CP Violation Studies in $B^0 \rightarrow D^{(*)}\pi$ in BABAR and BELLE

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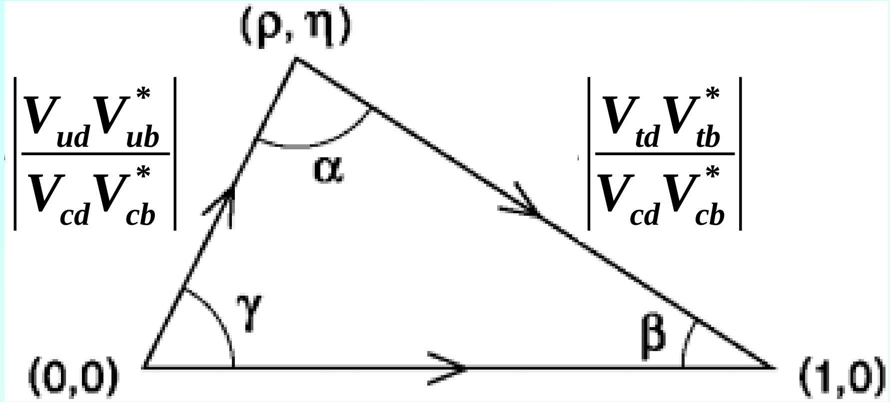
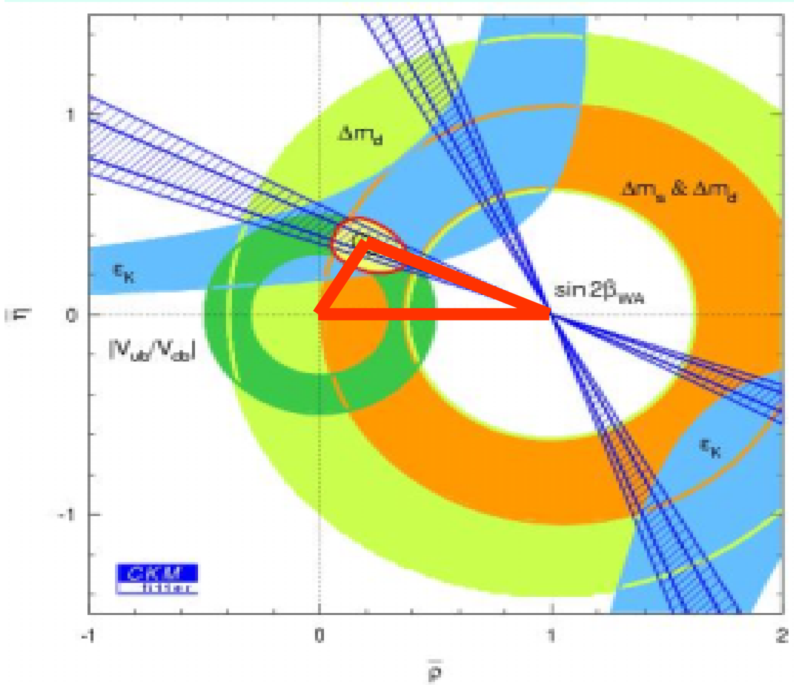
Theoretical Motivation



It is important to check the consistency of the CKM mechanism

➔ Over-constrain the Unitarity Triangle

➔Measure the angles



$$\boxed{\beta = \arg\left(-V_{cd}V_{cb}^* / V_{td}V_{tb}^*\right)}$$

W.A. Charmonium modes:

sin(2β) = 0.734 ± 0.055

- CP Violation is now well established

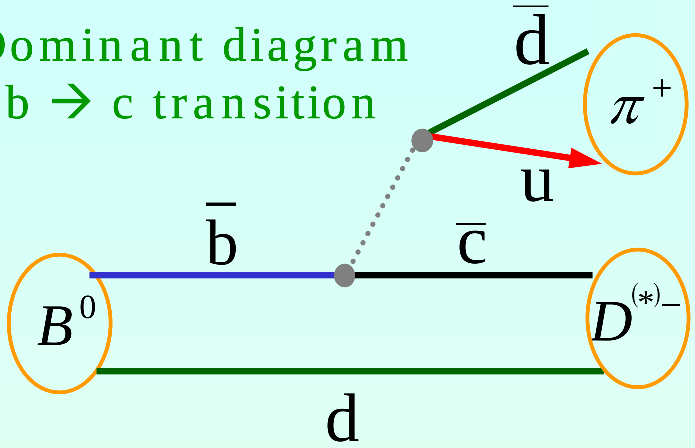
➔ Should measure other angles

$$\boxed{\gamma = \arg\left(-V_{ud}V_{ub}^* / V_{cd}V_{cb}^*\right)}$$ ⇐ This talk

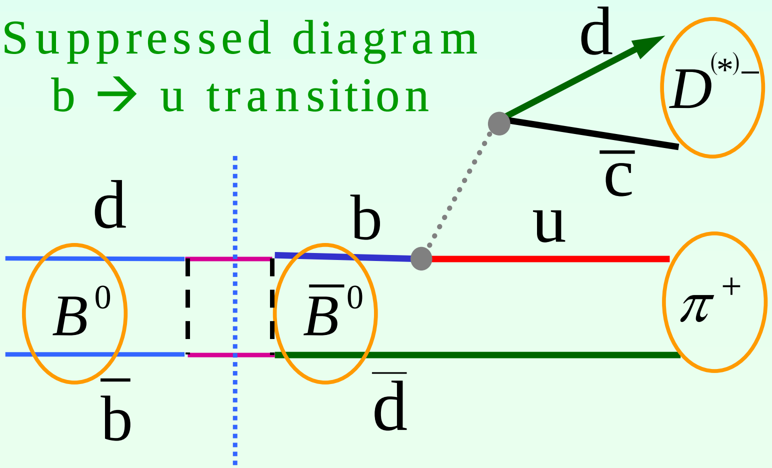
CP Violation in $B^0 \rightarrow D^{(*)}\pi$

CP violation appearing in interference between 2 amplitudes

Dominant diagram
$b \rightarrow c$ transition



Suppressed diagram
$b \rightarrow u$ transition



- **Final states are not CP eigenstates**
- **No penguin pollution**
  - **$b \rightarrow u$ transition ➔ relative weak phase γ between the 2 amplitudes**
  - **Mixing ➔ 2β**
  - **Relative strong phase δ between the 2 amplitudes**

$$\boxed{\Rightarrow \quad \text{Measure } \sin(2\beta+\gamma\pm\delta)}$$

$$\begin{cases} BF_{\text{favored}}\left(B^0 \rightarrow D^{(*)-}\pi^+\right) \approx 3.10^{-3} \\ BF_{\text{suppressed}}\left(B^0 \rightarrow D^{(*)+}\pi^-\right) \approx 10^{-6} \end{cases}$$

CP violation proportional to:

$$\boxed{r \approx \left|V_{ub}^{*} V_{cd} / V_{cb} V_{ud}^{*}\right| \approx 0.020}$$

Determination of sin(2β+γ) from Time Dependent Evolution

- **Time evolution for $D^-\pi^+$ final states:**

$$B^0 \text{ decays: } R\left(D^-\pi^+,\Delta t\right) = N e^{-\Gamma|\Delta t|}\left\{1 + C\cos\left(\Delta m_d \Delta t\right) + S\sin\left(\Delta m_d \Delta t\right)\right\}$$
$$\overline{B^0} \text{ decays: } R\left(D^-\pi^+,\Delta t\right) = N e^{-\Gamma|\Delta t|}\left\{1 - C\cos\left(\Delta m_d \Delta t\right) - S\sin\left(\Delta m_d \Delta t\right)\right\}$$

