Precision Muon Capture on the Proton and Very Light Nuclei

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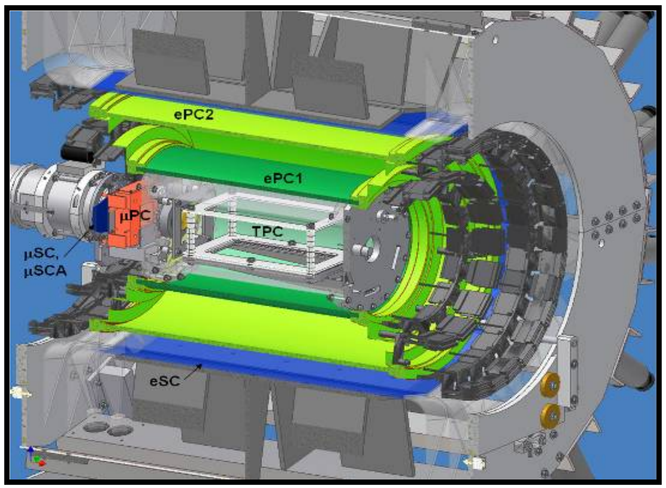
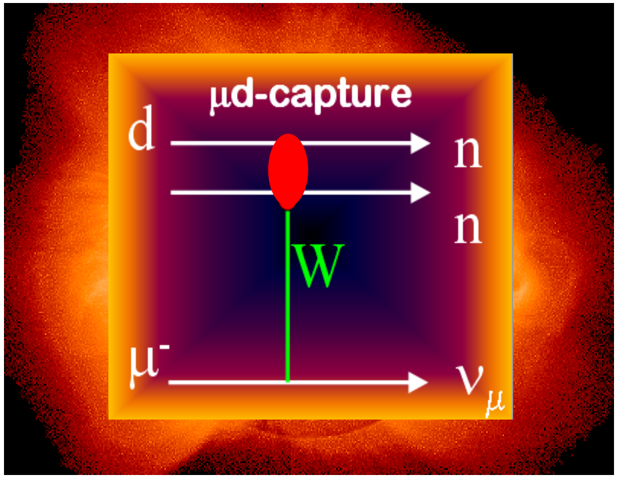
http://www.npl.washington.edu/muon/

MuCap



MuSun



INT-12-3: Light nuclei from first principles
September 17 - November 16, 2012

Outline

- $\mu \to e\,\nu\,\nu$ — **Strength of Weak Interaction**

  MuLan — G_F

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

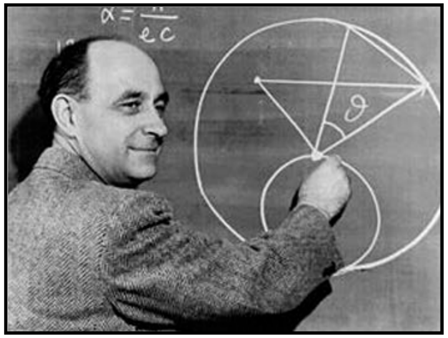
  MuCap — g_P

- $\mu + d \to n + n + \nu$ — Weak few nucleon reactions and astrophysics

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

  MuSun

Muon Lifetime

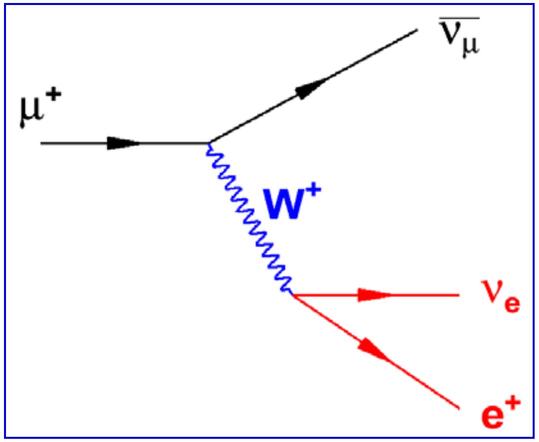


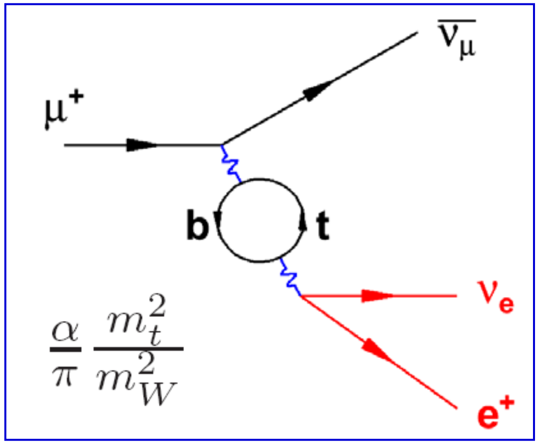
Fundamental electro-weak couplings

G_F	α	M_Z
9 ppm → 0.5 ppm	0.37 ppb	23 ppm
MuLan Collaboration		

Implicit to all EW precision physics

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

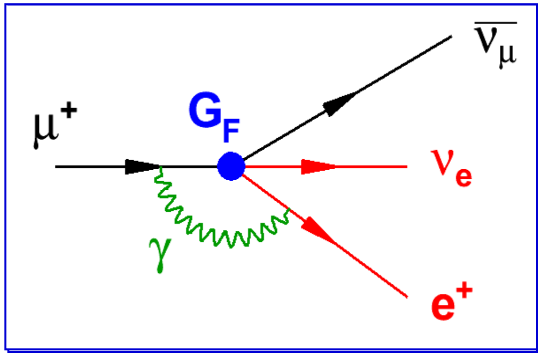




Uniquely defined by muon decay

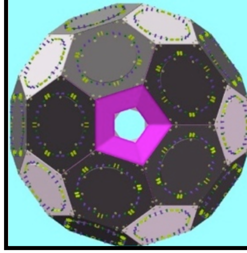
$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}(1 + q)$$

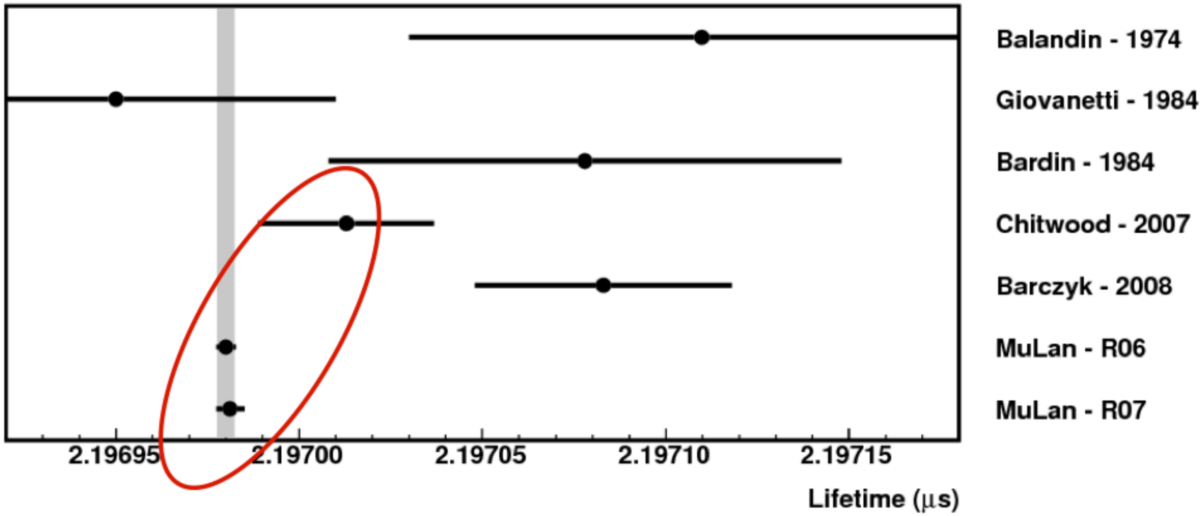
QED



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 œ2.5 ± 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)

The most precise particle or nuclear or atomic lifetime ever measured

New G_F

G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

MuLan PRL 106, 041803 (2011) and http://arxiv.org/abs/1211.0960

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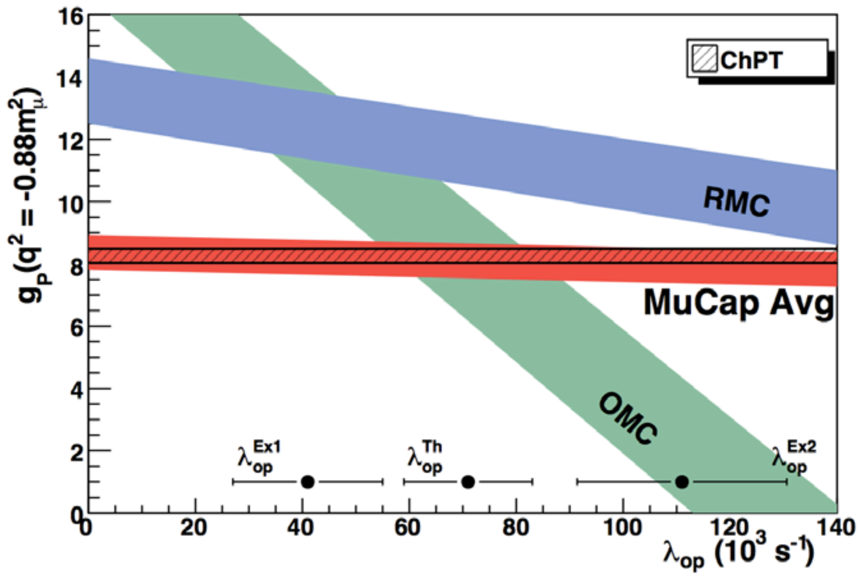
- $\mu \rightarrow e\,\nu\,\nu$ — Strength of Weak Interaction

  MuLan — G_F

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

  MuCap — g_P



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

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

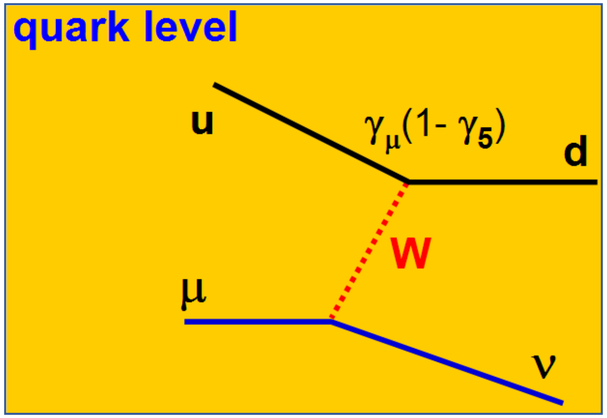
  MuSun

Muon Capture on the Proton

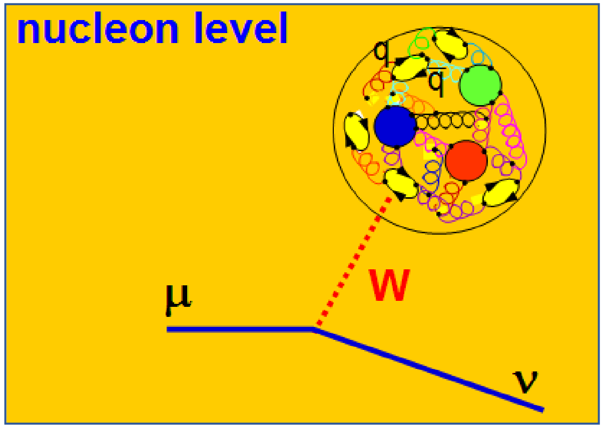
- **Historical: V-A and μ-e Universality**

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

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

Capture Rate Λ_S and Form Factors

- **Muon Capture**

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

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

- **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

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

~0.4 %

9 % pre MuCap

Axial Vector g_A

PDG 2008

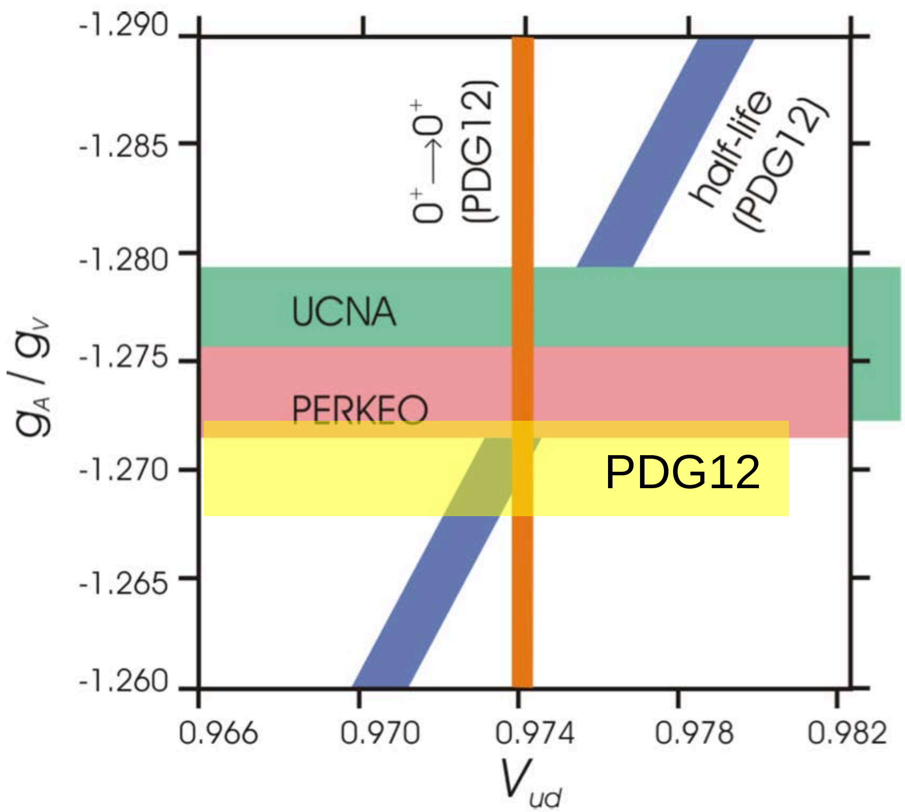
$g_A(0)$= 1.2695œ0.0029

PDG 2012

$g_A(0)$= 1.2701 œ0.0025

Future ?

