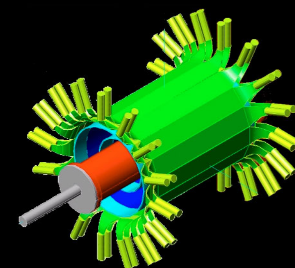
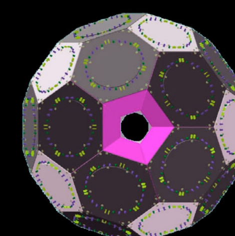
Precision Muon Physics - μX

MuCAP



& MuLAN



Bernhard Lauss

University of California @ Berkeley

Precision Measurement of the Positive Muon Lifetime

Muon Lifetime Analysis

μ^+ *lifetime*

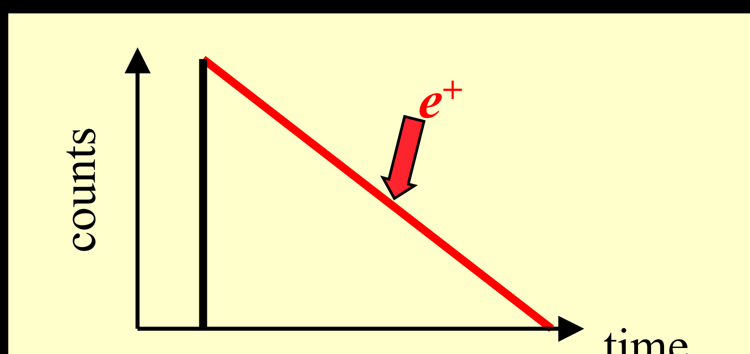
MuLAN

Courtesy D. Hertzog

Basics

μ^+ ***lifetime = 2.19703*** μs

$$\mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu$$



simple slope
measurement !

Scientific case: μ^+ lifetime + G_F

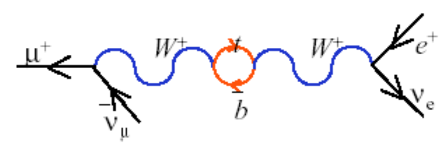
$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q)$$

radiative corrections, higher order QED

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

precision EW physics quantum loops

- **fundamental constant of nature**
- **dominant theoretical error (16 ppm) reduced to <0.3 ppm** (2-loop, '99)
- **impressive predictive power in EW sector**



- **dramatic improvement in other EW parameters**

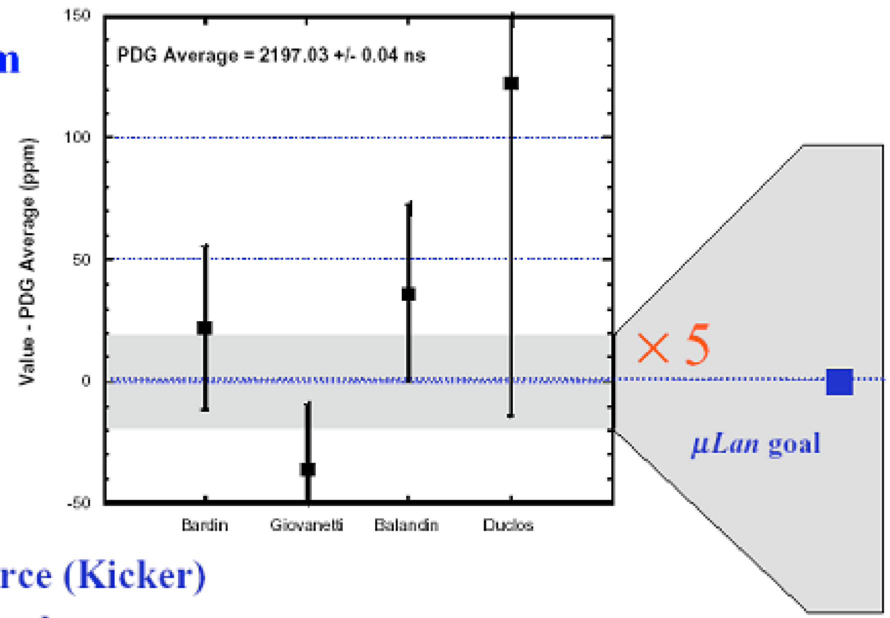
quantity	*symbol*	*value(error)*	*(ppm)*
Fermi constant	G_F	1.16637(1) 10^{-5} GeV^2	9
Fine-structure	$\alpha(0)$	1/137.03599976(50)	0.0037
constant	$\alpha(M_Z^2)$	1/127.934(27)	210
Z boson mass	M_Z	91.1876(21) GeV/c^2	22

experimental efforts at RAL (Riken) and PSI (FAST, μLAN)

μLan

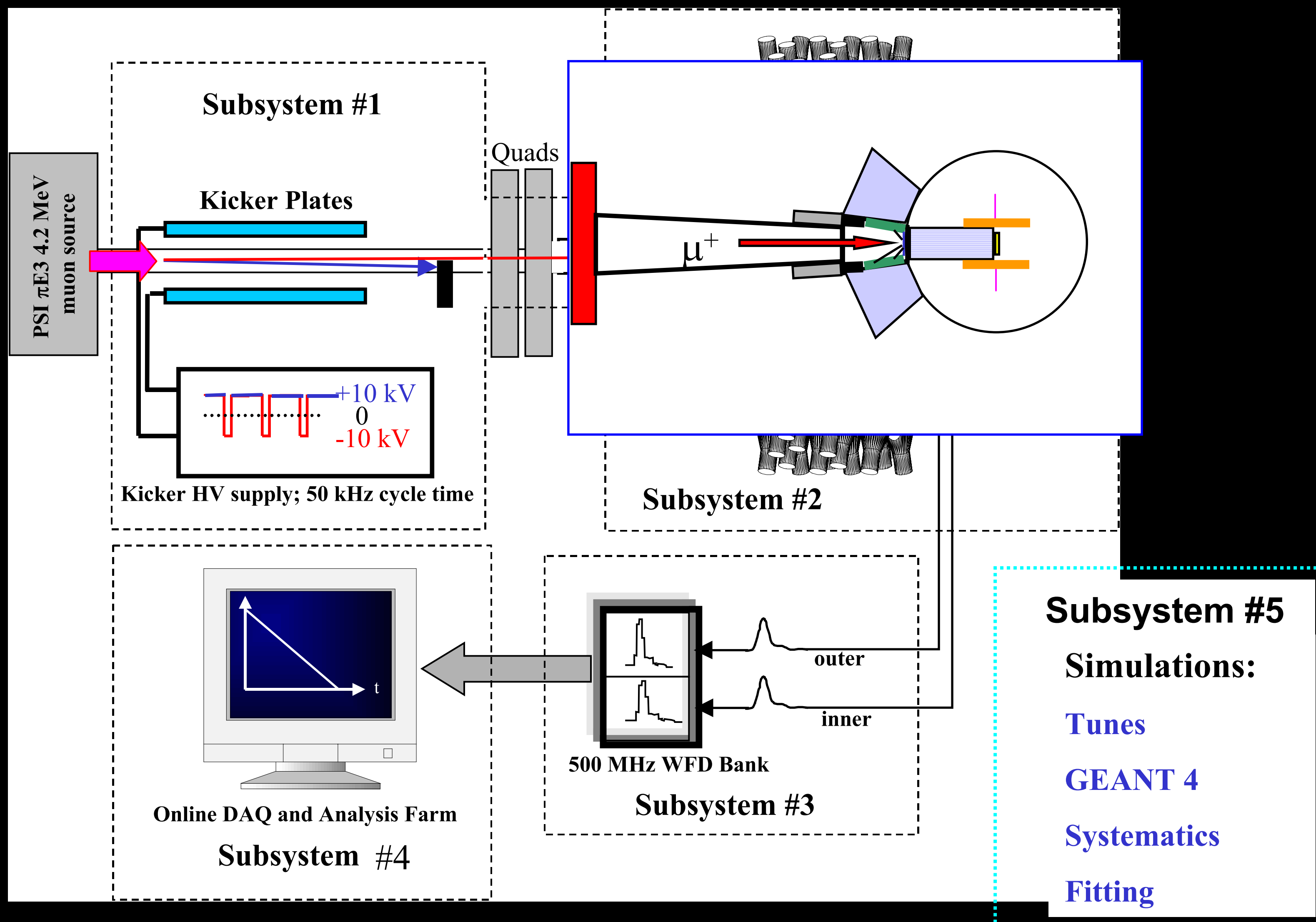
MuLAN Goals & Requirements

- **Determine μ^+ *lifetime* to 1 ppm**
  - This yields G_F to <1 ppm
  - *Helps* g_p determination from μ^+ / μ^- lifetime difference

