

Particle Physics

International teachers program

July 2018

2018 SOJX



European Organisation for Nuclear Research

„Magic is not happening at CERN, magic is explained at CERN“ - Tom Hanks





Understanding the fundamental building blocks of the universe

- 120 year of research in particle physics
 - condensed in 4.5 hours
- Focusing on:
 - Concepts / Ideas
 - Getting to the contemporary research
 - About chronological order

A request from me

Ask!

Anytime & anything

Ask!

Anytime & anything

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Anytime & anything

I'll try to incorporate wishes for tomorrow

Any
Feedback

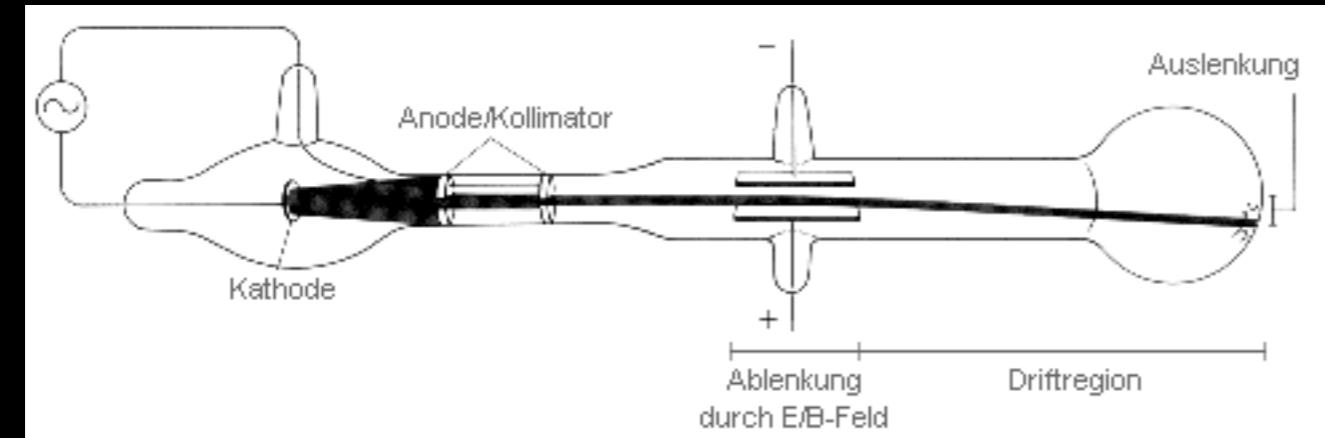
is very much appreciated

What is 'elementary'

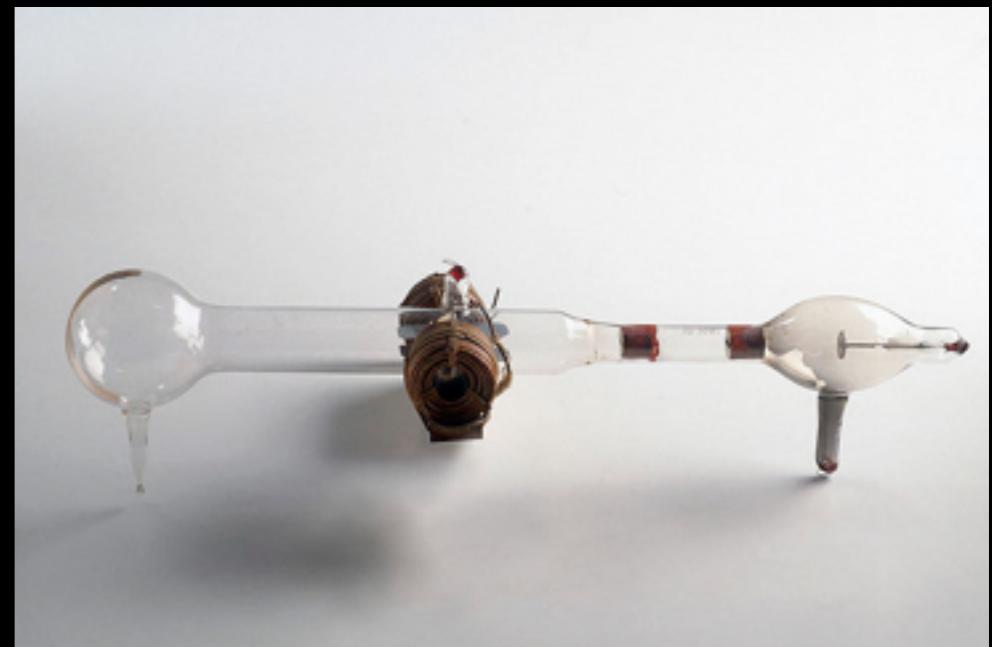
The beginning of particle physics

- Discovery of the **electron**

- Cathode rays: determination of e/m
- Independent of cathode material / residual gas
- Negatively charged (electrically)



Historical cathode ray tube

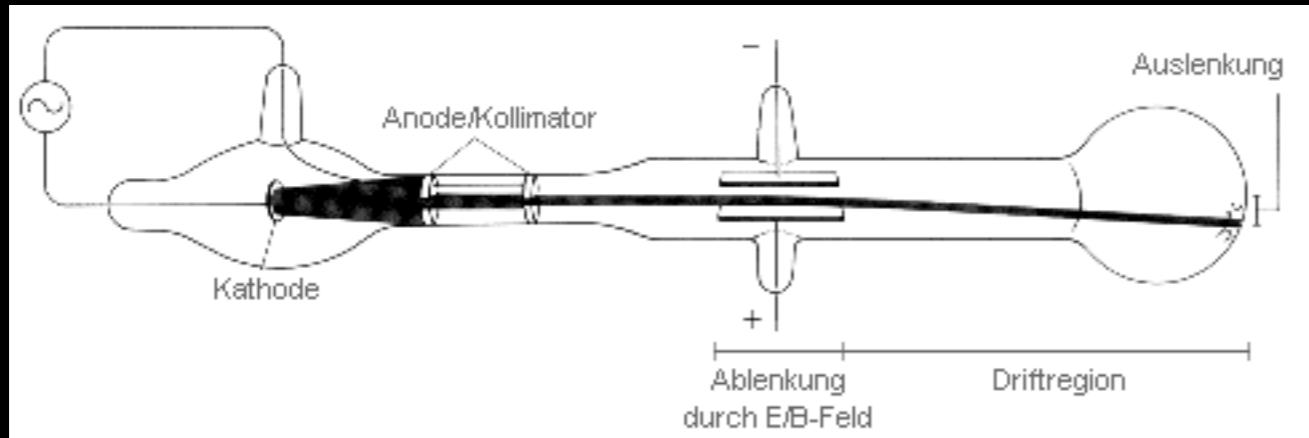


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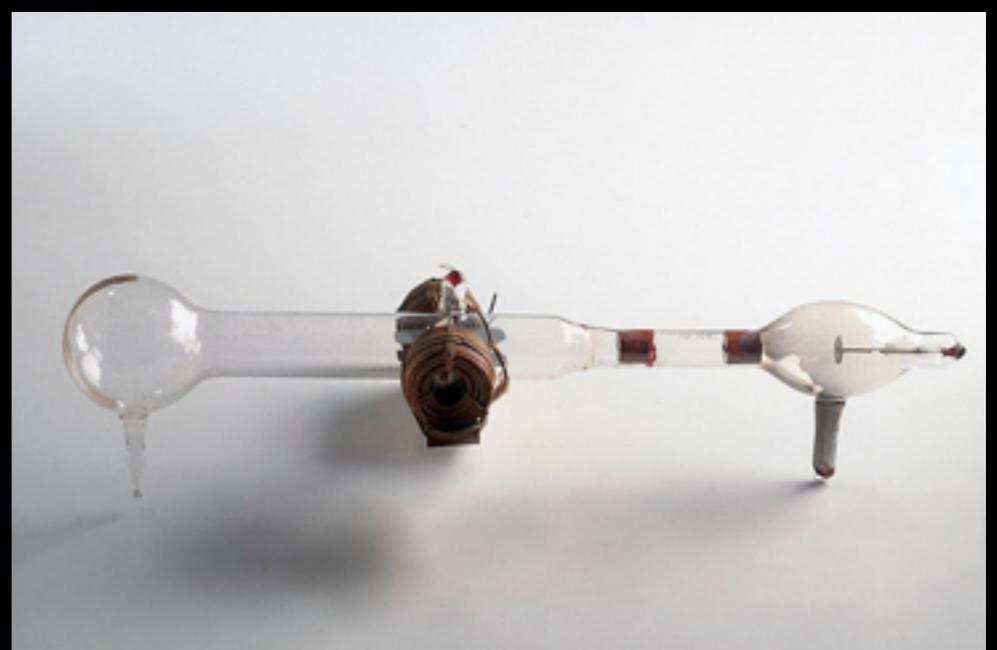
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1897: Thompson / Wiechert



Historical cathode ray tube

- Zeeman effect:**
 - Spectral lines split under magnetic field
 - Explained using electrons
 - (**Spin** introduced much later)

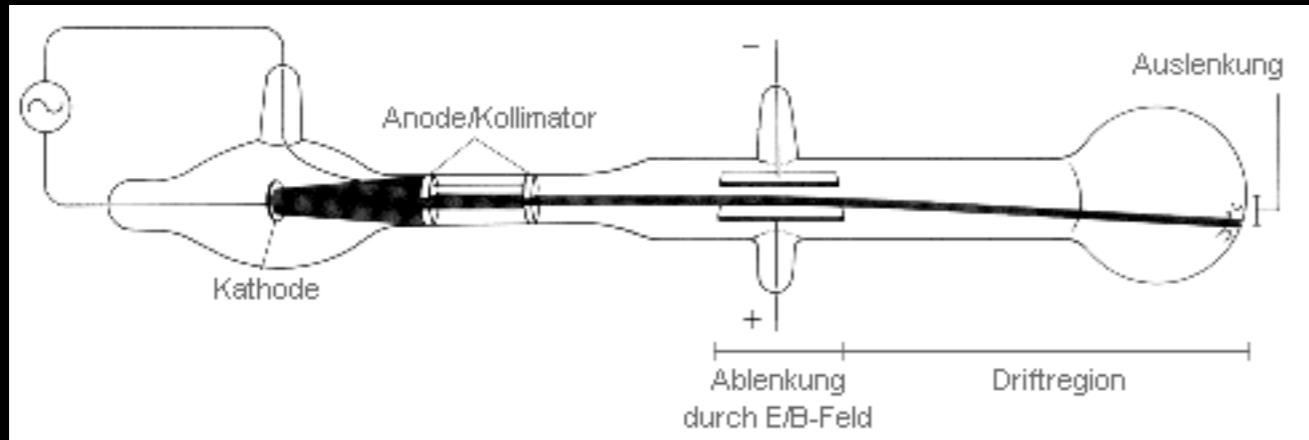


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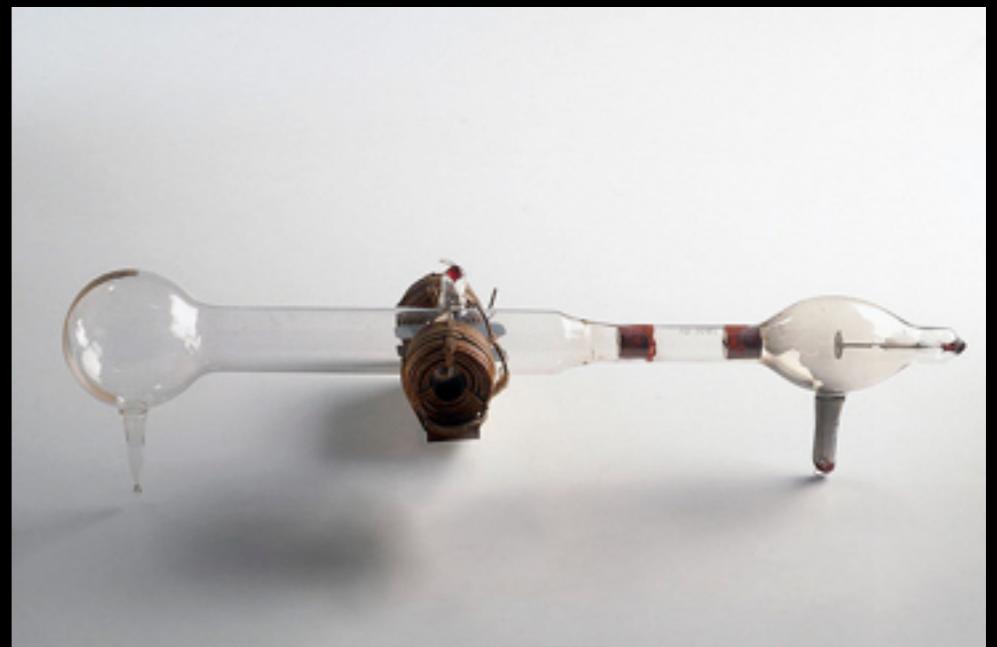


Historical cathode ray tube

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1896: Zeeman (Beobachtung)

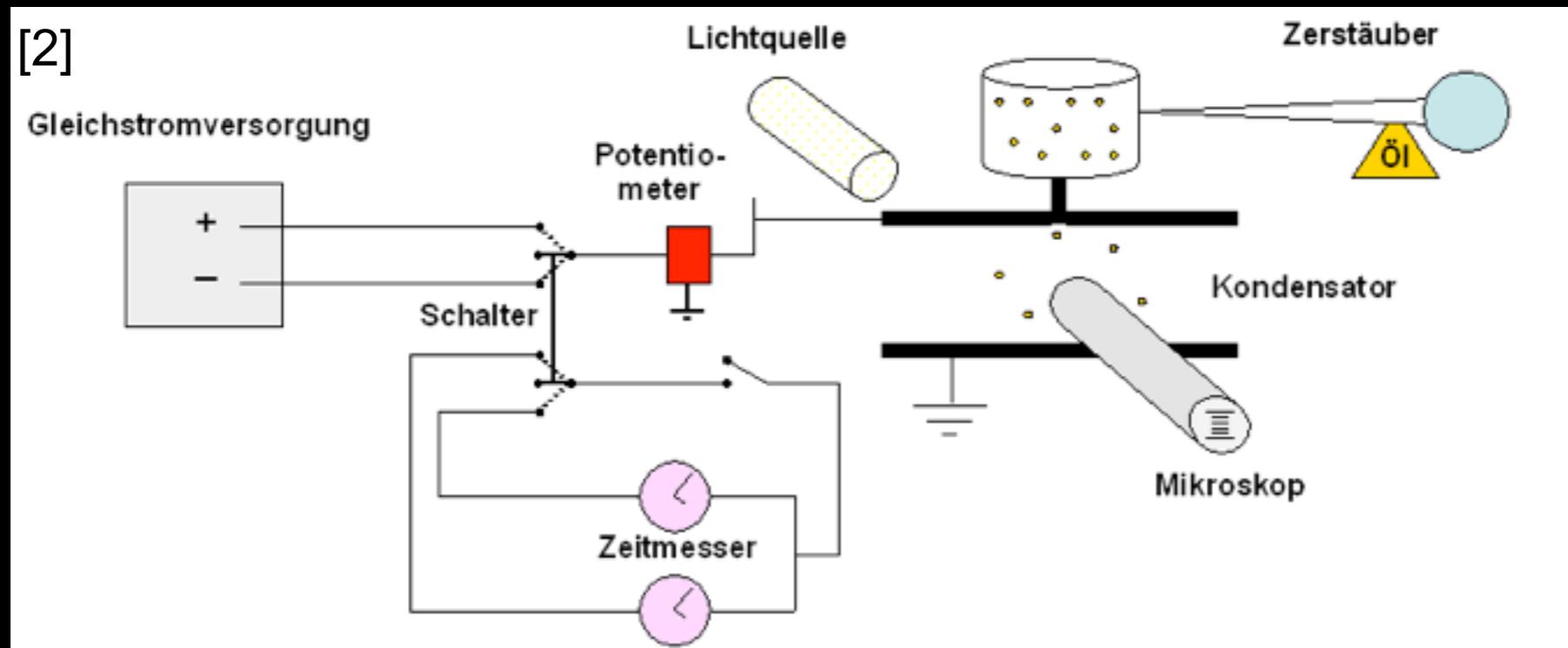
1899: Lorentz (Erklärung)



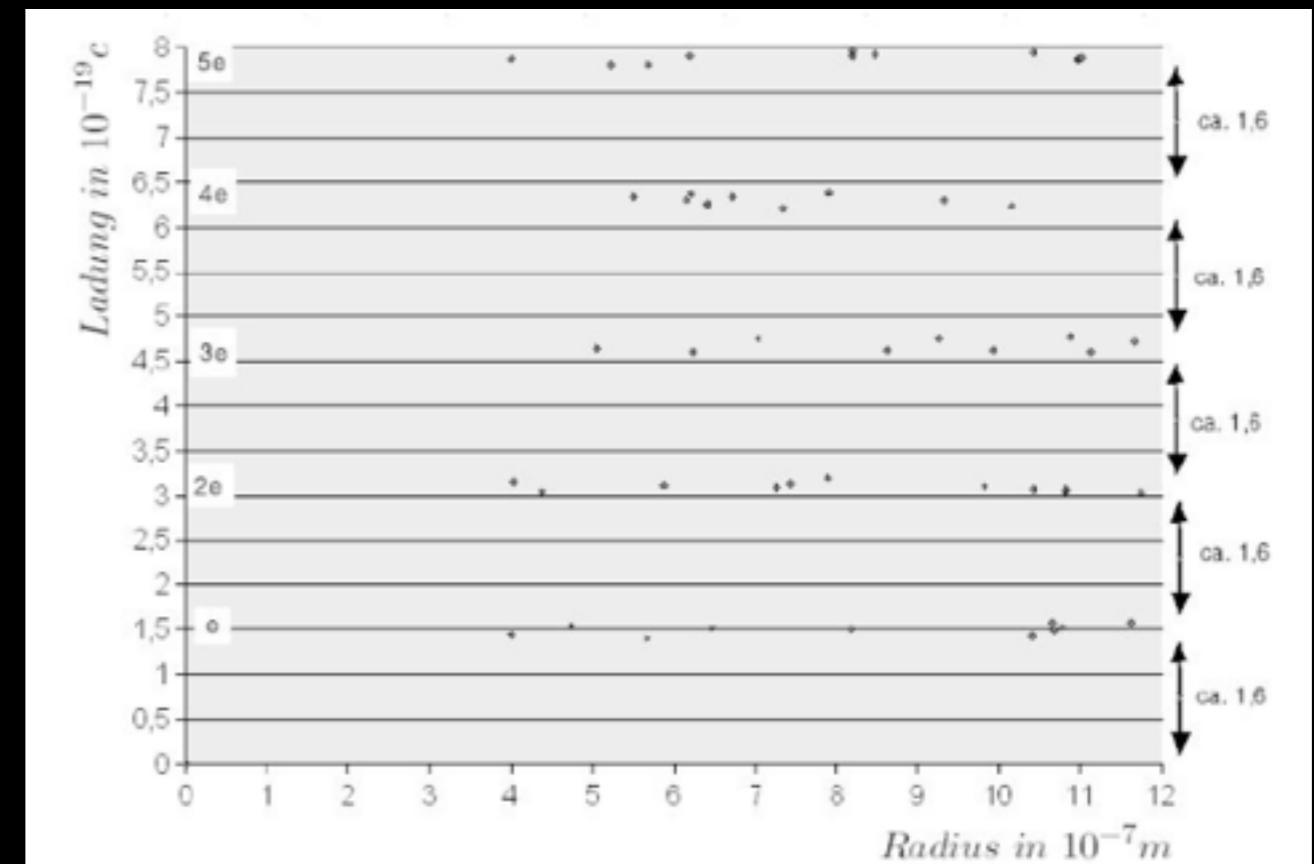
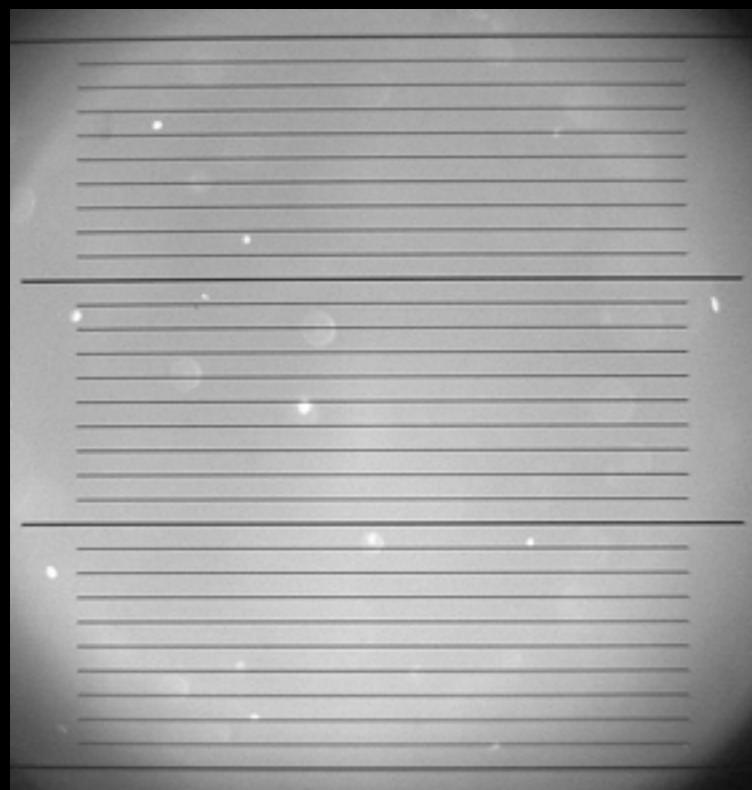
Determination of the elementary charge

- Millikan experiment

1910: Millikan / Fletcher

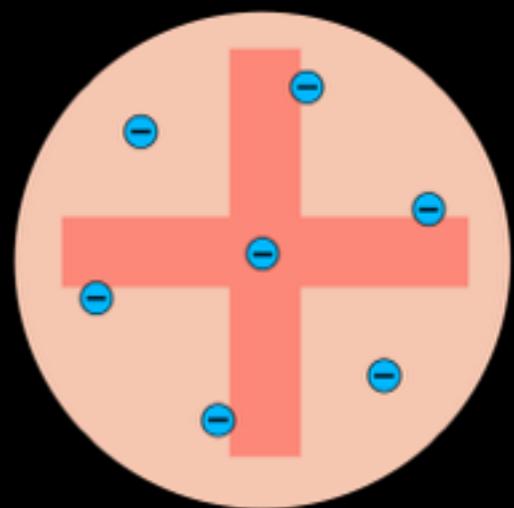


$$e = 1,6 \cdot 10^{-19} \text{ C}$$



Atomic models ~ 1900

- Thomson: „Plum pudding“-modell
 - Electrons inside homogeneous, el. pos. charge mass



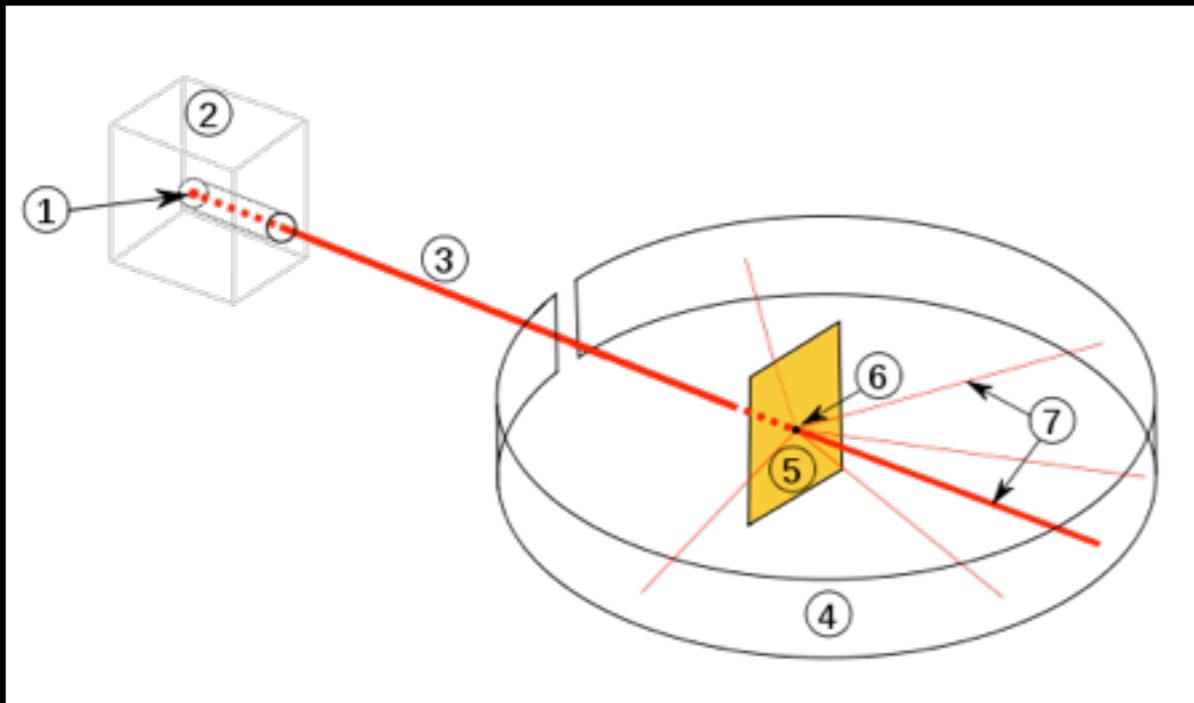
Rutherford Experiment



- Atom mainly empty!

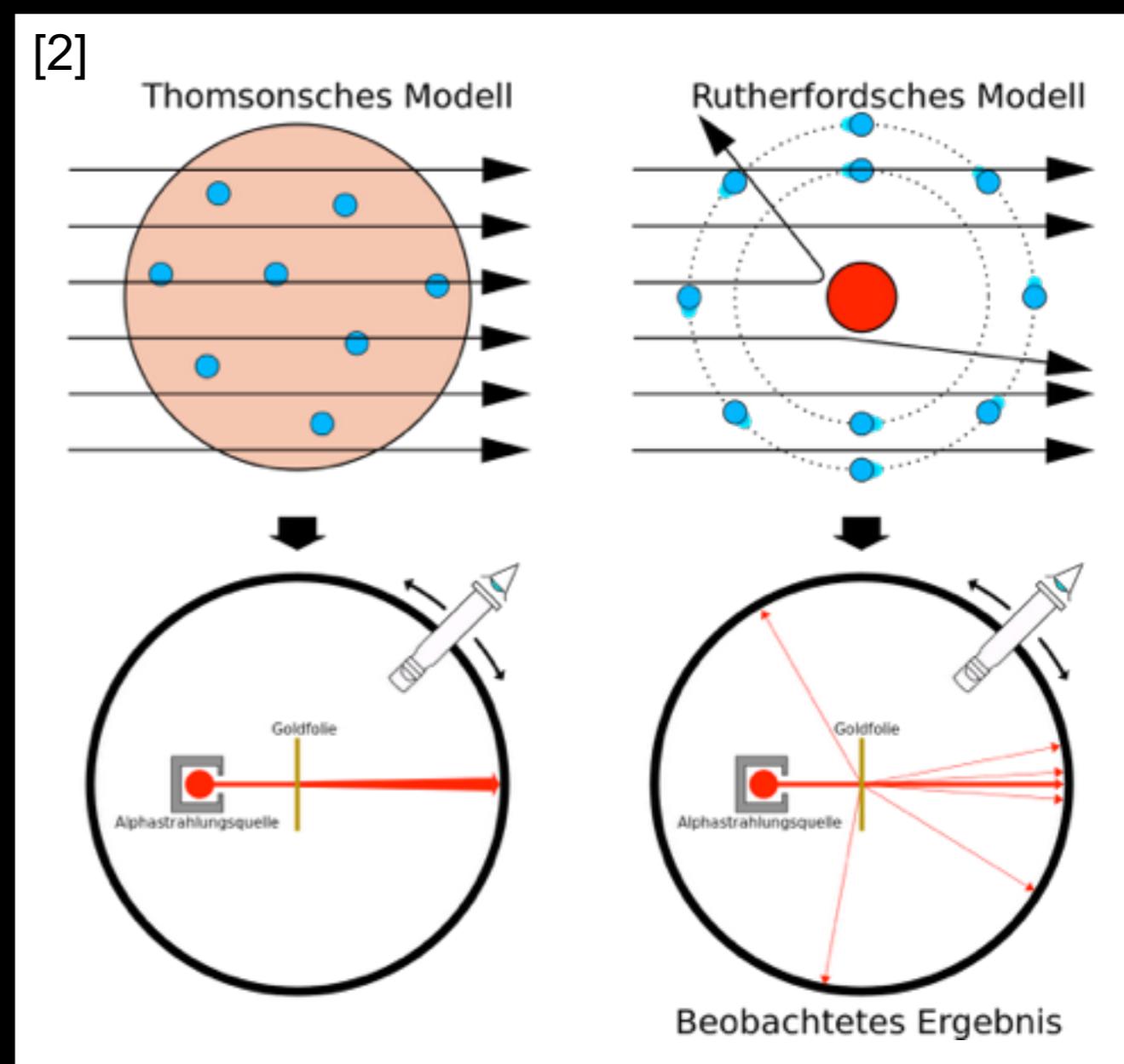
1909: Geiger / Marsden / Rutherford

- Nearly all mass & electric charge concentrated in small volume



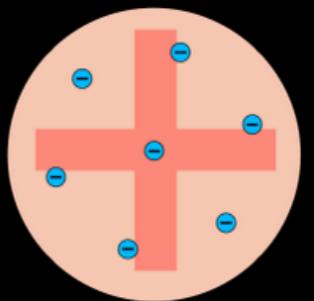
$$\frac{d\sigma}{d\Omega} = \left(\frac{1}{4\pi\varepsilon_0} \frac{Z_1 Z_2 e^2}{4E_0} \right)^2 \frac{1}{\sin^4\left(\frac{\vartheta}{2}\right)}$$

- Estimate of nucleus diameter:
 $\sim 10^{-3} * \text{Atomdurchmesser} = \sim 10^{-14}\text{m}$



Atomic models - 1913

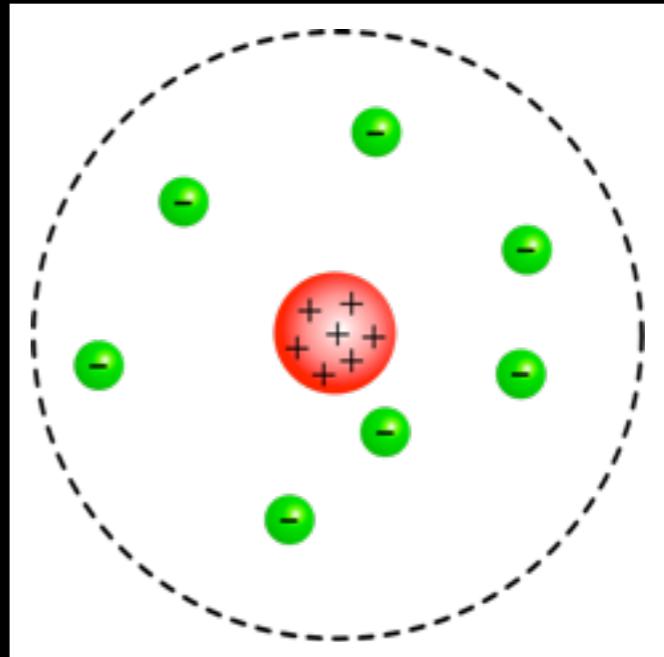
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1900

- Rutherford: Mass & pos. electric charge concentrated in nucleus, electron cloud

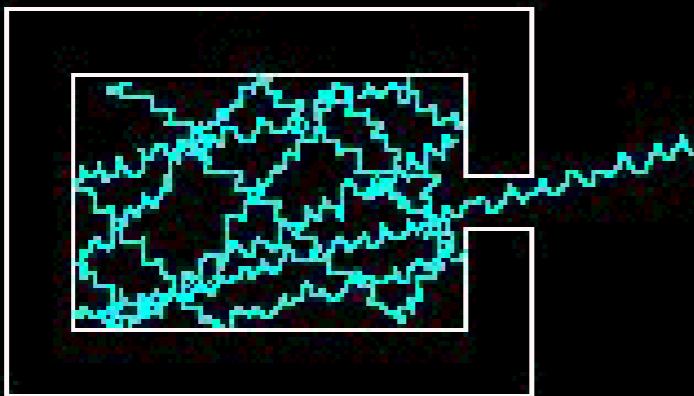
1911



Quanta - Black Body Radiation



Max Planck: 1900

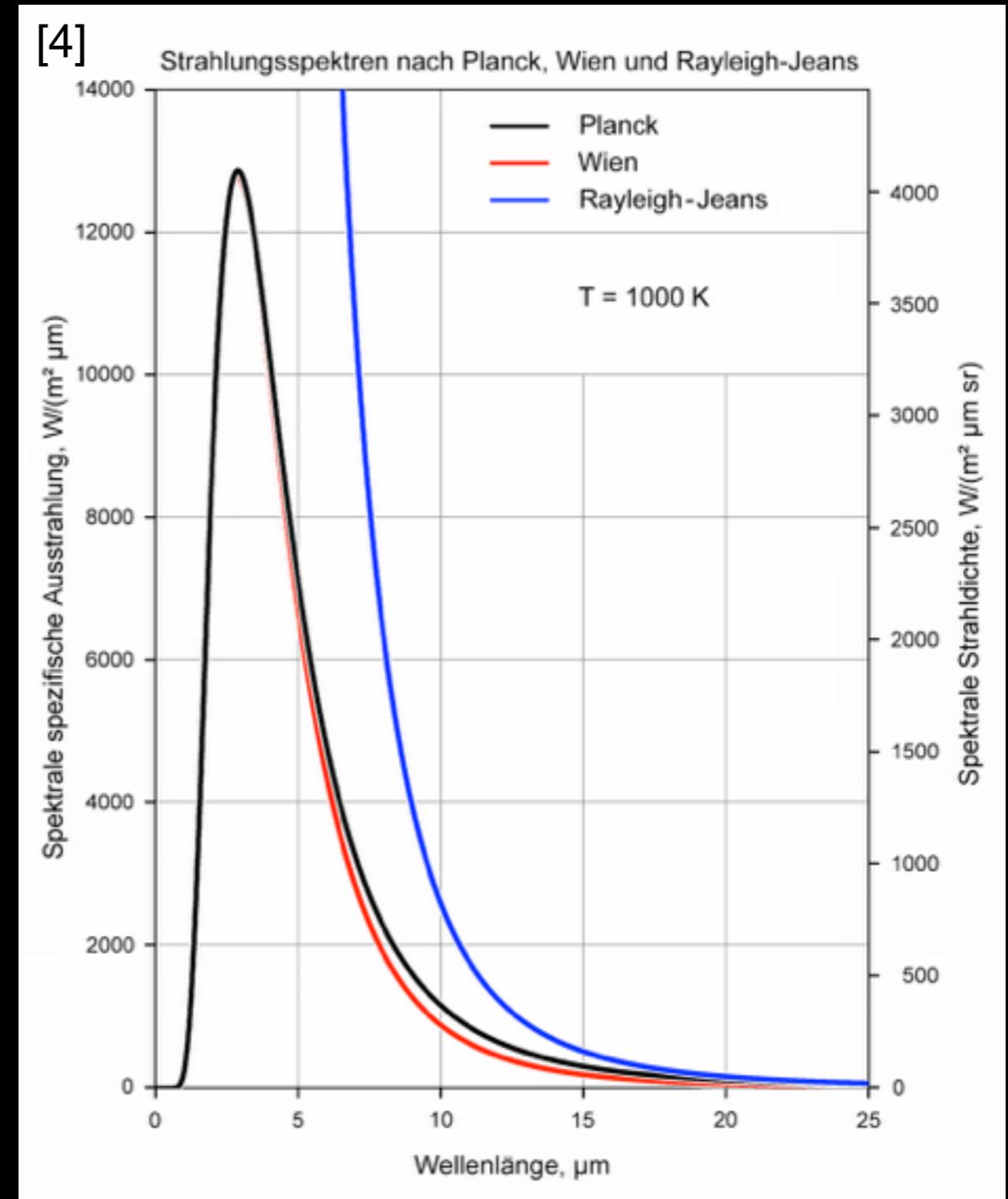


- Black body radiation only explicable introducing energy-quanta

- Oscillators in cavities (walls) will radiate energy as $\varepsilon = h\nu$
- Planck's law:

$$E(\nu, T) = \frac{h\nu}{e^{(h\nu/kT)} - 1}$$

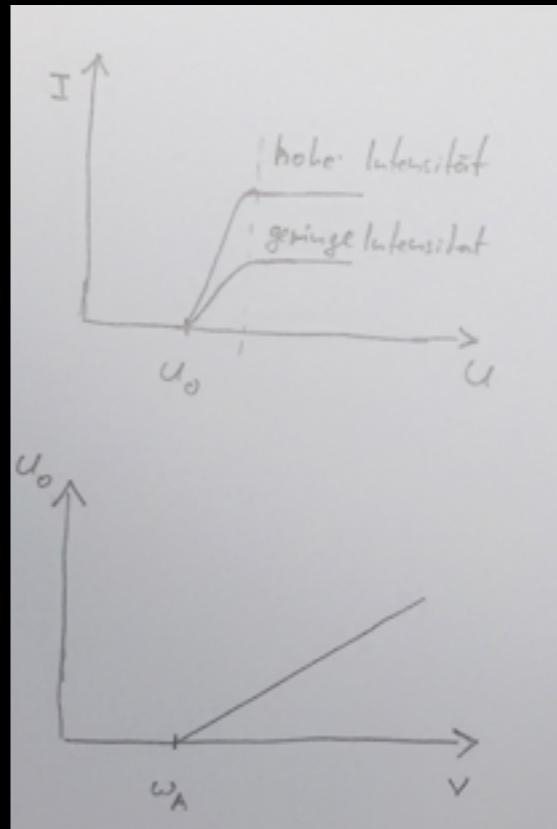
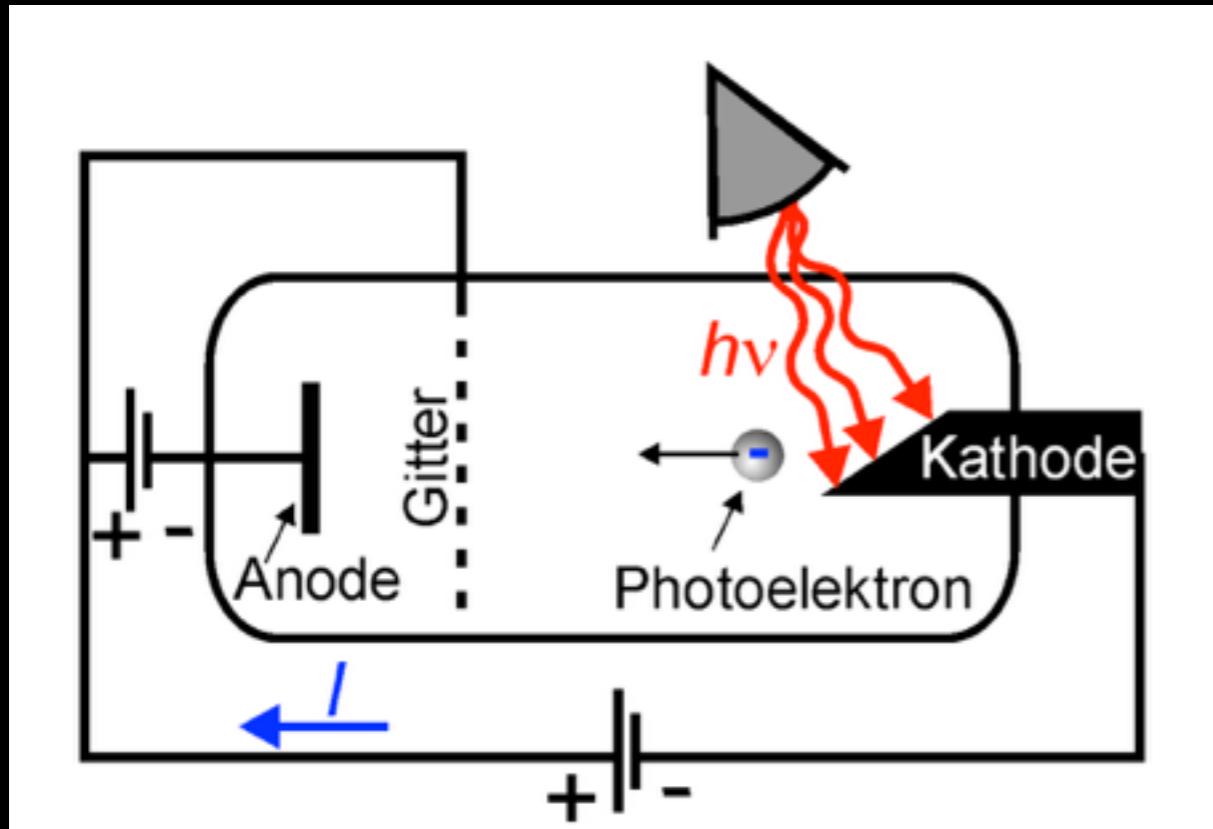
- new fundamental constant: h



