Rare Hadronic B decays at BaBar

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On behalf of the BaBar Collaboration

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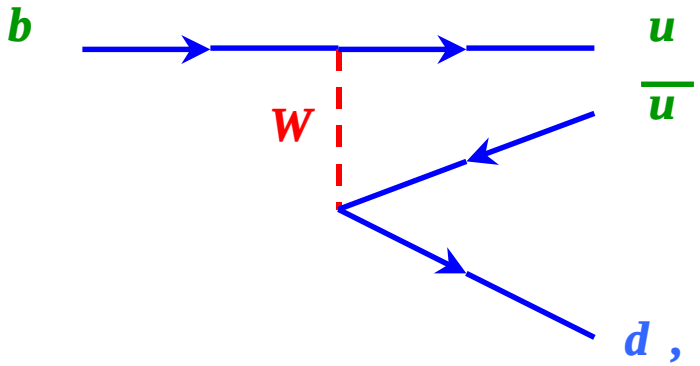
Motivation

- 2 main categories of rare decays:
  - b → u transition

    CKM suppressed:

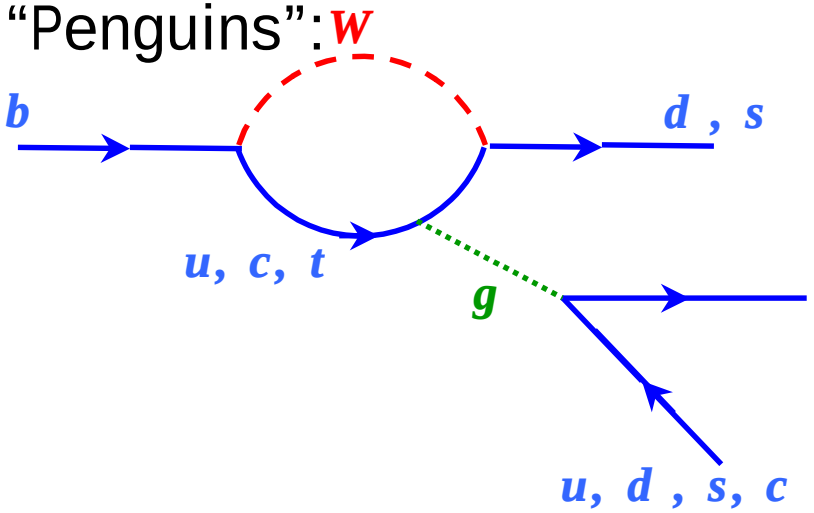
    $|V_{ub}/V_{cb}|$~6 10^{-3}



  - b → s,d

    Induced FCNC and

    "Penguins":



  - **Comparable order of magnitude to Penguin diagrams**
  - **Interferences → Phases, CP violation…**
  - **Massive particles can contribute to the loop: top, Higgs, SUSY …**
  - **Penguins complicate CP measurements**

Data Sample

- Rare Decays (Br ~ 10^{-5})

  $\Rightarrow$ Need high luminosity

Run1: ('99-'00)

20.7 fb^{-1} on-peak

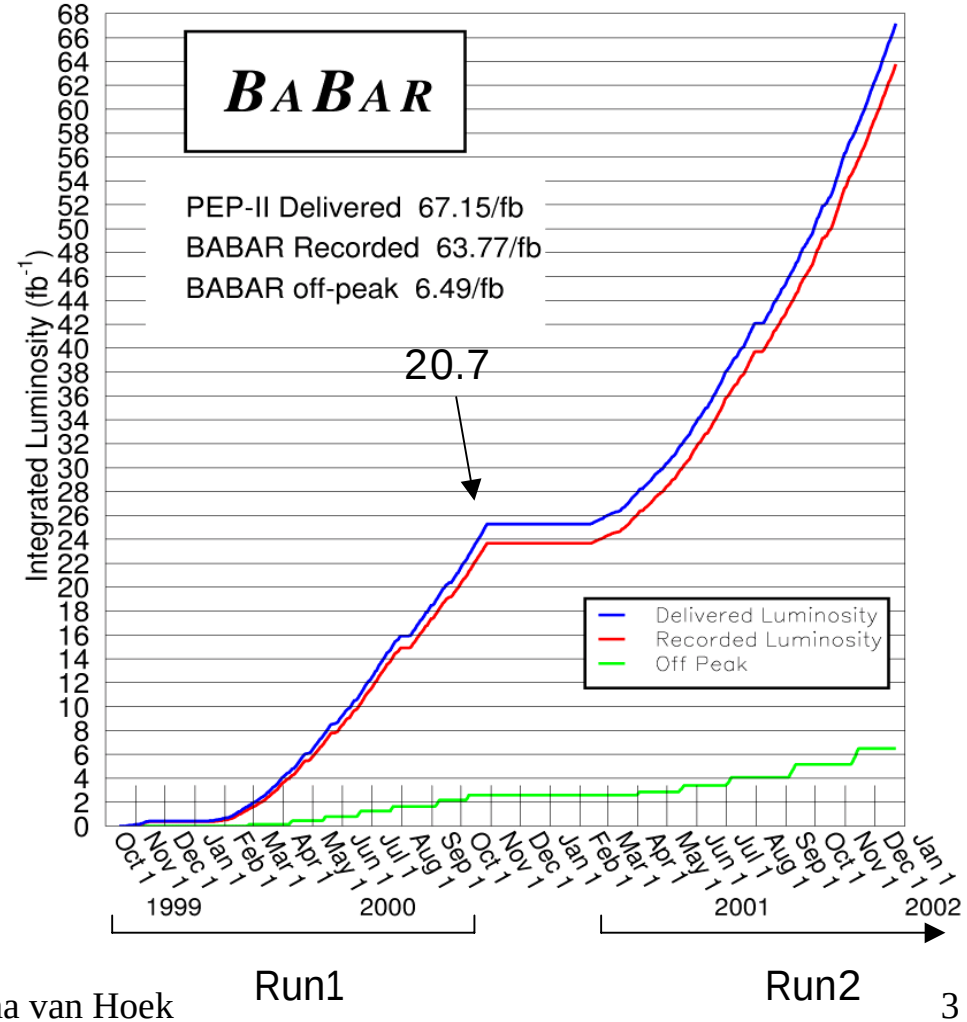
2.6 fb^{-1} off-peak

22.7 x 10^6 B pairs

Run2: ('01-'02)

up to now 40 fb^{-1}

(and counting)

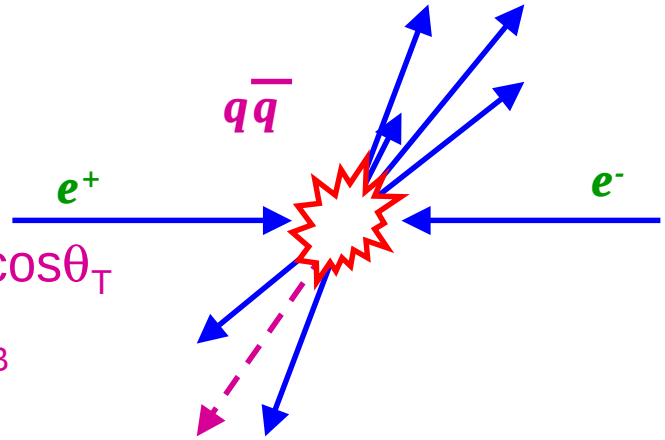


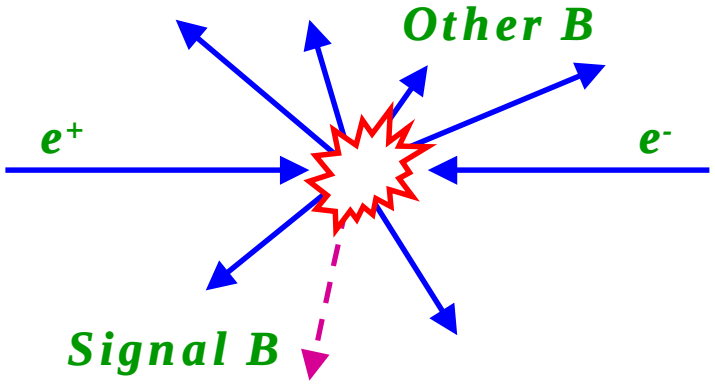
Common Analysis Strategies

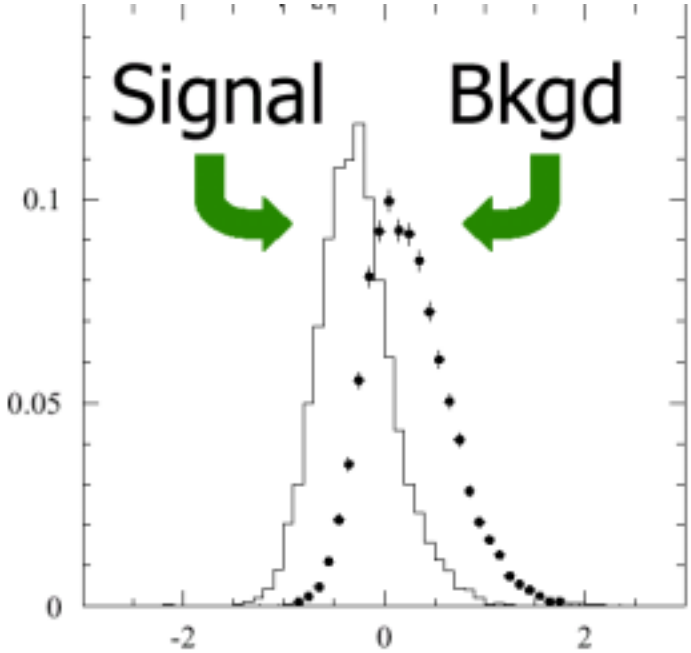
- Continuum background rejection:
  - Event shape
- B candidate selection:
  - ΔE, m_{ES}/m_{EC}
- Further pre-selection:
  - PID, resonance masses
- Signal extraction:
  - Cut and count, ML fit, Neural Net
- All Analyses Blind!

