Thomas Prokscha :: Low-Energy Muons Group :: Paul Scherrer Institut

Muon Properties and Muon Production

Lecture at the PSI Masterschool, Sep 8^{th} 2017, PSI

Outline of the Friday morning session

1. Muon Properties and Muon Production (TP)
   - Discovery of the muon
   - Pion decay, muon decay, parity violation, focus on positive muons μ^+
   - Muon properties, interaction with matter, basics of application of μ^+ in condensed matter physics
   - Generation of > MeV muons and eV- keV muons («low-energy muons»)
   - Overview of PSI proton accelerator facility HIPA («High Intensity Proton Accelerator»)
   - Application of cosmic muons: radiography of large objects
2. Introduction to Muon Spin Rotation and Relaxation (μSR): Instrumentation and Technique (Hubertus Luetkens)
3. μSR on Magnetic Materials (Alex Amato)
4. μSR and Superconductors (Alex Amato)

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The discovery of the muon

1910 T. Wulf, ionization measurements with electrometer on top of Eiffel tower

1911 V. Hess, balloon measurements

Ionization increases with altitude

R. Millikan, experiments with unmanned balloons (1925)

Discovery of cosmic radiation (1936 Nobel Price V. Hess)

1933 P. Kunze, first muon track (unrecognized)

1936 C. D. Anderson, S. H. Neddermeyer

main component of cosmic radiation: particle with 1/9 proton mass (mesotron)....

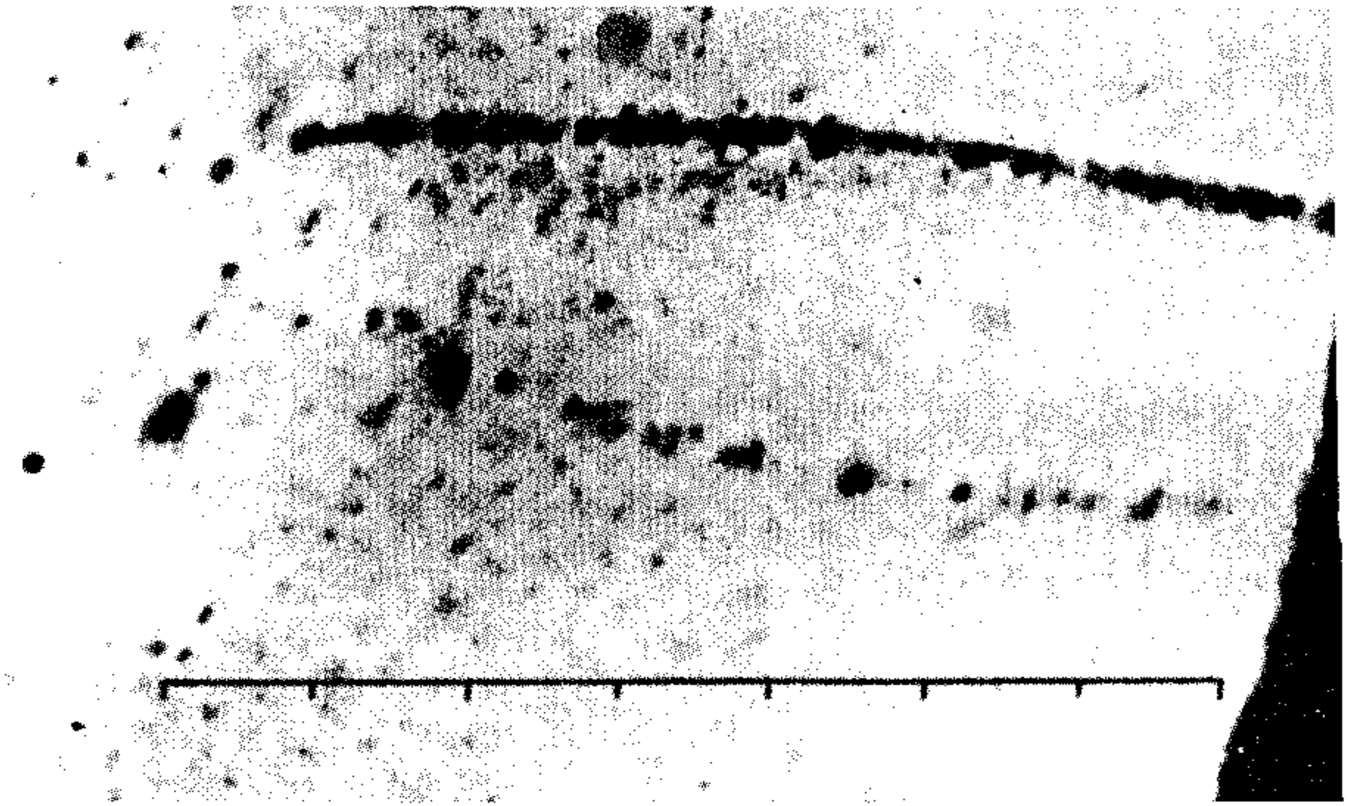
...interpreted as „Yukawa particle“ (strong interaction)

1942 B.Rossi, N. Nereson: τ_μ = 2.3(2) μs

1947 M. Conversi et al. : mesotron is weakly interacting with nuclei

C.F. Powell et al. : discovery of the pion (π^+, π^-) (1950 Nobel Price)
pion decays into muon

The discovery of the muon



(figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

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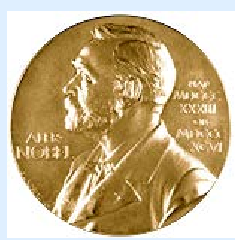
About the muon:

"Who ordered that?"

(…eventually I.I. Rabi won the *Nobel Prize in Physics* in 1944 for his invention of the atomic and molecular beam magnetic resonance method of observing atomic spectra).

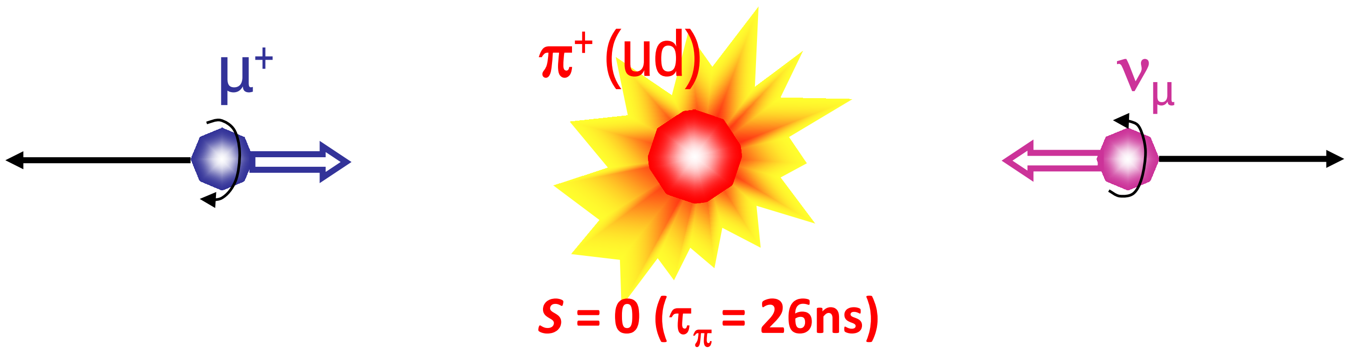


Isidor Isaac Rabi
(1898-1988)

Muon as a result of pion decay

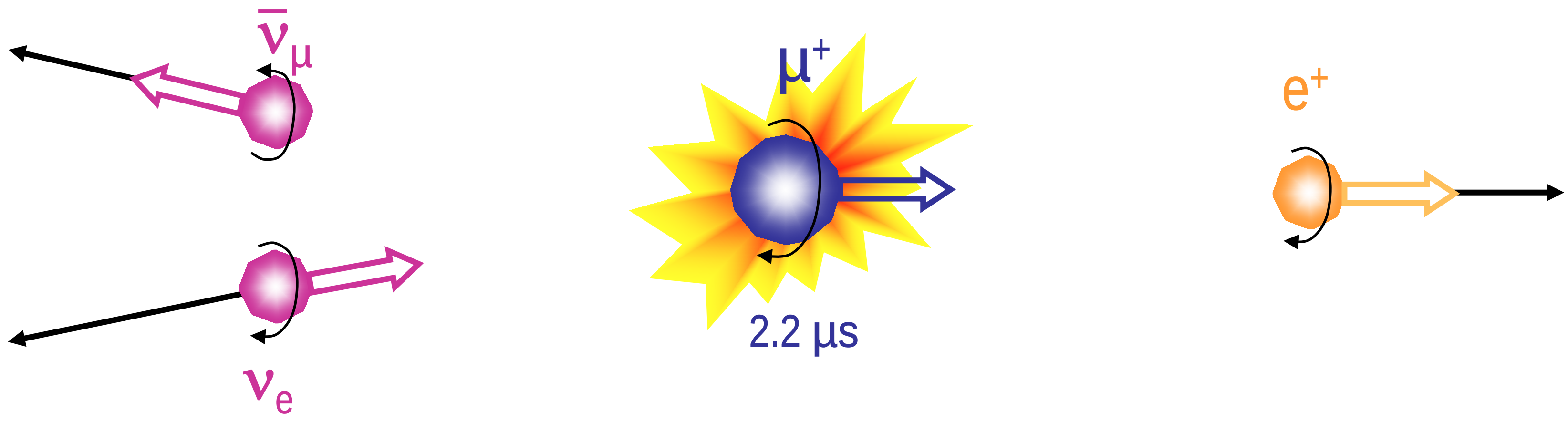
1956 T.D. Lee and C.N. Yang: predicted that any process governed by the weak interaction should lead to a violation of parity.

1957 R. Garwin, L. Ledermann, M. Weinrich and J. Friedmann, V. Telegdi: maximum violation of parity (spatial inversion) in weak decay of pion and muon



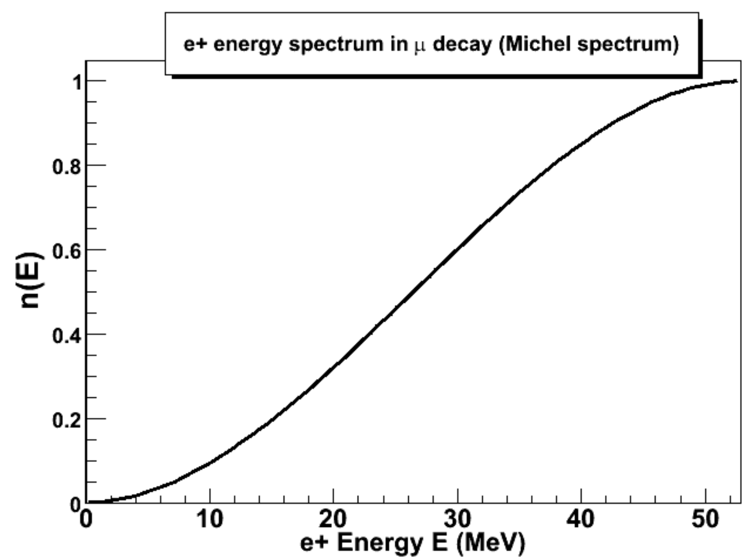
Two-body decay	▶	**muon has always the energy 4.1 MeV in the reference frame of the pion (assuming $m_\nu = 0$)**
Spin pion = 0	▶	**Muon has a spin 1/2 and is 100% polarized (as only left-handed neutrinos are produced)**

Muon decay properties



Three-body decay ▶ **Distribution of positrons energies**

Weak-decay of muon ▶ **Parity-violation leading to positrons emitted anisotropically**



Immediate recognition of the muon's potential...

THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 105, NO. 4 FEBRUARY 15, 1957

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

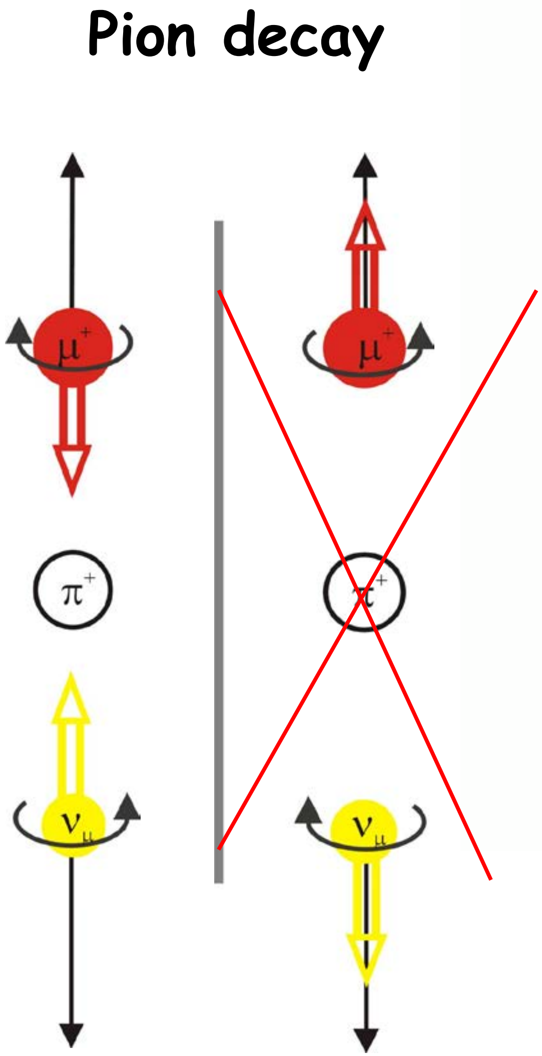
RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

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

(Received January 15, 1957)

It seems possible that polarized positive **[…]** muons will become a powerful tool for exploring magnetic fields in **[…]** interatomic regions.

Parity violation in pion and muon decay



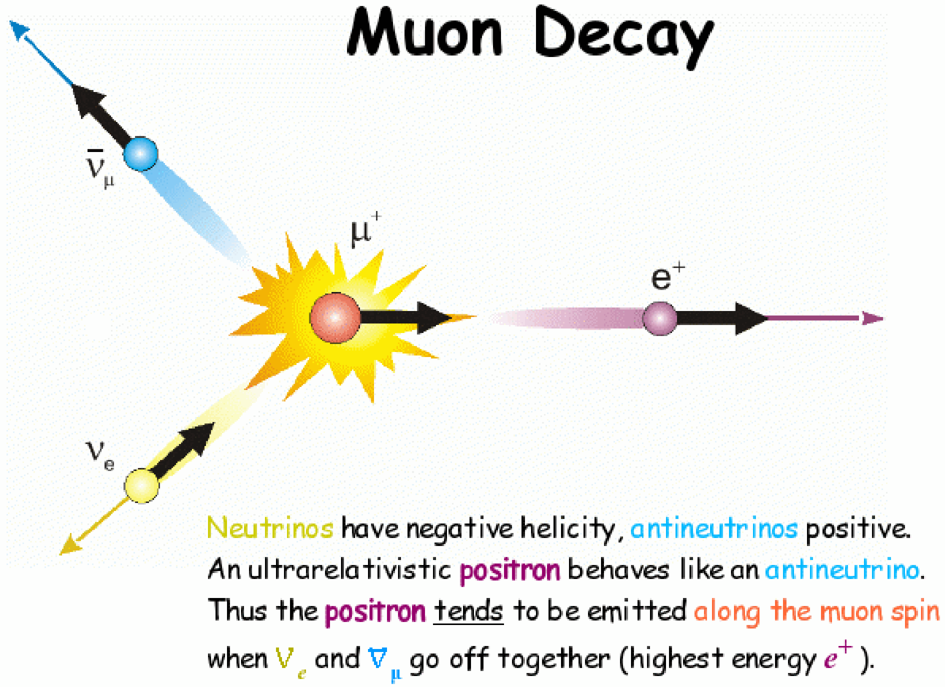


Figure from http://malct32.blogspot.ch/2010/07/proton-smaller-than-thought.html

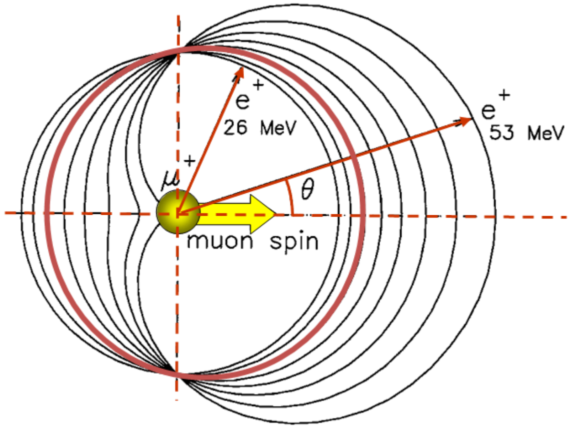
A relativistic e^+ ($E >> m_e$, m_e ~ 0.5 MeV) "wants" to have positive helicity. The decay with opposite μ^+ and e^+ spin direction is suppressed, causing the e^+ emission in the direction of μ^+ spin

The decay on the right side has never been observed; ν_μ are "left-handed", i.e. they have **negative helicity**.

