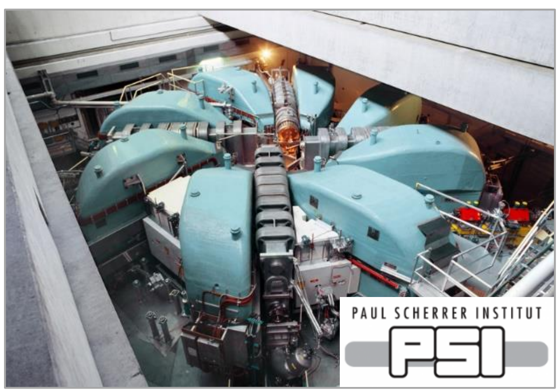
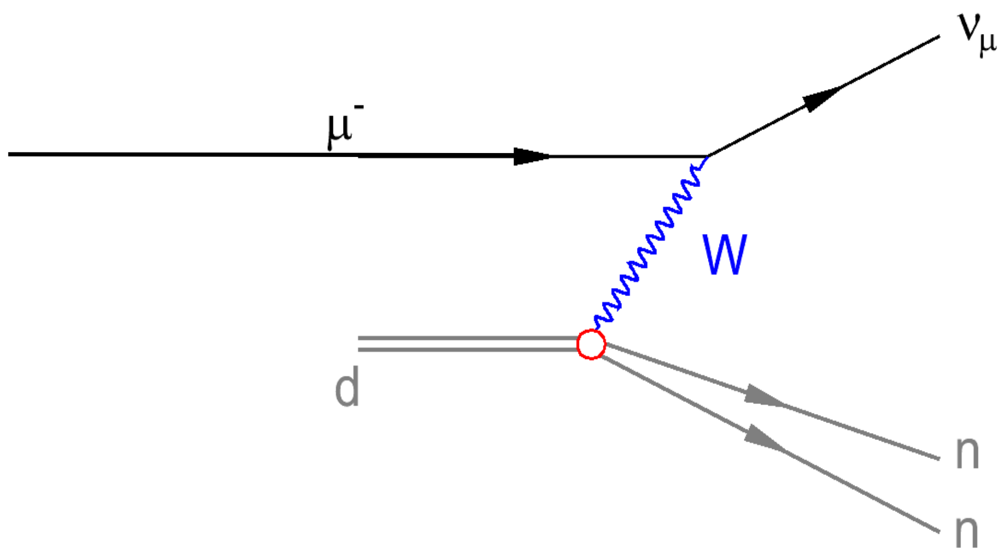
Muon capture on the deuteron: the MuSun experiment

Frederik Wauters





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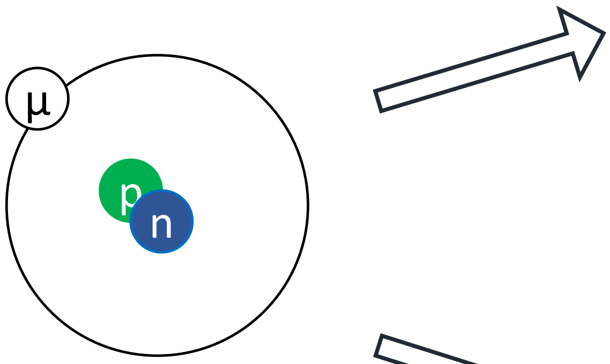
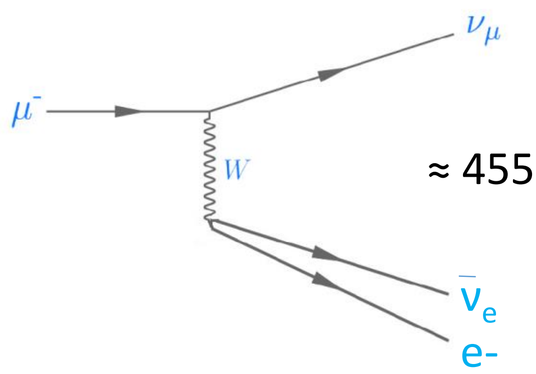
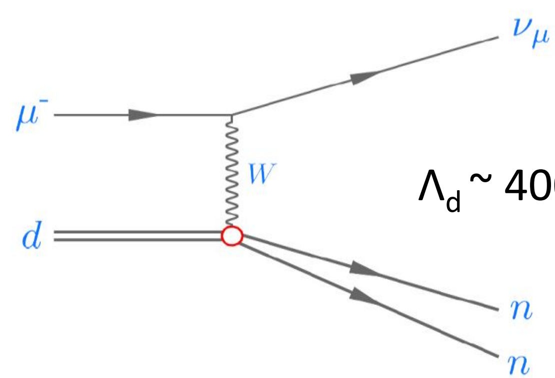




$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

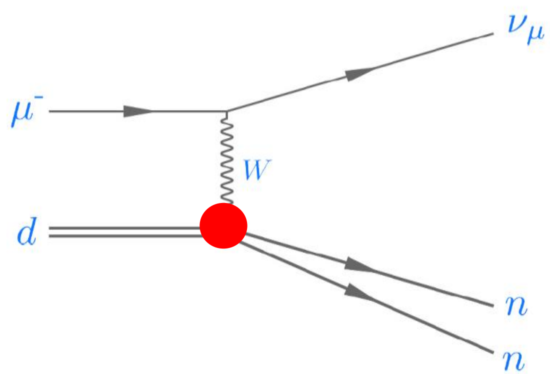
≈ 455 170 s^{-1} (or Hz)



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

Λ_d ~ 400 s^{-1} (or Hz)

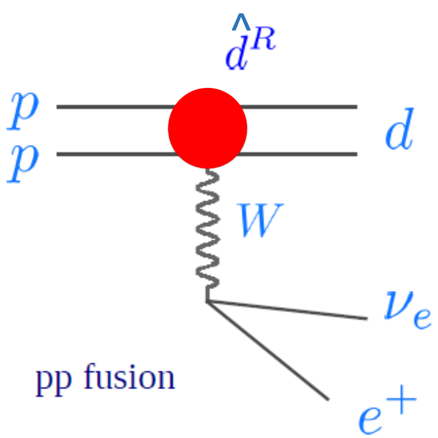
Muon capture on the deuteron



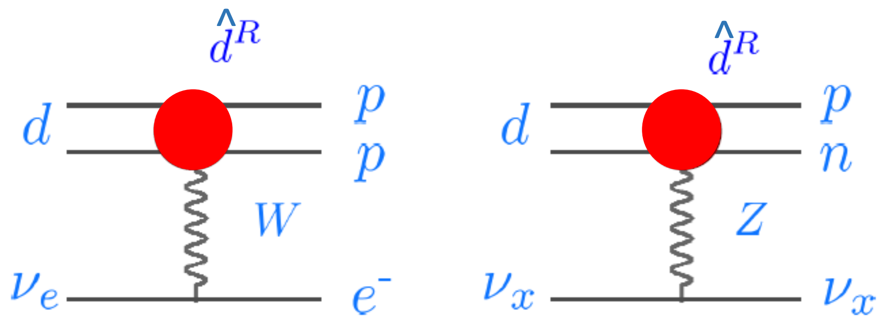
In Chiral Perturbation Theory, the two-body axial currents is parameterized by one Low Energy Constant $\hat{d}^R$.

- Nucleons and pions as d.o.f.
- Predictive (next order is always smaller)
- g_A for the 2N system

Can't measure these in the lab

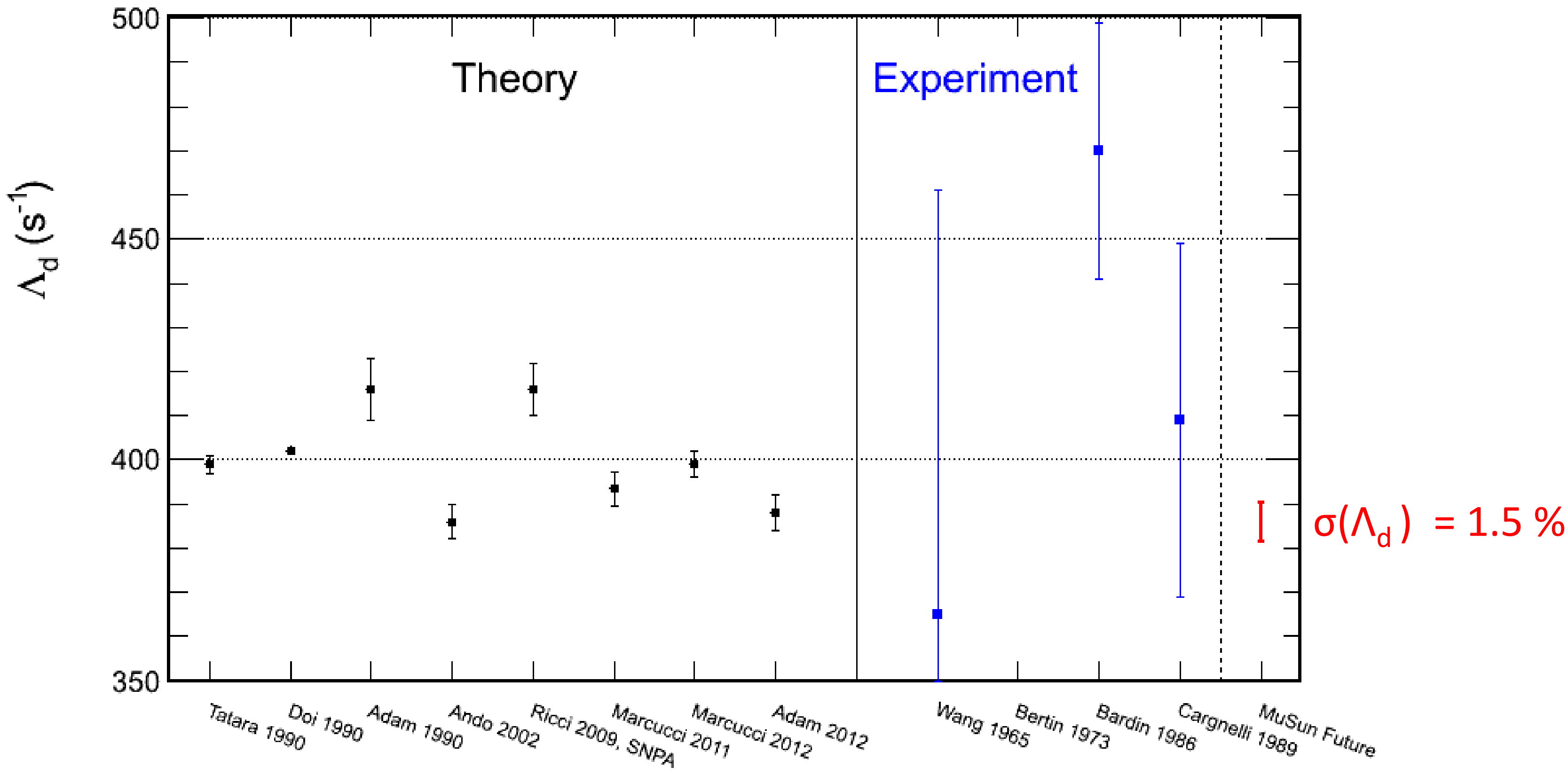


pp fusion



SNO charged, neutral current reactions

Muon capture on the deuteron



Calculation of doublet capture rate for muon capture in deuterium within chiral effective field theory

