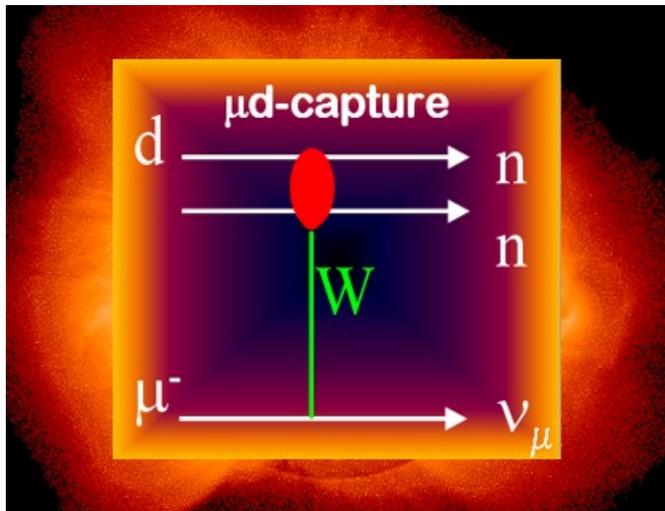


# MuSun – Muon Capture on the Deuteron

## An Update

Peter Kammel

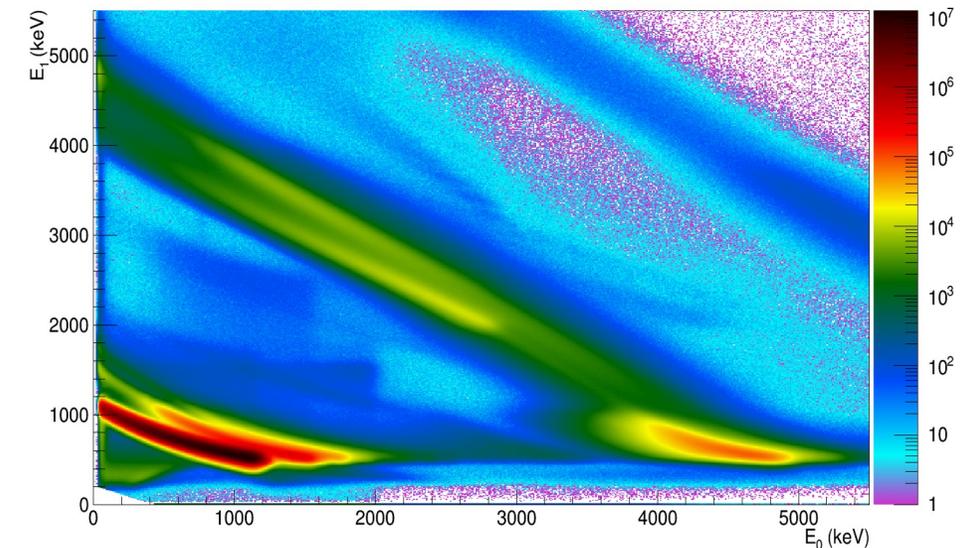
### Motivation



### Technique



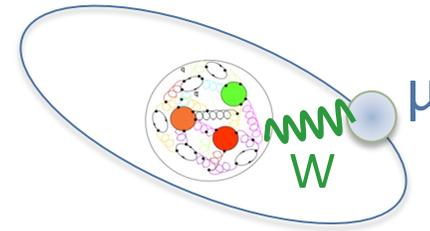
### Analysis



# MuSun: Goals/Motivation

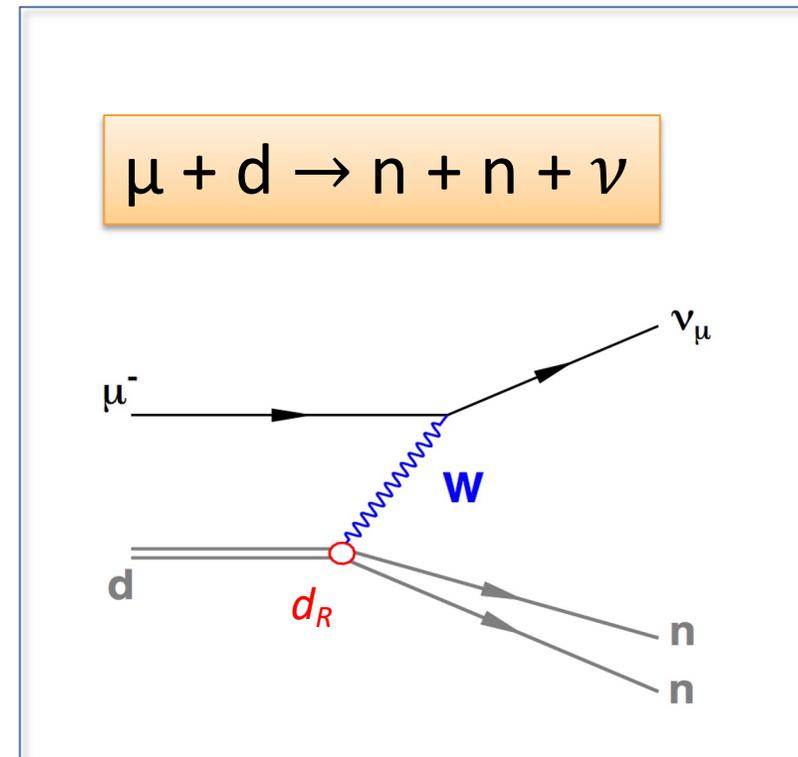
- Muon capture goal:
  - muon probes nucleon and nuclei with charge-current weak interaction
  
- MuSun specific goal:
  - Measure muon capture rate  $\Lambda_d$  on the deuteron to 1.5%
  - first precise measurement of weak process in 2N system
  - determine axial coupling to 2N system, important and poorly known low energy constant (LEC) in EFT

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



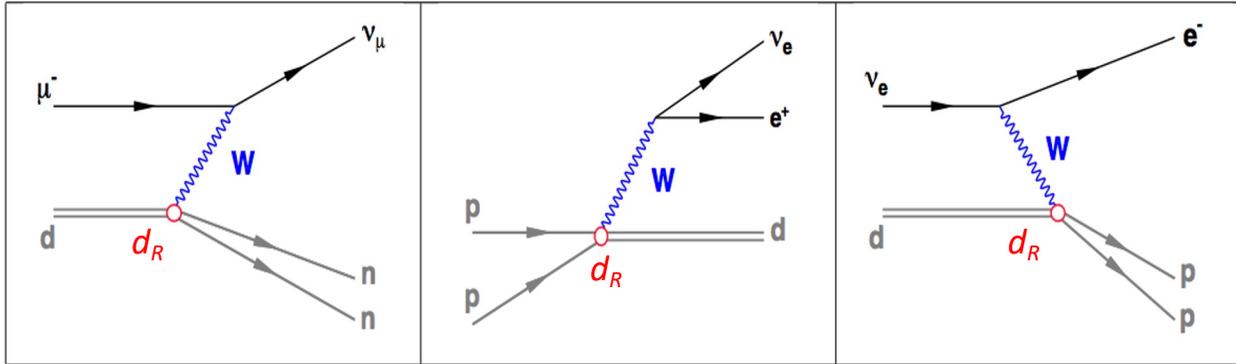
$$a_0 = \frac{1}{m_r \alpha}$$

$$q \approx 100 \text{ MeV}/c$$



# Relevance

- calibrate fundamental astrophysics reactions

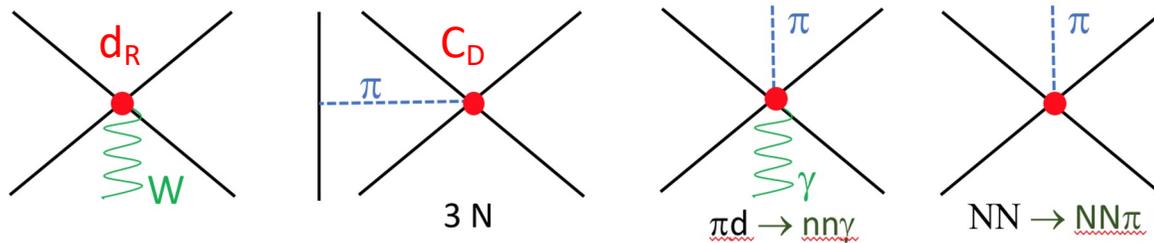


Family of weak 2N reactions

pp fusion (Sun)  
 vd scattering (SNO) \*)