Basics for muon spin rotation technique (μSR)

Generation of 100% polarized μ^+

Anisotropic muon decay, preferential emission of decay e^+ in μ^+ spin direction



$$W(E,\theta) = 1 + a(E,\theta)\cos(\theta)$$

Decay asymmetry a = 1/3 when integrating over all e^+ energies

Detecting spatial emission of e^+ as a function of time:

time evolution of muon spin/muon polarization P(t)

i) generation of polarized muons (parity violation)

ii) anisotropic muon decay (parity violation)

iii) precession of the muon magnetic moment *m* in a magnetic field *B*:

$$dm/dt = m \times B$$

$$m = \gamma_\mu \cdot \hbar \cdot S_\mu$$

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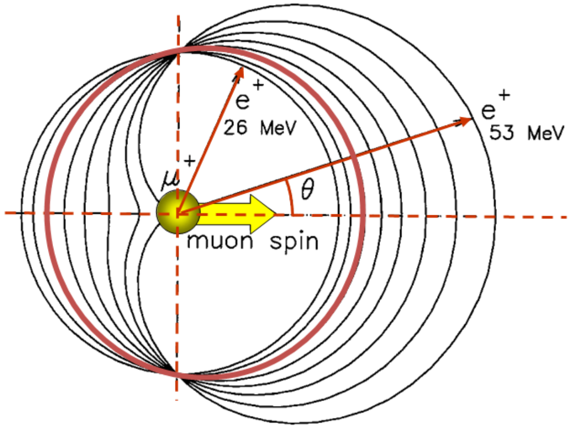

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iii) precession of the muon magnetic moment *m* in a magnetic field *B*:

$$dm/dt = m \times B$$

$$m = \gamma_\mu \cdot \hbar \cdot S_\mu$$

W(E,θ) is derived from the differential decay rate $d\Gamma(x,\theta)$, $x = 2E/m_\mu$:

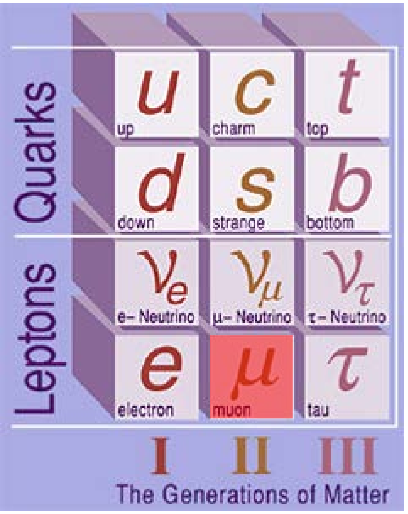
$$d\Gamma(x,\theta) \simeq \frac{1}{\tau_\mu}\{(3-2x) \mp P(2x-1)\cos\theta\}x^2\,dx\,d(\cos\theta)$$

Integrating over all energies x:

$$d\overline{\Gamma}(\theta) \simeq \frac{1}{2\tau_\mu}(1 \mp P\tfrac{1}{3}\cos\theta)d(\cos\theta).$$

F. Scheck, Physics Reports 44, 187 (1978)

Muon properties



elementary particle/antiparticle:

mass: 207x electron mass (105.6 MeV, 1/9x proton mass)
charge: + e, oder -e
spin: ½
magnetic moment : 3.18 μ_p

γ_μ = gyromagnetic ratio: $2\pi\cdot135.5$ MHz/T
(proton: $2\pi\cdot42.8$MHz/T,
electron: $2\pi\cdot28.1$GHz/T)

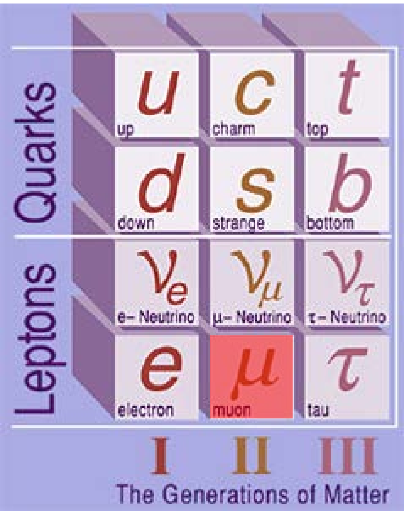
unstable particle:
mean lifetime: $\tau_\mu = 2.2\ \mu s$, $N(t)=N(0)\exp(-t/\tau_\mu)$

muon beams can be generated with 100% polarization

parity violation in muon decay makes it useful as a microscopic spin probe to measure local magnetic fields in a sample

→ **muon spin rotation technique (μSR)**

Muon properties

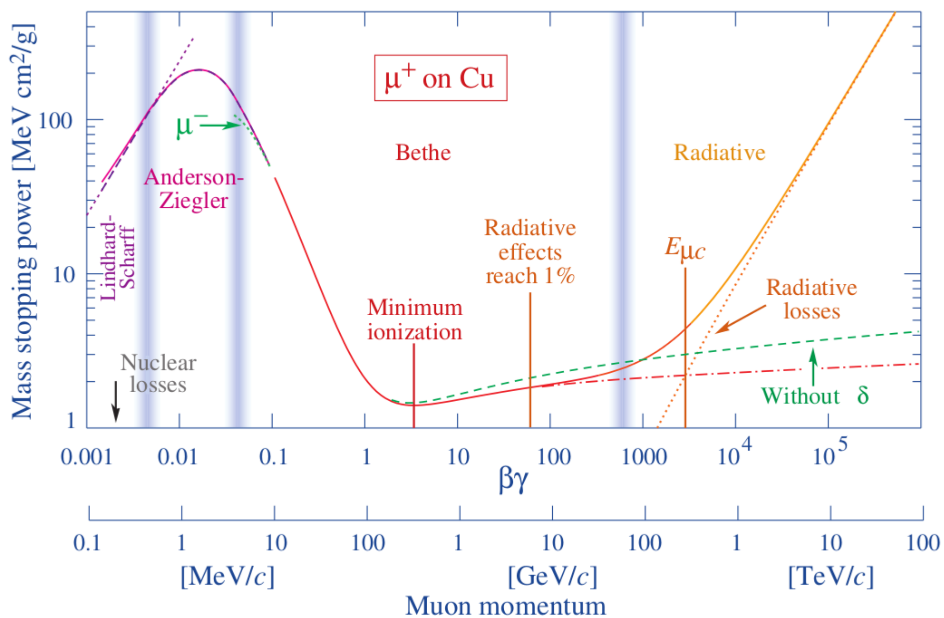


elementary particle/antiparticle:

mass: 207x electron mass (105.6 MeV, 1/9x proton mass)
charge: +e, oder -e
spin: ½

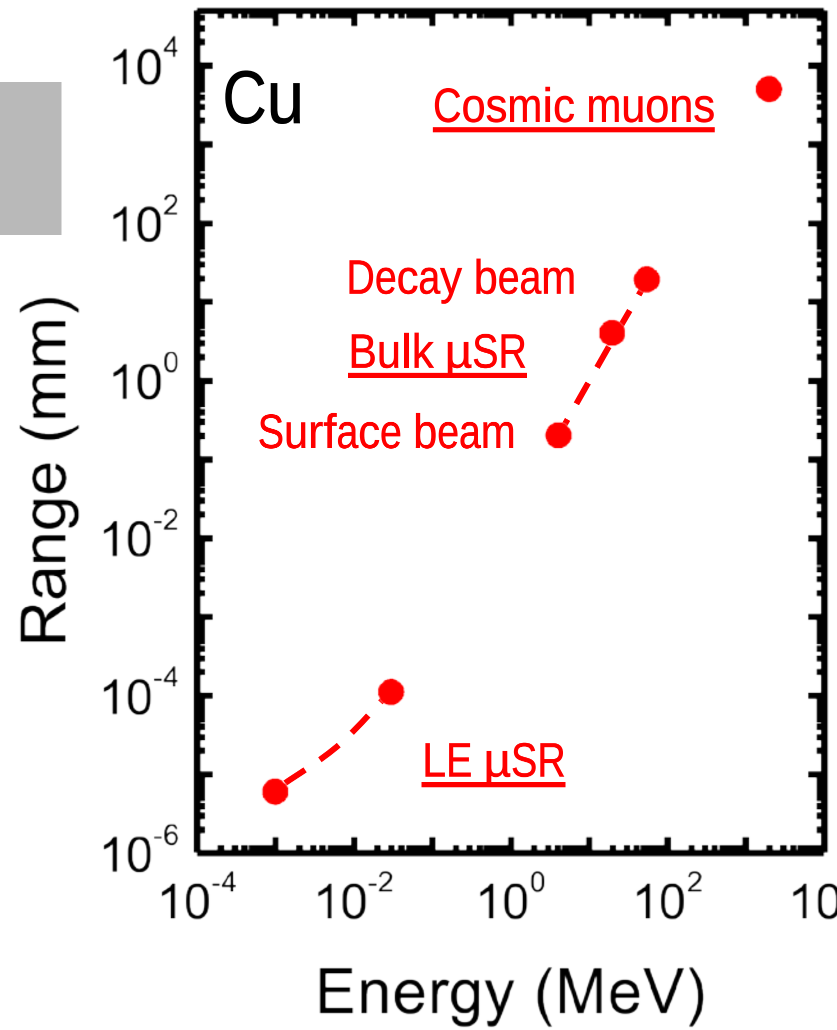
m_μ >> m_e: much smaller energy loss due to Bremsstrahlung (~m^{-4});
no strong interaction:

⟶ large range of „relativistic“ muons in matter, suitable for radiographic imaging of „massive“ objects



Particle data group, Chin. Phys. C **38**, 090001 (2014)

Range of muons in matter



Accelerator muons:

- “**decay beam**”, pions decaying in flight: muon energies $\mathbf{E_{\mu}}$ = 5 – 80 MeV
- “**surface muon beam**”, pions decaying at rest at surface of production target: $\mathbf{E_{\mu}}$ <= 4.1 MeV
- “**low energy muon beam**” ($\mathbf{E_{\mu}}$ < 30 keV), moderation of a surface muon beam

Bulk μSR:

▶ “Normal” samples (sub-mm), bulky samples + samples in containers or pressure cells

Low-Energy μSR (LE-μSR) (< 30 keV):

▶ Depth-selective investigations (1–200 nm)

Generation of muons

How to generate muons

Polarized muon production:

high energy protons generate pions (m_π ~ 140 MeV) in collisions with nuclei:

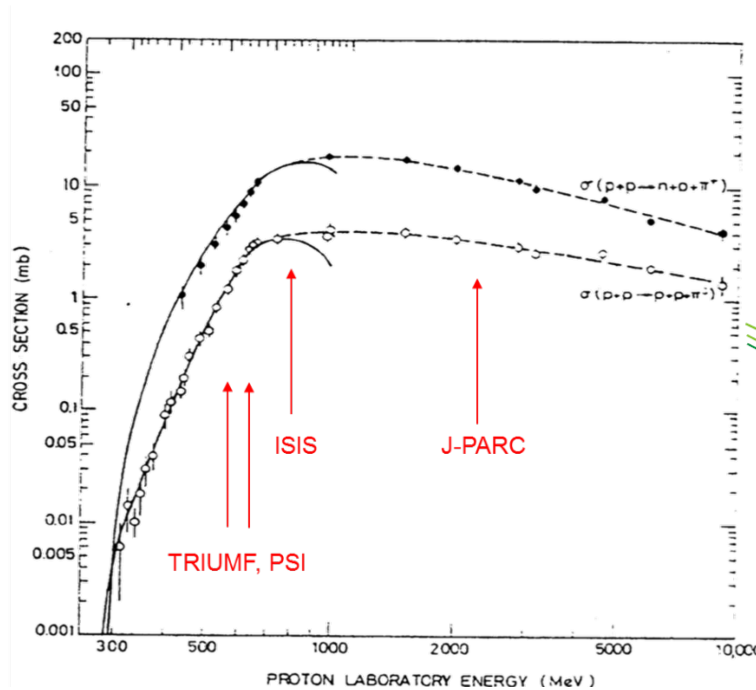
$p^+ + p^+ \rightarrow p^+ + n + \pi^+$

$p^+ + n \rightarrow n + n + \pi^+$

$p^+ + p^+ \rightarrow p^+ + p^+ + \pi^0$

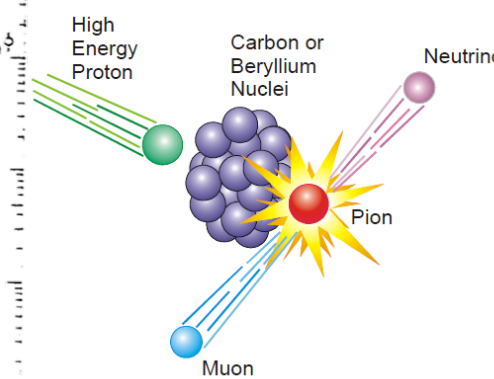
$p^+ + n \rightarrow p^+ + n + \pi^0$

$p^+ + n \rightarrow p^+ + p^+ + \pi^-$



$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$



For Beam-on-Fixed-Target it needs E_p > 290 MeV

"Meson factories" have E_p = 500 – 3000 MeV

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ ($\pi^{+/-}$ lifetime 26 ns, 100% μ^+ polarization in π^+ rest frame)

How to generate muons

Muons can be produced electromagnetically in e+/e- collisions:

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

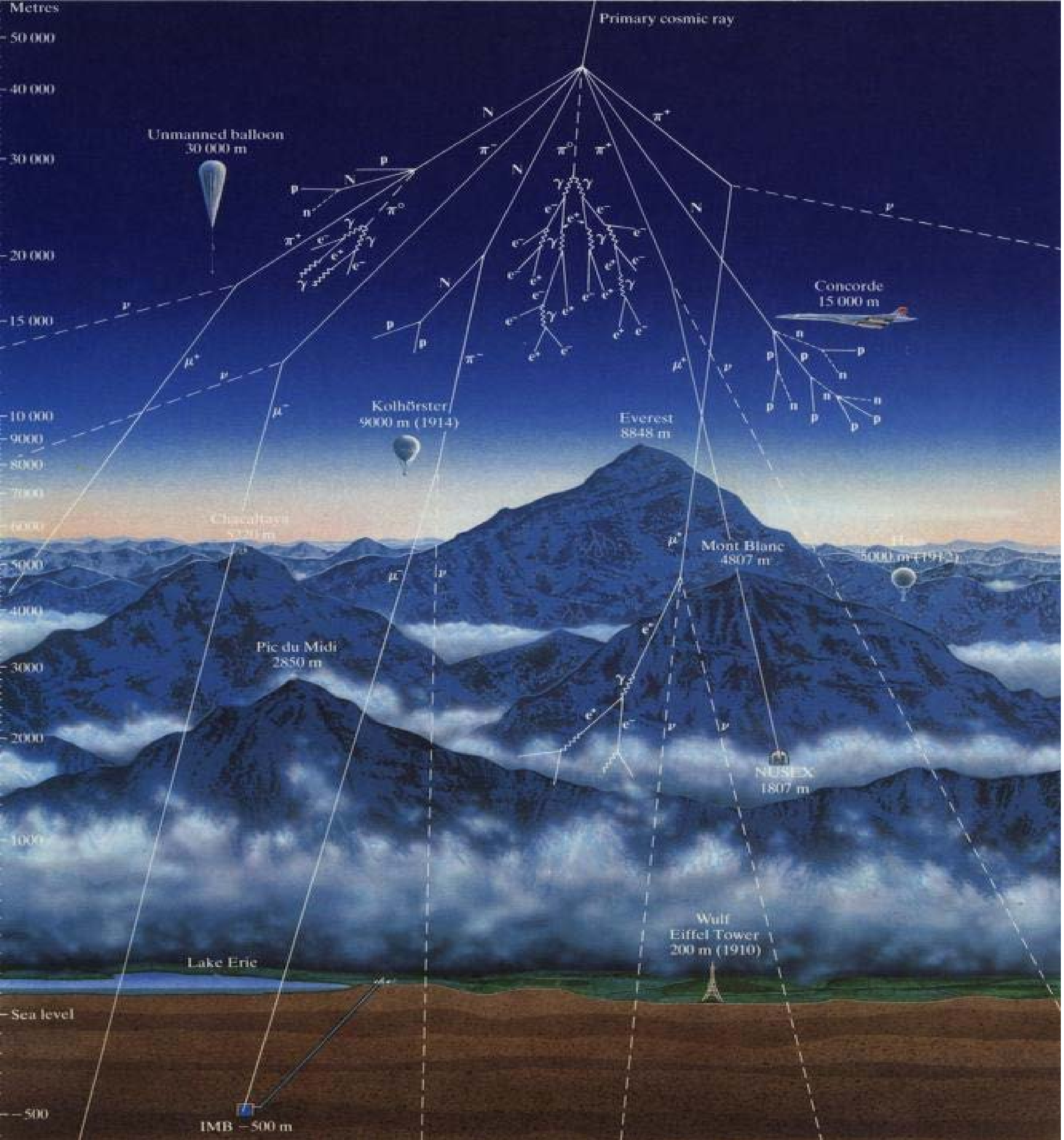
(Standard reaction of electron-positron physics)

However, the cross section is very small compared to pion production cross sections which is up to 20 mb = 2 x 10^{-26} cm^2:

$\sigma_{\mu\mu} \sim 4\pi\alpha^2/3s \sim 2 \times 10^{-32}$ cm^2 for 1 GeV colliding beam energy (= $\sqrt{s}$),

and this process does not generate polarized muons.

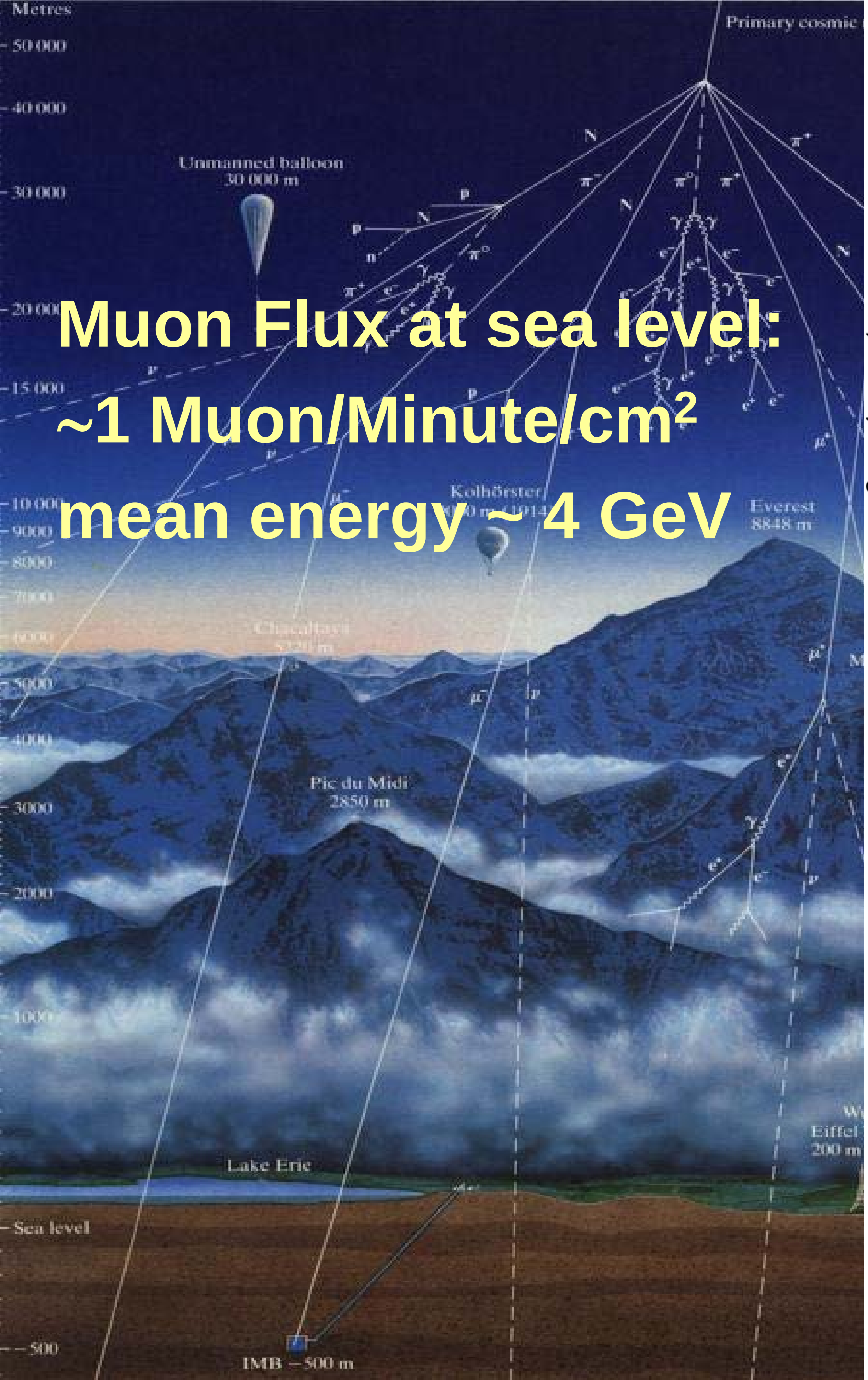
F. Scheck, *Muon physics*, Physics Reports 44, 187 (1978).

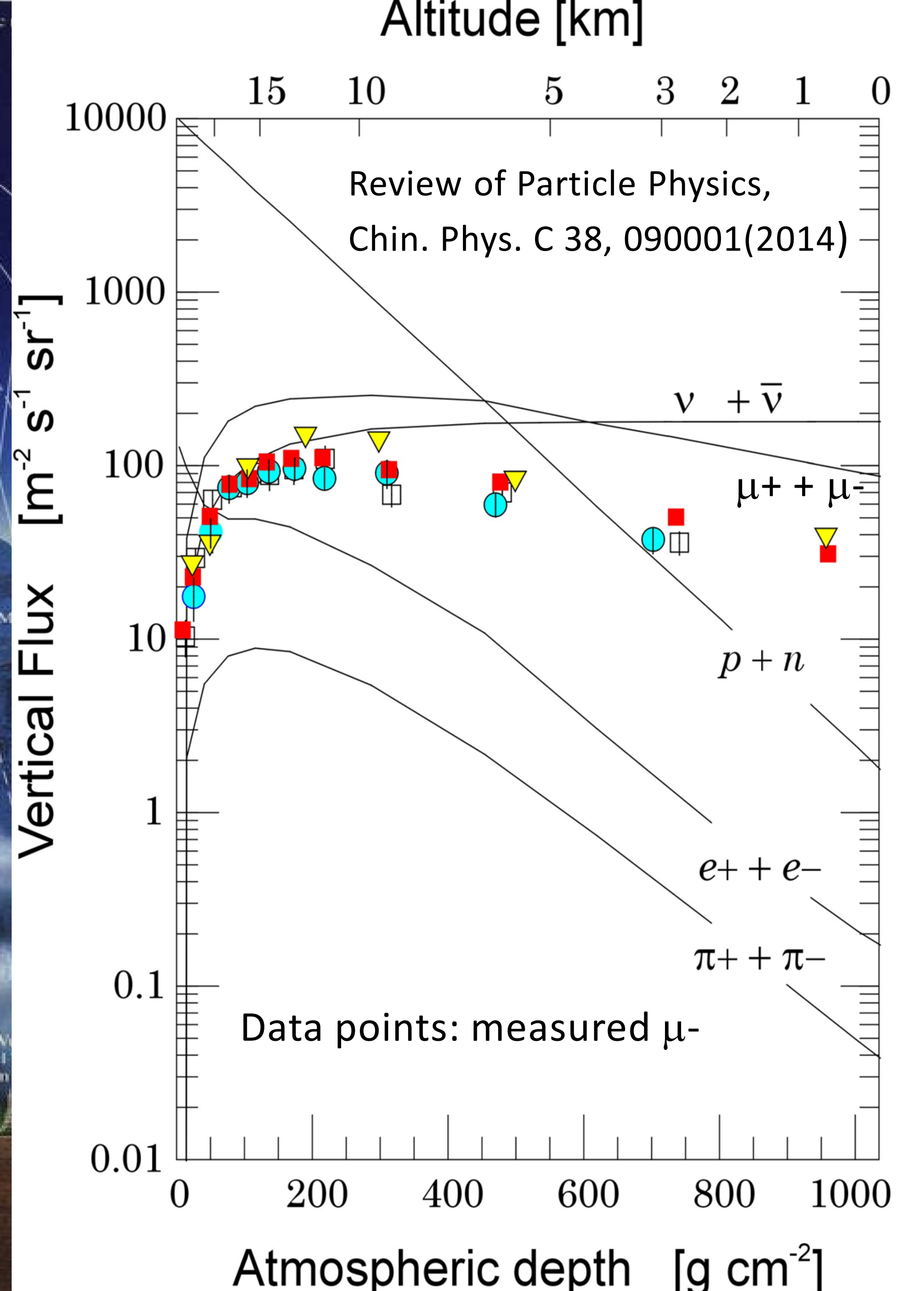


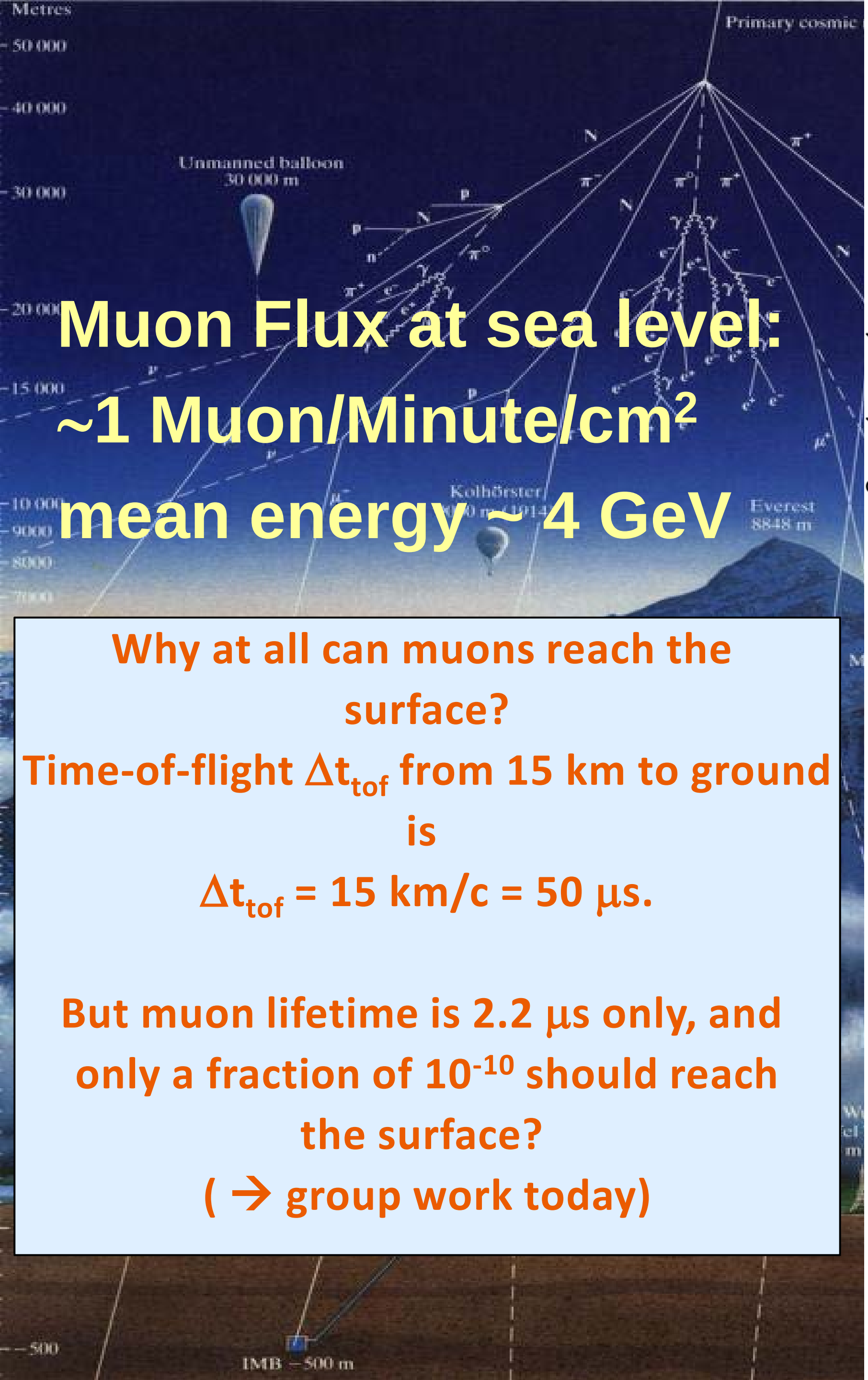
***Natural* muons:**

Cosmic muons (although the muons do NOT come from the cosmos…)

Muon Flux at sea level:
~1 Muon/Minute/cm^2
mean energy ~ 4 GeV







Muon Flux at sea level:

~1 Muon/Minute/cm^2

mean energy ~ 4 GeV

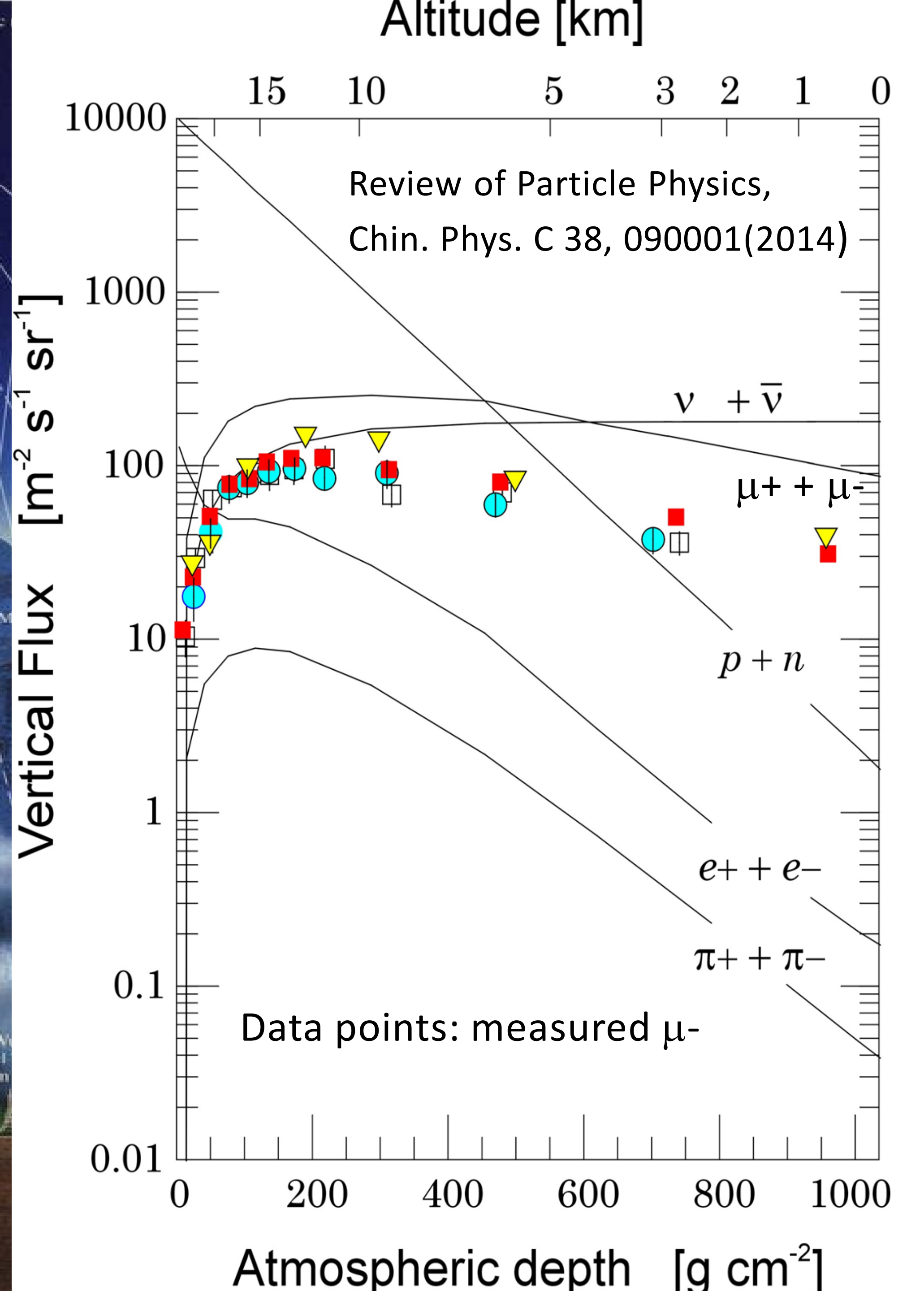
Why at all can muons reach the surface?

