

The discovery of the muon

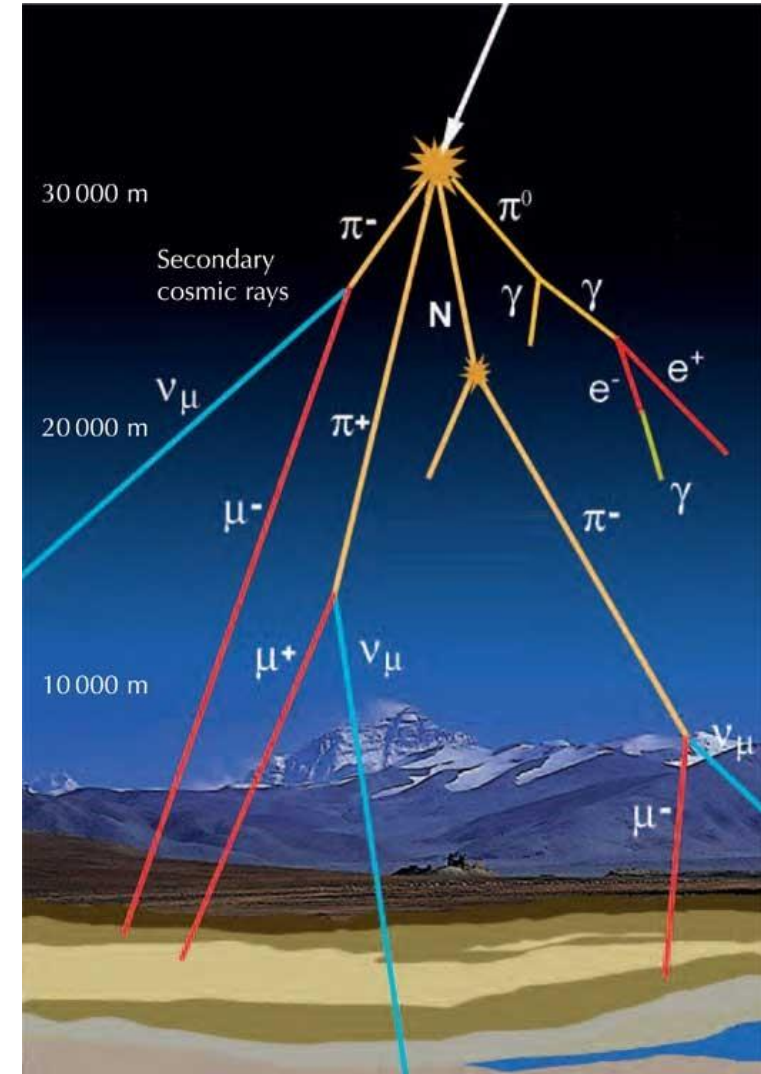
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27/11/2023: MUON GROUP SEMINAR @ LIVERPOOL

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

Known particles in 1937:

p e⁻ e⁺ n

Anderson's Nobel Prize speech, 1936

See previous presentation by Elia

Experimental discovery in 1937

Yukawa's prediction, 1935:
let's look for a particle of
mass $\sim 200 \text{ MeV}/c^2$

Are
muons
the particles
predicted by
Yukawa?

NO!

Riccardo will present



Consequences in literature

Yukon?

1. Particle X? $\rightarrow$ Mesoton $\rightarrow$ Mesotron $\rightarrow$ μ meson $\rightarrow$ Muon
«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

How?

Experimental and/or
theoretical efforts

By whom?

Something like 11
possible names

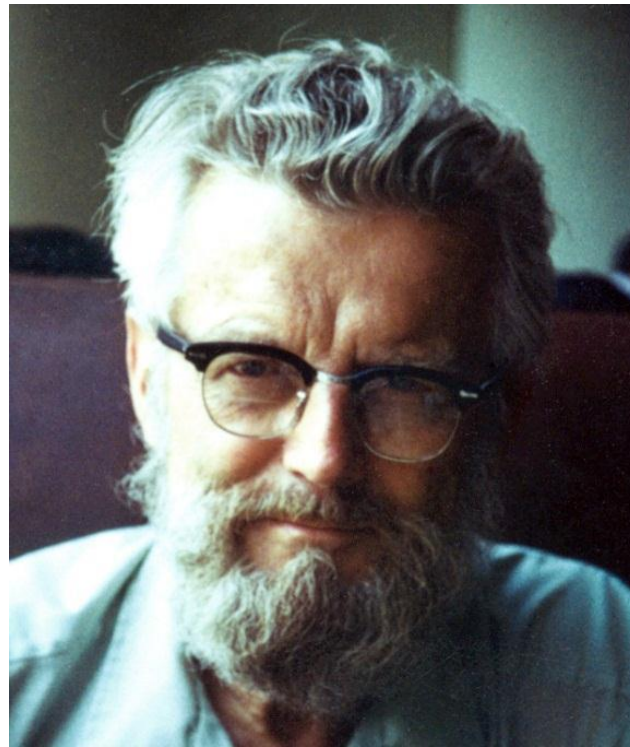


1937: four discoverers

Carl D. Anderson



Jabez C. Street



Seth H. Neddermeyer

Edward C. Stevenson



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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**»



