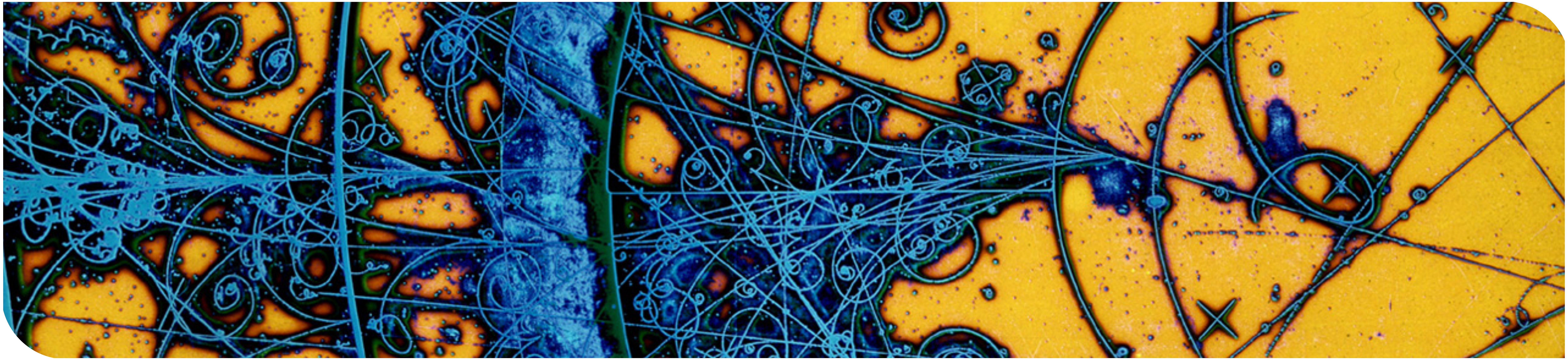
Karlsruhe Institute of Technology

Particle Physics 1
Lecture 2: History

Prof. Dr. Torben FERBER (torben.ferber@kit.edu, he/him), Institute of Experimental Particle Physics (ETP)
Winter 2023/2024


Credit: CERN

Open questions

- L=1ab^{-1}, σ=0.92fb → How many events?
  - $1\,\mathrm{ab}^{-1} = \frac{1}{1\,\mathrm{ab}} = \frac{1}{10^{-18}\,\mathrm{b}} = 10^{18}\,\mathrm{b}^{-1}$
  - $0.92\,\mathrm{fb} = 0.92 \times 10^{-9}\,\mathrm{b}$
  - $N = 10^{18}\,\mathrm{b}^{-1} \cdot 0.92 \times 10^{-9}\,\mathrm{b} \approx 10^{9}$

Open questions: Pseudorapidity and rapidity

$$1 + \frac{p_z}{p} = 1 + \cos\theta = 1 + \left(\cos^2\frac{\theta}{2} - \sin^2\frac{\theta}{2}\right) = 2\cos^2\frac{\theta}{2}$$

$$1 - \frac{p_z}{p} = 1 - \cos\theta = 1 - \left(\cos^2\frac{\theta}{2} - \sin^2\frac{\theta}{2}\right) = 2\sin^2\frac{\theta}{2}$$

$$\begin{aligned}
y &= \frac{1}{2}\ln\frac{E + p_z}{E - p_z} \\
&= \frac{1}{2}\ln\frac{\sqrt{p^2 + m^2} + p_z^2}{\sqrt{p^2 + m^2} - p_z^2} \\
&= \frac{1}{2}\ln\frac{p\sqrt{1 + \frac{m^2}{p^2}} + p_z^2}{p\sqrt{1 + \frac{m^2}{p^2}} - p_z^2} \\
&\approx \frac{1}{2}\ln\frac{p + p_z}{p - p_z} = \frac{1}{2}\ln\frac{1 + p_z/p}{1 - p_z/p} \\
&= \frac{1}{2}\ln\frac{\cos^2(\theta/2)}{\sin^2(\theta/2)} = -\ln\tan(\theta/2)
\end{aligned}$$

What do you expect from this lecture?

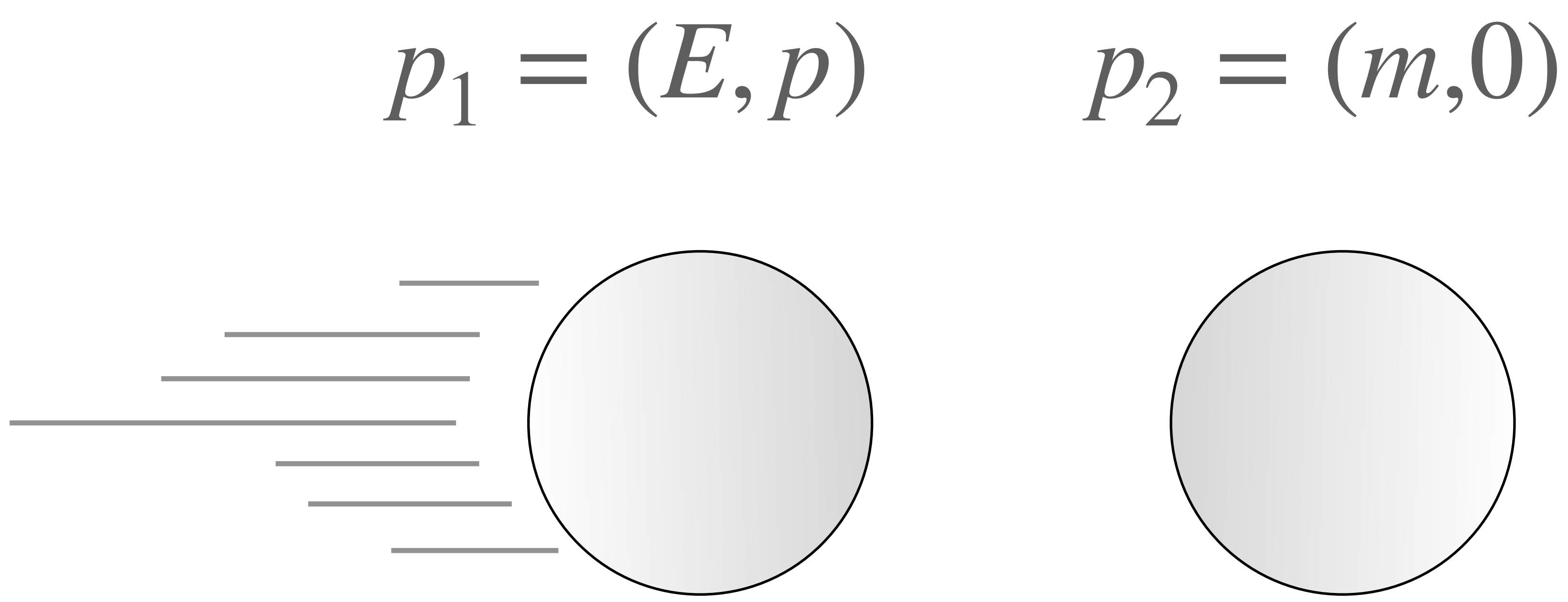
- More details, more information for the Ex6 topics
- Better understanding of the standard model
- Overview about particle physics and state of the art research

- How to analyse and interpret data → *Lecture 5 ("analysis flow") and exercises*
- Details about detectors and accelerators → *Lecture 4 ("detectors") and Lecture 6 ("accelerators")*

- Learn about detector simulation → *Lecture 4 (GEANT4), several exercises*

PINGO: Fixed target collision

- If LHC was a fixed target collider, what would the center of mass energy be if the proton beam has an energy of 7 TeV and the target is a proton at rest?
  - about 14 TeV
  - about 7 TeV
  - about 0.1 TeV



PINGO

- **PINGO:**
  - Umfrage: Teilchenphysik 1 (WS 23/24)
  - Zugangsnummer: 434521
  - Link: https://pingo.coactum.de/events/434521

PINGO: Fixed target collision

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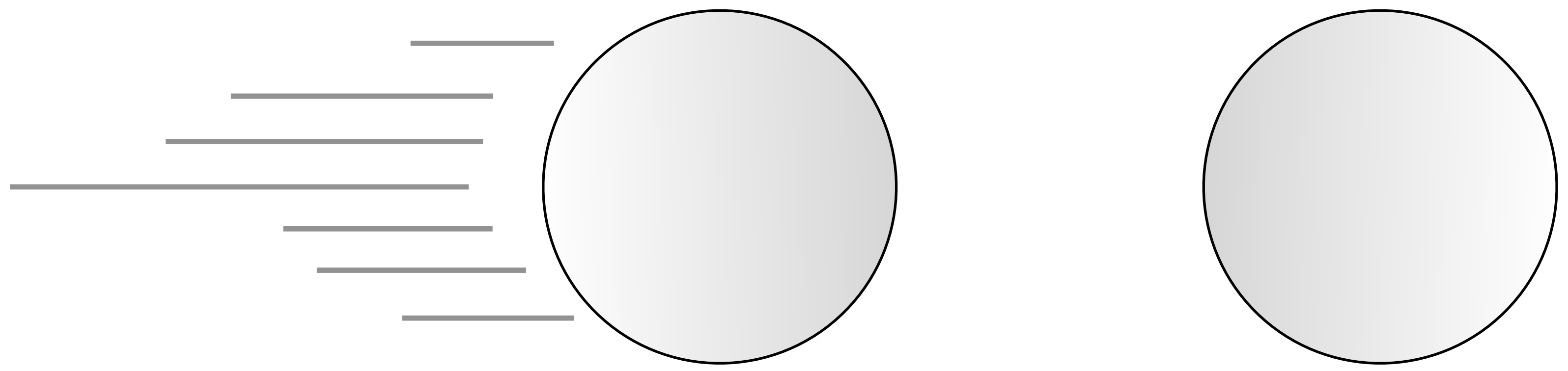
  - about 14 TeV
  - about 7 TeV
  - **about 0.1 TeV**

  (Lecture 1, slide 33)

  Bonus question: Why would you build such a collider anyhow?

$$p_1 = (E, p) \qquad p_2 = (m, 0)$$



$$s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2p_1p_2$$
$$= (E^2 - p^2) + m^2 + 2Em = 2m^2 + 2Em \approx 2Em$$

Learning goals

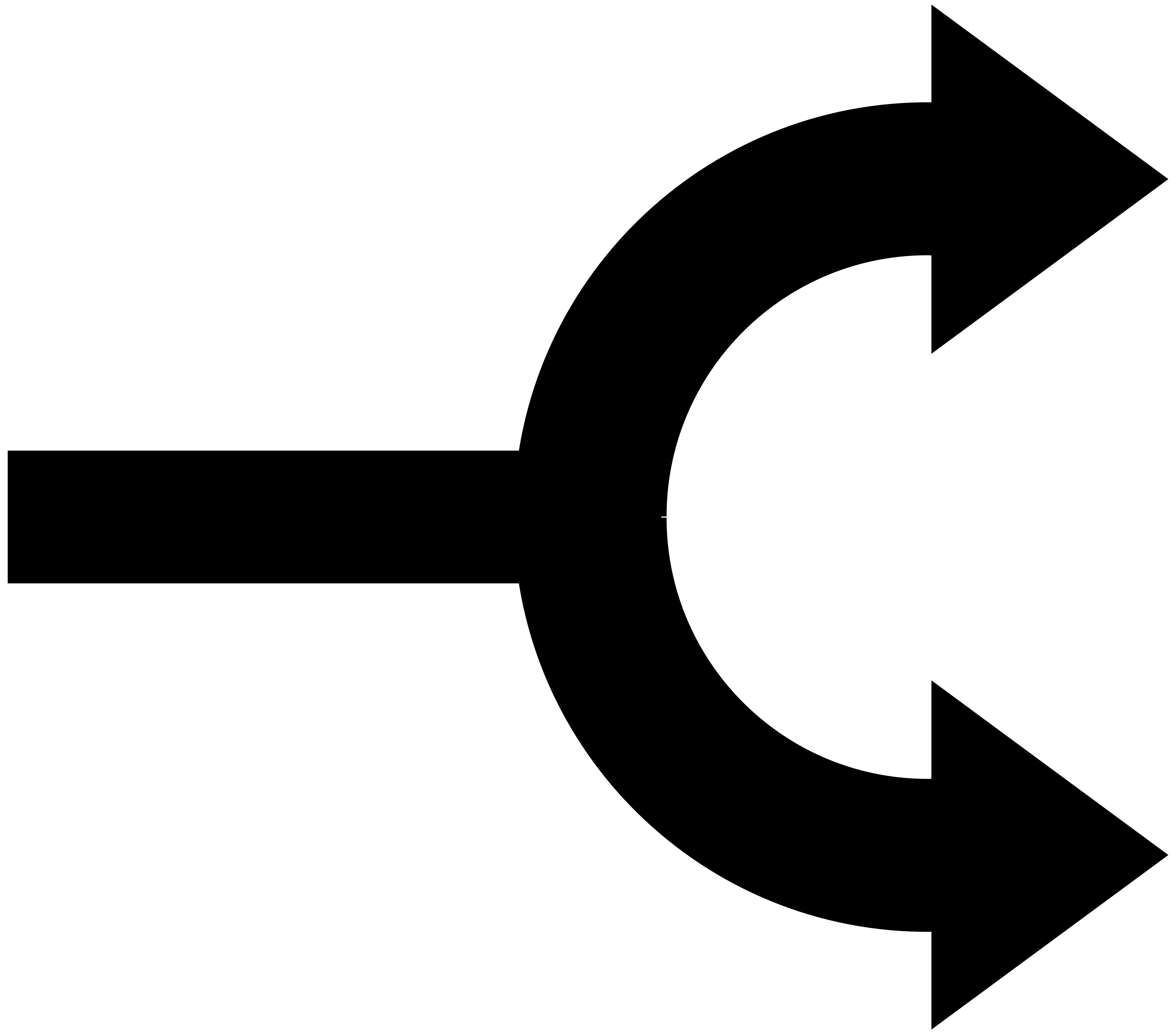
- Historical context of main ingredients that lead to nowadays description of particle physics
- Critical thinking towards theory vs. experiment interplay
- Usage of the Particle Data Group website

The beginning of particle physics

- “It is fashionable to carry the story all the way back to the Democritus and the Greek atomists, but apart from a few suggestive words their metaphysical speculations have nothing in common with modern science.” (D. Griffith)

Democritus (1705), by Giuseppe Torretti. Portego, Ca' Rezzonico, Venice

The classical era: 1890-1930

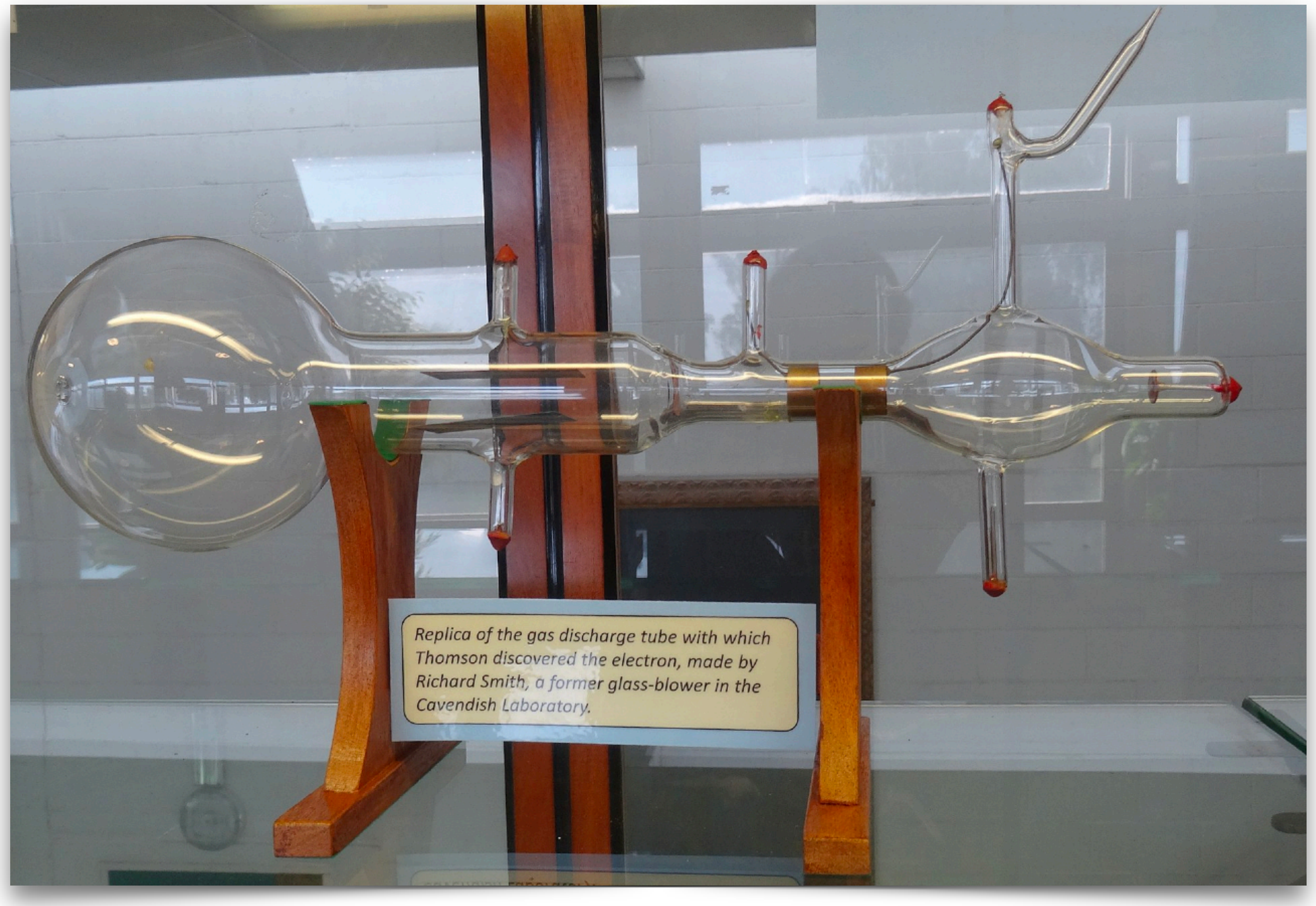


Atoms
(protons, neutrons,
electrons)

Photon

The beginning of particle physics: The electron

- Cathode rays emitted by a hot filament could be deflected by electric and magnetic fields (Thompson, 1897)
  - Previous attempts had failed due to experimental challenges
- Findings:
  - mass-to-charge ratio was very low compared to H^+ ions
  - mass-to-charge ratio did not change when changing anode materials
- Conclusion:
  - velocity and mass-to-charge ratio correct ✓
  - “plums in a pudding” atom model ✗

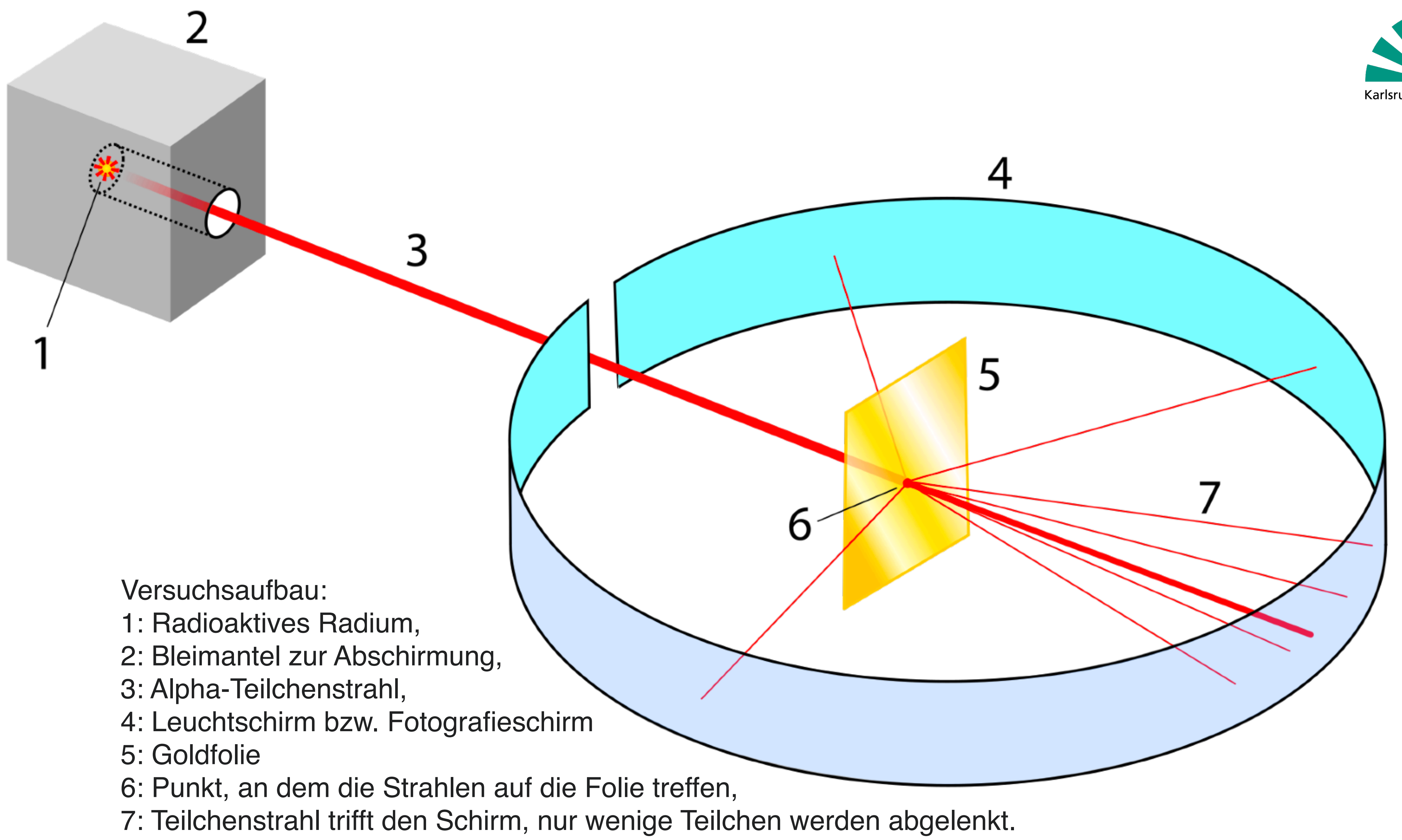


Discovery of the nucleus (1911)

