Cours/Lecture Series

1990-1991 ACADEMIC TRAINING PROGRAMME

LECTURE SERIES FOR POSTGRADUATE STUDENTS

SPEAKER	: P. ZERWAS / Rhein.-Westf. Technische Hochschule, Aachen
TITLE	: Heavy flavours and CP violation
DATES	: 1, 5 & 7 November
TIME	: 11.00 to 12.00 hrs – Auditorium
PLACE	: Auditorium

ABSTRACT

The lectures are divided into three parts :

1. *Heavy flavours at LEP : tests of the Standard Model and the physics beyond*
2. *Top quarks at the LHC and high energy $e^+ e^-$ colliders*
3. *CP violation in the standard model and predictions for the b-quark sector.*

Div. DG/PU
Distr. int. + ext.

Secretariat : tel. 2844 - 3674

HEAVY FLAVORS

MOTIVATION

a) Standard Model SM:

- find top quark : mass m_t
  decay properties [width, branching ratios]
- investigate quark mixing : 3×3 Cabibbo-Kobayashi-Maskawa
  CP in b-system
- strong interactions of b quarks : fragmentation
  hadronic decay matrix el.

b) Beyond SM:

heavy quarks closer to ~ TeV scale:

- precision measurements
- rare decay processes

} new thresholds : SUSY, Z', ...
compositeness scale
⋮

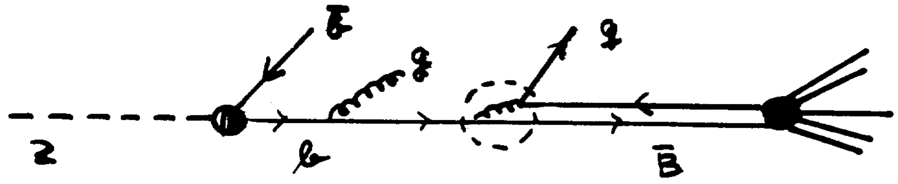
LAYOUT

1.) b physics at LEP / HE specific problems

2.) properties and production of top quarks

3.) CP violation / mainly B^0 system

A.) b at LEP



10^{-2} fm   1–10 fm   ~3 mm

(1) electroweak properties of b quarks

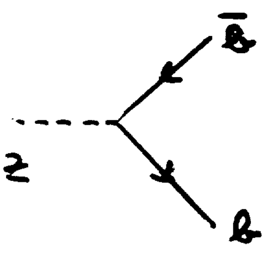
(2) hadronization

(3) electroweak properties of b hadrons:
lifetimes / mixing

LEP : 10^6 Z → 300,000 B mesons : $B_u \sim 130{,}000$
$B_d \sim 130{,}000$
$B_s \sim 40{,}000$

10% b baryons : $\Lambda_b \sim 5\%$

(1) b PRODUCTION ON THE Z



SM : $I_3(b) = -1/2$
$Q(b) = -1/3$

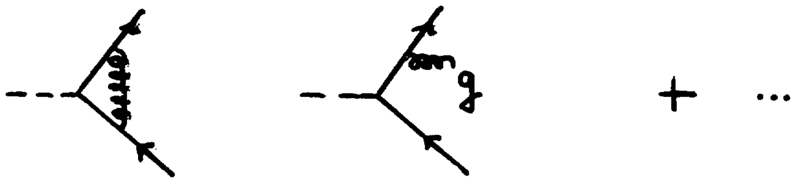
width [Born approximation]:

$$\boxed{\Gamma_0(Z \to b\bar{b}) = \frac{G_F M_Z^3}{8\sqrt{2}\pi}\beta\left[\frac{3-\beta^2}{2}v^2 + \beta^2 a^2\right]}$$

vector charge : $v = 2I_3 - 4Q\sin^2\theta_W$

axial charge : $a = 2I_3$

a) QCD corrections



vertex correction   g bremsstrahlung   higher orders

$$\Gamma(Z \to q\bar{q}) = \Gamma_0^V \left[1 + c_1\left(\frac{\alpha_s}{\pi}\right) + c_2\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots\right] + \Gamma_0^A \left[1 + d_1\left(\frac{\alpha_s}{\pi}\right) + d_2\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots\right]$$

} $d_i \neq c_i$: bkg
chiral sym.
isospin sym.

- <u>first order</u>:

Schwinger
Jersak
Laermann
Zerwas

$$c_1 = 1 + 12\frac{m^2}{s} + \cdots$$

$$d_1 = \underbrace{1 + 12\frac{m^2}{s}\log\frac{s}{m^2}}_{\approx 0.17} + \cdots$$

← log may be mapped into m^2/s term in Γ_0^A by defining running mass $\bar{m} = \bar{m}(s)$:

$$m^2 = \bar{m}^2(s)\left[1 + \frac{\alpha_s}{\pi}\left(\frac{8}{3} + 2\log\frac{s}{m^2}\right)\right]$$

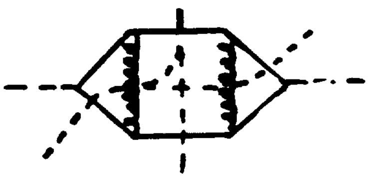
Kühn et al.

- <u>second order</u>:

$c_2 = 1.41$ $[\overline{MS}]$

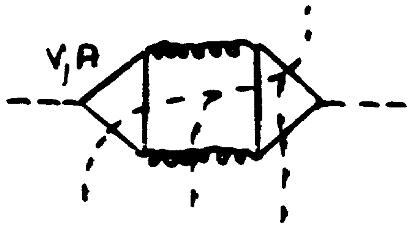
$d_2 = 1.41 + F(m_t)$

- box diagrams:



chirally symmetric : $V = A$ for $m^2/s = 0$

- triangle diagrams:



$F(m_t)$: FS

$V = 0$: Furry's theorem

$$I_3^V[g_s]^2 + (-I_3^V)[-g_s]^2 = 0$$

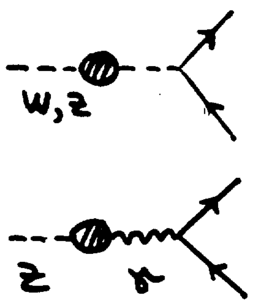
$A \neq 0$: $I_3^A[g_s]^2 + I_3^A[-g_s]^2 \neq 0$

except if a complete doublet with $\langle I_3 \rangle = 0$ added up: <u>not possible for top quarks</u>

b) <u>genuine electroweak corrections</u>

- bulk of rad. QED corrections absorbed into Born term because $G_F(m_Z^2) \simeq G_F(0)$ in leadg log

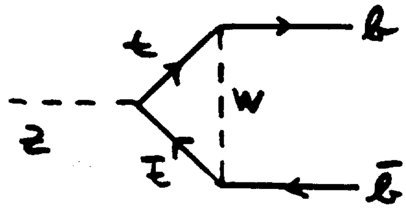
- universal electroweak corrections*:



$$\boxed{\begin{aligned} G_F &\Rightarrow [1+\Delta\rho]G_F \\ \sin^2\theta_W &\Rightarrow [1+\Delta\varkappa_{se}]\sin^2\theta_W \end{aligned}}$$

Sirlin
Marciano
Akhundov
Bardin
Riemann
[illegible]
Hollik
[illegible]
[illegible]
...

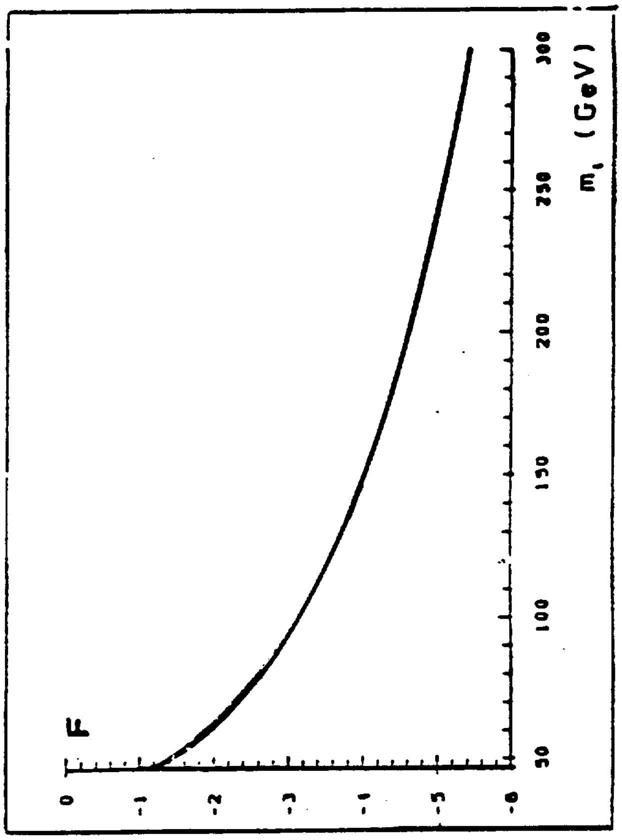
- b-specific vertex corrections:



$$\boxed{\begin{aligned} v_b &\to v_b + \tfrac{2}{3}\Delta\rho \\ a_b &\to a_b + \tfrac{2}{3}\Delta\rho \end{aligned}}$$

* on-shell ren. scheme à la Sirlin

Kniel
Kühn



summary

$$G_F \to G_F^{eff} = \rho\, G_F \qquad \rho_f = 1+\Delta\rho$$

$$\sin^2\vartheta_W \to \sin^2\vartheta_W^{eff} = \varkappa \sin^2\vartheta_W \qquad \rho_b = 1+\Delta\rho - \tfrac{4}{3}\Delta\rho$$

$$\varkappa = 1+\Delta\varkappa_{se}+\Delta\varkappa_{s,v}$$

$$\Delta\rho = \frac{3\sqrt{2}\,G_F m_t^2}{16\pi^2} + \dots$$

$$\Delta\varkappa_{se} = \mathrm{ctg}^2\vartheta_W \Delta\rho + \text{subleadg } t + \text{subleadg } H + \dots$$

$$\Delta\varkappa_{s,v} = \frac{2}{3}\Delta\rho + \text{subleadg } t + \dots$$

Veltman

$\Gamma(Z\to b\bar{b})$ F7: very weak dependence on top and Higgs mass [accidental cancelation between oblique / vertex corr.]
$\Rightarrow$ nearly param. free observable of SM

LEP RESULTS

Dydak

		$BR_\ell \cdot \Gamma_b/\Gamma_\ell$	Γ_b/Γ_ℓ
aleph	e,μ	0.0224 ± 0.0019	
Delphi	spher.		0.211 ± 0.037
L3	μ	0.0248 ± 0.0014	
opal	μ	0.0206 ± 0.0021	

confronted with overall SM fit: $\Gamma_b/\Gamma = 0.217$

$BR_\ell = 0.107 \pm 0.005$

PHYSICAL EVALUATION

(a) topless model: $I_3(b) = 0$ $\qquad \dfrac{\Gamma(b\bar{b})^{topless}}{\Gamma(b\bar{b})^{SM}} \approx \dfrac{e_b^2}{v_\ell^2+a_\ell^2} \approx \dfrac{1}{13}$

RULED OUT

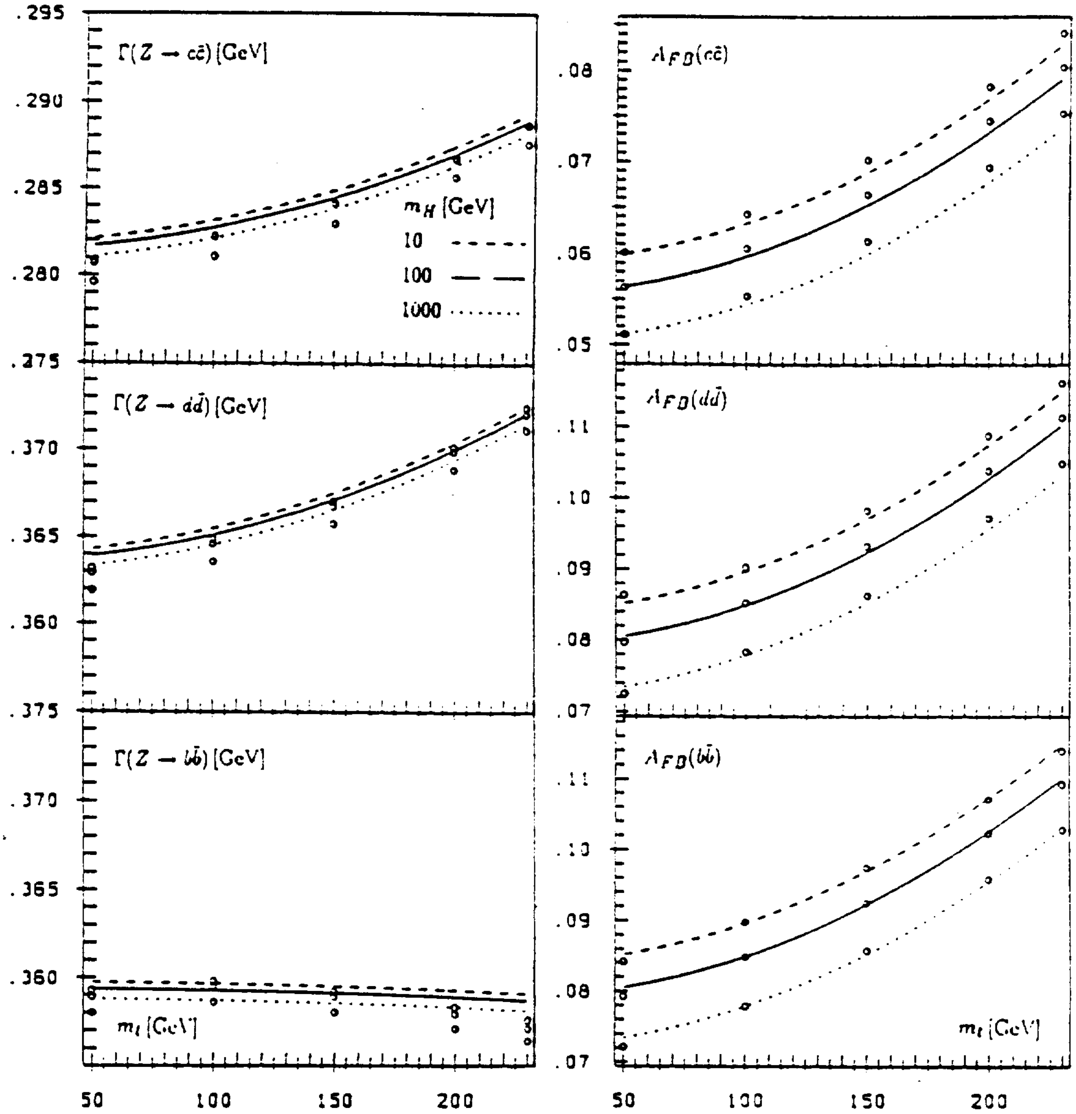


Fig. 2: The dependence of the partial Z widths (left) and of the forward-backward asymmetries (right) on the top and Higgs masses. Curves: approximate formulas as described in the text; diamonds: full one loop calculation from [3].