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

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

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

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

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

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



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 measurements² which had shown the presence of some particles less massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory

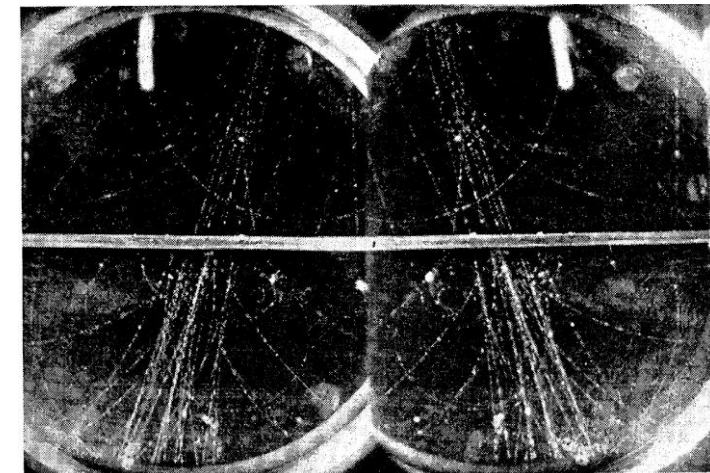
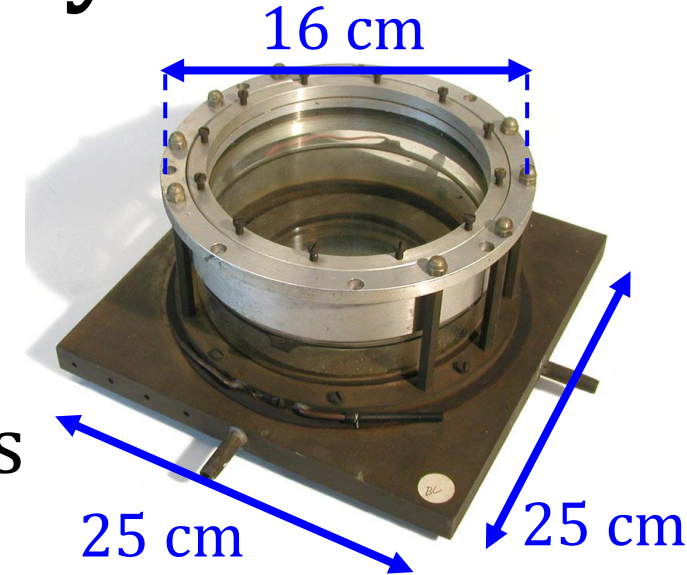
Collision
energy loss

Radiative
energy loss



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 $\rightarrow$ droplets
- Magnetic field $\rightarrow 0.3B\rho = p [\text{GeV}/c]/e$
Warning: it's $H\rho$ in their papers
- Plate of lead/platinum to cause energy loss
- Glass piston and mirrors on the side



