Cours/Lecture Series

1989-1990 ACADEMIC TRAINING PROGRAMME

SPEAKER : K.R. SCHUBERT / University of Karlsruhe
TITLE : Physics of B-mesons and B-meson factories
DATES : 26, 28, 29 & 30 March
TIME : 11.00 to 12.00 hrs
PLACE : Auditorium

ABSTRACT

Experiments with B-mesons have produced important contributions to our understanding of weak and strong interactions. Two results have been especially surprising : the B-meson mean life turned out to be much longer than expected in 1983, and the transition rate between B^0 and $\bar{B}^0$ much larger than expected in 1987. The first part of the lectures reviews our present knowledge on $B^\pm$ and B^0 mesons with special emphasis on the determination of five out of the 18 fundamental parameters of the Standard Model (m_b, m_t, ϑ_{13}, ϑ_{23}, and φ_{CKM}, where ϑ_{13} and ϑ_{23} are mixing angles of the Cabibbo-Kobayashi-Maskawa matrix and φ_{CKM} is the phase in this matrix). The second part describes open questions and expectations for the future. The lecture on B-meson factories will be limited to basic concepts of e^+e^- colliders and to a sruvey of present proposals based on these concepts. The description of open questions will concentrate on our understanding of CP violation in K^0 meson decays and on predictions and experimental strategies for CP violation in B-meson decays.

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K.R. Schubert, Universität Karlsruhe

CERN Academic Training 26-30/3/90

Four Lectures on B-meson Physics and B-meson Factories.

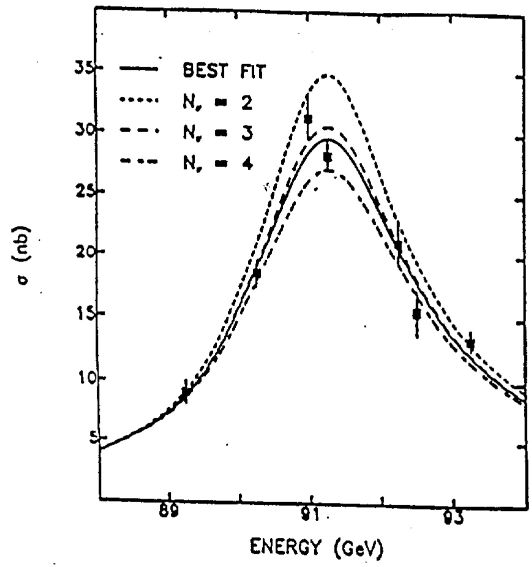
26/3 : Properties and decays of $B^\pm$ and B^0, their place in the standard model.

28/3 : $B\bar{B}$ oscillations, CKM matrix.

29/3 : B-meson Factories : e^+e^- colliders at $\sqrt{s} \approx 10$ GeV, basic concepts & proposals

30/3 : Open questions, $\not{C}\not{P}$ expectations.

The first four LEP publications, Oct. 89:



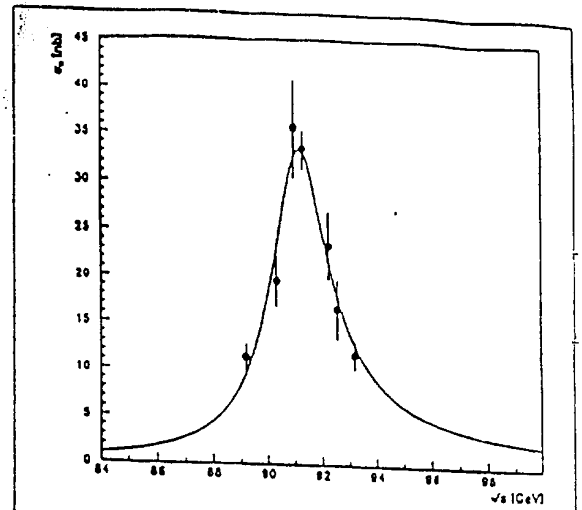
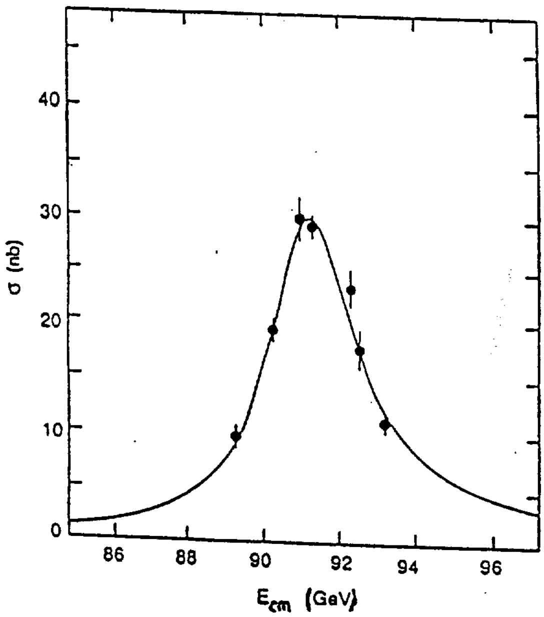
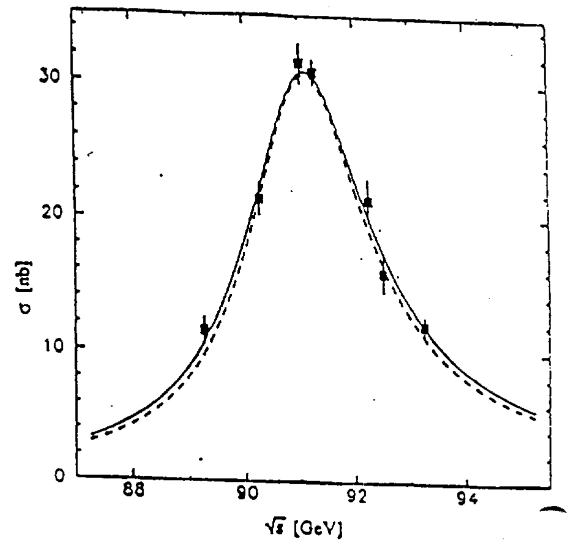


Figure 4: The measured Z° peak. The data and the fit are described in the text.





$$\boxed{N_{\nu\bar{\nu}}(Z^0) = 3.18 \pm 0.20 \; ; \quad N_{SF} = 3}$$

Exploration of Standard Model ending. Still need to

1.) determine all 18 free parameters

2.) develop more effective & reliable calculation me

3.) probe validity range ("new physics", CP ?)

Experiments with B-mesons have made significant contributions to all three areas and will continue to contribute.

These are experiments at "low" energies with "moderate" efforts.

Standard Model with $N_F = 3$:

$$\begin{pmatrix} \nu_e & u \\ e & d \end{pmatrix} \begin{pmatrix} \nu_\mu & c \\ \mu & s \end{pmatrix} \begin{pmatrix} \nu_\tau & t \\ \tau & b \end{pmatrix} \; ; \; g, \gamma, W, Z \; ; \; H.$$

18 free parameters if $m(\nu_e) = m(\nu_\mu) = m(\nu_\tau) = 0$:

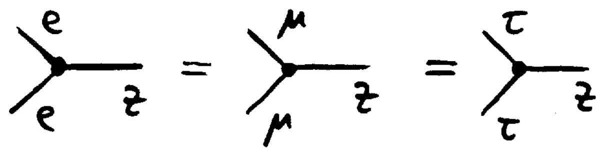
Masses: $m_e \; m_\mu \; m_\tau \; m_d \; m_u \; m_s \; m_c \; \boxed{m_b \; m_t} \; m_H$,

Coupling constants: $\alpha \; \alpha_s \; G_F \; \vartheta_W$,

Weak interaction mixing angles:

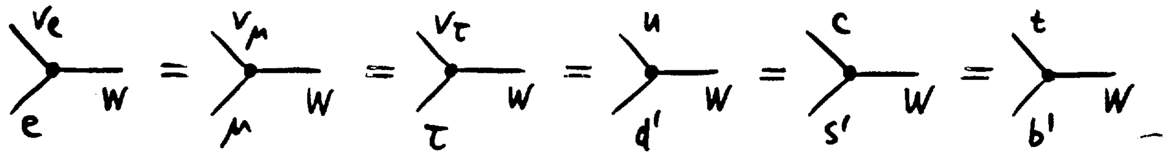
$$\vartheta_{12} \; \boxed{\vartheta_{23} \; \vartheta_{13} \; \varphi}$$

The standard neutral weak interaction:



also for $(\nu_e \nu_\mu \nu_\tau)$, $(u\,c\,t)$, $(d' s' b')$.

The standard charged weak interaction:



Universality of the weak interactions:

There is only one Z^0 and only one W^+W^- pair.

Complication from mass generation:

The weak partners ud', cs', tb' are not mass eigenstates

Conventional choice:

$u\,c\,t$ have fixed mass, $d' s' b'$ don't.

Consequence:

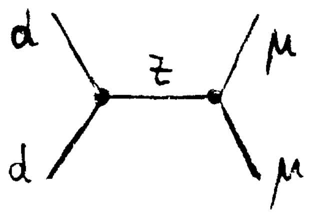
Since $d' s' b'$ are orthogonal states with $B = \frac{1}{3}$ and $Q = -\frac{1}{3}$ as well as $d\,s\,b$, we must have:

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = V \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \quad \text{with } VV^+ = 1.$$

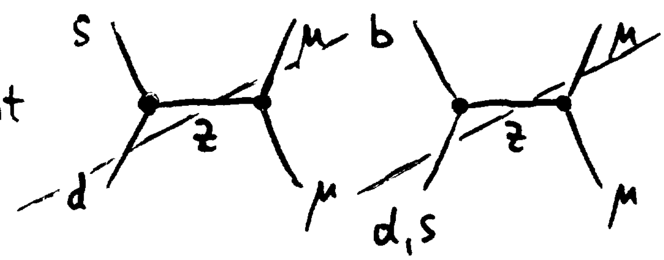
Between mass eigenstates, there are 3 leptonic and 9 quarkonic charged weak transitions:

In the neutral weak interaction, no change:

$$d'\bar{d}' + s'\bar{s}' + b'\bar{b}' = d\bar{d} + s\bar{s} + b\bar{b}, \text{ since } VV^+ = 1.$$



but



No family-changing neutral currents!

<u>Description of family-changing charged currents:</u>

$$g(Q_i W q_j) = g(\ell W \nu_\ell) \cdot \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} ; \; VV^+ = 1$$

4 free parameters: $\vartheta_{12} \approx V_{us}$; $\vartheta_{13} \approx |V_{ub}|$; $\vartheta_{23} \approx V_{cb}$; $\varphi = \arg V_{ub}^*$. 5 V_{ij} can be chosen real.

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\varphi} \\ 0 & 1 & 0 \\ -s_{13}e^{i\varphi} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\varphi} \\ -s_{13}c_{23}-c_{12}s_{13}e^{i\varphi}s_{23} & c_{12}c_{23}-s_{12}s_{13}e^{i\varphi}s_{23} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}e^{i\varphi}c_{23} & -c_{12}s_{23}-s_{12}s_{13}e^{i\varphi}c_{23} & c_{13}c_{23} \end{pmatrix}$$

with the four real parameters
$0 \leq \vartheta_{12} \leq \pi/2$, $0 \leq \vartheta_{13} \leq \pi/2$, $0 \leq \vartheta_{23} \leq \pi/2$, and φ,
and with the abbreviations $s_{12} = \sin \vartheta_{12}$, $c_{13} = \cos \vartheta_{13} \ldots$

This parametrization was introduced by Wolfenstein, Chau . . . 1984 modifying that of Maiani 1977. It has the advantage of the smallest imaginary parts. The original KM parametrization 1973 had large imaginary parts, but had the maximum number of five real matrix elements.

N. Cabibbo, PRL 10(1963)531 {weak mixing of hadrons}
M. Gell-Mann, PL 8(1964)214 {weak mixing of quarks}
J.D. Bjorken and S.L. Glashow, PL 11(1964)255 {"charm"}
M. Kobayashi and T. Maskawa, Progr.Th.Phys. 49(1973)652
H. Harari, PL 57B(1975)265 {"b" and "t"}
L. Maiani, Proc.Int.Symp.Lepton Photon Hamburg 1977, p.867
L. Wolfenstein, PRL 51(1984)1945
L.L. Chau and W.Y. Keung, PRL 53(1984)1802
B. Stech, Proc.Top.Conf.Flavour Mixing Erice 1984, p.735
H. Fritzsch, PR D32(1985)3058
H. Fritzsch and J. Plankl, PR D35(1987)1732

$\vartheta_{12}\, \vartheta_{23}\, \vartheta_{13}\, \varphi$ have their values from outside the standard model and must be determined by experiment. {The immediate success of Q.M. was based on earlier & precise measurements of $e\, \hbar\, m_e\, \varepsilon_0$}

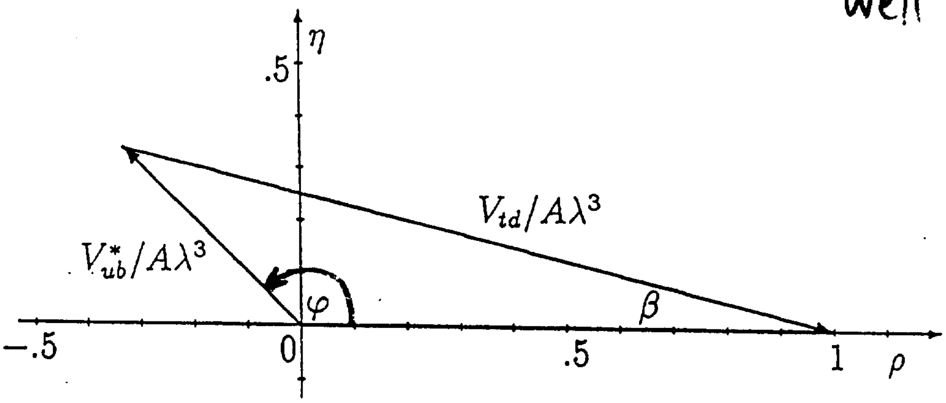
Unitarity: $\sum_i |V_{ij}|^2 = 1$; $\sum_i V_{ij} V_{ik}^* = \delta_{jk}$;

Convenient approximation of the CKM matrix:

Wolfenstein 1984 : $(\vartheta_{12}\, \vartheta_{23}\, \vartheta_{13}\, \varphi) \to (\lambda\, A\, \rho\, \eta)$.

$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix};$$

Experiments: $\lambda = 0.220 \pm 0.002$ [K + hyp. decays]
$A = 0.97 \pm 0.10$ $[\tau_B,\ \mathcal{B}(B \to \ell \nu X)]$. ρ and η not well known.



CP violation: The standard charged weak interaction violates CP-symmetry if $\varphi \neq 0$ and $\varphi \neq \pi$, i.e. if area(CP-triangle) $\neq 0$.

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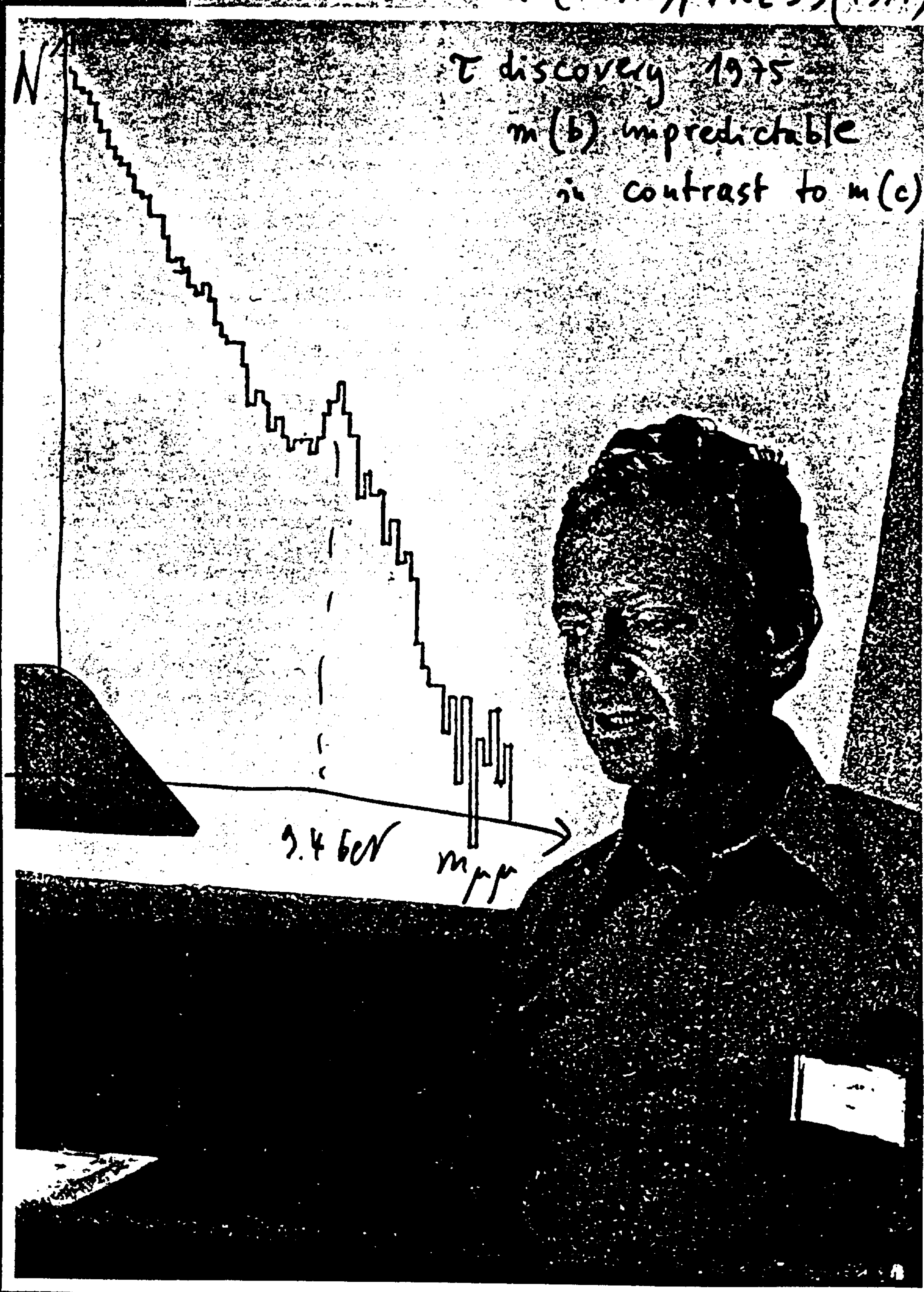
[illegible] of the b-quark: $pW \to \mu^+\mu^- X$

