

## VI. Fizyka zapachu, Macierz CKM, łamanie CP

# Parametryzacja Wolfensteina macierzy CKM i łamanie CP

## The Standard Model

Gauge group:  $SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{\text{SSB}} SU(3)_c \times U(1)_{\text{em}}$

$$\mathcal{L}_{\text{SM}} = \underbrace{\mathcal{L}_{\text{kinetic}} + \mathcal{L}_{\text{Yukawa}}}_{\text{dimension-four part}} - \underbrace{V(h)}_{\text{Higgs potential}} + \underbrace{\mathcal{O}\left(\frac{1}{\Lambda_{\text{Huge}}}\right)}_{\text{neutrino masses, gravity, ...}} \quad \langle 0|h|0\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Fermion fields:  $\begin{pmatrix} u_L^j \\ d_L^j \end{pmatrix}, u_R^j, d_R^j, \begin{pmatrix} \nu_L^j \\ e_L^j \end{pmatrix}, e_R^j \quad j = 1, 2, 3.$

$\mathcal{L}_{\text{Yukawa}} \xrightarrow{\text{SSB}} \mathcal{L}_{\text{fermion mass}} + \mathcal{L}_{\text{fermion-higgs interactions}}$

$$\mathcal{L}_{\text{fermion mass}} = -\frac{v}{\sqrt{2}} \left( \bar{u}_R^i Y_u^{ij} u_L^j + \bar{d}_R^i Y_d^{ij} d_L^j + \bar{e}_R^i Y_e^{ij} e_L^j + \text{h.c.} \right)$$

$Y_u, Y_d, Y_e$  : complex  $3 \times 3$  Yukawa coupling matrices. They are the only source of CP-violation in the dimension-four part of the SM Lagrangian.

The CP transformation maps the SM fields onto themselves:

$$\psi(t, \vec{x}) \xrightarrow{\text{CP}} \gamma_0 C \bar{\psi}^T(t, -\vec{x}), \quad C^\dagger \gamma_\mu C = -\gamma_\mu^T$$

$$h(t, \vec{x}) \xrightarrow{\text{CP}} h^*(t, -\vec{x}),$$

$$A_0^a(t, \vec{x}) \xrightarrow{\text{CP}} \mp A_0^a(t, -\vec{x}), \quad (T^a)^\star = \pm T^a$$

$$\vec{A}^a(t, \vec{x}) \xrightarrow{\text{CP}} \pm \vec{A}^a(t, -\vec{x}).$$

When applied to free fields, it is identified as mirror reflection combined with simultaneous interchange of particles and antiparticles.

The dimension-four part of the SM action would be CP-invariant if (and only if) the Yukawa couplings contained no physical phases.

$$\mathcal{L}_{\text{fermion mass}} = -\frac{v}{\sqrt{2}} \left( \bar{u}_R^i Y_u^{ij} u_L^i + \bar{d}_R^i Y_d^{ij} d_L^j + \bar{e}_R^i Y_e^{ij} e_L^j + \text{h.c.} \right).$$

The fermion mass terms are diagonalized via chiral rotations, e.g.  $u_L^{\text{new}} = S_{uL} u_L^{\text{old}}$ . The resulting  $3 \times 3$  diagonal fermion mass matrices read:

$$M_u = S_{uR} Y_u S_{uL}^\dagger, \quad M_d = S_{dR} Y_d S_{dL}^\dagger, \quad M_e = S_{eR} Y_e S_{eL}^\dagger.$$

$$\mathcal{L}_{\text{fermion mass}} = -\left( \bar{u}_R^i M_u^{ij} u_L^i + \bar{d}_R^i M_d^{ij} d_L^j + \bar{e}_R^i M_e^{ij} e_L^j + \text{h.c.} \right).$$

At the same time, the W-boson couplings to quarks become flavour off-diagonal:

$$W^- \bar{u}_L^i d_L^i \rightarrow W^- \bar{u}_L^i V_{ij} d_L^j \quad V = S_{uL} S_{dL}^\dagger - \text{unitary Cabibbo-Kobayashi-Maskawa matrix}$$

Standard parametrization of the CKM matrix  $V$ .

Three angles  $\theta_{ij}$  and one phase  $\delta$ . Notation:  $c_{ij} = \cos \theta_{ij}$ ,  $s_{ij} = \sin \theta_{ij}$ .

$$V \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Introducing the Wolfenstein parameters:

$$\lambda = s_{12} \simeq 0.22, \quad A = \frac{s_{23}}{s_{12}^2}, \quad \rho = \frac{s_{13}}{s_{23}s_{12}} \cos \delta, \quad \eta = \frac{s_{13}}{s_{23}s_{12}} \sin \delta.$$

$$\text{Then } c_{12} = \sqrt{1 - \lambda^2}, \quad c_{23} = \sqrt{1 - A^2\lambda^4}, \quad c_{13} = \sqrt{1 - A^2\lambda^6(\rho^2 + \eta^2)},$$

$$V = \begin{pmatrix} c_{12}c_{13} & \lambda c_{13} & A\lambda^3(\rho - i\eta) \\ -\lambda c_{23} - A^2\lambda^5(\rho + i\eta)c_{12} & c_{12}c_{23} - A^2\lambda^6(\rho + i\eta) & A\lambda^2c_{13} \\ A\lambda^3[1 - c_{12}c_{23}(\rho + i\eta)] & -A\lambda^2c_{12} - A\lambda^4(\rho + i\eta)c_{23} & c_{23}c_{13} \end{pmatrix}$$

$$\simeq \begin{pmatrix} 1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4) & \lambda + \mathcal{O}(\lambda^7) & A\lambda^3(\rho - i\eta) \\ -\lambda + \mathcal{O}(\lambda^5) & 1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4) & A\lambda^2 + \mathcal{O}(\lambda^8) \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) + \mathcal{O}(\lambda^7) & -A\lambda^2 + \mathcal{O}(\lambda^4) & 1 + \mathcal{O}(\lambda^4) \end{pmatrix},$$

$$\text{where } \bar{\rho} = \left(1 - \frac{\lambda^2}{2}\right)\rho \quad \text{and} \quad \bar{\eta} = \left(1 - \frac{\lambda^2}{2}\right)\eta.$$

$$V^\dagger V = 1 \Rightarrow 6 \text{ unitarity triangles, e.g. } V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0.$$

$$A\lambda^3(\bar{\rho} + i\bar{\eta}) - A\lambda^3 + A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) = \mathcal{O}(\lambda^7)$$



## Trójkąt unitarności

\* Unitarność:  $V^\dagger V = 1$

$1_{3 \times 3}$



$$\begin{pmatrix} \sum |V_{id}|^2 & V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} & V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} \\ & \sum |V_{is}|^2 & V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} \\ & & \sum |V_{ib}|^2 \end{pmatrix}$$

\* (11,22,33) -  $\sum$  prawdopodobieństw = 1

\* (12,21) - ~~małe~~  $|V_{ud}^* / V_{us}| \cong |V_{cs} / V_{cd}| \cong 1/\lambda$

\* (23,32) - ~~małe~~  $|V_{ts}| \cong |V_{cb}|$

\* (13,31) - **TRÓJKĄT UNITARNOŚCI**

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

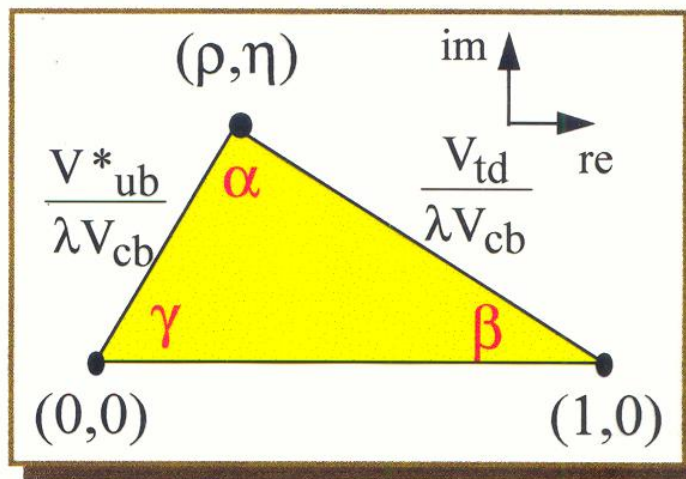
$$1 + A\lambda^3(\rho+i\eta) - \lambda + A\lambda^2 + A\lambda^3(1-\rho-i\eta) = 1$$



$$\sin 2\alpha = \frac{2\eta(\rho^2 + \eta^2 - \rho)}{((1-\rho)^2 + \eta^2)(\rho^2 + \eta^2)}$$

$$\sin 2\beta = \frac{2\eta(1-\rho)}{(1-\rho)^2 + \eta^2}$$

$$\sin 2\gamma = \frac{2\eta\rho}{(\rho^2 + \eta^2)}, \quad \sin \gamma = \frac{\eta}{\sqrt{\rho^2 + \eta^2}}$$



# Konferencja EPS Lisbona 2005

## Dopasowanie parametrów Wolfensteina

Current results for the CKM parameters

	$\lambda$	$A$	$\bar{\rho}$	$\bar{\eta}$
CKM Fitter (ferquentist)	$0.2262 \pm 0.0010$	$0.825^{+0.011}_{-0.019}$	$0.207^{+0.036}_{-0.043}$	$0.340 \pm 0.023$
UTfit (bayesian)	$0.2258 \pm 0.0014$	$0.816 \pm 0.017$	$0.216 \pm 0.036$	$0.342 \pm 0.022$

from  $K$  and  $\tau$  decays ( $|V_{us}|$ )

from  $b \rightarrow c$  decays ( $|V_{cb}|$ )

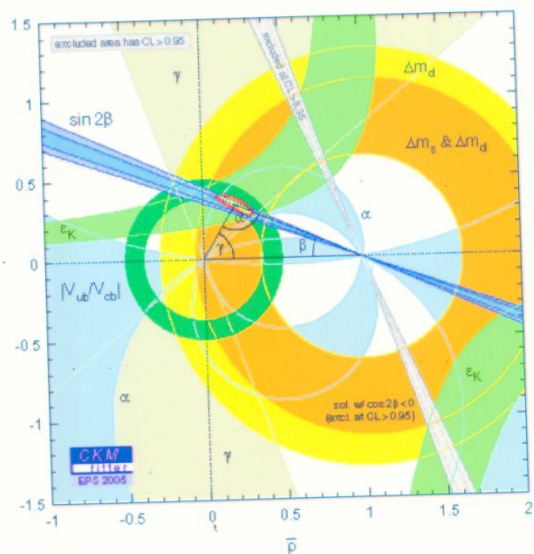
$b \rightarrow u$  decays ( $|V_{ub}|$ )

CP-violation in  $K^0\bar{K}^0$  mixing ( $\epsilon_K$ )

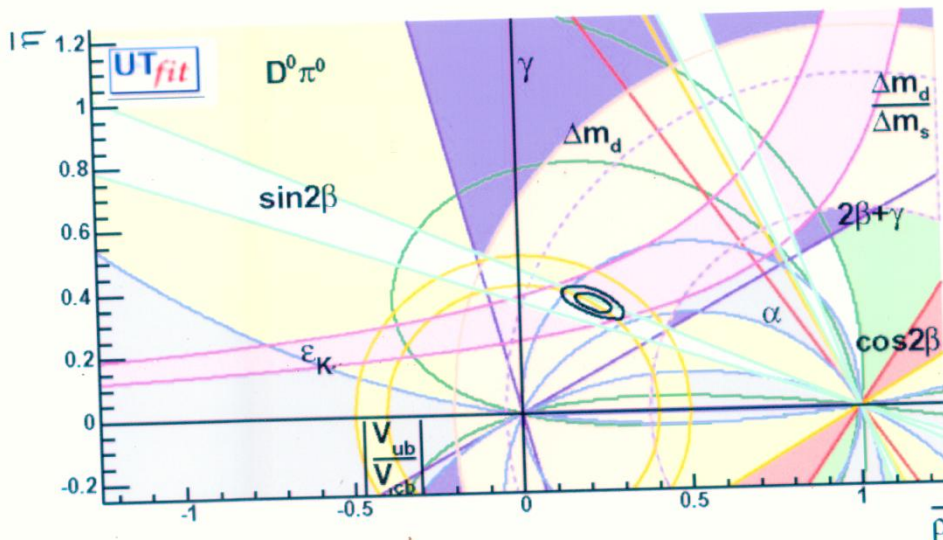
CP-violation in  $D^0\bar{D}^0$  decays ( $\sin 2\beta$ )

## Trójkąt unitarności HEP Lisbona 2005 CKM FITTER

## Trójkąt unitarności Lisbona 2005 UT FITTER



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$$V_{cb} \text{ i } V_{ub}$$

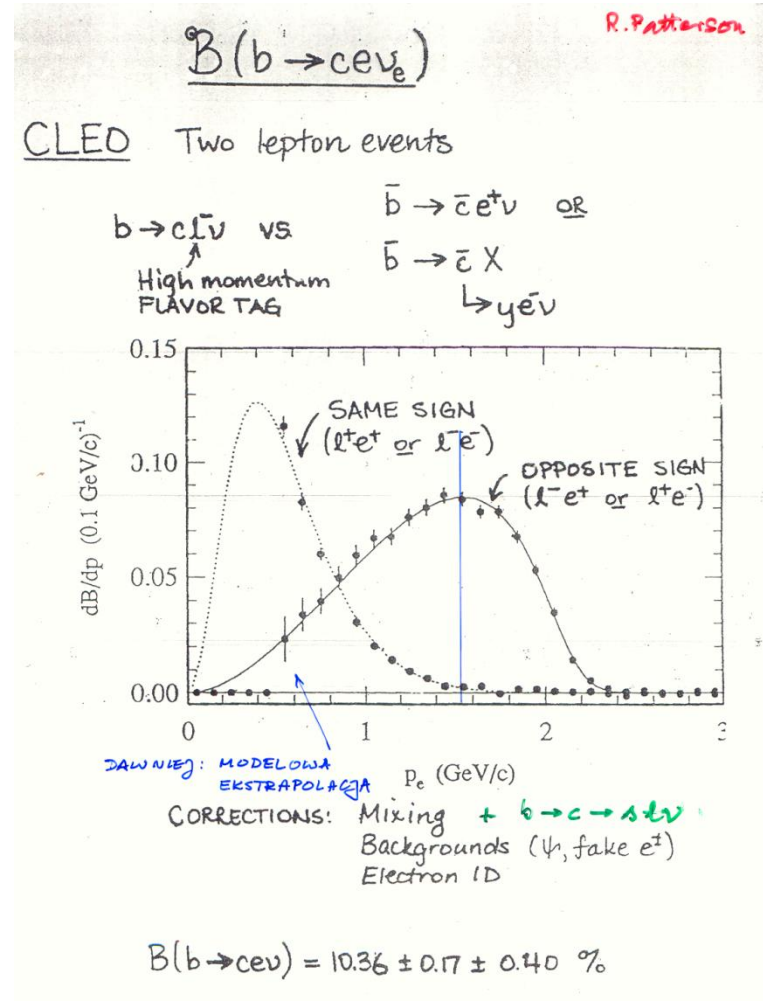
Najlepiej wyznaczone z inkluzywnych rozpadów semileptonowych b:

- CLEO w Cornell (upsilon 4S)

$$e^+ e^- \rightarrow b \bar{b}$$

$$lX \leftarrow \downarrow$$

$$l'X'$$



X. Paterson

**ROZPADY SEMILEPTONOWE B**

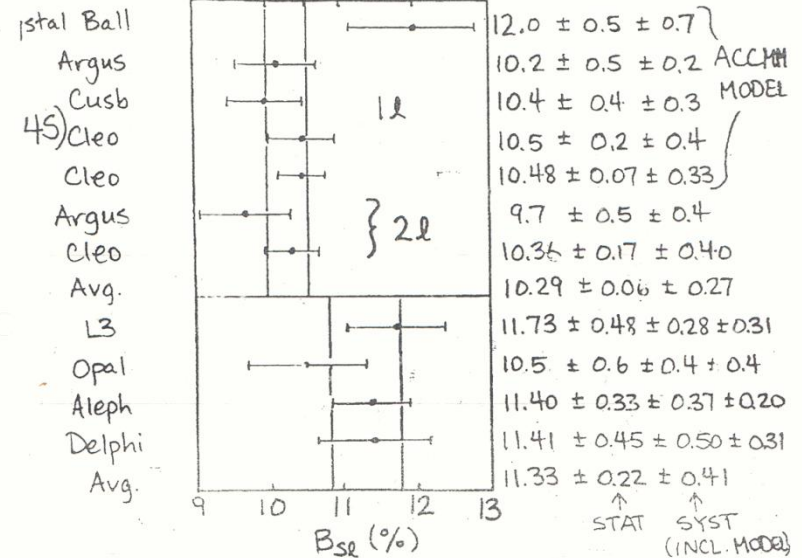
INKLUZYWNE  
 $\Gamma_{sl}^i(b \rightarrow c l \nu) = \frac{BR(c l \nu)}{\tau_B} = \frac{G_F^2 m_b^5}{192 \pi^3} |V_{cb}|^2 K$

PRZESTRZEŃ FAZOWA +  
 POPRAWKI NA STAN ZWIĄZANY

$\Gamma_{sl}^i(B^0) = \Gamma_{sl}^i(B^+) = \Gamma_{se}^i(B_s) = \Gamma_{se}^i(\Lambda_b)$  **DOUBLE TAG**

p.