$g_A(0)$= 1.275



A. Garcia

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

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

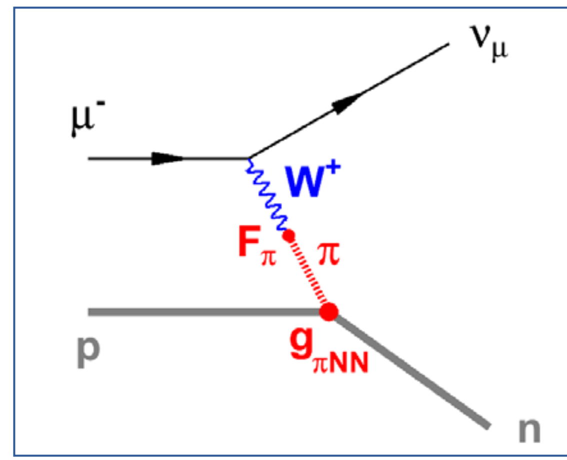
State-of-the-art

- Precision prediction of ChPT

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

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

leading order one loop two-loop <1%



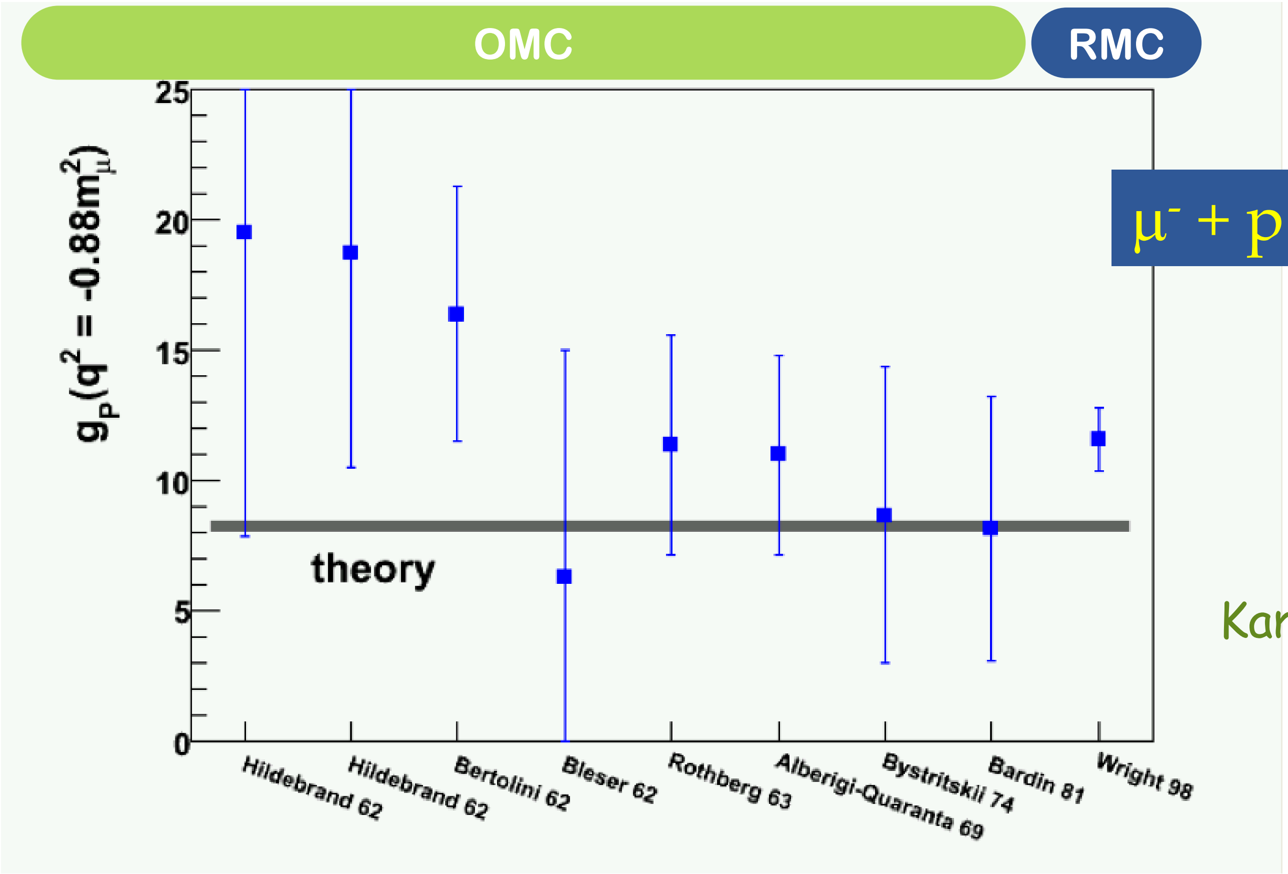
- g_P experimentally least known nucleon FF
- solid QCD prediction (2-3% level)
- basic test of QCD symmetries
- required to "use" muon capture

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



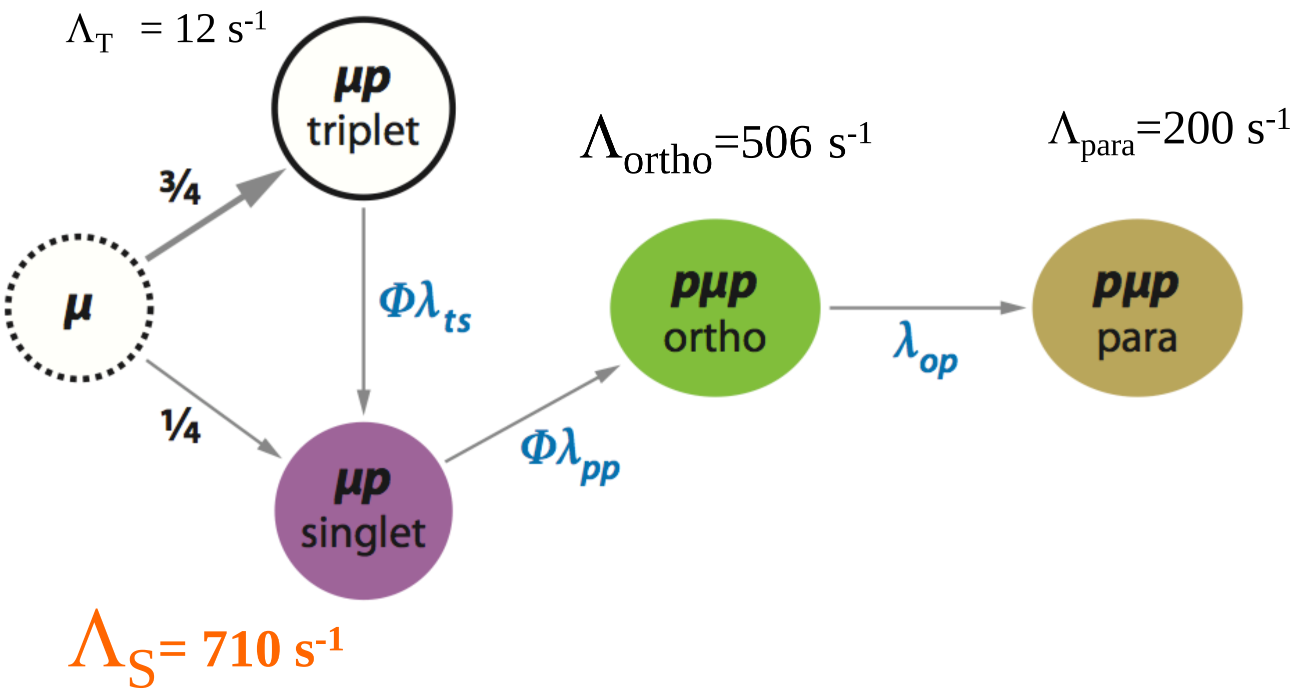
$\mu^- + p \rightarrow n + \nu + \gamma$

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.Rev.Nucl.Part.Sci. 2003)

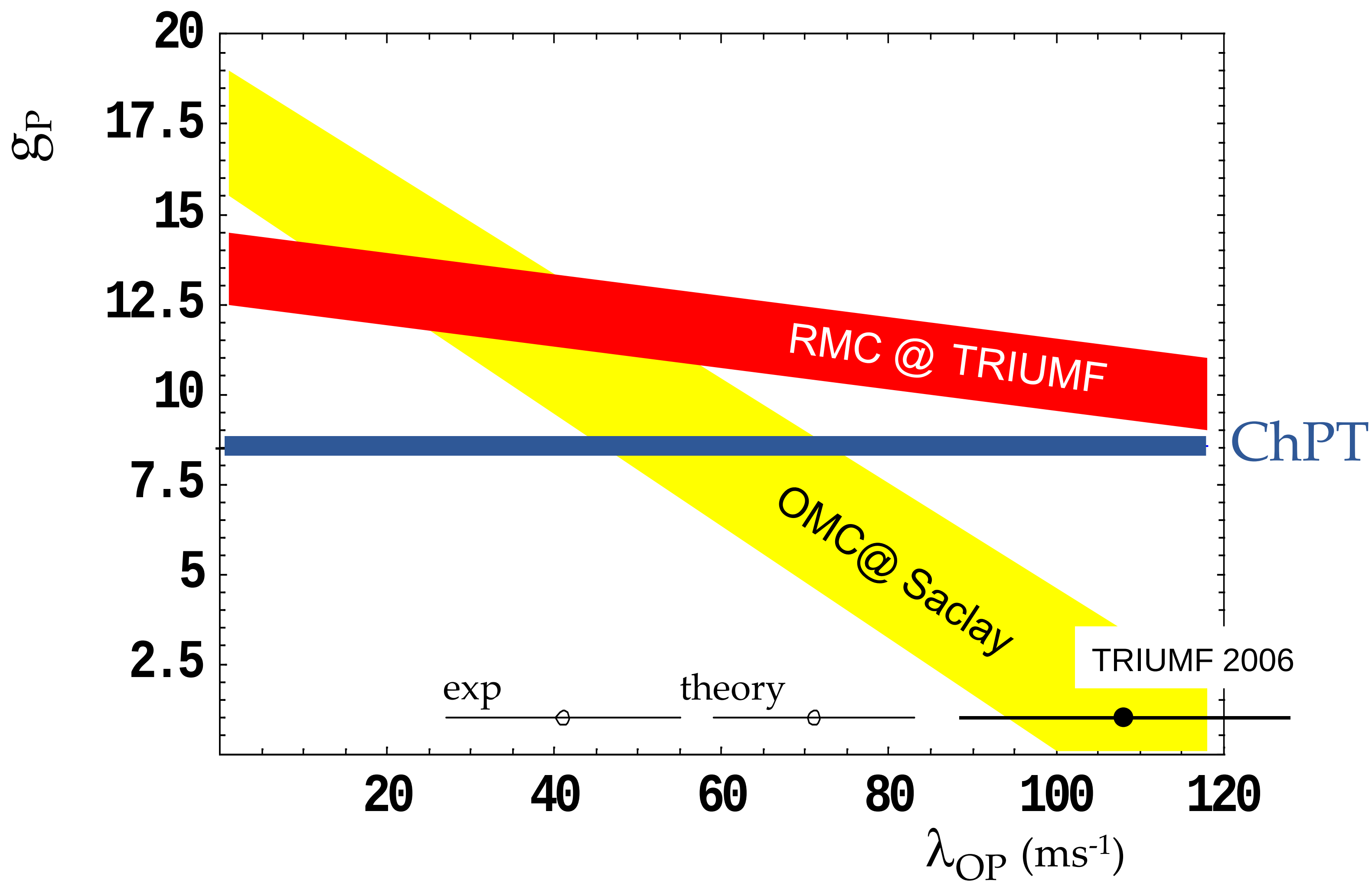
“Rich” Muon Atomic Physics Makes Interpretation Difficult



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

In LH_2 fast $pp\mu$ formation, but λ_{op} largely unknown

Precise Theory vs. Controversial Experiments



- no overlap theory & OMC & RMC
- large uncertainty in $\lambda_{OP} \rightarrow g_P \pm 50\%$?

