MuSun

Precision muon capture on the deuteron

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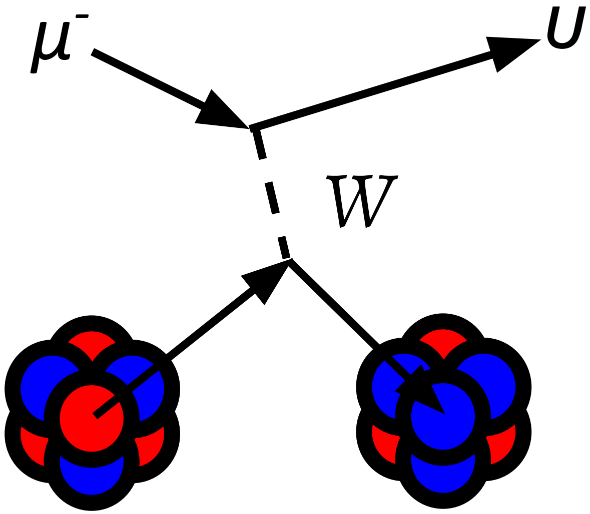
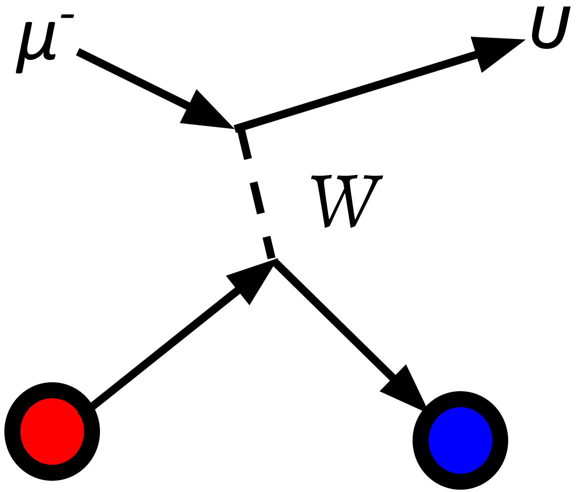
Muon capture



$q^2 \sim m_\mu^2$

Z (Z_{eff})	Element	Mean-life (ns)	Capture rate $\times 10^3 (\mathrm{s}^{-1})$	Huff factor
	μ^+	2197.03 (4)	455.16	
1 (1.00)	^{1}H	2194.90 (7)	0.450 (20)	1.00
	^{2}H	2194.53 (11)	0.470 (29)	
2 (1.98)	^{3}He	2186.70 (10)	2.15 (2)	1.00
	^{4}He	2195.31 (5)	0.356 (26)	
3 (2.94)	^{6}Li	2175.3 (4)	4.68 (12)	1.00
	^{7}Li	2186.8 (4)	2.26 (12)	
4 (3.89)	^{9}Be	2168 (3)	6.1 (6)	1.00
5 (4.81)	^{10}B	2072 (3)	27.5 (7)	1.00
	^{11}B (lhfs)	2089 (3)	23.5 (7)	1.00
6 (5.72)	^{12}C	2028 (2)	37.9 (5)	1.00
	^{13}C	2037 (8)	35.0 (20)	
7 (6.61)	^{14}N	1919 (15)	66 (4)	1.00
8 (7.49)	^{16}O	1796 (3)	102.5 (10)	0.998
	^{18}O	1844 (5)	88.0 (14)	
9 (8.32)	^{19}F (lhfs)	1463 (5)	229 (1)	0.998
13 (11.48)	^{27}Al (lhfs)	864 (2)	705 (3)	0.993
14 (12.22)	^{28}Si	758 (2)	868 (3)	0.992
20 (16.15)	Ca	334 (2)	2546 (20)	0.985
40 (25.61)	Zr	110.4 (10)	8630 (80)	0.940
82 (34.18)	Pb	74.8 (4)	12985 (70)	0.844
83 (34.00)	Bi	73.4 (4)	13240 (70)	0.840
90 (34.73)	Th	77.3 (3)	12560 (50)	0.824
92 (34.94)	U	77.0 (4)	12610 (70)	0.820

