Precision Muon Capture at PSI

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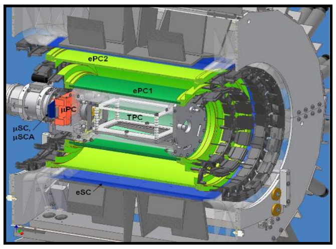
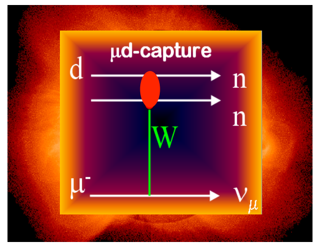
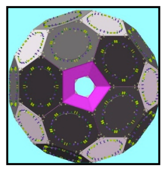
http://www.npl.washington.edu/muon/

MuCap



MuSun





MuLan

Chiral Dynamics, Aug 2012

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Outline

- $\mu \rightarrow e\,\nu\,\nu$ — Strength of Weak Interaction
  MuLan — G_F
- $\mu + p \rightarrow n + \nu$ — Basic QCD Symmetries
  MuCap — g_P
- $\mu + d \rightarrow n + n + \nu$
  $\mu + {}^3He \rightarrow t + \nu$ — Weak few nucleon reactions and astrophysics
  MuSun

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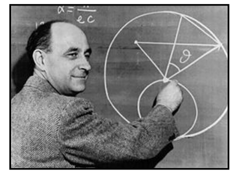
Muon Lifetime



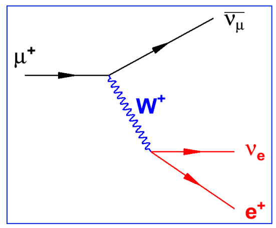
Fundamental electro-weak couplings

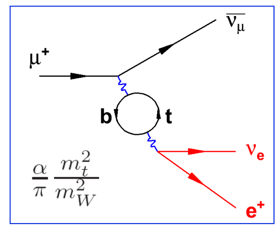
G_F	α	M_Z
9 ppm → 0.6 ppm	0.37 ppb	23 ppm

MuLan Collaboration
PRL **106**, 041803 (2011)

Implicit to all EW precision physics

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

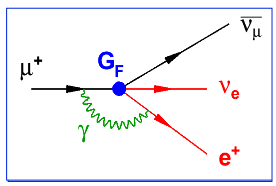




Uniquely defined by muon decay

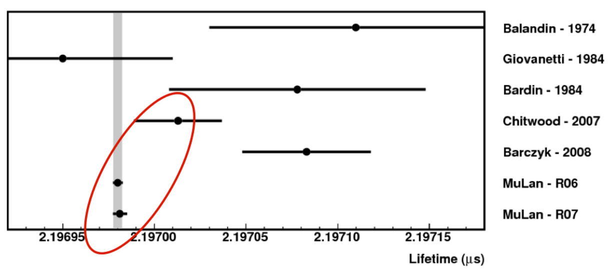
$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}(1+q)$$

QED



Extraction of G_F from τ_μ :
Recent two-loop calc.
reduced error from
15 to ~0.2 ppm

MuLan Final Results



τ(R06) = 2 196 979.9 ± 2.5 ± 0.9 ps
τ(R07) = 2 196 981.2 ± 3.7 ± 0.9 ps

τ(Combined) = 2 196 980.3 ± 2.2 ps (1.0 ppm)
Δτ(R07 – R06) = 1.3 ps

The most precise particle or nuclear or atomic lifetime ever measured

New G_F

G_F(MuLan) = 1.166 378 8(7) x 10^{-5} GeV^{-2} (0.6 ppm)

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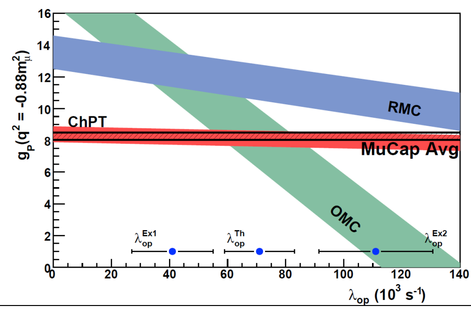
- $\mu + p \rightarrow n + \nu$ — Basic QCD Symmetries

  MuCap — g_P

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

  $\mu + {}^3He \rightarrow t + \nu$

  MuSun



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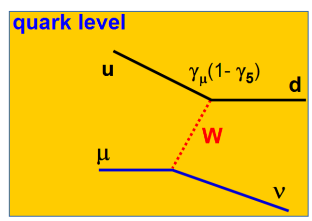
Muon Capture on the Proton

➢ **Historical: V-A and μ-e Universality**

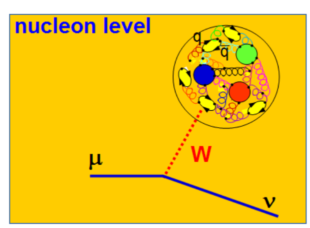
$\mu^- + p \rightarrow \nu_\mu + n$ charged current



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

Chiral Effective Theories

Lattice Calculations



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Capture Rate Λ_S and Form Factors

- **Muon Capture**

$\mu^- + p \rightarrow \nu_\mu + n$ rate Λ_S at $q^2 = -0.88\, m_\mu^2$

$$\mathcal{M} = \frac{-iG_F V_{ud}}{\sqrt{2}} \overline{u}(p_\nu)\gamma_\alpha(1-\gamma_5)u(p_\mu)\overline{u}(p_f)\tau_-\,[V^\alpha - A^\alpha]\,u(p_i)$$

- **Form factors**

Lorentz, T invariance

$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \frac{g_P(q^2)}{m_\mu}\,q_\alpha\,\gamma_5$$

+ second class currents suppressed by isospin symm.

