History of μSR

Keeping the Promise of Particle Physics

A science fiction adventure story

by

Jess H. Brewer

PHYSICS & ASTRONOMY

Early History of μSR:

Fantasy ➜ Fiction ➜ Physics

- **Fantasy**: violates the "known laws of physics"
- **Science Fiction**: possible in principle, but impractical with existing technology. (**Clarke's Law**: *"Any sufficiently advanced technology is indistinguishable from magic."*)
- **Routine Physics**: "We can do that . . ."
- **Applied Science**: " . . . and so can you!"

Cast of Characters

in approximate order of appearance

Fantasy Era

Yukawa; Anderson; Rasetti

Science Fiction Era

Theory: Lee & Yang
Exp't: Wu; Friedman & Telegdi;
Garwin, *Lederman* & Weinrich

Frontier Era

USSR: Firsov; Nosov & Yakovleva
Ivanter & Smilga; *Gurevich*
QED: Hughes; Telegdi; *Crowe*
$\mu^+e^-\rightarrow\mu^-e^+$: Bowen & Pifer

Golden Era

SIN→PSI: *Schenck*, Kündig, *Patterson*,
Fischer, Kalvius, *Kiefl ...*
LAMPF: Hughes, *Heffner*, MacLaughlin
TRIUMF: Warren, *Fleming*, Brewer, *Crowe*,
Walker, Vogt, *Uemura*, Williams ...
KEK/BOOM: Kubo, *Yamazaki*, *Nagamine ...*
RAL/ISIS: Stoneham, *Cox* ...

Modern Era at TRIUMF

Percival, Kreitzman, Kiefl, Luke, Sonier, MacFarlane, Uemura, Storchak, Sugiyama, *<u>hundreds</u> of **Users**, <u>dozens</u> of **PDFs** and **Students**, **Visitors**, . . .*

Before 1956: ***Fantasy***

- ## 1930s: **Mistaken Identity**

  Yukawa's "nuclear glue" mesons ≠ cosmic rays
  1937 Rabi: Nuclear Magnetic Resonance

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  1940 Phys. Rev. Analytical Subject Index: "mesotron"
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Problem:
What's the mean field inside a ferromagnet, ***B*** or ***H*** ?

Solution:
Deflection of cosmic ray "mesons" (*muons*)

THE

PHYSICAL REVIEW

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

SECOND SERIES, VOL. 66, NOS. 1 AND 2 — JULY 1 AND 15, 1944

Deflection of Mesons in Magnetized Iron

F. RASETTI
Laval University, Quebec, Canada
(Received May 8, 1944)

The deflection of mesons in a magnetized ferromagnetic medium was investigated. A beam of mesons was made to pass through 9 cm of iron, and the resulting distribution of the beam was observed. Two arrangements were employed. In the first arrangement, the deflection due to the field caused a fraction of the mesons to hit a counter placed out of line with the others. An increase of sixty percent in the number of coincidences was recorded when the iron was magnetized. In the second arrangement, all the counters were arranged in line, and the deflection due to the field caused an eight percent decrease in the number of coincidences. These results are compared with theoretical predictions deduced from the known momentum spectrum of the mesons and from the geometry of the arrangement. The observed effects agree as well as can be expected with those calculated under the assumptions that the effective vector inside the ferromagnetic medium is the induction B, and that the number of low energy mesons is correctly given by the range-momentum relation.

***First** application of muons to condensed matter physics.*

Monday, August 8, 2011

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PHYSICAL REVIEW VOLUME 70, NUMBERS 7 AND 8 OCTOBER 1 AND 15, 1946

Nuclear Induction

F. Bloch
Stanford University, California
(Received July 19, 1946)

The magnetic moments of nuclei in normal matter will result in a nuclear paramagnetic polarization upon establishment of equilibrium in a constant magnetic field. It is shown that a radiofrequency field at right angles to the constant field causes a forced precession of the total polarization around the constant field with decreasing latitude as the Larmor frequency approaches adiabatically the frequency of the r-f field. Thus there results a component of the nuclear polarization at right angles to both the constant and the r-f field and it is shown that under normal laboratory conditions this component can induce observable voltages. In Section 3 we discuss this nuclear induction, considering the effect of external fields only, while in Section 4 those modifications are described which originate from internal fields and finite relaxation times.

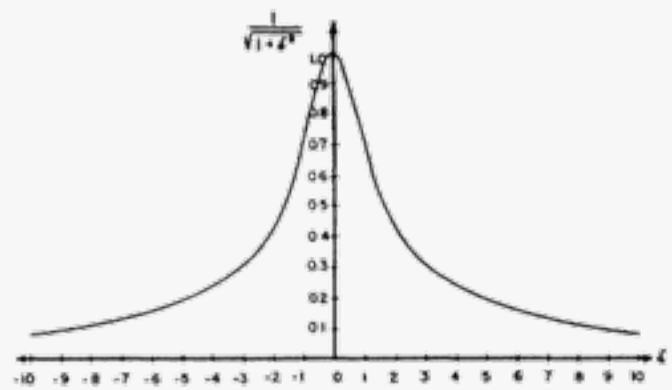

Fig. 1. Schematic representation of the voltage amplitude in the case of rapid passage. The abscissa δ is the deviation of the actual field from the resonance field in units of the half-amplitude of the oscillating field. The ordinate is proportional to the amplitude of the induced voltage and the y-component of the nuclear polarization.

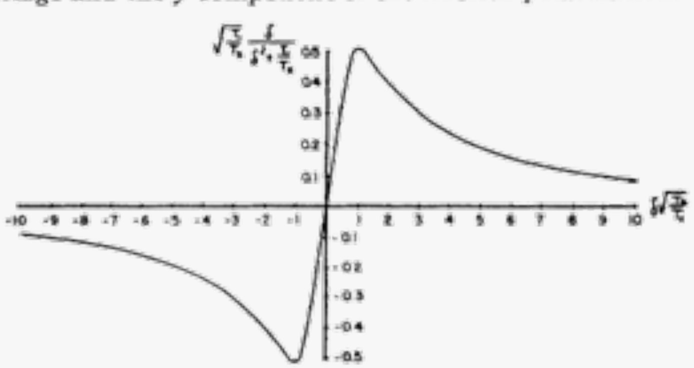

Fig. 2. Schematic representation of the voltage amplitude in the case of slow passage. T_1 and T_2 are the longitudinal and transversal relaxation times, respectively, and the scale is chosen such as to make the plot independent of their values. The significance of abscissa and ordinate is otherwise the same as in Fig. 1.

PHYSICAL REVIEW VOLUME 70, NUMBERS 7 AND 8 OCTOBER 1 AND 15, 1946

The Nuclear Induction Experiment

F. Bloch, W. W. Hansen, and M. Packard
Stanford University, California
(Received July 19, 1946)

The phenomenon of nuclear induction has been studied experimentally. The apparatus used is described, both as to principle and detail. Experiments have been carried out in which the signals from protons contained in a variety of substances were observed. The results show the role played by the relaxation time, which was found to vary between about 10^{-5} second and many seconds.

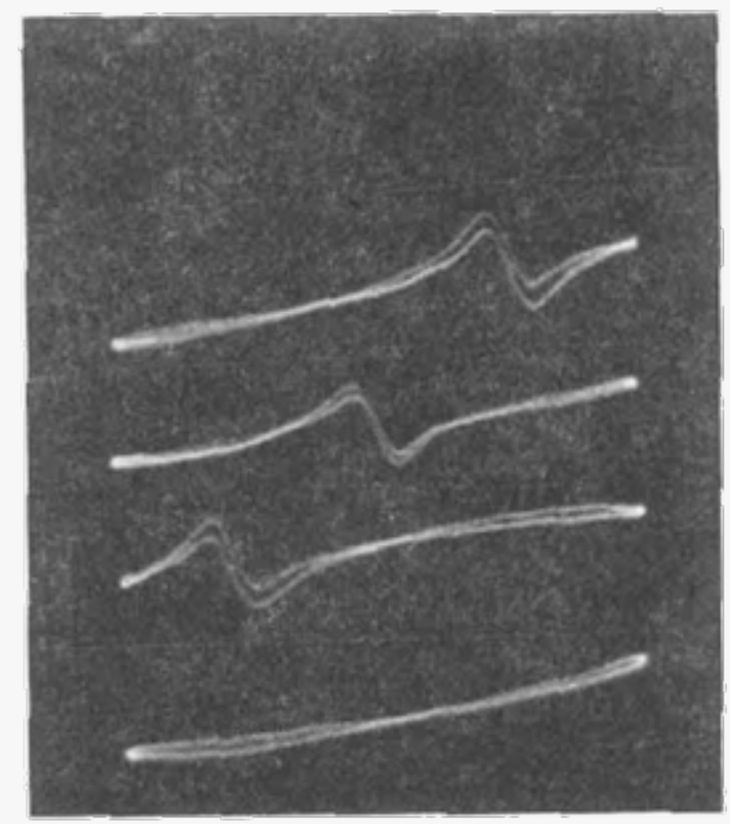

Fig. 12. Photographic record of the proton signal in a concentrated solution of $Fe(NO_3)_3$ in water. The four traces from top to bottom are in the text referred to as a, b, c, d.

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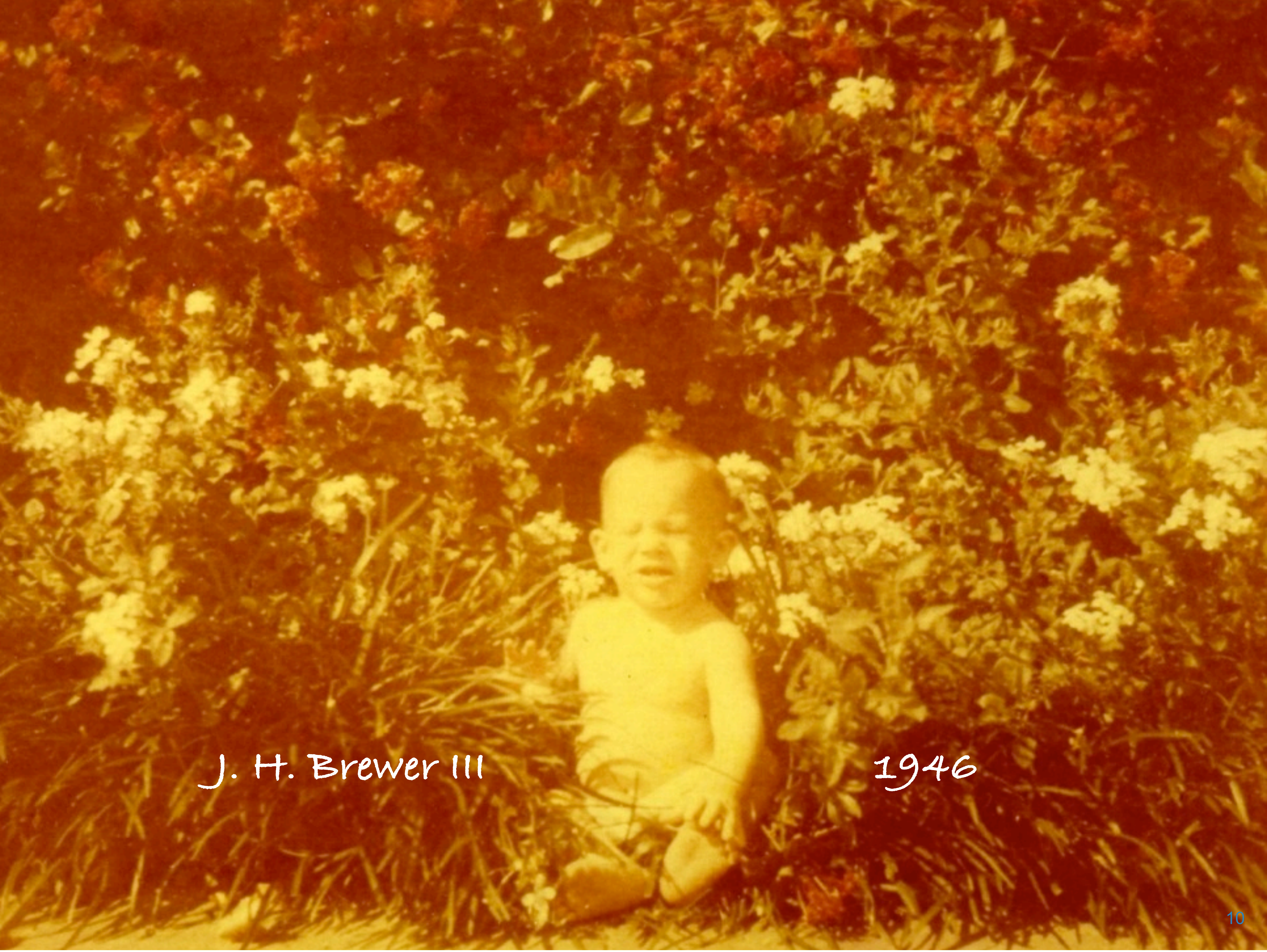
J. H. Brewer III
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“Two-Meson Hypothesis”

- First proposed in Japan in *1942-43* by *Tanikawa, Sakata* and *Inoue* (unbeknownst to Allied physicists, some of whom still give precedence to *Marshak*).

