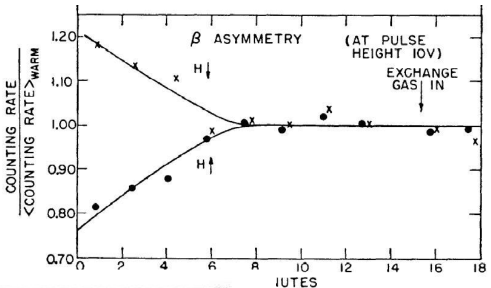
PART II

~1956-58

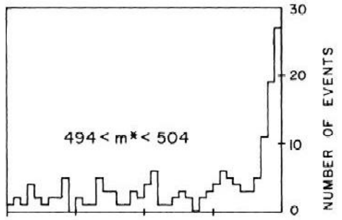
- **Parity Violation in weak decay (Wu + Goldabher)**



1964

- **CP Violation in K^0**

$$|\eta_{+-}| = \frac{A\left(\left|K_L^0\right\rangle \to 2\pi\right)}{A\left(\left|K_S^0\right\rangle \to 2\pi\right)} = (2.27 \pm 0.02)10^{-3}$$



~1973

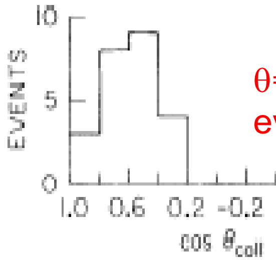
- **Kobayashi-Maskawa; CKM matrix and CP→ 3 families**

~1975

- **Tau lepton discovery**

$$e^+e^- \to \tau^+\tau^-$$

$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ and $\tau^- \to e^-\bar{\nu}_e\nu_\tau$

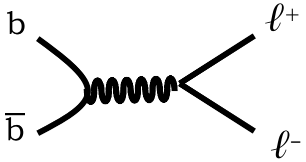


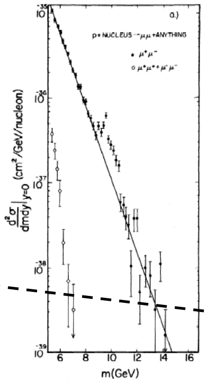
θ=180 : no events

cos θ

~1977

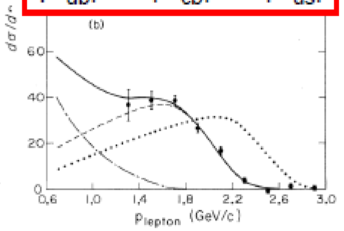
- **b quark discovery**





τ (B)~1,6ps

$|V_{ub}| << |V_{cb}| << |V_{us}|$



1982-88

- **B lifetime, Vcb and Vub**

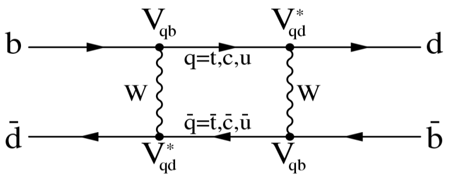
1983

- **CKM Matrix : Wolfestein Parametrisation**

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

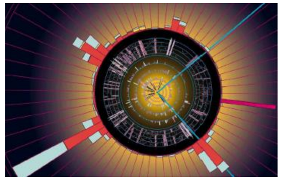
1985-90

- **B oscillations**



1995

- **Top quark discovery**

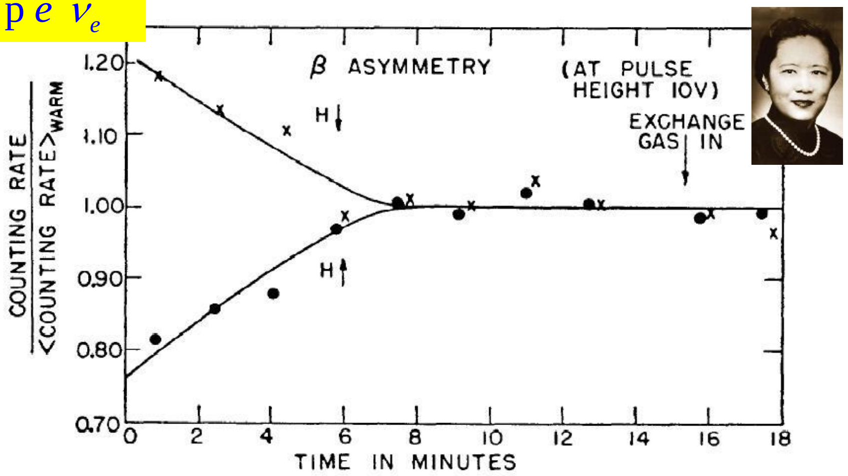


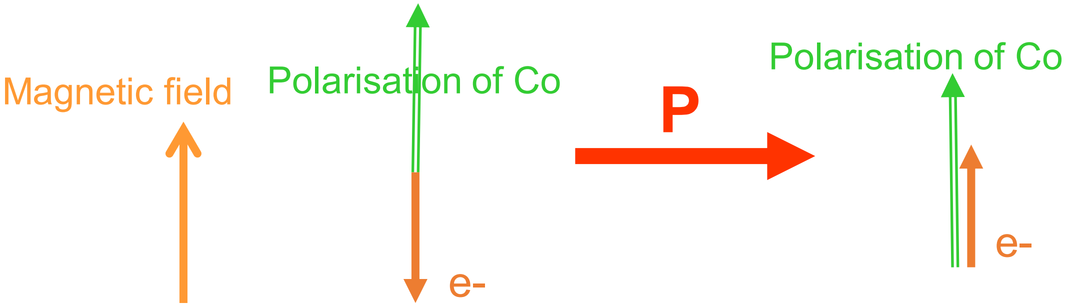
Parity Violation in weak interaction

- Spin of Co^{60} all aligned
- β decay of Co^{60}
- Recording the direction of the e- emitted

$Co^{60} \rightarrow Ni^{60*} e^- \overline{\nu}_e$ $\quad n \rightarrow p\, e^- \overline{\nu}_e$

C.S. Wu et al. (1957)





Emission of e- preferentially in the direction opposite to the Co spin !

Observation of an asymmetry forward/backward wrt direction of Co spin. if P conserved → no asymmetry

In fact the « strange » particles have been also fundamental for pointing out for the first time the fact that the parity is not conserved in the weak interaction…

- $\tau \rightarrow \pi^+ \pi^+ \pi^-$ (J=0, P=+1)
- $\theta \rightarrow \pi^+ \pi^0$ (J=0, P=-1)

Experimentally

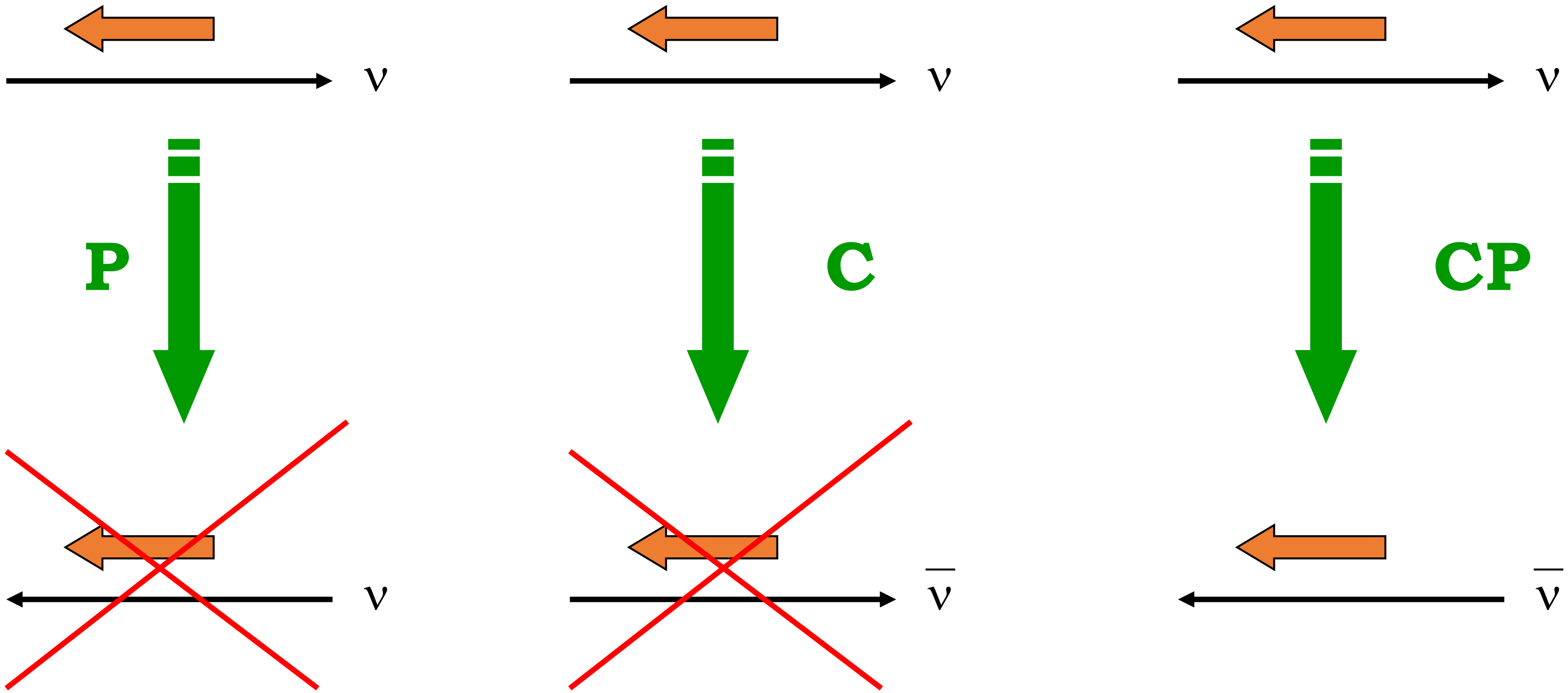
The mass and the lifetime of la τ and θ are identical.

- The parity of τ and of θ are different
- If τ=θ=K

Le puzzle τ-θ

-Violation of the parity in the weak interaction (1956 experiment-Wu)
-The neutrino has helicity left (1958 experiment-Goldabher)
-The helicity of the antiparticule is opposite to those of particules

P and **C** are maximally violated in weak interaction.



ν right $\bar{\nu}$ left $\bar{\nu}$ right

CP was thought to be conserved

Keep it in mind

$$P_{CL}^2 = P_{CL},\quad P_{CR}^2 = P_{CR},\quad P_{CL} + P_{CR} = 1,\quad P_{CL}P_{CR} = 0$$

$$\psi_{CL} = P_{CL}\psi \qquad \overline{\psi}_{CL} = \overline{\psi}P_{CR}$$

$$\psi_{CR} = P_{CR}\psi \qquad \overline{\psi}_{CR} = \overline{\psi}P_{CL}$$

$$P_{CL}\gamma^{\mu} = \gamma^{\mu}P_{CR} \qquad P_{CR}\gamma^{\mu} = \gamma^{\mu}P_{CL}$$

$$\boxed{\begin{aligned} P_{CL} &= \frac{1-\gamma_5}{2} = \begin{pmatrix} 0 & 0 \\ 0 & \mathbf{1} \end{pmatrix} \\ P_{CR} &= \frac{1+\gamma_5}{2} = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & 0 \end{pmatrix} \end{aligned}}$$

Take $\overline{\psi}\gamma^{\mu}\psi$ electromagnetism Vector current γ^{μ}

$$\overline{\psi}\gamma^{\mu}\psi = \overline{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(P_{CL} + P_{CR}\right)\psi =$$

$$\overline{\psi}P_{CL}\gamma^{\mu}P_{CL}\psi + \overline{\psi}P_{CR}\gamma^{\mu}P_{CL}\psi + \overline{\psi}P_{CL}\gamma^{\mu}P_{CR}\psi + \overline{\psi}P_{CR}\gamma^{\mu}P_{CR}\psi =$$

$$\overline{\psi}_{CL}\gamma^{\mu}\psi_{CL} + \overline{\psi}_{CR}\gamma^{\mu}\psi_{CR}$$

$$\overline{\psi}\gamma^{\mu}\psi = \overline{\psi}_{CL}\gamma^{\mu}\psi_{CL} + \overline{\psi}_{CR}\gamma^{\mu}\psi_{CR}$$

select ψ_{CL}, ψ_{CR}

Take $\overline{\psi}\gamma^{\mu}\left(1-\gamma_5\right)\psi$ weak current Vector-Axial $\gamma^{\mu}\left(1-\gamma_5\right)$

$$\overline{\psi}\gamma^{\mu}\left(1-\gamma_5\right)\psi = \overline{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(1-\gamma_5\right)\left(P_{CL} + P_{CR}\right)\psi =$$

$$2\overline{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(P_{CL}^2 + P_{CL}P_{CR}\right)\psi =$$