Beenakker
Hollik

(β) Υ variable

eliminate universal [oblique] corrections / isolate vertex corr.

$$\boxed{\Upsilon = \frac{3}{59}\frac{\Gamma_{had}}{\Gamma_e} - \frac{30}{59}\frac{9}{\alpha(m_Z^2)}\frac{\Gamma_e}{m_Z}}$$

Renard
Verzegnassi

$$\Upsilon = (0.521 \pm 0.007)\left[1 + \frac{2}{3}\Delta_{bV}\right]$$

≤ 0.530 $m_t \geq 80\,\text{geV}$ $\quad -\frac{30}{19}\frac{\alpha}{\pi}\left[\frac{m_t^2}{m_Z^2} + \frac{13}{6}\log\frac{m_t^2}{m_Z^2}\right]$

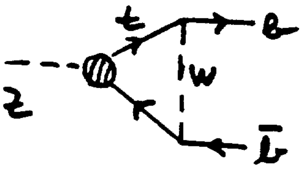
Phenomena beyond the SM affecting Υ : F9

(i) SUSY contributions to Δ_{bV} negative ⟷ same as top

(ii) Z' positive ⟹ could provide a unique signal

(γ) Form factor effects in $Zt\bar{t}$: affecting $Z \to b\bar{b}$ Peccei ...

[compositeness / $(t\bar{t})$ condensates ...]

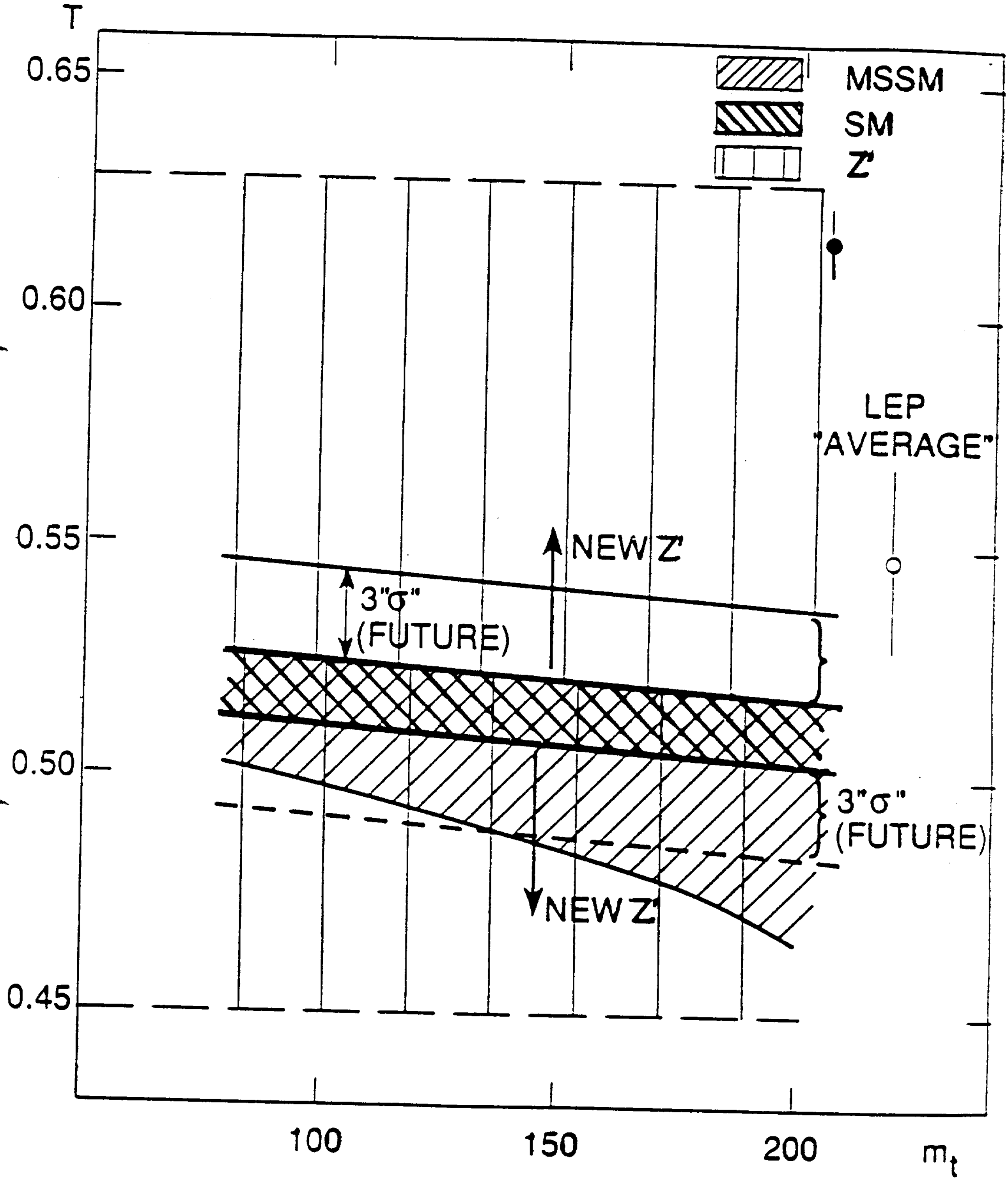


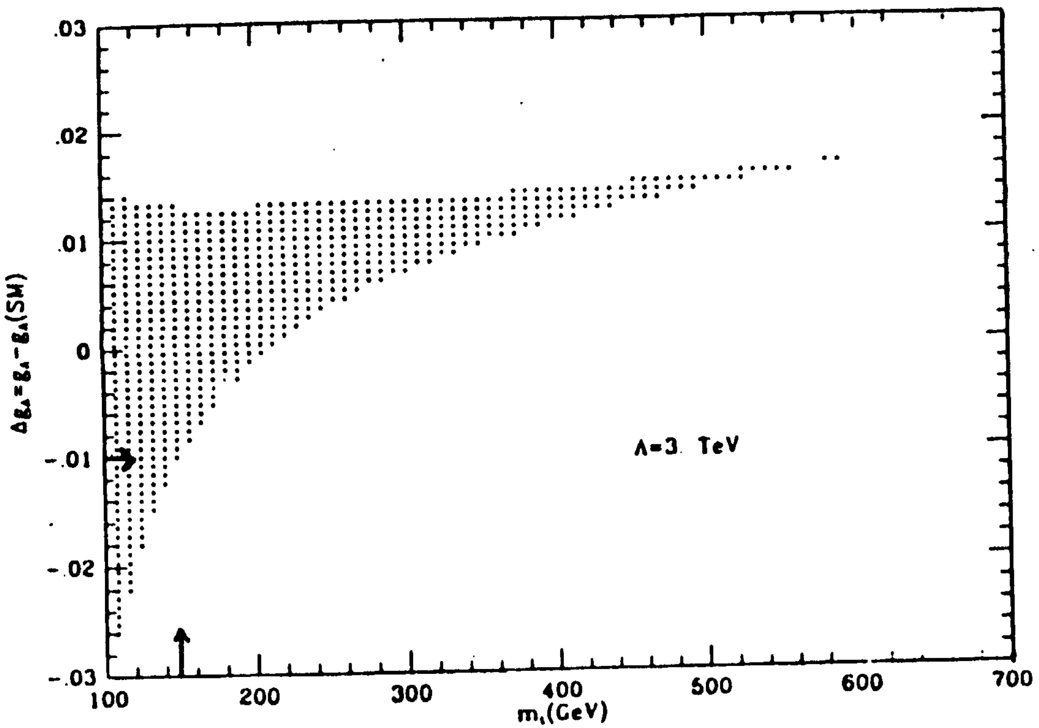
$\left.\begin{array}{l}\Delta g \\ \Gamma_{had}/\Gamma_e \\ \Upsilon\end{array}\right\}$ vector v_t : little constraint; axial a_t : < 10% F10

↑ dominant effect from QCD type goldstone $(t\bar{t})$ bosons

⟹ electroweak coupling of the yet to be discovered t quark experimentally constraint already now!

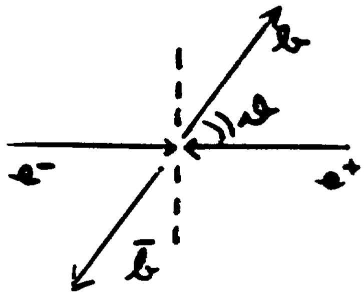
Verzegnassi




.03
.02
.01
0
-.01
-.02
-.03
$\Delta g_A = g_A - g_A(SM)$
100
200
300
400
500
600
700
m_t(GeV)
Λ=3 TeV

Peccei
et al.

(2) FORWARD-BACKWARD ASYMMETRY



$$\boxed{A_{FB} = \frac{3}{4}\;\frac{2v_e a_e}{v_e^2+a_e^2}\;\frac{2v_b a_b}{v_b^2+a_b^2}}$$

↑ Z polarisation (−)   ↑ analys. power

$a_{e,b} = -1$
$v_{e,b} = -1 - 4Q \sin^2\vartheta^{e,b}_{W,eff}$ } including all el.w. corrections

- second factor : ≈ 0.94 large, varying slowly with $\sin^2\vartheta^b_{W,eff}$ → $\sin^2\vartheta_W$ → $\sin^2\vartheta^e_{W,eff}$

- first factor : ∼ $2[1-4\sin^2\vartheta^e_{W,eff}]$ rapidly varying

⇒ $\sin^2\vartheta^e_{W,eff}$ dependence of $A_{FB}(b)$ similar to A_{LR} : rapid variation $\sim \frac{3}{4} \times 2 \times 4 = 6$

F12

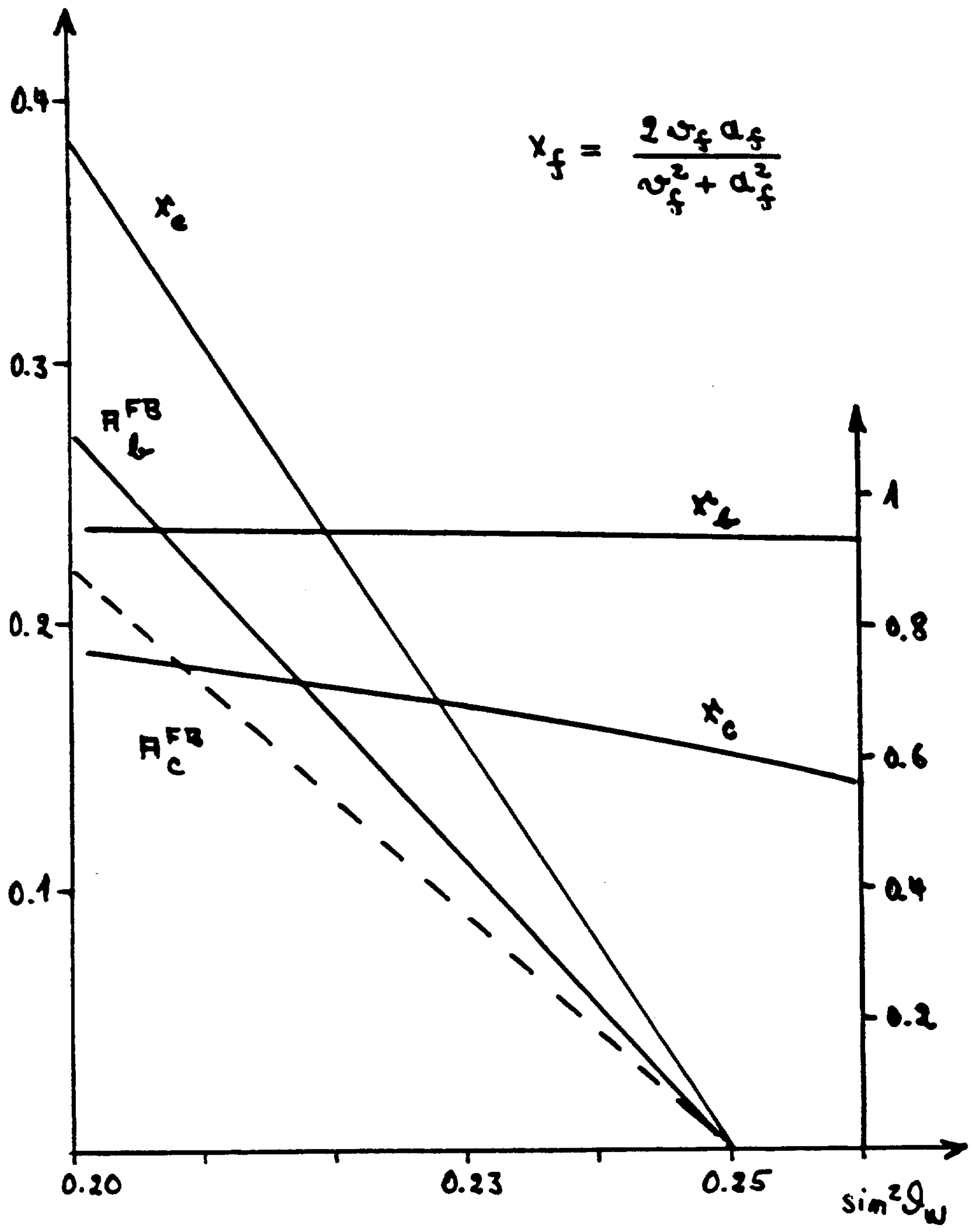
REFINEMENTS:

a) QCD corrections : $A_{FB} = A^0_{FB}\left[1 + k\frac{\alpha_s}{\pi}\right]$

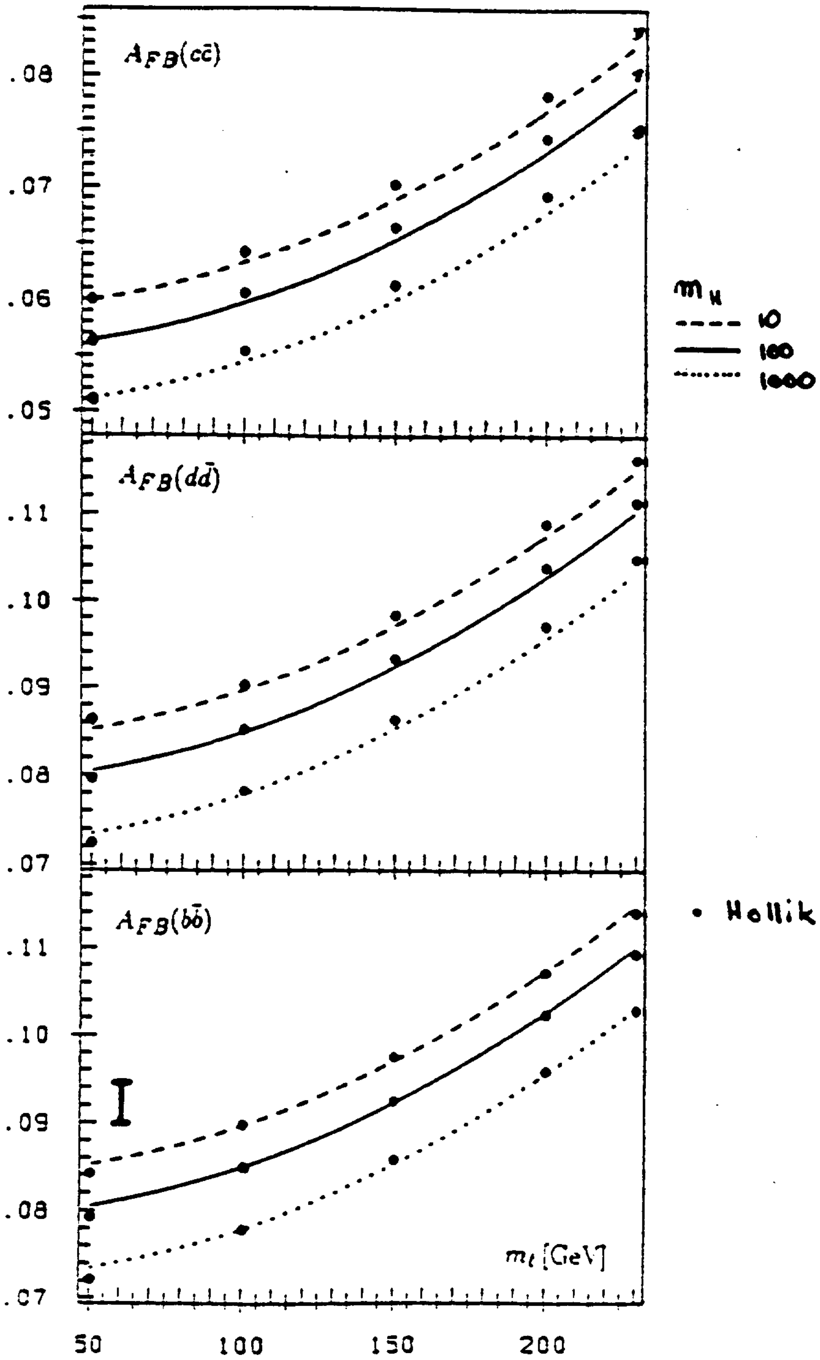
$k \approx -0.5$ for 2-jets

b) genuine electroweak corrections ⇒ strong dep. on m_t and m_H

F13



$x_f = \frac{2 v_f a_f}{v_f^2 + a_f^2}$
0.4
0.3
0.2
0.1
x_e
A_b^{FB}
x_b
x_c
A_c^{FB}
1
0.8
0.6
0.4
0.2
0.20
0.23
0.25
$\sin^2\vartheta_W$



$A_{FB}(c\bar{c})$
$A_{FB}(d\bar{d})$
$A_{FB}(b\bar{b})$
.08
.07
.06
.05
.11
.10
.09
.08
.07
.11
.10
.09
.08
.07
50
100
150
200
m_t [GeV]
m_H
10
100
1000
• Hollik

c) MIXING :

b tagging through ℓ^- : probability for $\bar{b} \in B$ in original b beam $= \bar{\chi}$
measured in like-sign dilepton rate :

$$R_{\ell\ell} = \frac{\ell^\pm \ell^\pm}{\text{all } \ell\ell} = 2\bar{\chi}(1-\bar{\chi}) \quad : \quad \text{UA1 / Aleph / L3}$$

$\bar{\chi} = 0.12 \pm 0.04$

$$\boxed{A_{FB}(\ell) = A_{FB}(b)\,[1-2\bar{\chi}]}$$

-32%

Biz.

overall sensitivity on $\sin^2\theta_W^{eff}$: F15

present L3 analysis : $A_{FB}(b) = -0.109 \pm 0.044$

future : $\delta A_{FB}(b) \lesssim \pm 0.010 \Rightarrow$

$\delta \sin^2\theta_W \approx 0.001$ to 0.002

competing well with other methods : $A_{FB}(\mu\mu)$

τ polarization

<u>HLEP variables</u> :

Djouadi, Girardi, Hollik, Renard, Verzegnassi

$$D = \frac{6}{23}\left[\frac{1}{4}\frac{\Gamma_{udsc}}{\Gamma_\ell} - \frac{26}{27}A_{FB}^b\right]$$

free of oblique and vertex corr.
$\Rightarrow$ sensitive to <u>Z' mixing</u>

$$M = \frac{3}{13}\left[\frac{\Gamma_b}{\Gamma_\ell} - \frac{26}{27}A_{FB}^b\right]$$

free of oblique corr. and Z' mix
$\Rightarrow$ sensitive to <u>SUSY vertex</u>

⋮

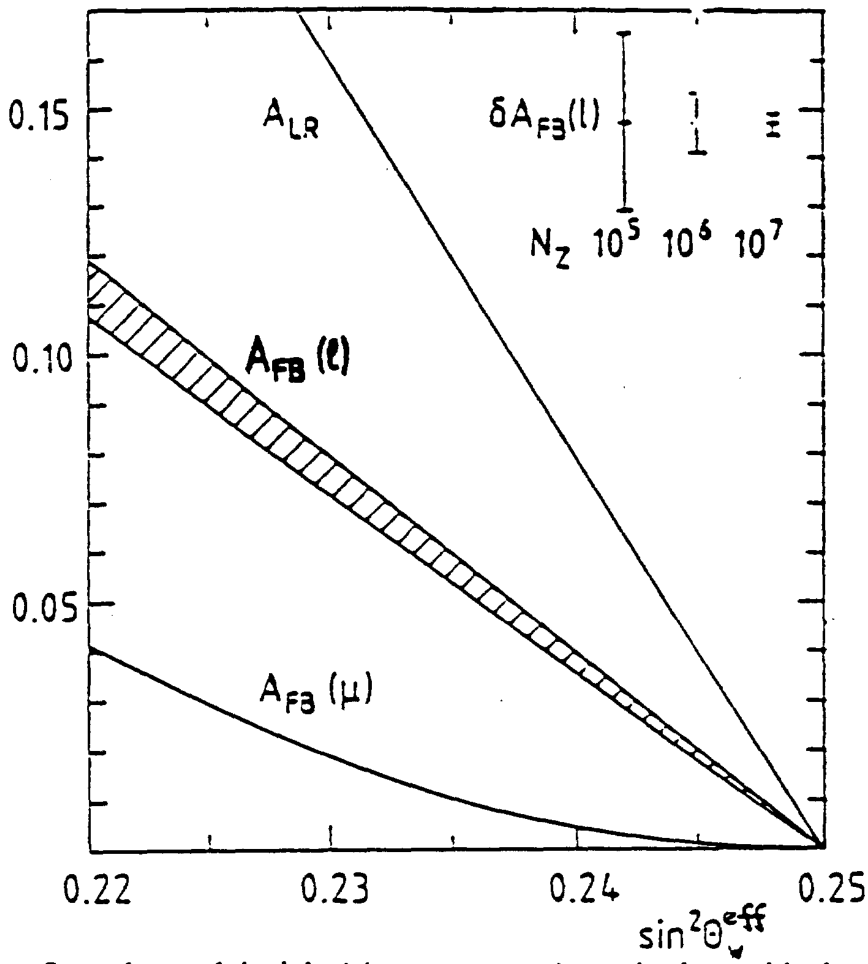


Fig. 4: Dependence of the left-right asymmetry A_{LR}, the forward-backward asymmetry of leptons from B-decays (including QCD corrections and mixing) $A_{FB}(\ell)$ and of μ-pairs $A_{FB}(\mu)$ on $\sin^2\theta_W$. Also shown is the combined uncertainty from fragmentation, QCD and mixing as described in the text.

(3.) FRAGMENTATION

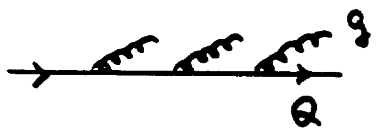
2 processes: (i) degrading of Q energy due to perturbative small-angle gluon bremsstrahlung

(ii) non-perturbative binding $Q \to (Q\bar{q})$

$$D(z) = \int_z^1 \frac{d\xi}{\xi}\, d^{NP}\!\left(\frac{z}{\xi}\right) d^{PT}(\xi)$$

$$\langle z \rangle = \langle z \rangle^{NP} \langle z \rangle^{PT}$$

(i) g bremsstrahlung



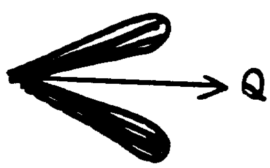
NS-AP equation:

$$\boxed{\langle z \rangle_{PT} = \left[\frac{\alpha_s(E^2)}{\alpha_s(m_Q^2)}\right]^{\frac{32}{3[33-2N_f]}}}$$

shape, next-to-leading order, F16b

perturbative g fragmentation non sufficient:

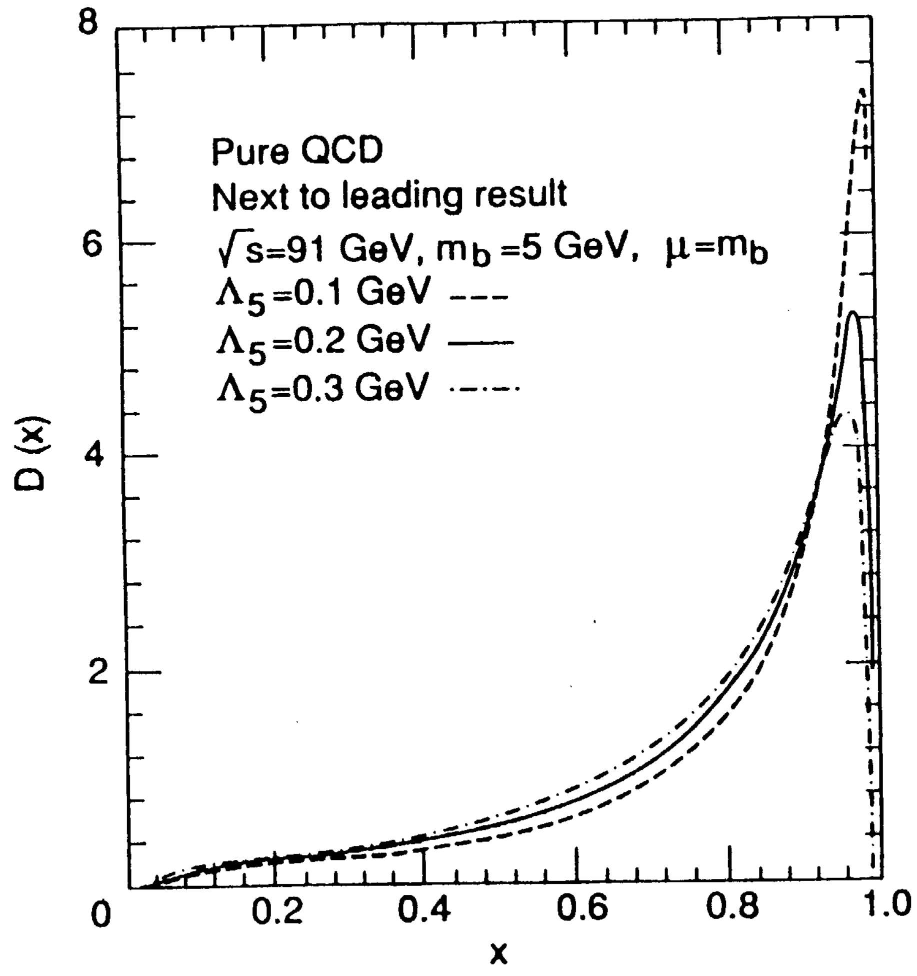
- $\langle z \rangle_{PT} \approx 0.8$ > exp. value for $Q = b$ at LEP
- prob ~ few % : no g bremsstrahlung at all → free quarks
- depletion of gluon density around heavy quark direction



$$dN^g = \frac{4}{3}\frac{\alpha_s}{\pi}\,\frac{\theta^2 d\theta^2}{[\theta^2 + (m_Q/E)^2]^2}$$

$\min(\theta_g) \sim 6°$ ⇒ perturbative color gaps ~ 10 fermi

Mele, Nason



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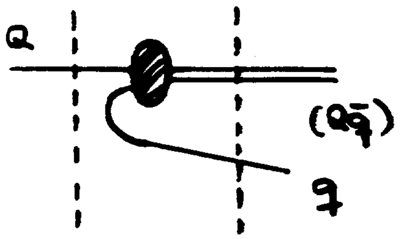
(ii) non-perturbative fragmentation:

Bjorken
Suzuki
...

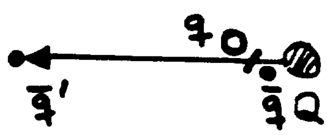
(a) QUALITATIVE PICTURE



Q heavy }
q light }
hadronization $Q \to (Q\bar{q})$ does not change much Q mom. because of inertia $\Rightarrow$ heavy Q fragm. hard

$\bar{\nu}_e e \to Q \bar{q}'$: REST FRAME of Q $\leftarrow$ ENVIRONMENTAL INDEPENDENCE

$\bar{q}'$ jet = jet as in $e^+e^- \to q'\bar{q}'$



$p(q) \sim m_{eff} \sim$ GeV

BOOST TO LAB: $E_q = \gamma m_{eff}$

$= \frac{E}{m_Q} m_{eff}$ $\quad E(Q\bar{q}) = E - \frac{m_{eff}}{m_Q} E$

in general: $\langle z \rangle_{NP} \approx 1 - \frac{1\,\text{GeV}}{m_Q}$

≈ 0.8 for b

Peterson
Schlatter
Schmitt
Zerwas

(b) PETERSON et al FORM

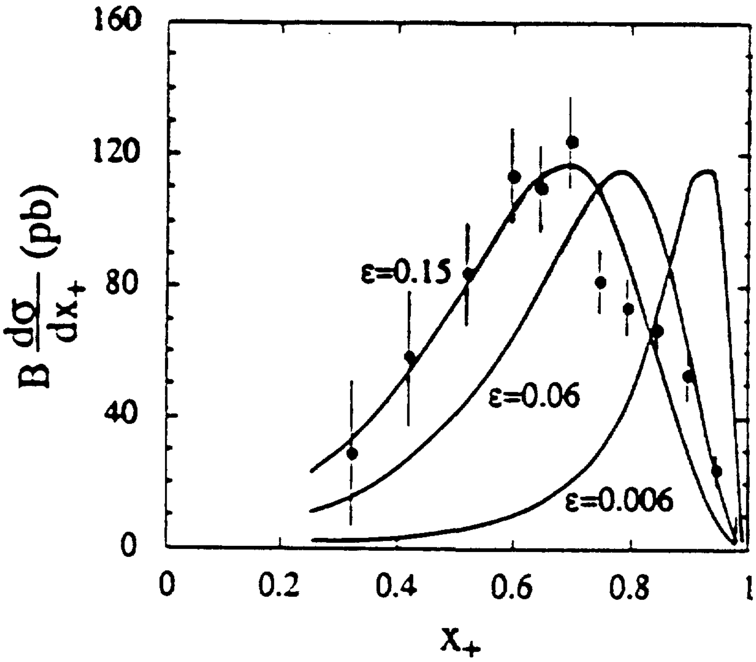
transition amplitude $Q \to (Q\bar{q}) + q$
$\sim [\text{energy transfer}]^{-1}$

exp: F18 D^* at 10 GeV

30 GeV : $\epsilon_c = 0.06^{+0.03}_{-0.02}$

$\epsilon_b = 0.008 \pm 0.002$

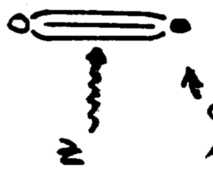
$$\boxed{\begin{aligned} D_{NP}(z) &= \frac{A}{z\left[1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z}\right]^2} \\ \epsilon_Q &= \frac{m_q^2}{m_Q^2} \Rightarrow \epsilon_c \sim 0.10 \\ \langle z \rangle_{NP} &= 1 - \sqrt{\epsilon_Q} \qquad \frac{\epsilon_b}{\epsilon_c} \sim \frac{1}{10} \end{aligned}}$$