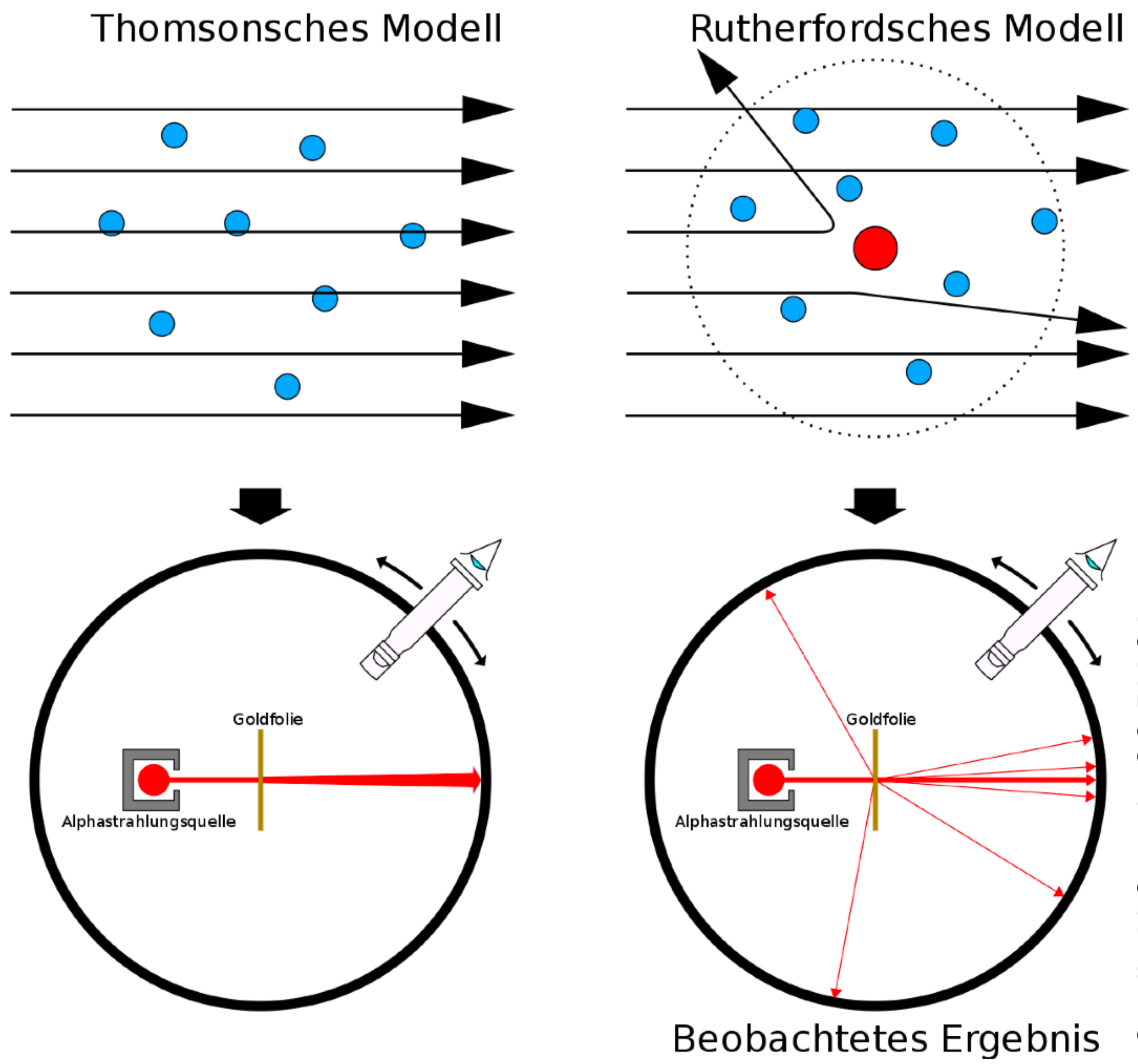
- Rutherford experiment (also Geiger-Marsden-experiment)
  - Beam of α-particles passes a gold foil almost undisturbed with a few crazy scatters:

$$\frac{dN}{d\theta} \propto \frac{1}{\sin^4(\theta/2)}$$

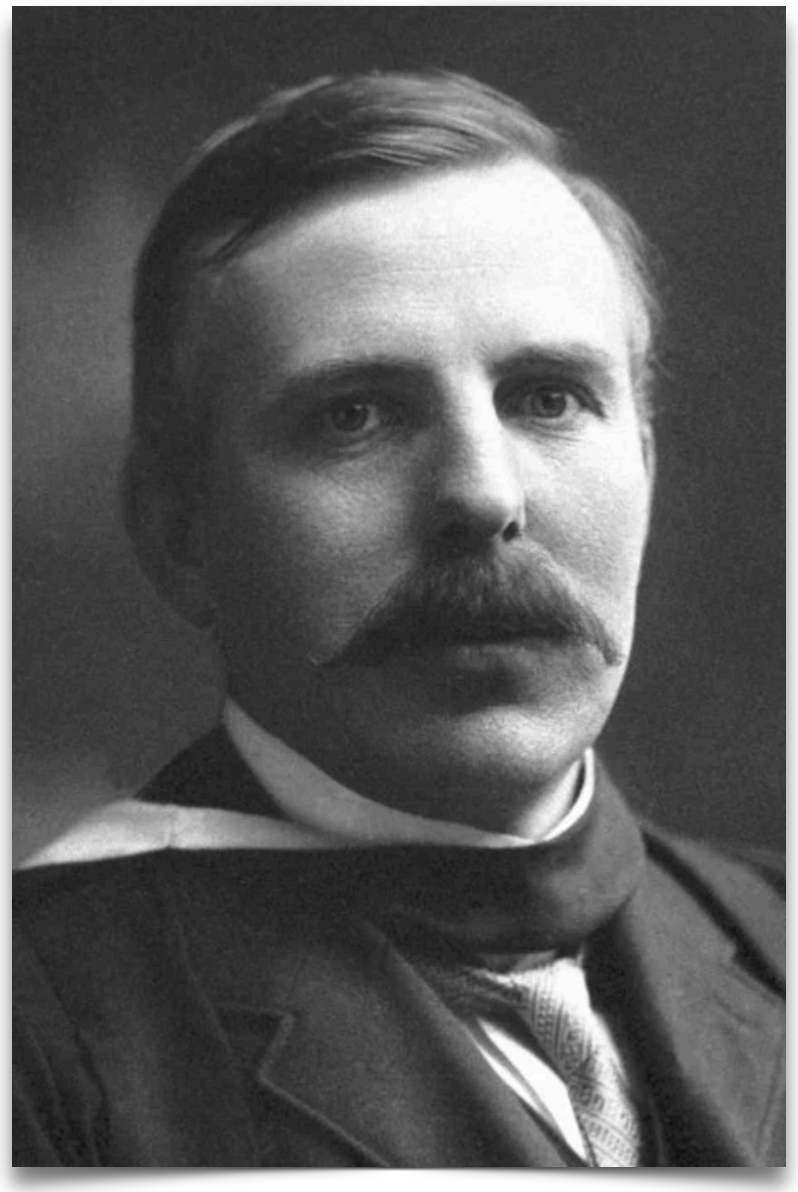
  - Angular distribution of Coulomb scattering on a very small, very heavy structure: atom = nucleus + shell



Credit: Sundance Raphael, gemeinfrei



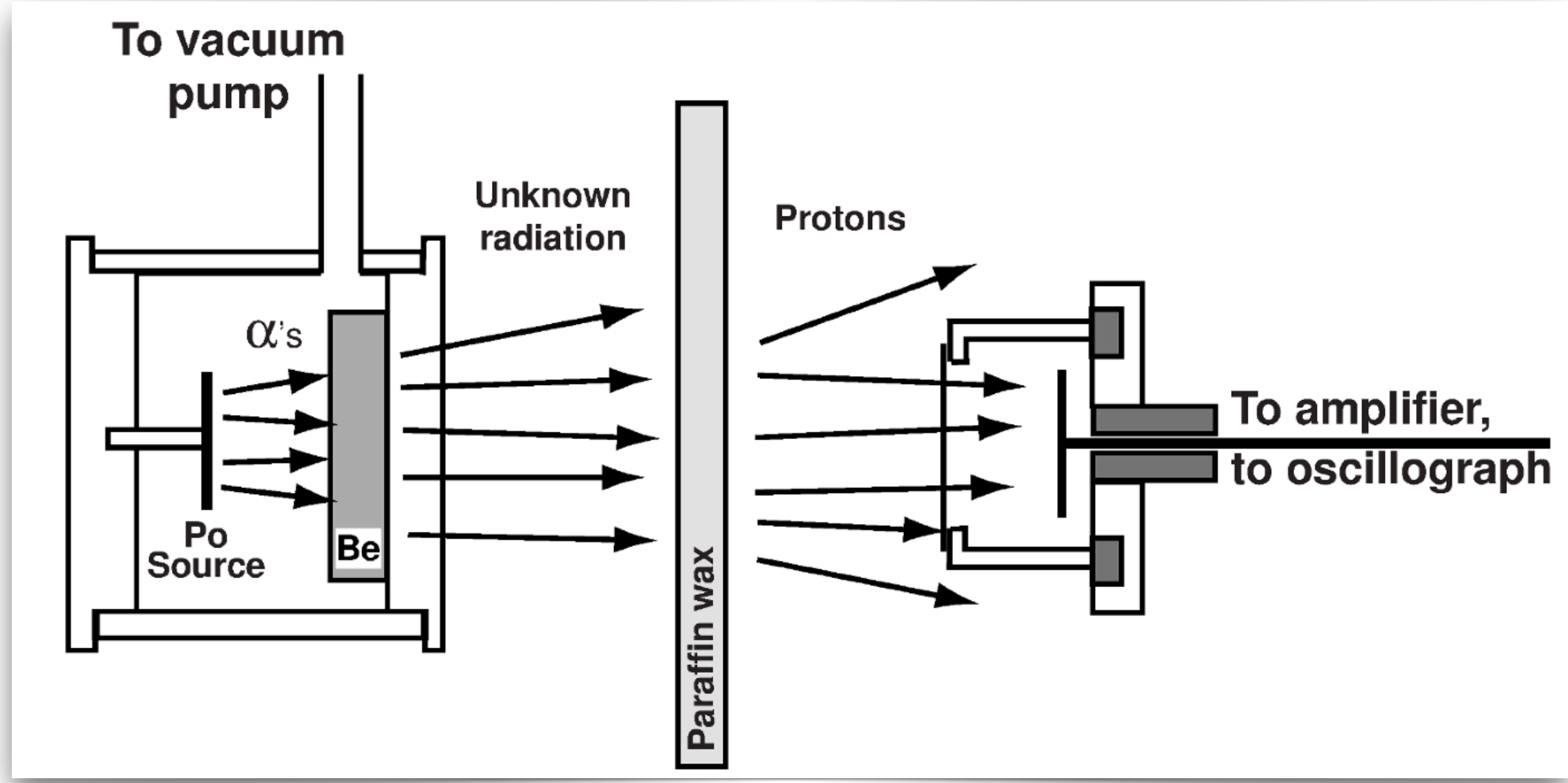
Credit: N Stoeck, CC BY-SA 4.0



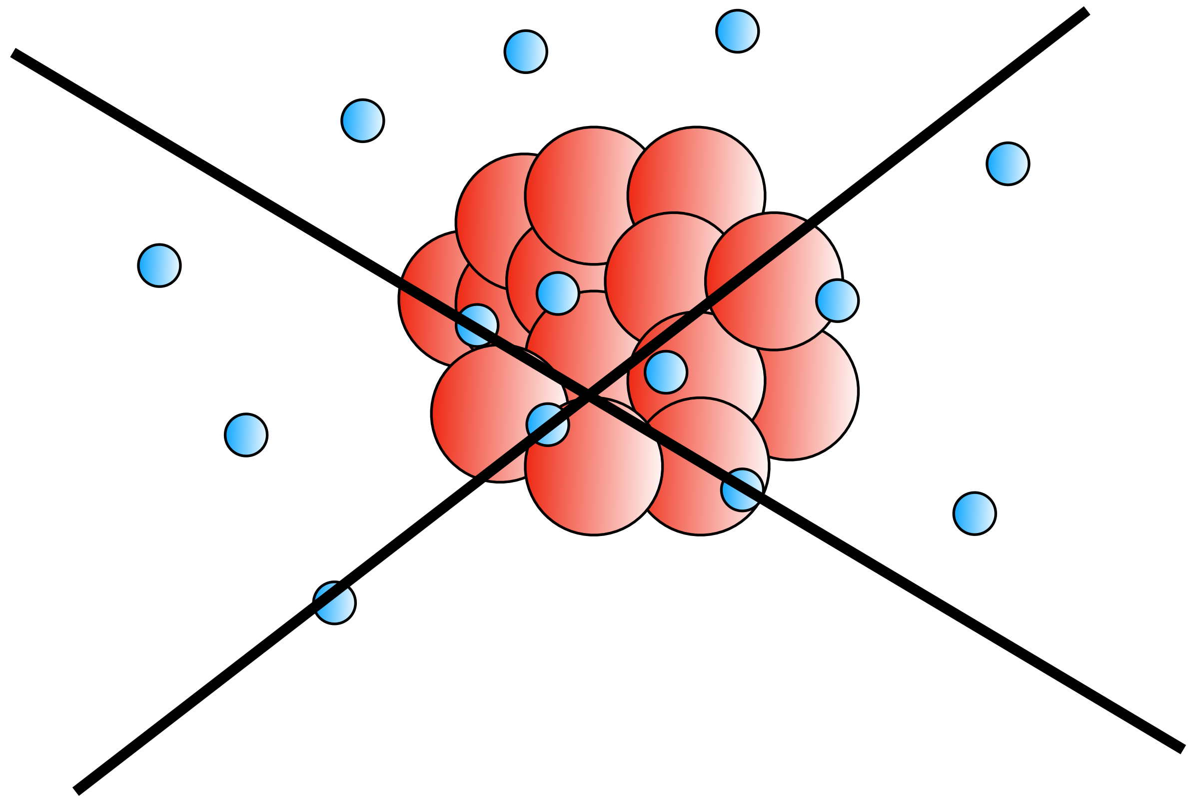
Credit: Nobel foundation
https://www.nobelprize.org/prizes/chemistry/1908/rutherford/facts/

Discovery of the neutron (1932)

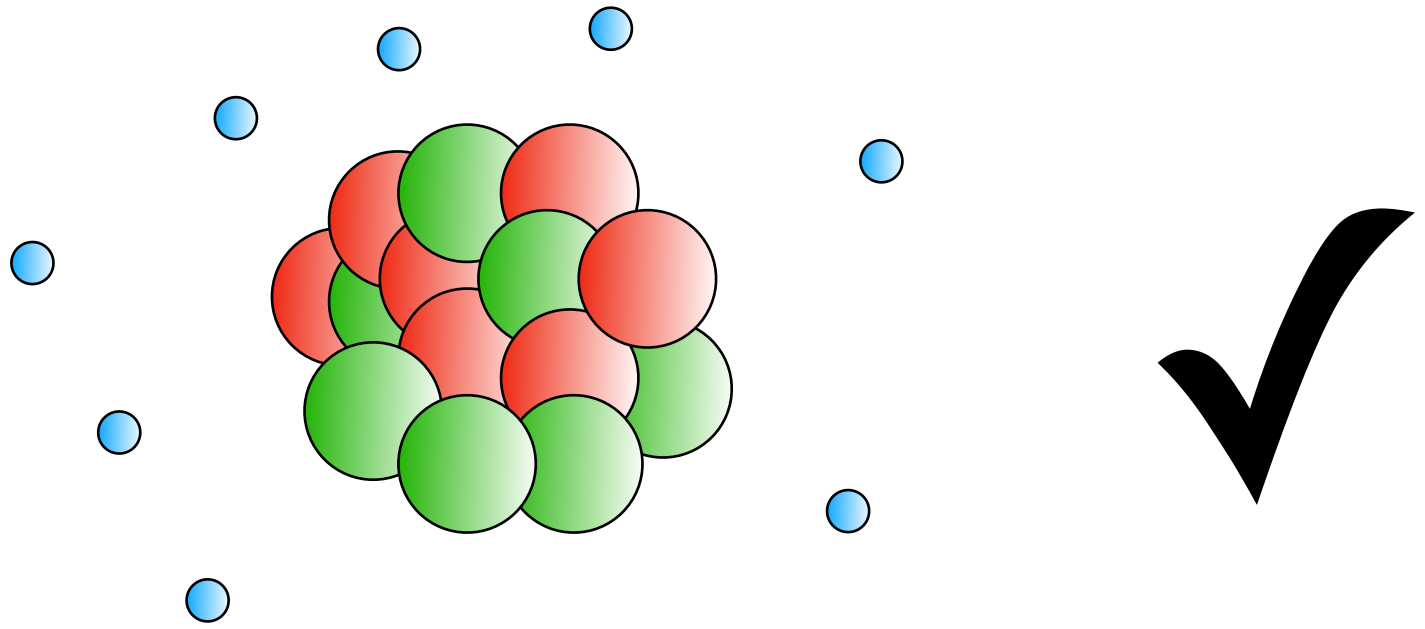
- Chadwick studied the reaction (in modern notation): $^{9}Be + {}^{4}He \rightarrow {}^{12}C + n$
- Alternative explanation: Photons hitting protons in the paraffin (a hydrocarbon) would have lead to very different energy spectra



Nitrogen: 14 protons, 7 "nuclear electrons", 7 electrons

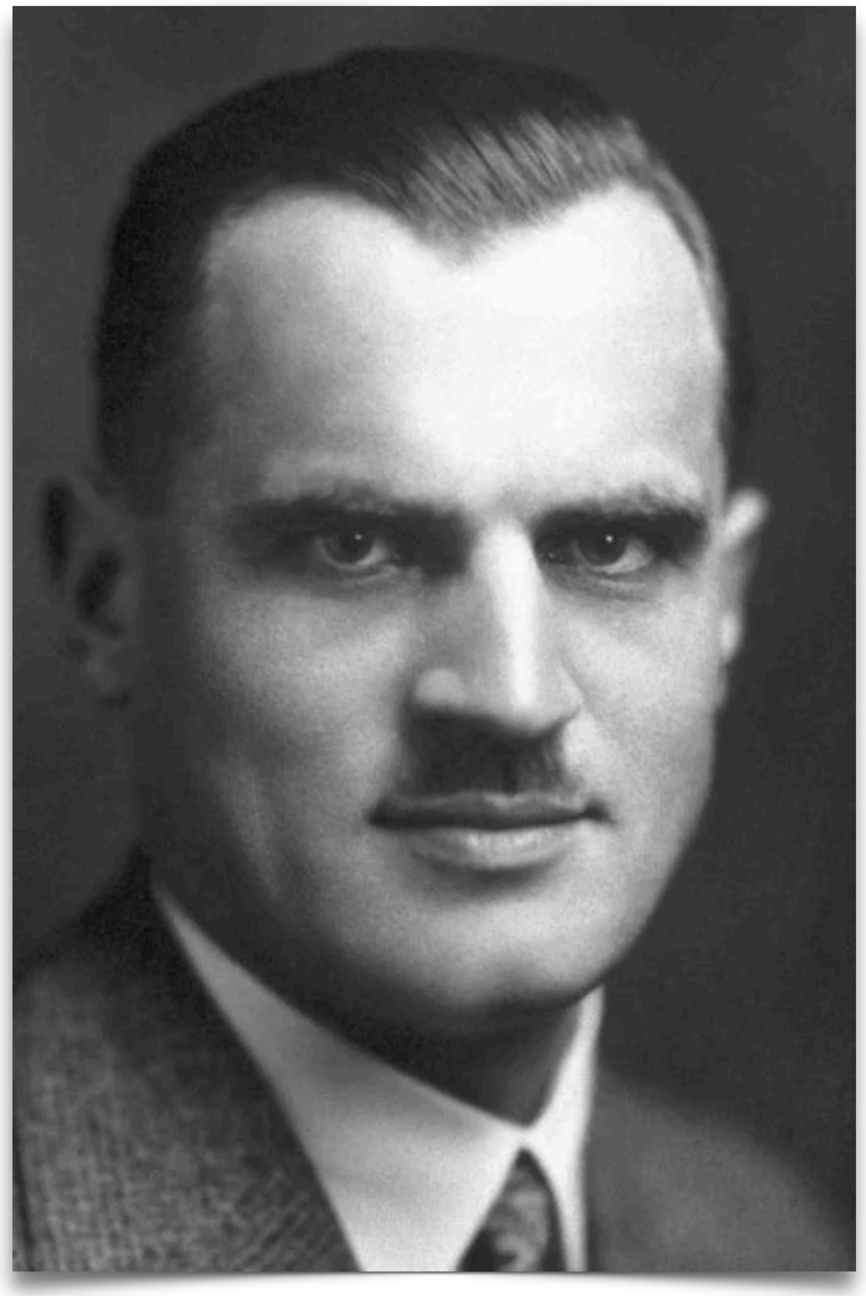


Nitrogen: 7 protons, 7 neutrons, 7 electrons

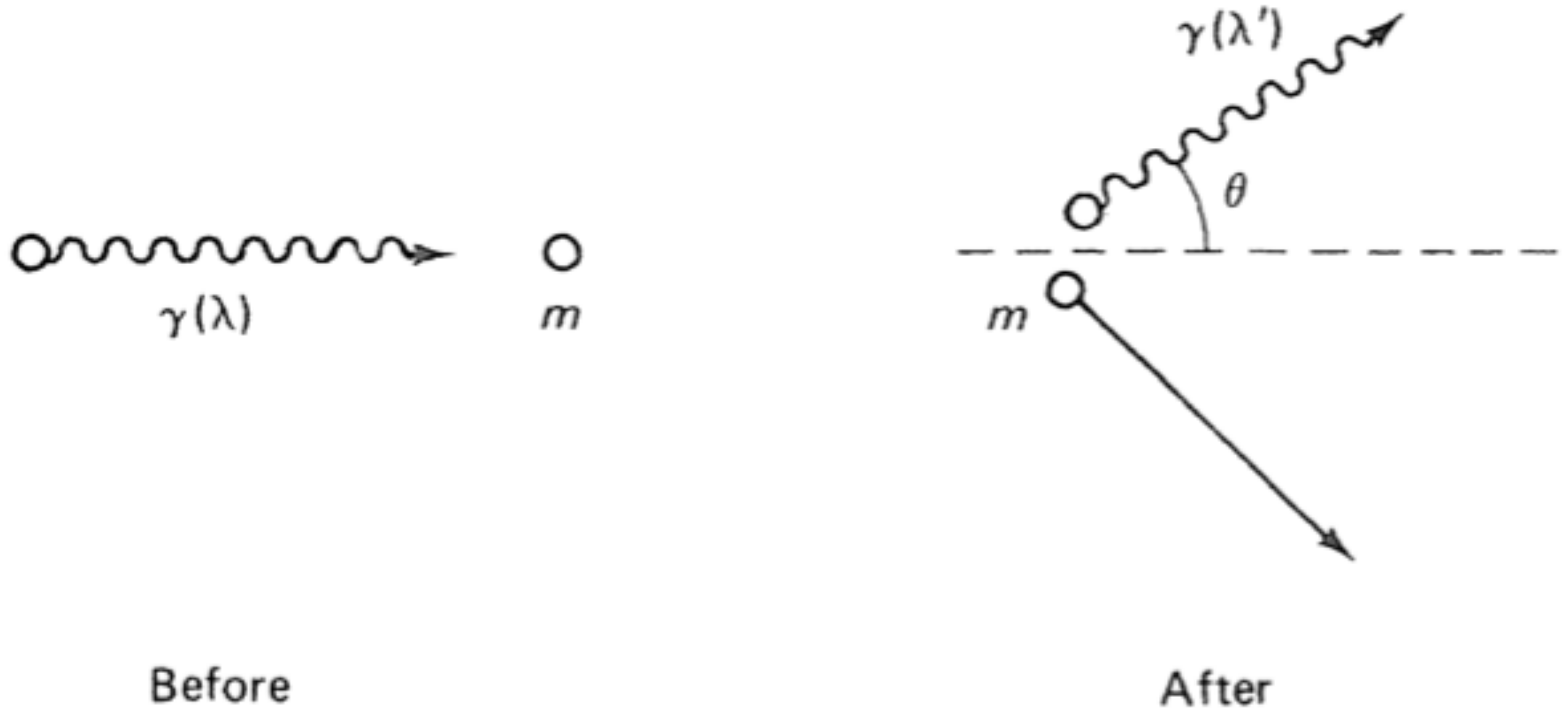


Photon as a particle

- Blackbody spectrum (Planck, ~1900) requires quantized radiation to avoid UV catastrophe
- Photoelectric-effect (Einstein, 1905) explained by light quanta as an intrinsic property of the electromagnetic field: E=hν-w
- Scattering photons off particles at rest (Compton, 1923) behave exactly like elastic collisions of a massless particle
- In modern notation, photons are the force carriers than bind electrons to protons in nuclei. In atomic physics, the effects of quantized energy spectra only became relevant much later (Lamb-shift, 1947).