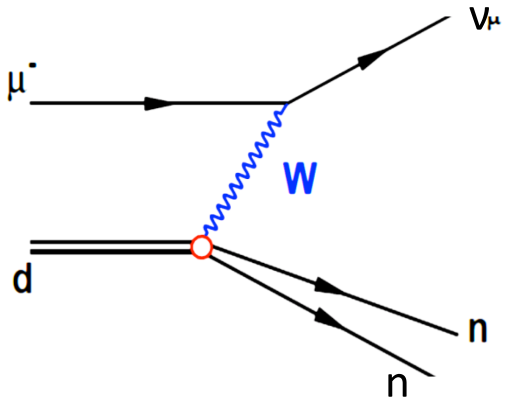
J. Adam Jr.[a], M. Tater[a], E. Truhlík[a,*], E. Epelbaum[b], R. Machleidt[c], P. Ricci[d]

Chiral Effective Field Theory Predictions for Muon Capture on Deuteron and ^{3}He

L. E. Marcucci, A. Kievsky, S. Rosati, R. Schiavilla, and M. Viviani
Phys. Rev. Lett. **108**, 052502 – Published 31 January 2012

MuSun, a precision lifetime experiment

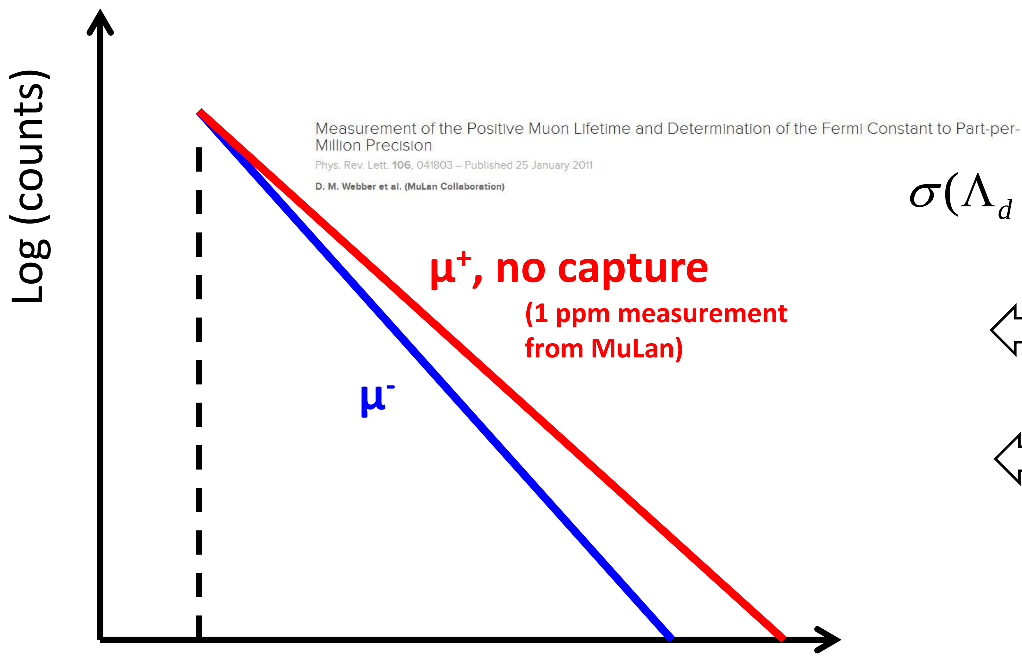
! No charged particles in final state



Decay of a μD atom:

$$N_{e^-}(t) \sim e^{-(\lambda_{\mu^+}+\Lambda_d)t}$$

455170 Hz ⟺ **~ 400 Hz**

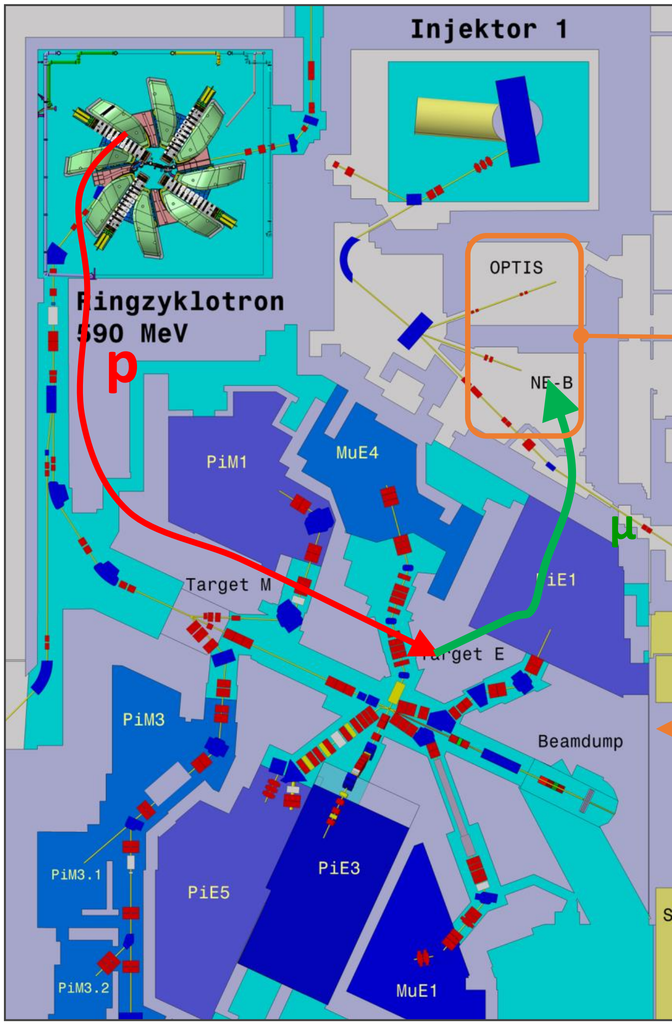


$$\sigma(\Lambda_d) \sim 1.5\ \% \rightarrow \sigma(\lambda_{\mu^-(D_2)}) \sim 10^{-5}$$

⟺ 10^{10} "good" muon decays

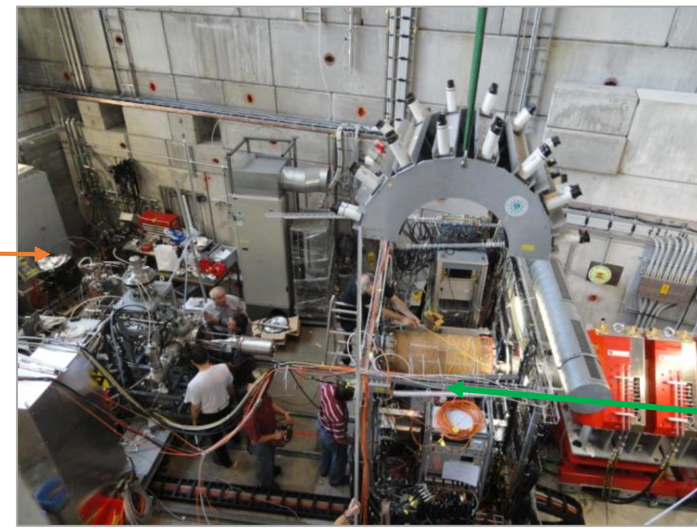
⟺ Control systematics

MuSun, a precision lifetime experiment



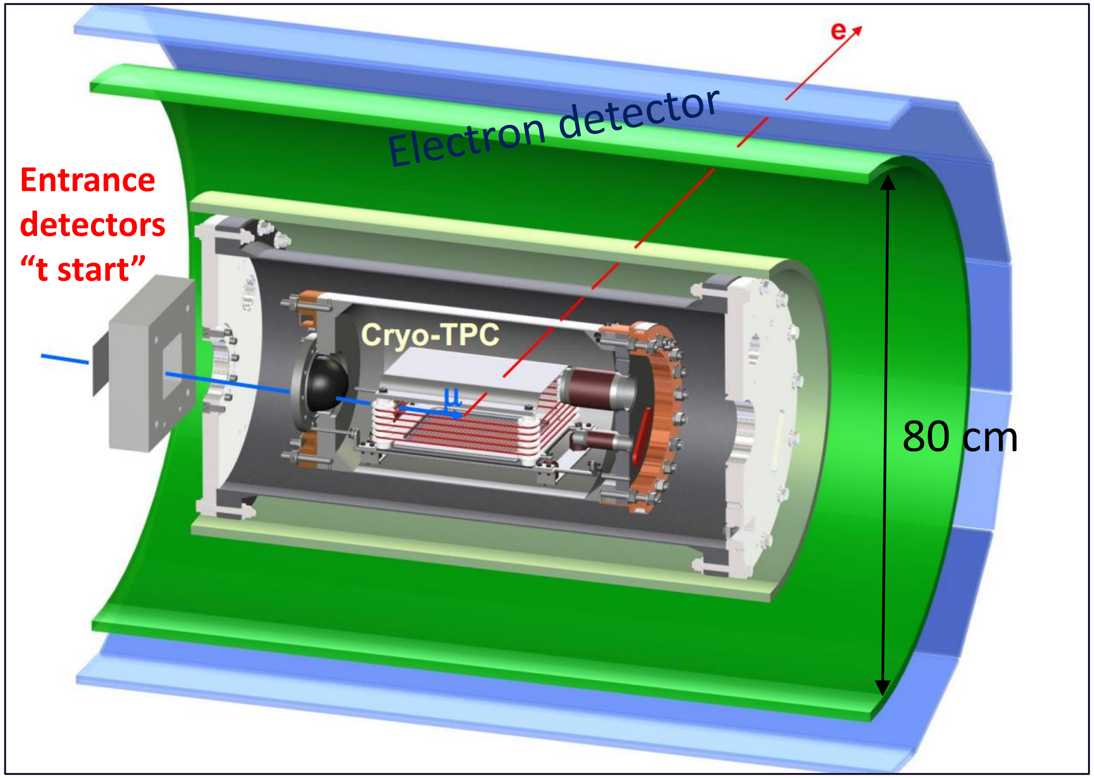
75 kHz 40 MeV/c μ^-

(3 kHz accepted μ-e pairs, 16 weeks live)