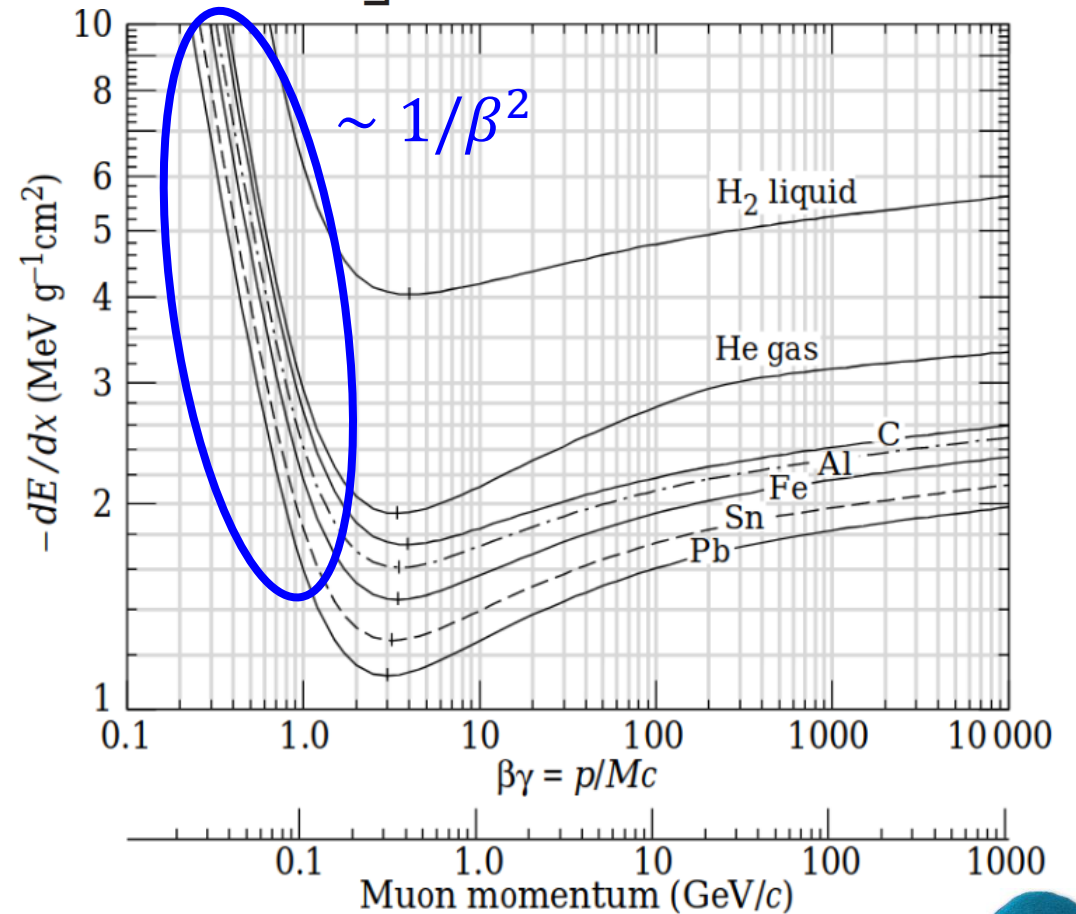
Energy loss through matter: collision

- 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



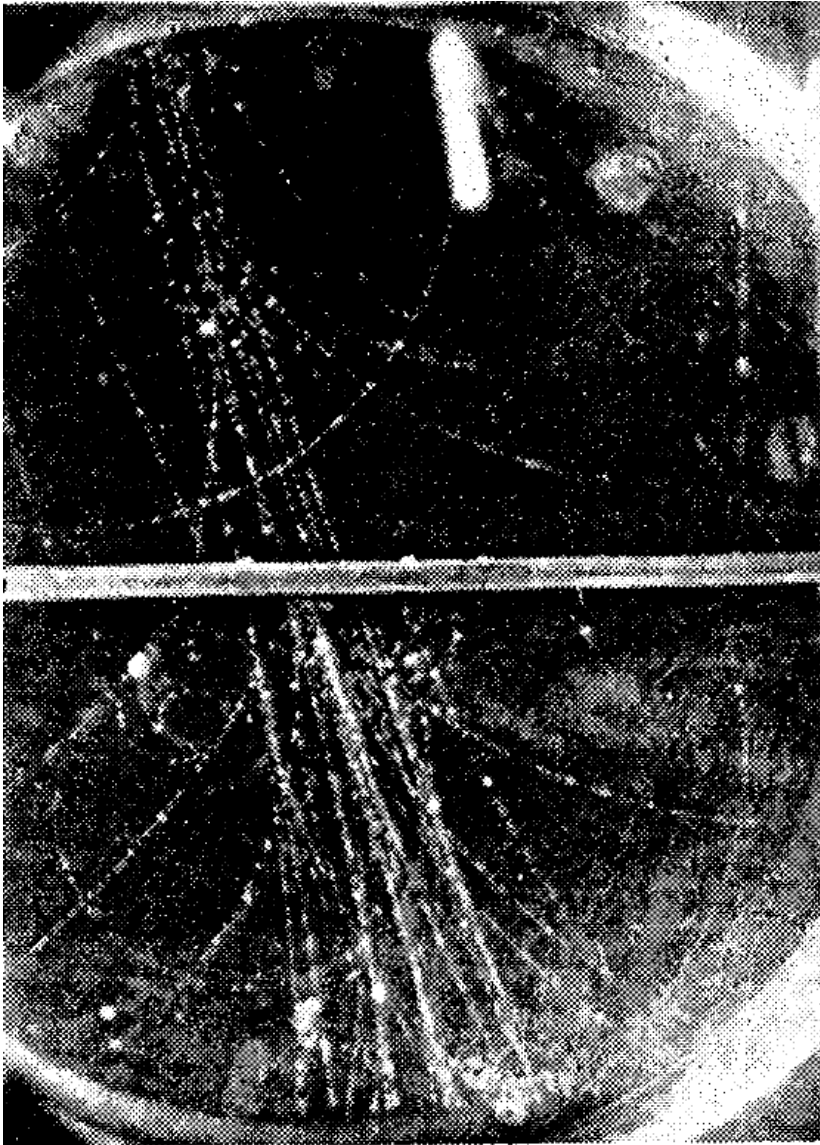
How could you discover muons in 1937?

