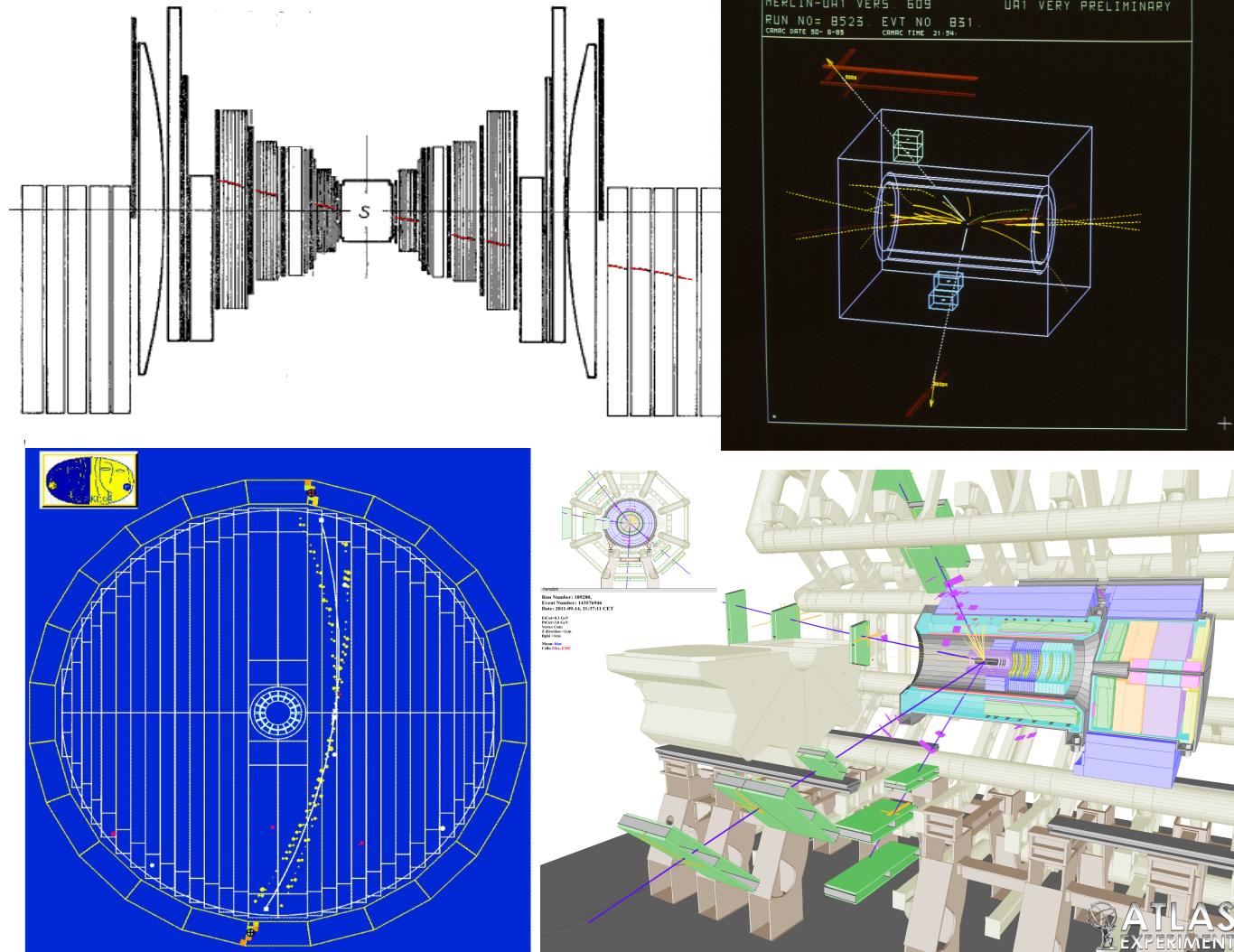
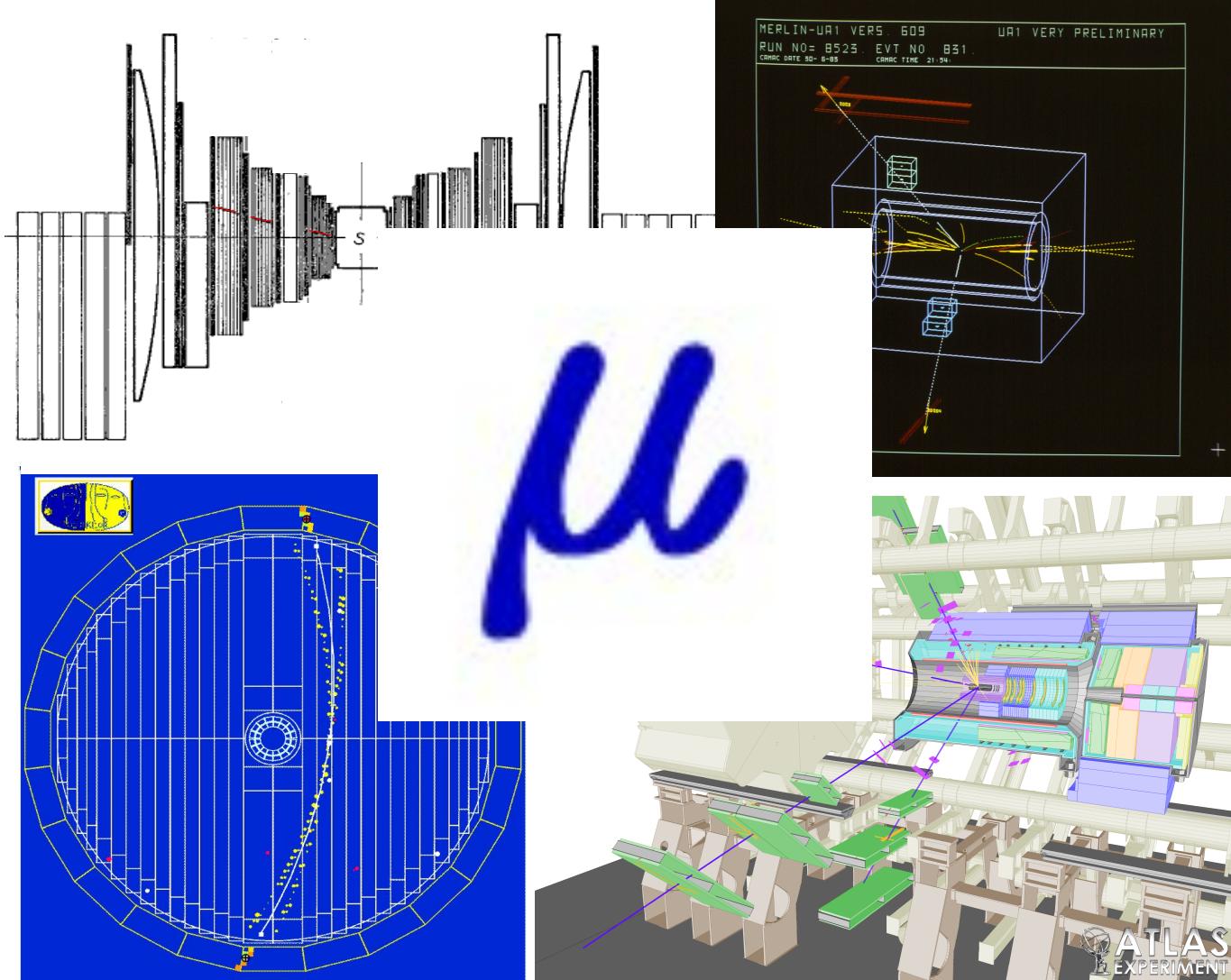


Istituzioni di Fisica Nucleare e Subnucleare - n.19



My favourite particle



The muon is 80 years old

Experimental techniques and theory are ready for the muon



- 1912 - Charles Wilson: the Cloud Chamber
- 1928 - the Geiger-Mueller counter
- 1934 - Enrico Fermi: Theory of beta decay
- 1935 - Hideki Yukawa: Theory of nuclear forces
- 1936 - Walter Heitler: Quantum theory of radiation

MAY 15, 1937

PHYSICAL REVIEW

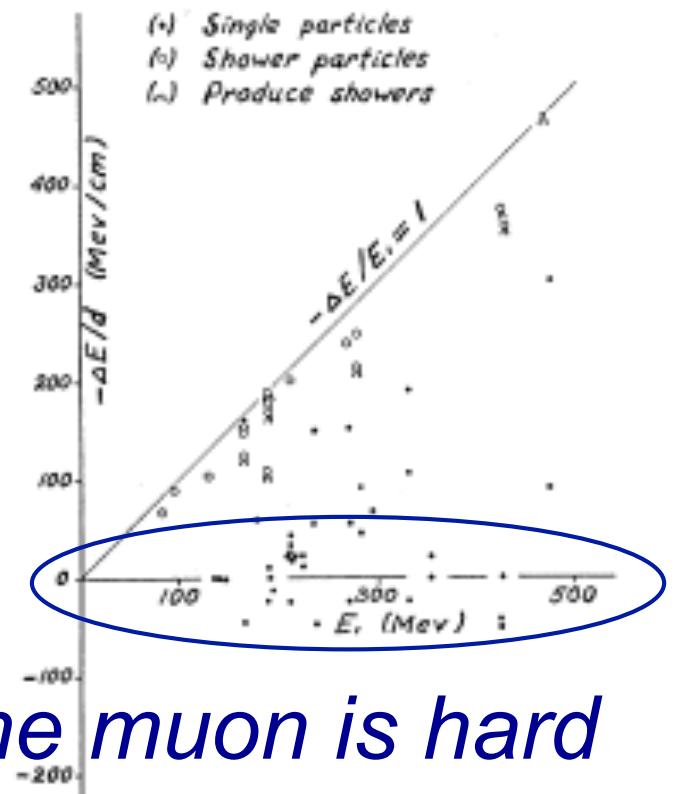
VOLUME 51

Note on the Nature of Cosmic-Ray Particles

SETH H. NEEDERMAYER AND CARL D. ANDERSON
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

The nonpenetrating particles are readily interpreted as free positive and negative electrons. Interpretations of the penetrating ones encounter very great difficulties,

that there exist particles of unit charge, but with a mass (which may not have a unique value) larger than that of a normal free electron⁶ and much smaller than that of a proton



The muon is hard

FIG. 1. Energy loss in 1 cm of platinum.

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 50, NO. 4

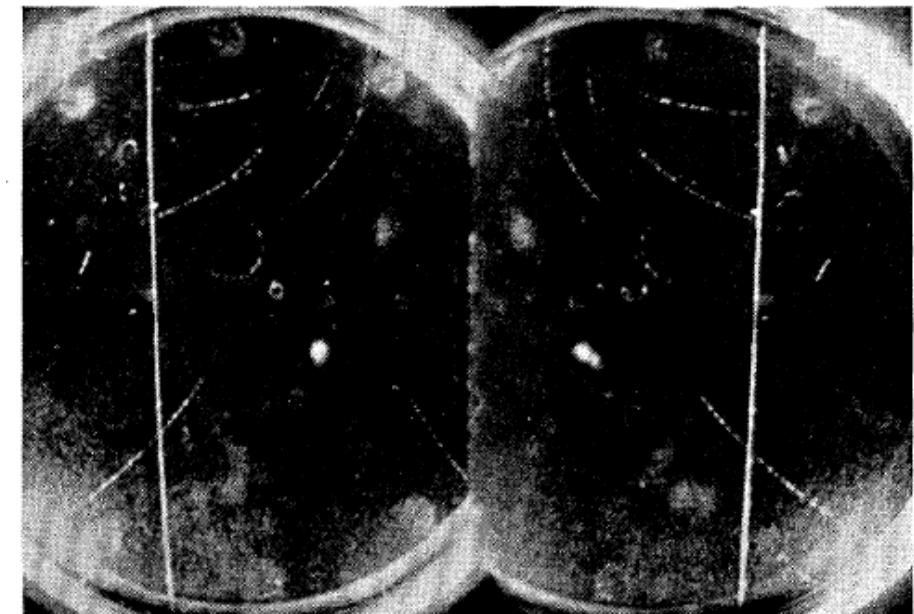
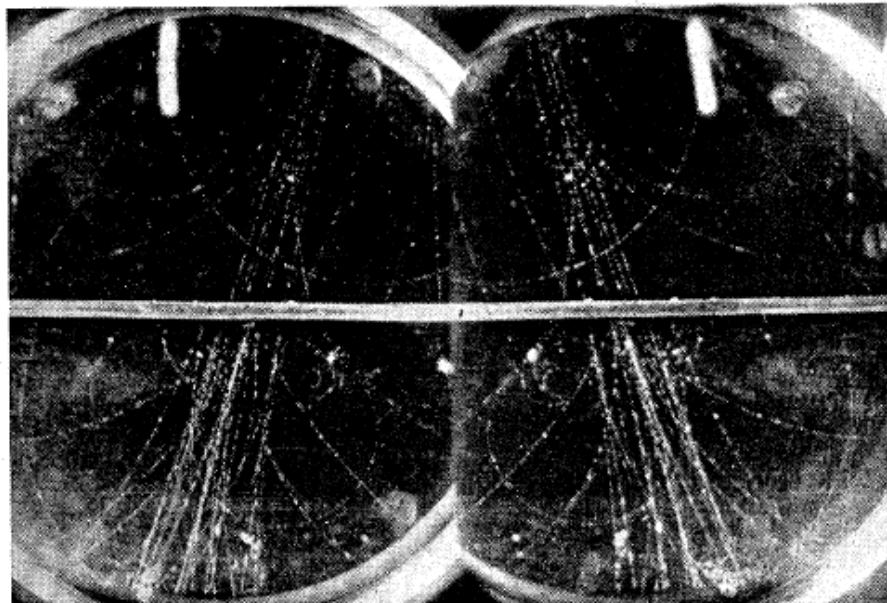
AUGUST 15, 1936

SECOND SERIES

Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

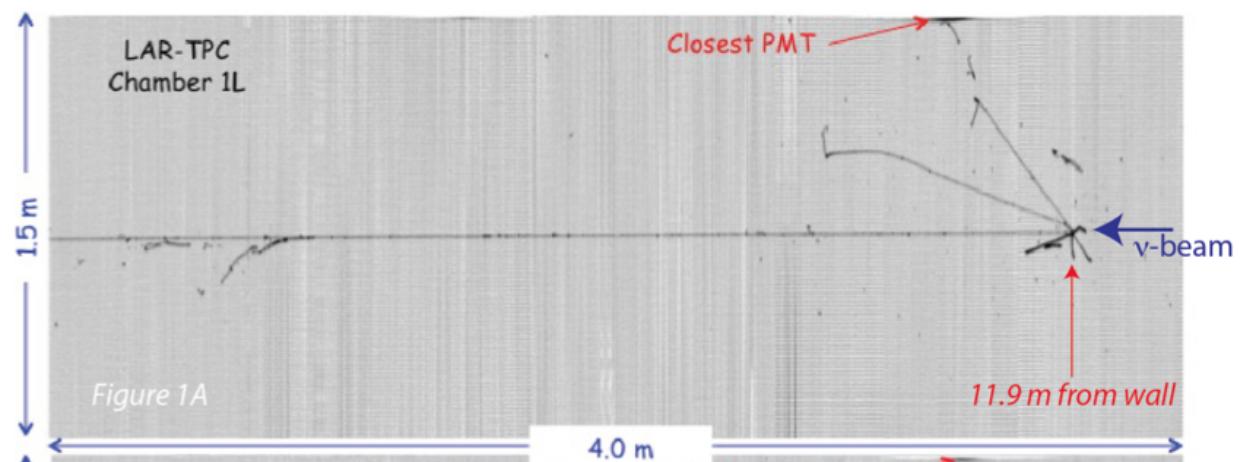
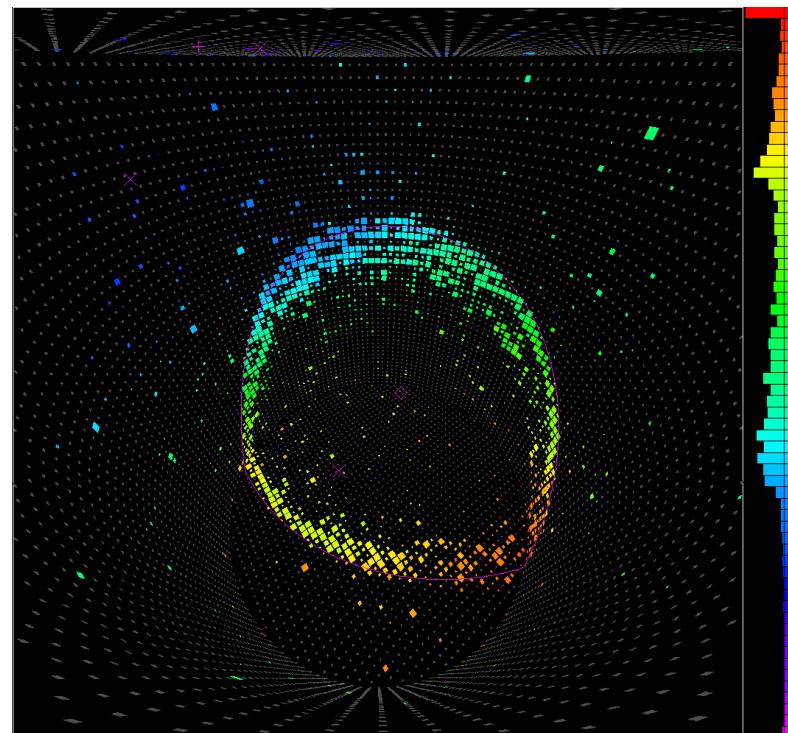
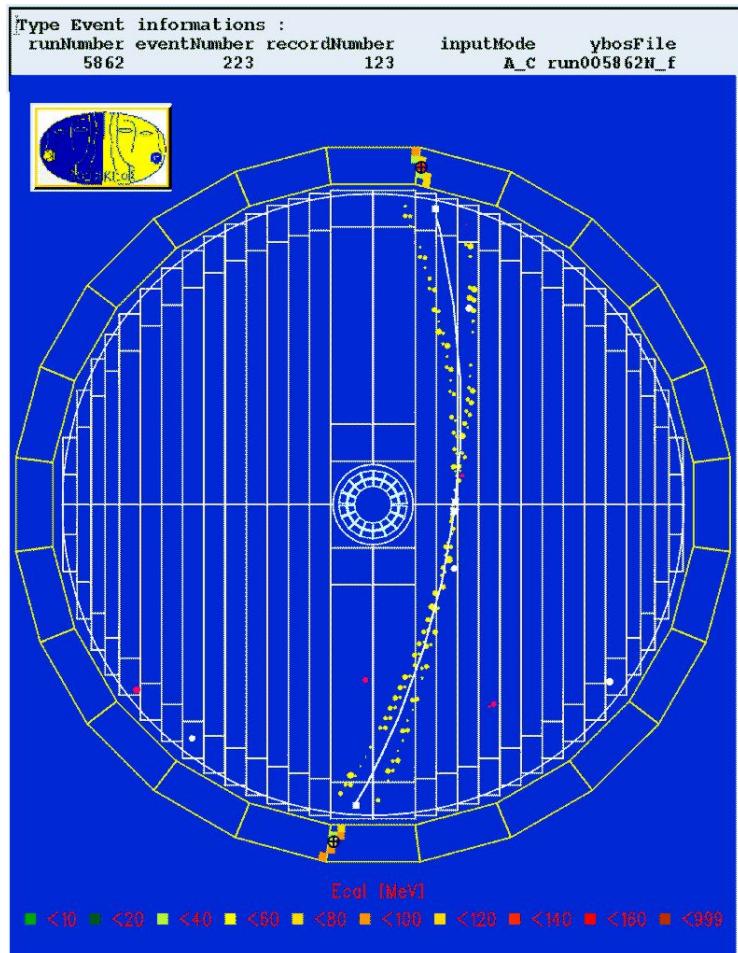
CARL D. ANDERSON AND SETH H. NEDDERMEYER, *Norman Bridge Laboratory of Physics, California Institute of Technology*

(Received June 9, 1936)



The muon is elegant

Tracking muons !



