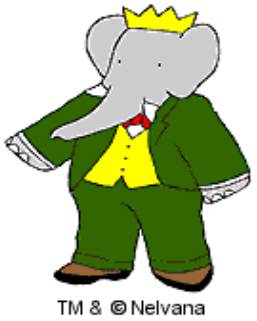
Time-dependent CP Asymmetry in $B^0 \to \pi^0 K_S$ and $B^0 \to \eta' K_S$ decays

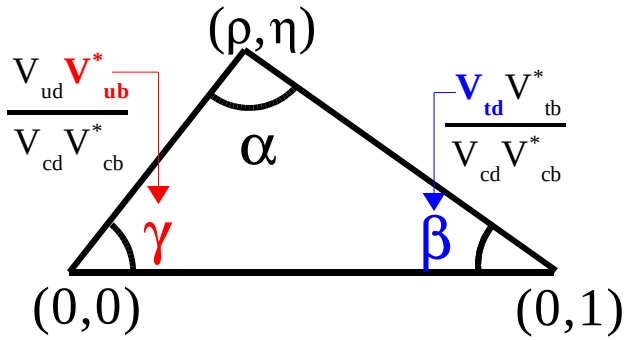


Fred Blanc
University of Colorado
(BABAR Collaboration)

presented at the
" Meeting of Division of Particles and Fields"
Riverside, CA
August 26-31, 2004

CP Violation in *B* decays

- In the standard model (SM), single complex phase in CKM matrix → **CP violation**
- Unitarity of CKM ⇒ Unitarity triangle (B system)
- *B* factories: $\Upsilon(4S) \rightarrow$ coherent $B^0\bar{B}^0$ pair
  - opposite flavor at time of first B^0 decay (B_{tag})
  - evolution of other B^0 (B_{rec}) as function of Δt:



$$F_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm S_f \sin(\Delta m_d \Delta t) \mp C_f \cos(\Delta m_d \Delta t)\right]$$

Sign depends on flavor of B_{tag}

$$S_f = \frac{-2Im\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

- Observables *S* and *C* depend on CP parameter λ_f:

η_f = CP eigenvalue of final state *f*

$$\lambda_f = \eta_f \cdot \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}}}{A_f}$$

Eigenstates: $|B_L\rangle = p\,|B^0\rangle + q\,|B^0\rangle$

$|B_H\rangle = p\,|B^0\rangle - q\,|B^0\rangle$

$|q/p| \neq 1$ ⇒ CP violation in mixing

$|\bar{A}_f/A_f| \neq 1$ ⇒ CP violation in decay

(direct CP violation)

SM: $|\bar{A}_f/A_f| \simeq 1$

Observable relative phase between q/p and $\bar{A}_f/A_f$

⇒ **CP-violation in interference between mixing and decay**

Measurements of β

Phase β from mixing
$\Rightarrow \lambda_f = -\eta_f \cdot \sin 2\beta$

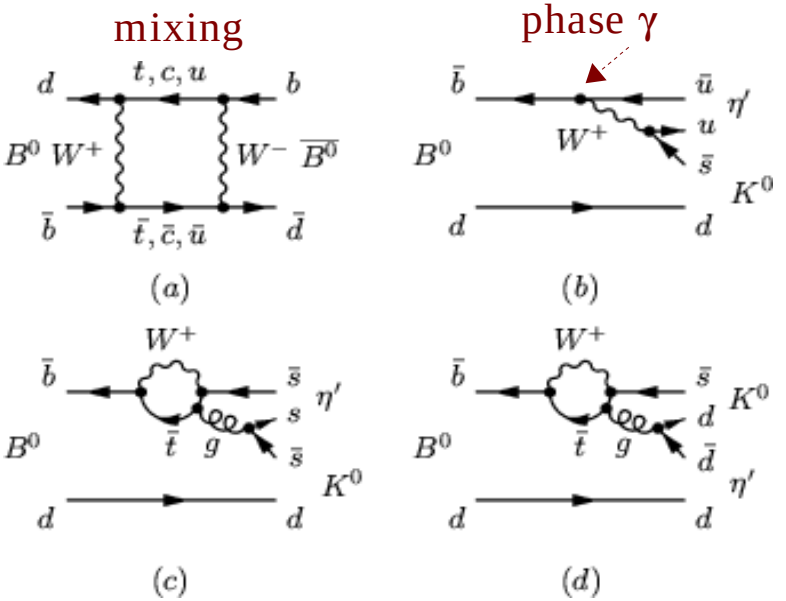
- $b \to c\bar{c}s$ (charmonium K^0)
  - theoretically clean measurement of $\sin 2\beta$
  - *BABAR*: $\sin 2\beta = 0.722 \pm 0.040_{stat} \pm 0.023_{syst}$
- $b \to s\bar{s}s$
  - penguin dominated, **sensitive to physics beyond SM**
    $\Rightarrow$ deviation from $\sin 2\beta$?
  - $B^0 \to \phi K^0 \Rightarrow \sin 2\beta$ (SM)
  - $B^0 \to f_0 K^0$, $\eta' K^0$, etc... tree diagram: not negligible + have difference weak phase $\Rightarrow \sin 2\beta_{eff}$ (SM)
- $b \to s\bar{d}d$ $(s\bar{u}u)$
  - $\pi^0 K^0$, $\rho^0 K^0$, $\omega K^0 \Rightarrow \sin 2\beta_{eff}$ (SM)

This presentation

SM expectations for $\eta' K_S$ and $\pi^0 K_S$

- $\Delta S = \sin 2\beta_{\text{charmonium}} - \sin 2\beta_{\text{eff}} \stackrel{?}{=} 0$
- $B^0 \to \eta' K_S$
  - ΔS bound from SU(3) analysis: using B^0 decays to pairs of light pseudoscalar mesons
    $\Rightarrow |\Delta S| < \sim 0.1$
    [Grosman et al., PRD68, 015004 (2003)]
    [Chiang et al., PRD68, 074012 (2003)]
  - Specific model calculations: $\Delta S \sim 0.01$
    [Beneke et al., NuclPhys B675, 333 (2003)]
- $B^0 \to \pi^0 K_S$ ($b \to s\bar{d}d$ is dominant)
  - SU(3): $\Delta S \sim 0.2$
    [Gronau et al., PLB579, 331 (2004)]
  - model-dependent QCD: $\Delta S \sim 0.1$
    [Buras et al., Ciuchini et al, Charles et al.]

