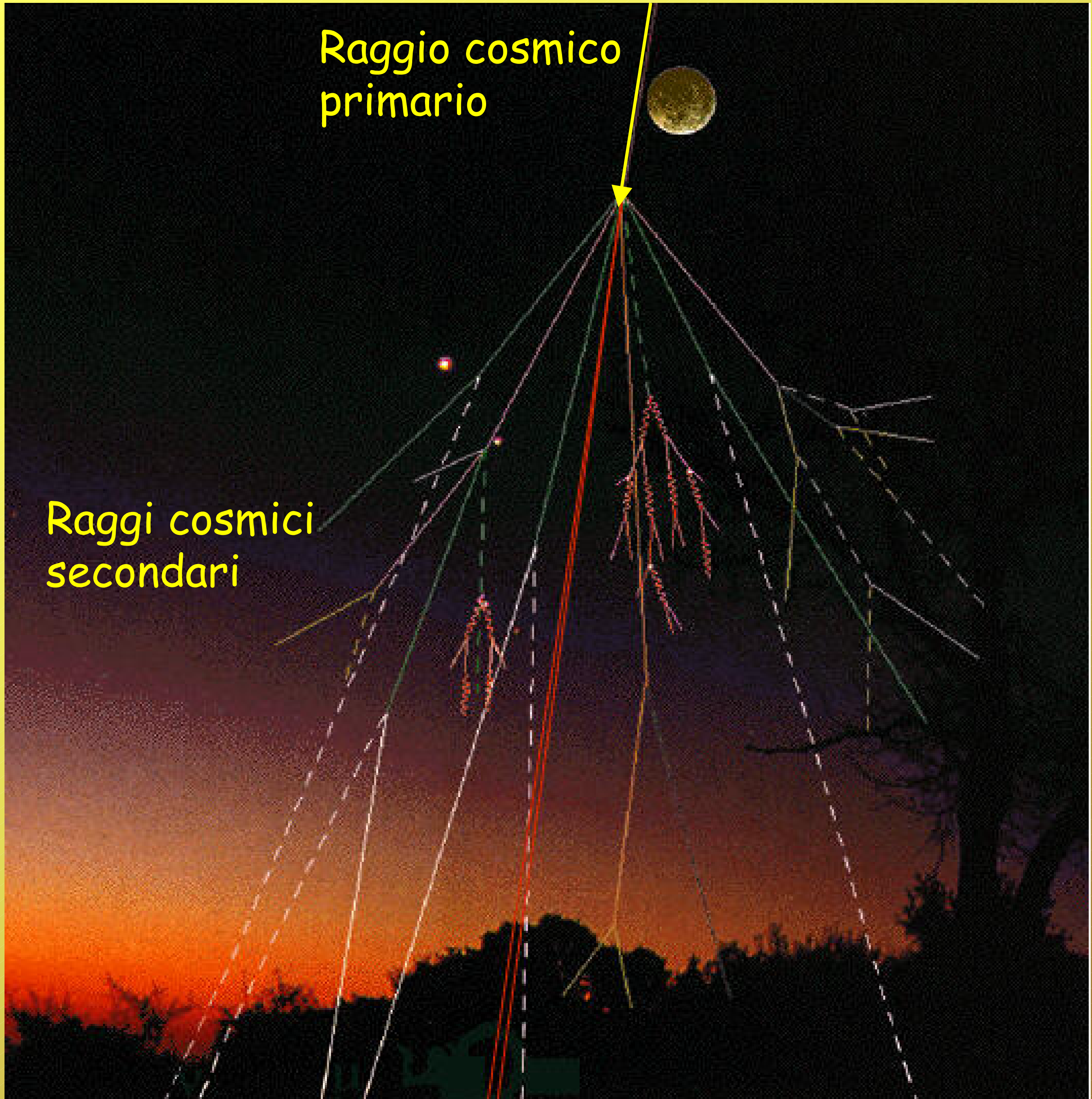
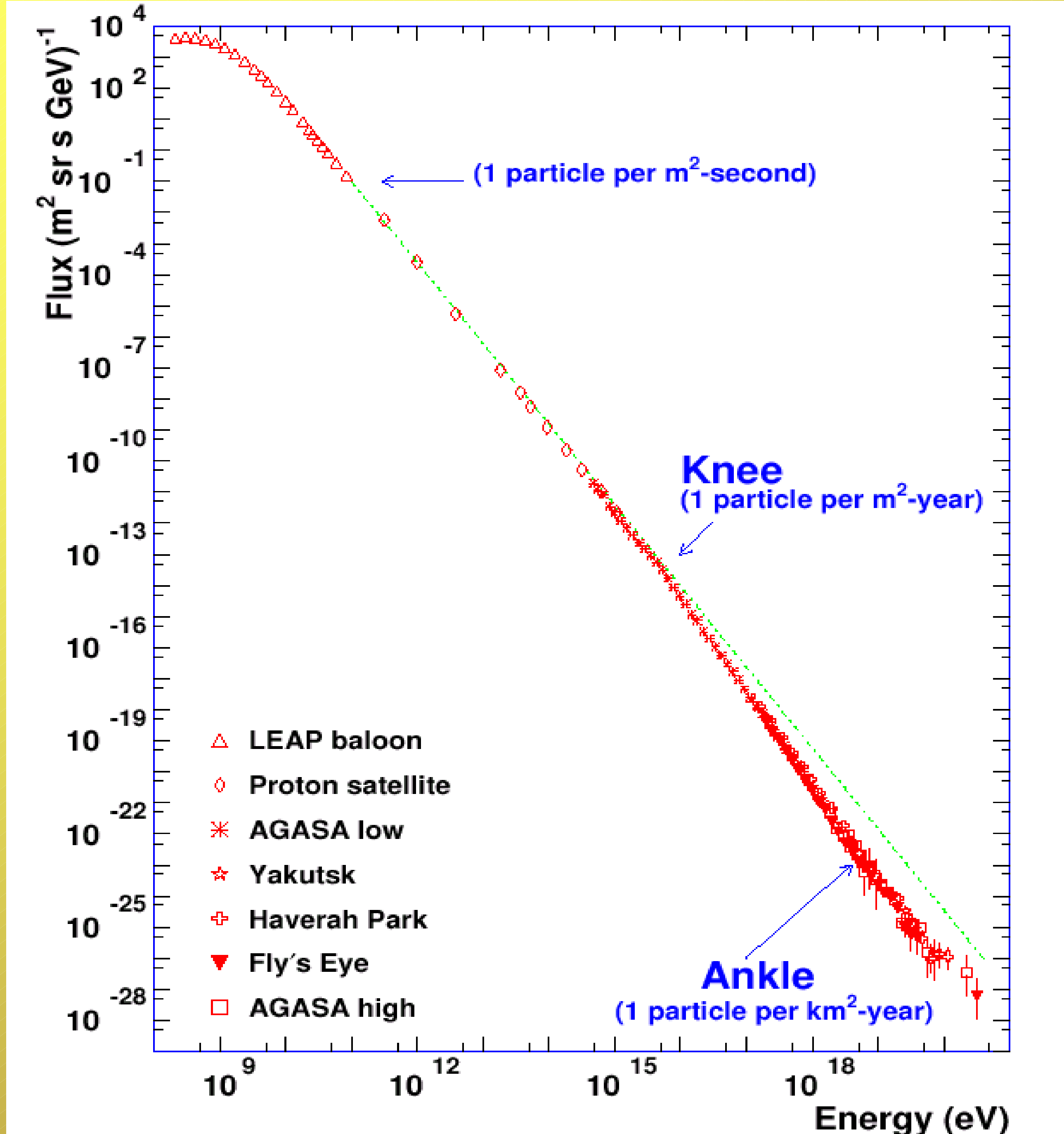
La fisica dei muoni

L'INIZIO

Victor Hess iniziò nel 1911 una serie di esperimenti salendo in quota con palloni aerostatici. Il volo del 7 agosto 1912 (6 ore da Aussig a Pieskow) raggiunse la quota di 5350 metri.

Man mano che il pallone si innalzava dal suolo, il livello di ionizzazione, come osservato da Wulf, diminuiva molto più lentamente di quanto atteso, fino a stabilizzarsi verso i 700 metri.

