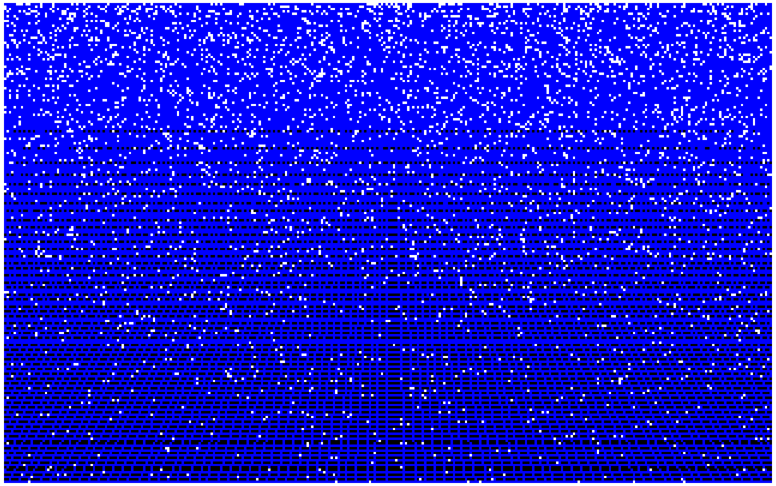
Elementaire Deeltjesfysica

FEW Cursus



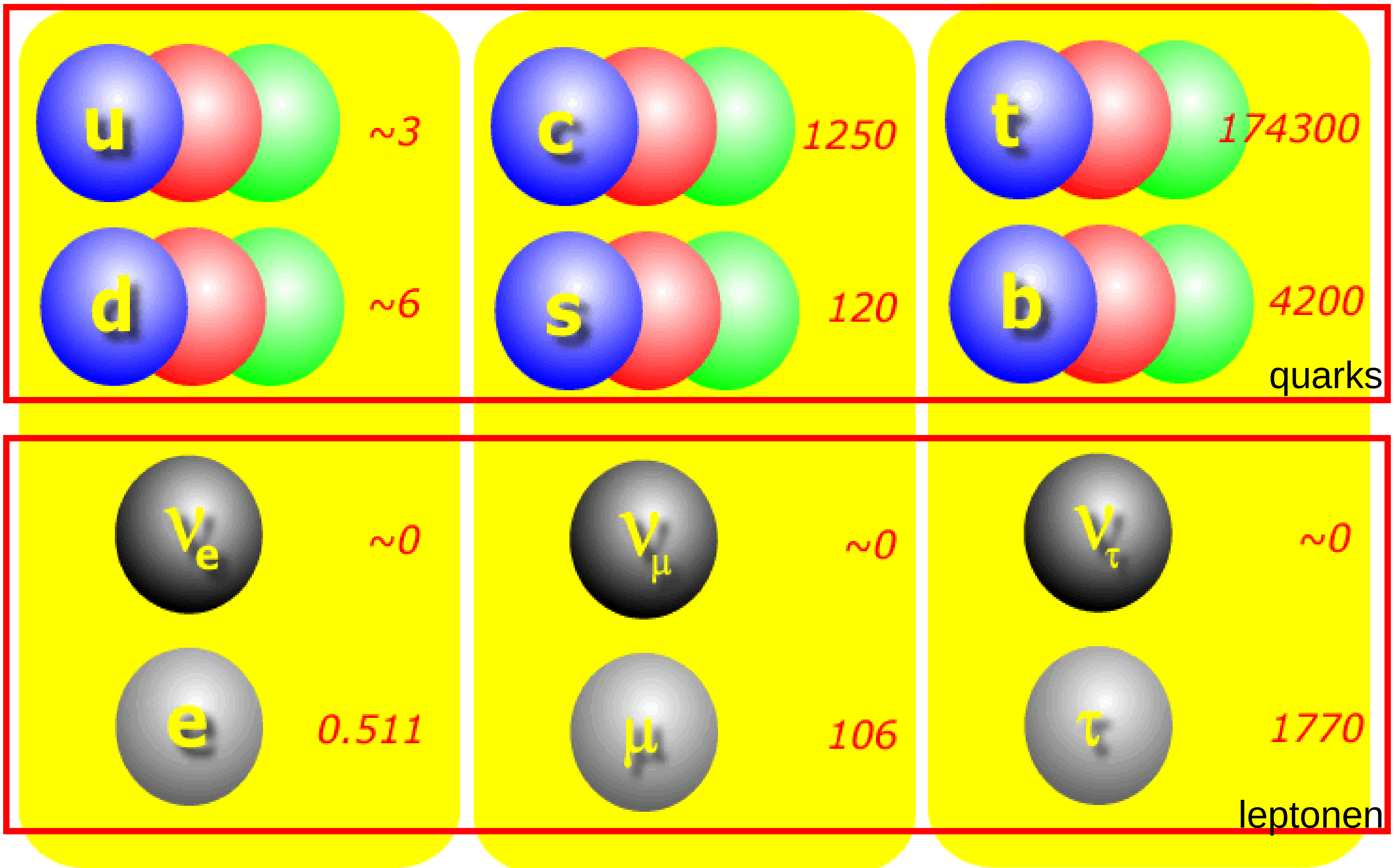
Jo van den Brand

3 November, 2009

Structuur der Materie

Inhoud

Drie families: 1897 - 2000



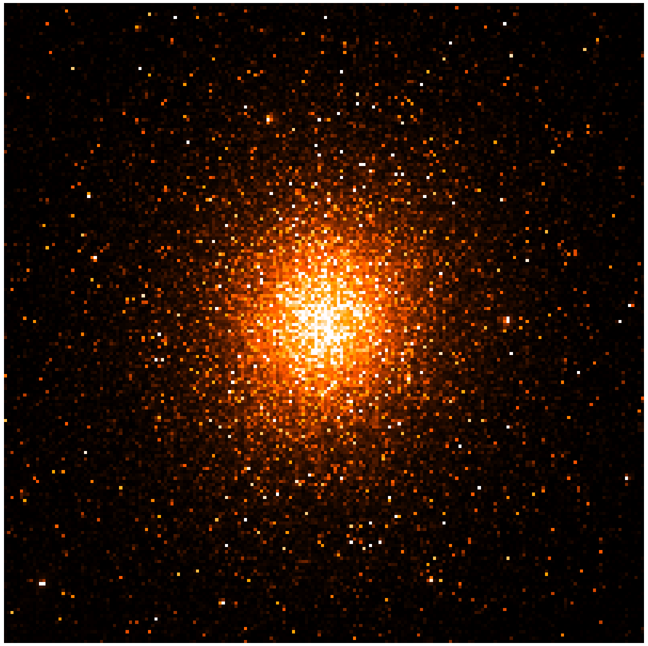
Massa's van deeltjes in MeV; 1 MeV ≈ 1.8×10^{-27} gram

Interacties - dynamica

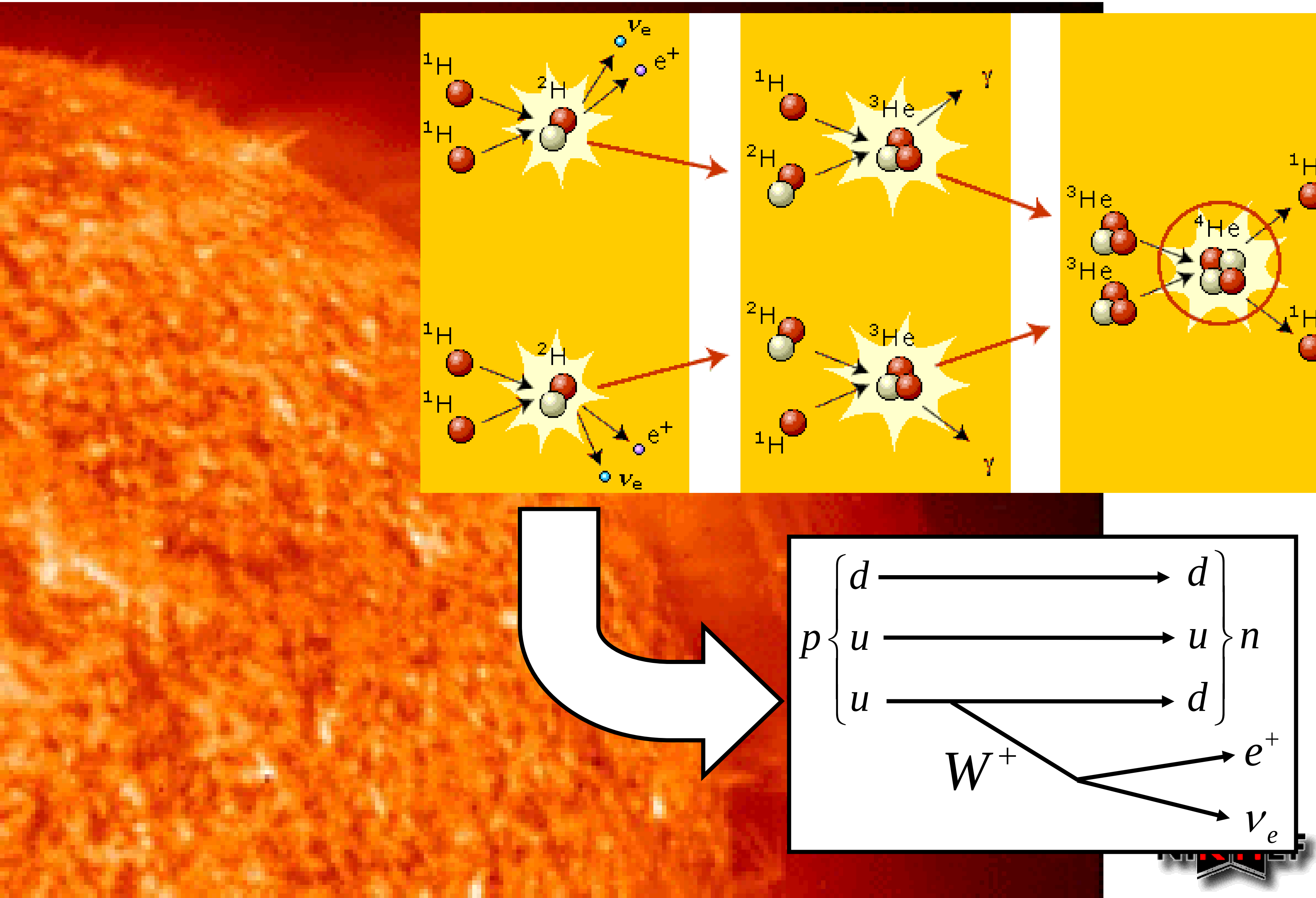
Krachten

- De bouwstenen van de natuur vormen structuren, van protonen to sterrenstelsels. Dit komt omdat deeltjes met elkaar wisselwerken.
- De bekendste kracht is *gravitatie*. Hierdoor staan we op aarde en bewegen de planeten rond de zon.
- Gravitatie is met name belangrijk in massieve objecten en is zwak tussen individuele bouwstenen.
- Een sterkere fundamentele kracht manifesteert zich in de effecten van elektriciteit en magnetisme.
- De *elektromagnetische kracht* bindt negatieve elektronen aan de positieve kernen in atomen. Het geeft ook aanleiding tot de vorming van moleculen en vaste stoffen en vloeistoffen.

Omega Centauri globular cluster



"Zwakke" wisselwerking



Interacties: QED, QCD, EZ, Gravitatie

Wisselwerking	Sterkte [e]	Dracht	Boson	Massa [GeV/c^2]	Koppelt aan
El. magn	$1/137$	∞	γ	0	Lading
Zwakke	3×10^{-12}	$\ll 10^{-15}$ m	$W^{\pm}$, Z^0	80, 91	Quarks, Lept.
Gravitatie	5.9×10^{-39}	∞	Graviton	0	Massa
~~Kernkracht~~	~~1~~	~~$\leq 1.4 \times 10^{-15}$ m~~	~~$\pi^{\pm}$, enz.~~	~~0.135, ..~~	~~Hadronen~~
Sterke	1	Confinement	8 Gluonen	0	Quarks

EM

$$U_{\rm em} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r} \rightarrow \left(\frac{e^2}{4\pi\epsilon_0 \hbar c}\right)\hbar c \frac{1}{r} = \alpha_{\rm em}\hbar c \frac{1}{r}$$

$$\alpha_{\rm em} = \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{1}{137.036},$$

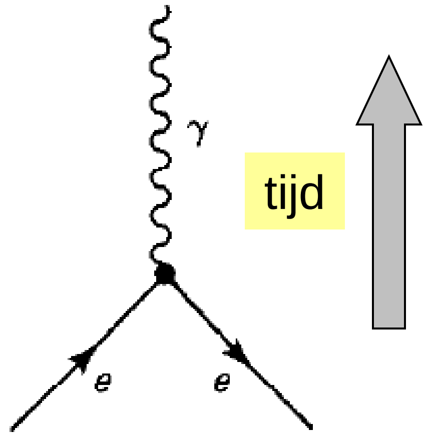
$$\boxed{\begin{aligned} \alpha_F &= 3 \times 10^{-12} \\ \alpha_S &= 0.07 - 14 \end{aligned}}$$

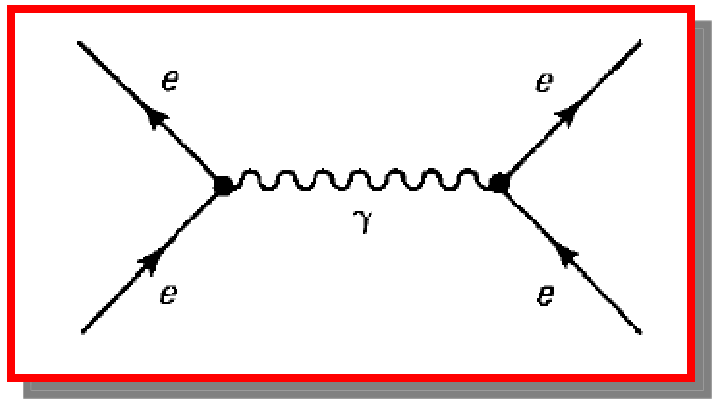
Gravitatie

$$\underline{U_{\rm grav} = -g_{\rm grav}\frac{m_1 m_2}{r}} \rightarrow -g_{\rm grav}\frac{m_p^2}{\hbar c}\hbar c \frac{1}{r} = -\alpha_{\rm grav}\hbar c\frac{1}{r}$$