Single-nucleon capture in MuCap

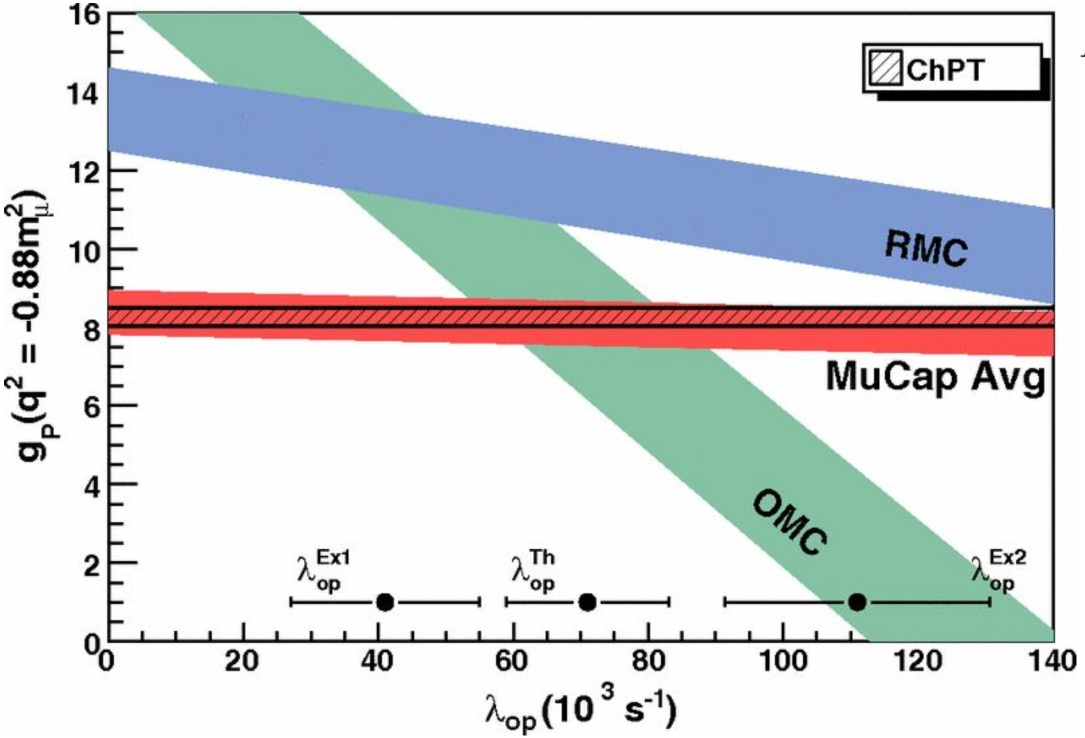


$q^2 = 0.88 m_\mu^2$

$$\bar{u}_n\Big(+ g_v\gamma^\mu + \frac{i g_m}{2m_N}\sigma^{\mu\nu}q_\nu + \frac{g_s}{m_\mu}q^\mu - g_a\gamma^\mu\gamma_5 - \frac{g_p}{m_\mu}q^\mu\gamma_5 - \frac{i g_t}{2m_N}\sigma^{\mu\nu}q_\nu\gamma_5\Big)u_p$$

With axial-vector charge as input, muon capture offers insight into the induced pseudoscalar coupling

Single-nucleon capture in MuCap

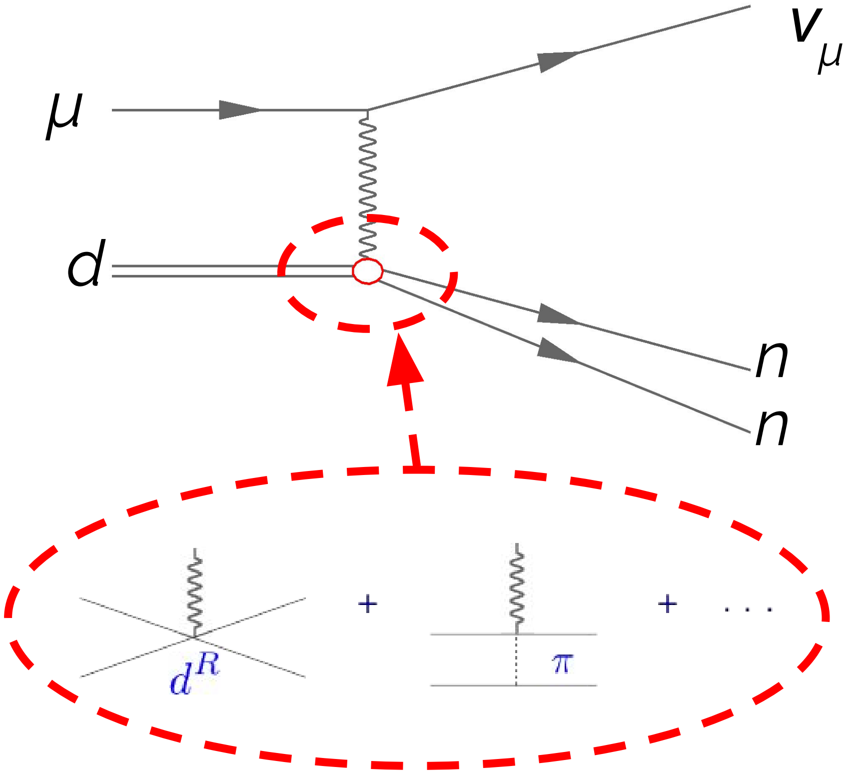


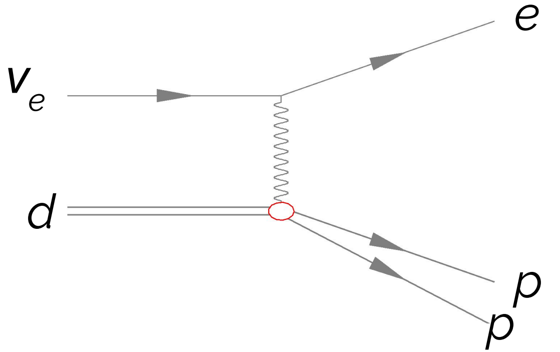
$$\Lambda_S^{\text{MuCap}} = 714.9 \pm 5.4_{\text{stat}} \pm 5.1_{\text{syst}}\ \text{s}^{-1}$$

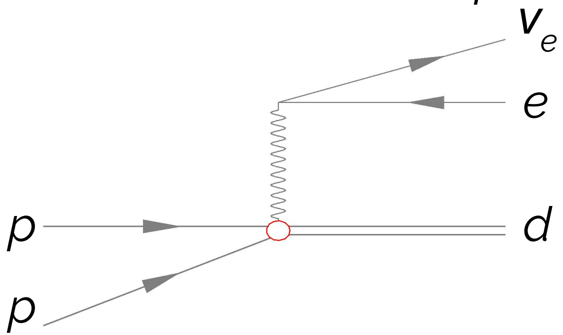
- Excellent agreement with chiral perturbation theory prediction
- Leverages an ultra-high purity hydrogen time projection chamber

What else can we learn from precision muon capture?

