Measurements of β in Charmless B Decays at BABAR

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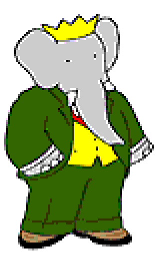


Outline

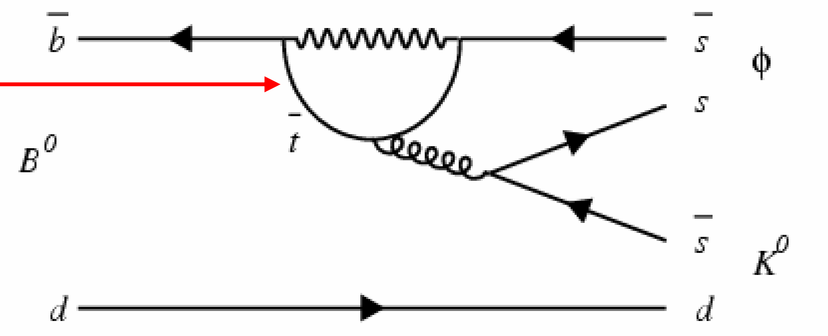
- Intro to time-dependent CP violation
  - Penguin diagrams as a window on New Physics
- sin2β in charmless decays at BaBar
  - $B^0 \rightarrow \rho^0 K_S$
  - $B^0 \rightarrow \pi^0 K_S$
  - $B^0 \rightarrow K_S K_S K_S$
  - $B^0 \rightarrow \pi^0 \pi^0 K_S$
- Measurements of β using Dalitz analysis
  - $B^0 \rightarrow K^+ K^- K^0$
- Summary

Motivation: Physics Beyond SM

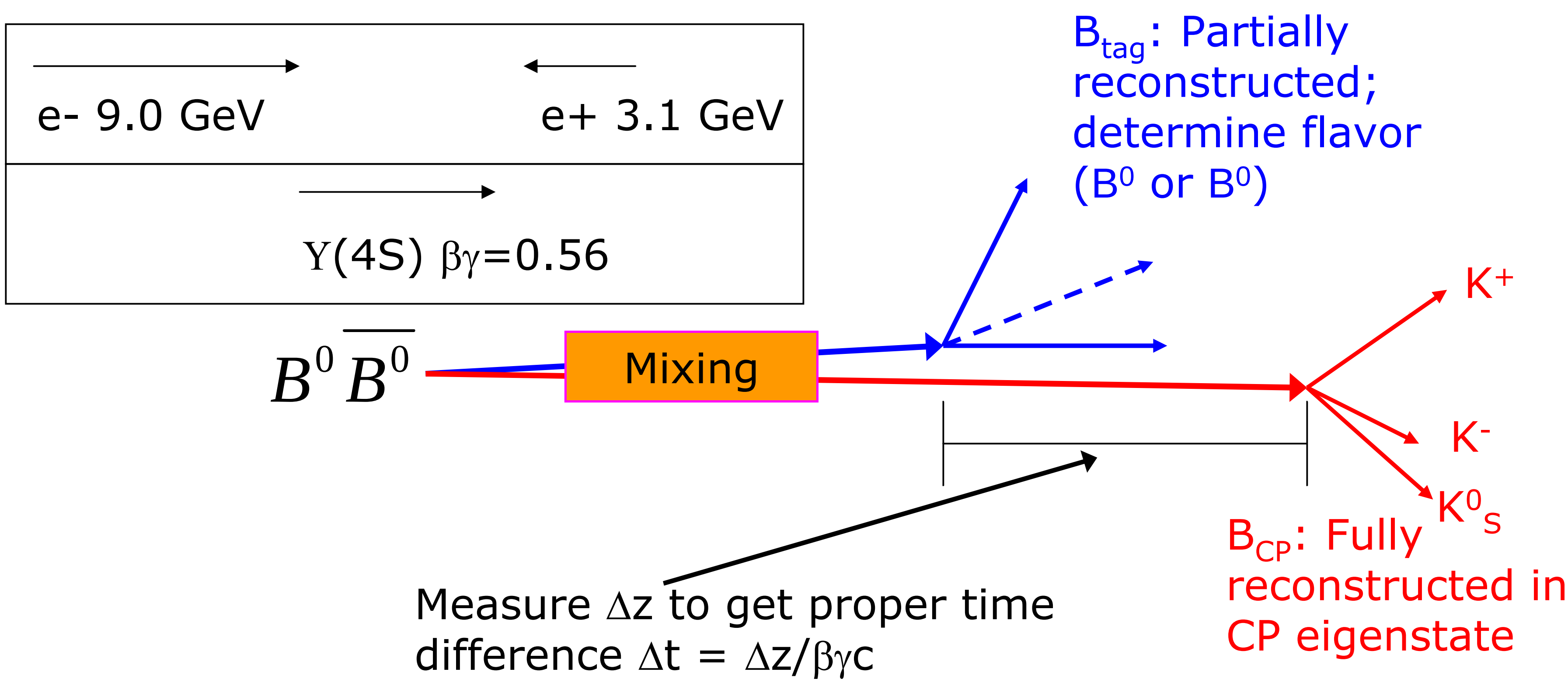
- Charmonium (*e.g.* $B^0 \rightarrow J/\psi K_S$) decays dominated by tree diagrams→good laboratory to measure SM values (see M. Bomben talk, this session):
  - $\sin 2\beta = 0.678 \pm 0.026$ ($\beta = 0.372 \pm 0.017$) *(HFAG Moriond 07)*
- Charmless b→s decays dominated by loop (penguin) diagrams:
  - In the SM, expect $\sin 2\beta_{eff} \approx \sin 2\beta$

• Massive particles beyond the SM could enter in the loop

• Could yield $\sin 2\beta_{eff} \neq \sin 2\beta$



BaBar: An Asymmetric B Factory



B_{CP} characterized w/standard kinematic variables: m_{ES}, ΔE

$e^+e^- \rightarrow qq$ background rejected using event shape variables

Time Dep. CP Violation Formalism

Decay rate as a function of Δt:

$$\frac{d\Gamma}{d\Delta t} \propto \frac{e^{-|\Delta t|/\tau}}{\tau} \times \left[\begin{array}{r} |A|^2 + |\overline{A}|^2 \pm 2\,\mathrm{Im}\left(\eta_{CP}\,\overline{A}A^* e^{-2i\beta}\right)\sin\Delta m\Delta t \\ \mp\left(|A|^2 - |\overline{A}|^2\right)\cos\Delta m\Delta t \end{array} \right]$$

This is usually simplified to

$$\frac{d\Gamma}{d\Delta t} \propto \frac{e^{-|\Delta t|/\tau}}{\tau} \times \left[1 \pm \left(-\eta S \sin\Delta m\Delta t - C\cos\Delta m\Delta t\right)\right]$$

CP violation parameters:

- in interference between decay w/ and w/o mixing : S (~sin2β in SM)
- in decay (direct): C (~0 in SM)