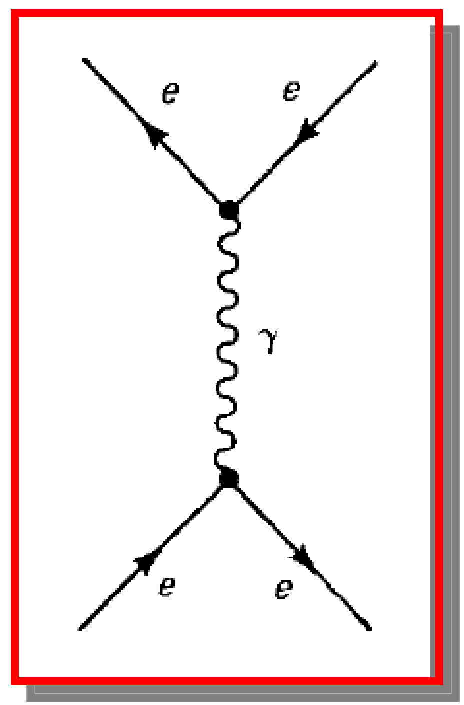
$$\alpha_{\rm grav} = g_{\rm grav}\frac{m_p^2}{\hbar c} = 5.9 \times 10^{-39}$$

Feynman diagrammen - QED





Moller scattering

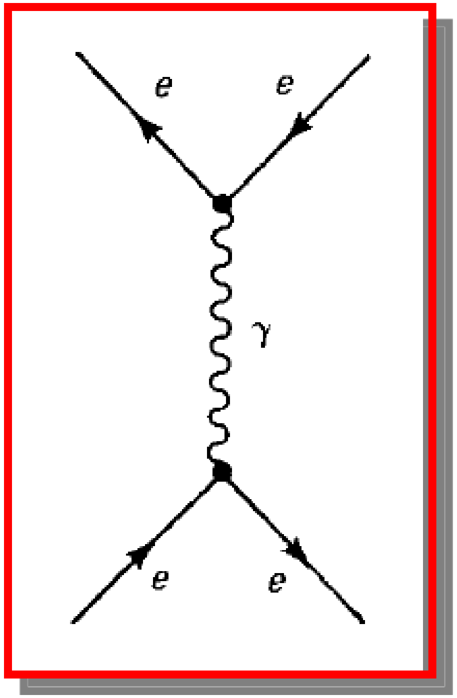


Bhabha scattering

Elementair process
- vertex
- propagator
- asymptotische toestand
- structuur $q\gamma q$
- antideeltje notatie

Feynman 1965

Feynman diagrammen - QED



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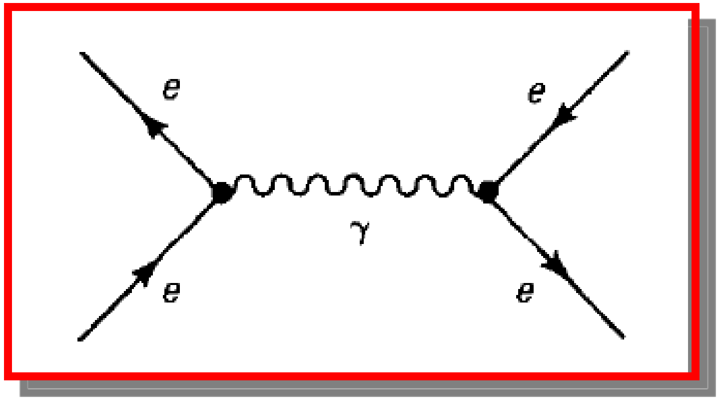
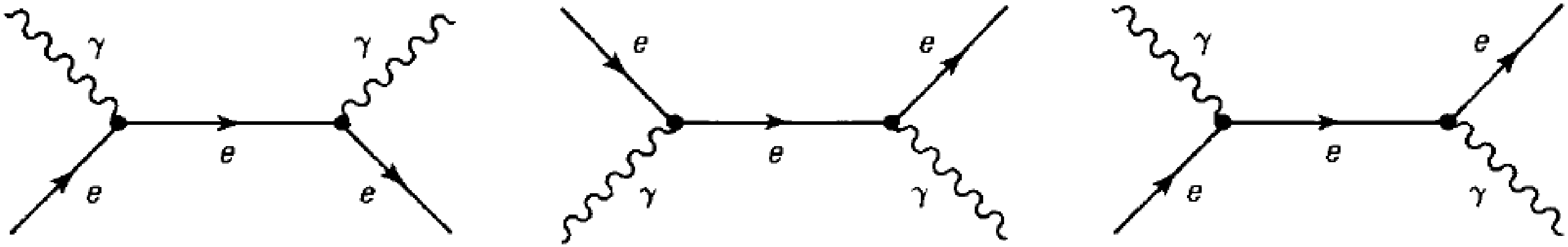


Bhabha scattering

Feynman diagrammen - QED



Pair annihilation

Pair production

Compton scattering

Hierbij wordt gebruik gemaakt van crossing symmetry:
als A + B → C + D toegestaan, dan is ook A + $\bar{C}$ → $\bar{B}$ + D dynamisch toegestaan.

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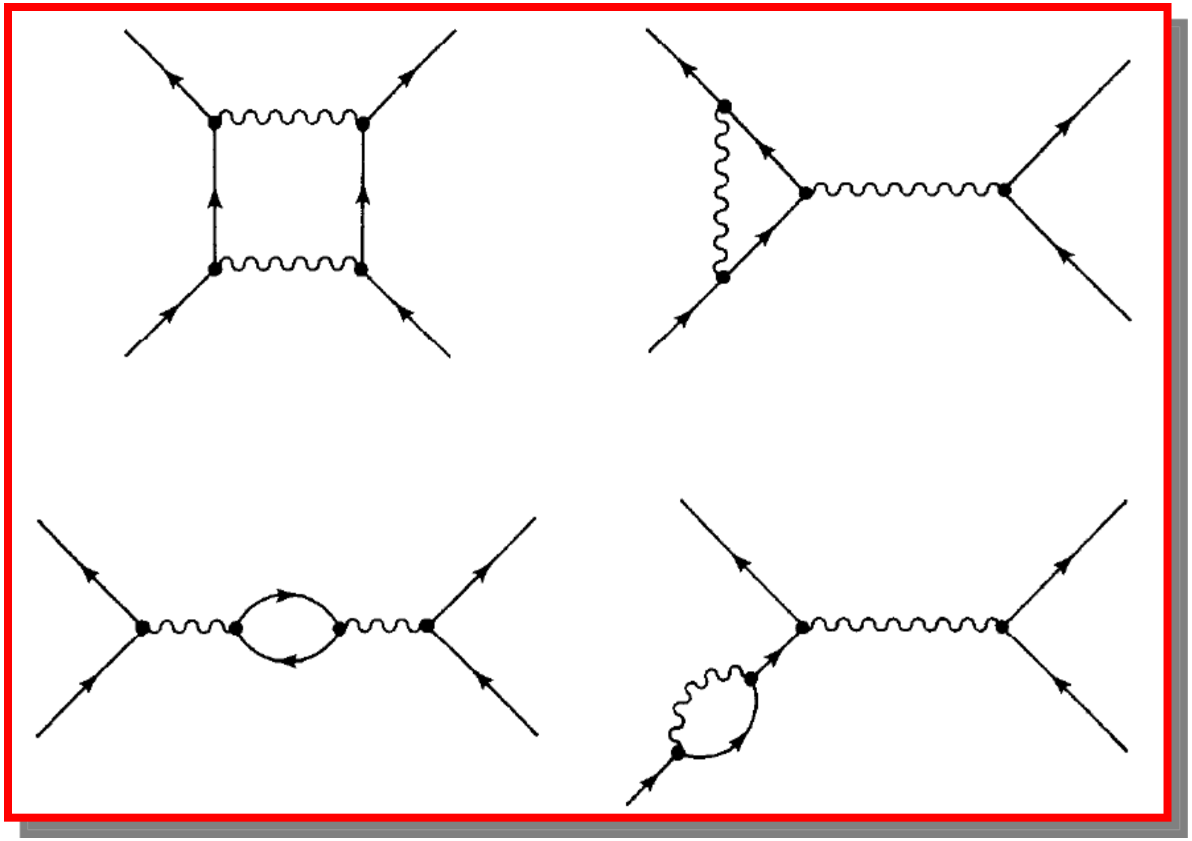
Feynman diagrammen - QED

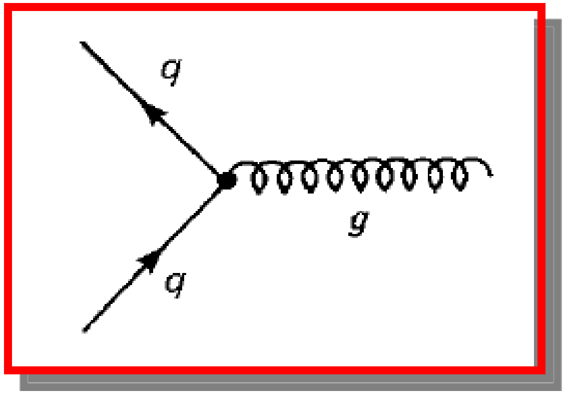
Hogere-orde bijdragen tot de overgangsamplitude

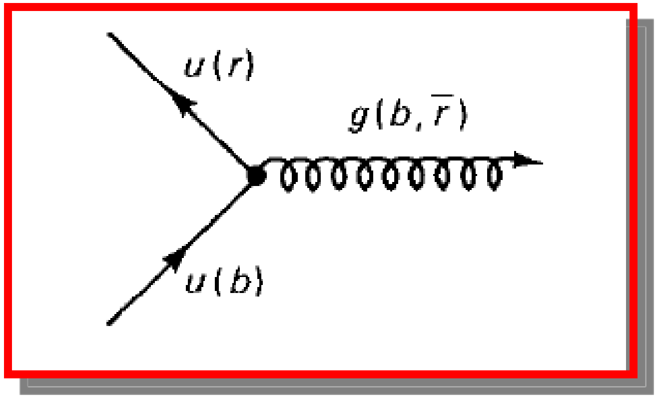
Interne deeltjes zijn *virtueel* (niet waarneembaar)

Elke vertex levert een factor 1/137



Feynman diagrammen - QCD



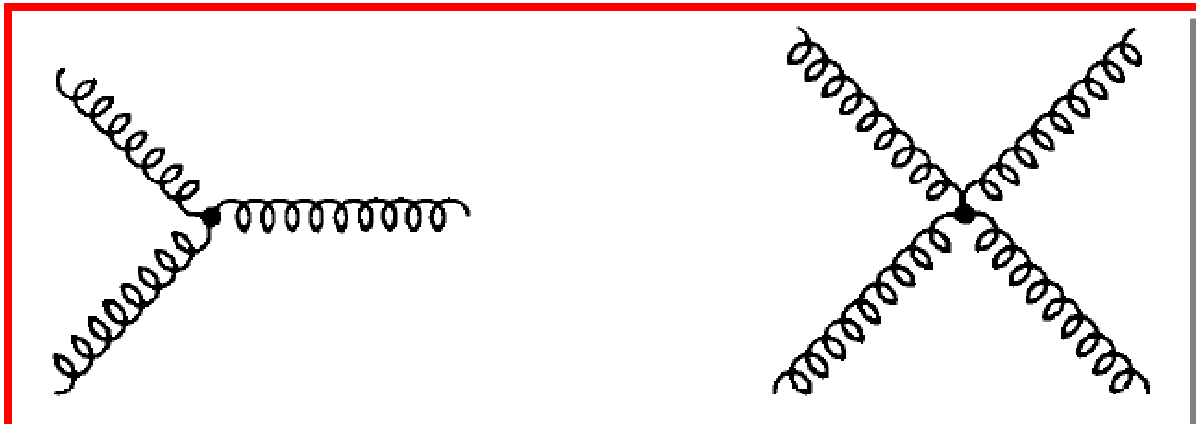


Elementair process
- structuur *qgq*
- vertex koppeling (~1)