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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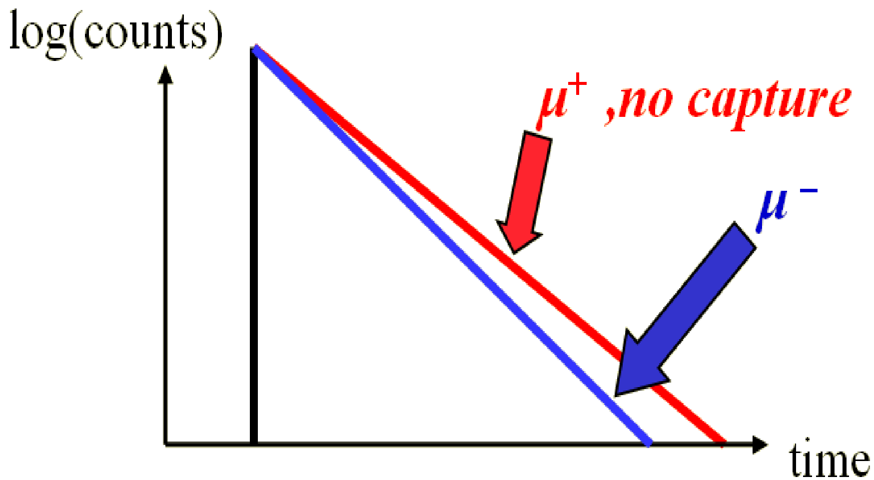
All requirements simultaneously

- $\mu p \rightarrow n\nu$ 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

MuCap Strategy

- Precision technique
- **Clear Interpretation**
- Clean stops in H_2
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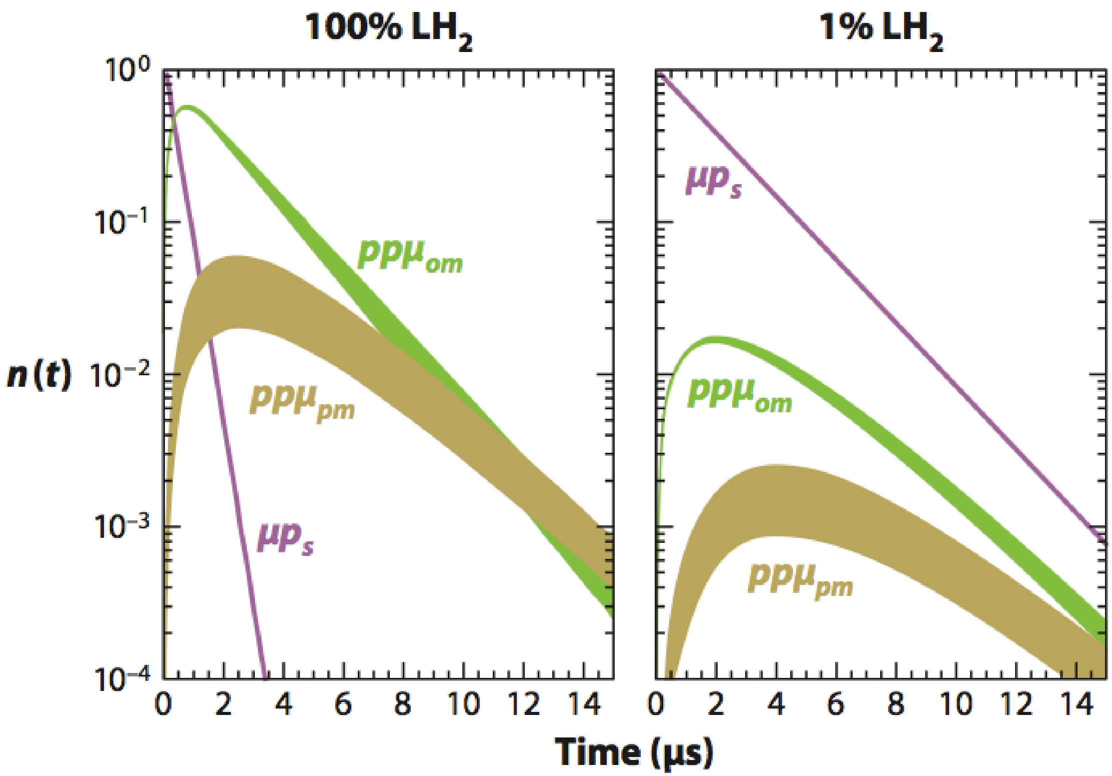
All requirements simultaneously

At 1% LH_2 density mostly pμ atoms during muon lifetime



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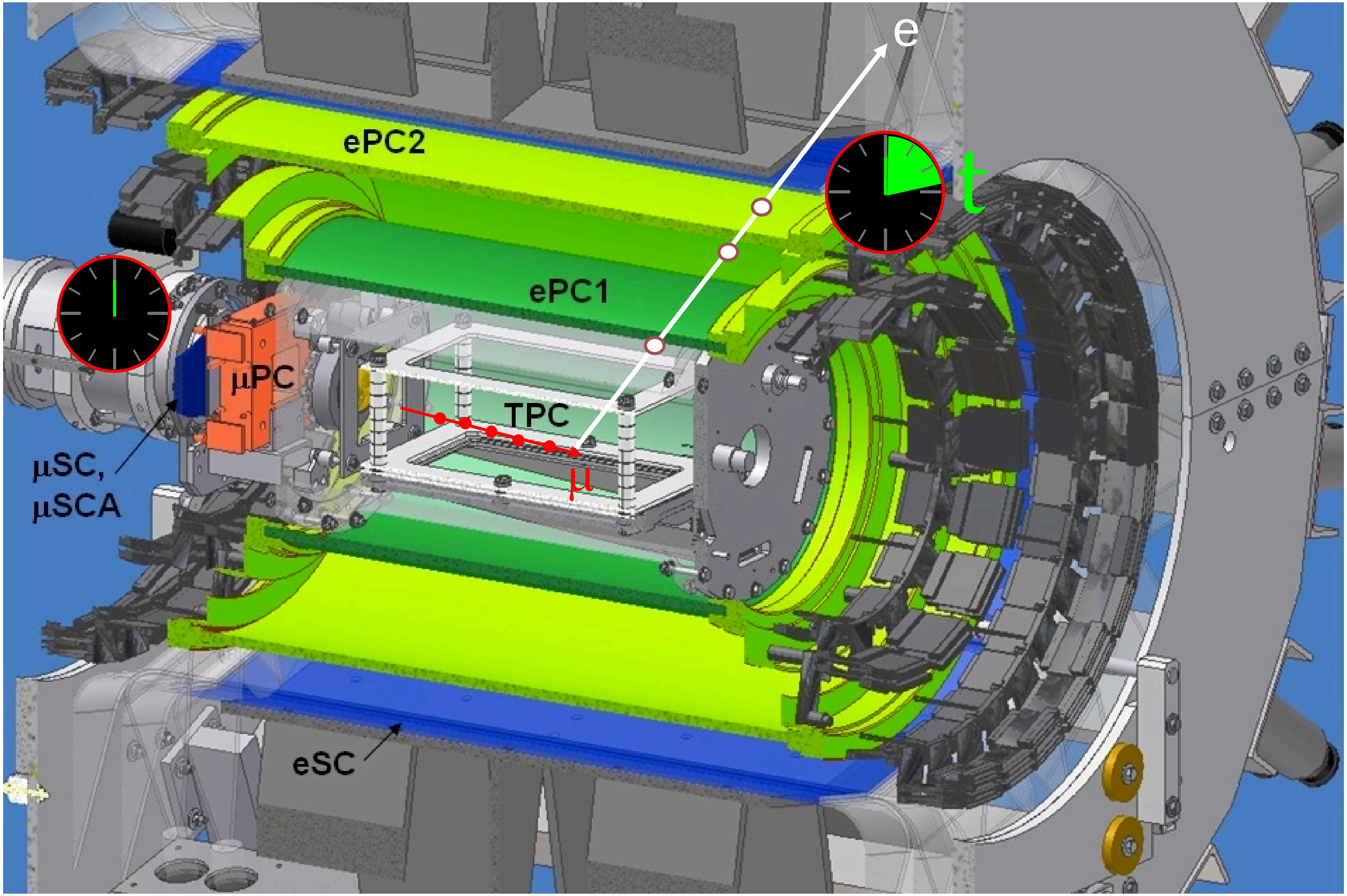
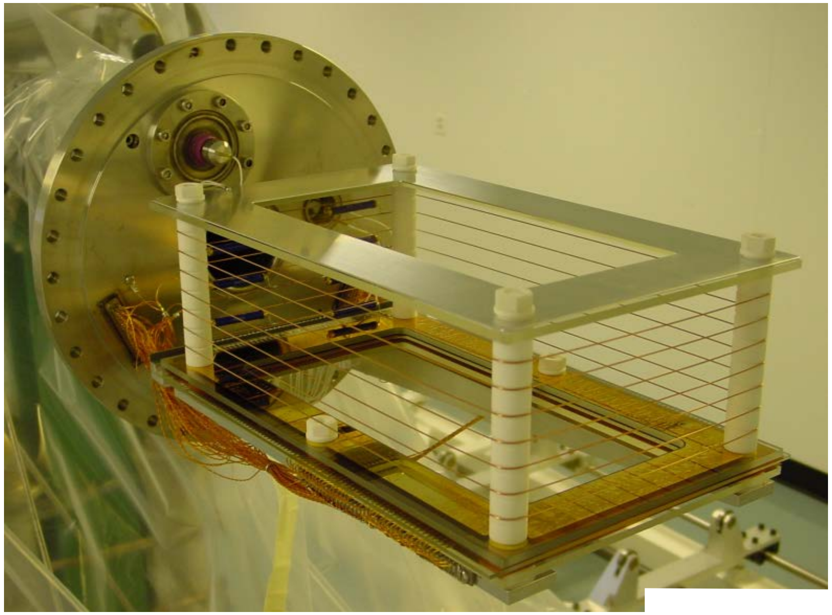
MuCap Technique



Muons Stop in Active TPC Target

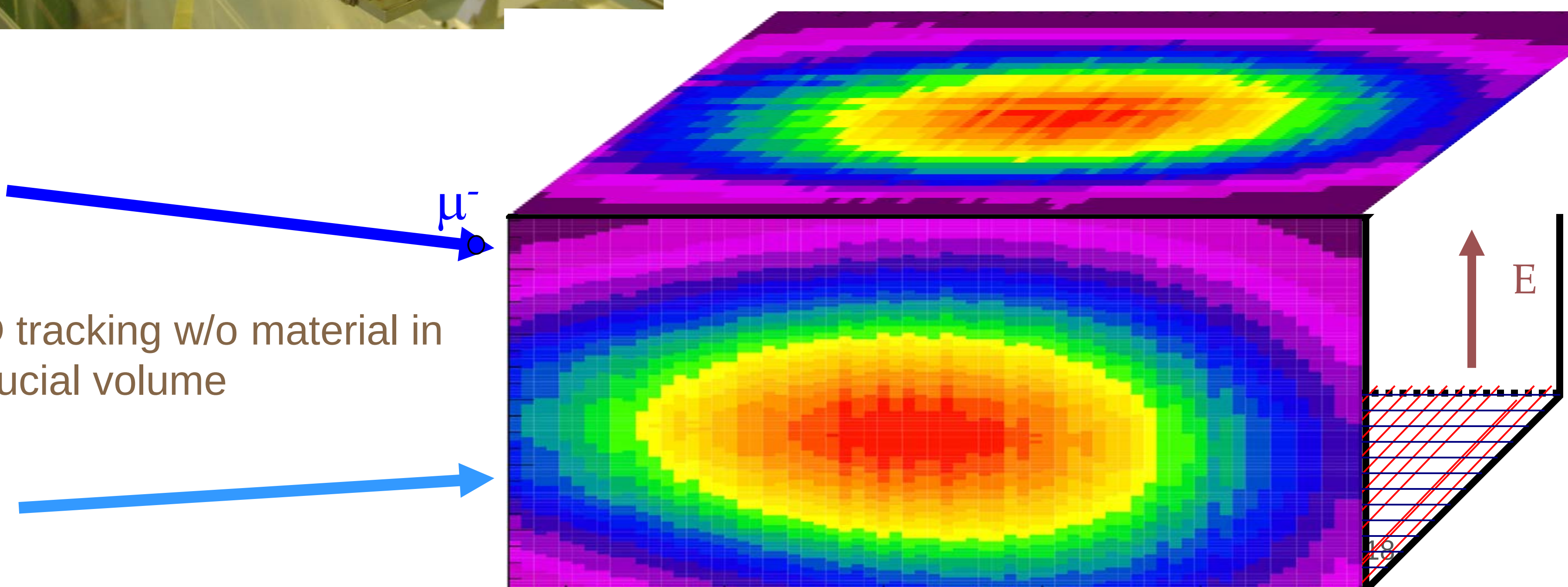


to prevent muon stops in walls
(Capture rate scales with ~Z^4)

