MUONIUM- ANTIMUONIUM OSCILLATION: MACS EXPERIMENT

Fermilab Muonium Workshop
July 14th, 2022

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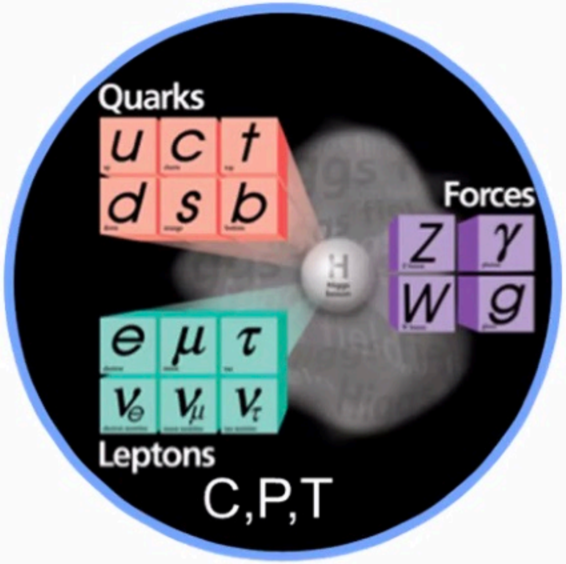
Standard Model and Beyond

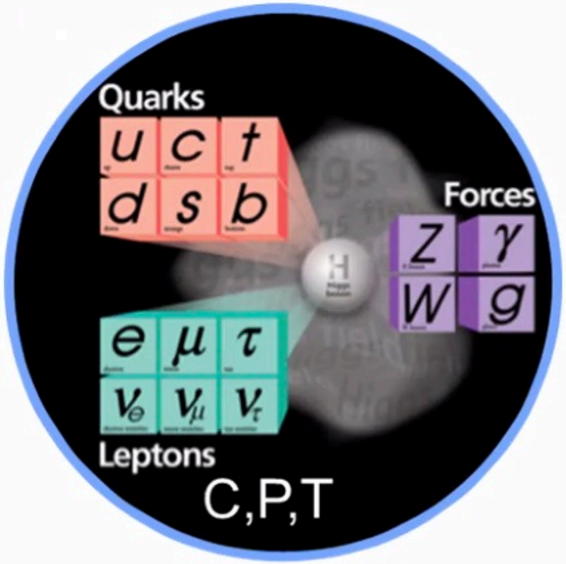


3 Families
3 Forces
some 30 Parameters

- **Excellent description of all particle physics experiments**
- **However, no explanation of many facts**
  - **Parity Violation**
  - **CP violation**
  - **Matter-antimatter asymmetry**
  - …
- **Large variety of models extending SM**
  - **Supersymmetry**
  - **LeftRight Symmetry**
  - …
- **These models provide amongst others**
  - **Motivation of P violation**
  - **New sources of CP violation**
  - …

Context

- Conservation Laws and Symmetries
  - Discrete Symmetries (T, P, C)
    - EDMs
    - Atomic Parity Violation
  - Number Conservation Laws
    - Rare and forbidden Decay Modes
- **Opportunities with intense Muon sources**
  - Lepton Number
  - Muon Mass
  - Magnetic Moments
  - g-2
  - …
- Experimental Strategies



SENSITIVITY

Physics Question

Choice of System

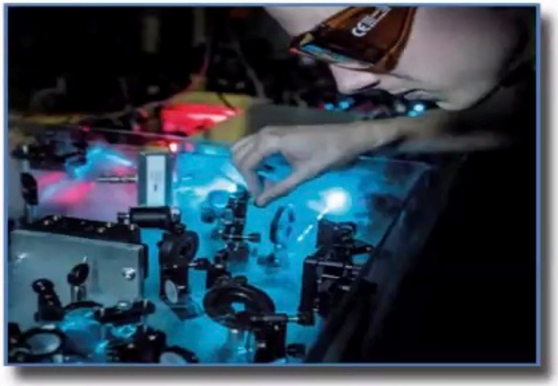
Number of Particles

Playground

Where is the antimatter?

What is Dark matter?

New particles ~ TeV



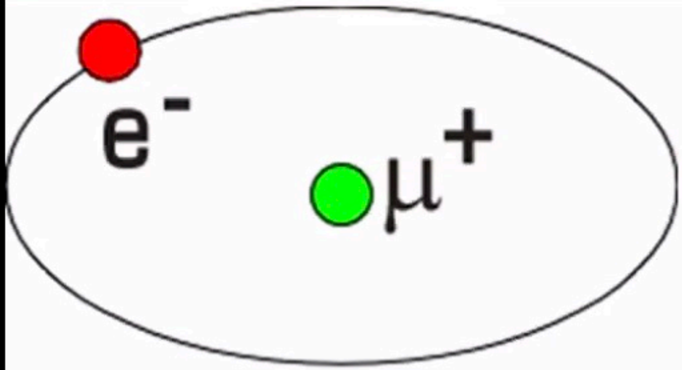
Precision measurement ~ peV

MUON

Fantastic versatile particle

Abundant

Long lifetime (long enough for great experiments)