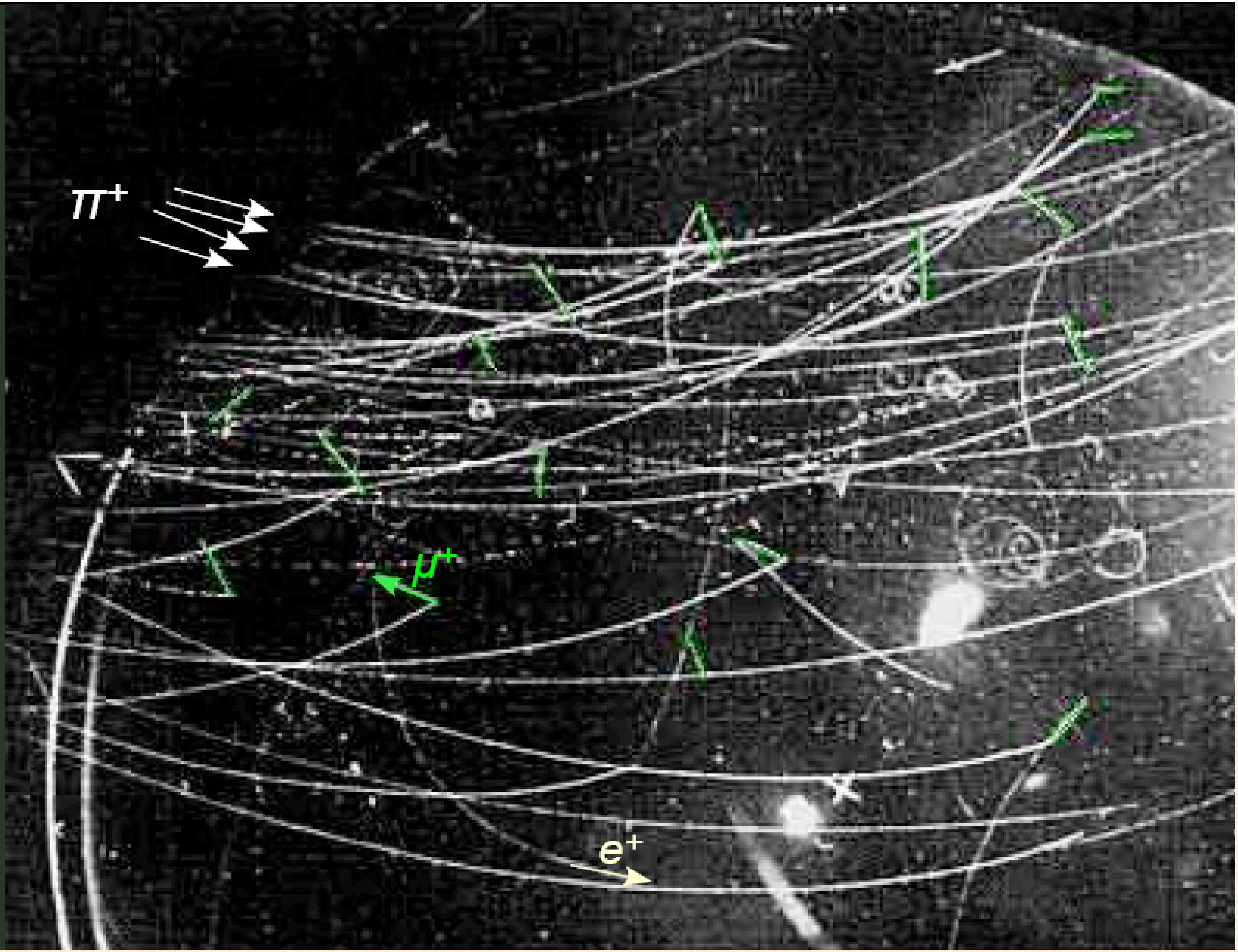
- Confirmed in *1947* by *Powell et al*., using photographic emulsions exposed to cosmic rays at high altitude.

- Produced artificially in *1947* by *Richardson et al*. at the Berkeley 184 in. Synchrocyclotron.

- Studied in bubble chambers at Nevis cyclotron. . .

TRIUMF

What do you see?



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1956-7: ***Revolution***

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  ***P*-violation** in weak interactions

- 1957: Wu confirms *P*-violation in β decay;
  Friedman & Telegdi confirm *P*-violation in π-μ-e decay;
  so do Garwin, Lederman & Weinrich, using a prototype ***μSR*** technique.

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

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

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

↓

Experimental Test of Parity Conservation in Beta Decay*

C. S. WU, *Columbia University, New York, New York*

AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPES, AND R. P. HUDSON,
National Bureau of Standards, Washington, D. C.
(Received January 15, 1957)

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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)

Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+ - \mu^+ - e^+$*†

Jerome I. Friedman and V. L. Telegdi

Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 17, 1957)

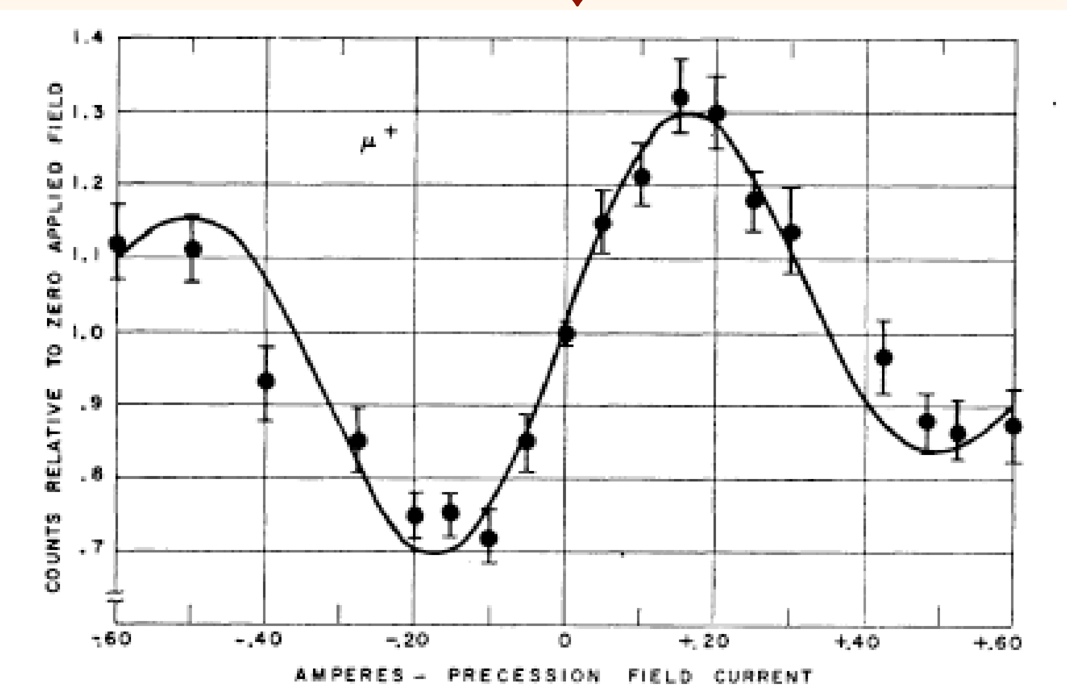


Fig. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

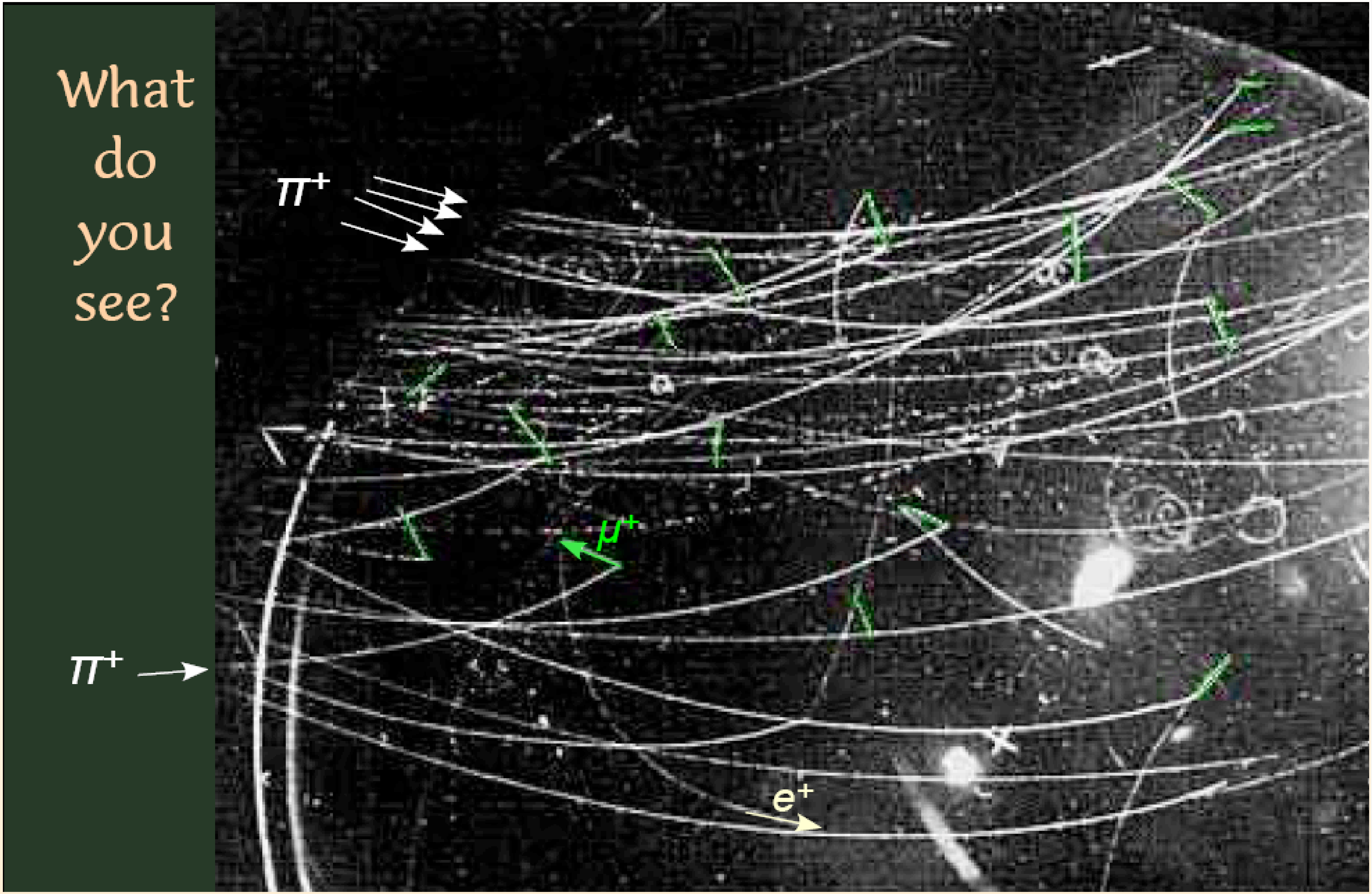
It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

(The Promise)

TRIUMF

So . . .

How does it work?


What do you see?
π^+
π^+
μ^+
e^+

Pion Decay: $\pi^+ \to \mu^+ + \nu_\mu$

A pion **stops** in the “skin” of the primary production target.
It has zero linear momentum and zero angular momentum.

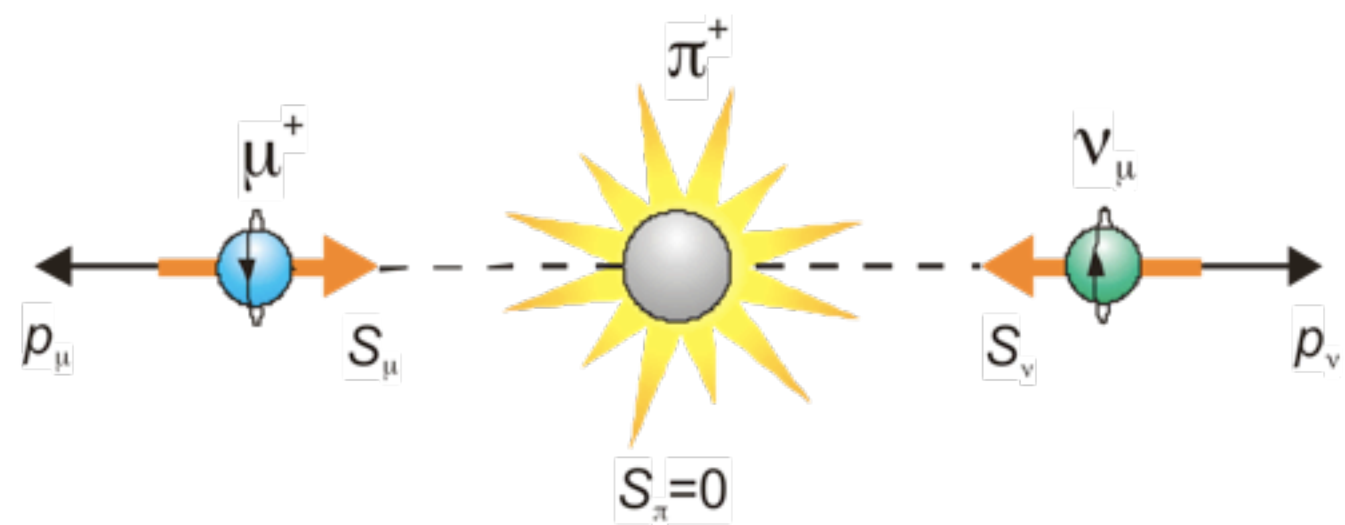
Conservation of Linear Momentum: The μ^+ is emitted with momentum equal and opposite to that of the ν_μ.

