Problems* & *Opportunities

The Story of

Muon Spin Rotation/Relaxation/Resonance

according to

Jess H. Brewer

TRIUMF and Dept. of Physics & Astronomy, **U**niv. of **B**ritish **C**olumbia

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!"

Acknowledgements

- **Discoverers** of $\mathcal{P}$-violation, who turned Fantasy to Science Fiction
- **Obsessors** who created μSR to test QED
- **Developers** who are still turning Science Fiction into Physics
- **Promoters** who support and encourage Developers & Users
- **Users** who apply the Developers' tools to continue the story
- **Students** who do most of the hard work
- **Technicians** who do the rest

Before 1956: ***μSR = Fantasy***

(violates "known laws of physics")

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

  Yukawa's "nuclear glue" mesons ≠ cosmic rays

  1937 Rabi: Nuclear Magnetic Resonance

- ## 1940s: "**Who Ordered That**?"

  1940 Phys. Rev. Analytical Subject Index: "mesotron"

  1944 Rasetti: 1st application of **muons** to **condensed matter physics**

  1946 Bloch: Nuclear Induction (modern NMR with FID *etc.*)

  1946 Various: "two-meson" π-μ hypothesis

  1947 Richardson: produced π & μ at Berkeley 184 in. Cyclotron

Problem:
What's the mean field inside a ferromagnet, ***B*** or ***H*** ?

Opportunity:
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.

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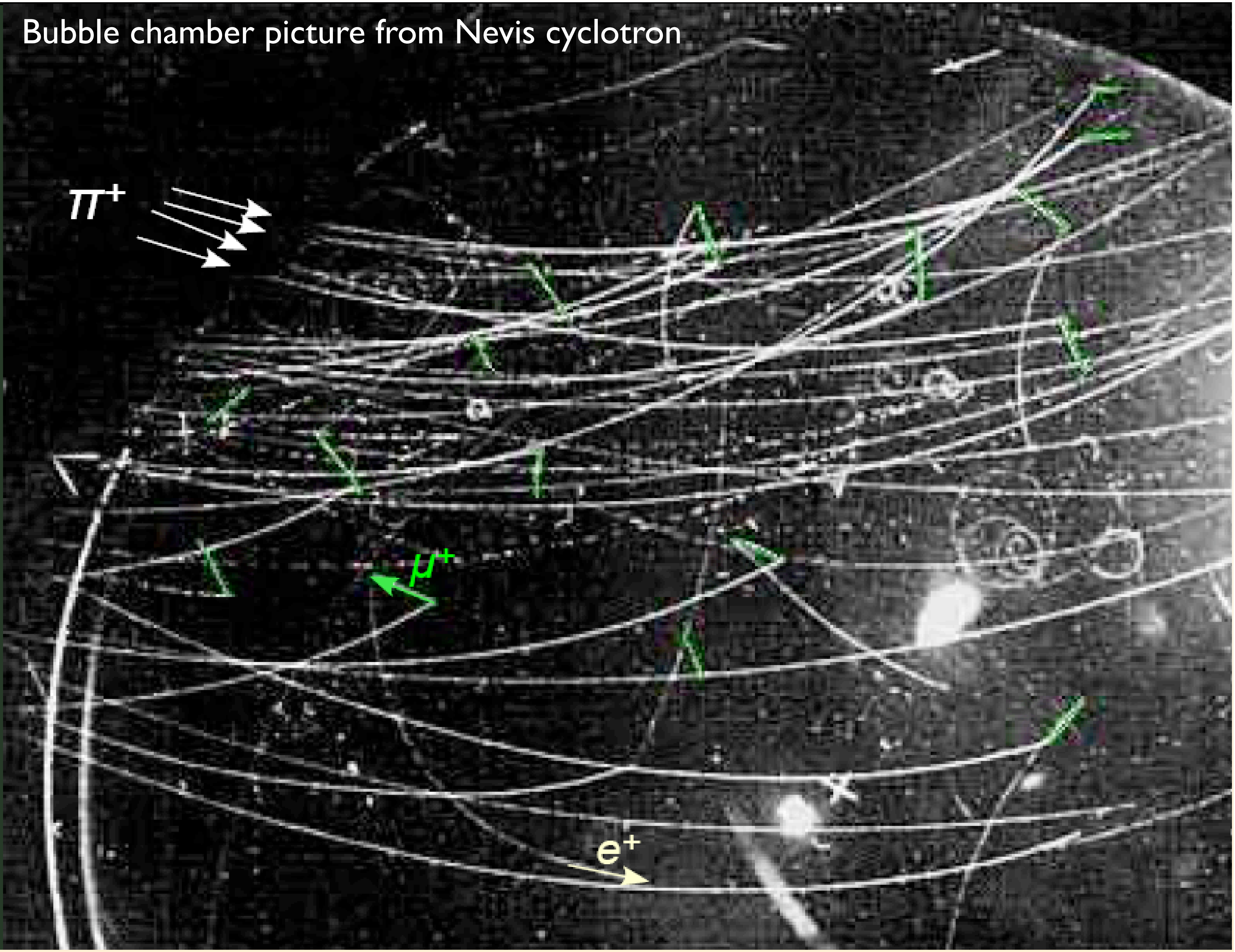
What do you see?



π+ →

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  1949 Kuhn: ***"The Structure of Scientific Revolutions"***

1956-7: *Revolution*

- 1950s: "**Particle Paradise**"
  culminating in weird results with strange particles:
  1956 Cronin, Fitch, . . . : "*τ - θ puzzle*" (K^+ decay)

  First <u>big</u> problem!

- 1956: Lee & Yang postulate
  $\mathcal{P}$-violation in weak interactions

  First <u>big</u> opportunity!

- 1957: Wu confirms $\mathcal{P}$-violation in β decay;
  Friedman & Telegdi confirm $\mathcal{P}$-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)

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

(Received January 15, 1957)

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

JEROME I. FRIEDMAN AND V. L. TELEGDI

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

(Received January 17, 1957)

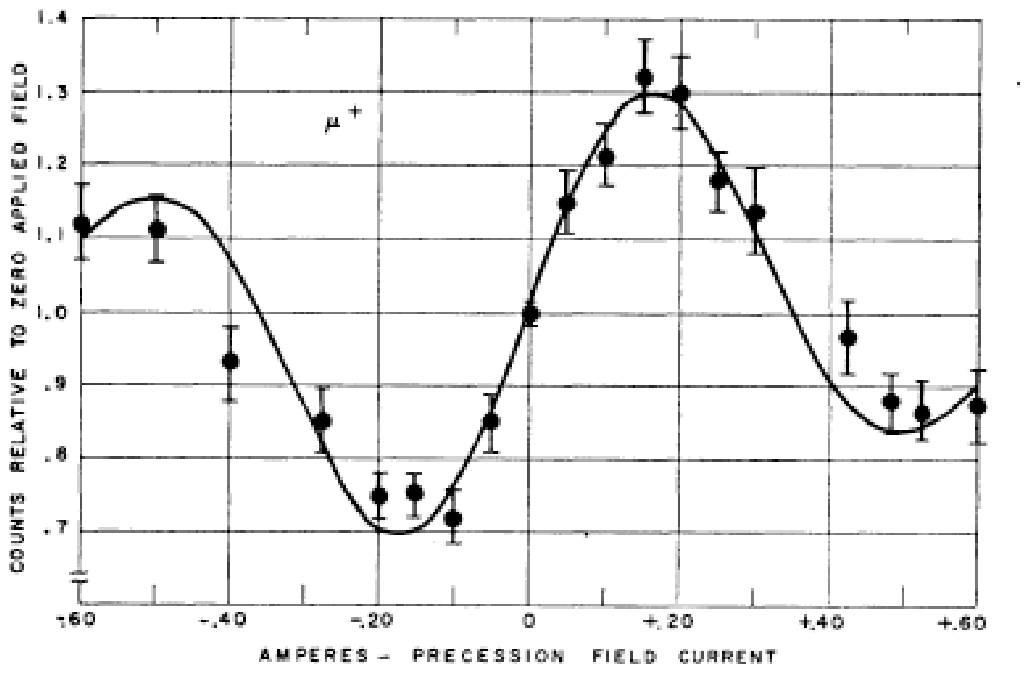


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

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.

