Muon Capture on the Deuteron
The MuSun Experiment

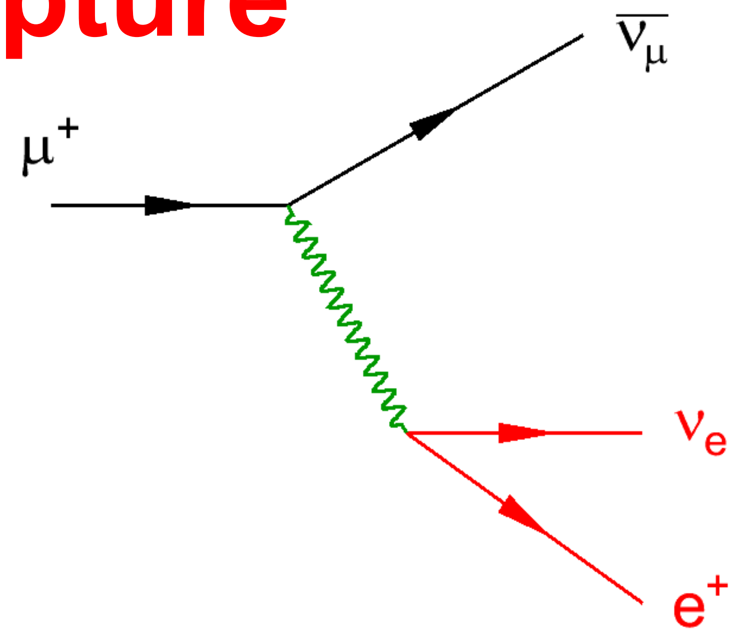
$$\mu^{-} + d \rightarrow n + n + \nu$$

Measure the capture rate, Λ_d, to 1.5% precision

Michael Murray

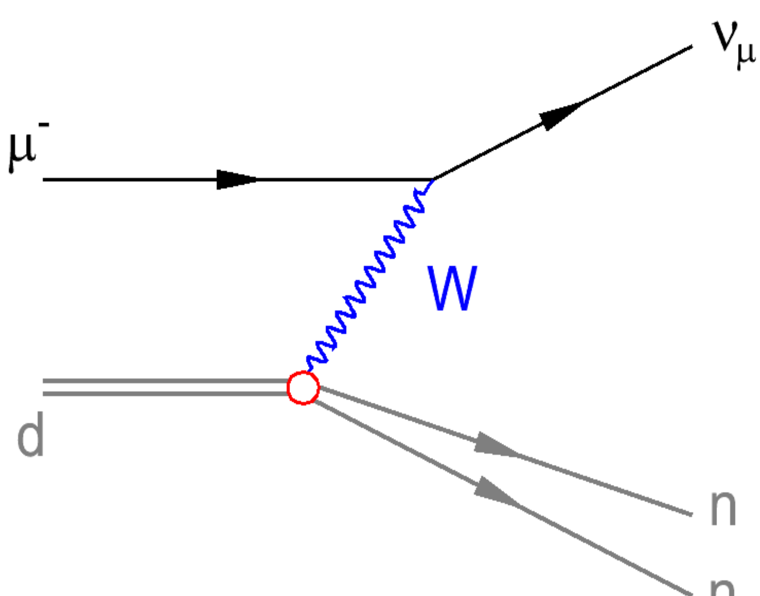
PSI2013, Fundamental Symmetries and Interactions

Muon Decay and Capture



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

$\Lambda_{decay} \sim 455{,}000\ s^{-1}$



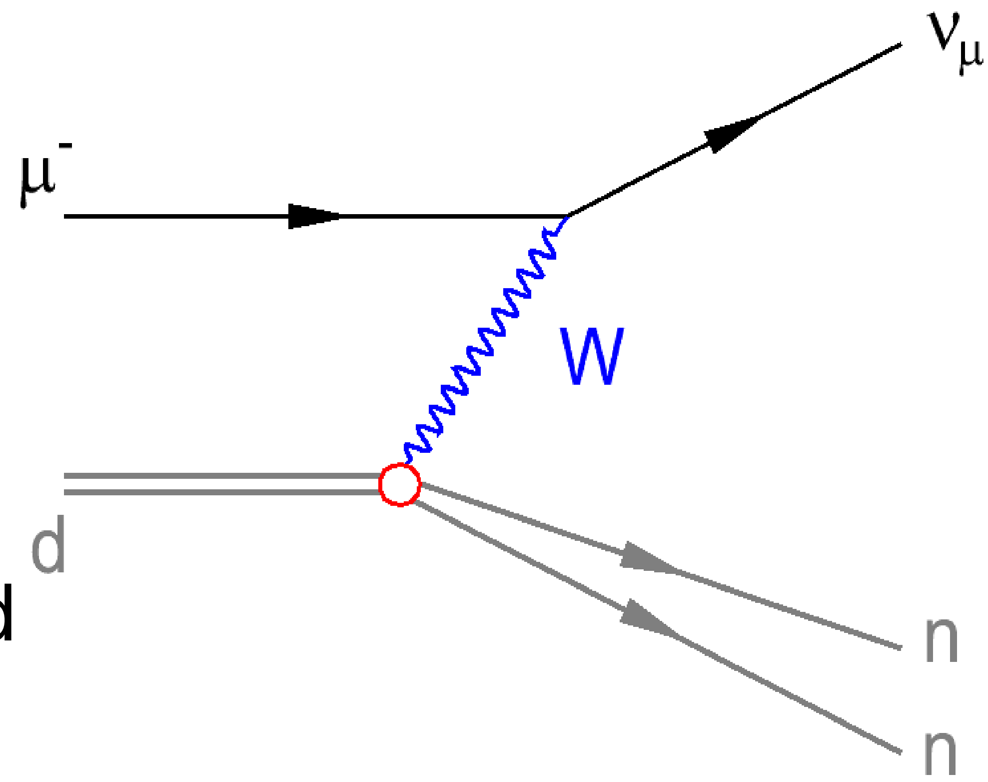
$$\mu^- d \rightarrow n + n + \nu_\mu$$

μd atom can form in doublet or quartet hyperfine state

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

$\Lambda_q \sim 12\ s^{-1}$

Muon Capture



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

The single-nucleon system is parameterized with form factors:

$$J_d^\alpha = \bar{\psi}_n(g_V\gamma^\alpha + \frac{ig_M}{2m_N}\sigma^{\alpha\beta}q_\beta - g_A\gamma^\alpha\gamma_5 - \frac{g_P}{m_\mu}q^\alpha\gamma^5)\psi_p$$

The 2-nucleon system is calculated using effective field theory, leaving a low-energy constant to be determined empirically.

