B Physics and CP Violation
Experimental Highlights

Herbstschule Maria Laach 2000

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Roadmap

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- **Das b Quark im Standard Modell**
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  - Masse und Spektroskopie
  - Lebensdauer
- **B Mesonen und die CKM Matrix**
- **Semileptonische Zerfaelle**
  - Verzweigungsverhaeltnisse
  - Heavy Quark Effective Theory
  - V_{cb}
  - V_{ub}
- **Hadronische Zerfaelle und QCD**
  - Faktorisierung
  - Color Suppression
- **Seltene Zerfaelle**
  - Verzweigungsverhaeltnisse
  - CP Asymmetrien
- **$B^0\bar{B}^0$ Oszillationen**
- **CP Verletzung und sin(2b)**

Elementarteilchenphysik vor 25 Jahren...

1974:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \; \textit{und} \; \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

1975:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \\ \tau \end{pmatrix} \textit{und} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

Dreiecksanomalien: #Leptonen == #Quarks

(genauer: $\Sigma Q = 0$)

⇨

die Suche nach dem 5. Quark

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

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[(a)] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
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(Received 1 July 1977)

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.

We have observed a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400-GeV proton-nucleus collisions. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass $m_{\mu^+\mu^-}$ greater than 5 GeV corresponding to 1.6×10^{16} protons incident on Cu and Pt targets:

$$p+(\mathrm{Cu},\mathrm{Pt})\rightarrow\mu^+ +\mu^- + \text{anything}.$$

The produced muons are analyzed in a double-arm magnetic-spectrometer system with a mass resolution $\Delta m/m$ (rms) $\approx 2\%$.

The experimental configuration (Fig. 1) is a modification of an earlier dilepton experiment in the Fermilab Proton Center Laboratory.[1-3] Narrow targets (~0.7 mm) with lengths corresponding to 30% of an interaction length are employed

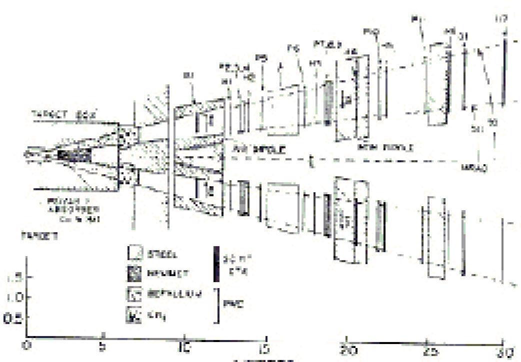

FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D, and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

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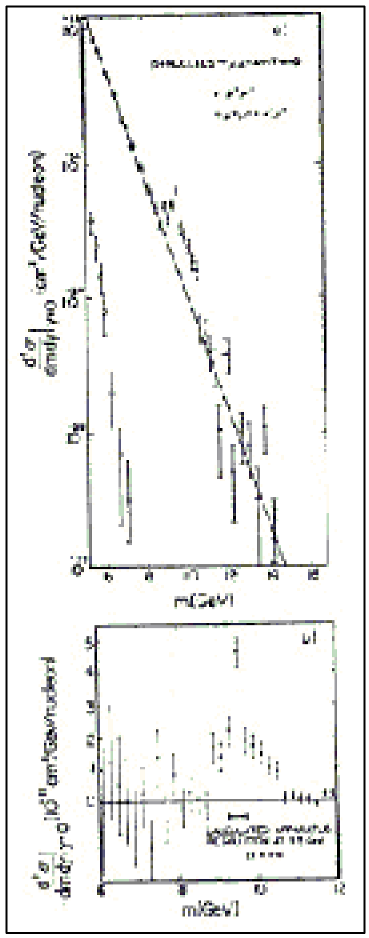
In 1997 Leon Lederman and his team sent A 400 GeV proton beam onto a beryllium target looking for a bump in the μμ mass spectrum ... again

Entdeckung des b Quarks

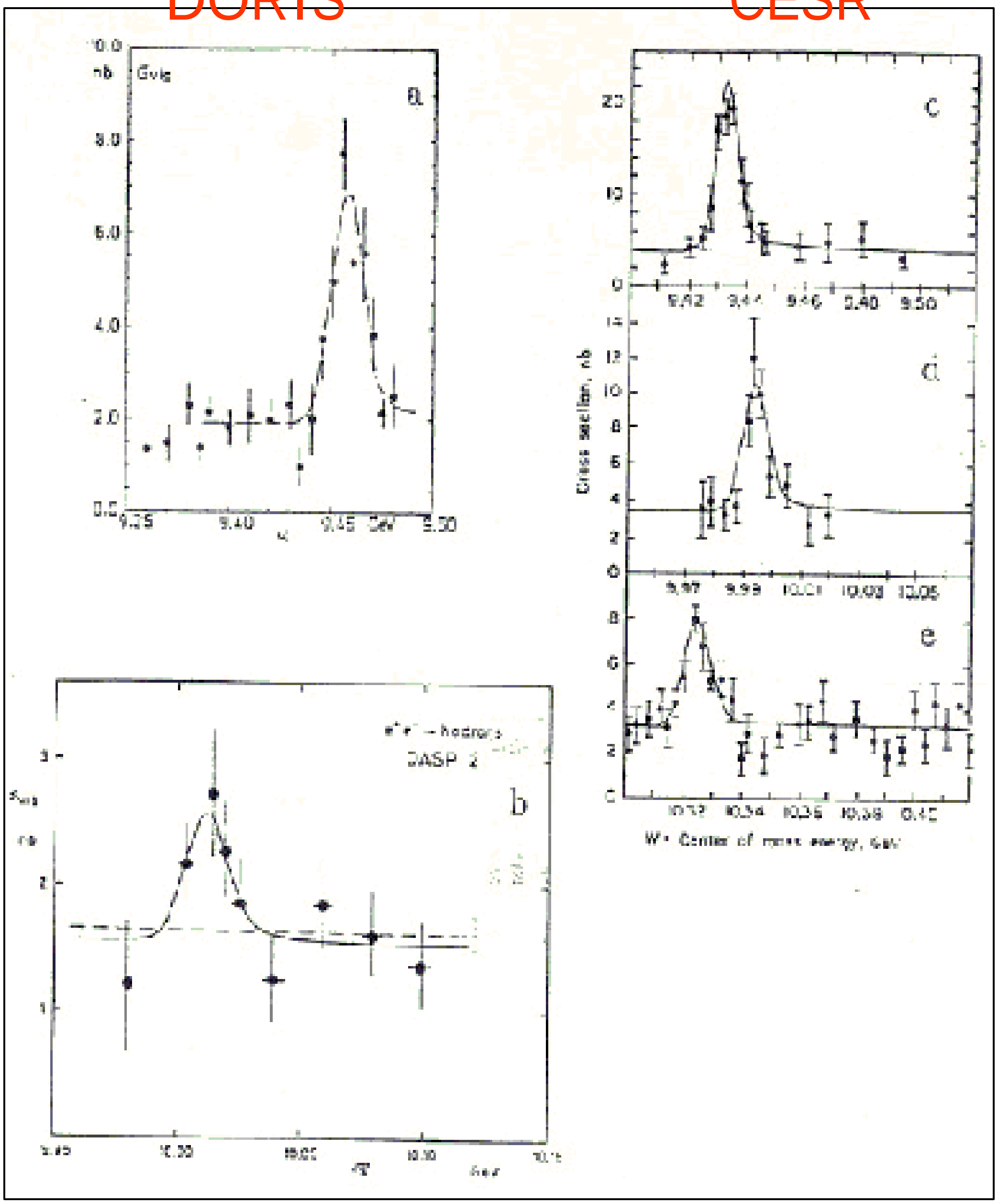


$\mu^+\mu^-$ Spectrum

Background subtracted

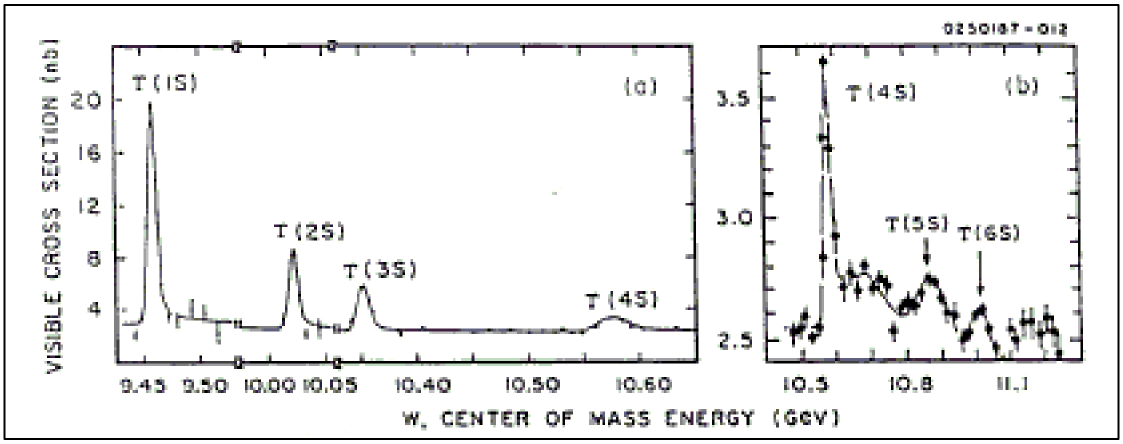
➡ Zwei schmale Resonanzen bei 9,47 und 10,17 GeV/c^2

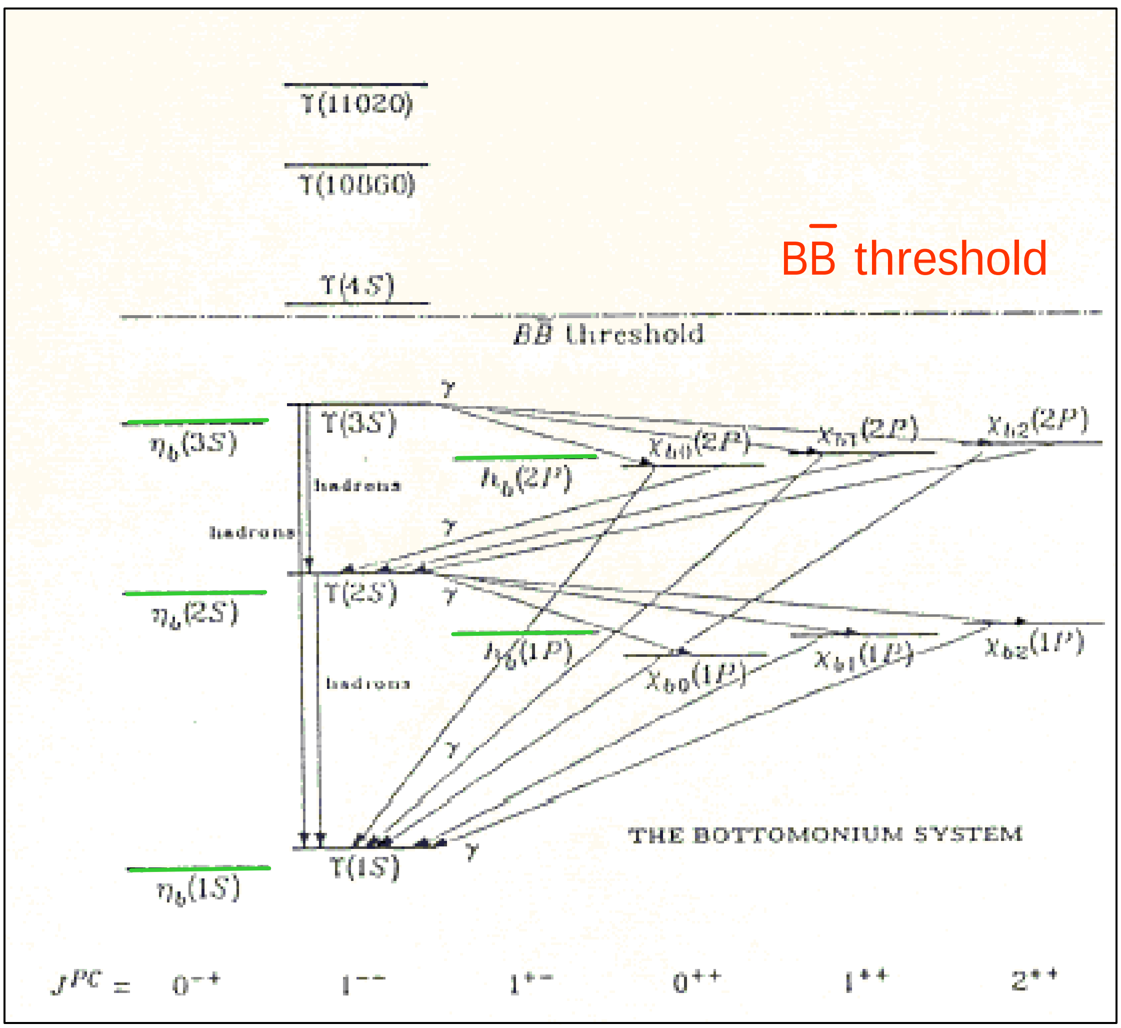
Ein Jahr spaeter:



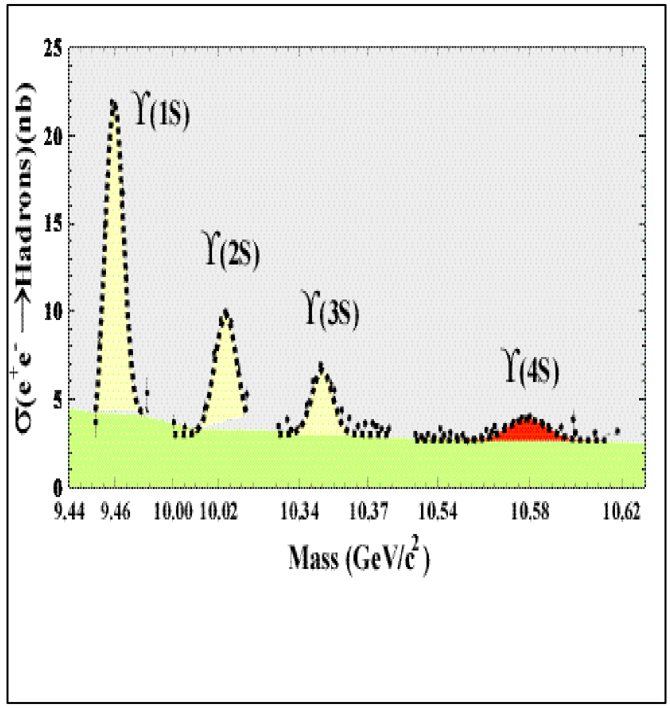
DORIS (Hamburg) und CESR (Cornell) sehen
Die Y Resonanzen in e^+e^- Wechselwirkungen

Υ Spektroskopie





B Physics at the Y(4S)



- **BB produced near threshold**

  $s\ (B\bar{B}) = 1.05\ \mathrm{nb}$

  $p_B \approx 300\ \mathrm{MeV/c}$

- **"Continuum" production**

  $s\ (cc) = 1.3\ \mathrm{nb}$

  $s\ (qq) = 2.1\ \mathrm{nb}$

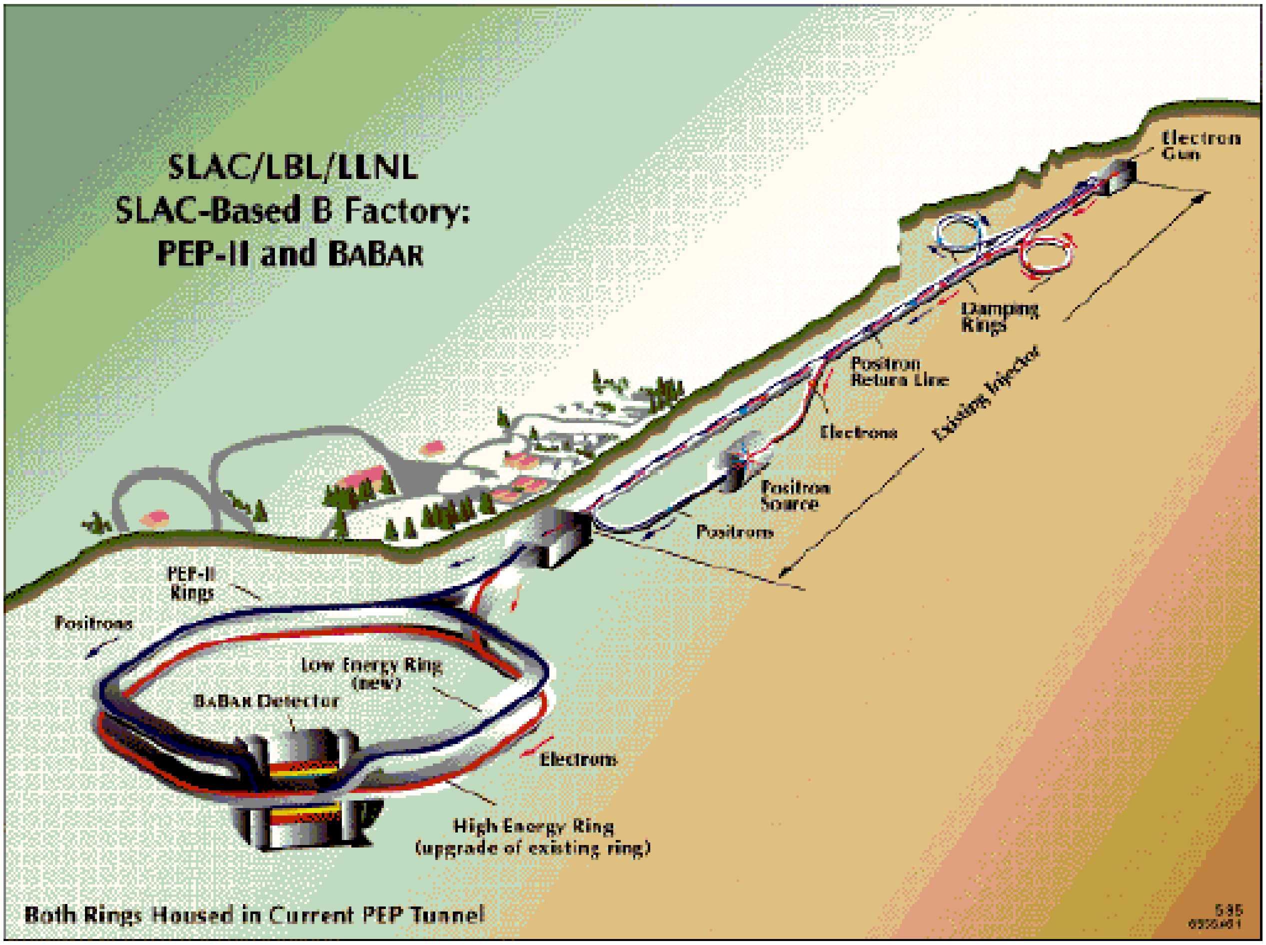
- **Assume equal production of B^0B^0 and B^+B^-**

$$f_{+-}/f_{00} = 1.04 \pm 0.07 \pm 0.04$$

- $E_{B\text{-}candidate}\ \text{o}\ E_{Beam}$

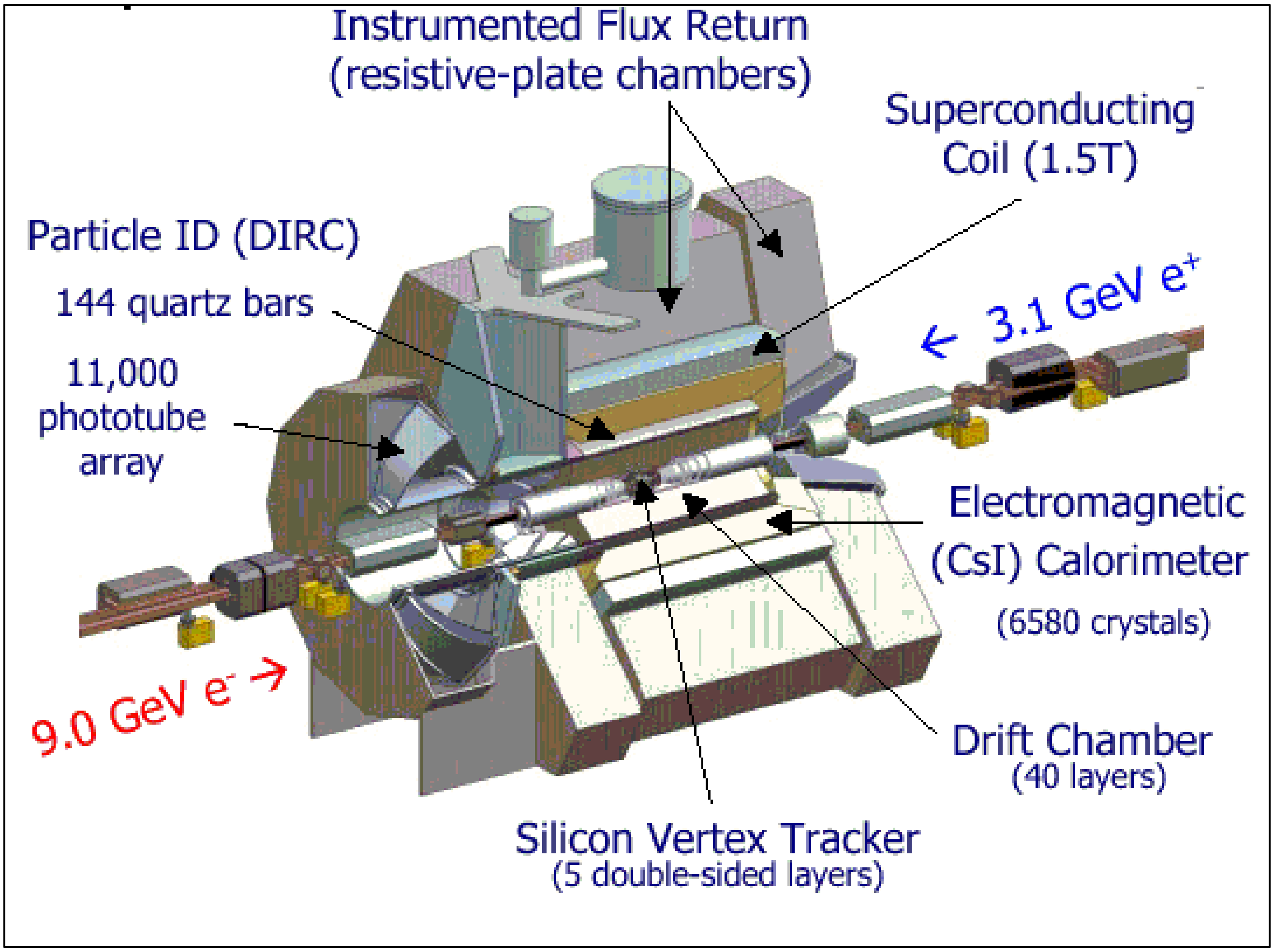
  $m_{beam\text{-}constraint}\ \text{o}\ \sqrt{E_{Beam}^{\ 2} - p_{B\text{-}candidate}^{\ 2}}$

- **Data sets**
  - CLEO **~ 14 fb^{-1} (9.5 on Y(4S), 4.5 off)**
  - BABAR **~ 15 fb^{-1}**
  - Belle **~ 10 fb^{-1}**