Even more elegant

LETTERS TO THE EDITOR

New Evidence for the Existence of a Particle of Mass
Intermediate Between the Proton and ElectronJ. C. STREET
E. C. STEVENSONResearch Laboratory of Physics,
Harvard University,
Cambridge, Massachusetts,
October 6, 1937.

arrangement of apparatus of Fig. 1. The three-counter telescope consisting of tubes 1, 2, and 3 and a lead filter L for removing shower particles, selects penetrating rays directed toward the cloud chamber C which is in a magnetic field of 3500 gauss.

If it is taken that the ionization density varies inversely as the velocity squared, the rest mass of the particle in question is found to be approximately 130 times the rest mass of the electron. Because of uncertainty in the ion count this determination has a probable error of some 25 percent. In any case it does not seem possible to explain

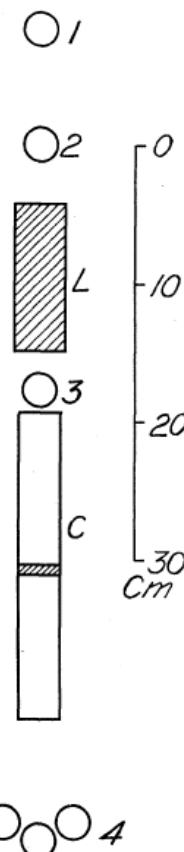


FIG. 1. Geometrical arrangement of apparatus.

Lifetime: comparing particle flux at different altitudes

JANUARY 1, 1940

PHYSICAL REVIEW

VOLUME 57

The Instability of the Meson*

MARTIN A. POMERANTZ

The Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania, and the Randal Morgan Laboratory of Physics, University of Pennsylvania, Philadelphia, Pennsylvania

(Received October 27, 1939)

Values of the proper lifetime of the meson have been deduced from a comparison of the intensity of mesons in an inclined direction under air with that in the vertical under a superposed lead shield equivalent in absorbing power to the difference between the masses of air traversed by the mesons before reaching the apparatus in the two directions. The required mass of lead was calculated from the Bethe and Bloch formula. The reliability of this use of the formula has been verified by an experimental determination of the relative stopping powers of water and lead. We calculate from our experimental data that the average proper lifetime of all mesons having energies exceeding 6.1×10^8 ev

upon reaching the apparatus is equal to 3.9 ± 0.3 microseconds, and the average proper lifetime of all mesons with energies exceeding 11.9×10^8 ev upon reaching the apparatus is equal to 3.8 ± 0.4 microseconds. From the same data, the proper lifetime of only those mesons having about 9×10^8 ev energy upon reaching the apparatus is equal to 2.6 ± 0.8 microseconds. With the theory of Euler and Heisenberg, the proper lifetime has also been calculated from measurements of the number of disintegration electrons and their secondaries in equilibrium with the mesons in air. The value obtained by this method is roughly equal to 6 microseconds.

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 57, No. 11

JUNE 1, 1940

SECOND SERIES

The Anomalous Absorption of the Hard Component of Cosmic Rays in Air

M. AGENO,¹ G. BERNARDINI,² N. B. CACCIAPUOTI,¹ B. FERRETTI¹ AND G. C. WICK³

Universities of Rome, Bologna, and Padua, Italy

(Received March 25, 1940)

The anomalously large absorption of mesotrons in air has been confirmed by a comparison of the vertical intensity of mesotrons at two different altitudes (500 m and 3460 m). At 3460 m the vertical intensity has also been compared with the intensity under a zenith angle of 45°. If the results obtained are interpreted according to the hypothesis of the instability of the mesotron, they are found to be consistent with the assumption of a proper lifetime of 4 or 5 microseconds for the mesotron.

Lifetime: comparing particle flux at different altitudes

APRIL 1, 1941

PHYSICAL REVIEW

VOLUME 59

Differential Measurement of the Meson Lifetime

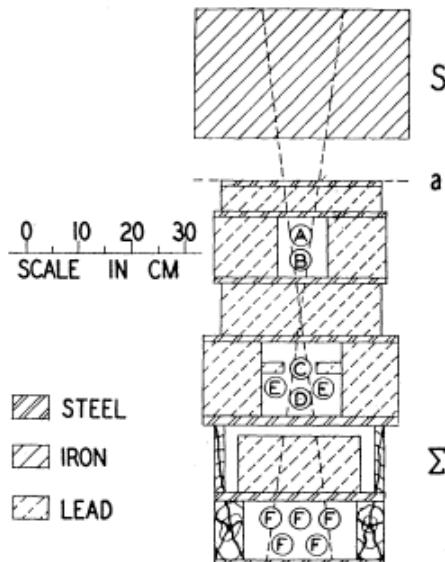
W. M. NIELSEN, C. M. RYERSON, L. W. NORDHEIM, *Duke University, Durham, North Carolina*

AND

K. Z. MORGAN, *Lenoir Rhyne College, Hickory, North Carolina*

(Received February 8, 1941)

Measurements of the meson lifetime were made by comparing the lead absorption curves of the cosmic radiation at two different elevations, and by compensating the air column at the higher level by a layer of graphite placed on top of the counter telescope. The method does not require any knowledge of the energy distribution or of the height of the producing layer of the mesons. All systematic errors are greatly reduced by the differential method used and can be shown to be insignificant. The value of the lifetime comes out to be appreciably shorter than in previous determinations, *viz.* $(1.25 \pm 0.3) \times 10^{-6} (\mu c^2 / 10^8 \text{ ev}) \text{ sec.}$



PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 59, No. 3

FEBRUARY 1, 1941

SECOND SERIES

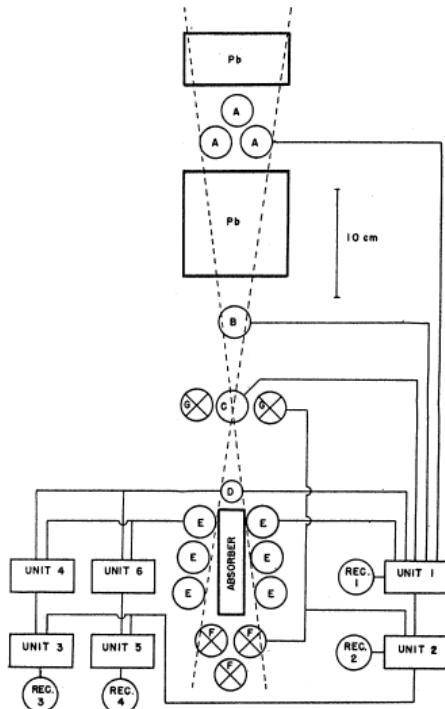
Variation of the Rate of Decay of Mesotrons with Momentum

BRUNO ROSSI* AND DAVID B. HALL
University of Chicago, Chicago, Illinois

In order to determine the dependence of the probability of decay on momentum, mesotrons with range between 196 and 311 g/cm² of lead and mesotrons with range larger than 311 g/cm² of lead were investigated separately. The softer group of mesotrons was found to disintegrate at a rate about three times faster than the more penetrating group, in agreement with the theoretical predictions based on the relativity change in rate of a moving clock. A new value of the proper lifetime of mesotrons of $(2.4 \pm 0.3) \times 10^{-6} \text{ sec.}$ is determined, based upon measurements with particles with momentum of approximately $5 \times 10^8 \text{ ev/c.}$

But the lifetime in matter is different for μ^+ and μ^- ...

Lifetime: the delayed coincidence method



NOVEMBER 1 AND 15, 1942

AUGUST 1, 1941

PHYSICAL REVIEW

VOLUME 60

Disintegration of Slow Mesotrons

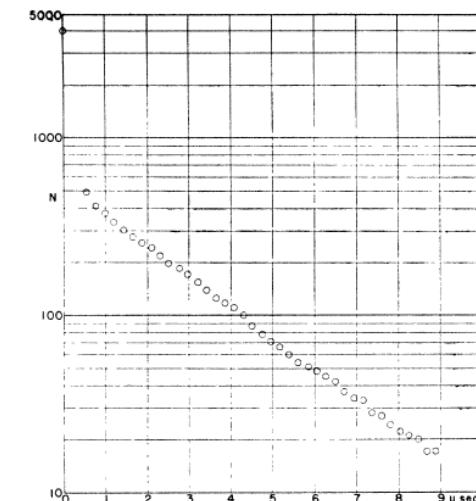
FRANCO RASETTI

Department of Physics, Laval University, Quebec, Canada

(Received June 13, 1941)

The disintegration of mesotrons at the end of their range was investigated by means of an improved arrangement of the type already described by the author. The absorption of a mesotron by a block of aluminum or iron is recorded by a system of coincidence and anticoincidence counters. Another system of counters and circuits registers the delayed emission of a particle, which is interpreted as the disintegration electron associated with the absorbed mesotron. The present apparatus enables one to determine the time distribution of the emitted particles and hence

the mean life of the decay process, independently of the effects produced by the scattering of mesotrons. The mean life is found to be 1.5 ± 0.3 microseconds, in substantial agreement with the value deduced from the atmospheric absorption effect. The absolute number of disintegration electrons per absorbed mesotron has also been determined (for an Al absorber) and found to be about one-half. This result suggests that, in agreement with theoretical predictions, positive mesotrons undergo spontaneous decay, while the negative ones react with nuclear particles.



PHYSICAL REVIEW

VOLUME 62

Experimental Determination of the Disintegration Curve of Mesotrons

BRUNO ROSSI AND NORRIS NERESON

Cornell University, Ithaca, New York

(Received September 17, 1942)

The disintegration curve of mesotrons has been experimentally determined by investigating the delayed emission of disintegration electrons which takes place after the absorption of mesotrons by matter. Within the experimental errors, the disintegration curve is exponential and corresponds to a mean lifetime of 2.3 ± 0.2 microseconds.

The muon is longlived

Is the mesotron the Yukawa particle?

Why the μ^+ and μ^- have different lifetime?

The pion is yet unknown



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LETTERS TO THE EDITOR

On the Decay Process of Positive and Negative Mesons

M. CONVERSI, E. PANCINI, AND O. PICCIONI

*Istituto di Fisica della R. Università di Roma Centro di Fisica nucleare
del C.N.R., Rome, Italy*

October 15, 1945

OME years ago Tomonaga and Araki¹ pointed out that on account of the electrostatic interaction with nuclei, the capture probability should be for negative mesons in dense material much greater than the decay probability; while for positive mesons the decay probability should prevail on the capture probability.

These results point out the greatly different behavior of negative and positive mesons, so that the prediction of Tomonaga and Araki seems to be confirmed experimentally.



On the Disintegration of Negative Mesons

M. CONVERSI, E. PANCINI, AND O. PICCIONI*

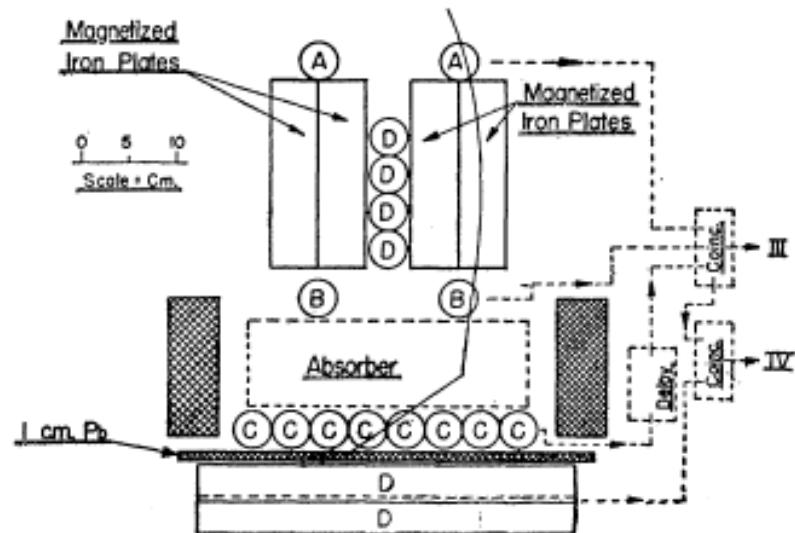
*Centro di Fisica Nucleare del C. N. R. Istituto di
Fisica dell'Università di Roma, Italia*

December 21, 1946

In a previous Letter to the Editor,¹ we gave a first account of an investigation of the difference in behavior between positive and negative mesons stopped in dense materials. Tomonaga and Araki² showed that, because of the Coulomb field of the nucleus, the capture probability for negative mesons at rest would be much greater than their decay probability, while for positive mesons the opposite should be the case. If this is true, then practically all the decay processes which one observes should be owing to positive mesons.

The results with carbon as absorber turn out to be quite inconsistent with Tomonaga and Araki's prediction. We

The great yield of negative decay electrons from carbon shows a marked difference between it and iron as absorbers. Tomonaga and Araki's calculation also give for carbon a much higher ratio of capture to decay probability for negative mesons, so we are forced to doubt their estimation.



Louis Alvarez Nobel lecture:

As a personal opinion, I would suggest that modern particle physics started in the last days of World War II, when a group of young Italians, Conversi, Pancini, and Piccioni, who were hiding from the German occupying forces, initiated a remarkable experiment. In 1946, they showed³ that the «mesotron» which had been discovered in 1937 by Neddermeyer and Anderson⁴ and by Street and Stevenson⁵, was not the particle predicted by Yukawa⁶ as the mediator of nuclear forces, but was instead almost completely unreactive in a nuclear sense.

After Conversi-Pancini-Piccioni evidence
the Muon abandons the ugly name of mesotron, it is not a mediator

After Isaac Rabi:

Who ordered that?

Muon is a great gift:

Hard

Elegant

Longlived

Generous

Faithful

Precise

The muon is elementary

Muon capture and μ -mesic atoms

REVIEWS OF MODERN PHYSICS

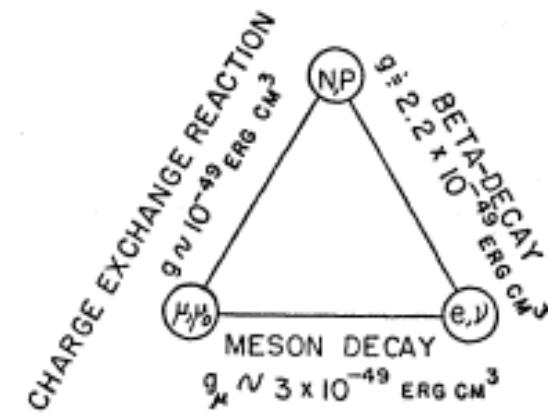
VOLUME 21, NUMBER 1

JANUARY, 1949

Charge-Exchange Reaction of the μ -Meson with the Nucleus*

J. TIOMNO** AND JOHN A. WHEELER

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey



PHYSICAL REVIEW

VOLUME 92, NUMBER 3

NOVEMBER 1, 1953

Studies of X-Rays from Mu-Mesonic Atoms*

VAL L. FITCH AND JAMES RAINWATER

Department of Physics, Columbia University, New York, New York

PHYSICAL REVIEW C

VOLUME 14, NUMBER 2

AUGUST 1976

Systematics of nuclear charge distributions in Fe, Co, Ni, Cu, and Zn deduced from muonic x-ray measurements*

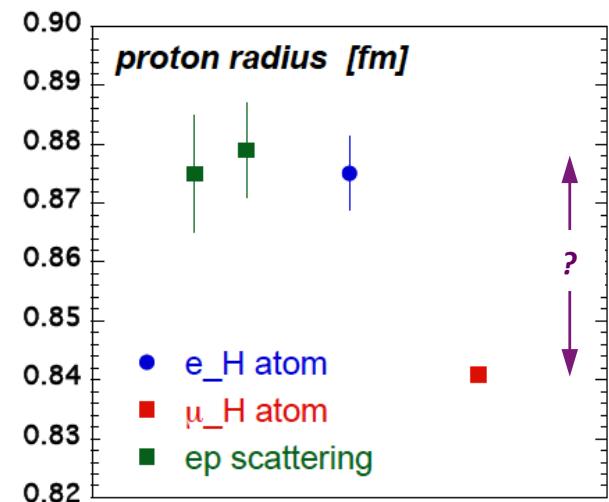
The muon measures the size of the nuclei

Today intriguing puzzle: the radius of the proton

Proton Structure from the Measurement of 2S-2P
Transition Frequencies of Muonic Hydrogen
Science 339, 417 (2013)

$^2\text{P}_{1/2} - ^2\text{S}_{1/2}$ transition $r_{e-H} = 0.8751 \pm 0.0061 \text{ fm}$
muon does it better $r_{\mu-H} = 0.84087 \pm 0.00039 \text{ fm}$

$$|\psi(0)|^2 = \frac{1}{\pi a^3} \quad a = \frac{\hbar c}{\alpha} \frac{1}{mc^2}$$



PRL 105, 242001 (2010)

PHYSICAL REVIEW LETTERS

10 DECEMBER 2010



High-Precision Determination of the Electric and Magnetic Form Factors of the Proton

$$r_{ep} = 0.879 \pm 0.08 \text{ fm} \quad \text{MAMI}$$

Physics Letters B 705 (2011) 59–64

$$r_{ep} = 0.875 \pm 0.10 \text{ fm} \quad \text{JLab}$$

High-precision measurement of the proton elastic form factor ratio $\mu_p G_E/G_M$
at low Q^2

The τ - θ puzzle and parity



PHYSICAL REVIEW

VOLUME 105, NUMBER 5

MARCH 1, 1957

Parity Nonconservation and a Two-Component Theory of the Neutrino

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(Received January 10, 1957; revised manuscript received January 17, 1957)

A two-component theory of the neutrino is discussed. The theory is possible only if parity is not conserved in interactions involving the neutrino. Various experimental implications are analyzed. Some general remarks concerning nonconservation are made.

