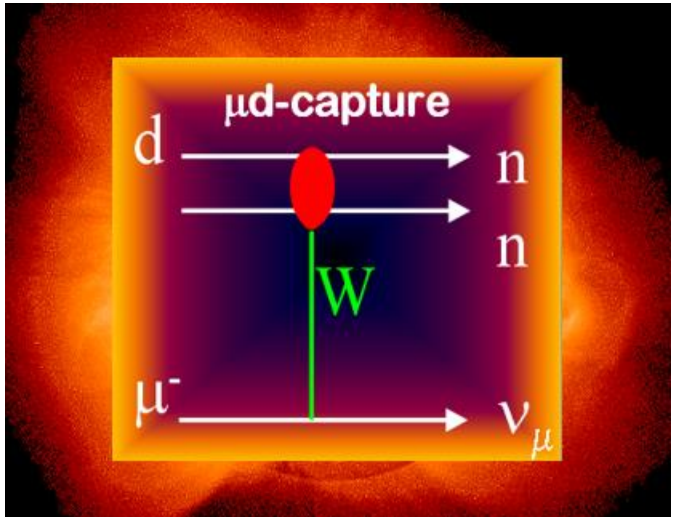
Center for Experimental Nuclear Physics and Astrophysics (CENPA)
University of Washington

U.S. DEPARTMENT OF ENERGY | Office of Science

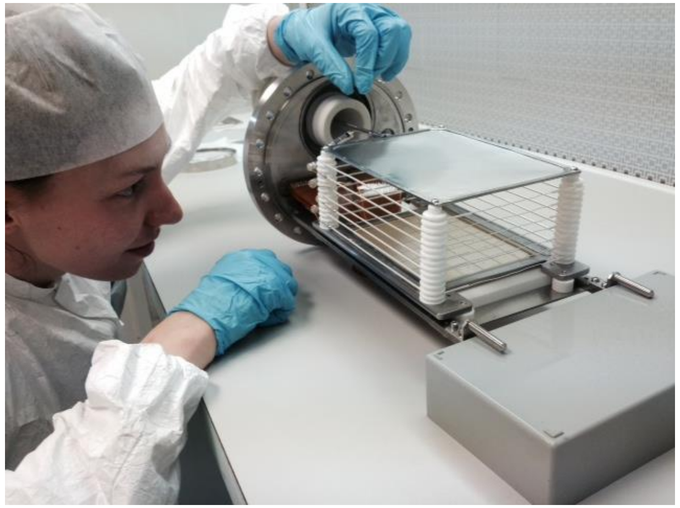
MuSun – Muon Capture on the Deuteron
An Update

Peter Kammel

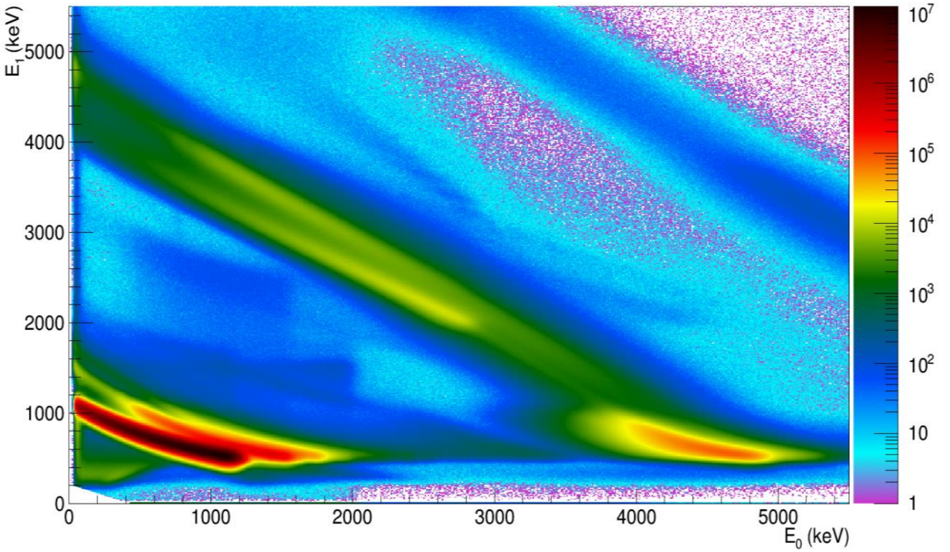
Motivation



Technique

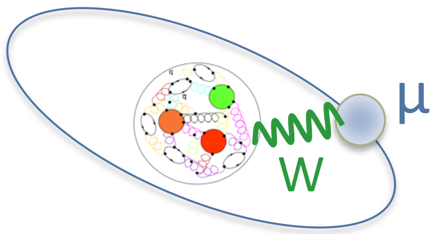


Analysis



MuSun: Goals/Motivation

- Muon capture goal:
  - muon probes nucleon and nuclei with charge-current weak interaction



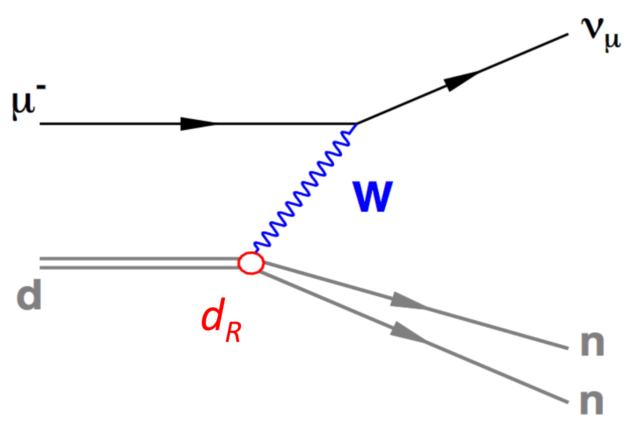
$$a_0 = \frac{1}{m_r \alpha}$$

$$q \approx 100\, MeV/c$$

- MuSun specific goal:
  - Measure muon capture rate Λ_d on the deuteron to 1.5%
  - first precise measurement of weak process in 2N system
  - determine axial coupling to 2N system, important and poorly known low energy constant (LEC) in EFT

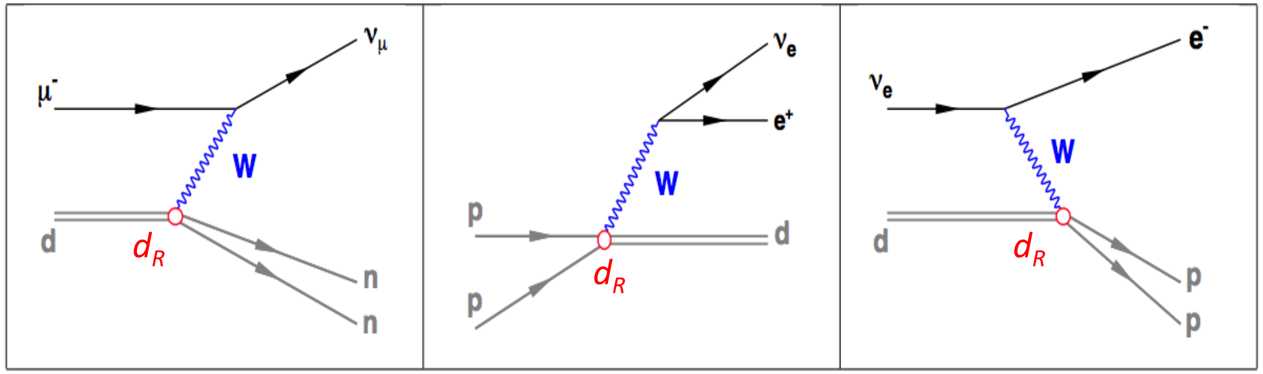
(5x more precise than currently known from 2B system)

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



Relevance

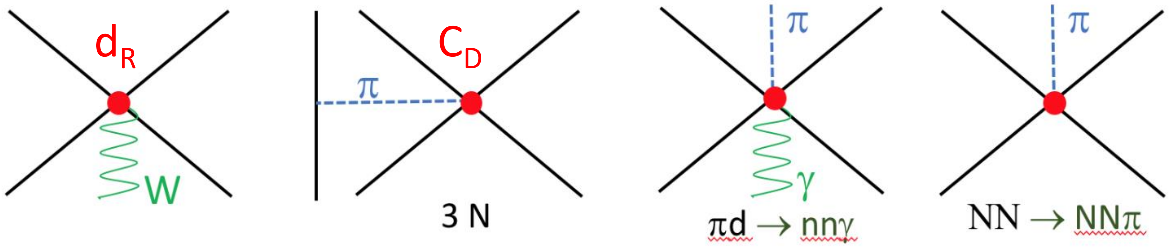
- calibrate fundamental astrophysics reactions



Family of weak 2N reactions
pp fusion (Sun)
νd scattering (SNO) *)