$B^0 \to \rho^0 K_S$

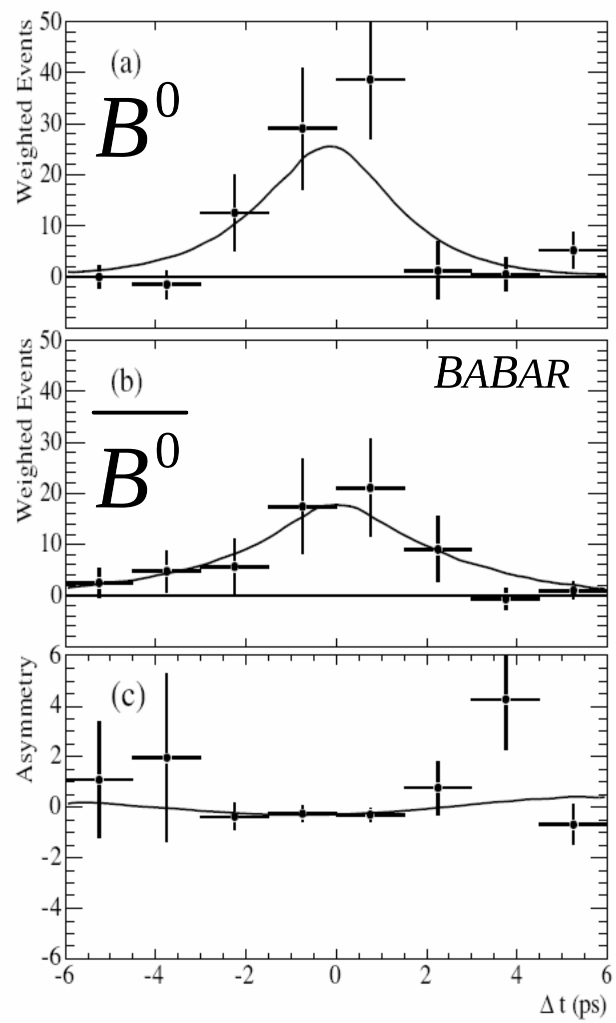
$\rho^0 \to \pi^+\pi^-$, $K_S \to \pi^+\pi^-$

- Maximum Likelihood fit to:
  - m_{ES}, ΔE, NN, $\cos\theta_{\pi+}$, $m_{\pi\pi}$, Δt
- $N_{signal} = 111 \pm 19$
  - $\mathcal{B}(B^0 \to \rho^0 K^0) = (4.9 \pm 0.8 \pm 0.9) 10^{-6}$
  - 5.0σ significance incl. syst.
- $S = 0.20 \pm 0.52 \pm 0.24$
- $C = 0.64 \pm 0.41 \pm 0.20$

Largest contribution: neglect of interference

PRL 98, 051803 (2007)

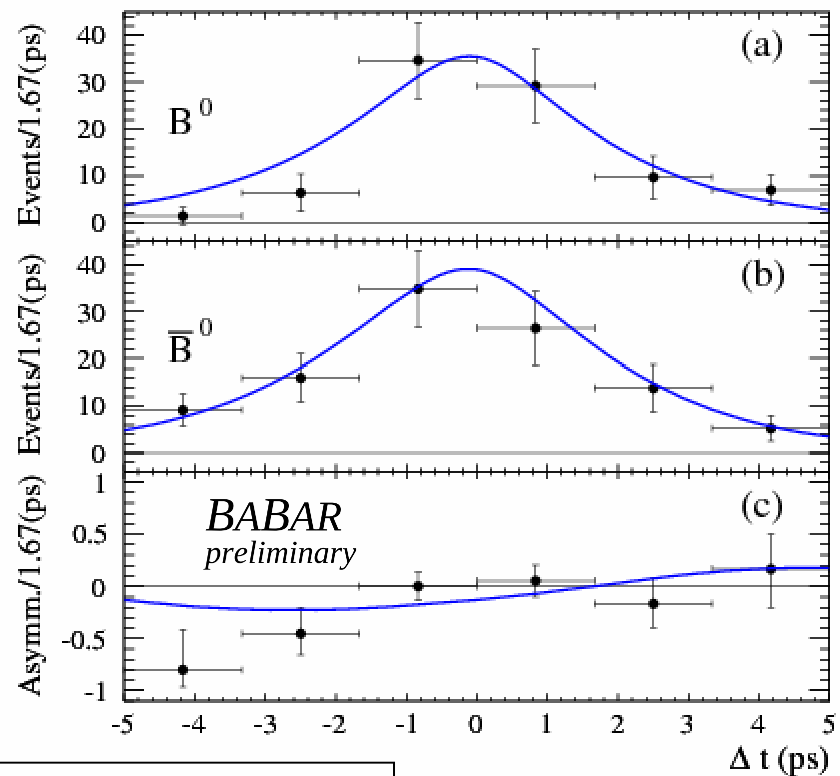
227×10^6 BB pairs



$B^0 \rightarrow \pi^0 K_S$

- Δt computed using technique pioneered by BaBar
  - K_S momentum vector pointed back to the IP
  - B production vertex is constrained to come from the beam axis
- N_{sig} = 459±29
  - $\mathcal{B}(B^0 \rightarrow \pi^0 K^0) = (10.34 \pm 0.66 \pm 0.58) 10^{-6}$
- S = 0.40±0.23±0.03
- C = 0.24±0.15±0.03

383 x 10^6 BB pairs



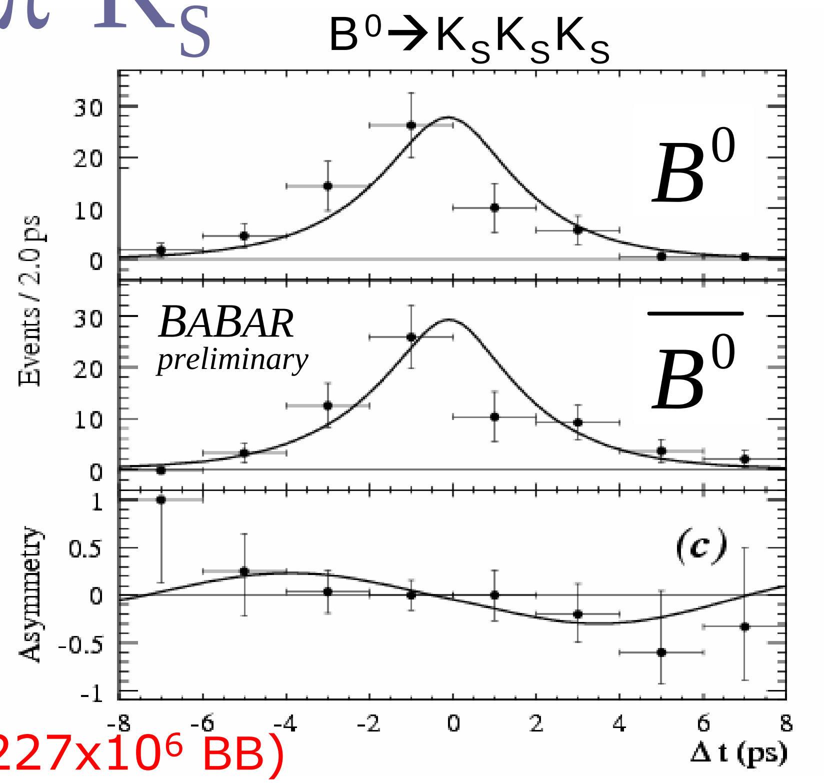
arXiv:0707.2980

Sub. to PRD-RC

New!

