

# Violazione di $CP$ nel Modello Standard

# Interazioni deboli

A basse energie: lagrangiana efficace V-A:

$$\mathcal{L} = \bar{\Psi}_1 \gamma_\mu (a + b \gamma_5) \Psi_2 \bar{\Psi}_3 \gamma^\mu (c + d \gamma_5) \Psi_4 + \\ \bar{\Psi}_2 \gamma_\mu (a^* + b^* \gamma_5) \Psi_1 \bar{\Psi}_4 \gamma^\mu (c^* + d^* \gamma_5) \Psi_3$$

che sotto trasformazione CP diventa:

$$\mathcal{L}^{\text{CP}} = \bar{\Psi}_2 \gamma_\mu (a + b \gamma_5) \Psi_1 \bar{\Psi}_4 \gamma^\mu (c + d \gamma_5) \Psi_3 + \\ \bar{\Psi}_1 \gamma_\mu (a^* + b^* \gamma_5) \Psi_2 \bar{\Psi}_3 \gamma^\mu (c^* + d^* \gamma_5) \Psi_4$$

Simmetria CP se  $a, b, c, d$  sono reali.

# Modello Standard

- Settore di gauge:  
non puo' accogliere violazione di  $CP$   
Con campi di gauge hermitiani  $t^a A_\mu^a$  l'hermiticita' della Lagrangiana impedisce costanti di accoppiamento complesse
- Settore di Higgs:  
non puo' accogliere violazione di  $CP$   
Il potenziale scalare con un singolo doppietto di Higgs conserva  $CP$
- Interazioni di gauge invarianti per  $CP$
- Settore di Yukawa?
- Vuoto?

# Settore di Yukawa



$$\ell_L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \cdots (m_\nu = 0) \quad q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \tilde{\phi} = i\sigma_2 \phi^*$$

Lagrangiana di Yukawa:

$$\begin{aligned} \mathcal{L}_Y^{(\ell)} &= -G^{(\ell)} \bar{\ell}_L \phi e_R - G^{(\ell)*} \bar{e}_R \phi^+ \ell_L \\ \mathcal{L}_Y^{(q)} &= -G^{(d)} \bar{q}_L \phi d_R - G^{(d)*} \bar{d}_R \phi^+ q_L \\ &\quad -G^{(u)} \bar{q}_L \tilde{\phi} u_R - G^{(u)*} \bar{u}_R \tilde{\phi}^+ q_L \end{aligned}$$

Rottura spontanea di simmetria:

$G \Rightarrow M = G \langle \Phi \rangle_0 \Rightarrow$  termini di massa per quark e leptoni

Le generazioni sono identiche tranne che in massa:  
*simmetria di sapore (flavour symmetry).*

Per i quark, in forma matriciale:

$$Q_L = \begin{pmatrix} q_L^{(u,d)} \\ q_L^{(c,s)} \\ q_L^{(t,b)} \end{pmatrix} \quad U_R = \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \quad D_R = \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_Y^{(q)} = & -\bar{Q}_L \mathbf{G}^{(d)} \phi D_R - \bar{D}_R \mathbf{G}^{(d)*} \phi^+ Q_L \\ & -\bar{Q}_L \mathbf{G}^{(u)} \tilde{\phi} U_R - \bar{U}_R \mathbf{G}^{(u)*} \tilde{\phi}^+ Q_L \end{aligned}$$

Da cui i termini di massa  $\mathcal{L}_Y^{(q)} = -\bar{D}_L \mathbf{M}^{(d)} D_R - \bar{U}_R \mathbf{M}^{(u)} U_R + \dots$

Matrici  $\mathbf{M}\mathbf{M}^\dagger$  e  $\mathbf{M}\mathbf{M}^\dagger$ : hermitiane con autovalori identici

Diagonalizzazione mediante matrici unitarie  $\mathbf{A}_{L,R}^\dagger = \mathbf{A}_{L,R}^{-1}$

$$\mathbf{M}^{(u,d)} \Rightarrow \mathbf{A}_L^{(u,d)+} \mathbf{M}^{(u,d)} \mathbf{A}_R^{(u,d)}$$

Ridefinendo i campi:  $Q_L \Rightarrow \mathbf{A}_L^{(u)+} Q_L$   $U_R \Rightarrow \mathbf{A}_R^{(u)+} U_R$   $D_R \Rightarrow \mathbf{A}_R^{(d)+} D_R$

si ottiene

$$\mathbf{M}^{(d)} \Rightarrow \mathbf{A}_L^{(u)+} \mathbf{A}_L^{(d)} \mathbf{D} = \mathbf{V} \mathbf{D}$$

con  $\mathbf{D}$  diagonale

Le correnti diventano:  $J_{(CC)}^\mu = -\frac{g}{\sqrt{2}} \bar{U}_L \gamma^\mu D_L \Rightarrow -\frac{g}{\sqrt{2}} \mathbf{V} \bar{U}_L \gamma^\mu D_L$

$$J_{(NC)}^\mu = -\frac{g}{2 \cos \theta_W} \left[ g_L \bar{U}_L \gamma^\mu U_L + g_R \bar{U}_R \gamma^\mu U_R \right] + (U \leftrightarrow D)$$

$$J_{(EM)}^\mu = -Q|e| \bar{U} \gamma^\mu U + (U \leftrightarrow D)$$

Le correnti neutre rimangono *diagonali* in sapore.

# Matrice CKM

**V: matrice di Cabibbo-Kobayashi-Maskawa (unitaria)**

N generazioni: matrice unitaria  $2N^2 - N^2$   
parametri reali

Fasi dei quark arbitrarie:  $2N - 1$  parametri.  
 $(N - 1)^2$  rimanenti:

$N(N - 1)/2$  angoli di rotazione (matrice  
ortogonale)

$(N^2 - 3N + 2)/2$  fasi

2 generazioni: 1 angolo (Cabibbo)

3 generazioni: 3 angoli (Eulero) + **1 fase**



$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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***CP-Violation in the Renormalizable Theory  
of Weak Interaction***

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(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

$V_{ud}$ $0.9742 \pm 0.0003$ $\cos\theta_C = (1-\lambda^2/2)$ $\beta$ nucleare Decad. n, ( $\pi$ beta)	$V_{us}$ $0.225 \pm 0.002$ $\sin\theta_C = \lambda$ $K \rightarrow \pi \ell \nu$ ( $K \rightarrow \ell \nu$ ) (decad. iperoni, $\tau$ )	$V_{ub}$ $0.0039 \pm 0.0004$ $A\lambda^3(\rho - i\eta + i\eta\lambda^2/2)$ $B \rightarrow X_u \ell \nu$ $B \rightarrow \pi \ell \nu$
$V_{cd}$ $0.23 \pm 0.01$ $-\sin\theta_C = -\lambda$ $vd \rightarrow \ell^- c$ ( $D \rightarrow \pi \ell \nu$ )	$V_{cs}$ $1.04 \pm 0.06$ $\cos\theta_C = 1 - \lambda^2/2 - i\eta A^2 \lambda^4$ $D \rightarrow K \ell \nu$ , $D_s \rightarrow \ell \nu$ ( $vs \rightarrow \ell^- c$ )	$V_{cb}$ $0.041 \pm 0.001$ $A\lambda^2(1 + i\eta\lambda^2)$ $B \rightarrow D \ell \nu$ , $B \rightarrow \text{charm}$
$V_{td}$ $0.0081 \pm 0.0006$ $A\lambda^3(1 - \rho - i\eta)$ $\Delta m(B^0)$	$V_{ts}$ $0.038 \pm 0.002$ $-A\lambda^2$ $\Delta m(B_s^0)$ ( $b \rightarrow s \gamma$ )	$V_{tb}$ $> 0.74$ $1$ $t \rightarrow Wb$

$$\lambda = \sin\theta_C \approx 0.226$$

$$A \approx 0.81$$

$$\rho \approx 0.14$$

$$\eta \approx 0.35$$



# Triangoli di unitarieta'

Si assume che  $VV^\dagger=1$

Sulla diagonale: universalita'

Fuori dalla diagonale:

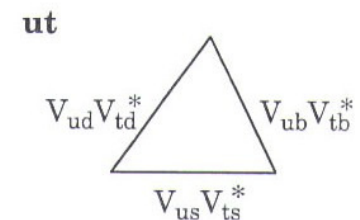
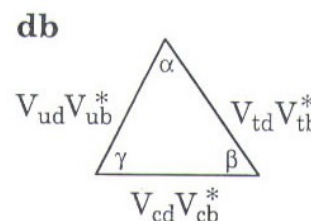
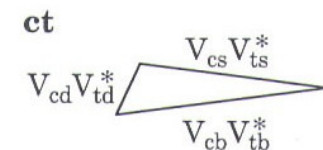
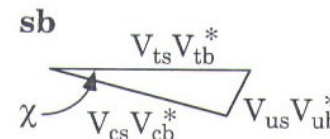
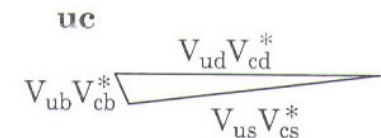
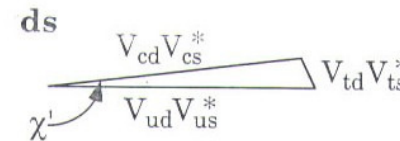
$$(es.) V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$$Area = J/2$$

$$J \equiv \text{Im}[V_{ik}^*V_{jk}V_{il}V_{jl}^*] \sim nA^2\lambda^6$$

Invariante (per ridefinizione delle fasi) di Jarlskog

Misura univoca della violazione di CP nella matrice CKM



M.S. Sozzi

La violazione di CP e' piccola

Violazione di CP

Necessarie **tre generazioni** per avere violazione di CP

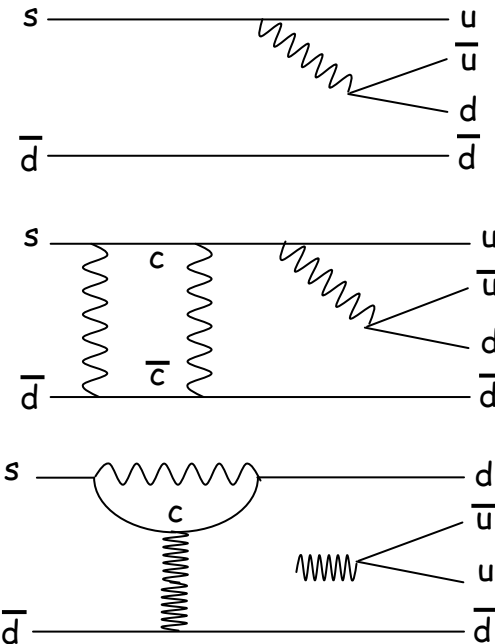
In un mondo con 2 generazioni:

Unitarieta'  $VV^\dagger=1$ :  $V_{ud}V_{us}^*+V_{cd}V_{cs}^* = 0$

$$V = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix}$$

*Esempio:*  $\bar{K}^0 \rightarrow \pi^0\pi^0$  ( $s\bar{d} \rightarrow u\bar{u} d\bar{d}$ )

1.  $V_{us}V_{du} = V_{us}V_{ud}^*$
2.  $V_{cs}V_{dc}V_{cd}^*V_{sc}^*V_{us}^*V_{ud} =$   
 $(V_{cs})^2(V_{cd}^*)^2V_{us}^*V_{ud} =$   
 $-|V_{cd}V_{cs}|^2V_{us}V_{ud}^* =$   
 $|V_{cd}V_{cs}|^2V_{us}V_{ud}^*$
3.  $V_{cs}V_{dc} = V_{cs}V_{cd}^* = -V_{us}V_{ud}^*$



- **Disaccoppiamento di una generazione:** matrice diagonale a blocchi 2x2 e nessuna fase ineliminabile  
necessario accoppiamento di tutte e tre le generazioni (tre angoli non nulli)
- **Quark degeneri:** ogni combinazione lineare e' ancora autostato di massa, possibile rotazione di UL o DL che elimina V  
necessarie masse differenti per i quark

Per avere violazione di CP:

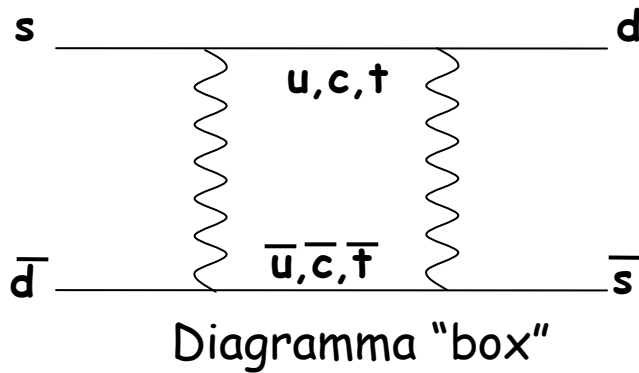
$$m_u \neq m_c \neq m_t + m_d \neq m_s \neq m_b + 3 \text{ angoli} \neq 0, \pi/2 + \text{fase} \neq 0, \pi/2$$

$$J (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2) \neq 0$$

# Violazione di CP nei $K^0$

Necessarie 3 generazioni:  
diagrammi del second'ordine

$$\Delta S=2: K^0 \leftrightarrow \bar{K}^0$$



Int. deboli al second'ordine

$$\Delta S=1: K^0 \rightarrow \pi^0 \pi^0$$

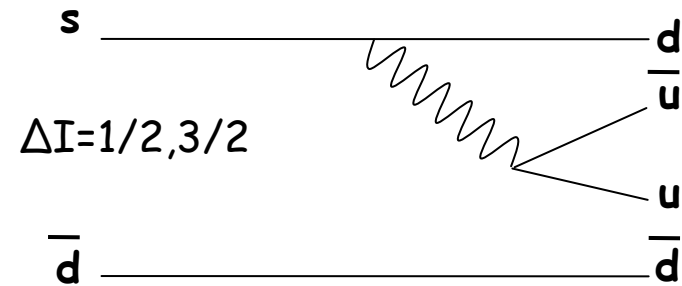


Diagramma "albero"

+

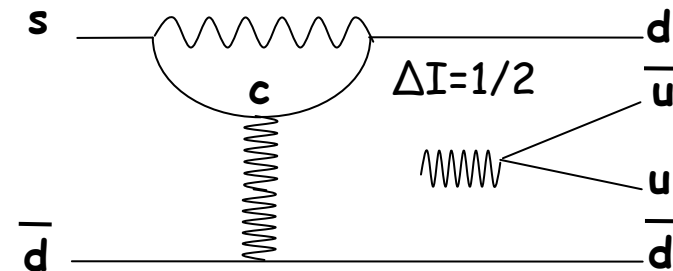
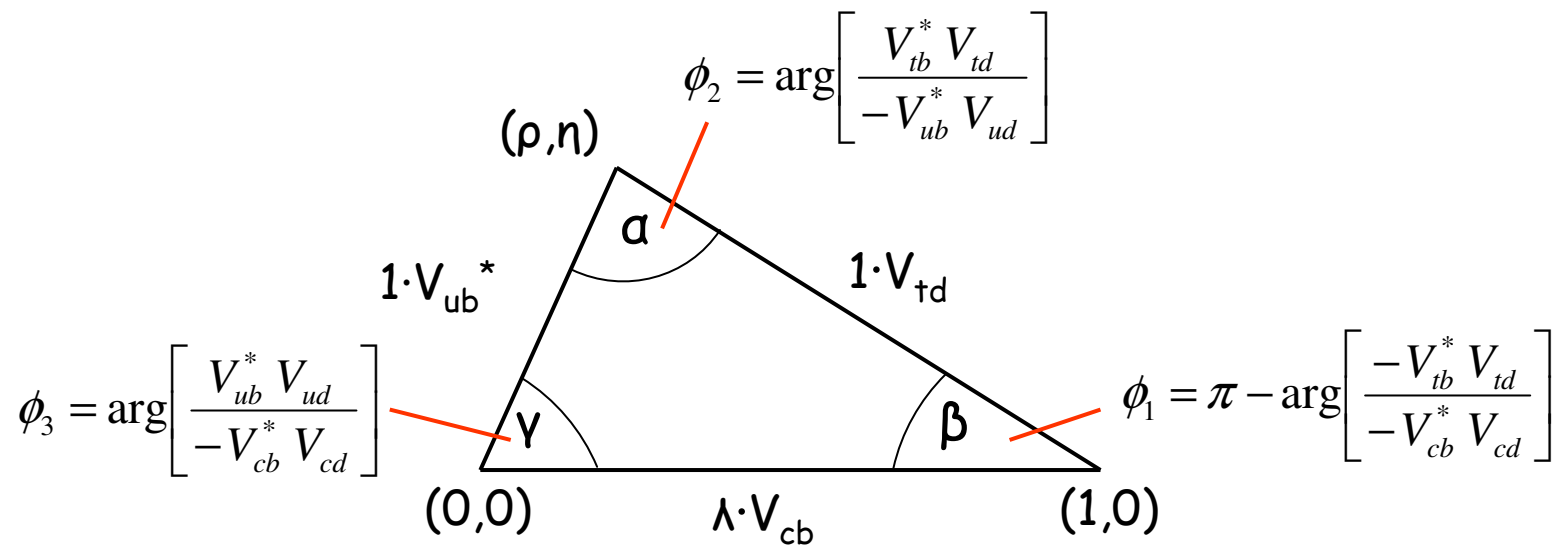


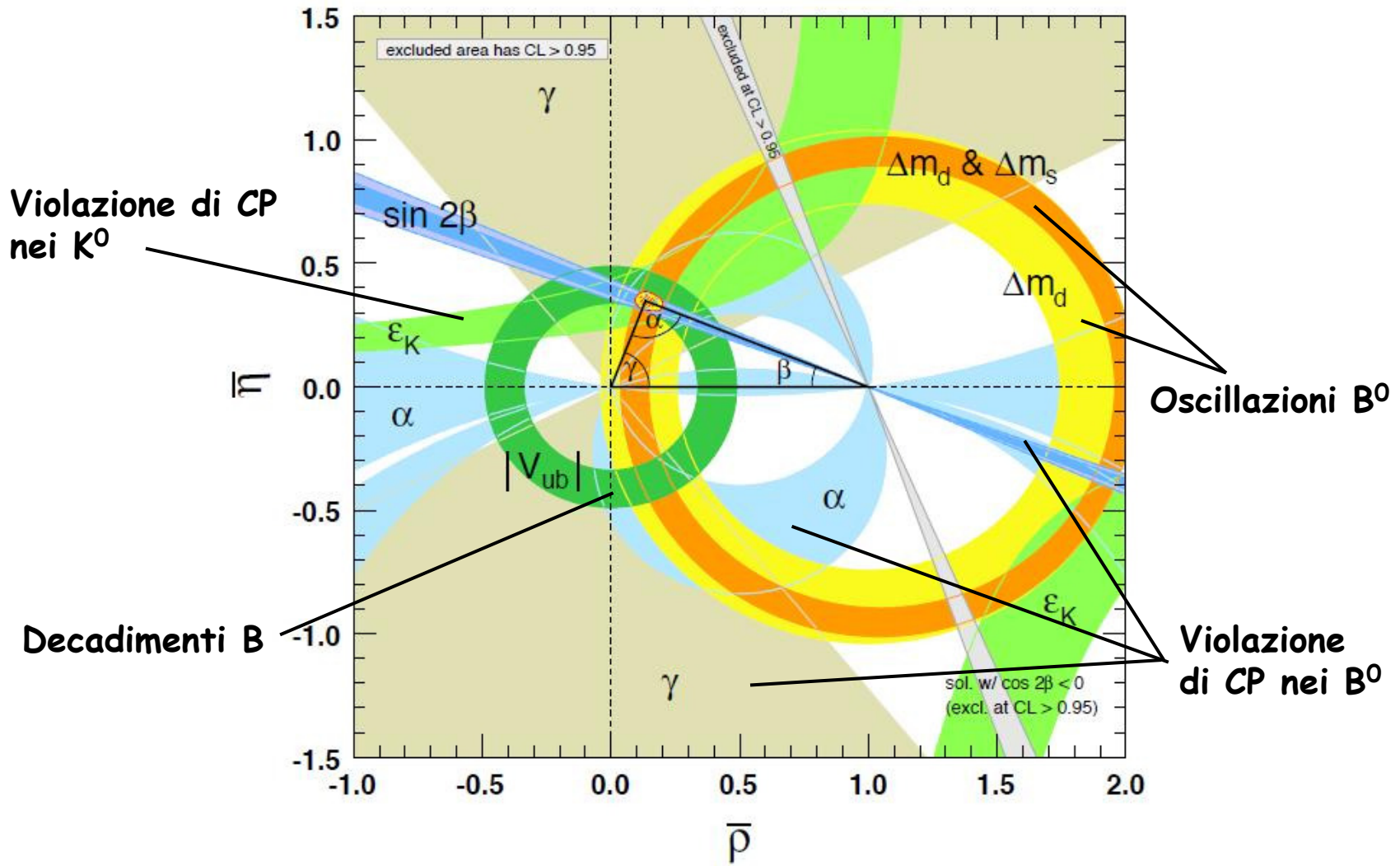
Diagramma "pinguino"

Dei 6 triangoli, quelli tra righe/colonne 1-3 hanno lati dello stesso ordine di grandezza ( $\lambda^3$ ) e coincidono a tale ordine:

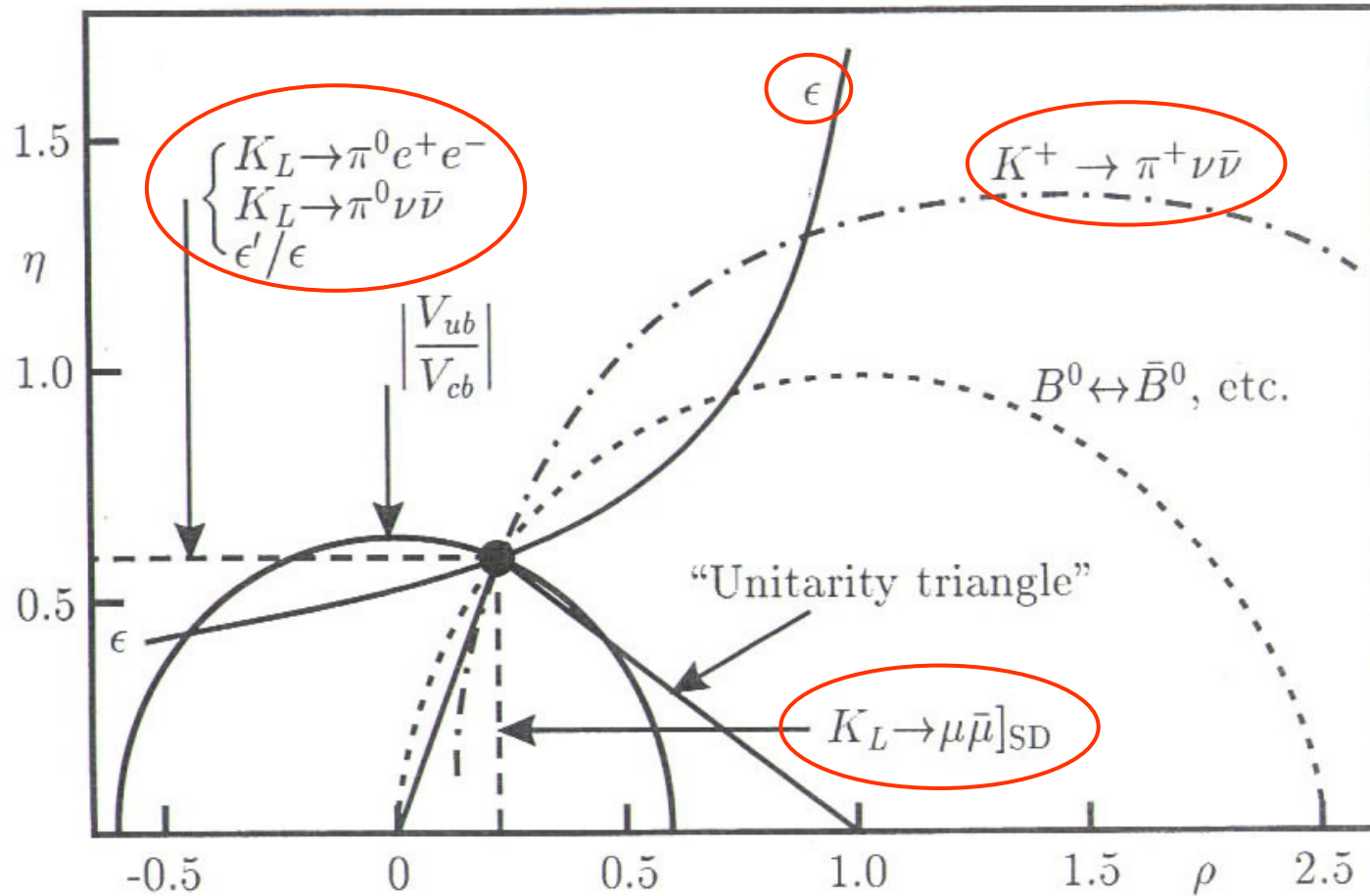
$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$



# Vincoli di unitarieta'



# Vincoli dai mesoni K



# Violazione forte di CP

Nella lagrangiana della QCD esiste un termine  $\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{\mu\nu}^a$

ineliminabile, necessario, con contributo elettrodebole

$\theta \neq 0$  viola le simmetrie P e T

Limiti da EDM:  $|\theta| < 10^{-9 \pm 1}$

Aggiungendo una simmetria U(1) rotta spontaneamente si puo' ottenere  $\theta = 0$  *dinamicamente* al prezzo di avere bosoni di Goldstone leggeri (*assioni*): ricerca attiva.



