Flavour Physics (I)
History and recent progress at LHC

Summer Institute 2013

17 - 23 August 2013, Jirisan National Park, Korea

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Laboratory for High Energy Physics (LPHE)

Swiss Federal Institute of Technology Lausanne (EPFL)

Lausanne, Switzerland

What is on the moon?

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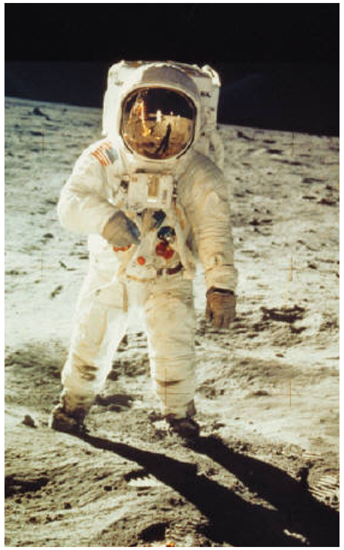

Of course going there...

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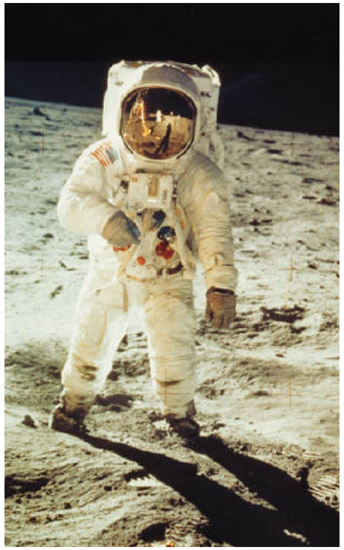

Of course going there...

But you can study a lot from here before

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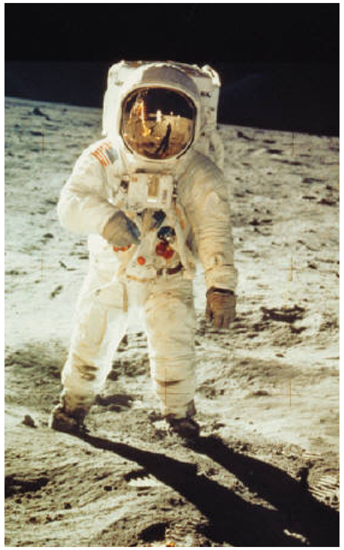

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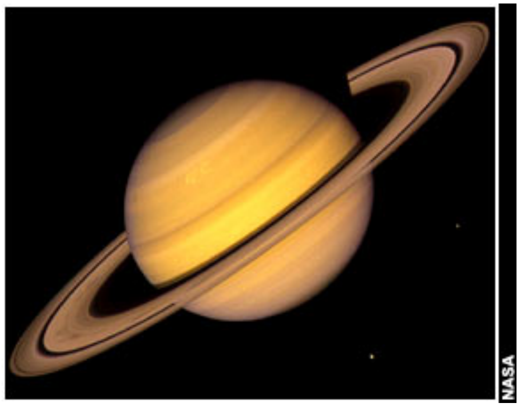
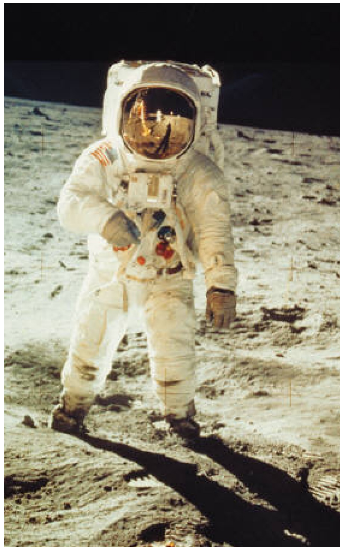


And may be finding something new?

What is on the moon?



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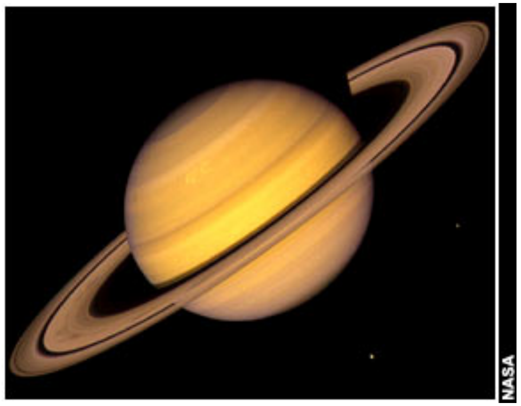
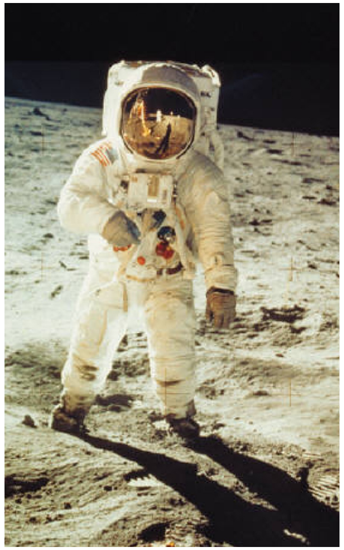


And may be finding something new?

Instruments can be improved and

What is on the moon?



Of course going there...

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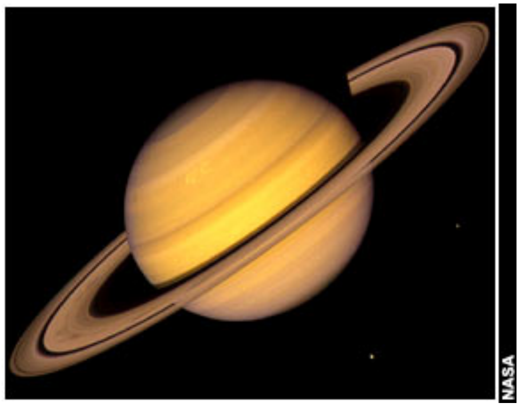
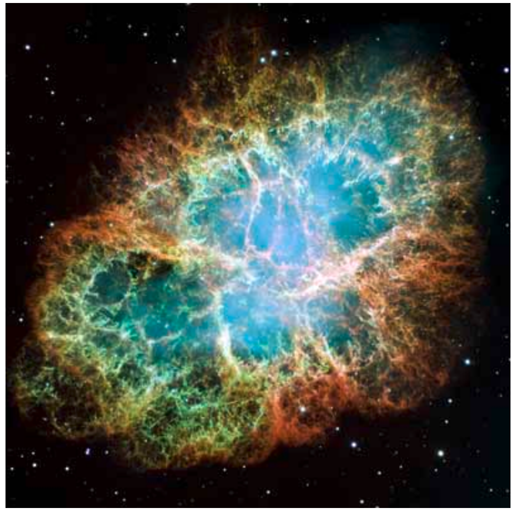


And may be finding something new?

Instruments can be improved and



We see far beyond the direct reach...

Plan of the lecture today

- Early History
  温故知新
  Let us make a slow start…
- Standard Model Flavour Framework

Early History

Start with Isospin (Heisenberg)...

$\rightarrow$ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

$\Downarrow$

p and n (or π^+, π^0 and π^-) are identical when switching off alectromagnetic interactions

Early History

Start with Isospin (Heisenberg)...

→ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

"Strangeness" played a role in establishing
the concept of flavour quantum numbers
(Gell-Mann 56, Nishijima 55)

⇓

Reflecting on the discovery of long living particles (1947)
selection rule based on a quantum number which is
conserved in strong and electromagnetic interactions
not conserved in weak interactions

Early History

Start with Isospin (Heisenberg)...

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"Strangeness" played a role in establishing the concept of flavour quantum numbers (Gell-Mann 56, Nishijima 55)

"quark" in early 1960's

(Gell-Mann, Ne'eman, Han-Nambu, Nishijima, Sakata, Zweig, etc.)

SU(3) flavour symmetry: (u, d, s)

$\Downarrow$

Reflecting on the particle zoo, in particular the hyperons

Early History

Start

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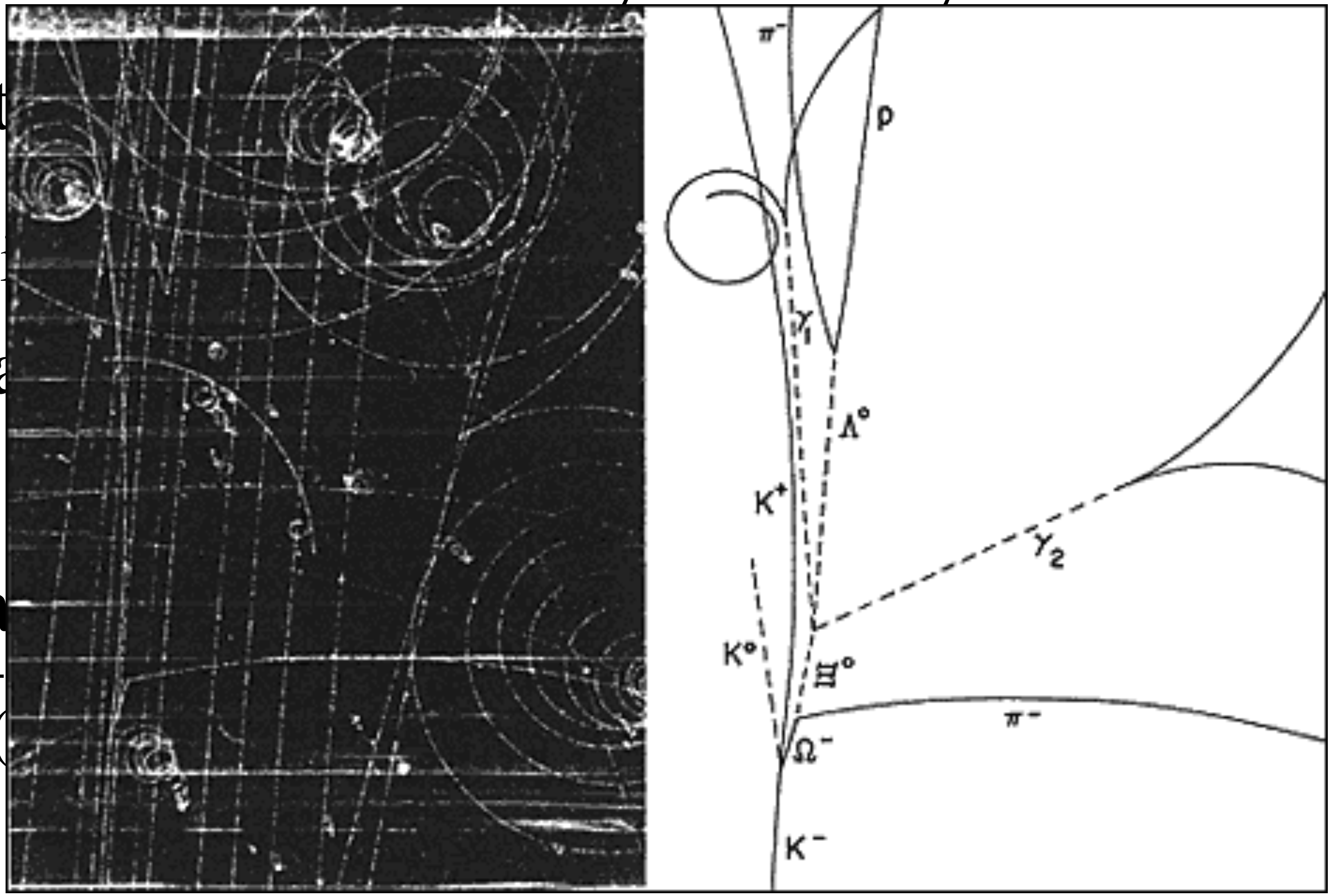

→Ω^- (sss) prediction,

discovered in 1964, Barmes et al.

Early History

Start with Isospin (Heisenberg)...

→ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

"Strangeness" played a role in establishing the concept of flavour quantum numbers

(Gell-Mann 56, Nishijima 55)

"quark" in early 1960's

(Gell-Mann, Ne'eman, Han-Nambu, Nishijima, Sakata, Zweig, etc.)

SU(3) flavour symmetry: (u, d, s)

My private reflection

Colour was needed for the constituent quark model:

Δ^{++}(Q=+2, Spin 3/2 baron) = (u↑, u↑, u↑).

We know now: the spin of baryon is little given by the valence quark

Early History

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing:

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

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 θ^0, a heavy boson that is known to decay by the process $\theta^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ 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 θ^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 all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

$$K^0 \leftrightarrow \pi^+\pi^- \leftrightarrow \overline{K}^0 \Longrightarrow \quad K_1 = \frac{K^0 + \overline{K}^0}{\sqrt{2}}, \quad K_2 = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$

under C symmetry, K_1 and K_2 two very different lifetimes

Why?

(later $C\!\!\!/$ discovered → change to CP conservation)

Early History

Observation of Long-Lived Neutral *V* Particles*

Phys Rev Lett. 1956

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)

cloud chamber exposure at BNL

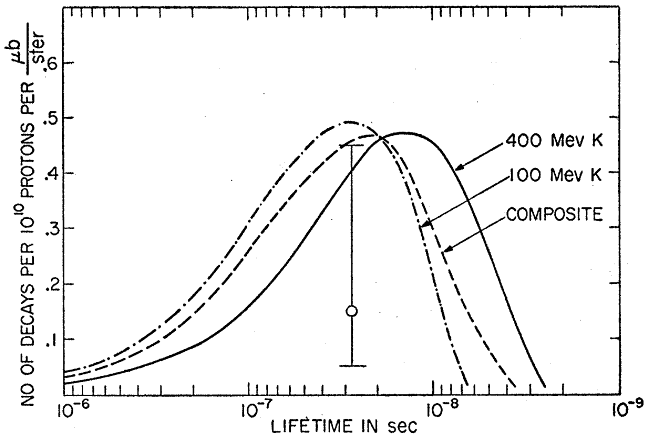

FIG. 2. Detection sensitivity for *K* mesons as function of lifetime. The composite curve is obtained with the spectra of reference 5. The point indicates the observed yield with a production cross section of ~20 μb/sterad.