μ

MuSun, a precision lifetime experiment

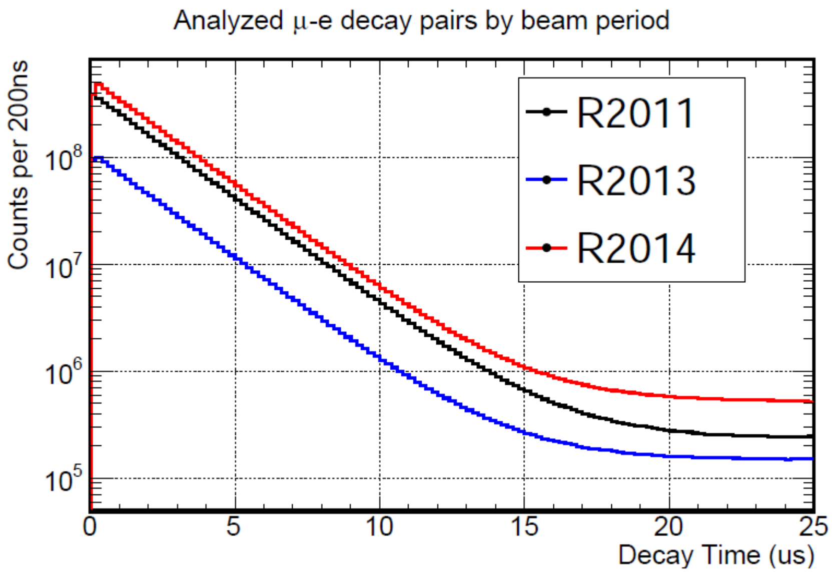


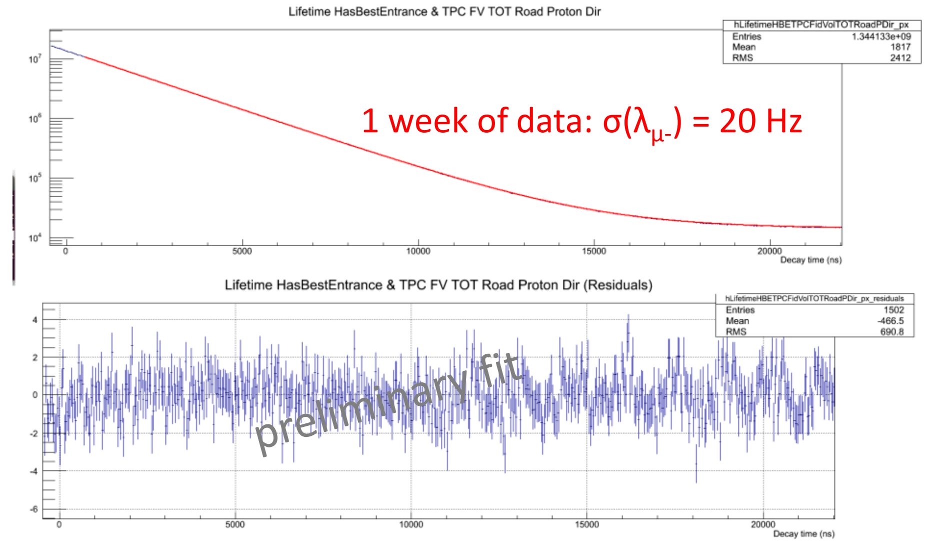
Entrance detectors
- t start
- pile up protection
- 2 scint. + MWPC

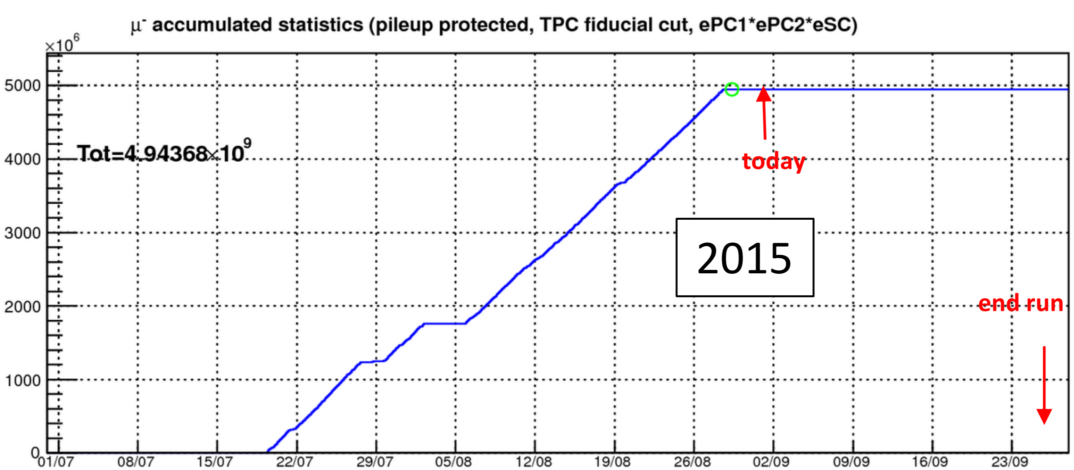
Cryo TPC
- event selection
- 48 anode ionization chamber
- 5 bar D_2, 30 K

Electron detector
- t stop
- 2 MWPC + 32 scint.

Gathering statistics





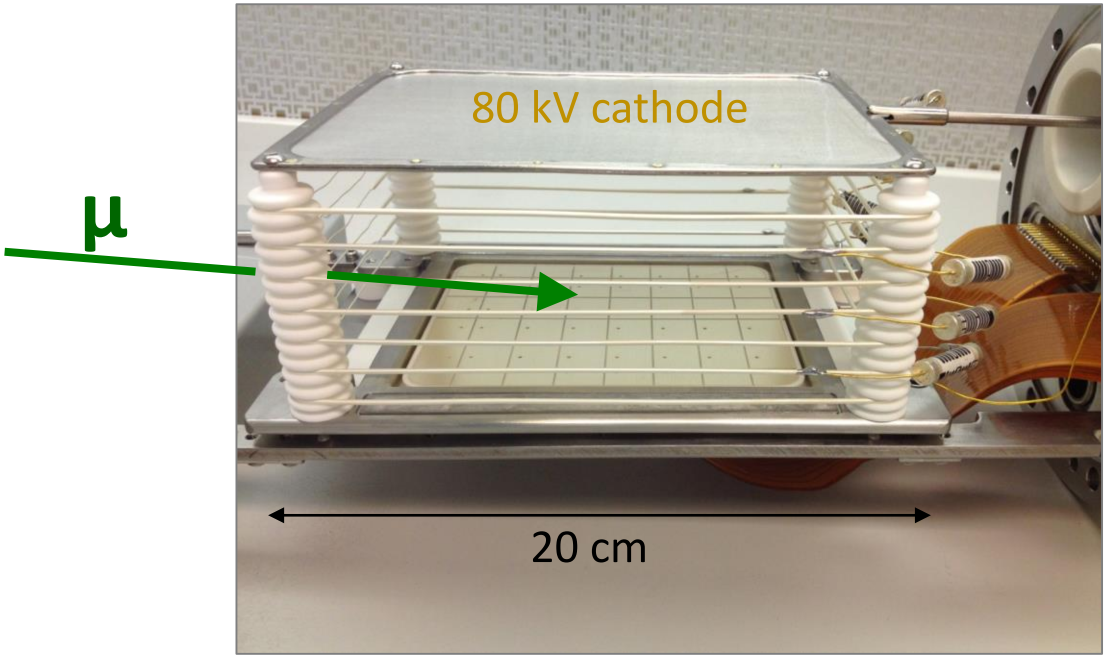


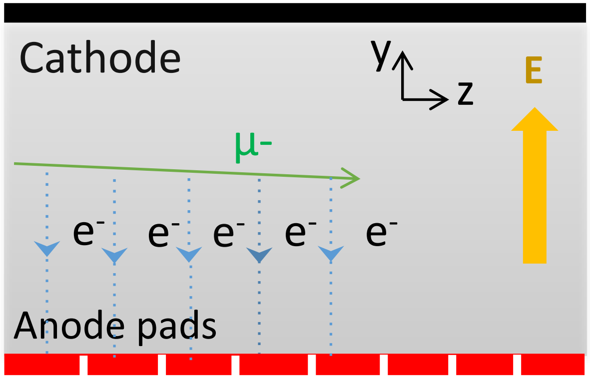
year	μ-	μ+
2011	4.5 10^9	0.5 10^9
2013	1.4 10^9	0.5 10^9
2014	6.0 10^9	1.0 10^9
2015	7-8 10^9	1.0 10^9

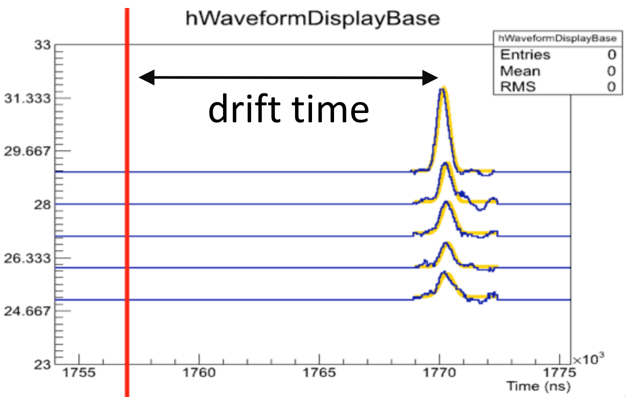
final/physics dataset

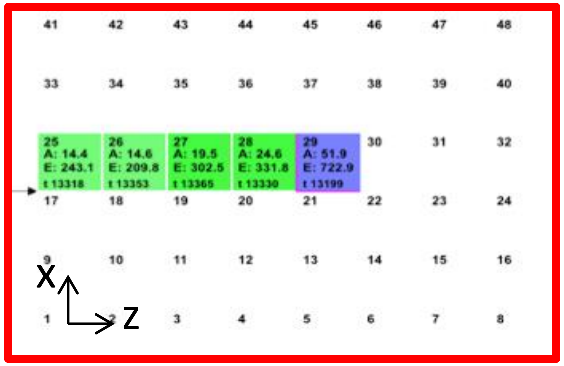
first results soon

- For “all” accepted events, the muon has to stop in the D2 gas
- This cut has to be made in a time independent way