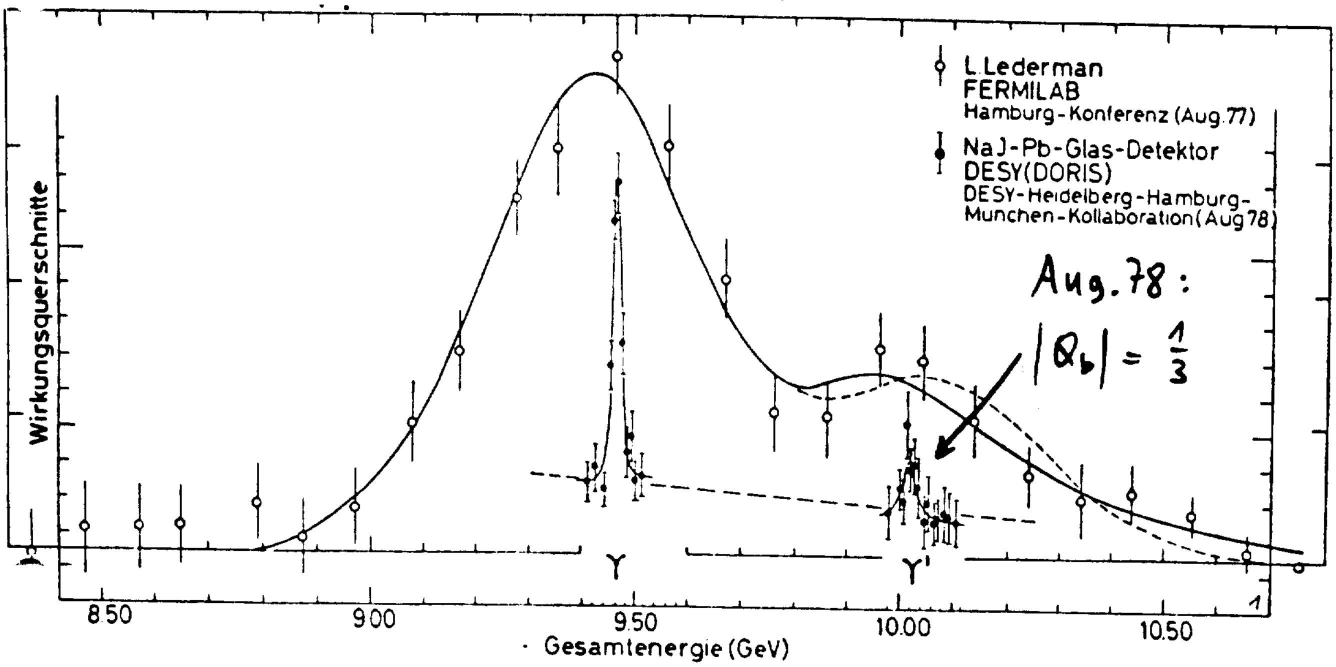
S.W. Herb et al (FNAL), PRL 39 (1977) 252

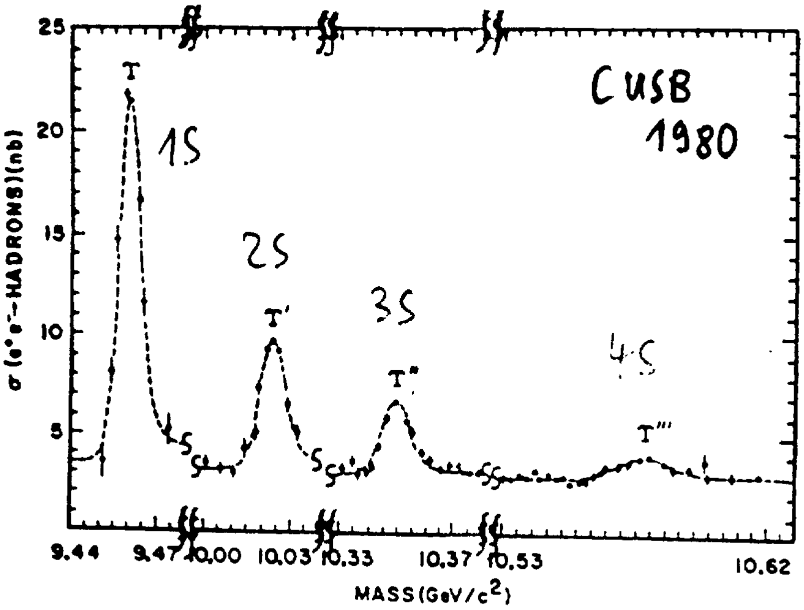


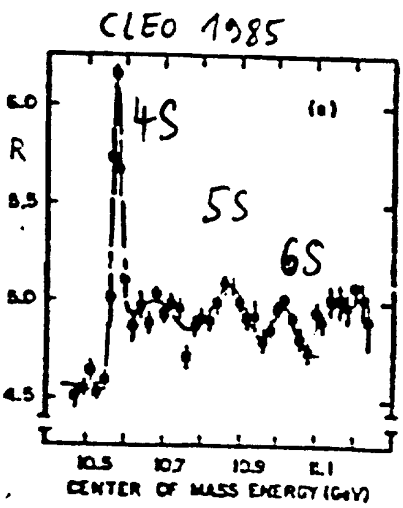
τ discovery 1975
m(b) unpredictable
in contrast to m(c).

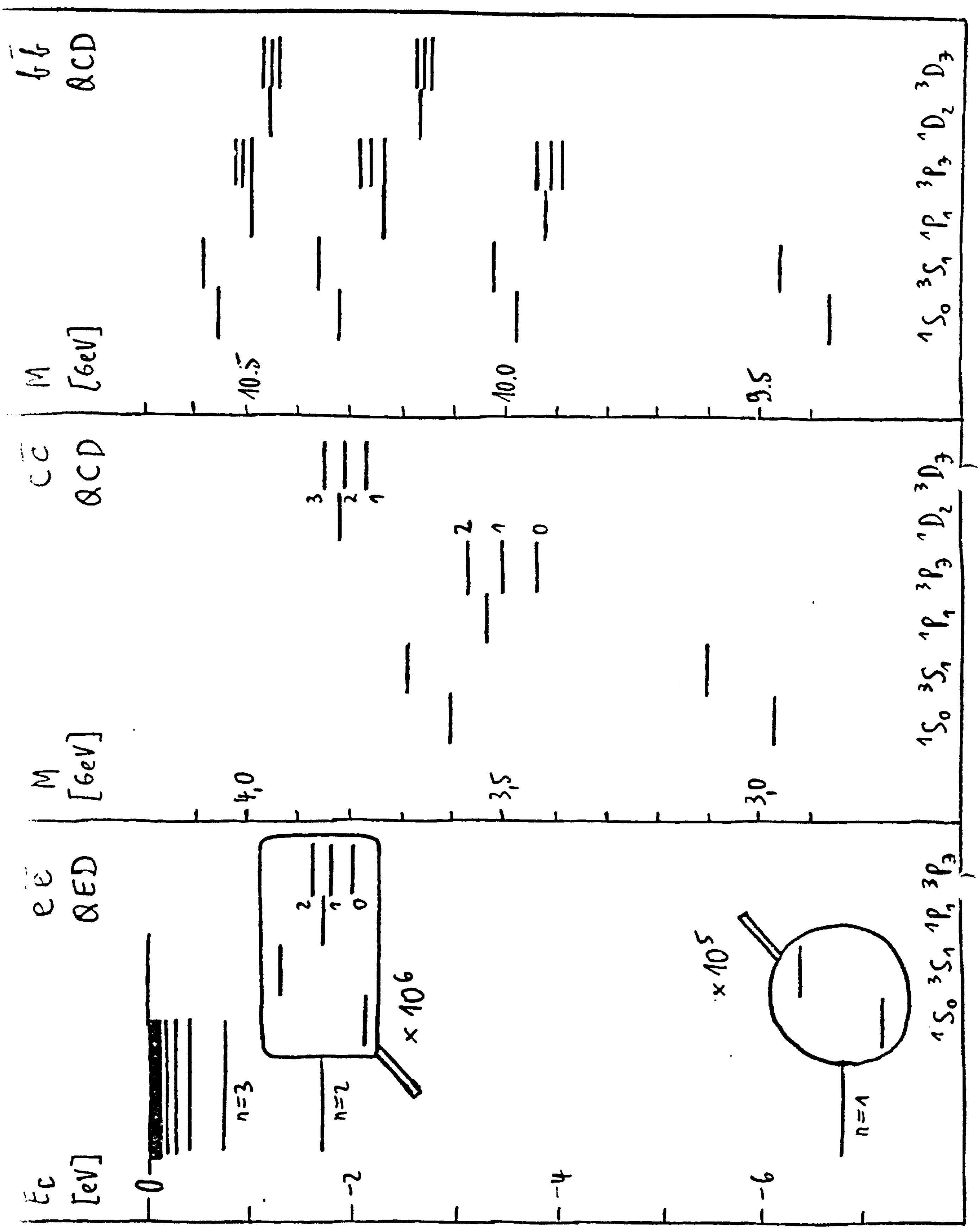
The name b ("bottom") for the 5^{th} quark from H. Harari, PL 57B (1975) 265, where a complete 3^{rd} family is assumed, together with the τ, just discovered, ν_τ, and t. H. was not aware of the Kobayashi-Maskawa paper 1973, where a 3^{rd} family was one of the possibilities to explain $\not{CP}$ in the gauge theory frame.

– Mai 1978: $e^+e^-(\sqrt{s} = 9.46\ \text{GeV}) \to \Upsilon \to$ hadrons at DORIS:





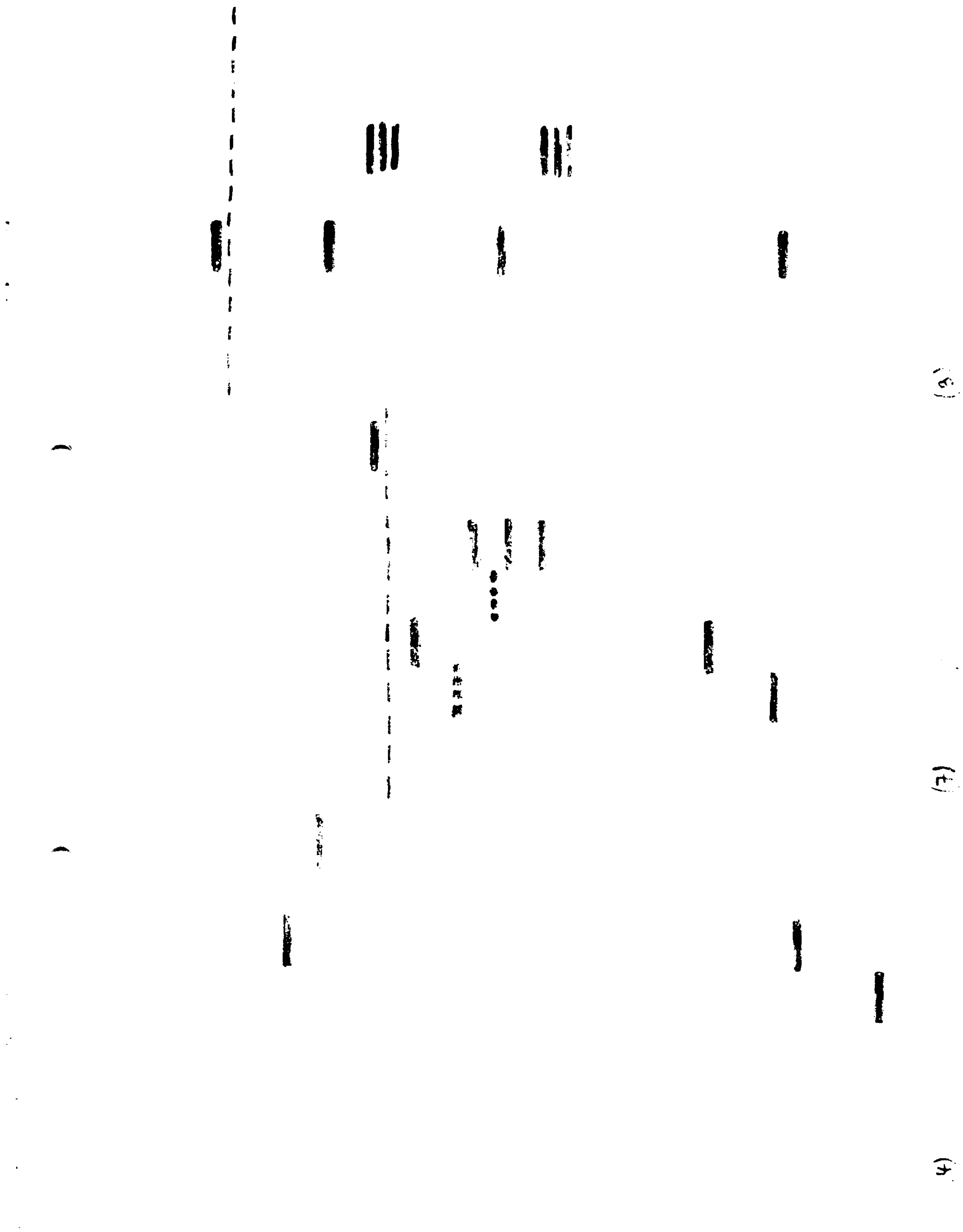




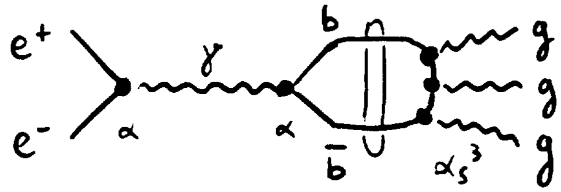
$e\bar{e}$ QED
$c\bar{c}$ QCD
$b\bar{b}$ QCD
E_C [eV]
M [GeV]
M [GeV]
0
-2
-4
-6
n=3
n=2
n=1
× 10^6
× 10^5
2 1 0
3 2 1
2 1 0
3.0
3.5
4.0
9.5
10.0
10.5
$^1S_0$ $^3S_1$ $^1P_1$ ^3P_J
$^1S_0$ $^3S_1$ $^1P_1$ ^3P_J $^1D_2$ ^3D_J
$^1S_0$ $^3S_1$ $^1P_1$ ^3P_J $^1D_2$ ^3D_J

1-4

6

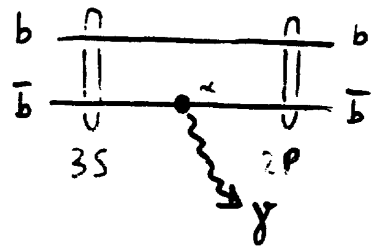


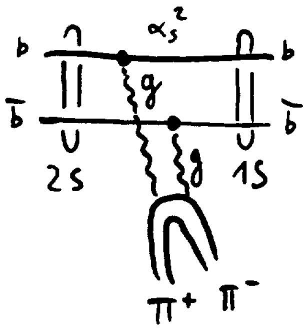
$\Upsilon(1S) = 1\,^3S_1\ b\bar{b}$ decays dominantly into 3 gluons:



$\Gamma_{tot} = 50$ keV.

$\left.\begin{array}{l}\Upsilon(2S) = 2\,^3S_1\ b\bar{b} \\ \Upsilon(3S) = 3\,^3S_1\ b\bar{b}\end{array}\right\}$ dto. and by γ & gg radiation:



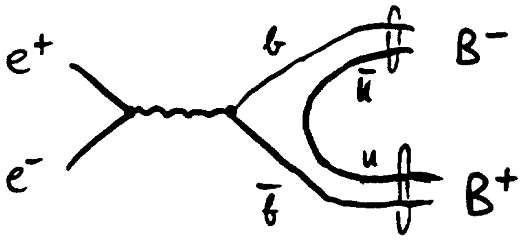


$\Gamma_{tot} = 45; 30$ keV.

$\Upsilon(1S, 2S, 3S)$ and $\chi_{b0,1,2}(1P, 2P)$ cannot decay into B-mesons because of too low mass.

Lightest $b\bar{b}$ state decaying into B-meson pairs is

$\Upsilon(4S) = 4\,^3S_1\ b\bar{b}$. $m = (10580 \pm 3.5)$ MeV, $\Gamma = (24 \pm 2)$ MeV.

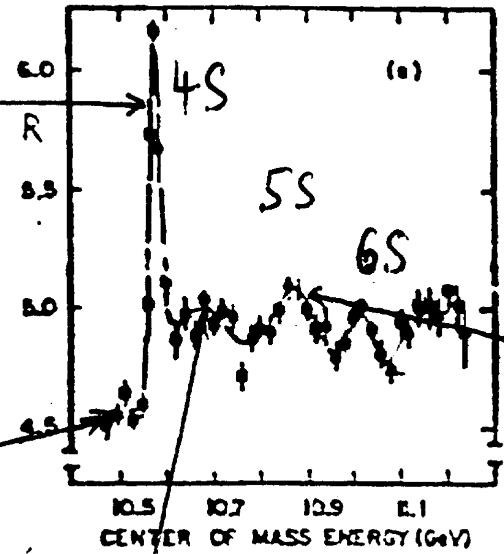


$\Upsilon(4S) \to B^+B^-$ or $B^0\overline{B^0}$ with no extra particles.

Assumption: $\mathcal{B}(\Upsilon 4S \to B^+B^-) = 50\%$

$\mathcal{B}(\Upsilon 4S \to B^0\overline{B^0}) = 50\%$

B^+B^-
$B^0\bar{B}^0$



continuum without $b\bar{b}$.

$B\bar{B}$, $B\bar{B}^*$
$B^*\bar{B}$, $B^*\bar{B}^*$
with $B = B^+, B^0, B_s$

B^+B^-, $B^0\bar{B}^0$, $B\bar{B}^*$, $B^*\bar{B}$

$\sigma(e^+e^- \to \Upsilon 4S \to B\bar{B}) = 1.1$ nb

$\sigma\left[e^+e^-(\sqrt{s} = m\,\Upsilon 4S) \to \mu^+\mu^-\right] = 0.77$ nb $\curvearrowright R_{4S} = 1.5.$

$\sigma\left[e^+e^-(\sqrt{s} = m\,\Upsilon 4S) \to q\bar{q}\right] \approx 3.6$ nb.

One quarter of all had. ev. at $m(\Upsilon 4S)$ are $B\bar{B}$.

Particle Names:

$1\,{}^1S_0\;\bar{b}u = B^+$, $b\bar{u} = B^-$.
$1\,{}^1S_0\;\bar{b}d = B^0$, $b\bar{d} = \bar{B}^0$.
(also B_d, B^0_d)
$1\,{}^1S_0\;\bar{b}s = B_s$, $b\bar{s} = \bar{B}_s$.
(also B^0_s)

decay only weakly: seen / seen / not yet seen

$1\,{}^3S_1\;\bar{b}q = B^*$, $B^* \to B\gamma\,(E = 50\text{ MeV})$ seen on $\Upsilon(5S)$
not yet seperated into B^{*+}, B^{*0}, B^*_s.

