The discovery of the muon

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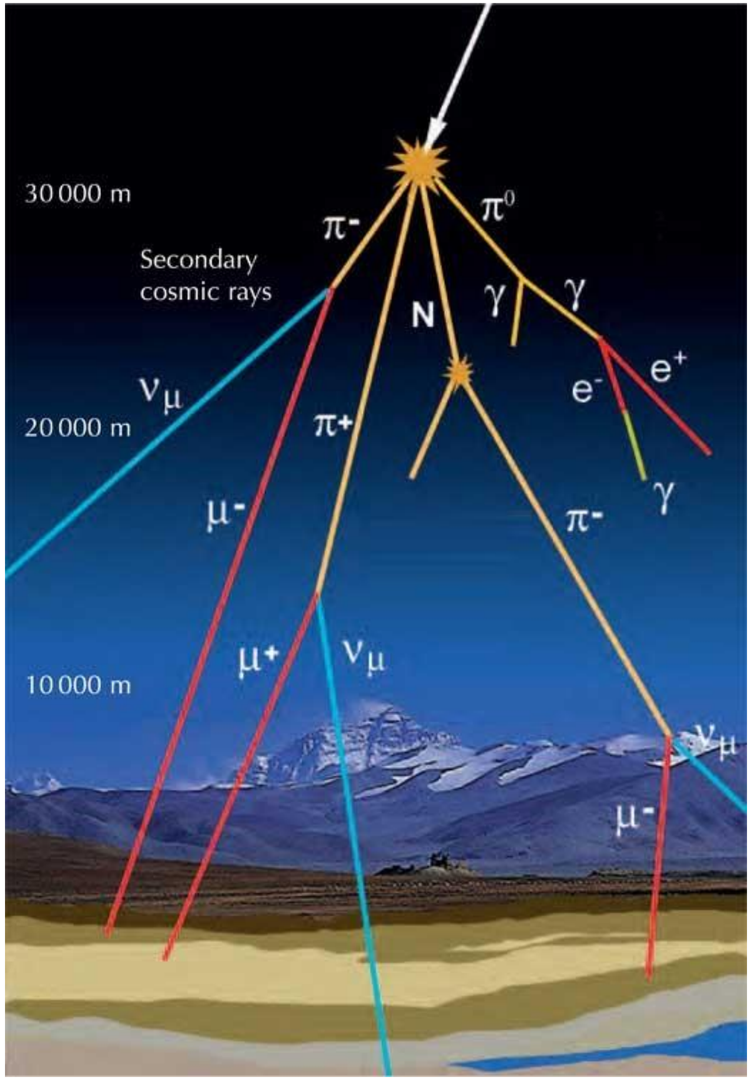
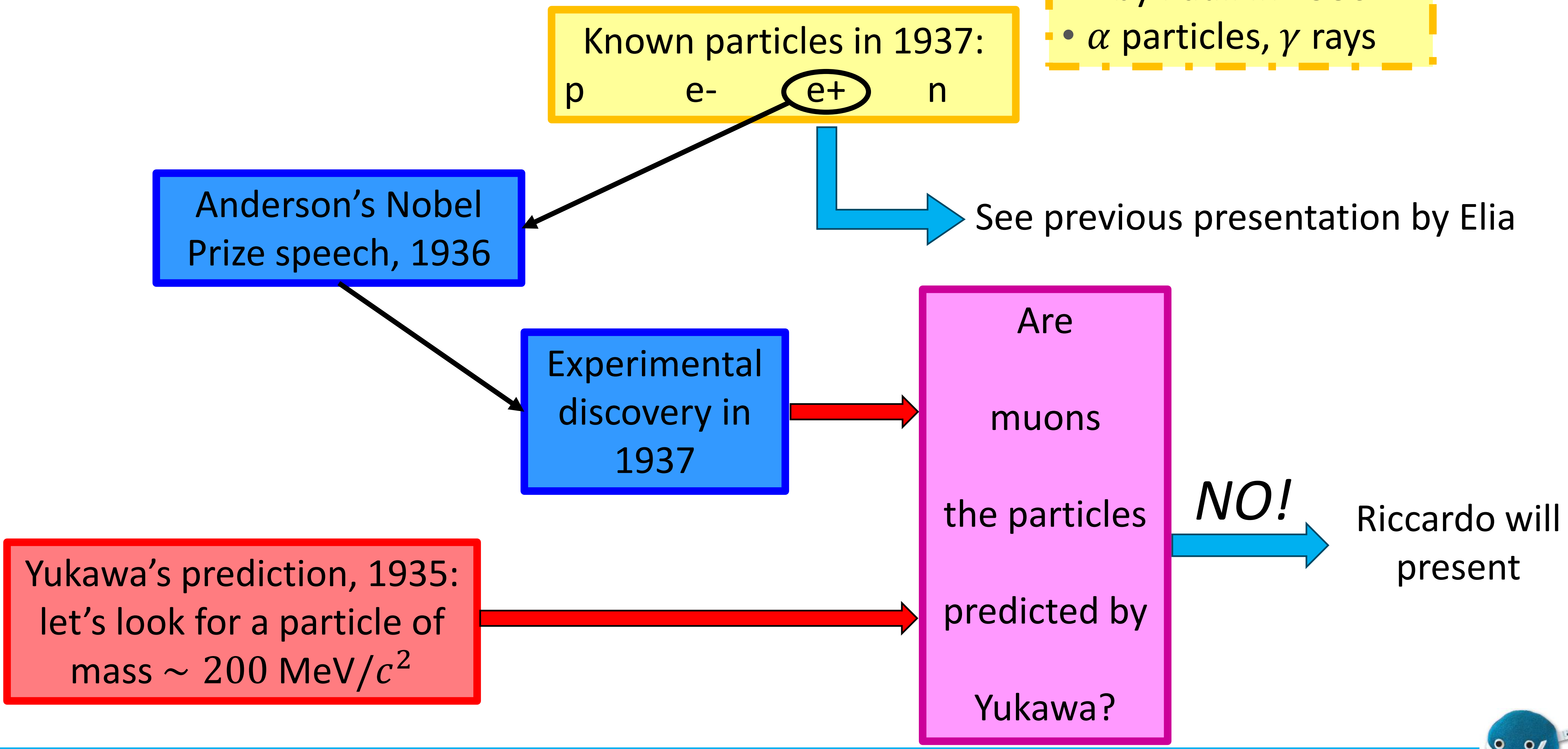
Outline