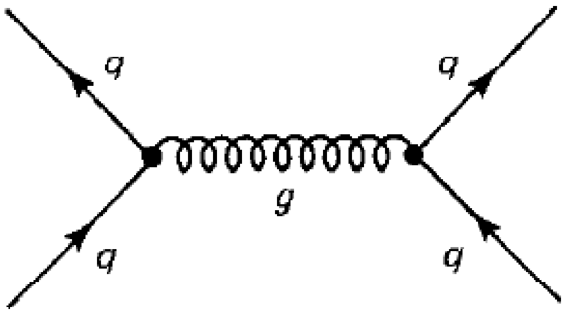
Gluonen dragen kleurlading

Gluonen hebben zelfkoppeling

D.J. Gross
H.D. Politzer
F. Wilczek
2004

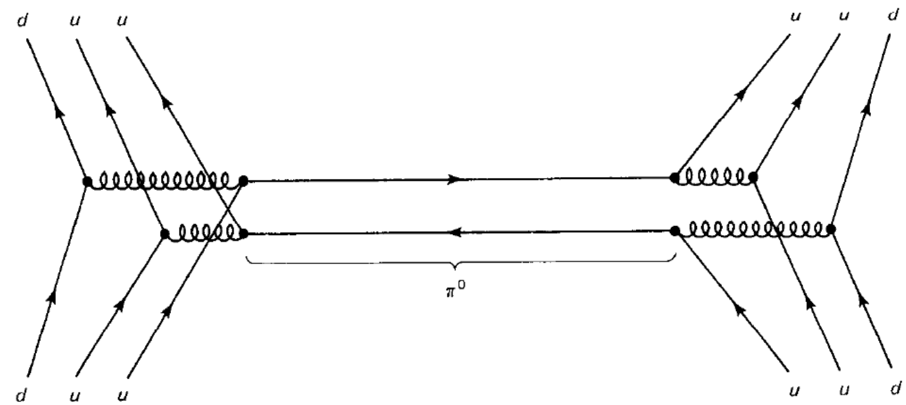


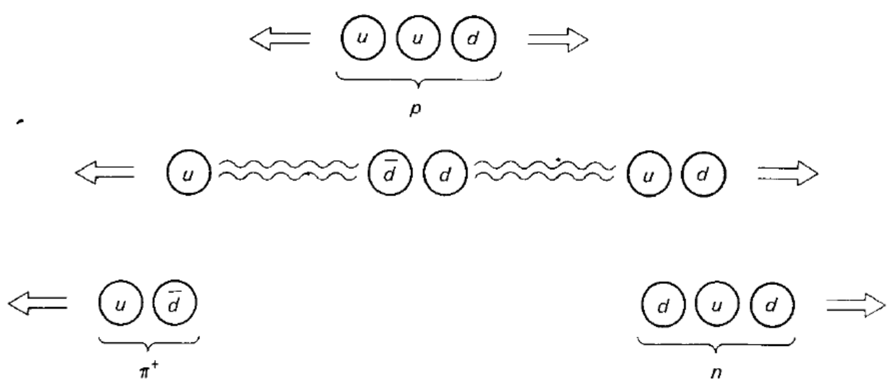
Feynman diagrammen - QCD



Kracht tussen twee quarks
door gluon uitwisseling

Kracht tussen twee protonen

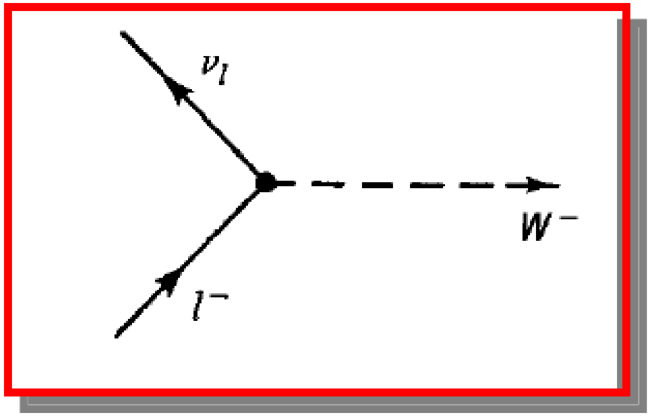


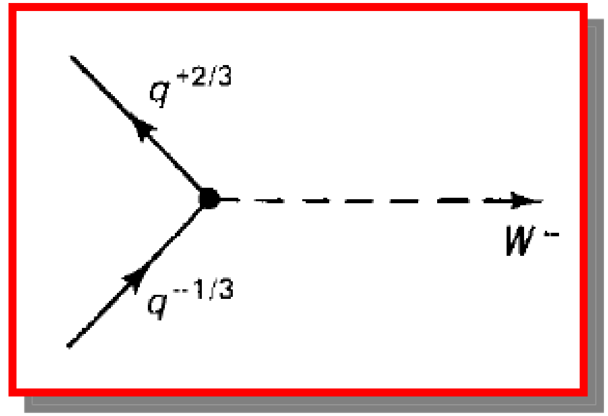


Een quark
uit een
proton
trekken

Confinement

Feynman diagrammen – Elektrozwakke kracht

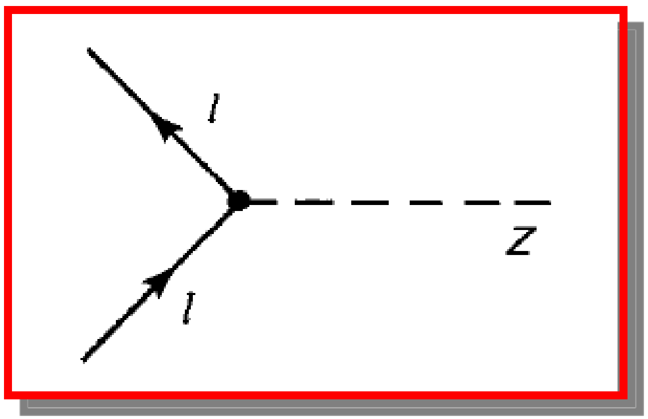


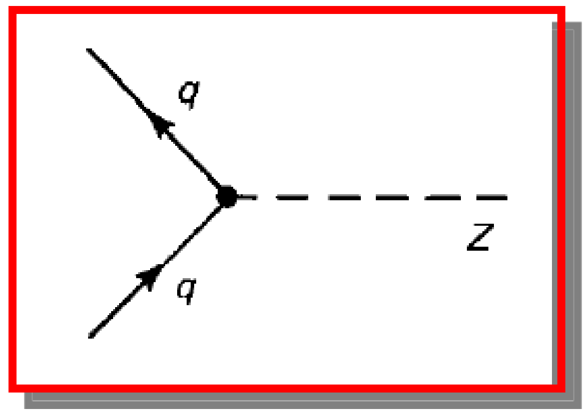


Of absorbeer een W^+

Lepton: geladen vertex

Quark: geladen vertex





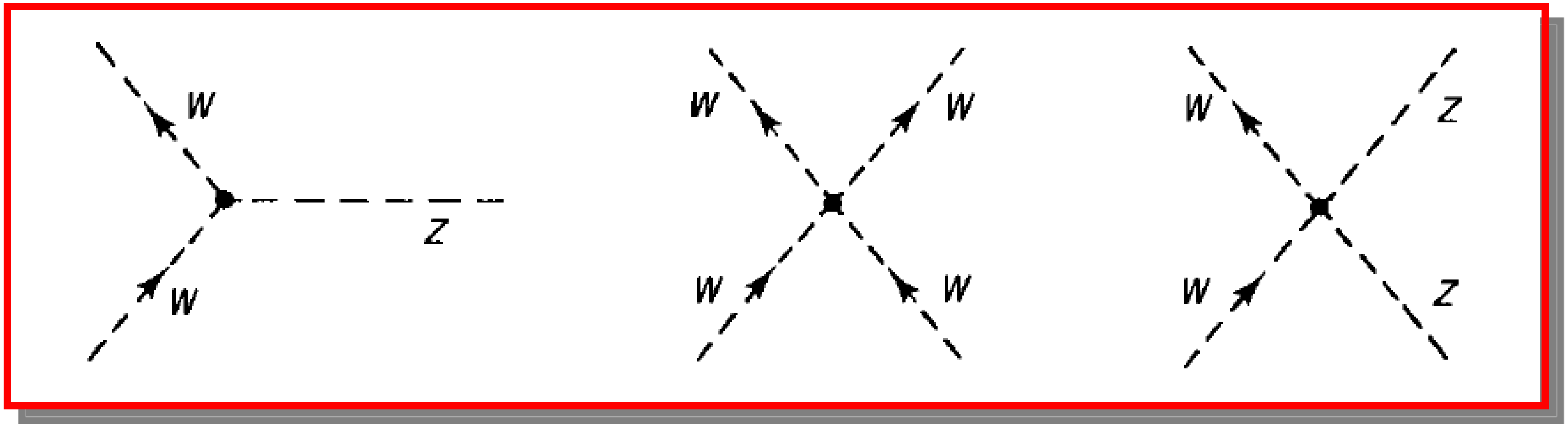
Voorspeld door GWS

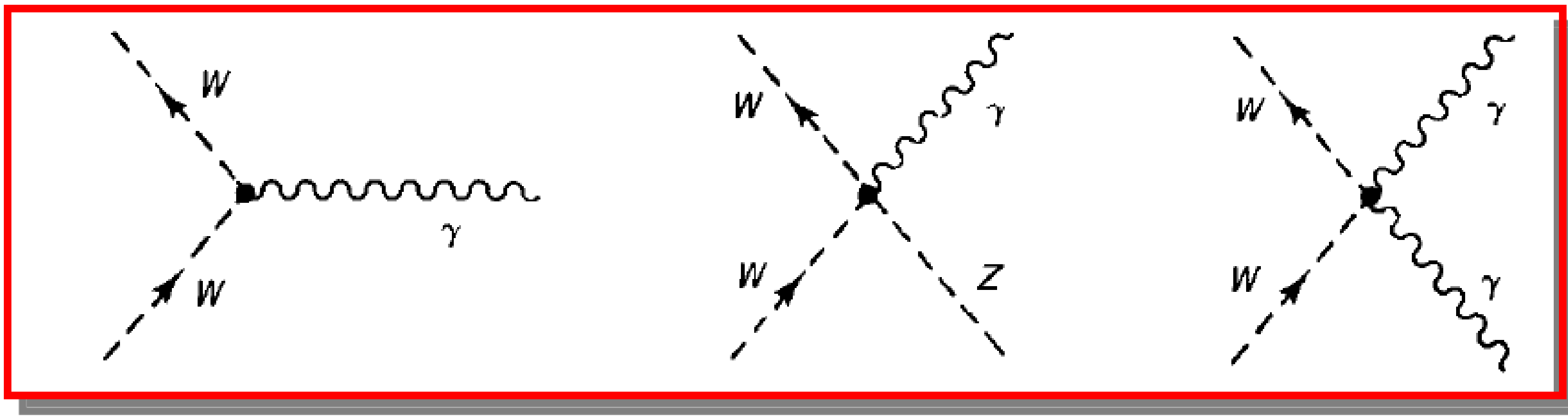
Lepton: neutrale vertex

Quark: neutrale vertex

Geen flavor changing neutral currents!

Feynman diagrammen – Elektrozwakke kracht



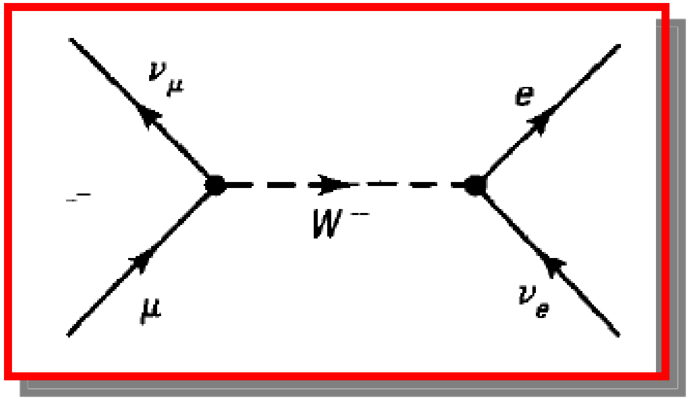


Glashow
Weinberg
Salam
1979

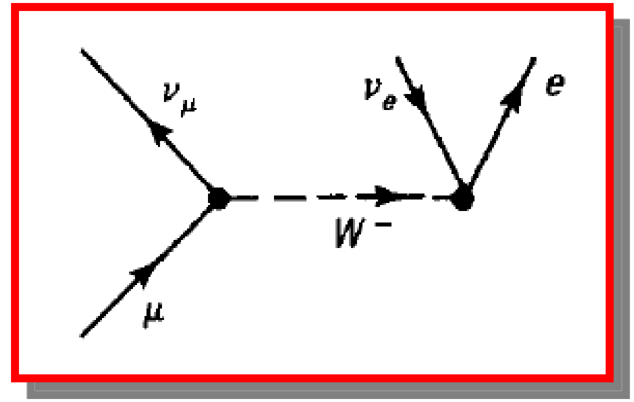
Nodig voor de interne consistentie van de Glashow, Weinberg en Salam (GWS) theorie

Geladen Ws koppelen aan het foton

Feynman diagrammen – Elektrozwakke kracht

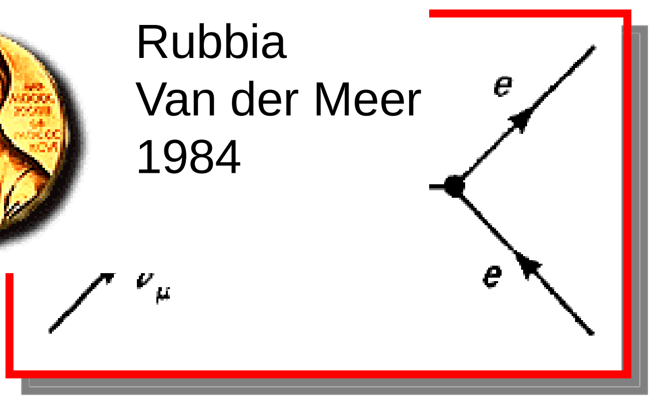


Muon-neutrino verstrooiing

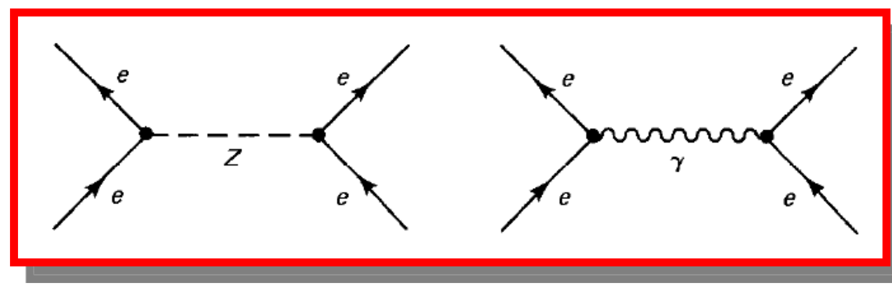


Muon verval $\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e$

Rubbia
Van der Meer
1984

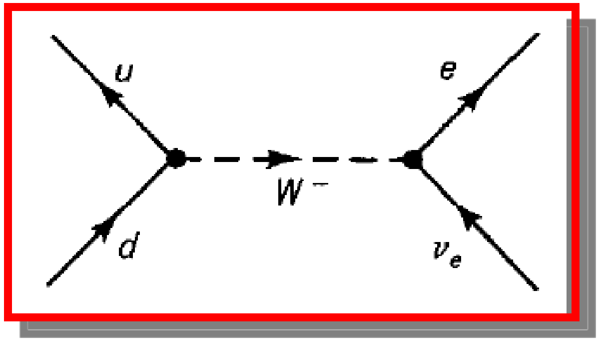


Neutrino verstrooiing
Ontdekking van Z op CERN (1973)

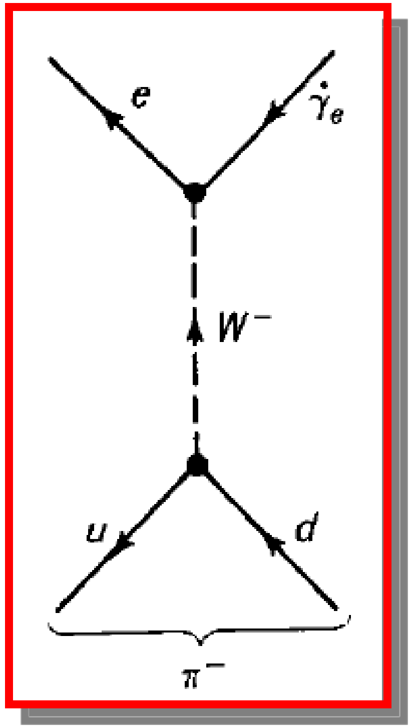


Correctie op de Coulomb interactie

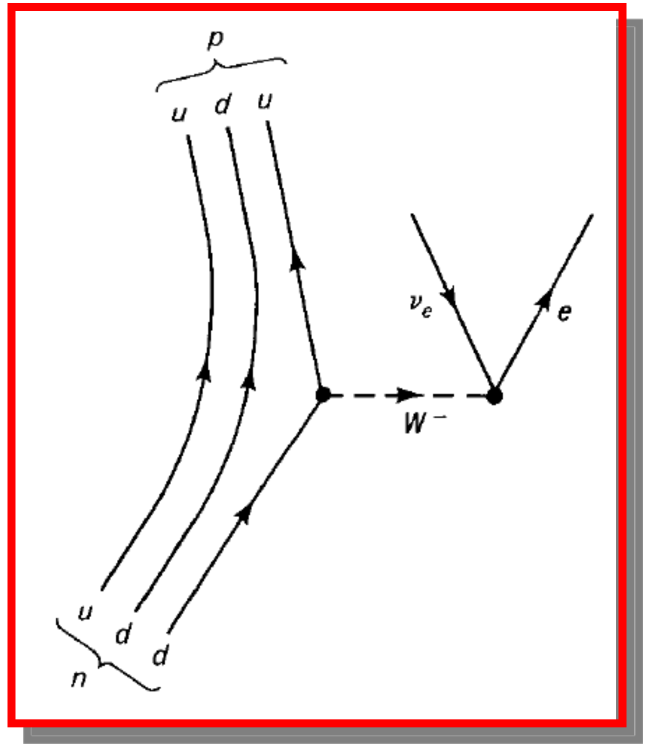
Feynman diagrammen – Elektrozwakke kracht



