



European School of Instrumentation  
in Particle & Astroparticle Physics

# Muon Detection

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February 2022

# Muon Detection

## Outline

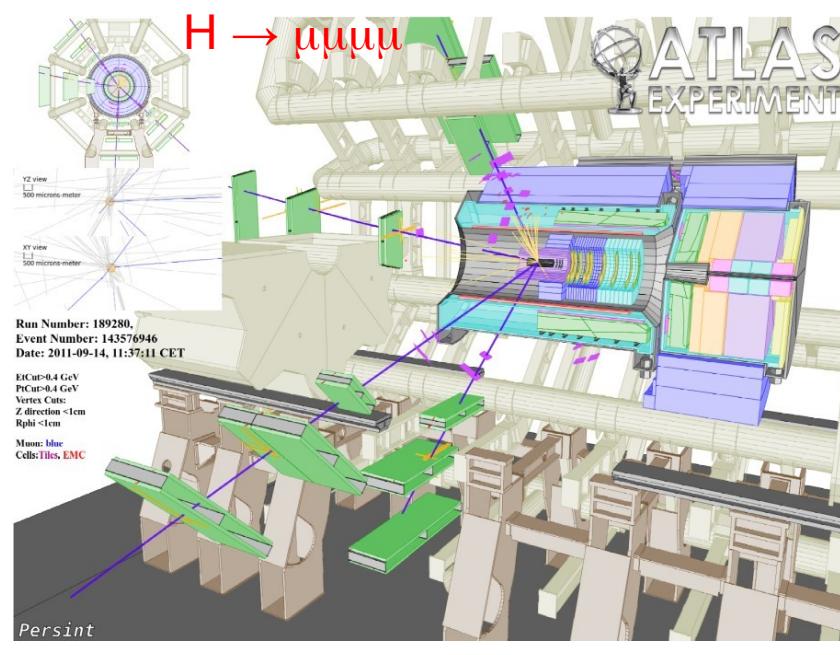
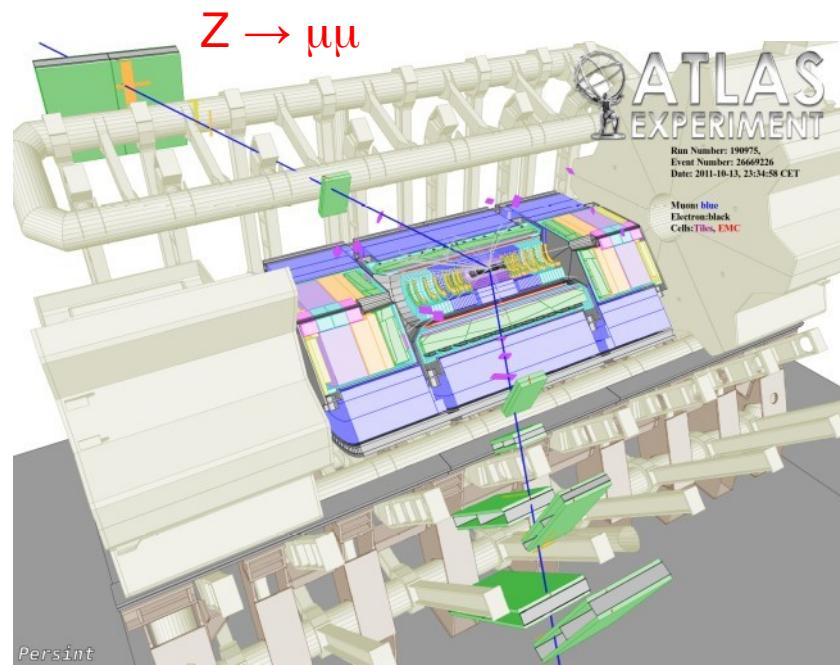
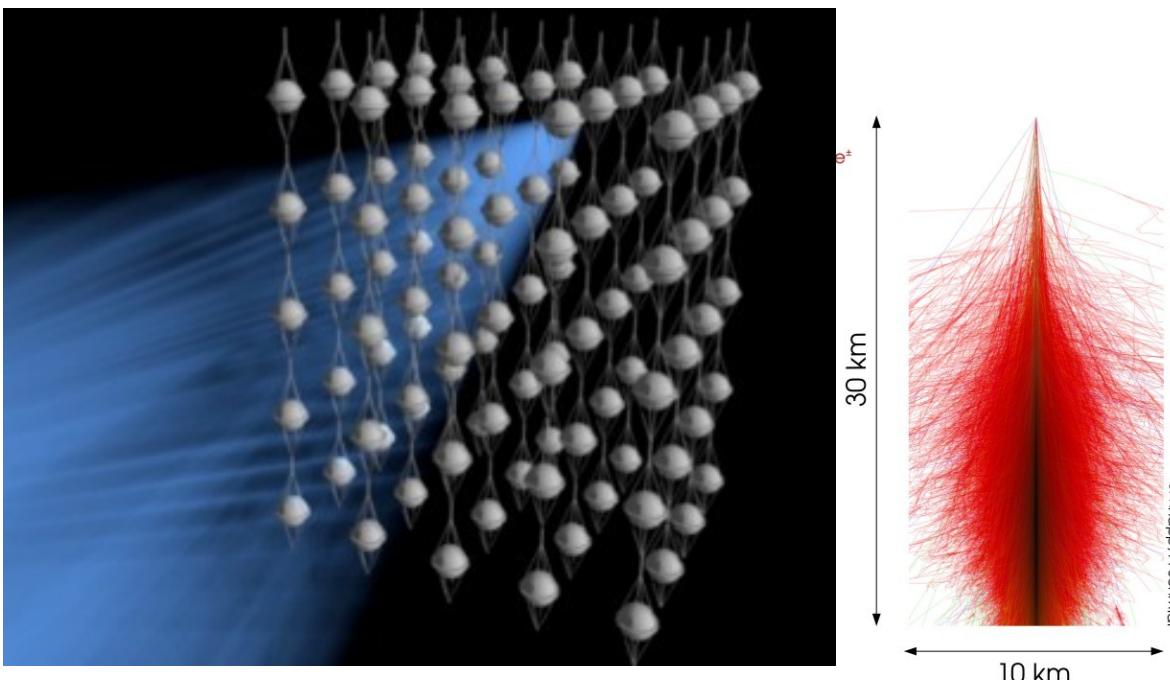
- **Introduction**

- Why Muon Detection?
- Muon in the Standard Model
- Muon Discovery
- Interaction Particle-Matter

- **Detectors**

- Gaseous, Solid, Liquid, Mix
  - Interlude: Charged particle in magnetic field
  - Interlude: Detector conception
  - Interlude: Muography

- Summary



# Muon Detection

## Main source

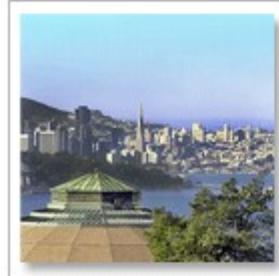
- Remark: not only for muon but for all infos on particle physics/cosmology

<http://pdg.lbl.gov>



### The Review of Particle Physics (2018)

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).