# Confronto con i mesoni pesanti (cenni)

# Violazione di CP osservata (1999)

## CP VIOLATION OBSERVED

charge asymmetry in  $K_{L3}^0$  decays

$$\delta_L = \text{weighted average of } \delta_L(\mu) \text{ and } \delta_L(e) \quad (0.327 \pm 0.012)\%$$

$$\delta_L(\mu) = [\Gamma(\pi^- \mu^+ \nu_\mu) - \Gamma(\pi^+ \mu^- \bar{\nu}_\mu)] / \text{sum} \quad (0.304 \pm 0.025)\%$$

$$\delta_L(e) = [\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \bar{\nu}_e)] / \text{sum} \quad (0.333 \pm 0.014)\%$$

parameters for  $K_L^0 \rightarrow 2\pi$  decay

$$|\eta_{00}| = |A(K_L^0 \rightarrow 2\pi^0) / A(K_S^0 \rightarrow 2\pi^0)| \quad (2.274 \pm 0.017) \times 10^{-3}$$

$$|\eta_{+-}| = |A(K_L^0 \rightarrow \pi^+ \pi^-) / A(K_S^0 \rightarrow \pi^+ \pi^-)| \quad (2.286 \pm 0.017) \times 10^{-3}$$

$$\text{Re}(\epsilon'/\epsilon) = (1 - |\eta_{00}/\eta_{+-}|)/3 \quad (1.8 \pm 0.4) \times 10^{-3} \quad (S = 2.3)$$

First  $\phi_{+-}$  or  $\phi_{00}$  assumes *CPT*, second does not.

$$\phi_{+-}, \text{ phase of } \eta_{+-} \quad (43.51 \pm 0.06)^\circ$$

$$\phi_{+-}, \text{ phase of } \eta_{+-} \quad (43.4 \pm 0.7)^\circ$$

$$\phi_{00}, \text{ phase of } \eta_{00} \quad (43.51 \pm 0.06)^\circ$$

$$\phi_{00}, \text{ phase of } \eta_{00} \quad (43.2 \pm 1.0)^\circ$$

CP asymmetry  $A$  in  $K_L \rightarrow \pi^+ \pi^- e^+ e^-$

$$\beta_{CP} \text{ from } K_L \rightarrow e^+ e^- e^+ e^- \quad -0.23 \pm 0.09$$

$$\gamma_{CP} \text{ from } K_L^0 \rightarrow e^+ e^- e^+ e^- \quad -0.09 \pm 0.09$$

parameters for  $K_L^0 \rightarrow \pi^+ \pi^- \gamma$  decay

$$|\eta_{+-\gamma}| = |A(K_L^0 \rightarrow \pi^+ \pi^- \gamma, CP \text{ violating}) / A(K_S^0 \rightarrow \pi^+ \pi^- \gamma)| \quad (2.35 \pm 0.07) \times 10^{-3}$$

$$\phi_{+-\gamma} = \text{phase of } \eta_{+-\gamma} \quad (44 \pm 4)^\circ$$

$$\Gamma(K_L^0 \rightarrow \pi^+ \pi^-) / \Gamma_{\text{total}} \quad (2.084 \pm 0.032) \times 10^{-3} \quad (S = 1.1)$$

$$\Gamma(K_L^0 \rightarrow \pi^0 \pi^0) / \Gamma_{\text{total}} \quad (9.42 \pm 0.19) \times 10^{-4} \quad (S = 1.1)$$

Parameters for  $B^0 \rightarrow J/\psi K_S^0$

$$\sin(2\beta) \quad 0.79 \pm 0.14 \quad (S = 1.3)$$

# Violazione di CP osservata (2009)

## CP VIOLATION OBSERVED

Re( $\epsilon$ )	$(1.596 \pm 0.013) \times 10^{-3}$
charge asymmetry in $K_{\ell 3}^0$ decays	
$A_L =$ weighted average of $A_L(\mu)$ and $A_L(e)$	$(0.332 \pm 0.006)\%$
$A_L(\mu) = [\Gamma(\pi^- \mu^+ \nu_\mu) - \Gamma(\pi^+ \mu^- \bar{\nu}_\mu)]/\text{sum}$	$(0.304 \pm 0.025)\%$
$A_L(e) = [\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \bar{\nu}_e)]/\text{sum}$	$(0.334 \pm 0.007)\%$
parameters for $K_L^0 \rightarrow 2\pi$ decay	
$ \eta_{00}  =  A(K_L^0 \rightarrow 2\pi^0) / A(K_S^0 \rightarrow 2\pi^0) $	$(2.221 \pm 0.011) \times 10^{-3}$ (S = 1.8)
$ \eta_{+-}  =  A(K_L^0 \rightarrow \pi^+ \pi^-) / A(K_S^0 \rightarrow \pi^+ \pi^-) $	$(2.232 \pm 0.011) \times 10^{-3}$ (S = 1.8)
$ \epsilon  = (2 \eta_{+-}  +  \eta_{00} )/3$	$(2.228 \pm 0.011) \times 10^{-3}$ (S = 1.8)
$ \eta_{00}/\eta_{+-} $	[f] $0.9951 \pm 0.0008$ (S = 1.6)
$\text{Re}(\epsilon'/\epsilon) = (1 -  \eta_{00}/\eta_{+-} )/3$	[f] $(1.65 \pm 0.26) \times 10^{-3}$ (S = 1.6)
Assuming CPT	
$\phi_{+-}$ , phase of $\eta_{+-}$	$(43.51 \pm 0.05)^\circ$ (S = 1.1)
$\phi_{00}$ , phase of $\eta_{00}$	$(43.52 \pm 0.05)^\circ$ (S = 1.1)
$\phi_\epsilon = (2\phi_{+-} + \phi_{00})/3$	$(43.51 \pm 0.05)^\circ$ (S = 1.1)
Not assuming CPT	
$\phi_{+-}$ , phase of $\eta_{+-}$	$(43.4 \pm 0.7)^\circ$ (S = 1.3)

Dramatic quantitative advance  
obtained from B factories

$\phi_{00}$ , phase of $\eta_{00}$	$(43.7 \pm 0.8)^\circ$ (S = 1.2)
$\phi_\epsilon = (2\phi_{+-} + \phi_{00})/3$	$(43.5 \pm 0.7)^\circ$ (S = 1.3)
CP asymmetry $A$ in $K_L^0 \rightarrow \pi^+ \pi^- e^+ e^-$	$(13.7 \pm 1.5)\%$
$\beta_{CP}$ from $K_L^0 \rightarrow e^+ e^- e^+ e^-$	$-0.19 \pm 0.07$
$\gamma_{CP}$ from $K_L^0 \rightarrow e^+ e^- e^+ e^-$	$0.01 \pm 0.11$ (S = 1.6)
parameters for $K_L^0 \rightarrow \pi^+ \pi^- \gamma$ decay	
$ \eta_{+-\gamma}  =  A(K_L^0 \rightarrow \pi^+ \pi^- \gamma, CP \text{ violating}) / A(K_S^0 \rightarrow \pi^+ \pi^- \gamma) $	$(2.35 \pm 0.07) \times 10^{-3}$
$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$	$(44 \pm 4)^\circ$
$\Gamma(K_L^0 \rightarrow \pi^+ \pi^-) / \Gamma_{\text{total}}$	[g] $(1.966 \pm 0.010) \times 10^{-3}$ (S = 1.6)
$\Gamma(K_L^0 \rightarrow \pi^0 \pi^0) / \Gamma_{\text{total}}$	$(8.65 \pm 0.06) \times 10^{-4}$ (S = 1.8)
$A_{CP}(B^0 \rightarrow K^+ \pi^-)$	$-0.098 \pm 0.013$
$A_{CP}(B^0 \rightarrow \eta K^*(892)^0)$	$0.19 \pm 0.05$
$S_{D^*(2010)^- D^+}(B^0 \rightarrow D^*(2010)^- D^+)$	$-0.78 \pm 0.21$
$S_{D^*(2010)^+ D^-}(B^0 \rightarrow D^*(2010)^+ D^-)$	$-0.61 \pm 0.19$
$C_{D^{*+} D^{*-}}(B^0 \rightarrow D^{*+} D^{*-})$	$0.07 \pm 0.09$
$S_{D^{*+} D^{*-}}(B^0 \rightarrow D^{*+} D^{*-})$	$-0.70 \pm 0.16$
$S_+(B^0 \rightarrow D^{*+} D^{*-})$	$-0.76 \pm 0.16$
$S_{D^+ D^-}(B^0 \rightarrow D^+ D^-)$	$-0.87 \pm 0.26$
$S_{J/\psi(1S)\pi^0}(B^0 \rightarrow J/\psi(1S)\pi^0)$	$-0.94 \pm 0.29$ (S = 1.9)
$S_{\eta' K^0}(B^0 \rightarrow \eta' K^0)$	$0.60 \pm 0.07$
$S_{K^+ K^- K_S^0}(B^0 \rightarrow K^+ K^- K_S^0)$	$-0.74^{+0.12}_{-0.10}$
$S_{K^+ K^- K_S^0}(B^0 \rightarrow K^+ K^- K_S^0 \text{ Inclusive})$	$-0.65 \pm 0.12$
$S_{\pi\pi}(B^0 \rightarrow \pi^+ \pi^-)$	$-0.61 \pm 0.08$
$\Delta C_{\rho\pi}(B^0 \rightarrow \rho^+ \pi^-)$	$0.37 \pm 0.08$
$S_{\eta_c K_S^0}(B^0 \rightarrow \eta_c K_S^0)$	$0.93 \pm 0.17$
$\sin(2\beta)(B^0 \rightarrow J/\psi K_S^0)$	$0.671 \pm 0.023$
$S_{J/\psi(nS)K^0}(B^0 \rightarrow J/\psi(nS)K^0)$	$0.658 \pm 0.024$
$S_{\chi_{c1} K_S^0}(B^0 \rightarrow \chi_{c1} K_S^0)$	$0.61 \pm 0.16$
$\sin(2\beta_{\text{eff}})(B^0 \rightarrow K^+ K^- K_S^0)$	$0.77^{+0.13}_{-0.12}$

# Mesoni B (1)

Lederman et al. (1977):

400 GeV p (Cu, Pt)  $\rightarrow \mu^+\mu^- X$

Spettrometro a doppio braccio

9000 eventi: 770-350 nel picco a 9.5 GeV/c<sup>2</sup>

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## Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

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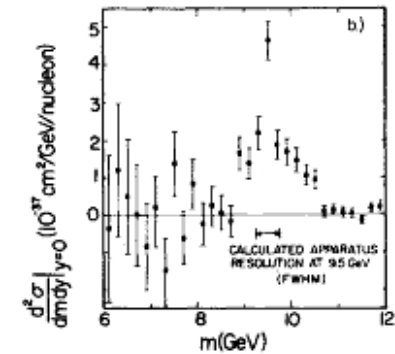
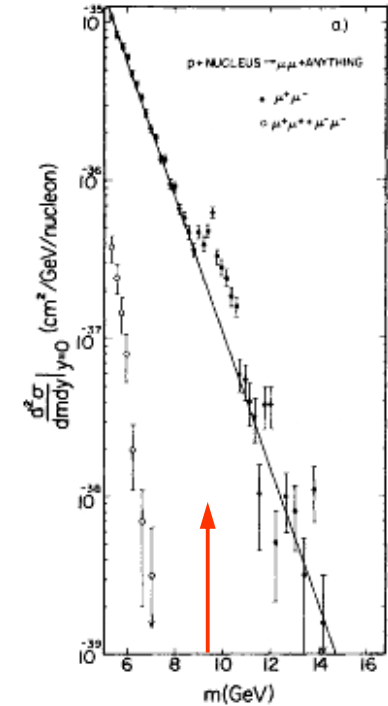
Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass  $m_{\mu^+\mu^-} > 5$  GeV.