$B^0 \rightarrow K_S K_S K_S$ and $\pi^0\pi^0 K_S$

- CP-even three body final states
- $K_S K_S K_S$: SM theory uncertainty small
- Δt computed using same technique as $\pi^0 K_S$
- In $K_S K_S K_S$, one K_S may decay to $\pi^0\pi^0$



$K_S K_S K_S$: (383×10^6 BB)

N_{sig} = 125±13, 64±12

S = -0.71 ± 0.24 ± 0.04

C = 0.02 ± 0.21 ± 0.05

hep-ex/0702046

$\pi^0\pi^0 K_S$: (227×10^6 BB)

N_{sig} = 117±27

S = 0.72 ± 0.71 ± 0.08

C = 0.23 ± 0.52 ± 0.13

hep-ex/0702010

Both sub. to PRD-RC

$K^+K^-K^0$: Time-Dependent Dalitz Analysis

- Challenges in $B^0 \to K^+K^-K^0$:
  - Mixture of CP-odd and CP-even
  - Potential for interference among different decay amplitudes
- Answer: Incorporate amplitude structure as a function of phase space into the fit

Plug into top expression on pg. 5:

$$\overset{(-)}{\mathcal{A}}(m_{K^+K^-}, \cos\theta_H) = \sum_r \overset{(-)}{\mathcal{A}}_r$$

$$= \sum_r c_r(1 \mp b_r)e^{i(\varphi_r \mp \delta_r)} \cdot f_r(m_{K^+K^-}, \cos\theta_H),$$

f_r describes the decay dynamics: *e.g.* Breit-Wigner

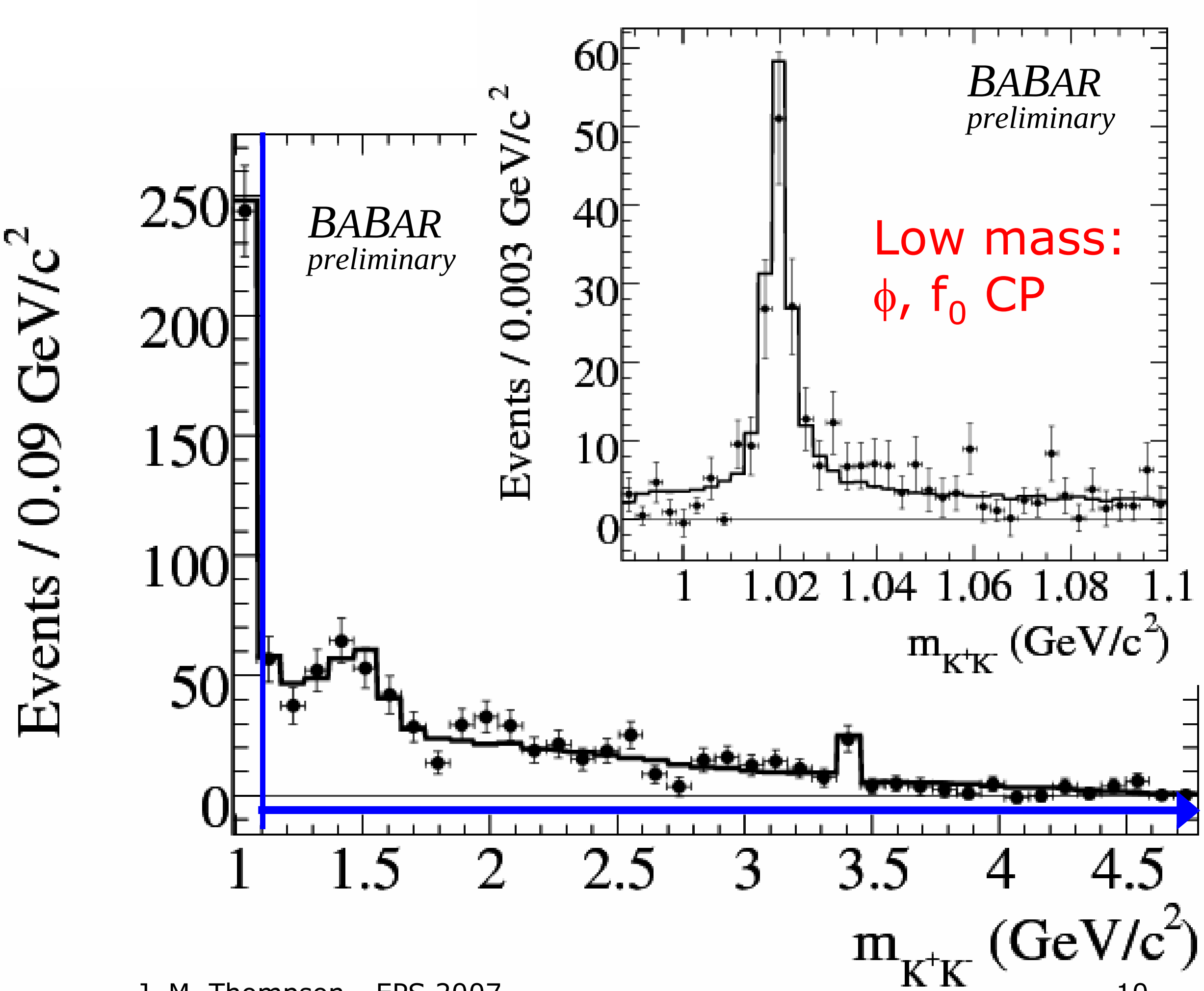
"Isobar" coefficients: c_r, φ_r

Allow for direct asymmetries: b_r, δ_r

$A_{CP,r} = -C = -2b_r/(1+b_r^2)$; $\beta_{eff,r} = \beta + \delta_r$

$K^+K^-K^0$: Analysis Strategy

- Combine:
  - $K_S \rightarrow \pi^+\pi^-$
  - $K_S \rightarrow \pi^0\pi^0$
  - K_L
- 3 steps:
  - Whole DP:
    - Average CP
  - "Low mass"
  - "High mass":
    - Average CP



Amplitude model in $K^+K^-K^0$

- Motivated by DP analysis of $B^+ \to K^+K^-K^+$
  - BaBar: PRD 74 032003 (2006); Belle: PRD 71 092003 (2005)
- Also BaBar angular moments analysis
  - PRD 71 091102 (2005)

Results: Fit to Whole DP

Fit fraction

Components of our Isobar Model

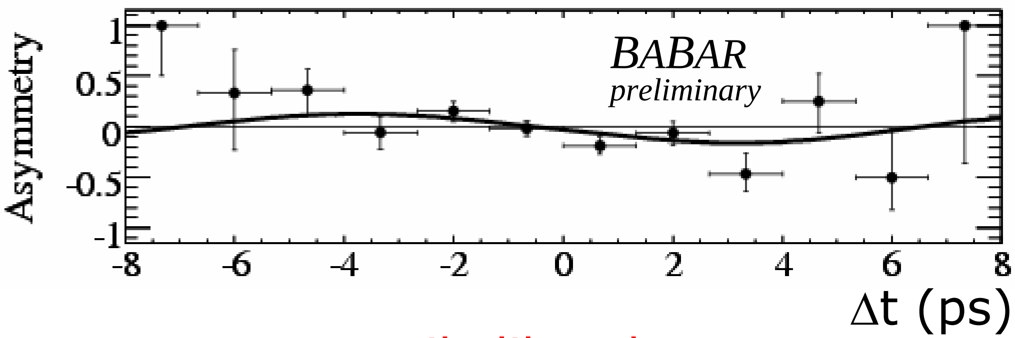
Isobar Mode	Amplitude c_r	Phase φ_r (rad)	$\mathcal{F}_r$ (%)
ϕK^0	0.0085 ± 0.0010	-0.016 ± 0.234	12.5 ± 1.3
$f_0 K^0$	0.622 ± 0.046	-0.14 ± 0.14	40.2 ± 9.6
$X_0(1550)K^0$	0.114 ± 0.018	-0.47 ± 0.20	4.1 ± 1.3
$(K^+K^-)_{NR}K^0$	1 (fixed)	0 (fixed)	
$(K^+K^0)_{NR}K^-$	0.33 ± 0.07	1.95 ± 0.27	112.0 ± 14.9
$(K^-K^0)_{NR}K^+$	0.31 ± 0.08	-1.34 ± 0.37	
$\chi_{c0}(1P)K^0$	0.0306 ± 0.0049	$^{0.81}_{-2.33} \pm 0.54$	3.0 ± 1.2
D^-K^+	1.11 ± 0.17		3.6 ± 1.5
$D_s^-K^+$	0.76 ± 0.14		1.8 ± 0.6

