CP violation in $B \to \pi\pi$ decays in the BABAR experiment

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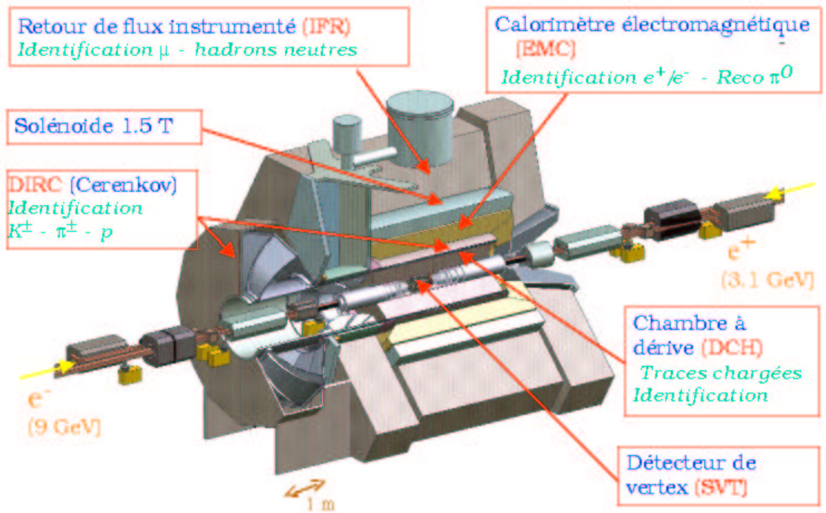
1 The BABAR experiment at SLAC

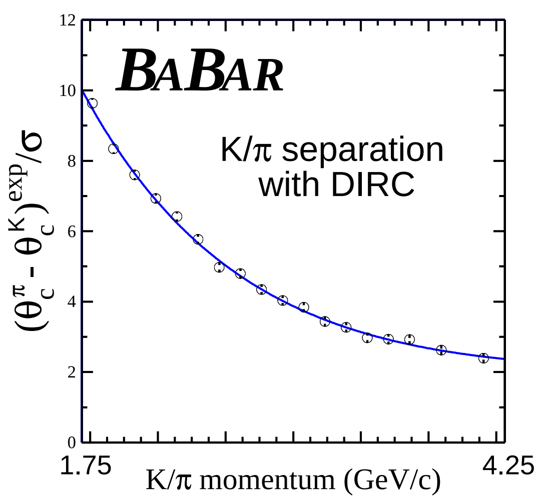
Detector on the PEP-II collider $e^+e^- \to \Upsilon(4S) \to B\overline{B}$



Essential for the $\pi^+\pi^-$ analysis:

- SVT
- DIRC

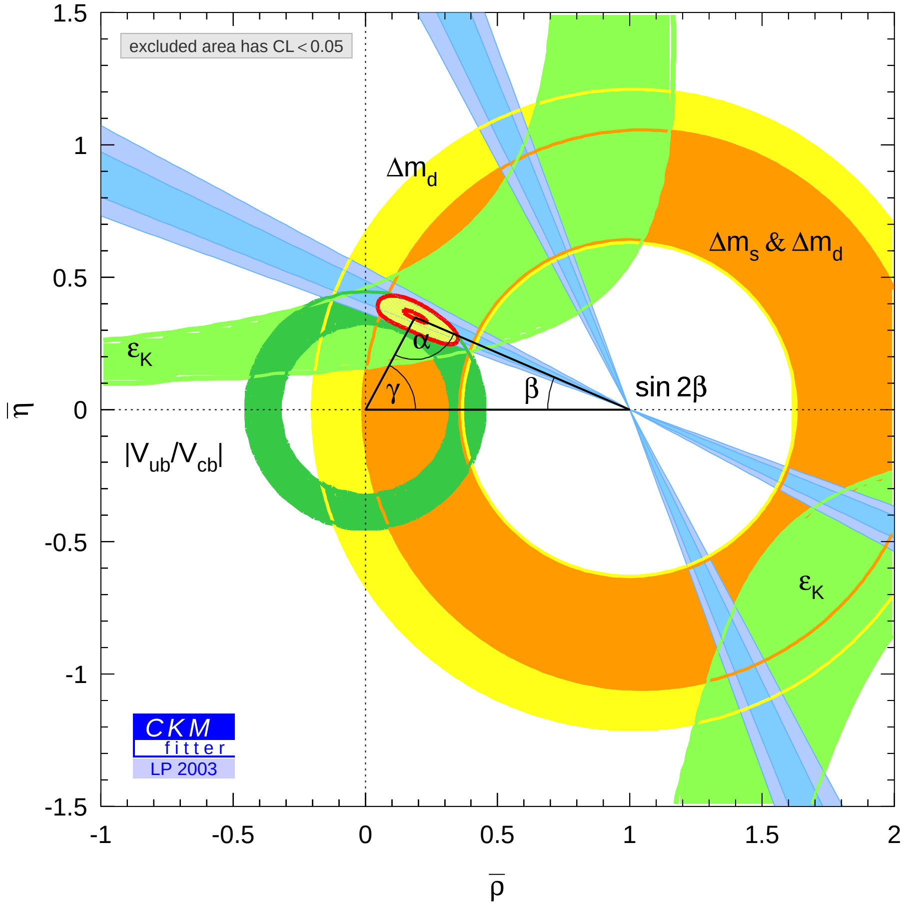
Separation between K and π thanks to the Cherenkov effect



Very good separation !