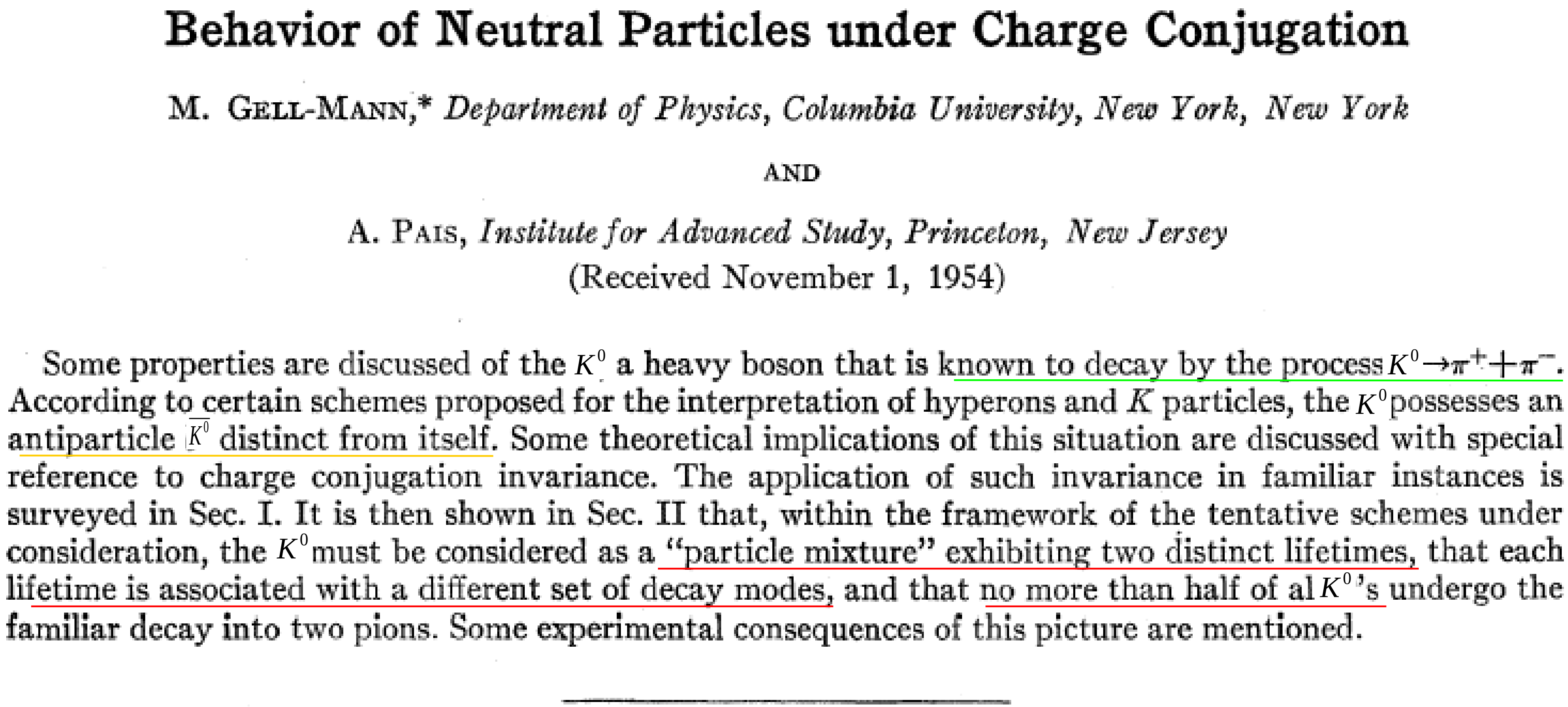
$$2\overline{\psi}P_{CL}\gamma^{\mu}P_{CL}\psi + 2\overline{\psi}P_{CR}\gamma^{\mu}P_{CL}\psi =$$

$$2\overline{\psi}\gamma^{\mu}P_{CR}P_{CL}\psi + 2\overline{\psi}_{CL}\gamma^{\mu}\psi_{CL}$$

The structure V-A gives ν left only

$$\overline{\psi}\gamma^{\mu}\left(1-\gamma_5\right)\psi = 2\overline{\psi}_{CL}\gamma^{\mu}\psi_{CL}$$

select only ψ_{CL} !



Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the K^0 a heavy boson that is known to decay by the process $K^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the K^0 possesses an antiparticle $\overline{K^0}$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the K^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of al K^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

Known:

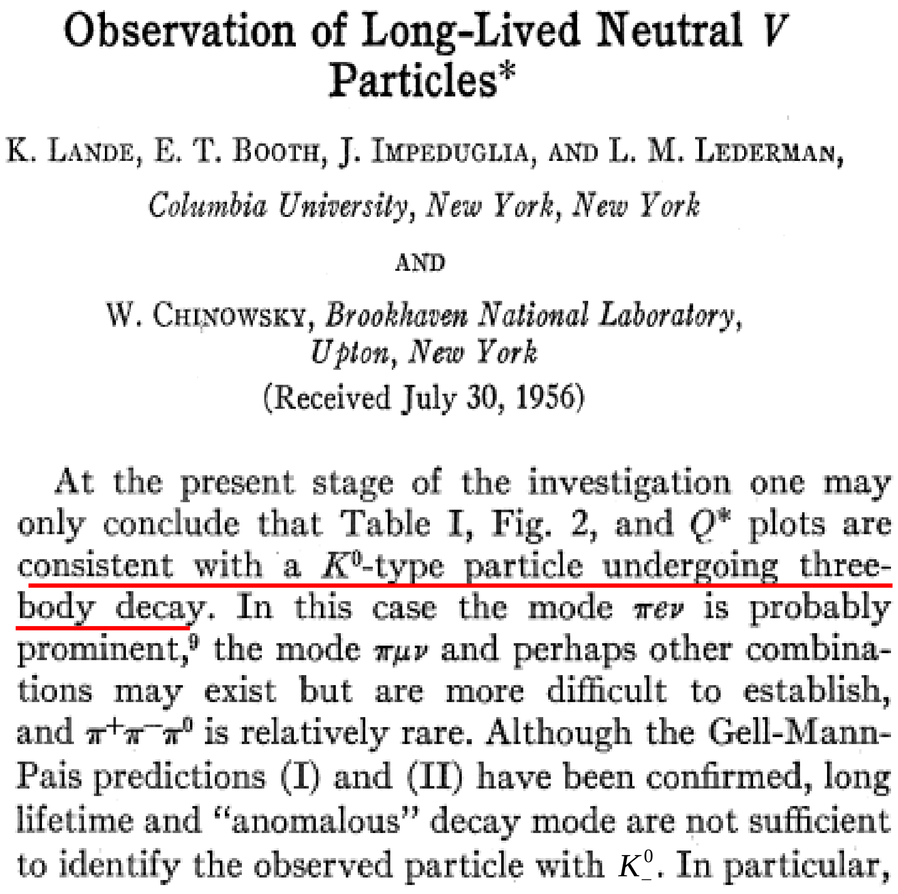
1. K^0 can decay to $\pi^+\pi^-$

Hypothesized:

1. K^0 has a distinct anti-particle K^0 In terms of quarks: us vs. u$\bar{s}$

Claims:

1. K^0 (K^0) is a "particle mixture" with two distinct lifetimes
2. Each lifetime has its own set of decay modes
3. No more than 50% of K^0 (K^0) will decay to $\pi^+\pi^-$



Observation of Long-Lived Neutral V Particles*

K. LANDE, E. T. BOOTH, J. IMPEDUGLIA, AND L. M. LEDERMAN,
Columbia University, New York, New York

AND

W. CHINOWSKY, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)

At the present stage of the investigation one may only conclude that Table I, Fig. 2, and Q^* plots are consistent with a K^0-type particle undergoing three-body decay. In this case the mode $\pi e \nu$ is probably prominent,[9] the mode $\pi \mu \nu$ and perhaps other combinations may exist but are more difficult to establish, and $\pi^+\pi^-\pi^0$ is relatively rare. Although the Gell-Mann-Pais predictions (I) and (II) have been confirmed, long lifetime and "anomalous" decay mode are not sufficient to identify the observed particle with K^0. In particular,

Phys Rev 103,1901 (1956)

There is a **HUGE** difference between $K^0 \rightarrow \pi\pi$ and $K^0 \rightarrow \pi\pi\pi$ in phasespace (~600x!).

The huge difference is because $m_{K0} - 3m_\pi = 75$ MeV/c^2

CP Violation in the Kaon sector - 1964

$$CP\left|K^0\right\rangle = \eta\left|\overline{K}^0\right\rangle$$

$$CP\left|\overline{K}^0\right\rangle = \eta'\left|K^0\right\rangle$$

def : $\eta = \eta' = 1$

$\Rightarrow$ K^0 and $\overline{K}^0$ are not CP eigenstates, but

$$\left|K_S^0\right\rangle = \sqrt{\frac{1}{2}}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right) \qquad CP=+1$$

$$\left|K_L^0\right\rangle = \sqrt{\frac{1}{2}}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right) \qquad CP=-1$$

System with 2 π ($\pi^0\,\pi^0$, $\pi^+\,\pi^-$) $P(\pi\pi)=+1$

$C=(-1)^{l+S}$ $P=(-1)^l$ $\Rightarrow CP=(-1)^{2l}=+1$

System with 3 π si $l=L=0$

$C=+1$ $P=(-1)^3(-1)^l=-1$ $\Rightarrow$ **CP = –1**

$$\underbrace{\pi^+ \quad \pi^-}_{l}\underbrace{\qquad \pi^0 \qquad}_{L}$$

If CP is conserved

	Prod		Decay		τ
	$\left\|K^0\right\rangle$	S=+1	$\left\|K_S\right\rangle$	CP=+1	$\sim 10^{-11}$
	$\left\|\overline{K}^0\right\rangle$	S=-1	$\left\|K_L\right\rangle$	CP=-1	$\sim 5.10^{-8}$

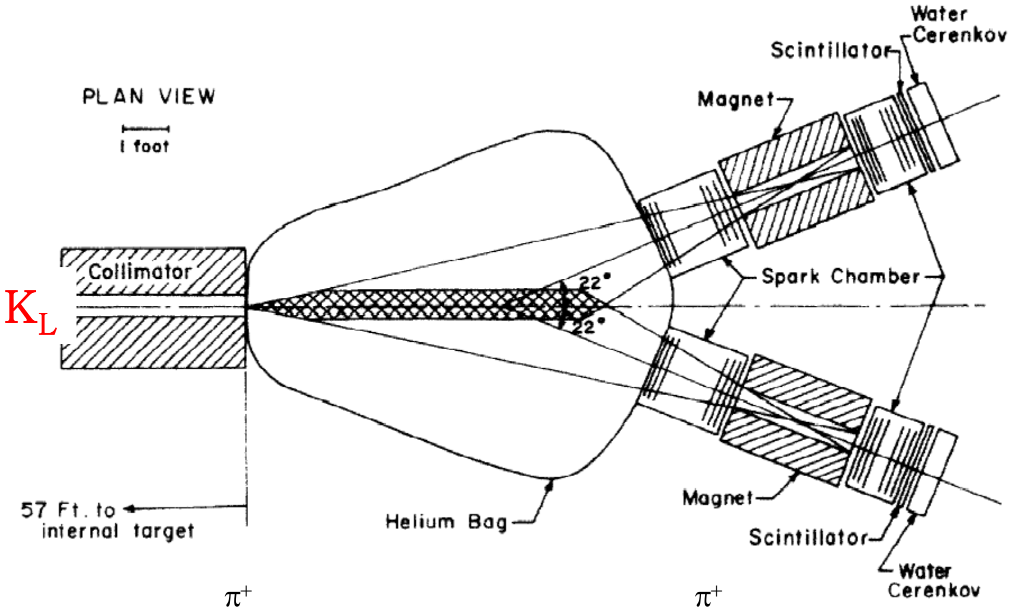
$$\left|K_s^0\right\rangle \rightarrow 2\pi$$

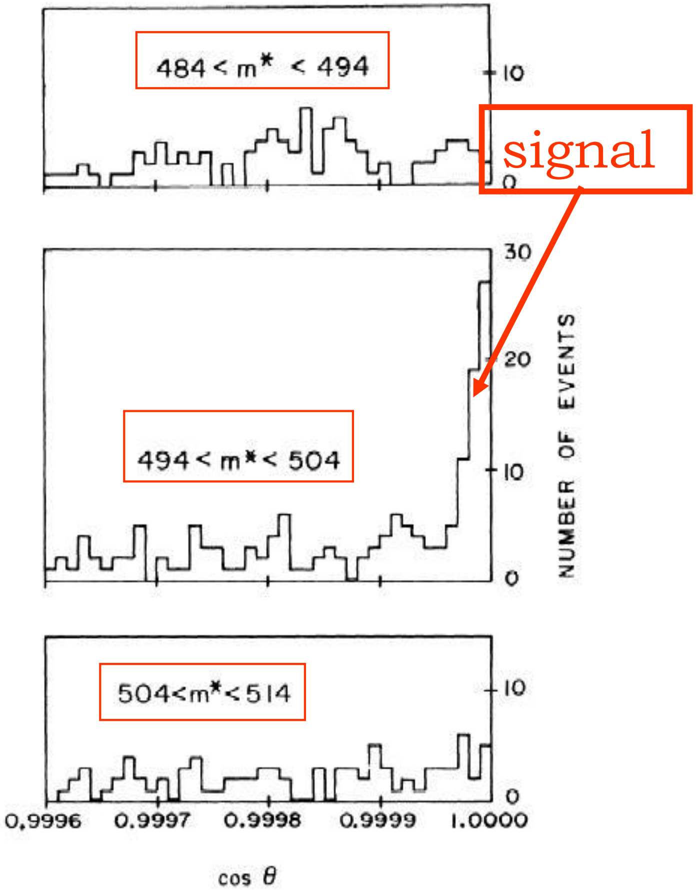
$$\left|K_L^0\right\rangle \rightarrow 3\pi$$ Long lifetime because of the reduced space phase

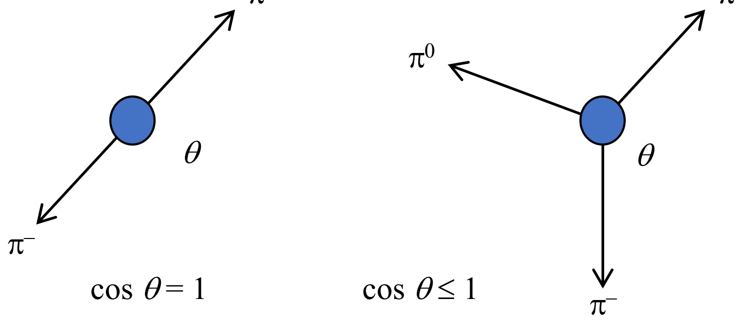
If $K_L \to 2\pi$ there is CP violation.