lifetime for $\pi^+\pi^-$ decay already known to be ~10^{-10} sec

lifetime measurement for
3-body decays ($\pi\mu\nu$, $\pi e\nu$, $\pi^+\pi^-\pi^0$)
>10^{-9} sec

Establish two particle states: short-living, K_S, decays into 2π and long-living, K_L, decays into 3π, $\pi l\nu$: $K^0-\overline{K}^0$ mixing

Early History

Cabibbo theory (Phys. Rev. Lett. 1963)

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

Why ΔS=1 decay process is suppressed?
e.g. $\Gamma(K\to\mu\nu) \ll \Gamma(\pi\to\mu\nu)$ after correcting the phase space

$\Downarrow$

Weak interaction charged current (ΔQ=1)

$J\mu = \cos\theta \times j_\mu(\Delta S=0) + \sin\theta \times j_\mu(\Delta S=1)$

θ: Cabibbo angle

(unitary through $\cos^2\theta + \sin^2\theta = 1$)

Early History

Cabibbo theory (Phys. Rev. Let. 1963)

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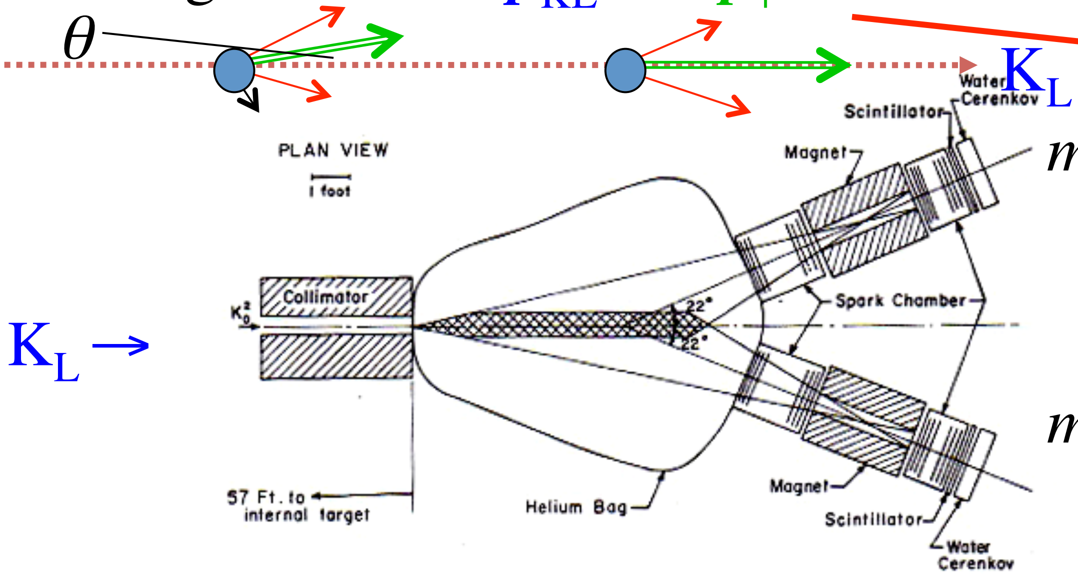
CP violating $K^0_L \to \pi^+\pi^-$ decays: 1964, J.H. Christenson et al.

$\boldsymbol{p}_{+-} = \boldsymbol{p}_{\pi+} + \boldsymbol{p}_{\pi-}$

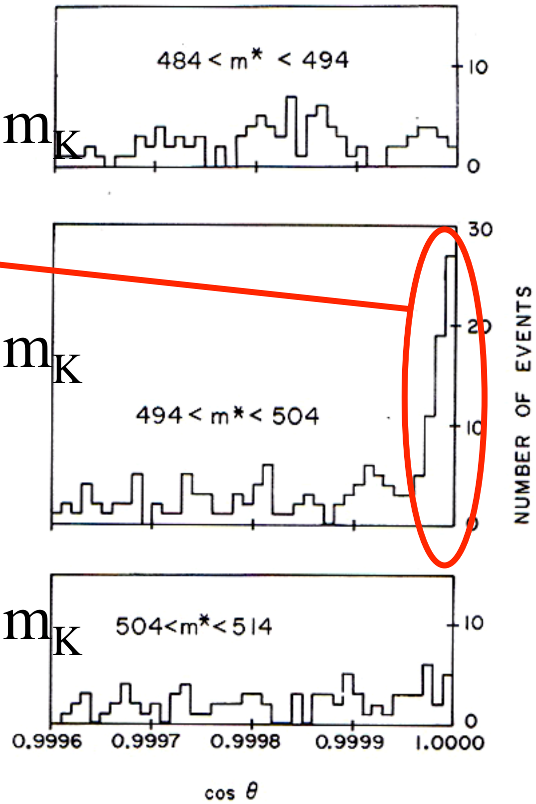
θ = angle between $\boldsymbol{p}_{KL}$ and $\boldsymbol{p}_{+-}$



$m(\pi^+\pi^-) < m_K$

$m(\pi^+\pi^-) = m_K$

$m(\pi^+\pi^-) > m_K$



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UNITARY SYMMETRY AND LEPTONIC DECAYS

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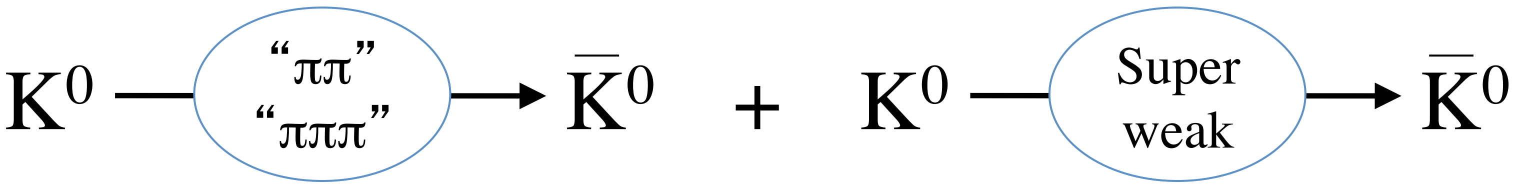
CP violating $K^0_L \to \pi^+\pi^-$ decays: 1964, J.H. Christenson et al.

This was beyond the comprehension of that time and no relation between the flavour considered:

e.g. Superweak model (Phys. Rev. Let. 1964)

VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 31 August 1964)



Early History

Glashow–Iliopoulos–Maiani mechanism (Phys Rev D 1970)

Why Δm_K is so small and $K_L \rightarrow \mu^+\mu^-$ very suppressed?

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Early History

Glashow–Iliopoulos–Maiani mechanism (Phys Rev D 1970)

Why Δm_K is so small and $K_L \to \mu^+\mu^-$ very suppressed?