Heavy quark fragmentation: Inclusive cross section for the production of $D^*(2010)^+$ mesons in e^+e^- annihilation at $\sqrt{s} \approx 10$ GeV, as a function of the scaling variable $x_+ = (E+p)/(E+p)_{\text{kinem. limit}}$. Also shown is the Peterson *et al.* form, $d\sigma/dz \sim z(1-z)^2/[(1-z)^2+\epsilon z]^2$, for $\epsilon = 0.15$. We note that instead of the scaling variable x or x_+, some experiments prefer to define a scaling variable z as $z = (E+p_{\parallel})_{\text{had.}}/(E+p)_{\text{quark}}$, correcting for gluon radiation before the final fragmentation. With this definition at $\sqrt{s} \approx 30$ GeV, $\langle z_C \rangle = 0.67 \pm 0.03$ $\langle z_B \rangle = 0.83 \pm 0.03$, corresponding to $\epsilon_C = 0.06^{+0.03}_{-0.02}$ and $\epsilon_B = 0.006 \pm 0.002$. The corresponding Peterson shapes are included here. References: D. Bortoletto *et al.*, Phys. Rev. D37, 1719 (1988); J. Chrin, Z. Phys. C36, 163 (1987); and C. Peterson *et al.*, Phys. Rev. D27, 105 (1983).

(c) BOWLER-MORRIS STRING PICTURE

Artru
Mennessier
Bowler
Morris



constant
nonpert.
flux-tube/
string force
[lattice]

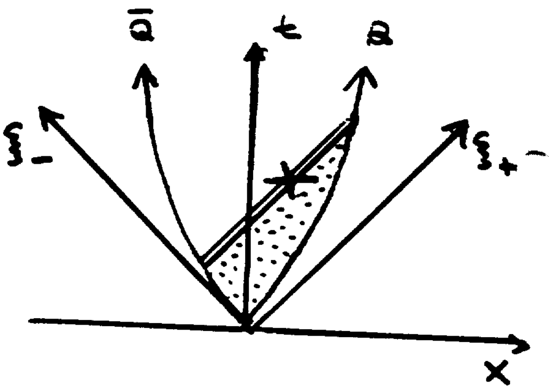
$$\frac{d}{dt}\frac{mv}{\sqrt{1-v^2}} = -\sigma$$

$$x(t) = \frac{1}{\sigma}\left[E_0 - \sqrt{(p_0-\sigma t)^2 + m^2}\right]$$

$$p(t) = p_0 - \alpha t$$

quarks move on hyperbolae in 4 dim. world

light-cone $\xi_\pm = \frac{t \pm x}{\sqrt{2}}$



__decay probability__

point particle:

$dP_{decay} = \lambda d\tau$

$dP(\tau) = \lambda e^{-\lambda\tau} d\tau$

string:

$dP_{decay} = \lambda dA$ $\quad A =$ inv. area

$dP(A) = \lambda e^{-\lambda A} dA$

× chosen randomly on light like boundary

$$\left.\begin{array}{l} E = E_0 - \sigma x \\ p = p_0 - \sigma t \end{array}\right\}$$

$M = \sqrt{E^2 - p^2}$

$$A = \int d\xi_- \left[\xi_+(Q) - \xi_+(\bar{Q})\right]$$

$$= \frac{m_Q^2}{2\sigma^2}\left[\frac{M^2}{m_Q^2}\frac{1}{z} - 1 - \log\left(\frac{M^2}{m_Q^2}\frac{1}{z}\right)\right]$$

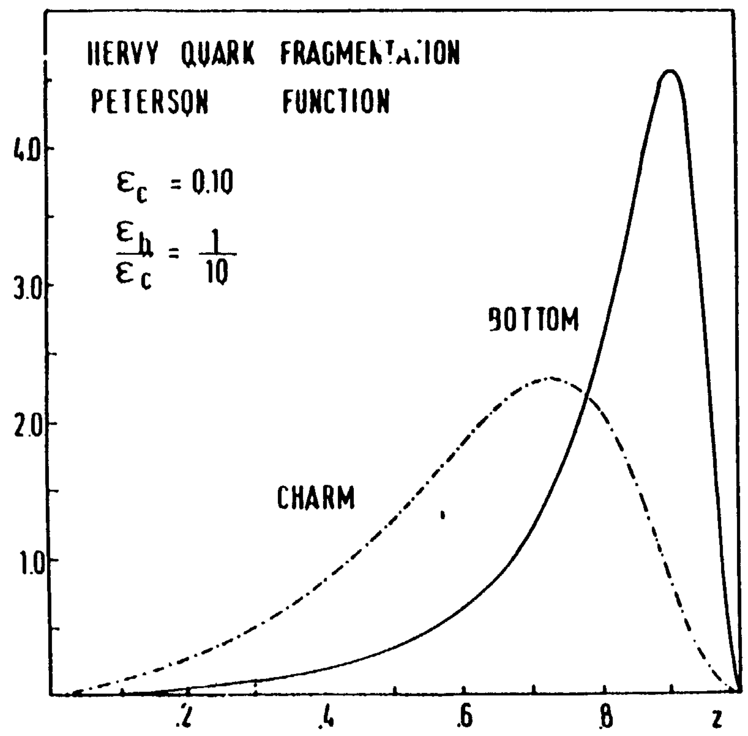
repeated breakings:

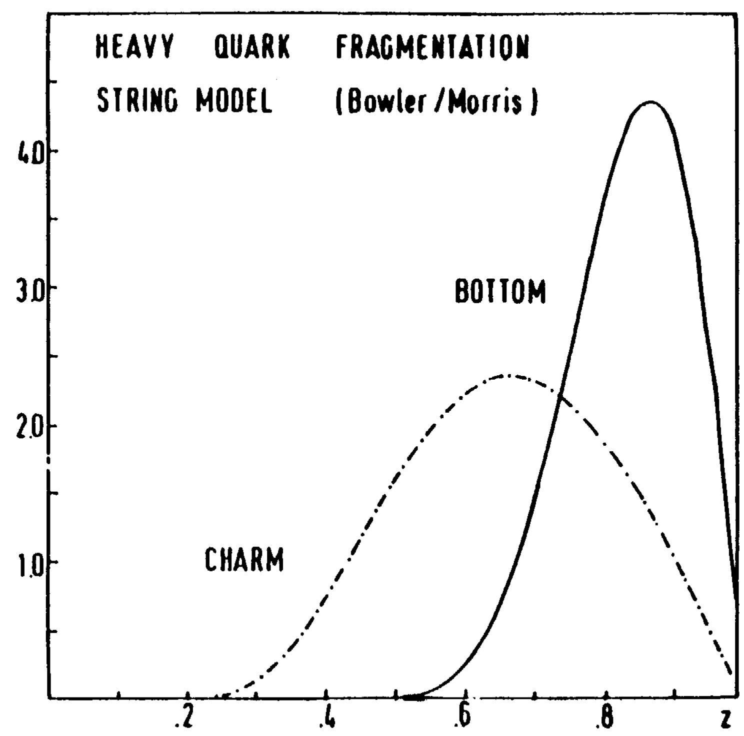
$$\boxed{D_{NP}(z) \propto \frac{(1-z)^a}{z^{1+b m_Q^2}} e^{-\frac{b m_Q^2}{z}}}$$

F20 : Bowler Morris ~ Peterson

L3 : $\langle x_b \rangle = 0.69 \pm 0.02 \pm 0.03$

$\sim \langle x \rangle_{NP} \langle x \rangle_{PT}$


HEAVY QUARK FRAGMENTATION
PETERSON FUNCTION
$\varepsilon_c = 0.10$
$\frac{\varepsilon_b}{\varepsilon_c} = \frac{1}{10}$
BOTTOM
CHARM
4.0
3.0
2.0
1.0
.2
.4
.6
.8
z


HEAVY QUARK FRAGMENTATION
STRING MODEL (Bowler/Morris)
BOTTOM
CHARM
4.0
3.0
2.0
1.0
.2
.4
.6
.8
z

2') TESTING QCD

b tagging can be used to discriminate quark vs gluon jets

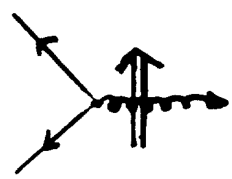
(1) Particle flow in different angular regions:

$$\frac{N_{qg}}{N_{q\bar{q}}} = \frac{5 - \frac{1}{N_c^2}}{2 - \frac{4}{N_c^2}} = \begin{cases} 3.15 & \text{for } N_c = 3 \\ 2.5 & \text{for } N_c = \infty \end{cases}$$

$\Rightarrow$ striking difference between quark and gluon jets
important $1/N_c^2$ terms

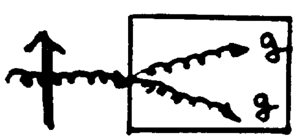
(2) ggg coupling in 4 jet events:

• $e^+e^- \to Z \to q\bar{q}g$ g $\approx$ linearly polarized in final state plane:

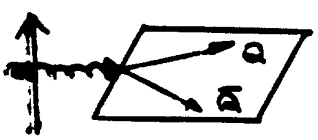


$$P_g = \frac{2(1 - x_g)}{x_q^2 + x_{\bar{q}}^2}$$

• $g \to gg$ and $g \to Q\bar{Q}$ decay distributions, relative to spin axis:



$$D_{g \to gg} = \frac{6}{2\pi}\left[\frac{(1-z+z^2)^2}{z(1-z)} + z(1-z)\cos 2\chi_4\right]$$



$$D_{g \to Q\bar{Q}} = \frac{1}{2\pi}\left[\frac{1}{2}(z^2 + (1-z)^2) - z(1-z)\cos 2\chi_4\right]$$

$\Rightarrow$ gg preferent. <u>in</u> event plane: small asymmetry
$Q\bar{Q}$ preferent. <u>out of</u> event plane: large asymmetry

F23: comparison gluons vs quarks in QCD
gluons in QCD vs ABELIAN model

F24: Opal/L3: comparison QCD vs. ABELIAN MODEL
Delphi: SU_{3C} Casimir invariant: $N_c/C_F = 9/4 = 2.25$
$= 2.25 \pm .4 \pm .4 \pm .45$

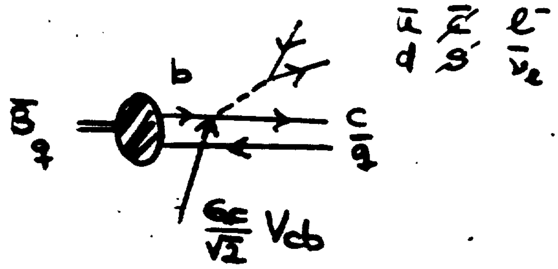
3.) <u>B LIFETIMES</u>

average lifetime: $\langle \tau_B \rangle = 1.13 \pm 0.15$ psec
$\Rightarrow$ macroscopic decay length at LEP
$\ell \sim \gamma_B \langle \tau_B \rangle c \sim 10 \times 10^{-12} \times 3 \times 10^{11}$ mm
~ 3 mm

(a) SPECTATOR MODEL

large b mass primarily determines lifetime; binding unimportant

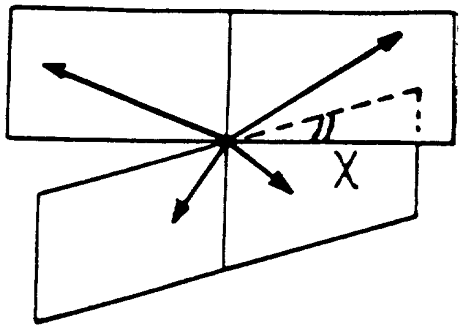
<u>Fermi decay</u>:

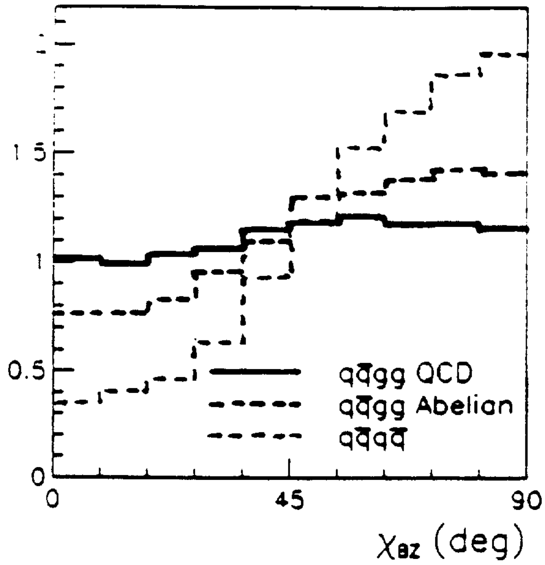


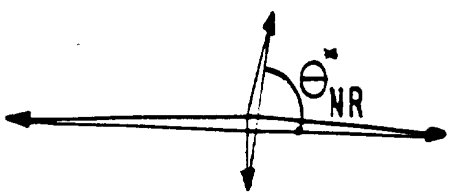
$\Rightarrow \boxed{V_{cb}}$

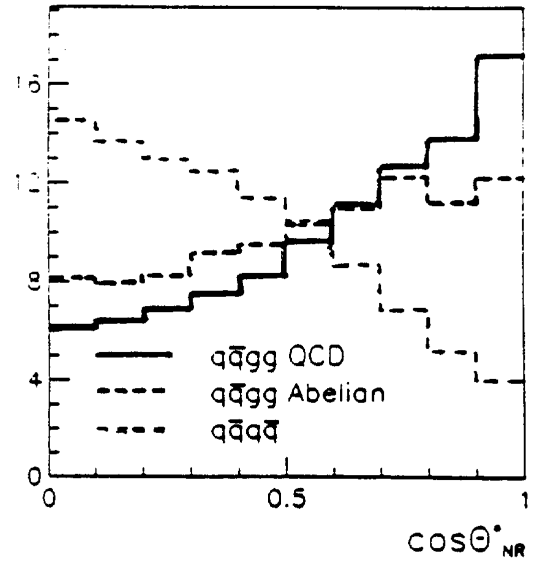
$$\boxed{\Gamma(b \to c \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} \eta_{QCD} F(m_c/m_b) |V_{cb}|^2}$$