Marcucci et al. 2012
Acharya et al. 2018
Checcarelli et al. 2022

- important for EFT formulation of nuclear physics

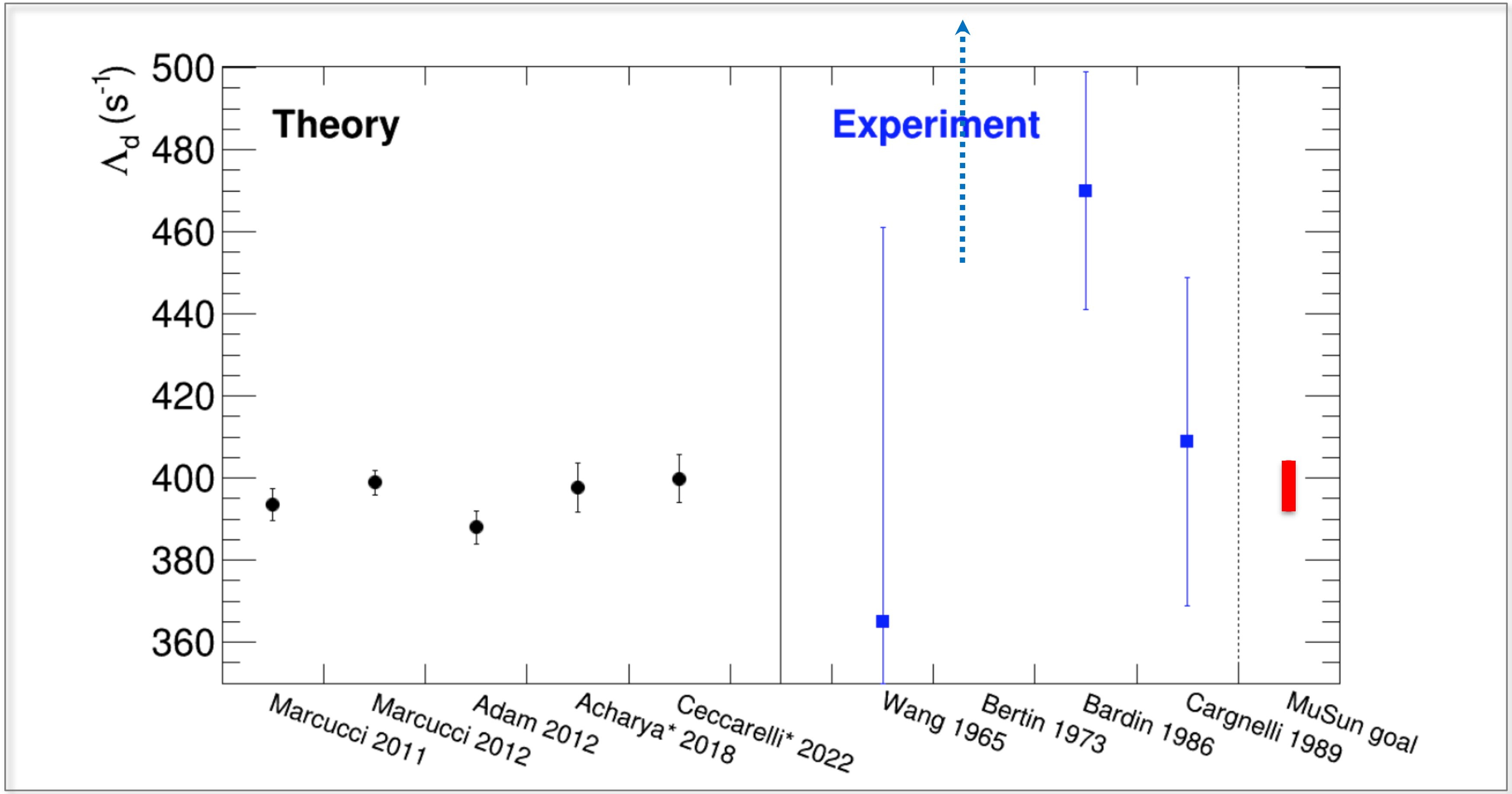


Gazit et al. 2009,2018
King et al. 2021

- relevant for a variety of weak and strong dynamics

*) D_2O normalization detector Coherent

Determine Basic LEC in μd Capture ?



Theoretical calculations fix LEC with tritium – decay,
a more complex 3-body system

$$\Lambda_d(^1S_0) = 252.8\,(1.8)_{NN}\,(4.6)_{EFT\,conv}\,(2.9)_{r_A}\ s^{-1}$$ Acharya 2018

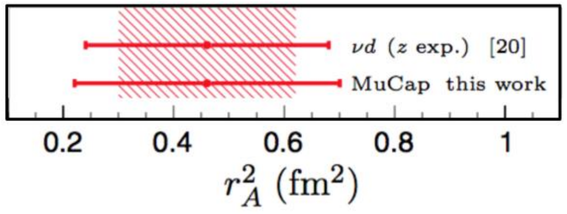
$$\Lambda_d(^1S_0) = 255.8\,(0.6)_{NN}\,(4.4)_{EFT\,conv}\,(2.9)_{r_A}\ s^{-1}$$ Ceccarelli 2022

Rep. Prog. Phys. **81** (2018) 096301 (23pp)

Nucleon axial radius and muonic hydrogen—a new analysis and review

Richard J Hill[1,2,3], Peter Kammel[4], William J Marciano[5] and Alberto Sirlin[6]

$r_A^2(\text{ave.}) = 0.46(16)\ \text{fm}^2$



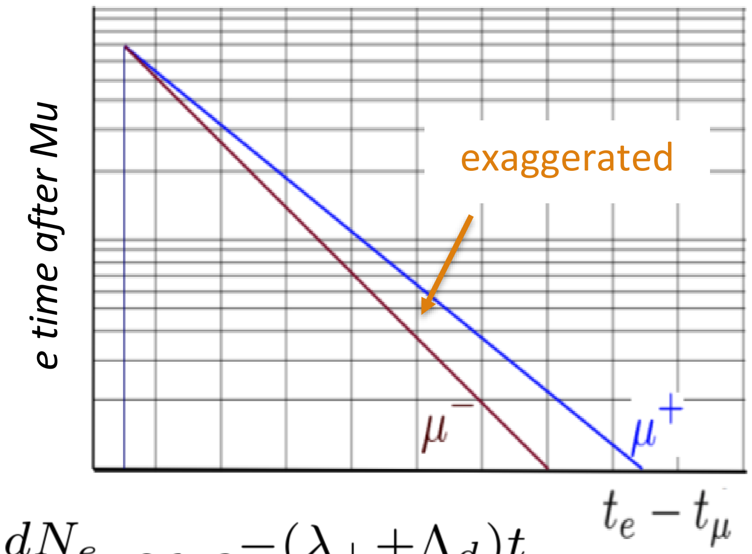
Technical Overview

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

Lifetime method

capture process rare

- only <10^{-3} of $\mu \rightarrow e\nu\nu$
- all neutral final state



$$\frac{dN_e}{dt} \propto e^{-(\lambda_+ + \Lambda_d)t}$$

$$\Lambda_d = \lambda_- - \lambda_+$$

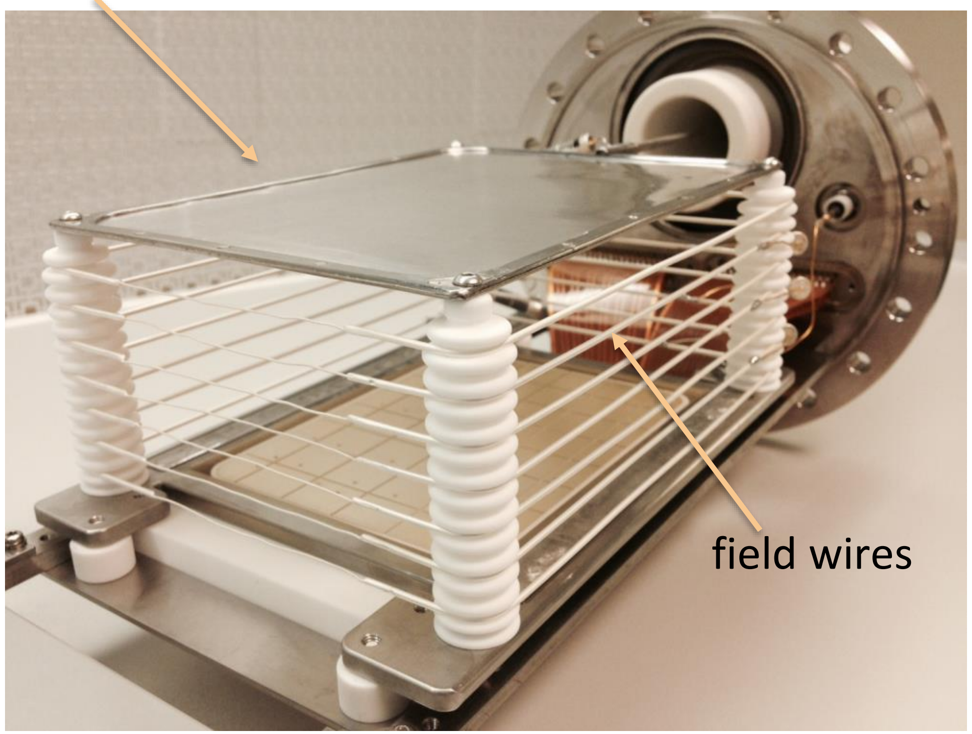
measure lifetime to 10 ppm !