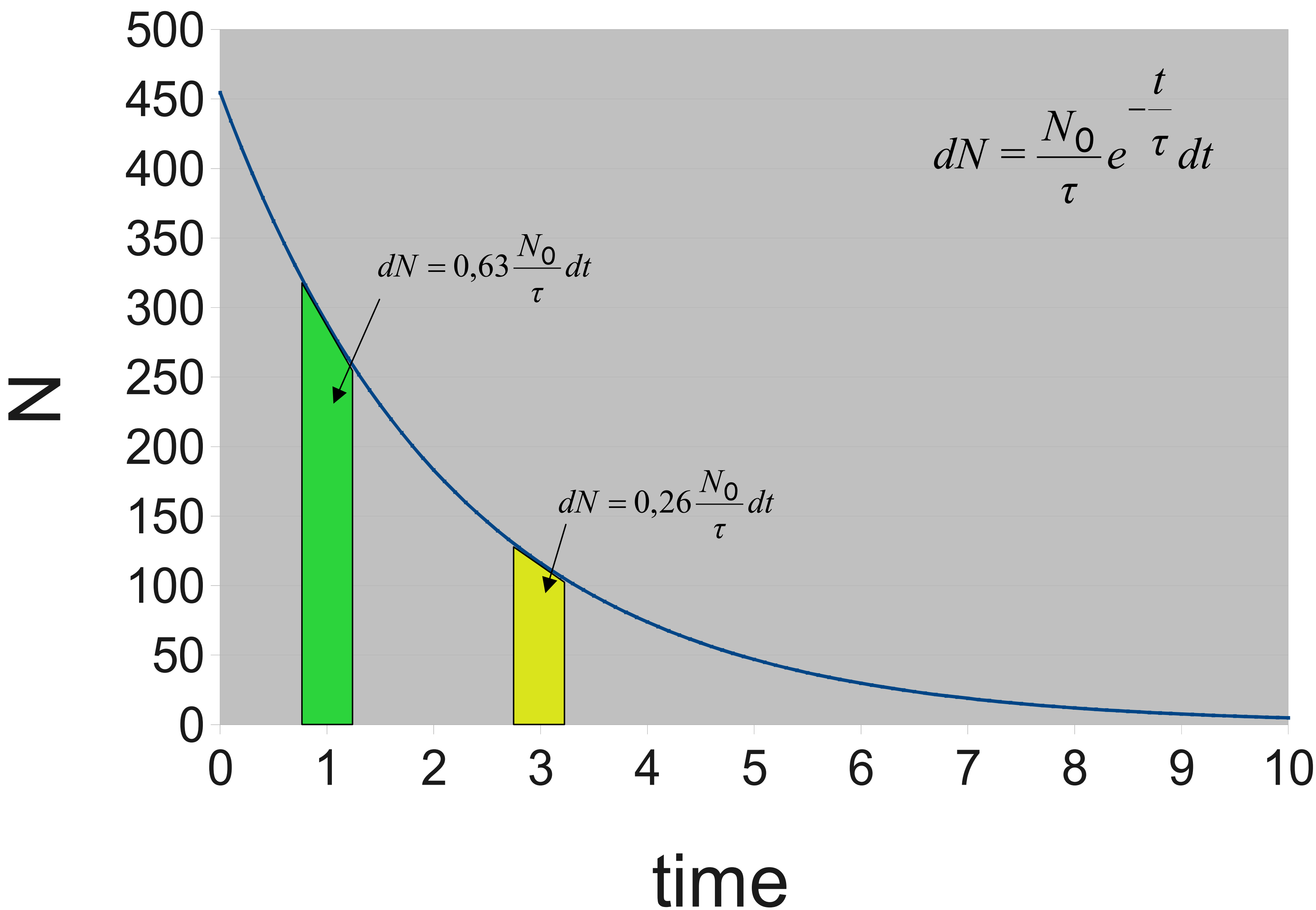

Raggio cosmico primario
Raggi cosmici secondari



Flux (m^2 sr s GeV)$^{-1}$
10^4
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
(1 particle per m^2-second)
Knee
(1 particle per m^2-year)
Ankle
(1 particle per km^2-year)
LEAP baloon
Proton satellite
AGASA low
Yakutsk
Haverah Park
Fly's Eye
AGASA high
10^9
10^{12}
10^{15}
10^{18}
Energy (eV)

L'interazione di un raggio **cosmico primario** con l'alta atmosfera produce raggi **cosmici secondari**, costituiti prevalentemente da:

Particella	Massa (MeV)	Vita media	Q	Tipo di interazioni
neutrino (ν)	< 2eV	stabile	no	d
fotone (γ)	0	stabile	no	em
elettrone ($e^{\pm}$)	0,5	stabile	si	d,em
muone ($\mu^{\pm}$)	**105**	**~ 2 μs**	si	d,em
pione ($\pi^{\pm}$, π^{0})	~140	10^{-8}, 10^{-16}	si, no	d,em,f
kaone ($K^{\pm}$ K^{0})	~495	10^{-8}, 10^{-9}	si, no	d,em,f
protone (p)	938	stabile	si	d, em, f
neutrone (n)	939	~ 12 min	no	d,em,f

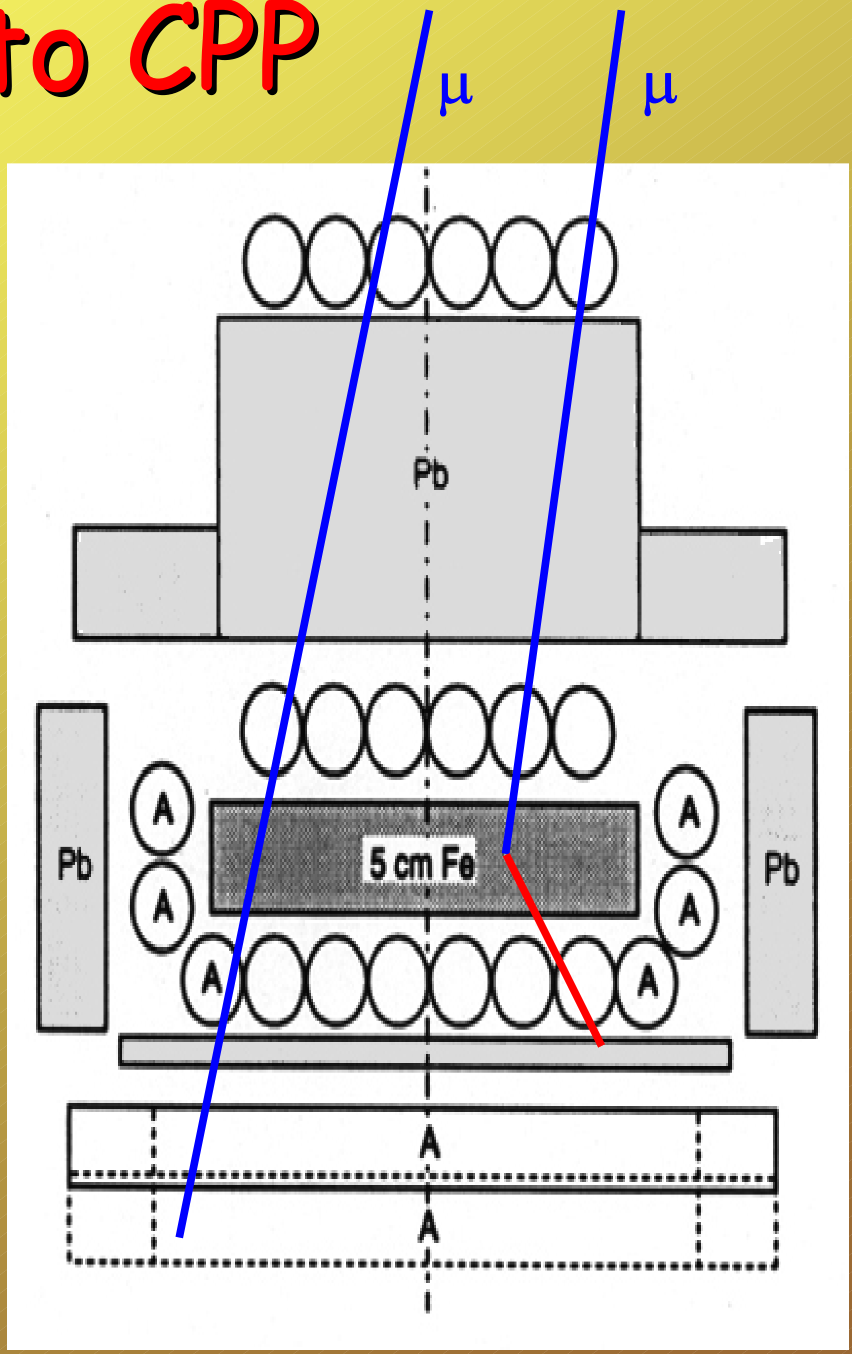


500
450
400
350
300
250
200
150
100
50
0
N
0
1
2
3
4
5
6
7
8
9
10
time
$dN = \frac{N_0}{\tau} e^{-\frac{t}{\tau}} dt$
$dN = 0{,}63 \frac{N_0}{\tau} dt$
$dN = 0{,}26 \frac{N_0}{\tau} dt$

Esperimento CPP

- Se il muone attraversa tutti i contatori in coincidenza, compresa l'ultima fila in basso, non viene registrato.
- Se il muone si ferma nel ferro ed emette nel seguito un elettrone, si ha una coincidenza ritardata in anticoincidenza con l'ultima fila di rivelatori, in quanto la sottile lastra di piombo impedisce agli elettroni di raggiungere i contatori in basso.

