Muon Physics

TRIUMF Student Lecture
March 2013

Glen Marshall, TRIUMF

Outline

- **Introduction**

- **Review of muon physics**
  - What is a muon?
  - How are they made?
  - How do they decay?
  - Different physics of negative and positive muons

- **Key experiments with muons**

  (*with some emphasis on TRIUMF research)
  - Lifetime
  - Magnetic moment $(g-2)$*
  - Decay properties
    - normal decay*
    - rare or unobserved processes
  - Muonic atoms
  - Muon catalyzed fusion*

- **Summary**

Introduction

- Muons occupy a unique place among fundamental subatomic particles:
  - not part of "normal" matter, *i.e.*, not in the first particle "generation"
  - main constituent of cosmic rays at sea level
  - light in mass, thus easy to produce in abundance
  - charged, thus easy to detect
  - not influenced by the strong interaction (maybe a little!)
  - possess a built-in polarizer and analyzer (PNC)

- Muons are used to study fundamental interactions, or as tools in other areas of science (chemistry, condensed matter, atomic physics, nuclear fusion).

- High precision measurements (g–2, rare decay searches, *TWIST*) extend limits of knowledge of subatomic science.

The pattern of fermions

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	tau	1.777	–1

Quarks spin =1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.002	2/3
d	down	0.005	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	173	2/3
b	bottom	4.2	–1/3

Fermions (particles of half-integral spin) include leptons, which do not take part in the strong interactions, and quarks, which make up the strongly interacting hadrons. Three generations of each have been observed. The muon is the lightest charged particle beyond the first generation, thus it is the easiest to produce and study.

Properties of the muon

- The answers to the question, “What is a muon?” are summarized by the muon’s properties.

  (PDG RPP 2012 http://pdg.lbl.gov)

- But why is there a muon? Or, as I.I. Rabi is supposed to have said, “Who ordered that?”

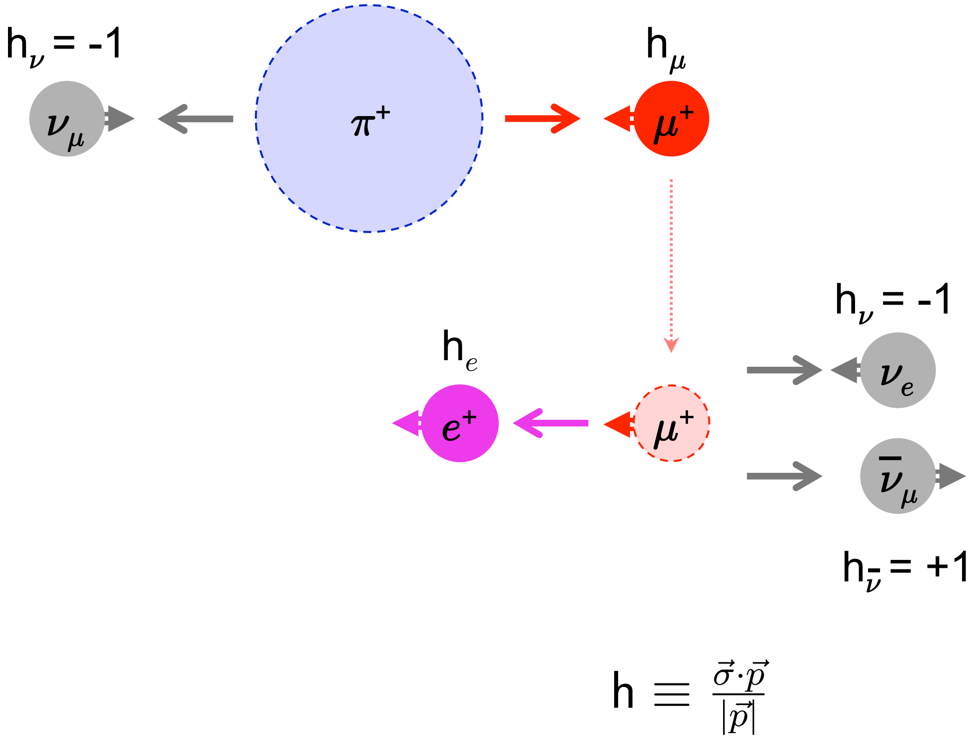
mass	m_μ	$105.6583715(35)$ MeV $0.1134289267(29)$ u ~ 206.8 m_e	
lifetime	τ_μ	$2.1969811(22)$ μs*	(μ^+)
spin	s_μ	$1/2$	
magnetic moment	μ_μ	$3.183345137(85)$ μ_p	
μ_μ anomaly	$\frac{(g-2)}{2}$	$11659208.9(5.4)(3.3) \times 10^{-10}$	
electric dipole moment	d_μ	$-1(9) \times 10^{-20}$ $e \cdot \mathrm{cm}$	
important decay modes		$\mu^- \to e^-\nu_\mu\bar{\nu}_e$ $\mu^- \to e^-\nu_\mu\bar{\nu}_e\gamma$ $\mu^- \to e^-\nu_\mu\bar{\nu}_e e^+ e^-$	$\sim 99\%$ $(1.4 \pm 0.4)\%$ $(3.4 \pm 0.4) \times 10^{-5}$
unobserved modes		$\mu^- \to e^-\nu_e\bar{\nu}_\mu$ $\mu^- \to e^-\gamma$ $\mu^- \to e^-e^+e^-$	$< 1.2\%$ $< 2.4 \times 10^{-12}$* $< 1.0 \times 10^{-12}$
capture		$\mu^- + p \to n + \nu_\mu$	

* Significant updates in past year J. Beringer et al., (Particle Data Group), Phys. Rev. D86, 010001 (2012)

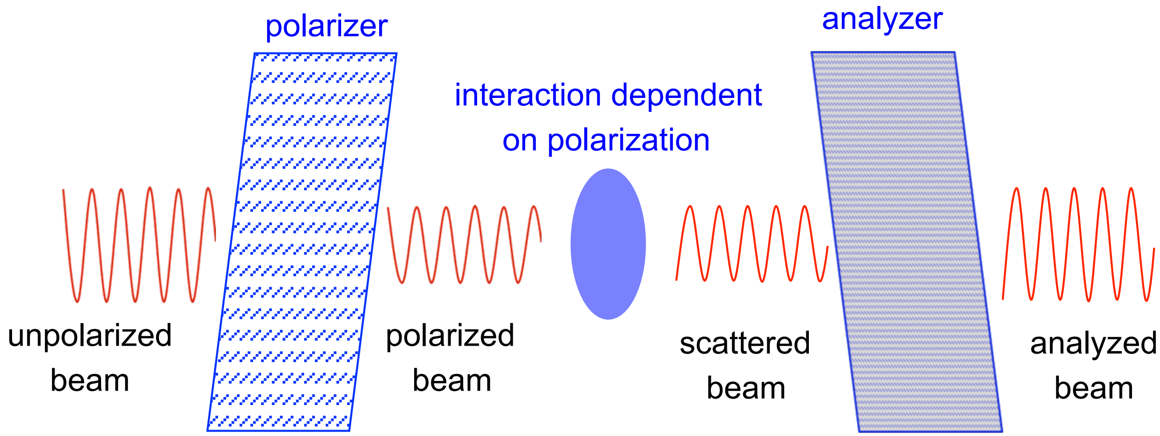
Neutrino helicity and muon polarization

- Top: The spinless pion decays at rest into a left-handed muon neutrino of definite helicity h = -1 and a muon. To conserve angular momentum, the muon must be completely polarized opposite to its direction of motion ($\mathcal{P}_\mu$= -1).

- Bottom: A muon decay positron is also correlated with the angular momentum of the muon in a more complicated way. Here, the positron with maximum energy takes the angular momentum of the decaying muon, since the left-handed electron neutrino and the right-handed muon antineutrino angular momenta cancel.

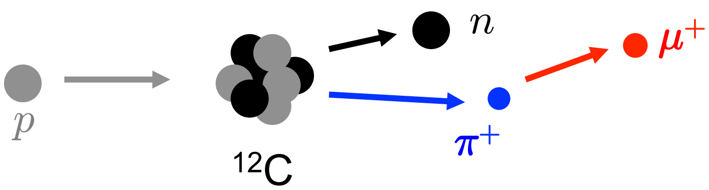


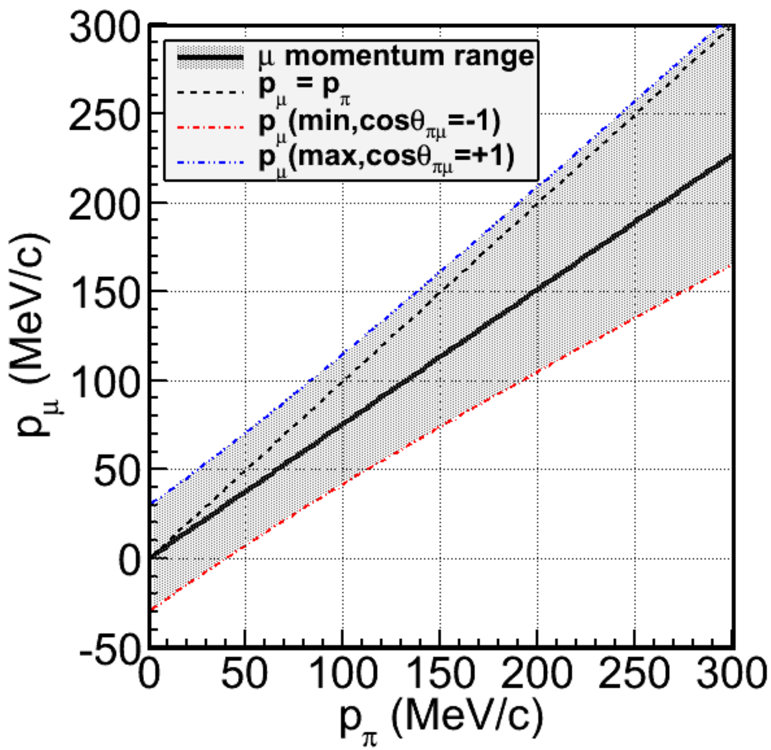
Polarization measurements



- The precision of a polarization measurement is limited by the qualities of the polarizer and analyzer.
- For a muon, the polarization $\mathcal{P}_\mu$ is the degree of correlation between the vectors of spin σ_μ and a given direction, such as the muon momentum $\boldsymbol{p}_\mu$ ("helicity") or a magnetic field direction.
- The muon has two advantages:
  - Due to parity violation in the weak interaction (the handedness of the (anti)neutrino), the muon can be produced with 100% polarization (except for small neutrino mass effects).
  - For a similar reason, polarized muon decay is highly asymmetric.

How are muons made at TRIUMF?

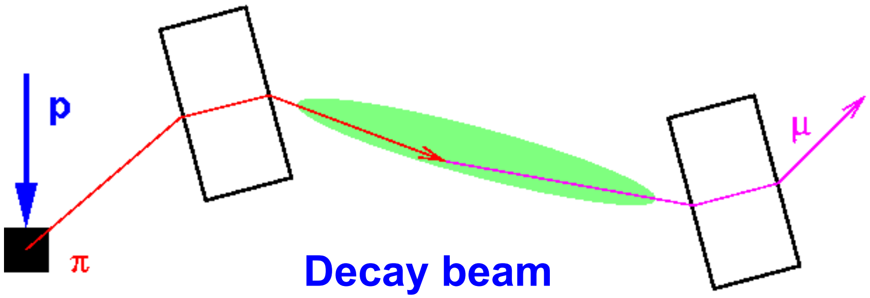




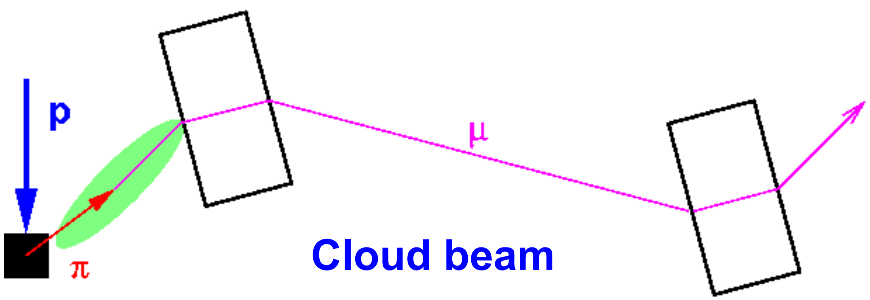
Range of decay muon momentum *vs.* pion momentum, showing extremes for forward ($\cos\theta_{\pi\mu}$=+1) and backward ($\cos\theta_{\pi\mu}$=-1) muons.

- Pions are produced by 500 MeV protons striking a production target of cooled graphite or Be metal.
- Muons are produced from the decay of pions (E_μ^k = 4.2 MeV in pion rest frame).
- The momentum of the muon is determined by the momentum of the pion and the angle of decay in the pion rest frame.
- There are three modes of muon production which are used, depending on where the pion decays:
  - decay muons (forward or backward).
  - cloud muons.
  - surface muons.
- Muons are also produced in decays of other particles (*e.g.* , kaons) at other accelerators.