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$
$m$ (GeV)	9.46	10.02	10.36	10.58	10.87	11.02
$\Gamma$ (keV)	52	44	26	14000	110000	79000

M.S. Sozzi

Violazione di CP



## Mesoni B (2)

$B_d (\bar{b}d) \quad \bar{B}_d (b\bar{d})$

$$m = 5.3 \text{ GeV}/c^2$$

$$\tau = 1.56 \cdot 10^{-12} \text{ s} \quad (c\tau = 460 \text{ } \mu\text{m})$$

$$\Delta m = 0.5 \cdot 10^{12} \text{ } \hbar \text{ s}^{-1} \quad (3.3 \cdot 10^{-4} \text{ eV})$$

$B_s (\bar{b}s) \quad \bar{B}_s (b\bar{s})$

$$m = 5.4 \text{ GeV}/c^2$$

$$\tau = 1.61 \cdot 10^{-12} \text{ s} \quad (c\tau = 450 \text{ } \mu\text{m})$$

$$\Delta m = 17.8 \cdot 10^{12} \text{ } \hbar \text{ s}^{-1} \quad (1.2 \cdot 10^{-2} \text{ eV})$$

• "Lunga" vita media:  $1/\tau_b \approx \frac{G_F^2}{192\pi^3} m_b^5 (2 \times 3 + 3) |V_{cb}|^2 \approx (1/10^{-15} \text{ s}) |V_{cb}|^2$

⇒ struttura "gerarchica" della matrice CKM

• Oscillazioni osservabili:  $x_b \equiv \Delta m/\Gamma = 0.73$

• "Grande" massa del quark b: calcoli in QCD piu' affidabili (in alcuni casi)

# Oscillazioni

ARGUS (1987) a DORIS II (DESY):

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$$

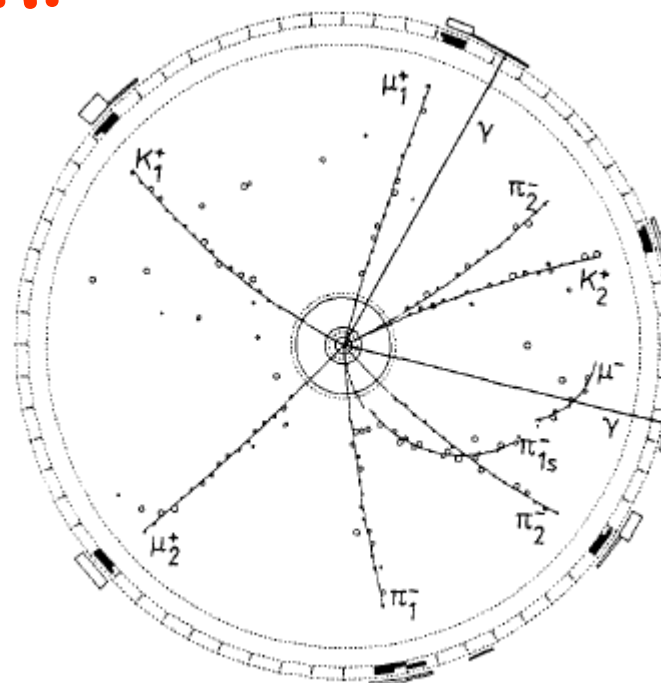
Decadimenti che identificano il sapore:

$$B^0 \rightarrow D^{*\pm} (n)\pi \quad D^{*\pm} \rightarrow D^0\pi \quad D^0 \rightarrow K\pi$$

$$B^0 \rightarrow D^{*\pm}\ell\nu$$

Decadimenti con *leptoni dello stesso segno*  
(eliminare  $\bar{B} \rightarrow DX$  con  $D \rightarrow \ell^+X$ )

$$r = \frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell^+\ell^-)} = \frac{x^2}{x^2 + 2} \quad x = \frac{\Delta m}{\Gamma}$$



$$B^0 \rightarrow D^{*-}\mu^+\nu$$

$$B^0 \rightarrow D^{*-}\mu^+\nu$$

$$D^{*-} \rightarrow \bar{D}^0\pi^-$$

$$D^{*-} \rightarrow D^-\pi^0$$

$$\bar{D}^0 \rightarrow K^+\pi^-$$

$$D^- \rightarrow K^+\pi^-\pi^-$$

# Fenomenologia dei mesoni B

- Masse elevate, molti canali di decadimento:  
canali di decadimento comuni a  $B^0$  e  $\bar{B}^0$  hanno  $BR \sim 10^{-3}$

⇒ **Piccole differenza di vita media**

$$\Delta\Gamma/\Gamma \sim 10^{-2} \quad \Rightarrow \quad \Delta\Gamma \ll \Delta m \quad (\Delta\Gamma \propto m_b, \Delta m \propto m_t)$$

Stati fisici non separabili:  $B_H$  (heavy) e  $B_L$  (light)

Una classe di esperimenti realizzabili con i  $K^0$  e' impossibile con i  $B^0$ .

- Per i  $B_s$  la situazione e' leggermente differente differente ( $\Gamma \ll \Delta m$ ):  
stati comuni non soppressi da angoli di mescolamento.

- Oscillazioni determinate dal quark top per entrambi i sistemi:

$$\Delta m(B_s)/\Delta m(B_d) \sim |V_{ts}|^2/|V_{td}|^2 \gg 1$$

- Possibili **grandi asimmetrie** contro piccoli rapporti di decadimento

⇒ Necessarie **elevate luminosita'** ( $\sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )

# Evoluzione temporale

$$\begin{aligned}
 |B^0(t)\rangle &= f_+(t)|B^0\rangle + \frac{1-\bar{\varepsilon}}{1+\bar{\varepsilon}} f_-(t)|\bar{B}^0\rangle \\
 |\bar{B}^0(t)\rangle &= f_+(t)|\bar{B}^0\rangle + \frac{1+\bar{\varepsilon}}{1-\bar{\varepsilon}} f_-(t)|B^0\rangle
 \end{aligned}
 \quad f_{\pm}(t) \equiv \frac{1}{2} e^{-im_1 t} e^{-i\Gamma_1 t/2} \left( 1 \pm e^{-i\Delta m t} e^{\Delta\Gamma t/2} \right)$$

Stato finale accessibile ad entrambi gli autostati di sapore:

$$\begin{aligned}
 \Gamma(B^0(t) \rightarrow f) &\propto |A_f|^2 \left[ |f_+(t)|^2 + |f_-(t)\lambda_f|^2 + 2\text{Re}(f_+^*(t)f_-(t)\lambda_f) \right] \\
 \Gamma(\bar{B}^0(t) \rightarrow f) &\propto |\bar{A}_f|^2 \left[ |f_+(t)|^2 + |f_-(t)/\lambda_f|^2 + 2\text{Re}(f_+^*(t)f_-(t)/\lambda_f) \right]
 \end{aligned}$$

$$\lambda_f = \frac{(1-\bar{\varepsilon})\bar{A}_f}{(1+\bar{\varepsilon})A_f}$$

Se  $\Delta\Gamma \approx 0$ :

$$\begin{aligned}
 |f_{\pm}(t)|^2 &\propto 1 \pm \cos(\Delta m t) \\
 |f_+^*(t)f_-(t)|^2 &\propto \sin(\Delta m t)
 \end{aligned}$$

$\lambda_f = 1$  se vale  
simmetria CP



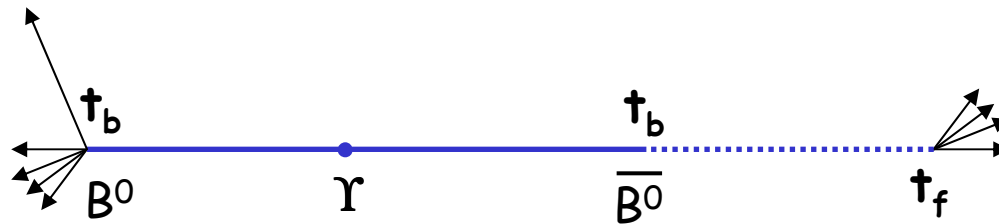
# Stati coerenti

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-, B^0\bar{B}^0$  (96%)  $(L=1, J^{PC} = 1^{--})$   $\sigma \approx 1.2 \text{ nb}$

Stato iniziale con  $C = -1$ :  $|\Psi(0)\rangle = e^{-\bar{\Gamma}t} \frac{1}{\sqrt{2}} \left[ \left| B_f^0(\mathbf{p})\bar{B}_b^0(-\mathbf{p}) \right\rangle - \left| \bar{B}_f^0(\mathbf{p})B_b^0(-\mathbf{p}) \right\rangle \right]$

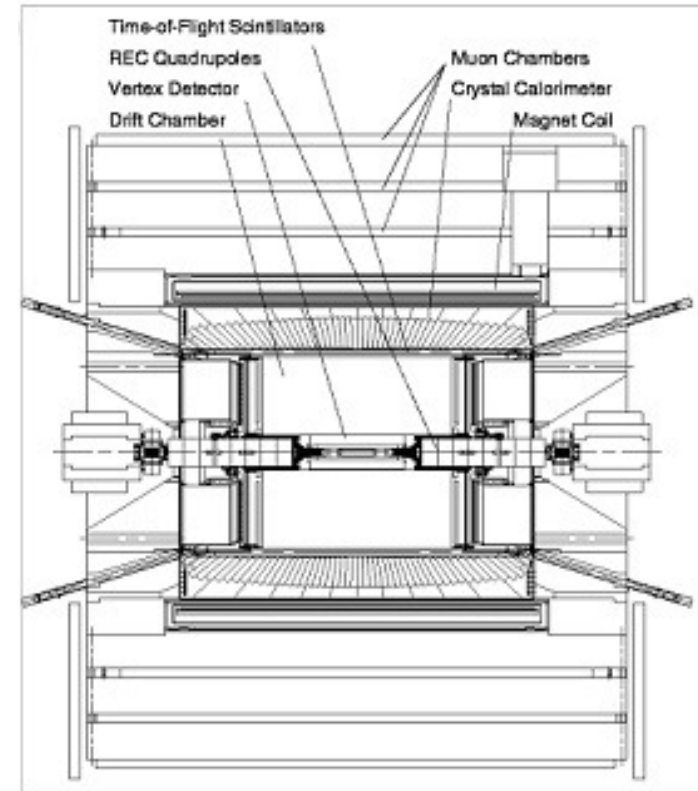
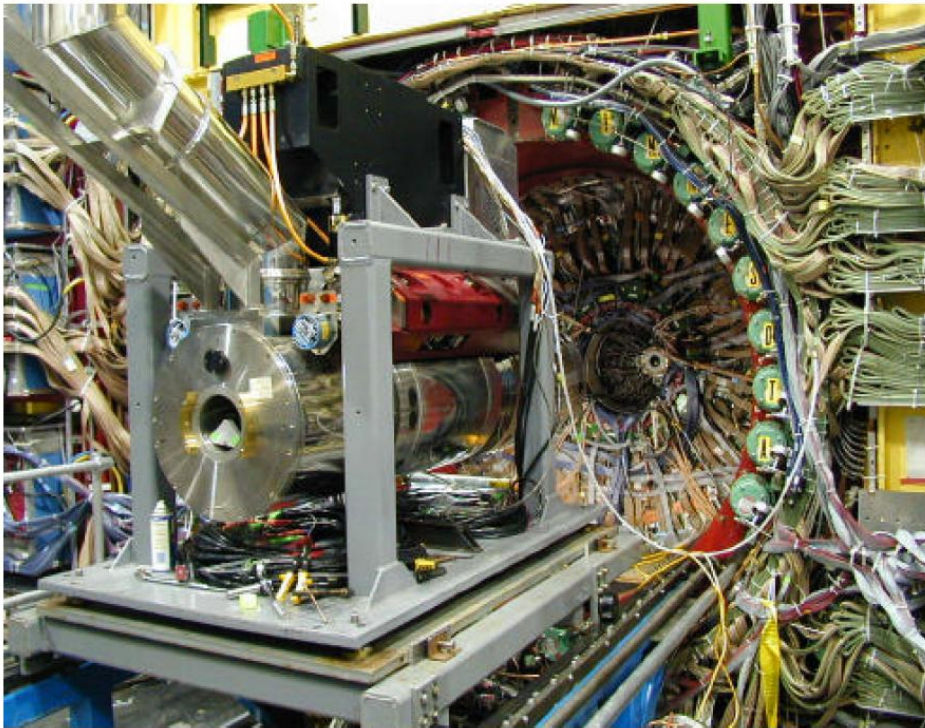
ha evoluzione coerente fino ad un decadimento

$$|\Psi(t)\rangle \propto e^{-\bar{\Gamma}(t_f+t_b)/2} \left\{ \cos[\Delta m(t_f - t_b)/2] \left( \left| B_f^0\bar{B}_b^0 \right\rangle - \left| \bar{B}_f^0B_b^0 \right\rangle \right) - i \sin[\Delta m(t_f - t_b)/2] \left( \frac{1+\varepsilon}{1-\varepsilon} \left| B_f^0B_b^0 \right\rangle - \frac{1-\varepsilon}{1+\varepsilon} \left| \bar{B}_f^0\bar{B}_b^0 \right\rangle \right) \right\}$$



# CLEO @ Cornell

Ha operato come B-factory a  $\Upsilon(4S)$



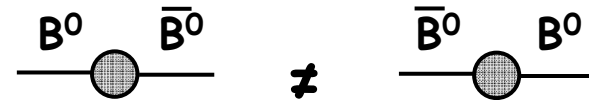
CESR (Cornell): 3.5-12 GeV,  
 $1.3 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

2 camere a deriva, RICH, calorimetro  
EM a cristalli, campo solenoidale 1.5 T

# Tipi di violazione di CP

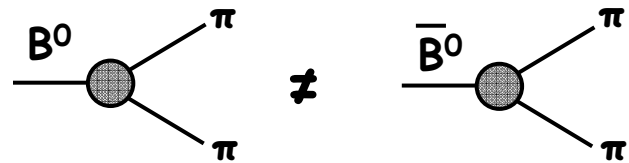
- Violazione di CP nel mescolamento (indiretta):

Difficile da calcolare



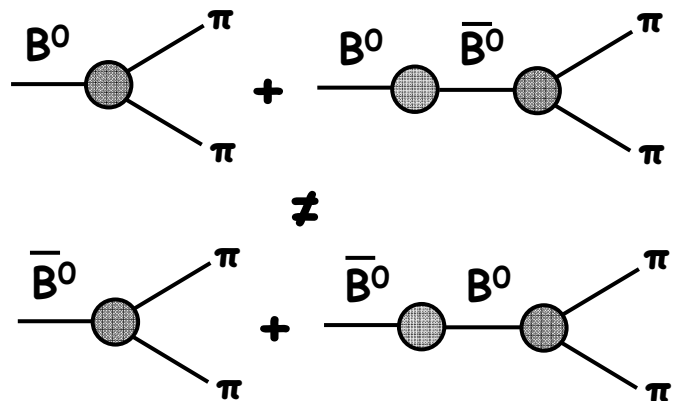
- Violazione di CP nei decadimenti (diretta):

Necessarie 2 ampiezze e fasi forti, difficile da calcolare



- Violazione di CP nell'interferenza tra decadimenti con e senza mescolamento (diretta-indiretta):

Non richiede fasi forti, in alcuni casi ben calcolabile, molti stati finali e molte asimmetrie



# (1) Violazione di CP nel mescolamento

Impossibile distinguere gli stati fisici, confronto delle oscillazioni di sapore (decadimenti specifici per sapore, semileptonici):

$$\frac{\Gamma(\bar{B}^0 \rightarrow \ell^+ X; t) - \Gamma(B^0 \rightarrow \ell^- X; t)}{\Gamma(\bar{B}^0 \rightarrow \ell^+ X; t) + \Gamma(B^0 \rightarrow \ell^- X; t)} = \frac{|1 + \bar{\varepsilon}|^4 - |1 - \bar{\varepsilon}|^2}{|1 + \bar{\varepsilon}|^4 + |1 - \bar{\varepsilon}|^4} \cong 4 \operatorname{Re}(\bar{\varepsilon})$$

indipendente dal tempo.