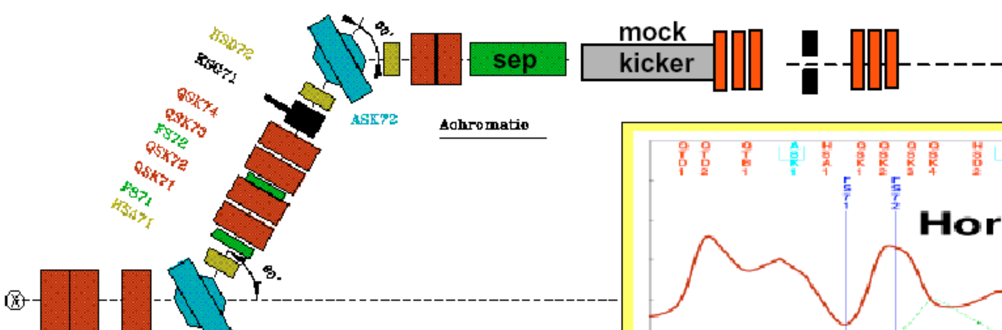


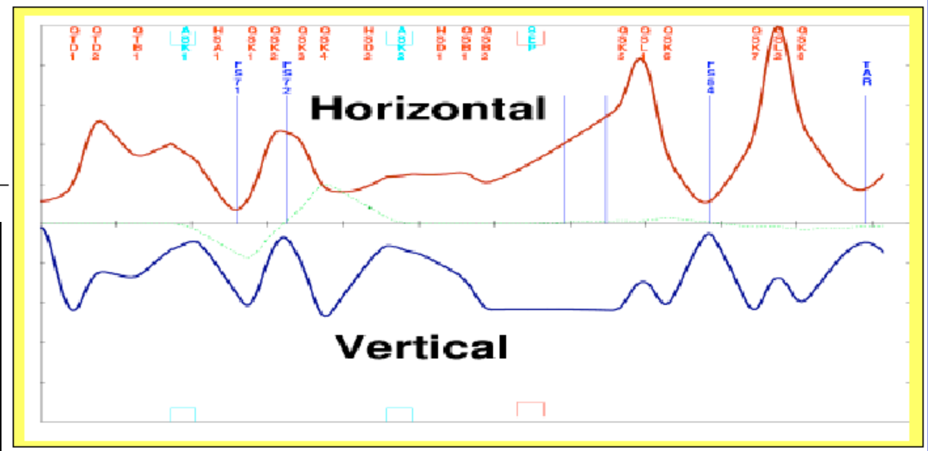
- **Require**
  - 10^{12} good events
  - Pulsed low-energy muon source (Kicker)
  - Symmetric, segmented timing detector

