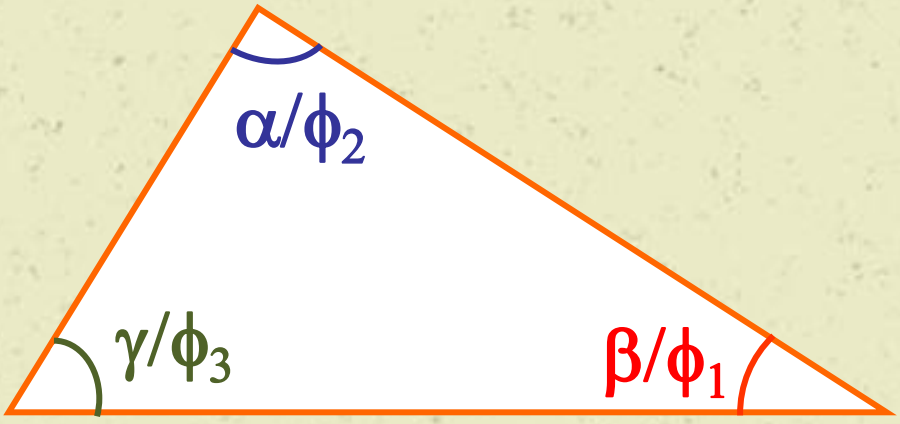
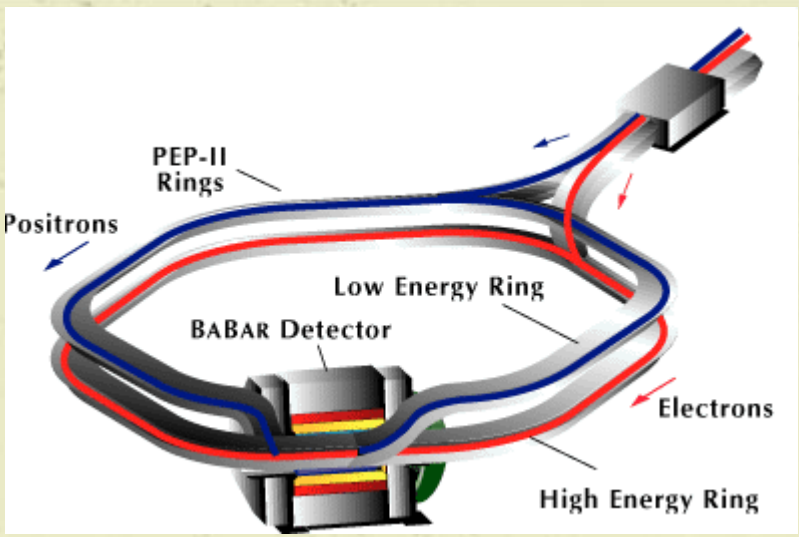
CP results from BaBar

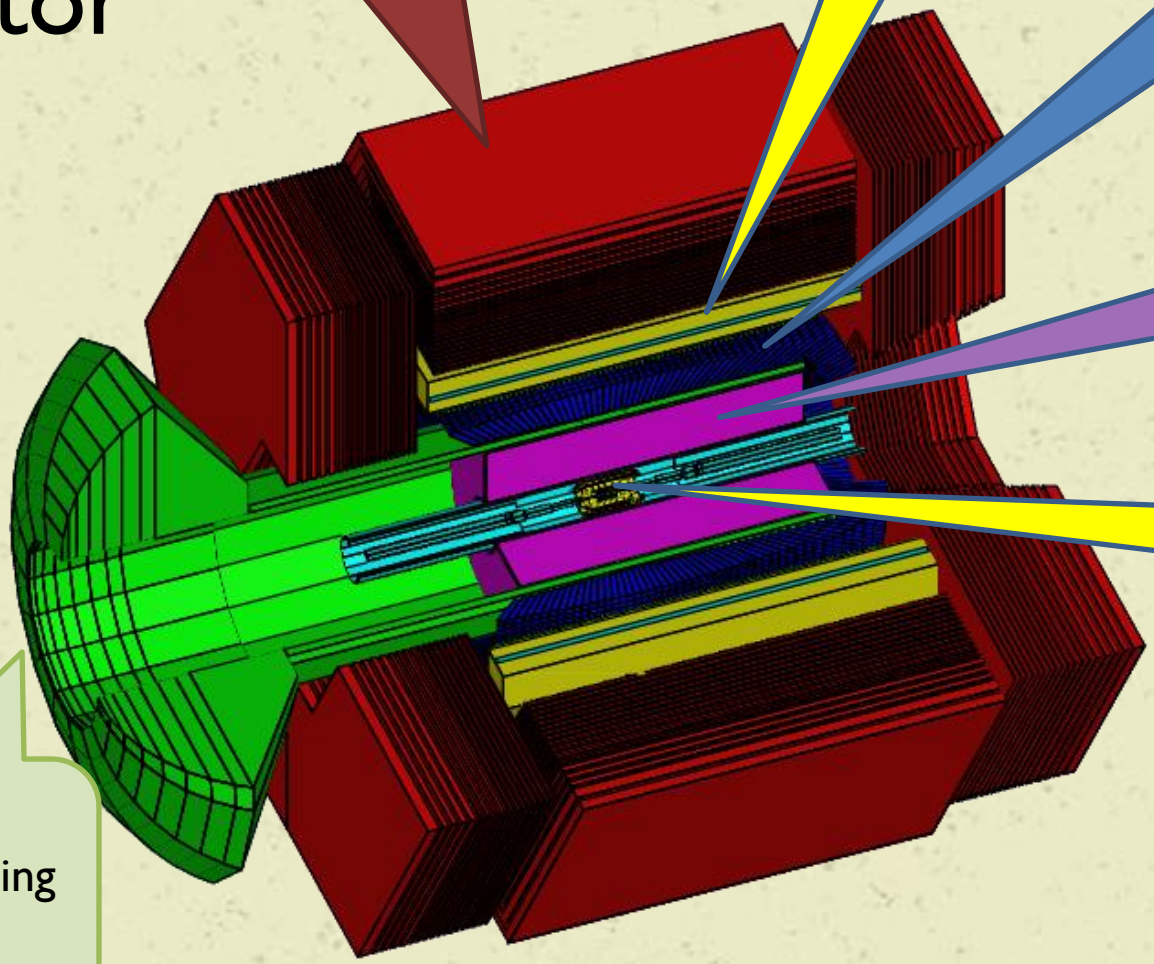


David Hutchcroft
University of Liverpool
Lancaster '08



- BaBar is a 4π detector on the PEP-II ring
- PEP-II collides e^+ and e^- at the $\Upsilon(4s)$ resonance
- Produces $B^0\overline{B}^0$ and B^+B^-
  with a boost of $\beta\gamma = 0.56$, [$ct\beta\gamma = 250\ \mu m$]