Stato coerente, con  $\Delta\Gamma/\Gamma \ll 1$ :

$$N(\ell^+ \ell^+ X; t_f t_b) \propto e^{-\Gamma(t_f + t_b)} \left| \frac{1 + \bar{\varepsilon}}{1 - \bar{\varepsilon}} \right|^2 \sin^2[\Delta m(t_f - t_b)/2]$$

$$N(\ell^- \ell^- X; t_f t_b) \propto e^{-\Gamma(t_f + t_b)} \left| \frac{1 - \bar{\varepsilon}}{1 + \bar{\varepsilon}} \right|^2 \sin^2[\Delta m(t_f - t_b)/2]$$

Integrando sui tempi di decadimento:

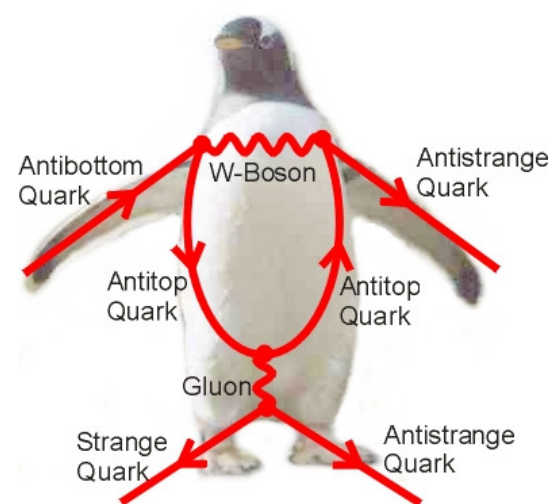
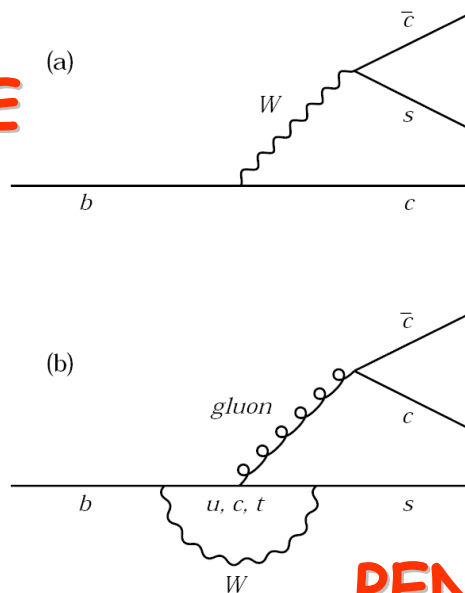
$$\frac{N(\ell^+ \ell^+; t) - N(\ell^- \ell^-; t)}{N(\ell^+ \ell^+; t) + N(\ell^- \ell^-; t)} \cong 4 \operatorname{Re}(\bar{\varepsilon})$$

## (2) Violazione di CP nel decadimento

- Decadimenti in autostati di CP con autovalori opposti
- Decadimenti di mesoni B carichi
- Evoluzione temporale di mesoni correlati
- Difficilmente calcolabile: non utile per CKM



TREE



PENGUIN

### (3) Violazione di CP nell'interferenza

Per i mesoni B, in assenza di violazione di CP diretta:

$$\frac{\Gamma(\bar{B}^0(t) \rightarrow f) - \Gamma(B^0(t) \rightarrow f)}{\Gamma(\bar{B}^0(t) \rightarrow f) + \Gamma(B^0(t) \rightarrow f)} = \frac{2 \operatorname{Im}(\lambda_f) e^{\Delta\Gamma t/2} \sin(\Delta m t)}{1 + e^{\Delta\Gamma t} + \operatorname{Re}(\lambda_f) (1 - e^{\Delta\Gamma t})}$$

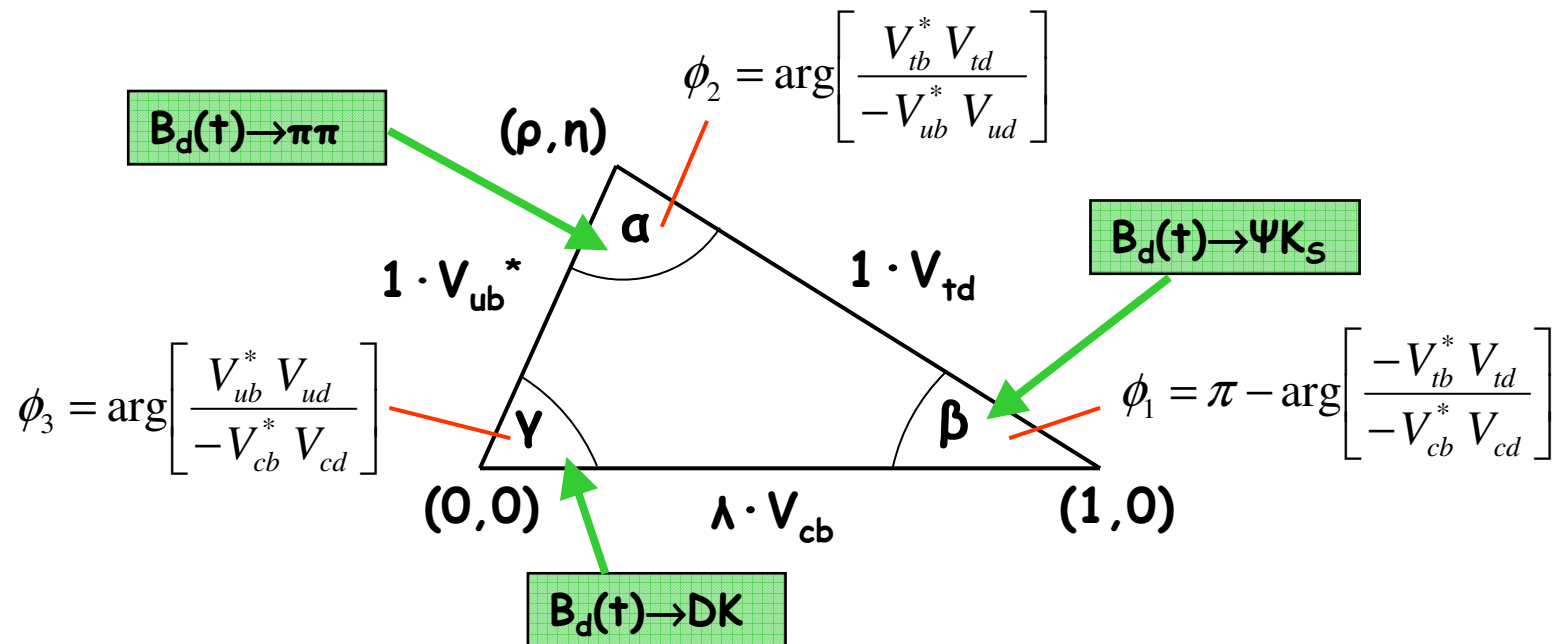
$$\frac{1 - \bar{\varepsilon}}{1 + \varepsilon} = e^{i\phi_{\Delta B=2}} \quad \frac{\bar{A}_f}{A_f} = e^{i\phi_{\Delta B=1}} \quad \arg(\lambda_f) = \phi_{\Delta B=2} + \phi_{\Delta B=1}$$

Singola ampiezza (albero): J/Ψ K<sub>S</sub>

(stato comune grazie a mescolamento dei K<sup>0</sup>)

$$\frac{1 - \bar{\varepsilon}}{1 + \varepsilon} \cong \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \quad \frac{\bar{A}_{J/\Psi K_S}}{A_{J/\Psi K_S}} \cong -\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \quad \lambda_{J/\Psi K_S} \cong -e^{-2i\beta}$$

# Triangolo di unitarieta' da $B_d(t)$



Lati con dimensioni comparabili in termini di  $\lambda$ : piu' agevole osservare se il triangolo non sia degenero (violazione di CP).

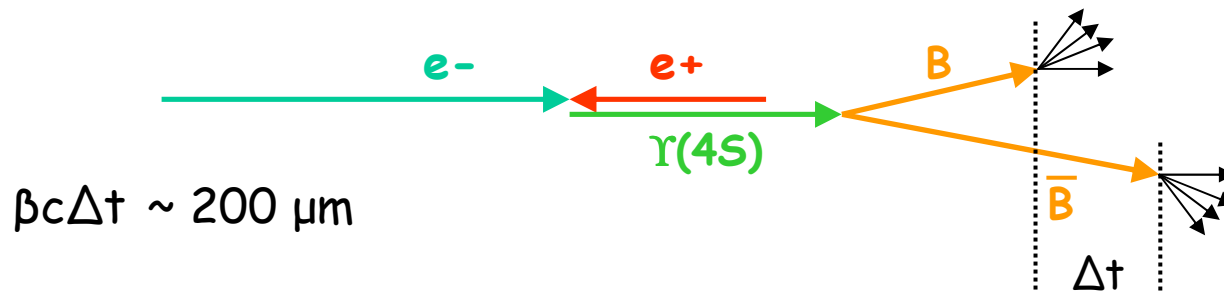
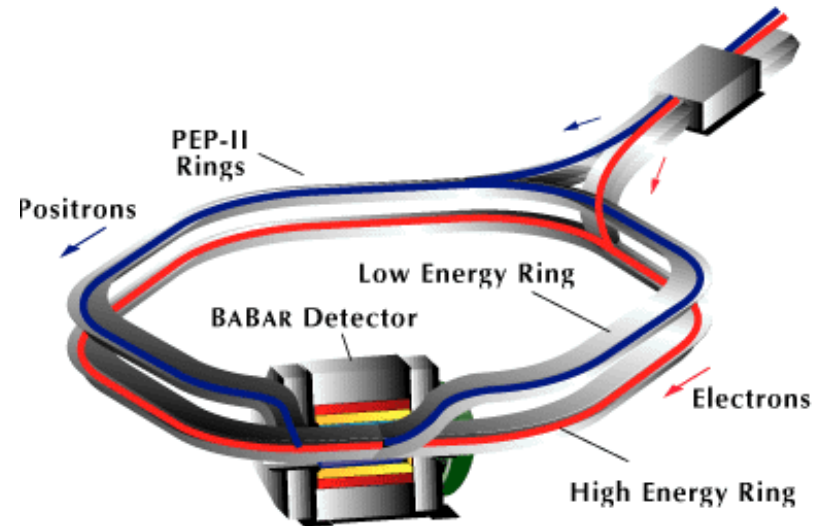


# B-factories

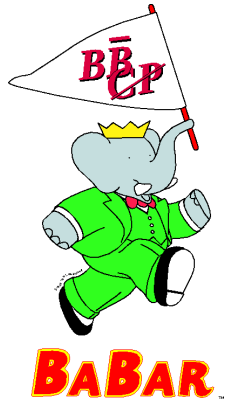
Le asimmetrie integrate nel tempo si annullano indipendentemente da CP  
⇒ Necessario misurare  $A(\Delta t)$

Per B prodotto in  $e^+e^-$   $\gamma\beta c\tau \sim 23 \mu\text{m}$  (!)  
e se ne deve misurare la differenza, con incertezza punto di produzione di varie centinaia di  $\mu\text{m}$