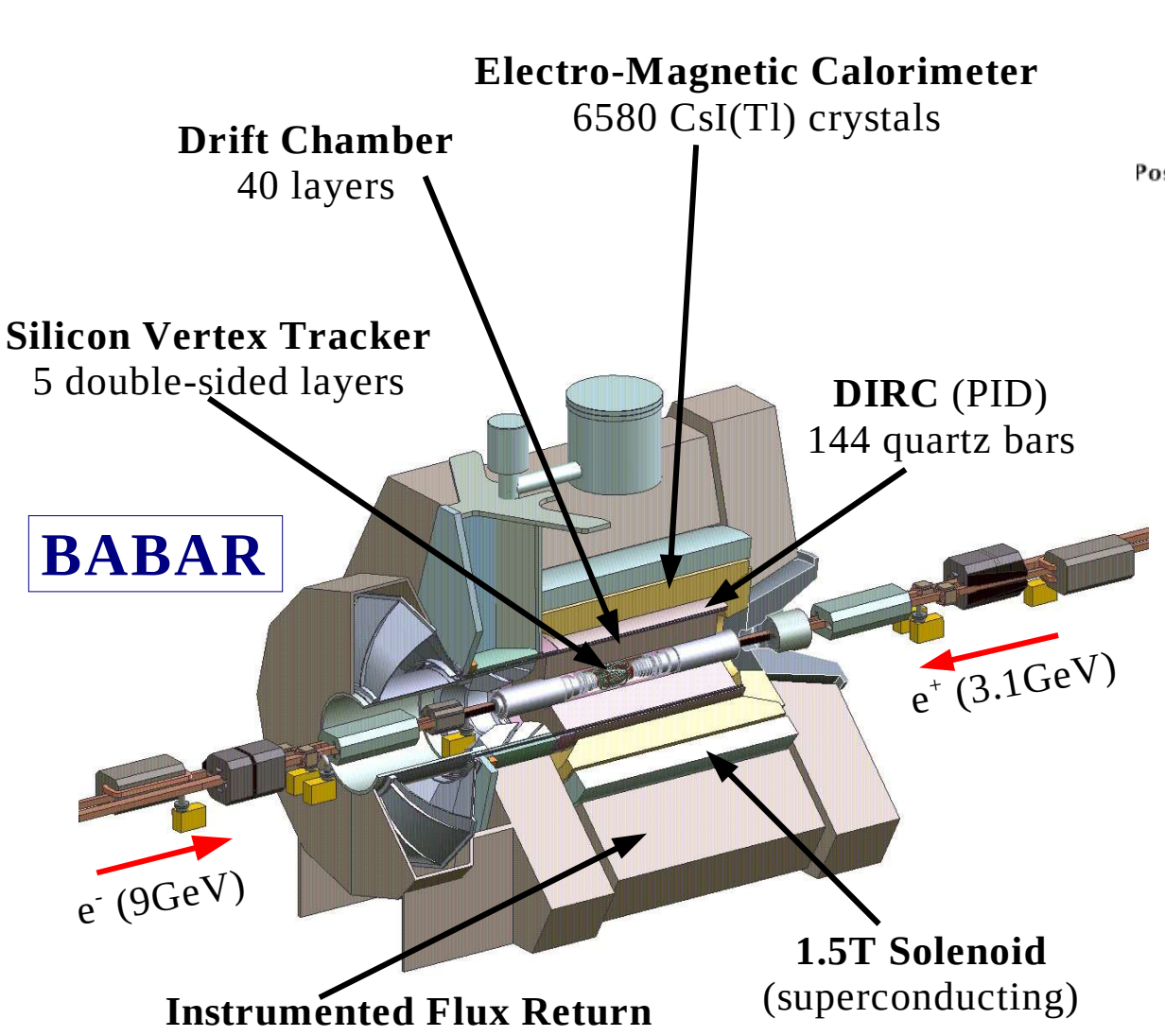
tree (CKM + color-supressed)

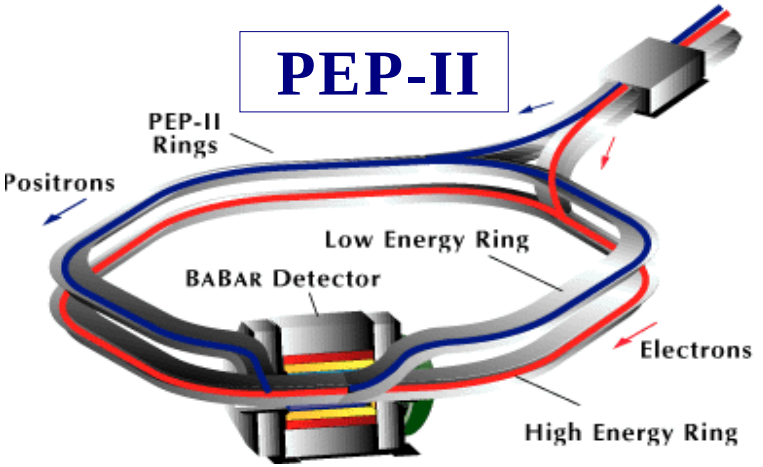


penguin (dominant)

Physics beyond the SM
may enter the loop
(sensitivity to high virtual mass)

PEP-II and the *BABAR* detector





$\mathcal{L}_{peak} = 9.2 \times 10^{33} cm^{-2} s^{-1}$

$\mathcal{L}_{int} = 221 fb^{-1}$ (on-peak)