BaBar Detector layout



Muon chambers and Magnet return yoke

Magnet

Electromagnetic Calorimeter

Drift chamber

Five layer silicon vertex detector

Particle ID: quartz bars leading to a Water Cherenkov box

Data used in analyses

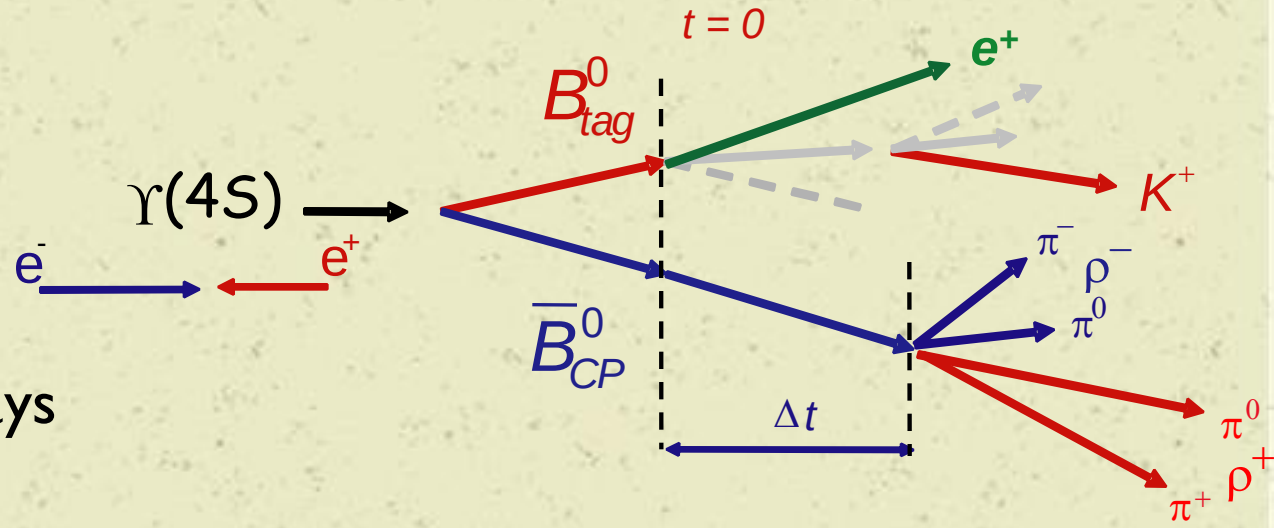
- Dataset is 467 ± 5 million BB events
- Backgrounds are predominantly non resonant annihilation so reconstruct B mesons
  - Variables $m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$

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

m_{ES} is mass of the B system using the initial beam energy constraint,
p^*_B is the CM frame B momentum and
E_B^* is the CM energy of the B meson

CP violation

- Direct CP violation : $Br(B^0 \to f) \neq Br(\overline{B}^0 \to \overline{f})$
  - Time integrated effect, event counting
- Indirect CP violation from mixing and decay interference
  - Time dependant effect
  - Relevant for CKM angle measurements
- Use coherence between B^0 and $\overline{B}^0$ to decide what meson actually decayed
  - Tag other side B decay
  - Also measure Δt between decays



CKM angles

- CKM matrix is a unitary matrix that connects the mass eigenstates and weak eigenstates
- Elements appear in weak current interactions

$|V_{ub}|\, e^{-i\gamma}$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda_c^2 & \lambda_c & A\lambda_c^3(\rho-i\eta) \\ -\lambda_c & 1-\lambda_c^2/2 & A\lambda_c^2 \\ A\lambda_c^3(1-\rho-i\eta) & -A\lambda_c^2 & 1 \end{pmatrix}$$

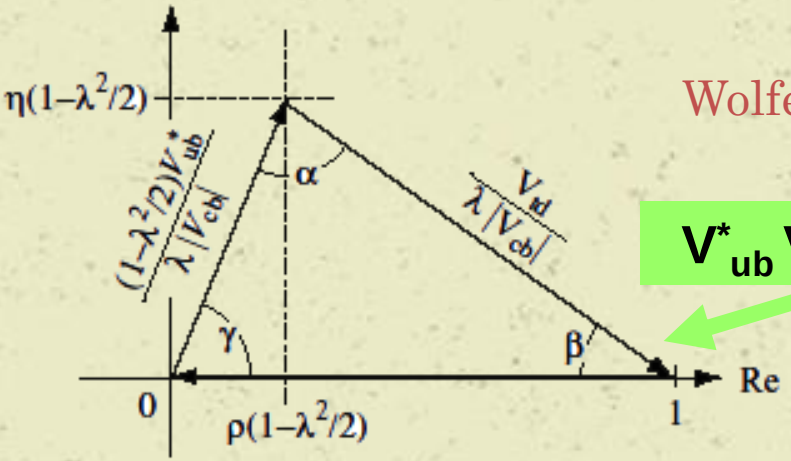
CP violation

$|V_{td}|\, e^{-i\beta}$

$+ O(\lambda_c^4)$ [$\lambda_c = \sin\theta_c$]

Wolfenstein parameterisation

A unitarity triangle :

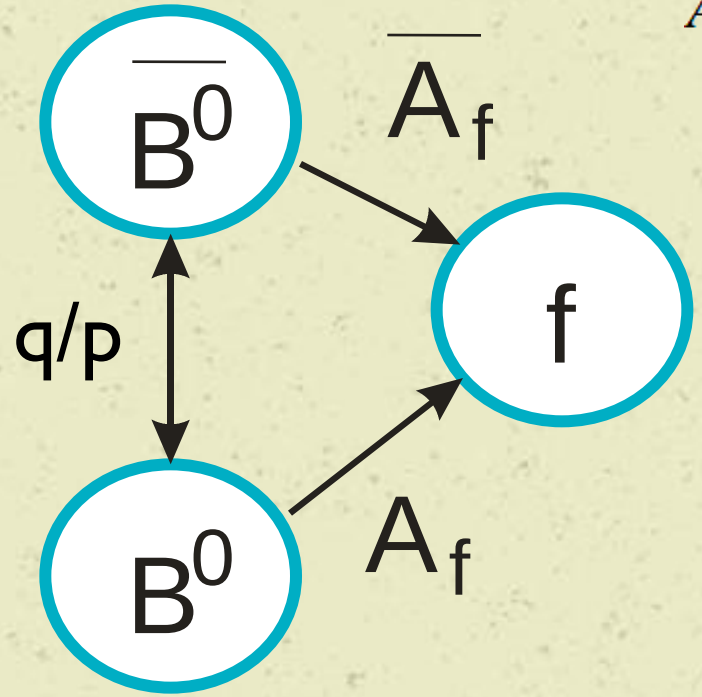


$$V^*_{ub} V_{ud} + V^*_{cb} V_{cd} + V^*_{tb} V_{td} = 0$$

Interference measurements

$$f(B^0 \to f, \Delta t) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1 + \eta S \sin(\Delta m_d \Delta t) - \eta C \cos(\Delta m_d \Delta t)\right]$$