$K^+K^-K^0$: CP Results – Whole DP

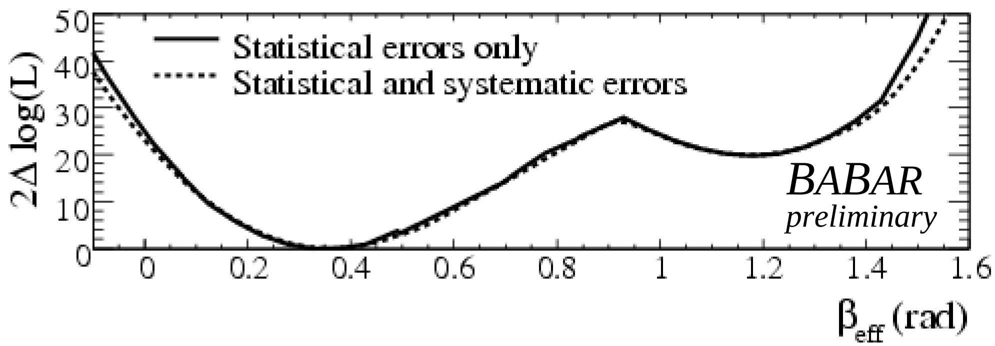
	A_{CP}	β_{eff} (rad)
Whole DP	$-0.015 \pm 0.077 \pm 0.053$	$0.352 \pm 0.076 \pm 0.026$

($\sin 2\beta_{eff} = 0.647 \pm 0.116 \pm 0.040$)

Asymmetry



Likelihood scan



Recall: charmonium
$\beta = 0.372 \pm 0.017$

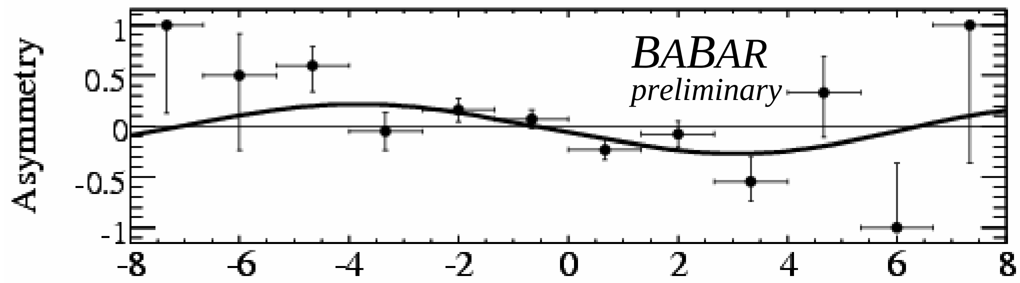
- $\beta_{eff}=0$ excluded at 4.8σ
- Interference between S- and P-waves leads to terms proportional to $\cos 2\beta$ → solution near $\pi/2-\beta$ excluded at 4.5σ
- Note: $\beta \rightarrow \beta+\pi$ ambiguity remains

$K^+K^-K^0$: CP Results – High Mass

	A_{CP}	β_{eff} (rad)
High-mass	$-0.054 \pm 0.102 \pm 0.060$	$0.436 \pm 0.087\ ^{+0.055}_{-0.031}$

($\sin 2\beta_{eff}$=0.764±0.111 +0.071-0.040)

Asymmetry



Δt (ps)

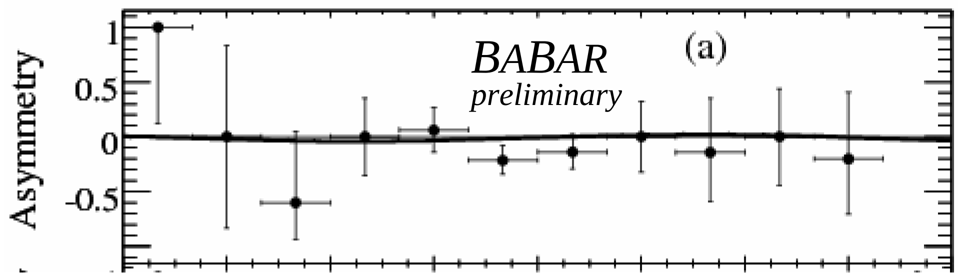
- High-mass result intended to replace "$K^+K^-K^0$ excluding ϕ" result
- Using likelihood difference, β_{eff}=0 excluded at 5.1σ
    - First observation of CP violation in $B^0 \rightarrow K^+K^-K^0$!
    - Second observation in penguin decays after $B^0 \rightarrow \eta' K^0$;
    BaBar: PRL 98 031801 (2007), Belle: PRL 98 031802 (2007)

$K^+K^-K^0$: CP Results – Low Mass

	A_{CP}	β_{eff} (rad)
(1) ϕK^0	$-0.08 \pm 0.18 \pm 0.04$	$0.11 \pm 0.14 \pm 0.06$
(1) $f_0 K^0$	$0.41 \pm 0.23 \pm 0.07$	$0.14 \pm 0.15 \pm 0.05$

(ϕK^0: $-\eta S=0.21\pm0.26 \pm0.11$)
(f_0K^0: $-\eta S=0.25\pm0.26 \pm0.10$)

