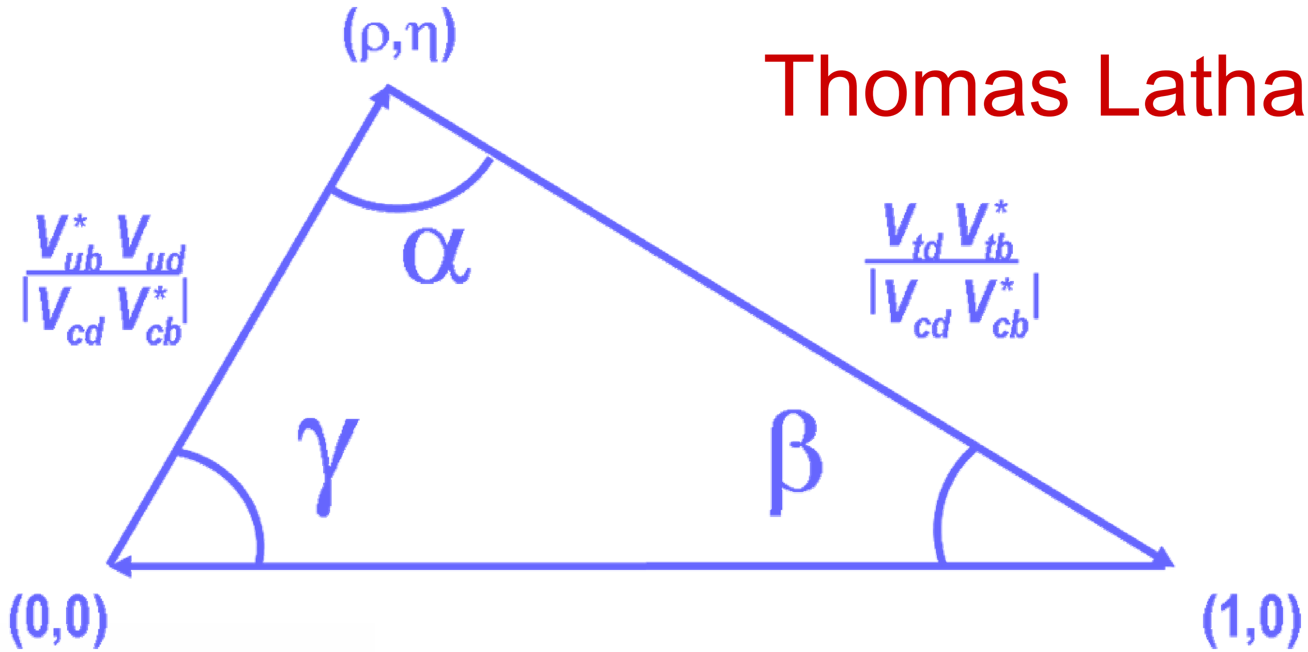
Unitarity Triangle Angle Measurements at BaBar



Thomas Latham

THE UNIVERSITY OF WARWICK

Les Rencontres de Physique de la Vallée d'Aoste, La Thuile, Feb 27 – Mar 5 2005

Overview

- CKM Matrix and the Unitarity Triangle
- Overview of BaBar Detector
- Analysis Techniques
  - Time dependent *CP* analysis
  - Discriminating variables
- Measuring β
- Measuring α
- Measuring γ
- Conclusions

CKM Matrix and the Unitarity Triangle

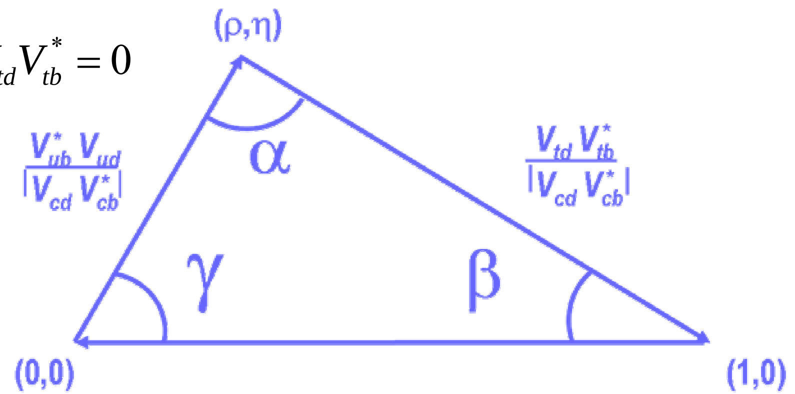
- Cabibbo-Kobayashi-Maskawa mixing matrix
  - relates weak (q') and mass (q) eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

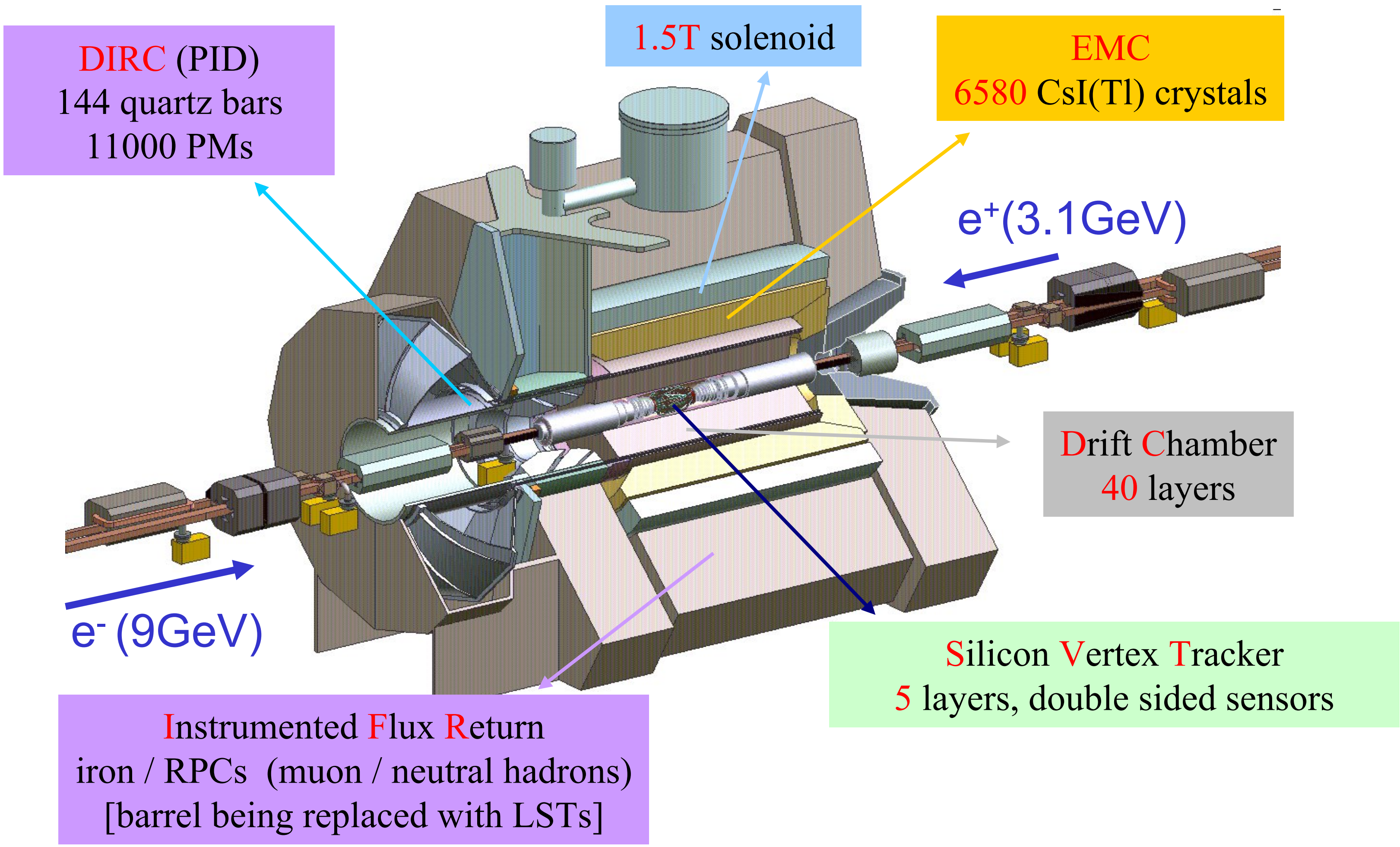
- Wolfenstein parameterisation
  - 4 parameters A, λ, ρ, η
  - *CP* violation from imaginary parameter η

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Unitarity Relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - represented as a triangle
  - sides of same order
  - area proportional to amount of *CP* violation