Credit: Nobel foundation
https://www.nobelprize.org/prizes/physics/1927/compton/facts/



Credit: Griffith

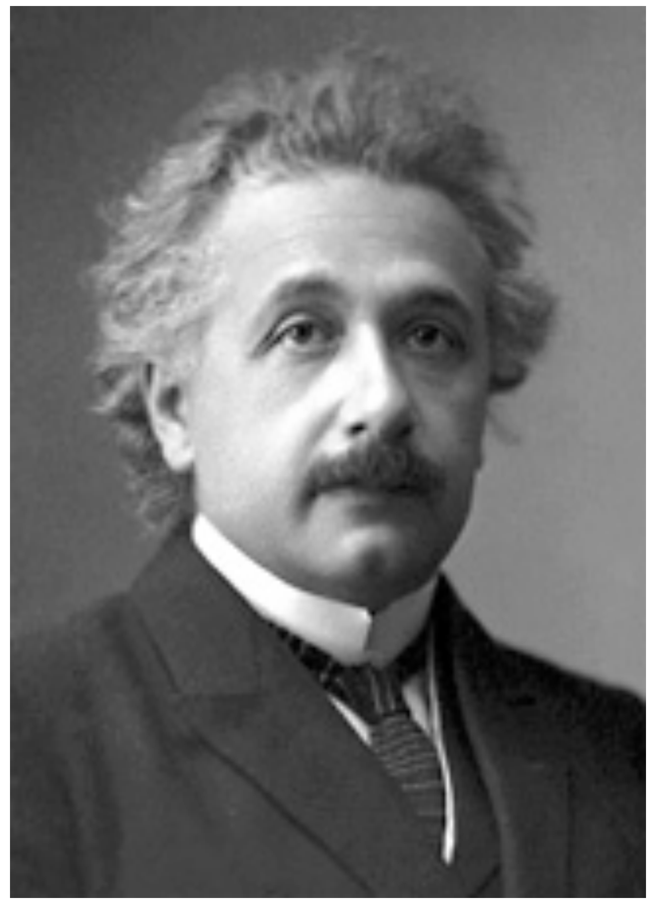
Quantum mechanics and special relativity

- Theoretical foundation of particle physics
  - Quantum mechanics (Heisenberg, Schrödinger, Dirac, …) in the 1920s
  - Special relativity (Einstein) in 1905
- Modern theories in particle physics: Relativistic quantum field theory QFT):
  - Lorentz invariant
  - Quantised fields (fields = quantum mechanical operators)
  - Physical particles = excitation (“quantum”) of the fields


Werner Heisenberg

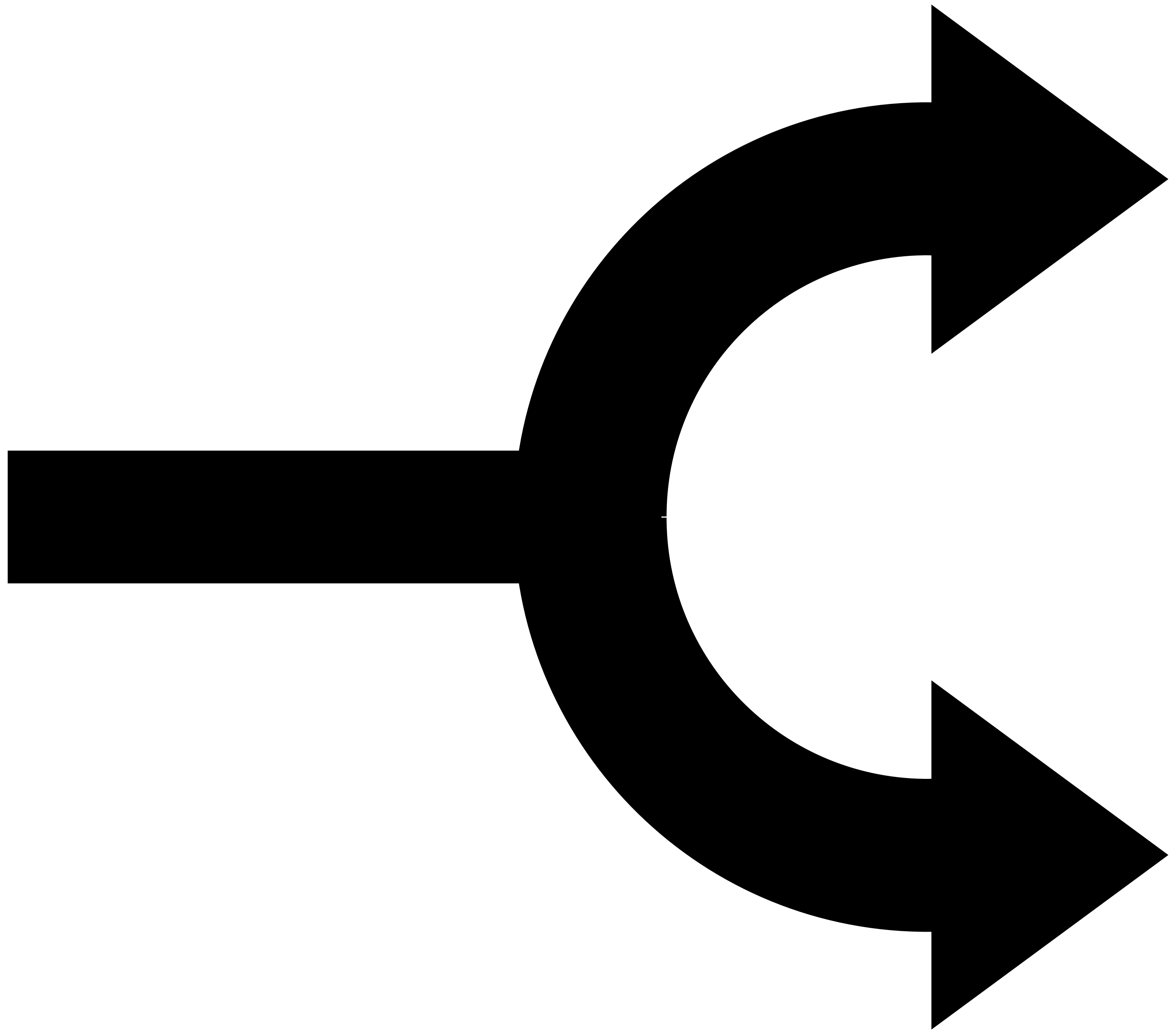

Erwin Schrödinger


Paul A. M. Dirac


Albert Einstein

nobelprize.org

The classical era: 1890-1930



Atoms
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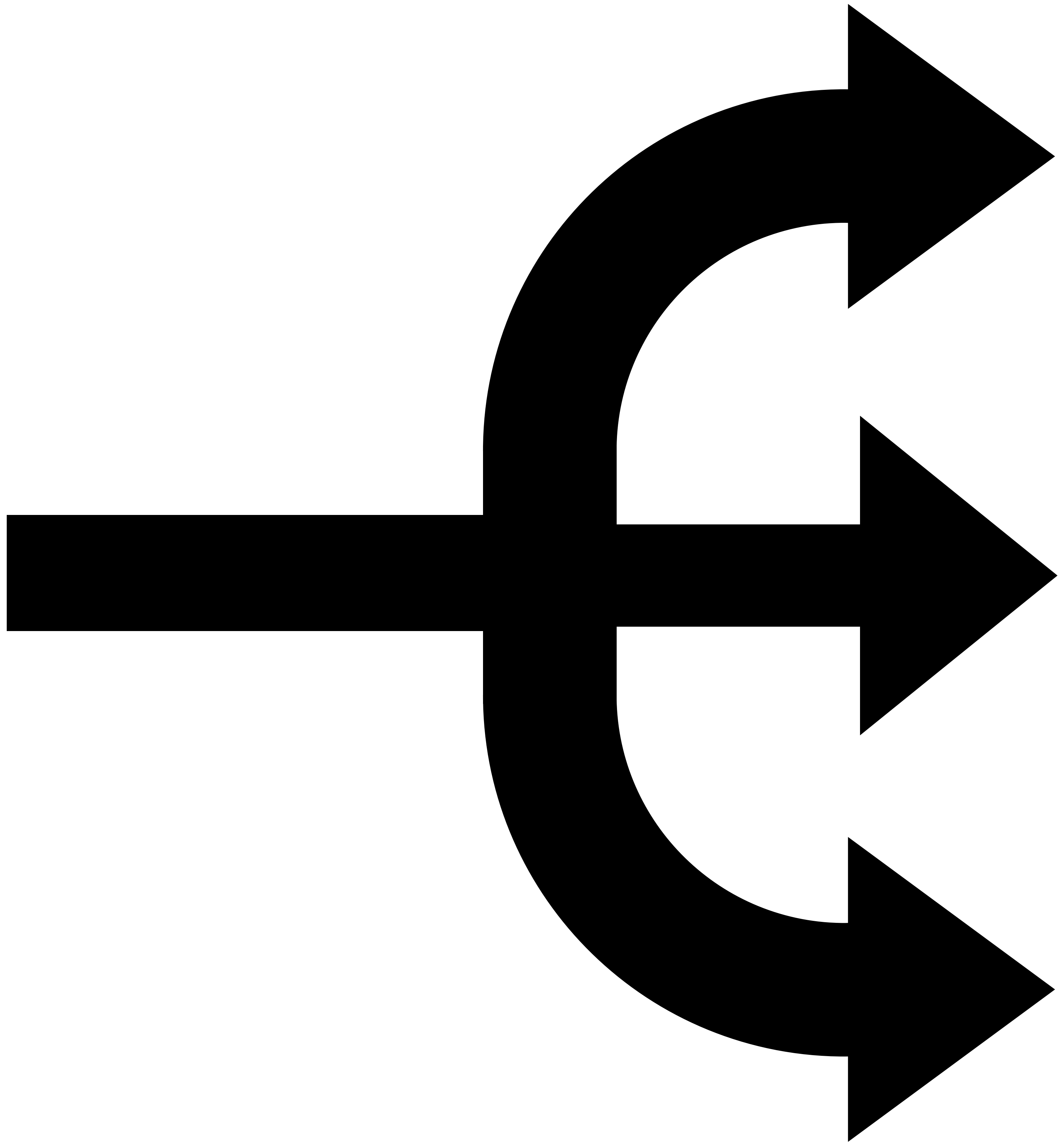
The post-atom era: 1930-1950



mesons and nuclear force

antimatter

neutrinos

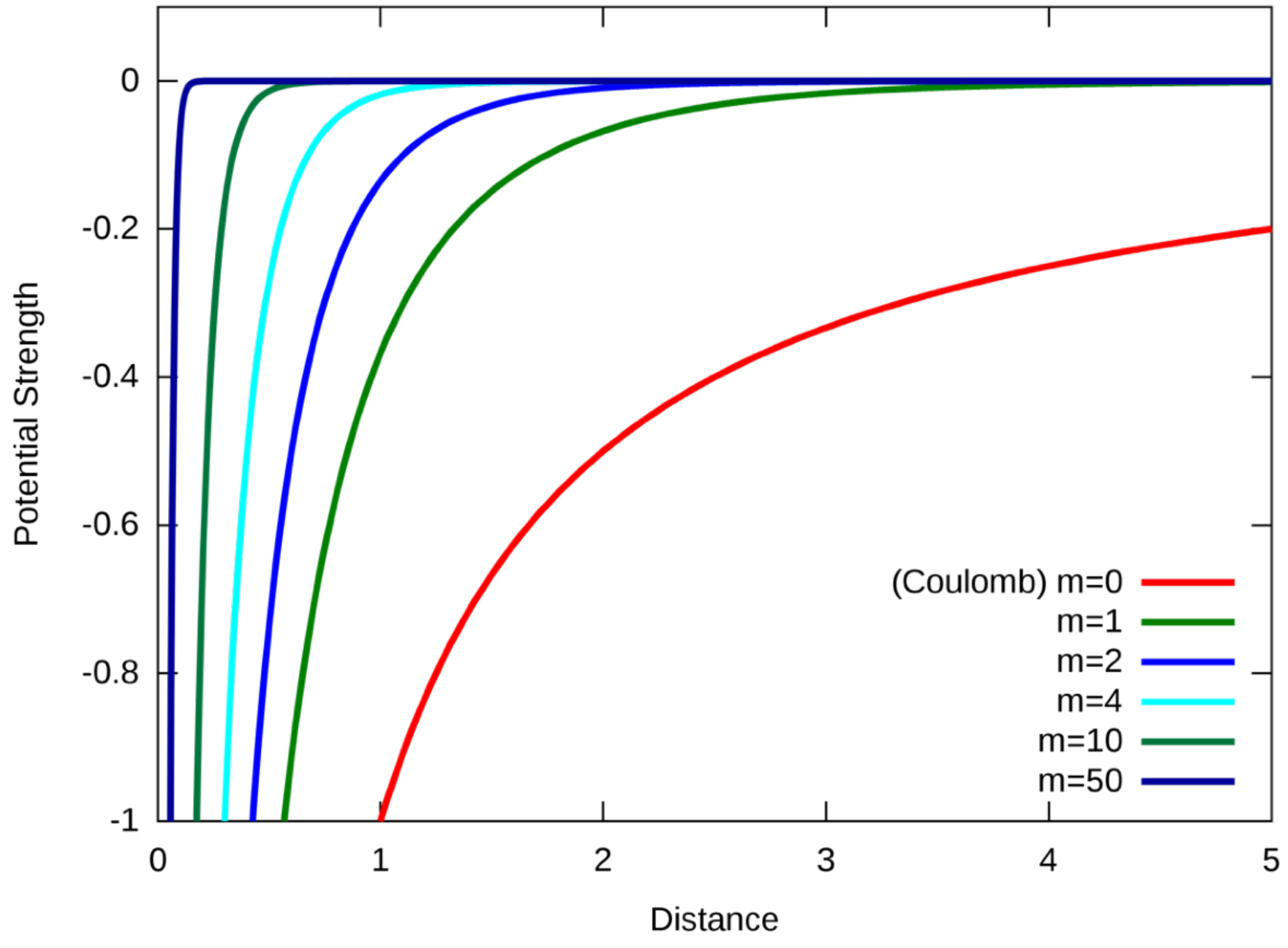
Nuclear force: What holds the nucleus together?

- Positively charged protons in the nucleus should repel one another
- New force must be very strong on short distances, but very weak on long distances
- Yukawa (1934) suggested a potential of form:

$$V(r) \propto -\frac{\exp(-r/\lambda)}{r}, \lambda \propto \frac{1}{m}$$

- Experimentally λ≈1fm (size of a nucleus) → m≈200 MeV… new middle-weight particle: “meson”*

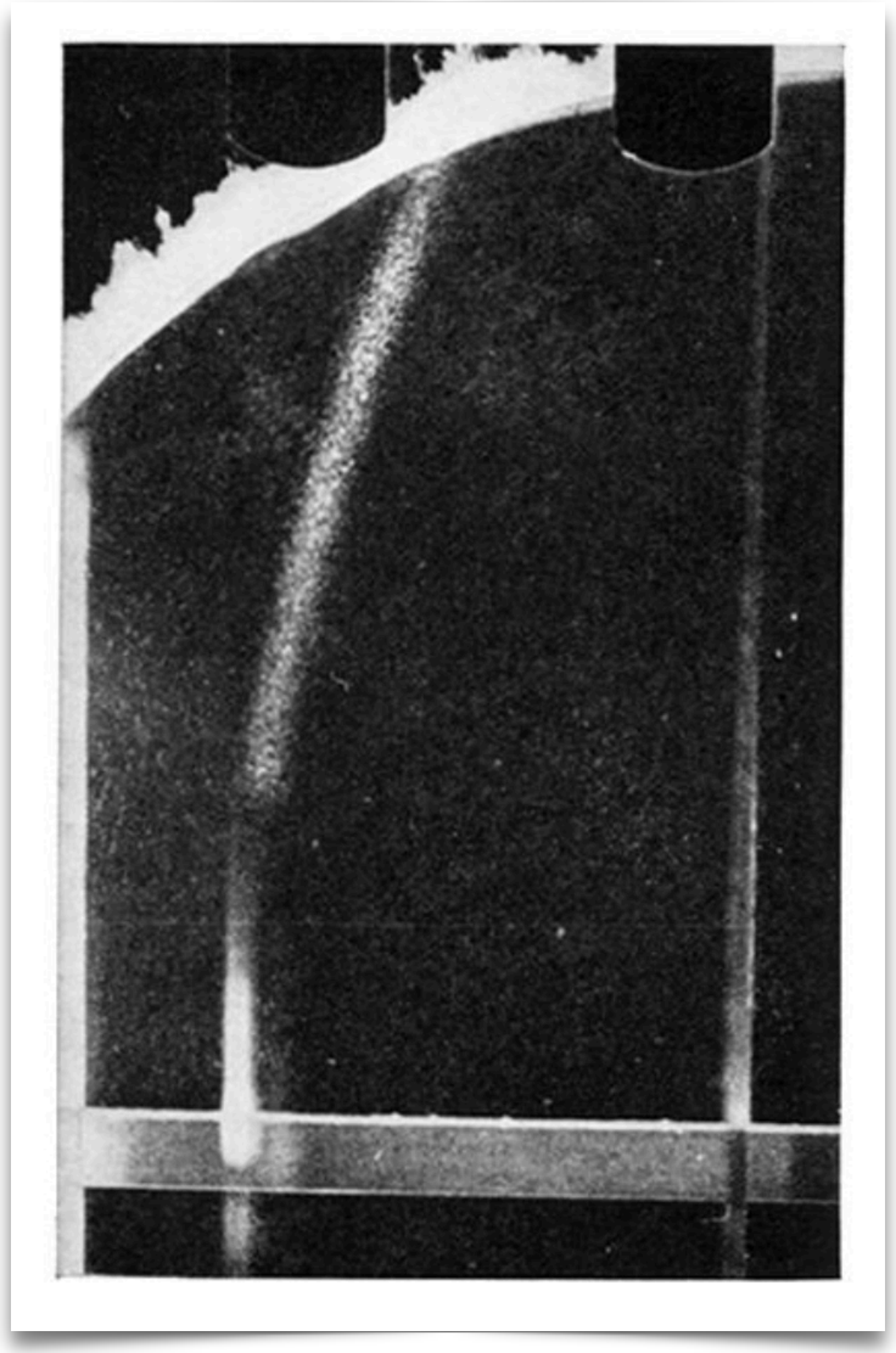
Credit: Nobel foundation
https://www.nobelprize.org/prizes/physics/1949/yukawa/facts/



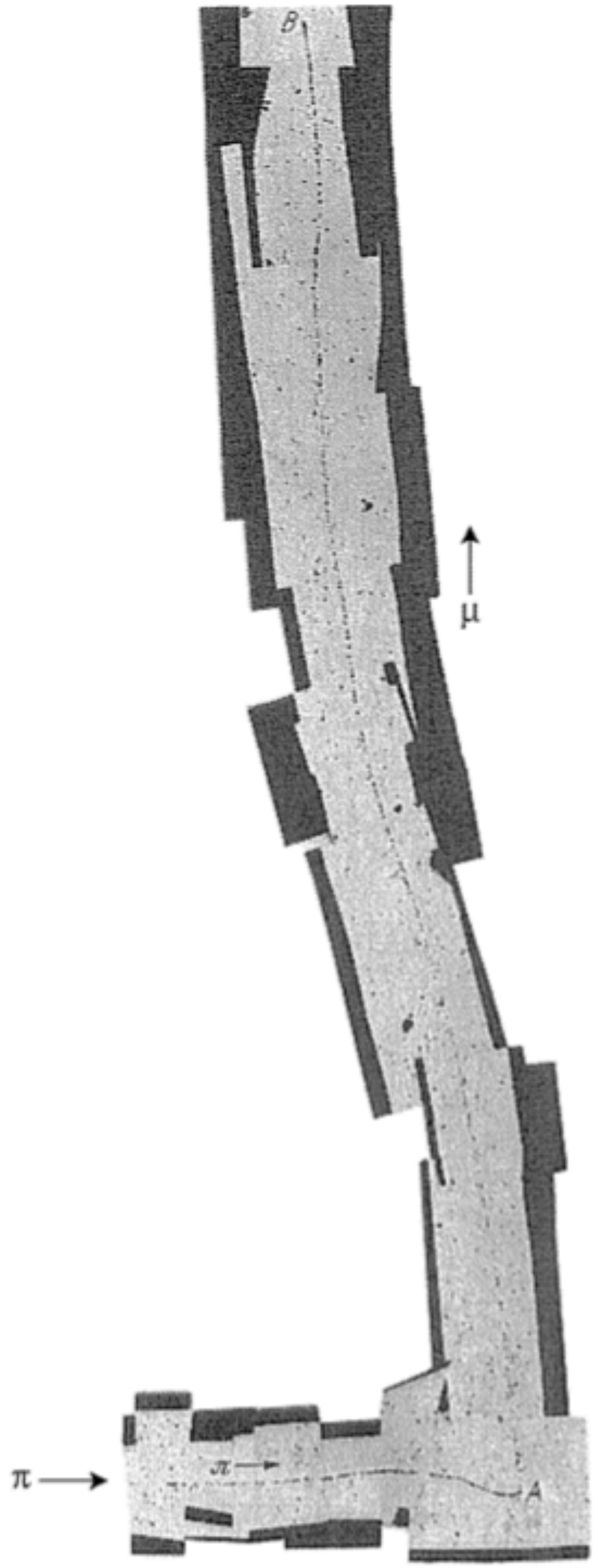
*similar notation:
“light-weight”: lepton
“middle-weight”: meson
“heavy-weight”: baryon

The Mu-meson and the pi-meson

- New particle discovered in 1937 in cosmic rays with a mass ~6 times less than the proton (modern notation: muon or μ)
  - However: too light, weak interaction with atoms
- Another particle discovered in 1947 in cosmic radiation: The pion or π ("pi-meson") that Yukawa predicted



Credit: Phys. Rev. **52**, 1003 (1937)



Credit: Nature 159, 694 (1947)

Antiparticles

- Dirac equation has two solutions for free electrons: One for positive and one for negative energies → interpreted (Dirac, 1931) as positive energy with opposite charge

- Discovery of different charges in cosmic rays (Anderson, 1931)