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

- important for EFT formulation of nuclear physics

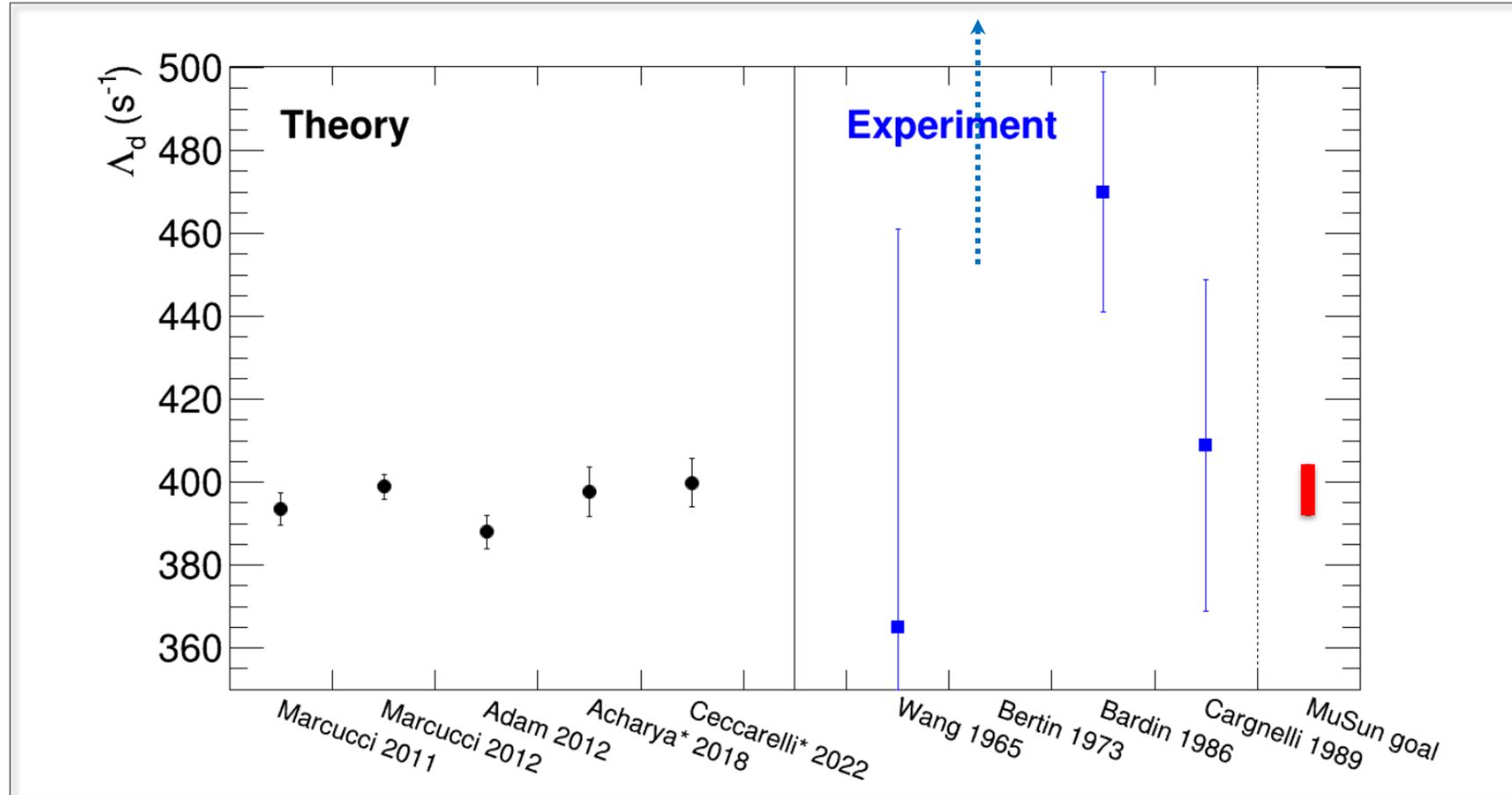


Gazit et al. 2009,2018  
 King et al. 2021

- relevant for a variety of weak and strong dynamics

\*) D<sub>2</sub>O normalization detector Coherent

# Determine Basic LEC in $\mu d$ Capture ?



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

$$\Lambda_d(^1S_0) = 252.8 (1.8)_{NN} (4.6)_{EFT\ conv} (3.9)_{r_A} s^{-1} \quad \text{Acharya 2018}$$

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

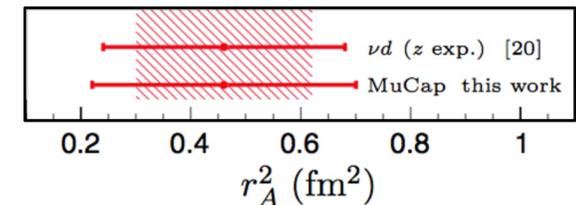
Rep. Prog. Phys. 81 (2018) 096301 (23pp)

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

Richard J Hill<sup>1,2,3</sup>, Peter Kammel<sup>4</sup>, William J Marciano<sup>5</sup> and Alberto Sirlin<sup>6</sup>

Peter Kammel – MuSun – PSI2022

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



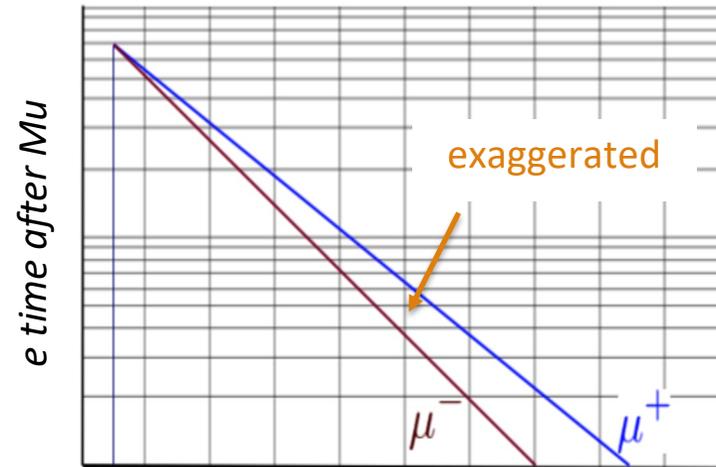
# Technical Overview

- **Precision technique**
- Clear Interpretation
- Clean stops in D<sub>2</sub>
- 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 !

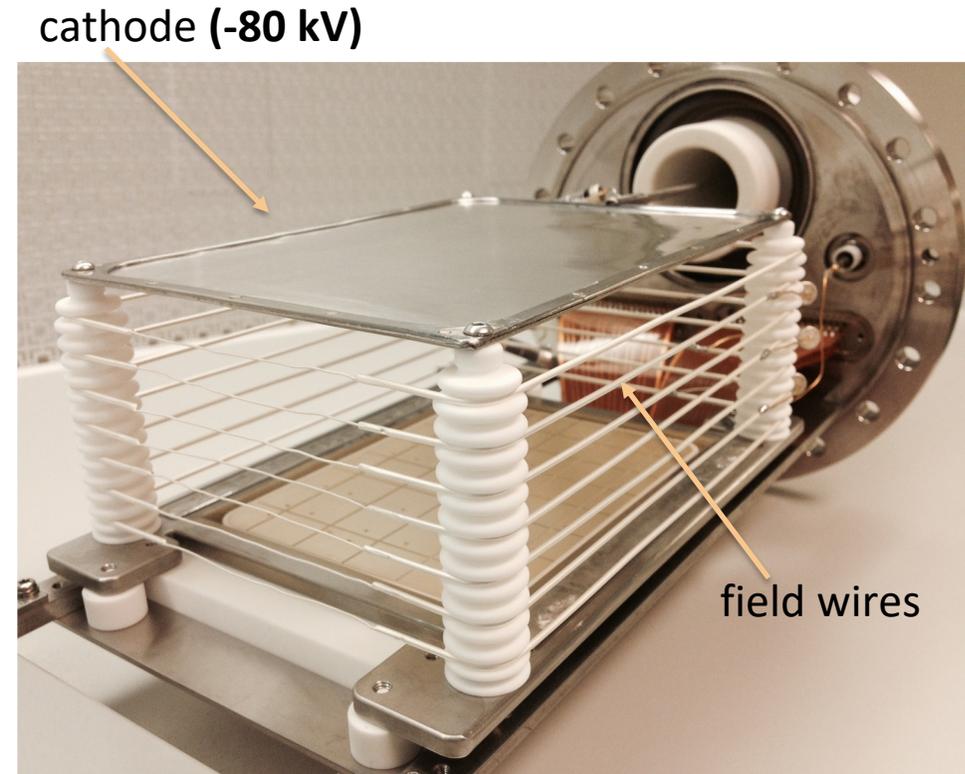
# Novel Cryo-TPC

- Clear Interpretation
- Precision technique
- **Clean stops in D<sub>2</sub>**
- Impurities < 1ppb
- H/D < 100 ppm

novel device:

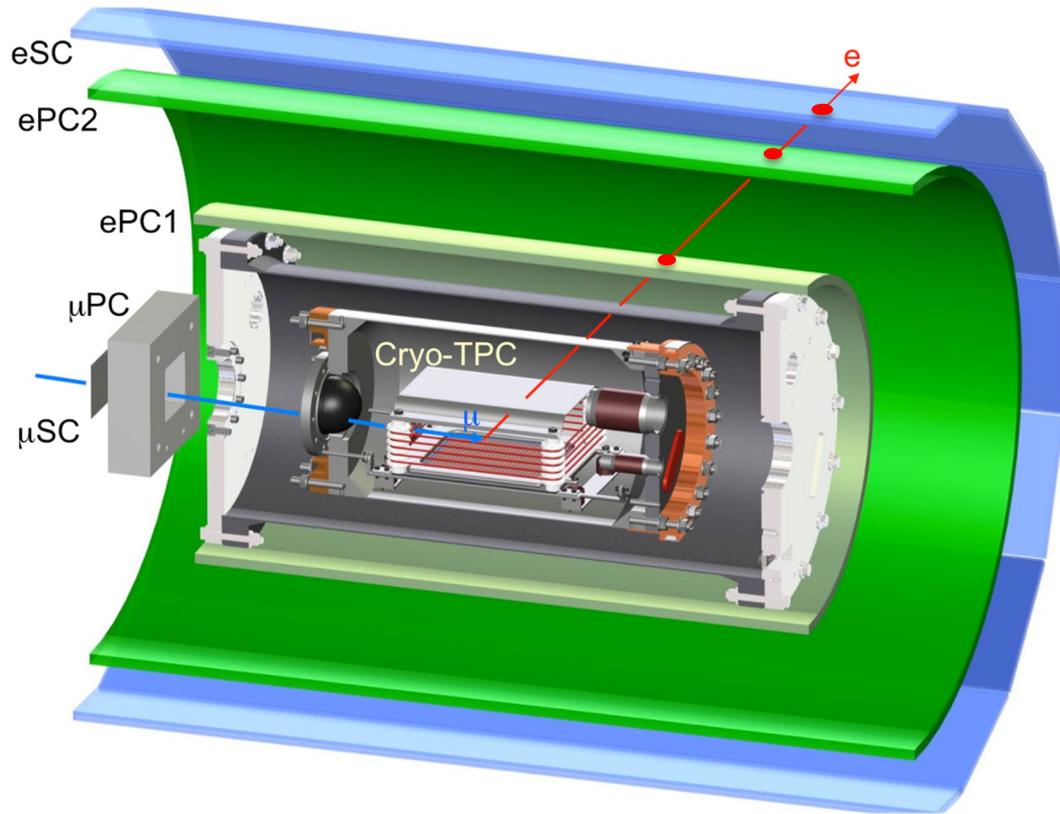
- high purity,
- high-pressure,
- cryogenic deuterium TPC

MuCap/MuSun pioneered this technique

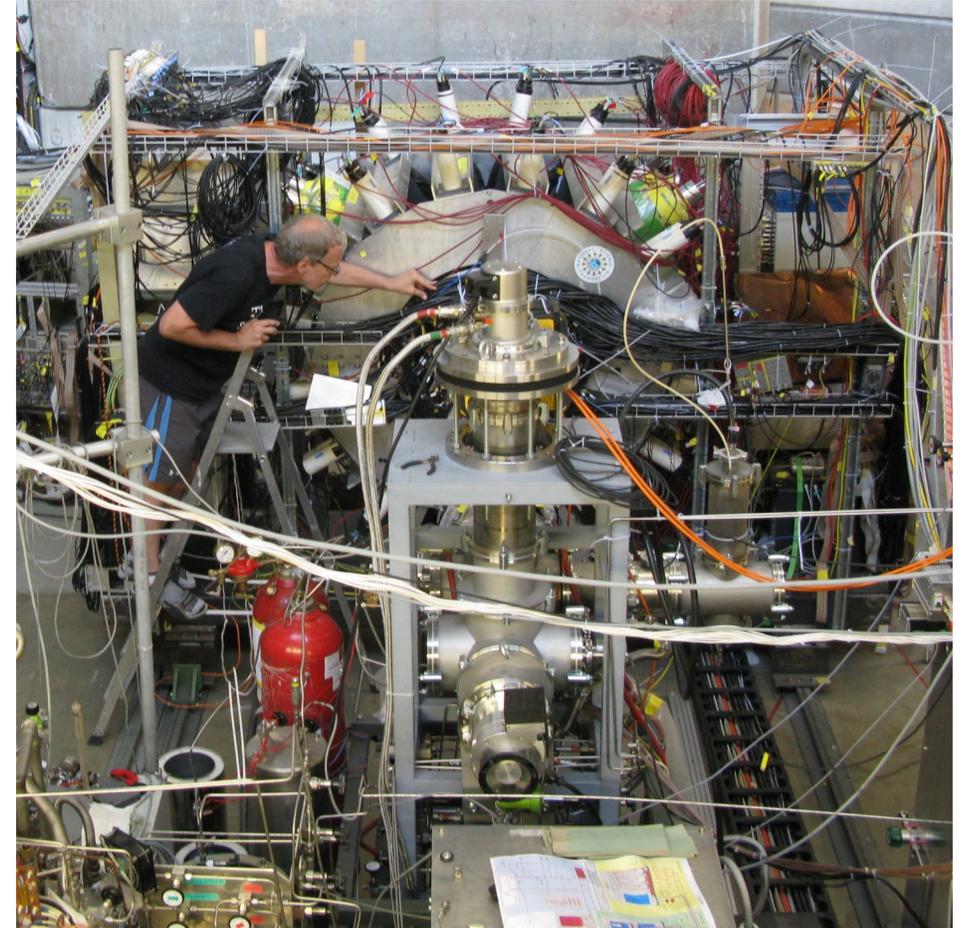


- 90x120x72 mm<sup>3</sup>
- 6% LH<sub>2</sub> density
- anode 48 pads
- 31 K, 5 bar
- continuous circulation & cleaning
- ultra-pure D<sub>2</sub>
- cyro preamplifier 250e rms @ 0.5 μs shaping
- v<sub>D</sub>=0.5 cm/μs at 10 kV/cm

# Experimental Setup at PSI, Switzerland



Measure the time of the decay electron  $t_e$  relative to the muon entrance  $t_\mu$  and fit to extract the lifetime.



