V0 – Administrative business
V1 – Introduction & Overview

KIT Faculty of Physics
Priv.-Doz. Dr. K. Rabbertz, Dr. N. Faltermann
Dr. Xunwo Zuo, Rufa Rafeek, Ralf Schmieder

Institut für Experimentelle Teilchenphysik

Organisational matters

Veranstaltungsliste: Vorlesungen im Master Physik

Ansicht

Veranstaltung:

Veranstaltungsart:

Suchen

ILIAS Links

Einträge 1 - 50 von 93 Seite 1 von 2 50 Einträge pro Seite

LV-Nr.	Titel	ILIAS	Dozierende	Art	Form	Sprache	B	SÜ	Nicht VVZ	SWS	Teilleistungen
4022161	Teilchenphysik II - W, Z, Higgs am Collider		Rabbertz, Faltermann	Vorlesung (V)	Präsenz		✓	✓	–	2	T-PHYS-108471, T-PHYS-108468, T-PHYS-108469, T-PHYS-108470
4022162	Übungen zu Teilchenphysik II - W, Z, Higgs am Collider		Rabbertz, Faltermann, Zuo	Übung (Ü)	Präsenz		✓	✓	–	1	T-PHYS-108470, T-PHYS-108469, T-PHYS-108468, T-PHYS-108471

- **This is the course on Particle Physics II – W, Z, Higgs at Colliders**
- **There is also an inscription page for the exercises in ILIAS ...**
  - **If you want to participate in the exercises, please register there, too. More details later.**
- **Web page other than ILIAS for this course:**
  - **https://www.etp.kit.edu/~rabbertz/Lehre/Teilchenphysik_II-WZH_am_Collider/**

Web page and links

Teilchenphysik II: W, Z, Higgs am Collider

Sommersemester 2023 (4022161)

Karlsruher Institut für Technologie

Institut für Experimentelle Teilchenphysik

Die Vorlesung Teilchenphysik II - W, Z, Higgs am Collider ist eine vertiefende Vorlesung im Rahmen des Masterstudiums Physik. Die Vorlesung kann als Teil eines Schwerpunkts- bzw. Ergänzungsfachs im Bereich Experimentelle Teilchenphysik verwendet werden.
Content: Historic introduction, electroweak symmetry breaking in the Standard Model, experimental techniques and modern methods of statistical data analysis, W and Z boson physics at colliders, properties of the Higgs bosons, search for and discovery of the Higgs boson, multi-boson processes, W/Z/Higgs processes in physics beyond the Standard Model.
Basic knowledge from the bachelor lectures â€œModerne Experimentalphysik IIIâ€, â€œModerne Theoretische Physik IIâ€ and â€œRechnernutzung in der Physikâ€ as well as from the master lecture â€œTeilchenphysik Iâ€œ is assumed.

Lecturers: Priv.-Doz. Dr. Klaus Rabbertz, Dr. Nils Faltermann.
Tutors: Dr. Xunwu Zuo, Rufa Rafeek, Ralf Schmieder

Schedule

Lecture: Fridays, 09:45-11:15h, kl Hörsaal B, see also ILIAS for inscription.
Start: 21.04.2023
Exercises: Following agreement during first lecture; inscription via ILIAS.
Inscription mandatory: 17.04.2023 --- 02.05.2023

- **ILIAS page to the lectures:**
  - **https://ilias.studium.kit.edu/goto.php?target=crs_2073357&client_id=produktiv**
- **ILIAS page to the exercises:**
  - **https://ilias.studium.kit.edu/goto.php?target=crs_2073358&client_id=produktiv**

Lehr-Modul - Formalities

- **Name:** Particle Physics II – W, Z, Higgs at Colliders
- **Course numbers:** Lecture 4022161, Exercises 4022162
- **Responsible persons from ETP:**
  - Lecture: K. Rabbertz (klaus.rabbertz@kit.edu), N. Faltermann (nils.faltermann@kit.edu)
  - Exercises: Xunwo Zuo (xunwu.zuo@kit.edu), R. Rufa (rufa.rafeek@kit.edu), Ralf Schmieder (ralf.schmieder@kit.edu)
- **Studies:** Master Physik
- **Topic:** Experimental Particle Physics
- **ECTS-Points:** 6 or 8
- **Semester:** 3-4 (V2, U1-2)
- **Record of achievement:** In case of this module being part of a "Schwerpunkt-" or "Ergänzungsfach", the ECTS points are acquired through the corresponding oral exam. A sufficient number of exercises must have been successfully worked out.

Lehr-Modul - Goals

- **Recommended previous knowledge:**
  - **Basic knowledge from the bachelor lectures "Moderne Experimentalphysik III", "Moderne Theoretische Physik II" and "Rechnernutzung in der Physik" as well as from the master lecture "Teilchenphysik I" is assumed.**
- **Qualification goals:**
  - **The students are able to present the theoretical and experimental basics of the physics of massive bosons in the Standard Model, together with the most important related measurements at colliders. Thus, they extend their knowledge in a specific field of experimental particle physics, and they are familiar with the current state of research. The students understand modern, computerbased techniques of data analysis and are able to apply them to simple problems in W/Z/H physics. The students solve problems as a team and improve their presentation skills. The students are able to research and analyse scientific publications in the field of particle physics.**

Lehr-Modul – Prel. Plan

- Lecture day/time and location:
  - V2 Fridays, 09:45 – 11:15: kleiner HS B
  - U1/2: in presence; day/time to be fixed here today!
- Preliminary planning on next slide and on course web page
- Participation in exercises:
  - Exercises 1 & 2 are calculational tasks (E1-2); the other are either paper seminars (P1-4) or computing tasks (C1-C3)
  - Presentation of solutions/answers to the calculational or computational tasks and to the questions concerning primary publications
  - Each participant should contribute at least for half of each day's topics and tasks
  - U1 – ECTS 6: at least six exercises, U2 – ECTS 8: at least eight exercises (of nine)
  - Does everybody have a notebook at disposal for the computing exercises?

Preliminary schedule

SS2023	Kalender	TBD	U2	Thema	Fr 09.45 kl. HS B	V2	Themen	Anmerkung
1	16	20. April	-		21. April	V K1	Organisation; Historical intro	
2	17	27. April	-		28. April	V K2	Exp. Basics	
3	18	04. May	E1	Calc 1	05. May	V K3	Theory basics I	Mo: 1. Mai
4	19	11. May	E2	Calc 2	12. May	V K4	Theory basics II	
5	20	18. May	-		19. May	V N1	EWK theory	Do: Himmelfahrt
6	21	25. May	P1	W mass	26. May	V N2	Higgs mechanism	no KR
7	22	01. June	-		02. June	-	-	Mo: Pfingstwoche
8	23	08. June	C1	NN	09. June	V K5	Early EWK measurements (GIM,NC)	Do: Fronleichnam
9	24	15. June	-		16. June	V N3	Stat. Tools for discoveries	no KR
10	25	22. June	C2	Stat.	23. June	V K6	W/Z discovery at SPPS & LEP, HERA	
11	26	29. June	P2	Z0	30. June	V K7	W/Z at the LHC	
12	27	06. July	-		07. July	V N4	Higgs search & discovery	
13	28	13. July	P3	H disc.	14. July	V N5	Higgs properties (CP, width)	
14	29	20. July	P4	H prop.	21. July	V N6	Higgs properties (Couplings, EFT)	
15	30	27. July	C3	limits	28. July	V N7	BSM Higgs	

A first exercise is planned for calendar week 18. Weekday & time for the exercises will be fixed today following discussions with you.

Lecture - Content

- Introduction and anthology of weak interaction (history)
- Experimental basics
- Theoretical basics I
- Theoretical basics II
- Electroweak theory
- Higgs mechanism
- Early electroweak measurements (GIM, NC)
- Statistical tools for discoveries
- W/Z discovery at SppS and at LEP, HERA
- W/Z at the LHC
- Higgs search and discovery
- Higgs properties I (CP, width)
- Higgs properties II (Couplings, EFT)
- Beyond Higgs

Exercise schedule

The agreed day and time for the exercises is:

To be determined NOW

Literature I

- **Theory:**
  - M.E. Peskin, D.V. Schroeder, "An Introduction to Quantum Field Theory", Westview Press, 1995.
  - V. D. Barger, R. J. N. Phillips: "Collider Physics", Westview Press (1996).
  - P. Schmüser: "Feynman-Graphen und Eichtheorien für Experimentalphysiker", 2nd ed., Springer (2013).
  - G. Münster: "Von der Quantenfeldtheorie zum Standardmodell", de Gruyter (2019).
- **Experiment:**
  - R. Cahn, G. Goldhaber, "The Experimental Foundations of Particle Physics", Cambridge University Press, 2009.
  - Particle Data Group, "The Review of Particle Physics", new online edition 2019 to be published, http://pdg.lbl.gov/

Literature II

- **Special topics:**
  - **Large Hadron Collider:**
    - **T. Plehn: Lectures on LHC Physics, Springer (2012), arXiv:0910.4182 [hep-ph].**
    - **I. Brock et al., “Physics at the Terascale”, Wiley-VCH Weinheim, 2011.**
    - **R. Alemany Fernandez et al., “The Large Hadron Collider --- Harvest of Run I”, Springer, 2015, ISBN:9783319150000.**

Literature III

- **Special topics:**
  - **WZH:**
    - **ALEPH, DELPHI, L3, OPAL, SLD: Precision Electroweak measurements on the Z Resonance, Phys.Rept. 427 (2006) 257.**
    - **ALEPH, DELPHI, L3, OPAL : Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP, Phys. Rept. 532 (2013) 119.**
    - **J. Ellis: Higgs Physics, arXiv:1312.567 [hep-ph]**
    - **A. Djouadi: The anatomy of electroweak symmetry breaking I, Phys. Rep. 457 (2008) 1**
    - **M. Mozer: Electroweak Physics at the LHC, Springer (2016).**
    - **R. Wolf: The Higgs Boson Discovery at the Large Hadron Collider, Springer (2015).**

Today: Fast Overview

- **Weak interaction anthology:**
  - Early years
  - Time of discoveries
  - Parity violation
  - The path to a unified theory