(da: M.Conversi, O.Piccioni, *Sulla disintegrazione dei mesoni lenti*, Nuovo Cimento 2, 71, 1944)

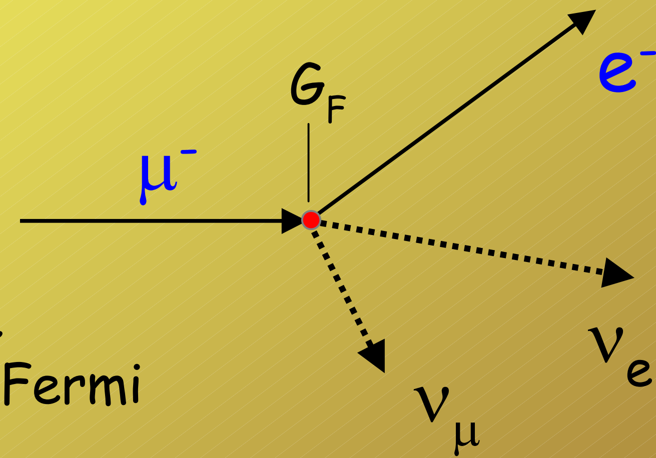


Il decadimento del muone

$$\mu^- \rightarrow e^- \, \bar{\nu}_e \, \nu_\mu$$

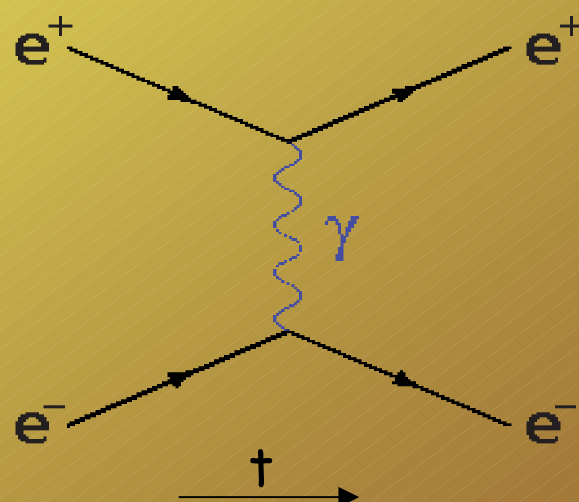
$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$$

$$\tau = \frac{192\,\pi^3}{G_F^2\, m_\mu^5}$$

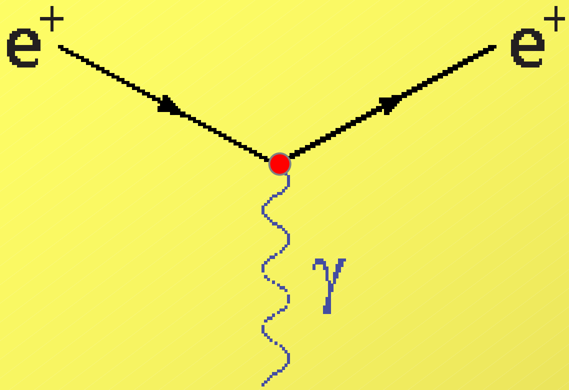


Interazione **puntuale** di Fermi (1934)

QED: tutte le interazioni avvengono mediante un **meccanismo di scambio**



Scattering Bhabha



Principio di indeterminazione:

$\Delta E \, \Delta t > h \longrightarrow \Delta E > h/\Delta t$

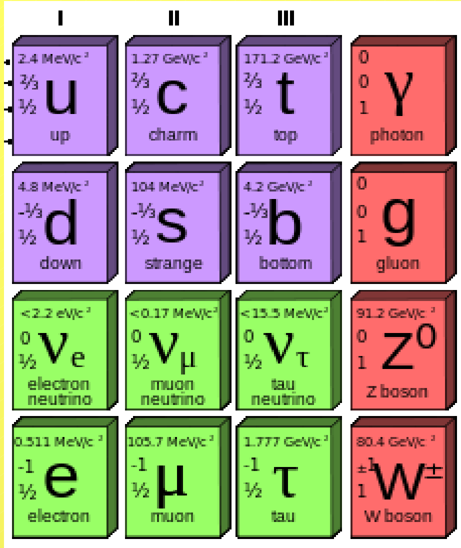
- Una violazione dell'energia $\leq$ **h/Δt NON potrà pertanto mai essere osservata.**

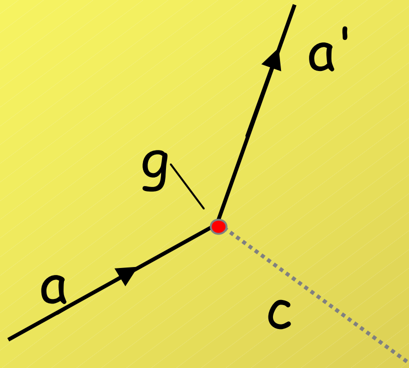
Grande violazione → Δt piccolo → mediatore a corto raggio

Piccola violazione → Δt grande → mediatore a lungo raggio

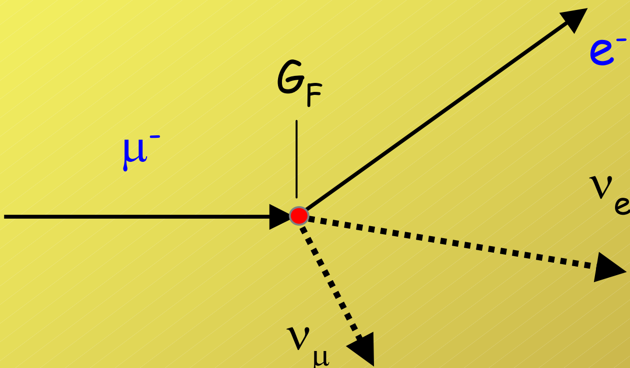
$\Delta E \sim 1$ MeV $\rightarrow d < 10^{-13}$ m

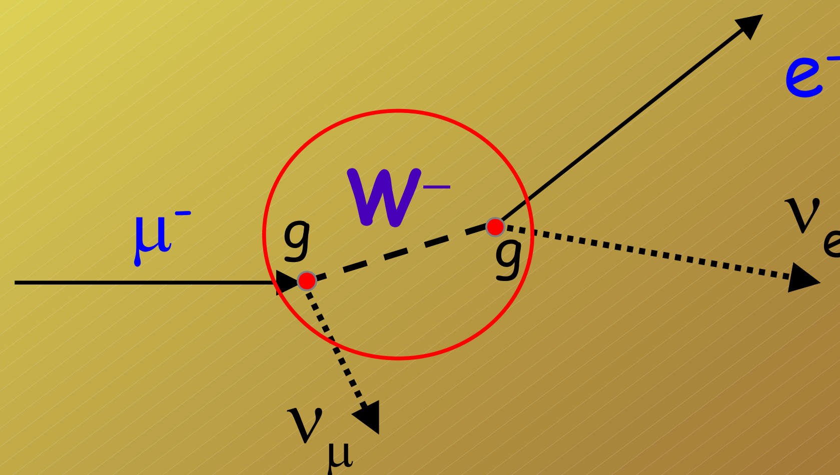
$\Delta E \sim 1$ GeV $\rightarrow d < 10^{-16}$ m





Vertice fondamentale
Processo virtuale
g ~ probabilita'





$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}$$

$M_\mu \sim 0{,}1$ GeV, $M_W \sim 100$ GeV

$\Delta E \sim 100$ GeV $\rightarrow d < 10^{-18}$ m

Forza debole: breve raggio d'azione

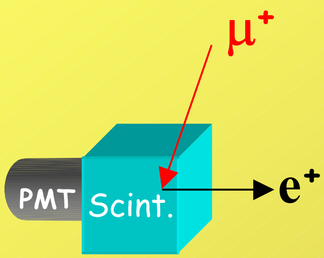
MuLan experiment

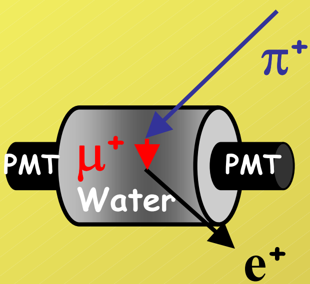
The goal of the Muon Lifetime Analysis (MuLan) experiment is to reduce the experimental uncertainty on G_F to 0.5 ppm by measuring the muon lifetime to 1 ppm.