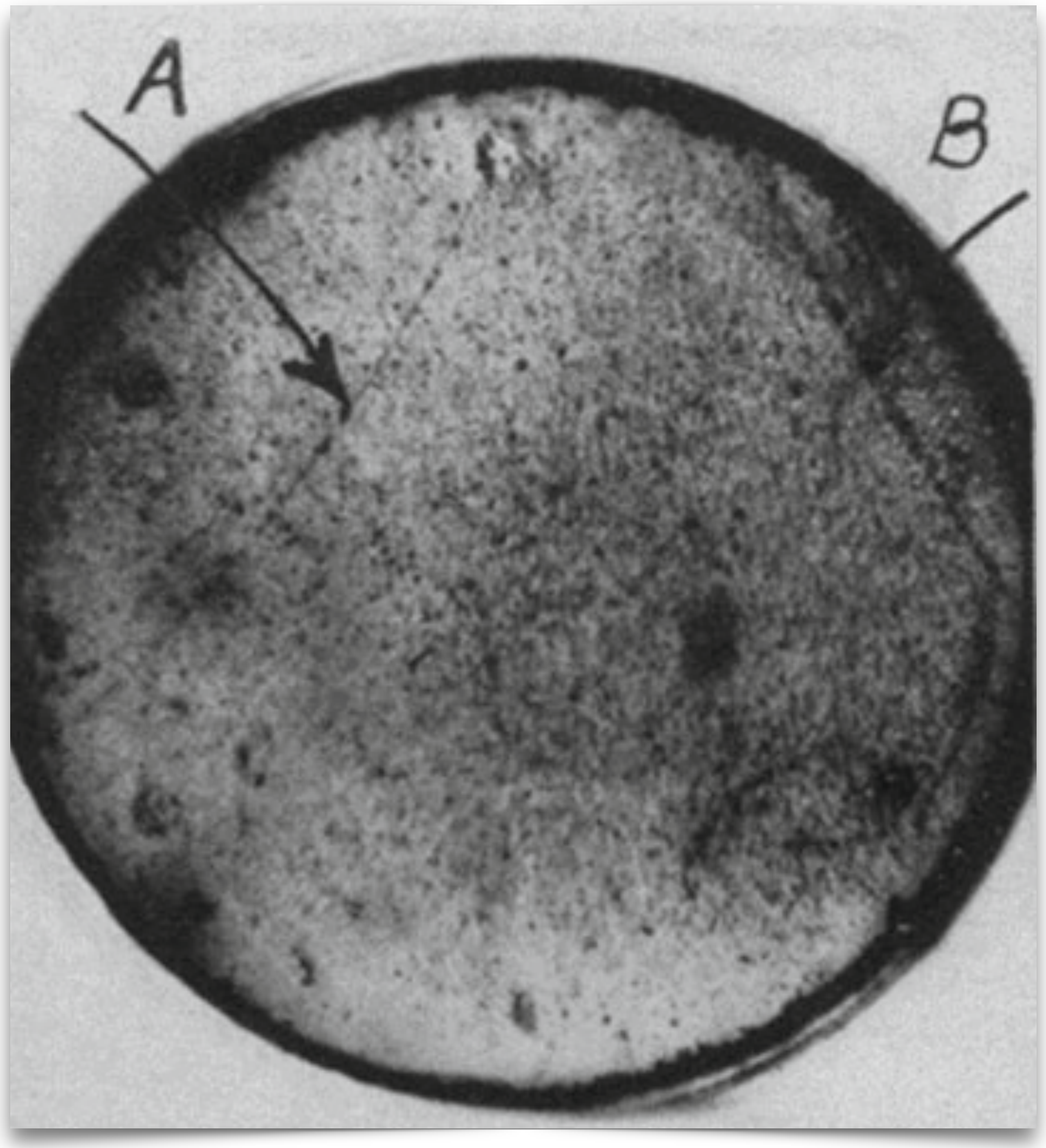
$$
\begin{aligned}
A + B &\to C + D \\
A &\to \bar{B} + C + D \\
A + \bar{C} &\to \bar{B} + D \\
&\vdots
\end{aligned}
$$

(Compton scattering)

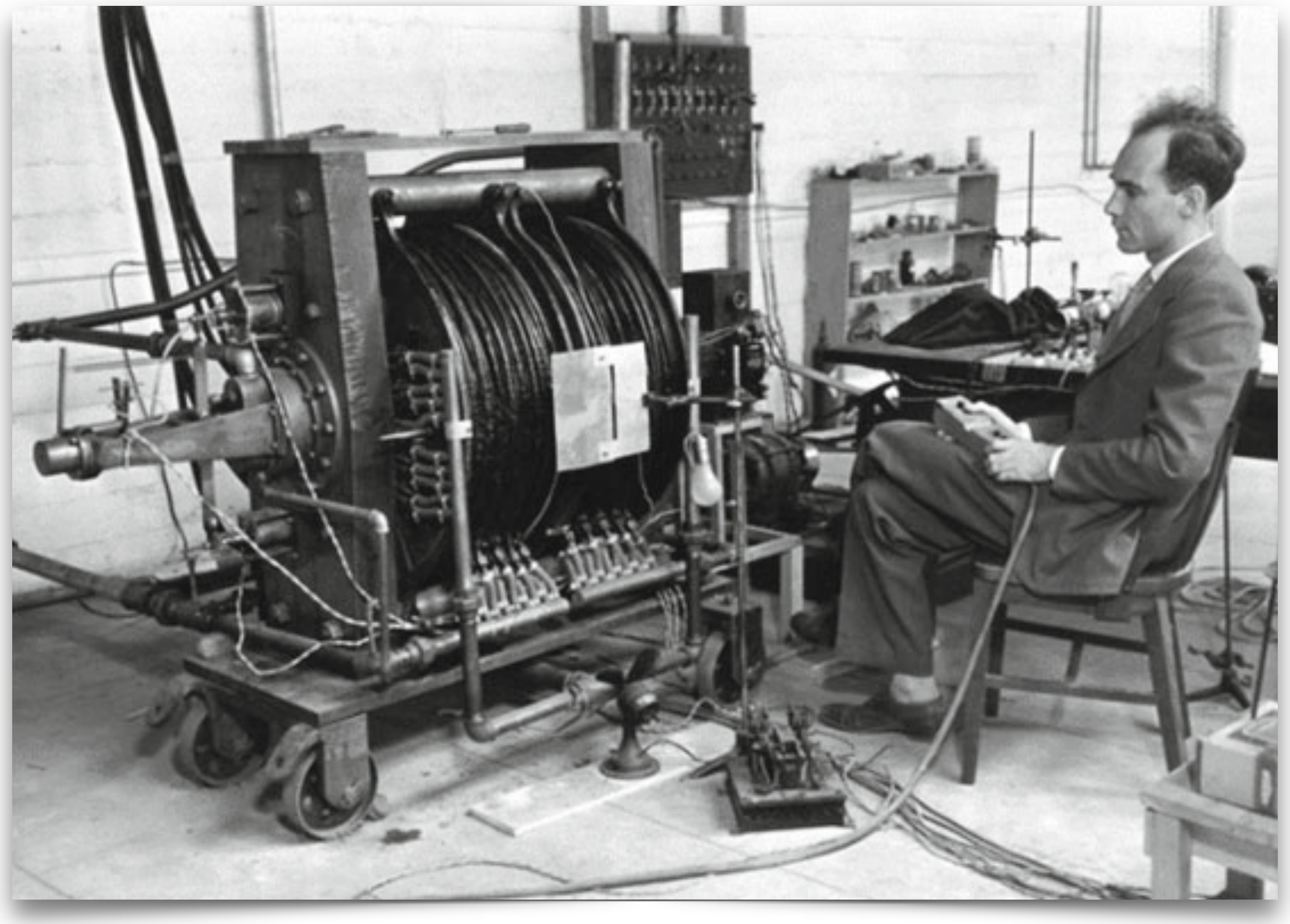
$$\gamma + e^- \to \gamma + e^-$$

(Pair annihilation)

$$e^+ + e^- \to \gamma + \gamma$$



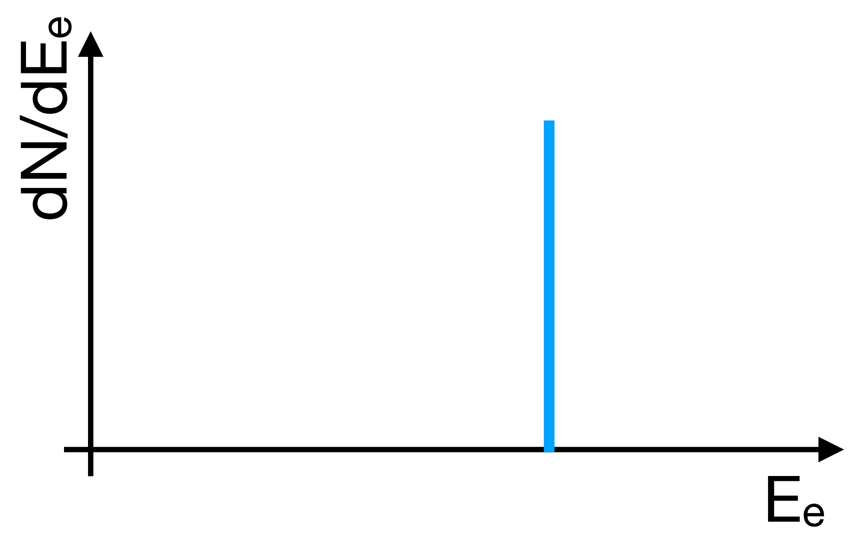
Credit: Caltech Archives



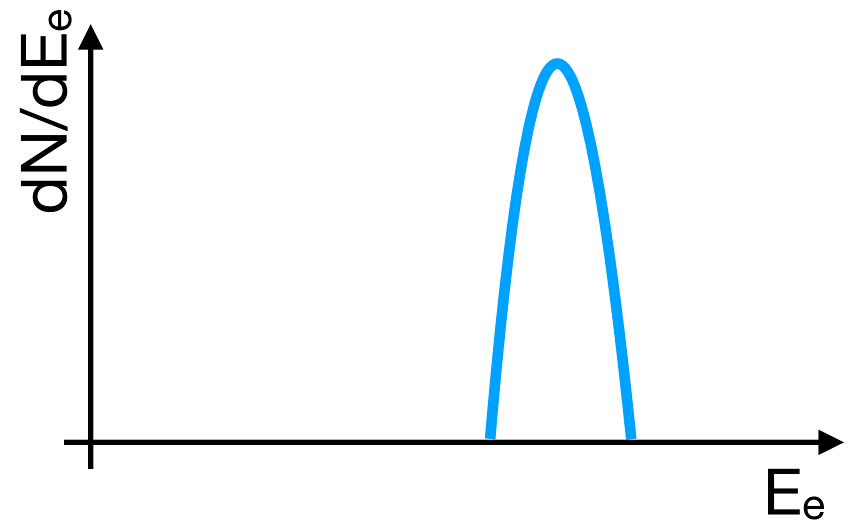
Credit: Caltech Archives

PINGO: β-Zerfall

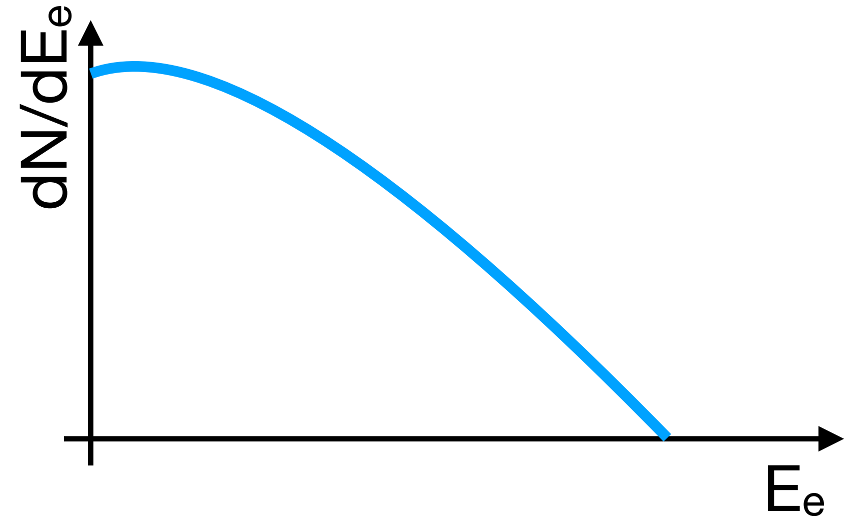
- In nuclear beta decays, a heavier nucleus A decays into a lighter nucleus B and an electron, A→B+e. What energy spectrum do you observe for the electron?
  - The same energy for each decay $E_e = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A}\right)$



  - The same energy but significantly smeared because of limited energy resolution



  - A smooth spectrum with all energies up to a maximum energy



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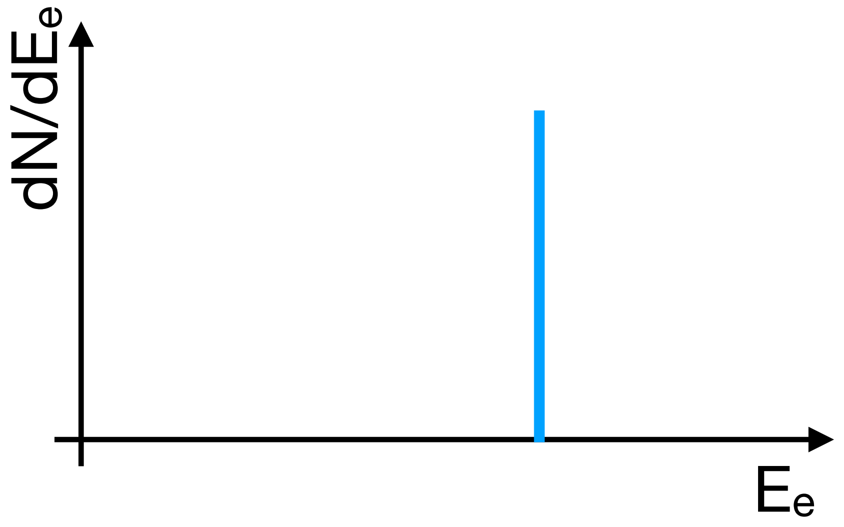

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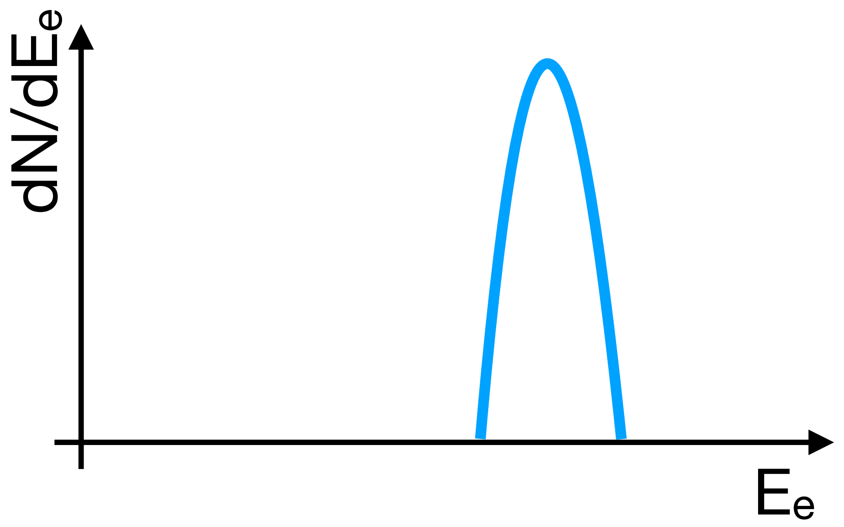
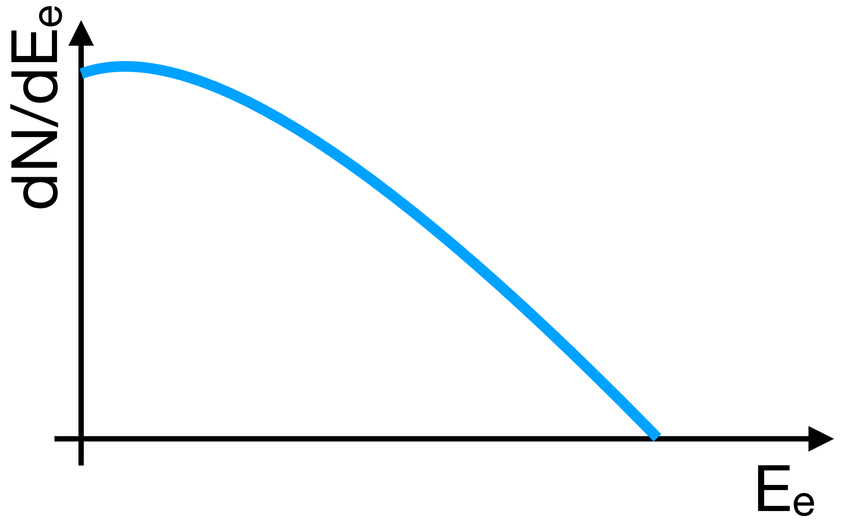
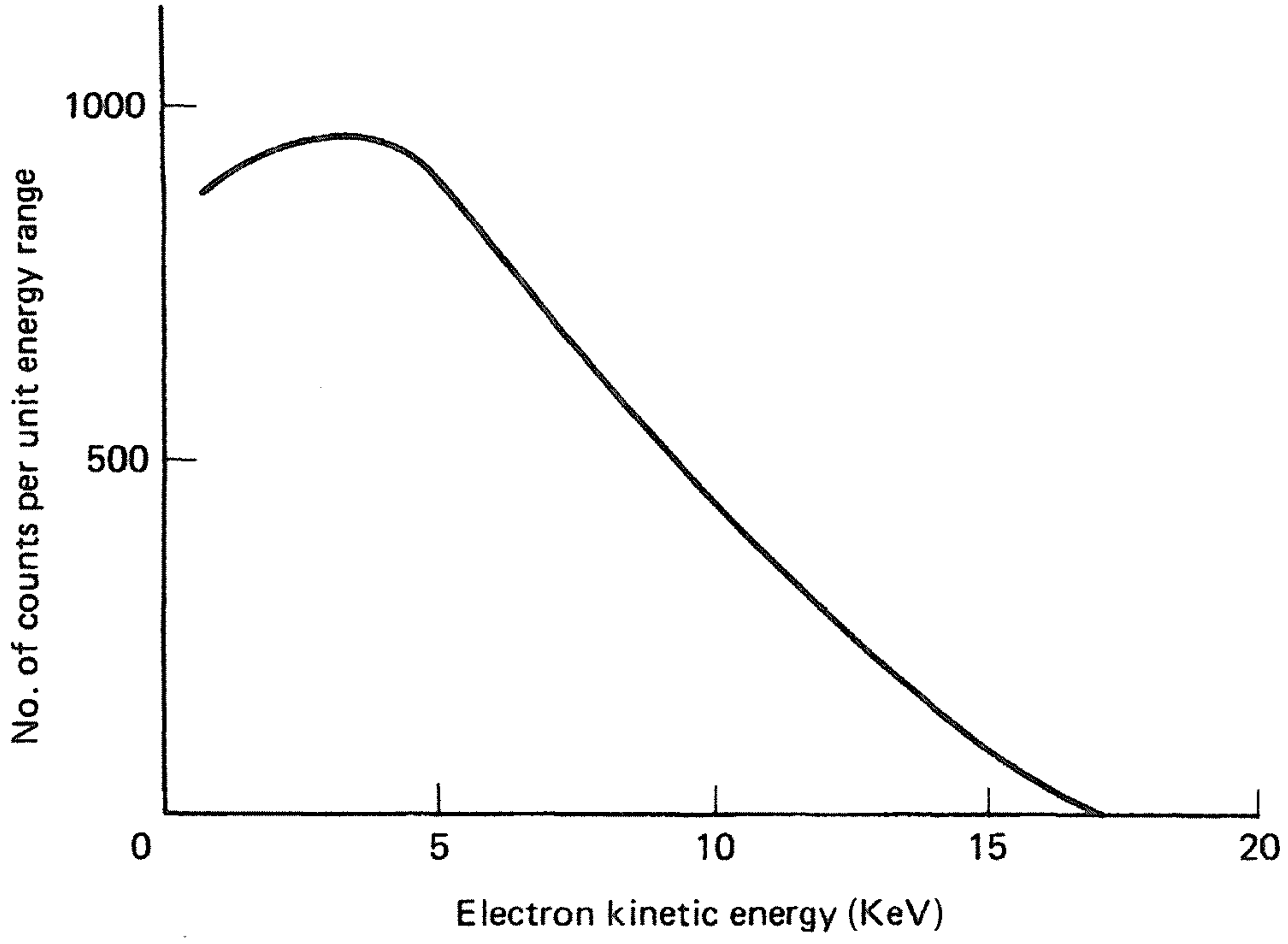


  - **A smooth spectrum with all energies up to a maximum energy**

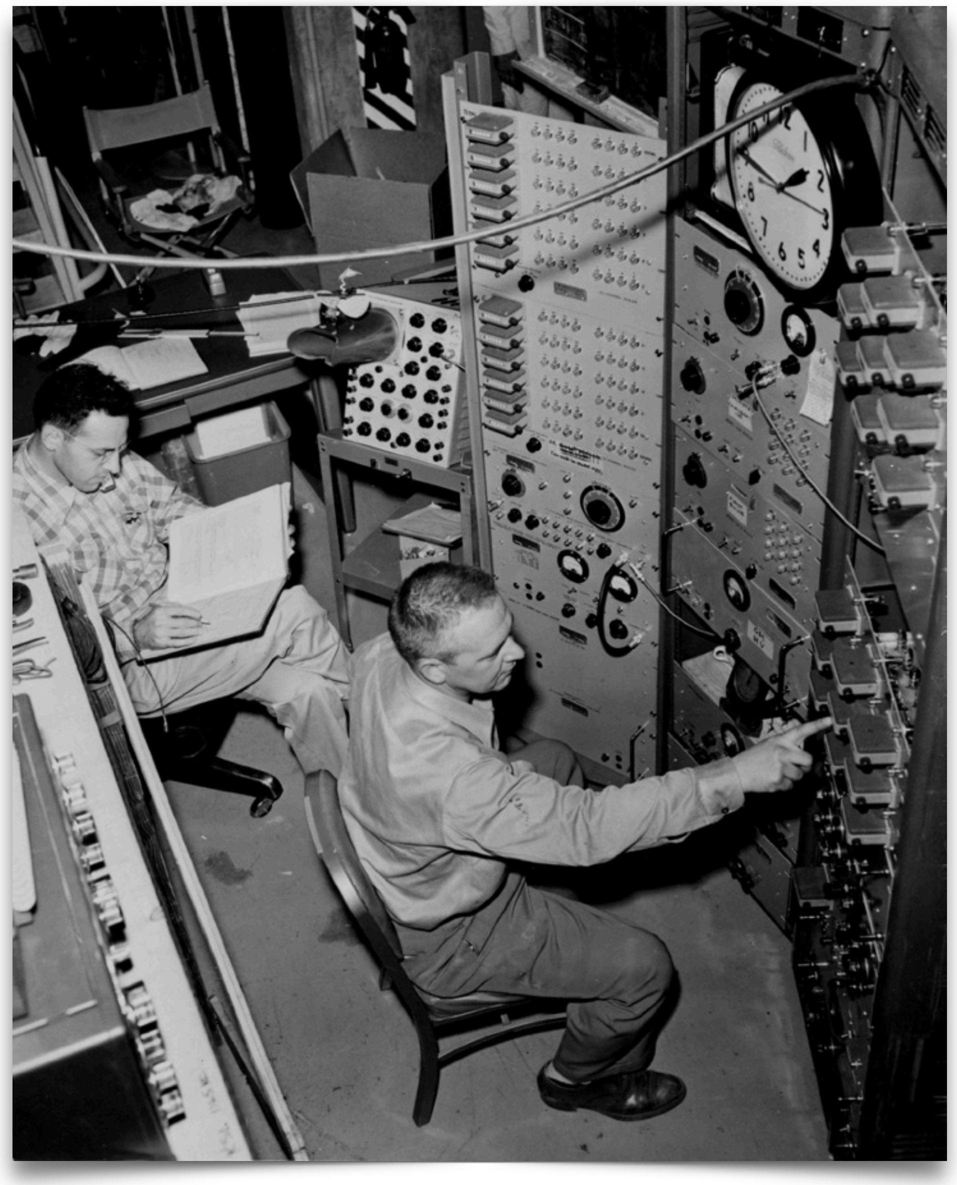


Neutrinos

- Observed electron spectrum pointed towards violation of energy conservation (Bohr) or the existence of a (very light) neutral particle A→B+e+N.
- The inverse beta decay, $\bar{\nu} + p \rightarrow n + e^{+}$ was only observed in 1956 (Cowan, Reines) using the Savanna River nuclear reactor as neutrino source

