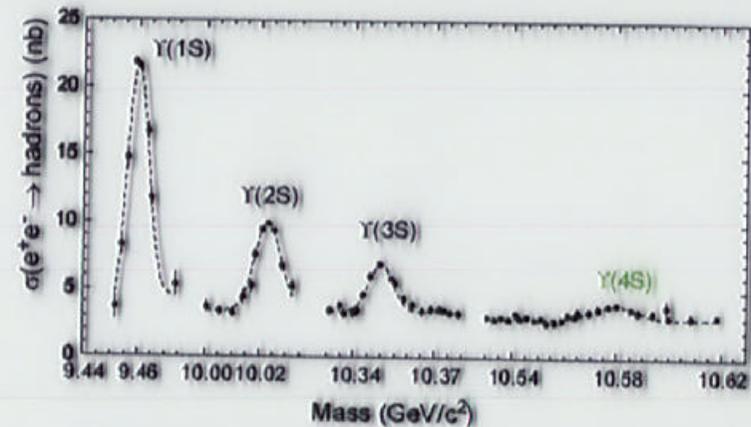


- ◆ CP Violation:

- ❖ Direct (decay amplitude interference)
- ❖ Mixing (mixing amplitude interference)

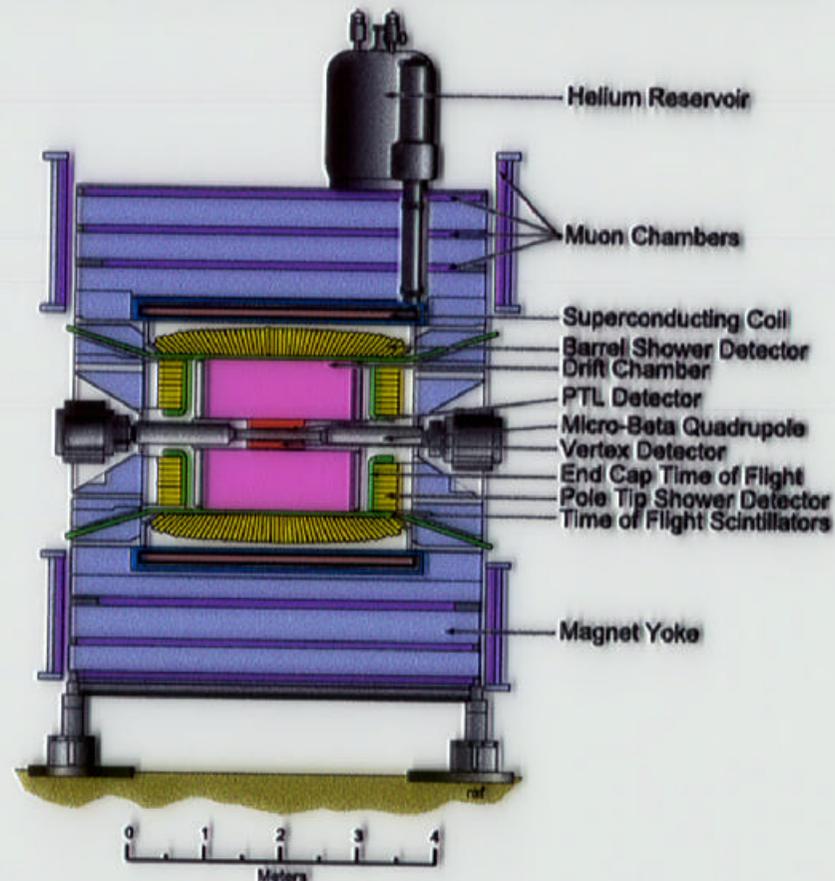
CESR and CLEO

- ◆ Symmetric e^+e^- accelerator at or near $\Upsilon(4S)$ ($P_B \sim 300 \text{ MeV}/c$)
- ◆ On the $\Upsilon(4S)$:
 - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ ($\sigma \sim 1 \text{ nb}$)
 - $e^+e^- \rightarrow q\bar{q}$, ($q = u, d, c, s$) ($\sigma \sim 3 \text{ nb}$)
- ◆ 1/3 running at OFF $\Upsilon(4S)$ for continuum bkg subtraction
- ◆ CLEO II + II.V collected
 - ON: 9.1 fb^{-1} (9.7M $B\bar{B}$)
 - OFF: 4.4 fb^{-1}



The CLEO Detector

- ◆ Cleo II (1989-1995):
 - ❖ 1.5T Solenoidal Field
 - ❖ 3 Tracking chambers
 - ❖ CsI Calorimeter
 - ❖ Time of Flight
 - ❖ Muon
 - ❖ 3.1 fb^{-1} ON, 1.6 fb^{-1} OFF
- ◆ Cleo II.V (1996-1999):
 - ❖ 3 layer silicon detector replaces innermost tracker
 - ❖ Replaced Drift Chamber Gas (Argon Ethane \rightarrow HePr)
 - ❖ 6.0 fb^{-1} ON, 2.8 fb^{-1} OFF



Charmless Hadronic: Common analysis techniques

◆ Selecting Signal

- ❖ Beam constrained mass

$$M_B = \sqrt{E_{beam}^2 - |\mathbf{p}|^2}$$

$\sigma \sim 2.5 \text{ MeV}$ (3.0 MeV if π^0)

- ❖ Energy difference

$$\Delta E = \sum_{B \text{ daughters}} E_i - E_{beam}$$

Resolution is mode dependent,
but generally
 $\sigma \sim 20\text{-}25 \text{ MeV}$
($\times 2$ worse if π^0)