- Asymmetric beam configuration:
  - 9.0 GeV electrons on 3.1 GeV positrons
- $\Upsilon(4S)$ is boosted in LAB frame ($\beta\gamma$=0.56)
  - 1.5 < p(B dtr) < 4.5 GeV/c in 2-body B decays

A typical B Physics Detector



Vertex	**SI Tracker**
Momentum	**SI Tracker, Drift chamber**
Photons	**EM Calorimeter**
Neutral Pions	**EM Calorimeter**
Muons	**Muon chambers in return iron**
Particle Identification	
dE/dx	**Drift chamber**
p**-K-p**	**RICH, DIRC, Aerogel**
TOF	**(Belle)**

b Production at higher Energies

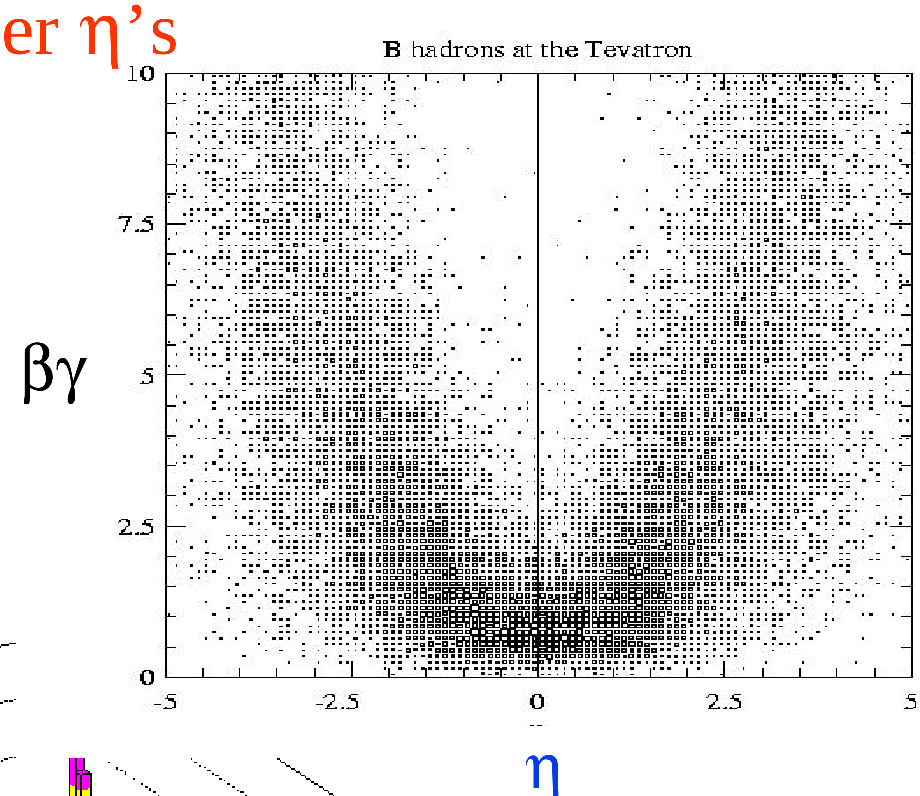
- **Higher cross section (~6 nb)**
- **B's are moving**
  - Lifetime measurements
  - Event selection
  - 2 hemispheres
- **B_s, B_c, b-baryon production**
  - f_+, f_0 38.9 +/- 1.3 %
  - f_s 10.7 +/- 1.4 %
  - $f_{b\text{-baryons}}$ 11.6 +/- 2.0 %
- **LEP (~ 10^6 b's per experiment)**
- **SLD (~10^5 b's)**

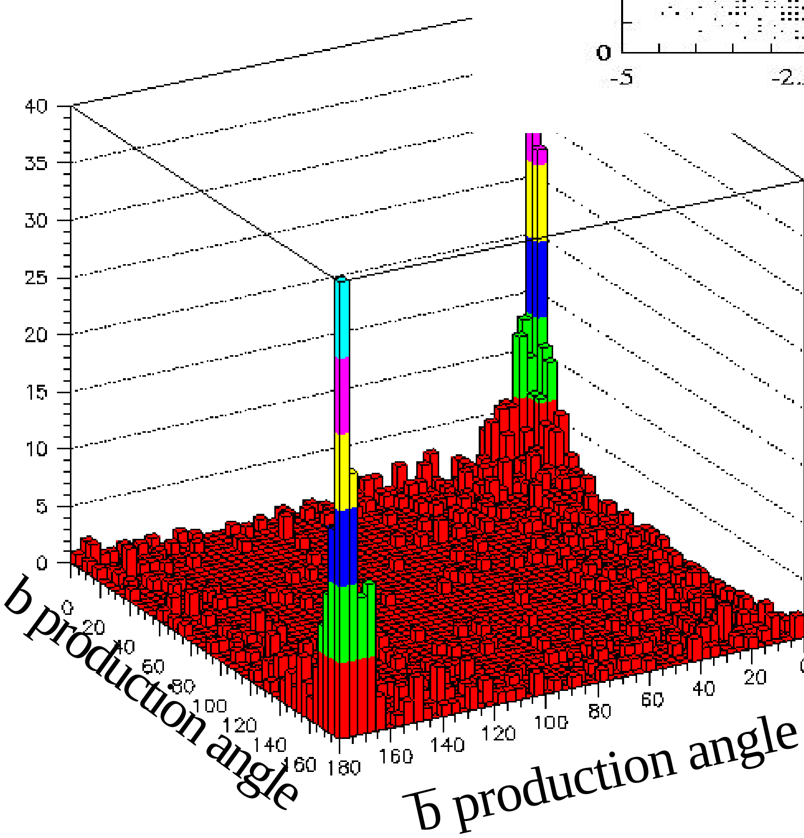
b & c physics at hadron colliders?

- Large samples of b quarks are available, with the Fermilab Main Injector, the collider will produce ~$4x10^{11}$ b hadrons per 10^7 sec at L = $2x10^{32}$ $cm^{-2}s^{-1}$.
- e^+e^- machines operating at the Y(4S) at L of $3x10^{33}$ produce $6x10^7$ B's per 10^7 s.
- B_s & L_b and other b-flavored hadrons are accessible for study.
- Charm rates are ~10x larger than the b rate
- Problems:
  - σ_b/σ_{tot} ~ 1/500 at Fermilab, 1/100 at LHC
  - Background from b's can overwhelm "rare" processes
  - Large data rate just from b's - 1 kHz into detector
  - Large rates cause Radiation damage to EM calorimeter; photon multiplicities may obscure signals

Characteristics of hadronic b production

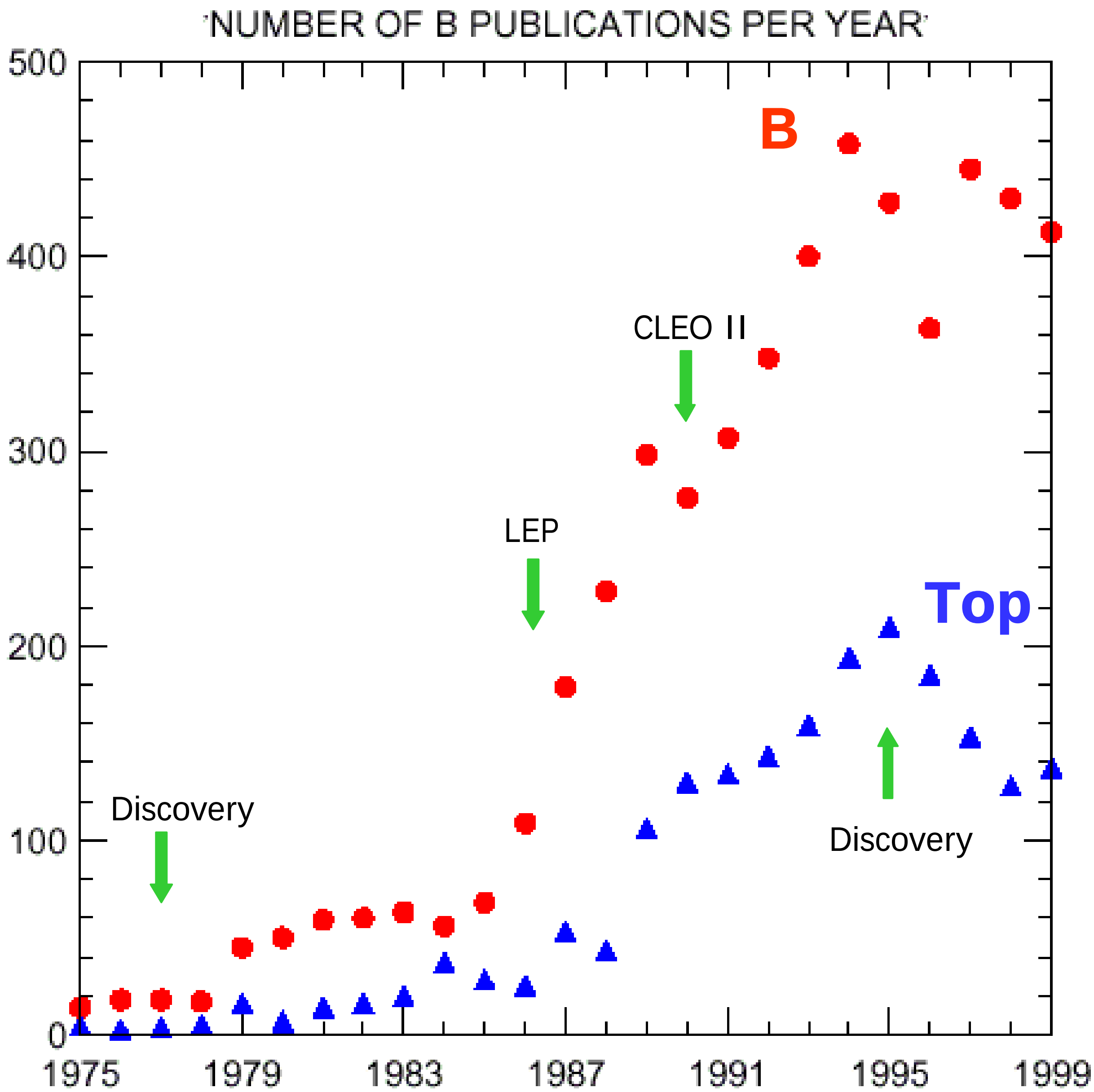
The higher momentum b's are at larger η's





b production peaks at large angles with large $b\bar{b}$ correlation

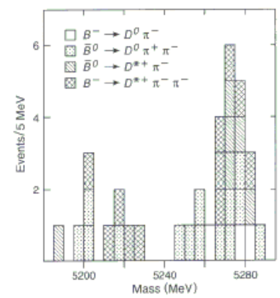
B Physics is quite popular



Der Rest der Geschichte

1980 e^+e^- -> Y(4S) CLEO (CESR)

1983 B Mesonen CLEO



1983 Lebensdauer τ_b PEP

V_{cb} ist klein

1987 $B^0\bar{B}^0$ Oszillationen ARGUS

Top Masse sehr gross

1990 b->u Uebergaenge CLEO/ARGUS

V_{ub} ungleich 0

1992 B_s, Λ_b LEP

1993 Penguin Zerfaelle CLEO

neue Physik?