Semi-leptonisch proces

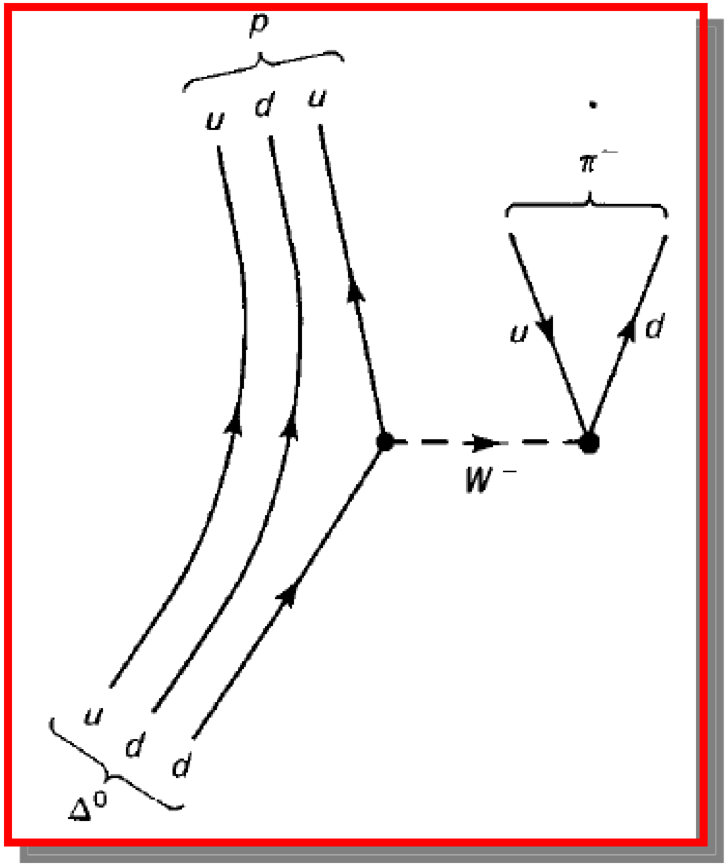


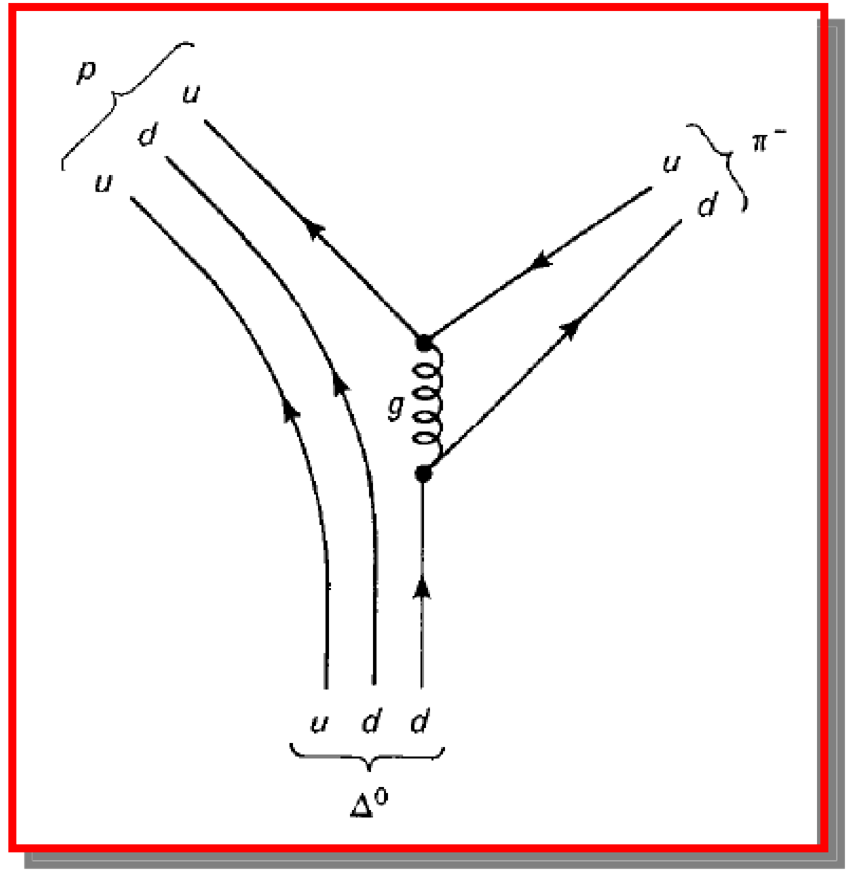
Pion verval



Neutron verval

Feynman diagrammen – Elektrozwakke kracht

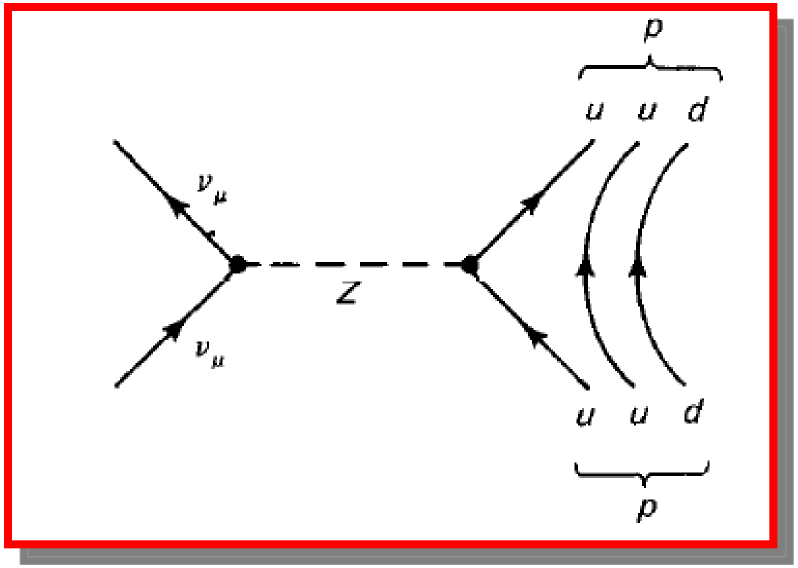




Verval van neutrale Delta:
via zwakke wisselwerking

Verval van neutrale Delta:
via sterke wisselwerking

Feynman diagrammen – Elektrozwakke kracht



M. Veltman
‘t Hooft
1999

Neutrino scattering

Het lijkt eenvoudig dat quarks de elektrozwakke wisselwerking op dezelfde wijze als leptonen ondergaan

Niet helemaal …

Universaliteit van de zwakke interactie

Zwakke doubletten: $$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}_L$$

VOLUME 10, NUMBER 12 PHYSICAL REVIEW LETTERS 15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

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

To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$
$$= \tan^2\theta M_K (1 - M_\mu{}^2/M_K{}^2)^2/M_\pi(1 - M_\mu{}^2/M_\pi{}^2)^2. \quad (3)$$

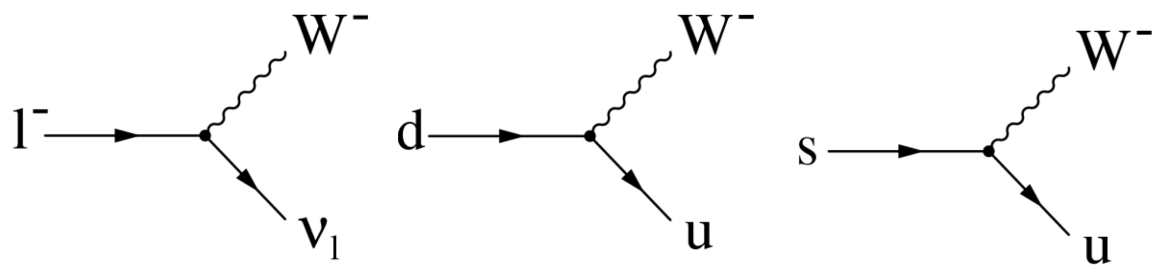
From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$

For an independent determination of θ, let us consider $K^+ \to \pi^0 + e^+ + \nu$. The matrix element for this process can be connected to that for $\pi^+ \to \pi^0 + e^+ + \nu$, known from the conserved vector-current hypothesis (2nd assumption). From the rate[6] for $K^+ \to \pi^0 + e^+ + \nu$, we get

$$\theta = 0.26. \quad (5)$$

The two determinations coincide within experimental errors; in the following we use $\theta = 0.26$.



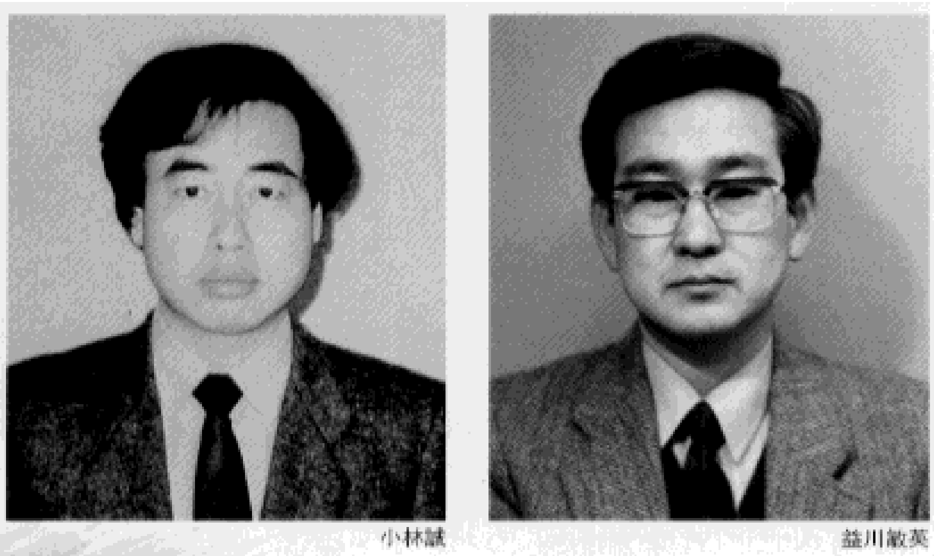
g $\qquad$ $g\cos\theta_C$ $\qquad$ $g\sin\theta_C$

$\Gamma\left(\mu^- \to e^- \bar{\nu}_e \nu_\mu\right) \propto g^4$ purely leptonic

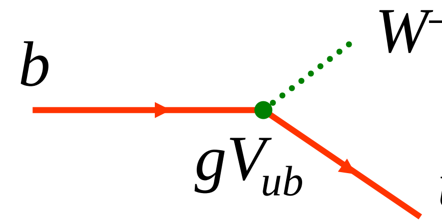
$\Gamma\left(n \to p e^- \bar{\nu}_e\right) \propto g^4 \cos^2\theta_C$ semi-leptonic, $\Delta S = 0$

$\Gamma\left(\Lambda^0 \to p e^- \bar{\nu}_e\right) \propto g^4 \sin^2\theta_C$ semi-leptonic, $\Delta S = 1$

Kobayashi, Maskawa and CP Violation



Progress of Theoretical Physics **49**, 652 (1973)



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

- **Sterkte van de vertex koppeling is gV_{ij}**
  - **g is de universele Fermi zwakke koppeling**
  - **V_{ij} hangt af van betrokken quarks**
  - **Voor leptonen is de koppeling g**
- **Voor 3 generaties is V_{ij} een 3x3 matrix**
  - **Deze matrix heet de CKM matrix (Cabibbo, Kobayashi, Maskawa)**
- **De matrix roteert de quarktoestanden van een basis met massa eigentoestanden in een waarin ze zwakke eigentoestanden zijn**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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Nobelprijs natuurkunde 2008

Yoichiro Nambu Makoto Kobayashi Toshihide Maskawa

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

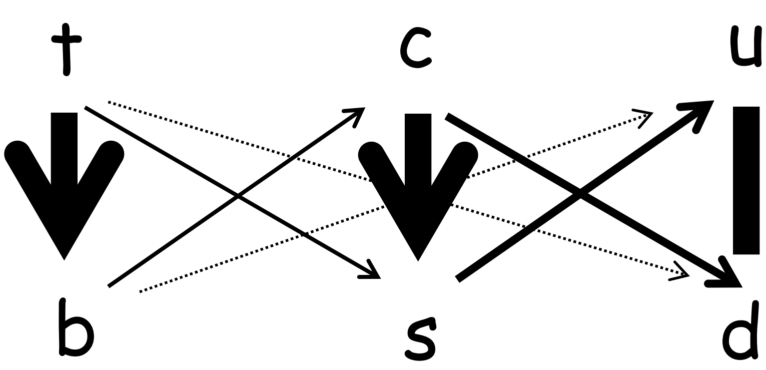
vrije Universiteit amsterdam

CKM matrixelementen

Grootte – 90% confindence level

$$\begin{pmatrix} 0.9739 \text{ to } 0.9751 & 0.221 \text{ to } 0.227 & 0.0029 \text{ to } 0.0045 \\ 0.221 \text{ to } 0.227 & 0.9730 \text{ to } 0.9744 & 0.039 \text{ to } 0.044 \\ 0.0048 \text{ to } 0.014 & 0.037 \text{ to } 0.043 & 0.9990 \text{ to } 0.9992 \end{pmatrix}$$

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



Matrix diagonaal: b en s stabiel
Bijna diagonaal: b en s verval onderdrukt
Dus, B mesonen en kaonen hebben lange levensduur

Samenvatting

Yukawa potentiaal

Relativistische golfvergelijking
Klein-Gordon vergelijking

$$E^2 = p^2c^2 + m^2c^4$$

$$p \rightarrow \frac{\hbar}{i}\nabla \quad \text{en} \quad E \rightarrow i\hbar\frac{\partial}{\partial t}$$

$$\boxed{-\hbar^2\frac{\partial^2\phi(\mathbf{x},t)}{\partial t^2} = -\hbar^2c^2\nabla^2\phi(\mathbf{x},t) + M_X^2c^4\phi(\mathbf{x},t).}$$