“Muonium is the bound state of
positive Muon and an Electro

- Hydrogen like
- Just stop Muons in matter

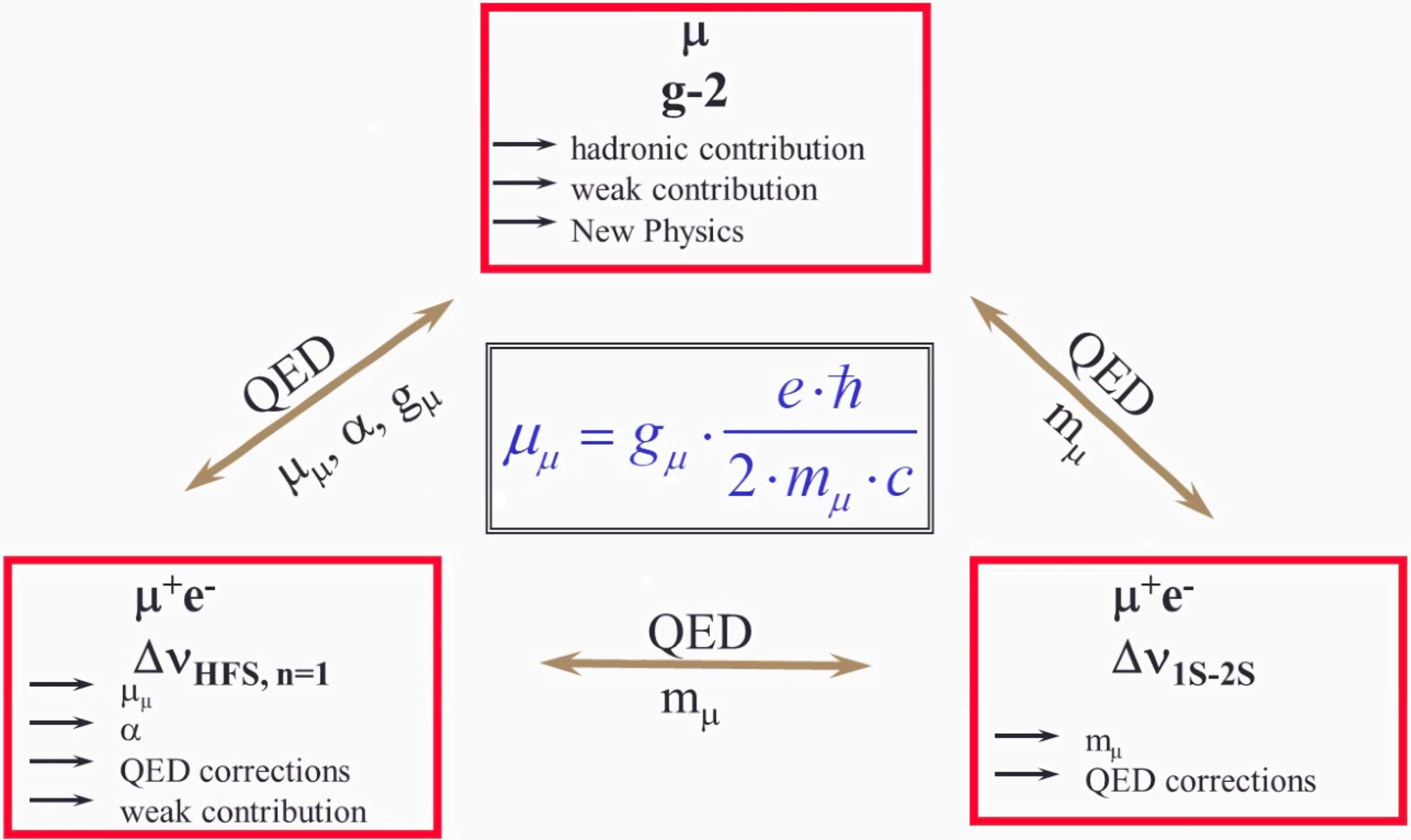
Muonium (M)

Features:

- **electromagnetic bound state**
- **fundamental constants**
- **search for New Physics**
- **Lepton Number Conservation**
- **tool for condensed matter research**
- **…**