Background Rejection

- Background dominated by continuum qq
- Use event shape variables:
  - Ratio of Fox-Wolfram moments: R_2/R_0
  - Cosine of B thrust axis / rest of event : $\cos\theta_T$
  - Cosine of B decay axis / beam axis : $\cos\theta_B$
  - Energy flow around B thrust axis
  - And many more







- **Combine these variables into a Fisher discriminant or a Neural Net**

B signal variables

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$

B mesons ~ at rest ($p^*_B \simeq 325$ MeV/c)

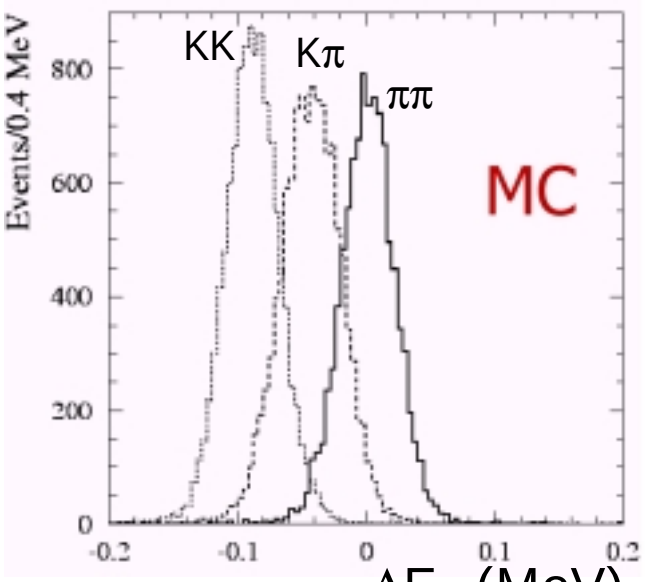
- $q^2_{B1} = q^2_{B2} \Rightarrow \Delta E \equiv E^*_B - E^*_{beam}$ (CMS)
  - Typical: $\sigma(\Delta E) \approx 25-40\,\mathrm{MeV}$

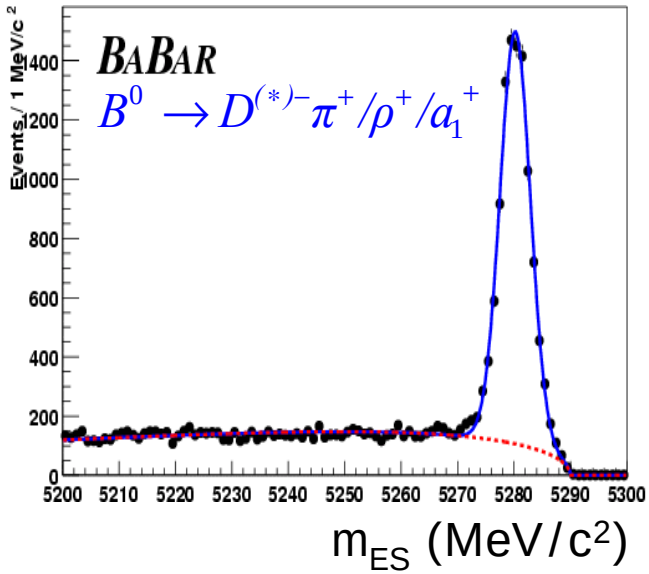
- $q^2_{B1} = m^2_B \Rightarrow$

$$m_{EC} \equiv \sqrt{E^*_B - p^*_B} \quad \text{(kinematic fit)} \quad \text{(CMS)}$$

$$m_{ES} \equiv \sqrt{(\tfrac{1}{2}s + \mathbf{p_0}\cdot\mathbf{p_B})^2 / E^2_0 - p^2_B} \quad \text{(LAB)}$$

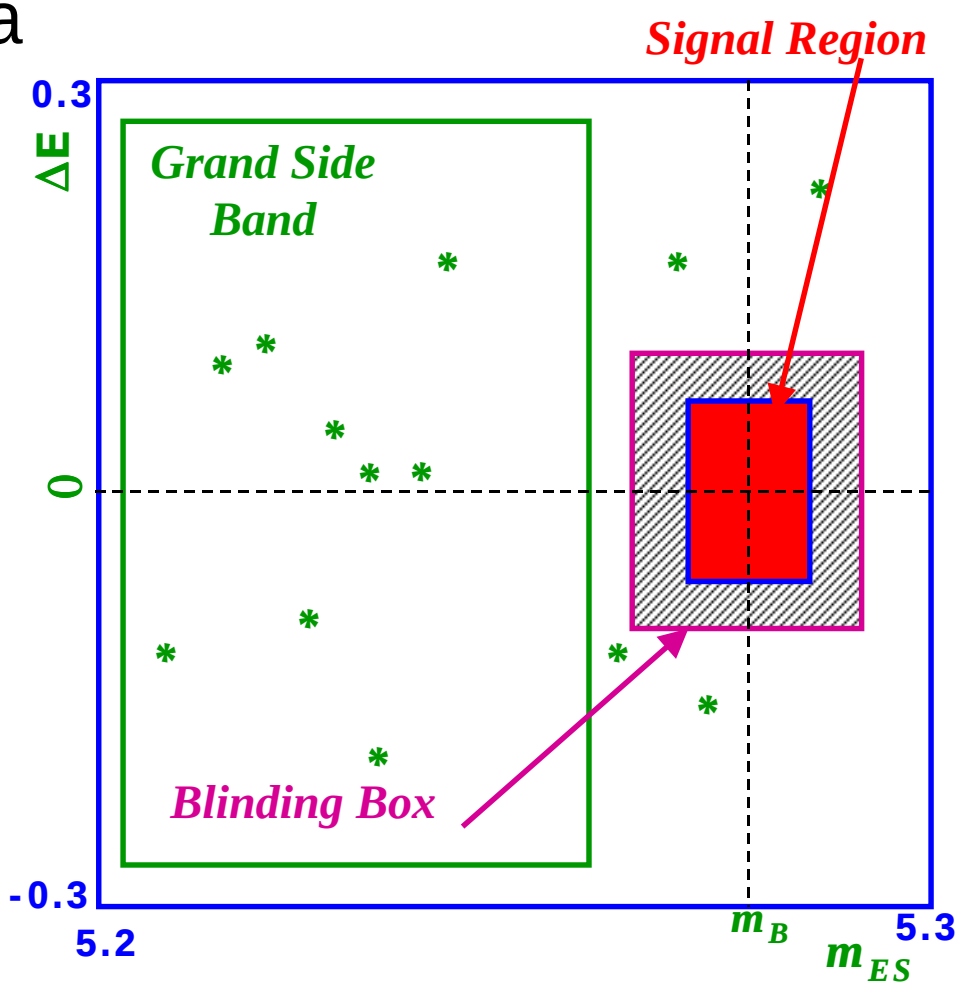
  - Beam energy better known than B energy
  - Typical: $\sigma(m) \approx 2.8$ MeV/c²





Cut & Count

- Cut optimisation
  (signal MC & on-peak data GSB)
- Efficiency determination
  (signal MC)
- Extrapolate bkg GSB → SR: $\#bkg_{SR}$
  (on-peak data GSB)
- Estimate $\#BB_{SR}$
  ($\overline{BB}$ MC)
- Signal:
  $\#SR - \#bkg_{SR} - \#BB_{SR}$



