Measurements of β / ϕ_1 from $B^0 \to \eta' K^0$ and $B^0 \to \omega K_S^0$

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Outline

- Motivations;
- Experimental techniques;
- $B^0 \to \eta' K^0$ at BaBar and Belle;
- $B^0 \to \omega K_s^0$ at BaBar and Belle;
- Flavor-SU(3) modes related to $B^0 \to \eta' K^0$;
- Summary.

Standard-Model expectations

- $b \to s$ penguin dominated decays $B^0 \to \eta' K^0$ and $B^0 \to \omega K^0$ are sensitive to the CKM angle $\beta\,(\phi_1)$;

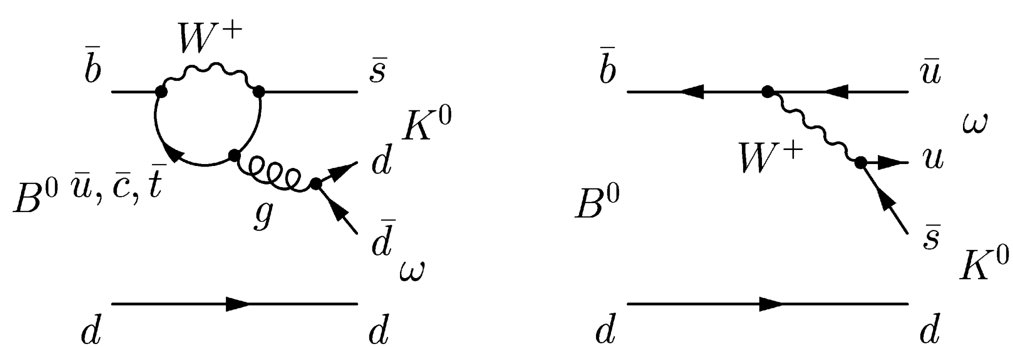
$$\mathcal{A}_f(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\overline{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)} = -C_f \cos(\Delta m_B \Delta t) + \underline{S_f} \sin(\Delta m_B \Delta t)$$

With only penguin amplitudes:

$S_f \simeq \sin 2\beta$

- However, the presence of color-suppressed tree amplitudes causes S_f to shift from $\sin 2\beta$;

Leading amplitudes for $B^0 \to \omega K_S^0$



- Verifying that $\Delta S_f = -\xi_f S_f - \sin 2\beta$ is within theory expectations is a crucial test for the validity of the Standard Model.

ξ_f = -1 for K_S, +1 for K_L

Estimates of Tree Pollution

- ΔS_f estimated/constrained using perturbative QCD, QCD factorization, and SCET;
- Also possible to get constraints on ΔS_f from SU(3) flavor symmetry: need experimental input from related decay modes;
- Small contribution of tree amplitude to $B^0 \to \eta' K^0$;
- Large contribution of tree amplitude to $B^0 \to \omega K^0$;

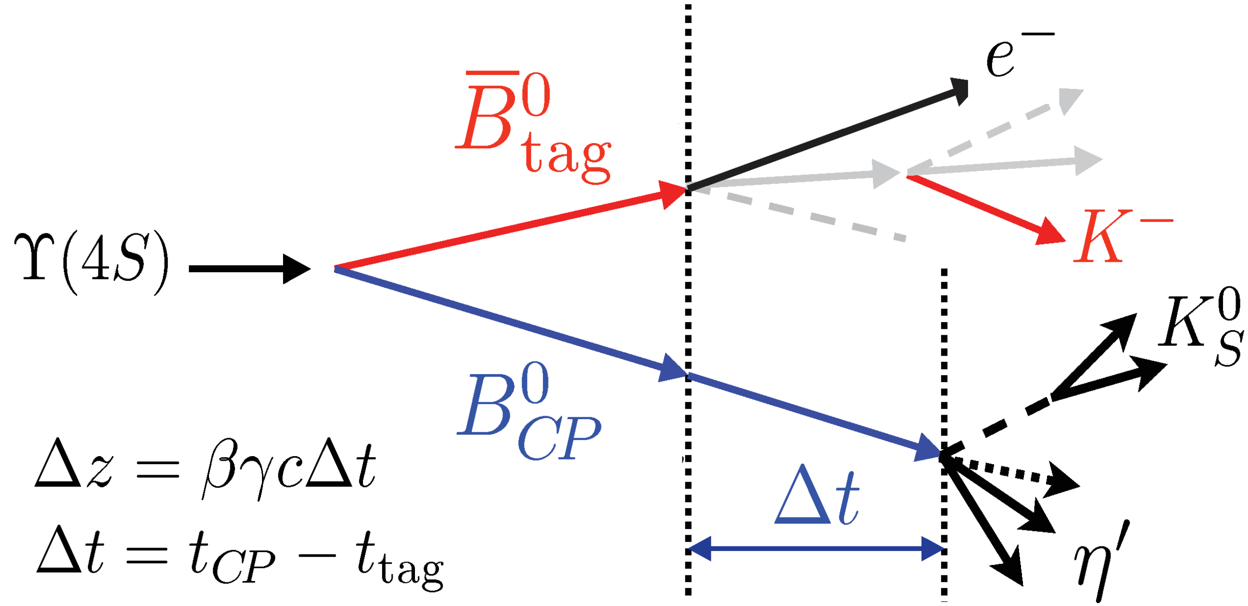
$$\boxed{\begin{array}{lcl} \Delta S_{\eta' K^0} & \in & [-0.03, +0.03] \\ \Delta S_{\omega K_S} & \in & [-0.0, +0.2] \end{array}}$$

C_f measures the direct CP-asymmetry: expected to be ~0.01 for $\eta' K^0$ and ~0.1 for ωK^0.

QCDF Beneke, PLB **620**, 143 (2005)
SCET/QCDF Williamson, Zupan, PRD **74**, 014003 (2006)
QCDF Cheng, Chua, Soni, PRD **72**, 014006 (2005)
SU(3) Gronau, Rosner, Zupan, PRD **74**, 093003 (2006)

Time dependent analysis

- Fully reconstruct B_{CP} , flavor-tag the other B ;
- Both BaBar and Belle use multivariate flavor-tagging algorithms;



$$\Delta z = \beta\gamma c \Delta t$$

$$\Delta t = t_{CP} - t_{\rm tag}$$

Effective tagging efficiency:

$Q = \varepsilon\,(1 - 2w)^2$

ε = efficiency

w = mistag probability

Q = (31.2 ± 0.3)% (BaBar)

Q = (29 ± 1)% (Belle)

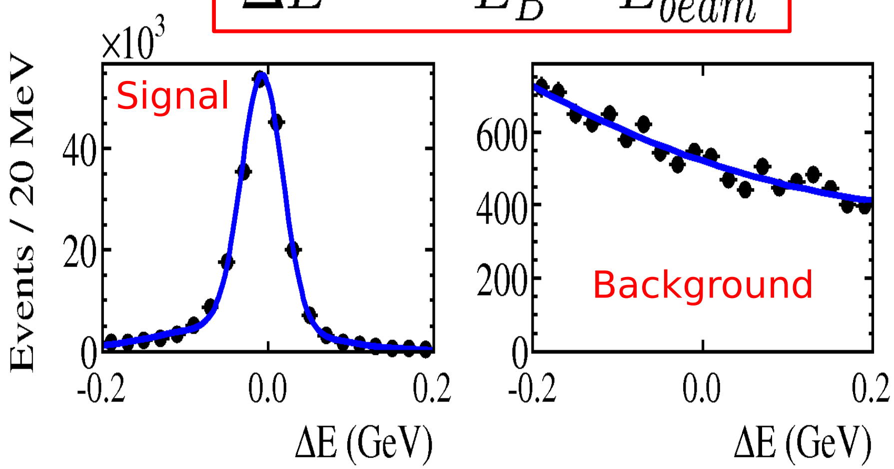
$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm \left(-\xi_f S_f \sin(\Delta m \Delta t) + C_f \cos(\Delta m \Delta t)\right)\right]$$

- $f_\pm$ modified for mistagging and Δt resolution. The relevant parameters are determined on a large sample of fully reconstructed self-tagging B decays.