- **Time evolution for $D^+\pi^-$ final states:**

$$\overline{B^0} \text{ decays: } R\left(D^+\pi^-,\Delta t\right) = N e^{-\Gamma|\Delta t|}\left\{1 + C\cos\left(\Delta m_d \Delta t\right) - \bar{S}\sin\left(\Delta m_d \Delta t\right)\right\}$$
$$B^0 \text{ decays: } R\left(D^+\pi^-,\Delta t\right) = N e^{-\Gamma|\Delta t|}\left\{1 - C\cos\left(\Delta m_d \Delta t\right) + \bar{S}\sin\left(\Delta m_d \Delta t\right)\right\}$$

- **Similar equation for $D^*\pi$**

$$C = \frac{1-r^2}{1+r^2} \approx 1$$

$$\left.\begin{aligned} S &= \frac{2r}{1+r^2}\sin\left(2\beta+\gamma-\delta\right) \\ \bar{S} &= \frac{2r}{1+r^2}\sin\left(2\beta+\gamma+\delta\right) \end{aligned}\right\} \approx \left[-0.04,+0.04\right]$$

Need to know both S and $\bar{S}$ to determine (2β+γ) and δ

☞ *There are four ambiguities in (2β+γ) determination*

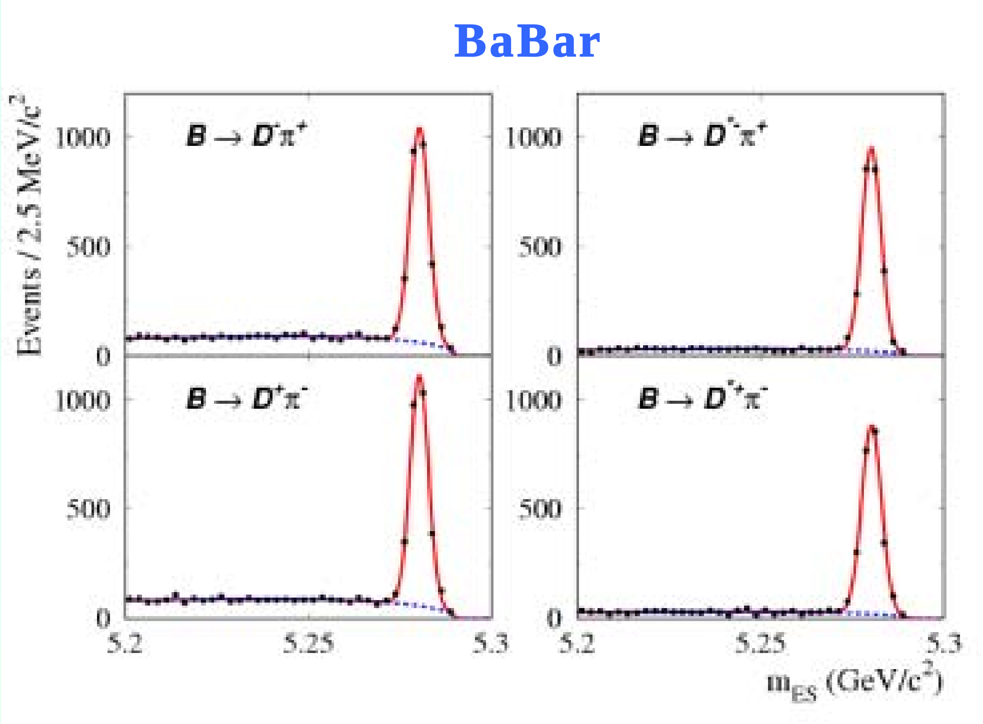
Experimental Technique (1)

With fully reconstructed $B^0 \rightarrow D^{(*)}\pi$

- **Advantages:**
  - **Small background**
- **<u>But:</u> relatively small number of events**

$N(D\pi) = 5207 \pm 87$
Purity = 85 %

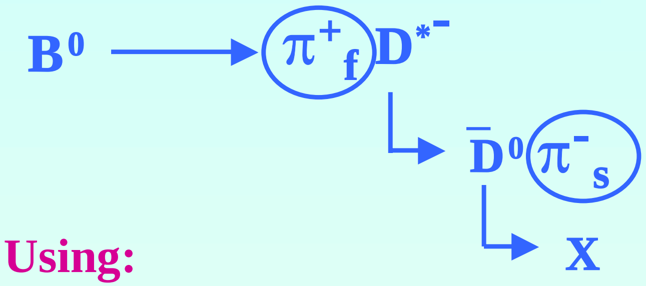
$N(D^*\pi) = 4746 \pm 78$
Purity= 94 %



- **Background mainly from combinatorics**
- **Peaking background mainly from**
  $B^+ \rightarrow D^{(*)0}\pi^+$ (~1%)

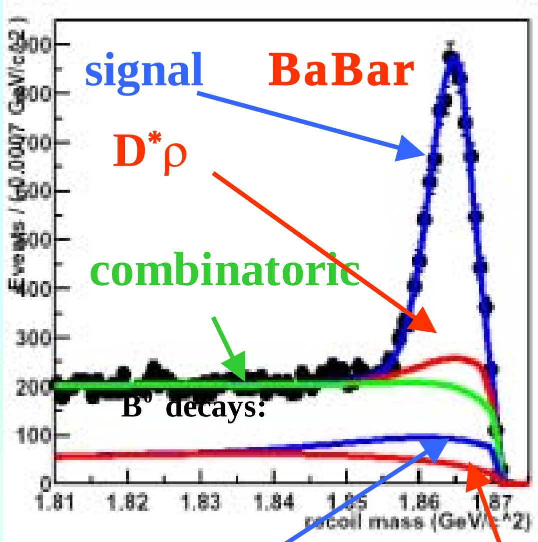
Experimental Technique (2)

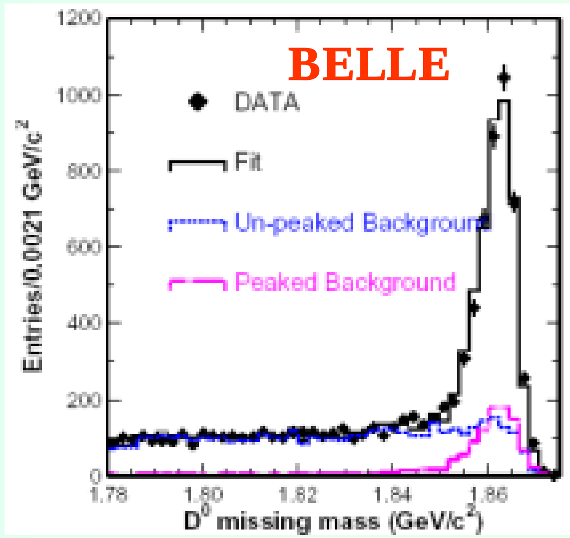
With partially reconstructed $B^0 \rightarrow D^{*+}\pi^-$