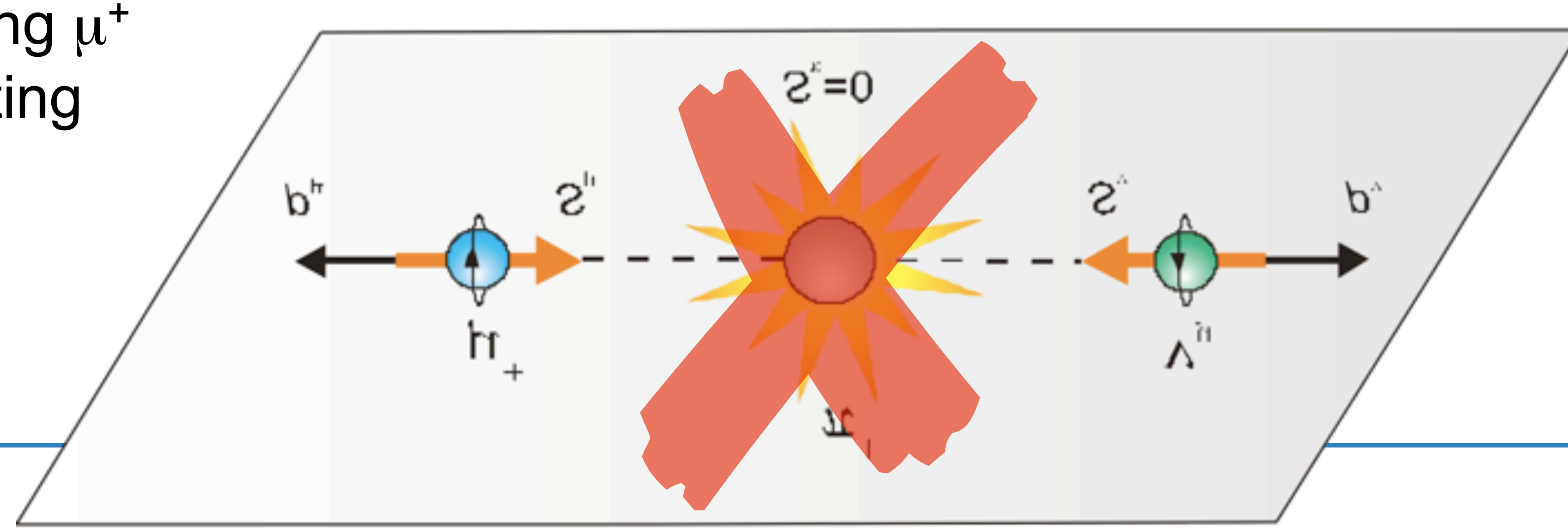
Conservation of Angular Momentum: μ^+ & ν_μ have equal & opposite spin.

Weak Interaction:

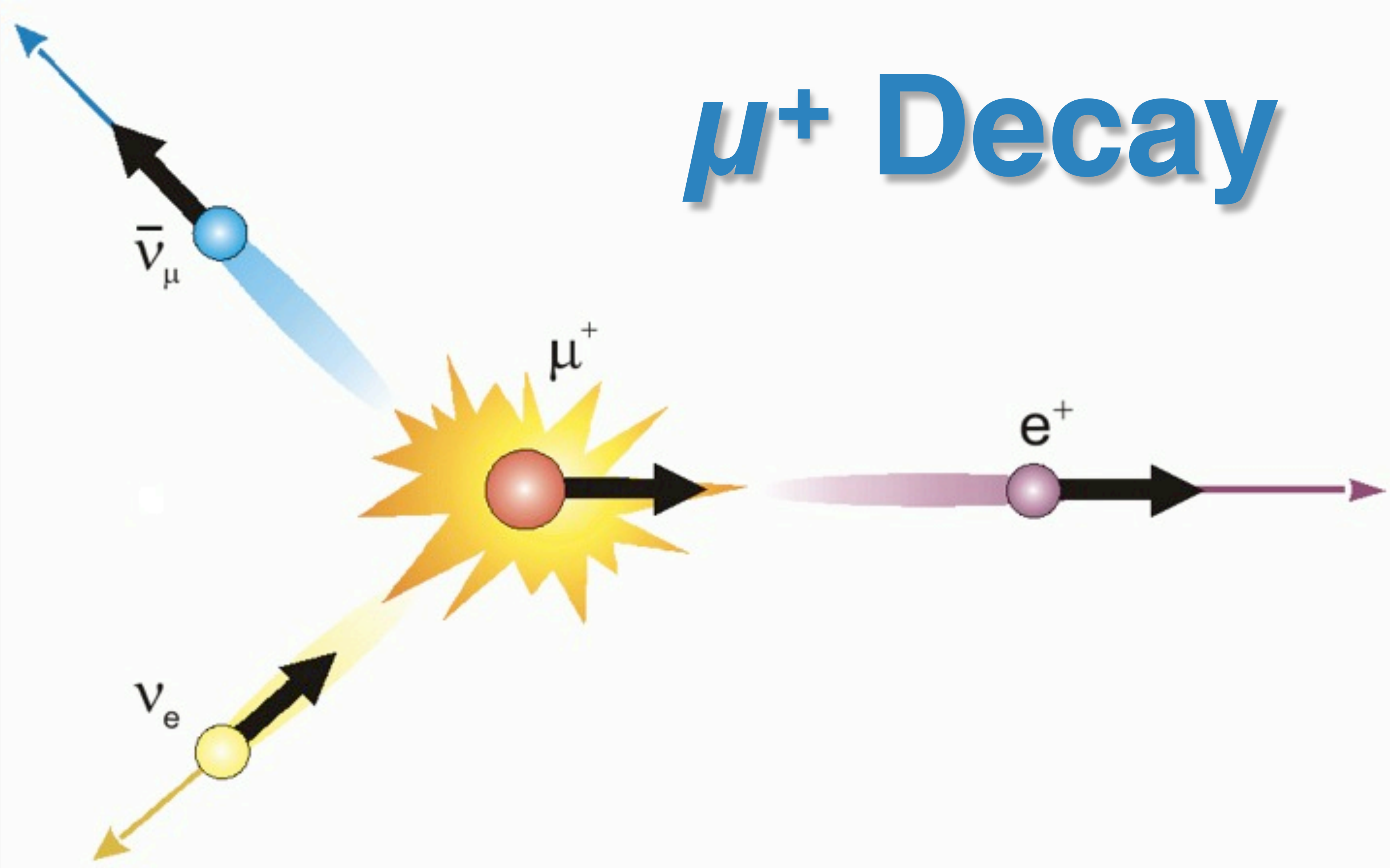
Only “left-handed” ν_μ are created.

Thus the emerging μ^+ has its spin pointing antiparallel to its momentum direction.





μ^+ Decay



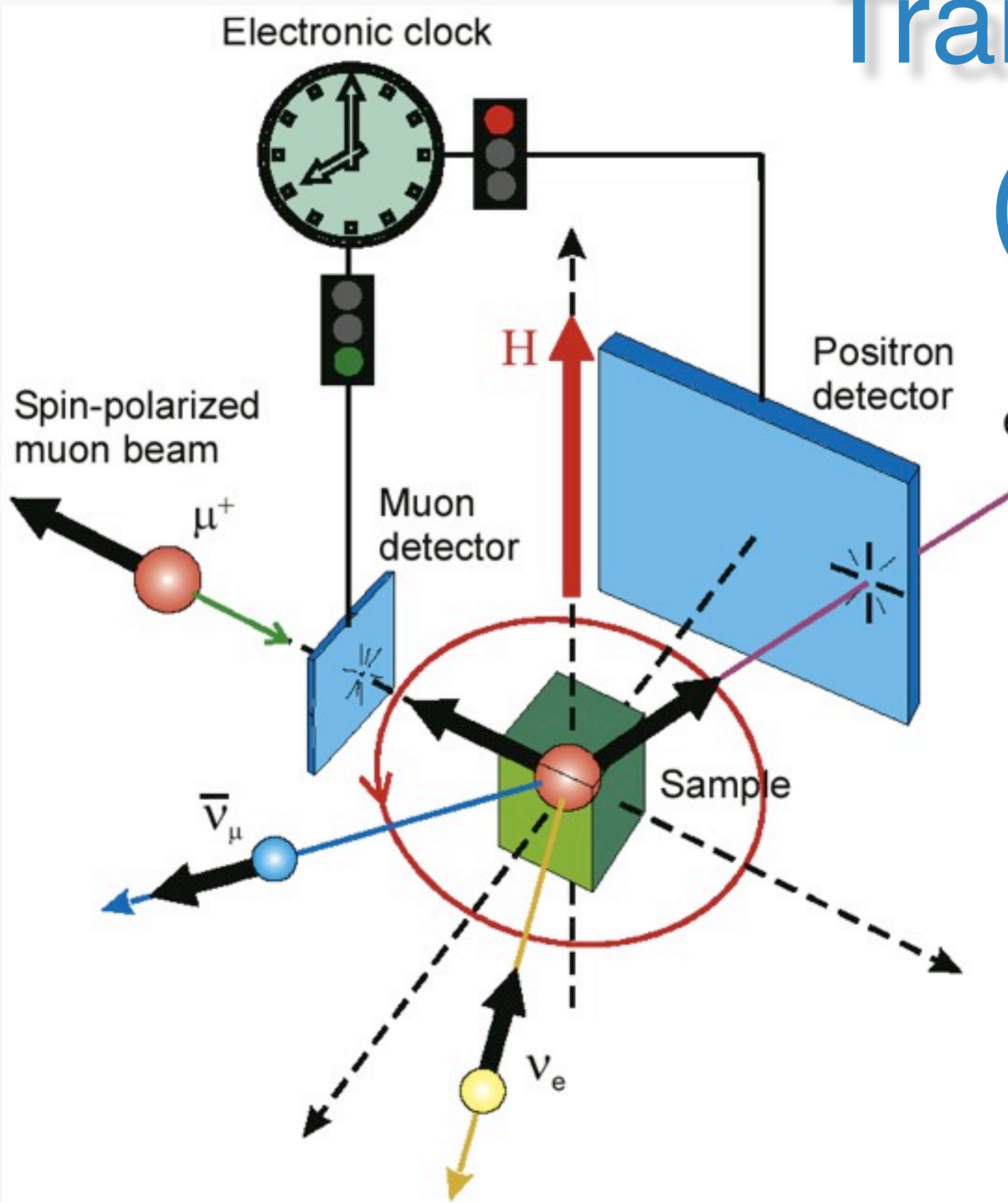
Neutrinos have *negative helicity*, antineutrinos positive.

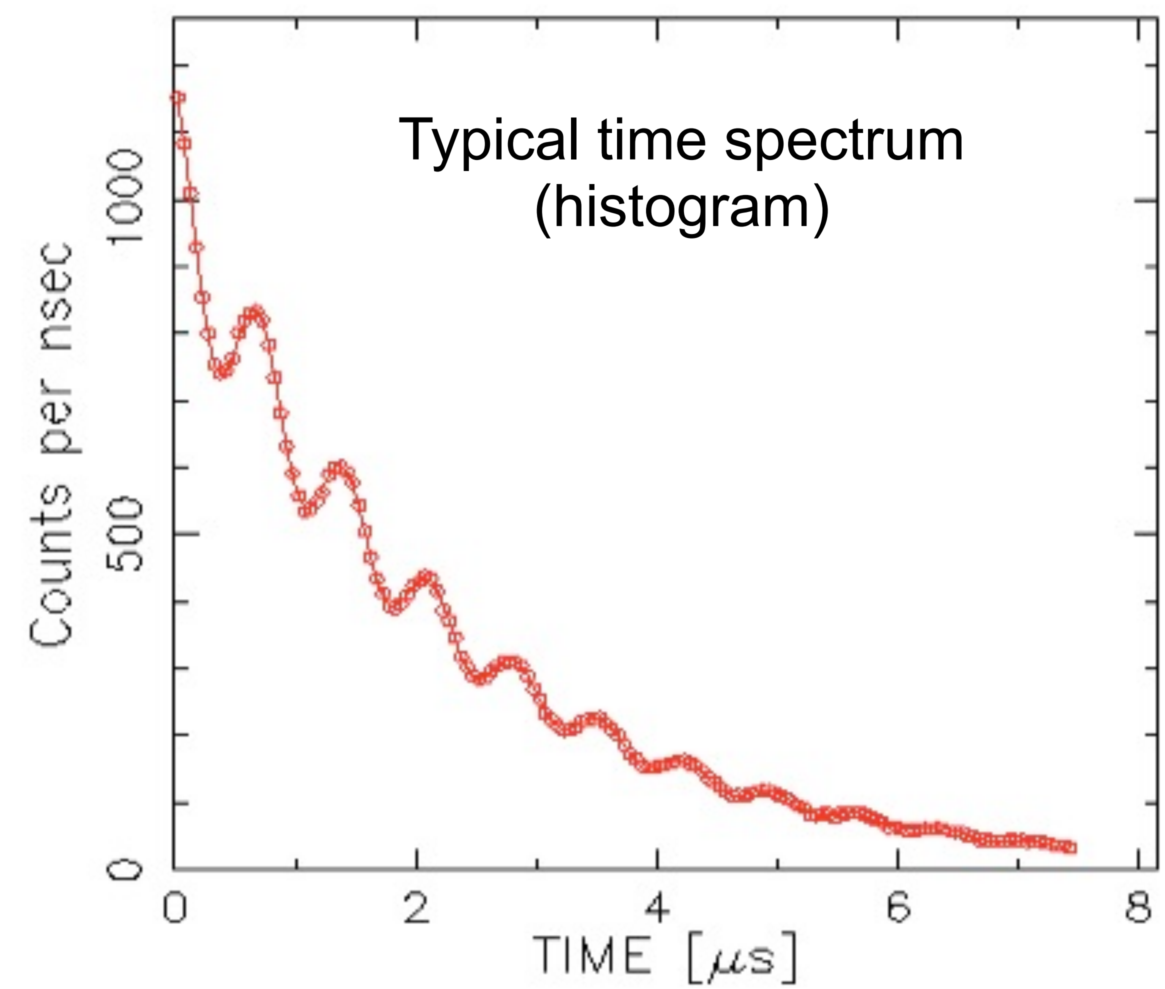
An ultrarelativistic positron behaves like an antineutrino.