For newcomers . . .

How does it work?

. . . a brief introduction to

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

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

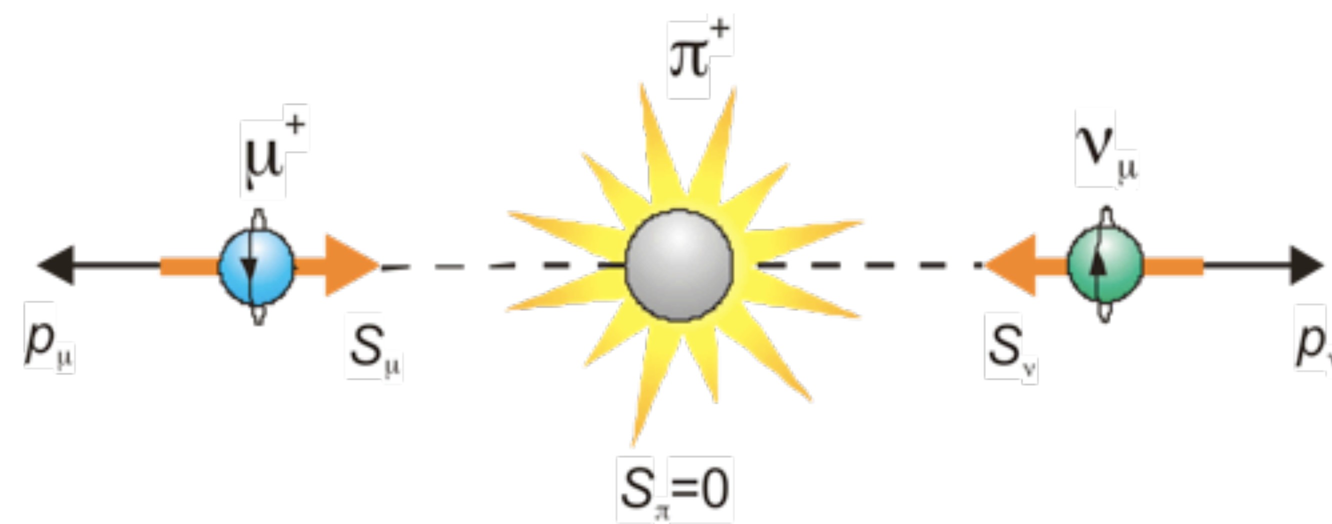
Conservation of Linear Momentum: The μ^+ is emitted with momentum equal and opposite to that of the ν_μ.

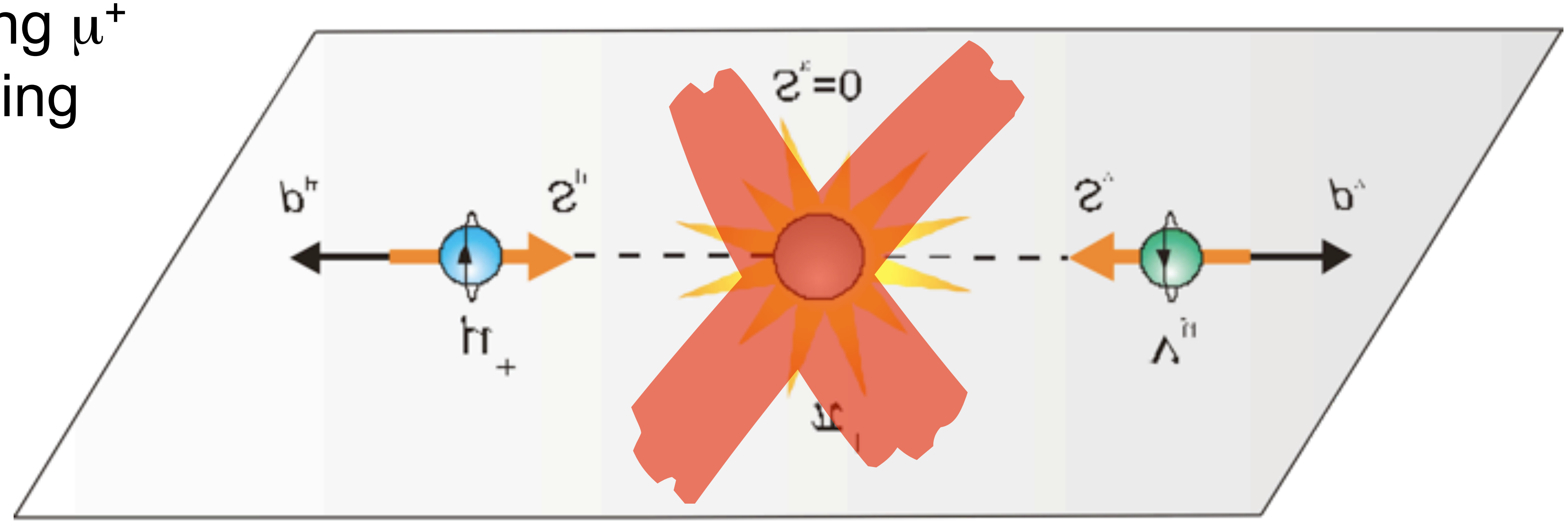
Conservation of Angular Momentum: μ^+ & ν_μ have equal & opposite spin.