- **Using:**
  - **Soft pion**
  - **Fast pion**
  - **Beam constraints**

➔ **Reconstruct missing mass peaking at the D^0 mass**



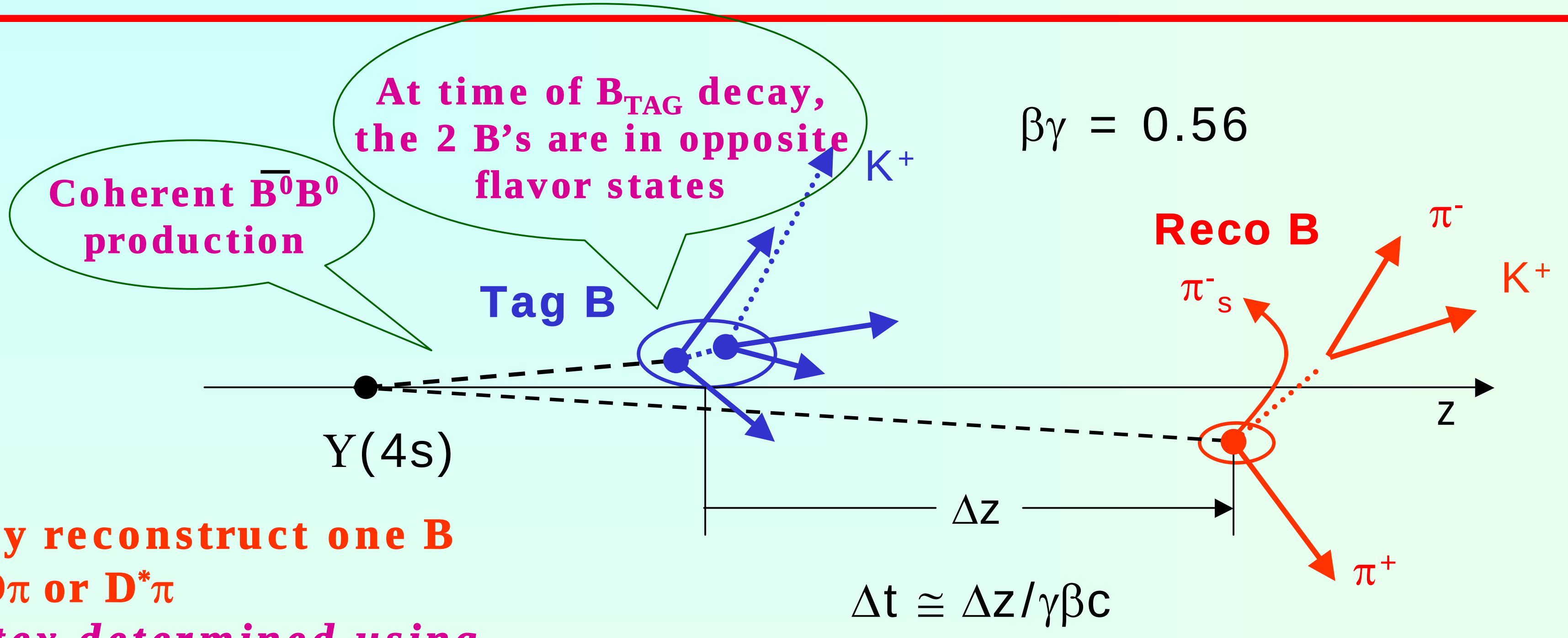


Other peaking

Continuum

- **Advantages:**
  - **More statistics:**
    - **Lepton tag: 6406 ± 129 events**
    - **Kaon tag: 25157 ± 323 events**
- **But …**
  - **More background**

Experimental Technique (3)



Fully reconstruct one B in $D\pi$ or $D^*\pi$
Vertex determined using all tracks

Or partially reconstruct one B in $D^*\pi$
Vertex determined using the fast π only and a beam spot constraint

Reconstruct vertex of B_{TAG} and compute proper time difference
$\Delta t \cong \Delta z / \gamma\beta c$

Determine flavor of other B meson B_{TAG} ("tagging") Using Kaon or lepton charge correlation

Difficulties (1)
Determination of Amplitude Ratio: r

$$r(D^{(*)}\pi) \equiv r_{(*)} = \left|\frac{A(\overline{B}^0 \to D^{(*)-}\pi^+)}{A(B^0 \to D^{(*)-}\pi^+)}\right| \approx 0.02$$

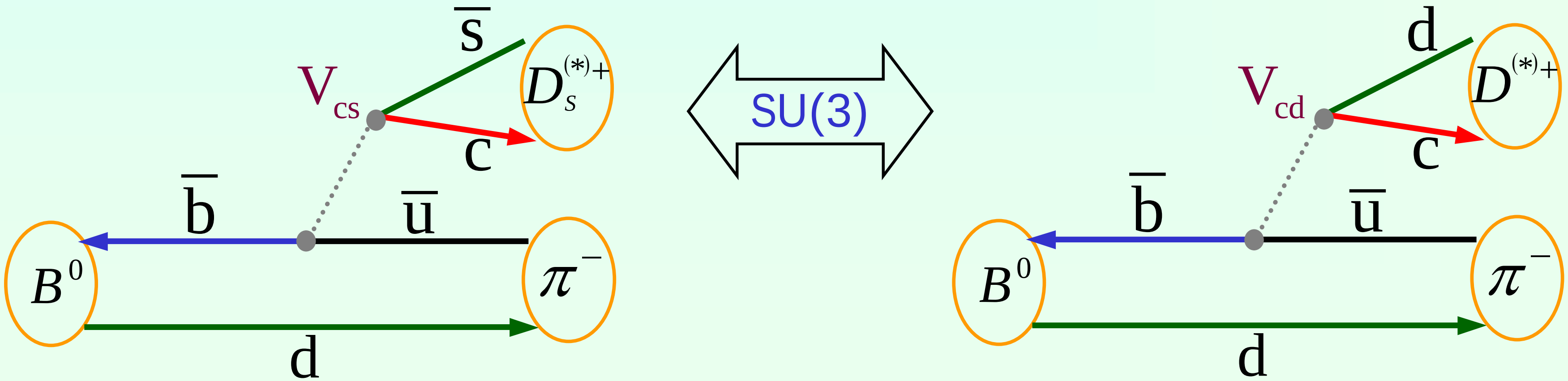
$$r_{(*)} \approx \sqrt{\frac{Br(B^0 \to D_s^{(*)+}\pi^-)}{Br(B^0 \to D^{(*)-}\pi^+)}}\left|\frac{V_{cd}}{V_{cs}}\right|\frac{f_{D^{(*)}}}{f_{D_S^{(*)}}}$$

BaBar – hep-ex/0207053 (2002)

- **Simultaneous determination of $\sin(2\beta+\gamma)$ and $r_{(*)}$ is not possible with the current statistics**
  - **Use $B^0 \to D_s^{(*)+}\pi^-$** (*I. Dunietz, Phys. Lett. B 427, 179 (1998)*)
  - **and SU(3) symmetry**

$$r(D\pi) = 0.021^{+0.004}_{-0.005} \qquad r(D^*\pi) = 0.017^{+0.005}_{-0.007}$$

Add another 30% systematic error for SU(3) breaking uncertainty and for missing W-exchange diagrams in calculation



See also: BELLE: PRL 89, 231804 (2002) and hep-ex/0305037

Difficulties (2)
b → u interference effects in the tag side

- We use b → u interference effects on the <u>reco</u> side to measure sin(2β+γ)
- The same kind of interference effects exist in the <u>tag</u> side

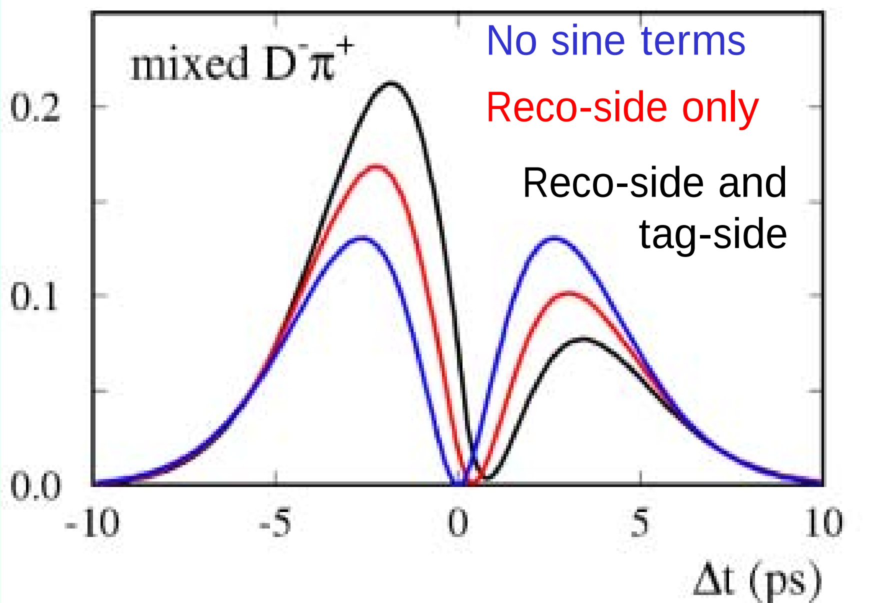
(Long, Baak, Cahn, Kirkby

hep-ex/0303030, accepted by PRD)