2 Phenomenology

CP violation in the B mesons decays



$\sin 2\beta$: $B^0 \to J/\psi\, K^0_S$

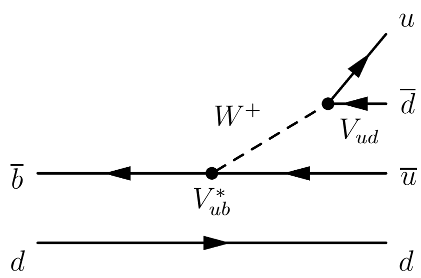
$\sin 2\alpha$: $\pi\pi$, $\rho\pi$, $\rho\rho$

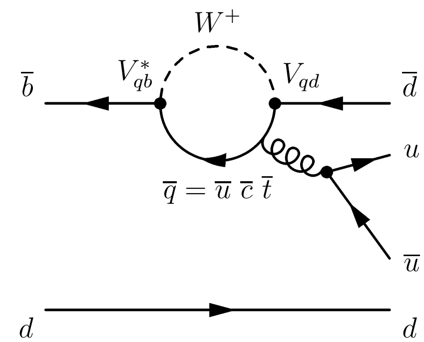
γ: DK, $DK\pi$

Eur. Phys. J. **C21**, 225 (2001)
hep-ph/0104062

$$\mathrm{f}(\,\Delta t|B^0_{\rm tag}/\overline{B}^0_{\rm tag}) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)\right]$$

Measurement of α thanks to $B^0 \to \pi^+\pi^-$





$$A^{+-} = |V_{ud}V_{ub}^*|e^{i\gamma}(T_u + P_u) - |V_{cd}V_{cb}^*|P_c + |V_{td}V_{tb}^*|e^{-i\beta}P_t$$

Using the unitarity relation:

$$A^{+-} = |V_{ud}V_{ub}^*|e^{i\gamma}(T_u + P_u - P_c) + |V_{td}V_{tb}^*|e^{-i\beta}(P_t - P_c) \quad (1)$$

$$T^{+-} \equiv T_u + P_u - P_c$$
$$P^{+-} \equiv P_t - P_c\ . \quad (2)$$

Asymmetry

$$A_{\pi\pi}(\Delta t) \equiv \frac{\Gamma(\overline{B}^0(\Delta t) \to \pi^+\pi^-) - \Gamma(B^0(\Delta t) \to \pi^+\pi^-)}{\Gamma(\overline{B}^0(\Delta t) \to \pi^+\pi^-) + \Gamma(B^0(\Delta t) \to \pi^+\pi^-)}$$

$$= S_{\pi\pi}\sin(\Delta m_d \Delta t) - C_{\pi\pi}\cos(\Delta m_d \Delta t) \quad (3)$$

$$S_{\pi\pi} = \frac{2\,\mathcal{I}m\,\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2} \quad \text{and} \quad C_{\pi\pi} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2} \tag{4}$$

$$\lambda_{\pi\pi} = e^{-2i\beta}\frac{e^{-i\gamma}+|V_{td}V_{tb}^*|/|V_{ud}V_{ub}^*|e^{i\beta}P^{+-}/T^{+-}}{e^{i\gamma}+|V_{td}V_{tb}^*|/|V_{ud}V_{ub}^*|e^{i\beta}P^{+-}/T^{+-}} \tag{5}$$

In a world without penguins

$$S_{\pi\pi}[P^{+-}=0] = \sin 2\alpha \quad \text{and} \quad C_{\pi\pi}[P^{+-}=0] = 0\ ,$$

In real world $P^{+-} \neq 0$

$$S_{\pi\pi} = \sqrt{1-C_{\pi\pi}^2}\,\sin 2\alpha_{\text{eff}} \quad \text{and} \quad C_{\pi\pi} \neq 0\ ,$$

$\Longrightarrow$ to measure α :

- isospin (Gronau/London, *Phys. Rev. Lett.* **65**, 3381 (1990))
  using $B^+ \to \pi^+\pi^0$, $B^0 \to \pi^0\pi^0$

$\Longrightarrow$ eight mirror solutions in $[0,\pi]$

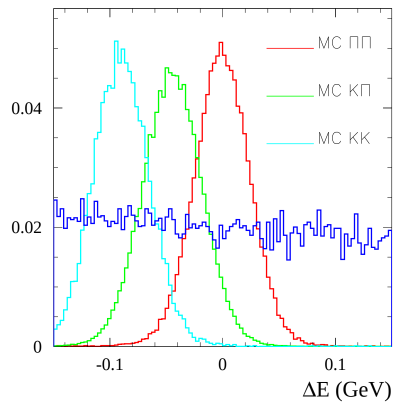
$\Longrightarrow$ Difficult !

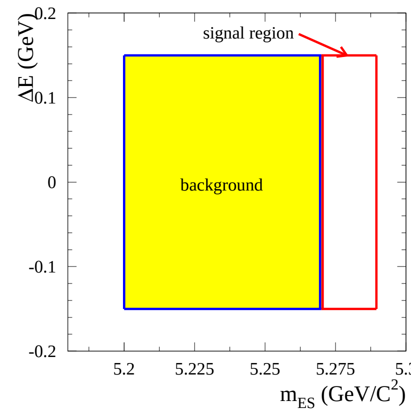
- theory : P^{+-}/T^{+-} ?
- experiment : rare desintegrations

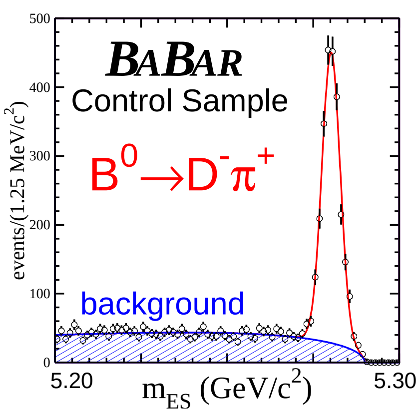
3.1 Event selection

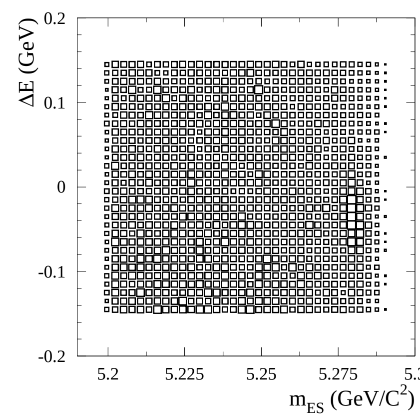
Two basic variables B almost at rest in the $\Upsilon(4S)$ CM