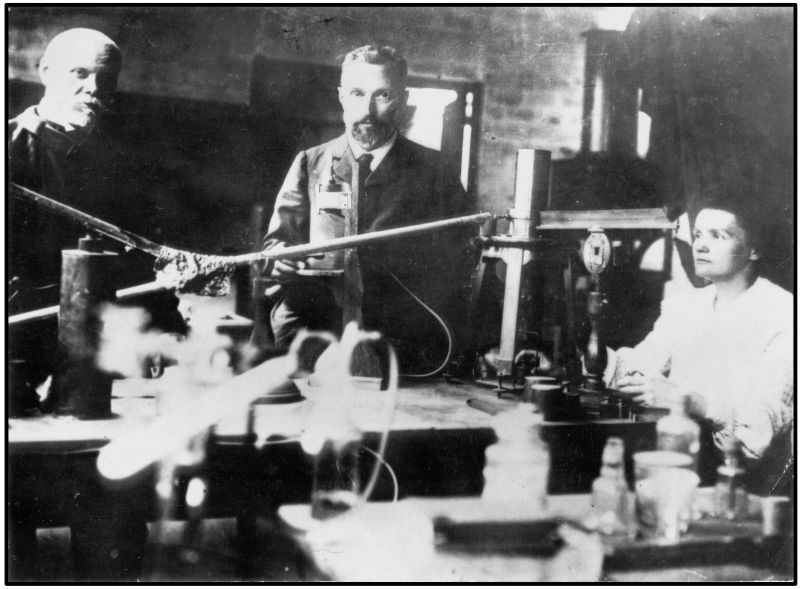
Radioactivity

- **Discovery of radioactivity**
  - **Invisible rays that can be detected using photographic plates**

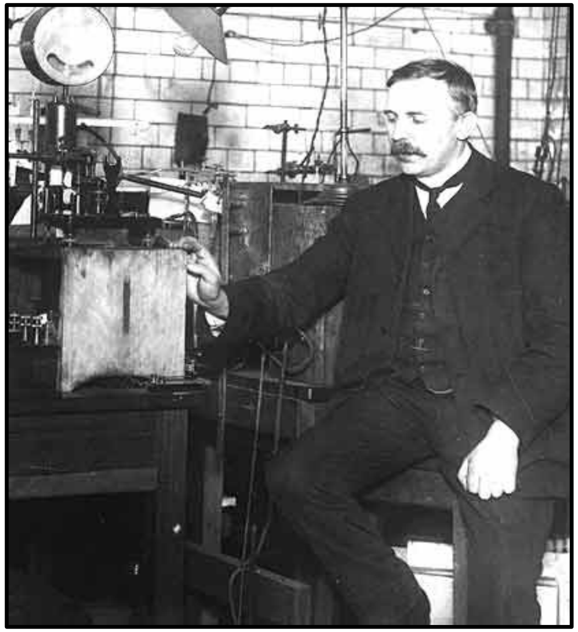
    H. Becquerel, C. R. Acad Sci. (Paris) 122, (1896) 501.

- **Discovery of different sorts of radioactivity**
  - **Radiation α and β have largely different penetrating powers with respect to material e.g. lead**

    E. Rutherford, Phil. Mag. 47, (1899) 109.



H. Becquerel



E. Rutherford

Mystery of lost energy

- **Discovery of a continuous energy spectrum in β decays**

J. Chadwick, Verh. Dtsch. Phys. Ges. 16, (1914) 383.

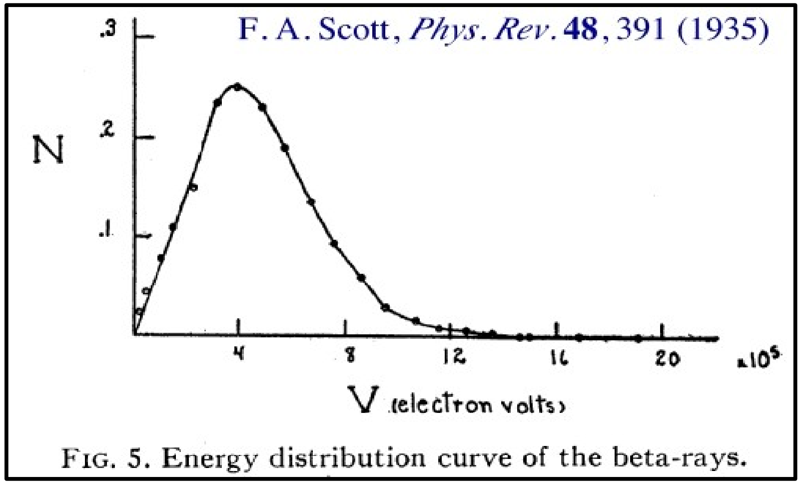
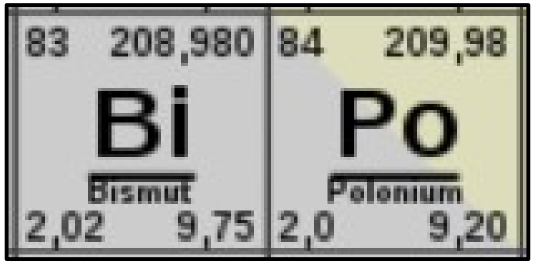


FIG. 5. Energy distribution curve of the beta-rays.


J. Chadwick

- **Measurement of the energy spectrum of β decays of** $^{210}_{83}\mathrm{Bi} \longrightarrow {}^{210}_{84}\mathrm{Po}$

C. D. Ellis & W. A. Wooster, Proc. Roy. Soc. London A 117, (1927) 109.



$$\langle E_\beta \rangle = 350\,\mathrm{keV} \qquad \Delta E\,(m_{\mathrm{Bi}} - m_{\mathrm{Po}}) = 1050\,\mathrm{keV}$$

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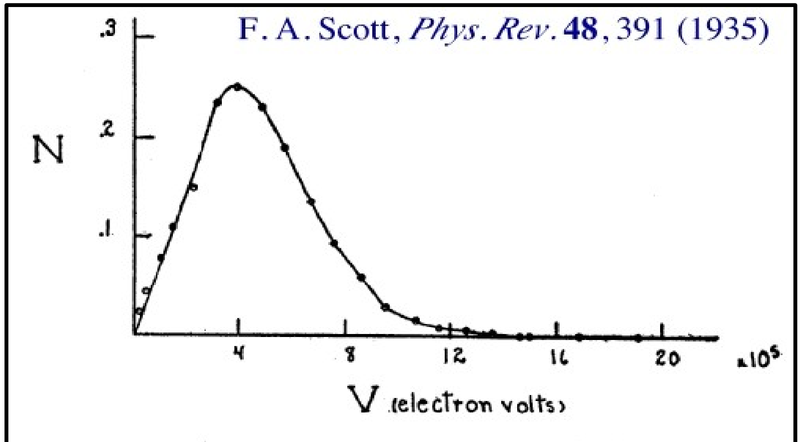

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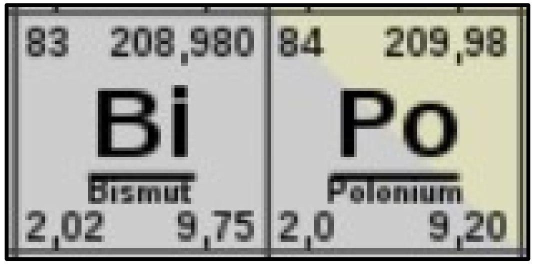

$$\langle E_\beta \rangle = 350\,\mathrm{keV} \qquad \Delta E\,(m_{\mathrm{Bi}} - m_{\mathrm{Po}}) = 1050\,\mathrm{keV}$$

Violation of energy-momentum conservation?

Postulate of W. Pauli

- **In β decays an additional particle is emitted. This particle must interact woth matter only weakly, otherwise it would have been observed already (1930).**

W. Pauli, Collected scientific papers, Vol. 2, 1313 (Interscience, New York, 1964).

W. Pauli

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

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W. Pauli

Discoveries of neutrinos

Science 124, 3212 (**1956**).

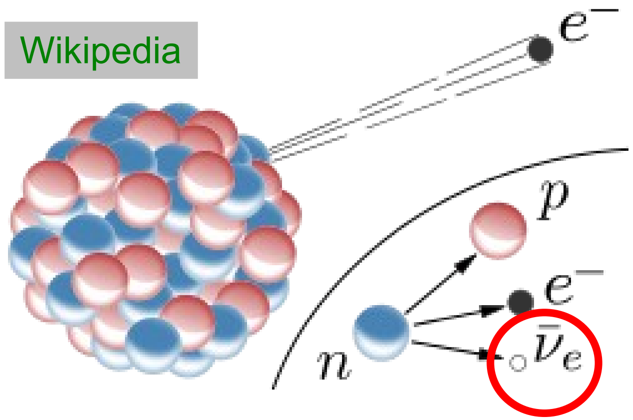
Phys. Rev. Lett. 9 (**1962**), 36.

Phys. Lett. B 504 (**2001**), 218.

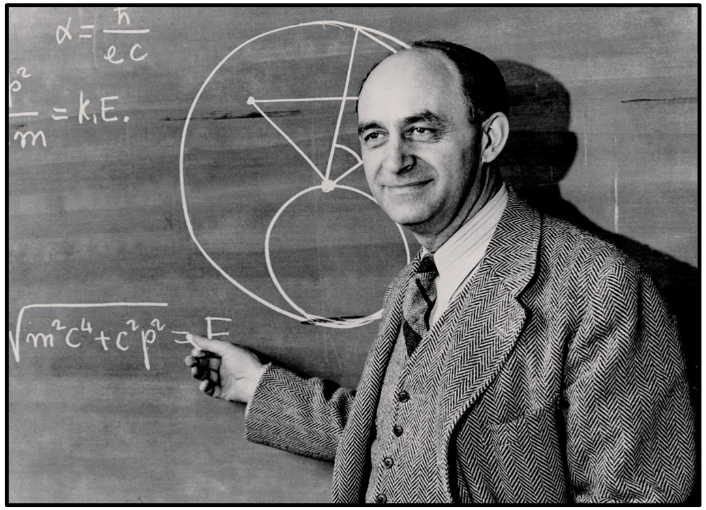
Fermi's four-fermion coupling

β-decay

Wikipedia



Pauli's “neutron”
→ neutrino



E. Fermi

Versuch einer Theorie der β-Strahlen. I[1]).