Production Rates:

		E_{CM} GeV	$\mathcal{L}_{peak}$ $cm^{-2}s^{-1}$	$\mathcal{L}_{av.}$ $pb^{-1}y^{-1}$	$\sigma_{b\bar{b}}$	$\dot{N}_{b\bar{b}}$ y^{-1}	$N_{b\bar{b}}/N_{had}$
→ DORIS-II	e^+e^-	10.6	$3 \cdot 10^{31}$	100	0.9 nb	10^5	0.19
→ CESR	e^+e^-	10.6	10^{32}	500	1.1 nb	$5 \cdot 10^5$	0.23
BFI-I	e^+e^-	**10.6**	10^{33}	10^4	**1.1 nb**	10^7	**0.23**
BFI-II	e^+e^-	**10.6**	10^{34}	10^5	**1.1 nb**	10^8	**0.23**
LEP	e^+e^-	91.1	$1.5 \cdot 10^{31}$	100	6 nb	10^6	0.22
$\text{LEP}_{\text{upgr.}}$	e^+e^-	91.1	$1.5 \cdot 10^{32}$	1000	6 nb	10^7	0.22
HERA	ep	300	10^{31}	100	4 nb	$4 \cdot 10^5$	10^{-3}
TEV-II	pW	~ 50	$\sim 10^{31}$	~ 100	$\sim 1\ \mu b$	$\sim 10^8$	10^{-6}
TEV-I	$\bar{p}p$	2000	10^{30}	10	15 μb	$1.5 \cdot 10^8$	$3 \cdot 10^{-4}$
$\text{TEV-I}_{\text{upgr.}}$	$\bar{p}p$	2000	$5 \cdot 10^{31}$	500	15 μb	$8 \cdot 10^9$	$3 \cdot 10^{-4}$
LHC	pp	16000	10^{34}	10^5	200 μb	$2 \cdot 10^{13}$	$3 \cdot 10^{-3}$
SSC	pp	40000	10^{33}	10^4	500 μb	$5 \cdot 10^{12}$	$5 \cdot 10^{-3}$

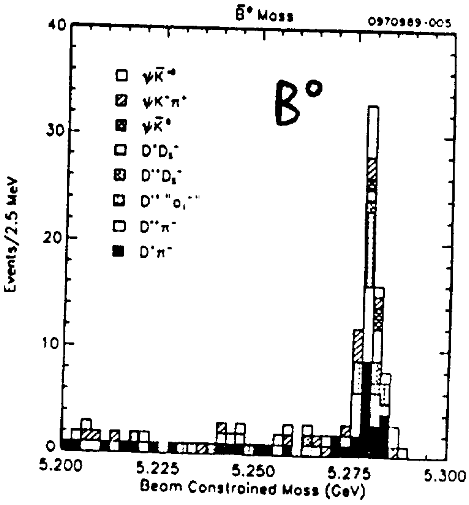
Until end 89, ARGUS at DORIS collected

$\mathcal{L}_{int} = \int \mathcal{L}\, dt = 210/pb$ on $\Upsilon(4S)$.

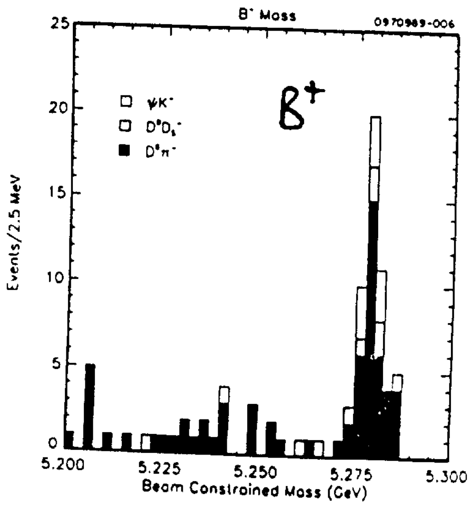
$N(B) = 2 \cdot \sigma \cdot \int \mathcal{L}\, dt = 380\,000.$

CLEO at CESR : $330/pb \curvearrowright N(B) = 730\,000.$

B-Meson Properties: (1) Mass



CLEO '89



$\sigma_m = 2.6$ MeV.

CLEO results from 8 B^0 and 3 $B^\pm$ channels:

$m(B^0) = (5279.3 \pm 0.4 \pm 2.0)$ MeV,

$m(B^+) = (5278.9 \pm 0.4 \pm 2.0)$ MeV,

mainly from $\sigma(m\,\Upsilon 4S) = \pm 3.5$ [illegible]

$\Delta m(B^0 - B^+) = (0.4 \pm 0.6)$ MeV.

World averages essentially the same.

How to reach σ_m [illegible] .4 MeV?

$2.6\ \text{MeV}/\sqrt{60} = 0.34$ MeV.

Mass resolution of 2.6 MeV follows from method of energy constraint.

$B^+ \to J/\psi\, K^+$ as example. $J/\psi \to \ell^+\ell^-$.

$\sigma[M_{inv}(\ell^+\ell^- K^+)] = \pm 59$ MeV.

after $m(\ell^+\ell^-) = m(J/\psi)$ constraint: ± 31 MeV.

B-mass [illegible] kinematic:

$E_B = \frac{1}{2}$ [illegible] $\pm$ [illegible] $= 5.29$ GeV ± 1.8 MeV CESR, ± 4 MeV DORIS

$|\vec{p}_B| = 325$ MeV. In CLEO measurable ± 30 MeV.

$m^2 = E^2 - p^2$. $(2m\,\sigma$ [illegible] $= (2E\sigma_E)^2 + (2p\sigma_p)^2$

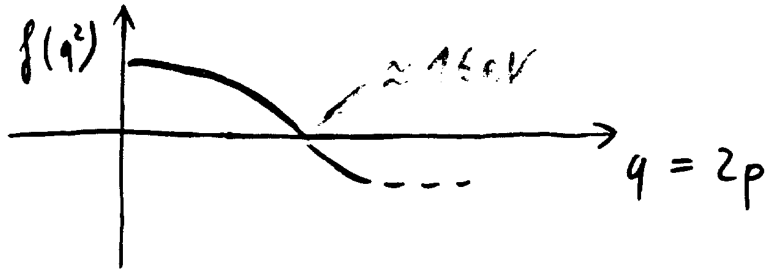
$\to \pm 2.6$ MeV

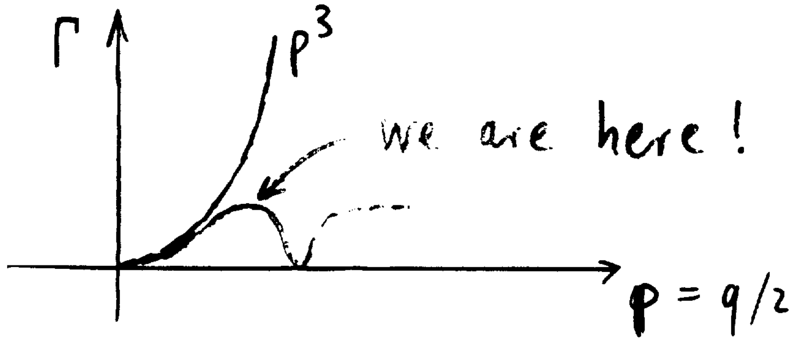
$m(B^0) - m(B^+)$ may be relevant for

$f_0 = \mathcal{B}(\Upsilon 4S \to B^0 \overline{B^0})$ and $f_+ = 1 - f_0$:

$$\Gamma = \frac{\mathcal{M}^2}{12\pi} \frac{p}{M^2} \;;$$

$$\mathcal{M} = K \cdot \varepsilon^\mu q^\mu \cdot f(q^2) \;\curvearrowright\; \Gamma = \frac{K^2}{12\pi} \frac{p^3}{M^2} f^2(q^2)$$





$d\Gamma/dp \approx 0 \;\curvearrowright\; f_0 : f_+ = 1{,}00.$

If $\mathcal{M} = \text{const} \;\curvearrowright\; f_0 : f_+ = 0{,}99 \pm 0{,}02.$

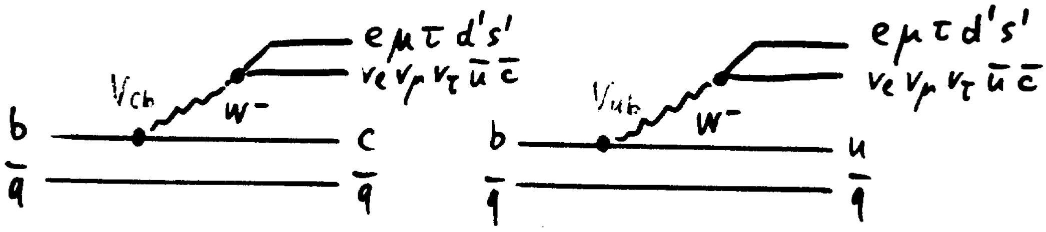
If $\mathcal{M} \propto p$, $\Gamma \propto p^3 \;\curvearrowright\; f_0 : f_+ = 0{,}96 \pm 0{,}08.$

Conservative conclusion : $f_0 : f_+ = 1{,}00 \pm 0{,}08.$

$f_0 = f_+ = 0{,}50 \pm 0{,}02.$

(2) Mean Life:

τ_B not predictable from standard model if V_{cb} and V_{ub} are unknown



$$\frac{1}{\tau_B} = \Gamma_B \approx \frac{G_F^2 m_b^5}{192\pi^3}\left\{ [illegible] \cdot 0.4 + |V_{ub}|^2 \cdot 0.8 \right\} \cdot (3 + 3 \times 2)$$

$$= \mathcal{O}\left(1/10^{-14}s\right) \quad \text{if } |V_{cb}| \approx |V_{ub}| \approx V_{us} = \sin\vartheta_c = 0.22.$$

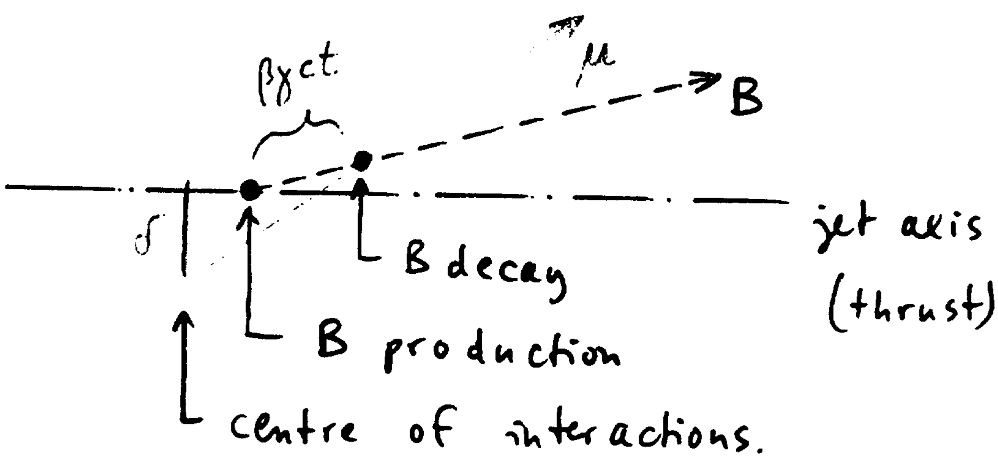
1983 big surprise: $\tau_B = \mathcal{O}(10^{-12}s)$ MARK2, MAC.

Even this is unmeasurable on $\Upsilon(4S)$ at rest:

$p_B = 325$ MeV ; $(\beta\gamma)_B = 0.06$; $\langle l \rangle = \beta\gamma c\tau = \mathcal{O}(20\,\mu m)$.

τ_B is only measured at PEP and PETRA.

Technique: $e^+e^- \to b\bar{b} \to$ two jets.

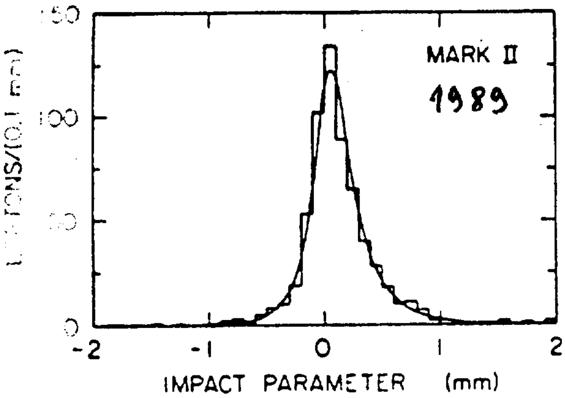


$\tau_B =$ [illegible]

The most recent impact parameter distribution

(e [illegible] μ, $p > 2$ GeV/c, $p_t > 1$ GeV/c):

R. A. Ong et al (MARK-II), PRL 62 (1989) 1236



$B \to \mu\nu X$
Monte Carlo

$\tau_B =$
$(9.8 \pm 1.2 \pm 1.3) \cdot 10^{-13}$ s.

<u>All results:</u>

$(12 {}^{+4.5}_{-3.6} \pm 3) \cdot 10^{-13}$ s	MARK-II 83
1[illegible] $\pm 6 \pm 4$	MAC 83
$18 {}^{+5}_{-4} \pm 4$	JADE 86
$12.9 \pm 2 \pm 2.1$	MAC 87
$10.$[illegible] ${}^{+4.2}_{-3.9}$	HRS 87
$11.7 {}^{+2.7}_{-2.2} {}^{+1.7}_{-1.6}$	DELCO 88
$9.8 \pm 1.2 \pm 1.3$	MARK-II 89
$13.5 \pm 1.0 \pm 2.4$	TASSO 89

<u>Average:</u> $\tau_B = (11.6 \pm 1.5) \cdot 10^{-13}$ s.

<u>Caution:</u> Average of B^0, B^+, B_s, Λ_b!

$\tau(K^+)/\tau(K^0_S) = 139$,
$\tau(D^+)/\tau(D^0) = 2.5$.

③ Separate Mean Lives for B^0 and B^+:

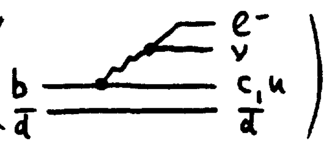
MARK-II has 4 reconstructed B^0 decays.

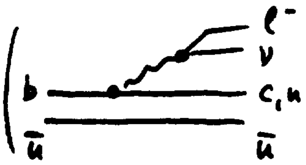
$$\tau(B^0) = \left(13\,^{+12}_{-6}\right) \cdot 10^{-13}\,s.$$

Better soon at LEP?

$$\sigma_\tau = \sqrt{\frac{\tau^2 + \sigma_t^2}{N}} \quad ; \qquad N = 100 \text{ wanted.}$$

ARGUS & CLEO have indirect ways:

$\Gamma \Big($ 

$\Big) = \Gamma \Big($ 

$\Big)$

Lifetime differences can only come from nonleptonic decays. Semileptonic rates are equal.

$$\curvearrowright \quad \tau(B^+)/\tau(B^0) = \mathcal{B}(B^+ \to \ell^+ \nu F^0)/\mathcal{B}(B^0 \to \ell^+ \nu F^-)$$

Four methods to measure $\mathcal{B}^+/\mathcal{B}^0$:

1. $\mathcal{B}(B^0 \to \ell^+ \nu X)$ from tagged $B^0\overline{B^0}$ events compared to $\mathcal{B}(\Upsilon 4S \to \ell \nu X)$
2. $\mathcal{B}(B^+ \to D^{*0} \ell^+ \nu)/\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu)$
3. $N(\Upsilon 4S \to \ell\ell X)/N^2(\Upsilon 4S \to \ell X)$
4. $N(D^0 \ell^- X)/N(D^+ \ell^- X)$

$$\curvearrowright \quad \mathcal{B}^+/\mathcal{B}^0 = \tau^+/\tau^0 = \underline{\underline{1.03 \pm 0.19.}}$$

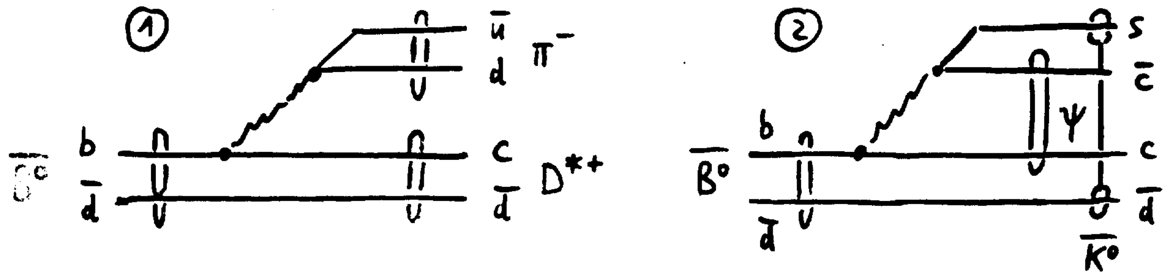
④ Nonleptonic Decays: 10 B^0 & 10 B^+ known.

	ARGUS [%]	CLEO 87 [%]	CLEO 89 [%]
$B^0 \to D^{*-}\pi^+$	0.35 ± 0.22	0.31 ± 0.17	0.30 ± 0.10
$D^{*-}\pi^+\pi^0$	2.0 ± 1.4		1.9 ± 1.6
$D^{*-}\pi^+\pi^+\pi^-$	4.3 ± 2.3		1.5 ± 1.1
$D^-\pi^+$	0.31 ± 0.16	0.59 ± 0.33	0.24 ± 0.11
$D^-\pi^+\pi^0$	2.2 ± 1.5		
$J/\psi\ K^0$	(1 ev.)		(3 ev.) 0.06 ± 0.04
$J/\psi\ K^{*0}$	0.33 ± 0.18	0.41 ± 0.19	0.10 ± 0.04
$J/\psi\ K^-\pi^+_{nr.}$			0.11 ± 0.05
$\psi(2S)\ K^{*0}$			0.13 ± 0.08
$D^-D_s^+$			3.6 ± 1.8
$B^+ \to D^{*-}\pi^+\pi^+$	0.66 ± 0.50	0.20 ± 0.15	
$D^{*-}\pi^+\pi^+\pi^0$	5.7 ± 3.8		
$\overline{D^0}\pi^+$	0.19 ± 0.12	0.47 ± 0.18	0.31 ± 0.08
$\overline{D^0}\pi^+\pi^0$	2.1 ± 1.2		
$D^-\pi^+\pi^+$		$0.25^{+0.47}_{-0.25}$	
$J/\psi\ K^+$	0.07 ± 0.04	0.09 ± 0.06	0.08 ± 0.02
$J/\psi\ K^{*+}$			0.13 ± 0.09
$J/\psi\ K^+\pi^+\pi^-$	0.11 ± 0.07		0.14 ± 0.05
$\psi(2S)\ K^+$	0.22 ± 0.17		
$\overline{D^0}D_s^+$			6.4 ± 3.2

All observed nonleptonic B decays are of the type $b \to c$, i.e. $\propto |V_{cb}|^2$.