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]	$0 \leq p \leq 474$	$30 \leq p \leq 600$
Coincidence logic	2 Geiger counters: 1 above and 1 below the cloud chamber	Counters: coincidences above the chamber, anti-coincidences below

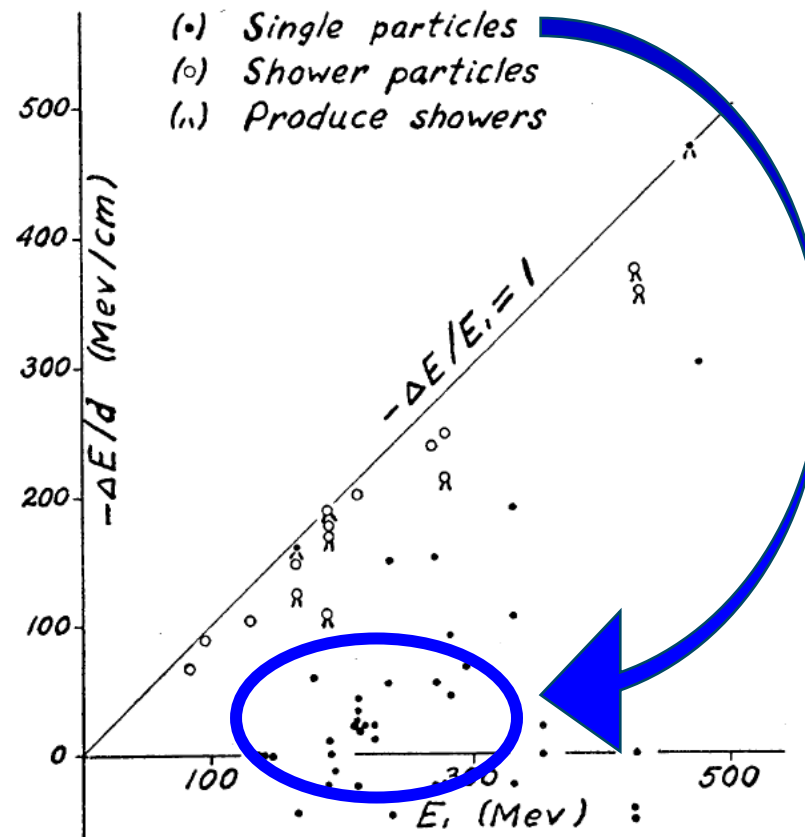
Method developed by Blackett and Occhialini in 1932



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 $HI\rho$ 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: $HI\rho = 4.5 \cdot 10^5 \text{ gauss} \cdot \text{cm}$
- Momentum of $\frac{0.3 \cdot 4.5 \cdot 10^5}{10^4 \cdot 10^2} \text{ GeV}/c = 135 \text{ MeV}/c$
- 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 $33 \text{ MeVcm}^2/g$ stopping power
- Instead, a $135 \text{ MeV}/c$ electron has $8 \text{ MeVcm}^2/g$ stopping power
- Not sure about a $14 \text{ MeV}/c$ muon... a $40 \text{ MeV}/c$ muon ionizes $5 \text{ MeVcm}^2/g$



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.