μ-d capture and chiral effective field theory

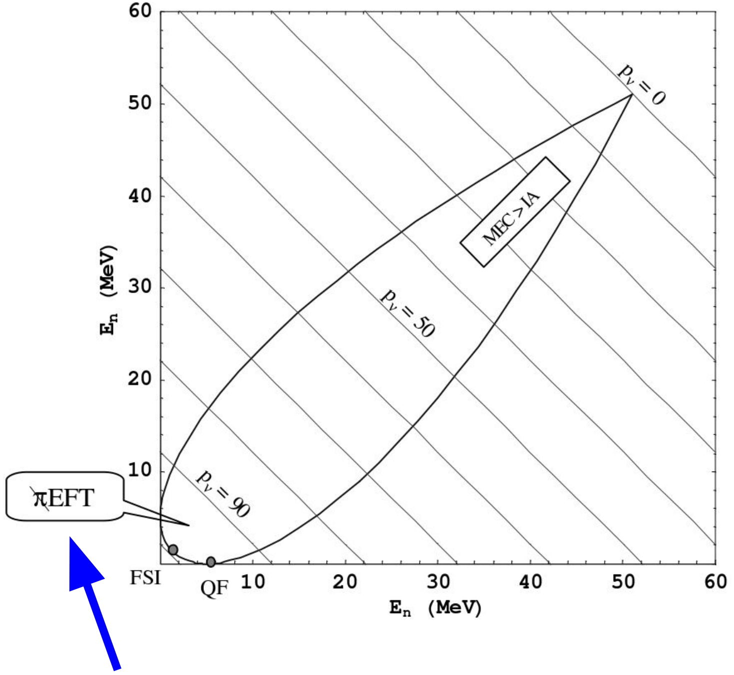


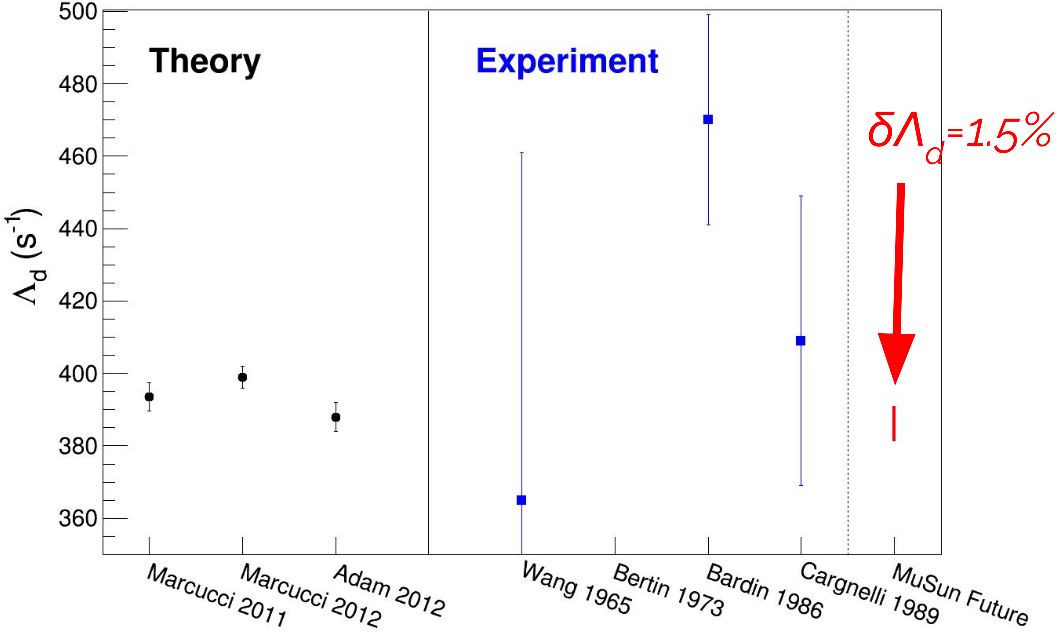




probe of two-body axial current,
relating other weak two-body reactions

The MuSun measurement





single contact term L_{1A}

By the numbers

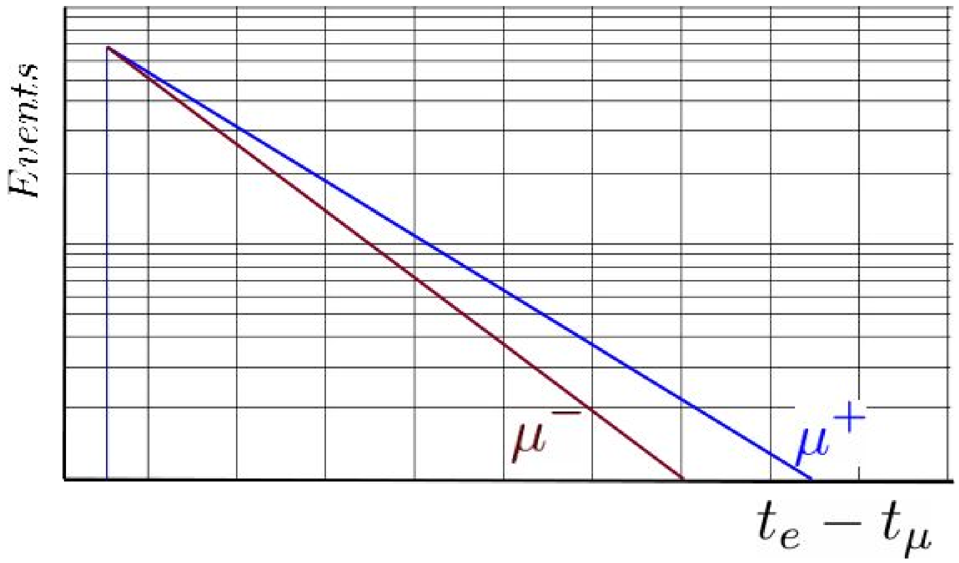
	method	L_{1A} (fm^3)
two-body		
	reactor $\bar{\nu} + d$	3.6 ± 5.5 [11]
	ES, CC, NC in SNO	4.0 ± 6.3 [41]
	MuSun proposal	$\pm$**1.25**
three-body		
	tritium beta decay	4.2 ± 3.7 [11], 4.2 ± 0.1 [41]
other		
	helioseismology	4.8 ± 6.7 [42]

The lifetime method

$$e^{-(\lambda_{\mu^+}+\Lambda_D)t}$$

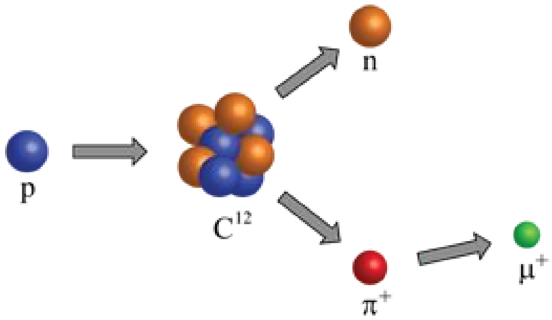
- measure μ^- lifetime in D_2 gas
- compare to known free μ^+ lifetime
- free decay 1000 times faster!
- 1.5% measurement of Λ_D requires ~10^{-5} precision in disappearance rate!