Having 4th quark already considered in ~1964 (even with the name "charm")
(Gell-Mann, Tarjanne and Teplitz, Hara, Bjørken and Glashow,)
ν_μ discovered in 1962, Lederman, Schwartz and Steinberger,

$$\begin{pmatrix} u \\ d' \end{pmatrix}\begin{pmatrix} c \\ s' \end{pmatrix}\begin{pmatrix} \nu_e \\ e \end{pmatrix}\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

$$d' = d\cos\theta + s\sin\theta$$

$$s' = -d\sin\theta + s\cos\theta$$

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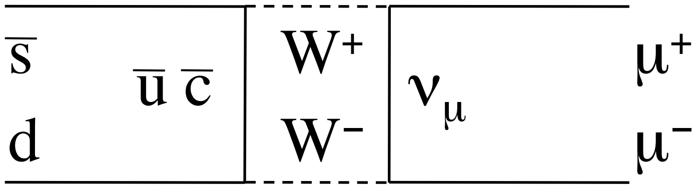
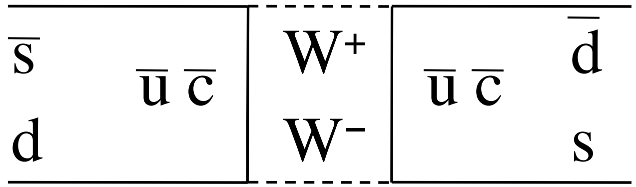
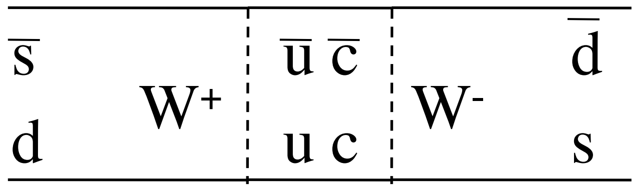


$$Br(K^0 \to \mu^+\mu^-) = F(m_c, \ldots)$$





$$\Delta m_K = G(m_c, \ldots)$$

$$\text{if } m_c = m_u,\ \propto \sin\theta\cos\theta - \sin\theta\cos\theta = 0$$

Early History

Glashow–Iliopoulos–Maiani mechanism (Phys Rev D 1970)

Why Δm_K is so small and $K_L \to \mu^+\mu^-$ very suppressed?

Estimation of m_c ~ 1.5 GeV (Gaillard and Lee, Phys Rev D 1974)

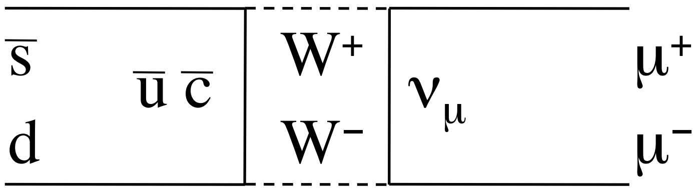
$K_L \to \mu^+\mu^-$ suppressed

$K_L \to \gamma\gamma$ not suppressed

$\Delta m_K = m_L - m_S$ experimentally measured

$$d' = d\cos\theta + s\sin\theta$$

$$s' = -d\sin\theta + s\cos\theta$$



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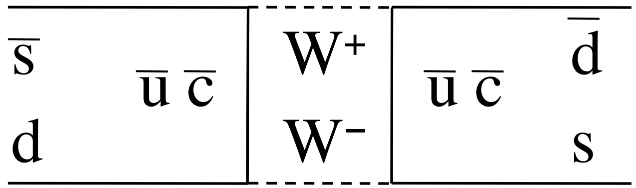

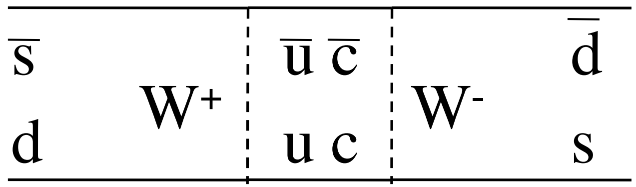

$$\Delta m_K = G(m_c, \ldots)$$

Early History

...echanism (Phys Rev D 1970)

...μ^- very suppressed?

...l and Lee, Phys Rev D 1974)

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973

(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Charm discovery with hadron and e^+e^- machines

Aubert et al. and Augustin et al., 1974

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

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Aubert et al. and Augustin et al., 1974

Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo
**Yokohama National University*

August 9, 1971

Emulsion exposed in a JAL Jet cargo plane
One event of $X \rightarrow \pi^0$ + one charged hadron

hypo.	$\pi^0\pi^{charged}$	$\pi^0 p$
τ(s)	2.2×10^{-14}	3.6×10^{-14}
m(GeV)	1.78	2.95

Observation of $D \rightarrow K\pi^0$ decay in 1971?

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Charm discovery with hadron and e^+e^- machines

Aubert et al. and Augustin et al., 1974

Third quark family (Kobayashi and Maskawa, Prog. Theor. Phys. 1973)

naturally introduces
CP violation
in weak interactions

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.

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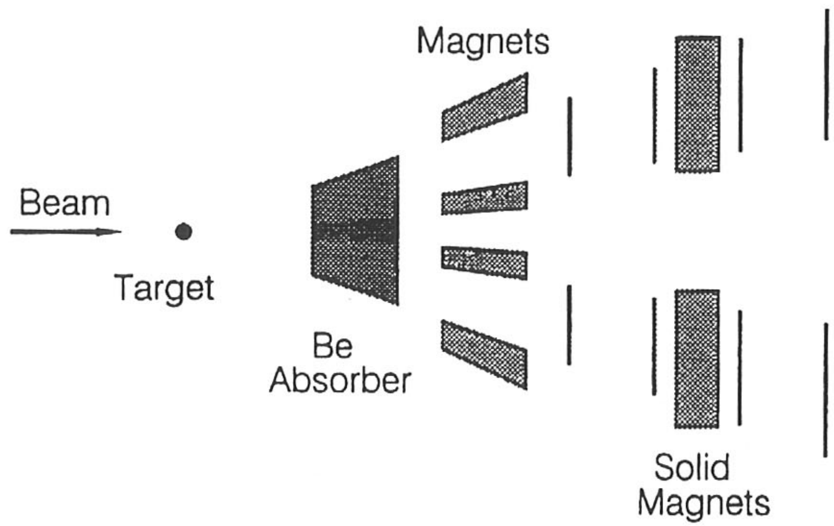
Flavour framework of the Standard Model established

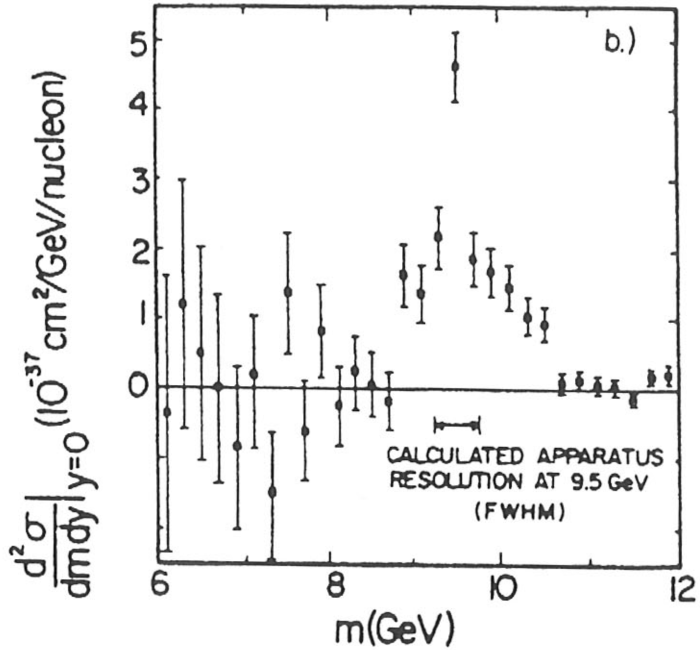
And b quark discovered in 1977

Early History

E288 experiment @ FNAL, S. Herb et al. in 1977

p(400 GeV) + Cu or Pt $\rightarrow \Upsilon(\rightarrow \mu^+ \mu^-) + X$





$(b\bar{b})$ bound states; $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