B(b → clν)



$\Gamma_{sl}^i = \frac{B_{sl}}{\tau} = \frac{G_F^2 m_b^5}{192 \pi^3} |V_{cb}|^2 K$

INKLUZYWNE

$(45) |V_{cb}| = 0.039 ± 0.001 ± 0.005 \quad \tau_B = 1.63 ± 0.07 ps$

$Z^0 |V_{cb}| = 0.042 ± 0.002 ± 0.005 \quad \tau_b = 1.55 ± 0.06 ps$

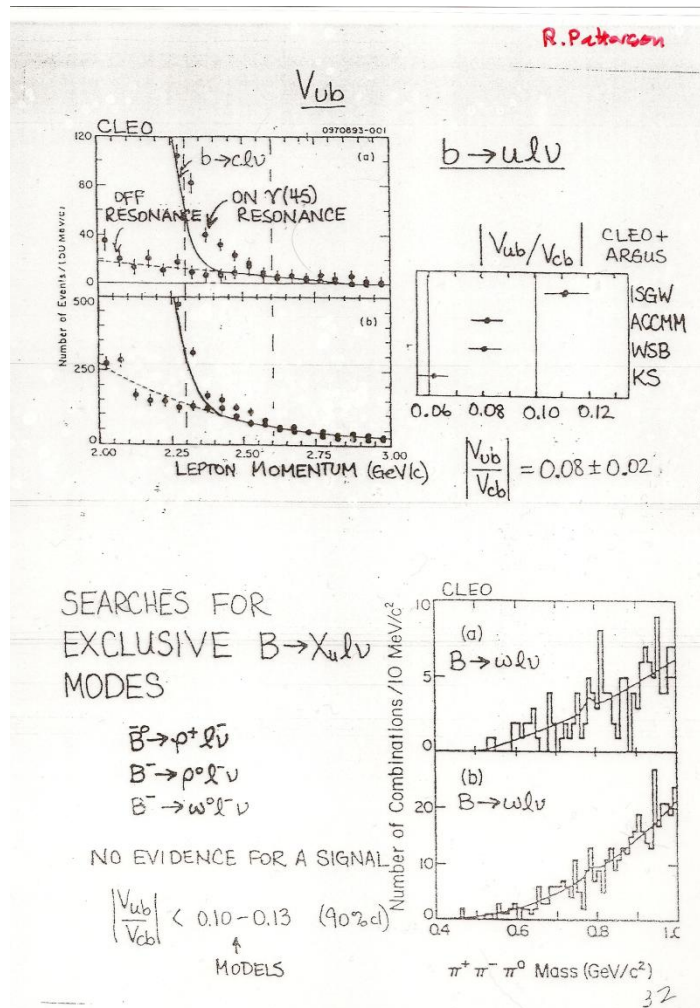
↑ EXPT. MODEL (see talk by P. Roudeau)  
 Bigi+Uraltsev, Shifman et al.  
 Ball+Nierste, Luke+Savage

EKSKLUZYWNE B → D l ν

$|V_{cb}| = 0.0404 ± 0.0022 ± 0.0020$



# $V_{ub}$ CLEO i inni

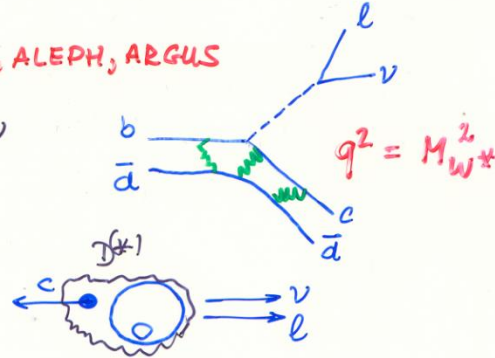


# Rozpady semileptonowe ekskluzywne

EKSKLUZYWNE

CLEO, ALEPH, ARGUS

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



$q^2_{MAX}$

$$\omega = 1$$

$$\frac{\Lambda_{QCD}}{m_b} \rightarrow 0$$

$q^2_{MIN}$

$$\omega \sim 1.5$$

w ul. B

$$\omega = v_B \cdot v_{D^*} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B \cdot m_{D^*}} = \frac{E_{D^*}}{m_{D^*}}$$

HQET

$$\xi(\omega^*) \sim \xi(q^2)$$

FUNKCJA ISGUR'A-WISE'A

$$\xi(\omega) = 1 - \rho^2(1-\omega)$$

$$0.5 < \rho^2 < 2$$

R.Y. Morrison, J.D. Richman w PDG'94 pp 1565:1602

$$P \rightarrow P' \ell \nu$$

$$\begin{matrix} D^0 \rightarrow K^* e^+ \nu \\ B \rightarrow D \ell \nu \end{matrix}$$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{qb}|^2 k_{Pl}^3 |f_+(q^2)|^2}{24\pi^3}$$

$$f_+^K = f_+^K(0) \frac{1}{1 - q^2/m_{D_s^*}^2}$$

$$P \rightarrow V L \nu$$

$$\begin{matrix} D^+ \rightarrow K^{*0} \ell^+ \nu \\ \bar{B} \rightarrow D^* \ell \nu \end{matrix} \quad \begin{matrix} \eta = -1 & (c\bar{q}) \\ \eta = +1 & (b\bar{q}) \end{matrix}$$

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_V d\chi} = \frac{3G_F^2 |V_{qb}|^2 k_V \cdot q^2}{8(4\pi)^4 M_P} \times$$

$$\left\{ (1+\eta)\cos\theta_\ell |H_+(q^2)|^2 + (1-\eta)\cos\theta_\ell |H_-(q^2)|^2 \sin^2\theta_V + \right.$$

$$+ 4\sin^2\theta_\ell \cos^2\theta_V |H_0(q^2)|^2 - 2\sin^2\theta_\ell \sin^2\theta_V \cos(2\chi) H_+ H_- +$$

$$- 4\eta \sin\theta_\ell (1+\eta\cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi H_+ H_0 +$$

$$+ 4\eta \sin\theta_\ell (1-\eta\cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi H_- H_0 \}$$

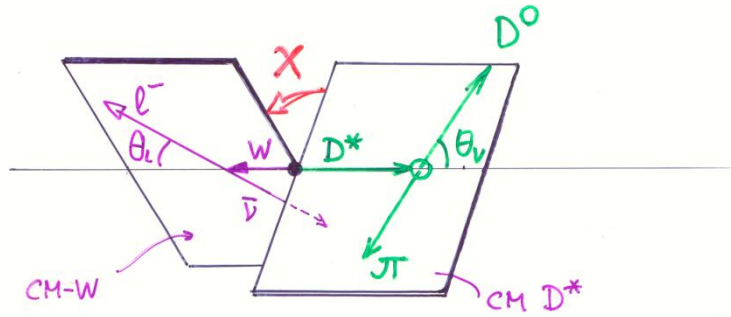
$H_i$ : amplitudy (skalarne)  $\rightarrow$  2 czynniki postaci skalarne V lub  $W^*$   $A_1, A_2$  (axialne) 1 czynnik postaci  $V_i$  (wektorowy)

$$H_{\pm} = (M_P + M_V) A_1 \mp \frac{2M_P k_V}{M_P + M_V} V$$

$$H_0 = \frac{1}{2M_V \sqrt{q^2}} \left\{ (M_P^2 - M_V - q^2)(M_V + M_P) A_1 - \frac{4M_P^2 k_V^2}{M_P + M_V} A_2 \right\}$$

DEFINICJA ZMIENNYCH UŻYTYCH PRZEZ CLEO

PDG '04



TEORIA  $\eta_A \hat{\xi}(1) = 0.93$   
 $\eta_A = 0.985 \pm 0.015$   
 $\hat{\xi}(1) = \begin{cases} 0.945 \pm 0.025 \\ 0.91 \pm 0.03 \end{cases}$  NEUBERT et al.  
 SHIFMAN et al.  
 $\rightarrow$  NIEPEWNOŚĆ  $\delta V_{cb} \sim 0.002$

- ARGUS  $0.0434 \pm 0.0047 \pm 0.0027$
- CLEO  $0.0389 \pm 0.0021 \pm 0.0022$
- ALEPH  $0.0427 \pm 0.0048 \pm 0.0038$

$|V_{cb}| = 0.0404 \pm 0.0022 \pm 0.0020$   
 exp theory

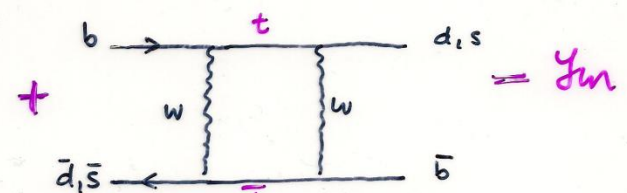
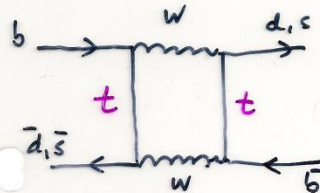
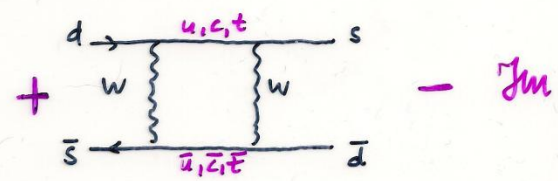
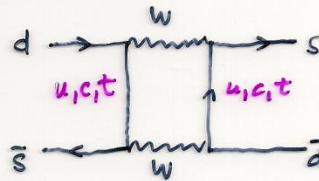
		$f_+(0)$	$A_1(0)$	$V(0)$	$A_2(0)$
Exp	$D \rightarrow K l \nu$	$0.75 \pm 0.03$	$0.56 \pm 0.04$	$1.1 \pm 0.2$	$0.40 \pm 0.08$
QUARK MODELS	ISGW	0.8	0.8	1.1	0.8
	WSR	0.76	0.88	1.3	1.2
	KS	0.7	0.82	0.8	0.8
	AW/6S	0.7	0.8	1.4	0.6
LATTICE	BKS	0.8	0.8	$1.4 \pm 0.6$	0.6
	LMMS	0.63	0.83	0.9	0.2
QCD.S.F	BBD	0.6	0.5	1.1	0.6

$B^0 \rightarrow D^{*+} l^+ \nu_l$   
 Neubert PL B 234, 455 (1991) & Phys. Rep. C (in prep)  
 $\frac{dBR}{d\omega} = \frac{G_F^2 m_{D^*}^2}{48\pi^3} (m_B - m_{D^*})^2 \eta_A^2 \sqrt{\omega^2 - 1} (\omega + 1)^2 \times$   
 $\left[ 1 + \frac{4\omega}{\omega + 1} \frac{1 - 2\omega r + r^2}{(1 - r)^2} \right] |V_{cb}|^2 \hat{\xi}(\omega)^2$   
 $r = m_{D^*} / m_B \Rightarrow \eta_A = 0.93$   
 $\hat{\xi}(1) = 1 + \delta\left(\frac{1}{m^2}\right) = 1.00 \pm 0.0$   
 GLASGOW:  $\left\{ \begin{array}{l} \text{NEUBERT '94} \\ \text{SHIFMAN et al.} \end{array} \right. \begin{array}{l} 0.98 \pm 0.04 \\ 0.88 \pm 0.03 \end{array}$

# Mieszanie w sektorze $K^0$ i $B^0$

MIESZANIE

$K^0 - \bar{K}^0, B^0 - \bar{B}^0$



$K^0 - \bar{K}^0$

$$|\epsilon|_K = \frac{G_F^2 f_K M_K M_W^2}{6\sqrt{2} \pi^2 \Delta M_K} B_K (A^2 \lambda^6 \eta) f_{QCD}$$

$0.33 < 3\eta < 1$   
K-M

$0.8 \pm 0.2$

↑  
rachunki na siatkach

$$\approx \left[ \eta_{ct} \{ \eta_{ct} f_3(y_c, y_t) - \eta_{cc} \} + \eta_{tt} y_t f_2(y_t) A^2 \lambda^2 (1 - \rho) \right]$$

POPRAWKI QCD

$$\eta_{ct} = 0.35 \quad \eta_{cc} = 0.82 \quad \eta_{tt} = 0.62$$

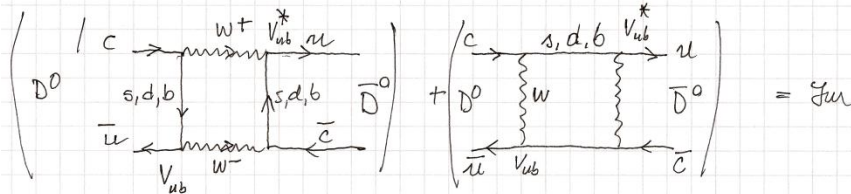
$\Lambda_{MS} = 200 \text{ MeV}$

[ Np Buras, Steinhilber, Steger Nucl. Phys. B238 (1984), 529  
B245, (1984), 369 ]



# Mieszanie $D^0$ - $\bar{D}^0$

MIESZANIE  $D^0$ - $\bar{D}^0$



Parametry mieszania

$$\begin{pmatrix} M_1 & M_{12} \\ M_{21} & M_2 \end{pmatrix} + i \begin{pmatrix} \Gamma_1 & \Gamma_{12} \\ \Gamma_{21} & \Gamma_2 \end{pmatrix}$$

$$x = \frac{M_1 - M_2}{\Gamma} = \frac{\Delta M}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = \frac{\Delta\Gamma}{\Gamma}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

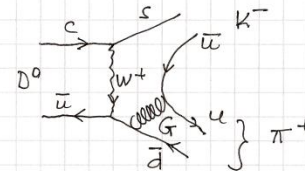
Brak mieszania

$$x = y = 0$$

W Modelu Standardowym na poziomie drzewowym

Bez poprawki QCD stanu związanego  $\rightarrow \mathcal{O}(10^{-2})$

małe  $V_{cb}$   
masy  $d$  i  $s$  bliskie sobie



BELLE (2007): rozkłady  $\tau(K^+K^-)$  i  $\tau(\pi^+\pi^-)$  CP = +1  
rozkłady  $\tau(K^-\pi^+)$

$$y_{CP} = \frac{\tau(K^+K^-)}{\tau(K^-\pi^+)} - 1 = y \cos\phi - \frac{1}{2} A_{\mu} \times \sin\phi = (1.31 \pm 0.32 \pm 0.25) \times 10^{-2}$$

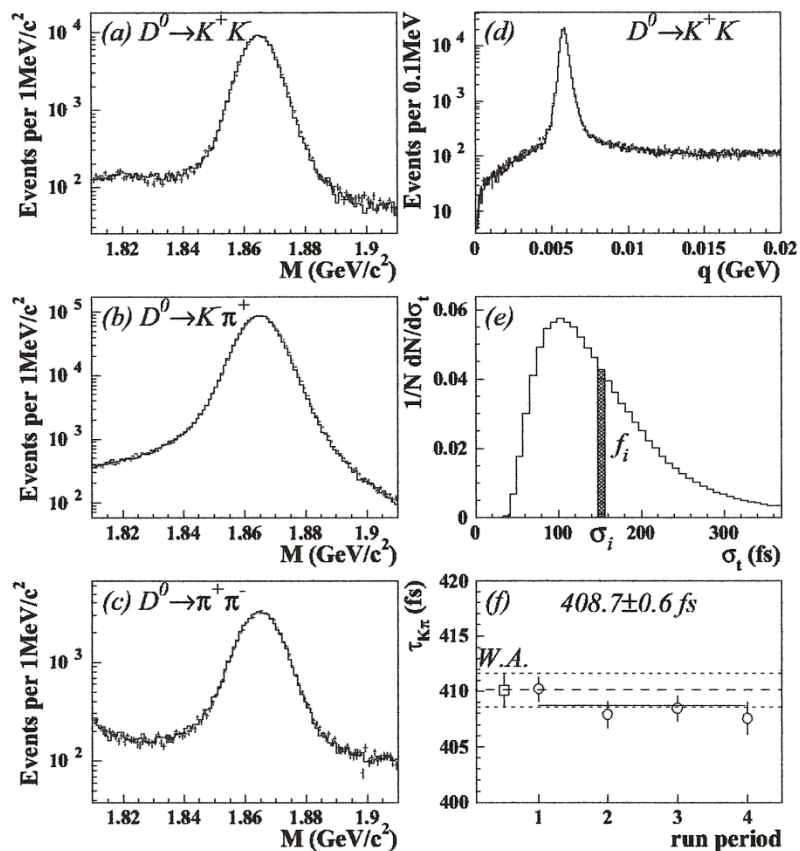
Gdy CP zachowane  $\phi, A_{\mu} = 0$ !

$$A_{\pi} = \frac{\tau(\bar{D}^0 \rightarrow K^+K^-) - \tau(D^0 \rightarrow K^+K^-)}{\tau(\bar{D}^0 \rightarrow K^+K^-) + \tau(D^0 \rightarrow K^+K^-)} = \frac{1}{2} A_{\mu} \cos\phi - x \sin\phi = A_{\pi} = (0.01 \pm 0.30 \pm 0.15) \times 10^{-2}$$

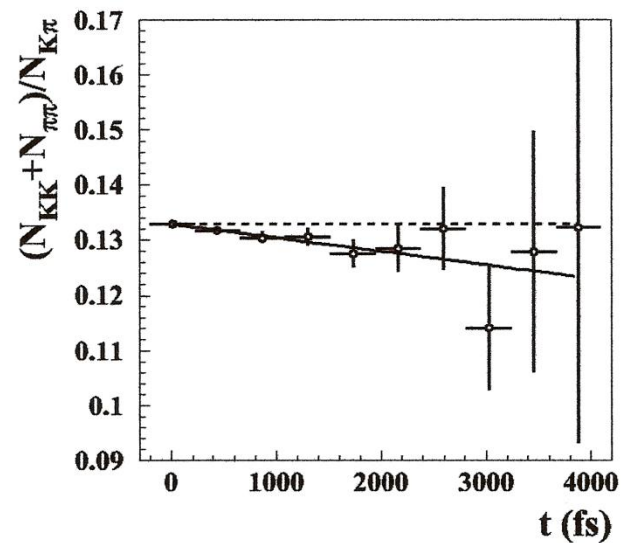
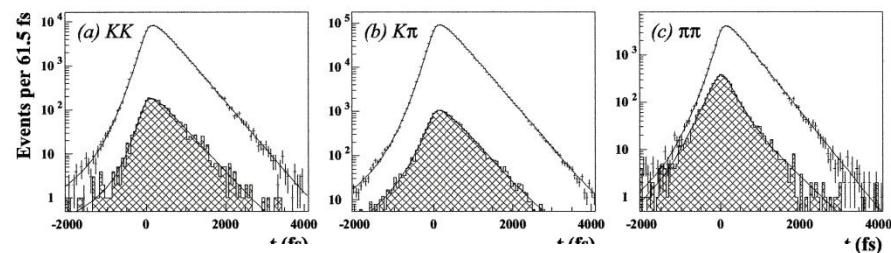


# BELLE 2007

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FIG. 1.  $M$  distribution of selected events (with  $\Delta A_{CP} >$ 