Level of CP violation is :

$$|\eta_{+-}| = \frac{A\left(\left|K_L^0\right\rangle \to 2\pi\right)}{A\left(\left|K_s^0\right\rangle \to 2\pi\right)} = (2.27 \pm 0.02)10^{-3}$$

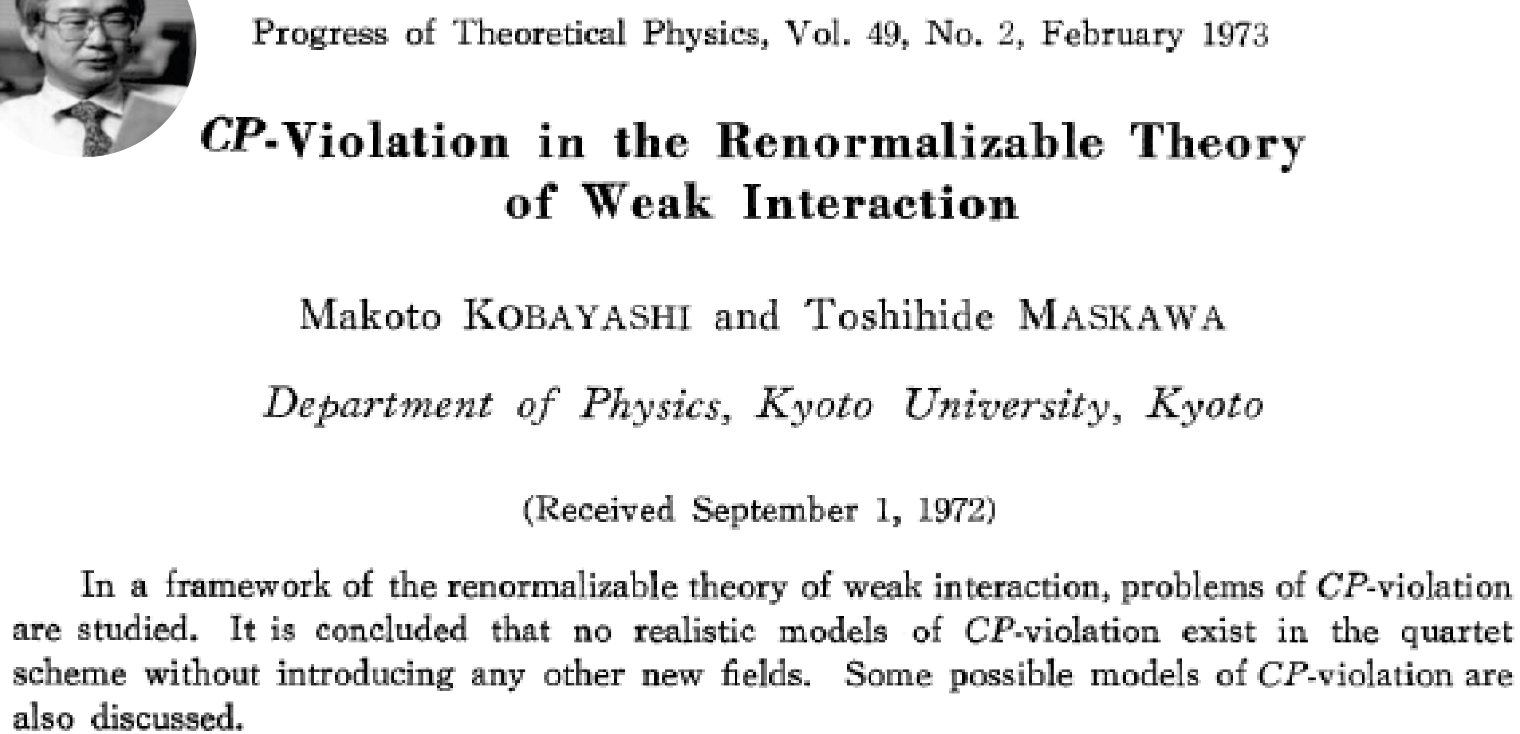






2-body decay : the two π

are back-to-back: $|\cos\theta| = 1$



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

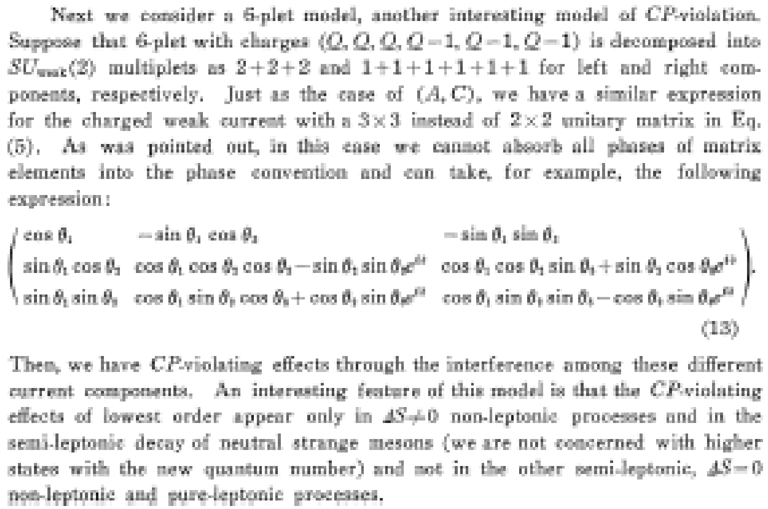
Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

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

Three families of quarks was mentionned at the end of the paper among few other possibilites



Next we consider a 6-plet model, another interesting model of *CP*-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have *CP*-violating effects through the interference among these different current components. An interesting feature of this model is that the *CP*-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

$$-\mathcal{L}_W = \frac{g}{\sqrt{2}} \left(\overline{u_L} \quad \overline{c_L} \right) \gamma^\mu \ \mathbf{V(CKM)} \begin{pmatrix} d_L \\ s_L \end{pmatrix} W_\mu^+ + \mathrm{h.c.}$$

is a 2 x 2 unitary matrix. As such, **it generally contains 4 parameters, of which one can be chosen as a real angle, θ_c, and 3 are phases**:

$$\mathbf{V(CKM)} = \begin{pmatrix} \cos\theta_C \, e^{i\alpha} & \sin\theta_C \, e^{i\beta} \\ -\sin\theta_C \, e^{i\gamma} & \cos\theta_C \, e^{i(-\alpha+\beta+\gamma)} \end{pmatrix}$$

By transformation **V'(CKM) = P_u V(CKM) P^*_d**

With

$$P_u = \begin{pmatrix} e^{-i\alpha} & \\ & e^{-i\gamma} \end{pmatrix}, \quad P_d = \begin{pmatrix} 1 & \\ & e^{i(-\alpha+\beta)} \end{pmatrix}$$

We eliminate the 3 phases from the mixing matrix !

Namely we redifine the mass eigenstates $u_{L,R} \to P_u u_{L,R}$ and $d_{L,R} \to P_d d_{L,R}$,

Notice that there are three independent phase differences(*) between the elements of P_u, and those o P_d, and three phases in V(CKM). Consequently, there are no physically meaningful phases in (CKM).

$$V = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

(*) $\begin{pmatrix} e^{-i\varphi_1} & 0 \\ 0 & e^{-i\varphi_2} \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} e^{-i\chi_1} & 0 \\ 0 & e^{-i\chi_2} \end{pmatrix} = \begin{pmatrix} a \ e^{-i(\varphi_1-\chi_1)} & b \ e^{-i(\varphi_1-\chi_2)} \\ c \ e^{-i(\varphi_2-\chi_1)} & d \ e^{-i(\varphi_2-\chi_2)} \end{pmatrix}$

I choose $\varphi_1 - \chi_1$

I choose $\varphi_1 - \chi_2$

I choose $\varphi_2 - \chi_1$

BUT: $(\varphi_2 - \chi_2) = (\varphi_2 - \chi_1) + (\varphi_1 - \chi_2) - (\varphi_1 - \chi_1)$

$$-\mathcal{L}_W = \frac{g}{\sqrt{2}} \left(\overline{u_L} \quad \overline{c_L} \quad \overline{t_L} \right) \gamma^\mu \ \mathbf{V(CKM)} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + \text{h.c.}$$

is a 3 x 3 unitary matrix. As such, it generally contains 9 parameters, of which three can be chosen as real angles, θ_{12}, θ_{13} θ_{23} and six are phases. We may again reduce the number of phases in the mixing matrix V by redefining the phases of the quark mass eigenstates:

$$\mathbf{V'(CKM) = P_u\, V(CKM)\, P^*_d}$$

The crucial point is that there are only FIVE independent phase differences between the elements of Pu and those of Pd, while there are 6 phases in **V(CKM)** Consequently, the mixing matrix **V(CKM)** contains one physically meaningful phase

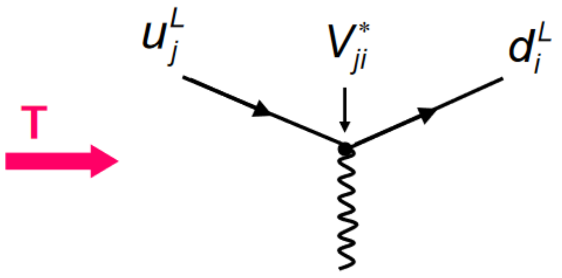
There are 2n – 1 reducible phase

Generally for a rotation matrix in complex plane

Quark families	# Angles	# Phases	# Irreducible Phases
n	n(n-1)/2	n(n+1)/2	n(n+1)/2-(2n-1)=(n-1)(n-2)/2
2	1	3	0
3	3	6	1
4	6	10	3

If 3 families the CKM matrix is complex

What are the consequences of a **complex coupling** ?



CP (T) violation $\Leftrightarrow$ $V_{ji} \neq V_{ji}^*$

i.e. Complex elements

Example of CP violation in decay

CP-conjugated amplitudes : $\begin{cases} A_f = A(B \to f) \\ \bar{A}_{\bar{f}} = A(\bar{B} \to \bar{f}) \end{cases}$

$$A_f = \sum_j a_j \cdot e^{i\theta_j} e^{i\phi_j}$$

$$\bar{A}_{\bar{f}} = \sum_j a_j \cdot e^{i\theta_j} e^{-i\phi_j}$$

ϕ_j alters sign under *CP* (weak phase)

θ_j *CP* invariant (strong phase)

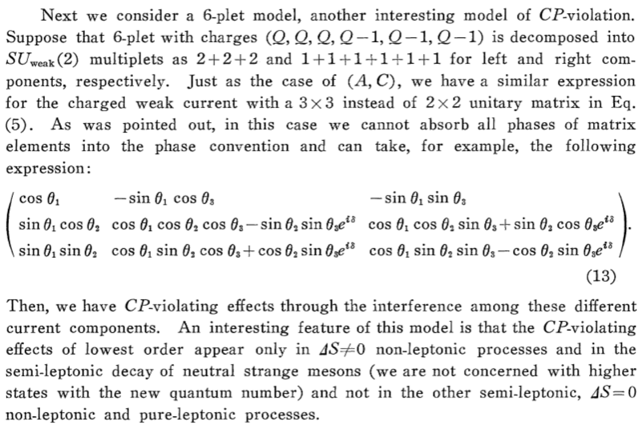
CP violation if $|A|^2 \neq |\bar{A}|^2$

$$A_{CP} \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{\left|\bar{A}_{\bar{f}}\right|^2 - \left|A_f\right|^2}{\left|\bar{A}_{\bar{f}}\right|^2 + \left|A_f\right|^2}$$

$$A_{CP} = \frac{\sum_{ij} a_i a_j \cdot \sin\left(\theta_i - \theta_j\right) \cdot \sin\left(\phi_i - \phi_j\right)}{\sum_{ij} a_i a_j \cdot \cos\left(\theta_i - \theta_j\right) \cdot \cos\left(\phi_i - \phi_j\right)}$$

Direct *CP* violation requires at least two amplitudes
with different weak *and* strong phases

CP Violation → 3 families
Cabibbo Matrix → CKM Matrix



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$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have *CP*-violating effects through the interference among these different current components. An interesting feature of this model is that the *CP*-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

Product of three rotation matrix **(3 angles + 1 phase with 3families)**

$$(\bar{u}\ \ \bar{c}\ \ \bar{t})\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V = \mathrm{R}_{ij}(\vartheta_{ij}, \delta_{ij}) \times \mathrm{R}_{kl}(\vartheta_{kl}, \delta_{kl}) \times \mathrm{R}_{mn}(\vartheta_{mn}, \delta_{mn})$$

$$\mathrm{R}_{12}(\vartheta_{12}, \delta_{12}) = \begin{pmatrix} c_{12} & s_{12}e^{i\delta} & 0 \\ -s_{12}e^{-i\delta} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \mathrm{R}_{23}(\vartheta_{23}, \delta_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23}e^{i\delta} \\ 0 & -s_{23}e^{-i\delta} & c_{23} \end{pmatrix} \quad \mathrm{R}_{13}(\vartheta_{13}, \delta_{13}) = \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}$$

$kl \neq ij \neq mn$

only 1 phase

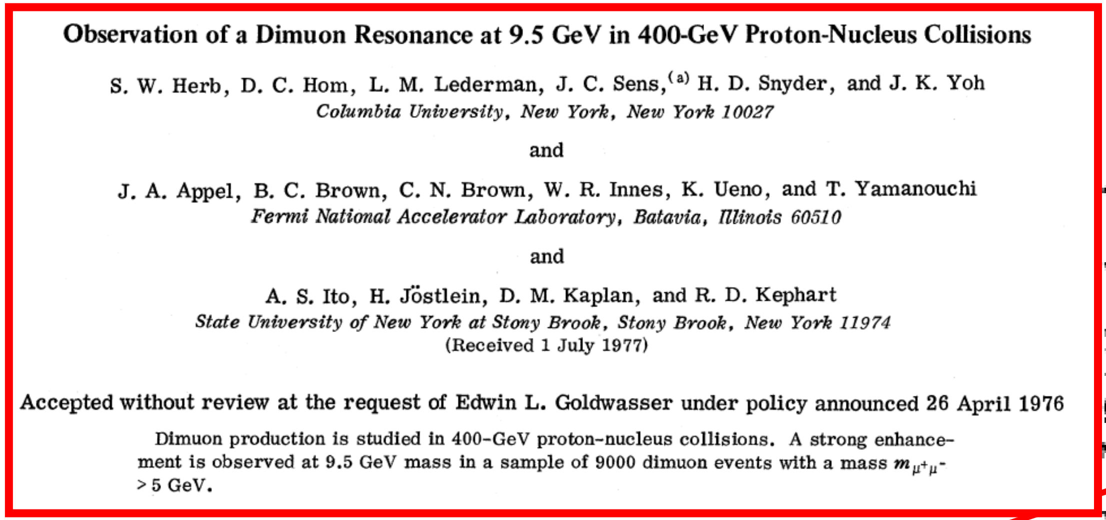
There are 36 possibilities [$(3\times2)_{\text{perm.}} \times 3_{\delta=0} \times 2_{\delta=\pm1}$]

$$V(std.) = \mathrm{R}_{23}(\vartheta_{23}, 0) \times \mathrm{R}_{13}(\vartheta_{13}, -\delta) \times \mathrm{R}_{12}(\vartheta_{12}, 0)$$

Standard Parametrization

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

1977 : b quark Discovery



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

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

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

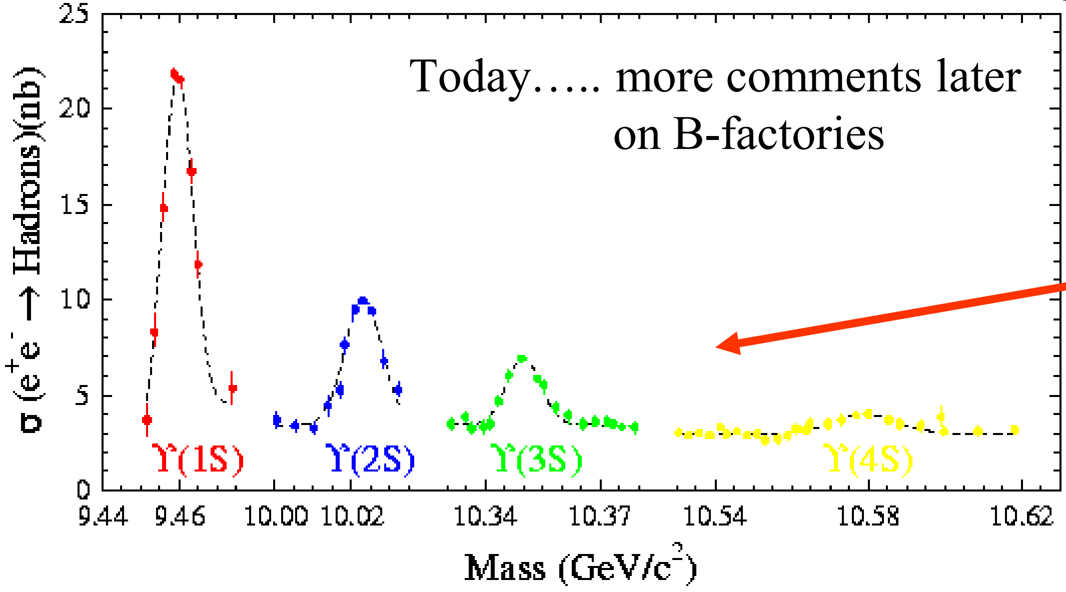
A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