- $m_{\mathrm{ES}} = \sqrt{(E^*_{\mathrm{beam}})^2 - (p^*_{\mathrm{rec}})^2}$
  resolution limited by the beam energy spread of the machine
- $\Delta E = E^*_{\mathrm{rec}} - E^*_{\mathrm{beam}}$
  resolution limited by the tracker



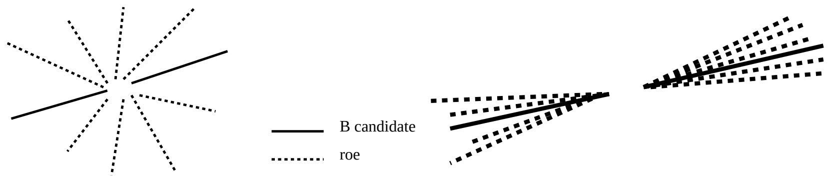


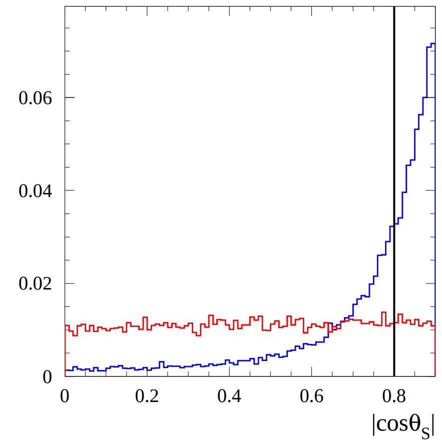




3.2 $q\bar{q}$ background rejection

Topology of the event



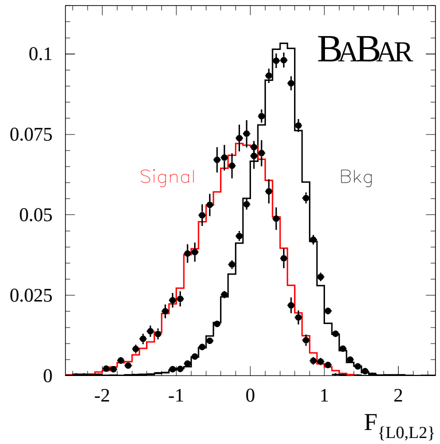


$\cos\theta_S$: sphericity axis of the B candidate and the rest of the event

Multidimentionnal analysis

Fisher discriminant

Two monomials $\{L_0, L_2\}$



$$L_j = \sum_i^{\rm roe} p_i \times |\cos\theta_i|^j$$

$$\mathcal{F}_{\{L_0,L_2\}} = 0.5319 - 0.6023 \times L_0 + 1.2698 \times L_2$$

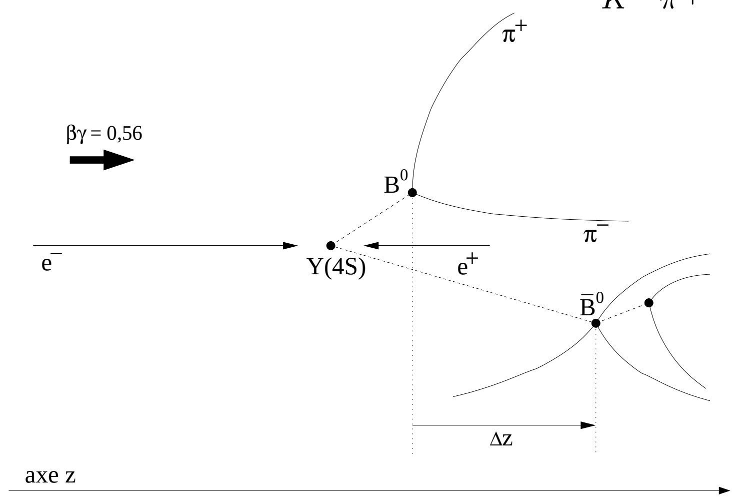
3.3 Likelihood fit

Variables

- discriminating variables: $m_{\rm ES}$ and ΔE
- signal/bkg separation: $\mathcal{F}_{\{L_0,L_2\}}$
- particules identification: θ_c
- B tagging : 5 categories (`Lepton, KPIouK, KouPI, Inclusive`)
- Δt variable

$$\Longrightarrow \mathcal{P}^{\rm s} = \mathcal{P}^{\rm s}(m_{\rm ES}).\mathcal{P}^{\rm s}(\Delta E).\mathcal{P}^{\rm s}(\mathcal{F}_{\{L_0,L_2\}}).\mathcal{P}^{\rm s}(\theta_c).\underbrace{\mathcal{P}^{\rm s}(\Delta t|\sigma_{\Delta t})}_{S_{\pi\pi},C_{\pi\pi}}$$

$\Longrightarrow$ physical observables: $N_{\pi\pi}$, $N_{K\pi}$, $A_{K\pi} = \frac{N_{K^-\pi^+}-N_{K^+\pi^-}}{N_{K^-\pi^+}+N_{K^+\pi^-}}$, $S_{\pi\pi}$, $C_{\pi\pi}$



4.1 ${}_s\mathcal{P}lot$: introduction

Data sample ≡ black box

Few signal events with lot of background

$\Longrightarrow$ How to extract the real distributions ?