Errors on the $\pm 30\%$ level are too large for detailed comparison with theory. Phenomenological models of two-body decays OK on this level.

Two classes of colour rearrangement:



Class 1: $\Gamma \propto |V_{cb}|^2 \cdot f_\pi^2 \cdot \left[\int \psi_B^* \psi_D \, dV\right]^2 \cdot 1$

Class 2: $\Gamma \propto |V_{cb}|^2 \cdot f_K^2 \left[\int \psi_B^* \psi_\psi \, dV\right]^2 \cdot \frac{1}{9}$

Class-2-decays are "colour-suppressed".

$\mathcal{B}(B \to J/\psi + X) = (1.12 \pm 0.10 \pm 0.15)\%$ CLEO 89.

Without colour suppression, $\approx 10\%$ was expected.

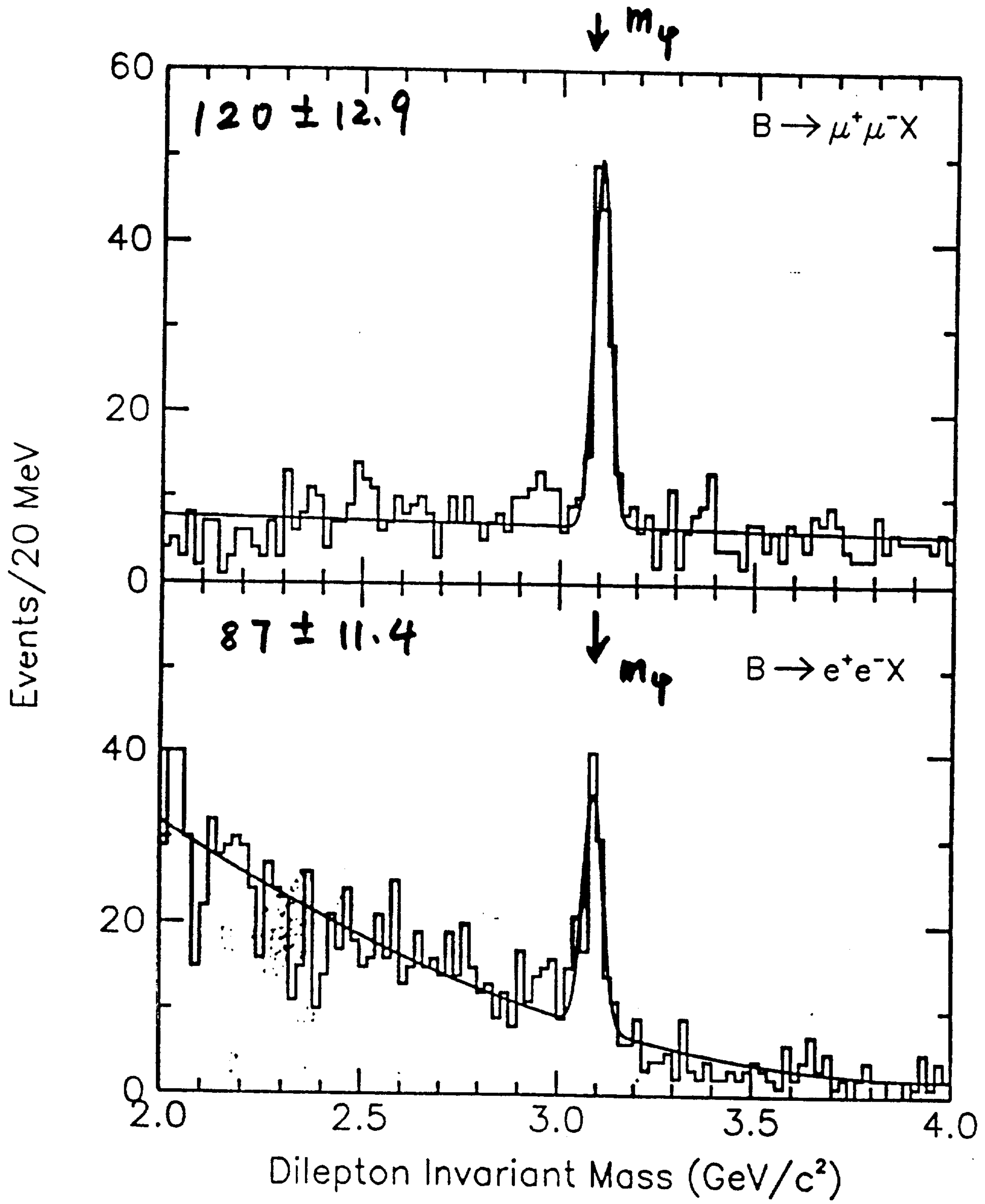
(5) Nonleptonic $b \to u$ Decays:

None seen. $\mathcal{B}(B^0 \to p\bar{p}) < 4 \cdot 10^{-5}$

$\mathcal{B}(B^0 \to \pi^+\pi^-) < 9 \cdot 10^{-5} \leadsto |V_{ub}/V_{cb}| < 0.2$

Inclusive News from CLEO: $B \to J/\psi + X$

$\psi 2S + X$



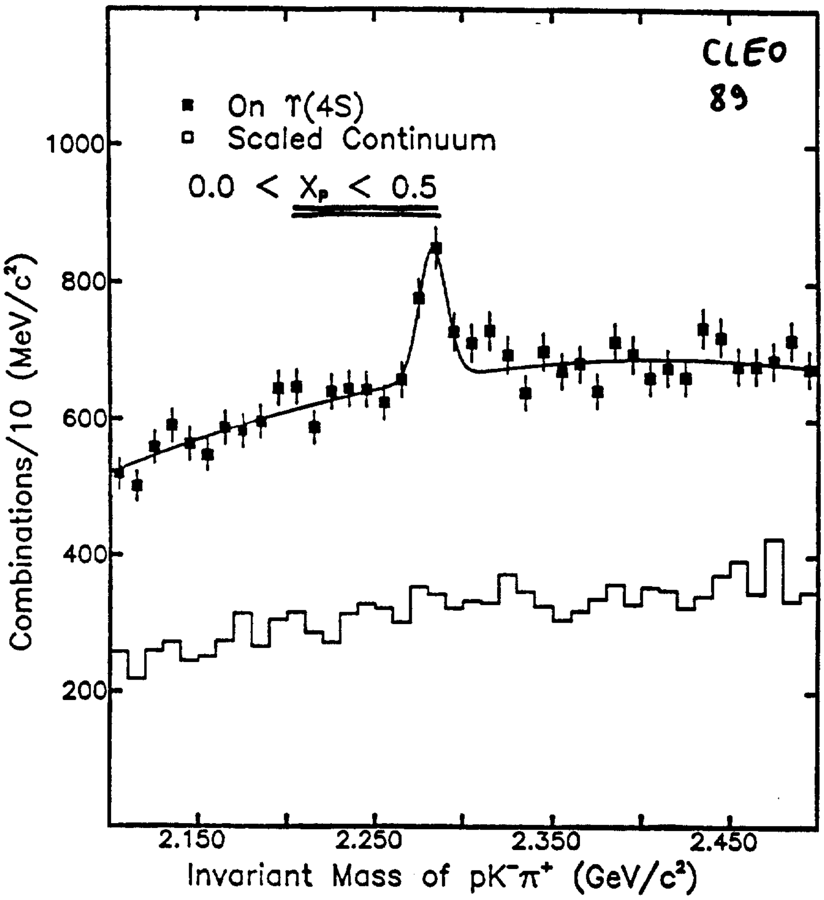
$\mathcal{B}(B \to J/\psi + X) = \underline{\underline{(1.12 \pm 0.10 \pm 0.15)\%}}$ CLEO 89

$1.07 \pm 0.16 \pm 0.22$ ARGUS 8?

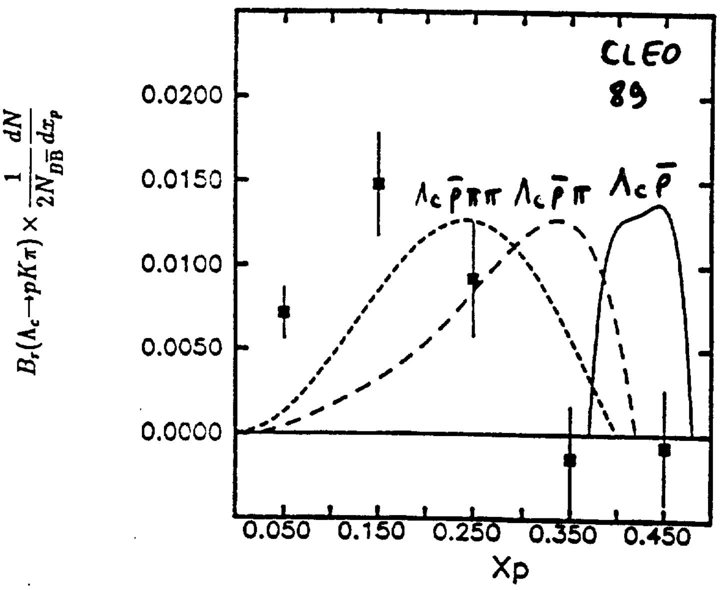
$1.09 \pm 0.16 \pm 0.21$ CLEO 87

⑥ Baryonic Decays:

Both ARGUS + CLEO see Λ_c in B-decays:



← Λ_c from $c\bar{c}$ continuum has $\underline{\underline{x > 0.5}}$



$\mathcal{B}(\bar{B} \to \Lambda_c X) \cdot \mathcal{B}(\Lambda_c \to p K^- \pi^+)$

$= (0{,}28 \pm 0{,}06 \pm 0{,}05)\%$ $= (0{,}30 \pm 0{,}12 \pm 0{,}06)\%$

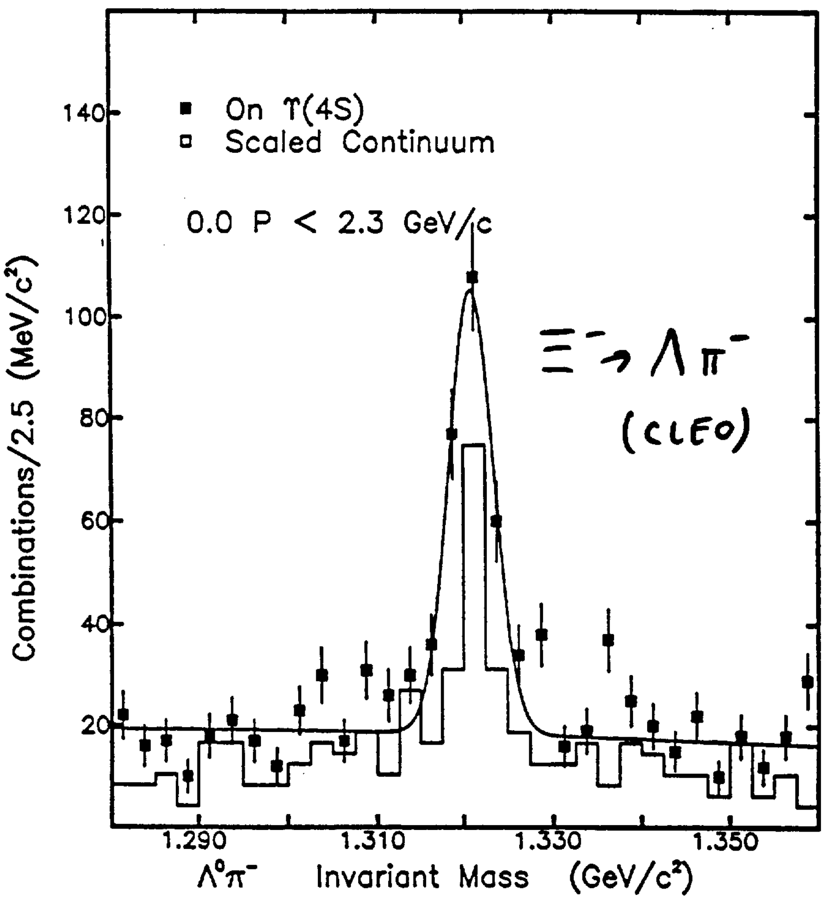
CLEO ARGUS

$= (0{,}29 \pm 0{,}07)\%.$

Additional measurements lead to $\mathcal{B}(\bar{B} \to \Lambda_c X)$ <u>and</u> $\mathcal{B}(\Lambda_c \to p K^- \pi^+)$ <u>without</u> requiring n measurments. Strict derivation with 3 assumptions (CLEO)

1. $(b \to u,\ b \to s) \ll (b \to c)$.
2. $\Lambda_c \gg \Xi_c^+, \Xi_c^0, \Omega_c$.
3. $\mathcal{B}(B \to \Lambda_c X) \gg \mathcal{B}(B \to \bar{D} N \bar{N} X)$.

i.e. $B \to$ baryons is dominated by $\Lambda_c(\bar{p}, \bar{n}, \bar{\Lambda}) X$

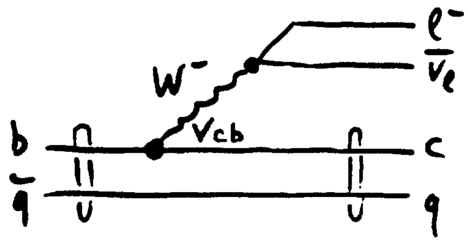


$B \to \Xi X$ seen, but small, either from $\bar{B} \to \Xi_c X$ $\{< 0.1 * \bar{B} \to \Lambda_c$ or from $\Lambda_c \to \Xi + X$ $\{\mathcal{B} < 6\%\}$

Other exclusive semileptonic channels are less clean. Summary without entering details:

	ARGUS [%]	CLEO [%]
$B^0 \to D^{*-} \ell^+ \nu$	$5.7 \pm 1.0 \pm 1.5$	$4.9 \pm 0.5 \pm 0.7$
$B^0 \to D^- \ell^+ \nu$	$1.6 \pm 0.6 \pm 0.5$	
$B^0 \to$ "D^{**}" $\ell^+ \nu$	< 1.0	2.2 ± 1.3
$B^+ \to \bar{D}^{*0} \ell^+ \nu$		$3.9 \pm 0.8 \, {}^{+1.1}_{-0.8}$
$B^+ \to \bar{D}^0 \ell^+ \nu$		$2.4 \pm 0.8 \pm 0.8$
$B^+ \to$ "D^{**}" $\ell^+ \nu$		1.9 ± 1.0

All these are V_{cb}-induced β-decays:



Search for the corresponding V_{ub}-induced decays by ARGUS 1989 from $\int \mathcal{L}\, dt = 180/pb$:

$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu) < 1.0 \cdot 10^{-3}$$

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) < 1.0 \cdot 10^{-3} \quad (90\% \, C)$$

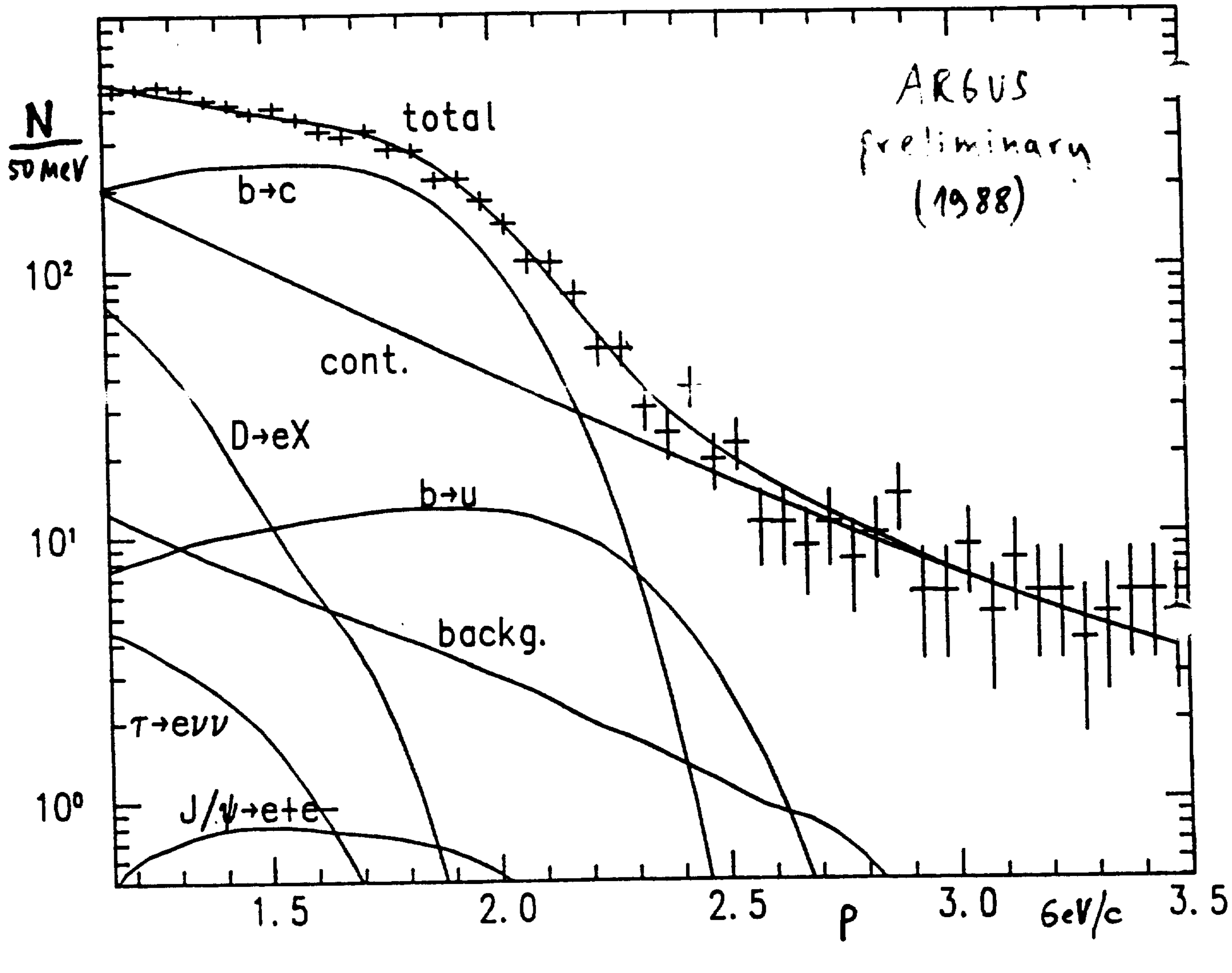
8 Inclusive Semileptonic Decays

$$e^+e^- \left(\sqrt{s} = 10.58 \text{ GeV}\right) \rightarrow \begin{pmatrix} e^\pm \\ \mu^\pm \end{pmatrix} + X$$