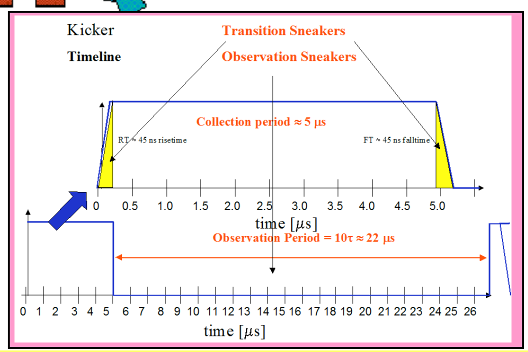
MuLAN concept / subsystems



Beam development πE3



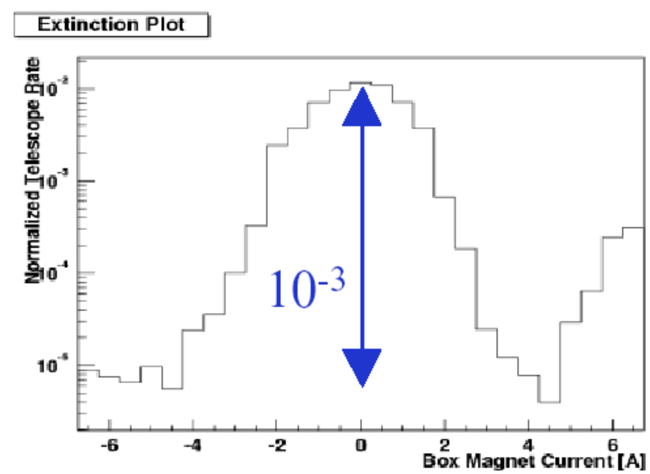




exp. milestone achieved ’02

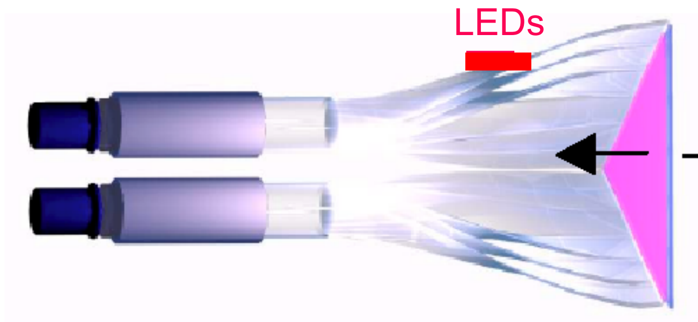
μ extinction 3×10^{-4}

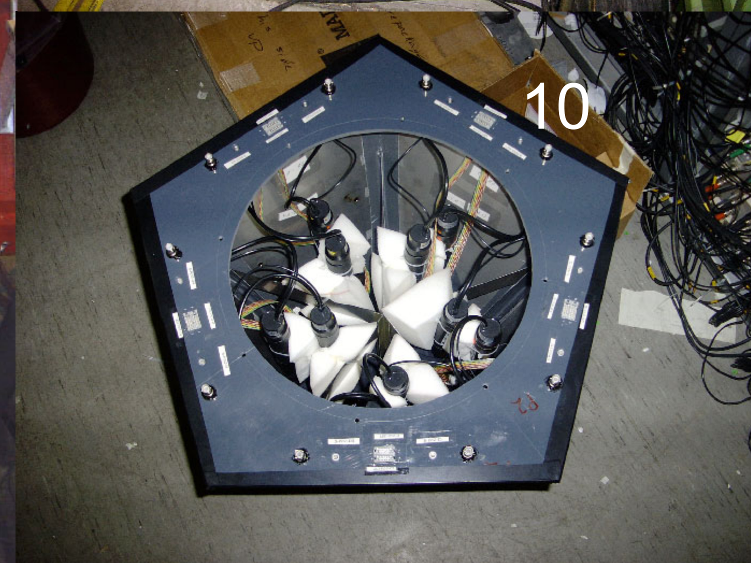
rate ~30 MHz



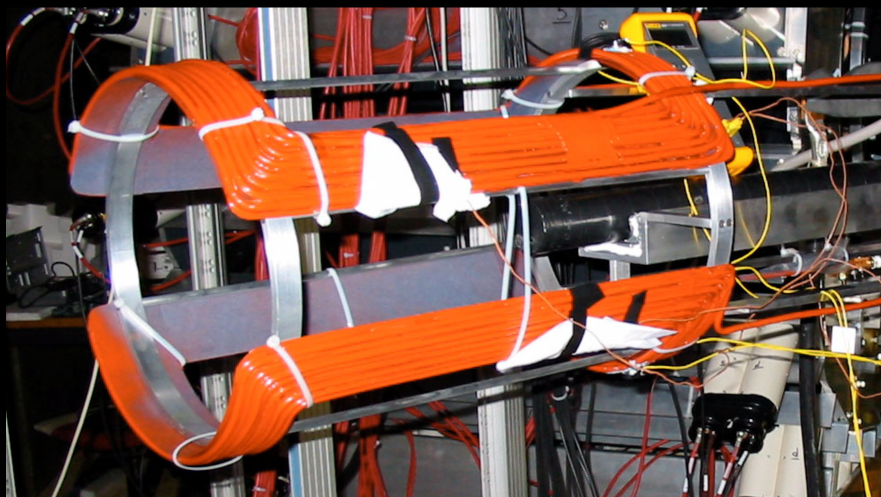
μLan

Detectors and Structure

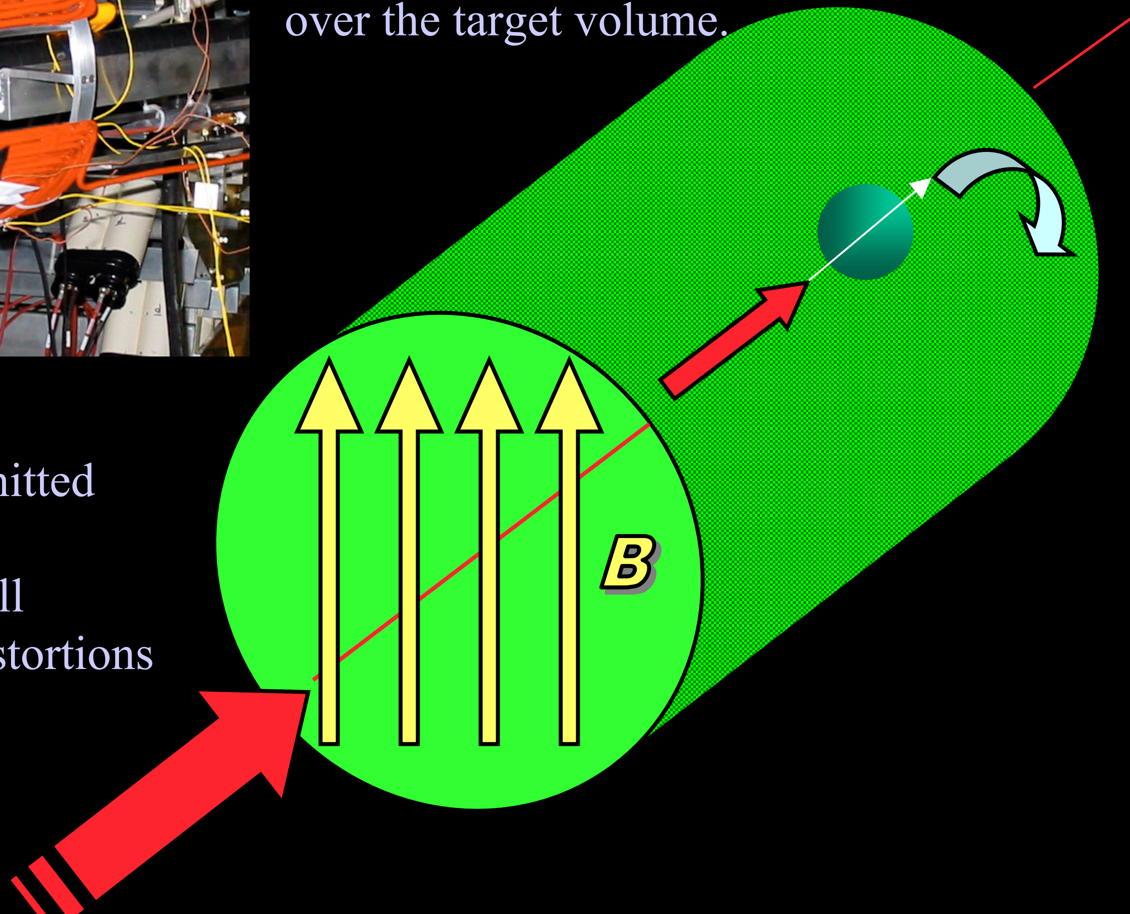




μ^+SR – Muon Spin Rotation



Helmholz coils supply a 70-gauss, transverse (x-y plane) magnetic field over the target volume.

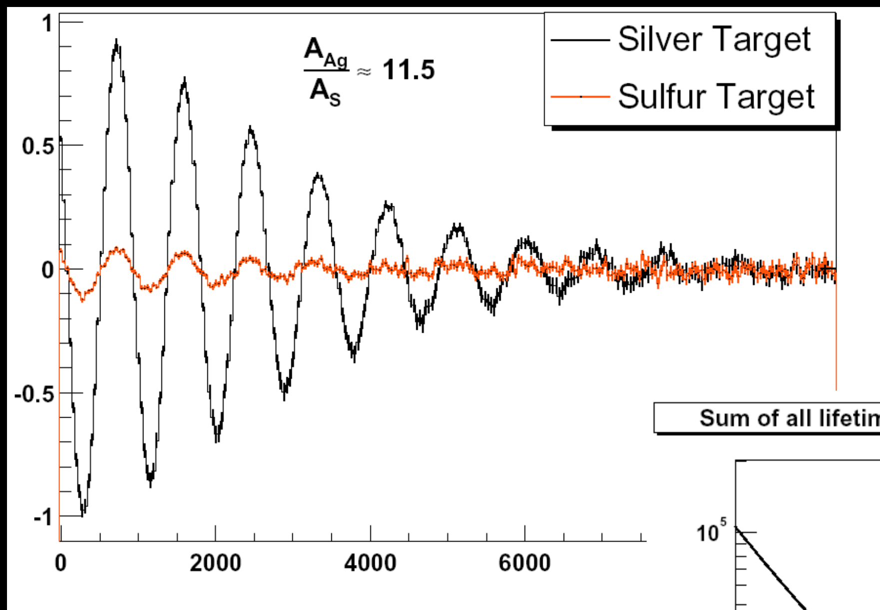


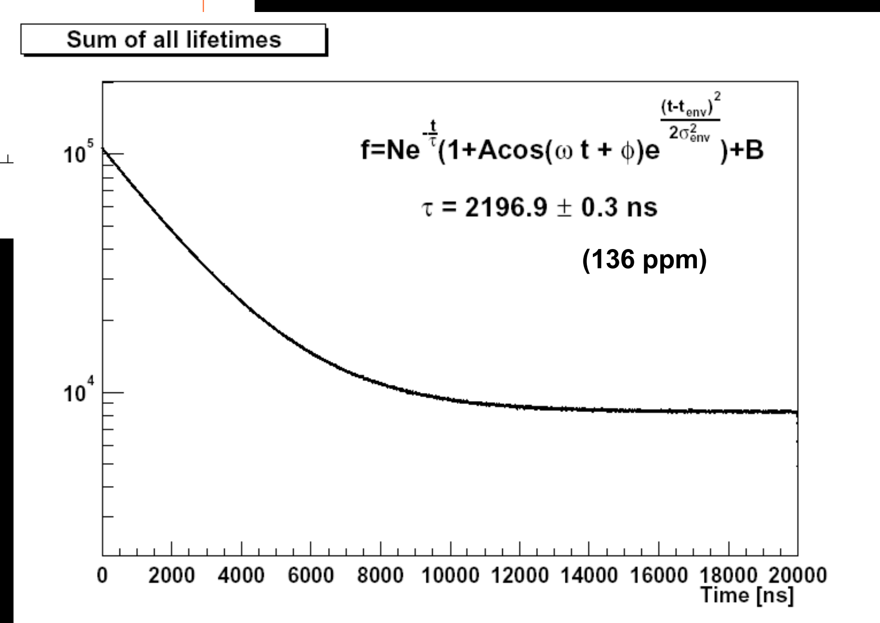
Decay e^+'s are preferentially emitted in the direction of the μ^+ spin. Residual polarization effects will produce direction-dependent distortions in the μ^+ lifetime histograms.

μ^+ beam,
spins partially polarized along ^+z-axis

First Test-Data

Courtesy D. Chitwood





MuLAN Schedule

Run Plan:

Summer 2003

- Setup and Test of final beam line with kicker
- Setup and test of DAQ
- Finalize Detectors and Electronics (WFDs)
- Detector Comissioning Run