($23 fb^{-1}$ off-peak)

These results based on
$\mathcal{L}_{int} = 205 fb^{-1}$
=> 227×10^6 *BB* pairs

Analysis technique: overview

- Use Maximum Likelihood (ML) fit technique
- Use **kinematic**, **event shape** and **decay time** variables
- Loose cuts ⇒ keep sidebands for background fitting
- Main background: $e^+e^- \rightarrow q\bar{q}$ continuum (q=u,d,s,c)
  - ➔ effectively identified/rejected using event shape variables
- Extracted from ML fit:
  - ➔ time-dependent CP parameters (S&C)
  - ➔ signal and background yields
  - ➔ background & signal modeling parameters, Δt resolution parameters

Discriminating variables

- **Kinematic variables**
  - Energy substituted B mass ($\sigma(m_{ES}) \approx 2.5\text{-}3.0$ MeV/c^2)

$$m_{ES} = \sqrt{\frac{1}{4}s - |\mathrm{p}_B|^2}$$

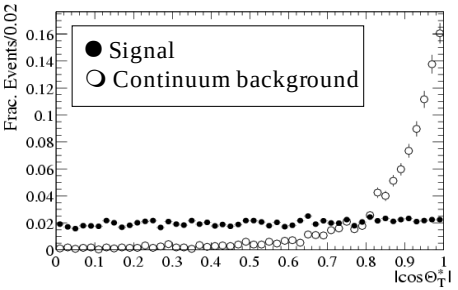
  - Energy difference ΔE ($\sigma(\Delta E) \approx 20\text{-}50$ MeV)

$$\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$$

B candidate energy; CM energy

  - η' candidate invariant mass

- **Event shape variables**
  Used to distinguish:
    - isotropic $B\bar{B}$ events
    - $q\bar{q}$ continuum
  - Angle (*B* thrust axis, ROE)

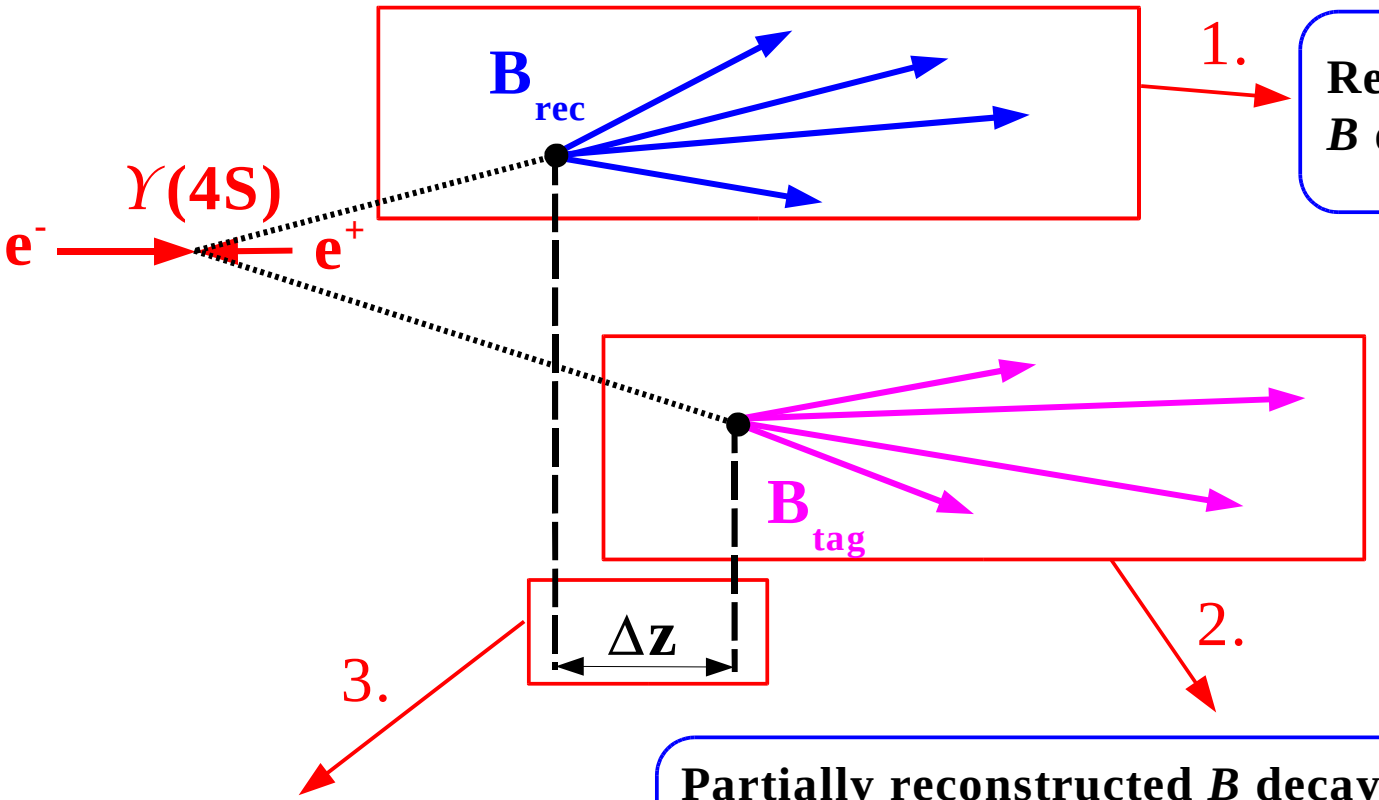


$|\cos\Theta_{thrust}|$

  - Momentum flow about *B* thrust axis (L_0, L_2)
  - Angle (p_B, beam axis)

- Apply preliminary cuts & use variables directly in ML Fit

Δt variable and flavor tagging



Determine Δt from Δz:

$\Delta z \simeq \beta\gamma c\tau_B \simeq 260\ \mu m$

$(\sigma_{\Delta z} \simeq 180\ \mu m)$

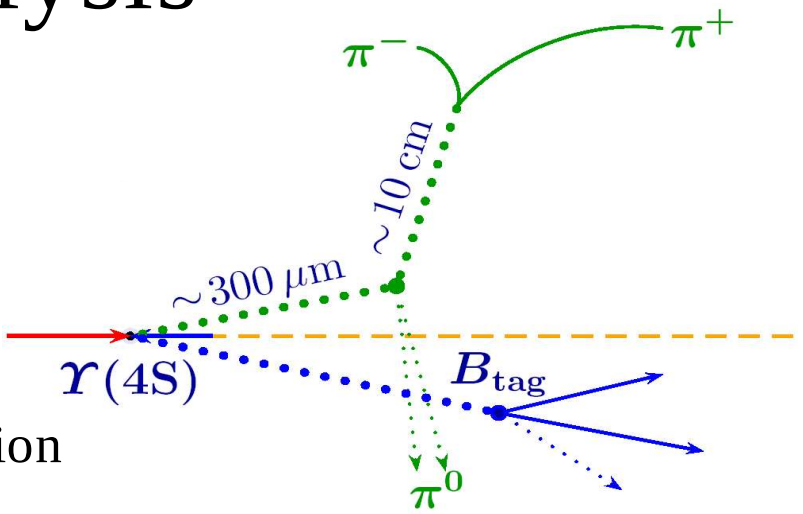
Partially reconstructed B decay (B_{tag})

→ ***B* flavor (lepton charge, kaon strangeness, etc...)**

→ **decay vertex**

- **~2/3 of the events are tagged**
- **Effective tagging efficiency Q ≈ 28.8%**

$B^0 \to \pi^0 K_S$ analysis



- $\pi^0 \to \gamma\gamma$ & K_S lifetime

  $\Rightarrow$ **challenging vertexing for $B^0 \to \pi^0 K_S$**

  Solution:

  - apply quality cuts for clean π^0 & K_S selection
  - **global fit to $\Upsilon(4S) \to B^0\bar{B}^0$ decay tree** (E_{beam}, IP, B^0 lifetime)

    - sub-sample of with 4 SVT hits/pion (~60%)

      $\Rightarrow$ **used for Δt measurements**
    - remaining 40% used in direct CP violation measurement

- m_{ES} and ΔE replaced by m_{miss} (mass constrained) and m_B

  - better resolution for modes with poor B energy resolution
  - smaller correlations between variables in signal

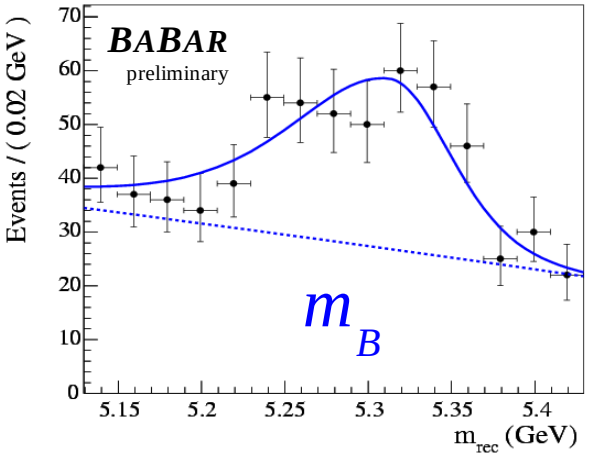
$B^0 \to \pi^0 K_S$ results: yields & BF

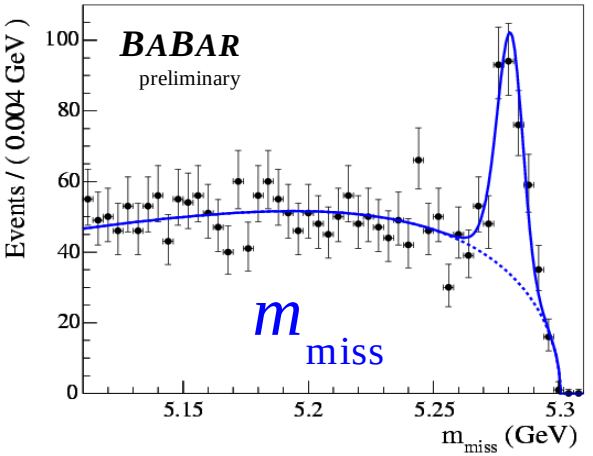
PRELIMINARY

[hep-ex/0408062]

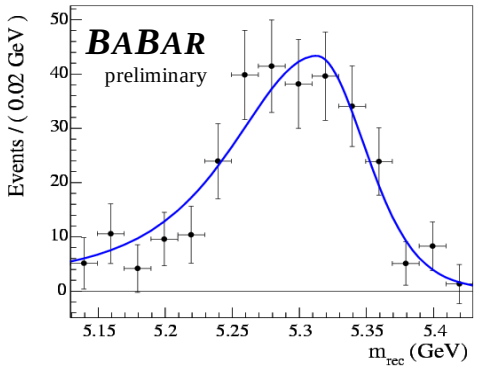
9726 events selected

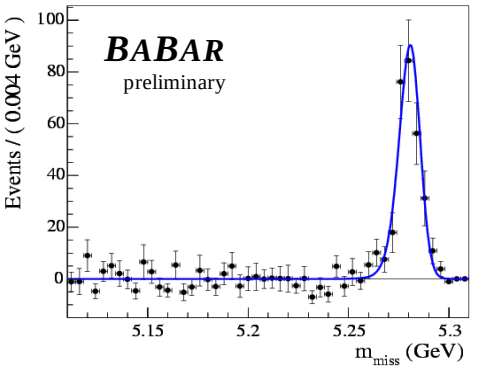
ML fit finds $\mathbf{N_s = 300 \pm 23}$ signal events





Projection plots
[cut on L_2/L_0 (&m_{miss})]