**pdgLive - Interactive Listings**

**Summary Tables**

**Reviews, Tables, Plots**

**Particle Listings**

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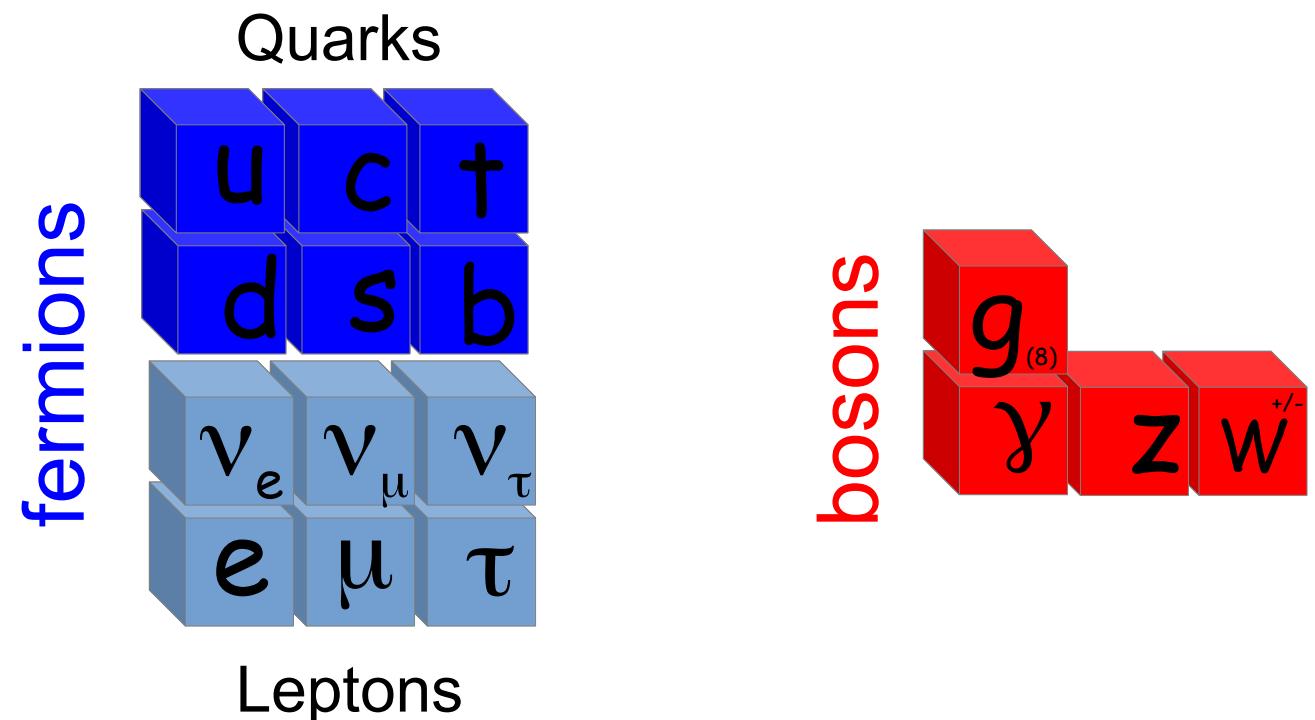
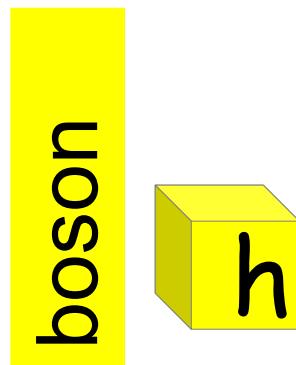
Previous Editions (& Errata) 1957-2017	Physical Constants
Errata in current edition	Astrophysical Constants
Figures in reviews	Atomic & Nuclear Properties
Mirror Sites	Astrophysics & Cosmology

# Muon Detection

## Introduction

# Muon

## Standard Model



Spin 0

Spin 1/2

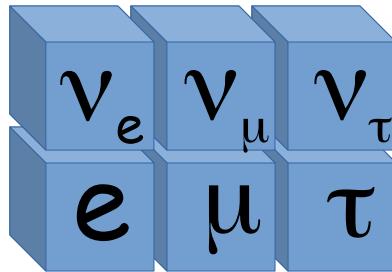
Spin 1

# Muon

fermions

Standard Model

Leptons



Muon	mass:	$105.6583715 \pm 0.0000035$ MeV
	spin :	1/2
	mean Life:	$(2.1969811 \pm 0.0000022) \times 10^{-6}$ s
	$\tau^+/\tau^-$ :	$1.00002 \pm 0.00008$ (CPT!)
	$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	~100%
	$\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$	~100%

Electromagnetic & weak interaction (& gravitation)



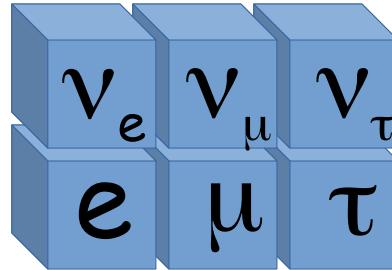
$$m(K^0) - m(\bar{K}^0) \sim 4 \cdot 10^{-10} \text{ eV}$$