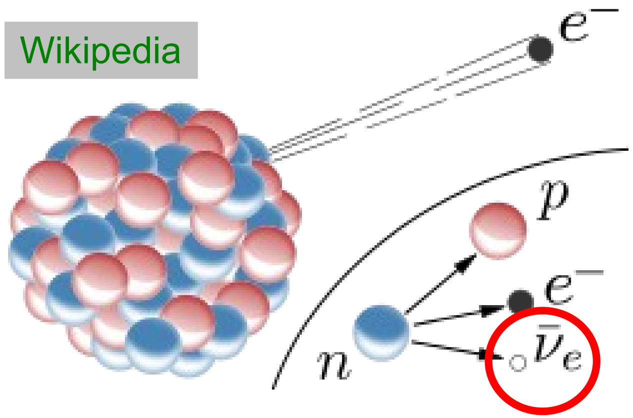
Von **E. Fermi** in Rom.

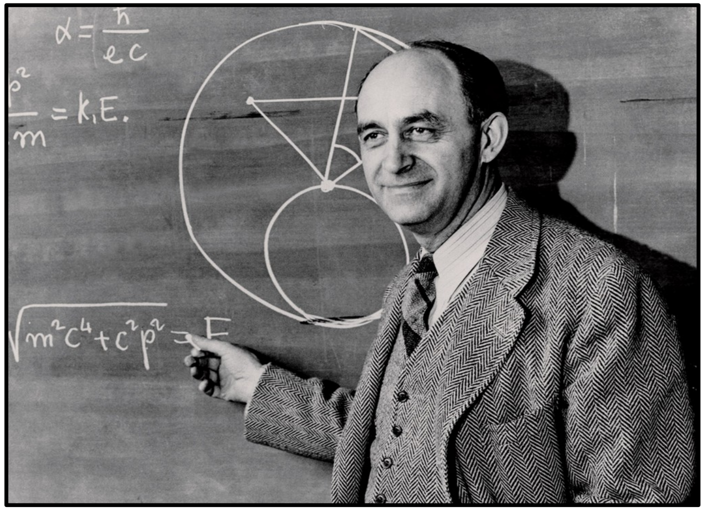
Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

Fermi, Z. Phys., 1934, 88, 16; Nuovo Cim., 1934, 11, 1

β-decay





E. Fermi

First publikation declined by "Nature" as too speculative
→ Appeared first in German and Italian!

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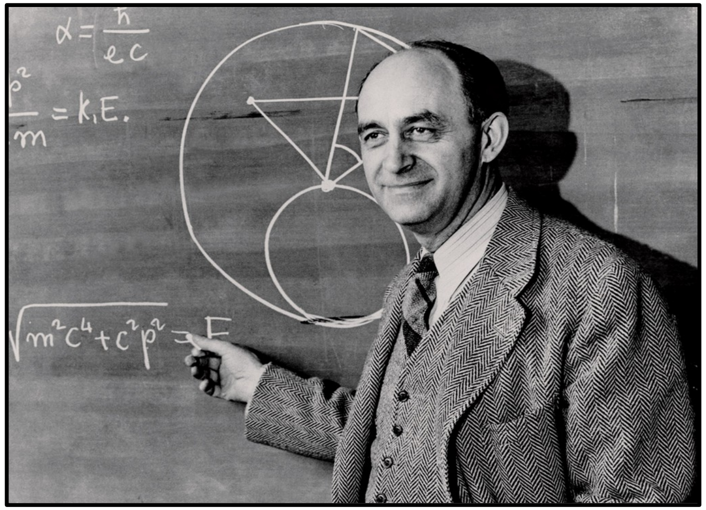
Fermi, Z. Phys., 1934, 88, 16; Nuovo Cim., 1934, 11, 1

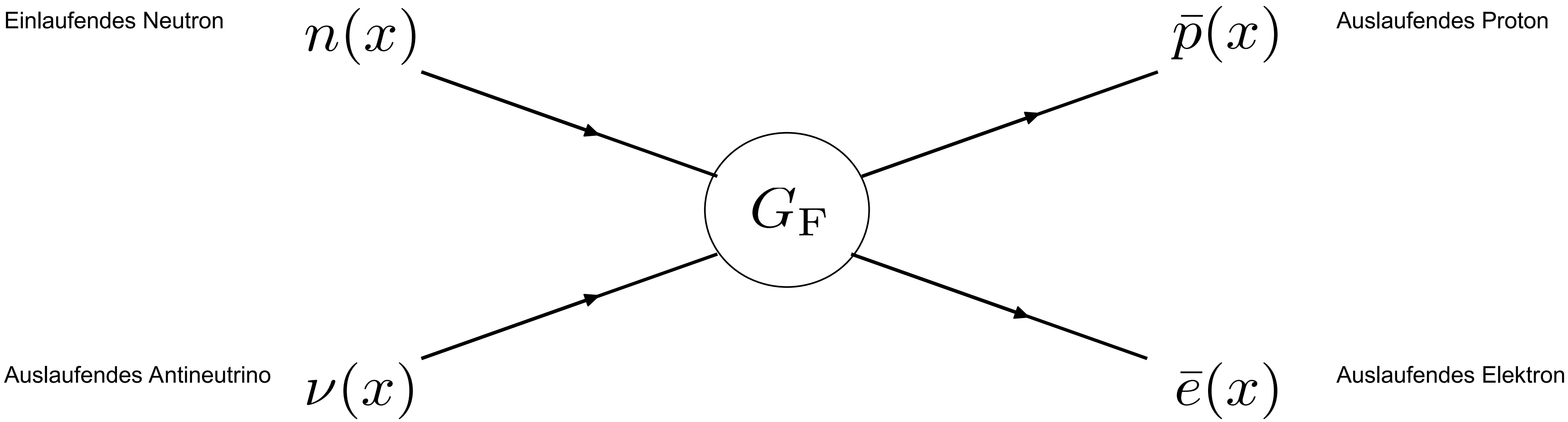
First idea of weak interaction

- **Current-current interaction analogously to the electromagnetic interaction**

$$\mathcal{H}_{\mathrm{IA}} = G_{\mathrm{F}} \int d^3x \, \underbrace{\left(\bar{p}(x)\gamma^{\mu}n(x)\right)}_{\text{Proton-Neutron Strom}} \underbrace{\left(\bar{e}(x)\gamma_{\mu}\nu(x)\right)}_{\text{Elektron-Neutrino Strom}} + h.c.$$



E. Fermi



Discovery of $\mu^\pm$ and $\pi^\pm$ "mesons"

Discovery

Particle	Scientist	Year	Technique
e+	C.D. Anderson	1932	Cloud chamber
n	J. Chadwick	1932	α scattering
μ±	C.D. Anderson, S. Neddermeyer	1936	Cosmic rays
π±	C. Lattes, G. Occhialini, H. Muirhead, C. Powell	1947	Cosmic rays

- **Approximately similar coupling strengths for various decays:**

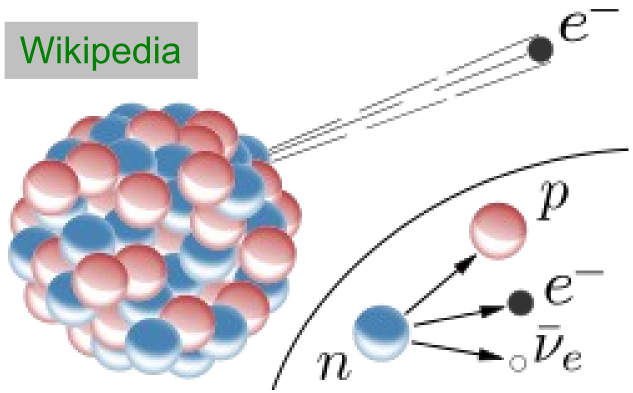
$$\left.\begin{array}{l} n \to p\,\bar{\nu}_e\,e \\ \mu^- \to e^-\,\bar{\nu}_e\,\nu_\mu \\ \pi^- \to \bar{\nu}_\mu\,\mu^- \end{array}\right\} \to \textbf{Universality of weak interaction?}$$

G. Occhialini with P. Blackett

Fermi's four-fermion coupling

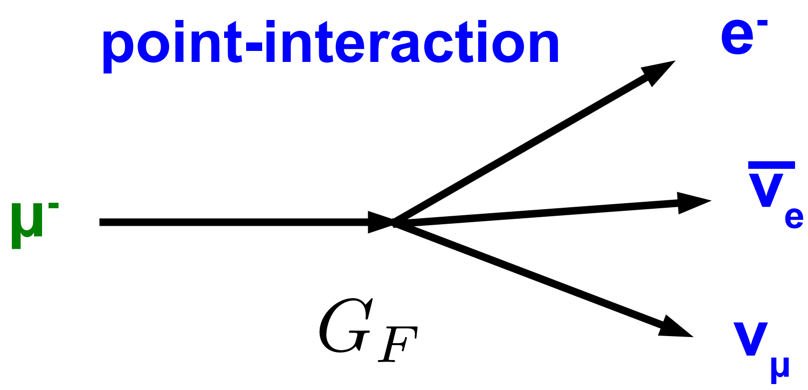
β-decay

Wikipedia



μ-decay

point-interaction



μ decay similar to β decay!

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

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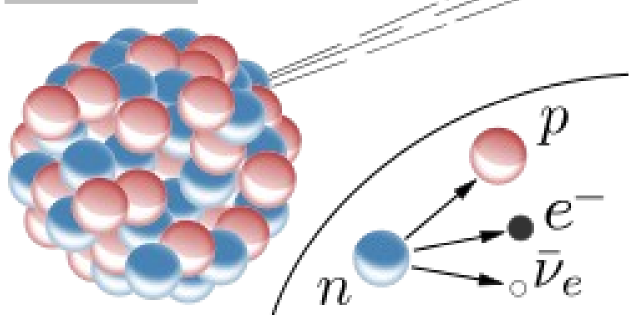
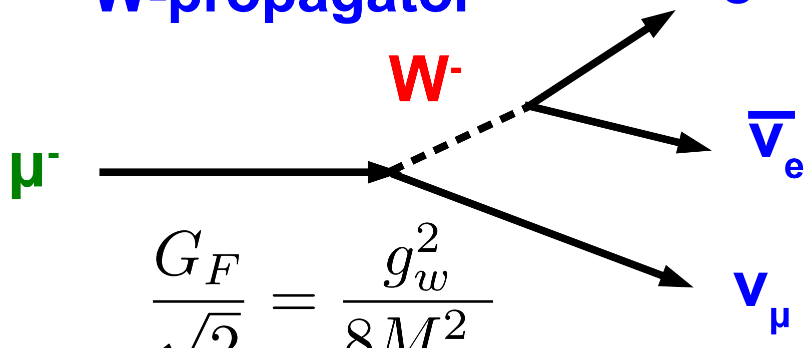


μ-decay

W-propagator



$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_W^2}$$

Modern interpretation as weak decays!