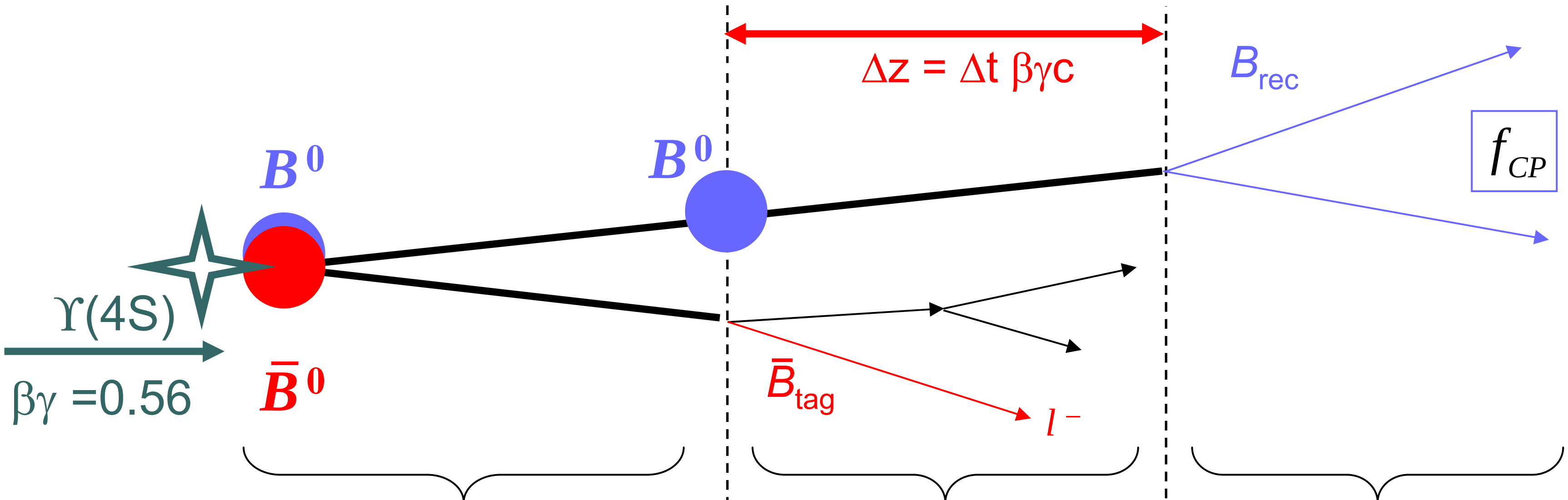


The BaBar Detector



Time Dependent Formalism

One B meson is fully reconstructed in a *CP*-eigenstate.
The time difference (Δt) between the two B decays must be known as well as the flavour of the reconstructed B at the time of the other B's decay.



Two mesons oscillate coherently : at given time, if one is a B^0 the other is <u>necessarily</u> a $\bar{B}^0$

Tag-side meson decays semi-leptonically; charge of lepton gives the flavour of the tag-side meson:

$$l^+ \Rightarrow B^0 \quad l^- \Rightarrow \bar{B}^0$$

At time Δt later, the B^0 (which could by now have oscillated into a $\bar{B}^0$) decays.

Time Dependent Analysis

Time evolution of $B^0 / \overline{B}^0$ asymmetry:

$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = \eta S_{f_{CP}} \sin(\Delta m_d \Delta t) - \eta C_{f_{CP}} \cos(\Delta m_d \Delta t)$$

$\Delta m_d = 0.502 \pm 0.006\,\mathrm{ps}^{-1}$

$\eta = +1(-1)$ for $B^0(\overline{B}^0)$

$$S_{f_{CP}} = \frac{2\,\mathrm{Im}(\lambda_{f_{CP}})}{1+|\lambda_{f_{CP}}|^2}$$

$S \neq 0$: *CPV* in interference between mixing and decay

$$C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}$$

$C \neq 0$: Direct *CPV*

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

Decay Amplitudes

from mixing:

$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$

$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$

Coefficient S sensitive to CKM angles:

Only 1 decay amplitude:

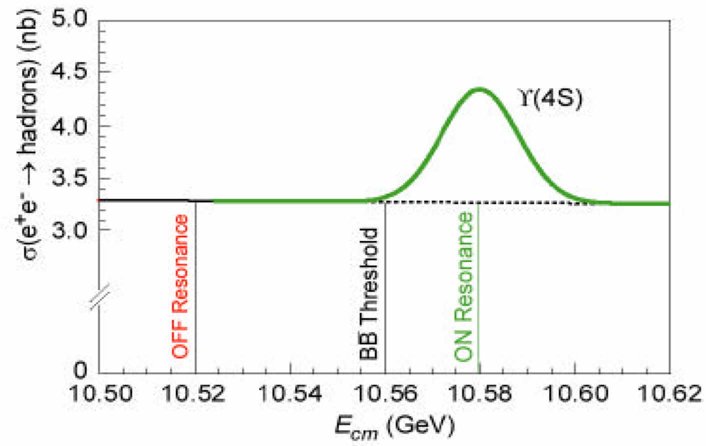
- $C_{f_{CP}} = 0$
- $S_{f_{CP}} = \mathrm{Im}(\lambda_{f_{CP}})$
- e.g. $= \sin(2\beta)$

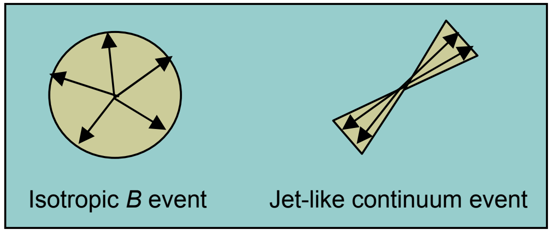
> 1 decay amplitude:

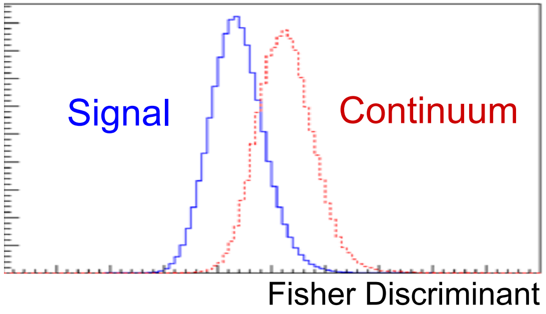
- $C_{f_{CP}} \neq 0$
- $S_{f_{CP}}$ not trivially related to CKM angles
- e.g. $= \sin(2\alpha_{eff})$

Analysis Variables – Topological

- Light quark continuum cross section ~3x $b\bar{b}$
- B mesons produced almost at rest since just above threshold
- Use event topology to discriminate
- Combine variables in a Fisher discriminant or neural network



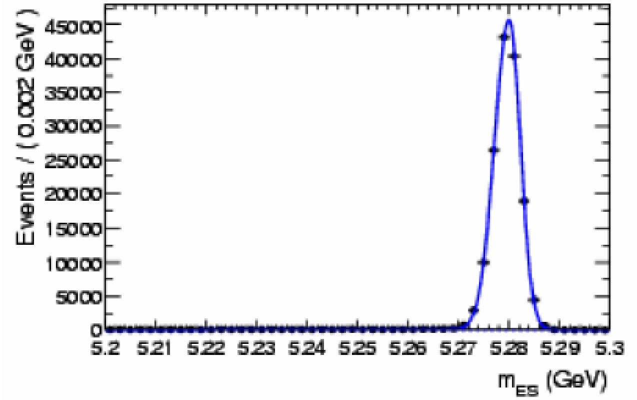


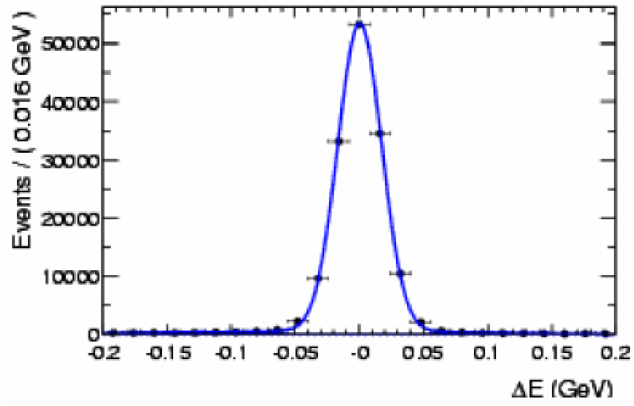


Analysis Variables – Kinematic

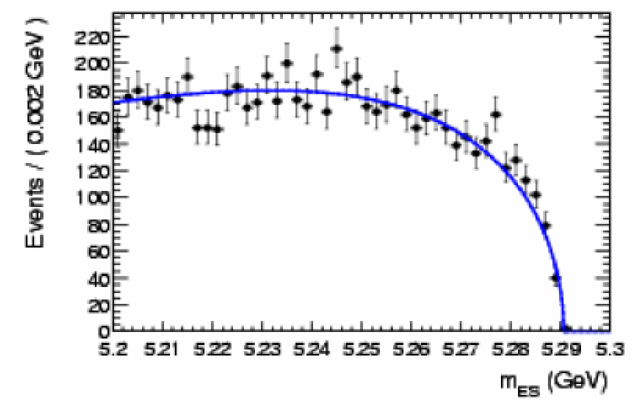
Make use of precision kinematic information from the beams.