Likelihood fit

$$L = \frac{e^{-(\sum n_j)}}{N!} \prod_{i=1}^{N} L_i$$

$$\text{where } L_i = \sum_{j=1}^{m} n_j P_j(\vec{x}_i)$$

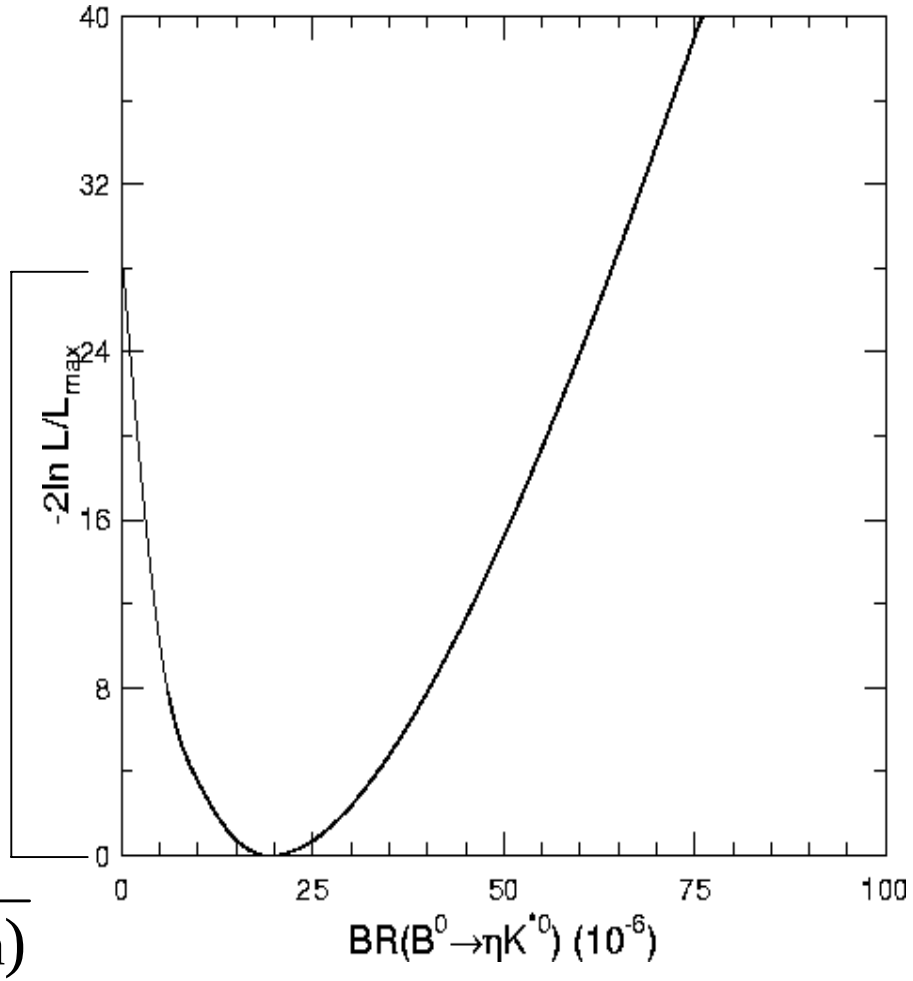
- n_j : population for each species (signal and/or background)
- $P_j(x_i)$: Probability distribution function evaluated with a set of observables x_i (m_{ES}, ΔE, Fisher etc …)

- Statistical error on the # of events:

$$\Delta(\chi^2 \equiv -2 \ln L/L_{max}) = 1$$

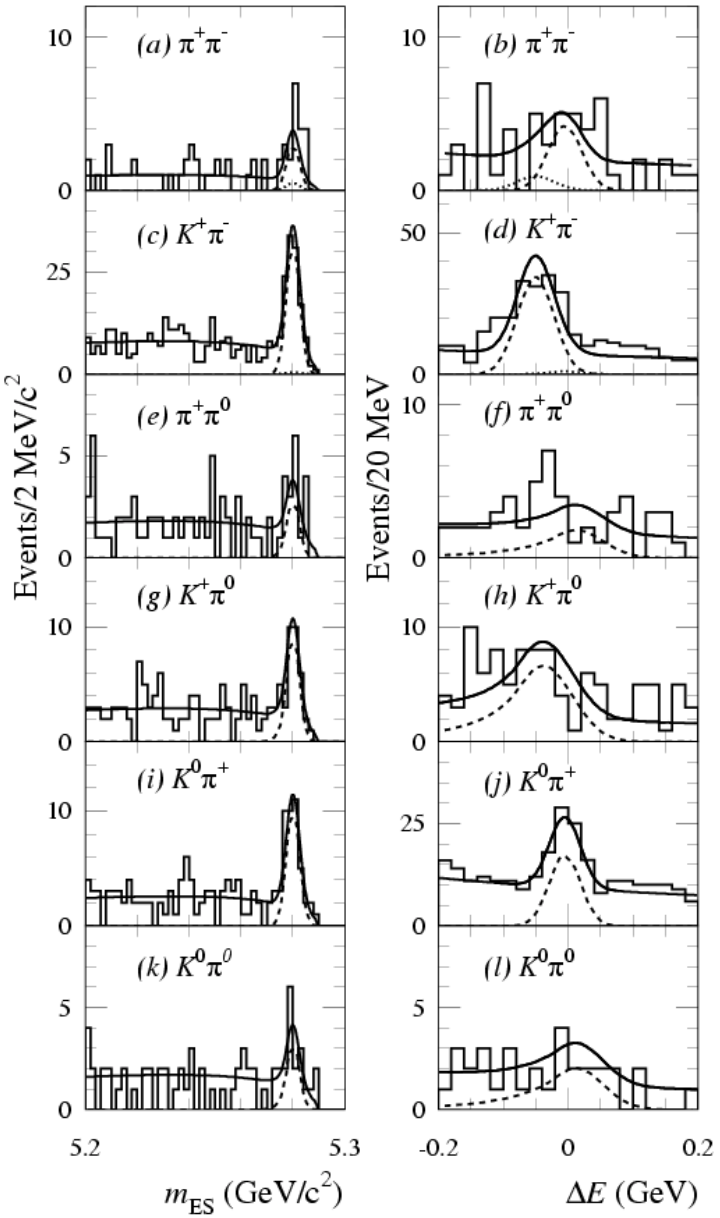
- Statistical significance

$$S = \sqrt{\chi^2(\text{no signal}) - \chi^2(\text{minimum})}$$



$B \to \pi\pi, K\pi, KK$

- Very important modes to constrain CKM angles α and γ
  - Time dependent asymmetry in B^0 ($\overline{B}^0$) $\to \pi^+\pi^-$ measures $\sin(2\alpha_{eff})$
    - In absence of penguins, $\alpha_{eff}=\alpha$
    - Unfortunately, penguins are *not* small
    - $B^+ \to \pi^+\pi^0$: ~Pure Tree
    - $B^+ \to \pi^+K^0$: ~Pure Penguin
    - $Br(B^+ \to \pi^+K^0) > BR(B^+ \to \pi^+\pi^0)$
  - Branching ratios constrain γ
- ML fit with ΔE, m_{ES}, $\mathcal{F}$ and Cherenkov angle
  - And Δt for $\sin(2\alpha_{eff})$



$B \to \pi\pi, K\pi, KK$

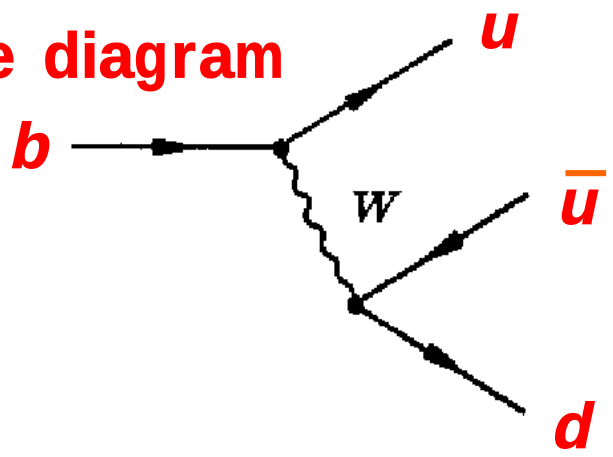
Mode	N_S	S (σ)	$\mathcal{B}$ (10^{-6})
$\pi^+\pi^-$	$41 \pm 10 \pm 7$	4.7	$4.1 \pm 1.0 \pm 0.7$
$K^+\pi^-$	$169 \pm 17 \pm 13$	15.8	$16.7 \pm 1.6 \pm 1.3$
K^+K^-	$8.2^{+7.8}_{-6.4} \pm 3.5$	1.3	<2.5 (90% C.L.)
$\pi^+\pi^0$	$37 \pm 14 \pm 6$	3.4	<9.6 (90% C.L.)
$K^+\pi^0$	$75 \pm 14 \pm 7$	8.0	$10.8^{+2.1}_{-1.9} \pm 1.0$
$K^0\pi^+$	$59^{+11}_{-10} \pm 6$	9.8	$18.2^{+3.3}_{-3.0} \pm 2.0$
$K^0\pi^+$	$-4.1^{+4.5}_{-3.8} \pm 7$	--	<2.4 (90% C.L.)
$K^0\pi^0$	$17.9^{+6.8}_{-5.8} \pm 1.9$	4.5	$8.2^{+3.1}_{-2.7} \pm 1.2$
K^0K^0	$3.4^{3.4}_{2.4} \pm 3.5$	1.5	<7.3 (90% C.L.)