Yukawa 1949

Statische oplossing

$$\nabla^2\phi(\mathbf{x}) = \frac{M_X^2c^2}{\hbar^2}\phi(\mathbf{x}),$$

Als $M_X = 0$ dan als elektrostatica

$$V(r) = -e\phi(r) = -\frac{e^2}{4\pi\varepsilon_0}\frac{1}{r}$$

Als $M_X \neq 0$

$$\boxed{V(r) = -\frac{g^2}{4\pi}\frac{e^{-r/R}}{r}}$$

$$\boxed{R = \hbar/M_Xc}$$

Relatie tussen range en massa …

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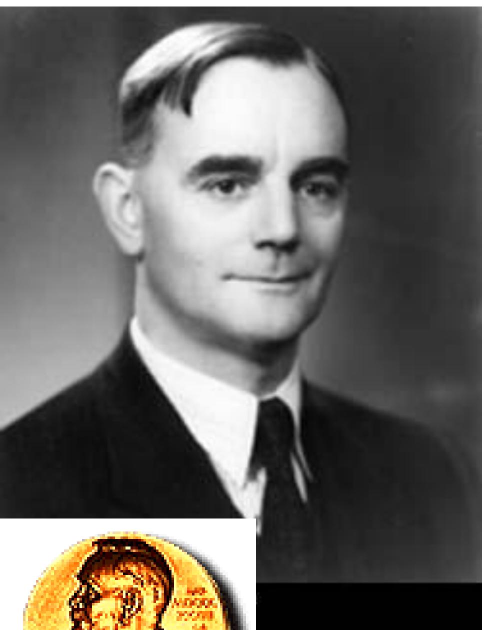
Mesonen - het pion

Yukawa (1934): uitgewisseld meson (analoog aan foton voor EM)

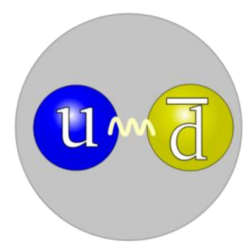
dracht (range) $e^{-(r/a)}/r^2$ a = 10^{-15} m

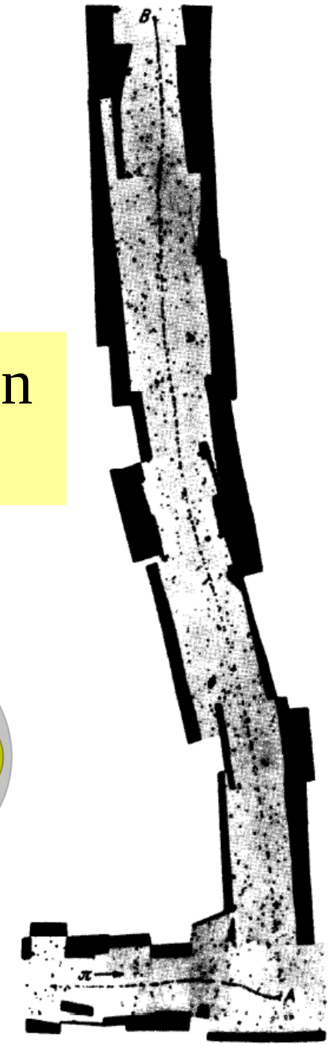
m_π = 140 MeV



C.F. Powell 1950

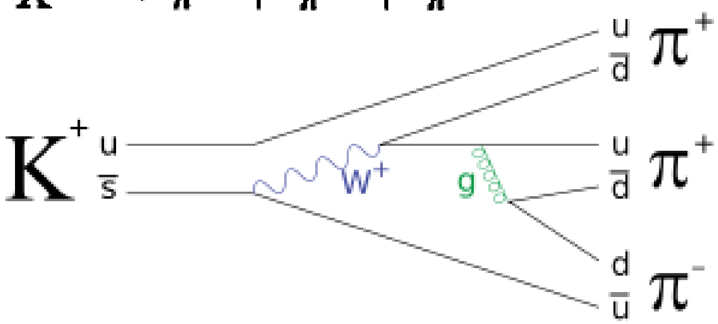
Powell (1947): ontdekking van het pion in kosmische straling $\pi^+ \rightarrow \mu^+ + \nu_\mu$

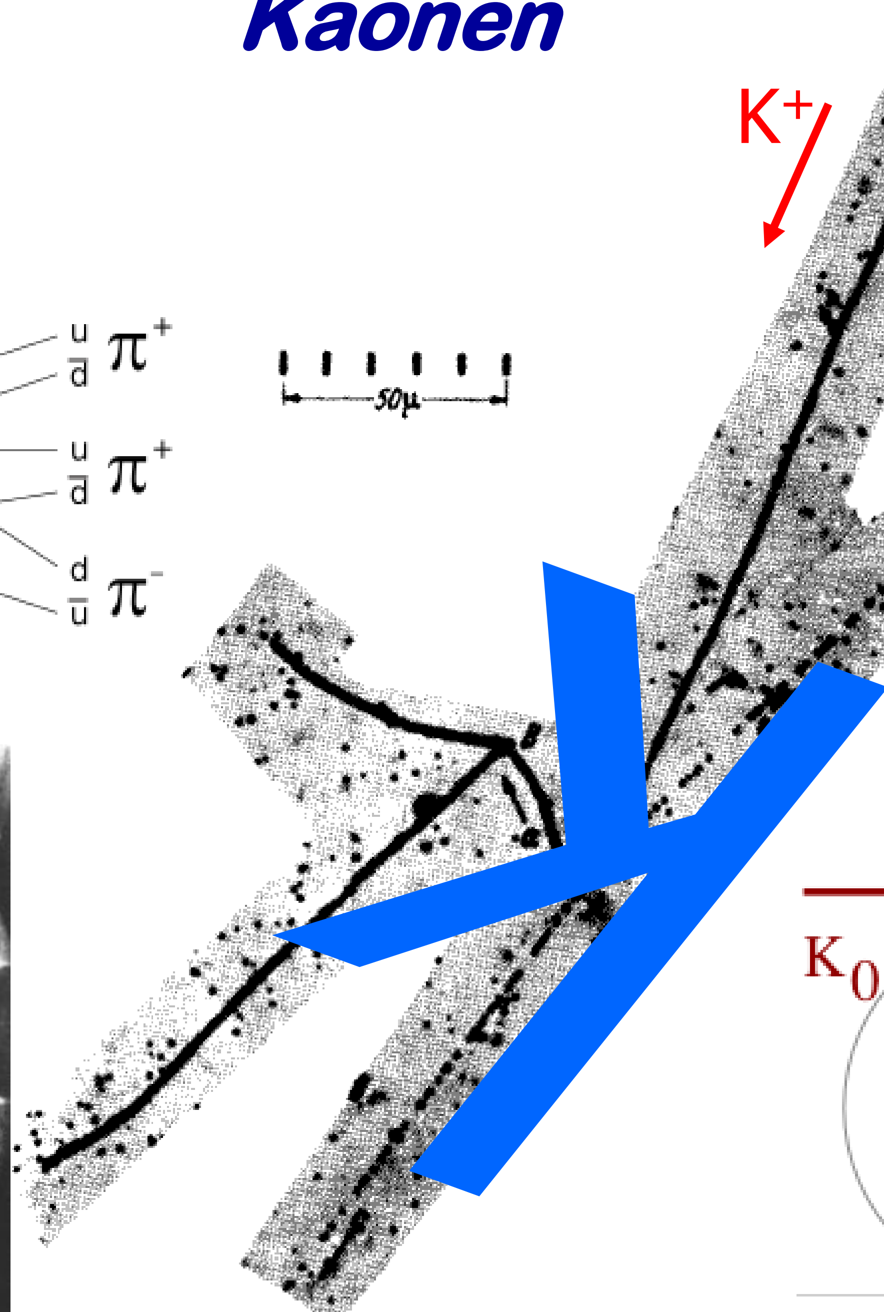


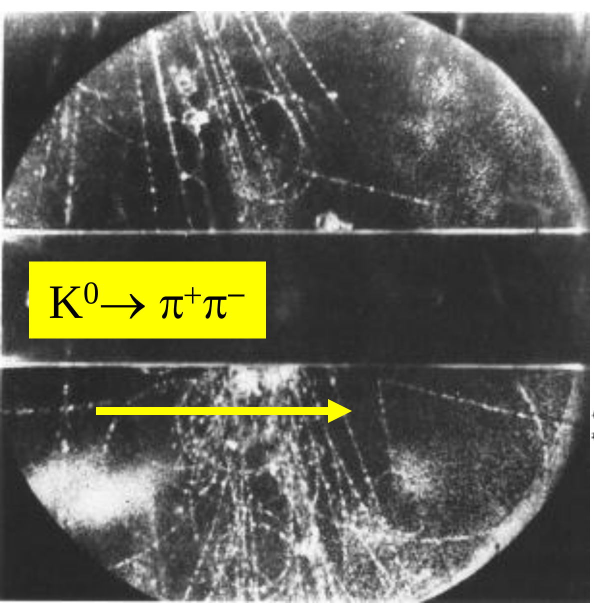


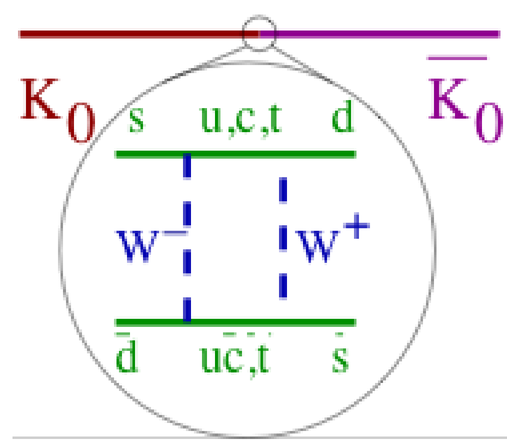
Kaonen

$$K^+ \longrightarrow \pi^+ + \pi^+ + \pi^-$$







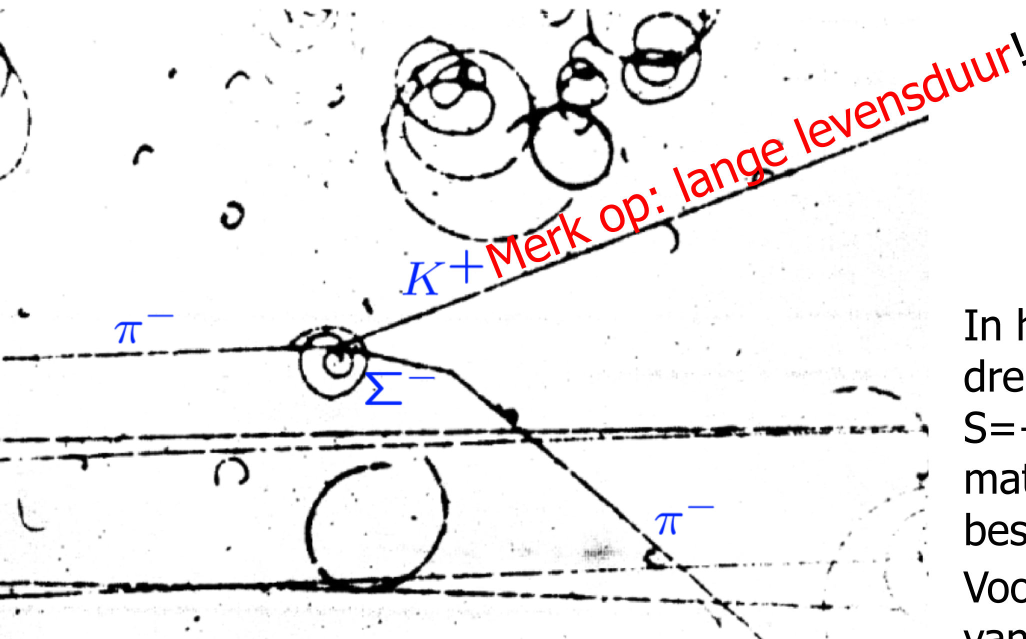


Vreemde deeltjes

Isospin

Isospin		
+1/2	$K^+(\bar{s}u)$	$\overline{K^0}(s\bar{d})$
-1/2	$K^0(\bar{s}d)$	$K^-(s\bar{u})$
"Vreemdheid"	+1	-1

	E_π drempel (GeV)
$\pi^- + p \to \Lambda^0 + K^0$	0.91
$\pi^- + p \to \overline{\Lambda}^0 + \overline{K}^0 + n + n$	6.0
$\pi^+ + p \to K^+ + \overline{K}^0 + p$	1.5



In het algemeen: moeilijker (i.e. hogere drempel) om S=-1 deeltjes te maken dan S=+1 als het target een p of n (i.e. materie!) is, en de bundel uit π^+ or π^- bestaat

Voor S=+1, dienen we ergens een *antiquark* vandaan te halen…

Een 'pure' K^0 of K^+ bundel maken: onder de drempel

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 86, NO. 5 JUNE 1, 1952

Some Remarks on the *V*-Particles*

A. PAIS

Institute for Advanced Study, Princeton, New Jersey

(Received January 22, 1952)

It is qualitatively investigated whether the abundance of *V*-particle production can be reconciled with their long lifetime by using only interactions of a conventional structure. This is possible, provided a *V*-particle is produced together with another heavy unstable particle (Sec. II). Two distinct groups of interactions are needed: for one, the coupling is strong (II); for the other, it is very weak (III). Two kinds of *V*-particles are considered, Fermions of mass $\sim 2200m$ and Bosons ($\sim 800m$). The arguments are some-

Observaties:
1) Grote productie werkzame doorsnede
2) Lange levensduur

→ deeltjes worden altijd in paren gemaakt

vrije Universiteit amsterdam

NIKHEF

Vreemdheid

Nieuwe mesonen en baryonen

$K^0,\ K^+,\ \overline{K}^0,\ K^-$

$\Lambda^0,\ \Sigma^-,\ \Sigma^0,\ \Sigma^+$

Eenvoudig in paren te produceren (`*associated production*')

$$\boxed{\begin{array}{llllll} \pi^- & + & p & \to & \Lambda & + & K^0 \\ & & & \to & \Sigma^- & + & K^+ \\ \pi^+ & + & p & \to & \Sigma^+ & + & K^+ \end{array}}$$

$$\begin{array}{lllllll} \pi^- & + & p & \not\to & \Lambda & + & \pi^0 \\ & & & \not\to & \Sigma^- & + & \pi^+ \\ & & & \not\to & \Sigma^+ & + & K^- \quad (!) \\ \pi^+ & + & p & \not\to & \Sigma^+ & + & \pi^+. \end{array}$$

$$\boxed{\begin{array}{lllllll} K^- & + & p & \to & \Lambda & + & \pi^0 \\ & & & \to & \Sigma^- & + & \pi^+ \\ & & & \to & \Sigma^0 & + & \pi^0 \\ & & & \to & \Sigma^+ & + & \pi^- \end{array}}$$

$$\begin{array}{lllllll} K^0 & + & p & \not\to & \Lambda & + & \pi^+ \\ K^+ & + & p & \not\to & \Sigma^+ & + & \pi^+ \end{array}$$