$$\frac{\delta G_F}{G_F} = \frac{1}{2}\left(\underbrace{\frac{\delta \tau_{mu}}{\tau_\mu}}_{\boxed{9\text{ ppm}}} \oplus 5 \underbrace{\frac{\delta m_\mu}{m_\mu}}_{\boxed{0.06\text{ ppm}}} \oplus \ldots \right)$$

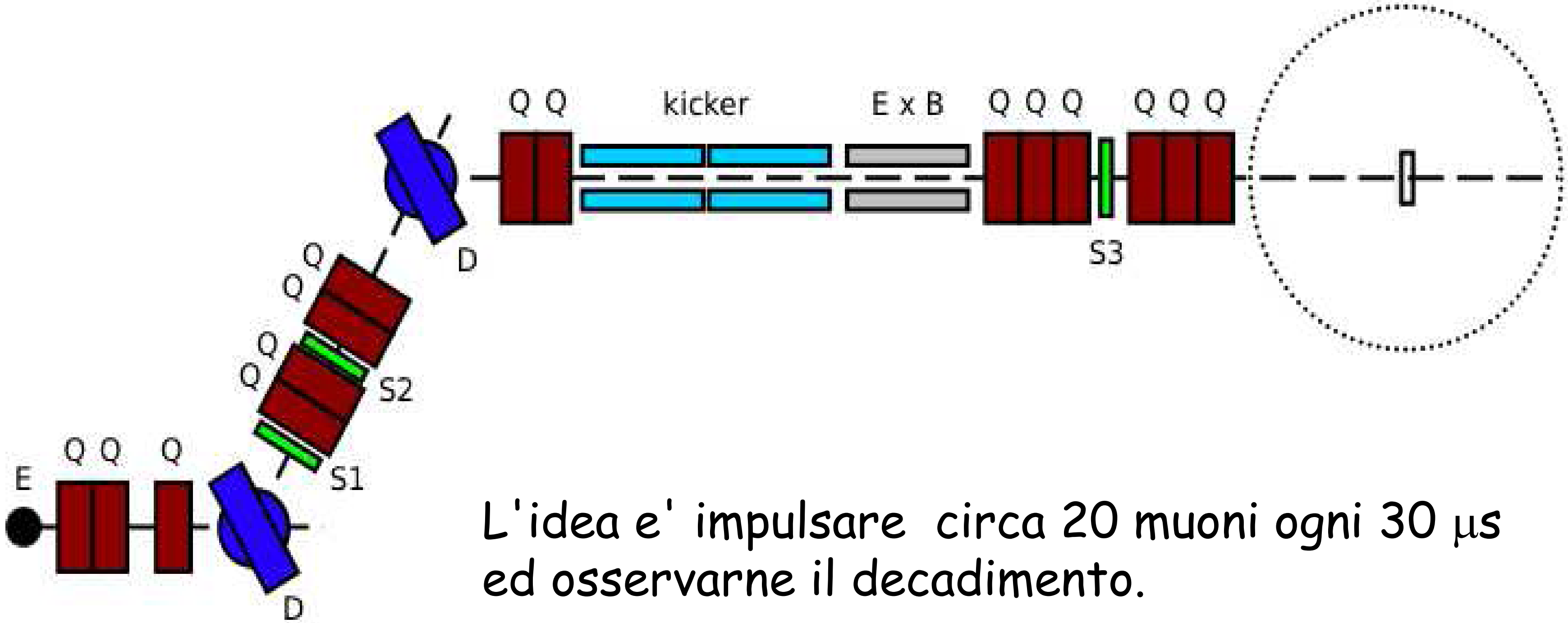
~10^{12} events necessary for 1 ppm measurement

Quanto tempo e' necessario ?

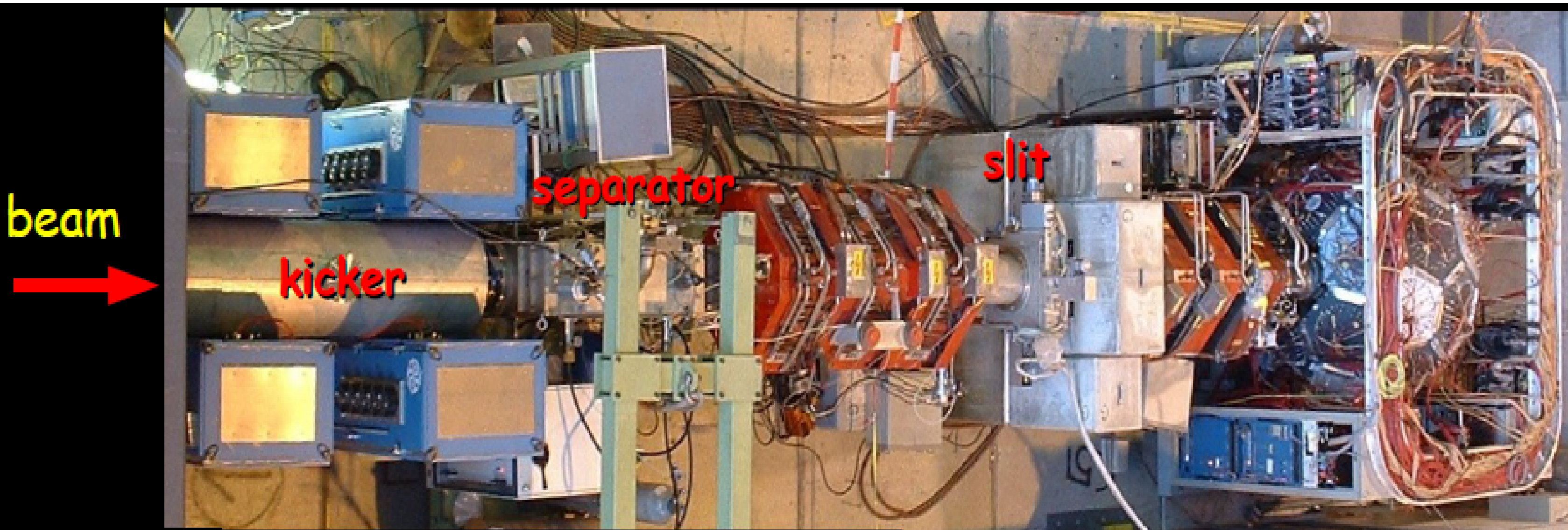


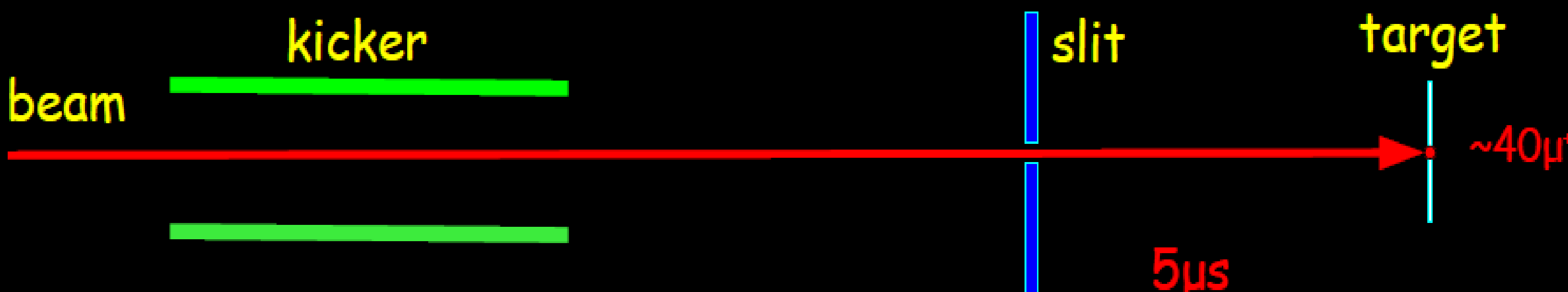


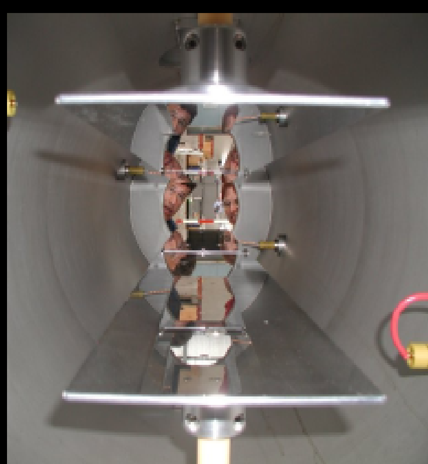
Source	Muon rate	Time to 10^{12}
Cosmic rays	$\sim 1\ cm^{-2}\ min^{-1}$	$\sim 10^4$ years
Continuous beam	20 kHz	~1.6 years beam time
Pulsed beam	20 / 30 μs (usable)	~ 3 weeks beam time



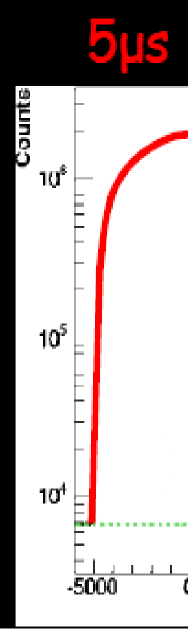
L'idea e' impulsare circa 20 muoni ogni 30 μs
ed osservarne il decadimento.