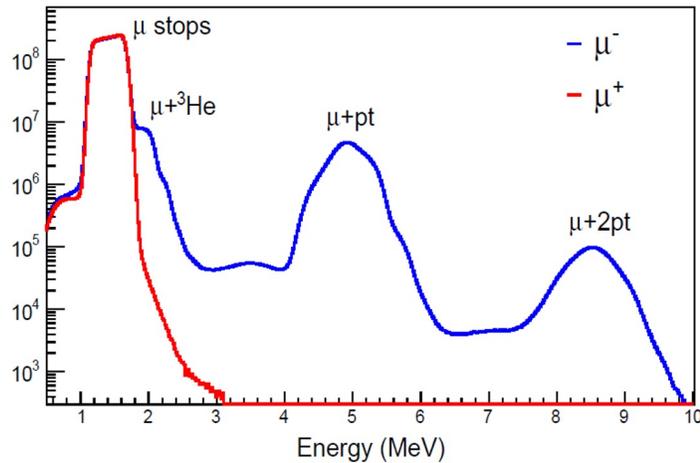
Detector and cryo / gas cleaning system

# Expected Challenges

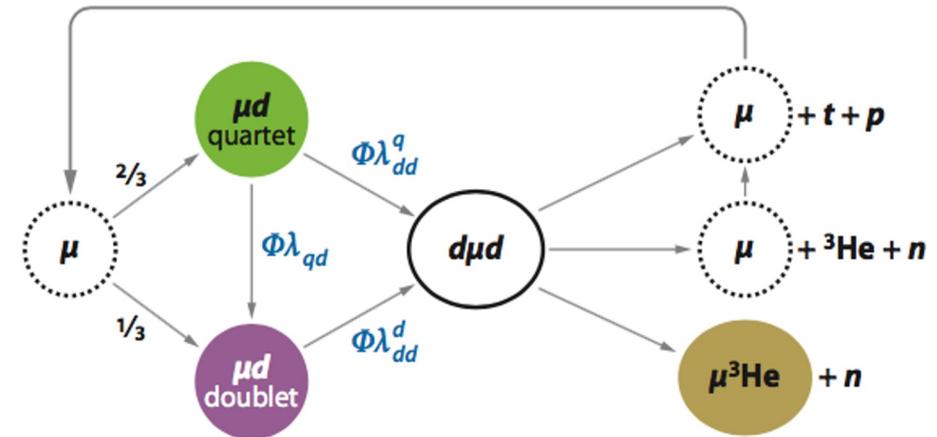
- Purity

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

- Muon-catalyzed fusion



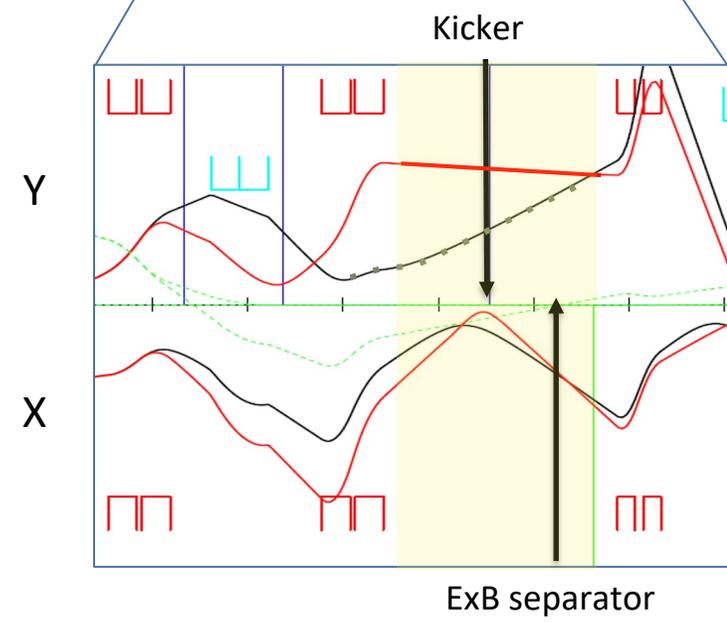
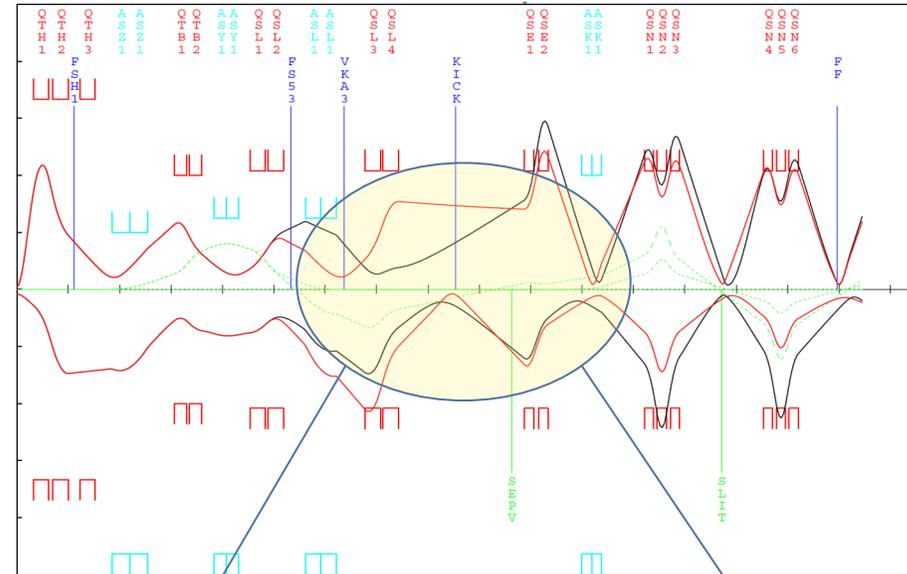
- Electron interference with muon signal
- Noise because of unamplified signals
- HV breakdown
- Clear interpretation
- and usual high precision lifetime requirements, a'la MuCap



# 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  $\mu$  suppression after trigger) separator (less electron suppression)

Lesson:  
study beam scrupulously



# Statistics and Systematics

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

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

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

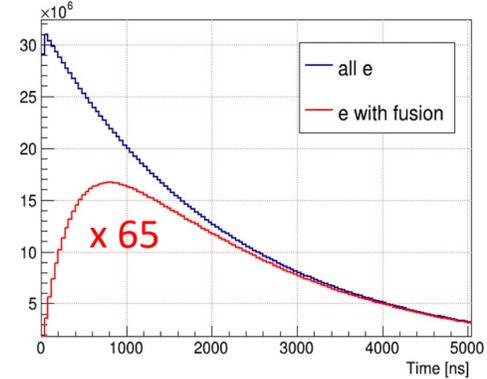
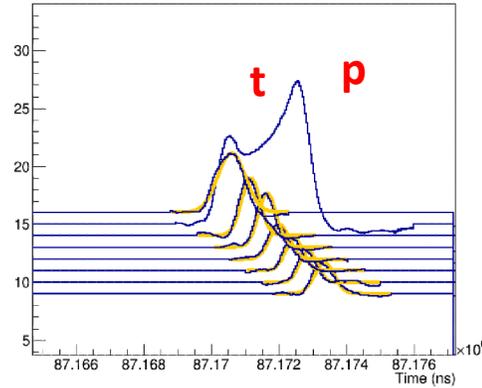
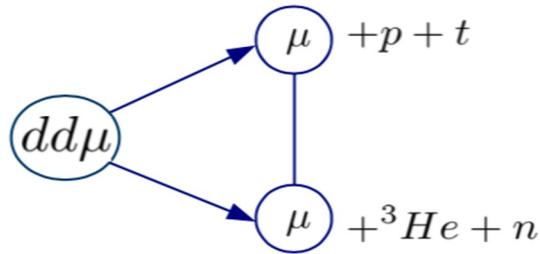
Data set	Statistics	Status
R2013		N2 calibration
R2014	$6 \times 10^9$	production
R2015	$8 \times 10^9$	production
R2016		N2 calibration, systematics run

subtopic	effect	$\Lambda_d (s^{-1})$	
		shift (R2014/R2015)	error
Beam	$\mu$ 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

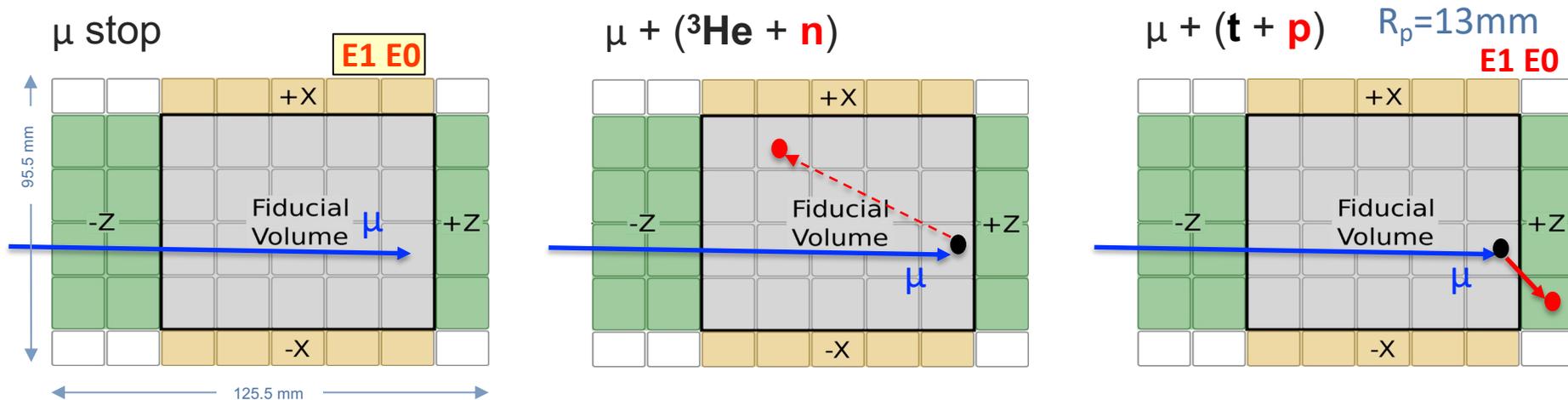
preliminary

# Fusion Interference

- Decay electrons **with fusion** have different time distribution than pure  $\mu$ -decay