Quanta - Photoelectric Effect

- Electron emission from metal surfaces due to exposure to light:

Einstein: 1905



- Electron energy independent of light intensity!
- Not explainable with classical view of light as electromagnetic wave!
- But: interaction of light-quanta with electrons
 - „A light quanta will give all its energy to an electron“

$$E_{\max}^{e^-} = h\nu - W_A$$

Elementary particles - 1905



- Electron
- Quantum of light (Photon)

Quanta - and spectral lines



Balmer: 1885

- Spectral lines of Hydrogen: Known but not understood
- Issues with atomic model of Rutherford:
 - Electrons orbit nucleus
→ accelerated el. charge → radiation of electromagnetic waves
 - **Why are atoms stable at all?**

$$13,6 \text{ eV} \Rightarrow 156.000 \text{ K}$$

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Bohr: 1913

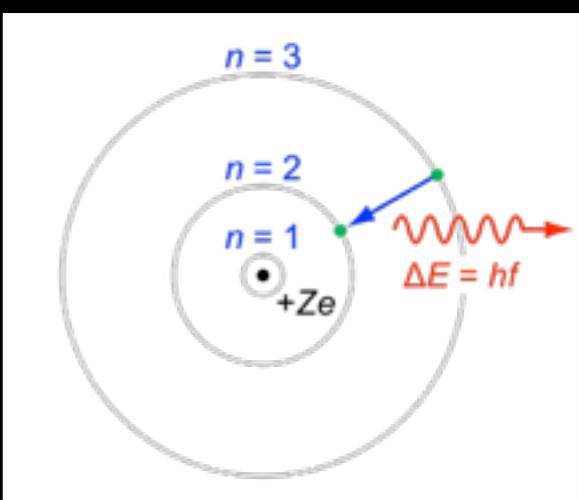
- **Solution:**
Electrons move on discrete, stable orbits
Electron's angular momentum quantized:

Energy change on orbit change:

$$\Rightarrow E_n = \frac{13,6 \text{ eV}}{n^2}$$

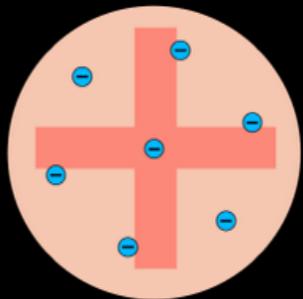
$$L = n\hbar = n \frac{\hbar}{2\pi}$$
$$\Delta E = f \cdot h$$

13,6 eV => 156.000K



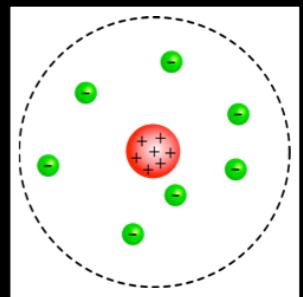
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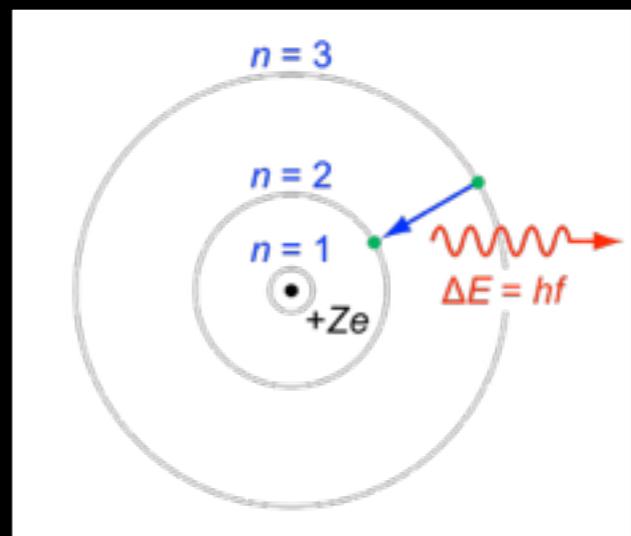
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- Bohr:
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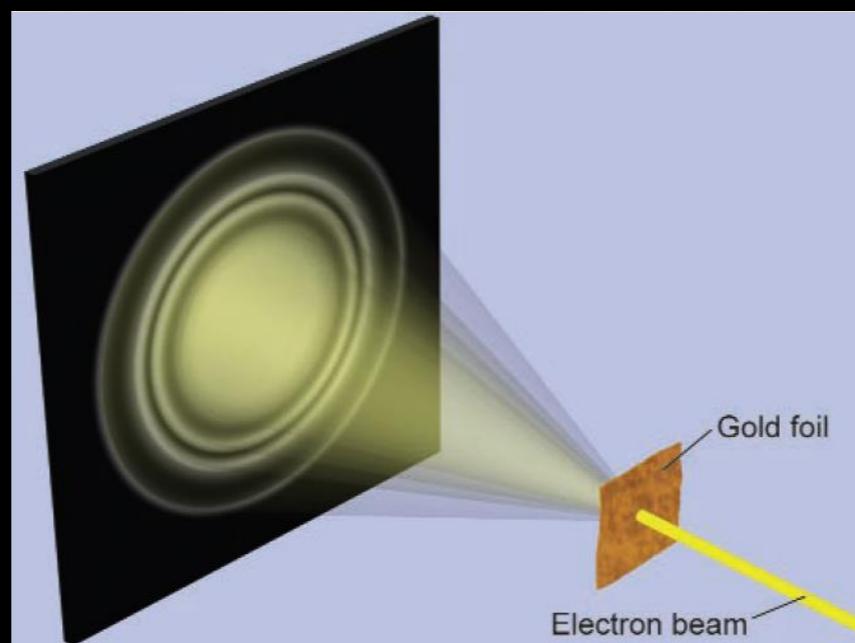


1913

Particle ↔ Wave

- Since explanation of photo effect:
 - Light-Quanta known as particles. Light can appear as **particle** as well as a **wave!**
 - Momentum: $p = h/\lambda$
 - Experimentally proven by Compton 1917
- Postulate: **Particles appear as waves with wavelength:**
 $\lambda = h/p$
 - Experimentally proven observing electron diffraction on gold foil

de Broglie: 1924

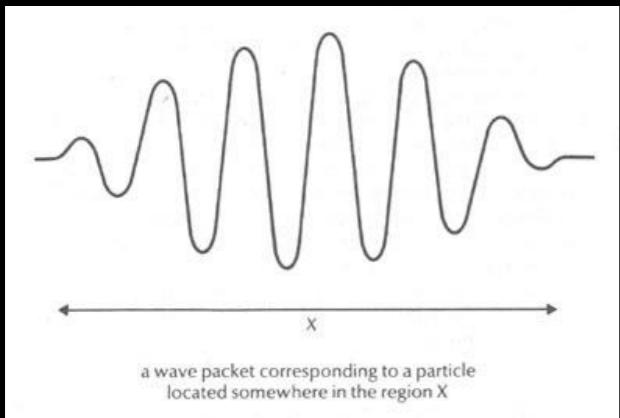


Davisson & Germer: 1927

The uncertainty principle

- If particles have wave characteristics:
 - Place & Momentum can **not be measured simultaneously!**

Heisenberg: 1925



$$\Delta x \cdot \Delta p \geq h$$



- Analogon:
 ,Pure' tone f gains ,uncertainty' Δf if it sounds only during time Δt
 (Fourier - transformation)

$$\Delta\omega \cdot \Delta t \geq \frac{1}{2}$$

with $E = \hbar\omega$

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$

Energy uncertainty

Life time Δt

Energy - Time - Uncertainty:

A quantum state that only exists for a short time can not have a definite energy

Waves - The key to modern physics

- **Waves** can describe behavior of particles

Schrödinger: 1926

- mathematical: **complex** function of space and time:

- **Interference** possible!

$$\Psi(\vec{x}, t) = A e^{i(\vec{k}\vec{x} - \omega t)}$$

- Classical **energy momentum** relation:

$$E = \frac{\vec{p}^2}{2m} + V(\vec{x}, t)$$

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- Operators in quantum mechanics (guessed via correspondence principle):

Momentum of wave: $p = h/\lambda = \hbar k$ $p \rightarrow i\hbar\nabla$

Energy of wave: $E = \hbar\omega$ $E \rightarrow i\hbar\frac{\partial}{\partial t}$

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Schrödinger equation: $i\hbar\frac{\partial}{\partial t}\Psi = -\frac{\hbar^2\nabla^2}{2m}\Psi + V\Psi$

What is the meaning of this?

- Probability interpretation (Born's rule):

$|\Psi(\vec{x}, t)|^2$ **Probability** to find a particle in location x at time t .

Max Born: 1926

N.b.:
Kopenhagen
interpretation: Bohr / Heisenberg 1927

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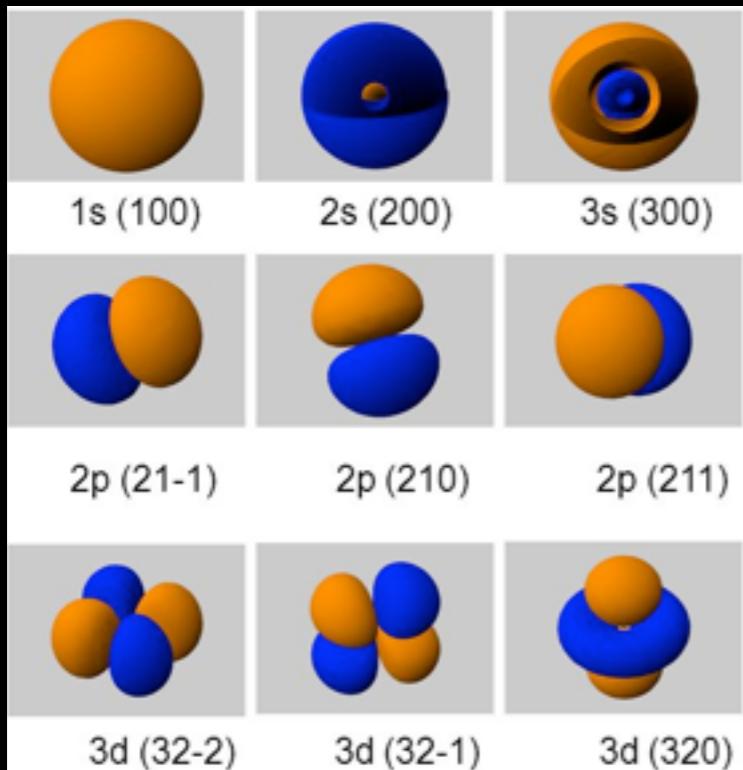
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- Example Atom:

- Electron shell → **standing wave** in atom, describes probability density to find electron at a given location
- OK for $v \ll c$

Orbitals of Hydrogen

[7]



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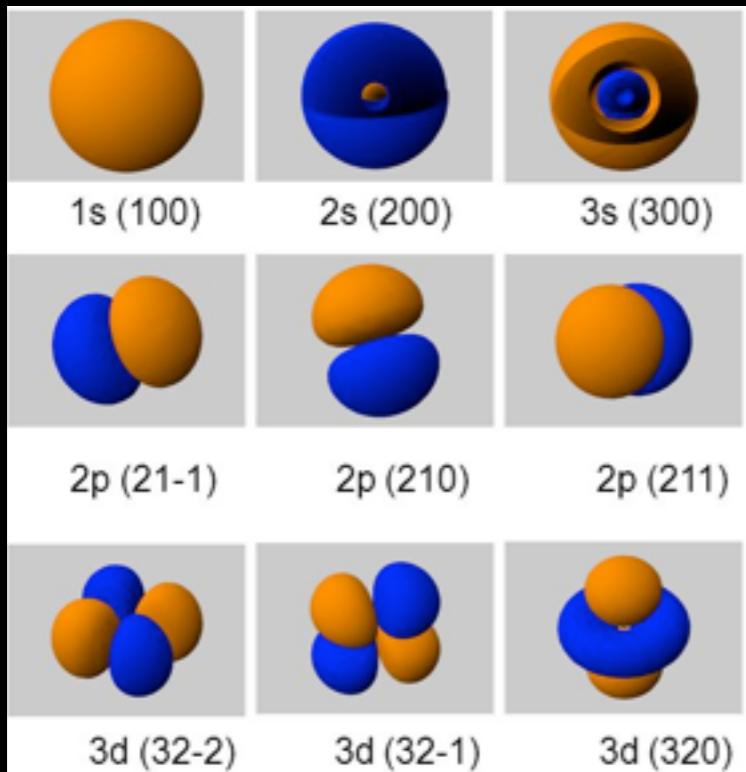
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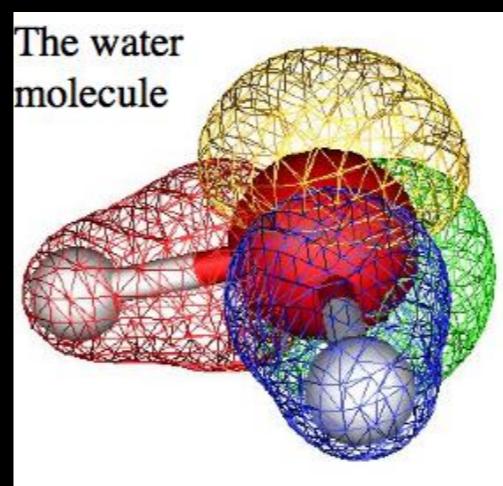
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Orbitals of Hydrogen

[7]



Chemical bindings reflect structure of orbitals

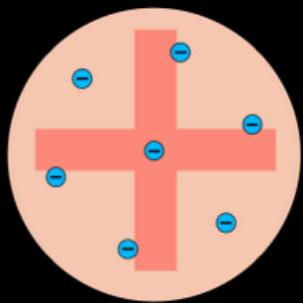


Understanding of macroscopic structures from microscopic properties!

Atomic models - 1928

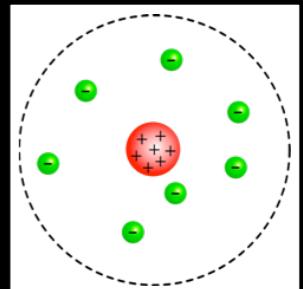


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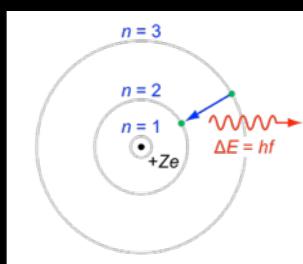
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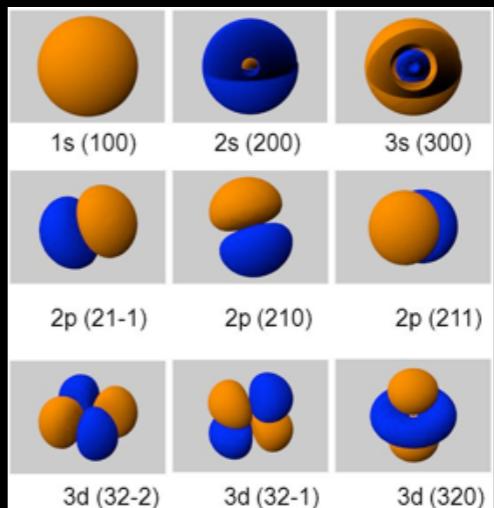
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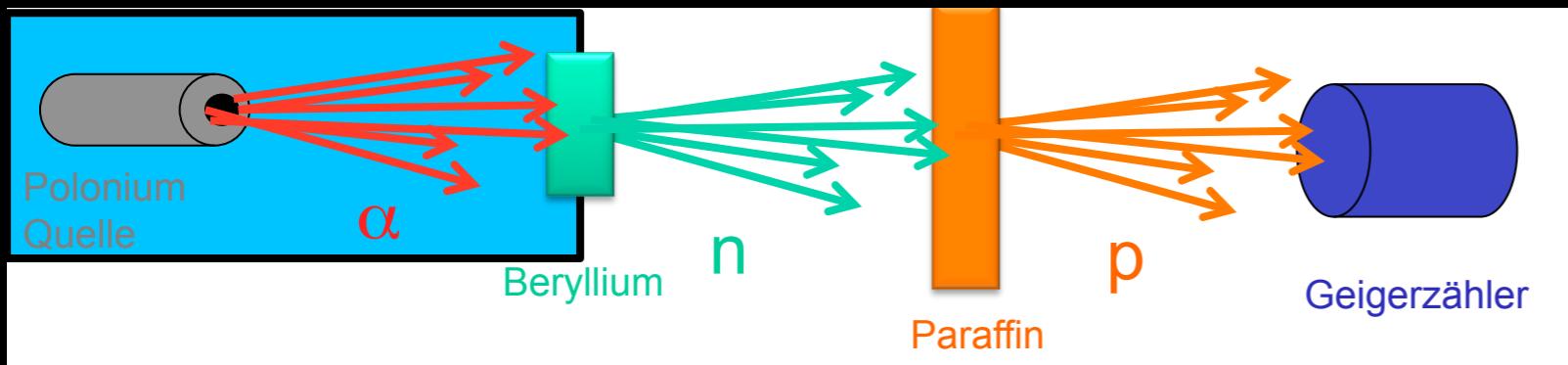
1913

- **Atomic orbital model (Born, Pauling):**
 - Quantum mechanical description of probability density to find an electron at a given location (Aufenthaltswahrscheinlichkeit)

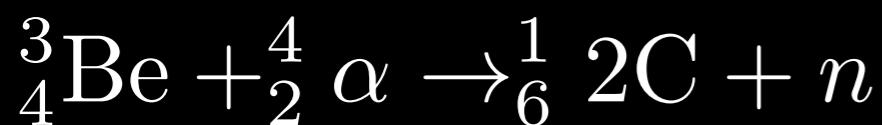


1928

The Neutron



Bothe & Becker: 1930
Joliot-Curie: 1931
Chadwick: 1932



- Already Rutherford postulated neutral particles in atom
- Experiment to investigate gamma rays
 - Observed neutral radiation with huge energy?
 - $E_\gamma \sim 50 \text{ MeV}$ needed to release proton with observed energy!
- Chadwick: neutral particles with mass about proton mass

Complete picture of atoms!

Now for something
different

- Anti-Particles -

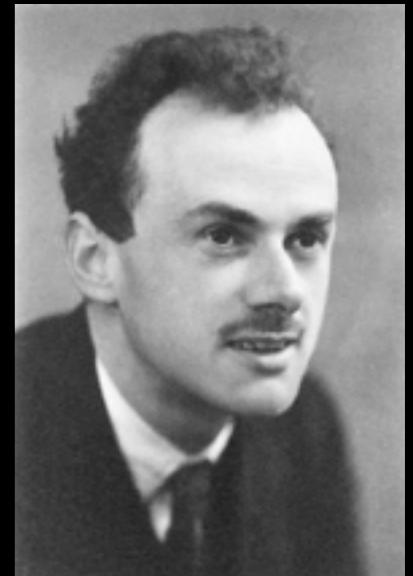
- ANTI-MATTER -

Quantum Mechanics & Relativity

- Combination of non-relativistic **wave equation** with **special relativity**:

Dirac equation: $(i\gamma^\mu \partial_\mu - m) \Psi = 0$

Dirac: 1928



- Energy eigenstates: $E = \pm \sqrt{m_0^2 c^4 + p^2 c^2}$

- Interpretation of neg. energy states?**

- **Anti-particles!**

- Discovery 4 years later

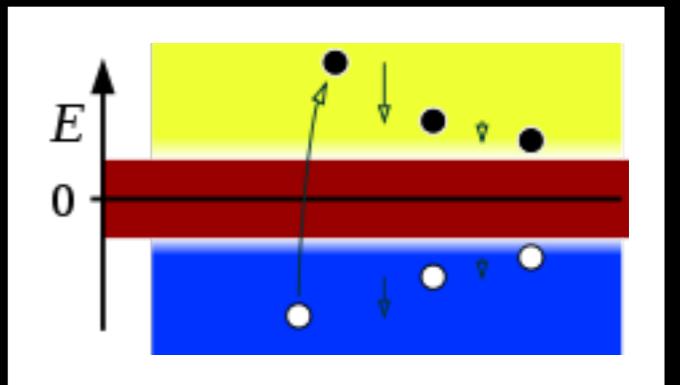
- Solutions of Dirac equation:
 - Dirac Spinor

$$\Psi = \begin{bmatrix} e^- & \uparrow \\ e^- & \downarrow \\ e^+ & \leftarrow \\ e^+ & \downarrow \end{bmatrix}$$

Spin 1/2
 → Pauli exclusion principle 1940
Prediction of anti-particles

Negative Energy States

- Historical: Dirac sea
 - Infinitely many particles occupy ALL states with neg. E
 - Particle with neg. energy = hole in Dirac sea
 - Analogy: semi-conductor



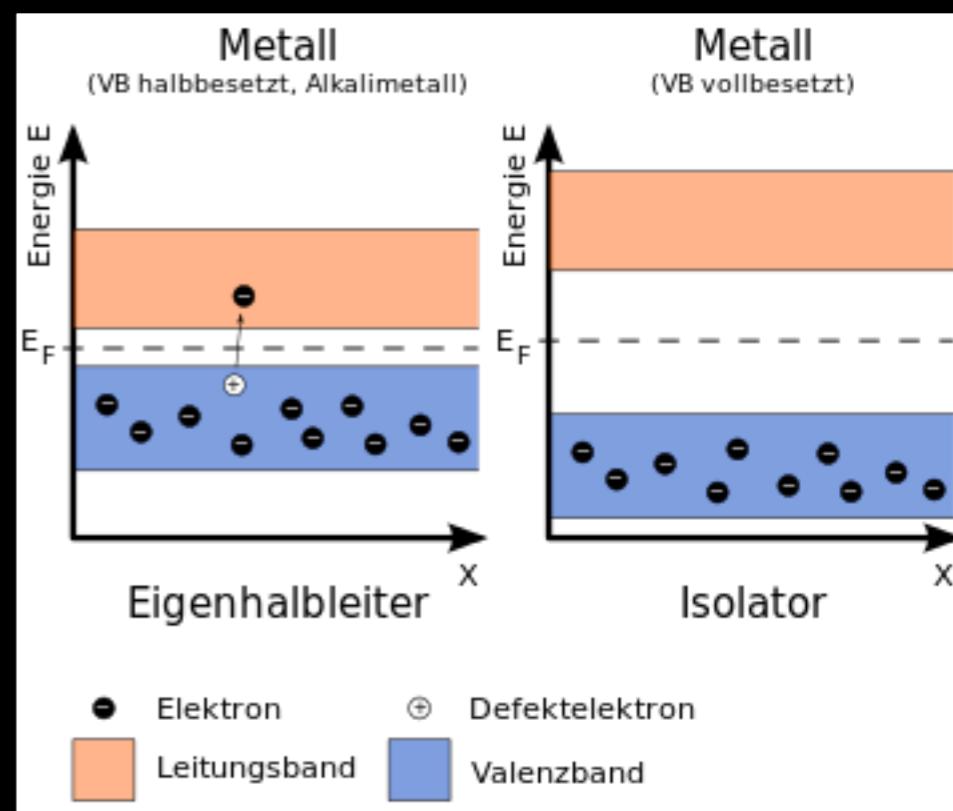
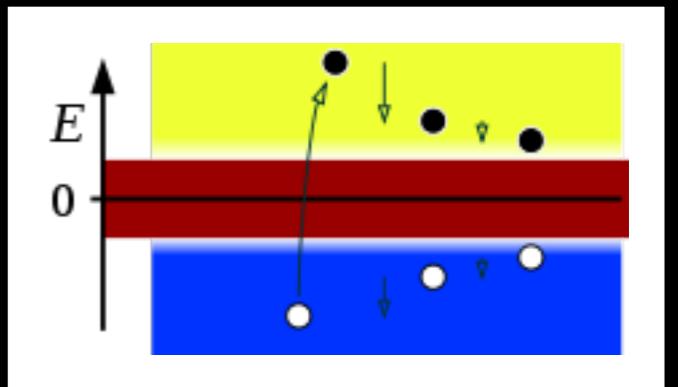
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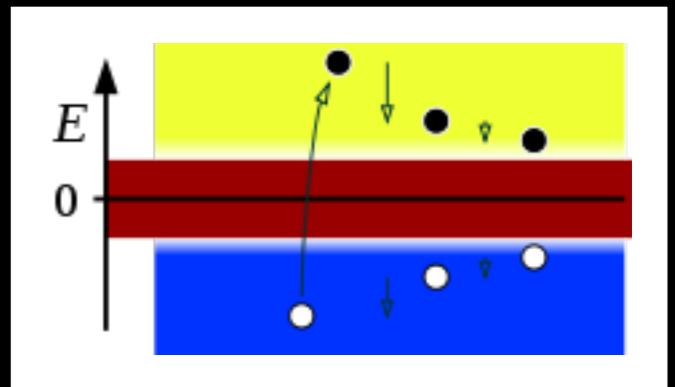
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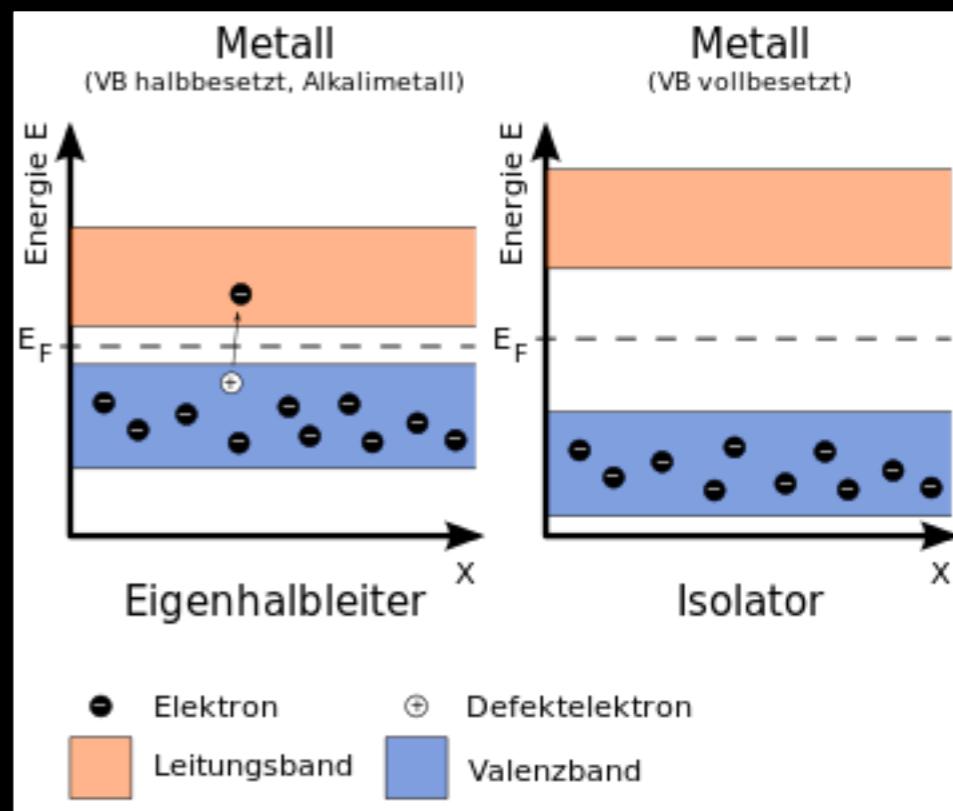


- New interpretation in quantum field theory

- Anti-particles and particles are treated identically

- Creation of particles => energy increases => $E > 0$
(Creation operator)

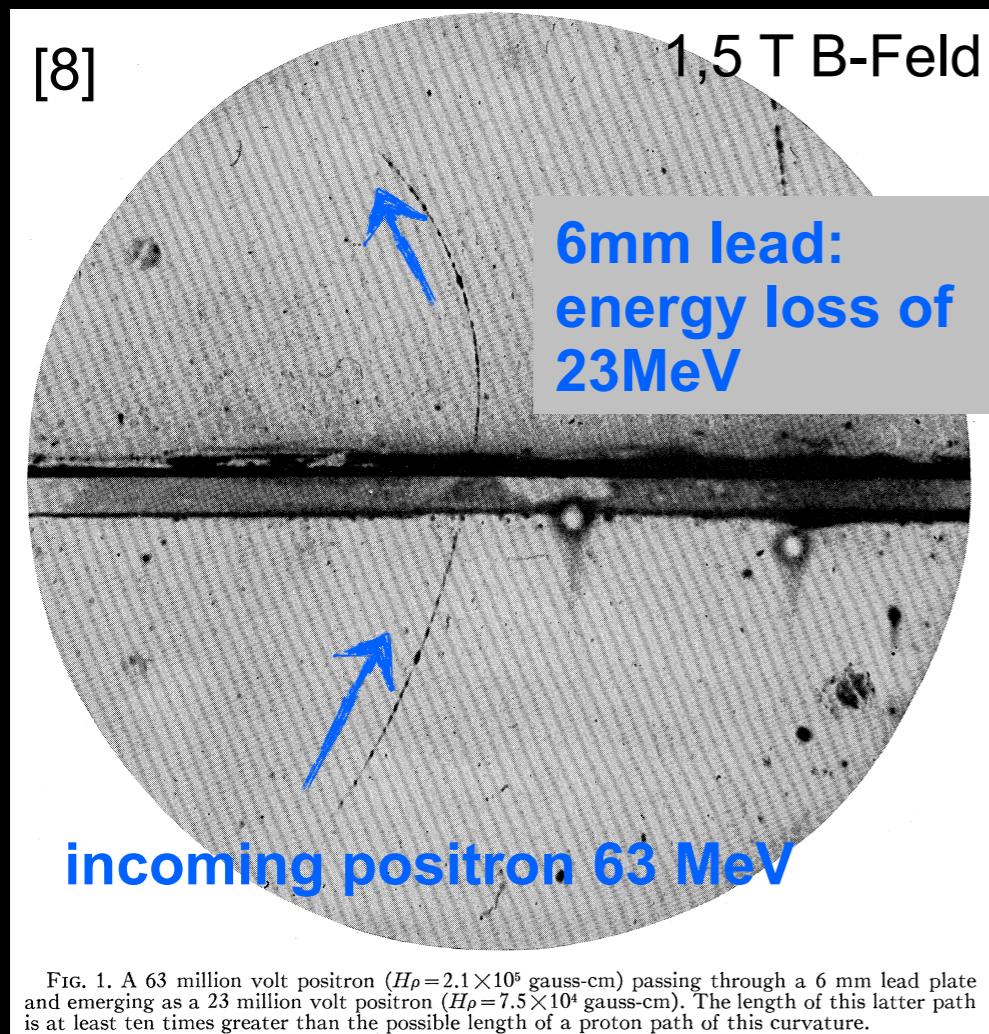
- Destruction of particles => energy decreases => $E < 0$
== Creation of anti-particles (Annihilation operator)



Discovery of the positron

Anderson: 1932

- Detection of positrons in cosmic rays using a cloud chamber



- Particle direction determined via energy loss
- Mass & E determined via curvature & energy loss
- Accidental discovery of **Muons** 1936
- „Who ordered that?“
- First known particle of „2. generation“



Anti-particles

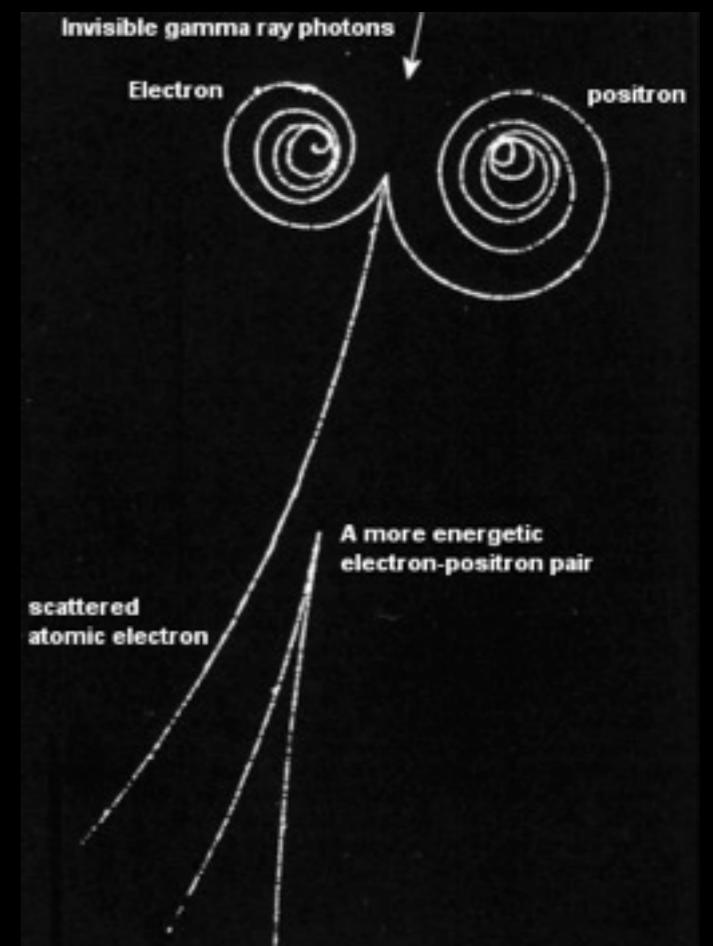
- Act identical to particles, but carry opposite electric charge
 - same mass, spin, parity ...