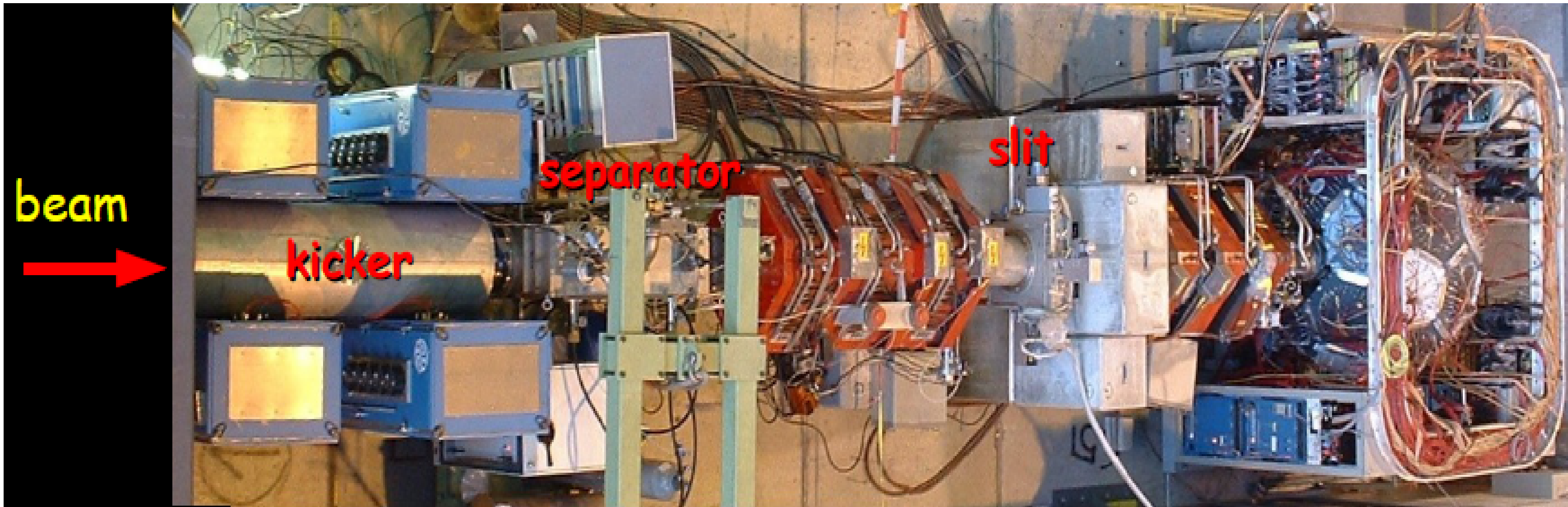


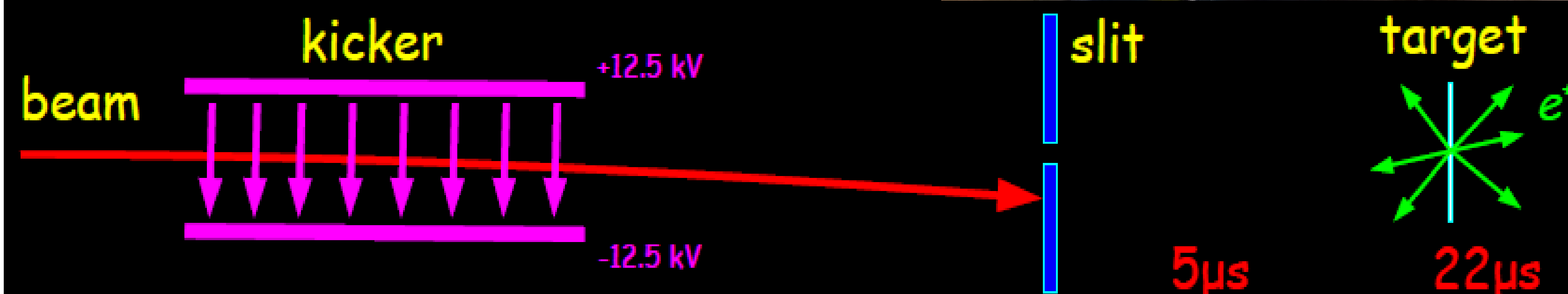


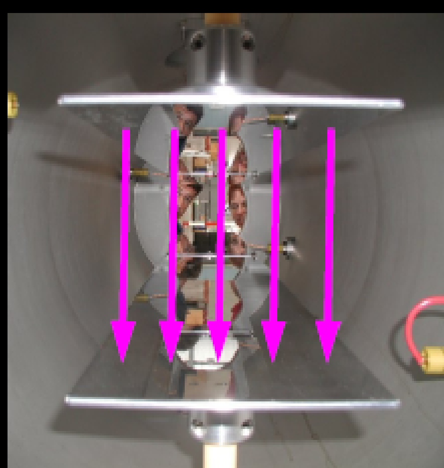
Al plates 12 cm x 75 cm



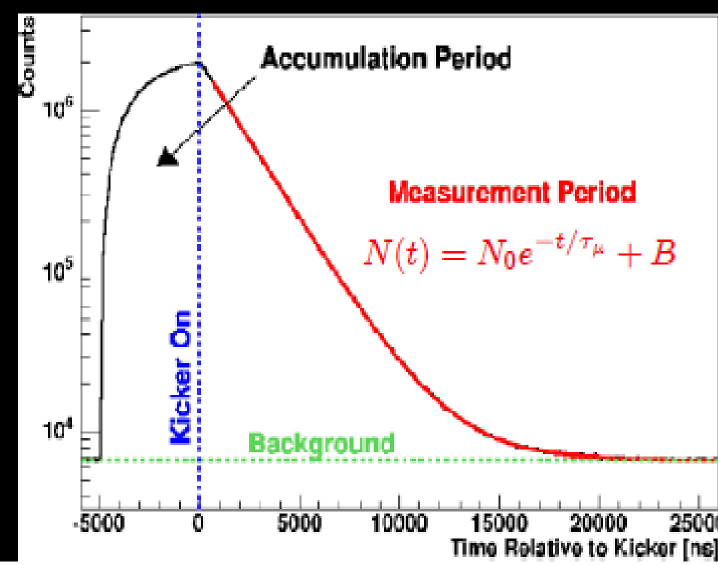
$$N_{\rm in}(t) = \nu_\mu \tau \left(1 - e^{-t/\tau_\mu}\right)$$

