Imperial College London

2-Body Charmless B-Decays at BABAR and BELLE

Physics at LHC
Prague

Daniel Bowerman
Imperial College

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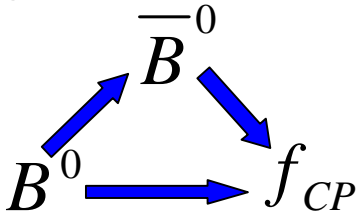
Overview

- Measuring sin2α (sin2φ_2) through B$\rightarrow \pi\pi$
- General analyses overview
- CP results from B$\rightarrow \pi^+\pi^-$, B$\rightarrow K^+\pi^-$
  - How compatible are Belle and BaBar?
- Isospin analyses: Adding in B$^+\rightarrow \pi^+\pi^0$ and B$\rightarrow \pi^0\pi^0$
- Results overview and prospects
- What does this mean for LHCb?

Measuring CP Asymmetries

- Three observable interference effects:
  - CP violation in mixing ($|q/p| \neq 1$)
  - (direct) CP violation in decay ($|A/\underline{A}| \neq 1$)
  - (indirect) CP violation in mixing and decay ($\mathrm{Im}\lambda \neq 0$)



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

Observable in time evolution of $B^0\overline{B}^0$ system (assume $\Delta\Gamma=0$)

$$f(B^0_{phys} \rightarrow f_{CP}, \Delta t) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1 - S_{f_{CP}} \sin(\Delta m_d \Delta t) + C_{f_{CP}} \cos(\Delta m_d \Delta t)\right]$$

$$f(\overline{B}^0_{phys} \rightarrow f_{CP}, \Delta t) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1 + S_{f_{CP}} \sin(\Delta m_d \Delta t) - C_{f_{CP}} \cos(\Delta m_d \Delta t)\right]$$

direct CP violation → C ≠ 0

indirect CP violation → S ≠ 0

$$S_f = \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \qquad C_f = -A_f = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$A(\Delta t) \equiv \frac{N(B^0_{tag}) - N(\overline{B}^0_{tag})}{N(B^0_{tag}) + N(\overline{B}^0_{tag})} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

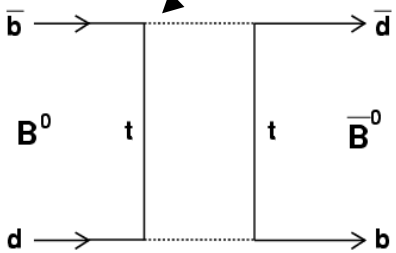
Measuring α with B→ ππ

Tree (T) Level:

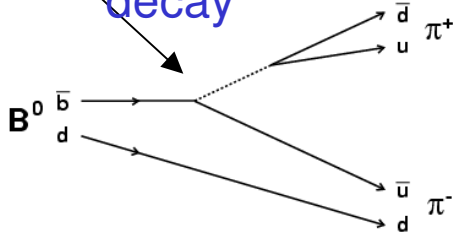
$$\lambda_{\pi\pi} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*} \propto e^{-i2\beta} e^{-i2\gamma}$$

$$\propto \sin(2(\pi-\beta-\gamma))$$

mixing



decay

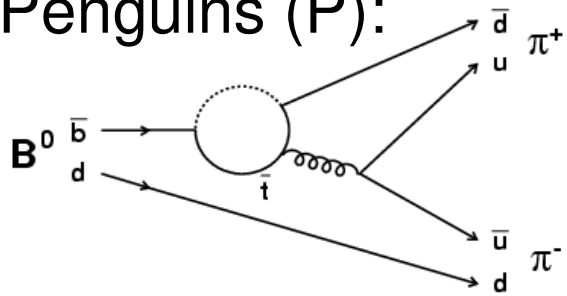


$$\lambda_{\pi\pi} = e^{2i\alpha}$$

$$C_{\pi\pi} = 0$$

$$S_{\pi\pi} = \sin(2\alpha)$$

With Penguins (P):



$$\lambda_{\pi\pi} = e^{2i\alpha} \frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$$

$$C_{\pi\pi} \propto \sin(\delta)$$

$$S_{\pi\pi} = \sqrt{1-C_{\pi\pi}^2}\,\sin(2\alpha_{\text{eff}})$$

Need branching fractions for $\pi^+\pi^-$, $\pi^\pm\pi^0$, and $\pi^0\pi^0$ to get α from α_{eff} : isospin analysis

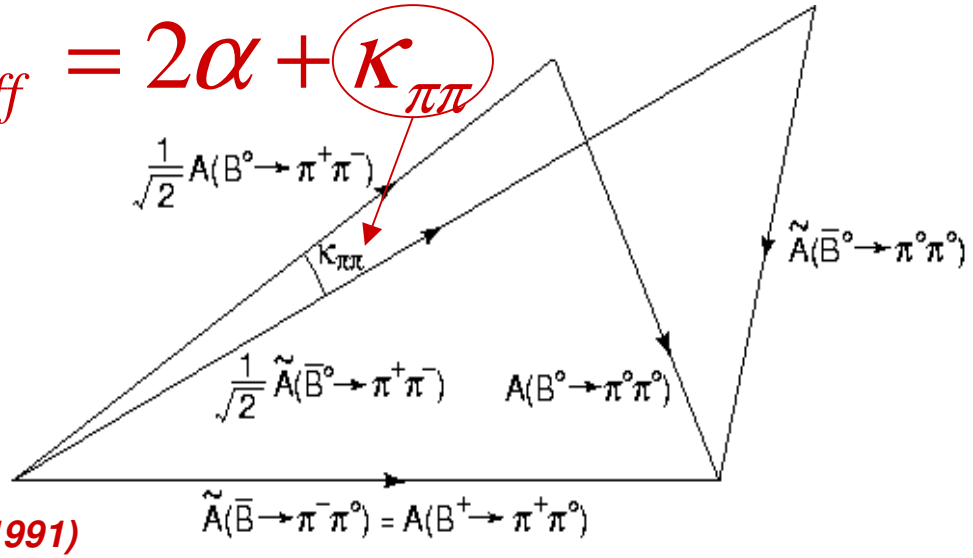
$\alpha_{eff} \rightarrow \alpha$:Isospin Analysis

- The decays $B \rightarrow \pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ are related by isospin
- Central observation is that $\pi\pi$ states can have I = 2 or 0
  - **(gluonic) penguins only contribute to I = 0 ($\Delta I = 1/2$)**
  - **$\pi^+\pi^0$ is pure I = 2 ($\Delta I = 3/2$) so has only tree amplitude**

  $\rightarrow (|A^{+0}| = |A^{-0}|)$
- Triangle relations allow determination of penguin-induced shift in α

Need branching fractions for all three decay modes, and for B^0 and $\overline{B}^0$ separately, even for $\pi^0\pi^0$

$$2\alpha_{eff} = 2\alpha + \kappa_{\pi\pi}$$



Gronau and London, Phys. Rev. Lett. 65, 3381 (1991)

Analysis Overview for $B \rightarrow \pi\pi$

- **Analysis issues: charmless B decays**
  - **Low branching ratios - BR ~ 10^{-5}-10^{-6}**
  - **Backgrounds:**
    - **Large background from $e^+e^- \rightarrow q\bar{q} \rightarrow$ need background suppression**
    - **Modes with π^0 suffer backgrounds from other B decays**
  - **Ambiguity between π and K - need excellent particle ID**
- **Time-dependent CP analysis issues:**
  - **Need to determine vertex position of both B mesons**
  - **Need to know the flavor of "other" B - particle ID**
- **Use maximum likelihood (ML) fits to extract signal yields and CP-violating asymmetries**
  - **Use as much information as possible**
- **The data sample corresponds to**
  - **88 million BB pairs (BaBar)**
  - **85 million BB pairs (Belle)**

Analysis Procedure B→ ππ

- Kinematically select B candidates with m_{ES}, ΔE

$$m_{\mathrm{ES}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}} \qquad \Delta E = E^{*}_{B} - E^{*}_{\mathrm{beam}}$$

- Suppress/separate $q\bar{q}$ background with Event-Shape discriminant
  - Linear Fisher (BaBar), Likelihood selector (Belle)