1. The fate of the μ «mesons»
2. The «recipe» for muon discovery
3. Energy loss through matter
4. Experimental setup and results
5. Muons yesterday vs today:
    - experiments
    - applications



In short

- Neutrino postulated by Pauli in 1930
- α particles, γ rays



Consequences in literature

1. Yukon?
   Particle X? → Mesoton → Mesotron → μ meson → Muon
   «Heavy e^-»?

	Mesoton	Mesotron	μ meson	Muon
Yukon? / Particle X? / «Heavy e^-»?	Anderson	Millikan and everybody else	Everybody until a few years later	Everybody today

2. We often focus more on the misidentification and less on the history of the discovery (not Cahn-Goldhaber)

   Vernon Hughes: «The story of the discovery of muon is long and intriguing (Nishijima, 1963)»

Muon discovery:

By Peter Galison, 1982

When?

4 possible years,
from 1929 to 1947

By whom?

Something like 11
possible names

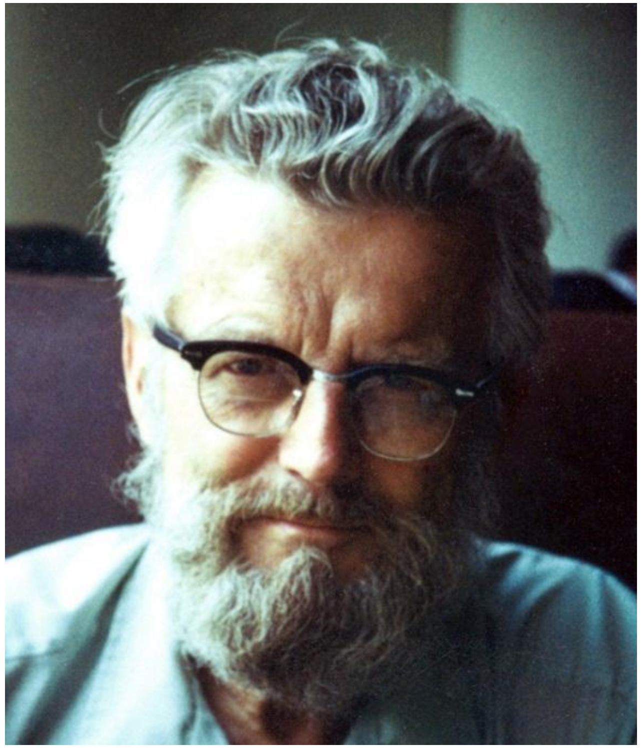
How?

Experimental and/or
theoretical efforts

1937: four discoverers

Carl D. Anderson

Jabez C. Street



Seth H. Neddermeyer

Edward C. Stevenson

Consequences in literature

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   Vernon Hughes: «The story of the discovery of muon is long and intriguing (Nishijima, 1963)»

Today: «The story of the discovery of muon is simple and fun»

Also see Elia’s presentation

Recap: who were Anderson and Neddermeyer?

Carl D. Anderson

-Was born in 1905 in New York City

-Studied Physics at Caltech (Pasadena, California): 1927 B.S., 1930 Ph.D.

-Worked on cosmic rays under the supervision of 1923 Nobel Laureate Millikan

-Discovered positrons in 1932

-Nobel Prize for his discovery in 1936

Seth H. Neddermeyer

-Was born in 1907 in Richmond, Michigan

-Bachelor of Arts in 1929 at Stanfod University

-Anderson’s first graduate student at Caltech, 1935 Ph.D. on electron energy losses in matter

-Participated in research that led to positron discovery

Working together, they discovered muons in 1937

Who were Street and Stevenson?

Jabez C. Street

-Was born in 1906 in Opelika, Alabama

-Studied electrical engineering: 1927 B.S. in Alabama Polytechnic Institute, 1931 Ph.D. in University of Virginia

-1932-1970: Harvard University, from Instructor to Professor of Physics

-Since Fall 1940 he headed group at MIT that created ground and ship radar systems (RADAR and LORAN)

Edward C. Stevenson

-I couldn't find many details about his personal life/background/early education

-Initially at Delaware University and Bartol Research Foundation at Franklin Institute

-Then became Street's graduate student at Harvard

-Last published work is muon discovery in 1937

Working together, they provided supporting evidence of muon discovery in 1937 and the first measurement of muon mass

No Nobel prizes won

Anderson: 18 nominations until 1953 (10 times by Millikan)
Neddermeyer: 20 nominations until 1952 (10 times by Millikan, 7 by Anderson)
Street: 9 nominations until 1967. Stevenson: 1 nomination in 1949

1982 Enrico Fermi Award to Neddermeyer

> For participating in the discovery of the positron, for his share in the discovery of the muon, the first of the subatomic particles; for his invention of the implosion technique for assembling nuclear explosives; and for his ingenuity, foresight, and perseverance in finding solutions for what at first seemed to be unsolvable engineering difficulties.

Yukawa's model, 1935

Electric potential: $\nabla^2 V = -4\pi q \delta(\vec{r})$ → Long-ranged static sol. $V(r) = \frac{q}{r}$

Wave equation in vacuum: $\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right)V = 0$ → search for sol. $e^{i(\vec{k}\cdot\vec{x} - \omega t)}$ → $\omega^2 - k^2 = 0$. Now: $\hbar\omega \sim E, \hbar k \sim p$ → $E^2 = p^2$, photons are <u>massless</u>

Strong interactions are short-ranged! $\sim$ 1fm ↔ mediator has mass m

$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 + \mu^2\right)V = 0$ corresponds to $\omega^2 - k^2 = \mu^2 \leftrightarrow E^2 = p^2 + m^2$

Search for static solution with spherical symmetry (also see backup):

$$\varphi(r) = \frac{A}{r}e^{-\frac{r}{1\,\mathrm{fm}}}$$ → mediator mass of $100 \div 200\ \mathrm{MeV}/c^2$

What was the motivation for the experiments?