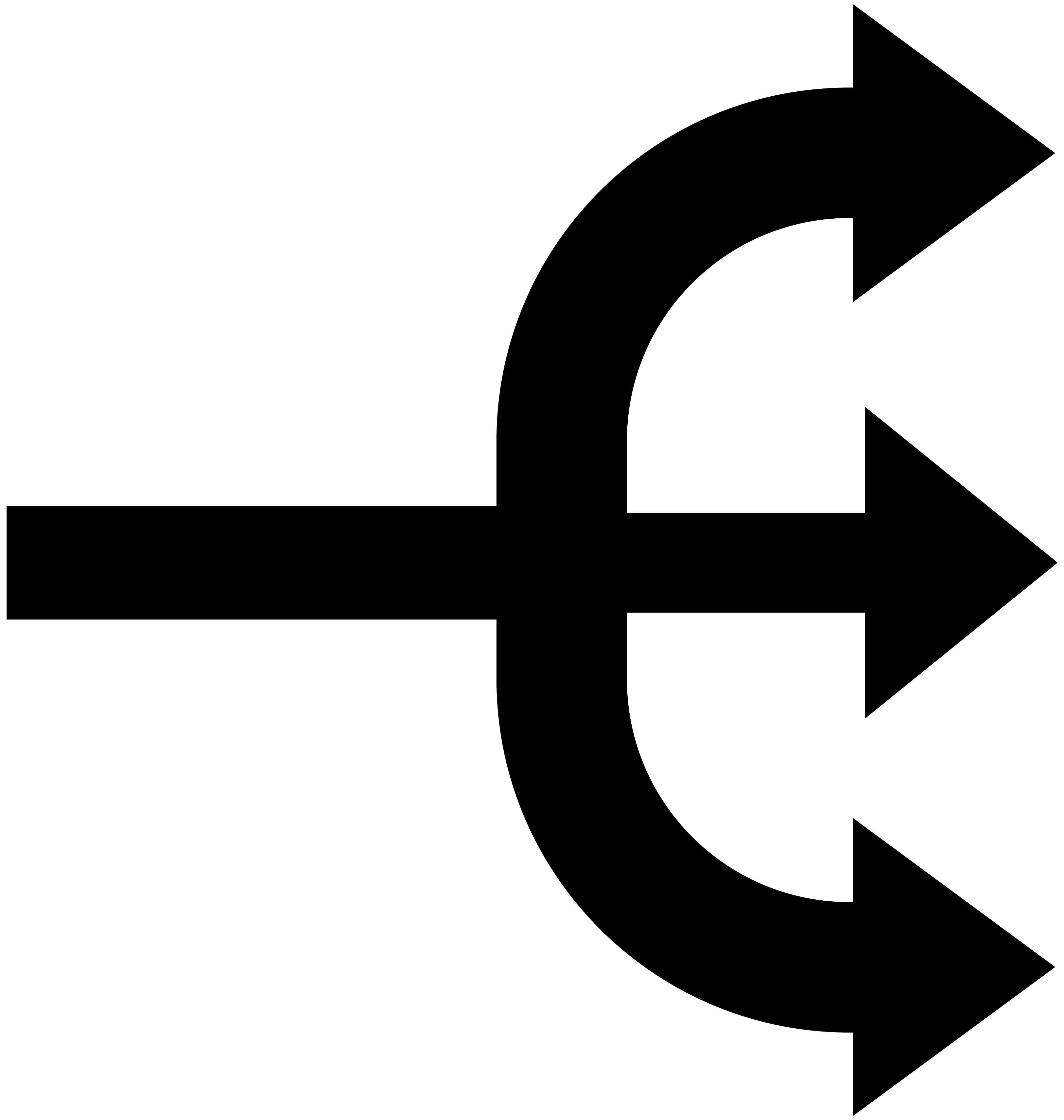


Credit: G.M. Lewis, Neutrinos, Wykeham, London (1970)



Credit: public domain

The post-atom era: 1930-1950

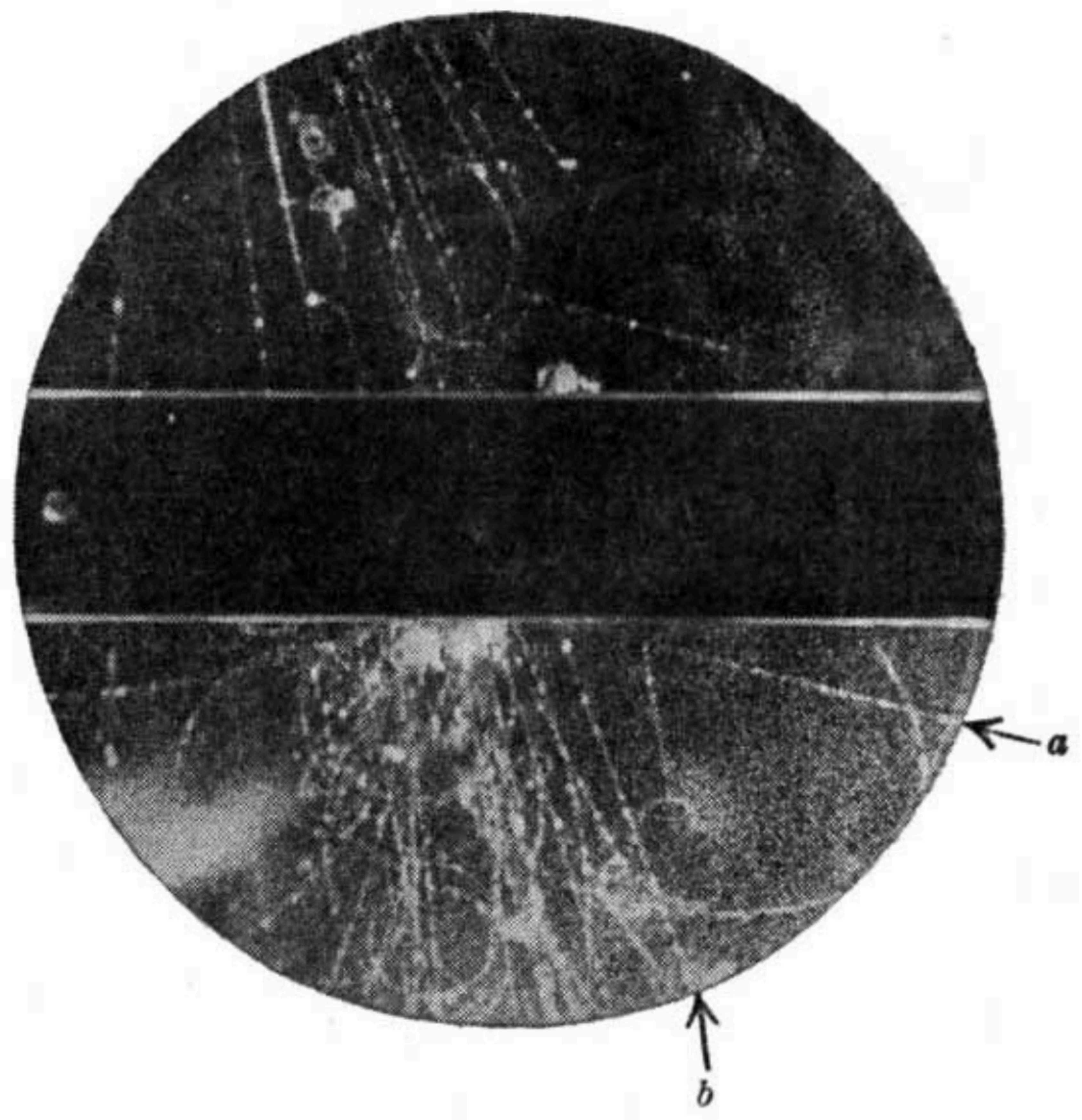


mesons and nuclear force

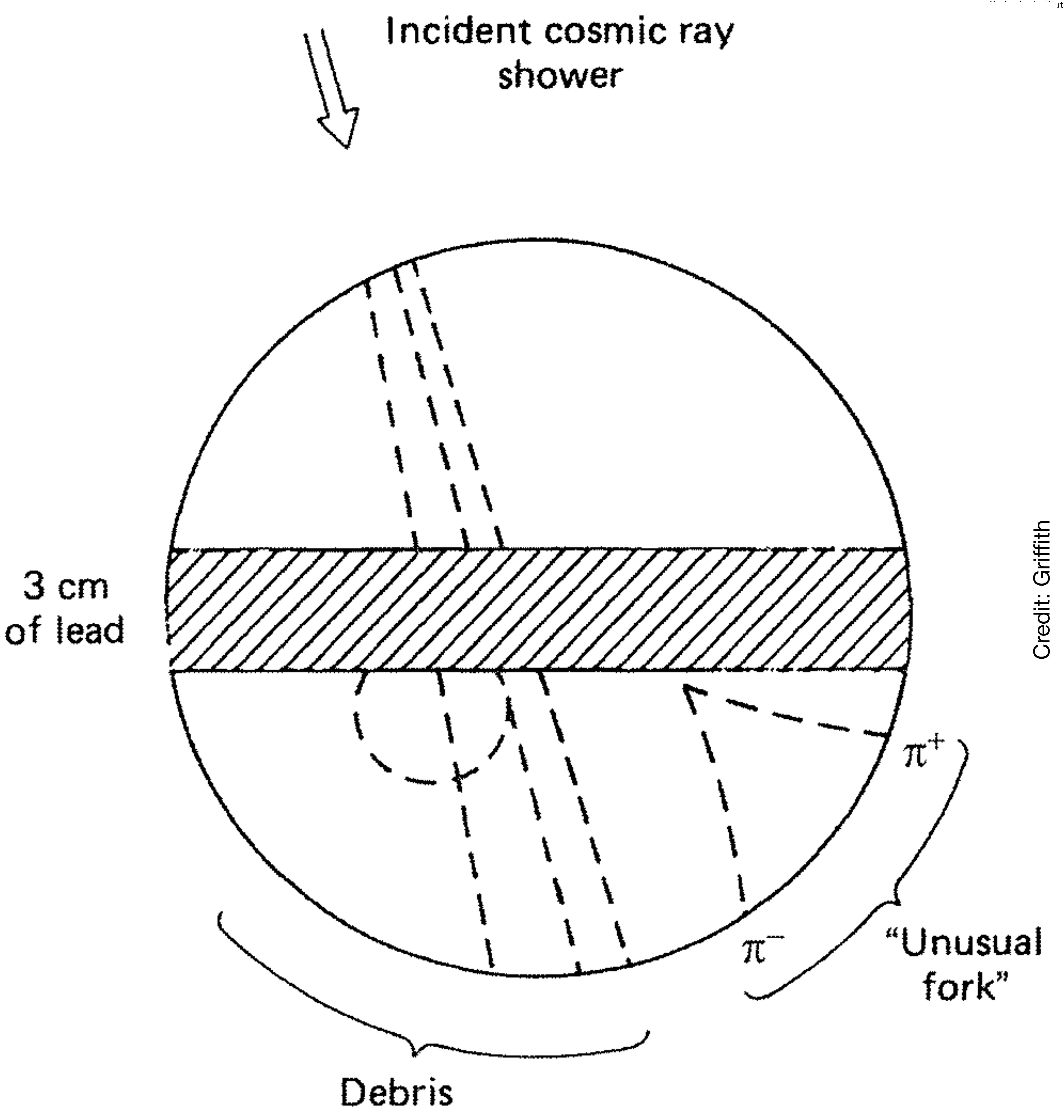
antimatter ✓*

neutrinos

*The existence of the muon was puzzling, and a lot of experiments were still done on neutrinos…



Credit: G. D. Rochester, C. C. Butler, Nature 160 (1947), 855-857



Credit: Griffith

New strange particles

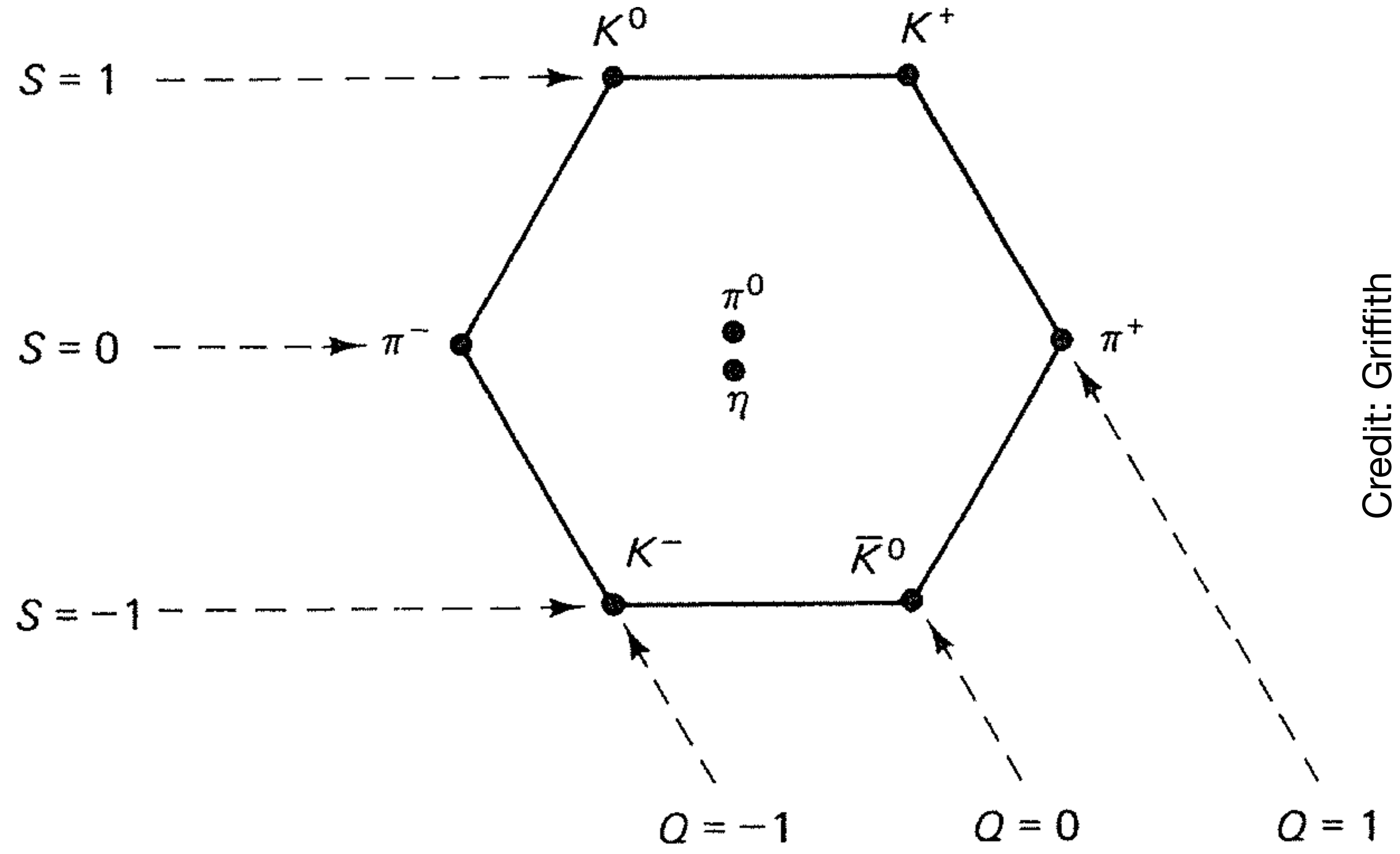
- Signature: a neutral particle was produced in the lead plate, decaying into two charged particles: “V^0” (“neutral vertex”)
  - Today, we identify this particle as neutral Kaon K^0
- Shortly later another V0 was discovered decaying into a proton and a pion
  - Today, we identify this particle as neutral baryon Λ^0

τ-θ-Puzzle

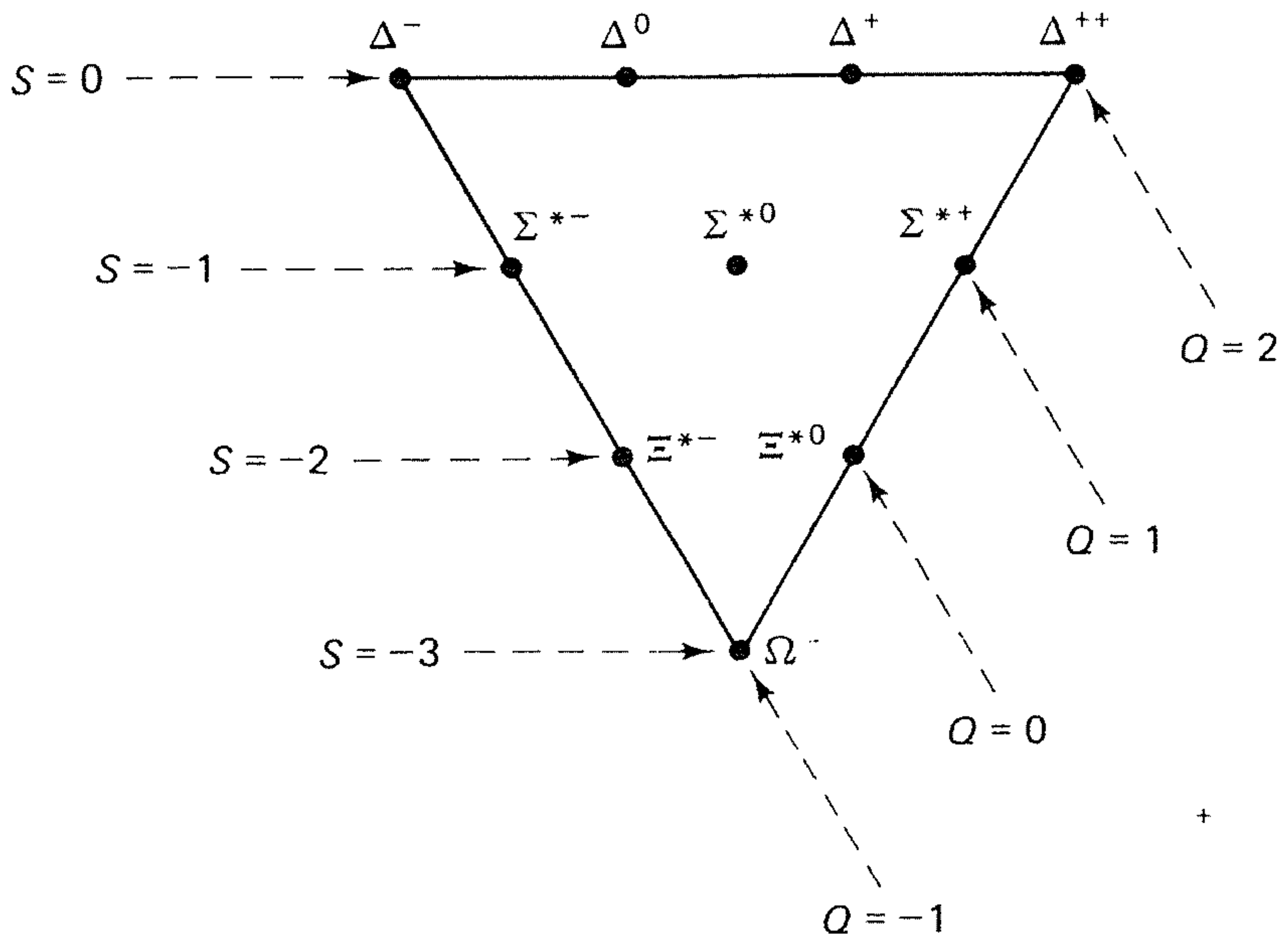
- In the early 1950s, experiments observed two new particles (yay!):
  - $\theta^+ \to \pi^+\pi^0$ and $\tau^+ \to \pi^+\pi^0\pi^0$
  - The puzzle was: The mass and lifetime of the two particles was identical…
  - The parity of the particle was different though since all pions have spin=0 and negative parity
- Solution: Parity is not conserved in these “weak” decays
  - Modern notation: $\tau^+ = \theta^+ \equiv K^+$ (charged Kaon)
- New quantum number: “strangeness” that is not conserved in “weak” interactions

Ordering the “particle zoo”

- Group-theory: Flavour-SU(3) to describe all known particles with just two quantum numbers:
  - Isospin component I_3 (or I_z) and strangeness S
  - or charge Q and S
    (Gell-Mann-Nishijima: $I_3 = Q - \frac{Y_F}{2} = Q - \frac{1}{2}(B+S)$)
  - or hypercharge $Y_F = B + S$ (baryon number B)
  - sometimes called the “eightfold-way”
- Breakthrough: Prediction and later discovery of Ω^- particle with the predicted mass and properties



Credit: Griffith



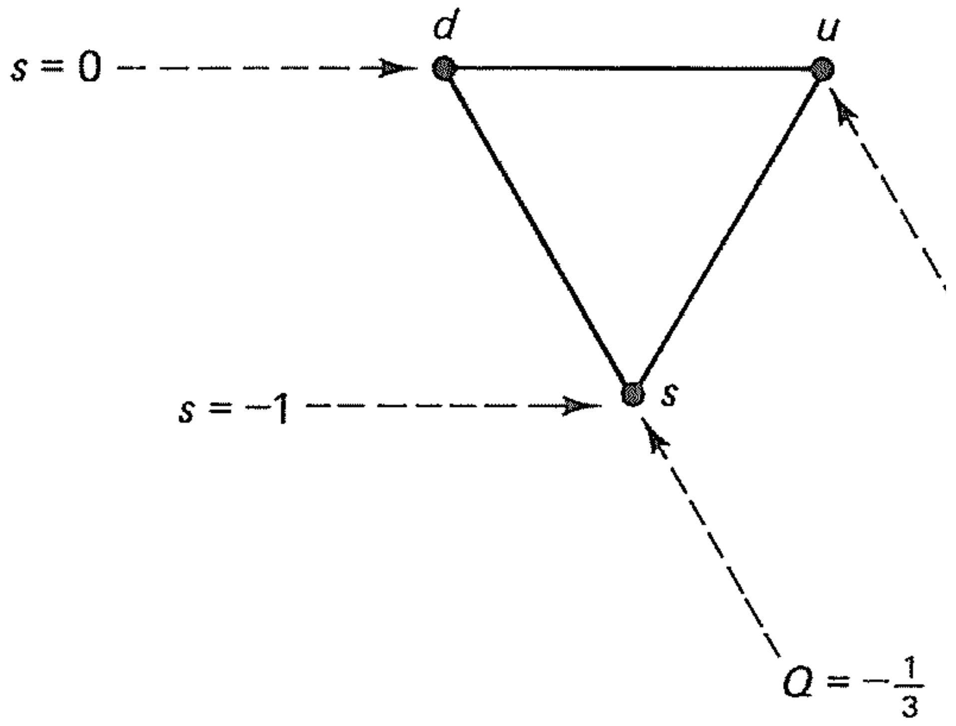
Credit: Griffith

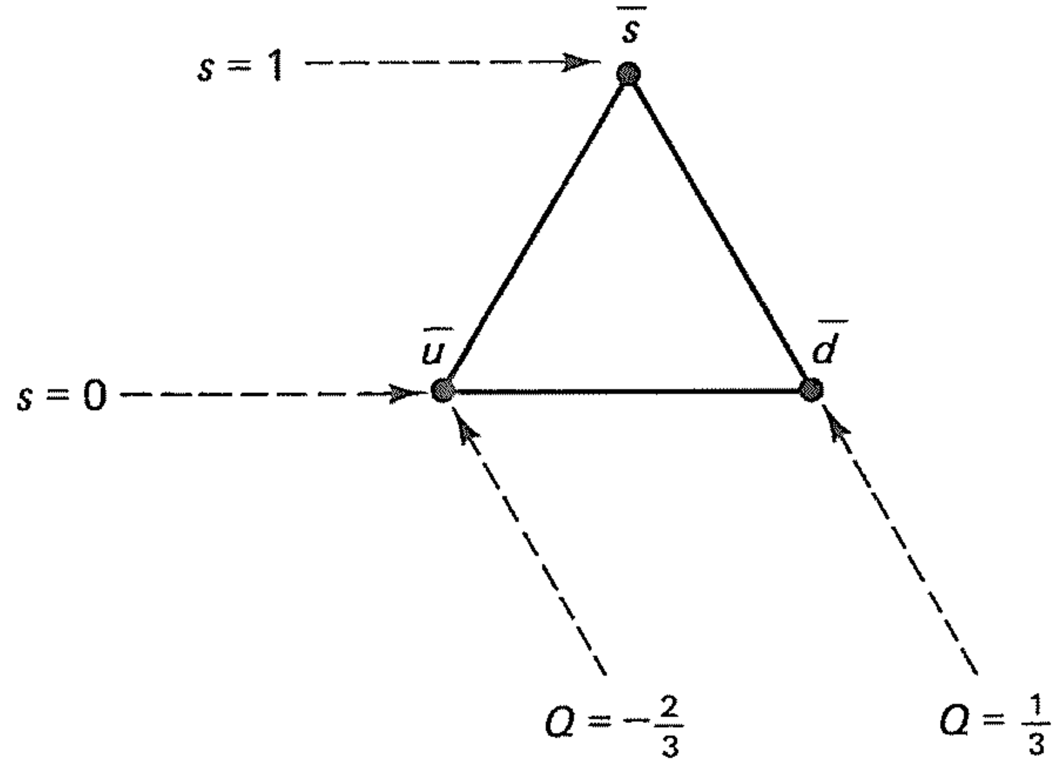
The quark model (1964)