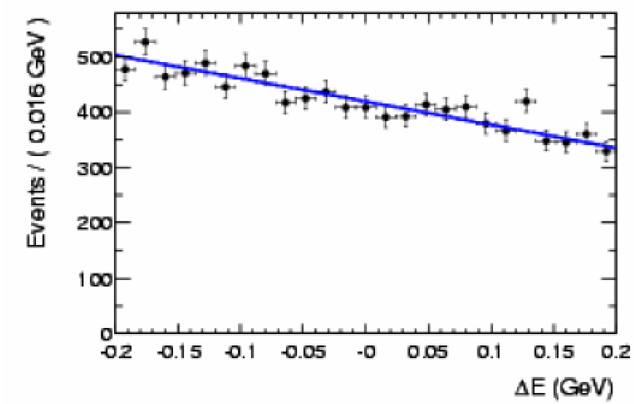
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}} \qquad \Delta E = E_B^* - E_{beam}^*$$





Signal Distributions





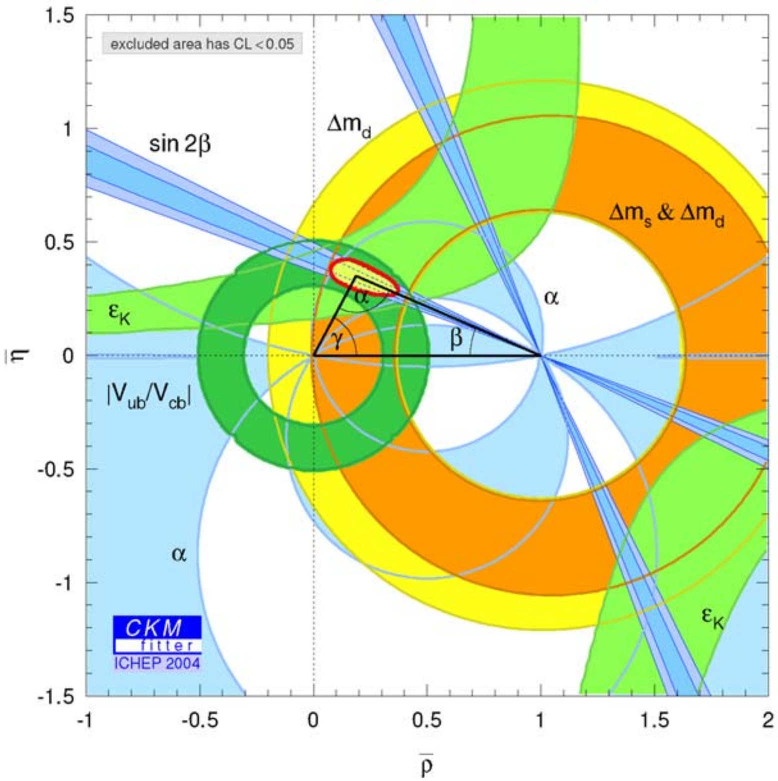
Continuum Distributions

CKM Angle β

- $\sin(2\beta)$ well measured in charmonium modes – only 1 weak phase, clean measurement
- Looking for new physics measuring $\sin(2\beta)$ in $b \to s$ "penguin" loop modes: $\phi K_S^0, K_S^0 K_S^0 K_S^0$ etc.
- Also measure $\cos(2\beta)$ in order to resolve the 4-fold ambiguity

$$\sin(2\beta) = 0.722 \pm 0.040 \pm 0.023$$

BaBar result from 227 million $B\bar{B}$ pairs (combined fit to all charmonium modes)



$\sin(2\beta)$ in $B^0 \to \phi K^0$ & $B^0 \to K^+K^-K^0_S$ (preliminary)

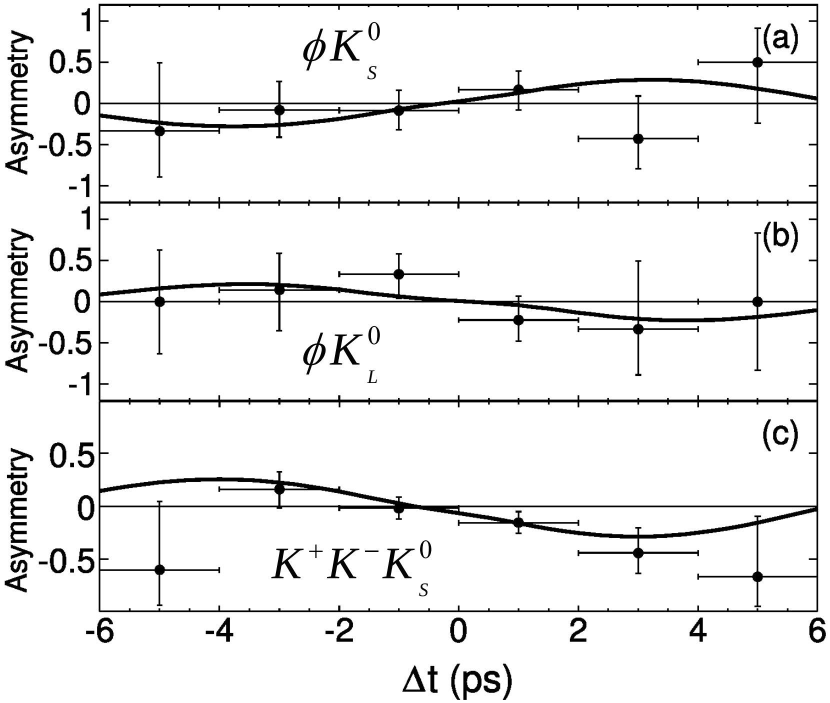
$B^0 \to \phi K^0$

- Combination of K_S and K_L modes
- 227 million $B\overline{B}$ pairs
- 1st error statistical, 2nd systematic

$$\sin(2\beta_{eff}) = 0.50 \pm 0.25^{+0.07}_{-0.04}$$
$$C_{\phi K^0} = 0.00 \pm 0.23 \pm 0.05$$

$B^0 \to K^+K^-K^0_S$

- Consider whole Dalitz plot excluding ϕ region (15MeV)
- Moments analysis using sPlots technique (physics/0402083) determines the *CP*-even fraction: $f_{CP-even} = 0.89 \pm 0.08 \pm 0.06$
- 3rd error from *CP*-even fraction uncertainty

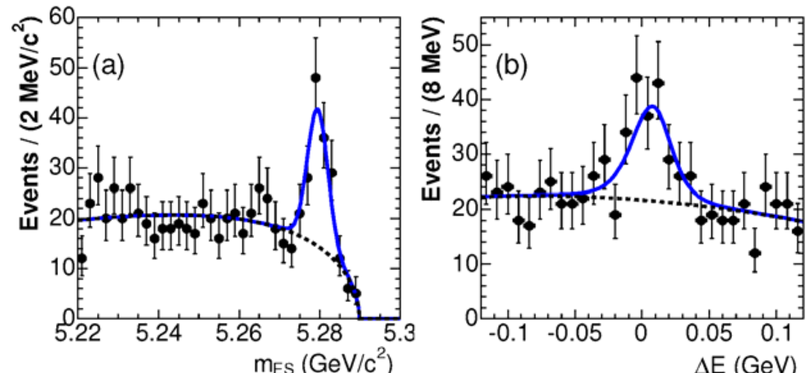


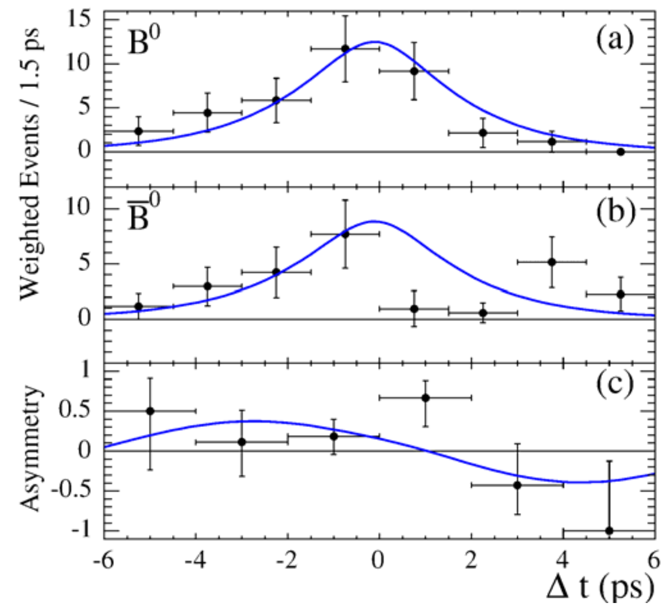
$$\sin(2\beta_{eff}) = 0.55 \pm 0.22 \pm 0.04 \pm 0.11$$