- **Creation:**

$$E = mc^2$$

- only paired with 'normal' particles:

- **Particle - anti-particle pair production**



Anti-particles

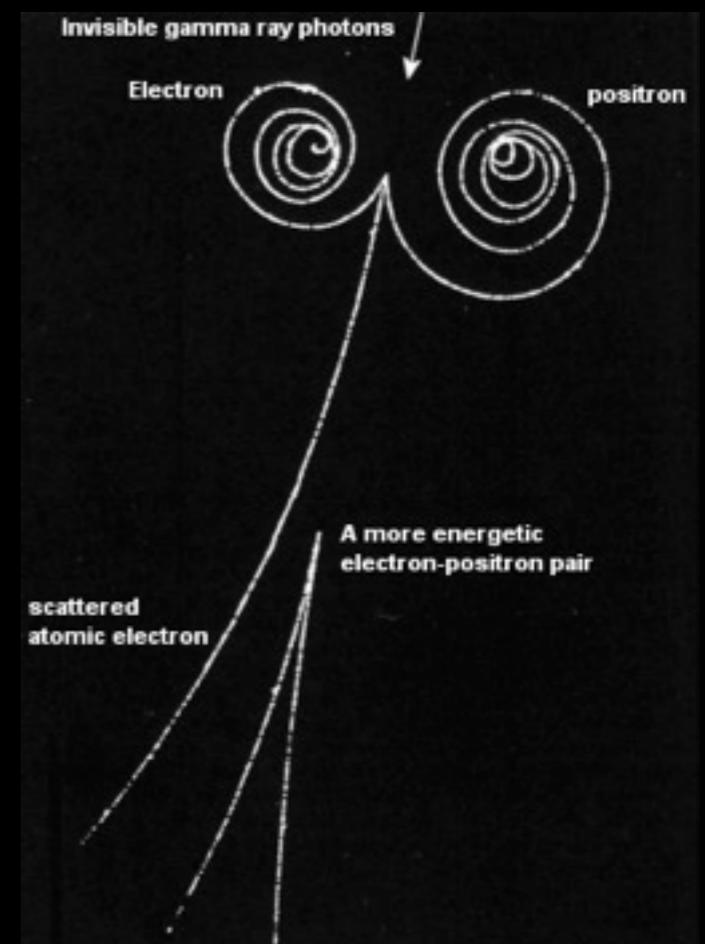
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- **Conservation of:**

- Lepton number → **neutrinoless double beta decay**
- Baryon number (Proton, Neutron, ...) → **baryogenesis / decay of protons**
- B-L (conserved in all theories)

The Vacuum and Anti-Particles

- Pair production:

$$E = mc^2$$

- Heisenberg's uncertainty principle

$$\Delta E \cdot \Delta t \approx \frac{\hbar}{2}$$

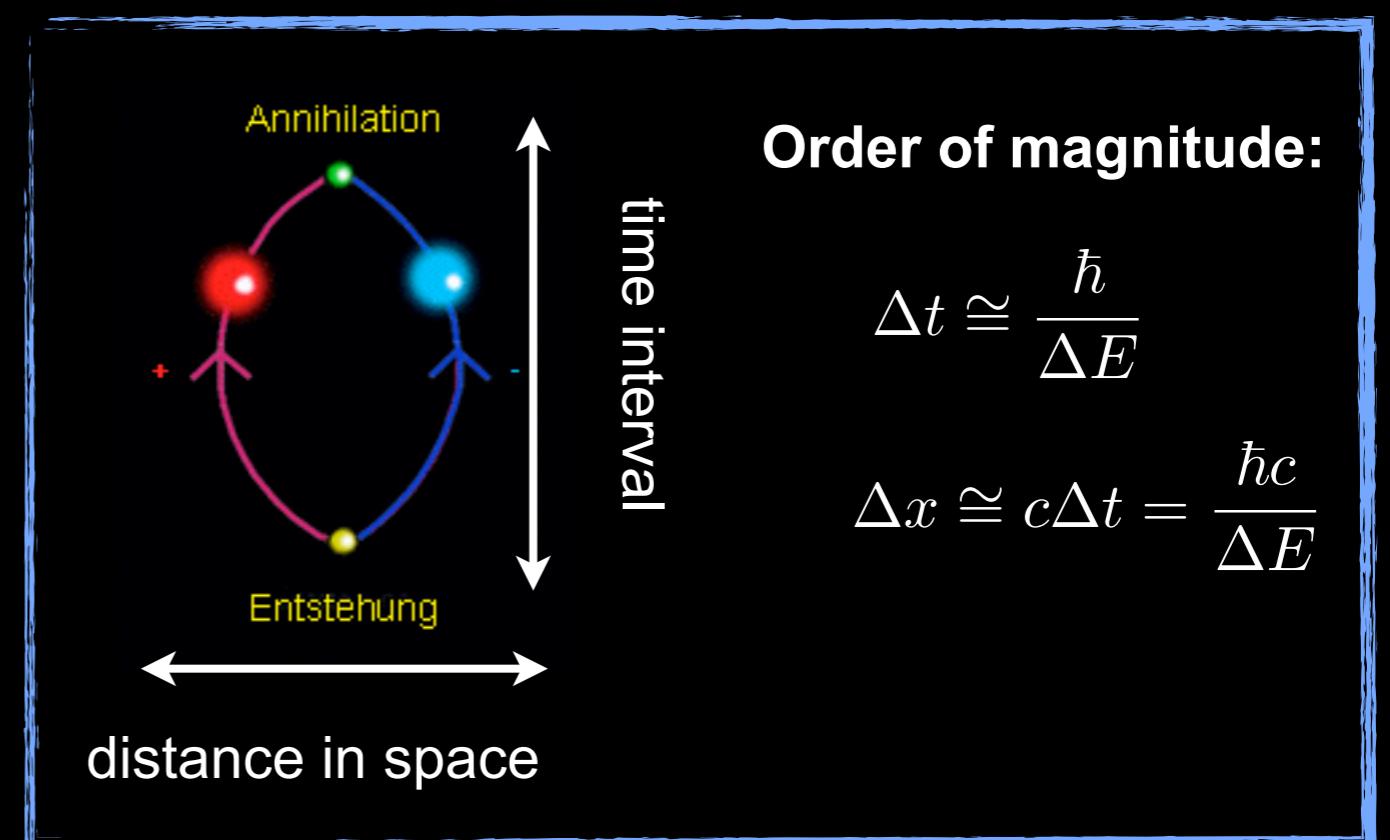
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- Within **short time interval** particle anti-particle pairs can form (virtual \rightarrow off mass shell: $m \neq m_0$)

• Vacuum fluctuations



The Vacuum and Anti-Particles

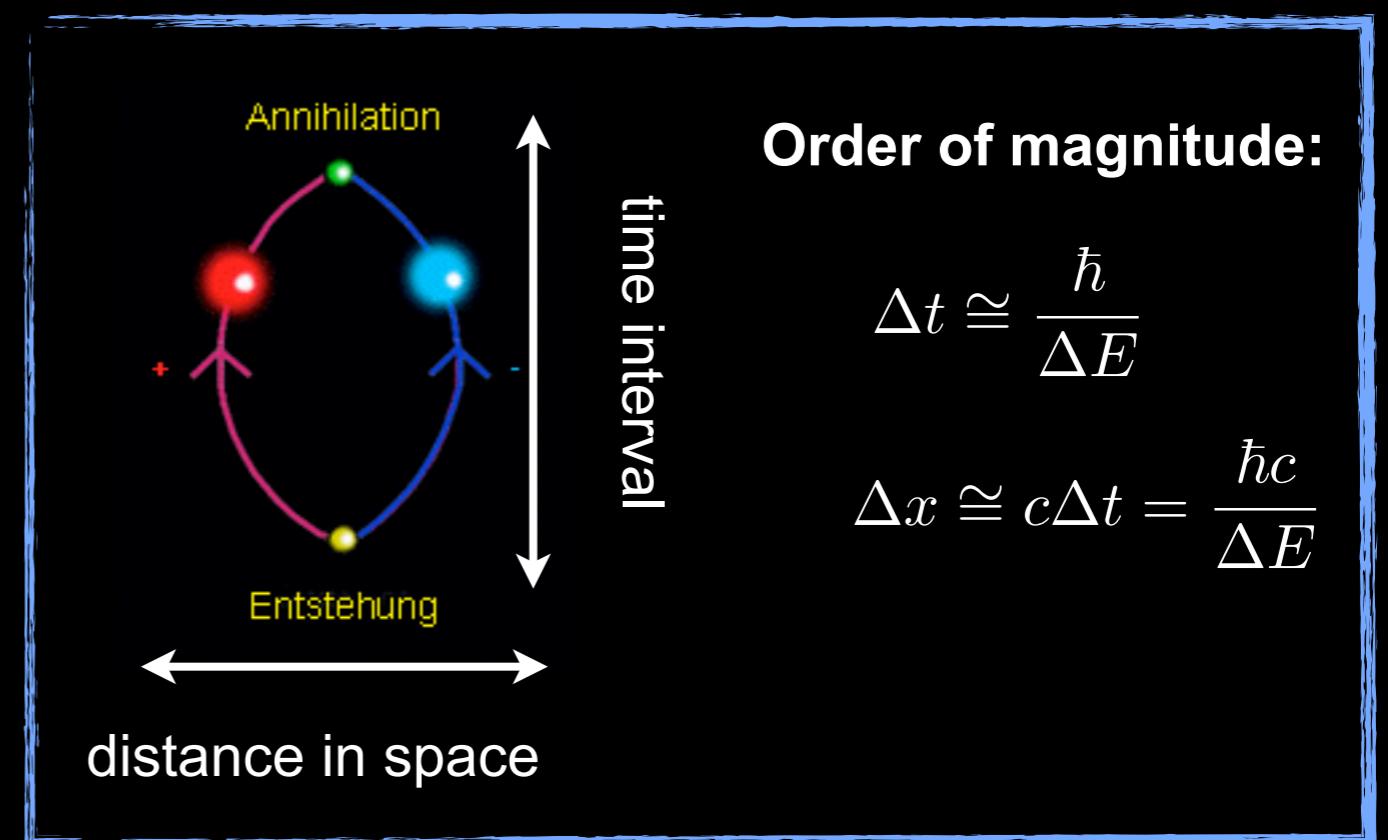
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- **Vacuum fluctuations**

- No absolute still stand in physical system
- Zero-point energy



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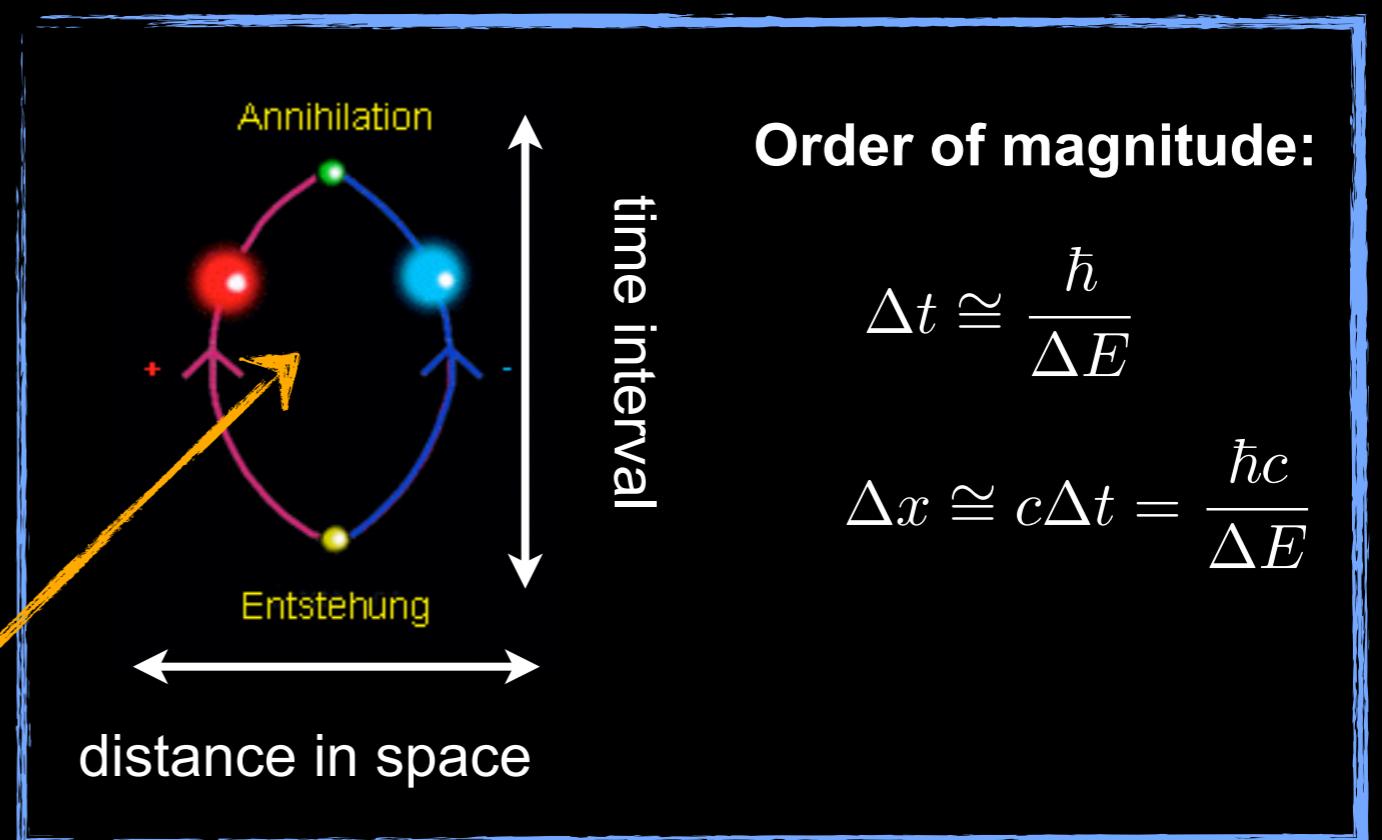
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virtual particles



Order of magnitude:

$$\Delta t \cong \frac{\hbar}{\Delta E}$$

$$\Delta x \cong c\Delta t = \frac{\hbar c}{\Delta E}$$

The Vacuum and Anti-Particles

- Pair production:

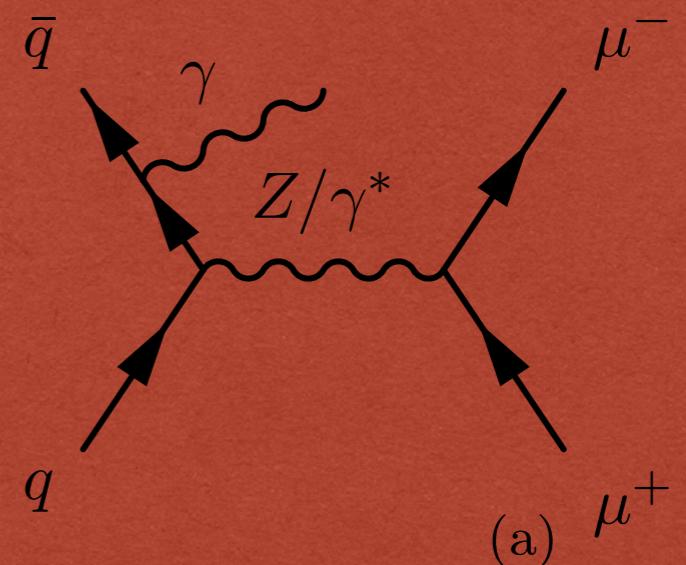
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- Heisenberg's uncertainty principle

$$\Delta E \cdot \Delta t \approx \frac{\hbar}{c}$$

Virtual particles & uncertainty principle - To be really accurate:

- Virtual particle = mathematical construct and imaginable concept
- Not observable



virtual particles

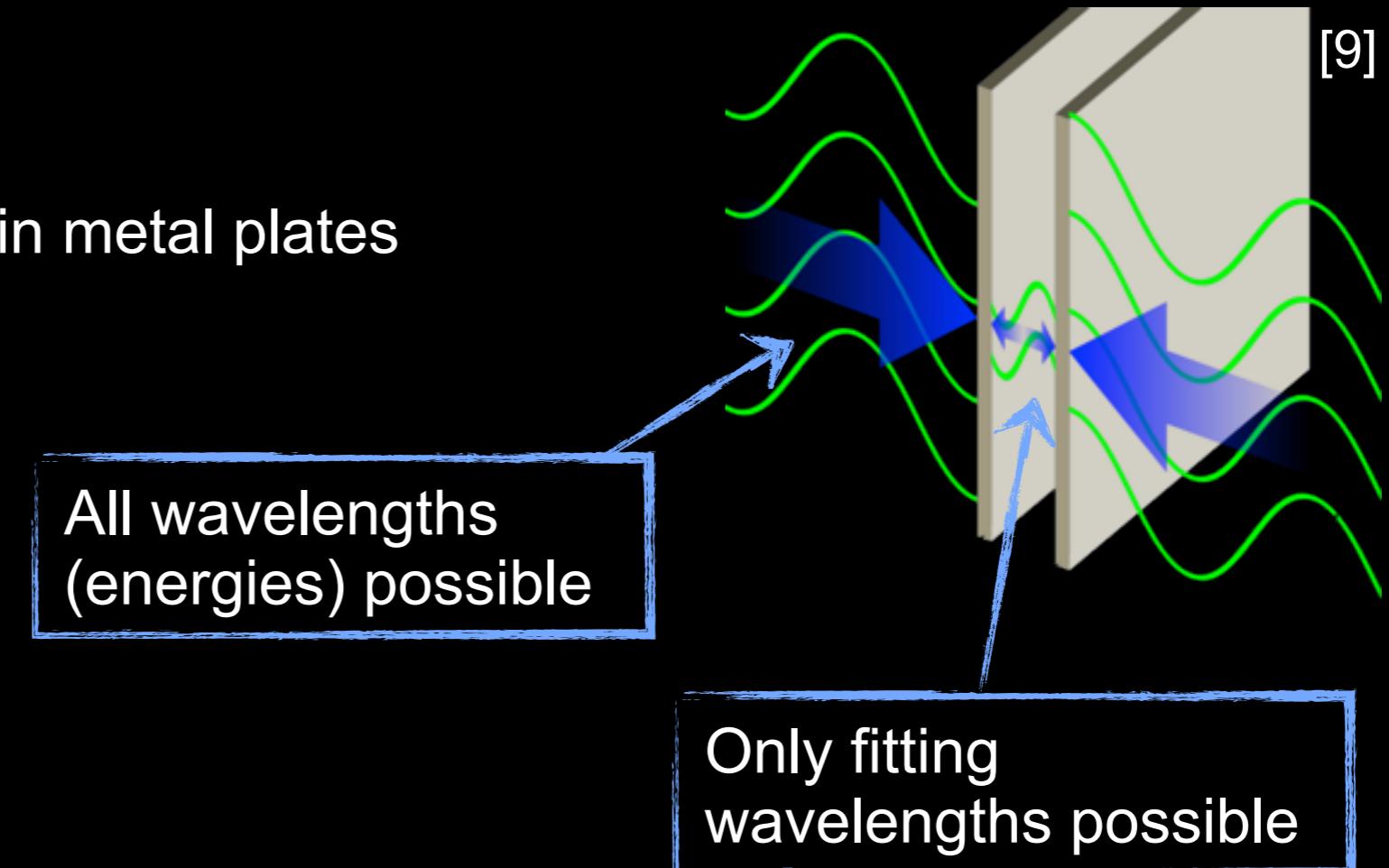
Vacuum fluctuations

Vacuum fluctuations

- Casimir effect:
- Macroscopic pressure in metal plates

$$p_c = \frac{F_c}{A} = \frac{2\pi\hbar c}{240 \cdot d^4}$$

- ~ 1 bar @ $d = 11\text{nm}$

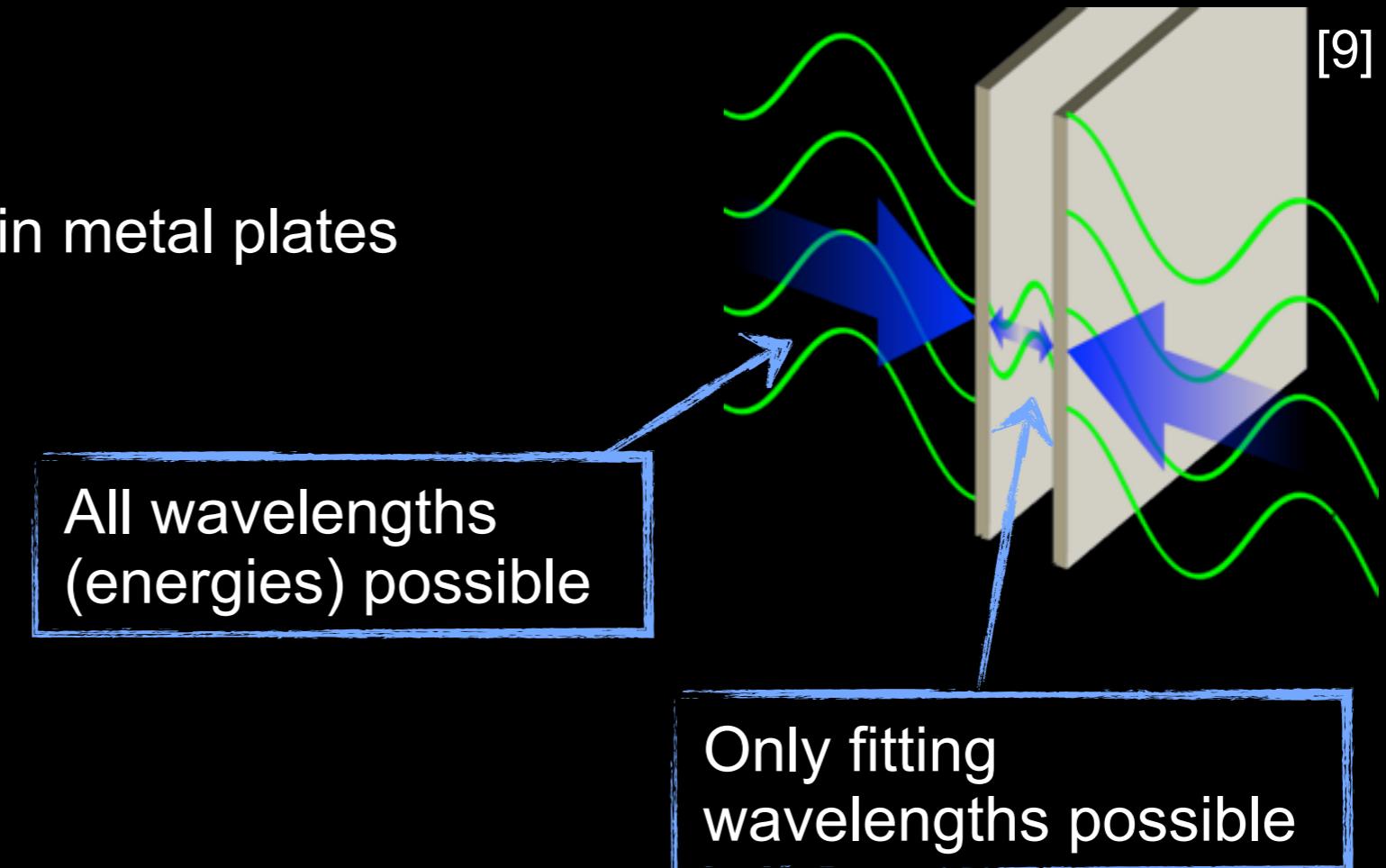


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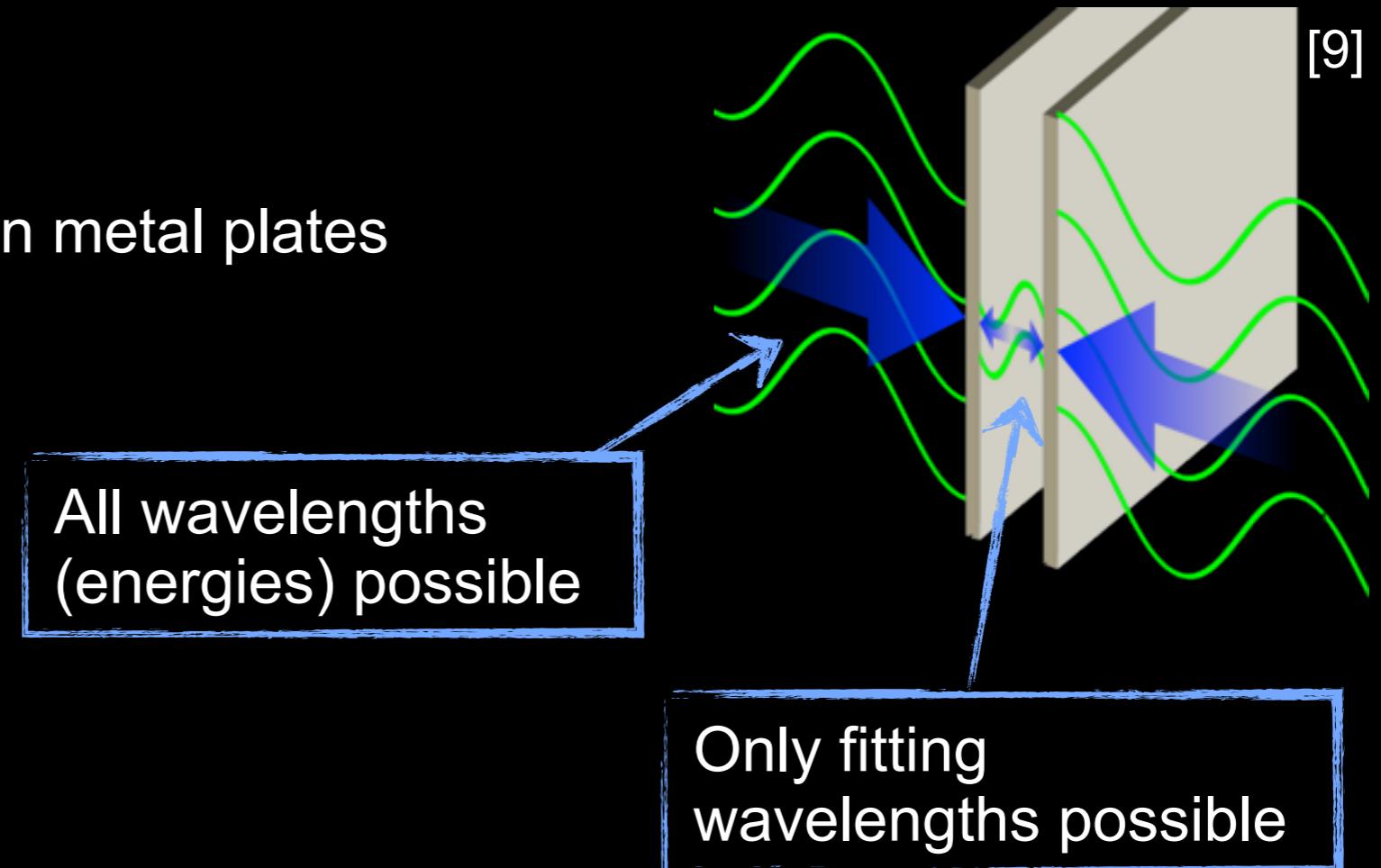
- Electron (el. charge) **polarises vacuum fluctuations!**
- Measured el. charge = ,bare' charge + polarisation effect
 - ▶ Apparent el. charge depends on distance!
 - ▶ „running“ electromagnetic coupling constant

Vacuum fluctuations

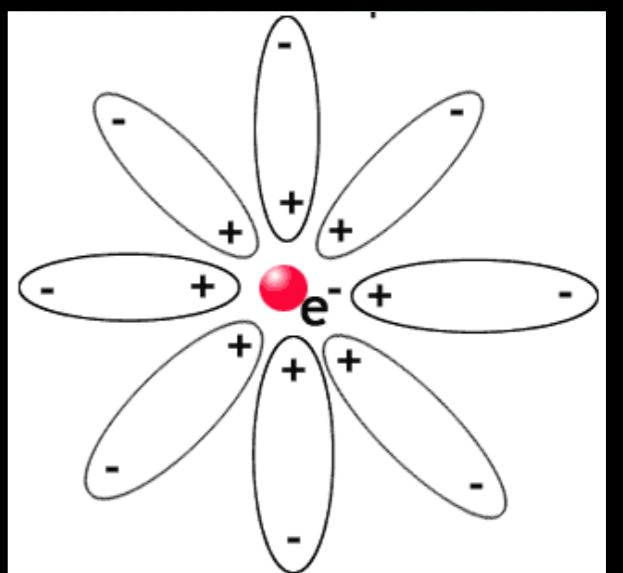
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Vacuum Fluctuations - Calculation?

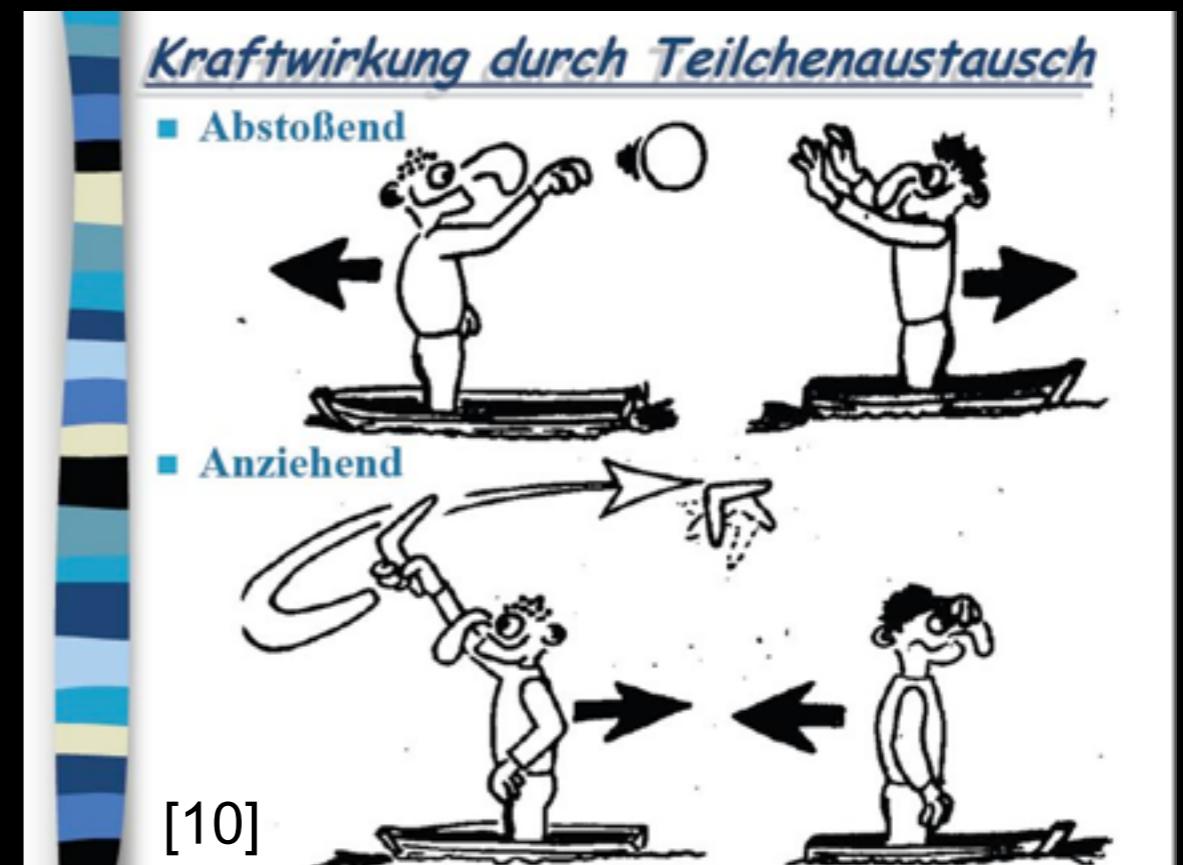
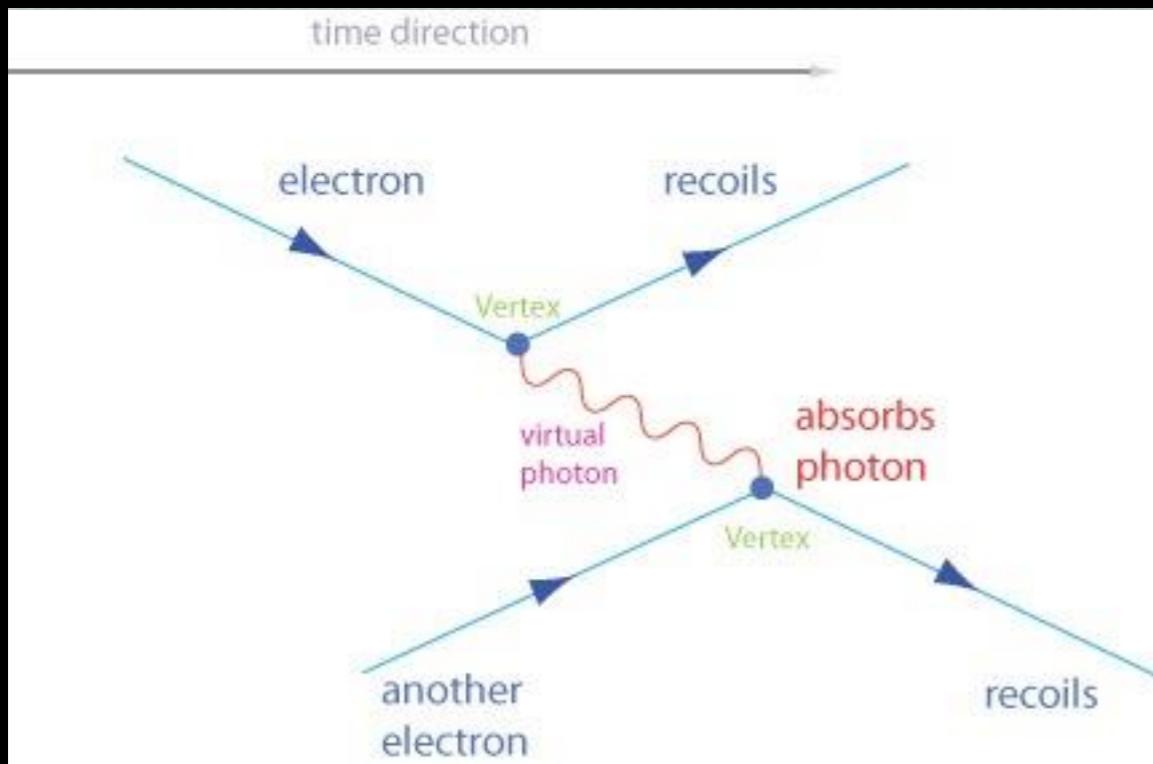


- How to calculate interaction between two electrons?

Feynman, Schwinger,
Tomonoga, Dyson:
1934-1948

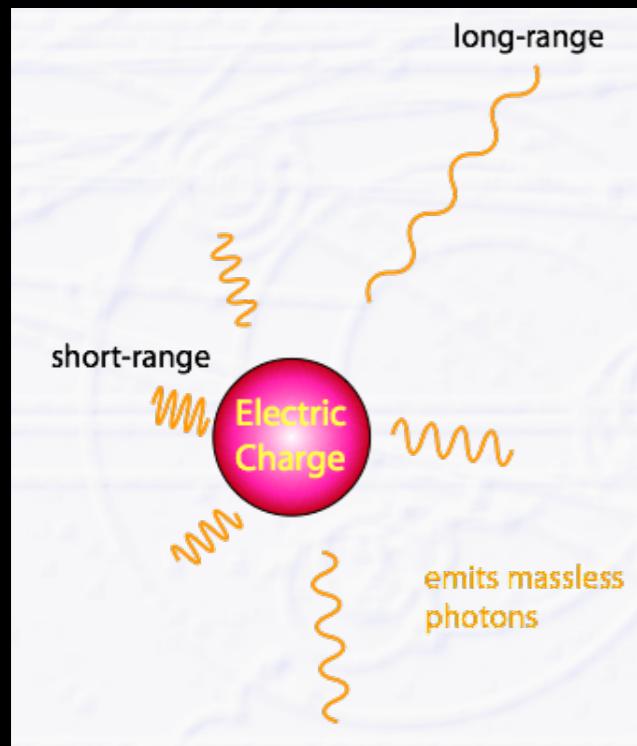
- Solution: Quantization of the electromagnetic field (2nd quantization)

- Photons correspond to **Field-Quanta**
- Field-quanta carry force - **exchange particles**
- **Virtual particles:** not observable, always connected to vertices

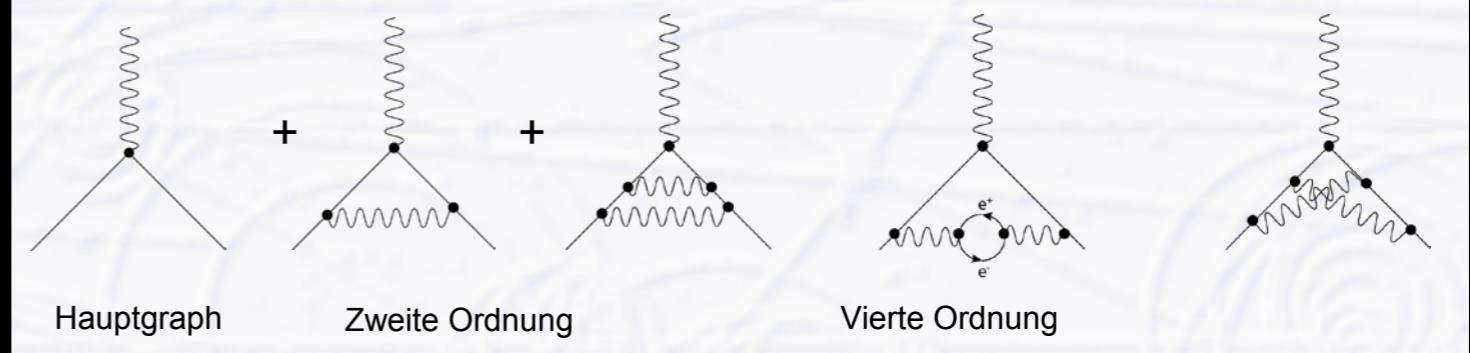


Everything becomes virtual

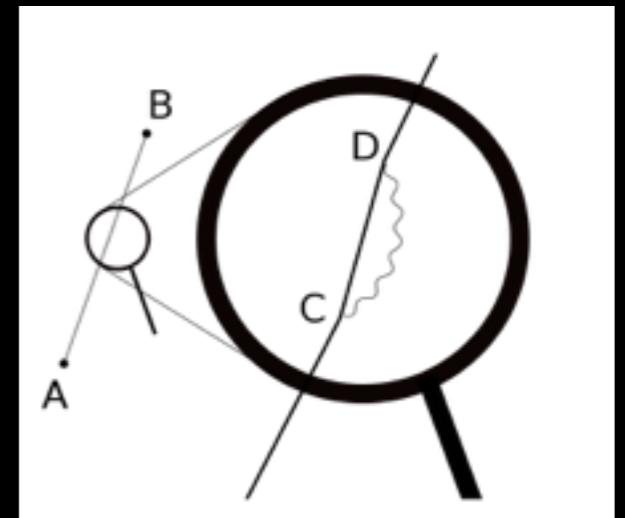
- Virtual particles
 - But, how many?



- Feynman graphs for QED ,higher order' corrections



- Electron self energy
 - Becomes ∞



- Infinitely many → results become **infinite**
- Only consider particles up to certain energy („renormalization“)
 - Results become finite → **physically meaningful!**
 - „Constants“ are not constant, but depend on renormalisation scale (couplings, masses)
 - **Results in quantum field theory are scale dependent**

Valid Predictions for Experimental Test

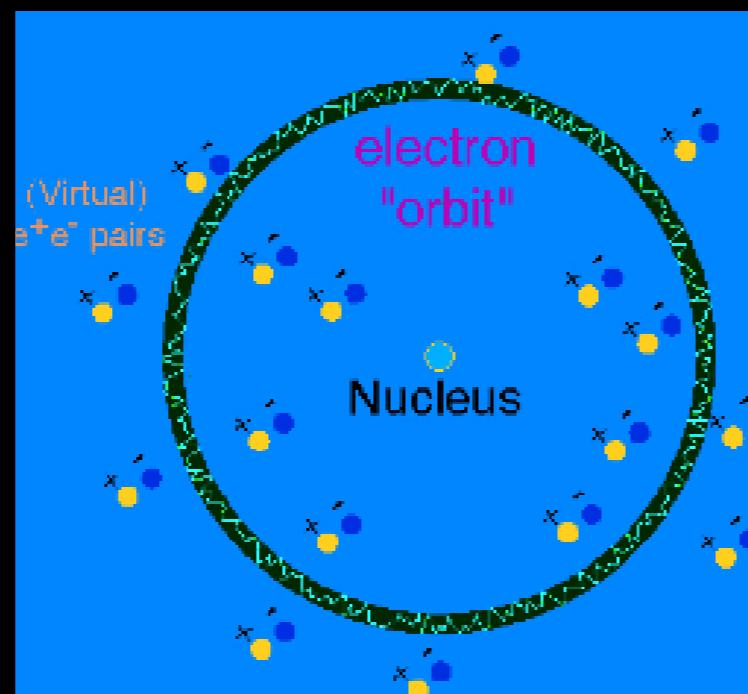
- Anomalous magnetic moment of the electron:
 - Experimental: 1,1% deviation from Dirac's theory
 - Described in QED
 - Today: Agreement at the level of 10^{-12} between experiment & theory!

1946

Valid Predictions for Experimental Test

- Anomalous magnetic moment of the electron:
 • Experimental: 1,1% deviation from Dirac's theory
 • Described in QED
 • Today: Agreement at the level of 10^{-12} between experiment & theory!
- Lamb shift 1948

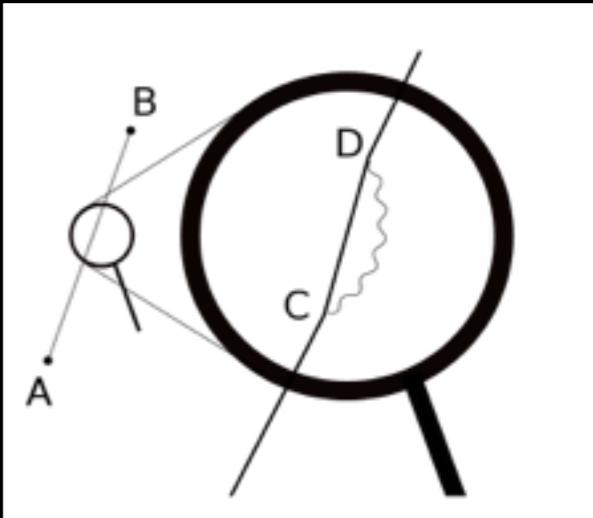
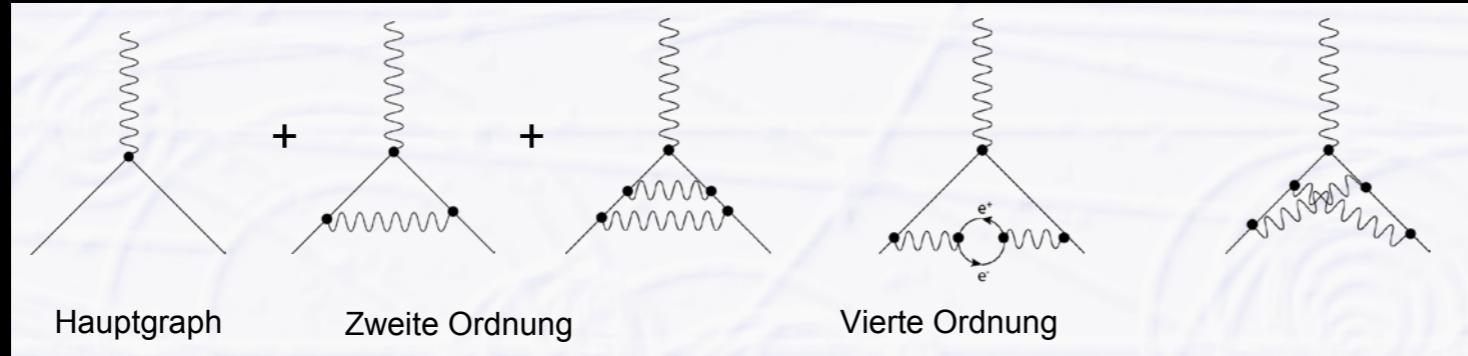
Splitting of the (degenerate) 2s / 2p levels in H-atom
 Calculated using QED



Intermezzo: Renormierung



- Feynman diagrams for QED corrections => Perturbation series



- Elektron Selbstenergie
- Wird ∞

- Perturbation series corresponds to ‚effective‘ field theory

- Only valid within a finite energy range
- For calculations regions outside of the valid range have to be taken into account due to the methodology
- Can yield infinite results

1) Only consider contributions up to a finite energy („Regularisation“)

2) Redefinition of theory parameters (Couplings, charges ..)