- Induces time-dependent effect
  - Change the time-dependent PDFs
  - r and r' can be of the same order of magnitude

- Lepton tags have no problem
- Kaon tags are affected

For r = r' = 0.1 (≈ 5× the expected value):



$$R\,(D^-\pi^+,\Delta t) = Ne^{-\Gamma|\Delta t|}\{1 \pm \cos(\Delta m_d \Delta t) + \sin(\Delta m_d \Delta t)[\pm 2r\sin(2\beta+\gamma-\delta) + 2r'\sin(2\beta+\gamma\pm\delta')]\}$$

signal side

tag side

Re-Parameterization

- Due to the tag side b → u interference effect, one needs to change the parameters in the time dependent decay rate formulas

Define:
$$\begin{cases} a \equiv 2r\sin(2\beta+\gamma)\cos\delta \\ b \equiv 2r'\sin(2\beta+\gamma)\cos\delta' \\ c \equiv 2\cos(2\beta+\gamma)(r\sin\delta - r'\sin\delta') \end{cases}$$

- **a:** Independent of tag side effects
- **b and c:** absorb the tag side interferences

- **For lepton tags:**

$$\begin{cases} a \equiv 2r\sin(2\beta+\gamma)\cos\delta \\ b \equiv 0 \\ c_{lep} \equiv 2r\cos(2\beta+\gamma)\sin\delta \end{cases}$$

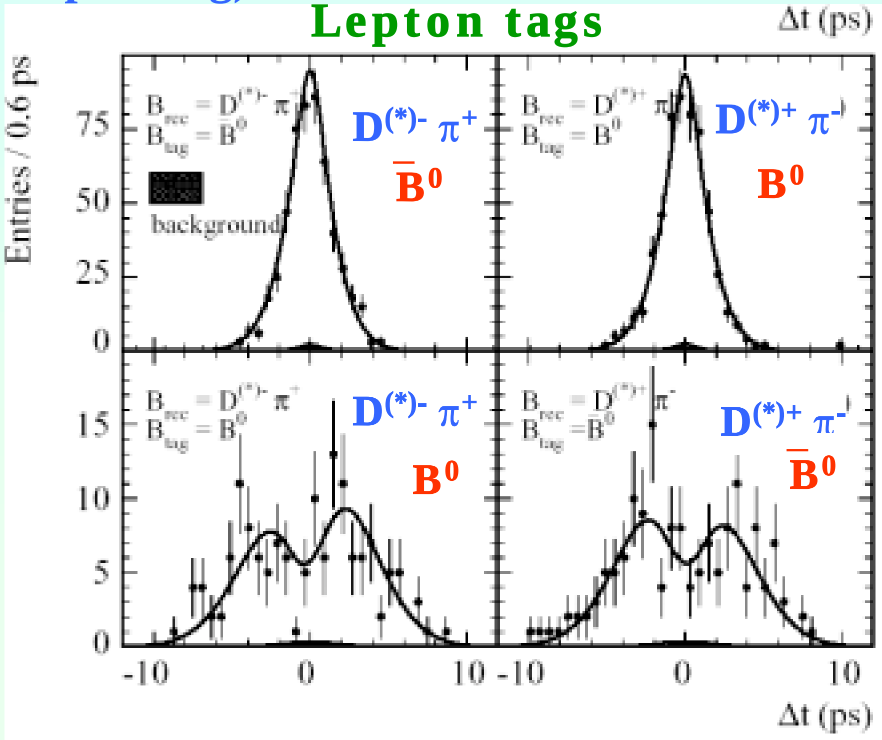
Handle on phase δ

Time Dependent Fits in BaBar

Fully reconstructed $B \rightarrow D^{(*)}\pi$

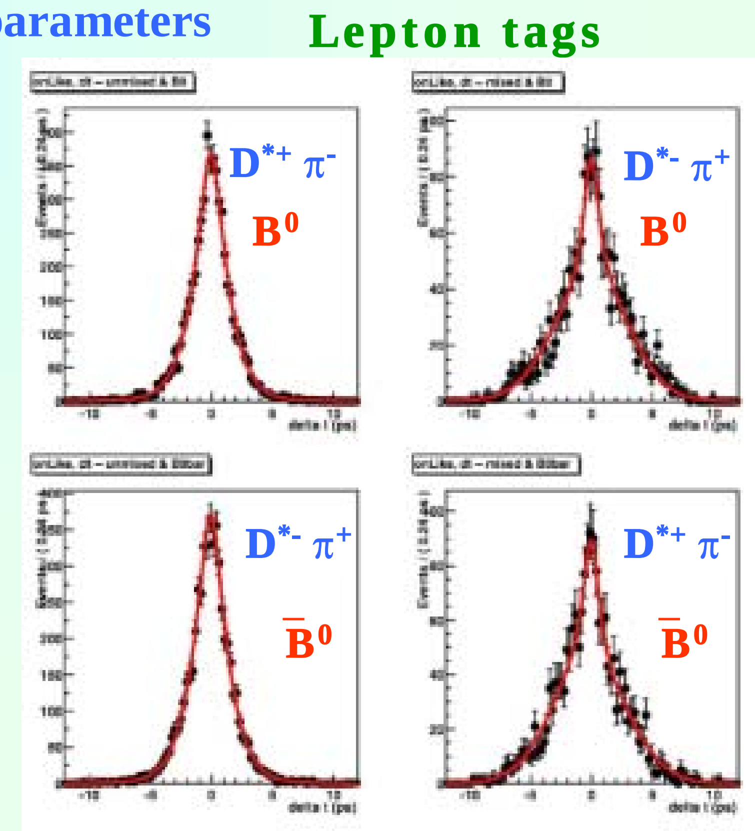
Unbinned ML fit to Δt spectra:

48 parameters – 13 parameters for the a,b and c coefficients ($D\pi$, $D^{*}\pi$, Kaon tags, lepton tag)



Partially reconstructed $B \rightarrow D^{*}\pi$

Fit is performed in 4 steps in order to determine the signal yield, the background contributions and the CP parameters



Results for Fully Reconstructed $B \to D^{(*)}\pi$ in BaBar (1)

Based on 81.9 fb^{-1} on-resonance events

From the fit to Δt spectra

$$\begin{cases} a[D\pi] = 2r\sin(2\beta+\gamma)\cos\delta[D\pi] = -0.022 \pm 0.038\ \text{(stat)}\ \pm 0.021\ \text{(sys)} \\ a[D^*\pi] = 2r_*\sin(2\beta+\gamma)\cos\delta[D^*\pi] = -0.068 \pm 0.038\ \text{(stat)}\ \pm 0.021\ \text{(sys)} \\ c_{lep}[D\pi] = 2r\cos(2\beta+\gamma)\sin\delta[D\pi] = +0.025 \pm 0.068\ \text{(stat)}\ \pm 0.035\ \text{(sys)} \\ c_{lep}[D^*\pi] = 2r_*\cos(2\beta+\gamma)\sin\delta[D^*\pi] = +0.031 \pm 0.070\ \text{(stat)}\ \pm 0.035\ \text{(sys)} \end{cases}$$