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



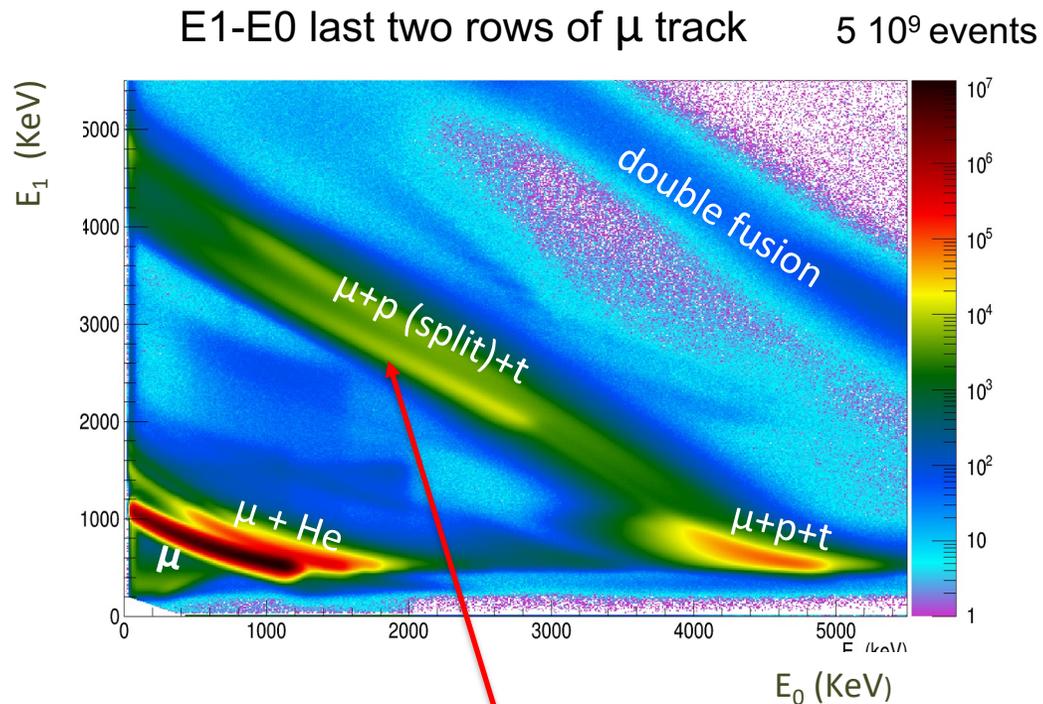
# Trackers and $\mu$ stop selection

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

- quantify correction to  $\lambda$  with two methods

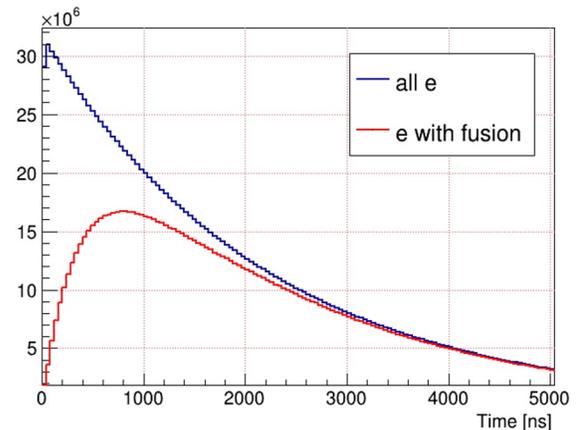
Measure fusion/muon ratio in fiducial volume  
should be constant if no p-t induced boundary crossings

Deviation of time distribution from pure exponential before 1  $\mu$ s  
where fits starts



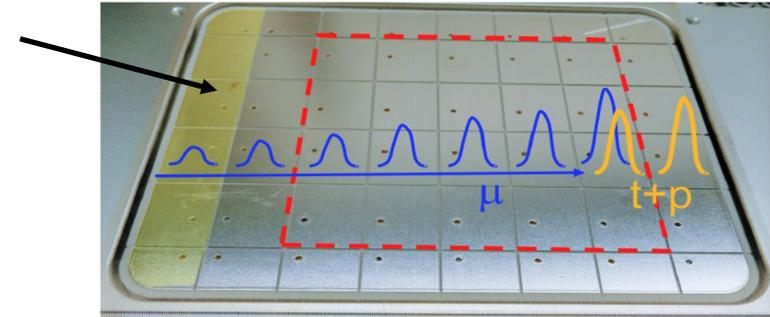
advanced tracker uses E1-E0 to discern forward-backward protons

Valuable lessons for PIONEER

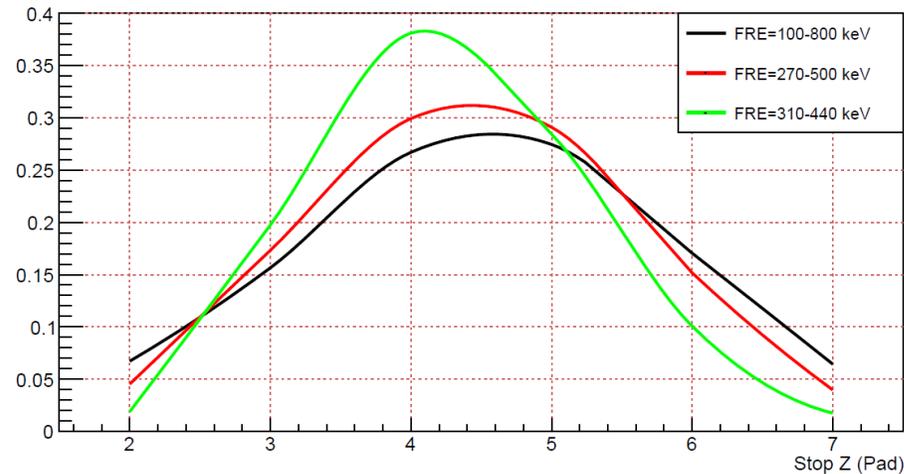


# Use first TPC row to shape $\mu$ -stop distribution

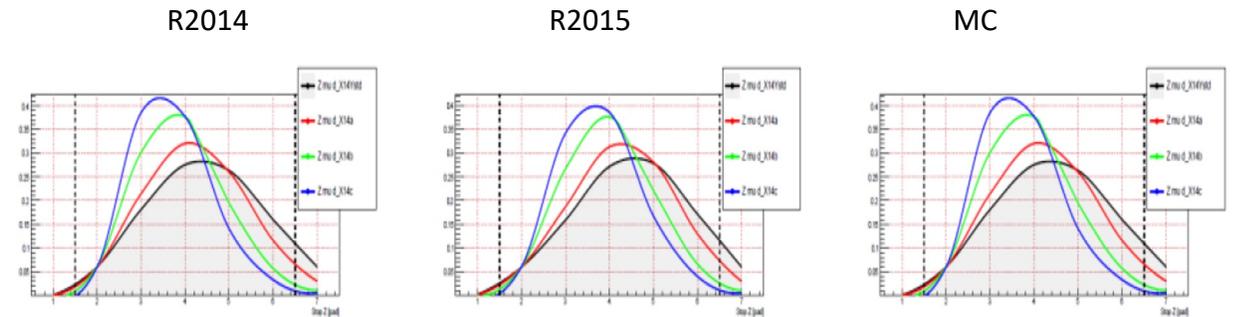
- For  $\mu$  stop in fiducial volume proton cannot reach first row
  - **unbiased** ? shaping of muon stopping distribution in X, Y, Z (via  $dE/dx$ )
  - Powerful tool to shape and shift longitudinal stopping distribution



narrow the z-distribution



shift the z-distribution through TPC



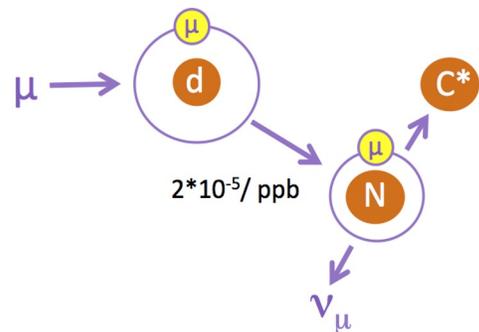
z-distributions with different first row  $dE/dx$  cuts

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

# Determine Gas Purity at ppb Level

– gas chromatography

– in-situ



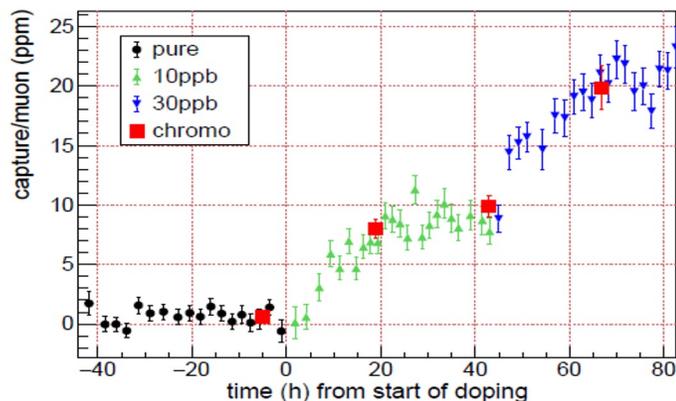
$$C_N = 1.03^{+0.24}_{-0.40} \text{ ppb}$$