Time dependent $\not{CP}$ in $B^0 \to \pi^+\pi^-$

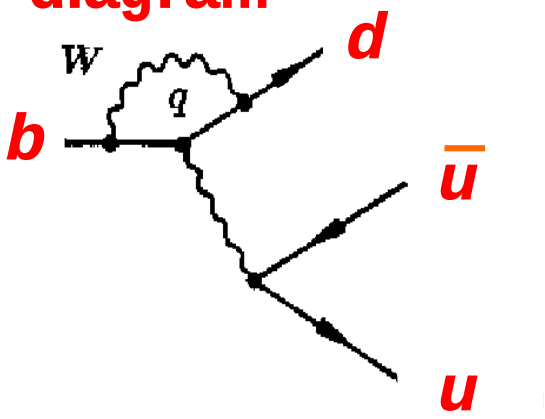
Decay distributions $f_+(f_-)$ when "other" B tagged as $B^0(\bar{B}^0)$

$$f_{\pm}(\Delta t) = \frac{e^{-\Delta t/\tau}}{4\tau}[1 \pm S_{\pi\pi}\sin(\Delta m_d \Delta t) \mp C_{\pi\pi}\cos(\Delta m_d \Delta t)]$$

tree diagram



penguin diagram



Weak phase (only tree diagram)

$$\lambda \equiv \frac{q}{p}\frac{\overline{A}_{\bar{f}}}{A_f} = \eta_f e^{-2i(\beta+\gamma)} = \eta_f e^{2i\alpha}$$

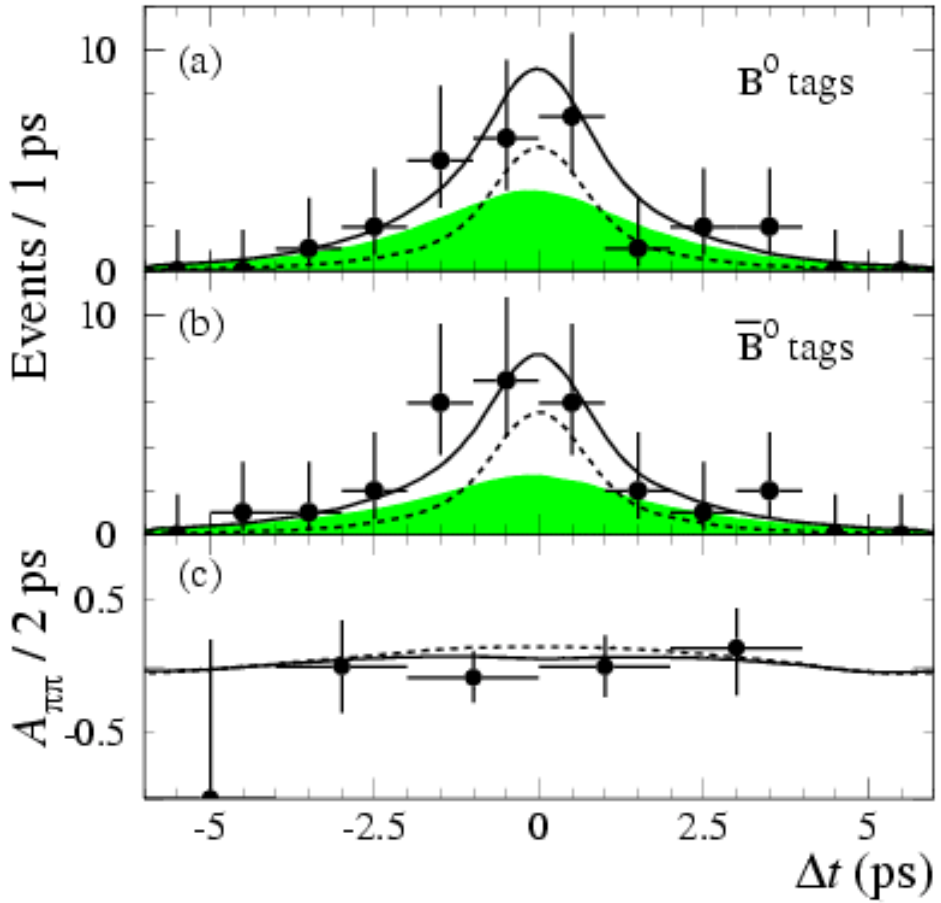
$C_{\pi\pi} = 0,\ S_{\pi\pi} = \sin 2\alpha$

Additional phase from penguin diagram

$|\lambda| \neq 1 \Rightarrow$ **must fit for direct CP**
Im $(\lambda) \neq \sin 2\alpha \Rightarrow$ need to relate asymmetry to α

$C_{\pi\pi} \neq 0,\ S_{\pi\pi} = \sin 2\alpha_{eff}$

$B^0 \to \pi^+\pi^-$ asymmetry result



To appear in PRD Rapid Communications

$$S(\pi^+\pi^-) = 0.03^{+0.53}_{-0.56} \pm 0.11$$

$$C(\pi^+\pi^-) = -0.25^{+0.45}_{-0.47} \pm 0.14$$

$$A_{CP}(K^{\pm}\pi^{\mp}) = -0.07 \pm 0.08 \pm 0.02$$

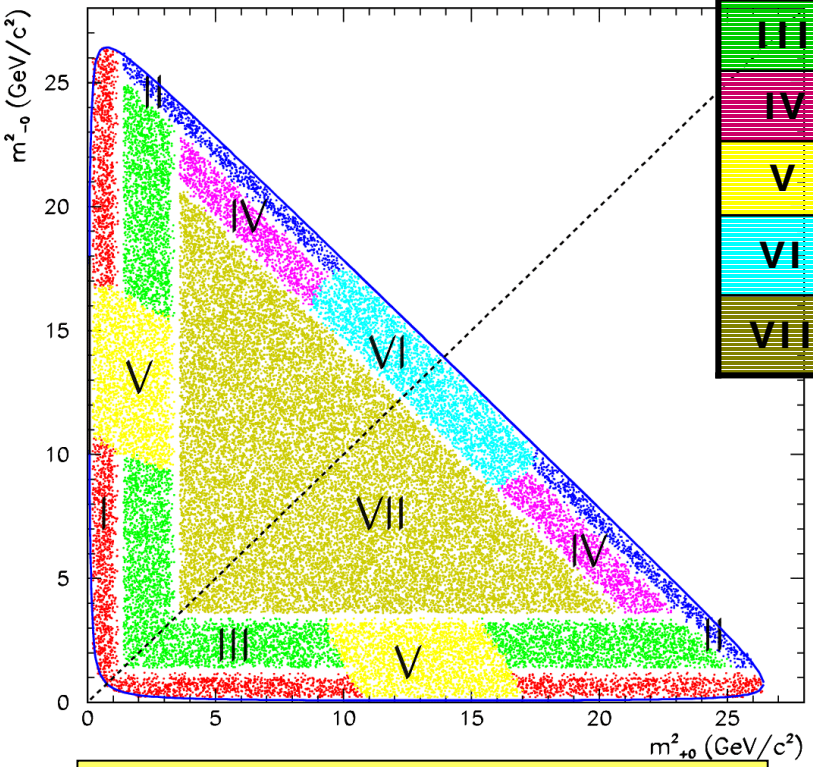
- Measurement compatible with no ~~CP~~ in $B^0 \to \pi^+\pi^-$
- Statistically limited due to small branching fraction
- Need ~500 fb^{-1} for $\sigma(S_{\pi\pi})$ ~ 0.10-0.15

$B^0 \to \pi^+\pi^-\pi^0$

- Important for determination of α:

-Enough info to disentangle penguins

zone	[putative dominant resonance]	ε (%)	yields
I	$\rho^{\pm}(770)\pi^{\mp}$	13.5 ±1.6	89 ±16 ±6
II	$\rho^0(770)\pi^0$	7.4 ±0.9	6.1 ±5.8 ±2.8
III	$\rho^{\pm}(1450)\pi^{\mp}$	15.0 ±2.1	17.4 ±9.7 ±6.9
IV	$\rho^0(1450)\pi^0$	8.7 ±1.8	-4.7 ±3.6 ±2.2
V	(charged scalar)$\pi^{\pm}$	15.0 ±2.3	8.6 ±7.3 ±2.3
VI	$f^0(400\text{-}1200)\pi^0$	6.7 ±1.4	-0.3 ±3.2 ±3.2
VII	$\pi^+\pi^-\pi^0$ (NR)	7.5 ±1.0	-4.2 ±7.3 ±3.8