# Muon

fermions

Standard Model

Leptons



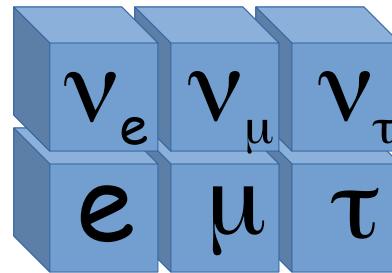
Muon

- ~207 times more massive than electron
- ~ 17 times less massive than the tau
- Unstable  $c\tau \sim 660m$   
but the second longest mean life time  
after the neutrons
- Means: stable for some simulation in G4

Electromagnetic & weak interaction (& gravitation)

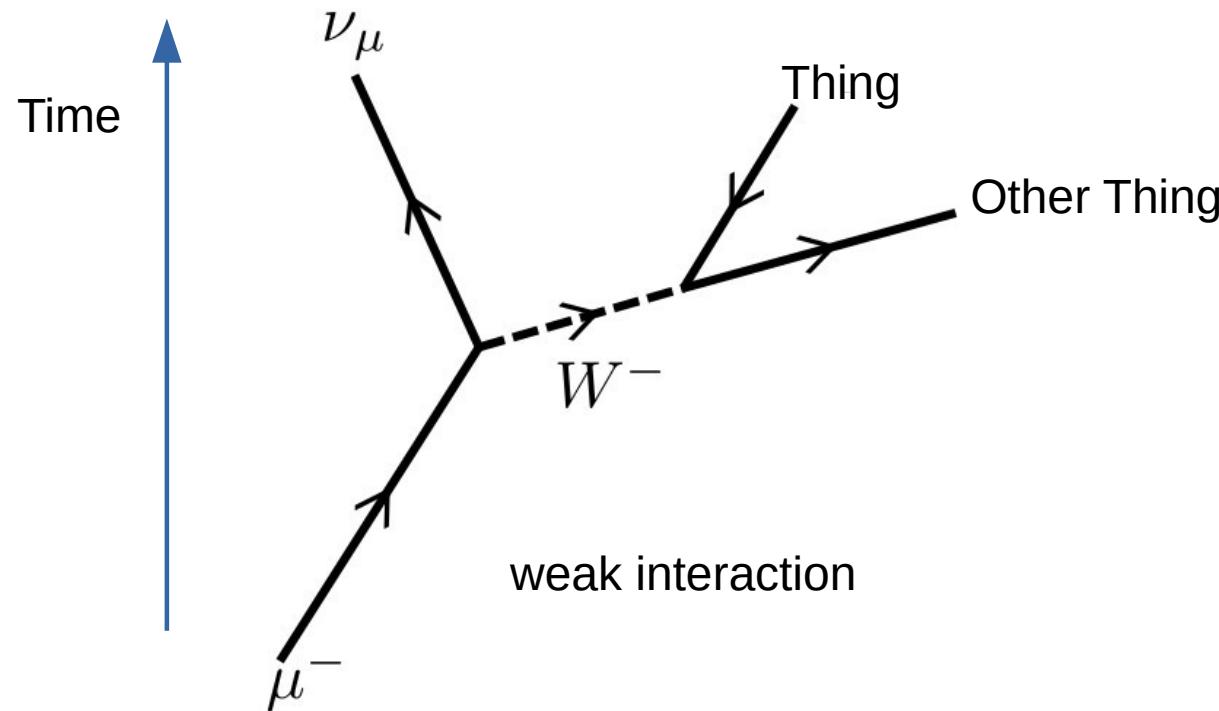
# Muon

Leptons  
fermions



Standard Model

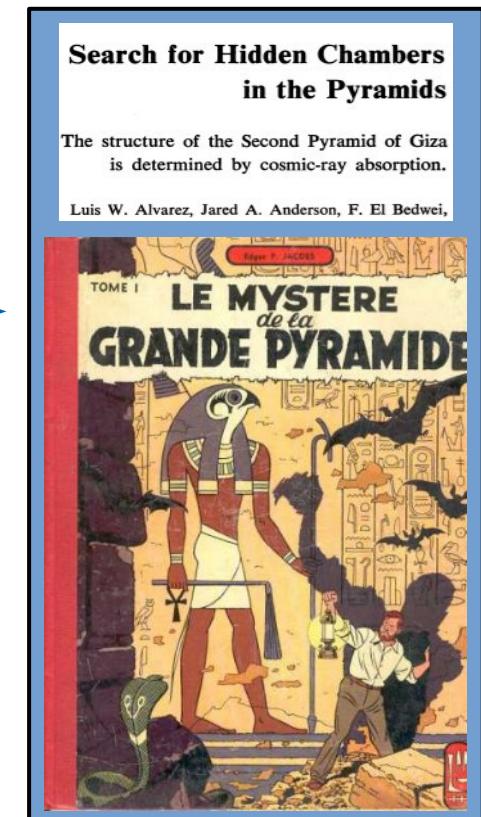
Electromagnetic & weak interaction (& gravitation)



# Muon Detection

## Why Muon Detection?

- Determine intrinsic properties of this **elementary particle**
  - Constraint on the Standard Model (SM) ex:  $g_{\mu} - 2$
- Very clean probe for many physic domains
  - Astroparticle: cosmic rays + atm  $\rightarrow \pi \rightarrow \mu$
  - Particle physics: Higgs  $\rightarrow 4 \mu$
  - Neutrino signature for both domain
- As a tool:
  - Trigger
  - Veto
  - Detector calibration: MIP
  - Muo-graphy
- How?
  - Detection mechanism:
    - Ionisation, Scintillation, Cherenkov radiation
  - Identification:
    - Tag after “walls”, dE/dx, Cherenkov