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And b quark discovered in 1977 (Herb et al., Phys. Rev. Lett. 1977)

Standard Model Flavour Framework

flavour eigenstatetates	⇒	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

Standard Model Flavour Framework

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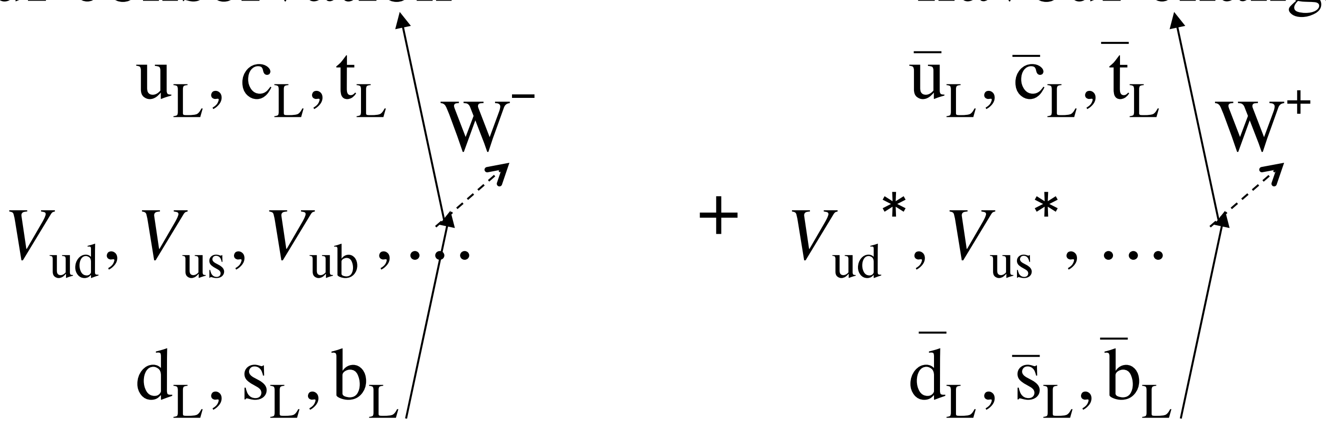

$$L \propto V_{ij}\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger + V_{ij}^*\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu$$

Standard Model Flavour Framework

flavour eigenstatetates	$\Rightarrow$	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

u_L, c_L, t_L — W^- — d_L, s_L, b_L: $V_{ud}, V_{us}, V_{ub}, \ldots$ $+$ $\bar{u}_L, \bar{c}_L, \bar{t}_L$ — W^+ — $\bar{d}_L, \bar{s}_L, \bar{b}_L$: $V_{ud}^*, V_{us}^*, \ldots$

$$L \propto V_{ij}\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger + V_{ij}^*\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu$$

$\Updownarrow$ CP conjugation

$$L_{CP} \propto V_{ij}\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu + V_{ij}^*\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger$$

Standard Model Flavour Framework

flavour eigenstatetates ⇒ masseigenstates

flavour eigenstatetates	⇒	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

$$u_L, c_L, t_L \quad W^-$$
$$V_{ud}, V_{us}, V_{ub}, \ldots$$
$$d_L, s_L, b_L$$

$$+ \quad \bar{u}_L, \bar{c}_L, \bar{t}_L \quad W^+$$
$$V_{ud}^*, V_{us}^*, \ldots$$
$$\bar{d}_L, \bar{s}_L, \bar{b}_L$$

$$L \propto V_{ij}\,\bar{U}_i\,\gamma^\mu(1-\gamma_5)\,D_j\,W_\mu^\dagger + V_{ij}^*\,\bar{D}_i\,\gamma^\mu(1-\gamma_5)\,U_j\,W_\mu$$

⇕ CP conjugation

$$L_{CP} \propto V_{ij}\,\bar{D}_i\,\gamma^\mu(1-\gamma_5)\,U_j\,W_\mu + V_{ij}^*\,\bar{U}_i\,\gamma^\mu(1-\gamma_5)\,D_j\,W_\mu^\dagger$$

If $V_{ij}^* = V_{ij} \rightarrow L = L_{CP}$: i.e. CP conservation

Standard Model Flavour Framework

flavour eigenstatetates ⇒ masseigenstates

-non-diagonal mass matrix

-strong and EM interactions

-flavour conservation

masseigenstates

-diagonal mass matrix

-weak interactions

-flavour changing

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

V_{CKM}: generally called CKM (mass mixing) matrix

$$V_{\mathrm{CKM}}^{\dagger} \times V_{\mathrm{CKM}} = 1$$

Standard Model Flavour Framework

flavour eigenstatetates ⇒ masseigenstates

flavour eigenstatetates	masseigenstates
-non-diagonal mass matrix	-diagonal mass matrix
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$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

V_{CKM}: generally called CKM (mass mixing) matrix

$$V^{\dagger}_{\mathrm{CKM}} \times V_{\mathrm{CKM}} = 1$$

Can you show this explicitly by using the arbitrary quark phases and unitarity?

Pre KM, V_{CKM} was 2×2

With 2×2 unitary matrix, one angle (1-2 rotation)

Standard Model Flavour Framework

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$$V_{\mathrm{CKM}}^{\dagger} \times V_{\mathrm{CKM}} = 1$$

Pre KM, V_{CKM} was 2×2

With 2×2 unitary matrix, one angle (1-2 rotation)

With 3×3 matrix, three angles (1-2, 2-3, 1-3 rotations) and one phase

$\Rightarrow$ with three families, some of V_{ij}'s are intrinsically complex

Standard Model Flavour Framework

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$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \rho\left(1-\frac{\eta^2}{2}\right)$$

λ, A, ρ, η: Wolfenstein's parameterization

Approximation with expansions in λ

NB $A \neq 0$, $\rho \neq 0$, $\eta \neq 0$ for CP violation

Standard Model Flavour Framework

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JADE Physics Letters B 1983

$\tau < 1.4\times10^{-12}$ s (95% CL)

Theoretical predictions e.g. V. Barger et al.