Not Yukawa's prediction, apparently…

About the positron discovery, Anderson had said:

«I was not familiar in detail with Dirac's work. I was too busy operating this piece of equipment to have much time to read his papers. […] I was looking at the cloud chamber data and going by that.»

On the muon discovery:

«I didn't know about Yukawa's predictions until after we published the paper in the spring of '37. When I heard of Yukawa's work, the first reaction was 'Of course these are the same particles'.» -Anderson

«Presumably nuclear forces were not involved. I didn't know how to think about Yukawa's theory; I wasn't enough of a theoretician to have grasped it..» -Neddermeyer

But instead, from their paper:

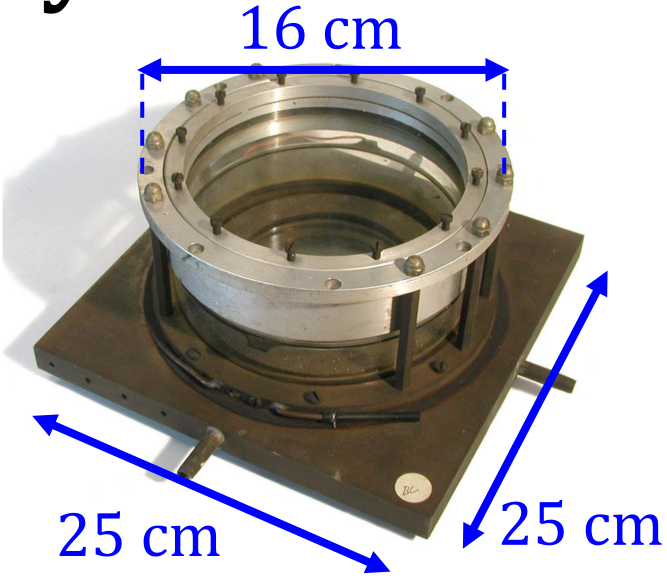
for checking our previous measurements[2] which had shown the presence of some particles less massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory

Collision energy loss

Radiative energy loss

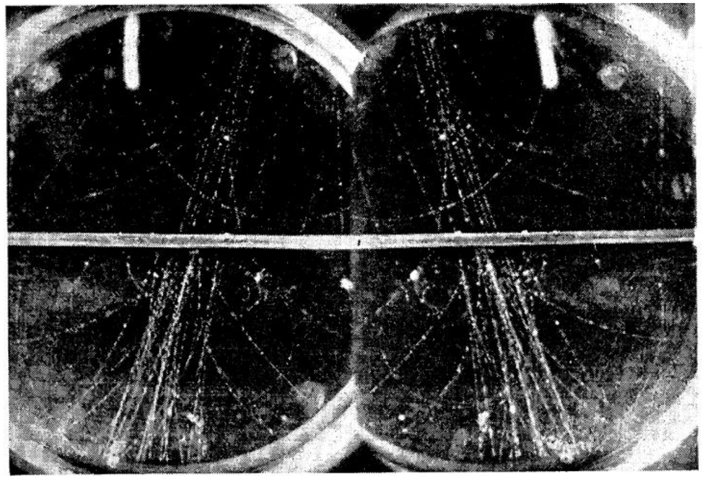
Also see Elia's presentation

Recap: Wilson's cloud chamber used by Anderson



- Saturated gas (argon) becomes supersaturated after adiabatic expansion; cosmic rays ionize the gas; ions act as condensation nuclei→droplets
- Magnetic field → $B\rho = 0.3p[\mathrm{GeV}/c]/e$

  Warning: it's $H\rho$ in their papers
- Plate of lead/platinum to cause energy loss
- Glass piston and mirrors on the side



Energy loss through matter: collision

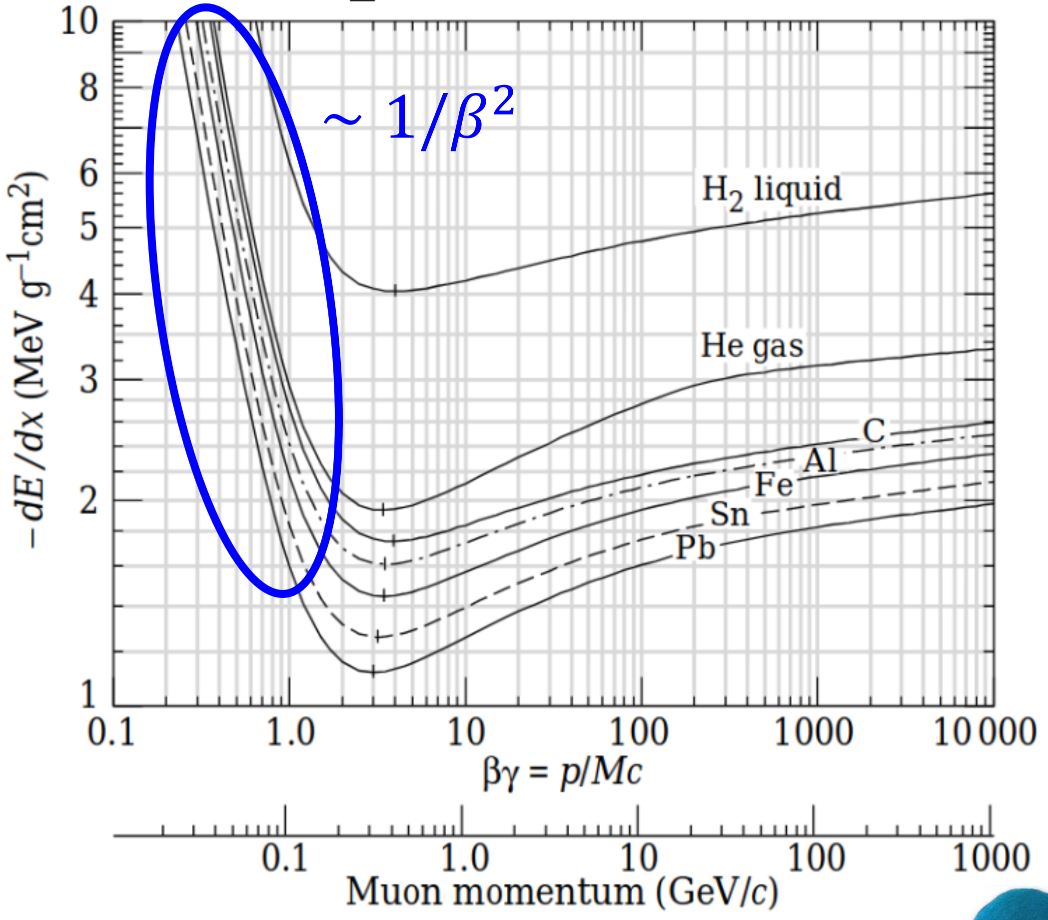
- Bethe-Bloch: $\frac{dE}{dx} = \frac{N_A Z}{A}\frac{4\pi z^2\alpha^2(\hbar c)^2}{m_e v^2}\left[\ln\frac{2m_e v^2\gamma^2}{I} - \frac{v^2}{c^2}\right] \propto \frac{\ln\left(\frac{2m_e}{I}\beta^2\gamma^2\right) - \beta^2}{\beta^2}$