All form factors precisely known from SM symmetries and data.

apart from g_P = 8.3 ± 50%

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

$$\frac{\delta\Lambda_S}{\Lambda_S} = 2\frac{\delta V_{ud}}{V_{ud}} + 0.466\frac{\delta g_v}{g_v} + 0.151\frac{\delta g_m}{g_m} + 1.567\frac{\delta g_a}{g_a} - 0.179\frac{\delta g_p}{g_p}$$

0.45 % **9 % pre MuCap**

Axial Vector g_A

PDG 2008
$g_A(0)=-1.2695\pm0.0029$

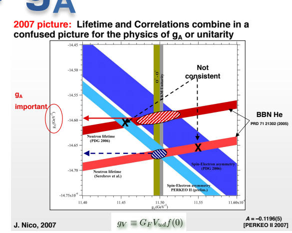
PDG 2012
$g_A(0)=-1.2701 \pm0.0025$

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

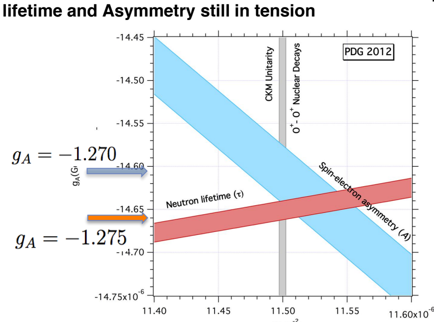
Axial Mass

$$G_A(q^2) = g_A/(1-q^2/\Lambda_A^2)^2$$

Λ_A= 1 GeV νp, π electro production
1.35 nuclear targets



2012 Picture: Lifetime and Correlations in better shape, but lifetime and Asymmetry still in tension



J. Nico, 2012 $g_V \equiv G_F V_{ud} f(0)$ 8

Pseudoscalar Form Factor g_P

History

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

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

Foundations for
mass generation
chiral perturbation theory of QCD

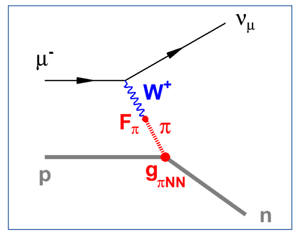
State-of-the-art

- Precision prediction of ChPT

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

g_P = (8.74 ± 0.23) – (0.48 ± 0.02) = 8.26 ± 0.23

leading order | one loop | two-loop <1%



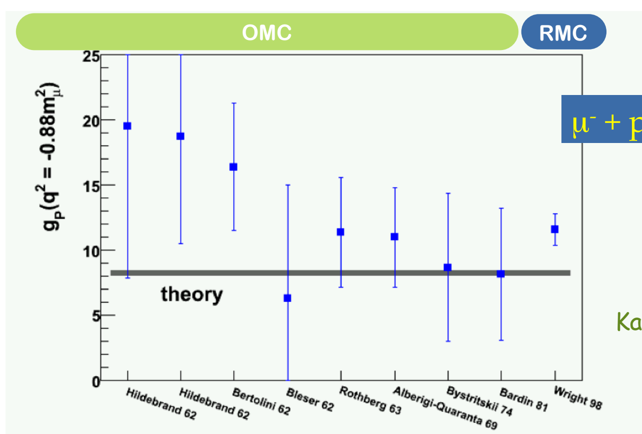
- g_P experimentally least known nucleon FF
- solid QCD prediction (2-3% level)
- basic test of QCD symmetries
- recent lattice results

Kammel & Kubodera, Annu. Rev. Nucl. Part. Sci. 2010.60:327

Gorringe, Fearing, Rev. Mod. Physics 76 (2004) 31

Bernard et al., Nucl. Part. Phys. 28 (2002), R1

45 years of effort to determine g_P



$\mu^- + p \rightarrow n + \nu + \gamma$

Kammel&Kubodera

" 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... "

— *Lincoln Wolfenstein (Ann.ReNucl.Part.Sci. 2003)*

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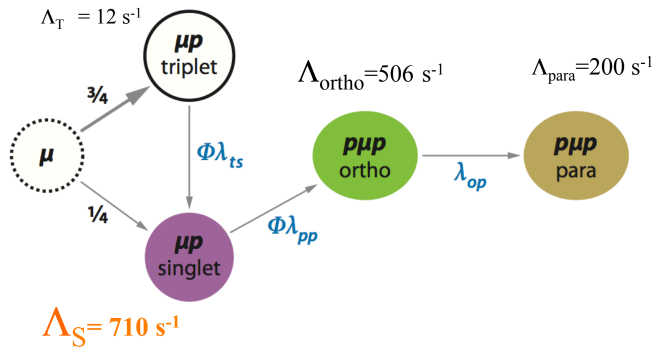
“Rich” Muon Atomic Physics Makes Interpretation Difficult



Strong sensitivity to hydrogen density ϕ (rel. to LH_2)

