Direct and indirect CP violation in BABAR

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for the BABAR collaboration

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dapnia
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CKM matrix and unitarity triangle

- Cabibbo-Kobayashi-Maskawa quark mixing matrix
  - ➠ relates weak mass (q') to mass eigenstates (q)

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

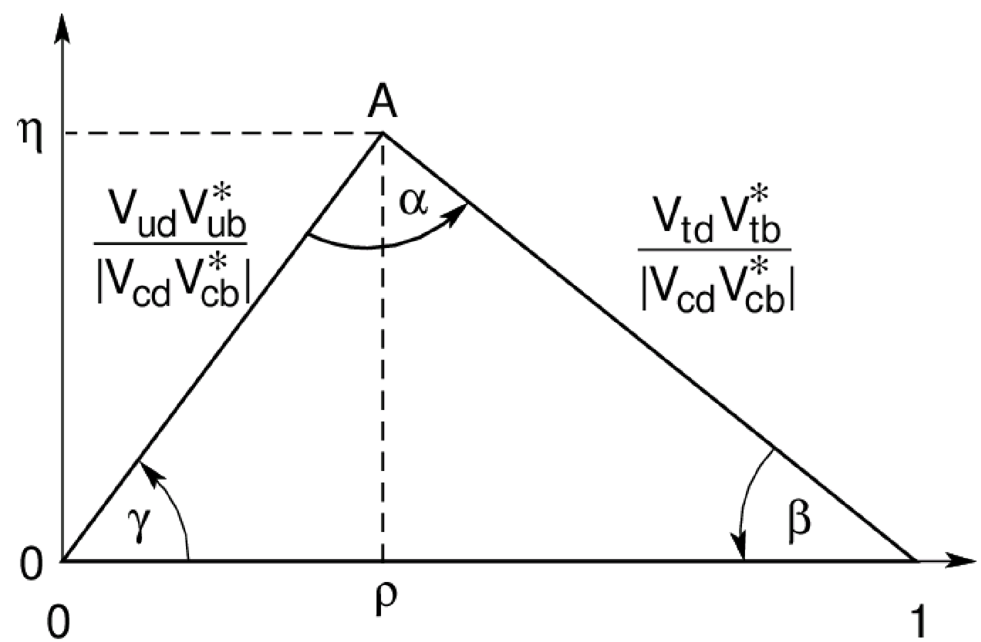
- Wolfenstein parametrisation of V_{CKM}
  - ➠ 4 parameters : A, λ, ρ, η

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

- $\not{C}\not{P}$ originates from the irreducible phase η
- CKM unitary relation :

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

  - ➠ can be represented as a triangle,
  - ➠ length of the sides of same order,
  - ➠ area proportional to amount of $\not{C}\not{P}$.



other notation : $\beta = \phi_1$, $\alpha = \phi_2$ and $\gamma = \phi_3$

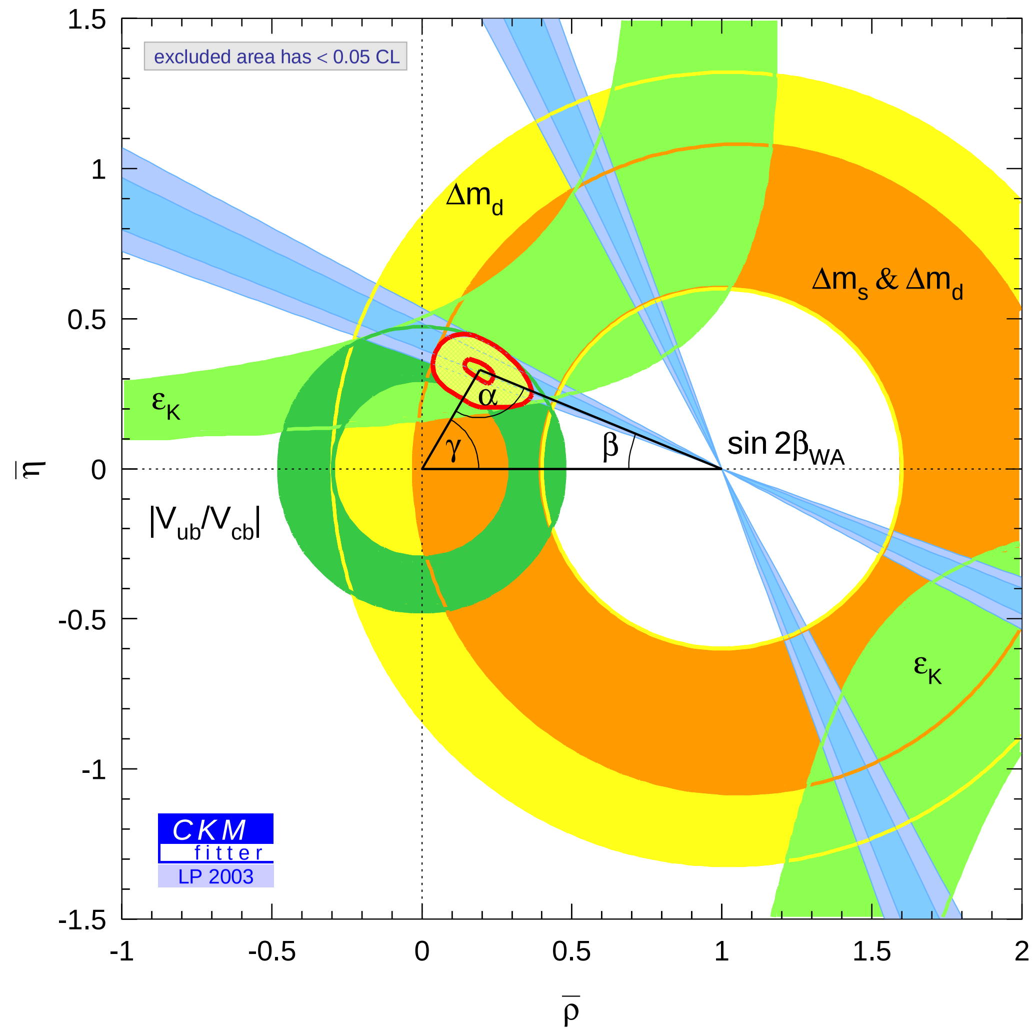
Constraining the triangle

- measure 2 sides and 3 angles independently (sides : see talk of O. Igonkina),
- test CKM sector of Standard Model, e.g., check $\alpha + \beta + \gamma = \pi$
- probe for new physics, e.g., deviations on sin 2β
- use redundancies to resolve ambiguities on the angles,
- consistency with global CKM fit :

$$20.2^\circ < \beta < 26.0^\circ$$
$$77^\circ < \alpha < 120^\circ$$
$$39^\circ < \gamma < 80^\circ$$
$$18.0^\circ < \beta \text{ (w/o WA}_{exp}) < 26.4^\circ$$

at 95% C.L.

- angles measured in $\not{C}\!\!\not{P}$ processes

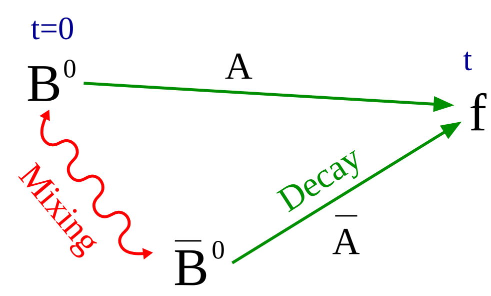


CKM fit with : $|V_{ub}|$, $|V_{cb}|$, Δm_d, Δm_s, ϵ_K

[A Höcker et al, Eur. Phys. J. C21, 225 (2001)]

Time dependent analyses

$\not{CP}$ in the interplay between mixing and decay :



☞ time evolution of the CP asymmetry (with f CP-even) :

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

➠ 2 coefficients : $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$ and $S_f = \frac{2Im\lambda_f}{1+|\lambda_f|^2}$

with $\lambda_f = \frac{p}{q} \cdot \frac{\bar{A}_f}{A_f}$

$(|B_\pm\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle)$

☞ Coefficient S sensitive to CP angles :

➠ only 1 decay amplitude :

– $C_f = 0$

– $S_f =$ Im λ

(e.g., sin 2β, sin 2α)

➠ more than 1 decay amplitude :