L_{1A} $\qquad\qquad$ d_R

Neutrinos & Astrophysics

Connection to the SNO reactions

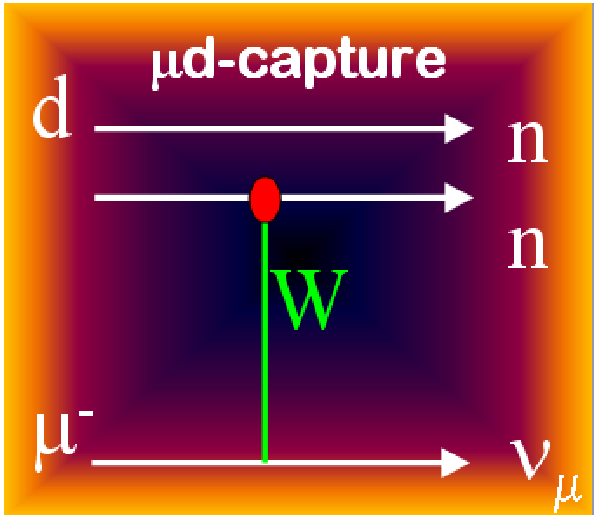
$$\nu + d \rightarrow p + n + \nu$$

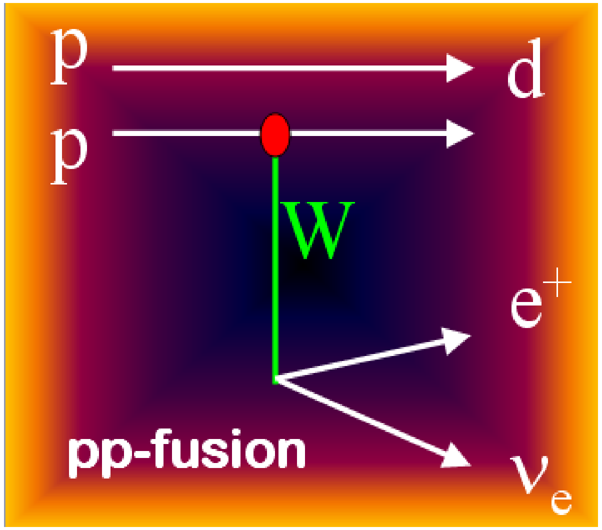
$$\nu_e + d \rightarrow p + p + e^-$$

as well as p-p fusion

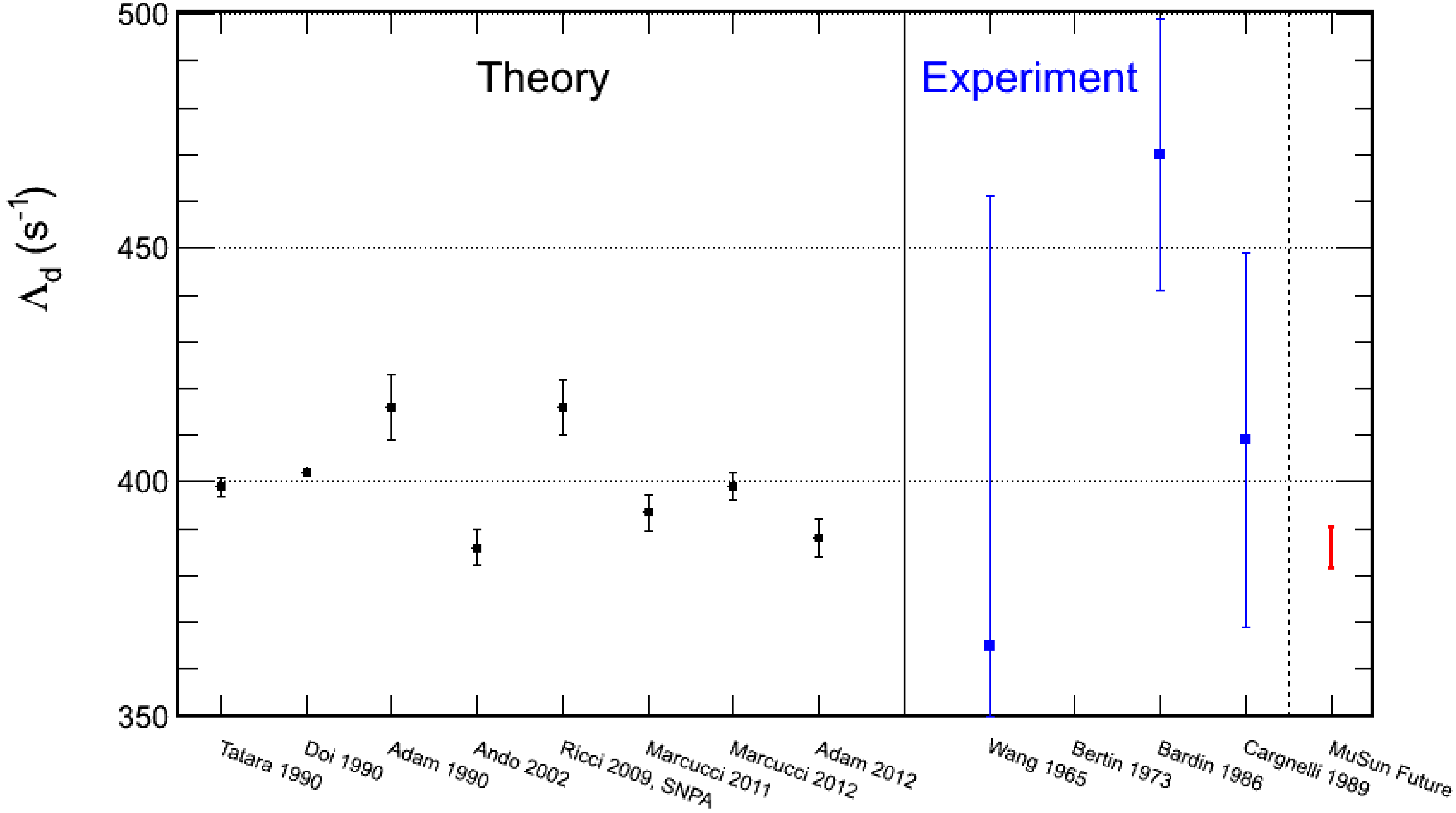
$$p + p \rightarrow d + e^+ + \nu_e$$

through the LEC d_R (or L_{1A})





Theory/Experiment status



Lifetime Method

Positive muon disappearance rate

$$\Lambda_{\mu+} = \Lambda_{decay}$$

Muon lifetime is known to 1ppm

$$\boxed{\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu}$$

Negative muon disappearance rate

$$\Lambda_{\mu-} = \Lambda_{decay} + \Lambda_d$$

<u>Measure</u> the negative muon lifetime in deuterium

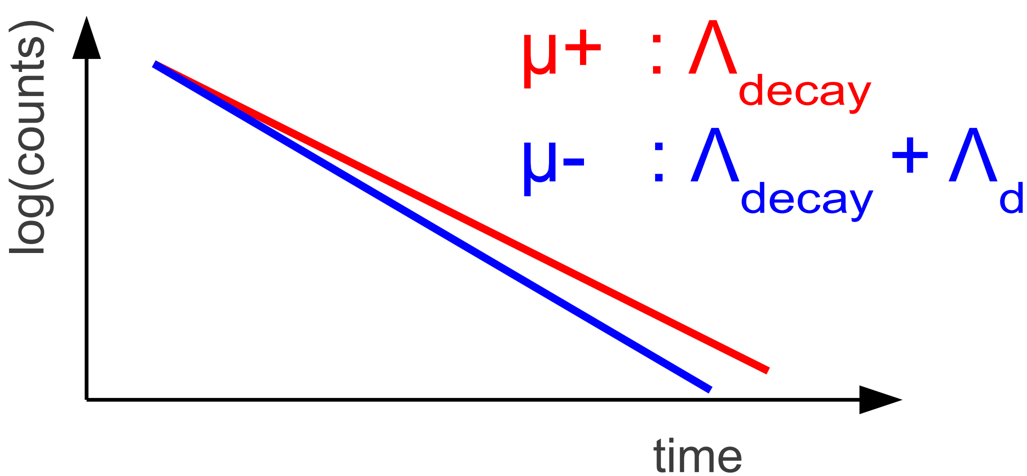
$$\boxed{\begin{array}{l} \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \\ \mu^- d \rightarrow n + n + \nu_\mu \end{array}}$$

$$\boxed{\Lambda_d = \Lambda_{\mu-} - \Lambda_{\mu+}}$$

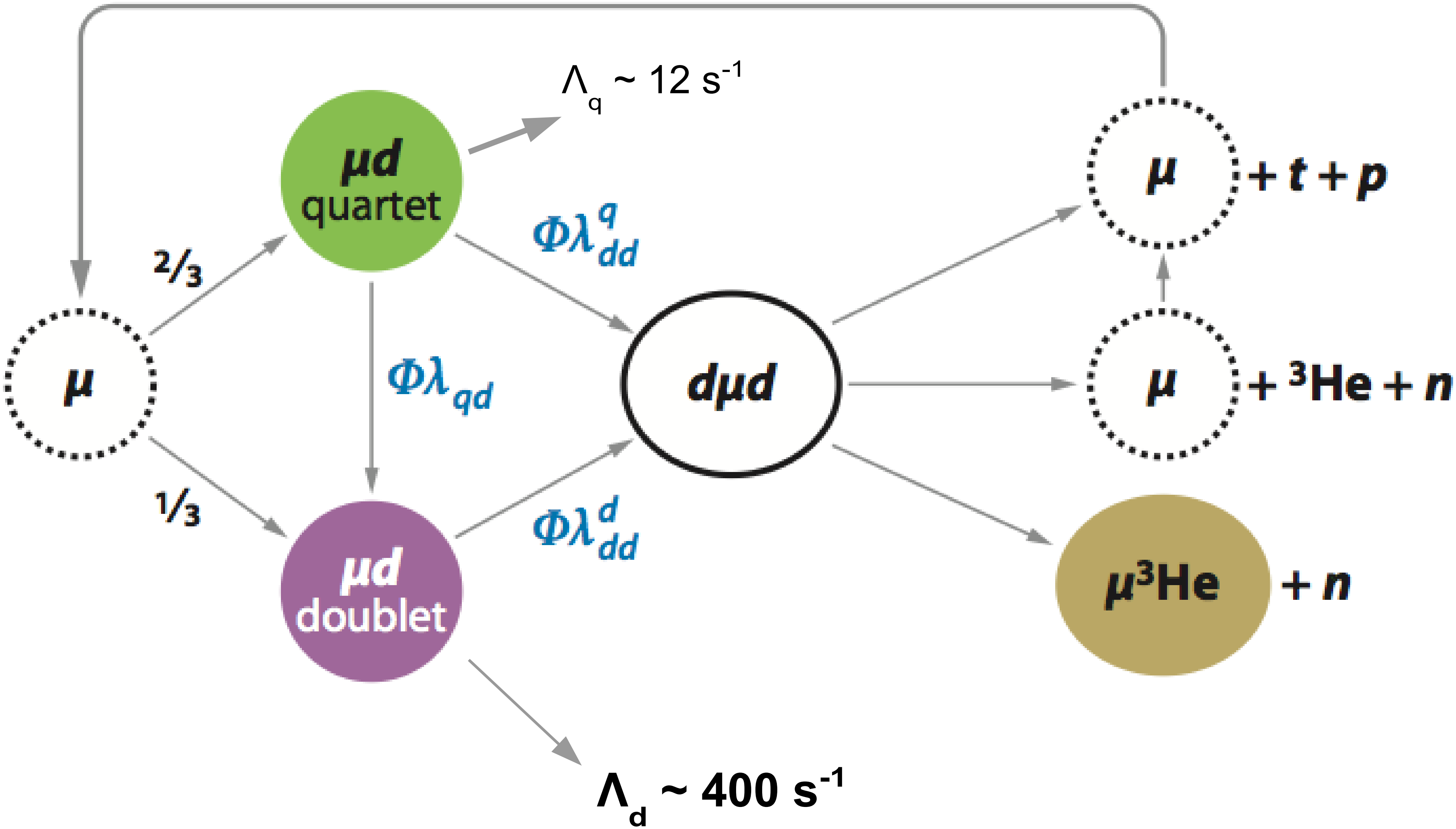
Reminder:

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

$\Lambda_{\mu+} \sim \Lambda_{\mu-} \sim 455{,}000\ s^{-1}$



Muons in Deuterium

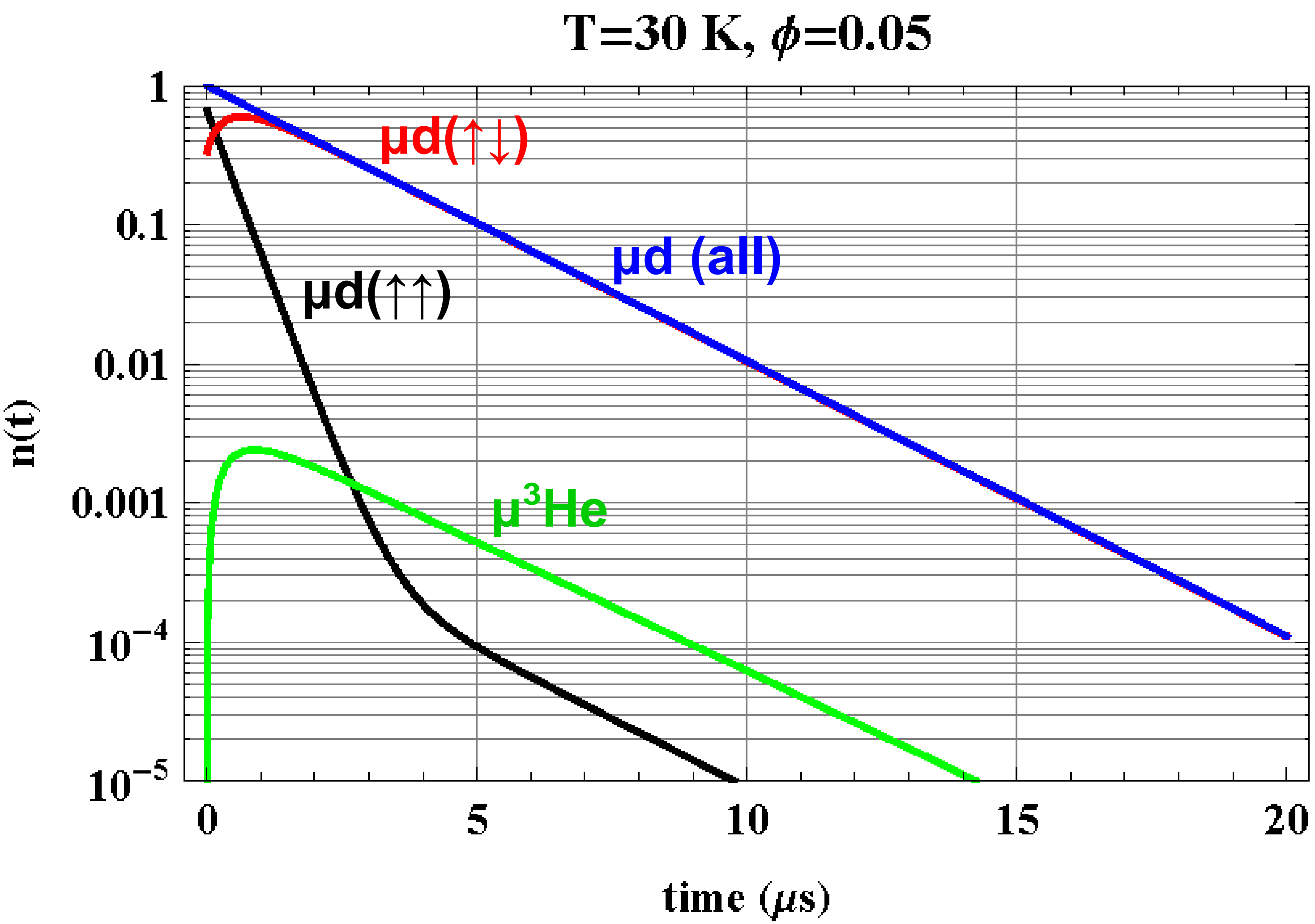


Optimize Target Conditions

Gas density must be 5% of liquid H_2 density

T = 30 K

P = 5 bar



Experimental Challenges

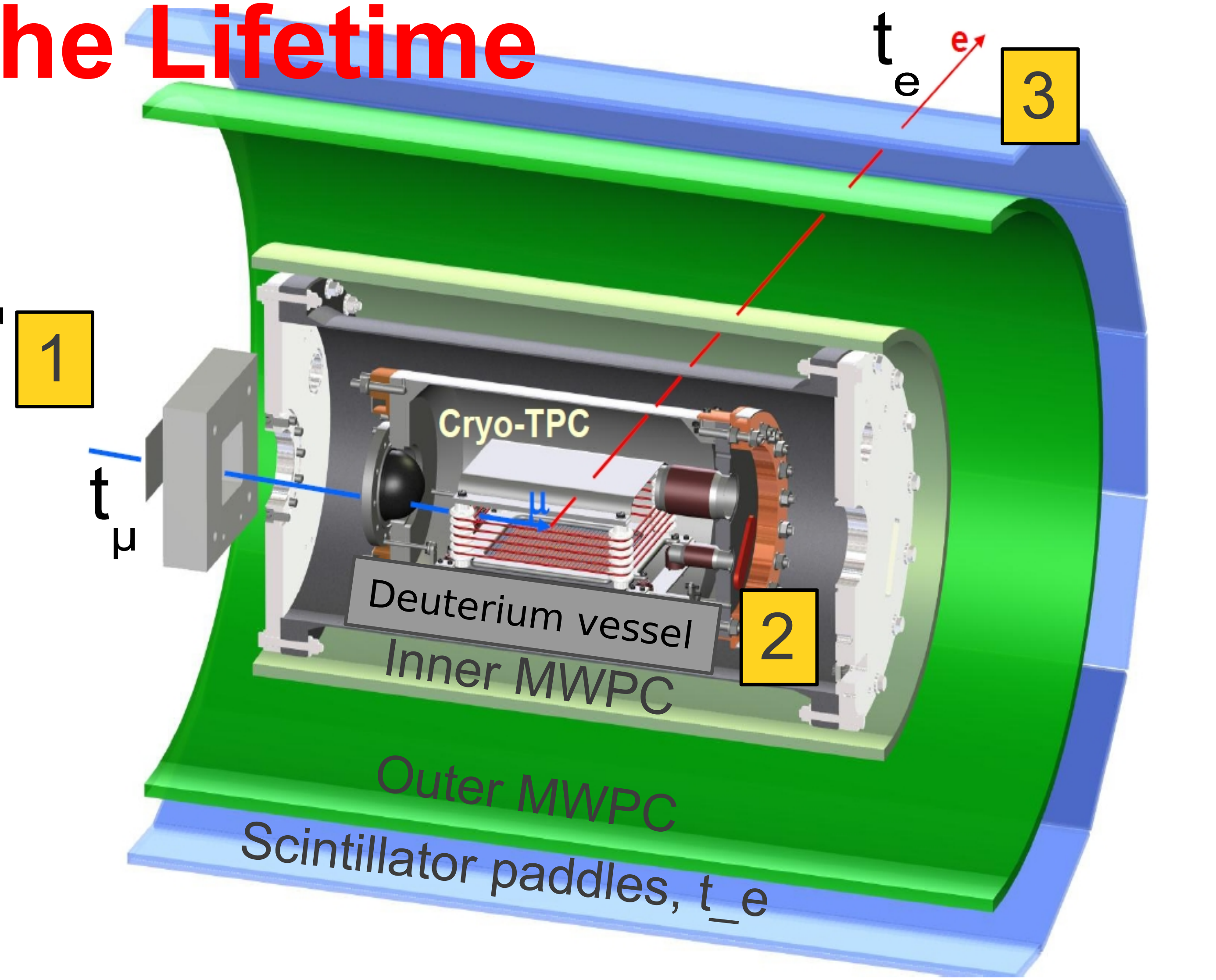
- Statistics: 10 ppm requires 10^{10} decays
  $\Lambda_d \sim 400\ s^{-1}$, $\Lambda_{\mu+} \sim 455{,}000\ s^{-1}$
- Muonic atoms must be in the doublet (F=1/2) state
- Chemical Purity: < 1ppb O_2, N_2
  - Capture rate goes as Z^4
  - Continuous cleaning and circulation - CHUPS
- Isotopic purity: ^1H concentration < 100 ppm
- Muon-catalyzed fusion backgrounds in the TPC

Measuring the Lifetime

1: Beam scintillator registers muon time, t_μ

2: TPC provides 3D stopping position of the muon in D_2

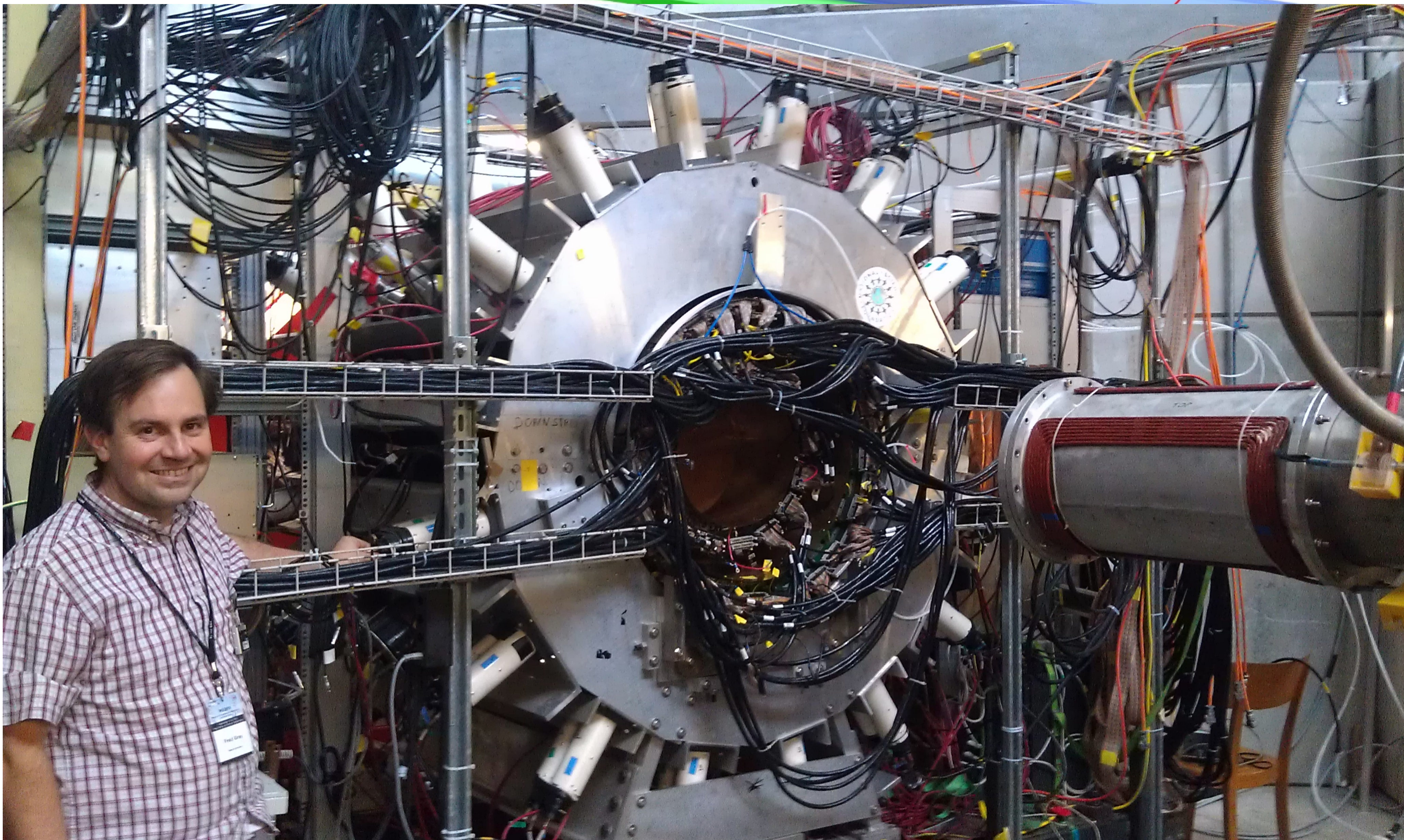
3: Scintillator registers decay electron time, t_e