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# Mieszanie $D^0$ - $\bar{D}^0$ (2)

$$\underline{D^0 - \bar{D}^0} \quad (2)$$

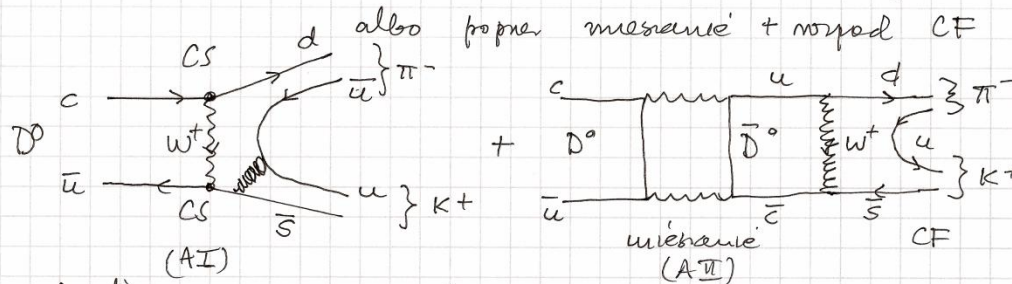
BABAR (2007):

$$\boxed{D^{*+} \rightarrow D^0 \pi_s^+}$$

$D^0 \rightarrow K^- \pi^+$  OK w SM

$D^0 \rightarrow K^+ \pi^-$  WRONG SLEN (WS) wzbrośnię w SM  $\frac{1.2 \times 10^6 \text{ [mwp.]}}{64 \cdot 10^3 \text{ [przygodziw]}}$

Można zobaczyć albo przez procesy (+transone) przez  $\sin \theta_c$  (CS)



Analiza nr zmiennych

$$m_{K\pi}, \Delta m = m_{D^0} - m_{K\pi}, t, \delta t$$

$\uparrow$  czas rozpadu       $\uparrow$  błąd czas rozpadu

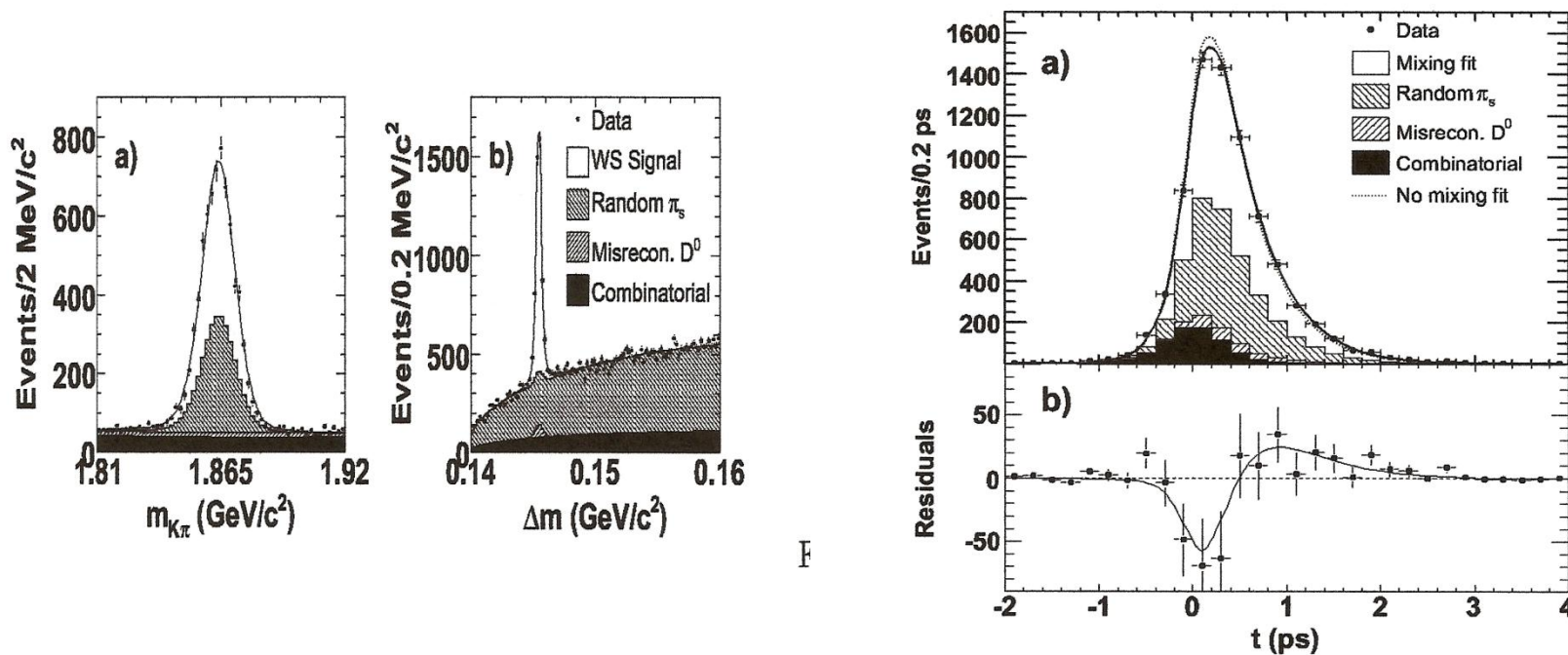
$$\frac{dN}{dt} = e^{-\Gamma t} \left( R_D + \sqrt{R_D} \eta' (\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2 \right)$$

dla macicy  $(1 \times 1, |y| \ll 1$ , CP conservation

$$\eta' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}; \quad \eta' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}$$

$\delta_{K\pi}$  faza między amplitudami: AI i AII

## BABAR 2007

FIG. 2: a) The proper-time distribution of combined  $D^0$

## Mieszanie $D^0$ - $D^0$ bar (3)

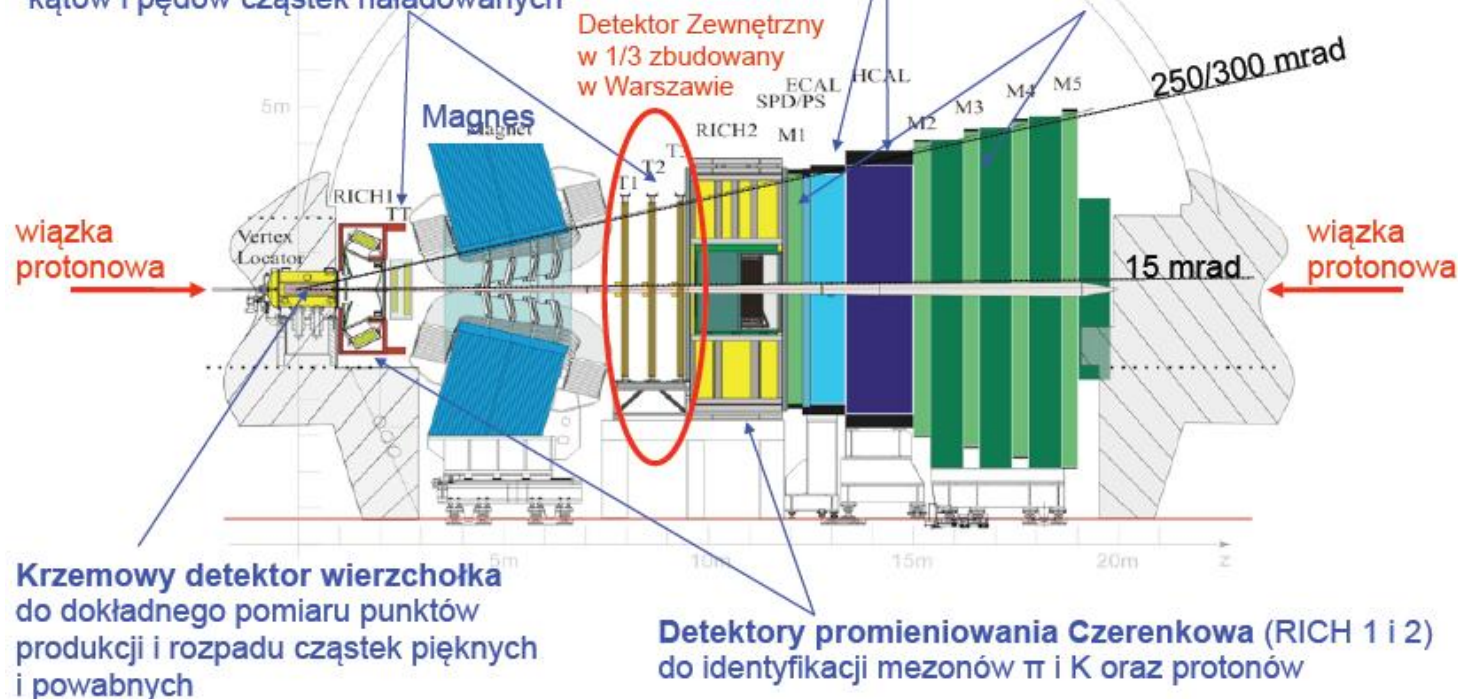
- Na poziomie 3-4 odchyłeń standardowych zaobserwowano mieszanie w układzie  $D^0$
- LHCb zaobserwowało łamanie CP w sektorze cząstek powabnych w 2011

# LHCb 2011

## Detektor LHCb

Detektory śladowe do pomiaru kątów i pędów cząstek naładowanych

Kalorymetry elektromagnetyczny (ECAL) i hadronowy (HCAL) do identyfikacji elektronów, hadronów i cząstek neutralnych oraz pomiaru ich energii



Krzemowy detektor wierzchołka do dokładnego pomiaru punktów produkcji i rozpadu cząstek pięknych i powabnych

Detektory promieniowania Czerenkowa (RICH 1 i 2) do identyfikacji mezonów  $\pi$  i K oraz protonów

**VELO** – wysoka precyzja: rozdzielczość IP:  $38 \mu\text{m}$  dla 1 GeV

**System rekonstrukcji torów** – dokładność czasu życia  $\sim 50 \text{ fs}$ :  $0.1 \tau(D^0)$

**RICH** - bardzo dobra identyfikacja cząstek  $\pi$  i K: błędna identyfikacja  $< 5 \%$



# LHCB 2011

## Mieszanie i łamanie symetrii CP



Dwa stany zapachu: 
$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

$$m \equiv (m_1 + m_2)/2$$

$$\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$$

Propagują się w przestrzeni dwa stany własne masy ( $m_1, m_2$ ):

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

Dwa parametry opisują mieszanie:

**różnica mas  $x$ :**

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}$$

**różnica szerokości rozpadów  $y$ :**

$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

- $\Delta m$  częstość **mieszania** (oscylacji)
- $\Delta m, \Delta\Gamma$  – **mierzone eksperymentalnie**
- $M_{12}, \Gamma_{12}, \phi$  – **parametry teoretyczne**

$$\phi \equiv \arg(-M_{12}/\Gamma_{12})$$

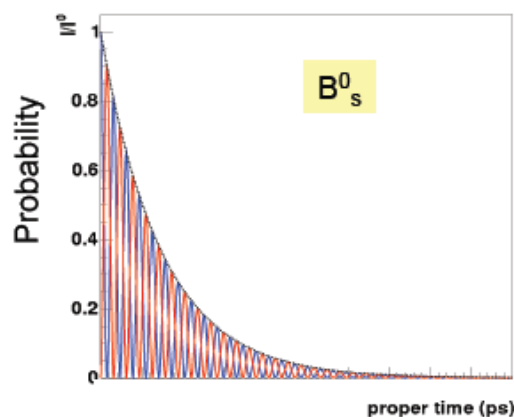
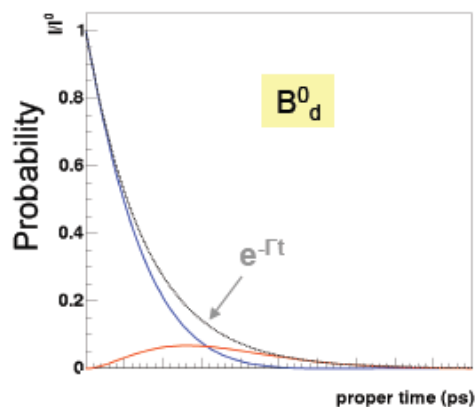
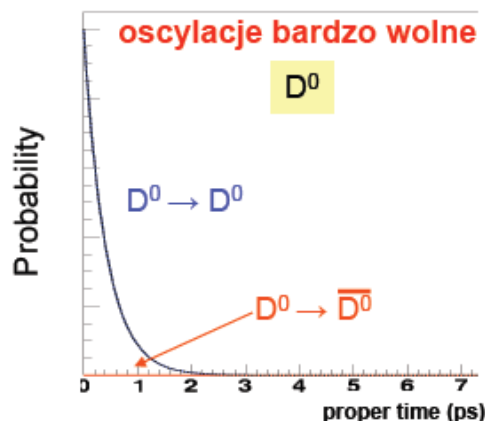
$$\Delta m = M_H - M_L = 2|M_{12}|\left(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + \dots\right)$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L = 2|\Gamma_{12}|\cos\phi\left(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + \dots\right)$$

Jeśli:  $D^0 \longrightarrow \text{anty-}D^0 \neq \text{anty-}D^0 \longrightarrow D^0$  to łamanie symetrii CP  
wtedy stany własne  $m_1, m_2$  zawierają różną domieszkę stanów  $D^0$  i  $\text{anty-}D^0$

Faza **łamania CP**:  $\phi_D \neq 0$  lub  $|q/p| \neq 1$

## LHCb 2011

Mieszanie neutralnych D, B<sub>d</sub> i B<sub>s</sub>

$$\text{Prob}(P^0 \rightarrow P^0, t) = \frac{1}{2} e^{-\Gamma t} \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) + \cos(\Delta m t) \right\}$$

$$\text{Prob}(\bar{P}^0 \rightarrow \bar{P}^0, t) = \text{Prob}(P^0 \rightarrow P^0, t) \quad \text{CPT}$$

$$\text{Prob}(P^0 \rightarrow \bar{P}^0, t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) - \cos(\Delta m t) \right\}$$

$$\text{Prob}(\bar{P}^0 \rightarrow P^0, t) = \frac{1}{2} \left| \frac{p}{q} \right|^2 e^{-\Gamma t} \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) - \cos(\Delta m t) \right\}$$

$$P^0 = D^0, B_d^0, B_s^0$$

Dla cząstek B dobrym przybliżeniem jest  $\Delta\Gamma \approx 0$

$$\longrightarrow \text{Prob} \sim \frac{e^{-\Gamma t}}{2} \{1 \pm \cos(\Delta m t)\}$$

$$x = \frac{\Delta m}{\Gamma}$$

Z pomiarów:

$$x_{B_d} = 0.774 \pm 0.008$$

$$x_{B_s} = 26.2 \pm 0.5$$

$$x_D = 0.0098 \pm 0.0025$$

Aby wyznaczyć  $x_D$   
(i  $y_D$ ) potrzeba  
bardzo precyzyjnych  
pomiarów  $\rightarrow$  LHCb

## Asymetria cząstka-antycząstka

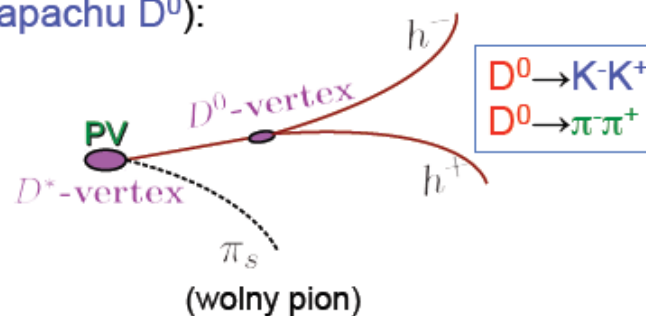
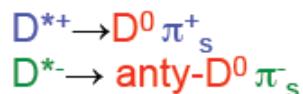


Chcemy zmierzyć **asymetrię** między cząstkami a antycząstkami

$$A_{CP} \equiv \frac{N_{CP}(D^0 \rightarrow h^- h^+) - N_{CP}(\bar{D}^0 \rightarrow h^- h^+)}{N_{CP}(D^0 \rightarrow h^- h^+) + N_{CP}(\bar{D}^0 \rightarrow h^- h^+)}$$

gdzie  $h=K,\pi$

- **Konieczne jest zidentyfikowanie cząstek  $D^0$  i anty- $D^0$**
- W tym celu używamy rozpadów naładowanych  $D^{*\pm}$   
(znak wolnego pionu służy do oznaczenia zapachu  $D^0$ ):



Mierzona asymetria między  $D^0$  a anty- $D^0$ :

$$A_{RAW}(f)^* \equiv \frac{N(D^{*+} \rightarrow D^0(f)\pi^+) - N(D^{*-} \rightarrow \bar{D}^0(\bar{f})\pi^-)}{N(D^{*+} \rightarrow D^0(f)\pi^+) + N(D^{*-} \rightarrow \bar{D}^0(\bar{f})\pi^-)}$$

$f = K-K^+, \pi\pi^+$



## Pomiar $\Delta A_{CP}$ w LHCb

Mierzona asymetria  $A_{RAW}$  jest sumą kilku asymetrii:

$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^*)$$

asymetria  
pochodząca  
z łamania  
symetrii CP

asymetria  
detektorowa  
związana z  
rekonstrukcją  $D^0$

asymetria  
detektorowa  
związana z  
rekonstrukcją  $\pi_s$

asymetria produkcji  $D^*$   
w wierzchołku  
pierwotnym (różna  
liczba  $D^{*+}$  i  $D^{*-}$ )

$$A_{CP}, A_D, A_P \equiv \frac{N_{CP}(D^0) - N_{CP}(\bar{D}^0)}{N_{CP}(D^0) + N_{CP}(\bar{D}^0)}$$