QED of the Muon

Fundamental Constants



μ

g-2

→ hadronic contribution

→ weak contribution

→ New Physics

QED

μ_μ, α, g_μ

$$\mu_\mu = g_\mu \cdot \frac{e \cdot \hbar}{2 \cdot m_\mu \cdot c}$$

QED

m_μ

$\mu^+ e^-$

$\Delta\nu_{\mathrm{HFS},\, n=1}$

→ μ_μ

→ α

→ QED corrections

→ weak contribution

QED

m_μ

$\mu^+ e^-$

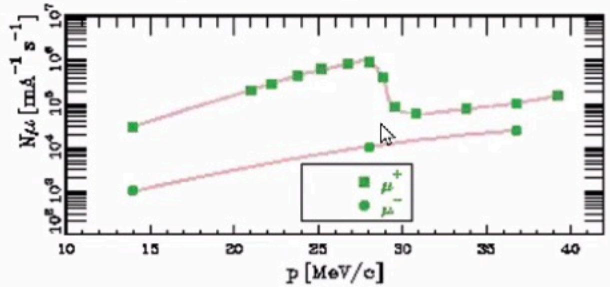
$\Delta\nu_{\mathrm{1S-2S}}$

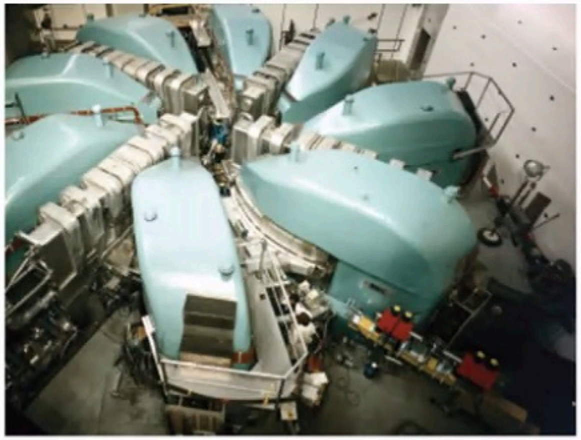
→ m_μ

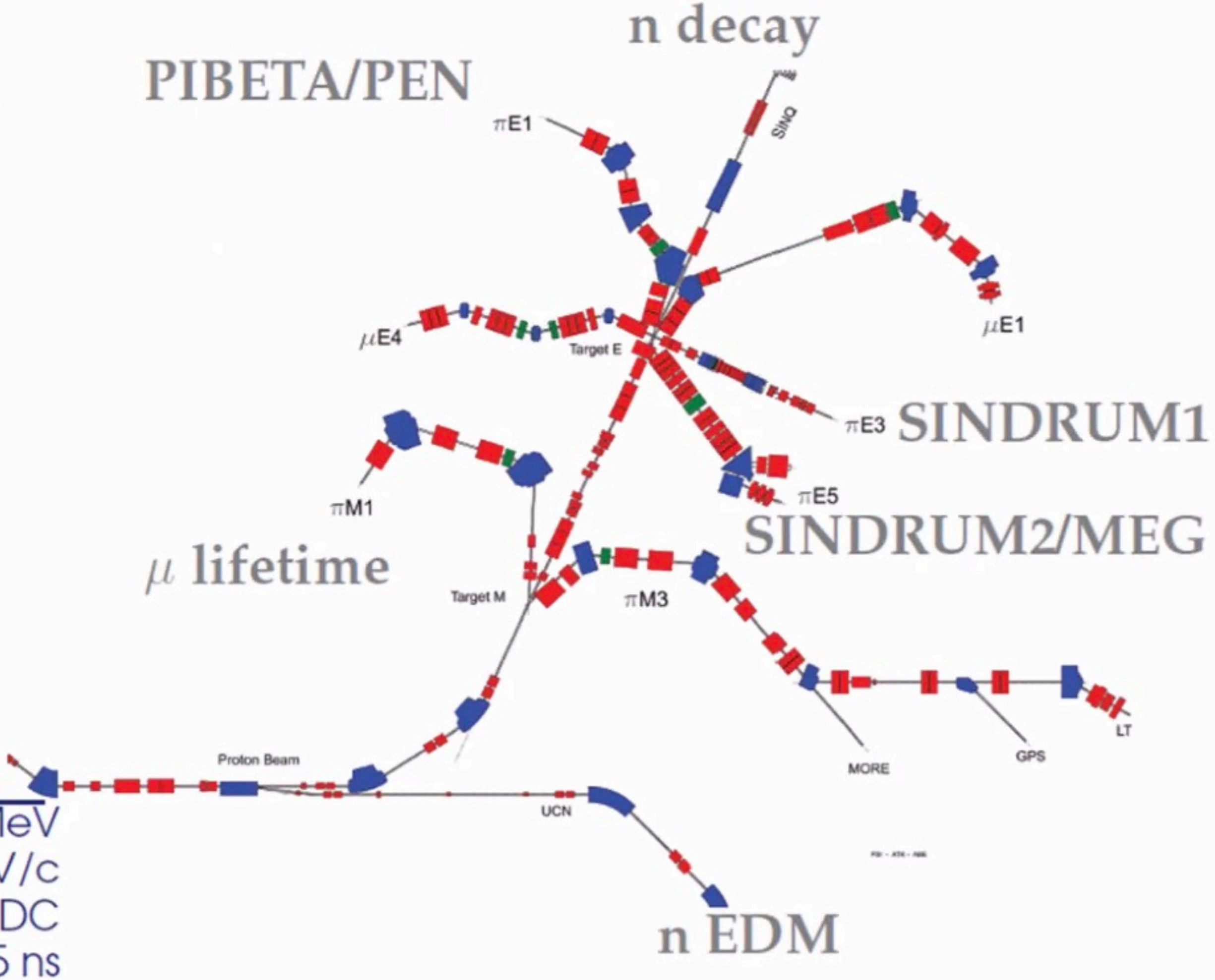
→ QED corrections

K. Jungmann, 1993

My experience: Intense Beams @ PSI



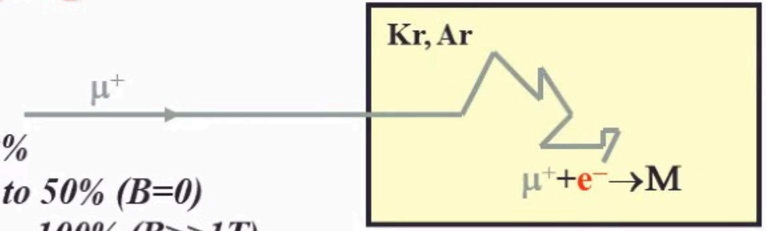




Injection Energy	70-72 MeV
Extraction Momentum	1.2 GeV/c
Beam Current	2.2 mA DC
Time Between Pulses	19.75 ns

Muonium Production Methods

- **Gas Stopping**

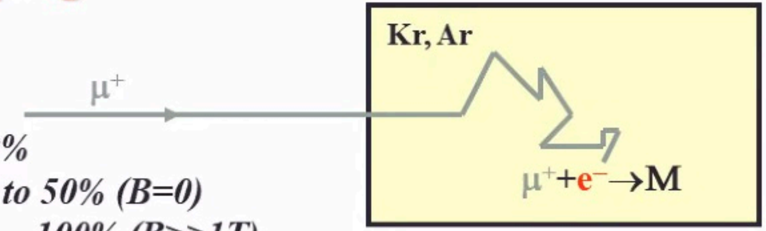


Yields up to 100%
Polarization up to 50% (B=0)
100% (B>>1T)

in matter

Muonium Production Methods

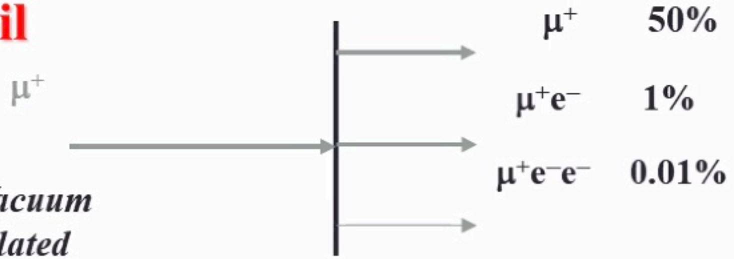
- **Gas Stopping**



Yields up to 100%
Polarization up to 50% (B=0)
100% (B>>1T)

in matter

- **Beam Foil**

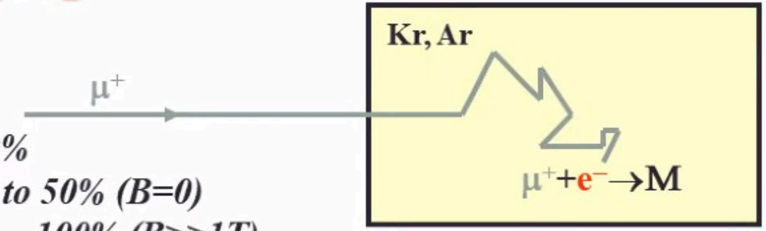


Muonium in Vacuum
n=2 state populated
fast muonium

Fast: keV energy

Muonium Production Methods

- **Gas Stopping**



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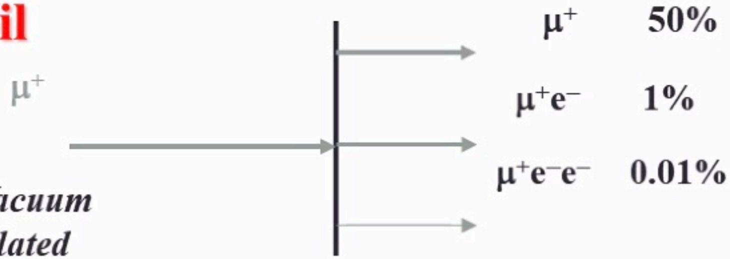
in matter