Types of muon beams at TRIUMF

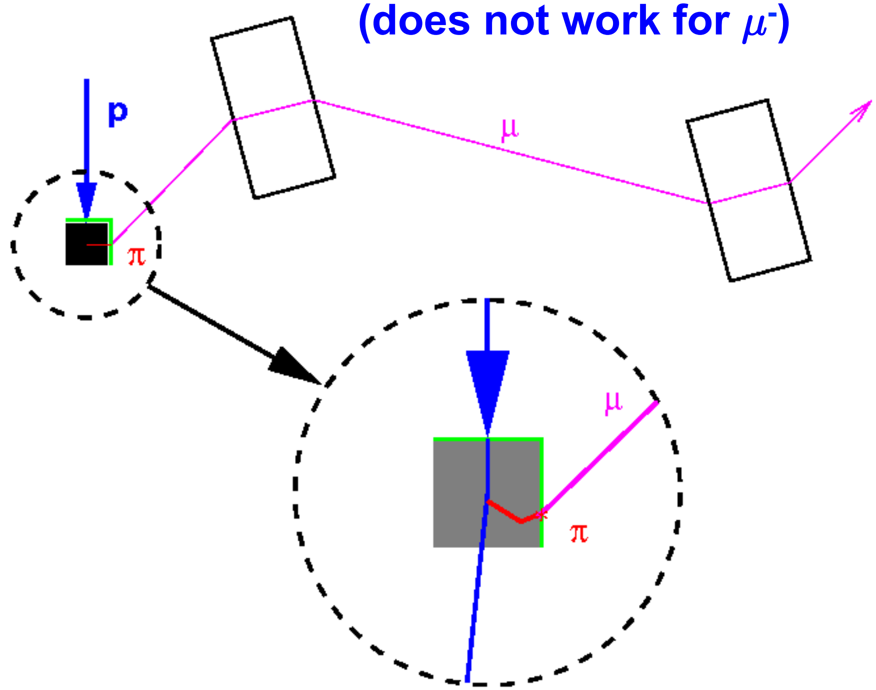


Decay beam



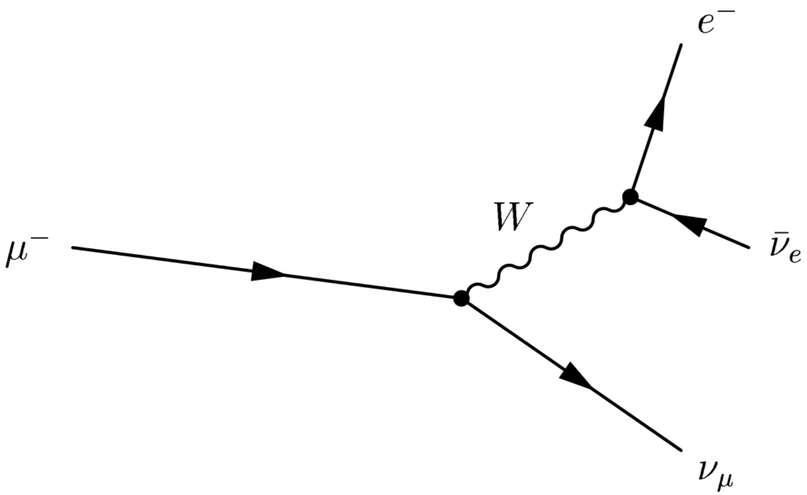
Cloud beam

Surface μ^+ beam
(does not work for μ^-)



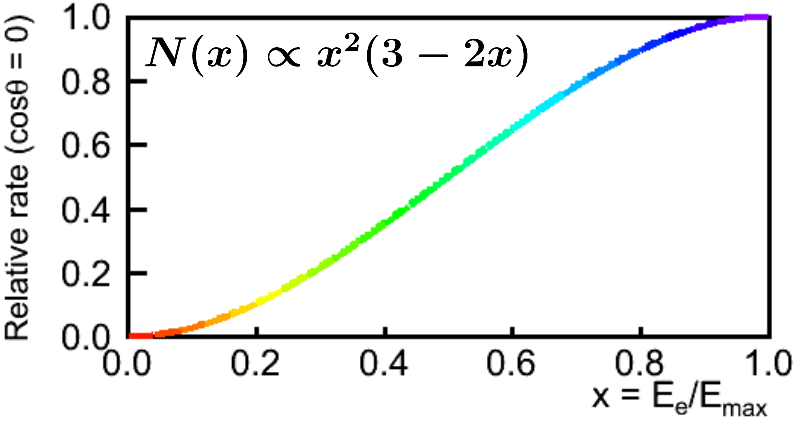
Surface muons have high polarization (opposite the direction of muon momentum) and high luminosity at low momentum (<29.79 MeV/c, or 4.1 MeV).

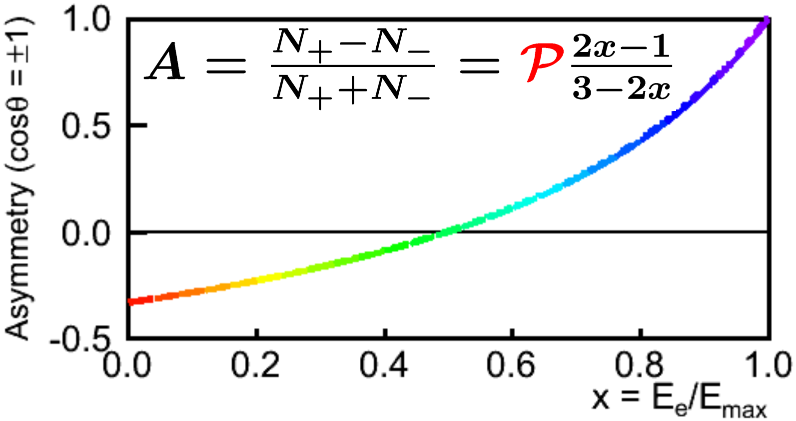
How do muons decay?

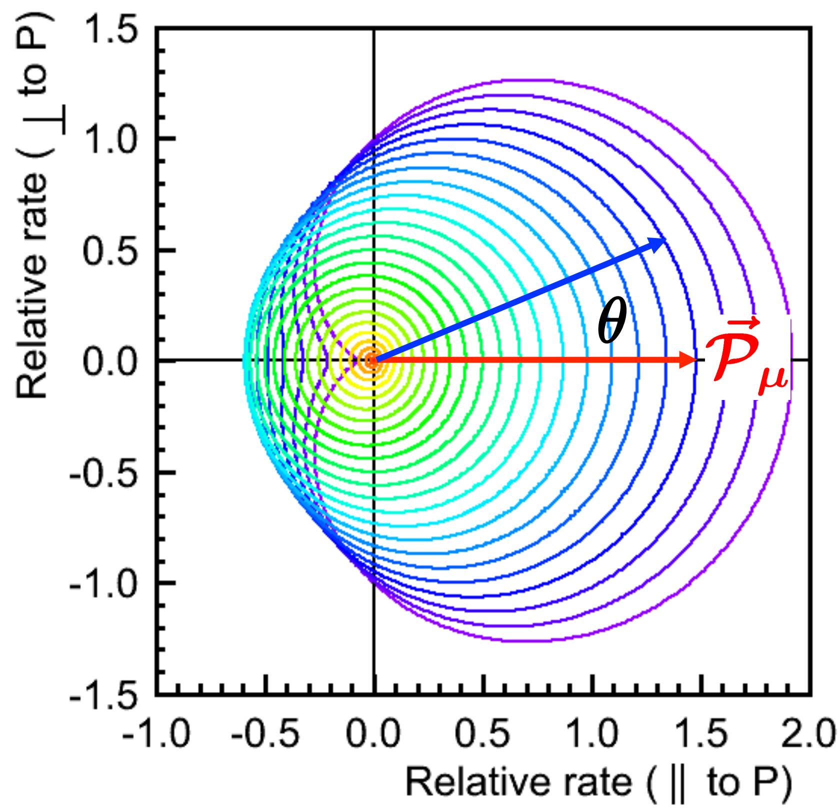


- Major decay mode (99%) for a free muon is:
  - $\mu^- \to e^- \nu_\mu \bar{\nu}_e$
  - $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$
- $m_W \gg m_\mu$, so the four-fermion interaction is a good approximation.
- The parity-violating weak interaction (V-A) describes the decay very well; this is what *TWIST* tested.

Relative decay rates and asymmetry

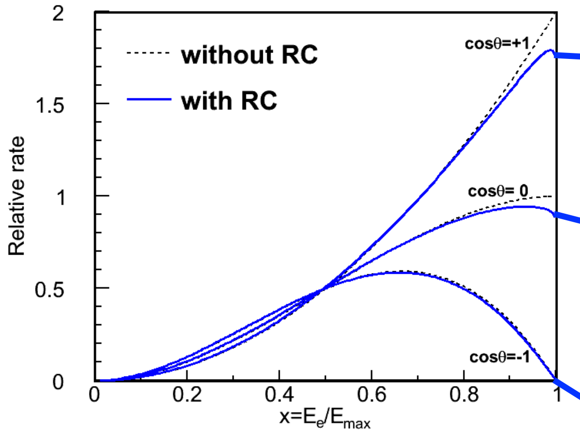




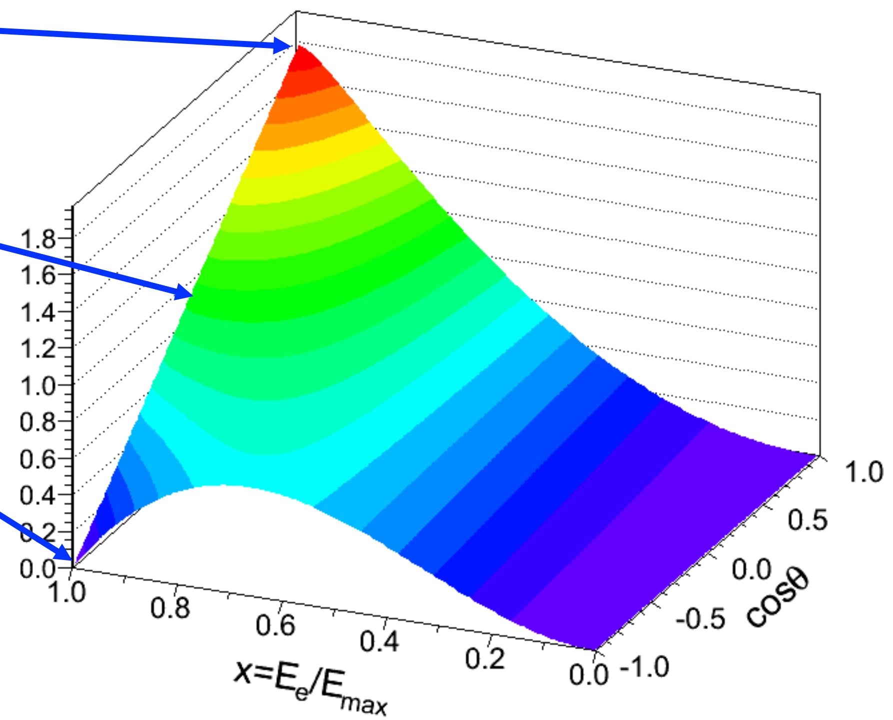


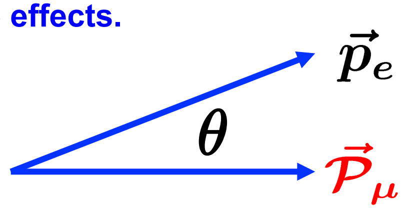
- Rate is maximum at highest energy for unpolarized (or cosθ=0) decays.
- Asymmetry changes sign at x=0.5
- Decay rate polargram shows limaçon shape.

Momentum distribution in μ^+ decay



Momentum distributions of e^+ in μ^+ decay, for different angles, showing the asymmetry and the corrections necessary due to radiative effects.