•BaBar

–Loose cut on event shape $|\cos(\theta_S)|$

–Fit for ππ, Kπ, and KK using m_{ES}, ΔE, Fisher, θ_C

–Add tagging and Δt, fit for S and C

•Belle

–Optimize cut on event-shape

–Select pions

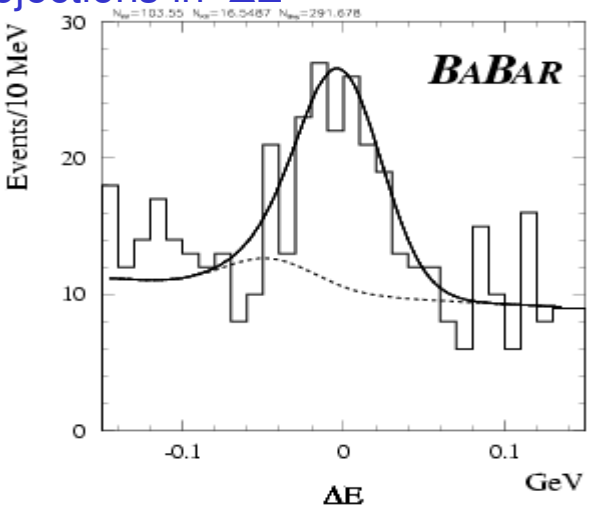
–Cut ~3σ in m_{ES} and ΔE

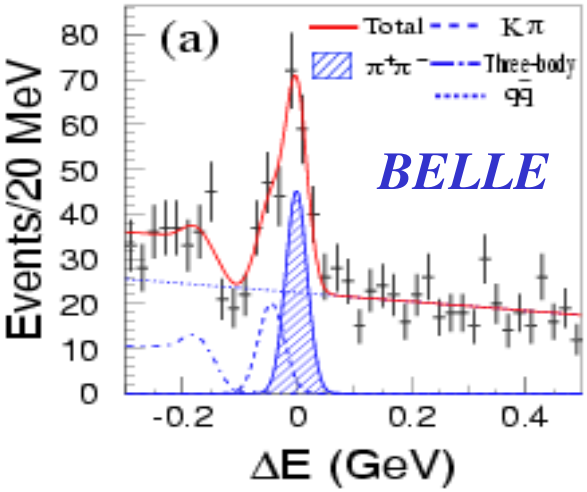
–Fit S and C using m_{ES}, ΔE, and Δt

Branching Fraction Results

Mode	BaBar			Belle		
	Yield	BR (10^{-6})	$A_{CP}(K\pi)$	Yield	BR (10^{-6})	$A_{CP}(K\pi)$
$B^0 \to \pi^+\pi^-$	157 ±19	4.7 ± 0.6 ± 0.2		133 ± 19	4.4 ± 0.6 ± 0.3	
$B^0 \to K^+\pi^-$	589 ± 30	17.9 ± 0.9 ± 0.7	-0.10 ± 0.05 ± 0.02	596 ± 33	18.5 ± 1.0 ± 0.7	-0.07 ± 0.06 ± 0.01
$B^0 \to K^+K^-$	1 ± 8	<0.6 (90%) CL		-1 ± 7	< 0.7 (90%) CL	

Projections in ΔE

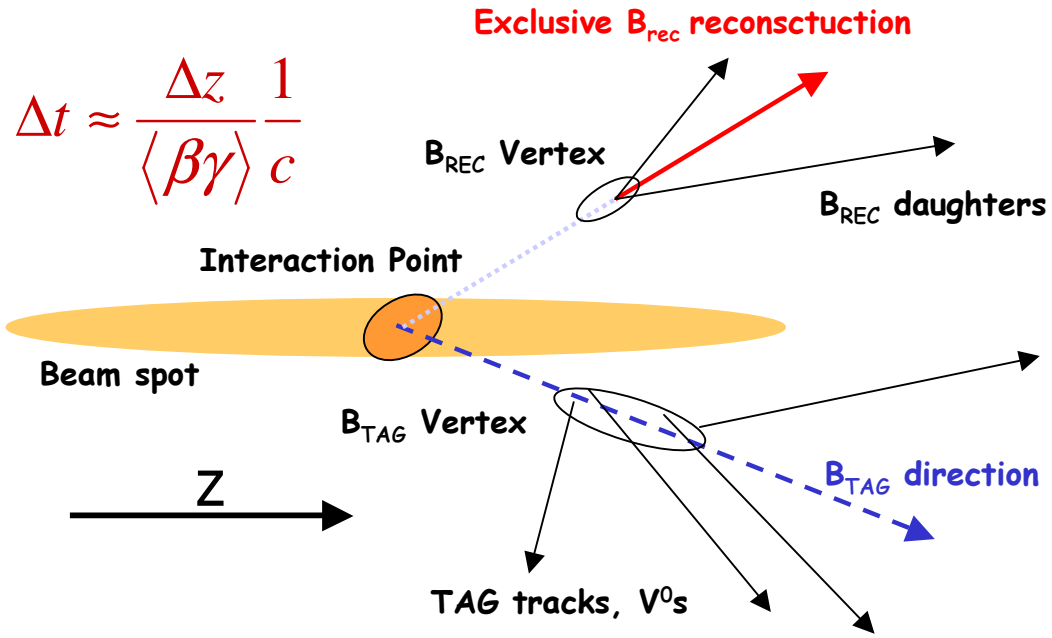




- **Branching fractions are consistent**
- **2σ direct CP effect in $K^+\pi^-$**

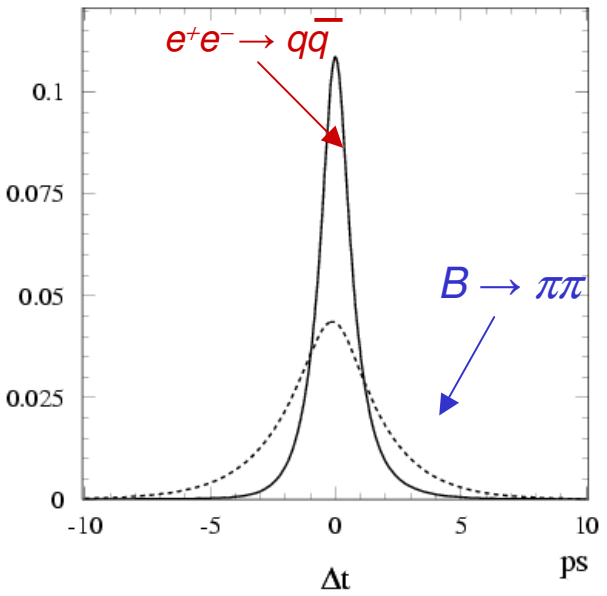
Reconstructed Vertex and Flavour tagging

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle} \frac{1}{c}$$



- **Δz resolution dominated by tag side**
- **Same resolution function as charmonium (sin2β) sample**
- **Resolution functions determined in data**

Example in $B \to \pi\pi$



- **Same Tagging algorithms as with sin2β analysis**
- **Primarily use Lepton and Kaon tags, and more complex NN based approach**
- **Event shape and Δt resolution functions are dependent on tagging category**

Time Dependent CP Results

With no penguins expect: $S_{\pi\pi} = \sin(2\alpha) \quad C_{\pi\pi} = 0$

BaBar

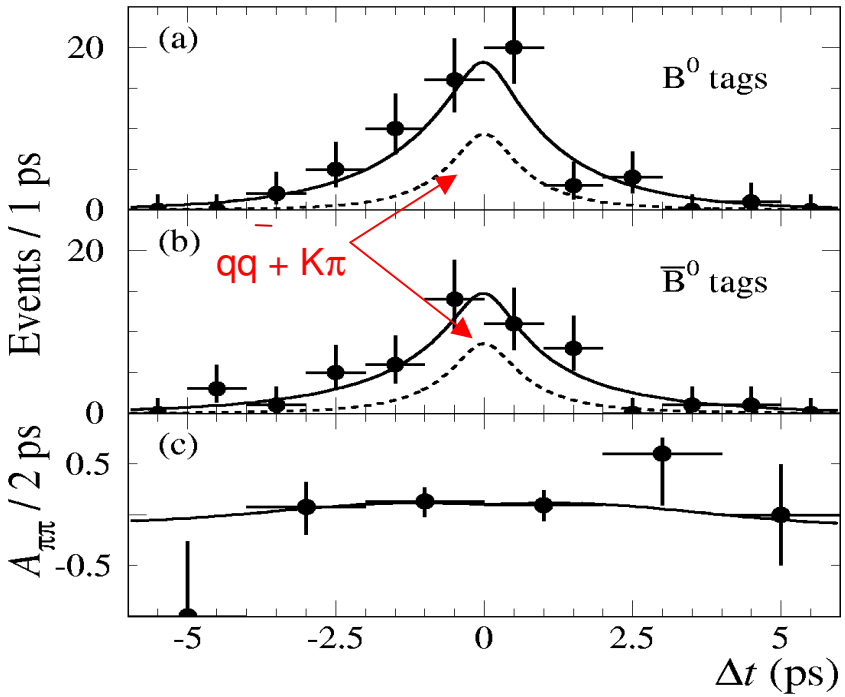
$C_{\pi\pi} = -0.30 \pm 0.25(\text{stat}) \pm 0.04(\text{syst})$