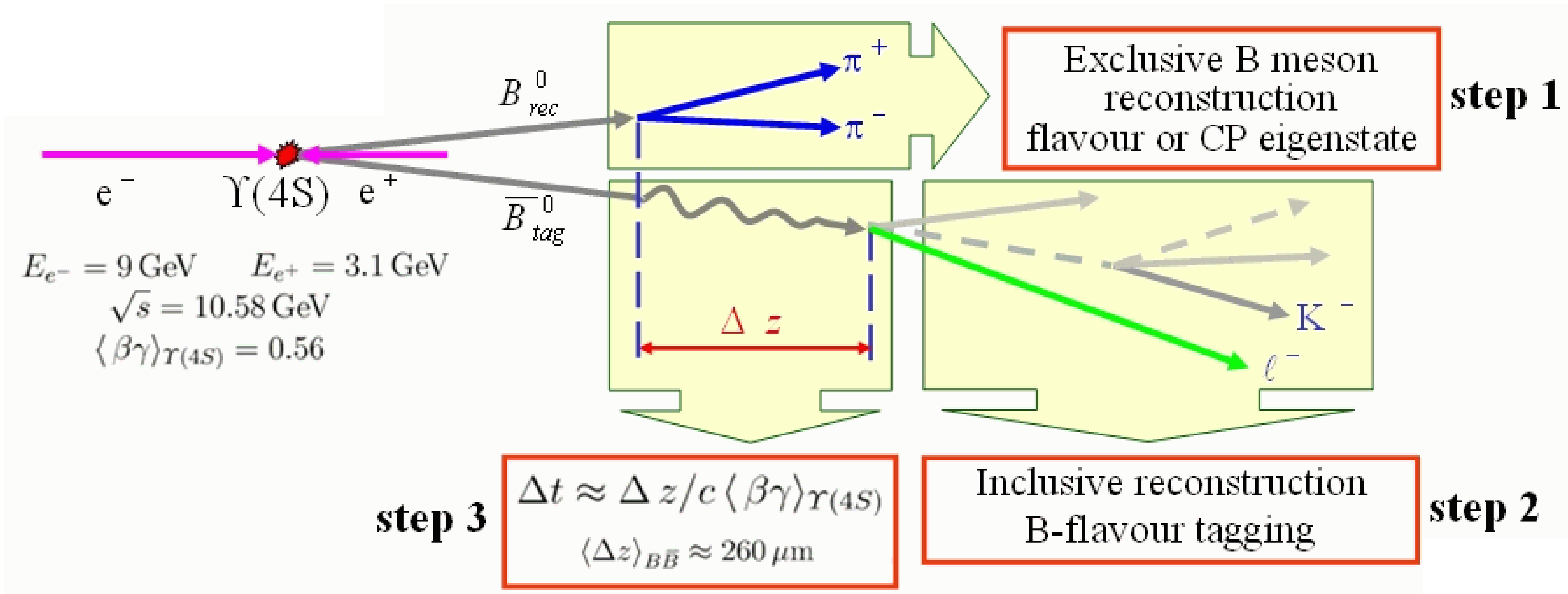
– $C_f \neq 0$, due to direct $\not{CP}$

– S_f not trivially related to CKM angles

and extraction complicated (e.g., α_{eff})

Measurement of time dependent CP asymmetries

☞ performed in 3 steps :



Usual variables in the analyses

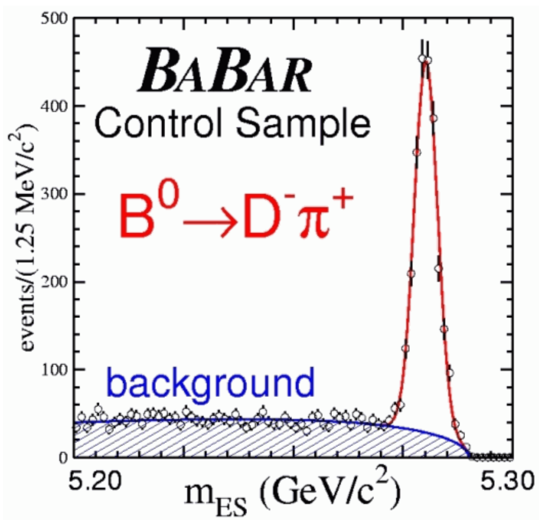
signal selection

discrimination of B and $q\bar{q}$

(needed due to $\mathcal{B} \sim 10^{[-4,-6]}$)

B mass

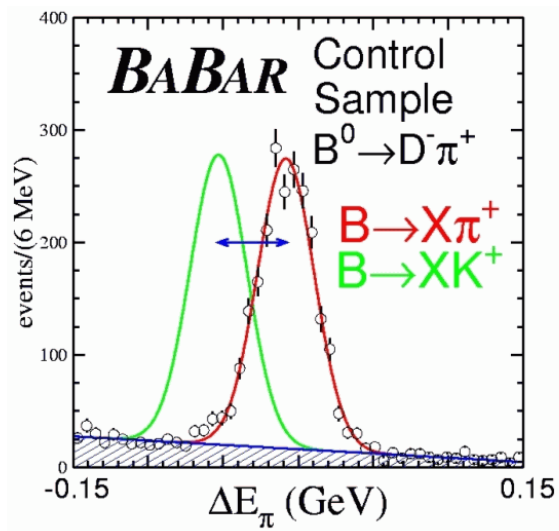
$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$



$\sigma(m_{ES}) \equiv 2.5 - 3$ MeV/c^2

missing energy

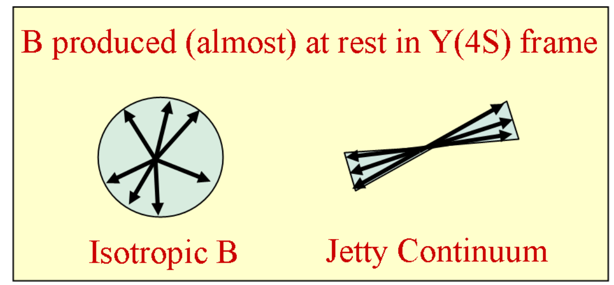
$$\Delta E = E^*_B - E^*_{beam}$$



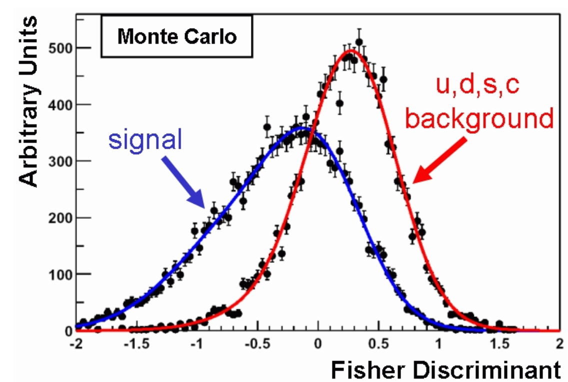
$\sigma(\Delta E) \equiv 15 - 80$ MeV

(depends on final state)

with event shape variables



$\Rightarrow$ combined into a Fisher (or NN)



CKM angle β

I will present *BABAR* results in the analyses :

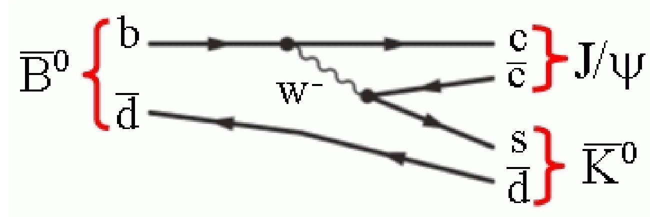
- ☞ $B^0 \to \phi K^0_S, \phi K^0_L,$
- ☞ $B^0 \to K^0_S \pi^0,$

☞ other recent results skipped in this presentation.

sin 2β

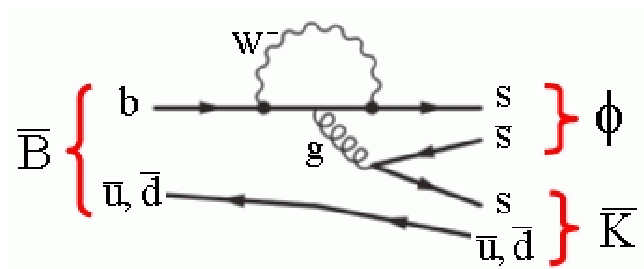
- $\not{C}\not{P}$ now well established in B decays :
  - in charmonium modes ($J/\psi K^0_S, \ldots$) : [BABAR, PRL **89**, 201802 (2002) with 88 M $B\overline{B}$] :

only one weak phase $\Rightarrow$ clean measurement possible



sin $2\beta = 0.741 \pm 0.067 \pm 0.034$

- looking for new physics :
  - in $b \to s$ processes with pure penguins (beyond SM contribution possible through the loop)