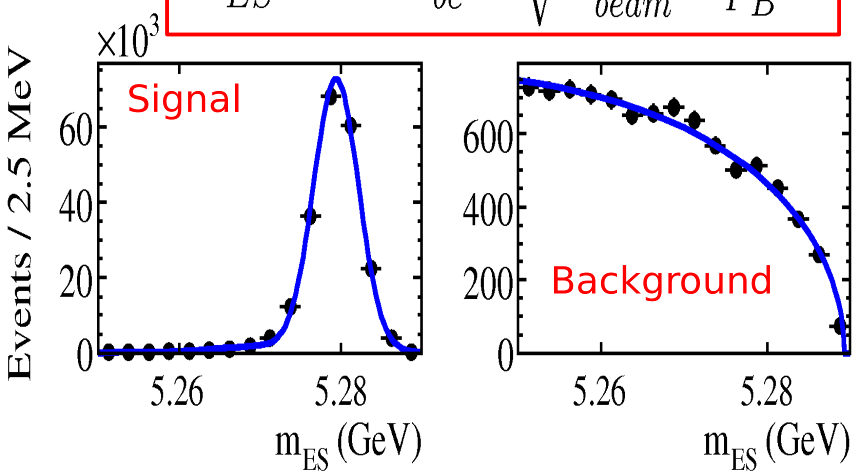
Background discrimination

- Dominant background: $q\bar{q}$ (q = u, d, s, c);
- Exploit B meson kinematics (well determined at B-factories) and event-shape ($q\bar{q}$ tends to be jet-like, while B decay products are 'spherical');

$$\Delta E = E_B - E_{beam}$$



$$m_{ES} = M_{bc} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$



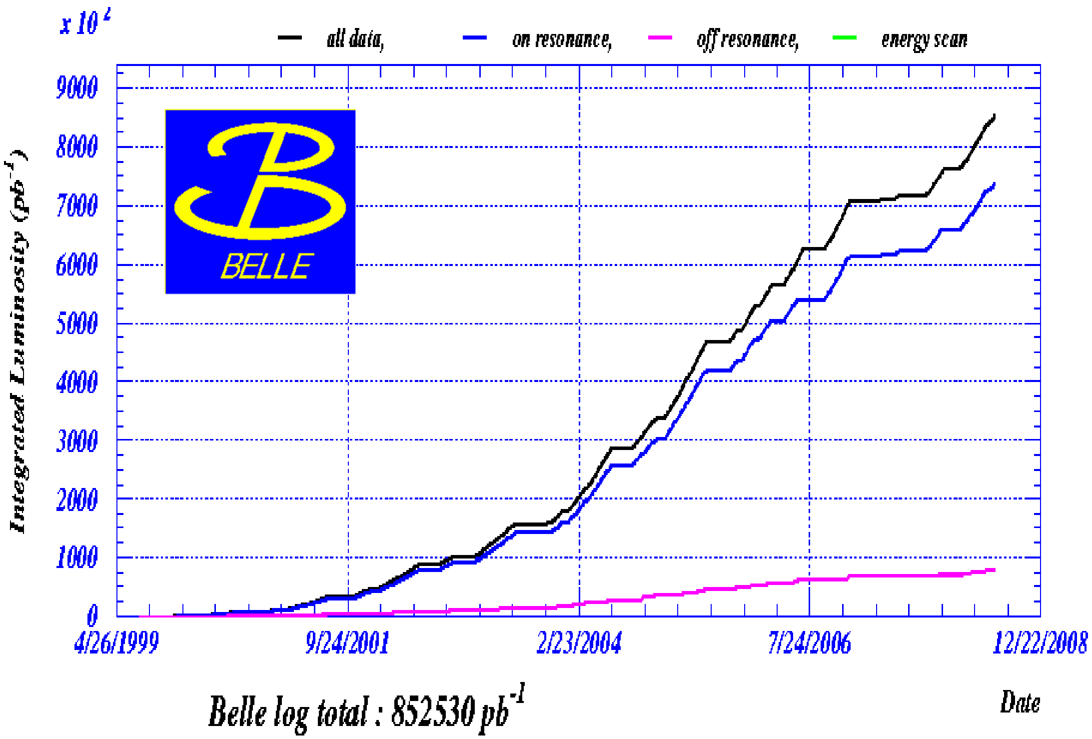
Signal from simulation, background from data sidebands

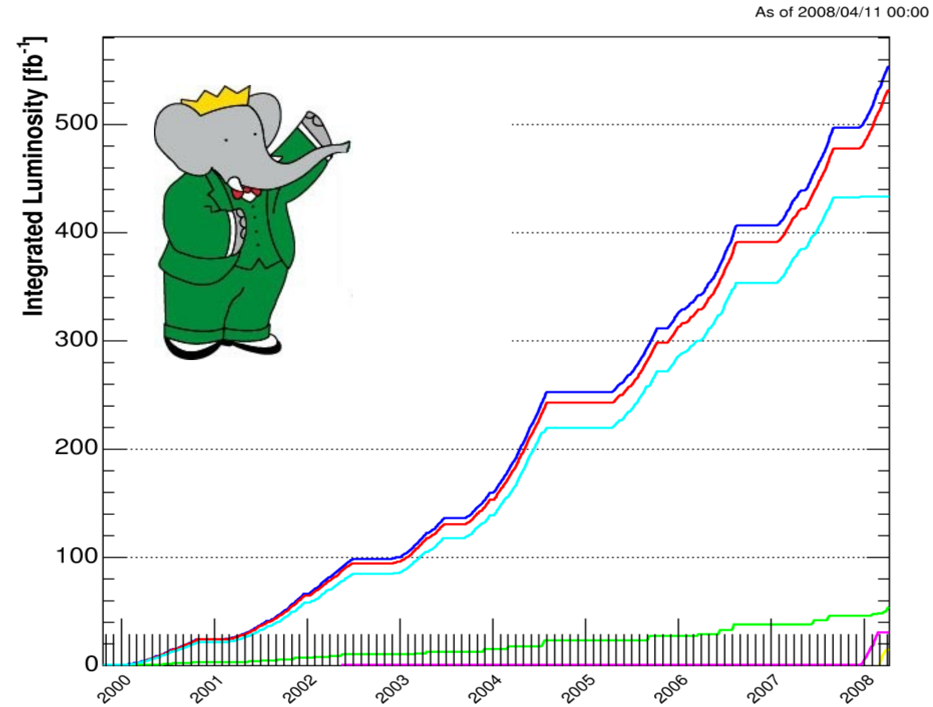
(from BaBar)

Event-shape discriminating variable:

Fisher discriminant $\mathcal{F}$ (BaBar) or Likelihood Ratio $\mathcal{R}_{s/b}$ (Belle) exploiting variables related to the event topology: Legendre or Fox-Wolfram moments, direction of momentum and thrust with respect to beam axis, ...