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

3D tracking w/o material in fiducial volume

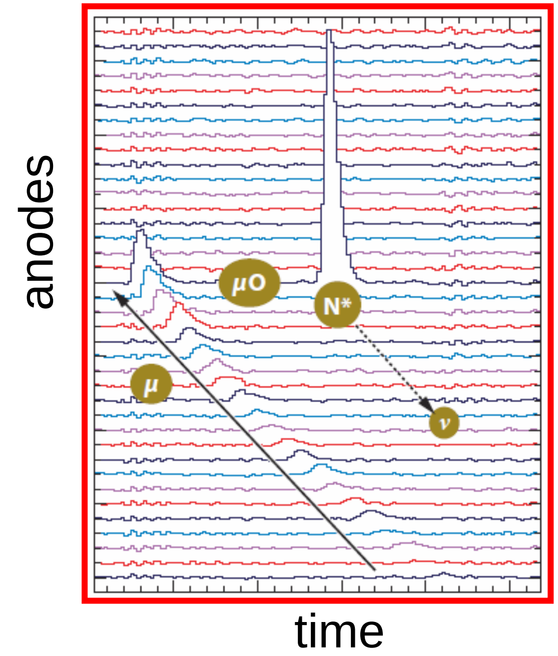


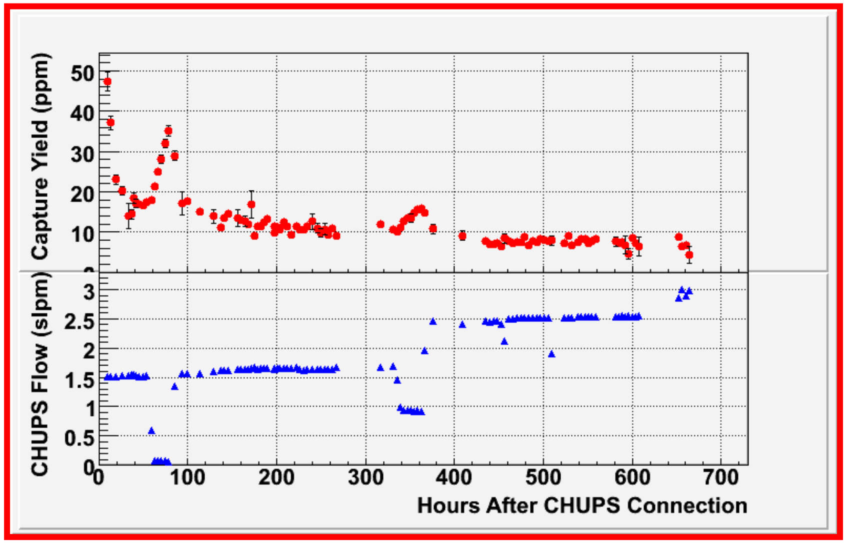
MuCap Strategy

- 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

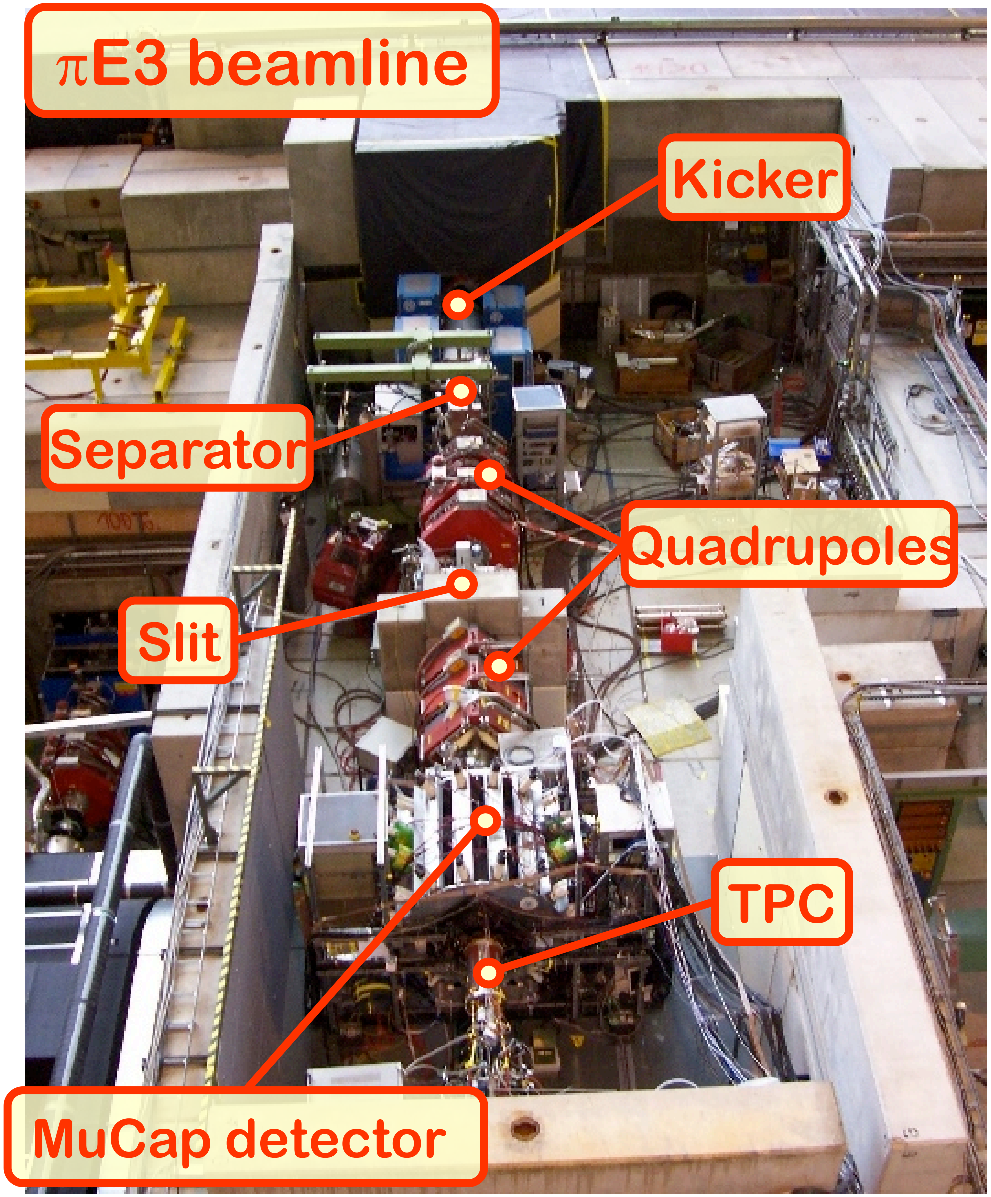




2004: $c_N < 7$ ppb, $c_{H2O} \sim 20$ ppb

2006 / 2007: $c_N < 7$ ppb, $c_{H2O} \sim 9\text{-}4$ppb

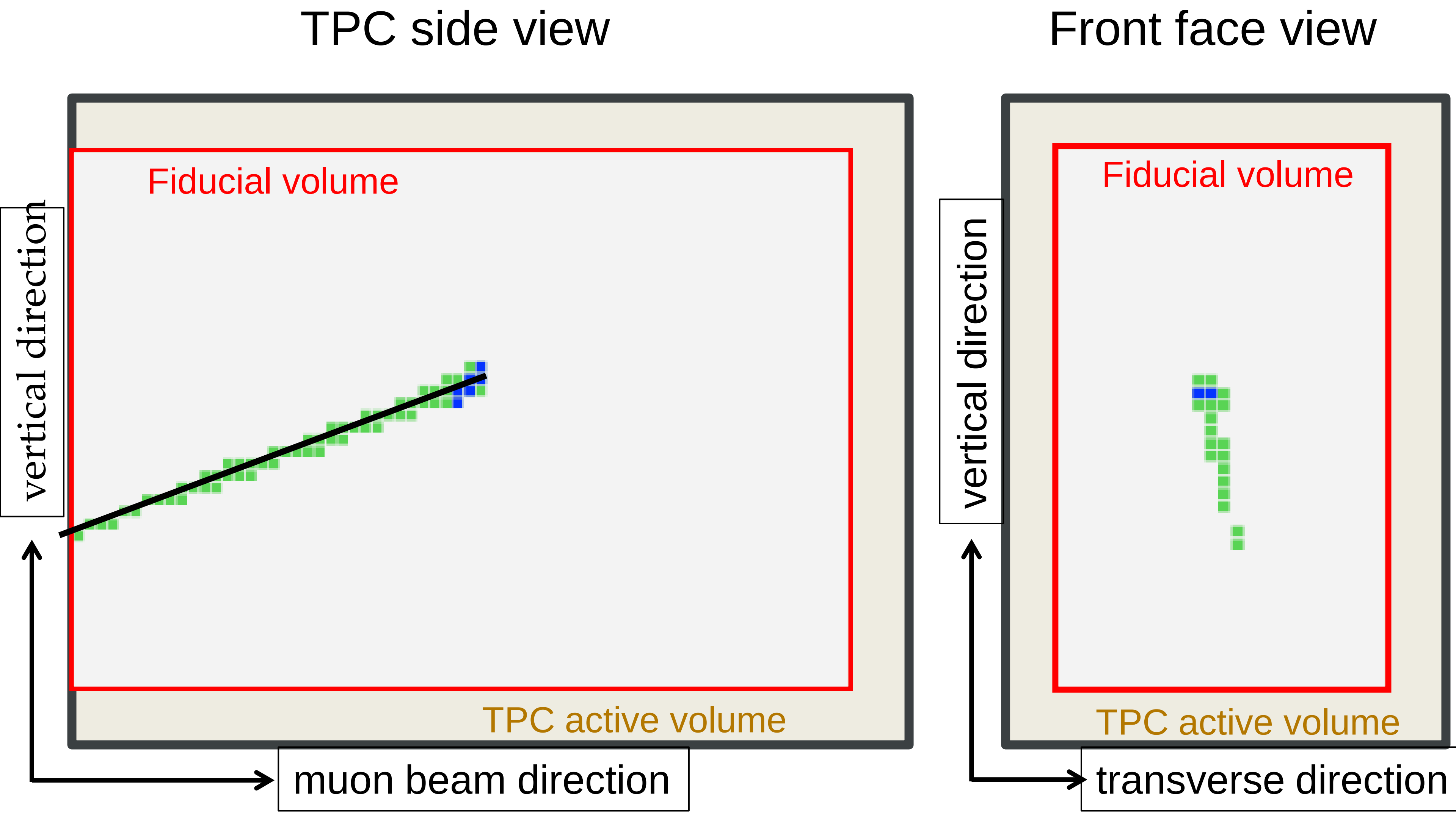
Experiment at PSI



Muon On Request

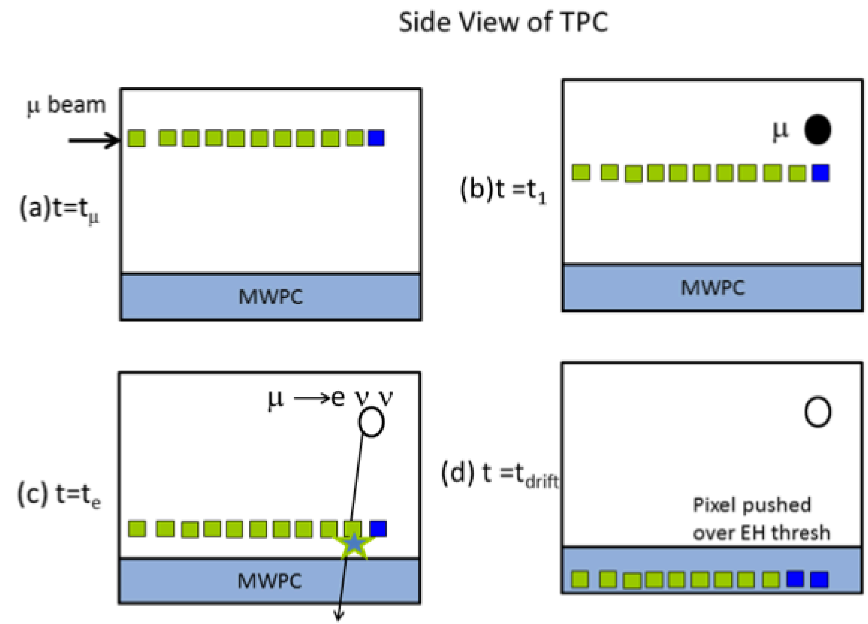
Muon defined by TPC

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

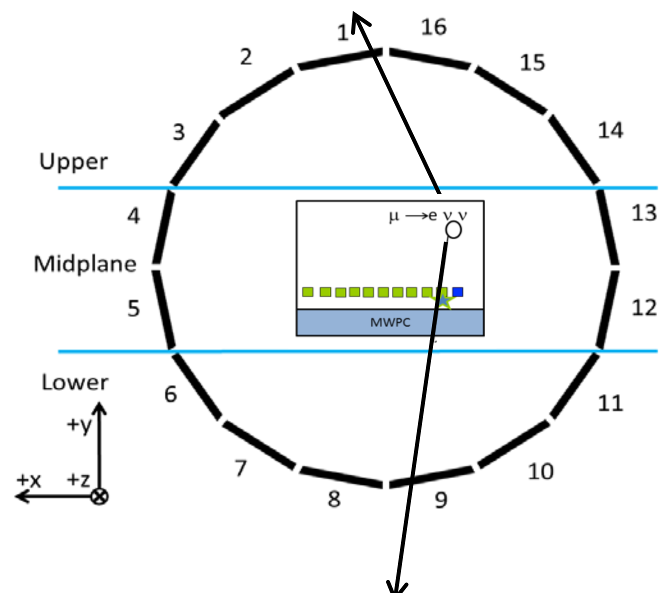


Electron defined by Independent e-Tracker

- Small, but significant interference with μ track

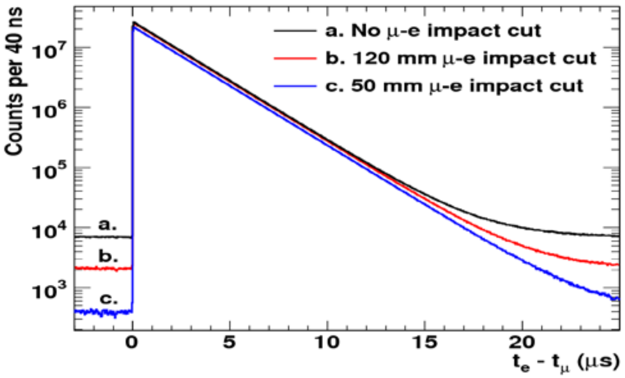


- simple, robust track reconstruction and its **verification** essential

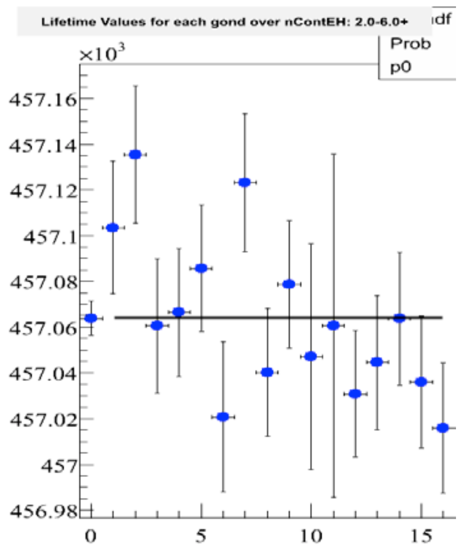


Time Distributions are Consistent

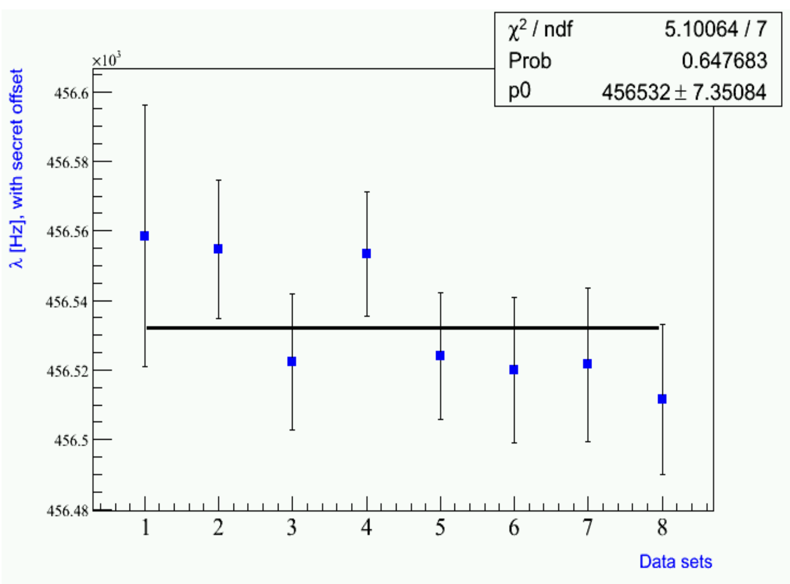