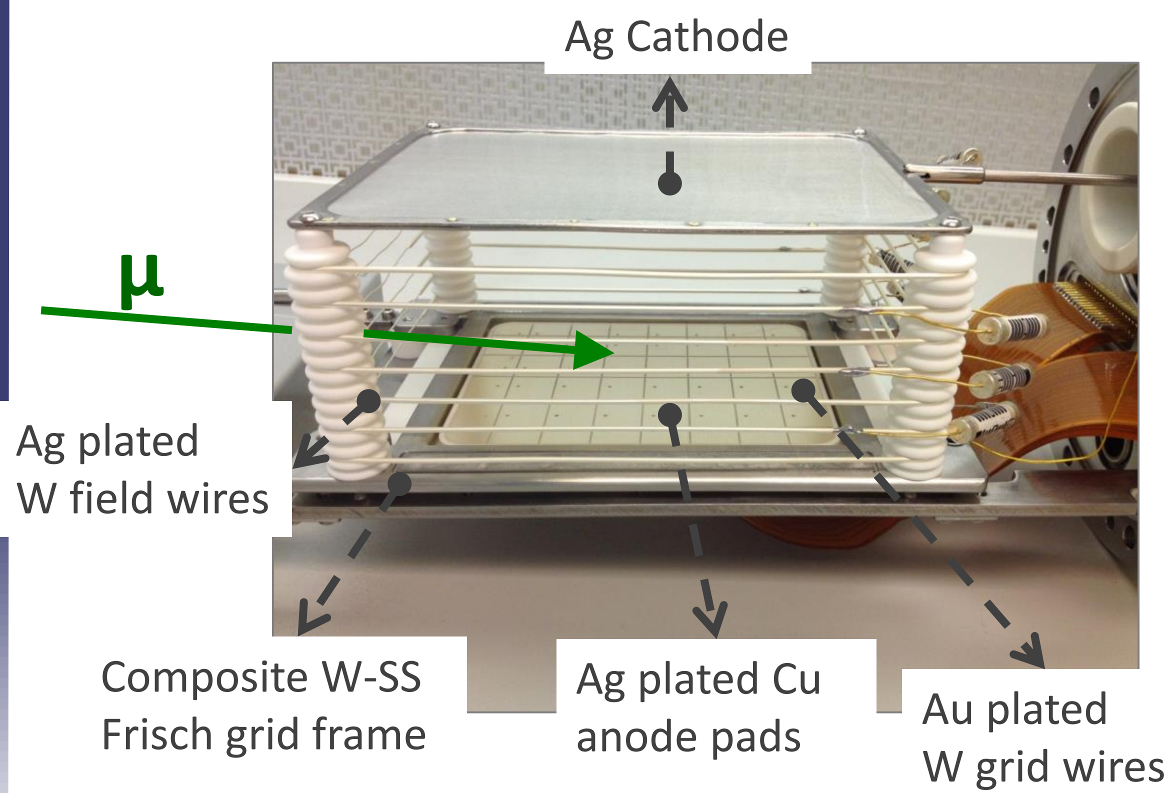




Systematics: event selection with cryo-TPC

- For "all" accepted events, the muon has to stop in the D2 gas: wall stops

Cryo-TPC:
- 80 kV
- 30 Kelvin
- 5 Bar of D_2

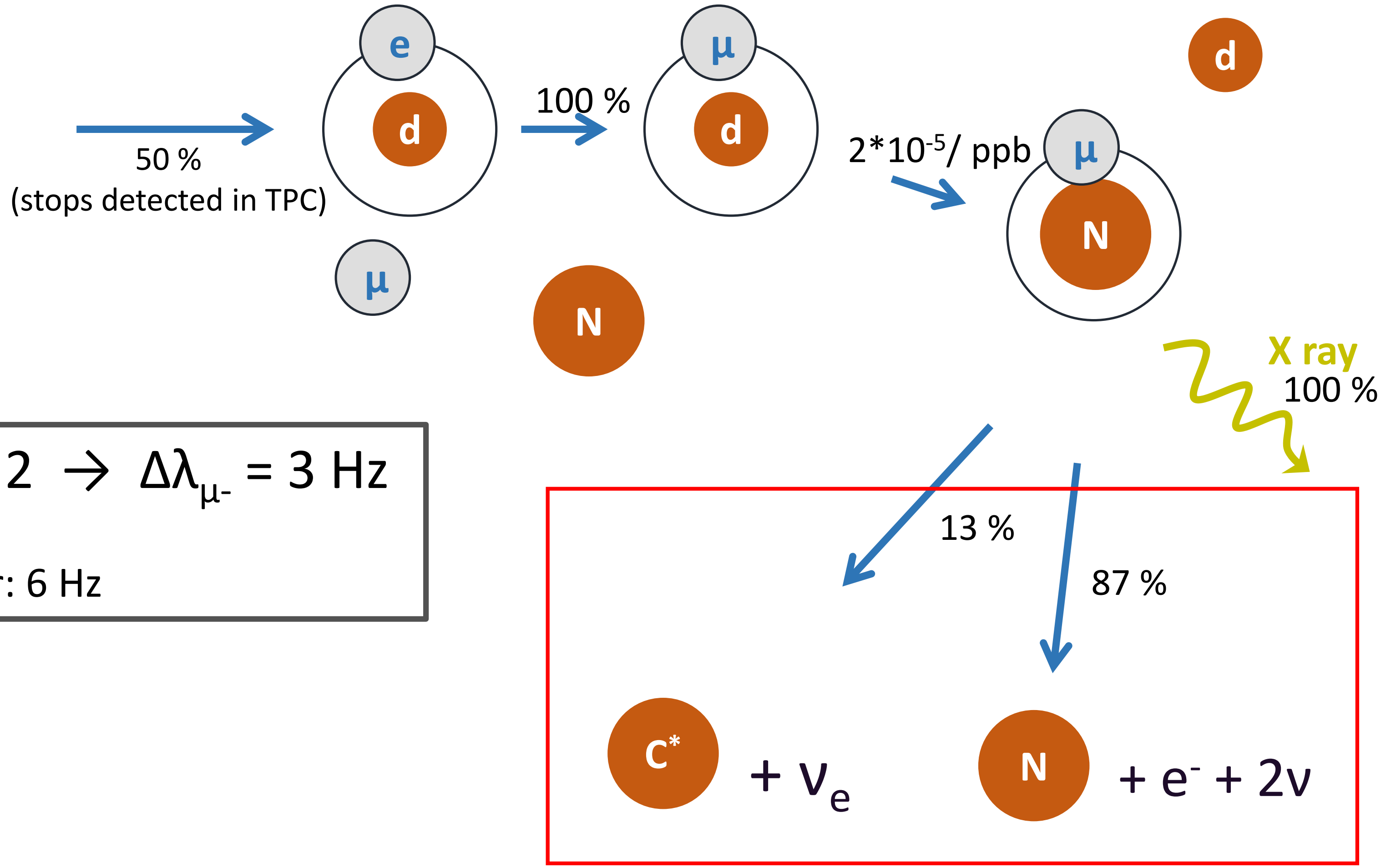


element	μ capture rate (Hz)	lifetime (ns)
D	~400	2243
N	65 10^3	1930
O	98 10^3	1810
Si	850 10^3	760
Fe	4400 10^3	207
Au	12 000 10^3	74

BAD

High Z stops: gone before t_{start} fit

- For “all” accepted events, the muon has to stop in the D2 gas: gas impurities



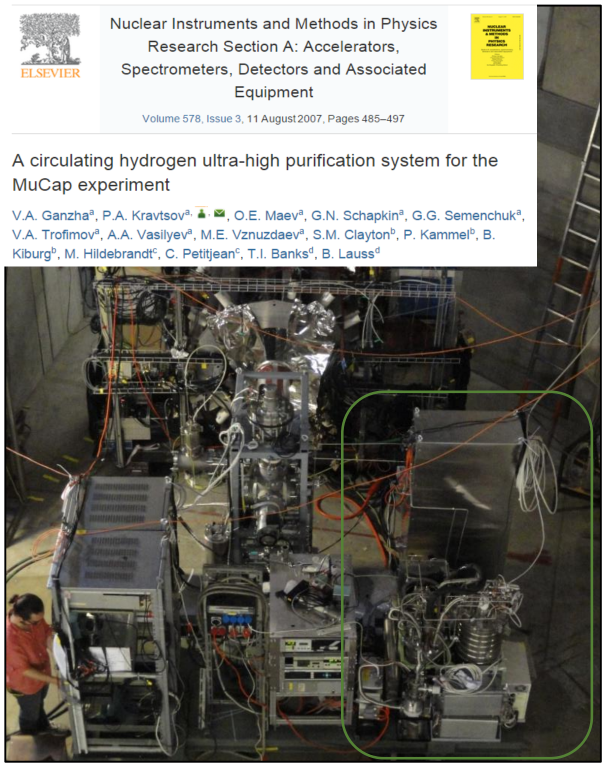
1 ppb of N2 → $\Delta\lambda_{\mu^-}$ = 3 Hz

final error bar: 6 Hz

- For "all" accepted events, the muon has to stop in the D2 gas: gas impurities

Zeolite filters @ 77K

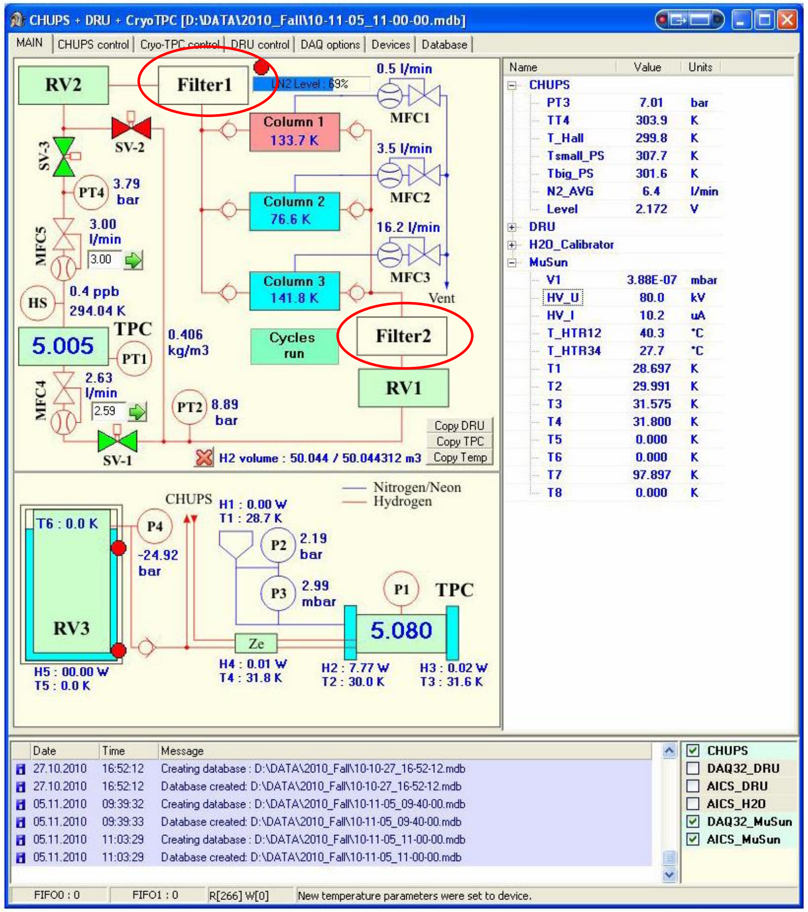
<u>step 1:</u> Continuous gas purification to ~1ppb on N_2 and O_2 or better


Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 578, Issue 3, 11 August 2007, Pages 485–497

A circulating hydrogen ultra-high purification system for the MuCap experiment

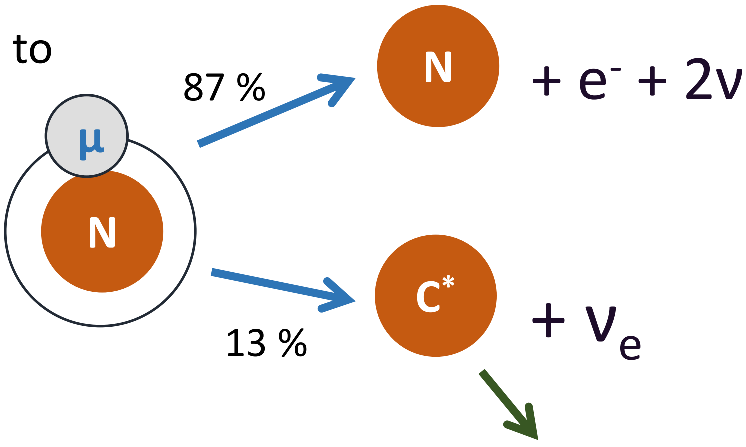
V.A. Ganzha[a], P.A. Kravtsov[a], O.E. Maev[a], G.N. Schapkin[a], G.G. Semenchuk[a], V.A. Trofimov[a], A.A. Vasilyev[a], M.E. Vznuzdaev[a], S.M. Clayton[b], P. Kammel[b], B. Kiburg[b], M. Hildebrandt[c], C. Petitjean[c], T.I. Banks[d], B. Lauss[d]



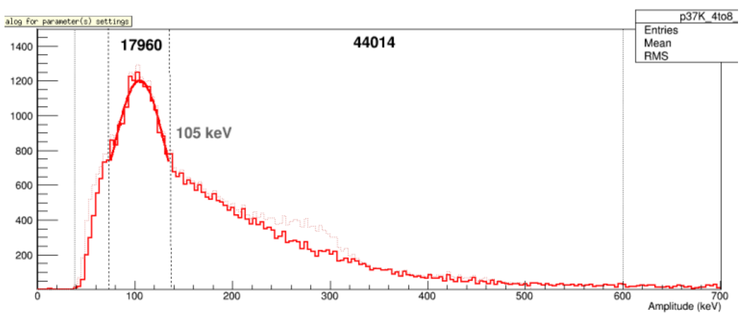
Systematics: event selection with cryo-TPC

- For "all" accepted events, the muon has to stop in the D2 gas: gas impurities

<u>step 2:</u> Direct impurity detection

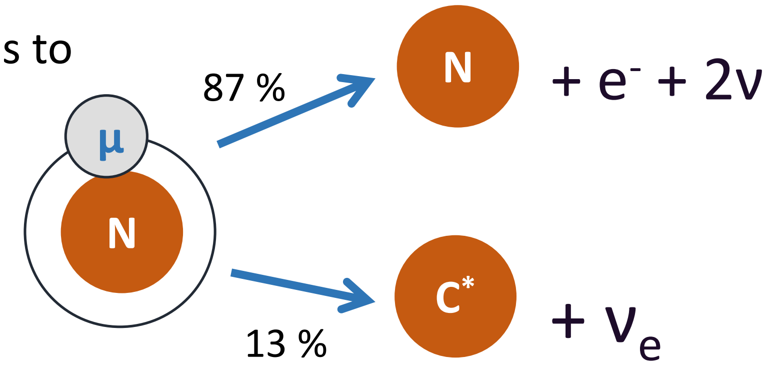


2013 N_2 doped data

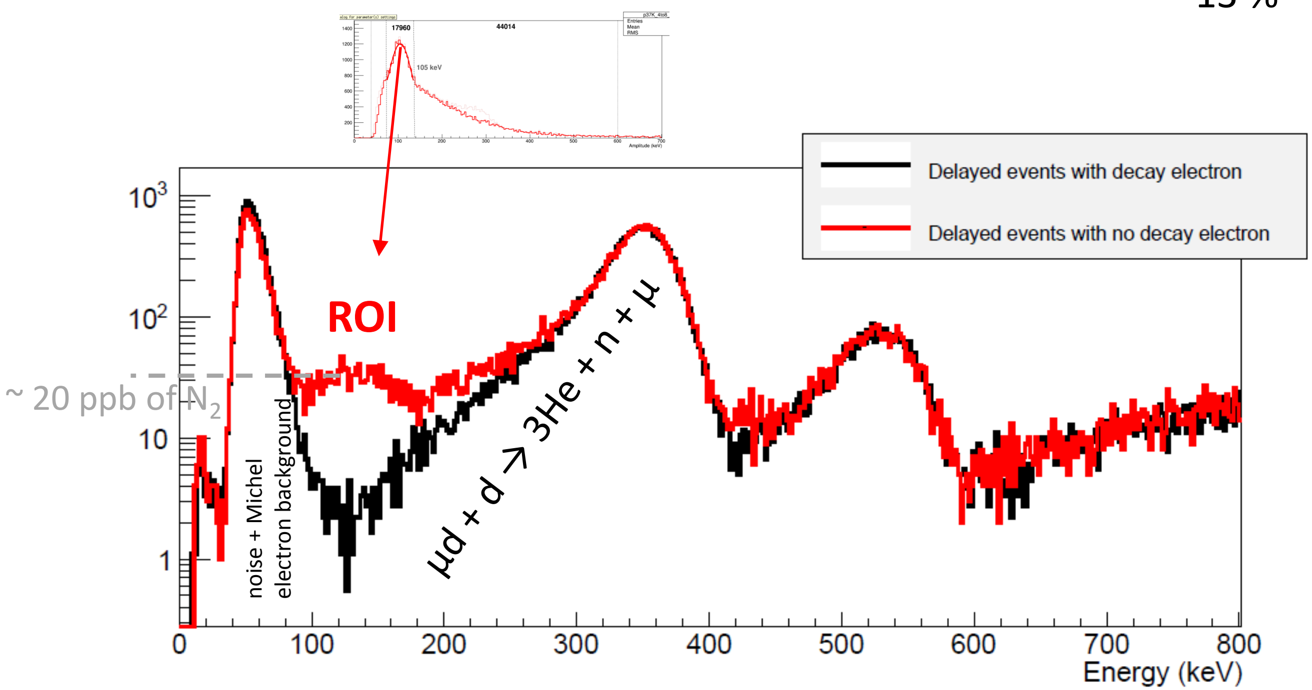


Systematics: event selection with cryo-TPC

- For "all" accepted events, the muon has to stop in the D2 gas: gas impurities



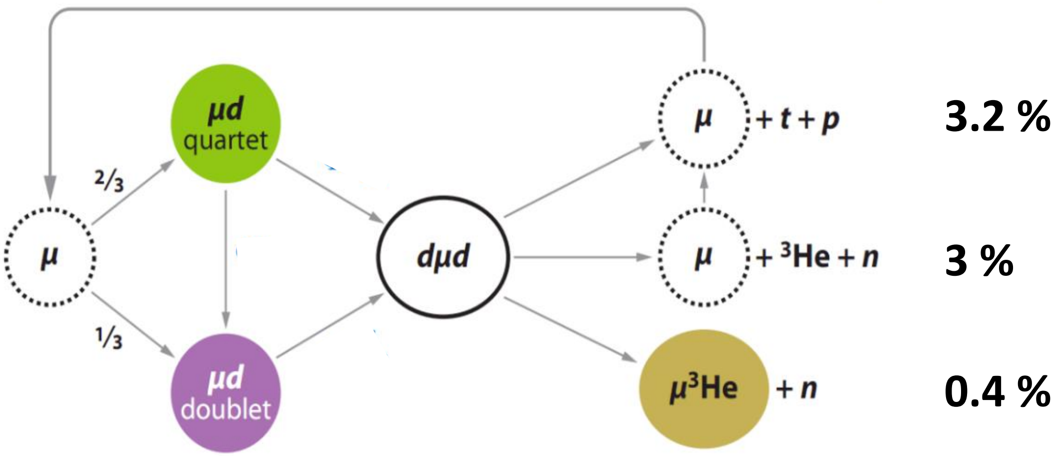
<u>step 2:</u> Direct impurity detection



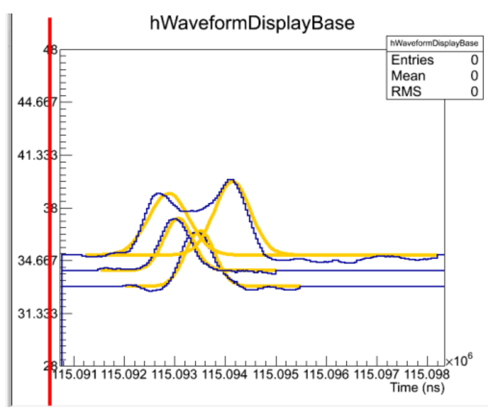
- Current sensitivity at the 2-3 ppb level (6-9 Hz) for N2 (that's what we care for)
- muon catalyzed fusion and electron background under control
- neutron background under analysis to get < 1 ppb N_2

Systematics: event selection with cryo-TPC

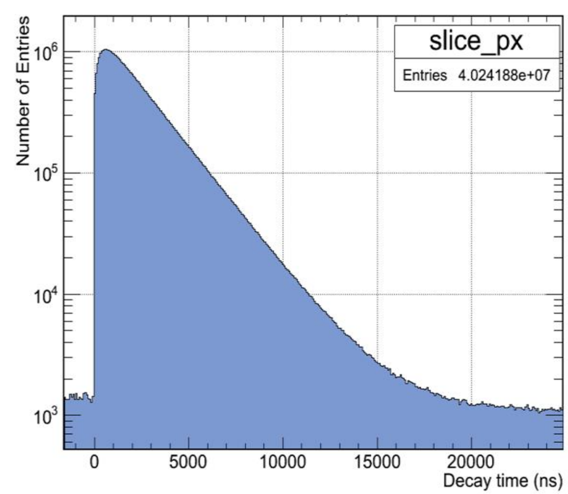
- The event selection has to be made in a time independent ways
  - Muon catalyzed fusion (MCF)
  - Michel (decay) electron interference



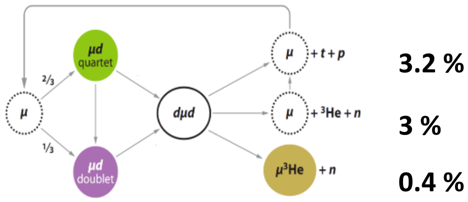
Any delayed process which biases the event selection distorts the observed time distribution



Decay time of muons w/ prior fusion



- The event selection has to be made in a time independent ways
  - Muon catalyzed fusion (MCF)