Weak Interaction:

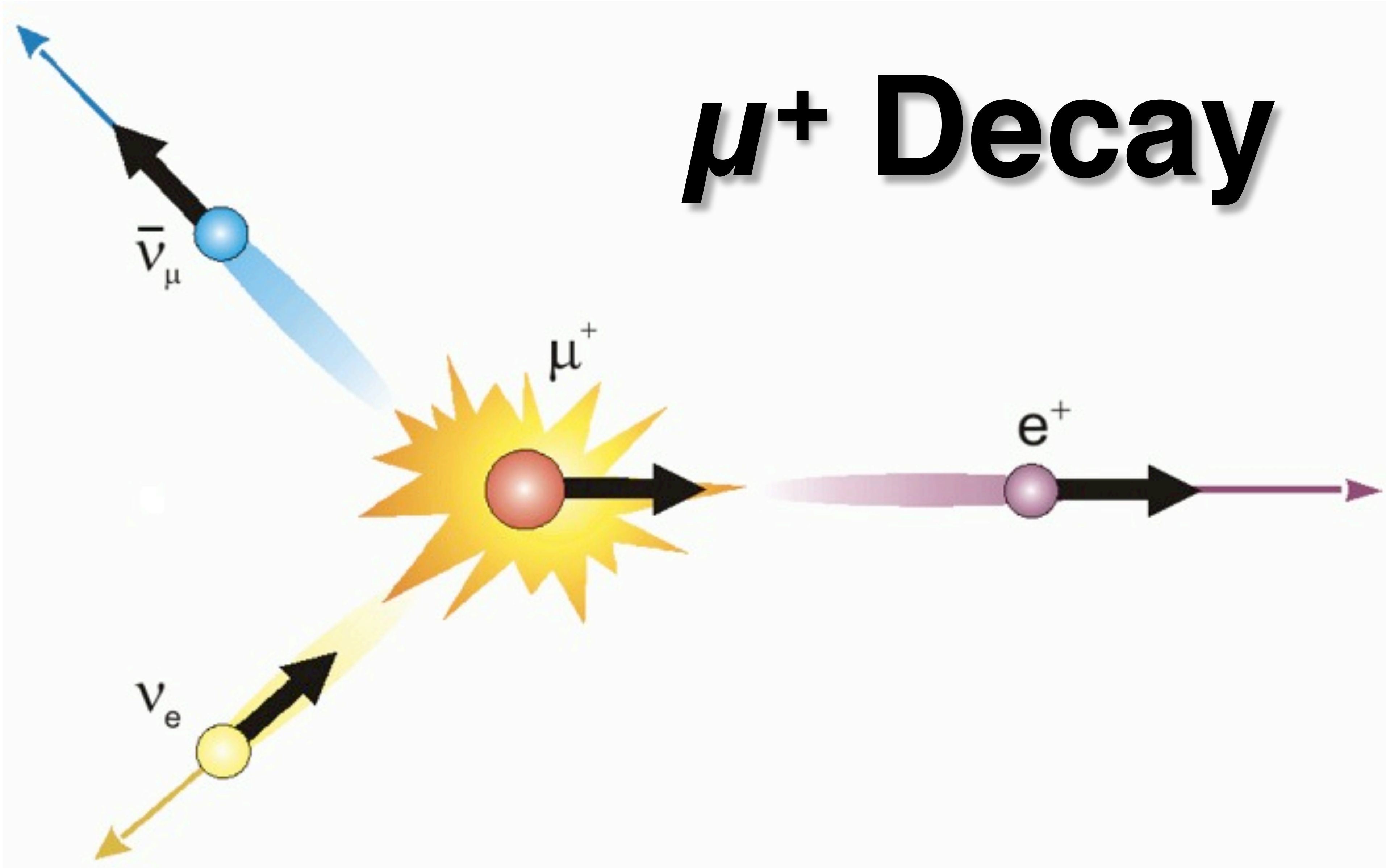
Only "left-handed" ν_μ are created.