- ❖ dE/dx and ΔE for PID

-
- ◆ *Put all this and more into ML fit*

◆ Rejecting continuum

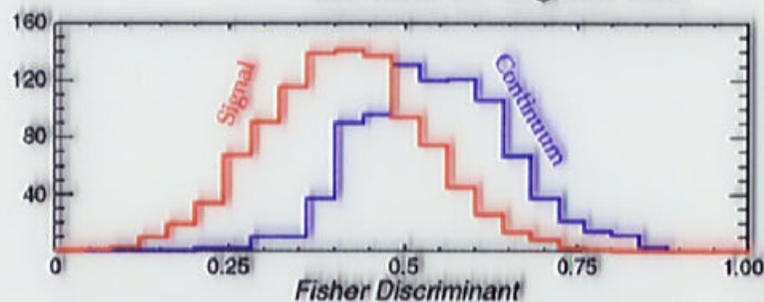
Signal = isotropic (2 uncorrelated B 's),
continuum = jetty

- ❖ Thrust angle

- ❖ Fisher discriminant:

Linear combination of 11 shape variables:

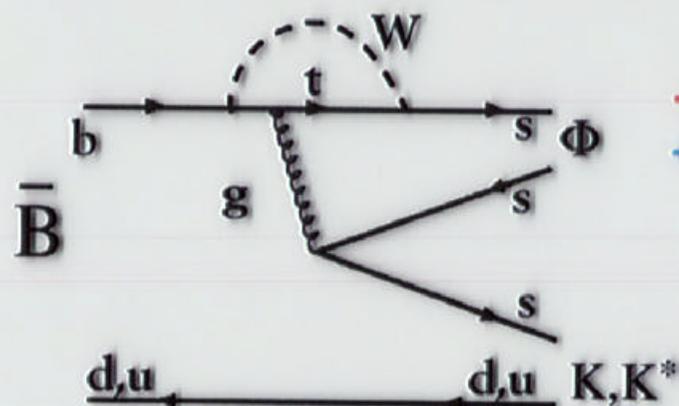
- Sphericity angle (signal isotropic)
- R_2 (signal < continuum)
- Energy distribution about Sphericity axis
use nine 10° angular bins



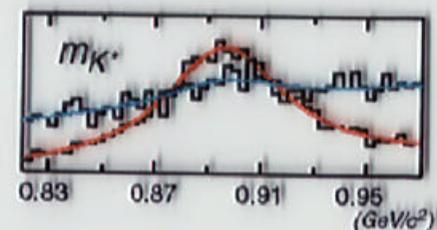
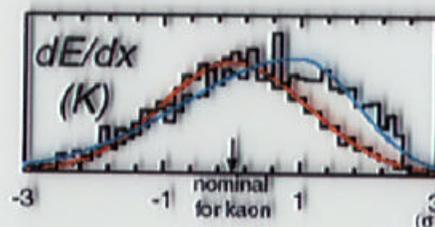
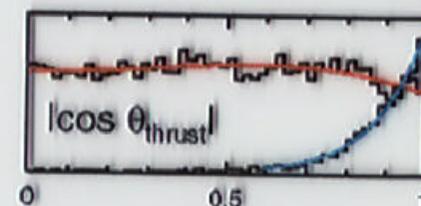
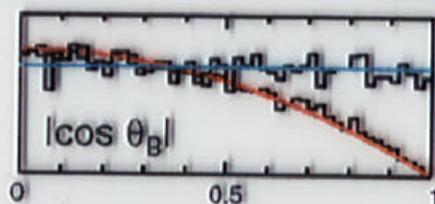
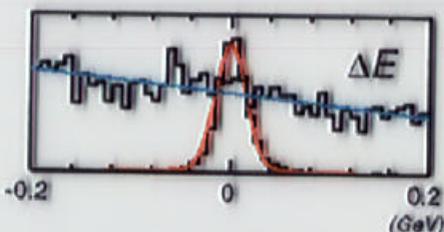
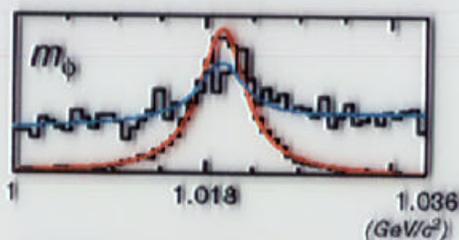
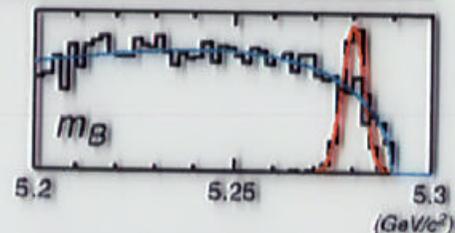
$B \rightarrow \phi K^{(*)}$

Submitted to PRL
hep-ex/0101032

new



PDF shapes for $\phi K^{*0} \rightarrow K^- \pi^+$
 — Signal (MC)
 — Continuum (Off data)



- ◆ Clean signature for gluonic penguin (no $B\bar{B}$ bkg)
- ◆ Maximum likelihood fits for each topology:

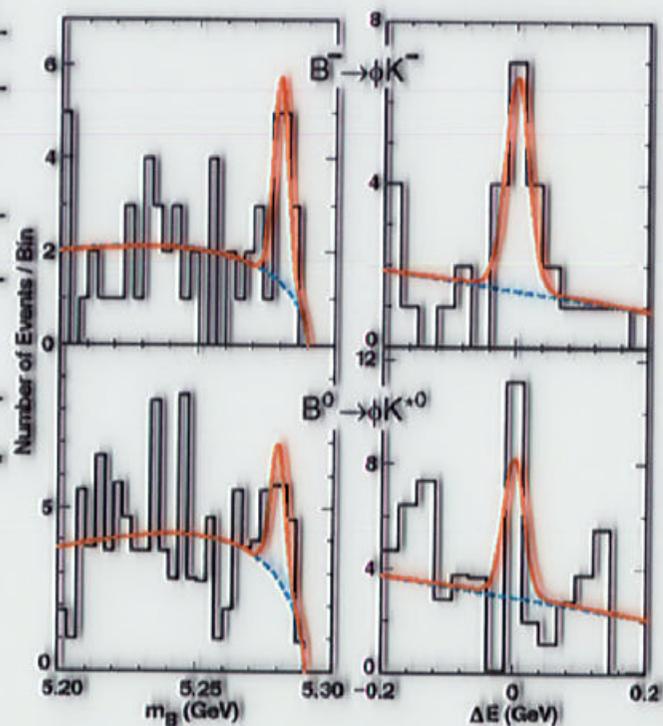
$$\phi K^-, \phi K^0, \phi K^{*0} \rightarrow K^- \pi^+,$$

$$\phi K^{*0} \rightarrow K^0 \pi^0, \phi K^{*-} \rightarrow K^- \pi^0, \phi K^{*-} \rightarrow K^0 \pi^-$$