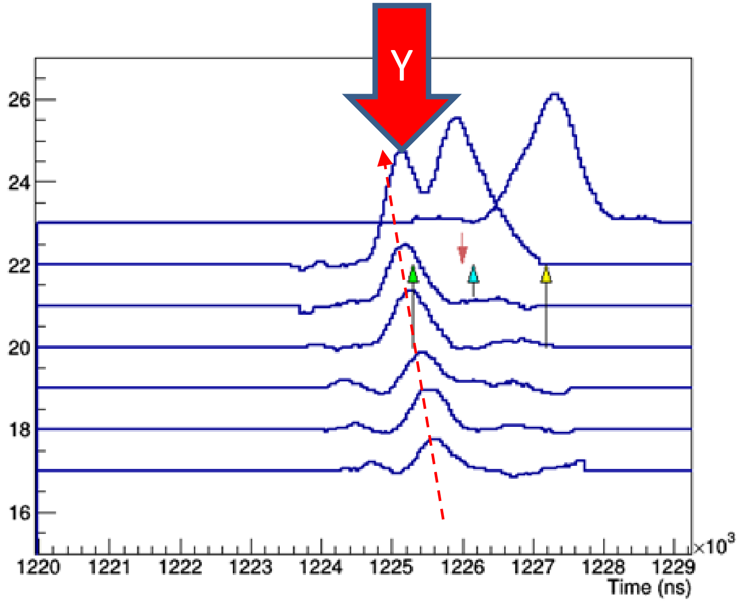


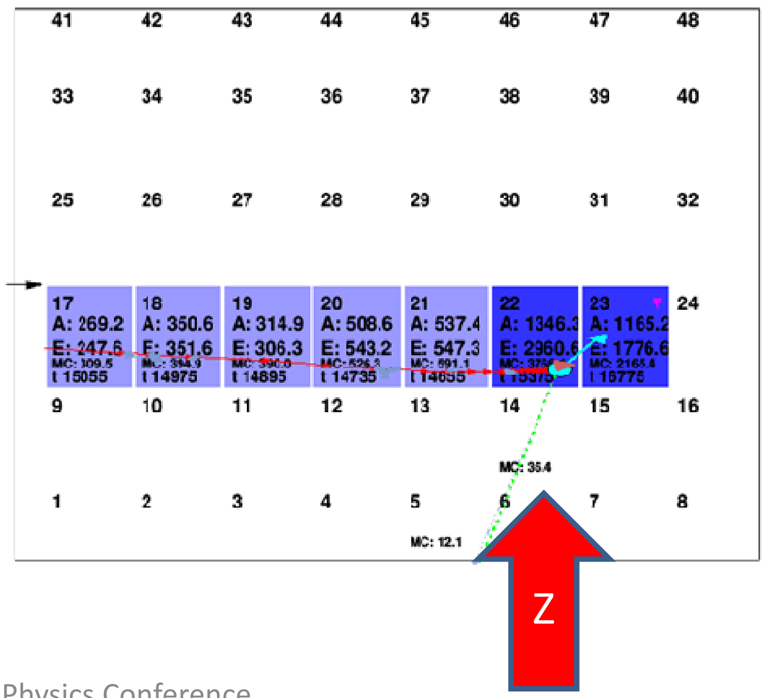
→ 0.5% bias on MCF introduces a 6 Hz shift in the observed λ_{μ}

Solution: good muon tracker ≠ accurate track reconstruction

= make unbiased fiducial volume cut

→ projection trackers which behaviour is validated by a full MC of the experiment





Moving forward towards a first physics result

Data taking: Full statistics by the end of this month. 2014 + 2015 data run = 1.3 10^{10} accepted events in stable conditions

Analysis: Most challenging systematic effects are being quantified, approaching the required precision for a first physics result.

A precise determination of Λ_d is crucial to determine the 2-body LEC (L_{1A} or $\hat{d}^R$) for the axial weak current.

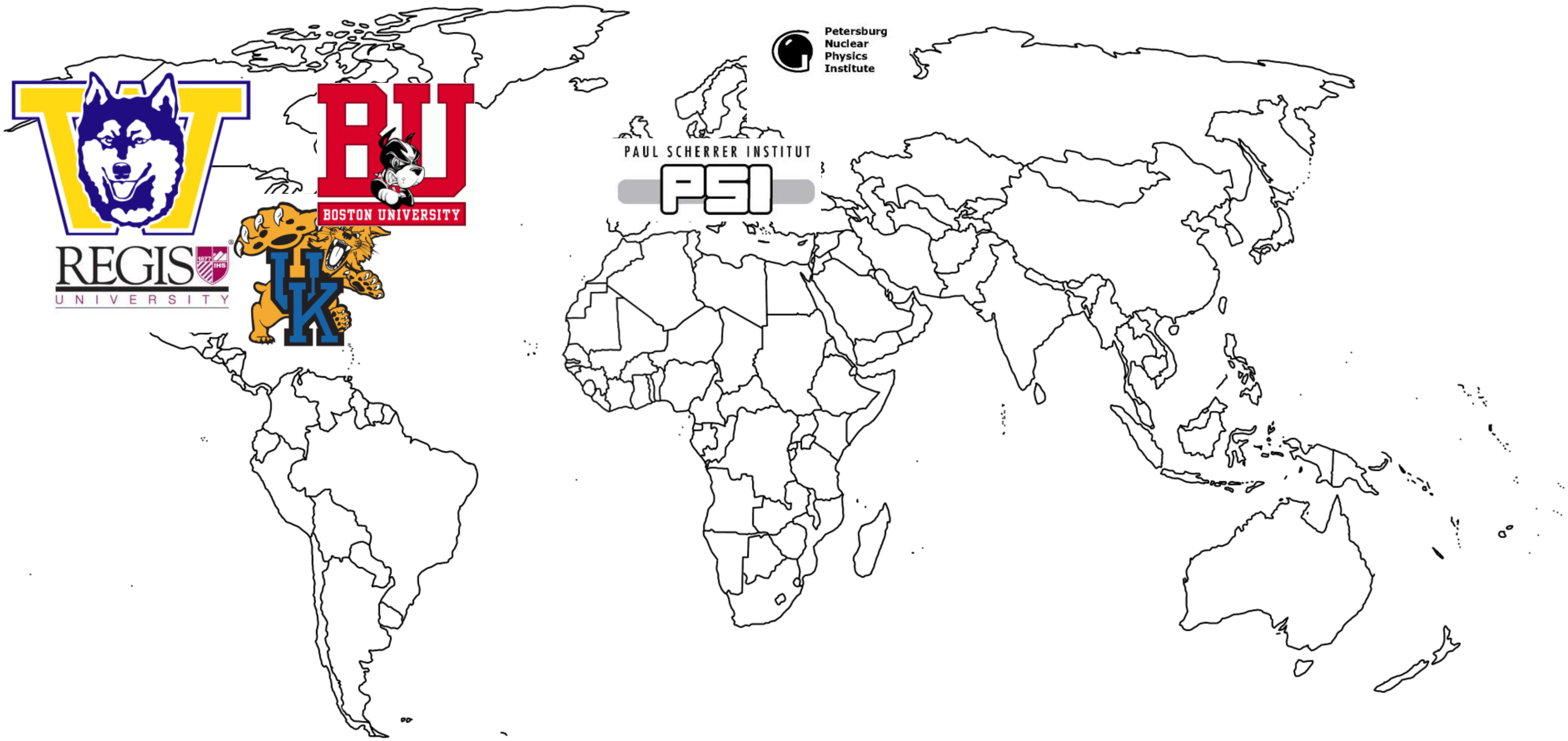
Proton-Proton Weak Capture in Chiral Effective Field Theory
L. E. Marcucci, R. Schiavilla, and M. Viviani
Phys. Rev. Lett. **110**, 192503 – Published 10 May 2013

- Precise S factor for p-p fusion independent of 3B physics
- Model independent determination of the ^{8}B ν flux from SNO
- EFT fully determined for two body system

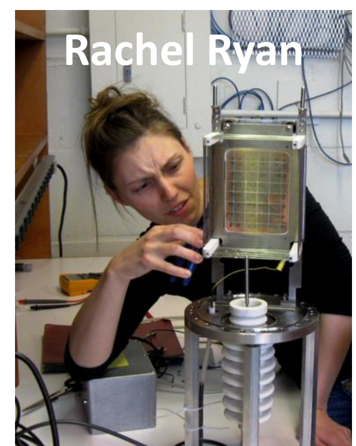
further reading:

P. Kammel and K. Kubodera, Annu. Rev. Nucl. Part. Sci. **60**, 327 (2010).

Collaboration



Thanks to the UW team



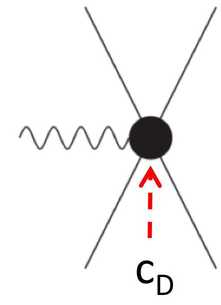
Ethan Muldoon

extras

Quest for the Unknown LEC

"Calibrate the Sun"

Axial current d^R (or c_D)



Extract from axial current reaction in

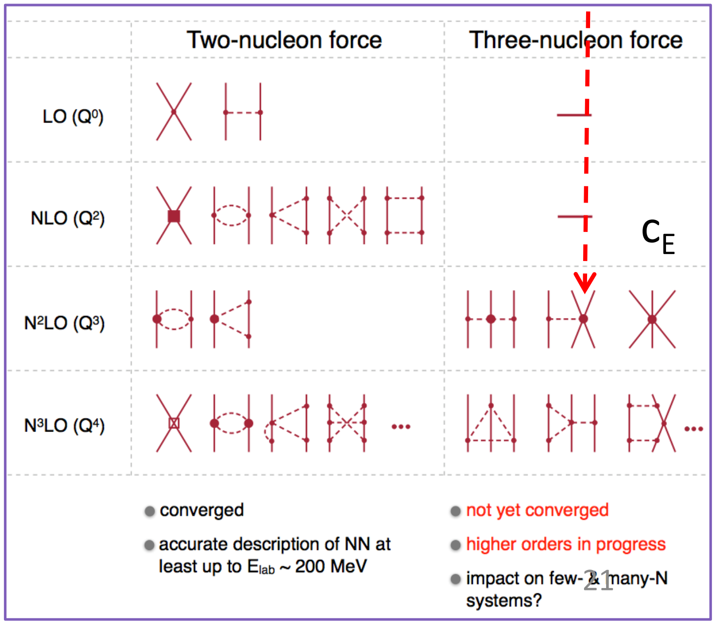
2-body system $\sigma \approx \sigma_0(1 + 0.013\,\frac{L_{1A}}{fm^3})$ with $L_{1A} \sim 6\ fm^3$

	method	$L_{1A}\ (fm^3)$
two-body system		
	reactor $\bar{\nu}$ + d	3.6 ± 5.5
	ES, CC, NC in SNO	4.0 ± 6.3
	MuSun proposal	$\pm\ 1.25$