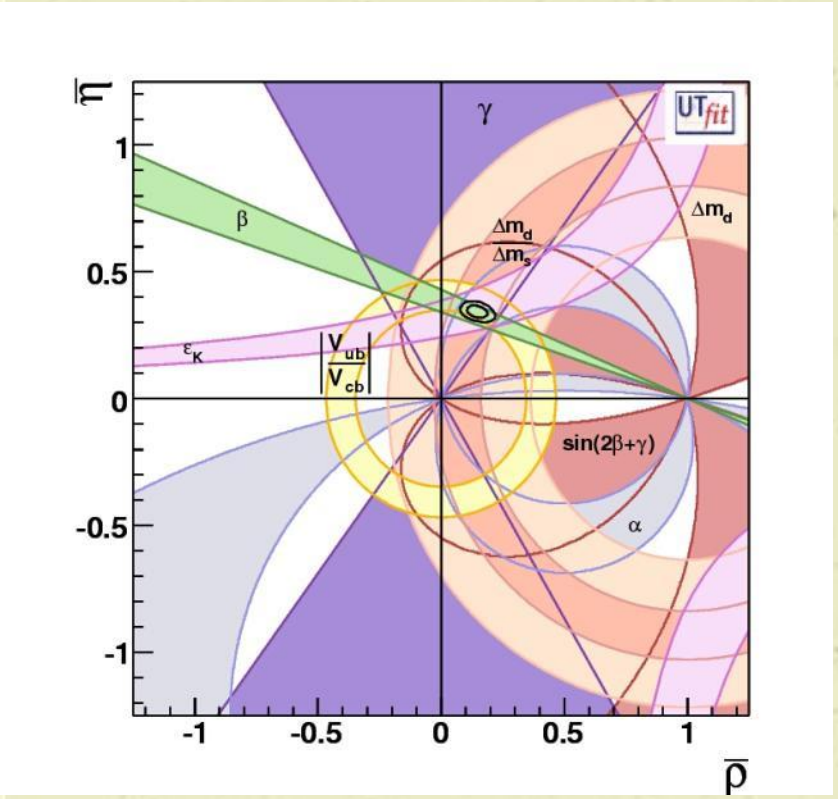
$$\eta = +1(-1) \text{ for } B^0(\bar{B}^0)$$



$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S_f \sin \Delta m t - C_f \cos \Delta m t$$

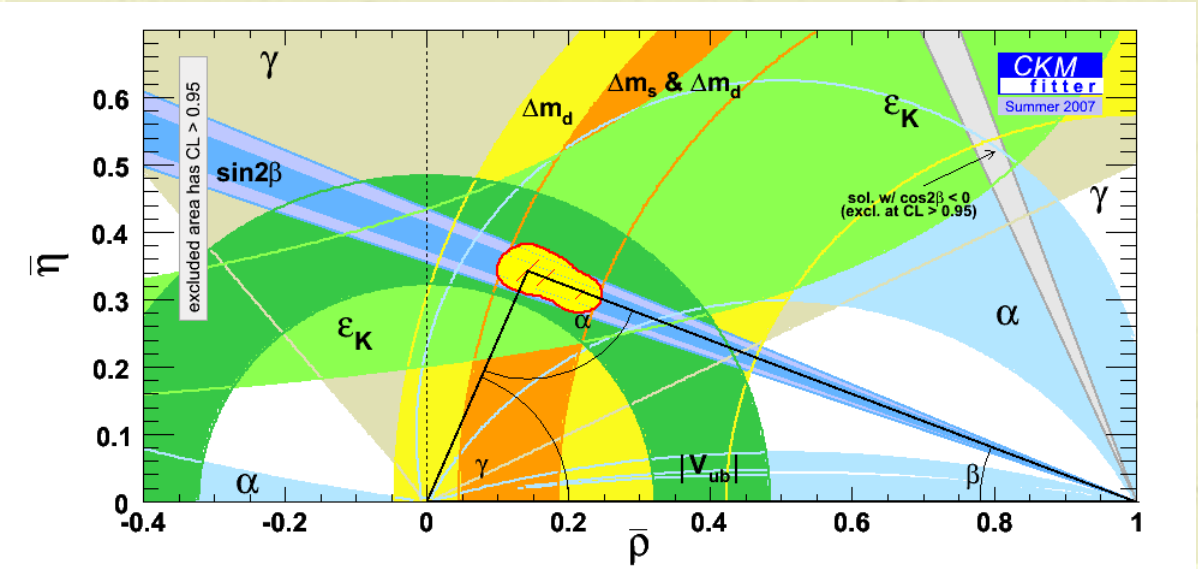
$$S_f = \frac{2\mathrm{Im}\lambda}{1 + |\lambda|^2} \qquad C_f = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}$$

$$\lambda \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$



Current status

Both CKM-Fitter and UT-Fit groups have combined the results and have consistent values for the CKM angles