- **Beam Foil**

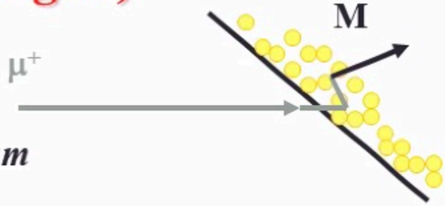


μ^+ 50%
μ^+e^- 1%
$\mu^+e^-e^-$ 0.01%

Muonium in Vacuum
n=2 state populated
fast muonium

Fast: keV energy

- **SiO_2 Powder (Aerogels)**

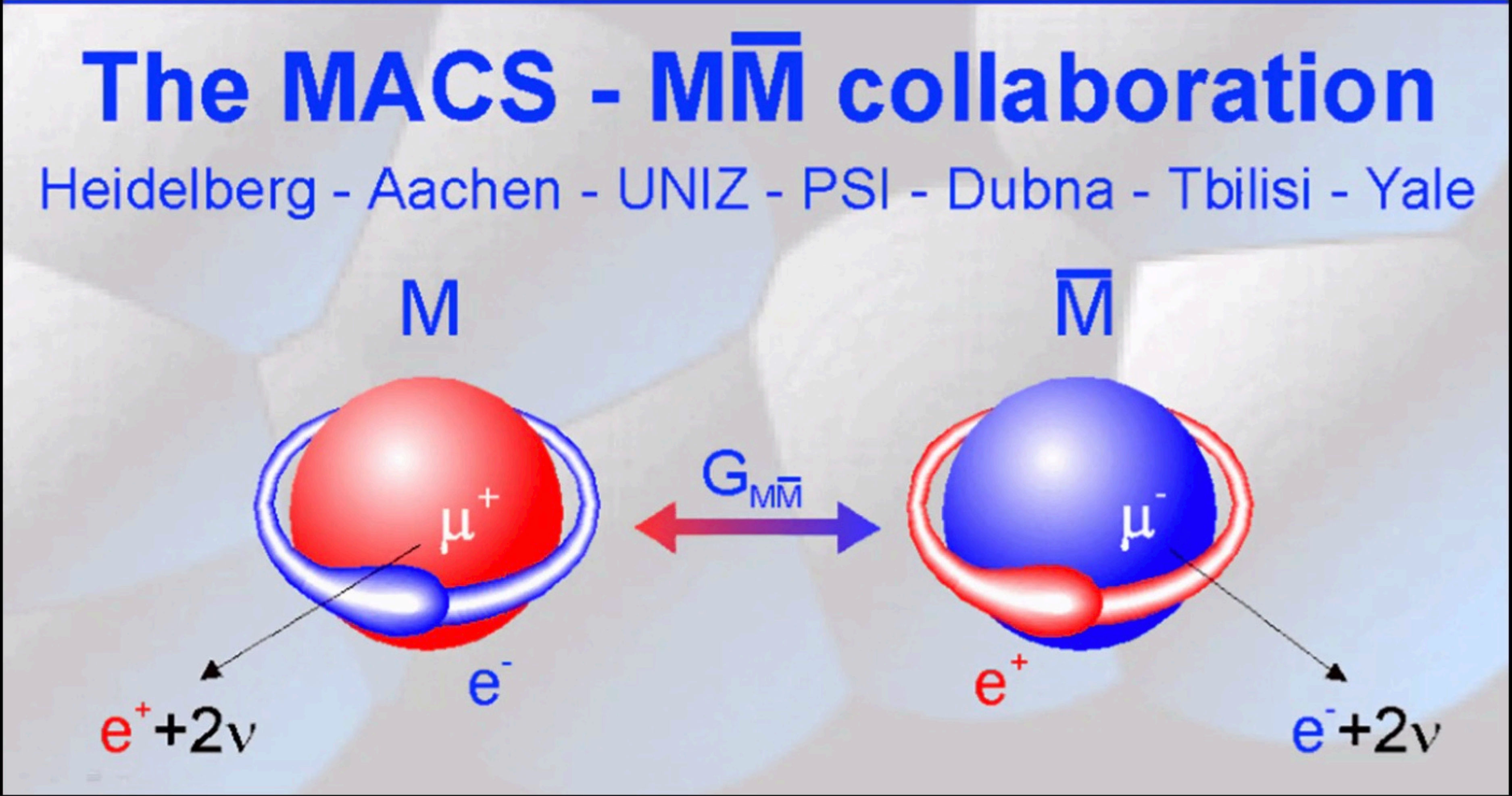


thermal Muonium in Vacuum
Yields up to 12%
Polarization 39(9)%

$M(2s) / M(1s) < 10^{-4}$

velocity $1.5 cm/\tau_\mu$

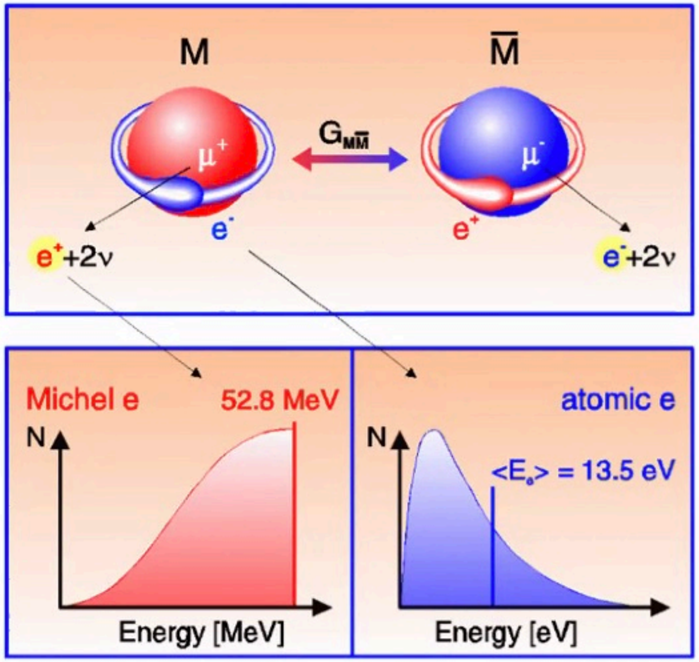
MMbar (1988 – 1996)



The MACS - M$\overline{\text{M}}$ collaboration

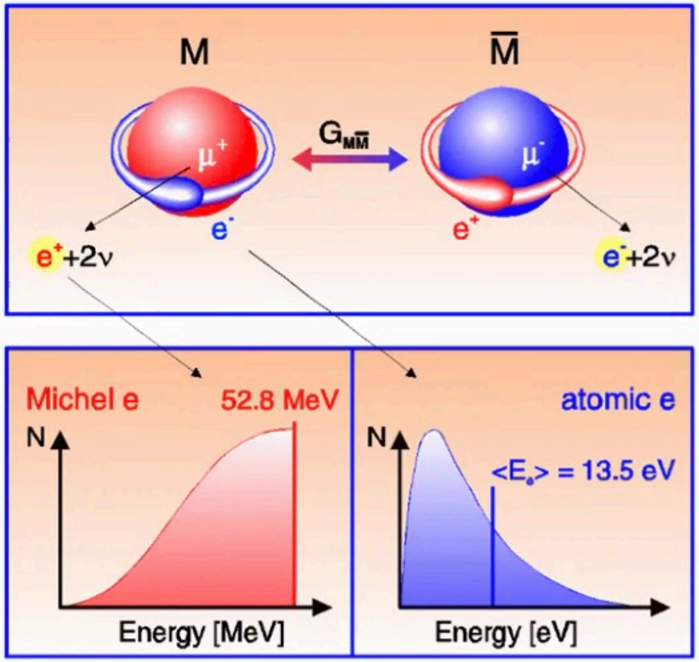
Heidelberg - Aachen - UNIZ - PSI - Dubna - Tbilisi - Yale