- Taking into account (radiative-) corrections from outside of valid region
- All results will be finite → physically meaningful

- Running coupling constants
- Non constant charges
depending on the energy range considered

QED remains most
precise physics theory
BECRZS BNRCZS ENGOLD

Are there any other
forces?
TOLCESZI

How are protons and neutrons glued together?



- Force that is
 - Stronger than Coulomb repulsion
 - Short ranged (determines size of nucleus)

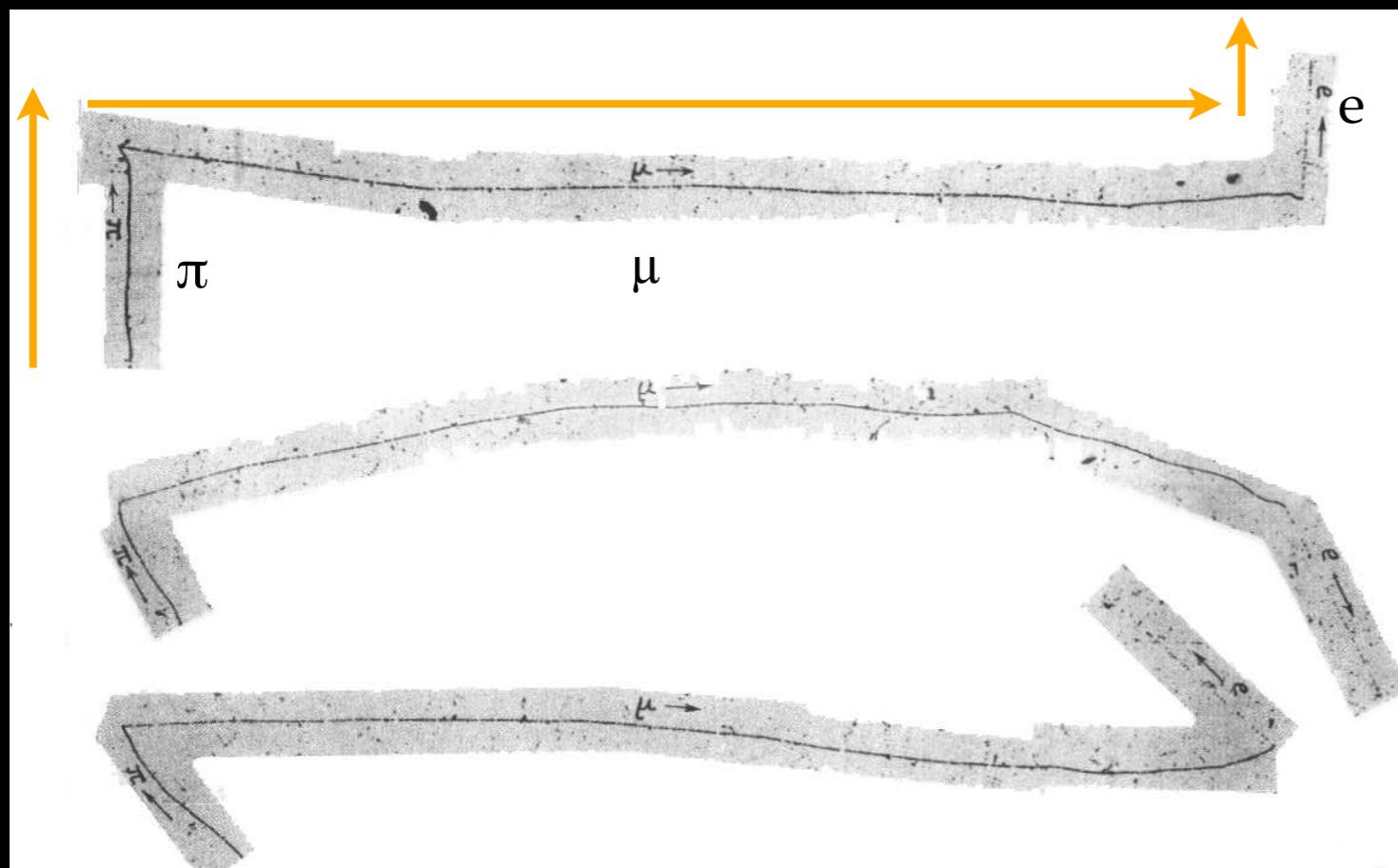
Yukawa: 1935

- Exchange of heavy particles: **Pions**
 - Predicted by Yukawa:

$$V_{\text{Coulomb}} = -g^2 \frac{1}{r}$$
$$V_{\text{Yukawa}} = -g^2 \frac{e^{-mr}}{r}$$

- Discovered in cosmic rays:

Powell / Perkins: 1947



$$m_{\text{Pion}} = 140 \text{ MeV}$$

$$\text{Range of force: } \Delta E \cdot \Delta t \approx \frac{\hbar}{2}$$

$$\sim 10^{-15} \text{ m}$$

- Small compared to radius of nuclei
- Explains const. binding energy per nucleon!

The world of particles ~1950

- Elementary particles: Elektron, Muon, Proton, Neutron, Photon, Pion
 - (Neutrino predicted in order to explain beta decay)
 - Concept of anti-particles
- Forces: electromagnetism, strong force
 - Interaction mediated via exchange particles
- Quantum mechanics & quantum field theory developed
- Complete description of: Electromagnetism using QED

more
elementary particles
GEMENEGOLD bOLLCORES

Hadrons

- 1935: Pion predicted by Yukawa as exchange particle of strong force
 - Mass predicted from radius of nuclei: 100 - 200 MeV
- Frenetic search in cosmic rays (at high altitudes)
 - Discovery: 1947 (Powell / Perkins) (at the Pic du Midi / Pyrenees)
 - During this search μ discovered
- 1948: Pions artificially created using accelerators
 - Cyclotron at Berkley

Seek, and you shall find

- Fast development in accelerator technique
 - 1938: 80 keV - 1939: 19 MeV - 1946: 195 MeV - 1947: 6 GeV - 1960: 30 GeV
- Discovery of new particles
 - 'Resonances' in invariant mass spectrum of detected particles

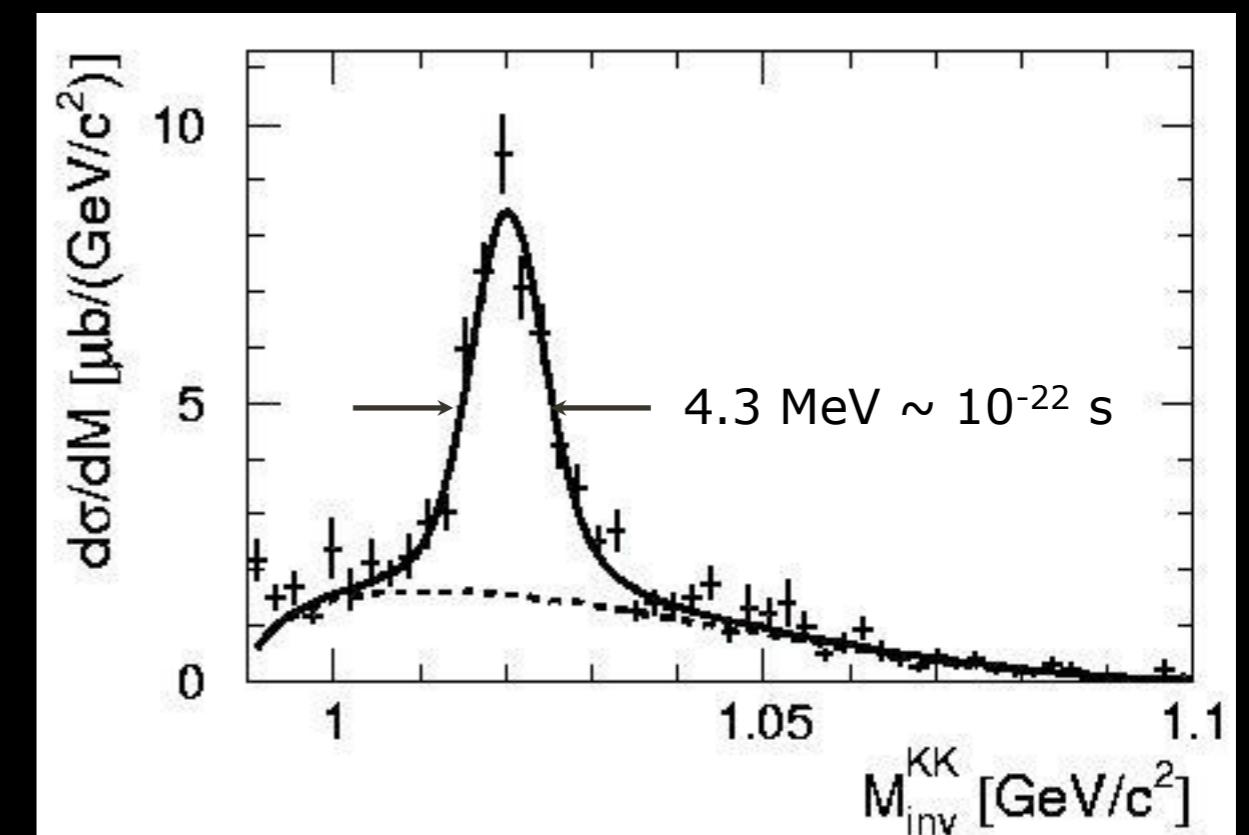
- Invariant mass M:

$$E^2 = (mc^2)^2 + \vec{p}^2 c^2$$

$$(mc^2)^2 = E^2 - \vec{p}^2 c^2$$

$$\rightarrow (Mc^2)^2 = \sum (E)^2 - \left(\sum \vec{p}c \right)^2$$

invariant under particle transformation!

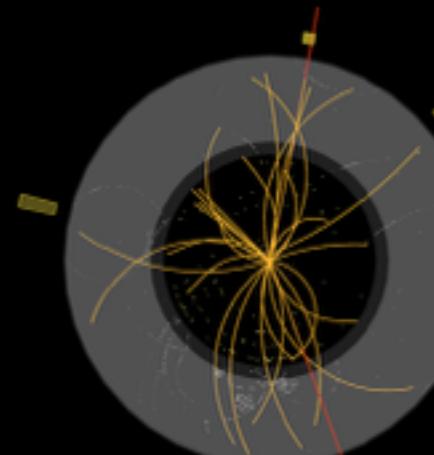


Intermezzo - Statistics & Particle Physics



Run: 154822, Event: 14321500

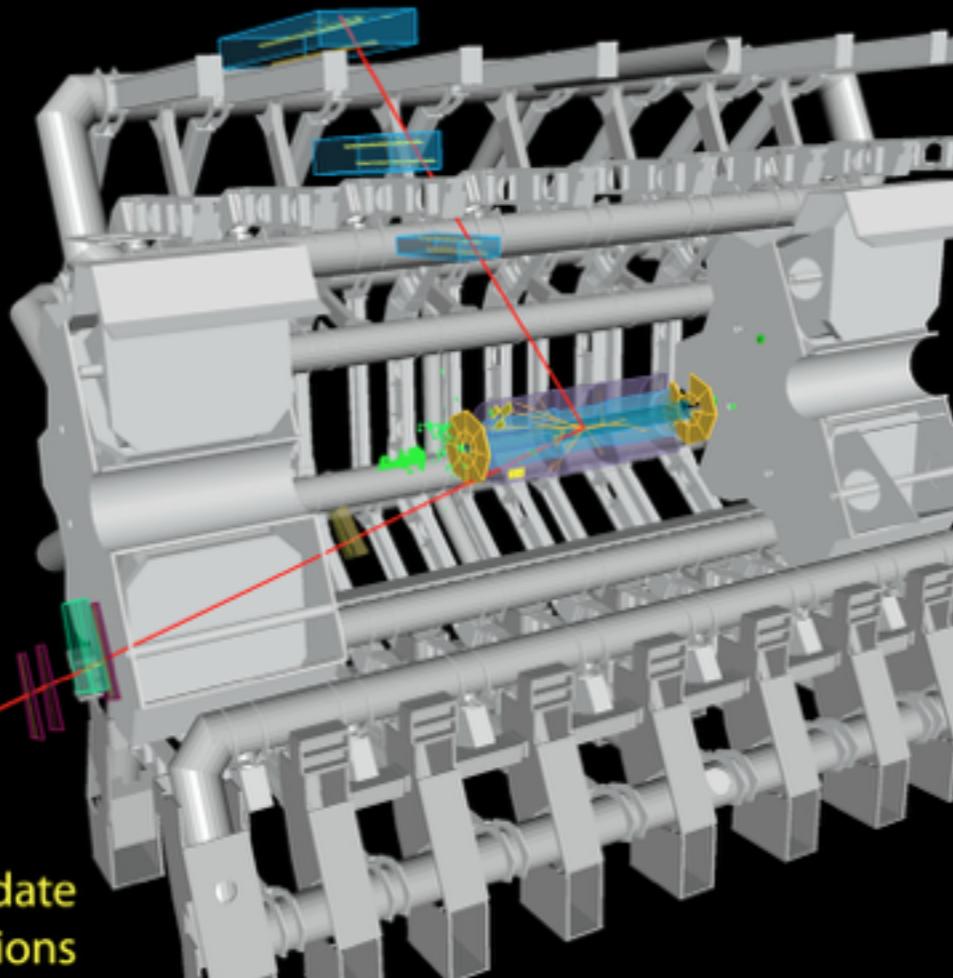
Date: 2010-05-10 02:07:22 CEST



$p_t(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_t(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$

$M_{\mu\mu} = 87 \text{ GeV}$

Z \rightarrow $\mu\mu$ candidate
in 7 TeV collisions



Intermezzo - Statistics & Particle Physics



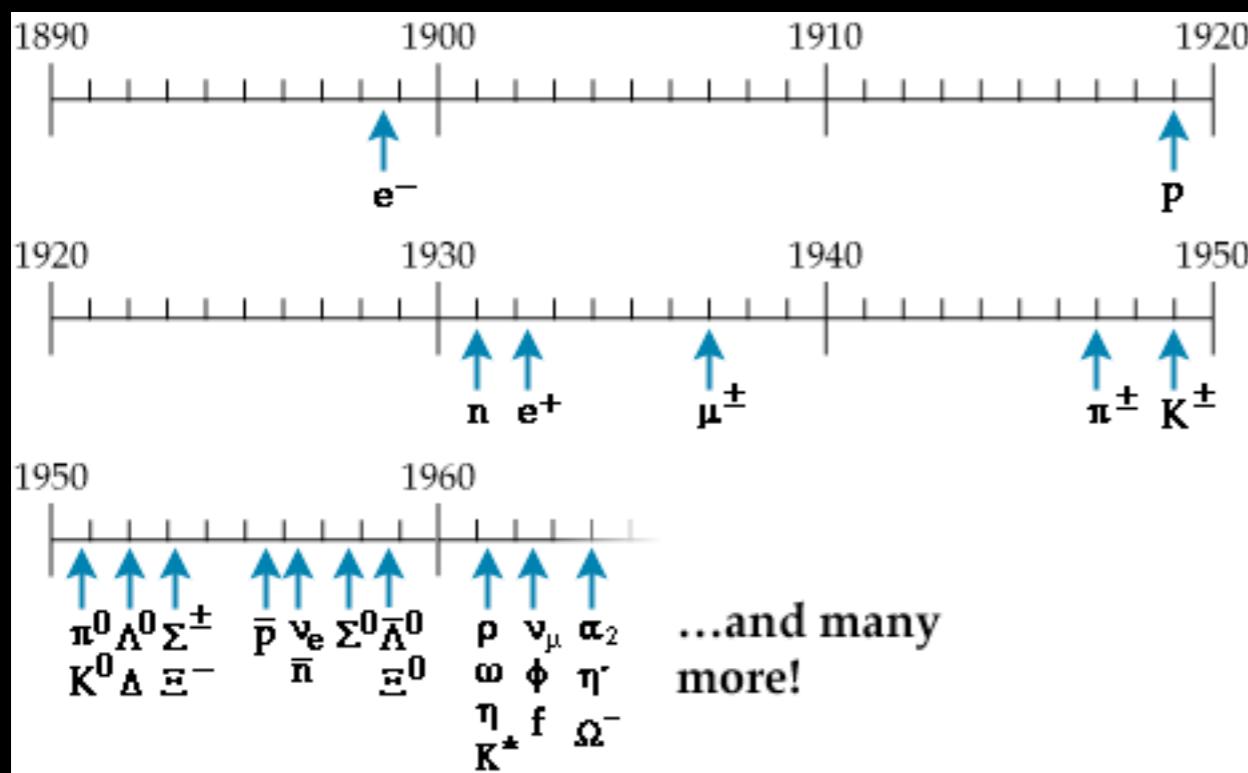
ATLAS
EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST

Seek, and you shall find more than expected



- Fast development in accelerator technique
 - 1938: 80 keV - 1939: 19 MeV - 1946: 195 MeV - 1947: 6 GeV - 1960: 30 GeV
- Discovery of many new particles ⇒ „particle zoo“



How to order this chaos?

Baryons

p^\pm (938.3), n (939.6), $N(1440)$, $N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$, $N(1720)$, $N(1875)$, $N(1900)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$, $\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$, $\Delta(2420)$, $\Lambda(1116)$, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$, $\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$, $\Lambda(2110)$, $\Lambda(2350)$, $\Sigma^+(1189)$, $\Sigma^0(1193)$, $\Sigma^-(1197)$, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$, $\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, $\Xi^0(1315)$, ...

Mesons

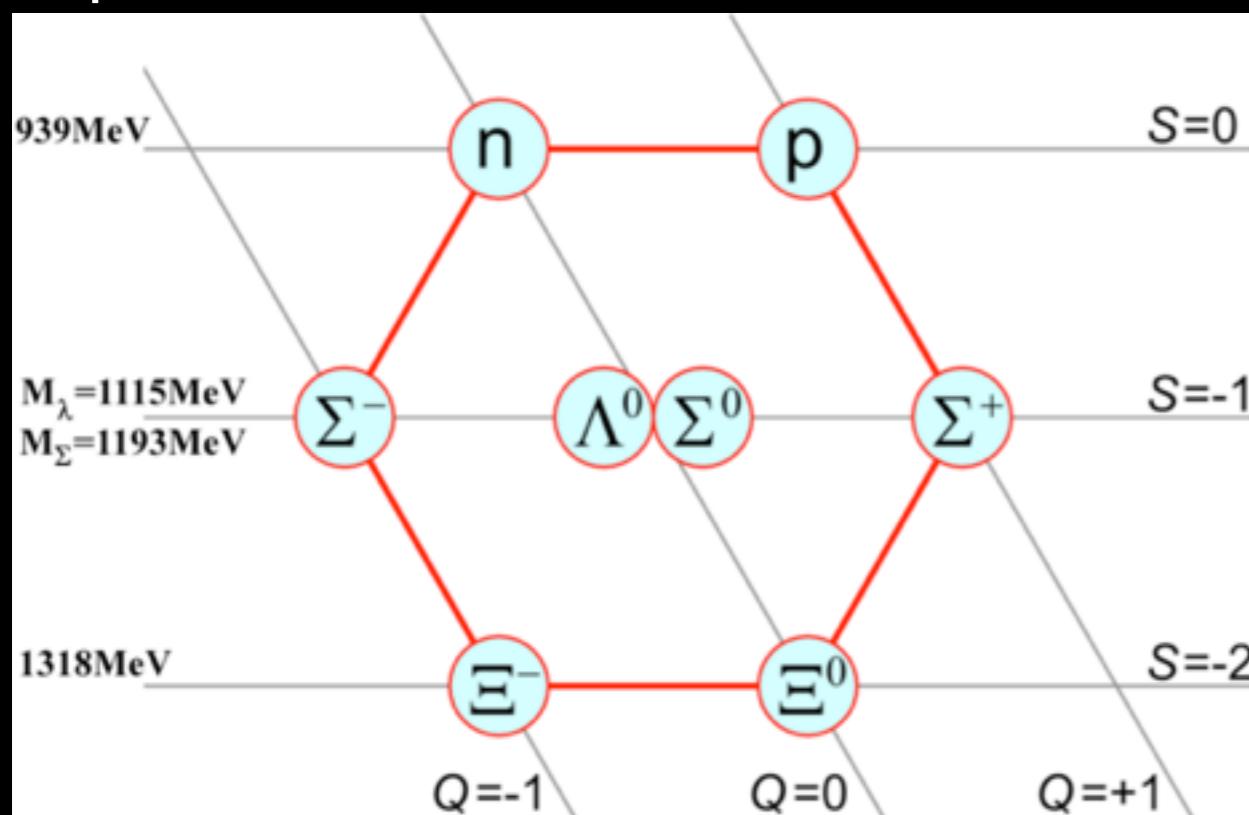
π^\pm (139.6), π^0 (135.0), η (547.9), σ (400-550), ρ (770), ω (782.7), η' (957.8), f_0 (990), a_0 (980), ϕ (1019), h_1 (1170), b_1 (1229), a_1 (1230), f_2 (1275), f_1 (1282), η (1295), π (1300), a_2 (1318), f_0 (1370), π_1 (1400), η (1409), f_1 (1426), ω (1400-1450), a_0 (1474), ρ (1465), η (1476), f_0 (1505), f'_2 (1525), π_1 (1662), η_2 (1617), ω (1670), ω_3 (1667), π_2 (1672), ϕ (1680), ρ_3 (1689), ρ (1720), f_0 (1720), π (1812), ϕ_3 (1854), π_2 (1895), f_2 (1944), f_2 (2011), a_4 (1996), f_4 (2018), ϕ (2175), f_2 (2297), f_2 (2339), K^\pm (493.7), K^0 (497.6), K^0_S , K^0_L , $K^*(891.7)$, K_1 (1272), K_1 (1403), $K^*(1414)$, K^*_0 (1425), K^*_2 (1426), $K^*(1717)$, K_2 (1773), K^*_3 (1776), K_2 (1816), K^*_4 (2045), ...

Hadron - Multiplets

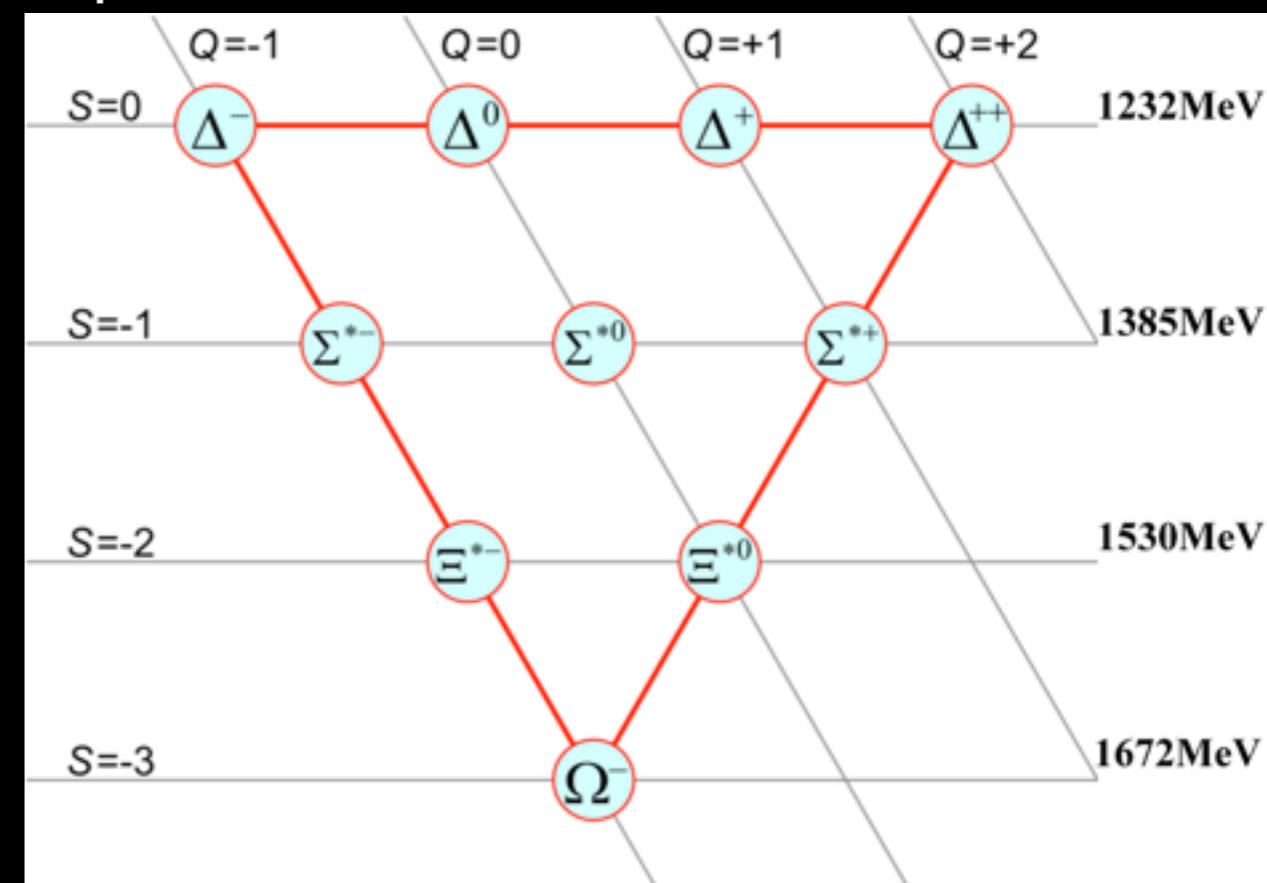


- The quest for structures:

Spin = 1/2

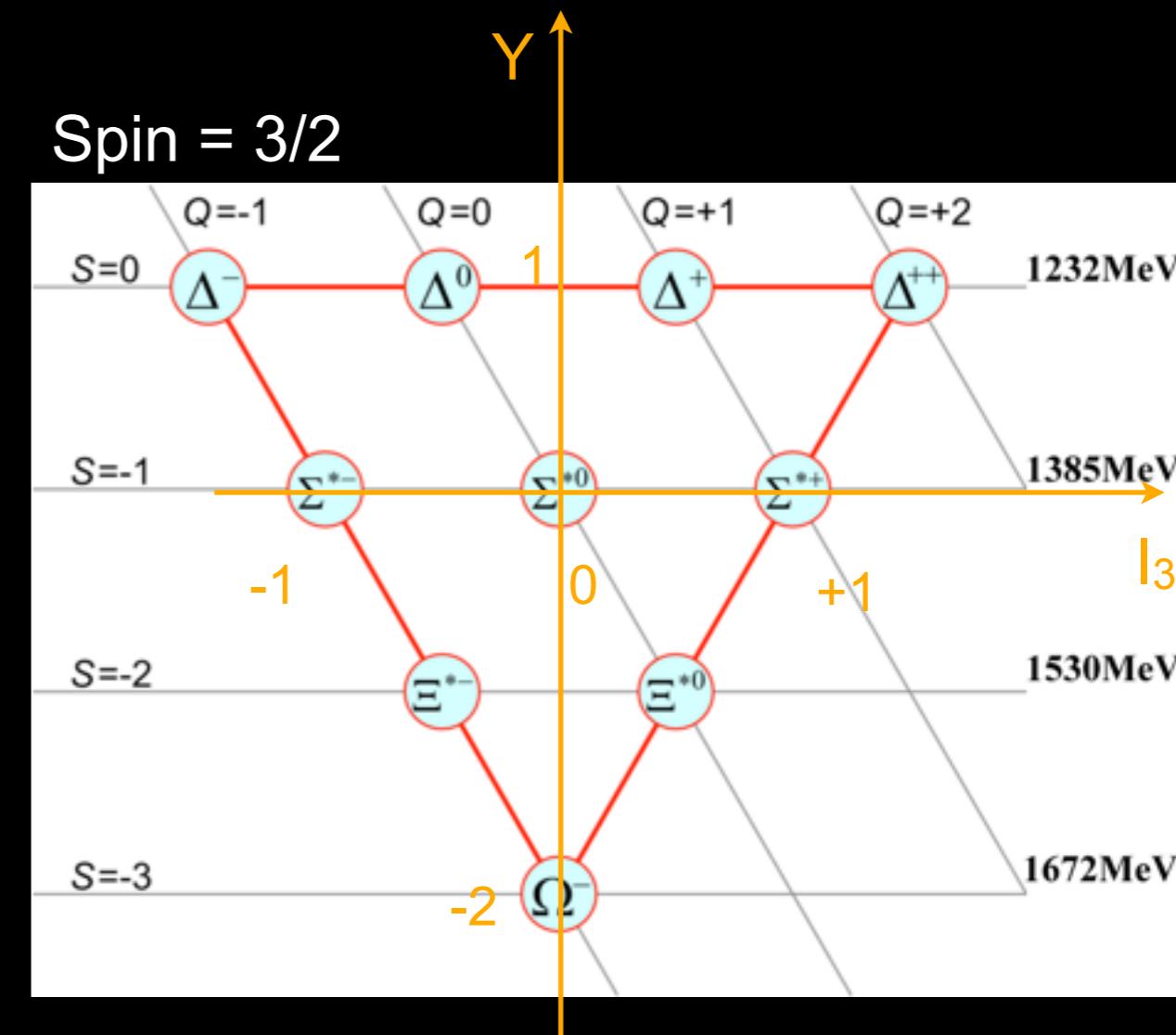
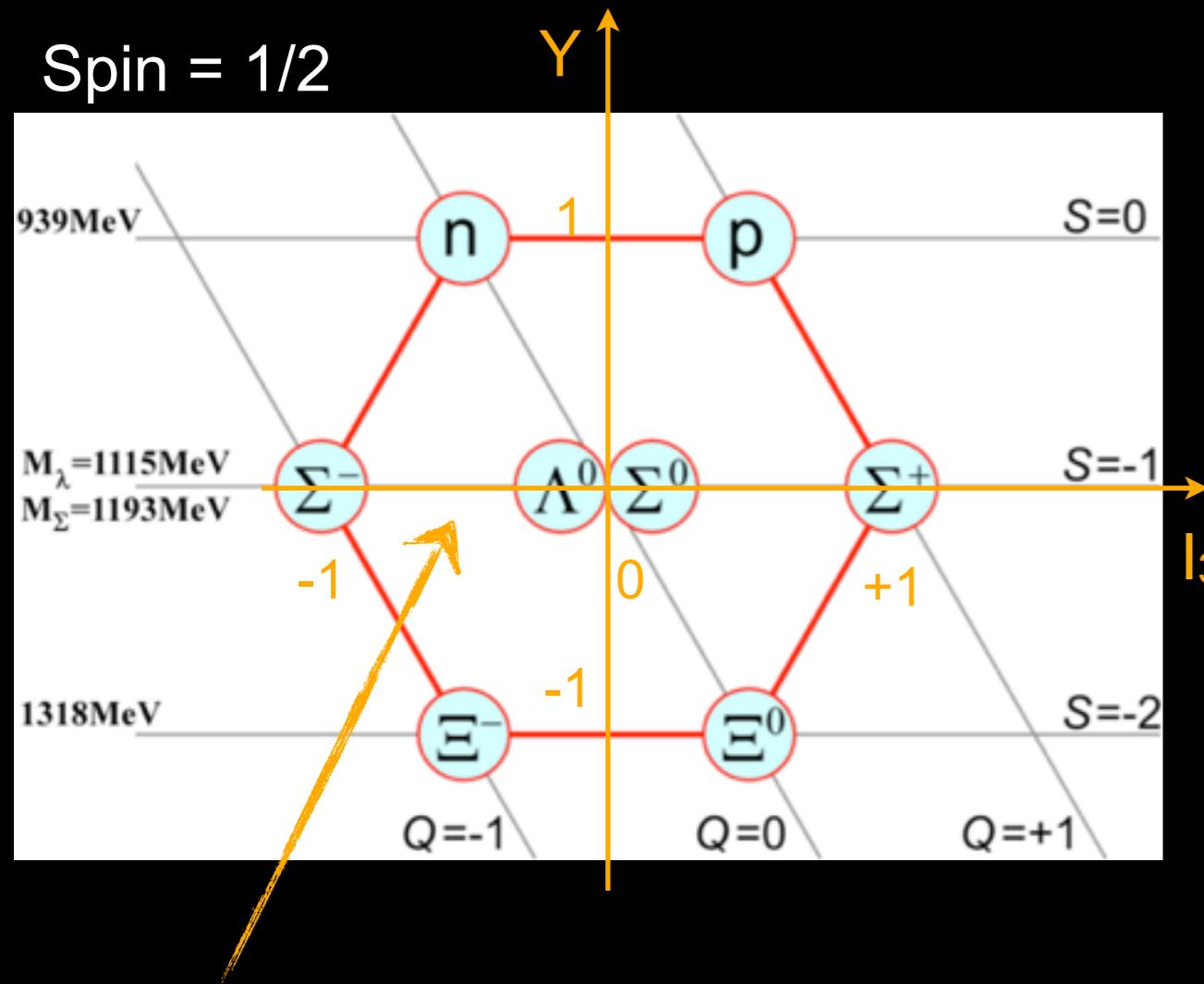


Spin = 3/2



Hadron - Multiplets

- The quest for structures:



Isospin:

Symmetry between p & n:
2 states of one „particle“

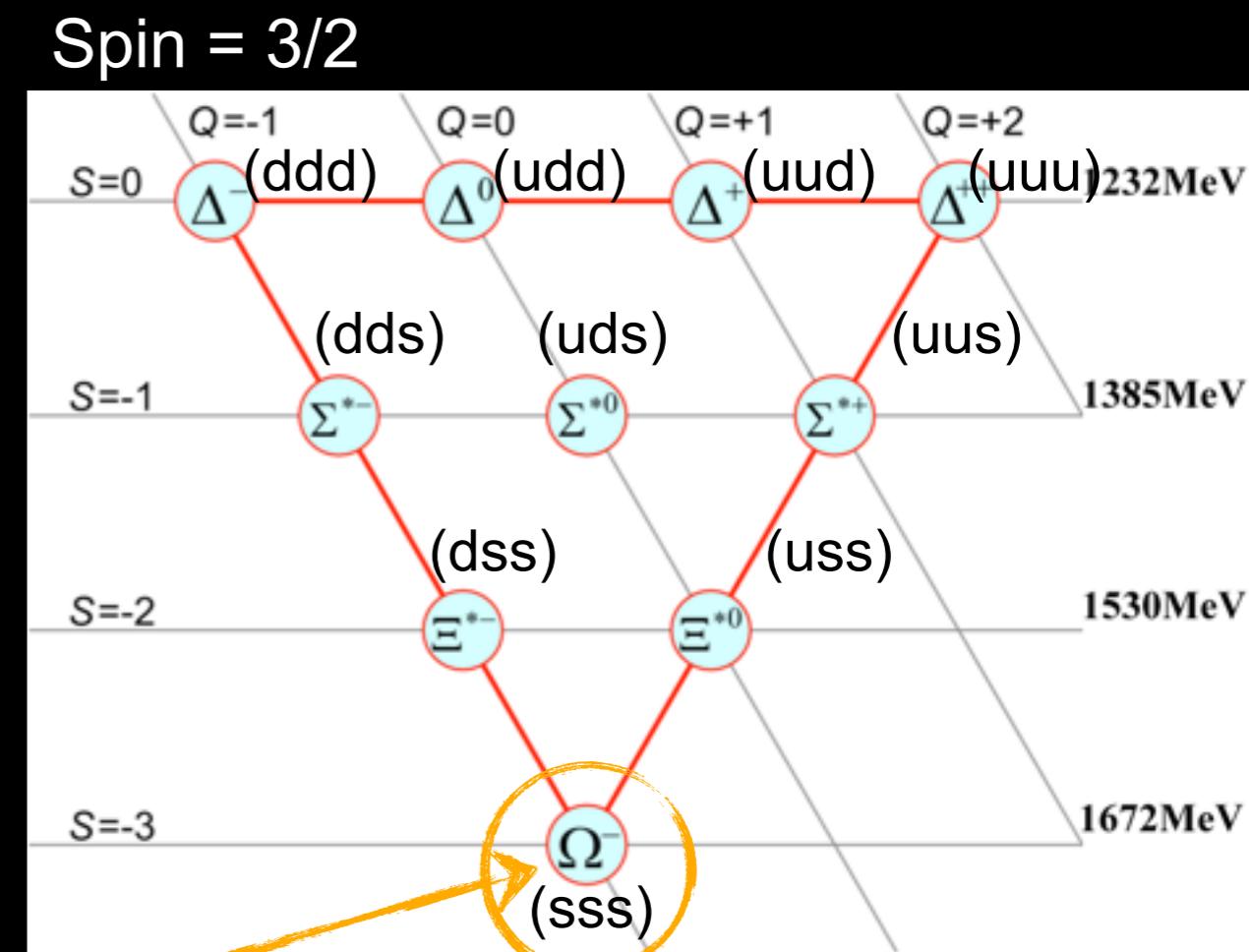
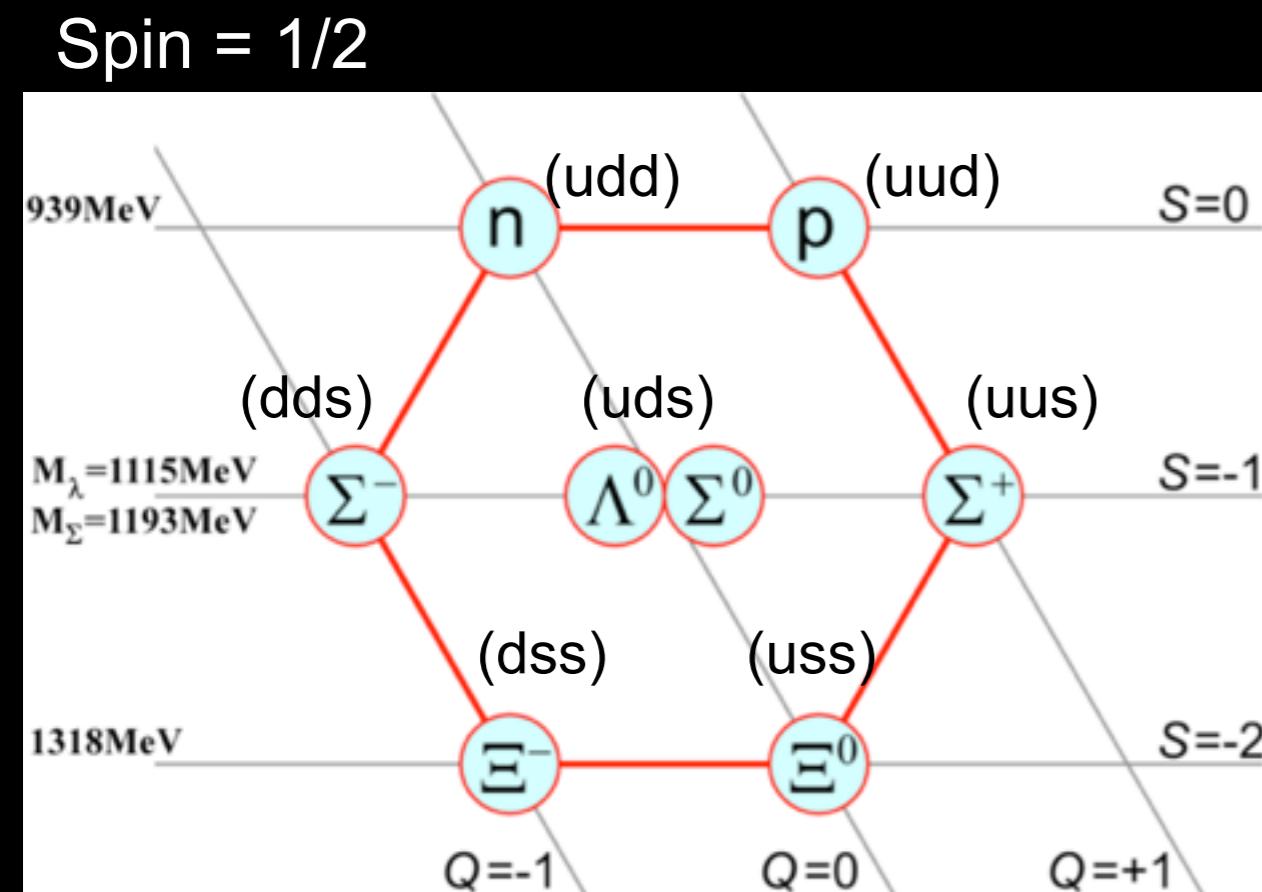
mathematical analogue with spin