Asymetrie detektorowe dla  $K^-K^+$  i  $\pi^-\pi^+$  kasują się bo stany końcowe symetryczne

$$A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$$

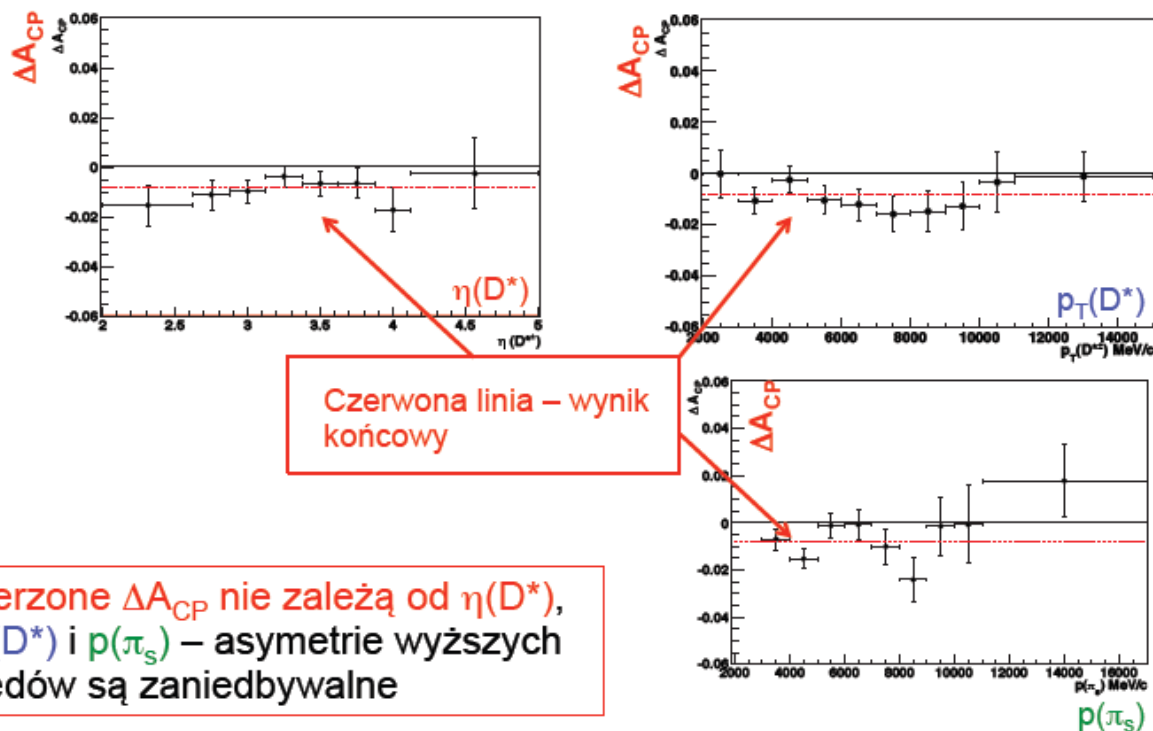
Asymetrie detektorowa  $A_D(\pi_s)$  i produkcji  $A_P(D^*)$  skasują się jeżeli odejmiemy asymetrie mierzone  $A_{RAW}$  dla  $K^-K^+$  i  $\pi^-\pi^+$  (dlatego mierzymy ich różnicę)

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= A_{RAW}(K^+K^-)^* - A_{RAW}(\pi^+\pi^-)^* \end{aligned}$$

## Zależność od zmiennych kinematycznych



Mierzone  $\Delta A_{CP}$  w trzech zmiennych  $\eta(D^*)$ ,  $p_T(D^*)$  i  $p(\pi_s)$





# LHCb2011

## Pomiar $\Delta A_{CP}$



Średnia ważona (LHCb 2011, 580 pb<sup>-1</sup>):

$$\Delta A_{CP} = [-0.82 \pm 0.21^{stat} \pm 0.11^{syst}] \%$$

znaczącość:  $3.5 \sigma$

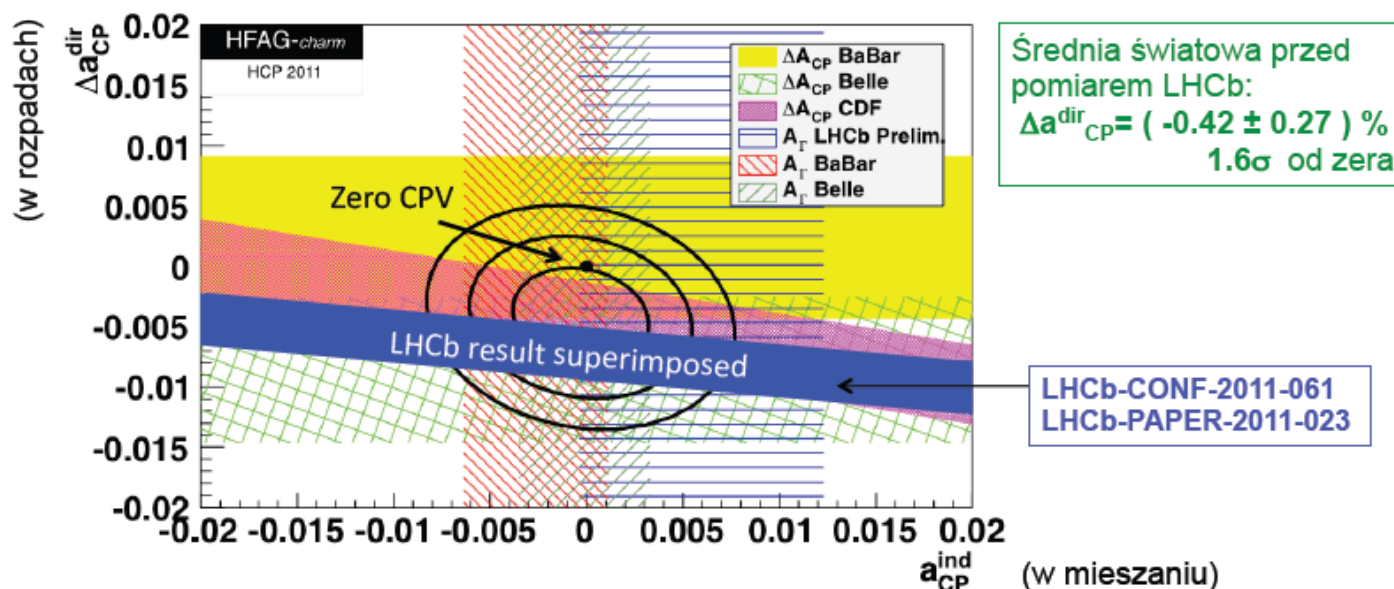
Prawdopodobieństwo, że nie ma łamania symetrii CP: **0.15%**

# LHCb 2011

## Pomiar $\Delta A_{CP}$ : porównanie



Pierwszy pomiar asymetrii CP w rozpadach cząstek powabnych  
Dotychczas najważniejszy wynik z LHC



LHCb 2011, 580 pb<sup>-1</sup>:

$$\Delta A_{CP} = [-0.82 \pm 0.21^{stat} \pm 0.11^{syst}] \% \quad \text{znaczącość: } 3.5 \sigma$$

LHCb 2011 całkowite 1.1 fb<sup>-1</sup> (pozostałe 500 pb<sup>-1</sup> jest analizowane)

## Parametry mieszania neutralnych mezonów

Układ	$\Delta m$	$\tau=1/\Gamma$	$x=\Delta m / \Gamma$	$y= \Delta\Gamma / \Gamma$
$K^0 - \overline{K}^0$	L-S= $(3.483 \pm 0.006) \times 10^{-12}$ MeV	S= $(0.8953 \pm 0.0006) \times 10^{-10}$ s L= $(5.18 \pm .04) \times 10^{-8}$ s		
$B_d^0 - \overline{B}_d^0$	H-L= $(3.304 \pm 0.046) \times 10^{-10}$ MeV		$0.771 \pm 0.012$	
$B_s^0 - \overline{B}_s^0$	H-L= $(3.304 \pm 0.046) \times 10^{-10}$ MeV			
$D^0 - \overline{D}^0$				

OSCYLACJE  $B_d^0 - \bar{B}_d^0$  i  $B_s^0 - \bar{B}_s^0$

$$P(B^0 \rightarrow \bar{B}^0) \rightarrow \frac{e^{-\Gamma t/\hbar}}{2\tau_B} \left[ 1 - \cos \frac{\Delta m t}{\hbar} \right]$$

$$\int dt P(B^0 \rightarrow \bar{B}^0) = \chi = \frac{1}{2} \frac{(\frac{\Delta m}{\Gamma})^2}{1 + (\frac{\Delta m}{\Gamma})^2} \quad \chi = \frac{\Delta m}{\Gamma}$$

$I(4s) \rightarrow \chi_d, \chi_s$

$\chi = f_d \chi_d + \alpha f_s \chi_s$  (LEP)

Oscylacje  $B^0$

METODY BADANIA

1)  $l^\pm e^\pm$  leptony z rozpadów SL  $B R = \frac{N_{l^\pm l^\pm}}{N_{l^\pm l^\pm} + N_{l^\pm l^\mp}}$   
 $l^{++} / l^{--} \rightarrow$  MIESZANIE

(Poprawki na mod.  $B_d^+ B^+ \leftarrow I(4s)$   
 $B_d^0 B_s^0 \leftarrow$  LEP

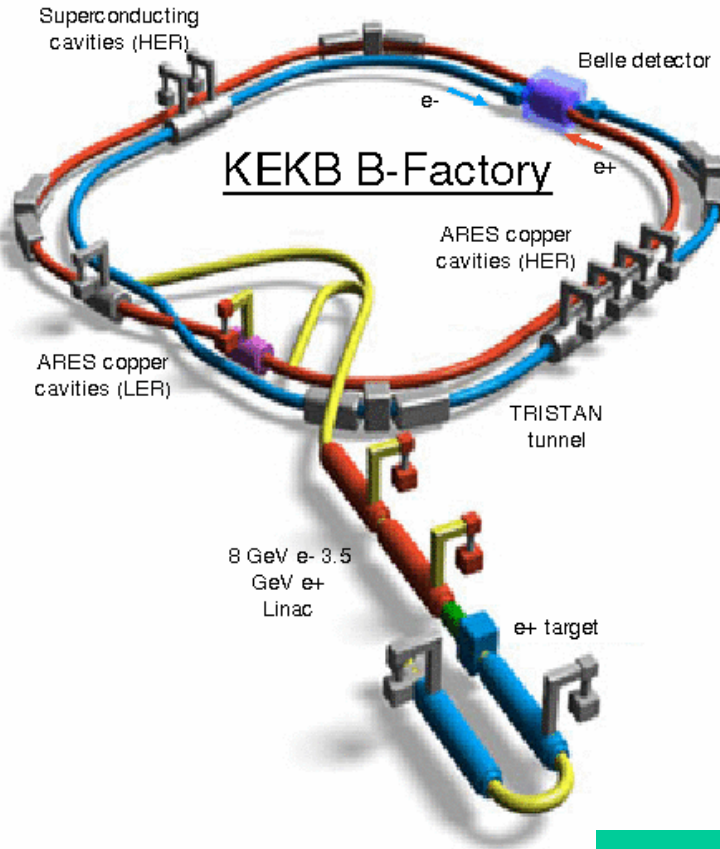
2) TABUNKI JETÓW

3) TABUNKI JETÓW + ZNAK  $D^*$  (DELPHI)

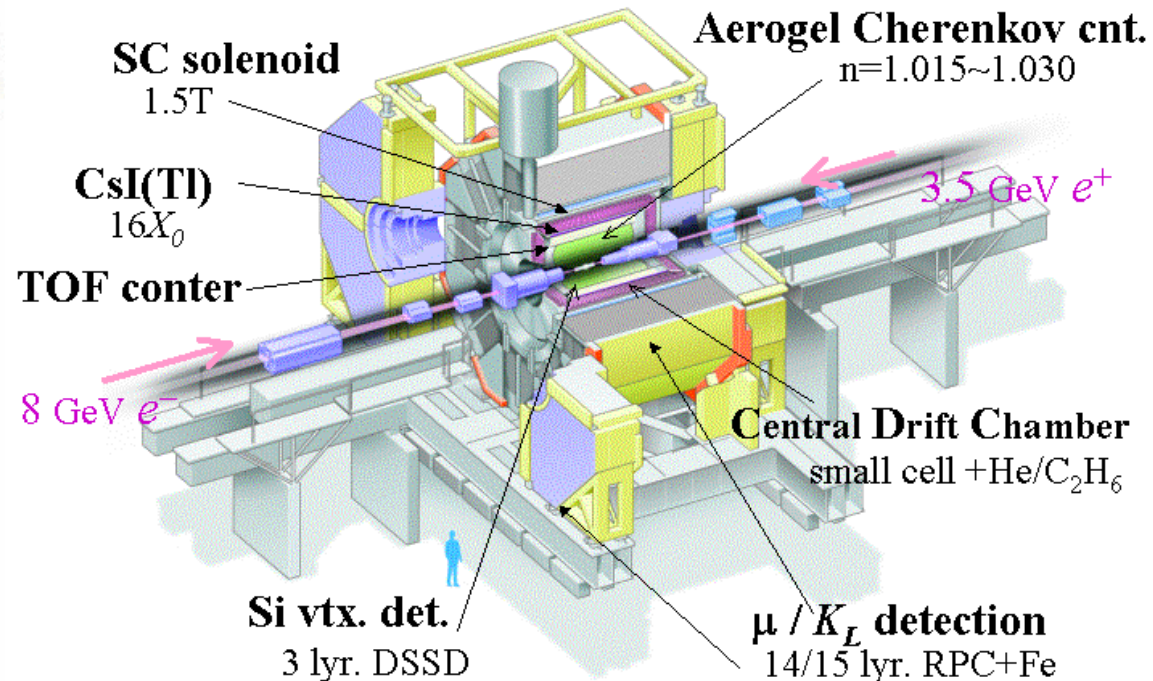
4)  $l^\pm$  + TABUNKI  $D^*$  (OPAL, ALEPH)

$\chi_d \rightarrow$   
 $\bar{\chi} \rightarrow$   
 $\Delta m_d \rightarrow$

# Belle Experiment



## Belle Detector



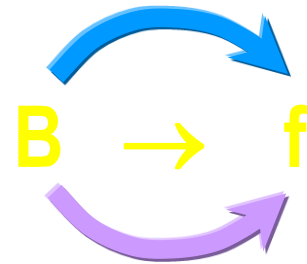
1.3 million  $\bar{B} B$  pairs  
/ day

Total  $\approx 770 \times 10^6 \bar{B} B$

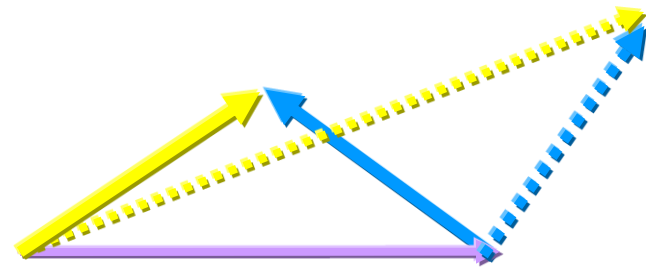


# OBSERWACJA FAZY MACIERZY CKM

*Co najmniej dwie amplitudy:*



*porównywalnej wielkości*



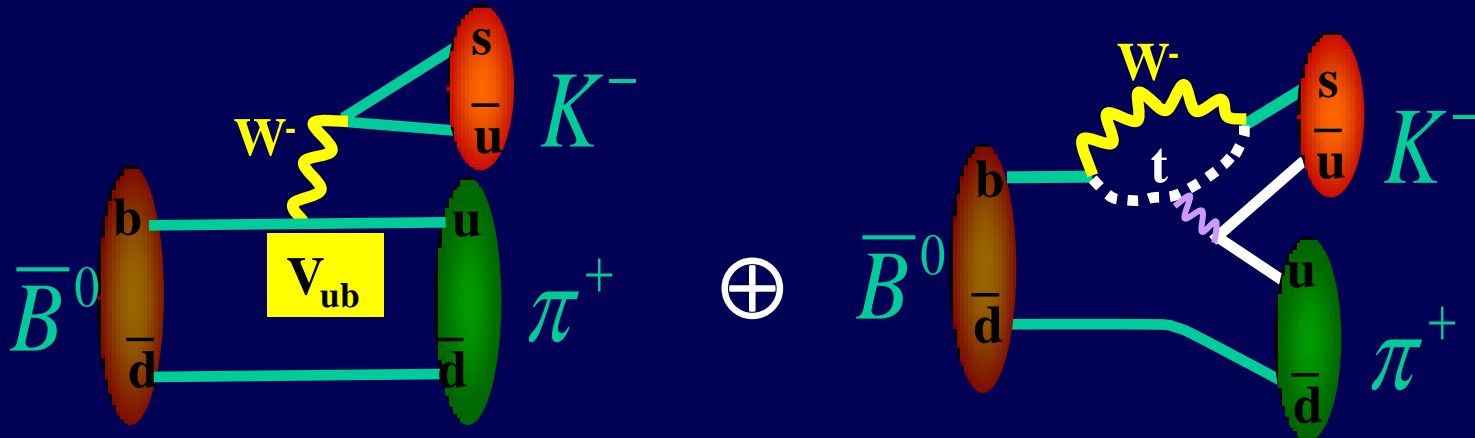
*efekty znacznie słabsze gdy*

$$A_2 \ll A_1$$



# CPV w rozpadach

$$\Gamma(\bar{B}^0 \rightarrow K^- \pi^+) \stackrel{?}{=} \Gamma(B^0 \rightarrow K^+ \pi^-)$$



$$Br(\bar{B}^0 \rightarrow K^- \pi^+) = 1.8 \times 10^{-5}$$

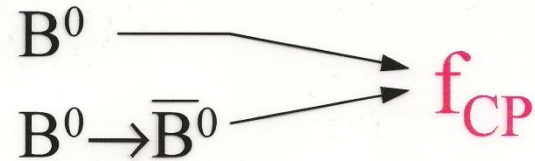
Belle  $\oplus$  BaBar 2006

$$A_{CP}(K^+ \pi^-) = -0.093 \pm 0.015$$

## Lamanie CP w sektorze B



łamanie CP - obserwabla



$$r = \frac{q}{p} \cdot \frac{\langle f | \bar{B}^0 \rangle}{\langle f | B^0 \rangle}$$

$$q/p = \xi_t^* / \xi_t$$

$$\xi_t = V_{tb} V_{t\alpha}^*$$

$\alpha = d, s$

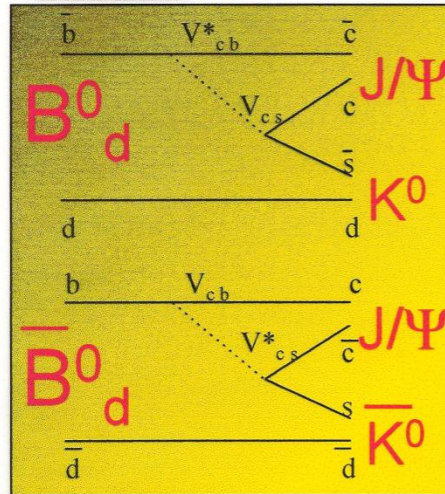
Niezmiennik reprezentacji  $V_{CKM}$

$$N(B^0(t) \rightarrow f_{CP}) \propto N(B^0) \cdot e^{-\gamma t} \cdot [1 - \text{Im } r_{CP} \cdot \sin(\Delta m t)]$$

$$N(\bar{B}^0(t) \rightarrow f_{CP}) \propto N(\bar{B}^0) \cdot e^{-\gamma t} \cdot [1 + \text{Im } r_{CP} \cdot \sin(\Delta m t)]$$