$$N(t) = N_0 \cdot w \cdot \lambda \cdot e^{(-\lambda t)} + B$$



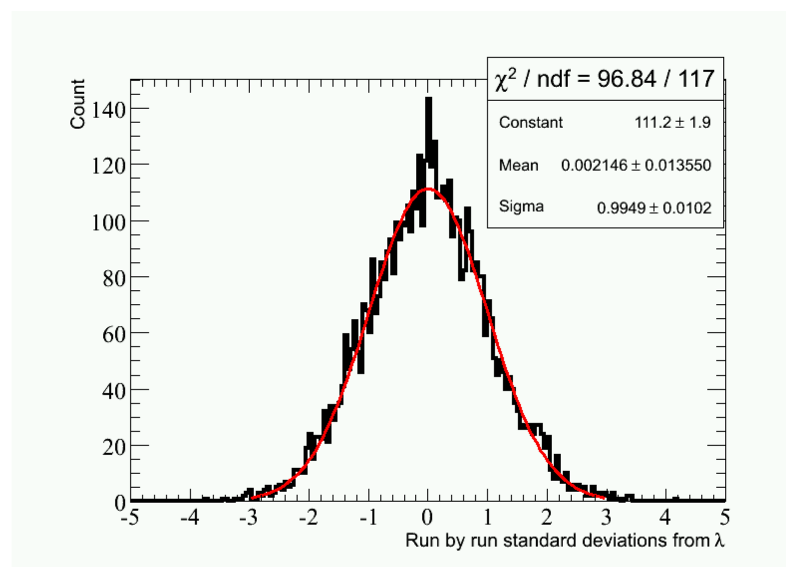
No azimuth dependence



fitted λ is constant

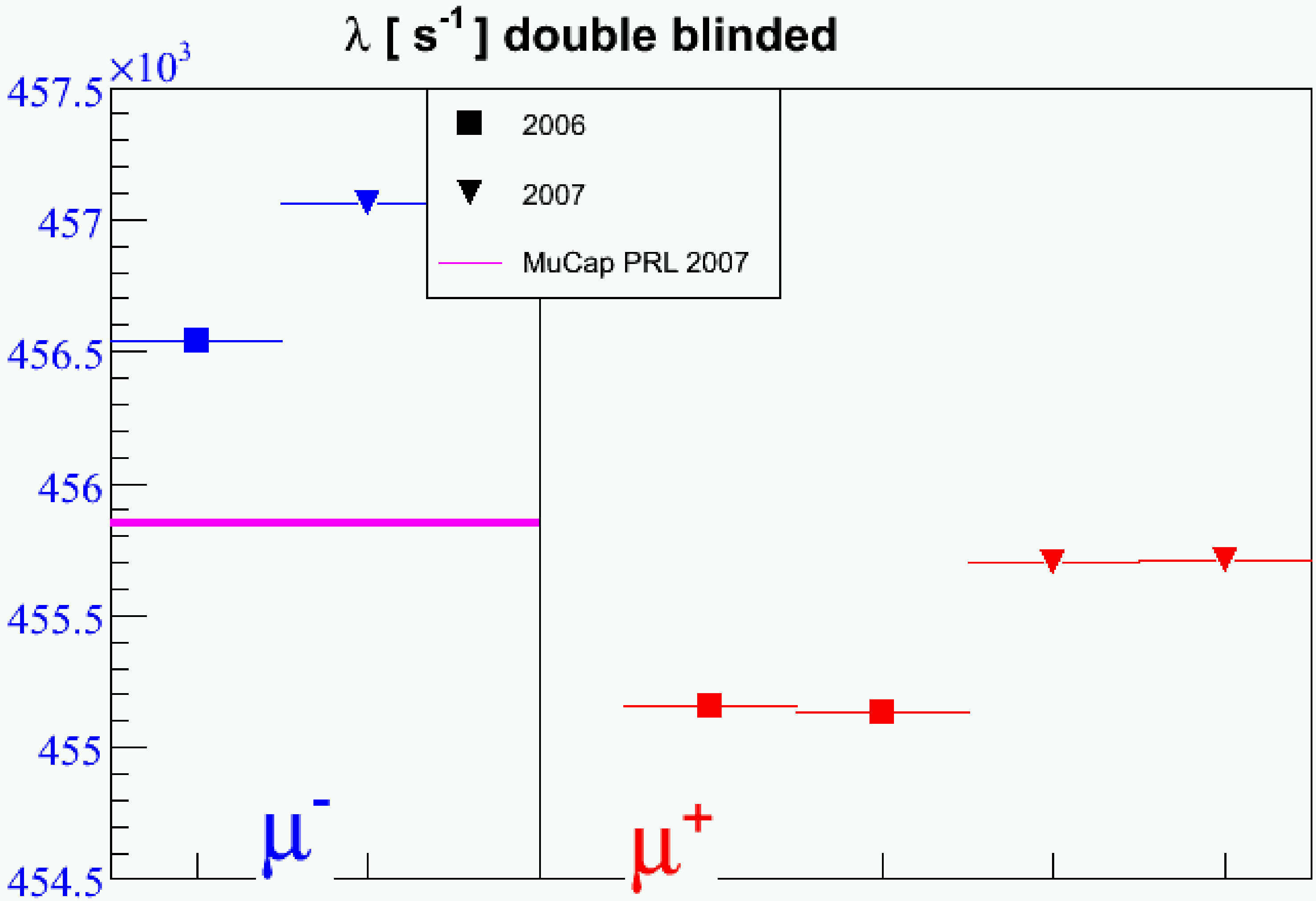


Run groups



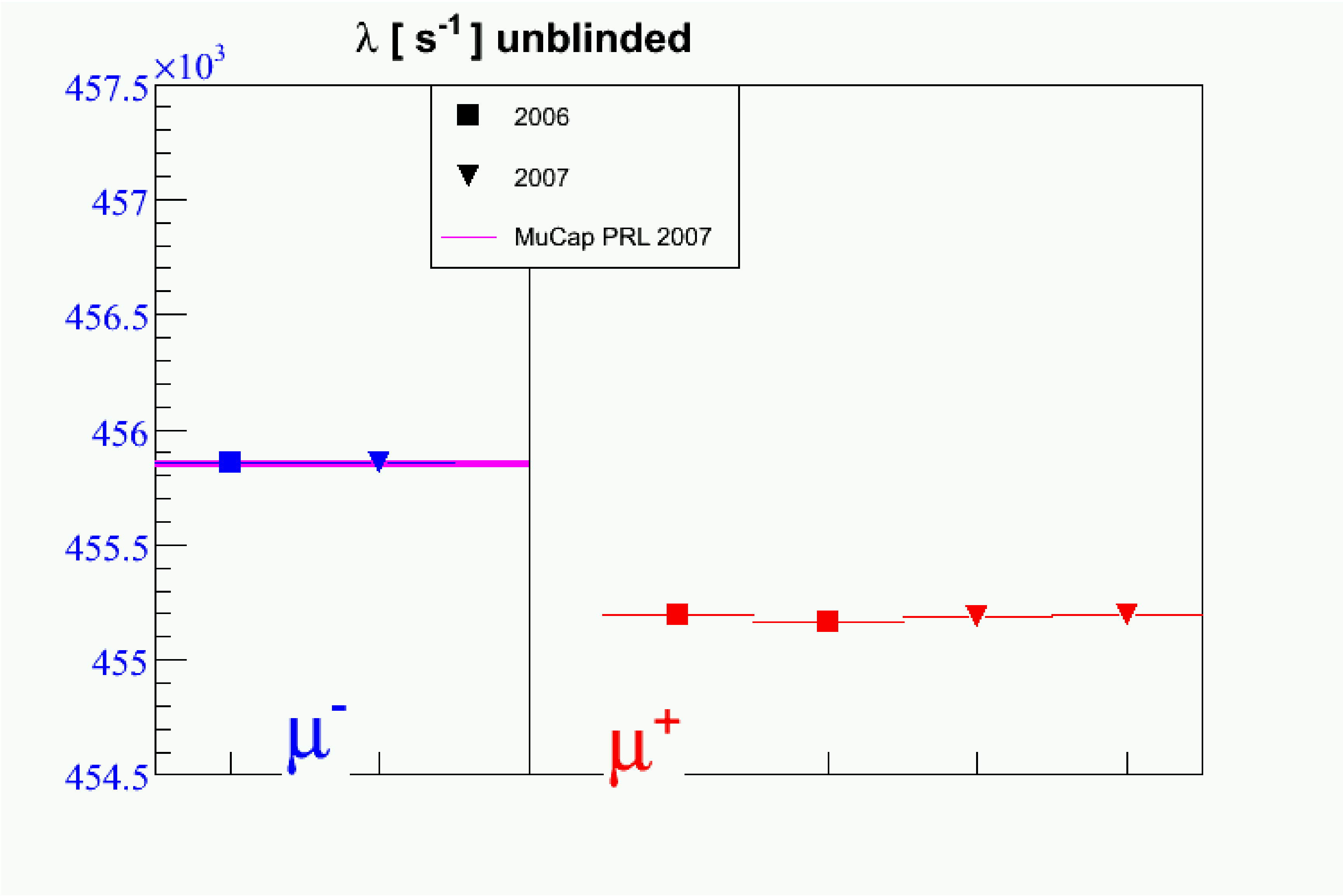
Data run number (~3 minutes per run)

MuCap Results



rates with secret offset, stat. errors only

Disappearance Rate λ



Determination of Λ_S

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

molecular formation

MuCap: precision measurement

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

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

MuLan

bound state effect

$$\Lambda_S(\text{R06}) = 717.3 \pm 7.73_{\text{stat}} \pm 5.55_{\text{syst}} \text{ s}^{-1}$$

$$\Lambda_S(\text{R07}) = 713.1 \pm 8.33_{\text{stat}} \pm 4.34_{\text{syst}} \text{ s}^{-1}$$

$$\Lambda_S(\text{R04}) = 713.5 \pm 12.5_{\text{stat}} \pm 8.6_{\text{syst}} \text{ s}^{-1}$$

MuCap PRL 2007

Error Budget

TABLE II: Applied corrections and systematic errors.