Order through Internal Structure



- Postulate:
 - There exist **3 fundamental particles** which build up all hadrons (+ anti-particles)
 - Quarks:** up, down, strange

Gell-Mann /
Zweig: 1963

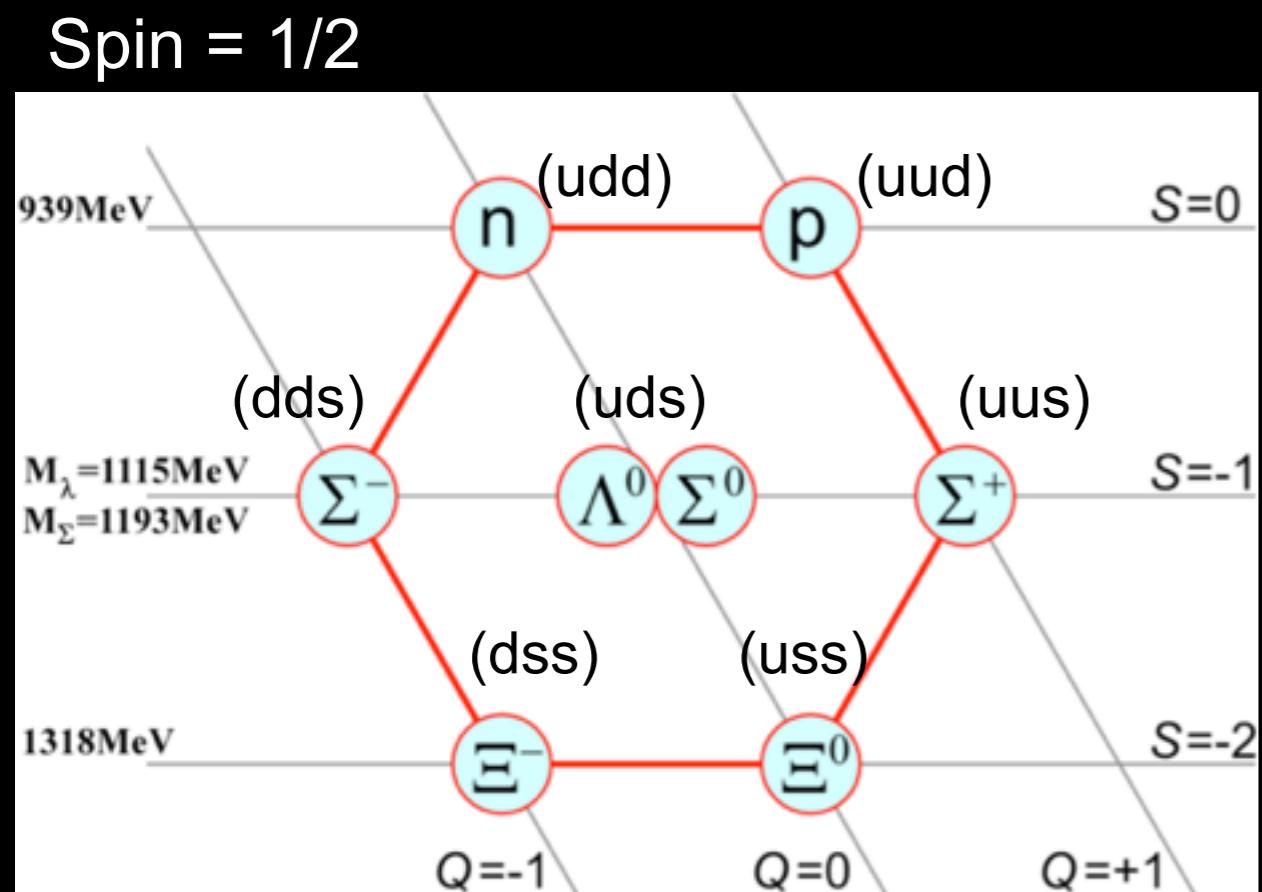


Predicted before experimental discovery

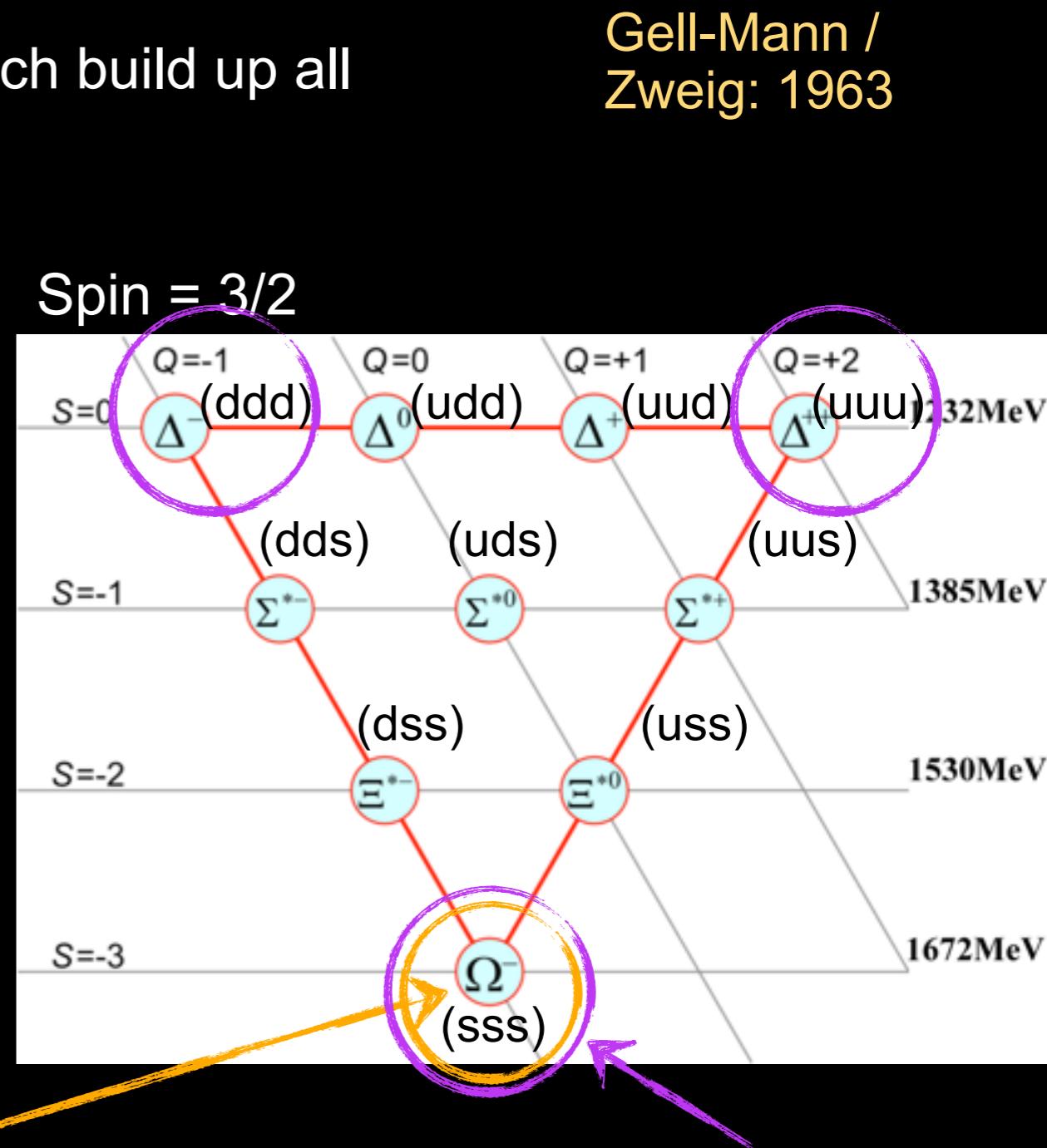
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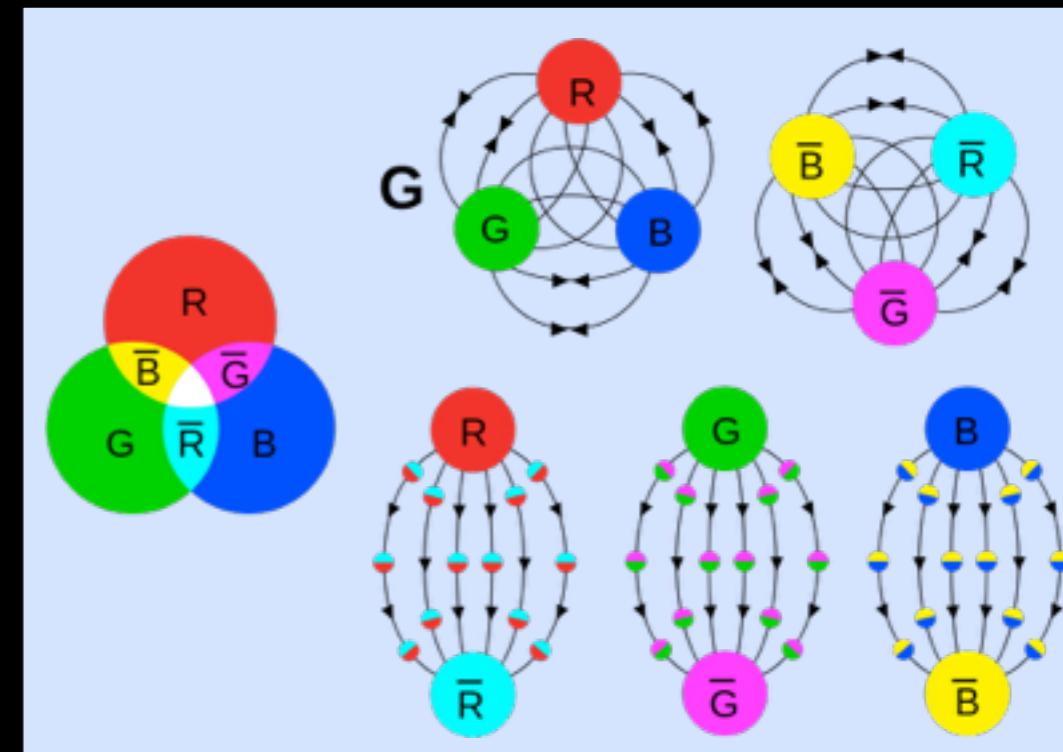


Problem: violates Pauli exclusion principle: 2 identical quarks!
⇒ color charge

Quantum Chromo Dynamic



- Quarks carry additional charge (quantum number):
 - Color - 3 states necessary to explain multiplets (red, green, blue)
 - behaves vector-like
 - Color = charge of 'strong' interaction
 - Exchange particle: Gluon (massless)
 - Changes color of quarks
⇒ Carry color & anti-color



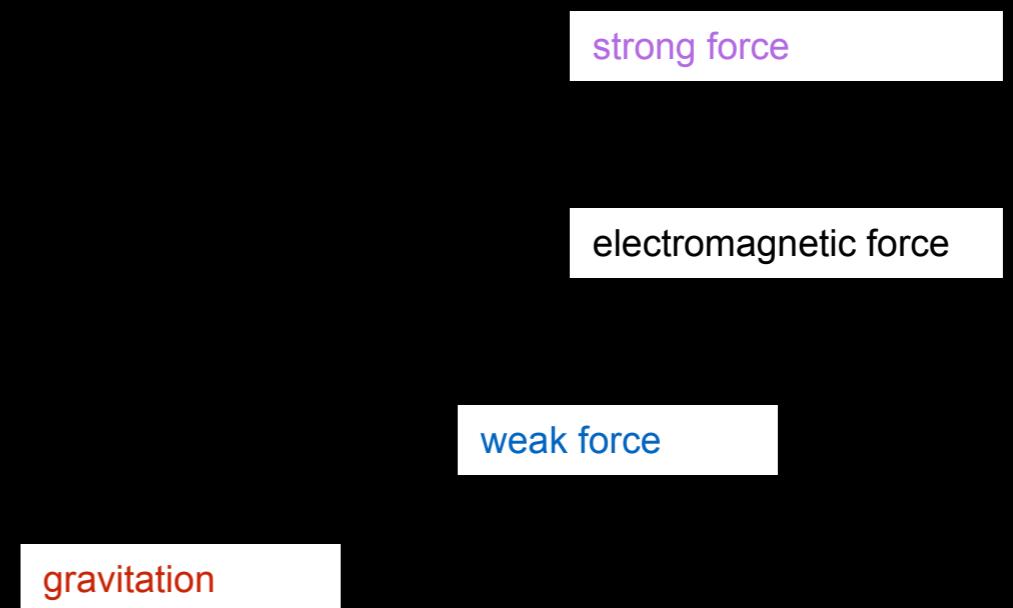
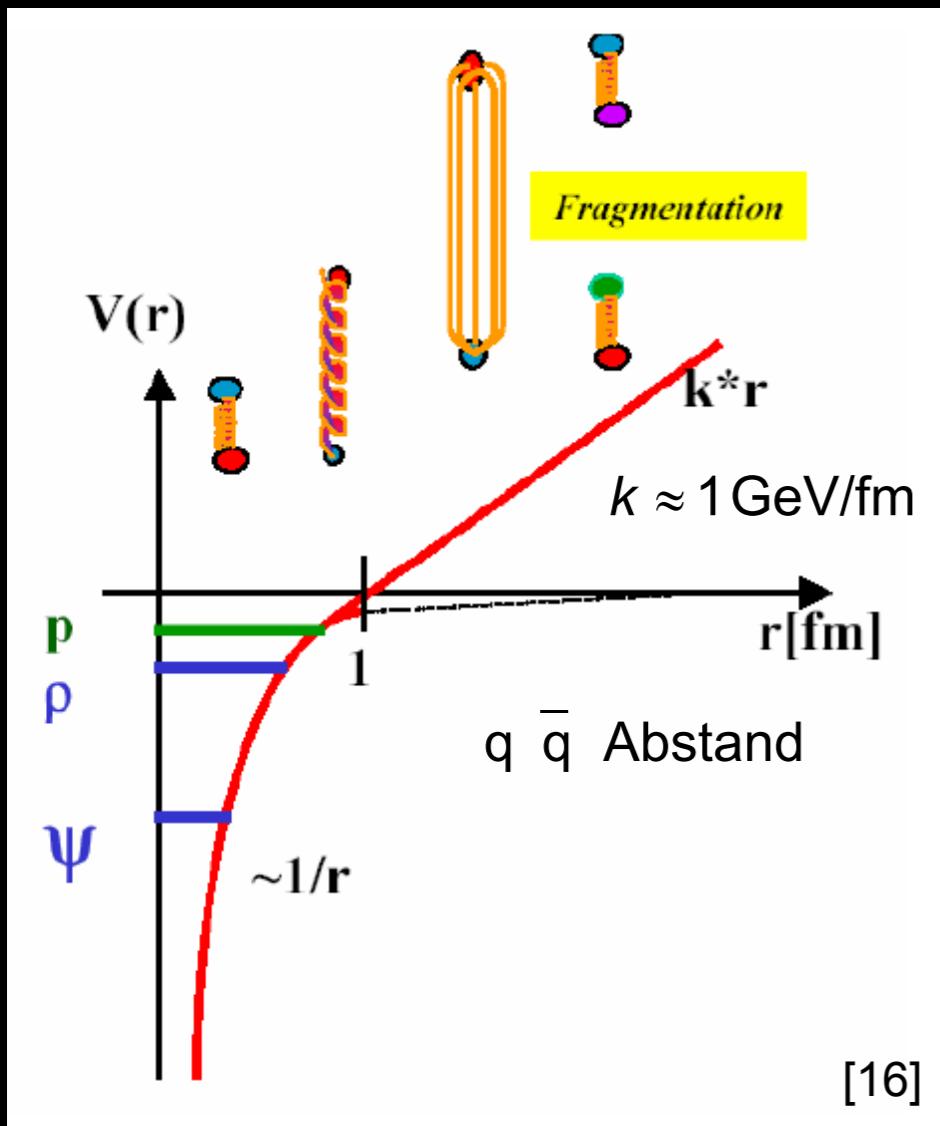
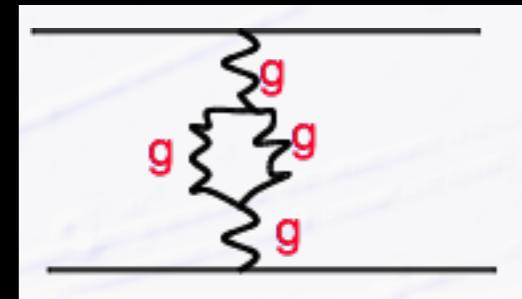
- Dogma of QCD:
 - Only color neutral objects exist
 - Color + anti-color (Mesons)
 - red + green + blue (Baryons)

Gluons - plaguy glue

- Gluons carry color → interact with each other!

- Fundamental difference to QED

- Potential: $V(r) = -\frac{4}{3} \frac{\alpha_s^{eff}}{r} + kr$



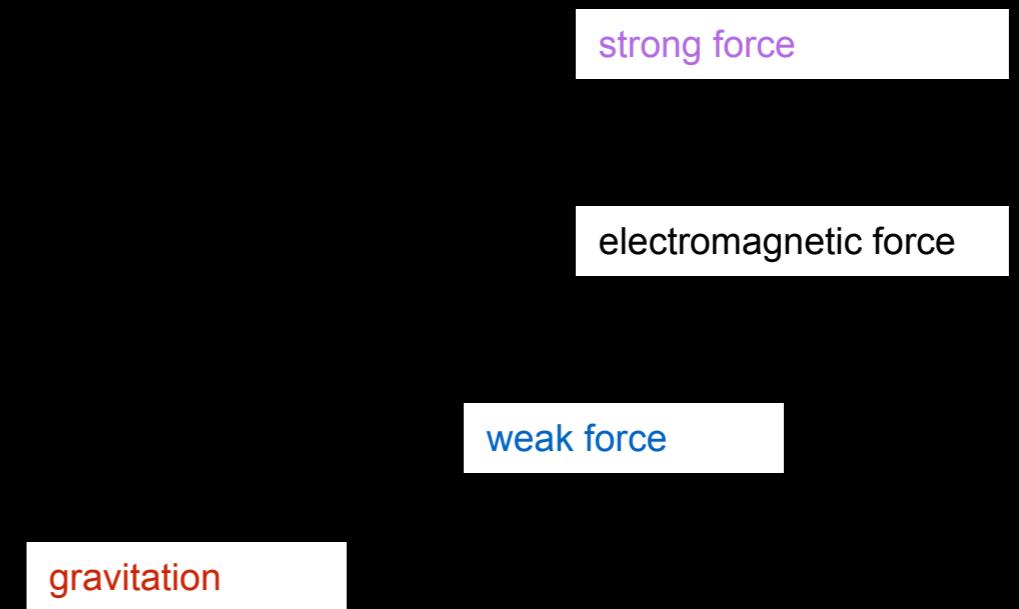
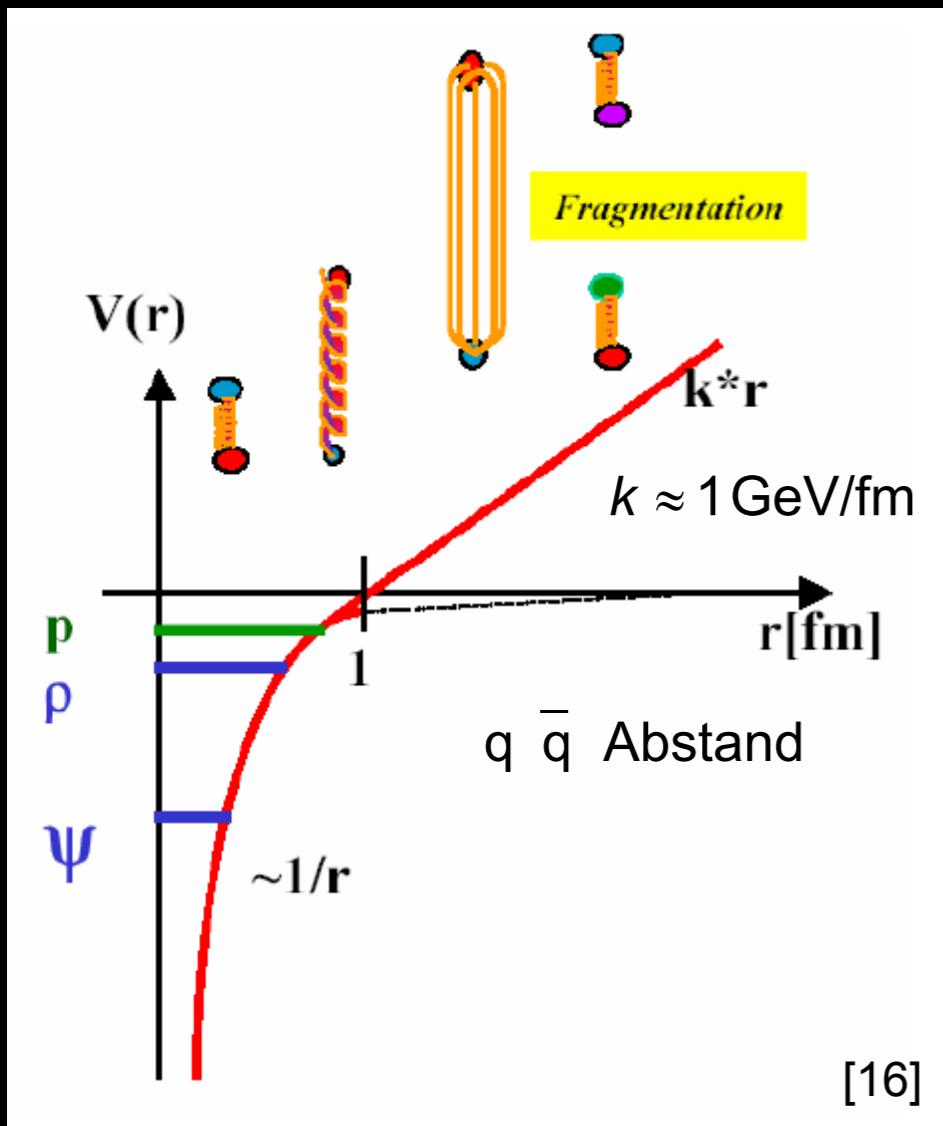
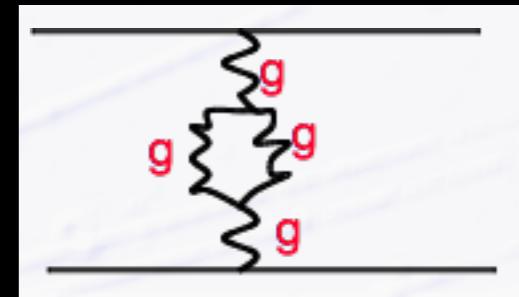
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,^{eff} - effective:
coupling depends
on r



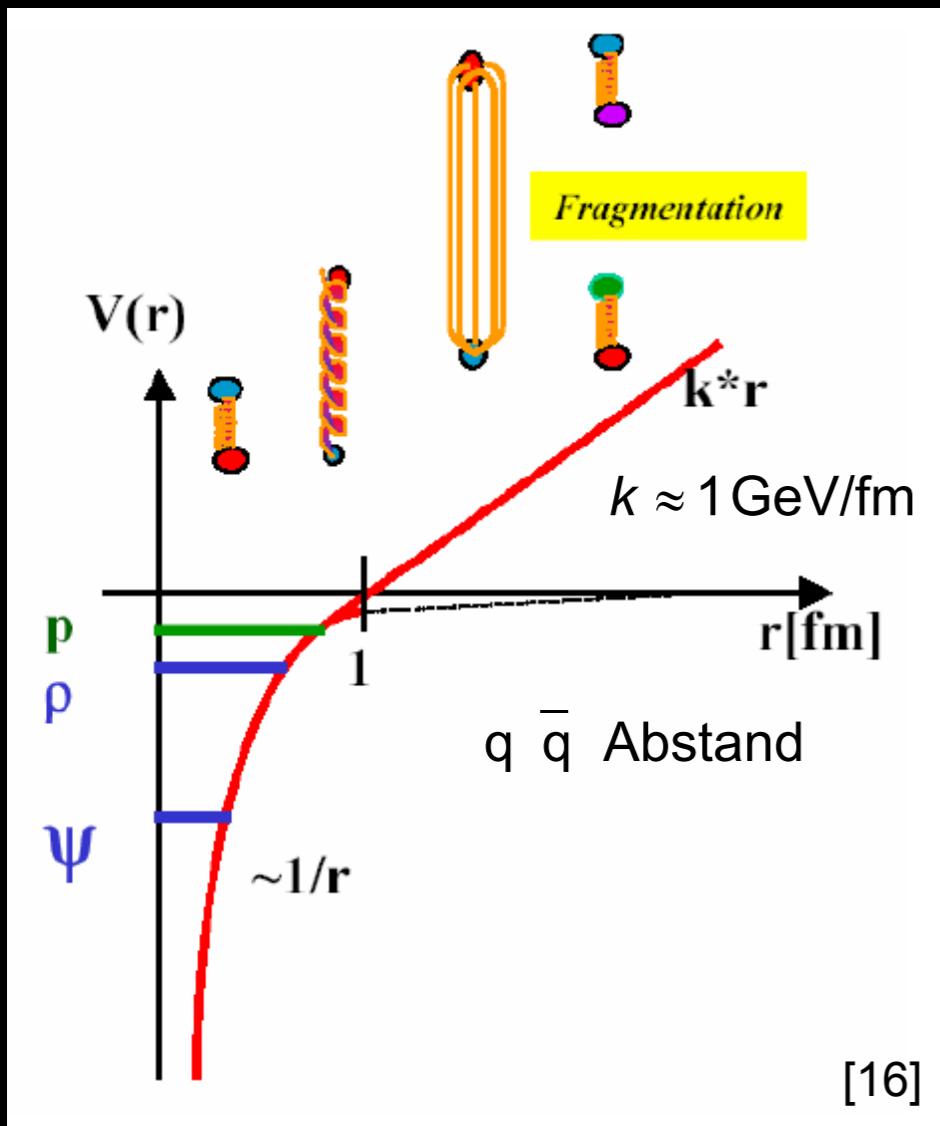
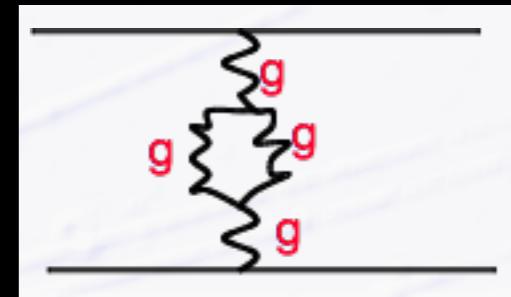
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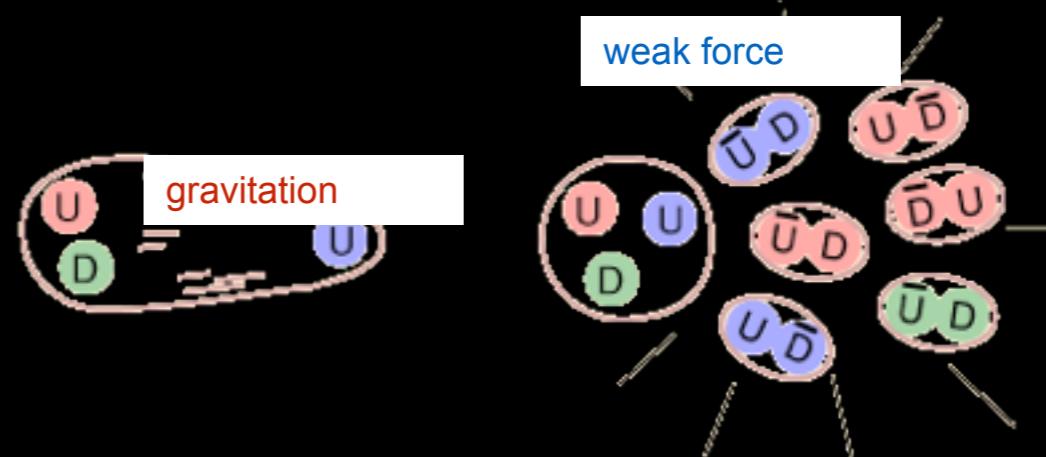
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- große Abstände
 - Potentielle Energie zwischen zwei quarks nimmt linear mit Abstand zu!
 $\sim 1 \text{ GeV pro fm}$
 - ,Confinement'



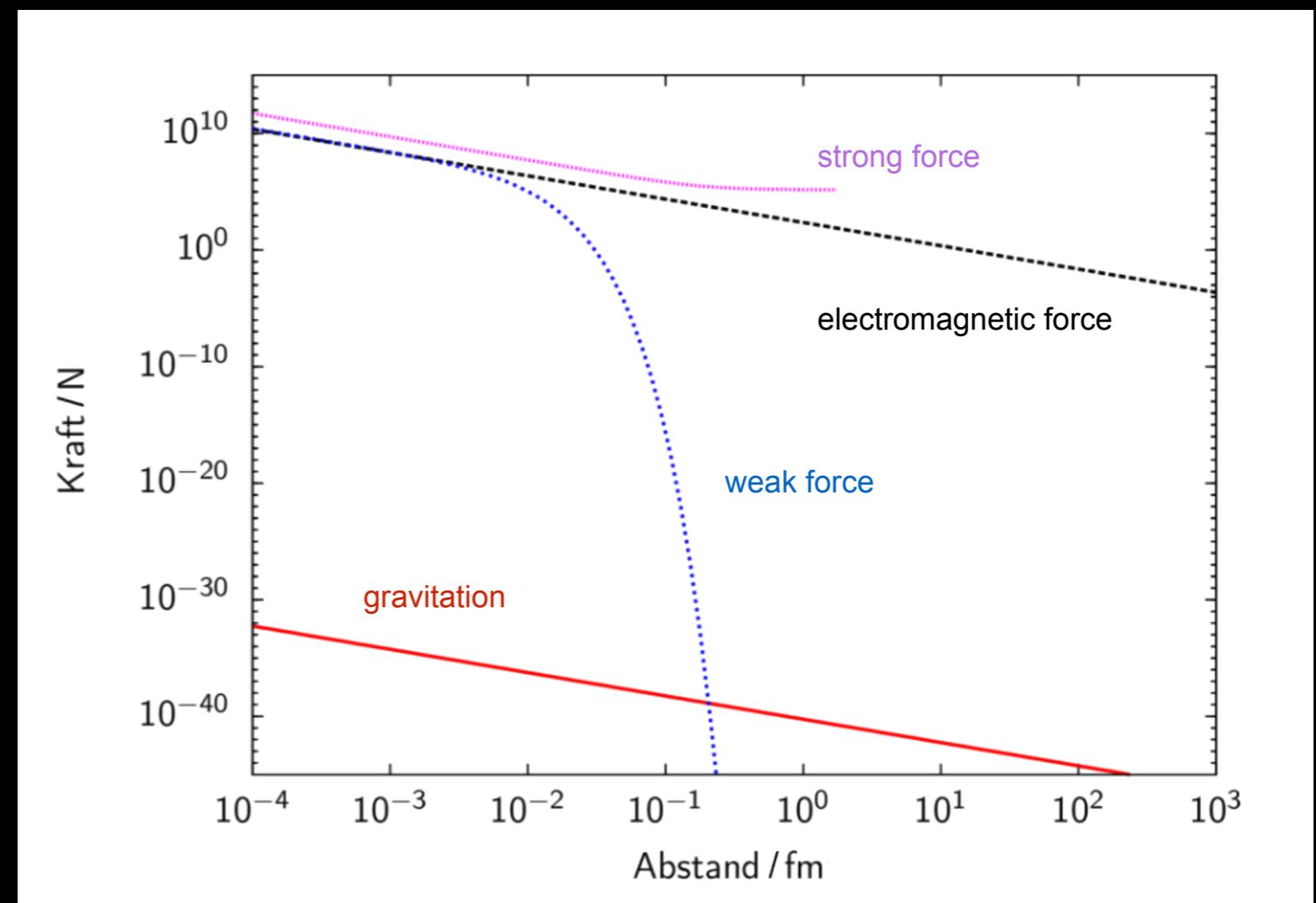
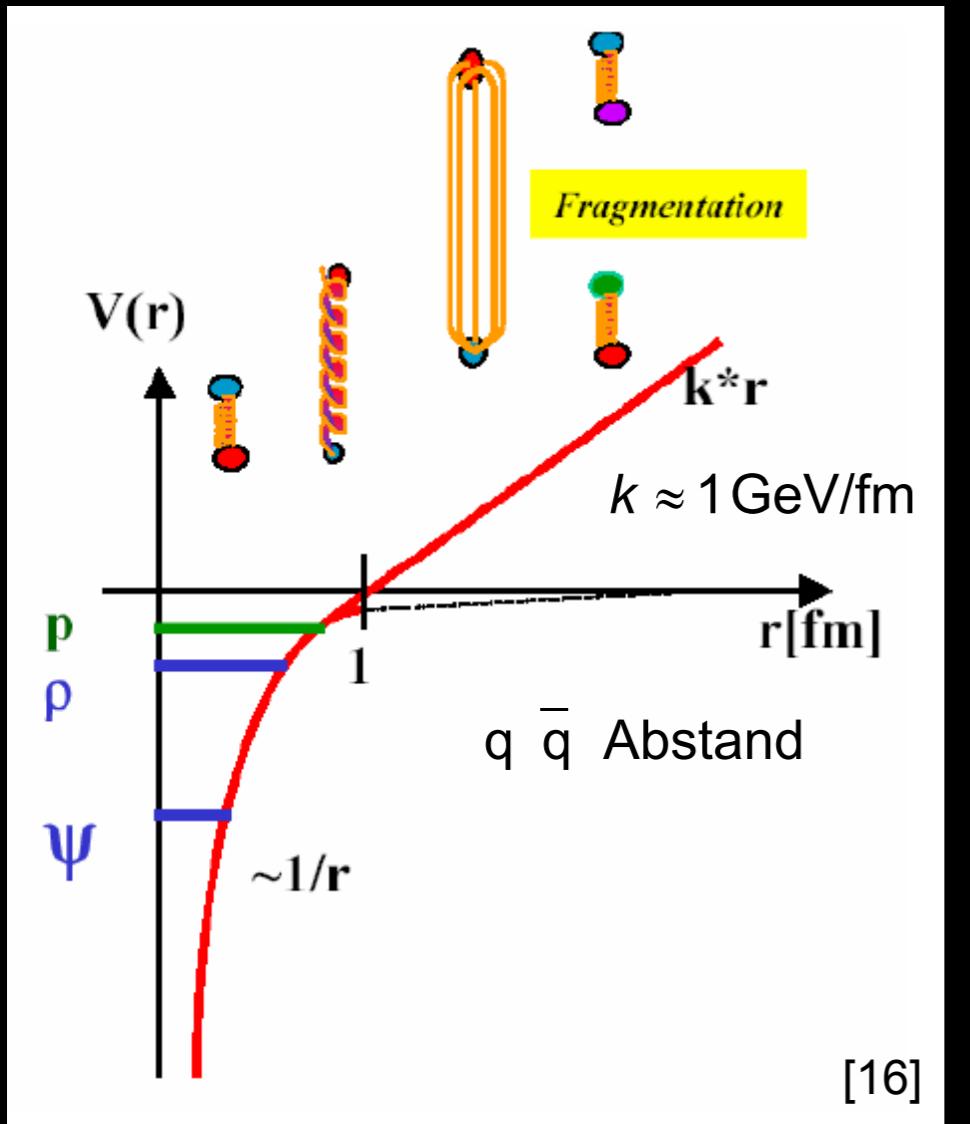
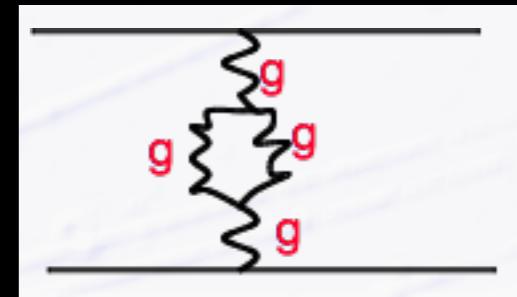
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Intermezzo: Color & other Charges

- Charges are the source of forces
- Every fundamental force requires corresponding charge
 - Only particles carrying specific charge take part in interaction

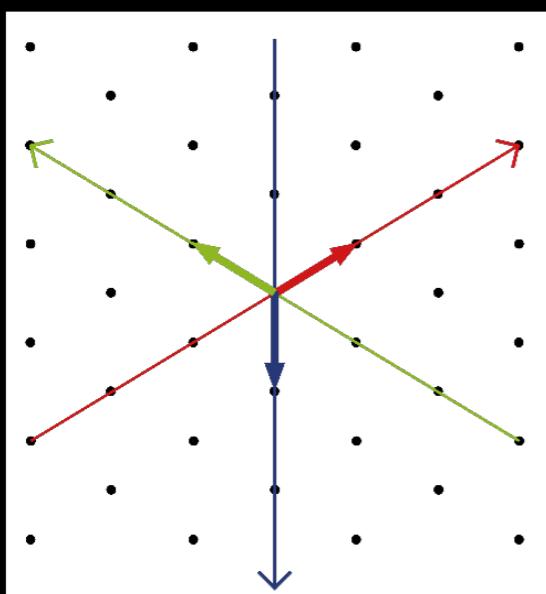
Force	Charge	Symbol = Unit
electromagnetism	electric	$q = 1$ electron
weak force	weak	$I = 1/2$
strong force	color	$\vec{C} =$ red, green, blue

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- Charges are **additive**
 - E.g.: el. charge of nucleus = sum of proton charges
 - Similar for weak charge
 - What about color?