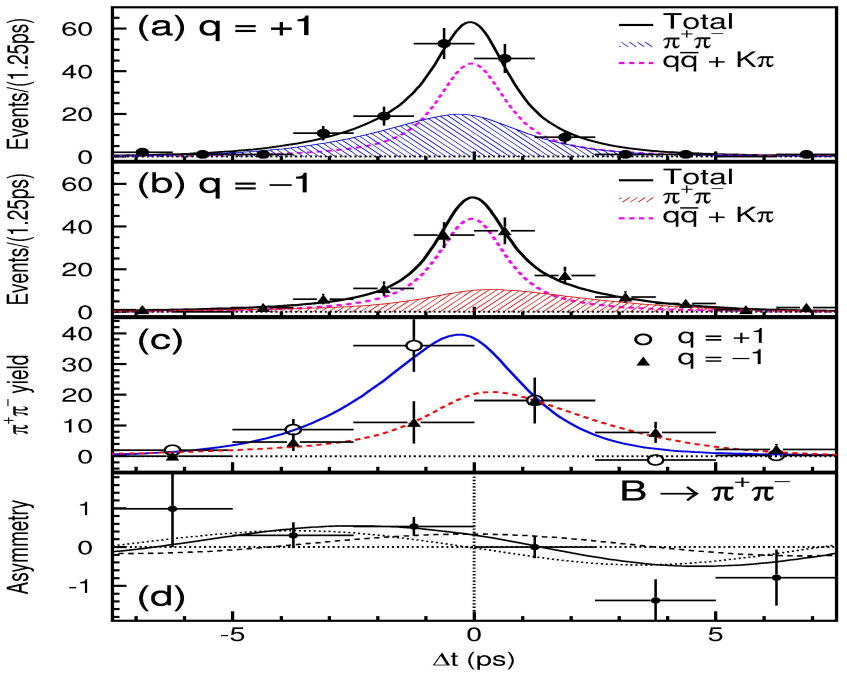
$S_{\pi\pi} = +0.02 \pm 0.34(\text{stat}) \pm 0.05(\text{syst})$

Belle

$C_{\pi\pi} = -0.77 \pm 0.27(\text{stat}) \pm 0.08(\text{syst})$

$S_{\pi\pi} = -1.23 \pm 0.41(\text{stat})^{+0.08}_{-0.07}(\text{syst})$

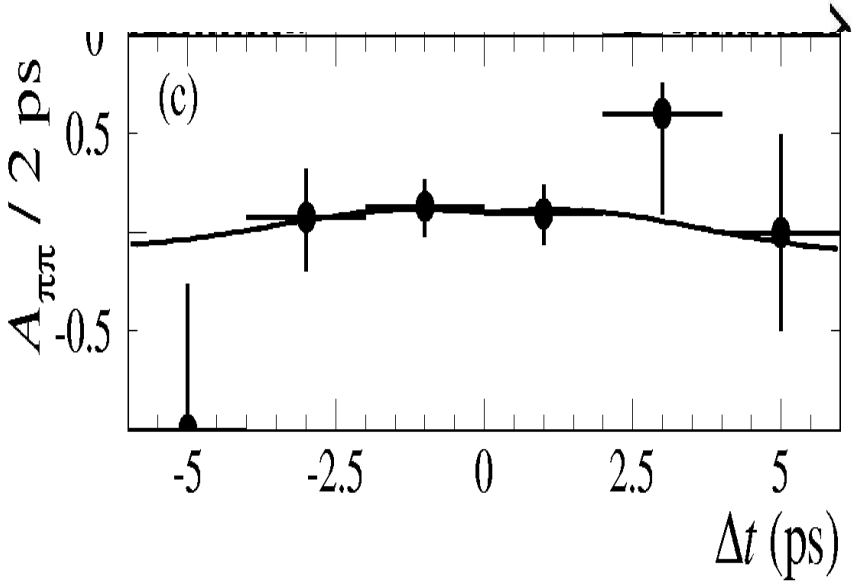




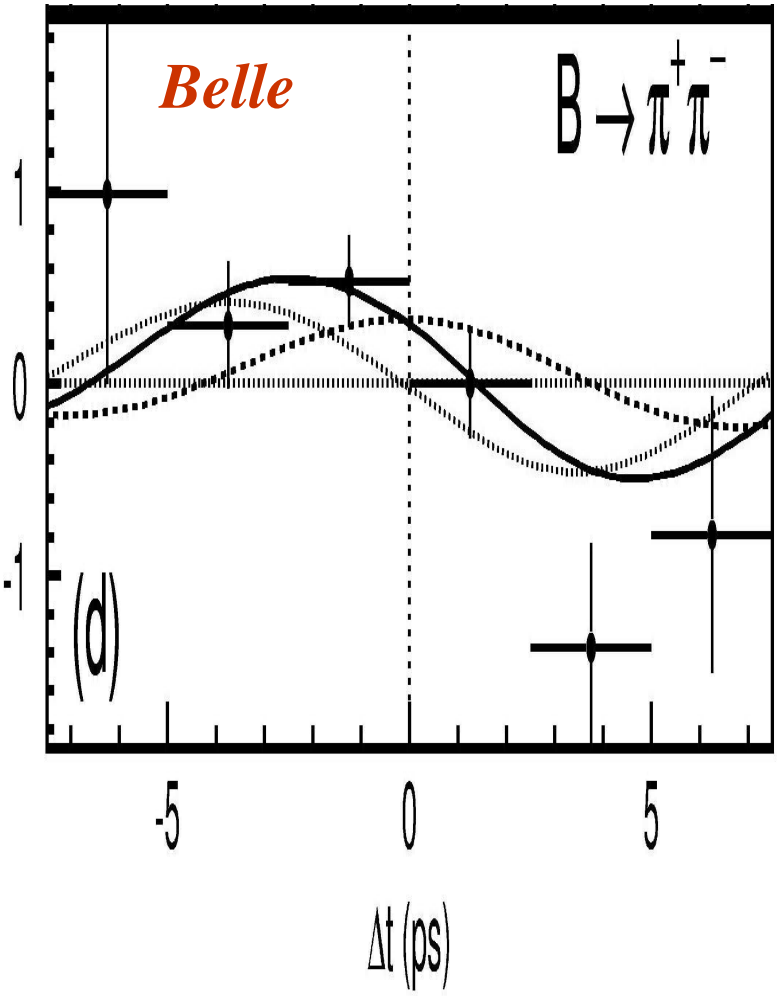
Time Dependent CP Results

Very crudely put both asymmetries on the same scale

BaBar

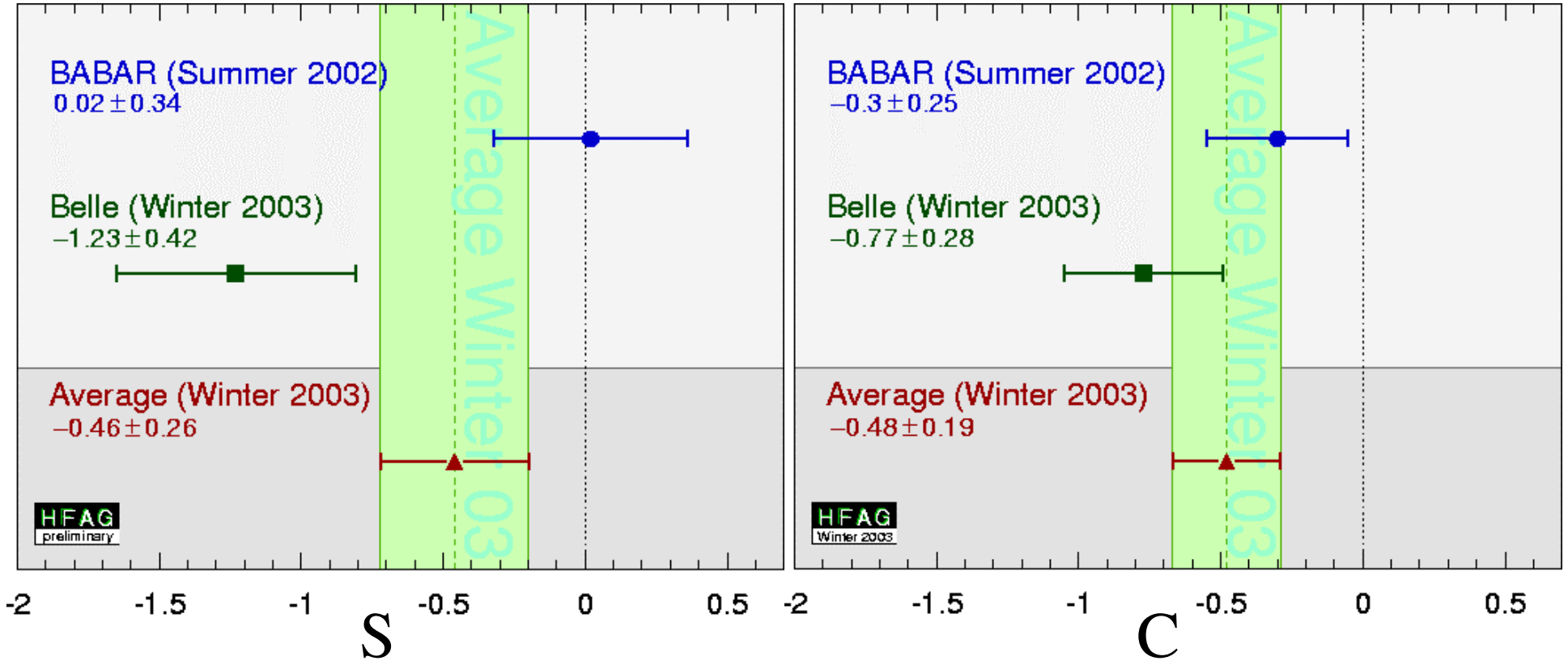


Belle



Highlights how different the measurements are!

