Precision Muon Capture at PSI

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Outline

- \( \mu \rightarrow e \nu \nu \)
  - MuLan
  - \( G_F \)
  - Strength of Weak Interaction

- \( \mu + p \rightarrow n + \nu \)
  - MuCap
  - \( g_P \)
  - Basic QCD Symmetries

- \( \mu + d \rightarrow n + n + \nu \)
  - \( \mu + ^3\text{He} \rightarrow t + \nu \)
  - MuSun
  - Weak few nucleon reactions
  - and astrophysics
Muon Lifetime

Fundamental electro-weak couplings

<table>
<thead>
<tr>
<th>$G_F$</th>
<th>$\alpha$</th>
<th>$M_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 ppm $\rightarrow$ 0.6 ppm</td>
<td>0.37 ppb</td>
<td>23 ppm</td>
</tr>
</tbody>
</table>

Implicit to all EW precision physics

$$G_F \frac{\alpha^2}{\sqrt{2}} \frac{\pi}{m_W^2} \left( 1 + \Delta \right)$$

Uniquely defined by muon decay

$$\frac{1}{\tau_{\mu^-}} = \frac{G_F^2 m_{\mu}^7}{192 \pi^3} \left( 1 + q \right)$$

QED

Extraction of $G_F$ from $\tau_{\mu}$:
Recent two-loop calc. reduced error from 15 to $\sim$0.2 ppm

$\tau$ (MuLan) = $1.1663788(7) \times 10^{-5}$ GeV$^{-2}$ (0.6 ppm)

The most precise particle or nuclear or atomic lifetime ever measured

New $G_F$

$G_F$(MuLan) = $1.1663788(7) \times 10^{-5}$ GeV$^{-2}$ (0.6 ppm)
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  MuLan

• $\mu + p \rightarrow n + \nu$
  MuCap

• $\mu + d \rightarrow n + n + \nu$
  $\mu + ^3\text{He} \rightarrow t + \nu$
  MuSun

Strength of Weak Interaction
$G_F$

Basic QCD Symmetries
$g_P$

Muon Capture on the Proton

➢ Historical: V-A and $\mu$-e Universality

$\mu^+ + p \rightarrow \nu_\mu + n$
charged current

➢ Today: EW current key probe for
  ▪ Understanding hadrons from fundamental QCD
  ▪ Symmetries of Standard Model
  ▪ Basic astrophysics reactions

Chiral Effective Theories
Lattice Calculations
Capture Rate $\Lambda_S$ and Form Factors

- **Muon Capture**: $\mu^- + p \rightarrow \nu_\mu + n$ rate $\Lambda_S$ at $q^2 = -0.88 \, m_\mu^2$

$$\mathcal{M} = -i G_F V_{ud} \bar{u}(p_n) \gamma_\mu (1 - \gamma_5) u(p_\mu) \bar{\nu}(p_\nu) \tau^- \nu [V^\alpha - A^\alpha] u(p_\mu)$$

- **Form factors**
  - Lorentz, T invariance
  - Second class currents suppressed by isospin symm.

All form factors precisely known from SM symmetries and data.

- $g_V$, $g_M$ from CVC, e scattering
- $g_A$ from neutron beta decay

$$\frac{\delta \Lambda_S}{\Lambda_S} = 2 \delta V_{ud}^2 + 0.466 \delta g_V + 0.151 \delta g_m + 1.567 \delta g_A$$

$0.45\%$ $9\%$ pre MuCap

Axial Vector $g_A$

**PDG 2008**
$$g_A(0) = -1.2695 \pm 0.0029$$

**PDG 2012**
$$g_A(0) = -1.2701 \pm 0.0025$$

**Future? (Marciano PDG12)**
$$g_A(0) = -1.275$$

**Axial Mass**
$$G_A(q^2) = g_A / (1 - q^2 / \Lambda_A^2)^2$$
$$\Lambda_A = 1 \text{ GeV} \nu p, \pi \text{ electro production}$$
$$1.35 \text{ nuclear targets}$$
Pseudoscalar Form Factor $g_P$

History
- PCAC
- Spontaneous broken symmetries in subatomic physics, Nambu. Nobel 2008

State-of-the-art
- Precision prediction of ChPT

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

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

• $g_P$ experimentally least known nucleon FF
• solid QCD prediction (2–3% level)
• basic test of QCD symmetries
• recent lattice results

45 years of effort to determine $g_P$

"Radiative muon capture in hydrogen was carried out only recently with the result that the derived $g_P$ was almost 50% too high. If this result is correct, it would be a sign of new physics..."