$B \rightarrow \phi K^{(*)}$ results

	Yield	Reco eff (%)	Stat signif	BF (10^{-6})	Theory BF (10^{-6})
ϕK^-	$14.2^{+5.5}_{-4.5}$	54	5.4σ	$5.5^{+2.1}_{-1.8} \pm 0.6$	0.7 - 16
ϕK^0	$4.2^{+2.9}_{-2.1}$	48	2.9σ	< 12.3	0.7 - 13
$B \rightarrow \phi K$			6.1σ	$5.5^{+1.8}_{-1.5} \pm 0.7$	
$\phi K^{*0} \rightarrow K^- \pi^+$	$12.1^{+5.3}_{-4.3}$	38	4.5σ	↓	
$\phi K^{*0} \rightarrow K^0 \pi^0$	$5.1^{+3.9}_{-2.8}$	20	2.7σ		
$B \rightarrow \phi K^{*0}$			5.1σ	$11.5^{+1.5+1.8}_{-3.7-1.7}$	0.2 - 31
$\phi K^{*-} \rightarrow K^- \pi^0$	$3.8^{+4.1}_{-2.8}$	25	1.5σ	↓	
$\phi K^{*-} \rightarrow K^0 \pi^-$	$4.0^{+2.1}_{-2.2}$	32	2.7σ		
$B \rightarrow \phi K^{*-}$			3.1σ	< 22.5	0.2 - 31
$B \rightarrow \phi K^*$			5.9σ	$11.2^{+3.6+1.8}_{-3.1-1.7}$	

— Data
— Fit Proj Bkg Proj



Belle: $BF(B \rightarrow \phi K) = (17.2^{+6.7}_{-5.4} \pm 1.8) \times 10^{-6}$
(ICHEP2000)

$B \rightarrow K\pi, KK, \pi\pi$ Results

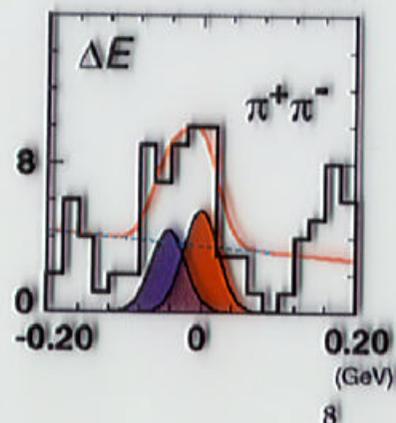
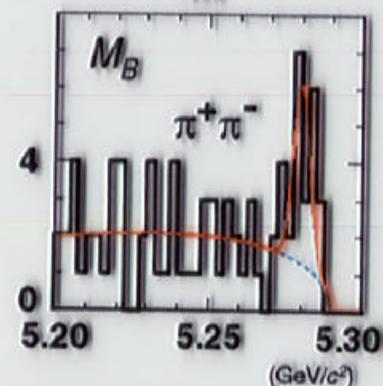
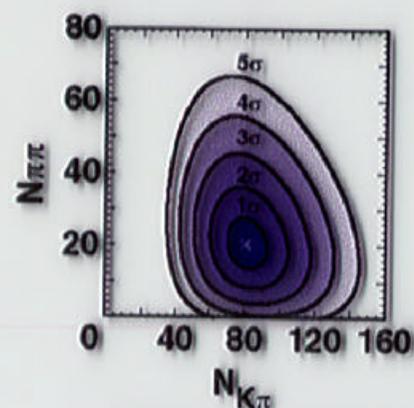
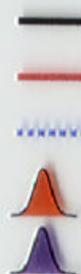
CLEO $K\pi$: PRL 85, 515 (2000)
BaBar/Belle ICHEP2000

Mode	CLEO (9.7M $B\bar{B}$)				Theory BF $\times 10^{-6}$	Belle (ICHEP2000) [5.5M $B\bar{B}$]	BaBar (ICHEP2000) [8.6M $B\bar{B}$]
	N_{Sig}	Signif.	Eff (%)	BF $\times 10^{-6}$		BF $\times 10^{-6}$	BF $\times 10^{-6}$
$\pi^+\pi^-$	$20.0^{+7.6}_{-6.5}$	4.2σ	48	$4.3^{+1.6}_{-1.4} \pm 0.5$	8-26	< 16.5	$9.3^{+2.6+1.2}_{-2.3-1.4}$
$\pi^+\pi^0$	$21.3^{+9.7}_{-8.5}$	3.2σ	39	< 12.7	3-20	< 10.1	
$\pi^0\pi^0$	$6.2^{+4.8}_{-3.7}$	2.0σ	29	< 5.7	0.3-4.6		
$K^+\pi^-$	$80.2^{+11.8}_{-11.0}$	11.7σ	48	$17.2^{+2.5}_{-2.4} \pm 1.2$	7-24	$17.4^{+5.1}_{-4.6} \pm 3.4$	$12.5^{+3.0+1.3}_{-2.6-1.7}$
$K^0\pi^+$	$25.2^{+6.4}_{-5.6}$	7.6σ	14	$18.2^{+1.6}_{-1.0} \pm 1.6$	3-15	< 34	
$K^+\pi^0$	$42.1^{+10.9}_{-9.9}$	6.1σ	38	$11.6^{+3.0+1.4}_{-2.7-1.3}$	8-26	$18.8^{+5.5}_{-4.9} \pm 2.3$	
$K^0\pi^0$	$16.1^{+5.9}_{-5.0}$	4.9σ	11	$14.6^{+5.9+2.4}_{-5.1-3.3}$	3-9	$21.0^{+9.3+2.5}_{-7.8-2.3}$	
K^+K^-	$0.7^{+3.4}_{-0.7}$	0σ	48	< 1.9		< 6	< 6.6
K^+K^0	$1.4^{+2.4}_{-1.3}$	1.1σ	14	< 5.1	0.7-1.5	< 5	$1.9^{+0.6}_{-0.5} \pm 0.2$
$K^0\bar{K}^0$	0	0σ	5	< 17			$2.1^{+0.9}_{-0.8} \pm 0.2$