In LH_2 fast ppμ formation, but λ_{op} largely unknown

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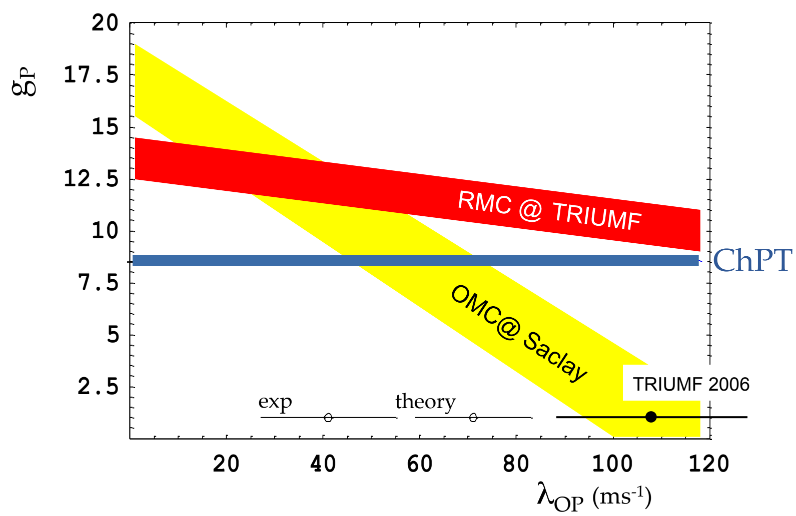
Precise Theory vs. Controversial Experiments



- no overlap theory & OMC & RMC
- large uncertainty in λ_{OP} → g_P ± 50% ?

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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

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MuCap Strategy

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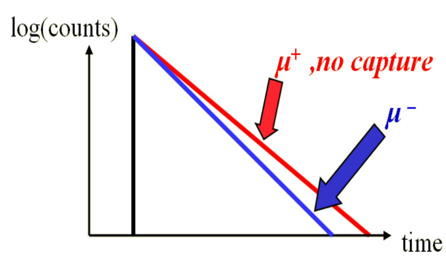
All requirements simultaneously

- $\mu p \rightarrow n\nu$ rare, only 0.16% of $\mu \rightarrow e\nu\nu$
- neutron detection not precise enough

Lifetime method



$\Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$

measure τ_μ to 10ppm

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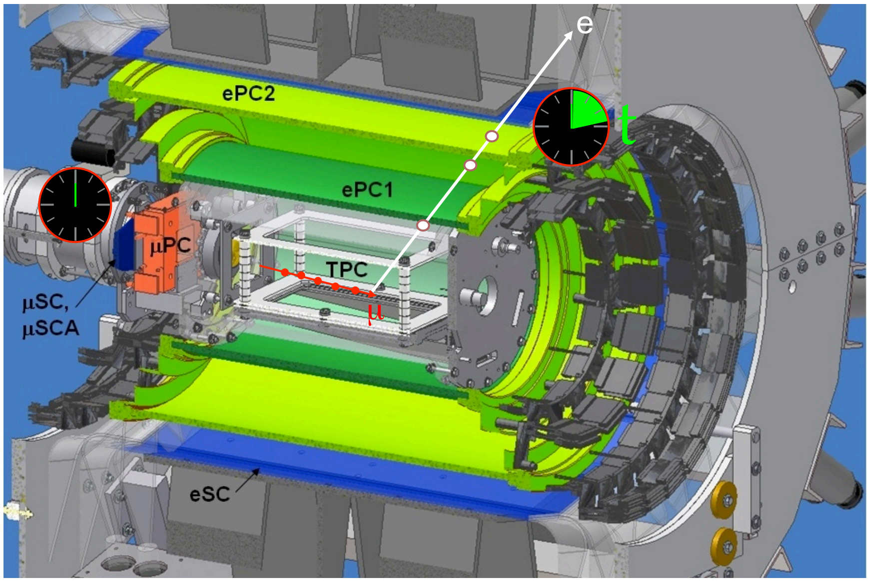
MuCap Technique



MuCap Strategy

- Precision technique
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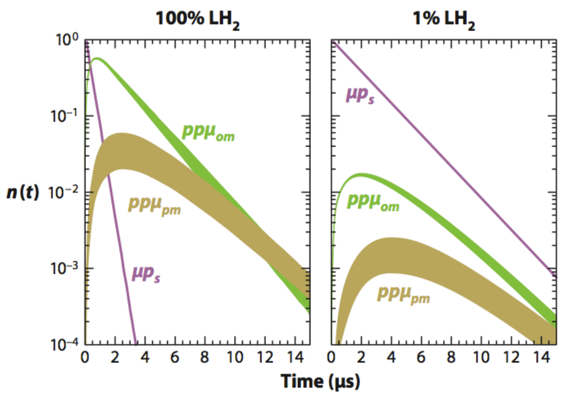
All requirements simultaneously

At 1% LH_2 density mostly pμ atoms during muon lifetime



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All requirements simultaneously

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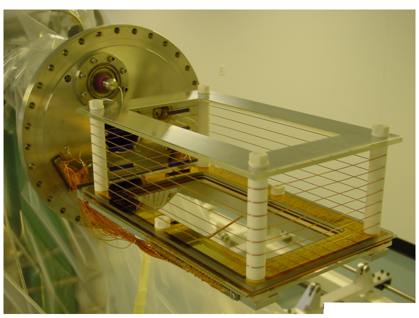
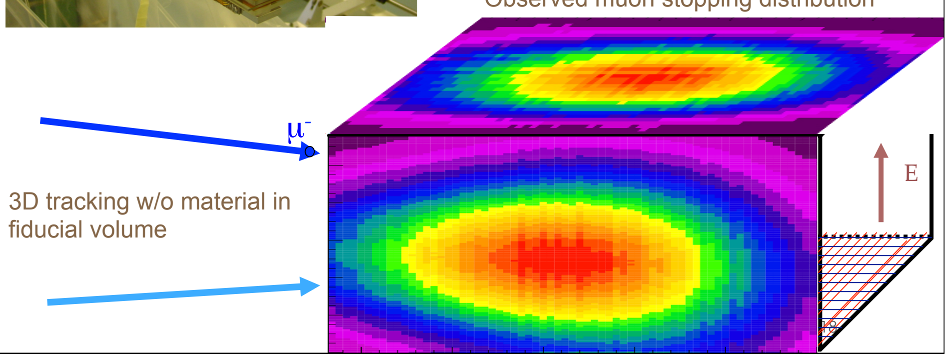
Muons Stop in Active TPC Target