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



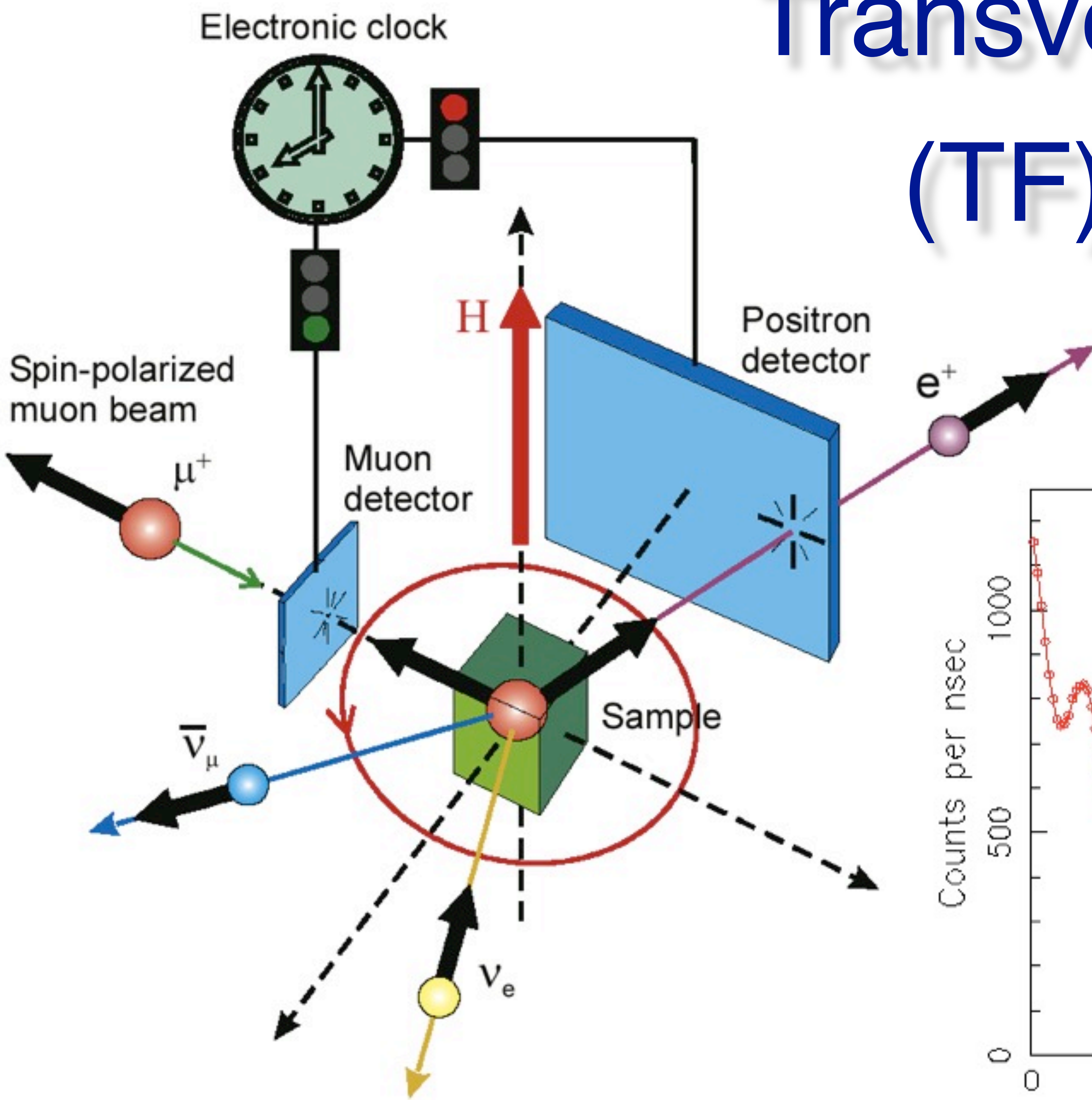


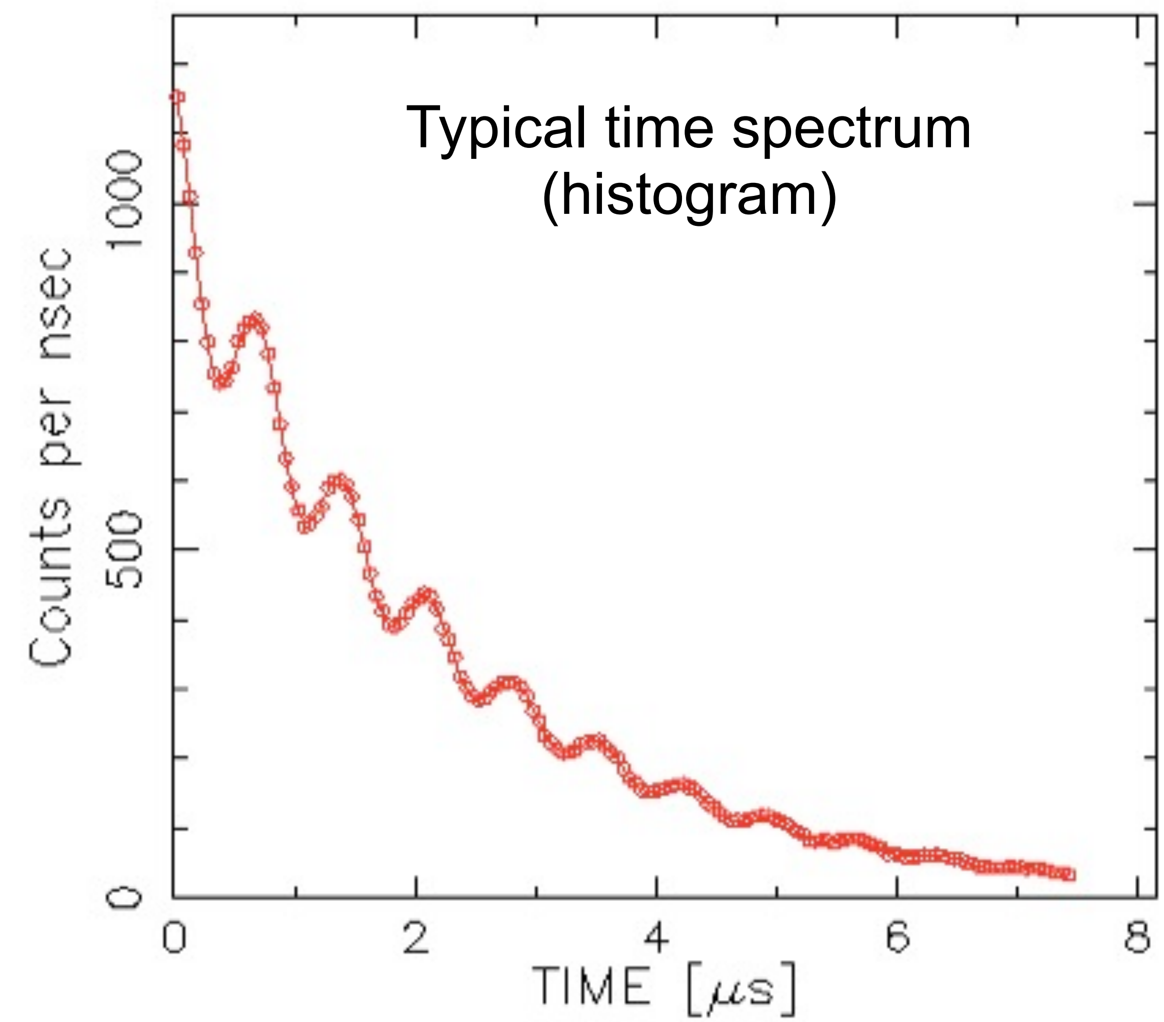
μ^+ Decay



Neutrinos have negative helicity, antineutrinos positive.
An ultrarelativistic positron behaves like an antineutrino.
Thus the positron <u>tends</u> 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





1958-1973: ***Science Fiction era***

- *Problem*: *How to make all this practical?*

- Solution (mid-1970s): Meson Factories – *Intensity x 1000!*

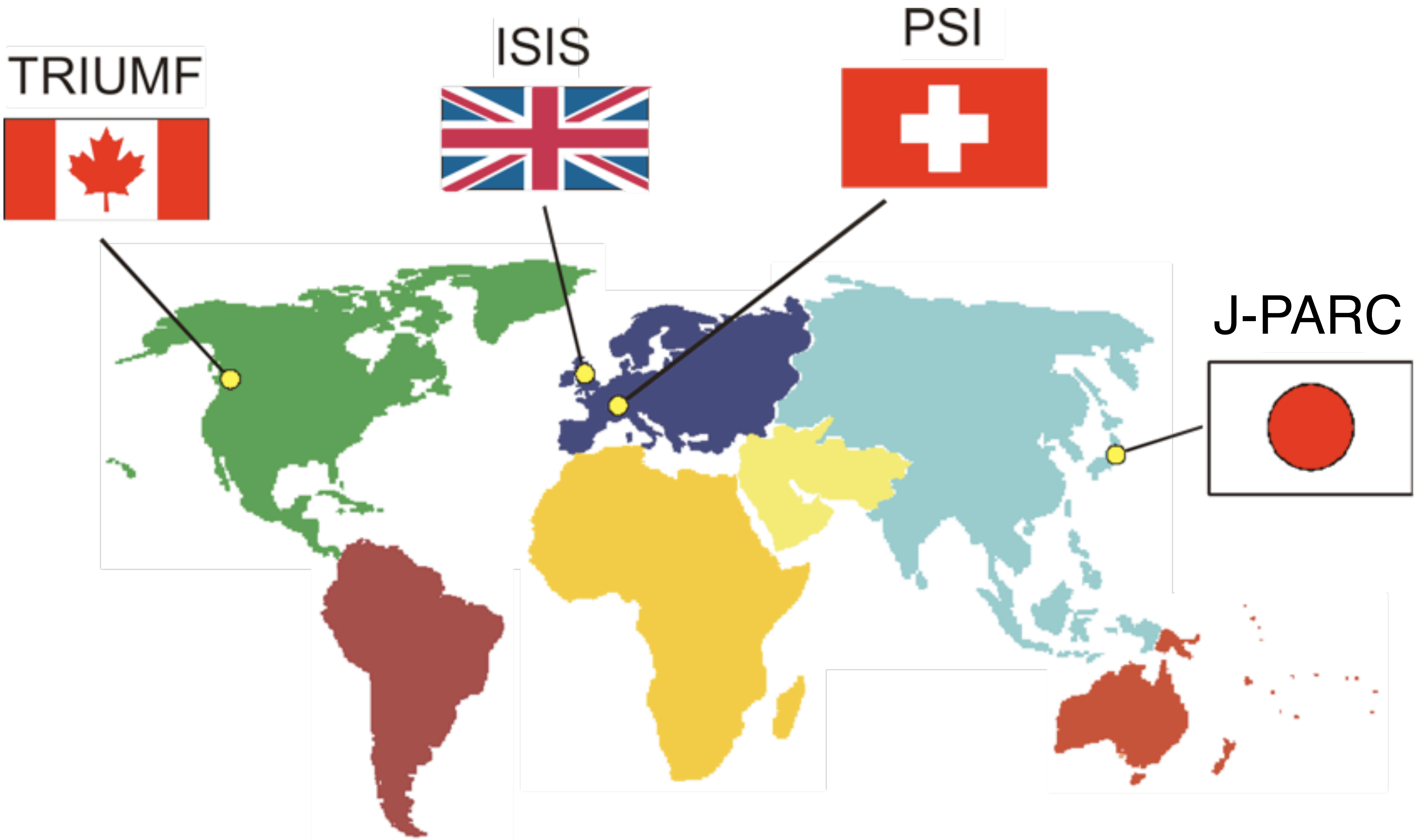
  Switzerland: **SIN** (→ **PSI**)
  Canada: **TRIUMF**

  USA: **LAMPF** (now defunct)

  Japan: **KEK/BOOM** (→ **J-PARC**)
  UK: **RAL/ISIS**

- *Opportunity*: *Science Fiction → Routine Science.*

Where in the World is μSR?