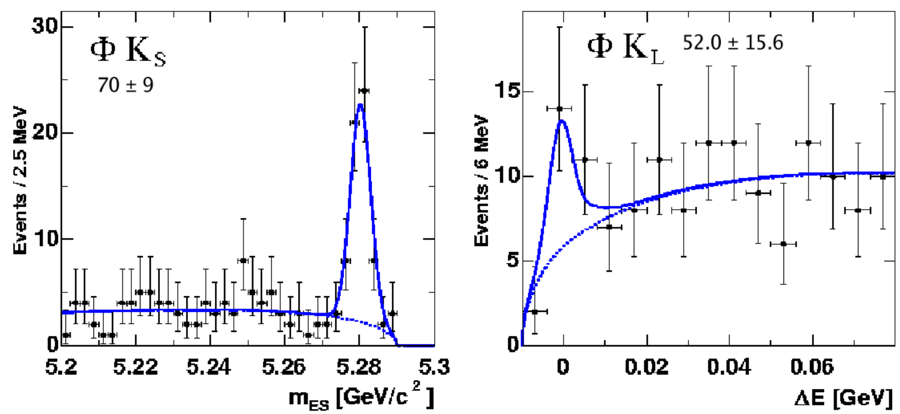


- results of $B^0 \to \phi K^0_S$, ϕK^0_L and $B^0 \to K^0_S \pi^0$ presented here.

sin 2β in $B^0 \to \phi K^0_S$, $B^0 \to \phi K^0_L$ (preliminary)

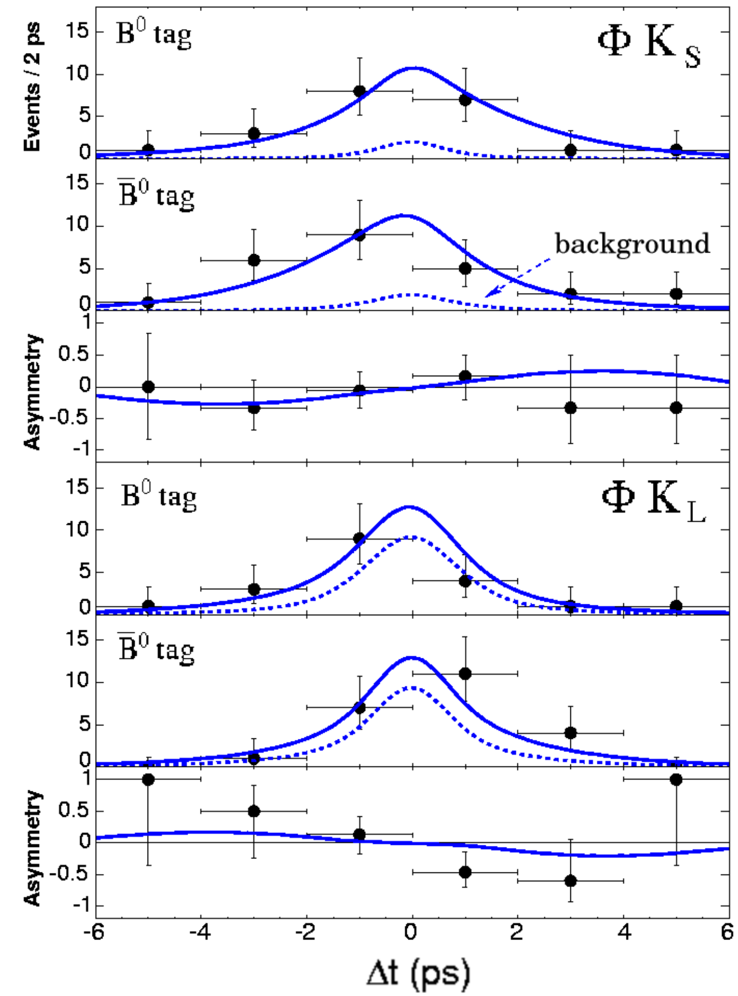
- new result for $B^0 \to \phi K^0_L$ (with $\phi \to K^+K^-$)
- pure $b \to s\bar{s}s$ penguin modes
  - expect same sin 2β as charmonium modes
- combined results with 114 M $B\overline{B}$

$$S_{\phi K^0} = 0.47 \pm 0.34(stat)^{+0.08}_{-0.06}(syst)$$
$$C_{\phi K^0} = 0.01 \pm 0.33(stat) \pm 0.10(syst)$$



- consistent at 1 σ level with charmonium results
- control channel, $B^+ \to \phi K^+$ (no asymmetry expected)

$$C_{\phi K^+} = -0.14 \pm 0.18 \quad \text{and} \quad S_{\phi K^+} = 0.23 \pm 0.24$$



$$A_{CP}(t) = -C cos(\Delta m t) + S sin(\Delta m t)$$

sin 2β in $B^0 \to K^0_S\pi^0$ (preliminary)

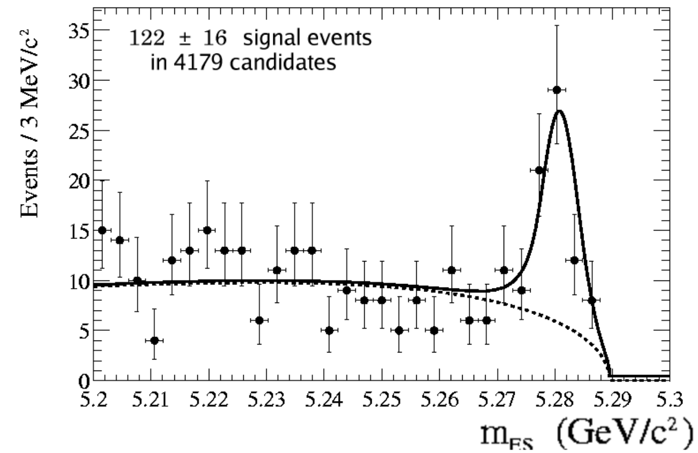
- new result for $S_{K^0_S\pi^0}$
- CKM and colour suppression of tree diagram
  - ➠ $b \to u\bar{u}s$ penguin dominates
- small branching fraction : $\mathcal{B} = (11.9 \pm 1.5) \cdot 10^{-6}$
- special vertexing required
  - ➠ beam-spot constraint on the $K^0_S(\to \pi^+\pi^-)$
- results with 124 M $B\overline{B}$ pairs

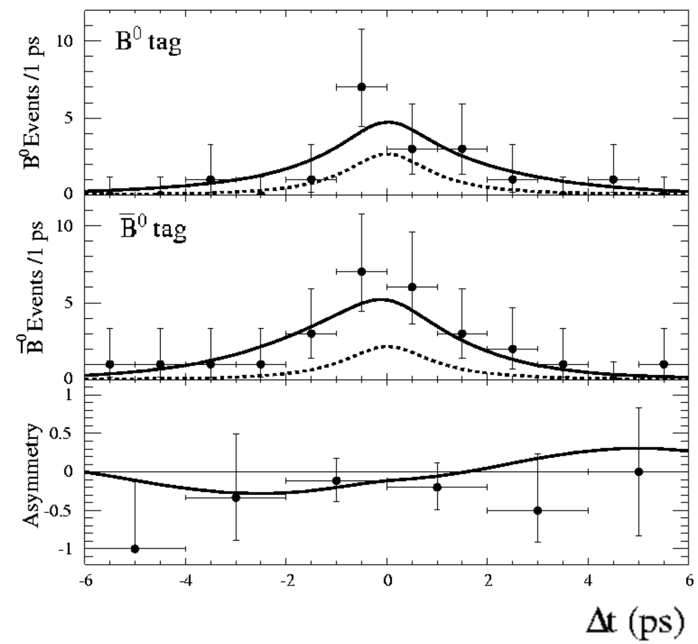
  [hep-ex/0403001, submitted to PRL]

$$C_{K^0_S\pi^0} = 0.40^{+0.27}_{-0.28} \pm 0.09$$
$$S_{K^0_S\pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.06$$