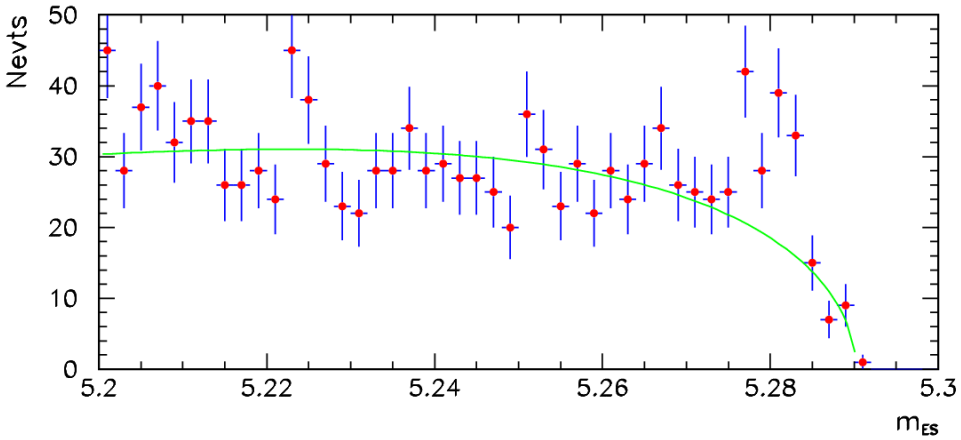
$m^2(\pi^-\pi^0)$ vs $m^2(\pi^+\pi^0)$

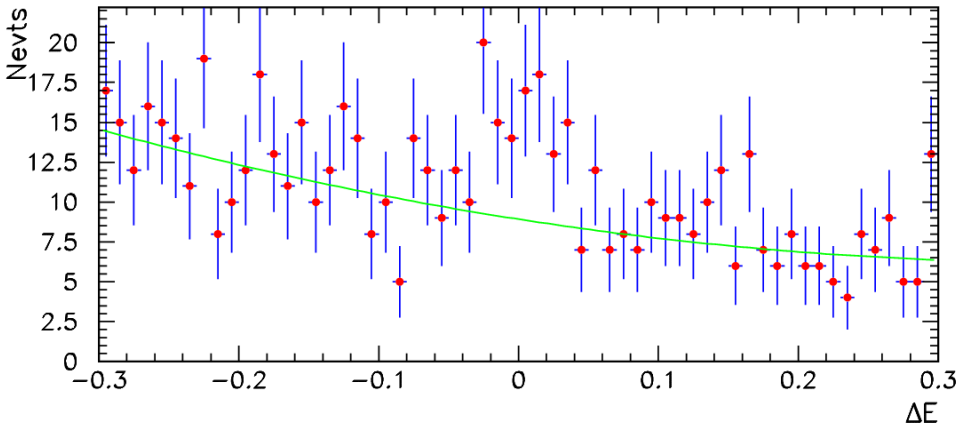
Significant signal observed!

Cuts optimized for each Dalitz region separately

$B^0 \to \rho\pi$

$$Br(B^0 \to \rho^{\pm}(770)\pi^{\mp}) = (28.9 \pm 5.4 \pm 4.3) \times 10^{-6}$$
$$Br(B^0 \to \rho^{0}(770)\pi^{0}) < 10.6 \times 10^{-6}$$
$$Br(B^0 \to \pi^{+}\pi^{-}\pi^{0}(NR)) < 7.3 \times 10^{-6}$$



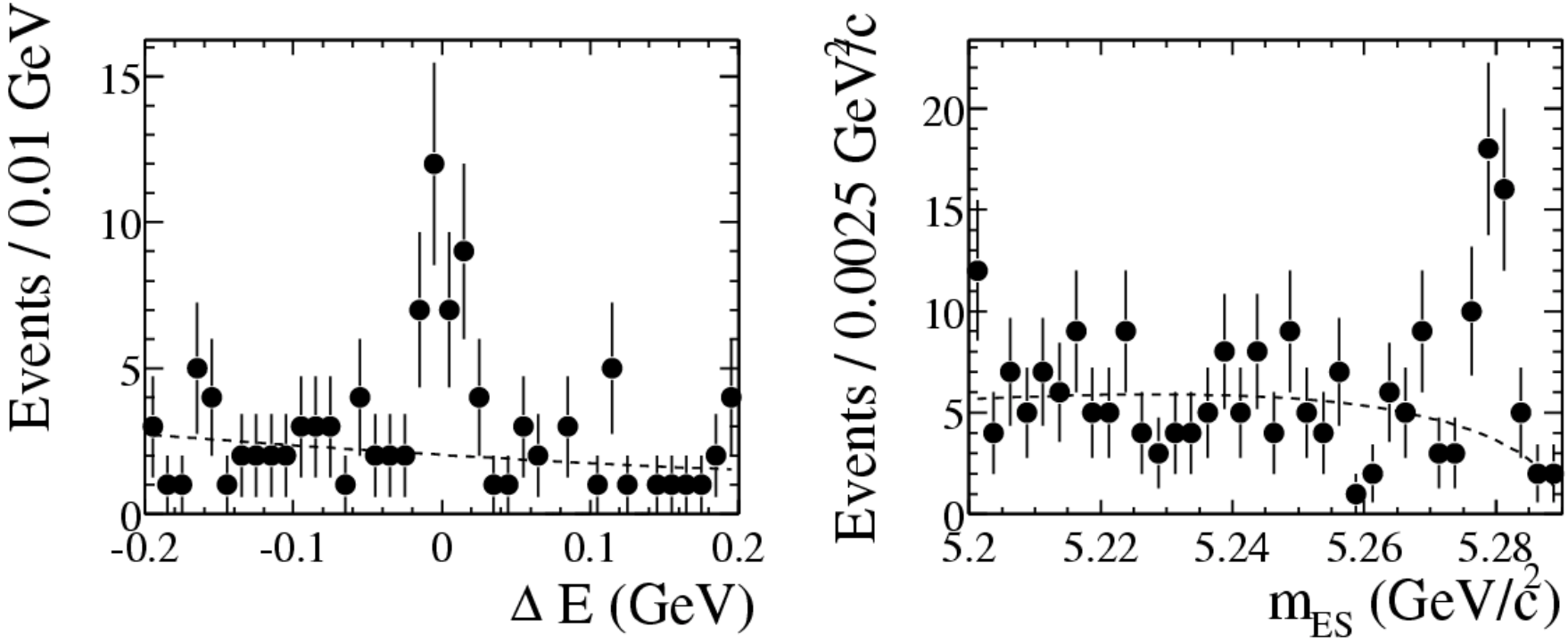


No evidence for direct CP violation:

$$A_{\rho\pi} = \frac{\Gamma(\rho^{+}\pi^{-}) - \Gamma(\rho^{-}\pi^{+})}{\Gamma(\rho^{+}\pi^{-}) + \Gamma(\rho^{-}\pi^{+})}$$
$$= -0.04 \pm 0.18 \pm 0.02$$

$B \rightarrow K^{*0}\pi^{+}$

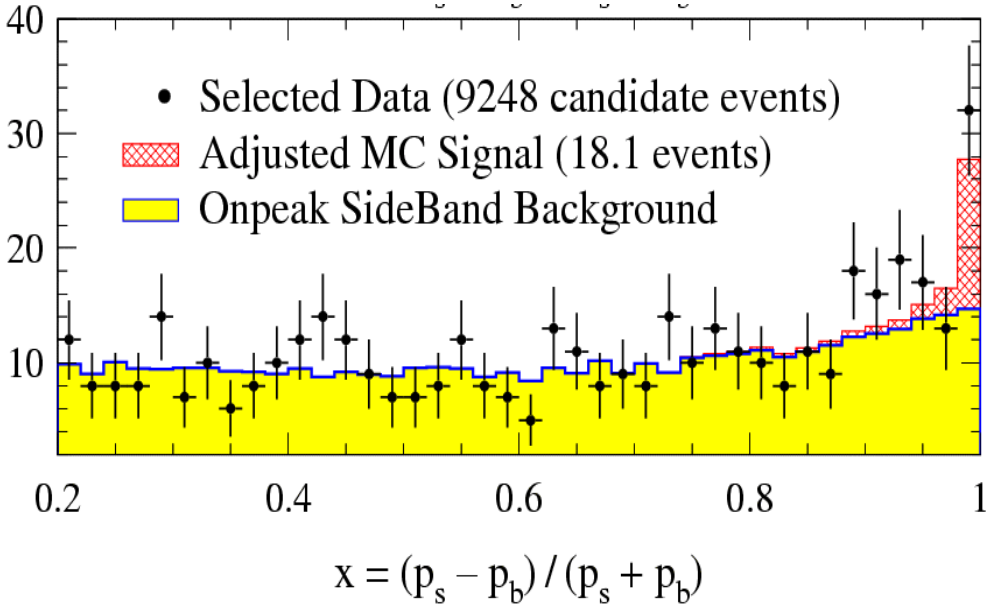
- Similar to $\rho\pi$
- Cut based analysis
- $K^{*0} \rightarrow K^{+}\pi^{-}$

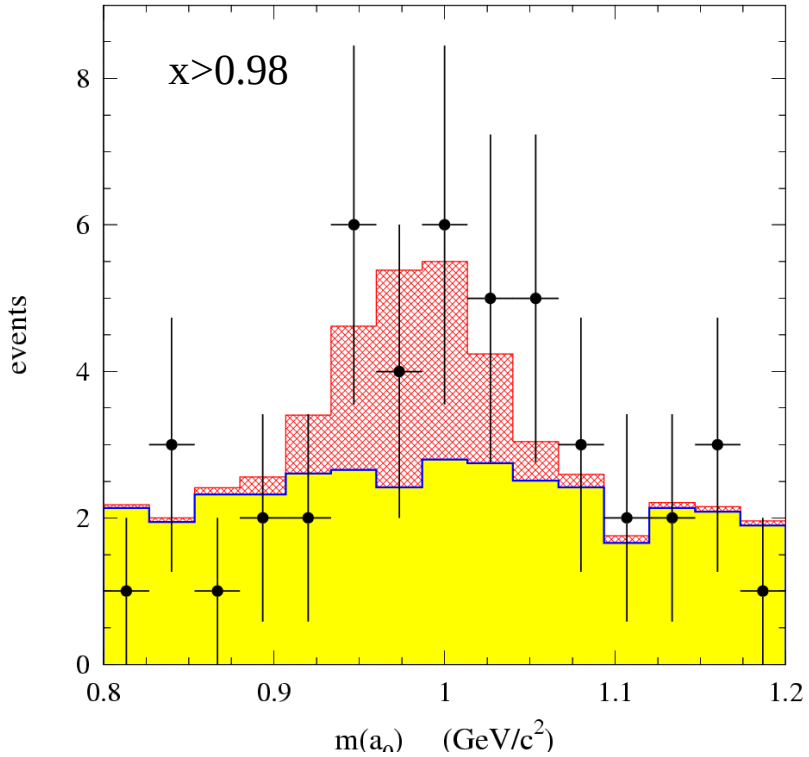


$Br(B^{+} \rightarrow K^{*0}\pi^{+}) = (15.5 \pm 3.4 \pm 1.5) \times 10^{-6}$ (5.3 σ significance)