Thus the positron tends to be emitted along the μ^+ spin

when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

Transverse Field (TF)-μ^+SR





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  Michel Parameters = Weak Interaction Laboratory

  Heroic **QED** tests: A_{HF}(Mu), μ_μ, $g_\mu - 2$

  All lead to *refined μSR techniques*.

  Applications: Muonium Chemistry, Semiconductors, Magnetism

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QED & Muons

QUANTITY MEASURED	THEORETICAL QUANTITY	±	"CORRECTIONS" (New Topics)
"$g-2$" $(\omega_s - \omega_c)$	$\equiv a_\mu (eB/m_\mu c)$ $\uparrow$ $(g_\mu-2)/2$ ("pure QED")	±	(muon electric dipole moment) (time dilation validity) (validity of CPT for μ^+-μ^- diff.)
"μ_μ" ω_μ/ω_p	$\equiv \mu_\mu/\mu_p \equiv g_\mu m_p/g_p m_\mu$	±	(μ^+ *vs.* p Knight shifts) (μ^+ *vs.* p Chemical shifts) ($\mu^+ \rightarrow$ Mu $\rightarrow$ mol. Chemistry)
"ν_{Mu}" ν_{Mu}	$\equiv (16\alpha^2 cR_\infty/3)\,(\mu_\mu/\mu_B)\,[1+(m_e/m_\mu)]^{-3} \cdot [1 + QED(\alpha, m_e/m_\mu)]$	±	(collisional shifts) (Mu formation in gases) (Mu chemistry in gases)

Treating B, e, c, m_p, g_p, m_e, μ_B, α and R_∞ as "known" [not really legitimate], we have 3 measured quantities, functions of 2 parameters (m_μ and g_μ) so we can "**TEST QED**".

New Science comes from understanding systematic errors in the precise measurement of a "fundamental" quantity.

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40 years later . . .

2007

FUTURES

Giving up meat

Run faster and remember everything.

My death was not nearly as traumatic as I had expected.

By the time my DNA had used up its quota of replications, I had got used to 'seeing' with both my old eyes and my new ones — being inside my skull and outside looking at it. So it wasn't so strange as you might think to watch myself die. In particular, it wasn't as scary as everyone imagines: after all, I already knew I would 'go on' in this new form, and at 137 I had already grown accustomed to the loss of most of those bodily functions you youngsters consider so essential.

Yes, I know your opinion on that. We agreed not to turn this interview into a shouting match, remember?

Never mind.

I remember the beginning very well. As you know, I had a climbing accident in which my spinal cord was severed at the fourth lumbar vertebra. This was just after Dr Anfrager had developed the hypoallergenic neural nanocontacts that make stable nerve–wire junctions possible. They bound the major nerves to wire bundles on both sides of the break. After that it was just a matter of hooking the wires up to a neural network and training it to make the right connections.

My memories from before the repair are pretty fuzzy, sort of like

stories I was told repeatedly by a good friend. I guess that's just what they are, in effect. I don't really have the sense of having 'been there' until the neural network was fully integrated and had built a model of how I think. What? Oh. Yes, I guess it's sort of confusing for you when I talk about the NN as an external agency, a technology that keeps me alive. From your point of view, I suppose 'it' is me. But I'm no machine. I'm the patterns that are stored in it — the ghost in the machine, as it were.

Really, that's why I agreed to this interview. People don't understand. Everyone's afraid a PC will steal their soul, or something. Back when I was the first, no one really cared — I was a novelty, a marvel of technology. But now that kids are getting PCs, there's a lot of hostility out there, and I don't want them — the kids — to be subjected to that.

Anyway, at first I was a poster child: 'Miracle cure for spinal cord injuries!' But when I took up sprinting, they didn't know quite what to make of me. The 'artificial spinal cord' actually worked better than the original. And when I first broke the world 100-metre record, it was disallowed, as you probably remember.

No? Well, it was a big deal for a while, but that was just the beginning of public reaction to 'unfair performance enhancing prostheses' — and I suppose they were right, it really isn't fair to put microseconds up against milliseconds.

Things got more interesting when the new NNs and propagating connections came out. The higher up the spinal cord the NN could explore, the more intricate a model it could build of my nervous system — and inevitably it started working on a model of my cerebral cortex. That was when they first started calling it a PC.

After that — well, you know the recent history.

Best thing about being in a machine? Cute.

The best thing isn't the mediated ESP — although it's great to talk to people without having to make sounds with my vocal chords and all. The best part is being able to remember stuff! I mean, I can remember the Library of Congress just like what I did yesterday. Well, not quite, I guess: I have all the data, but I have to make a model of them before they actually belong to me like regular memories. But my uplinks make that a lot easier than learning ever was. My NN processes information the same way my old brain did; that's the whole idea! But when I need to digest massive quantities of information, I can load a program into any QC and do it fast. When I was meat, I could only grasp really simple ideas, sort of the grand overview of things. And I still have that, from the NN. But now I can also see the details, and make a model of the world that is far more elaborate and complex than I could ever see before.

I'll give you an example. I always thought the purpose of physics was to find simple, intuitive ways of understanding the complex, messy world. But I was bitterly disappointed by the most successful physical theory of all: after almost two centuries, we truly understood electrodynamics — and it wasn't simple! It was really complicated, and hard! What a letdown that was.

I use the past tense because now I get it. I really do. I don't have any trouble remembering the details of Maxwell's equations or propagators and vertices in Feynman diagrams, because I use a QC for that and leave the 'intuition' to my NN. It's allowed me to clean up a lot of the slop in physics. I guess that's why you wanted to interview me, right? 'Axiomatic physics developed by a machine mind!' I can see the headline now. Well, have it your way — as long as you also publish this conversation verbatim, like you promised.

Jess H. Brewer

Jess H. Brewer is at the University of British Columbia. He started a physics PhD for credibility as a SF author, but was seduced by muons at Berkeley. He helped develop μSR at TRIUMF.

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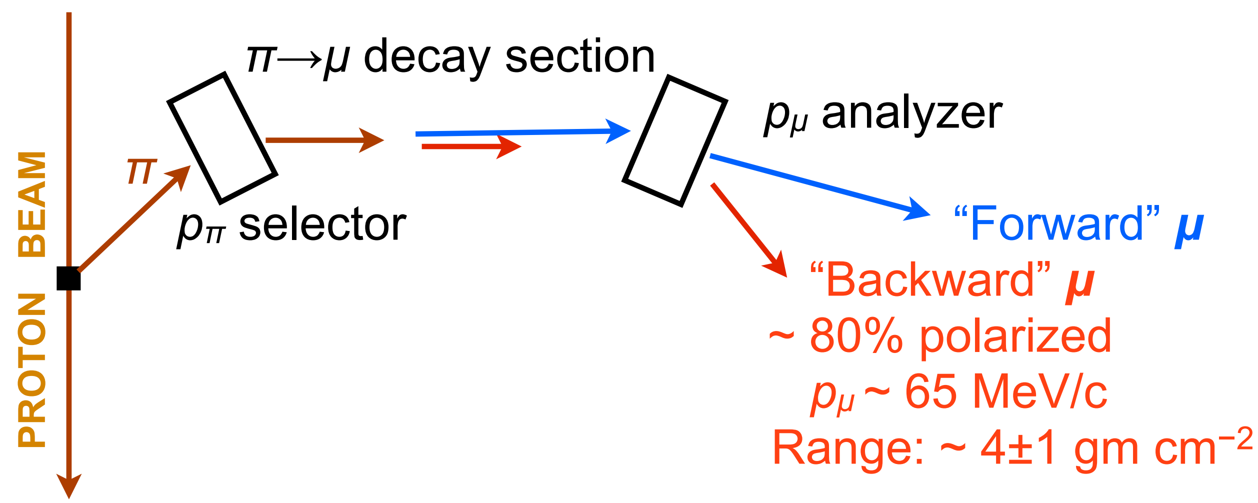
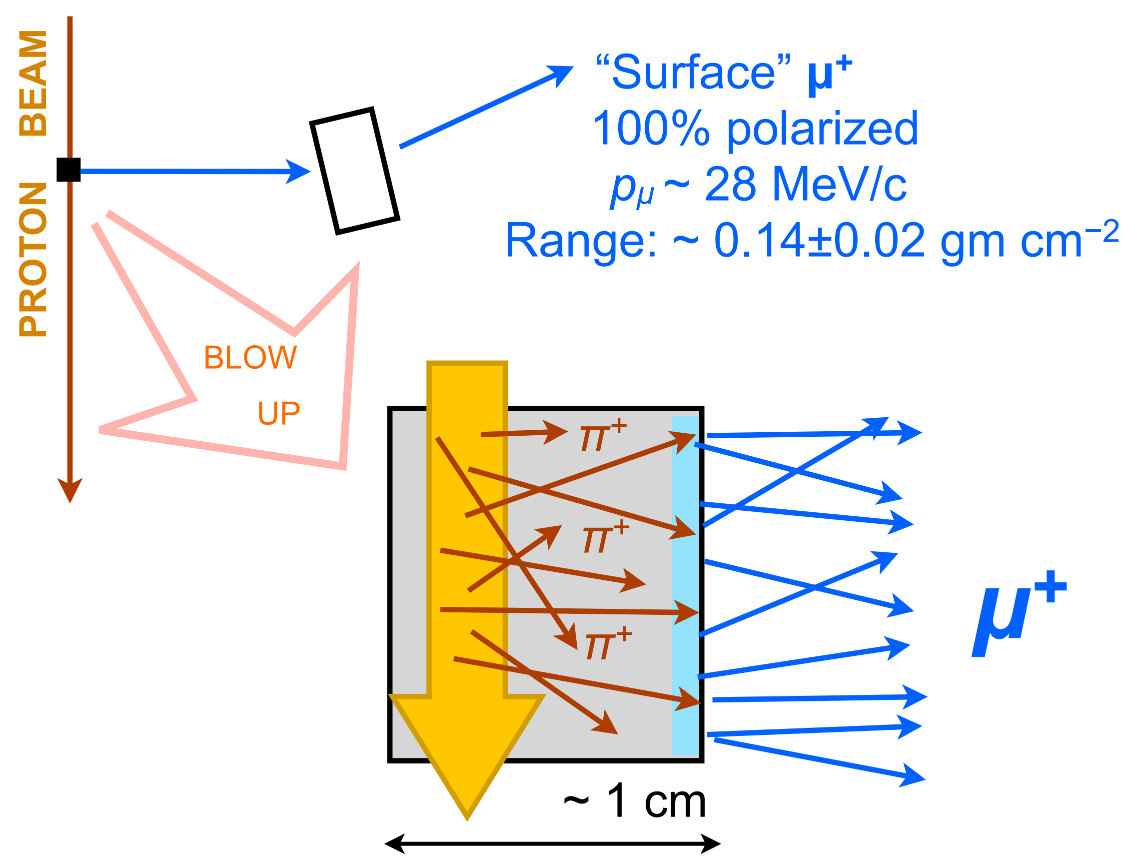
Muon Beams → Quality Factors

- **DECAY MUON CHANNEL** (μ^+ or μ^-)



- "Arizona" or **SURFACE μ⁺ CHANNEL**



PERFORMANCE of MUON BEAMS for μSR

REQUIREMENTS:

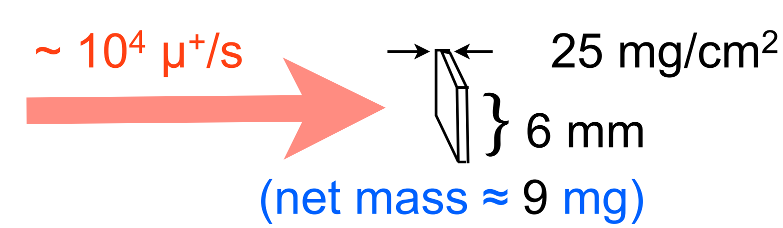
- HIGH POLARIZATION
- HIGH FLUX (>2x10^4 s^{-1} on target) } **LUMINOSITY**
- SMALL SPOT SIZE (< 1 cm^2) } **LUMINOSITY**
- SHORT STOPPING RANGE ⇒ low momentum
- LOW CONTAMINATION of π, e etc.