## łamanie CP - observable



$$\frac{q}{p} = \frac{V_{td}}{V_{td}^*} = \frac{1-\rho-i\eta}{1-\rho+i\eta}$$

$$\frac{\langle f | \bar{B}^0 \rangle}{\langle f | B^0 \rangle} = \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} = 1$$

$$\text{Im } r_{CP} = \sin 2\beta$$

(CP | J/ψ K<sub>s</sub> > = - | J/ψ K<sub>s</sub> >)

$$A_{J/\psi K_s} = -\frac{x_d}{1+x_d^2} \sin 2\beta$$

$$a(t)_{J/\psi K_s} = -\sin 2\beta \cdot \sin \Delta m t$$

$$\beta: B_d \rightarrow J/\psi K_s \quad \Rightarrow \text{Im } r_{CP} = +\sin 2\beta$$

$$\alpha: B_d \rightarrow \pi^+ \pi^- \quad \Rightarrow \text{Im } r_{CP} = \sin 2\alpha$$

$$\gamma: B_s \rightarrow \rho K_s \quad \Rightarrow \text{Im } r_{CP} = -\sin 2\gamma$$

$$B_s \rightarrow J/\psi \phi \quad \Rightarrow \text{Im } r_{CP} \approx 2 \frac{|V_{cd} V_{ub}|}{V_{cb}} \sin \gamma \approx 2\lambda^2 \eta$$



## łamanie CP - observable

$$\begin{aligned}
 a(t) &= \frac{N(B^0(t) \rightarrow f_{CP}) - N(\bar{B}^0(t) \rightarrow f_{CP})}{N(B^0(t) \rightarrow f_{CP}) + N(\bar{B}^0(t) \rightarrow f_{CP})} \\
 &= -\text{Im } r_{CP} \cdot \sin(\Delta m t)
 \end{aligned}$$

$$\begin{aligned}
 A_{CP} &= \frac{N(B^0 \rightarrow f_{CP}) - N(\bar{B}^0 \rightarrow f_{CP})}{N(B^0 \rightarrow f_{CP}) + N(\bar{B}^0 \rightarrow f_{CP})} \\
 &= \frac{\int dt N(B^0(t) \rightarrow f_{CP}) - \int dt N(\bar{B}^0(t) \rightarrow f_{CP})}{\int dt N(B^0(t) \rightarrow f_{CP}) + \int dt N(\bar{B}^0(t) \rightarrow f_{CP})} \\
 &= -\frac{x}{1+x^2} \text{Im } r_{CP}
 \end{aligned}$$

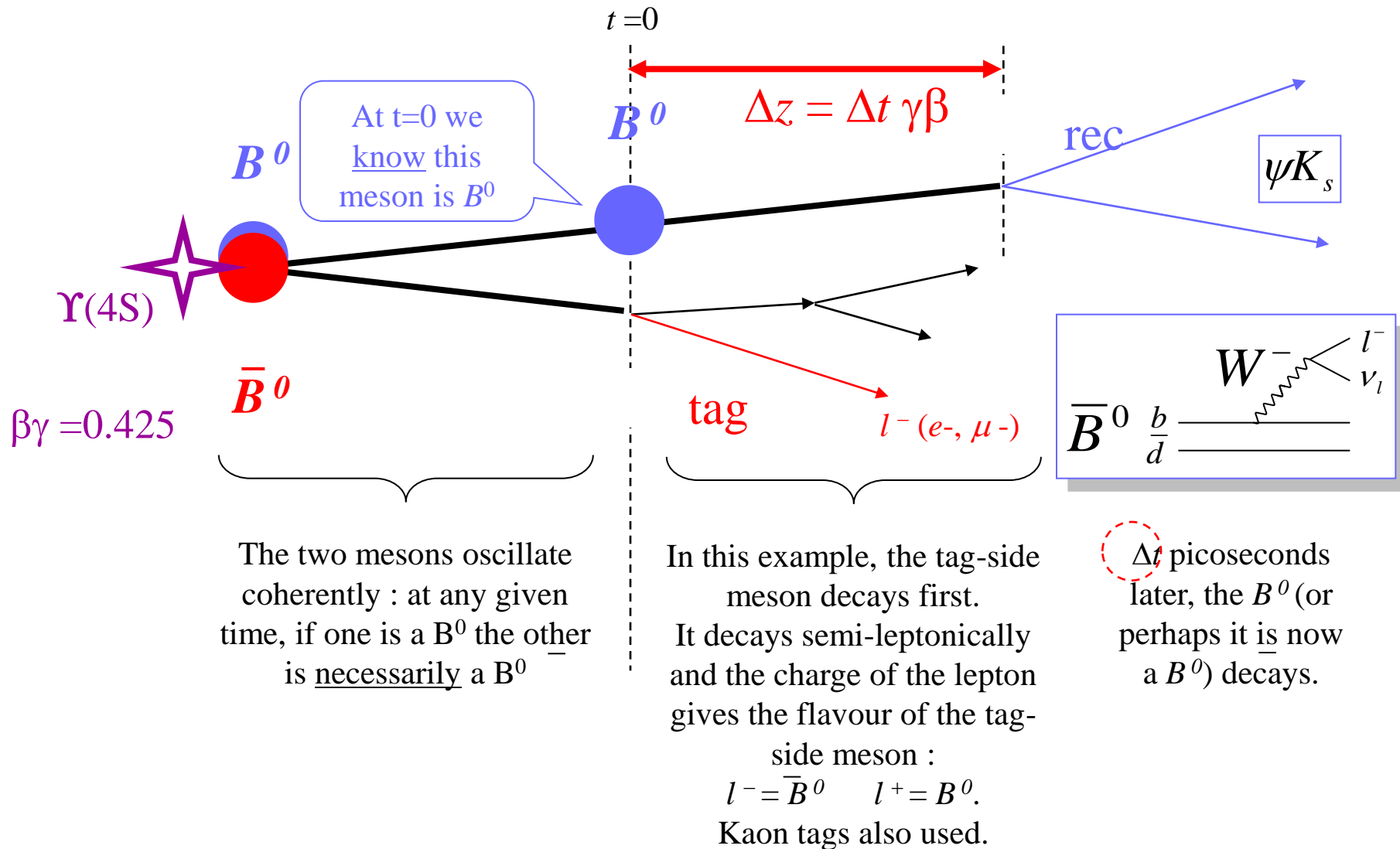
$$x = \Delta m / \gamma$$

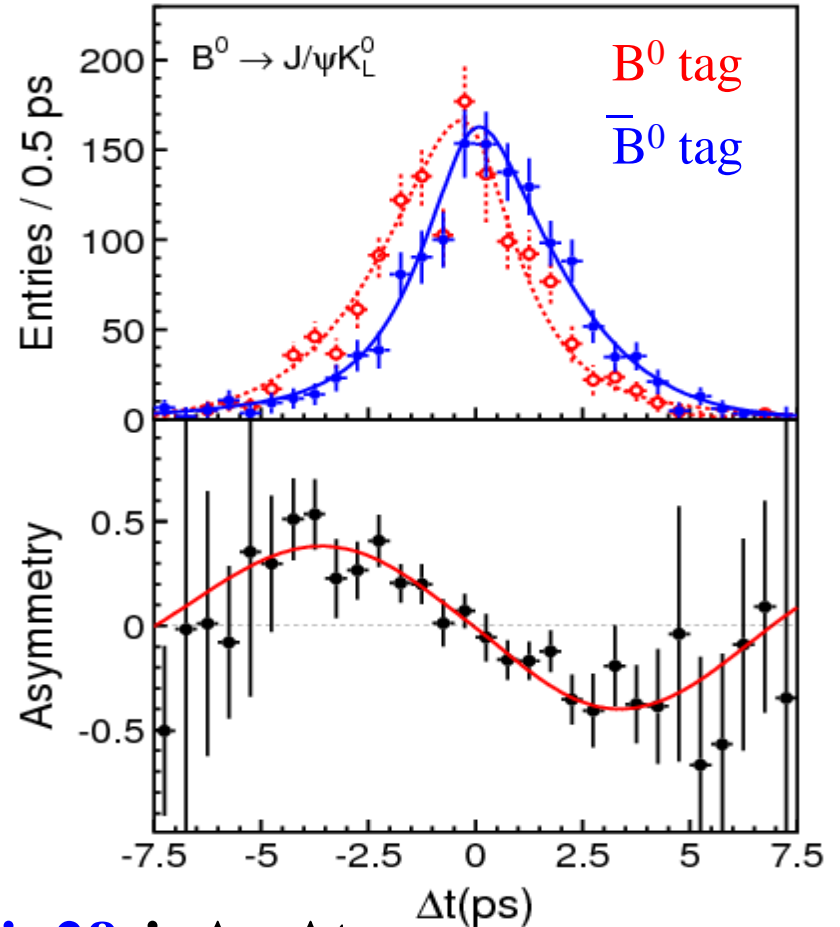
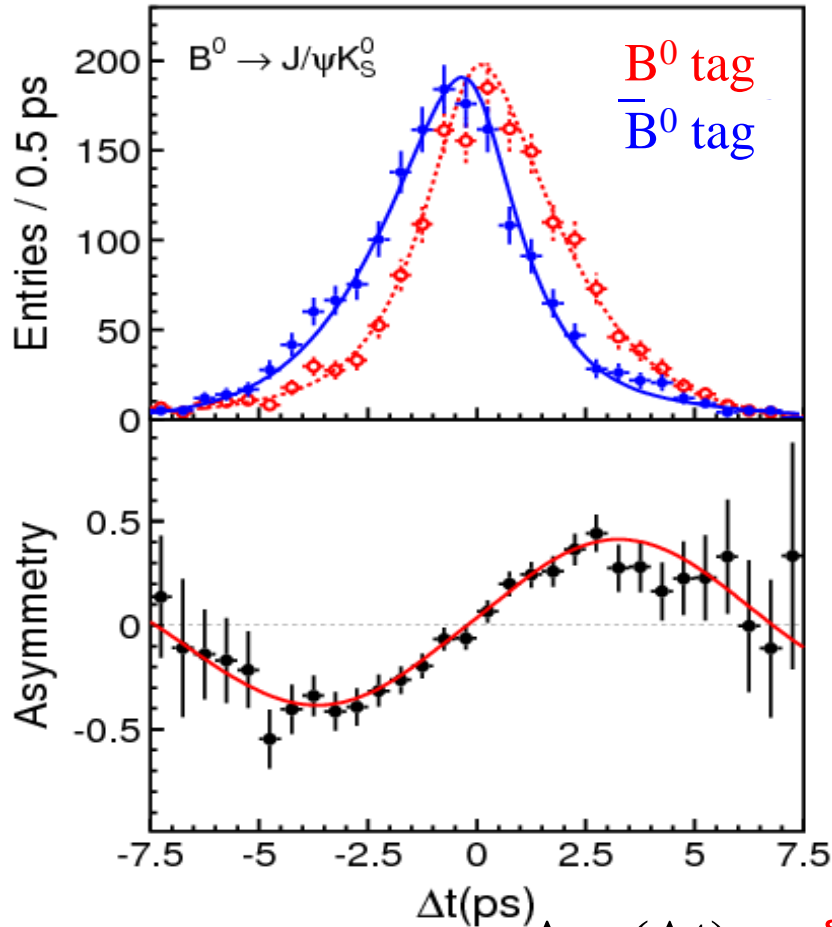
$$x_d = 0.73 \pm 0.05$$

$$x_s > \text{kilkanaście}$$



# Jak mierzyć $d\Gamma/dt$





$$A_{CP}(\Delta t) = -\xi_{CP} \sin 2\beta \sin \Delta m \Delta t$$

$\sin 2\beta = +0.643 \pm 0.038$

$\sin 2\beta = +0.641 \pm 0.057$

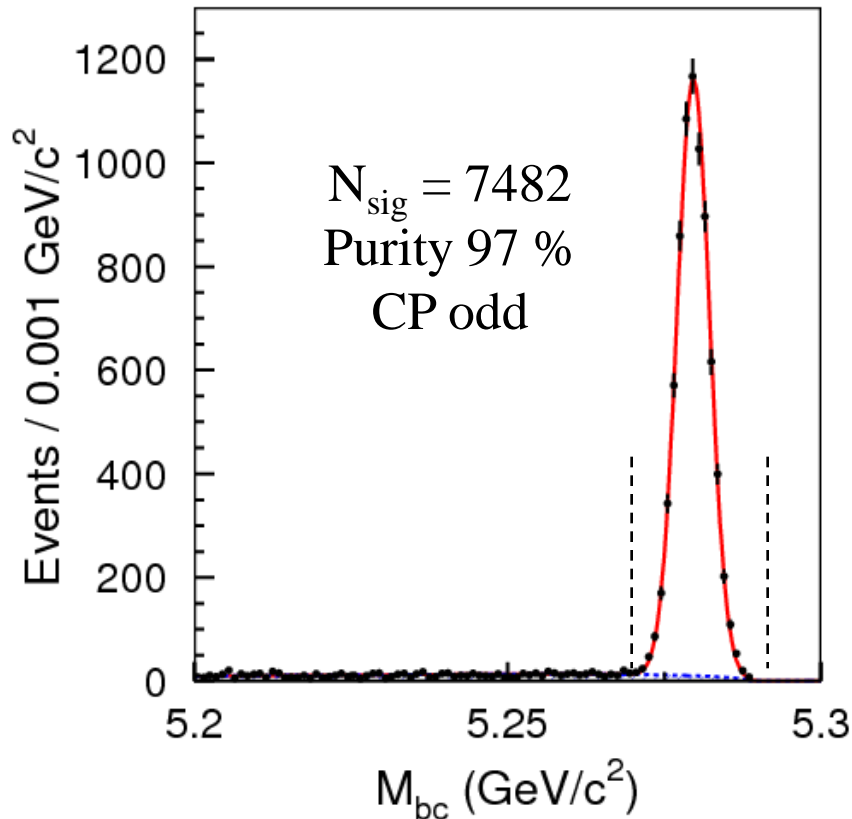
$\sin 2\beta = 0.642 \pm 0.031 \text{ (stat)} \pm 0.017 \text{ (syst)}$

hep-ex/0608039

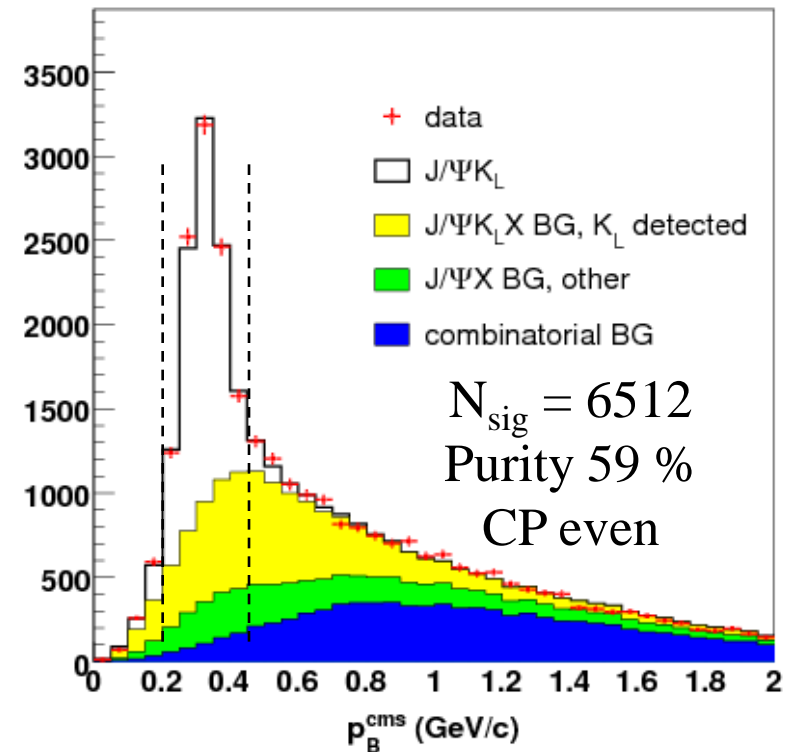
# $B^0 \rightarrow J/\psi K^0 : 535 \times 10^6$ par $\bar{B}B$