“Rich” Muon Atomic Physics Makes Interpretation Difficult

Strong sensitivity to hydrogen density $\phi$ (rel. to LH$_2$)
In LH$_2$ fast pp$\mu$ formation, but $\lambda_{op}$ largely unknown

$\Lambda_S = 710$ s$^{-1}$

Precise Theory vs. Controversial Experiments

- no overlap theory & OMC & RMC
- large uncertainty in $\lambda_{op} \rightarrow \pm 50\%$
MuCap Strategy

- Precision technique
- Clear Interpretation
- Clean stops in H\textsubscript{2}
- Impurities < 10 ppb
- Protium D/H < 10 ppb
- Muon-On-Request

All requirements simultaneously

MuCap Strategy

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\[ \Lambda_{S} = \frac{1}{\tau_{\mu^{-}}} - \frac{1}{\tau_{\mu^{+}}} \]

measure \( \tau_{\mu} \) to 10 ppm

\[ \mu^{+} \rightarrow n \nu, \text{only 0.16\% of } \mu^{-} \rightarrow e \nu \]

neutron detection not precise enough

Lifetime method

\[ \log(\text{counts}) \]

\[ \text{time} \]
MuCap Technique

MuCap Strategy

- Precision technique
- Clear Interpretation
- Clean stops in H₂
- Impurities < 10 ppb
- Protium D/H < 10 ppb

At 1% LH₂ density mostly µ atoms during muon lifetime

All requirements simultaneously
MuCap Strategy

- Precision technique
- Clear Interpretation
- **Clean stops in H\textsubscript{2}**
- Impurities < 10 ppb
- Protium D/H < 10 ppb

All requirements simultaneously

Muons Stop in Active TPC Target

to prevent muon stops in walls (Capture rate scales with \(\sim Z^4\))

- 10 bar ultra-pure hydrogen, 1.12\% LH\textsubscript{2}
- 2.0 kV/cm drift field
- \(~5.4\) kV on 3.5 mm anode half gap
- Bakeable glass/ceramic materials

![3D tracking w/o material in fiducial volume](image)
MuCap Strategy

- Precision technique
- Clear Interpretation
- Clean stops in $H_2$
- Impurities $< 10$ ppb
- Protium D/H $< 10$ ppb
- Muon-On-Request

All requirements simultaneously

2004: $c_N < 7$ ppb, $c_{H_2O} \sim 20$ ppb
2006 / 2007: $c_N < 7$ ppb, $c_{H_2O} \sim 9-4$ ppb

Experiment at PSI

Muon On Request

$\pi$E3 beamline
Kicker
Separator
Slit
Quadrupoles
TPC
MuCap detector


**MuCap Data**

<table>
<thead>
<tr>
<th>Year</th>
<th>Statistics [10^{10} muon decays]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \mu^- )</td>
<td>( \mu^+ )</td>
</tr>
<tr>
<td>2004</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>2006</td>
<td>0.55</td>
<td>0.16</td>
</tr>
<tr>
<td>2007</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>Total</td>
<td>( \sim 1.21 )</td>
<td>( \sim 0.61 )</td>
</tr>
</tbody>
</table>


\( \lambda^+ \) known to 1 ppm from MuLan

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**Muon defined by TPC**

Signals digitized into pixels with three thresholds (green, blue, red)

TPC side view

Front face view

Fiducial volume

TPC active volume

Muon beam direction

Vertical direction

Transverse direction
Electron defined by **Independent e-Tracker**

- Small, but significant interference with μ track
- simple, robust track reconstruction and its verification essential

**Time Distributions are Consistent**

\[ N(t) = N_0 \cdot w \cdot \lambda \cdot e^{(-\lambda t)} + B \]

- No azimuth dependence
- fitted \( \lambda \) is constant

Data run number (~3 minutes per run)
Start and stop-time-scans consistency

\[ \lambda_{\text{fit}} \text{ vs. Fit Start Time} \]

\[ \chi^2/\text{ndf} \]

\[ 0.1 \rightarrow 1 \]

\[ \chi^2/\text{NDF}_{\text{fit}} \text{ vs. Fit Start Time} \]

\[ \chi^2/\text{NDF}_{\text{fit}} \text{ vs. Fit Stop Time} \]

MuCap Results

\[ \lambda \ [s^{-1}] \text{ double blinded} \]

\[ 2006 \]

\[ 2007 \]

\[ \text{MuCap PRL 2007} \]

rates with secret offset, stat. errors only
Disappearance rate $\lambda$

$\lambda$ [ s$^{-1}$ ] unblinded

<table>
<thead>
<tr>
<th></th>
<th>Run 2006</th>
<th>Run 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda$ (s$^{-1}$)</td>
<td>$\delta\lambda$ (s$^{-1}$)</td>
</tr>
<tr>
<td>High-Z impurities</td>
<td>-7.8</td>
<td>1.87</td>
</tr>
<tr>
<td>$\mu^p$ scatter</td>
<td>-12.4</td>
<td>3.22</td>
</tr>
<tr>
<td>$\mu^p$ diffusion</td>
<td>-3.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Fiducial volume cut</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Entrance counter inefficiencies</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Choice of electron detector def.</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-23.3</strong></td>
<td><strong>5.1</strong></td>
</tr>
</tbody>
</table>