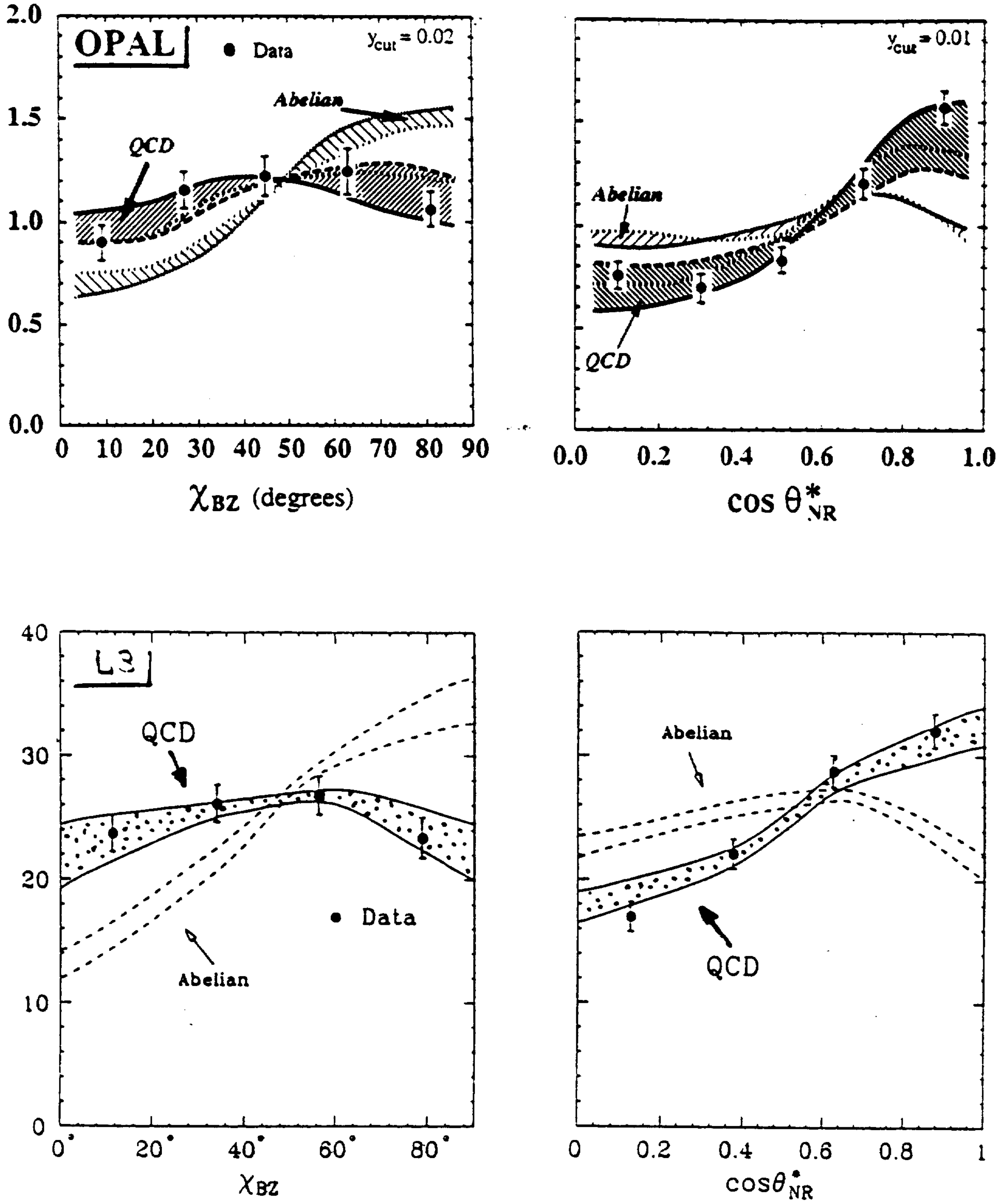
$\eta_{SL} \approx 0.9$
$F \approx 0.5$
$m_b \sim 5$ GeV/c^2


χ


1.5
1
0.5
0
0
45
90
χ_{BZ} (deg)
$q\bar{q}gg$ QCD
$q\bar{q}gg$ Abelian
$q\bar{q}q\bar{q}$


Θ^*_{NR}


8
4
0
0
0.5
1
$\cos\Theta^*_{NR}$
$q\bar{q}gg$ QCD
$q\bar{q}gg$ Abelian
$q\bar{q}q\bar{q}$


OPAL
Data
$y_{cut} = 0.02$
Abelian
QCD
χ_{BZ} (degrees)
$y_{cut} = 0.01$
Abelian
QCD
$\cos\theta^*_{NR}$
L3
QCD
Data
Abelian
χ_{BZ}
Abelian
QCD
$\cos\theta^*_{NR}$

extension to all final states SL+NL :

$$\boxed{\Gamma_b = \frac{G_F^2 m_b^5}{192\pi^3}\left[392\,|V_{cb}|^2 + 7.55\,|V_{ub}|^2\right]}$$

← current quark masses
next-to-leading log

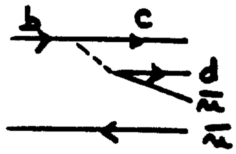
$\downarrow$

Rückl ...

$$\boxed{|V_{cb}| = 0.05 \pm 0.004 \pm 15\% \text{ theoretical uncertainty}}$$

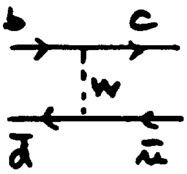
$|V_{cb}| \sim \sin^2\theta_c$ $\quad$ $b\to c$ quadr. suppressed rel. to $s \to u$
$\Rightarrow$ long b lifetimes

(b) NON-SPECTATOR CORRECTIONS

(i) 

: $B^- = (b\bar u)$
$\quad \hookrightarrow cd\bar u$

destructive interference between $\bar u$'s $\Rightarrow$
PROLONGING $\tau(B^-)$

(ii) 

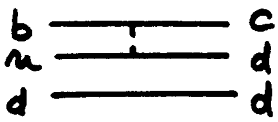
: B_d^0 W exchange contribution $\Rightarrow$
SHORTENING $\tau(B_d^0)$

$\bar s \quad \bar u$
$\bar s \quad \bar c$

: B_s^0 W exchange suppressed: Cabibbo-phase space

(iii) $\Lambda = bud$
$\quad \hookrightarrow c\bar u d$

: destructive interference $\Rightarrow$ PROL. $\tau(\Lambda_b)$



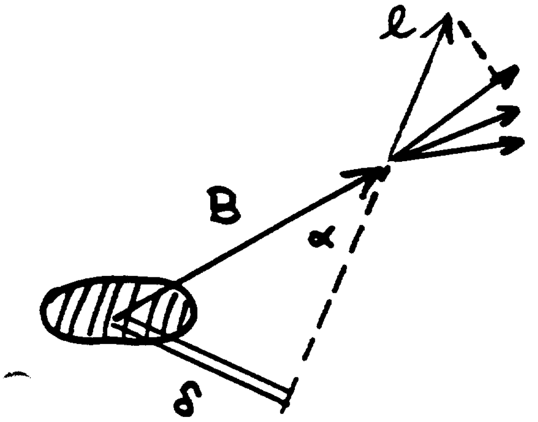
: W exchange $\Rightarrow$ SHORT. $\tau(\Lambda_b)$

RÉSUMÉ

$$\boxed{\begin{array}{c}\tau(B^-) > \tau(B_s^0) > \tau(B_d^0) > \tau(\Lambda_b) \\ \hookrightarrow \approx \tau_{spec} \qquad \delta\tau < 10\%\end{array}}$$

EXPERIMENTAL TECHNIQUES

(i) lepton impact parameter



"2 body decay (high energy)":

B flight distance $\propto \gamma\tau$

$$\alpha \simeq \frac{p_\perp}{E/2} \simeq \frac{m/2}{E/2} = \frac{1}{\gamma}$$

$$\delta \approx \alpha\gamma\tau \propto \tau$$

general 3-body decay:

$$\boxed{\text{impact parameter } \delta \approx \tfrac{3}{2}\tau}$$

insensitive to fragm. function

prod. vertex $\approx \pm 15 / \pm 100\,\mu m$

$\delta \approx 250 \pm 50\,\mu m$

$\delta\tau/\tau \sim 10\%$ syst. error

(ii) individual lifetime

(partial) reconstruction of B required:
decay length $\sim 2{,}5\,mm \pm 0.2\,mm$

		10^6 Z's
semileptonic:	$B_d^0 \to \ell^+ D^{-*}$, $\hookrightarrow \bar{D}^0\pi^-$, $\hookrightarrow K^+\pi^-$	400
	$B_s^0 \to \ell^+ D_s^-$, $D_s^{*-} \to D_s^- + \gamma$, $\hookrightarrow \phi\pi^-$	160

$\delta\tau/\tau \sim 10\%$

non-leptonic: F27

SEMILEPTONIC / 10^7 Z

$B_u^+ \to l^+ \overline{D}^0$		4600
	$\overline{D}^{*0} \to \overline{D}^0 + (\pi^0, \gamma)$ 100%	
$B_d^0 \to l^+ D^-$		4600
	$D^{*-} \to \overline{D}^0 + \pi^-$ 50%	
	$D^- + (\pi^0, \gamma)$ 50%	
$B_s^0 \to l^+ D_s^-$		1600
	$D_s^{*-} \to D_s^- + \gamma$ 100%	

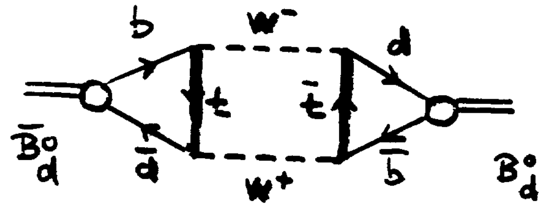
Table 1: The expected number of B mesons per $10^7 Z^0$ are calculated with the theoritical values of the B branching fractions. No acceptance or efficiencies are included. For D mesons and light mesons the PDG values for the branching fractions, except for $Br(D_s \to \phi\pi)$ where 4% is used

≈ 2.3

	Decay Channel	ARGUS	CLEO	THEORY [1]	Nb B/$10^7 Z^0$
$B_d^0 \to$	$D^{*-}\pi^+$ $D^{*-} \to \overline{D}^0 + \pi^+$ $\overline{D}^0 \to K^+\pi^-$	0.35±0.18±0.13	0.46±0.12±0.10	0.45	200
$B_d^0 \to$	$D^+\pi^-$ $D^- \to K^+\pi^-\pi^-$	0.33±0.12±0.10	$0.60^{+0.32+0.15}_{-0.28-0.12}$	0.58	550
$B_u^+ \to$	$\overline{D}^0\pi^+$	0.21±0.10±0.06	$0.51^{+0.17+0.11}_{-0.15-0.07}$	0.37	170
$B_s^0 \to$	$D_s^-\pi^+$ $D_s^- \to \phi\pi^-$ $\phi \to K^+K^-$			0.5	30
$B_d^0 \to$	$J/\Psi \overline{K}^{*0}$ $J/\Psi \to l^+l^-$ $\overline{K}^{*0} \to K^+\pi^-$	0.33 ± 0.18	0.38±0.18±0.03 0.06 ± 0.03 (new 1989)	0.39	430
$B_u^+ \to$	$J/\Psi K^+$ $J/\Psi \to l^+l^-$	0.07 ± 0.04	0.05 ± 0.02	0.09	150
$B_s^0 \to$	$J/\Psi\phi$ $J/\Psi \to l^+l^-$ $\phi \to K^+K^-$			0.3	70

(5) B–B̄ MIXING

B–B̄ oscillations



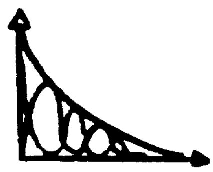
sensitive to the heavy quark sector of the SM

- past : first indication of top quark mass > 50 GeV
- future : measurement of CKM matrix element V_{td} and V_{ts}

<u>time evolution</u> of a $B^0(t=0)$ beam:

$$\text{prob}\{B^0(t)\} = \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + 2e^{-\Gamma t}\cos \Delta m t\right]$$

$$\text{prob}\{\bar{B}^0(t)\} = \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-\Gamma t}\cos \Delta m t\right]$$



$\Gamma_{1,2}$ = widths of CP = ± states $B_{1,2} = (B^0 \pm \bar{B}^0)/\sqrt{2}$

$\Delta m = m_1 - m_2$ mass difference

<u>time integrated probability:</u>

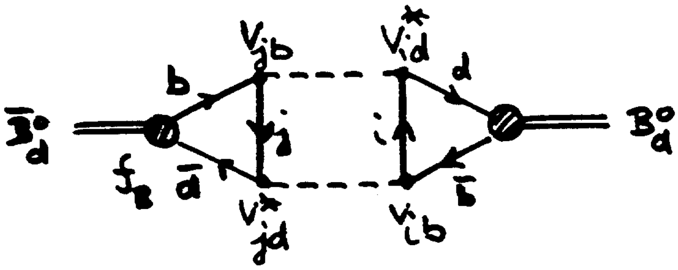
$$\chi = \text{prob}\{B^0 \to \bar{B}^0\} = \frac{1}{2}\,\frac{x^2+y^2}{x^2+1}$$

$$x = \frac{\Delta m}{\Gamma} = \frac{\text{oscill. frequ.}}{\text{decay frequ.}}$$

$$y = \frac{\Delta\Gamma}{\Gamma}$$

physical interpretation of $B^0-\bar{B}^0$ mixing

oscillation amplitude

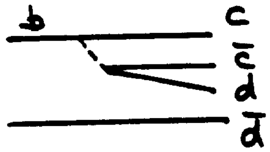


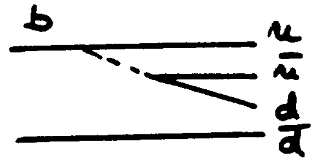
(i) lifetime difference:

$\Leftarrow$ real self-conjugate states n in box diagram

$B \searrow n$, $\bar{B} \nearrow$

$\bar{B}^0_d$:

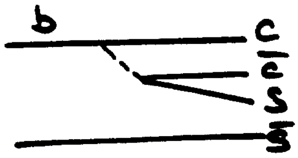




Cabibbo / phase space suppressed / many interfering amplitudes

$\Rightarrow$ $\Delta\Gamma/\Gamma$ small

$\bar{B}^0_s$:



only PS suppressed $\Rightarrow$

$\Delta\Gamma/\Gamma \sim 1$ up to 2

(ii) mass difference:

GIM: box $\sim (\sum_j V_{jb} V^*_{jd})^2 = (V^+V)^2_{db} = 0$ for degen. up masses $\Rightarrow$