1958-1973: ***Science Fiction era***

- 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 *problems* requiring refined μSR techniques (*opportunities*).

- 1972: **Bowen** & **Pifer** search for for $\mu^+ e^- \to \mu^- e^+$ conversion

- *Problem*: *How to produce slow Mu in vacuum?*

  Solution: build first Arizona/surface muon beam.

- *Opportunity*: *Study Mu chemistry in gases.*

- *Opportunity*: (later) ~10^3 x *smaller solid samples.*

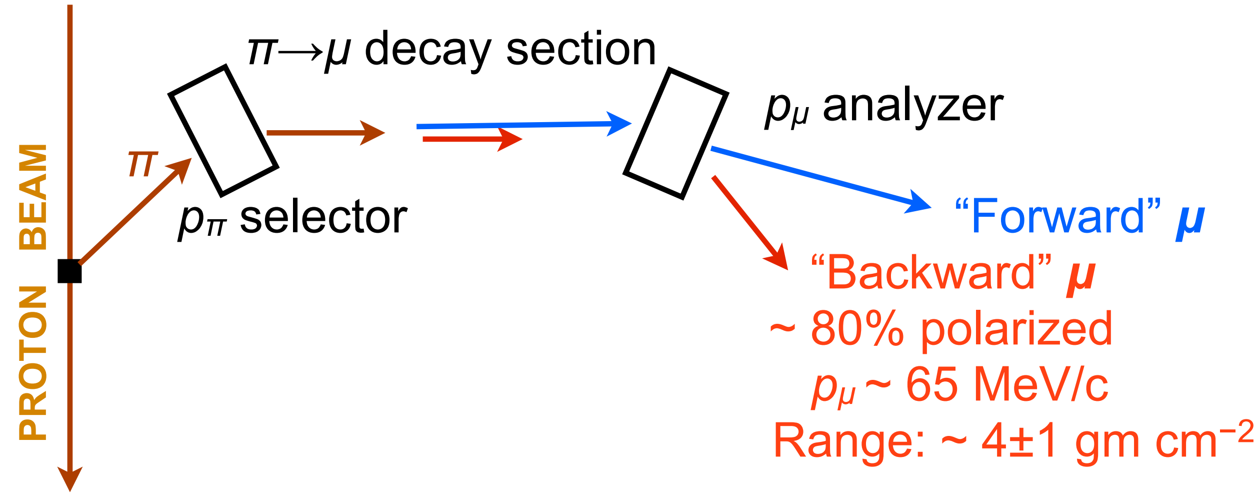
- *Opportunity*: (much later) *Ultra-Low Energy Muons*

  that can stop in thin films and probe *interfaces*.

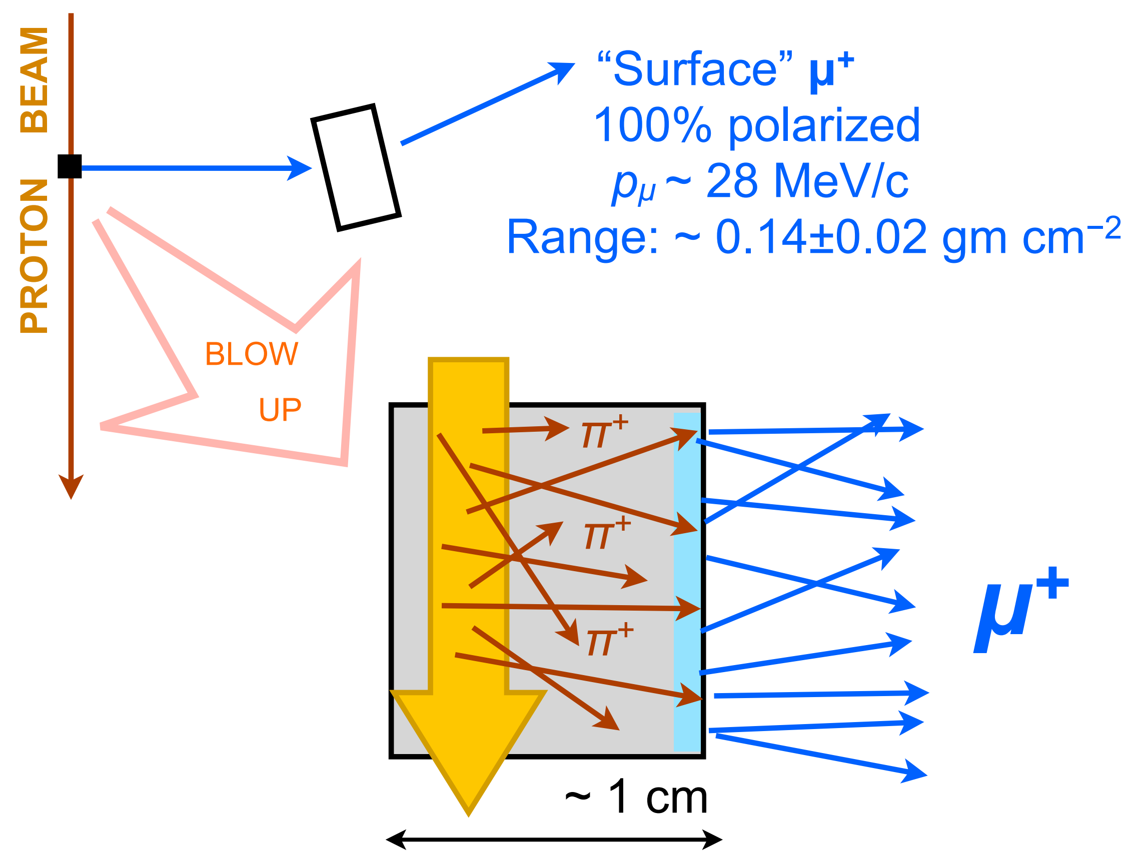
  (Requires ~10^4 incoming muons for each LEM.)

Muon Beams → Quality Factors

- **DECAY MUON CHANNEL** (μ^+ or μ^-)



- "Arizona" or **SURFACE μ⁺ CHANNEL**



PERFORMANCE of MUON BEAMS for μSR

REQUIREMENTS:

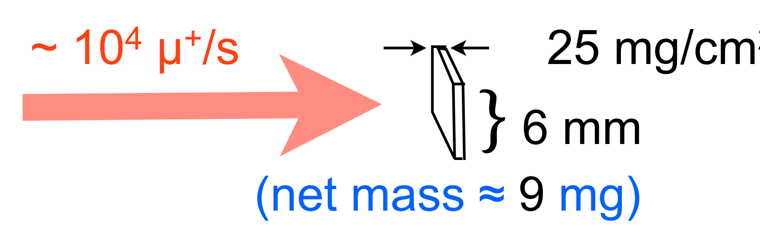
- HIGH POLARIZATION
- HIGH FLUX (>2x10^4 s^{-1} on target) } **LUMINOSITY**
- SMALL SPOT SIZE (< 1 cm^2) } **LUMINOSITY**
- SHORT STOPPING RANGE ⇒ low momentum
- LOW CONTAMINATION of π, e etc.