  $x \equiv \rho l$ is the path length in gcm^{-2}

- Minimum at $\beta\gamma \approx 3$

- At the time it was highly believed at lower energies (below 400MeV), whereas QED at high energies was questioned

«Infant theory still plagued with perplexing infinities»



Energy loss through matter: bremsstrahlung

- Bethe-Heitler model in 1934: $\frac{dE}{dx} = \frac{N_A}{A}\frac{4Z(Z+1)\alpha^3(\hbar c)^2}{m_e^2 c^4} E \ln\frac{183}{Z^{1/3}} \equiv E/X_0$
- Energy loss by radiation: photons may contribute to e.m. shower by converting in e^+e^- pairs
- Peculiar to electrons: suppressed by $\sim 1/m^2$
- Above critical energy $\left(\sim \frac{600\ \text{MeV}}{Z}\right)$ bremsstrahlung losses exceed collision losses

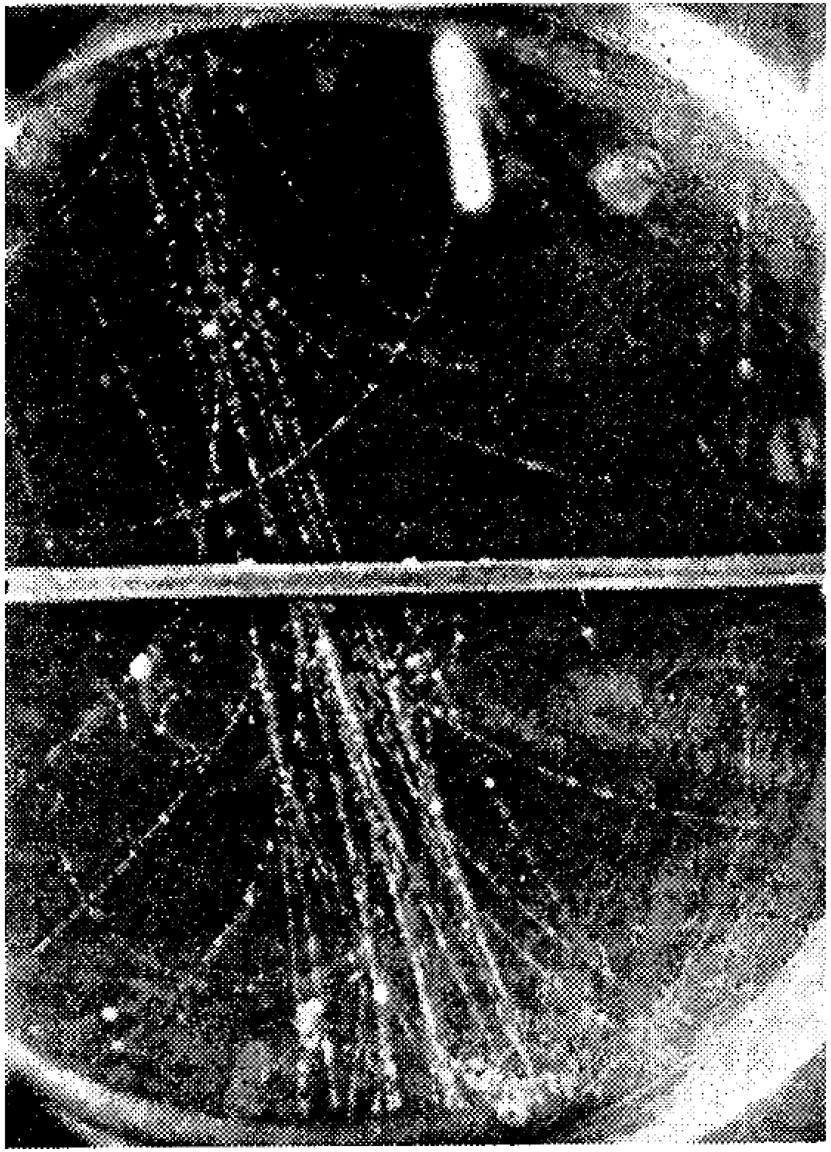
Radiation length

How could you discover muons in 1937?