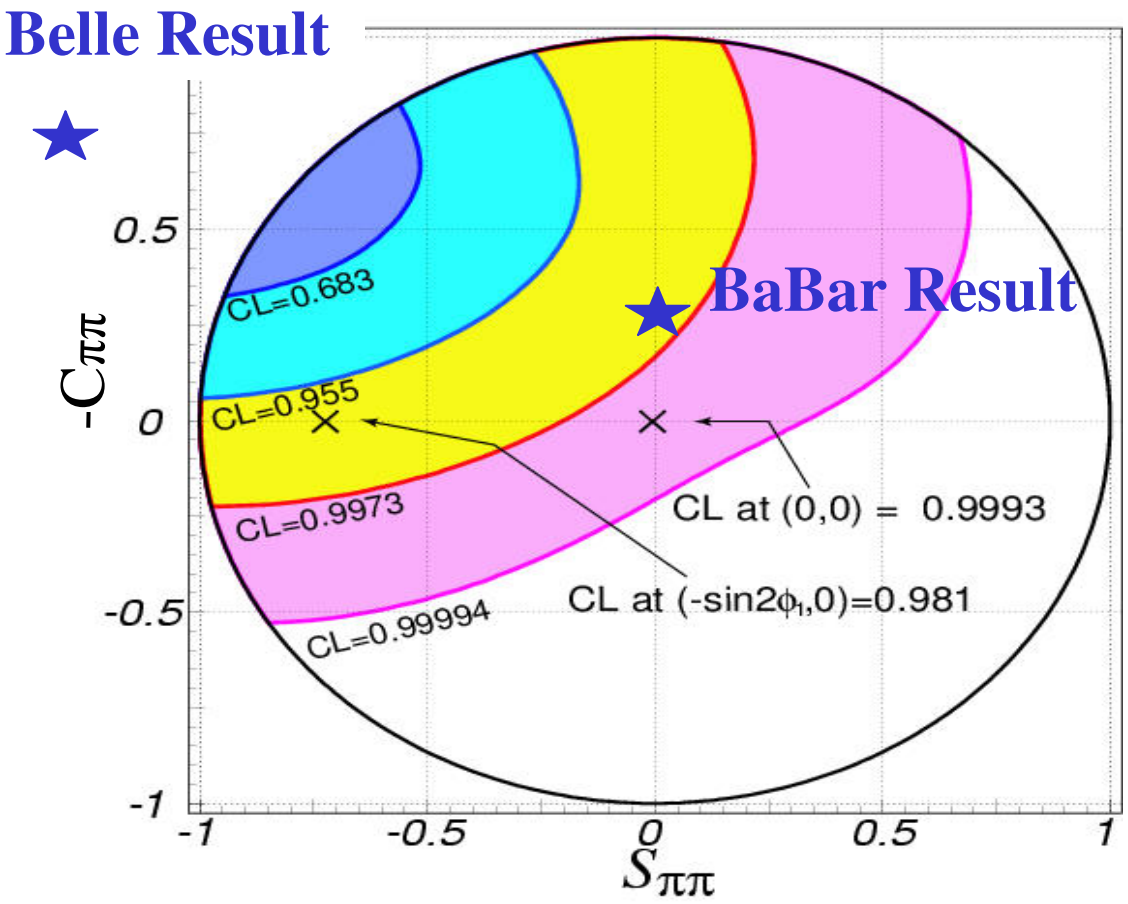
Compatibility of the CP results



Belle inconsistent with (C=S=0) at 99.93% C.L.

BaBar is still consistent with C=S=0

Compatibility of the CP results

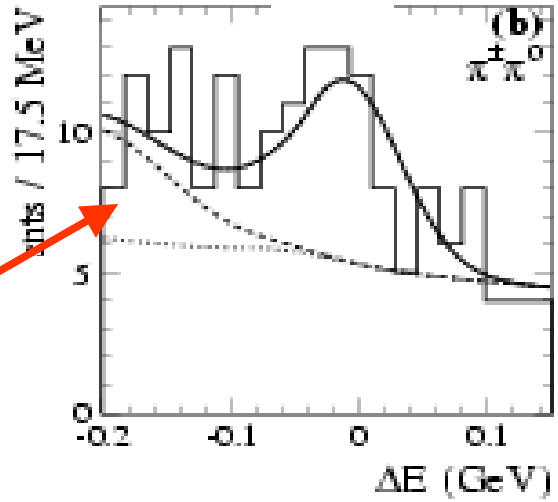


- Belle results and contour plot
- Note the y-axis scale change (-C = A)
- Physical boundary at $C^2 + S^2 = 1$
- Inconsistent with (C = S = 0) at the 99.93% CL (3.4σ)
- BaBar and Belle are compatible at the 2-2.5σ level

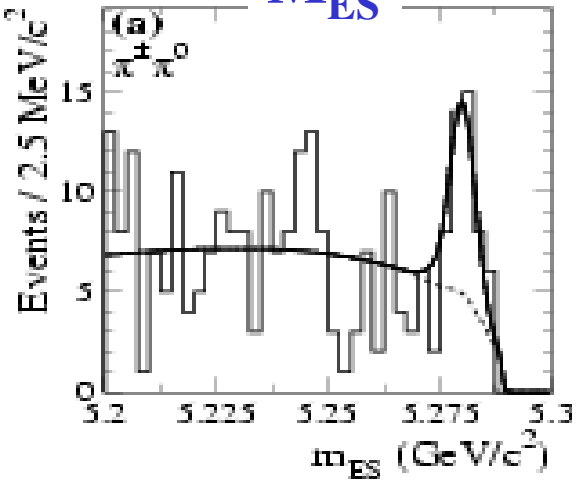
Completing the Triangle: $B^+ \to \pi^+\pi^0$

BaBar

ΔE



M_{ES}

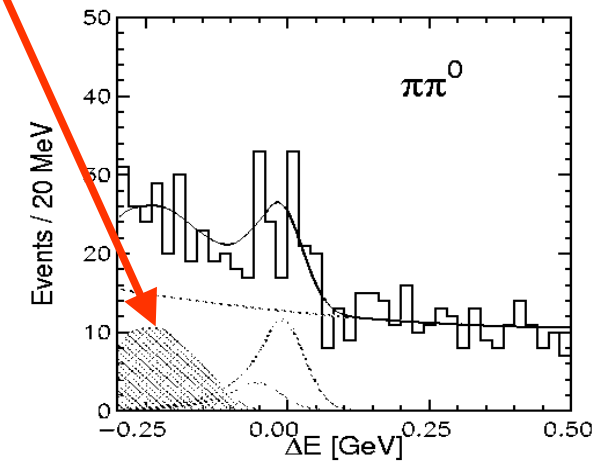


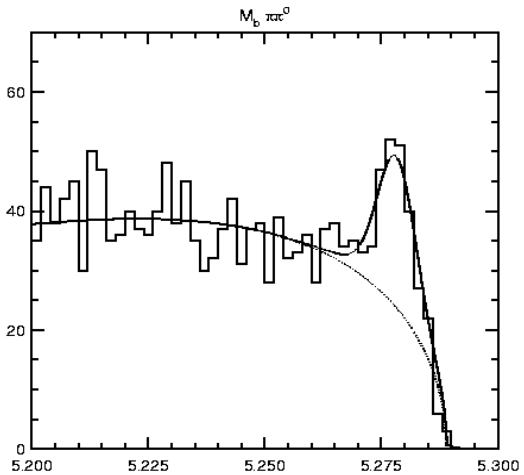
125 ± 22

(7.7σ)

3-body feedthrough

Belle





72.4 ± 17.4

(4.5σ)

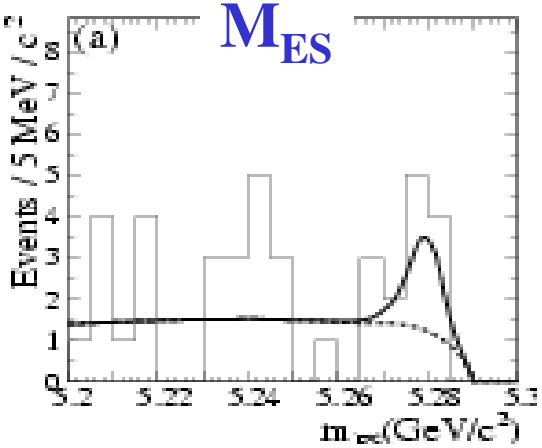
No direct CP violation seen here!