$\sin(2\beta)$ in $B^0 \to K_S^0 K_S^0 K_S^0$ (preliminary)

- Like $B^0 \to \phi K_S^0$ has been noted to have small theoretical uncertainty
- Pure *CP*-even state
- Requires beam-spot constraint vertexing
- Results with 227M $B\bar{B}$ pairs:
  - $BF = \left(6.9^{+0.9}_{-0.8} \pm 0.6\right) \times 10^{-6}$
  - $S = -0.71^{+0.38}_{-0.32} \pm 0.04$
  - $C = -0.34^{+0.28}_{-0.25} \pm 0.05$
- Assuming single penguin amplitude ($C = 0$):

$$\sin\left(2\beta_{eff}\right) = 0.79^{+0.29}_{-0.36} \pm 0.04$$





Consistent with the SM at precision comparable with other penguin modes

sin(2β) Comparison

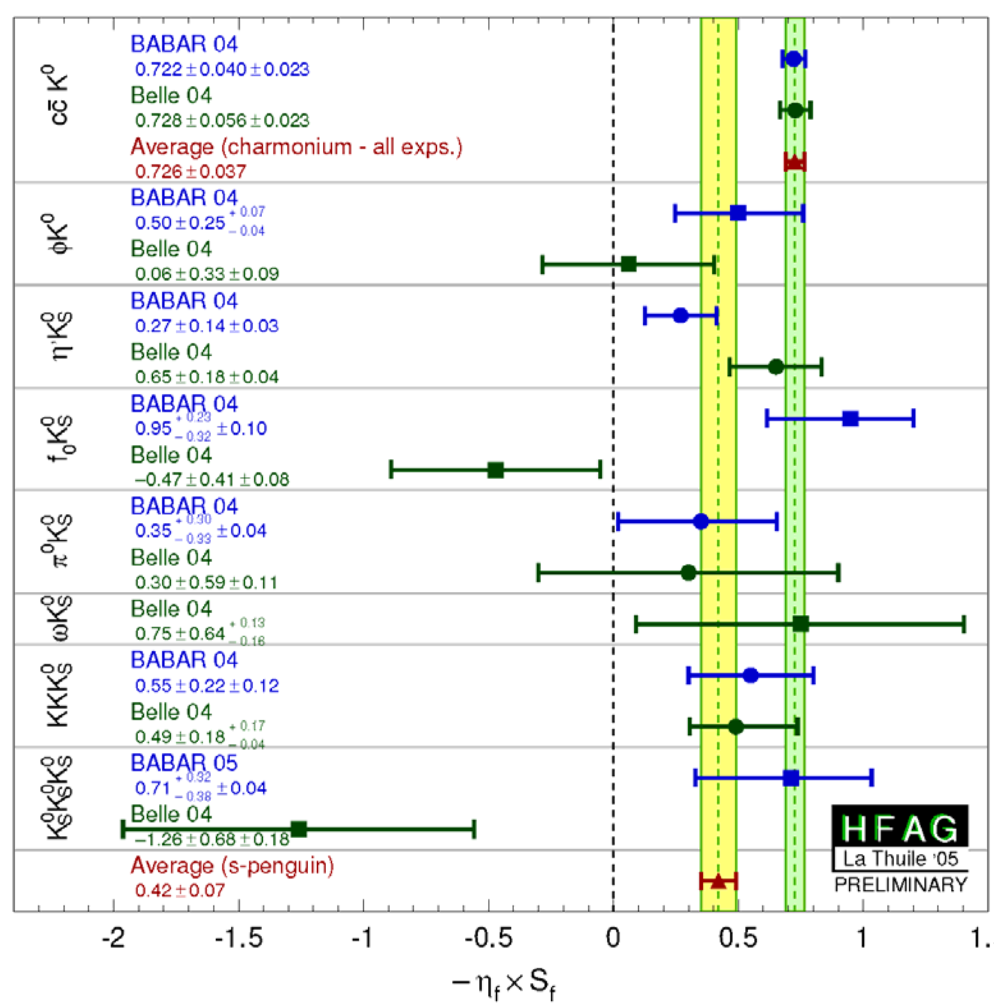
- Compare tree and penguin decays

- BaBar alone:

$$\Delta \sin(2\beta) \sim -2.9\sigma$$

- BaBar+Belle:

$$\Delta \sin(2\beta) \sim -3.7\sigma$$



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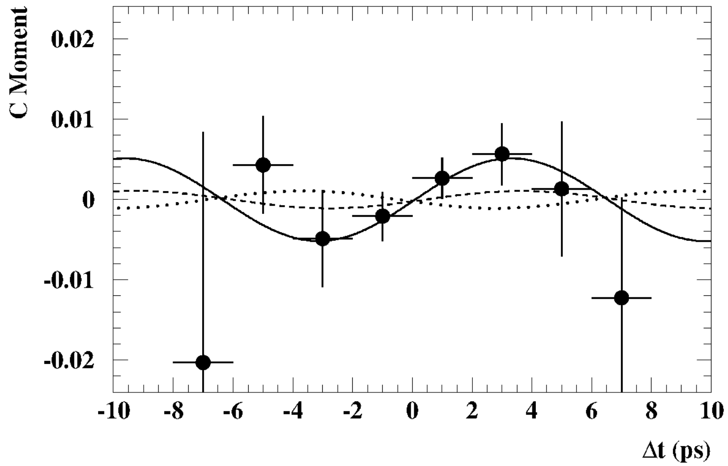
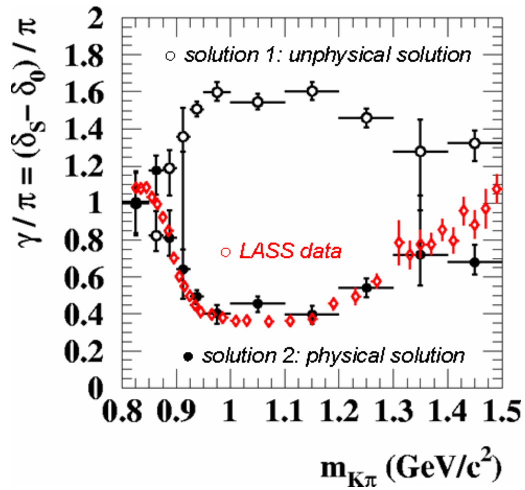
$\cos(2\beta)$ from $B \to J/\psi \left(K\pi\right)_{\text{P-wave}}$ (preliminary)

- $B \to VV$ decays proceed through 3 partial waves, L=0,2 (*CP*-even) and L=1 (*CP*-odd)
- $\cos(2\beta)$ appears in the interference
- Angular analysis allows separation of partial waves
- Sign of $\cos(2\beta)$ still ambiguous when P-wave is considered on its own…
  - Broad S-wave also present [Nucl. Phys. B**296**, 493 (1988)]
  - Include this amplitude and examine the phase motion
  - Only one solution shows physical phase behaviour
- $\cos(2\beta)$ positive at 86% CL
- Result from 88M $B\bar{B}$ pairs – more data to add!!



$$\cos(2\beta) = 2.72^{+0.50}_{-0.79} \pm 0.27$$



CKM Angle α

- Measured in $B \rightarrow \pi\pi$, $\rho\pi$ and $\rho\rho$
- Tree and penguin diagrams present:
- Measure α_{eff} instead of α

$$C_{hh} = 0$$
$$S_{hh} = \sin(2\alpha)$$

$\Rightarrow$

$$C_{hh} \propto \sin(\delta)$$
$$\delta = \delta_P - \delta_T$$
$$S_{hh} = \sqrt{1 - C_{hh}^2}\,\sin(2\alpha_{eff})$$