(Received 1 July 1977)

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

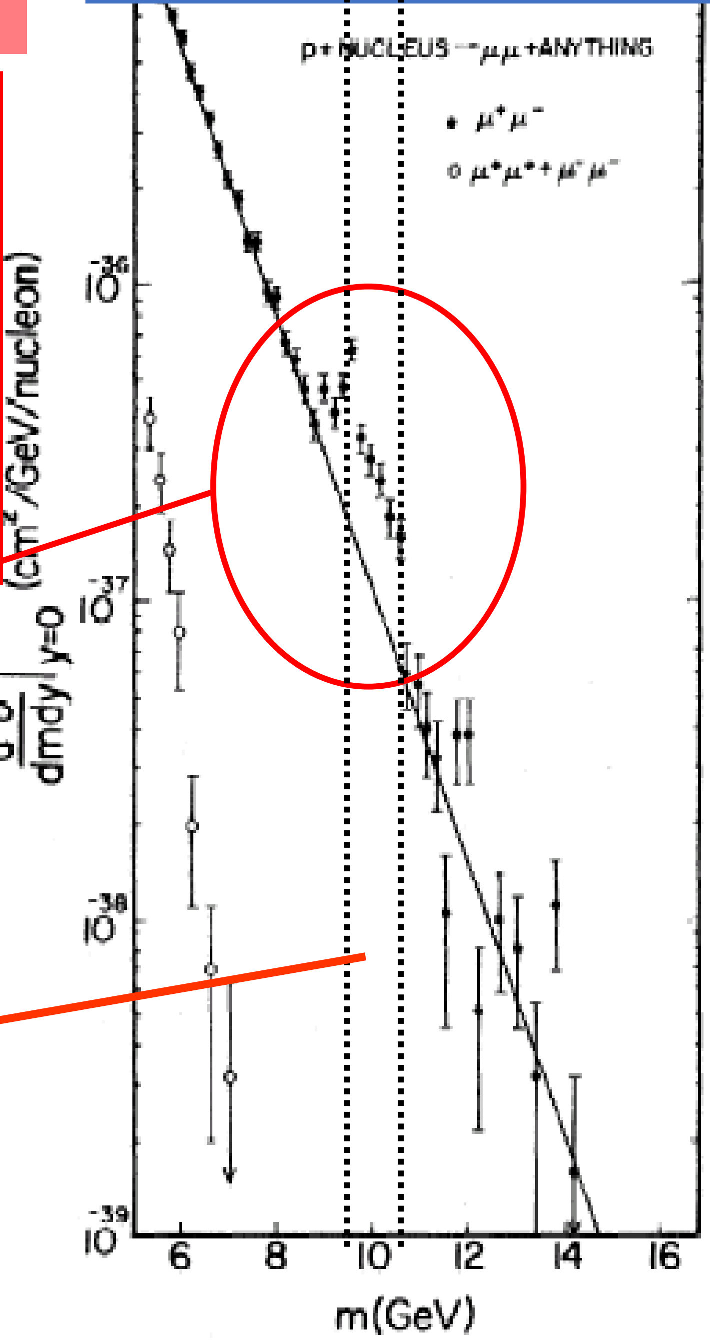
Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

Excess larger than the experimental resolution ⇒
presence of more than one resonance



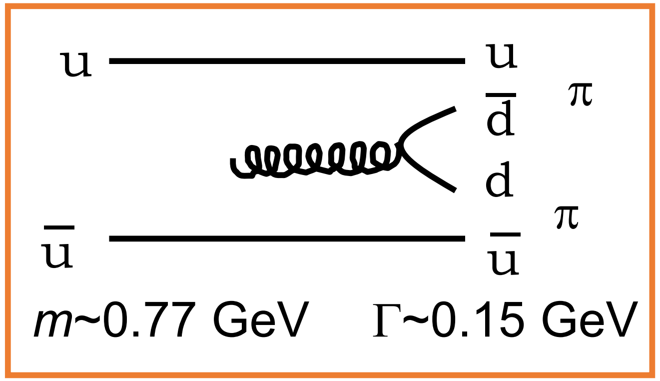
Today….. more comments later
on B-factories

9.5-10.5 GeV : The series of Υ



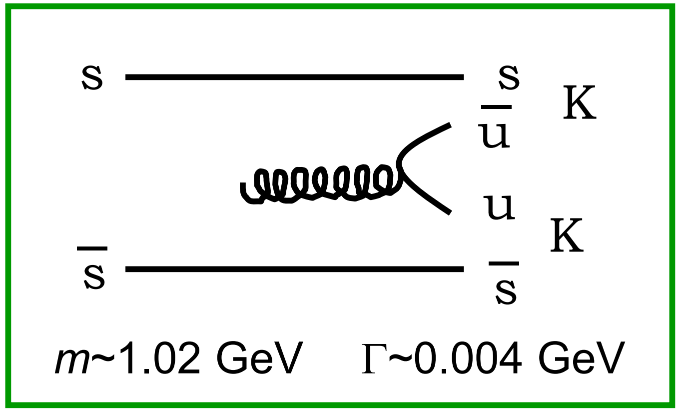
The $q\bar{q}$ resonances and the R ratio

ρ



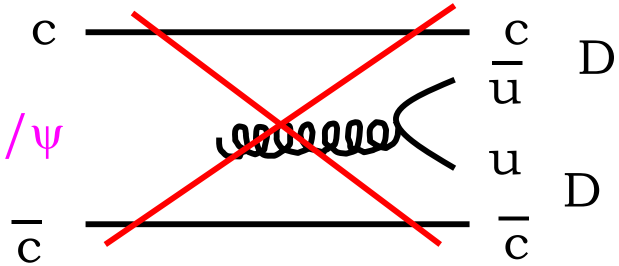
m~0.77 GeV Γ~0.15 GeV

ϕ

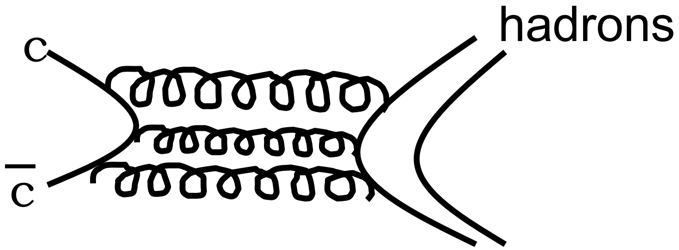


m~1.02 GeV Γ~0.004 GeV

J/ψ

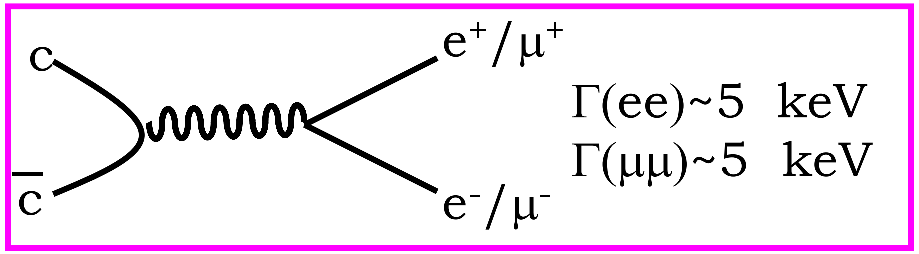


Forbidden because m(J/ψ)<2 m(D^0)



Γ~70 keV

J/ψ

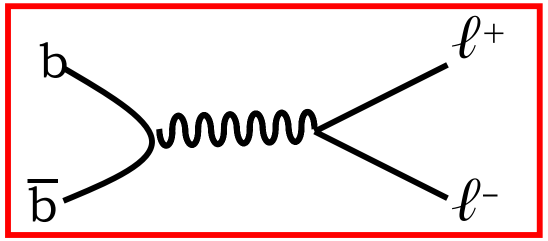


Γ(ee)~5 keV

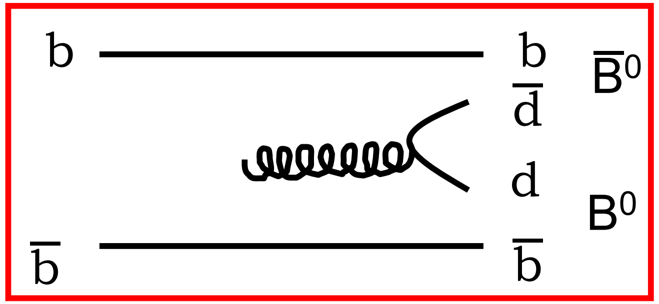
Γ(μμ)~5 keV

The decay through the strong interaction is extremely suppressed ⇒ the decay through electromagnetic interaction becomes competitive !

ϒ (1S)



ϒ (4S)

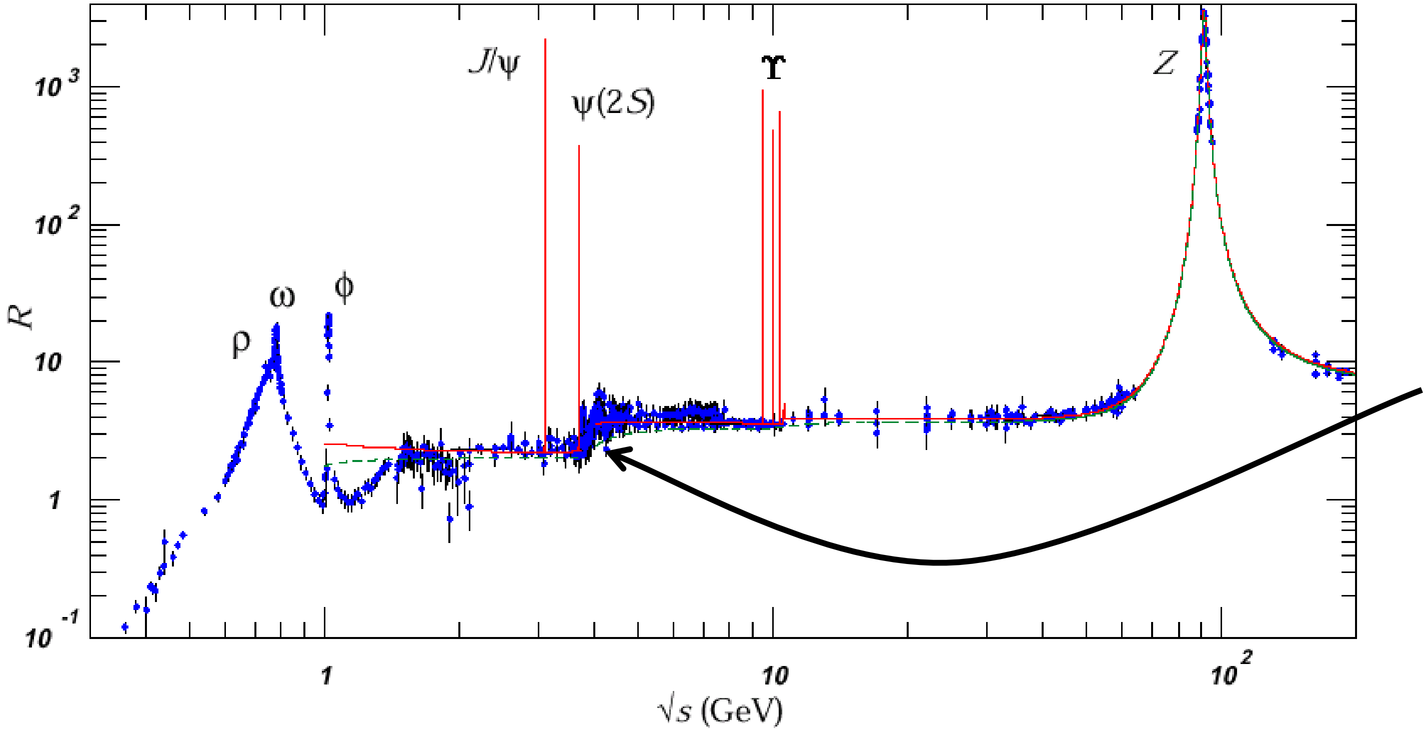


- The *R* ratio :

$$R = \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = N_c \Sigma_i q_i^2$$

$$= \underset{u}{\left(\frac{2}{3}\right)^2} + \underset{d}{\left(\frac{1}{3}\right)^2} + \underset{s}{\left(\frac{1}{3}\right)^2} + \underset{c}{\left(\frac{2}{3}\right)^2} + \underset{b}{\left(\frac{1}{3}\right)^2} = \frac{11}{9} \times 3 \text{ colours}$$