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



no charged particles in the final state
It's either this, or count fast neutrons
with known efficiency

μ production at the Paul Scherrer Institute



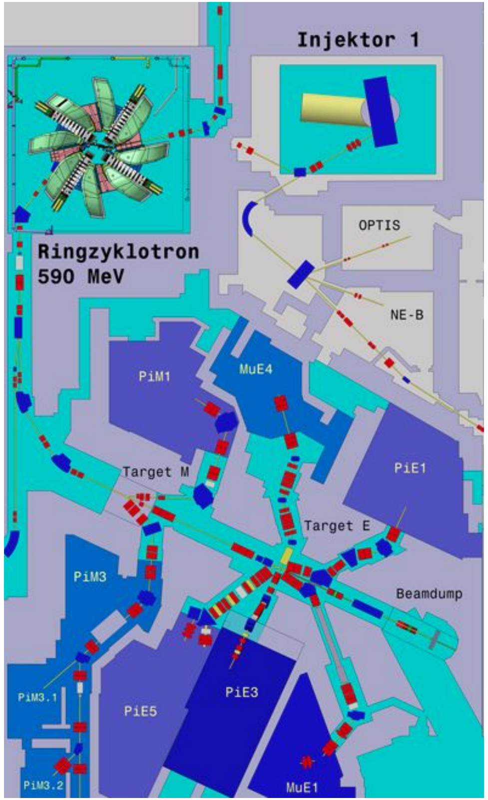
590 MeV protons on carbon target

⇩

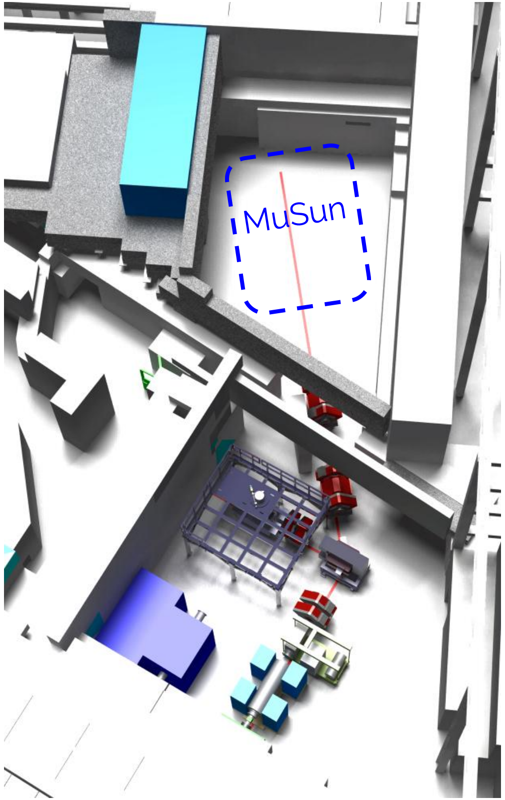
stopped pions

⇩

decay into muons



πE1 at the Paul Scherrer Institute

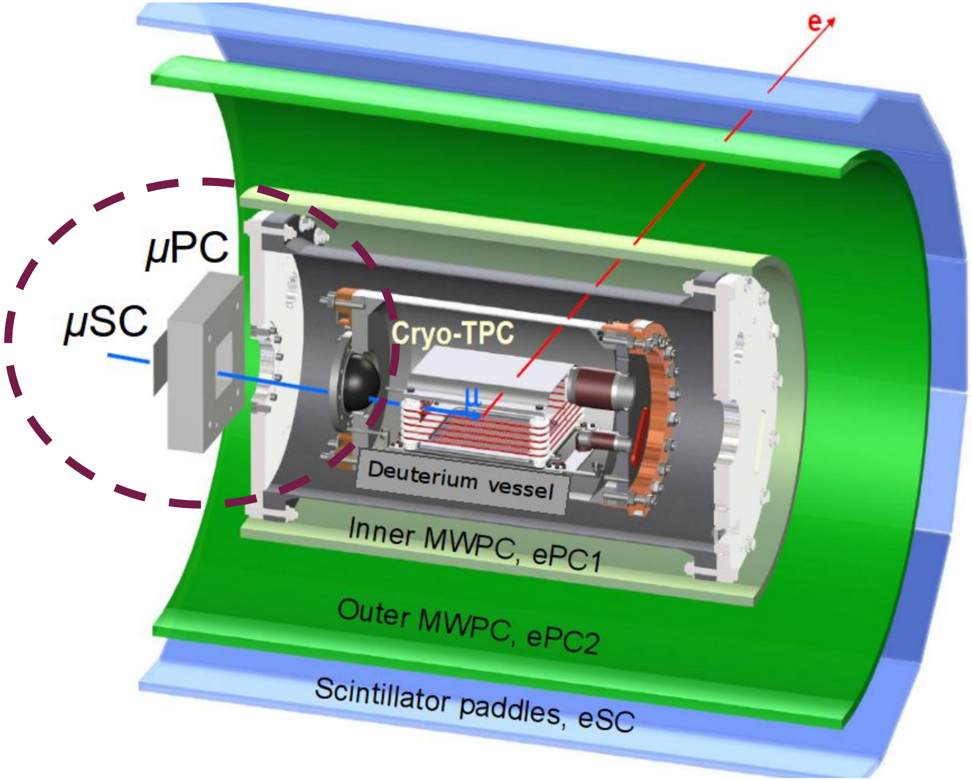


- ~few MeV muons (p~40 MeV/c)
- Electrostatic beam kicker for one muon at a time
- $E \times B$ separator to remove electron contamination