Systematic uncertainties

Source	$\sigma_a = \sigma_{a^*}$	$\sigma_c = \sigma_{c^*}$
Vertexing	0.015	0.026
Tagging	0.004	0.003
Background	0.001	0.003
Fit	0.014	0.023
Total (σ_{tot})	0.021	0.035

From BaBar measurement of $B^0 \to D_S^{(*)}\pi$

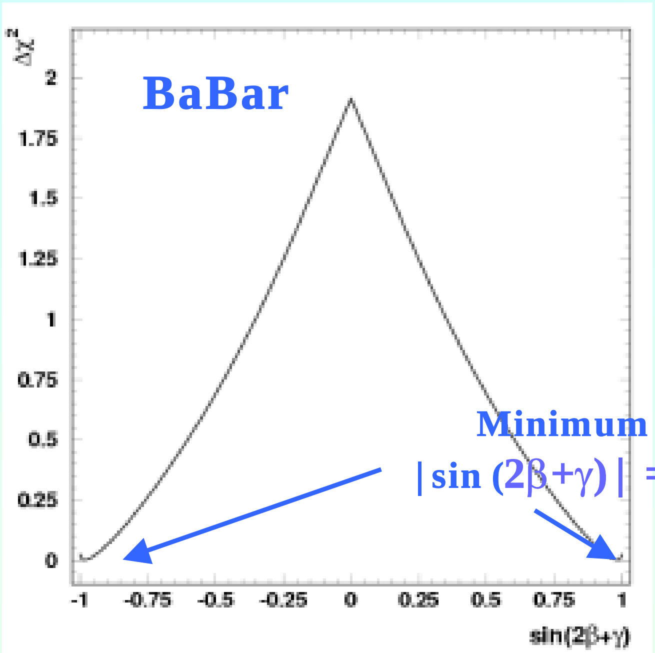
$$\begin{cases} r = 0.021^{+0.004}_{-0.005} \\ r_* = 0.017^{+0.005}_{-0.007} \end{cases}$$

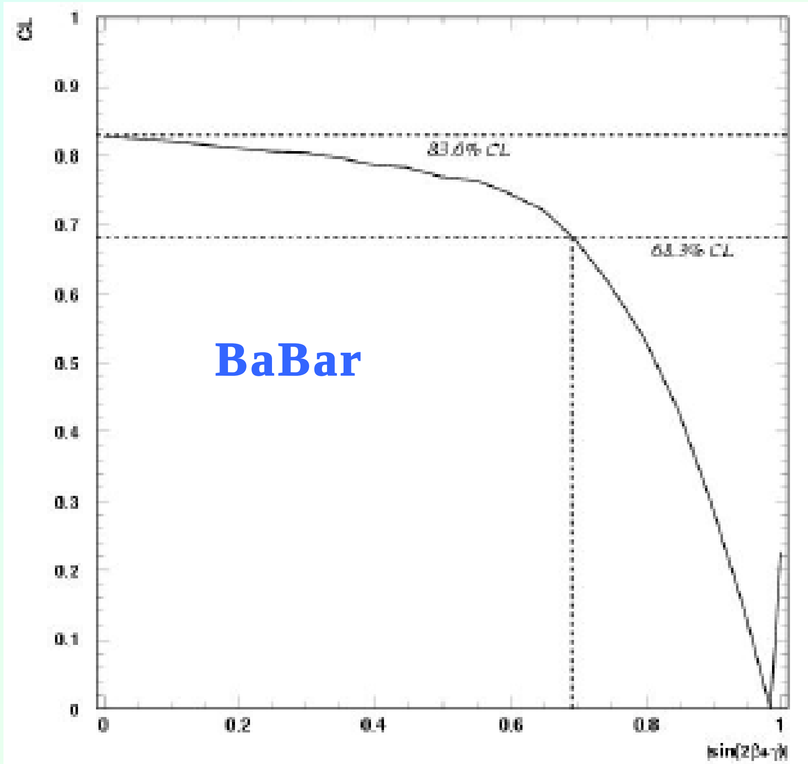
→ 30% additional theoretical error assigned to r and r_* values

Results for Fully Reconstructed $B \rightarrow D^{(*)}\pi$ in BaBar (2)

Minimize a χ^2 with respect to $(2\beta+\gamma)$, $\delta[D\pi]$, $\delta[D^*\pi]$, r and r_*

χ^2 is highly non-parabolic ➔ Use a toy Monte-Carlo approach to interpret results in terms of confidence levels for $|\sin(2\beta+\gamma)|$





$$|\sin(2\beta+\gamma)| > 0.69 \, @ \, 68.3\% \text{ CL}$$
$$|\sin(2\beta+\gamma)| = 0 \text{ excluded } @ \, 83\% \text{ CL}$$

$$\text{C.L.}(|\sin(2\beta+\gamma)|) = 1 - \text{frac}(\Delta\chi^2_{toy} > \Delta\chi^2_{data})$$
$$\Delta\chi^2 = \chi^2(\sin(2\beta+\gamma)) - \chi^2_{\min}$$

Results for Partially Reconstructed $B \rightarrow D^*\pi$ in BaBar (1)

- Lepton tag → fit S and $\bar{S}$
- Kaon tag → fit a, b and c

Based on 76,4 fb^{-1} on resonance events

Combining lepton and Kaon results:

Deviates from 0 by ≈ 2.1σ

$$a[D^*\pi] = 2r\sin(2\beta+\gamma)\cos\delta = -0.063 \pm 0.024\ (\text{stat}) \pm 0.017\ (\text{sys})$$

$$c_{lep}[D^*\pi] = 2r\cos(2\beta+\gamma)\sin\delta = -0.004 \pm 0.037\ (\text{stat}) \pm 0.020\ (\text{sys})$$

Systematic uncertainties

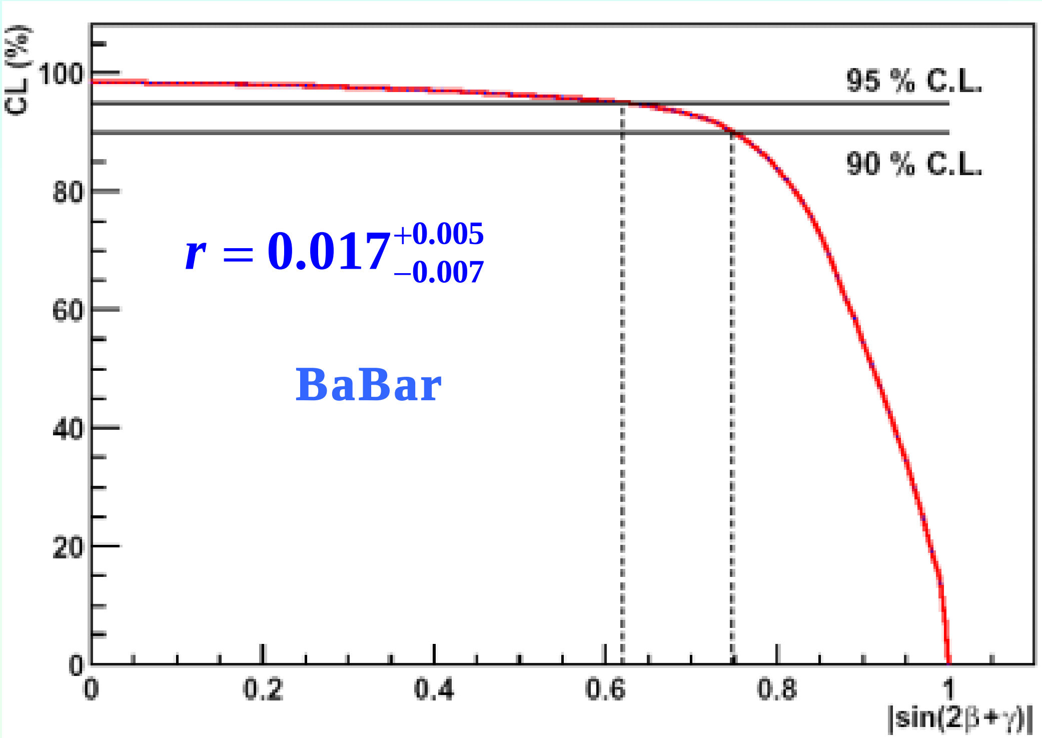
Error ($\times 10^{-3}$)