# Muon Detection

## Why Muon Detection?

- Determine intrinsic properties of an **elementary particle**
- Electron anomalous magnetic moment

$$\mu = g \frac{e}{2m} \mathbf{S}$$

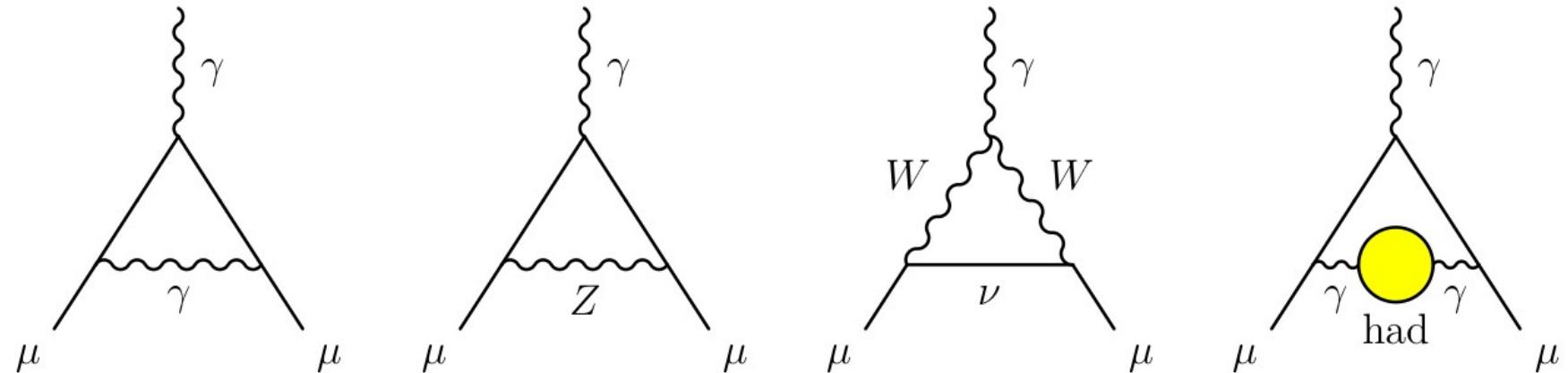
- $g = 1$  (classique: orbital angular momentum)  
 $= 2$  (Dirac: spin angular momentum)  
 $= 2.0023193043\textcolor{red}{06}$  (Theoretical, higher order corrections)  
 $= 2.0023193043\textcolor{red}{60}$  (experimental)

# Muon Detection

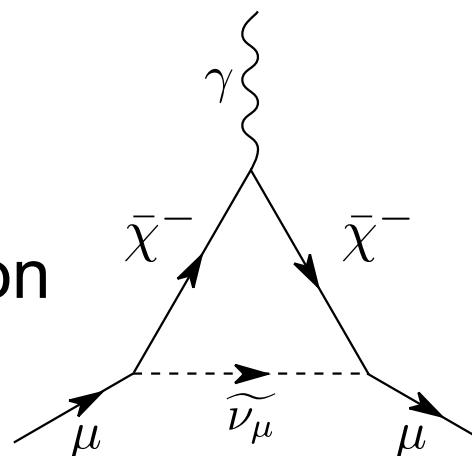
$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

## Why Muon Detection?

- Muon anomalous magnetic moment
- Constraint on the Standard Model (SM) ex:  $g_\mu - 2$
- Potential new contributions from unknown particle