- Gell-Mann (and Zweig) proposed that hadrons are not fundamental particles but instead they are composed of three quarks: up, down, and strange
  - (Anti-)Baryons are composed of three (anti-)quarks
  - (Anti-)Mesons are composed of a quark and an antiquark
  - Today we also know tetraquarks ($qq\bar{q}\bar{q}$, 2014) and pentaquarks ($qqqq\bar{q}$, 2015)
- Avoid Pauli's exclusion principle: quarks have colors, all particles are colorless

Credit: Nobel foundation
https://www.nobelprize.org/prizes/physics/1969/gell-mann/facts/

qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	−1	0	Δ^{-}
uus	1	−1	Σ^{*+}
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	Ω^{-}

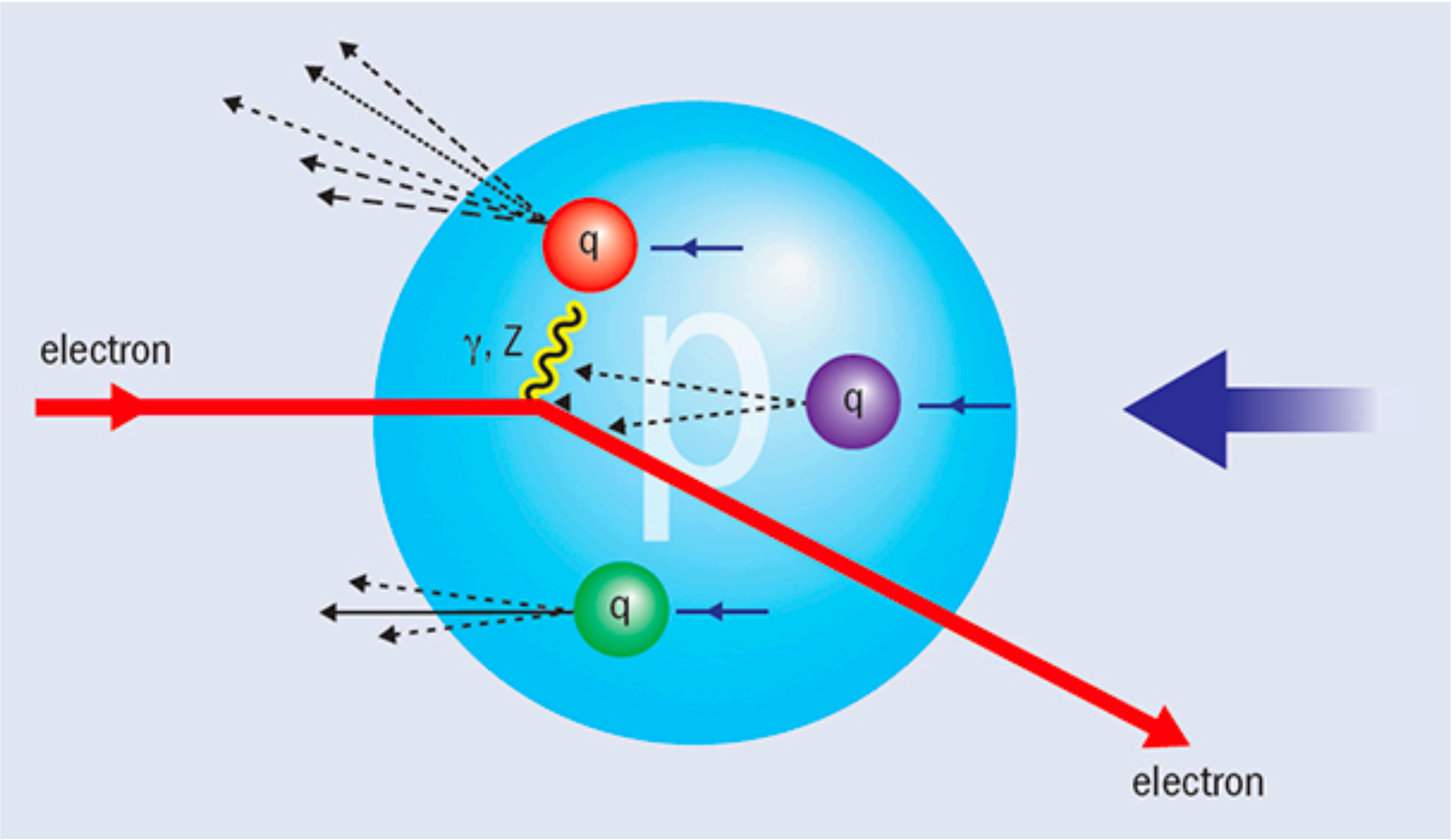




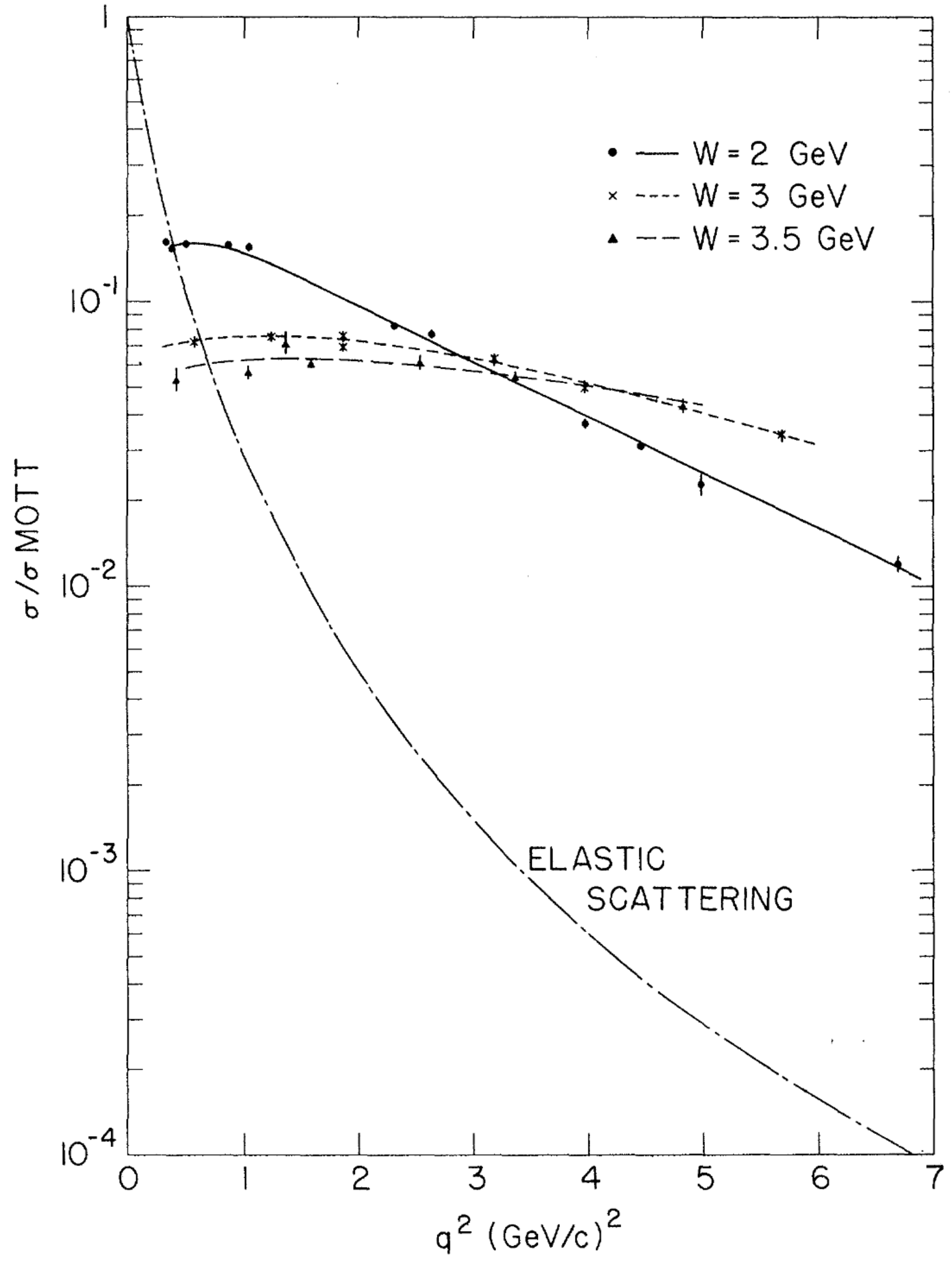
Credit: Griffith

The proton substructure

- Since 1960s: 20 GeV electrons on fixed targets at SLAC
- Probes nucleon structure via deep inelastic scattering (DIS) and strongly supports proton substructure



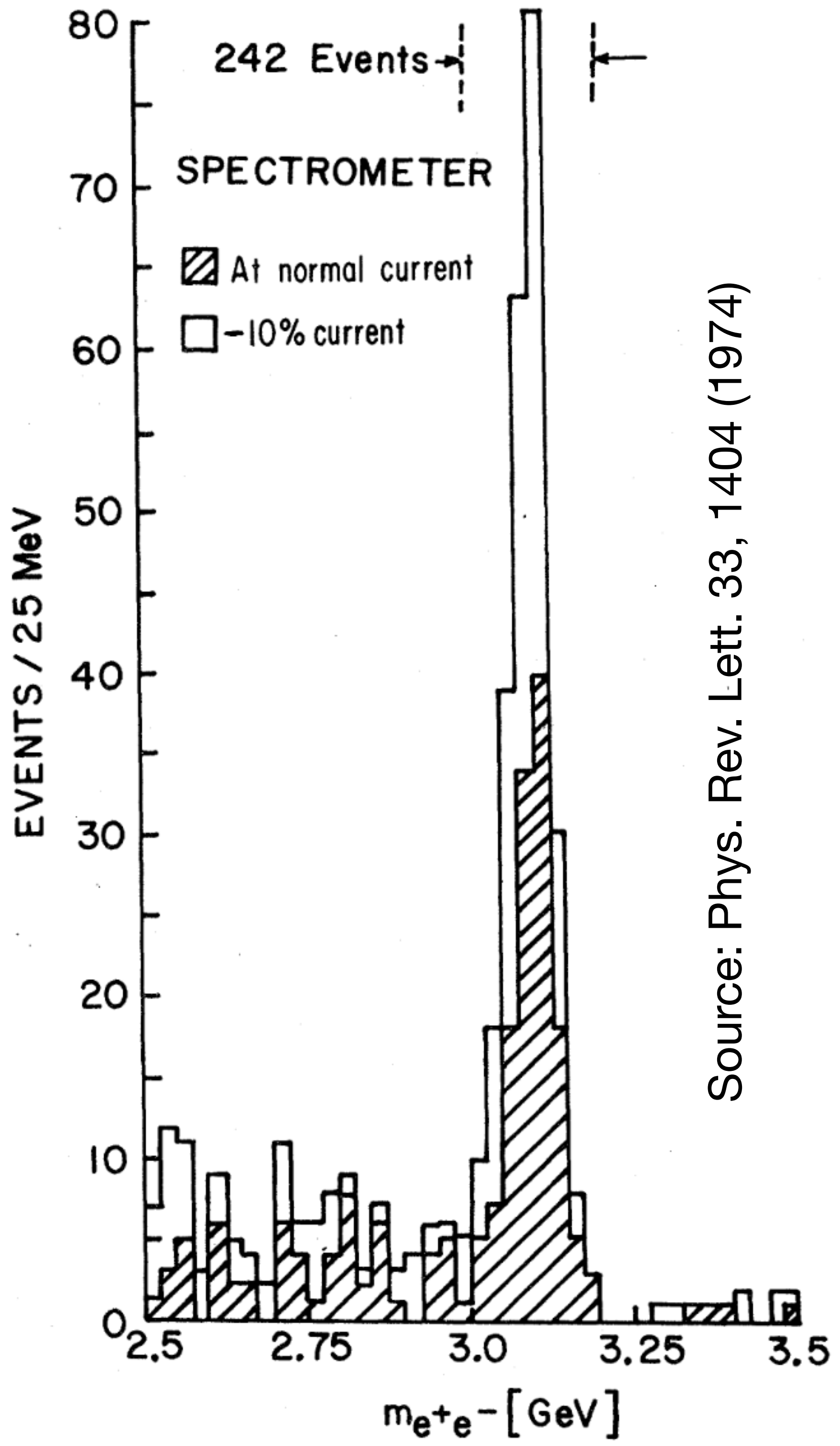
Credit: DESY



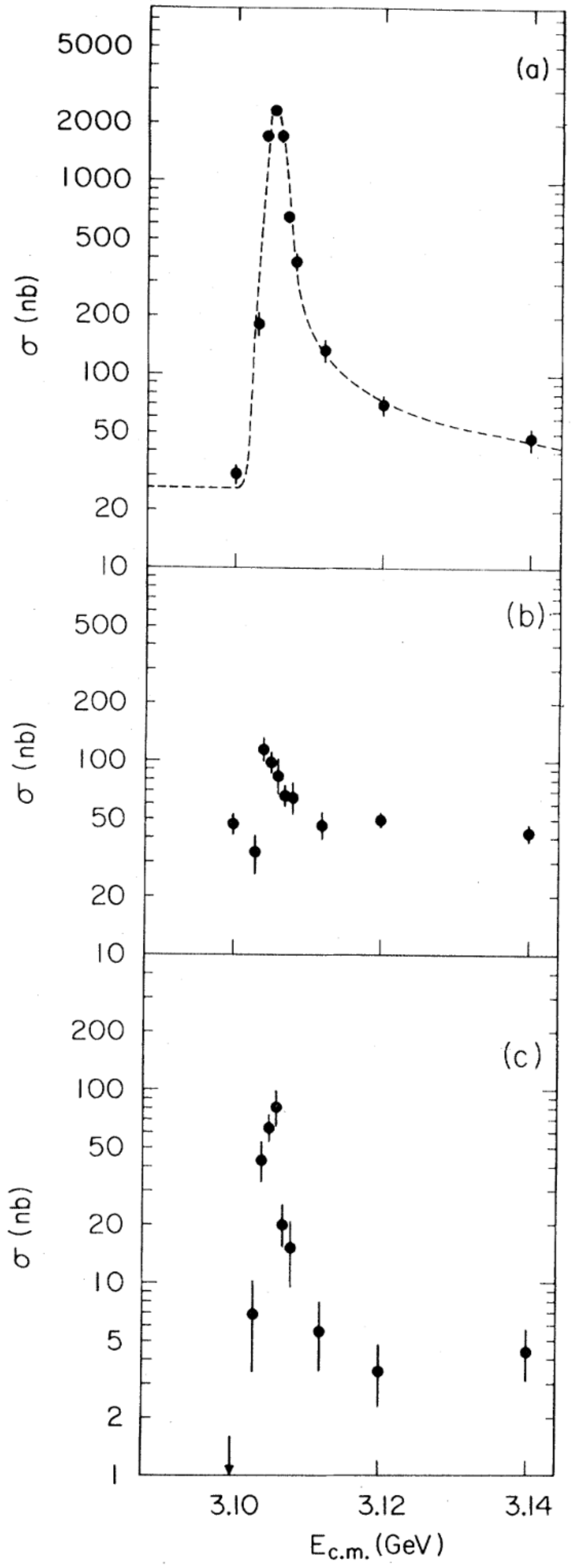
Source: Phys. Rev. Lett. **23**, 935 (1969)

The November revolution

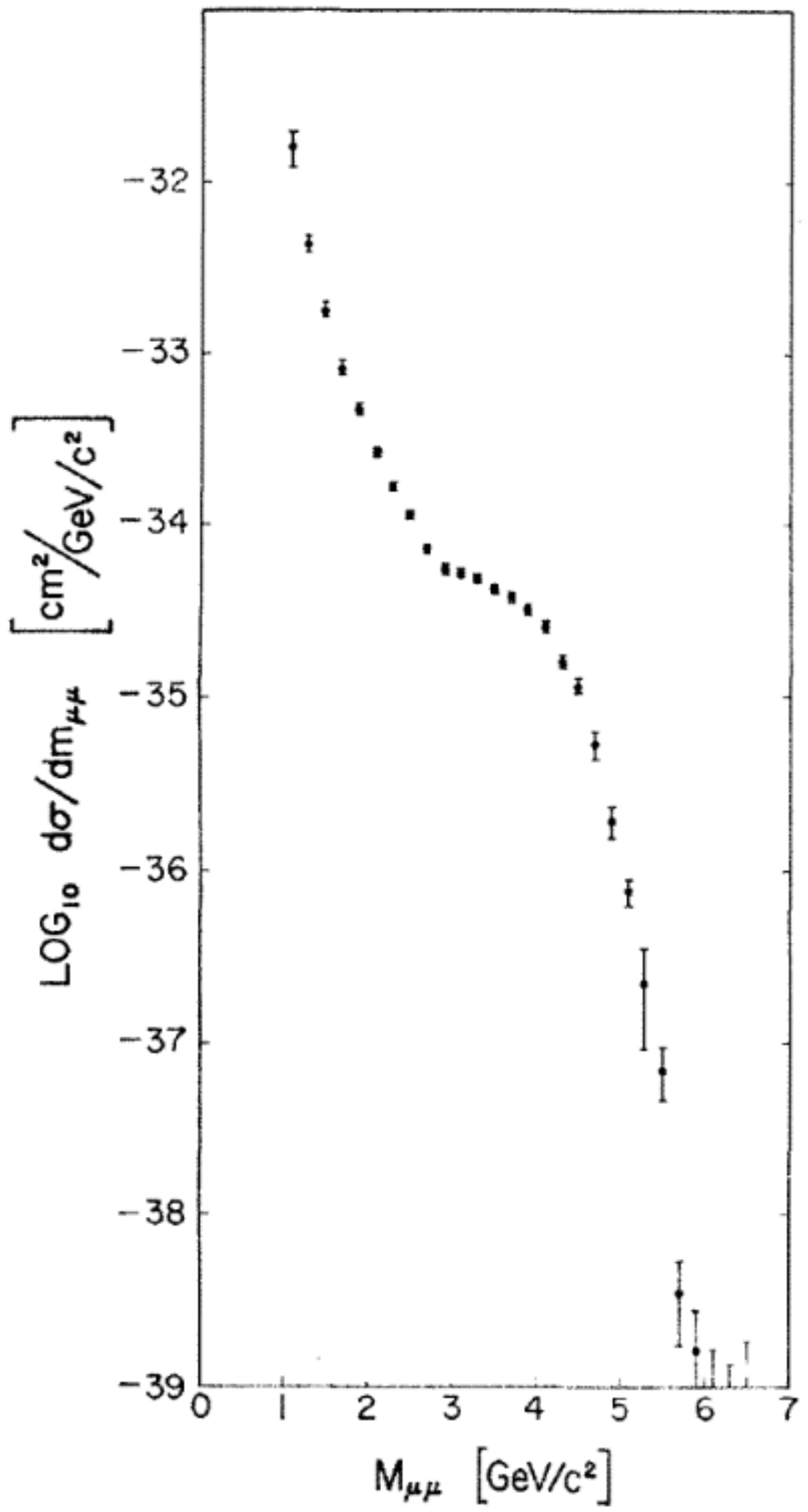
- Discovery of a new particle, about three times heavier than the proton in 1974: J/Ψ
  - Very long lifetime: 10^{-20}s
  - A fourth quark called “charm”
- Theoretically postulated already 1970 based on symmetry arguments (“GIM”-Mechanism)



Source: Phys. Rev. Lett. 33, 1404 (1974)



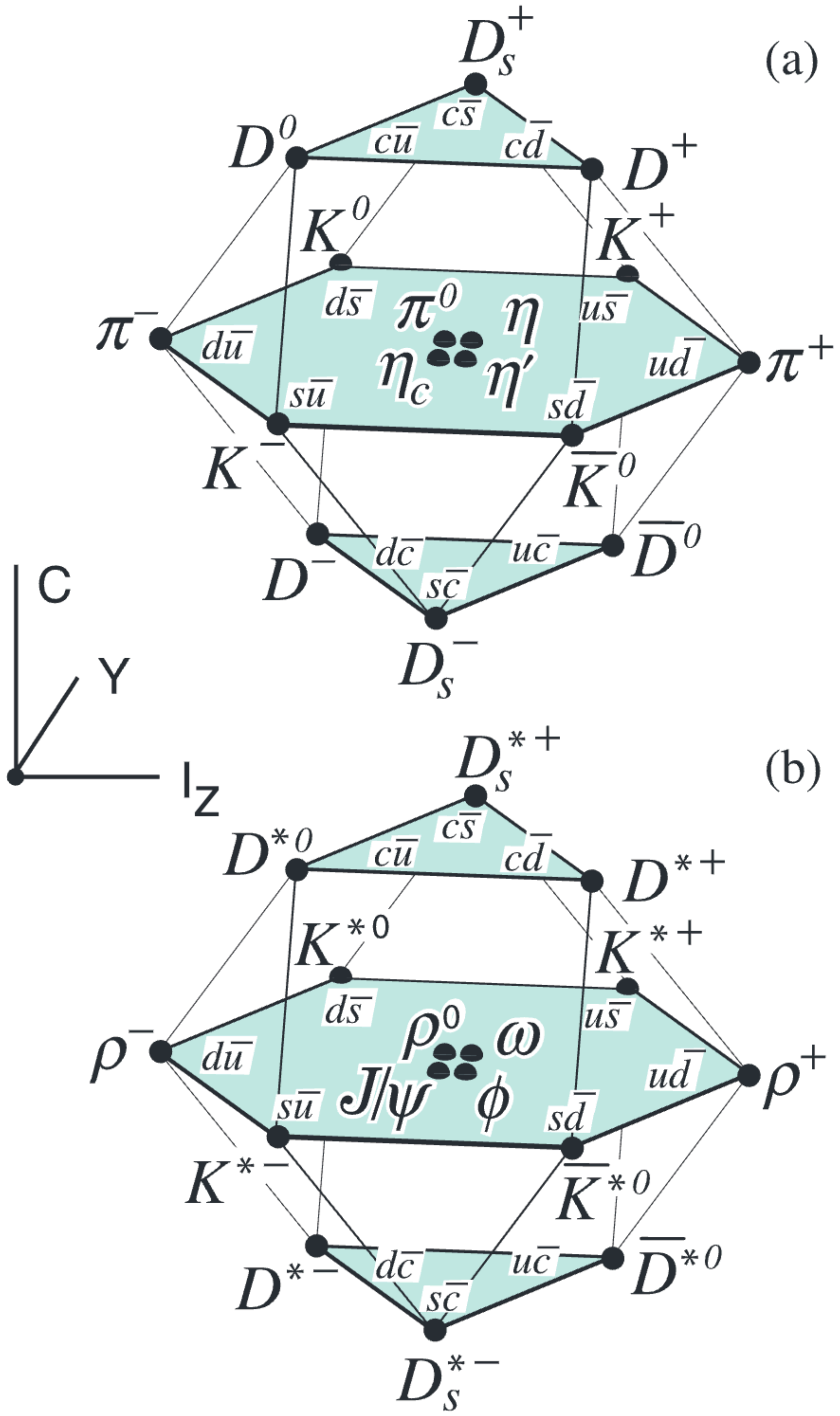
Source: Phys. Rev. Lett. 33, 1404 (1974)