Completing the Triangle: $B \to \pi^0\pi^0$

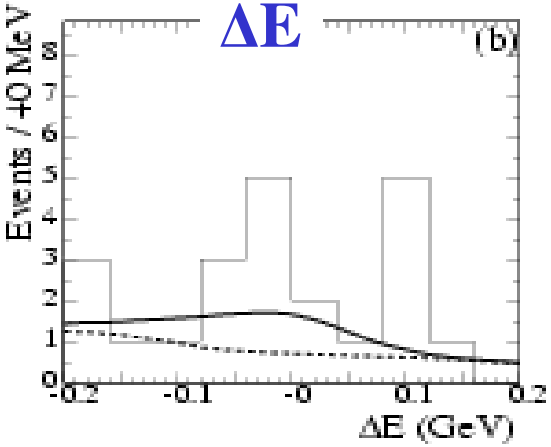
Most challenging of the modes – lower efficiency, poor resolutions, 3-body background, correlations

BaBar

M_{ES}



ΔE



N=23 ± 10

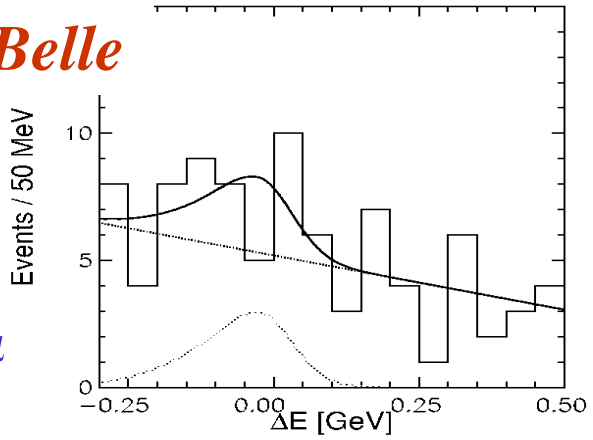
(2.5σ)

- **Hints of a signal at :**

  $BR(B \to \pi^0\pi^0) \sim 1.7 * 10^{-6}$

- **At the very top end of expectations**
- **Have to measure both B^0 and $\overline{B^0}$ rates**
- **Would have big impact on measuring α**

Belle

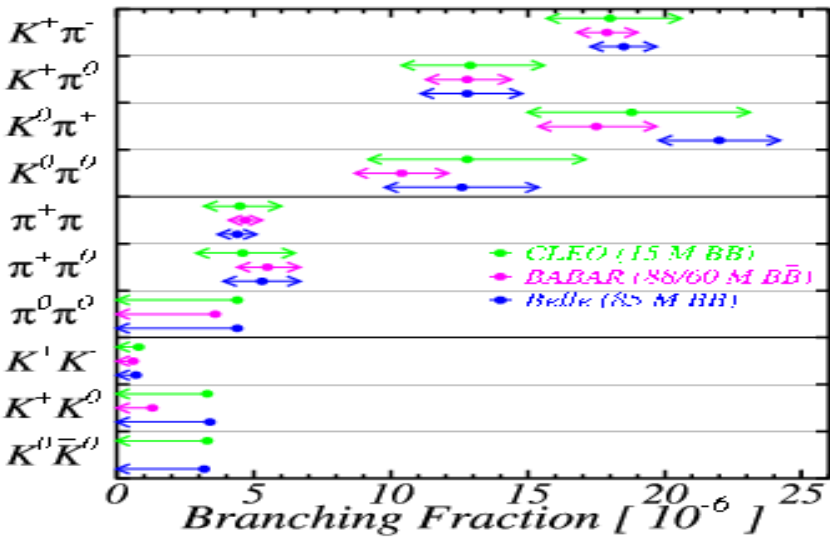


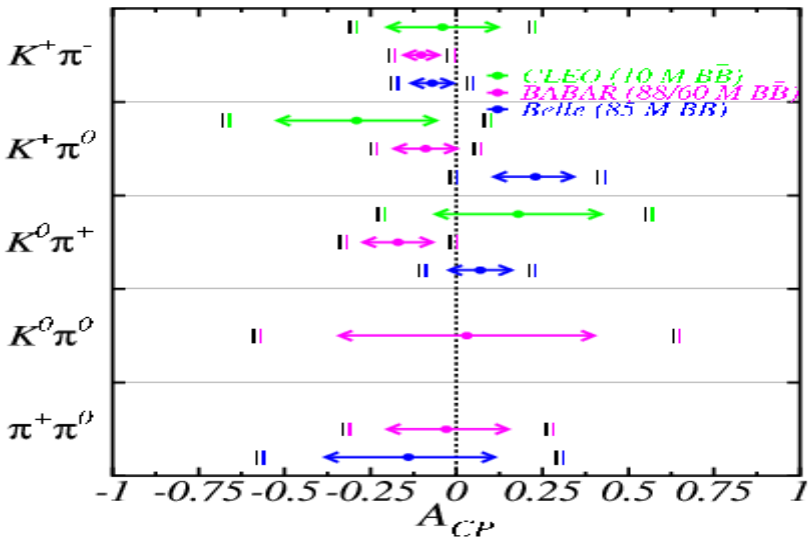
N=12 ± 9

(1.9σ)

Summary of the results

Decay Mode	*BABAR*		Belle	
	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{CP}$	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{CP}$
$K^+\pi^-$	$17.9 \pm 0.9 \pm 0.7$	$-0.10 \pm 0.05 \pm 0.02$	$18.5 \pm 1.0 \pm 0.7$	$-0.07 \pm 0.06 \pm 0.01$
$K^0\pi^+$	$20.0 \pm 1.6 \pm 1.0$	$-0.05 \pm 0.08 \pm 0.01$	$22.0 \pm 1.9 \pm 1.1$	$0.07^{+0.09+0.01}_{-0.08-0.03}$
$K^+\pi^0$	$12.8 \pm 1.2 \pm 1.0$	$-0.09 \pm 0.09 \pm 0.01$	$12.8 \pm 1.4^{+1.4}_{-1.0}$	$0.23 \pm 0.11 \pm 0.02$
$K^0\pi^0$	$10.4 \pm 1.5 \pm 0.8$	$0.03 \pm 0.36 \pm 0.09$	$12.6 \pm 2.4 \pm 1.4$	
$\pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$		$4.4 \pm 0.6 \pm 0.3$	
$\pi^+\pi^0$	$5.5^{+1.0}_{-0.9} \pm 0.8$	$-0.03 \pm 0.18 \pm 0.02$	$5.3 \pm 1.3 \pm 0.5$	$-0.14 \pm 0.24 \pm 0.04$
$\pi^0\pi^0$	< 3.6 $(1.6^{+0.7+0.6}_{-0.6-0.3})$		$< 4.4 (1.8^{+1.4+0.5}_{-1.3-0.7})$	
K^+K^-	< 0.6		< 0.7	
$K^+\overline{K}^0$	< 2.2		< 3.4	
$K^0\overline{K}^0$	< 1.6		< 3.2	



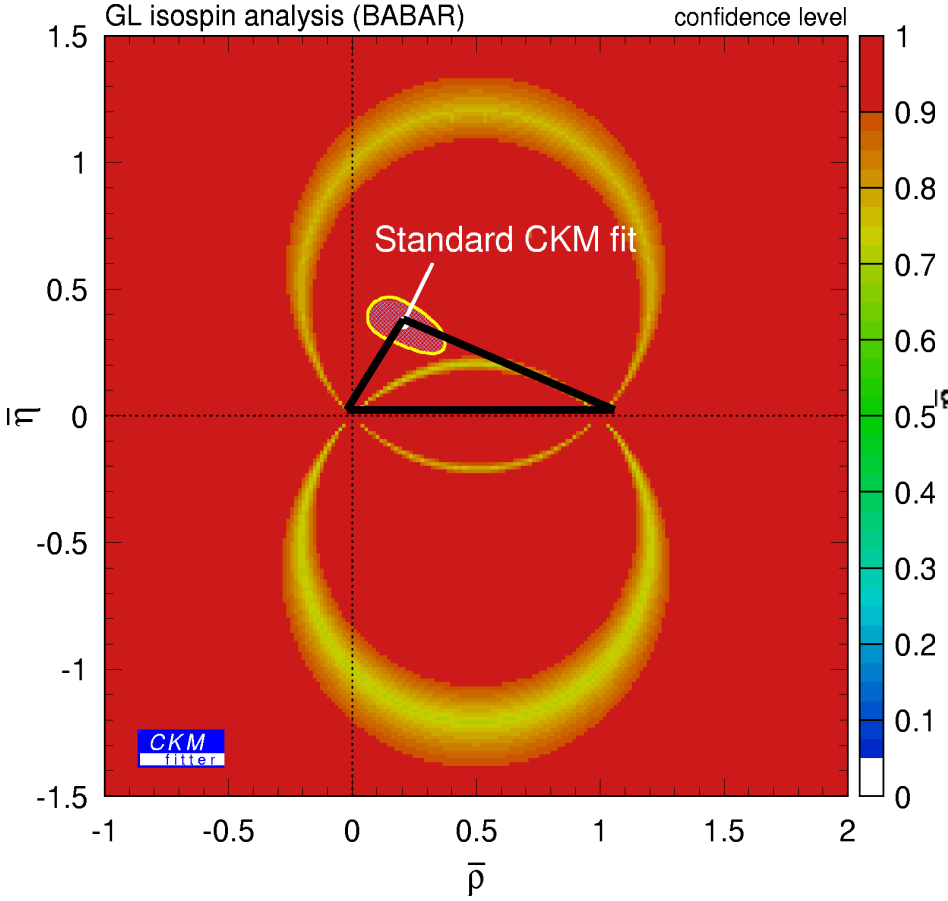


Branching ratio's show that Penguin contribution is not negligible!