Main contributions: $\underline{\underline{B \rightarrow \ell\nu X_c}}$, $\underline{\underline{B \rightarrow \ell\nu X_u}}$,

$B \rightarrow D X$
$\quad \hookrightarrow \ell \nu Y$

$c\bar{c} \rightarrow \ell\nu X.$



Inclusive $B \rightarrow \ell\nu X$ description by Altarelli et al:

μ-like β-decay of moving b-quark. Parameters for $\frac{dN}{dp}$: m_b, $m_c (m_u)$, p_F

A set of 10 measurements

$\mathcal{B}(B \to p \text{ or } \bar{p}, X)$ $\qquad$ $\mathcal{B}(B \to \Lambda \ell^+ X)$

$\mathcal{B}(B \to p\bar{p} X)$ $\qquad$ $\mathcal{B}(B \to \ell^+ \bar{\Lambda} X)$

$\mathcal{B}(B \to \Lambda \text{ or } \bar{\Lambda}, X)$ $\qquad$ $\mathcal{B}(B \to p \ell^+ X)$

$\mathcal{B}(B \to \Lambda\bar{p} \text{ or } \bar{\Lambda}p, X)$ $\qquad$ $\mathcal{B}(B \to \ell^+ \bar{p} X)$

$\mathcal{B}(B \to \Lambda\bar{\Lambda} X)$ $\qquad$ $\mathcal{B}(B \to \ell^+ p\bar{p} X)$

Constrains 4 branching fractions

and 3 fragmentation fractions:

$$\mathcal{B}(\bar{B} \to \Lambda_c X) = \underline{\underline{(7.9 \pm 0.9)\%}}$$

$$\mathcal{B}(\Lambda_c \to \Lambda X) = (37 \pm 7)\%$$

$$\mathcal{B}(\Lambda_c \to p X, \ p \text{ not from } \Lambda) = (31 \pm 8)\%$$

$$\mathcal{B}(\Lambda_c \to n X, \ n \text{ not from } \Lambda) = (32 \pm 11)\%$$

$$f_\Lambda = \frac{\bar{B} \to \Lambda_c \bar{\Lambda} X}{\bar{B} \to \Lambda_c X} = (14 \pm 4)\%$$

$$f_p = (47 \pm 8)\%, \quad f_n = (39 \pm 9)\%.$$

and, very difficult to obtain from somewhere else,

$$\mathcal{B}(\Lambda_c \to p K^- \pi^+) = \underline{\underline{(3.7 \pm 1.0)\%}}$$

7 Exclusive Semileptonic Decays

$B^0 \to D^{*-} \ell^+ \nu$ first seen by ARGUS 1987

$\ell^\pm$ selected with $p_\ell > 1$ GeV/c.

$D^{*-} \to \overline{D^0} \pi^+$, $\overline{D^0} \to K^+ \pi^-$, $x(D\pi) < 0.5$.

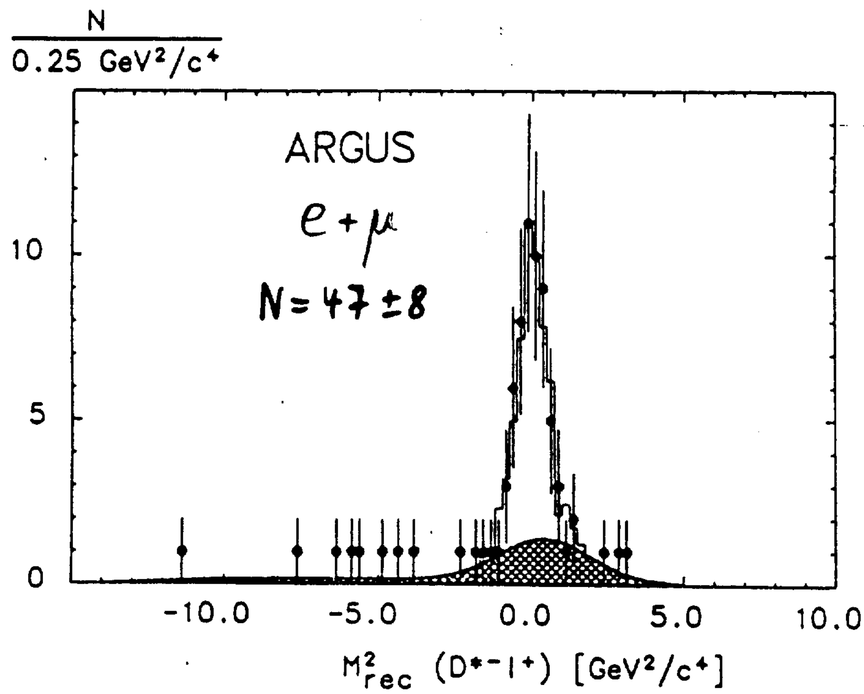
Missing mass :

$$MM^2 = (E_B - E_{D^*} - E_\ell)^2 - (\vec{p}_B - \vec{p}_{D^*} - \vec{p}_\ell)^2$$

known

measured

assumed to be 0 :

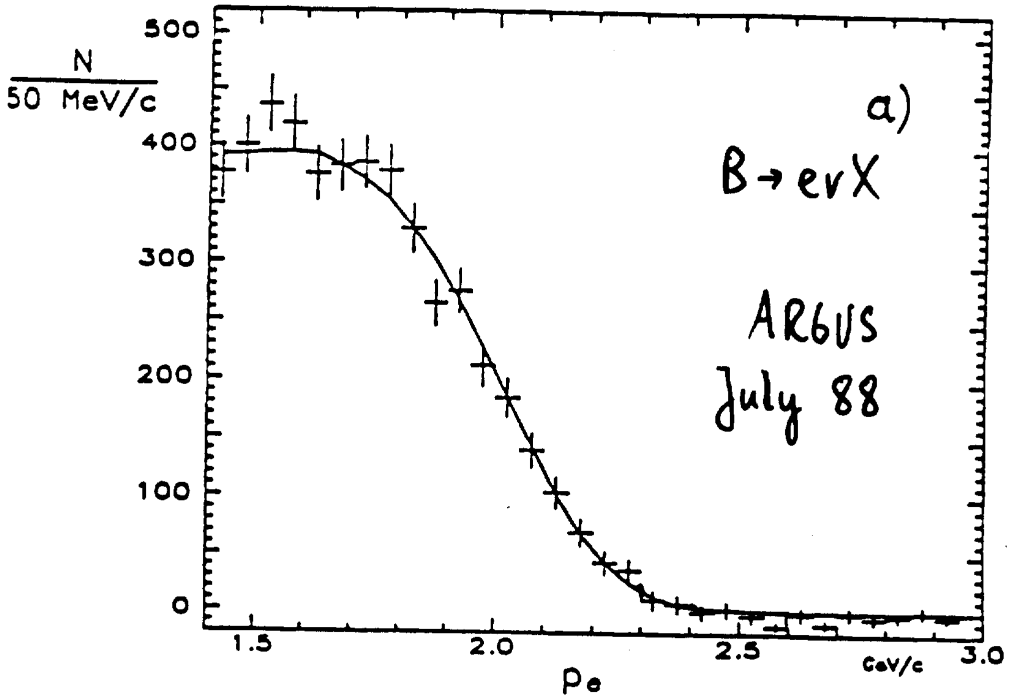


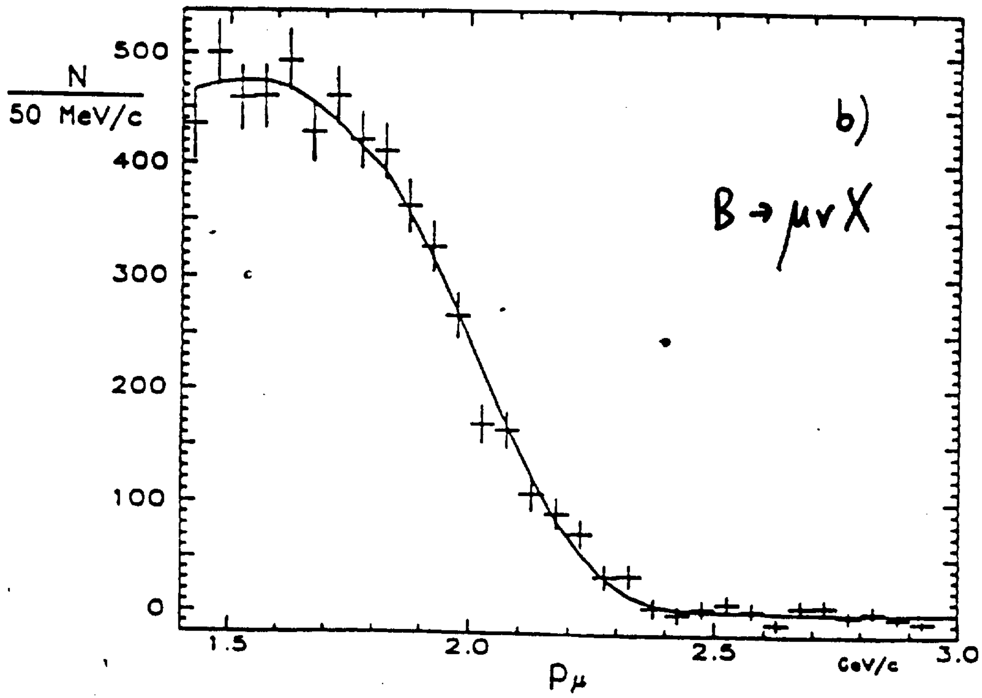
$MM^2 = 0$ for B at rest [$MM^2 = m_\nu^2$]

Result: $\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu) = (5.7 \pm 1.0 \pm 1.5)\%$.

CLEO 1989: $(4.9 \pm 0.5 \pm 0.7)\%$.

$\mathcal{B}/\tau \to \Gamma \to V_{cb}$.





ARGUS results: Perfect fits with Altarelli et al,

$p_F = (300 \pm 50)$ MeV/c. $\langle m_b \rangle = m_B - \frac{2 p_F}{\sqrt{\pi}} = (4.94 \pm 0.06)$ GeV

$m_c = (1.56 \pm 0.06)$ GeV. $\langle m_b \rangle - m_c = (3.38 \pm 0.02)$ GeV.

$\mathcal{B}(B \to e\nu X) = \mathcal{B}(B \to \mu\nu X) = (10.3 \pm 0.7)\%$.

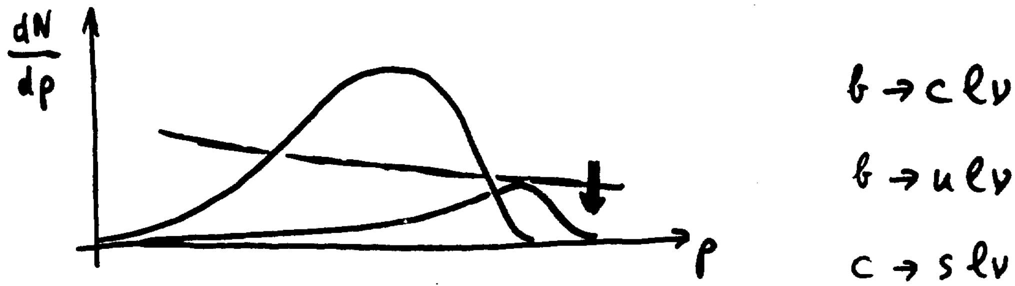
$\mathcal{B}(b \to u \ell \nu) / \mathcal{B}(b \to c \ell \nu) = (1.7 \pm 1.0)\%$.

Altarelli model $\curvearrowright$ $|V_{ub}/V_{cb}| < 0.14$ (90%)

$$\mathcal{B}(B \to \ell \nu X) = (10.3 \pm 0.7)\%, \quad \text{ARGUS 89}$$
$$(11.7 \pm 0.4 \pm 1.0)\%, \quad \text{Crystal Ball 89}$$
$$(10.1 \pm 0.5 \pm ?)\%, \quad \text{CLEO 89, prelim.}$$

$$\text{av.} = (10.5 \pm 0.6)\% \quad \curvearrowright |V_{cb}|.$$

Similar limits on $|V_{ub}/V_{cb}|$ {< 0.14, ARGUS using Altarelli model} are obtained from the <u>inclusive</u> semileptonic studies of CUSB, Crystal Ball, CLEO.



Drastic anti-continuum cuts reject also $B \to \ell \nu X$ events and introduce uncertainties on $\mathcal{B}(B \to \ell \nu X_c)$ and $\mathcal{B}(B \to \ell \nu X_u)$. But they led to first evidence for $b \to u \ell \nu$ and to a first rough $|V_{ub}|$ determination by ARGUS & CLEO in '89.

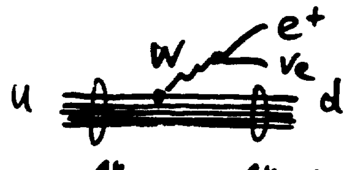
Determination of CKM Matrix Elements:

$\boxed{V_{ud}}$ from nuclear β decays in one isospin triplet.

$0^+ \to 0^+$ transitions are pure vector,

CVC $\rightsquigarrow$ $\mathfrak{M} = \sqrt{2}$

with 3 - 8 ‰ nuclear structure corrections

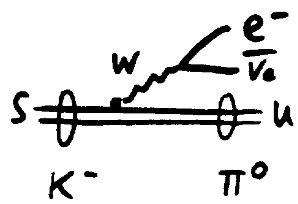


compared to

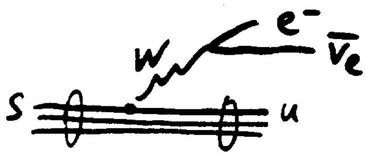
e.g. $^{14}O \to {}^{14}N$

$\rightsquigarrow$ $V_{ud} = 0.9744 \pm 0.0010$

$\boxed{V_{us}}$ from



and

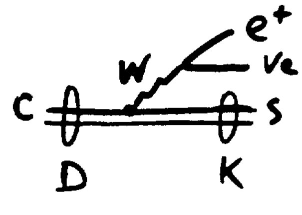


$\Xi^- \to \Lambda$
$\Lambda \to p$
$\Sigma^- \to n$ ...

$V_{us} = 0.220 \pm 0.002$

{meson wave functions needed. $\int \psi_K^* \psi_\pi \, dV = 0.98$

$\boxed{V_{cs}}$ from

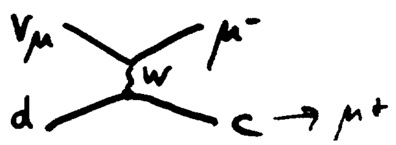


$V_{cs} = 1.00 \pm 0.09$

6% error from experiment, 7% from theory:

$\int \psi_D^* \psi_K \, dV = 0.75 \pm 0.05$

$\boxed{V_{cd}}$ not from β-decays, but from charm production in neutrino reactions:



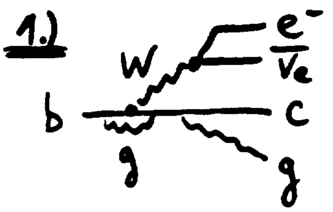
$V_{cd} = 0.21 \pm 0.03$

$$V_{CKM} = \begin{pmatrix} 0.9744 \pm 0.0010 & 0.220 \pm 0.002 & V_{ub} \\ -0.21 \pm 0.03 & 1.00 \pm 0.09 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

From V_{ud}, V_{us}, V_{cd}, V_{cs} alone, we could not conclude existence of a 3rd family. The (2×2)-submatrix is unitary within errors. It is <u>real</u>, i.e. CP violation in the K^0 system could not be an effect of the standard weak interaction with only two quark families.

$\boxed{V_{cb}}$ from β decays of the b-quark. 3 ways:

<u>1.)</u>



$$\Gamma(B \to \ell \nu X) = \Gamma_{corr}(b \to c \ell \nu) =$$

$$= \frac{G_F^2 V_{cb}^2}{192 \pi^3} \cdot m_b^5 \cdot \phi\left(\frac{m_c}{m_b}\right) \cdot \eta_{QCD}$$

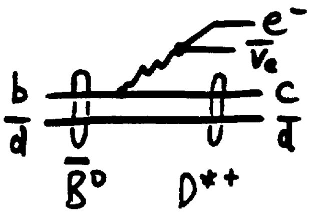
$$\Gamma_{exp}(B \to \ell \nu X) = \mathcal{B}/\tau = (0.105 \pm 0.006)/(1.15 \pm 0.16)\,ps$$
$$= (9.1 \pm 1.4)\, 10^{10}/s.$$

m_b, m_c from Altarelli fit to ARGUS data

$$\leadsto \underline{\underline{V_{cb}(\text{incl.}) = 0.047 \pm 0.005}}$$

$$V_{cb}\,(\text{incl.}) = \underline{\underline{0.047 \pm 0.005.}}$$

2.)



$$\Gamma(B^0 \to D^{*-} \ell^+ \nu) = V_{cb}^2\,(2.2 \pm 0.5)\cdot 10^{13}/s.$$

uncertainty range over 4 models for B-D-overlap.

Γ_{exp} : average of B^0(ARGUS), B^0(CLEO), B^+(CLEO)

$$\curvearrowright \quad V_{cb}\,(\text{excl.}) = \underline{\underline{0.042 \pm 0.006}}$$

3.) Combine inclusive experimental result with exclusive model calculations:

$$\Gamma(B \to \ell \nu X) = V_{cb}^2 \left[\underbrace{\underset{D^*}{2.2 \pm 0.5} + \underset{D}{1.0 \pm 0.2}}_{\substack{\text{average over models} \\ \text{GISW, KS, BSW, AW}}} + \underset{\substack{\text{"}D^{**}\text{"} \\ \text{from GISW alone}}}{0.4 \pm 0.1}\right] 10^{13}/s.$$

$$\curvearrowright \quad \underline{\underline{V_{cb}\,(\text{mixed}) = 0.051 \pm 0.005}}$$

Reasonable agreement between 3 methods.

"average" $= 0.047 \pm 0.005.$

$$\lambda = V_{us} = 0.220 \quad \curvearrowright \quad A = \frac{V_{cb}}{\lambda^2} = \underline{\underline{0.97 \pm 0.10}}$$

$\boxed{V_{ub}}$

Nothing seen in nonleptonic B decays.

$$\mathcal{B}(B^0 \to \pi^+\pi^-) < 9 \cdot 10^{-5}, \quad |V_{ub}/V_{cb}| < 0.20$$

$$|V_{ub}| < 0.01. \qquad [WSB]$$

Nothing seen in "fully inclusive" semileptonic decays.