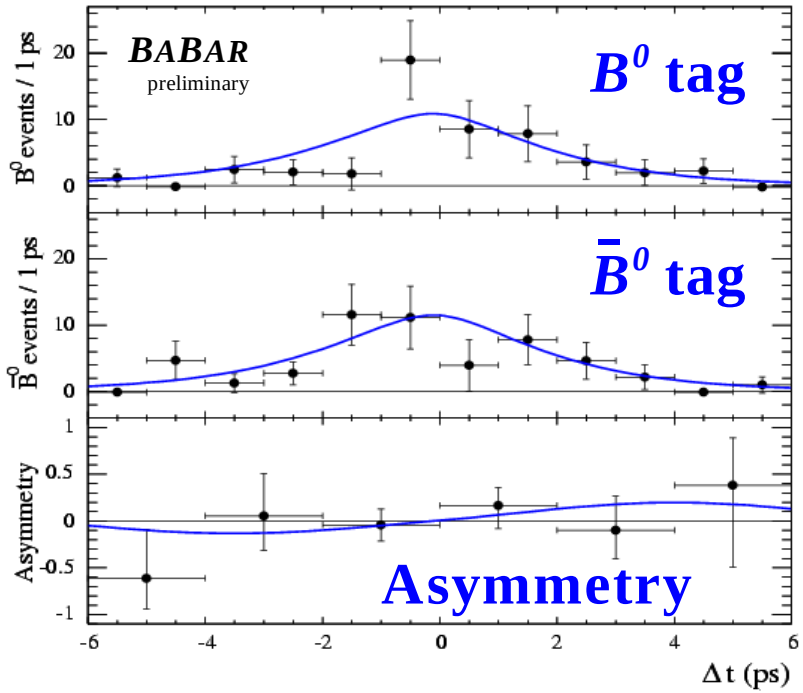
← sPlot
each event weighted
by signal probability
⇒ optimal background subtraction
[Pivk&LeDiberder, physics/0402083]

$$\mathcal{B}(B^0 \to \pi^0 K_S) = (11.4 \pm 0.9_{stat} \pm 0.6_{syst}) \times 10^{-6}$$

$B^0 \to \pi^0 K_S$ results: S & C

PRELIMINARY

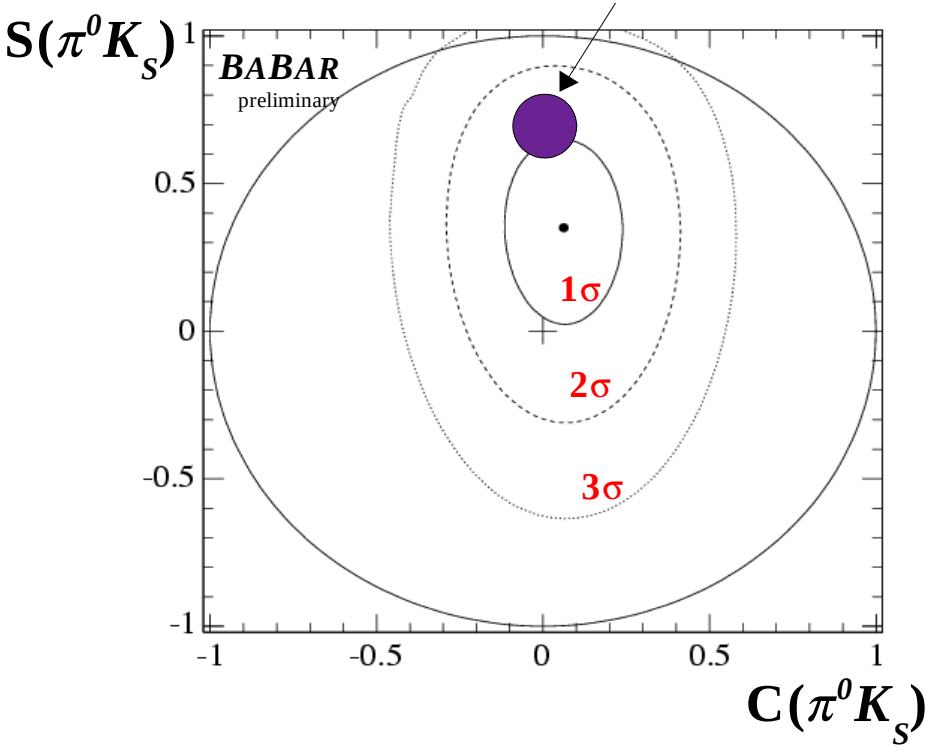
[hep-ex/0408062]



$$S(\pi^0 K_S) = +0.35\ ^{+0.30}_{-0.33} \pm 0.04$$

$$C(\pi^0 K_S) = +0.06 \pm 0.18 \pm 0.06$$

sin2β value from BABAR charmonium decays [BABAR-CONF-04/38]



Systematics dominated by

- background tagging asymmetry [±0.05 on $C(\pi^0 K_S)$]
- SVT alignment [±0.03 on $S(\pi^0 K_S)$]

$B^0 \to \eta' K_S$ analysis

- Large BF: $\mathcal{B}(B^0 \to \eta' K^0) \approx 65 \times 10^{-6}$
- Use m_{ES} and ΔE
- Consider the decays
  - $\eta' \to \rho^0 \gamma$ and $\eta' \to \eta \pi^+ \pi^-$ (with $\eta \to \gamma\gamma$ or $\eta \to \pi^+ \pi^- \pi^0$)
  - $K_S \to \pi^+ \pi^-$ and $K_S \to \pi^0 \pi^0$ ← added since previous result
- Use $B^+ \to \eta' K^+$ as control mode
  - find 2124 ± 57 $\eta' K^+$ signal events
  - CP fit obtains the expected results of S and C compatible with no asymmetry