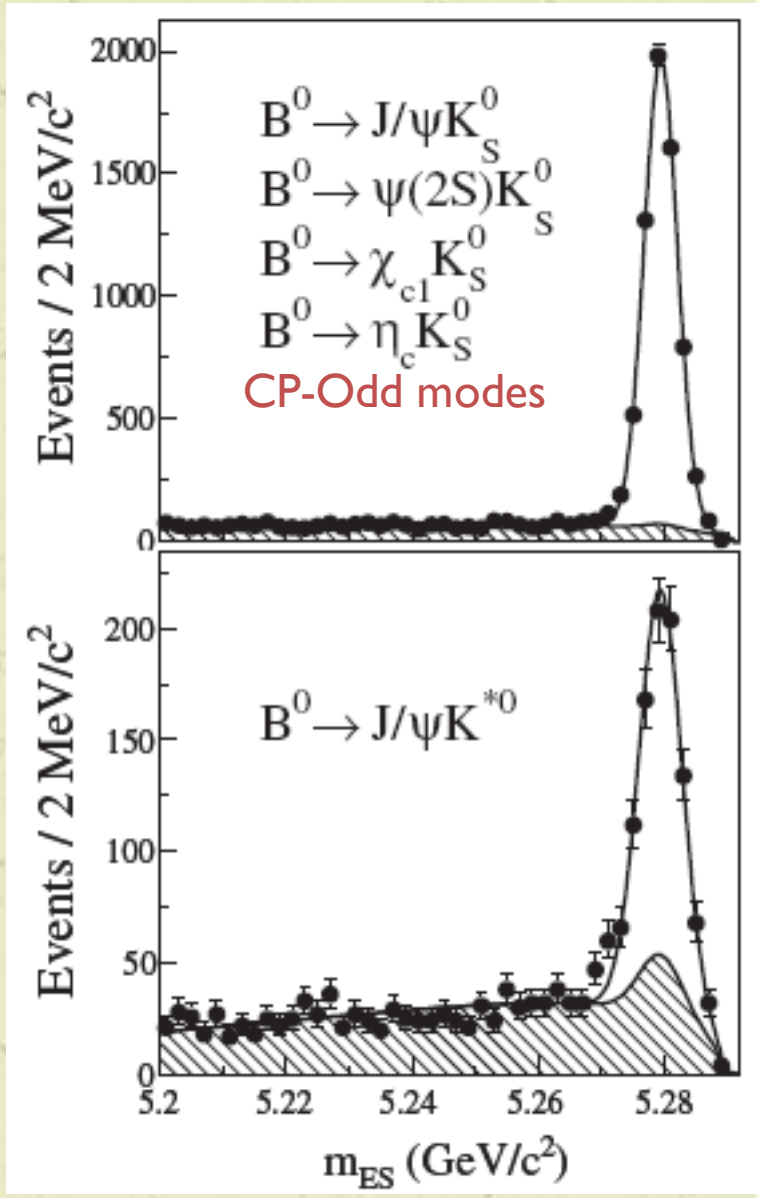
BaBar results for β

Still dominated by sin2β from golden modes

$$B \to c\bar{c}K^{(*)0}$$

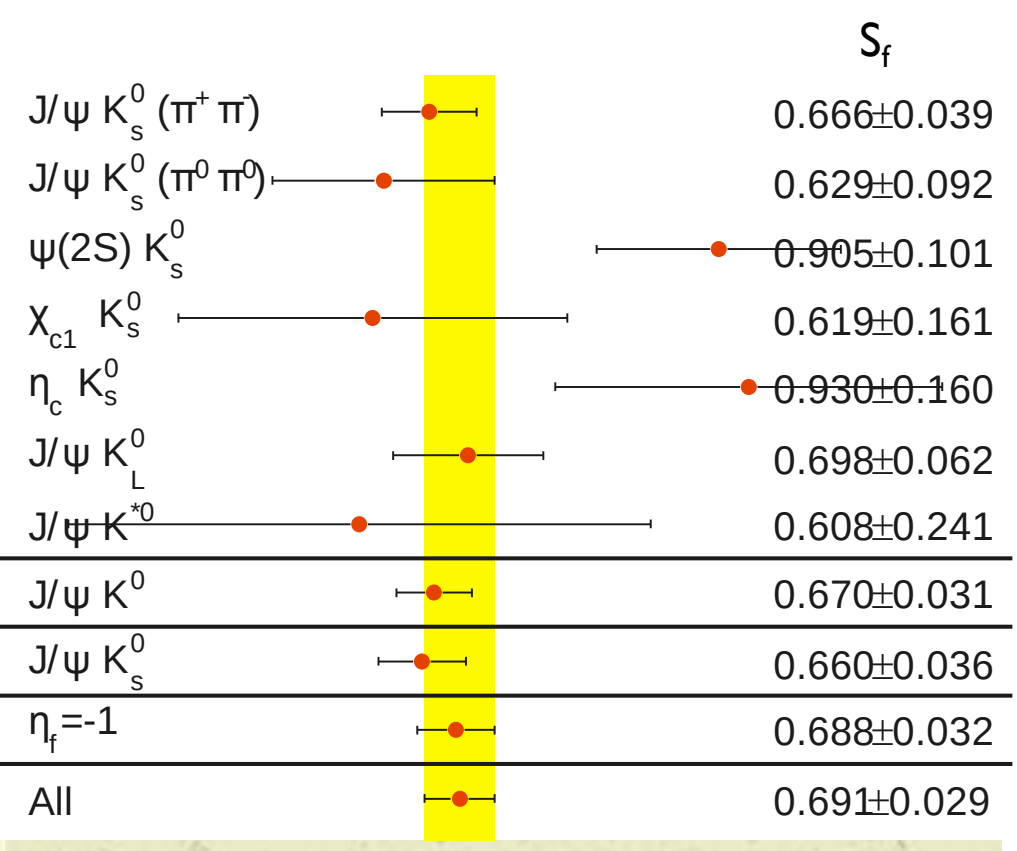
all of the available cc modes are used in the measurement

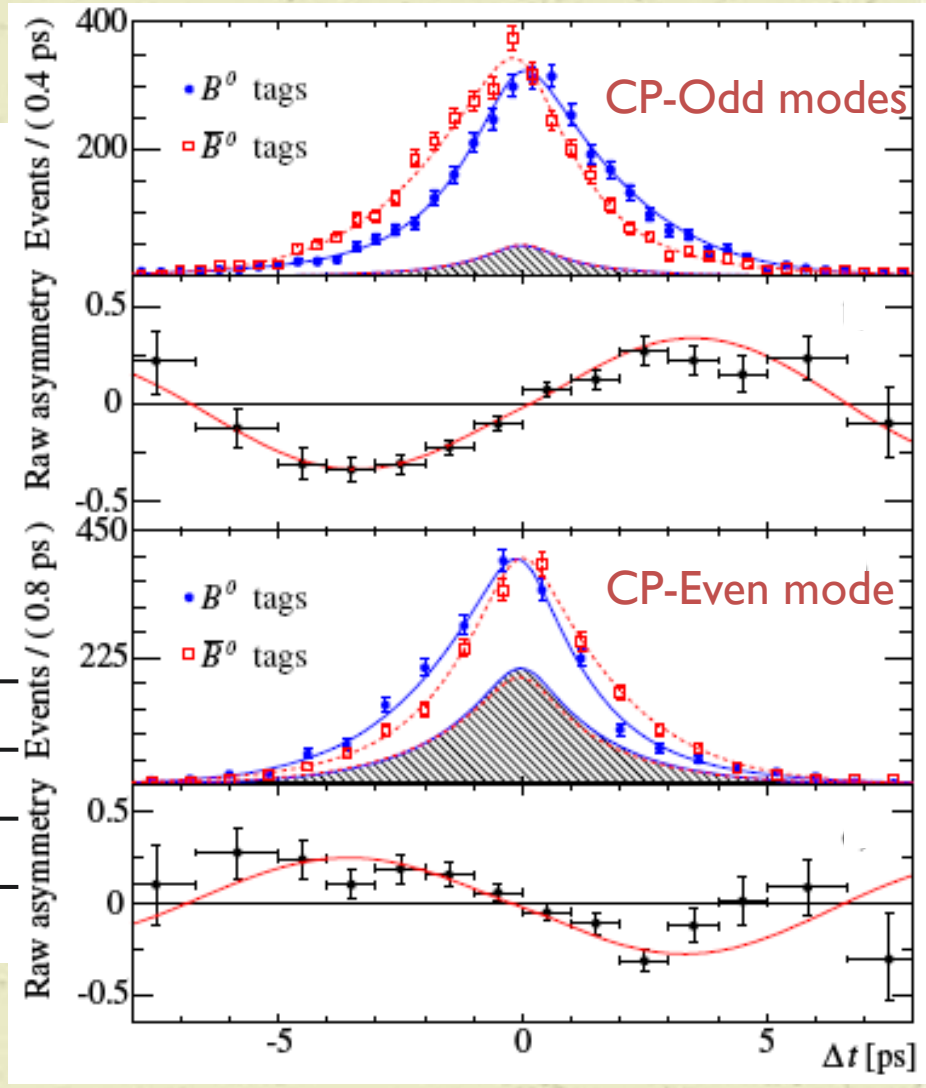
The decay to K_s and K_L have the opposite CP signs