$\downarrow$

By using ${}_s\mathcal{P}lot$!!

4.2 ${}_s\mathcal{P}lot$: the tool

physics/0402083

New tool ${}_s\mathcal{P}lot$: weight computed for each event

$\mathrm{N_s}$ species in the sample, discriminating variables y, $\mathrm{f}(y)$ their distributions. For species n:

$$ {}_s\mathcal{P}_\mathrm{n}(y_e) = \frac{\sum_{j=1}^{\mathrm{N_s}} \mathbf{V}_{\mathrm{n}j}\mathrm{f}_j(y_e)}{\sum_{k=1}^{\mathrm{N_s}} N_k \mathrm{f}_k(y_e)} \quad (6) $$

with $\mathbf{V}_{\mathrm{n}j}$ the covariance-matrix of the fit of the yields

The reconstructed distribution of x ($x \notin y$) is the true distribution of x:

$$ N_\mathrm{n}\ {}_s\tilde{\mathrm{M}}_\mathrm{n}(x)\delta x \equiv \sum_{e\subset\delta x}^{N} {}_s\mathcal{P}_\mathrm{n}(y_e) \quad (7) $$

$$ \Downarrow $$

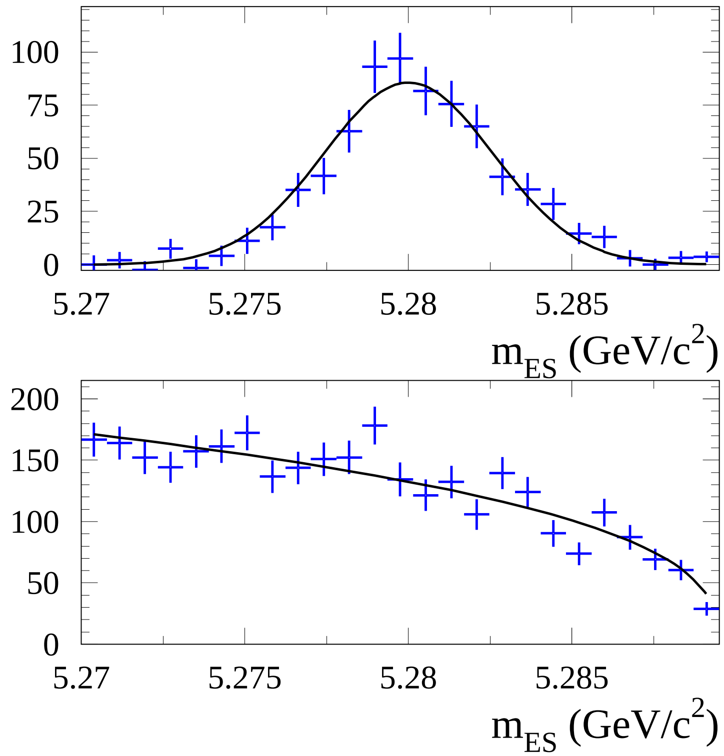
$$ N_\mathrm{n}\ {}_s\tilde{\mathrm{M}}_\mathrm{n}(x) = N_\mathrm{n}\mathbf{M}_\mathrm{n}(x) \quad (8) $$

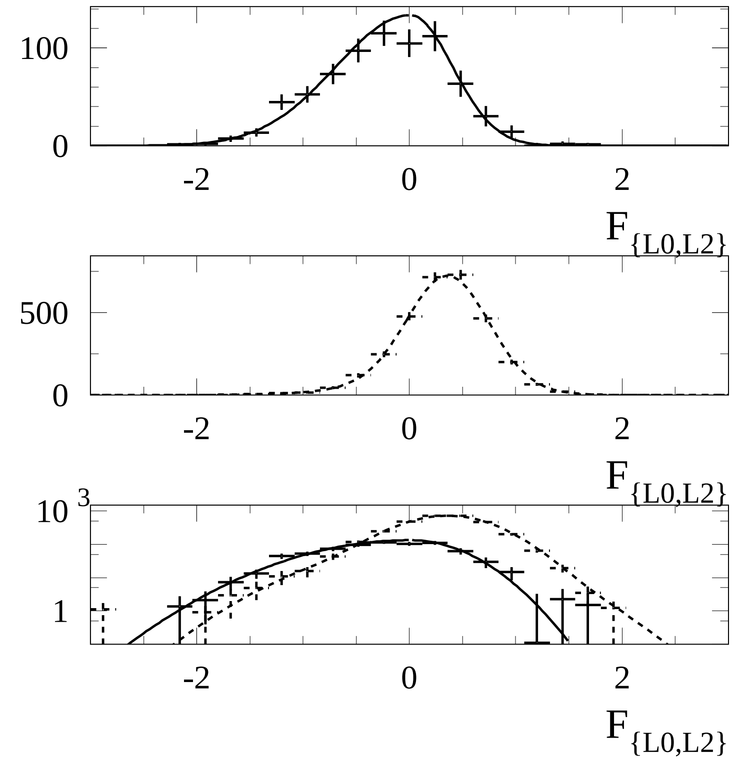
Cute properties of ${}_s\mathcal{P}lots$ Normalization and errors

1. Each x-distribution is properly normalized: $\sum_{e=1}^{N} {}_s\mathcal{P}_\mathrm{n}(y_e) = N_\mathrm{n}$
2. In each x-bin, for any event: $\sum_{\mathrm{n}=1}^{\mathrm{N_s}} {}_s\mathcal{P}_\mathrm{n}(y_e) = 1$
3. For each species: $\sum_{e=1}^{N}({}_s\mathcal{P}_\mathrm{n}(y_e))^2 = \sigma^2(N_\mathrm{n})$