- Color charge can be seen as 2D vector

$$p(u^{\textcolor{red}{\nearrow}} u^{\textcolor{green}{\searrow}} d^{\textcolor{blue}{\downarrow}})$$

$$\vec{C}_{u^{\textcolor{red}{\nearrow}}} + \vec{C}_{u^{\textcolor{green}{\searrow}}} + \vec{C}_{d^{\textcolor{blue}{\downarrow}}} = \textcolor{red}{\nearrow} + \textcolor{green}{\searrow} + \textcolor{blue}{\downarrow} = \vec{0}.$$

- E.g.: **Proton**:
- Sum of color vectors = 0 (**white**)

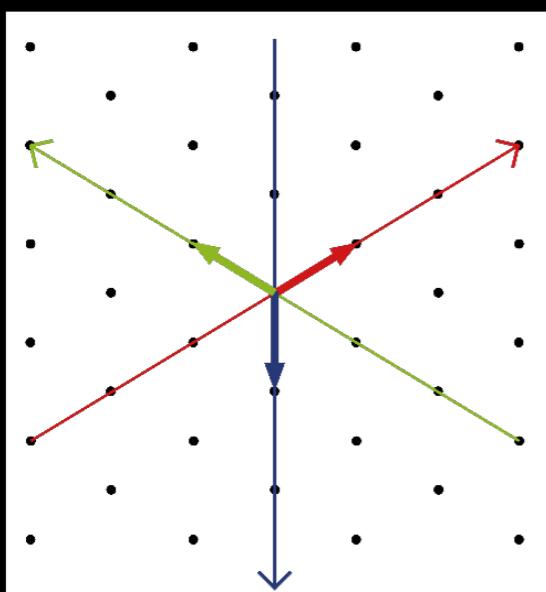
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 - What about color?

- Charges are conserved
 - In all reactions



- Color charge can be seen as 2D vector

$$p(u^{\textcolor{red}{\nearrow}} u^{\textcolor{green}{\searrow}} d^{\textcolor{blue}{\downarrow}})$$

$$\vec{C}_{u^{\textcolor{red}{\nearrow}}} + \vec{C}_{u^{\textcolor{green}{\searrow}}} + \vec{C}_{d^{\textcolor{blue}{\downarrow}}} = \textcolor{red}{\nearrow} + \textcolor{green}{\searrow} + \textcolor{blue}{\downarrow} = \vec{0}.$$

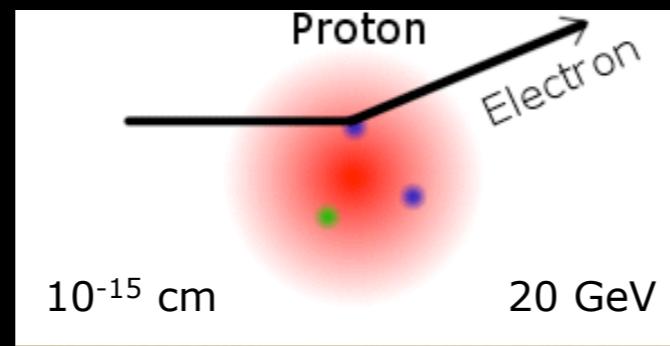
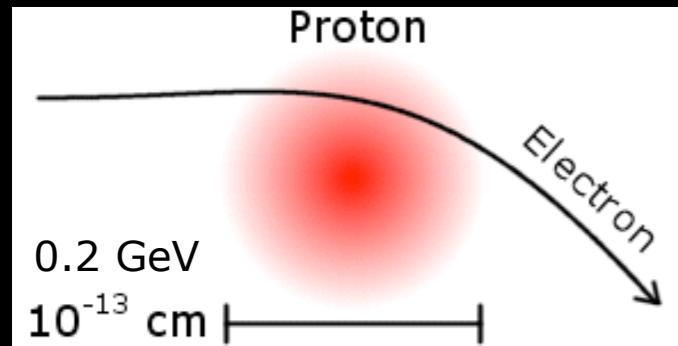
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Discovery of the quarks



Electrons scattered off protons

Friedmann, Kendall,
Taylor: 1969

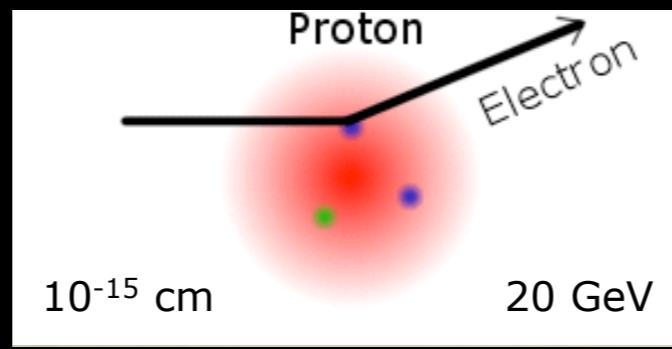
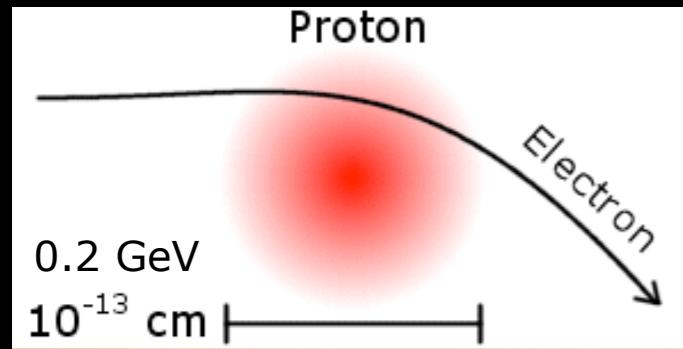


- Elastic scattering:
 - Sensitive to radius of proton
- Inelastic scattering:
 - Scattering off constituents!
- Relativistic events
 - Characterised via momentum transfer² = q^2 , instead of scattering angle
 - $(\Delta E + m_p c^2)^2 = (\Delta \vec{p})^2 c^2 + (m_W c^2)^2$
 - $m_W = m_p$: elastic scattering

Discovery of the quarks

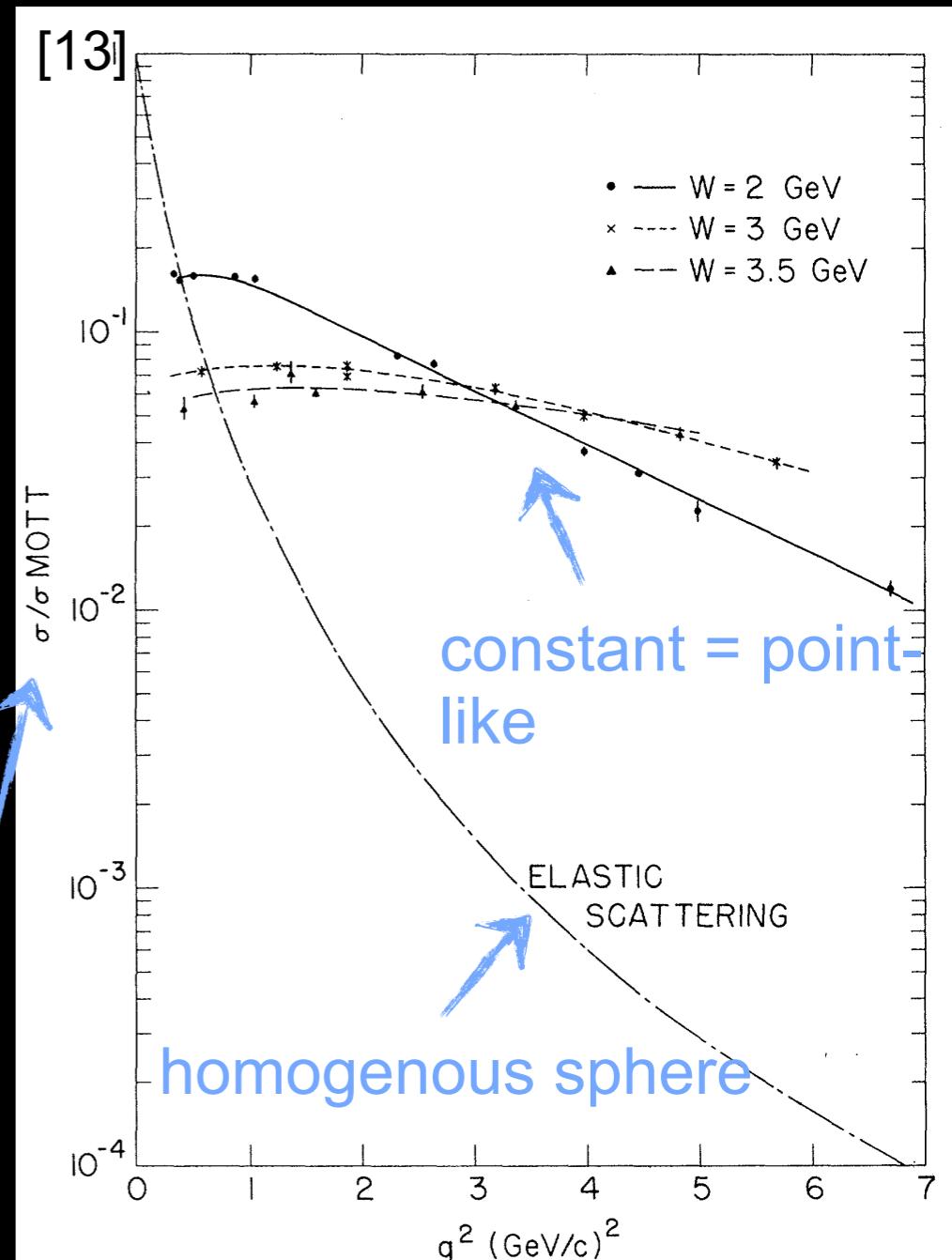


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- Relativistic events
 - Characterised via momentum transfer² = q^2 , instead of scattering angle
 - $(\Delta E + m_p c^2)^2 = (\Delta \vec{p})^2 c^2 + (m_W c^2)^2$
 - $m_W = m_p$: elastic scattering

Friedmann, Kendall,
Taylor: 1969



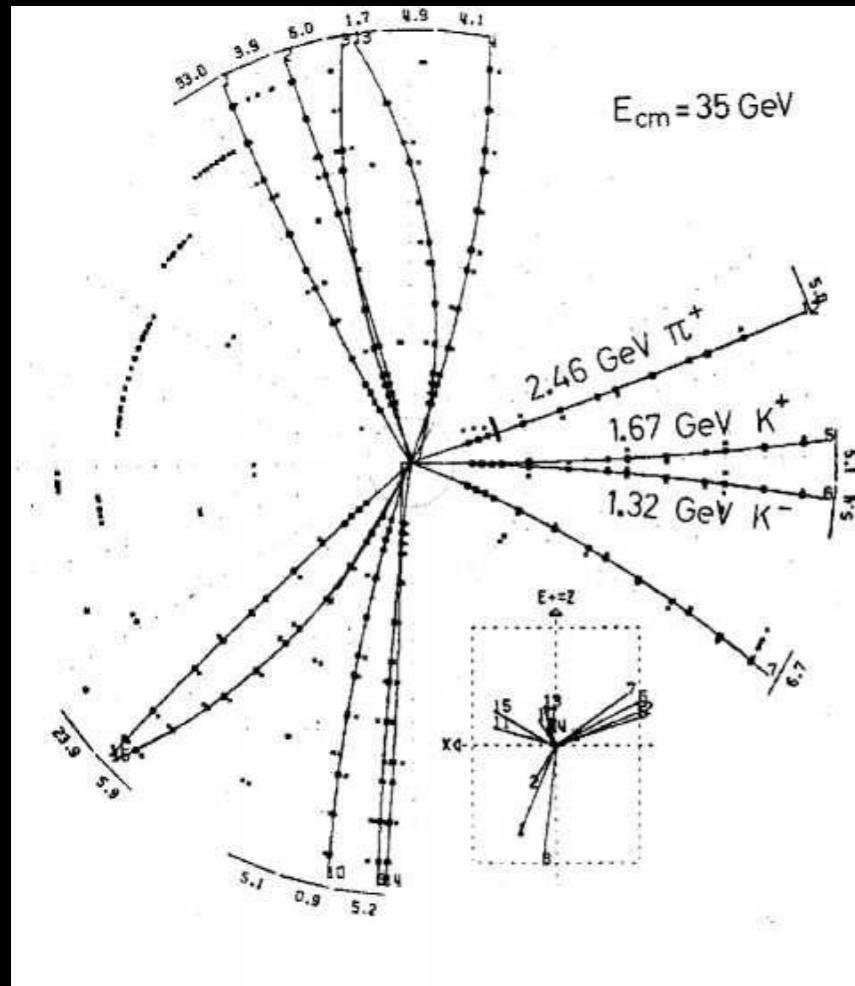
Formfactor F

Discovery of the Gluons



- Creation of quark anti-quark pairs
 - 3rd „jet“ emerges from gluon radiation

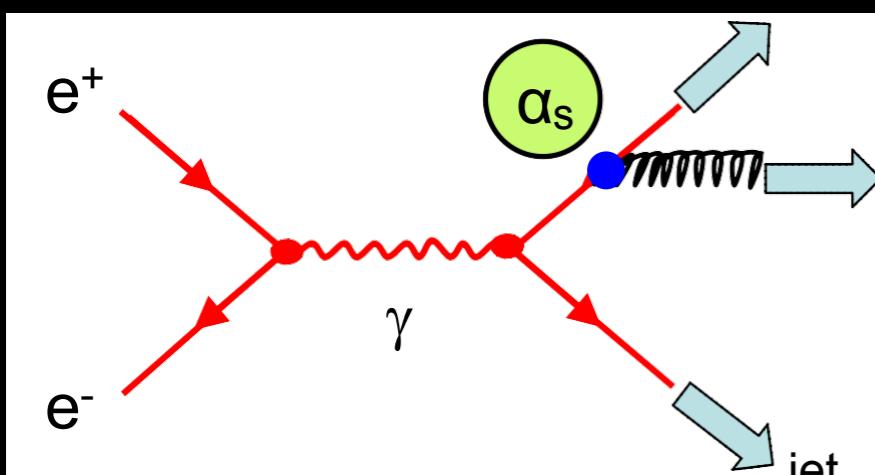
Desy (Petra): 1979



- Measurement of the strong coupling constant:

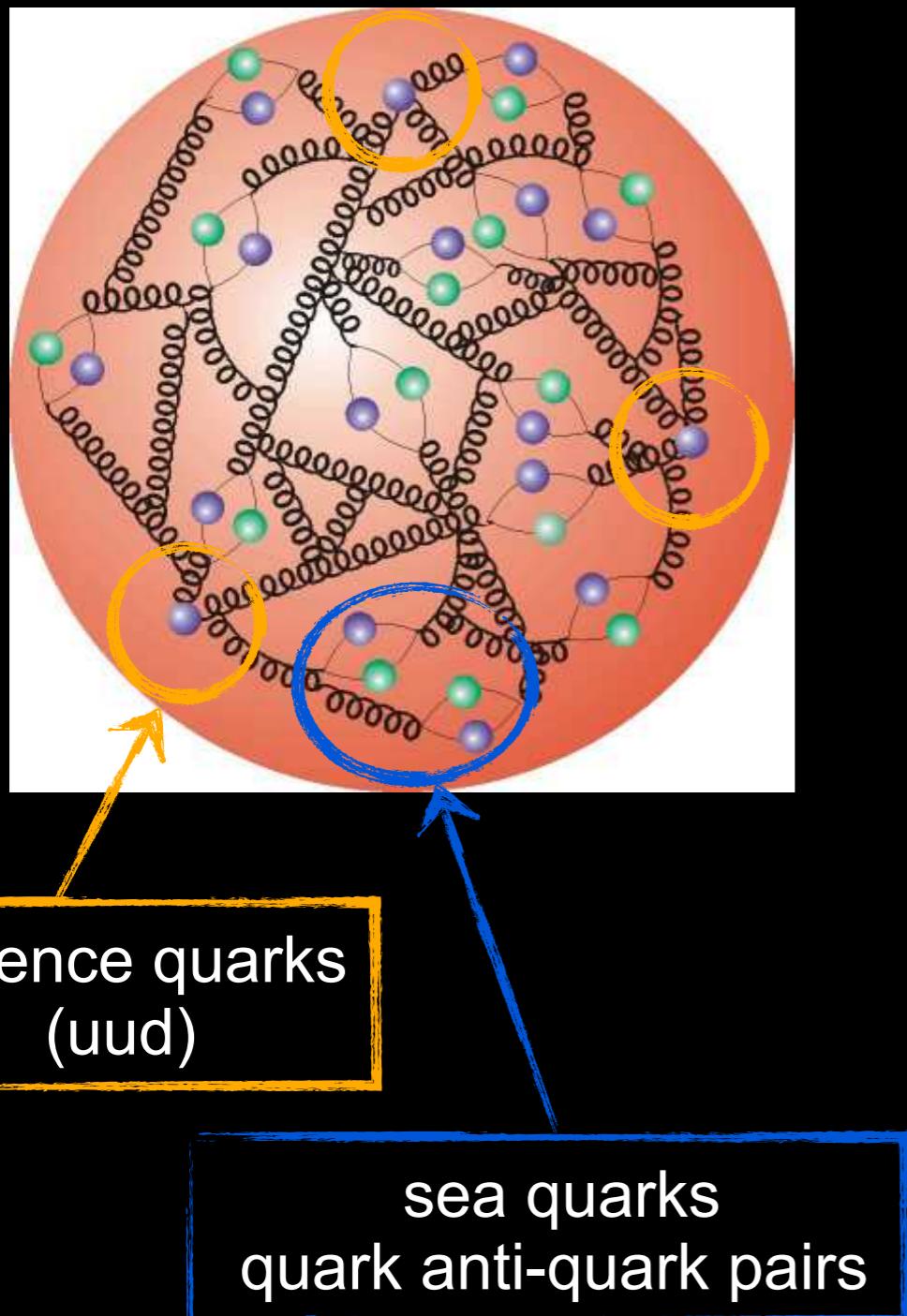
$$\alpha_s \sim \frac{\# \text{ 3 jet events}}{\# \text{ 2 jet events}}$$

- Experiments at the Petra e^+e^- accelerator at DESY
 - Experiments TASSO, Pluto, Mark-J, JADE

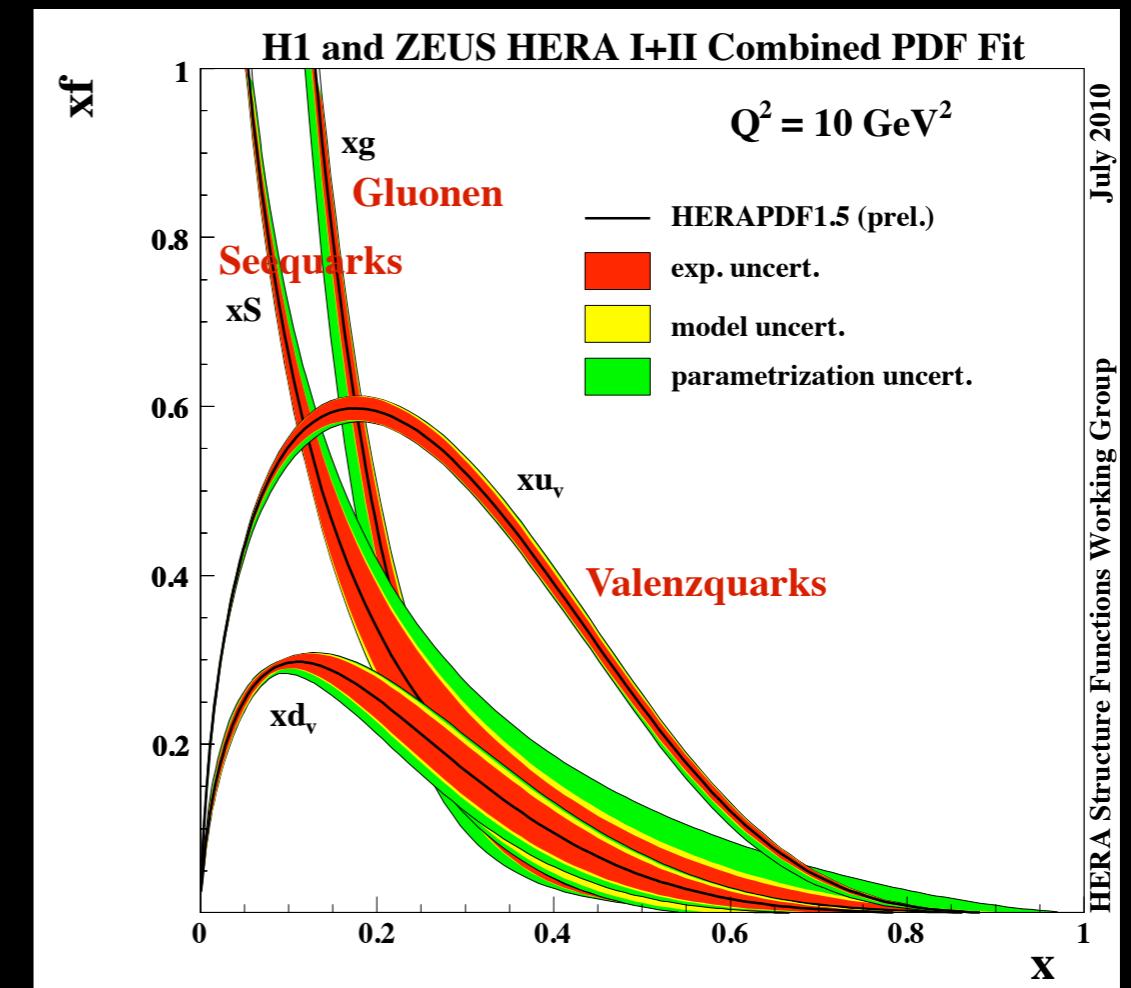


The Proton - todays view

- Complex many particle system
- Quarks, anti-quarks, gluons



- High energetic collisions:
 - Collisions of individual 'partons'
 - Which momentum carry partons?
- PDFs (Parton density function)

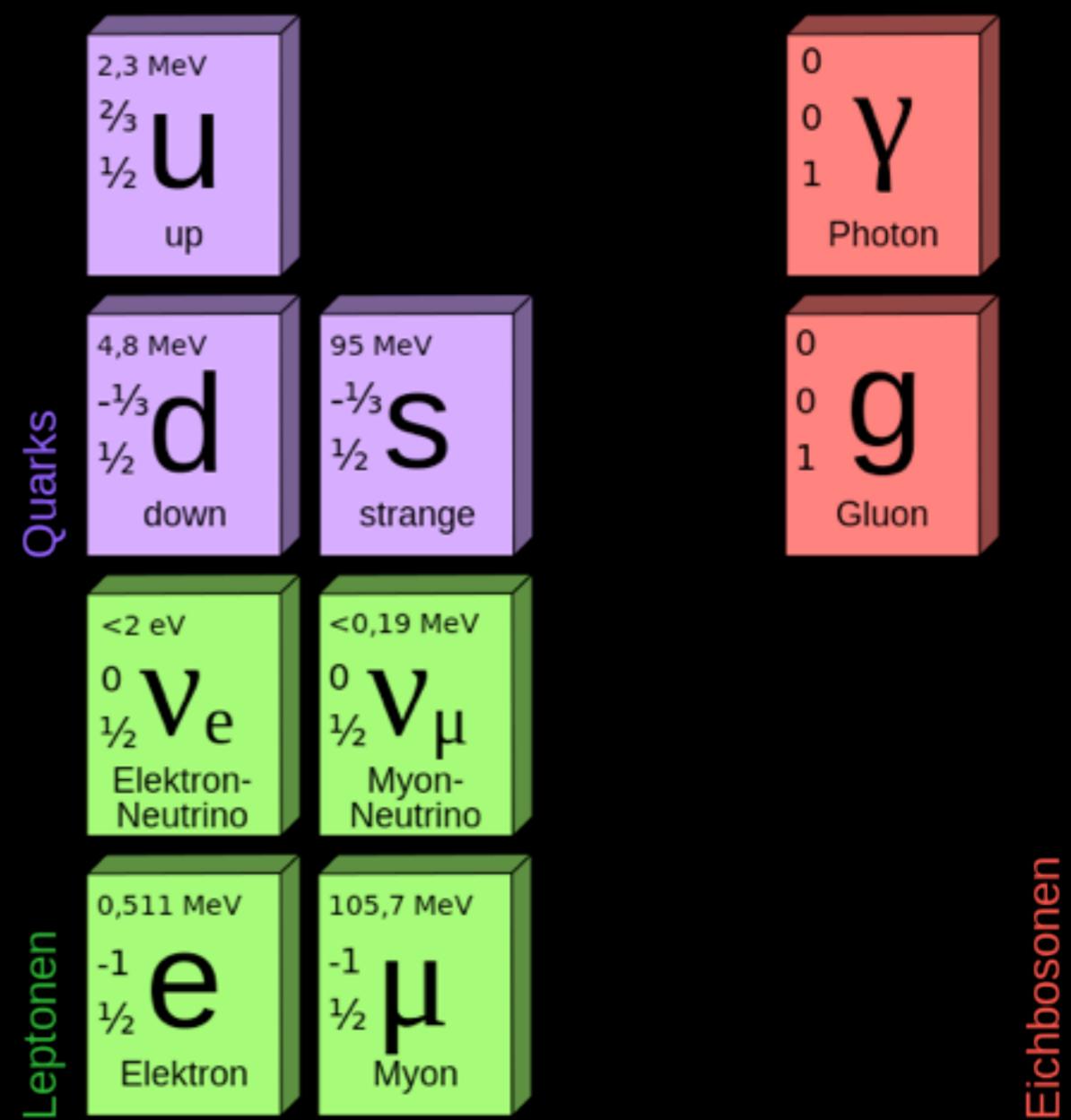


x: Fractional momentum of parton on proton momentum (Björken x)

What we covered so far

- Elementary particles

- Constituents of matter
 - Fermions ($S=1/2$)
- Force carries
 - Bosons ($S=1$)

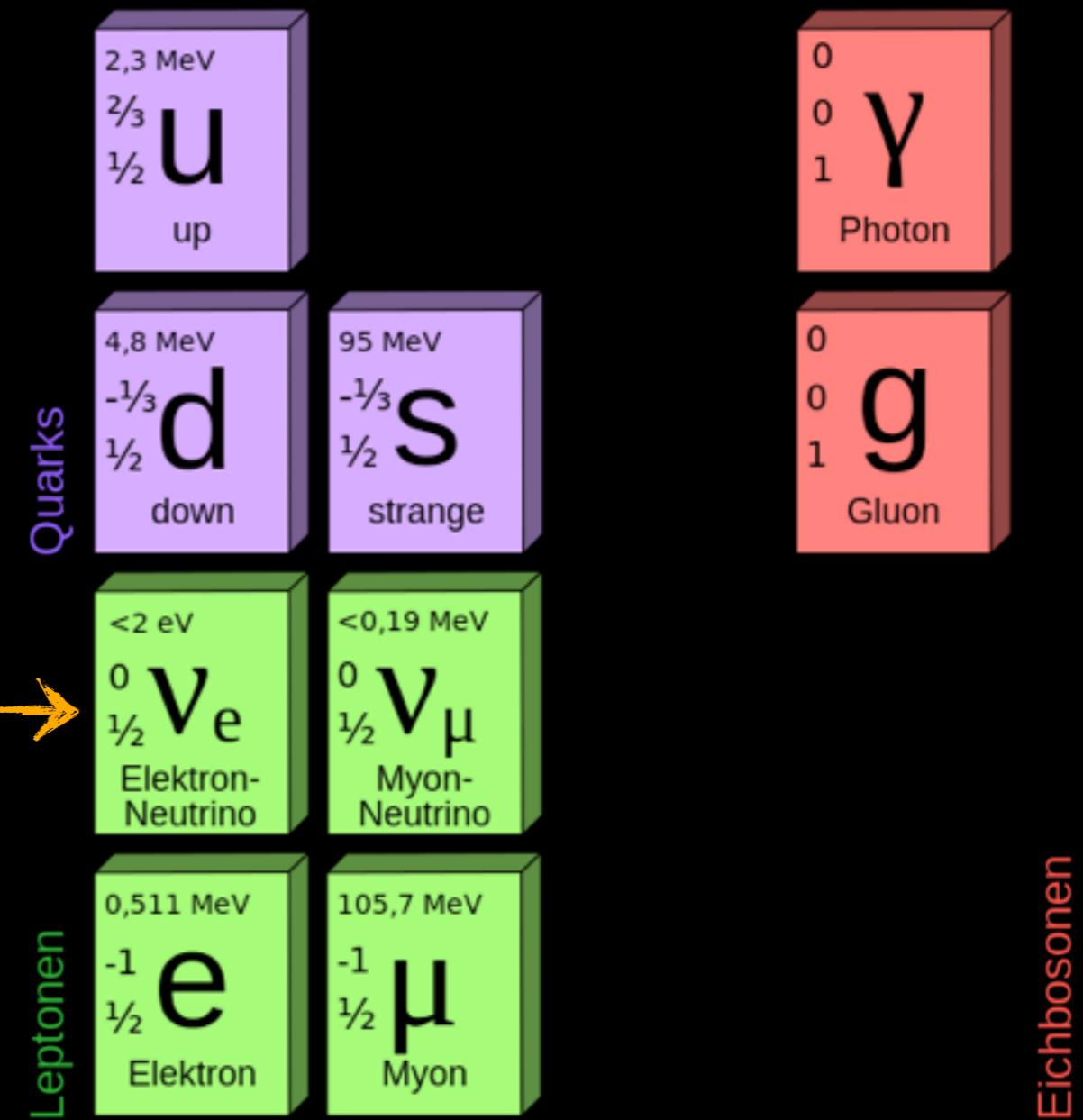


What we covered so far

- Elementary particles

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- Force carries
 - Bosons ($S=1$)

Neutrinos: neglected so far



weak interaction

Radioactivity



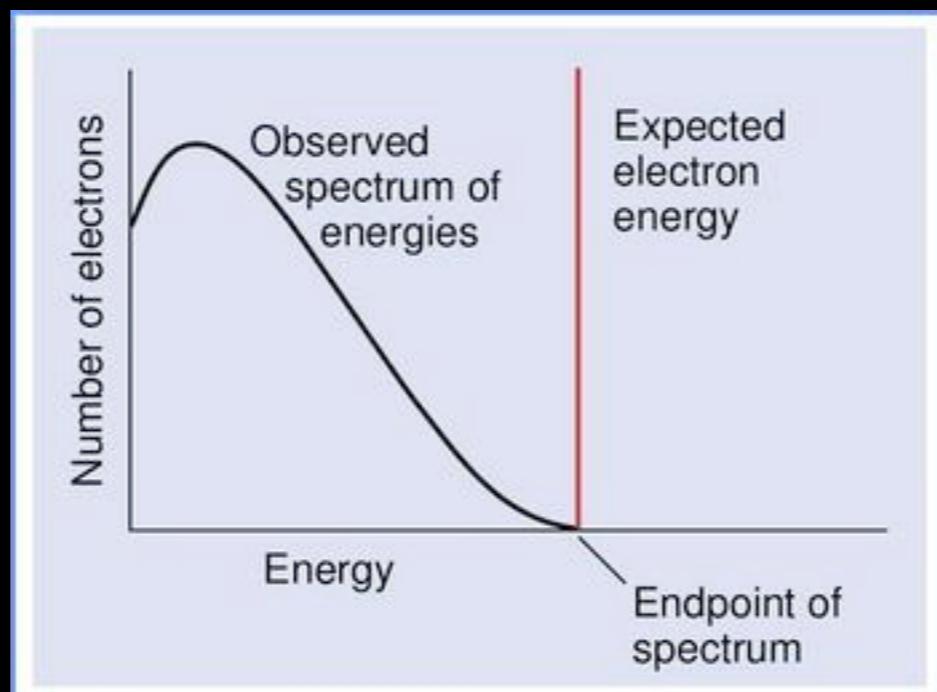
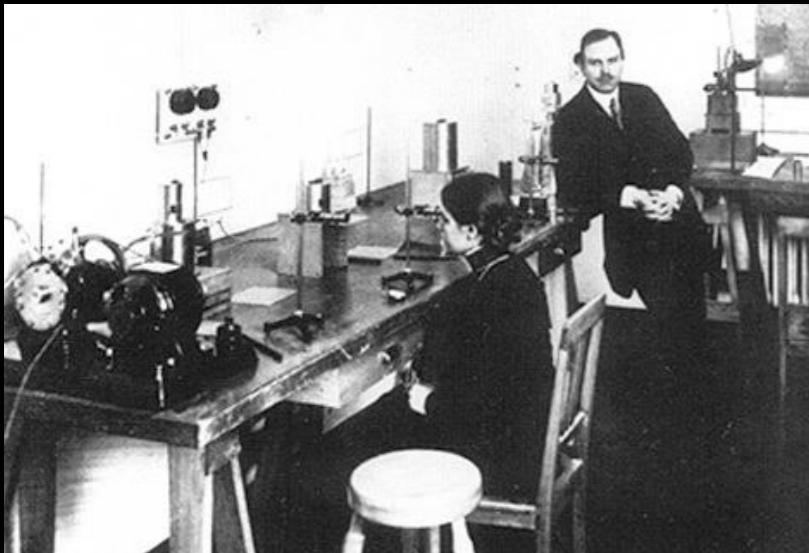
- Back to beginning of 20th century
 - 1895: Wilhelm Röntgen discovered **x-rays**
 - 1896: Henri Becquerel discovered **radiation from uranium crystals**
 - 1898: Marie & Pierre Curie: **radiation from pitch (U + Polonium)**
- It took 35 years to get basic understanding of these phenomena

β -Decay

- β - decay of atoms

Meitner, Hahn: 1911

Visible: $A_z \rightarrow A_{z+1} + e^-$



- **Violation of energy conservation?**

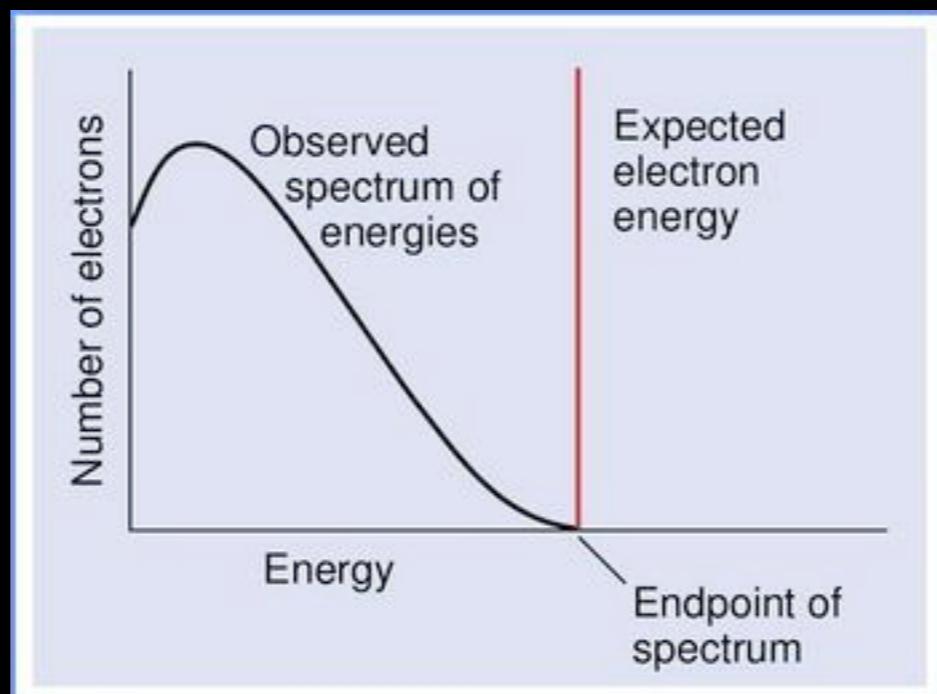
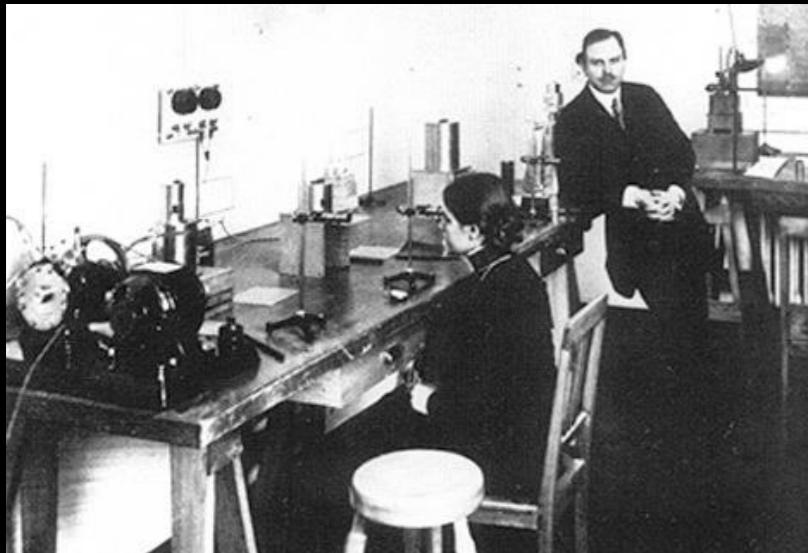
Pauli: 1930

β -Decay

- β - decay of atoms

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Visible: $A_z \rightarrow A_{z+1} + e^-$



- **Violation of energy conservation?**

Pauli: 1930

- Solution: additional very light particle produced in decay

Postulate: $A_z \rightarrow A_{z+1} + e^- + \bar{\nu}$

Neutrino (little neutron)
Direct observation 1956.