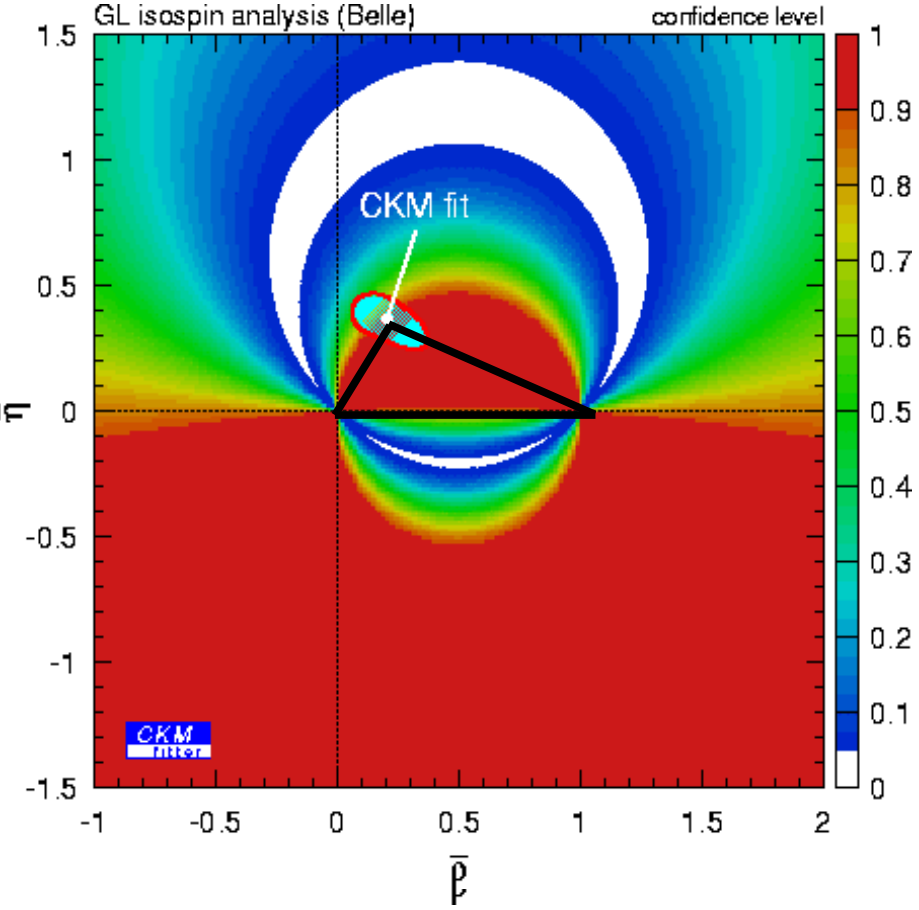
$B \to \pi\pi$ conclusions

Currently an Isospin analysis provides no new information

BaBar



Belle



The need for an Isopsin Analysis

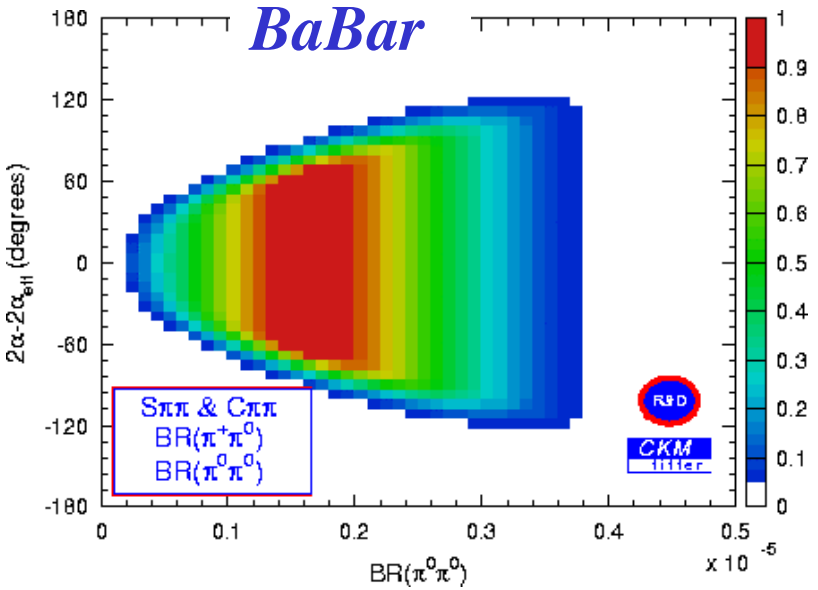
- Can still get information on α with only an upper bound on $\pi^0\pi^0$:
  - For example: Grossman-Quinn bound (assume only isospin)

$$\sin^2(\alpha_{\text{eff}} - \alpha) < \frac{\frac{1}{2}\left[BR(B^0 \to \pi^0\pi^0) + BR(\overline{B}^0 \to \pi^0\pi^0)\right]}{BR(B^\pm \to \pi^\pm\pi^0)}$$

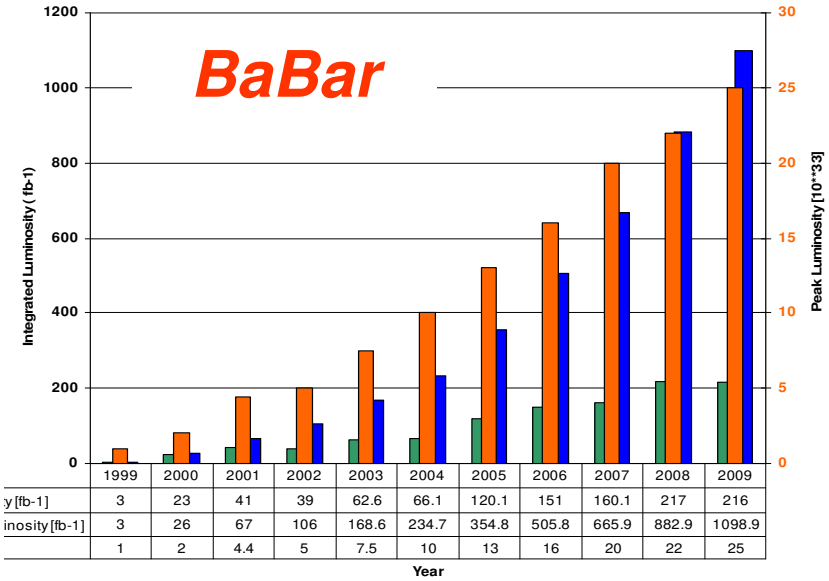
$$< 0.61 \text{ @ } 90\% \text{ C.L.}$$

$$|\alpha_{\text{eff}} - \alpha| < 51^\circ \text{ @ } 90\% \text{ C.L.}$$

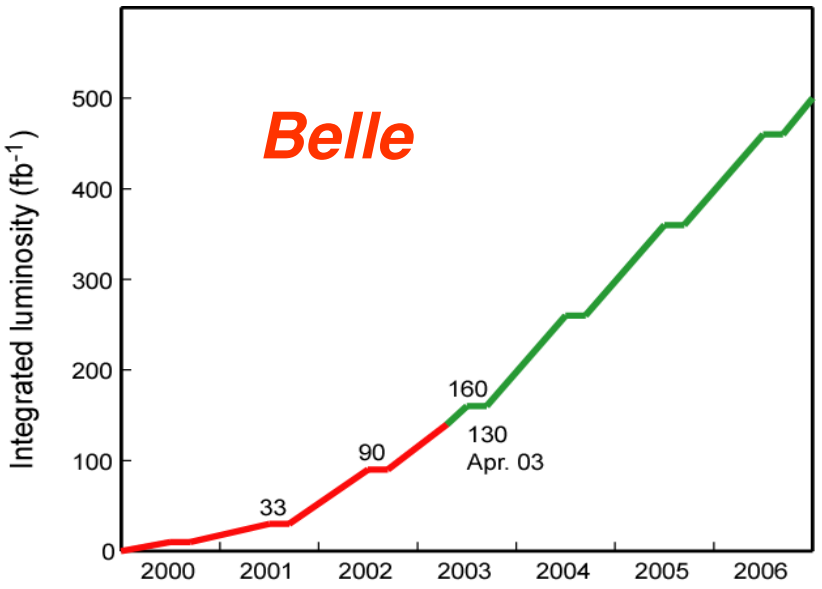
If the Branching fraction for $B \to \pi^0\pi^0$ holds up - Isospin analysis is necessary!