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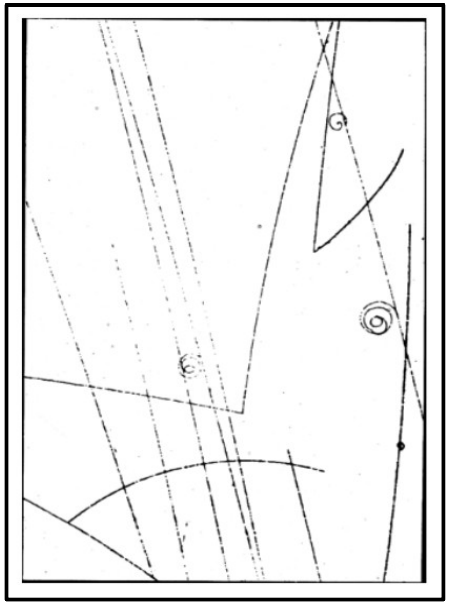
Fermi, Z. Phys., 1934, 88, 16; Nuovo Cim., 1934, 11, 1

Discovery of “V” particles

Discovery

Particle	Scientist	Year	Technique
e+	C.D. Anderson	1932	Cloud chamber
n	J. Chadwick	1932	α scattering
μ±	C.D. Anderson, S. Neddermeyer	1936	Cosmic rays
π±	C. Lattes, G. Occhialini, H. Muirhead, C. Powell	1947	Cosmic rays
K0, K±	G.D. Rochester, C.C. Butler	1947-1949	Cosmic rays
Λ0	V.D. Hopper, S. Biswas	1950	Cosmic rays
π0	R. Bjorklund et al.	1950	Accelerator



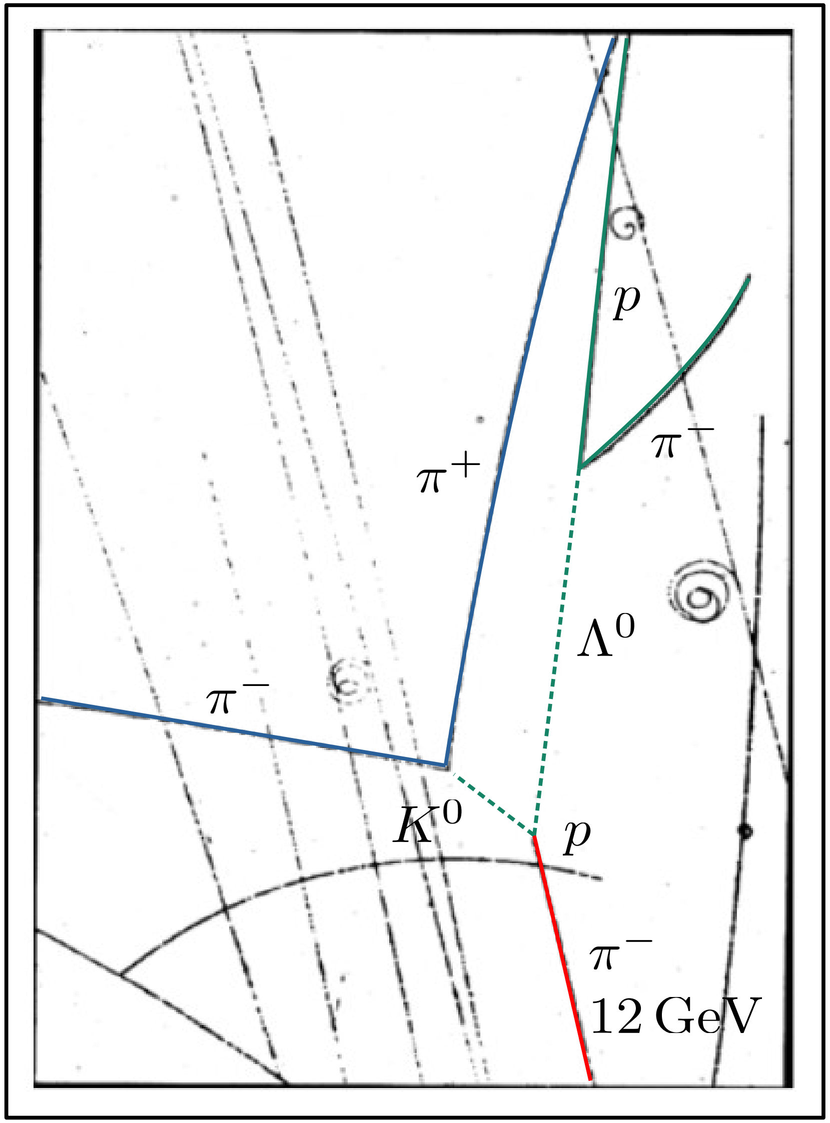
G. D. Rochester, C. C. Butler, Nature 160 (1947) 855.

“V” shaped tracks of charged particles with mass between pion and proton

G. D. Rochester

C. C. Butler

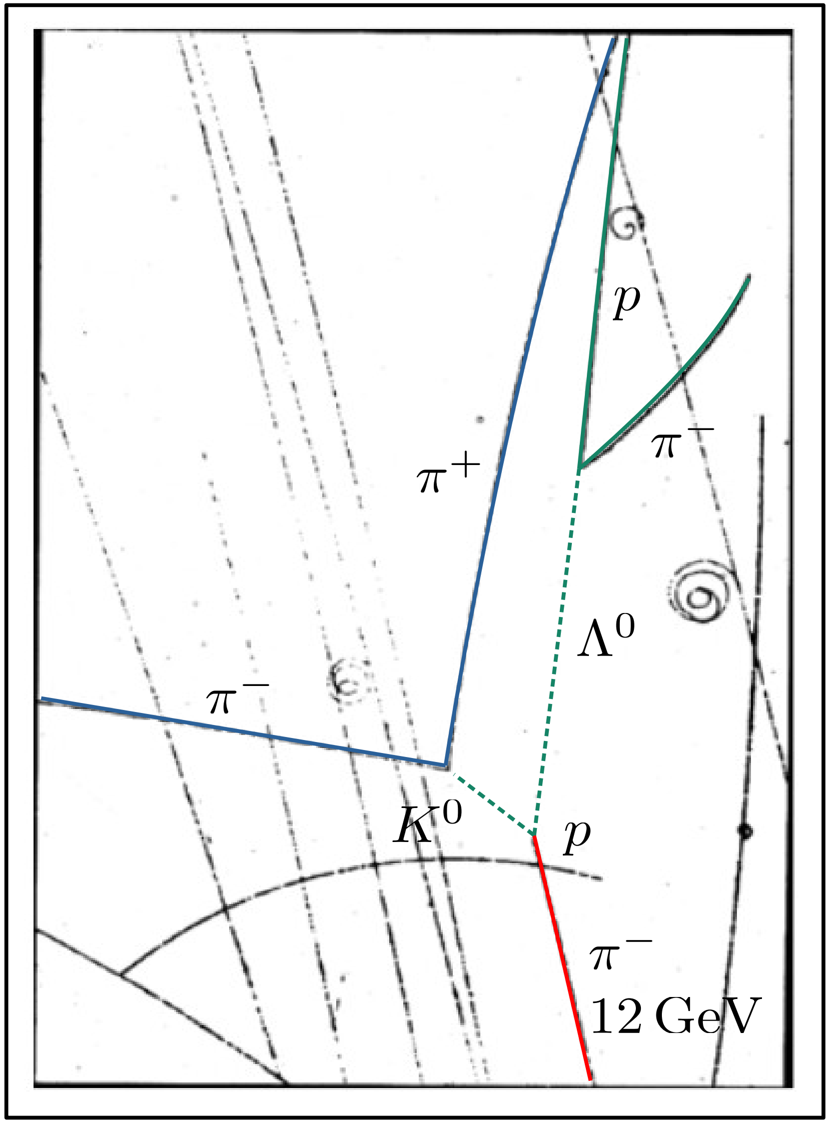
Mystery of strange "V" particles



- **"V" particles massive enough to decay → $\pi^{\pm}$ or p, but:**
  - **Lifetimes longer than usual for strong interactions**
  - **Weak decays? Why?**

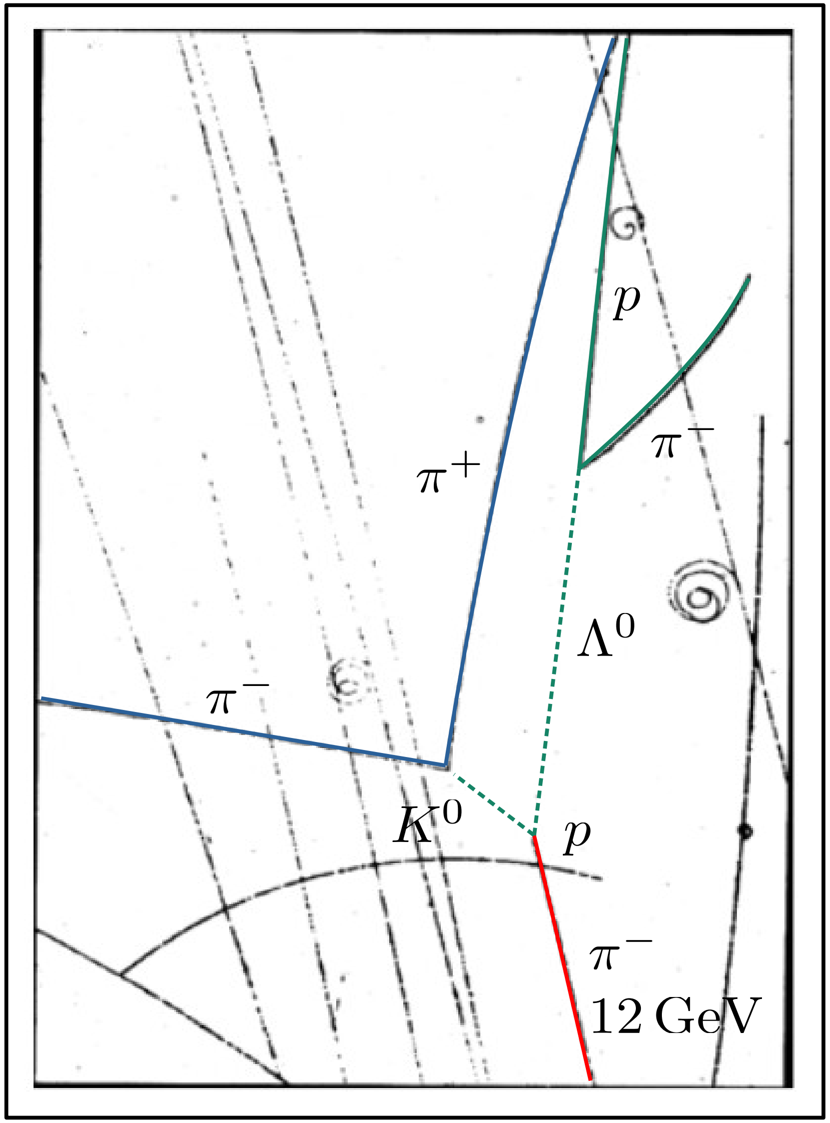
Mystery of strange "V" particles

Can you draw the Feynman diagrams for the production and decays?