Fermi's Theory

- Observation:

- Transformation of matter particles
- Weak force (long lifetimes compared to em decays)
- Short ranged

Fermi: 1934

⇒ **new interaction!** (1934 only gravity & EM known)

Fermi's Theory

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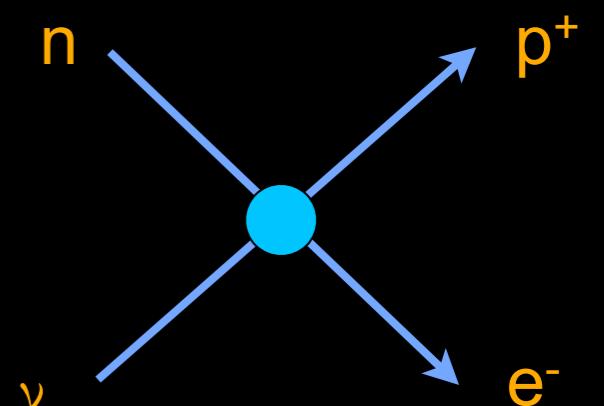
Fermi: 1934

⇒ **new interaction!** (1934 only gravity & EM known)

- Phenomenological interpretation by Enrico Fermi:

- Point-like interaction of 4 particles
- Weak: G_F 10^{-5} relativ to EM interaction
- Analogy: 2 currents of particles: p,n / e, ν

⇒ Calculation of β^- - decays & cross sections possible

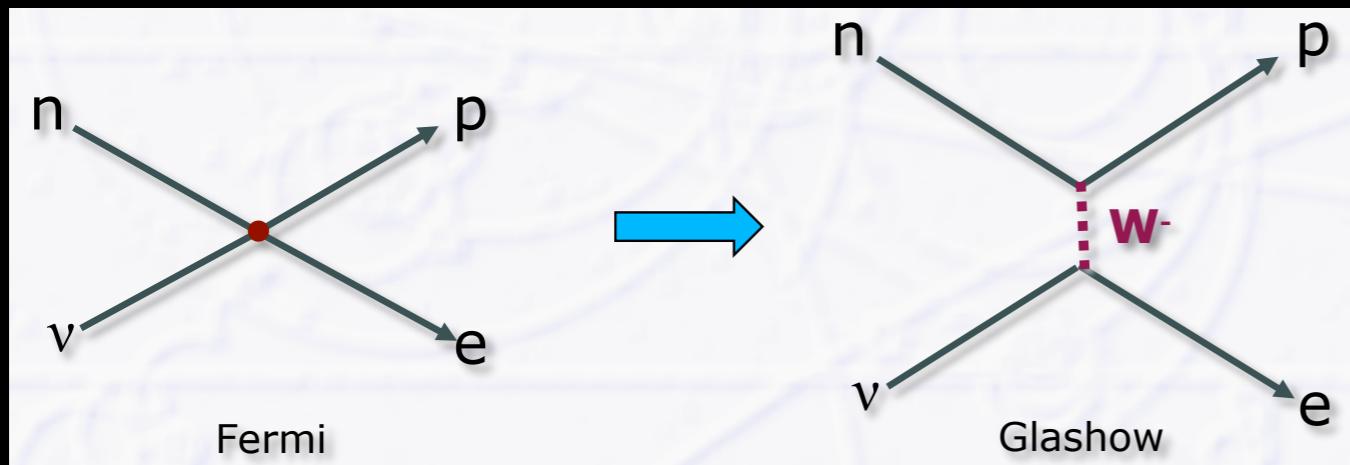


Conservation of Probability

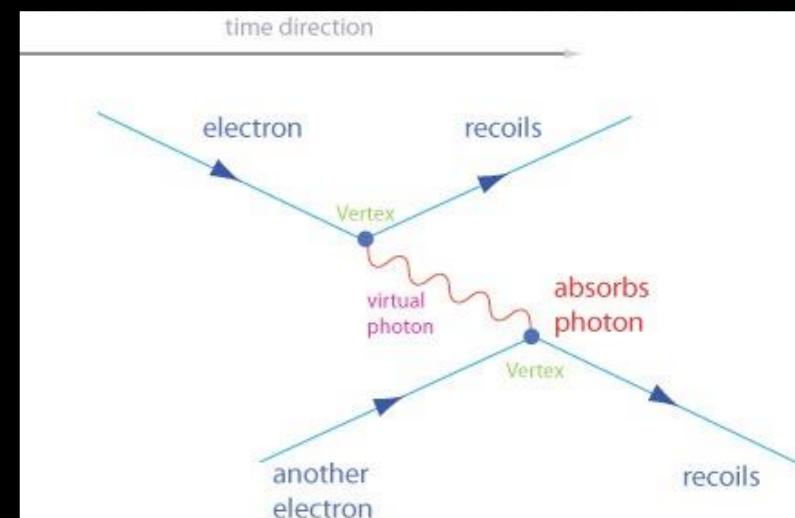
- Huge problem in ~ 1950
 - Cross section for the reaction $p + \nu \sim (G_F E_\nu)$
 - **Violates unitarity** for $E > 300$ GeV (probability > 1)

- A way out:
 - Weak interaction is transmitted via heavy force carriers
 - (Photons already known as exchange particles of em interaction)

Glashow: 1958



Electron scattering



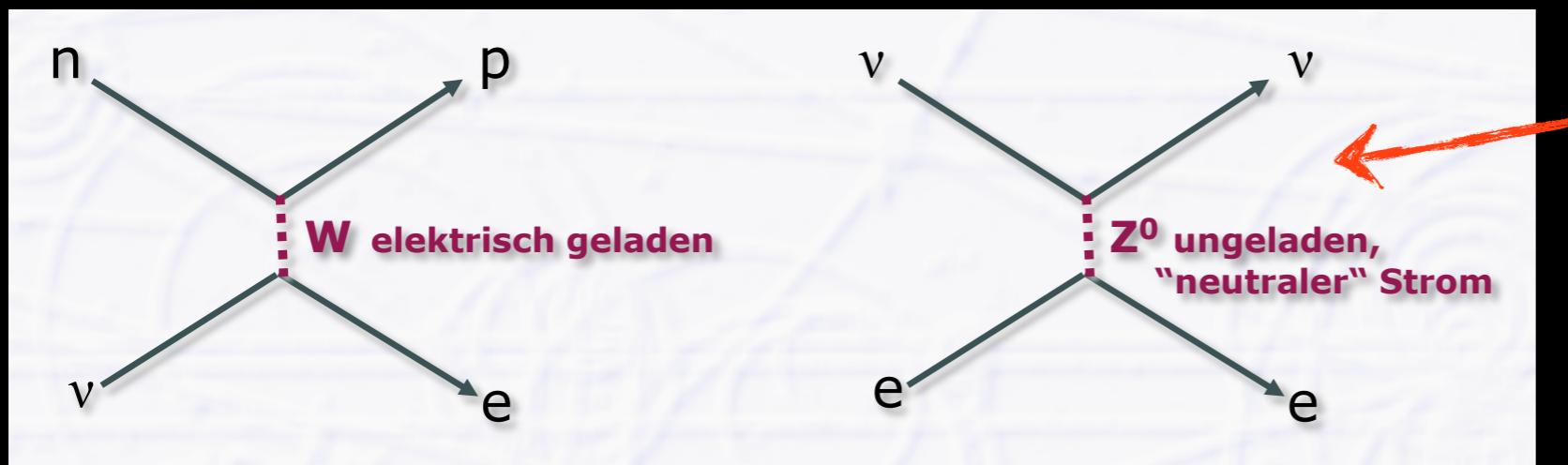
- Large mass of W - particle explains short range ($\sim 10^{-18}$ m) and small cross section of weak interaction

Electroweak Interaction



- Realisation: electromagnetic & weak interactions are manifestations of **same underlying force**
- Unified in **electroweak interaction!**
- New „weak“ charge: carried by quarks & leptons

Glashow, Salam,
Weinberg: 1968

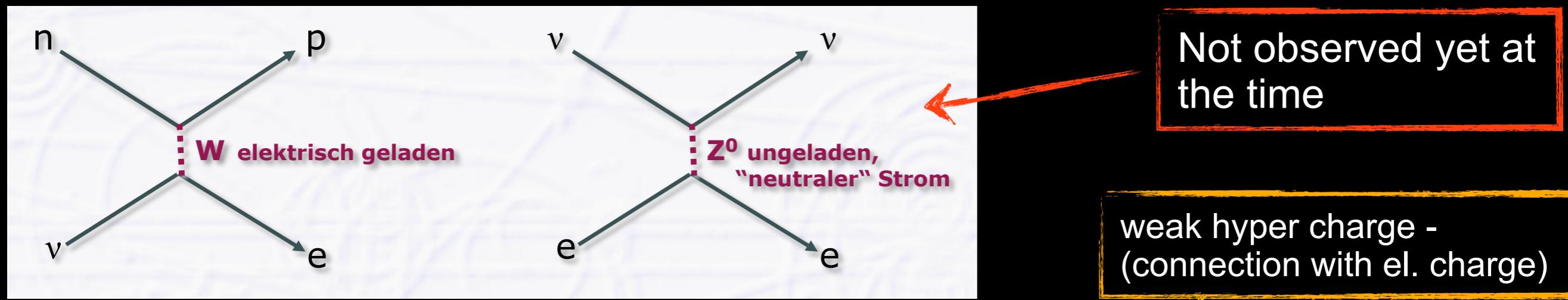


- 2 el. charged exchange particles: W^+ , W^- (massive)
- 2 neutral exchange particles: γ (mass less), Z^0 (massive)

Electroweak Interaction

- Unified in **electroweak** interaction!
 - New „weak“ charge: carried by quarks & leptons

Glashow, Salam,
Weinberg: 1968



- New symmetry belonging to this approach ($SU(2) \times U(1)$)
 - Symmetry only realized at large energies (~ 250 GeV):
 - Same coupling for weak & em. interactions!
 - At low energies:
 - Symmetry „spontaneously“ broken
- W&Z Bosons gain mass via interaction with Higgs field
 - more on that later

weak isospin - connecting e^- & ν (see strong isospin for p,n)

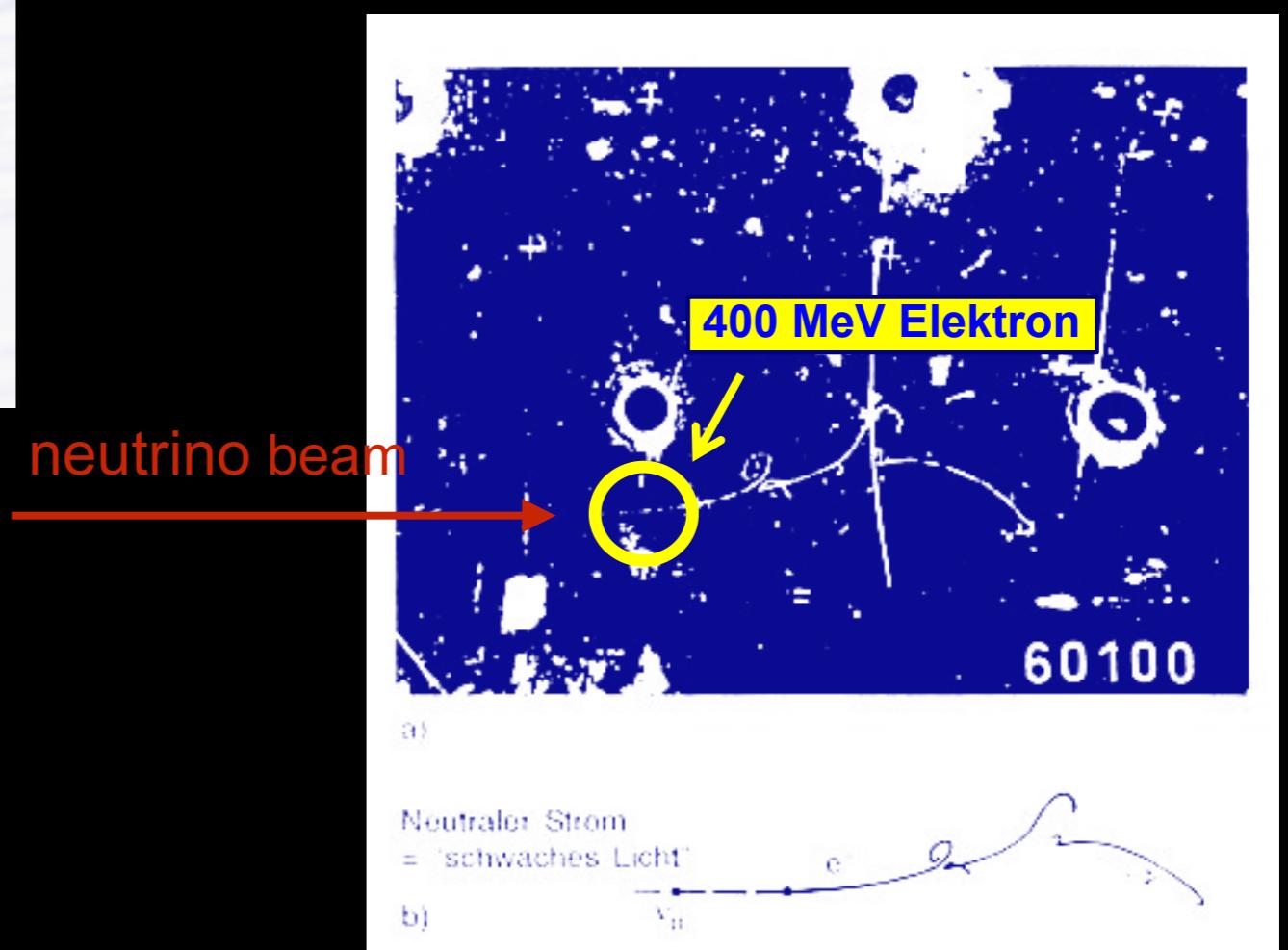
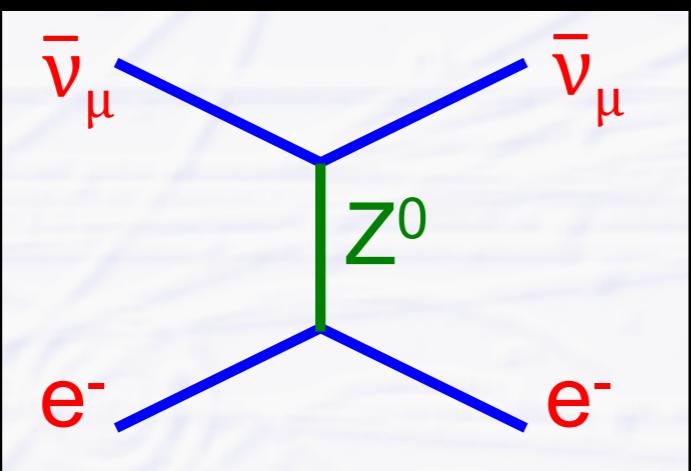
Discovery of neutral currents



- Indirect observation of Z^0

CERN: 1973

- Elastic scattering of neutrino on electron from atomic shell



Experimental Discovery of W & Z Bosons



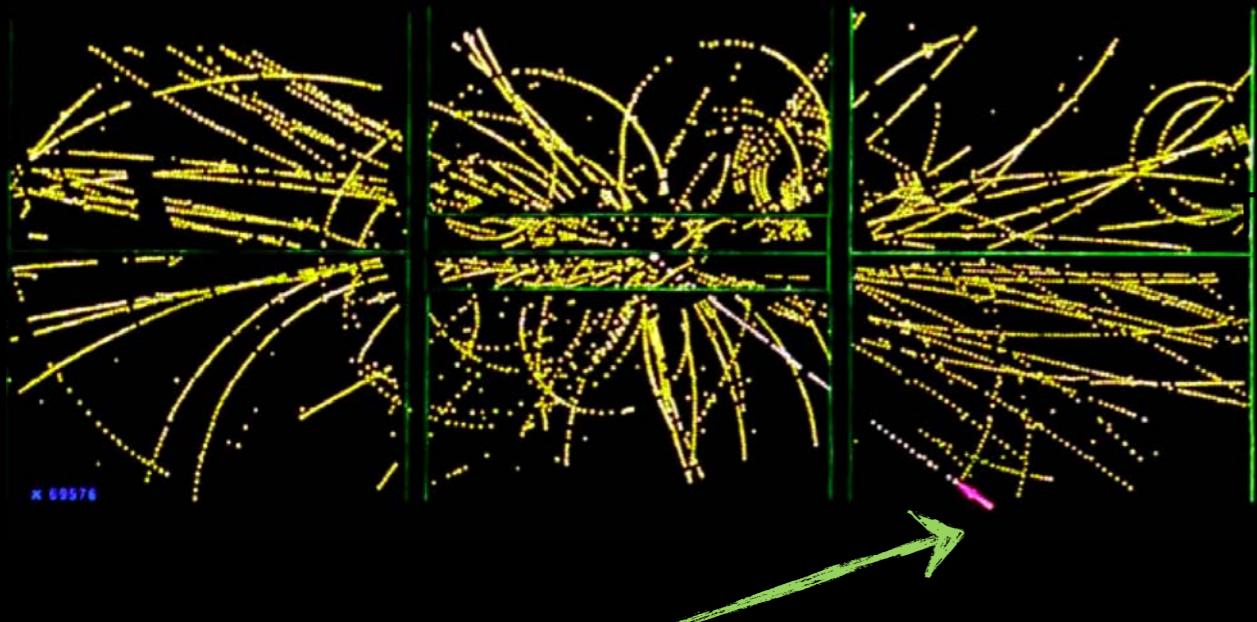
- SPS Accelerator in collision mode:

CERN: 1983

- Proton - anti-proton collision ($p\bar{p}$ S)

- Experimente UA1 & UA2

$$p\bar{p} \rightarrow W_- + X \rightarrow e^- \bar{\nu}_e + X$$



High energy electron



Rubio, van der Meer

Experimental Discovery of W & Z Bosons



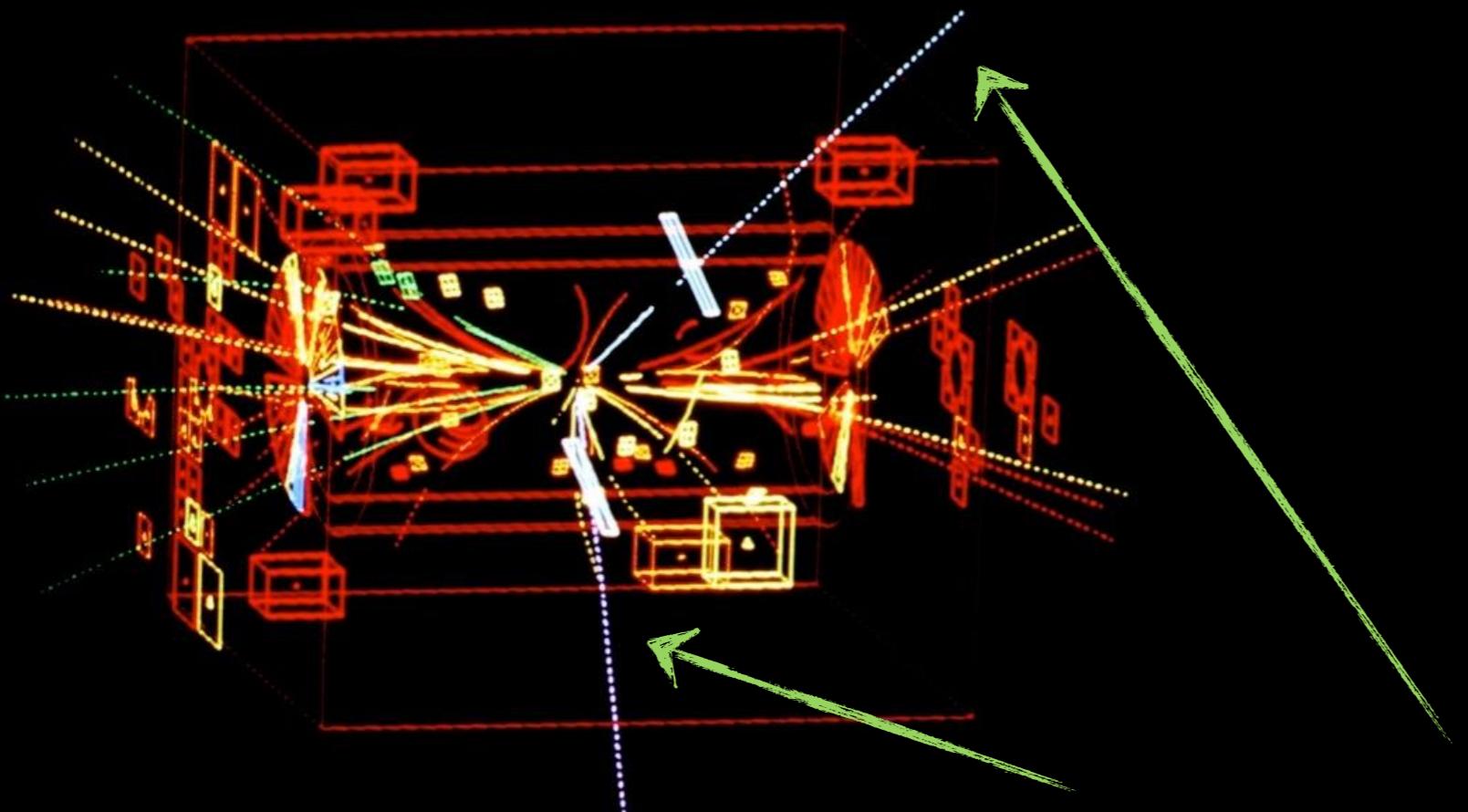
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High energy electrons

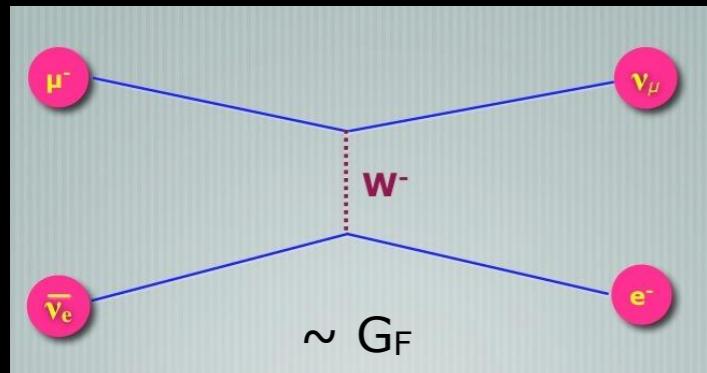


Rubio, van der Meer

Electroweak theory

- Quarks: u, d, s
- Weak interactions

Muon decay

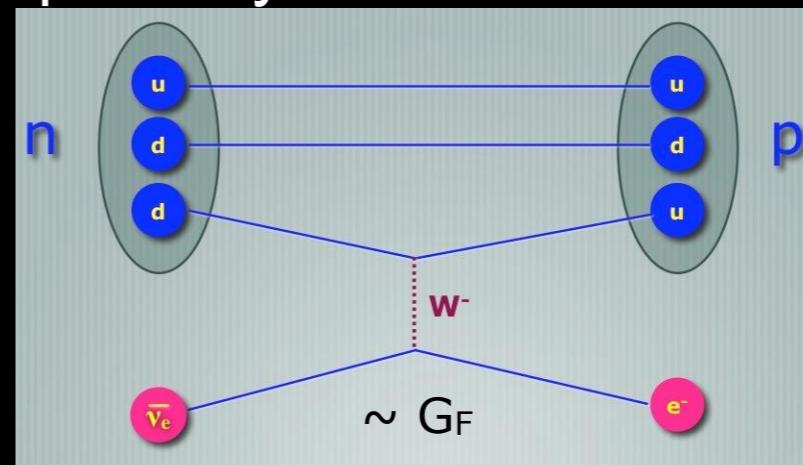


- Leptons: $\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$



weak isospin 1/2 doublets!

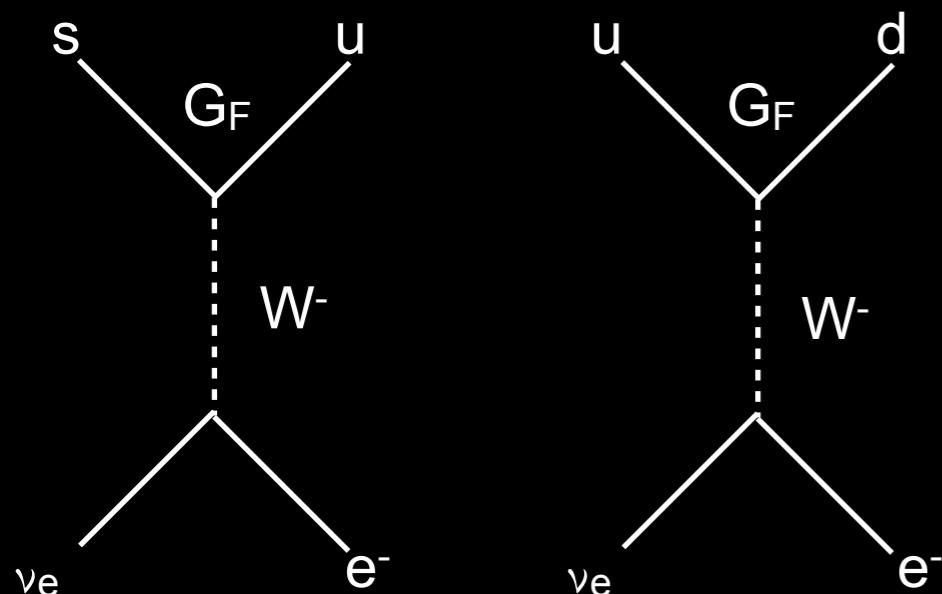
β -decay



- Coupling strength should be **identical**: same weak charge for quarks & leptons
- measured to be slightly different!

Electroweak theory

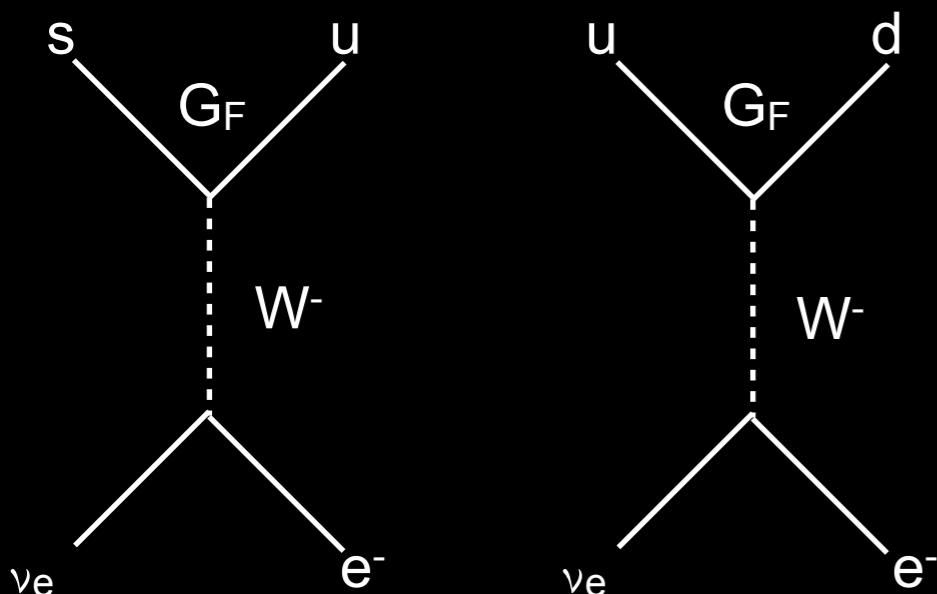
Observation in other particle reactions



Electroweak theory



Observation in other particle reactions

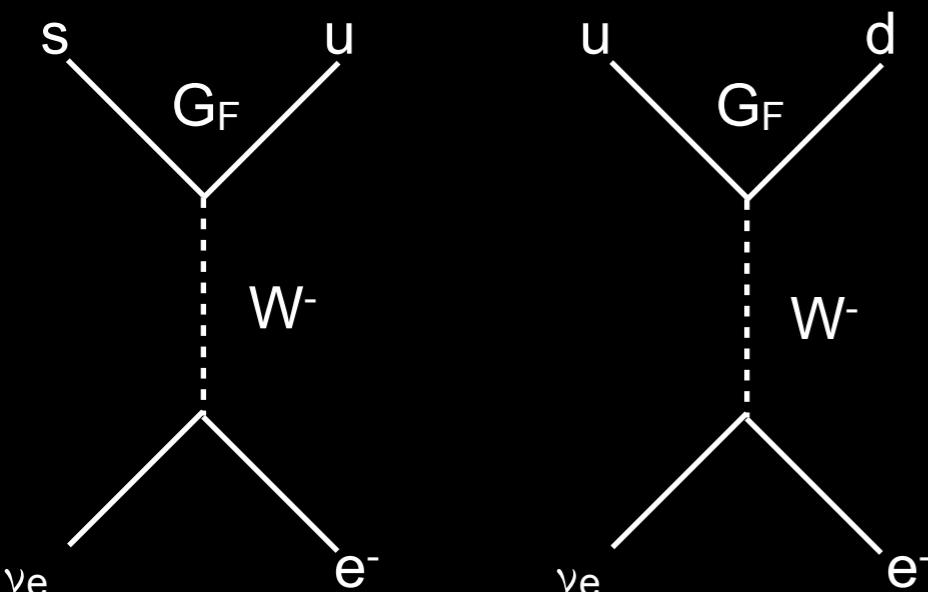


Both reactions should have identical rate!

Electroweak theory



Observation in other particle reactions



Both reactions should have identical rate!

$$\frac{(sdd) \quad (udd)}{(udd) \quad (uud)} \sum^- \rightarrow n + e^- + \bar{\nu}_e \sim 20$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Electroweak theory

- Quarks (u,d,s) are **eigenstates** under the **strong force!**
 - Interact via strong force
- Remember: Particles are waves!
 - Can superimpose, interfere, mix (similar to electric signals!)
- Mix of strong quark eigenstates takes part in weak interaction

Eigenstates of strong force != Eigenstates under weak force

Cabibbo: 1963
(5 Jahre nach
Einführung des W
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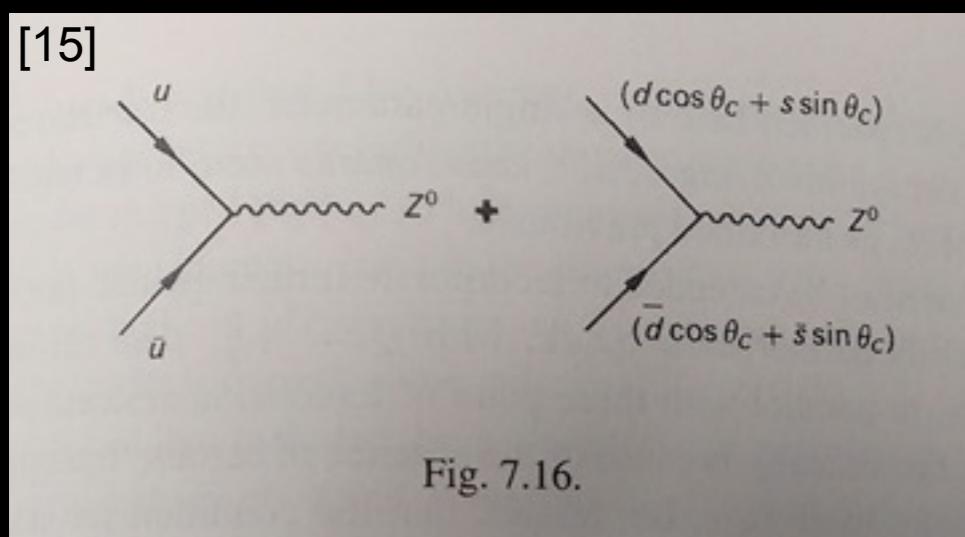
- Base transformation:
$$\begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \end{pmatrix} = \begin{pmatrix} \cos \theta_C |d\rangle + \sin \theta_C |s\rangle \\ -\sin \theta_C |d\rangle + \cos \theta_C |s\rangle \end{pmatrix}$$
- Eigenstates of weak interaction
 - weak isospin doublets
- Quarks:
$$\begin{pmatrix} |u\rangle \\ \cos \theta_C |d\rangle + \sin \theta_C |s\rangle \end{pmatrix} (-\sin \theta_C |d\rangle + \cos \theta_C |s\rangle)$$
- Leptons:
$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$$

This solves previous mystery!

Further measurements - further surprises ...

- Neutral currents (Z^0 exchange) - no flavor change observed!

$$\frac{(u\bar{s})}{(u\bar{s})} \frac{K^+ \rightarrow \pi^+ + \nu + \bar{\nu}}{(u\bar{u})} \leq 10^{-5}$$



[15]

$$\underbrace{\bar{u}\bar{u} + (\bar{d}\bar{d} \cos^2 \theta_c + \bar{s}\bar{s} \sin^2 \theta_c)}_{\Delta S = 0} + \underbrace{(\bar{s}\bar{d} + \bar{d}\bar{s}) \sin \theta_c \cos \theta_c}_{\Delta S = 1}$$

„Flavor“ change:
not observed!

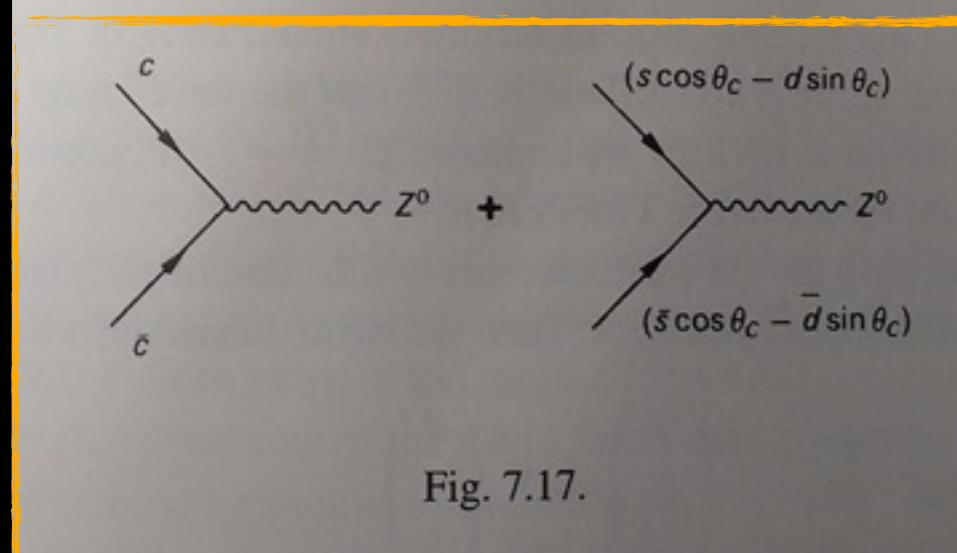
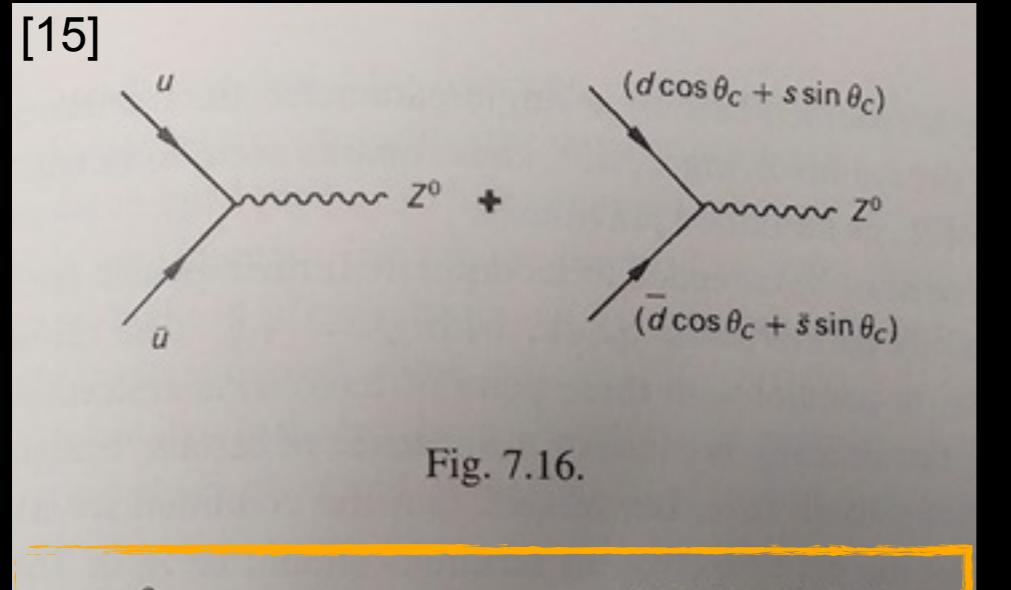
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Glashow, Iliopoulos,
Maiani: 1970

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→ GIM mechanism



New particle: „charm“ quark

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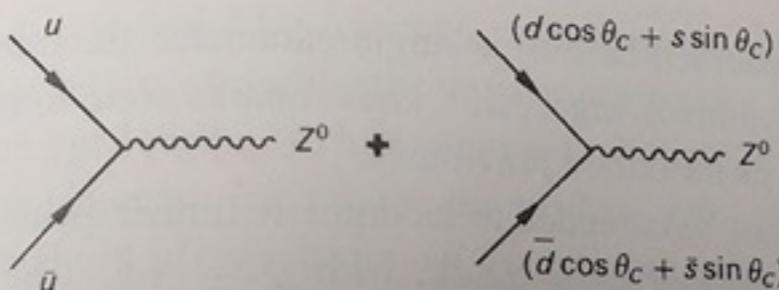


Fig. 7.16.

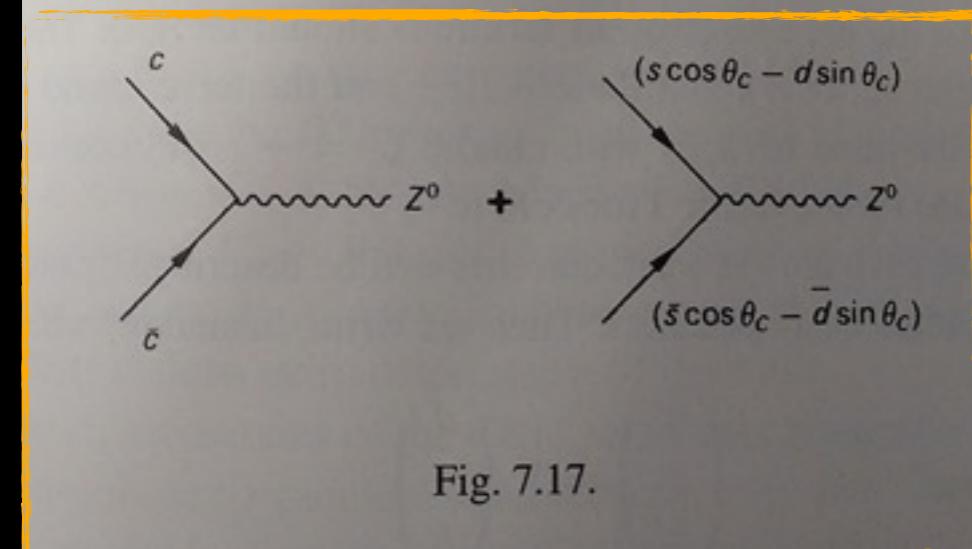


Fig. 7.17.