Sterke wisselwerking behoudt vreemdheid

Additief quantumgetal *S* (vreemheid): *s*-quark

K^0 en K^+ een vreemdheid $S = 1$

$\Lambda^0,\ \Sigma^-,\ \Sigma^+,\ \Sigma^0,\ K^-,\ \overline{K}^0$ vreemdheid $S = -1$

Lange levensduur

$$\pi^- + p \to \Delta^0 \to \pi^- + p \qquad \tau \sim 5 \times 10^{-24}\ \mathrm{s}$$

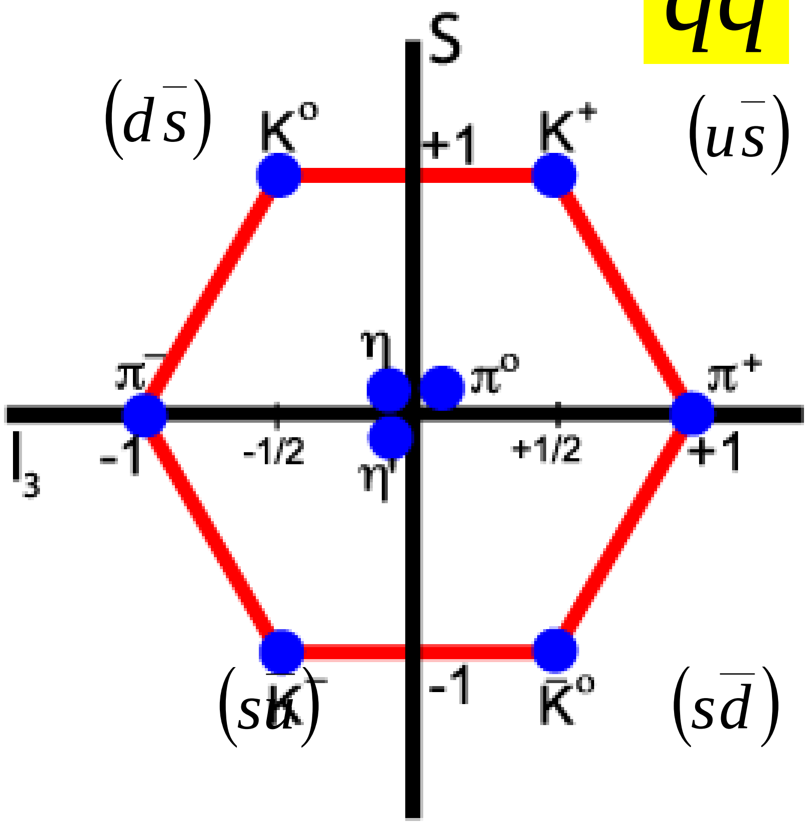
$$\begin{array}{llllll} \Lambda^0 & \to & p^+ & + & \pi^- & \quad \tau \sim 3 \times 10^{-10}\ \mathrm{s} \\ & \to & n & + & \pi^0 & \end{array}$$

Zwakke wisselwerking niet!

Quarksystemen: hadronen

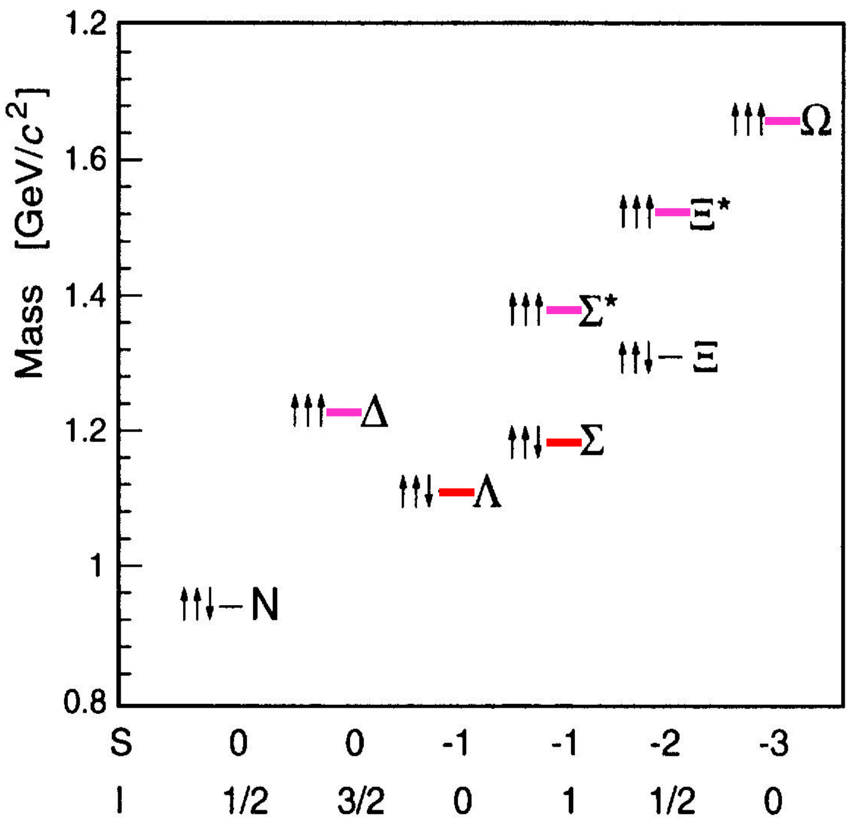
u, d, s quarks: meson en baryon multipletten

$q\bar{q}$

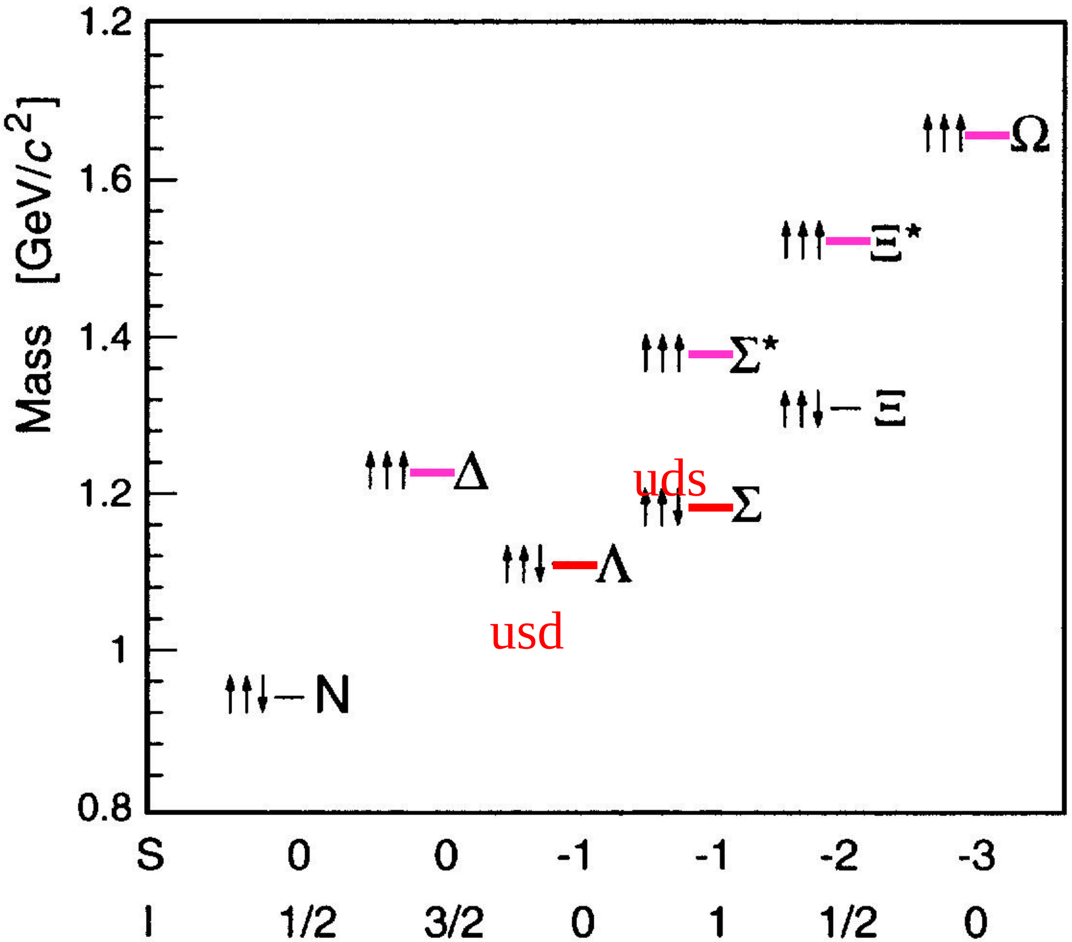


pseudoscalar ($J^P = 0^-$) octet + singlet

qqq



Baryon massa spectrum



Gell-Mann 1969

Λ- Σ mass splitsing
80 MeV/c^2
vanwege
spin-spin interactie

Systematiek leidt tot diverse empirische massa formules

Ontdekking van de J/ψ

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 $p + \text{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

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

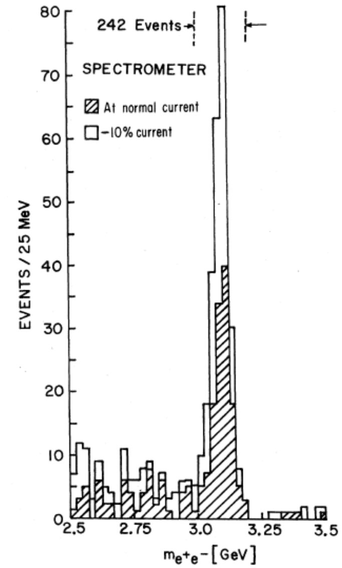
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡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

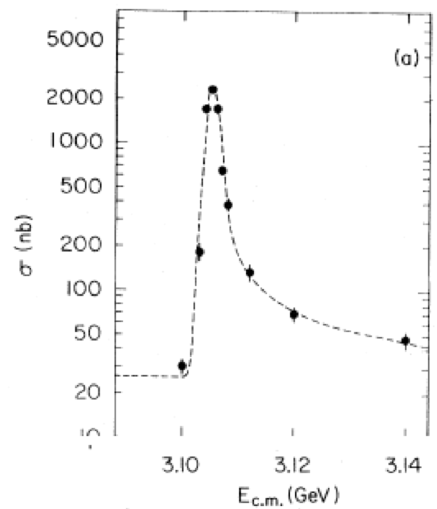
and

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 $e^+e^- \rightarrow$ 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.

Sam Ting en Burt Richter kregen in 1976 de Nobelprijs voor hun ontdekking





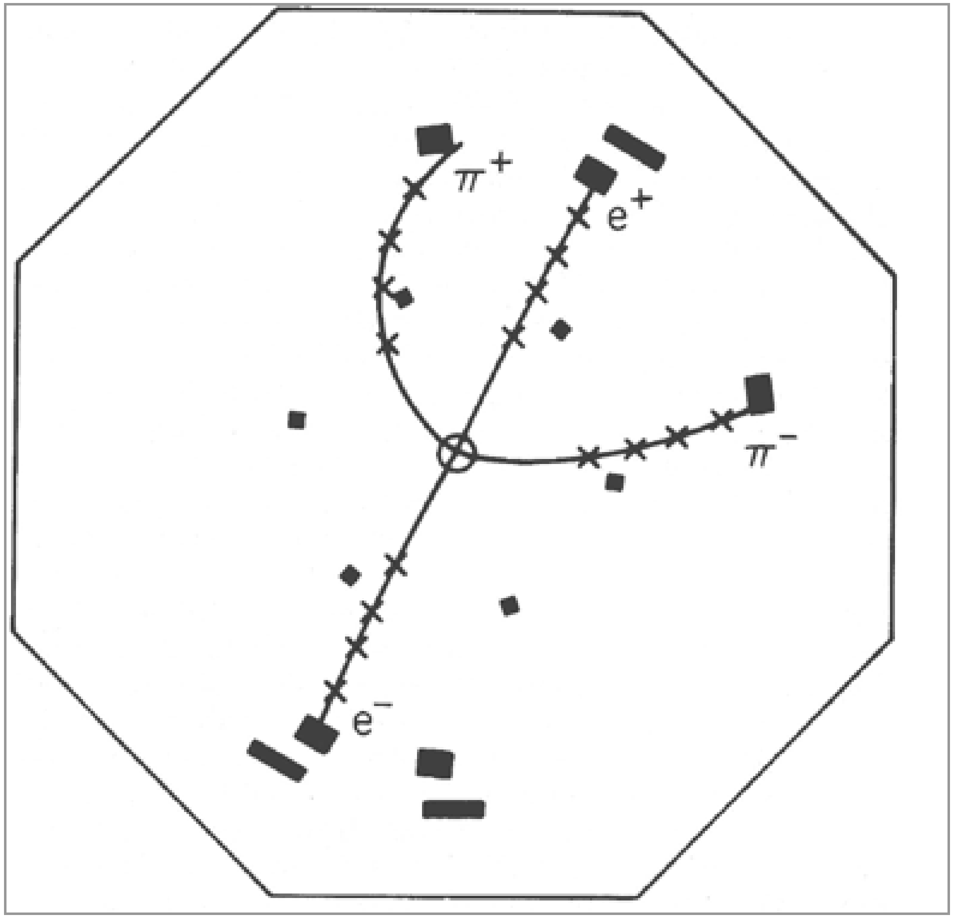
Brookhaven: J

SLAC: ψ(3105)

$c\bar{c}$

vrije Universiteit amsterdam

Wat de naam betreft: Waarom ψ?



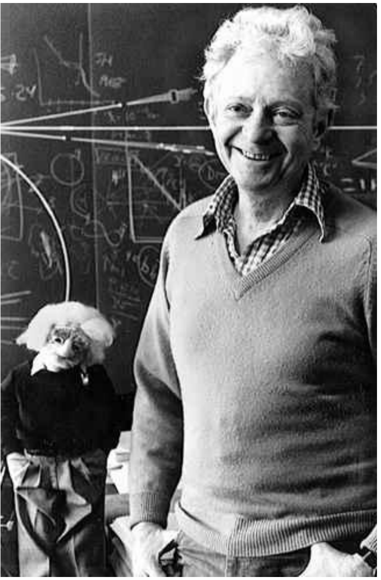
Verval is:
$\psi(2S) \rightarrow J/\psi + \pi^+ + \pi^-$

Gevolgd door $J/\psi \rightarrow e^+e^-$

Het is handig als een deeltje zich zelf een naam geeft!