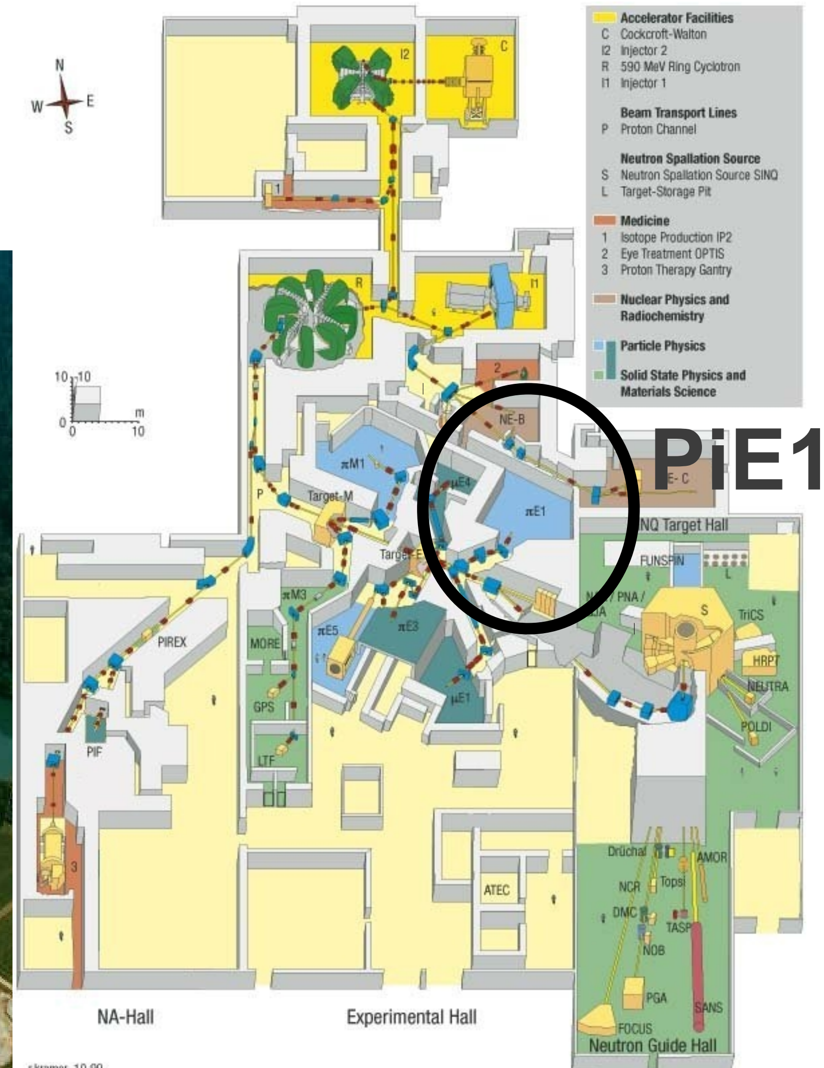
4: Histogram t_e - t_μ and fit to an exponential to extract $\Lambda_{\mu-}$

$$\boxed{4} \quad N(t_e - t_\mu) = \mathrm{N_0 Exp}[-\Lambda_{\mu^-}(\mathrm{t_e} - \mathrm{t}_\mu)]$$