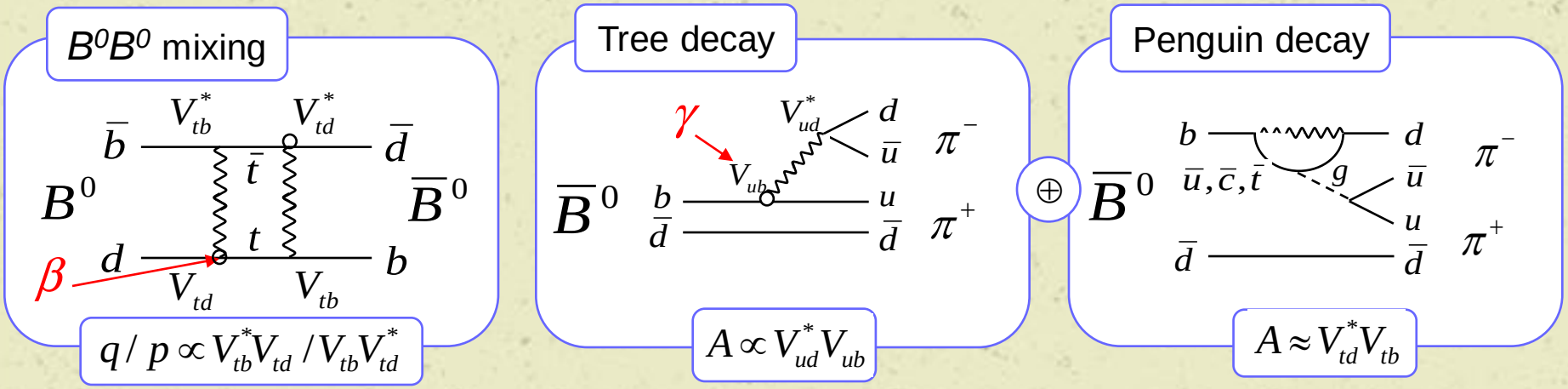
BABAR-CONF-08/017,
SLAC-PUB-13324
arXiv:0808.1903v1

Clear and consistent time dependant oscillation in all ccK modes





Decays depending on α



- Tree decays of B^0 and $\bar{B}^0$ to two charmless mesons depend on $\pi-(\beta+\gamma) = \alpha$
- Trees only

$$C_f = 0$$

$$S_f = \sin(2\alpha)$$

Trees + Penguins

$$C_f \propto \sin(\delta)$$

$$S_f = \sqrt{1-C_f^2}\,\sin(2\alpha_{\text{eff}})$$

$$\delta = \delta_P - \delta_T$$ strong phase

Separating trees and penguins

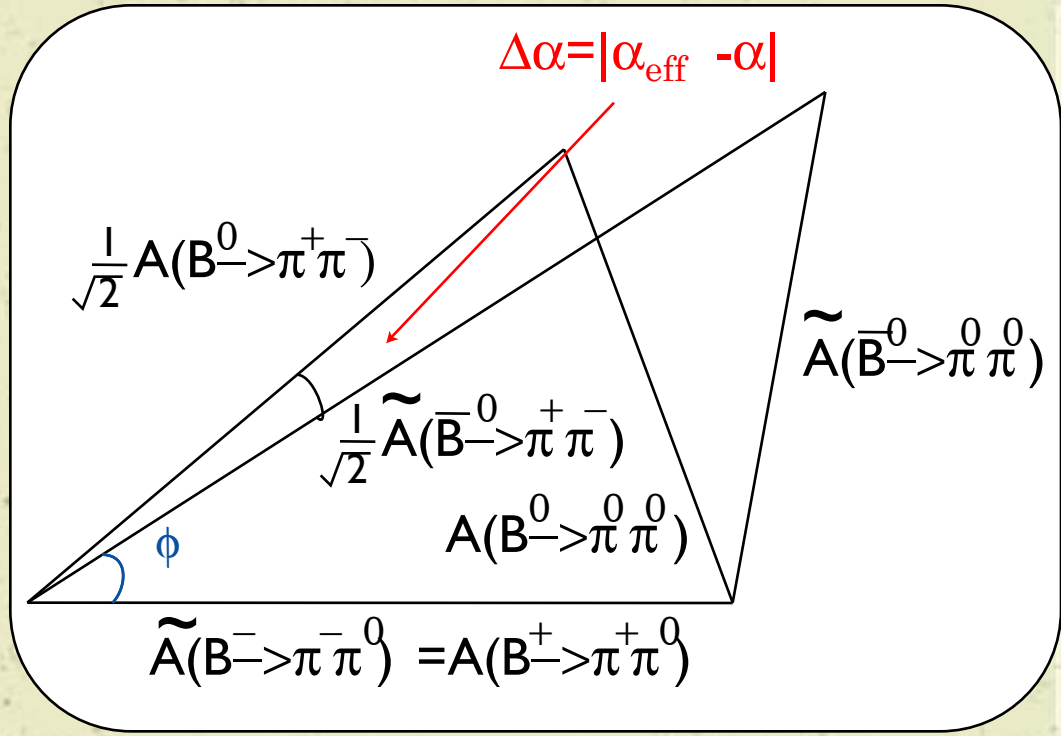
Use an isospin relation between similar decays to measure the amount of each type of decay

Used to set a limit on $\Delta\alpha = \alpha - \alpha_{eff}$

Need to measure all of the related decays of $\pi\pi$

Penguin contribution depends on $Br(\pi^0\pi^0)$

Charged B decay is tree only



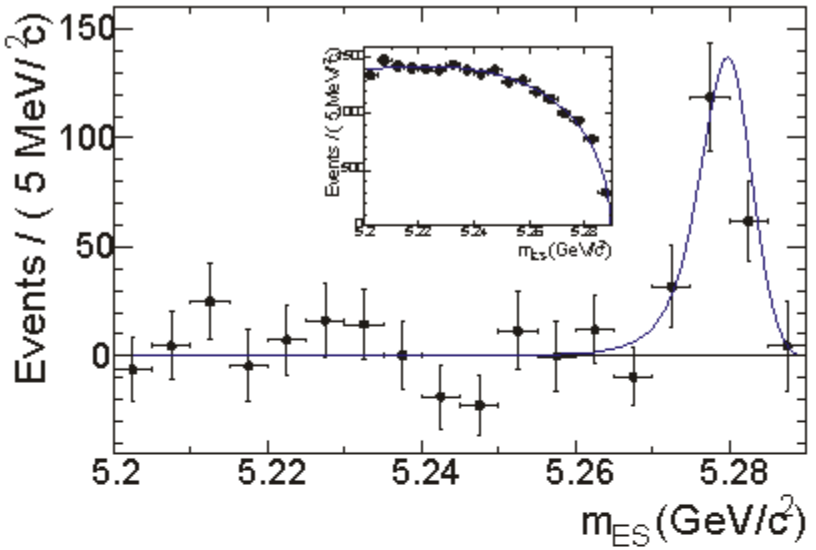
Gronau-London: PRL**65**, 3381 (1990) etc

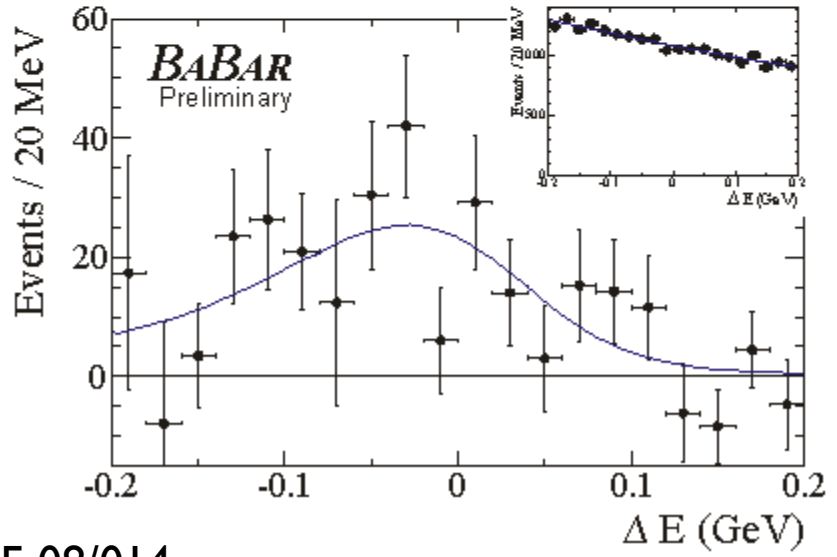
$B \rightarrow \pi^0 \pi^0$

SPlots of m_{ES} and ΔE

The branching ratio is measured as
$Br = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$