- assuming pure penguin dominance ($C_{K^0_S\pi^0} = 0$)

$$S_{K^0_S\pi^0} = 0.41^{+0.41}_{-0.48} \pm 0.06$$





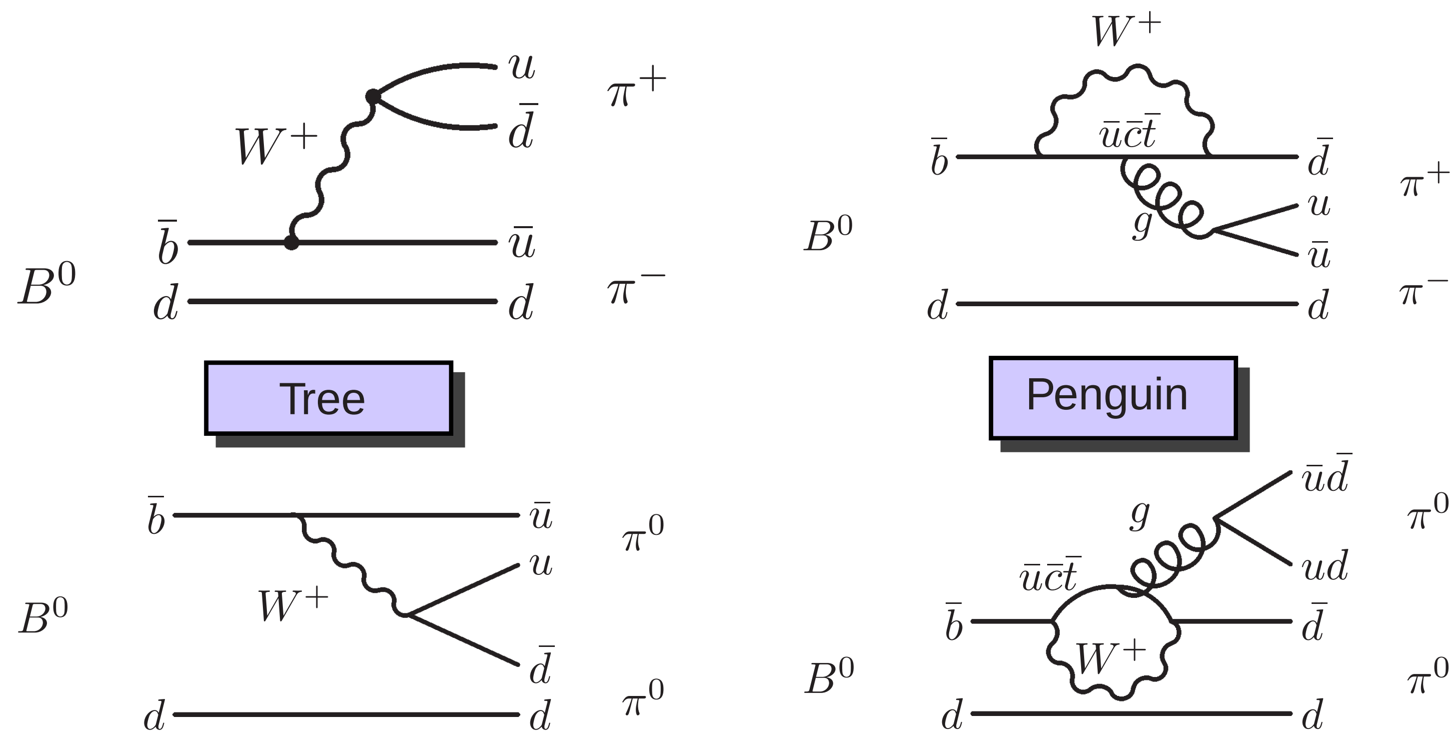
CKM angle α

I will present *BABAR* results in the analysis :

- ☞ $B \to \pi\pi$ (summary),
- ☞ $B^0 \to \rho^+\rho^-$.

Measurements of α

- In $\pi\pi$, $\rho\pi$, $\rho\rho$ tree and penguin contributions
  - **measure α_{eff} instead of α**



- $\rho^0\rho^0$ tree amplitude is colour suppressed and $\mathcal{B}(B^0 \to \rho^0\rho^0) < 2.1 \cdot 10^{-6}$ at 90 % C.L. [*BABAR*, PRL **91**, 171802 (2003)] while $\mathcal{B}(B^0 \to \rho^+\rho^-) \sim 30 \cdot 10^{-6}$
  - eventually small penguin pollution in $\rho\rho$ system $\Rightarrow$ good mode for α ?

Extraction of α

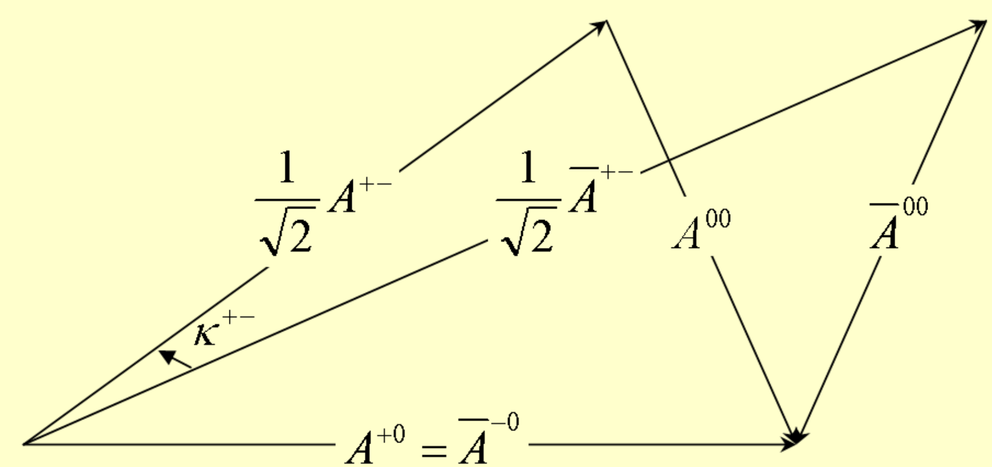
☞ We measure α_{eff} ! How to disentangle tree and penguin contributions ? $\Rightarrow$ assuming isospin symmetry

☞ 1) method of Gronau & London [PRL **65**, 3381]

- ➠ need to measure 5 branching ratios
- ➠ theoretically clean

$$S^{+-} = sin(2\alpha + \kappa^{+-})\sqrt{1 - C^{+-2}}$$

$$A^{+-} = A(B^0 \to \pi^+\pi^-),\ \bar{A}^{+-} = A(\overline{B}^0 \to \pi^+\pi^-),$$
$$A^{+0} = A(B^0 \to \pi^+\pi^0) = \bar{A}^{-0} = A(\overline{B}^0 \to \pi^-\pi^0),$$
$$A^{00} = A(B^0 \to \pi^0\pi^0),\ \bar{A}^{00} = A(\overline{B}^0 \to \pi^0\pi^0).$$



☞ 2) Grossman-Quinn bound [PR **D58**, 017504]

- ➠ simplification of 1) when A^{00} is small

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

at 68 % C.L.	$\pi^+\pi^-$	$\rho^+\rho^-$
Grossman-Quinn bound	48°	13°

☞ these methods also hold for VV modes : $\rho\rho$

Summary of $B \to h^+h^-$ results ($h = K, \pi$)

- published in [PRL **89**, 281802] and [PRL **91**, 241801]
- branching fractions in h^+h^- with 88 M $B\overline{B}$ pairs

$$\mathcal{B}(B \to \pi^+\pi^-) = (4.7 \pm 0.6 \pm 0.2) \cdot 10^{-6}$$
$$\mathcal{B}(B \to K^+\pi^-) = (17.9 \pm 0.9 \pm 0.7) \cdot 10^{-6}$$
$$\mathcal{B}(B \to K^+K^-) < 0.6 \cdot 10^{-6} \text{ at 90\% C.L.}$$

- asymmetries in h^+h^- with 120 M $B\overline{B}$ pairs

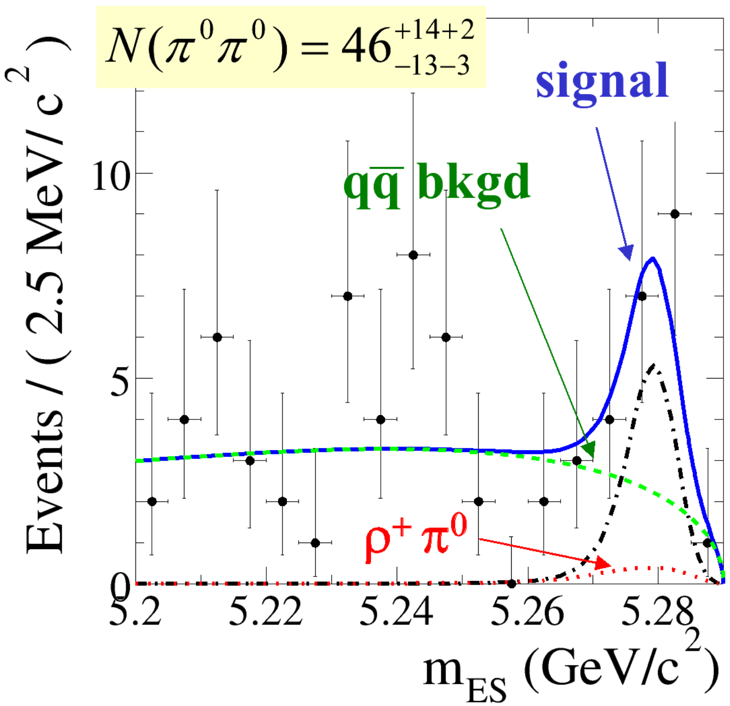
$$S_{\pi\pi} = -0.40 \pm 0.22 \pm 0.03$$
$$C_{\pi\pi} = -0.19 \pm 0.19 \pm 0.05$$
$$A_{K\pi} = -0.107 \pm 0.041 \pm 0.013$$