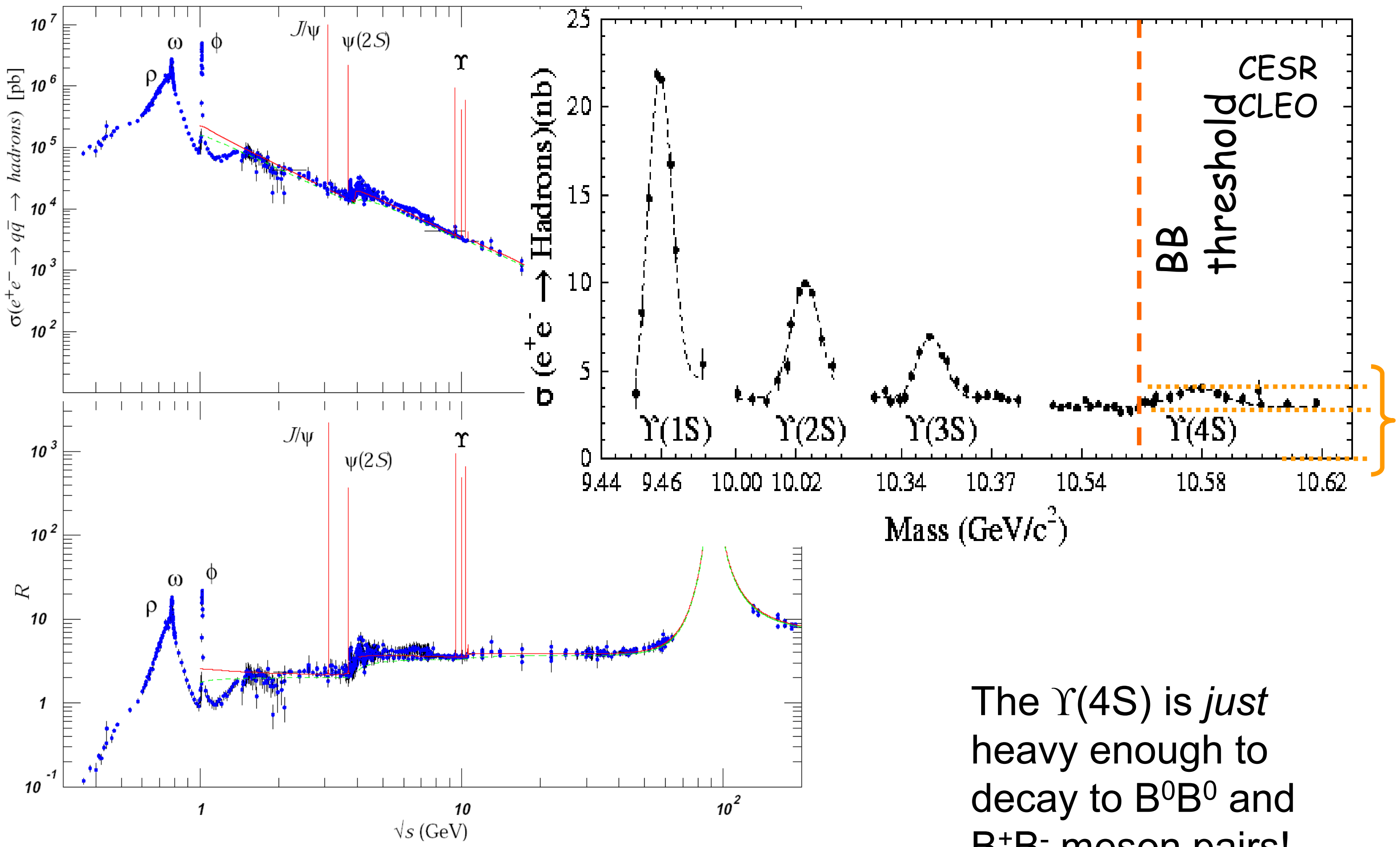
(sensitive to the number of colours)



All articles about the J/ψ discovery start mentioning that an increase of the cross section around 3.2 GeV was already observed

More ϒ's…

σ and R in e^+e^- Collisions



$$\frac{\sigma(b\bar{b})}{\sigma(\text{hadr})} = 0.28$$

Figure 39.6, Figure 39.7: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-$, QED simple pole). The curves are an educative guide. The solid curves are the 3-loop pQCD predictions for $\sigma(e^+e^- \to hadrons)$ and the R ratio, respectively [see our Review on Quantum chromodynamics, Eq. (9.12)] or, for more details, K.G. Chetyrkin *et al.*, Nucl. Phys. **B586**, 56 (2000), Eqs. (1)–(3)). Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS), n = 1..4$ are also shown. **Note:** The experimental shapes of these resonances are dominated by the machine energy spread and are not shown. The dashed curves are the naive quark parton model predictions for σ and R. The full list of references, as well as the details of R ratio extraction from the original data, can be found in O.V. Zenin *et al.*, `hep-ph/0110176` (to be published in J. Phys. **G**). Corresponding computer-readable data files are available at `http://wwwppds.ihep.su/≈zenin_o/contents_plots.html`. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, November 2001.)

The ϒ(4S) is *just* heavy enough to decay to B^0B^0 and B^+B^- meson pairs! (NO additional particles!)

The τ lepton discovery

- In 1975 at SLAC (e^+e^-)

$$e^+e^- \rightarrow \tau^+\tau^- \rightarrow e^\pm\mu^\mp + \text{ missing energy}$$

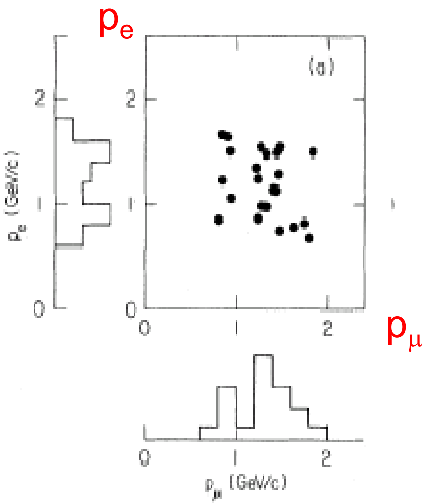
$$e^+e^- \rightarrow \tau^+\tau^-$$

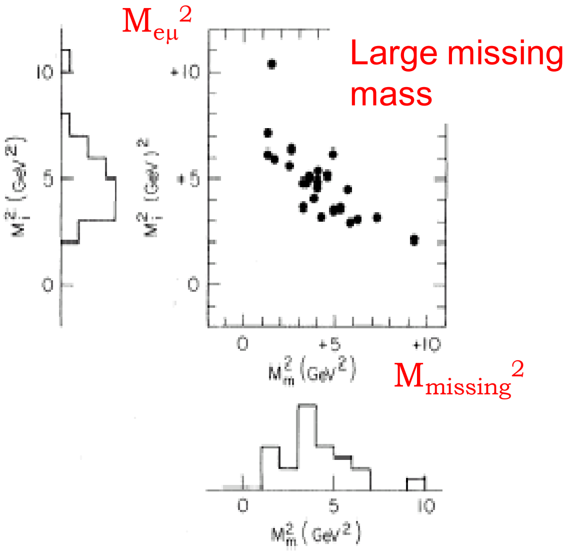
$$\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau \quad \text{and} \quad \tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau$$

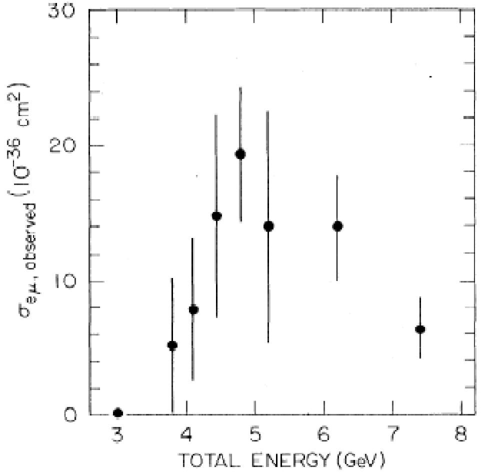
24 eμ events among 35000.

- Complicated analysis !

Example of discriminating variables :



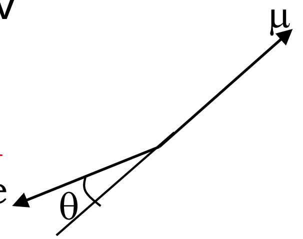


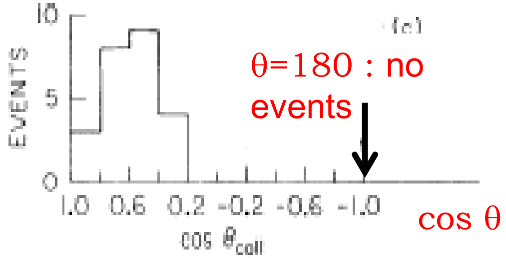


Correction for acceptance effects
⇒m(τ) between 1.6 and 2 GeV

PDG : m(τ) =1784 MeV

$$\cos\theta = \frac{-\vec{p}_e \cdot \vec{p}_\mu}{|\vec{p}_e||\vec{p}_\mu|}$$



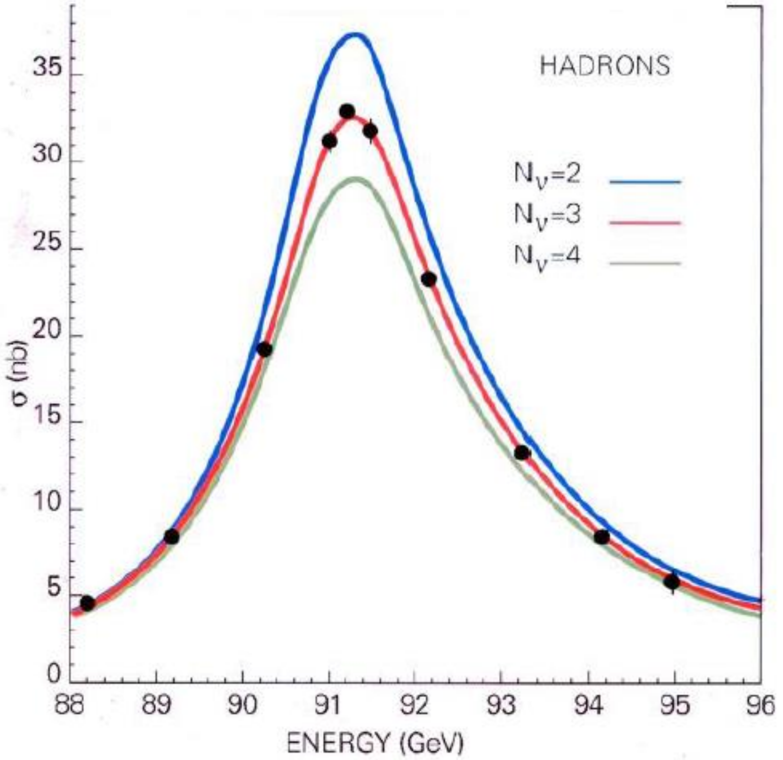


3 FAMILIES

One of the fundamental results from LEP :

There are 3 generations of neutrino (left-handed, active) with mass < M(Z)/2.

LEP :
ALEPH,DELPHI,OPAL,L3

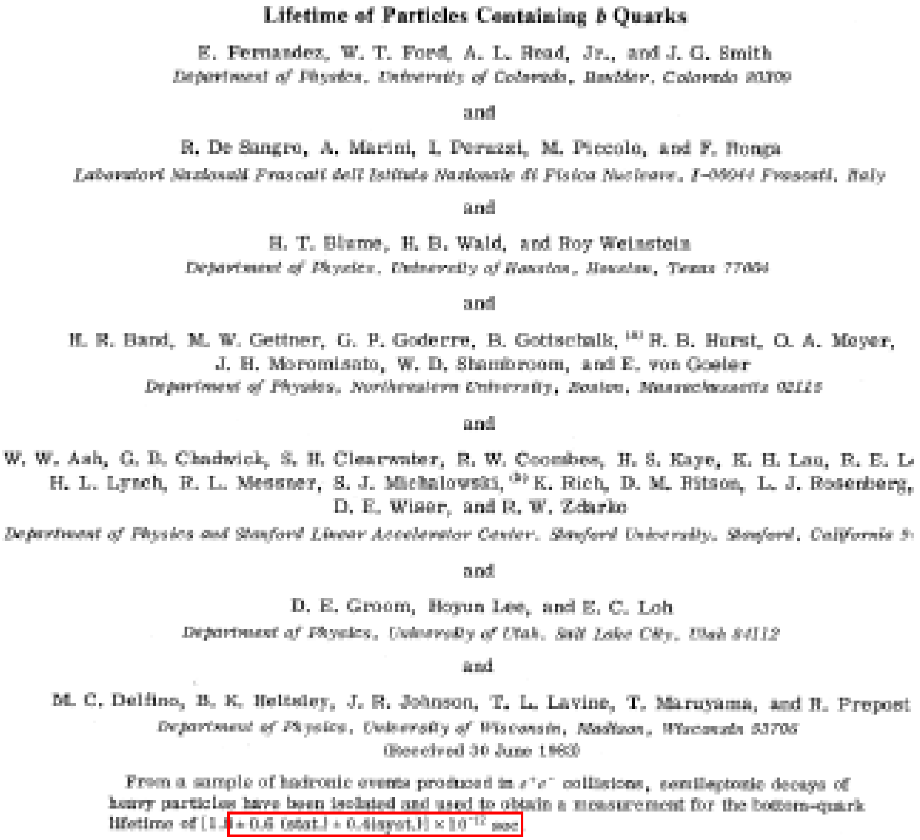


The expected B meson lifetime

$$\Gamma = \frac{G_F^2 M^5}{192\pi^3},$$

$$\Gamma_{b\to u,c} = \Gamma_{\mu\to e} \times \underset{3\cdot10^8}{\left(\frac{m_b}{m_\mu}\right)^5} \left[|V_{cb}|^2 \underbrace{\frac{PS(b\to c)}{PS(\mu\to e)}}_{2.8} + |V_{ub}|^2 \underbrace{\frac{PS(b\to u)}{PS(\mu\to e)}}_{7.7}\right]$$

$$\boxed{\tau_b \approx \frac{6\cdot10^{-15}}{2.8|V_{cb}|^2 + 7.7|V_{ub}|^2}\,s.}$$



Lifetime of Particles Containing *b* Quarks

E. Fernandez, W. T. Ford, A. L. Read, Jr., and J. G. Smith
Department of Physics, University of Colorado, Boulder, Colorado 80309

and

R. De Sangro, A. Marini, I. Peruzzi, M. Piccolo, and F. Ronga
Laboratori Nazionali Frascati dell Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy

and

H. T. Blume, R. B. Wald, and Roy Weinstein
Department of Physics, University of Houston, Houston, Texas 77004

and

H. R. Band, M. W. Gettner, G. P. Goderre, B. Gottschalk,[a] R. B. Hurst, O. A. Meyer,
J. H. Moromisato, W. D. Shambroom, and E. von Goeler
Department of Physics, Northeastern University, Boston, Massachusetts 02115

and

W. W. Ash, G. B. Chadwick, S. H. Clearwater, R. W. Coombes, H. S. Kaye, K. H. Lau, R. E. L
H. L. Lynch, R. L. Messner, S. J. Michalowski,[b] K. Rich, D. M. Ritson, L. J. Rosenberg,
D. E. Wiser, and R. W. Zdarko
Department of Physics and Stanford Linear Accelerator Center, Stanford University, Stanford, California

and

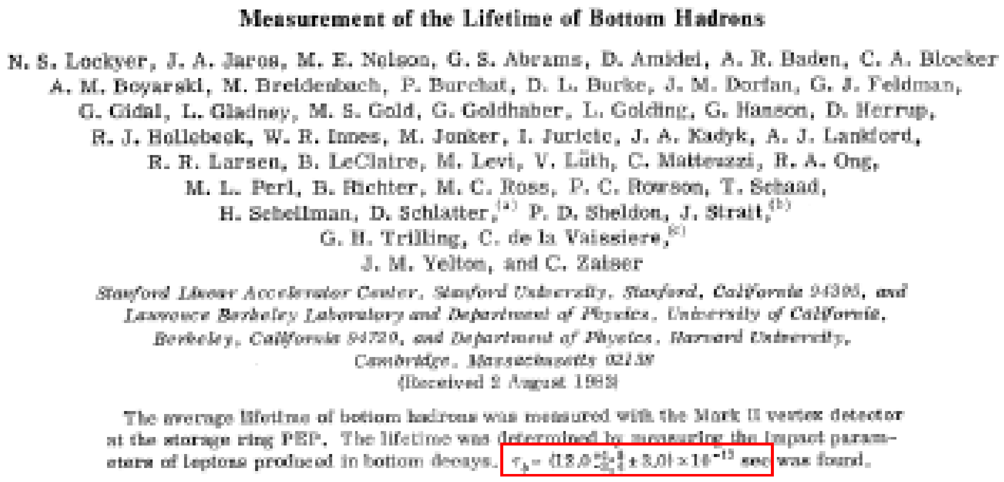
D. E. Groom, Hoyun Lee, and E. C. Loh
Department of Physics, University of Utah, Salt Lake City, Utah 84112

and

M. C. Delfino, B. K. Heltsley, J. R. Johnson, T. L. Lavine, T. Maruyama, and R. Prepost
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
(Received 30 June 1983)

From a sample of hadronic events produced in e^+e^- collisions, semileptonic decays of heavy particles have been isolated and used to obtain a measurement for the bottom-quark lifetime of $\boxed{[1.8 \pm 0.6\ (\text{stat.}) \pm 0.4(\text{syst.})] \times 10^{-12}\ \text{sec}}$.