The Experimental Concept

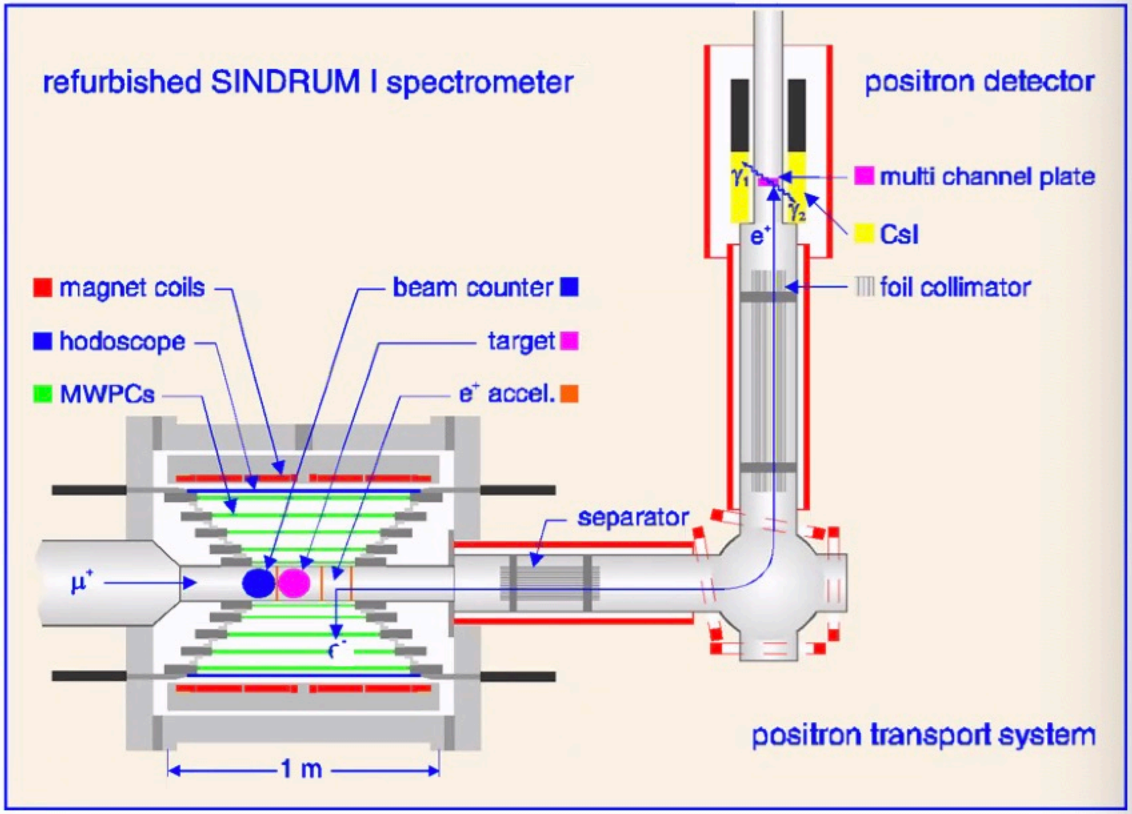


Symmetry in detection of
M and Mbar

The Experimental Concept



Symmetry in detection of
M and Mbar

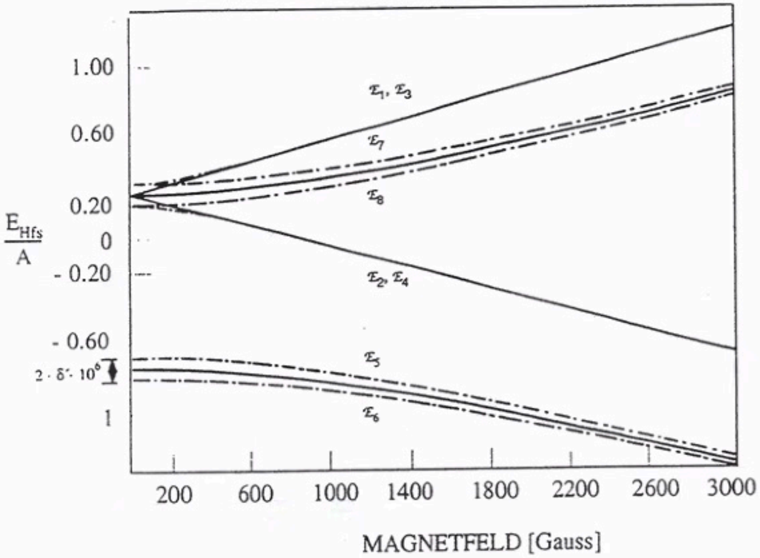


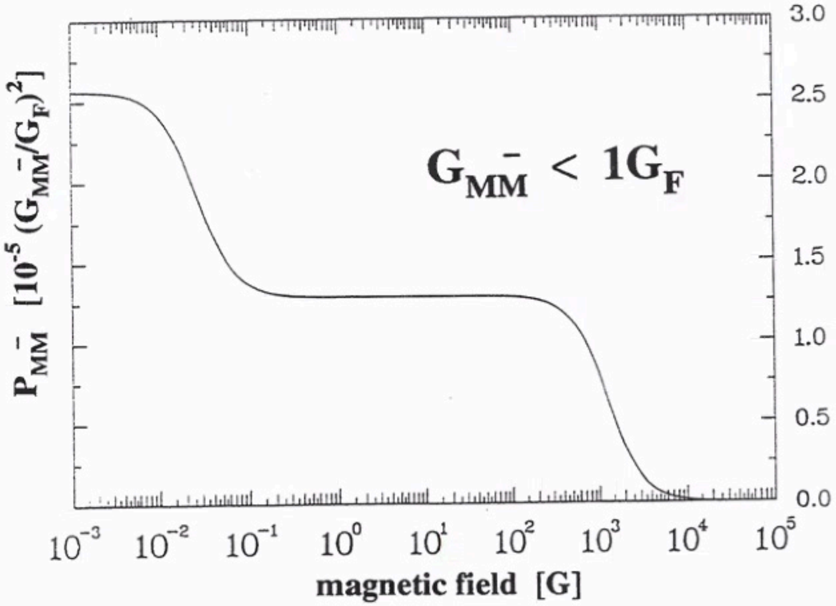
Coincident detection of decay particles

Suppression in B Field

Due to difference in Hyperfine energies for M and Mbar

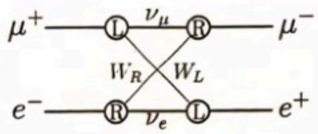
➡ MMbar only sensitive with M in vacuum





Models predicting $M \rightarrow \overline{M}$

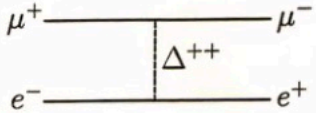
- **Left-Right-symmetric models with heavy Majorana neutrinos**