∴ "***QUALITY FACTOR***"

$$\boxed{Q = \frac{(\text{POLARIZATION})^2 \times \text{FLUX}}{(1 + \text{CONTAM.}) \times \text{RANGE} \times (\text{SPOT SIZE})}} \quad \text{s}^{-1}\text{gm}^{-1}$$

HISTORY of IMPROVEMENTS:

Before Meson Factories:	Q ~ 10^2	(1970)
Decay channels at Meson Factories:	Q ~ 10^5	(1975)
Surface μ⁺ beams at Meson Factories:	Q ~ 10^6	(1980)
"3rd generation" surface muon beams:	Q ~ 10^7	(1990)



Low **E**nergy (moderated) **M**uons at PSI: Q ~ 10^9 (2005)

1958-1973: *Science Fiction*

- 1960s: **Fundamental Physics Fun!** – *Tours de Force*

  Michel Parameters = Weak Interaction Laboratory
  Heroic **QED** tests: A_{HF}(Mu), μ_μ, $g_\mu - 2$
  All lead to *refined μSR techniques*.
  Applications: Muonium Chemistry, Semiconductors, Magnetism

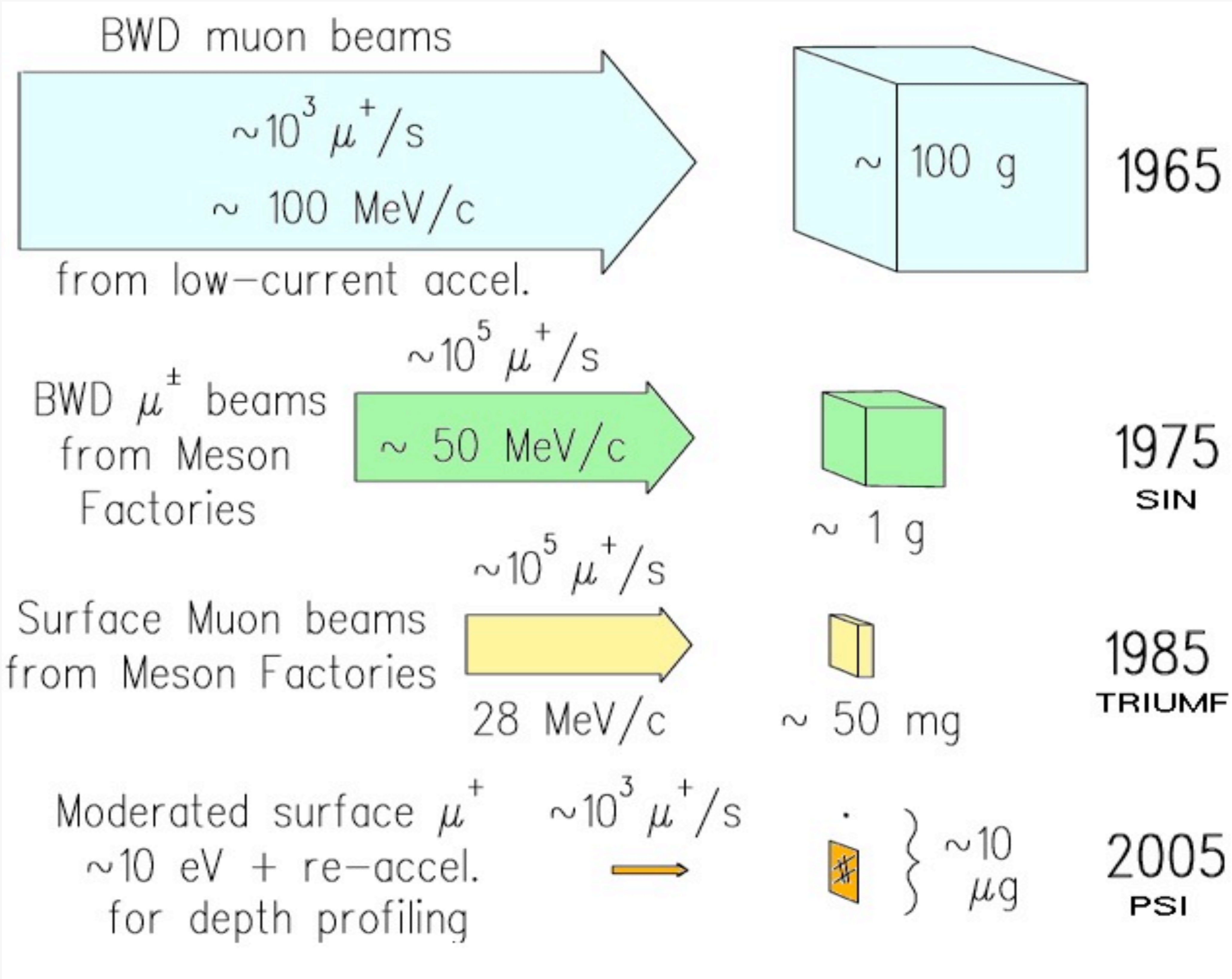
- 1967: **Brewer goes to Berkeley** – *to study Radicals*
  Rationale: a *science fiction author* needs credibility; what better credential than a Ph.D. in Physics? (But *μSR* was too much fun!)

- 1972: **Bowen & Pifer** build first Arizona/surface muon beam to search for for $\mu^+e^- \rightarrow \mu^-e^+$ conversion

- mid-1970s: **Meson Factories** – *Intensity Enables!*

  USA: **LAMPF** (now defunct)
  Canada: ***TRIUMF***
  Japan: **KEK/BOOM** (→ **J-PARC**)
  Switzerland: **SIN** (now **PSI**)
  UK: **RAL/ISIS**

μ^+ Stopping Luminosity



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Performance of Muon Beams for μSR

REQUIREMENTS:

- HIGH POLARIZATION
- HIGH FLUX (>2x10^4 s^{-1} on target)
- SMALL SPOT SIZE (< 1 cm^2)
- SHORT STOPPING RANGE
  ⇒ low momentum
- LOW CONTAMINATION of *π*, *e* etc.

∴ ***"QUALITY FACTOR"***

$$\boldsymbol{Q} = \frac{(\text{POLARIZATION})^2 \times \text{FLUX}}{(1 + \text{CONTAM.}) \times \text{RANGE} \times (\text{SPOT SIZE})}$$

HISTORY of IMPROVEMENTS:

Before Meson Factories:	$\boldsymbol{Q} \sim 10^{2}$	(1970)
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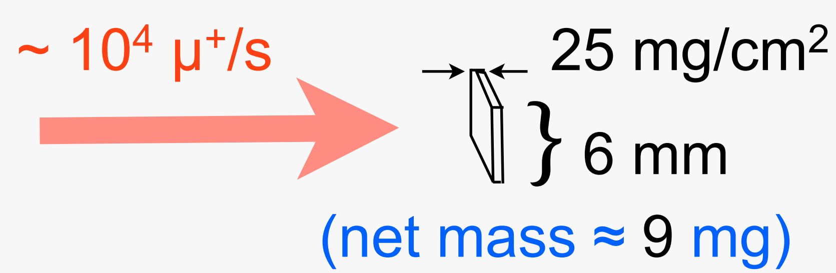
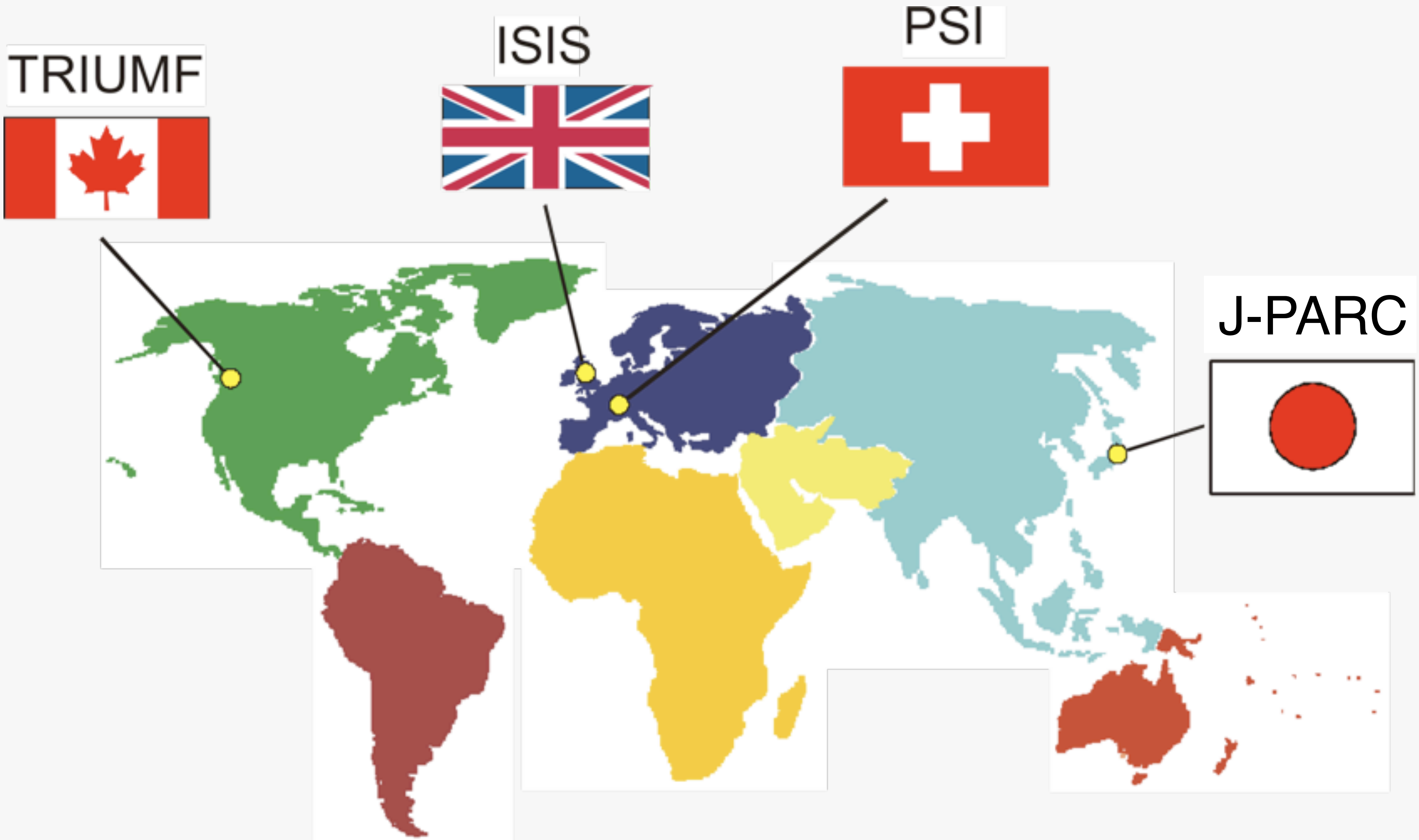


Low **E**nergy (moderated) **M**uons at PSI: $\boldsymbol{Q} \sim 10^{9}$ (2005)

Where in the World is μSR today?