- **MuSun only realistic option, reduce uncertainty 100% to ~20%**

3-body system

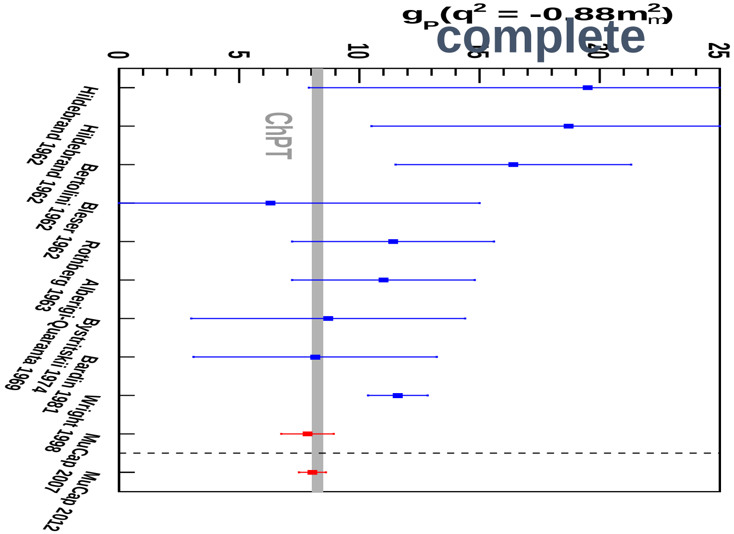
- 2 LECs and additional complexity enter
- tritium beta decay
- current state of the art



g_P

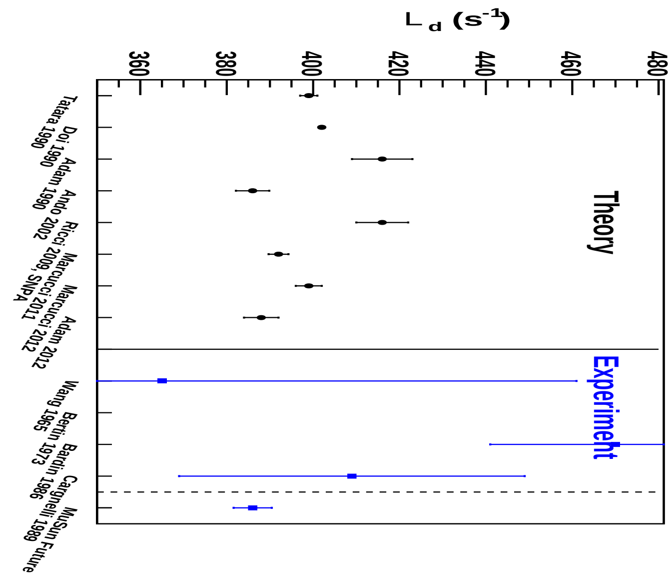
= 8.04 ± 0.56 (μp)
= 8.2 ± 0.7 (μ^3He exp+MKRSV theo)

complete



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

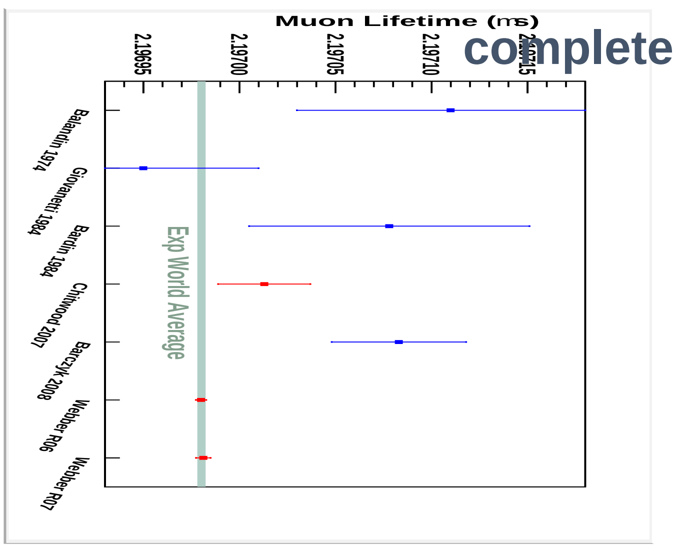
in progress



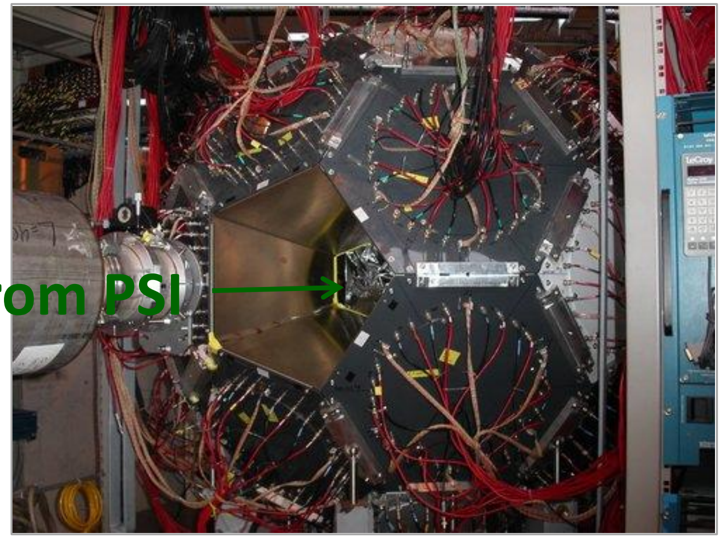
future

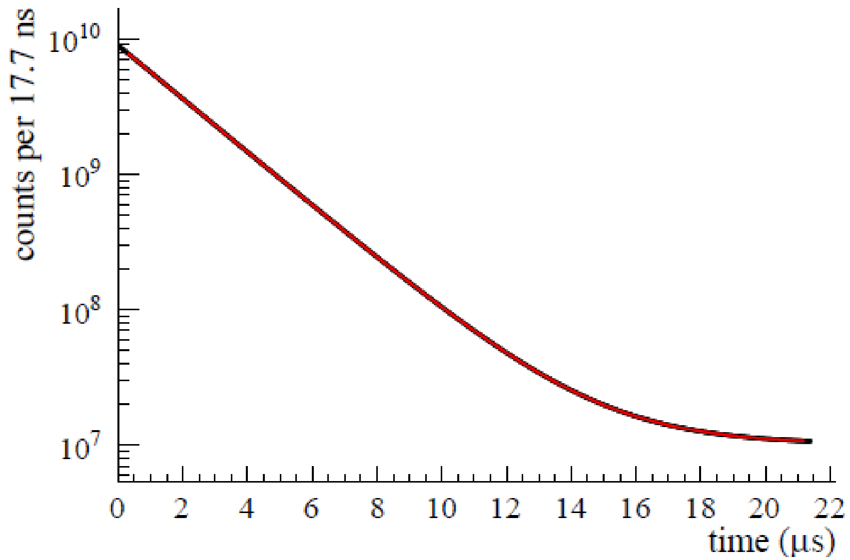
G_F

complete

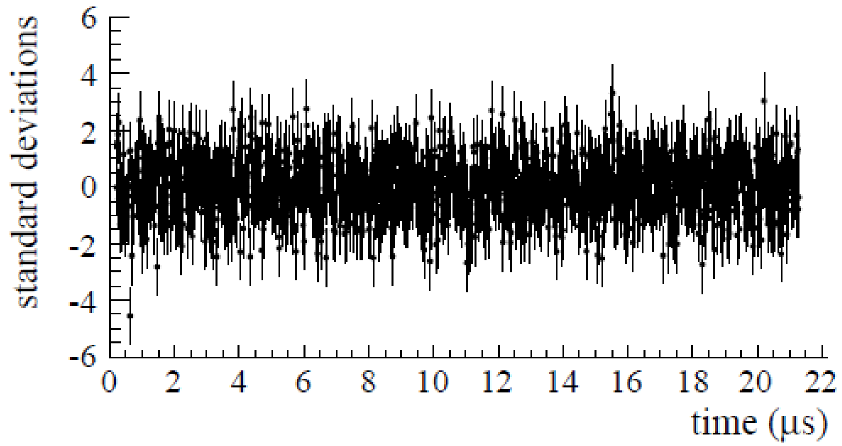


Precision muon physics: μ^+





$$\tau_\mu(\text{MuLan}) = 2\,196\,980.3(2.2)\ \text{ps}\ \ (1.0\ \text{ppm})$$



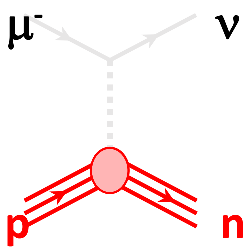
$$G_F(\text{MuLan}) = 1.166\,378\,7(6) \times 10^{-5}\ \text{GeV}^{-2}\ \ (0.5\ \text{ppm})$$

Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant to Part-per-Million Precision

Phys. Rev. Lett. **106**, 041803 – Published 25 January 2011

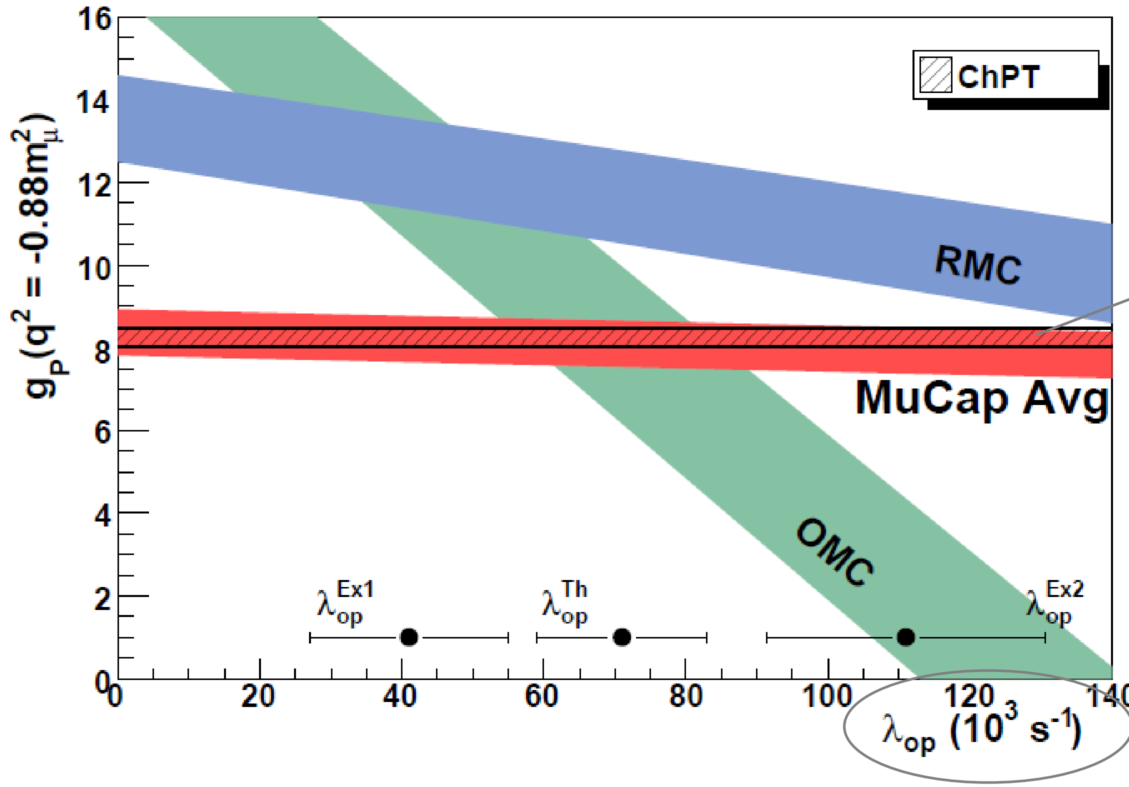
D. M. Webber et al. (MuLan Collaboration)