${}_s\mathcal{P}lot$ of $m_{\rm ES}$ and $\mathcal{F}_{\{L_0,L_2\}}$

Distributions used in the fit superimposed





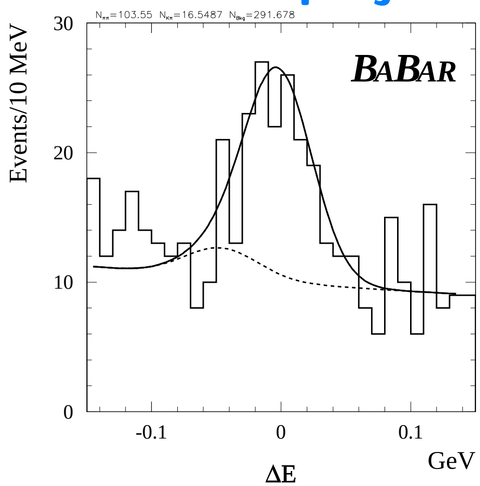
- ΔE and $\mathcal{F}_{\{L_0,L_2\}}$ only
- No knowledge on $m_{\rm ES}$

- $m_{\rm ES}$ and ΔE only
- No knowledge on $\mathcal{F}_{\{L_0,L_2\}}$

$\Longrightarrow$ Wonderful agreement !

4.3 $_{s}\mathcal{P}lot$ at work (2)

Comparison with “projection plots”



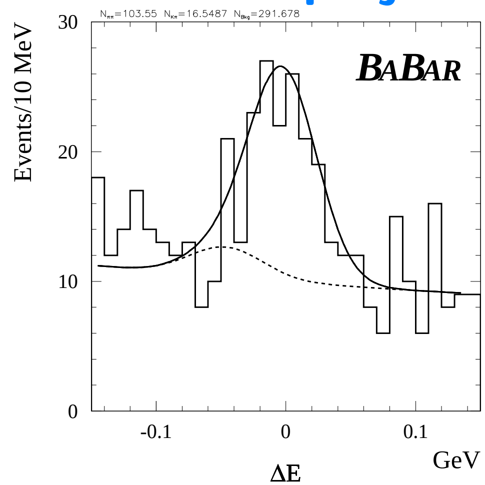
Projection plot:

- Cut applied on the ($\mathcal{L}$ ratio): loss of signal and remaining background
- Uncertainties related to signal + background

$\Longrightarrow$ Excess of event: signal ? background ?

4.3 $_s\mathcal{P}lot$ at work (2)

Comparison with "projection plots"



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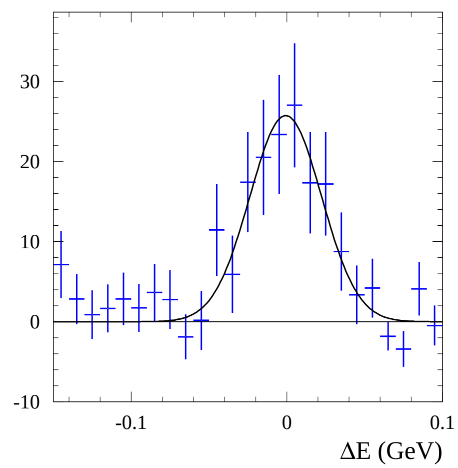


$_s\mathcal{P}lot$: subtelties can be found !

- No cut applied: keep all the signal and remove background
- Uncertainties of the signal

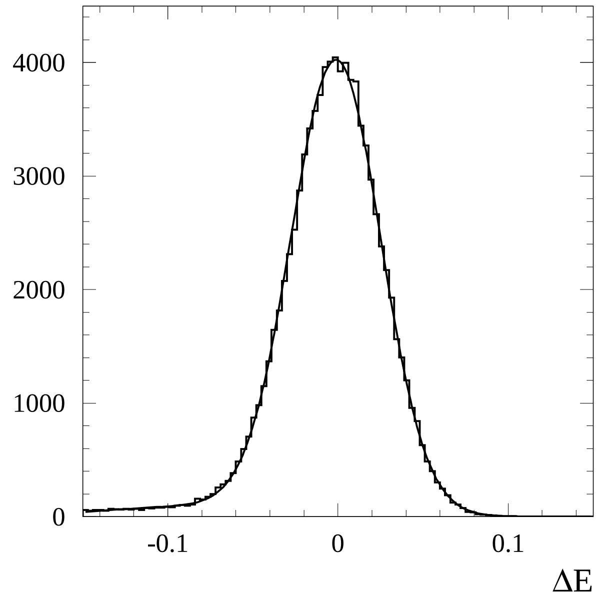
$\Longrightarrow$ Signal ! But what can it be ?!

4.3 $_s\mathcal{P}lot$ at work (3)

Radiative events ignored in the analysis

Loss of events $B^0 \to \pi^+\pi^-\gamma$:

1. By the cut on ΔE
2. In the fit due to the distribution



Shift by $-4\ \mathrm{MeV}$ on the average

$\Longrightarrow$ $\mathcal{B}(B^0 \to h^+h^-)$ underestimated by about 10% (!!)

Belle: Same status, what is the effect ?