Novel Cryo-TPC

MuCap/MuSun pioneered this technique

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

cathode **(-80 kV)**



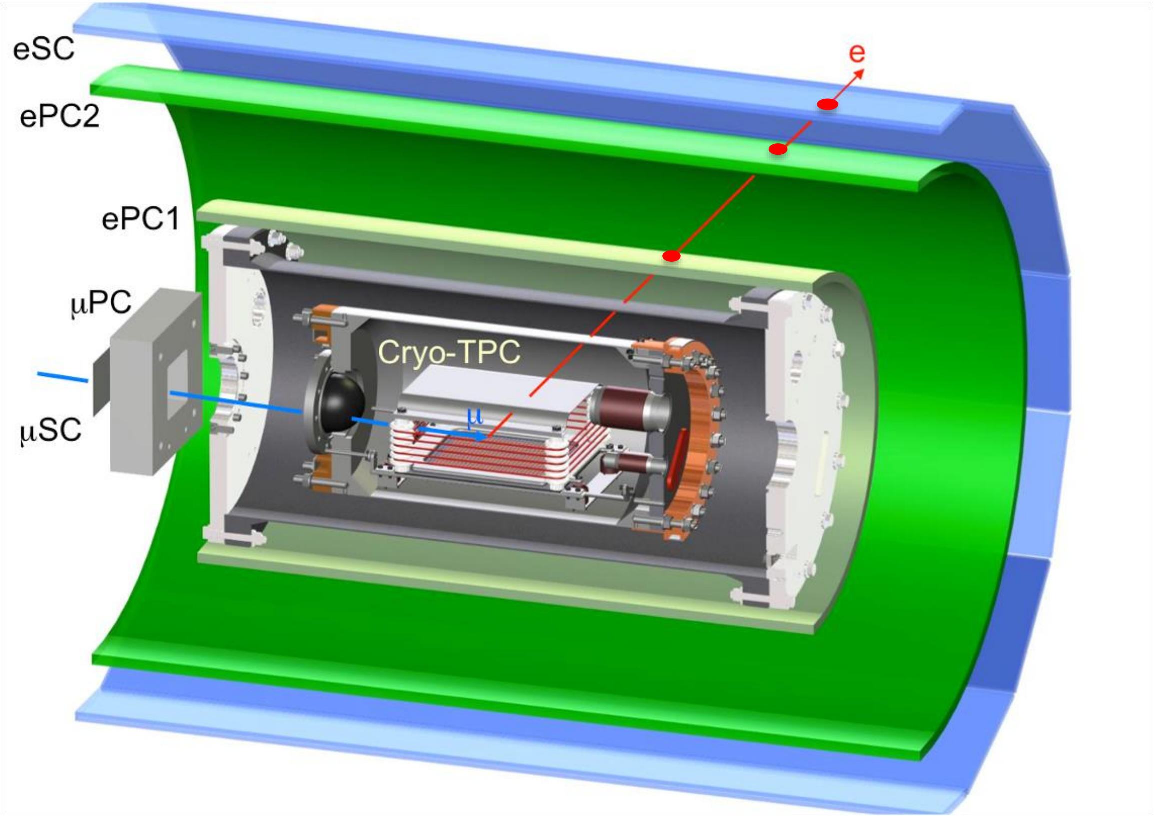
novel device:
- high purity,
- high-pressure,
- cyrogenic deuterium TPC

$90 \times 120 \times 72$ mm^3
anode 48 pads

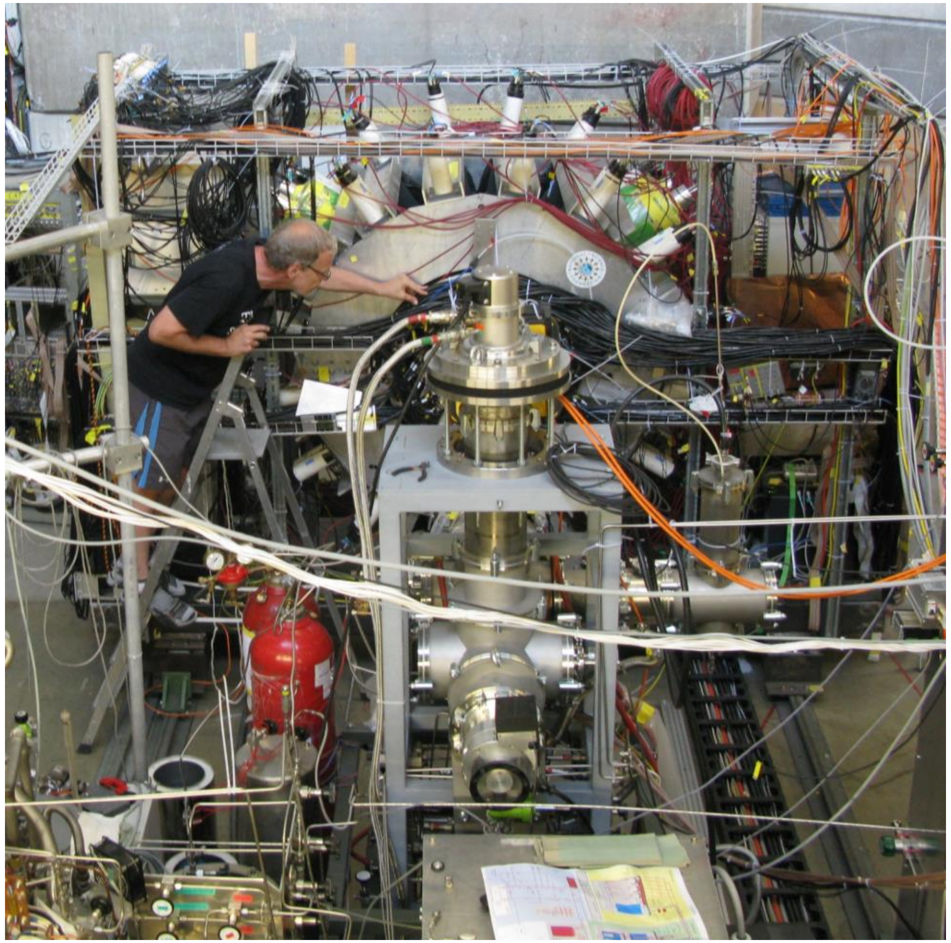
6% LH_2 density
31 K, 5 bar

- continuous circulation & cleaning
- ultra-pure D_2
- cyro preamplifier 250e rms @ 0.5 µs shaping
- v_D=0.5 cm/µs at 10 kV/cm

Experimental Setup at PSI, Switzerland



Measure the time of the decay electron t_e relative to the muon entrance t_μ and fit to extract the lifetime.



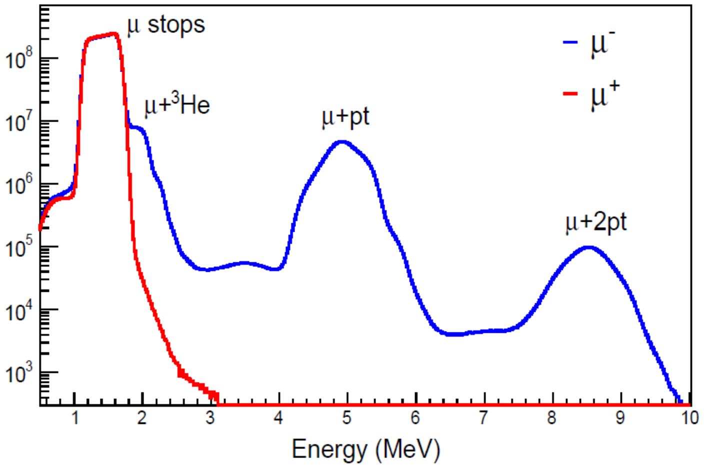
Detector and cyro / gas cleaning system

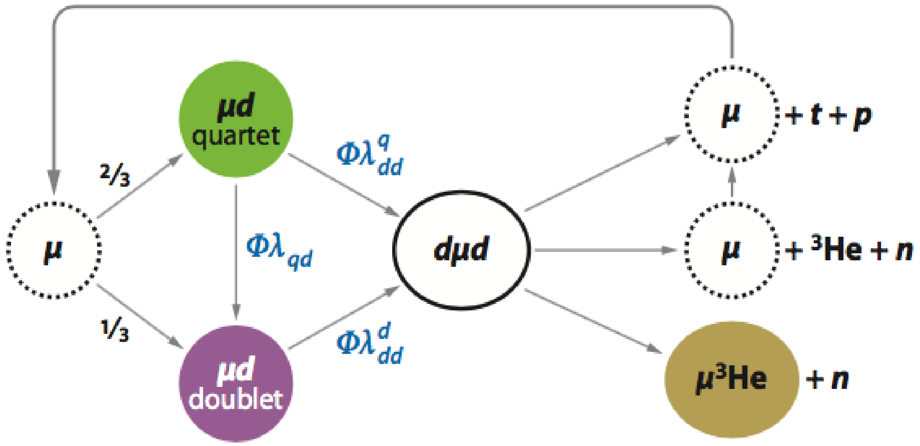
Expected Challenges

- Purity

$$\frac{\partial \Lambda_d}{\partial C_N} \approx 4Hz/ppb \qquad \text{(MuCap 0.5 Hz/ppb)}$$