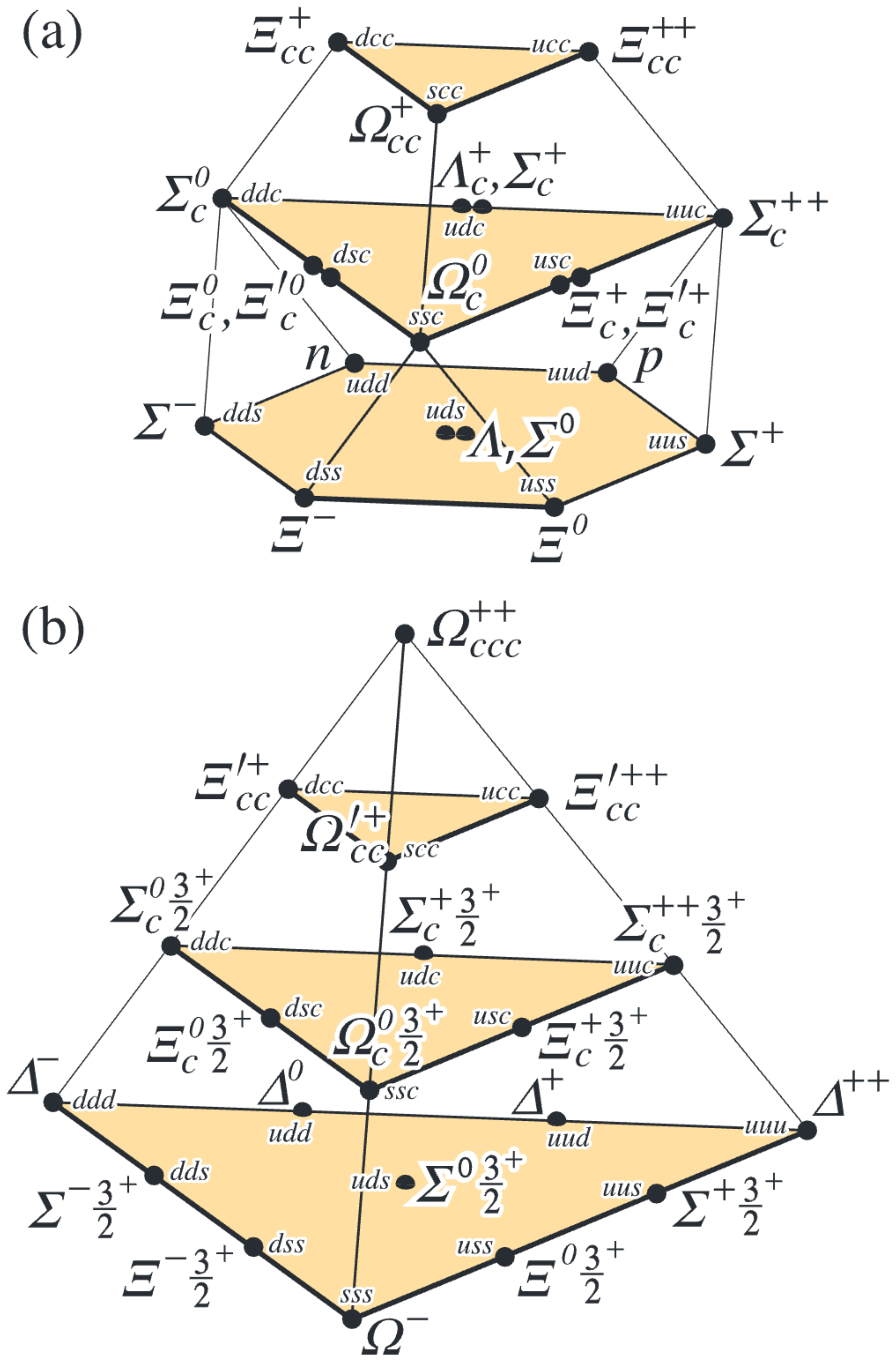
Source: Phys. Rev. Lett. 25, 1524 (1970)

Particle zoo with four generations

Mesons



Baryons



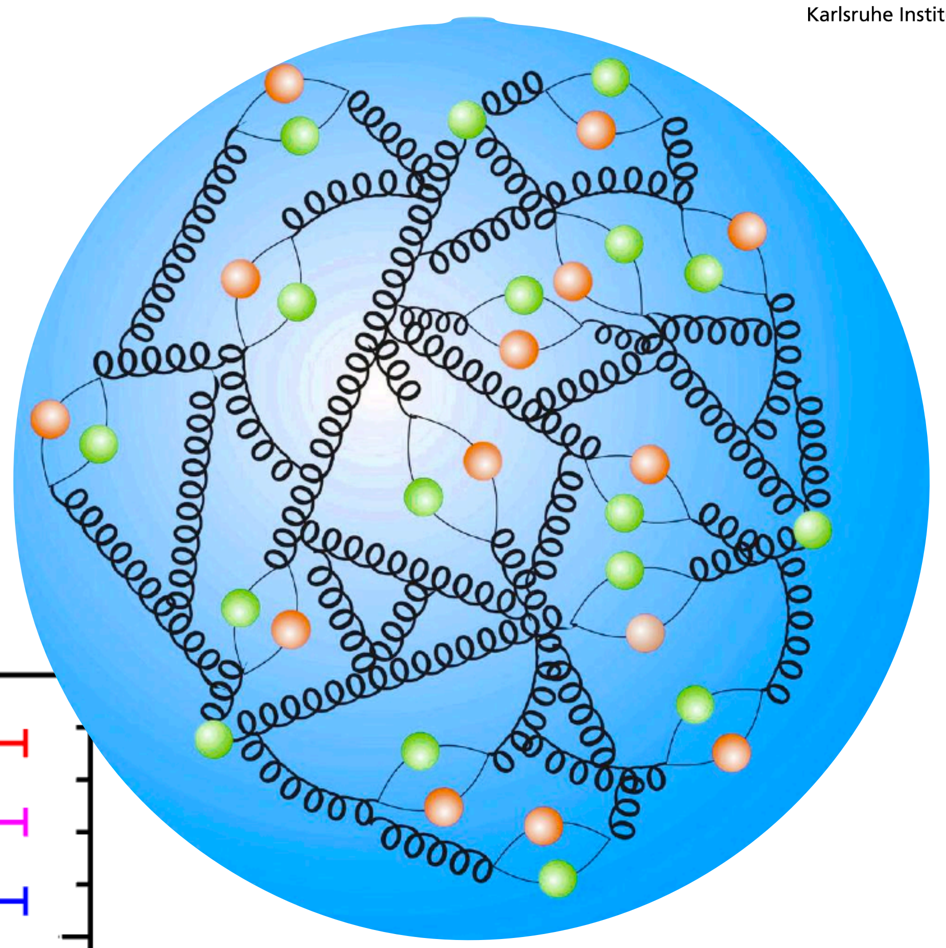
Source: PDG 2020

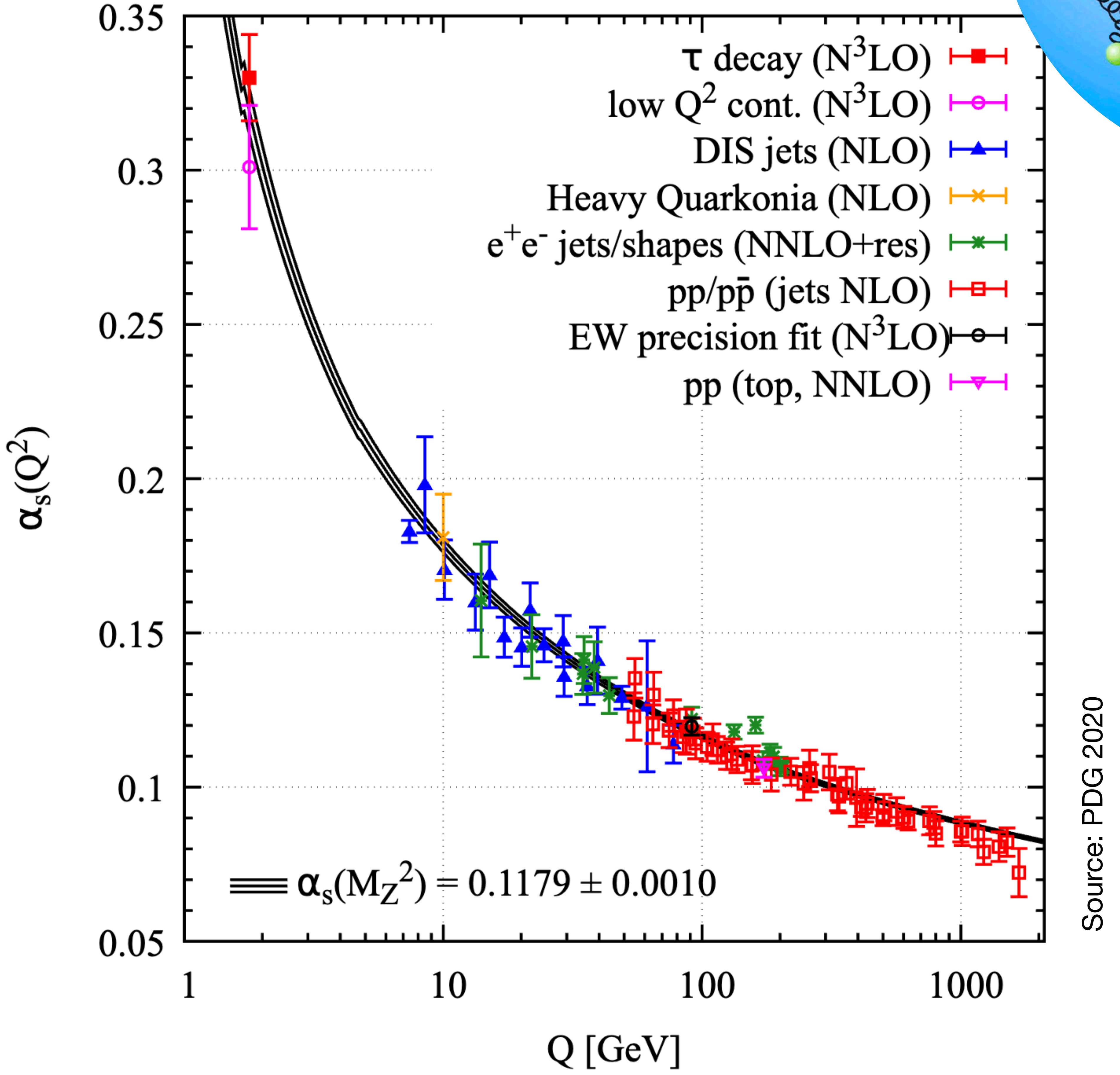
Quarks and leptons

u	c	t
d	s	b
e	μ	τ
ν_e	ν_μ	ν_τ

Quantum Chromodynamics (QCD)

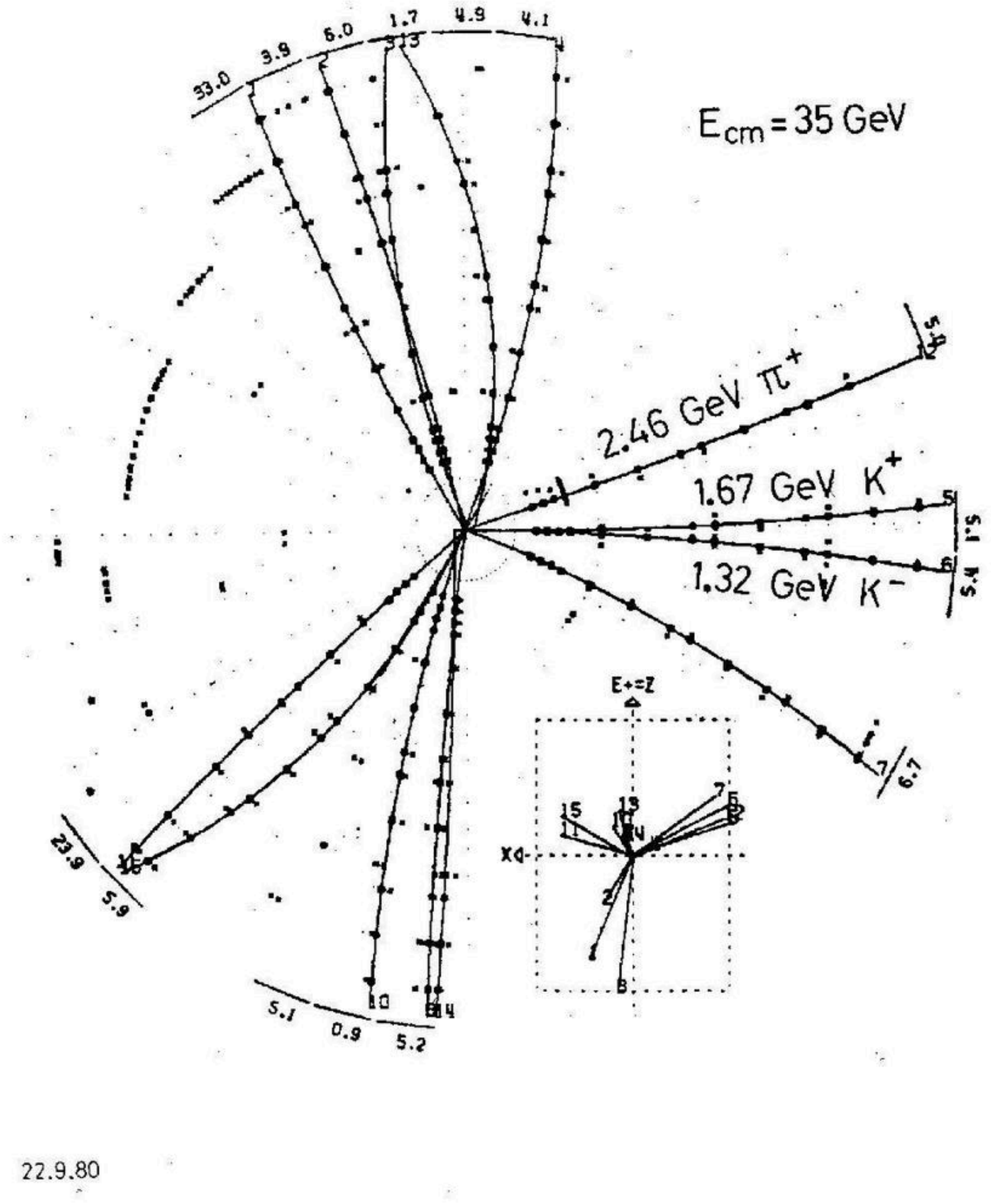
- Asymptotic freedom (Gross, Wilczek, Politzer 1973)
  - QCD coupling strength α decreases with larger energy
  - Quarks behave like (quasi) free particles in DIS scattering
  - At lower energies: Confinement and bound quarks





Quantum Chromodynamics (QCD)

- Massless mediator particles that carry a colour-charge: gluons
- Experimental discovery at DESY in Hamburg (1979) at four experiments in three-jet events at the PETRA collider

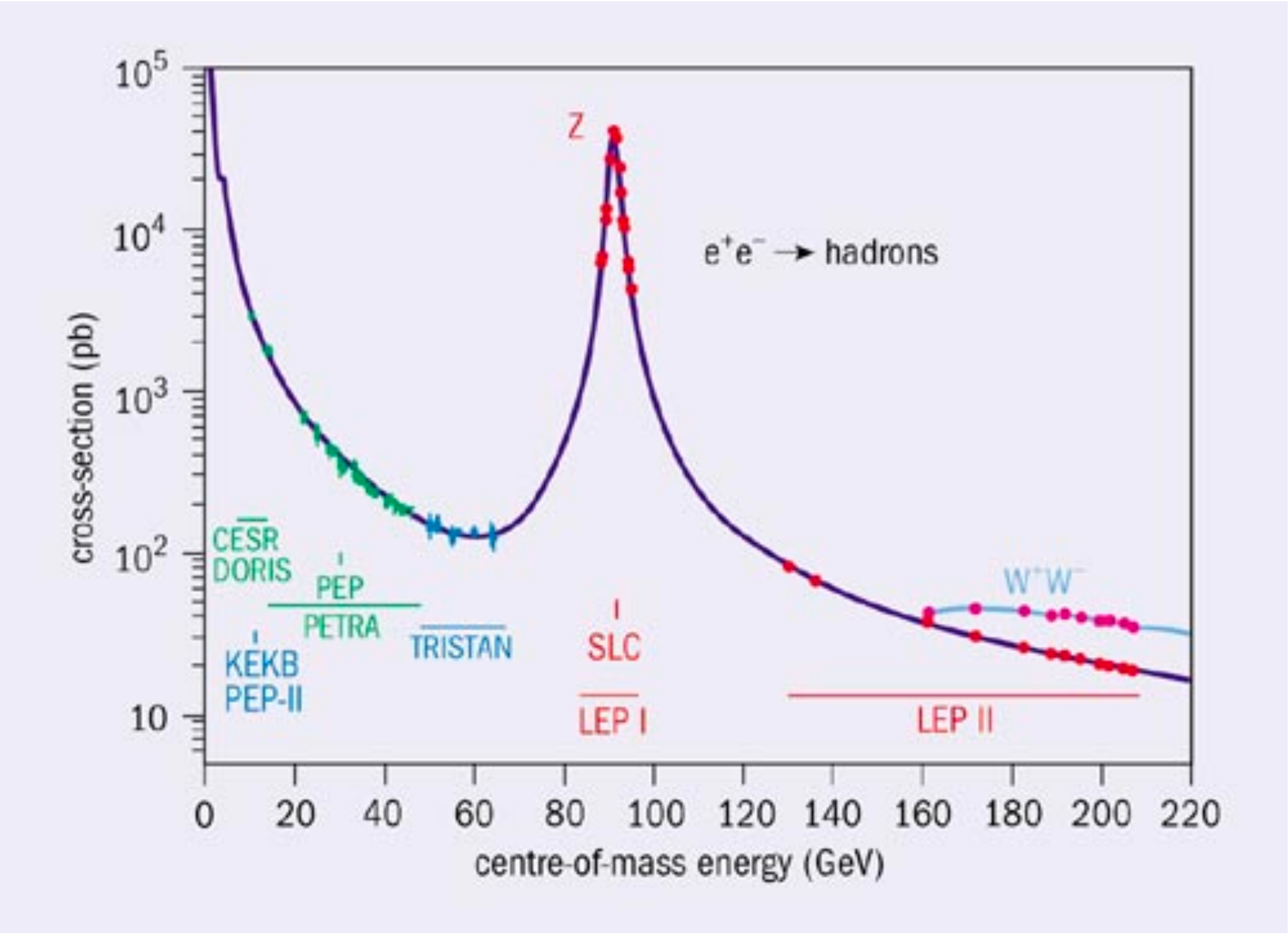


Source: TASSO

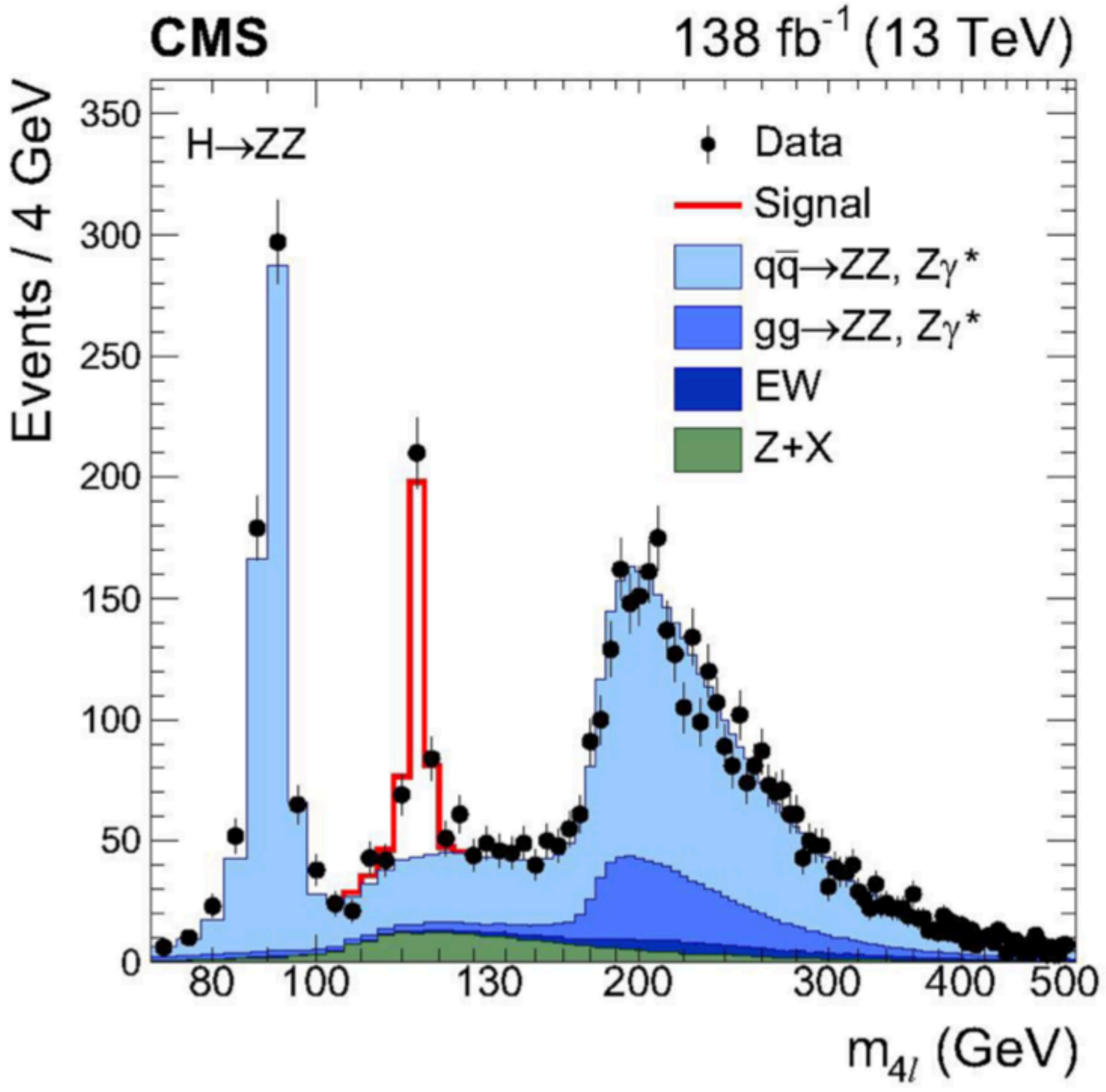
Weak interaction

- Fermi (1934) formulated the β decay as so-called contact interaction with an effective coupling G_F with $[G_F]=GeV^2$
  - Today we identify the mediator particle with the (heavy) W-Boson
- Glashow, Salam, Weinberg (GSW) unified the weak and the electromagnetic interaction
- Electroweak symmetry breaking allows massive W and Z bosons but massless photons
  - Prediction of a massive Higgs boson (= excitation of the Higgs field)