5 Results

Presented at ICHEP 2002 $81\,\text{fb}^{-1}$ (88 million $B\overline{B}$ pairs)

Phys. Rev. Lett. **89**, 281802 (2002)

$$\mathcal{B}(B^0 \to \pi^+\pi^-) = 4.7 \pm 0.6 \pm 0.2\ 10^{-6}$$
$$\mathcal{B}(B^0 \to K^+\pi^-) = 17.9 \pm 0.9 \pm 0.7\ 10^{-6}$$

156 $\pi^+\pi^-$
588 $K^+\pi^-$

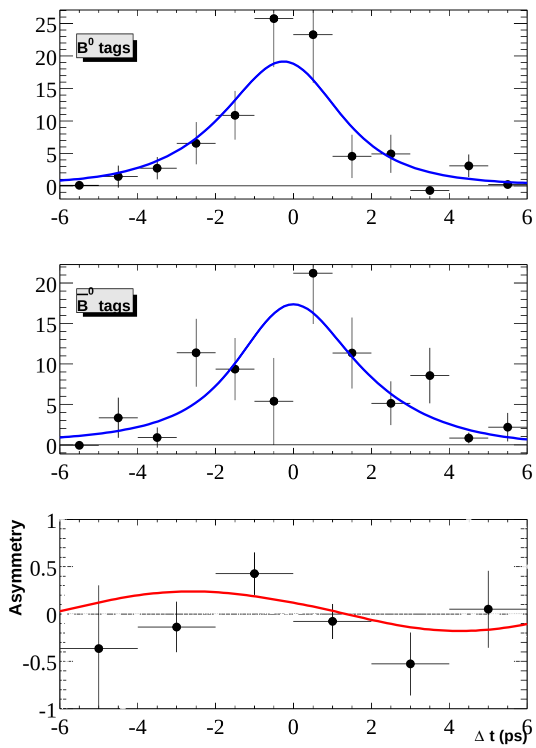
Presented at Lepton-Photon 2003 $113\,\text{fb}^{-1}$

$$C_{\pi\pi} = -0.19 \pm 0.19 \pm 0.05$$
$$S_{\pi\pi} = -0.40 \pm 0.22 \pm 0.03$$

$\Longrightarrow$ CP violation ?

$$A_{K\pi} = -0.11 \pm 0.04 \pm 0.01$$

$\Longrightarrow$ 2.5σ effect (direct)

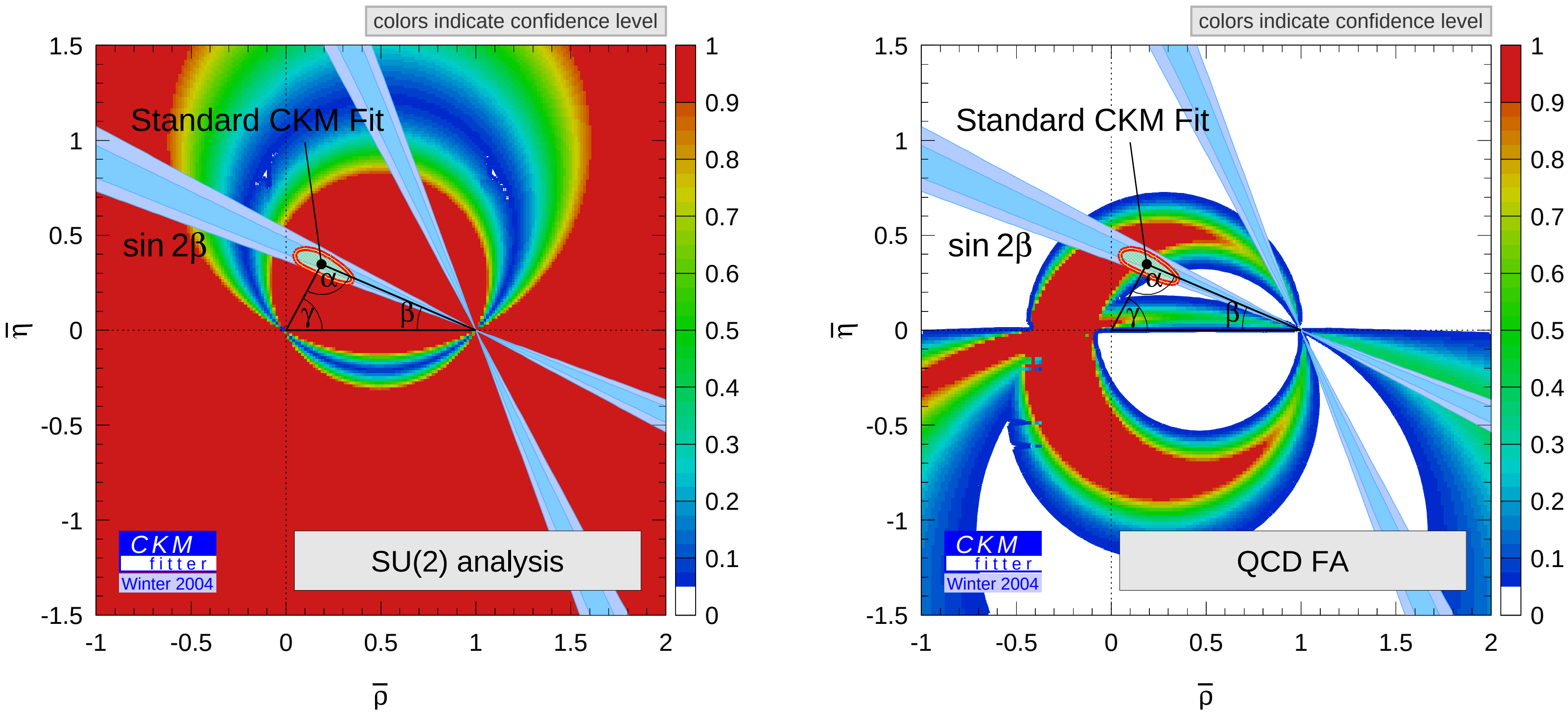


6 Interpretation of the results

Two theoretical frameworks

1. Isospin analysis: $\frac{1}{\sqrt{2}}A^{+-} + A^{00} \;=\; A^{+0}$
2. QCD factorisation (BBNS): prediction of P^{+-}/T^{+-}, module and phase

In the $(\bar{\rho}, \bar{\eta})$ plane



$\Longrightarrow$ No constraint with isospin only (C_{00} not yet measured !)