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



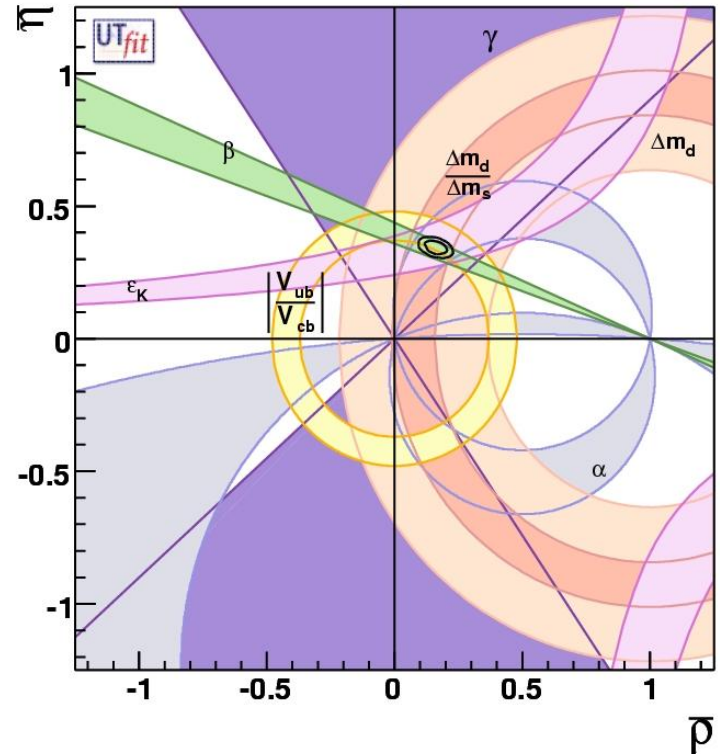
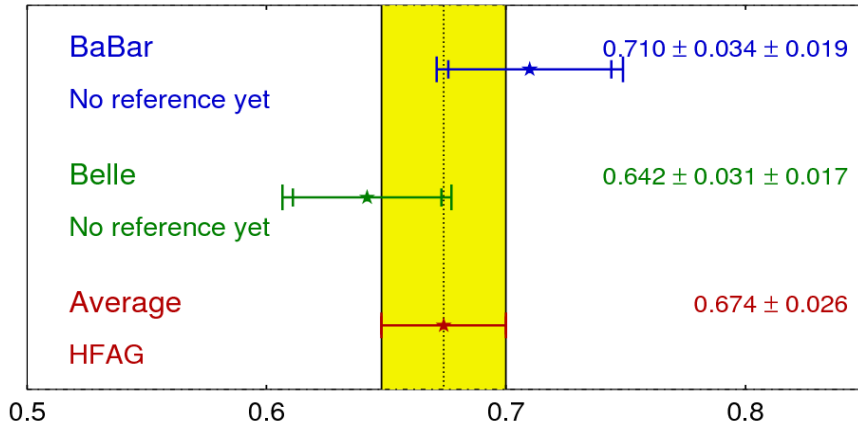
$B^0 \rightarrow J/\psi K_L^0$



# 2006: BaBar + Belle

$$\sin(2\beta) \equiv \sin(2\phi_1)$$

**HFAG**  
ICHEP 2006  
PRELIMINARY



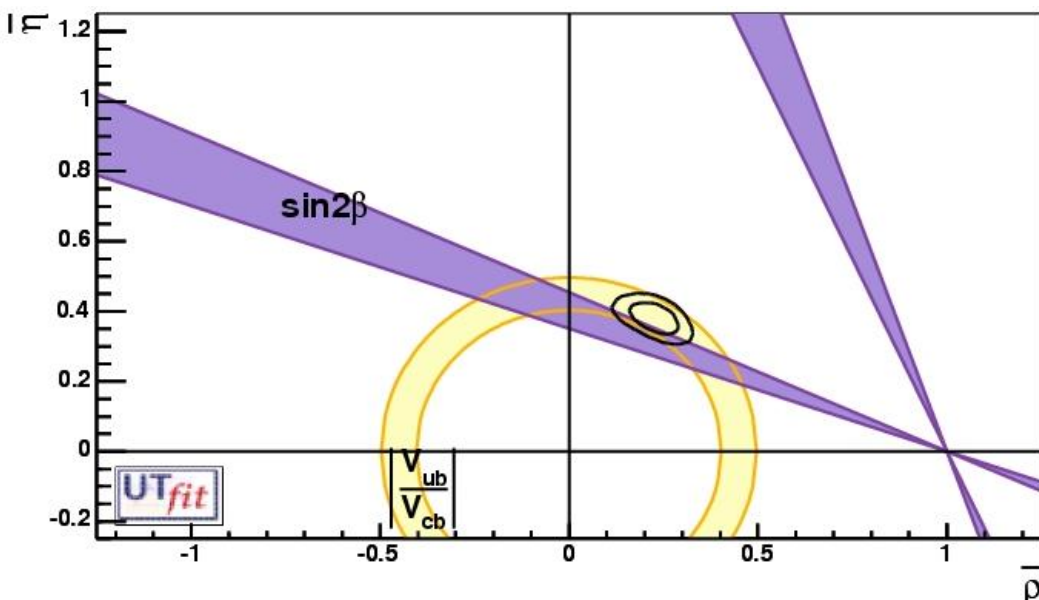
**CPV  $\sim O(1)$  !**

- faza CKM wyznaczona bez niepewności hadronowych (w przeciwieństwie do  $\epsilon, \epsilon'$  z rozpadów kaonów)

(1 $\sigma$ )  $\alpha/\phi_2 = [83^{+12}_{-23}]^\circ$   $B^0 \rightarrow \pi$   
 $\pi, \rho\pi, \rho$

$\gamma/\phi_3 = [62^{+38}_{-24}]^\circ$   $B^0 \rightarrow D^{(*)}$   
 $K^{(*)}$

# $\sin 2\beta$ vs $|V_{ub}|/|V_{cb}|$



**$\sin 2\beta = 0.675 \pm 0.026$**   
**bezpośrednie pomiary**

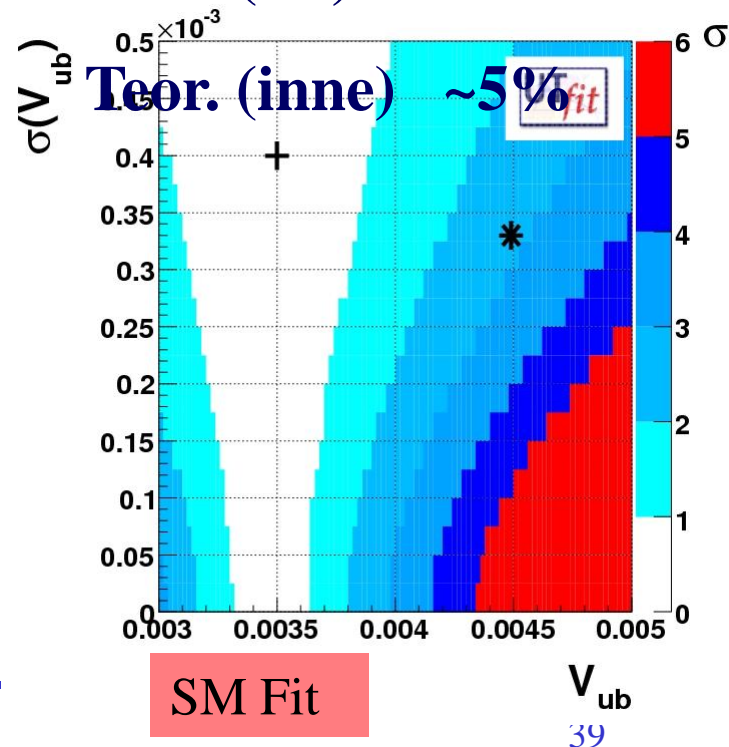
**$\sin 2\beta = 0.764 \pm 0.039$**   
**pośredni pomiar**  
**(pozostałe pomiary bez  $\sin 2\beta$ )**

**$|V_{ub}|$  @ 7.4%**

**Exp. stat  $\pm 2.2\%$**

**Exp. syst  $\pm 2.7\%$**

**Teor. (SF)  $\pm 4.1\%$**



**SM Fit**

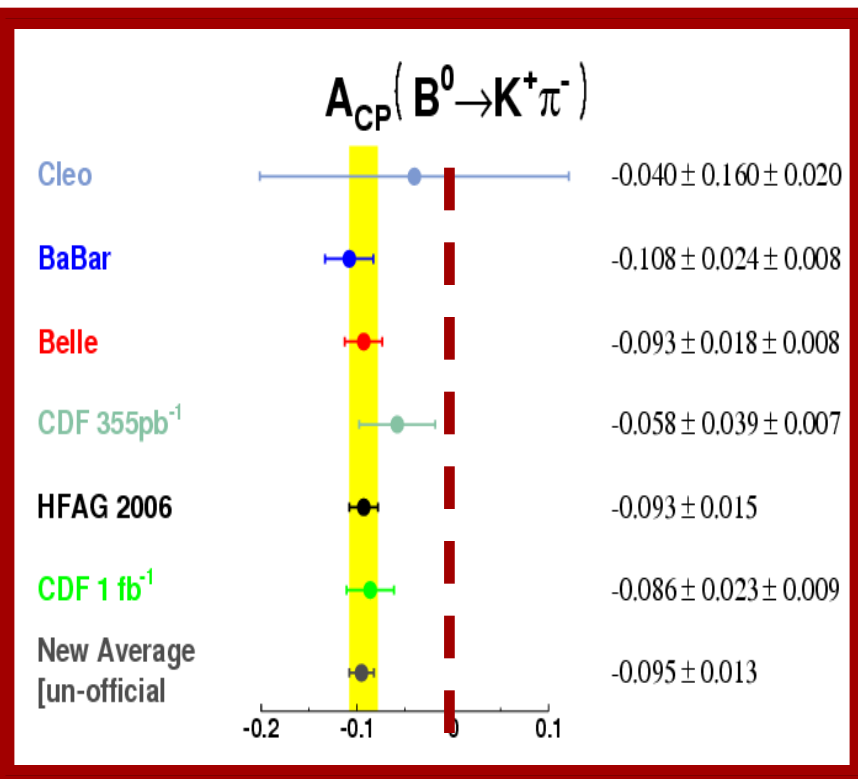
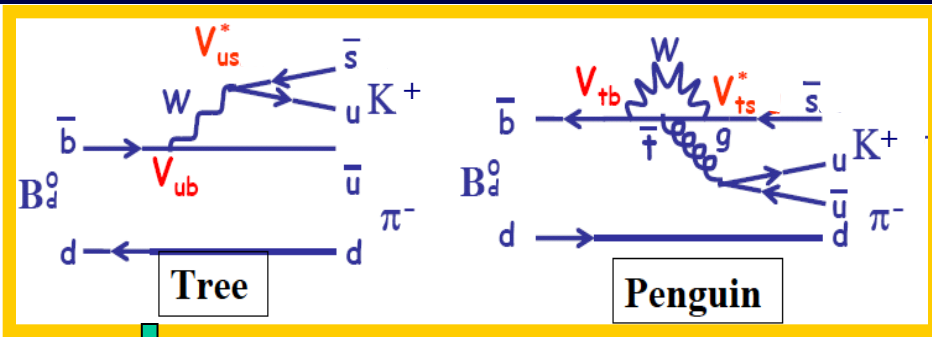
**$V_{ub}$**   
39



# Czego się dowiedzieliśmy ?

- **Zaobserwowano różne przejawy łamania CP w rozpadach B, przewidywane przez mechanizm Kobayashiego-Maskawy**
  - łamanie CP wprost
  - łamanie CP poprzez interferencję mieszania i rozpadów
- **Asymetrie CP w sektorze B są duże ( $\mathcal{O}(0.1) \div \mathcal{O}(1)$ )**
  - duża wartość fazy odpowiedzialna za CPV ustalona doświadczalnie
  - przybliżona symetria CP (mogła być zgodna z CPV w rozpadach kaonów) jest wykluczona
- **Pomiary z fabryk B „nadokreślają” Trójkąt Unitarności**
- **Model łamania CP Kobayashiego-Maskawy jest sprawdzoną teorią**

# $A_{CP}(B \rightarrow K\pi)$



- $A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.095 \pm 0.013$   $7 \sigma$
- $A_{CP}(B^+ \rightarrow K^+ \pi^0) = 0.04 \pm 0.04$   
niezgodność z  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$   $4.9 \sigma$
- Czy niezgodność z MS ?

# Jak się pozbyć “niepewności hadronowych”

## 1. Uprościć

np.  $A_{CP}(\Delta t)$

$$A_{CP}(t) = -\xi_{CP} \sin 2\phi \sin(\Delta m_d t)$$

w rozpadach z przejściem  $b \rightarrow s$  ( $\phi K, \eta' K, \dots$ )

## 2. Unikać hadronów

rozpady leptonowe, półleptonowe, radiacyjne

$B \rightarrow \mu\mu, B \rightarrow \tau\nu, B \rightarrow D\tau\nu, b \rightarrow s\gamma, B \rightarrow (\rho, \omega)\gamma, b \rightarrow sll$

## 3. Jedno i drugie

$A_{CP}$  w  $b \rightarrow s\gamma$

$A_{FB}$  w  $B \rightarrow K^* ll$

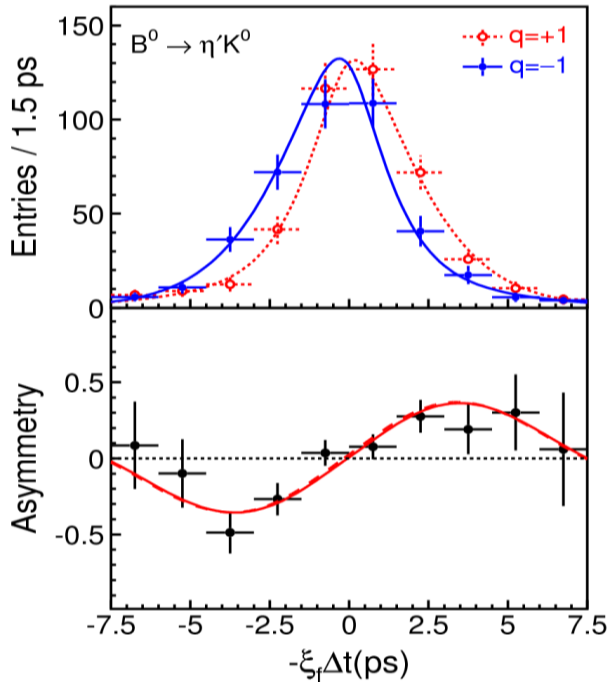
# $A_{CP}(t)$ w $B^0 \rightarrow \eta'K^0$



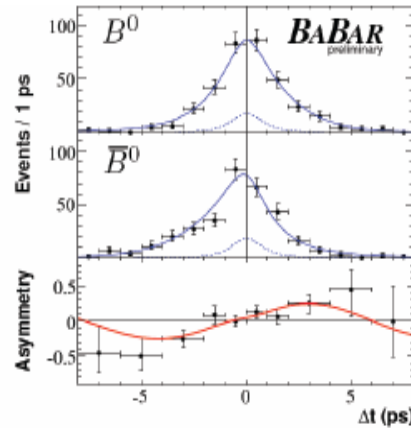
535M  $B\bar{B}$



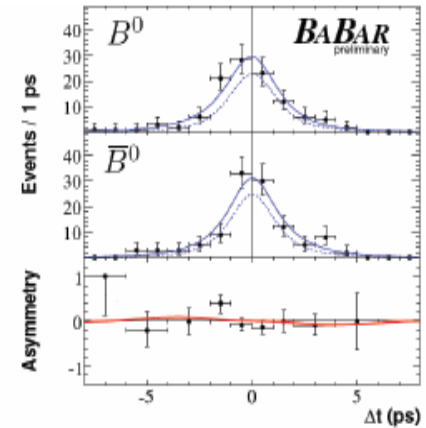
347M  $B\bar{B}$



$\eta'K_S^0$



$\eta'K_L^0$



Mode	Signal yield	$-\eta S$	$C$
$\eta'K_S^0$	$936 \pm 41$	$0.57 \pm 0.11$	$-0.18 \pm 0.08$
$\eta'K_L^0$	$168 \pm 21$	$0.39 \pm 0.30$	$0.20 \pm 0.23$

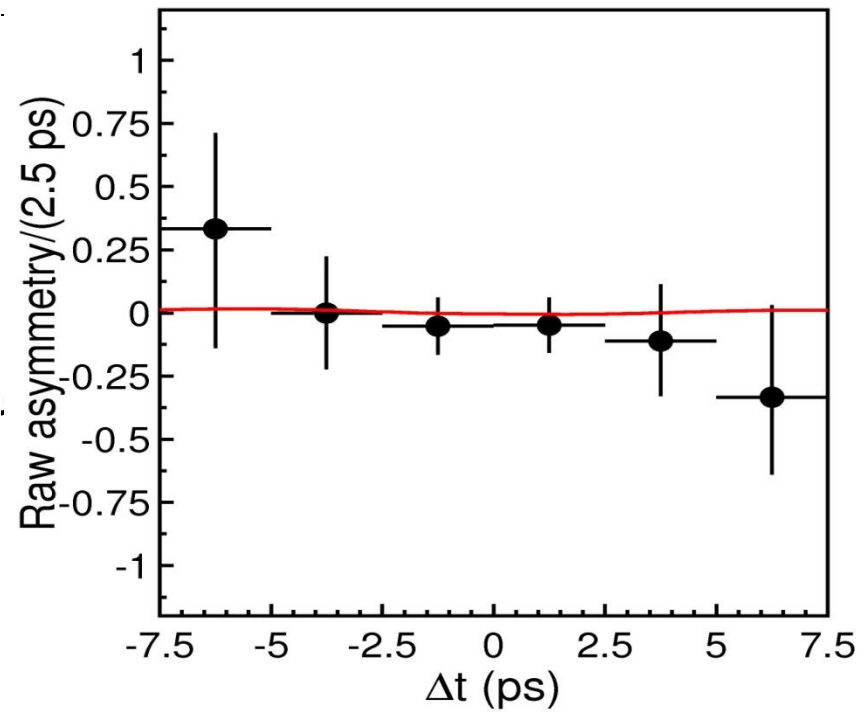
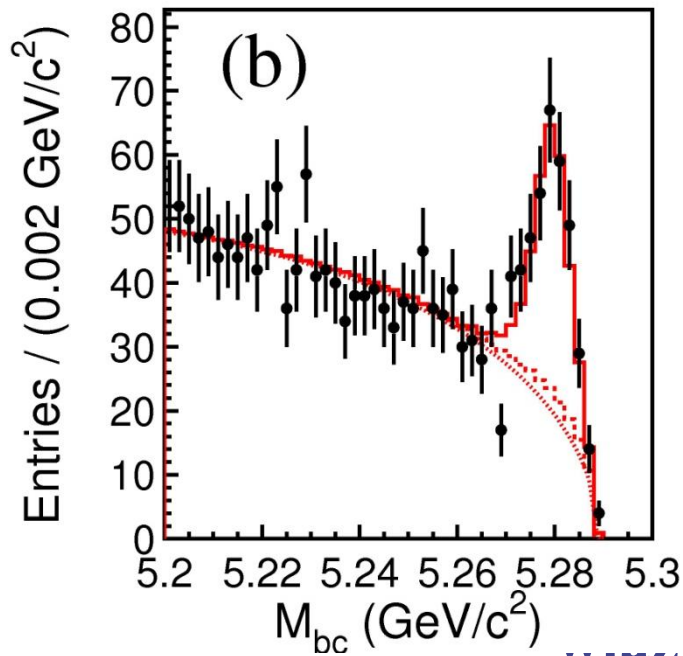
**pierwsza obserwacja  $tCPV$  ( $5.6\sigma$ )  
w pojedynczym kanale  $b \rightarrow s$**