In the decay $\pi \rightarrow \mu\nu$ muons are polarised,
and the decay electron should keep memory

The proof, few months later:

LETTERS TO THE EDITOR

1415

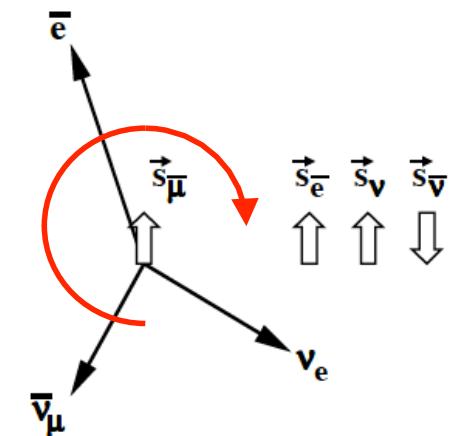
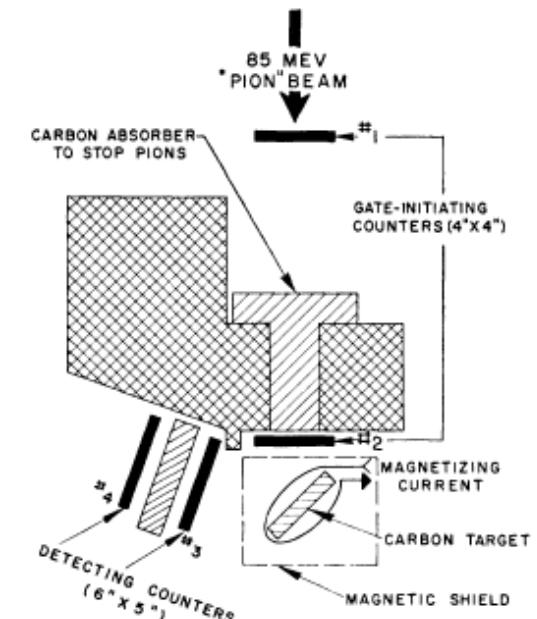
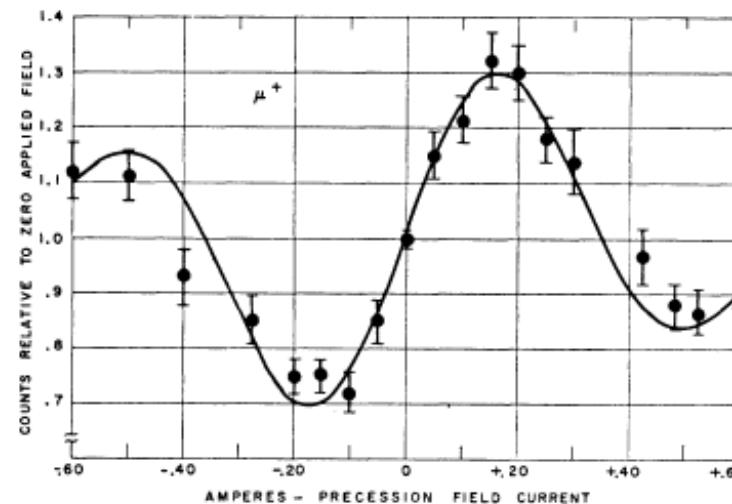
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,[†] LEON M. LEDERMAN,
AND MARCEL WEINRICH

*Physics Department, Nevis Cyclotron Laboratories,
Columbia University, Irvington-on-Hudson,
New York, New York*

(Received January 15, 1957)

$$g_\mu = 2$$



The muon is generous

Few years later: when does the g-2 saga begin

PHYSICAL REVIEW

VOLUME 118, NUMBER 1

APRIL 1, 1960

Accurate Determination of the μ^+ Magnetic Moment*

R. L. GARWIN,[†] D. P. HUTCHINSON, S. PENMAN,[‡] AND G. SHAPIRO[§]

Columbia University, New York, New York

(Received August 4, 1959)

Using a precession technique, the magnetic moment of the positive mu meson is determined to an accuracy of 0.007%. Muons are brought to rest in a bromoform target situated in a homogeneous magnetic field, oriented at right angles to the initial muon spin direction. The precession of the spin about the field direction, together with the asymmetric decay of the muon, produces a periodic time variation in the probability distribution of electrons emitted in a fixed laboratory direction. The period of this variation is compared with that of a reference oscillator by means of phase measurements of the "beat note" between the two. The magnetic field at which the precession and reference frequencies coincide is measured with reference to a proton nuclear magnetic resonance magnetometer. The ratio of the muon precession frequency to that of the proton in the same magnetic field is thus determined to be 3.1834 ± 0.0002 . Using a re-evaluated lower limit to the muon mass, this is shown to yield a lower limit on the muon g factor of $2(1.00122 \pm 0.00008)$ in agreement with the predictions of quantum electrodynamics.

VOLUME 6, NUMBER 3

PHYSICAL REVIEW LETTERS

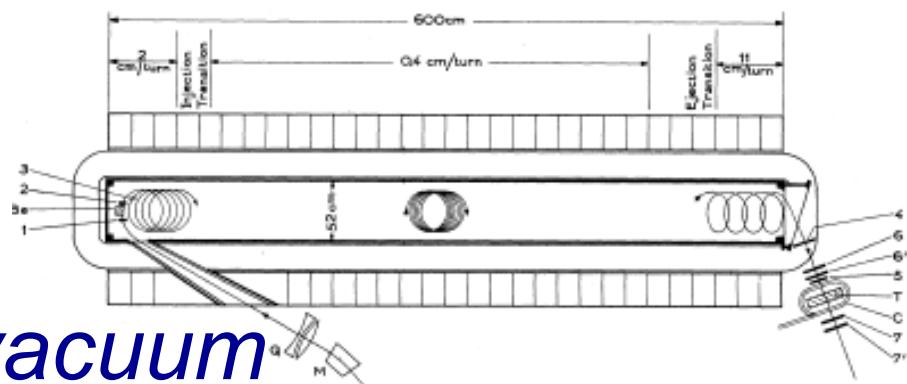
FEBRUARY 1, 1961

MEASUREMENT OF THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

G. Charpak, F. J. M. Farley, R. L. Garwin,* T. Muller, J. C. Sens, V. L. Telegdi,[†] and A. Zichichi
CERN, Geneva, Switzerland
(Received January 16, 1961)

$$a_{\text{th}} \equiv (g - 2)/2 = (\alpha/2\pi) + 0.75(\alpha^2/\pi^2) + \dots = 0.001165,$$

$$a_{\text{exp}} = a_{\text{th}} (0.983 \pm 0.019) = 0.001145 \pm 0.000022$$



The muon explores the vacuum

Twin muons confirm the paradox

Volume 28B, number 4

PHYSICS LETTERS

9 December 1968

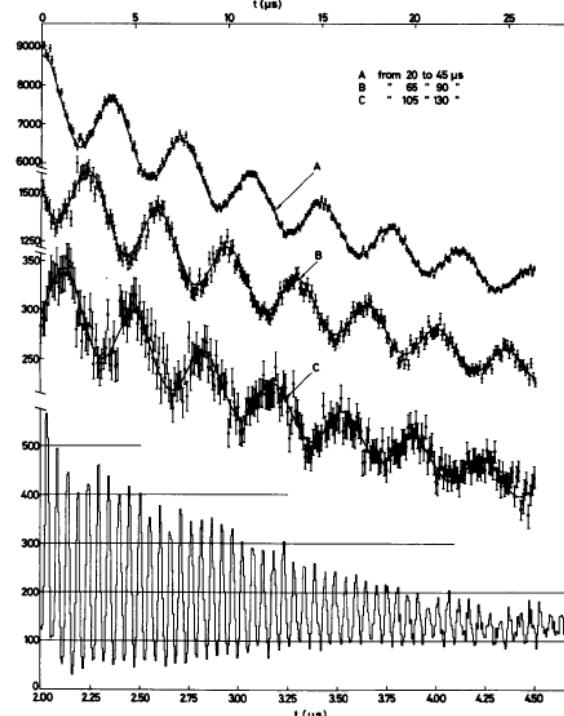
PRECISION MEASUREMENT OF THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

J. BAILEY, W. BARTL *, G. Von BOCHMANN †, R. C. A. BROWN, F. J. M. FARLEY **,
H. JÖSTLEIN †, E. PICASSO and R. W. WILLIAMS ***

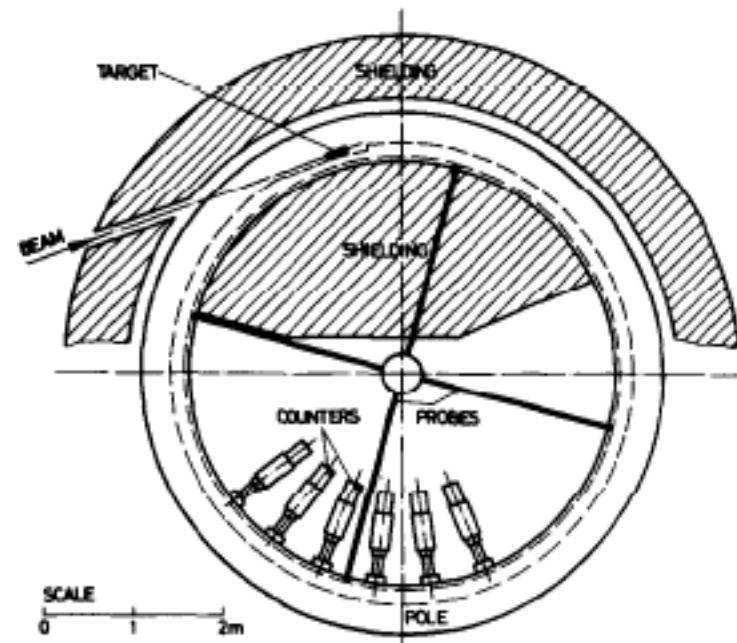
CERN, Geneva, Switzerland

$$a_{\text{theory}} = 11656.0 \times 10^{-7}$$

$$a_{\text{exp}} = (11661.6 \pm 3.1) \times 10^{-7}$$



the first CERN muon storage ring
at the 'magic' energy



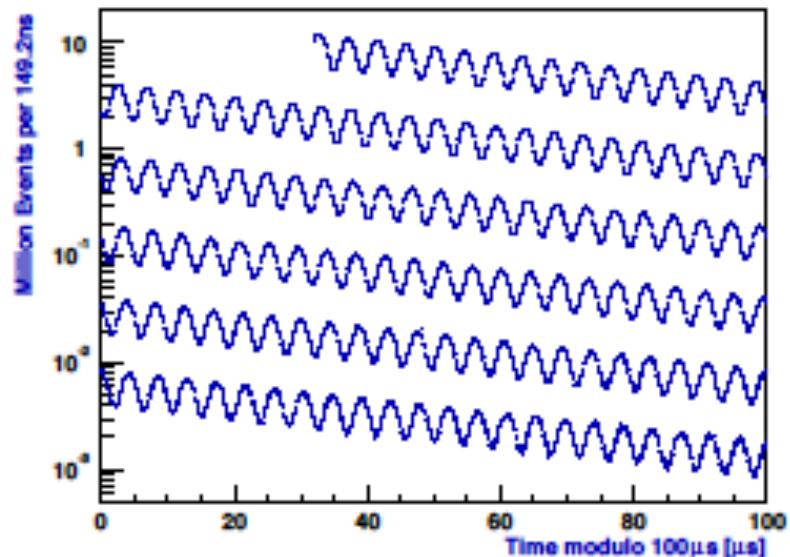
The muon gets impressive

PHYSICAL REVIEW D 87, 052003 (2013)

Detailed report of the MuLan measurement of the positive muon lifetime and determination of the Fermi constant

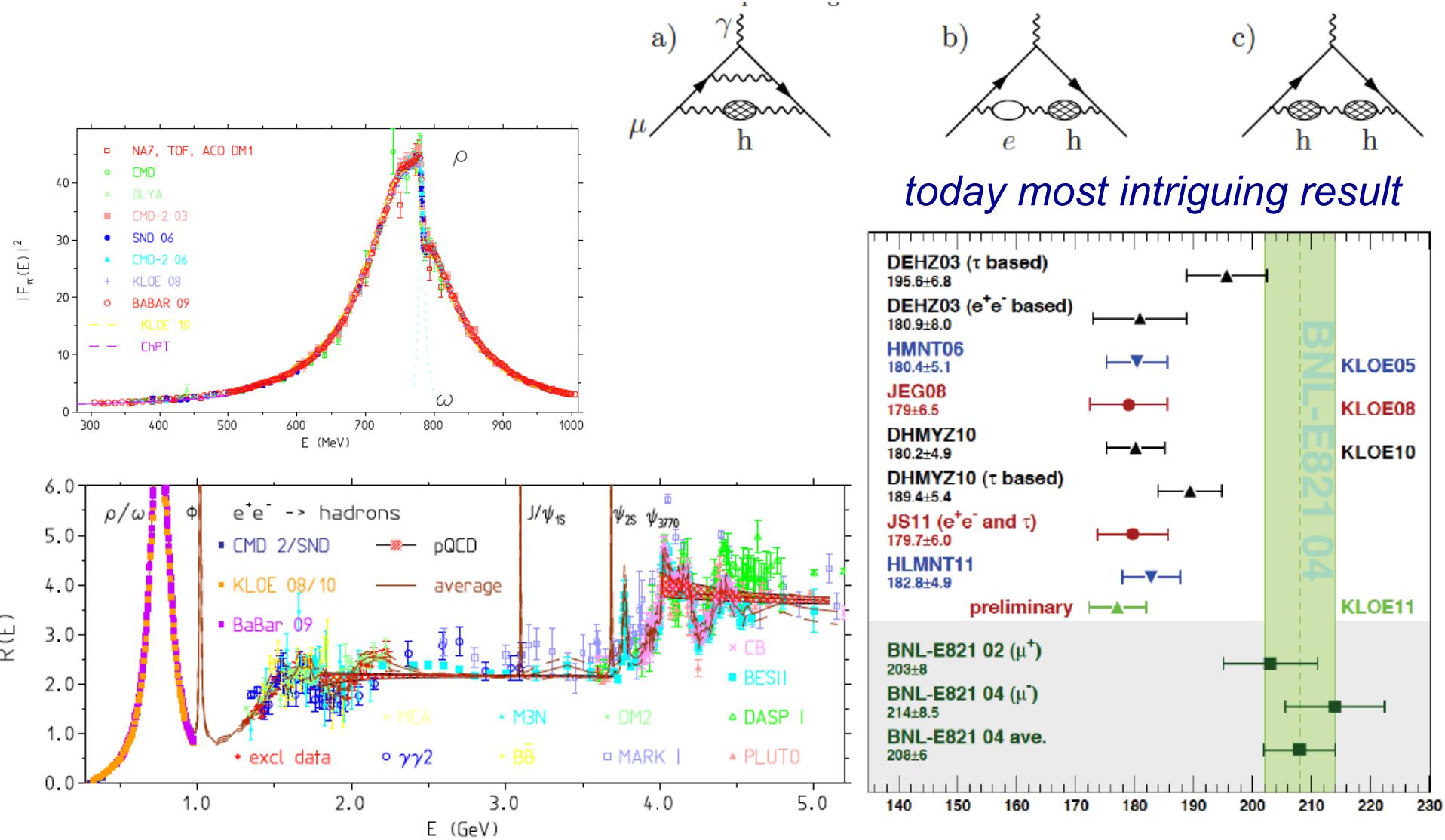
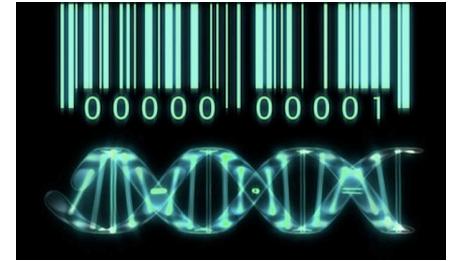
V. Tishchenko,¹ S. Battu,¹ R. M. Carey,² D. B. Chitwood,³ J. Crnkovic,³ P. T. Debevec,³ S. Dhamija,¹ W. Earle,² A. Gafarov,² K. Giovanetti,⁴ T. P. Gorringe,¹ F. E. Gray,⁵ Z. Hartwig,² D. W. Hertzog,^{3,6} B. Johnson,⁷ P. Kammler,^{3,6} B. Kiburg,³ S. Kizilgul,³ J. Kunkle,³ B. Lauss,⁸ I. Logashenko,² K. R. Lynch,^{2,9} R. McNabb,³ J. P. Miller,² F. Mulhauser,^{3,8} C. J. G. Onderwater,^{3,10} Q. Peng,² J. Phillips,² S. Rath,¹ B. L. Roberts,² D. M. Webber,³ P. Winter,³ and B. Wolfe³

Table 6.2. Summary of CERN and E821 Results



Experiment	Year	Polarity $a_\mu \times 10^{10}$	Precision [ppm]
CERN I	1961	μ^+ 11 450 000(220000)	4300
CERN II	1962-1968	μ^+ 11 661 600(3100)	270
CERN III	1974-1976	μ^+ 11 659 100(110)	10
CERN III	1975-1976	μ^- 11 659 360(120)	10
BNL	1997	μ^+ 11 659 251(150)	13
BNL	1998	μ^+ 11 659 191(59)	5
BNL	1999	μ^+ 11 659 202(15)	1.3
BNL	2000	μ^+ 11 659 204(9)	0.73
BNL	2001	μ^- 11 659 214(9)	0.72
Average		11 659 208.0(6.3)	0.54

The muon probes the unknown



The V-A theory:

1860

LETTERS TO THE EDITOR

Chirality Invariance and the Universal Fermi Interaction*

E. C. G. SUDARSHAN, *Harvard University,
Cambridge, Massachusetts*

AND

R. E. MARSHAK, *University of Rochester, Rochester, New York*

(Received January 10, 1958)



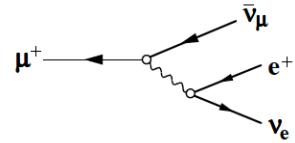
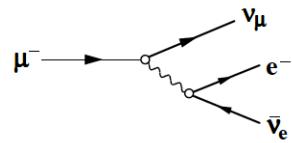
PHYSICAL REVIEW