$B^0 \rightarrow a_0^{\pm}(\eta(\gamma\gamma)\pi^{\pm})\pi^{\mp}$

- Goal: measure α
- Assumption: factorization
  - Main tree vanish (second class currents forbidden)
  - Possible enhancement direct CP violation





ML fit with NN, m(γγ), m_{EC},ΔE

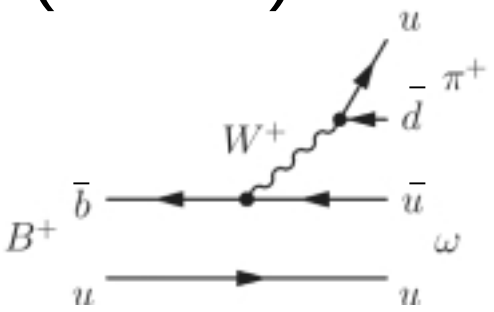
$$Br(B^0 \rightarrow a_0^{\pm}(\eta\pi^{\pm})\pi^{\mp})$$

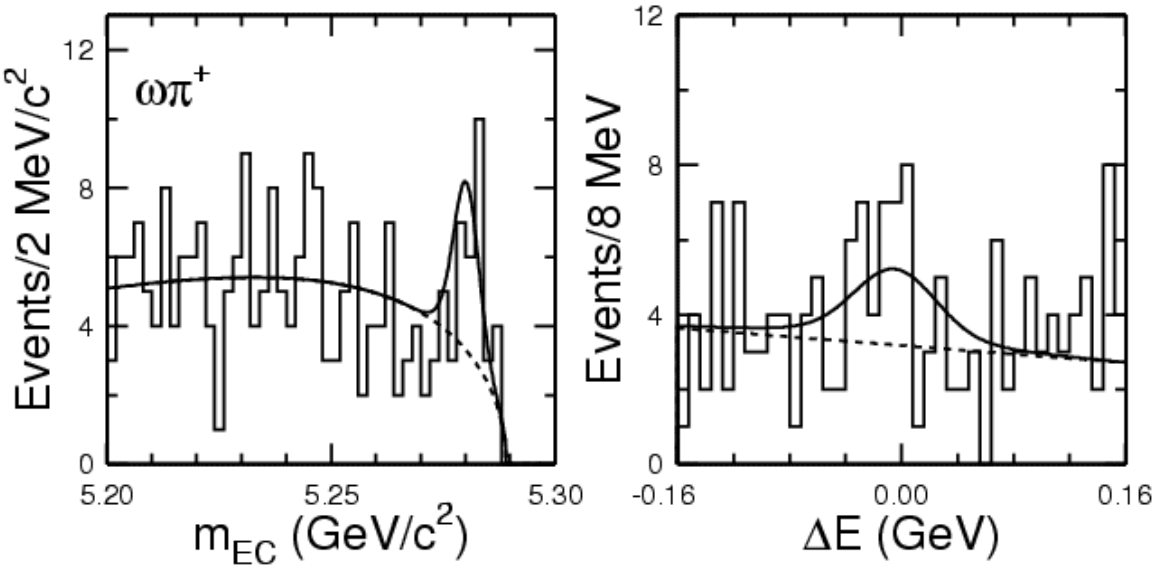
$$= (6.2^{+3.0}_{-2.5} \pm 1.1) \times 10^{-6} \quad (S(\sigma)=3.7)$$

$$< 11.5 \times 10^{-6} (90\% CL)$$

B→ωh

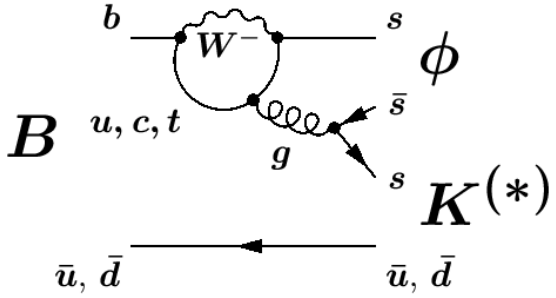
- Tree dominates
  (b → u)



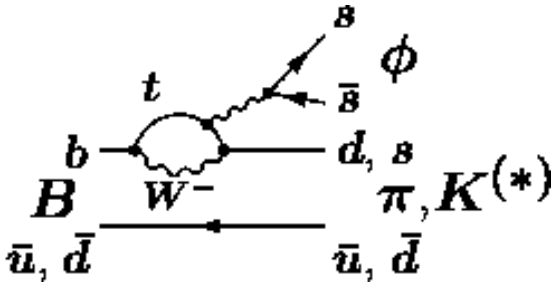


Mode	N_{Signal}	S (σ)	$\mathcal{B}$ (10^{-6}) (90%CL)
ωK^+	$6.4^{+5.6}_{-4.4}$	1.3	$1.4^{+1.3}_{-1.0}\pm0.3$ (<4)
ωK^0	$8.1^{+4.6}_{-3.6}$	3.2	$6.4^{+3.6}_{-2.8}\pm0.8$ (<13)
$\omega\pi^+$	$27.6^{+8.8}_{-7.7}$	4.9	$6.6^{+2.1}_{-1.8}\pm0.7$ ← clear signal
$\omega\pi^0$	$-0.9^{+.5.0}_{-3.2}$	-	$-0.3\pm1.1\pm0.3$ (<3)