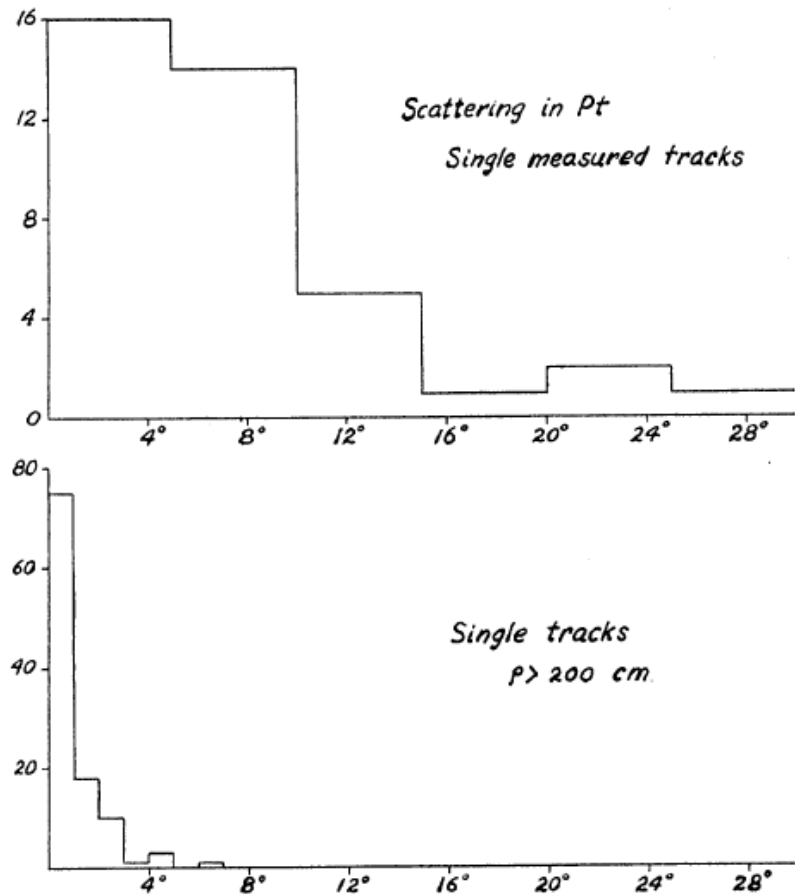


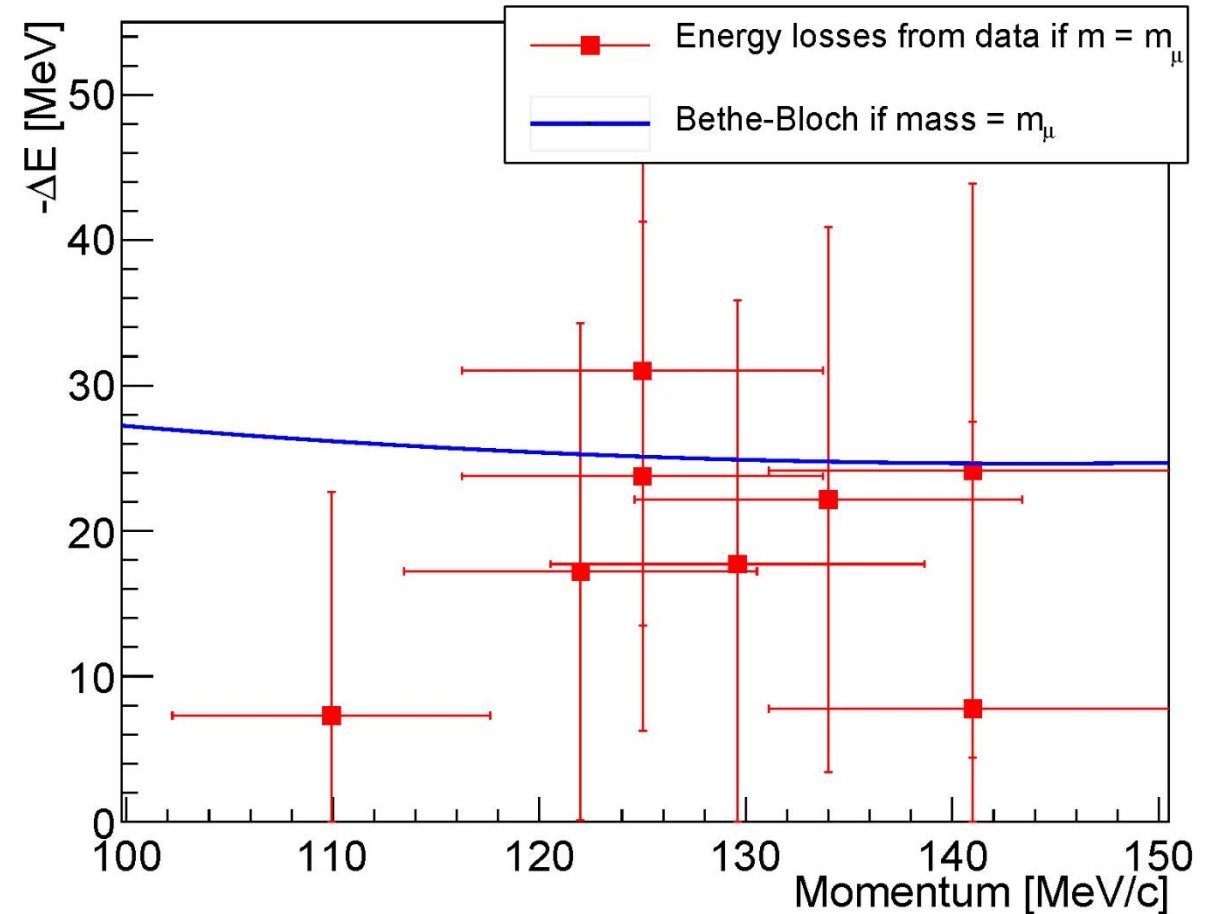
FIG. 3. Scattering distributions in 1 cm of platinum.