- **There are more e^+ of the maximum momentum in the direction of the muon polarization.**
- **The asymmetry $A \equiv (N_+ - N_-)/(N_+ + N_-)$ becomes unity for the extremes of energy and angle.**
- **The energy-integrated asymmetry is 1/3; angular integration reduces it to 1/6.**
- **Radiative processes are very important if the asymmetries are to be measured precisely.**

Differences of μ^+ and μ^-

- The μ^- and μ^+ are particle and antiparticle:
  - conjugate under charge inversion (C) to precision of observations,

    e.g. , $(\tau_{\mu^+} / \tau_{\mu^-}) - 1. = (2.4 \pm 7.8)\times 10^{-5}$ (Particle Data Group)
- Interactions with normal matter (*not* conjugate under C) very different at atomic eV-keV energies (chemistry):
  - μ^+ forms bound state with electron, *e.g.* ,

    $\mu^+ + \mathrm{Ar} \rightarrow \mu^+ e^- + \mathrm{Ar}^+$

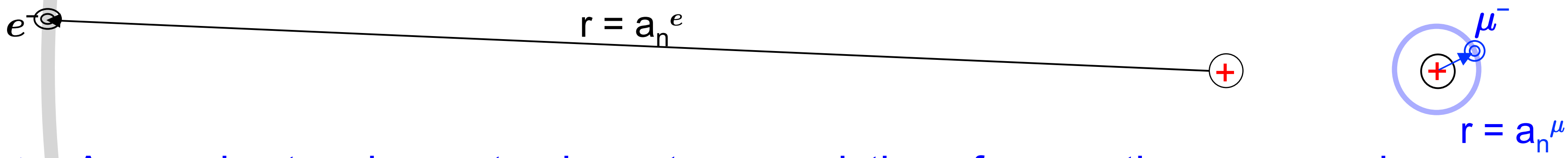
    where $\mu^+ e^-$ is the **muonium** atom, an analogue of the hydrogen atom, with similar chemical reactions.
  - μ^- forms bound state with a nucleus, *e.g.* ,

    $\mu^- + \mathrm{Ar} \rightarrow \mu^- \mathrm{Ar} + e^-$

    where μ^-Ar is a **muonic atom**, in which the muon occupies an atomic orbital independent of *and smaller than* the electronic atomic orbitals.

    $\Rightarrow$ The muon is significantly "inside" the nucleus; nuclear muon capture becomes likely.

Muonic atoms



- A muonic atom is an atomic system consisting of a negative muon and a positive nucleus, perhaps also containing electrons.

- How are the muon's special properties manifested in muonic atoms?
  - For a one electron (or muon) atom of nuclear charge Z and principal quantum number n:
    - the Bohr radius is given by $a_0 = \hbar / (mc\alpha)$.
    - the radius of the atom is $\langle a_n \rangle = n^2 a_0/Z$.
    - the corresponding binding energy is $E_n = -Z^2 e^2/(2\, a_0\, n^2)$.
  - $a_0^\mu = a_0^e/207$, and the muon is much closer to the nucleus in a muonic atom
  - The mass changes the scales of atomic properties, *e.g.* energy and size.

- The variety of interactions is very rich in physics content. In particular, the special case of muonic hydrogen isotopes ($p\mu$, $d\mu$, $t\mu$) leads to some very complex atomic and molecular systems ($dd\mu$, $dt\mu$,$(dt\mu)^+dee$) as well as muon-catalyzed fusion reactions ($dt\mu \rightarrow {}^4He^{2+} + n + \mu + 17$ MeV).

μ^- decay and nuclear muon capture

- A muon in a muonic atom will interact due to its proximity to the nucleus, via the weak semi-leptonic process:
  - μ^- + (Z,A) $\rightarrow \nu_\mu$ + (Z-1,A)
  - The final state can be an excited nuclear state.
- The capture rate of a muon by a nucleus depends on the charge Z, and is roughly proportional to Z^4.
- Capture reduces the mean lifetime of the muon from 2.197 μs:

Element	H	C	Si	Ca	Au
Z	1	6	14	20	79
Lifetime (μs)	2.195	2.02	0.81	0.33	0.073

Key experiments with muons

- Tests of Standard Model of particle physics:
  - Lifetime, to determine weak coupling constant, G_F.
  - Magnetic moment anomaly, $(g–2)/2$.
  - Decay distribution, $d^2\Gamma/(dE\, d\cos\theta)$.
  - Search for rare decays and charged lepton flavor violation:
    - muon-electron conversion, μ^- (Z,A) $\rightarrow e^-$ (Z,A)
    - $\mu^+ \rightarrow e^+ \gamma$
    - muonium conversion to antimuonium, $\mu^+ e^- \rightarrow \mu^- e^+$

- Muonic atoms
  - proton size from $\mu^- p$ energy level differences
  - fundamental precision muon nuclear capture experiments
    - *seminar by P. Kammel (UW) tomorrow at 14:00!*
- Muon catalyzed fusion
  - fusion of dt, dd , pt , *etc.*, from muonic hydrogen isotopes

Muon lifetime in the Standard Model

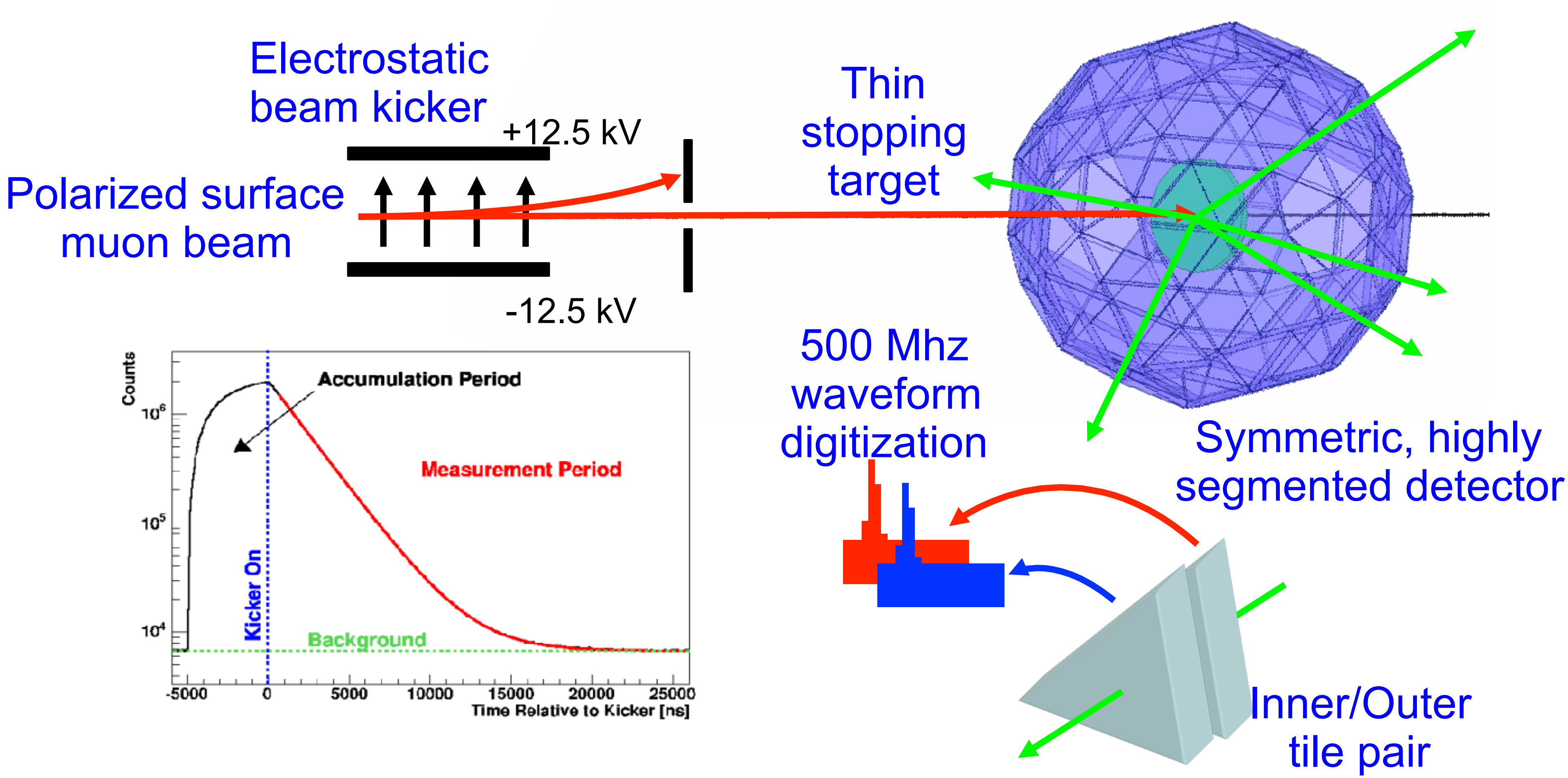
$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}(1 + \Delta q)$$

- Δq represents precisely calculable QED radiative corrections.
- G_F (the “Fermi coupling constant”) is a fundamental Standard Model parameter.

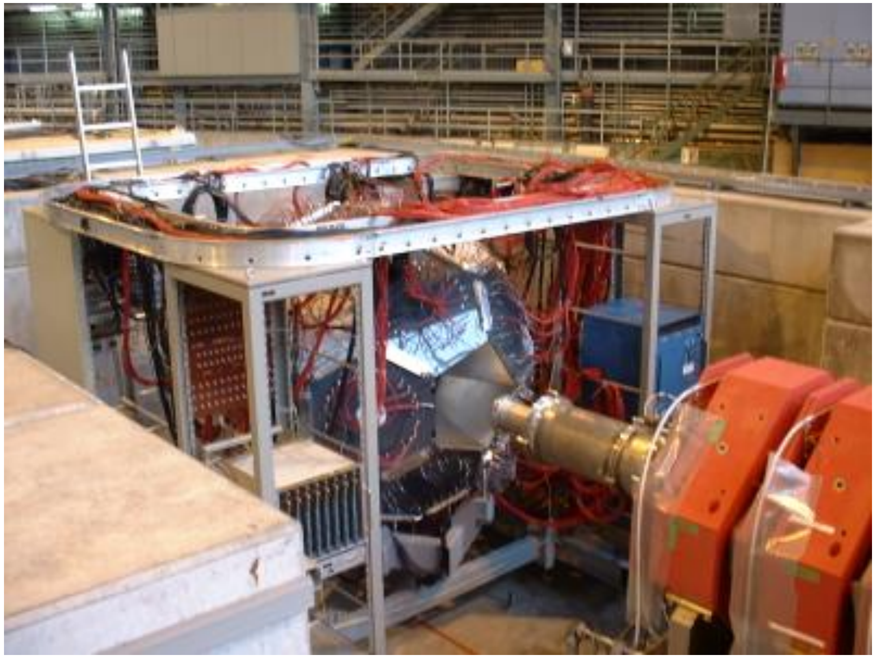
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}(1 + \Delta r(m_t, m_H, \ldots))$$

- Δr represents corrections dependent on Standard Model parameters that can be constrained.
- Two experiments at PSI in Switzerland, MuLan (completed) and FAST, devoted to measuring muon lifetime.

Muon lifetime: MuLan at PSI



Muon lifetime: MuLan at PSI



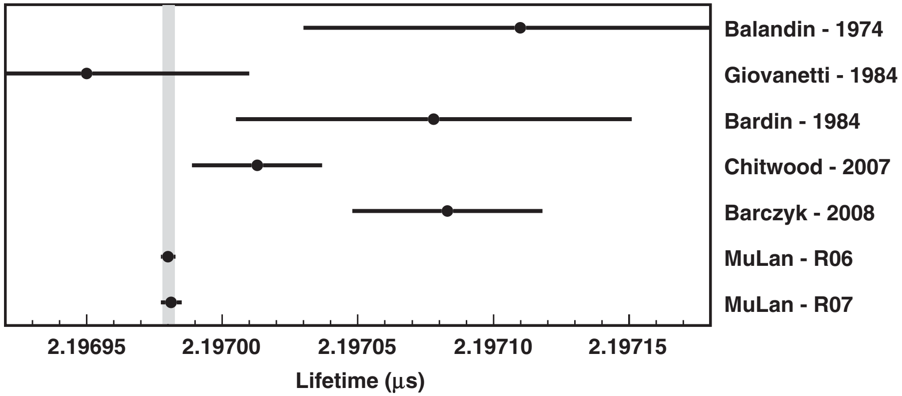


FIG. 2. Lifetime measurement summary. The MuLan R06 and R07 results are plotted separately to illustrate the consistency. The vertical shaded band is centered on the MuLan weighted average with a width equal to the combined uncertainty.

$$\tau_{\mu^+} = 2\ 196\ 980.3 \pm 2.2 \text{ ps (1.0 ppm)}$$

$$G_F = 1.166\ 378\ 8(7) \times 10^{-5} \text{ GeV}^{-2} \text{ (0.6 ppm)}$$

D.M. Webber et al., Phys. Rev. Lett. 106, 041803 (2011).