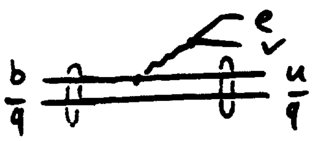
$$\mathcal{B}(B \to \ell\nu X_u)/\mathcal{B}(B \to \ell\nu X_c) \lesssim 3\%, \quad |V_{ub}| < 0.007.$$

[ACM]

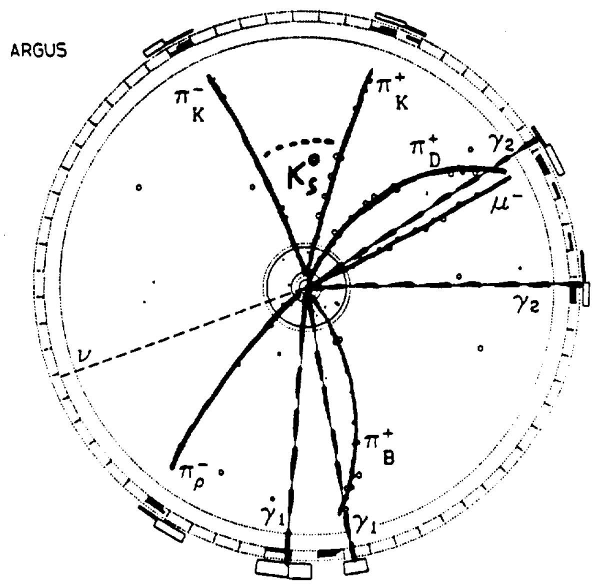
Nothing seen in exclusive semileptonic channels.

$$\left.\begin{array}{l} \mathcal{B}(B^+ \to \rho^0 \ell^+ \nu) < 1.0 \cdot 10^{-3} \\ \mathcal{B}(B^0 \to \pi^- \ell^+ \nu) < 1.0 \cdot 10^{-3} \end{array}\right\} \begin{array}{lll} |V_{ub}| & < 0.013 & \text{GISW} \\ & < 0.007 & \text{WSB} \\ & < 0.007 & \text{KS} \\ & < 0.008 & \text{DP} \end{array}$$

Results are model-dependent!



Wave functions of light mesons are problematic!



Evidence for $|V_{ub}| \neq 0$:

1 ARGUS event:

$$\Upsilon(4S) \to B^0 \overline{B^0} \to \overline{B^0}\,\overline{B^0}$$

$$\overline{B^0} \to D^{*+} \rho^-$$

$\quad \rho^- \to \pi^-_\rho \pi^0_1$

$\quad D^{*+} \to D^0 \pi^+_D$

$\qquad D^0 \to \overline{K^0} \pi^0_2$

$$\overline{B^0} \to \pi^+_B \mu^- \bar{\nu}_\mu.$$

New ARGUS analysis on inclusive leptons with strong anti-continuum cuts:

H. Albrecht et al, PLB 234 (1990) 409

$\int \mathcal{L} dt = 201/pb$ on $\Upsilon 4S$, 69/pb off-resonance.

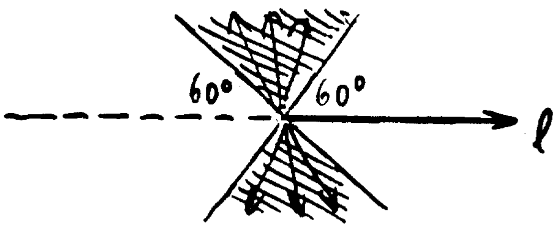
$\downarrow$ $\frac{1}{4} B\bar{B} + \frac{3}{4}$ continuum

$\downarrow$ only continuum.

Search for e & μ with $p > 2$ GeV/c. Good ID,

misid (e) = $(0.5 \pm 0.2)\%$, misid (μ) = $(1.5 \pm 0.3)\%$.

<u>Event selection criteria</u>: 1.) $\sum_{\text{cone}} |p_t| > 2.0$ GeV/c



2.) $\vec{p}_{miss} \in [1.0, 3.5]$ GeV/c.

3.) $\cos\vartheta(\vec{p}_{miss}, \vec{p}_\ell) < -0.5$

$\curvearrowright$ continuum leptons reduced by factor 40.
leptons from B decays reduced by ≈ 3.

$N_{e+\mu}$ (2.3 - 2.6 GeV/c) = 60,
expected background = 33.3 ± 5.2.

Method 2:

Lepton Pairs.

$p(\ell_1) \in [1.2, 2.3]$ GeV/c

$p(\ell_2) \in [2.3, 2.6]$ GeV/c

$\cos\vartheta_{\ell\ell} > -0.8$

$p_{miss} \in [1.0, 3.5]$ GeV/c

$N_2(e+\mu) = 21$

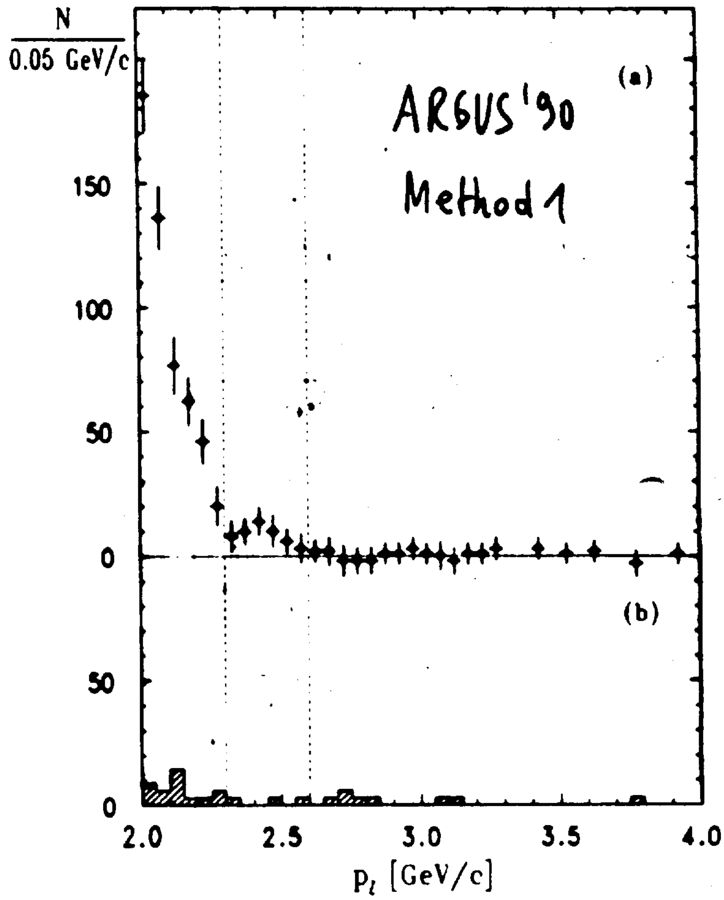
expected bg: 6.7 ± 2.2.

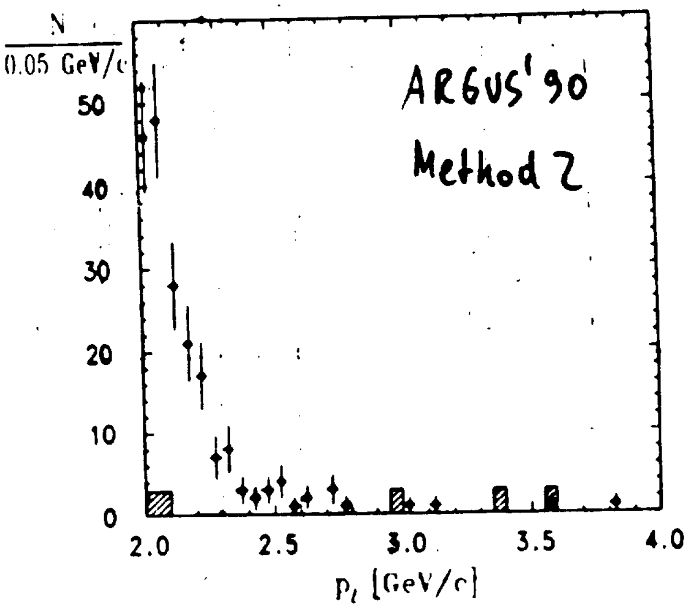
Combined:

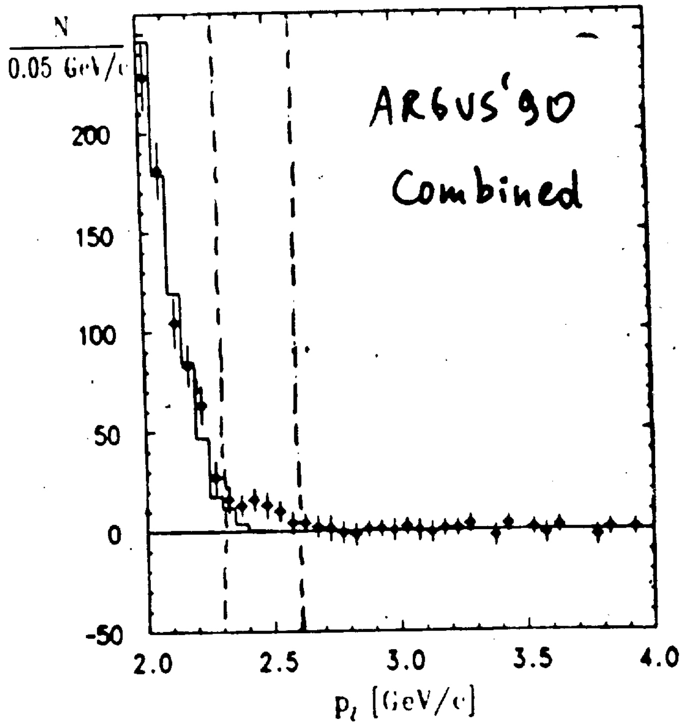
$N_\ell(2.3-2.6) = \underline{81.}$

$N(\cancel{b \to u \ell \nu}) = \underline{\underline{40.0 \pm 5.6}}$

$S \approx 4\sigma$



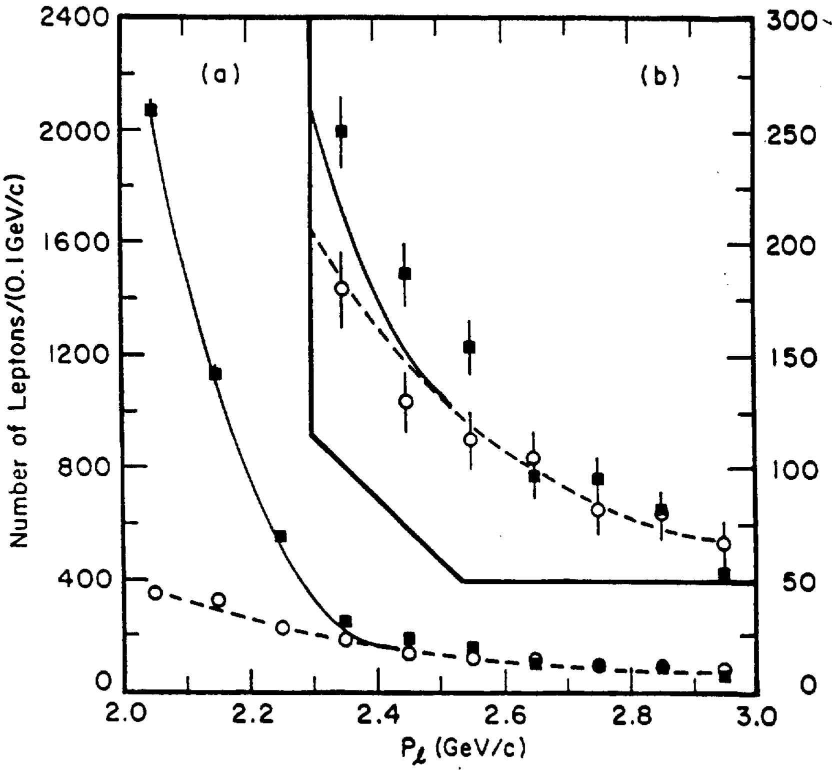




The $|V_{ub}|$ result of this ARGUS observation is strongly model-dependent.

inclusive Altarelli et al model:	$\lvert V_{ub}/V_{cb}\rvert =$	0.10 ± 0.013
WSB meson-wavefunction model:		0.12 ± 0.016
KS —"— :		0.09 ± 0.012
GISW —"— :		0.18 ± 0.023

An also 4σ effect with nearly exactly the same four $|V_{ub}/V_{cb}|$ values as above is seen by CLEO:



R. Fulton et al
(CLEO)
PRL 64 (1990) 16

$|V_{ub}/V_{cb}| = 0.08 \div 0.20$; $|V_{ub}| = 0.004 \div 0.010$;

$\sqrt{\rho^2+\eta^2} = 0.35 \div 1.0.$

$$|V_{CKM}| = \begin{pmatrix} 0.9744 \pm 0.0010 & 0.220 \pm 0.002 & (0.004 \div 0.010)\ \text{[redacted]} \\ 0.21 \pm 0.13 & 1.00 \pm 0.09 & 0.047 \pm 0.005 \\ ? & ? & ? \end{pmatrix}$$

<u>Unitarity is well fulfilled experimentally:</u>

$$V_{ud}^2 + V_{us}^2 + |V_{ud}|^2 = 0.9977 \pm 0.0022,$$
$$V_{cd}^2 + V_{cs}^2 + V_{cb}^2 = 1.05 \pm 0.18,$$
$$\sum V_{ui}^* V_{ci} = 0.005 \pm 0.035$$ with suitable choice of signs.

<u>One may therefore perform a unitarity-constraint-fit:</u>

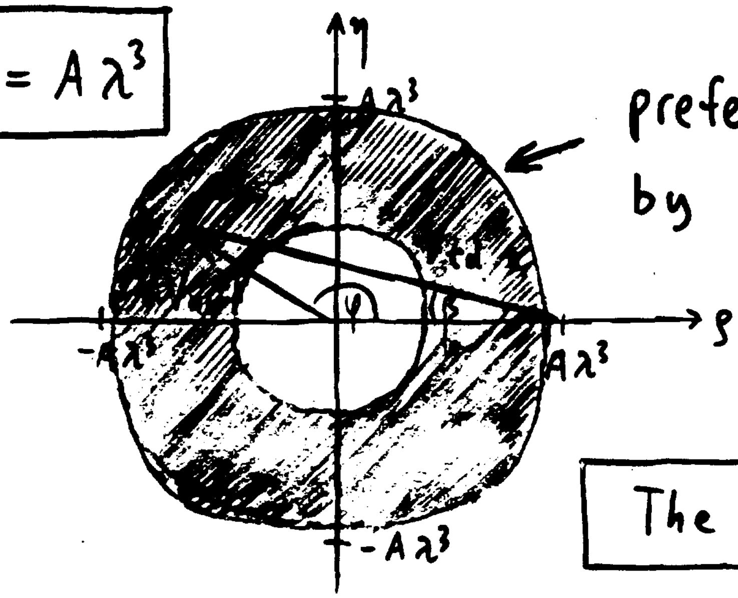
$$V_{CKM} = \begin{pmatrix} .9753 \pm .0005 & .2207 \pm .0020 & (.004 \div .010)\, e^{-i\gamma} \\ -.2204 \pm .0021 & .9742 \pm .0005 & .0470 \pm .0050 \\ (0 \div 0.20)\, e^{-i\beta} & -.0458 \pm .0050 & .9989 \pm .0002 \end{pmatrix}$$

<u>Three comments:</u> ① $|V_{ub}|$ & V_{cb} do not improve by fit.
{B physics is decoupled from rest of the world}

② The unmeasured V_{tb} gets the smallest error.

③ V_{ub} and V_{td} are unitarity-related in an easy-memorizable way:

$$\boxed{V_{ub}^* + V_{td} = A\lambda^3}$$



preferred region by ARGUS & CLEO & present models.

The "CP triangle"

- We have <u>more information</u> on ρ and η, i.e. on this triangle if
  1. $B^0\overline{B^0}$ oscillations,
  2. CP violation in $K^0\overline{K^0}$ oscillations (ε), and
  3. CP viol. in $K^0 \to \pi\pi$ ($I=2$) decays (ε')
- have their origin completely in the standard weak interaction with the standard 3-family-fermions.

Flavour Oscillations in the $K^0\overline{K^0}$-System:

$$K^0(\bar{s}d) \leftrightarrow \overline{K^0}(sd)$$

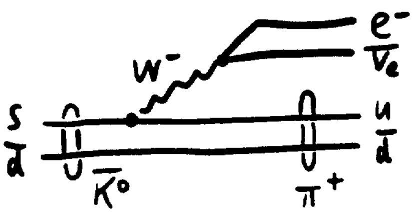
by second order weak interaction:

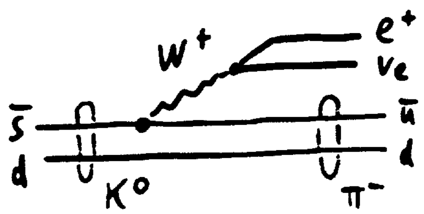
$$K_1 = \frac{K^0 - \overline{K^0}}{\sqrt{2}} \quad \text{with} \quad \psi(t) = \psi(0)\, e^{-iM_1 t - \Gamma_1 t/2}$$

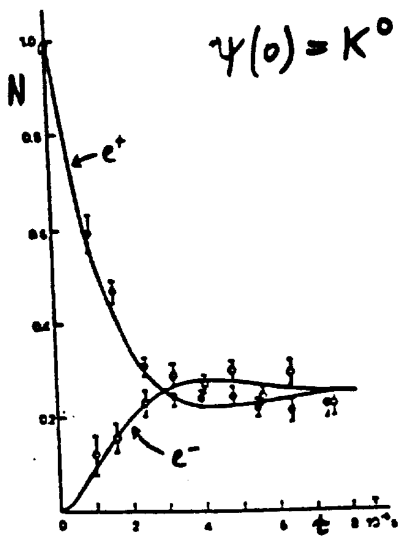
$$K_2 = \frac{K^0 + \overline{K^0}}{\sqrt{2}} \quad \text{with} \quad \psi(t) = \psi(0)\, e^{-iM_2 t - \Gamma_2 t/2}$$

Many experiments 1960/70

e.g. with semileptonic decays:



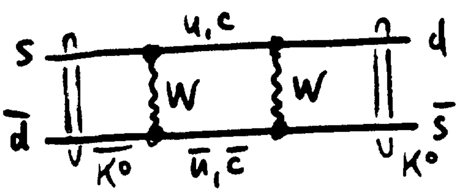




F. Niebergall et al (CHOV) 1974

$$\Delta M = M_2 - M_1 = 3.5 \cdot 10^{-6}\,eV = 7 \cdot 10^{-15} \cdot M = 0.45 \cdot \Gamma_1$$

Explanation in the Standard Model:



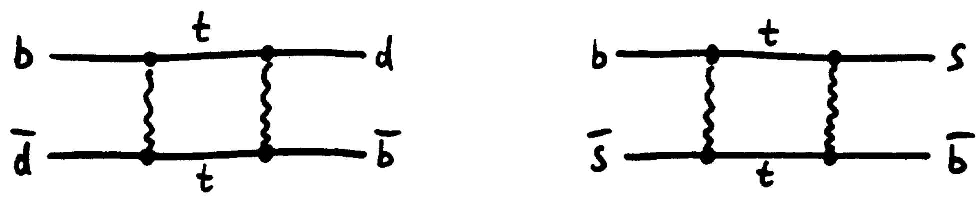
M.K. Gaillard + B.W. Lee, 1974

$$\Delta M_{box} = \frac{G_F^2}{6\pi^2}\, m_c^2\, V_{cd}^2\, V_{cs}^2\, B_K\, f_K^2\, m_K\, i$$

≈ ΔM_{exp} for $B_K = 1$, $m_c = 1.6$ G

With 3 fermion families and $m_t \gtrsim 130$ GeV, there are only 4 systems in nature which can show such flavour oscillations: $K^0\bar{K}^0$, $D^0\bar{D}^0$, $B^0\bar{B}^0$, $B_s\bar{B}_s$.
The standard model expectation for $\Delta M(D^0)$ is very small, experimentally $\Delta m(D^0)/\Gamma(D^0) < 0.10$.