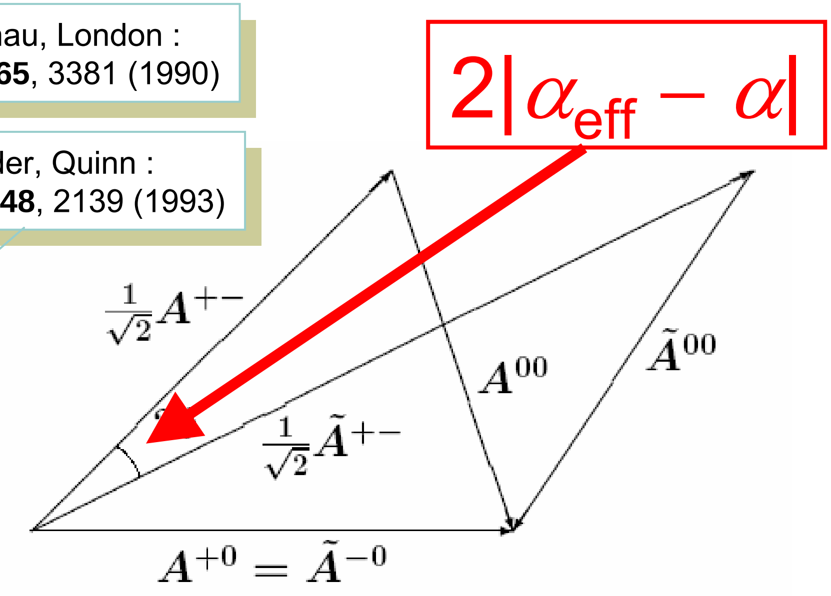
- Need to bound the shift $|\alpha_{\text{eff}} - \alpha|$
- Penguin:Tree ratio different for different decays

Untangling α_{eff}

- Use isospin symmetry to relate the decay rates:
  - Triangles for $\pi\pi/\rho\rho$
  - Pentagons for $\rho\pi$

Gronau, London : PRL**65**, 3381 (1990)

Snyder, Quinn : PRD**48**, 2139 (1993)



$$\mathbf{A}^{+-} = A(B^0 \to \pi^+\pi^-)$$
$$\tilde{\mathbf{A}}^{+-} = A(\overline{B}^0 \to \pi^+\pi^-)$$
$$\mathbf{A}^{+0} = A(B^+ \to \pi^+\pi^0)$$
$$\tilde{\mathbf{A}}^{-0} = A(B^- \to \pi^-\pi^0)$$
$$\mathbf{A}^{00} = A(B^0 \to \pi^0\pi^0)$$
$$\tilde{\mathbf{A}}^{00} = A(\overline{B}^0 \to \pi^0\pi^0)$$

- Making fewest assumptions gives the bound:

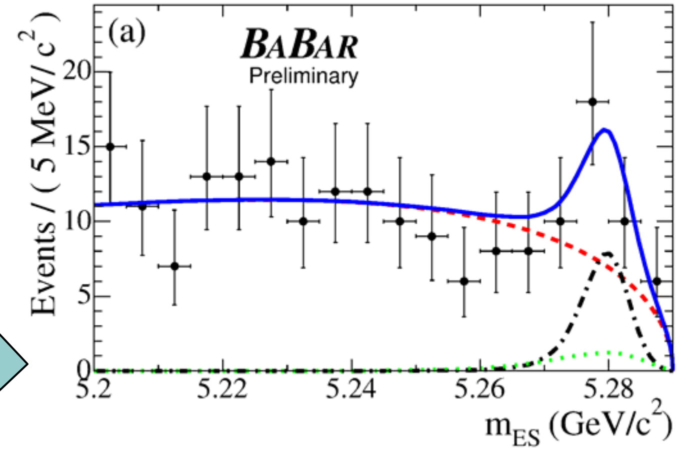
$$\sin^2(\alpha_{eff} - \alpha) < \frac{BF(B^0 \to \pi^0\pi^0)}{BF(B^\pm \to \pi^\pm\pi^0)}$$

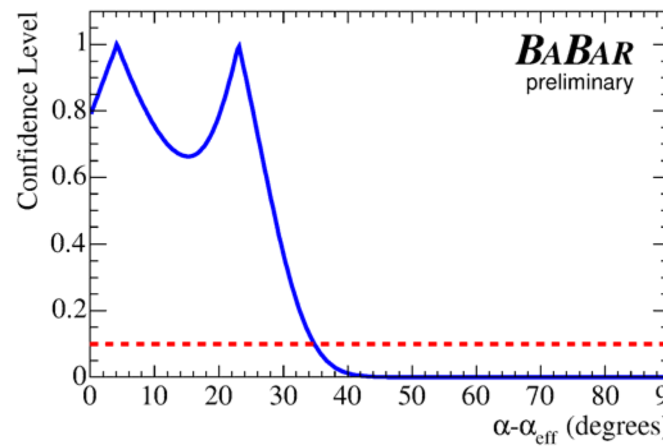
Grossman, Quinn : PRD**58**, 017504

α in $B \rightarrow \pi\pi$ (preliminary)

All results use 227M $B\overline{B}$ pairs except $\pi^+\pi^-$ *BF* which uses 97M

- $B^0 \rightarrow \pi^+\pi^-$
  - $BF = (4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$
  - $S_{\pi^+\pi^-} = -0.30 \pm 0.17 \pm 0.03$
  - $C_{\pi^+\pi^-} = -0.09 \pm 0.15 \pm 0.04$
- $B^0 \rightarrow \pi^0\pi^0$
  - $BF = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$
  - $C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06$
- $B^\pm \rightarrow \pi^\pm\pi^0$
  - $BF = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$
  - $A_{CP} = -0.01 \pm 0.10 \pm 0.02$

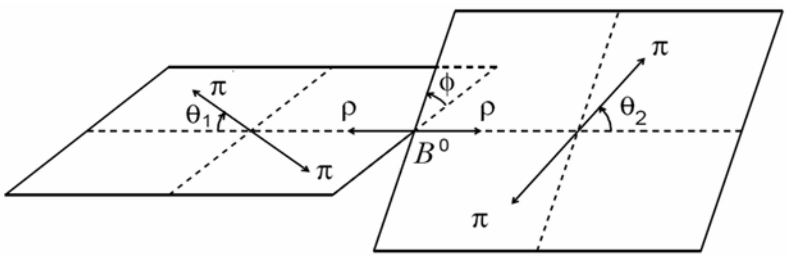




Isospin: $|\alpha - \alpha_{eff}| < 35^o$ at 90% CL $\Longrightarrow$ Isospin analysis of $\pi\pi$ gives only very loose bound with current statistics

$B \to \rho^+\rho^-$ (89M $B\bar{B}$ pairs)

- VV final state
- Requires angular analysis to untangle different *CP* states



$$\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} \propto \underbrace{f_L \cos^2\theta_1 \cos^2\theta_2}_{\text{Longitudinal CP+1 eigenstate}} + \underbrace{\tfrac{1}{4}(1-f_L)\sin^2\theta_1 \sin^2\theta_2}_{\text{Transverse non-CP eigenstate}}$$

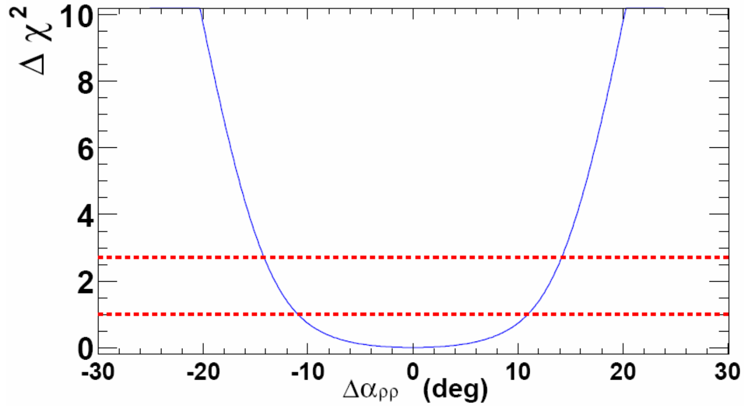
- Longitudinal part in $\rho^+\rho^-$ system measured to be:

  $f_L = 0.99 \pm 0.03 \pm 0.04$
- *CP*-even component dominates
- Branching fraction measured to be: $BF = (30 \pm 4 \pm 5) \times 10^{-6}$

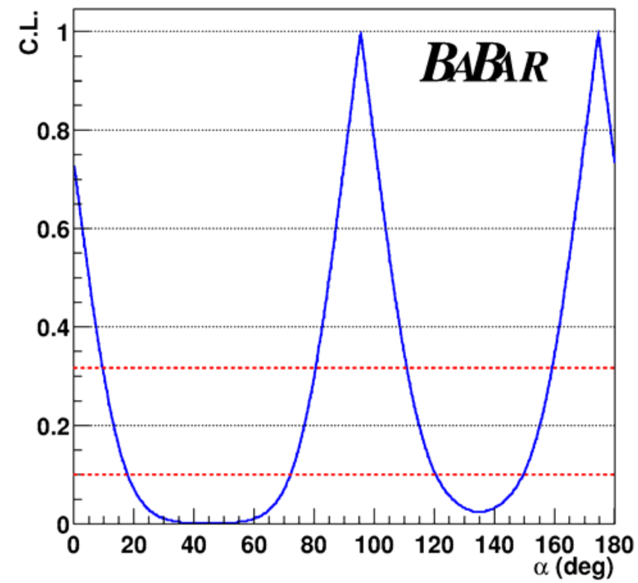
α in $B \to \rho\rho$ (preliminary)