Effect	Corrections and uncertainties [s^{-1}] R06	R07
$Z > 1$ impurities	-7.8 ± 1.87	-4.54 ± 0.93
$\mu - p$ scatter removal	-12.4 ± 3.22	-7.2 ± 1.25
μp diffusion	-3.1 ± 0.10	-3.0 ± 0.10
μd diffusion	± 0.74	± 0.12
Fiducial volume cut	± 3.00	± 3.00
Entrance counter ineff.	± 0.50	± 0.50
Electron track def.	± 1.80	± 1.80
Total λ_{μ^-} corr.	-23.30 ± 5.20	-14.74 ± 3.88
μp bound state: $\Delta\lambda_{\mu p}$	-12.3 ± 0.00	-12.3 ± 0.00
$pp\mu$ states: $\Delta\Lambda_{pp\mu}$	-17.73 ± 1.87	-17.72 ± 1.87

MuCap Final Results

MuCap Collaboration, *Oct 2012*
e-Print: arXiv:1210.6545 [nucl-ex]

- **Capture Rate**

Λ_S (MuCap) = 714.9 œ5.4$_{stat}$ œ5.1$_{syst}$ s^{-1}

Λ_S (theory) = 712.7 œ3.0$_{gA}$ œ3.0$_{RC}$ s^{-1}

PDG12 updated
Czarnecki, Marciano, Sirlin calculation

recent calculations

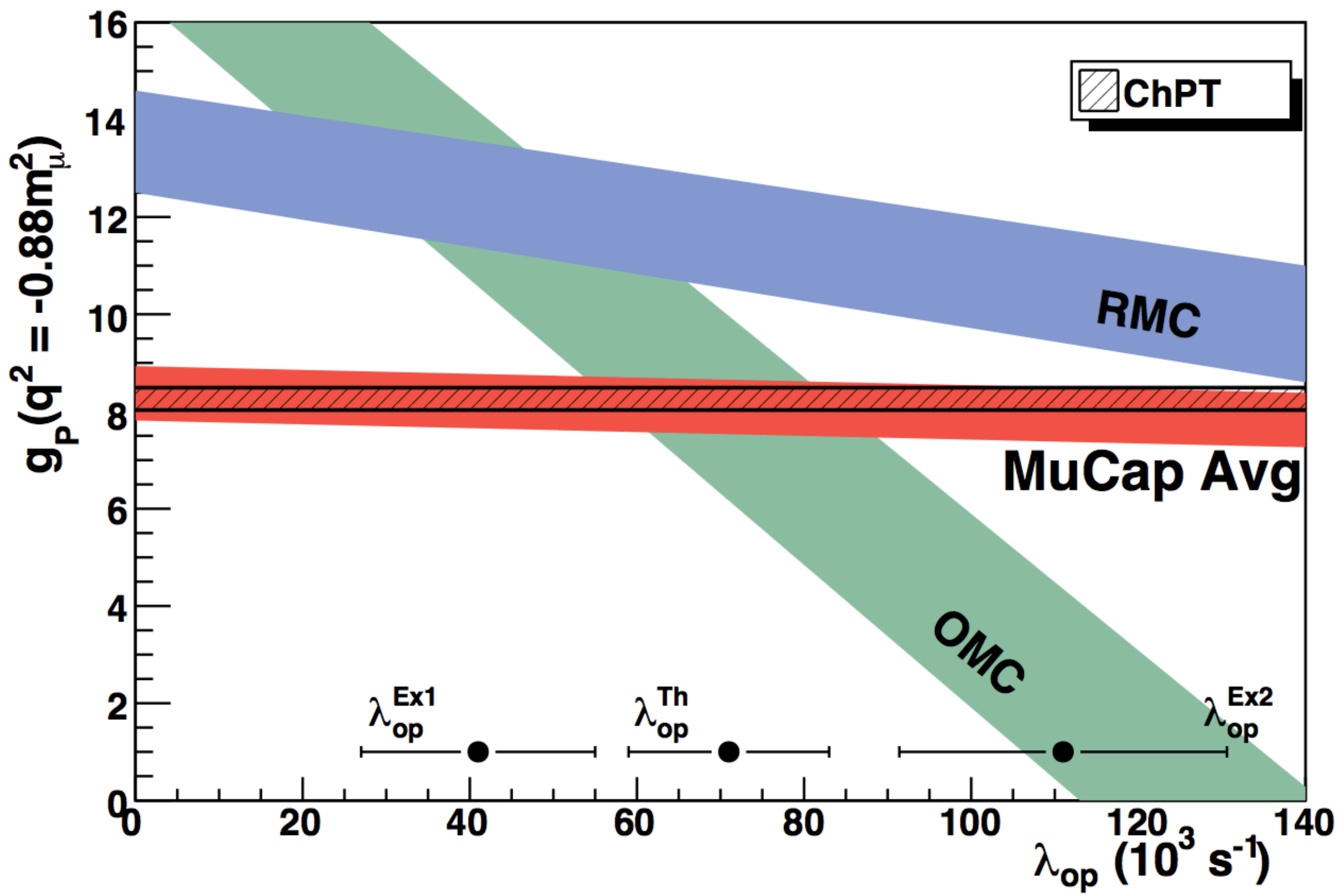
711.4	Pheno	CMS
706.6	HBChPT	BHM
714.5	HBChPT	AMK

- **Pseudoscalar Coupling**

g_P(MuCap) = 8.06 œ0.48$_{\Lambda s(ex)}$ œ0.28$_{\Lambda s(th)}$

for $g_A(0) \rightarrow -1.275$ $\quad$ g_P(MuCap) $\rightarrow$ 8.34

Precise and Unambiguous MuCap Result Verifies Basic Prediction of Low Energy QCD



g_P(MuCap) = 8.06 œ0.55

g_P(theory) = 8.26 œ0.23

Outline

- $\mu \to e\,\nu\,\nu$ — Strength of Weak Interaction

  MuLan — G_F

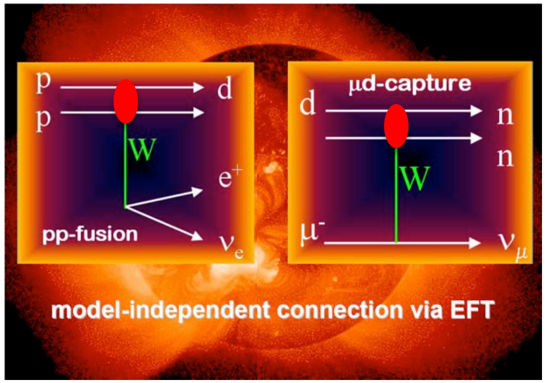
- $\mu + p \to n + \nu$ — Basic QCD Symmetries

  MuCap — g_P

- $\mu + d \to n + n + \nu$ — Weak few nucleon reactions and astrophysics

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

  MuSun — $L_{1A}\ \hat{d}^R$



Motivation

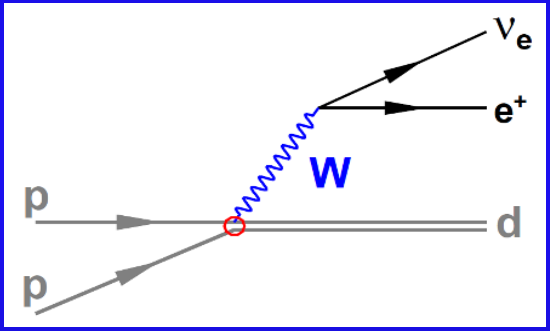
$\mu^- + d \to$ ½+ n + n *measure rate Λ_d in $\mu d(\uparrow\downarrow)$ atom to <1.5%*

- simplest nuclear weak interaction process with precise th. & exp.

  nucleon FF (g_P) from MuCap

  rigorous QCD based calculations with

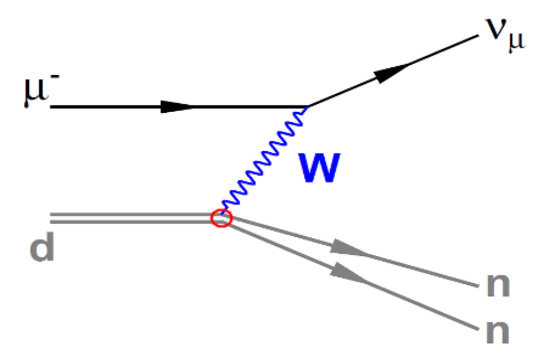
  effective field theory



- close relation to neutrino/astrophysics

  solar fusion reaction pp → $de^+\nu$

  {d scattering in SNO exp.



- model independent connection to μd by single Low Energy Constant (LEC)

Quest for "unknown" Axial LEC

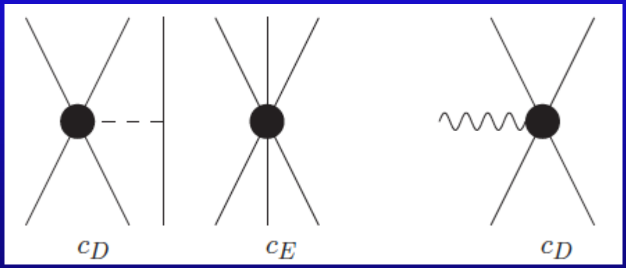
"Calibrate the Sun"

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

Extract from axial current reaction in

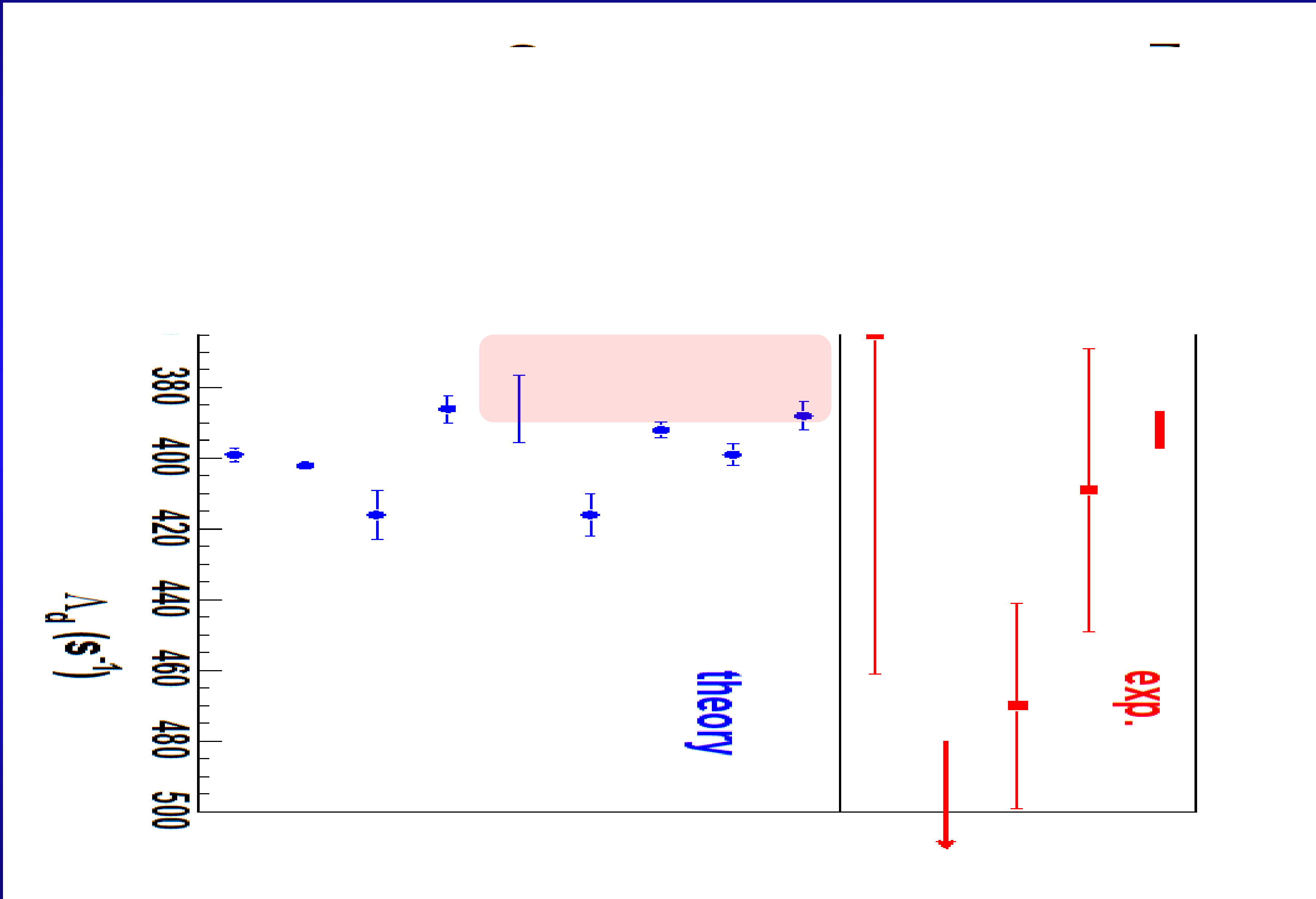
- 2-body system
  - theoretical clean, natural progression
  - experimental information scarce: ~100% uncertainty in LEC
  - **MuSun only realistic option, reduce uncertainty 100% to ~20%**