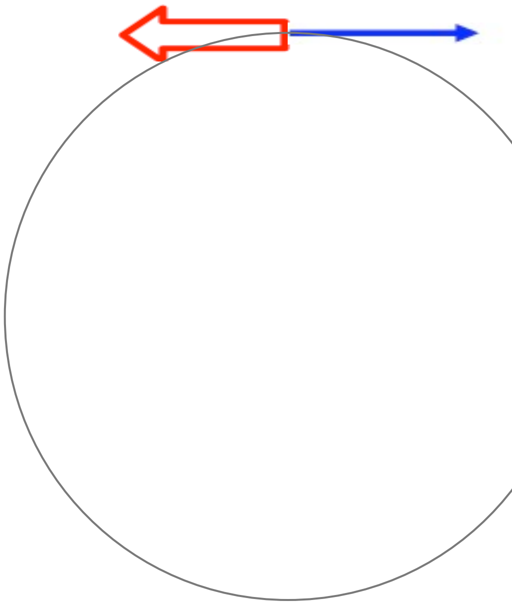
Measuring the muon magnetic moment

- The magnetic moment μ of a particle with spin is determined by its mass, charge, spin S and g-factor:

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S}$$

- For a Dirac particle $g \equiv 2$, but radiative corrections add an anomaly a:

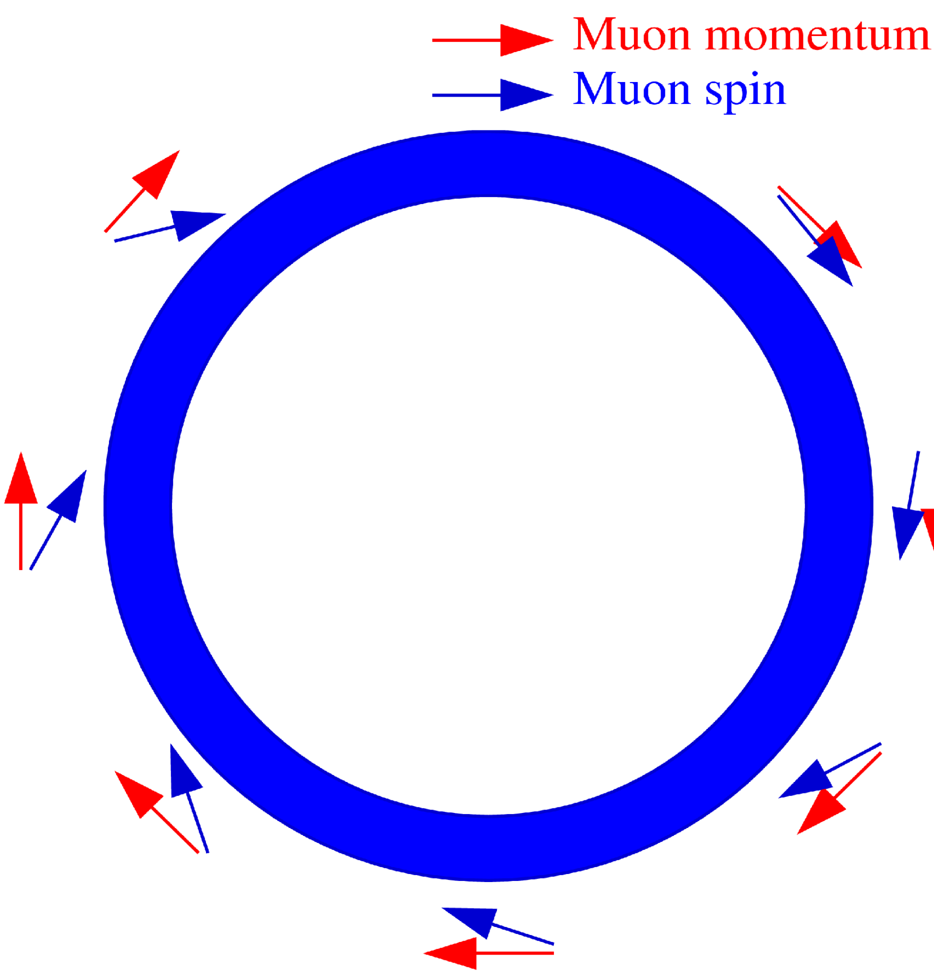
$$\mu = (1+a)\left(\frac{e\hbar}{2m}\right), \quad a \equiv \frac{g-2}{2}$$

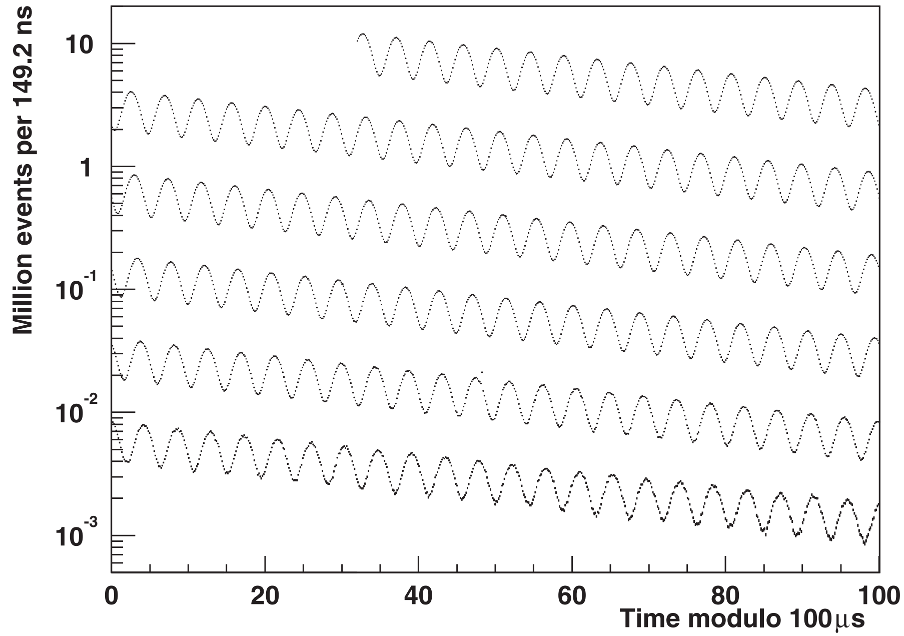


- For a muon with velocity perpendicular to a magnetic field B and electric field E, there will be cyclotron motion with frequency ω_c while the polarization will precess with frequency ω_s, with difference ω_a:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Muon magnetic moment: BNL E821

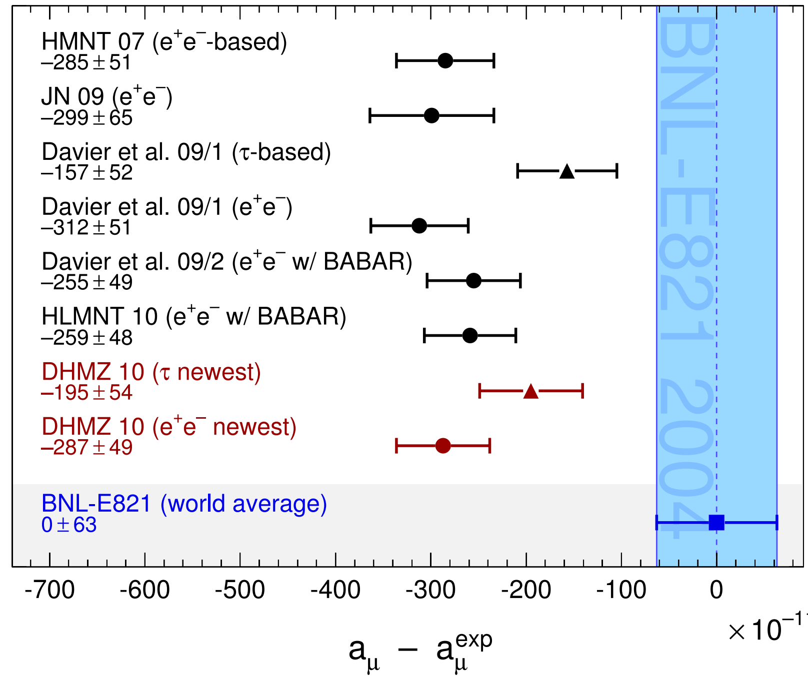




e^+ or e^- detectors inside the ring measure the frequency ω_a of muon spin rotation in the precise magnetic field B of the muon storage ring.

G.W. Bennett et al., Phys. Rev. D 73, 072003 (2006).

Status of measurement: 3.6σ difference



M. Davier et al. (DHMZ), Eur. Phys. J. C 71, 1515 (2011)
K. Hagiwara et al. (HLMNT), J. Phys. G 38, 085003 (2011)
G.W. Bennett et al., Phys. Rev. D 73, 072003 (2006)

$$a_\mu^{\mathrm{E821}} = 116\,592\,089(54)(33) \times 10^{-11}$$
$$a_\mu^{\mathrm{SM}} = 116\,591\,802(2)(42)(26) \times 10^{-11}$$
$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 287(63)(49) \times 10^{-11}$$

An improved experiment is proposed in the USA for FNAL, similar to BNL E821.
A competitive yet quite different experiment has also been proposed at J-PARC in Japan.

a_μ beyond the standard model

- Muon g–2 is sensitive to parameters of a variety of new physics, e.g.:
  - SUSY parameters μ and tan β

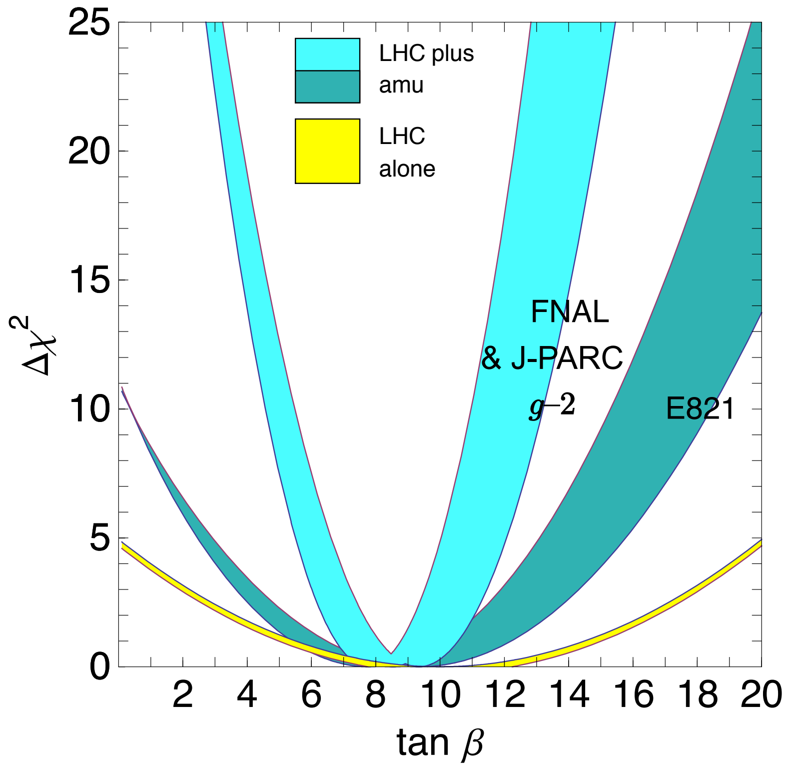
$$a_\mu^{SUSY} \sim (\text{sgn}\mu) \cdot 13 \times 10^{-10} \left(\frac{100\ GeV}{\tilde{m}}\right) \tan\beta$$

Dominik Stockinger, J. Phys. G 34, R45 (2007).
Andrzej Czarnecki and William J. Marciano, Phys. Rev. D 64, 013014 (2001).

  - "charged see-saw models"

K. Kannike et al., arXiv:1111.2551v2, February 2012.

- Many suggested theories predict Δa_μ to be large or small
  - a more precise measurement, even if consistent with zero, can discriminate between interpretations of LHC data
- May provide constraints on new theories not accessible to LHC verification



A "blueband" plot showing the LHC and muon g–2 sensitivities to tan β.

B. Lee Roberts, arXiv:1001.2898v2, January 2010.

Two new proposals: Fermilab and J-PARC

Fermilab (similar to BNL)

$$-\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

- eliminate effect of E-field via "magic" momentum:
  - $\gamma^2 = 1 + a^{-1}$
  - p_μ = 3.09 GeV/c
- very uniform B
- electric quad field focusing
- B = 1.45 T, ρ = 7 m

J-PARC

$$-\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

- eliminate effect of E-field via E = 0
- very uniform B, smaller magnet
- no focusing – must use "ultracold" μ beam
- choose p_μ = 0.3 GeV/c
- B = 3 T, ρ = 0.33 m
- systematics different than BNL or Fermilab

J-PARC $g-2$ ingredients

Muon beam:

High luminosity surface muon transport delivers beam for muonium production (also for DeeMee).