- results in $h^\pm\pi^0$ with 88 M $B\overline{B}$ pairs

$$\mathcal{B}(B \to \pi^\pm\pi^0) = (5.5^{+1.0}_{-0.9} \pm 0.6) \cdot 10^{-6}$$
$$\mathcal{B}(B \to K^\pm\pi^0) = (12.8^{+1.2}_{-1.1} \pm 1.0) \cdot 10^{-6}$$

- observation of $\pi^0\pi^0$ with 120 M $B\overline{B}$ pairs
  - with 4.2σ significance

$$\mathcal{B}(B \to \pi^0\pi^0) = (2.1 \pm 0.6 \pm 0.3) \cdot 10^{-6}$$



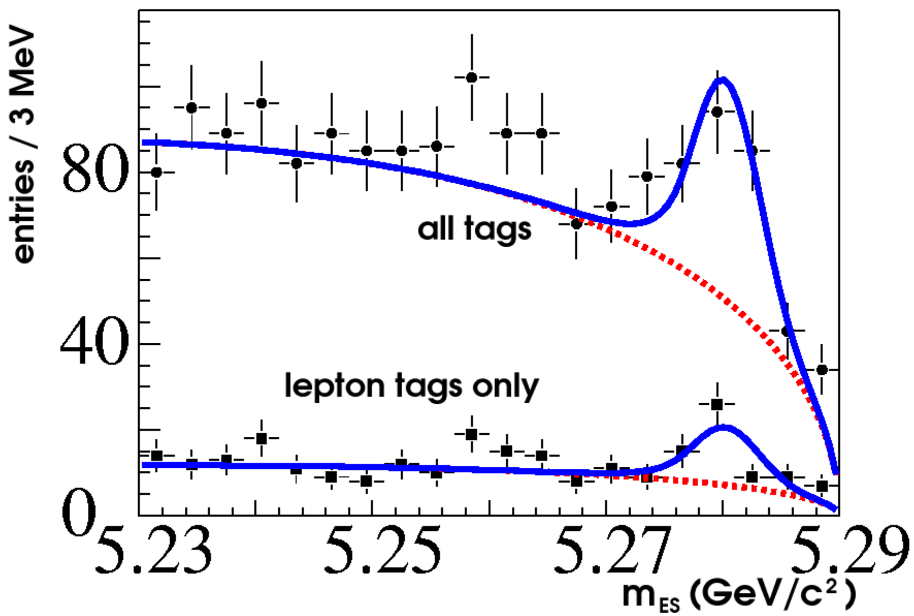
- Grossman-Quinn bound :

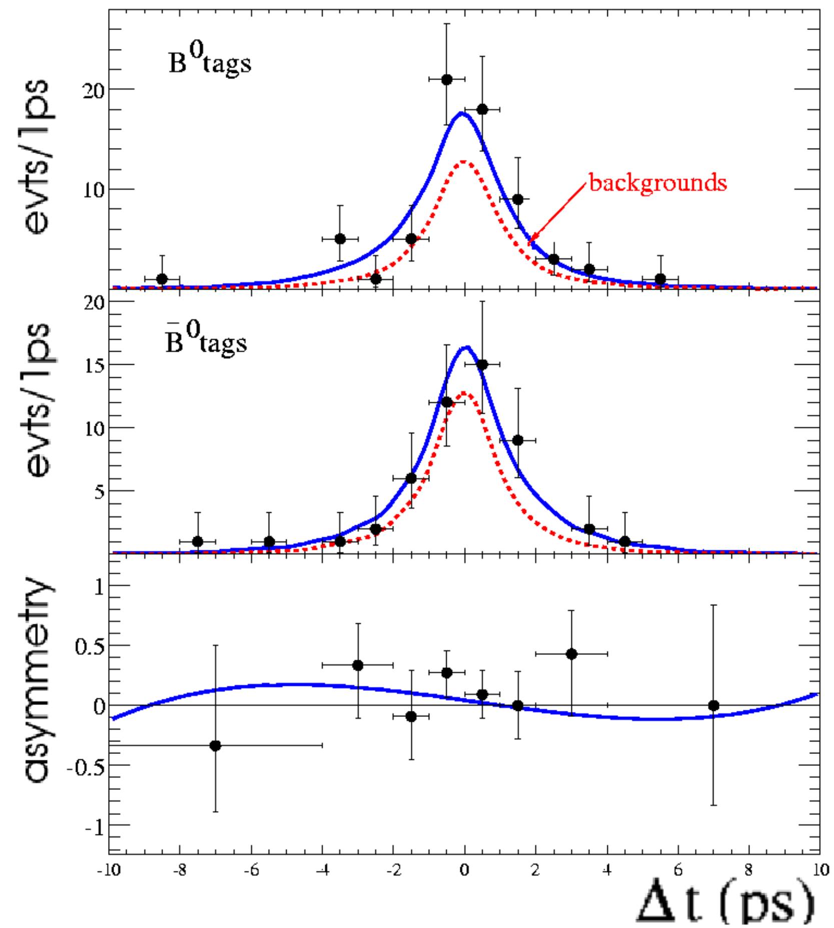
$$|\alpha_{eff} - \alpha| < 48^\circ \text{ at 68\% C.L.}$$

CP violation in $\rho^+\rho^-$

- Vector-Vector decay : analysis in helicity basis
- Interesting mode for α :
  - large $\mathcal{B}$: $\mathcal{B}(B^0 \to \rho^+\rho^-) \sim 30 \cdot 10^{-6}$ while $\mathcal{B}(B^0 \to \pi^+\pi^-) \sim 5 \cdot 10^{-6}$,
  - longitudinal polarization dominates ($f_L \sim 1$) $\Rightarrow$ almost pure CP-even eigenstate,
  - small penguin pollution in the $\rho\rho$ system.
- But :
  - two π^0 in the final state & ρ is broad ($\sim$ 150 MeV) $\rightarrow$ many sources of backgrounds
  - need to make assumptions.
- Maximum likelihood analysis :
  - ΔE, m_{ES}, neural network, $\rho^{\pm}$ masses & helicity angles, Δt, tagging,
  - model : signal, continuum, 7 categories of B-backgrounds (and other studied),
  - measure : $\mathcal{B}$, f_L, S_{long}, C_{long}.

Results of the $\rho^+\rho^-$ analysis (preliminary)





☞ results with 89 M $B\overline{B}$ pairs :

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (33 \pm 4(stat) \pm 5(syst)) \cdot 10^{-6}$$
$$f_L = 0.99 \pm 0.03(stat)^{+0.04}_{-0.03}(syst)$$
$$C_{long} = -0.17 \pm 0.27(stat) \pm 0.14(syst)$$
$$S_{long} = -0.42 \pm 0.41(stat) \pm 0.14(syst)$$

Interpretation of $\rho^+\rho^-$ $\not{C}\not{P}$ results (preliminary)

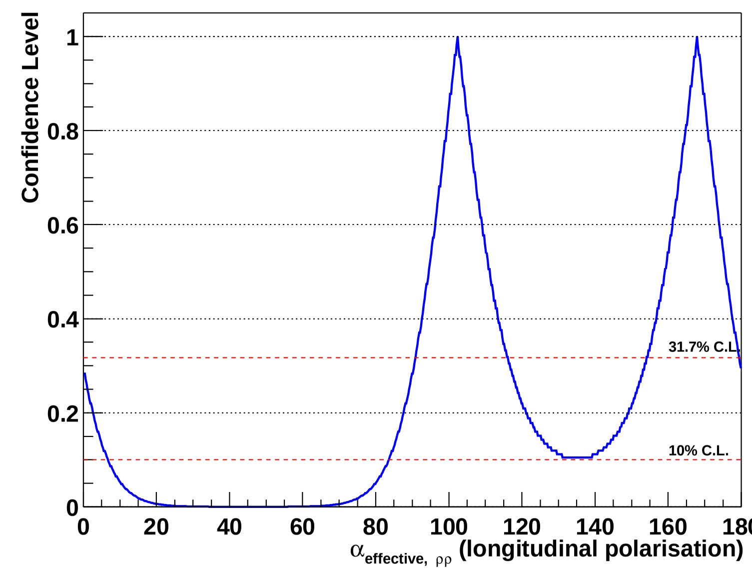
- assumptions :
  - isospin symmetry holds,
  - no interference with non-resonant ($\pi^+\pi^0\pi^-\pi^0$) or other resonant modes ($a_1^+\pi^-$, $\rho^+\pi^-\pi^0$),
  - no isospin I=1 amplitudes under the ρ.