1994 Direkte Messung von Δm_d LEP

1998 B_c CDF

1999 Seltene Zerfaelle CLEO

2000 CP Verletzung (beinahe) BABAR, BELLE CDF, LEP

200x alles passt und wir gehen nach Hause ... oder auch nicht

Das b Quark im Standard Model

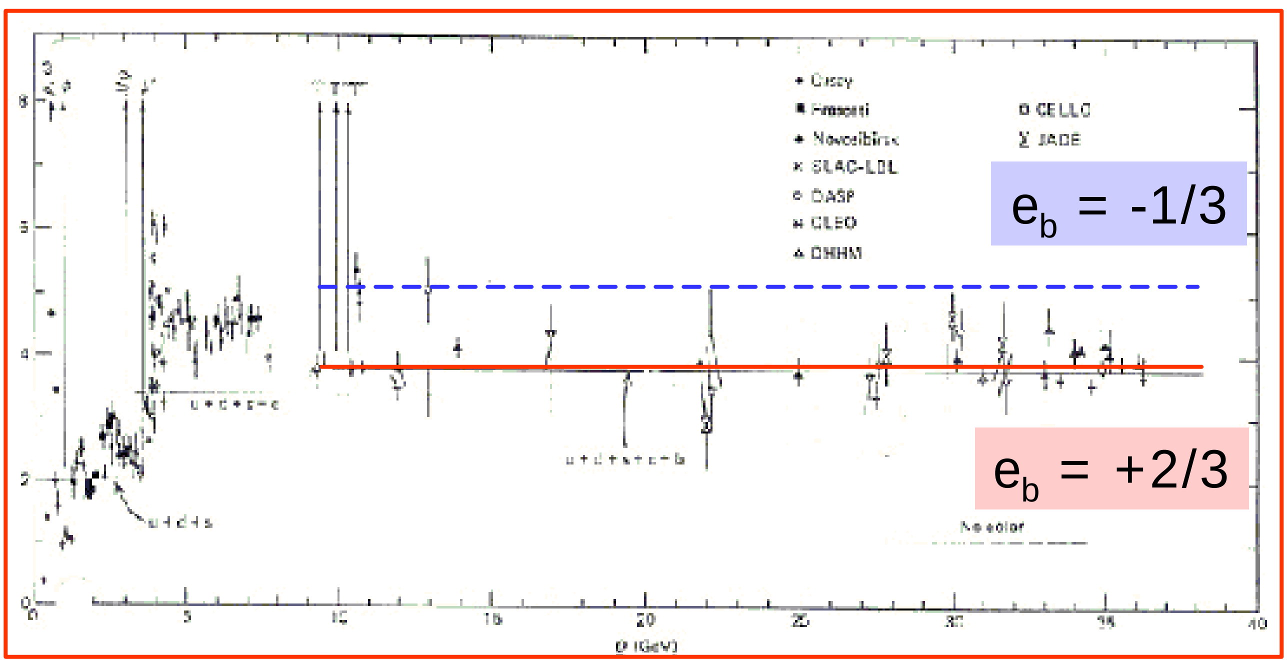
- **Elektrische Ladung**
- **Elektroschwache Parameter**
  - V-A Strom
  - Schwacher Isospin
- **Masse**
- **Lebensdauer**

Oben oder unten?
(Top or Bottom)

Die elektrische Ladung des b Quarks

$$R \equiv \frac{s\left(e^+e^- \rightarrow hadrons\right)}{s\left(e^+e^- \rightarrow m^+m^-\right)} = 3\sum e_q^2$$

$$= \frac{10}{3} + e_b^2$$



Lederman hat das Bottom Quark gefunden

das b quark im Standardmodell:

1.) beteiligte Teilchen

Leptonen: e, μ, τ, ν_e, ν_μ, ν_τ

Quarks: u, d, s, c, b, t

Eichbosonen: $W^\pm, Z, \gamma$ $\leftrightarrow$ (W^μ, B^μ) vor Symmetriebrechung

Higgs: h $\leftrightarrow$ $\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

2.) Schwache Ww. wirkt nur auf Linkshändige Komponenten

$\Rightarrow$ $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$; e_R, μ_R, τ_R

$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$; $u_R, d_R, s_R \dots$

mit

Projektionsoperator

$$e_L = \frac{1-\gamma_5}{2} e \quad \text{und} \quad e_R = \frac{1+\gamma_5}{2} e$$

$$\left(\text{bzw} \quad \bar{e}_L = \bar{e} \frac{1+\gamma_5}{2} \right)$$

$\left[\gamma_5 = i \gamma^0 \gamma^1 \gamma^2 \gamma^3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \right]$; $\left[\bar{e}_L = e_L^\dagger \gamma^0 \right]$

Lepton sector:

- no flavor changing currents
- V−A ⇒ parity violating

⇒ charged weak current

$$j_\mu^{cc} = \bar{\nu} \, \frac{1}{2} \gamma_\mu (1-\gamma^5) \, e$$

⇑ only lefthanded components

$$= \bar{\nu} \, \frac{1}{2}(1+\gamma^5) \gamma_\mu \frac{1}{2}(1-\gamma^5) \, e$$

$$= \bar{\nu}_L \, \gamma_\mu \, e_L$$

↳ $\hat{=}$ e.m current $\approx \bar{e} \gamma_\mu e$

use:
- γ^5 is hermitian $\gamma^{5+} = \gamma^5$
- $\gamma_\mu \left(\frac{1-\gamma^5}{2}\right) = \left(\frac{1+\gamma^5}{2}\right) \gamma_\mu$
- $\left(\frac{1-\gamma^5}{2}\right)^2 = \frac{1}{4}\left[1 - 2\gamma^5 + (\gamma^5)^2\right] = \left(\frac{1-\gamma^5}{2}\right)$

Quark sector

•) K^0 decays: $K^0 \to \pi\pi$

↳ Generations mix

$u, d, s, c \Rightarrow$ Cabibbo angle

$u, d, s, c, b, t \Rightarrow$ CKM matrix (3×3)

$$j_\mu^{cc} = (\bar{u}, \bar{c}, \bar{t})_L \gamma_\mu V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

$$V_{CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

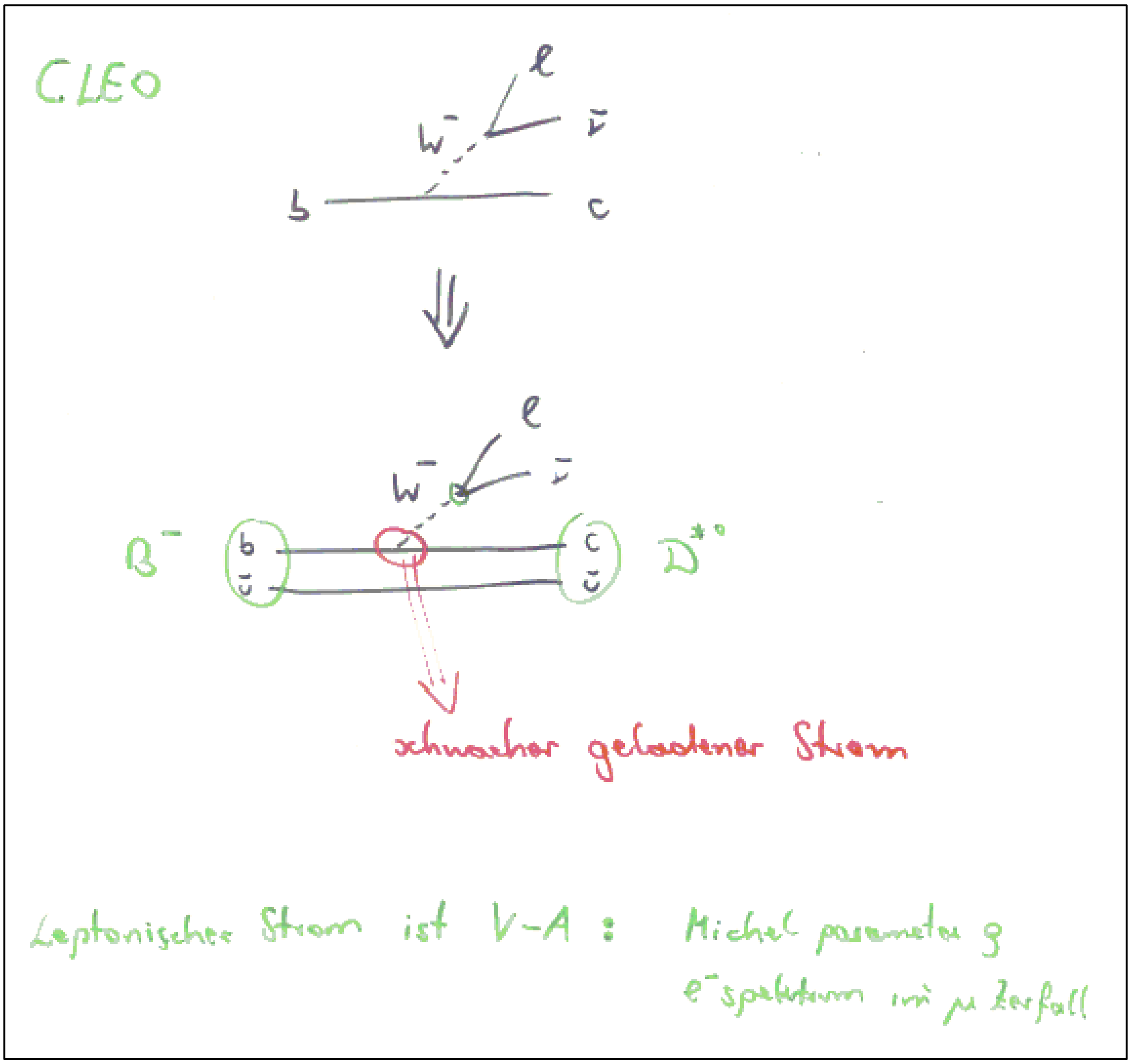
•) BUT: we still have V-A structure for $b \to c$:

$$j_\mu^{cc} = \bar{c}_L \gamma_\mu V_{cb} b_L$$

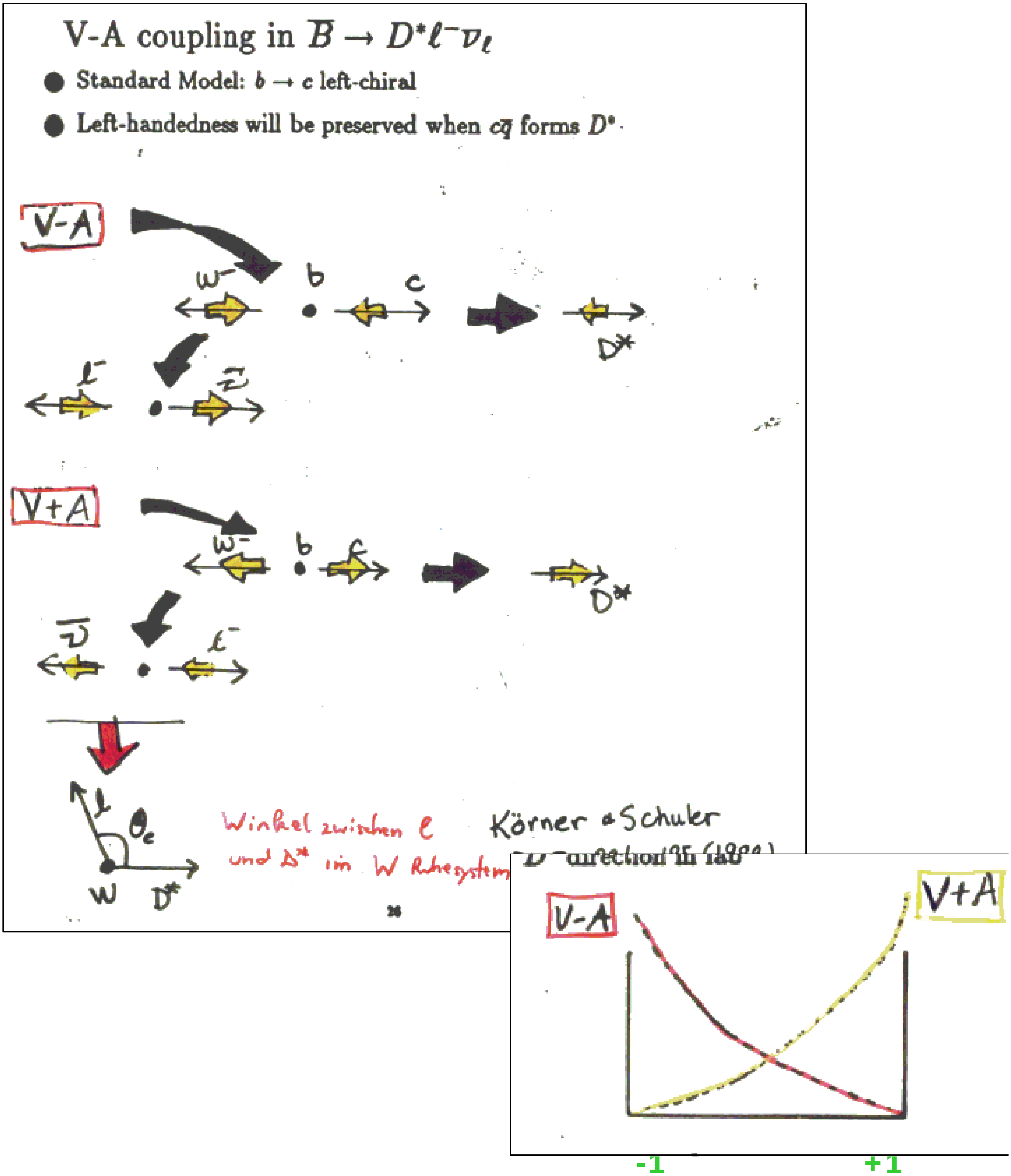
$$= \bar{c} \, \tfrac{1}{2} \gamma_\mu (1-\gamma^5) \, b \, V_{cb}$$