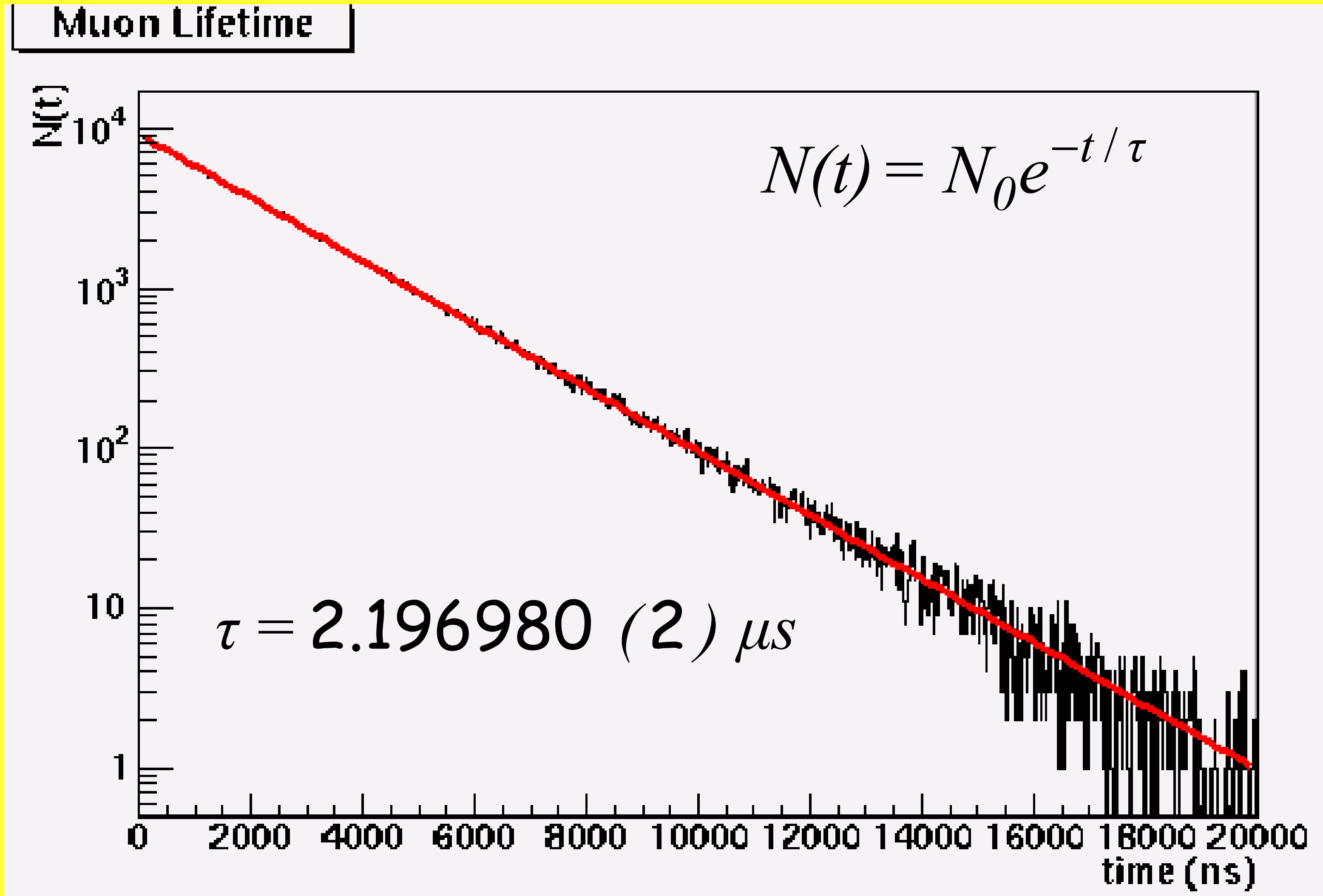






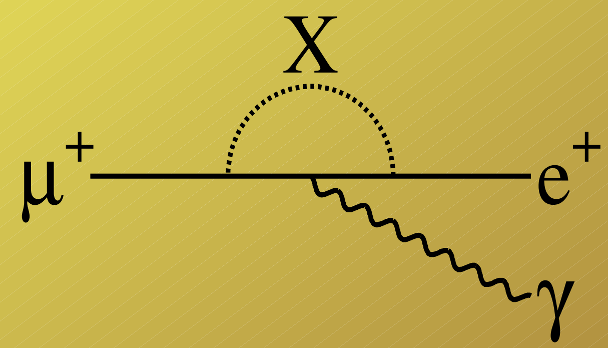
Al plates 12 cm x 75 cm




Muon Lifetime
N(t)
10^4
10^3
10^2
10
1
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
time (ns)
$N(t) = N_0 e^{-t/\tau}$
$\tau = 2.196980\ (2)\ \mu s$

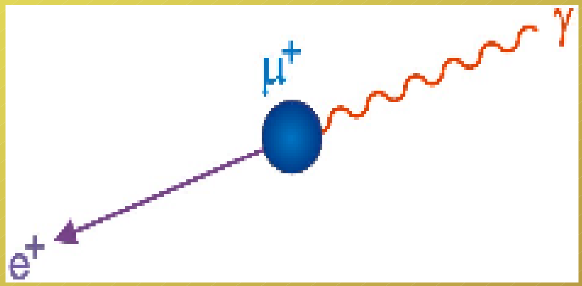
MEG experiment

LFV decays as $\mu^+ \to e^+\gamma$ are forbidden in the SM. On the other hand, several SUSY, GUT models beyond the SM predict this decay rate at a level experimentally accessible.



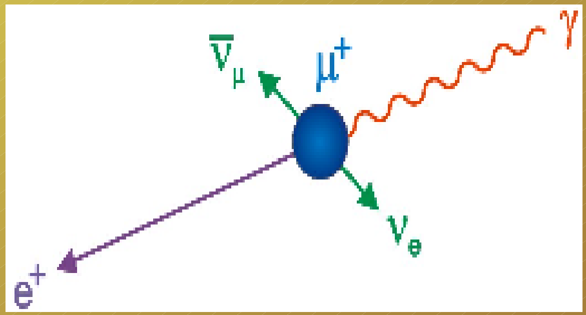
Signature of a $\mu^+ \to e^+\gamma$ event (decay at rest):

- Emitted back-to-back
- Each particle carries an energy equal ½ muon mass (52.8 MeV)
- Coincident in time



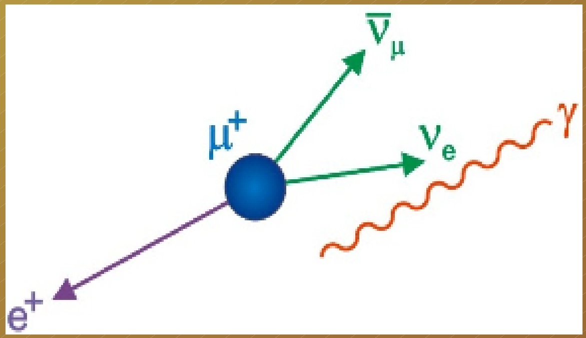
Background

Radiative muon decay: $\mu \to e\ \gamma\ \nu\ \nu$



Accidentals :

coincidence: $\mu \to e\ \nu\ \nu + \gamma$



Experiment	Year	Upper Limit
TRIUMF	1977	$< 3.6 \cdot 10^{-9}$
SIN	1980	$< 1.0 \cdot 10^{-9}$
LANL	1982	$< 1.7 \cdot 10^{-10}$
Crystal Box	1988	$< 4.9 \cdot 10^{-11}$
MEGA	1999	$< 1.2 \cdot 10^{-11}$

Muon Electron Gamma experiment result is (2012, March) :

$$\mathrm{BR}\ (\mu^+ \rightarrow e^+\ \gamma) < 2.4 \times 10^{-12}$$

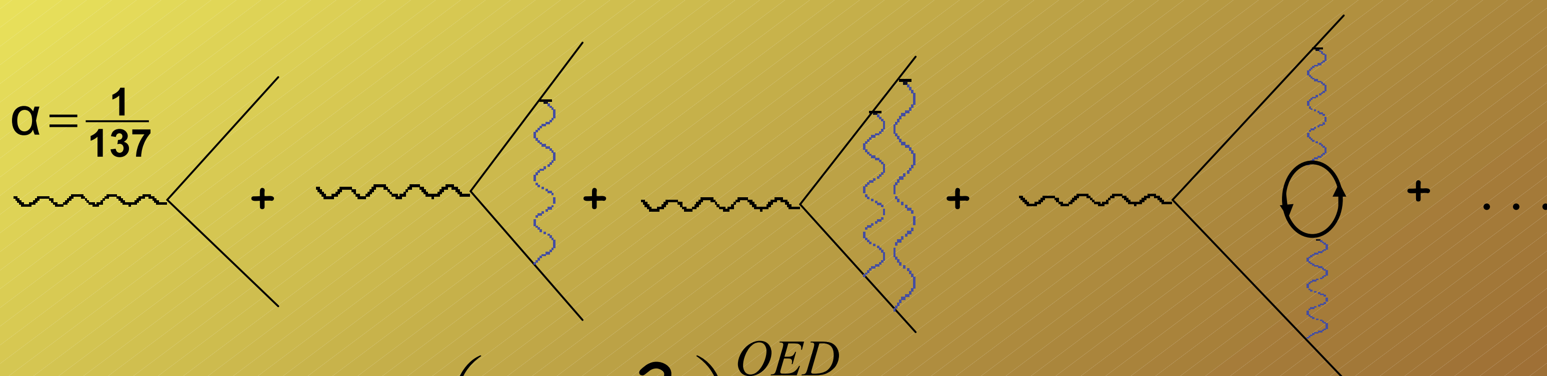
g-2 experiment

• La teoria di Dirac per particelle puntiformi (1927) implica che il momento magnetico μ sia proporzionale allo spin **s** :

$$\boldsymbol{\mu} = g\,\mu_B\,\boldsymbol{s} \qquad \text{dove: } \mu_B = \frac{e}{m} \times \frac{h}{4\pi c}$$

• Per l'elettrone ed il muone essa prevede g=2. In realta', seguendo le previsioni QED, bisogna apportare delle piccole correzioni. Esse sono dovute ai processi di emissione/riassorbimento di particelle **virtuali** e possono essere **calcolate** con estrema precisione.