The direct CP asymmetry is
$C_f = -0.43 \pm 0.26 \pm 0.05$





BABAR-CONF-08/014,
SLAC-PUB-13326
arXiv:0807.4226

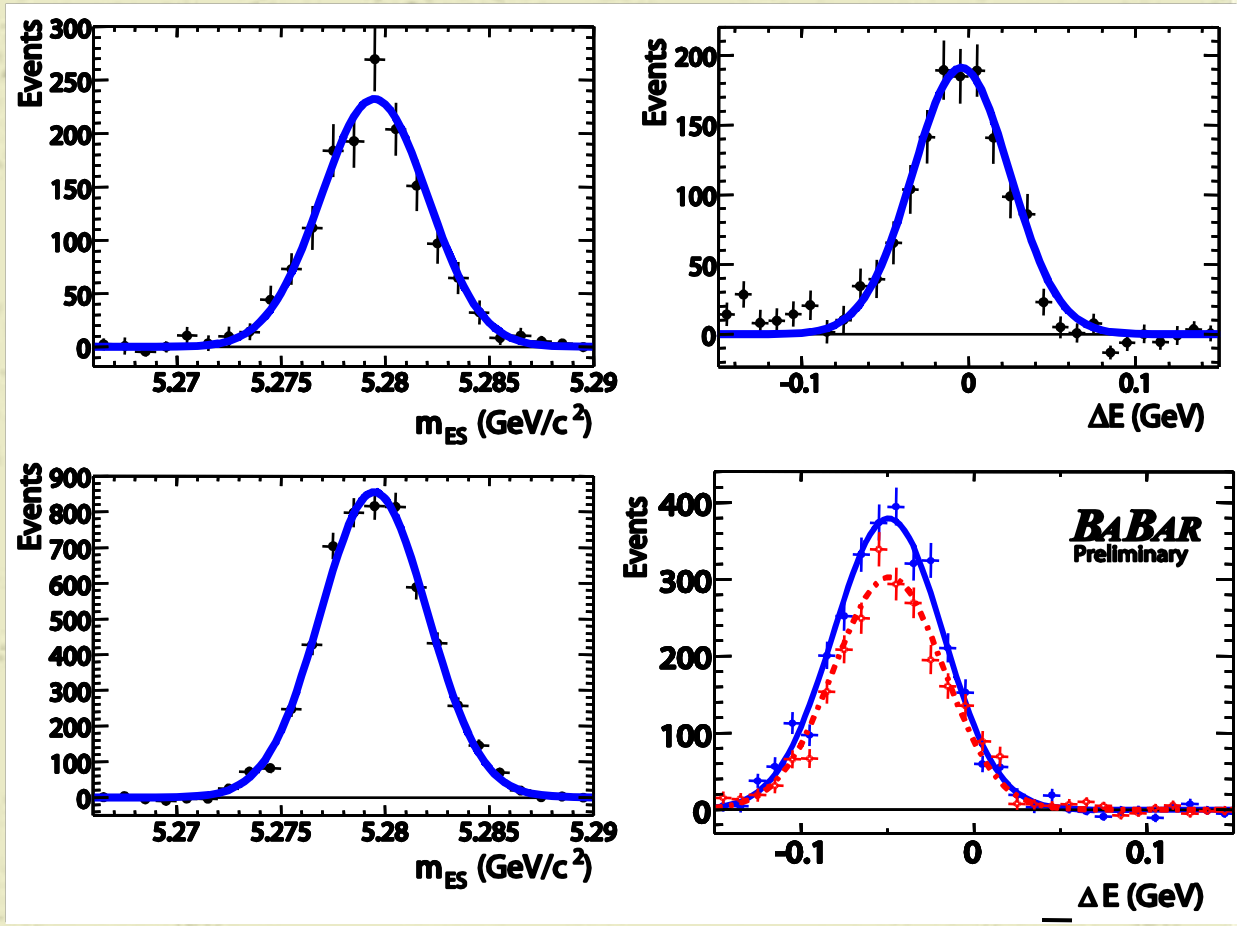
[stat. then syst. errors]

$B \to \pi^+\pi^-$ (top) and $B \to K^+\pi^-$ (bottom)

Reconstruct all $B \to h^+h'^-$ decays together with tracks assumed to be pions

In total 1395±54 $\pi^+\pi^-$ and 5410±91 $K^+\pi^-$ events were fit

The direct CP asymmetry in the $K\pi$ system is visible in the ΔE plot



Blue B^0 Red $\bar{B}^0$

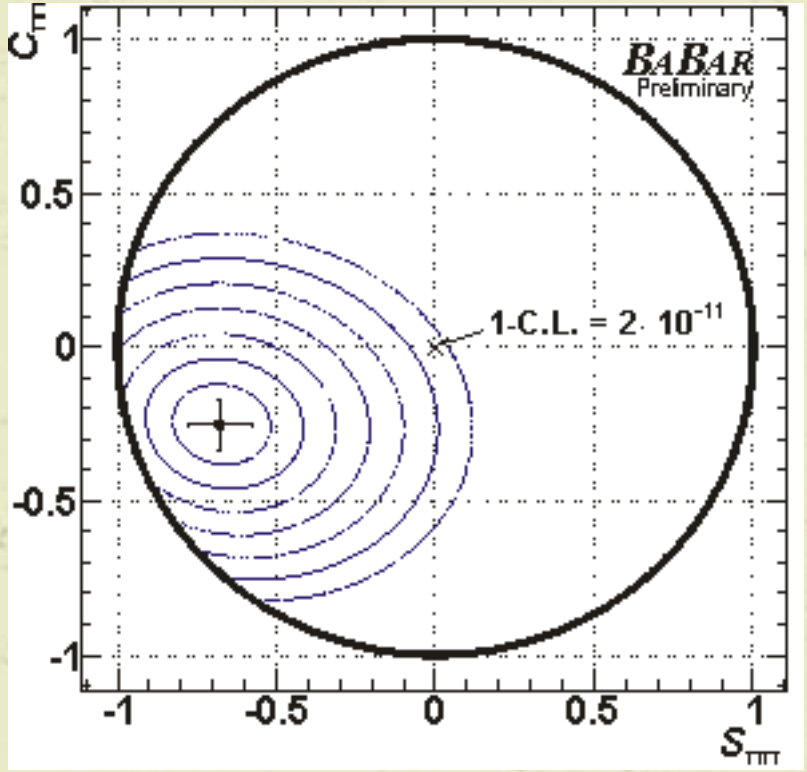
$$A_{K\pi} = -0.107 \pm 0.016^{+0.006}_{-0.004}$$