Time-of-flight Δt_{tof} from 15 km to ground is

Δt_{tof} = 15 km/c = 50 μs.

But muon lifetime is 2.2 μs only, and only a fraction of 10^{-10} should reach the surface?

(→ group work today)



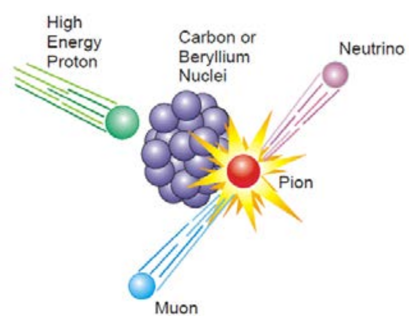
Accelerator muons

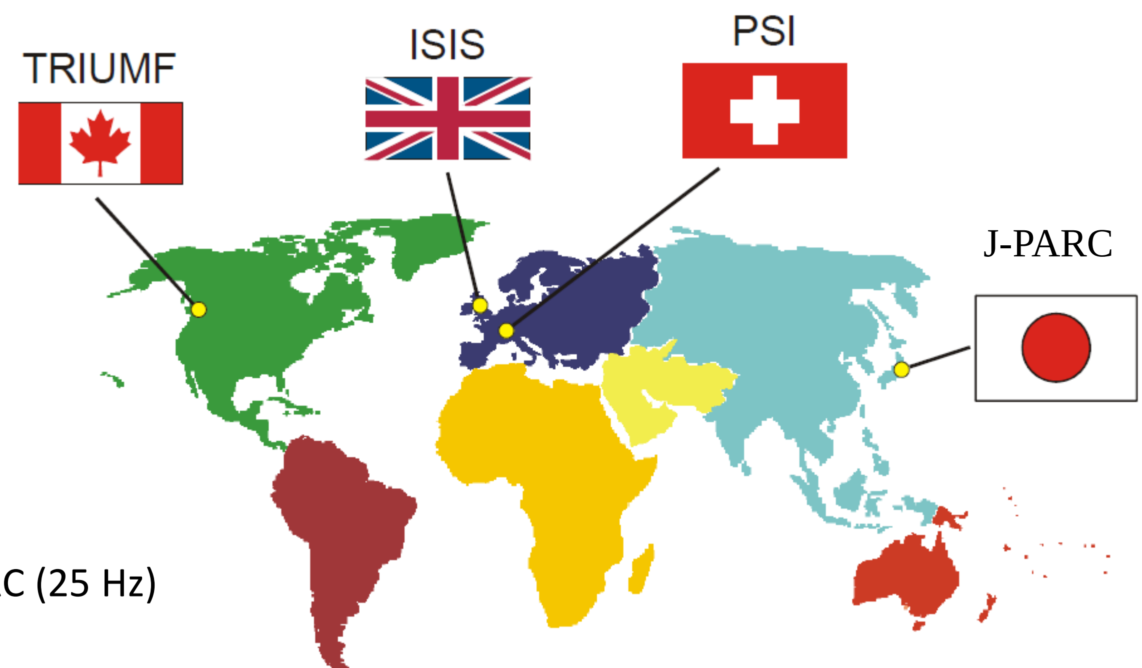
Accelerator muons (keV-MeV): ~100% polarization, depth resolution few nm to mm, lateral resolution mm to cm
measuring magnetic field distributions/fluctuations

intensity: 1000 Muons/second/cm^2 (keV) up to 10^7 Muons/second/cm^2 (MeV)

requires a proton accelerator (E_p > 500 MeV, I_p > 100 μA)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$





μSR facilities of the world.

continuous μ beams: TRIUMF, PSI

pulsed μ beams: ISIS (50 Hz), J-PARC (25 Hz)

Projects: MuSIC, Osaka (continuous)
CSNS (China, pulsed)
RAON (South Korea, continuous)

http://musr.ca/intro/musr/muSRBrochure.pdf

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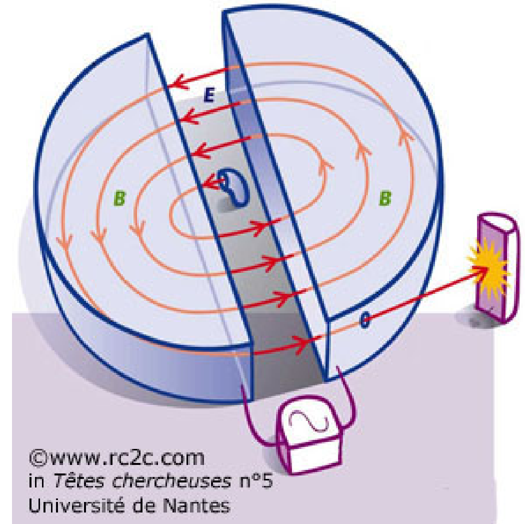
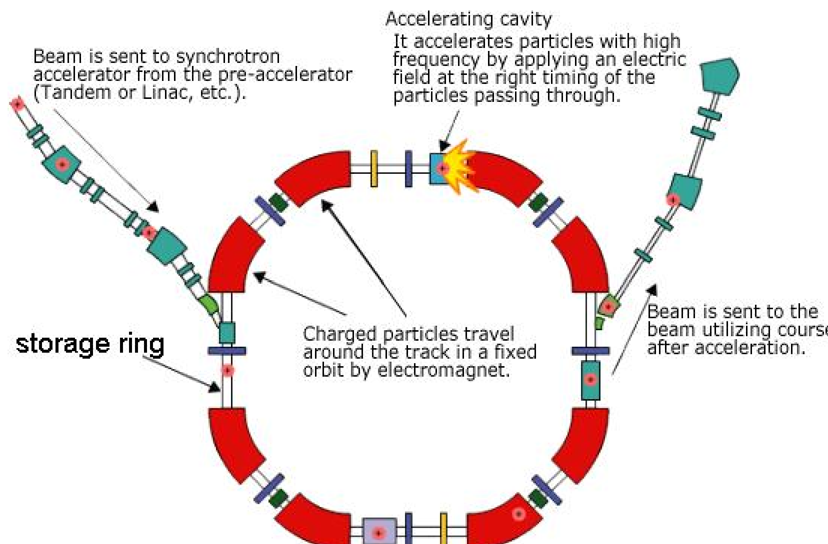
Accelerator muons

How to accelerate protons to energies > 300 MeV (pion production threshold) **and proton beam currents I_p > 100 μA** (to generate muon/pion beam with high intensities > 10^7/s) ?

Isochronous Cyclotron: compact, operated at tens of MHz RF frequency (**quasi-continuous muon beams**), constant RF frequency, constant (in time) magnetic field increasing with radius. Beam energy < 1 GeV (limited by magnetic field of magnets with saturation field of 2 T).



Synchrotron: can be very large (CERN LHC: 27 km) to achieve highest energies (TeV). Magnetic field synchronized with particle energy: this requires ramping of magnets which can be done at GeV energies with 50 Hz (**pulsed muon beams, with muon pulse widths of typically 100 ns**). Needs an "injection accelerator".



http://www.science20.com/mei/blog/synchrotron_radiation

Continuous versus pulsed muon beams

continuous muon beams

"Continuous Wave (CW)"

- **No distinct time structure**
- **Each muon individually counted.**
  "Start" signal (muon detector)
- **Very small time resolution**
  (< 100 ps possible)
  - **Detection of large magnetic fields**
  - **Detection of fast relaxing signals**
- **Reduction of muon rate to avoid "pileup"**
- **Non-negligible background**

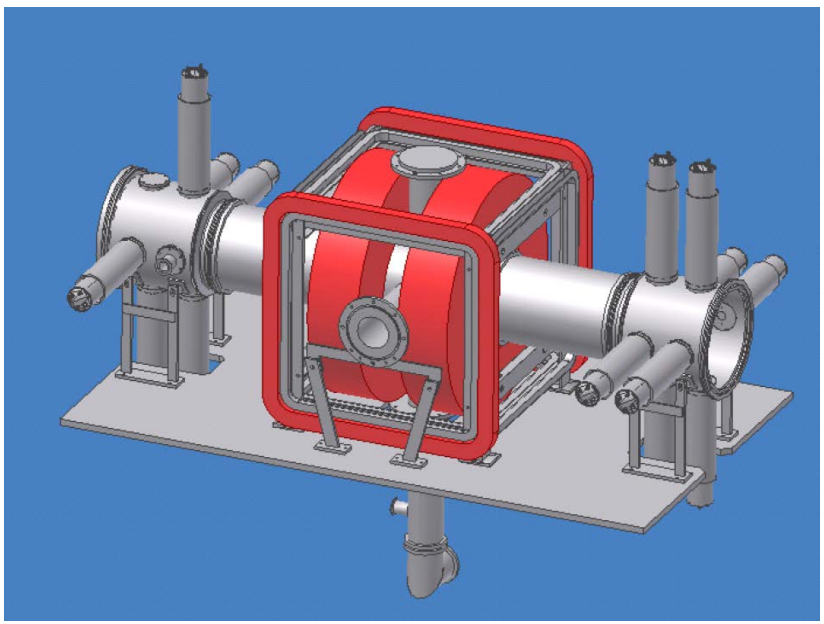
pulsed (50Hz) muon beams

- **Distinct time structure**
  (pulse structure of proton beam)
- **All muons coming at (almost) the same time.**
  No need of muon detector.
  (Pulse width 10ns – 100ns)
- **Very low background (possibility to measure slow depolarization rates)**
- **Limited time resolution**
  - **Detection of large magnetic fields and/or fast relaxing signals <u>impossible</u>**
- **High rates requires very high detector segmentation**

Continuous versus pulsed muon beams

continuous
muon beams

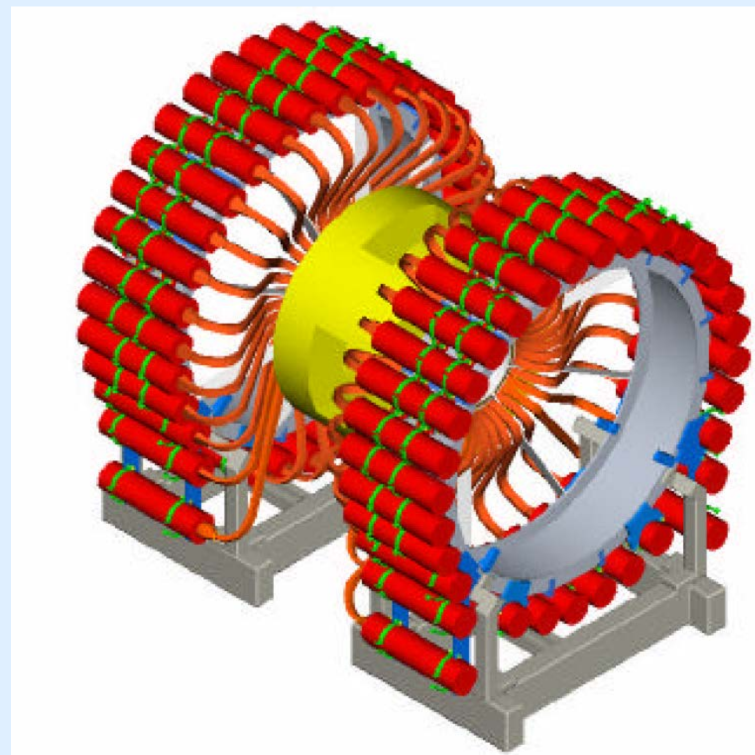
No need of high detector segmentation



Example: "GPS" instrument at PSI
1 backward + 1 forward detectors

pulsed (50Hz)
muon beams

High detector segmentation mandatory



Example: "MuSR" instrument at ISIS
32 backward + 32 forward detectors

Continuous versus pulsed muon beams

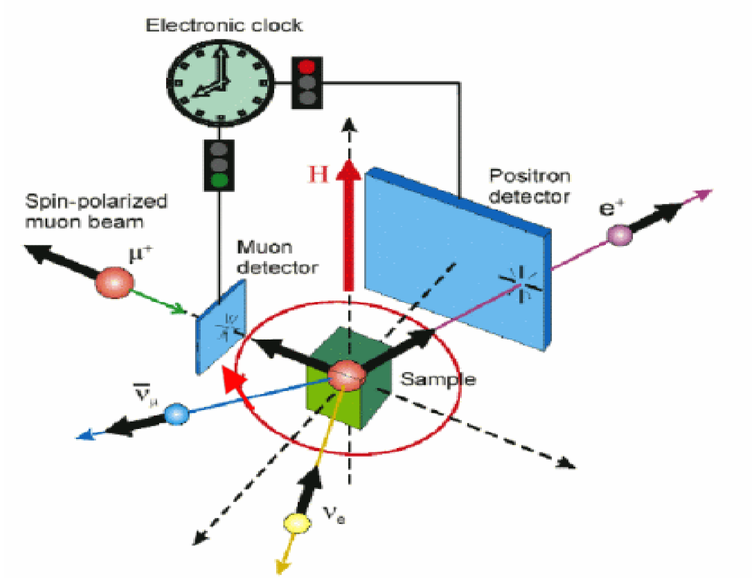
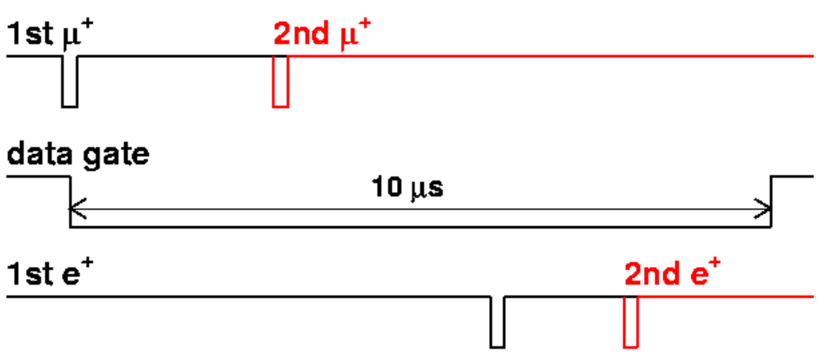


Figure 1. The transverse field μSR experiment. Drawing by Jeff Sonier, TRIUMF.