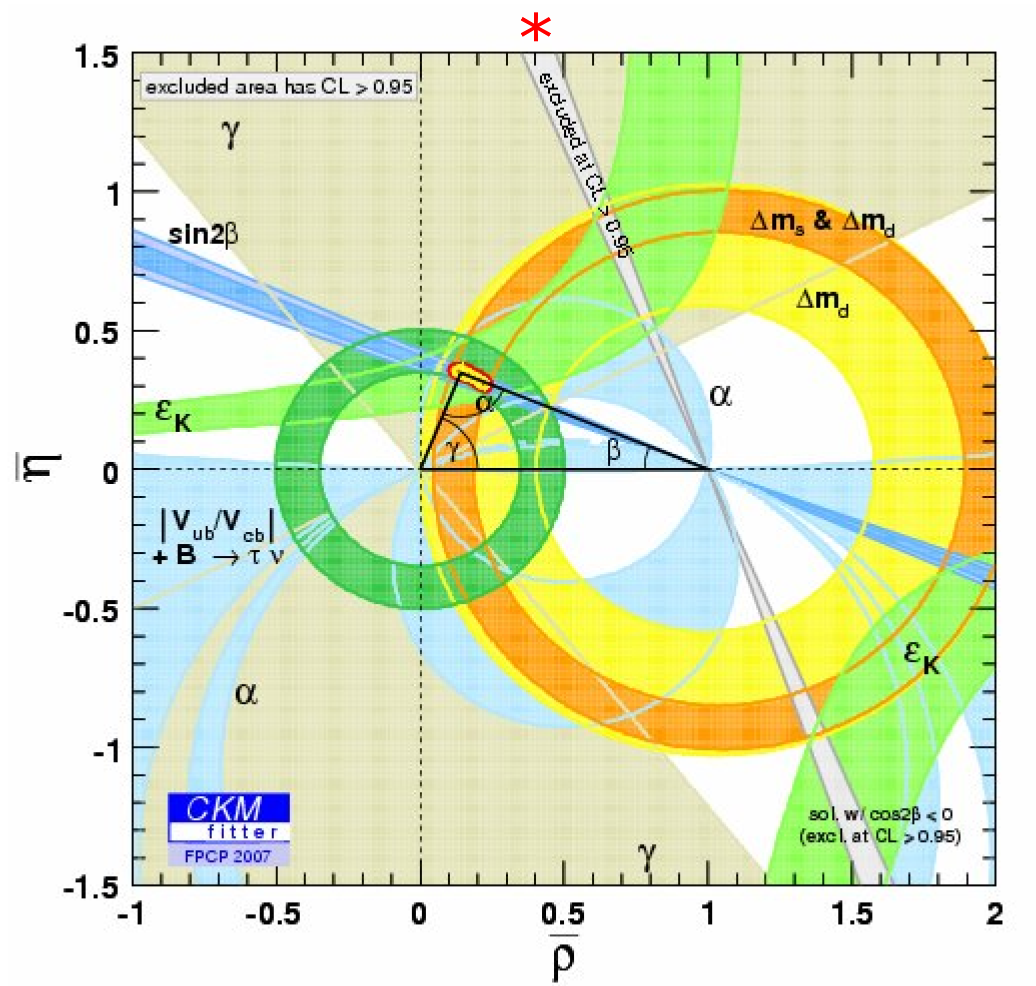
Asymmetry



- Fit finds 2 solutions w/Δ log L = 0.1
- We choose sol'n compatible with the Standard Model

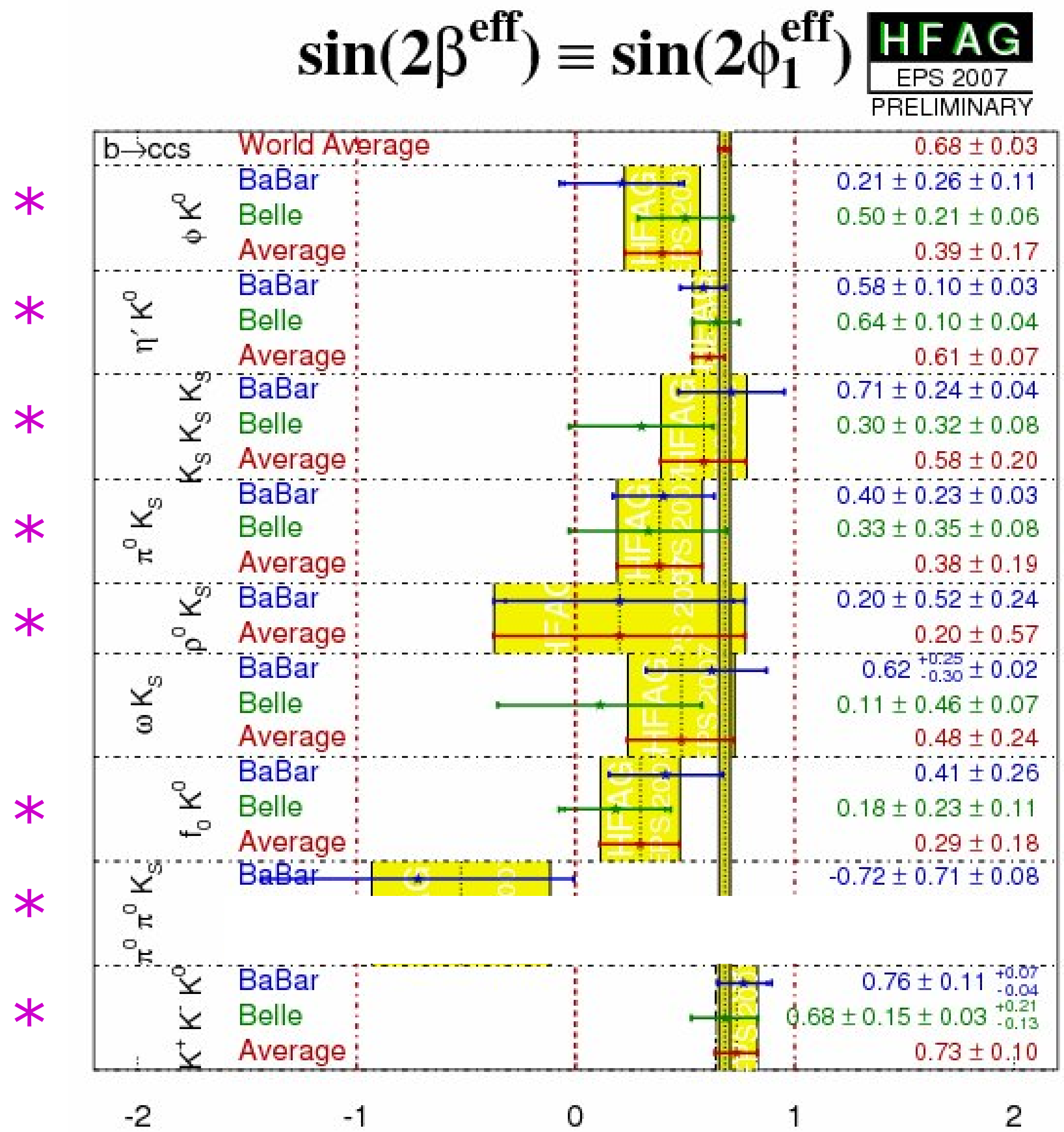
$K^+K^-K^0$ Summary

- Results on 383×10^6 BB pairs, submitted to PRL (arXiv:0706.3885)
- Exclude $\pi/2-\beta$ sol'n at 4.5σ (*)
- Observe CP violation in high-mass $K^+K^-K^0$
- ϕ, f_0 $>1.5\sigma$ from SM



Summary

- Moriond 2007: HFAG average = 0.53 ± 0.05
  - 2.6σ from b→ccs
- w/new $\pi^0 K_S$,$K^+K^-K^0$: HFAG average = 0.56 ± 0.05
  - 2.1σ from b→ccs
- * = BaBar results recently submitted or published