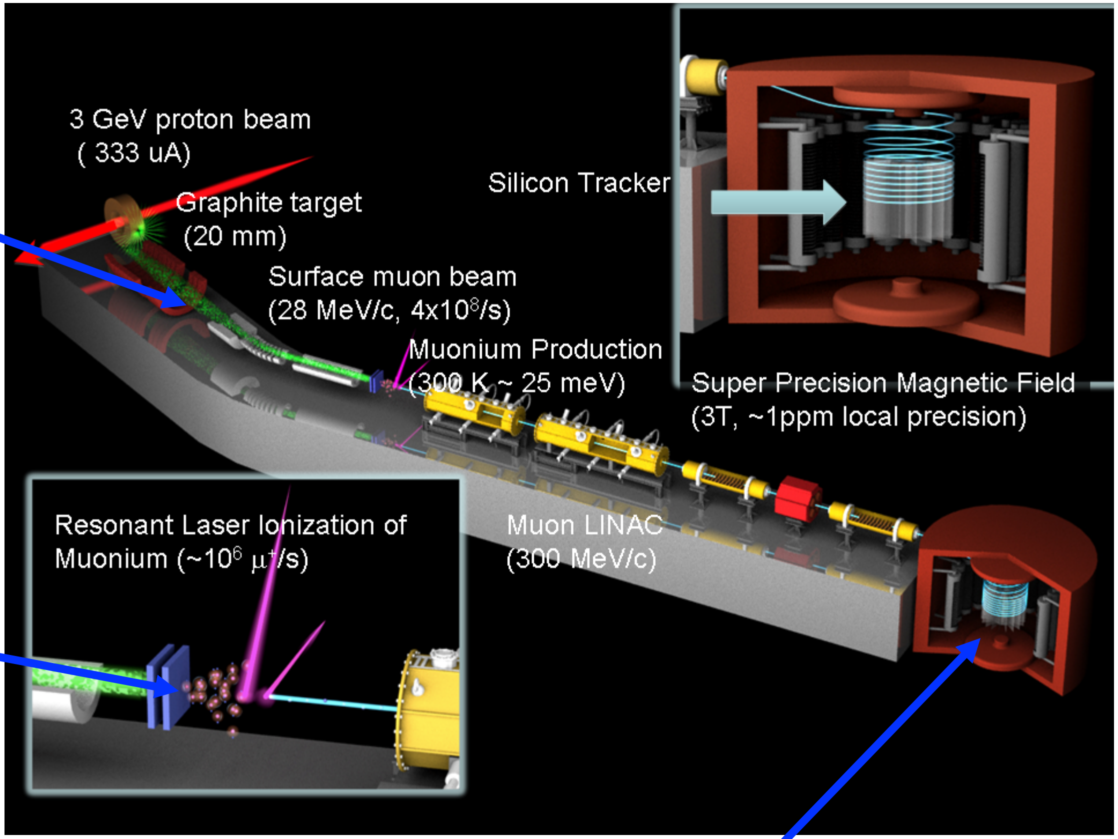
⇒ Beam line designed at TRIUMF (J. Doornbos).

Cold μ^+ ion source:

Muonium (μ^+e^-) must be in a vacuum environment to permit laser ionization.

⇒ Method of μ^+e^- emission into vacuum from silica layers was developed largely at TRIUMF.

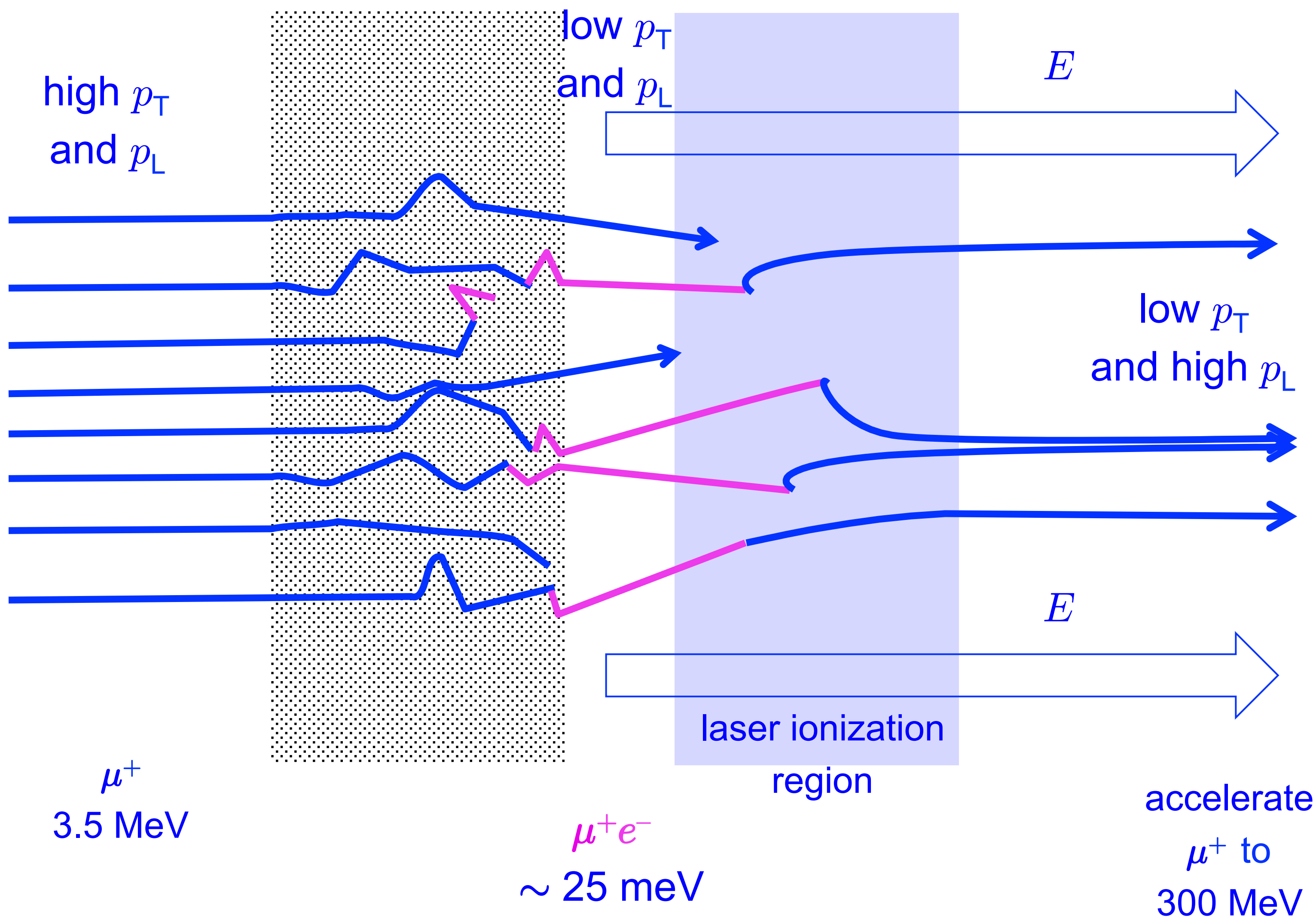
⇒ TRIUMF S1249 continues to characterize emission from silica aerogel.



Decay positron detection:

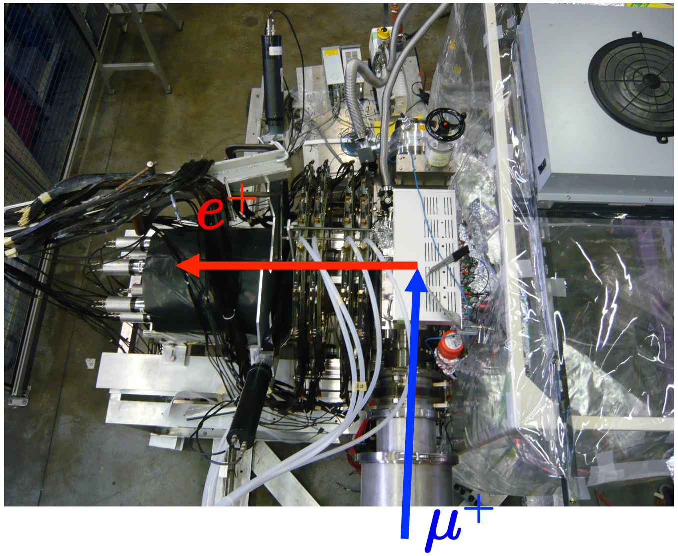
Precision tracker uses double-sided silicon strip detectors.

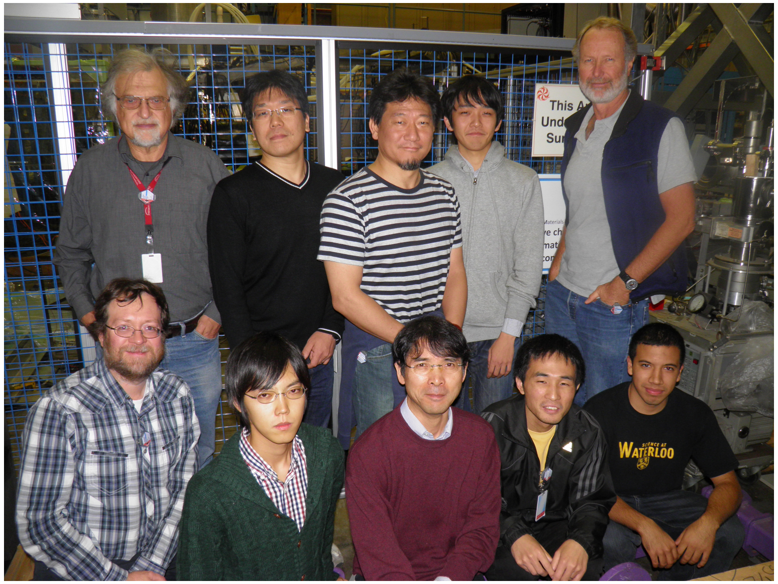
μ^+ ion source: thermal μ^+e^- in vacuum



S1249 in M15 muon beam at TRIUMF

- S1249
  - KEK-RIKEN-TRIUMF collaboration
  - Goal is to find best material for production of muonium in vacuum for J-PARC $g\text{–}2$ experiment
  - Preliminary μSR experiment (June 2010) showed aerogel was promising
    - self-supporting, uniform
    - high muonium formation probability
    - high specific surface area (~ 400 m^2/g, 3 nm scale)
- November 2010
  - one week only − accelerator problem
  - RIKEN vacuum system, TRIUMF MWDCs, KEK MCP
- October 2011
  - several aerogel targets to search for possible density enhancement
  - solid silica glass plate for background estimates

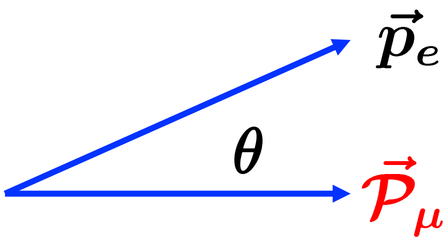


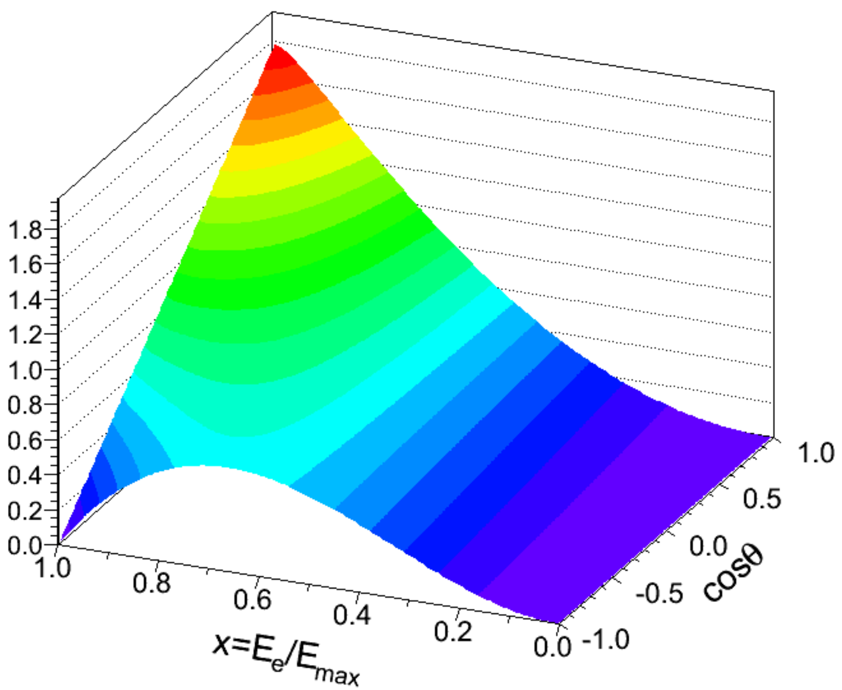


Muon decay distribution: *TWIST*

$$\frac{d^2\Gamma}{dx\ d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot \{\mathcal{F}_{IS}(x, \rho, \eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x, \xi, \delta)\}$$