- Muon-catalyzed fusion

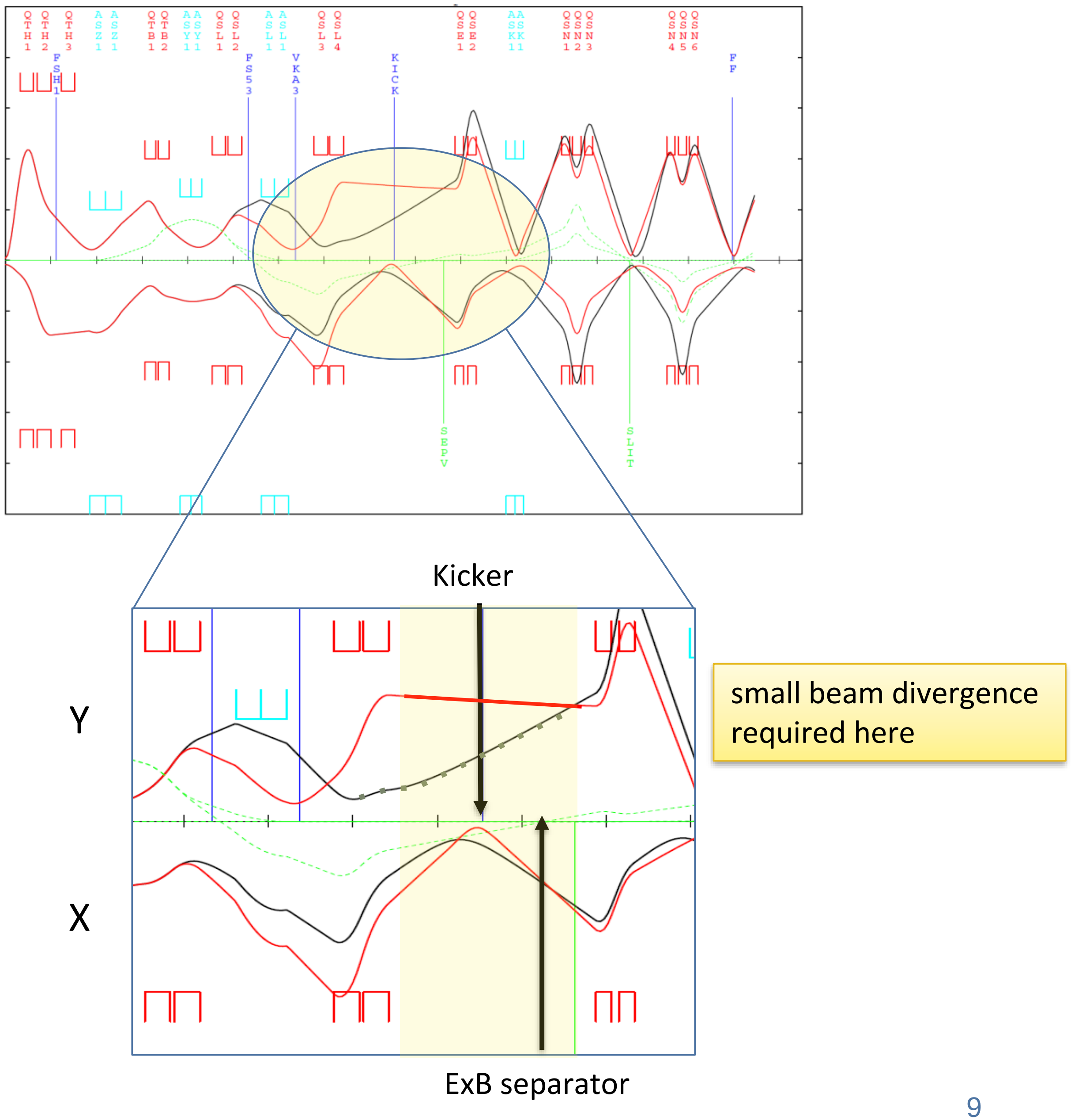




- Electron interference with muon signal
- Noise because of unamplified signals
- HV breakdown
- Clear interpretation
- and usual high precision lifetime requirements, a'la MuCap

Unnecessary Challenges

- Move to new beam area piE1
  - unfortunate error in PSI device data base discovered after production runs
  - significantly compromised performance of kicker (less μ suppression after trigger) separator (less electron suppression)



Lesson:
study beam scrupulously

Statistics and Systematics

$$\Lambda_d \approx 400 s^{-1}$$

- Statistics:
  - Data taking complete
  - 1.4 x 10^{10} events
  - goal: $\delta\Lambda_d = 4\ s^{-1}$

Data set	Statistics	Status
R2013		N2 calibration
R2014	6×10^9	production
R2015	8×10^9	production
R2016		N2 calibration, systematics run

- Systematics:
  - goal: $\delta\Lambda_d = 4\ s^{-1}$

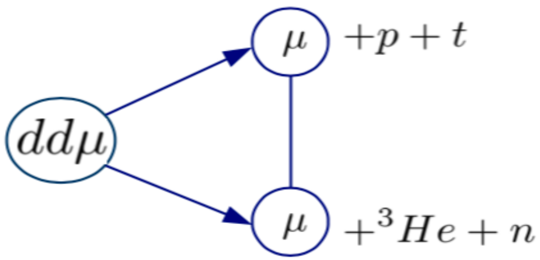
preliminary

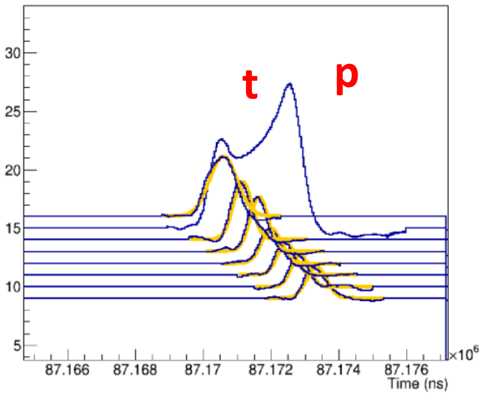
subtopic	effect	Λ_d (s^{-1}) shift (R2014/R2015)	Λ_d (s^{-1}) error
Beam	μ pileup	<1.5	0.5
	Kicker		0.25
	Accidentals	7.5/6	3
TPC	Fusion Interference	n/a	3
	First Row Energy Cuts	n/a	n/a
	Electron Interference		2
Purity	Isotopic	-0.8	0.5
	Chemical	-5.2/-4.1	1.2
	Wall Stops		1
Kinetics		small	n/a
total		1.5/1.1	5

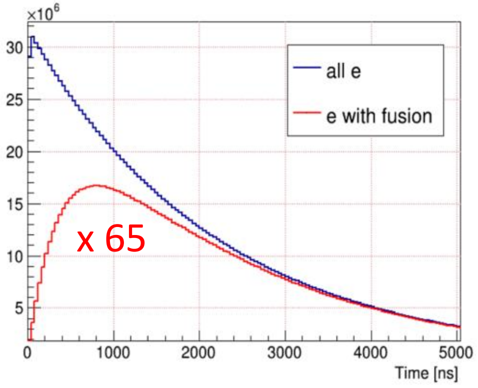
analysis during last 3 years with UW team, thanks to TACC Extreme Science and Engineering Discovery Environment (NSF)

Fusion Interference

- Decay electrons with fusion have different time distribution than pure μ-decay

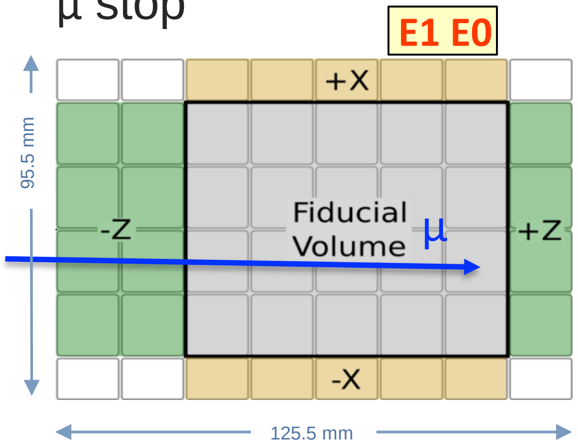




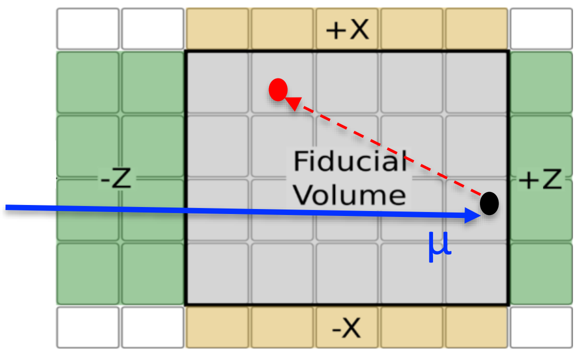


- Fusion induced mis-reconstruction leads to losses from fiducial volume
  - 1% efficiency difference between μ and μ+fusion event $\delta\Lambda_d$= 6 Hz

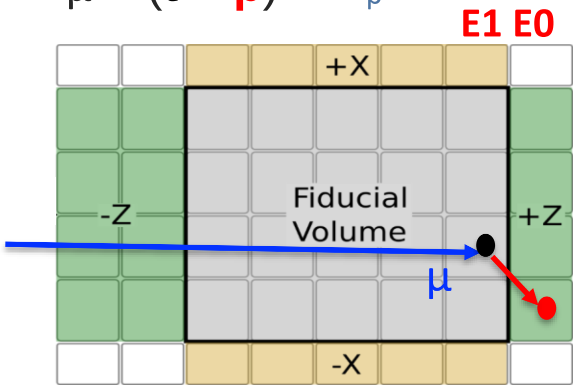
μ stop



μ + (^{3}He + n)