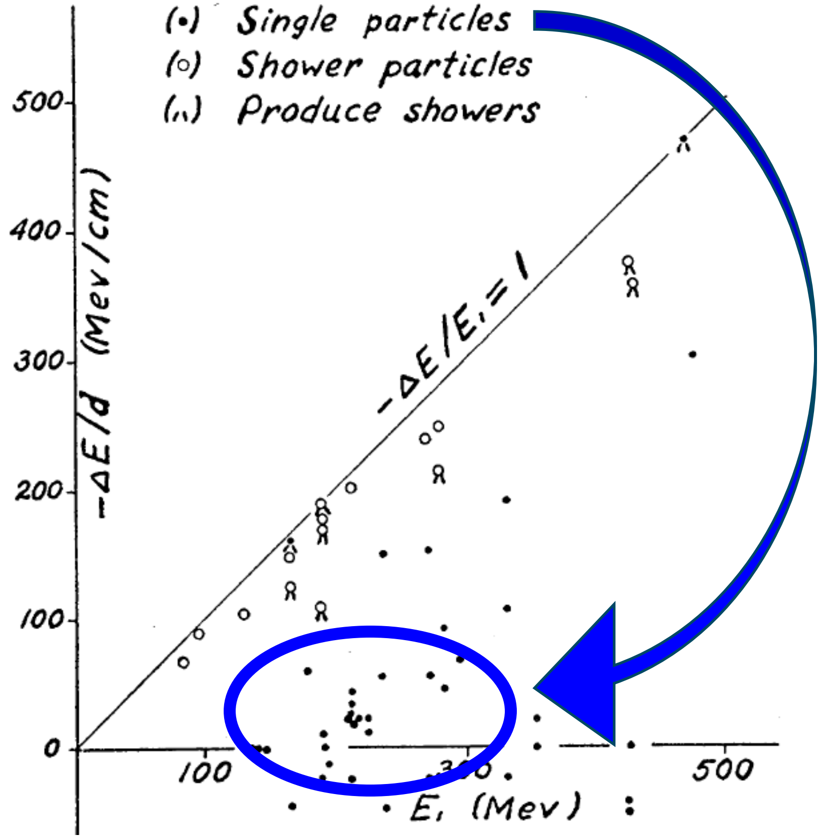
Experimental setup	Anderson and Neddermeyer	Street and Stevenson
N(events of interest)/N(pictures)	55/6000	3/1000
Technique	Curvature measurement	Curvature measurement Ion count (for muon mass)
Material width, fraction of X_0	1 cm of Platinum = $3.29X_0$	0.8 cm of Lead (Pb) = $1.4X_0$
Magnetic field [gauss]	7900	3500
Measured momenta [MeV/c]	0≤p≤474	30≤p≤600
Coincidence logic	2 Geiger counters: 1 above and 1 below the cloud chamber	Counters: coincidences above the chamber, anti-coincidences below

Method developed by Blackett and Occhialini in 1932

Anderson and Neddermeyer's experiment



Measure curvature before and after: momentum of incident particles, energy loss (assuming m_e)



Electrons produced showers and lost almost all their energy; what were these penetrating particles!?!?

Not protons!

> Moreover, the penetrating particles in this range do not ionize perceptibly more than the non-penetrating ones, and cannot therefore be assumed to be of protonic mass. The lowest $H\rho$ among the penetrating group is 4.5×10^5 gauss cm. A proton of this curvature would ionize at least 25 times as strongly as a fast electron.

- Smallest curvature among penetrating particles: $H\rho = 4.5 \cdot 10^5 \text{gauss} \cdot \text{cm}$
- Momentum of $\frac{0.3\cdot4.5\cdot10^5}{10^4\cdot10^2}\text{GeV}/c = 135\text{MeV}/c$
- If proton: $\beta\gamma = 0.14, \beta = 0.1414, \gamma = 1.01$, kinetic energy $T_p = 9.38\text{MeV}$
- From NIST database, such proton in ^{18}Ar has 33 MeVcm^2/g stopping power
- Instead, a 135 MeV/c electron has 8 MeVcm^2/g stopping power
- Not sure about a 14 MeV/c muon… a 40 MeV/c muon ionizes 5 MeVcm^2/g

Cross checks

> The chief source of error in these experiments lies not in the curvature measurements themselves, but in the track distortions produced by irregular motions of the gas in the chamber.

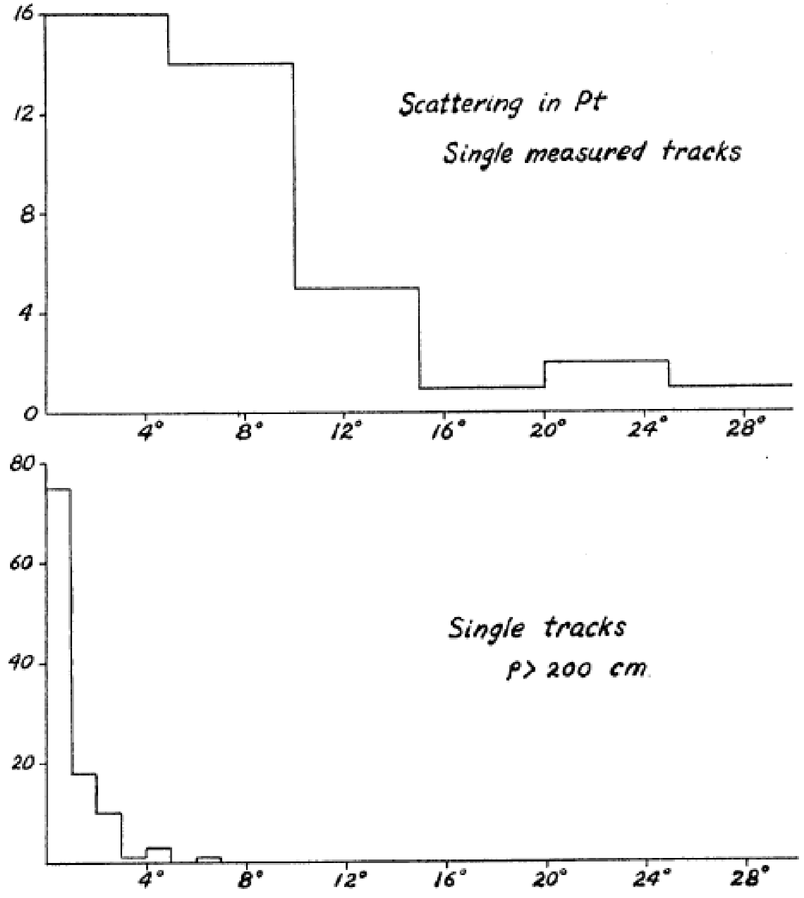
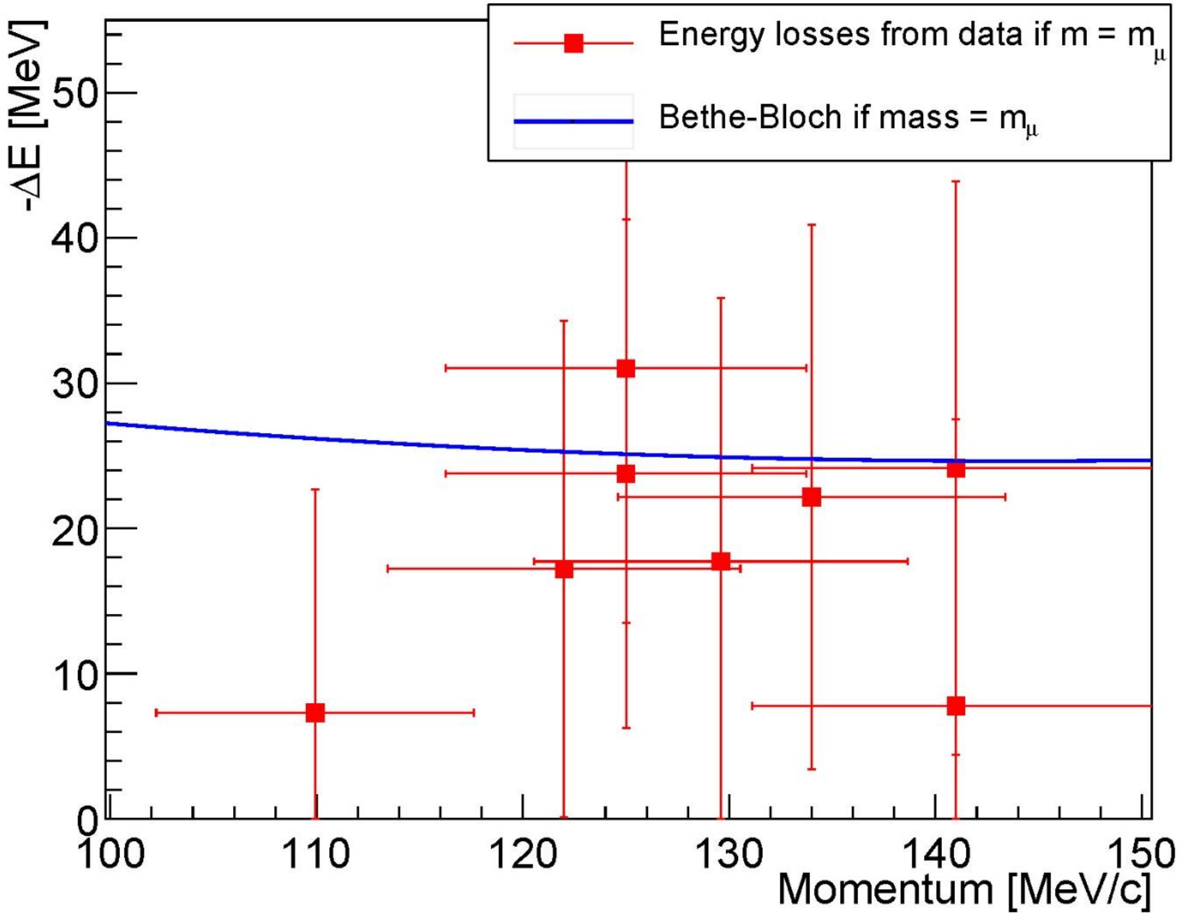