- from S_{long}, solution nearest CKM best fit gives :

$$\alpha_{eff} = 102^{\circ}{}^{+16}_{-12}(stat)^{+5}_{-4}(syst)$$

- with bound on additional contribution from penguins (Grossman-Quinn) $|\alpha_{eff} - \alpha| < 13^{\circ}$ at 68% C.L.
  - using other inputs :

mode	$\mathcal{B}(\times 10^{-6})$	$f_L = \Gamma_L/\Gamma$
$B^{\pm} \to \rho^{\pm}\rho^0$	26.4±6.4	0.975±0.045
$B^0/\overline{B}^0 \to \rho^0\rho^0$	<2.1 at 90% C.L.	1



- most stringent constrain on α

CKM angle γ

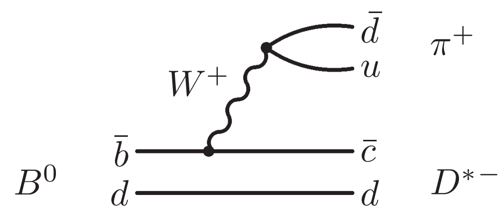
No golden mode ; decays with either large $\not{CP}$ or large $\mathcal{B}$.

I will present *BABAR* results in the analyses :

- ☞ $B^0 \to D^+\pi^-$ and $B^0 \to D^{*+}\pi^-$ ($2\beta + \gamma$),
- ☞ $B^+ \to [K^-\pi^+]_D K^+$ (ADS)

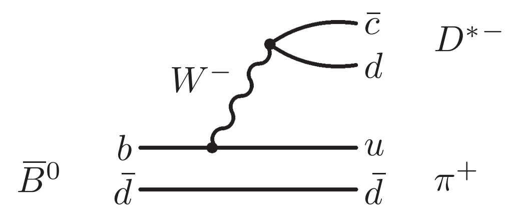
Measuring sin$(2\beta+\gamma)$ in $B^0 \to D^{(*)+}\pi^-$

- Large branching fractions : $\mathcal{B} \sim 0.3\%$
- Two tree amplitudes :



favoured $b \to c$ amplitude

$|A_1| V_{cb} V_{ud}^*$



suppressed $b \to u$ amplitude

$|A_2| e^{i\delta} e^{-i\gamma} |V_{ub}| V_{cd}^*$

strong phase δ,

weak phase $2\beta+\gamma$

(-2β from mixing)

- $\not{C}\not{P}$ from interference of mixing and decay
- Time evolution :

$$P(B^0 \to D^{(*)\mp}\pi^\pm, \Delta t) \propto 1 \pm C^{(*)} cos(\Delta m_d \Delta t) + S^{(*)\mp} sin(\Delta m_d \Delta t)$$
$$P(\overline{B}^0 \to D^{(*)\mp}\pi^\pm, \Delta t) \propto 1 \mp C^{(*)} cos(\Delta m_d \Delta t) - S^{(*)\pm} sin(\Delta m_d \Delta t)$$

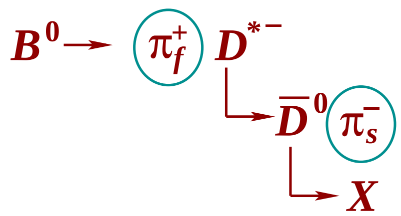
$$S^{(*)\pm} = \frac{2r_{(*)}}{1+r_{(*)}^2} sin(2\beta+\gamma \pm \delta_{(*)}) \qquad C^{(*)} = \frac{1-r_{(*)}^2}{1+r_{(*)}^2} \approx 1 \qquad r_{(*)} = \frac{A(\overline{B}^0 \to D^{(*)-}\pi^+)}{A(B^0 \to D^{(*)-}\pi^+)} \approx 0.02$$

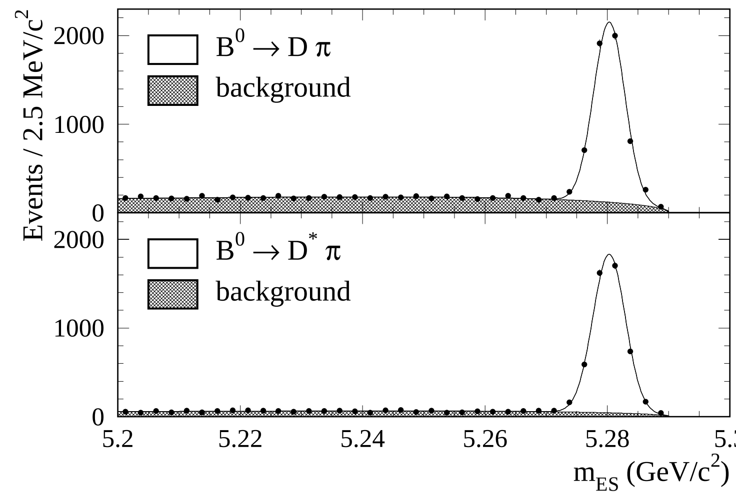
- small CP violating asymmetries

$B^0 \to D^{(*)+}\pi^-$ analyses

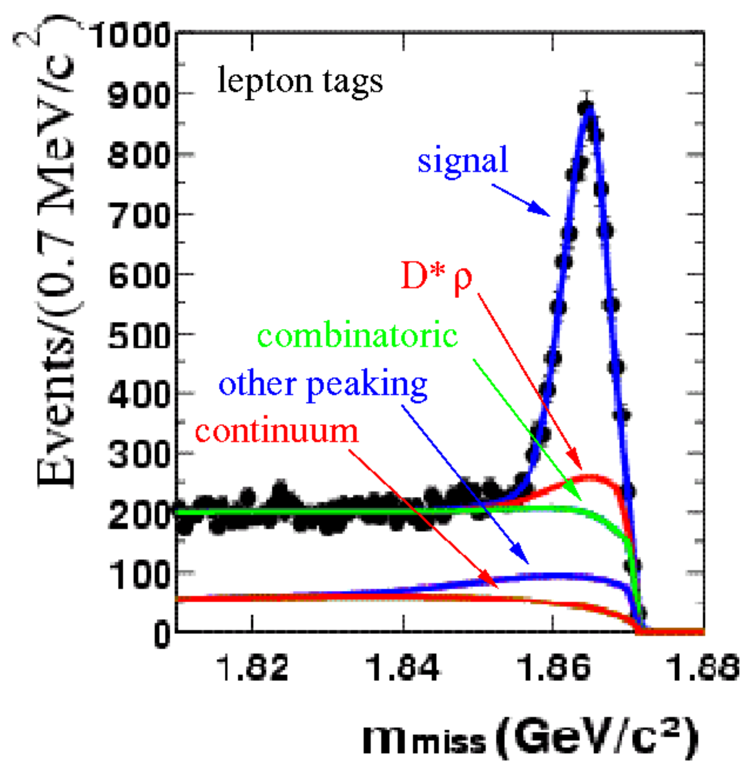
☞ two analyses in *BABAR* :

- exclusive reconstruction : $D^-\pi^+$ and $D^{*-}\pi^+$
  - higher purity
- partial reconstruction :
  - higher efficiency
  - more backgrounds





Sample	N events	Purity
Fully Reconstructed		
$D^{\pm}\pi^{\mp}$	5207 ± 87	85%
$D^{*\pm}\pi^{\mp}$	4746 ± 78	94%
Partially Reconstructed		
$D^{*\pm}\pi^{\mp}$ (ℓ)	6406 ± 129	54%
$D^{*\pm}\pi^{\mp}$ (K)	25157 ± 323	31%



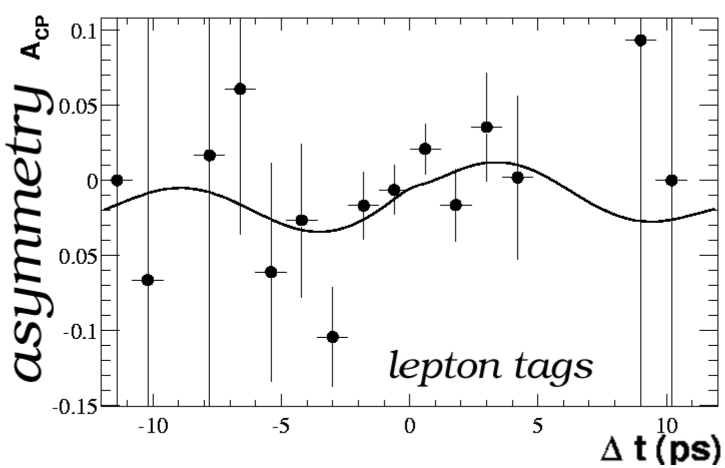
$B^0 \to D^{(*)+}\pi^-$ results (preliminary)