$\Rightarrow$ $\sim$ up quark mass difference

$\Rightarrow$ $\sim m_t$ leading

$$\boxed{\Delta m \sim f_B^2\, m_t^2\, |V_{tb} V^*_{td}|^2}$$

$f_B \sim \varphi(0)/\sqrt{m_B}$ quark wave function at the origin
not well known:

$\begin{cases} \text{QCD sum rules: } f_{B_d} \sim 140\ \text{MeV} \\ \text{lattice} \quad : \quad \sim 250\ \text{MeV} \end{cases}$ ± large errors

$\boxed{B_d^0 - \bar{B}_d^0}$

$$|V_{td}|^2 = x_d \times 2.7 \cdot 10^{-4} \left[\frac{1.13\ \text{ps}}{\tau_B}\right]\left[\frac{140\ \text{MeV}}{f_{B_d}}\right]^2 \left[\frac{140\ \text{GeV}}{m_t}\right]^2$$

measurement: $x_d = 0.70 \pm 0.13$
ARGUS/CLEO

- oscill ~ decay frequ.
- $\boxed{|V_{td}| \sim \sin^2\theta_c}$

$\boxed{B_s^0 - \bar{B}_s^0}$

$$x_s = x_d \left(\frac{V_{ts}}{V_{td}}\right)^2 \left(\frac{f_{B_s}}{f_{B_d}}\right)^2$$

1.2 to 2 ⇐ quark model

>6 ⇐ $\not\exists$ SM $[\tau_B ; b \to u]$

$\boxed{\begin{array}{l} 3 < x_s < 20 \\ \chi_s = 0.45 \ldots 0.499 \end{array}}$

- rapid oscill. F31
- very close to max. mixing

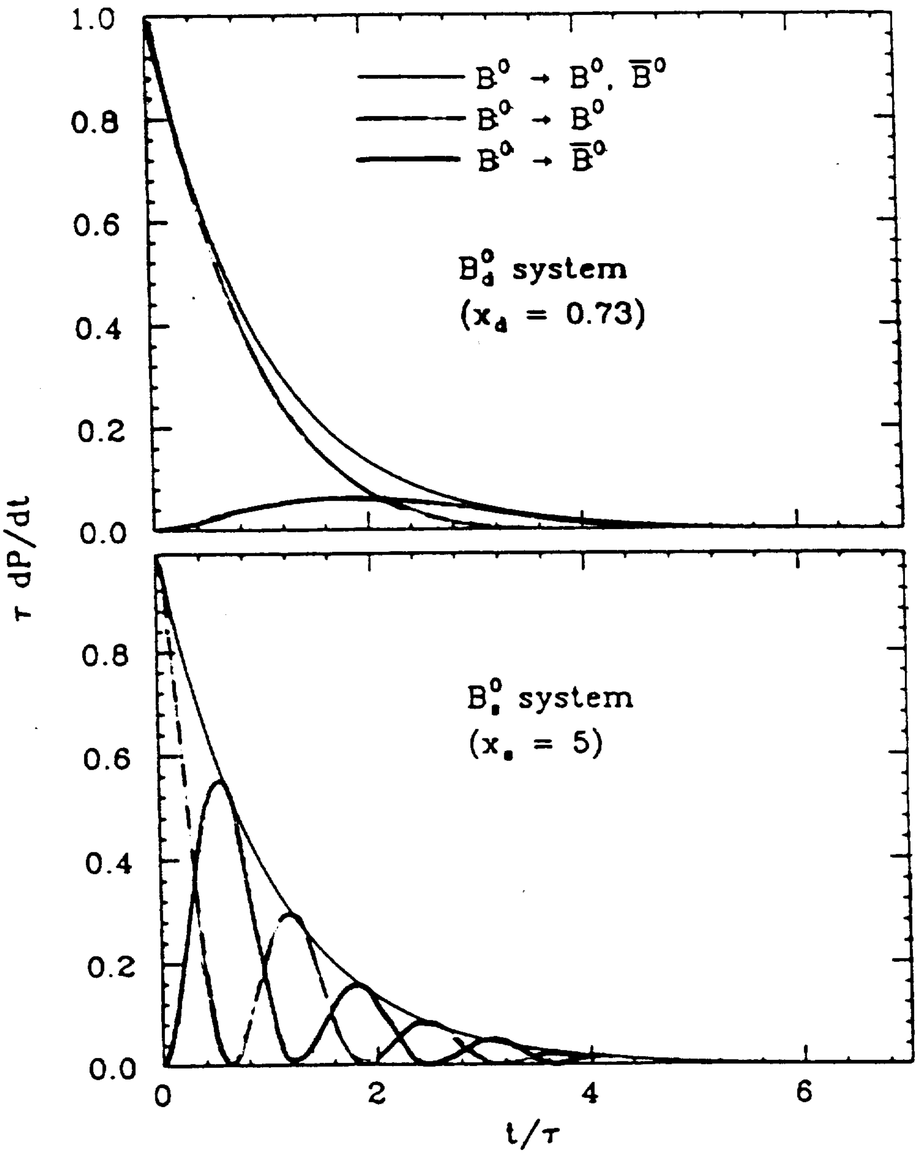


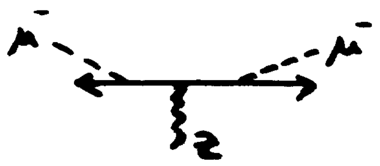
Figure 2: Time evolution for the B^0_d and B^0_s system fig. from ref.4

Gratta et al.

EXPERIMENTAL TECHNIQUES

- <u>time integrated</u>

(1) <u>like-sign dileptons</u>



$$P_{\ell\ell} = \frac{\ell^\pm \ell^\pm}{\text{all } \ell\ell} = 2\bar{\chi}_t(1-\bar{\chi}_t)$$

with $\bar{\chi} = f_d \chi_d + f_s \chi_s$

$f_{d,s}$ - fraction $B_{d,s} \in b$

$\left.\begin{array}{l} f_d \approx 0.32 \text{ to } 0.38 \\ f_s \approx 0.12 \text{ to } 0.15 \end{array}\right\}$

<u>presently</u>:

$\left.\begin{array}{lll} \chi_d & = 0.17 \pm 0.04 & \text{Argus, CLEO} \\ \bar{\chi} & = 0.12 \pm 0.05 & \text{UA1} \\ & 0.129 \pm 0.046 & \text{Aleph} \\ & 0.11 {}^{+0.08}_{-0.06} & \text{L3} \end{array}\right\}$

F33: weak constraint yet on χ_s

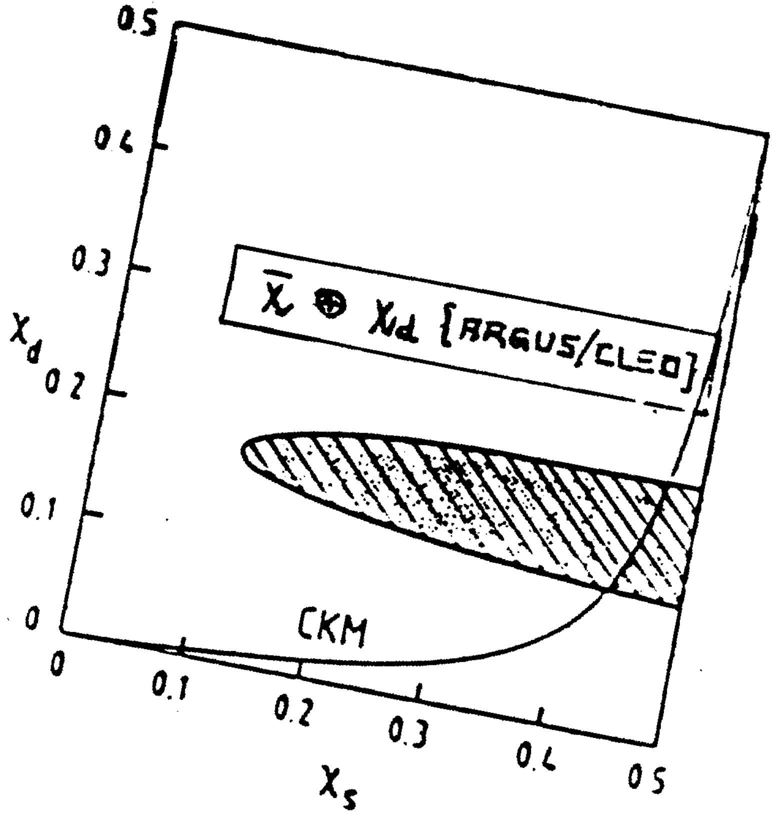
F34: future $\bar{\chi}$ up to $\pm 10\% \pm 10\%$ → no upper bound on χ_s

(2) <u>identified B^0_s's</u>

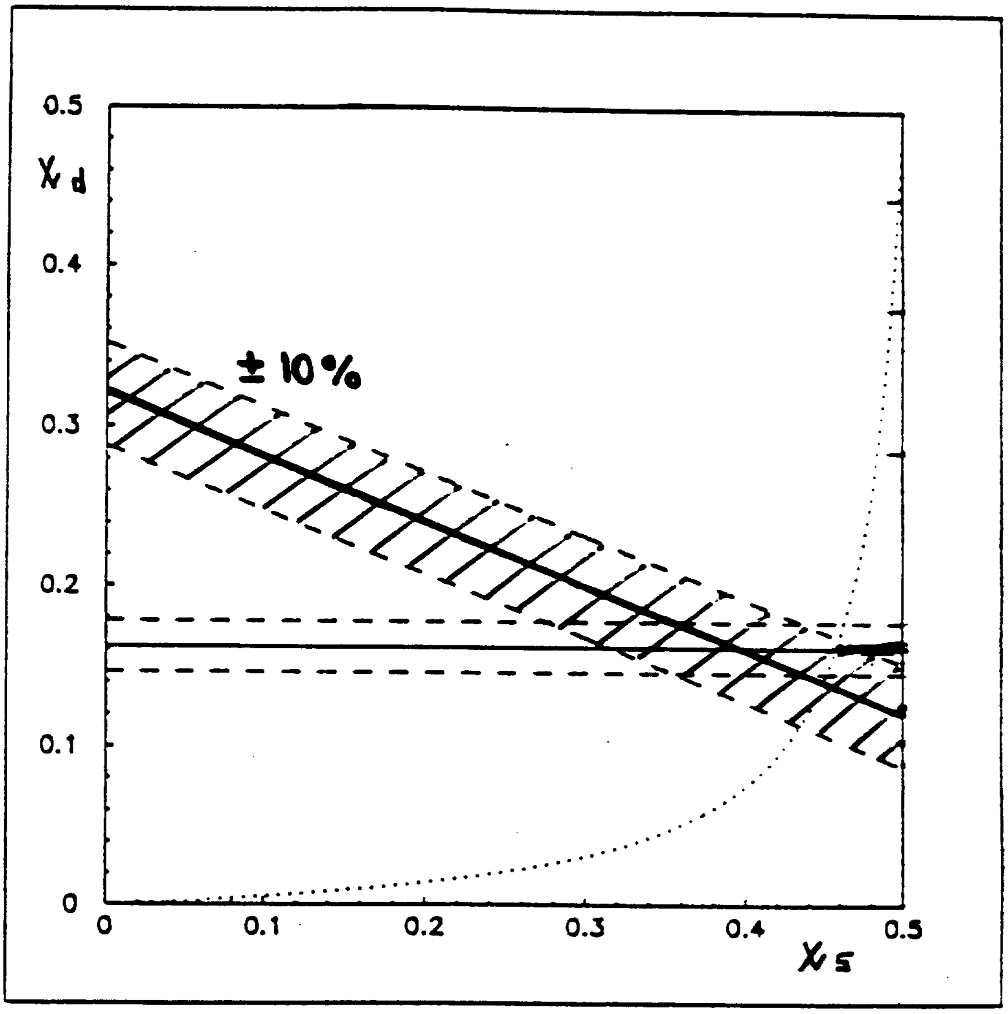
$\left.\begin{array}{l} \text{tag } \bar{b} \text{ through } \ell^+ \text{ on one side} \\ \text{tag } \bar{b} \text{ through } B_s^0 \text{ on other side} \end{array}\right\}$

$$P_{\ell B_s^0} = \frac{\ell^+ B_s^0}{\text{all } \ell B_s^0} = \chi_s(1-\bar{\chi}) + \bar{\chi}(1-\chi_s)$$

10^7 Z's ⇒ 400 ℓB_s : $\delta\chi_s/\chi_s \sim 25\%$


0.5
0.4
0.3
0.2
0.1
0
χ_d
$\bar{\chi}$ ⊕ χ_d [ARGUS/CLEO]
CKM
0
0.1
0.2
0.3
0.4
0.5
χ_s

Kopke



0.5
0.4
0.3
0.2
0.1
0
χ_d
± 10 %
0
0.1
0.2
0.3
0.4
0.5
χ_s

- time evolution for B_s

tag leptons (time integrated) on one side
reconstruct decay vertex on the opposite side

$10^7\ Z \Rightarrow 30\ \ell B_s^0$
↳ $D_s\pi$: RESOLUTION ~ 10%
↳ $D_s\ell$: " ~ 25%

RÉSUMÉ

x_s	# Z
$\lesssim 5$	5×10^6
$\lesssim 10$	13×10^6
$\lesssim 15$	55×10^6

⟸ HLEP!

Dreyfus
Treille et al

RARE PRODUCTION / RARE DECAYS

(a) $B^-\to\tau^-\bar\nu_\tau$

$$BR(B\to\tau\nu_\tau) \simeq 8\cdot10^{-3}\left(\frac{f_B}{f_K}\right)^2\left|\frac{V_{ub}}{V_{cb}}\right|^2 \sim 10^{-4}$$

↗ measurement in conjunction with other $b\to u$ transitions

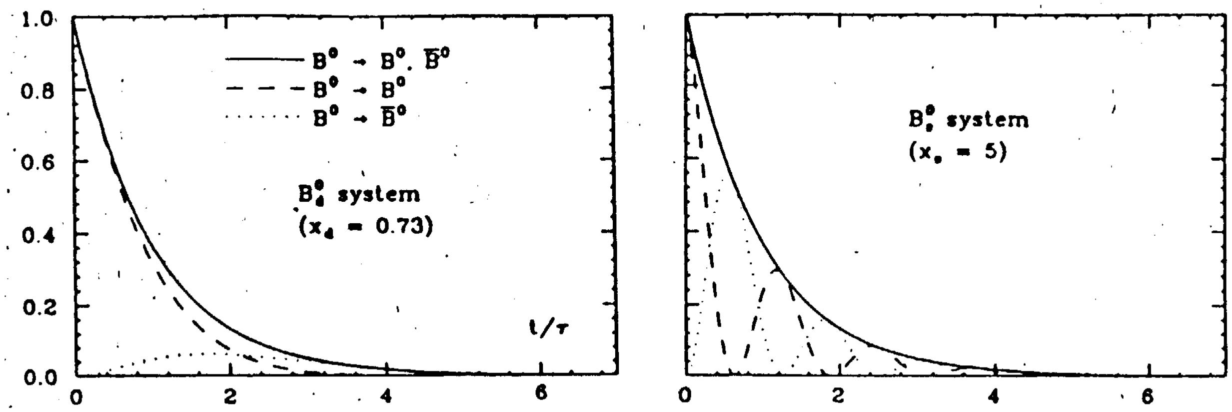


Fig. 2.37: Time evolution for the B_d^0 and B_s^0 system. From [21].