VOLUME 109, NUMBER 1

JANUARY 1, 1958

Theory of the Fermi Interaction

R. P. FEYNMAN AND M. GELL-MANN
California Institute of Technology, Pasadena, California
(Received September 16, 1957)



$$\mathcal{H} = \frac{G}{\sqrt{2}} \bar{\psi}_\mu(x) \gamma_\alpha \frac{1 - \gamma_5}{2} \psi_{\nu_\mu}(x) W^\alpha(x) \frac{G}{\sqrt{2}} \bar{\psi}_{\nu_e}(y) \gamma_\beta \frac{1 - \gamma_5}{2} \psi_e(y) W^\beta(y)$$

$$\frac{d^2\Gamma(\mu^\pm)}{dE_e d\cos\theta} = \frac{4\pi^2 G^2}{3(2\pi)^5} [(3m_\mu - 4E_e) \mp (m_\mu - 4E_e) \cos\theta] \frac{1 \pm h_e}{2} m_\mu p_e E_e$$

The proof:



VOLUME 14, NUMBER 12

PHYSICAL REVIEW LETTERS

22 MARCH 1965

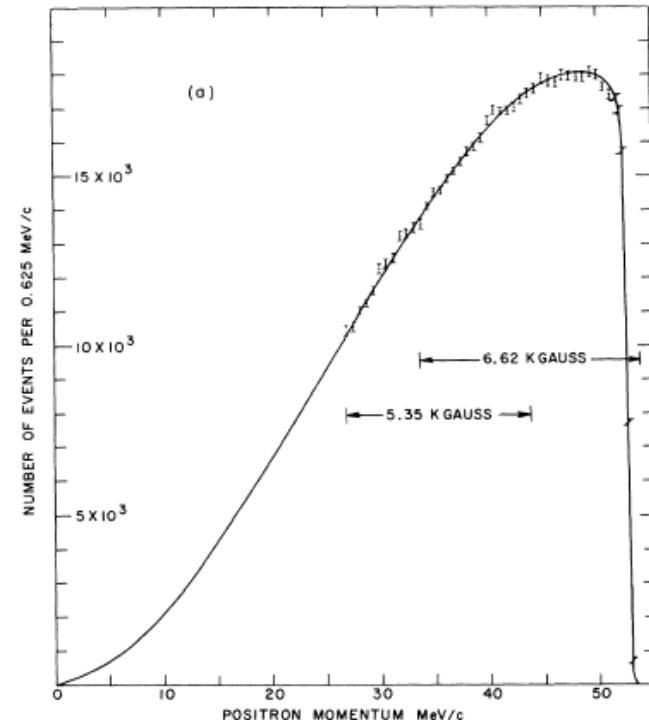
MEASUREMENT OF THE MOMENTUM SPECTRUM OF POSITRONS FROM MUON DECAY*

Marcel Bardon, Peter Norton, John Peoples,[†] and Allan M. Sachs
Columbia University, New York, New York

and

Juliet Lee-Franzini
State University of New York at Stony Brook, Stony Brook, New York
(Received 16 February 1965)

Michel spectrum
 $\rho = 0.747 \pm 0.005$



The muon is faithful

The muonium atom

VOLUME 5, NUMBER 2

PHYSICAL REVIEW LETTERS

JULY 15, 1960

FORMATION OF MUONIUM AND OBSERVATION OF ITS LARMOR PRECESSION*

V. W. Hughes, D. W. McColm, and K. Ziock
Gibbs Laboratory, Yale University, New Haven, Connecticut

VOLUME 82, NUMBER 4

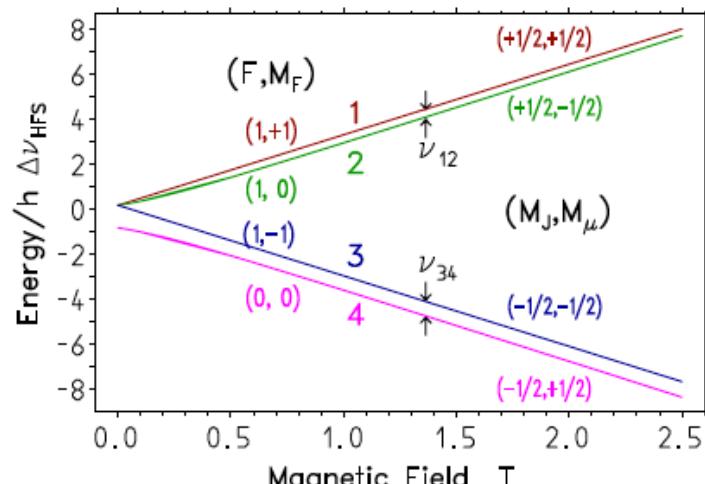
PHYSICAL REVIEW LETTERS

25 JANUARY 1999

High Precision Measurements of the Ground State Hyperfine Structure Interval of Muonium and of the Muon Magnetic Moment

W. Liu,¹ M. G. Boshier,¹ S. Dhawan,¹ O. van Dyck,² P. Egan,³ X. Fei,¹ M. Grosse Perdekamp,¹ V. W. Hughes,¹ M. Janousch,^{1,4} K. Jungmann,⁵ D. Kawall,¹ F. G. Mariam,⁶ C. Pillai,² R. Prigl,^{1,6} G. zu Putlitz,⁵ I. Reinhard,⁵ W. Schwarz,^{1,5} P. A. Thompson,⁶ and K. A. Woodle⁶

Muonium hyperfine Zeeman splitting



$$m_\mu / m_e = 206.7682826 \pm 46$$

$$m_\mu = 105.658345 \pm 24 \text{ MeV}$$

The muon family

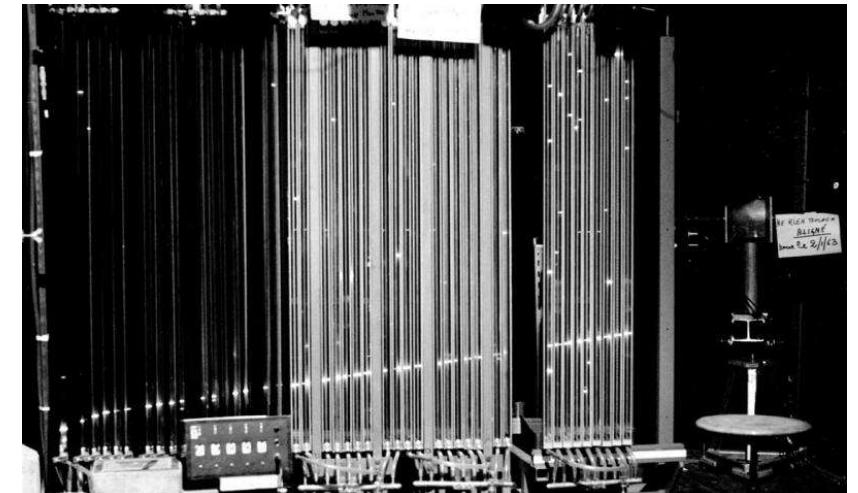
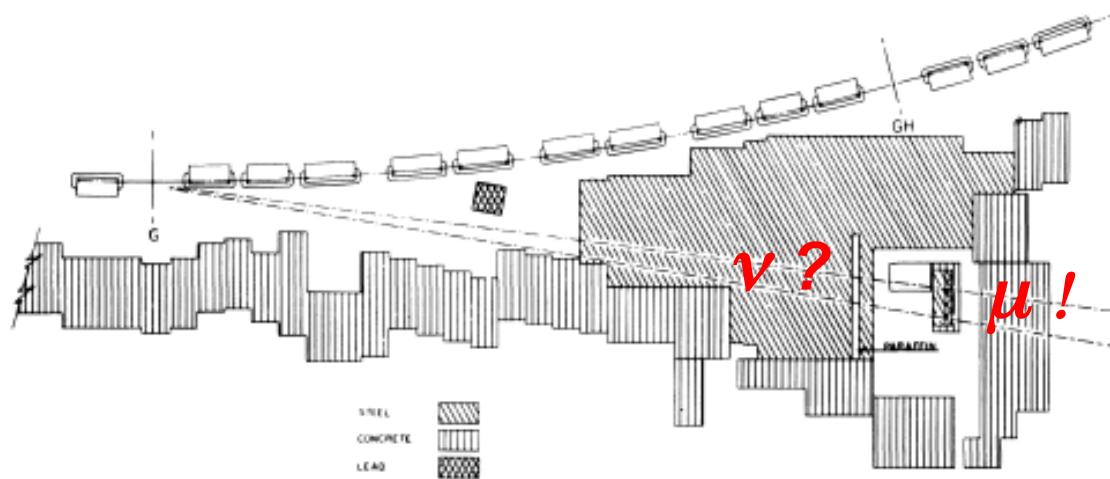
VOLUME 9, NUMBER 1

PHYSICAL REVIEW LETTERS

JULY 1, 1962

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J.-M. Gaillard, K. Goulian, L. M. Lederman, N. Mistry,
M. Schwartz,[†] and J. Steinberger[†]



The muon has its own daughter

The muon determines the Fermi constant

PHYSICAL REVIEW

VOLUME 132, NUMBER 6

15 DECEMBER 1963

Precision Lifetime Measurements on Positive and Negative Muons*

S. L. MEYER, E. W. ANDERSON, E. BLESER,[†] L. M. LEDERMAN,
J. L. ROSEN, J. ROTHBERG,[‡] AND I-T. WANG

Columbia University, New York, New York

(Received 31 July 1963)

$$\tau_{\mu^+} = 2.197 \pm 0.002 \text{ } \mu\text{sec}$$

$$\tau_{\mu^-} = 2.198 \pm 0.002 \text{ } \mu\text{sec}$$

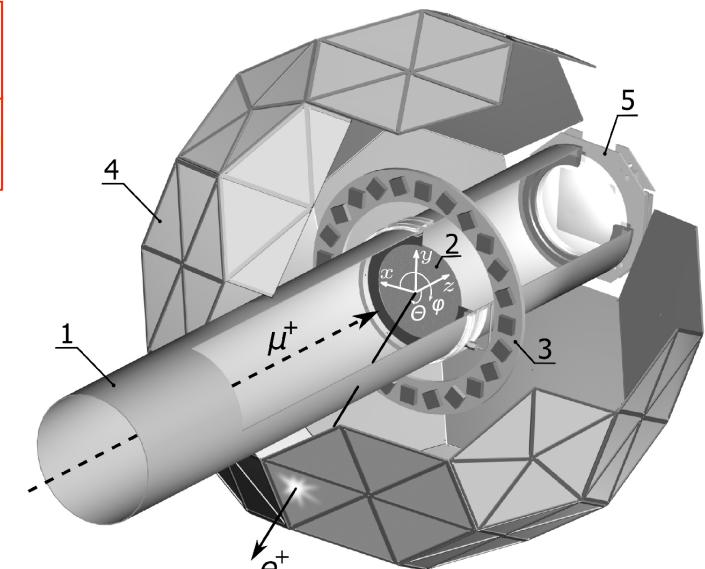
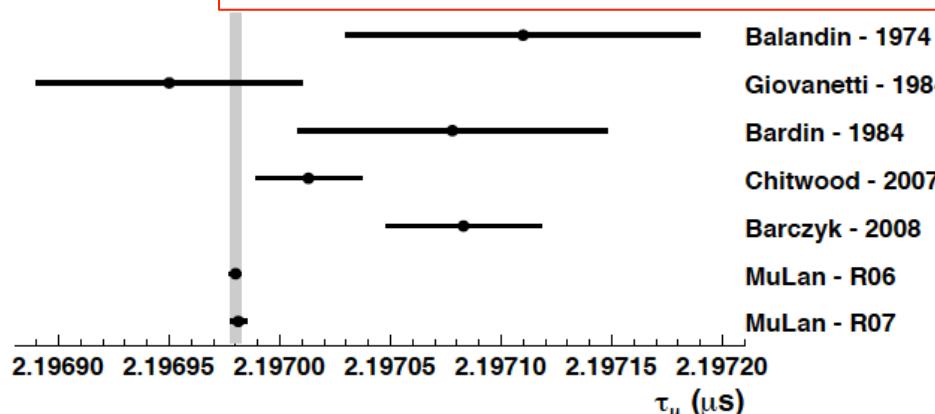
PHYSICAL REVIEW D 87, 052003 (2013)

Detailed report of the MuLan measurement of the positive muon lifetime and determination of the Fermi constant

V. Tishchenko,¹ S. Battu,¹ R. M. Carey,² D. B. Chitwood,³ J. Crnkovic,³ P. T. Debevec,³ S. Dhamija,¹ W. Earle,² A. Gafarov,² K. Giovanetti,⁴ T. P. Gorringe,¹ F. E. Gray,⁵ Z. Hartwig,² D. W. Hertzog,^{3,6} B. Johnson,⁷ P. Kammel,^{3,6} B. Kiburg,³ S. Kizilgul,³ J. Kunkle,³ B. Lauss,⁸ I. Logashenko,² K. R. Lynch,^{2,9} R. McNabb,³ J. P. Miller,² F. Mulhauser,^{3,8} C. J. G. Onderwater,^{3,10} Q. Peng,² J. Phillips,² S. Rath,¹ B. L. Roberts,² D. M. Webber,³ P. Winter,³ and B. Wolfe³

$$\tau_{\mu}(\text{MuLan}) = 2196980.3 \pm 2.1(\text{stat}) \pm 0.7(\text{syst}) \text{ ps}$$

$$G_F(\text{MuLan}) = [1.1663787(6) \times 10^{-5}] \text{ GeV}^{-2}$$



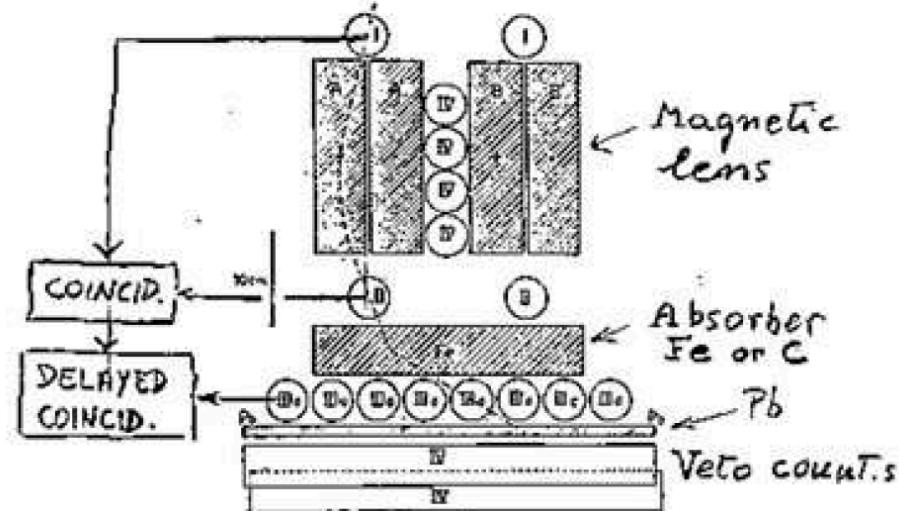
When did I meet the muon

1968: lectures of Fisica Superiore

il Maestro: Marcello Conversi



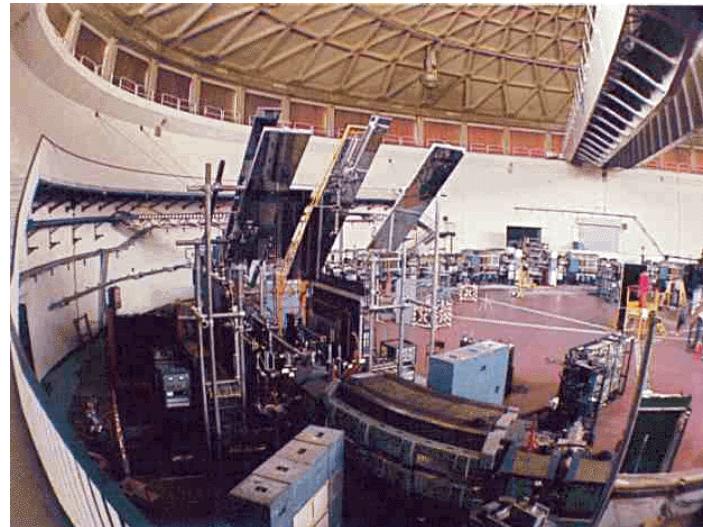
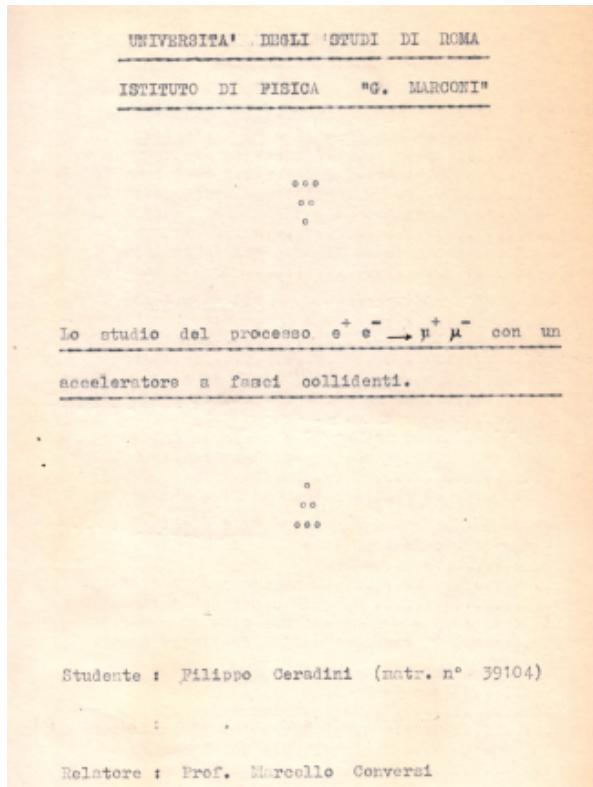
M.C. + E.PANCINI + O.PICCIONI



Marcello Conversi handwriting

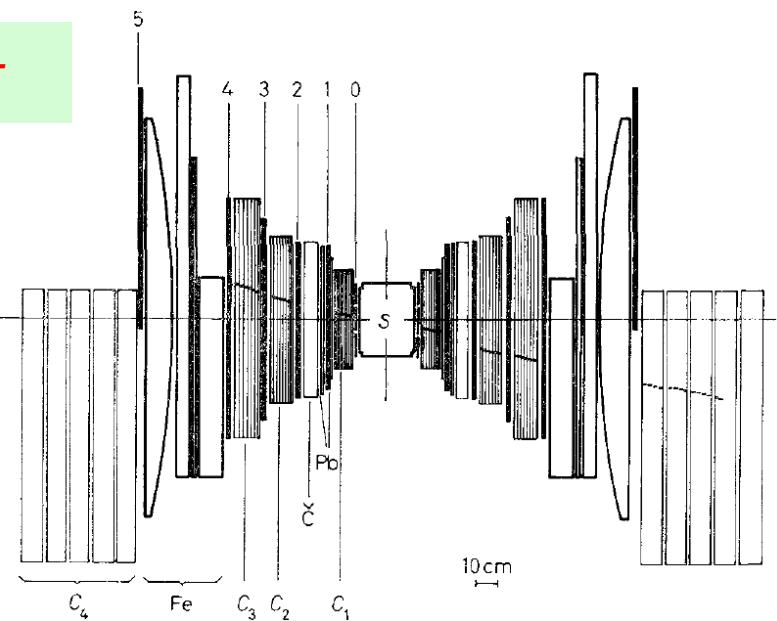
it was love at first sight and I decided for my diploma thesis at ADONE