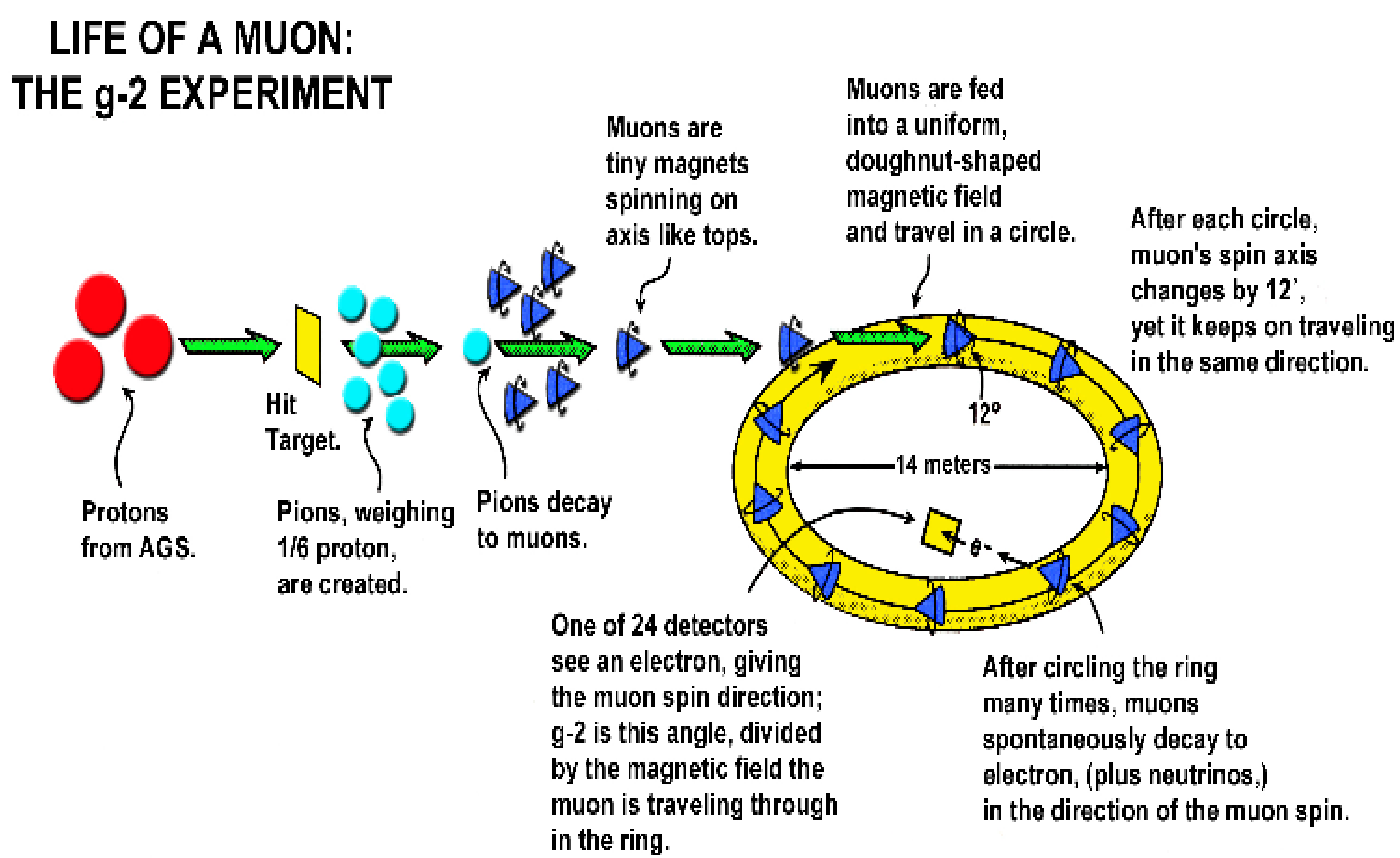
$$\alpha = \frac{1}{137}$$

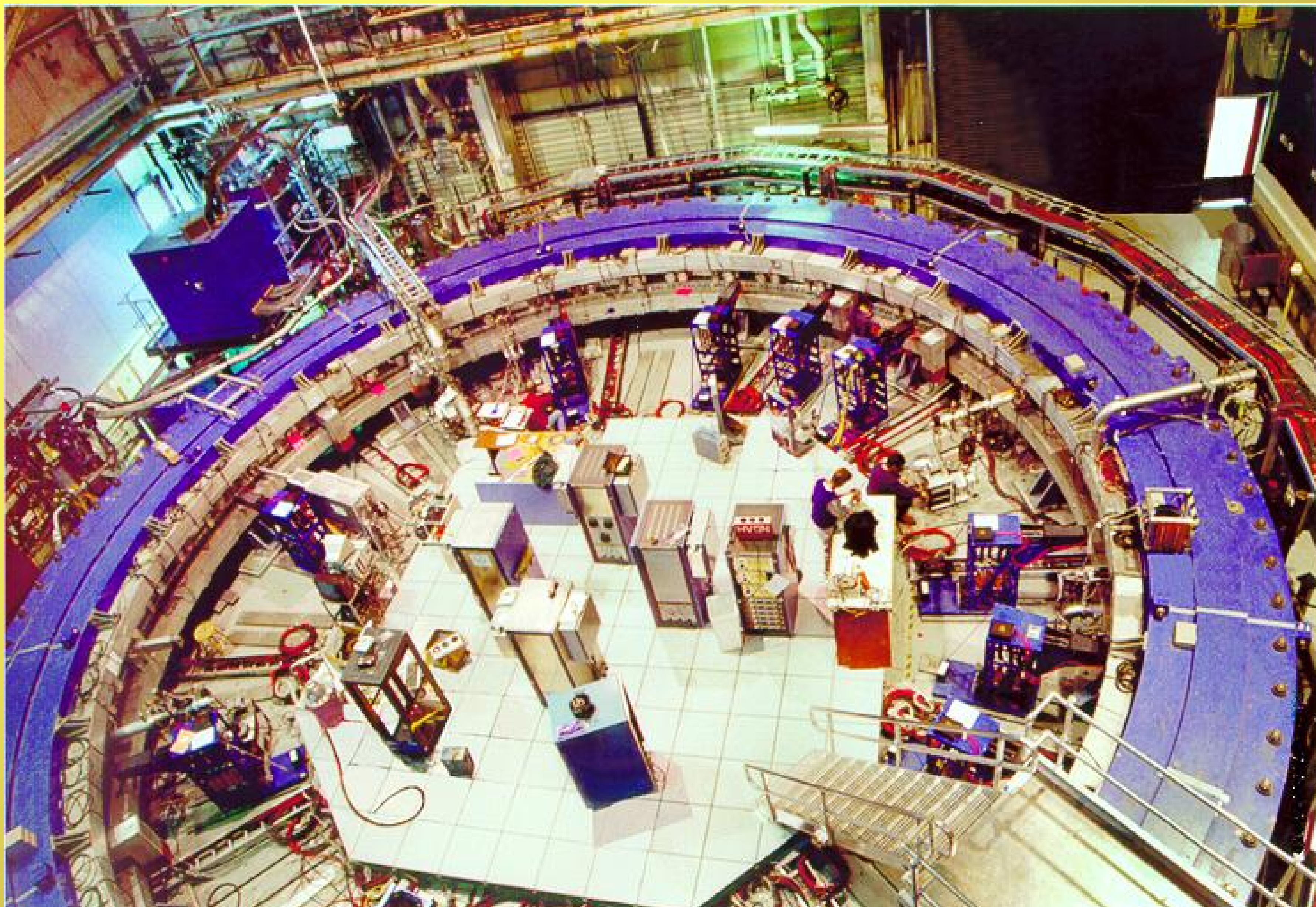


da cui deriva :