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

10 bar ultra-pure hydrogen, 1.12% LH_2
2.0 kV/cm drift field
~5.4 kV on 3.5 mm anode half gap
bakeable glass/ceramic materials

Observed muon stopping distribution

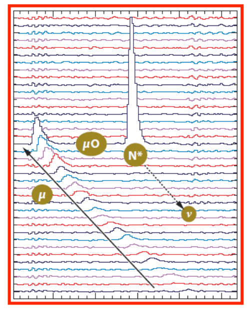


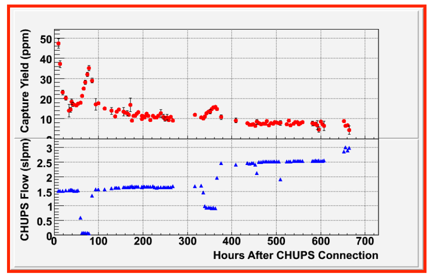
MuCap Strategy

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

All requirements simultaneously

- CHUPS purifies the gas continuously
- TPC monitors impurities
- Impurity doping calibrates effect





2004: c_N < 7 ppb, c_{H2O}~20 ppb

2006 / 2007: c_N < 7 ppb, c_{H2O}~9-4ppb

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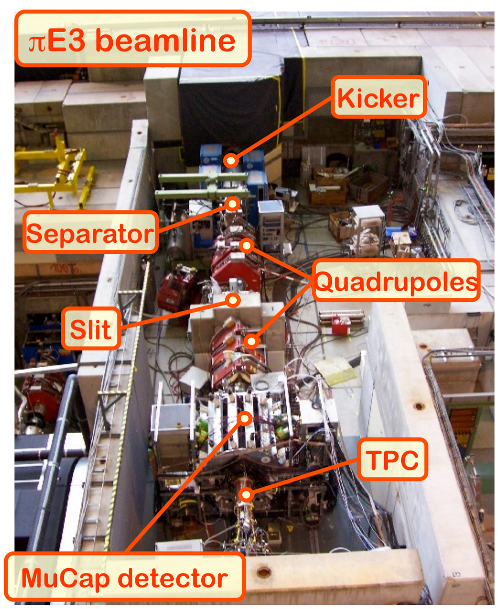
Experiment at PSI



Muon On Request

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MuCap Data

Year	Statistics [10^{10} muon decays]		Comment
	μ-	μ+	
2004	0.16	0.05	published *
2006	0.55	0.16	This talk
2007	0.50	0.40	This talk
Total	**~1.21**	**~0.61**	**~60TB raw data**

*V.A. Andreev et al., Phys. Rev. Lett. 99, 03202 (2007)

λ^+ known to 1 ppm from MuLan

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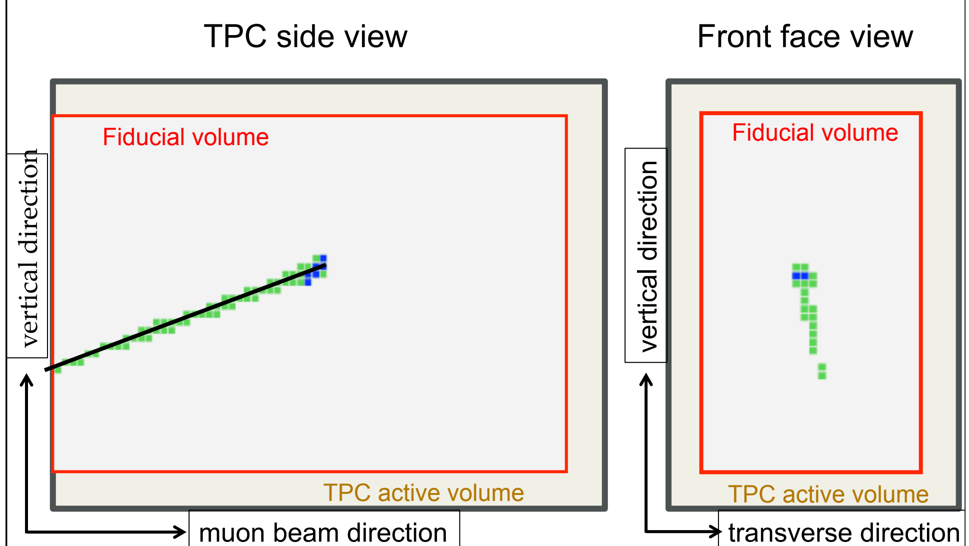
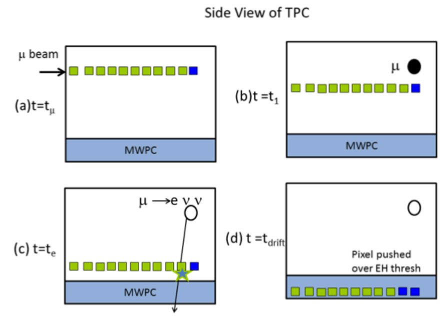
Muon defined by TPC