Experiment 1: Test V-A character of $b \to c$ current

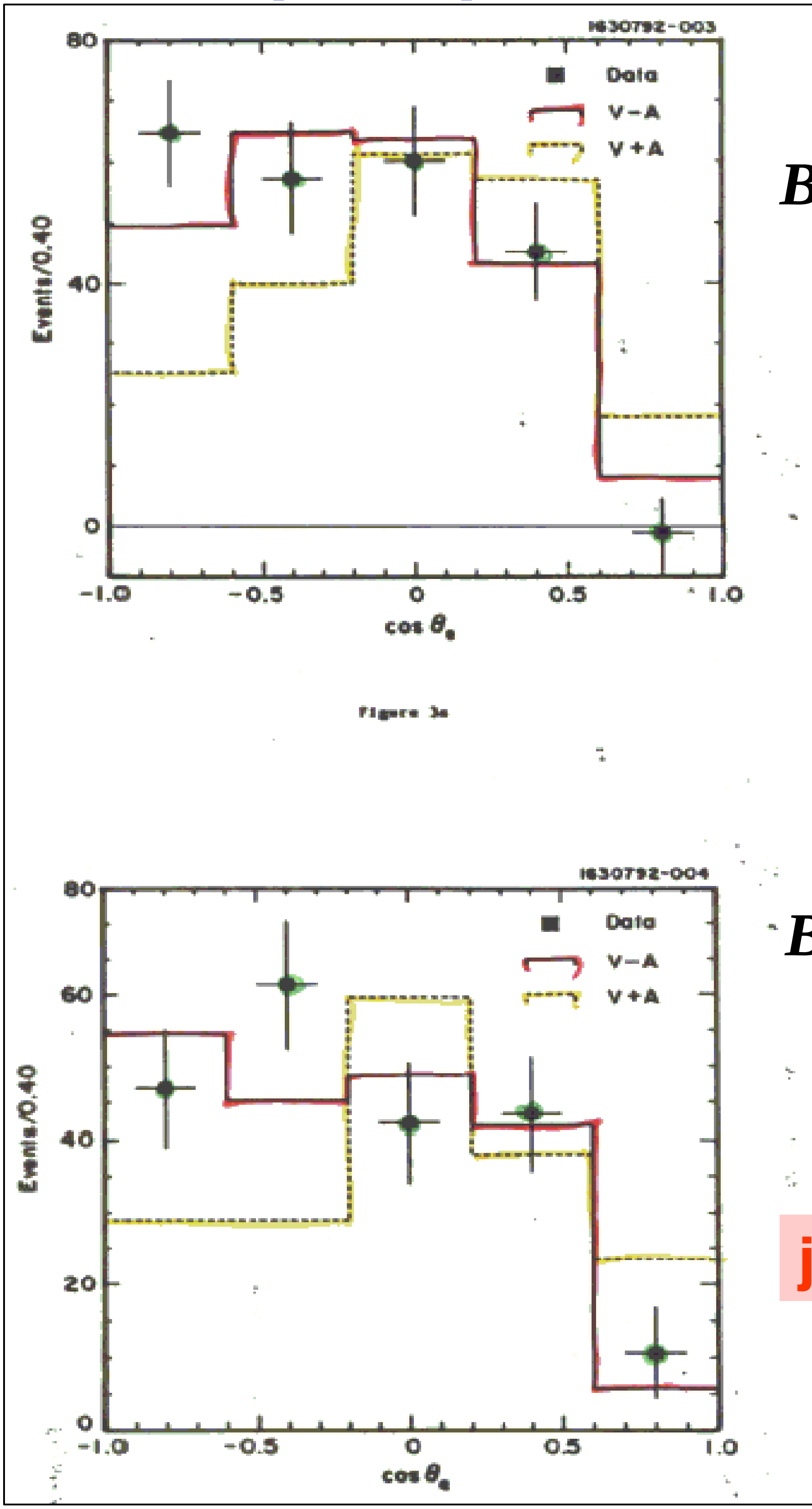
Experiment 1:
b->c current has V-A character



Forward Backward Asymmetry



Result (1992)



$\boldsymbol{B}^{-}$ ® $\boldsymbol{D}^{*0}\lambda^{-}\bar{\mathrm{n}}$

$\boldsymbol{B}^{0}$ ® $\boldsymbol{D}^{*+}\lambda^{-}\bar{\mathrm{n}}$

$j_{b->c}$ is V-A

Hyperladung und Schwacher Isospin

	ν_L	e^-_L	e^-_R	u_L	u_R	d_L	d_R
Q	0	-1	-1	2/3	2/3	-1/3	-1/3
I_3	1/2	-1/2	0	1/2	0	-1/2	0
Y	-1	-1	2	1/3	4/3	1/3	-2/3

⇒ Standardmodell $SU(2)_I \otimes U(1)_Y$

Spontane Symmetrie brechung ⇓

$$SU(2)_I \otimes U(1)_Y \longrightarrow U(1)_{e.m.}$$

Gell Mann – Nishijima Gleichung:

$$Q = I_3 + \tfrac{1}{2} Y$$

Neutral Current j_μ^{nc}

Symmetry breaking :

Photon ⇒ $A_\mu = B_\mu \cos\Theta_W + W_\mu^3 \sin\Theta_W$

Z^0 ⇒ $Z_\mu = -B_\mu \sin\Theta_W + W_\mu^3 \cos\Theta_W$

↳ j_μ^{NC} gets his right handed components

$$j_\mu^{NC} = \bar{u}_f \gamma_\mu \frac{1}{2} (v_f - a_f \gamma^5) u_f$$

with $v_f = I_3^f - 2 Q_f \sin^2\Theta_W$

$a_f = I_3^f$

Experiment 2: Measure v_b, a_b.
Verify $(I_3^b)_L = -\frac{1}{2}$; $(I^b)_R = 0$

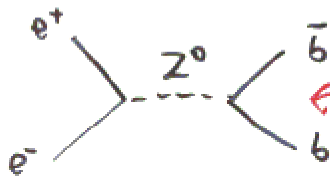
Experiment 2:
Schwacher Isospin des b Quarks

Ansatz: $v_b = (I_3^L + I_3^R) - 2 e_b \sin^2\theta_W$

$a_b = (I_3^L - I_3^R)$

$\Rightarrow$ experiments with neutral current:

1) LEP:



$\leftarrow$ Kopplung $\propto \frac{g_2}{2\cos\theta_W} \gamma_\mu [v_b - a_b \gamma^5]$

$$\Rightarrow \Gamma(Z \to b\bar{b}) = \frac{G_F M_Z^3}{2\pi\sqrt{2}} \left[v_b^2 + a_b^2 \right]$$

2) LEP + PEP, PETRA, TRISTAN

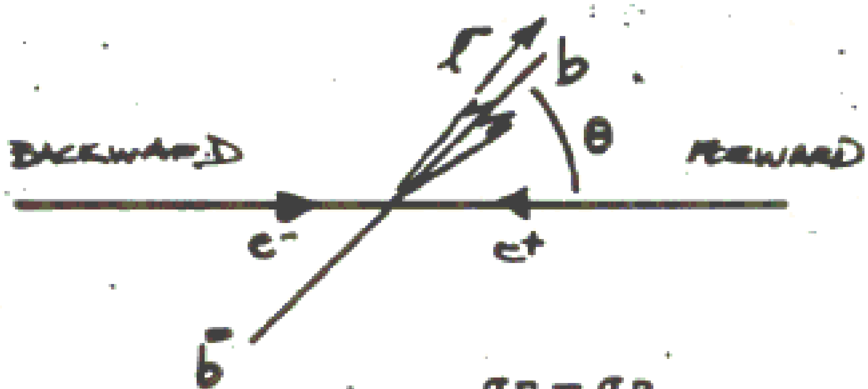
$$\Rightarrow A_{FB} = \frac{\int_0^1 \frac{d\sigma}{d\Omega} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\Omega} d\cos\theta}{\int_0^1 \frac{d\sigma}{d\Omega} d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\Omega} d\cos\theta}$$

$$Z^0: \quad A_{FB} = \frac{3}{4} \, \frac{2 v_e a_e}{v_e^2 + a_e^2} \, \frac{2 v_b a_b}{v_b^2 + a_b^2}$$

B Quark Asymmetry

The angular distribution for $Z^0 \to b\bar{b}$ is:

$$\frac{d\sigma}{d\cos\theta} \propto (1 + \cos^2\theta + \frac{8}{3}\widehat{A^b_{FB}}\cos\theta)$$