$B^0 \to \eta' K_S$ results: yields

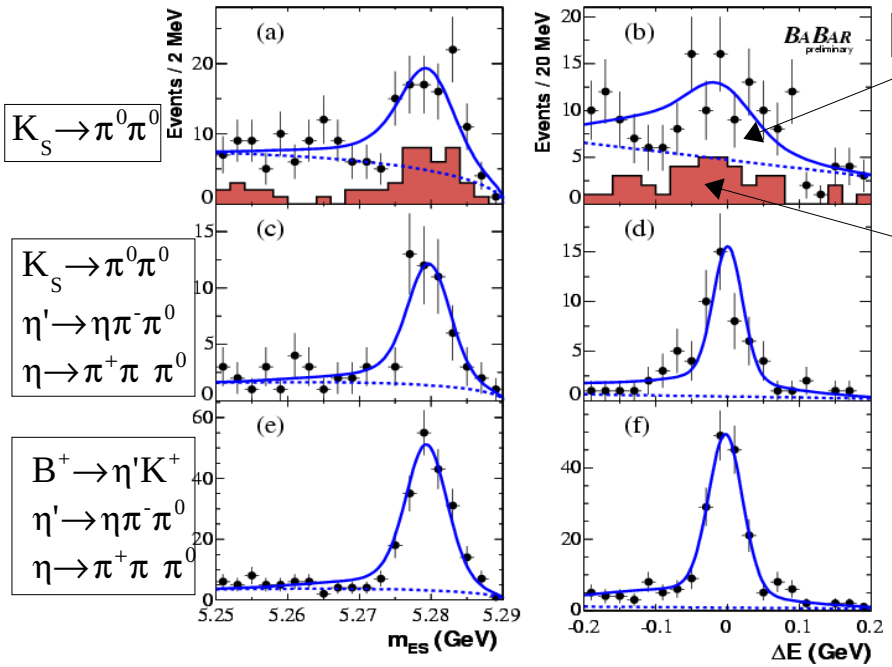
PRELIMINARY

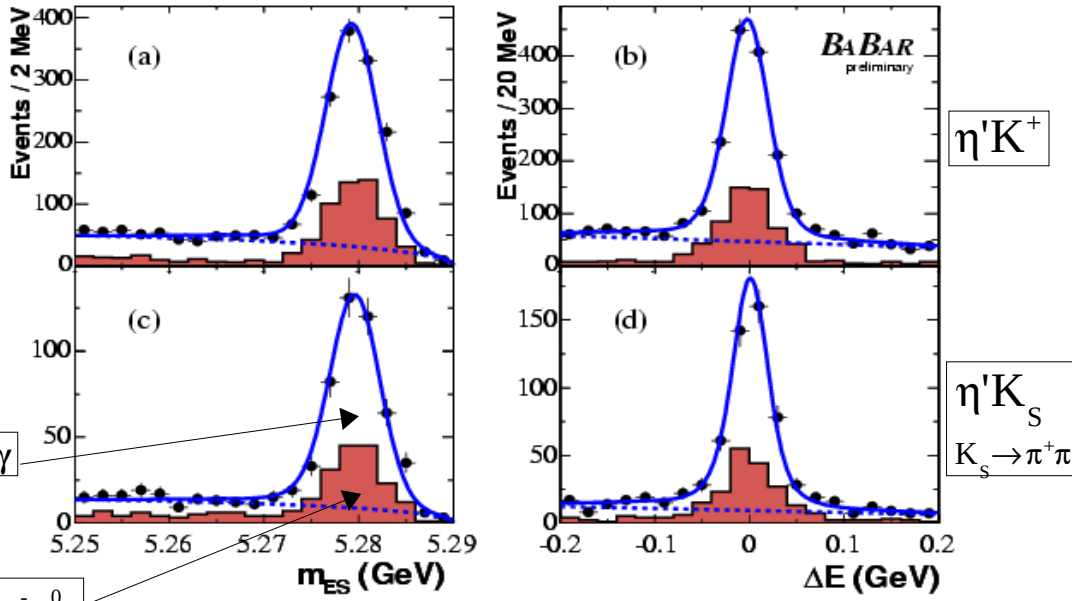
[hep-ex/0408090]

ML fit finds:

$N_S = 819 \pm 38$ signal events

~2/3 are tagged ($\Rightarrow$ use in CP fit)