New particle: „charm“ quark

[15]

$$\underbrace{u\bar{u} + c\bar{c} + (d\bar{d} + s\bar{s}) \cos^2 \theta_c + (s\bar{s} + d\bar{d}) \sin^2 \theta_c}_{\Delta S = 0}$$

$$+(s\bar{d} + \bar{s}d - \bar{s}d - s\bar{d}) \sin \theta_c \cos \theta_c$$

$$\Delta S = 1$$

„Flavor“ change: = 0

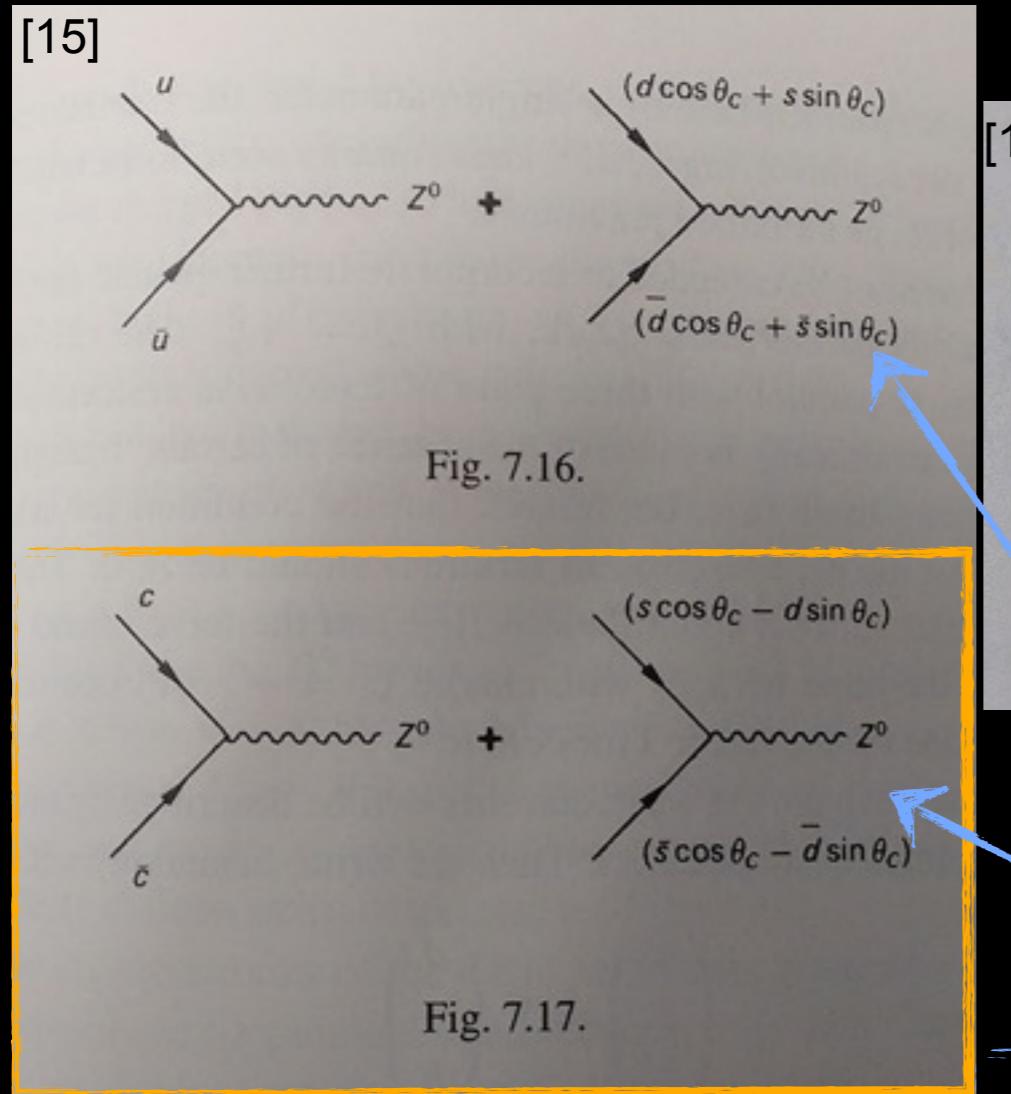
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„Flavor“ change: = 0

Quantum mechanical: interference of diagrams

Further measurements - further surprises ...

weak eigenstates

$$\left(\begin{array}{c} |u\rangle \\ \cos\theta_C|d\rangle + \sin\theta_C|s\rangle \end{array} \right) \left(\begin{array}{c} |c\rangle \\ -\sin\theta_C|d\rangle + \cos\theta_C|s\rangle \end{array} \right)$$

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Rotation in 'flavor' space

New particle: „charm“ quark

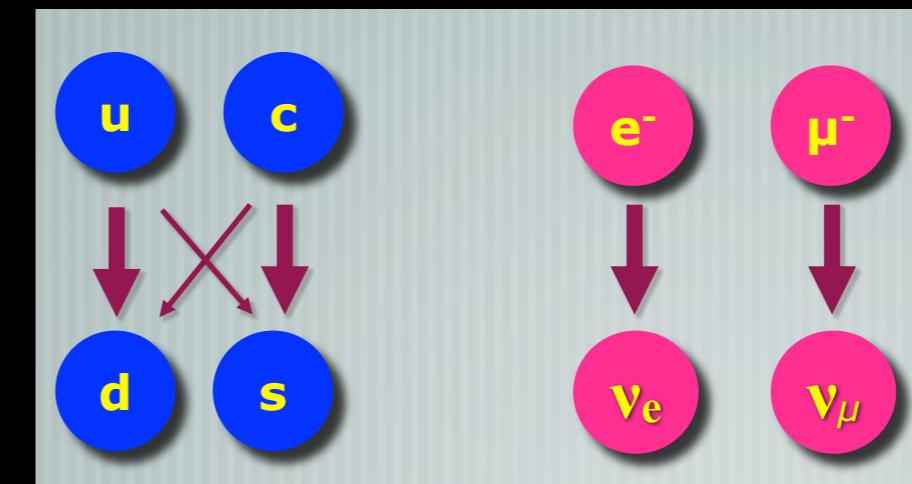
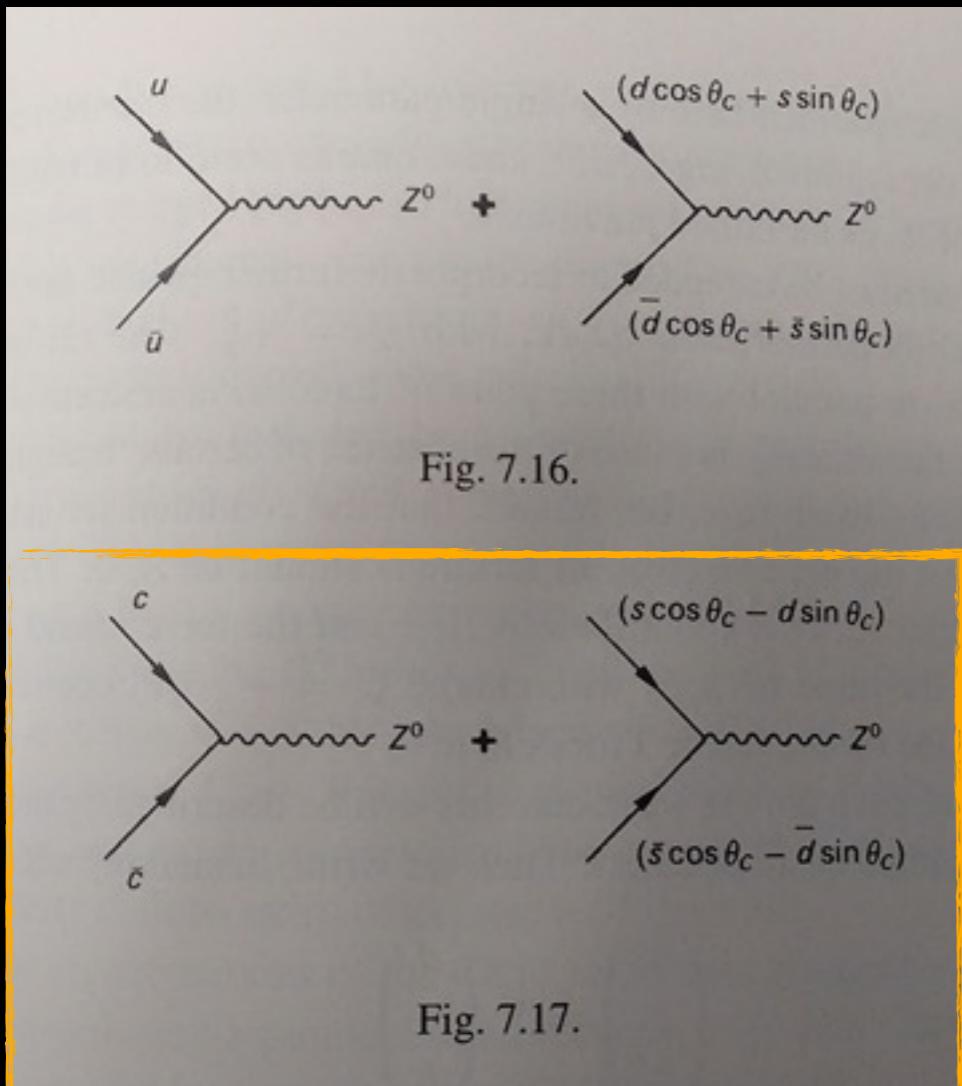


Fig. 7.17.

Further measurements - further surprises ...

weak eigenstates

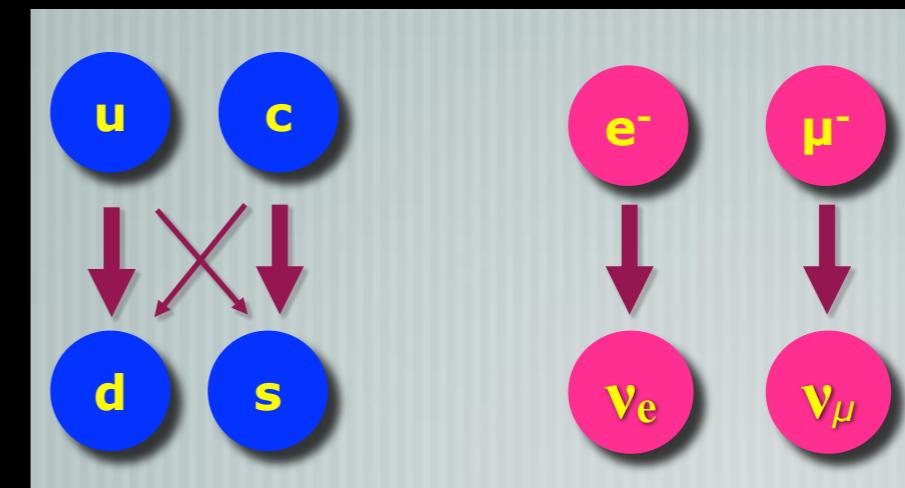
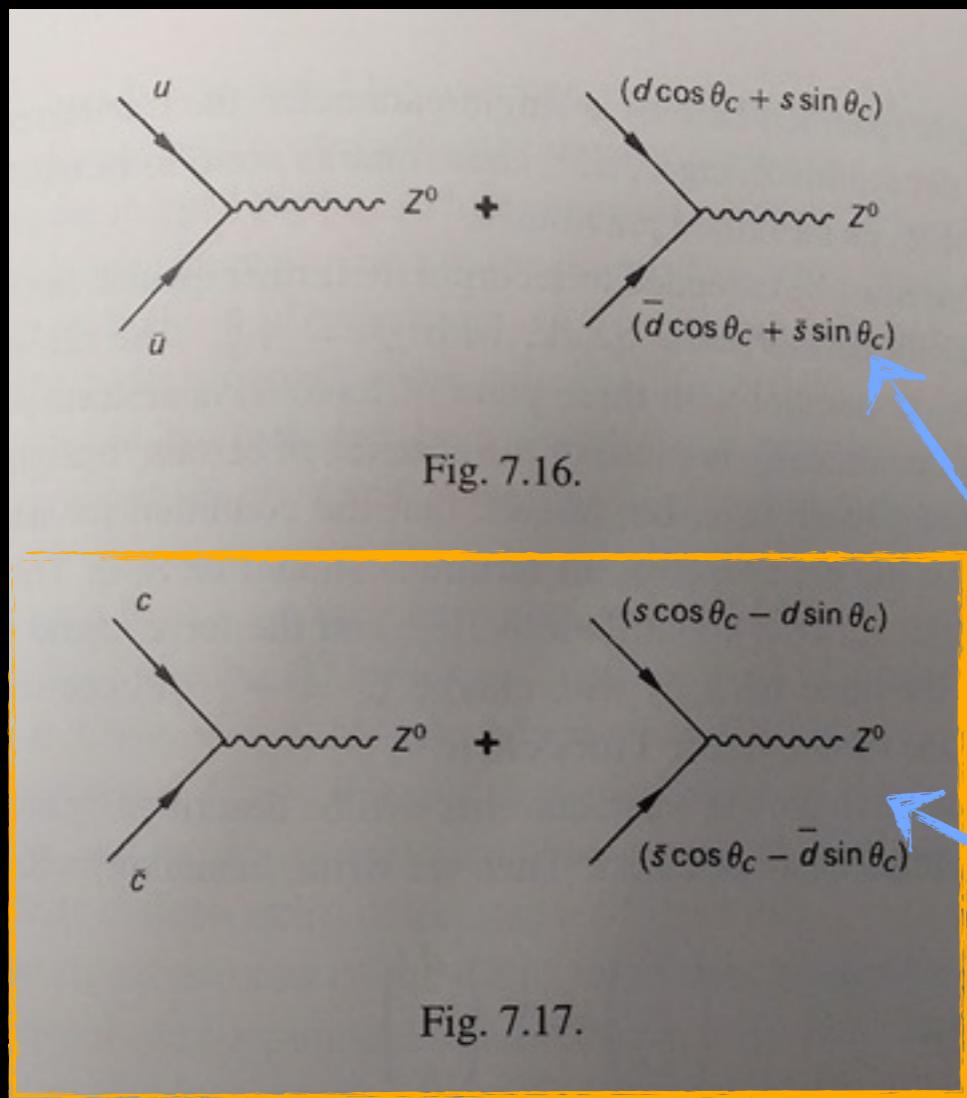
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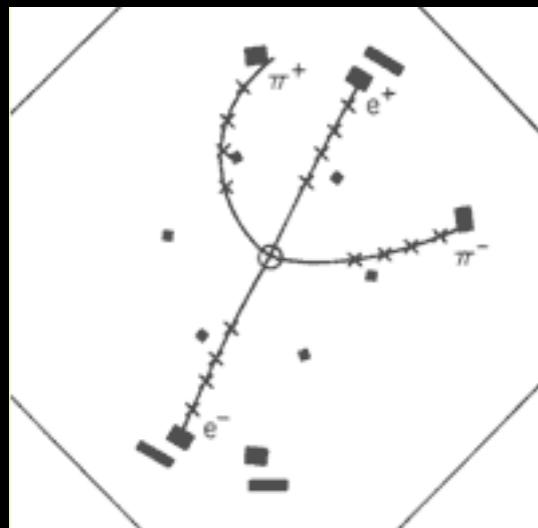
Quantum mechanical: interference of diagrams

Discovery of the charm quark

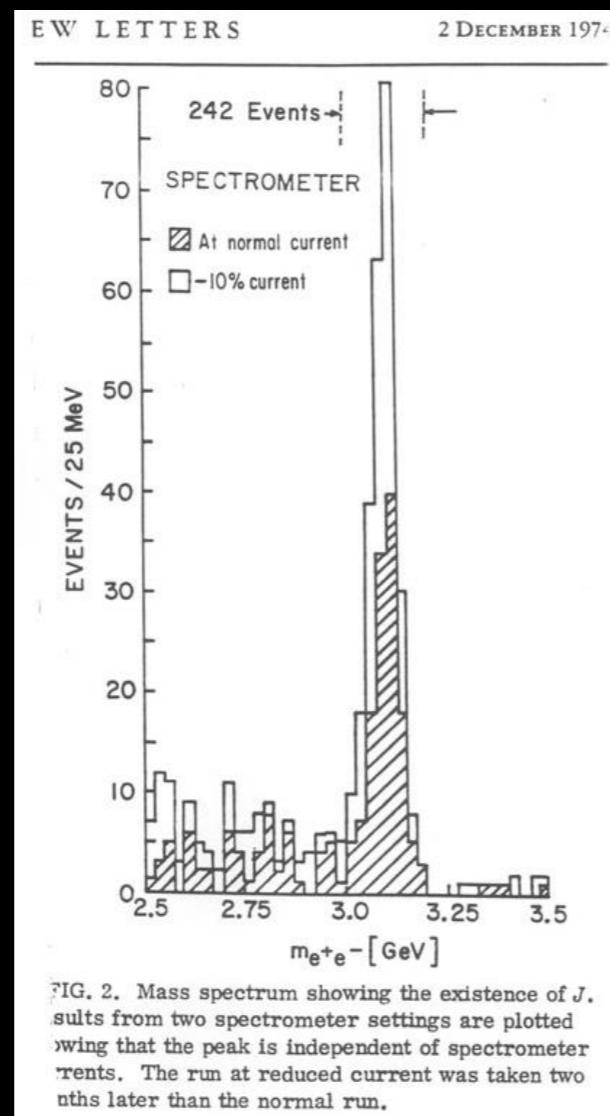
- Dedicated experiments
 - Simultaneously found by 2 independent groups

Richter (Slac) &
Ting (Brookhaven):
November 1974

Richter: Ψ



Ting: J



Particle labeled J/Ψ !

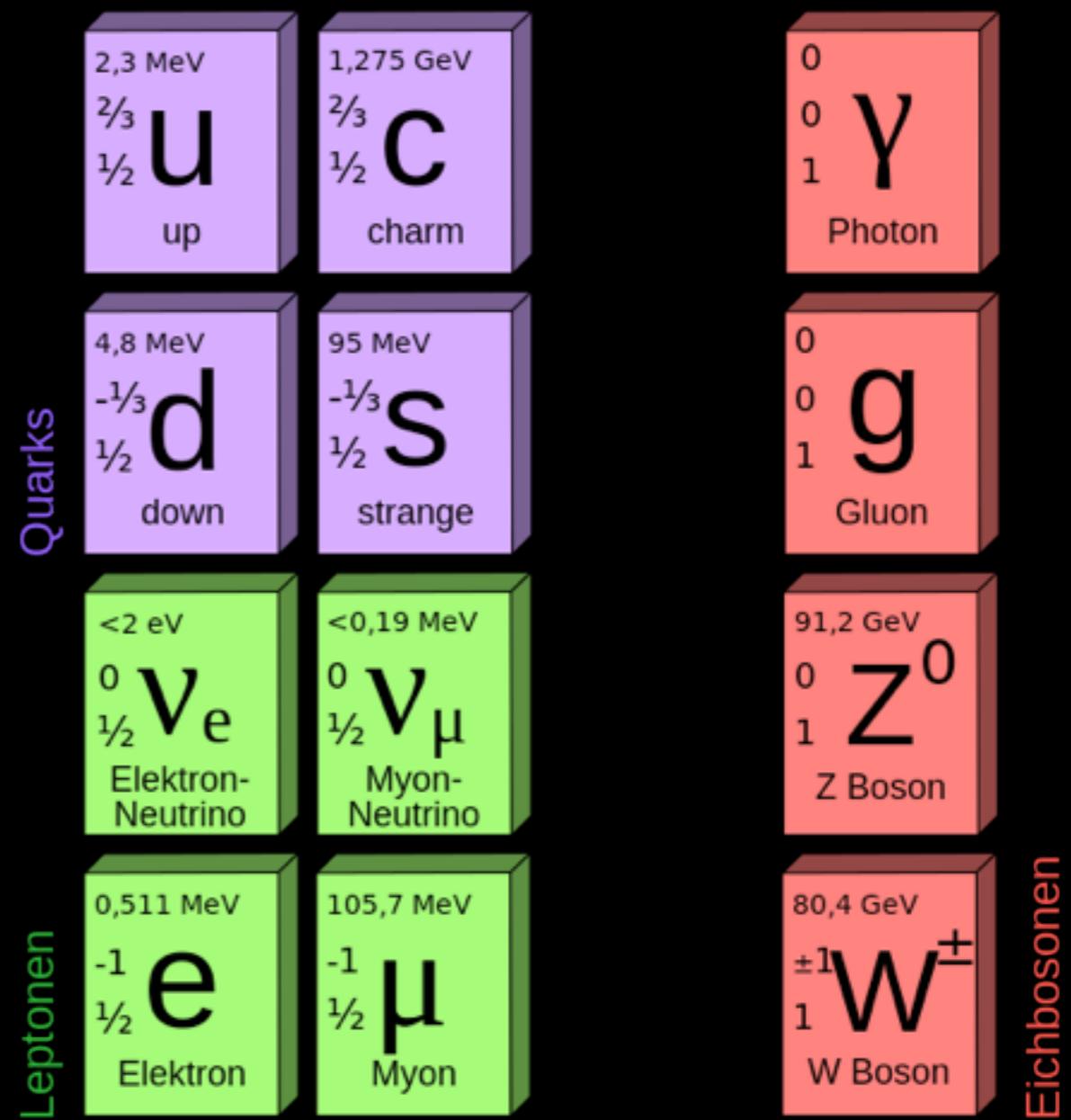
- Bound state of charm & anti-charm quarks
- Decay exclusively via weak interaction
- long lived! (10^{-20} sec)
- => narrow resonance (mass peak)

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Quarks	2,3 MeV $\frac{2}{3}$ $\frac{1}{2}$ U up	1,275 GeV $\frac{2}{3}$ $\frac{1}{2}$ C charm	0 0 1 Y Photon
	4,8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	95 MeV $-\frac{1}{3}$ $\frac{1}{2}$ S strange	0 0 1 g Gluon
Leptonen	<2 eV 0 $\frac{1}{2}$ V_e Elektron-Neutrino	<0,19 MeV 0 $\frac{1}{2}$ V_μ Myon-Neutrino	91,2 GeV 0 1 Z⁰ Z Boson
	0,511 MeV -1 $\frac{1}{2}$ e Elektron	105,7 MeV -1 $\frac{1}{2}$ μ Myon	80,4 GeV ± 1 1 W⁺ W Boson
Eichbosonen			

Doublets under weak interaction

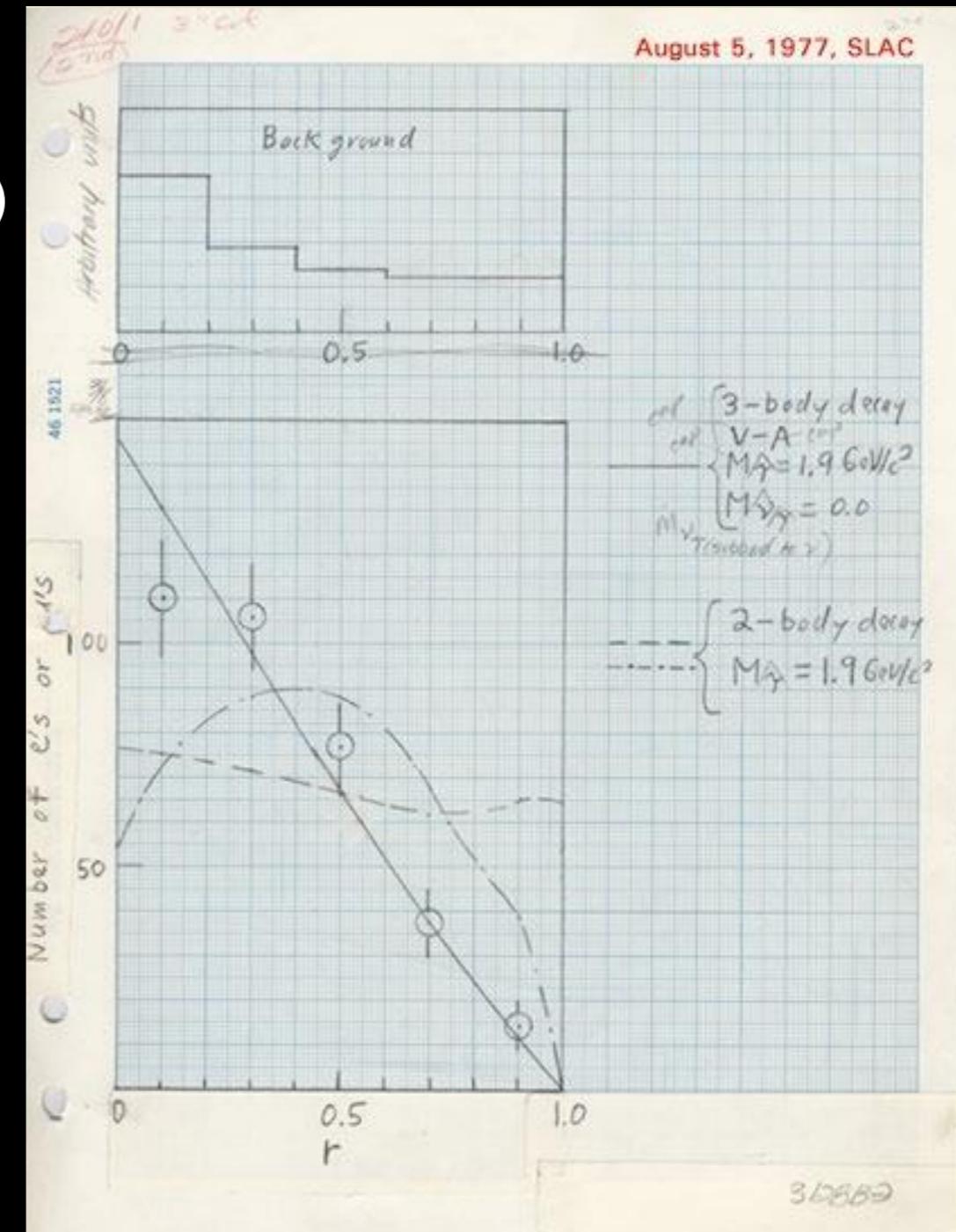
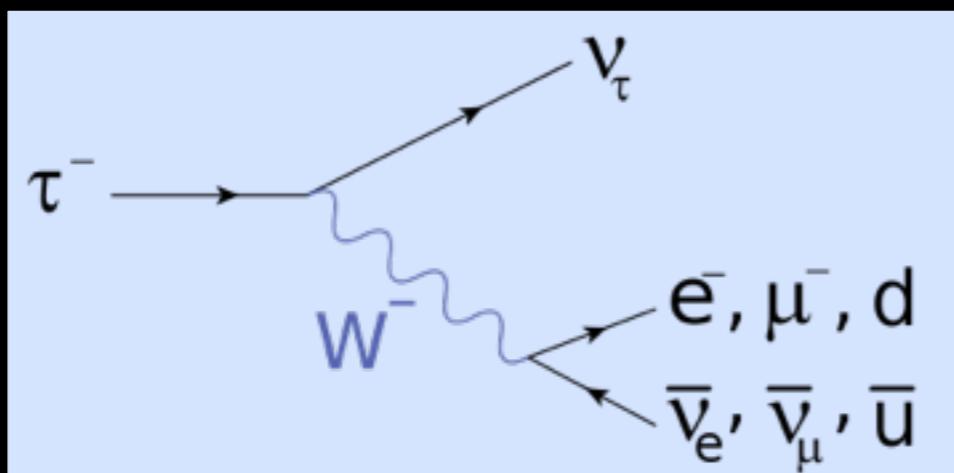
What else?

- Discovery of a 3rd lepton

SLAC: 1975

- Called tauon: τ
- Yet another, heavy copy of electron ($3500 m_e$)

- Requires existence of another neutrino
- As well as 2 additional quarks



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	1.	2.	3.	generation
Quarks	2,3 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1,275 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	173,07 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 Photon
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Eichbosonen				

Bottom & Top discovered @ Fermilab
 1977 1995

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Doublets under weak interaction

Bottom & Top discovered @ Fermilab
1977 1995

3 Generations ...



- Weak interaction: Base transformation by 3x3 matrix

Cabibbo, Kobayashi, Maskawa:
(Nobelpreis 2008)

- Transitions within & between generations

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

Diagram illustrating CKM matrix elements and their connections to various particle transitions:

- V_{ud} : e.g. $n \rightarrow p \bar{e} v$
- V_{cd} : e.g. $D \rightarrow \pi \ell \nu$
- V_{td} : e.g. $K_L \rightarrow \pi \ell \nu$
- V_{us} : e.g. $B \rightarrow D \ell \nu$
- V_{cs} : e.g. $B \rightarrow \pi \ell \nu$
- V_{ts} : e.g. BB oscillations
- V_{ub} : e.g. $B \rightarrow K \ell \nu$
- V_{cb} : e.g. $B \rightarrow D \ell \nu$
- V_{tb} : e.g. $t \rightarrow W b$

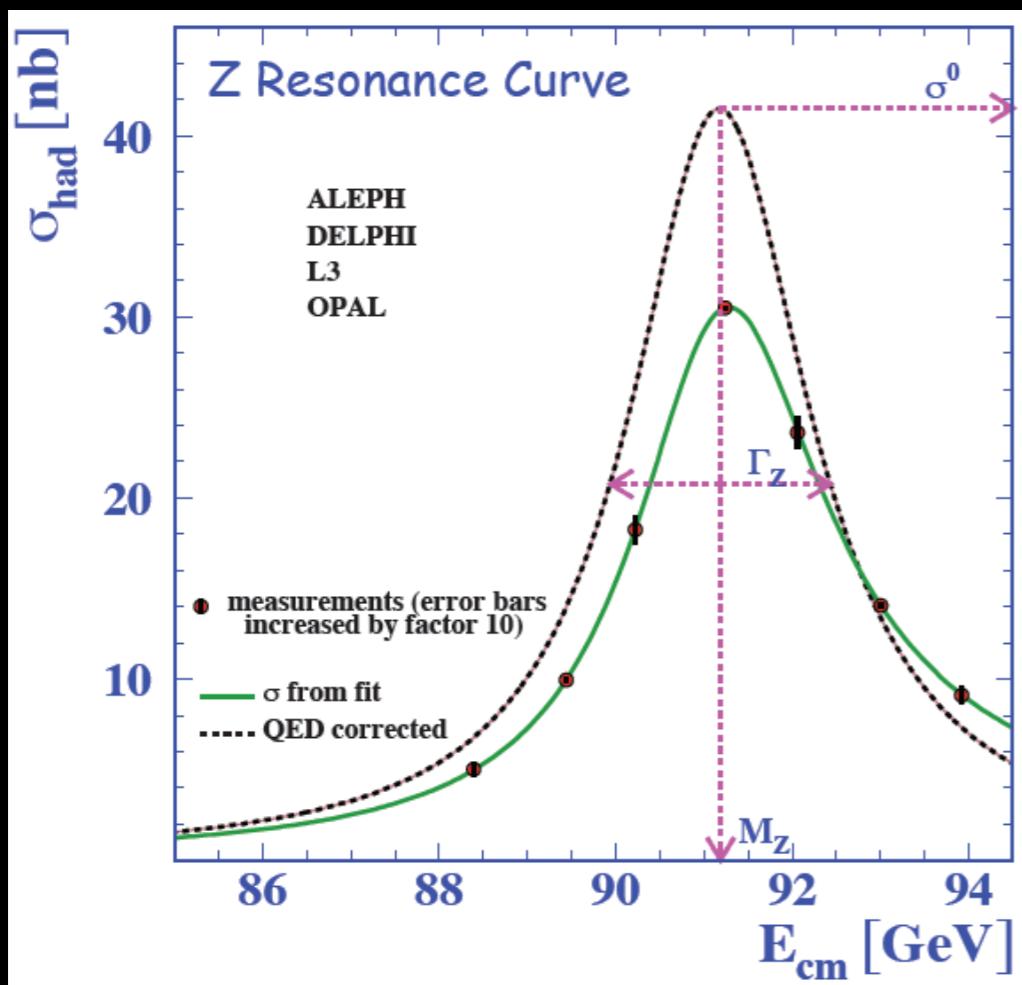
- Free parameters: 3 angles + 1 complex phase
- Essential to explain 'CP' violation:
 - CP violation: physic laws can distinguish between matter & anti-matter!
 - Requires at least 3 generations
 - Initial trigger to postulate a 3rd generation

Are there more than 3 generations

- Study of Z boson in detail:

Mass distribution: Breit-Wigner curve
 → harmonic oscillator

Measured in reaction: $e^+ e^- \rightarrow Z \rightarrow e^+ e^-$



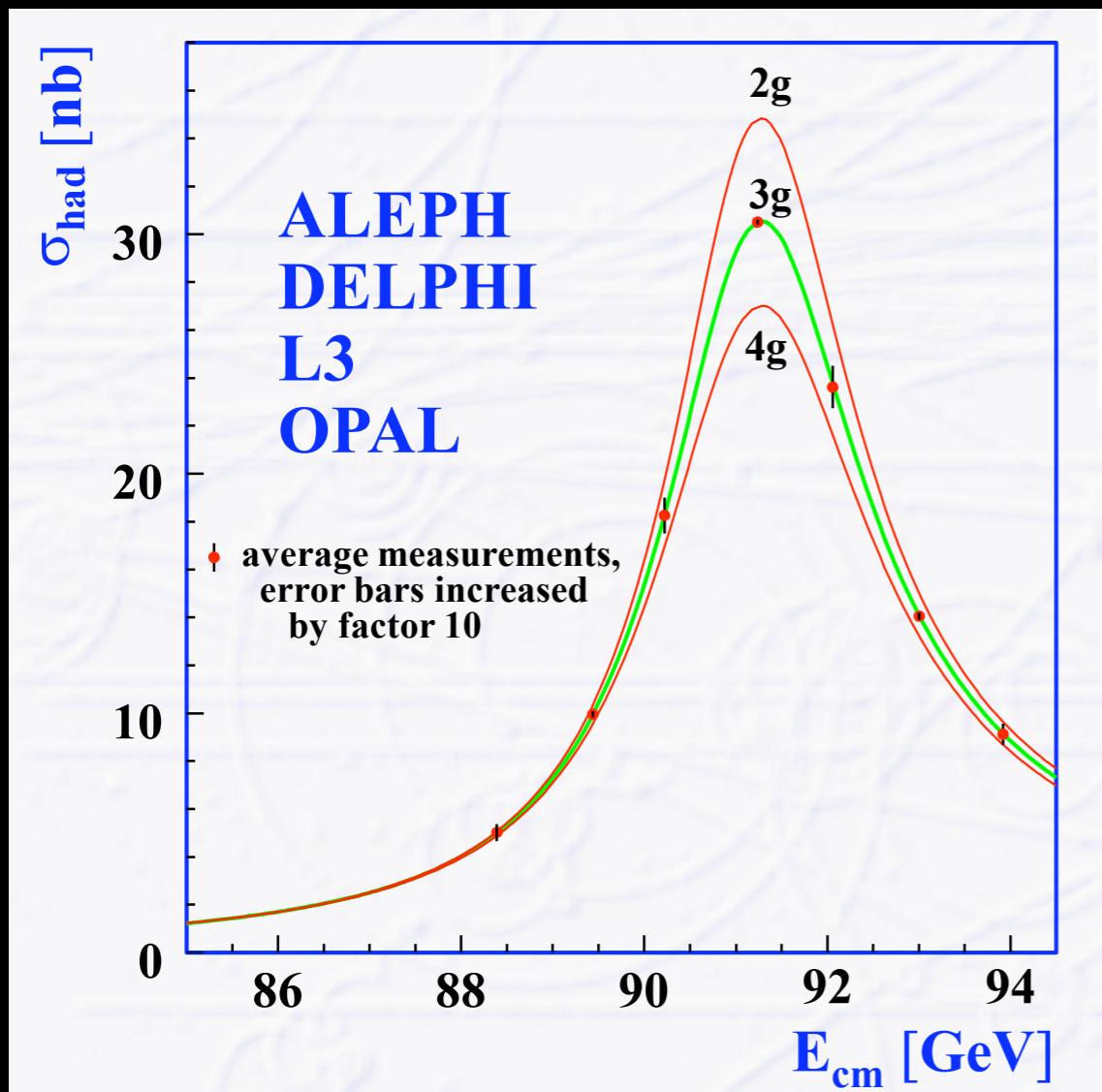
Exact shape depends on

- Vacuum fluctuations
- Radiation of photons
- Virtual photons between electrons

Gibt es mehr als 3 Familien? - Nein

- Untersuchung des Z-Teilchens im Detail:

Measured in reaction: $e^+ e^- \rightarrow Z \rightarrow e^+ e^-$



Exact shape depends on

- Vacuum fluctuations
- Radiation of photons
- Virtual photons between electrons
- Number of **light** neutrino flavours
 - Width depends on accessible decay channels

Standard model of particle physics



• Elementary particles

- Constituents of matter
 - Fermions ($S=1/2$)
- Force carries
 - Bosons ($S=1$)

1. 2. 3. generation

Quarks	2,3 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1,275 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	173,07 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ Photon	125,9 GeV 0 0 H Higgs Boson
	4,8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	95 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4,18 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g Gluon	
	<2 eV 0 $\frac{1}{2}$ νe Elektron-Neutrino	<0,19 MeV 0 $\frac{1}{2}$ νμ Myon-Neutrino	<18,2 MeV 0 $\frac{1}{2}$ ντ Tau-Neutrino	91,2 GeV 0 1 Z⁰ Z Boson	
Leptonen	0,511 MeV -1 $\frac{1}{2}$ e Elektron	105,7 MeV -1 $\frac{1}{2}$ μ Myon	1,777 GeV -1 $\frac{1}{2}$ τ Tau	80,4 GeV ± 1 W⁺ W Boson	Eichbosonen

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Doublets under weak interaction

Quarks

Leptonen

Questions?

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Frage - haben Bosonen Anti-Teilchen?

- Ja
- Allgemein: Teilchen die keine Ladung haben sind ihre eigenen Anti-teilchen
 - Ladungen: Elektrisch, Schwach, Farbe

Frage - haben Bosonen Anti-Teilchen?

- Ja
- Allgemein: Teilchen die keine Ladung haben sind ihre eigenen Anti-teilchen
- Ladungen: Elektrisch, Schwach, Farbe
 - $W^+ W^-$ sind Anti-Teilchen zueinander
 - Z^0 & Photon sind ihre Eigenen Anti-Teilchen
 - Vektor-Boson-Fusion: $W^+ + W^- \rightarrow Z^0$; $Z^0 + Z^0 \rightarrow H$
 - Gluonen besitzen Farbe & Anti-Farbe: Teilchen-Antiteilchen Paare
- Bosonen gehorchen Bose-Statistik:
 - können einzeln erzeugt und Vernichtet werden!
- Fermionen gehorchen Fermi-Statistik
 - können nur Paarweise erzeugt / Vernichtet Werden
 - Leptonzahl / Baryonzahl Erhaltung

Victor Hess

1912

- Beobachtungen der „durchdringenden Strahlung“ in Abhangigkeit der Hohe bei Ballonfahrten
- Instrument: „Wulfscher Strahlungsapparat“
 - Ionisationskammer mit elektrostatischer Auslese => Ionen / Volumen / Zeit
- Zunahme der Ionisationsrate bei groen Hohen (>3000m)
- Erklarung: Naturliche Strahlung hat 3 Komponenten:
 - Radioaktive Zerfalle in der Erdkruste
 - Radioaktive Zerfalle in der Atmosphare
 - Quellen auerhalb der Erd (nicht die Sonne)
- Bekannt zu dieser Zeit:
 - α, β, γ Strahlung & Rontgenstrahlung
 - Elektron / Elementarladung / Rutherford-Atommodell
 - (seit 1-2 Jahren) (gerade entwickelt)
- Muon noch unbekannt

Interpretationen der Quanten Theorie

- Praktische Verwendung in der Teilchenphysik: Kopenhagener Deutung
 - Quadrat der Wellenfunktion = Aufenthaltswahrscheinlichkeit
- Messproblem:
 - Jeder Messapparat ist auch ein Quantensystem und interagiert = ändert den Zustand des zu beobachten Quantensystems
 - Widerspruch zwischen deterministischer zeitlicher Systementwicklung und indeterministischen Messergebnissen
 - Kopenhagener Deutung in der Philosophie abgeschrieben
- Heutige Interpretationen:
 - Viele-WeltenTheorie:
 - Alle möglichen Messausgänge sind realisiert in parallelen Welten
 - De-Broglie-Bohm-Theorie (bohmische Mechanik):
 - Teilchenzustand beschrieben durch exakten Ort & Wellenfunktion. In orthodoxer QM ist Position verborgene Variable
 - Dynamik ist deterministisch
 - Anfangszustand nicht exakt bestimmbar => Indeterministischer Charakter von Quantenphänomenen
 - Mathematisch weit ausgearbeitet

Intermezzo: Quantisierung der elektrischen Ladung



- Standard Modell der Teilchenphysik:
 - Quantisierung der elektrischen Ladung rein phänomenologisch! Keine theoretische Motivation
 - Summe aller Ladungen innerhalb einer Familie muss 0 ergeben:
 - $3_{\text{color}} * (Q_{\text{up}} + Q_{\text{down}}) + Q_e + Q_v = 0$
- Sprachgebrauch:
 - Quantum der elektrischen Ladung: 1/3 (wobei auch 1 gebräuchlich ist, je nach Kontext)
 - 1/3 tritt nur in gebundenen Systemen auf, niemals als freies Teilchen
 - Elementarladung = Ladung des Elektrons bzw. Protons
- Theoretische Seite
 - Im SM der Teilchenphysik:
 - Stake und schwache Kraft beschrieben durch Symmetriegruppen SU(3) bzw. SU(2)
 - Nur diskrete Ladungen erlaubt! (\rightarrow Quantisierung zwingend in Theorie)
 - Hyperladung beschrieben durch abelsche U(1) Gruppe
 - Beliebige Ladungen erlaubt!
 - Ausweg: Große vereinheitlichte Theorien (GUT)
 - Hyperladung eingebettet in größere Symmetrie \rightarrow natürliche Quantisierung