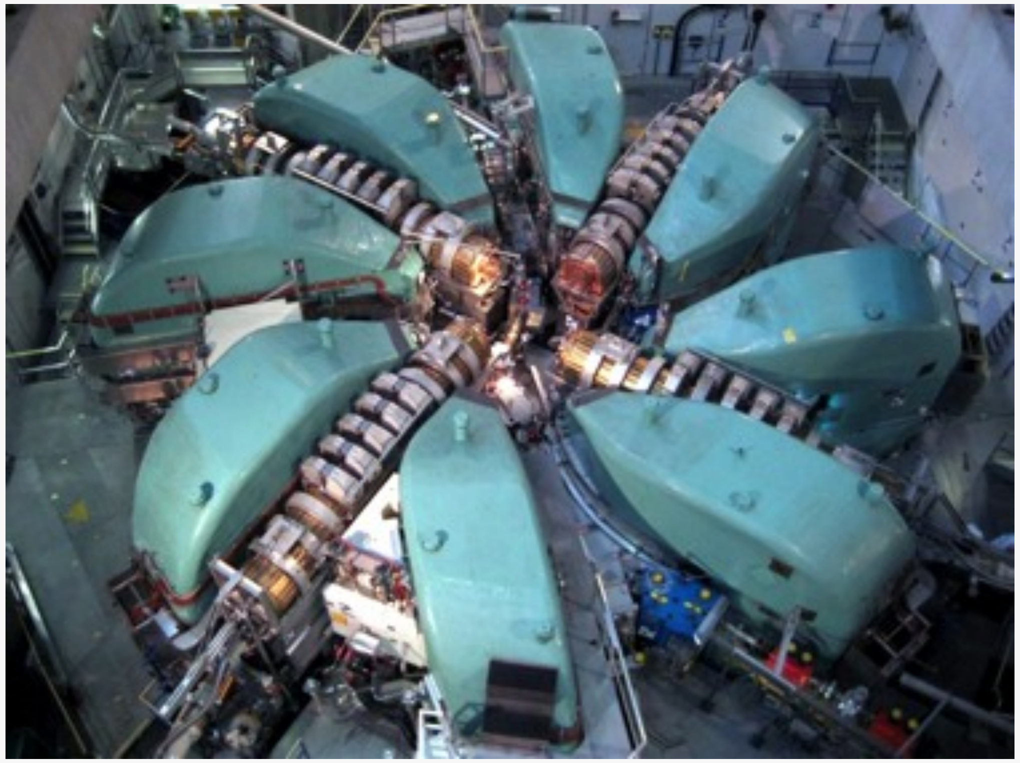


TRIUMF

1972

ISIS site plan

PSI Ring Cyclotron

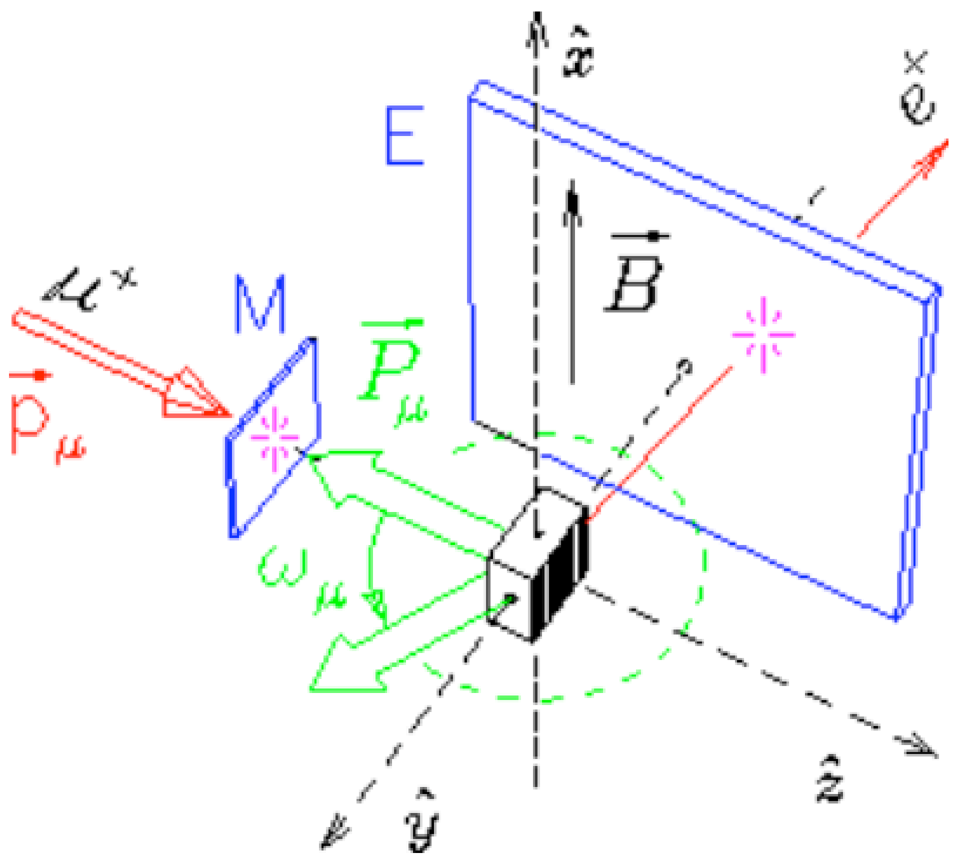


J-PARC synchrotron

Back to μSR . . .

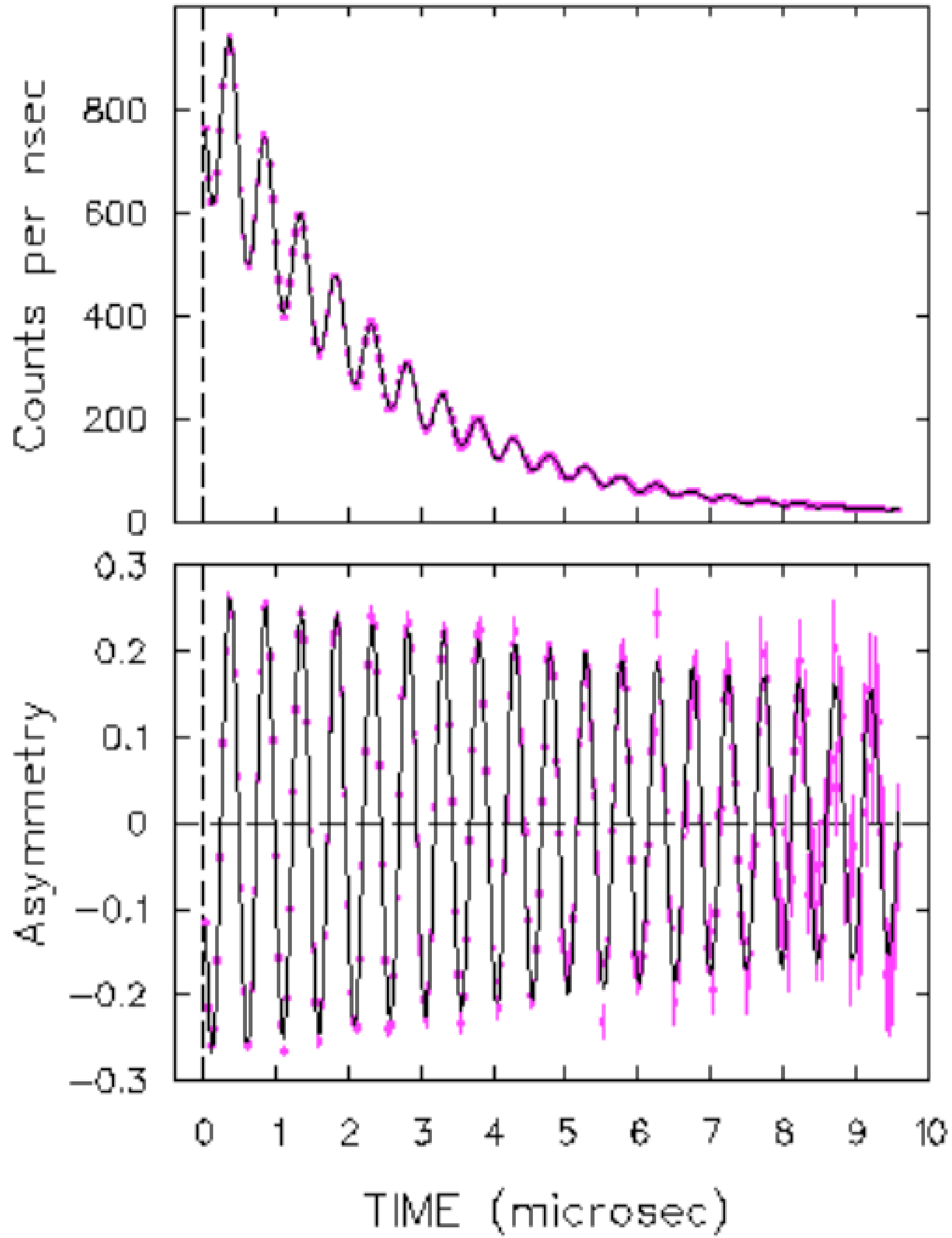
wTF-μ⁺SR:

$$N(t) = N_0 \left\{ B + e^{-t/\tau_\mu} \left[1 + A_0 G_{xx}(t) \cos(\omega_\mu t + \phi) \right] \right\}$$



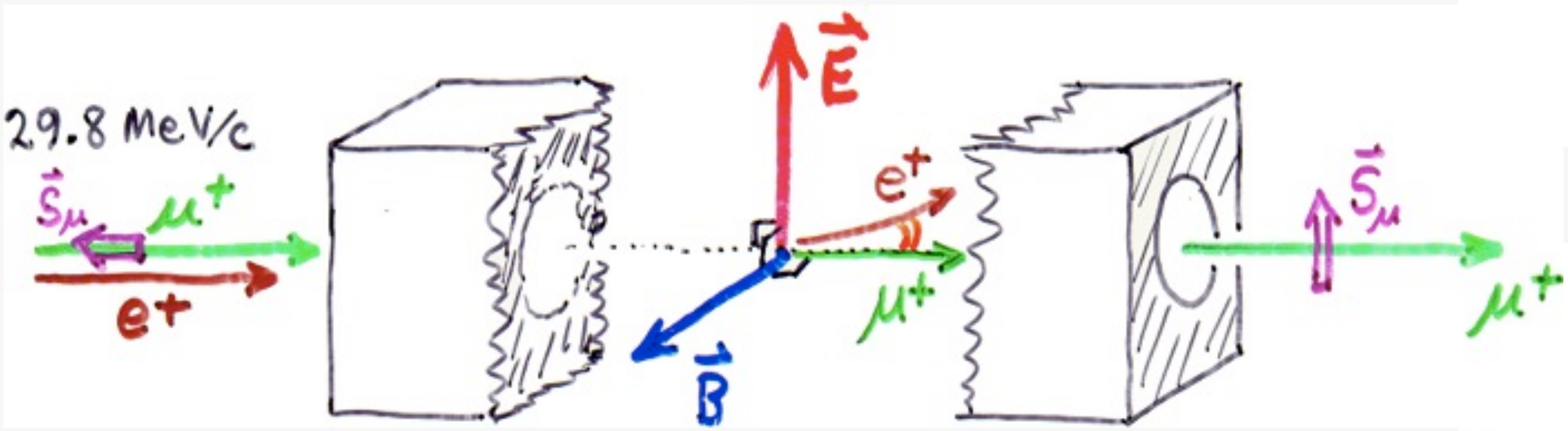
$$A(t) = [N(t) - N_0 B] e^{+t/\tau_\mu} - 1$$

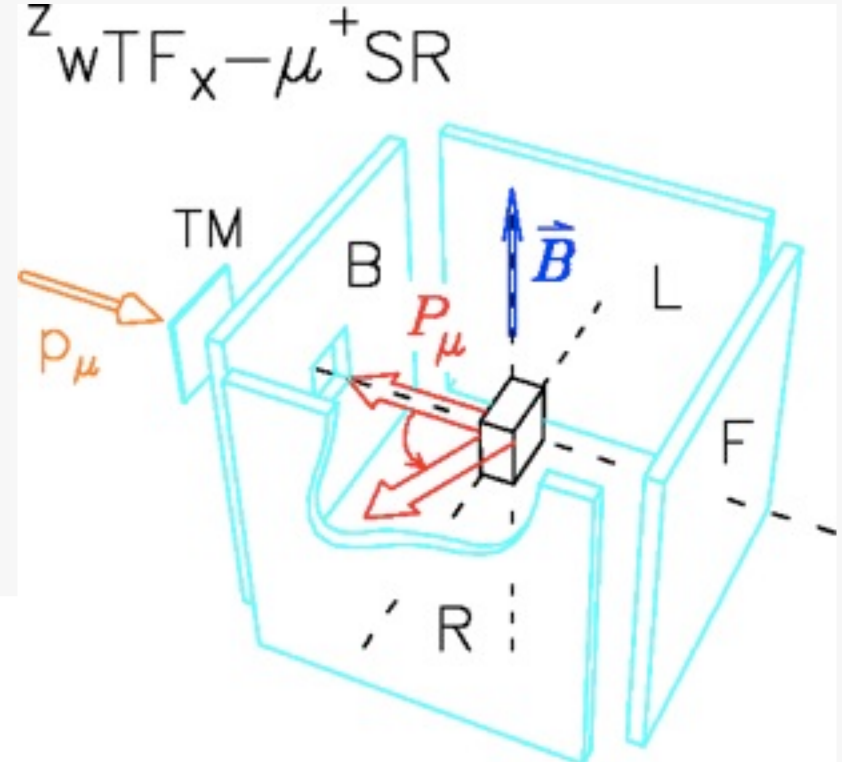
$$= A_0 G_{xx}(t) \cos(\omega_\mu t + \phi)$$

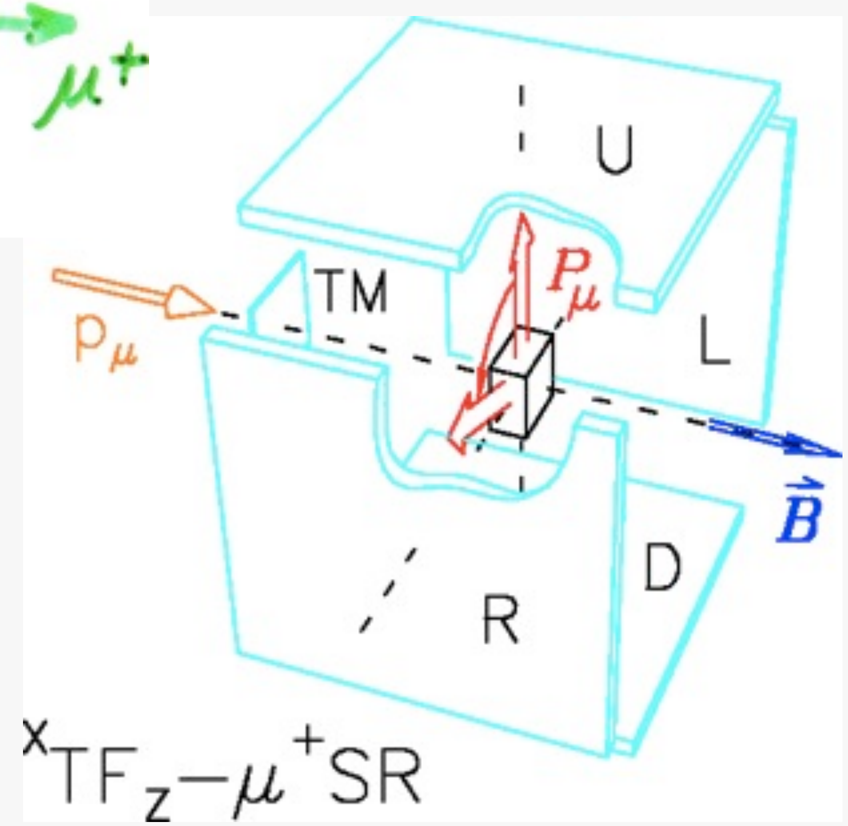


$E \times B$ velocity selector

("DC Separator" or Wien filter) for **surface muons**:







- Removes beam positrons
- Allows TF-μ^+SR in high field (otherwise B deflects beam)

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High Field μSR

TRIUMF: Fields of up to 8 T are now available, requiring a "business end" of the spectrometer only 3 cm in diameter (so that 30-50 MeV decay positron orbits don't "curl up" and miss the detectors) and a time resolution of ~150 ps. Muonium precession frequencies of over 2 GHz have been studied.