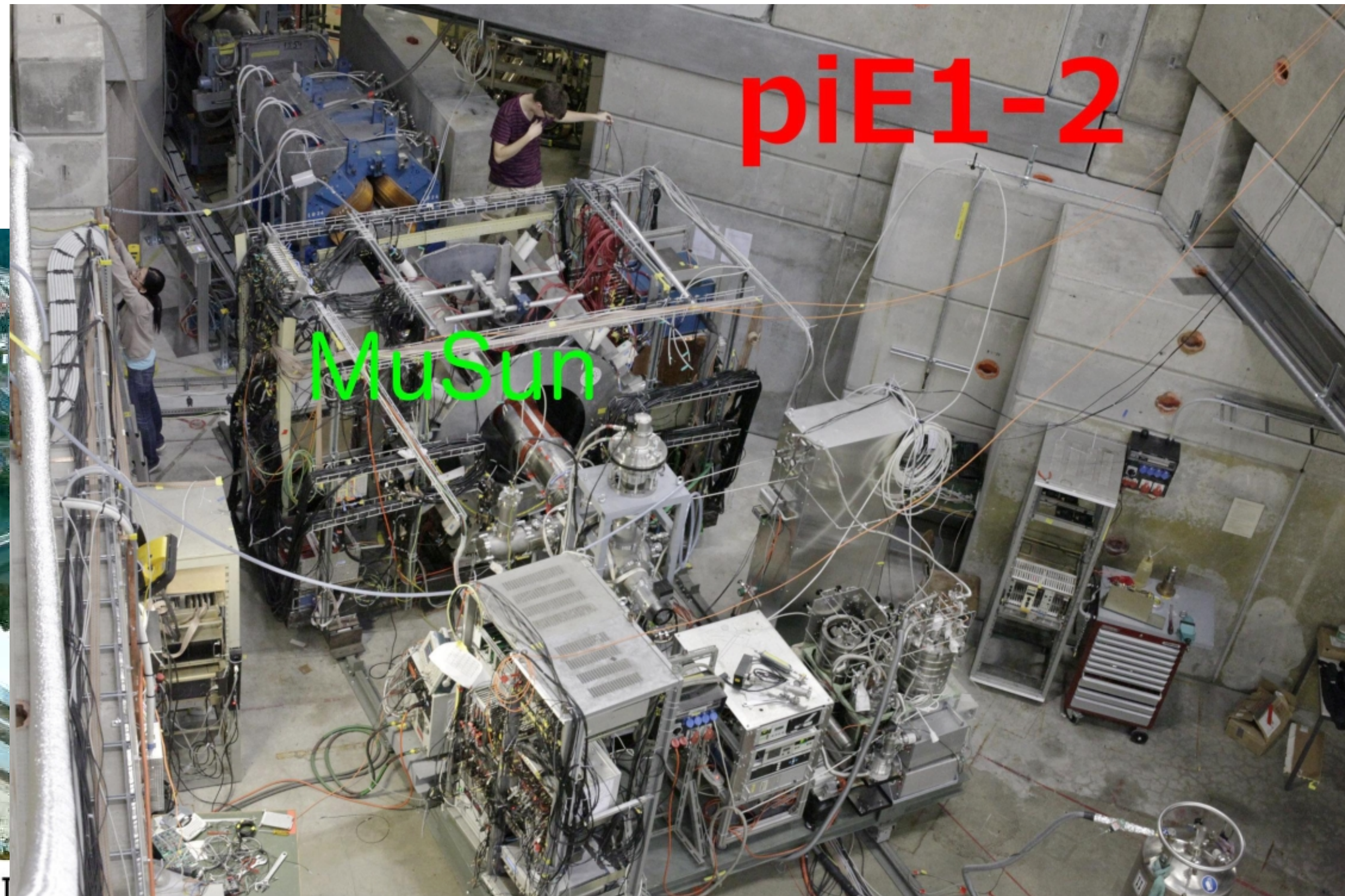
Detectors



PiE1 Muon Beam at PSI



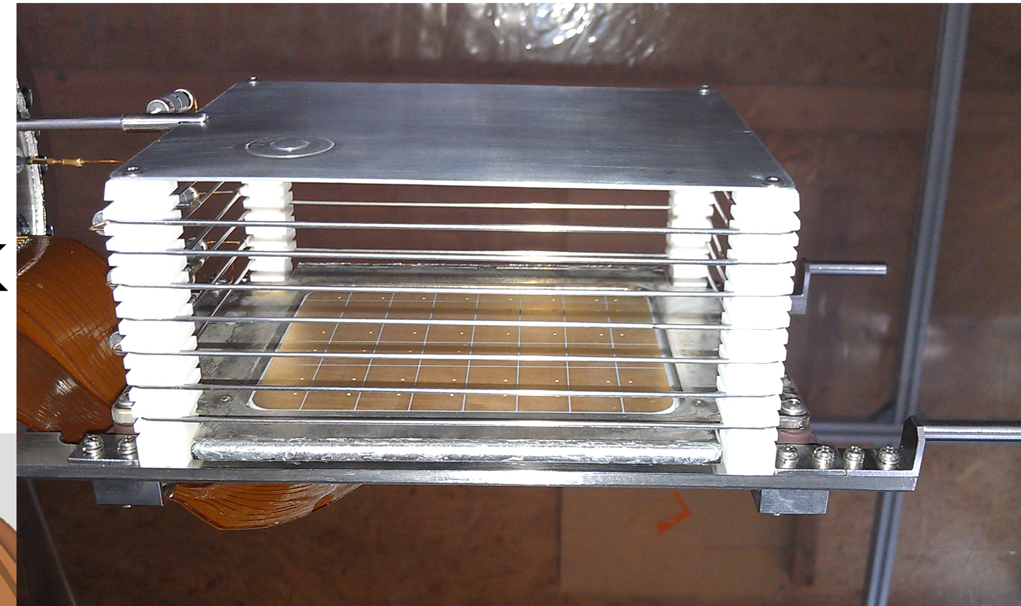
PiE1 muon Beam at PSI

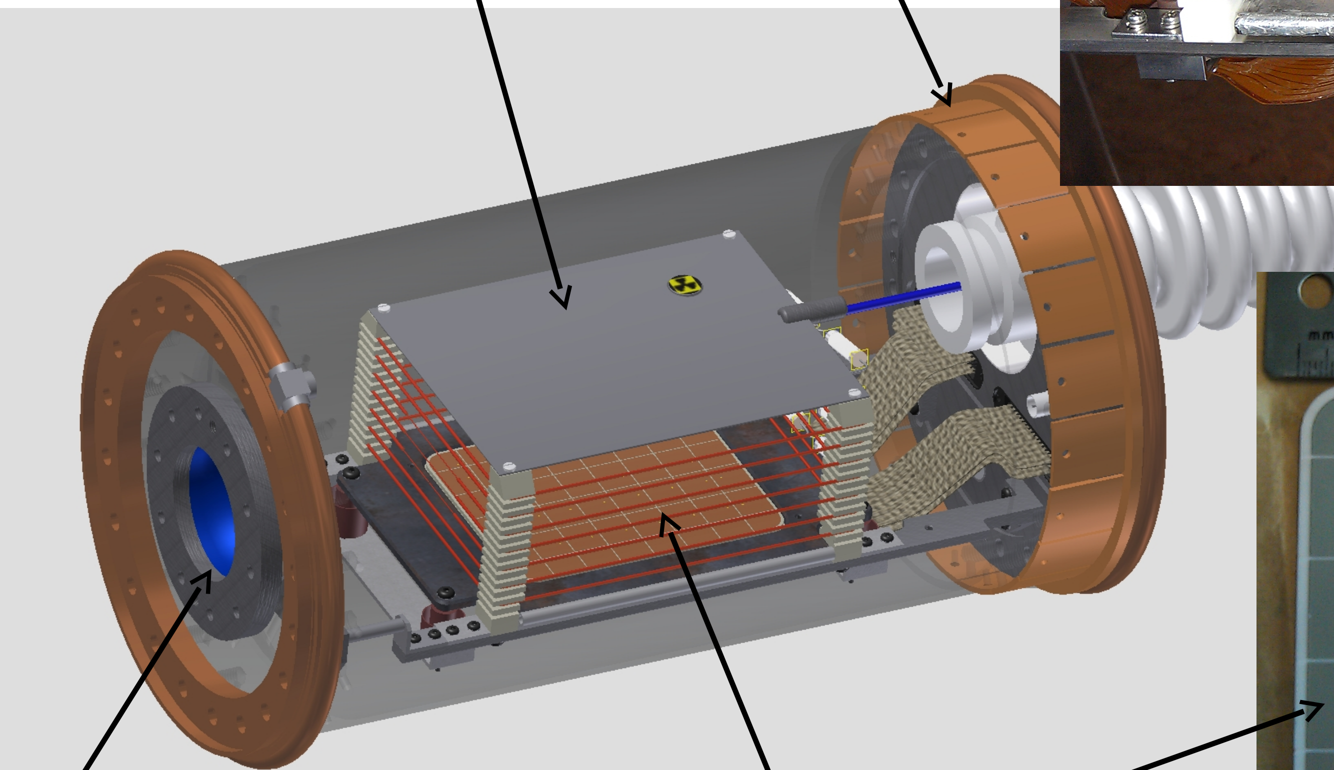


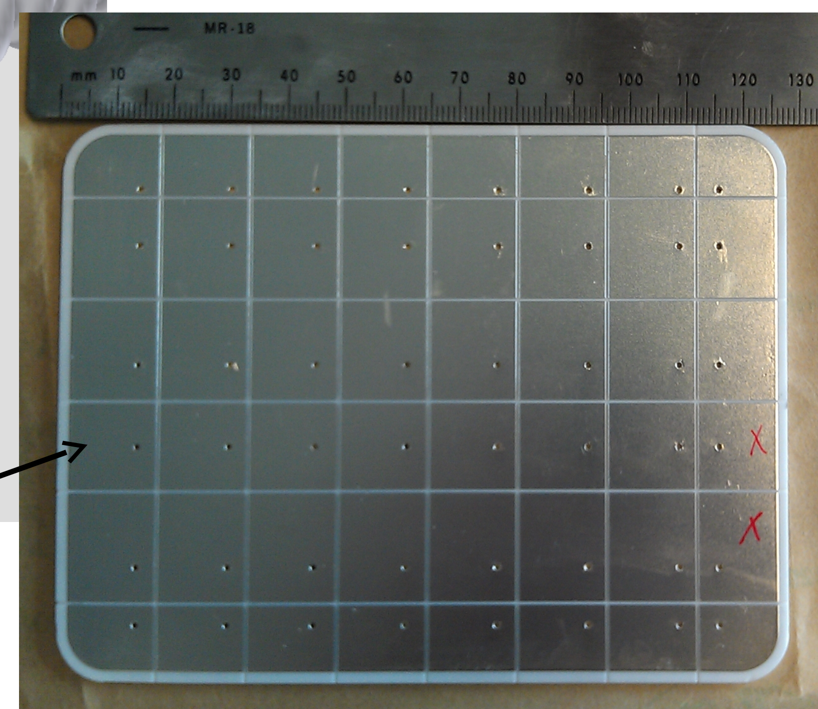
CryoTPC

Cathode drift voltage 80kV over 71 mm

Liquid Neon cooling at 30K



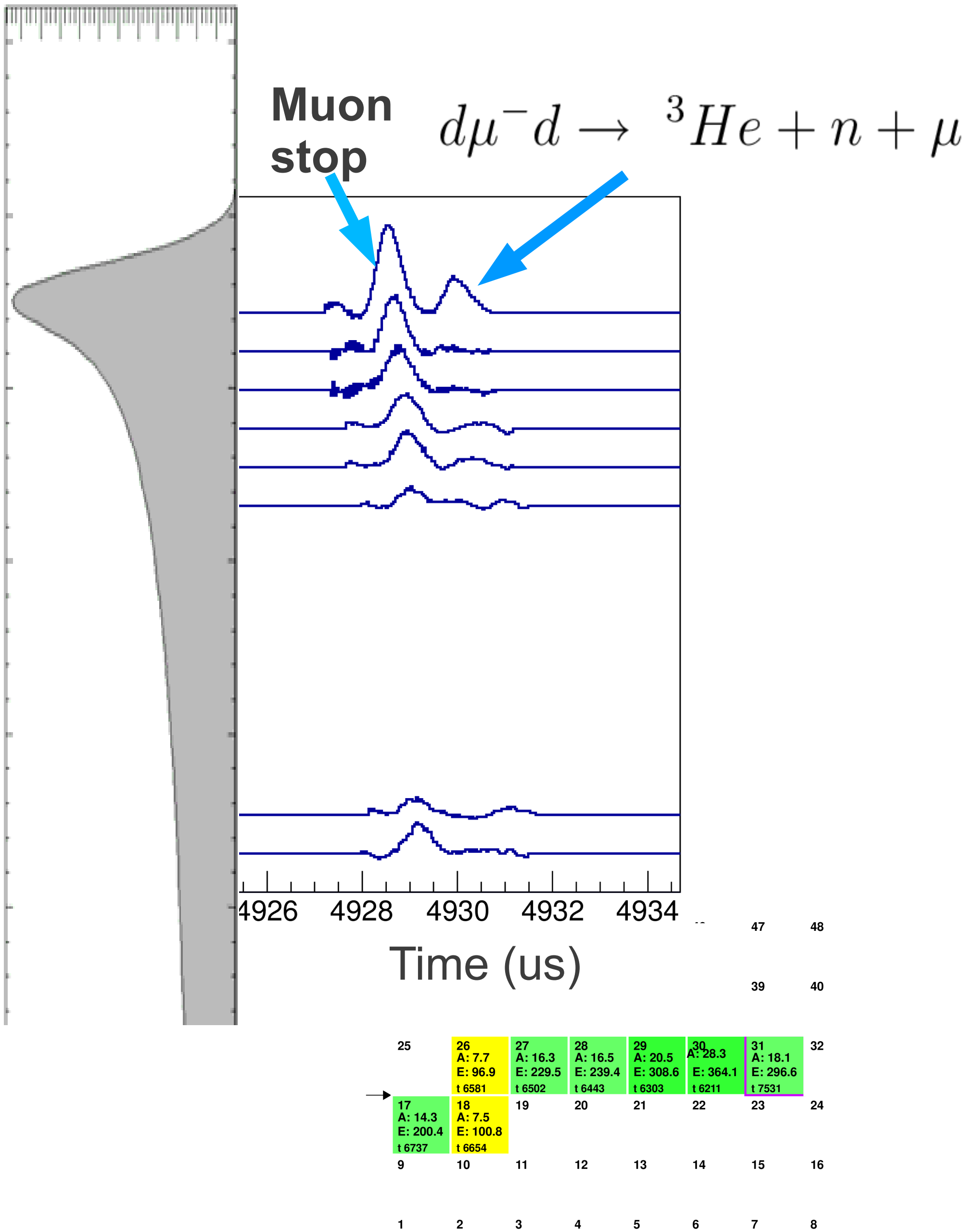


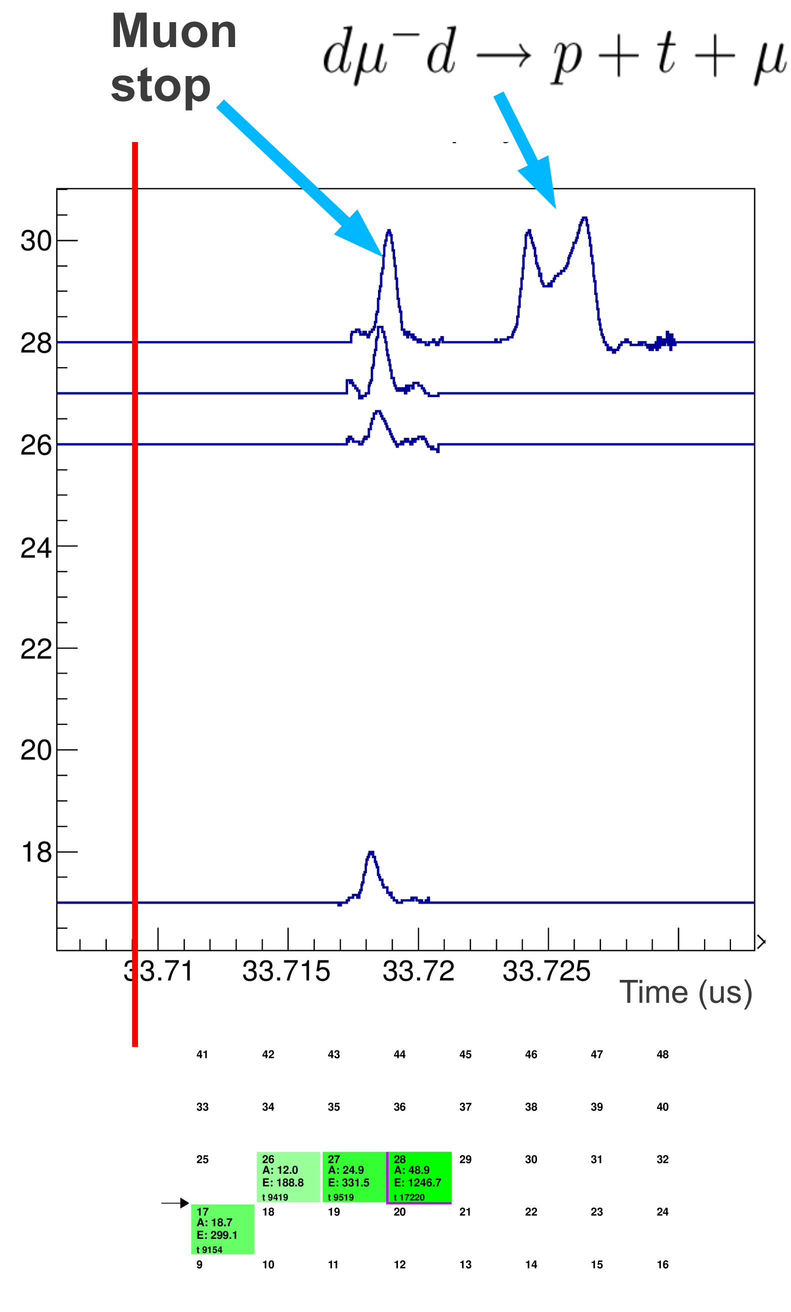


Be beam window

6 x 8 anode pad plane
90 mm x 120 mm
Ag plated on alumina

CryoTPC tracking

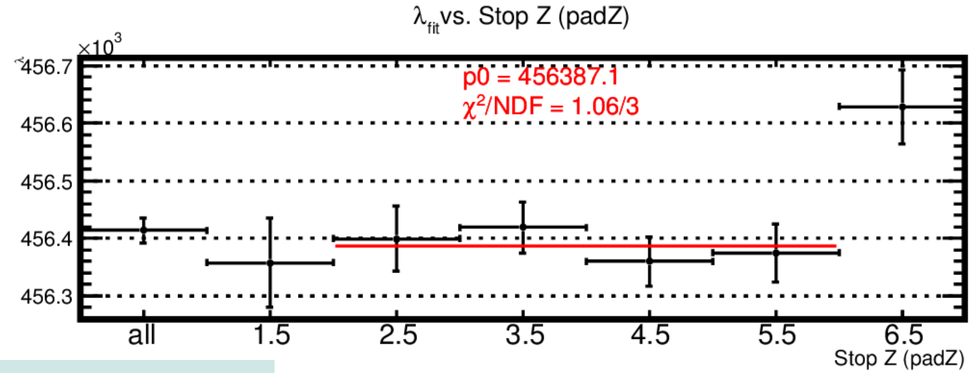




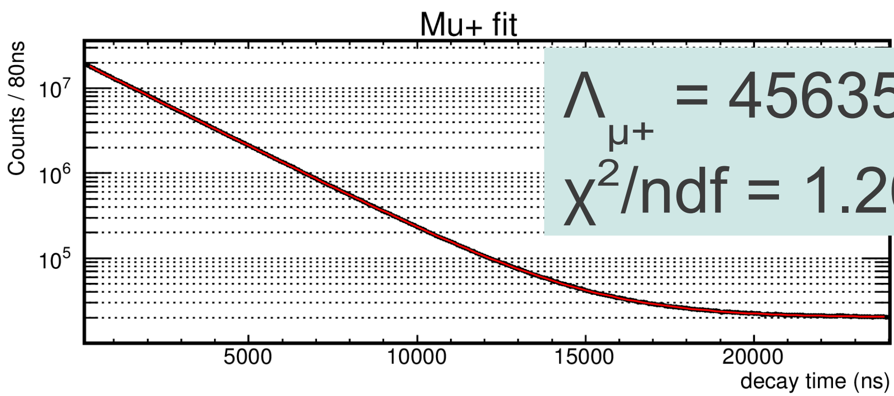
Analysis of 2011 data

5 x 10^9 muon decays in Summer 2011

Analysis is ongoing

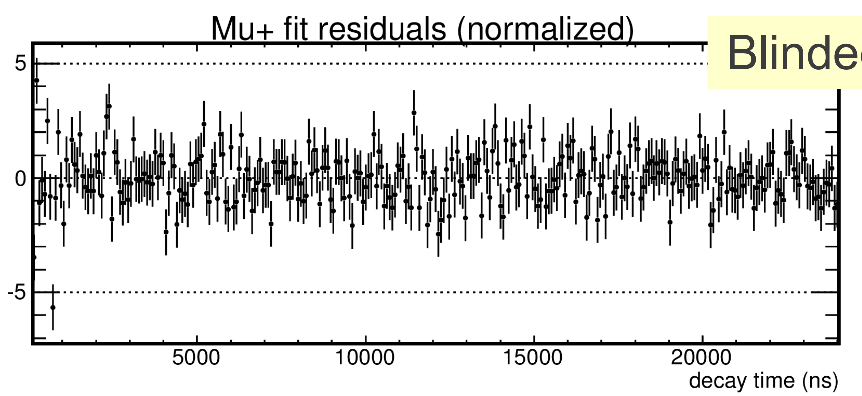


Consistency checks for μ+ data



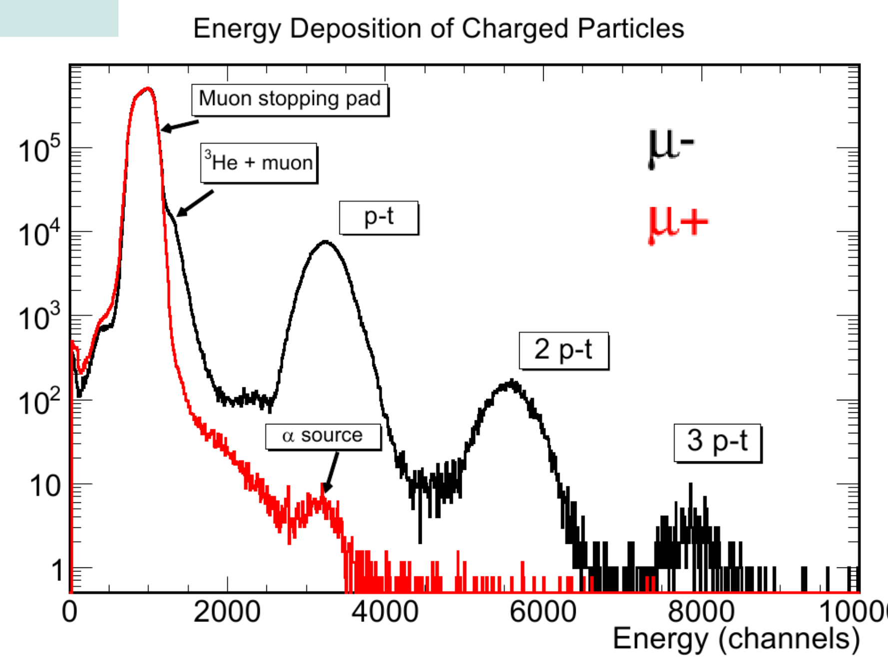
$\Lambda_{\mu+}$ = 456358 +/- 22 s^{-1}

χ^2/ndf = 1.26



Blinded!

Muons & fusion in the TPC

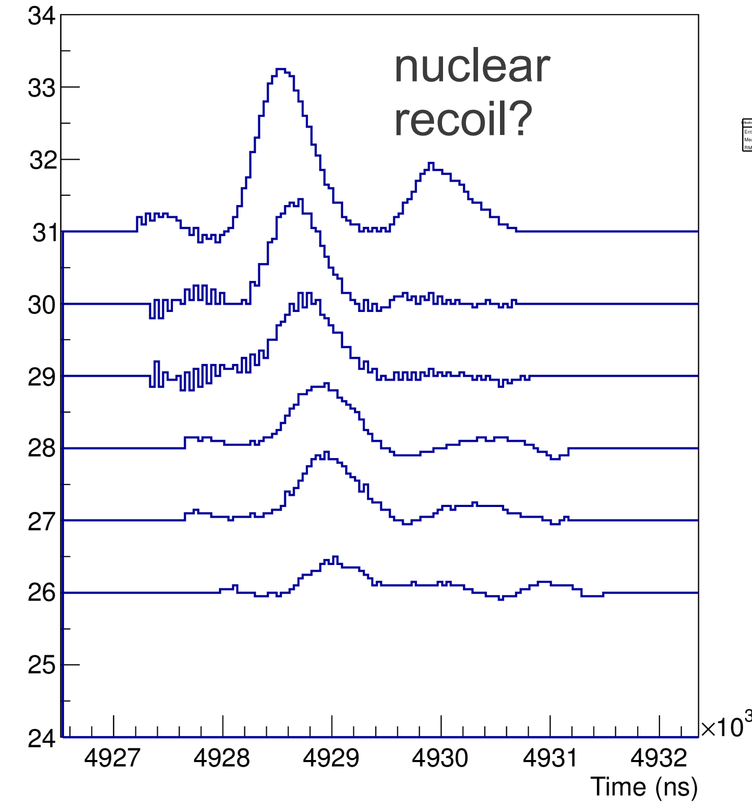


Chemical impurity