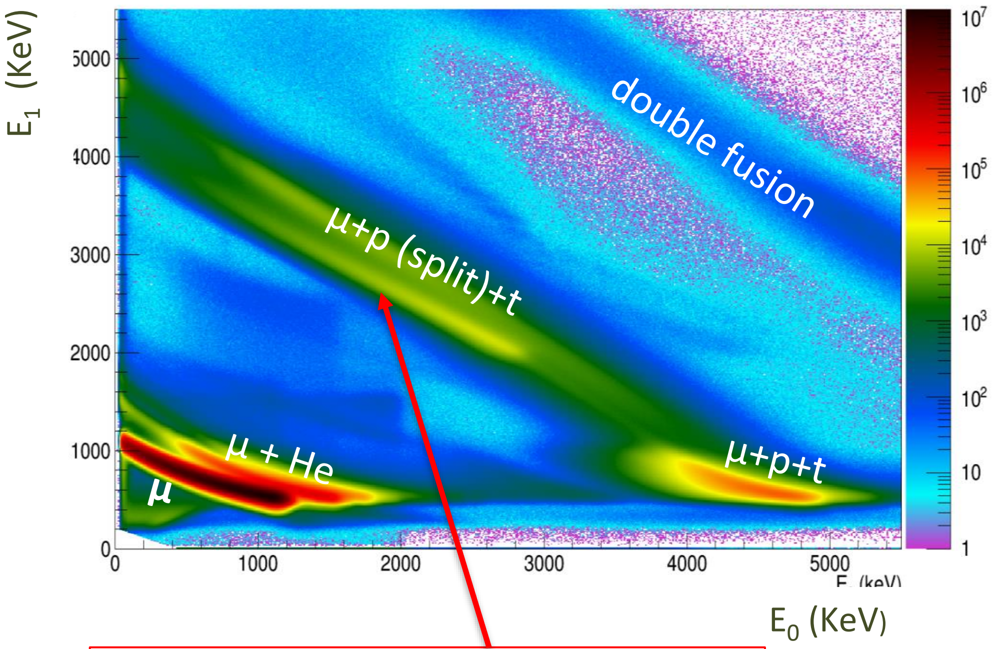
μ + (t + p) R_p=13mm



Trackers and μ stop selection

- μ and μ+(p+t) tracks slightly different topology
- minimize effect on tracking
  - with specialized tracking algorithms
  - TPC slow, but excellent energy resolution

E1-E0 last two rows of μ track   5 10^9 events



advanced tracker uses E1-E0 to discern forward-backward protons

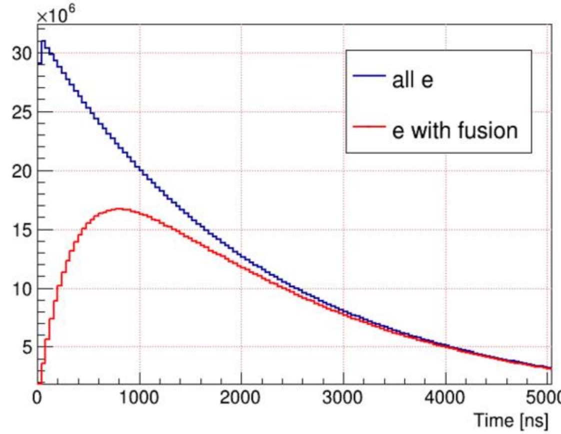
- quantify correction to λ_- with two methods

Measure fusion/muon ratio in fiducial volume

should be constant if no p-t induced boundary crossings

Deviation of time distribution from pure exponential before 1 μs

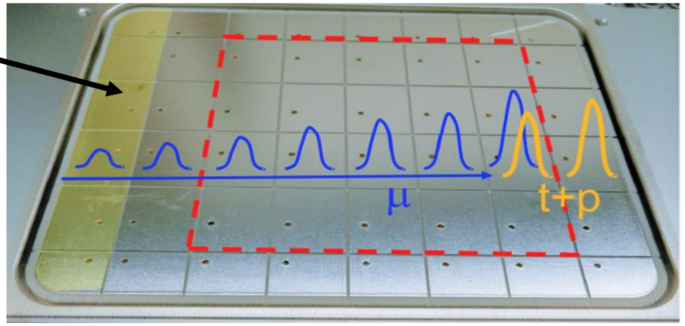
where fits starts



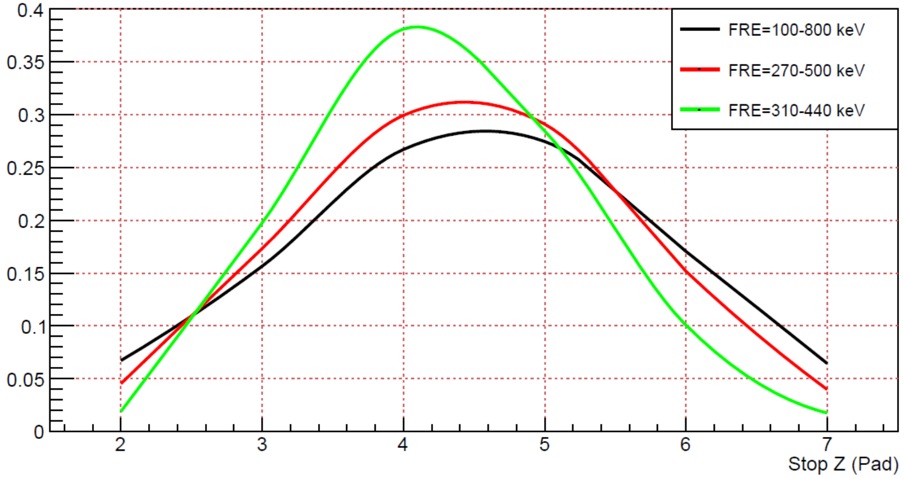
Valuable lessons for PIONEER

Use first TPC row to shape μ-stop distribution

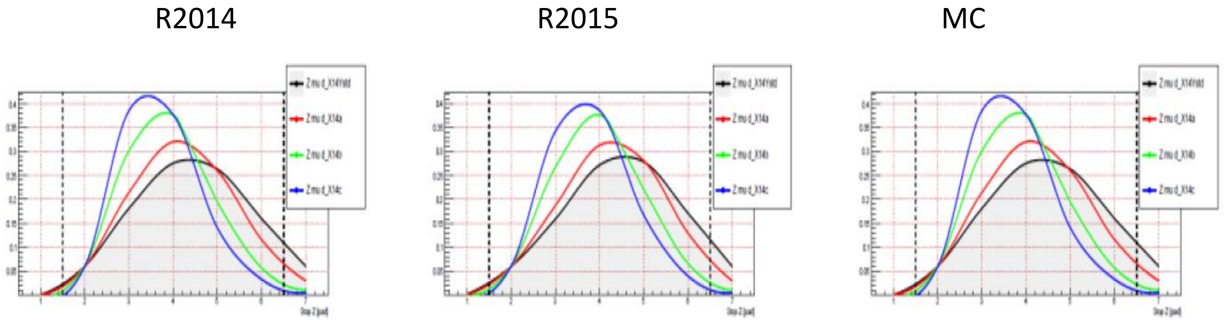
- For μ stop in fiducial volume proton cannot reach first row
  - unbiased ? shaping of muon stopping distribution in X, Y, Z (via dE/dx)
  - Powerful tool to shape and shift longitudinal stopping distribution



narrow the z-distribution



shift the z-distribution through TPC



z-distributions with different first row dE/dx cuts

- Unfortunately, dE/dx cut introduces subtle bias between fusion/no-fusion events

Determine Gas Purity at ppb Level

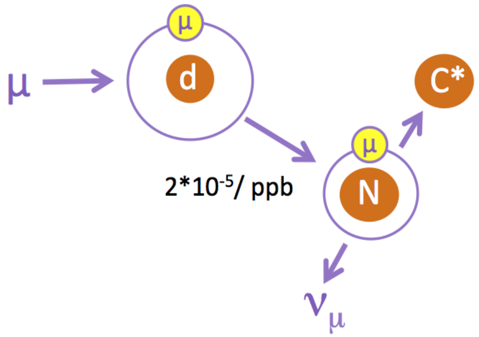
- gas chromatography

$$C_N = 1.03\ ^{+0.24}_{-0.40}\ \text{ppb}$$

R2015

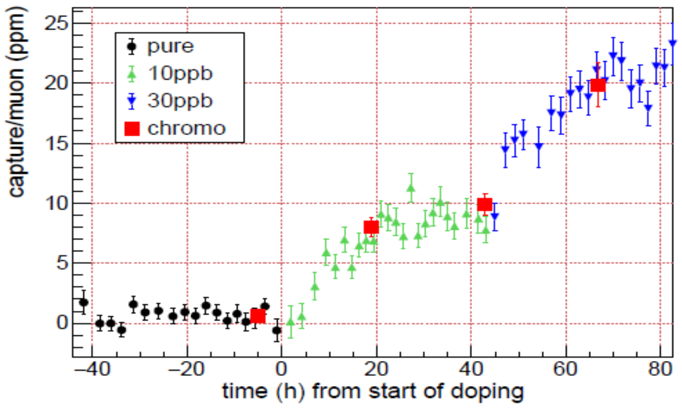
Ganzha et al NIM A 880, 181 (2018)