$\Longrightarrow$ QCD FA: lots of hypotheses

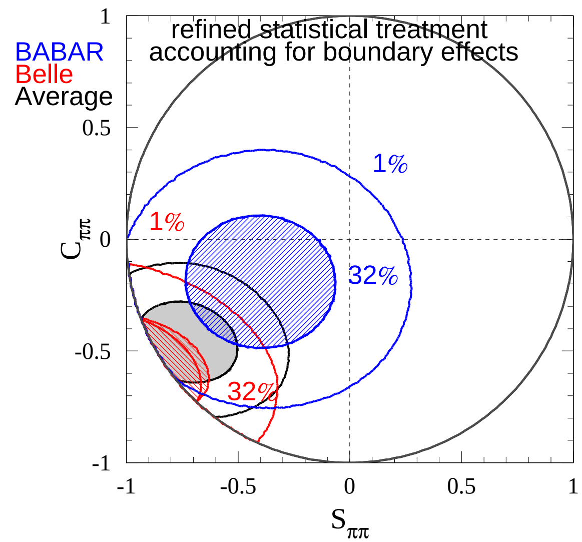
7 BABAR / Belle comparison

	BABAR	Belle
$S_{\pi\pi}$	-0.40 ± 0.22	-1.0 ± 0.22
$C_{\pi\pi}$	-0.19 ± 0.20	-0.58 ± 0.16

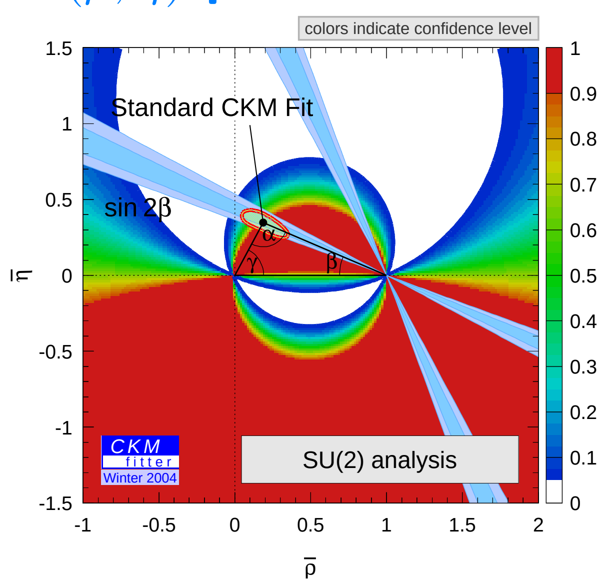
hep-ex/0401029

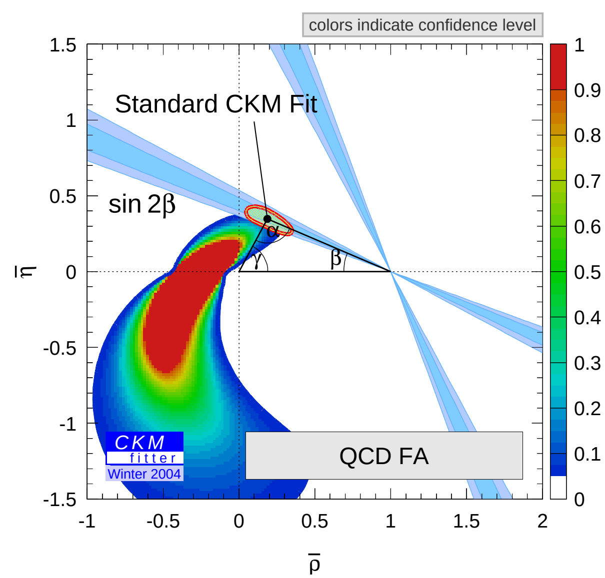
$\Longrightarrow$ Belle results outside the physical domain

$\Longrightarrow$ BABAR and Belle in marginal agreement



In the $(\bar\rho, \bar\eta)$ plane





8 News on the isospin in $B \to \pi\pi$

Bounds on $\mathcal{B}(B^0 \to \pi^0\pi^0)$

So far: Gronau-London-Sinha-Sinha (Phys. Lett. B514: 315 (2001))

$$\mathcal{B}^{00}_{\rm GLSS} = \mathcal{B}^{+0} + \frac{1}{2}\mathcal{B}^{+-} \pm \sqrt{\mathcal{B}^{+0}\mathcal{B}^{+-}\left(1 + \sqrt{1 - C^2_{\pi\pi}}\right)} \quad (9)$$

New bound including angle α: M. Pivk and F. R. Le Diberder (ref. coming)
($\alpha = 96^o \pm 13^o$)

$$\mathcal{B}^{00}_{\alpha} = \mathcal{B}^{+0} + \frac{1}{2}\mathcal{B}^{+-} \pm \sqrt{\mathcal{B}^{+0}\mathcal{B}^{+-}(1 + D)} \quad (10)$$

$$D = \sqrt{(1 - \sin^2(2\alpha))(1 - C^2_{\pi\pi} - S^2_{\pi\pi})} + \sin(2\alpha)S_{\pi\pi} \quad (11)$$

Constraints on α

So far: Grossman-Quinn bound (*Phys. Rev. D*58: 017504 (1998))

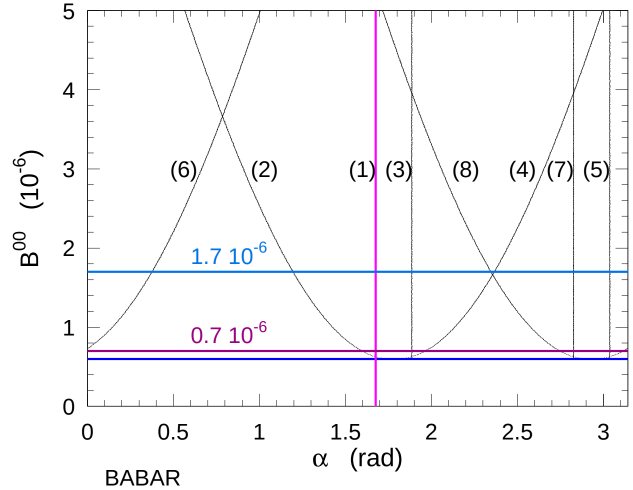
$$\sin^2(\alpha - \alpha_{\rm eff}) \leq \frac{\mathcal{B}^{00}}{\mathcal{B}^{+0}} \quad (12)$$

$\Longrightarrow$ Need a small $\mathcal{B}^{00}$ but approximation !