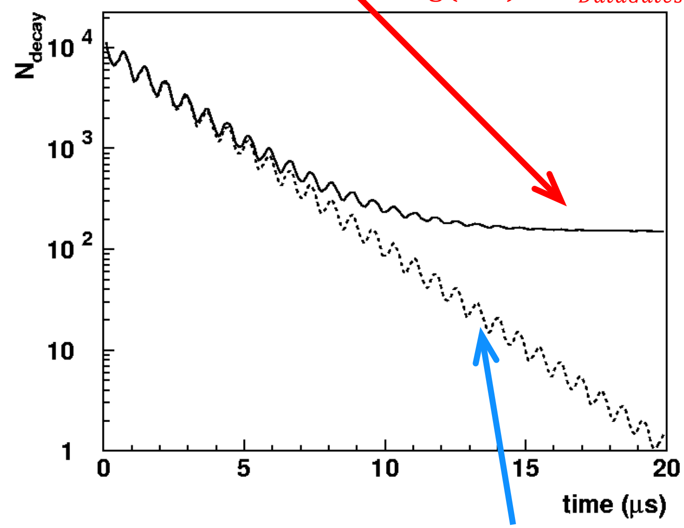
1st μ^+: there was no other μ^+ for at least 10μs in the past

Good Event = (data gate) • (1st e^+) • (no 2nd μ^+) • (no 2nd e^+)

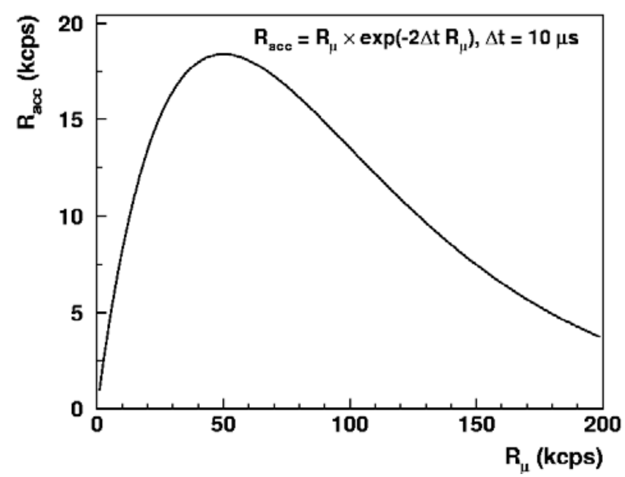
$R_{acc} = R_\mu \times \exp(-2\Delta t\, R_\mu)$, $\Delta t = 10\ \mu s$

background due to uncorrelated detector hits

$\text{bkg(bin)} \cong N_{DataGates} * \Delta t_{bin} * R_{e+}$



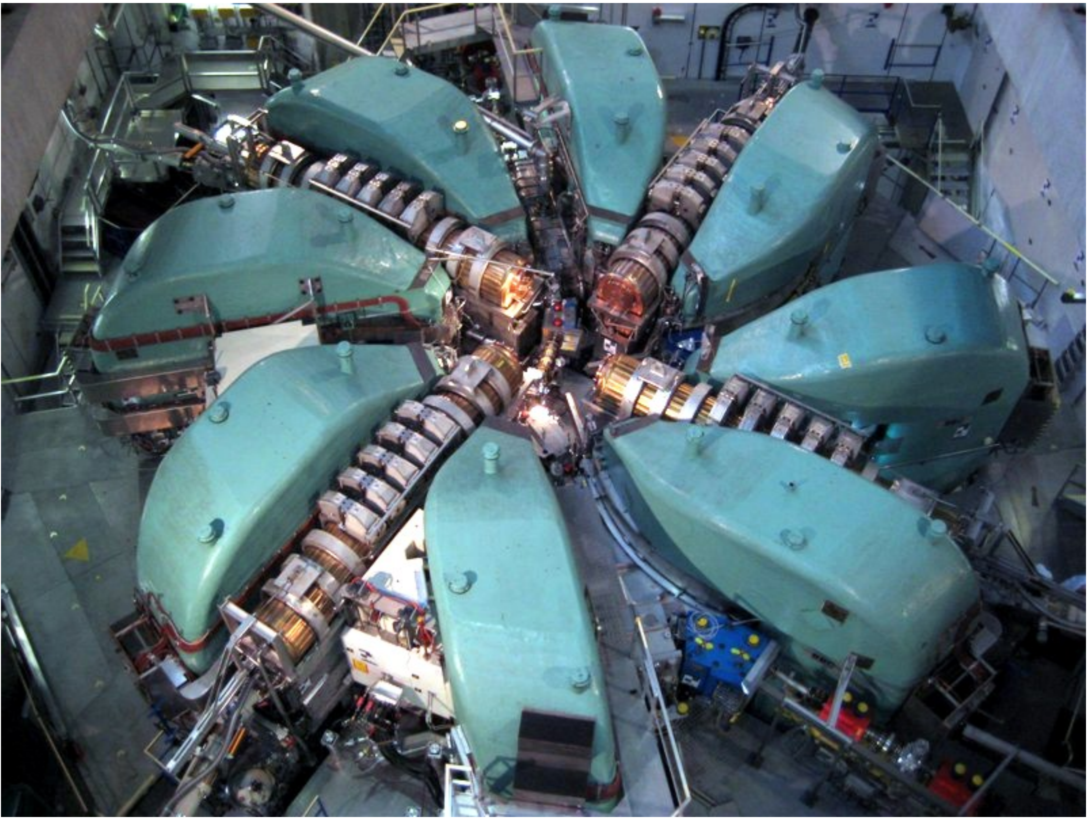
Low background at a pulsed beam



The PSI isochronous cyclotron

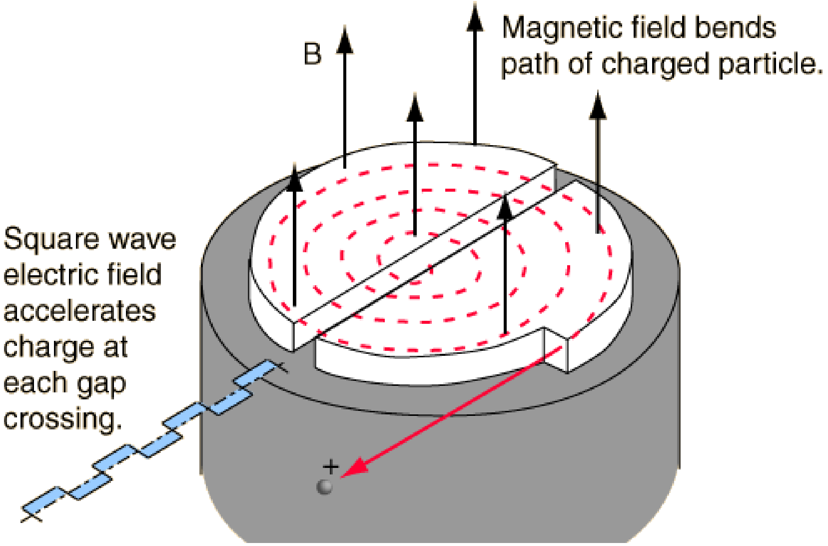
2.4 mA: ~1.5 x 10^{16} protons/sec @ 590 MeV:
1.4 MW on 5x5 mm^2 = 50 kW/mm^2, stainless steel melts in ~0.1 ms;
electric power demand of 3000 households

A MW proton beam allows to generate 100% polarized 4-MeV μ^+ beams with rates $>10^8$/sec

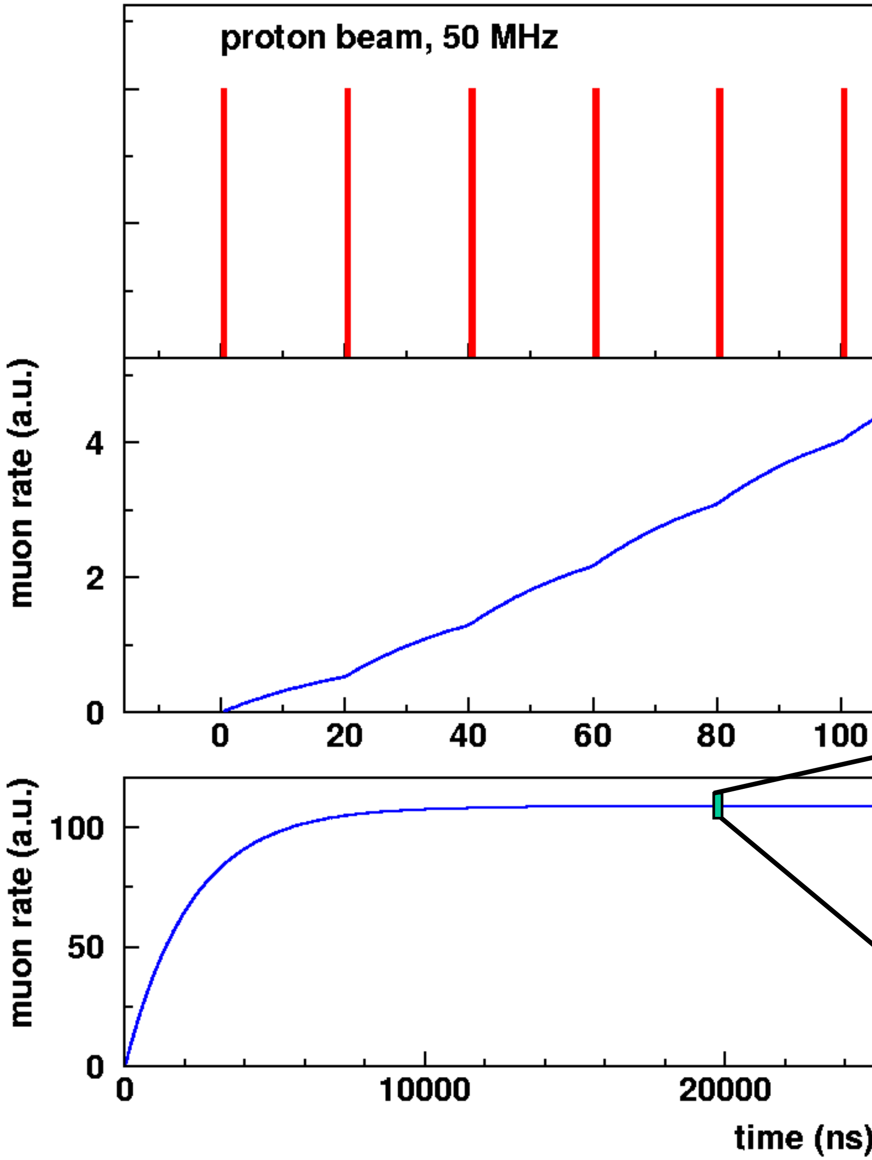


Larmor frequency of protons: $q/(2\pi m)$ = 15.25 MHz/T
$\boldsymbol{\nu_0 = q/(2\pi\gamma m)\cdot B,\ \gamma = E_{tot}/mc^2}$
$\boldsymbol{\nu_{rf} = n\cdot\nu_0}$, frequency of accelerating radio-frequency

Isochronous cyclotron: $\mathbf{B_0(R) \sim \gamma(R)}$, constant ν_{rf}!
PSI cyclotron: $\mathbf{B_0}$ = 0.554 T, $\boldsymbol{\nu_0}$ = 8.45 MHz, **n** = 6,
→ ν_{rf} = 50.7 MHz



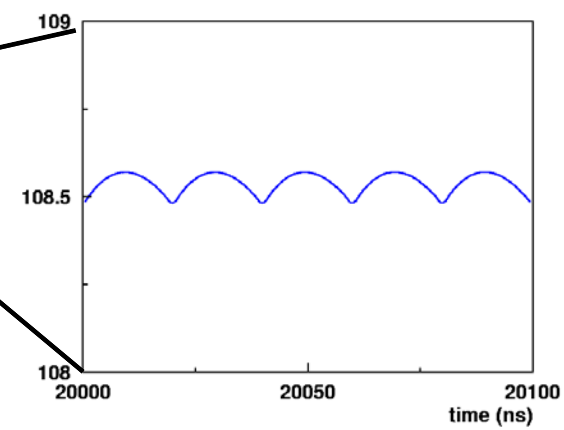
PSI muon beam time structure



Pion decay time of 26 ns is "smearing" the proton beam structure in the muon beam. This results in a "continuous" muon beam.

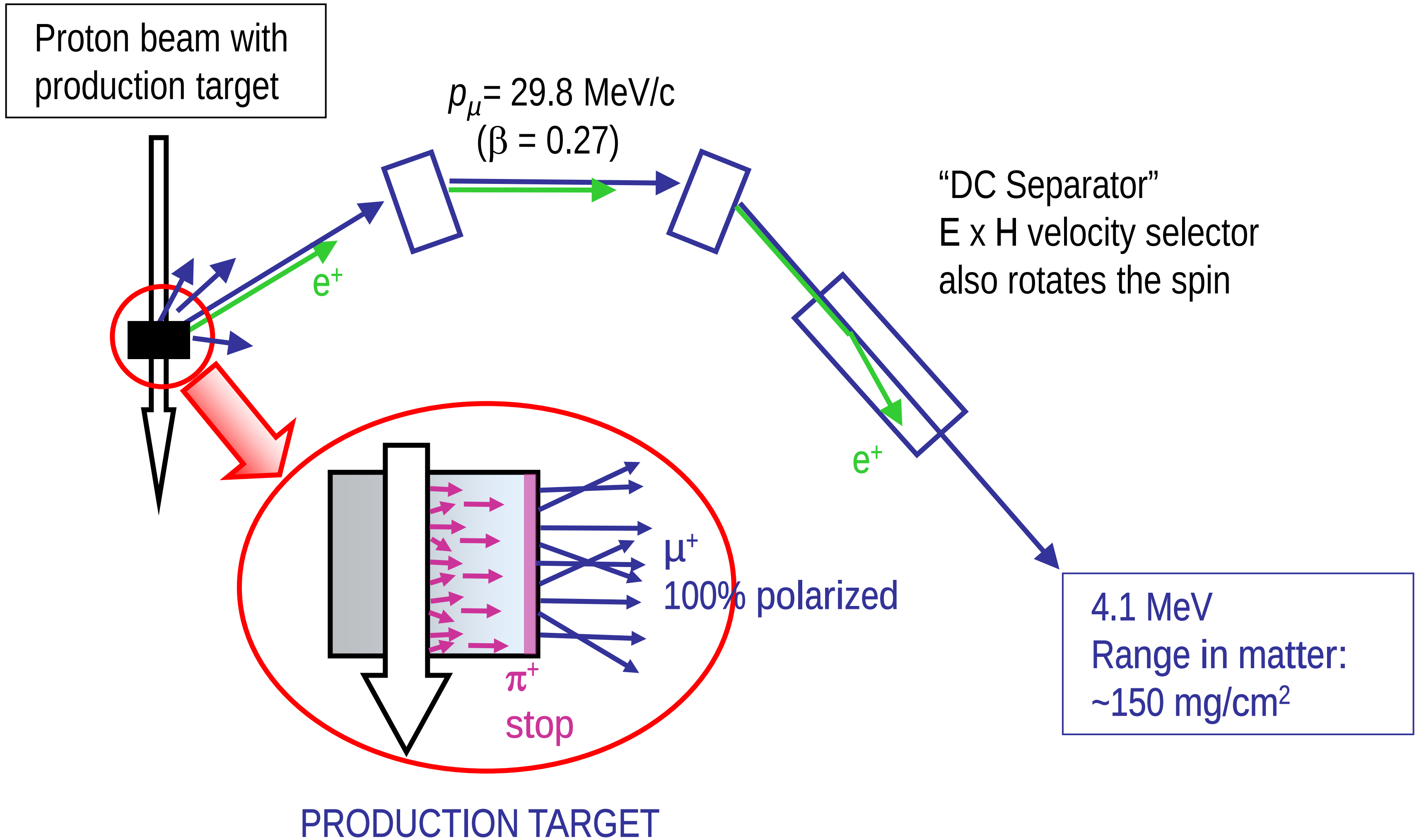
A μ^+ rate R of 10^5/s means: average time between two μ^+ is $1/R$ = 10 μs. Probability p to have ***the next*** μ^+ at time t:
$p = 1 - \exp(-Rt)$ ("pile-up", follows from Poisson statistics)

Single μ^+ can be detected with very good time resolution (< 0.1 ns), compared to a bunch width of 50-100 ns at pulsed beams. →measurement of GHz frequencies and fast relaxation rates (>100 μs^{-1}) possible. But "accidental" background in μ-decay histograms (can be reduced by muons-on-request).