Surprise: the B meson lifetime



Measurement of the Lifetime of Bottom Hadrons

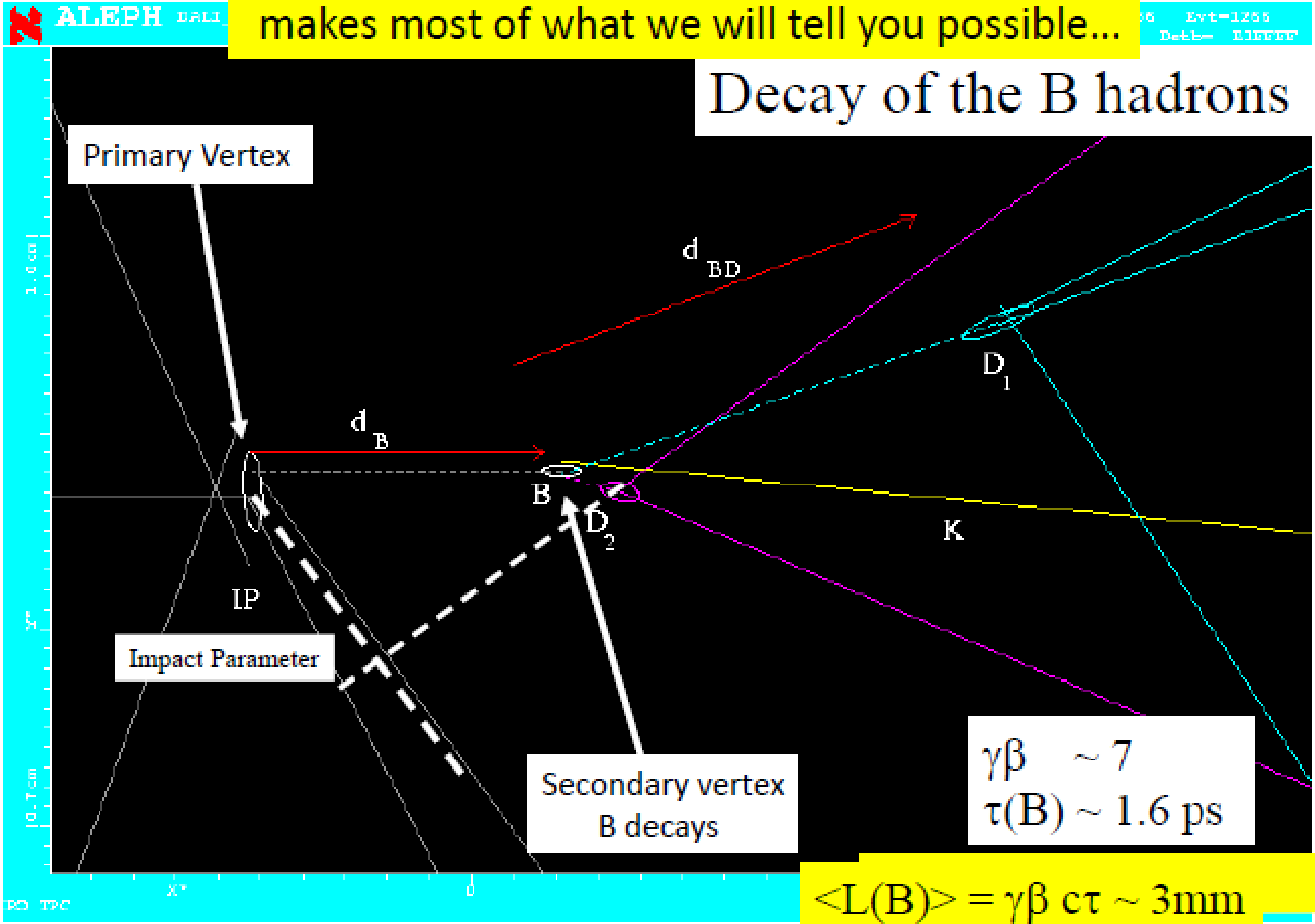
N. S. Lockyer, J. A. Jaros, M. E. Nelson, G. S. Abrams, D. Amidei, A. R. Baden, C. A. Blocker
A. M. Boyarski, M. Breidenbach, P. Burchat, D. L. Burke, J. M. Dorfan, G. J. Feldman,
G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber, L. Golding, G. Hanson, D. Herrup,
R. J. Hollebeek, W. R. Innes, M. Jonker, I. Juricic, J. A. Kadyk, A. J. Lankford,
R. R. Larsen, B. LeClaire, M. Levi, V. Lüth, C. Matteuzzi, R. A. Ong,
M. L. Perl, B. Richter, M. C. Ross, P. C. Rowson, T. Schaad,
H. Schellman, D. Schlatter,[a] P. D. Sheldon, J. Strait,[b]
G. H. Trilling, C. de la Vaissiere,[c]
J. M. Yelton, and C. Zaiser
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and
Lawrence Berkeley Laboratory and Department of Physics, University of California,
Berkeley, California 94720, and Department of Physics, Harvard University,
Cambridge, Massachusetts 02138
(Received 2 August 1983)

The average lifetime of bottom hadrons was measured with the Mark II vertex detector at the storage ring PEP. The lifetime was determined by measuring the impact parameters of leptons produced in bottom decays. $\boxed{\tau_b = (12.0^{+4.5}_{-3.6} \pm 3.0) \times 10^{-13}\ \text{sec}}$ was found.

Both MAC and MARK-II were detectors at PEP, a 30 GeV e^+e^- collider at SLAC (Stanford)

The fact that B lifetime is $\tau(B)$~1,6 ps
makes most of what we will tell you possible…

Decay of the B hadrons



Primary Vertex

Impact Parameter

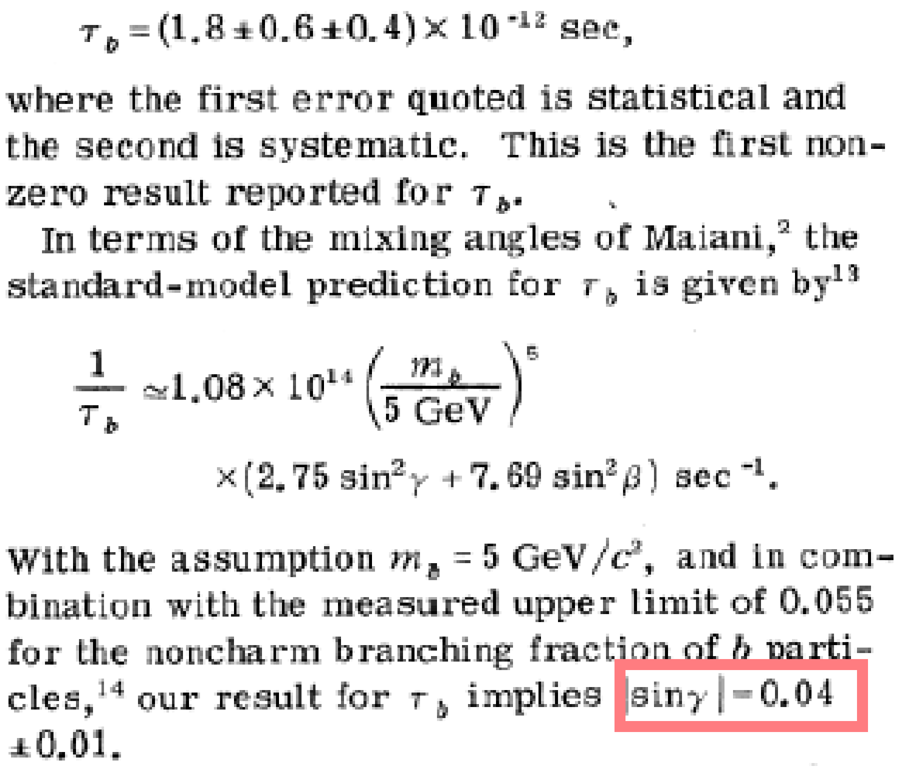
Secondary vertex
B decays

$\gamma\beta \sim 7$
$\tau(B) \sim 1.6$ ps

$\langle L(B) \rangle = \gamma\beta\, c\tau \sim 3\text{mm}$

MAC paper

Surprise: V_{cb} is very small!



$$\tau_b = (1.8 \pm 0.6 \pm 0.4) \times 10^{-12}\ \text{sec},$$

where the first error quoted is statistical and the second is systematic. This is the first non-zero result reported for τ_b.

In terms of the mixing angles of Maiani,[2] the standard-model prediction for τ_b is given by[13]

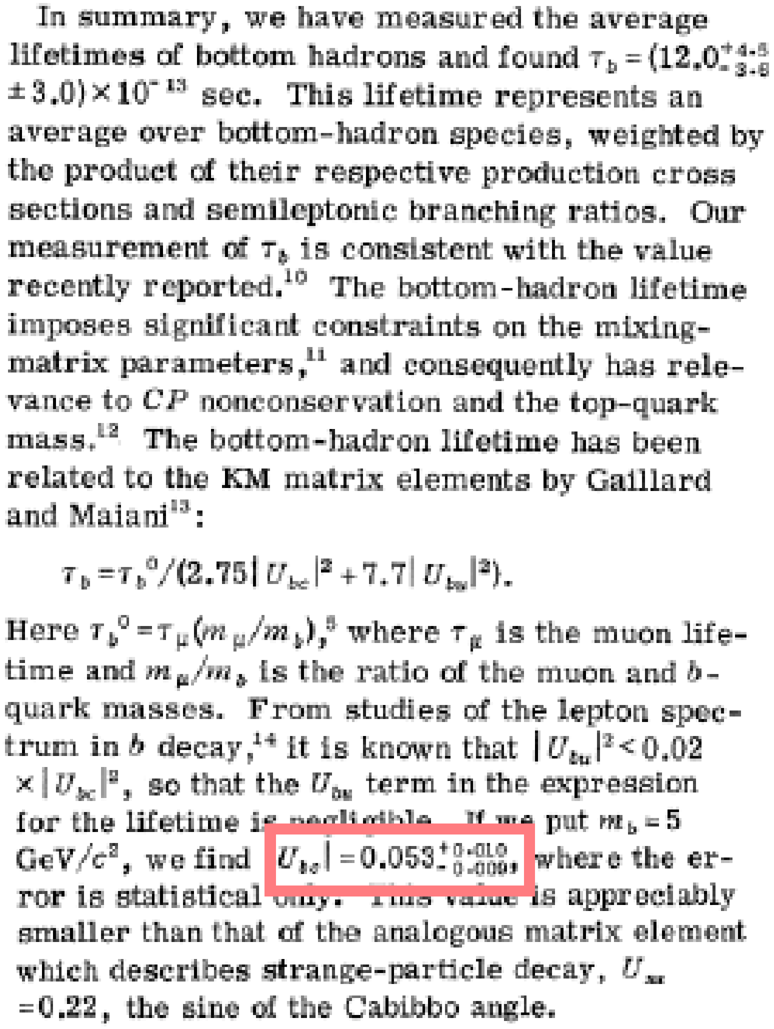
$$\frac{1}{\tau_b} \simeq 1.08 \times 10^{14} \left(\frac{m_b}{5\ \text{GeV}}\right)^5 \times (2.75 \sin^2\gamma + 7.69 \sin^2\beta)\ \text{sec}^{-1}.$$

With the assumption $m_b = 5\ \text{GeV}/c^2$, and in combination with the measured upper limit of 0.055 for the noncharm branching fraction of b particles,[14] our result for τ_b implies $|\sin\gamma| = 0.04 \pm 0.01$.

V_{us} ~0.22

V_{cb} ~0.04

Mark-II paper

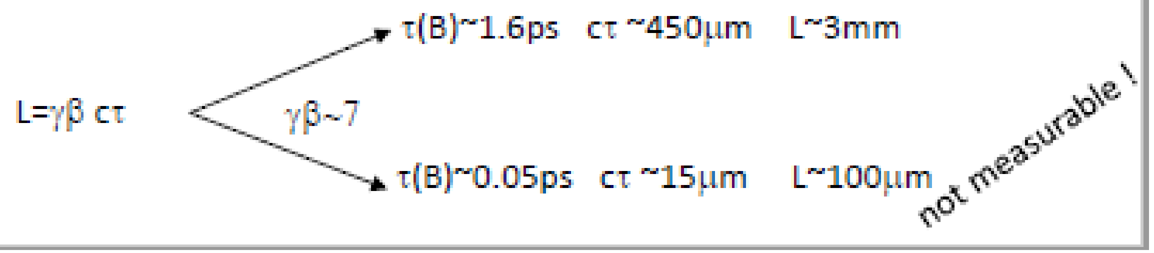


In summary, we have measured the average lifetimes of bottom hadrons and found $\tau_b = (12.0^{+4.5}_{-3.6} \pm 3.0) \times 10^{-13}$ sec. This lifetime represents an average over bottom-hadron species, weighted by the product of their respective production cross sections and semileptonic branching ratios. Our measurement of τ_b is consistent with the value recently reported.[10] The bottom-hadron lifetime imposes significant constraints on the mixing-matrix parameters,[11] and consequently has relevance to CP nonconservation and the top-quark mass.[12] The bottom-hadron lifetime has been related to the KM matrix elements by Gaillard and Maiani[13]:

$$\tau_b = \tau_b^0 / (2.75 |U_{bc}|^2 + 7.7 |U_{bu}|^2).$$

Here $\tau_b^0 = \tau_\mu (m_\mu / m_b)^5$ where τ_μ is the muon lifetime and m_μ / m_b is the ratio of the muon and b-quark masses. From studies of the lepton spectrum in b decay,[14] it is known that $|U_{bu}|^2 < 0.02 \times |U_{bc}|^2$, so that the U_{bu} term in the expression for the lifetime is negligible. If we put $m_b = 5\ \text{GeV}/c^2$, we find $|U_{bc}| = 0.053^{+0.010}_{-0.009}$, where the error is statistical only. This value is appreciably smaller than that of the analogous matrix element which describes strange-particle decay, $U_{su} = 0.22$, the sine of the Cabibbo angle.