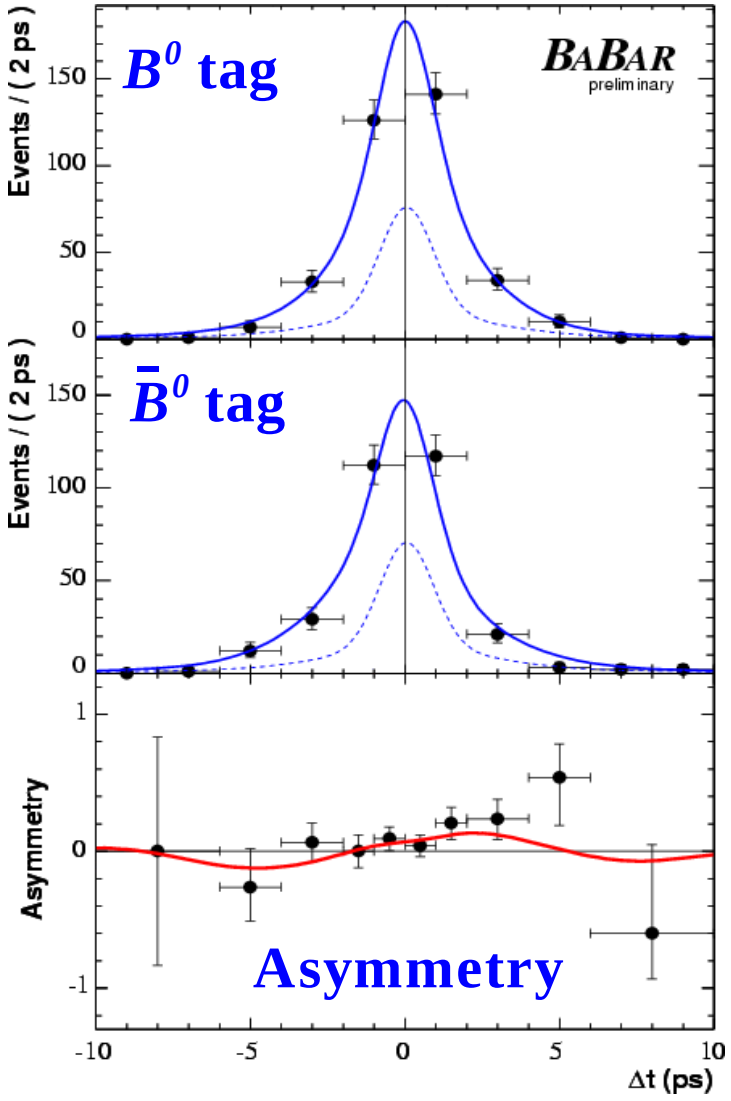


Mode	Yield
$\eta'_{\eta\pi\pi} K^0(\pi^+\pi^-)$	192 ± 15
$\eta'_{\rho\gamma} K^0(\pi^+\pi^-)$	438 ± 27
$\eta'_{\eta(3\pi)\pi\pi} K^0(\pi^+\pi^-)$	55 ± 9
$\eta'_{\eta\pi\pi} K^0(\pi^0\pi^0)$	50 ± 9
$\eta'_{\rho\gamma} K^0(\pi^0\pi^0)$	86 ± 20

$B^0 \to \eta' K_s$ results: S & C

PRELIMINARY

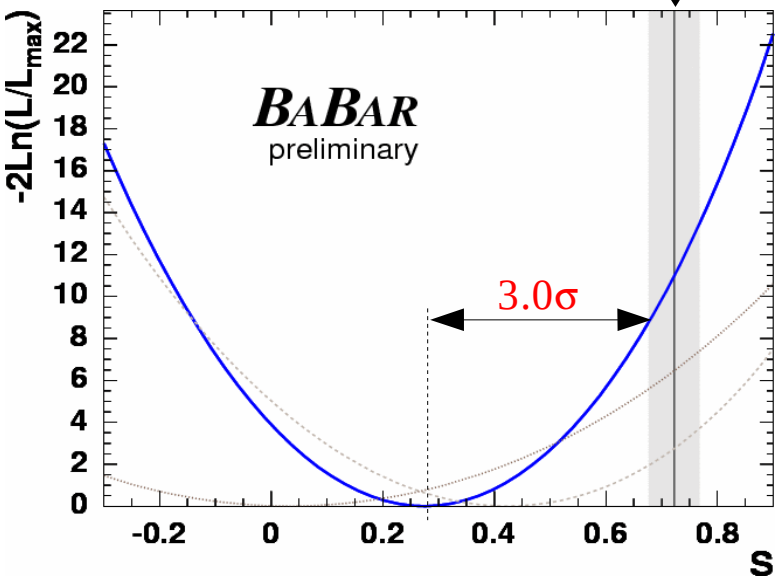
[hep-ex/0408090]



$$S(\eta' K_s) = +0.27 \pm 0.14_{stat} \pm 0.03_{syst}$$
$$C(\eta' K_s) = -0.21 \pm 0.10_{stat} \pm 0.03_{syst}$$

- Systematics dominated by MC statistics and signal modeling $\Rightarrow \pm 0.02$
- Single most accurate measurement from non-charmonium mode!

sin2β value from BABAR charmonium decays [BABAR-CONF-04/38]



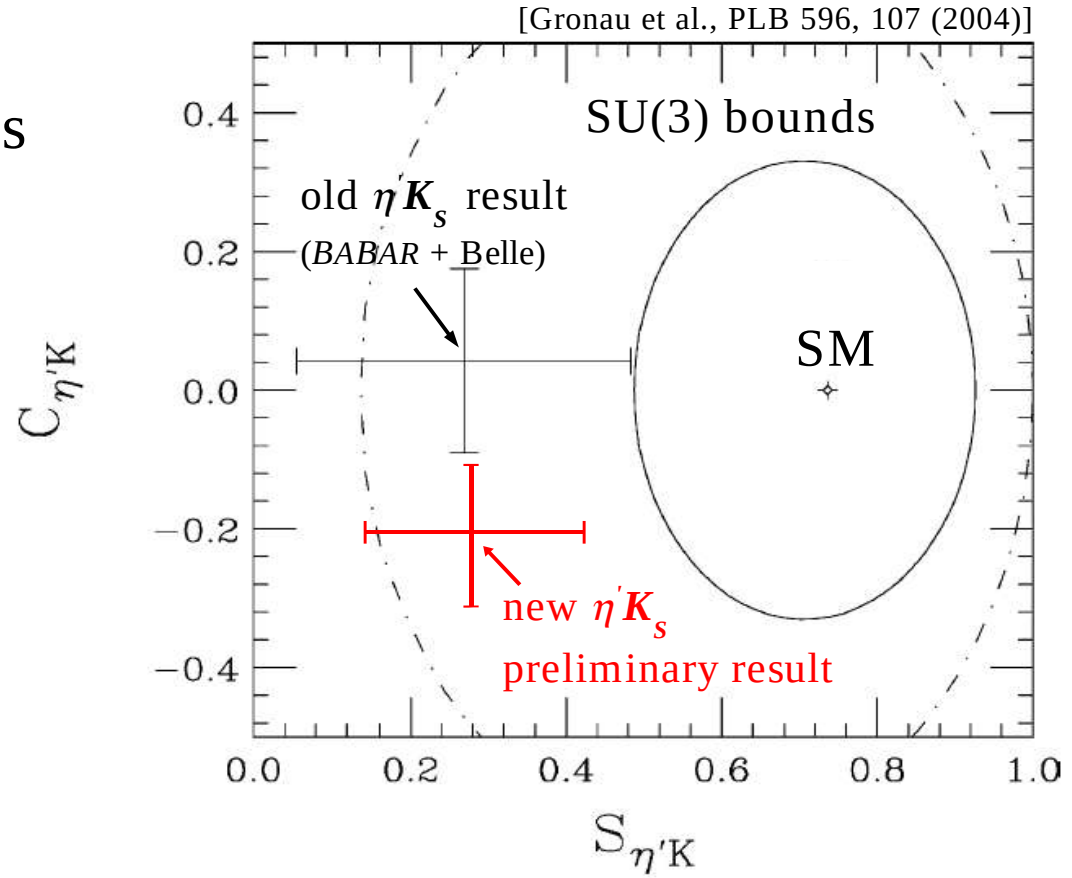
Comparison to SU(3) limits on $\Delta S_{\eta' K_S}$