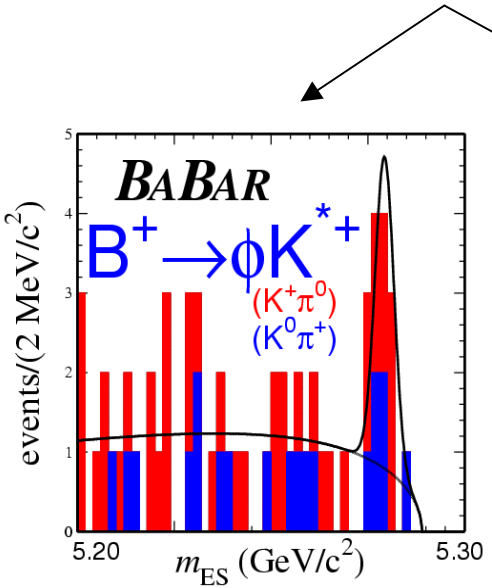
$B \to \phi K^{(*)}$

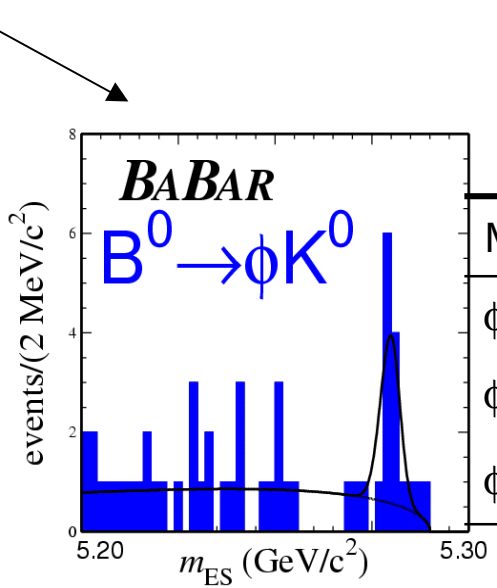


- b → s(d) $s\bar{s}$ (pure) penguins



First observations



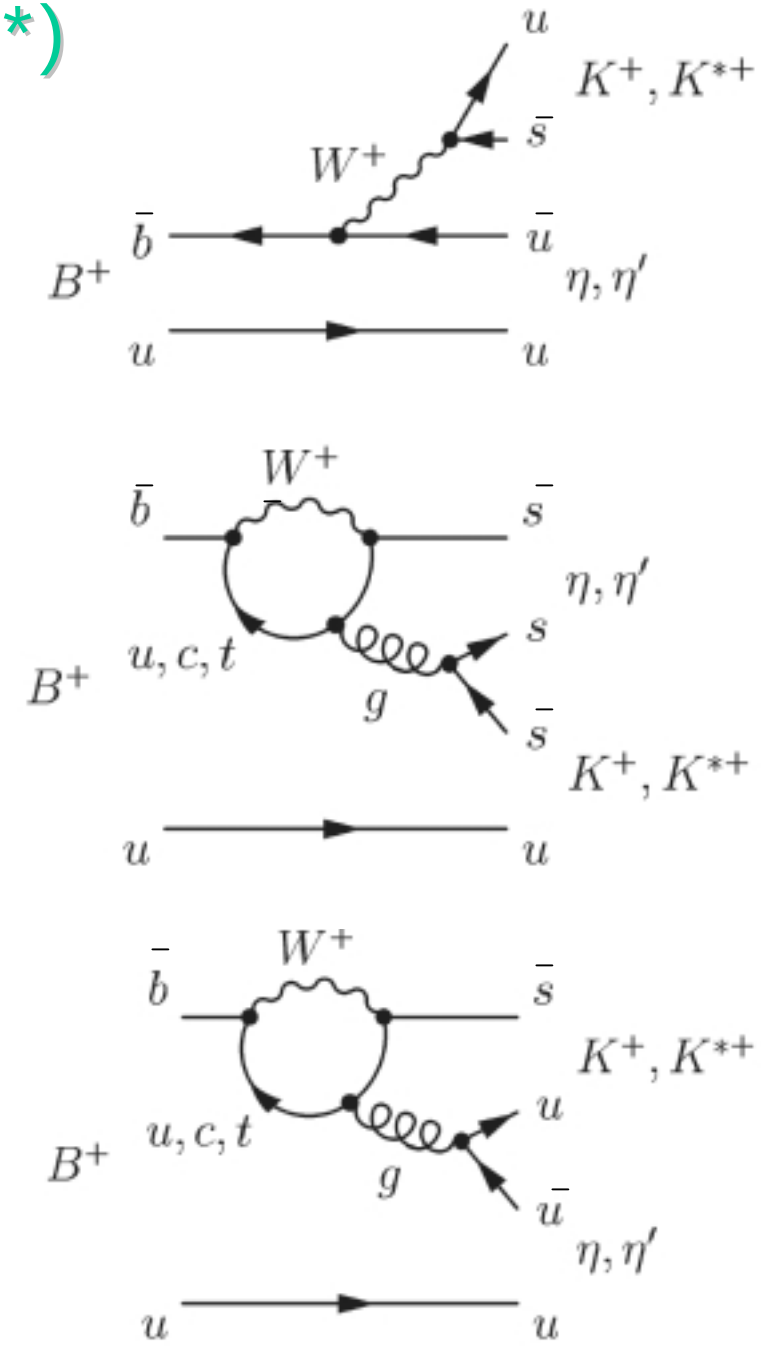


Mode	N_{Signal}	S (σ)	$\mathcal{B}$ (10^{-6})
ϕK^+	$31.4^{+6.7}_{-5.9}$	10.5	$7.7^{+1.6}_{-1.4} \pm 0.8$
ϕK^0	$10.8^{+4.1}_{-3.3}$	6.4	$8.1^{+3.1}_{-2.5} \pm 0.8$
ϕK^{*+}	--	4.5	$9.7^{+4.2}_{-3.4} \pm 1.7$
$\phi K^{*+}{}_{K^+\pi^0}$	$7.1^{+4.3}_{-3.4}$	2.7	$12.8^{+7.7}_{-6.1} \pm 3.2$
$\phi K^{*+}{}_{K^0\pi^+}$	$4.4^{+2.7}_{-2.0}$	3.6	$8.0^{+5.0}_{-3.7} \pm 1.3$
ϕK^{*0}	$20.8^{+5.9}_{-5.1}$	7.5	$8.7^{+2.5}_{-2.1} \pm 1.1$
$\phi\pi^+$	$0.9^{+2.1}_{-0.9}$	0.6	< 1.4 (90% CL)

- ϕK^0 : CP eigenstate ⇒ can measure sin2β

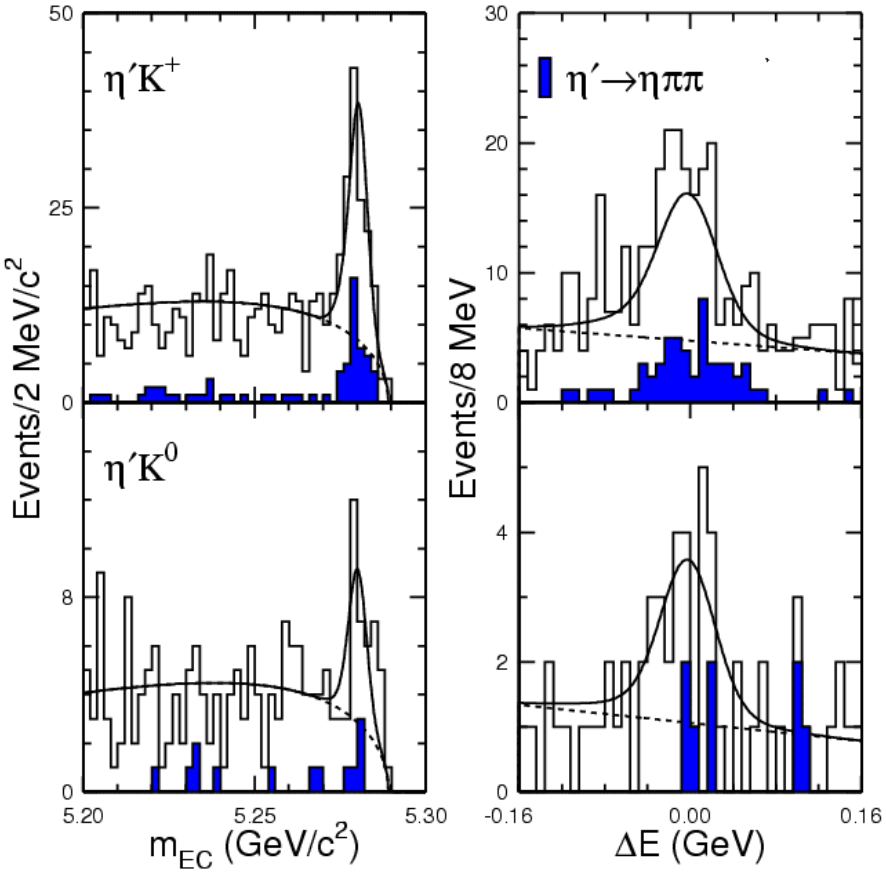
$B \to \eta^{(\prime)} K^{(*)}$

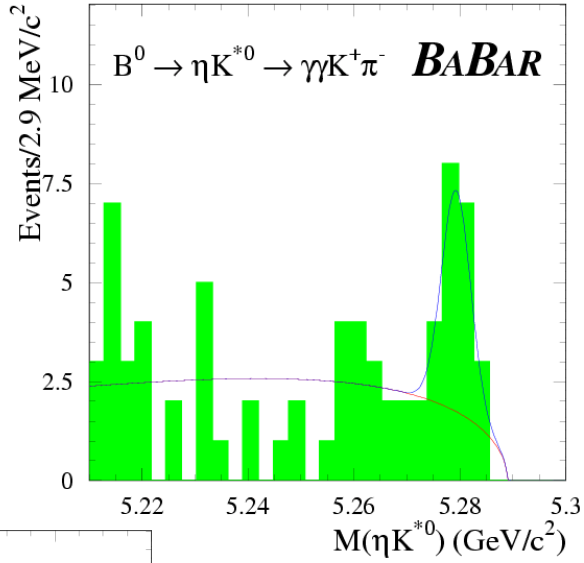
- Tree CKM suppressed
- Interference between Penguins $(g \to u\bar{u}(s\bar{s}))$
  - Enhance $B \to \eta' K$; $B \to \eta K^*$
  - Suppress $B \to \eta K$; $B \to \eta' K^*$

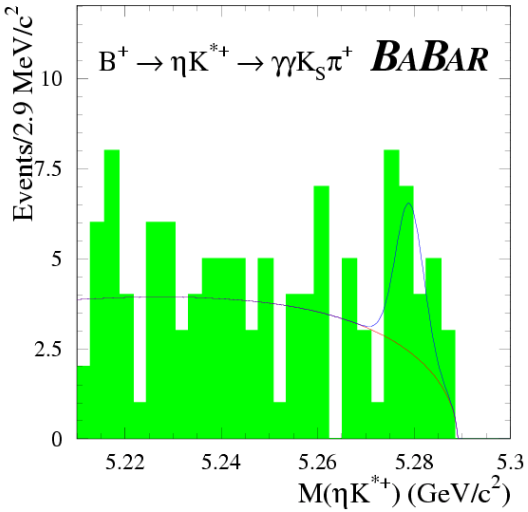


$B \to \eta^{(\prime)} K^{(*)}$

- ML fit with $\Delta E, m_{EC}, \mathcal{F}, m_{res}, (\mathcal{H}$, PID pulls)