Adone finally works



the beauty of tracking muons

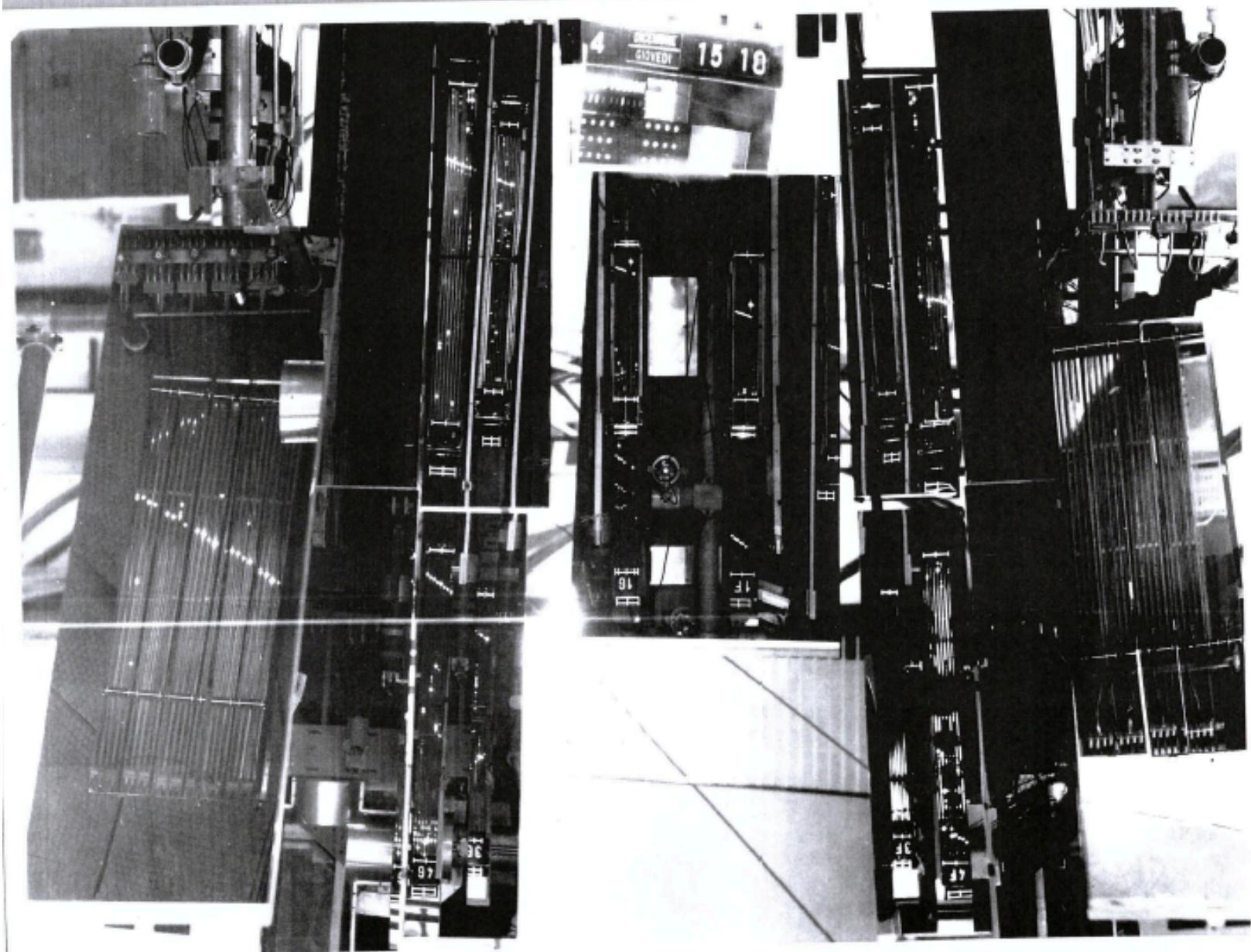
$$e^+ e^- \rightarrow \mu^+ \mu^-$$



(ricevuto il 30 Settembre 1971)

Thursday December 4, 1969 15:18

$e^+ e^- \rightarrow \mu^+ \mu^-$



muon production in light-by-light scattering

VOLUME 32, NUMBER 7

PHYSICAL REVIEW LETTERS

18 FEBRUARY 1974

Muon Pair Production by Photon-Photon Interactions in e^+e^- Storage Rings

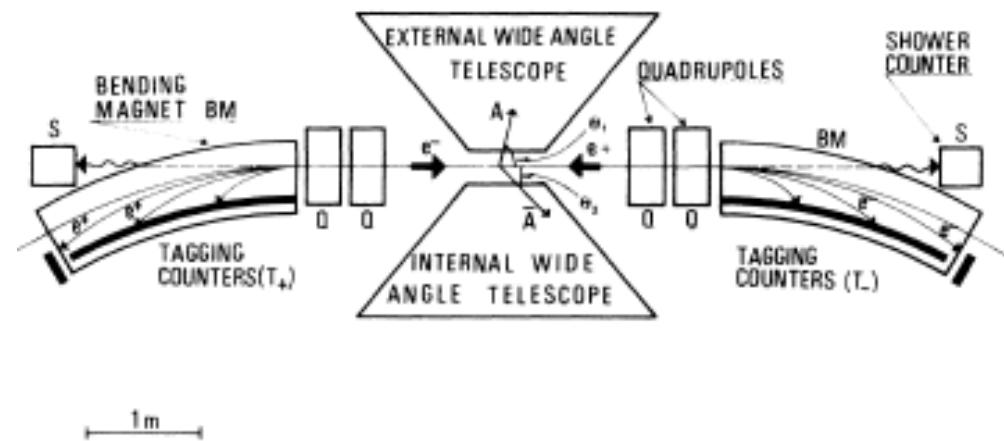
G. Barbiellini, S. Orito, T. Tsuru, and R. Visentin

Laboratori Nazionali del Comitato Nazionale per l'Energia Nucleare, Frascati, Rome, Italy

and

F. Ceradini, M. Conversi, S. d'Angelo, M. L. Ferrer, L. Paoluzi, and R. Santonico
Istituto di Fisica dell'Università di Roma and Sezione di Roma dell'Istituto Nazionale di Fisica Nucleare,
Rome, Italy

(Received 10 December 1973)



$$\gamma\gamma \rightarrow \mu^+\mu^-$$

the first tagger in e^+e^-



Multihadron production! the muon is the reference

Volume 47B, number 1

PHYSICS LETTERS

15 October 1973

MULTIHADRON PRODUCTION IN e^+e^- COLLISIONS UP TO 3 GeV TOTAL C.M. ENERGY

F. CERADINI, M. CONVERSI, S. D'ANGELO,
L. PAOLUZI and R. SANTONICO

*Istituto di Fisica dell'Università di Roma, Italy
and Sezione di Roma dell'INFN, Rome, Italy*

and

R. VISENTIN
Laboratori Nazionali del CNEN, Frascati, Italy

Received 7 August 1973

Hadron Production in e^+e^- Collisions (*).

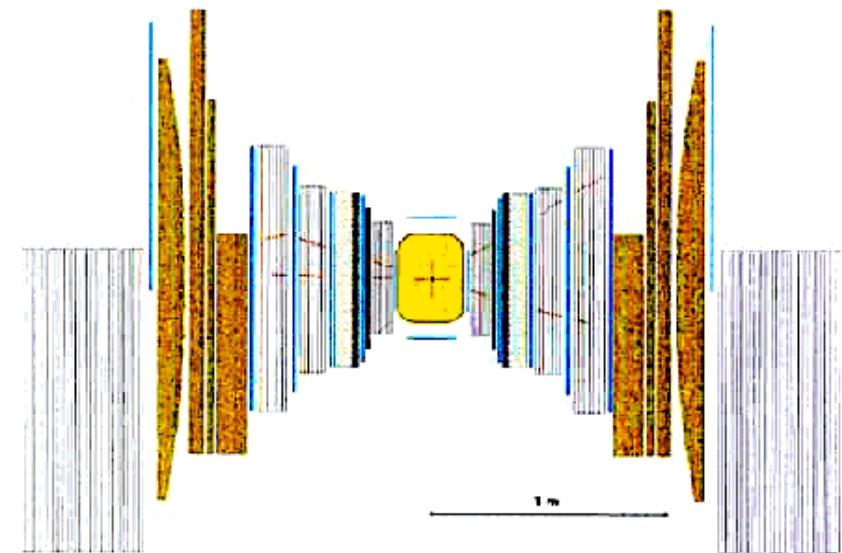
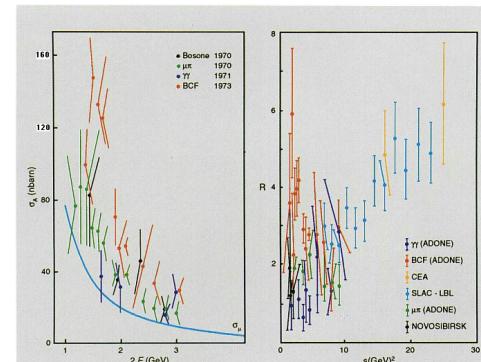
N. CABIBBO

*Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma*

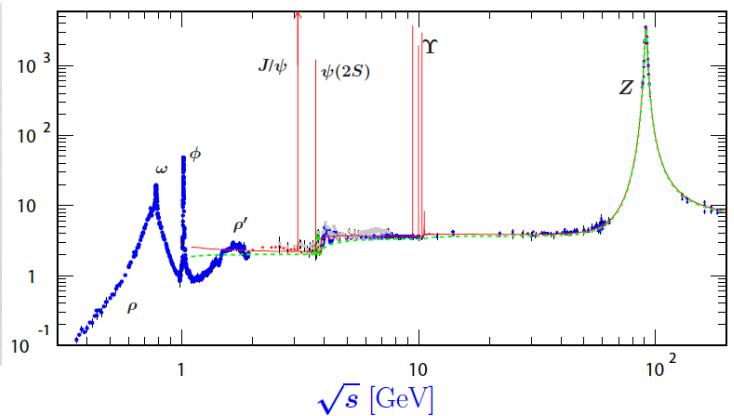
G. PARISI and M. TESTA
Istituto di Fisica dell'Università - Roma

(ricevuto il 30 Maggio 1970)

$$\sigma \rightarrow \frac{\pi \alpha^2}{12 E^2} \left[\sum_{\text{spin } 0} (Q_i)^2 + 4 \sum_{\text{spin } \pm} (Q_i)^2 \right]$$



how all this initiated



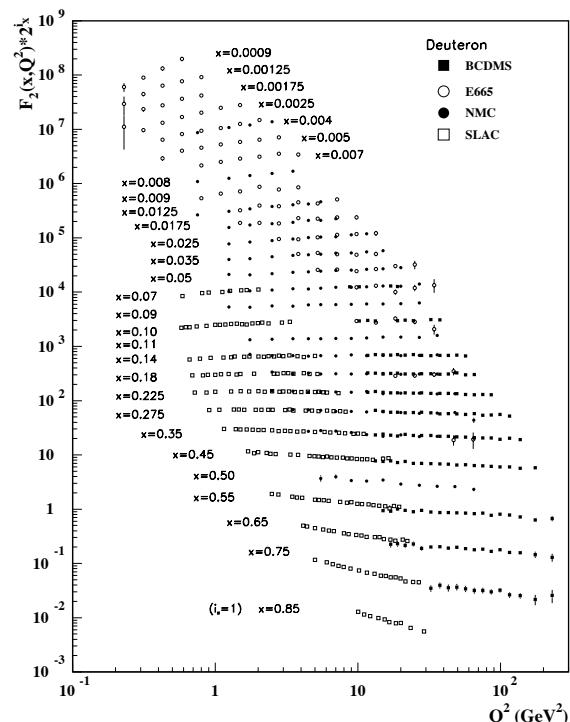
The muon as a probe of strong interactions

the muon strikes again



AN EXPERIMENT TO EXTEND THE INCLUSIVE DEEP INELASTIC MUON SCATTERING
ON HYDROGEN AND DEUTERIUM TO THE HIGHEST ENERGIES AND FOUR-MOMENTUM
TRANSFERS AVAILABLE AT THE SPS^{*}

I. Golutvin and I. Savin
Joint Institute for Nuclear Research, Dubna, USSR
F. Krienen, F. Muller, B. Naroska, C. Rubbia^{**} and G. Tarnopolsky
CERN, Geneva, Switzerland
L. Baum, H. Hilscher, U. Meyer-Berkhout, D. Schinzel,
A. Staude and R. Voss
Sektion Physik der Universität, München, Germany
G. Brosco, F. Cerdadini, M. Conversi, M. Ferrer and R. Santonico
Istituto di Fisica dell'Università, Roma
INFN - Sezione di Roma, Italy



CERN/SPSC/74-79
SPSC/PI9
1 August 1974



Volume 223, number 3,4

PHYSICS LETTERS B

15 June 1989

A HIGH STATISTICS MEASUREMENT OF THE PROTON STRUCTURE FUNCTIONS
 $F_2(x, Q^2)$ AND R FROM DEEP INELASTIC MUON SCATTERING AT HIGH Q^2

BCDMS Collaboration

Volume 195, number 1

PHYSICS LETTERS B

27 August 1987

TEST OF QCD AND A MEASUREMENT OF Λ FROM SCALING VIOLATIONS
IN THE NUCLEON STRUCTURE FUNCTION $F_2(x, Q^2)$ AT HIGH Q^2

BCDMS Collaboration

Altarelli-Parisi-Dokshitzer-Gribov-Lipatov at work !

The muon as a probe of the electroweak theory

Volume 120B, number 1,2,3

PHYSICS LETTERS

6 January 1983

ELECTROWEAK ASYMMETRY IN DEEP INELASTIC MUON- NUCLEON SCATTERING

A. ARGENTO, A.C. BENVENUTI, D. BOLLINI, T. CAMPORESI, G. HEIMAN,
L. MONARI, F.L. NAVARRA

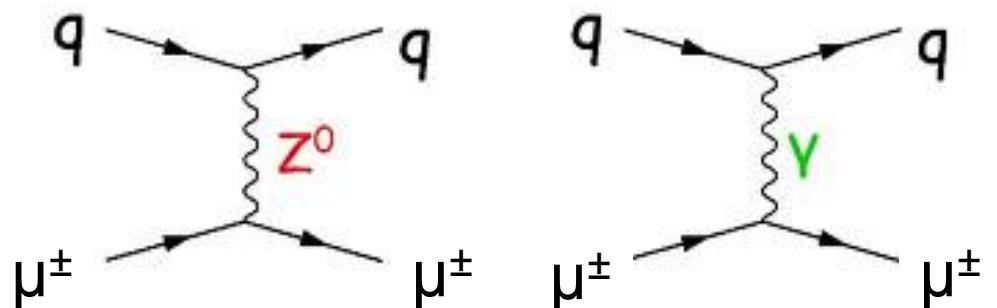
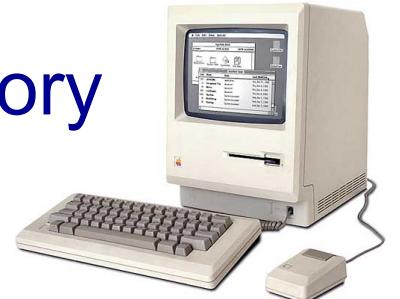
*Istituto di Fisica dell'Università, Bologna, Italy
and INFN, Bologna, Italy*

M. BOZZO ¹, R. BRUN, H. GENNOW ², M. GOOSSENS, R. KOPP ³, W.D. NOWAK ⁴,
L. PIEMONTESE, J. PILCHER ⁵, D. SCHINZEL, G. VESZTERGOMBI ⁶
CERN, Geneva, Switzerland

D.YU. BARDIN, J. CVACH, N.G. FADEEV, I.A. GOLUTVIN, Y.T. KIRYUSHIN,
V.S. KISSELEV, M. KLEIN ⁴, A. KONDOR, V.G. KRIVOKHIZHIN, V.V. KUKHTIN,
I.A. SAVIN, G.I. SMIRNOV, P. TODOROV, A.G. VOLODKO, J. ŽAČEK ⁷
Joint Institute for Nuclear Research, Dubna, USSR

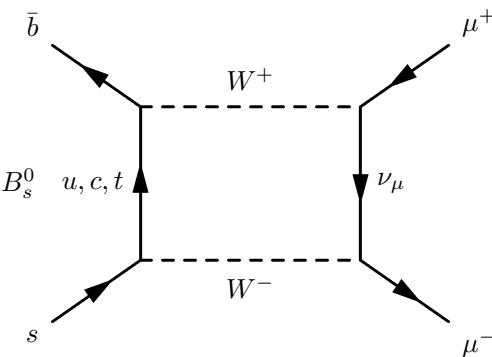
D. JAMNIK ⁸, U. MEYER-BERKHOUT, J. O'CONNOR, A. STAUDE, K.M. TEICHERT,
R. TIRLER, R. VOSS, S. WOJCICKI ⁹, Č. ZUPANČIČ
Sektion Physik der Universität ¹⁰, Munich, Germany

M. CRIBIER, T. DOBROWOLSKI, J. FELTESSE, P. RICH-HENNION,
A. MILSZTAJN, J.F. RENARDY, Y. SACQUIN, G. SMADJA,
P. VERRECCHIA and M. VIRCHAUX
CEN, Saclay, France



Muon beam is naturally longitudinally polarised.
The γ -Z interference differs for the g_L g_R couplings of the muons
and the quarks of a Carbon isoscalar target,
as in the famous SLAC experiment.