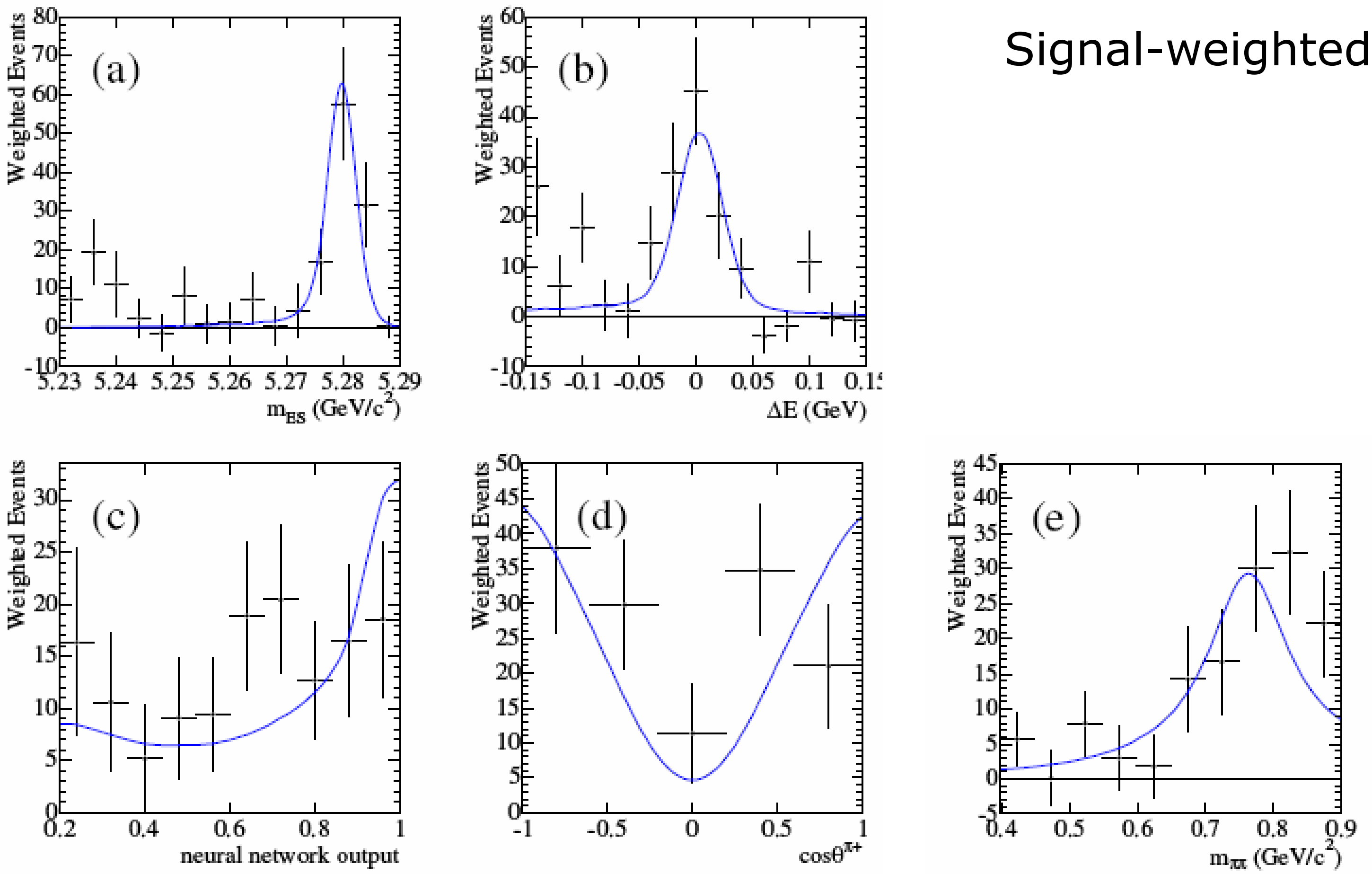


Plot thanks to T. Gershon

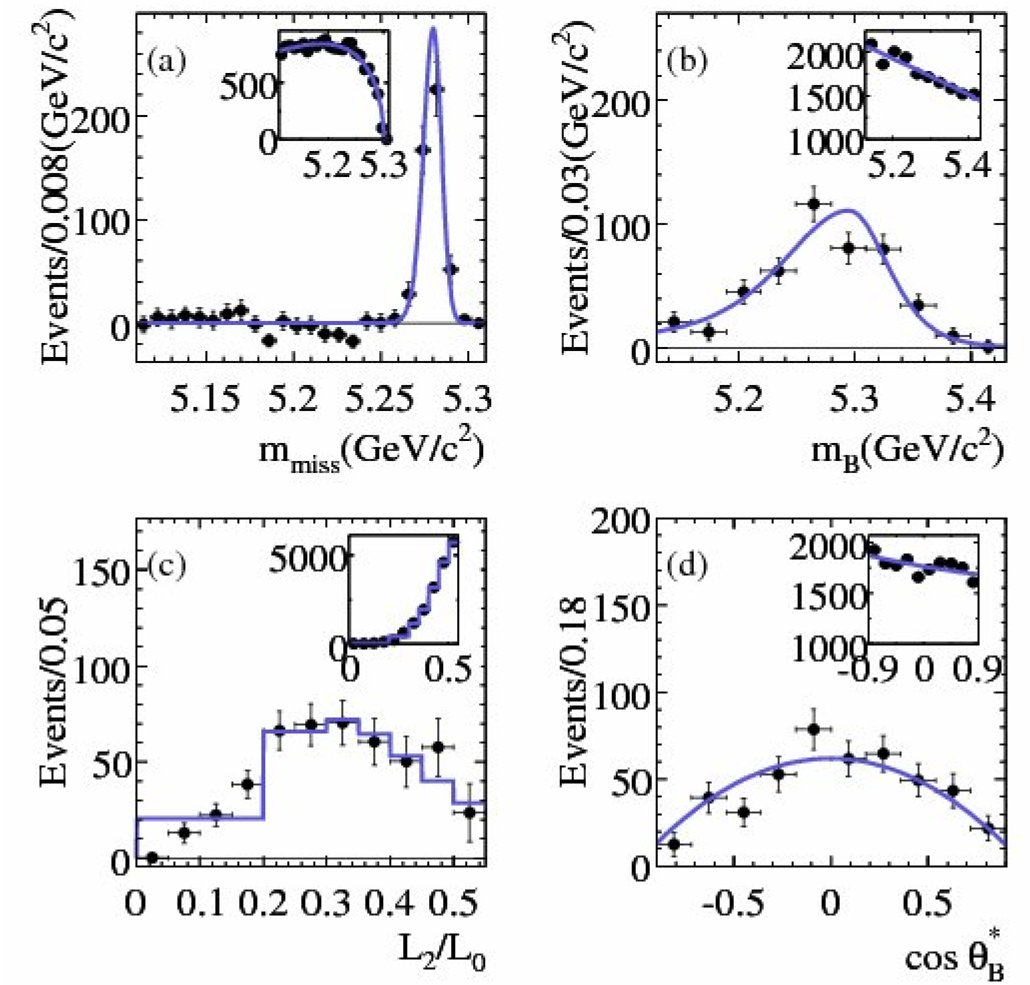
Extra Slides

$B^0 \rightarrow \rho^0 K_S$: Likelihood Variables

Signal-weighted events



$B^0 \rightarrow \pi^0 K_S$: Likelihood Variables



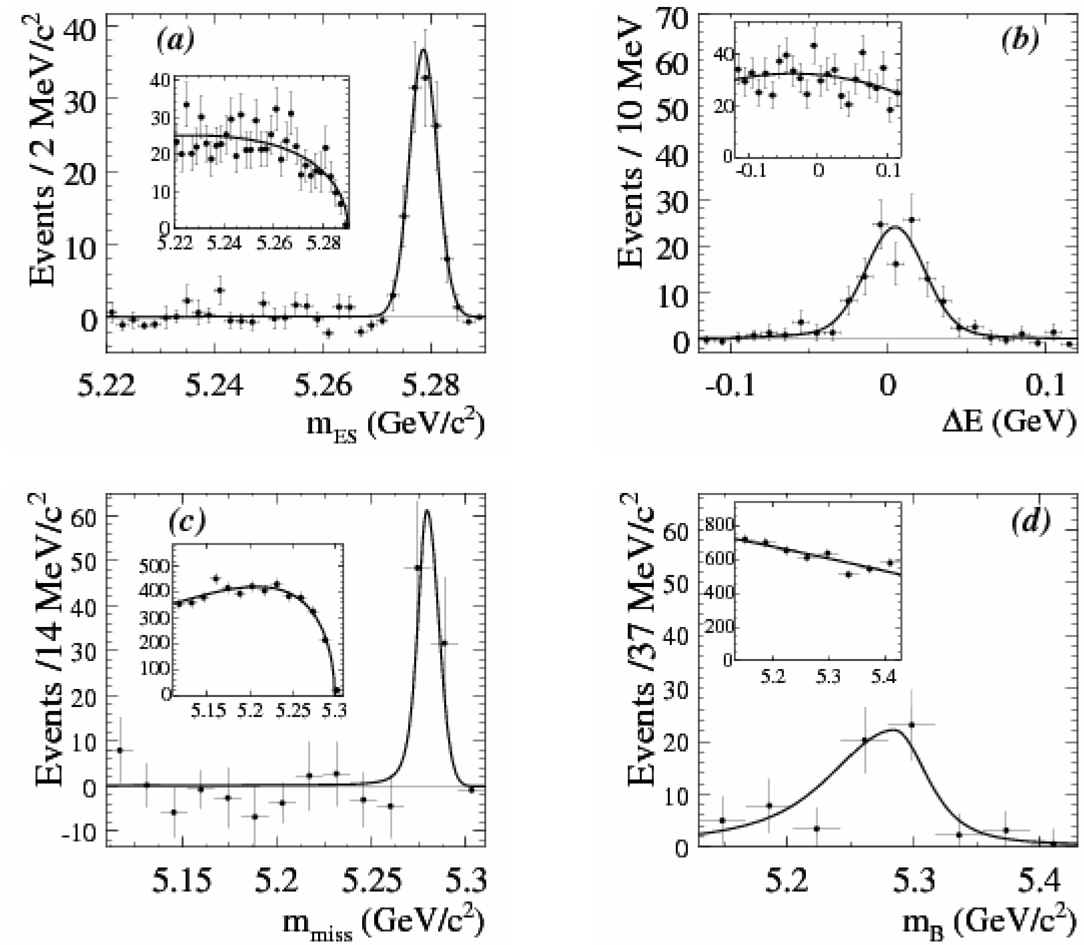