This fact is also very important and allow to perform B physics, since the B mesons can be identified (their lifetime measured)



b→u versus b → c

VOLUME 52, NUMBER 13 PHYSICAL REVIEW LETTERS 26 MARCH 1984

Limit on the *b* → *u* Coupling from Semileptonic *B* Decay

A. Chen, M. Goldberg, N. Horwitz, A. Jawahery, P. Lipari, G. C. Moneti, C. G. Trahern, and H. van Hecke
Syracuse University, Syracuse, New York 13210

and

M. S. Alam, S. E. Csorna, L. Garren, M. D. Mestayer, R. S. Panvini, and Xia Yi
Vanderbilt University, Nashville, Tennessee 37235

and

P. Avery, C. Bebek, K. Berkelman, D. G. Cassel, J. W. DeWire, R. Ehrlich, T. Ferguson, R. Galik,
M. G. D. Gilchriese, B. Gittelman, M. Halling, D. L. Hartill, S. Holzner, M. Ito,
J. Kandaswamy, D. L. Kreinick, Y. Kubota, N. B. Mistry, F. Morrow,
E. Nordberg, M. Ogg, A. Silverman, P. C. Stein,
S. Stone, D. Weber, and R. Wilcke(a)
Cornell University, Ithaca, New York 14853

and

A. J. Sadoff
Ithaca College, Ithaca, New York 14850

and

R. Giles, J. Hassard, M. Hempstead, K. Kinoshita, W. W. MacKay, F. M. Pipkin, and Richard Wilson
Harvard University, Cambridge, Massachusetts 02138

and

P. Haas, T. Jensen, H. Kagan, and R. Kass
Ohio State University, Columbus, Ohio 43210

and

S. Behrends, K. Chadwick, J. Chauveau,(b) T. Gentile, Jan M. Guida, Joan A. Guida, A. C. Melissinos,
S. L. Olsen, G. Parkhurst, D. Peterson, R. Poling, C. Rosenfeld, E. H. Thorndike, and P. Tipton
University of Rochester, Rochester, New York 14627

and

D. Besson, J. Green, R. G. Hicks,(c) R. Namjoshi, F. Sannes,
P. Skubic,(d) A. Snyder,(e) and R. Stone
Rutgers University, New Brunswick, New Jersey 08854
(Received 30 January 1984)

We have used the momentum spectrum of leptons produced in semileptonic *B*-meson decays to set a 90%-confidence-level upper limit on $\Gamma(b \to u l \nu)/\Gamma(b \to c l \nu)$ of 4%. We also measure the semileptonic branching fractions of the *B* meson to be $(12.0 \pm 0.7 \pm 0.5)\%$ for electrons and $(10.8 \pm 0.6 \pm 1.0)\%$ for muons.

CLEO collaboration
at CESR (Cornell): $\sqrt{s} = M_{\Upsilon(4S)}$

From a sample of 42.2K BB events (40.6/pb)

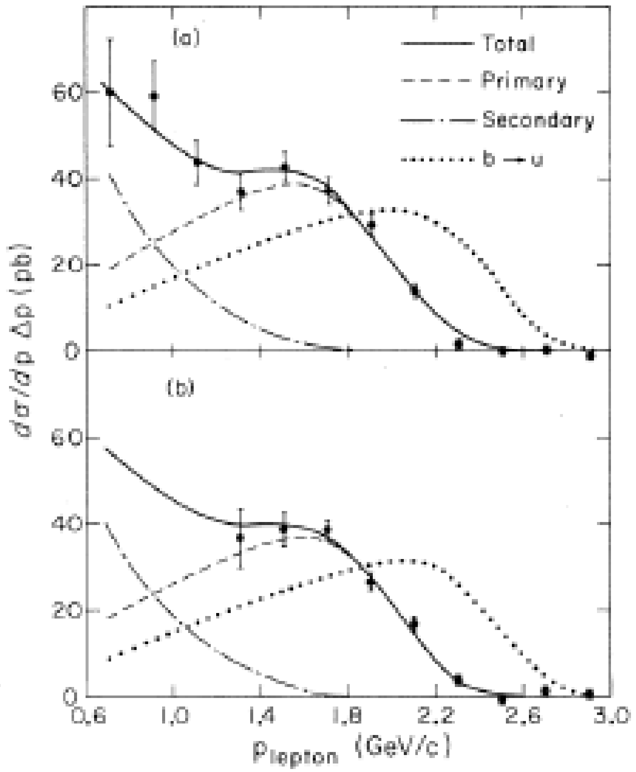


FIG. 1. The efficiency-corrected momentum spectra for (a) electrons and (b) muons from *B*-meson decay. The curves are Monte Carlo calculations of the lepton spectra based on model II (described in the text). The primary leptons are produced directly in semileptonic *B* decays ($b \to c l \nu$), and the secondary leptons are produced in semileptonic decays of *D* mesons produced in *B* decays. Also shown for comparison are the calculated spectra for semileptonic *B* decays by $b \to u l \nu$.

$|V_{ub}| \ll |V_{cb}| \ll |V_{us}|$

L. Wolfenstein, Phys. Rev. Lett. 51 (1983) 1945.

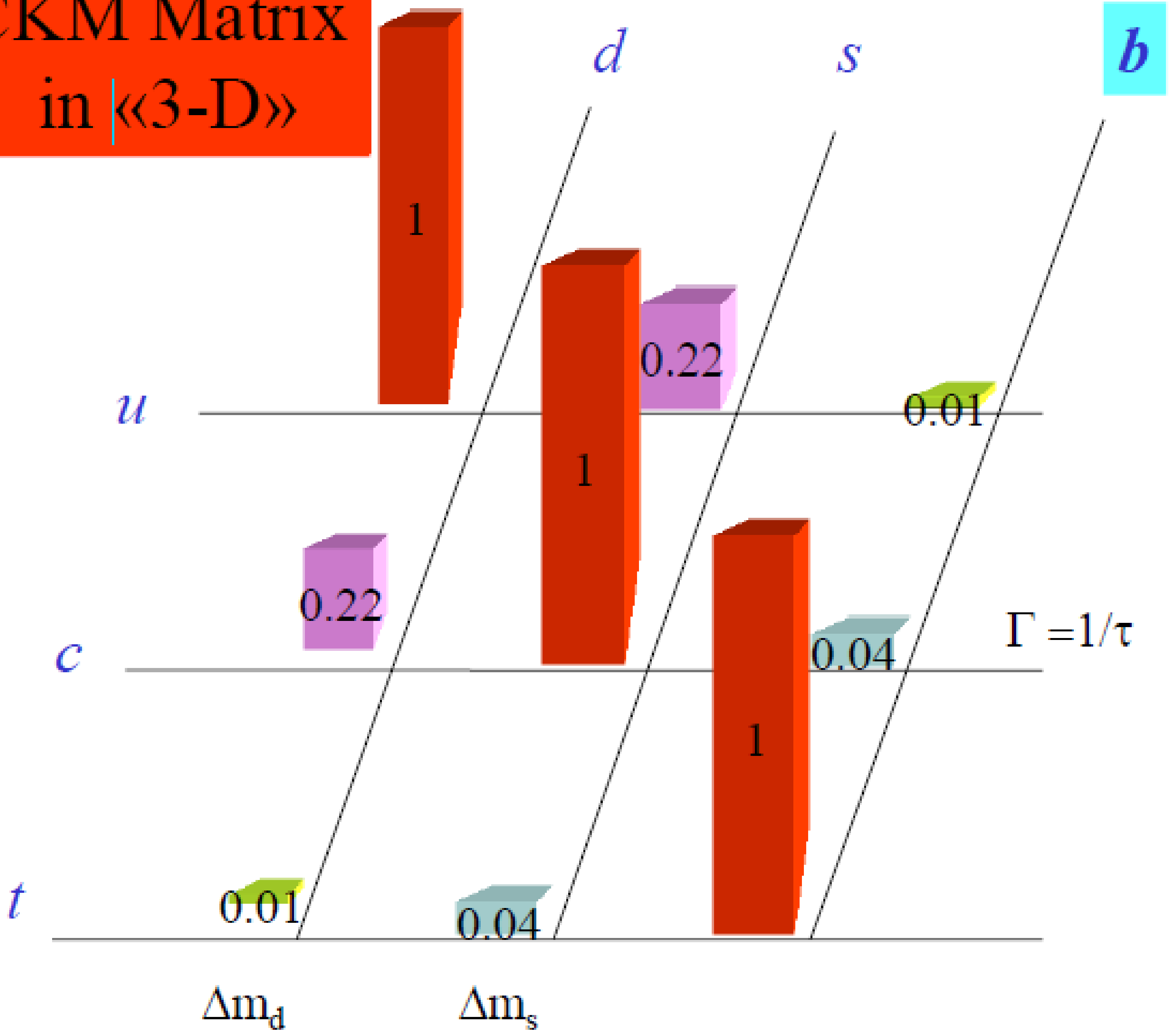
Parametrization of the Kobayashi-Maskawa Matrix

Lincoln Wolfenstein
Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

Received 22 August 1983

The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured *B* lifetime. Two remaining parameters, including the *CP*-non conservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ε'/ε possible in an ongoing experiment would tightly constrain the *CP*-non conservation parameter and could rule out the hypothesis that the only source of *CP* non conservation is the Kobayashi-Maskawa mechanism.

CKM Matrix in «3-D»



Approximate Parametrization

Each element of the CKM matrix is expanded as a power series in the small parameter $\lambda = |V_{us}| \sim 0.22$

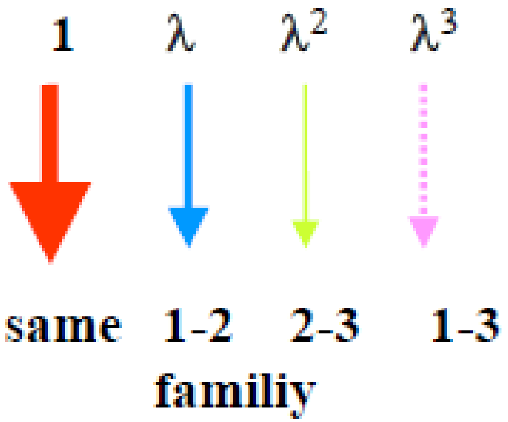
We observe that :

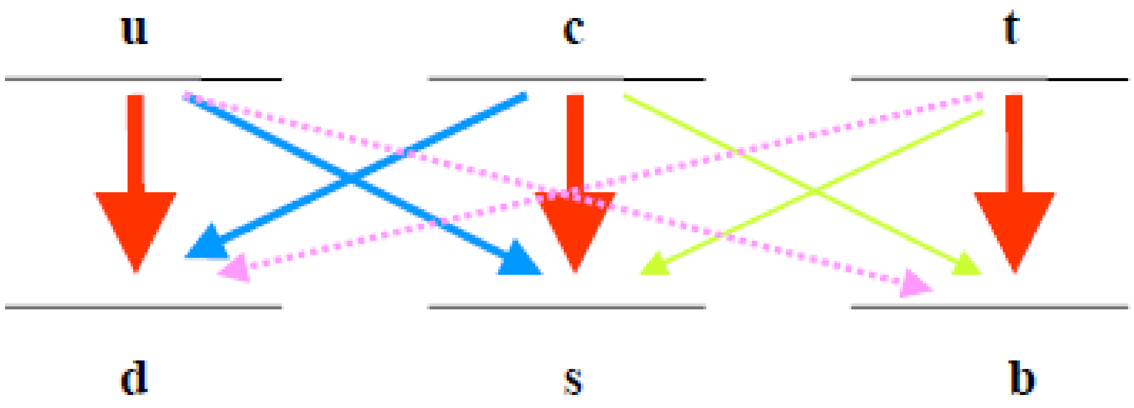
Diagonal elements ~ 1

V_{us} , V_{cd} ~ 0.2

V_{cb} , V_{ts} ~ 4×10^{-2}

V_{ub} , V_{td} ~ 4×10^{-3}





Wolfenstein parametrization

Parameters λ ,A, ρ and η

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

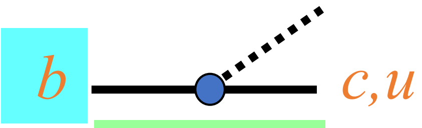
The **CKM** Matrix

Wolfenstein parametrization

4 parameters : λ ,A, ρ, η

$$
\begin{array}{c|ccc}
 & d & s & b \\
\hline
u & 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\
c & -\lambda & 1-\lambda^2/2 & A\lambda^2 \\
t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{array}
$$

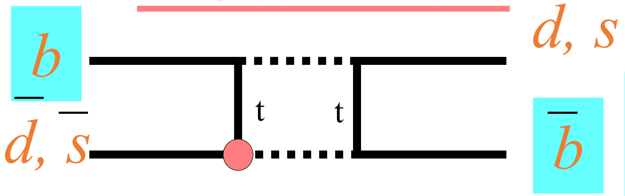
V_{tb}



V_{ub},V_{cb}

B decays

B Oscillations



V_{td} ,V_{ts}

The *b-Physics* plays a very important role in the determination of those parameters

To have a CKM matrix expressed with Wolfenstein parameters valid up to λ^6

We define : $s_{12}=\lambda,\quad s_{23}=A\lambda^2,\, s_{13}e^{-i\delta}=A\lambda^3(\rho-i\eta)$

$$\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\dfrac{A^2\lambda^5}{2}(1-2\rho)-i\,A^2\lambda^5\eta & 1-\lambda^2/2-\lambda^4(\dfrac{1}{8}+\dfrac{A^2}{2}) & A\lambda^2 \\ A\lambda^3(1-(1-\lambda^2/2)(\rho+i\eta)) & -A\lambda^2(1-\lambda^2/2)(1+\lambda^2(\rho+i\eta)) & 1-\dfrac{A^2\lambda^4}{2} \end{pmatrix}$$