- in-situ

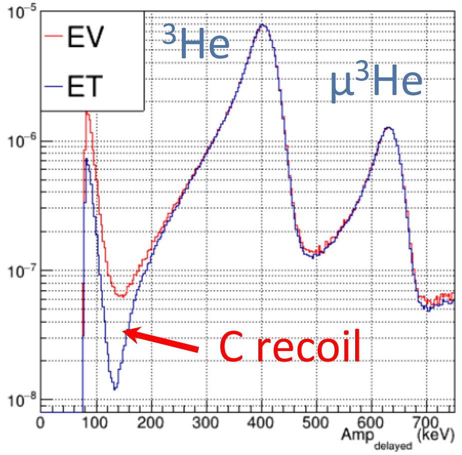


TPC excellent neutron detector

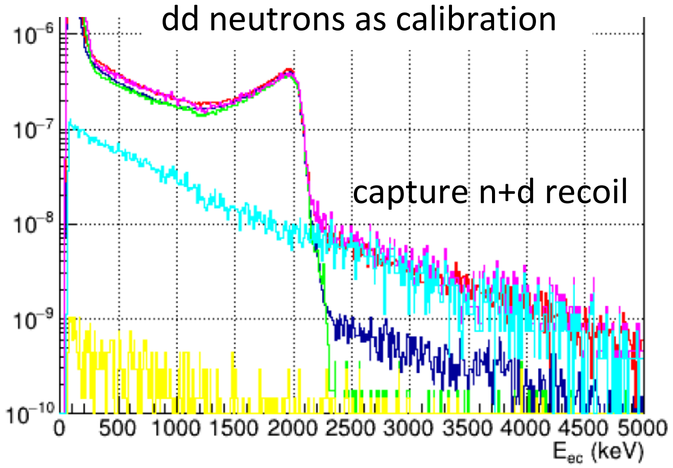
calibration with N_2 doping



capture signal in data



n+d scattering in TPC, data vs. MC



- results
  prelim.

run	C_{N2} (ppb)	C_{N2} corr (ppb)
R2014	1.8(3)	1.3(3)
R2015	1.6(2)	1.0(3)

$$\frac{\partial \Lambda_d}{\partial C_N} \approx 4Hz/ppb$$

$\Delta\lambda$_≈ 4.6 ± 1.2 s^{-1}

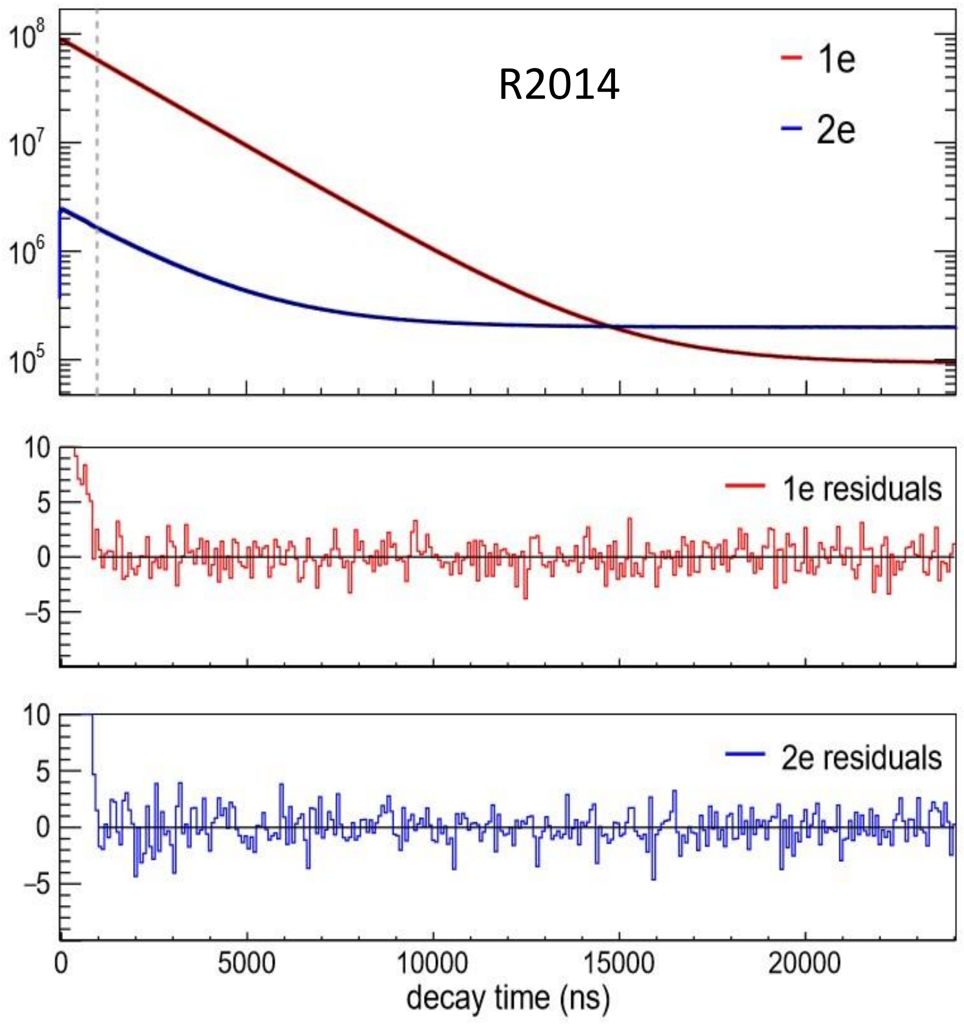
Time dependence of accidentals

- Electron selections enhance
  - 1e: signal
  - 2e: acc. BG
  - fitted λ_- differ

- Additional evidence points to small $10^{-4}/\mu s$ decrease of BG
  likely due to poor beam kick

- combined fit of 1e/2e determines corrections (prelim.)

	$\Delta\lambda\_$
R2014	$7.5 \pm 3\ s^{-1}$
R2015	$6 \pm 3\ s^{-1}$



MuSun Status

- Uncertainty budget quantified within design goals, with the exception of
  - Fusion systematics
    - Defining fiducial volume with Z cut is robust and consistent between methods
      main approach for final analysis
    - dE/dx cut to sharpen muon stop distribution introduces subtle systematics
      continue to study this puzzle
  - First physics publication with R2014 data, unblinding this year

first precise measurement of weak process in 2N system
clarify 3+ σ discrepancy most precise experiment vs theory

  - Long paper about novel experimental method and analysis
  - Final analysis of all data

capture rate to with 1-2% uncertainty commensurate with precision of theory
clean determination of basic low energy constant
still surprises in 2N weak coupling ?

Thanks

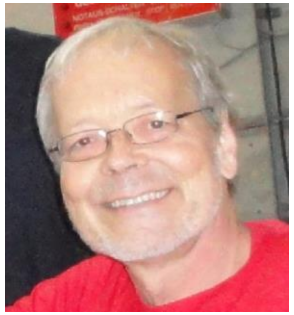
MuSun Collaboration

Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
Paul Scherrer Institute (PSI), Villigen, Switzerland
University of Washington, Seattle, USA
University of Kentucky, Lexington, USA
Boston University, USA
Regis University, Denver, USA
University of South Carolina, USA

Funding agencies

The UW work was supported by the U.S. Department of Energy Office of Science, Office of Nuclear Physics under Award Number DE-FG02-97ER41020. Collaboration funding includes support by the US National Science Foundation and the Russian Science Foundation (Project No. 14-12-01056). This work used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1548562.

UW/Cenpa team



Ethan Muldoon

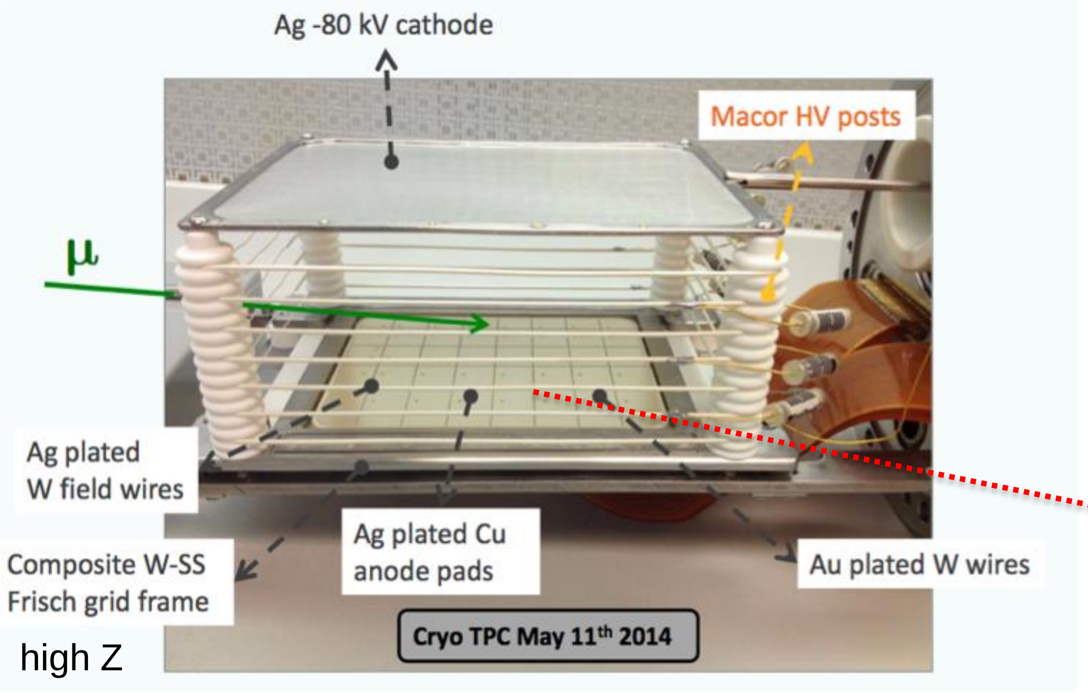
Supplement

MuSun Cryo-TPC

R A Ryan *et al* 2014 *JINST* **9** P07029

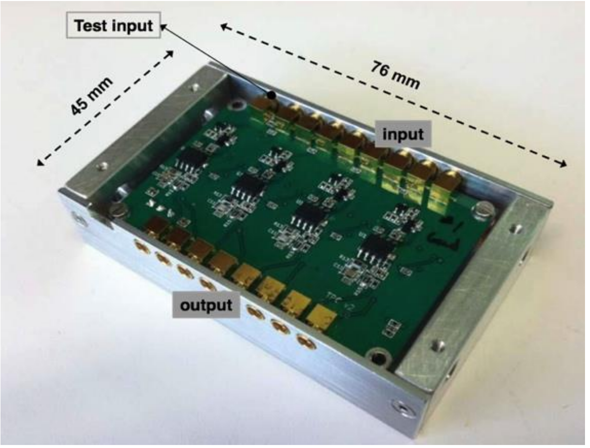
novel device:

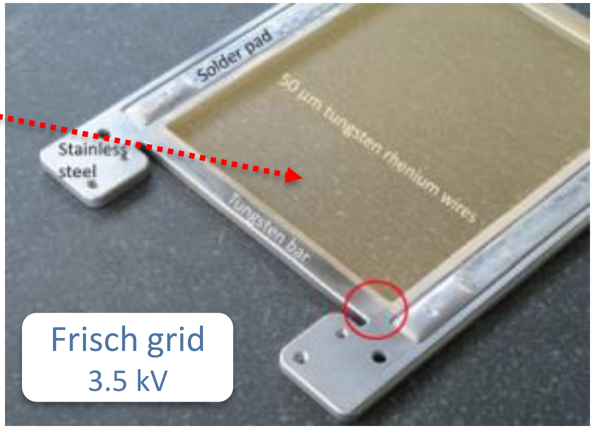
- high purity D_2, 6.5% LHD
- high pressure 5.1 bar = 55 bar @
- cryogenic deuterium TPC @ 31K



UW/PNPI   9.6 x 7.1 x 12.5 cm^3

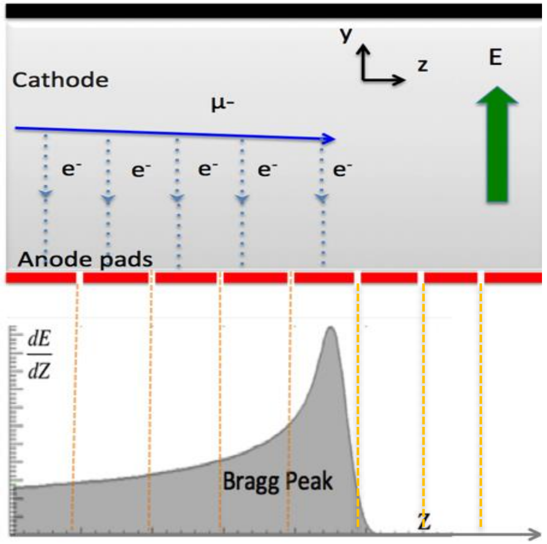
- Cryo preamps
  - 140K
  - 250e rms @ 0.5ms shaping
  - excellent resolution 17 keV

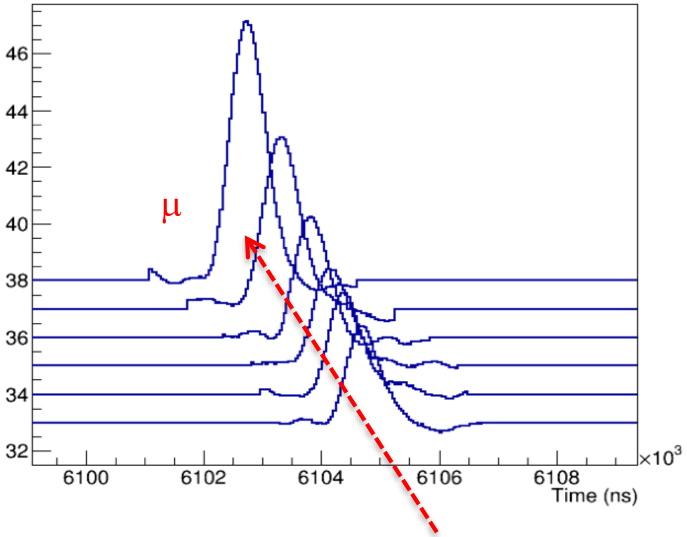


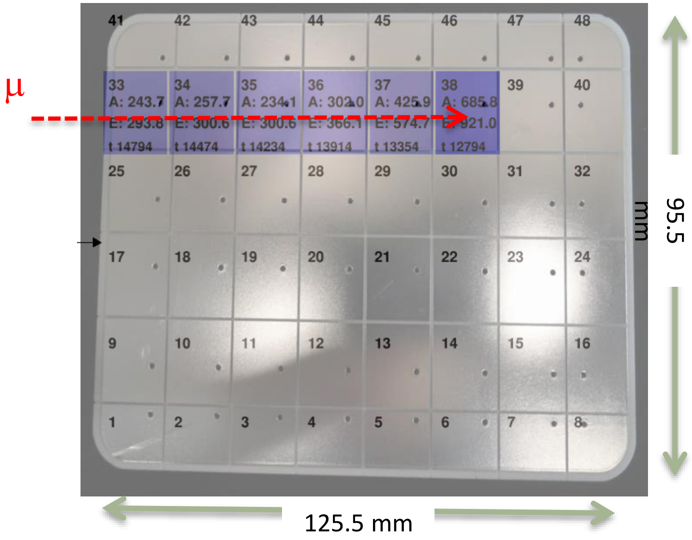


MuSun TPC Performance

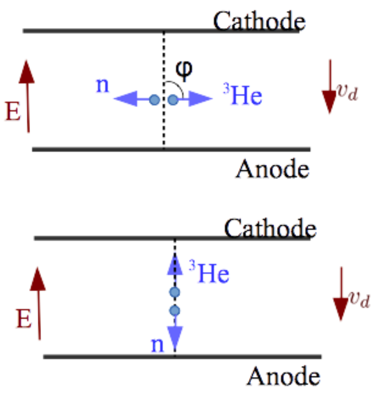
- Events

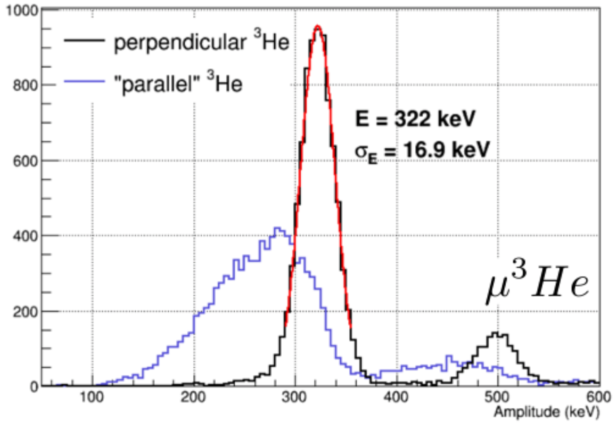






- Recombination
  - for dE/dx > dE/dx_{MIPS}
  - angle dependence





$$dd\mu \to {}^3He(820\ \text{keV}) + n(2.5\ \text{MeV}) + \mu$$

Related Publications

- **MuSun** in Particle Physics at PSI

SciPost Phys. Proc. 5, 018 (2021)

MuSun - Muon Capture on the Deuteron

P. Kammel[1*] on behalf of the MuSun collaboration[1]

1 Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA 98195, USA

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PAUL SCHERRER INSTITUT

Review of Particle Physics at PSI
doi:10.21468/SciPostPhysProc.5

- **Fusion** in Physics of Particles and Nuclei Letters

accepted

arXiv.org > nucl-ex > arXiv:2001.09927

Nuclear Experiment

[Submitted on 27 Jan 2020 (v1), last revised 17 Jun 2021 (this version, v3)]

Search for muon catalyzed d^3He fusion

V.D. Fotev (1), V.A. Ganzha (1), K. A. Ivshin (1), P.V. Kravchenko (1), P.A. Kravtsov (1), E.M.Maev (1), A.V. Nadtochy (1), A.N. Solovev (1), I.N. Solovyev (1), A.A. Vasilyev (1), A.A.Vorobyov (1), N.I. Voropaev (1), M.E. Vznuzdaev (1), P. Kammel (2), E.T. Muldoon (2), R.A. Ryan (2), D.J. Salvat (2), D. Prindle (2), M. Hildebrandt (3), B. Lauss (3), C. Petitjean (3), T. Gorringe (4), R.M. Carey (5), F.E. Gray (6) ((1) Petersburg Nuclear Physics Institute, Gatchina, Russia, (2) University of Washington, Seattle, WA, USA, (3) Paul Scherrer Institute, Villigen PSI, Switzerland, (4) University of Kentucky, Lexington, KY, USA, (5) Boston University, Boston, MA, USA, (6) Regis University, Denver, CO, USA)

- **AlCap** in Phys. Rev. C, accepted (see suppl. slides)

A Measurement of Proton, Deuteron, Triton and Alpha Particle Emission after Nuclear Muon Capture on Al, Si and Ti with the AlCap Experiment

Kammel co-spokes

  - muon capture topic relevant to nuclear and particle physics (nuclear structure, **charged lepton flavor violation**)
  - data taking completed before present grant

- **MuCap and ν scattering** in Rep. Prog. Phys.