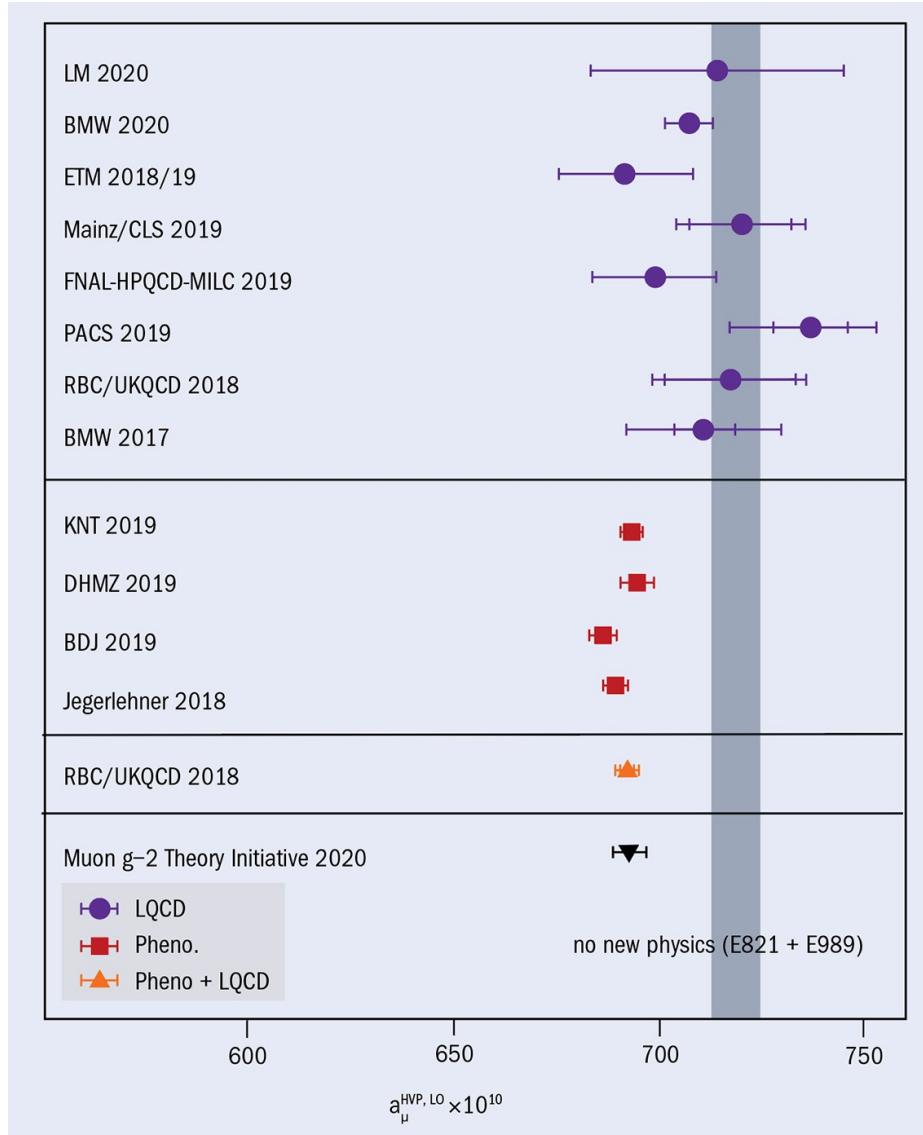
- Susy contribution



# Muon Detection

## Why Muon Detection?

- Constraint on the Standard Model (SM) ex:  $g_{\mu} - 2$



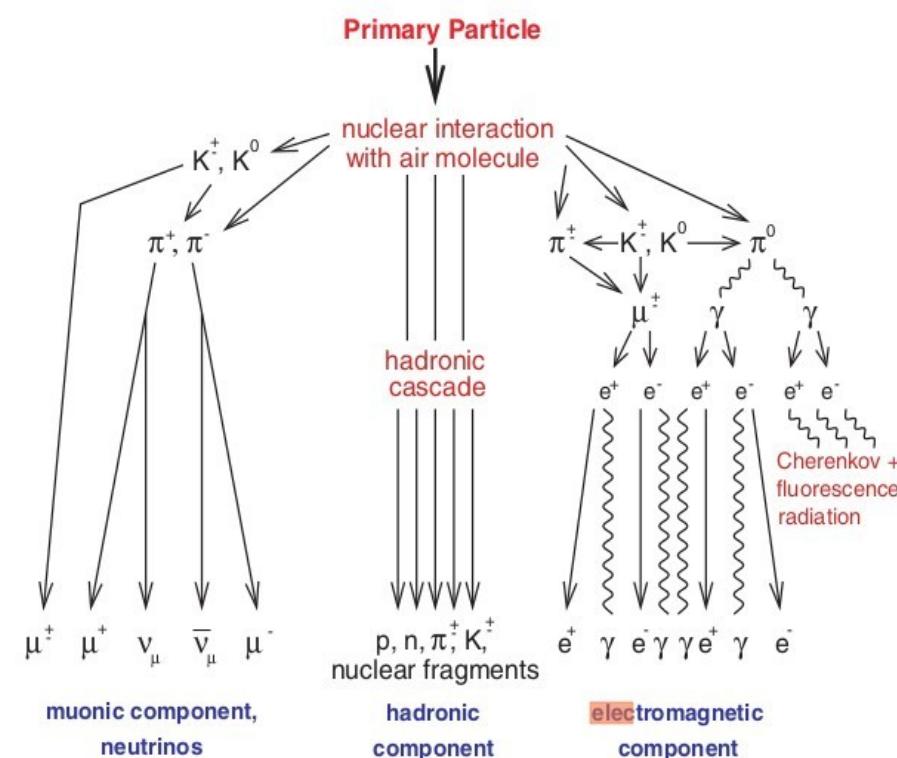
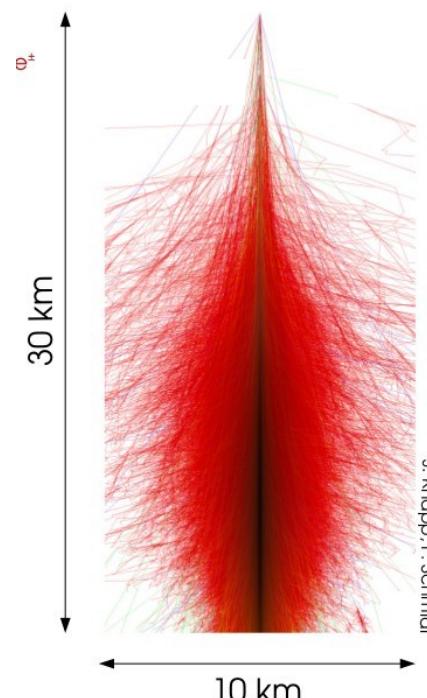
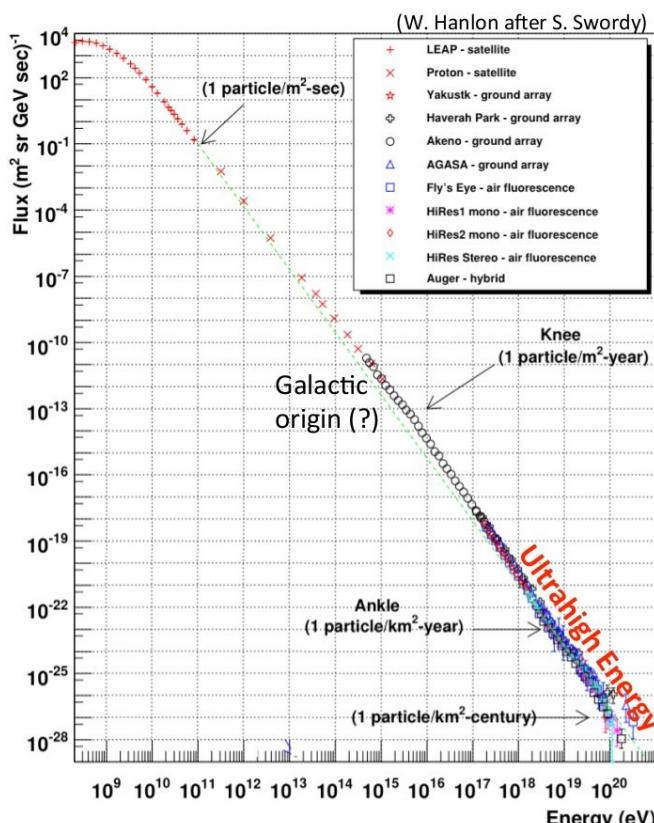
$$a_{\mu} \equiv \frac{g_{\mu} - 2}{2}$$

4.2 $\sigma$  significance:

$$a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = (251 \pm 59) \times 10^{-11}.$$