Precision muon physics: μ^-



$$\langle n|V^\alpha - A^\alpha|p\rangle$$

$$\Lambda_S = (714.9 \pm 5.4_{\mathrm{stat}} \pm 5.1_{\mathrm{syst}})\ \mathrm{s}^{-1}$$



theory

Atomic physics
$\mu p \rightarrow p\mu p$
formation

Measurement of Muon Capture on the Proton to 1% Precision and Determination of the Pseudoscalar Coupling g_P

Phys. Rev. Lett. **110**, 012504 – Published 3 January 2013

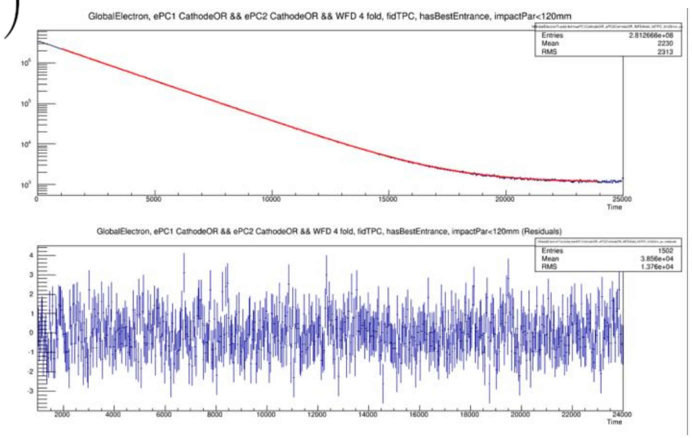
V. A. Andreev et al. (MuCap Collaboration)

$$e(t) = \frac{N * \lambda_\mu}{\Lambda_{eff} - \Lambda_N} \left(\Lambda_{eff}\, e^{-(\Lambda_N + \lambda_\mu)t} - \Lambda_N e^{-(\lambda_\mu + \Lambda_{eff})t} \right)$$

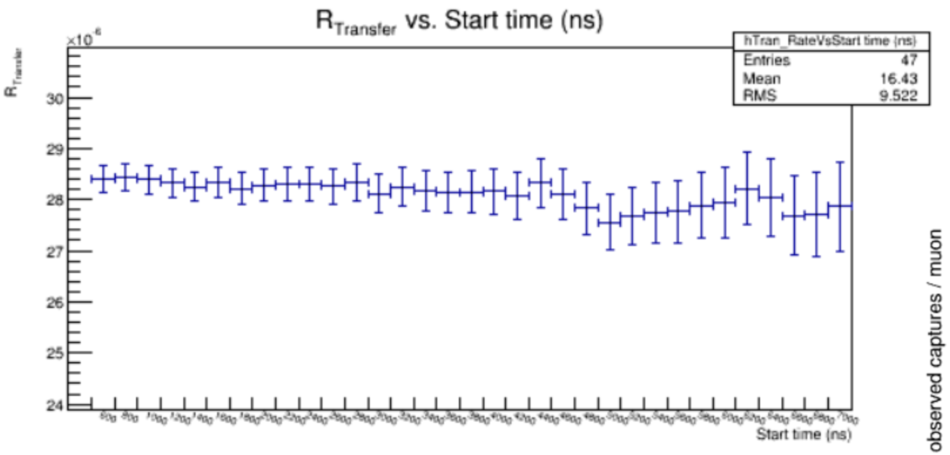
Λ_N = capture rate on Nitrogen

Λ_{eff} = effective transfer rate

production λ_μ (σ45 Hz) as input



3 parameter fit

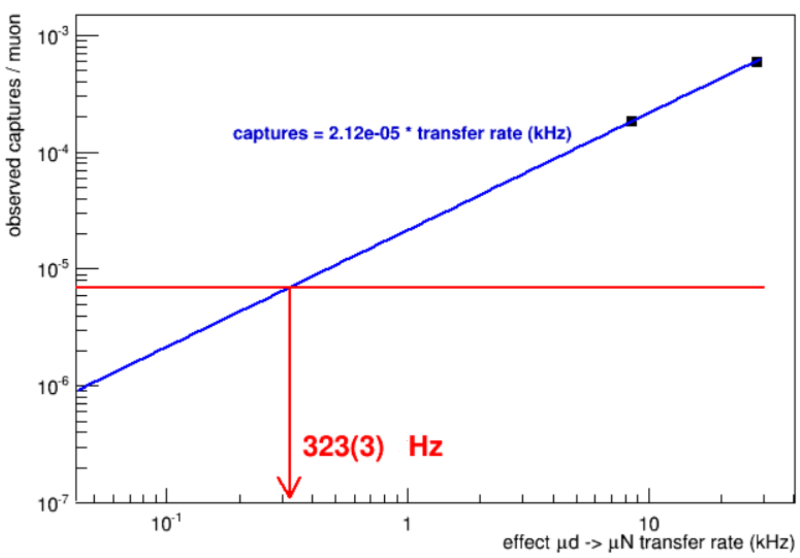


37K : 28.3(3) kHz

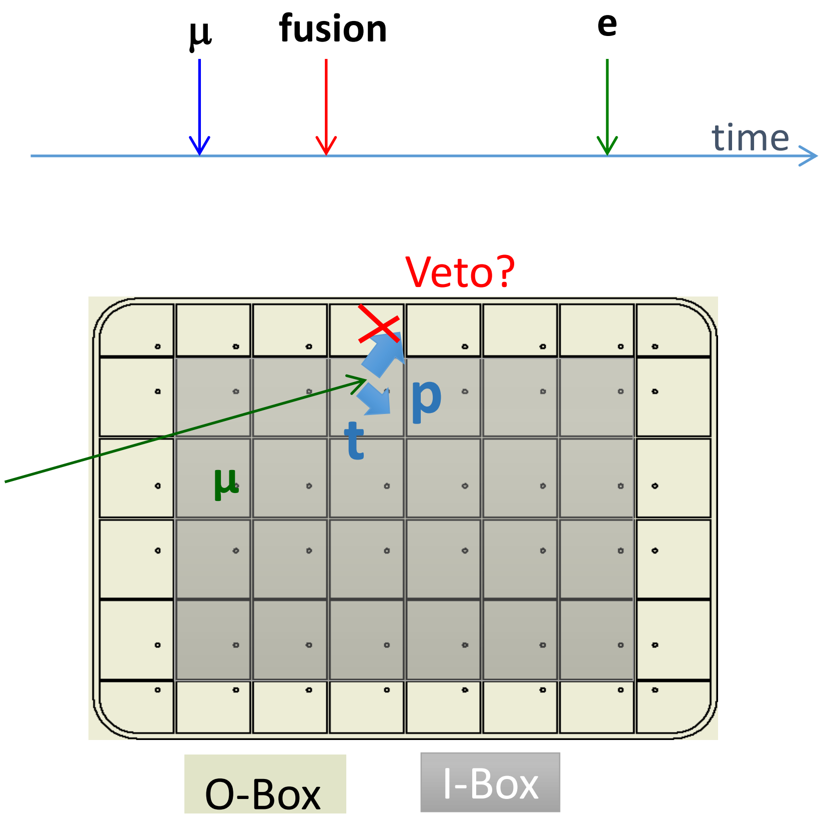
34K : 8.5(2) kHz

Δλ :

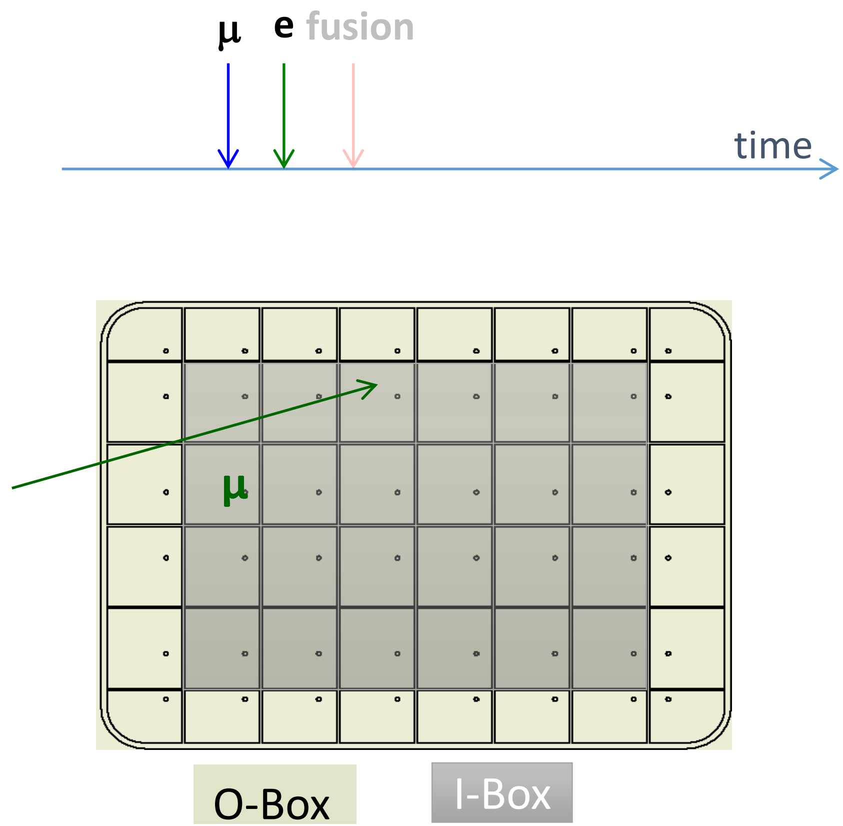
- 79 Hz from first moment
- 83 Hz from fit
- All systematic errors ~1 %
  ! energy dependence 5-10 %
- neutron BG ignored



Late decay with early fusion



Early decay no fusion



fusion interference < 1%