Mark I (SPEAR) Event Display

1977: Ontdekking van de Υ



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 $m_{\mu^+\mu^-}$

1988

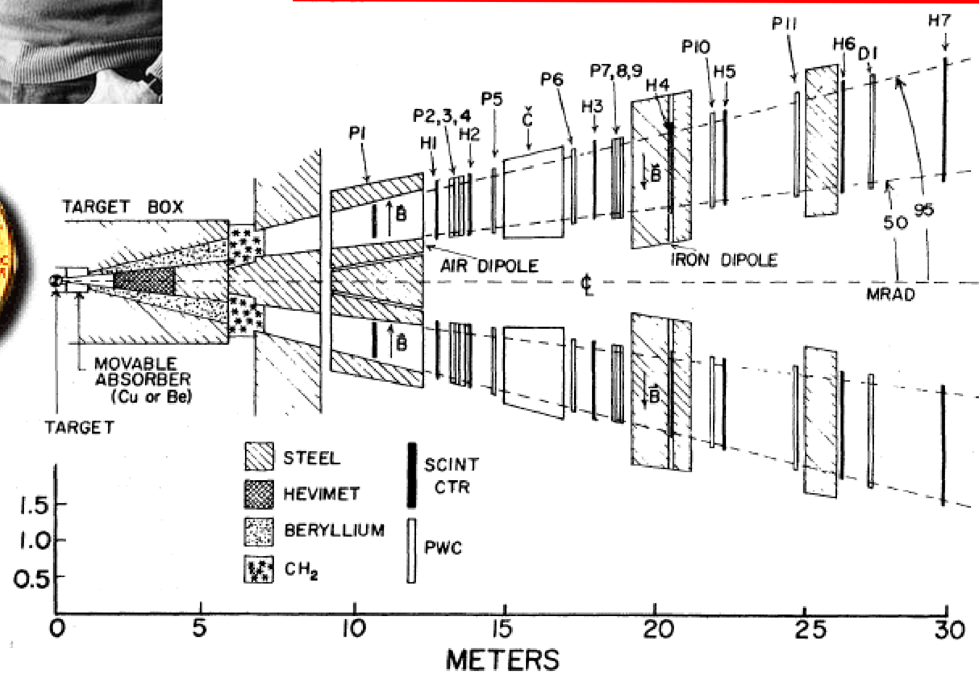
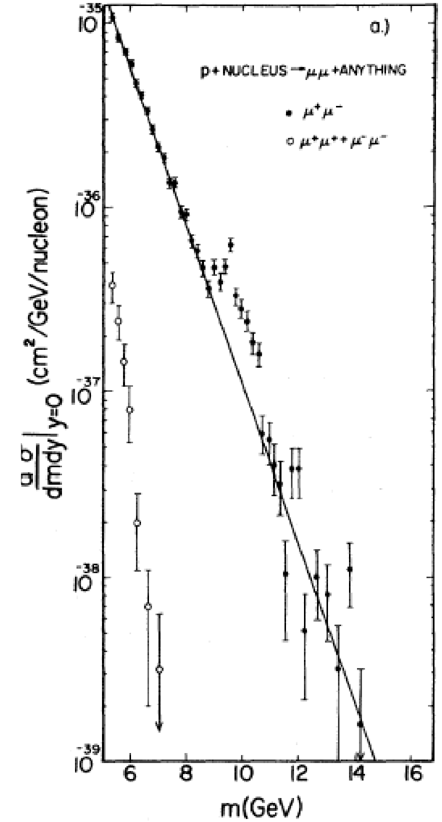


FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

$$b\bar{b}$$



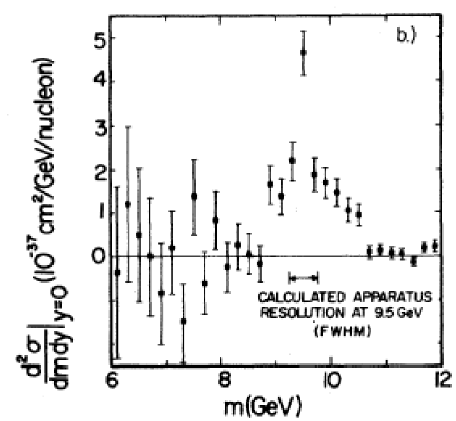


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

Verrassing: de B meson levensduur

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, H. 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, Massachussetts 02115

and

W. W. Ash, G. B. Chadwick, S. H. Clearwater, R. W. Coombes, H. S. Kaye, K. H. Lau, R. E. H. L. Lynch, R. L. Messner, S. J. Michalowski,[b] K. Rich, D. M. Ritson, L. J. Rosenber D. E. Wiser, and R. W. Zdarko
Department of Physics and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

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

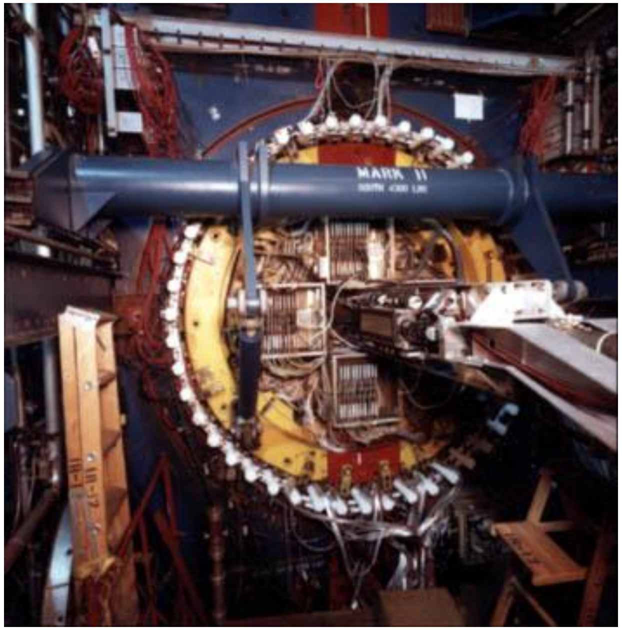
(Received 30 June 1983)

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 $\boxed{1.8 \pm 0.6\ (\text{stat.}) \pm 0.4 (\text{syst.})] \times 10^{-12}\ \text{sec}}$.

Measurement of the Lifetime of Bottom Hadrons

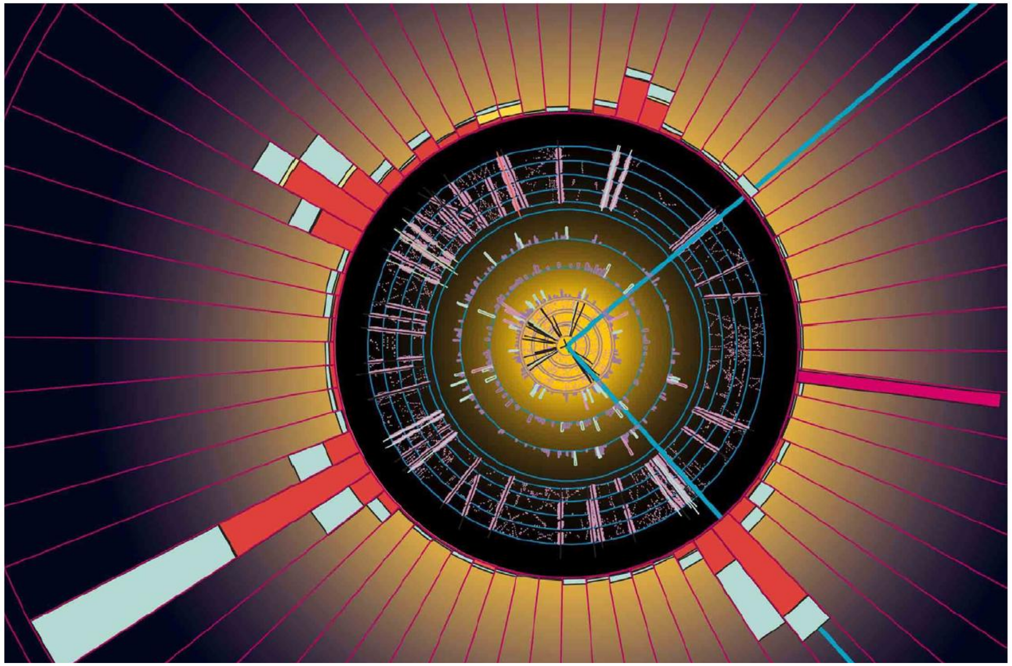
N. S. Lockyer, J. A. Jaros, M. E. Nelson, G. S. Abrams, D. Amidei, A. R. Baden, C. A. Blocker, A. M. Boyarski, M. Breidenbach, P. Burchat, D. L. Burke, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber, L. Golding, G. Hanson, D. Herrup, R. J. Hollebeek, W. R. Innes, M. Jonker, 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.



MAC en MARK-II waren Detectoren bij PEP, een 30 GeV e^+e^- collider op SLAC (Stanford)

Ontdekking 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
$199\ ^{+19}_{-21}\ \pm 22$	ABACHI	95	D0	lepton + jets
176 ± 8 ±10	ABE	95F	CDF	lepton + b-jet
$174\ \pm 10\ ^{+13}_{-12}$	ABE	94E	CDF	lepton + b-jet

Behoud van lading

Verval van elektron:
$\tau > 4.6 \times 10^{26}$ jaar

$$\cancel{e \to \gamma + \nu_e}$$

Lading is
veelvoud van *e*

$$q = Qe$$

$$a + b + .. + i \to c + d + .. + f$$

Additief quantumgetal

$$\sum Q_i = \sum Q_f$$

Ladingsbehoud ⇔ corresponderende symmetrie?

Behoud van baryongetal

Proton is ook stabiel
$\tau > 2.1 \times 10^{29}$ jaar

$$\begin{array}{lll} p & \rightarrow e^+\pi^0 & \tau > 5.5 \times 10^{32} \text{ jaar} \\ p & \rightarrow \mu^+\pi^0 & \tau > 2.7 \times 10^{32} \text{ jaar} \\ p & \rightarrow e^+\gamma & \tau > 4.6 \times 10^{32} \text{ jaar} \\ p & \rightarrow e^+ \text{ wat dan ook} & \tau > 0.6 \times 10^{30} \text{ jaar} \end{array}$$

Baryongetal ***B*** = 1
voor *p* en *n*

$$\boxed{\begin{array}{llccccccccc} & & n & \rightarrow & p & + & e^- & + & \bar{\nu}_e \\ \\ Q & : & 0 & = & 1 & - & 1 & + & 0 \\ B & : & 1 & = & 1 & + & 0 & + & 0 \\ \hline L_e & : & 0 & = & 0 & + & 1 & - & 1 \end{array}}$$

quarks ***B*** = 1/3
antiquarks ***B*** = -1/3

Leptonen, mesonen
hebben ***B*** = 0

Behoud van leptongetal

Pion verval

$$\begin{aligned} \pi^+ &\to \mu^+ + \nu_\mu & \text{B.R.} &= 0.999878 \\ \pi^+ &\to e^+ + \nu_e & \text{B.R.} &= 1.2 \times 10^{-4} \end{aligned}$$

Antideeltjes hebben dezelfde levensduur en B.R.

$$\begin{aligned} \pi^- &\to \mu^- + \bar{\nu}_\mu \\ \pi^- &\to e^- + \bar{\nu}_e. \end{aligned}$$

Reacties

$$\begin{array}{llccccccccl} & & \nu_e & + & n & \to & p & + & e^- & \\ L_e & : & 1 & + & 0 & = & 0 & + & 1 & \underline{\text{treedt op}} \\ L_\mu & : & 0 & + & 0 & = & 0 & + & 0 & \\ \\ & & \nu_\mu & + & n & \to & p & + & e^- & \\ L_e & : & 0 & + & 0 & \neq & 0 & + & 1 & \text{treedt niet op} \\ L_\mu & : & 1 & + & 0 & \neq & 0 & + & 0 & \\ \\ & & \nu_\mu & + & n & \to & p & + & \mu^- & \\ L_e & : & 0 & + & 0 & = & 0 & + & 0 & \underline{\text{treedt op}} \\ L_\mu & : & 1 & + & 0 & = & 0 & + & 1 & \end{array}$$

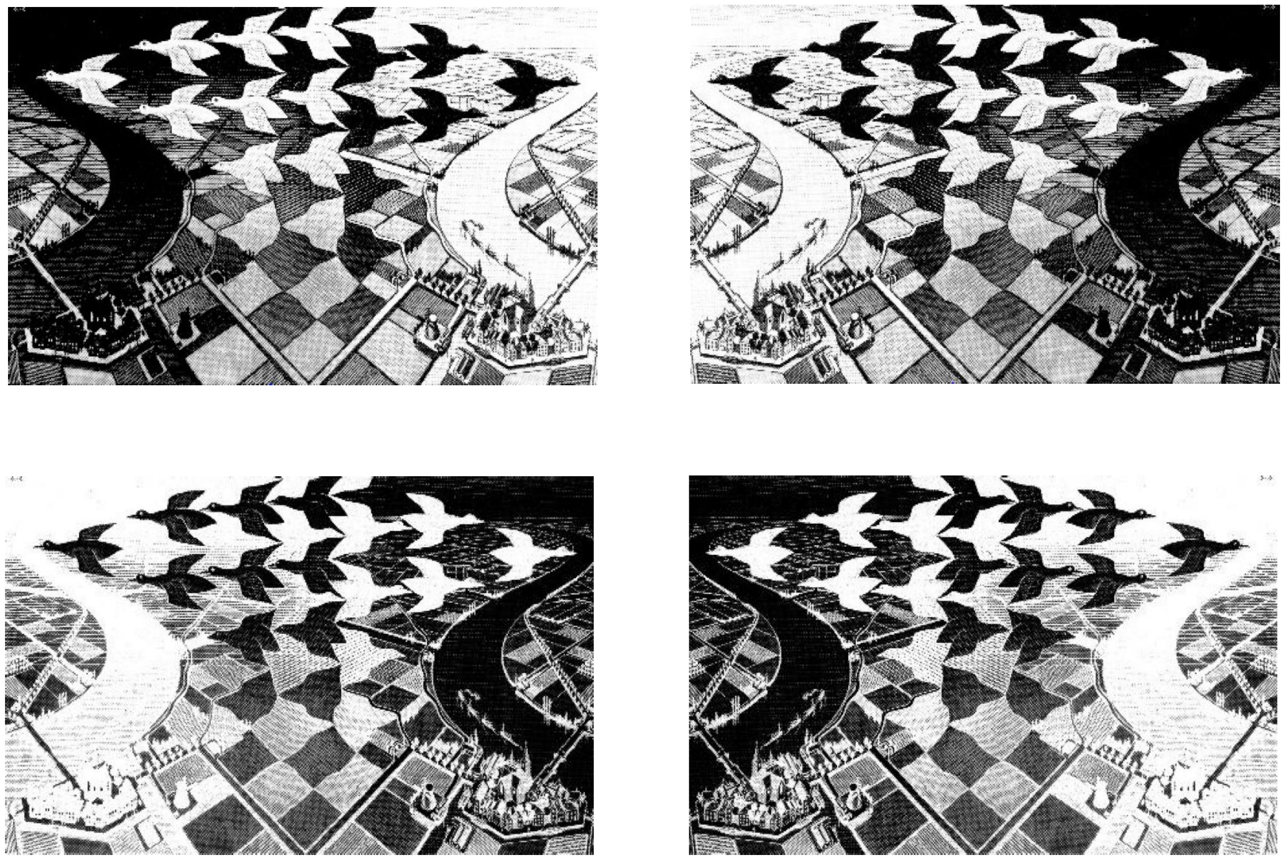
B.R. $< 10^{-12}$

$$\mu^- \to e^- + e^+ + e^-$$

$$\begin{aligned} \mu^- + {}^{32}\text{S} &\to e^- + {}^{32}\text{S}, & \sigma/\sigma_{\nu,\ \text{capture}} &< 7 \times 10^{-11} \\ \mu^- + {}^{32}\text{S} &\to e^+ + {}^{32}\text{Si}, & \sigma/\sigma_{\nu,\ \text{capture}} &< 9 \times 10^{-10} \end{aligned}$$