$\lambda_{\mu^-} (R06) = 455857.3 \pm 7.7_{stat} \pm 5.1_{syst}$

$\lambda_{\mu^-} (R07) = 455853.1 \pm 8.3_{stat} \pm 3.9_{syst}$
Determination of $\Lambda_S$

$$\lambda^- = \lambda_0 + \Lambda_S + \Delta \lambda_{\mu \nu}$$

$$\lambda^+ + \Delta \lambda_{\mu \nu}$$

$\Lambda_S$ (MuCap prelim) $= 714.9 \pm 5.4\text{ stat} \pm 5.0\text{ syst} \text{ s}^{-1}$

$\Lambda_S$ (theory) $= 711.5 \pm 4.6 \text{ s}^{-1}$

Czarnecki, Marciano, Sirlin, RC=2.8%

$g_p$: Precise and unambiguous MuCap result solves long-standing puzzle

$g_p$(MuCap prelim) $= 8.04 \pm 0.56$

$g_p$(theory) $= 8.26 \pm 0.23$
Outline

• $\mu \rightarrow e \nu \nu$
  MuLan
  Strength of Weak Interaction $G_F$

• $\mu + p \rightarrow n + \nu$
  MuCap
  Basic QCD Symmetries $g_P$

• $\mu + d \rightarrow n + n + \nu$
  $\mu + ^3\text{He} \rightarrow t + \nu$
  MuSun
  Weak few nucleon reactions and astrophysics $L_{1A} \hat{d}^R$

Motivation

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

- simplest nuclear weak interaction process with precise th. & exp.
  - nucleon FF ($g_P$) from MuCap
  - rigorous QCD calculations with effective field theory
  - pion less EFT
  - ChPT

- close relation to neutrino/astrophysics
  - solar fusion reaction $pp \rightarrow d e^+\nu$
  - $d$ scattering in SNO exp.

- model independent connection to $\mu d$ by single Low Energy Constant (LEC)
  - $\mu + d$ determines this LEC in clean 2 N system → "Calibrates the Sun"
  - reduce LEC uncertainty from 100% to ~20%
Precise Experiment Needed

MuSun proposed $\sigma = 1.2\%$
- Cargnelli 1989
- Bardin 1986
- Bertin 1973
- Wang 1965
- Adam 2012, full EFT
- Marcucci 2012, full EFT
- Marcucci 2011, hEFT
- Ricci 2009, SNPA, hEFT
- Chen 2005, pionless EFT
- Ando 2002, hEFT
- Adam 1990, SNPA
- Doi 1990, SNPA
- Tatara 1990, SNPA

$\Lambda_d$ (s$^{-1}$)

MuSun Physics and Interpretation

- Precision technique
- Clear Interpretation
- Clean stops in $D_2$
- Impurities < 1ppb
- H/D < 100 ppb

Muon-Catalyzed Fusion
Breunlich, Kammel, Cohen, Leon
Precise Experiment Possible?

- Precision technique
- Clear Interpretation
- Clean stops in D\textsubscript{2}
- Impurities < 1 ppb
- H/D < 100 ppb

Active muon target

- liquid Neon cooling at 34K
- HV Cathode 80 kV
- drift field 11 kV/cm
- vertical drift 72 mm
- grid 3.5 kV
- Be window 0.4 mm
- 48 anode pads 90x120 mm\textsuperscript{2}
- cont. circulation & cleaning of the D\textsubscript{2} gas at 5 bar
- density \( \varphi = 6\% \) of liquid hydrogen

MuSun Detector System

- Liquid Ne Circulation
- Electron Tracker
- TPC Digitizer
- Electronics
- Impurity filtering

8/9/12
**Fusions in TPC**

- Muon and helium tracks

**Status and Plans**

**Analysis**
- analysis run 2011 data
  - $4.8 \times 10^9$ good $\mu^-$ stop
  - $4 \times 10^8$ $\mu^+$ stop events
- first physics publication
- study detector upgrades

**Upgrades**
- detector upgrades 2012
  - cryo preamp
  - TPC optimization
  - improved purity and monitoring

**New beam line at PSI**

**Commissioning run 2012**

**Final runs 2013-14**
Summary: Evolution of Precision

- $g_P = 8.04 \pm 0.56$ (up)
- $g_P = 8.2 \pm 0.7$ ($\mu^3$He exp+MKRSV theo)

$\mu = -0.88 \text{m}$

$\lambda_s = 8.04 \pm 0.56$ ($\mu_p$)
$\lambda_s = 8.2 \pm 0.7$ ($\mu_3$He exp+MKRSV theo)

Collaborations

**MuLan**
Boston University, USA
University of Illinois at Urbana-Champaign, Urbana, USA
James Madison University, Harrisonburg, USA
University of Kentucky, Lexington, USA
KVI, University of Groningen, Groningen, The Netherlands
Paul Scherrer Institute (PSI), Villigen, Switzerland
Regis University, Denver, USA
University of Washington, Seattle, USA
Université Catholique de Louvain, Belgium
University of South Carolina, USA

**MuCap/MuSun**
Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
Paul Scherrer Institute (PSI), Villigen, Switzerland
University of Illinois at Urbana-Champaign, Urbana, USA
University of California, Berkeley (UCB and LBNL), USA
University of Washington, Seattle, USA
University of Lexington, Lexington, USA
Boston University, USA
Regis University, Denver, USA

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