2004 - Obtain full statistics

MuLAN **Collaborating Institutions** *MuCap*

Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia

Paul Scherrer Institute (PSI), Villigen, Switzerland

University of California, Berkeley (UCB and LBNL), USA

University of Illinois, Urbana-Champaign (UIUC), USA

Université Catholique de Louvain, Belgium

TU Muenchen, Garching, Germany

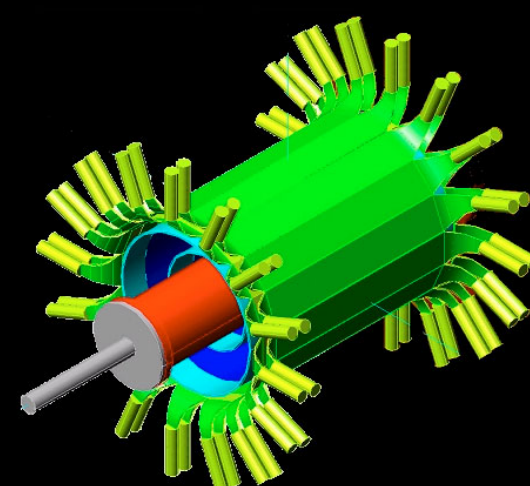
University of Kentucky, Lexington, USA

Boston University, USA

Precision Measurement of the Singlet Muon Capture Rate on the Proton

μ^- capture on hydrogen

MuCAP



Basics

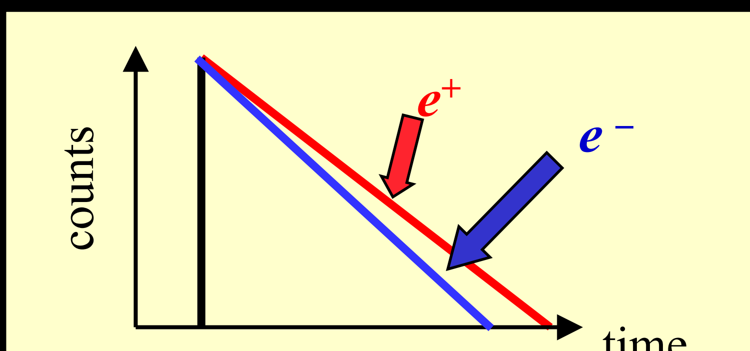
μ^+ ***lifetime = 2.19703*** μs

$$\mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu$$

μ^-, muon capture competes with muon decay:

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e \qquad (99.85\%)$$

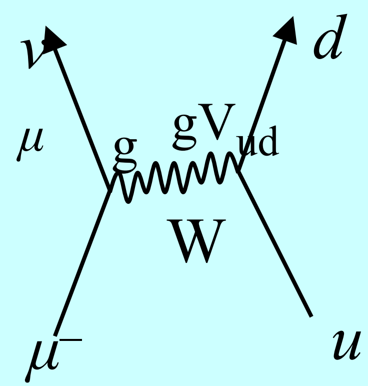
$$(p\mu^-)_{\uparrow\downarrow} \rightarrow n + \nu_\mu \qquad (0.15\%)$$



Lifetimemethod

$$\Lambda_S = \Lambda_{(\mu^-)'} - \Lambda_{\mu^+} = \left(\tau_{(\mu^-)'}\right)^{-1} - \left(\tau_{\mu^+}\right)^{-1}$$

Weak-Interaction V-A, g_V, g_A



At the elementary particle level, the weak interaction is fundamentally **V–A**.

Muon Capture involves hadrons -> QCD effects are encapsulated in the nucleonic charged-current's four "induced form factors

involving Hadrons -> more complex
-> 6 Formfactors

Nucleon charged current at $q^2 = -\,0.88\ m_\mu^{\,2}$

$J_\alpha = V_\alpha - A_\alpha$

$V_\alpha = \cancel{g_V(q^2)\,\gamma_\alpha} + \cancel{i g_M(q^2)/2M\,\sigma_{\alpha\beta}\,q^\beta} + \cancel{g_S(q^2)/m\,q_\alpha}$

$A_\alpha = \cancel{g_A(q^2)\,\gamma_\alpha\,\gamma_5} + g_P(q^2)\,q_\alpha/m\,\gamma_5 + \cancel{i g_T(q^2)/2M\,\sigma_{\alpha\beta}\,q^\beta\,\gamma_5}$

Capture Rate

$$d\Lambda = \frac{\delta(E_f - E_i)\,d^3 p_{\nu_\mu}}{(2\pi)^2}\,|A|^2$$

$$A = \frac{G_F \cos\theta}{\sqrt{2}} \int d^3x \cdot \bar{\psi}_n \left[\ldots(F.F.)\ldots\right]_\alpha \psi_p \cdot \bar{\psi}_{\nu_\mu} \left[\gamma^\alpha (1-\gamma_5)\right] \psi_\mu$$

nucleon weak formfactors g_V, g_M, g_A

- determined by SM symmetries and data
- contribute <0.4% uncertainty to Λ_S

$g_V = 0.9755(5)$

$g_M = 3.5821(25)$

$g_A = 1.245(3)$

remains

$g_P = ?$

- Vector current in SM determined via CVC
  $g_V(0)=1$, $g(q^2)=1+q^2 r^2/6$, $r_V^2=0.59\ \mathrm{fm}^2$
  $g_M(0)=\mu_p-\mu_n-1=3.70589$, $r_M^2=0.80\ \mathrm{fm}^2$
  q^2 dependence from e scatt.
- Axial vector FF from experiment
  $g_A(0)=1.2670(35)$, $r_A^2=0.42\pm0.04\ \mathrm{fm}^2$
  q^2 dependence from quasi-elastic ν scattering,
  π e-production
- 2nd class FF g_S, g_T forbidden by G symmetry, e.g.
  $g_T/g_A=-0.15 \pm 0.15$ (exp),
  -0.0152 ± 0.0053(QCD sum rule, up-down mass difference)
- error from $V_{ud} = 0.16$ %

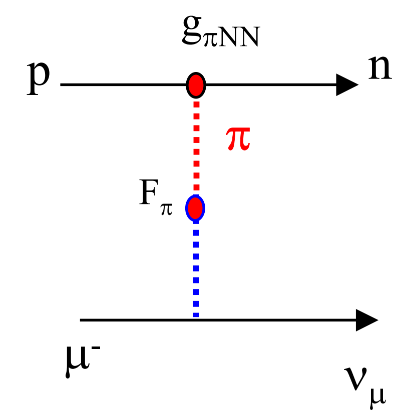
Courtesy P.Kammel

pseudoscalar form factor g_P

PCAC:

$$g_P(q^2) = \frac{2\, m_\mu M}{m_\pi^2 - q^2}\, g_A(0)$$

$g_P = 8.7$



heavy baryon chiral perturbation theory:

$$g_P(q^2) = \frac{2\, m_\mu\, g_{\pi NN}\, F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}\, g_A(0) m_\mu M\, r_A^2$$

$g_P = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.26 \pm 0.23$

Λ calculations O(p³) show good convergence:	100 %	25 %	3 %
delta effect small	LO	NLO	NNLO

$g_{\pi NN}$
13.31(34)
13.0(1)
13.05(8)

fundamental and least known weak nucleon FF
solid theoretical prediction at 2-3% level
basic test of QCD symmetries

Recent reviews:

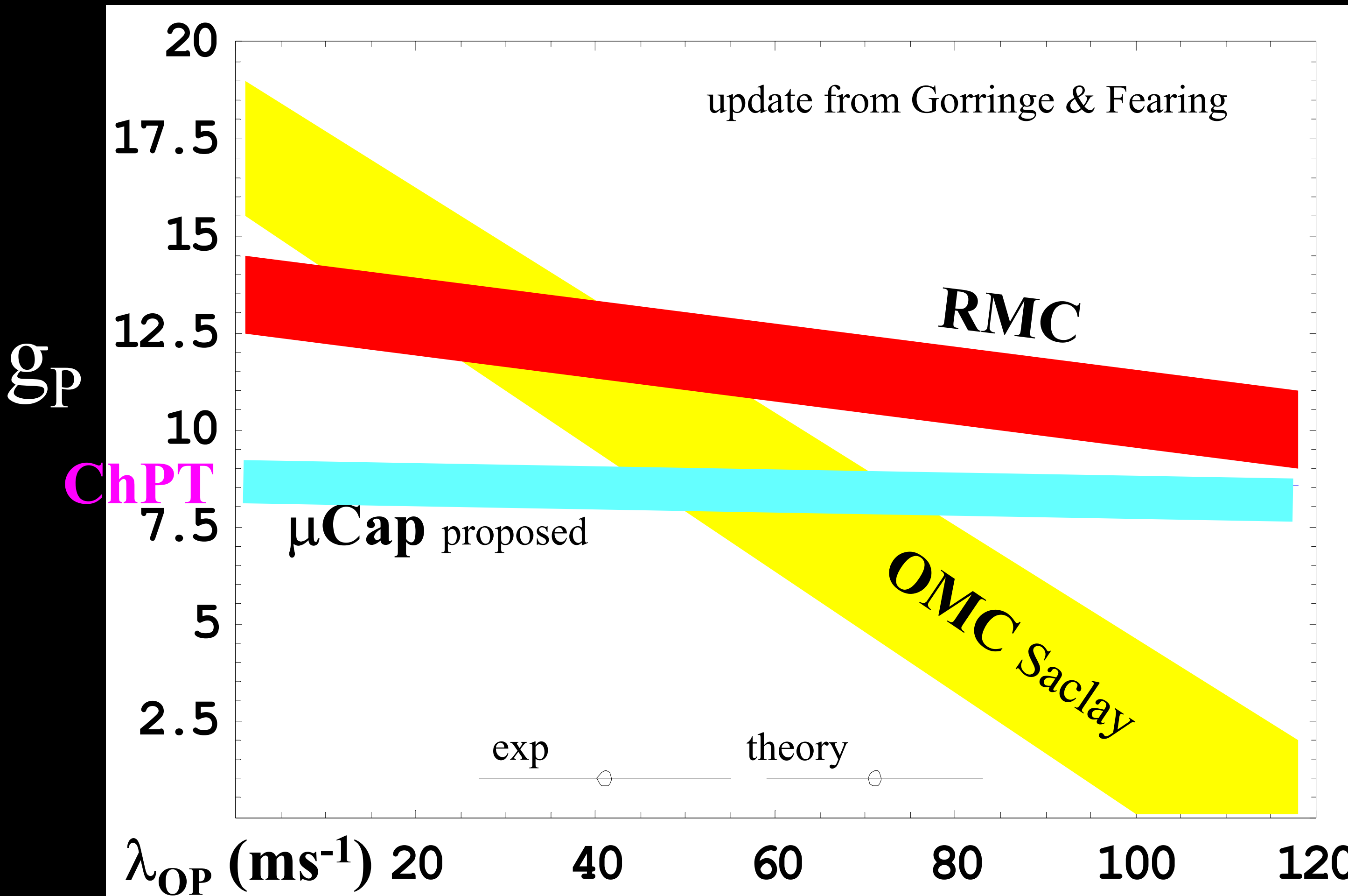
T. Gorringe, H. Fearing, ***Induced pseudoscalar coupling of the proton weak interaction***, nucl-th/0206039, Jun 2002