The muon as a probe of heavy quark coupling



$\mathcal{B}(K_L^0 \rightarrow \mu^+ \mu^-)$ is not seen ! Glashow-Iliopoulos-Maiani: ~~FCNC~~

VOLUME 84, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 2000

Improved Branching Ratio Measurement for the Decay $K_L^0 \rightarrow \mu^+ \mu^-$

D. Ambrose,¹ C. Arroyo,² M. Bachman,³ D. Connor,³ M. Eckhause,⁴ S. Graessle,¹ A. D. Hancock,⁴ K. Hartman,² M. Hebert,² C. H. Hoff,⁴ G. W. Hoffmann,¹ G. M. Irwin,² J. R. Kane,⁴ N. Kanematsu,³ Y. Kuang,⁴ K. Lang,¹ R. Lee,³ R. D. Martin,⁴ J. McDonough,¹ A. Milder,¹ W. R. Molzon,³ M. Pommot-Maia,² P. J. Riley,¹ J. L. Ritchie,¹ P. D. Rubin,⁵ V. I. Vassilakopoulos,¹ R. E. Welsh,⁴ and S. G. Wojcicki²

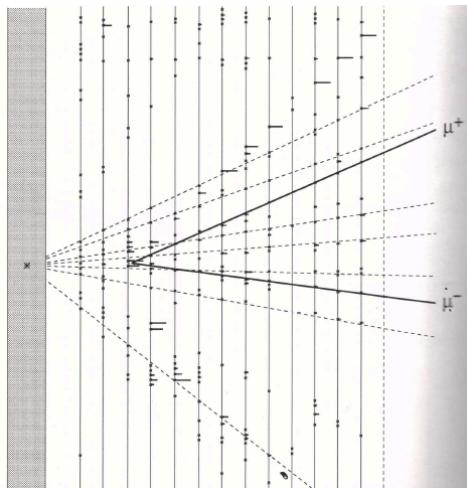
$$\mathcal{B}(K_L^0 \rightarrow \mu^+ \mu^-) = (7.18 \pm 0.17) \times 10^{-9}$$

Physics Letters B 353 (1995) 563–570

Search for the decay $D^0 \rightarrow \mu^+ \mu^-$

BEATRICE Collaboration

$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 7.6 \times 10^{-6} \text{ at 90% C.L.}$$



Manuela thesis

Physics Letters B 725 (2013) 15–24

Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$

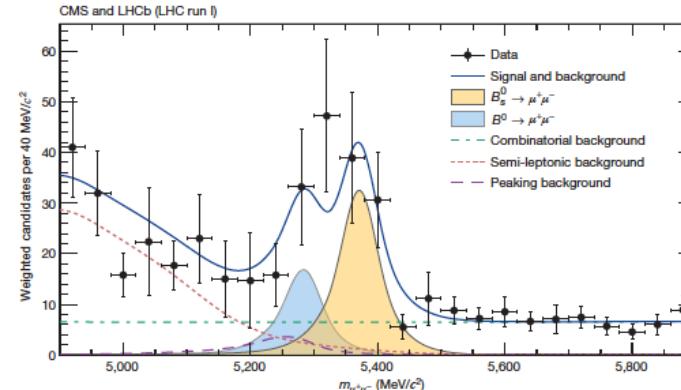
LHCb Collaboration

$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 6.2 \times 10^{-9} \text{ at 90% C.L.}$$

Nature 522 (2015) 68-72

Observation of the rare $B_s^0 \rightarrow \mu^+ \mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*



$$\mathcal{B}(B_S^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

The muon as a probe of heavy quark coupling

Volume 186, number 2

PHYSICS LETTERS B

5 March 1987

SEARCH FOR B^0 - \bar{B}^0 OSCILLATIONS AT THE CERN PROTON-ANTIPROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

A natural explanation for the excess of like-sign events is the existence of a significant amount of $B^0 \leftrightarrow \bar{B}^0$ transitions. The fraction of beauty particles that produce first-generation decay muons with the opposite electric charge from that expected without mixing is deduced to be $\chi = 0.121 \pm 0.047$. Combined with the null result from searches for $B^0 \leftrightarrow \bar{B}^0$ oscillations at e^+e^- colliders, our results are consistent with transitions in the B_s^0 system, as favoured theoretically.

PHYSICAL REVIEW D, VOLUME 60, 051101 1999

Measurement of the $B_d^0\bar{B}_d^0$ oscillation frequency using dimuon data in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV (CDF Collaboration)

We present a measurement of the mass difference Δm_d of the two B_d^0 mass eigenstates. We use a flavor tagging method based on the lepton charge, in a sample of events with two muons at low transverse momentum. The sample corresponds to an integrated luminosity of 90 pb^{-1} collected by the Collider Detector at Fermilab. The result obtained is $\Delta m_d = 0.503 \pm 0.064(\text{stat}) \pm 0.071(\text{syst}) \text{ ps}^{-1}$.

The muon hunting for new particles

VOLUME 25, NUMBER 5

PHYSICAL REVIEW LETTERS

3 AUGUST 1970

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 25 May 1970)

VOLUME 39, NUMBER 5

PHYSICAL REVIEW LETTERS

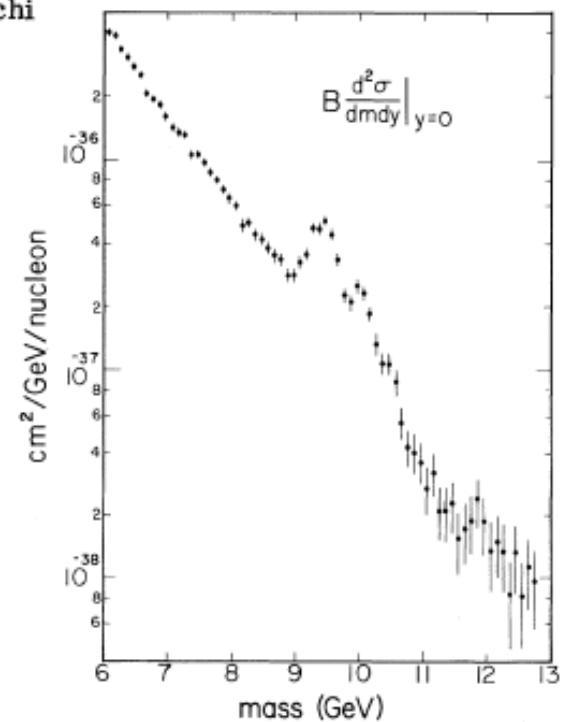
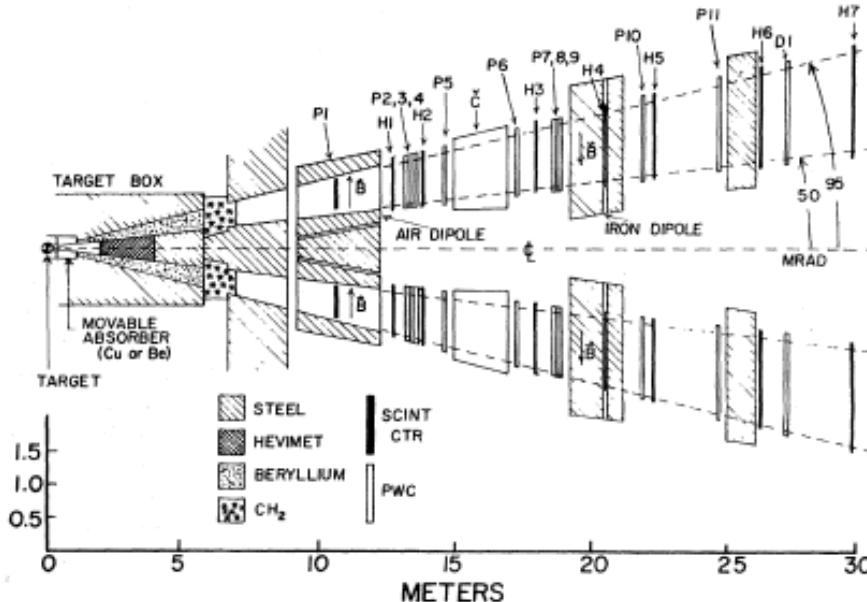
1 AUGUST 1977

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,^(a) H. D. Snyder, and J. K. Yoh

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi

A. S. Ito, H. Jostlein, D. M. Kaplan, and R. D. Kephart



The muon unveiling new gauge bosons

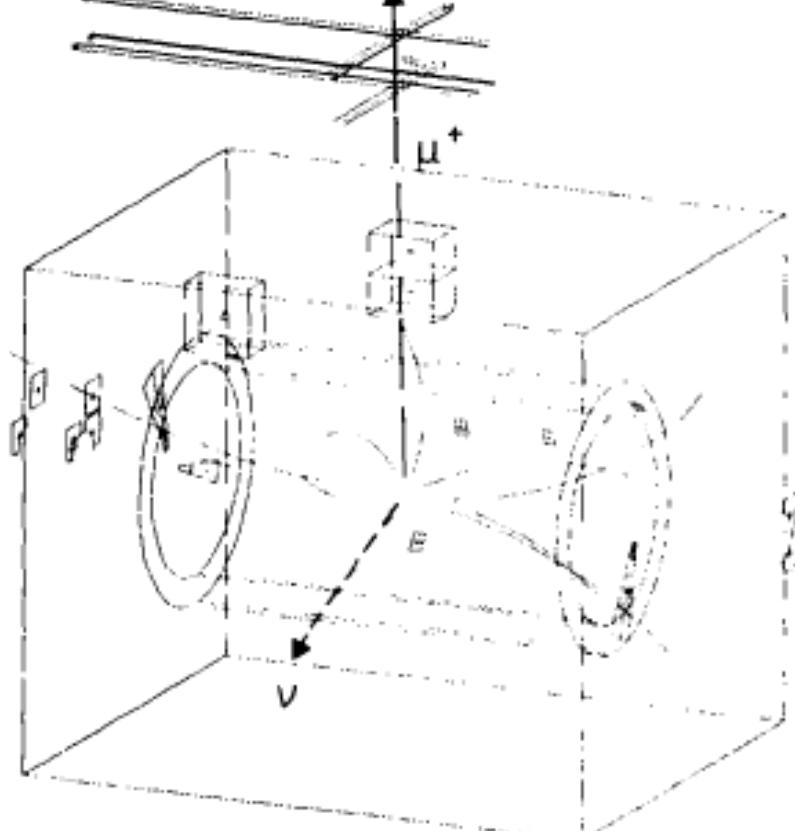
Volume 134B, number 6

PHYSICS LETTERS

26 January 1984

OBSERVATION OF THE MUONIC DECAY OF THE CHARGED INTERMEDIATE VECTOR BOSON

UA1 Collaboration, CERN, Geneva, Switzerland



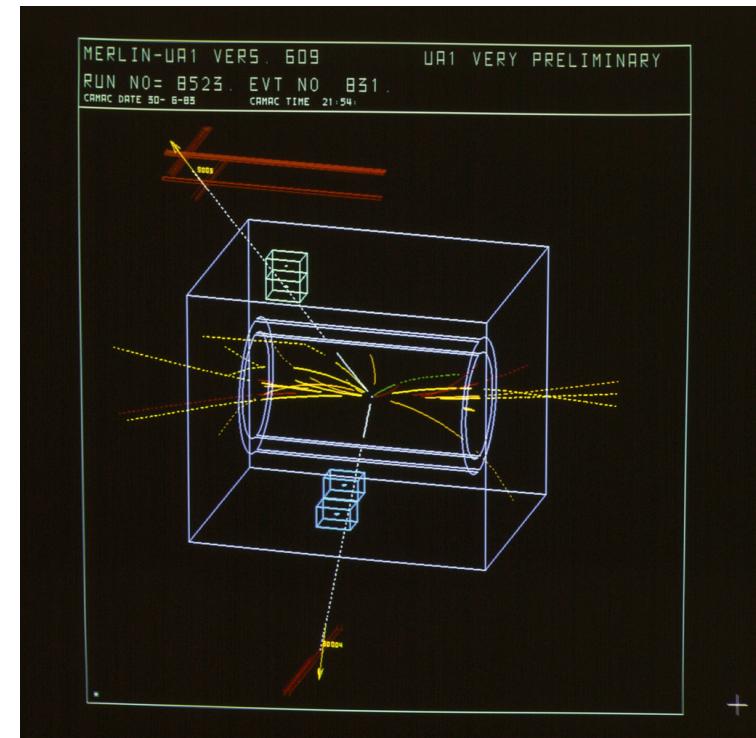
Volume 147B, number 1,2,3

PHYSICS LETTERS

1 November 1984

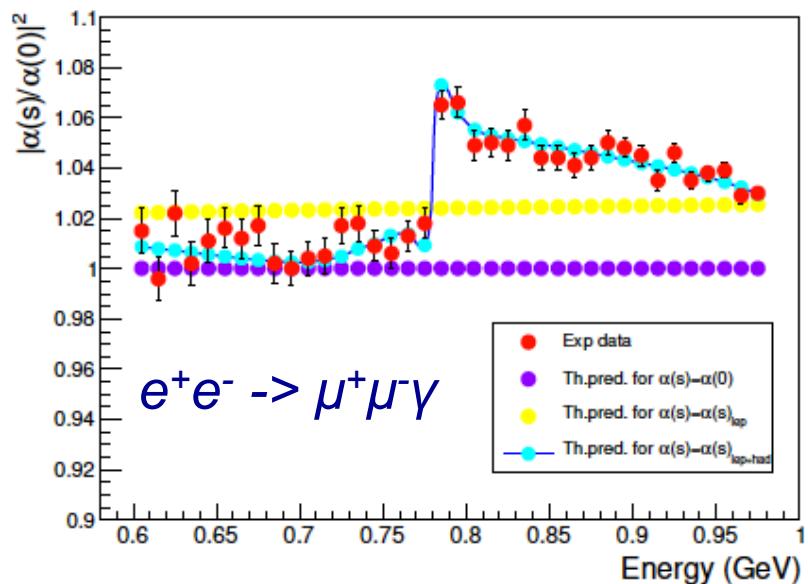
OBSERVATION OF MUONIC Z^0 -DECAY AT THE $\bar{p}p$ COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland



What the muons can do

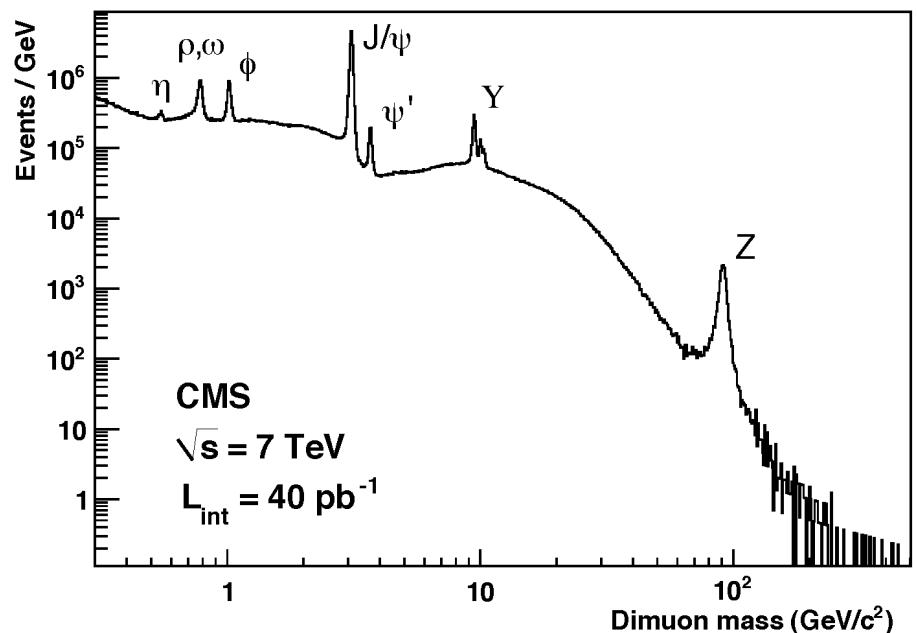
explore α_{QED} running



Measurement of the running of the fine structure constant below 1 GeV with the KLOE detector

The KLOE-2 Collaboration

We have measured the running of the effective QED coupling constant $\alpha(s)$ in the time-like region $0.6 < \sqrt{s} < 0.975$ GeV with the KLOE detector at DAΦNE using the Initial State Radiation process $e^+e^- \rightarrow \mu^+\mu^-\gamma$. It represents the first measurement of the running of $\alpha(s)$ in this energy region.



explore the whole spectrum

Physics Letters B ARTICLE IN PRESS

The muon and the W mass

PRL 108, 151803 (2012)

PHYSICAL REVIEW LETTERS

week ending
13 APRIL 2012

Precise Measurement of the W-Boson Mass with the CDF II Detector

Distribution	W-boson mass (MeV)
$m_T(e, \nu)$	$80\,408 \pm 19_{\text{stat}} \pm 18_{\text{syst}}$
$p_T^\ell(e)$	$80\,393 \pm 21_{\text{stat}} \pm 19_{\text{syst}}$
$p_T^\nu(e)$	$80\,431 \pm 25_{\text{stat}} \pm 22_{\text{syst}}$
$m_T(\mu, \nu)$	$80\,379 \pm 16_{\text{stat}} \pm 16_{\text{syst}}$
$p_T^\ell(\mu)$	$80\,348 \pm 18_{\text{stat}} \pm 18_{\text{syst}}$
$p_T^\nu(\mu)$	$80\,406 \pm 22_{\text{stat}} \pm 20_{\text{syst}}$