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

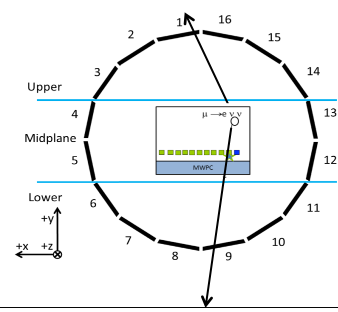


Electron defined by Independent e-Tracker

- Small, but significant interference with μ track

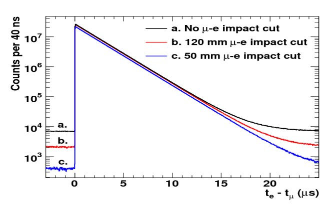


- simple, robust track reconstruction and its **verification** essential

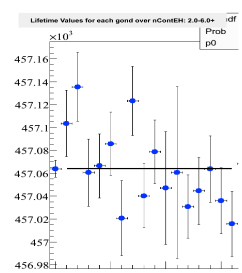


Time Distributions are Consistent

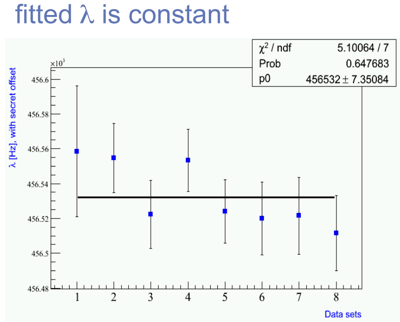
$$N(t) = N_0 \cdot w \cdot \lambda \cdot e^{(-\lambda t)} + B$$

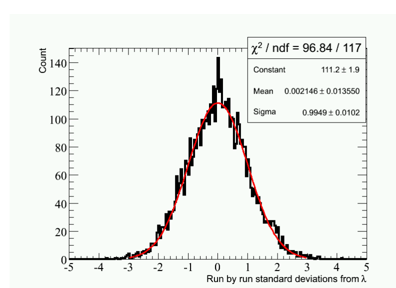


No azimuth dependence



fitted λ is constant

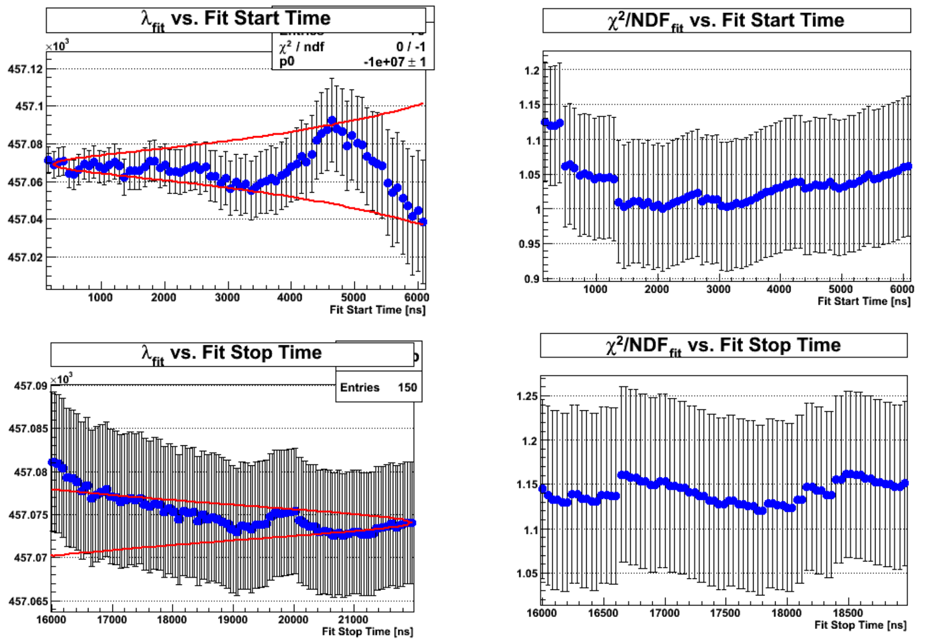




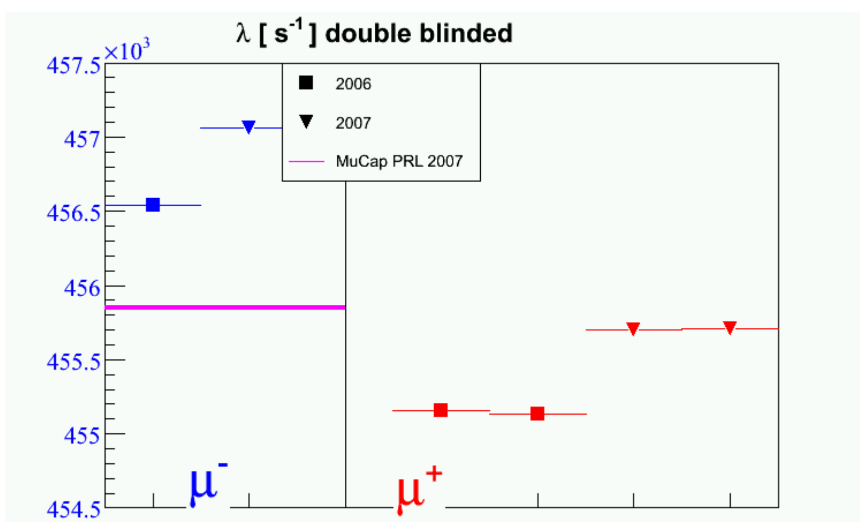
Run groups

Data run number (~3 minutes per run)