Vector bosons and Higgs



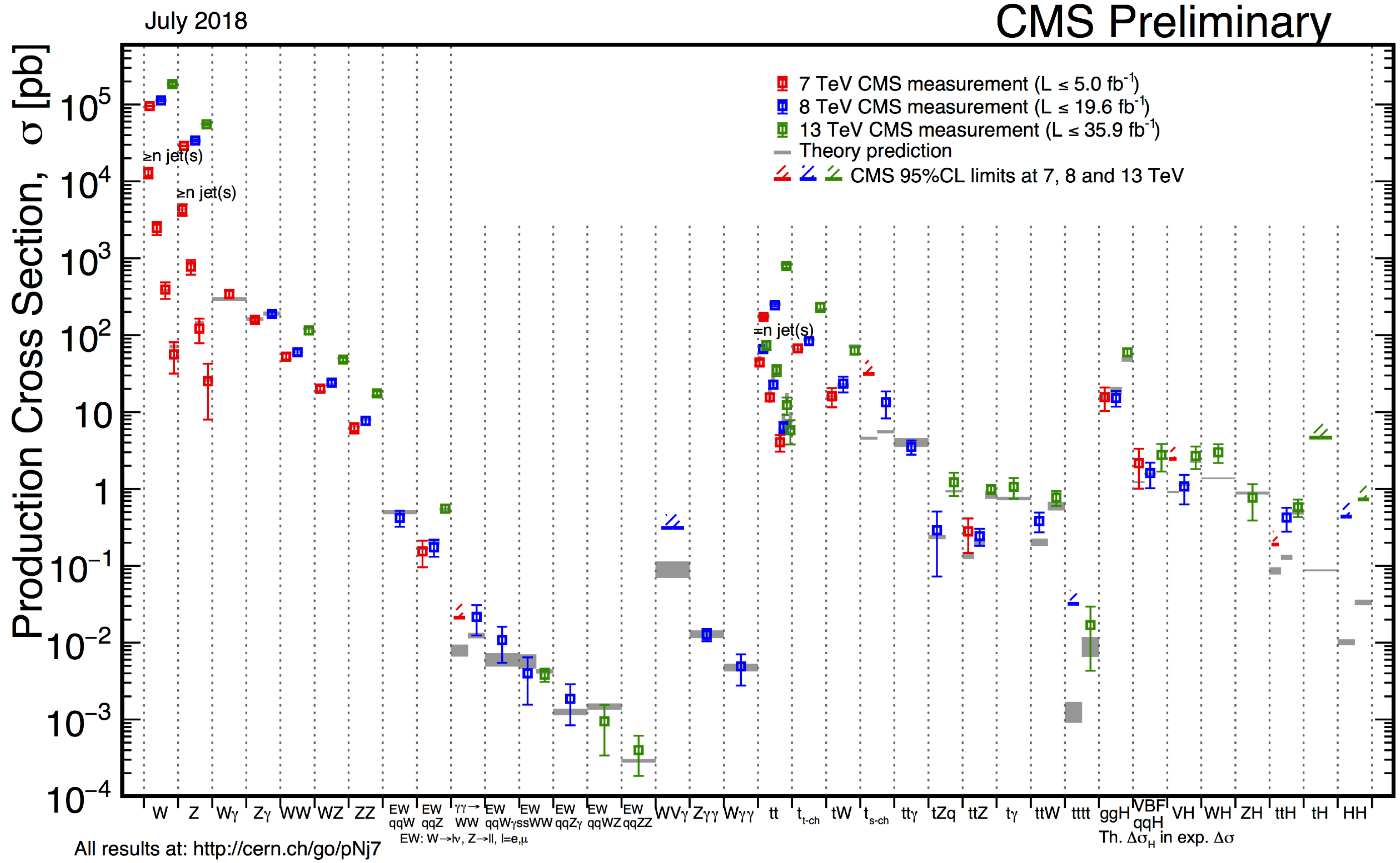
Source: cerncourier

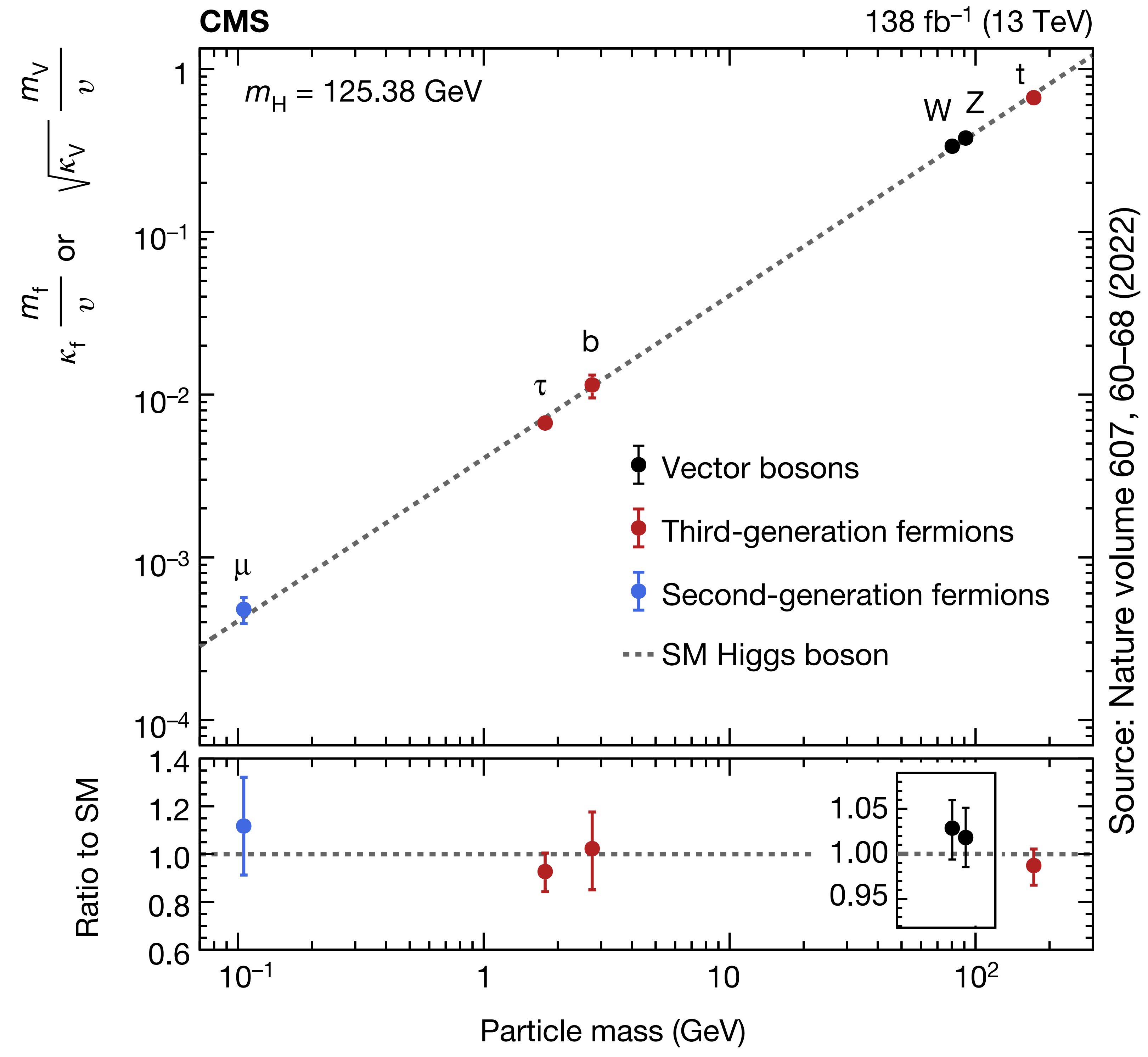


Source: Nature volume 607, 60–68 (2022)

u	c	t		
d	s	b	γ	
e	μ	τ	g	
ν_e	ν_μ	ν_τ	Z^0	H
			$W^{+/-}$	

The Standard Model of particle physics





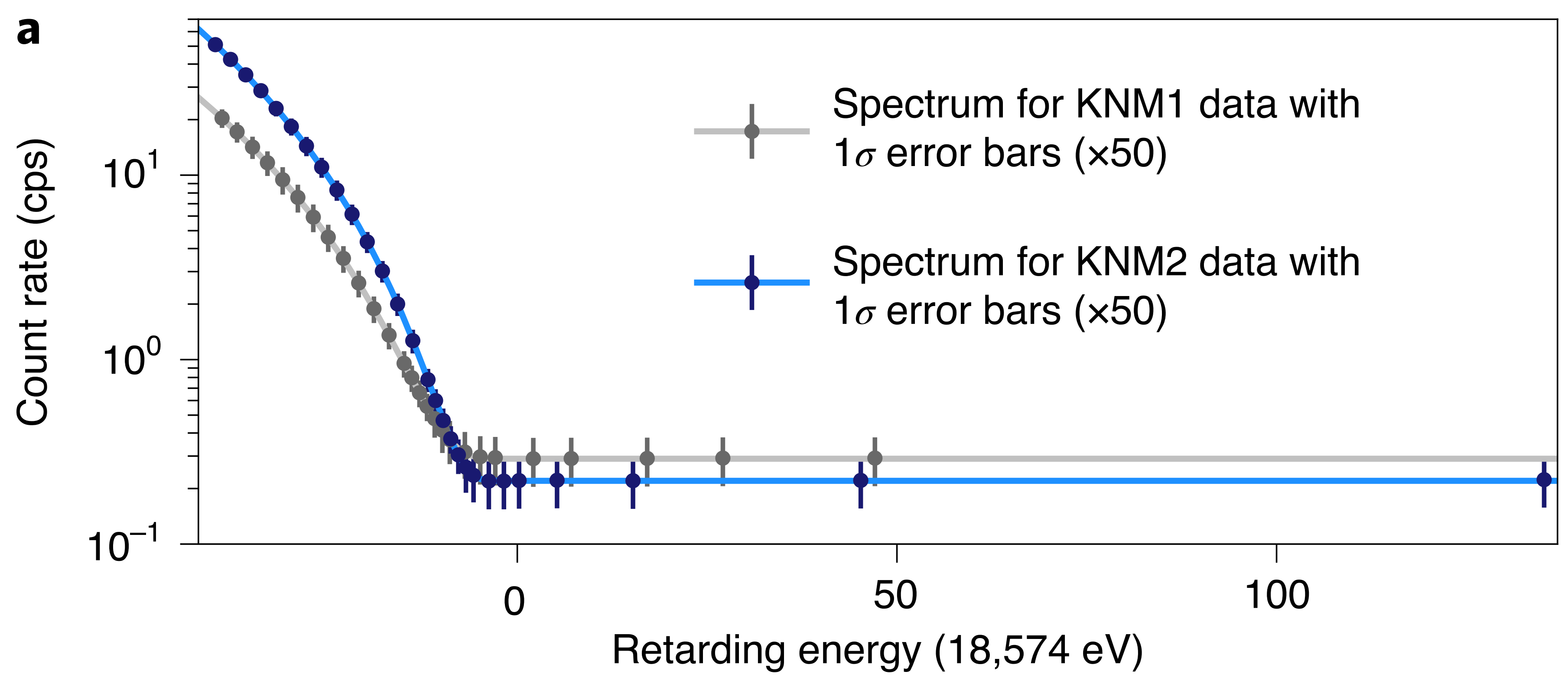

Google
the standard model is
the standard model is wrong
the standard model is brilliant but completely flawed
a standard model is
Unangemessene Vervollständigungen melden
Weitere Informationen

Neutrino masses

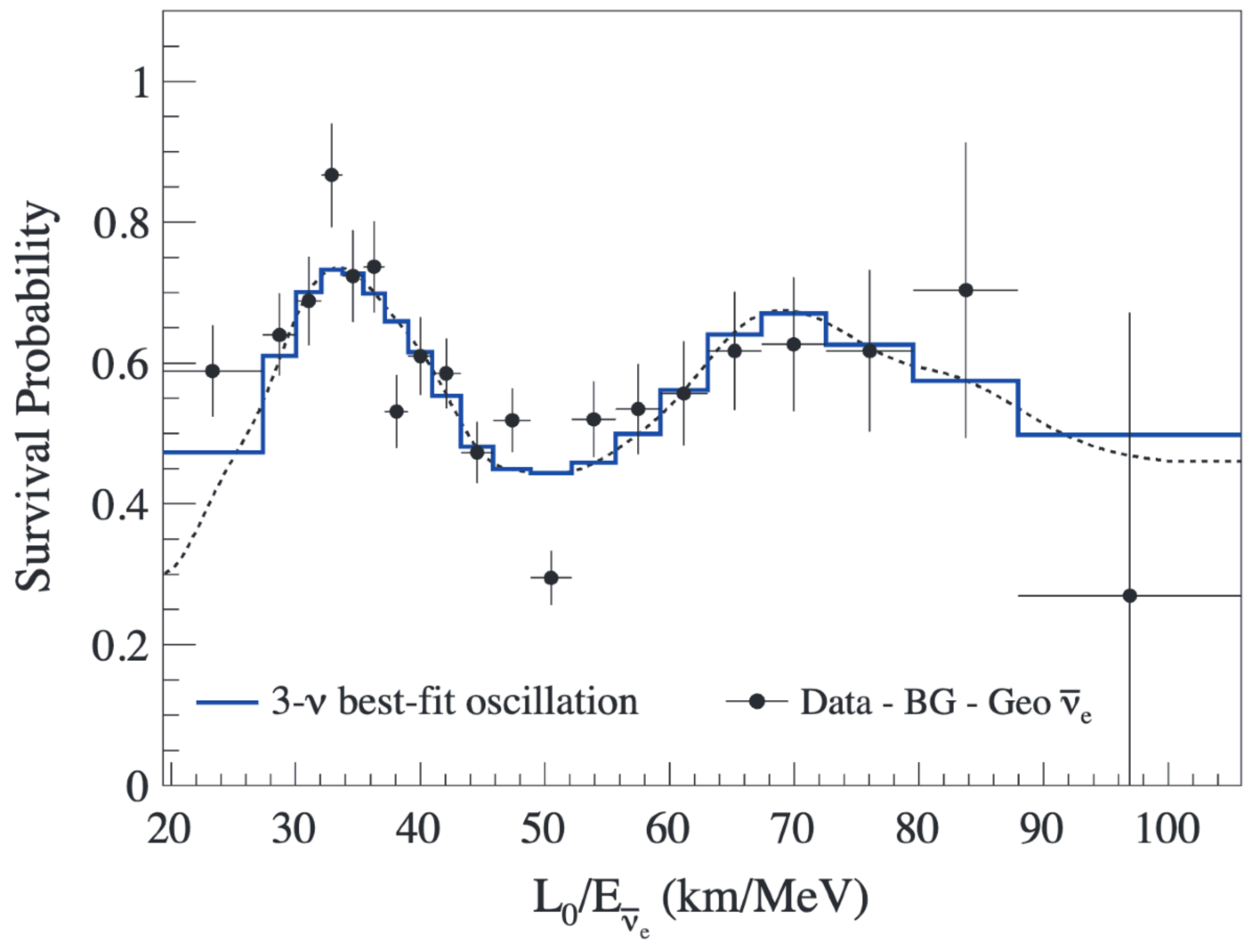
- Neutrino oscillations (ν from the sun, nuclear reactor, and accelerators): $\Delta m \ll \text{eV}$

- Direct electron antineutrino mass measurement at KATRIN (Campus North): $m < 0.8$ eV

- The SM assumes massless neutrinos…



Credit: Nature Physics volume 18, pages160–166 (2022)

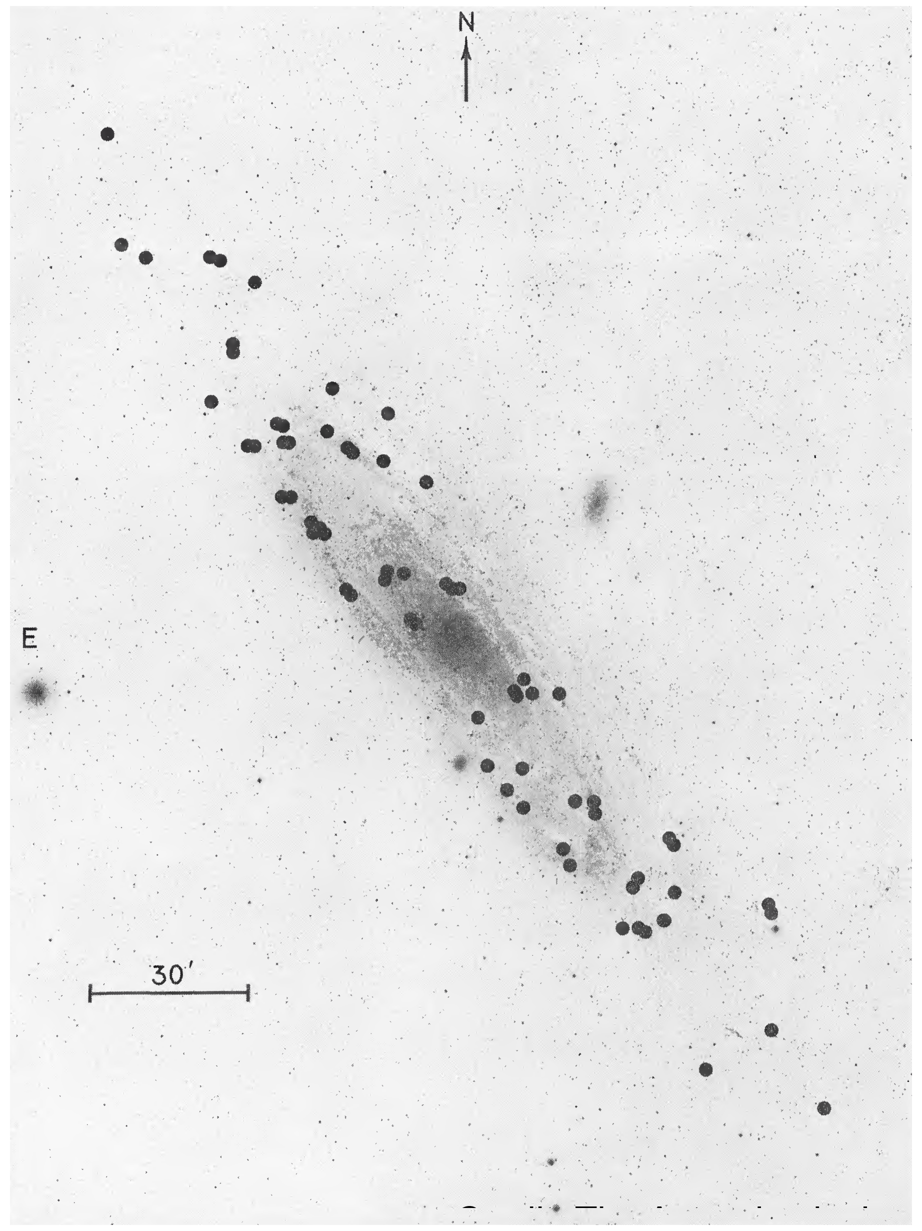


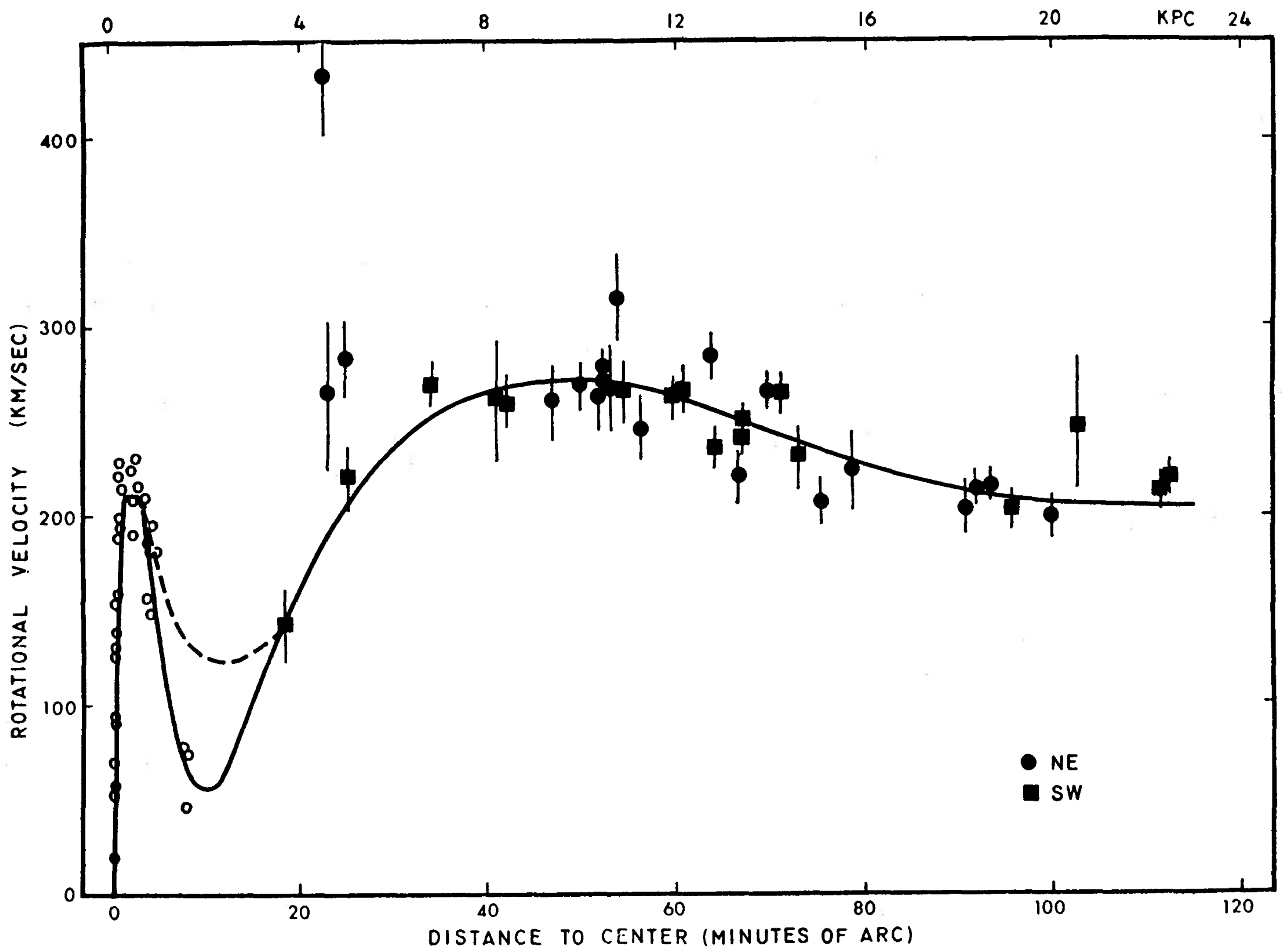
Credit: PDG (2020)

Dark Matter

- Striking evidence for the existence of a new form of matter that amounts to about 80% of all matter in the universe
  - Galaxy rotation curves (Vera Rubin)
  - Cosmic microwave background
  - Galaxy collisions
  - Structure formation
  - …
- No particle in the SM is a suitable candidate…

Credit: Carnegie Institution of Washington





Credit: The Astrophysical Journal, Vol. 159, February 1970

Where is the antimatter?

- The SM has a mechanism for CP violation that has been observed in strange, charm, and bottom quarks: CKM Matrix
- The observed matter/antimatter baryon asymmetry $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-9}$ in the universe is much larger than predicted in the SM…
- … and many more "anomalies" that we will meet again during this lecture.

What questions do you have?