Datasets





Data taking still on-going:

Measurements presented today based on an integrated luminosity of **492 fb^{-1}**

Data taking ended on Apr 7th 2008:

BaBar's last word on $B^0 \to \eta' K^0$ and $B^0 \to \omega K_S^0$, based on the full Y(4S) sample (**425 fb^{-1}**)

$B^0 \to \eta' K^0$

- Pretty high Branching Fraction: $(65 \pm 4) \times 10^{-6}$;
- Both BaBar and Belle reconstruct 7 final states:

$$\eta'(\rho\gamma,\ \eta_{\gamma\gamma}\,\pi^+\pi^-,\ \eta_{3\pi}\,\pi^+\pi^-)K^0_S\,(\pi^+\pi^-)$$
$$\eta'(\rho\gamma,\ \eta_{\gamma\gamma}\,\pi^+\pi^-)K^0_S\,(\pi^0\pi^0)$$
$$\eta'(\eta_{\gamma\gamma}\,\pi^+\pi^-,\ \eta_{3\pi}\,\pi^+\pi^-)K^0_L$$

- Unbinned Maximum Likelihood Fit to the variables:

BaBar	Belle
ΔE, m_{ES}, Fisher	ΔE, M_{bc}, $\mathcal{R}_{s/b}$
K_L modes: drop m_{ES}	K_L modes: drop ΔE

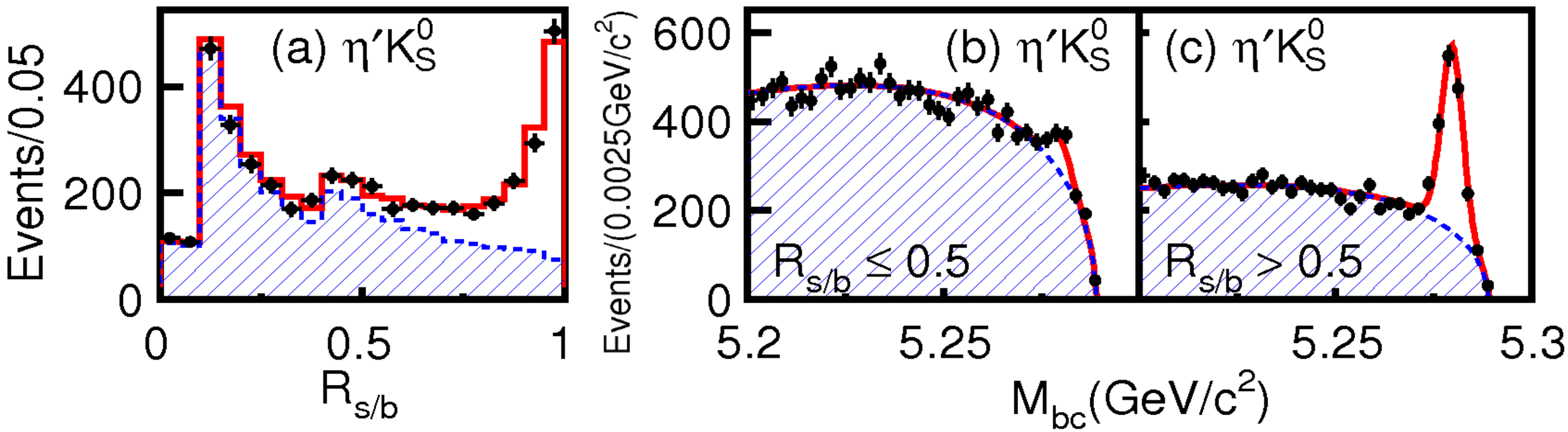
- Dominant background: $q\bar{q}$ events, modeled from data sidebands;
- $B\bar{B}$ background component modeled from the simulation.

535M $B\bar{B}$

$B^0 \to \eta' K^0$

Belle Collaboration, PRL **98**, 031802 (2007)

Mode-dependent cuts applied on ΔE



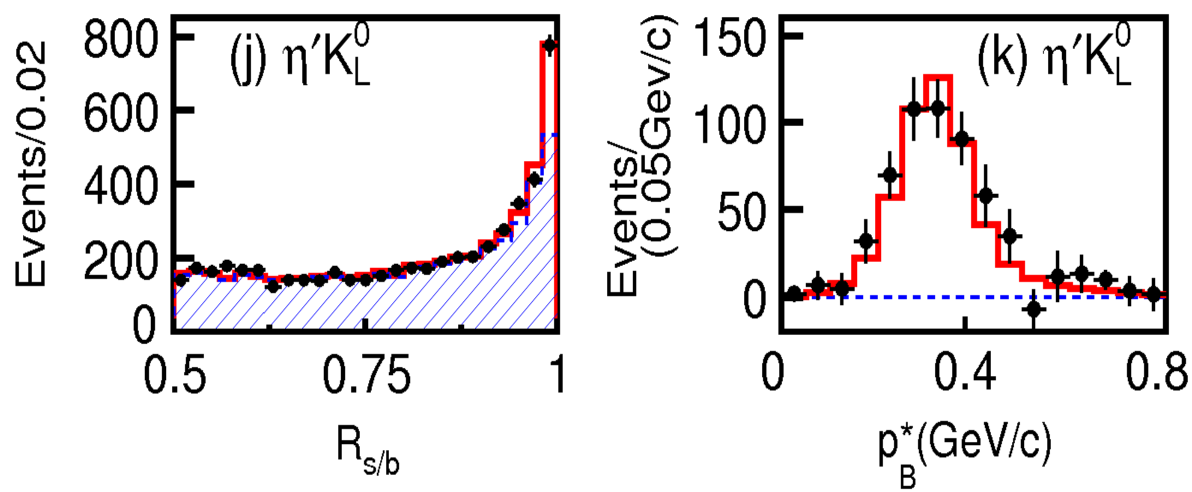
All
Background

Signal yields:

$\eta' K_S$: 1421 ± 46

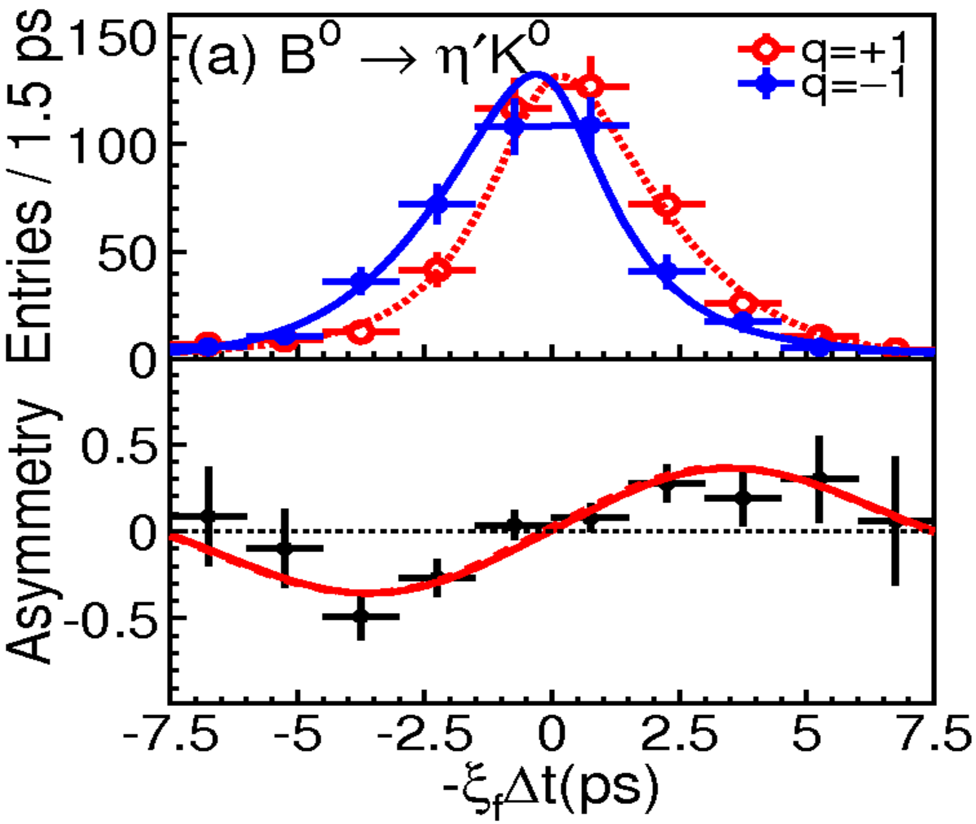
$\eta' K_L$: 454 ± 39

total: 1875 ± 60



535M $B\bar{B}$

$B^0 \rightarrow \eta' K^0$



Maximum Likelihood fit simultaneously to K_S and K_L:

$$-\xi_{\eta' K^0} S_{\eta' K^0} = 0.64 \pm 0.10 \pm 0.04$$

$$C_{\eta' K^0} = 0.01 \pm 0.07 \pm 0.05$$

Separating K_S from K_L:

$$-\xi_{\eta' K_S} S_{\eta' K_S} = 0.67 \pm 0.11$$

$$C_{\eta' K_S} = 0.03 \pm 0.07$$

$$-\xi_{\eta' K_L} S_{\eta' K_L} = 0.46 \pm 0.24$$

$$C_{\eta' K_L} = -0.09 \pm 0.16$$

Dominant systematic uncertainties:

S: uncertainties on resolution function

C: interference from DCSD on tag side

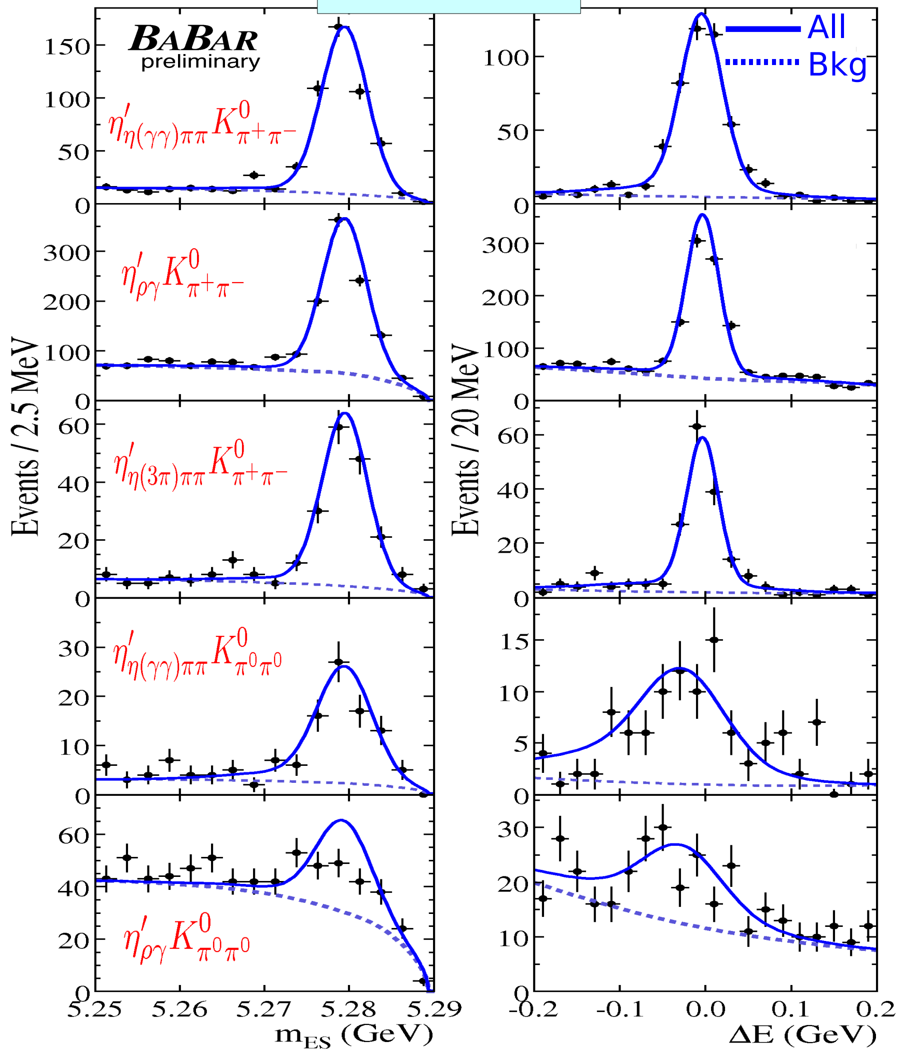
467M $B\bar{B}$

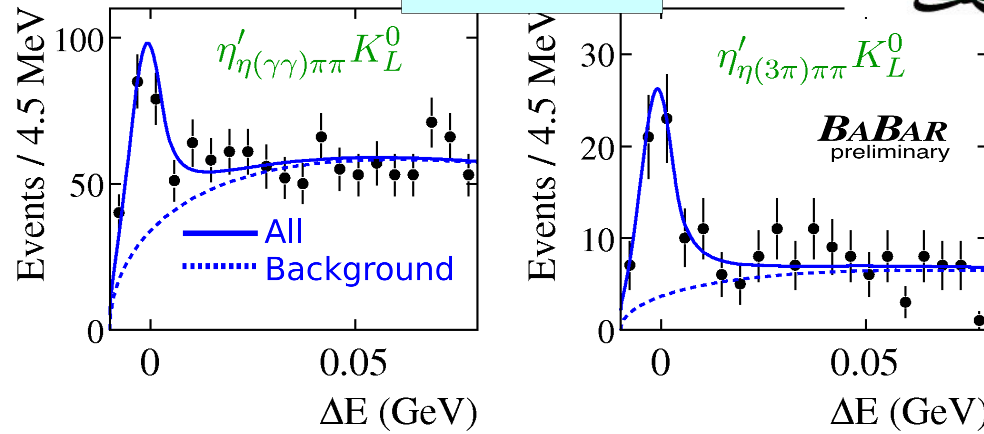
$B^0 \to \eta' K^0$

K_S modes

Signal enhanced projection plots

K_L modes





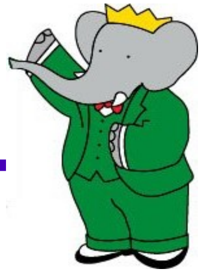
K_L modes: purity of the sample further improved by a Neural Network which exploits variables related to the shape of the clusters in the calorimeter