$\boxed{G_{M\overline{M}} \leq 10^{-5} \cdot G_F}$

A. Halprin (1982)
M.L. Swartz (1989)

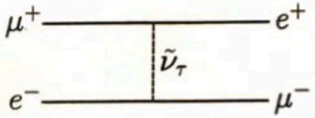
- **Minimal Left-Right-symmetric models**



$$\boxed{\begin{array}{ll} G_{M\overline{M}} \geq 2 \cdot 10^{-4}\, G_F & (m_{\nu_\mu} \leq 170 \mathrm{keV/c^2}) \\ \quad\;\; \geq 5 \cdot 10^{-4}\, G_F & \end{array}}$$

A. Halprin (1982)
P. Herczeg, R.N. Mohapatra (1992)

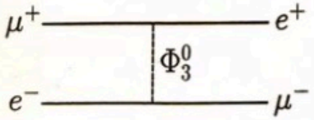
- **SUSY models with broken R-parity**



$\boxed{G_{M\overline{M}} \leq \text{present limit}}$

R.N. Mohapatra (1992)
A. Halprin, A. Masiero (1993)

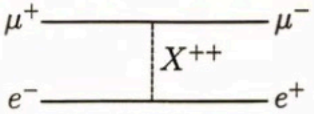
- **GUT Z_8-models with 4th generation of heavy particles**



$\boxed{G_{M\overline{M}} > 10^{-2}\, G_F}$

G. Wong, W. Hou (1994)

- **Models with bileptonic gauge bosons**



GUT models:

$\boxed{G_{M\overline{M}} \leq \text{present limit} \quad (m_{X^{\pm\pm}}/g_{3l} \geq 360 \text{ GeV/c}^2)}$

H. Fujii, K. Sasaki et al. (1994)

331 model:

$\boxed{G_{M\overline{M}} \leq \text{present limit} \quad (m_{X^{\pm\pm}} < 800 \text{ GeV/c}^2)}$

P.H. Frampton (1997)

Muonium Production MMbar

Largest amount of M in vacuum produced for any experiment

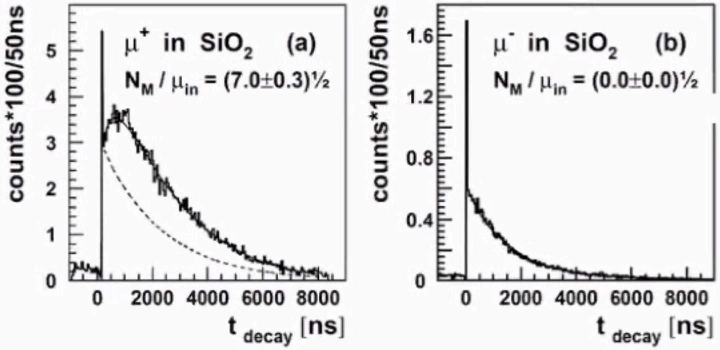


FIG. 3. Muonium production was continually monitored using the characteristic time distribution t_{decay} of atomic electrons on the MCP (a). The indicated exponentially decaying background was verified by demonstrating that there is only such background for negative muons on SiO_2 powder (b).

MACS Collaboration, L. Willmann et al., PRL 82, 49 (1999)

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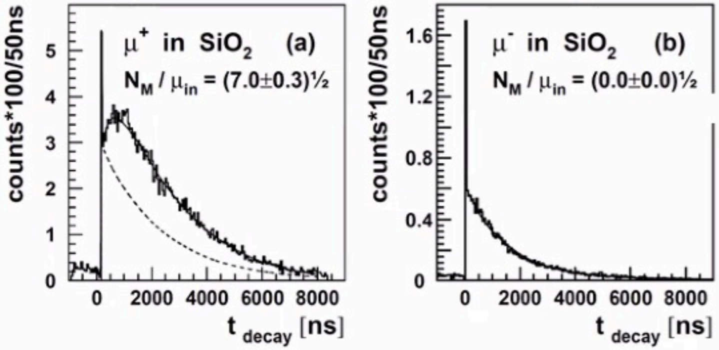

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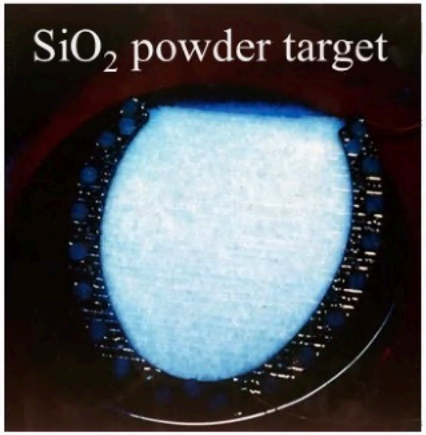
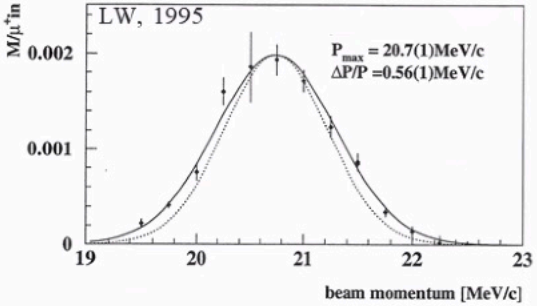
MACS Collaboration, L. Willmann et al., PRL 82, 49 (1999)