Greetings from Villigen

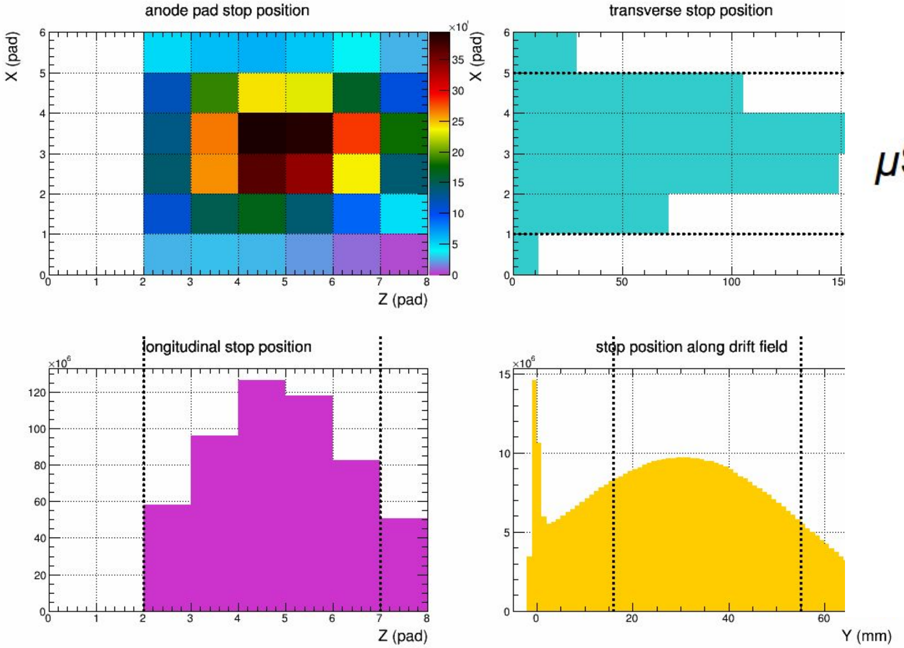
Muons enter the apparatus at t_{start}

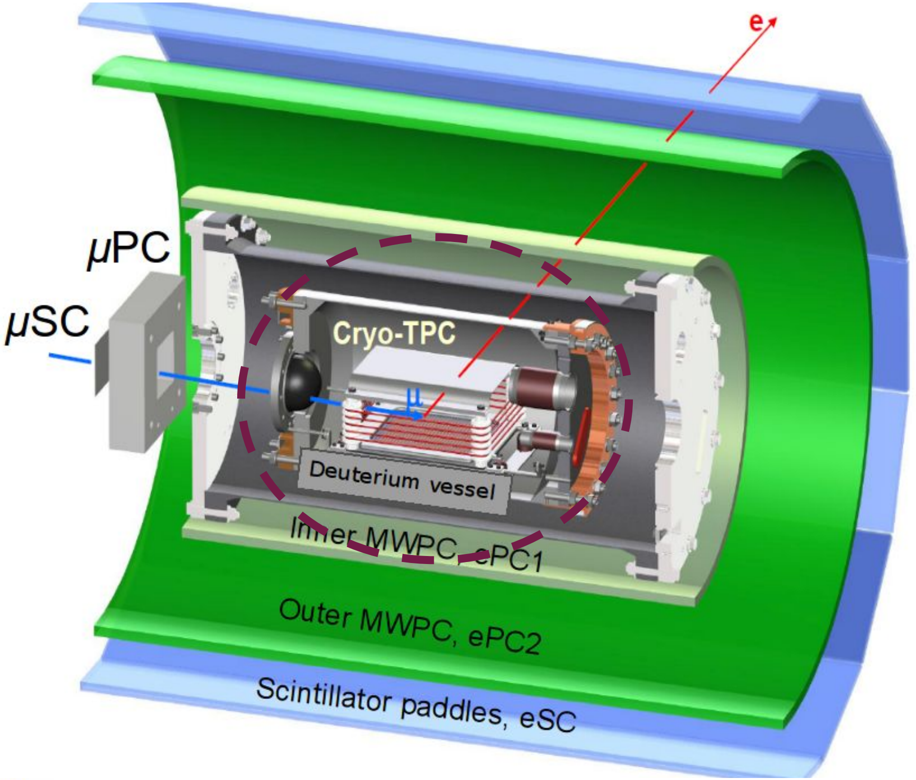
- fast scintillator to set t=0
  - send signal to beam kicker -- one μ at a time
- MWPC for beam profile
- annular scintillator for veto
- thin beryllium window to enter D_2 volume



Muons stop in D_2 gas

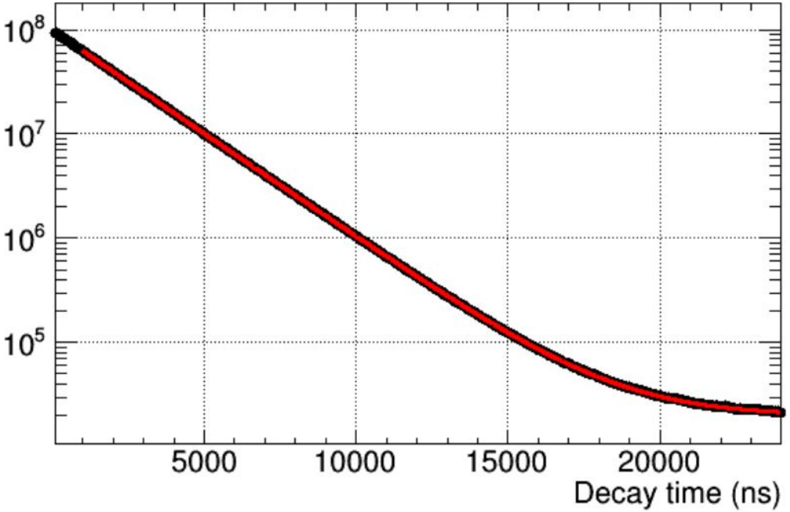
- 48 anode ion chamber
- reconstruct *x*-*y*-*z* position
- make fiducial cuts