⇒ "B-factories" *asimmetriche*



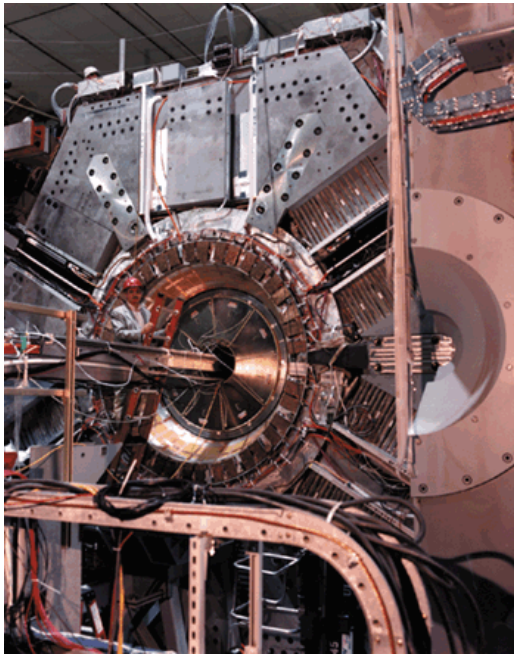




# BaBar @ Stanford

PEP-II: 3.1 GeV + 9 GeV,  $8 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , zero angle crossing

Si VTX, camera a deriva, Č con barre di quarzo, TOF, calorimetro EM a CsI(Tl), campo da solenoide 1.5 T



M.S. Sozzi



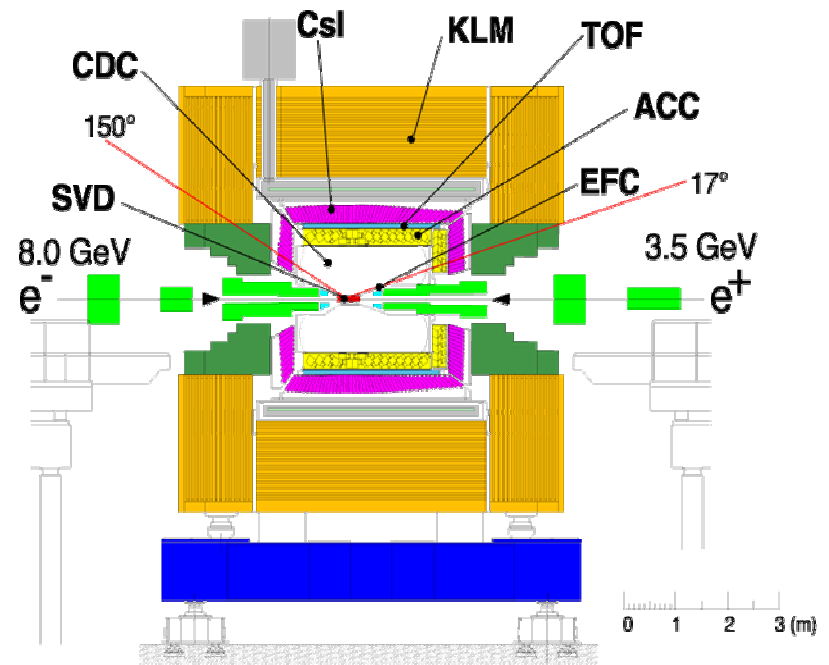
Violazione di CP



# Belle @ KEK

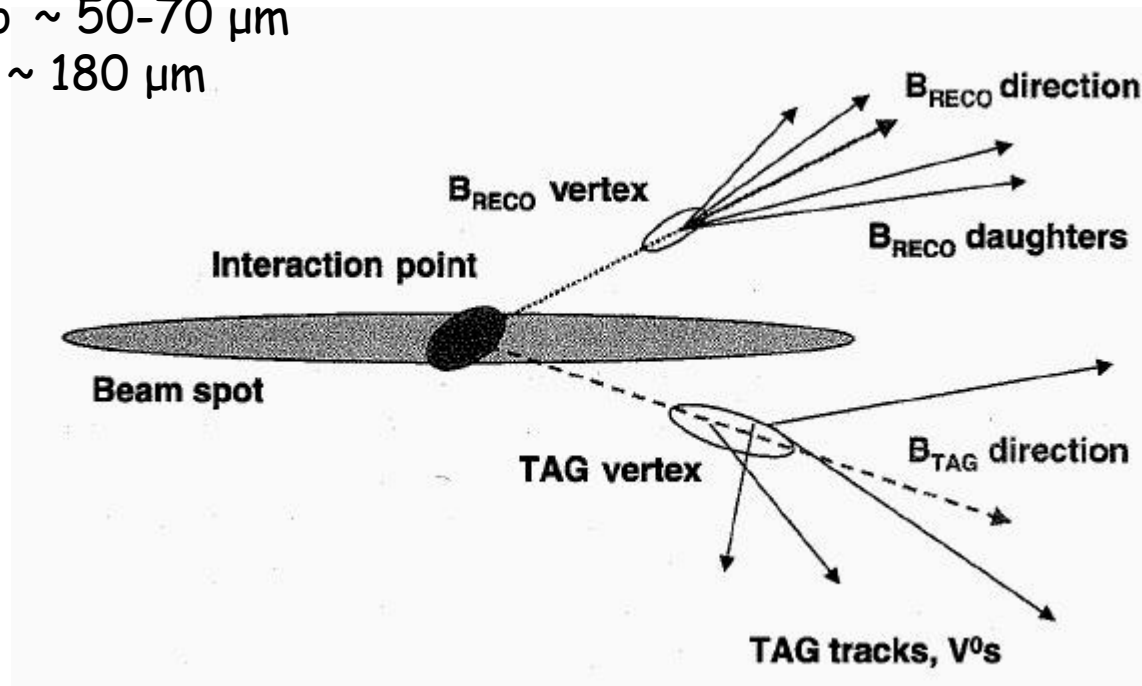
KEKB: 3.5 GeV + 8 GeV,  $1.2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , non-zero angle crossing

Si VTX, camera a deriva, Č ad aerogel, TOF, calorimetro EM a CsI(Tl),  
campo da solenoide 1.5 T



# Misura di $A(\Delta t)$

$\sigma(\Delta z)_{B_{\text{reco}}} \sim 50\text{-}70 \mu\text{m}$   
 $\sigma(\Delta z)_{B_{\text{tag}}} \sim 180 \mu\text{m}$



*Flavour tagging:*  
efficienze  $\sim 10\text{-}50\%$   
errori  $\sim 2\text{-}50\%$

# Violazione di CP nei mesoni B

BaBar, Belle (2001):

Asimmetria temporale nei decadimenti  $B^0 \rightarrow J/\psi K_S$

Prima misura di violazione di CP in un sistema diverso da quello dei K.

VOLUME 87, NUMBER 9

PHYSICAL REVIEW LETTERS

27 AUGUST 2001

Observation of CP Violation in the  $B^0$  Meson System

VOLUME 87, NUMBER 9

PHYSICAL REVIEW LETTERS

27 AUGUST 2001

Observation of Large CP Violation in the Neutral B Meson System

$$a_{CP}(t) = \frac{\Gamma(\bar{B}^0 \rightarrow f; t) - \Gamma(B^0 \rightarrow f; t)}{\Gamma(\bar{B}^0 \rightarrow f; t) + \Gamma(B^0 \rightarrow f; t)} = -\eta_{CP}(f) \sin(2\beta) \sin(\Delta mt)$$

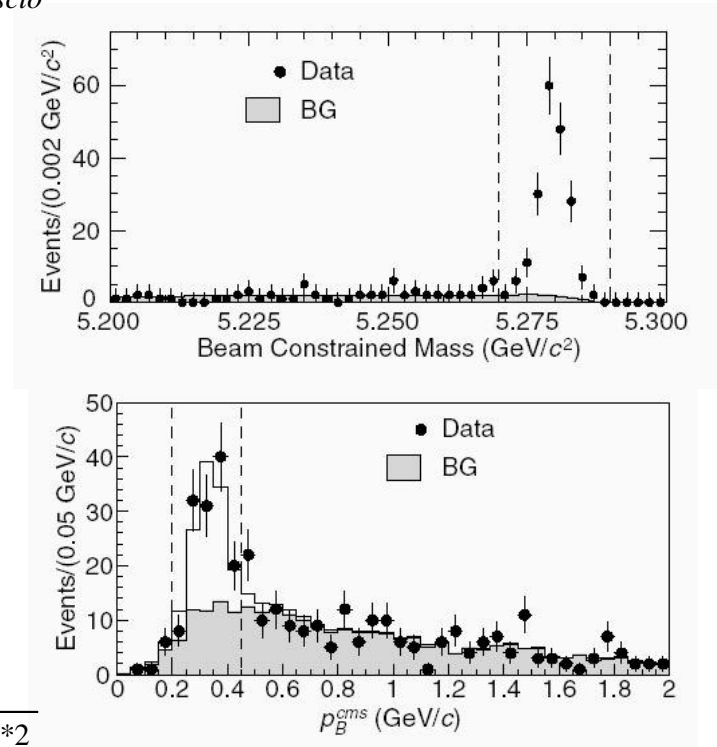
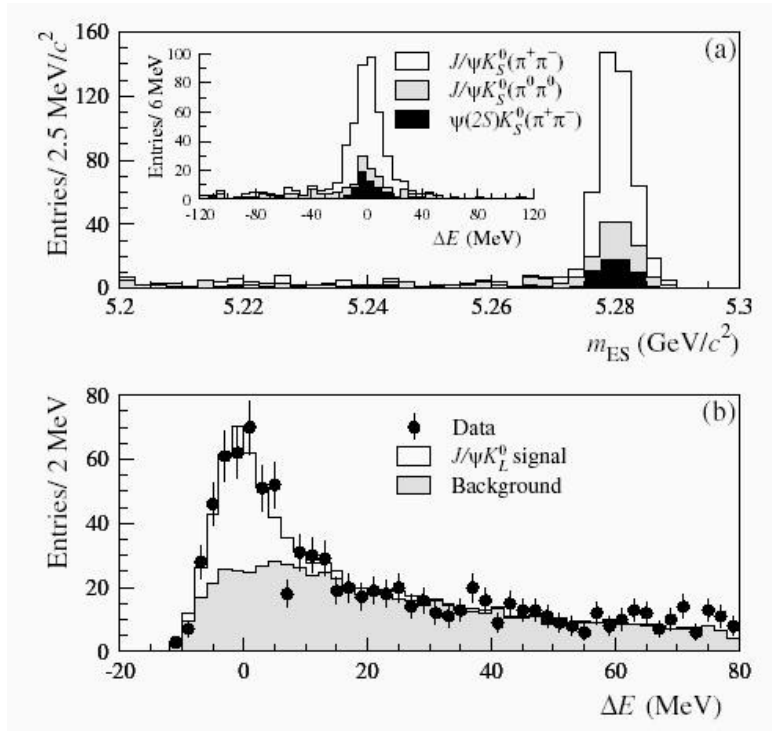
Violazione di CP nell'*interferenza*  
tra decadimenti con e senza mescolamento

# $B^0 \rightarrow J/\psi K_S$

**BaBar**  
32M coppie  
803 eventi

**Belle**  
32 M coppie  
569 eventi

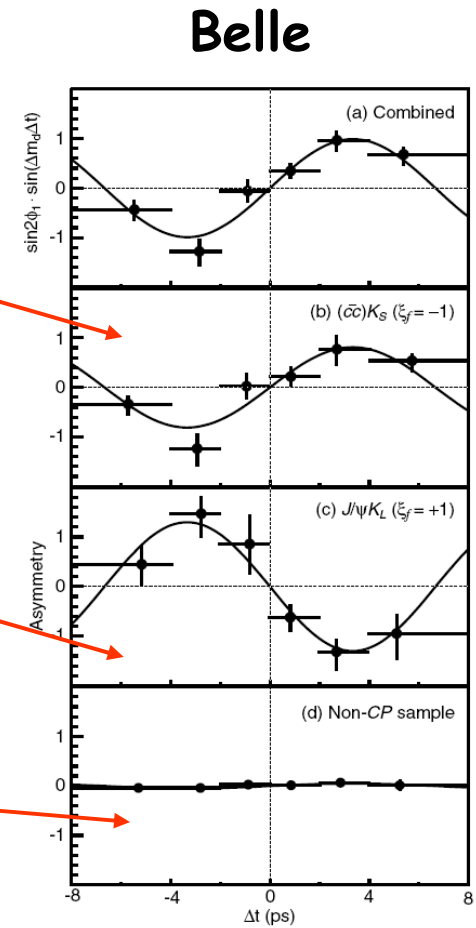
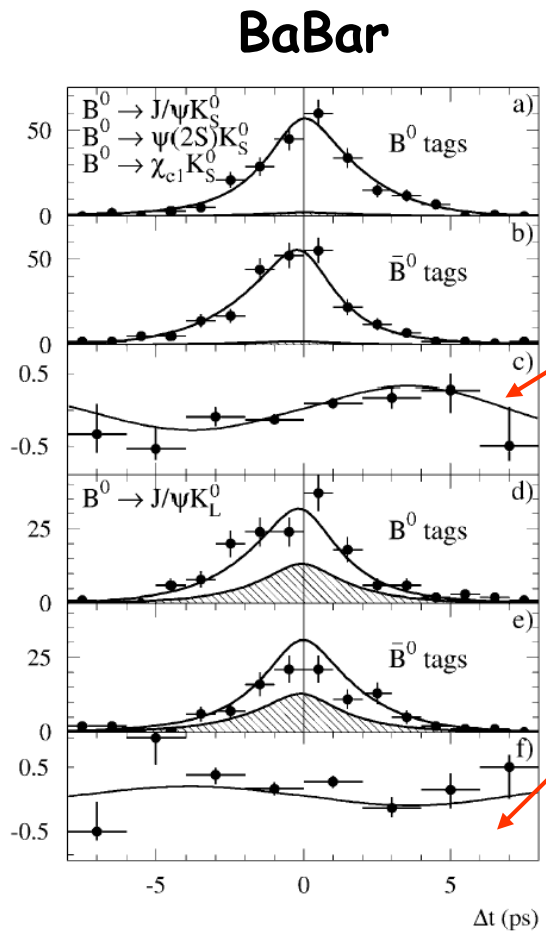
$$\Delta E = E_B - E_{fascio}$$