The right way M.P & F.R.L.D

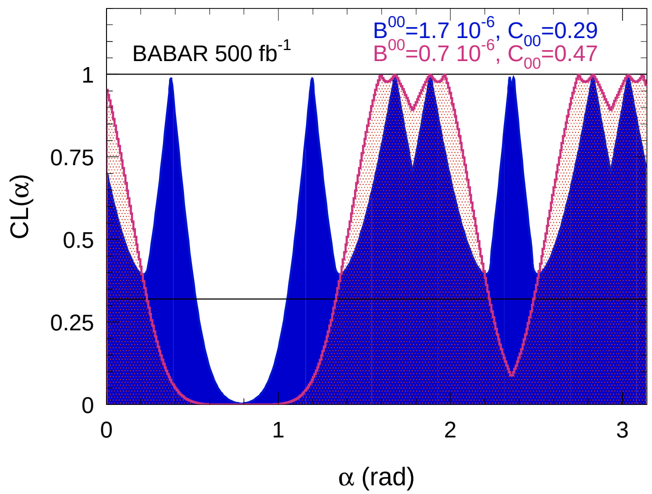
$$\sin^2(\alpha - \alpha_{\rm eff}) \leq \frac{(\mathcal{B}^{00} - \mathcal{B}^{00}_{\rm GLSS-})(\mathcal{B}^{00}_{\rm GLSS+} - \mathcal{B}^{00})}{2\mathcal{B}^{+-}\mathcal{B}^{+0}\sqrt{1 - C^2_{\pi\pi}}} \quad (13)$$

Evolution of the mirror solutions



- $\alpha \ = \ 96^o \pm 13^o$
- Large variation ($\mathcal{B}^{00}$)

Two different scenarii at 500 fb^{-1}



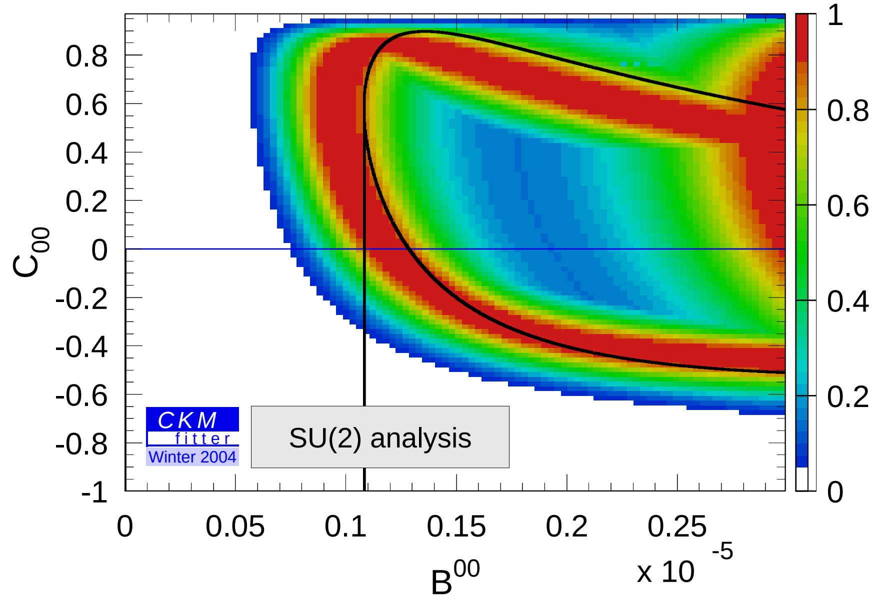
- need C_{00}
- Lift the degeneracy

The C_{00} parameter

$$C_{00}^{\pm} = \frac{1}{\mathcal{B}^{00}(1+D)}\left\{-C_{\pi\pi}\left(\mathcal{B}^{+0} - \frac{\mathcal{B}^{+-}}{2}D - \mathcal{B}^{00}\right)\right.$$
$$\left.\pm\sqrt{(\mathcal{B}^{00}-\mathcal{B}^{00}_{\alpha-})(\mathcal{B}^{00}_{\alpha+}-\mathcal{B}^{00})(1-D^2-C^2_{\pi\pi})}\right\} \qquad (14)$$

$\Longrightarrow$ Two values of C_{00} for a given $\mathcal{B}^{00}$

Test the Standard Model: the $(\mathcal{B}^{00}, C_{00})$ plane



- No need for bounds
- No need to deal with mi. sol.
- World average at $1000\ \text{fb}^{-1}$

$\Longrightarrow$ Difficult to rule out the SM

9 Conclusion

The $B^0 \to \pi^+\pi^-$ decays

- Well understood in *BABAR* !
- Radiative corrections should be included
- Marginal agreement with Belle: need for data

$\Longrightarrow$ Let's work !

New statistical tool: ${}_s\mathcal{P}lot$

- Already very useful
- Can be used in any analysis of any experiment

$\Longrightarrow$ Let's try !

Measurement on α with $B \to \pi\pi$

- Difficult with only isospin analysis
- With more data, everything possible !

$\Longrightarrow$ Let's dream !