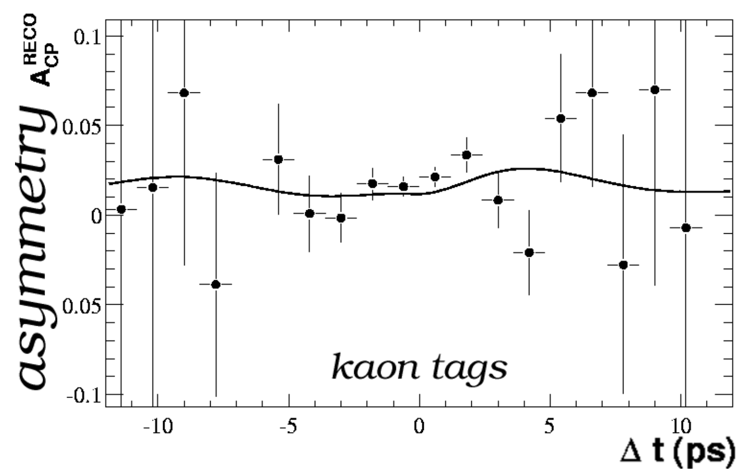
- results with exclusive reconstruction (with 88 M $B\overline{B}$) [hep-ex/0309017, submitted to PRL]

$$2r\,sin(2\beta+\gamma)cos\delta = -0.022 \pm 0.038 \pm 0.020$$
$$2r_*sin(2\beta+\gamma)cos\delta_* = -0.068 \pm 0.038 \pm 0.020$$

- results with partial reconstruction (with 82 M $B\overline{B}$) [hep-ex/0310037, submitted to PRL]

$$2r_*sin(2\beta+\gamma)cos\delta_* = -0.063 \pm 0.024 \pm 0.014$$





- kaon tags : possible $\not{CP}$ on the tag side ($b \to u$ transitions) $\Rightarrow$ parametrized,
- statistical error dominates $\Rightarrow$ will improve,
- no assumption done on $r_{(*)}$.

Constrains on sin$(2\beta+\gamma)$ (preliminary)

Interpretation with 2 approaches :

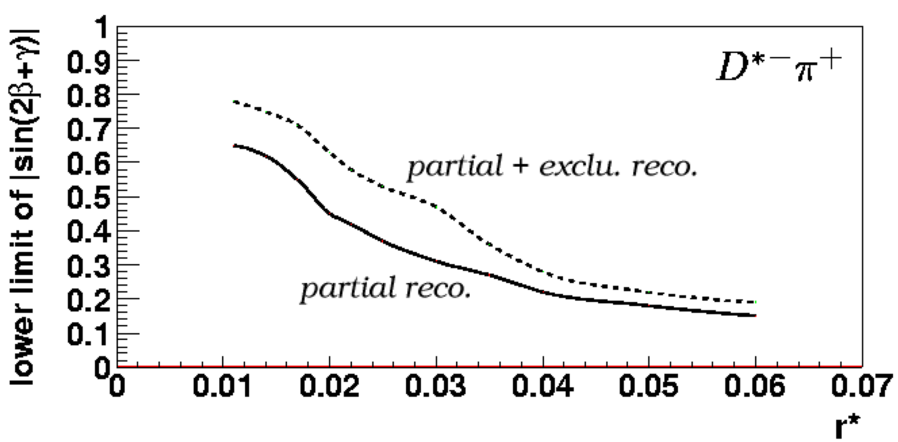
- ☞ estimate r using : $\mathcal{B}(D_s^{(*)}\pi)$ and SU(3) symmetry (30% theory error assigned)

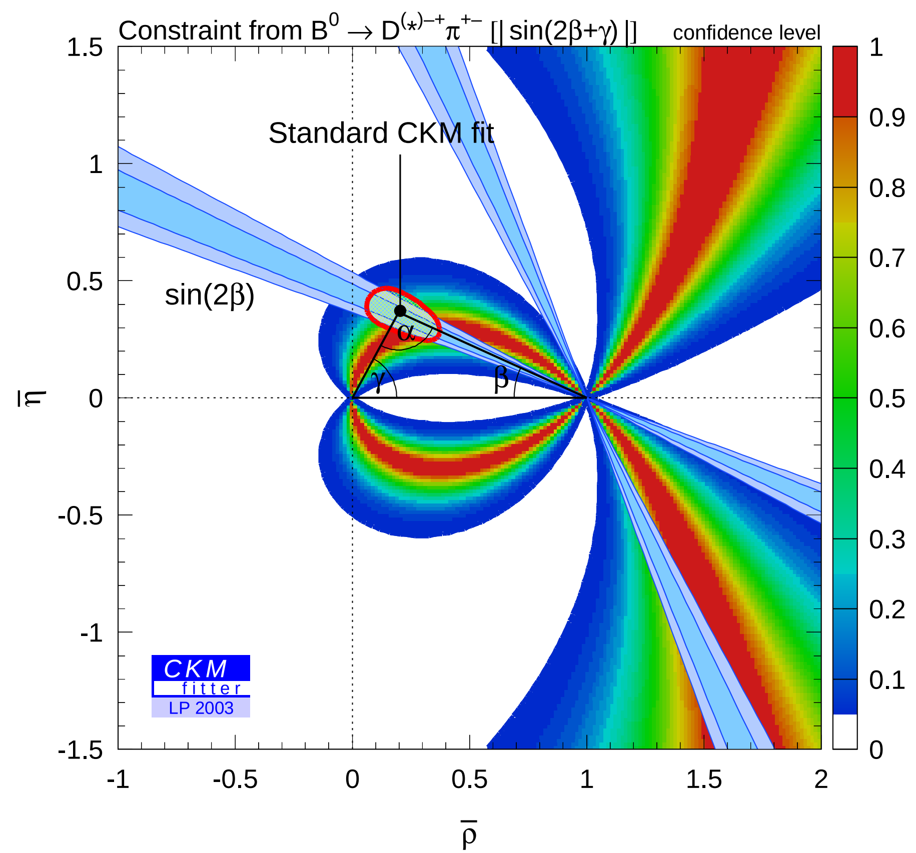
$r = 0.019 \pm 0.004$
$r_* = 0.017^{+0.005}_{-0.007}$

- ☞ frequentistic approach : minimise χ^2 combined from the observables [Feldman and Cousins, PRD **57**, 3873]
  - ➠ all results combined :

$|sin(2\beta+\gamma)| > 0.87$ at 68% C.L.
$|sin(2\beta+\gamma)| > 0.58$ at 95% C.L.

r_* scan : limits at 95% C.L.





- ➠ consistent with standard CKM fit

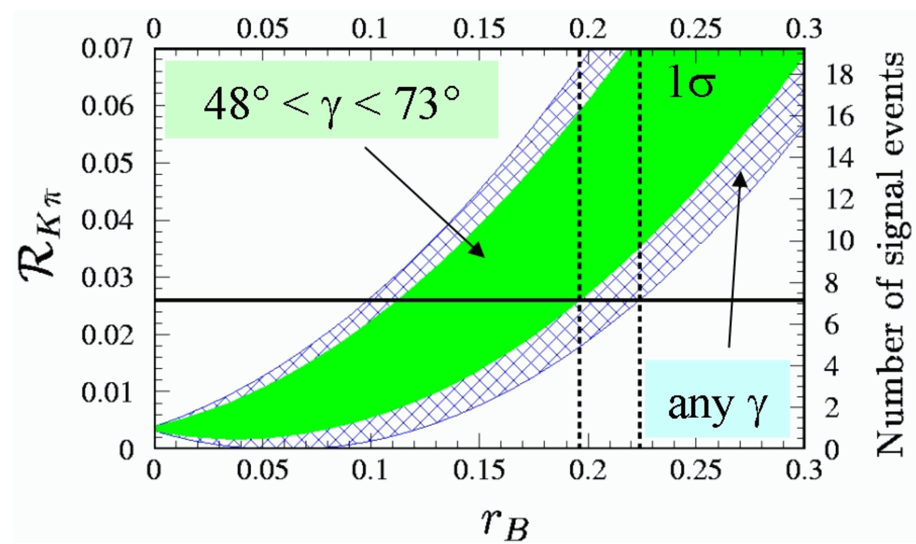
Analysis with ADS method (preliminary)