Start and stop-time-scans consistency



MuCap Results



rates with secret offset, stat. errors only

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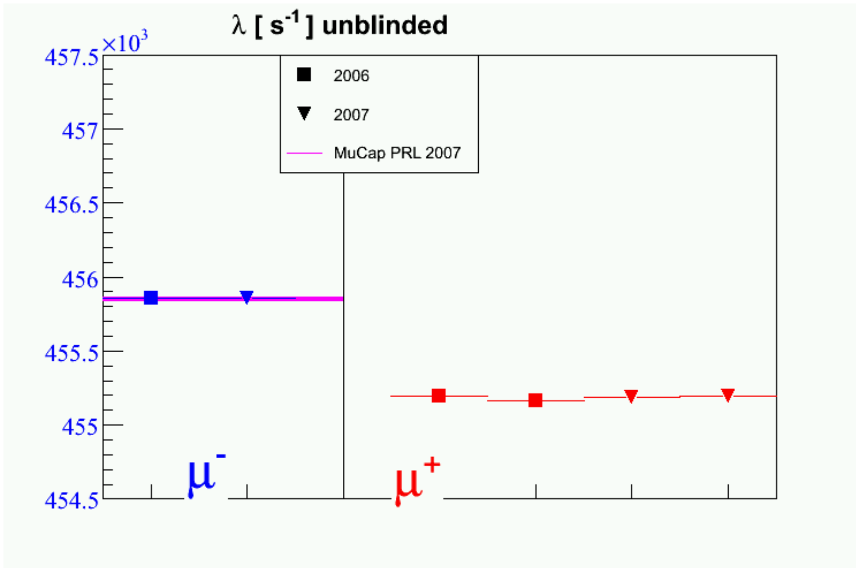
Disappearance rate λ



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Error budget

Systematic errors	Run 2006		Run 2007	
	λ (s⁻¹)	δλ (s⁻¹)	λ (s⁻¹)	δλ (s⁻¹)
High-Z impurities	-7.8	1.87	-4.54	0.93
μp scatter	-12.4	3.22	-7.20	1.25
μp diffusion	-3.1	0.1	-3.0	0.1
Fiducial volume cut		3.0		3.0
Entrance counter inefficiencies		0.5		0.5
Choice of electron detector def.		1.8		1.8
Total	**-23.3**	**5.1**	**-14.7**	**3.9**

$$\lambda_{\mu^-}(R06) = 455857.3 \pm 7.7_{stat} \pm 5.1_{syst}$$
$$\lambda_{\mu^-}(R07) = 455853.1 \pm 8.3_{stat} \pm 3.9_{syst}$$

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Determination of Λ_S

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

molecular formation

MuCap: precision measurement

$\lambda_{pp\mu} = (1.937 \pm 0.06) \times 10^6\ \mathrm{s}^{-1}$

$$\lambda_\mu^+ + \Delta\lambda_{\mu p}$$

MuLan

bound state effect

Λ_S (MuCap prelim) = $714.9 \pm 5.4_{stat} \pm 5.0_{syst}\ \mathrm{s}^{-1}$

Λ_S (theory) = $711.5 \pm 4.6\ \mathrm{s}^{-1}$

Czarnecki, Marciano, Sirlin, **RC=2.8%**

711.4	Pheno	CMS
706.6	HBChPT	BHM
714.5	HBChPT	AMK

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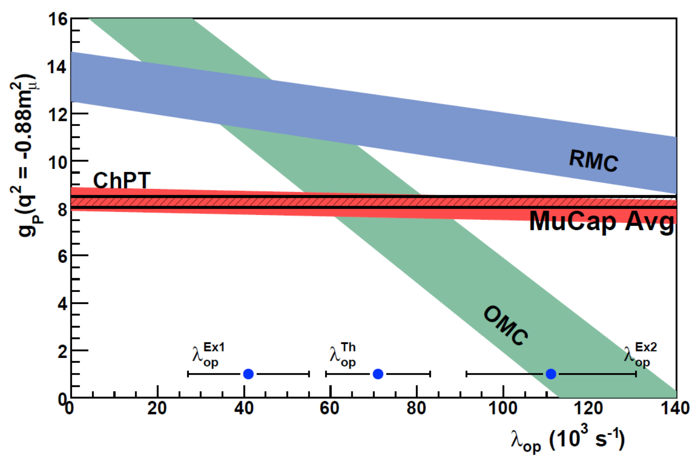
g_P: Precise and unambiguous MuCap result solves long-standing puzzle



g_P(MuCap prelim) = 8.04 ± 0.56

g_P(theory) = 8.26 ± 0.23

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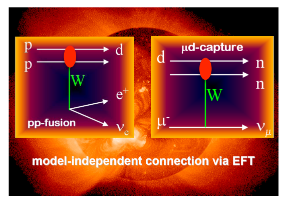
Outline

- μ → e ν ν — Strength of Weak Interaction
  MuLan — G_F
- μ + p → n + ν — Basic QCD Symmetries
  MuCap — g_P

Laura Marcucci, Tuesday

- μ + d → n + n + ν
  μ + ^{3}He → t + ν — Weak few nucleon reactions and astrophysics
  MuSun — L_{1A} $\hat{d}^R$



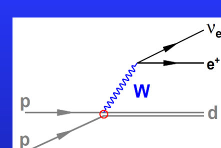
Motivation

μ⁻ + d → ν + n + n — measure rate Λ_d in μd(↑↓) atom to <1.5%

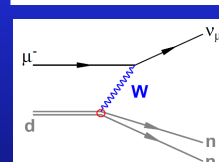
- simplest nuclear weak interaction process with precise th. & exp.
  nucleon FF (g_P) from MuCap
  rigorous QCD calculations with
  effective field theory

pion less EFT	$\frac{q}{m_\pi}$	L_{1A}
ChPT	$\frac{q}{\Lambda_\chi}$	$\hat{d}^R$

- close relation to neutrino/astrophysics
  solar fusion reaction pp → de⁺ν
  νd scattering in SNO exp.