Source	S	$\bar{S}$	a	b	c
Background	3.0	8.0	5.0	4.0	6.0
Bkg CP content	10.0	10.0	13.0	7.0	13.0
Fit	5.0	7.0	5.0	2.0	1.0
Detector	10.0	10.0	10.0	6.0	10.0
MC stat	13.0	13.0	8.0	4.0	9.0
Total	20.0	21.0	19.0	11.0	20.0

Results for Partially Reconstructed $B \rightarrow D^{*}\pi$ in BaBar(2)

- Minimize a χ^2 to determine $|\sin(2\beta+\gamma)|$ and δ

- Interpretation in terms of C.L. using a toy Monte-Carlo approach



$|\sin(2\beta+\gamma)| > 0.88$ at 68.3% C.L.

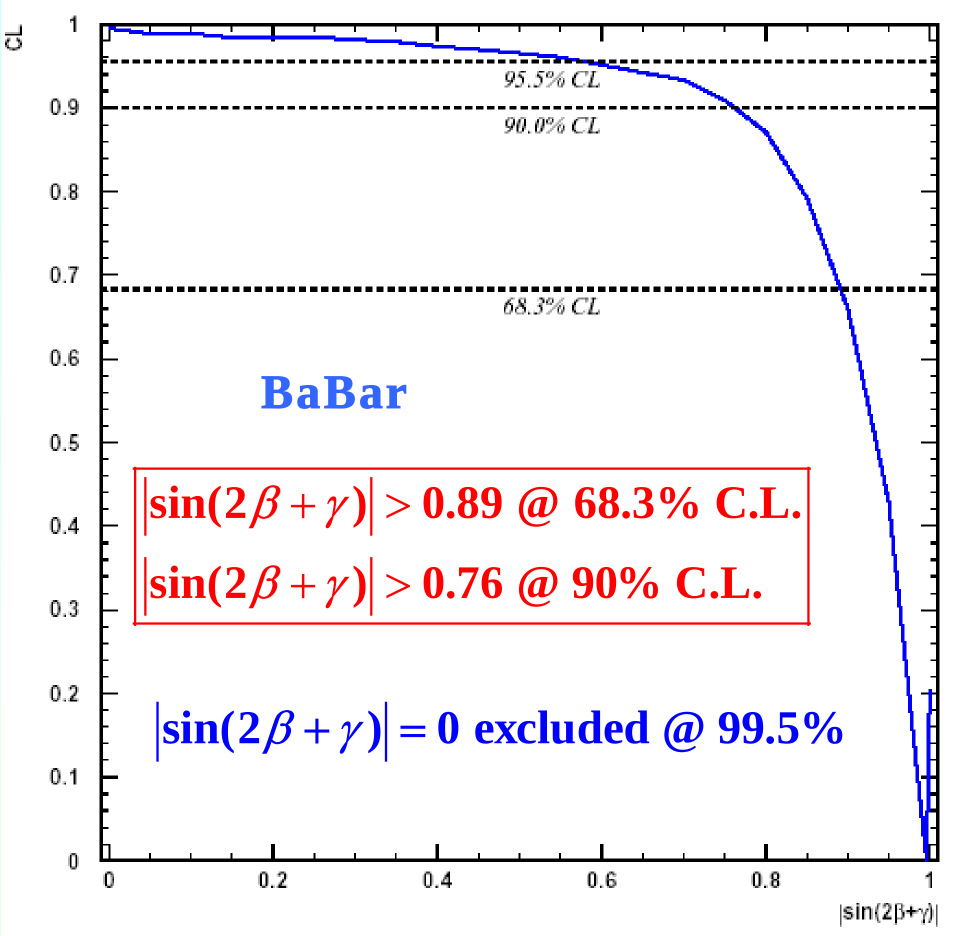
$|\sin(2\beta+\gamma)| > 0.75$ at 90% C.L.

$|\sin(2\beta+\gamma)| > 0.62$ at 95% C.L.

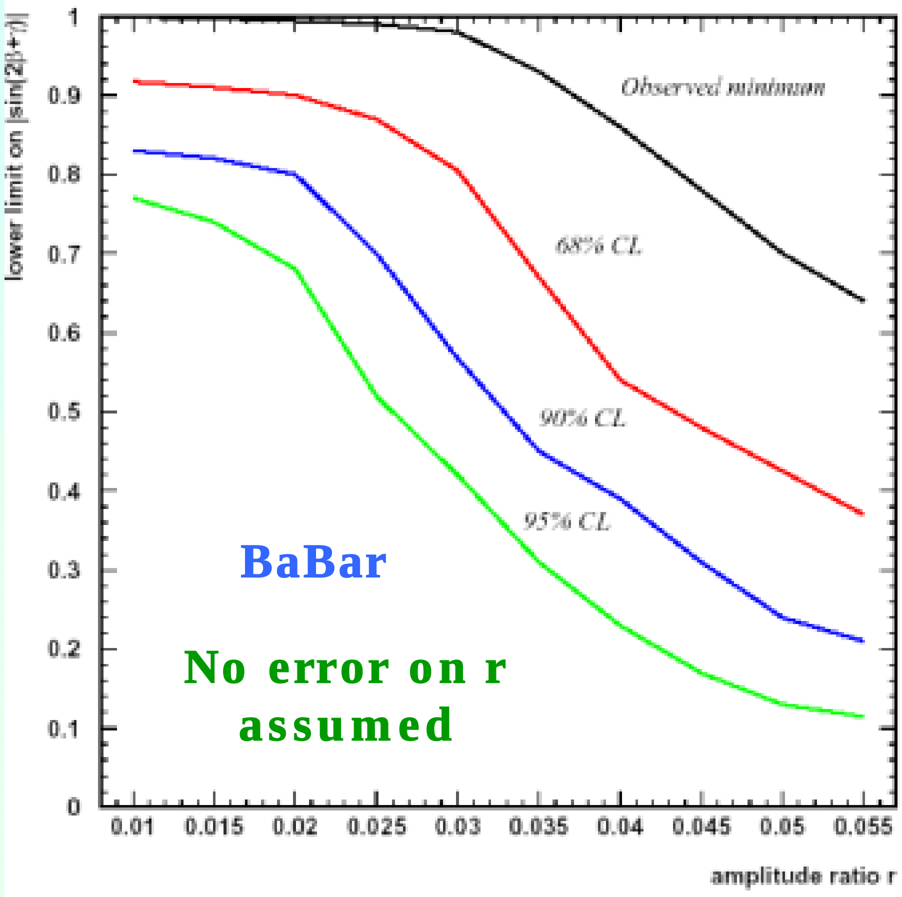
$|\sin(2\beta+\gamma)| = 0$ excluded at 98.3% C.L.