IOP Publishing — Reports on Progress in Physics

Rep. Prog. Phys. 81 (2018) 096301 (23pp) https://doi.org/10.1088/1361-6633/aac190

Review

Nucleon axial radius and muonic hydrogen—a new analysis and review

Richard J Hill[1,2,3], Peter Kammel[4], William J Marciano[5] and Alberto Sirlin[6]

r_A determination from MuCap
impact on Mup, Mud and νA

MuMu2019 Workshop @ PSI

Exploring synergies between Muon Capture and Neutrino Scattering

Physics of fundamental Symmetries and Interactions – PSI2019

Kammel co-organizer

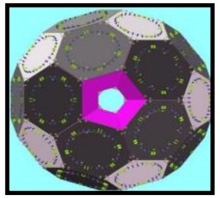
Precision Muon Group at CENPA/UW

Past

Present

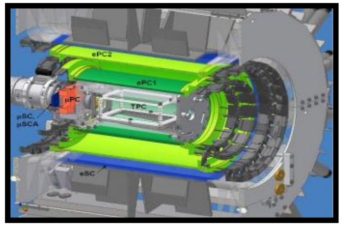
Future

- MuLan, MuCap

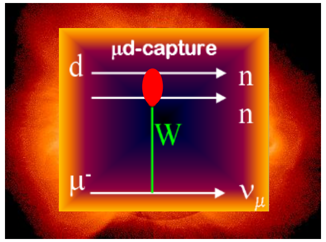


Fermi Constant

QCD Symmetries



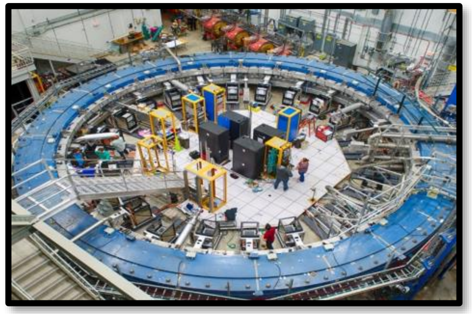
- MuSun



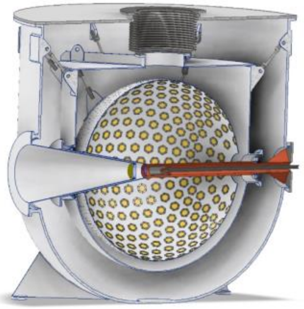
QCD coupling
"Calibrating the Sun"

- Muon g-2

New Physics?



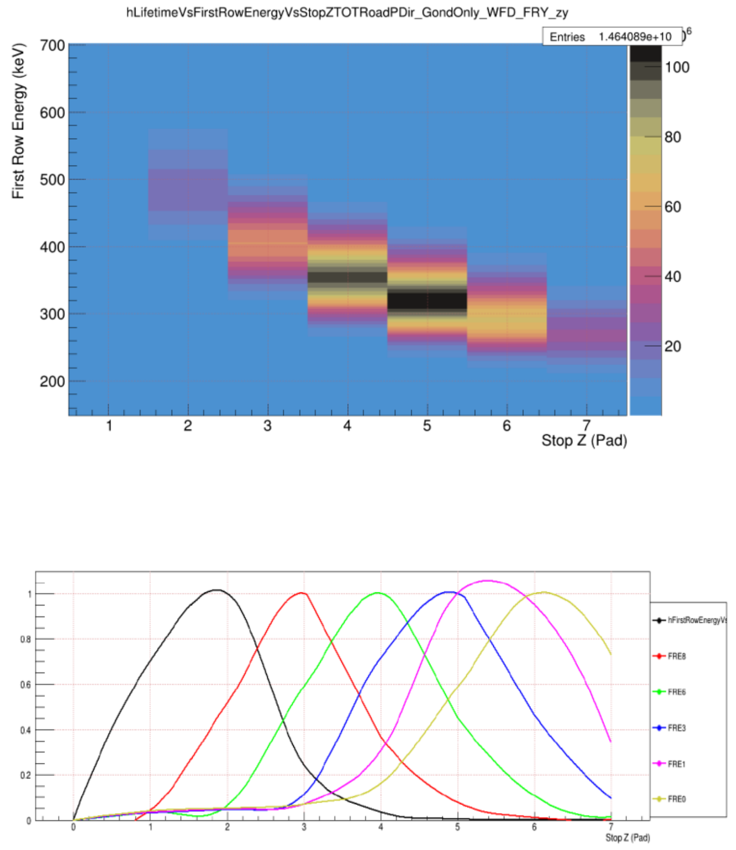
- PIONEER



Lepton Flavor Universality
and CKM Unitarity

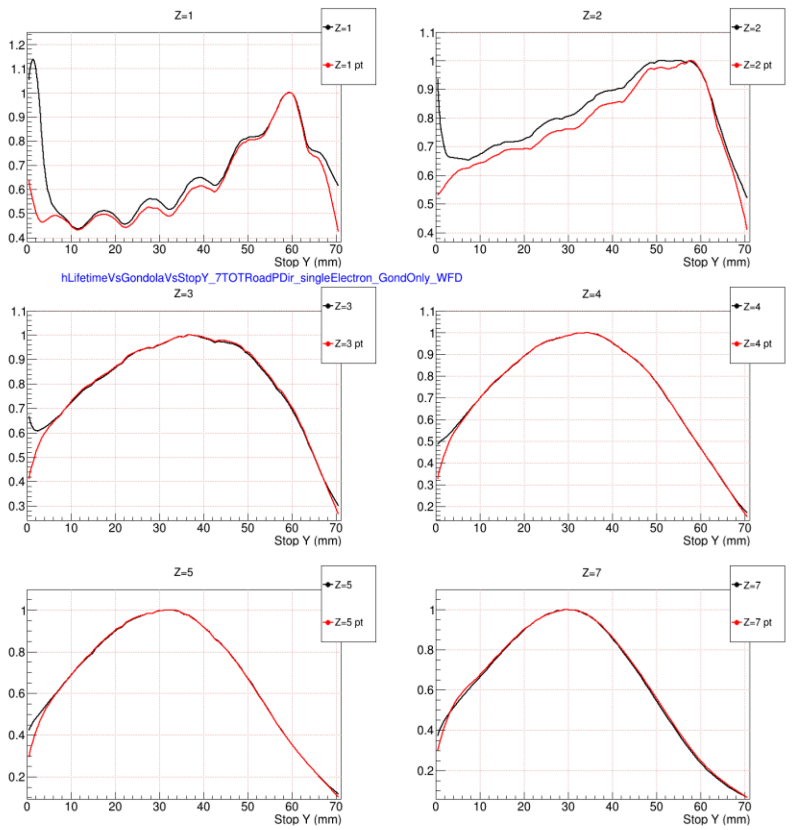
FRE Puzzle: fusion/μ ratio is Y dependent

FRE vs. Z

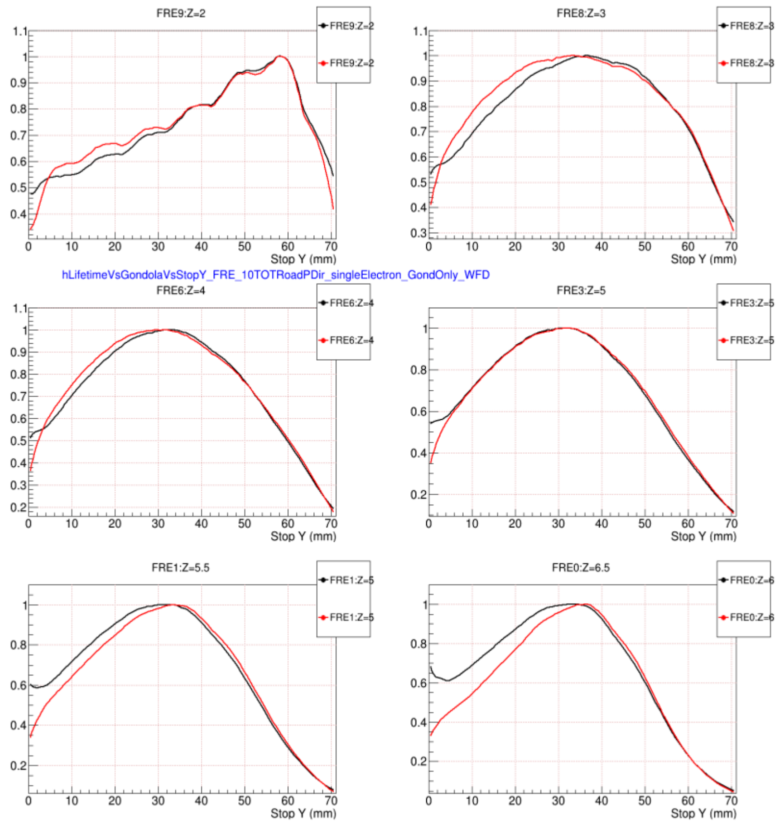


fusion/μ Y dependence

for Z slices



for FRE slices



pp and MuSun

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Effective-field-theory predictions of the muon-deuteron capture rate

Bijaya Acharya,[1,2,*] Andreas Ekström,[3,†] and Lucas Platter[2,4,‡]