∴ ***"QUALITY FACTOR"***

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

HISTORY of IMPROVEMENTS:

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



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

Spin-Rotated Muon Beams

- *Problem*: μ^+ *beam has huge* e^+ *background.*

  Solution: Use $\boldsymbol{E} \times \boldsymbol{B}$ velocity selector to remove positrons.

- *Problem*: *How to do* TF-μ^+SR *in **high fields**?*

  ($\boldsymbol{S} \parallel \boldsymbol{p} \perp \boldsymbol{B}$ $\Rightarrow$ muon beam is deflected)

  Solution: Use $\boldsymbol{E} \times \boldsymbol{B}$ velocity selector to rotate muon spins 90^o.

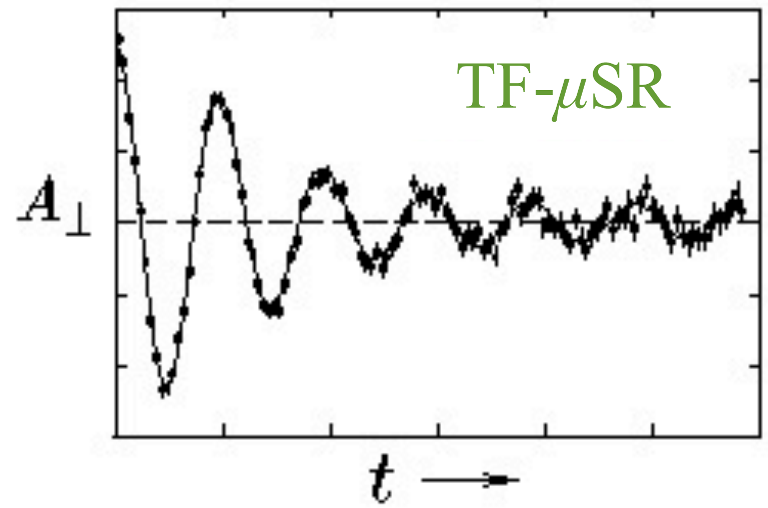
- *Opportunity*: TF *spectroscopy in high-field limit!*

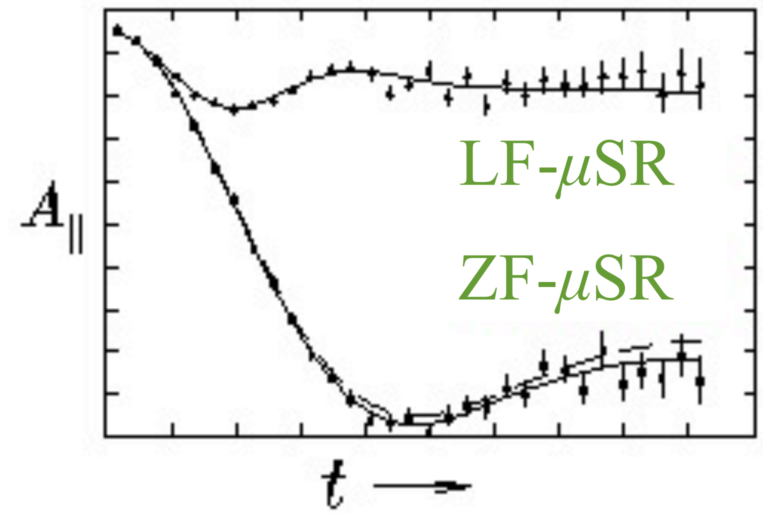
High Field μSR

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. **PSI**: 9.5 T spectrometer coming in 2011. **ISIS**: 5 T spectrometer (LF only).