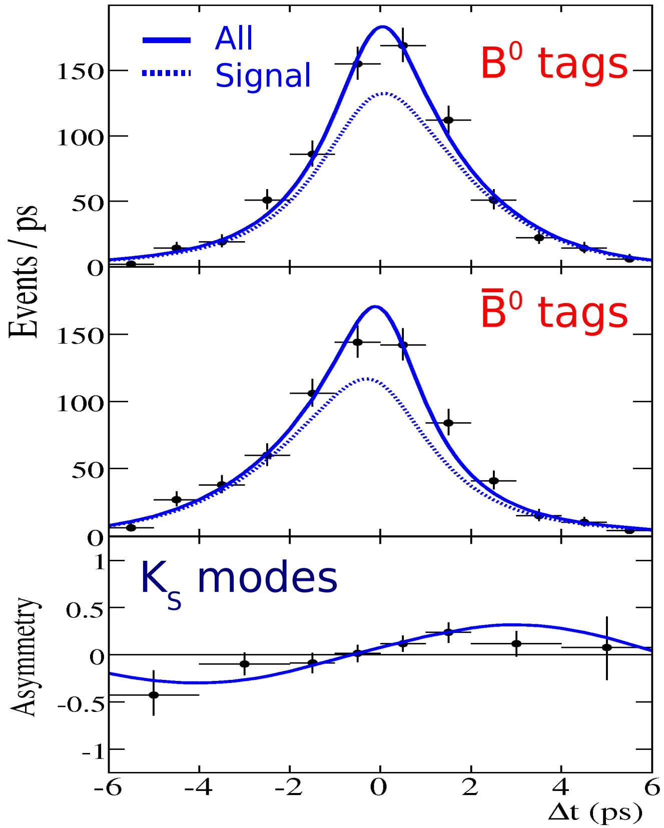
Signal yields (flavor tagged):

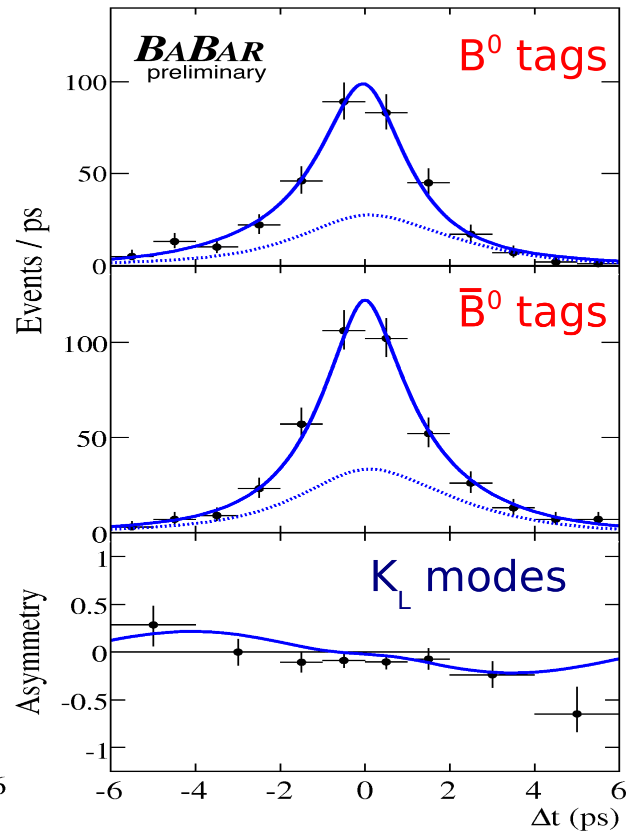
$\eta' K_S$:	1959 ± 58 (1457 ± 43)
$\eta' K_L$:	556 ± 38 (341 ± 23)
total:	2515 ± 69 (1798 ± 49)

BaBar Collaboration, arXiv 0809.1174 [hep-ex] submitted to PRD

$B^0 \to \eta' K^0$







Maximum Likelihood fit separately to K_S and K_L modes:

$$-\xi_{\eta' K_S} S_{\eta' K_S} = 0.53 \pm 0.08 \pm 0.02$$
$$C_{\eta' K_S} = -0.11 \pm 0.06 \pm 0.02$$

$$-\xi_{\eta' K_L} S_{\eta' K_L} = 0.82 \pm 0.19 \pm 0.02$$
$$C_{\eta' K_L} = 0.09 \pm 0.14 \pm 0.02$$

Final results computed through scans of -2 ln $\mathcal{L}$:

Dominant systematic uncertainties:

S: $B\bar{B}$ background and resolution model

C: Interference from DCSD on tag side

$$\boxed{\begin{aligned} -\xi_{\eta' K^0} S_{\eta' K^0} &= 0.57 \pm 0.08 \pm 0.02 \\ C_{\eta' K^0} &= -0.08 \pm 0.06 \pm 0.02 \end{aligned}}$$

$B^0 \to \omega K_S^0$

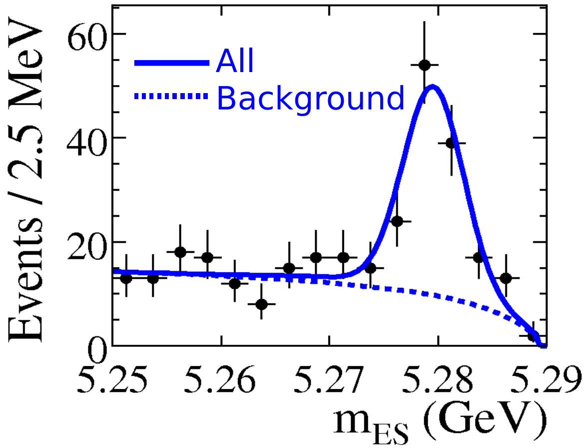
- Branching Fraction ~5.5 x 10^{-6};
- Only usable decay mode: $\omega \;\to\; \pi^+\pi^-\pi^0, K_S \;\to\; \pi^+\pi^-$;
- Discriminating variables:

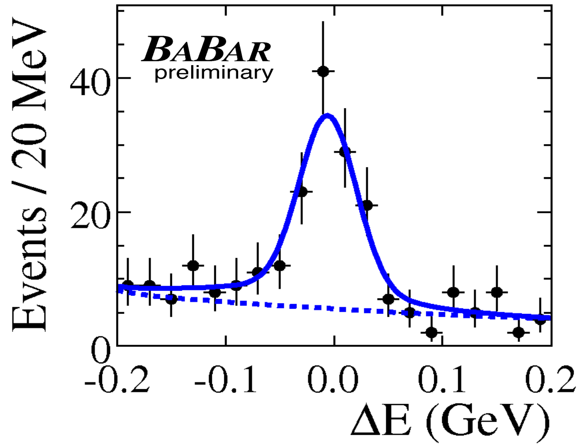
m_{ES} ΔE Fisher ω mass ω helicity	M_{bc} ΔE $\mathcal{R}_{s/b}$ ω mass

- Dominant background: $q\bar{q}$ events, modeled from data sidebands;
- $B\bar{B}$ background component modeled from the simulation.