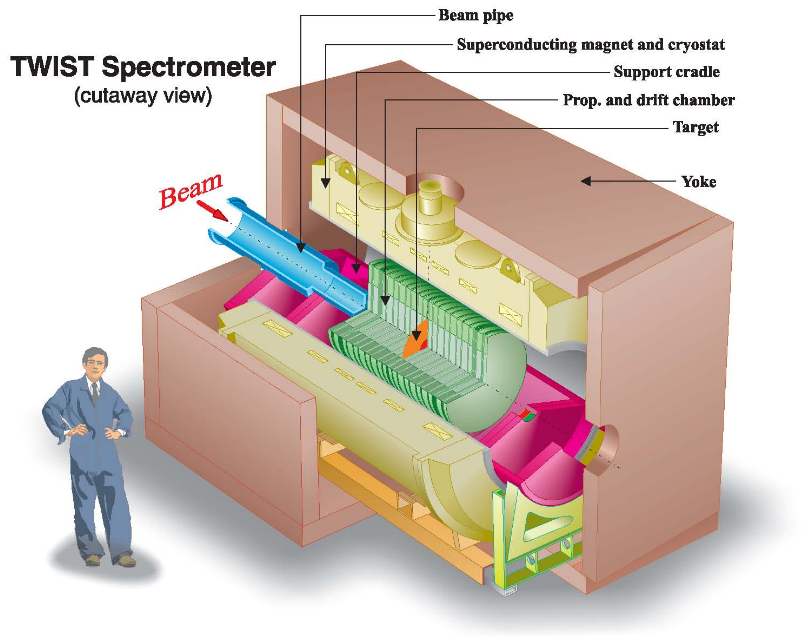
$$W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu}, x = \frac{E_e}{W_{\mu e}}, x_0 = \frac{m_e}{W_{\mu e}}$$

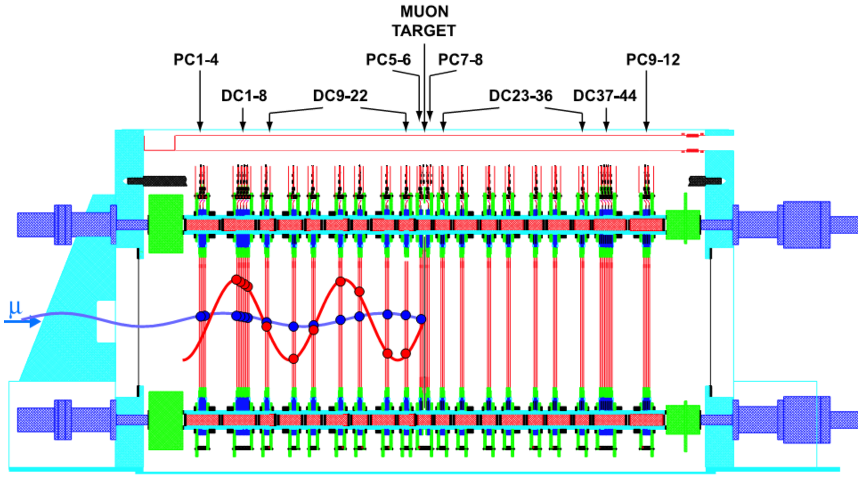




- Standard Model:
  - ρ = 0.75, η = 0.
  - $\mathcal{P}_\mu\xi$ = 1.0, δ = 0.75
- Deviations test:
  - "handedness" of the muon
  - left-right-symmetric (LRS) SM extensions

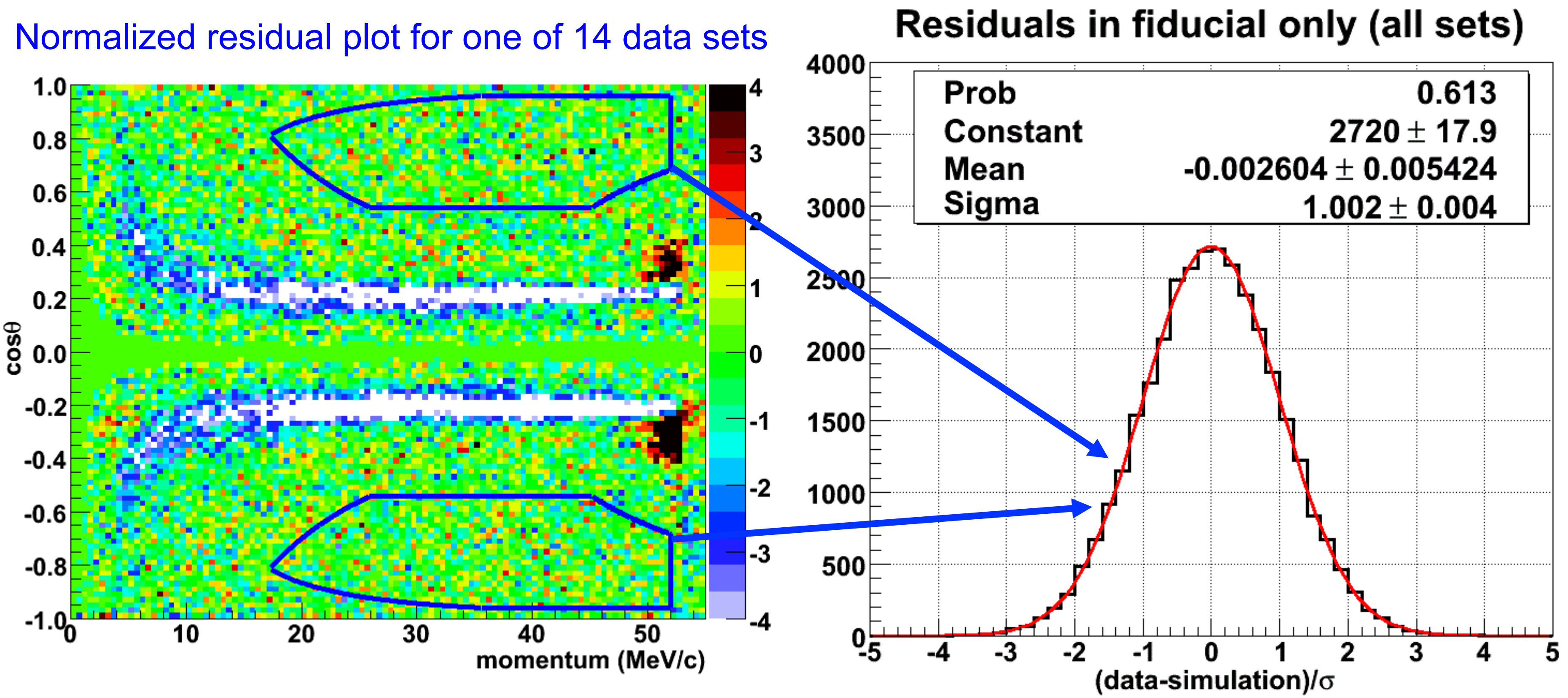
TWIST detector





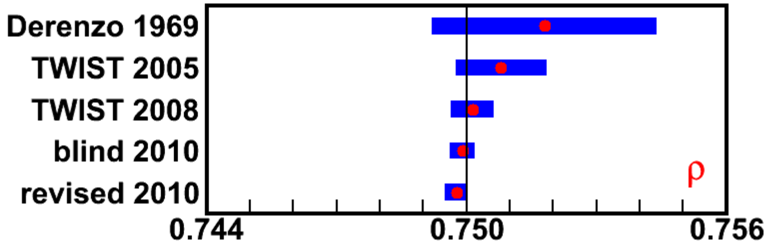
- Fit decay e^+ track distribution in p and $\cos\theta$ to detailed simulation (blind analysis).

TWIST data

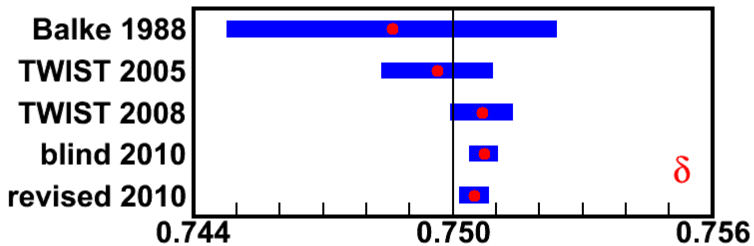


- All data sets: $\mathbf{11\times10^9}$ events, $\mathbf{0.55\times10^9}$ in $(p, \cos\theta)$ fiducial
- Simulation sets: **2.7** times data statistics

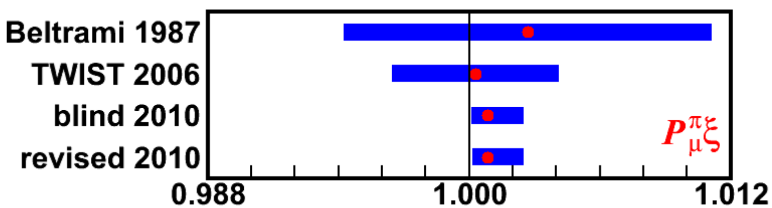
Decay parameter results



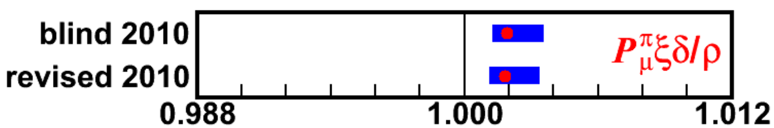
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)
(<1σ from SM)



δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)
(+1.4σ from SM)



$\mathcal{P}_\mu^\pi\xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)
(+1.2σ from SM)

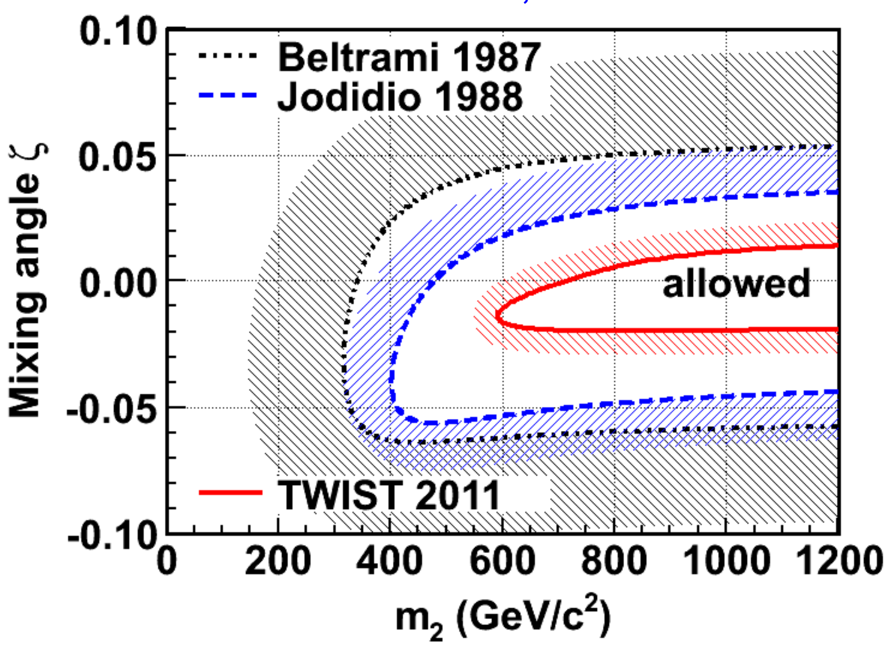


$\mathcal{P}_\mu^\pi\xi\delta/\rho$ > 0.99909 (90%CL)
from global analysis

TWIST Collaboration, R. Bayes et al., Phys. Rev. Lett. 106, 041804 (2011).

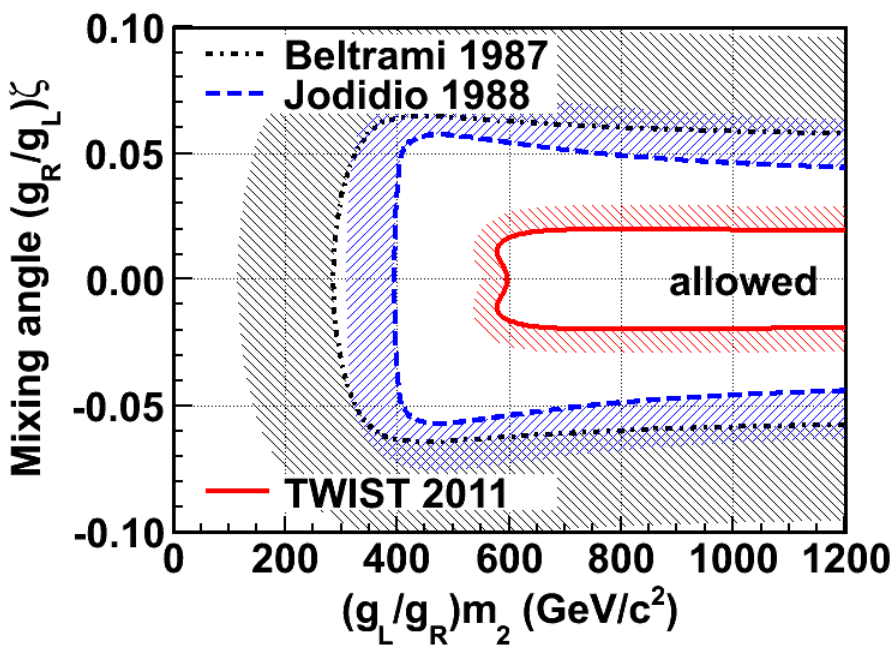
Left-Right Symmetric limit comparison

"manifest" LRS, 90%CL



$m_2 > 592$ GeV/c²
$-0.020 < \zeta < +0.017$

generalized or non-manifest LRS, 90%CL



$(g_L/g_R)m_2 > 578$ GeV/c²
$-0.020 < (g_R/g_L)\zeta < +0.020$

- W' direct search mass limits
  - ATLAS: >1.49 TeV/c², 95%CL (LLWI11)
  - CMS: >1.58 TeV/c², 95%CL (LLWI11)
  - CMS: >1.36 TeV/c², 95%CL (2011)
  - CDF: >1.12 TeV/c², 95%CL (2011)
  - D0: >1.0 TeV/c², 95%CL (2008)