- ◆ Good agreement with theory
- ◆ Small rate and limit for $\pi\pi$ modes
 - ❖ No strong phase enhancement
 - ❖ Large gluonic penguins

A. Lyon (CLEO) - 2001

Data
Fit Proj
Continuum
 $\pi\pi$ signal
 $K\pi$ bkg



$B \rightarrow \eta' K, \eta K^*$ η', η : PRL 85, 520 (2000) η_c : hep-ex/0007012

◆ Significant modes:

$$\text{BF}(B^\pm \rightarrow \eta' K^\pm) = (8.0_{-0.9}^{+1.0} \pm 0.7) \times 10^{-5}$$

$$\text{BF}(B^0 \rightarrow \eta' K^0) = (8.9_{-1.6}^{+1.8} \pm 0.9) \times 10^{-5}$$

$$\text{BF}(B^\pm \rightarrow \eta' \pi^\pm) < 1.2 \times 10^{-5}$$

$$\text{BF}(B^\pm \rightarrow \eta' K^{*\pm}) < 3.5 \times 10^{-5}$$

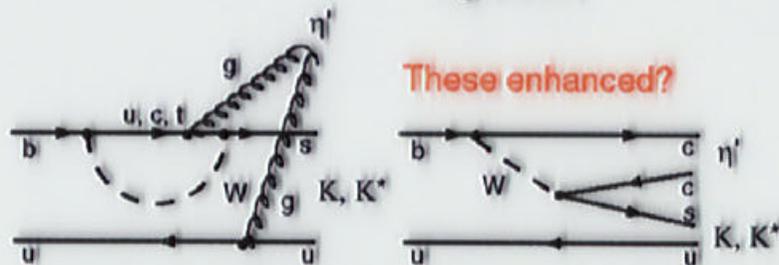
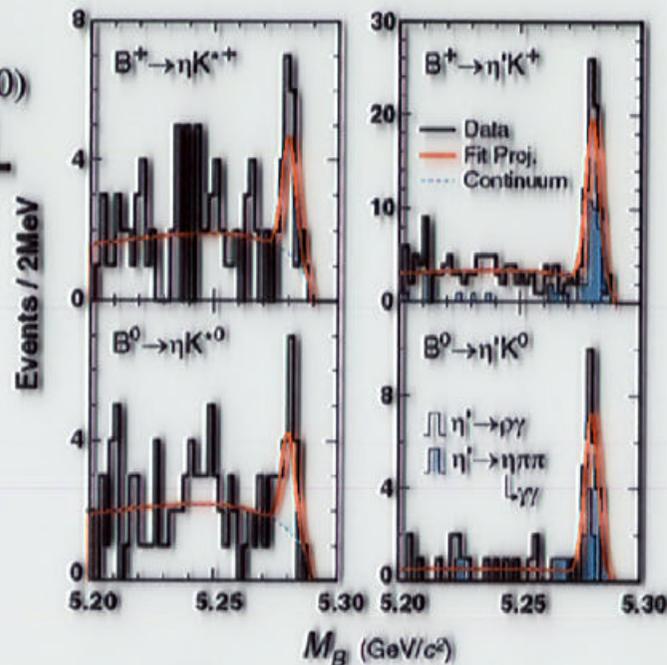
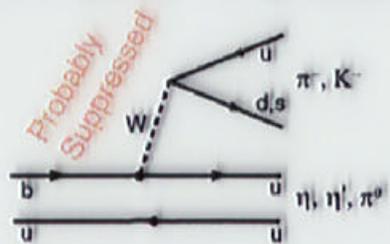
$$\text{BF}(B^\pm \rightarrow \eta K^{*\pm}) = (2.6_{-0.8}^{+1.0} \pm 0.3) \times 10^{-5}$$

$$\text{BF}(B^0 \rightarrow \eta K^*0) = (1.4_{-0.5}^{+0.6} \pm 0.2) \times 10^{-5}$$

$$\text{BF}(B^\pm \rightarrow \eta \pi^\pm) < 0.6 \times 10^{-5}$$

$$\text{BF}(B^\pm \rightarrow \eta K^\pm) < 0.7 \times 10^{-5}$$

◆ $\text{BF}(B \rightarrow \eta') > \text{BF}(B \rightarrow \eta)$ and large!



These enhanced?