$0.8\times10^{-14} < \tau < 1.4\times10^{-13}$ sec, J. Phys. G 5, L147 (1979)

i.e. general prejudice was $|V_{cb}| \approx |V_{us}|$

Standard Model Flavour Framework

MAC

Phys. Rev. Lett. 51, (1983) 1022

Lifetime of Particles Containing *b* Quarks

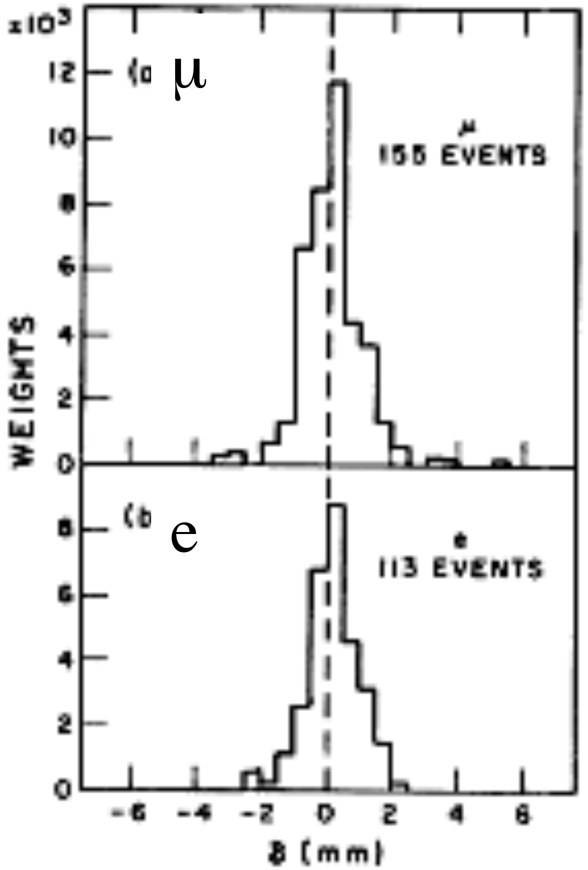
$[1.8\pm0.6(\text{stat.})\pm0.4(\text{syst.})]\times10^{-12}$ sec.

Mark II

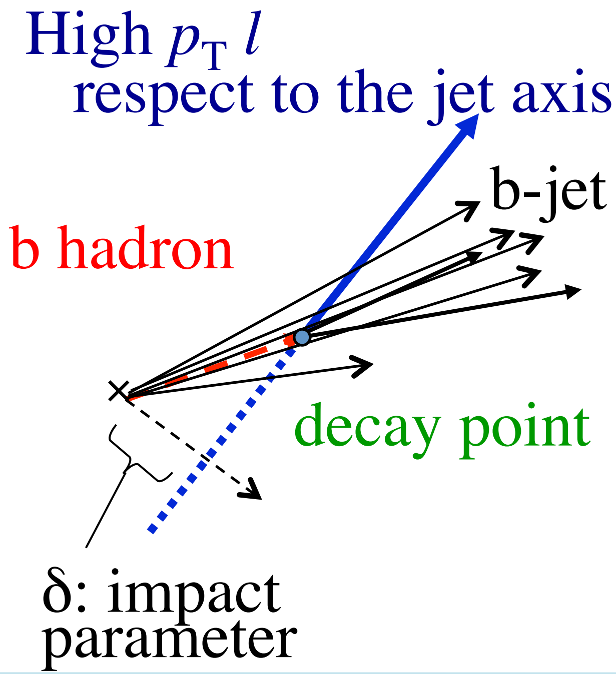
Phys. Rev. Lett. 51, (1983) 1316

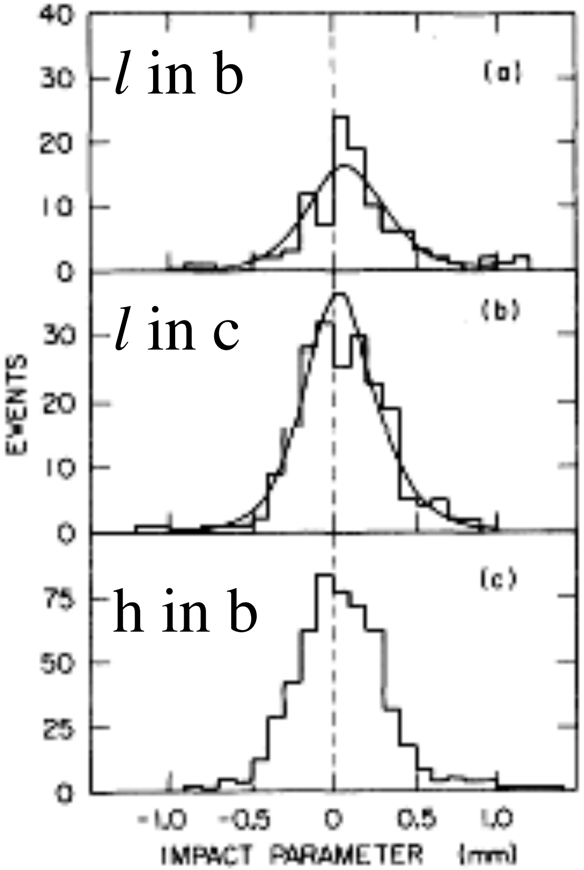
Measurement of the Lifetime of Bottom Hadrons

$\tau_b=(12.0^{+4.5}_{-3.6}\pm3.0)\times10^{-13}$ sec



Impact parameter distributions for b→$l\nu$X decays.





Standard Model Flavour Framework

flavour eigenstatetates $\Rightarrow$ masseigenstates

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$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

discovery of large b lifetime, i.e. small $|V_{\mathrm{cb}}|$

MAC: Phys. Rev. Lett. 51, (1983) 1022
Mark II: Phys. Rev. Lett. 51, (1983) 1316

$\tau_B \sim 10^{-12}$ sec, $|V_{\mathrm{cb}}| \sim 0.05$,
i.e. << $\sin\theta_{\mathrm{Cabibbo}} \sim 0.2$

Standard Model Flavour Framework

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$\lambda = \sin\,\theta_{\text{Cabibbo}} \approx 0.22$

$A \approx 0.8$

Standard Model Flavour Framework

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$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

$$A \approx 0.8$$

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

Observation of b → ulν decays: $|V_{\mathrm{ub}}| \neq 0$

(cf. like θ_{13} in ν now)