R2015

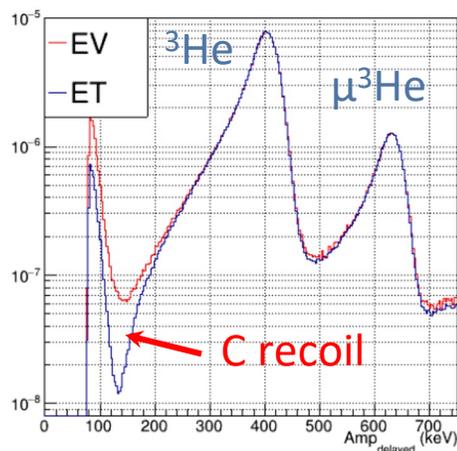
Ganzha et al NIM A 880, 181 (2018)

TPC excellent  
neutron detector

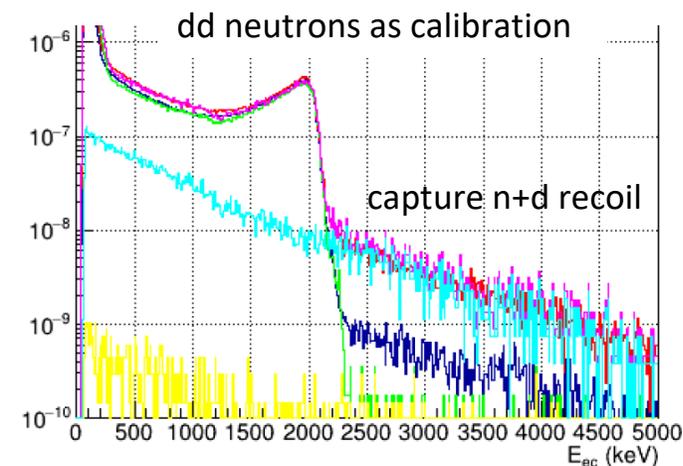
calibration with  $N_2$  doping



capture signal in data



n+d scattering in TPC, data vs. MC



– results  
prelim.

run	$C_{N_2}$ (ppb)	$C_{N_2}$ corr (ppb)
R2014	1.8(3)	1.3(3)
R2015	1.6(2)	1.0(3)

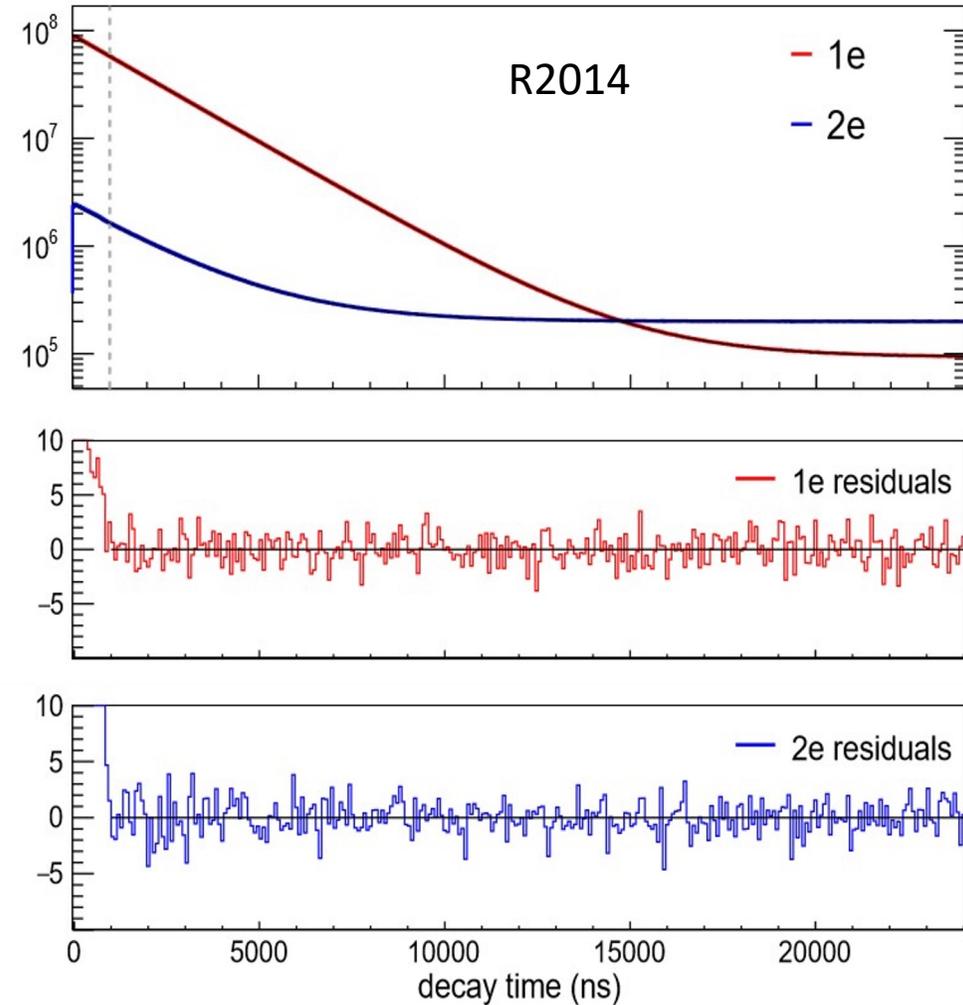
$$\frac{\partial \Lambda_d}{\partial C_N} \approx 4Hz / \text{ppb}$$

$$\Delta \lambda_{-} \approx 4.6 \pm 1.2 \text{ s}^{-1}$$

# Time dependence of accidentals

- Electron selections enhance
  - 1e: signal
  - 2e: acc. BG
  - fitted  $\lambda$  differ
- Additional evidence points to small  $10^{-4}$ /  $\mu\text{s}$  decrease of BG likely due to poor beam kick
- combined fit of 1e/2e determines corrections (prelim.)

	$\Delta\lambda_{-}$
R2014	$7.5 \pm 3 \text{ s}^{-1}$
R2015	$6 \pm 3 \text{ s}^{-1}$



# 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+  $\sigma$  discrepancy most precise experiment vs theory*

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

*capture rate to within 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

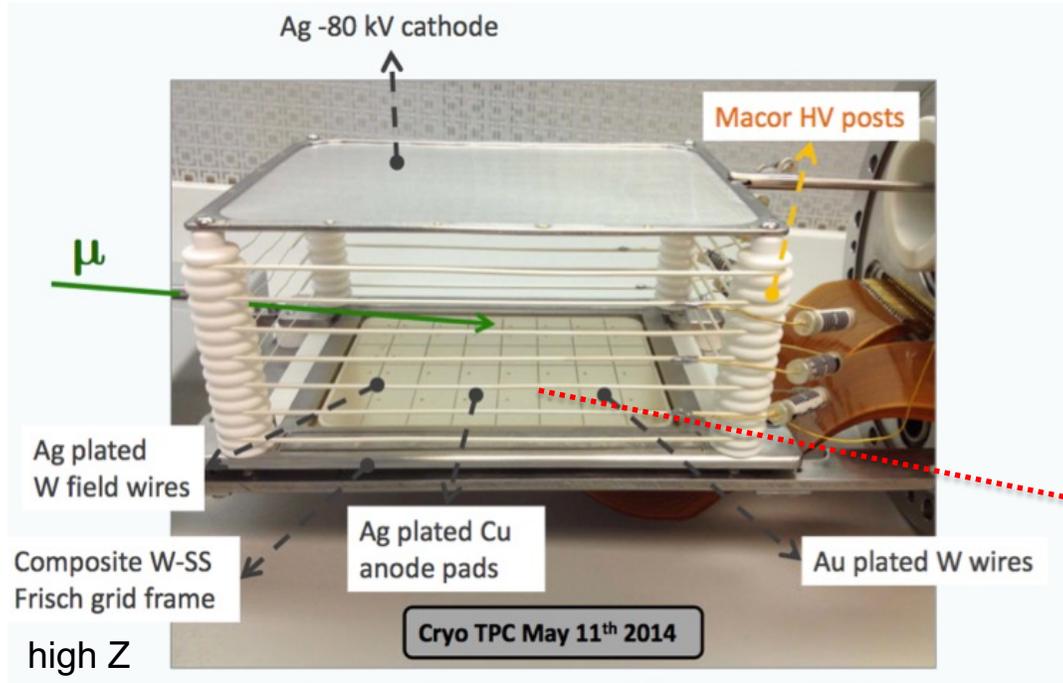
R A Ryan *et al* 2014 *JINST* **9** P07029

novel device:

- high purity D<sub>2</sub>, 6.5% LHD
- high pressure 5.1 bar = 55 bar @
- cryogenic deuterium TPC @ 31K