# $A_{CP}(\Delta t) \text{ B} \rightarrow X_s \gamma$

$\gamma$   
 $\pi^-$

- Model Standardowy  $\Rightarrow$   
 $A_{CP}(\Delta t) \approx 0$   
 - foton jest spolaryzowany

$A_{CP}(\Delta t)$



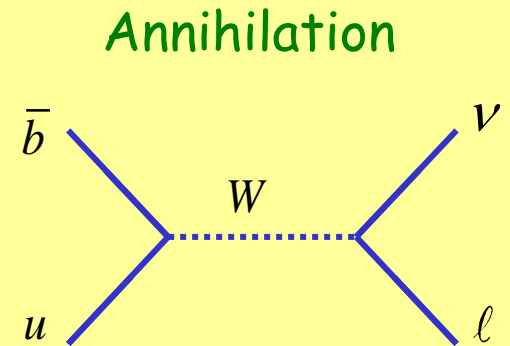
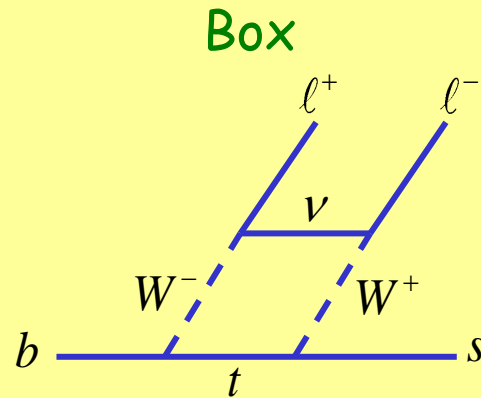
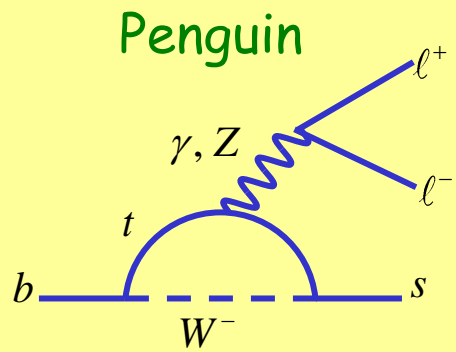
$\pi^-$

pomiar dla super-fabryk B



# Rozpady leptonowe B

## Wiele różnych procesów



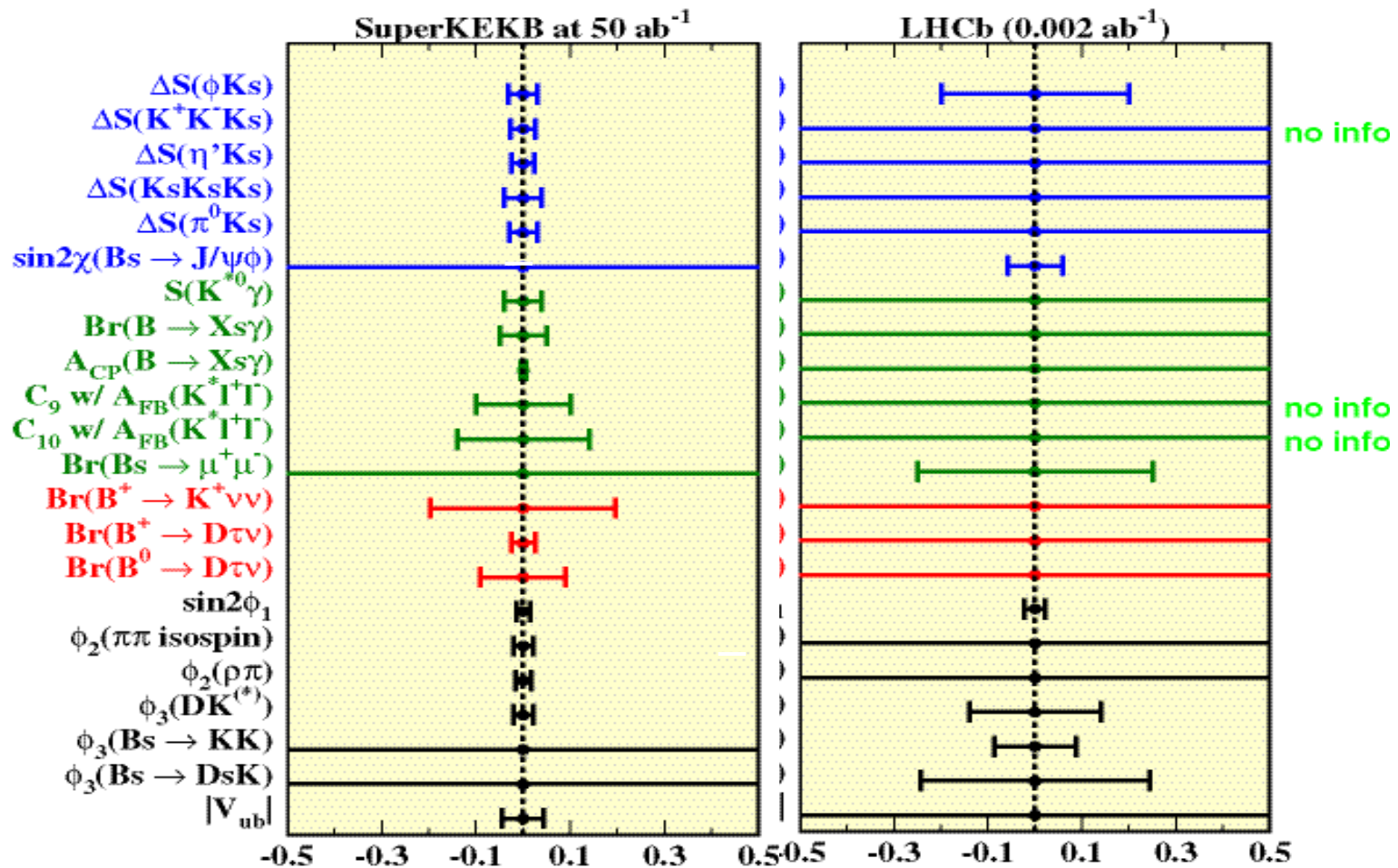
# Identyfikacja Nowej Fizyki

## Odchylenia od Modelu Standardowego

Observables SUSY models	Bd- unitarity	$\varepsilon$	$\Delta m(Bs)$	B- $\rightarrow\phi Ks$	B- $\rightarrow M s \gamma$ indirect CP	b- $\rightarrow s \gamma$ direct CP
<b>mSUGRA</b>	-	<p>“DNA identification” of new physics</p>				+
<b>SU(5)SUSY GUT + <math>\nu_R</math> (degenerate)</b>	-					-
<b>SU(5)SUSY GUT + <math>\nu_R</math> (non-degenerate)</b>	-					+
<b>U(2) Flavor symmetry</b>	+	+	+	++	++	++

++: duże, +: znaczne, -: małe

# SuperKEKB vs LHCb



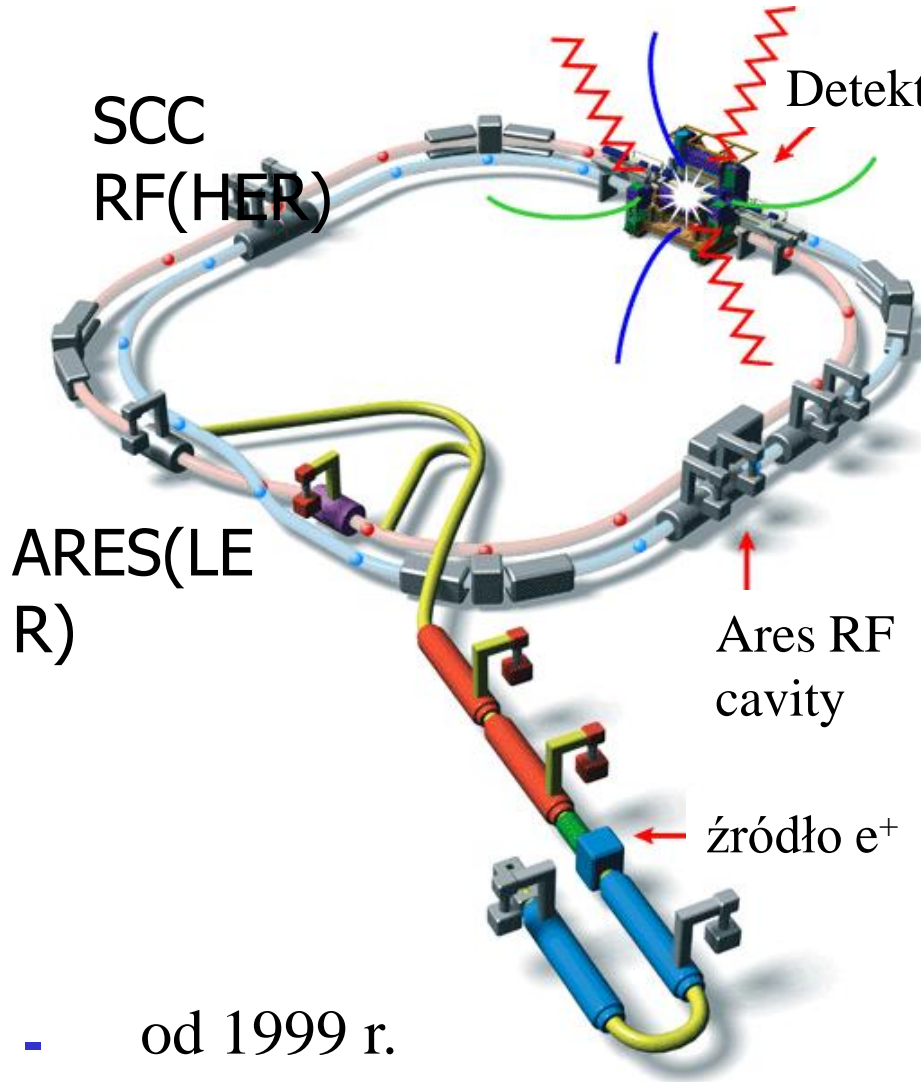
$$\text{B}(B_s \rightarrow \gamma) < 0.53 \times 10^{-4}$$

(90% CL)

< 2  $\text{fb}^{-1}$  (3 dni naświetlań @)



# The KEKB Collider



8 x 3.5 GeV

22 mrad kąt przecięcia wią

światłość:

$$L = 1.6 \times 10^{34} / \text{cm}^2 / \text{sec}$$

od 1999 r.



POMIAR  $R_B = BR(Z^0 \rightarrow B \ B\bar{A}R)$   
W LEPIE

# Oznaczanie dżetów b za pomocą detektorów wierzchołka

EPS-BRUSSELS

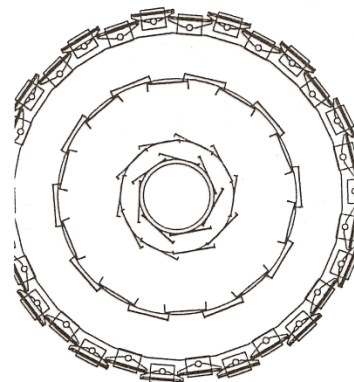
C. TRONCON

Comparison of Vertex Detectors

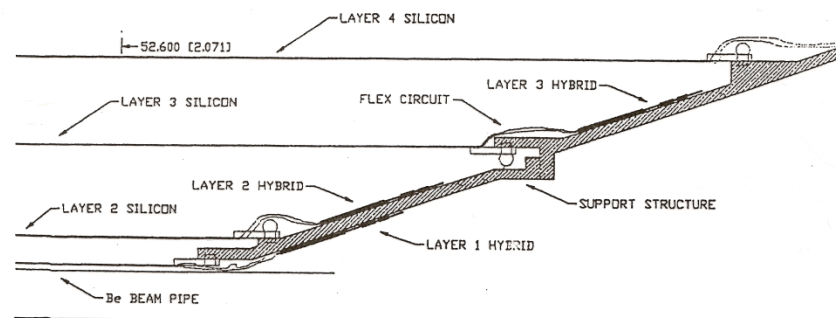
Experiment	SLD-VXD3	CDF-SVXII	CLEOIII	DELPHI	HI-CST
layers	3	5	4	3	2
radii [cm]	2.8, 3.8, 4.8	2.4, 4.1, 6.5, 8.3, 10.2	2.5, 3.75, 7.5, 12.	6.3 (ds), 9 (ss), 10.9 (ds)	5.75, 9.7
active length [cm]	16	96	variable	22.7, 22.7, 27.3	35
barrels	1	3	$\cos(\theta)=.93$		
$\phi$ modularity	12, 16, 20	12	7, 10, 20, 30	24	12, 18
detectors	96	720	566	288	180
strip pitch					
rphi [ $\mu\text{m}$ ]	20 (CCD)	60, 62, 60, 60, 65	50 n-side	25	25
z [ $\mu\text{m}$ ]	20 (CCD)	150, 133, 60, 150, 65	100 p-side	49.5, 99, 150; 42	88
readout pitch					
rphi [ $\mu\text{m}$ ]	20 (CCD)	60, 62, 60, 60, 65	50	50	50
z [ $\mu\text{m}$ ]	20 (CCD)	150, 133, 60, 150, 65	100	49.5, 99, 150; 42, 84	88
detector area [cm <sup>2</sup> ]	8.0 x 1.6	7.8 x (1.7, 2.5, 3.9, 4.7, 5.9)	5.12 x 2.56	8.0 x 1.9, 6 x 1.9 (ds) 5.8 x 2.6 (ss) 5.8 x 3.2 (ds)	5.63 x 3.20
detectors/ladder	2	4	4-12	4	6
S/N	20	14 (expect.)	48 - 15 (expect.)	13-18 (meas.)	15 (expect.)
spatial resolution					
R $\phi$ [ $\mu\text{m}$ ]	5			7.6	
z [ $\mu\text{m}$ ]	6			9	
I.P. resolution					
R $\phi$ [ $\mu\text{m}$ ]	9 (exp.), 13	$\sim 15$	$\sim 15$	20 (meas.)	$\sim 30$ in 1995
z [ $\mu\text{m}$ ]	14 (exp.), 35			39 (meas.)	$\sim 60$ in 1994

at 1 GeV/c

CLEO 3 SILICON VERTEX DETECTOR



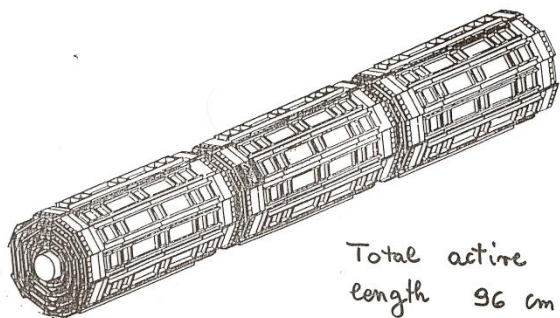
Layer	r (cm)	# detectors in $\phi$	# detectors in Z	$\Sigma$
1	2.4	7 or 8	3 or 4	28
2	3.75	10	4	40
3	7.5	20	8	160
4	12.0	30	12	360

 $\Sigma$  588 detectors

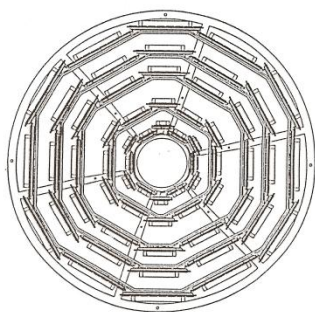


# VTX detectors

CDF SVX II



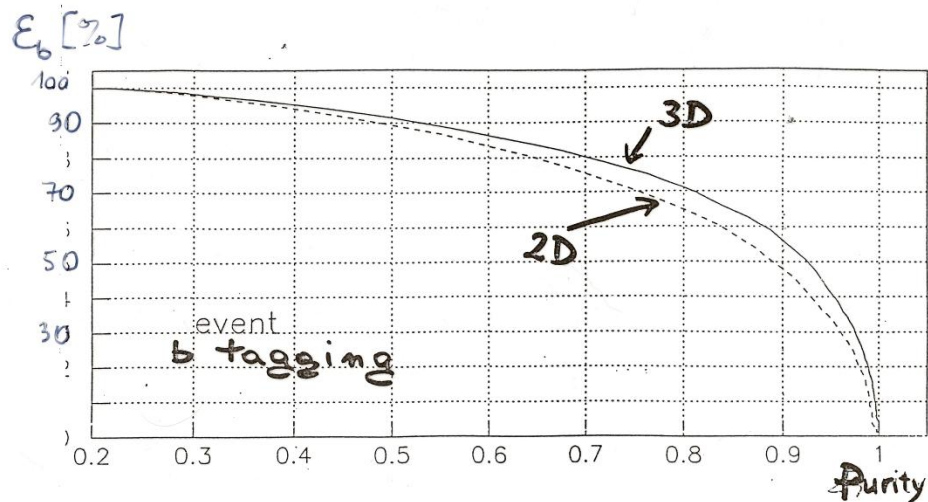
Total active length 96 cm



CDF - SVX II

Tracks	4 layers SVX II	5 Layers SVX II
$\epsilon_t$	$97 \pm 1\%$	$99 \pm 1\%$
axial purity	$93 \pm 1\%$	$95 \pm 1\%$
stereo purity	$82 \pm 1\%$	$90 \pm 1\%$