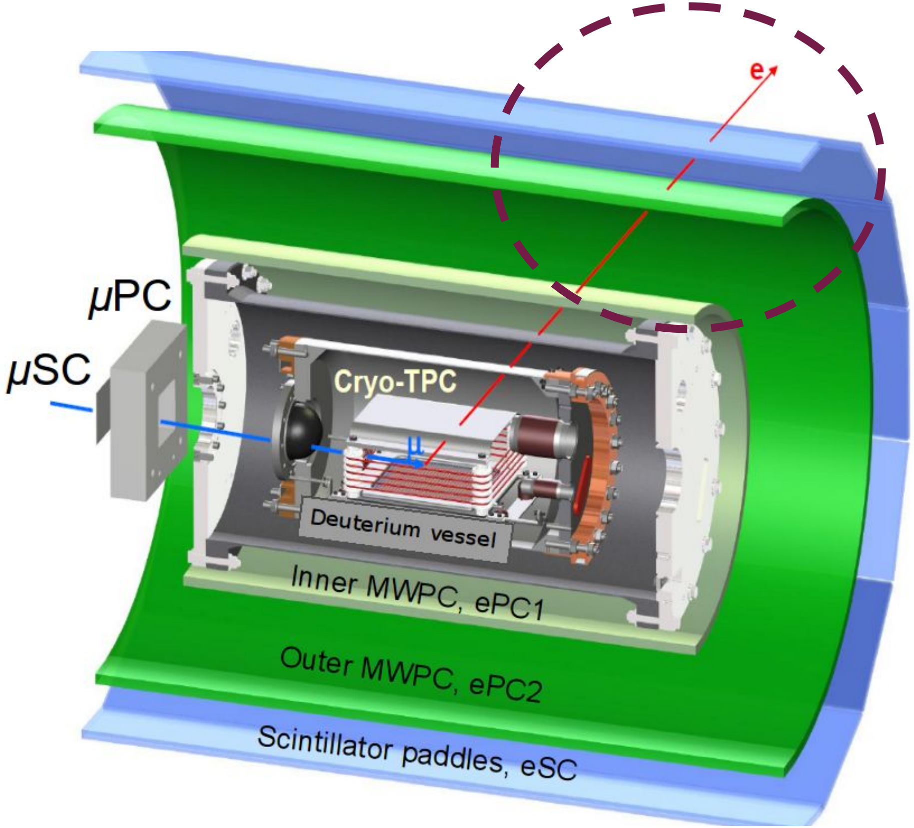


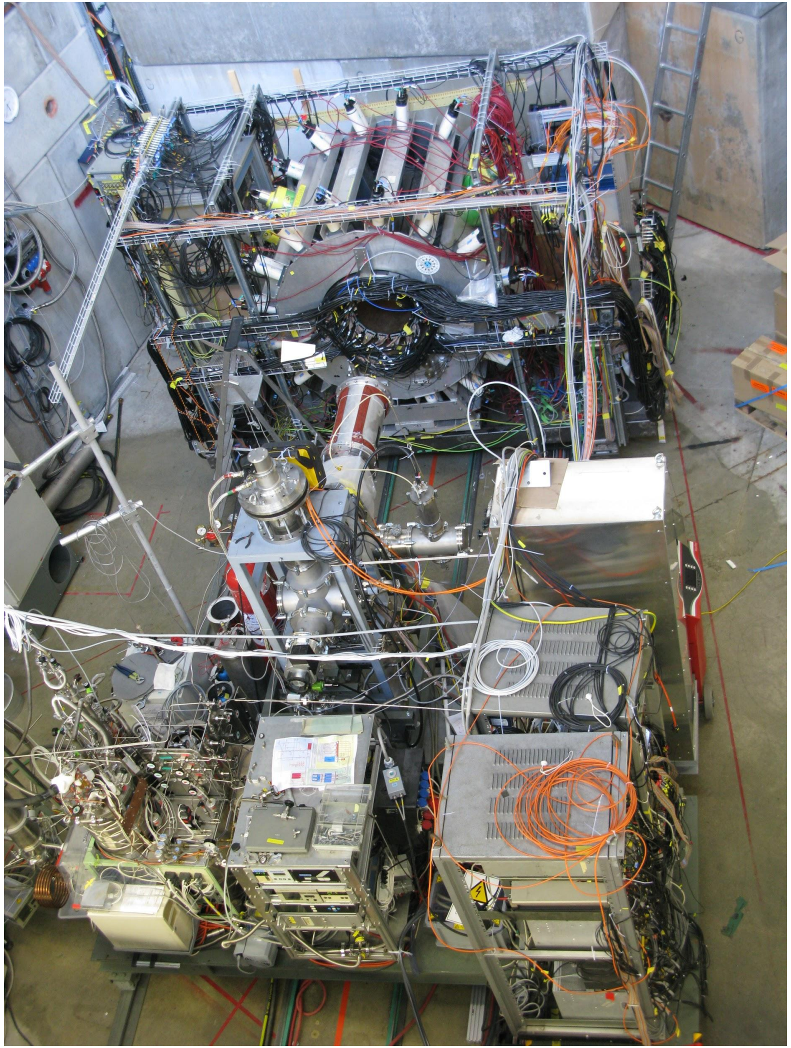


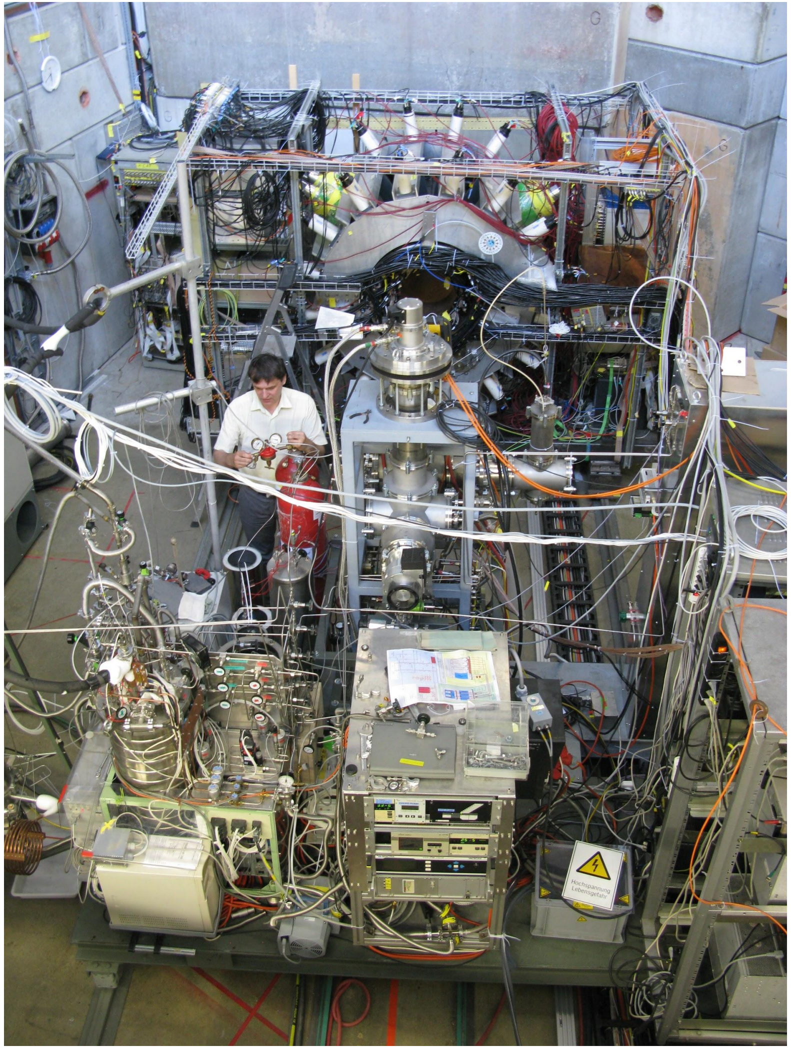
Muons decay at t_{stop}

- 32 scint. paddles for timing
- track reconstruction using two cylindrical MWPCs