PSI: 9.5 T spectrometer commissioned in 2011.

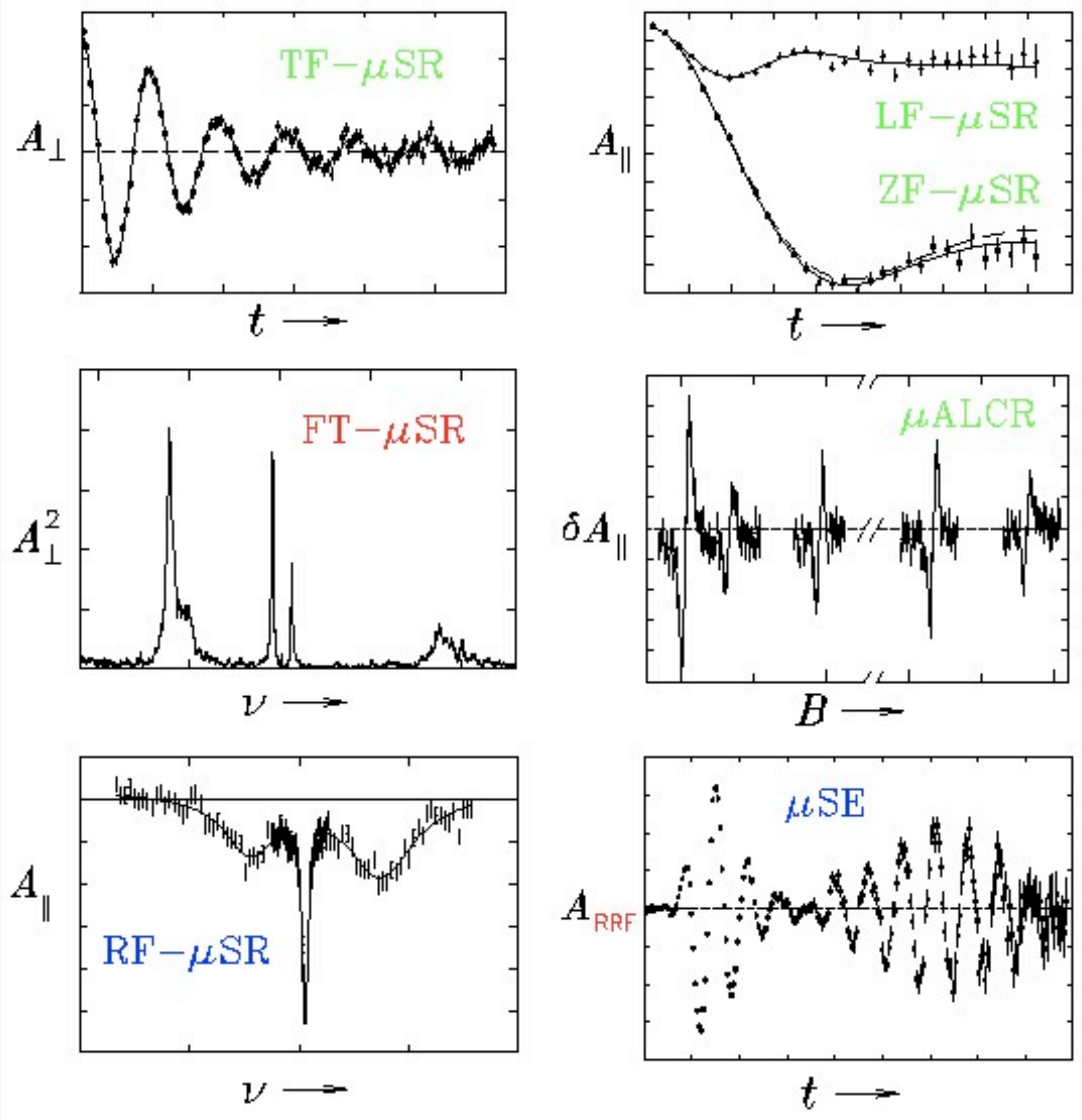
ISIS: 5 T spectrometer (LF only).

Brewer's List of μSR Acronyms

Transverse Field

Fourier Transform μSR

Muon Spin Resonance



Longitudinal Field

Zero Field

Avoided Level Crossing Resonance

Muon Spin Echo

Motion of Muon Spins in Static Local Fields

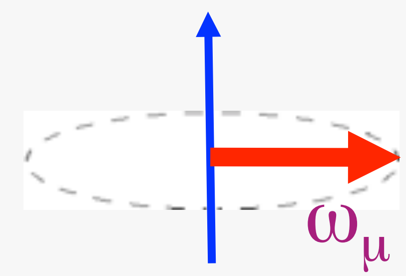
$\vec{S}_\mu$ = Expectation value of a muon's spin direction

(a) All muons "see" same field $\boldsymbol{B}$: for $\boldsymbol{B} \parallel \boldsymbol{S}_\mu$ nothing happens.

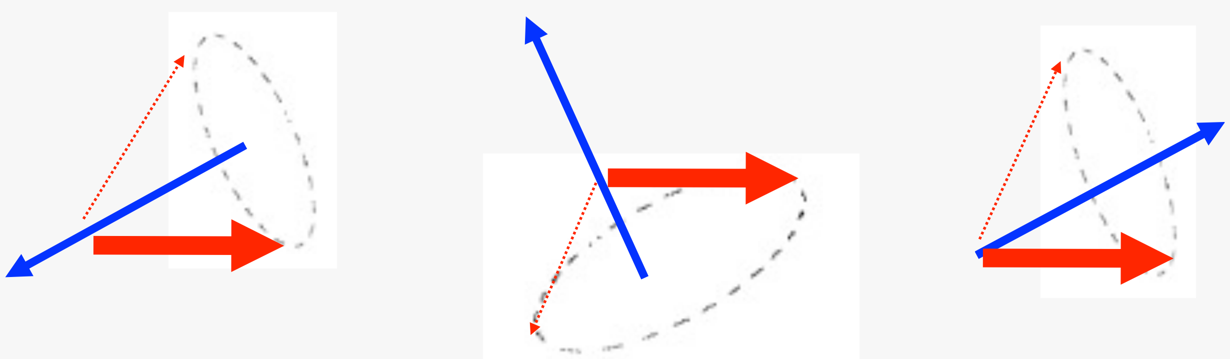
$\omega_\mu = 2\pi\, \gamma_\mu \left|\boldsymbol{B}\right|$

$\gamma_\mu = 135.5$ MHz/T

for $\boldsymbol{B} \perp \boldsymbol{S}_\mu$ Larmor precession:



(b) All muons "see" same $\left|\boldsymbol{B}\right|$ but **random direction** :



2/3 of $\boldsymbol{S}_\mu$ **precesses** at ω_μ

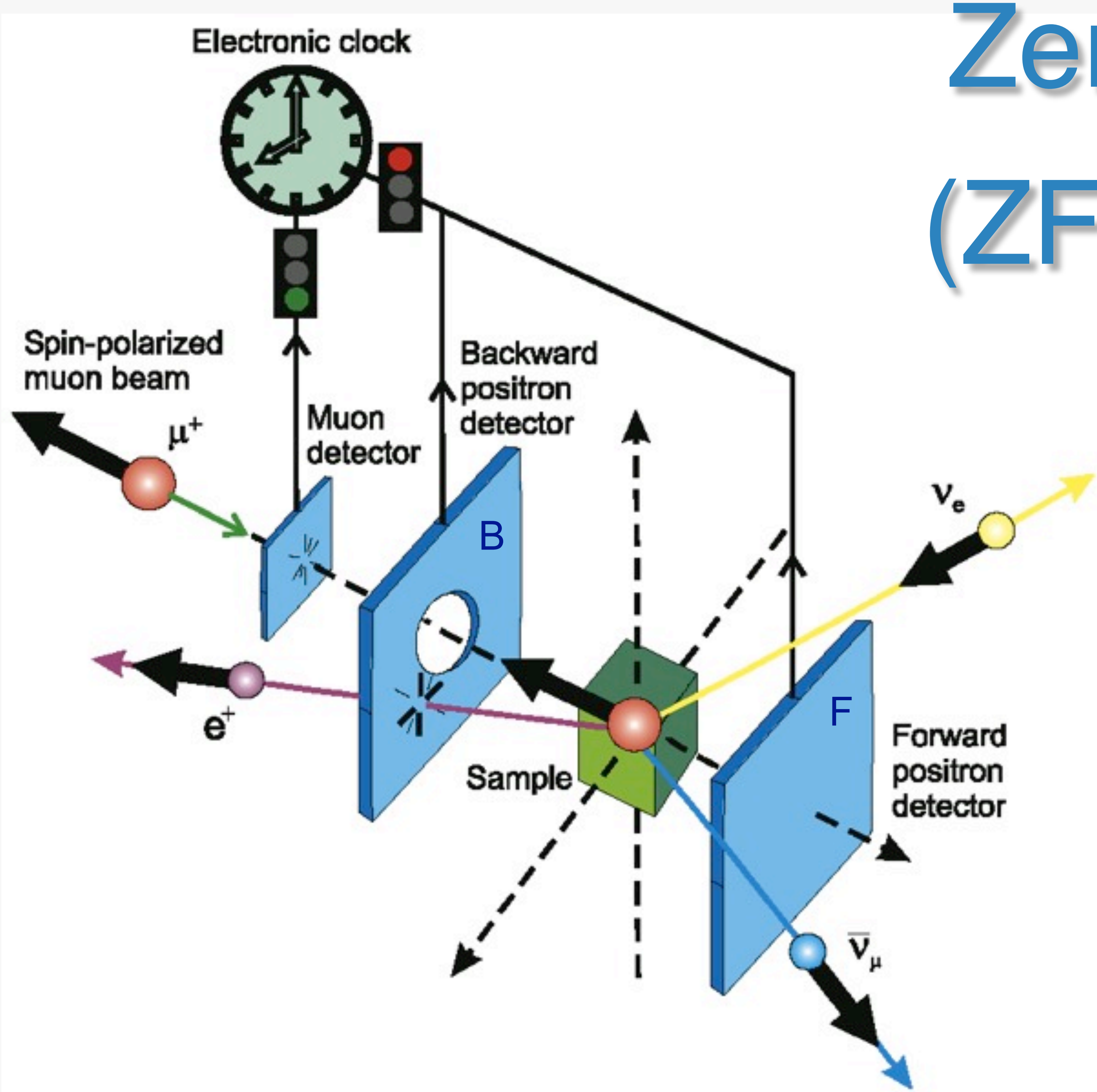
1/3 of $\boldsymbol{S}_\mu$ **stays constant**

(c) Local field $\boldsymbol{B}$ **random** in **both** magnitude **and** direction:

All do not return to the same orientation at the same time

(dephasing) $\Rightarrow$ $\boldsymbol{S}_\mu$ "**relaxes**" as $G_{zz}(t)$ [Kubo & Toyabe, 1960's]