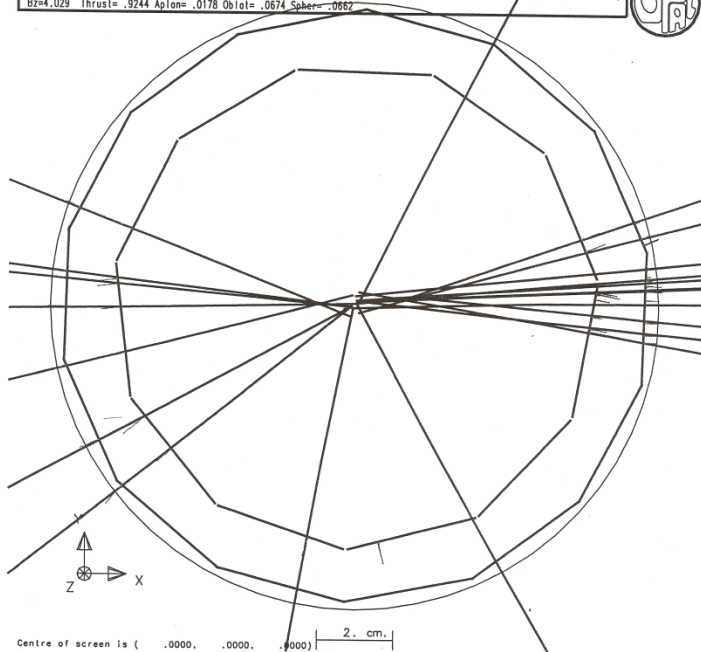
DELPHI '94



# Poszukiwanie wtórnego wierzchołka

## Double Lifetime Tagged Event

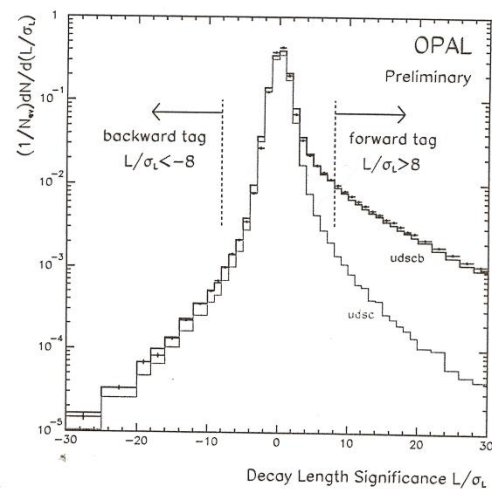
Run: event 3149: 12065 Date 920609 Time 90258 Ctrk(N= 28 Sump= 48.0) Ecol(N= 37 SumE= 33.5) Hcp(N=13 SumE= 13.5)  
 Ebeam 45.653 Evis 71.5 Emiss 19.8 Vtx ( -13, -.02, .20) Muon(N= 1) Sec Vtx(N= 1) Fst(N= 0 SumE= .0)  
 Bz=4.029 Thrust= .9244 Aplan= .0178 Oblat= .0674 Spher= .0662



## Secondary Vertex b Flavour Tag

Used by OPAL

- Reconstruct secondary vertices from tracks in each jet
- Reject vertices with fewer than four tracks
- Construct physics signed decay length significance



- Folded tag: subtract statistically backwards vertices from forwards vertices → reduces resolution uncertainties

# Oznaczanie dżetów b

## Impact Parameter Probability b Flavour Tag

- Construct "no-lifetime" probability for tracks with physics-signed impact parameter  $b > 0$ :

$$\mathcal{P}_T = \int_b^{\infty} \mathcal{R}(x) dx$$

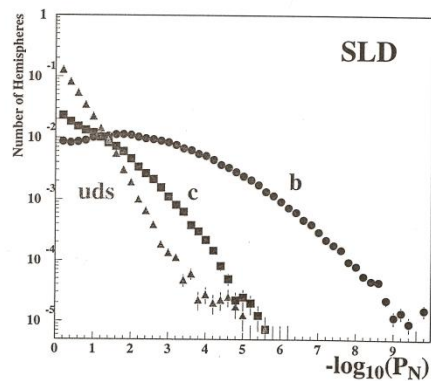
resolution function  $\mathcal{R}$  measured from  $b < 0$  distribution

- Construct joint probability for "no-lifetime" in the hemisphere:

$$\mathcal{P}_N \equiv \Pi \sum_{j=0}^{N-1} \frac{(-\ln \Pi)^j}{j!}$$

where

$$\Pi \equiv \prod_{i=1}^N (\mathcal{P}_T)_i$$



Used by ALEPH, DELPHI, SLD

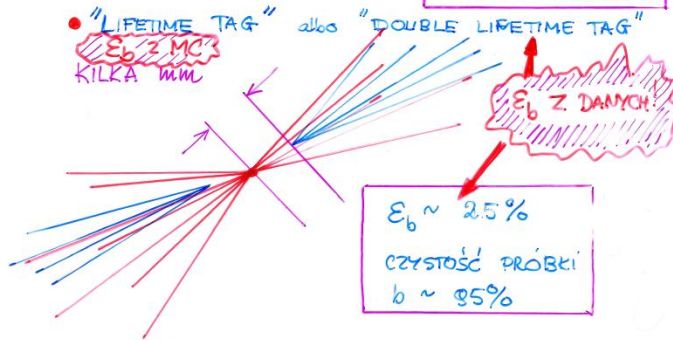
# Metoda pomiaru $R_b$ i $R_c$

## METODA POMIARU $R_b$ i $R_c$

- $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$
  - $e^+e^- \rightarrow Z^0 \rightarrow c\bar{c}$
- MUSIMY WYBRAĆ PRZYPADKI  $b\bar{b}$  LUB  $c\bar{c}$ .
- EFEKTYWNOŚĆ WYBORU I CZYSTOŚĆ PRÓBEK MUSZĄ BYĆ DOBRZE ZNANE

### METODY WYBORU PRÓBKI $b\bar{b}$

NIE PORWAĆ NA WYBRANIE CZYSTYCH  $c\bar{c}$



- LEPTON ( $e, \mu$ ) O DUŻYM ( $\approx 1-2 \text{ GeV}/c$ )  $\vec{p}_T$  WZGLĘDEM OSI DZETU (OŚ T, S, ...)

BR. ( $b \rightarrow l^+ \gamma X$ )  $\approx 10\%$  ← ZNAJOMOŚĆ WIDMA  $\gamma$

$E_b \sim 10\%$   
CZYSTOŚĆ  $\sim 90\%$

Widma  $l^+$  z  $b \rightarrow D^{**} l \nu$  } są inne?  
 $D^0 \pi l \nu \dots$

$N_{tot}$  = LICZBA  $Z^0 \rightarrow$  hadrony

**DOUBLE TAG**

$N_b$  = LICZBA ZNALEZIONYCH DZETÓW  $b$

(JEŻELI ZNALEZIONO 2 DZETU  $b$  W 1 PRZYPADKU  $\equiv$  LICZYMY 2 RAZY)

$N_{bb}$   $\equiv$  LICZBA PRZYPADKÓW, W KTÓRYCH OBA DZETU BYŁY ROZPOZNANE JAKO  $b$ .

$$\epsilon_b = \frac{2 N_{bb}}{N_b} \quad \text{EFEKTYWNOŚĆ ZNALEZIENIA DZETU } b$$

$$R_b = \frac{N_b}{2 N_{tot} \epsilon_b} = \frac{N_b^2}{4 N_{tot} N_{bb}}$$

- AKCEPTACJE  $N_{tot}$  i  $N_b$  SA W PRZYBLIŻENIU RÓWNE
- ZANIEDBUJEMY KORELACJE
- OBECNOŚĆ TEA KOMPLIKUJE OBRAZ  $\rightarrow$  DOMINUJĄCYM TEEM JEST  $Z^0 \rightarrow c\bar{c}$

# Metoda pomiaru $R_b$ i $R_c$

Uwzględniając korelacje

$N_t \equiv N$  "tagowanych", znaczonek cząstek

$N_{tt} \equiv N$  przypadków z 2 znaczoneymi cząstkami

$$R_{tt} = \frac{N_t}{N_{tot}} = R_b \cdot \epsilon_b + R_c \epsilon_c + (1 - R_b - R_c) \epsilon_{uds}$$

$$\begin{aligned} R_{tt} &= \frac{N_{tt}}{N_{tot}} = R_b \epsilon_{bb} + R_c \epsilon_{cc} + (1 - R_b - R_c) \epsilon_{uds} \epsilon_{uds} \\ &= R_b (\epsilon_b^2 + \rho_b (\epsilon_b - \epsilon_b^2)) + R_c \epsilon_c^2 + \\ &\quad + (1 - R_b - R_c) \epsilon_{uds}^2 \end{aligned}$$

$\epsilon_b$  DUNE ( $\sim 20\%$ )

$\epsilon_c, \epsilon_{uds}$  małe  $\rightarrow$  zaniedbyjemy ( $\epsilon_i^2$ )  
korelacja

ROZWIĄZUJEMY SZUKAJĄC  $R_b$  i  $\epsilon_b$

ZAKŁADAJĄC np  $R_c^{SM}$

DELPHI 195

$\epsilon_c, \epsilon_b, \epsilon_{uds} = \text{symulacji}$

$$(1.7 \pm 0.03 \pm 0.16) \times 10^{-2}$$

$$(-0.26 \pm 0.15 \pm 0.09) \times 10^{-2}$$

$$(0.323 \pm 0.006 \pm 0.024) \times 10^{-2}$$

$$\Delta R_b = -0.13 (R_c - R_c^{SM})$$

$$R_b = 0.2224 \pm 0.0027 \pm 0.0034 \pm 0.018 (R_c)$$

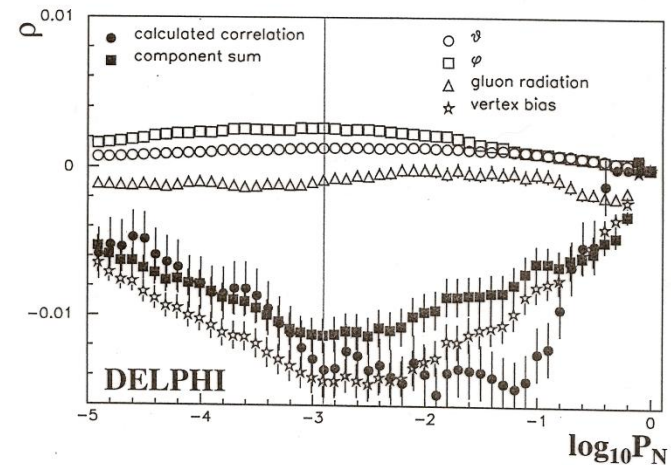
$$\epsilon_b = 0.201 \pm 0.003 \text{ (MC: 0.195)}$$

Total efficiency correlation  $\rho$ :

$$\rho = \frac{C_b(\epsilon^b)^2 - \epsilon^b}{(\epsilon^b - (\epsilon^b)^2)}$$

typically:

- $\rho$  -1% to -2% for IP probability tag
- $\rho$  +0.2% for secondary vertex tag



Systematics from statistics, residual MC-data differences



# Metoda pomiaru $R_b$ i $R_c$

## METODY WYBORU PRÓBKI $c\bar{c}$

- WYBÓR  $D^{*\pm}$  O DUŻYM PĘDZIE  
W JEDNYM Z DEZETÓW ( $b \rightarrow D^{*\pm}$  małe)
- LIFETIME /  $p_T^L$  / KSZTAŁT PRZYPADKU  
SĄ KRYTERIAMI POMOCNICZYMI  $c/b$

$f(c \rightarrow D^{*\pm})$  NIE JEST DOBRZE ZNANE  
CZYSTY SYGNAŁ  $D^{*\pm} \rightarrow D^0 J_S^{\pm}$  !

- $D^0$  LUB  $D^{\pm}$

WYŻSZE TŁO, ALE LEPIEJ ZNANE ( $f(c \rightarrow D^{0\pm})$ )

- PRÓBKA  $Z^0 \rightarrow b\bar{b}$  JEST INKLUZYWNA
- PRÓBKA ( $Z^0 \rightarrow D^{*\pm}, D^{0\pm}$ ) JEST  
EKSKLUZYWNA.
- WYZNACZENIE  $Z^0 \rightarrow c\bar{c}$  WYMAGA WIĘC  
ZNAJOMOŚCI  $f(c \rightarrow D^{*\pm})$  LUB  $f(c \rightarrow D^{0\pm})$   
I STOSUNKÓW ROZGAŁĘZIENI (np z CLEO)

$$R_c = \frac{N(D^*)}{N_{\text{tot}}(\text{hadr})} \frac{1}{f(c \rightarrow D^*)}$$

ZANIEDBANIE PRODUKCJI NP  $\Sigma_c$ , (barionów powabny)  
POWODZI PODWYŻSZENIE  $f(c \rightarrow D^*)$ , A WIĘC  $R_c \downarrow$

## Charm Systematics

### Production fractions

- Tagging probability of different c hadron species differs (lifetime)
- From  $D^+$  to  $\Lambda_c^+$ , typically factor four difference
- Take from CLEO and ARGUS measurements

$$f(D^0) : f(D^+) : f(D_s^+) : f(\Lambda_c^+) = \\ 0.557 : 0.248 : 0.120 : 0.075$$

- Variations according to CLEO/ARGUS errors  
 $f(D^0) \pm 0.053$ ;  $f(D^+) \pm 0.037$ ;  
 $f(D^0 + D^+) \pm 0.070$ ;  $f(D_s^+) \pm 0.050$
- LEP measurements now competitive: consistent with above numbers (see talk by M.Hauschild)

### Decay multiplicity

MARK III measurements (Phys.Lett.B263(1991)1)

- $D^0, D^+, D_s^+$  mean charged decay multiplicities and distributions
- $B(D \rightarrow K^0(\text{or } \bar{K}^0)X)$

Add a large error on mean charge multiplicity for unmeasured  $\Lambda_c^+$  ( $\pm 0.5$  on mean about JETSET prediction)



# Metoda pomiaru $R_b$ i $R_c$

DELPHI

LEPTON  
TAG

$$\bullet b \rightarrow \begin{pmatrix} B_d^\pm \\ B_d^0 \\ B_s^0 \\ \Lambda_b \dots \\ B^{**} \end{pmatrix} \rightarrow \begin{pmatrix} D^{**} l \nu \\ D^{0\pm} l \nu \\ \underline{D^{\pm\pi} l \nu} \\ \underline{D^*} \end{pmatrix} \left\{ \begin{array}{l} \text{SIMULACJA} \\ \text{a la' Isgru-wise...} \\ \frac{D^{**}}{D^0 + D^* + D^{**}} \sim 32\% \\ \text{CLEO} \\ \text{ZAMIAST 11\% z ISGW} \end{array} \right.$$

$$\bullet 1) b \rightarrow l^- X$$

$$2) \begin{array}{l} b \rightarrow \bar{c} X \rightarrow l^- X \\ b \rightarrow \bar{c} X \rightarrow l^- X \end{array}$$

$$3) b \rightarrow c X \rightarrow l^+ X$$

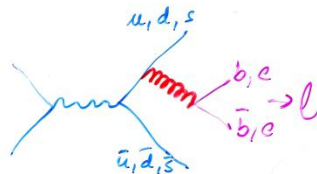
$$4) \begin{array}{l} c \rightarrow l^+ X \\ c \rightarrow \tau^+ X \rightarrow l^+ X \end{array}$$

$$5) s/\bar{t} \rightarrow \mu\mu, ee$$

$$\begin{array}{l} c\bar{c} \rightarrow l \\ b\bar{b} \end{array} \text{ albo } b\bar{b} \text{ W KASKADZIE}$$

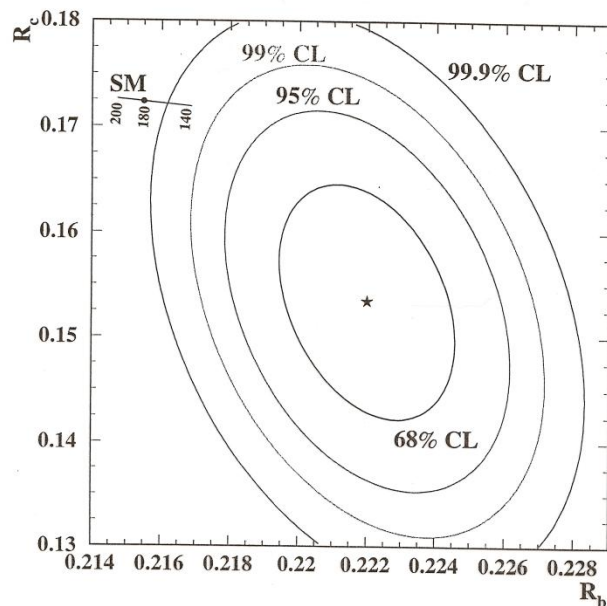
$$6) \text{ lekkie hadrony} \rightarrow l$$

lekkie hadrony b'isbnie zidentyfikowane jako  $l^\pm$

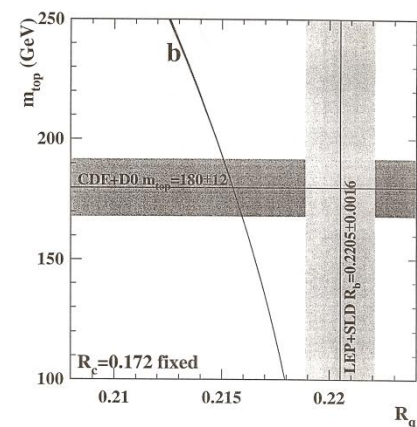


Wynik  $R_b$  i  $R_c$ 

## Antykorelacja dwóch mierzonych wielkości

Comparison with Standard Model:  $R_c$  vs.  $R_b$ 

$\Delta\chi^2$  between best fit with Standard Model  $R_b$  and  $R_c$   
 ( $m_{\text{top}} = 180 \text{ GeV}$ ,  $R_b = 0.2155$ ,  $R_c = 0.172$ ),  
 and best overall fit, is 16.0

Comparison with Standard Model:  $R_c$  Fixed

Standard Model predictions from ZFITTER 4.9:  
 $m_{Z^0} = 91.1888 \text{ GeV}$ ,  $60 \text{ GeV} < m_H < 1000 \text{ GeV}$ ,  
 $\alpha_s(m_{Z^0}) = 0.12$ ,  $\alpha(m_{Z^0}) = 1/128.67$

For  $m_{\text{top}} = 180 \pm 12 \text{ GeV}$ , Standard Model prediction  
 $R_b = 0.2155 \pm 0.0005$