- Some limits on mixing angle ζ (MLRS only)
  - Hardy and Towner: <0.0005 (MLRS), <0.04 (generalized)
  - K decay: <0.004 (MLRS)

Global analysis result

- Include new results with other muon decay observables to restrict coupling constants
  - summary of all terms (pre-*TWIST* in parentheses)

$$
\begin{array}{lll}
|g^S_{RR}| < 0.035\ (0.066) & |g^V_{RR}| < 0.017\ (0.033) & |g^T_{RR}| \equiv 0 \\
|g^S_{LR}| < 0.050\ (0.125) & |g^V_{LR}| < 0.023\ (0.060) & |g^T_{LR}| < 0.015\ (0.036) \\
|g^S_{RL}| < 0.420\ (0.424) & |g^V_{RL}| < 0.105\ (0.110) & |g^T_{RL}| < 0.105\ (0.122) \\
|g^S_{LL}| < 0.550\ (0.550) & |g^V_{LL}| > 0.960\ (0.960) & |g^T_{LL}| \equiv 0
\end{array}
$$

  - influences mostly right-handed muon terms

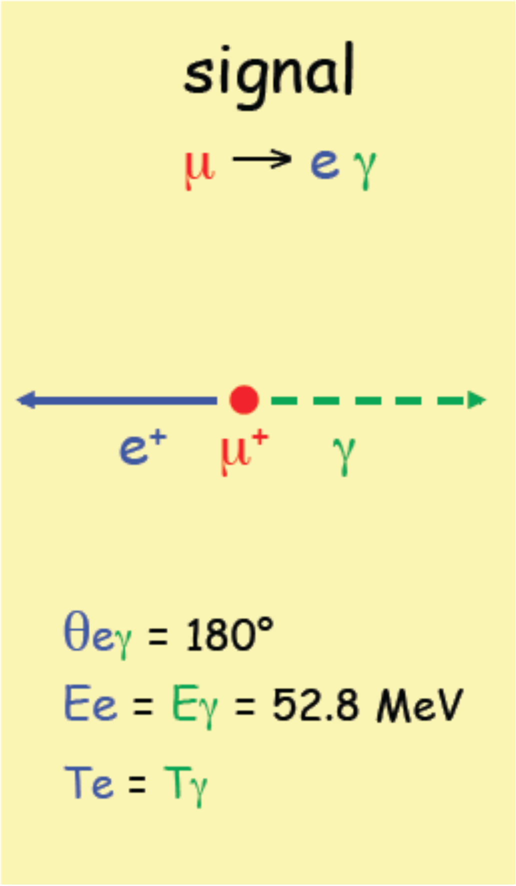
$$
\begin{aligned}
Q^\mu_R &= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \\
&= \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \\
&< 8.2 \times 10^{-4} \quad (90\%\text{C.L.})
\end{aligned}
$$

Rare decays of muons

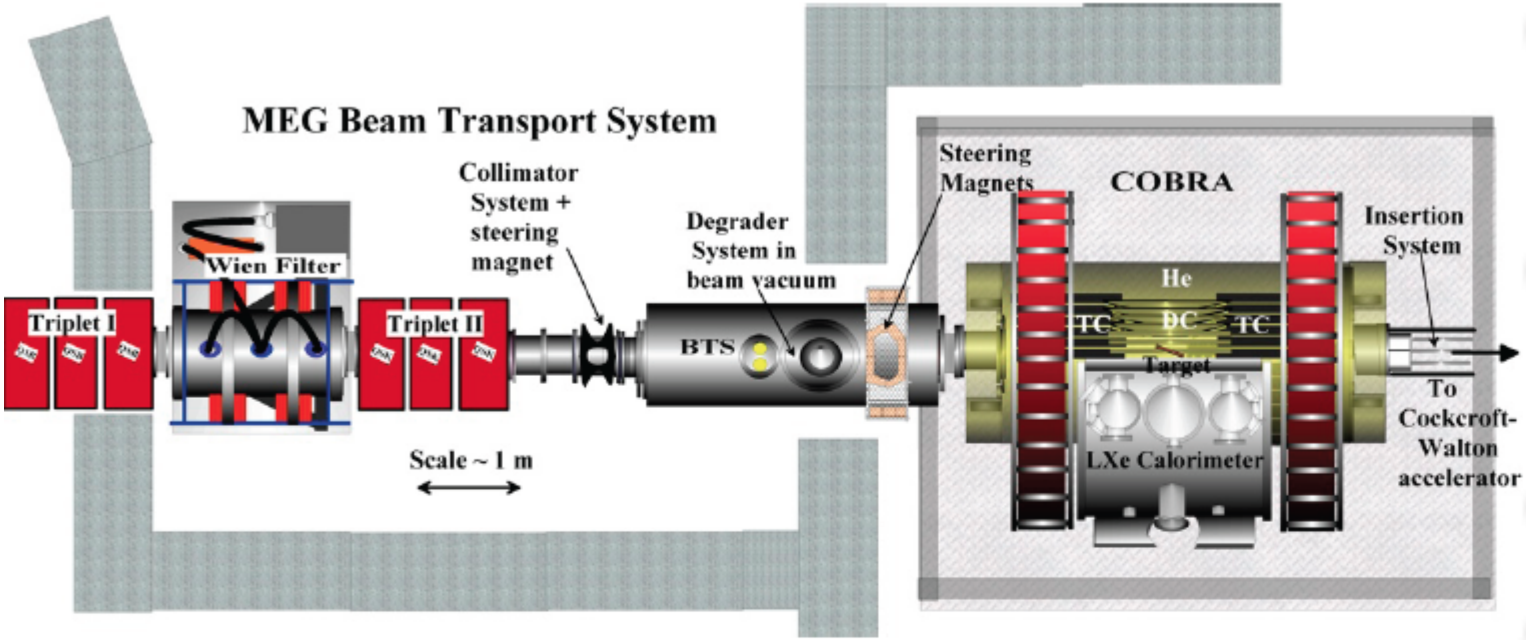
- Rare decays and charged lepton flavor violation:
  - violate lepton family number conservation
  - predicted "just beyond existing limits" in many SM extensions
  - $\mu^+ \rightarrow e^+ \gamma$
    - $\Gamma(e\gamma)/\Gamma(\text{all}) <$ **1.2×10^{-11}**
    - new experiment in progress at PSI (MEG): < **2.4×10^{-12}**
  - muon-electron conversion, μ^- (Z,A) $\rightarrow e^-$ (Z,A)
    - $\sigma(\mu^-\text{Ti} \rightarrow e^-\text{Ti})/\sigma(\mu^-\text{Ti} \rightarrow \text{capture}) <$ **4.3×10^{-12}**
    - $\sigma(\mu^-\text{Au} \rightarrow e^-\text{Au})/\sigma(\mu^-\text{Au} \rightarrow \text{capture}) <$ **7×10^{-13}**
    - new experiments proposed in USA (mu2e at FNAL) and in Japan (COMET at J-PARC)
  - muonium conversion to antimuonium, $\mu^+ e^- \rightarrow \mu^- e^+$
    - $G_C/G_F < 0.003$

$\mu \rightarrow e\,\gamma$

- Signal is coincident e and γ
- Background
  - $\mu \rightarrow e\,\nu\,\nu\,\gamma$
  - accidental γ with e
- ➔ need good energy resolution, good timing



MEG at PSI



- Use graded magnetic field to reduce pile-up
- Drift chambers for e
- LXe for photon calorimeter
- Goal is $\lesssim 10^{-13}$
- New result $< 2.4\times10^{-12}$ (90%CL)
  - J. Adam et al., Phys. Rev. Lett. 107, 171801 (2011).

Muon-electron conversion

- μ^- (Z,A) $\rightarrow e^-$ (Z,A)
- signal is e^- with energy equal to muon rest mass minus muonic atom binding energy ($\sim$100 MeV)
- background is high energy tail of normal muon decay-in-orbit
- ➔ maintain energy resolution, reduce other backgrounds
- (μ^-Au $\rightarrow e^-$Au$_{gs}$) per μ^- capture: $< 7\times10^{-13}$

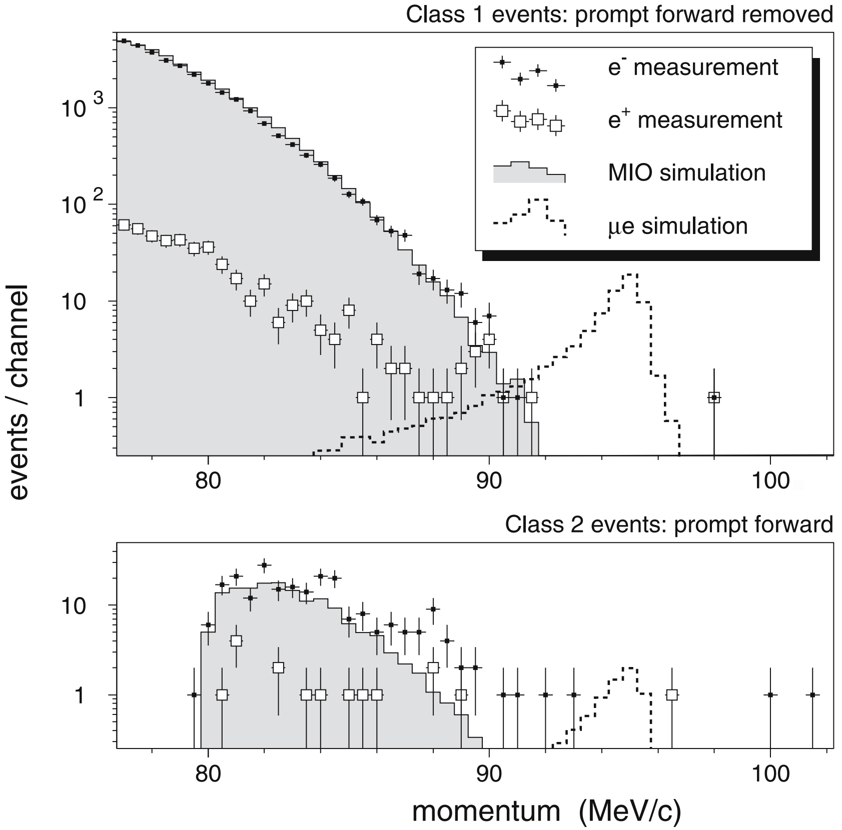
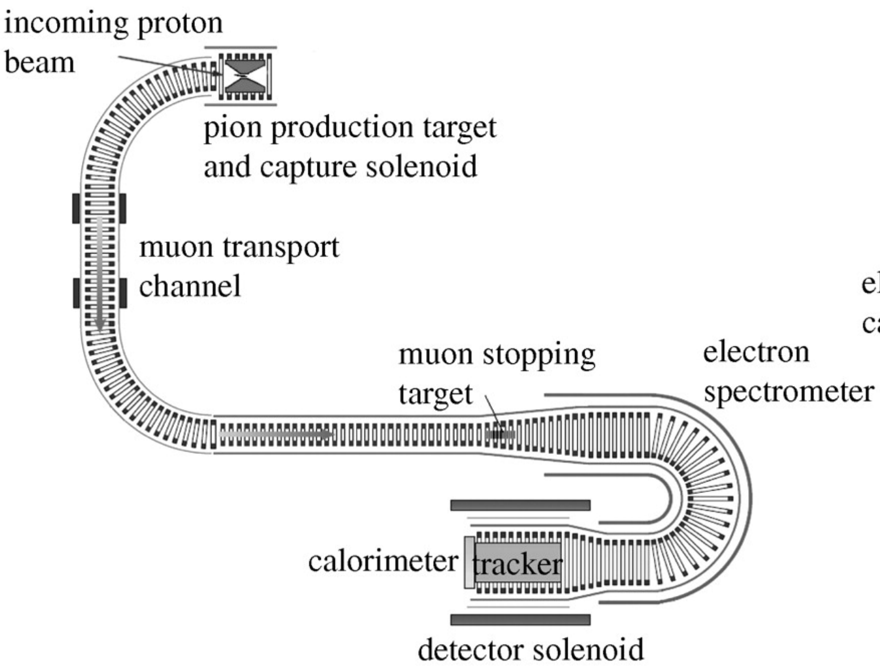


Fig. 11. Momentum distributions of electrons and positrons for the two event classes. Measured distributions are compared with the results of simulations of muon decay in orbit and $\mu - e$ conversion

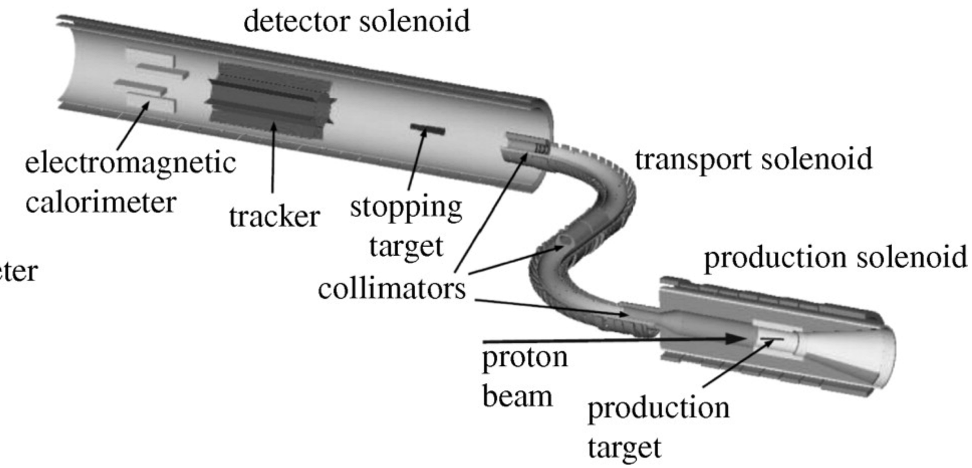
W. Bertl et al., Eur. Phys. J. C 47, 337 (2006).