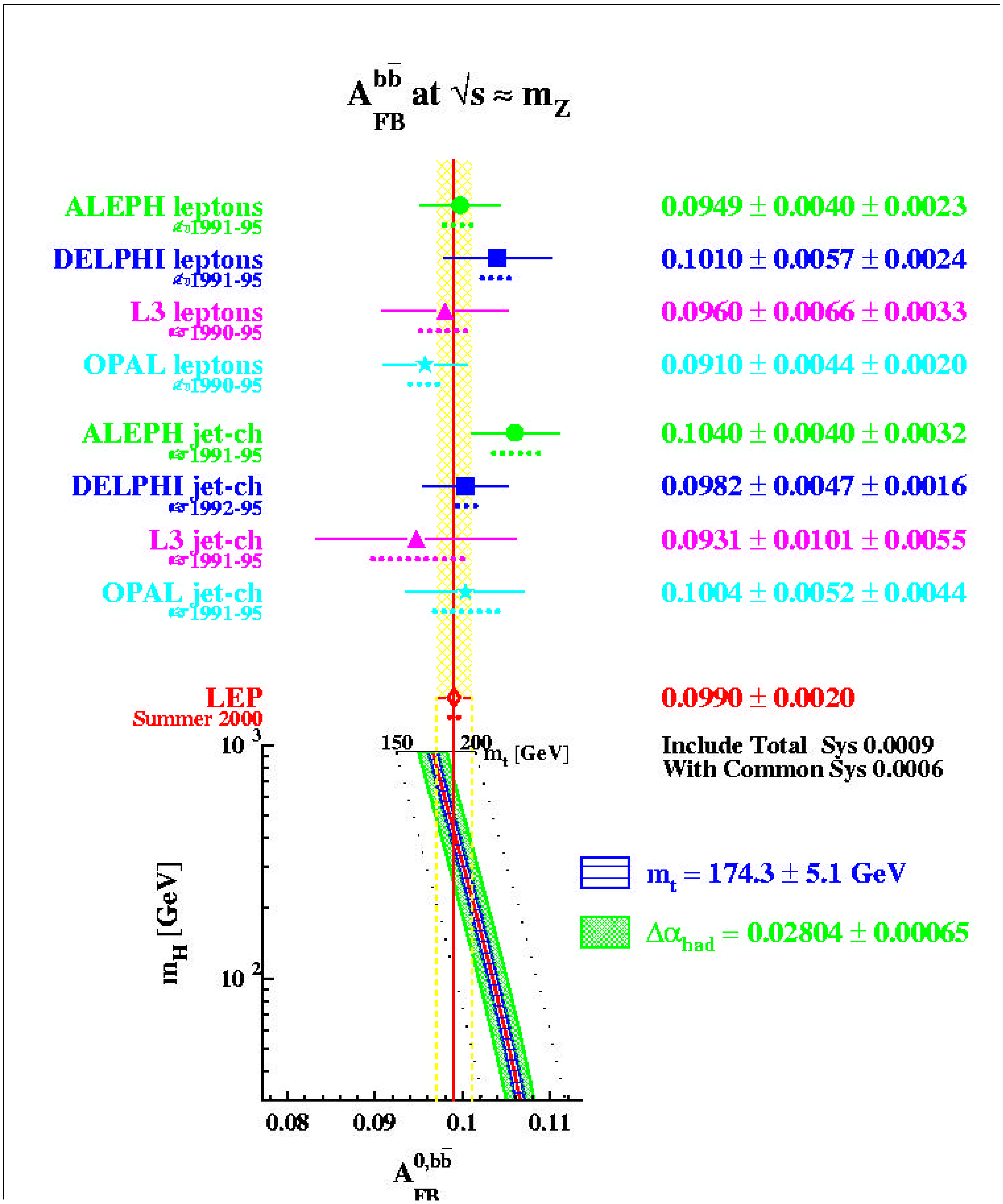
$$A^b_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

b quark direction : thrust axis tagged by the lepton charge

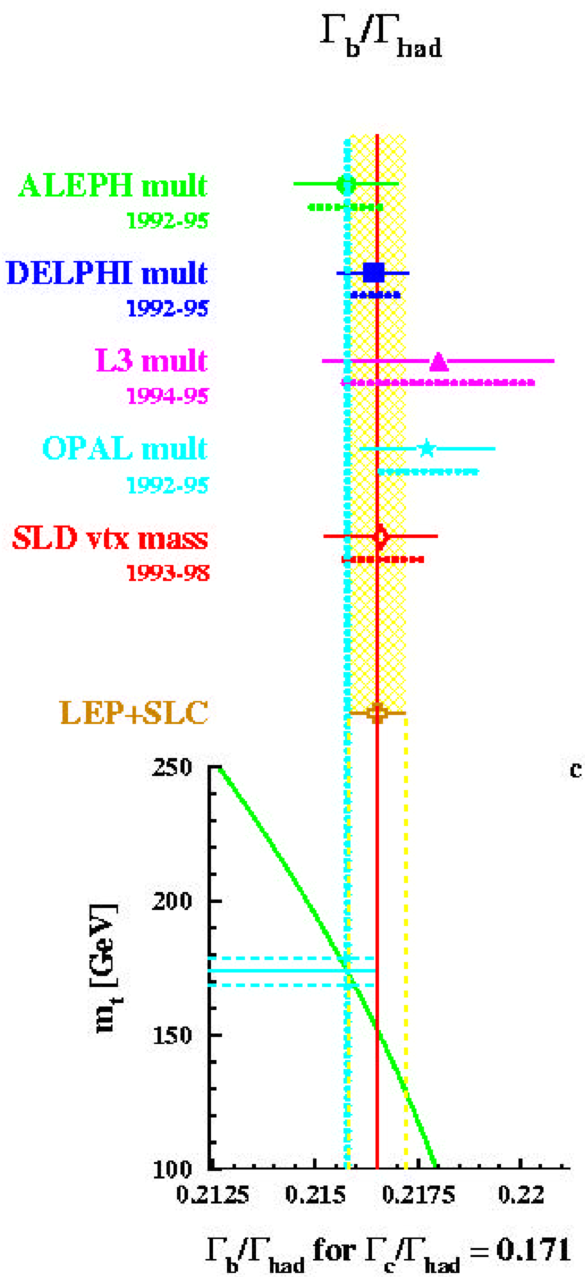
However, the observed asymmetry is :

$$A^{obs}_{FB} = A^b_{FB}(\underline{f_{b\to\ell}} - f_{b\to c\to\ell} + f_{b\to\bar{c}\to\ell}) \cdot (1 - 2\chi)$$
$$- A^c_{FB} f_{c\to\ell} - A^{back}_{FB} f_{back}$$

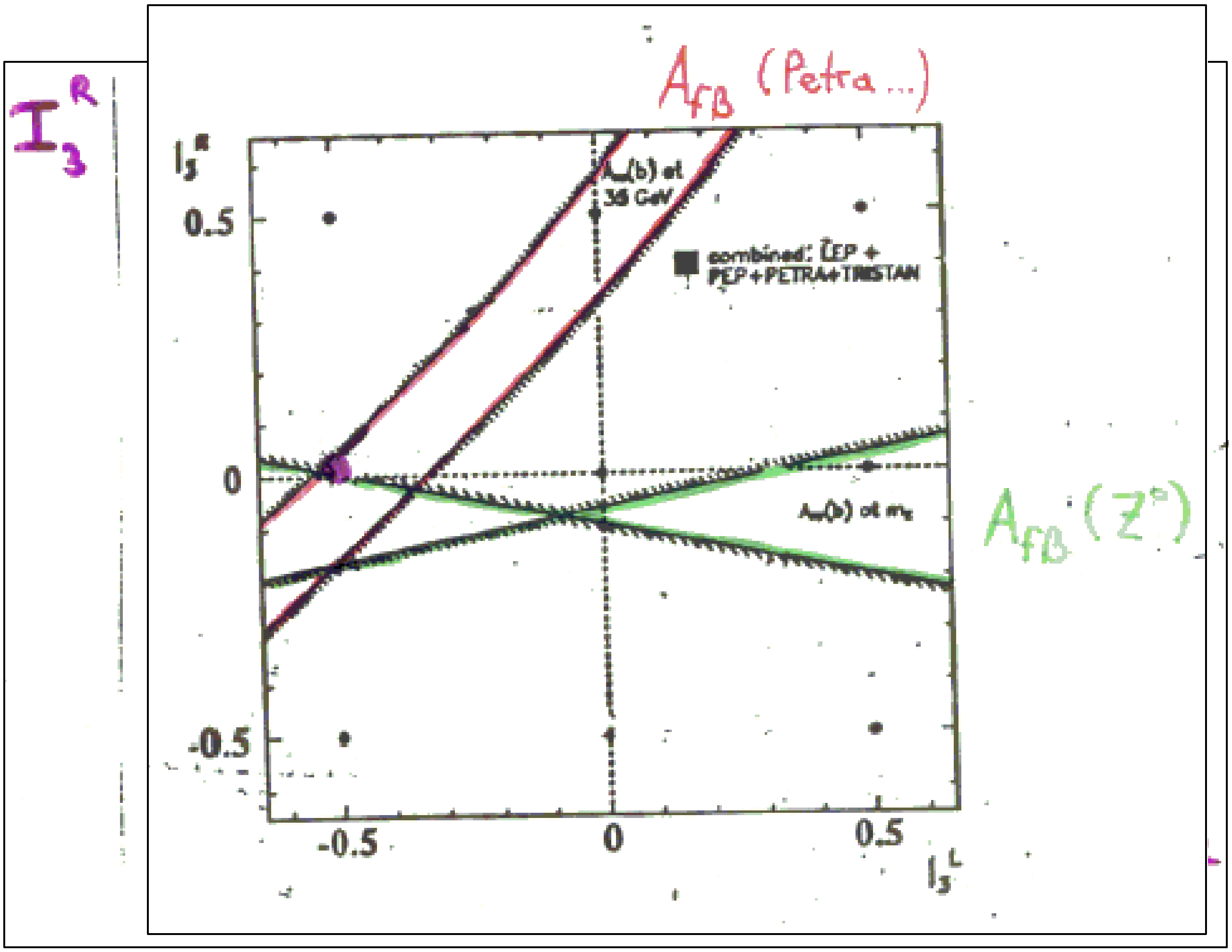
Electroweak results from LEP

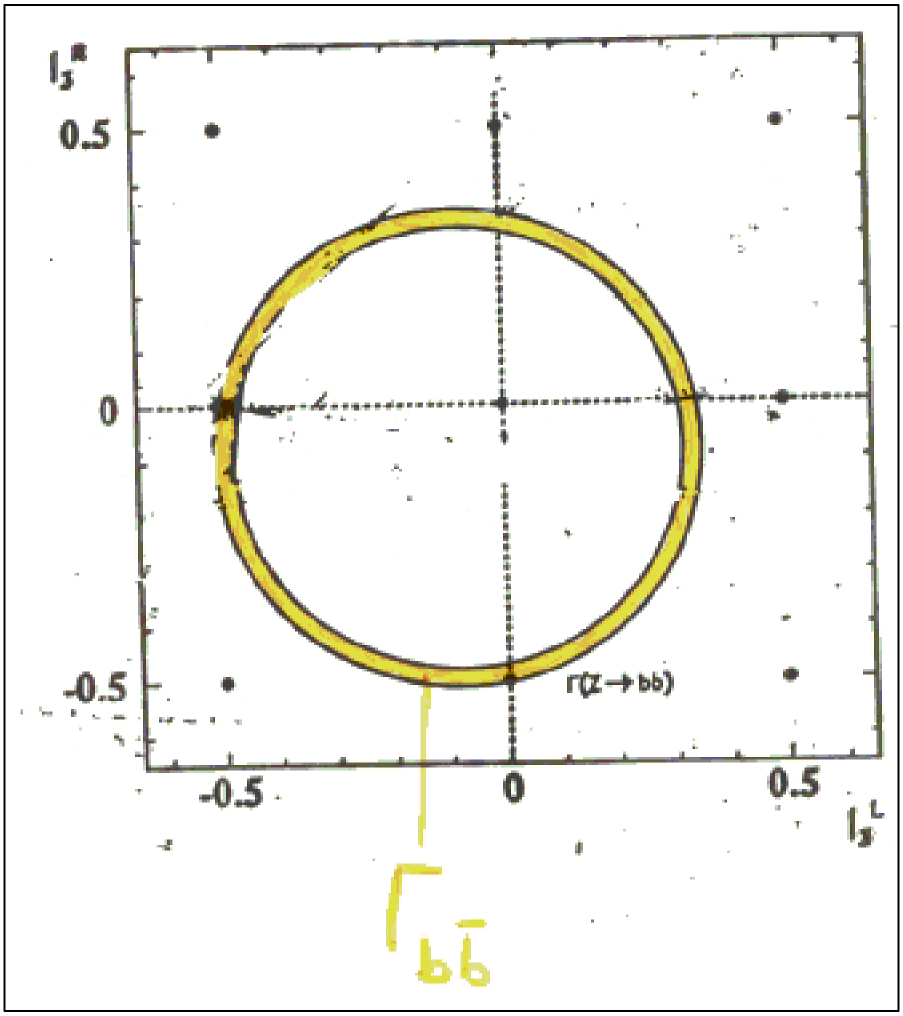


Electroweak results from LEP (2)