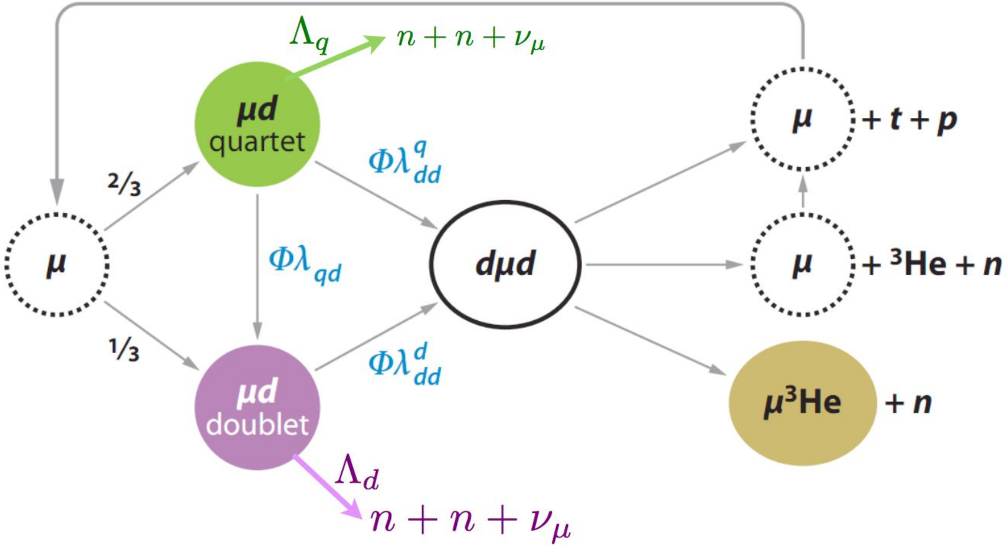


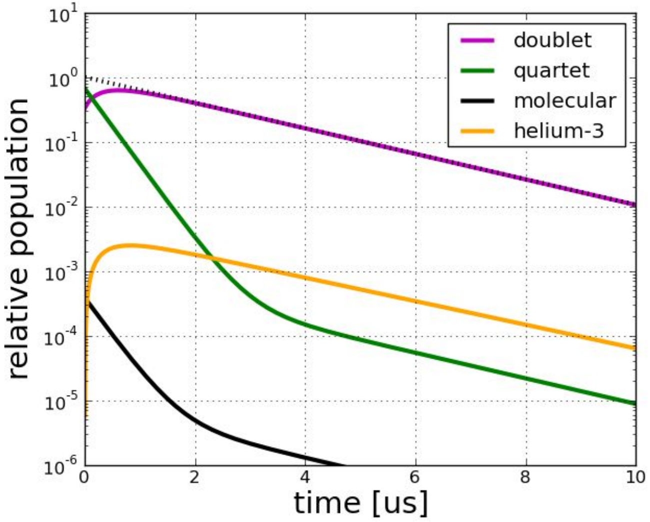





Hochspannung
Lebensgefahr

Muon kinetics in deuterium

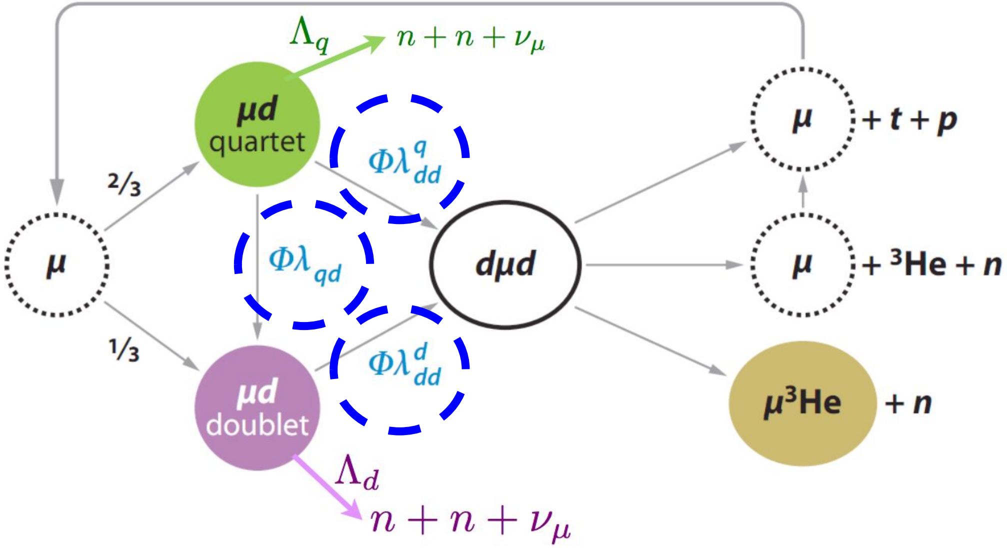


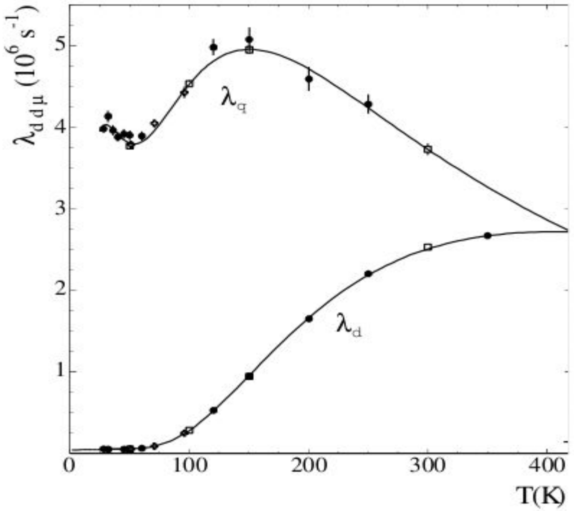


- statistical population of *μd* states
- hyperfine transition to doublet state
- *dμd* forms ~5% of the time (mostly from quartet), m.c.f
- most are recycled to *μd* to start cycle again