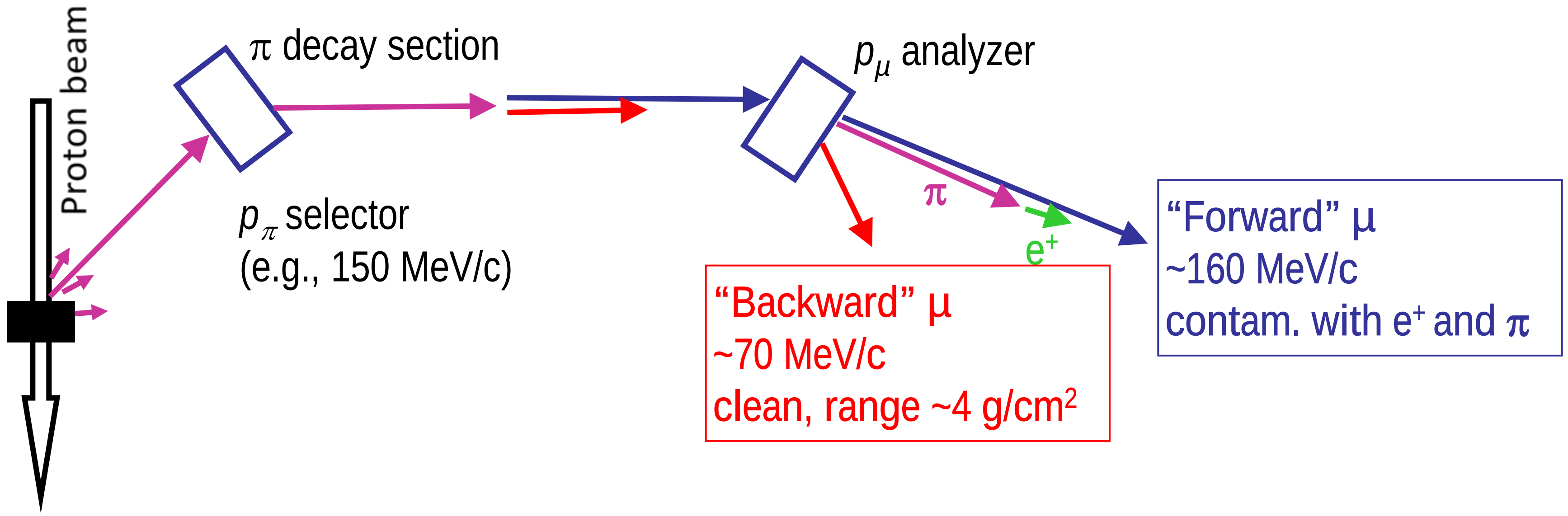
Generation of muon beams

“Arizona” or “Surface Muon Beam” (only μ^+), ~100% polarization



Generation of muon beams

(Traditional) "Decay Muon Beam" (μ^+ or μ^-), ~80% polarization



to select beam momentum *p*: magnetic dipole magnets (bending magnets)

to focus beam: magnetic quadrupole dublets or triplets, solenoids (for «surface muons»)

to vary beam intensity, momentum width *Δp/p*: slits

to remove positrons from beam, to rotate muon spin (for «surface muons» only):
ExB velocity filter (separator, spin-rotator)

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How to generate a low-energy μ^+ beam with tunable energies between 1 and 30 keV?

Muons are born energetically in pion decay (~4 MeV)

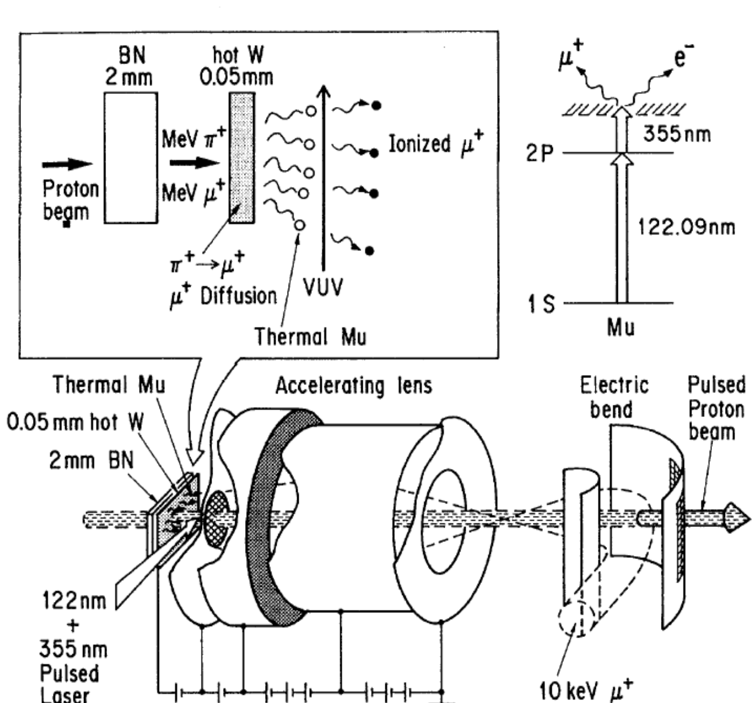
Need a special moderation technique to slow down energetic muons from the MeV to keV energies

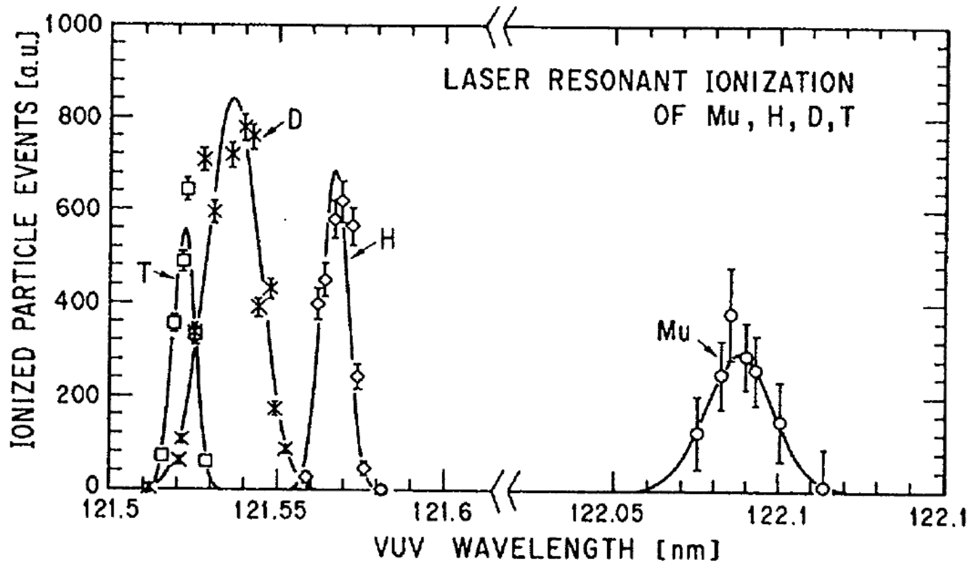
Generation of thermal μ^+ at a pulsed accelerator

VOLUME 74, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 1995

Ultraslow Positive-Muon Generation by Laser Ionization of Thermal Muonium from Hot Tungsten at Primary Proton Beam

K. Nagamine,[1,2] Y. Miyake,[1] K. Shimomura,[1] P. Birrer,[1] J. P. Marangos,[1,3] M. Iwasaki,[1] P. Strasser,[2,4] and T. Kuga[5]





P. Bakule,Y.Matsuda,Y.Miyake, K. Nagamine, M. Iwasaki, Y. Ikedo, K. Shimomura, P. Strasser, S. Makimura, Nucl. Instr Meth. B **266**, 335 (2008).

Pulsed LE-μ^+ beam (25Hz) @ ISIS/RIKEN-RAL and J-PARC:

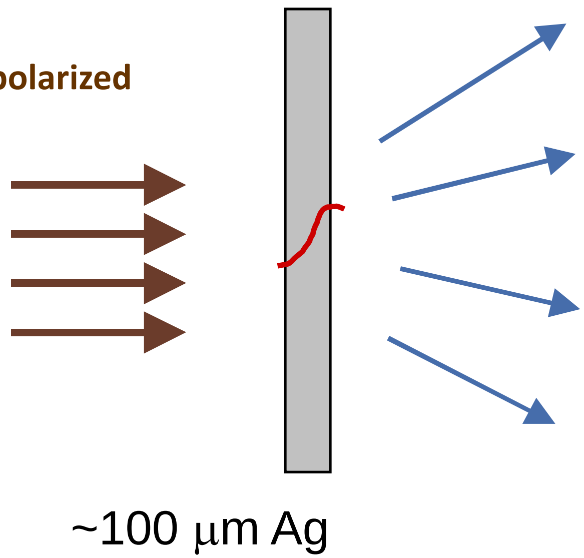
Intensity: ~15 LE-μ^+/sec (>10^3/s at J-PARC expected)
Polarization: ~ 50% (1/2 of polarization lost in muonium)

Generation of polarized epithermal (~eV) μ^+

„Surface“ Muons

~ 4 MeV

~ 100% polarized

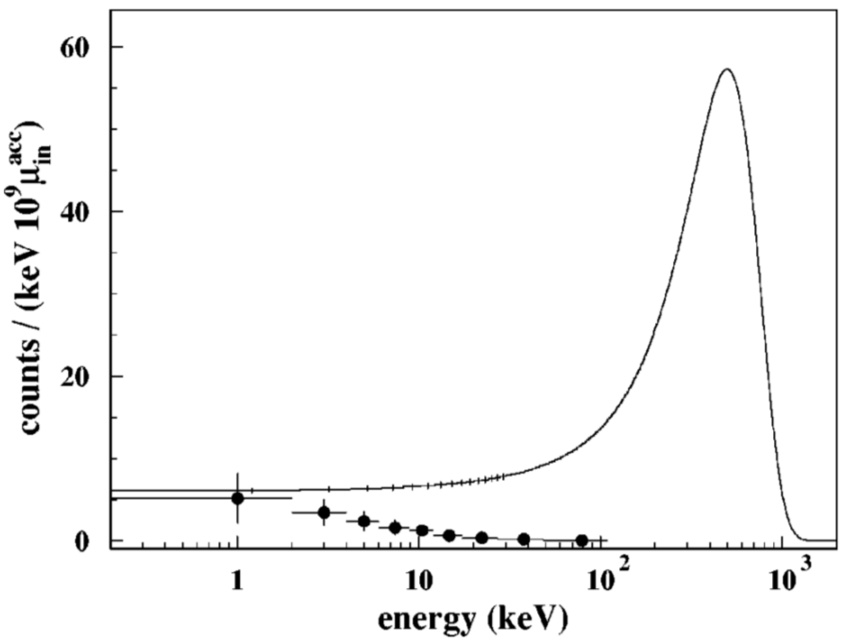


Using a proper moderator:

motivated by experiments for positron moderation, a solid film of a rare-gas should work!

Energy spectrum after a degrader

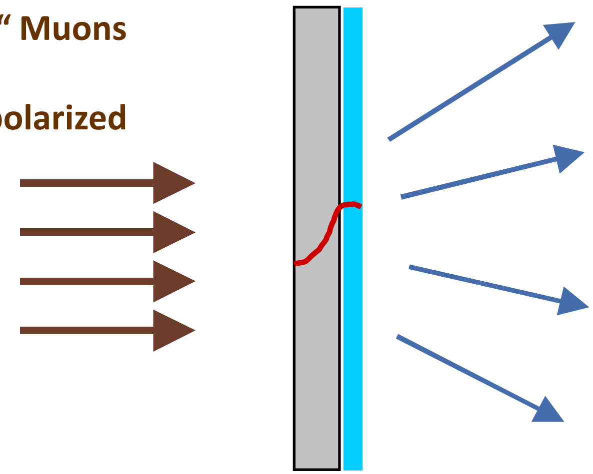
Solid line: muon energy spectrum



T. Prokscha et al., Phys. Rev. **A58**, 3739 (1998).

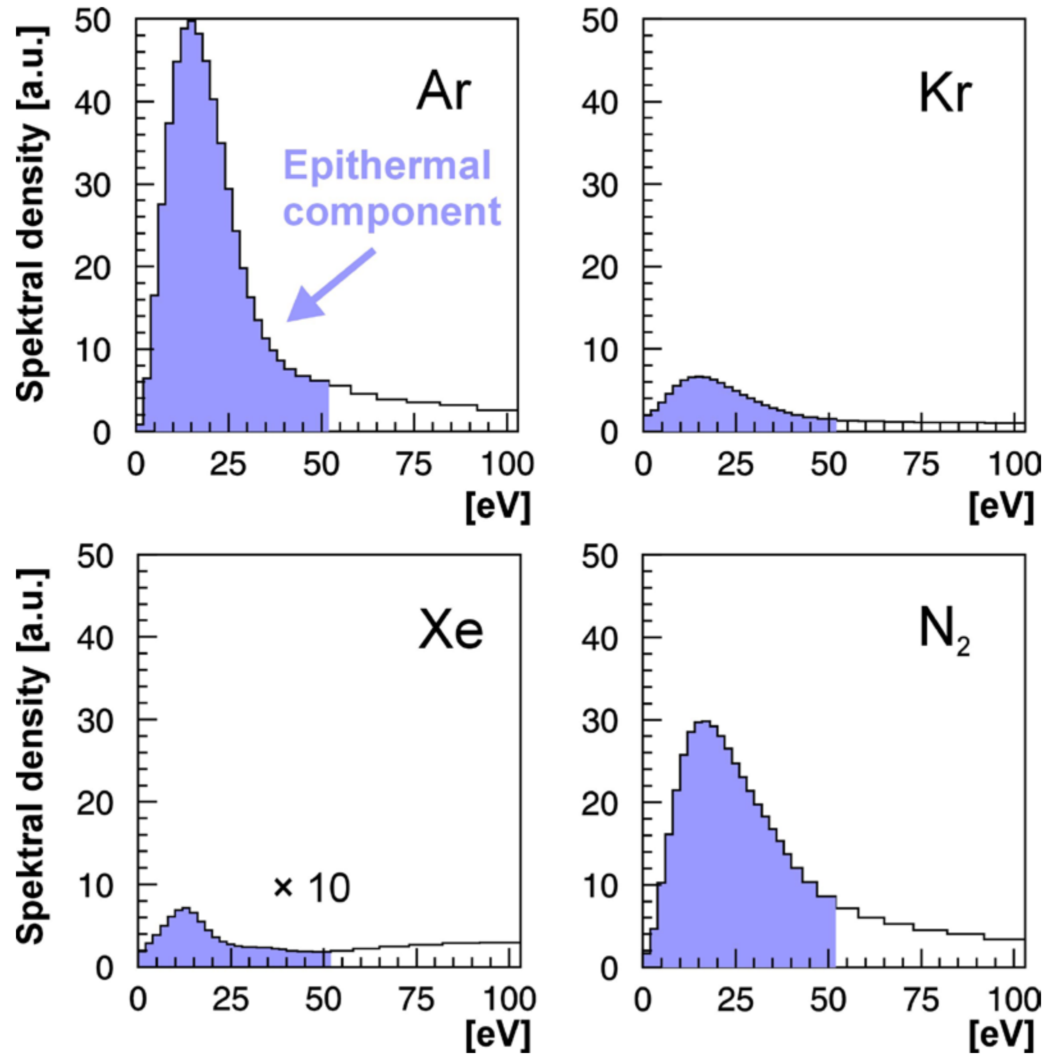
Generation of polarized epithermal (~eV) μ^+