FIG. 3. Scattering distributions in 1 cm of platinum.

- Validity of curvature measurements must be checked
- Scattering angles for $\rho < 200$ cm, p<475 MeV/c, vs $\rho > 200$ cm, p>475 MeV/c
- «Scarcely conceivable that distortions can influence scattering angles by 5°» →confidence that tracks lie in the measured energy ranges
- r.m.s. multiple scattering angle projected on plane is $\frac{13.6}{pc[\text{MeV}]\beta}\sqrt{x/X_0}(1+0.038\ln(x/X_0))\text{rad} \approx 3°$ for 475 MeV/c particles in 1cm of platinum

Re-interpreting data assuming muon mass

- For 100 MeV$/c$ electrons we can expect a $-\frac{\Delta E}{E} \approx 1$ because 1cm of platinum is equal to $3.29X_0$
- I digitized the energy loss and kinetic energy data for non-penetrating particles from Anderson's plots, and re-evaluated assuming muon mass instead of electron mass
- Conservative error of 10% on energies
- **Good match** between expected loss from Bethe-Bloch and data



Warning: I did this 5 years ago…

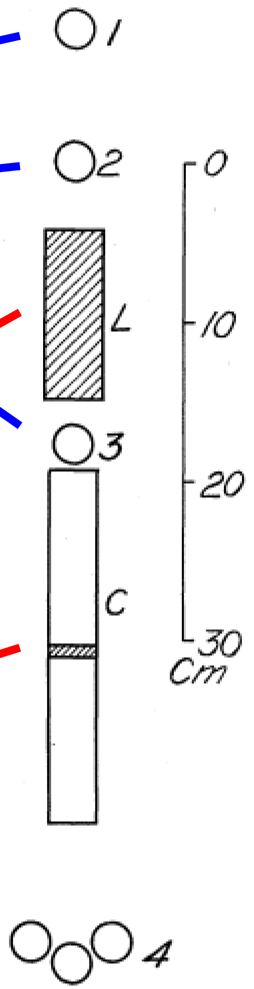
Street and Stevenson's experiment

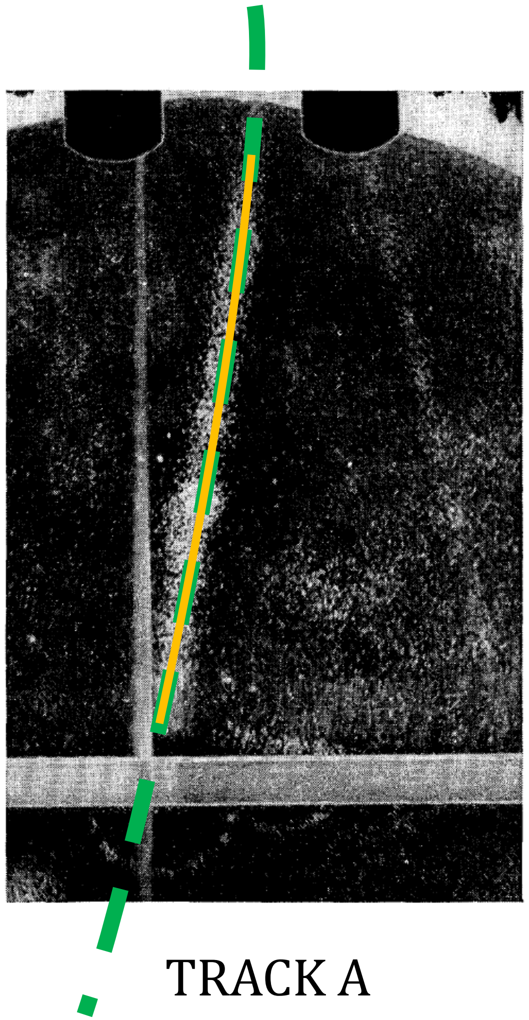
Coincidences 123 to trigger pictures

Lead, to filter showering particles

0.8 cm of lead

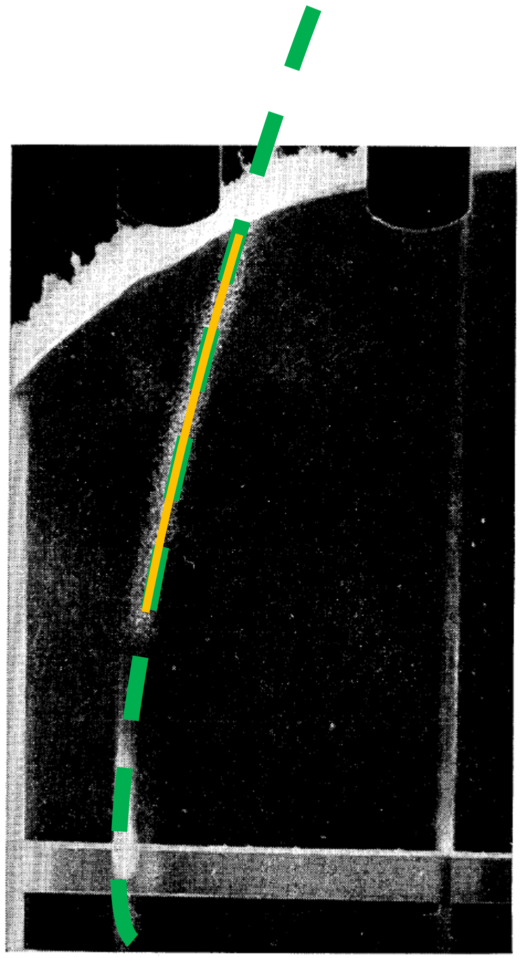
Anticoincidence $\bar{4}$ to select particles near the end of their range





TRACK A

Proton: 2.4 ionization than electrons, positively charged



TRACK B

Muon?

See next slide

First estimation ever of the muon mass