Combined BaBar Results

- Assuming 30% theoretical error on $r(D\pi)$ and $r(D^* \pi)$



- One can also plot the lower limit on $|\sin(2\beta+\gamma)|$ as a function of r
- In this case, $r(D\pi) = r(D^* \pi)$ is assumed



Status of B→ $D^{(*)}\pi$ in BELLE

- Similar studies on B→ $D^{(*)}\pi$ are being performed by BELLE:

- For the partial reconstruction technique:
  - With 78 fb^{-1} BELLE is expecting a statistical error of:

$$\sigma(2r.\sin(2\Phi_1+\Phi_3\pm\delta)) = \pm 0.029$$

- Computed from the data
- Includes background effects

- For the full reconstruction technique
- With the full data sample available this summer, BELLE is expecting:

$$\sigma(2r.\sin(2\Phi_1+\Phi_3\pm\delta)) = \pm 0.028$$

- Estimated from the MC
- Does not include background effects

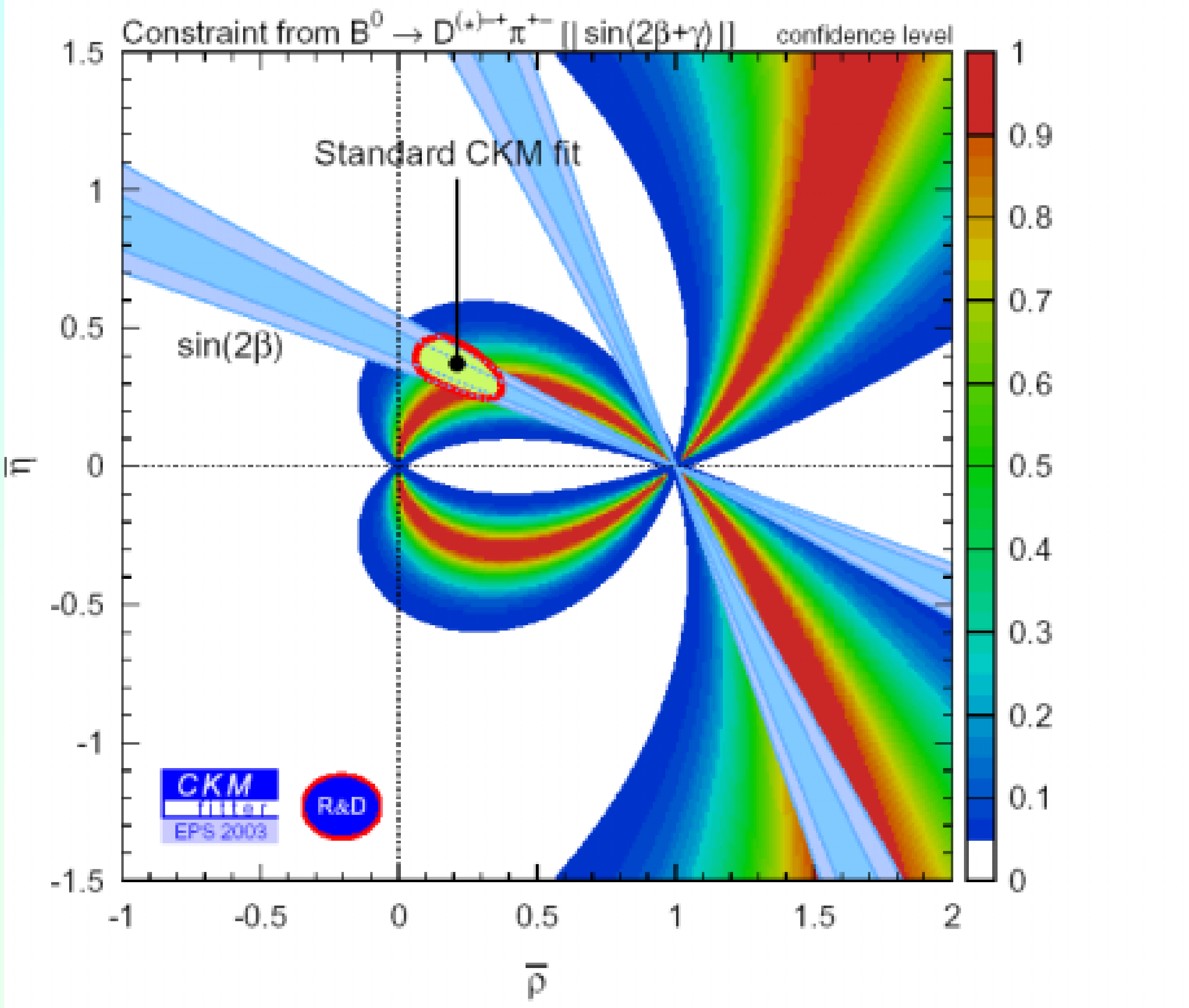
Summary

- A study of time dependent CP asymmetry in $B^0 \rightarrow D^{(*)+}\pi^-$ has been performed by BaBar using both partial and full reconstruction techniques
- With full reconstruction:
  - A limit is set at: $|\sin(2\beta+\gamma)|>0.69$ @ 68.3% C.L.
  - No limit is set at 90% CL
- With partial reconstruction:
  - A limit is set at: $|\sin(2\beta+\gamma)|>0.75$ (0.62) @ 90 % (95 %) C.L.
- Combining both methods:
  - $|\sin(2\beta+\gamma)|>0.89$ (0.76) @ 68.3 % (90%) C.L.
  - $|\sin(2\beta+\gamma)| = 0$ is excluded @ 99.5% C.L.
  - Limits are also set as a function of the ratio between favored and suppressed amplitudes: r

- Similar studies are going on in BELLE, results will come soon…

Constraints in the ρ, η Plane from BaBar Measurements

Constraint from sin(2β+γ) assuming a given value of r with 30% theoretical error



Backup Slides

Monte-Carlo Validation
Fully Reconstructed Method

No generated asymmetry: a=b=c=0

9.4x data statistics for $B \to D\pi$ and 6.9x data statistics for $B \to D^{*}\pi$

MC	$a[D\pi]$	$a[D^{*}\pi]$	$c_{LEP}[D\pi]$	$c_{LEP}[D^{*}\pi]$
no asym.	$+0.009 \pm 0.011$	$+0.003 \pm 0.014$	-0.027 ± 0.019	-0.029 ± 0.024

Generated asymmetry: a=0.04 b=c=0

4.6x data statistics for $B \to D\pi$ and 3.8x data statistics for $B \to D^{*}\pi$

MC	$a[D\pi]$	$a[D^{*}\pi]$	$c_{LEP}[D\pi]$	$c_{LEP}[D^{*}\pi]$
with asym.	$+0.058 \pm 0.016$	$+0.055 \pm 0.020$	-0.006 ± 0.028	-0.009 ± 0.033

$\rightarrow$ **No significant biases observed**

Monte-Carlo Validation
Partially Reconstructed Method

	$D^*\pi$ without CP		$D^*\pi$ with CP
Parameter	non-CP signal	non-CP sig. fitting CP par.	CP sig. fitting CP par.
$\Delta m_{D^*\pi}(ps^{-1})$	0.456 ± 0.004	0.456 ± 0.004	0.465 ± 0.006
$\tau_{D^*\pi}(ps)$	1.512 ± 0.009	1.512 ± 0.009	1.507 ± 0.012
$\omega_{D^*\pi}$	0.093 ± 0.002	0.093 ± 0.002	0.093 ± 0.003
$S^+_{D^*\pi}$	0. (fixed)	-0.015 ± 0.013	0.026 ± 0.018
$S^-_{D^*\pi}$	0. (fixed)	0.004 ± 0.013	0.088 ± 0.018
$b^n_{D^*\pi}$	-0.145 ± 0.011	-0.152 ± 0.011	-0.155 ± 0.016
$b^w_{D^*\pi}$	-1.150 ± 0.415	-1.233 ± 0.424	-1.333 ± 0.837
$f^n_{D^*\pi}$	0.967 ± 0.006	0.967 ± 0.006	0.984 ± 0.007
$f^o_{D^*\pi}$	0.006 ± 0.002	0.006 ± 0.002	0.000 ± 0.002
$s^n_{D^*\pi}$	0.982 ± 0.020	0.982 ± 0.020	1.058 ± 0.026
$s^w_{D^*\pi}$	3.468 ± 0.425	3.468 ± 0.425	4.501 ± 0.864