# Muon discovery

# Cosmic rays

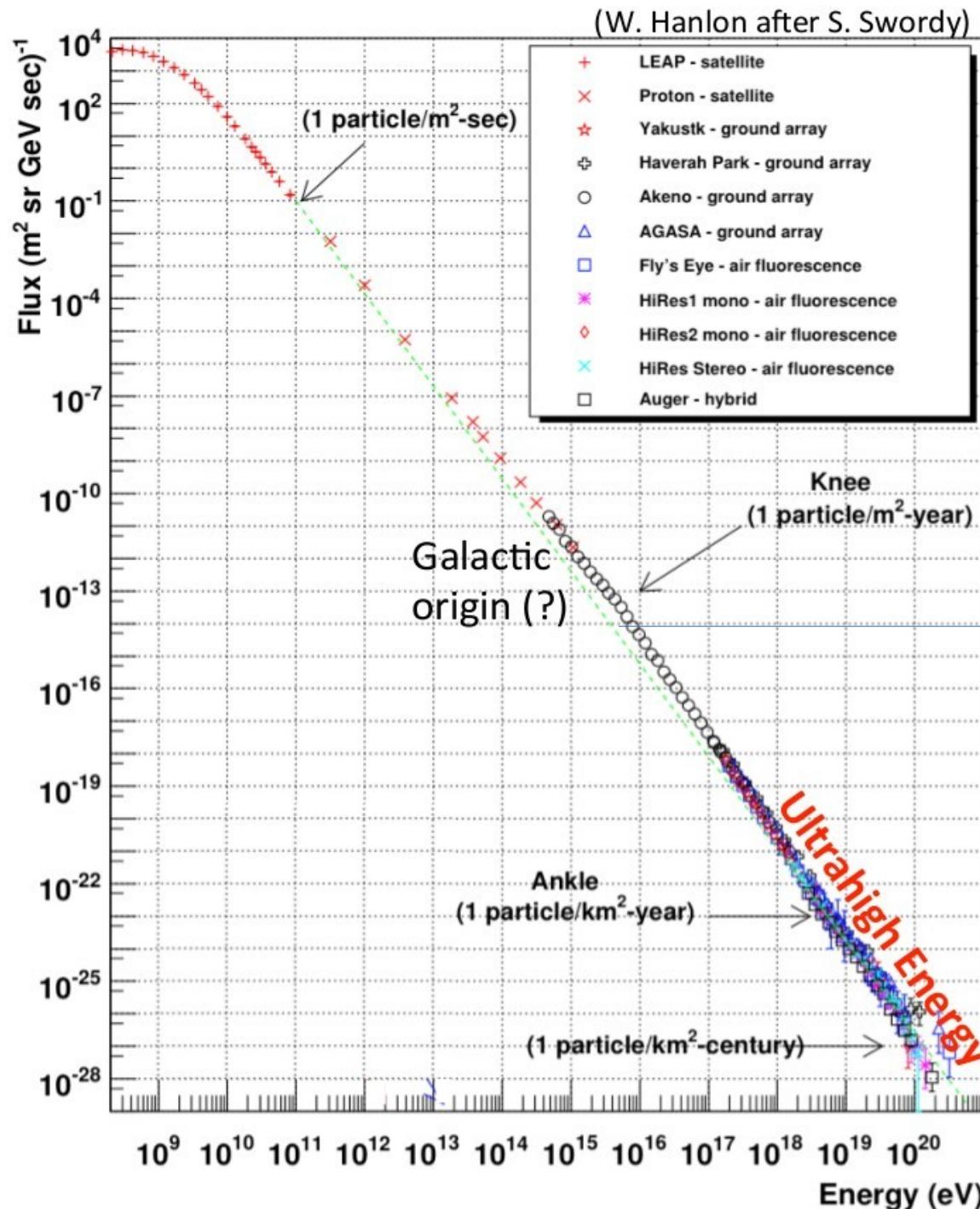


Simulation proton  $10^{14}$  eV

- The most penetrating component of atmospheric showers: the muon component
- At sea level muons represent about 80% of the cosmic ray flux
  - averaged over all energies
  - above  $E \approx 1$  GeV they contribute almost 100%
- Below 1 GeV the energy spectrum of muons is almost flat
- Above 100 GeV falls exponentially
- It extends to extremely high energies
- The average cosmic ray muon energy is 4 GeV

# Muon discovery

# Cosmic rays



Galactic phenomenon

- Super Novae
- Neutron stars
- ???

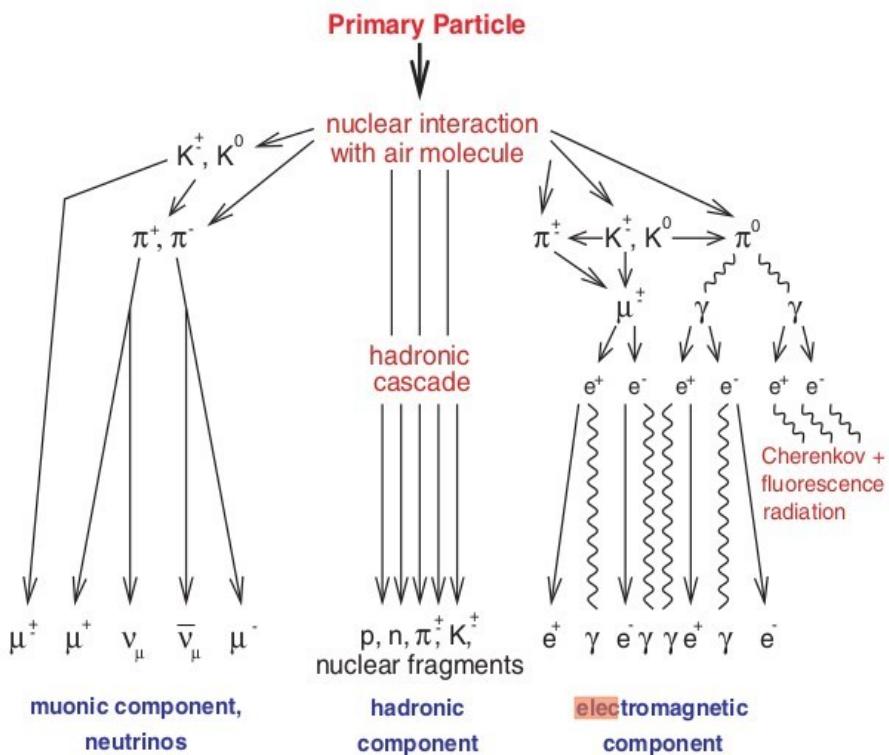
Satellite detection

Ground detection

Extra-galactic phenomenon

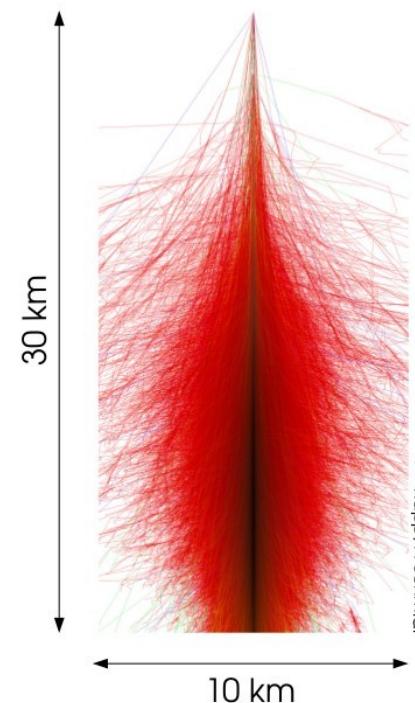
- Galaxy collisions
- Gamma Ray Burst
- Active Galactic Nucleus
- ???