- Validity of curvature measurements must be checked
- Scattering angles for $\rho < 200 \text{ cm}$, $p < 475 \text{ MeV}/c$, vs $\rho > 200 \text{ cm}$, $p > 475 \text{ MeV}/c$
- «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 $\frac{13.6}{pc[\text{MeV}]\beta} \sqrt{x/X_0} (1 + 0.038 \ln(x/X_0)) \text{ rad} \approx 3^\circ$ for 475 MeV/c particles in 1cm of platinum



Re-interpreting data assuming muon mass

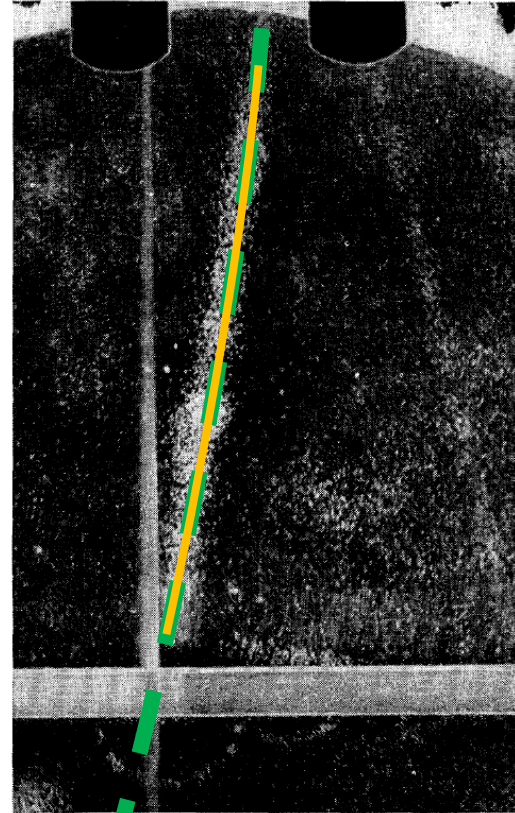
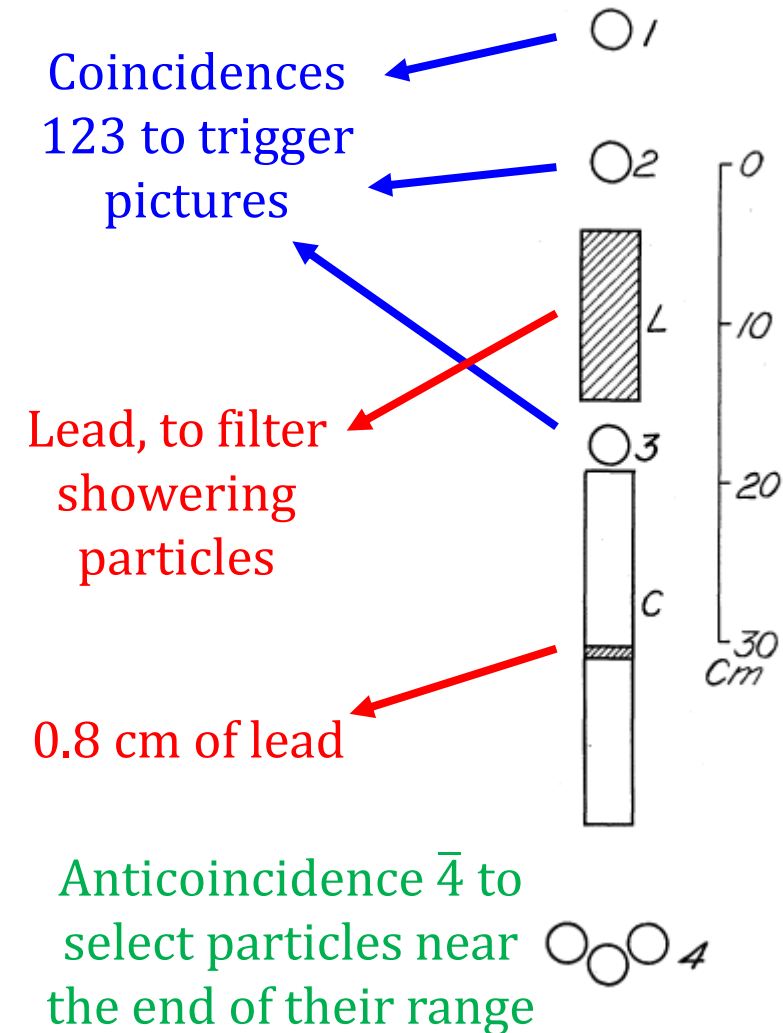
- For 100 MeV/c electrons we can expect a $-\frac{\Delta E}{E} \approx 1$ because 1cm of platinum is equal to $3.29X_0$
- I digitized the energy loss and kinetic energy data for non-penetrating particles from Anderson's plots, and re-evaluated assuming muon mass instead of electron mass
- Conservative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