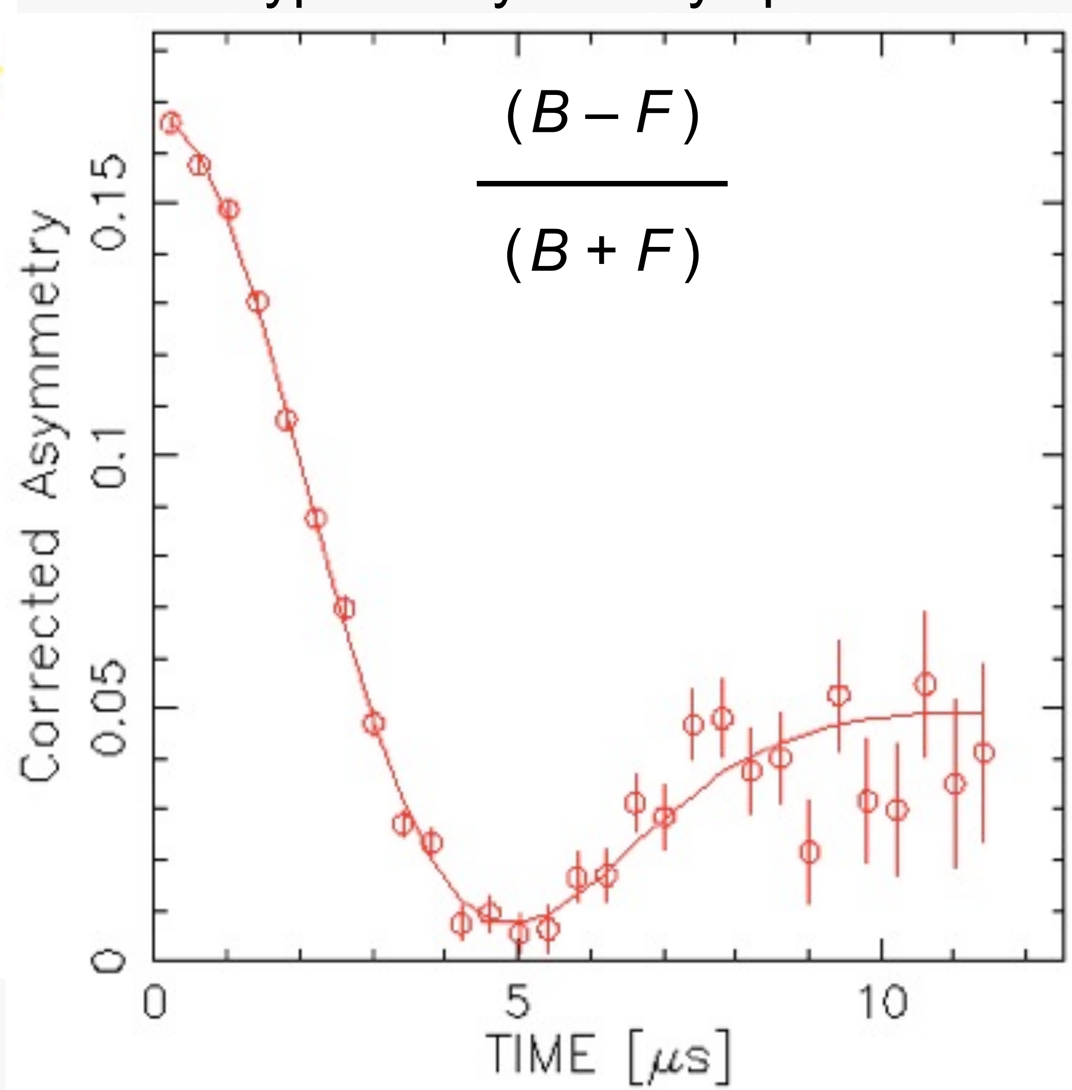
Zero Field (ZF)-μ^+SR



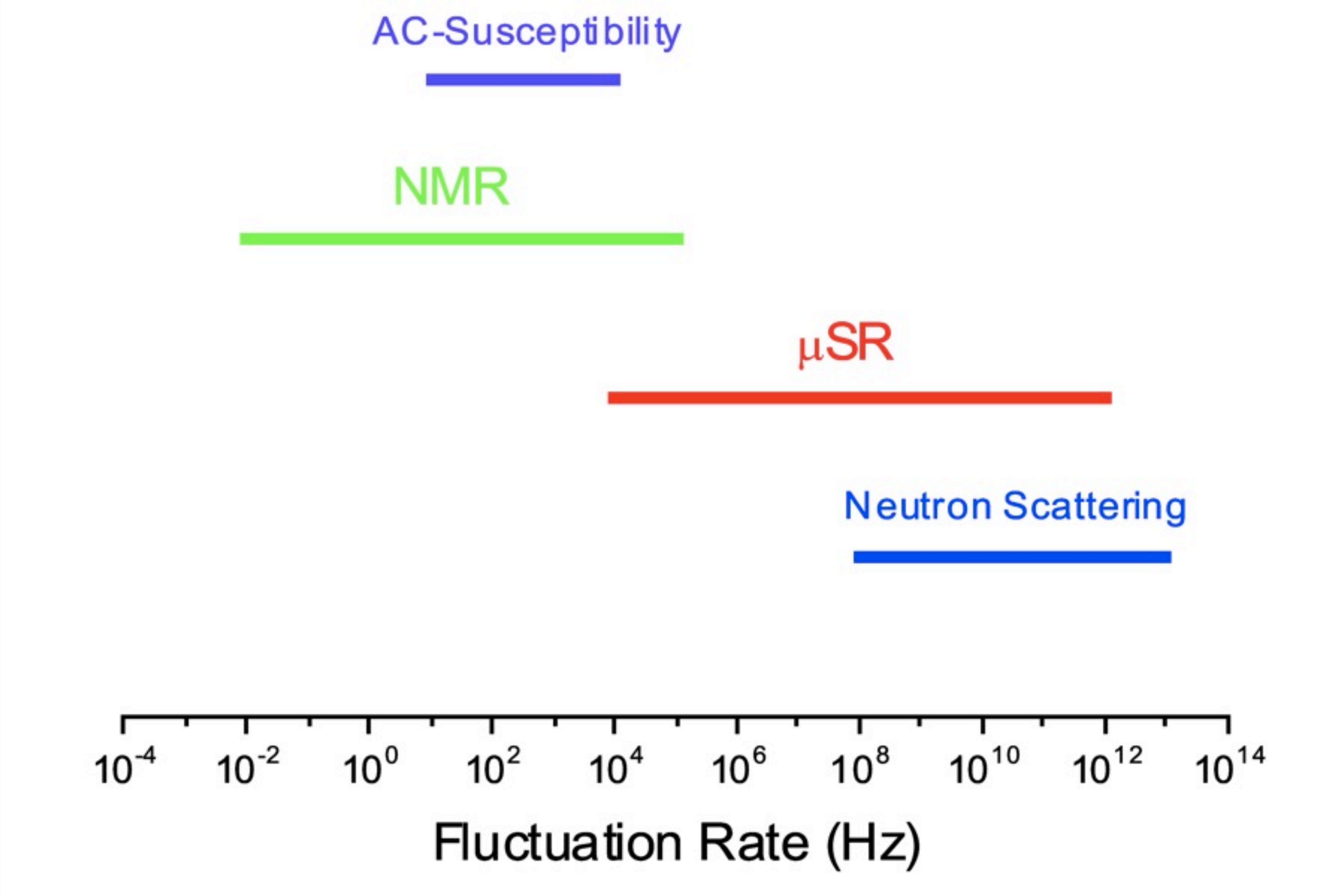
Hayano, Uemura ... Yamazaki & Kubo - *TRIUMF 1978*

PRB **20**, 850 (1979).

Typical asymmetry spectrum



Time Scales



AC-Susceptibility
NMR
μSR
Neutron Scattering
10-4 10-2 10^0 10^2 10^4 10^6 10^8 10^10 10^12 10^14
Fluctuation Rate (Hz)

TRIUMF

"Themes" in μSR

Muonium as light Hydrogen

(Mu = μ^+e^-) (H = p^+e^-)

- **Mu vs. H atom Chemistry:**
  - gases, liquids & solids
  - Best test of reaction rate theories.
  - Study "unobservable" H atom rxns.
  - Discover new radical species.
- **Mu vs. H in Semiconductors:**
  - Until recently, μ^+SR → **only** data on metastable H states in semiconductors!

The Muon as a Probe

- **Probing Magnetism:** unequalled sensitivity
  - Local fields: electronic structure; ordering
  - Dynamics: electronic, nuclear spins
- **Probing Superconductivity:** (esp. HT_cSC)
  - Coexistence of SC & Magnetism
  - Magnetic Penetration Depth λ
  - Coherence Length ξ

- **Quantum Diffusion:** μ^+ in metals (compare H^+); Mu in nonmetals (compare H).

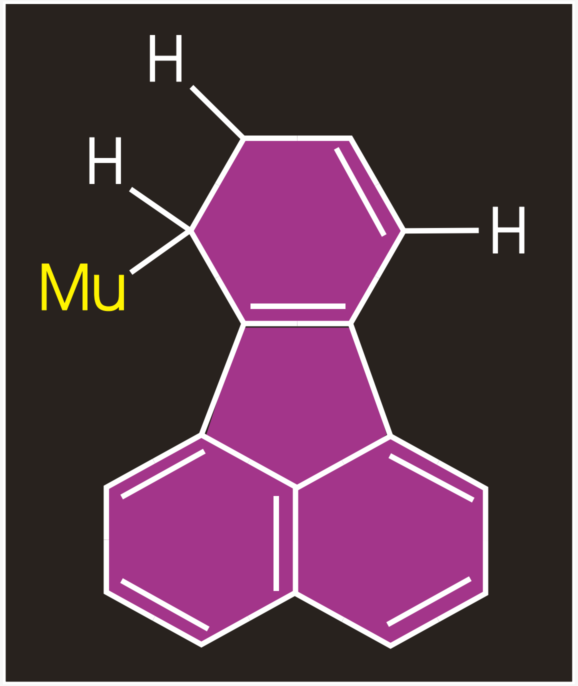
2000s: CMMS

The TRIUMF ***C***entre for ***M***olecular and ***M***aterials ***S***cience is an NSERC funded Facility at the TRIUMF National Laboratory, in Vancouver, Canada. It represents an expansion of the former TRIUMF *μSR* User Facility, with a mandate to facilitate research in chemistry and solid state physics using *μSR* and other accelerator-based techniques such as *β-NMR*.

Visit http://musr.ca for selected Research Highlights:

Chemistry Semiconductors Magnetism

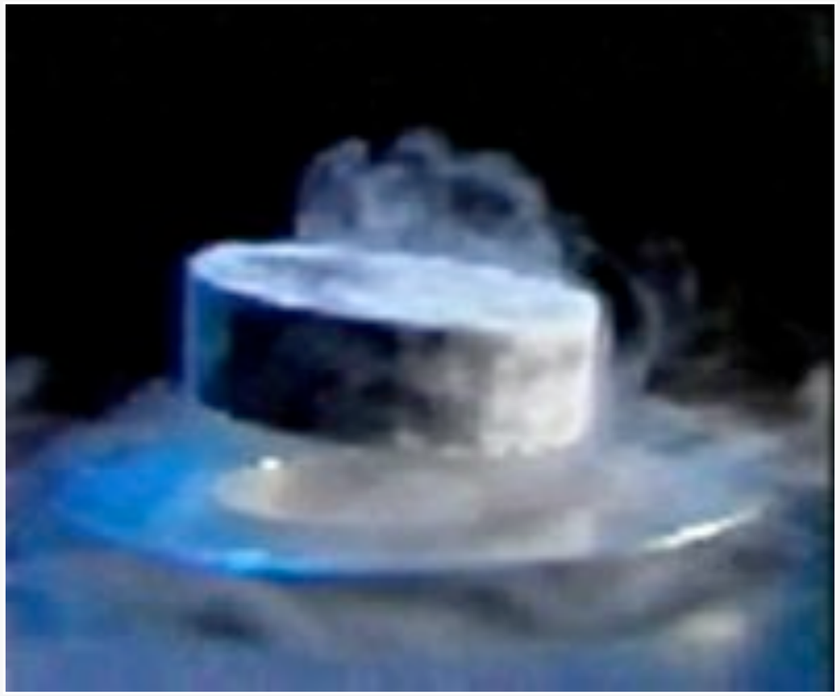
Superconductors Fundamental Physics



Recent Applications of μSR

> Molecular Magnets & Clusters
> Hydrogen in Semiconductors
> **Magnetic Polarons**
> Charged Particle Transport
> Quantum Impurities
> Metal-Insulator Transitions
> Colossal Magnetoresistance
> Spin Ice Systems
> Thermoelectric Oxides
> Photo-Induced Magnetism
> Magnetic Vortices
> Heavy Fermions
> Frustrated Magnetic Systems
> Quantum Diffusion
> **Exotic Superconductors**

> Molecular Structure & Conformational Motion of Organic Free Radicals
> Hydrogen Atom Kinetics
> "Green Chemistry" in Supercritical CO_2
> Catalysis
> Mass Effects in Chemical Processes
> Ionic Processes at Interfaces
> **Reactions in Supercritical Water**
> Radiation Chemistry & Track Effects in Condensed Media
> Reaction Studies of Importance to Atmospheric Chemistry
> Reaction Kinetics as Probes of Potential Energy Surfaces
> Electron Spin Exchange Phenomena in Gases & Condensed Media.



History of μSR

- pre-1956: Fantasy
- 1956-7: Revolution!
  π-μ-e decay and μSR
- 1958-73: Science Fiction
  Michel Parameters
  QED tests with Muonium
  "Problems" → Applications
- 1970s: Meson Factories
  SIN/PSI, LAMPF, TRIUMF,
  KEK/BOOM, RAL/ISIS
- '80s & '90s: Routine Science
  μSR Methods developed
  "Themes" in μSR
- 2000s: TRIUMF **CMMS**:
  Chemistry & Semiconductors
  Magnetism & Superconductors
  Fundamental Physics
- FUTURE: Applied Science
  (No more magic? Don't count on it!)

C'est fini!