- $B^0 \to \rho^+ \rho^-$ hep-ex/0407051
  - $S_{\rho^+\rho^-} = -0.19 \pm 0.33 \pm 0.11$
  - $C_{\rho^+\rho^-} = -0.23 \pm 0.24 \pm 0.14$
- $B^0 \to \rho^0 \rho^0$ hep-ex/0408061
  - $BF < 1.1 \times 10^{-6}$
- $B^\pm \to \rho^\pm \rho^0$ PRL 91 (2003) 171802, PRL 91 (2003) 221801
  - $BF = \left(26.4^{+6.1}_{-6.4}\right) \times 10^{-6}$
  - $f_L = 0.96^{+0.05}_{-0.07}$

$$\alpha = \left(96 \pm 10 \pm 4 \pm 11\right)^\circ$$

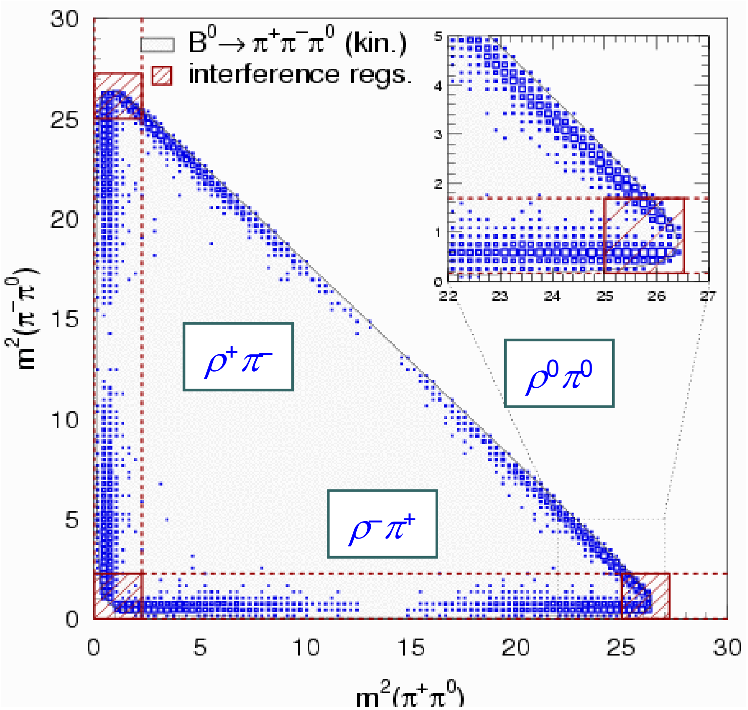


Isospin: $|\alpha - \alpha_{eff}| < 11^o$ at 68% CL



α in $B^0 \to (\rho\pi)^0$ (preliminary)

- $\rho^{\pm}\pi^{\mp}$ not a *CP* eigenstate
- Previous analyses have selected out the $\rho\pi$ bands from the Dalitz plot and removed the interference regions
- Better to do an amplitude analysis



Extract α & strong phases using interference between amplitudes

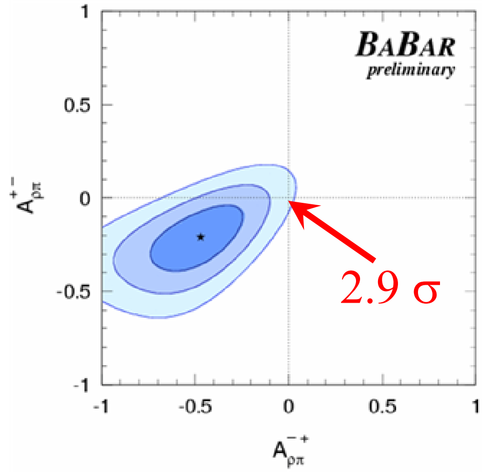
Dalitz plot dominated by $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ and radial excitations

Analysis uses 213M $B\bar{B}$ pairs

1184 ± 58 signal events

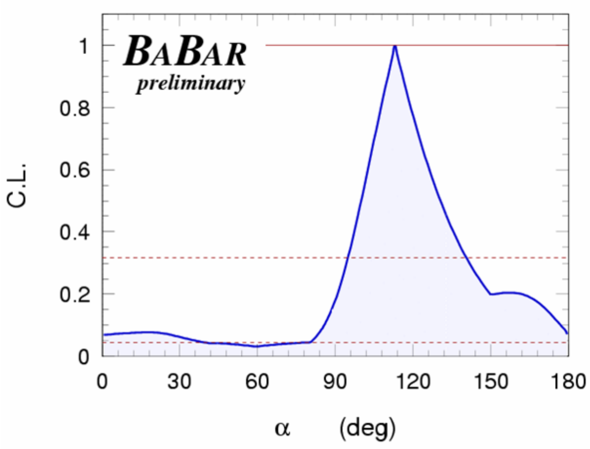
α in $B^0 \to (\rho\pi)^0$ (preliminary)

- *CP* violating observables:
  - $A_{CP} = -0.088 \pm 0.049 \pm 0.013$
  - $S_{\rho\pi} = -0.10 \pm 0.14 \pm 0.04$
  - $C_{\rho\pi} = 0.34 \pm 0.11 \pm 0.05$
- Non-*CP* observables:
  - $\Delta S = 0.22 \pm 0.15 \pm 0.03$
  - $\Delta C = 0.15 \pm 0.11 \pm 0.03$
  - $\delta_{+-} = \left(-67^{+28}_{-31} \pm 7\right)^\circ$
- $\alpha = \left(113^{+27}_{-17} \pm 6\right)^\circ$



$A^{+-}_{\rho\pi} = -0.21 \pm 0.11 \pm 0.04$

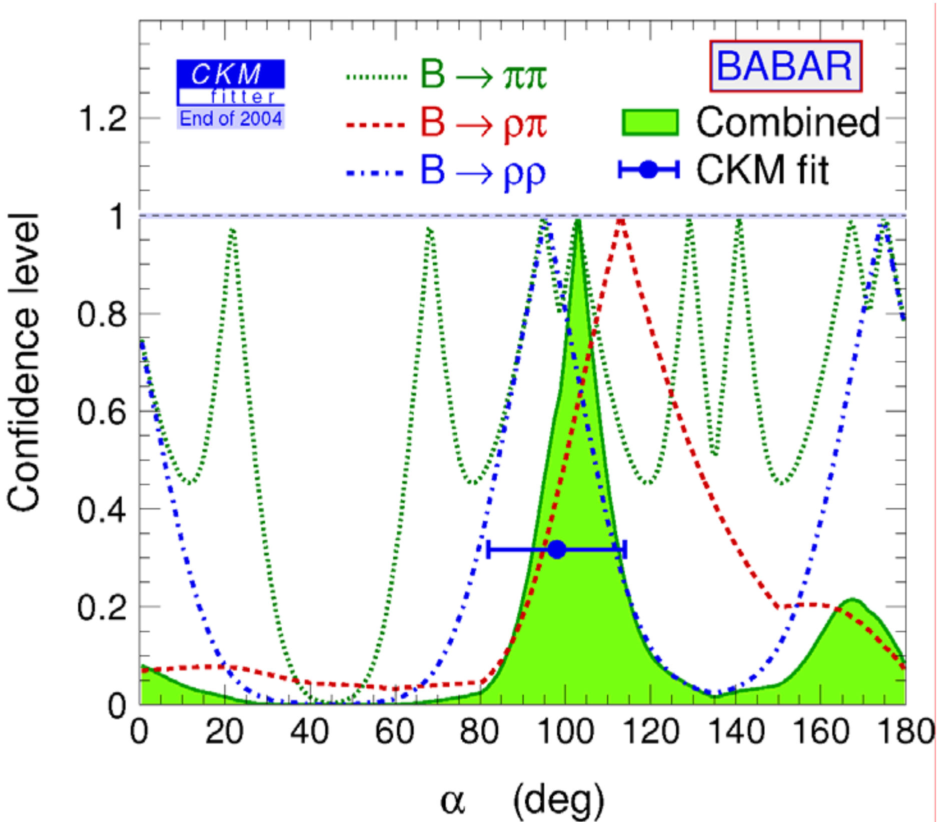
$A^{-+}_{\rho\pi} = -0.47^{+0.14}_{-0.15} \pm 0.06$