- 3-body system
  - 2 LECs and additional complexity enter
  - tritium beta decay
  - current state of the art



potential current

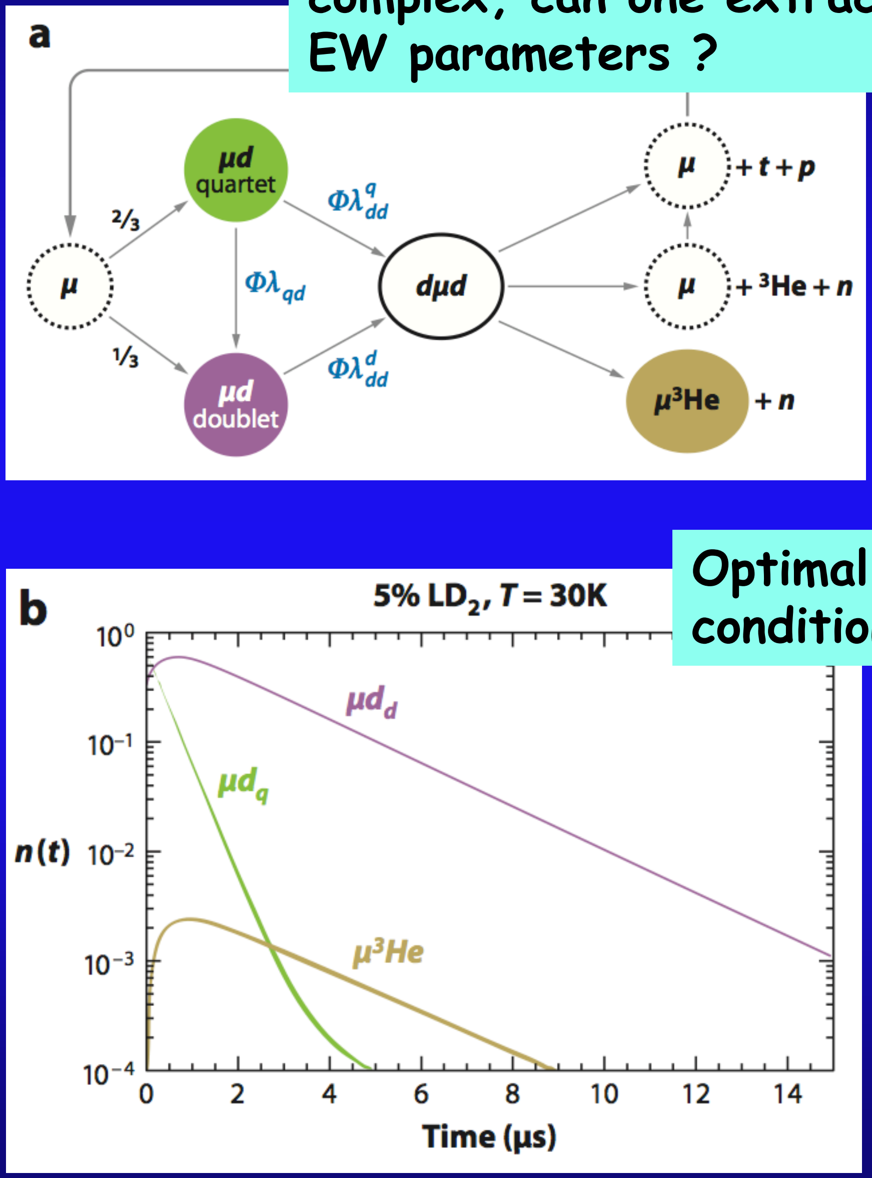
Precise Experiment Needed



Muon Physics and Interpretation

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

complex, can one extract EW parameters ?



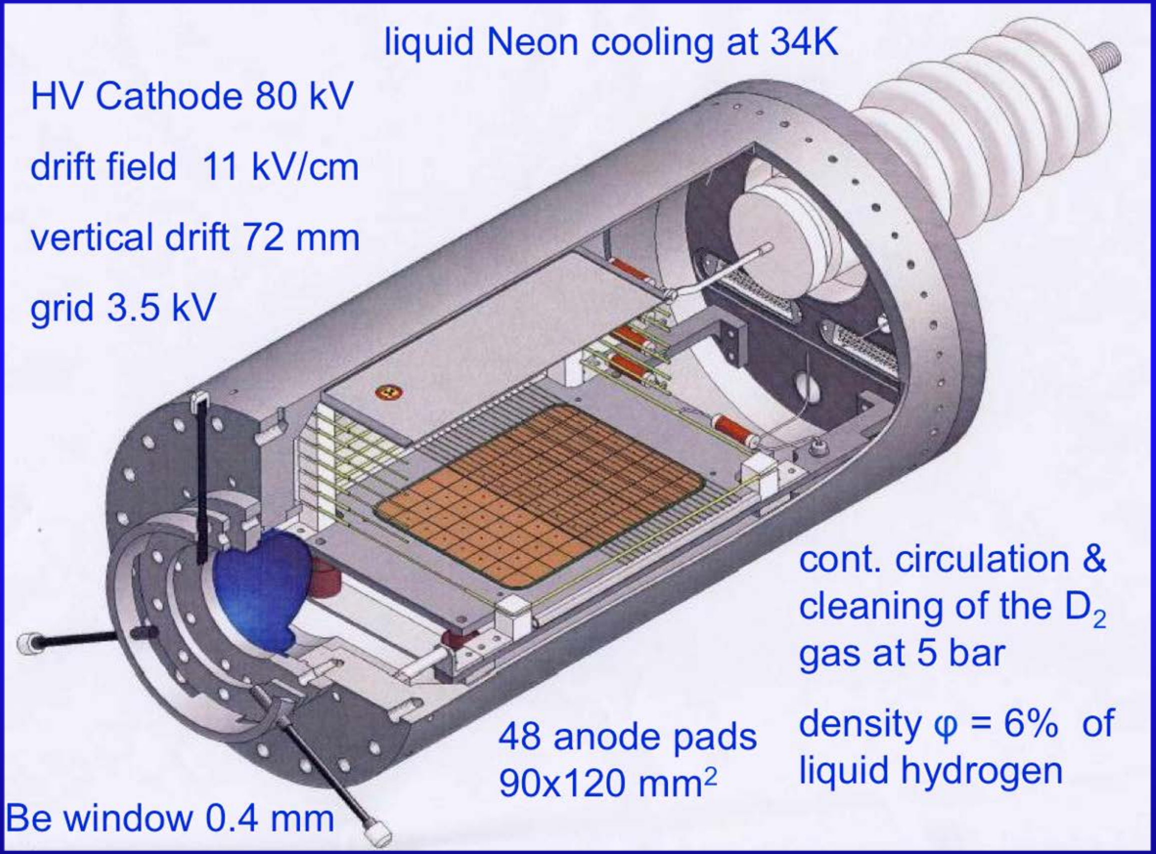
Optimal conditions

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

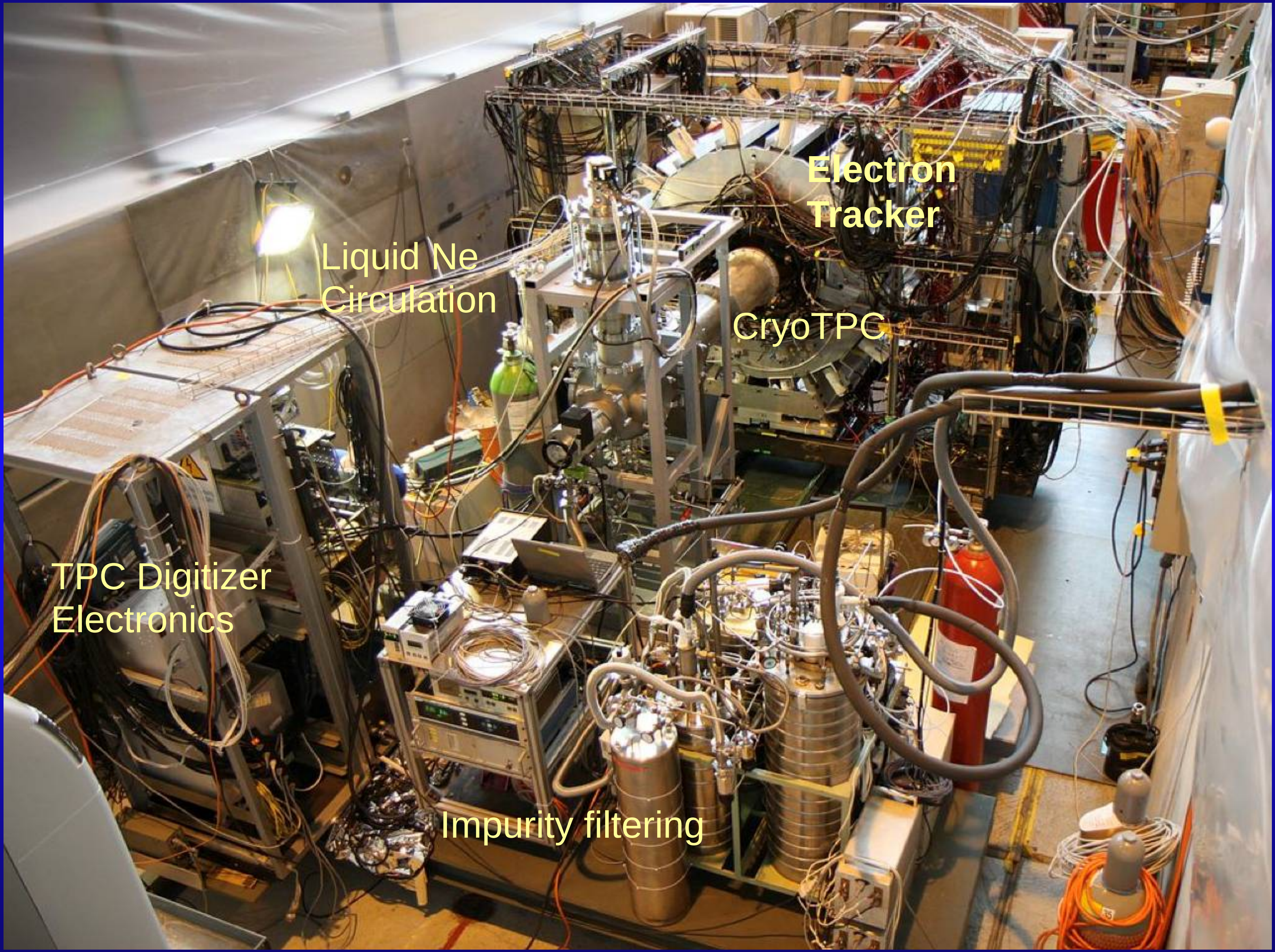
Precise Experiment Possible?