V. Bernard et al., ***Axial Structure of the Nucleon***, Nucl. Part. Phys. 28 (2002), R1

Courtesy P.Kammel

μCap

Experimental Status: g_P and muon capture - *unsatisfying*

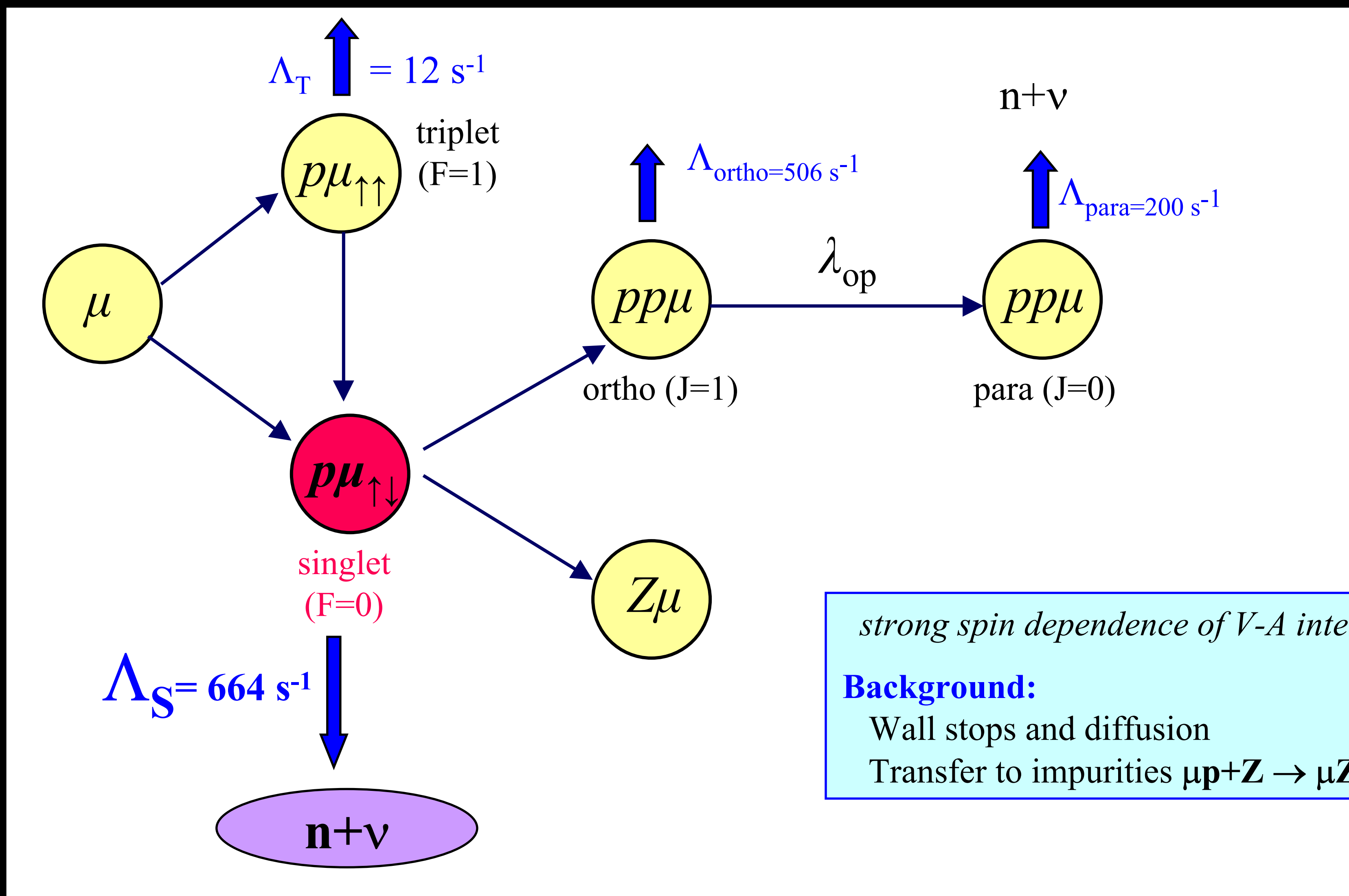


RMC 4σ discrepancy exp/th

OMC not precise, ambiguous interpretation

No overlap between theory/RMC/OMC… **!**

μ^- *Kinetics in Hydrogen -> Experimental Challenges*



strong spin dependence of V-A interaction

Background:

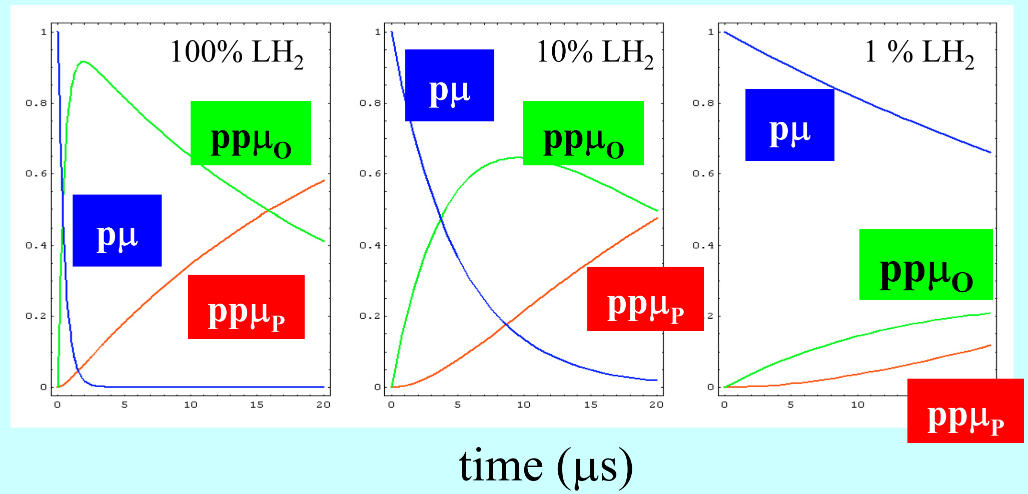
Wall stops and diffusion

Transfer to impurities **μp+Z** → **μZ +p**

Experimental Challenges / Solutions

Physics

- **Unambigous interpretation**
  At low density (1% LH_2) mostly capture from **$\mu p(F=0)$** atomic state.