Large yield
but:
degrading on a
few day scale



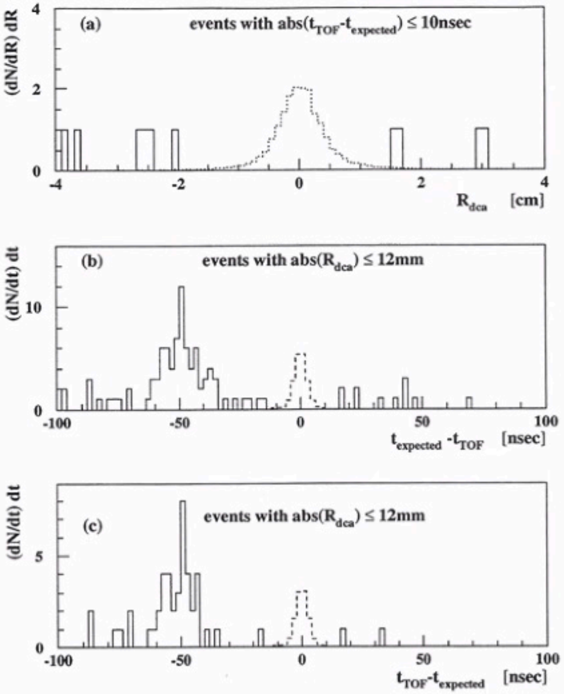
Muons stopped near surface count

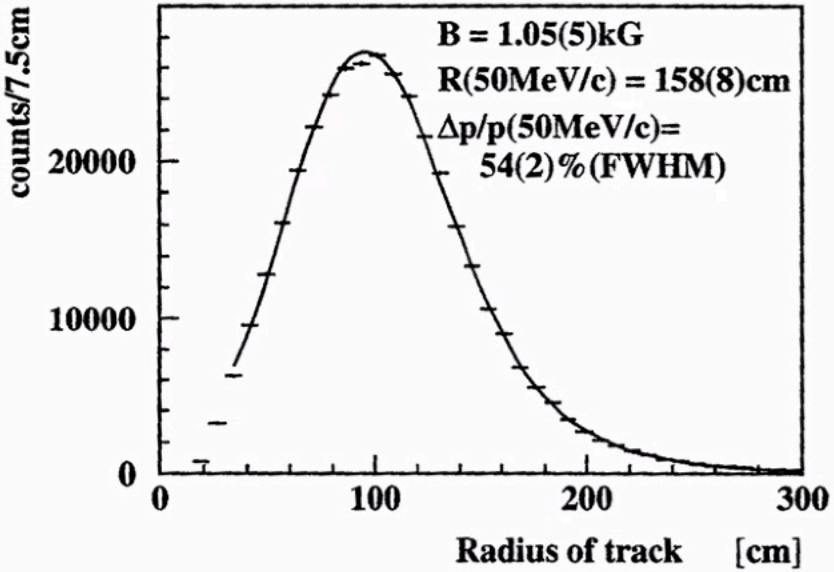
Described by integrating diffusion equation

$$
\begin{aligned}
j_{M(y=a,t)} &= -D_M \left.\frac{\partial\rho}{\partial y}\right|_{y=a} \\
&= \frac{exp(-\lambda_\mu t)}{2\sqrt{\pi D_M t^3}} f \int_0^a dy' S(y') \\
&\times \sum_{n=1,3,\cdots}^{\infty} \Big[(na-y')e^{(-(na-y')^2/4D_M t)} \\
&- (na+y')e^{(-(na+y')^2/4D_M t)}\Big] ,
\end{aligned}
$$

Final Result MMbar

$G_{\mathrm{Mu}\overline{\mathrm{Mu}}} < 3 \times 10^{-3} G_F$ (Probability of spon. transition $< 8.2 \times 10^{-11}$)

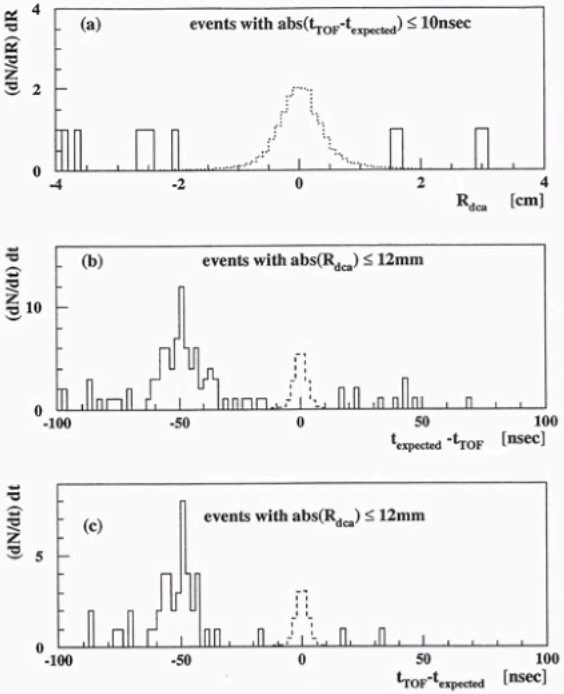




Spatial resolution: 0.80(4) cm
t_{TOF} resolution: 76(6) nsec
Momentum Resolution: limited by B ~ 1kG

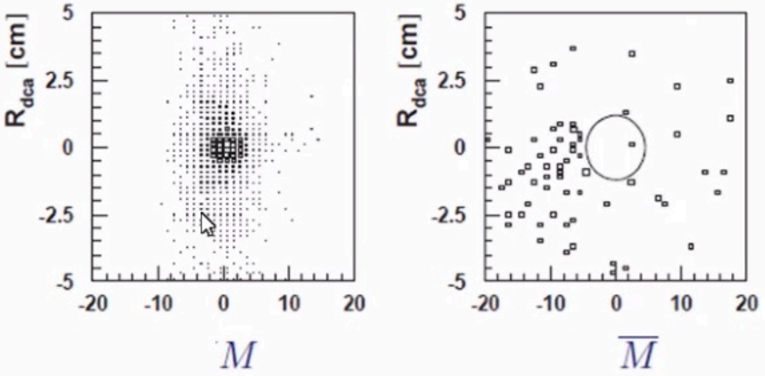
Final Result MMbar

$G_{\mathrm{Mu}\overline{\mathrm{Mu}}} < 3 \times 10^{-3} G_F$ (Probability of spon. transition $< 8.2 \times 10^{-11}$)



MACS Collaboration: L. Willmann et al., Phys. Rev. Lett. 82, 49 (1999)

Still attracting theorists



Main Features:

- Detector calibrated with Muonium
    - Every 4h for 1/2h Muonium production
- Only small differences in detection effciencies