Prospects at the B-factories



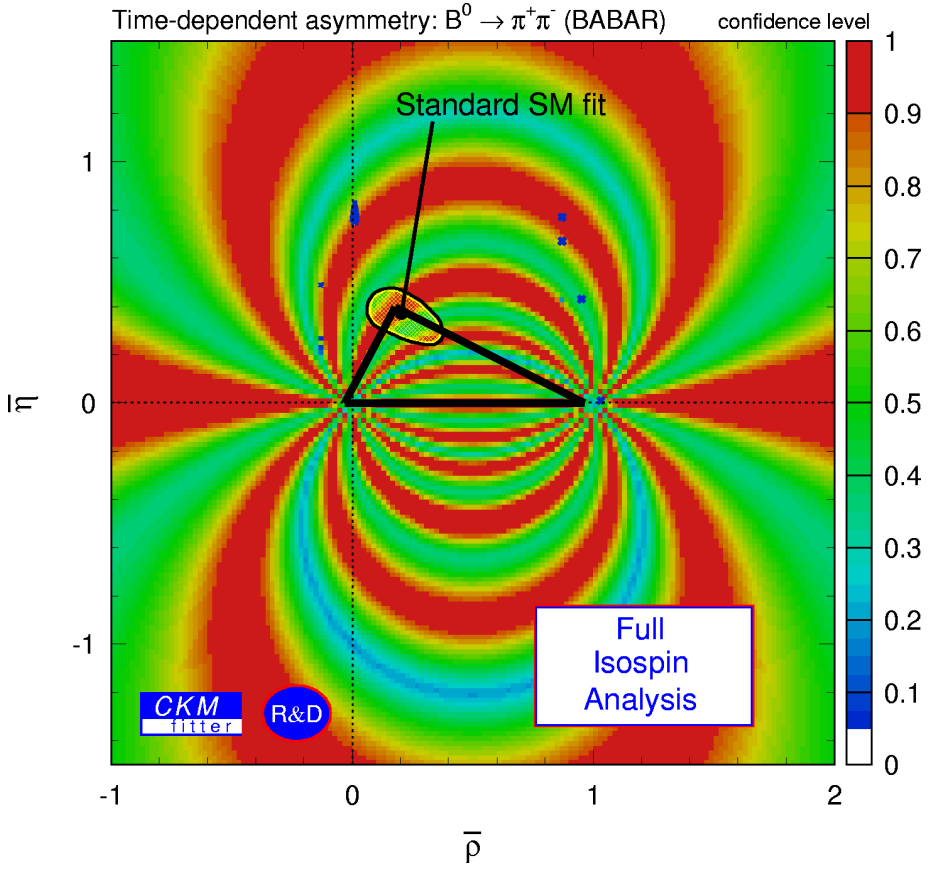
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
y [fb-1]	3	23	41	39	62.6	66.1	120.1	151	160.1	217	216
inosity [fb-1]	3	26	67	106	168.6	234.7	354.8	505.8	665.9	882.9	1098.9
	1	2	4.4	5	7.5	10	13	16	20	22	25

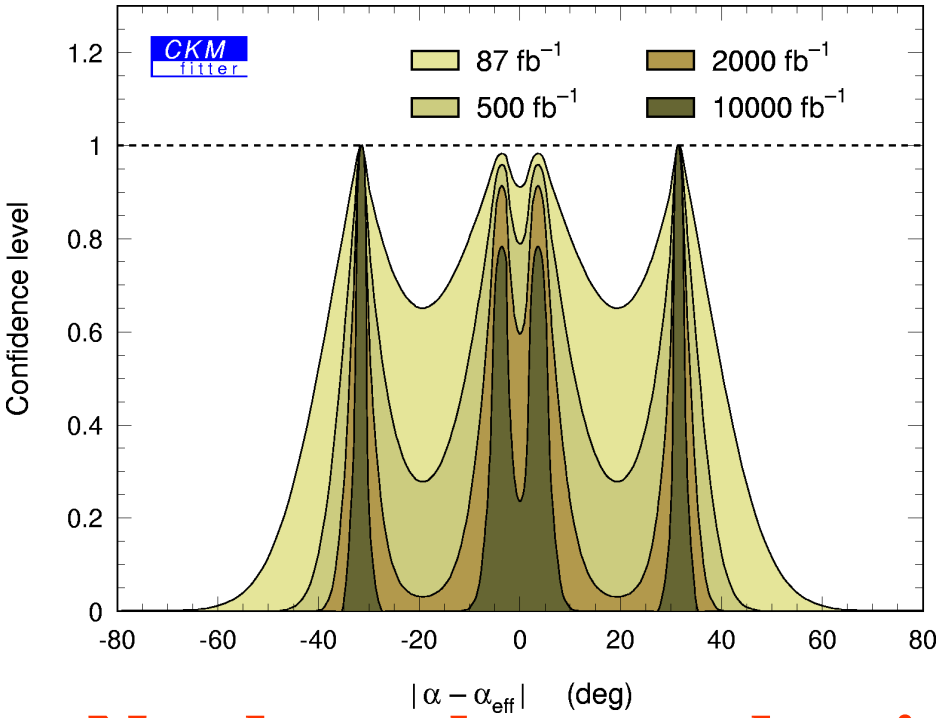


- Belle collecting average 450pb^{-1}/day, BaBar collecting 300pb^{-1}/day
- Next set of results should fully test B → ππ compatibility
- Both experiments expect ~500fb^{-1} by 2006
- May go much higher with 'Super' B-factories
- What does this mean for α through B → ππ ?

Prospects at the B-factories

- **Isospin Analysis**
- **Using present BaBar branching fractions extrapolated to 500fb^{-1}**





Need much more data!

Prospects for B-factories and LHC

If the branching ratio for $B \to \pi^0\pi^0$ holds at (~1.7 *10^{-6}) then:

- $|\alpha_{\text{eff}} - \alpha| < 20^\circ$
- **Will need an Isospin analysis to extract α**
- **Probably not possible at LHC**
- **Only possible at Super B-factory (maybe)**

We should hope that

- **$B \to \pi^0\pi^0$ disappears!**
- **That α through ρπ is feasible at the LHC**

Still much to be learnt from the 2-body modes!

- **Perhaps measure γ through Kπ**
- **Direct CP violation in Kπ**

Conclusions

- **2-body results have provided many highlights for the B-factory programmes**
- **Belle results are inconsistent with $C = S = 0$ in $B \to \pi\pi$ at the 3.4σ level**
- **BaBar and Belle results disagree at the 2σ level**
- **Results indicate large Penguin contributions**
- **$B \to \pi^0\pi^0$ results indicate that Isospin analysis will be necessary - but very difficult at B-factories**
- **Probably not possible to measure α through $B \to \pi\pi$ at LHC (hopefully through $\rho\pi$)**

Thanks to Jim Olsen, Belle and Babar 2-body groups and the CKM fitters : http://ckmfitter.in2p3.fr

Back up Slides

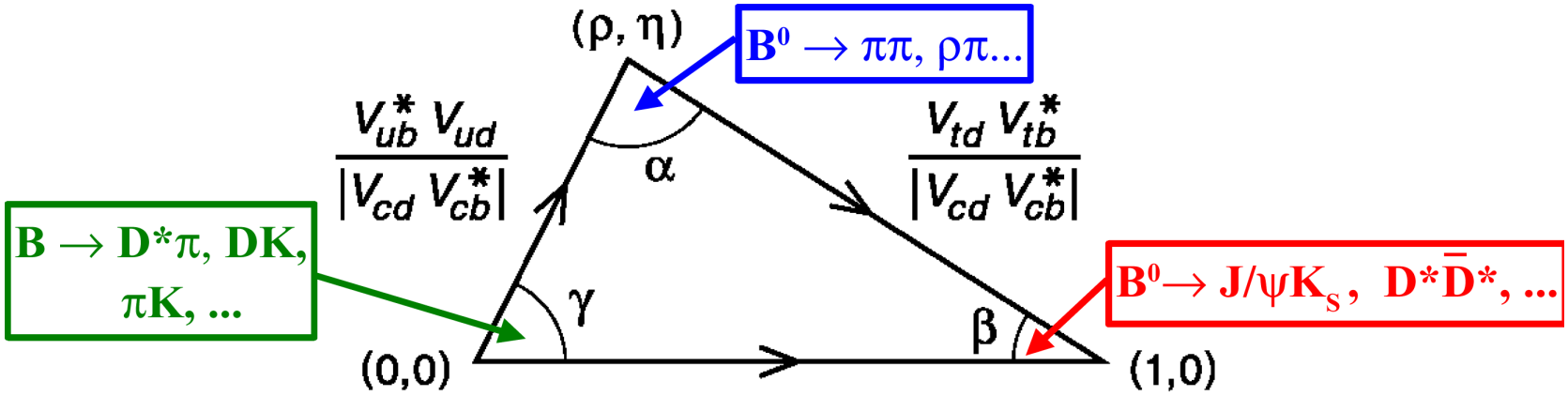
CP Violation in the SM

CP violation arises in Standard Model through a single phase in the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