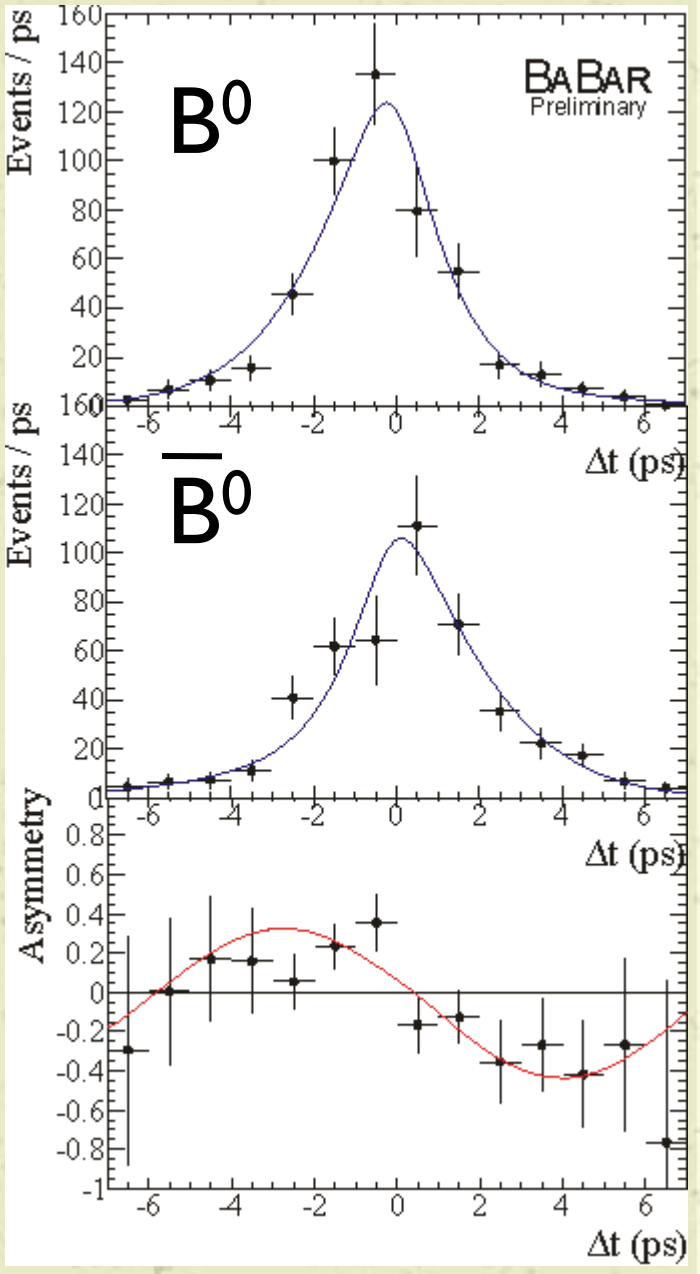
$B \to \pi^+\pi^-$

$S_f = -0.68 \pm 0.10 \pm 0.03$

$C_f = -0.25 \pm 0.08 \pm 0.02$

$6.7\,\sigma$

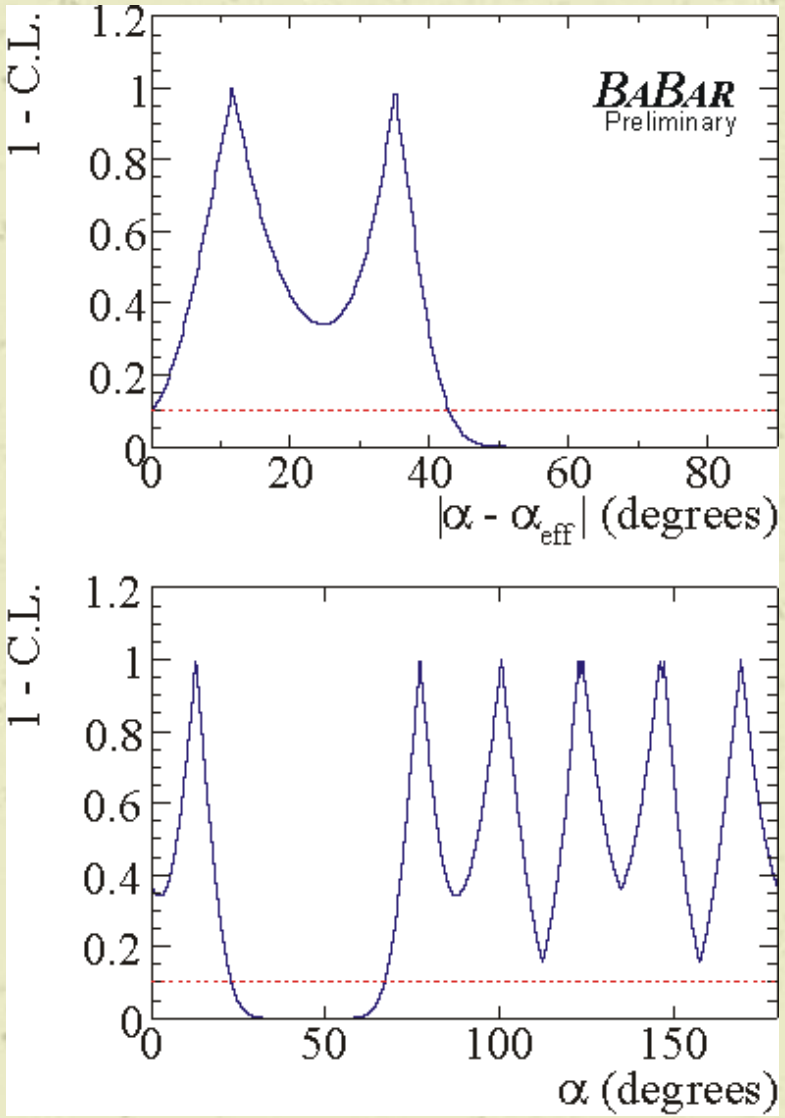




α Scan

Eight fold ambiguity due to the value and sign of $|\alpha - \alpha_{eff}|$ and orientation of the iso-spin triangle