**Fondo**

$$m = \sqrt{s/4 - \mathbf{p}^2}$$

# B<sup>0</sup> → J/ψ K<sub>S</sub>



**CP = -1**

**CP = +1**

**Fondo**

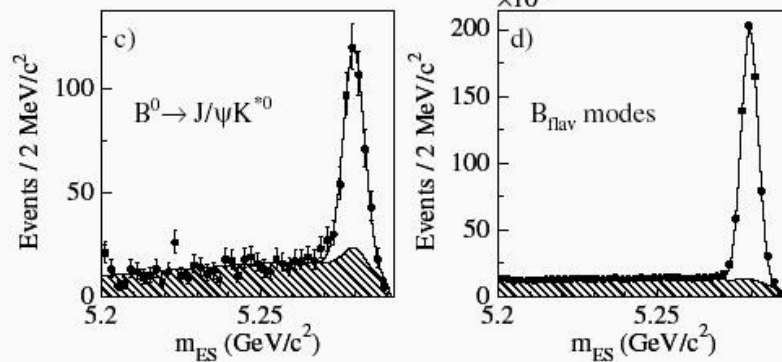
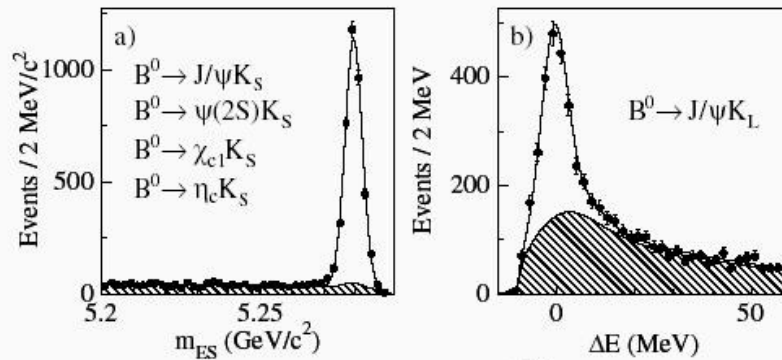


# $B^0 \rightarrow J/\psi K_S$ (2005)

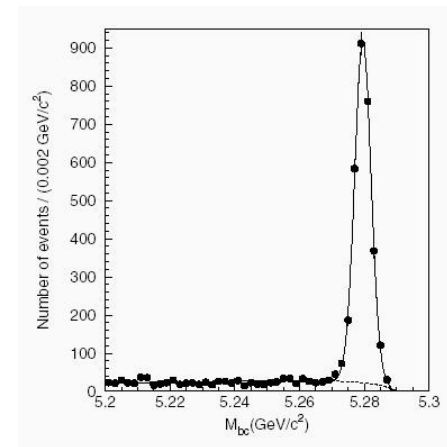
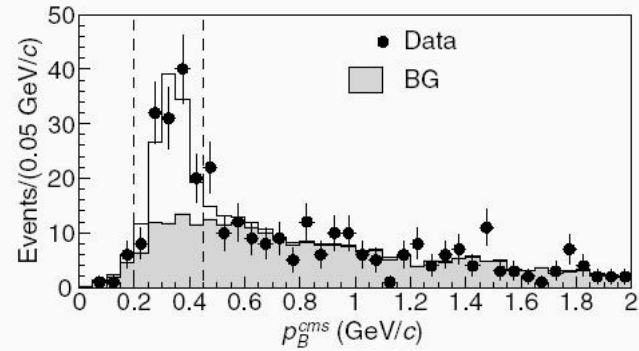
BaBar

Belle

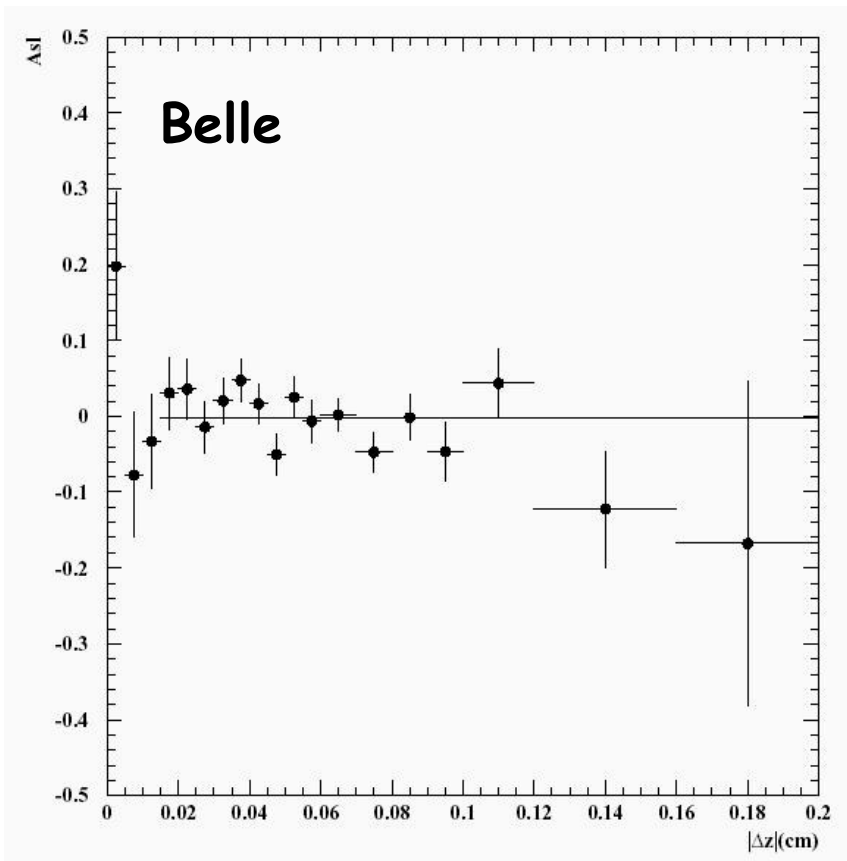
$$\Delta E = E_B - E_{fascio}$$



$$m = \sqrt{s/4 - p^{*2}}$$



# No violazione di CP nel mescolamento (2005)



Decadimenti semileptonici

Asimmetria integrata

$$A = \frac{\Gamma(\ell^+\ell^+) - \Gamma(\ell^-\ell^-)}{\Gamma(\ell^+\ell^+) + \Gamma(\ell^-\ell^-)}$$

$$A = (-1.1 \pm 7.9 \pm 7.0) \times 10^{-3}$$



# Violazione diretta di CP (2004)

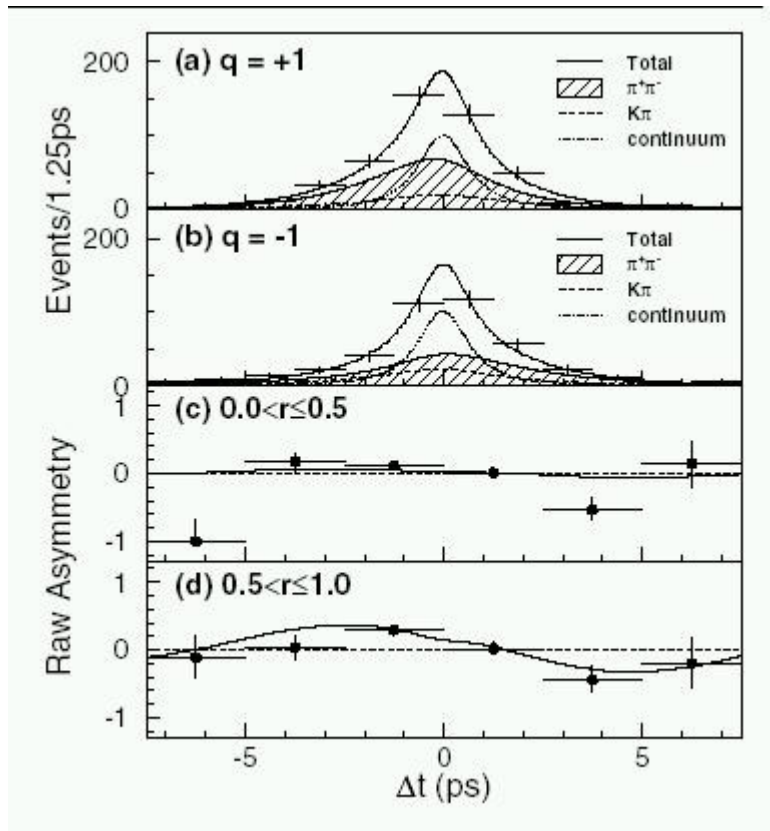
VOLUME 93, NUMBER 2

PHYSICAL REVIEW LETTERS

week ending  
9 JULY 2004

Observation of Large CP Violation and Evidence for Direct CP Violation in  $B^0 \rightarrow \pi^+\pi^-$  Decays

Belle



Asimmetria in funzione  
del tempo

$$A = \frac{(|\lambda_f|^2 - 1) \cos(\Delta mt) + 2 \operatorname{Im}(\lambda_f) \sin(\Delta mt)}{1 + |\lambda_f|^2}$$

$$\frac{2 \operatorname{Im}(\lambda_f)}{1 + |\lambda_f|^2} = -1.00 \pm 0.21 \pm 0.07$$

M.S. Sozzi

Violazione di CP

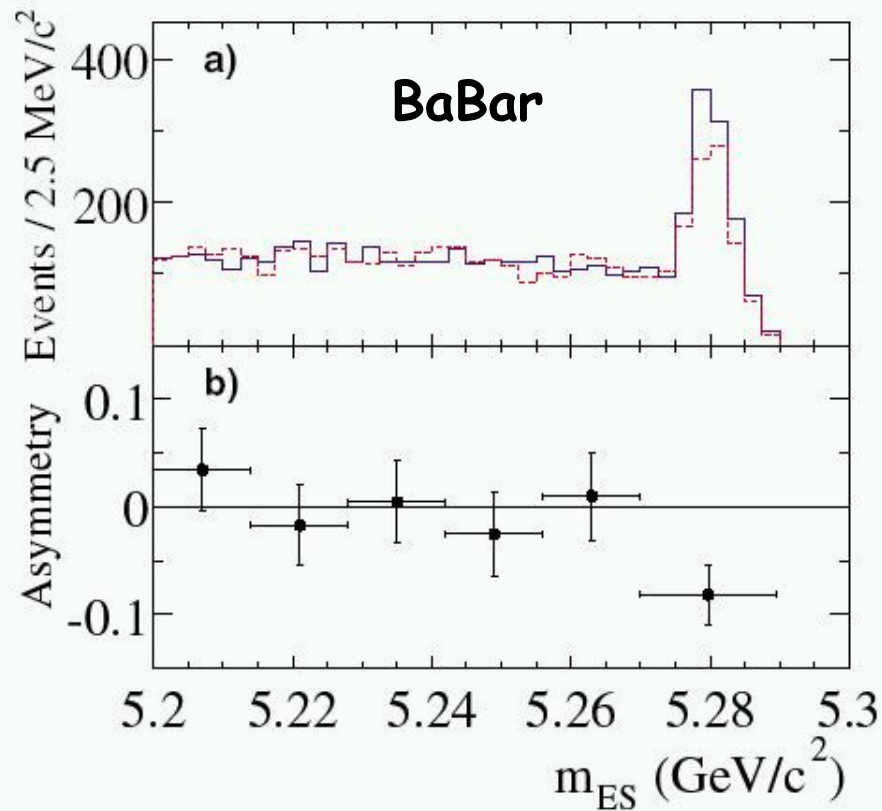
# Violazione diretta di CP (2004)