3 facts:

- $H\rho = 9.6 \text{ gauss} \cdot \text{cm}$ → momentum of 28.8 MeV/c
- Track B (muon) ionized 6 times more than typical thin tracks (electrons)
- Ionization scales with velocity as $1/\beta^2$

Math:

- Not a proton! A $28.8\text{MeV}/c$ proton would have a range of about 1 cm in the cloud chamber, whereas this particle clearly ionized for 7 cm!!
- $\beta_e[28.8\text{MeV}/c] = 0.99984$ → $\beta_\mu = \beta_e/\sqrt{6} = 0.4081, \beta\gamma_\mu = 0.4471$
- $m_\mu = \frac{28.8\text{MeV/c}}{0.4471} \approx 130 m_e$, with 25% error based on ion count uncertainty

Short-term impact of muon discovery

① Rabi's reaction was: «Who ordered that?»

② Gell-Mann and Rosenbaum, 1957: «The muon was the unwelcome baby on the doorstep, signifying the end of days of innocence»

③

WILLIS E. LAMB, JR.

Fine structure of the hydrogen atom

Nobel Lecture, December 12, 1955

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called « elementary particles »: the electron and the proton. A deluge of other « elementary » particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine ».

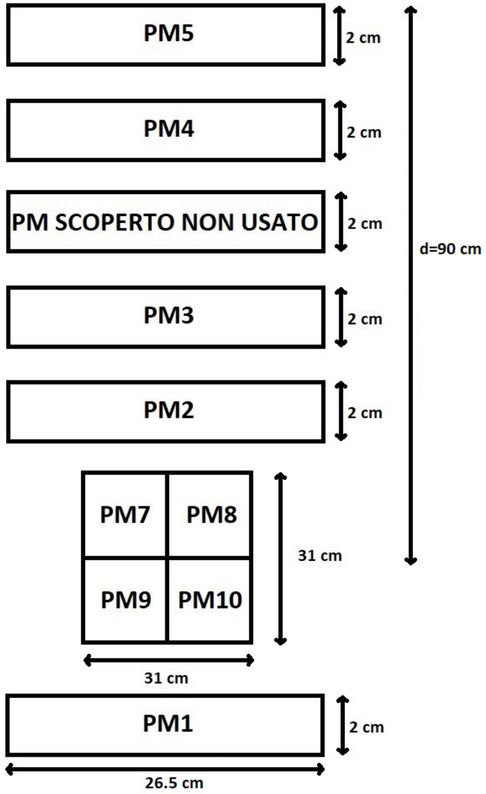
Fact: pions decay preferentially in muons

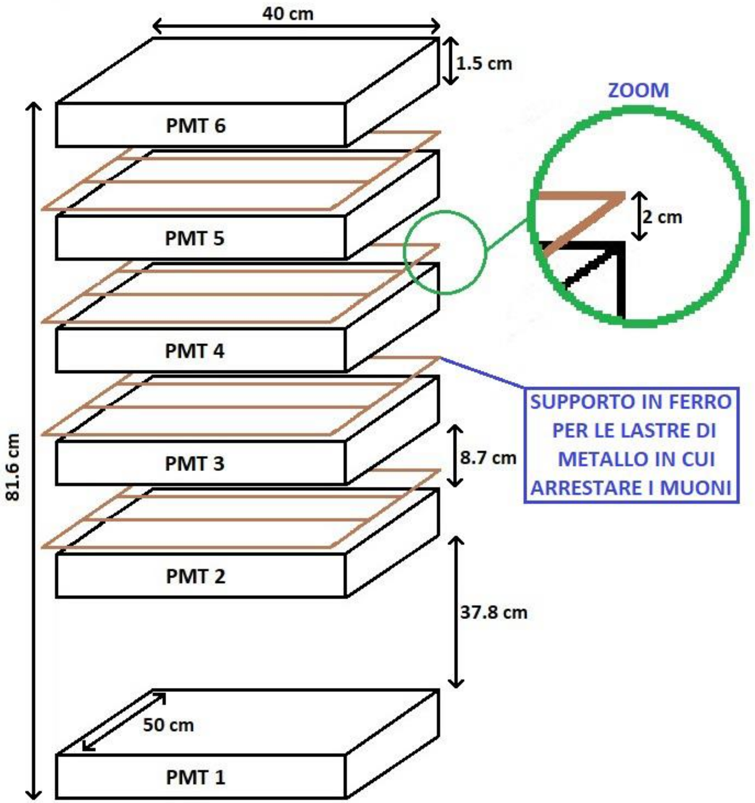
Frustration — Bewilderment

Muon applications today

- Elementary particle physics
- Atomic and molecular physics
- Solid-state physics
- Chemistry
- Medical physics
- Muometric positioning system (μPS) indoors, underwater and underground