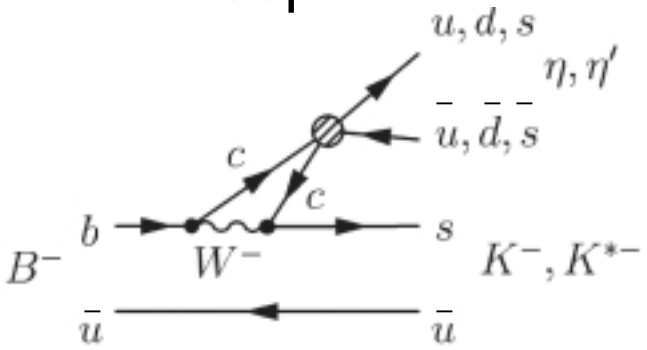






$B \to \eta^{(\prime)} K^{(*)}$

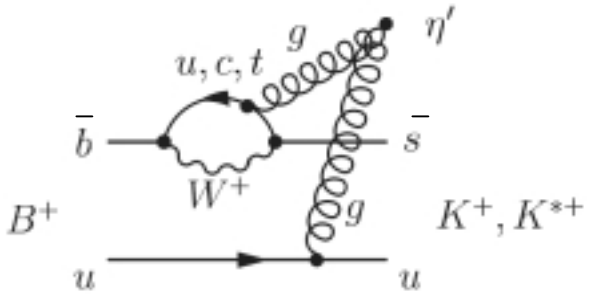
$\eta'K$:
- Confirm Cleo
- Larger than expected!
- Possibly due to
  - QCD anomaly: gluon coupling to η'
  - "Charming Penguins" charm enhanced in loop

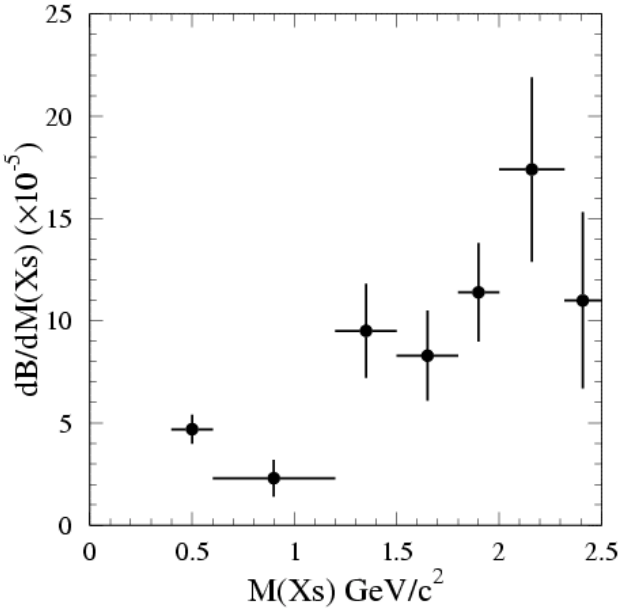


Mode	N_{Signal}	S (σ)	$\mathcal{B}$ (10^{-6}) (90%CL)
ηK^{*0}	20.5 ± 6.0	5.4	$19.8^{+6.5}_{-5.6} \pm 1.7$
ηK^{*+}	14.3 ± 6.6	3.2	$22.1^{+11.1}_{-9.2} \pm 3.3$ (<33.9)
$\eta'_{\eta\pi\pi} K^+$	$49.5^{+8.1}_{-7.3}$	15	63^{+10}_{-95}
$\eta'_{\rho\gamma} K^+$	$87.6^{+13.4}_{-12.5}$	11	80^{+12}_{-11}
$\eta' K^+$		17	$70 \pm 8 \pm 5$
$\eta'_{\eta\pi\pi} K^0$	$6.3^{+3.3}_{-2.5}$	4.7	28^{+15}_{-11}
$\eta'_{\rho\gamma} K^0$	$20.8^{+7.4}_{-6.5}$	4.2	61^{+22}_{-19}
$\eta' K^0$		5.9	$42^{+13}_{-11} \pm 4$
$\eta'_{\eta\pi\pi} \pi^+$	$5.7^{+3.8}_{-2.8}$	3.2	$7.1^{+4.8}_{-3.5}$
$\eta'_{\rho\gamma} \pi^+$	$-0.9^{+7.8}_{-6.2}$	0.1	$-0.7^{+6.7}_{-.5.3}$
$\eta' \pi^+$		2.8	$5.4^{+3.5}_{-2.6} \pm 0.8$ (<12)

Semi-exclusive B→η´X_s

- b →sg measurements → direct CP violation
- High rate first observed in Cleo
  - Interpreted as due to "QCD anomaly"
    - η' coupling to 2 gluons





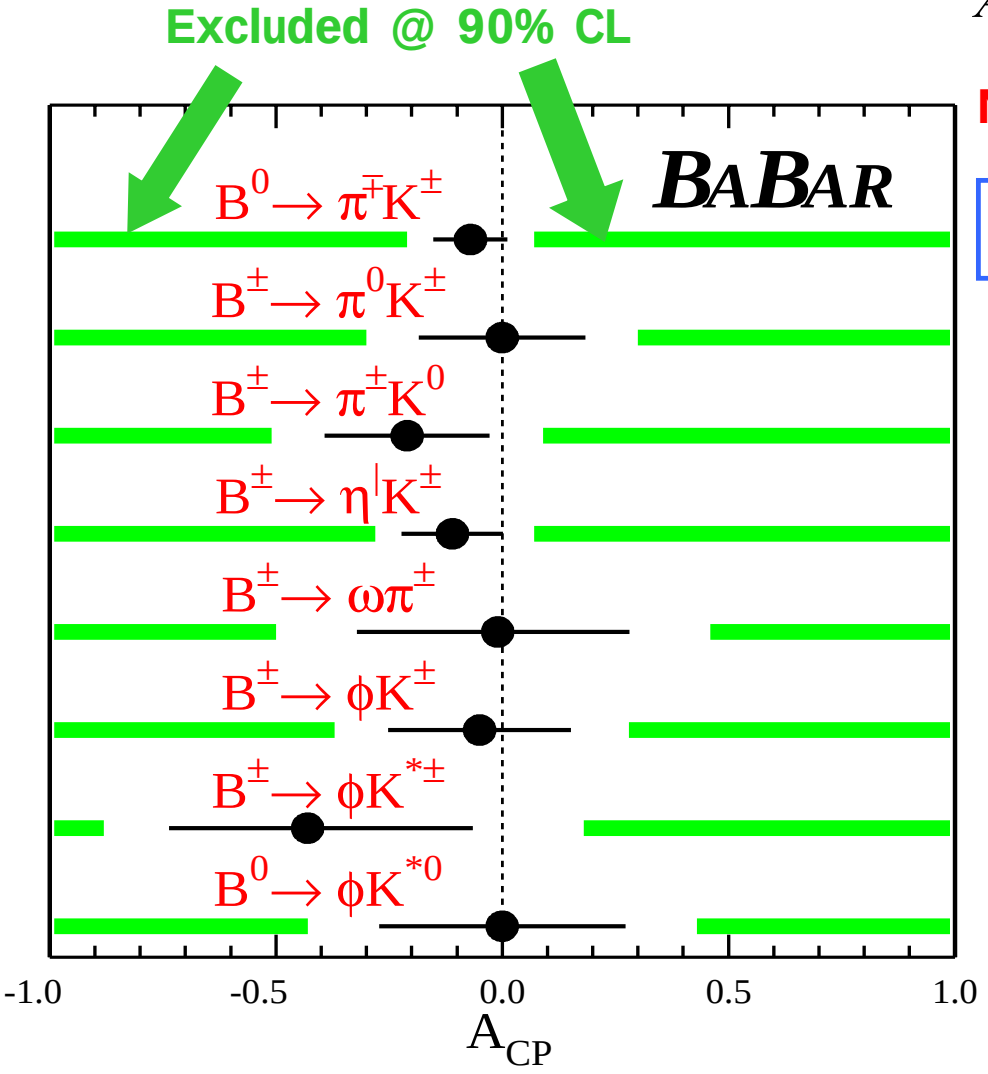
- Select η' with p* > 2 GeV/c to remove most of $b \to c \to \eta'$ bkgd
- Reconstruct X_S in 16 modes: $B \to \eta' K^+ n\pi^\pm(\pi^0)$ with $n = 0 \to 3$

$$B \to \eta' K^0_S n\pi^\pm(\pi^0)$$

$$Br(B \to X_S\eta') = (6.8^{+0.7}_{-1.0} \pm 1.0^{+0.0}_{-0.5}) \times 10^{-4}$$

Account for possible η'$D^{0(*)}$

Summary of direct CP asymmetries



$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

No Evidence for direct CP violation yet

$-0.07 \pm 0.08 \pm 0.02$ **Updated 30.4 fb^{-1}**

$0.00 \pm 0.18 \pm 0.04$

$-0.21 \pm 0.18 \pm 0.03$

$-0.11 \pm 0.11 \pm 0.02$

$-0.01\ ^{+0.29}_{-0.31} \pm 0.03$

$-0.05 \pm 0.20 \pm 0.03$

$-0.43\ ^{+0.36}_{-0.30} \pm 0.06$

$0.00 \pm 0.27 \pm 0.03$

20.7 fb^{-1}

Summary and Outlook

- Large data sample (Run1: ~23 million BB pairs)
  - Sensitive to Br down to few $x10^{-6}$
  - ~30 modes analyzed -- 18 with clear signals
  - No evidence (yet) for direct CP violation (σ down to ~8%)
- Important to understand:
  - Penguin/Tree contributions
  - Factorization hypothesis
  - Constraining (and measuring!) α
  - Measuring β in $B \rightarrow \phi K^0_S$
- Run2: until summer 2002: ~ 100 million BB pairs
  - More rare decays results + higher sensitivity
  - Stay tuned!!!