FUTURE

Background and Detectors

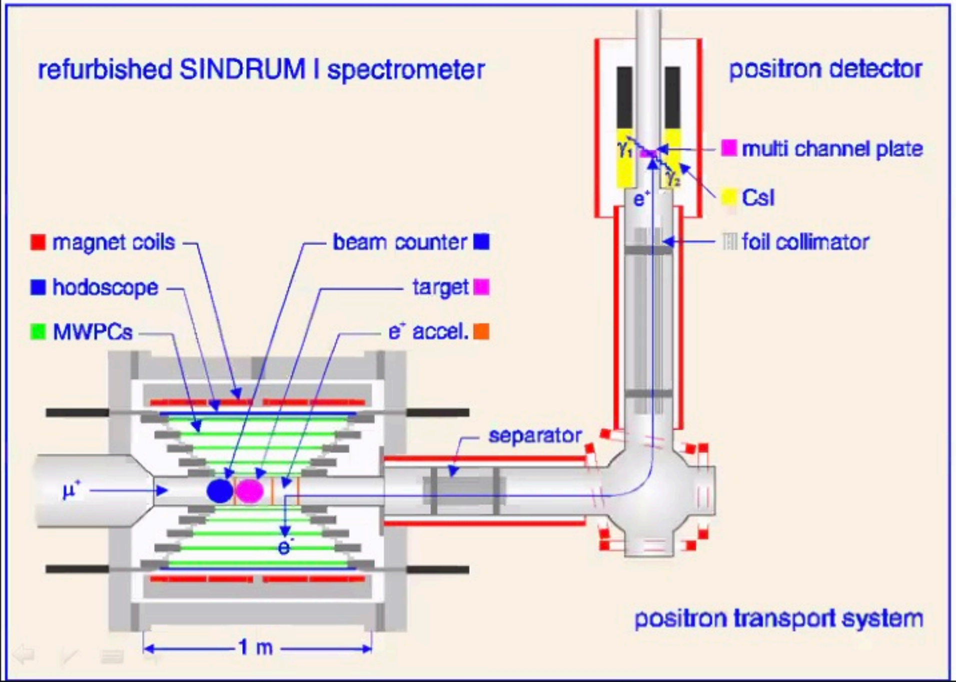
Experimental Strategy

Muon Sources

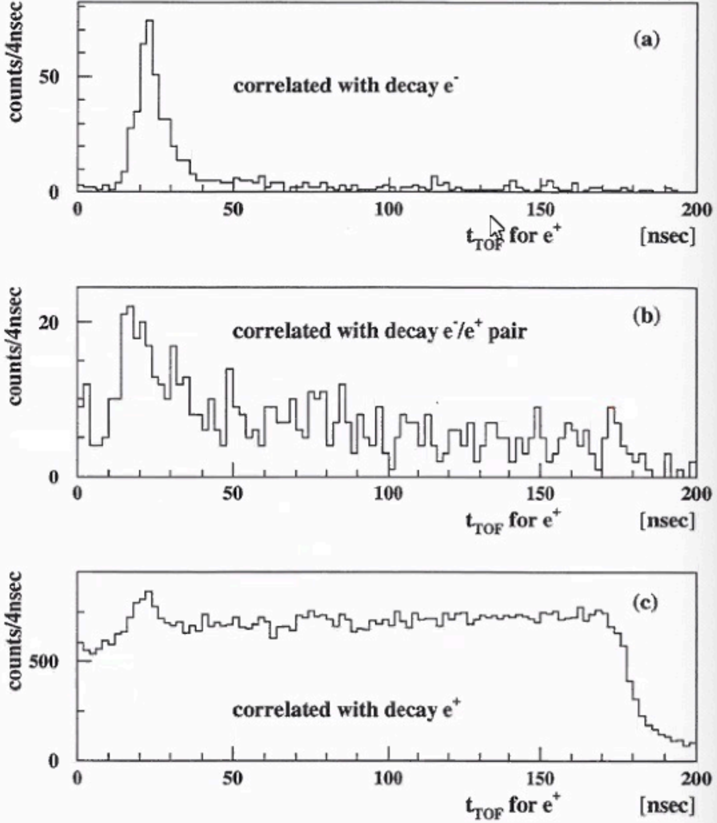
μ -> 3e 2ν @ MACS

- Observed in small range of phase space
  - Major background in future experiments
- Low energy part of positron spectrum

- No quantitative analysis
  - Needs calculation of phase space including final state interactions

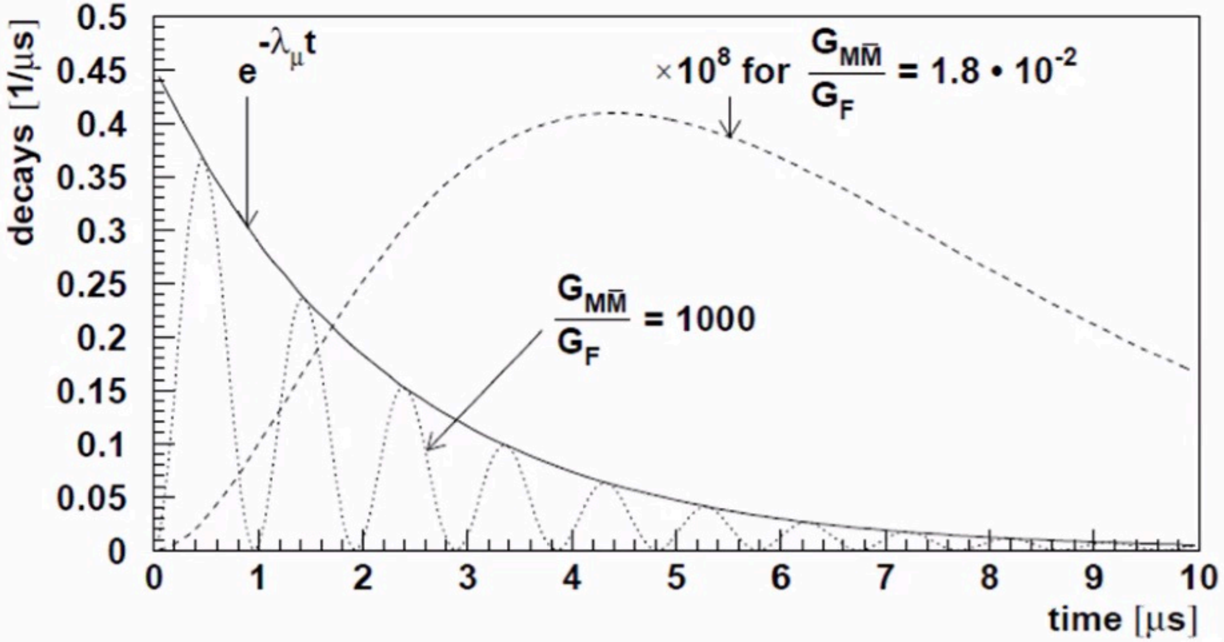


LW, (1995)



Low Energy Positron mimic Mbar event

Future MMbar Experiment? Old Muonium



- **P(M) $\propto$ sin^2 [const * (G_{MM}/G_F)*t]*exp[-λ_μ*t]**
- **Background $\propto$ exp(- n λ_μ*t) ; n-fold coincidence detection**
- **For G_{MM} << G_F M gains over Background**
- **P(M) / Background $\propto$ t^2 * exp[+(n-1)* λ_μ*t]**

⇒ Pulsed ACCELERATOR

Muonium-Antimuonium Conversion, L. Willmann and K. Jungmann, SciPost Phys. Proc. 5, 009 (2021)

Conclusions

- New muon sources offer new possibilities for many experiments
  - Performance of M production essential
- Improving limit on MMbar is worthwhile and possible
  - Major background:
    - scientific: *μ -> 3e 2ν*
    - Instrumental: ***scattering of decay positrons***
- Limitation of MACS experiment
  - Rate handling
  - Momentum resolution magnetic spectrometer
- Pulsed Time Structure of Muon beam:
  - Major gain in sensitivity when looking for $t > \tau_\mu$

    (Old Muonium)