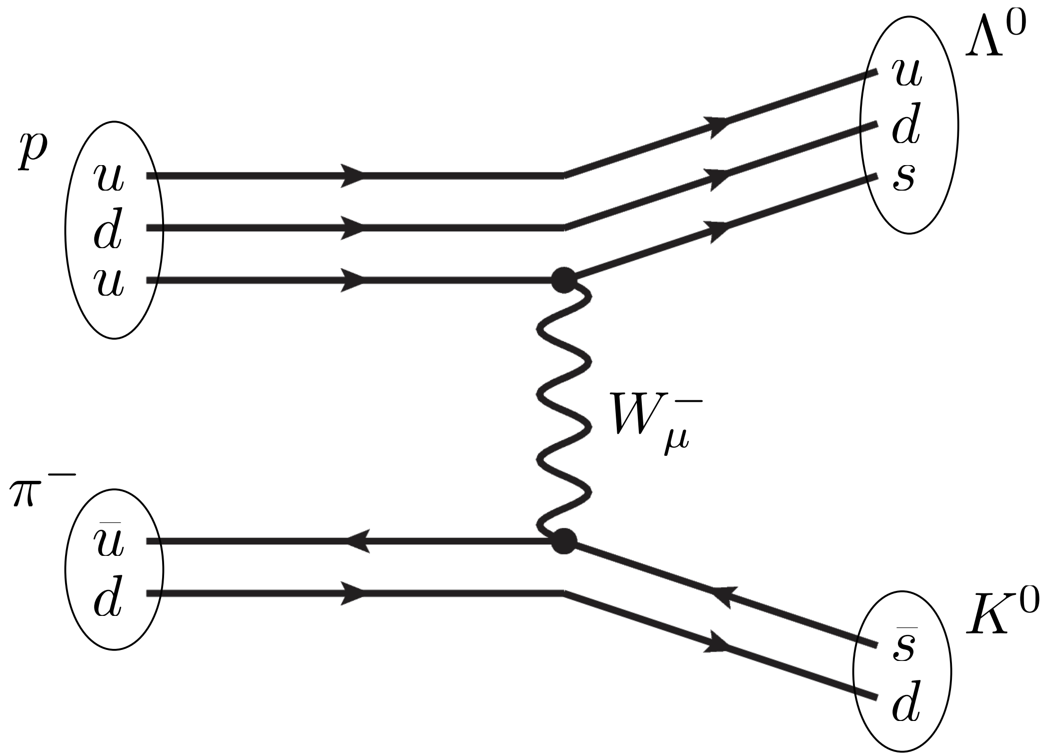
- "V" particles massive enough to decay → $\pi^\pm$ or p, but:
  - Lifetimes longer than usual for strong interactions
  - Weak decays? Why?

Can you draw the Feynman diagrams for the production and decays?



- **Production of two “V” particles:**

$$\pi^- \, p \rightarrow K^0 \, \Lambda^0$$



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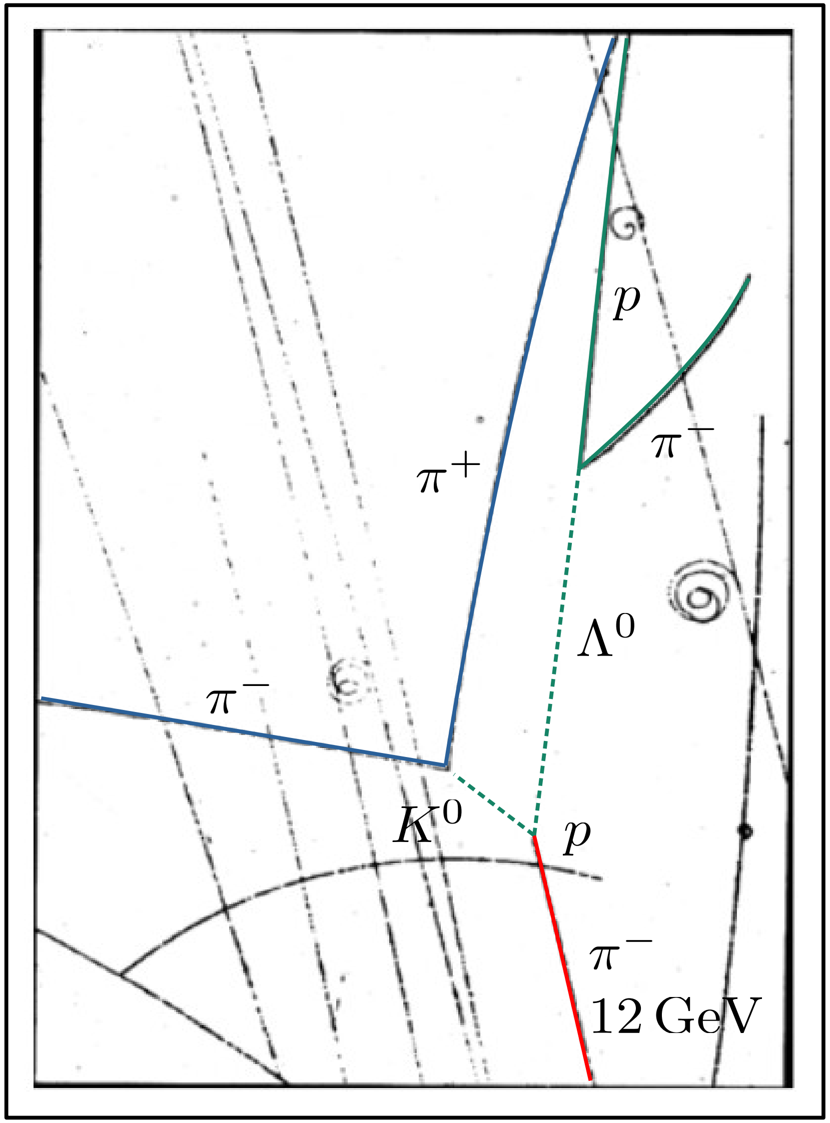
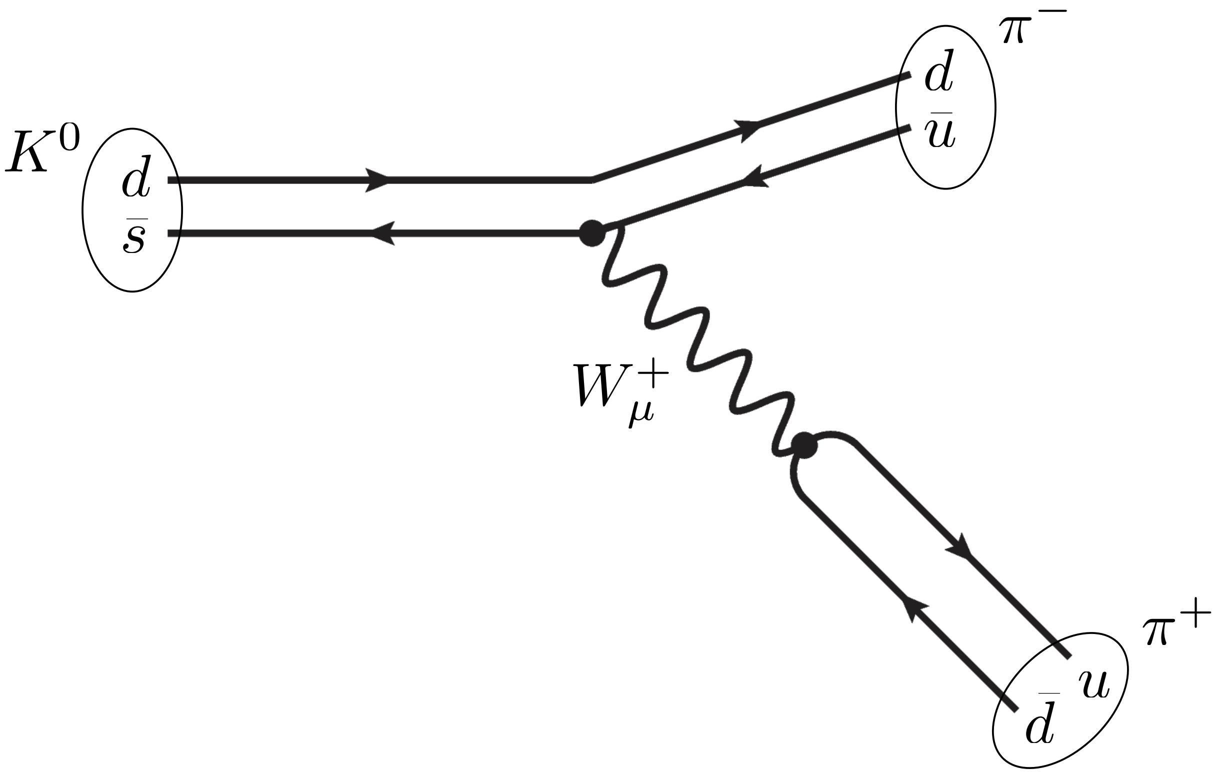