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



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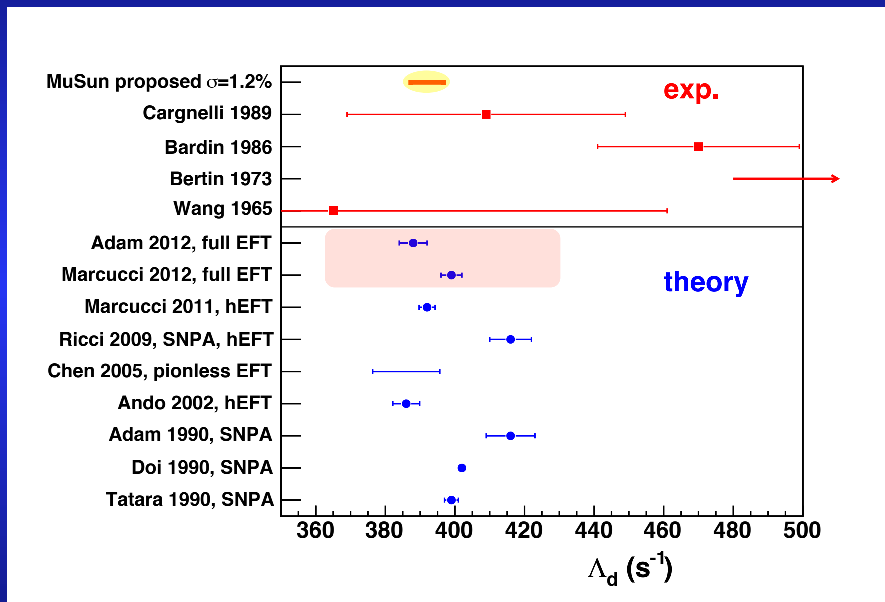
Precise Experiment Needed



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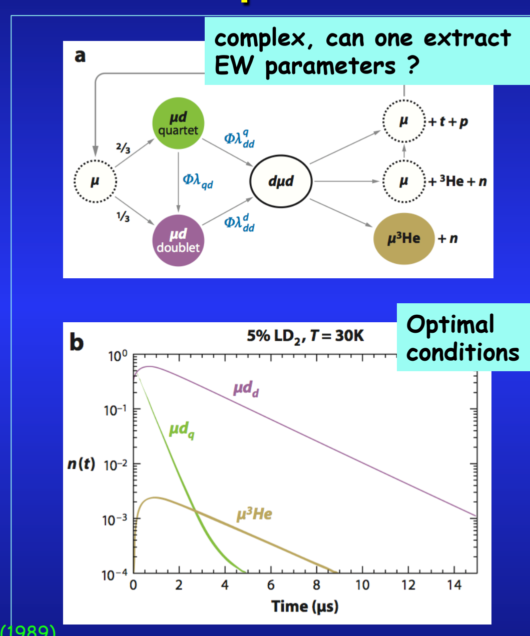
Muon Physics and Interpretation

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



Muon-Catalyzed Fusion
Breunlich, Kammel, Cohen, Leon
Ann. Rev. Nucl. Part. Science, 39: 311-356 (1989)

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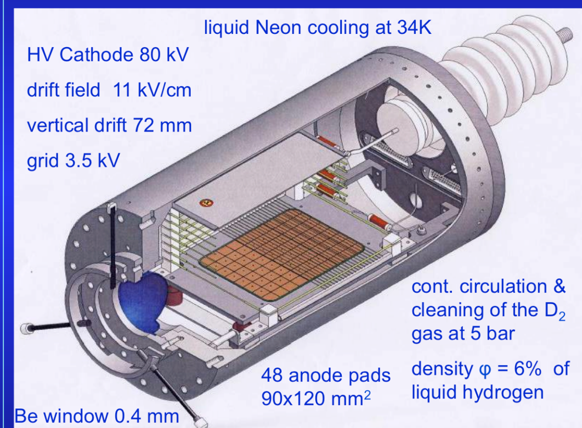
Precise Experiment Possible?

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

Active muon target



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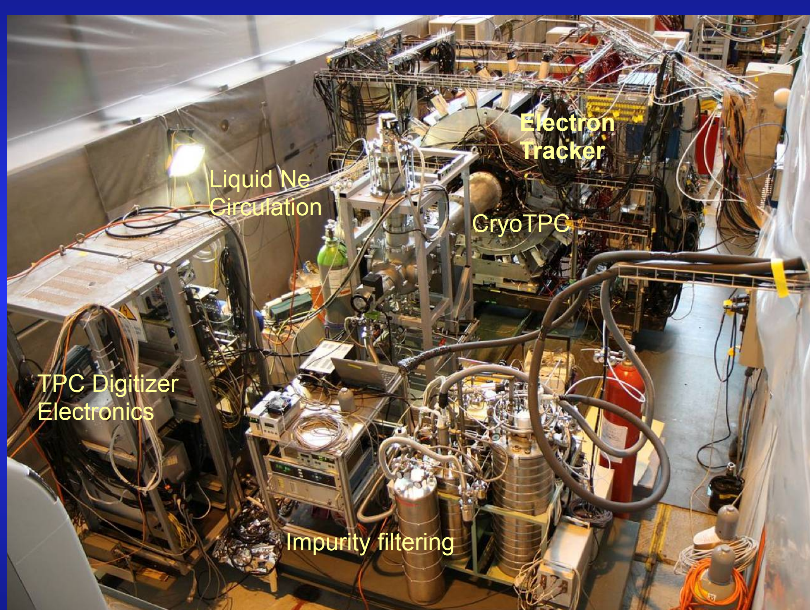
MuSun Detector System