COMET and mu2e

COMET (J-PARC, Japan)

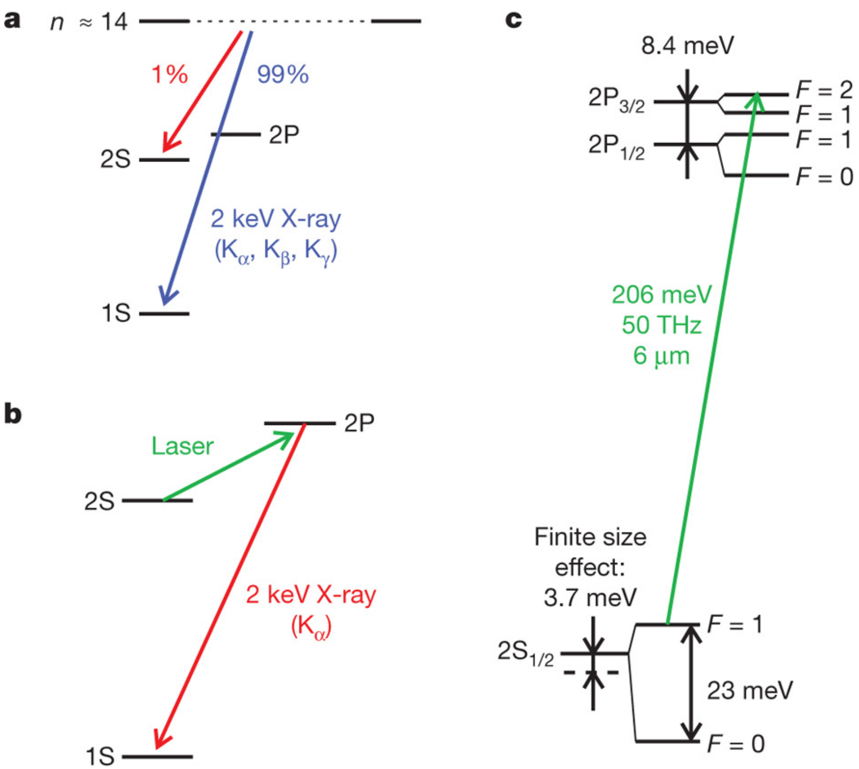


mu2e (Fermilab, USA)



Branching ratio goals of COMET and mu2e are $\lesssim 10^{-16}$

Muonic hydrogen and the proton radius



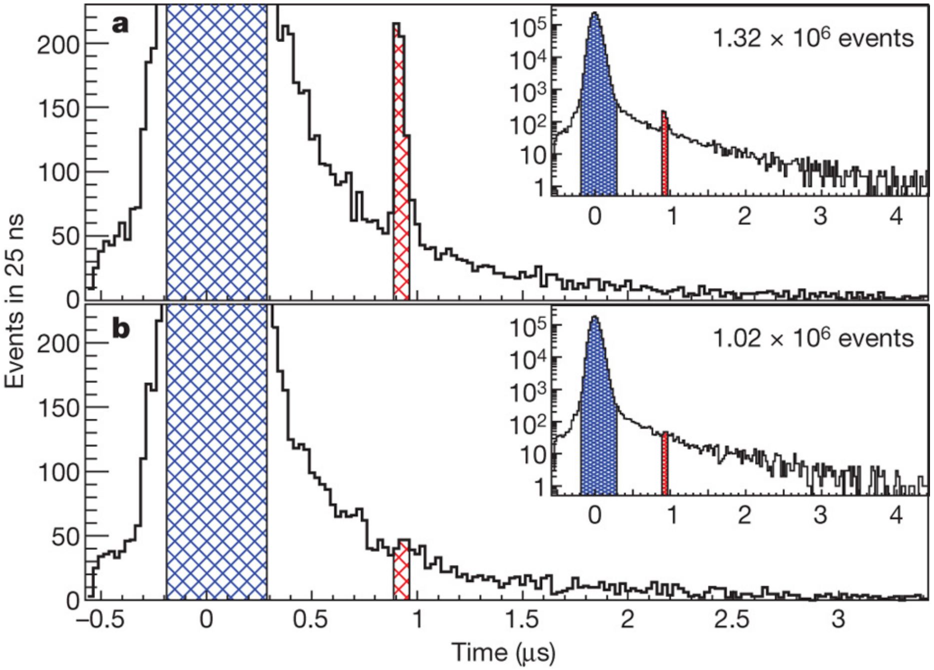
R. Pohl *et al.*, Nature 466, 213 (2010)

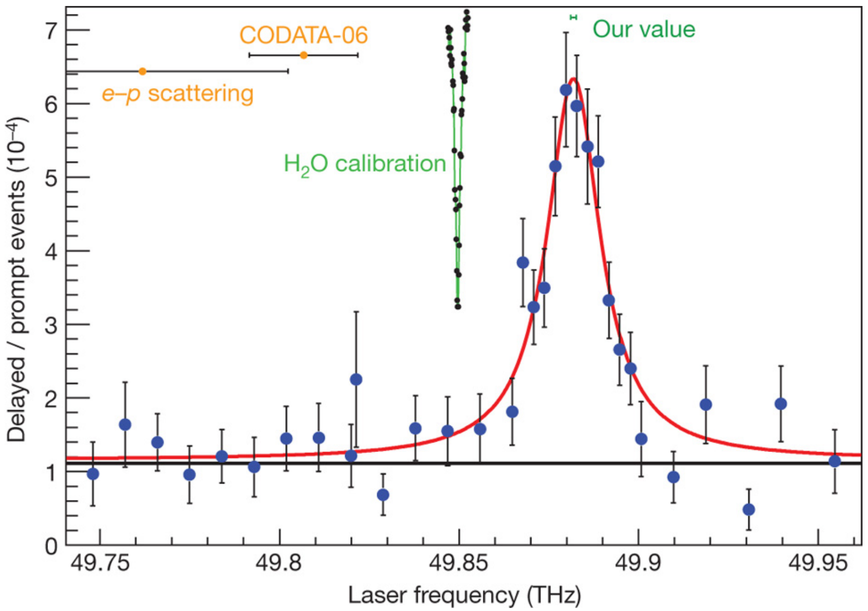
A. Antognini *et al.*, Science 339, 417 (2013)

- Small size of $\mu^- p$ system means that muon is more sensitive to finite proton size than e^- in hydrogen
- Energy levels and therefore transition energies are more sensitive to size effects

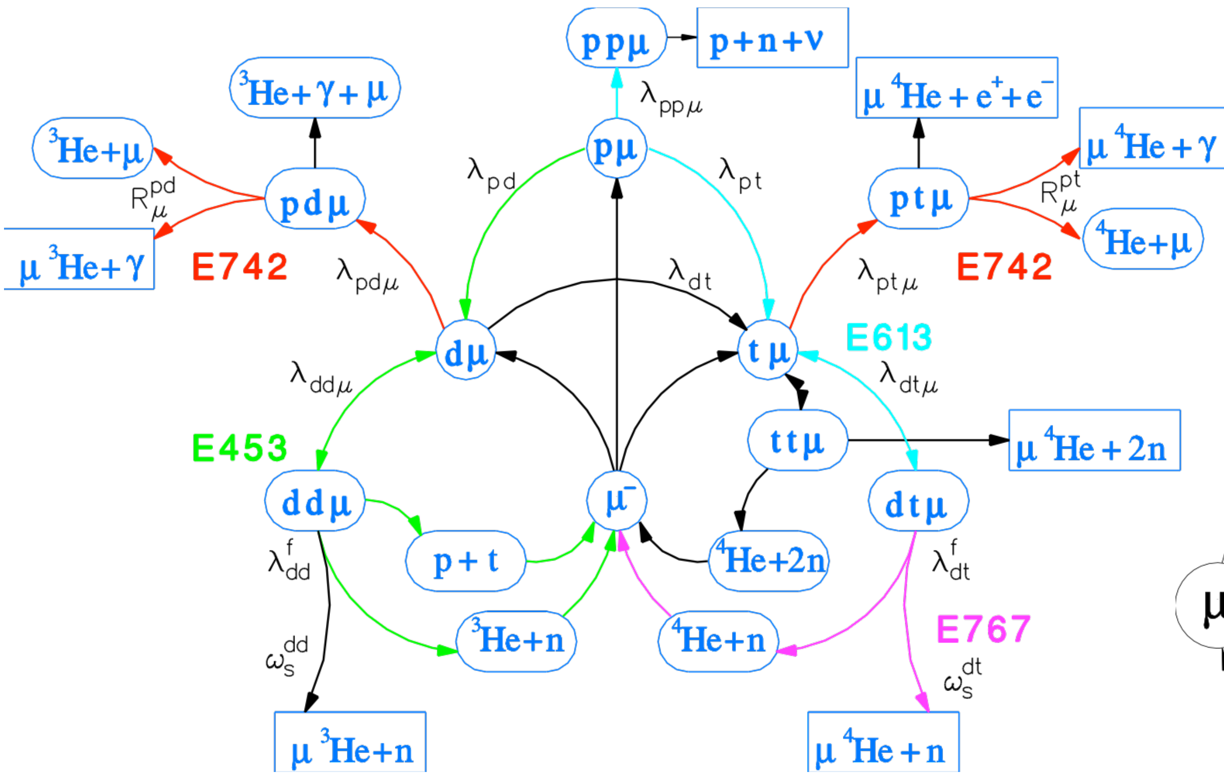
Muonic hydrogen data

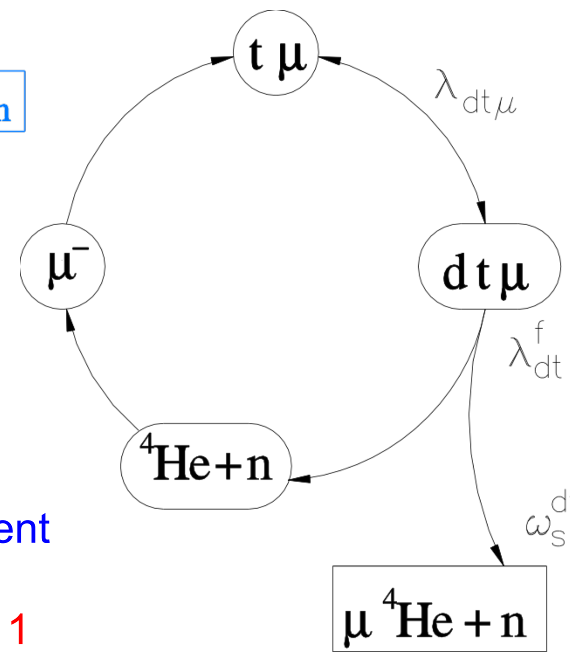
- Principle is deceptively simple, but experiment is the culmination of decades of muon beam development coupled with state-of-the-art laser science.
- Surprising result: r_p = 0.84184(67) fm, $\sim 5\sigma$ smaller than measured in electron scattering experiments. No explanation yet…
  - at least one experimental result incorrect? theoretical prediction incorrect? new force?





Muon catalyzed fusion





A μ^- can take part of many, many processes in an environment of hydrogen isotopes (^{1}H, ^{2}H=D, and ^{3}H=T). "Chemical" processes ($\Delta E \approx$ 0.1 eV) control nuclear processes ($\Delta E \approx$ 1 MeV).

Summary

- There is a wide range of science that can be studied with low energy muons: particle, nuclear, and atomic physics (not to mention the "applications" of $\mu\mathcal{SR}$)
- Many experiments take advantage of built-in tools in production and decay to exploit muon polarization
- High-power (1 MW) accelerators can make muon beams with intensities adequate for high precision measurements and searches for rare processes beyond the Standard Model