- Muons will transfer preferentially to nitrogen and oxygen impurities.
- The μZ atoms can undergo capture
  - $\mu N \rightarrow C^* + nu$
  - $\mu O \rightarrow N^* + nu$
- Capture rate goes as Z^4
- The effect on the lifetime is $\sim 2s^{-1}$ / ppb
- Gas chromatography monitor not sufficient
- Can we observe capture recoils in TPC?

Chemical impurity

- Muons will transfer preferenti
  and oxygen impurities.
- The μZ atoms can undergo ca
  - $\mu N \rightarrow C^* + \text{nu}$
  - $\mu O \rightarrow N^* + \text{nu}$
- Capture rate goes as Z^4
- The effect on the lifetime is ~



- Gas chromatography monitor not sufficient
- Can we observe capture recoils in TPC?

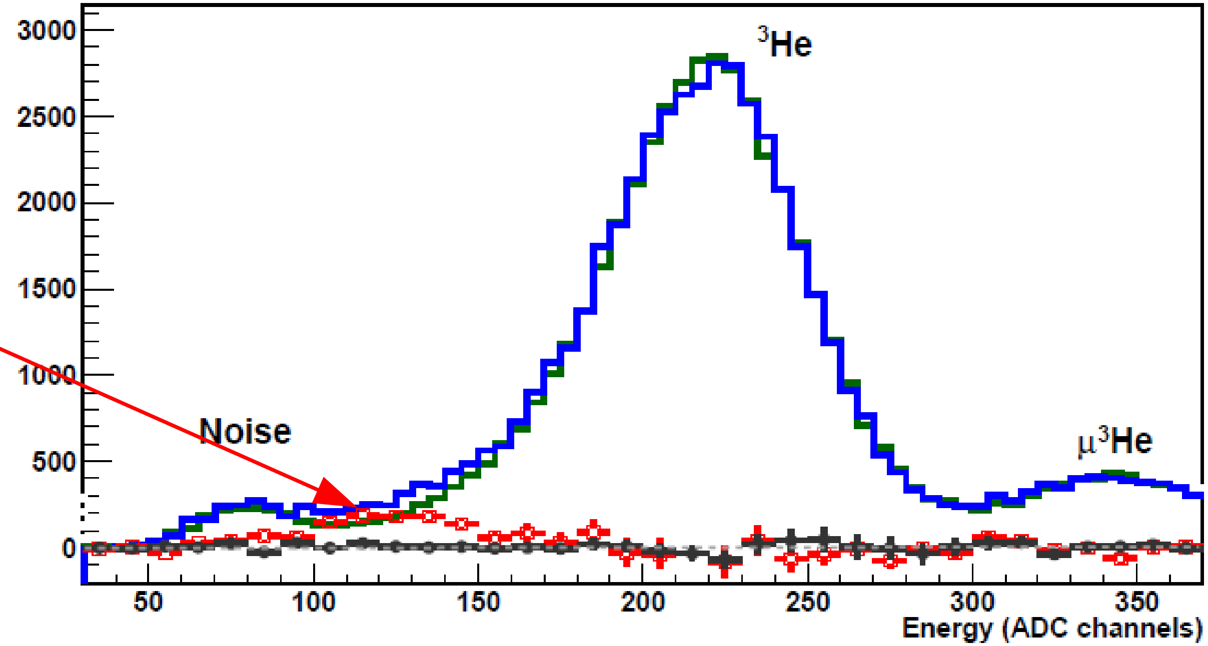
Impurity measurement with TPC

Large background from ^{3}He fusion

Data from 2011

^{3}He spectrum

Capture recoils for impurity doped dataset

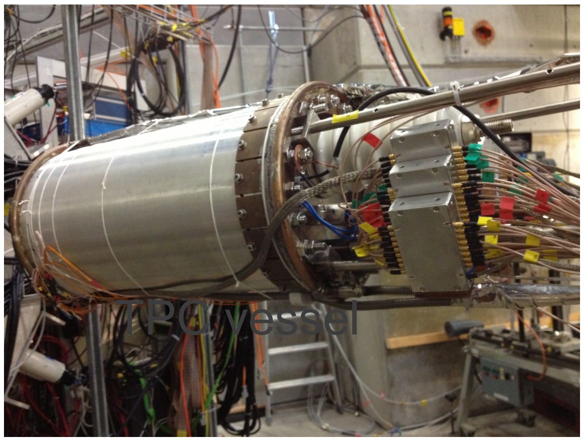


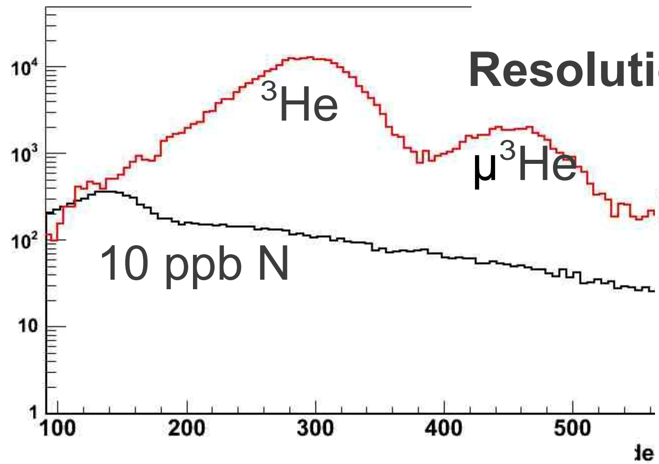
Background reduction:

- Higher resolution TPC readout
- Tag X-rays from muonic atom formation

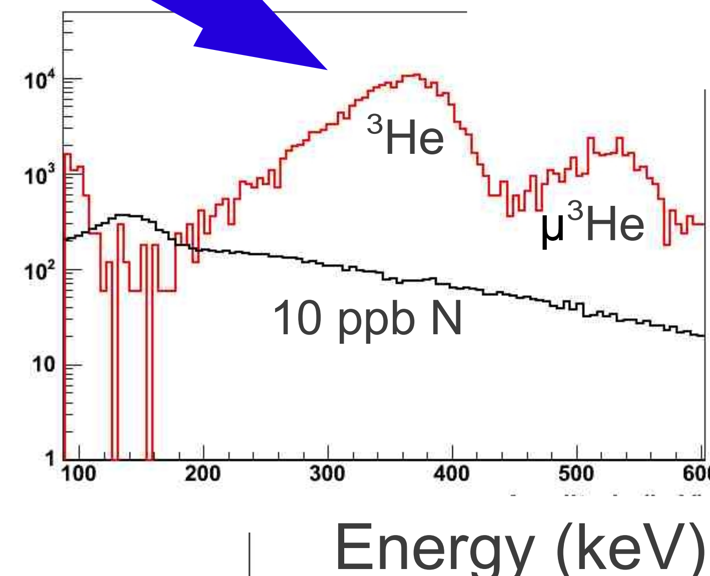
Background reduction

High resolution cold pre-amplifiers

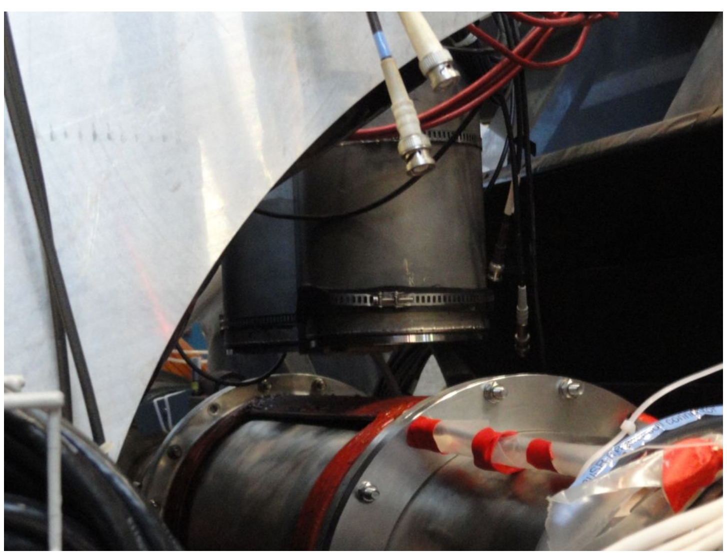


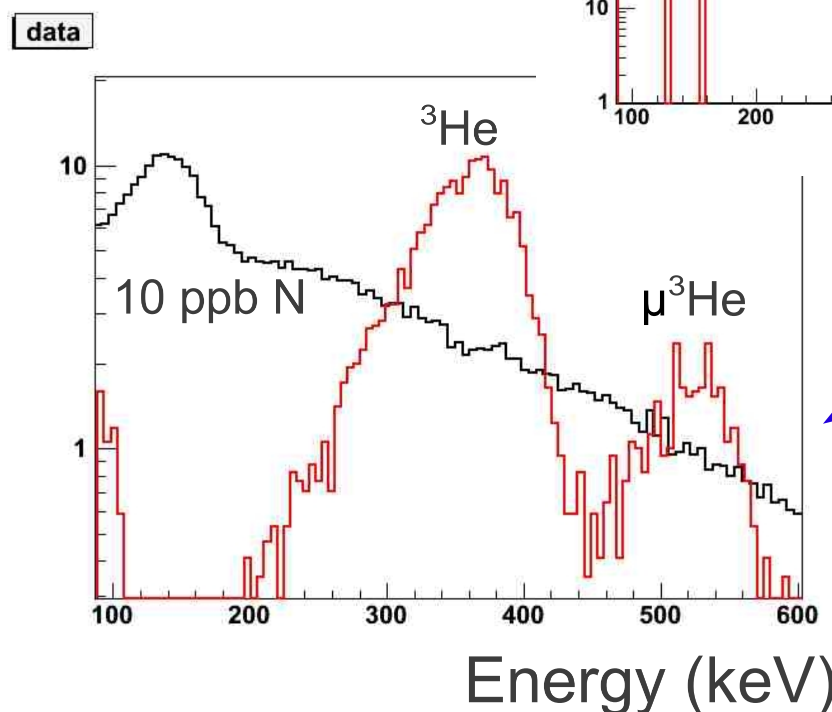


Resolution: sigma = 30 keV → 10 keV



NaI array to tag 100keV *μN* X-rays





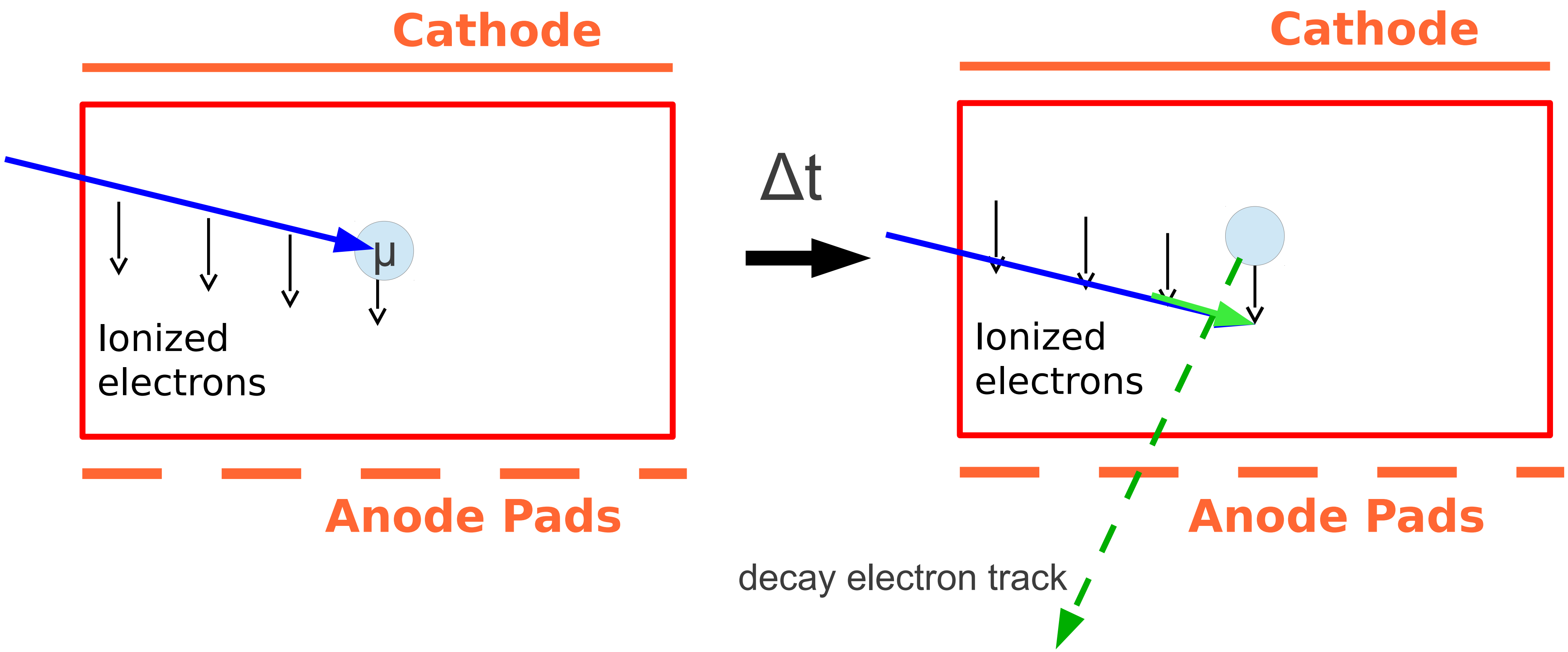
Summary

- Analysis of the 2011 run data is ongoing
- Test run and upgrade development 2012
- Currently running in the PiE1 beamline through November 2013 with upgrades to handle the most troubling systematics
- Further data collection in 2014 (TBD)

backup slides

Electron interference

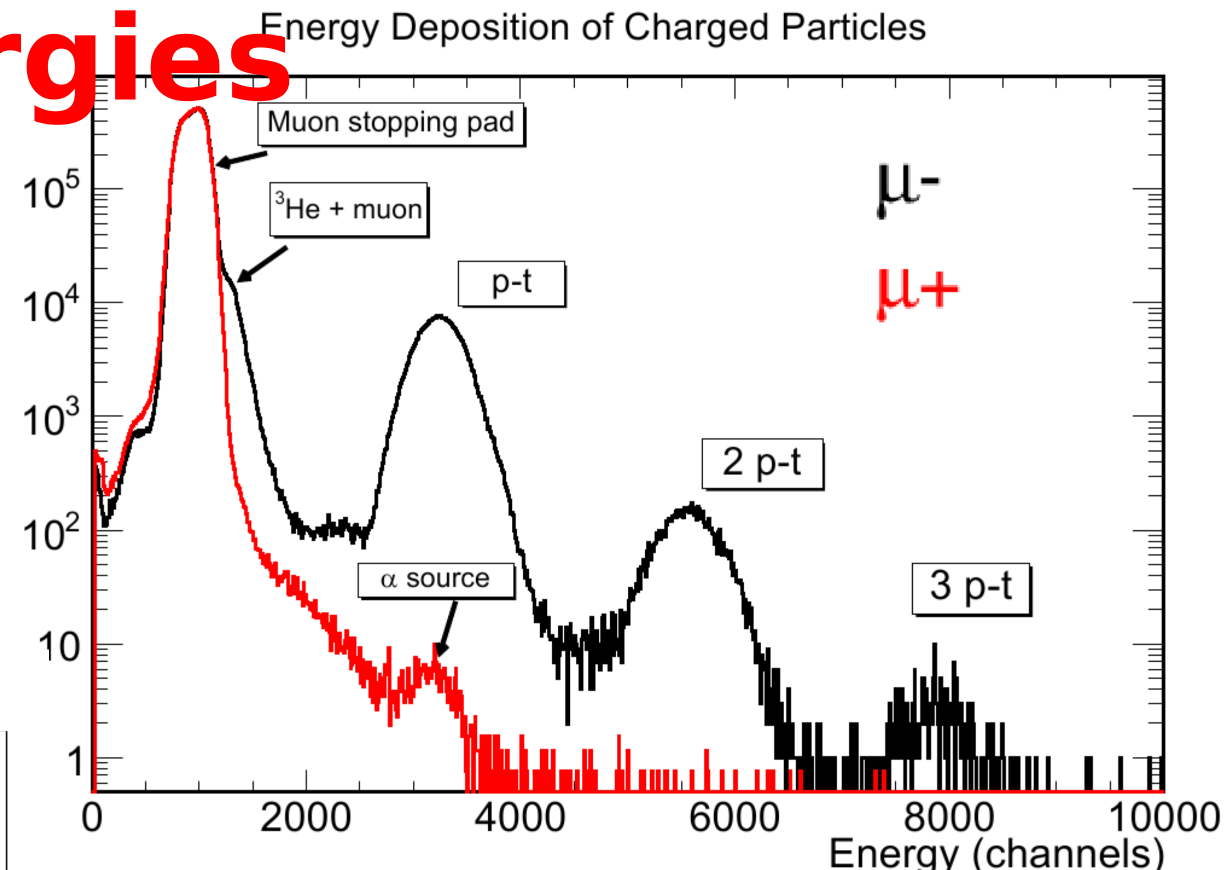
- Electrons ionization is small, below threshold
- Still possible to "promote" muons barely below threshold