Combined Constraints on α

- Combine all α results
- Compare with global CKM fit
- α is measured
- Mirror solutions disfavoured

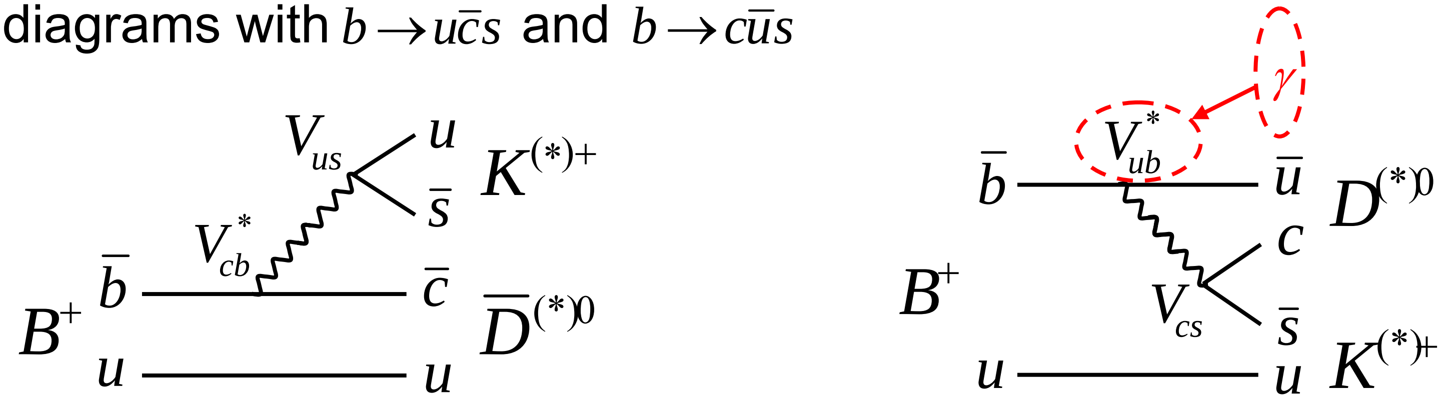
$$\alpha = \left(103^{+11}_{-10}\right)^{\circ}$$



http://ckmfitter.in2p3.fr/

CKM Angle γ

- Access γ through direct *CP*-violation in the interference of diagrams with $b \to u\bar{c}s$ and $b \to c\bar{u}s$



- Reconstruct $D^{(*)0}$ and $\bar{D}^{(*)0}$ in the same final state
- Charged B's – time independent measurement
- Amplitudes have relative weak phase of γ
- Need to also determine the relative strong phase (δ_B) and ratio of magnitudes of the two diagrams:

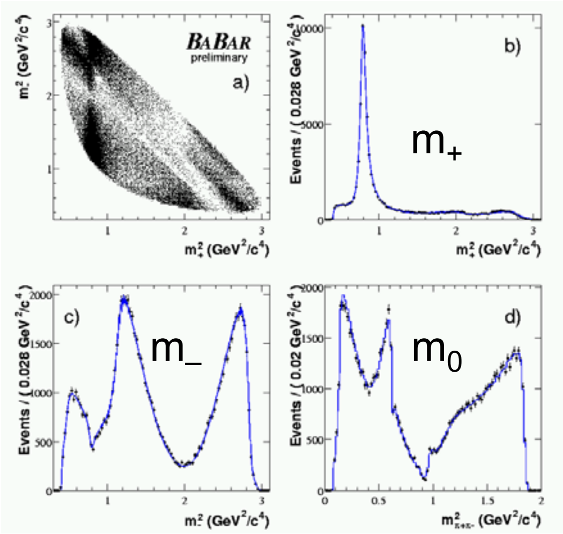
c.f. neutral B's $\to 2\beta + \gamma$
hep-ex/0408038

$$r_B = \frac{\left|A\left(B^+ \to D^0 K^+\right)\right|}{\left|A\left(B^+ \to \bar{D}^0 K^+\right)\right|}$$

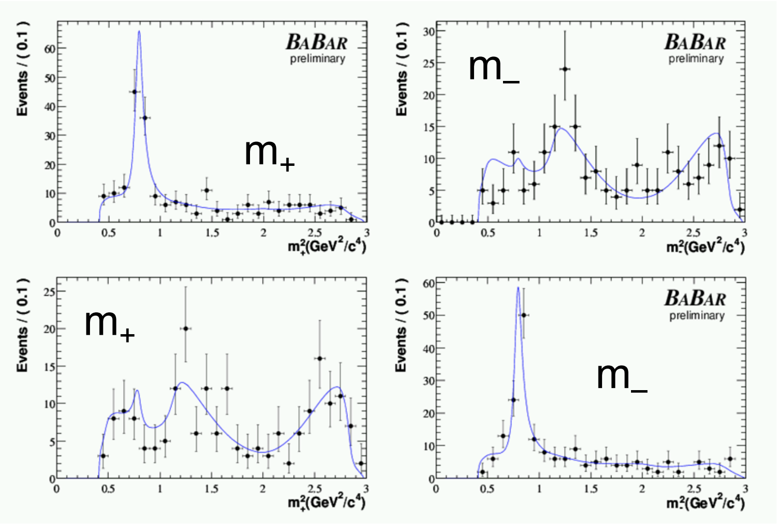
Expected to be ~ 0.1 – 0.2
Sensitivity to γ dependent on size of r_B.

D^0 to 3-body Dalitz Method

- Choose D^0 decay to 3-body state $K_S\pi^+\pi^-$
- Dalitz analysis of the D^0 decay with isobar model fixes the phase variation δ_D across the Dalitz plot
  - Use high stats D^{*+} sample
  - Assume no D mixing or *CP* violation in the D decays
- Fixing the D^0 model, fit simultaneously to B^+ and B^- samples to determine γ, r_B and δ_B



$D^{*\pm}$ Data



B^+

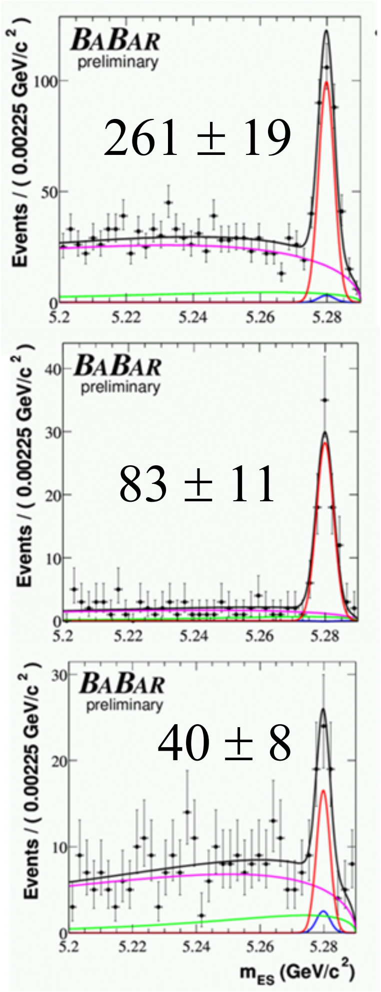
B^-

$B^\pm$ Data

D^0 Dalitz Method Preliminary Results

- Results from 211M $B\bar{B}$ pairs
- $r_B < 0.19$
- $\delta_B = (114 \pm 41 \pm 8 \pm 10)^\circ$
- $r_B^* = 0.155^{+0.070}_{-0.077} \pm 0.040 \pm 0.020$
- $\delta_B^* = (303 \pm 34 \pm 14 \pm 10)^\circ$
- $\gamma = (70 \pm 26 \pm 10 \pm 10)^\circ$