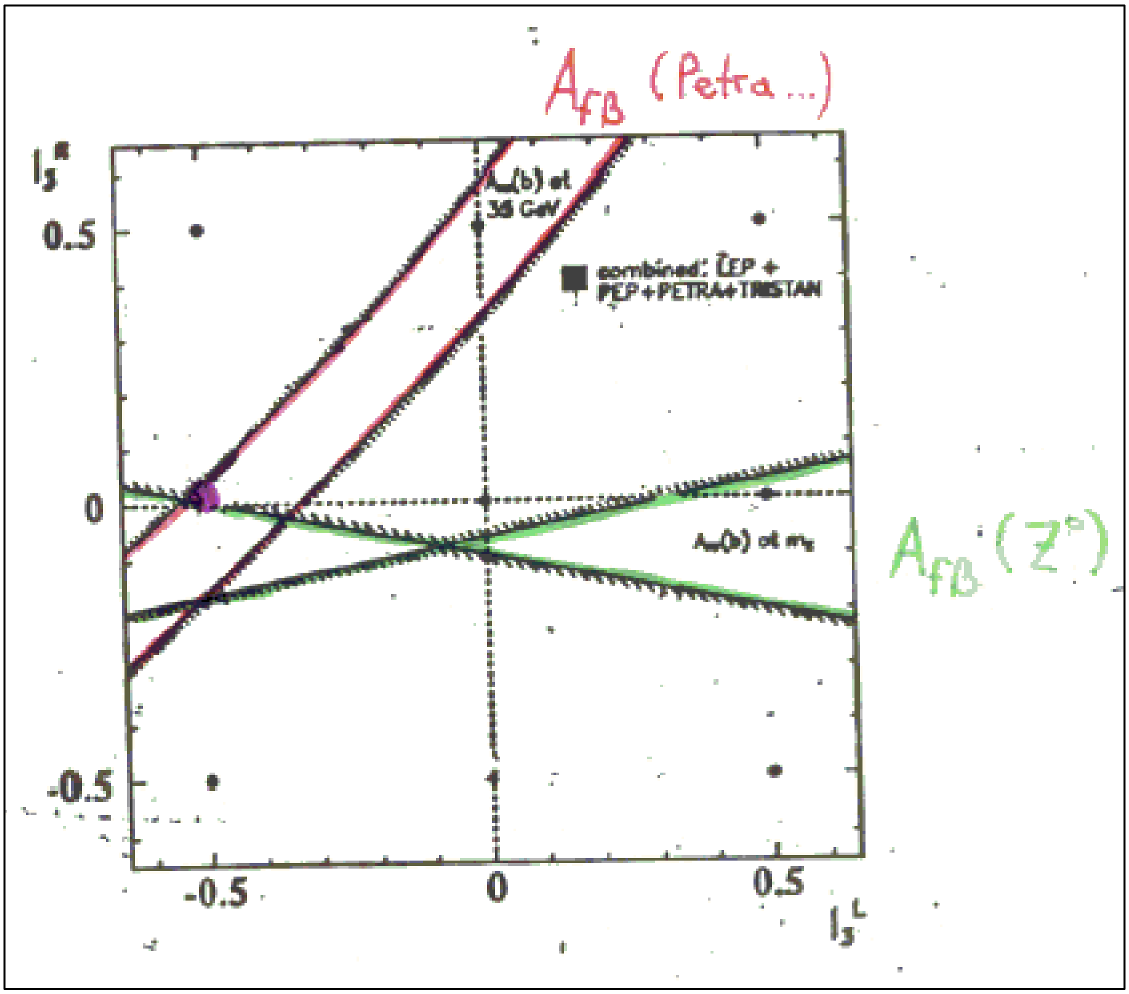


Weak Isospin of the b Quark





I_3^R
0.5
0
-0.5
-0.5
0
0.5
I_3^L
Γ(Z→bb)
$\Gamma_{b\bar{b}}$

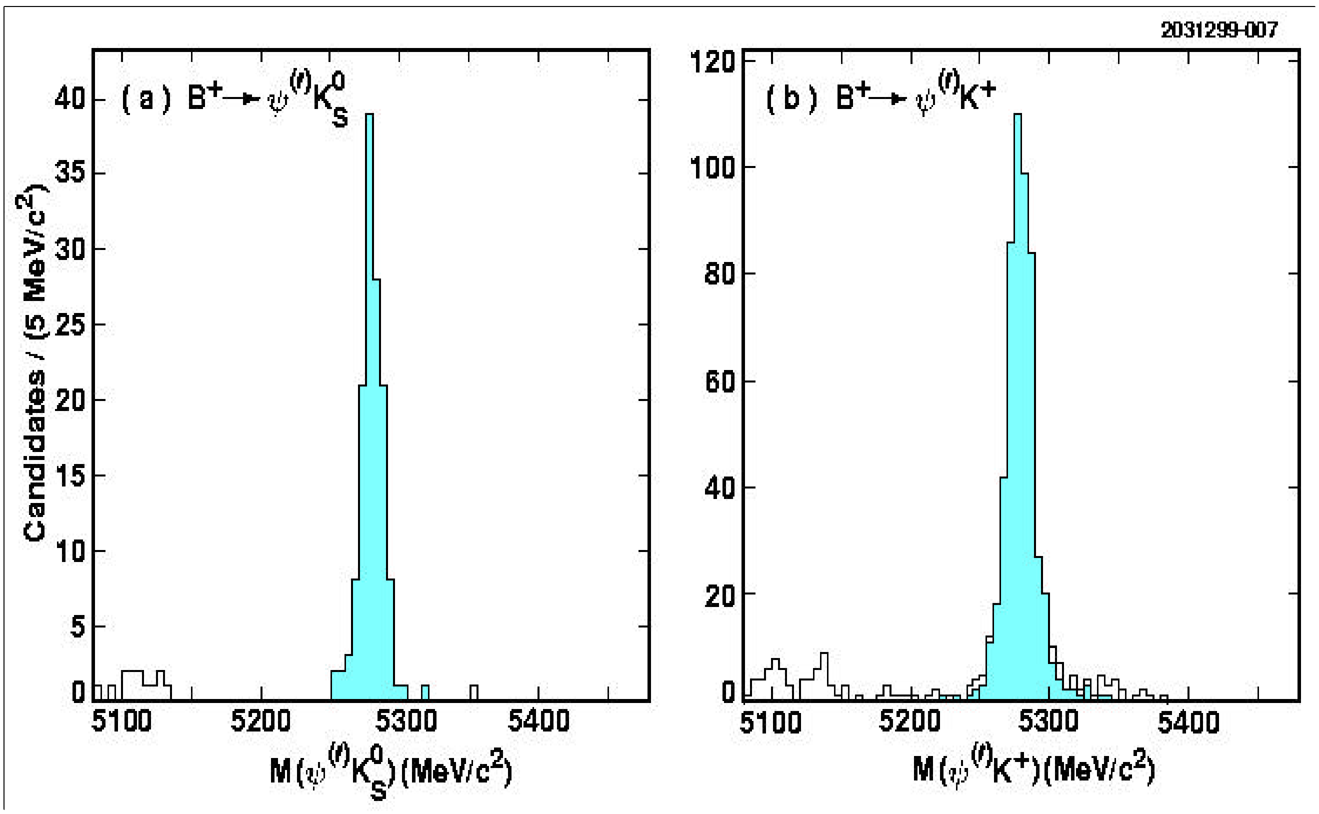


$I_3^R = 0$ and $I_3^L = -1/2$

B Meson Mass

- **Use fully reconstructed (hadronic) B decays**
- **Previous CLEO measurements**
  - fit beam constrained mass for B-> D(*)nπ and ψK(*)
    $M_{bc}^2 = E^2_{beam} - p^2$ and $\sigma(M_{bc}) \sim \sigma(E_{beam}) \sim 2.7$ MeV
  - Systematic limited:
    - error on beam energy scale ~ 2 MeV
    - error on initial state radiation correction ~0.5 MeV
- **New result**
  - exclusively reconstruct B-> $\psi^{(\prime)}$K
  - do not use beam energy constraint
  - constrain $\psi^{(\prime)}$ to PDG values

B Meson Mass (2)



$m(B^0)$ [MeV] = 5279.1 +/- 0.7 +/- 0.3

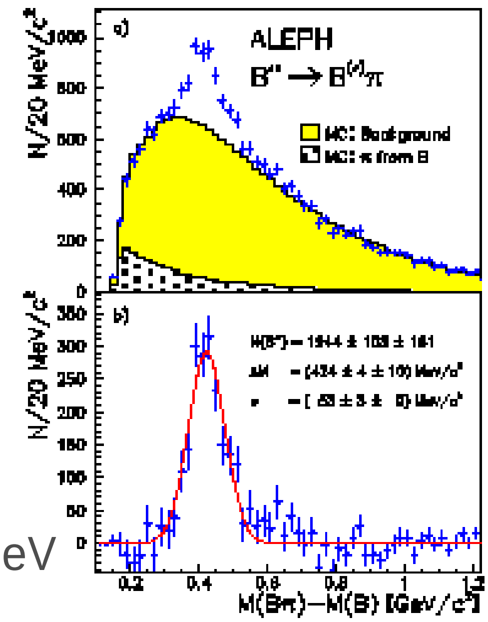
$m(B^+)$ [MeV] = 5279.1 +/- 0.4 +/- 0.4

(for reference: Δm_B = 0.34+/- 0.32)

$m_b >> L_{QCD}$

b-flavored Hadrons

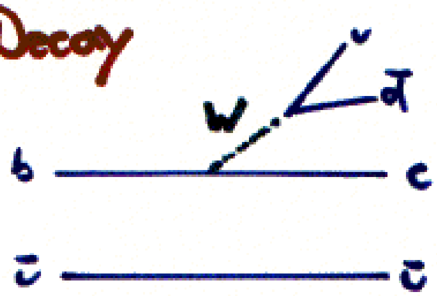
- $\bar{B}^0$ ($b\bar{d}$), B^- ($b\bar{u}$)
  - m = 5.279 GeV
  - First excitation B* (Δm = 45.78+/-0.35 MeV)
  - Orbital excitation (L=1) B** around 5.697 GeV



- B_s ($b\bar{s}$)
  - m = 5.3696 +/- 0.0024 GeV
- B_c ($b\bar{c}$)
  - m = 6.40 +/- 0.39 +/- 0.13 GeV
- b Baryons
  - Λ_b (bud) at 5.624 +/- 0.009 GeV
  - Evidence for Ξb

Lifetimes of b Hadrons

Spectator Decay



$\Rightarrow$ expect equal lifetimes

$$\Gamma = \frac{1}{\tau} = \frac{G_F^2 \, m_b^5}{192 \, \pi^2} \, |V_{cb}|^2 \, \underbrace{\mathcal{F}}_{\text{phase space}}$$

add non spectator effects:

$$\tau_{B^-} \gtrsim \tau_{\bar{B}^0} \approx \tau_{B_s} > \tau_{\Lambda_b^0} \gg \tau_{B_c}$$

and

$$\frac{\tau_{B^-}}{\tau_{\bar{B}^0}} \simeq 1.05 \; ; \quad \frac{\tau_{B_s}}{\tau_{\bar{B}^0}} \simeq 1 \; ; \quad \frac{\tau_{\Lambda_b}}{\tau_{\bar{B}^0}} = 0.9$$