- Correlated limits on S & C for $B^0 \to \eta' K_S$ based on SU(3) [Gronau et al., PLB 596, 107 (2004)]

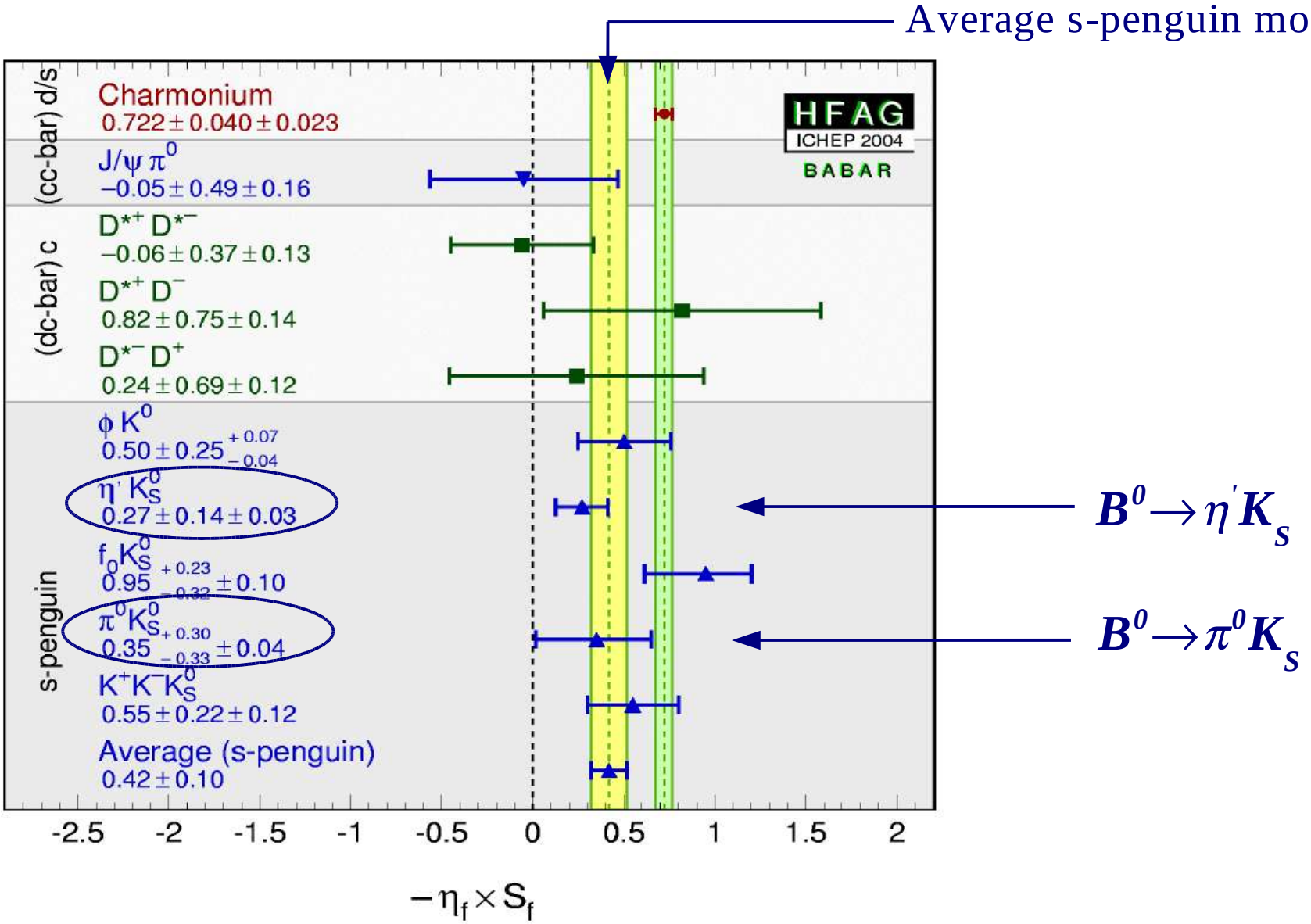
- Uses experimental results on B decays to pairs of light mesons

  $\Rightarrow$ limits on S & C

- See talk by A. Lazarro (session VII, Tuesday)



Comparison to other *BABAR* sin2β results



Conclusion

- Developed vertexing technique to allow time-dependent measurement in $B^0 \to \pi^0 K_S$
- Large BF for $B^0 \to \eta' K^0$ provide high statistics sample
- New ***preliminary*** measurements of *S* and *C*:

[hep-ex/0408062]

$$S(\pi^0 K_S) = +0.35\ ^{+0.30}_{-0.33} \pm 0.04$$
$$C(\pi^0 K_S) = +0.06 \pm 0.18 \pm 0.06$$

[hep-ex/0408090]

$$S(\eta' K_S) = +0.27 \pm 0.14 \pm 0.03$$
$$C(\eta' K_S) = -0.21 \pm 0.10 \pm 0.03$$

[Belle: $S(\pi^0 K_S)=+0.30 \pm 0.59 \pm 0.11$ $S(\eta' K_S)=+0.65 \pm 0.18 \pm 0.04$ $N(B\bar{B})=274M$]

- These modes contribute significantly to an increasingly more accurate measurement of *S* and *C* in loop-dominated *B* decay modes