3rd error due to uncertainty on Dalitz model



D^0K

$D^{*0}(D^0\pi^0)K$

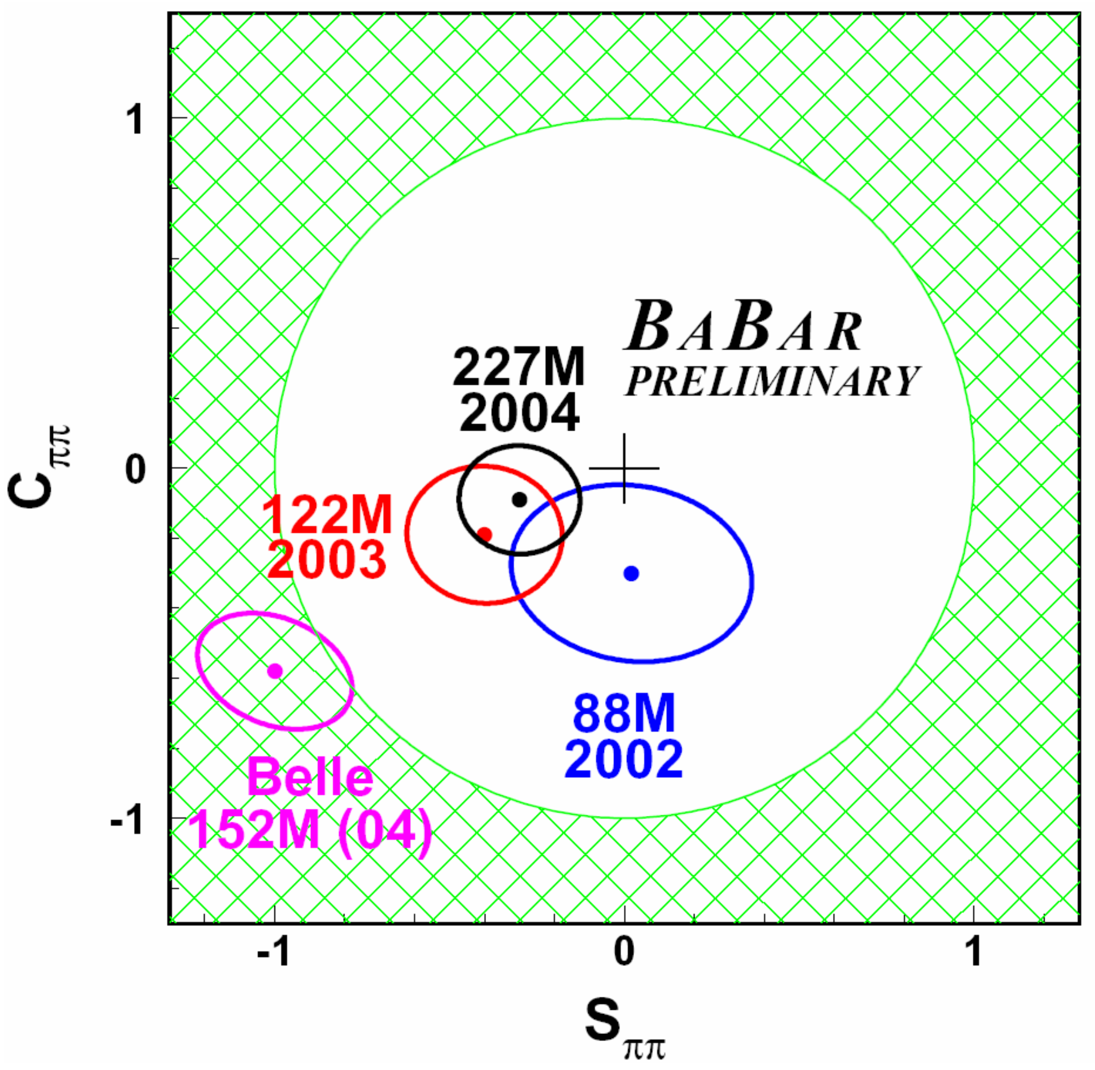
$D^{*0}(D^0\gamma)K$

Conclusions

- BaBar producing great number of measurements
- β
  - Well measured in charmonium modes
  - Comparison with b→s penguin modes shows possible indication of potential new physics – more statistics required
- α
  - Measurements from three modes: $\pi\pi$, $\rho\pi$, $\rho\rho$
  - Constraint dominated by $\rho\rho$ and $\rho\pi$
- γ
  - Many possible approaches
  - Dalitz analysis of D^0 decay most sensitive at present
  - Greater statistics essential for this measurement
  - Development of further methods in pipeline

Backup Slides

Comparison with Belle : CPV in $B^0 \to \pi^+\pi^-$

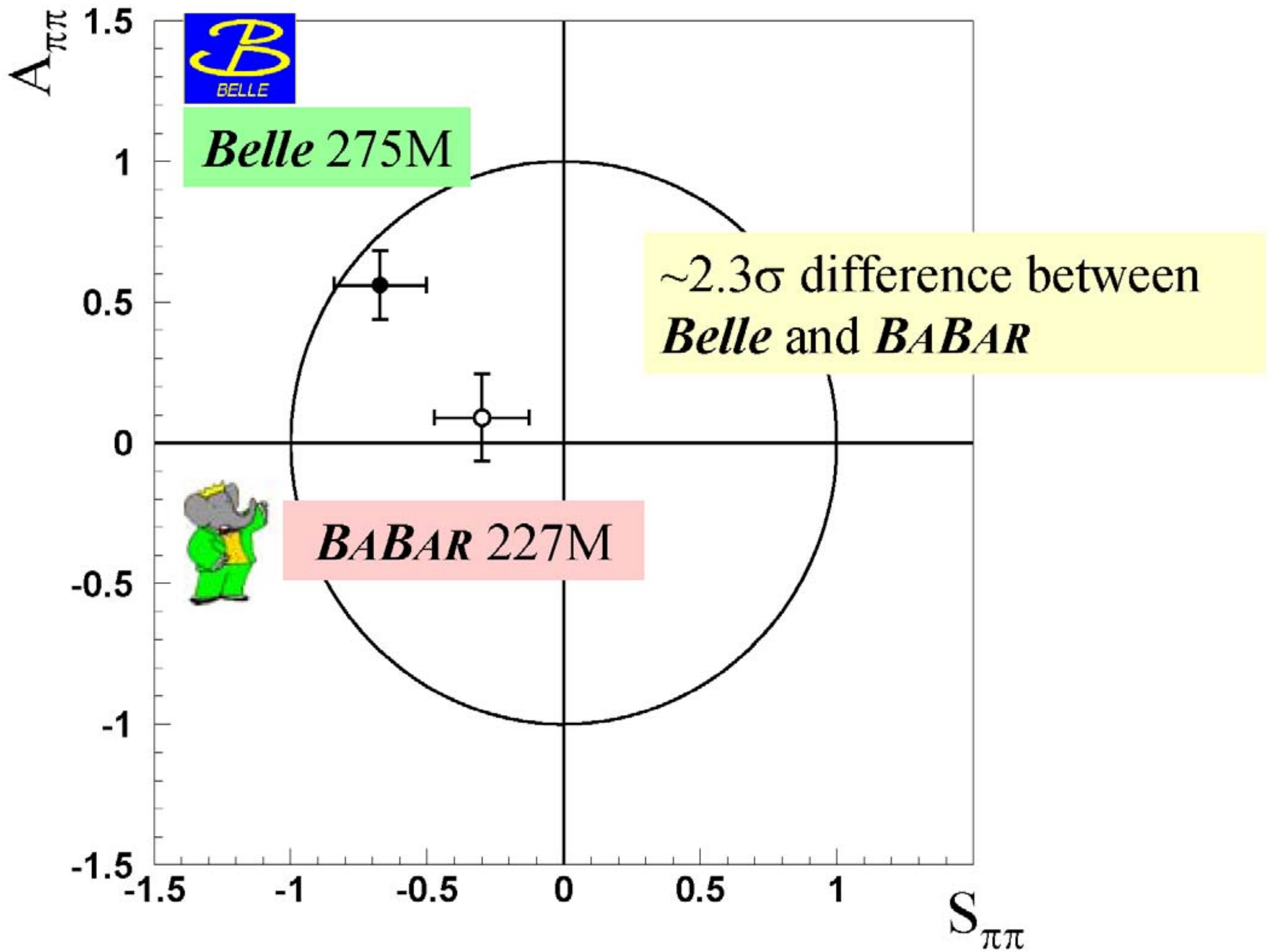


Belle report observation of CPV in $B^0 \to \pi^+\pi^-$

$>3\sigma$ discrepancy between BABAR & Belle

Belle 3.2σ evidence for Direct *CP* violation <u>not supported</u> by *BABAR* measurements

New experimental situation



GLW and ADS methods for γ

Gronau, London, Wyler

- Reconstruct both $D^0 / \overline{D}^0$ in decays to *CP* eigenstates
- Compare decay rates of B^+ and B^- to both *CP*-even and *CP*-odd final states of the *D*
- Four observables determine the three unknowns γ, r_B and δ_B
- Significant signals observed in several modes
- Only loose bound on r_B possible with current statistics
- $r_B^2 = 0.24 \pm 0.23$

Atwood, Dunietz, Soni

- Reconstruct $D^0 / \overline{D}^0$ in decay to $(K\pi)^0$
- Both *D* flavours can decay to kaons of either charge – again four observables
- Two further parameters: r_D, the ratio of the *D* decay magnitudes and δ_D their relative strong phase
  - r_D has been measured: 0.060 ± 0.003
  - but δ_D is unknown
- No significant signals observed in 227M *BB* pairs
- $r_B < 0.23$ @ 90% CL

Small value of r_B will make extraction of γ by these methods difficult.