- **Clean muon stop definition:**
  Wall stops and diffusion eliminated by 3-D muon tracking

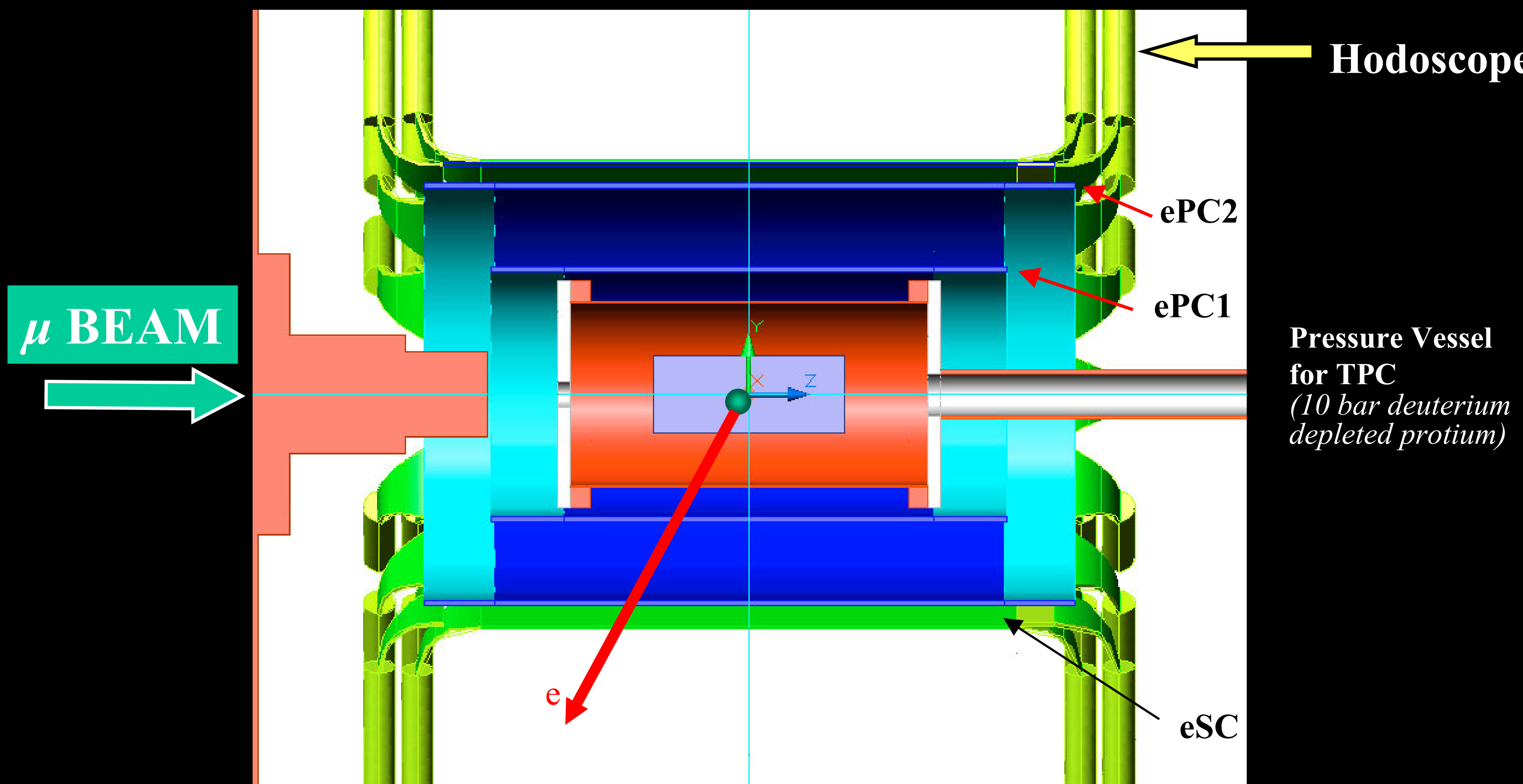
- **In situ gas impurity control** ($c_Z<10^{-8}$, $c_d<10^{-6}$)
  hydrogen chambers bakeable to 150 C, continuous purification
  TPC monitors capture on impurity and transfer to deuterium
  10^{-8} sensitivity with gas chromatograph

- **μ^+SR**: calibrated with tranverse field 70 G

Statistics

- **10^{10} statistics**: Complementary analysis methods

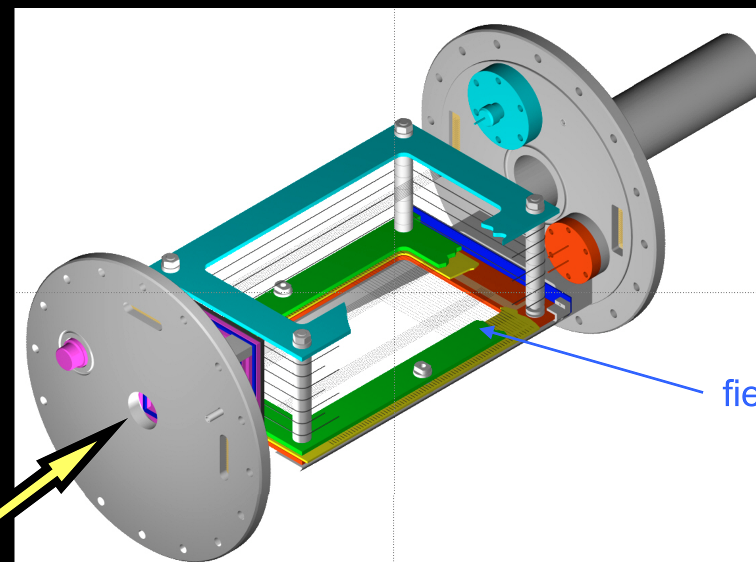
Experimental idea: active target of ultra-pure H_2 gas 10 bar
measure $\tau_{\mu+}$ and $\tau_{\mu-} \Rightarrow \Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$, τ_μ to 10^{-5}



- Detectors cover 75% of 4π
- μ,e detectors are decoupled to prevent cross-talk

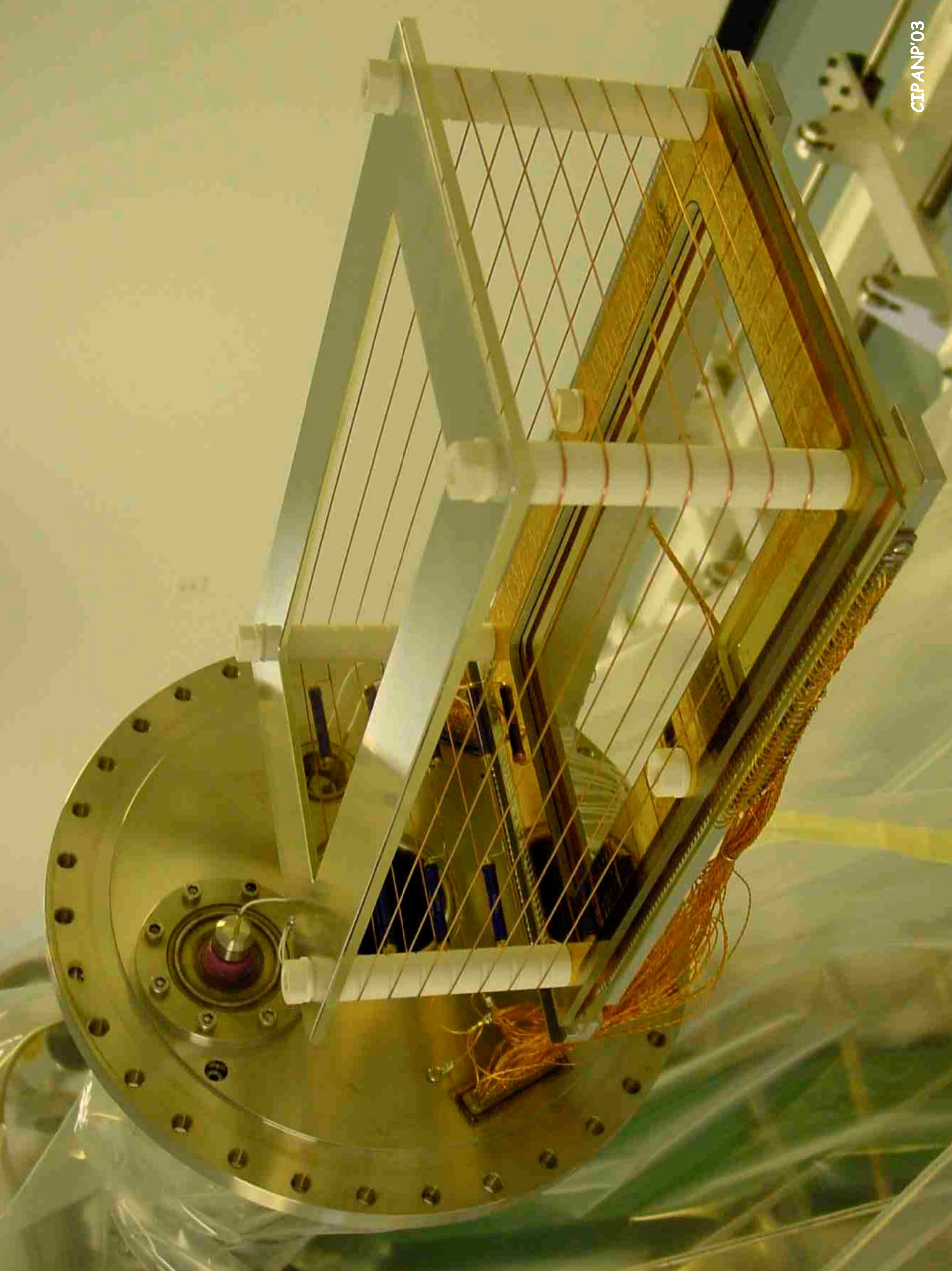
Experimental Setup – TPC

The time projection chamber (TPC) operates in *proportional mode* (gain ~10^4)