VOLUME 93, NUMBER 13

PHYSICAL REVIEW LETTERS

week ending  
24 SEPTEMBER 2004

Direct CP Violating Asymmetry in  $B^0 \rightarrow K^+ \pi^-$  Decays



Asimmetria integrata

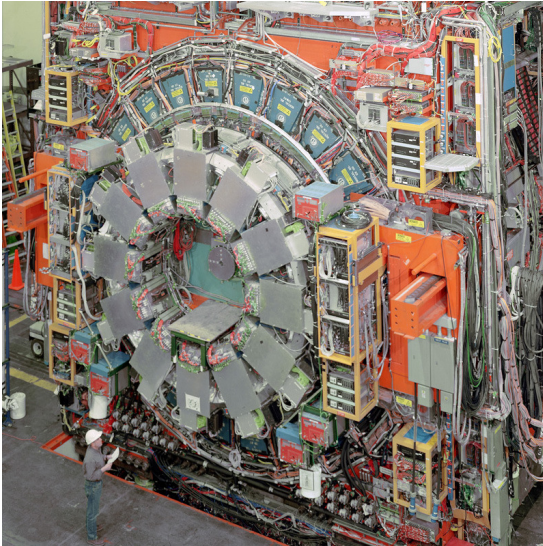
$$A = \frac{n(K^- \pi^+) - n(K^+ \pi^-)}{n(K^- \pi^+) + n(K^+ \pi^-)}$$

$$A = -0.133 \pm 0.030 \pm 0.009$$

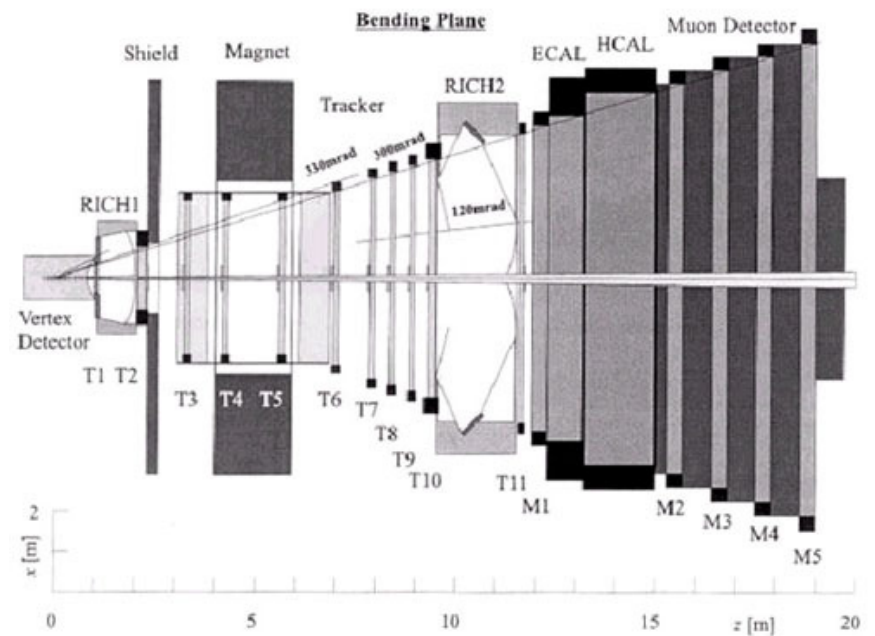
# Macchine adroniche

- Sezioni d'urto molto elevate  $\approx 100 \mu\text{b}$
- Ad alte energie: produzione di b elevata  $\approx 1\% \sigma_{\text{tot}}$
- Fondi molto elevati
- Identificazione del sapore
  - dal mesone B "opposto" (es. decadimento semileptonico)
  - dal mesone B stesso (correlazione con carica di  $\pi$ , decadimento di  $B^{**}$ )
- Mesoni  $B_s$  accessibili
  
- Esperimenti in corso: **CDF, D0** (Fermilab Tevatron) @ 2 TeV
- Esperimenti futuri: **ATLAS, CMS** (CERN LHC) @ 14 TeV
- Esperimenti futuri dedicati: **LHC-b** (CERN LHC)

# Macchine adroniche



LHCb @ CERN

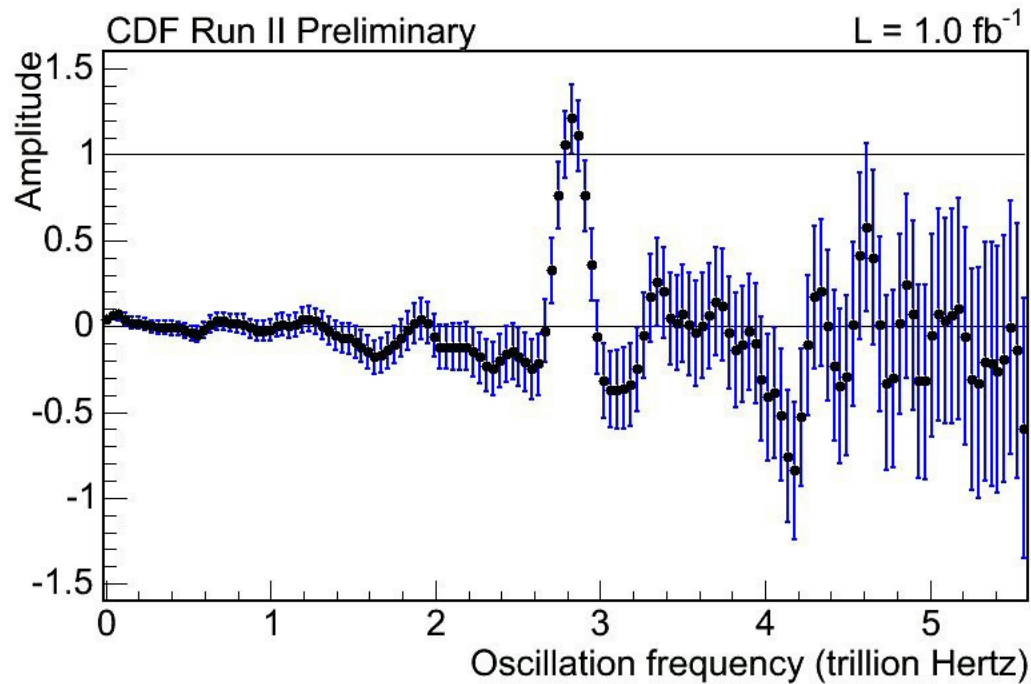


CDF @ FNAL

M.S. Sozzi

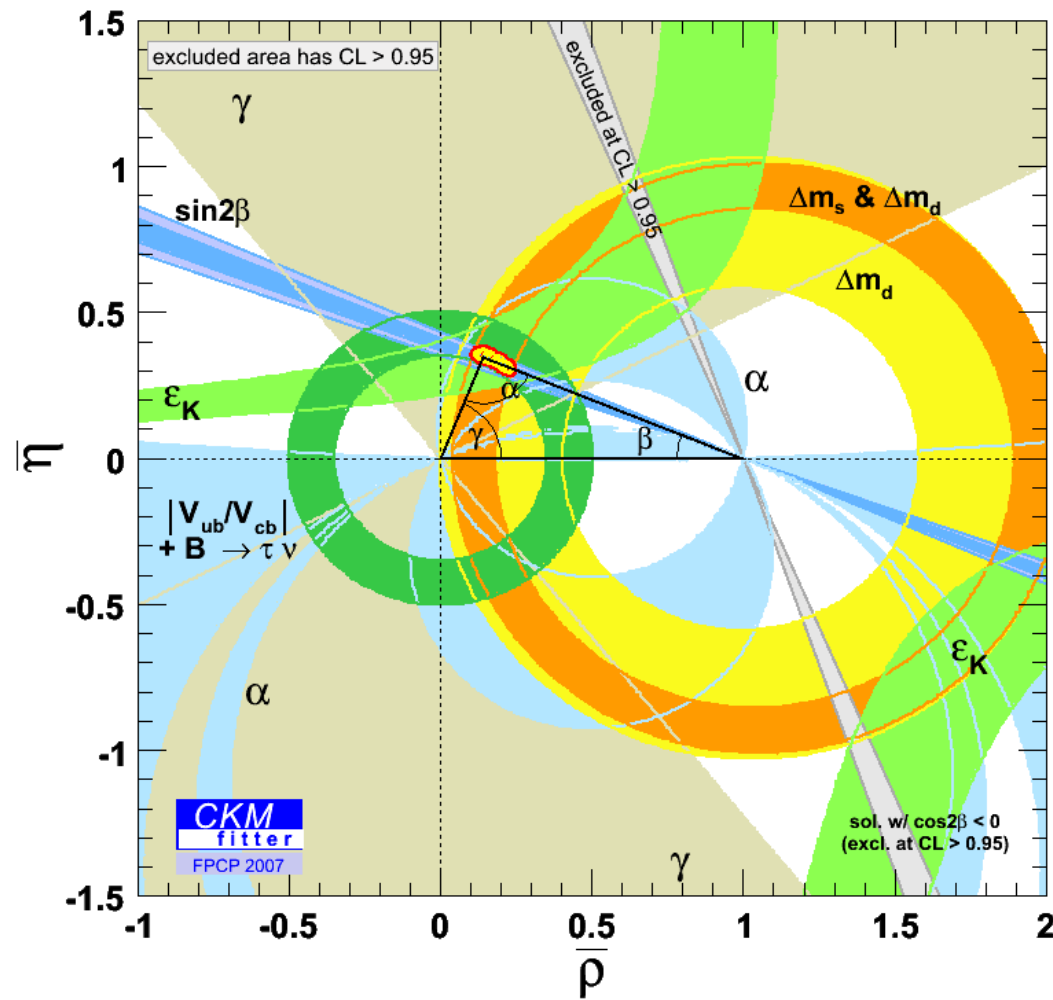
Violazione di CP

# Oscillazioni dei mesoni $B_s$ (2006)



$$\Delta m(B_s) = 17.31^{+0.33}_{-0.18} \pm 0.07 \text{ ps}^{-1}$$

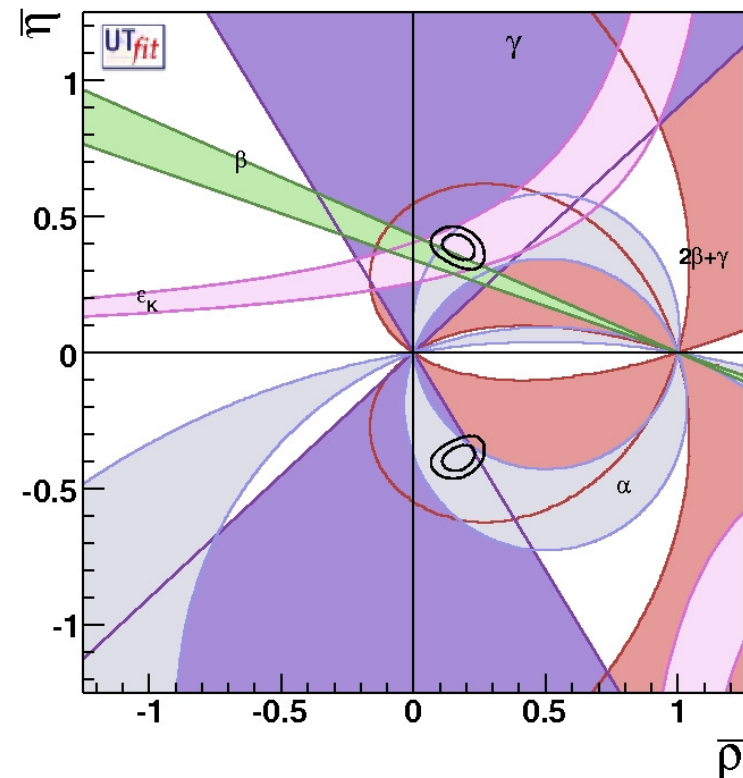
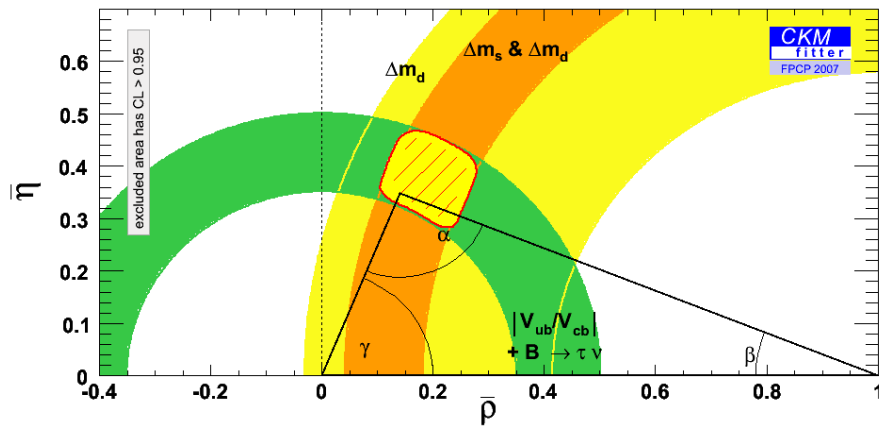
# Triangolo di unitarieta' (2007)



M.S. Sozzi

Violazione di CP

# Triangolo di unitarieta' (2007)



Le misure di quantita' che  
NON violano CP implicano  
la violazione di CP: verifica  
del Modello Standard