But no enhancement in $B \rightarrow \eta_c K$

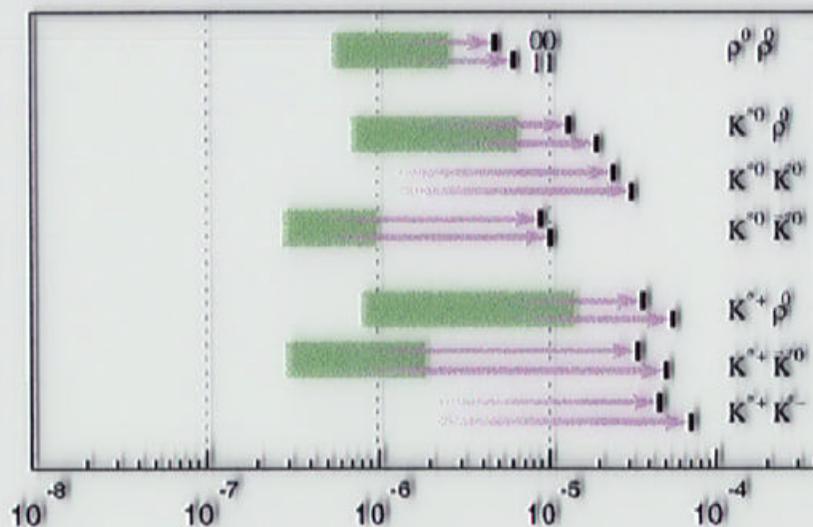
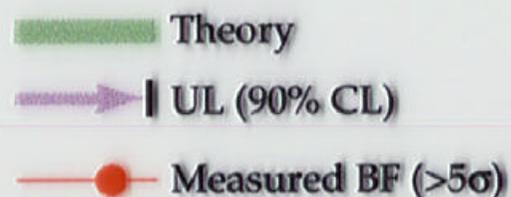
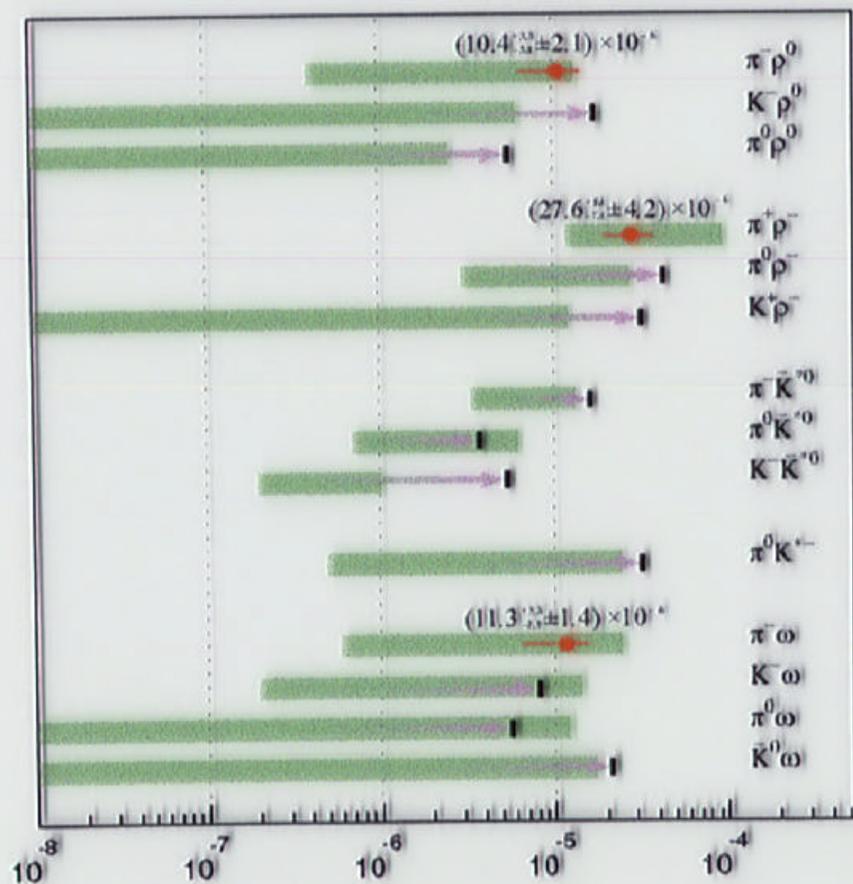
$$\text{BF}(B^\pm \rightarrow \eta_c K^\pm) = (0.7_{-0.2}^{+0.3} \pm 0.1 \pm 0.2) \times 10^{-3}$$

$$\text{BF}(B^0 \rightarrow \eta_c K^0) = (1.1_{-0.4}^{+0.6} \pm 0.1 \pm 0.3) \times 10^{-3}$$

$B \rightarrow PV, B \rightarrow VV$ modes

PV: PRL **85**, 2881 (2000)

VV: Submitted to PRL (hep-ex/0101029)



Direct CP Asymmetry

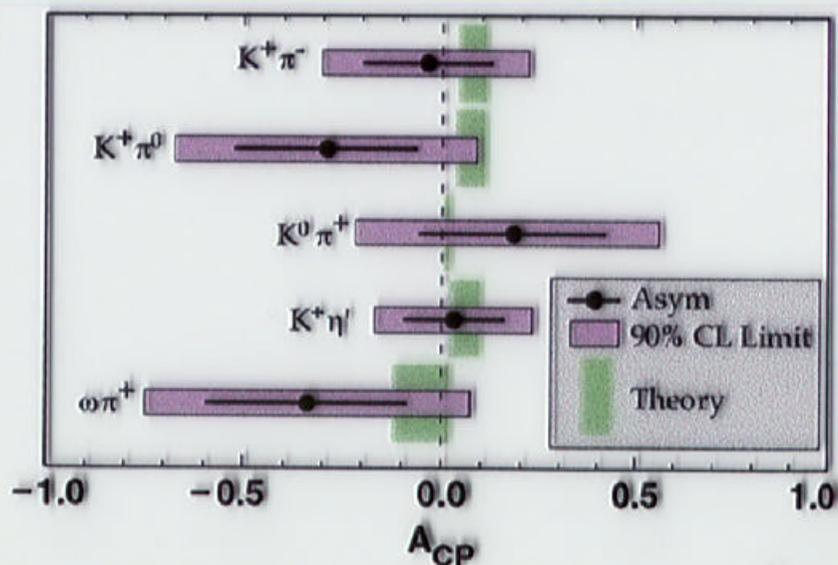
Theory: Ali, Kramer & Lü, PRD 59, 014005 (1999)
 CLEO Results: PRL 85, 525 (2000)

- ◆ A_{CP} comes from two or more amplitudes with different weak and strong phases

$$A_{CP} \equiv \frac{BF(\bar{B} \rightarrow \bar{f}) - BF(B \rightarrow f)}{BF(\bar{B} \rightarrow \bar{f}) + BF(B \rightarrow f)}$$

- ◆ Use self tagging modes (high- p daughter tags B flavor)
- ◆ A_{CP} free parameter in ML fits
- ◆ Factorization: $A_{CP} < 0.1$, but final state interaction or new physics could enhance