Experiments in University labs





Searching for muons in 2019

Muon mass measurement

- Latest value comes from [1999 measurement] by W. Liu *et al.* at Los Alamos with muonium spectroscopy at 22 ppb, mostly dominated by statistical error.
  Latest value provided by CODATA2018: 105.6583755(23) MeV/c^2
- Future experiments that will improve on muon mass:
  - MuSEUM at J-PARC: New muonium HFS measurements at J-PARC/MUSE
  - Mu-MASS at PSI: The Mu-MASS (muonium laser spectroscopy) experiment

Useful links and papers I'll finish reading

- ❖Store for plushies
- ❖Discovery papers in 1937: Anderson and Neddermeyer, Street and Stevenson
- ❖Databases for range and stopping power: electron, proton, muon
- ❖Interviews to Anderson (1966, 1982) and Neddermeyer (1983)
- ❖P. Galison, «The Discovery of the Muon and the Failed Revolution against Quantum Electrodynamics», Centaurus (26) 262, 1982. DOI
- ❖V. W. Hughes and C. S. Wu, «Muon Physics», Link to Volume 1
- ❖Gell-Mann and Rosenbaum, «Elementary particles», Scientific American (197) 72, 1957. Link

THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS?

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BACKUP SLIDES

Yukawa's model for strong interactions

Strong interactions are short-ranged! $\sim$ 1fm $\leftrightarrow$ mediator has mass m

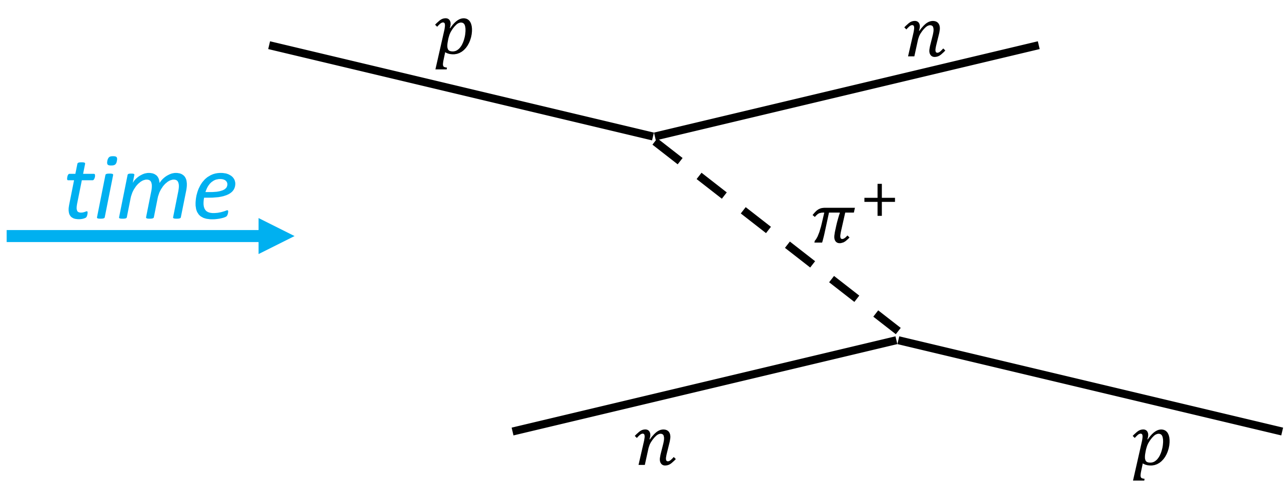
$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 + \mu^2\right)V = 0$ corresponds to $\omega^2 - k^2 = \mu^2 \leftrightarrow E^2 = p^2 + m^2$ (just insert wave solution of the type $e^{i(\vec{k}\cdot\vec{x}-\omega t)}$)

Search for static solution with spherical symmetry: $(\nabla^2 - \mu^2)\varphi = -4\pi q\delta(\vec{r})$

$\nabla_R^2\varphi = \frac{1}{R}\frac{d^2}{dR^2}(R\varphi), u(r) \equiv \varphi R \rightarrow \frac{1}{R}\frac{d^2}{dR^2}u - \mu^2\frac{u}{R} = 0 \rightarrow u'' - \mu^2 u = 0$, the solution is a harmonic oscillation with imaginary frequency. We require that $u \rightarrow 0$ for $R \rightarrow \infty$ (short-ranged): $u = Aexp(-\mu r) + Bexp(\mu r) \rightarrow B = 0$

$\varphi(r) = \frac{A}{r}e^{-\mu r}$. We require $\frac{1}{\mu} \sim 1\text{fm} \rightarrow \frac{\hbar c}{mc^2} \sim 1\text{fm} \rightarrow m \sim \mathcal{O}(100\text{MeV})$

Another approach to estimate the pion mass



The process $p \to n\pi^+$ violates energy conservation, but only temporarily, for a time of the order of magnitude $\Delta t \sim \hbar/\Delta E$, with $\Delta E = m_\pi c^2$

During this time, the maximum distance that the virtual pion can travel is: $\Delta r = \mathrm{c}\Delta t$. Nuclear interactions are short-ranged!

Impose $\Delta r \sim 1\mathrm{fm}$ → $m_\pi \sim \hbar c/(1\mathrm{fm} \cdot c^2)$, thus $m_\pi \sim \mathcal{O}(100 \div 200\mathrm{MeV})$