<u>Weighted events</u>
Main: Signal
Insets: Background

$B^0 \rightarrow K_S K_S K_S$: Kinematic Variables

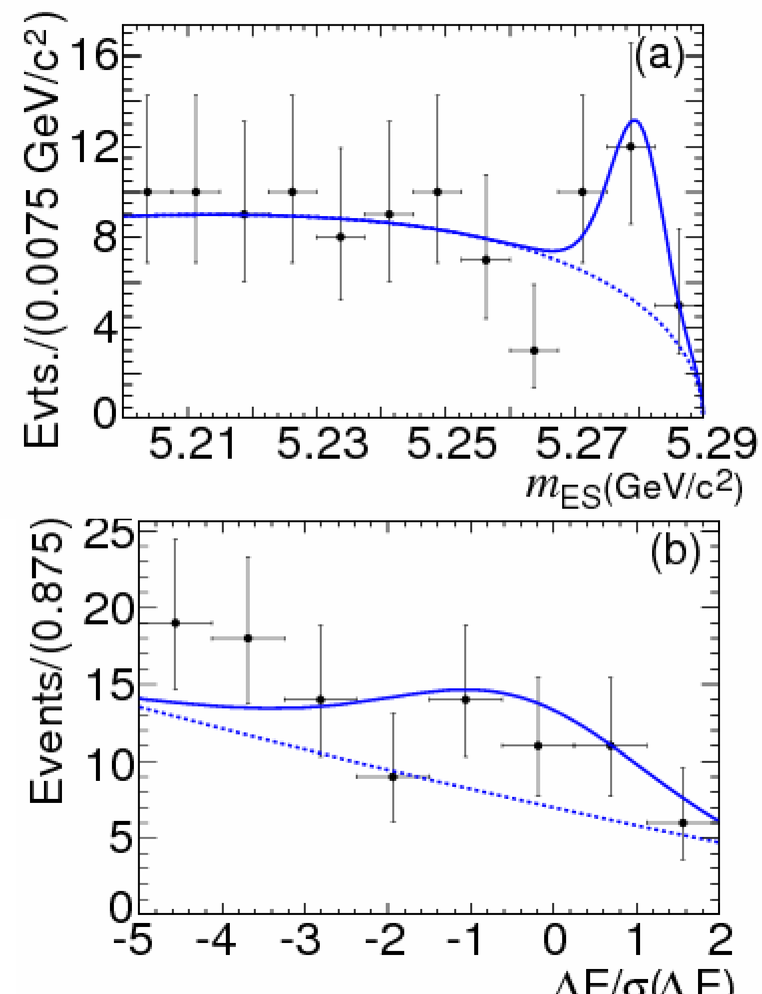
All $K_S \rightarrow \pi^+\pi^-$

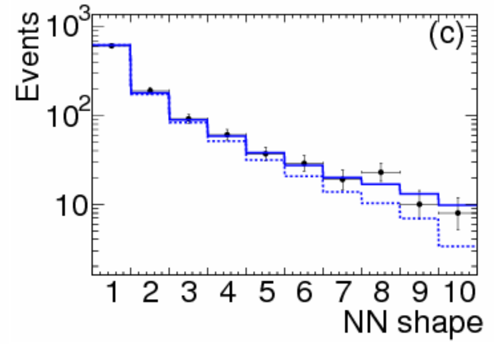
<u>Weighted events</u>
Main: Signal
Insets: Background