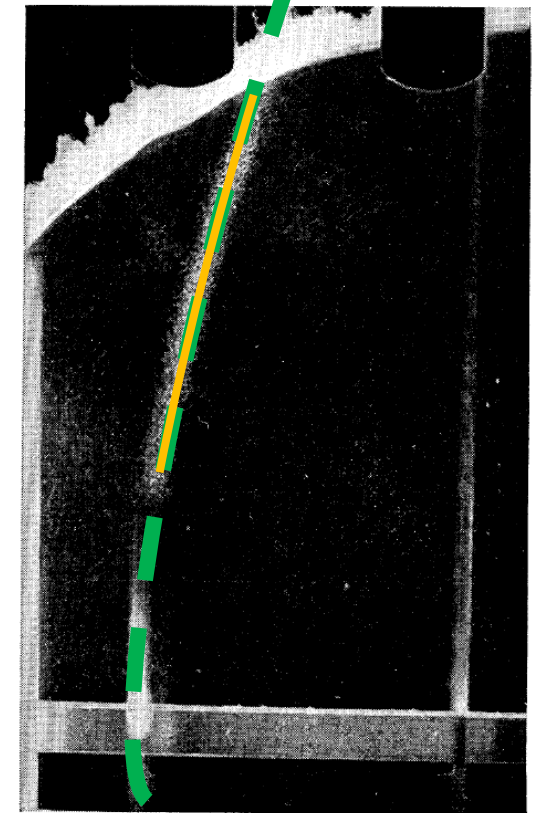
Warning: I did this 5 years ago...



Street and Stevenson's experiment



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:

- $H\rho = 9.6 \text{ gauss} \cdot \text{cm} \rightarrow$ 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 MeV/c proton would have a range of about 1 cm in the cloud chamber, whereas this particle clearly ionized for 7 cm!!
- $\beta_e[28.8 \text{ MeV}/c] = 0.99984 \rightarrow \beta_\mu = \beta_e/\sqrt{6} = 0.4081, \beta\gamma_\mu = 0.4471$
- $m_\mu = \frac{28.8 \text{ MeV}/c}{0.4471} \approx 130m_e$, 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