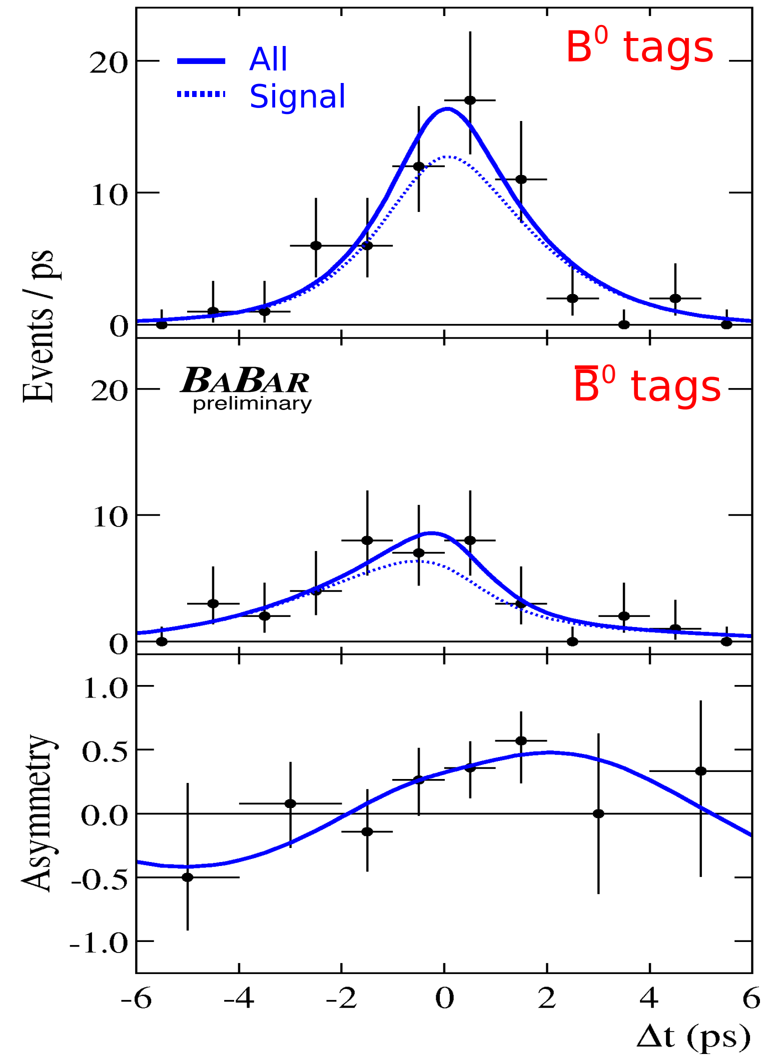
467M $B\bar{B}$

$B^0 \to \omega K_S^0$





Signal enhanced projection plots



Signal yield: **163 ± 18** (**121 ± 13** flavor tagged) events

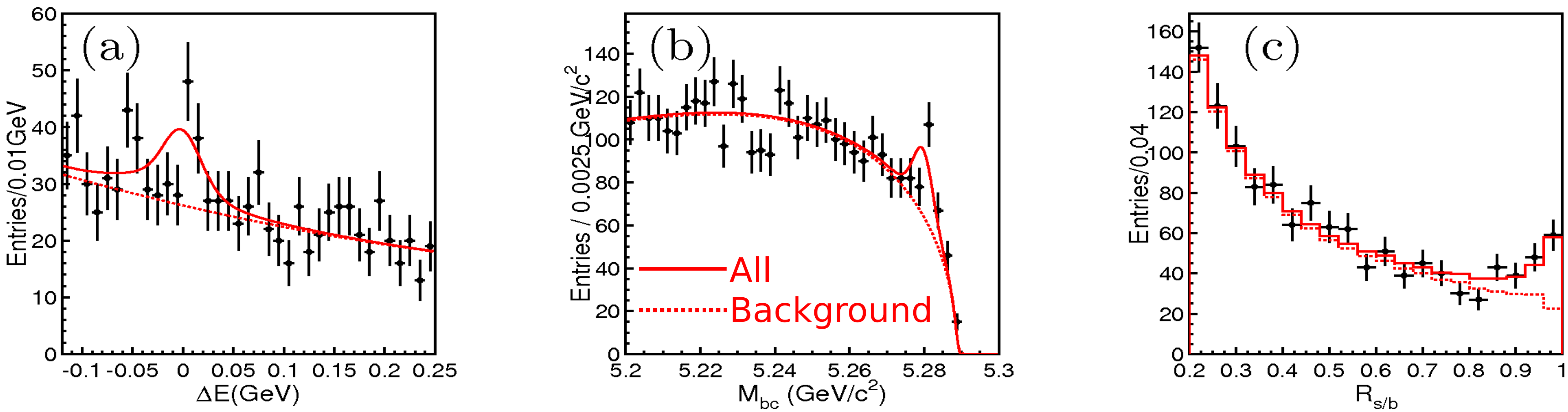
Results on the CP-violation parameters:

$$
\begin{aligned}
-\xi_{\omega K_S} S_{\omega K_S} &= 0.55^{+0.26}_{-0.29} \pm 0.02 \\
C_{\omega K_S} &= -0.52^{+0.22}_{-0.20} \pm 0.03
\end{aligned}
$$

BaBar Collaboration, arXiv 0809.1174 [hep-ex] submitted to PRD

535M $B\bar{B}$

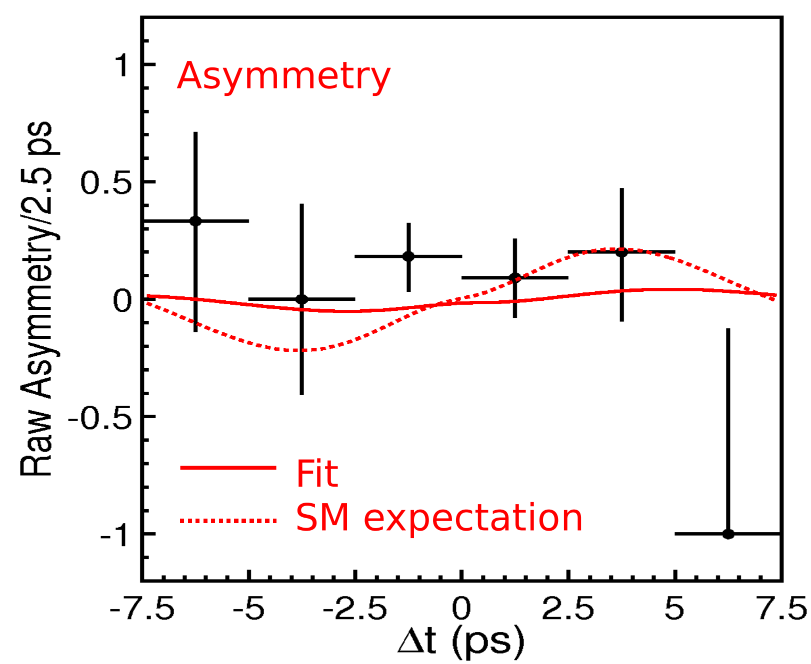
$B^0 \to \omega K_S^0$



Signal yield: **118 ± 18** events

Results on the CP-violation parameters:

$$\boxed{\begin{aligned} -\xi_{\omega K_S} S_{\omega K_S} &= 0.11 \pm 0.46 \pm 0.07 \\ C_{\omega K_S} &= 0.09 \pm 0.29 \pm 0.06 \end{aligned}}$$



Belle Collaboration, PRD **76** 091103 (2007)

SU(3) related channels

- The decay amplitude for $B^0 \to \eta' K^0$ can be written as:

$$\boxed{A(B^0 \to \eta' K^0) = A'_P + A'_C = |A'_P|e^{i\delta} + |A'_C|e^{i\gamma}}$$