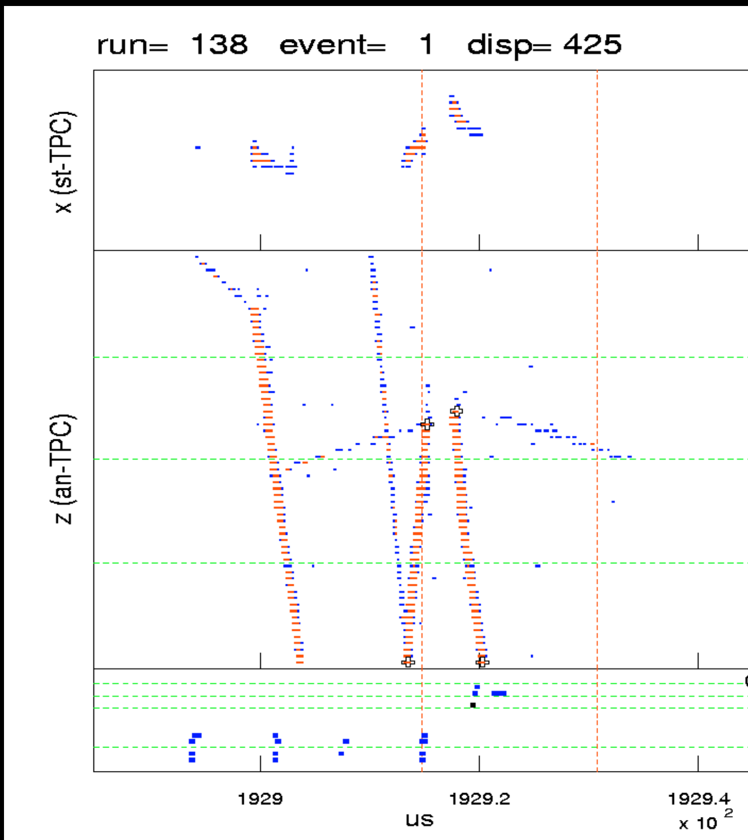
muon entrance window

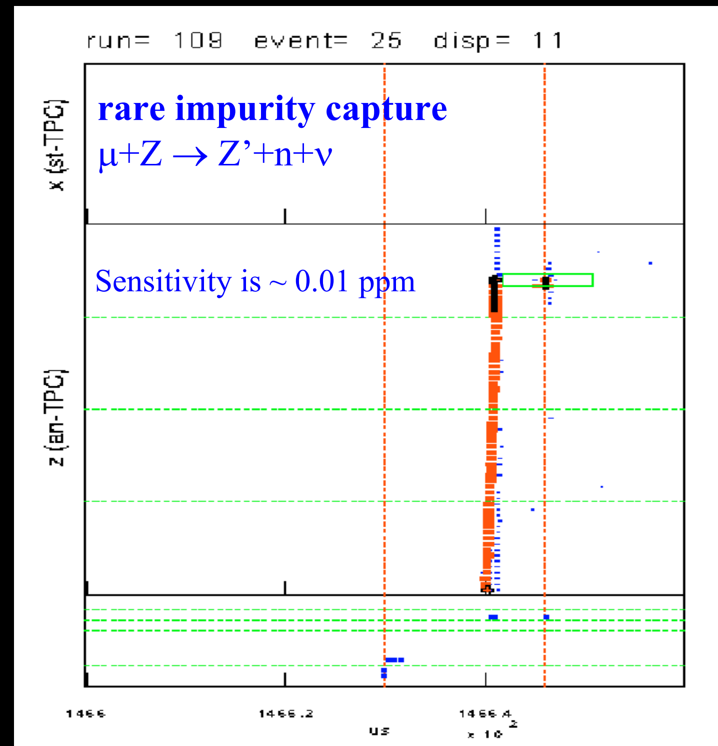
- bakeable
- quartz glass with very low thermal expansion



TPC features

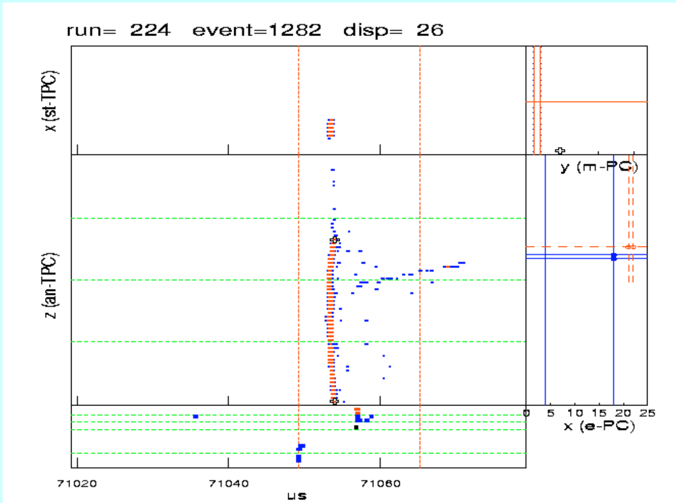
- track reconstruction
- pileup protection
- vertex matching between muon and decay electron
- determination of low levels of $Z>1$ impurities in the H_2 gas





Analysis	Conditions	Admixtures levels		
		O_2	N_2	H_2O, ppm
H- 1174	After filling	~ 0.01 ppm	1.2 ppm	0.075(20)
H- 1176	After 22 hours	~ 0.01 ppm	1.4 ppm	0.11(2)
H-1180	After 192 hours	~ 0.013 ppm	2.7 ppm	0.15(3)

μ transfer to deuterium, diffusion, μCF



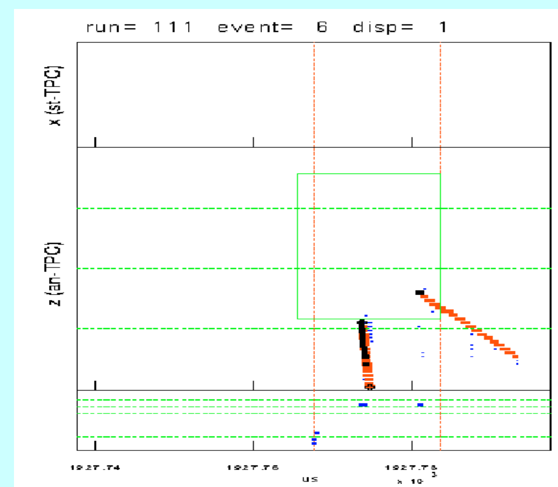
Diffusion $\mu p + d \rightarrow \mu d + p$