„Surface“ Muons
~ 4 MeV
~ 100% polarized



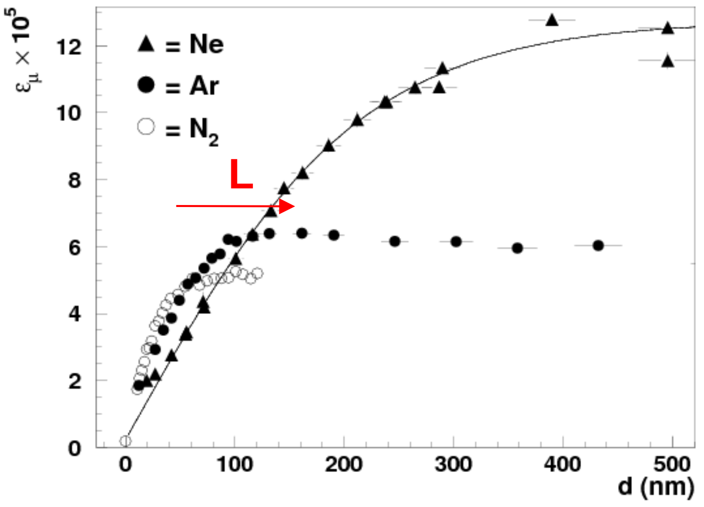
~100 μm Ag
6 K

~500 nm
s-Ne, Ar,
s-N_2

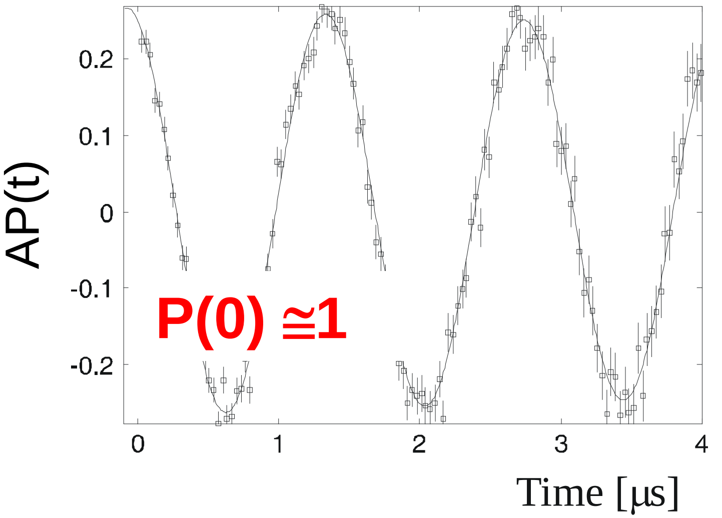


T. Prokscha et al., Appl. Surf. Sci. **172**, 235 (2001).
T. Prokscha et al., Phys. Rev. **A58**, 3739 (1998).
E. Morenzoni et al., J. Appl. Phys. **81**, 3340 (1997).
D. Harshmann et al., Phys. Rev. **B36**, 8850 (1987).

Characteristics of epithermal (~eV) μ^+



E. Morenzoni, T. Prokscha, A. Suter, H. Luetkens, R. Khasanov, J.Phys.: Cond. Matt. **16**, S4583 (2004).



E. Morenzoni, F. Kottmann, D. Maden, B. Matthias, M. Meyberg, T. Prokscha, T. Wutzke, U. Zimmermann, PRL **72**, 2793 (1994).

→ suppression of electronic energy loss for $E > E_g$, large band gap E_g (10-20 eV) „soft, perfect“ insulators

→ large escape depth L (10-100 nm), no loss of polarization during moderation (~10 ps)

→ **moderation efficiency is low (requires highest intensities μ^+ beams, > 10^8 μ^+/s, i.e. MW proton beam):**

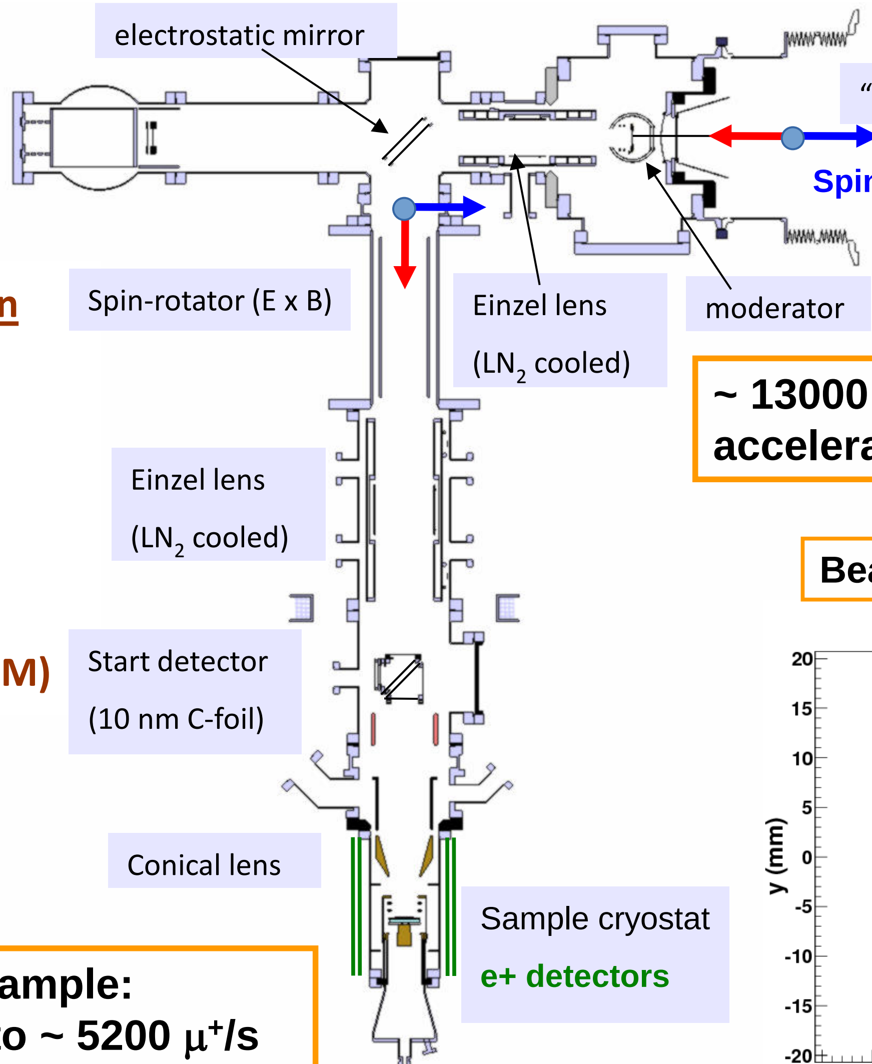
$$\varepsilon_{\mu+} = N_{epith}/N_{4MeV} \approx \Delta\Omega\,(1-F_{Mu})\,L/\Delta R \approx 0.25\,L/\Delta R \approx 10^{-4} - 10^{-5}$$

$\Delta\Omega$: probability to escape into vacuum (~50% for isotropic angular distribution)
F_{Mu}: muonium formation probability

Low-energy (keV) μ⁺ facility at PSI

Rates are for 6-cm target E and 1.8 mA proton current (2017)

- UHV system, 10^{-10} mbar
- some parts LN_2 cooled



~2.2 • 10^8 μ^+/s

~ 13000 LE-μ^+/s; accelerate up to 20 keV

at sample: up to ~ 5200 μ^+/s

Polarized Low Energy Muon Beam

Energy: 1-30 keV

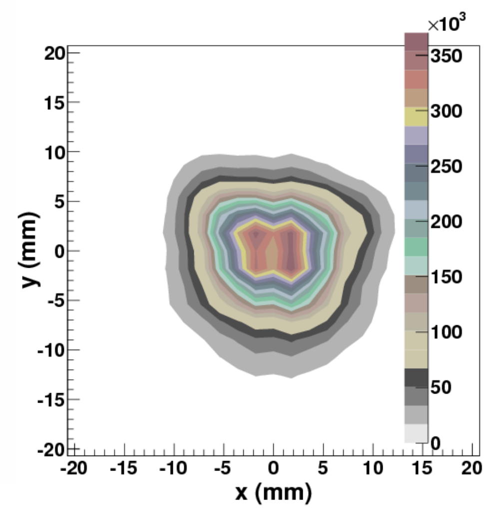
ΔE, Δt: 400 eV, 5 ns

Depth: 1 – 300 nm

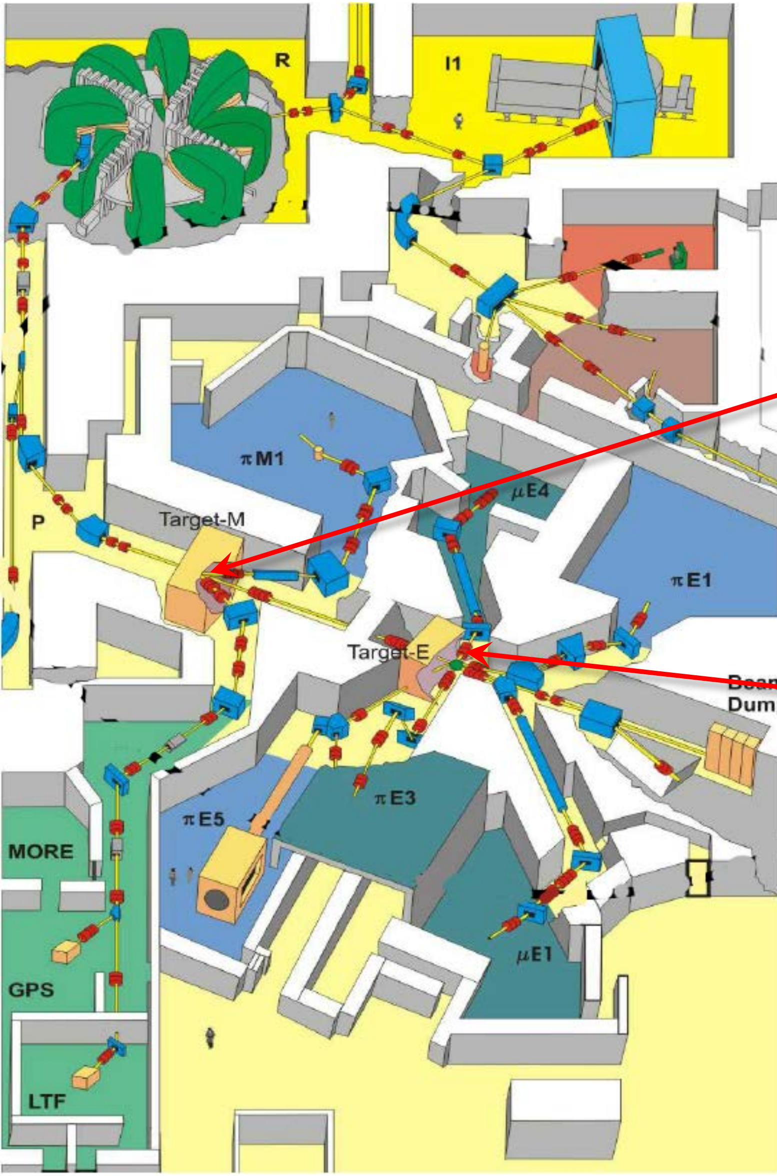
Polarization ~100 %

Beam Spot: 12 mm (FWHM)

Beam spot at sample

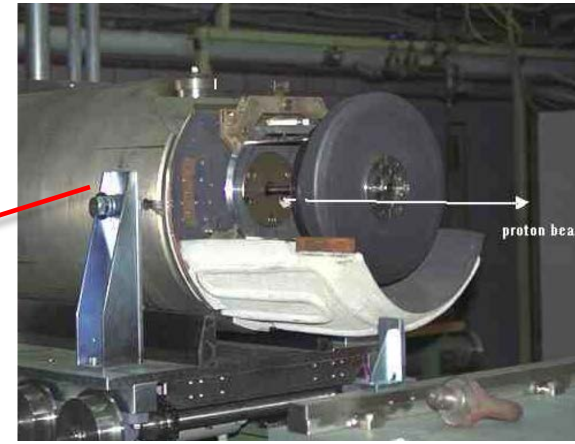


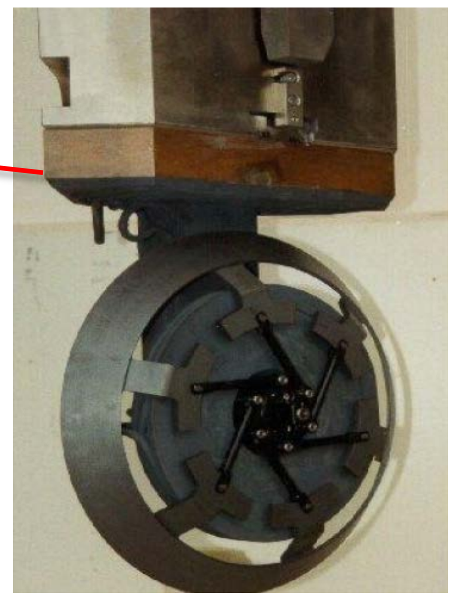
The PSI Experimental Hall



Target M

Thin graphite (5 mm)



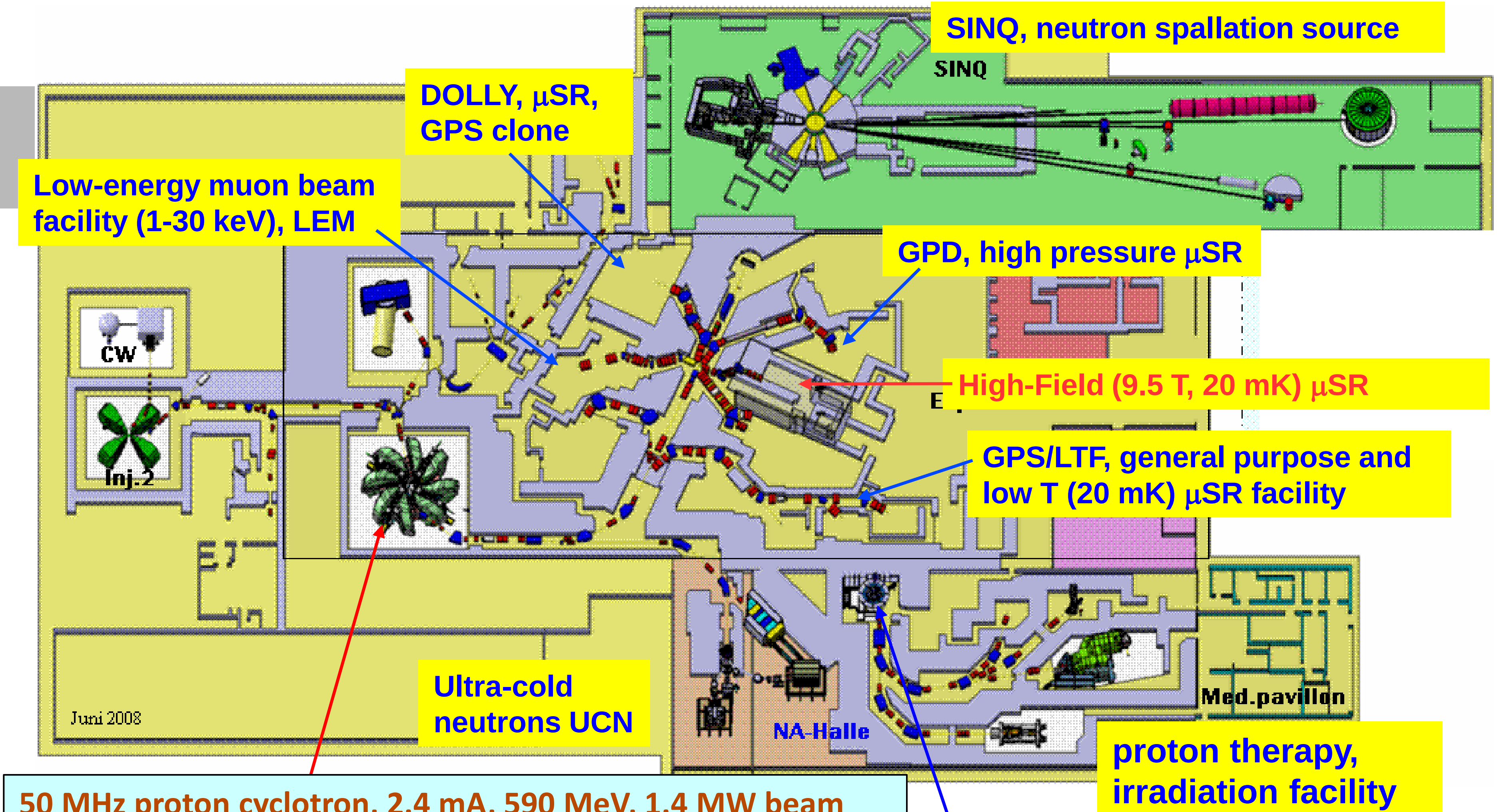


Target E

4 or 6 cm graphite

“necessary component to expand proton beam before SINQ”