# Muon discovery

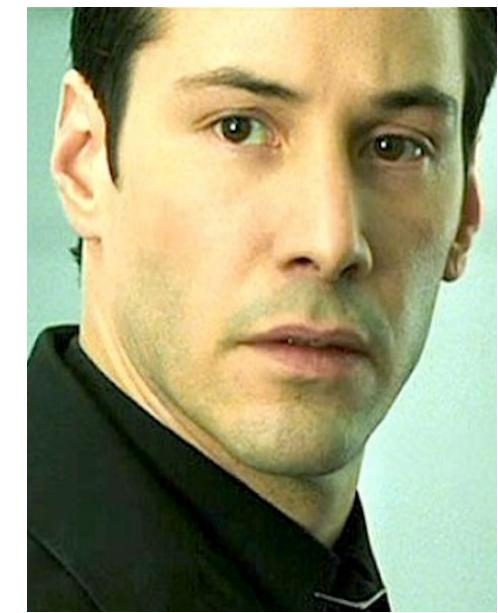
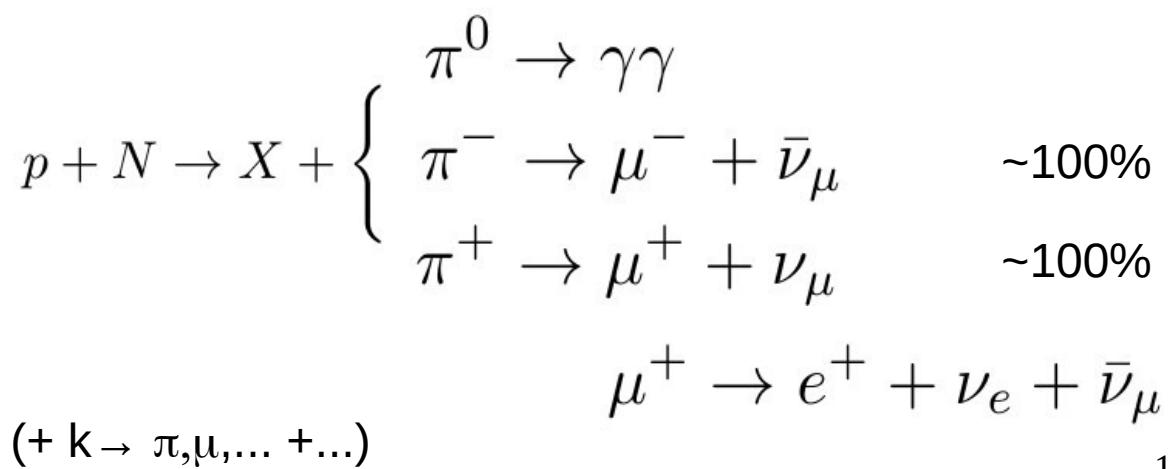


Cloud chamber

# Cosmic rays



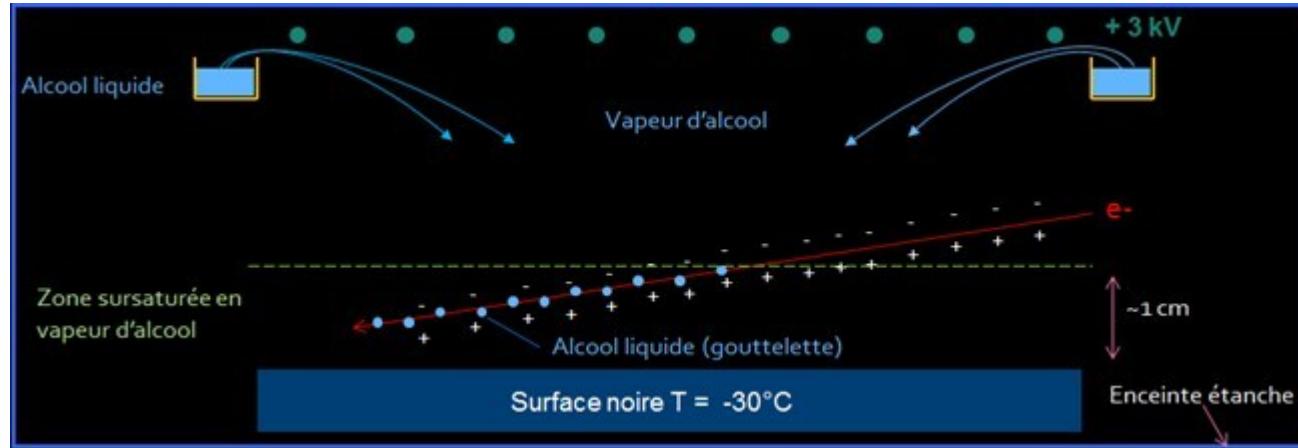
Simulation proton  $10^{14}$  eV



Thomas A. Anderson  
(matrix 1)

# Muon discovery

## Cosmic rays



Cloud chamber



Carl David Anderson  
(1905-1991)