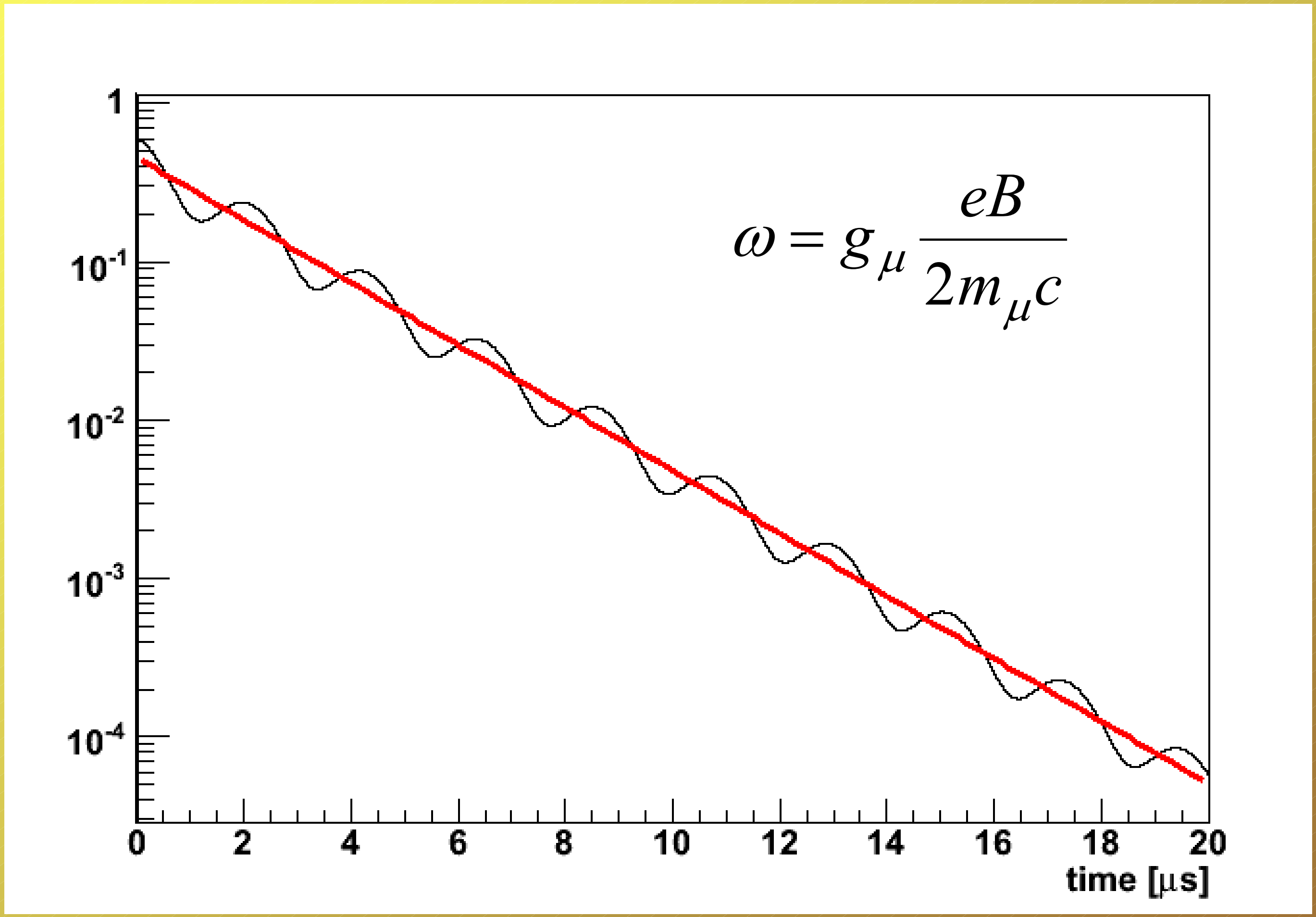
$$\left(\frac{g-2}{2}\right)^{QED} = \sum c_k \alpha^k$$

• The FermiLab Muon g-2 Collaboration goal → misura a ~ 0,1 ppm





$$N(t) = N_0 e^{-t/\tau}\left[1 + AP_2 \cos(\omega t + \varphi_0)\right]$$

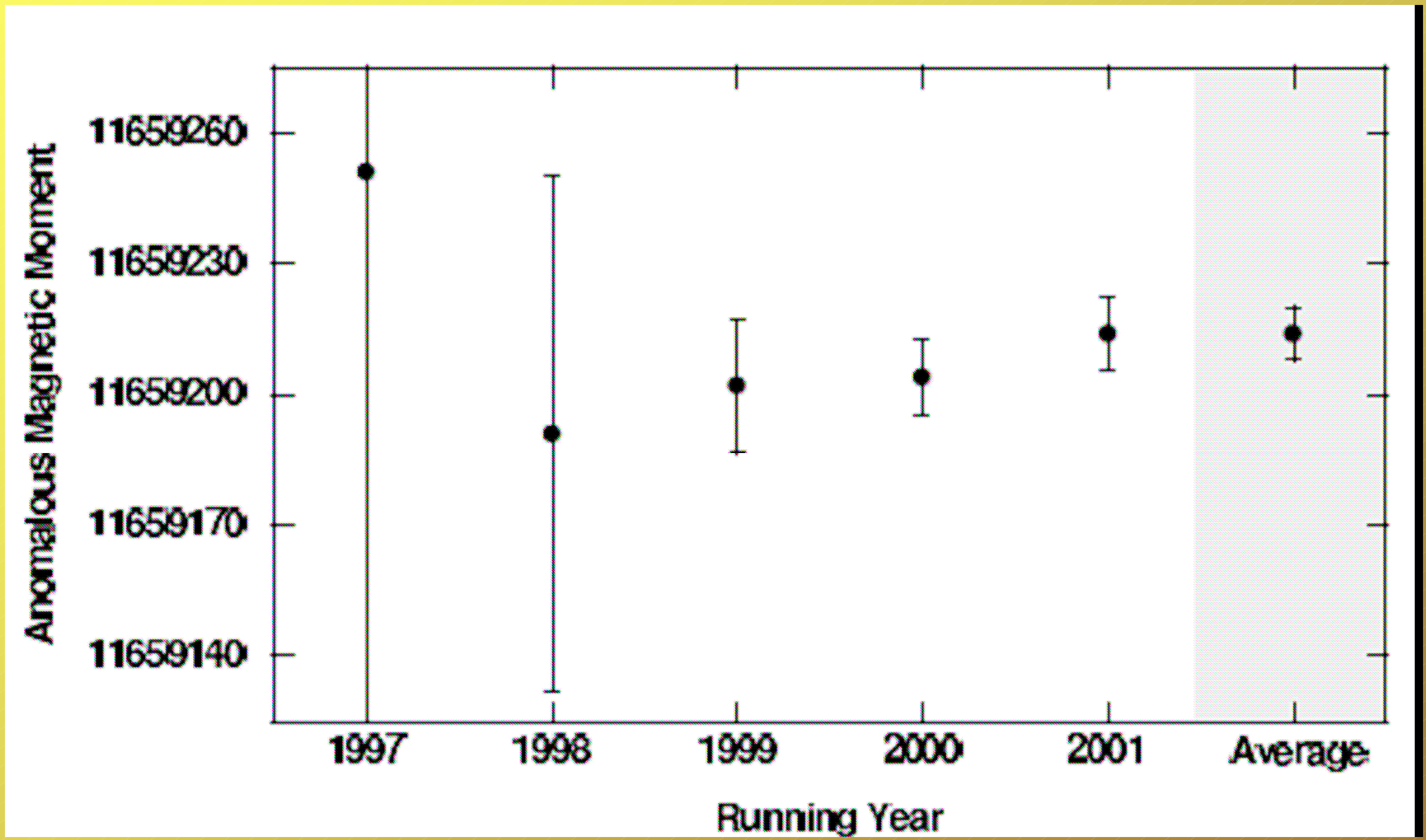


• Sorprendentemente può essere anche **misurata** con altrettanta precisione e finora l'accordo tra i valori sperimentali e i loro valori teorici era una prova straordinaria della validità del modello standard.

	electron	muon
$\left(\frac{g-2}{2}\right)^{QED}$	0.00115965218086 (57)	0.00116591786 (68)
$\left(\frac{g-2}{2}\right)^{meas}$	0.00115965218073 (28)	0.00116592080 (63)

~ 3σ

• Il muone è circa 200 volte più pesante dell'elettrone e questo fa sì che l' "anomalia" del suo momento magnetico sia molto più evidente rispetto a quella dell'elettrone



Anomalous Magnetic Moment
11659260
11659230
11659200
11659170
11659140
1997
1998
1999
2000
2001
Average
Running Year