One $K_S \rightarrow \pi^0\pi^0$

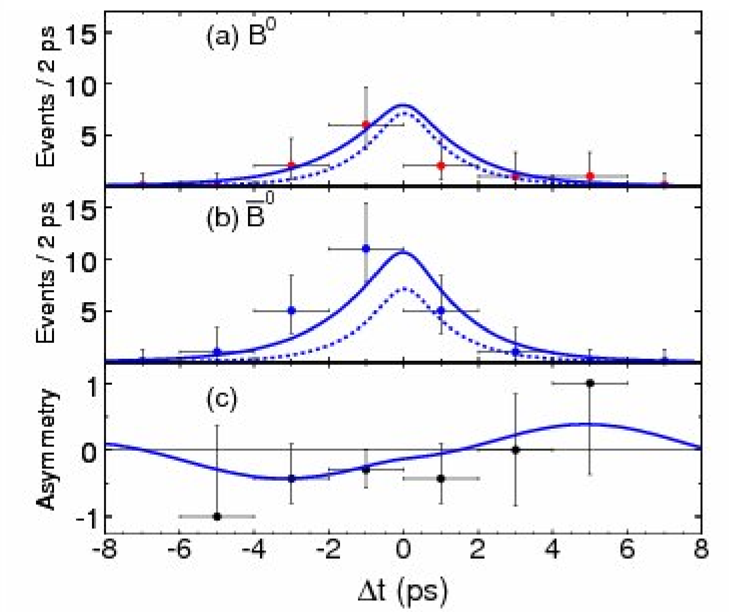


$B^0 \rightarrow \pi^0\pi^0K_S$: Likelihood Variables

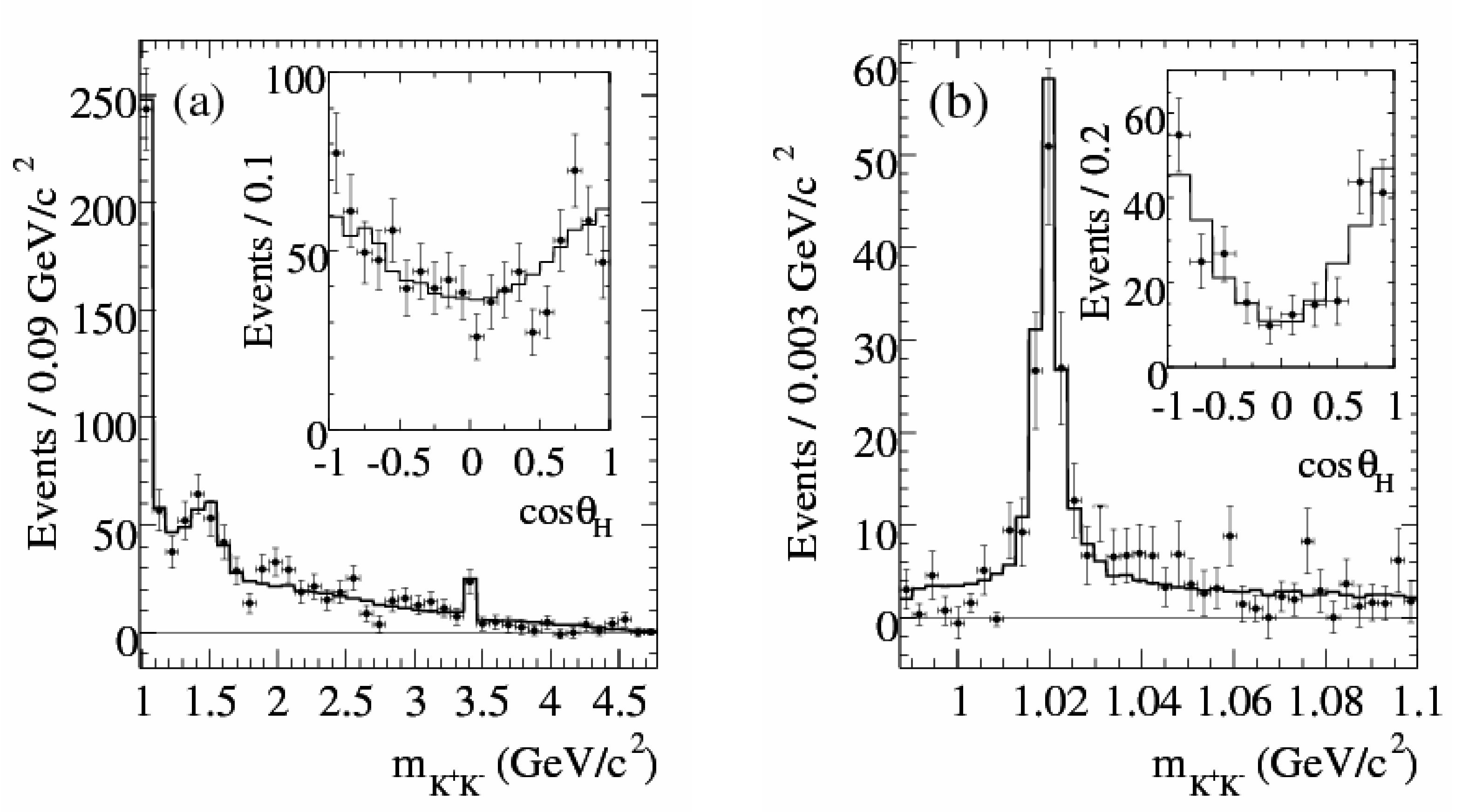




Fit projections w/cut on likelihood ratio



$K^+K^-K^0$: DP Fit Projections



Whole DP Fit (signal) | Low-mass Fit (signal)

$K^+K^-K^0$: Low-mass fit solutions

	A_{CP}	β_{eff} (rad)
(1) ϕK^0	$-0.08 \pm 0.18 \pm 0.04$	$0.11 \pm 0.14 \pm 0.06$
(1) $f_0 K^0$	$0.41 \pm 0.23 \pm 0.07$	$0.14 \pm 0.15 \pm 0.05$
(2) ϕK^0	-0.11 ± 0.18	0.10 ± 0.13
(2) $f_0 K^0$	-0.20 ± 0.31	3.09 ± 0.19

2 solutions w/$\Delta \log L = 0.1$ – Multiple sol'ns common in DP analyses

- ϕ isobar coefficients significantly different
- Solution (2) is completely inconsistent w/the SM due to β_{eff} in f_0K^0
  - Wrong quadrant of ρ-η plane!
  - We choose (1), as it is consistent w/SM
- For both sol'ns, there is a mathematical ambiguity of $\pm\pi$ in $\beta_{eff,\phi}$, correlated with a $\pm\pi$ shift in φ_ϕ

$K^+K^-K^0$: Systematic Errors

Source	Whole DP A_{CP}	Whole DP β_{eff}	High-mass A_{CP}	High-mass β_{eff}	ϕK^0 A_{CP}	ϕK^0 β_{eff}	$f_0 K^0$ A_{CP}	$f_0 K^0$ β_{eff}
Fit Bias	0.003	0.001	0.014	0.008	0.03	0.06	0.06	0.03
Isobar model	0.004	0.009	0.025	$^{+0.051}_{-0.024}$	0.00	0.01	0.01	0.03
Other	0.052	0.024	0.053	0.018	0.02	0.01	0.03	0.02
Total	0.053	0.026	0.060	$^{+0.055}_{-0.031}$	0.04	0.06	0.07	0.05

- Fit Bias: negligible in pure toy MC
  - Use values from fits to signal MC + toy background
  - Low-mass bias due to (unmodeled) resolution in KL
- Isobar model: vary model parameters by errors; replace BaBar’s $X_0(1550)$ w/Belle’s $f_X(1500)$
  - Motivation for low-mass fit: keep uncertainty in scalar sector from introducing a large systematic
- Other: Standard uncertainties in time-dependent analysis; largest contribution: conservative allowance for CP in background

$K^+K^-K^0$: Q2B Parameters

Results of DP fit translated to C and S using:

$$
\begin{aligned}
C &\equiv -A_{CP}, \text{ and} \\
-\eta S &\equiv \frac{1-b^2}{1+b^2}\sin(2\beta_{\mathit{eff}}),
\end{aligned}
$$

	C	$-\eta S$
Whole DP	$0.015 \pm 0.077 \pm 0.053$	$0.647 \pm 0.116 \pm 0.040$
High-mass	$0.054 \pm 0.102 \pm 0.060$	$0.764 \pm 0.111\ ^{+0.071}_{-0.040}$
(1) ϕK^0	$0.08 \pm 0.18 \pm 0.04$	$0.21 \pm 0.26 \pm 0.11$
(1) $f_0 K^0$	$-0.41 \pm 0.23 \pm 0.07$	$0.25 \pm 0.26 \pm 0.10$

$B^0 \rightarrow \rho^0 K_S$: Systematic Errors

	S	C	N
Mis-reco'd events and fit bias	0.12	0.09	10
PDF uncertainties	0.13	0.18	2
Tagging parameters	0.02	0.01	-
Neglect of intereference	0.14	0.09	7
ρ^0 mass shape	0.07	0.05	3
B Background BF	0.02	0.10	13
CP of background	0.04	0.00	-
Tracking efficiency & B counting	-	-	6
Total	0.24	0.20	19

TABLE II: Summary of contributions to the systematic error.