- **K^0 decay:**

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



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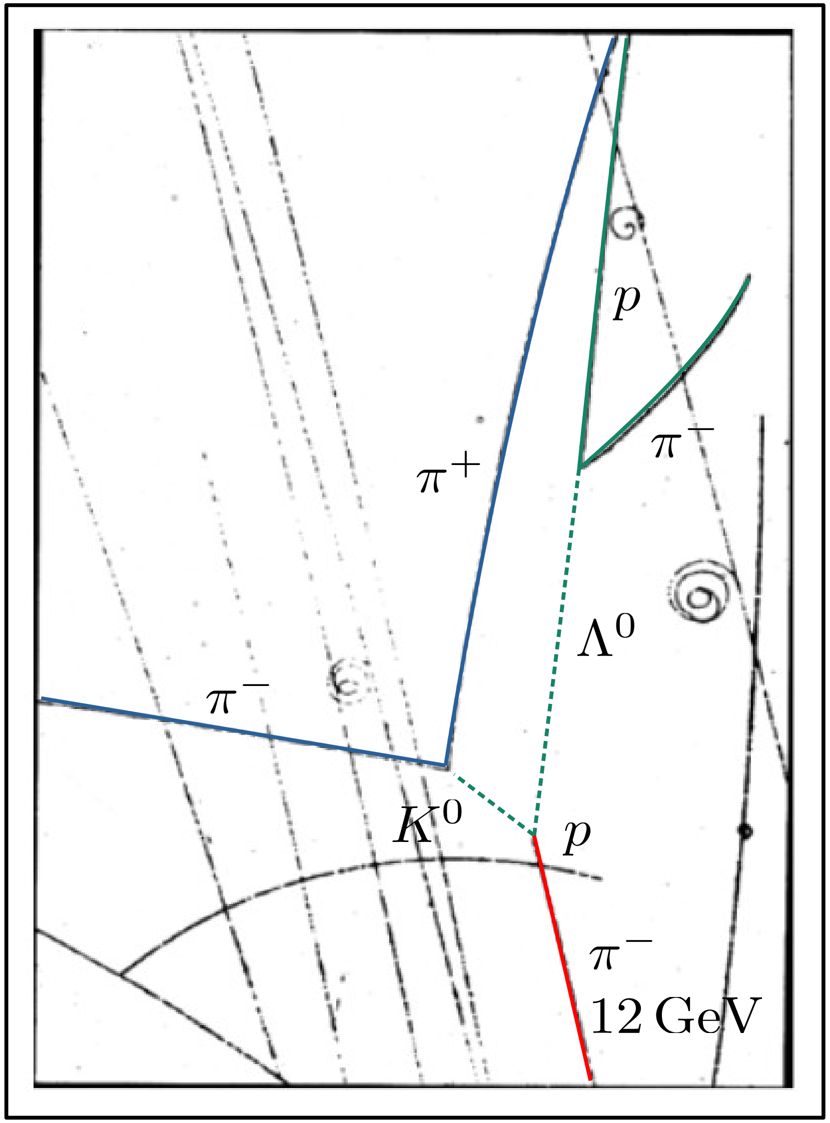
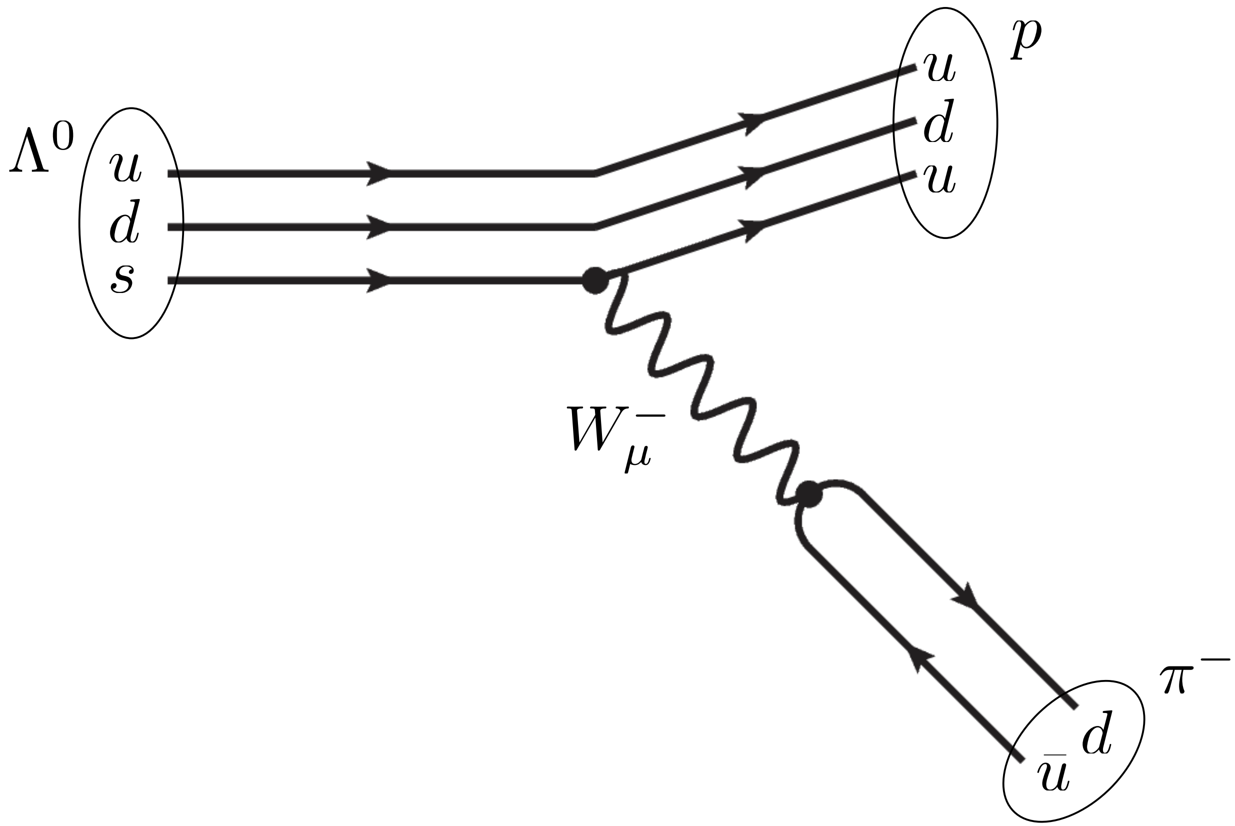


- **Λ^0 decay:**

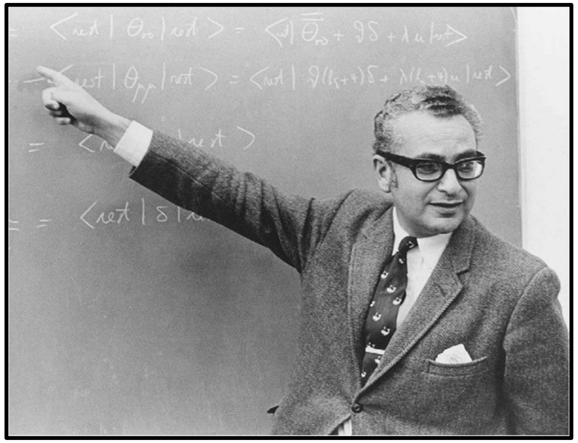
$$\Lambda^0 \to p\,\pi^-$$



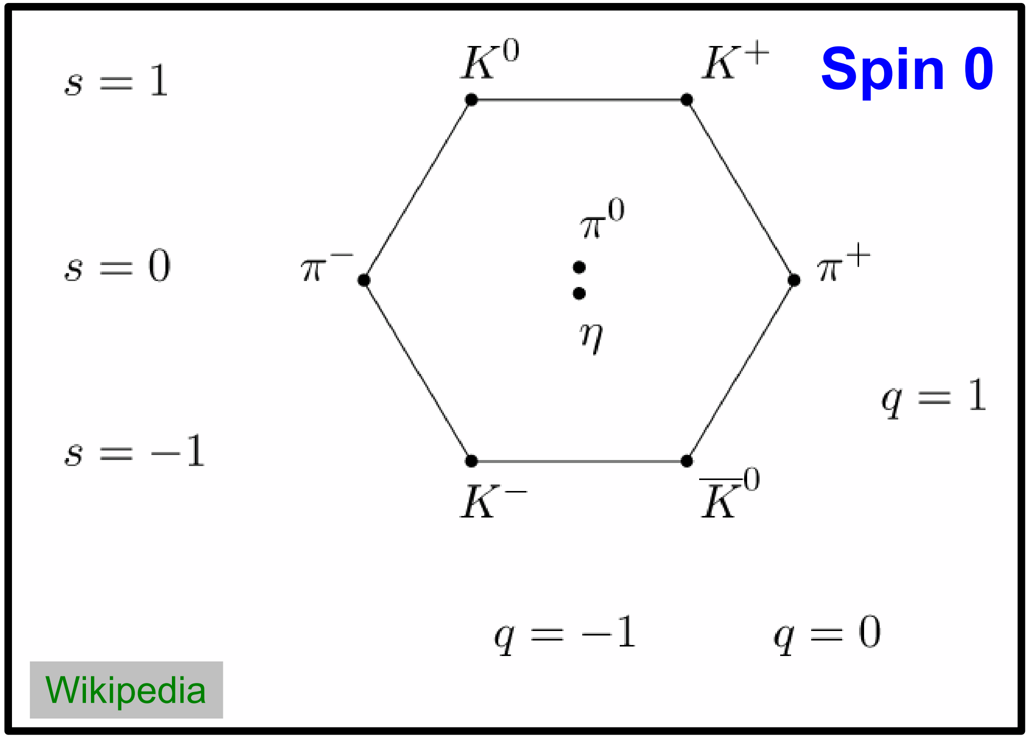
Postulate of M. Gell-Mann

- **Existence of new quantum number "strangeness" S**
  - **Strangeness is conserved by the strong interaction**
  - **Strangeness can be changed by weak interactions**
  - **"Strange" particles only decay weakly**

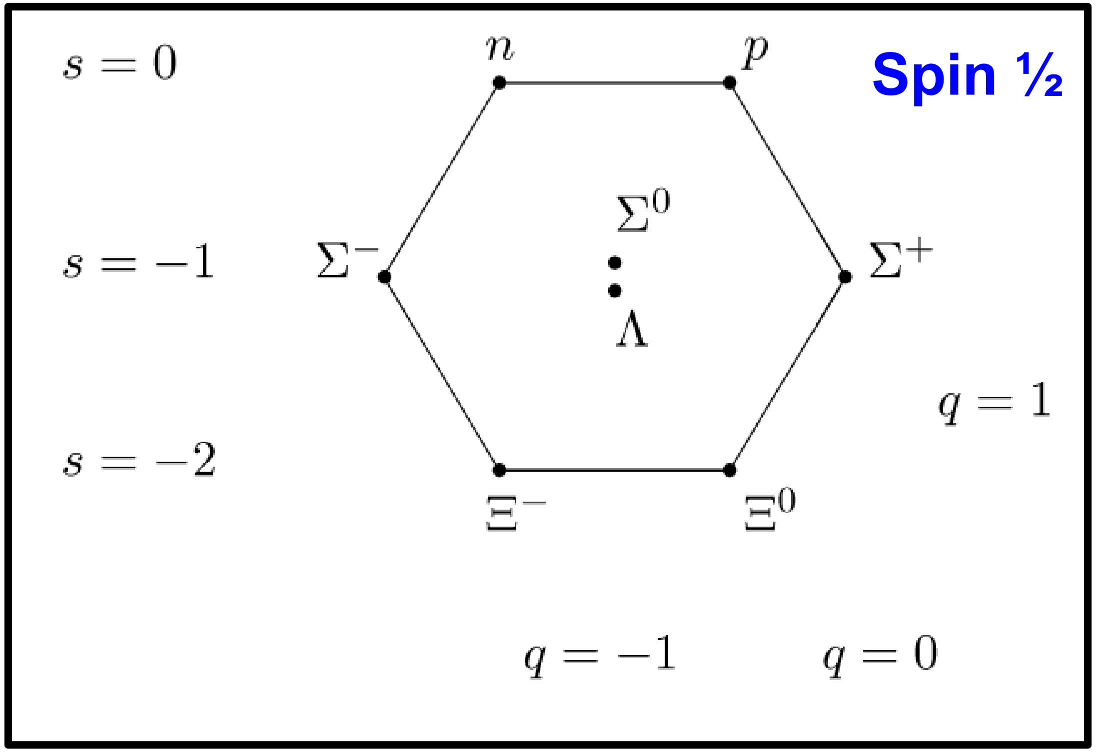
M. Gell-Mann, Phys. Rev. 92, (1953) 833.