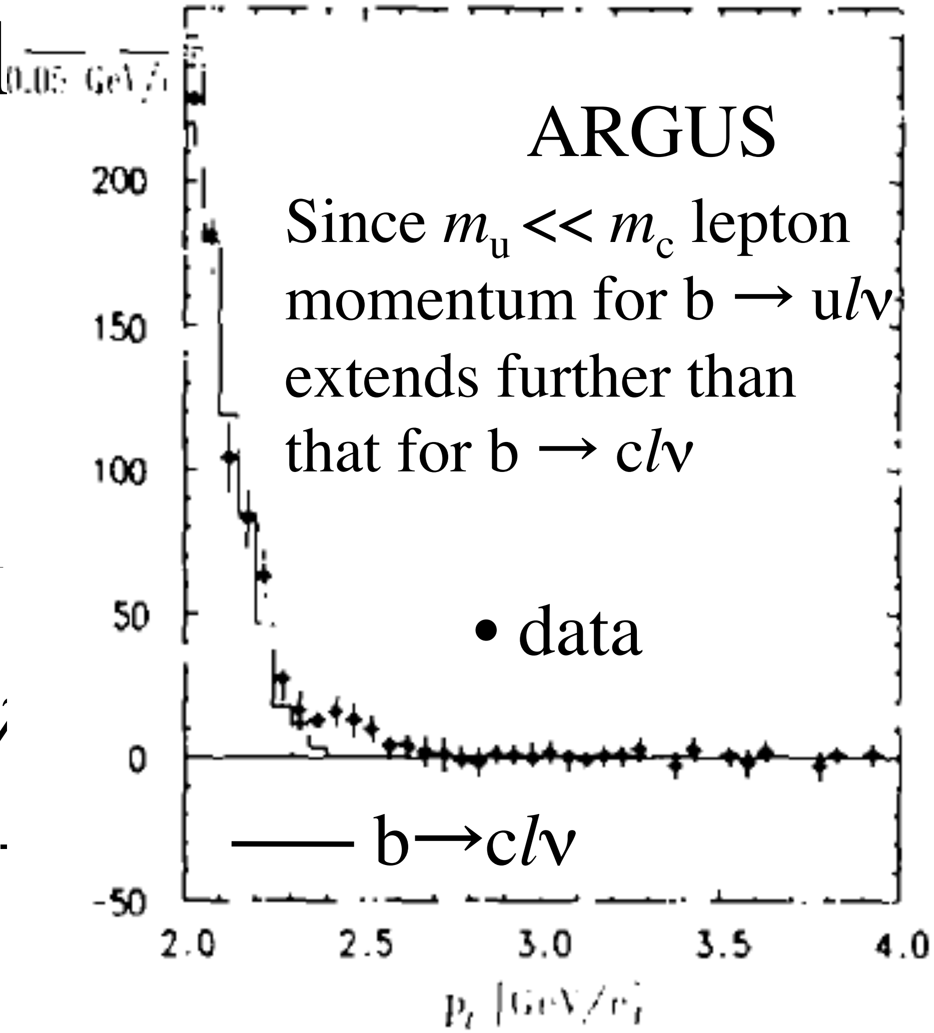
Standard Model Fl

flavour eigenstatetates
-non-diagonal mass matrix
-strong and EM interactions
-flavour conservation

$$V_{\rm CKM} = \begin{pmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} \\ -\lambda - iA^2\lambda \\ A\lambda^3(1-\hat{\rho} \end{pmatrix}$$

$\lambda = \sin\,\theta_{\rm Cabibbo} \approx 0.22$

$A \approx 0.8$



Observation of b → u$l\nu$ decays: $|V_{\rm ub}| \neq 0$

$|\boldsymbol{p}_l|$ = 2.4 - 2.6 GeV/c in the B rest frame

$|V_{\rm ub}|$ is very small ≈ 0.005

= 76 ± 18 ± 8 in 2.4-2.6 GeV/c CLEO 1990

= 49 − $(18.2 \pm 3.3)_{\rm background}$ ARGUS 1990

Standard Model Flavour Framework

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$A \approx 0.8$

$\rho^2 + \eta^2 \approx 0.3$

Standard Model Flavour Framework

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$$A \approx 0.8$$

$$\rho^2 + \eta^2 \approx 0.3$$

Observation of B^0-$\overline{B}^0$ oscillations: $|V_{\rm td}| \neq 0$

Standard Model Flavour Framework

Phys. Lett. B 192 (1987) 245

ARGUS, 1987

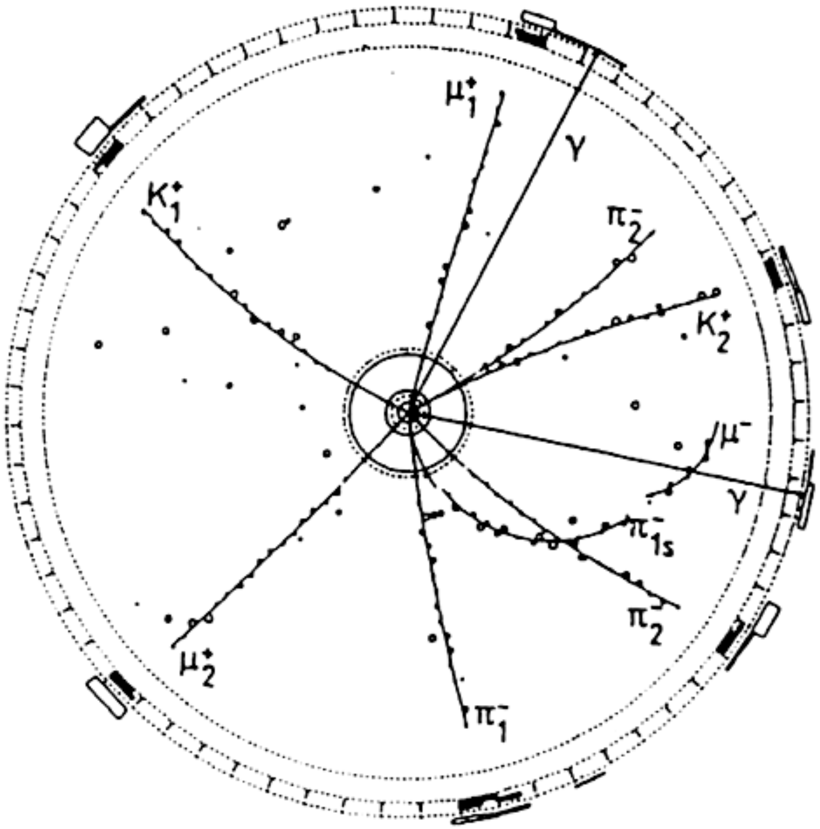
$\Upsilon(4S) \rightarrow B_d^0 \overline{B}_d^0$

$\rightarrow B_d^0 B_d^0$ or $\overline{B}_d^0 \overline{B}_d^0$

$\rightarrow \ell^+ \ell^+$ or $\ell^- \ell^-$

24.8±7.6±3.8

$\Delta m(B_d) \sim 100 \times \Delta m(K^0)$



Volume 192, number 1,2 PHYSICS LETTERS B

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

Using the ARGUS detector at the DORIS II storage ring we have searched in three different ways for B^0–$\bar{B}^0$ mixing in Υ (4S) decays. One explicitly mixed event, a decay Υ (4S)$\rightarrow B^0B^0$, has been completely reconstructed. Furthermore, we observe a 4.0 standard deviation signal of 24.8 events with like-sign lepton pairs and a 3.0 standard deviation signal of 4.1 events containing one reconstructed $B^0(\bar{B}^0)$ and an additional fast $\ell^+(\ell^-)$. This leads to the conclusion that B^0–$\bar{B}^0$ mixing is substantial. For the mixing parameter we obtain $r=0.21\pm0.08$.