The proton accelerators, muon and neutron beams



50 MHz proton cyclotron, 2.4 mA, 590 MeV, 1.4 MW beam power (2.6 mA, 1.5 MW test operation);

most powerful cyclotron worldwide and most intense muon beams (quasi-continuous)

Comet cyclotron (superconducting) 250 MeV, 500 nA, 72.8 MHz

Application of cosmic muons:

Radiography of large objects

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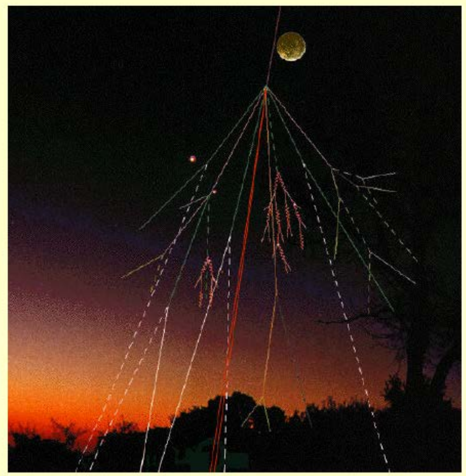
Radiography with cosmic muons

Cosmic muons (GeV energy) imaging: objects of dimension meters
very low intensity: 1 Muon / minute / cm^2

Cosmic Rays

- Very high energy "primary" cosmic rays - typically protons - interact in upper atmosphere
- Shower of unstable sub-nuclear particles created: typically pions, kaons
- Muons and neutrinos are decay products of pions and kaons

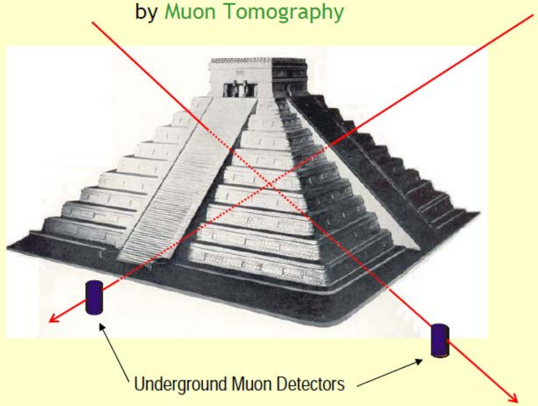


Imaging Maya Pyramids with Cosmic Ray Muons

An Application of the Tools of High Energy Physics

What is the internal structure?

Measure Spatial Distribution of Material *Inside*
by Muon Tomography



First attempts with pyramids in the 1960's by Luis Alavarez in the Pyramid of Chephren, Giza.

Radiography with cosmic muons

Cosmic-ray muon imaging of magma in a volcano (Satsuma-Iojima, Japan):

H.K.M. Tanaka et al., Geophysical Research Letters **36**, L01304, 2009.

L01304 TANAKA ET AL.: COSMIC-RAY MUON IMAGING OF MAGMA L01304

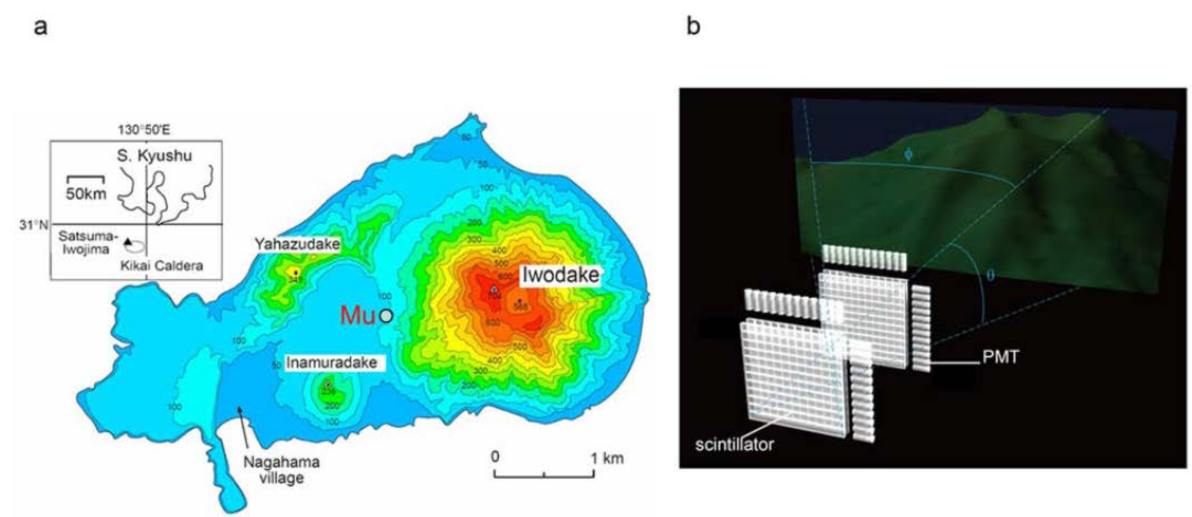
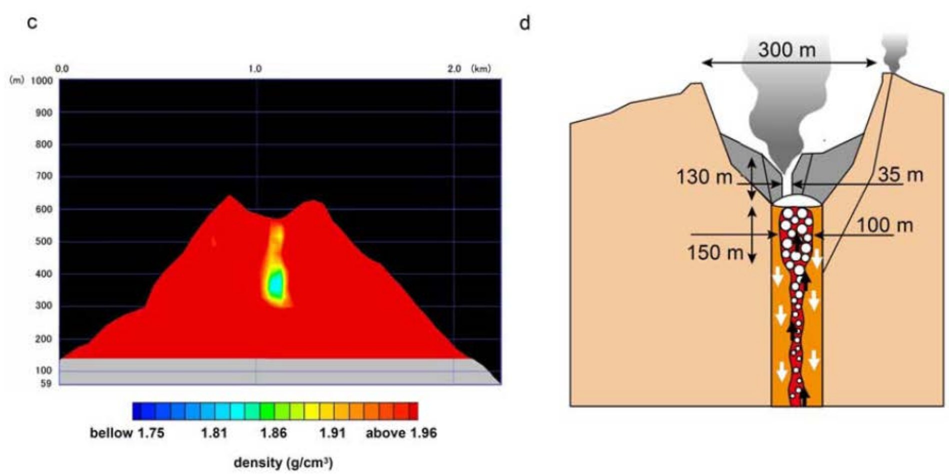


Figure 1. (a) Map of Satsuma-Iojima volcano showing the location of the cosmic-ray muon detector (Mu). (b) Portable assembly type cosmic-ray muon telescope system. The detector matrix counts 12 × 12 square pixels of 8 cm.



Muon image of magma chamber and model of magma convection

very low intensity: 1 Muon / minute / cm^2

Homeland security with cosmic muons

Aim: detection of hidden special nuclear material (high-Z material)

C.L. Morris et al, Science and Global Security 16, 37-53 (2008)

Example: muon image of a car engine, and a car engine with a 10x10x10 cm^3 lead cube

42 *Morris et al.*

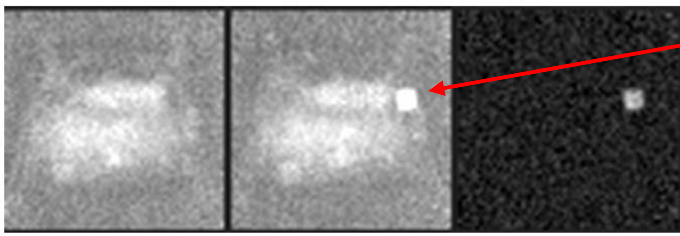


Figure 3: Mean scattering angle for a slice through the scene 50 cm above the base plate. The left panel shows the engine, the middle panel the engine plus the 10 × 10 × 10 cm^3 lead sample, and the right panel the difference.

Suggestion for a counting station for muon radiography and simultaneous neutron and γ counting to detect fissile nuclear material

Decision Sciences International Corp. is offering such muon tomography systems

Tomographic Imaging with Cosmic Ray Muons 51

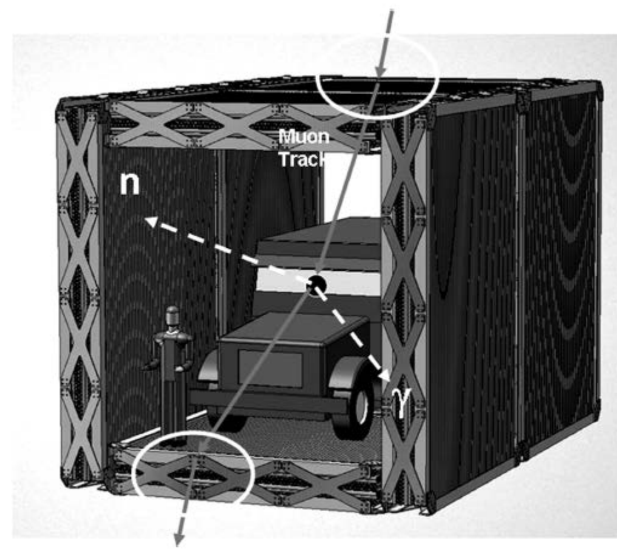


Figure 13: A schematic view of how a counting station might look. Vehicles would be stopped within the area covered by the counting station for a counting period ~20 s.

Imaging the core of Fukushima reactors

PRL **109**, 152501 (2012) PHYSICAL REVIEW LETTERS week ending 12 OCTOBER 2012

Cosmic Ray Radiography of the Damaged Cores of the Fukushima Reactors

Konstantin Borozdin,[1] Steven Greene,[1] Zarija Lukić,[2] Edward Milner,[1] Haruo Miyadera,[1]
Christopher Morris,[1,*] and John Perry[1]
[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*
[2]*Computational Cosmology Center, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 9 August 2012; published 11 October 2012)

7x7 m^2 drift tube detectors

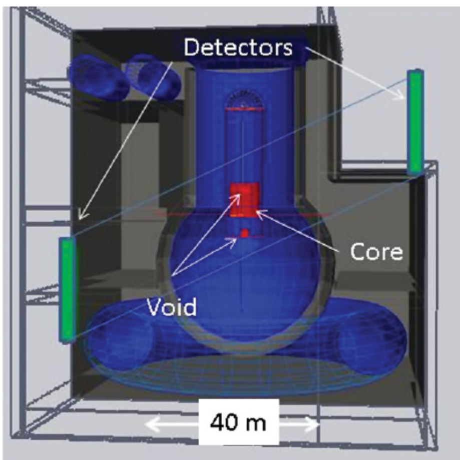


FIG. 1 (color). Cutaway view of a boiling water reactor and a schematic of the detector placement for the Monte Carlo calculation. In the case of attenuation radiography, only trajectory information from the lower detector was used. The location of the 1 m diameter void in the core and its placement in the bottom of the pressure vessel are indicated by arrows.

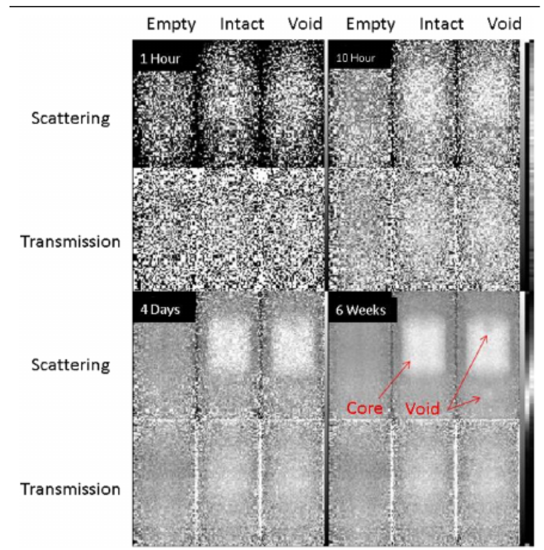


FIG. 3 (color online). Reactor reconstructions at different exposure times. In scattering radiography, the reactor core can be detected after about 10 hours of exposure. After four days, a 1 m diameter (1%) void can be detected when compared to an intact core. After 6 weeks, the void is clear and the missing material can be observed. With the attenuation method, the core can be observed when compared to an empty scene in four days. The void is undetectable even after 6 weeks of exposure.

Transmission tomography scan of unit 1 indicates complete reactor meltdown (March 2015)
https://www.extremetech.com

Installed at Fukushima Daiichi reactor unit 2 end of 2015
http://www.lanl.gov/org/padste/adeps/physics/_assets/docs/muon-tomography.pdf

Imaging the core of Fukus

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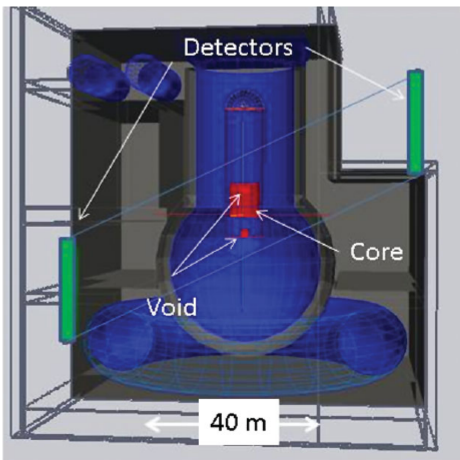

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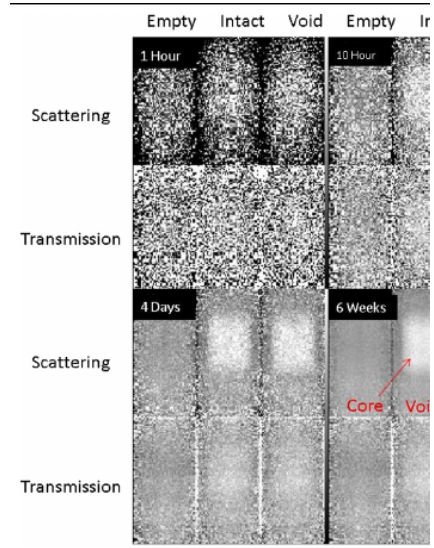

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scattering. The many small interactions add up to yield an angular deviation that roughly follows a gaussian distribution,

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

with the width, θ_0, related to the scattering material through its radiation length, L_0, as follows:

$$\theta_0 = \frac{13.6}{\beta c p}\sqrt{\frac{L}{L_0}}\left[1 + 0.038\ln(L/L_0)\right]$$

where p is the particle's momentum in MeV c^{-1} and βc is its velocity[2]. The radiation length decreases rapidly as the atomic number of a material increases, and θ_0 increases accordingly: in a layer 10 cm thick, a 3-GeV muon will scatter with an angle of 2.3 milliradians in water, 11 milliradians in iron and 20 milliradians in lead. By tracking the scattering angles of individual particles, the scattering material can be mapped.

K. Borozdin et al, Nature 422, 277 (2003)

Installed at Fukushima Daiichi reactor unit 2 end of 2015

http://www.lanl.gov/org/padste/adeps/physics/_assets/docs/muon-tomography.pdf

Next:

Introduction to Muon Spin Rotation and Relaxation (μSR):

Instrumentation and Technique