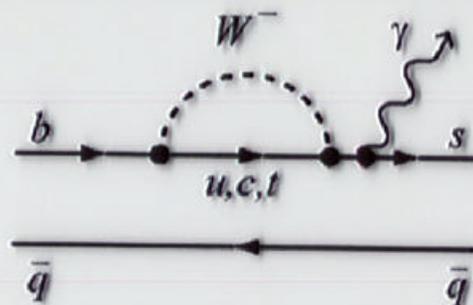
Mode	Yield	A_{CP}
$K^{\pm}\pi^{\mp}$	$80.2^{+11.8}_{-11.0}$	-0.04 ± 0.16
$K^{\pm}\pi^0$	$42.1^{+10.9}_{-9.9}$	-0.29 ± 0.23
$K^0\pi^{\pm}$	$25.2^{+6.4}_{-5.6}$	$+0.18 \pm 0.24$
$K^{\pm}\eta'$	100^{+13}_{-12}	$+0.03 \pm 0.12$
$\omega\pi^{\pm}$	$28.5^{+8.2}_{-7.3}$	-0.34 ± 0.25



Inclusive $b \rightarrow s \gamma$

◆ Electroweak Penguin

- ❖ No FCNC at tree level
- ❖ Provides direct look at loops and boxes
- ❖ Sensitive to $V_{tb} V_{ts}$

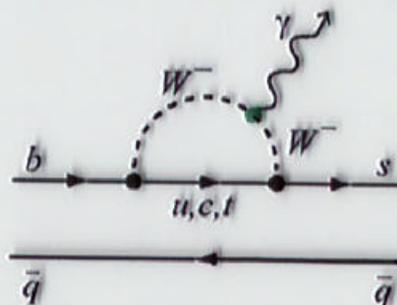
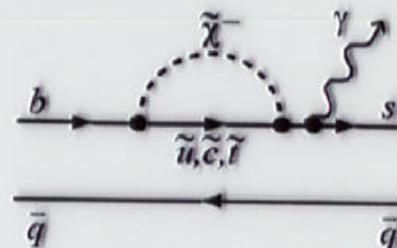


◆ $b \rightarrow s \gamma$

- ❖ SM NLO prediction:
 $\text{BF}(b \rightarrow s \gamma) = (3.28 \pm 0.33) \times 10^{-4}$

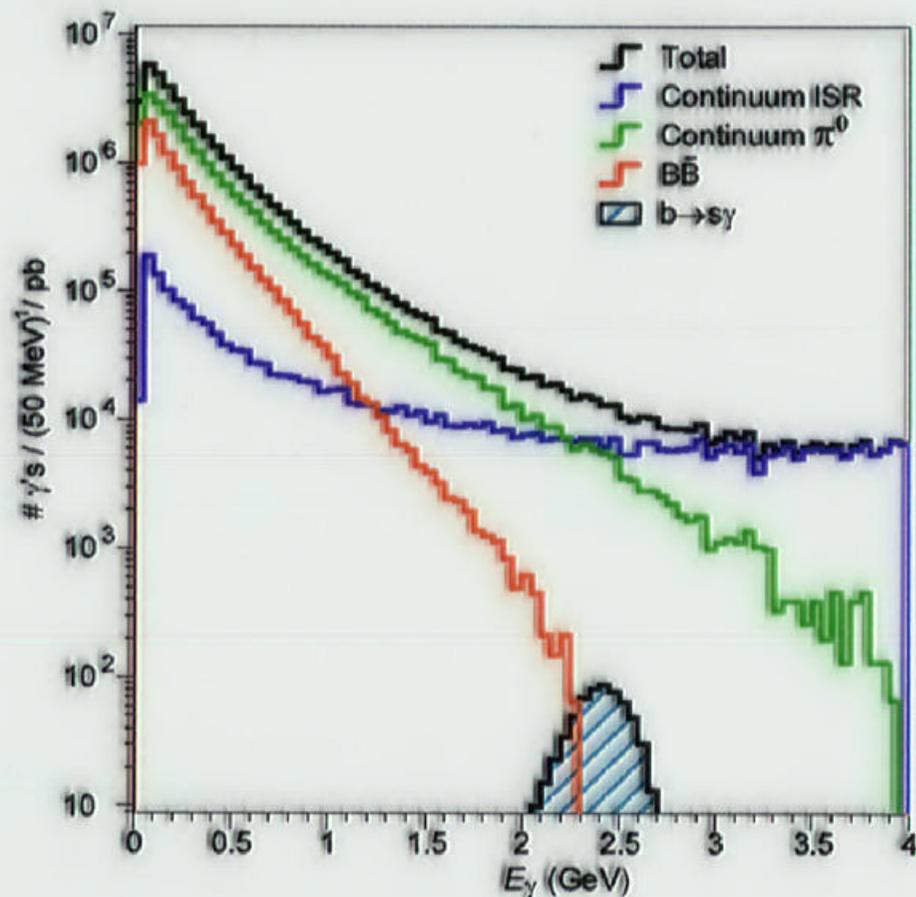
◆ Perhaps there's new physics in the penguin!