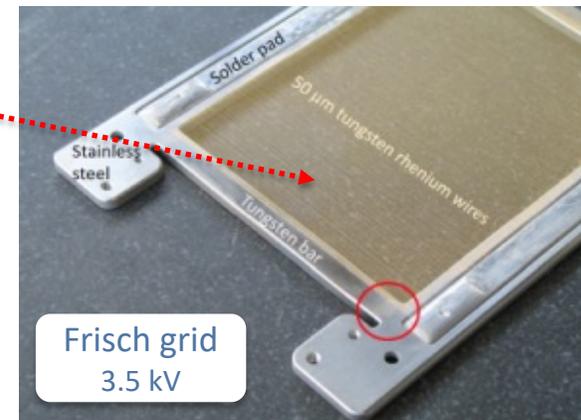
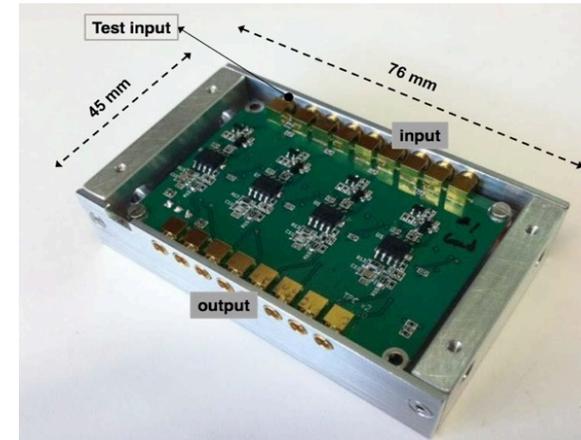
## • Cryo preamps

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



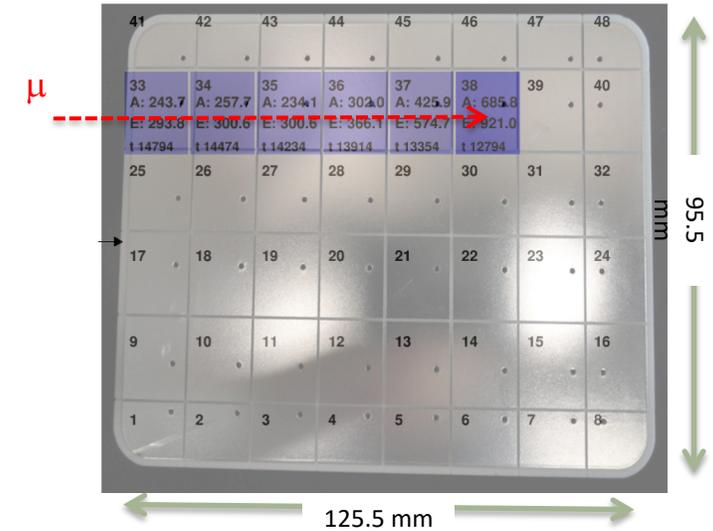
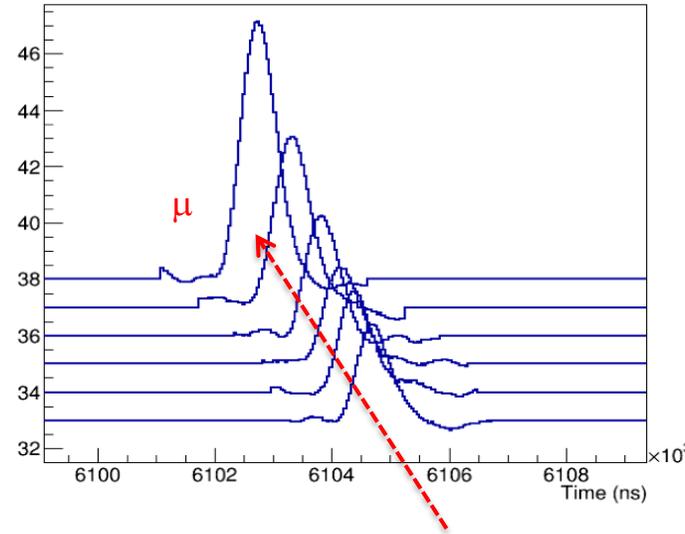
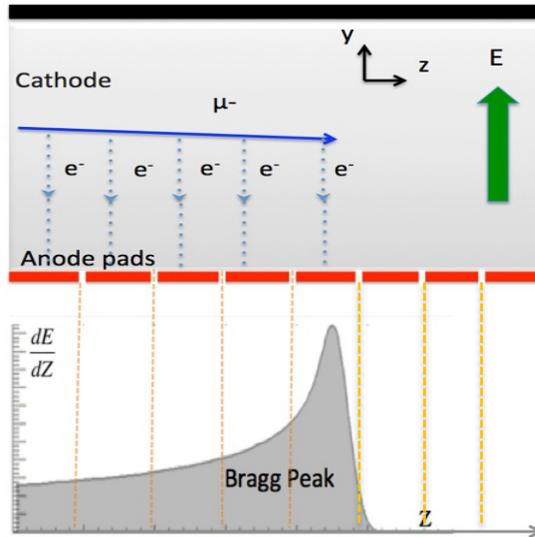
UW/PNPI

9.6 x 7.1 x 12.5 cm<sup>3</sup>



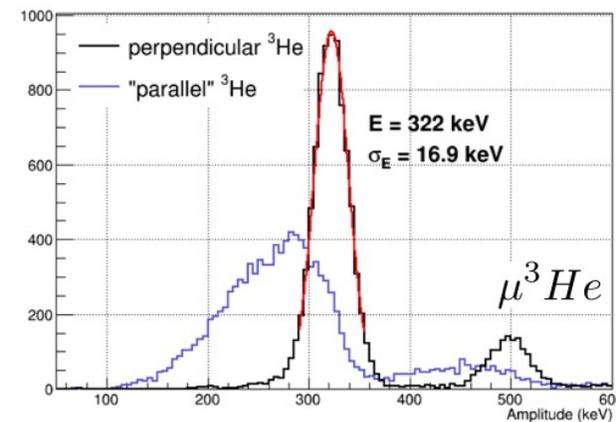
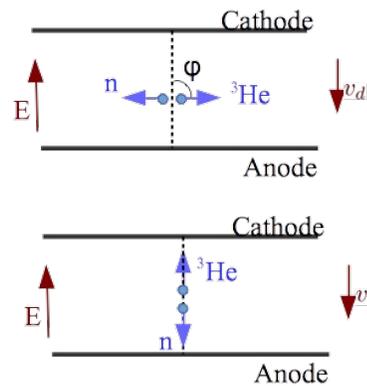
# MuSun TPC Performance

- Events



- Recombination

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



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

# Related Publications

- **MuSun** in Particle Physics at PSI

SciPost Phys. Proc. 5, 018 (2021)

## MuSun - Muon Capture on the Deuteron

P. Kammel<sup>1\*</sup> on behalf of the MuSun collaboration<sup>1</sup>

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

\* [pkammel@uw.edu](mailto:pkammel@uw.edu)

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. Solovlev (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. Gorringer (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  $\nu$  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<sup>1,2,3</sup>, Peter Kammel<sup>4</sup>, William J Marciano<sup>5</sup> and Alberto Sirlin<sup>6</sup>

$r_A$  determination from MuCap  
impact on  $M_{\mu p}$ ,  $M_{\mu d}$  and  $\nu A$

MuMu2019 Workshop @ PSI

Exploring synergies between Muon  
Capture and Neutrino Scattering

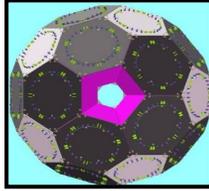
Physics of fundamental Symmetries and Interactions – PSI2019

Kammel co-organizer

# Precision Muon Group at CENPA/UW

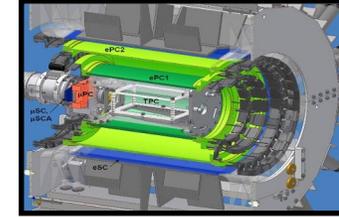
Past  
Present  
Future

- MuLan, MuCap

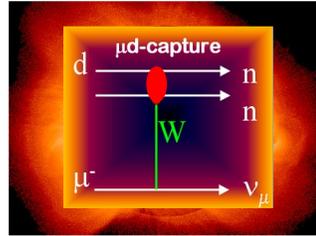


Fermi Constant

QCD Symmetries



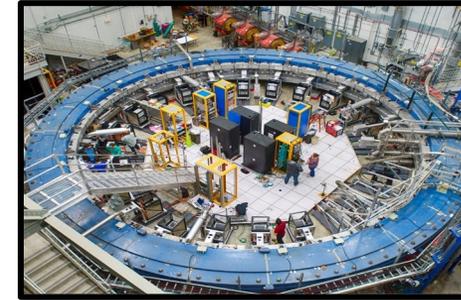
- MuSun



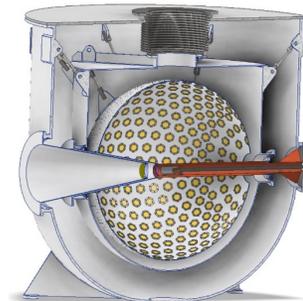
QCD coupling  
"Calibrating the Sun"

- Muon  $g-2$

New Physics?