A_P: amplitudes containing $V_{cb}^* V_{cd}$
A_C: amplitudes containing $V_{ub}^* V_{ud}$
δ : strong phase
γ : CKM angle

$$\begin{aligned} S_{\eta' K} &= \frac{\sin 2\beta + 2|A'_C/A'_P|\cos\delta\sin(2\beta+\gamma) - |A'_C/A'_P|^2\sin(2\alpha)}{R_{\eta' K}} \\ C_{\eta' K} &= \frac{2|A'_C/A'_P|\sin\delta\sin\gamma}{R_{\eta' K}} \\ R_{\eta' K} &\equiv 1 + 2|A'_C/A'_P|\cos\delta\cos\gamma + |A'_C/A'_P|^2 \end{aligned}$$

- Using the flavor-SU(3) decomposition, A'_P/A'_C can be expressed in terms of SU(3) related amplitudes, and bound:

$$\frac{|\mathcal{R} - \bar{\lambda}^2|}{1+\mathcal{R}} \leq |A'_C/A'_P| \leq \frac{\mathcal{R} + \bar{\lambda}^2}{1-\mathcal{R}}$$

$$\mathcal{R}^2 \equiv \frac{\bar{\lambda}^2[|\Sigma_f a_f A(f)|^2 + |\Sigma_f a_f \bar{A}(f)|^2]}{|A(B^0 \to \eta' K^0)|^2 + |A(\bar{B}^0 \to \eta' \bar{K}^0)|^2}$$

λ : sine of Cabibbo angle
f : SU(3) related final state

SU(3) related channels

- Among the several relations that can be used:

1)
$$\Sigma_f a_f A(f) = \frac{1}{4\sqrt{3}}A(\pi^0\pi^0) - \frac{1}{3}A(\pi^0\eta) + \frac{5}{6\sqrt{2}}A(\pi^0\eta') + \frac{2}{3\sqrt{3}}A(\eta\eta) - \frac{11}{12\sqrt{3}}A(\eta'\eta') - \frac{5}{3\sqrt{3}}A(\eta\eta')$$

Y. Grossman, Z. Ligeti, Y. Nir, H. Quinn
PRD **68**, 074012 (2003)

2)
$$\Sigma_f a_f A(f) = -\frac{5}{6}A(\pi^0\eta) + \frac{1}{3\sqrt{2}}A(\pi^0\eta') - \frac{\sqrt{3}}{2}A(\eta\eta')$$

M. Gronau, J. L. Rosner, J. Zupan
PRD 74, 014003 (2006)

2) Assumes exchange and penguin annihilation to be negligible

- Using the available experimental information, GRZ quote:

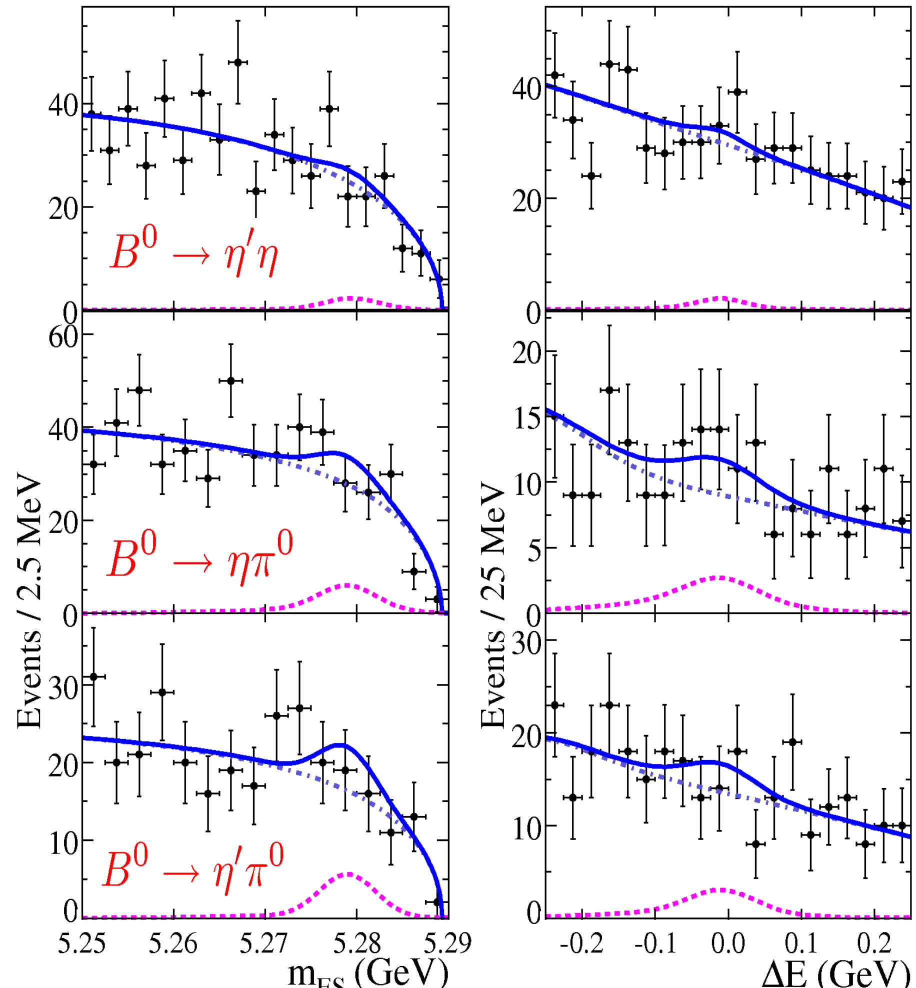
1) $\mathcal{R} < 0.116$	2) $\mathcal{R} < 0.070$
$-0.133 < \Delta S_{\eta' K_S} < 0.152$	$-0.046 < \Delta S_{\eta' K_S} < 0.094$

459M $B\bar{B}$

SU(3) related channels

- BaBar searched for $B^0 \to \eta'\eta$, $B^0 \to \eta\pi^0$ and $B^0 \to \eta'\pi^0$ with the full dataset;

Mode	$\mathcal{B}(10^{-6})$ (90% C.L. upper limit)
$B^0 \to \eta'\eta$	$0.5 \pm 0.4 \pm 0.1$ (< 1.2)
$B^0 \to \eta\pi^0$	$0.9 \pm 0.4 \pm 0.1$ (< 1.5)
$B^0 \to \eta'\pi^0$	$0.9 \pm 0.4 \pm 0.1$ (< 1.5)



- Improvement by a factor ~1.5 on the upper limit of $\eta'\eta$ with respect to previous results, no improvement on $\eta\pi^0$ and $\eta'\pi^0$.

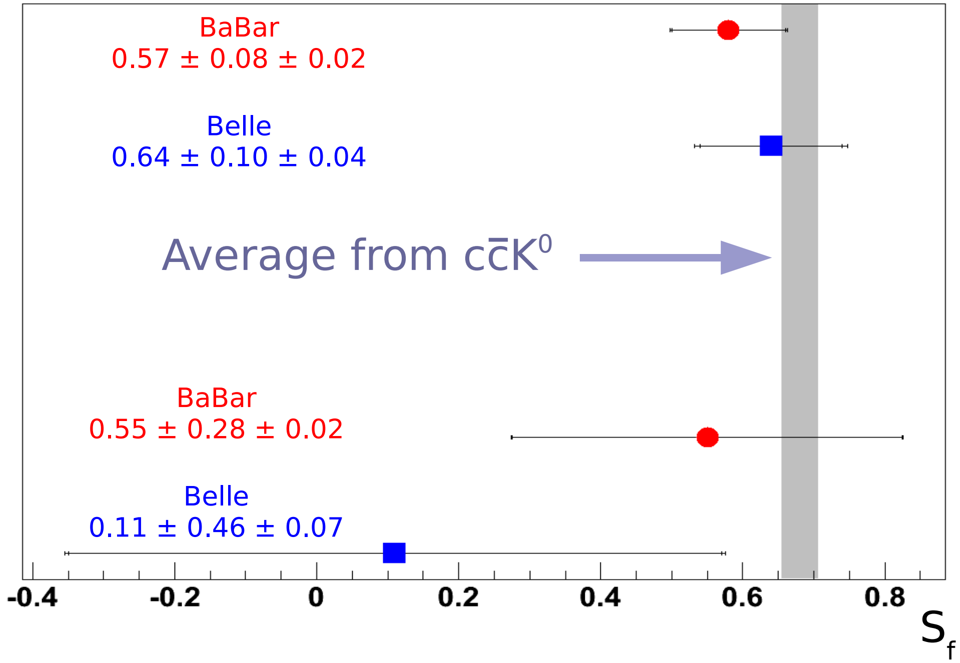
Theory predictions:

Mode	SU(3)	QCD fact.	SCET	PQCD
$B^0 \to \eta'\eta$	1.2 ± 0.1	$0.3^{+0.6}_{-0.2}$	2^{+6}_{-2}	–
$B^0 \to \eta'\pi^0$	1.0 ± 0.1	$0.4^{+0.3}_{-0.2}$	2^{+3}_{-1}	$0.2^{+0.2}_{-0.1}$
$B^0 \to \eta\pi^0$	1.0 ± 0.1	$0.3^{+0.5}_{-0.3}$	1 ± 1	0.2 ± 0.1

BaBar Collaboration, PRD-RC **78** 011107 (2008)

Conclusions

- BaBar and Belle get consistent results on the CP-violation parameters for $B^0 \to \eta' K^0$ and $B^0 \to \omega K_S^0$, no significant discrepancy with the Standard Model is seen;



$\eta' K^0$

ωK_S

- Some progress on flavor-SU(3) bounds, but probably we are getting close to the limits of the method.

Backup Slides

SU(3) related channels

Modes related to through SU(3) flavor symmetry:

$$
\begin{aligned}
A(B^0 \to K^+K^-) &= -e - pa \\
A(B^0 \to K^0\bar{K}^0) &= p + pa \\
\sqrt{2}A(B^0 \to \pi^0\pi^0) &= p - c + e + pa \\
\sqrt{6}A(B^0 \to \pi^0\eta) &= -2p - s + 2e \\
\sqrt{3}A(B^0 \to \pi^0\eta') &= p + 2s - e \\
(3/\sqrt{2})A(B^0 \to \eta\eta) &= p + s + c + e + (3/2)pa \\
3\sqrt{2}A(B^0 \to \eta'\eta') &= p + 4s + c + e + 3pa \\
3\sqrt{2}A(B^0 \to \eta\eta') &= -2p - 5s - 2c - 2e
\end{aligned}
$$

p: penguin
s: singlet penguin
c: color suppressed
e: exchange
pa: penguin annihilation

SU(3) related channels

More experimental results:

$$BR(B^0 \longrightarrow \eta\eta) = (0.8 \pm 0.4 \pm 0.1) \times 10^{-6} \qquad (< 1.4)$$

$$BR(B^0 \longrightarrow \eta'\eta') = (0.9^{+0.8}_{-0.7} \pm 0.1) \times 10^{-6} \qquad (< 2.1)$$

Preliminary result presented at **FPCP**, Taipei 2008

$$BR(B^0 \longrightarrow \pi^0\pi^0) = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$$

arXiv: 0807.4226 [hep-ex]

$B^0 \to \omega K_S^0$

- Selection:

Belle	BaBar
$5.27 < M_{bc} < 5.29$ GeV $-0.10 < \Delta E < 0.08$ GeV	$5.25 < m_{ES} < 5.29$ GeV $-0.20 < \Delta E < 0.20$ GeV
$468 < m(K_S^0) < 528$ MeV	$486 < m(K_S^0) < 510$ MeV
$E(\gamma) > 50$ MeV $118 < m(\gamma\gamma) < 150$ MeV $p^*(\pi^0) > 350$ MeV	$E(\gamma) > 50$ MeV $120 < m(\gamma\gamma) < 150$ MeV $E(\pi^0) > 250$ MeV
$752 < m(\omega) < 812$ MeV	$735 < m(\omega) < 825$ MeV

$B^0 \to \omega K_S^0$

ΔE

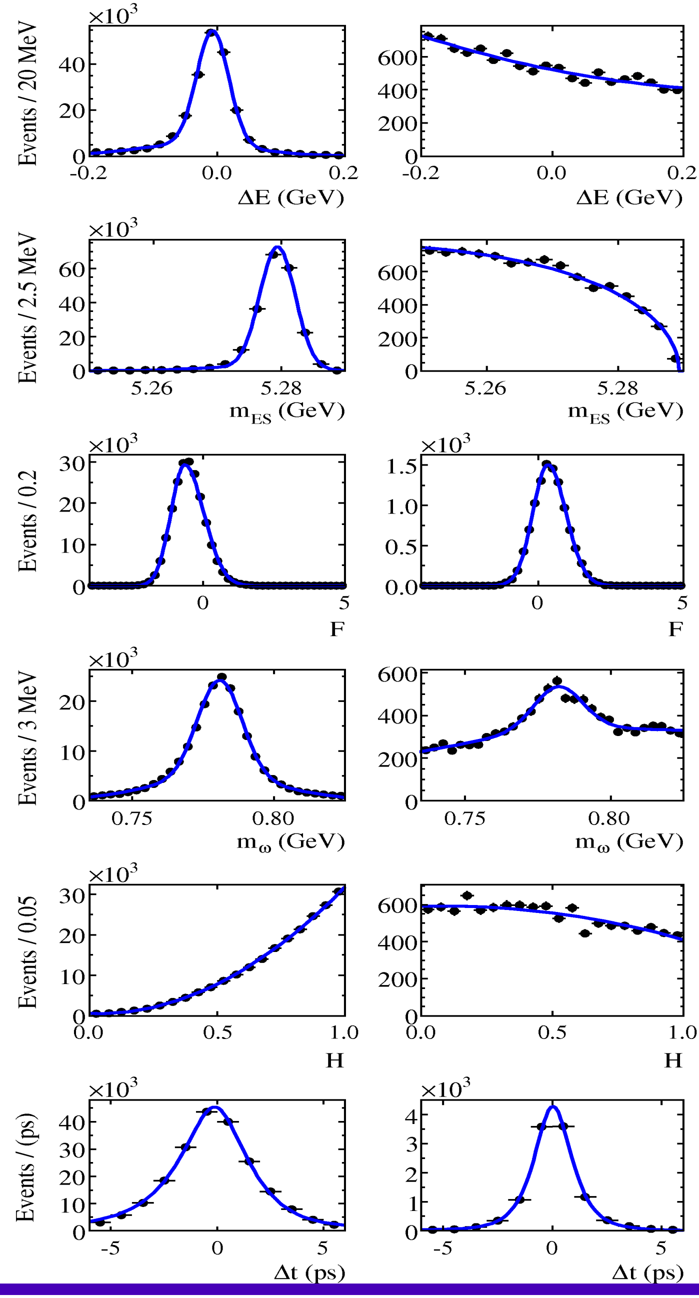
m_{ES}

Fisher

$m(\omega)$

$H(\omega)$

Δt



Signal (MC) Background (data sidebands)