M. Gell-Mann



Wikipedia



Mystery of θ / τ particles

- Together with the K^0 two other starnge particles were discovered, the $\theta^{\pm}$ and the $\tau^{\pm}$
  - Masses: $$m_\theta = m_\tau = 493.7 \text{ MeV}$$
  - Lifetimes: $$\tau_\theta = \tau_\tau = 1.24 \cdot 10^{-8} \text{ s}$$
  - Decay modes differ in terms of parity P:
    - $\theta^+ \to \pi^+ + \pi^0 \qquad P(\pi\pi) = +1$
    - $\tau^+ \to \pi^+ + \pi^+ + \pi^- \qquad P(\pi\pi\pi) = -1$

Do you recall from TP I how to get the final state parity?

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Do you recall from TP I how to get the final state parity?

$$P(\pi\pi) = (-1)^L \cdot P(\pi) \cdot P(\pi) = +1$$

$$P(\pi\pi\pi) = \underbrace{(-1)^L}_{L=0} \cdot P(\pi) \cdot P(\pi) \cdot \underbrace{P(\pi)}_{=-1} = -1$$

- **Pions are composed of $q\bar{q}$ and have no spin (L = 0)**
- **Fermions and anti-fermions have opposite relative parity**
- **The pions intrinsic parity is -1**

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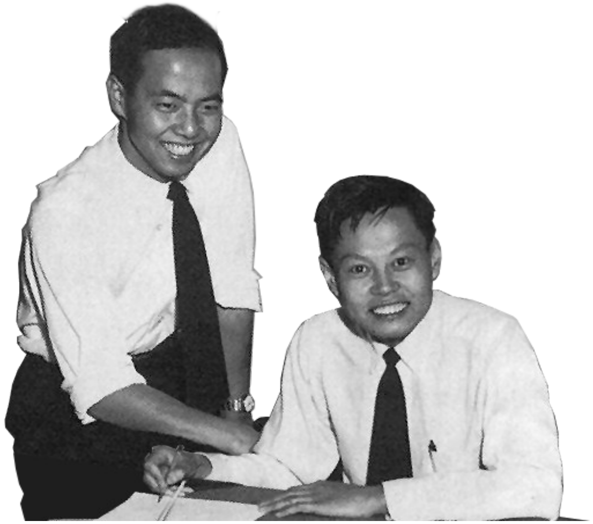
Originally: All interactions like elm. & strong one conserve parity!

→ But why two identical particles just with $P(\theta^{\pm})$ = 1 and $P(\tau^{\pm})$ = -1 ?

Postulate by Lee & Yang

- **The $\theta^{\pm}$ and $\tau^{\pm}$ particles are the same ($K^{\pm}$)**
  - **The weak interaction violates parity conservation**
  - **Experimental proof → Wu experiment**

T. D. Lee, C. N. Yang, Phys. Rev. 104, (**1956**) 254.



Tsung Dao Lee **Chen-Ning Yang**

$$K^+ \to \pi^+ + \pi^0 \qquad P(\pi\pi) = +1 \qquad \Gamma_{\pi\pi}/\Gamma = 20.7\%$$

$$K^+ \to \pi^+ + \pi^+ + \pi^- \qquad P(\pi\pi\pi) = -1 \qquad \Gamma_{\pi\pi\pi}/\Gamma = 7.3\%$$

Quotation of W. Pauli: “Gott ist doch kein schwacher Linkshänder…“

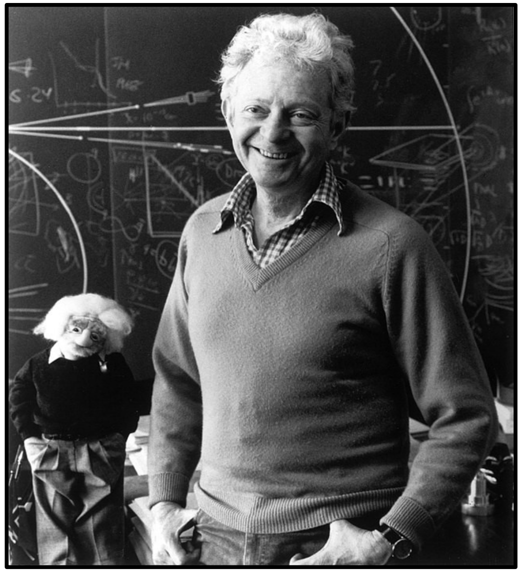
Experimental proof

- Experimental proof of parity violation in weak interactions
  - By C.S. Wu and
  - By R. Garwin, L. Ledeman, M. Weinreich

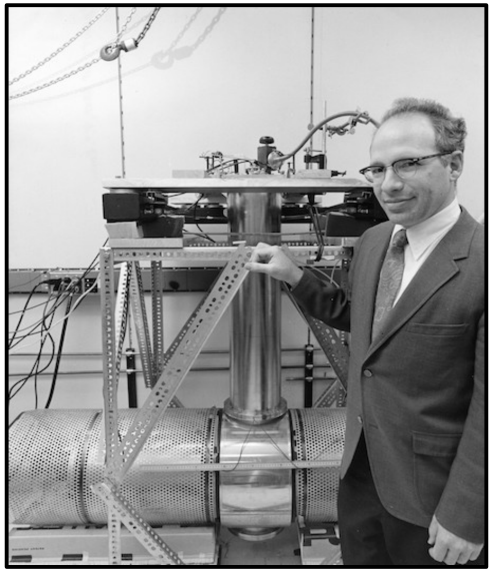
C. S. Wu, et al, Phys. Rev. 105, (1957) 1413.

R. Garwin, L. Ledemann, M. Weinreich, Phys. Rev. 105, (1957) 1415..

Chien-Shiung Wu



Leon M. Ledermann



Richard Garwin

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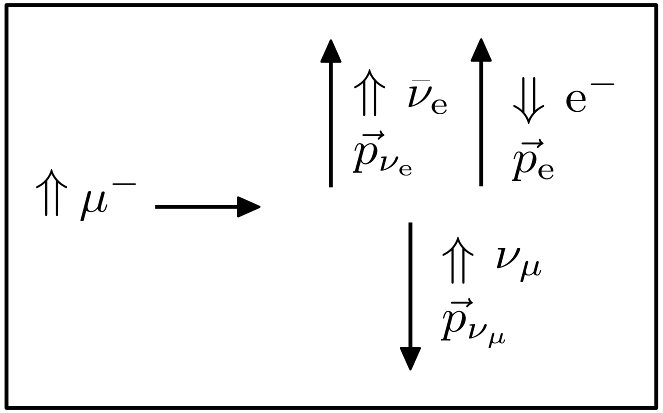

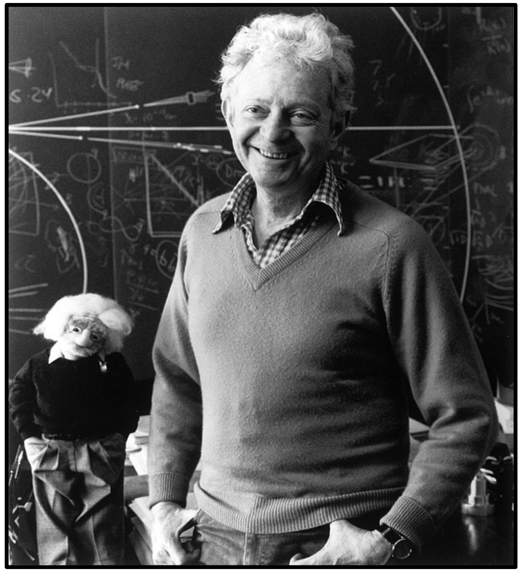

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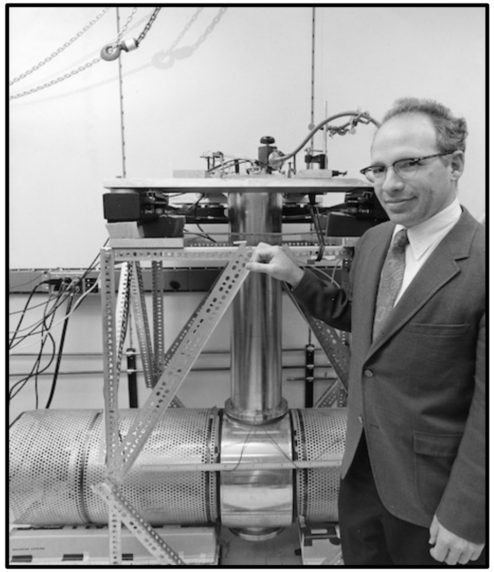