- PIONEER

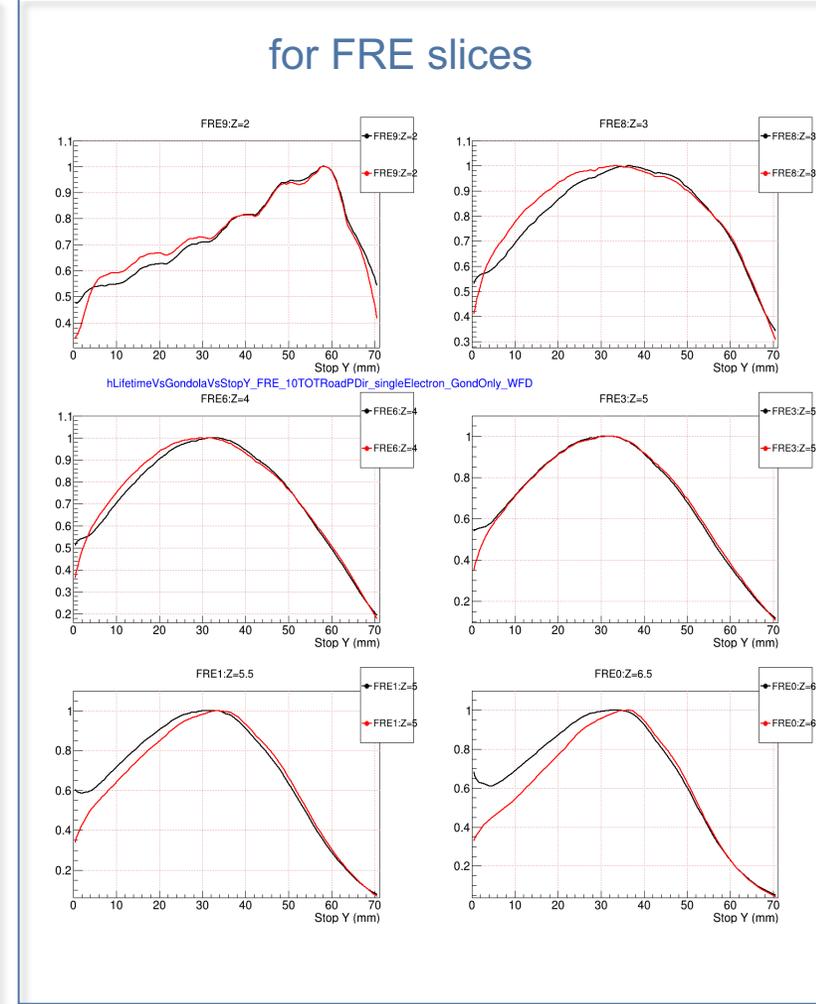
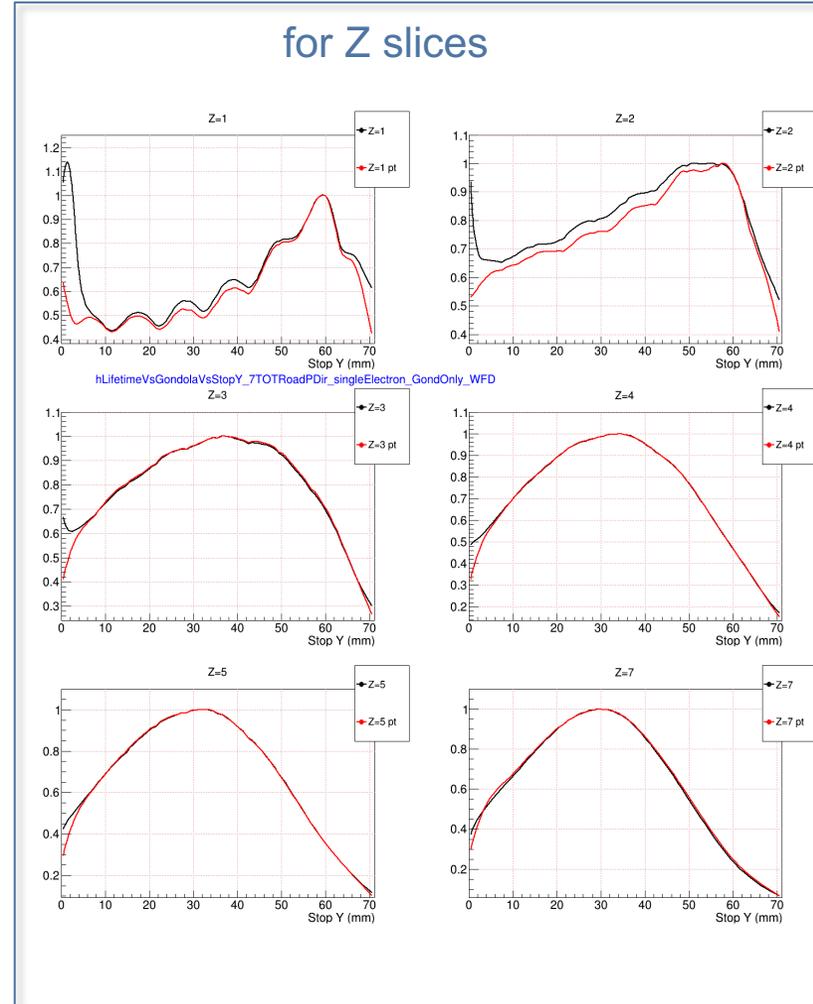
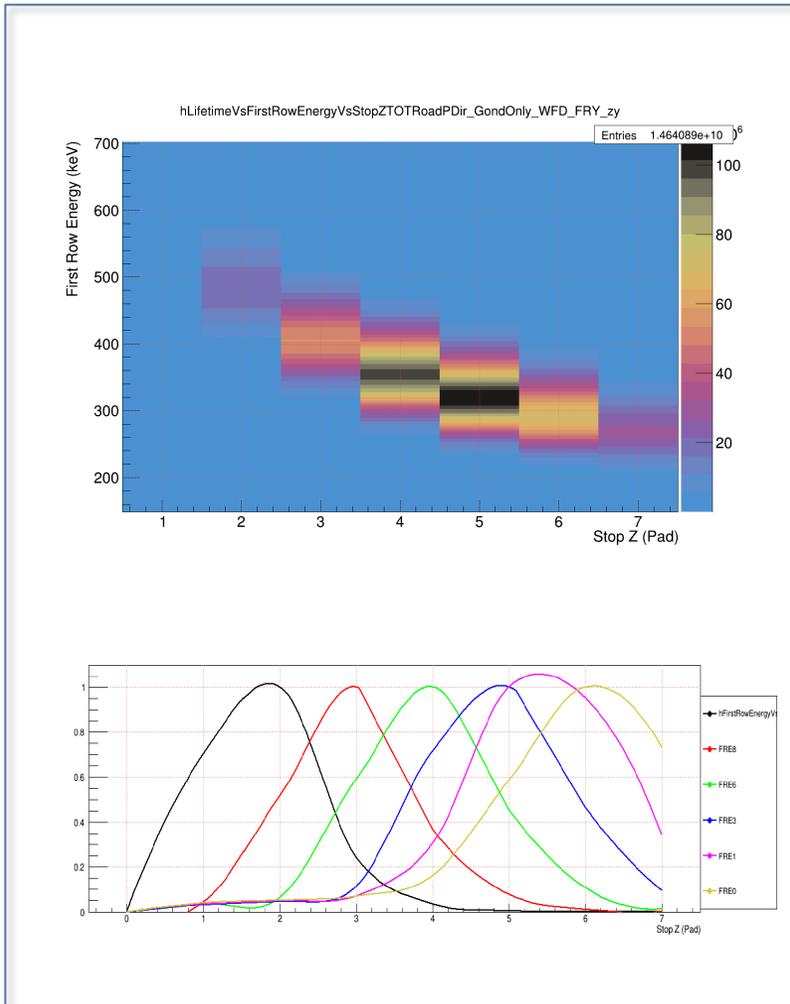


Lepton Flavor Universality  
and CKM Unitarity

# FRE Puzzle: fusion/ $\mu$ ratio is Y dependent

FRE vs. Z

fusion/ $\mu$  Y dependence



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

Bijaya Acharya,<sup>1,2,\*</sup> Andreas Ekström,<sup>3,†</sup> and Lucas Platter<sup>2,4,‡</sup>