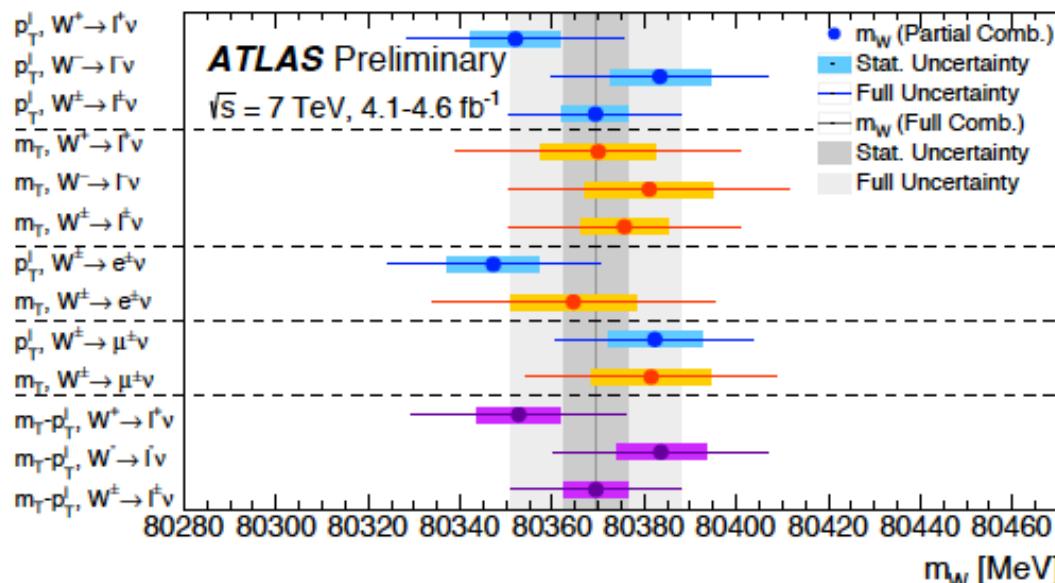
the muon does it (slightly) better

ATLAS-CONF-2016-113

13th December 2016

Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

$$m_W = (80387 \pm 19) \text{ MeV}$$



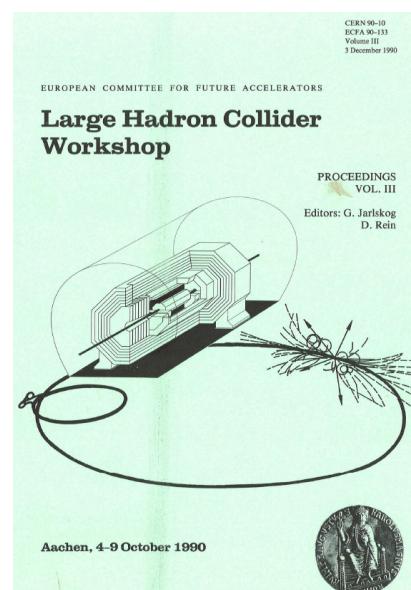
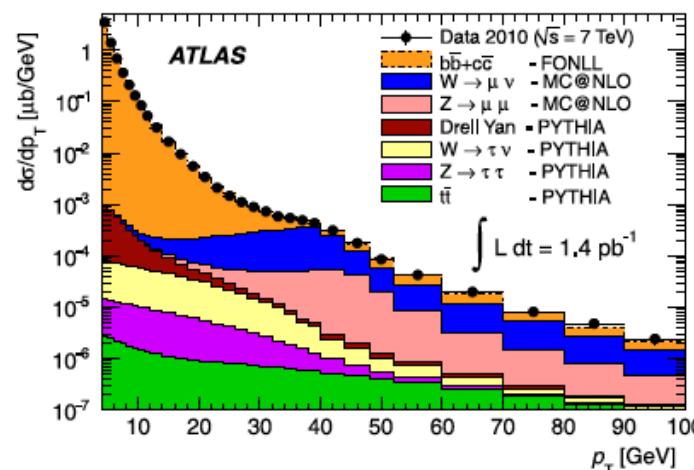
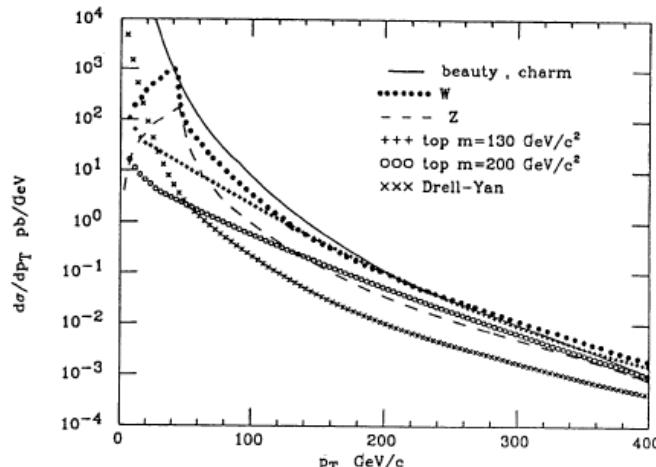
$$m_W = (80370 \pm 19) \text{ MeV}$$

The muon and the LHC

Muon Rates at the LHC

Aleandro Nisati

Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy.



Muon trigger and identification

C. Bacci⁶, A. Bettini⁵, R. Cardarelli⁷, S. Centro⁵, F. Ceradini⁶, G. Ciapetti⁶, D. Cline⁹, D. Dau³, M. Della Negra¹, L. Di Lella¹, A. Di Ciaccio⁷, K. Eggert¹, A. Ferrando⁴, W. Gorn⁸, A. Hervé¹, V. Karimäki², R. Kinnunen², F. Lacava⁶, J. Layter⁸, S. Lazić⁹, R. Martinelli⁵, A. Meneguzzo⁵, M. Mohammadi⁹, A. Nisati⁶, J. Park⁹, E. Petrolo⁶, M. Pimia², L. Pontecorvo⁶, R. Santonico⁷, B.C. Shen⁸, F. Szoncsó¹⁰, E. Torrente-Lujan⁴, J. Tuominiemi², S. Veneziano⁶, G. Walzel¹⁰, F. Wittgenstein¹, C.-E. Wulz¹⁰, L. Zanello⁶, P. Zotto⁵

FAST MUON TRACKING WITH RESISTIVE PLATE CHAMBERS

R. Santonico

INFN - Sezione di Roma "Tor Vergata"

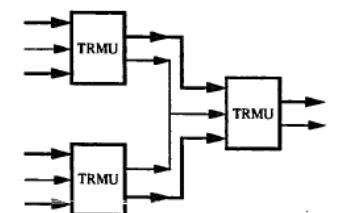
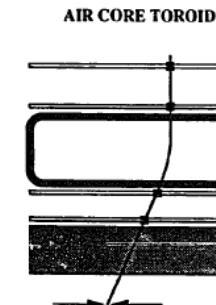
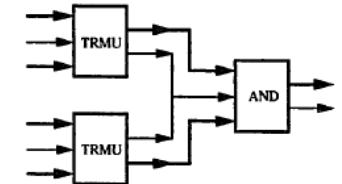
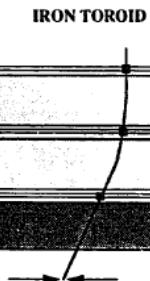
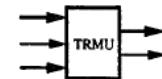
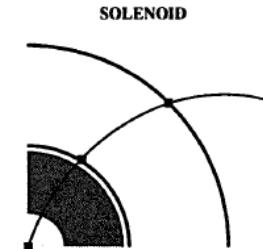
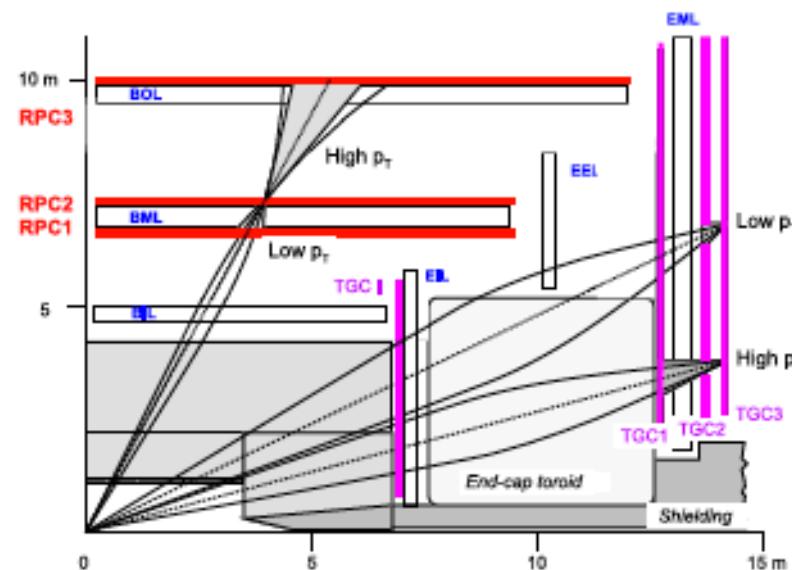
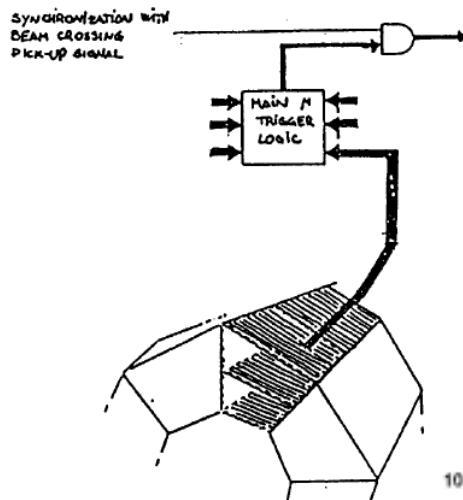


The $\pi \times \pi$ fast tracking muon trigger

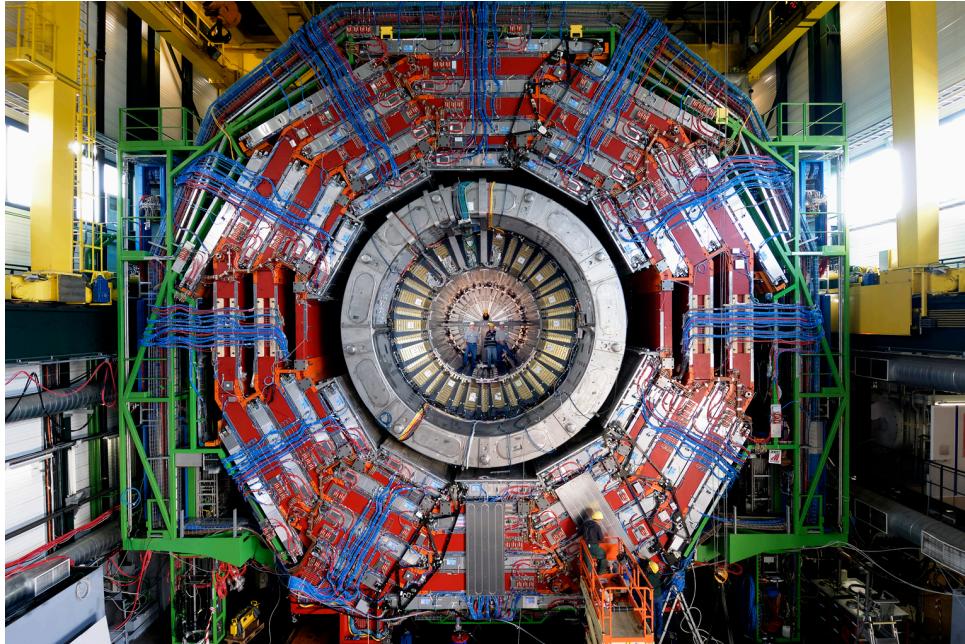


A FAST TRACKING LEVEL1 MUON TRIGGER FOR HIGH LUMINOSITY COLLIDERS USING RESISTIVE PLATE CHAMBERS

F. Ceradini, F. Cesaroni, F. Lacava, A. Nisati,
E. Petrolo, L. Sorrentino, S. Veneziano.
Istituto Nazionale di Fisica Nucleare e Università "La Sapienza" - Roma

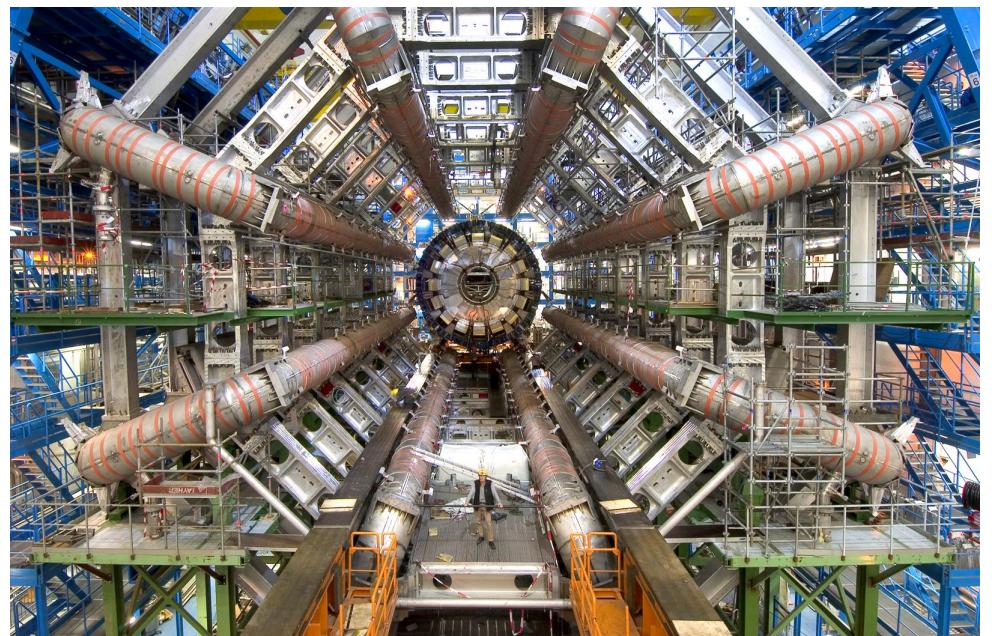


The muon determines the experiment's structure



The Compact Muon Solenoid

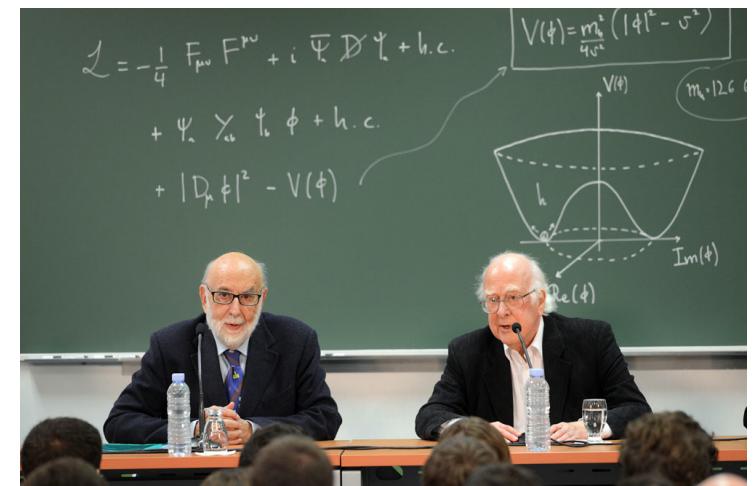
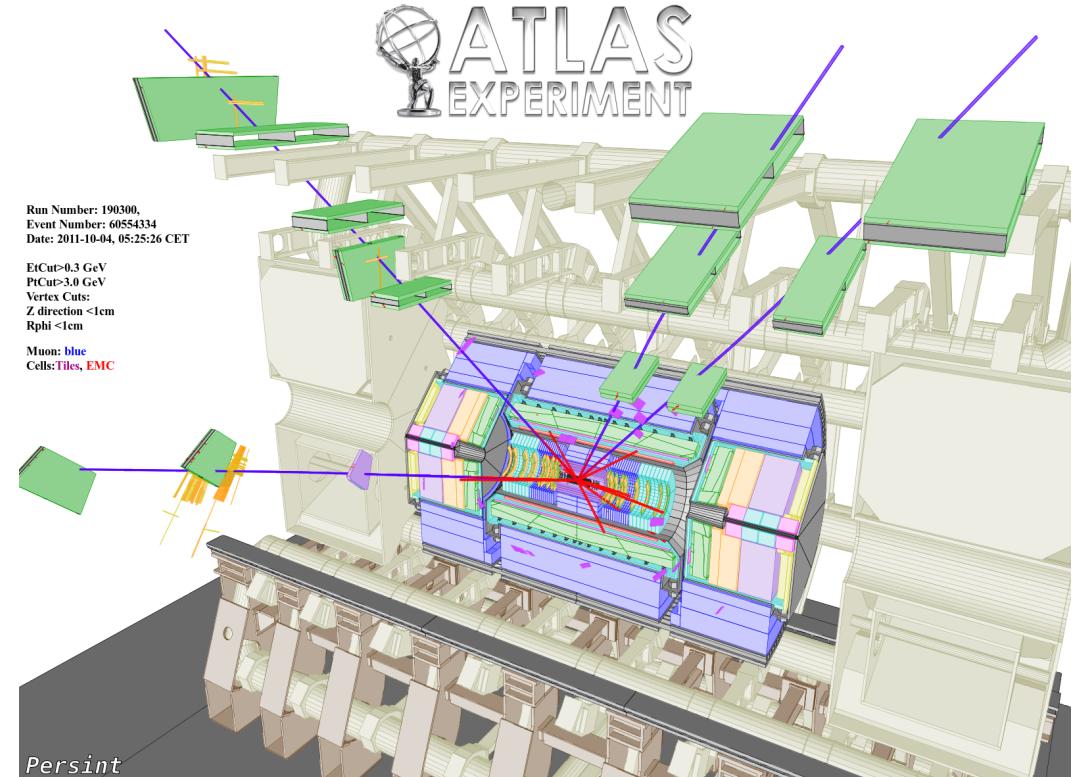
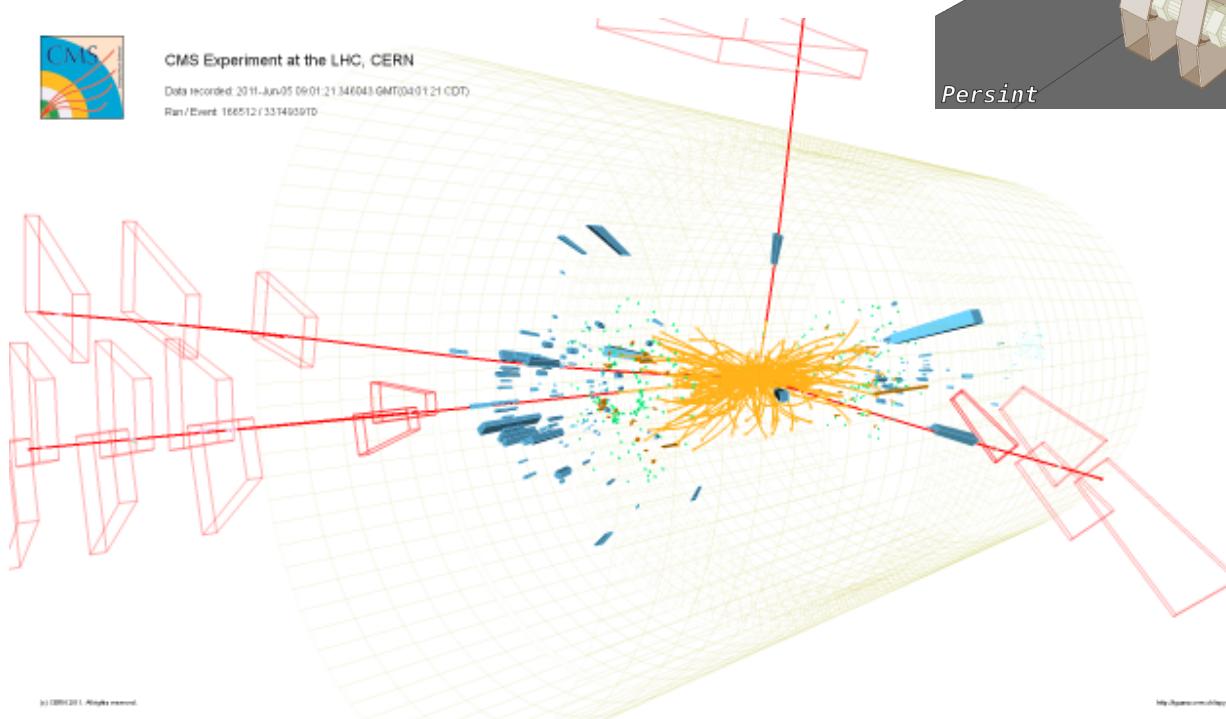
The ATLAS muon toroid



The muon and the Higgs



CMS Experiment at the LHC, CERN
Data recorded: 2011-Jun-05 09:01:21.346043 GMT (04/01/21 CDT)
Run / Event: 168512 / 3374939/0



The muon and the lepton number

Physical Review 73 (1948)

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. HINCKS AND B. PONTECORVO

National Research Council, Chalk River Laboratory,
Chalk River, Ontario, Canada

December 9, 1947

Our negative result is consistent with the experiments on the genetic relationship⁴ between the hard and soft components in the lower atmosphere. The mechanism of the 2.2-microsecond decay process remains, however, unknown. Should it consist of the emission of an electron and a neutral meson, as recent evidence^{5,6} seems to indicate, the nuclear *capture* of a light negative meson may be accompanied by the emission of one neutrino, as previously suggested.³

VOLUME 5, NUMBER 3

PHYSICAL REVIEW LETTERS

AUGUST 1, 1960

SYMMETRY BETWEEN MUON AND ELECTRON

N. Cabibbo and R. Gatto

Istituto di Fisica dell'Università di Roma e di Cagliari Laboratori Nazionali
di Frascati del Comitato Nazionale per le Ricerche Nucleari, Roma, Italia

mal; (3) show that it is impossible to satisfy such a symmetry when universal weak interactions are included, if only one neutrino exists; (4)

VOLUME 6, NUMBER 7

PHYSICAL REVIEW LETTERS

APRIL 1, 1961

LAW OF CONSERVATION OF MUONS*

G. Feinberg[†]

Department of Physics, Columbia University, New York, New York

S. Weinberg

Department of Physics, University of California, Berkeley, California

The apparent absence of muon-electron transitions without neutrinos, such as $\mu \rightarrow e + \gamma$, $\mu \rightarrow 3e$, and $\mu^- + p \rightarrow e^- + p$, leads one to suspect that there is a new conservation law forbidding them. Cal-

Charged lepton flavour violation ?