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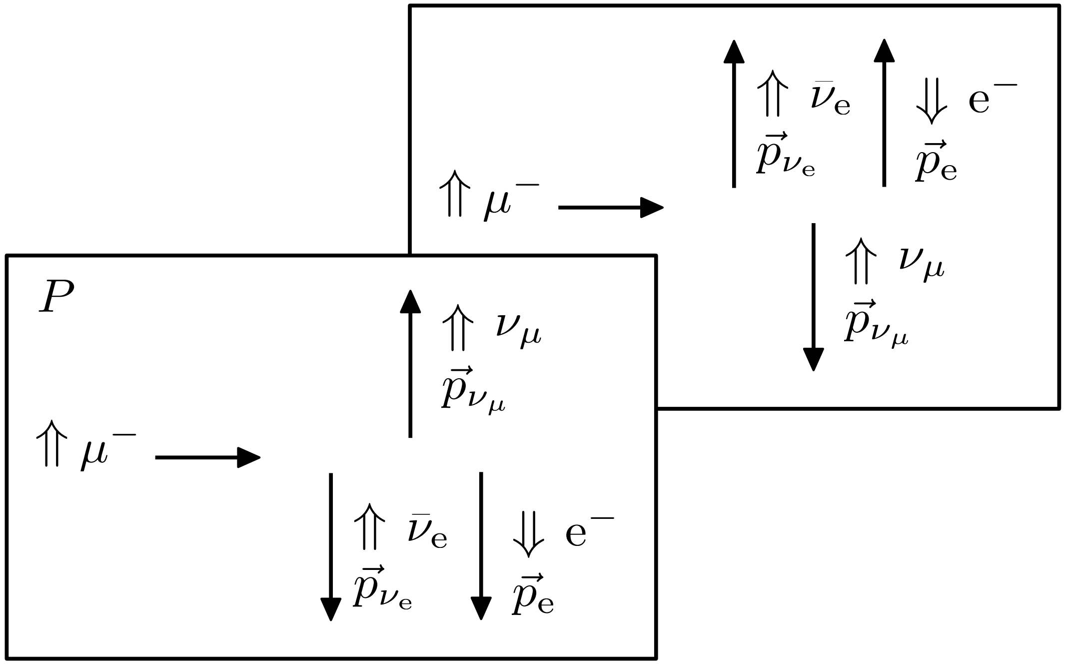

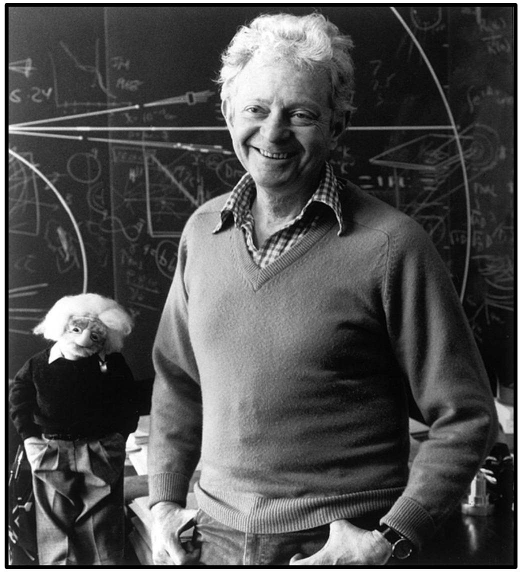

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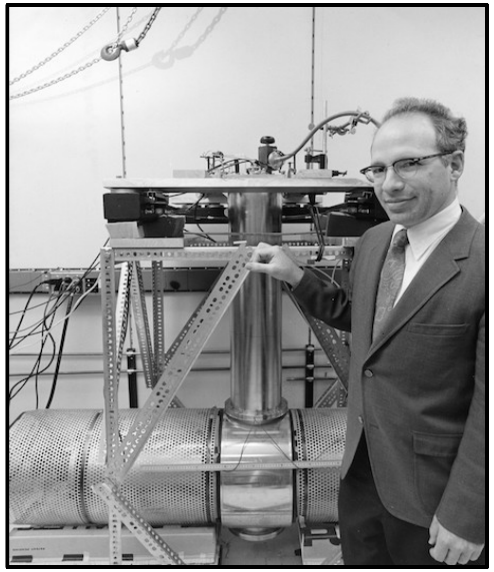


Richard Garwin

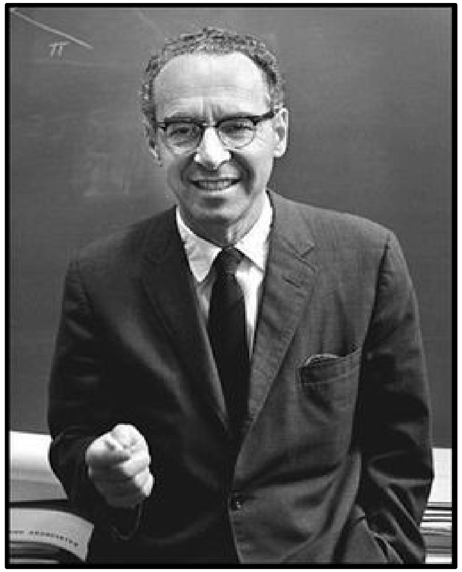
Neutrino helicity

- Experimental result by M. Goldhaber
- Helicity h is the projection of a particles spin onto its momentum vector
  - Neutrinos have negative helicity
  - Anti-neutrinos have positive helicity

  provided $m_\nu \approx 0$

$$h \equiv \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|}$$

M. Goldhaber, et al, Phys. Rev. 109 (1958) 1015.



Maurice Goldhaber

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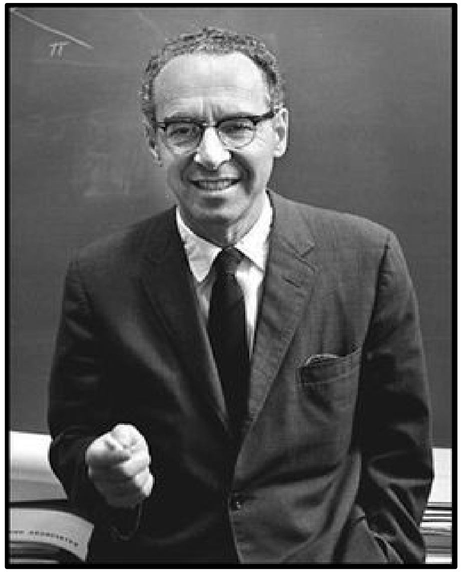


Maurice Goldhaber

- For massless particles (moving with speed of light) helicity is identical to chirality (left- or right-handedness)
- For particles with mass (and v < c) one can always Lorentz-boost into another reference frame with inverted helicity

(Anti-)particle chirality

- **The weak interaction differentiates between the chirality**
- **For massive spin-1/2 fermions four states can be differentiated**
- **Projectors onto left-/right-handed states are:**

$$P_{R/L} = \frac{(1 \pm \gamma^5)}{2}$$

	f	$\bar{f}$
L	f_L	$\bar{f}_L$
R	f_R	$\bar{f}_R$

Problems with weak reactions

- Fermi theory corresponds to contact interaction
  - Coupling constant G_F has dimensions $[G_F] = [E]^{-2}$

$$G_F \approx 1.166 \cdot 10^{-5} \mathrm{GeV}^{-2}$$

  - Cross sections grow beyond all bounds

$$\sigma \sim G_F^2 E_{\mathrm{cms}}^2 = G_F^2 \cdot s$$

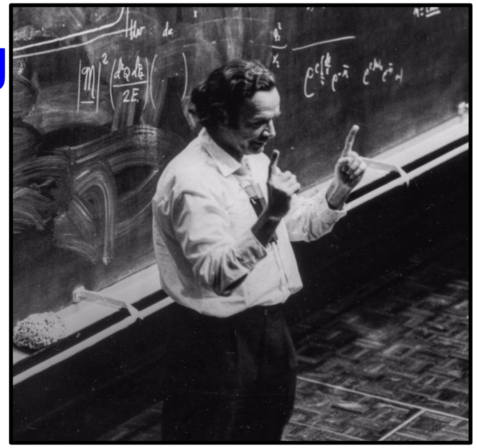
- Interaction becomes very weak at large distances (low energies)
- Parity conservation is maximally violated
  - Weak reactions differentiate between left- and right-handed particles
- Particles change charge
- Particles change “flavor”

$\longrightarrow$ How to describe something so different?

Extension of Fermi theory

- **Extension of Fermi theory to a maximally parity violating theory by R. Feynman & M. Gell-Mann (1958)**

$$\mathcal{H}_{\mathrm{IA}} = \frac{G_{\mathrm{F}}}{2} \int d^3x \, \underbrace{\left(\bar{p}(x)\gamma^{\mu}\left(1-\gamma^5\right)n(x)\right)}_{\text{Proton-Neutron Strom}} \underbrace{\left(\bar{e}(x)\gamma_{\mu}\left(1-\gamma^5\right)\nu(x)\right)}_{\text{Elektron-Neutrino Strom}} + h.c.$$



Richard Feynman

- **Only left-handed fermions and right-handed anti-fermions participate in weak interactions**

- **Unified description of decays**

$$\left.\begin{aligned} n &\to p\,\bar{\nu}_{\mathrm{e}}\,\mathrm{e} \\ \mu^- &\to \mathrm{e}^-\,\bar{\nu}_{\mathrm{e}}\,\nu_{\mu} \\ \pi^- &\to \bar{\nu}_{\mu}\,\mu^- \end{aligned}\right\} \to \text{universality of weak interaction}$$

Explanation of suppressed decay: $\pi^- \to \bar{\nu}_e\,\mathrm{e}^-$

Cabibbo angle

- To explain differences in weak decays, matrix elements are
  - multiplied by sin(θ) for strangeness non-conserving reactions,
  - and by cos(θ) for strangeness conserving ones
  - → one gets: $\vartheta = 13^\circ$

N. Cabbibo, Phys. Rev. Lett. 10, (1963) 531.

Nicola Cabbibo

Cabibbo angle

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Nicola Cabbibo

Weak eigenstates of quarks	$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$	Mass eigenstates of quarks

- Weak interaction of quarks $g\,\bar{u}\gamma^\mu \left(\frac{1-\gamma^5}{2}\right) d$
  - modifies to

Cabibbo angle

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- Weak interaction of quarks
  - modifies to $g\,\bar{u}\gamma^\mu \left(\frac{1-\gamma^5}{2}\right) d' = g\,\bar{u}\gamma^\mu \left(\frac{1-\gamma^5}{2}\right) \left(d\,\cos\vartheta + s\,\sin\vartheta\right)$
  - with Cabibbo mixing angle
  - Weak coupling keeps universality

Summary

- Quick run through of historical events and developments
- Many items of first part were topic of TP I → assumed to be known
- In the following the lectures we will deal with
  - a few necessary experimental basics
  - a few necessary theoretical basics
  - discovery and collider measurements with W and Z bosons
  - discovery and collider measurements with Higgs bosons