1932 Positron discovery  
anti-electron, Paul Dirac's theoretical prediction

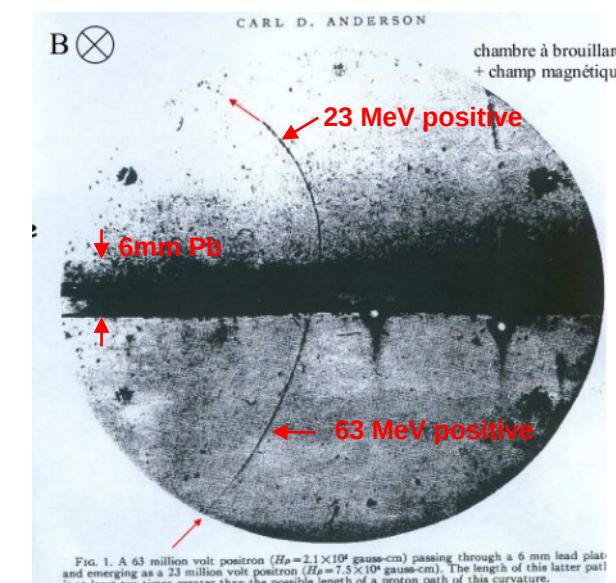
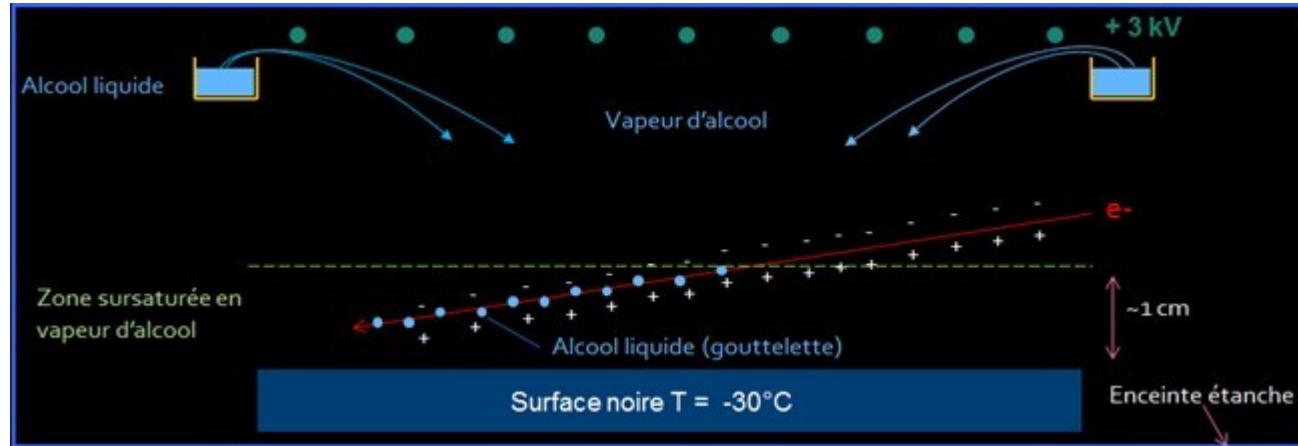


FIG. 1. A 63 million volt positron ( $H_D = 2.1 \times 10^8$  gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ( $H_D = 7.5 \times 10^8$  gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

# Muon discovery

## Cosmic rays



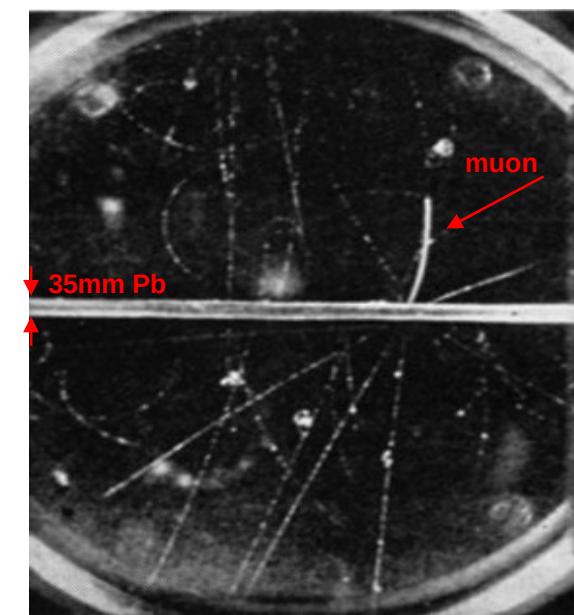
Cloud chamber



Carl David Anderson  
(1905-1991)

1932 Positron discovery  
anti-electron, Paul Dirac's theoretical prediction

1936 Muon discovery  
Mu-meson<sup>\*</sup>! (wrong naming)  
"Who ordered that?" (I. I. Rabi )



\* meson: 1 quark + 1 anti-quark

# Muon discovery

Phys. Rev. 51 (1937) 884

The experimental fact that penetrating particles occur both with positive and negative charges suggests that they might be created in pairs by photons, and that they might be represented as higher mass states of ordinary electrons.

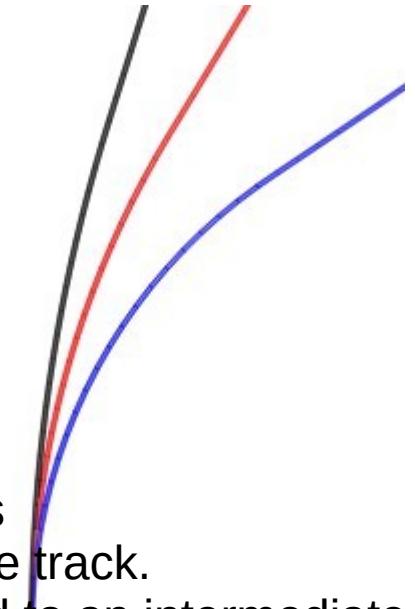
Independent evidence indicating the existence of particles of a new type has already been found, based on range, curvature and ionization relations; for example, Figs. 12 and 13 of our previous publication.<sup>1</sup> In particular the strongly ionizing particle of Fig. 13 cannot readily be explained except in terms of a particle of  $e/m$  greater than that of a proton. The large value of  $e/m$  apparently is not due to an  $e$  greater than the electronic charge since above the plate the particle ionizes imperceptibly differently from a fast electron, whereas below the plate its ionization definitely exceeds that of an electron of the same curvature in the magnetic field; the effects, however, are understandable on the assumption that the particle's mass is greater than that of a free electron. We should like to suggest, merely as a possibility, that the strongly ionizing particles of the type of Fig. 13, although they occur predominantly with positive charge, may be related with the penetrating group above.



Carl David Anderson  
(1905-1991)

## Observation

B



For a given  $B$  and  $P$   
the black track corresponds  
to a heavier object than blue track.  
So the red track correspond to an intermediate  
mass object

Example:proton,muon,electron