- Expectations for $B^0\bar{B}^0$ and $B_s\bar{B}_s$:



$$|\Delta M(B^0)| = \frac{G_F^2}{6\pi^2} \cdot m_t^2 \cdot V_{tb}^2 \, |V_{td}|^2 \cdot B_{B^0} \cdot f_{B^0}^2 \cdot m_{B^0} \, \eta_{QCD} \; ;$$

$$|\Delta M(B_s)| = \frac{G_F^2}{6\pi^2} \cdot m_t^2 \cdot V_{tb}^2 \, V_{ts}^2 \cdot B_{B_s} \cdot f_{B_s}^2 \cdot m_{B_s} \cdot \eta_{QCD} \; ;$$

- In 1987: $23 \text{ GeV} \leq m_t \lesssim 200$ GeV, $0 \leq |V_{td}| \leq 0.02$.
  If $m_t \simeq 40$ GeV assumed $\rightsquigarrow$ ΔM very small.

Time-integrated observables:

With $\tau_B = 1.2$ psec, direct measurements of Γ_1, Γ_2 and $\Delta M(B)$ are not (yet!) possible. $\frac{1}{\tau_B} = \frac{1}{2}(\Gamma_1 + \Gamma_2)$.

Since $b \to e^- \nu c$ & $\bar{b} \to e^+ \nu \bar{c}$, lepton charge identifies B-flavour at any time of decay.

Assume $\psi(0) = B^0$ at $t = 0$.

$$\psi(t) = \frac{1}{2}\left[e^{-iM_1 t - \Gamma_1 t/2}\left(B^0 - \overline{B^0}\right) + e^{-iM_2 t - \Gamma_2 t/2}\left(B^0 + \overline{B^0}\right)\right]$$

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

$$\overline{w}(t) = \left|\langle \overline{B^0} | \psi(t)\rangle\right|^2 = \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-\Gamma t}\cos\Delta m t\right]$$

$$W = \int_0^\infty w(t)\,dt = \frac{1}{4}\left[\frac{1}{\Gamma_1} + \frac{1}{\Gamma_2} + \frac{2\Gamma}{\Gamma^2 + (\Delta M)^2}\right]$$

$$\overline{W} = \int_0^\infty \overline{w}(t)\,dt = \frac{1}{4}\left[\frac{1}{\Gamma_1} + \frac{1}{\Gamma_2} - \frac{2\Gamma}{\Gamma^2 + (\Delta M)^2}\right]$$

<u>Def:</u> $\chi(B^0) = \dfrac{\overline{W}}{W + \overline{W}} = \dfrac{N(B^0 \to \overline{B^0} \to \ell^- X)}{N(B^0 \to \ell^\pm X)}$

= fraction of all B^0 decaying as a $\overline{B^0}$.

$\chi = \dfrac{x^2 + y^2}{2 + 2x^2}$ with $x = \dfrac{\Delta M}{\Gamma}$, $y = \dfrac{\Delta\Gamma}{2\Gamma} = \dfrac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1}$;

Some people prefer $r = \dfrac{\chi}{1-\chi} = \dfrac{\overline{W}}{W}$; $\chi = \dfrac{r}{1+r}$;

In the K^0 system: $x = .953$, $y = -.997$, $\chi = .498$

In $b\bar{b}$-Jet events (UA1, PEP/PETRA, LEP):

$$\frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell\ell)} = 2\cdot\chi\cdot(1-\chi);$$

[if only ℓ from $B^0, \overline{B^0}$]

In $\Upsilon(4S) \to B^0\overline{B^0}$ events (ARGUS, CLEO):

$$\frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell\ell)} = \chi.$$

Reason: Einstein-Podolski-Rosen. $\psi(0) = B^0\overline{B^0} - \overline{B^0}B^0$.

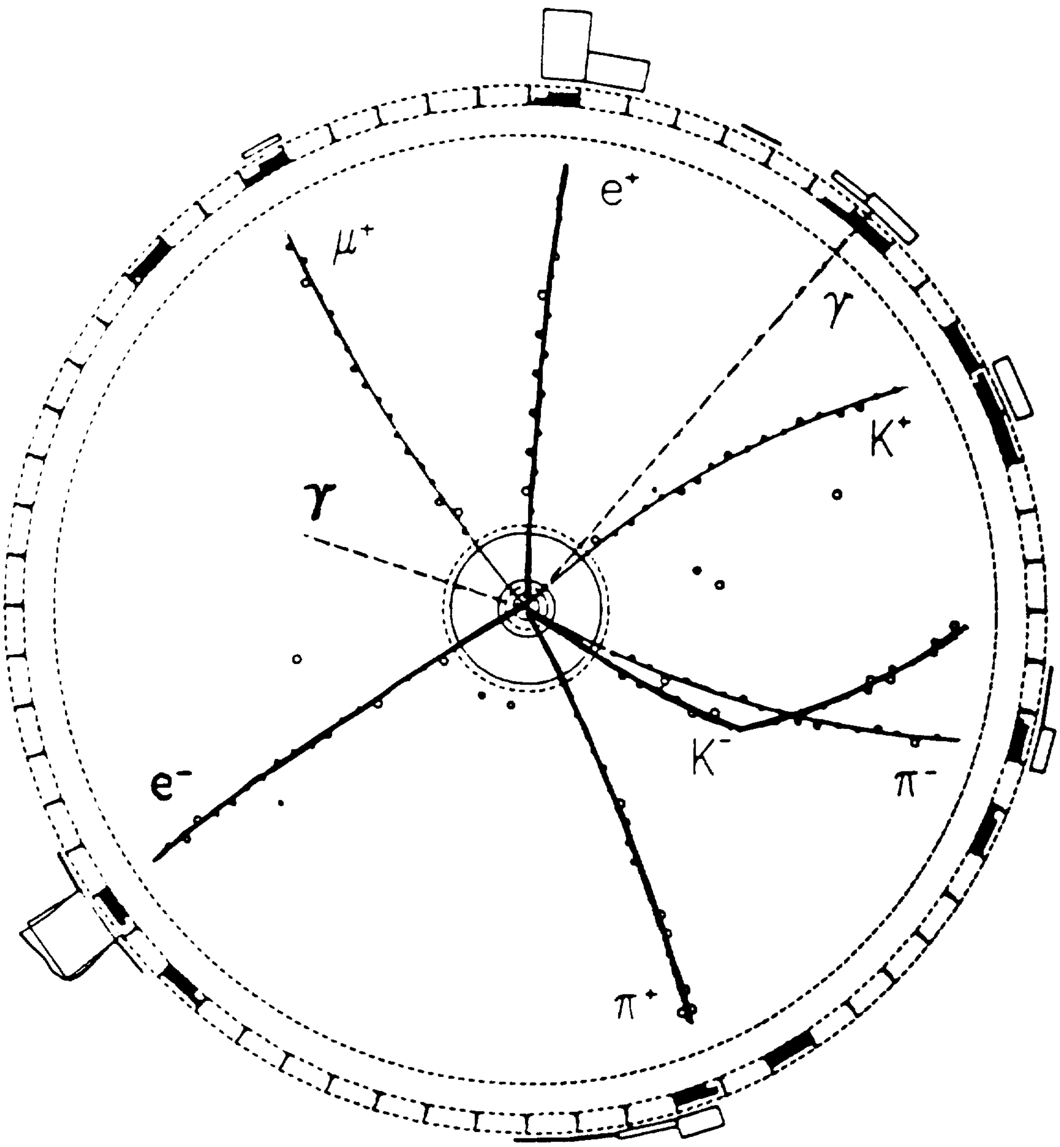
ARGUS 1987 [H. Albrecht et al, PL.B 192(1987)245]

3 methods for finding $B^0 \bar{B}^0$ oscillations:

1.) fully reconstructed events,

2.) inclusive lepton pairs,

3.) one reconstructed B^0 or $\bar{B}^0$ and one lepton.



$e^+e^- \to \Upsilon(4S) \to B^0 \bar{B}^0 \to J/\psi\, K^-\pi^+,\ J/\psi \to e^+e^-$

$\mu^+ D^{*-} \nu,\ D^{*-} \to \pi^-_{miss} \bar{D}^0,\ \bar{D}^0 \to K^+\pi^-$

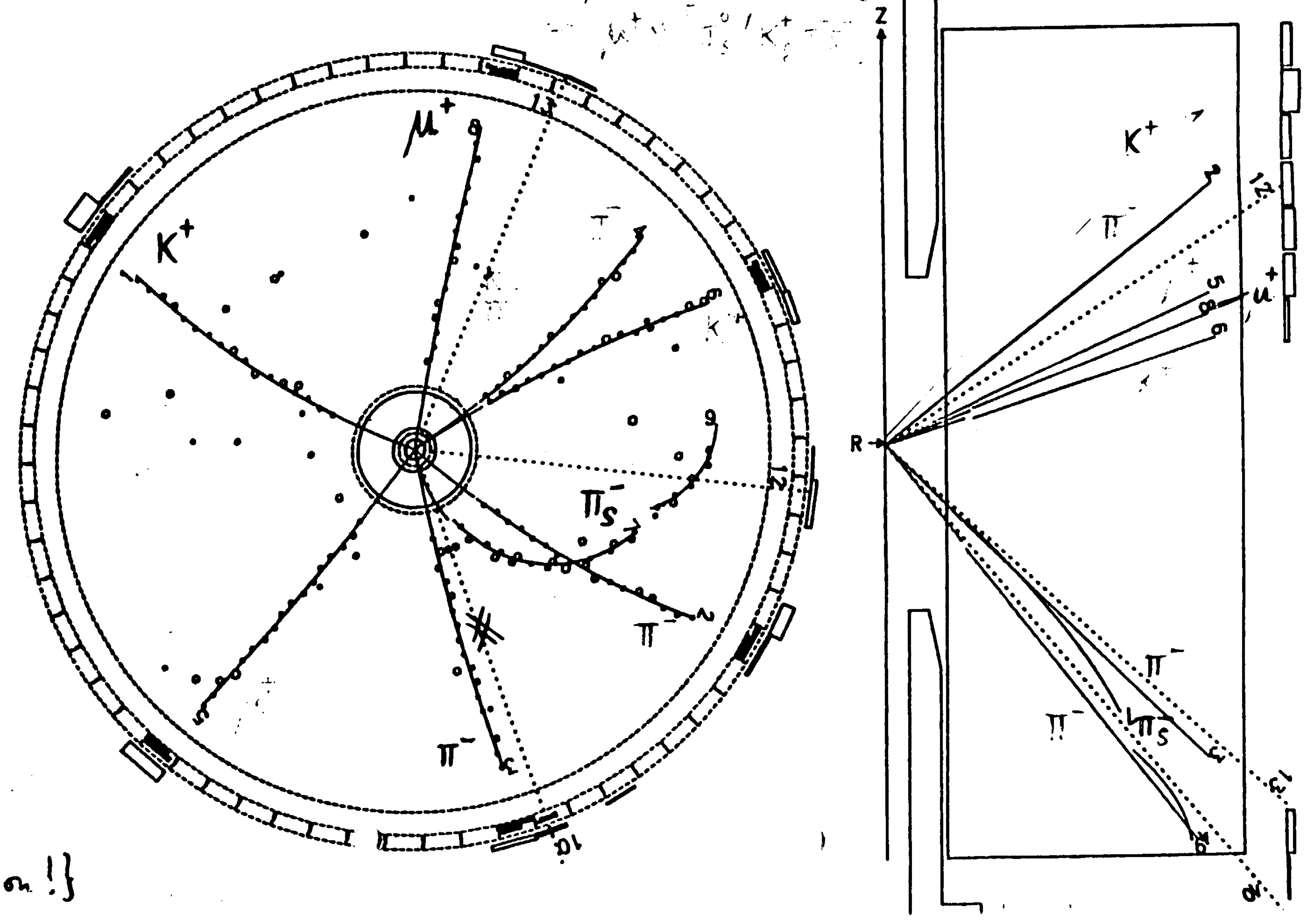
{No oscillation!}

EXP 2
RUN 4012
EVT 6284
TRIG 0
PROJ RZ
SCAL 0.053

ARGUS

Ereignis 2: $\Upsilon(4S) \to B^0 B^0$

$\longrightarrow \mu^+ \nu \overbrace{\left[\pi_s^- \left(\overbrace{K_1^+ \pi^-}^{\bar{D}^0}\right)\right]}^{D}$



{Oscillation!}

Method 2: Inclusive lepton pairs.

$B^0 \to \ell^+ \nu (\bar{c} q)$; $\mathcal{B}(e^+) = 10.5\%$, $\mathcal{B}(\mu^+) = 10.5\%$

$\bar{B}^0 \to \ell^- \nu (c \bar{q})$; –〃– –〃–

$B^0 \bar{B}^0 \to \ell^+ \ell^-$, $B^0 B^0 \to \ell^+ \ell^+$, $\bar{B}^0 \bar{B}^0 \to \ell^- \ell^-$, $B^+ B^- \to \ell^+ \ell^-$.

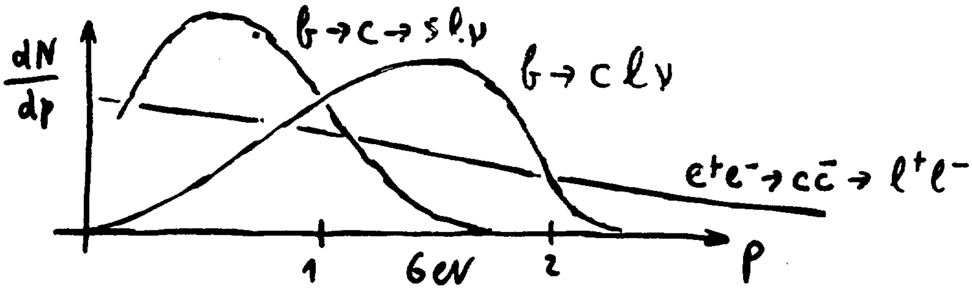
Backgrounds: $e^+ e^- \to c\bar{c} \to \ell^+ \ell^-$

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

$\hookrightarrow D^- X$

$\hookrightarrow \ell^- K^0 \bar{\nu}$.

Different momentum spectra:



– Ask for both leptons to be above 1.4 GeV/c

$N(\ell^+\ell^-) = 301$, bg $= 31 \pm 5$, signal $= 270 \pm 20$.

including $\ell^+\ell^-$ from $\Upsilon(4S) \to B^+ B^-$.

$N(\ell^\pm \ell^\pm) = 50$, bg $= 25 \pm 4$, signal $= \underline{\underline{25 \pm 8.}}$

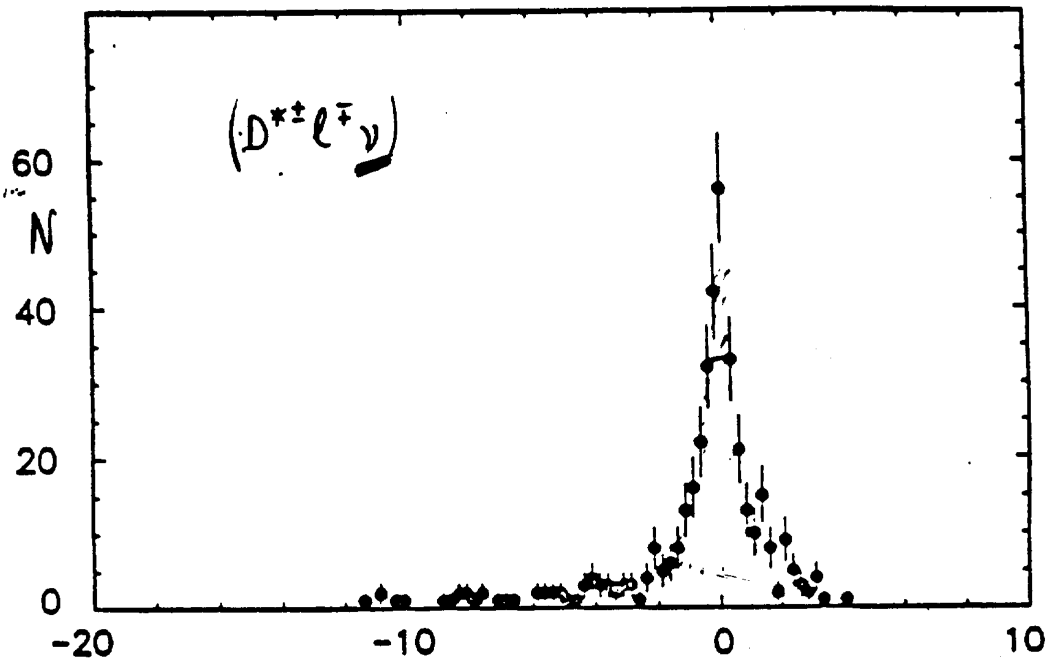
significance $= 3.3\sigma$.