Brewer's List of μSR Acronyms

Transverse Field

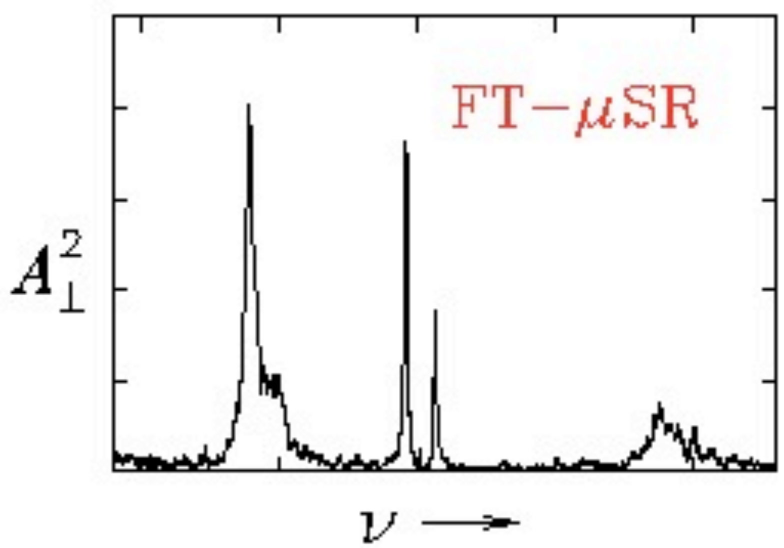


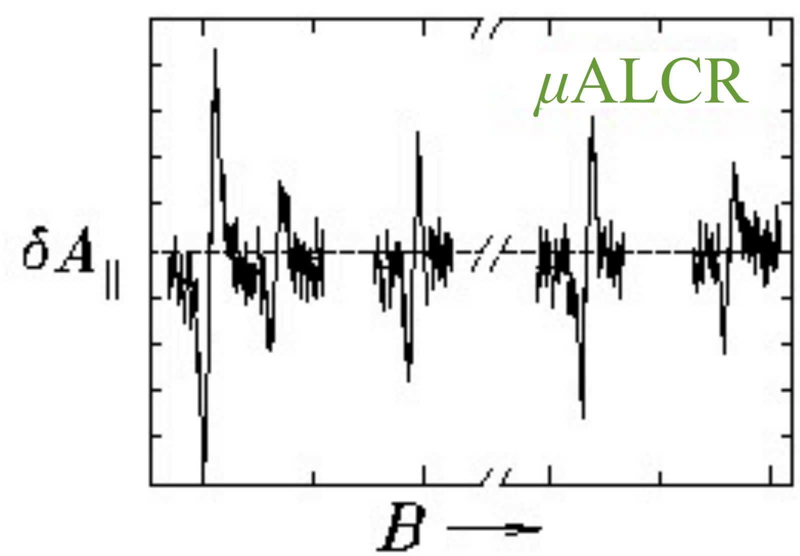


Longitudinal Field

Zero Field

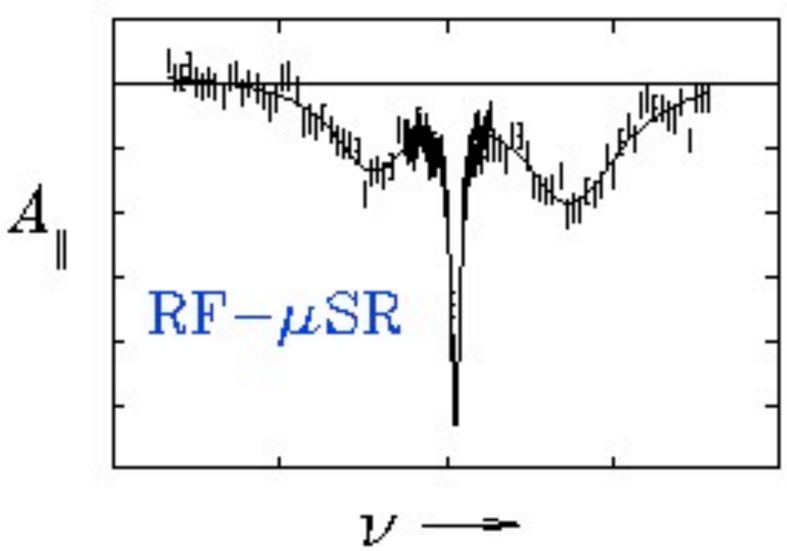
Fourier Transform μSR

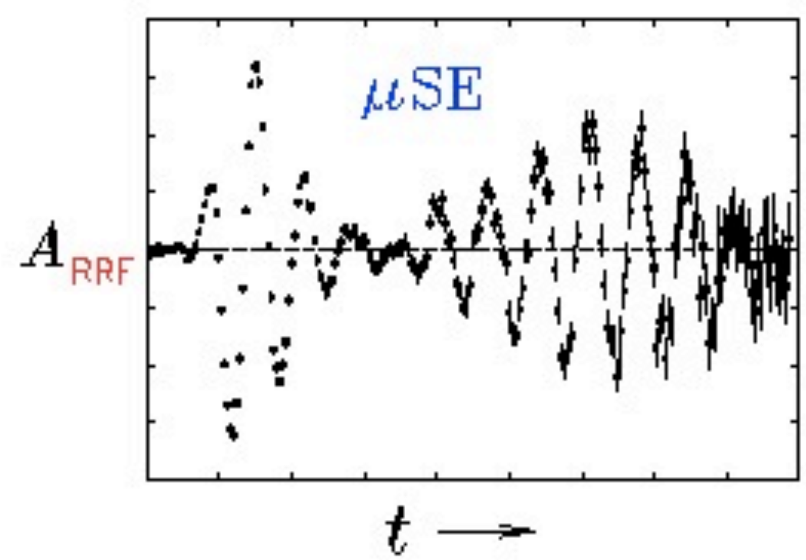




Avoided Level Crossing Resonance

Muon Spin Resonance





Muon Spin Echo

"Themes" in *μSR*

Muonium as light Hydrogen

($Mu = \mu^+e^-$) ($H = p^+e^-$)

- **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

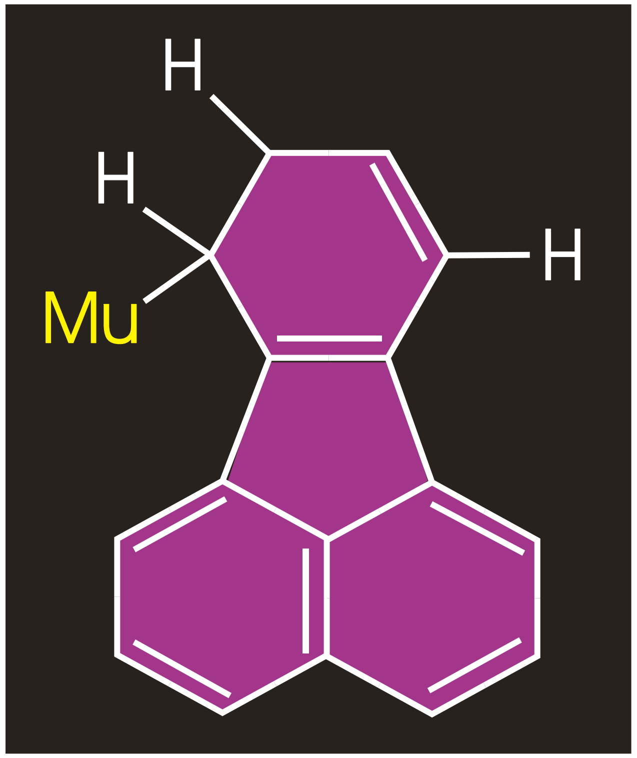
- **Probing Magnetism:** unequalled sensitivity

  - 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

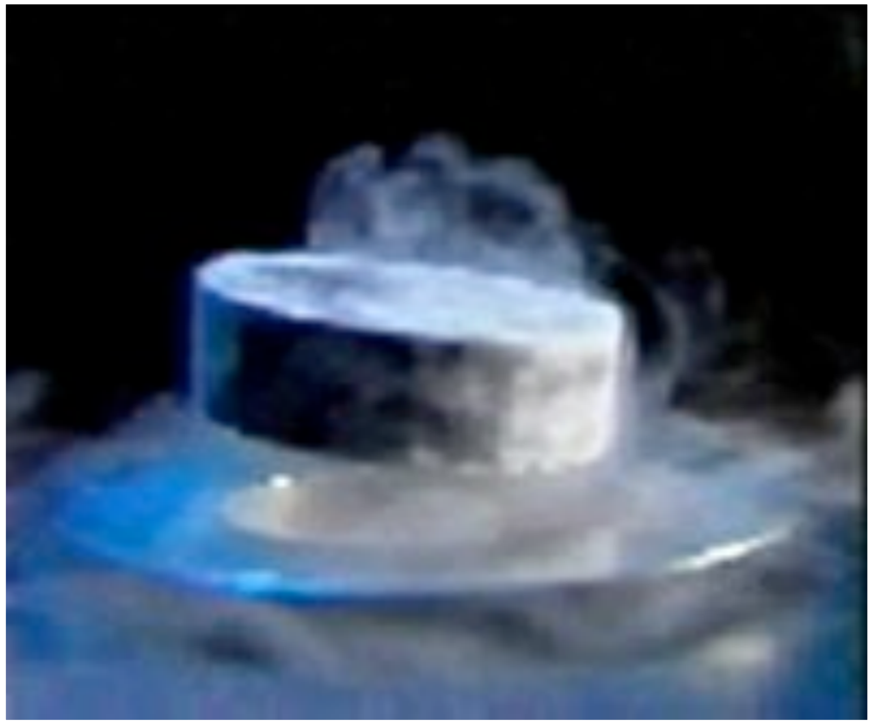
- **Quantum Diffusion:** μ^+ in metals (compare H^+); Mu in nonmetals (compare H).



Some 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.