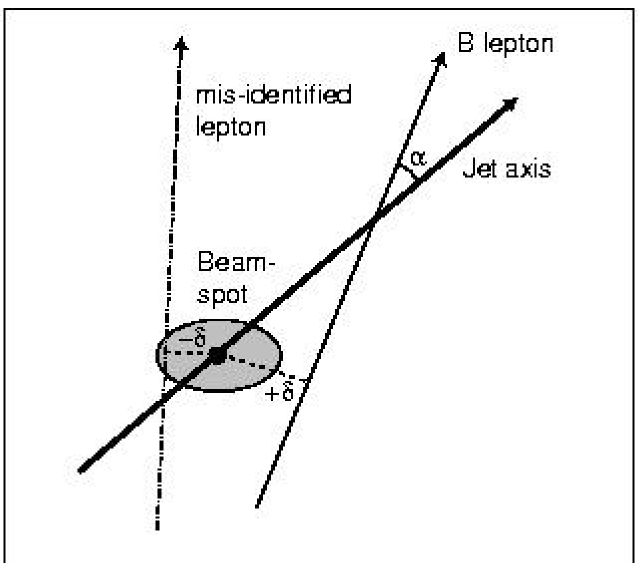
Lifetime Measurements

$$t_b = \frac{L_b}{gb\; c} \qquad L_b = decay \quad length$$

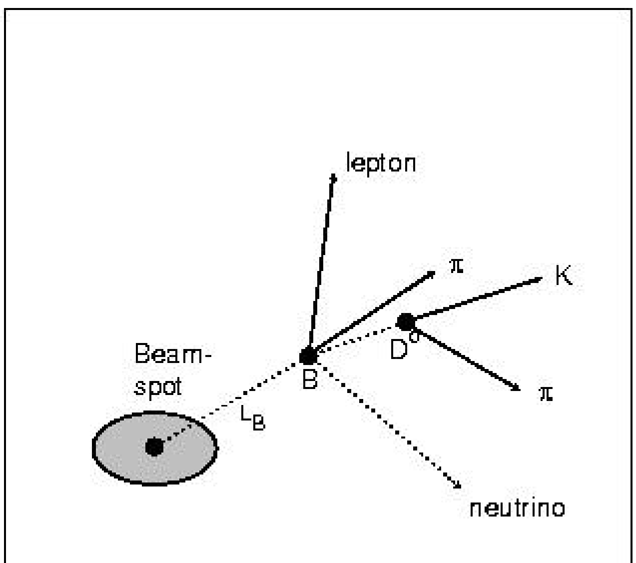
LEP: <L_b> ~ 2.5 mm
CDF: <L_b> ~ 0.9 mm
Technique:

select enriched sample
measure b momentum (gb)
measure vertex (L_b)
or impact parameter

$$d = gbc\,t_b \sin a \,\sin q \qquad \left(Trick : \sin a \propto {}^{1}\!/_{gb} \right)$$



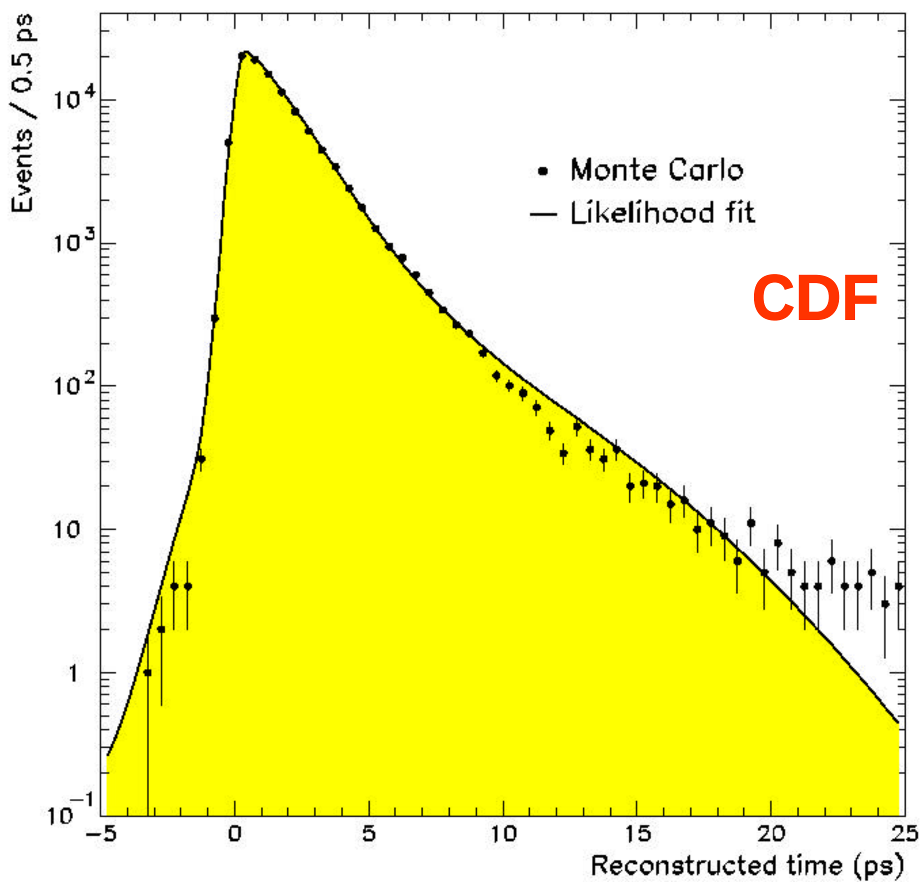
a) Impact Parameter Method



b) Vertex Reconstruction Method

Inclusive b Lifetime

Include all b hadrons



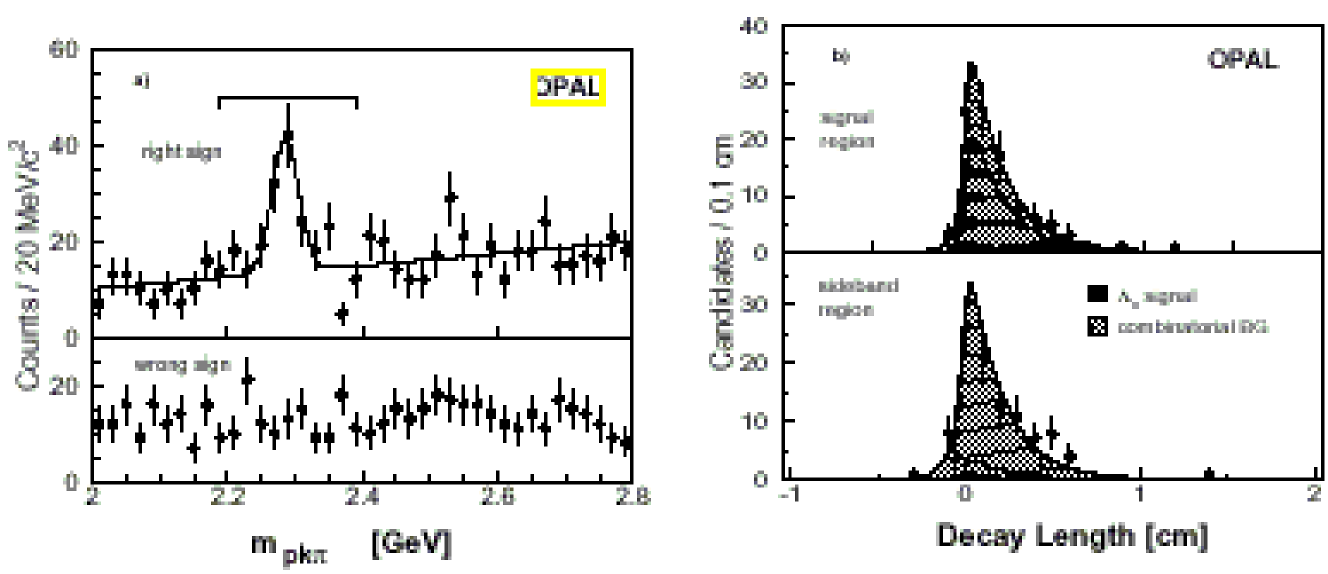
World average: 1.564 + / - 0.014

- ➡ **fairly long lived**
- ➡ **V_{cb} is small**

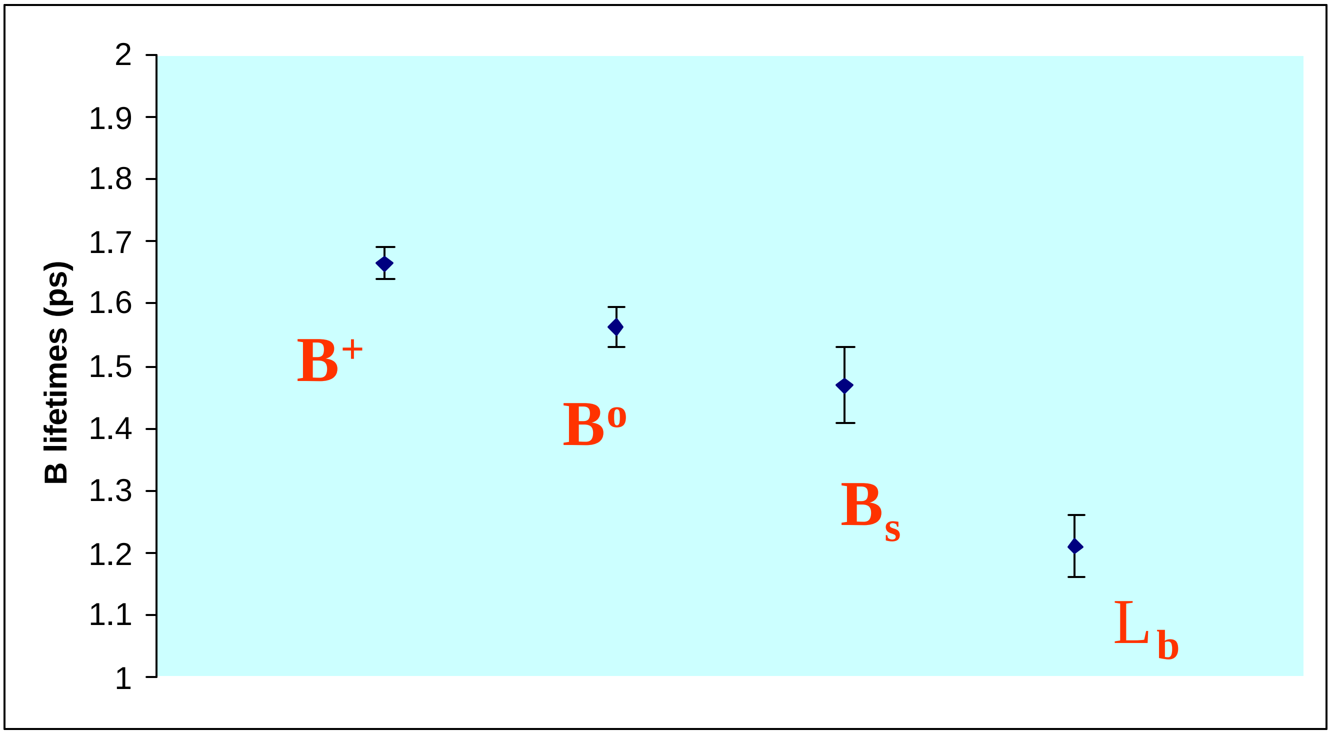
Lifetimes for specific Hadrons

- **Select enriched sample**
  - full reconstruction
  - Particle - Lepton correlations

$$e.g.: \quad \overline{B}^0 \rightarrow D^{*+}\bar{\lambda} n, D^{*+} \rightarrow D^0 p^+, D^0 \rightarrow K^- p^+$$



Lifetime Summary



Particle	Lifetime [ps]
B^0	1.548 +/- 0.032
B^+	1.653 +/- 0.028
B_s	1.493 +/- 0.062
B_c	0.46+/-0.17+/-0.03
b-baryon	1.208+/- 0.051

Good agreement but baryon lifetime is significantly below theo. expectations