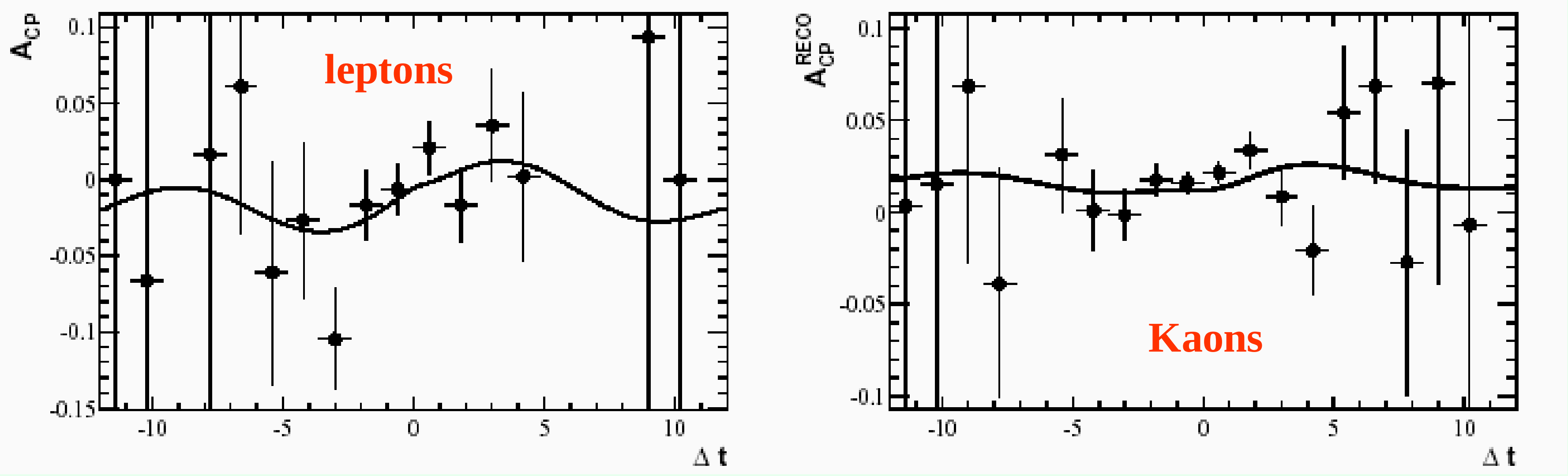
Consistent with 0

Generated values :
$S^+ = 0.030$
$S^- = 0.048$

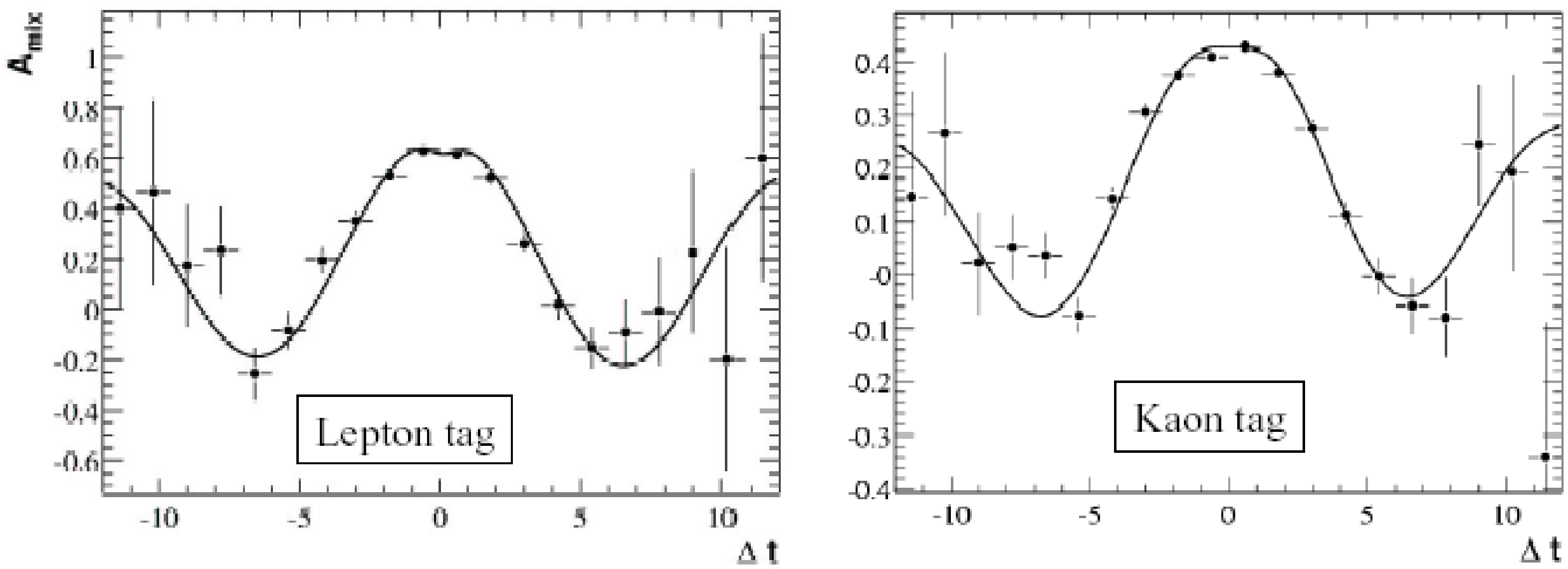
CP Asymmetry with Partial Reconstruction Method in BaBar

CP asymmetry

$$A_{CP} = \frac{\left(N_{B^0_{tag}} - N_{\overline{B}^0_{tag}}\right)}{\left(N_{B^0_{tag}} + N_{\overline{B}^0_{tag}}\right)}$$



Partial Reconstruction Method Cross-Check – Mixing Asymmetries



Complementary cross-check : measure Δm :

Lepton tag : $\Delta m_d = 0.520 \pm 0.016$ (stat.) ± 0.017 (syst.)
Kaon tag : $\Delta m_d = 0.479 \pm 0.012$ (stat.) ± 0.033 (syst.)

Measurement of B^0 Lifetime with Partially Reconstructed $B \rightarrow D^*\pi$ in BaBar

- **B^0 lifetime has been measured in BaBar with partially reconstructed $B \rightarrow D^*\pi$ events**
  - **hep-ex/0212012 - Phys.Rev.D67:091101,2003**

$$\tau_{B0} = 1.533 \pm 0.034\ (\text{stat}) \pm 0.038\ (\text{sys})\ \text{ps}$$

- **In good agreement with World Average:**

$$\tau_{B0} = 1.542 \pm 0.016\ \text{ps}$$

Impact of a Δt bias

The problem: if we get Δt wrong by δt ($<<1/\Delta M_d$)

$\cos(\Delta M_d \Delta t) + S \sin(\Delta M_d \Delta t) \rightarrow \cos(\Delta M_d \Delta t) + (\underline{S - \Delta M_d \delta t}) \sin(\Delta M_d \Delta t)$

A bias of 10μm would cause a shift $\delta\sin(2\beta+\gamma)=0.75$

NOTE: given the sign combinations only the "c" parameters are biased

The answer: we let the Δt biases free in the fit and we are therefore insensitive to δt

The objection: can you prove that you are insensitive to it also if the resolution function is different from your model (3 Gaussians)

The proofs:

- SVT misalignment tests: we include in the systematic error the variation due to using different misalignments in MC. They represent very different resolution function. They correspond to $\delta t<4\mu m \rightarrow$ the scale of the possible bias is $\delta\sin(2\beta+\gamma)=0.3$ and it is anyhow accounted for in the error

- Toy MC test: since in our model biases are proportional to $\sigma_{\Delta t}$ toys have been generated with flat 10μm biases. Fit results show biases $\delta c<0.005$, 15% of the systematic error assigned to these parameters