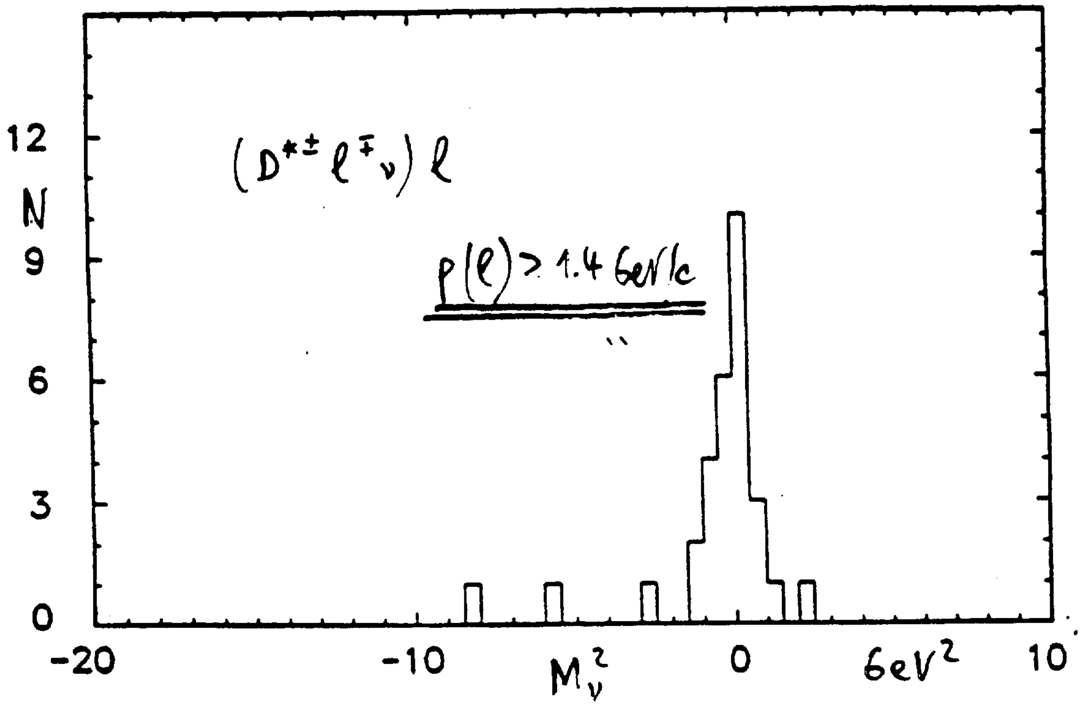
$$\chi(B^0) = \frac{25 \pm 8}{295/2} = 0.17 \pm 0.05.$$

Method 3: One reconstructed $B^0, \bar{B}^0$ & one lepton.

("Tagging") $\eta_{tag} = \mathcal{B} \cdot \eta_{rec}$ =

$0.13 \cdot 10^{-3}$	$D^{*-}\pi^+$
$0.21 \cdot 10^{-3}$	$D^{*-}\pi^+\pi^0$
$0.07 \cdot 10^{-3}$	$J/\psi\, K^-\pi^+$
→ $1.3 \cdot 10^{-3}$	$D^{*-}e^+\nu$
Use these two with MM method → $1.3 \cdot 10^{-3}$	$D^{*-}\mu^+\nu$





28 events
23 $\ell^+\ell^-$
5 $\ell^\pm\ell^\pm$
$\{\eta = .9 \pm .3\}$

Combined:

$$\chi(B^0) = \frac{25 + 5 \pm 2.3}{295/2 + 23} = \underline{\underline{0.18 \pm 0.05}}.$$

The ARGUS'87 result has been confirmed by CLEO'88. Present results, updated, with $f_+ B_+^2 / f_0 B_0^2 = \underline{\underline{1.0 \pm 0.2}}$ $\{ B_{+,0} = B(B^{+,0} \to \ell \nu X) \}$:

$$\chi(B^0)_{ARGUS} = 0.16 \pm 0.05 \; ;$$
$$\chi(B^0)_{CLEO} = 0.15 \pm 0.06 \; ; \qquad \chi = \frac{x^2}{2+2x^2}$$

with $y = \Delta\Gamma / 2\Gamma \ll x = \Delta M / \Gamma \curvearrowright \underline{\underline{|x| = 0.68 \pm 0.12}}$

$$|M_1 - M_2| = (0.4 \pm 0.1)\ \text{meV} = (8 \pm 2) \cdot 10^{-14} \cdot M$$
$$= 100 \times \Delta M(K^0)\ !!$$

Recall: $|\Delta M| = \frac{G_F^2}{6\pi^2} m_t^2 V_{tb}^2 |V_{td}|^2 B_B f_B^2 m_B \eta .$

With $B_B \approx 3/4$, $V_{tb} = 1$, $\eta_B \approx 0{,}85$, $f_B \approx 130$ MeV:

$$\underline{\underline{m_t \cdot |V_{td}| \approx (1.5 \pm 0.3)\ \text{GeV}}}$$

$m_t > 50$ GeV quoted in 1987.

<u>Second consequence:</u>

$$x(B_s)/x(B^0) \approx \left| \frac{V_{ts}}{V_{td}} \right|^2 \gtrsim 4 \curvearrowright \underline{\underline{\chi(B_s) \gtrsim 0.40}}$$

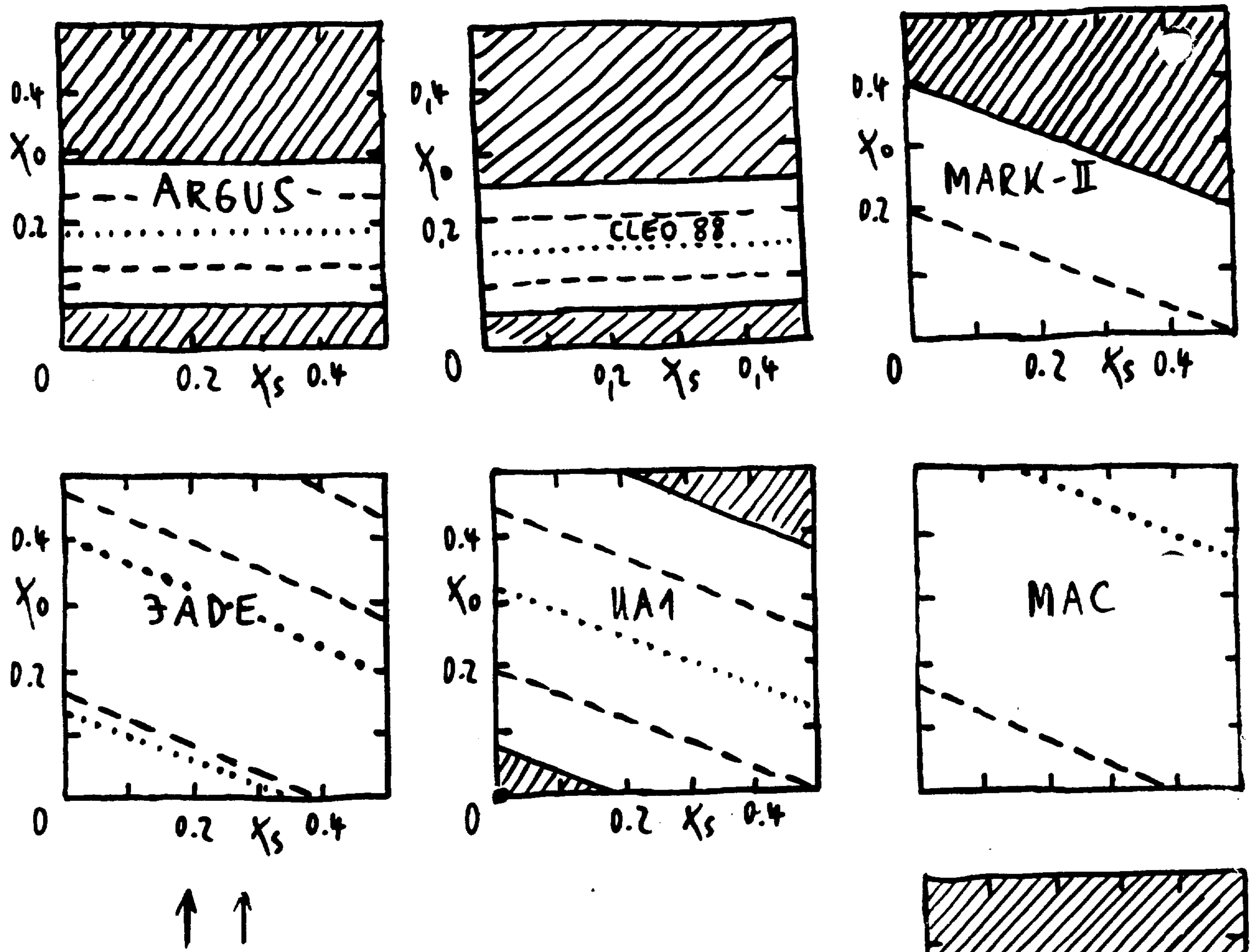
What do we know about $\chi(B_s)$?

UA1 in 1987 [C. Albajar et al, PLB 186 (1987) 247]

$$f_0\,\chi(B^0) + f_s\,\chi(B_s) = 0.121 \pm 0.047.$$

from like-sign di-muon events in $p\bar{p}$ annihilation at $Sp\bar{p}S$ collider, $f_0 = N(B^0)/N(b) \approx 0.38$,

$f_s = N(B_s)/N(b) \approx 0.15$.

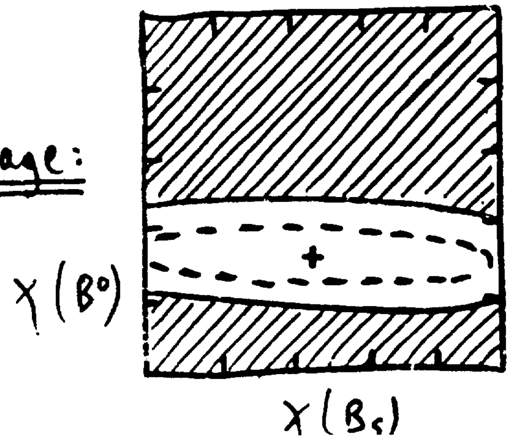


from e^+e^--asymmetry:

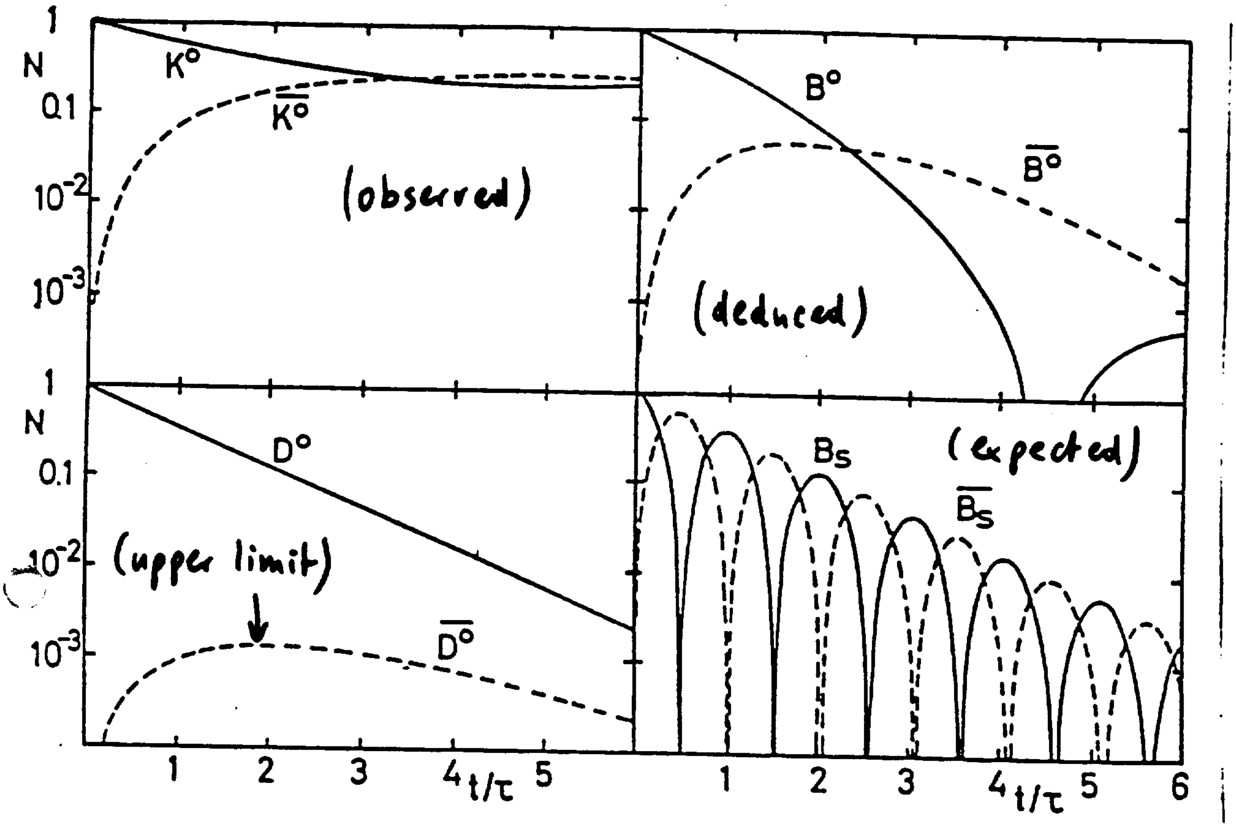
$$A_{obs} = A_{GWS}(1-2\chi)$$

[all expts. compiled by R. [illegible]]

Average:

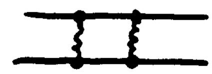


The four types of flavour oscillations:

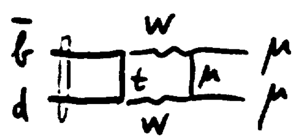


Other loop processes:

Observed B-decays : tree level 

Observed $B\bar{B}$-oscillations: loop level 

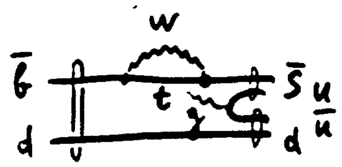
Expected loop-induced decays:

$B^0 \to \ell^+\ell^-$ 

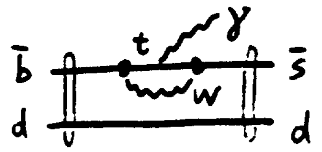
$\mathcal{B}_{ee} < 3 \cdot 10^{-5}$ CLEO

$\mathcal{B}_{\mu\mu} < 1.4 \cdot 10^{-4}$ UA1

$\mathcal{B}(B_s \to \mu^+\mu^-) < 3 \cdot 10^{-4}$ UA1

$B^0 \to K^+\pi^-$ 

$\mathcal{B} < 9 \cdot 10^{-5}$ CLEO

$B^0 \to K^{*0}\gamma$ 

$\mathcal{B} < 2.8 \cdot 10^{-4}$ CLEO

$\rightsquigarrow$ No flavour-ch. neutral currents

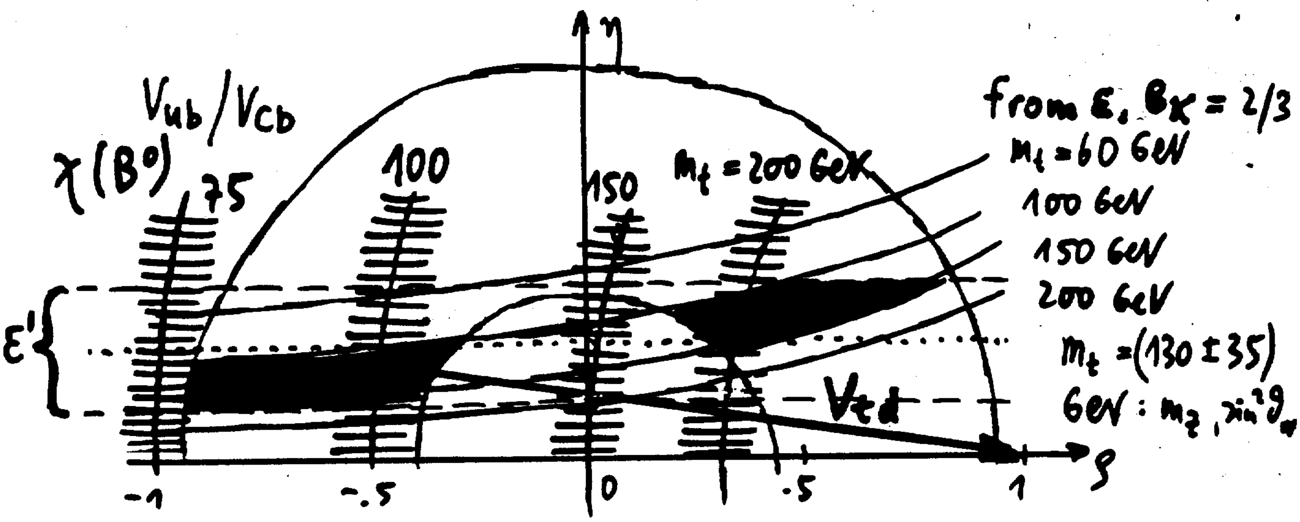
CP violation in the K^0 system:

1.) $\Gamma(K^0 \to \bar{K}^0) \neq \Gamma(\bar{K}^0 \to K^0)$ $\quad \varepsilon = (2.28 \pm 0.02) 10^{-3} e^{i\pi/4}$

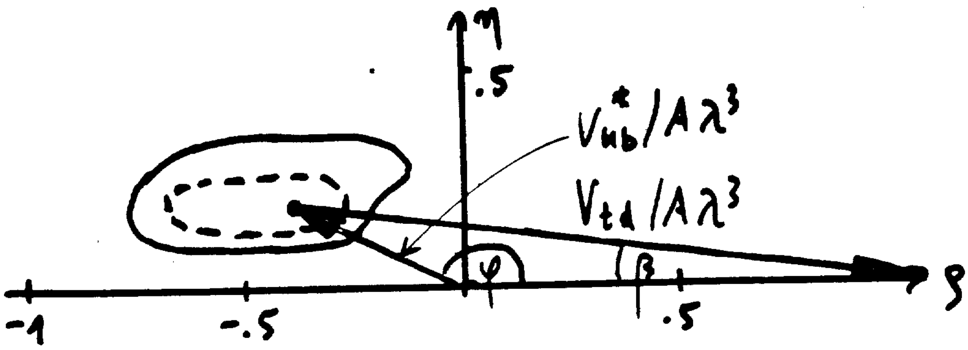
2.) $\Gamma(K^0_L \to 2\pi, I=2) \neq 0$ $\quad \varepsilon' = (4.7 \pm 2.0) 10^{-6} e^{i\pi/4}$

Both effects can be explained by standard charged weak interaction, if $A\lambda^3 \eta \neq 0$. $\curvearrowright$ $\eta > 0.$

With some strong interaction assumptions:



Overall (ρ, η) fit taking into account hadronic uncertainties [$B_K = 0.75 \pm 0.15$, $f_B \sqrt{B_B} = (160 \pm 40)$ MeV ...]



$\rho = [-.8, -.1]$; $\eta = [.1, .25]$; $\varphi = [110°, 170°]$; $\beta = [7°, 15°]$

~~CP~~ (B^0), lecture 4 $\longrightarrow$