- ADS method, search for : $B^+ \to [K^-\pi^+]_D K^+$ [Atwood, Dunietz, Soni, PRL **58**, 3257]
- define ratio of suppressed to favoured amplitudes : $R^{\pm}_{K\pi} \equiv \frac{\Gamma([K^{\mp}\pi^{\pm}]_D K^{\pm})}{\Gamma([K^{\pm}\pi^{\mp}]_D K^{\pm})}$
  - low statistics $\Rightarrow$ re-define :

$$R_{K\pi} = \frac{R^+_{K\pi}+R^-_{K\pi}}{2} = r_B^2 + r_D^2 + 2 r_B r_D \cos\gamma \cos(\delta_B + \delta_D)$$

$$r_B \equiv \left|\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)}\right|, \qquad r_D \equiv \left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right| = 0.060 \pm 0.003$$

- analysis with 120 M $B\overline{B}$ [hep-ex/0402024, submitted to PRL]
  - measure $N_{sig.} = 1.1 \pm 3.0$
  - $\Rightarrow$ $R_{K\pi} < 0.026$ at 90% C.L.
- interpretation : (with/without CKM contraint on γ)
  - $r_B < 0.22$ at 90% C.L.
  - measure of γ with $D^0_{CP}K^{\pm}$ (GLW method, same r_B) : optimistic scenario ruled out



Direct CP asymmetries

Definition :

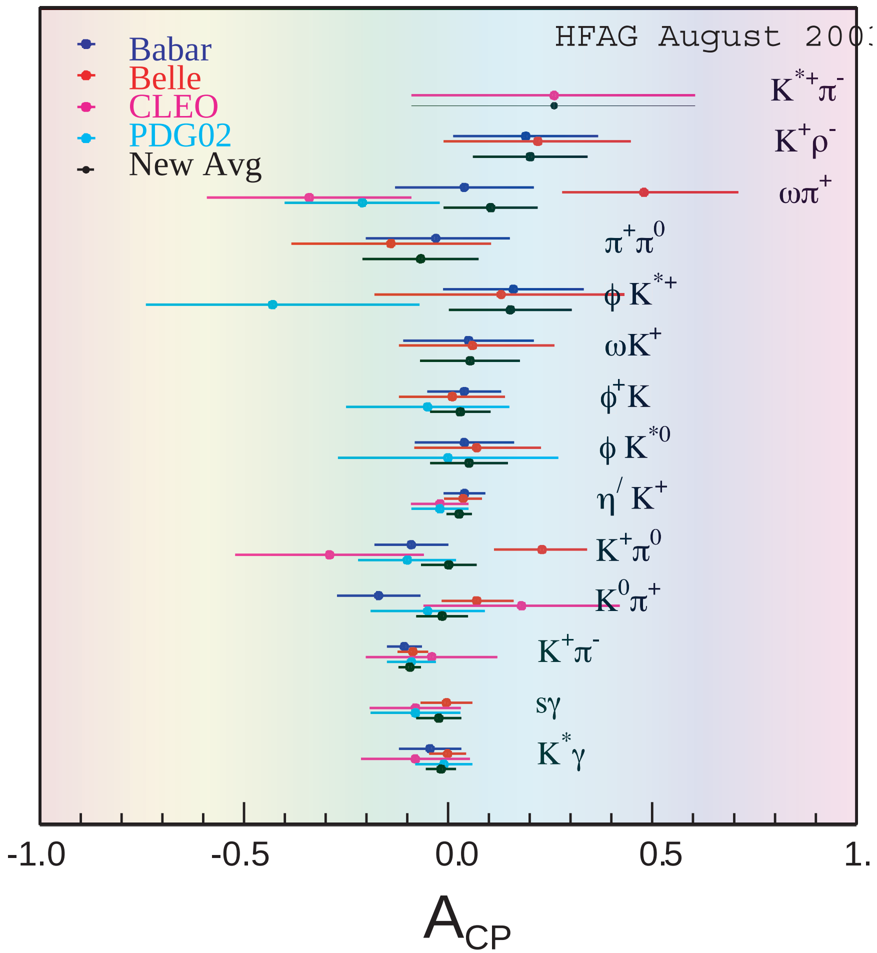
$$A_{CP} = \frac{N(\bar{B}\to\bar{f}) - N(B\to f)}{N(\bar{B}\to\bar{f}) + N(B\to f)}$$

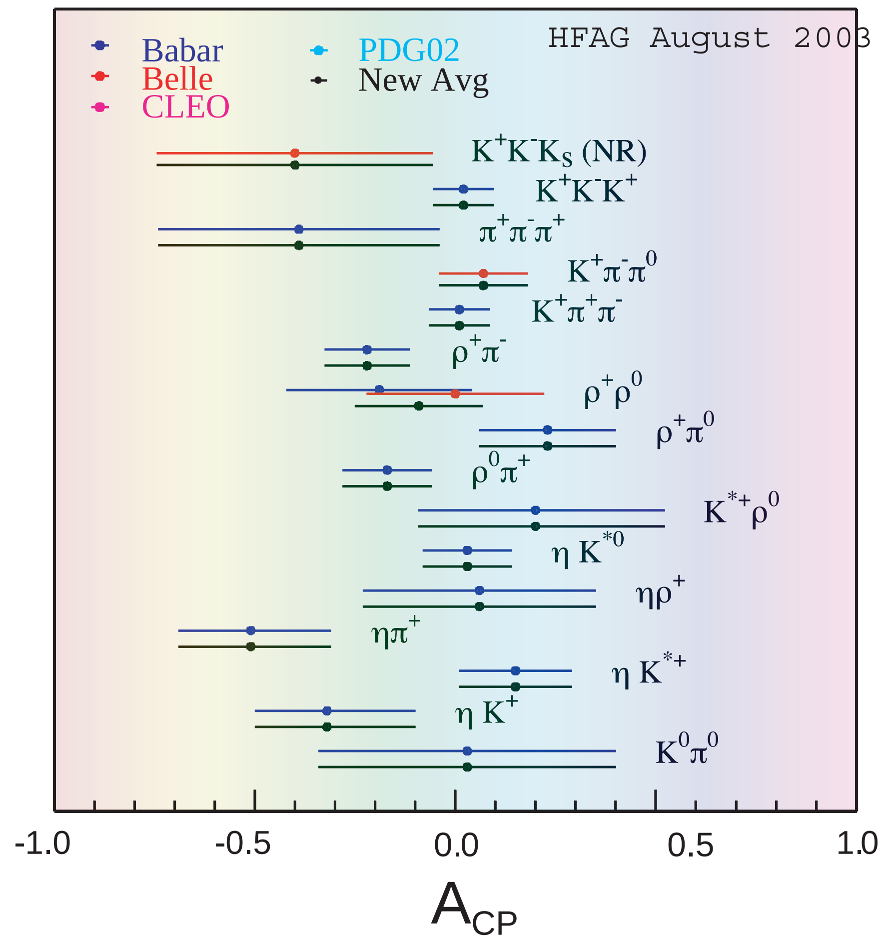
- new results : [PRL **92**, 061801]

mode	$\mathcal{B}$	A_{charge}
$\eta\pi^+$	$5.3 \pm 1.0 \pm 0.3$	$-0.44 \pm 0.18 \pm 0.01$
ηK^+	$3.4 \pm 0.8 \pm 0.2$	$-0.52 \pm 0.24 \pm 0.01$
$\omega\pi^+$	$5.5 \pm 0.9 \pm 0.5$	$0.03 \pm 0.16 \pm 0.01$
ωK^+	$4.8 \pm 0.8 \pm 0.4$	$-0.09 \pm 0.17 \pm 0.01$

- no evidence of direct $\not{C}\not{P}$ in *BABAR*,
- measurements dominated by stat. errors $\Rightarrow$ will improve in the future,
- plenty of modes inverstigated and their $\mathcal{B}$ measured (can test theoretical models of $B\overline{B}$ decays).

Direct CP asymmetries (summer ’03)





☞ tables from the Heavy Flavor Averaging Group (summer ’03) [http ://www.slac.stanford.edu/xorg/hfag/]

Conclusion

- *BABAR* in great condition ; many new results being issued and more to come.
- β
  - CP violation well established in the B system ; very good agreement with SM,
  - CP asymmetries in ϕK^0_S and other modes with loops give values of $sin(2\beta)$ consistent with ψK^0_S,
  - more data needed for new physics searches.
- α
  - 3 analyses to approach α : $B^0 \to \pi^+\pi^-$, $B^0 \to \rho^+\pi^-$, $B^0 \to \rho^+\rho^-$,
  - 1^{st} observation and time dependent analysis of $B^0 \to \rho^+\rho^-$,
    - most stringent constraints on α (under assumptions).
- γ
  - toward a measurement,
  - 1^{st} limits on $sin(2\beta + \gamma)$ from $B^0 \to D^{(*)+}\pi^-$,
  - results with ADS method $\Rightarrow$ limited sensitivity on γ in $B^+ \to D^0K^+$?
- we don't have evidence of large direct CP violation yet