- ❖ Charginos
- ❖ Charged Higgs
- ❖ Anomalous $WW\gamma$ couplings



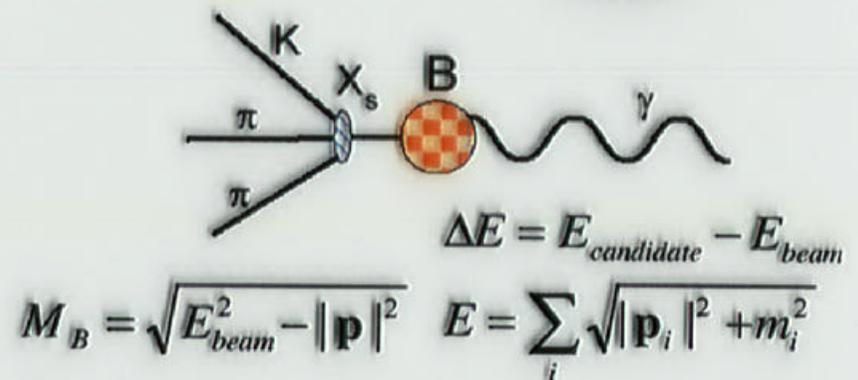
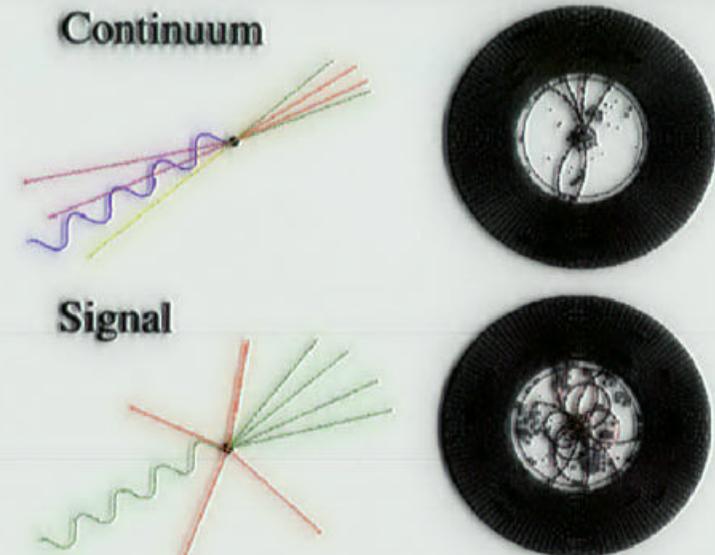
Analysis Strategy

- ◆ Basic idea:
Measure E_γ spectrum
for ON and OFF
resonance and subtract
- ◆ But, must suppress
huge continuum
background!
[veto is not enough]
- ◆ Three attacks:
 - ❖ Shape analysis
 - ❖ Pseudoreconstruction
 - ❖ Leptons



Analysis Details

- ◆ Require $2.0 < E_\gamma < 2.7 \text{ GeV}$
- ◆ Shape Analysis:
 - ❖ Exploit shape differences
 - ❖ Combine shape variables (energy cones, event topology, photon isolation) with Neural Net
- ◆ Pseudoreconstruction:
 - ❖ Loosely find the X_s system
 - ❖ $K + \text{up to } 4\pi$ (at most 1 π^0)
 - ❖ χ^2 to choose best combination
 - ❖ Use NN to combine shape analysis, χ^2 , $\cos \theta_{\text{thrust}}$

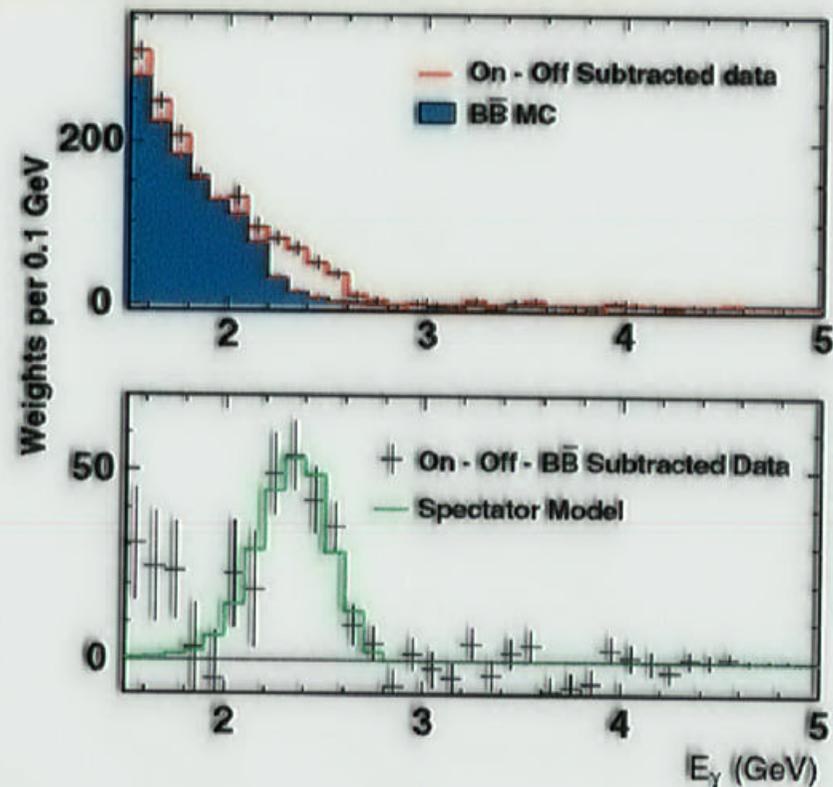


Inclusive $b \rightarrow s \gamma$ Results

Preliminary

$$BF(b \rightarrow s \gamma) = (2.85 \pm 0.35_{\text{stat}} \pm 0.22_{\text{sys}}) \times 10^{-4}$$

- ◆ Cleo II + II.V data
9.1 fb⁻¹ ON, 4.4 fb⁻¹ OFF
- ◆ BF measured for
 $2.0 < E_\gamma < 2.7$ GeV
Factor of 0.94 \rightarrow Full spectrum
- ◆ NLO Prediction:
 $(3.28 \pm 0.33) \times 10^{-4}$
Chetyrkin, Misiak, and Münz
- ◆ Belle (ICHEP2000) measures:
 $(3.34 \pm 0.50^{+0.34}_{-0.37} \text{ } ^{+0.26}_{-0.28}) \times 10^{-4}$



CP Asymmetry in $b \rightarrow s\gamma$?