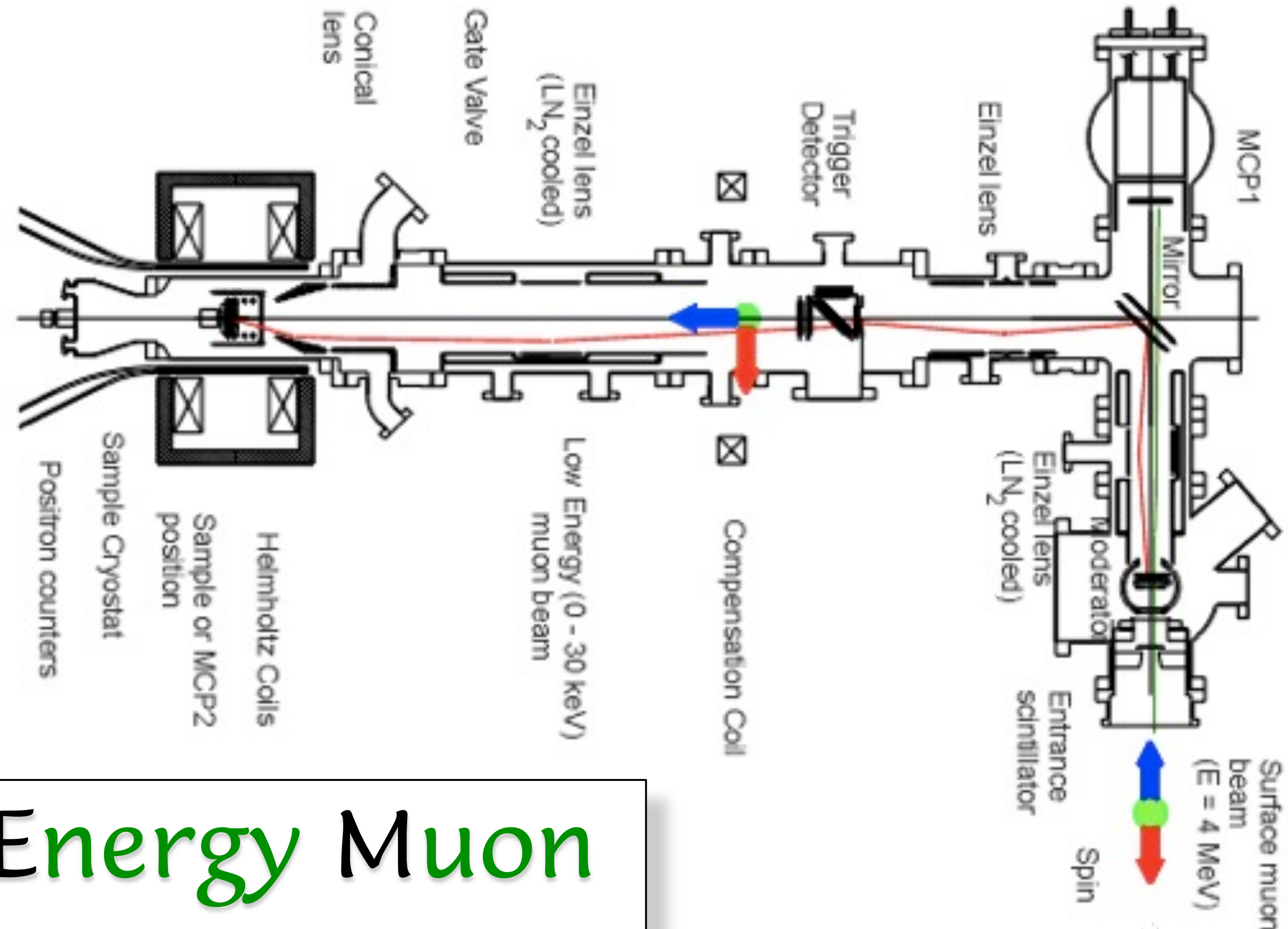
Finis

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:
  Chemistry & Semiconductors
  Magnetism & Superconductors
  Fundamental Physics
- FUTURE: Applied Science
  (No more magic? Don't count on it!)

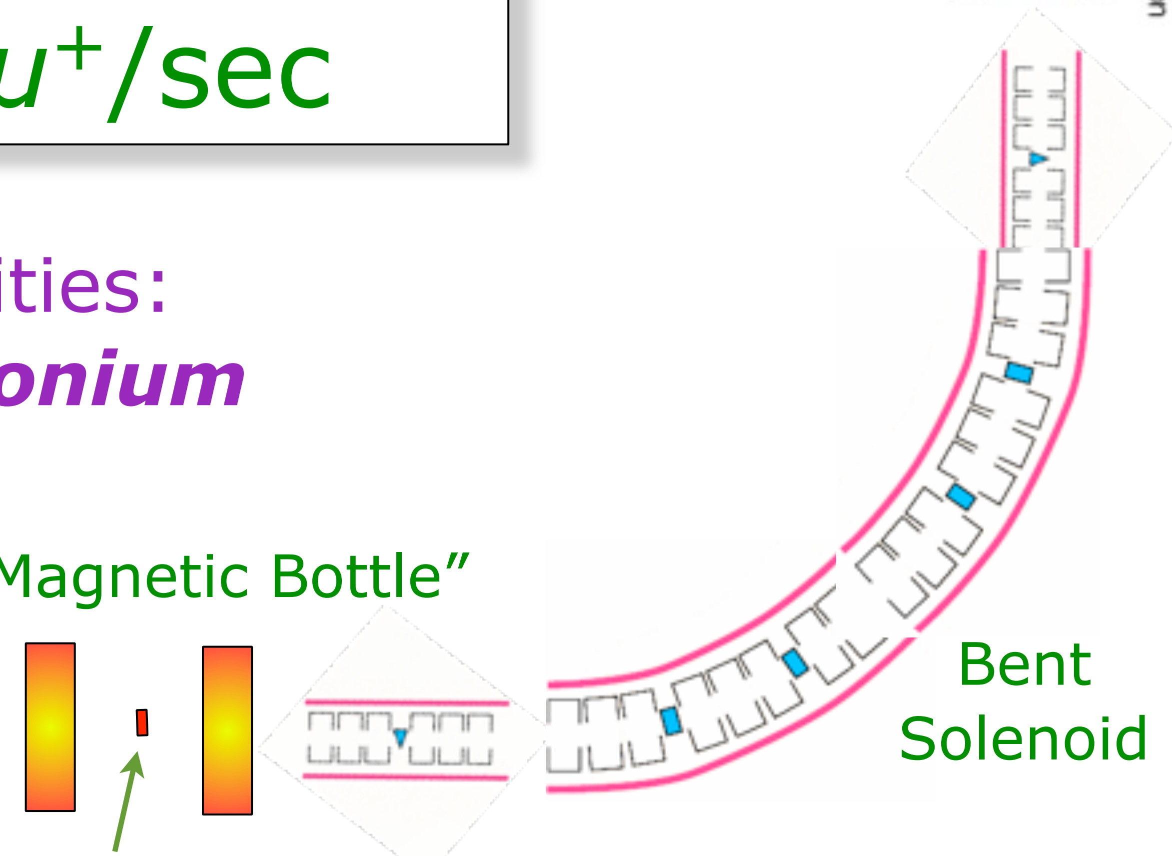
OR . . . re-accelerate
to ~ 500 keV and

focus on ***very*** small spot.
(**S**canning **M**uon **M**icroscope?)



High Flux, ultra-Low Energy Muon beam facility: >10^4 μ^+/sec

Alternative for *pulsed* facilities:
laser-ionized thermal muonium



New Science Opportunities

- Simply increasing Low Energy Muon intensity from 10^3 to 10^4 μ^+/s = a **huge** step for LE-μSR.
- Combined with β-NMR, probe thin films, multilayers, magnetic nanostructures, . . .
- Re-accelerate LEM to ~ 1 MeV → parallel beam can be focused onto μm-sized spot:

"Scanning μSR Microscope" (SMM)?