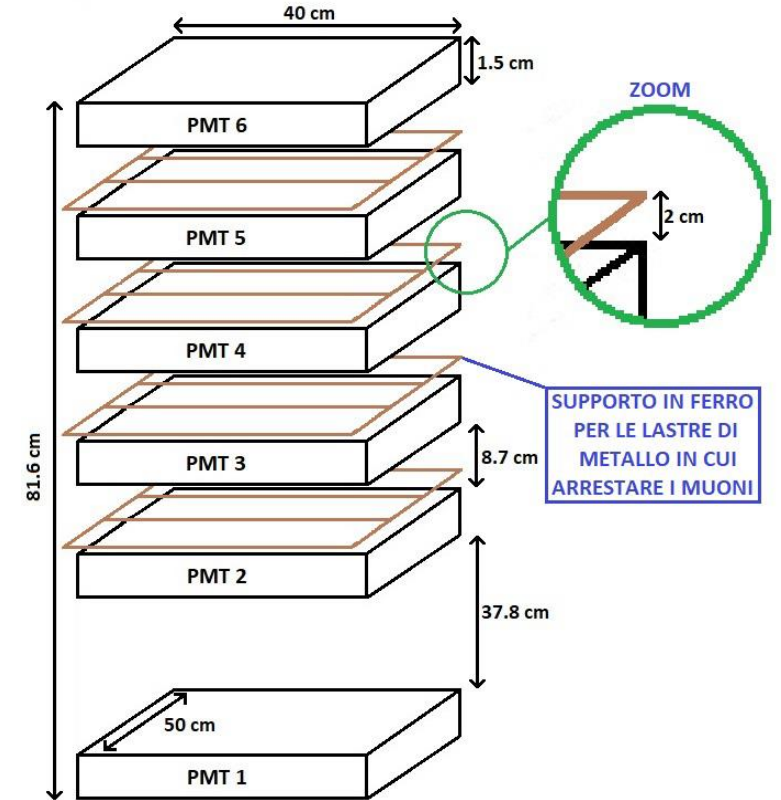
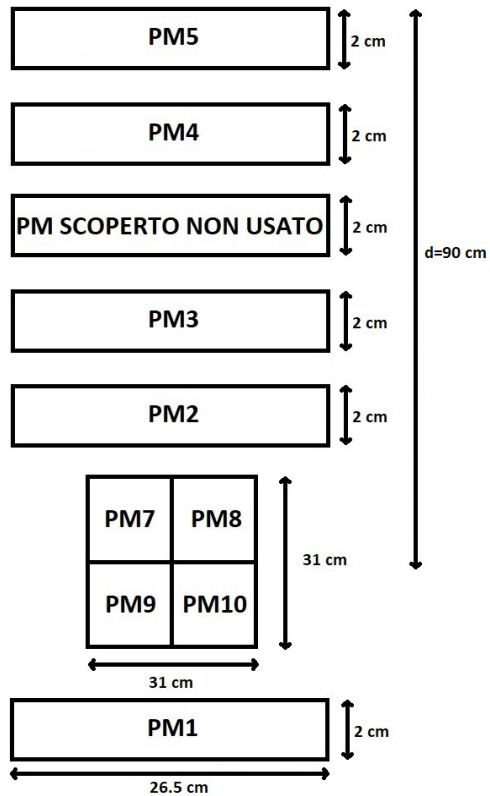


Muon applications today

- ❖Elementary particle physics
- ❖Atomic and molecular physics
- ❖Solid-state physics
- ❖Chemistry
- ❖Medical physics
- ❖Muometric positioning system (μ PS) [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](#): $105.6583755(23) \text{ MeV}/c^2$

❖ 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! $\sim 1\text{fm} \leftrightarrow$ 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 $e^{i(\vec{k} \cdot \vec{x} - \omega t)}$)

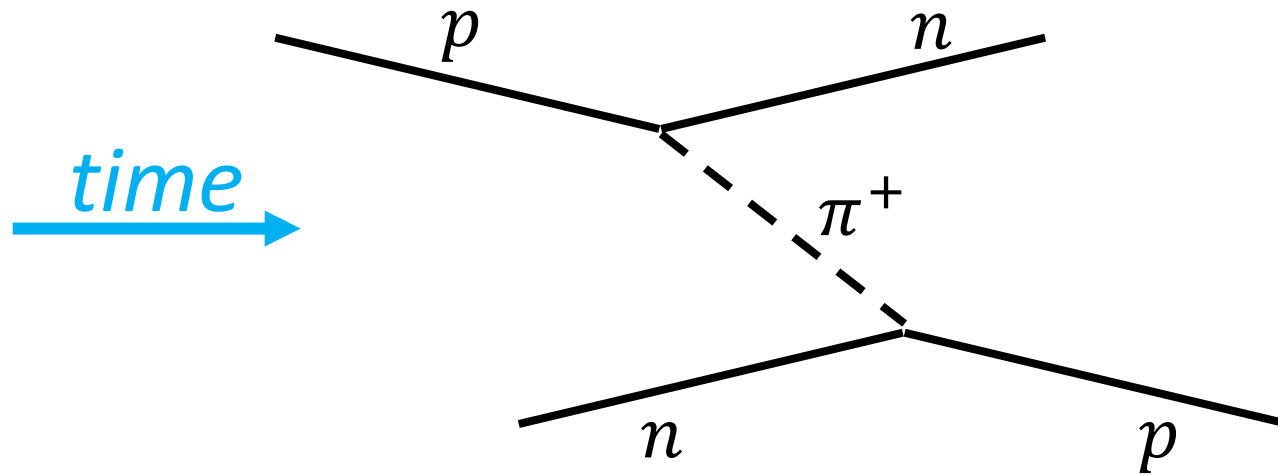
Search for static solution with spherical symmetry: $(\nabla^2 - \mu^2)\varphi = -4\pi q\delta(\vec{r})$

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

$\varphi(r) = \frac{A}{r} e^{-\mu r}$. 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 $p \rightarrow n \pi^+$ 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: $\Delta r = c\Delta t$. Nuclear interactions are short-ranged!

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