- ◆ SM says its small! Another window on new physics?

$$b \rightarrow s\gamma = A_{sm} + A_{new} e^{i\theta_s} e^{i\theta_w}$$

$$\bar{b} \rightarrow \bar{s}\gamma = A_{sm} + A_{new} e^{i\theta_s} e^{-i\theta_w}$$

$$BF = |b \rightarrow s\gamma|^2 + |\bar{b} \rightarrow \bar{s}\gamma|^2$$

$$\sim A_{sm}^2 (1 + 2\rho \cos\theta_s \cos\theta_w + \rho^2) \quad \rho = \frac{A_{new}}{A_{sm}}$$

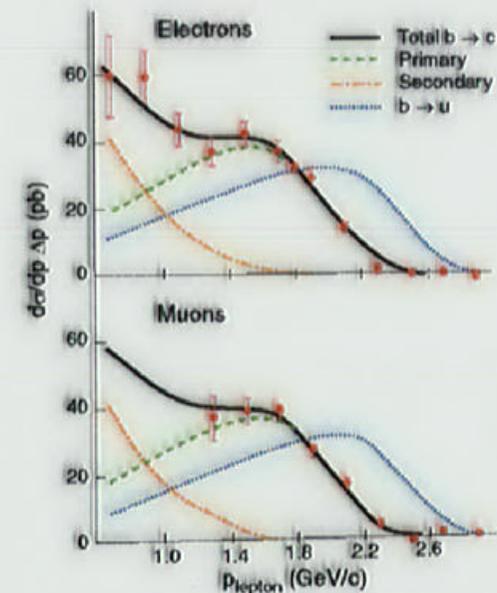
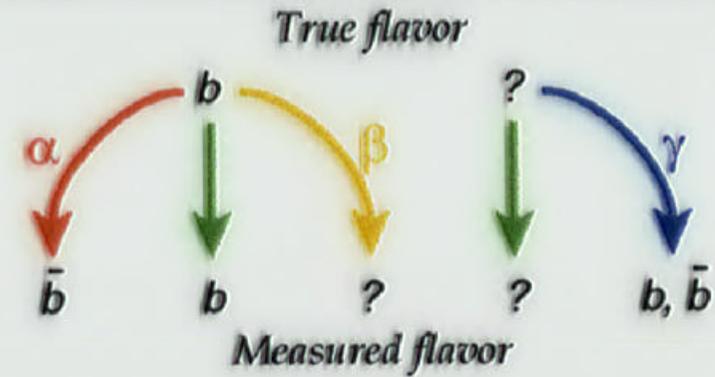
$$A_{CP} = \frac{|b \rightarrow s\gamma|^2 - |\bar{b} \rightarrow \bar{s}\gamma|^2}{|b \rightarrow s\gamma|^2 + |\bar{b} \rightarrow \bar{s}\gamma|^2} \sim 2\rho \sin\theta_s \sin\theta_w$$

New physics could appear in Asymmetry that would not alter branching fraction

- ◆ A. Kagan, M. Neubert PRD 58, 094012 (1998); Aoki, Cho, Oshimo PRD 60, 035004 (1999)

$b \rightarrow s \gamma$ CP Asymmetry (Tagging)

- ◆ Require $2.2 < E_\gamma < 2.7$ GeV
- ◆ Pseudoreconstruction:
 - ❖ Same algorithm as for BF
 - ❖ Aggressive particle ID
 - ❖ If K^0_S and neutral pions, then ambiguous flavor (?)
 - ❖ $\alpha \sim 9\%$, $\beta \sim 1.7\%$, $\gamma \sim 25\%$
- ◆ Lepton Tag:
 - ❖ Tag lepton from the *other* B
 - ❖ $1.4 < P_{lepton} < 2.2$ GeV / c
 - ❖ Recover events not pseudoreconstructed
 - ❖ If event has a lepton, ignore pseudoreconstruction
 - ❖ $\alpha \sim 11\%$ (most from mixing)



$b \rightarrow s \gamma$ A_{CP} Results

- ◆ Data: Full CLEO II + II.V
9.1 fb⁻¹ ON (9.7M BB̄)
4.4 fb⁻¹ OFF Resonance

- ◆ PseudoReco (TOF + dE/dx):

	N	W(b)	W(b-bar)	W(?)
ON	5542	171.2 ± 6.8	174.7 ± 7.0	23.0 ± 2.7
OFF	4878	111.6 ± 6.6	101.5 ± 6.1	11.5 ± 2.0
BB-bar	113	8.7	8.7	1.2
Yield	551	57.0 ± 9.5	64.6 ± 9.2	10.3 ± 3.4

(dE/dx only):

	N	W(b)	W(b-bar)	W(?)
ON	2408	65.5 ± 3.8	72.3 ± 4.3	8.2 ± 1.3
OFF	2114	47.5 ± 4.2	40.7 ± 3.7	5.5 ± 1.4
BB-bar	35	2.9	2.9	0.4
Yield	260	15.0 ± 5.7	28.7 ± 5.6	2.3 ± 2.0

$$A_{CP}^{pseudo} = -0.178 \pm 0.132$$

- ◆ Lepton tag:

	N	W(b)	W(b-bar)
ON	507	127.1 ± 8.9	107.3 ± 7.8
OFF	280	51.7 ± 6.8	48.0 ± 7.0
BB-bar	40	12.8	12.8
Yield	187	62.6 ± 11.1	46.5 ± 10.5

$$A_{CP}^{lepton} = +0.191 \pm 0.181$$

- ◆ Pseudo & Lepton analyses are statistically independent: combine, weighting by expected statistical accuracy

$$A_{CP}^{combined} = -0.079 \pm 0.108$$

$b \rightarrow s \gamma$ Asymmetry Results

Submitted to PRL
hep-ex/0010075

$$A_{CP} = (-0.079 \pm 0.108_{stat} \pm 0.022_{addsys}) * (1.0 \pm 0.03_{multsys})$$

- ◆ Data: Full CLEO II + II.V
9.1 fb⁻¹ ON (9.7M BB)
4.4 fb⁻¹ OFF Resonance
- ◆ 90% CL Limit:
 $-0.27 < A_{CP} < +0.10$
- ◆ Systematics
 - ❖ Multiplicative: Mistake rates; on, off subtraction; ambiguous events, f_{+-}/f_{00}
 - ❖ Additive: Particle detection biases

Lepton	Detection Asymmetry [All ON-OFF Data]
Central electrons	0.0032±0.0029
More forward e	0.0097±0.0077
Muons	-0.0005±0.0021