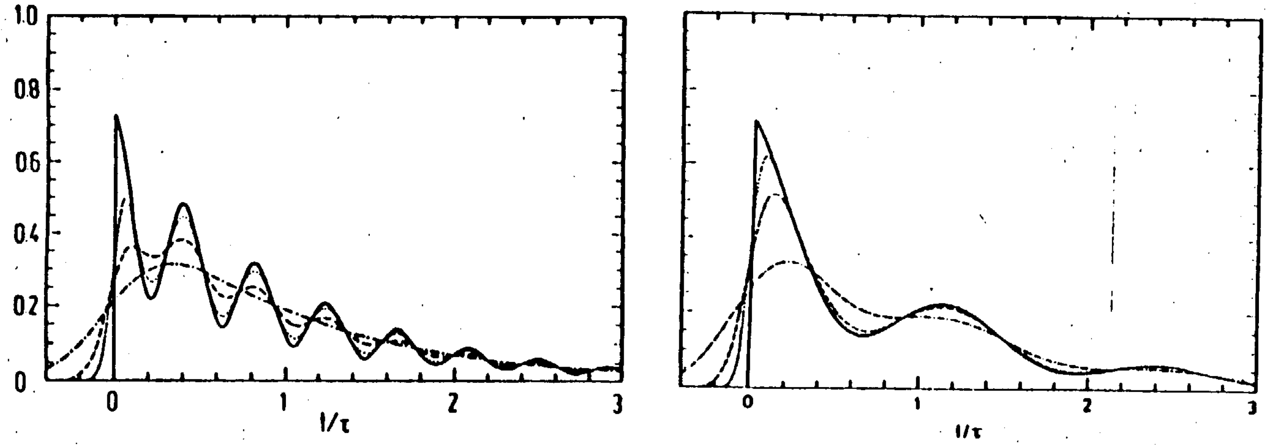
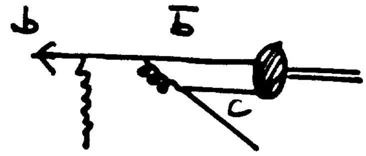


Fig. 2.38: (a) Time evolution for the B_s^0 system for $x_s = 15$ and assuming a 10 % mistagging probability of the sign of the b quark. The full line is the theoretical distribution. The dotted, dashed and dashed-dotted lines are the convolutions with 5, 10 and 25 % experimental resolution on $\frac{\delta t}{\tau}$; from [22]. *(b) The same for $x_s = 5$; from* [23].

(b) $B_c^- = (\bar{b}c)$ mesons:



PRODUCTION at LEP:

$$\boxed{10^7\, Z \Rightarrow 1{,}400\ B_c,\ B_c^*}$$

DECAY: spectator model

$B_c^- = (\bar{b}c)$: $\bar{b}$ and c decay independently & equal lifetime

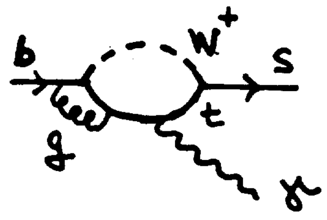
$$\Rightarrow \boxed{\tau(B_c) \approx 0.5\,ps}$$

decay modes : $J/\psi\, D_s^{*+}$, $J/\psi\, \rho^+$ ...
$\sim \%$

(c) FC γ decays:

[illegible]

$b \to s + \gamma$



log enhancement in QCD corr.

$$\Rightarrow \boxed{BR(b \to s\gamma)^{SM} \sim 10^{-4}}$$

$$\Rightarrow BR(B \to K^*\gamma) \sim 10^{-5}$$

sensitivity to effects beyond the SM:

	SM	2Higgs, $v_2 > v_1$	$v_1 < v_2$	t'
$BR(b \to s\gamma)$	10^{-4}	$10^{-4} \ldots 10^{-3}$	$\ldots 10^{-2}$	$\ldots 10^{-3}$

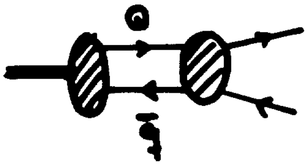
(d) FLAVOR-CHANGING LEPTONIC D AND B DECAYS

look beyond the Standard Model: heavy quarks particularly interesting

D^0

B_d^0

B_s^0



e^- μ^- τ^-

e^+ μ^+ τ^+

present bounds / 10^{-5}

	$\mu\mu$	ee	μe
D^0	1	3	4
B_d^0	4	3	3

parametrisation:

$$\mathcal{L}_{eff}^{scalar} = \frac{1}{\Lambda_S^2}\, \bar{u}_L c_R\, \bar{l}_{1L} l_{2R}$$

$$\mathcal{L}_{eff}^{vector} = \frac{1}{\Lambda_V^2}\, \bar{u}_L \gamma_\mu c_L\, \bar{l}_{1L} \gamma_\mu l_{2L}$$

standard model: $\left.\begin{array}{l} \Lambda_V(D^0) \sim 4\ \text{TeV} \\ \Lambda_V(B_s^0) \sim 30\ \text{TeV} \end{array}\right\}$

present and expected bounds : F 38

PROCESS	Particle Data		LEP	
	Λ_V [GeV]	Λ_S [TeV]	Λ_V [TeV]	Λ_S [TeV]
$D^0 \to \mu^+\mu^-$	800	2	1	4
e^+e^-	30	1	0.1	4
$\mu^\pm e^\mp$	400	1	1	4
$B^0 \to \mu^+\mu^-$	700	3	2	9
e^+e^-	40	3	0.1	9
$\mu^\pm e^\mp$	700	3	2	9
$B_s \to \mu^+\mu^-$	—		2	8 *
e^+e^-			0.1	8 *
$\mu^\pm e^\mp$			2	8 *

Comparison with "compositeness" mass scale:

$$\Lambda_{ELP} = \sqrt{4\pi}\,\Lambda = 3.5\,\Lambda$$

Buchmüller

B.) TOP

(1) indirect evidence for top quarks
and mass estimate

(2) decay: SM and beyond

(3) production: hadron colliders
e^+e^- high energy colliders

(1) INDIRECT EVIDENCE FOR TOP QUARKS

SM fermion spectrum $\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L e^-_R$ $\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \mu^-_R$ $\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L \tau^-_R$

$\begin{pmatrix}u\\ d'\end{pmatrix}_L \begin{matrix}u_R\\ d_R\end{matrix}$ $\begin{pmatrix}c\\ s'\end{pmatrix}_L \begin{matrix}c_R\\ s_R\end{matrix}$ $\begin{pmatrix}t\\ b'\end{pmatrix}_L \begin{matrix}t_R\\ b_R\end{matrix}$

- FB asymmetry in $e^+e^- \to b\bar{b}$ requires isospin partner to b

$$A^b_{FB} = \frac{3}{4}\,\frac{2v_e a_e}{v_e^2+a_e^2}\,\frac{2v_b a_b}{v_b^2+a_b^2} \qquad a_b = +2\left[I_{3L}(b) - I_{3R}(b)\right] = \begin{cases}-1 & \text{in SM}\\ 0 & \text{for isosinglet } b\end{cases}$$

b tagged through leptons $\Rightarrow A^{obs}_{FB}$ reduced by B-$\bar{B}$ mixing:

$$A^{obs}_{FB} = A^b_{FB}\,(1-2\bar{\chi}) \qquad \text{with } \bar{\chi} = 0.139 \pm 0.032$$

F40B: A_{FB}^{b} and A_{FB}^{obs} in PETRA/PEP/TRISTAN/LEP

clear evidence for $a_b \neq 0$

- partial width: $\Gamma(Z \to b\bar{b})$

$$\frac{\Gamma(Z\to b\bar{b})^{I_3=0}}{\Gamma(Z\to b\bar{b})^{SM}} = \frac{(4e_b \sin^2\vartheta_W)^2}{1+(1+4e_b\sin^2\vartheta_W)^2} \approx \frac{1/9}{1+4/9} = \frac{1}{13}$$

	SM	Aleph	Delphi	L3	Opal
$\Gamma(Z\to b\bar{b})$	378(2)	396(50)	365(66)	367(39)	364(53)

- missing top → FCNC b decays through GIM violation

2-family example:

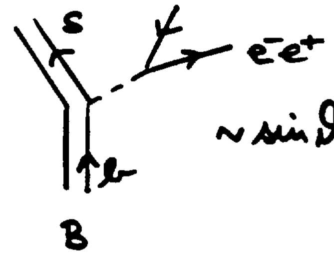
$\binom{c}{s'}_L \; b'_L$

$s' = s\cos\vartheta + b\sin\vartheta$
$b' = -s\sin\vartheta + b\cos\vartheta$

SM neutral current:

$\langle I_3 \rangle = +\frac{1}{2}(c_L, c_L) - \frac{1}{2}(s'_L, s'_L)$
$= \text{diag} - \frac{1}{2}\sin\vartheta\cos\vartheta\,(s_L, b_L)$

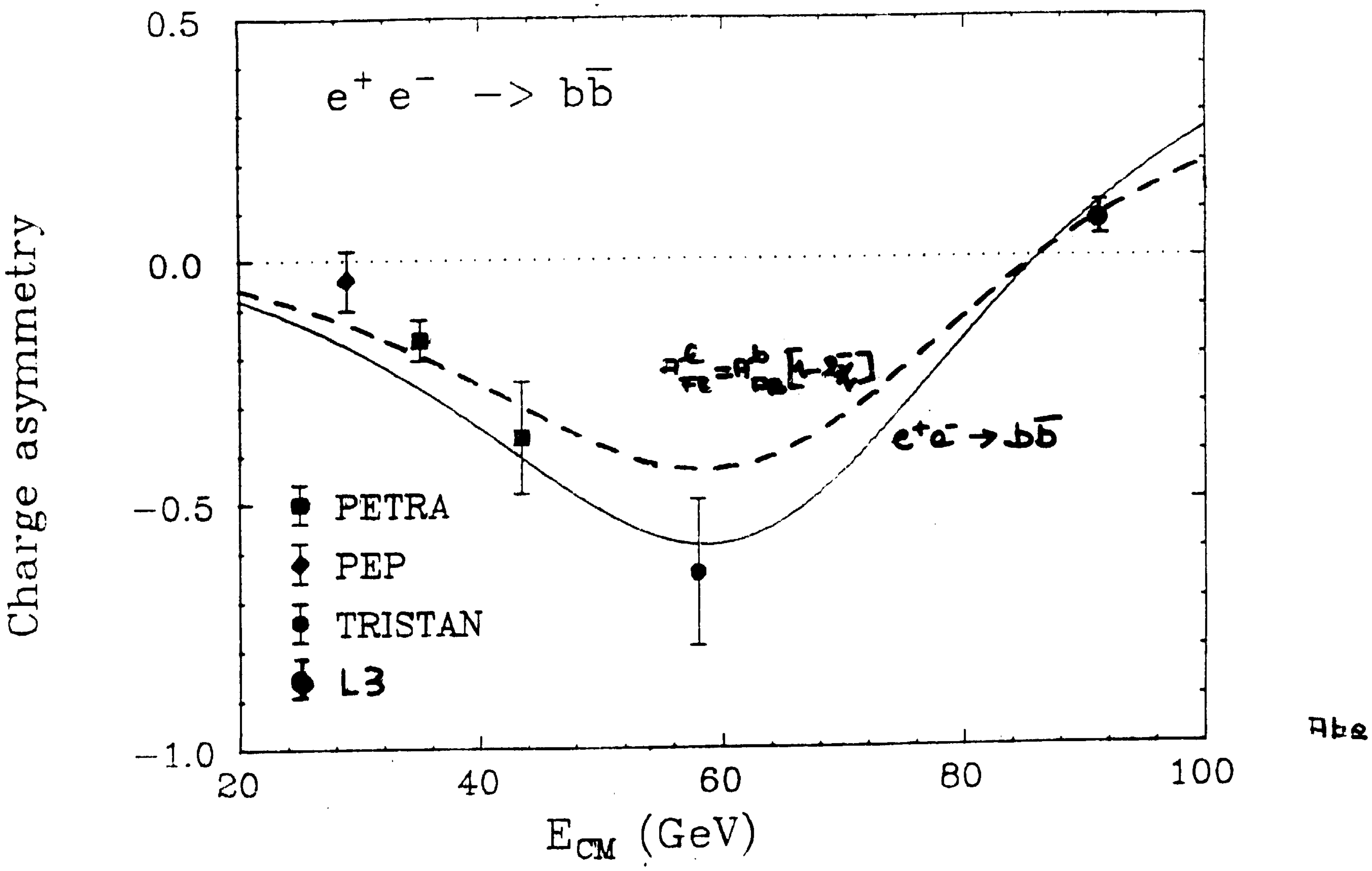
⇒ $b \to s$ NC transitions



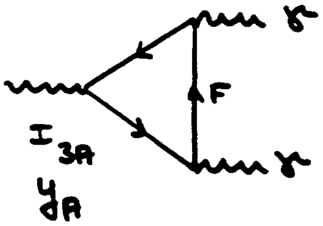
$\sim \sin\vartheta\cos\vartheta$

generalization to 3 families
estimate of mix. angle $\Big\}$ $\boxed{\frac{BR(B\to \ell^+\ell^- X)}{BR(B\to \ell^+\nu X)} \geq 0.12}$

UA1: $\frac{BR(B^0 \to \mu^+\mu^- X)}{BR(B^0 \to \mu\nu_\mu X)} < \frac{5.0\times 10^{-5}}{0.110 \pm 0.008}$


e+ e- -> b b̄
0.5
0.0
−0.5
−1.0
20
40
60
80
100
Charge asymmetry
E_CM (GeV)
PETRA
PEP
TRISTAN
L3
e+e- → b b̄

- theoretical consistency of SM : absence of triangle anomalies :



$$\sim \sum_F I_{3A}(F) Q(F)^2 = -\sum_{F_L} I_3 \left[I_3 + \tfrac{1}{2} y\right]^2$$

$$\sim \sum_{F_L} y \sim \sum_{F_L} Q(F) \text{ etc.}$$

$$\boxed{\sum_L Q = 0}$$

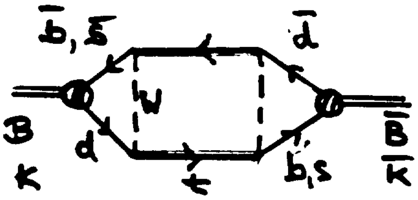
1st family: $\binom{\nu_e}{e^-}_L$ $\binom{u}{d}_L$ $\sum_{F_L} Q(F) = -1 + 3 \times \left[+\frac{2}{3} - \frac{1}{3}\right] = 0$