Standard Model Flavour Framework

Phys. Lett. B 192 (1987) 245

ARGUS, 1987

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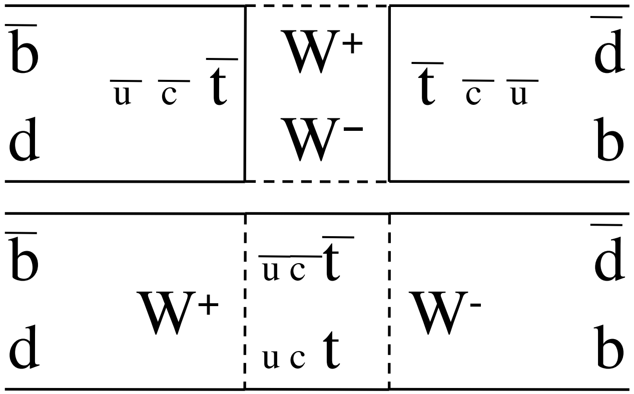

$\Delta m_B = G(|V_{td}V_{tb}|, m_t, \ldots)$

Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

$m_t > 50\ \text{GeV}/c^2$

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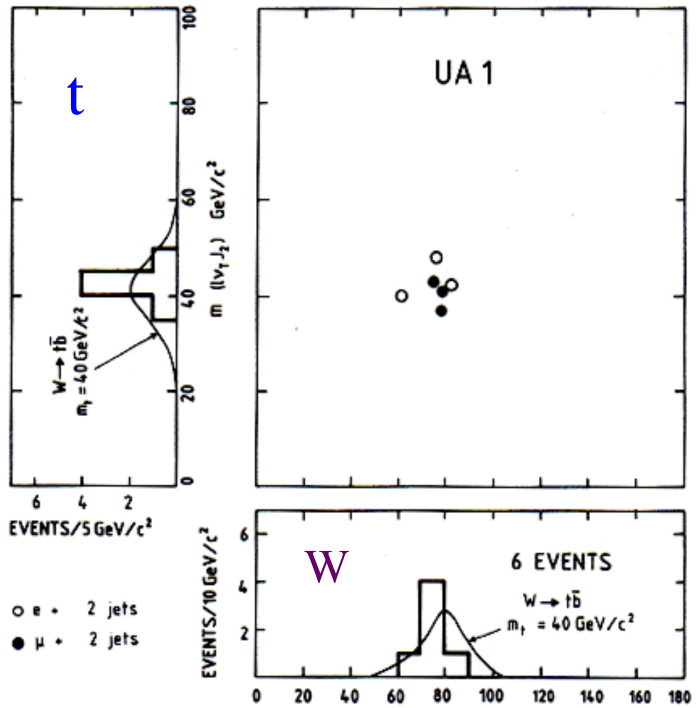
UA1, 1984

$p\bar{p} \rightarrow W^+ + X$

$\hookrightarrow W^+ \rightarrow t\,\bar{b}$ → jet

$t \hookrightarrow b\ell\nu$ → jet

$m_t = 30\sim50$ GeV/c^2



Phys. Lett. 147B (1984) 493

Standard Model Flavour Framework

Phys. Lett. B 192 (1987) 245

ARGUS, 1987

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LEP
electroweak fit
150~210 GeV/c^2

1995
CDF
175±8±10 GeV/c^2
D0
199^{+19}_{-21}±22 GeV/c^2

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$A \approx 0.8$

$\rho^2 + \eta^2 \approx 0.3$

$(1 - \hat{\rho})^2 + \hat{\eta}^2 \approx 0.9$

Standard Model Flavour Framework

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$A \approx 0.8$

$\rho^2 + \eta^2 \approx 0.3$

$(1 - \hat{\rho})^2 + \hat{\eta}^2 \approx 0.9$

It shows clearly $\eta \neq 0$, i.e. CPV!

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$$A \approx 0.8$$

$$\rho^2 + \eta^2 \approx 0.3$$

$$(1-\hat{\rho})^2 + \hat{\eta}^2 \approx 0.9$$

b→sγ decays and B_s^0-$\overline{B}_s^0$ oscillations for $|V_{ts}|$

Standard Model Flavour Framework

- By the early 90's, the Standard Model model description of "flavour" through the Cabibbo-Kobayashi-Maskawa mass mixing matrix established well enough (nuclear β decays, kaon decays, charm decays and b decays, in particular with ε_K and Δm_d with little uncertainty from the still unmeasured m_t), to make a firm statement such as
  - If CPV is generated by the CKM phase, CPV in the $B \rightarrow J/\psi K_S$ decays must be observed with >5σ within a few years of running with an asymmetric B factory with a luminosity of $\sim 10^{33} cm^{-2} s^{-1}$

→ This was the main motivation for asymmetric B factories

Standard Model Flavour Framework

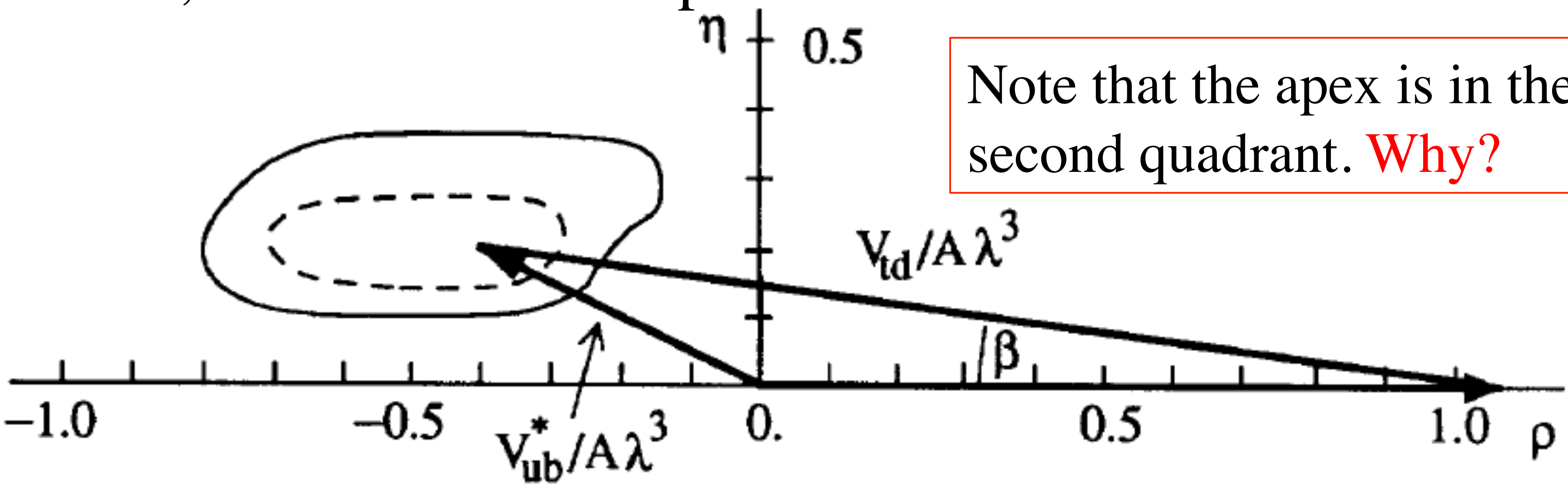
- For example

$$\mathrm{Im}(\lambda) \approx \frac{2\sqrt{2}|\varepsilon|}{A^2 S_c^4}\left(\frac{\Delta m_K}{\Delta m_B}\right)\left(\frac{m_B}{m_K}\right)\left(\frac{\eta_B}{\eta_3}\right)\left(\frac{f_B^2 B_B}{f_K^2 B_K}\right)$$

$$\approx 0.3\cdot\left(\frac{1}{A^2}\right)\cdot\left(\frac{f_B^2 B_B}{f_K^2 B_K}\right).$$

f_B was considered to be $\approx$ 110 MeV at that time
Now $\approx$ 230 MeV

- From "Feasibility study for a B-meson factory in the ISR tunnel", CERN Yellow Report CERN 90-02



Note that the apex is in the second quadrant. Why?