Annu. Rev. Nucl. Part. Sci. 2013. 63:531–52

Charged Lepton Flavor–Violation Experiments

S. Mihara,¹ J.P. Miller,² P. Paradisi,³ and G. Piredda⁴

$\mu^+ e^- \rightarrow \mu^- e^+$ conversion

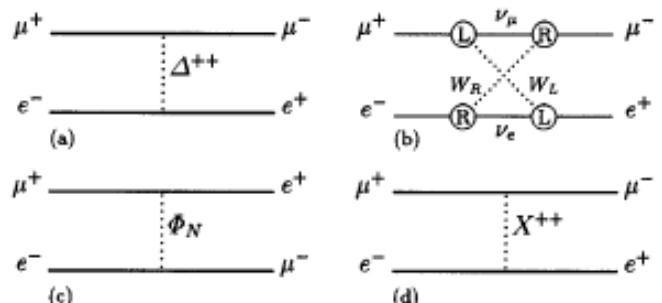
VOLUME 82, NUMBER 1

PHYSICAL REVIEW LETTERS

4 JANUARY 1999

New Bounds from a Search for Muonium to Antimuonium Conversion

L. Willmann¹, P. V. Schmidt¹, H. P. Wirtz², R. Abela³, V. Baranov⁴, J. Bagaturia⁵, W. Bertl³, R. Engfer², A. Großmann¹, V. W. Hughes⁶, K. Jungmann¹, V. Karpuchin⁴, I. Kisel⁴, A. Korenchenko⁴, S. Korenchenko⁴, N. Kravchuk⁴, N. Kuchinsky⁴, A. Leuschner², V. Meyer¹, J. Merkel¹, A. Moiseenko⁴, D. Mzavia⁵, G. zu Putlitz¹, W. Reichart², I. Reinhard¹, D. Renker³, T. Sakhelashvili⁵, K. Träger¹, and H. K. Walter³



doubly charged Higgs boson Δ^{++}
heavy Majorana neutrino
susy s-neutrino Φ_N
bilepton diagonal gauge boson X^{++}

mass limit
2 – 3 TeV

CLFV $\mu \rightarrow e$ conversion

Eur. Phys. J. C 47, 337–346 (2006)

A search for $\mu - e$ conversion in muonic gold

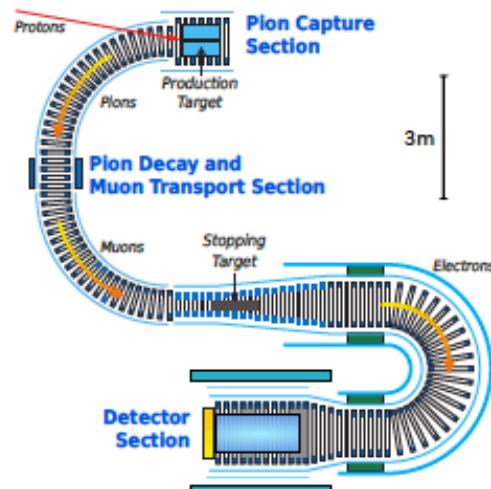
The SINDRUM II Collaboration

W. Bertl¹, R. Engfer², E.A. Hermes², G. Kurz², T. Kozlowski³, J. Kuth⁴, G. Otter⁴, F. Rosenbaum¹, N.M. Ryskulov¹, A. van der Schaaf², P. Wintz⁴, I. Zychor³

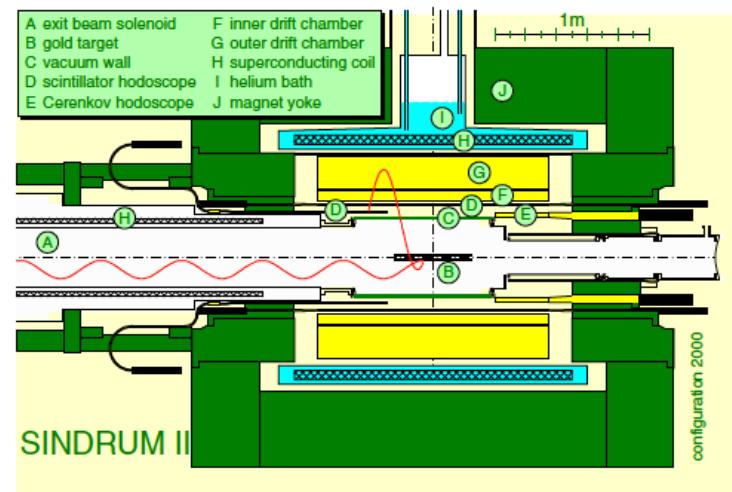


$$\frac{\Gamma(\mu^- Au \rightarrow e^- Au)}{\Gamma_{capture}(\mu^- Au)} < 7 \times 10^{-13} \text{ at 90\% C.L.}$$

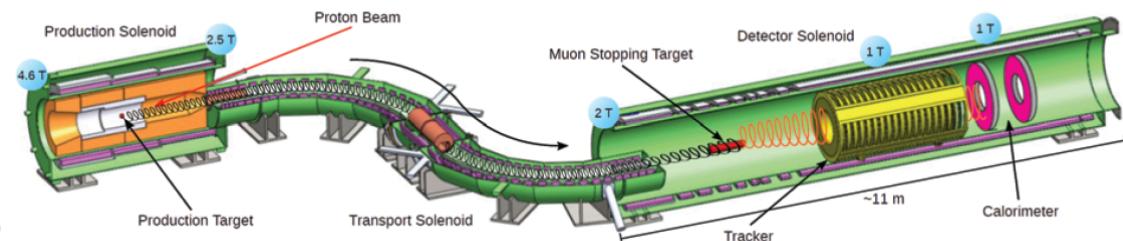
COMET @ JPark



SINDRUM @ PSI



Mu2e @ Fermilab



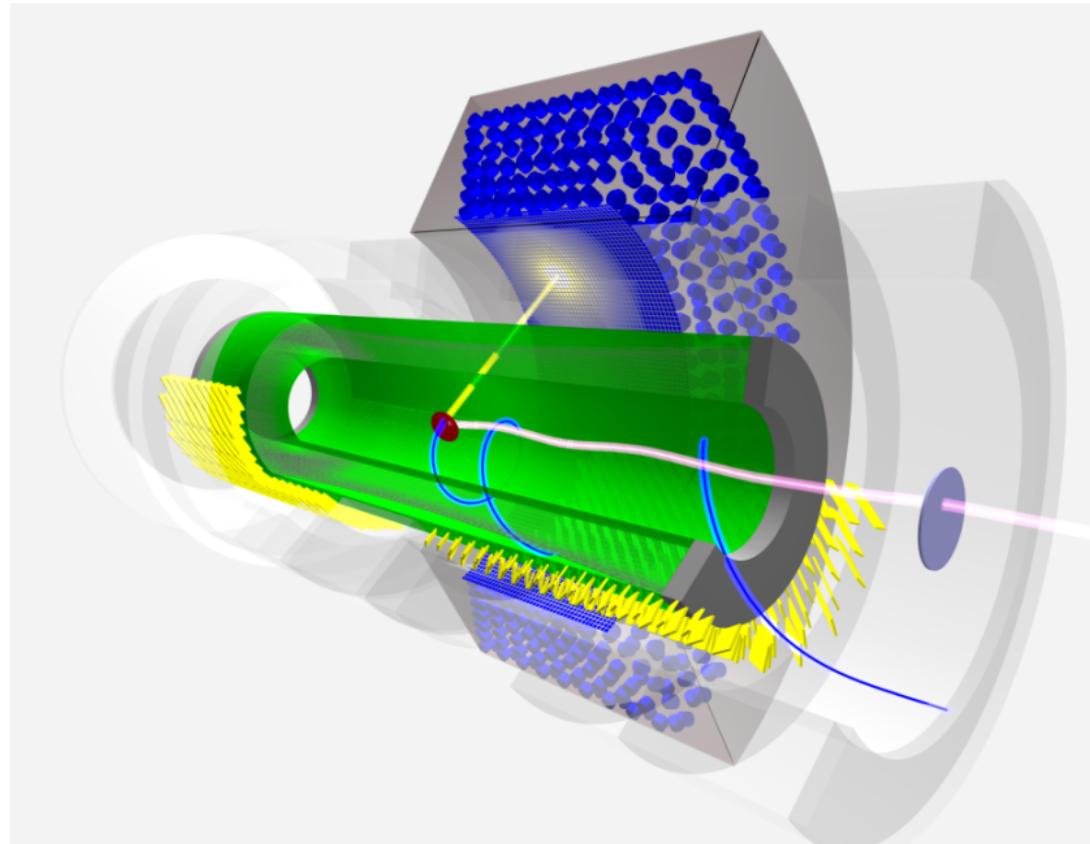
CLFV - $\mu \rightarrow e\gamma$ decay

Eur. Phys. J. C (2016) 76:434

**Search for the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$
with the full dataset of the MEG experiment**

MEG Collaboration

$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13} \text{ at 90% C.L.}$$



CLFV - exotic muon decays: $\mu \rightarrow 3e$

Nuclear Physics B299 (1988) 1–6

North-Holland, Amsterdam

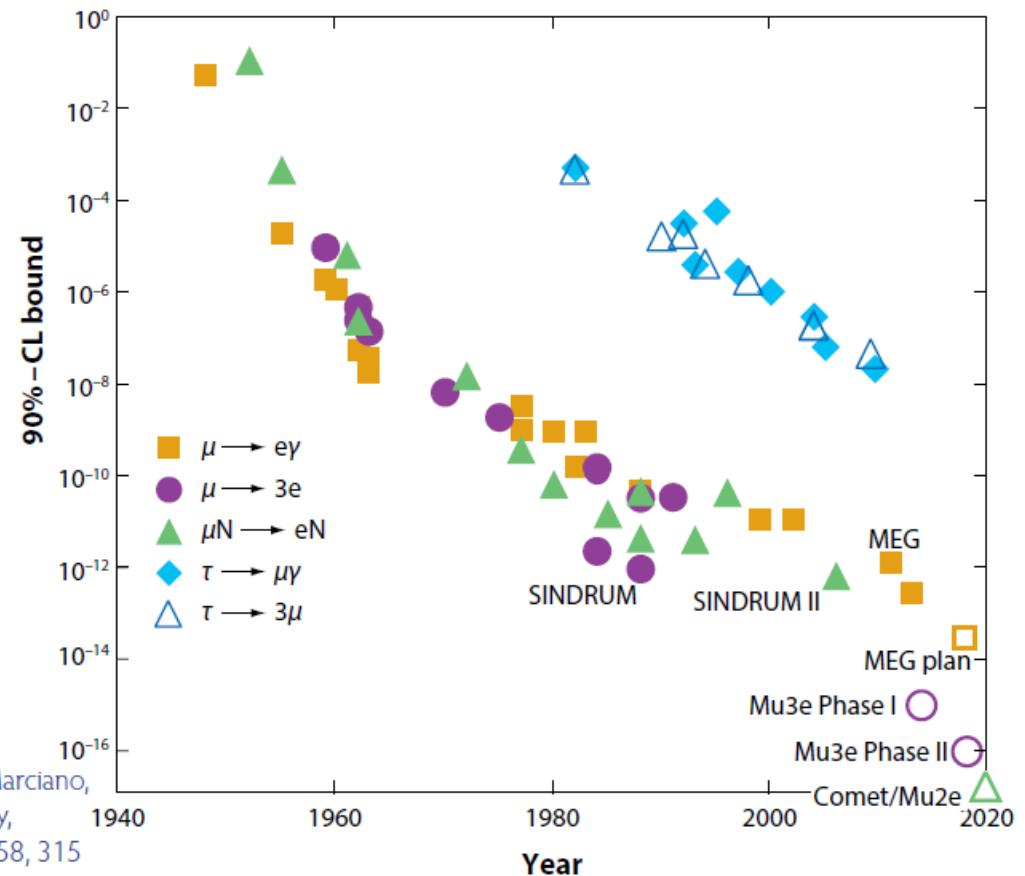
SEARCH FOR THE DECAY $\mu^+ \rightarrow e^+ e^+ e^-$

SINDRUM Collaboration

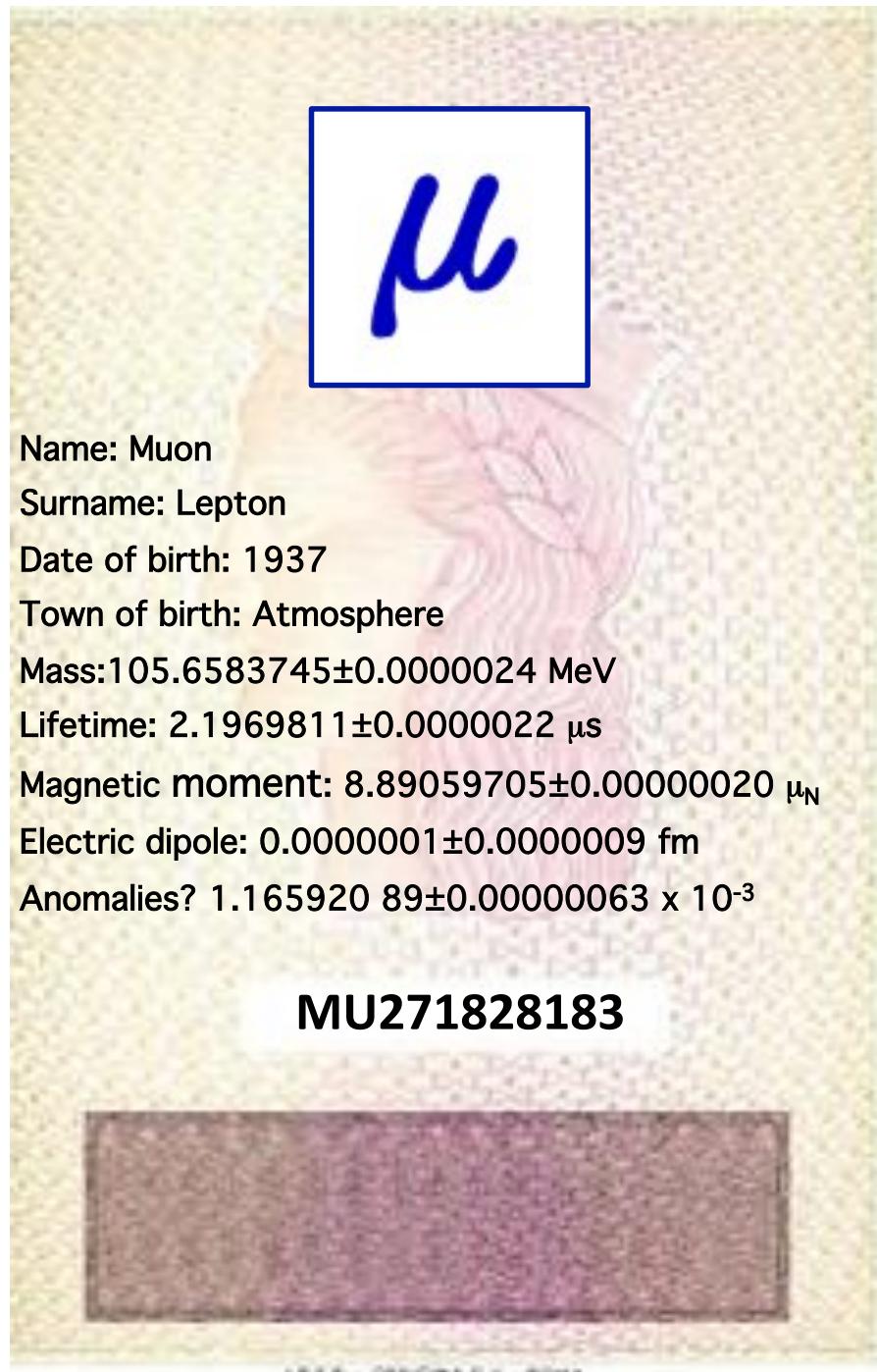
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

(Updated from W.J. Marciano,
T. Mori and J.M. Roney,
Ann.Rev.Nucl.Part.Sci. 58, 315
(2008))

$$\mathcal{B}(\mu \rightarrow eee) < 1.0 \times 10^{-12} \text{ at 90% C.L.}$$



The muon does not mix



Name: Muon

Surname: Lepton

Date of birth: 1937

Town of birth: Atmosphere

Mass: $105.6583745 \pm 0.0000024$ MeV

Lifetime: 2.1969811 ± 0.0000022 μs

Magnetic moment: $8.89059705 \pm 0.00000020$ μ_N

Electric dipole: 0.0000001 ± 0.0000009 fm

Anomalies? $1.165920\ 89 \pm 0.00000063 \times 10^{-3}$

MU271828183

IPZS - OFFICINA E - ROMA

February 2, 2017



Filippo Cerdini - Dipartimento di Matematica e Fisica - Università Roma Tre

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