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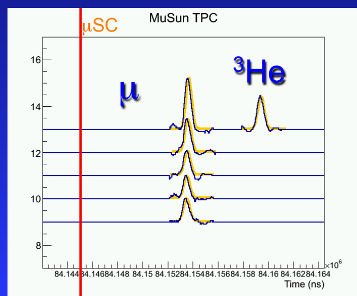
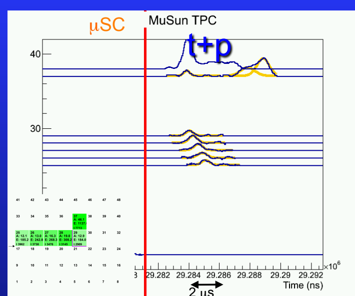
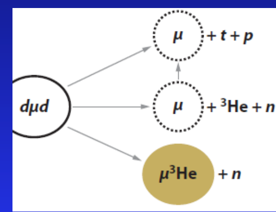
Fusions in TPC

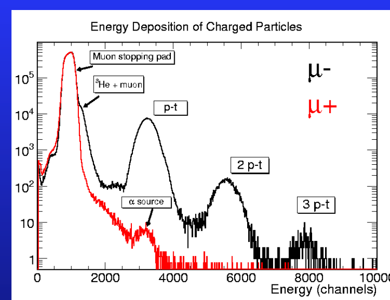
run2011, prelim







robust muon tracking algorithm at 10^{-5} level required !



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Status and Plans

Analysis

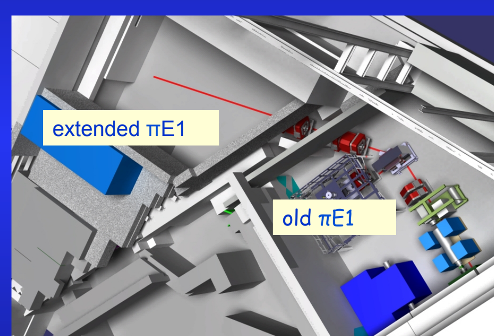
- analysis run 2011 data
  4.8 x 10^9 good μ- stop
  4 x 10^8 μ+ stop events
- first physics publication
- study detector upgrades

Upgrades

detector upgrades 2012

- cryo preamp
- TPC optimization
- improved purity and monitoring

New beam line at PSI



Commissioning run 2012

Final runs 2013-14

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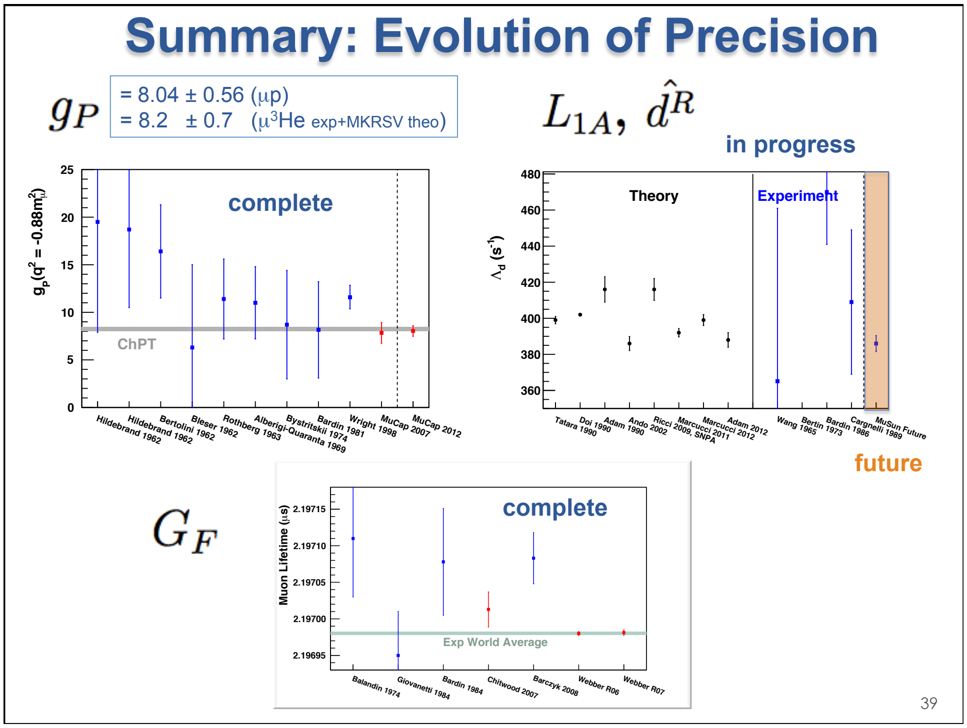

Collaborations

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

MuCap/MuSun

Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
Paul Scherrer Institute (PSI), Villigen, Switzerland
University of California, Berkeley (UCB and LBNL), USA
University of Illinois at Urbana-Champaign, Urbana, USA
University of Washington, Seattle, USA
Université Catholique de Louvain, Belgium
University of Kentucky, Lexington, USA
Boston University, USA
Regis University, Denver, USA
University of South Carolina, USA

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