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

Active muon target

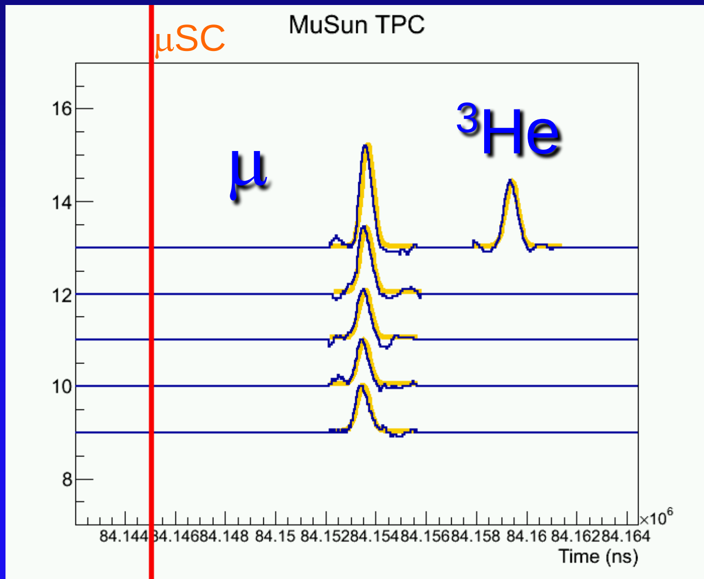


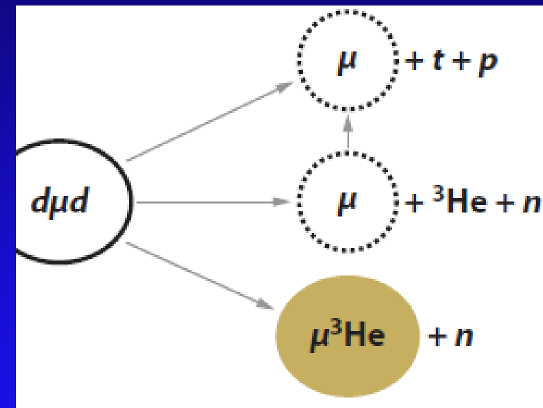
MuSun Detector System



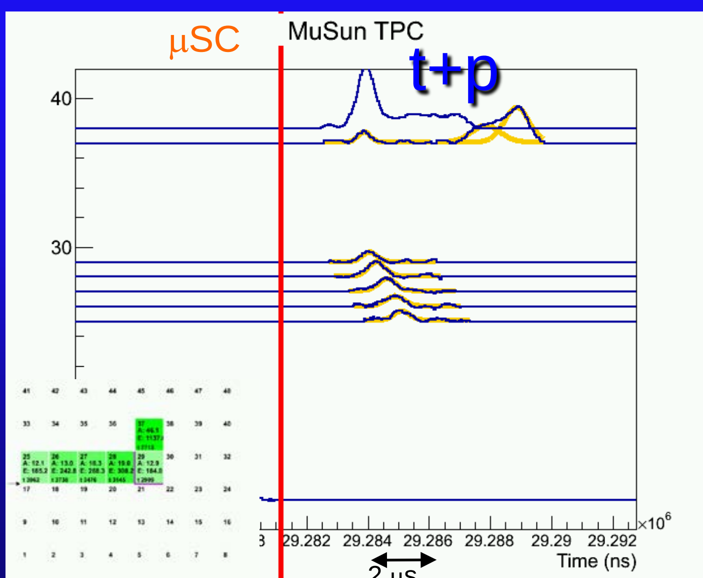
Fusions in TPC

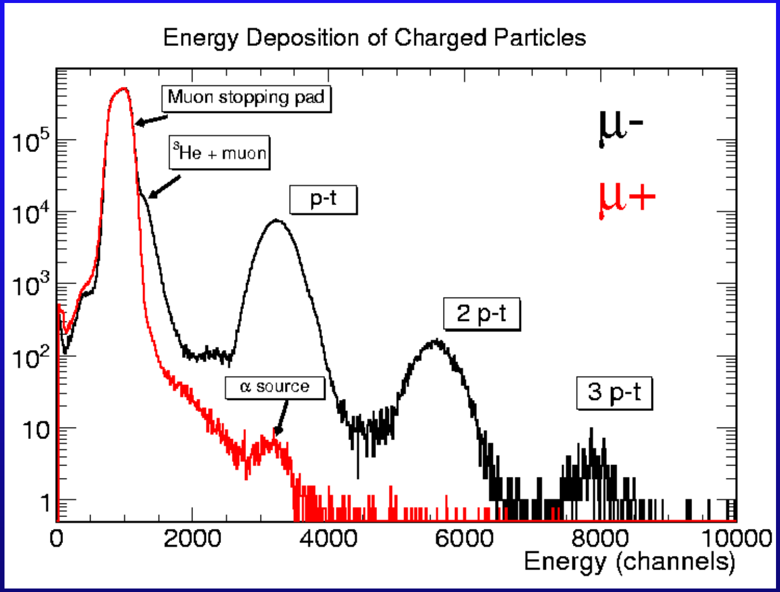
run2011, prelim





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





Status and Plans

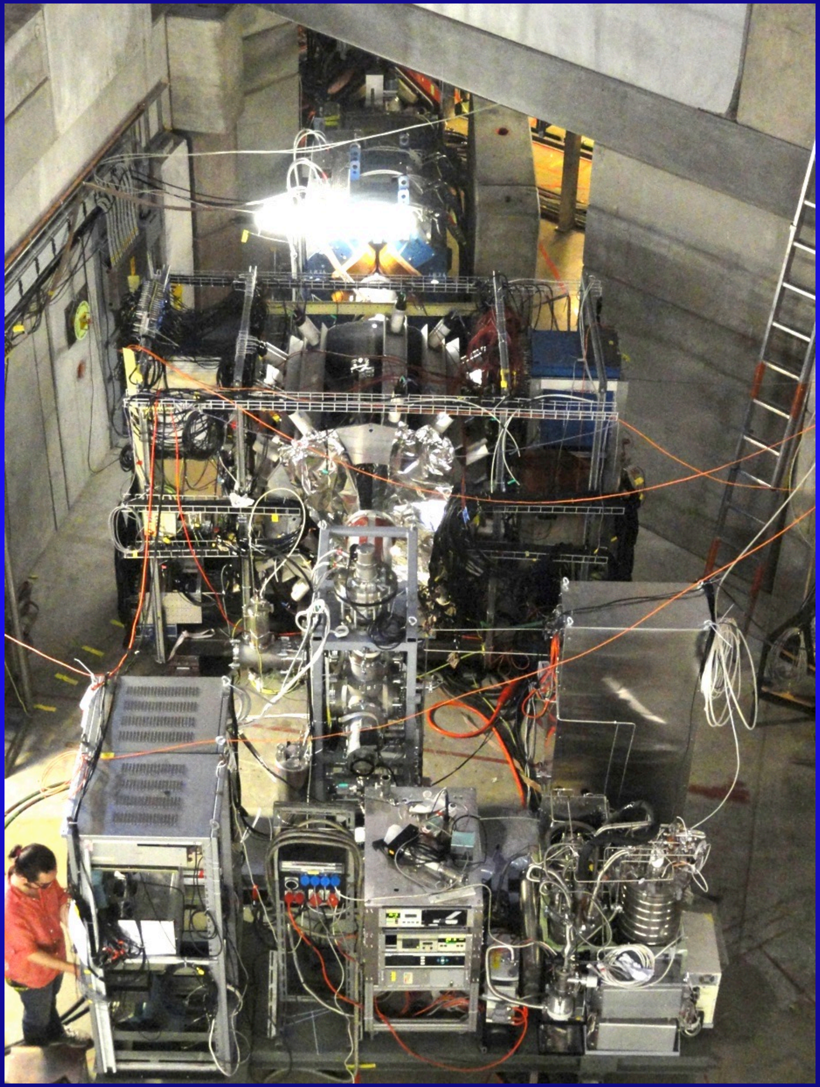
Analysis

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

Upgrades

- **new beamline at PSI**
- cryo preamp
- TPC optimization
- improved purity and monitoring

Final runs 2013-14



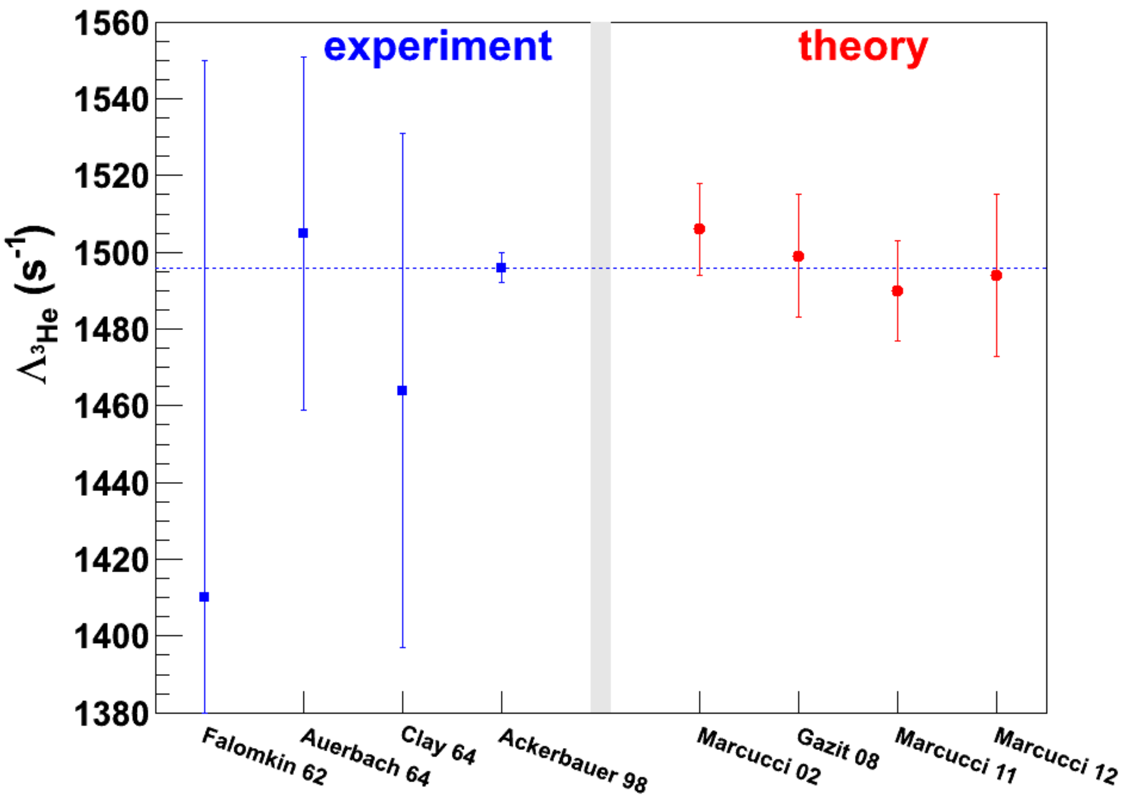
Commissioning October 2012

μ^3He

Reaction

μ + ^{3}He ’ ^{3}H + ν

$$\begin{aligned} \mu^- + {}^3He &\rightarrow t + \nu_\mu \\ \mu^- + {}^3He &\rightarrow d + n + \nu_\mu \\ \mu^- + {}^3He &\rightarrow p + n + n + \nu_\mu \end{aligned}$$



Updated Results

PSI experiment: 1496œ4 /s (0.3%)

Pisa-JLab theory: 1494œ21 /s

➔ $g_P(q^2=-0.954m_\mu{}^2)$=8.2œ0.7

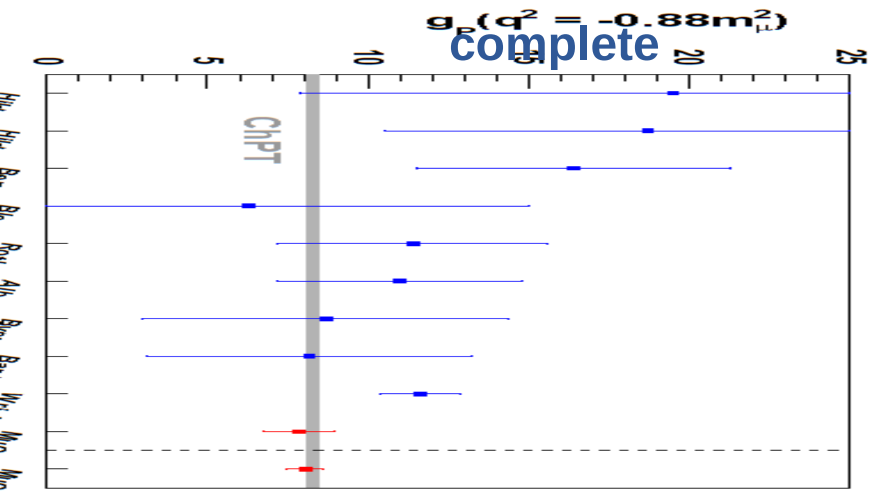
Summary: Evolution of Precision

g_P

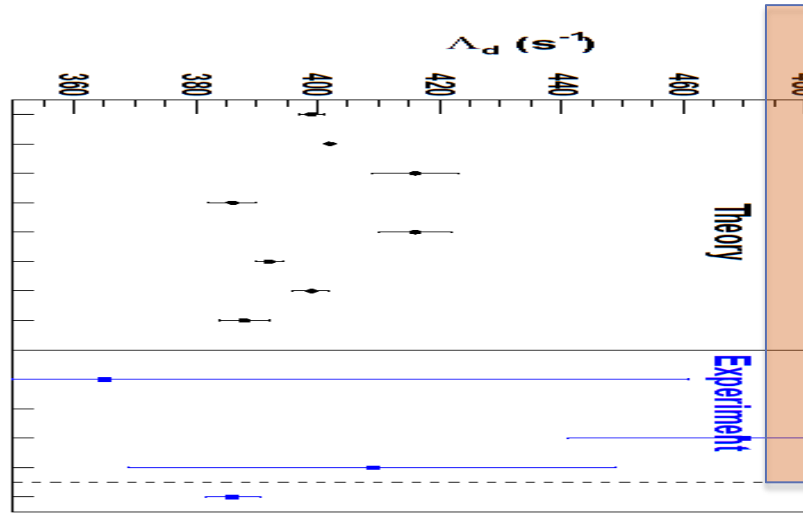
= 8.06 œ0.55 (μp)
= 8.2 œ0.7 (μ^{3}He exp+MKRSV theo)

$L_{1A},\ \hat{d}^R$

complete

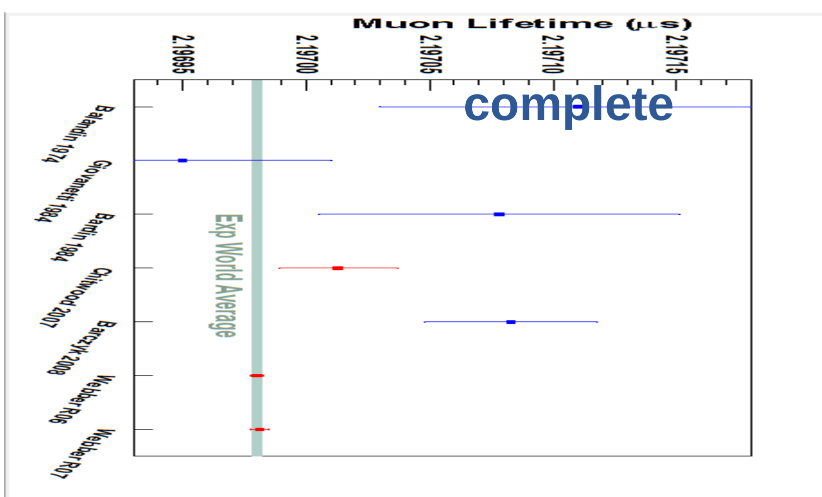


in progress



G_F

complete



future

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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