3rd family: <u>no top</u> $\binom{\nu_\tau}{\tau^-}_L$ b_L $\sum_{F_L} Q(F) = -1 + 3 \times \left[-\frac{1}{3}\right] = -2 \neq 0$

2) <u>MASS ESTIMATES</u>

virtual top quarks affect : CP violation parameter ε(ε') in K system
B-$\bar{B}$ oscillations
rad. corrections to electroweak processes

- MIXING PARAMETER ε AND B-$\bar{B}$ OSCILLATIONS

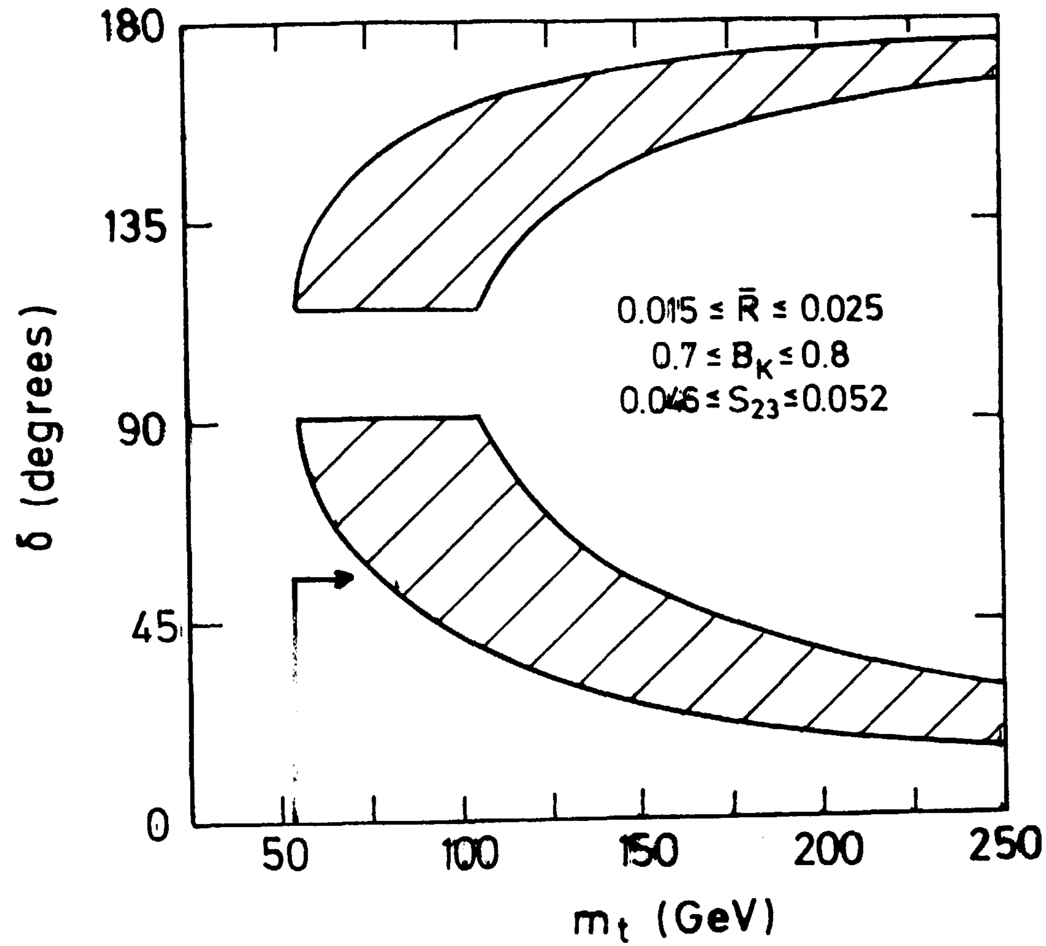


$$x(B_d) = \tau_b \frac{G_F^2}{6\pi^2} m_B f_B^2 \hat{B} m_t^2 \eta_{QCD} F(m_t/m_W) |V_{td}|^2$$

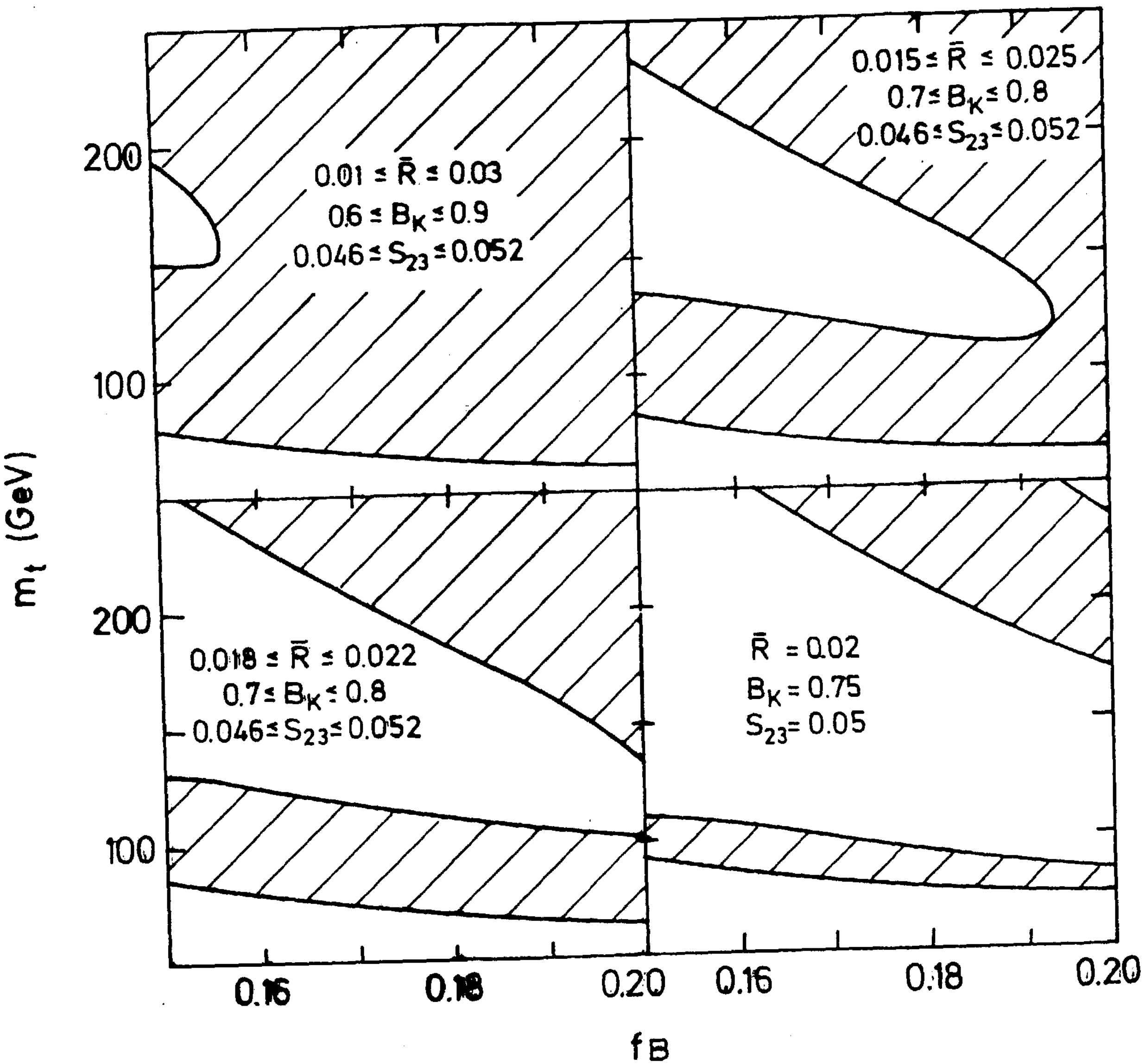
$$|\varepsilon(K)| = \frac{G_F^2}{12\pi^2} \frac{m_K B_K f_K^2}{\sqrt{2}\Delta m_K} m_t^2 \eta'_{QCD} F \operatorname{Im}(V_{td}^*)^2$$

F42 : ε(K) restricts $m_t \gtrsim 50$ GeV , indep. of CP phase δ

F43 : B-$\bar{B}$ oscillations, also $m_t \gtrsim 50$ GeV
2-band solution : $m_t \sim 100$ GeV, $m_t \gtrsim 200$ GeV



Buchalla
Buras
Harlander

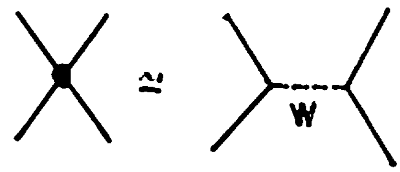


0.01 ≤ R̄ ≤ 0.03
0.6 ≤ B_K ≤ 0.9
0.046 ≤ S_23 ≤ 0.052
0.015 ≤ R̄ ≤ 0.025
0.7 ≤ B_K ≤ 0.8
0.046 ≤ S_23 ≤ 0.052
0.018 ≤ R̄ ≤ 0.022
0.7 ≤ B_K ≤ 0.8
0.046 ≤ S_23 ≤ 0.052
R̄ = 0.02
B_K = 0.75
S_23 = 0.05
200
100
200
100
m_t (GeV)
0.16
0.18
0.20
0.16
0.18
0.20
f_B

<u>example</u>: $\sin^2\vartheta_W$ in SM model, related to α, G_F and m_t

Fermi theory: $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 m_W^2} = \frac{\pi\alpha}{2\sin^2\vartheta_W m_W^2}$

Sirlin def.: $m_W^2 = \cos^2\vartheta_W m_Z^2$



$$\sin^2\vartheta_W\cos^2\vartheta_W m_Z^2 = \frac{\pi\alpha}{\sqrt{2}G_F} \longrightarrow = \frac{\pi\alpha}{\sqrt{2}G_F[1-\Delta\alpha+\mathrm{ctg}^2\vartheta_W\Delta\rho]}$$

QED rad cor $\alpha \to \alpha(m_Z^2)$

genuine elw. $\Delta\rho = \frac{3G_F m_t^2}{16\pi^2}$

$$\boxed{\sin^2\vartheta_W\cos^2\vartheta_W m_Z^2 = \frac{\pi\alpha}{\sqrt{2}G_F\left[1-\Delta\alpha+\mathrm{ctg}^2\vartheta_W\frac{3G_F m_t^2}{16\pi^2}\right]}}$$

F45 : solution : $\sin^2\vartheta_W = f(m_Z^2, m_t^2)$ [$m_Z \in$ LEP]

exp. constraints : m_W mass : $\sin^2\vartheta_W = 1-\frac{m_W^2}{m_Z^2}$

νe, νq, ℓq scattering
atomic parity violation
Z width / Z cross section
FB asymmetries

↓

$$\boxed{m_t = 137 \pm 40 \text{ GeV}}$$

<u>Note</u>: LE processes prefer lower limit
HE processes prefer upper limit

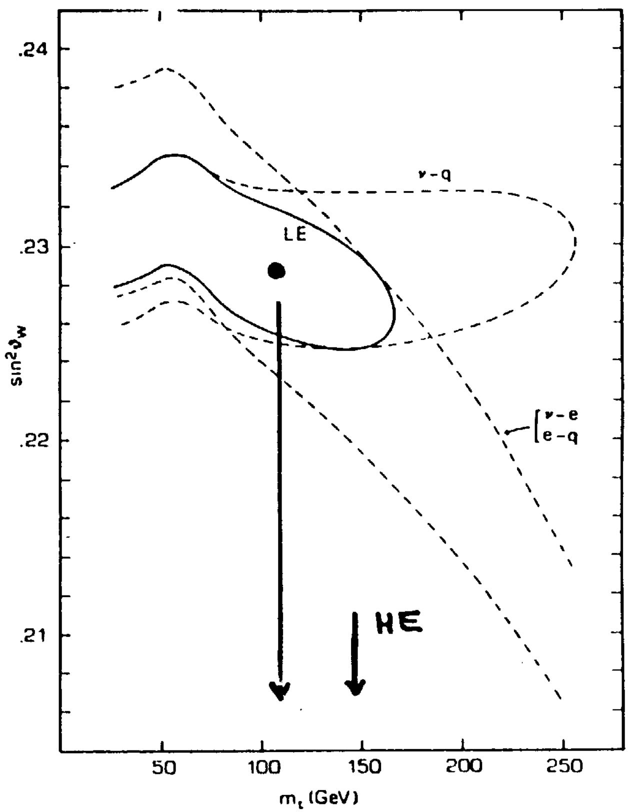


Fig. 1 — One–standard–deviation error bands on $\sin^2\vartheta_w$ as functions of m_t for the low-energy (LE) data. We show the ν-q sector, the ν-e and e-q sectors combined, and the region allowed by the complete set of LE data. We have assumed $m_c = 1.45$ GeV and $M_H = M_Z$.

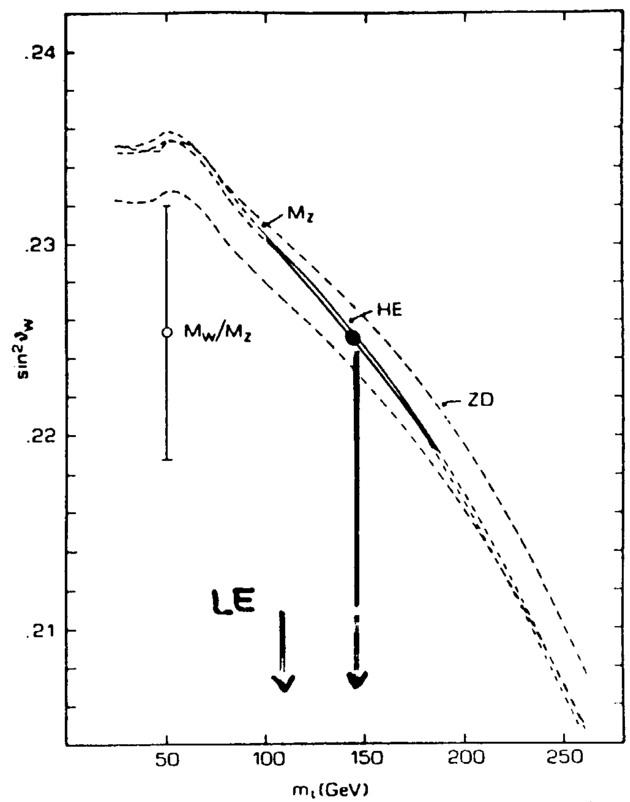


Fig. 2 — One–standard–deviation error bands on $\sin^2\vartheta_w$ as functions of m_t assuming $M_H = M_Z$ for the high–energy (HE) data. We show the bands corresponding to the LEP measurements of the Z mass (M_Z) and Z decays (ZD). The error on $\sin^2\vartheta_w$ from measurements of M_W/M_Z is shown as a vertical error bar. Shown is also the region allowed by the complete set of HE data.

Ellis
Fig. 1