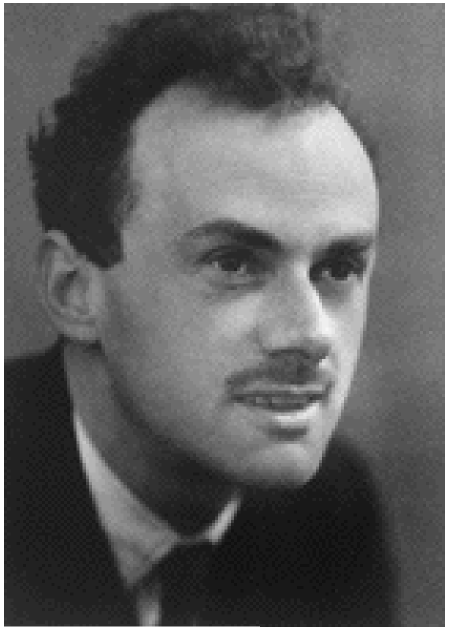
treedt niet op

CP schending: materie-antimaterie asymmetrie



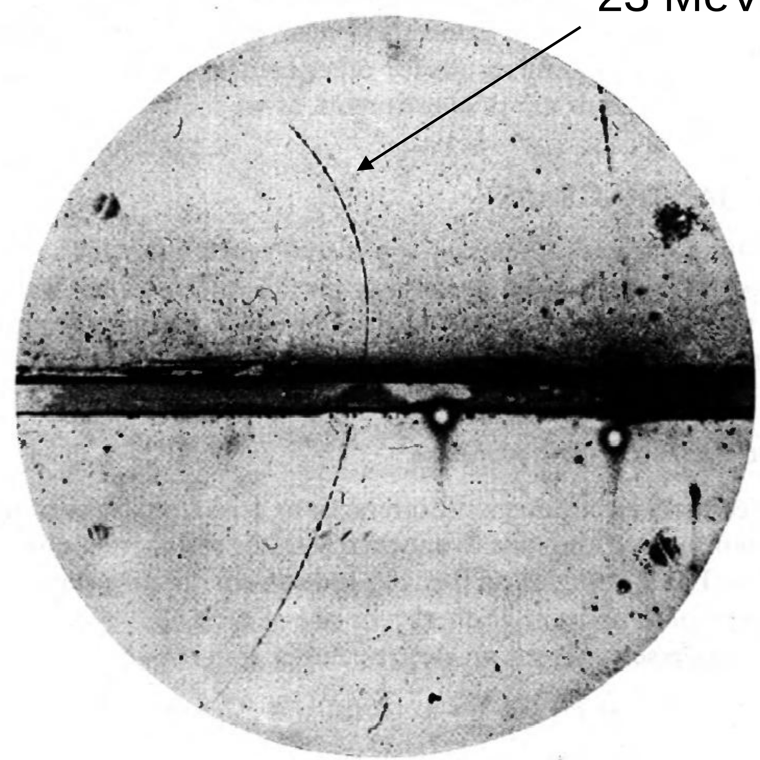
Antimaterie

- Elk deeltje heeft antideeltje met dezelfde
  - massa
  - levensduur
  - spin
- maar tegenovergestelde
  - lading
  - magnetisch moment
  - en andere quantumgetallen
- Deeltjes en antideeltjes annihileren
  - $e^+ + e^- \rightarrow \gamma + \gamma$
- Maar ook gecreeerd worden
  - $\gamma \rightarrow e^+ + e^-$



P. Dirac 1933

De ontdekking van antimaterie



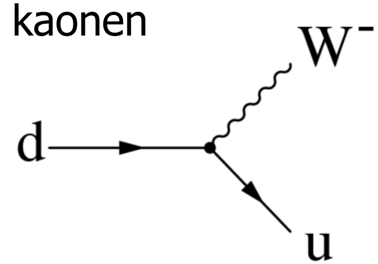
Anderson (1932) ontdekte het door
Dirac voorspelde positron

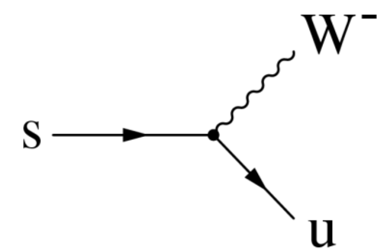
C. Anderson
1936

Kaon verval

$m_K \sim 494$ MeV/c^2

1. Er bestaan geen vreemde deeltjes lichter dan de kaonen
   - Verval schendt dus "vreemdheid"
2. Sterke wisselwerking behoudt "vreemdheid"
   - Verval is zuivere zwakke interactie





Hadronic decays:

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

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

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

$$\overline{K}^0 \to \pi^0\pi^0, \pi^0\pi^0\pi^0, \pi^+\pi^-, \pi^+\pi^-\pi^0$$

Semi-leptonic decays:

$$K^+ \to \pi^0\mu^+\nu_\mu, \pi^0 e^+\nu_e$$

$$K^- \to \pi^0\mu^-\nu_\mu, \pi^0 e^-\nu_e$$

$$K^0 \to \pi^-\mu^+\nu_\mu, \pi^- e^+\nu_e$$

$$\overline{K}^0 \to \pi^+\mu^-\nu_\mu, \pi^+ e^-\nu_e$$

leptonic decays:

$$K^+ \to \mu^+\nu_\mu, e^+\nu_e$$

$$K^- \to \mu^-\nu_\mu, e^-\nu_e$$

$$K^0 \to \mu^+\mu^-, e^+e^-$$

$$\overline{K}^0 \to \mu^+\mu^-, e^+e^-$$

Hadronisch en leptonisch verval:

- **Deeltje en anti-deeltje gedragen zich *hetzelfde***

Semi-leptonisch verval:

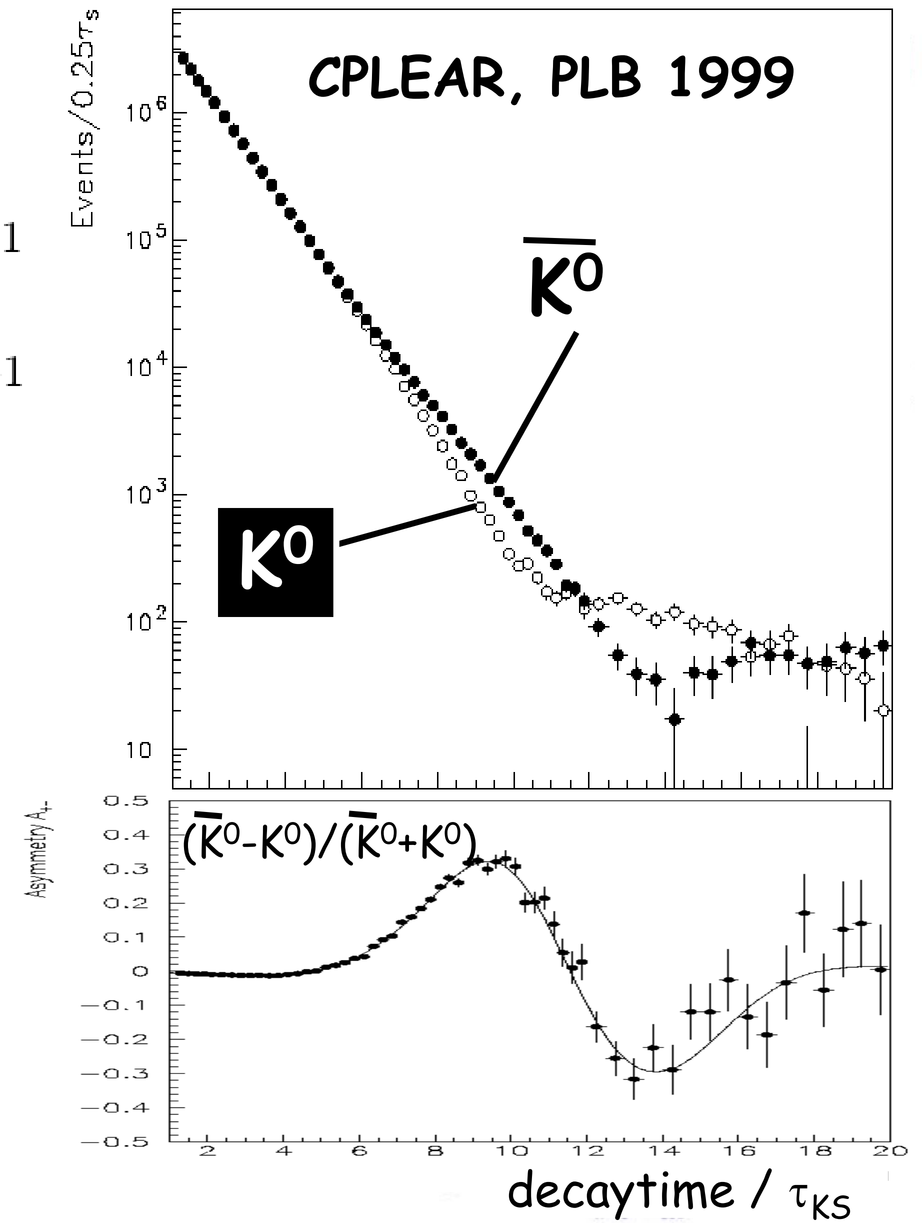
- **Deeltje en anti-deeltje zijn *verschillend* van elkaar!**

Vreemdheid oscillaties

Semi-leptonisch verval

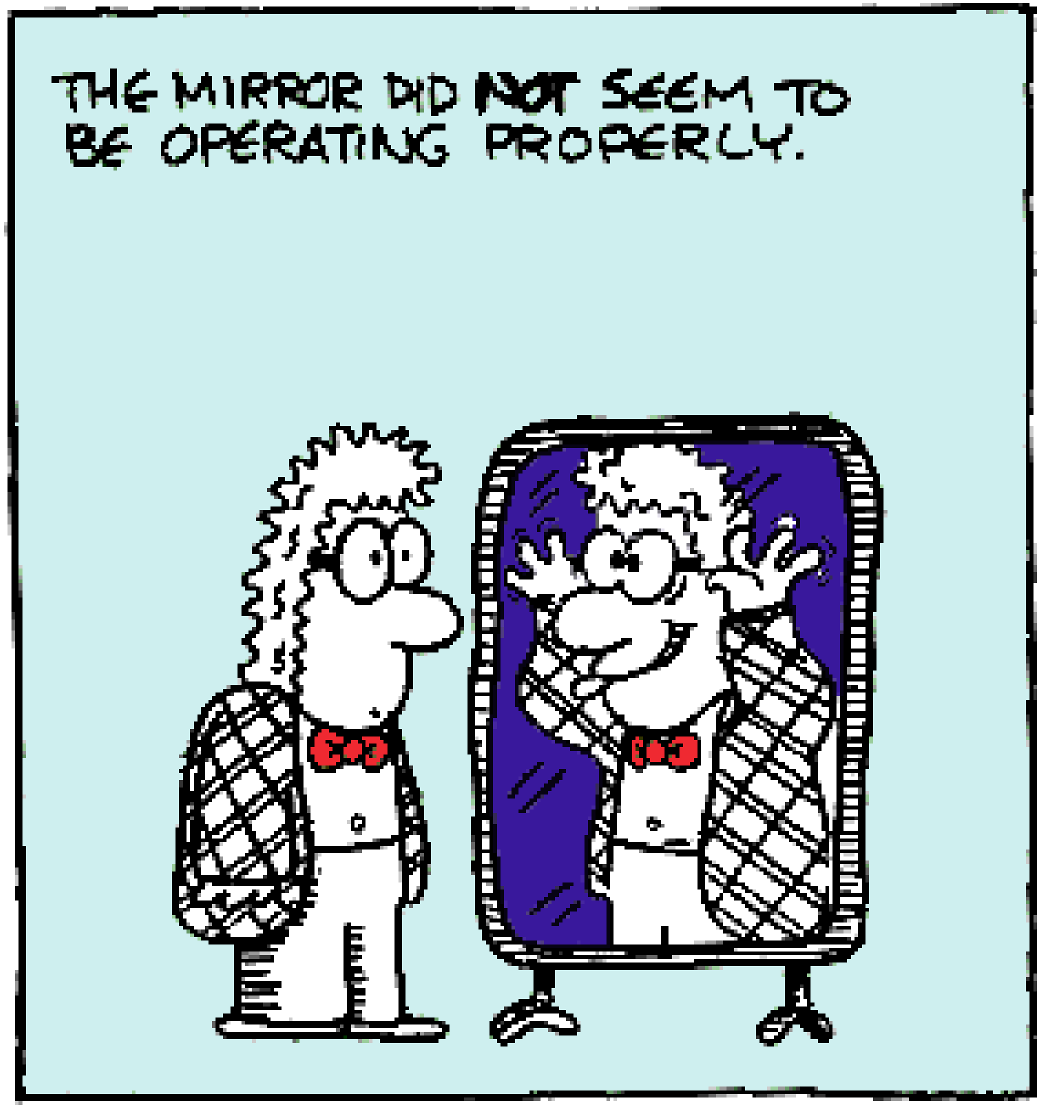
$$K^0 \rightarrow \pi^- + e^+ + \nu_e; \quad \Delta S = -1, \ \Delta Q = -1$$

$$\overline{K}^0 \rightarrow \pi^+ + e^- + \bar{\nu}_e; \quad \Delta S = +1, \ \Delta Q = +1$$



Verschil tussen materie en antimaterie

Cronin & Fitch 1980


THE MIRROR DID NOT SEEM TO BE OPERATING PROPERLY.