Ramsauer Townsend minimum in $\mu d + p$ scattering at 1.6 eV

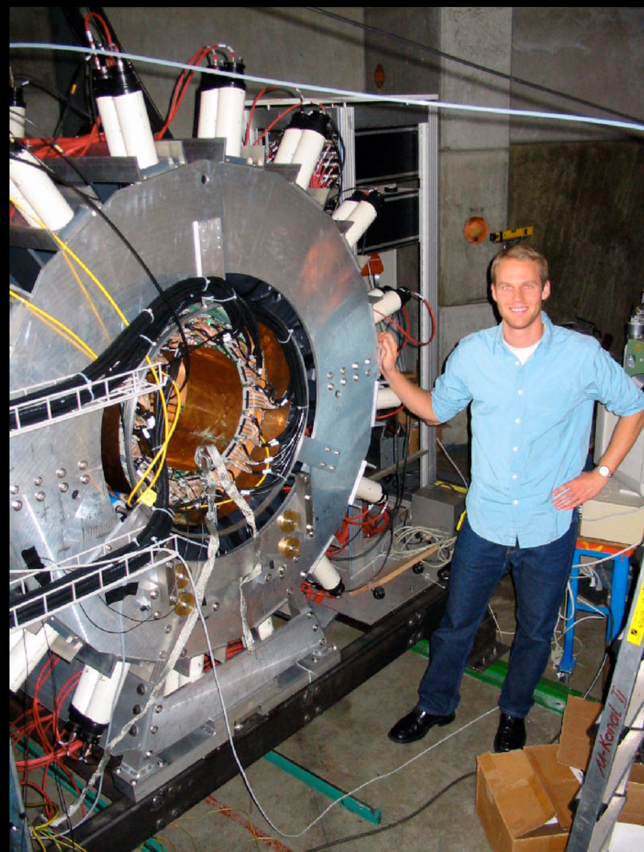
Check by comparing μ^+ and μ^-

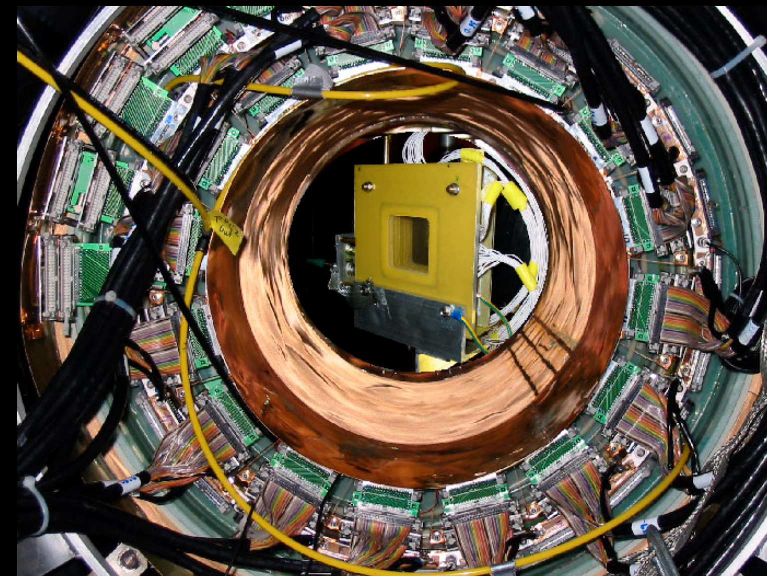
μ-catalyzed pd fusion (Alvarez)

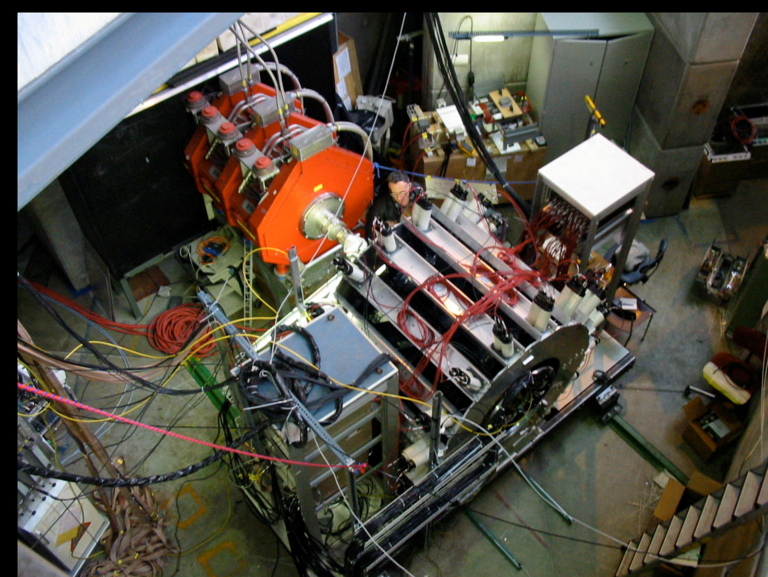
$\mu d + p \rightarrow p\mu d \rightarrow \mu(5.3\text{MeV}) + {}^3\text{He}(0.2\text{KeV})$



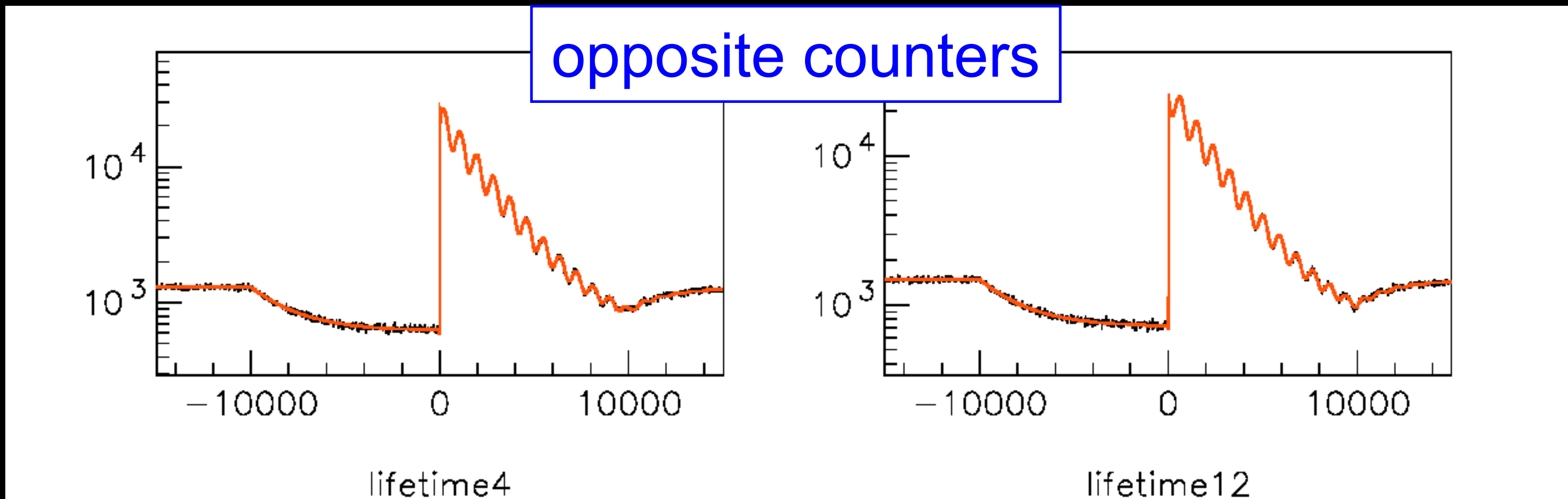
μCap e-detector

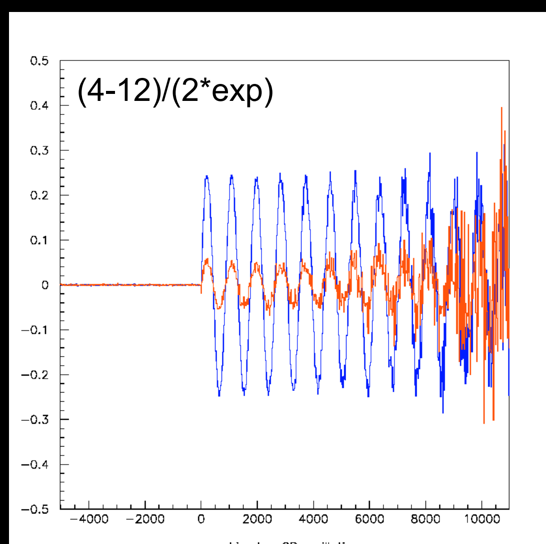






Observed μ^+SR





Comparison of
silver target and
scintillator target
- depolarization differs

MuCap Timetable

Summer 2003: Finalize detector integration and full speed DAQ

Fall 2003: First attempt at accumulating full 10^{10} statistics. Λ_s 3%

2004: Further statistics recording as needed Muons on request beam -> Λ_s 3%

Summary

muon capture on proton

$\mu^- + p \rightarrow \nu_\mu + n$

Λ to 1 %

Nucleon form factors,
chiral symmetry of QCD

μ Cap experiment
g_P to < 7% (3% with μLan kicker)

muon decay

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\tau_{\mu+}$ to 1 ppm

Fermi Coupling Constant

μ Lan experiment

G_F to < 1ppm

Future

muon capture on deuteron

$\mu^- + d \rightarrow \nu_\mu + n + n$

Λ to 1 %

Basic EW two nucleon reaction,
calibrate ν-d reactions L_{1a}

μD project

CIPANP'03