Only the region between $[23^0, 67^0]$ is excluded at 90% confidence



BaBar results for γ

Measure sin(2β+γ) with the decays

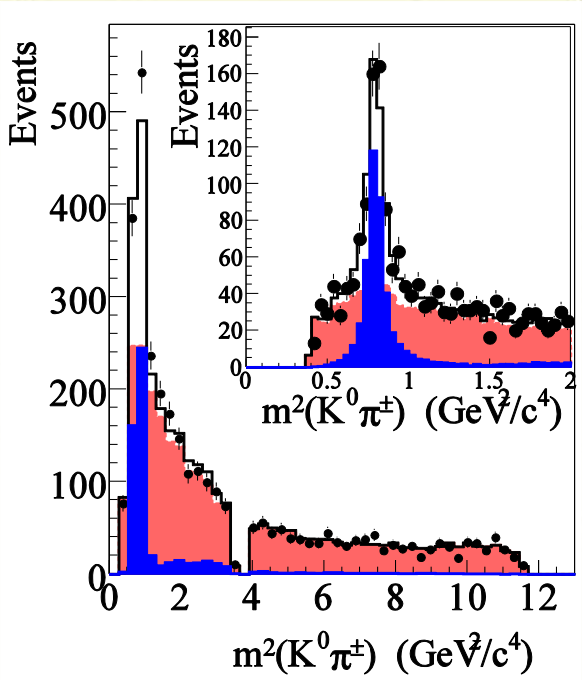
$$B^0 \to D^{\mp} K_s^0 \pi^{\pm}$$

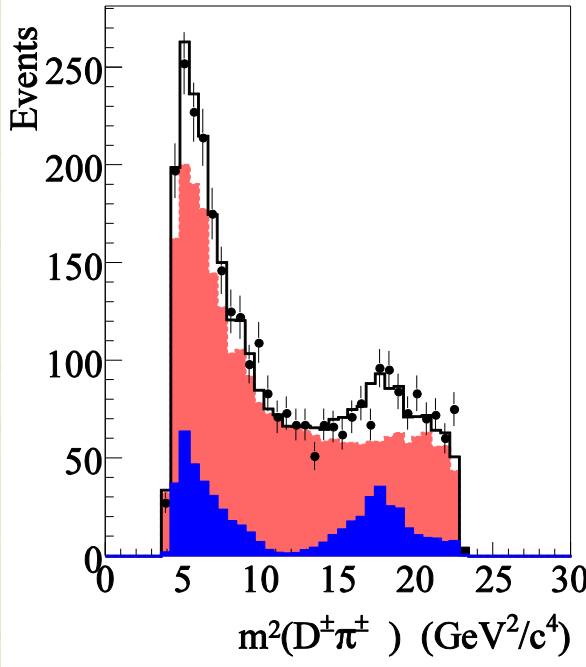
using the reconstructed the time dependant Dalitz plot

Remove Kπ [3.4,3.95] to remove $D^+D^-_{(s)}$ decays

Blue is background PDF
Rose is signal PDF
Points are data
Line is full fit PDF

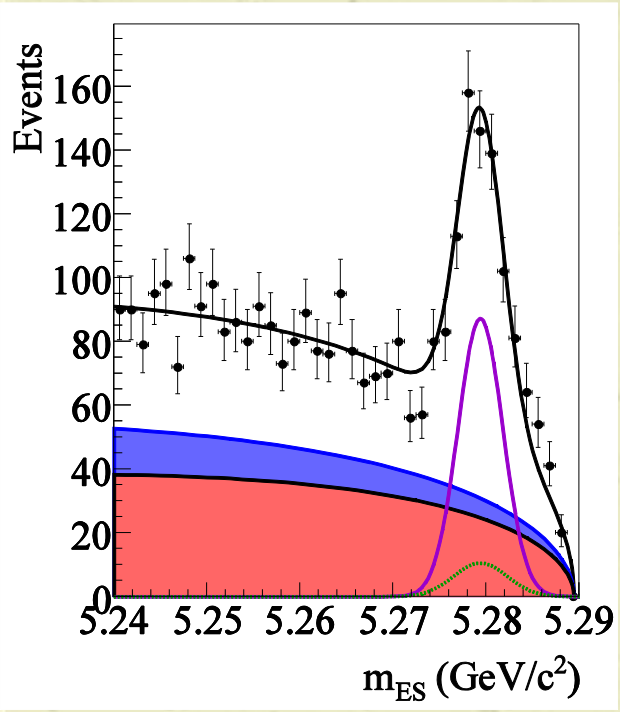
347 x 10^6 BB events





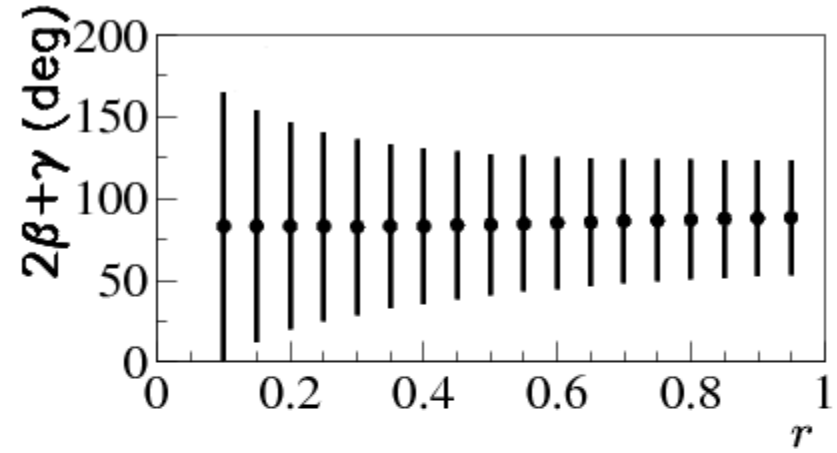
BABAR-PUB-07/065
SLAC-PUB-13050
arXiv:0712.3469v1

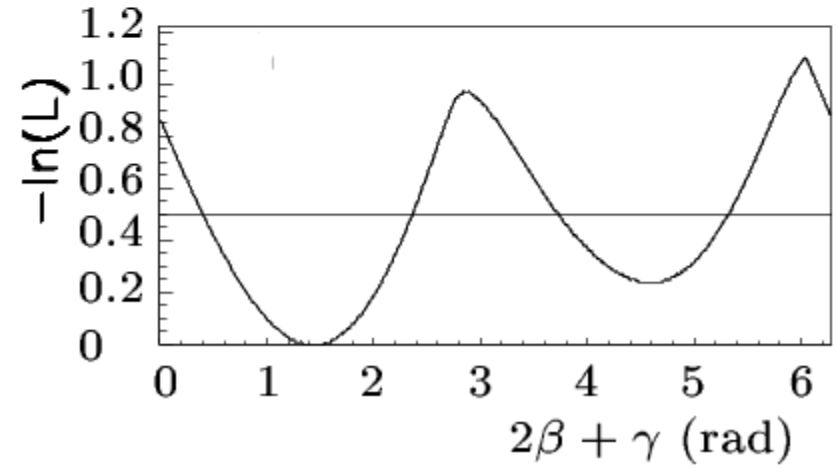
Results



Purple is signal PDF

Others are backgrounds





Solution is a function of $r = \dfrac{A(b \to u)}{A(b \to c)}$

Assuming r = 0.3 there are two solutions

$2\beta+\gamma = (83 \pm 53 \pm 20)^0$ and $(263 \pm 53 \pm 20)^0$

Timeline for BaBar first CKM angle measurements

"Measurement of the CP-violating Asymmetry Amplitude sin 2β" Phys. Rev. Lett. **89:201802,2002**

Referenced in the 2008 Nobel prize award to K&M, with the equivalent Belle paper, cited 396 times so far

"Study of the decay B^0(anti-B^0) $\rightarrow \rho^+\rho^-$, and constraints on the CKM angle α", Phys.Rev.Lett. **93:231801,2004**

Cited 73 times so far

"Measurement of branching fractions and CP-violating charge asymmetries for B meson decays to $D^{(*)}$ anti-$D^{(*)}$, and implications for the CKM angle γ", Phys.Rev. **D73:112004,2006**.

Cited 17 times so far

Conclusion

- BaBar has measured each of the angles α, β and γ
- Also both of the unconstrained sides
- So far the results are all consistent with the Standard Model
- In 2007 BaBar published 74 papers, with 43 so far in 2008
- The final measurements from the BaBar dataset will continue to improve the measurements of the CKM matrix for a few years yet