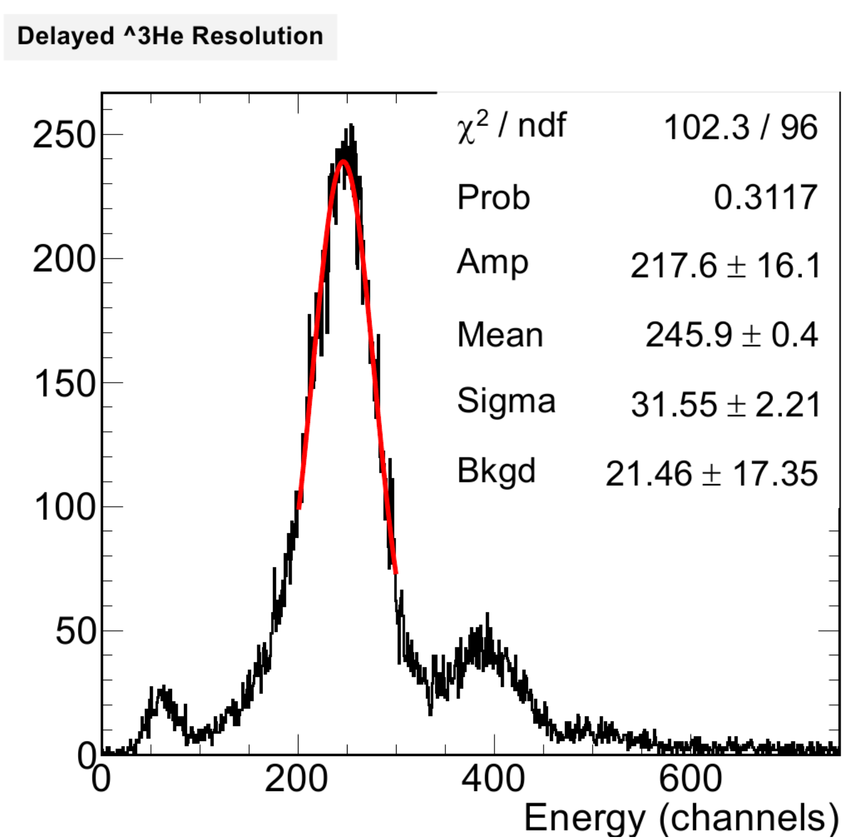


Promotes early decays: Lambda++

Particle energies

Pile-up with
the
muon pulses

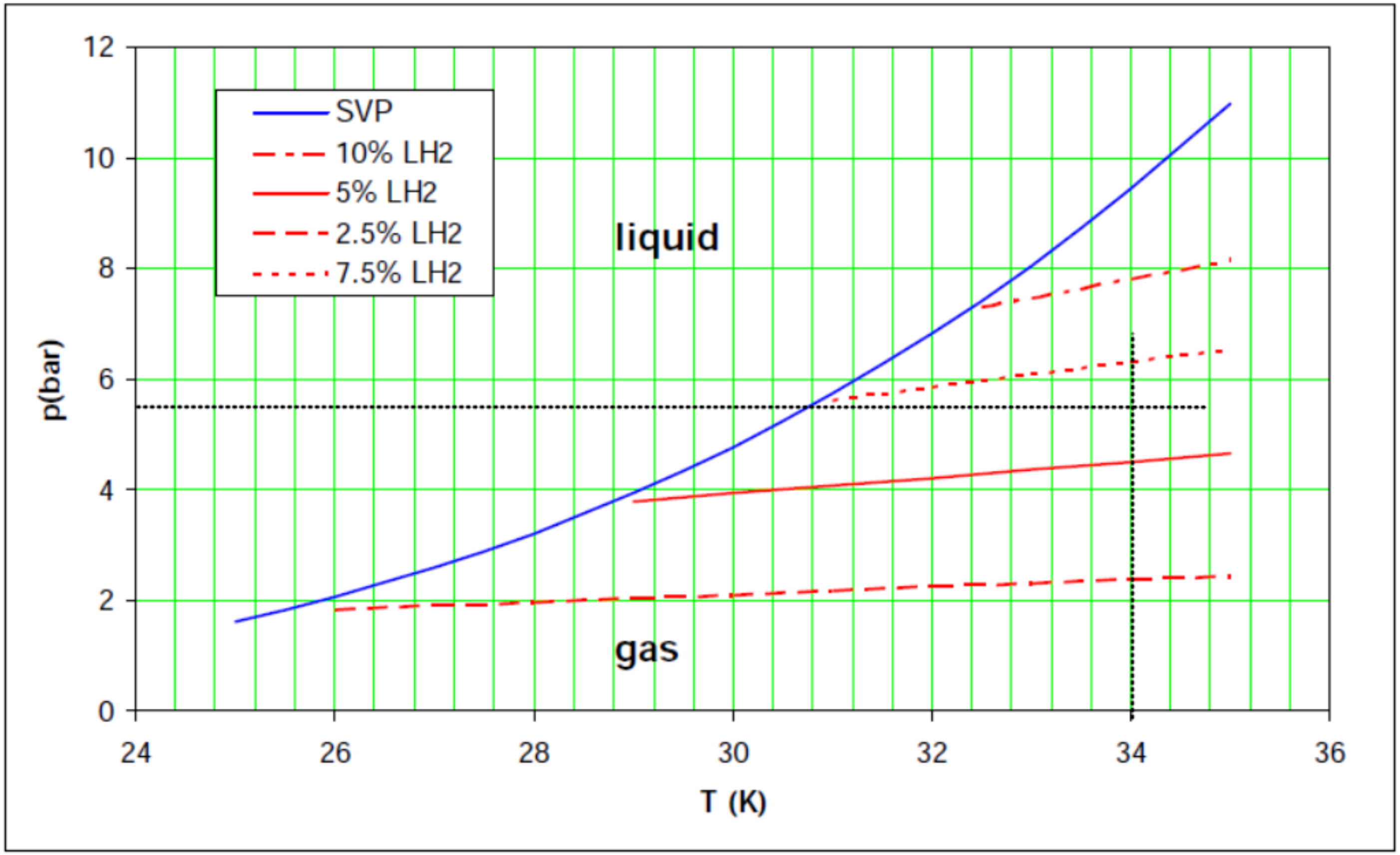




3us delayed from muon stop

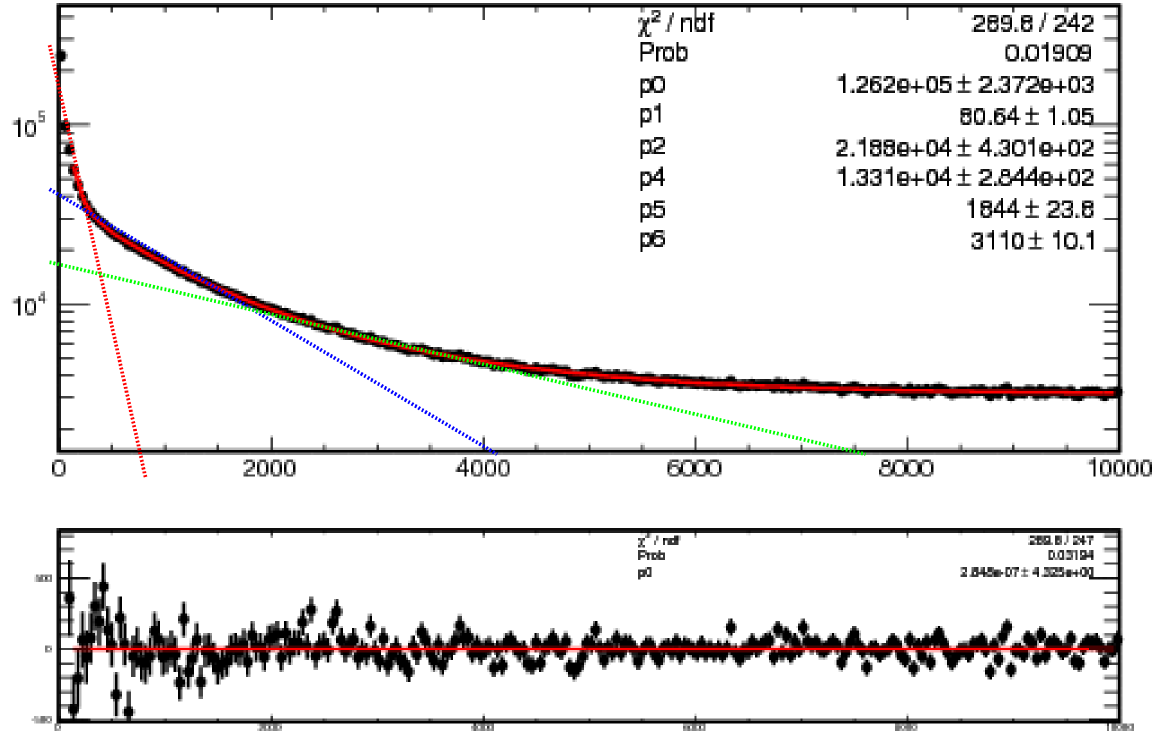
Phase diagram

- Experiment operates at T=34K, P=6 bar, ϕ=6%LHD
- We've explored the D2 phase diagram a little.
- 31 - 50 K
- 4 - 9 bar
- 5 - 11% density



Stops in other materials

- Capture rate, ΛZ ~ Z^4
- High Z captures quickly – start fit later
- Very low Z has small capture rate – small effect
- Medium-Z is the worst (eg. Si, Al, Cr, Cu)



Muon kinetics