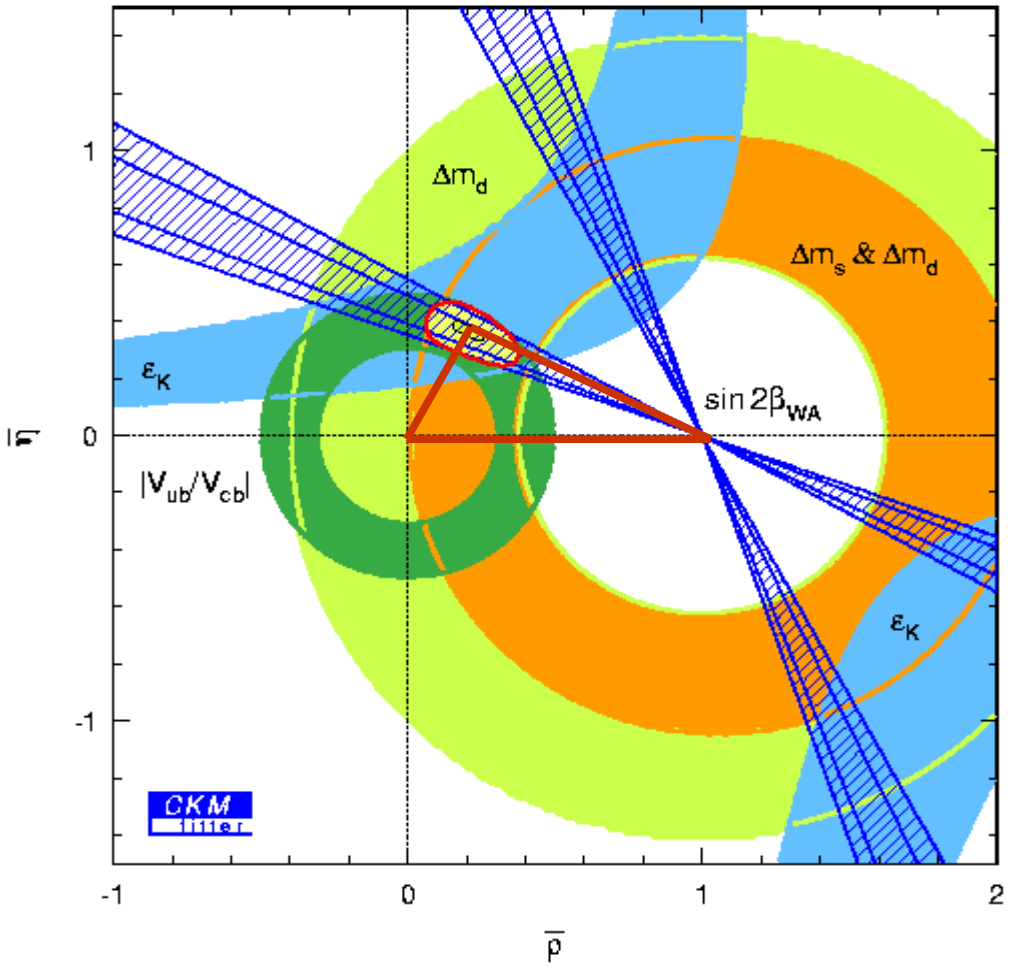
Unitarity of V requires e.g. $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

Can be represented as "unitarity" triangle in the complex plane



***CP* violating asymmetries A(Δt) in B^0 decays measure α, β, γ**

CP violation in the SM



World Average
$\sin 2\beta = 0.734 \pm 0.055$

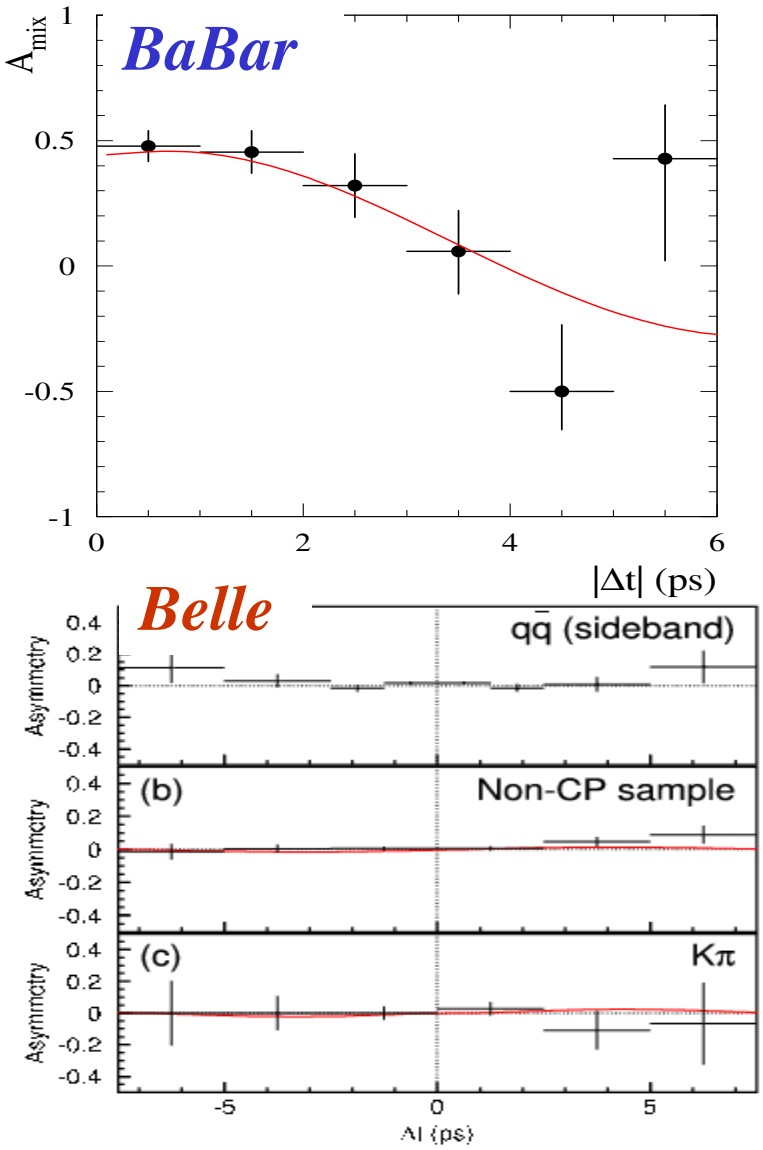
http://ckmfitter.in2p3.fr

BaBar and Belle crosschecks

Both BaBar and Belle have undertaken many cross-checks:

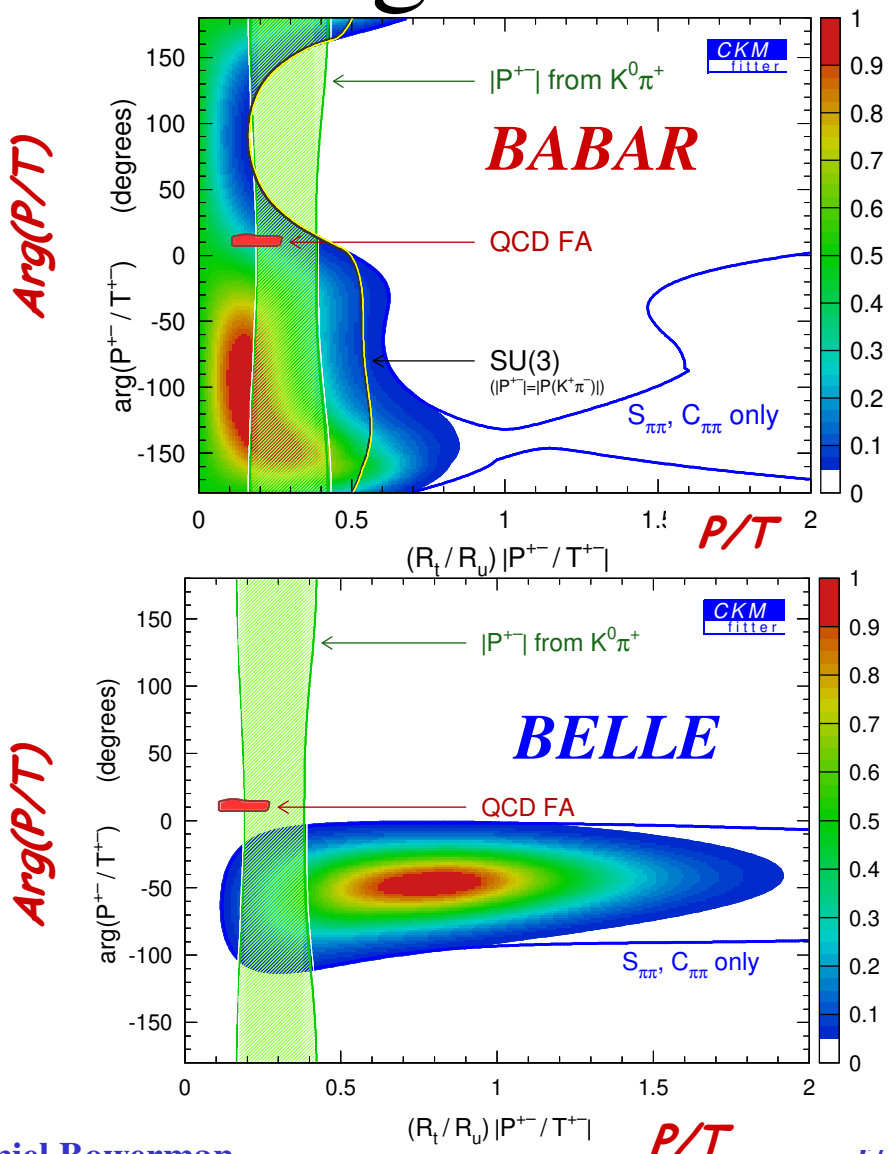
- ✓**Fitting sideband and $B^0 \to K^+\pi^-$ samples**
- ✓**Lifetime and mixing validation with $B^0 \to K^+\pi^-$ sample**
- ✓**More stringent cuts to select signal events**
- ✓**Repeat analysis on previous published data samples**
- ✓**Toy MC validation of errors**

Interesting one event effect in Belle dataset, but overall things seem fine



Conclusions: Penguins

Constraints on P/T

- Use data
  - P from $K^0\pi^+$
  - Two-body BFs
  - $S_{\pi\pi}$ and $C_{\pi\pi}$
  - CKM indirect constraint on α
- BaBar prefers:
  - $0.1 < |P/T| < 0.4$
  - $-170 < \arg(P/T) < -40$
- Belle prefers:
  - $0.5 < |P/T| < 1.1$
  - $-70 < \arg(P/T) < -30$

Penguins not negligible!