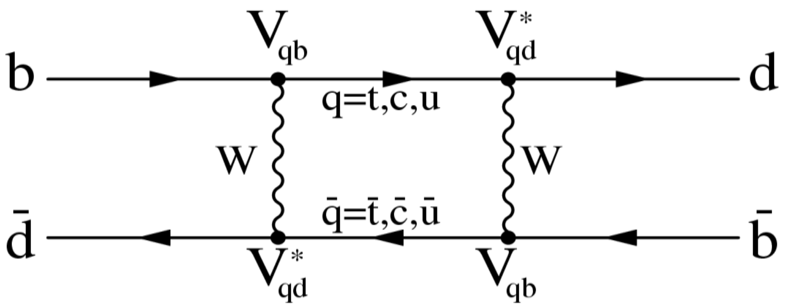
In particular the corrections to V_{us} are at λ^7

to V_{cb} are at λ^8

$$V_{td}=A\lambda^3(1-\overline{\rho}-i\overline{\eta})\quad;\qquad \overline{\rho}(\overline{\eta})=(1-\lambda^2/2)\rho(\eta)$$

Which we will see will allow a generalization of the unitarity triangle in $\overline{\rho}$ and $\overline{\eta}$ plane

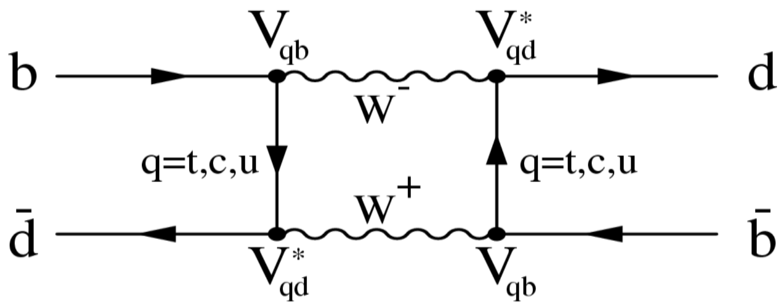
FCNC : B Oscillations in the B system (1985-1990)



$t-\bar{t}: \quad \propto m_t^2 \left|V_{tb}V_{td}^*\right|^2$

$c-\bar{c}: \quad \propto m_c^2 \left|V_{cb}V_{cd}^*\right|^2$

$c-\bar{t}, \bar{c}-t: \quad \propto m_c m_t V_{tb}V_{td}^* V_{cb}V_{cd}^*$



$t-\bar{t}: \quad \propto m_t^2 \lambda^6$

$c-\bar{c}: \quad \propto m_c^2 \lambda^6$

$c-\bar{t}, \bar{c}-t: \quad \propto m_c m_t \lambda^6$

Dominated by top quark mass (GIM!):

$B^0\overline{B^0}$ mixing: ARGUS, 1987 **Phys.Lett.B192:245,1987**

$$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1}$$

$$\approx 0.5\mathrm{ps}^{-1}$$

First hint of a *really large* $\mathrm{m}_{\mathrm{top}}$!

directly observed in 1995

$$\left.\begin{array}{l}\Delta m_B \approx 0.00002 \cdot \left(\dfrac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1} \\ \qquad\qquad \tau \approx 1.5\ \mathrm{ps}\end{array}\right\} x = \frac{\Delta m}{\Gamma} \approx 0.00003 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2$$

x give the number of oscillation in a lifetime

If m_t would be order of 10 GeV/c^2, B mesons would decay long before they have the chance to oscillate…

B^0B^0 mixing: ARGUS, 1987 **Phys.Lett.B192:245,1987**

$$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1}$$

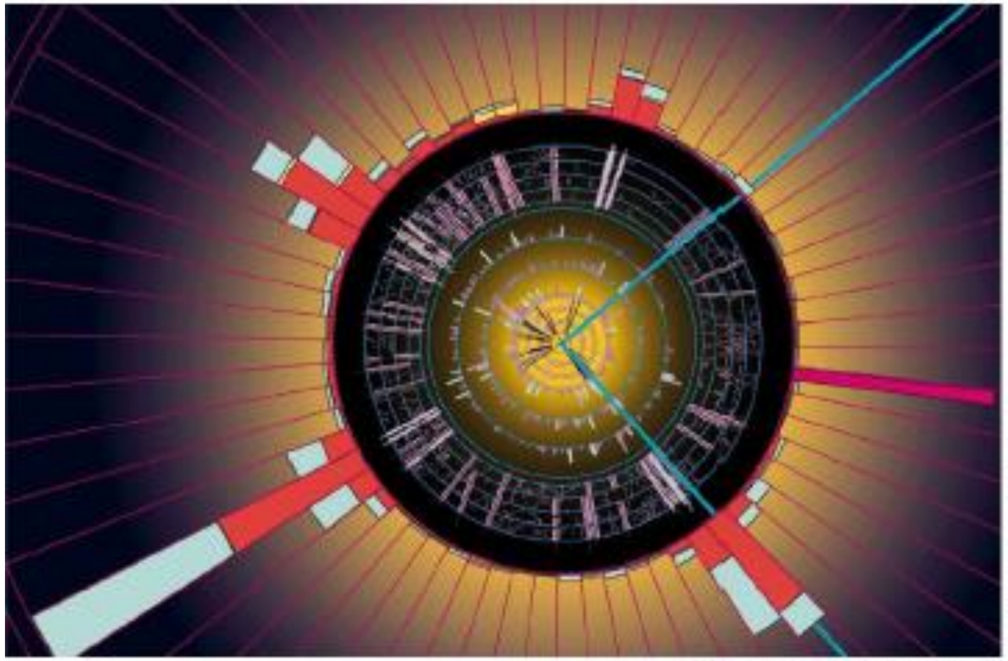
$$\approx 0.5\mathrm{ps}^{-1}$$

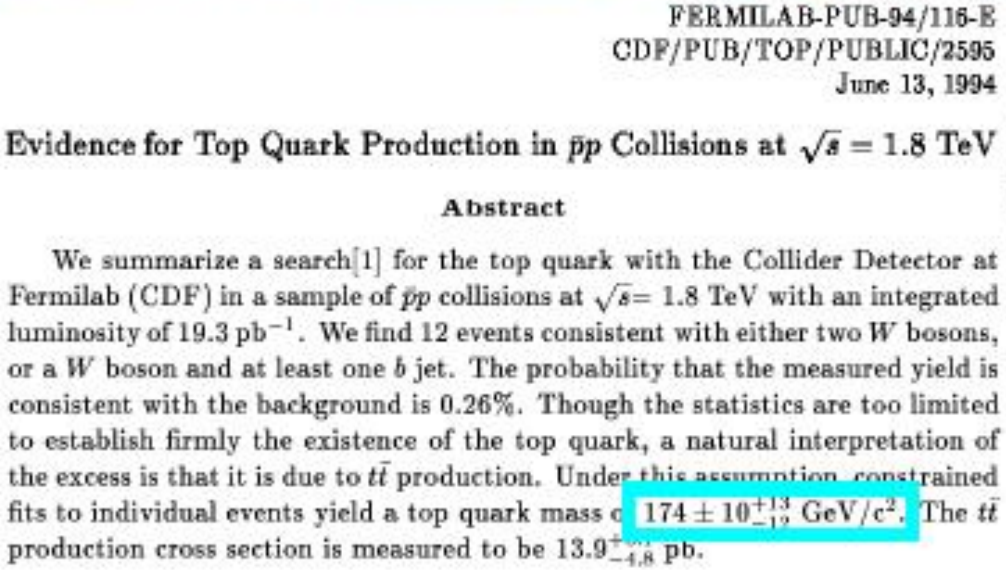
→

First hint of a *really large* m_{top}!

directly observed in 1995

Discovery of the Top Quark: CDF & D0, 1994/5



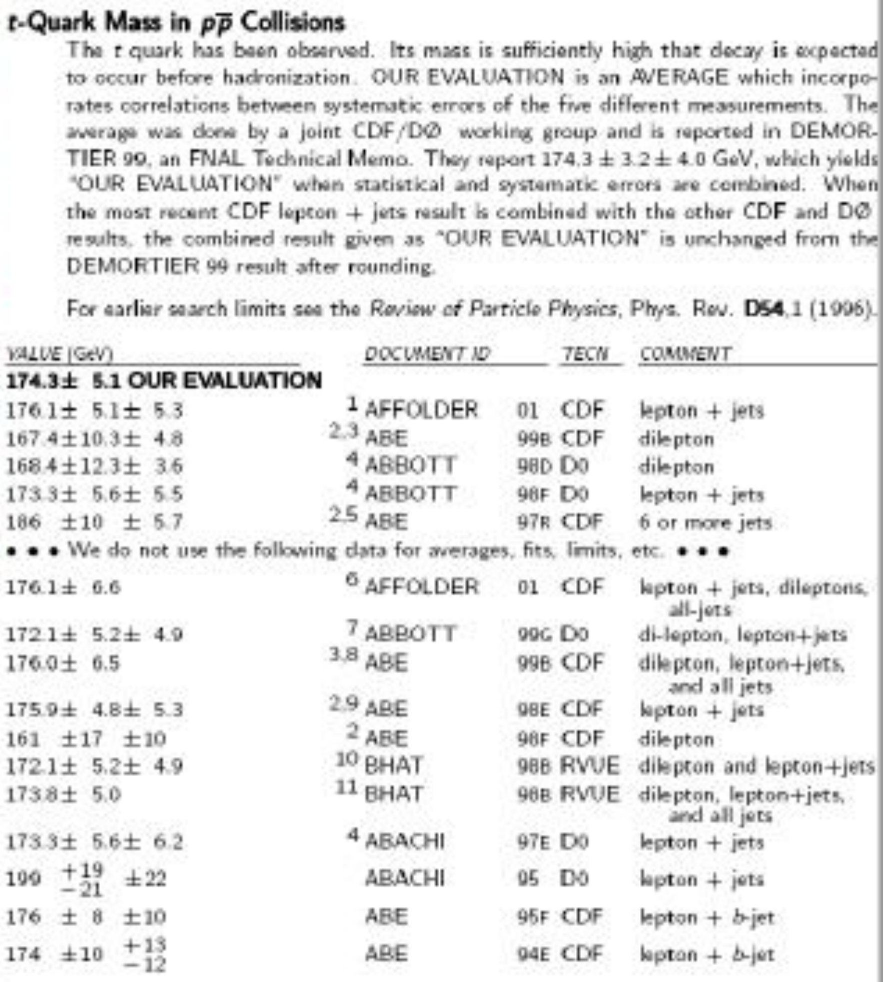


FERMILAB-PUB-94/116-E
CDF/PUB/TOP/PUBLIC/2595
June 13, 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

Abstract

We summarize a search[1] for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.



t-Quark Mass in $p\bar{p}$ Collisions

The t quark has been observed. Its mass is sufficiently high that decay is expected to occur before hadronization. OUR EVALUATION is an AVERAGE which incorporates correlations between systematic errors of the five different measurements. The average was done by a joint CDF/DØ working group and is reported in DEMORTIER 99, an FNAL Technical Memo. They report $174.3 \pm 3.2 \pm 4.0$ GeV, which yields "OUR EVALUATION" when statistical and systematic errors are combined. When the most recent CDF lepton + jets result is combined with the other CDF and DØ results, the combined result given as "OUR EVALUATION" is unchanged from the DEMORTIER 99 result after rounding.

For earlier search limits see the *Review of Particle Physics*, Phys. Rev. **D54**,1 (1996).

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
174.3 ± 5.1 OUR EVALUATION				
176.1 ± 5.1 ± 5.3	[1] AFFOLDER	01	CDF	lepton + jets
167.4 ± 10.3 ± 4.8	[2,3] ABE	99B	CDF	dilepton
168.4 ± 12.3 ± 3.6	[4] ABBOTT	98D	D0	dilepton
173.3 ± 5.6 ± 5.5	[4] ABBOTT	98F	D0	lepton + jets
186 ± 10 ± 5.7	[2,5] ABE	97R	CDF	6 or more jets
• • • We do not use the following data for averages, fits, limits, etc. • • •				
176.1 ± 6.6	[6] AFFOLDER	01	CDF	lepton + jets, dileptons, all-jets
172.1 ± 5.2 ± 4.9	[7] ABBOTT	99G	D0	di-lepton, lepton+jets
176.0 ± 6.5	[3,8] ABE	99B	CDF	dilepton, lepton+jets, and all jets
175.9 ± 4.8 ± 5.3	[2,9] ABE	98E	CDF	lepton + jets
161 ± 17 ± 10	[2] ABE	98F	CDF	dilepton
172.1 ± 5.2 ± 4.9	[10] BHAT	98B	RVUE	dilepton and lepton+jets
173.8 ± 5.0	[11] BHAT	98B	RVUE	dilepton, lepton+jets, and all jets
173.3 ± 5.6 ± 6.2	[4] ABACHI	97E	D0	lepton + jets
199 $^{+19}_{-21}$ ± 22	ABACHI	95	D0	lepton + jets
176 ± 8 ± 10	ABE	95F	CDF	lepton + b-jet
174 ± 10 $^{+13}_{-12}$	ABE	94E	CDF	lepton + b-jet

174 GeV !

The fact that the top is so heavy implies that it cannot hadronize.
Top hadrons do not exist :

$$\frac{1}{\tau} = \Gamma_t = \frac{G_F^2 m_t^5}{192\pi^3}$$

$$\tau(\mathrm{top}) = m^5(\mu)/m^5(\mathrm{top})\ \tau(\mu) \sim 2 \times 10^{-23}\ \mathrm{sec}$$

Lifetime is too short to form aggregate

b is the heaviest quark forming hadrons
c is the heaviest 2/3 quark forming hadron

The Quantum path

The indirect searches
look for "New Physics"
through virtual effects from new particles in loop corrections

..Or the heavyness of the top quark…seen by B physics

Before the top discovery, the top mass was predicted to be larger than 150 GeV within an error of about 30 GeV.
Through the radiative corrections it was even better known at about 10 GeV error.

The quarks c b and t were discovered in an indirect way by using **rare decays**, and more precisely **FCNC**, such as

$K^0 \rightarrow \mu\mu$, $K_L \rightarrow \pi\pi$ and **B oscillations**

① ~1970 charm quark from FCNC and GIM-mechanism $K^0 \rightarrow \mu\mu$

② ~1973 3rd generation from CP violation in kaon (ε_K) KM-mechanism

③ ~1990 heavy top from B oscillations Δm_B