We want to maximize population of doublet state

Muon kinetics in deuterium





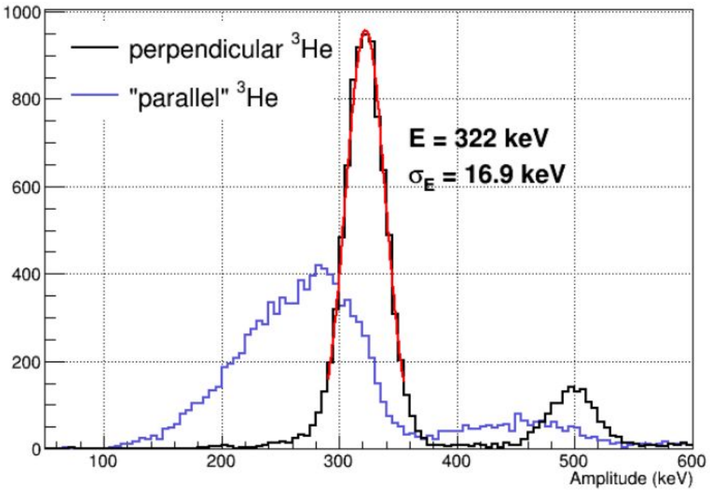
- doublet to quartet rate suppressed at low *T*
- resonant molecular formation (*T* dependence)
- density dependence

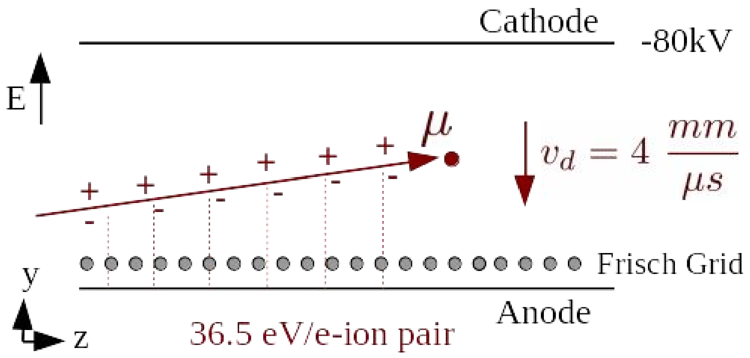
- *P*=5 bar
- *T*=31 K

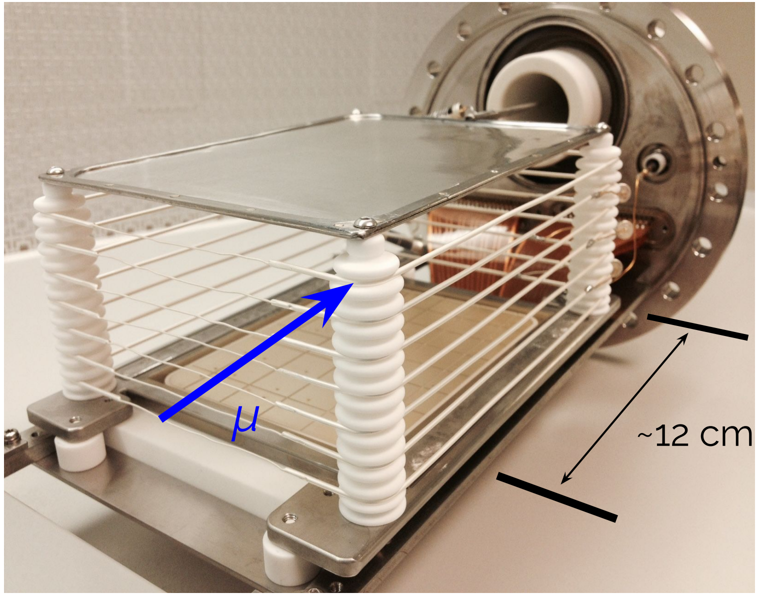
⟺ *φ*=6%

Ultrapure cryo-TPC

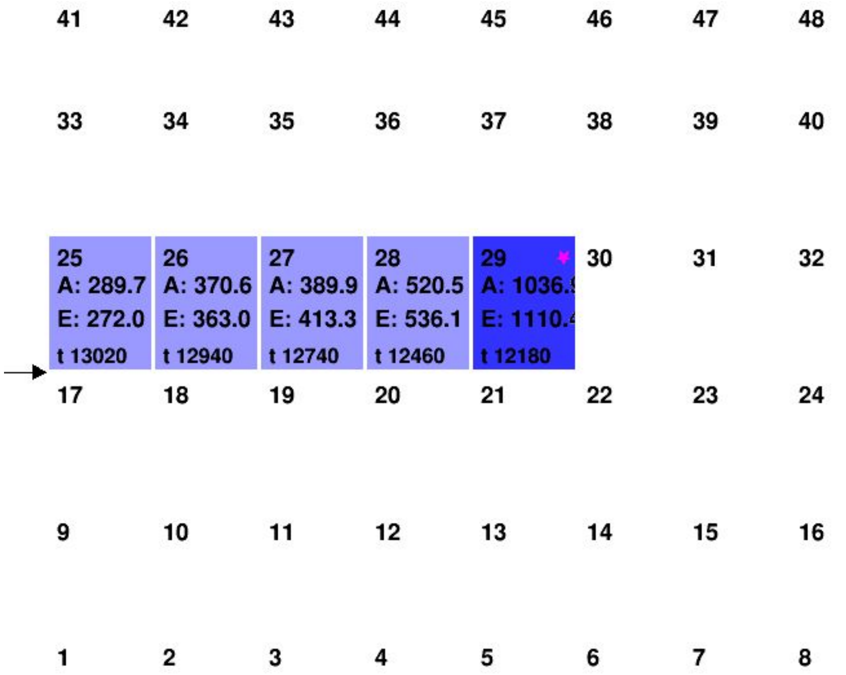
- High *Z* materials
  - Ag cathode
  - Ag plated Cu anode
  - Ag/Au-plated W wires
- Low-noise cryo-preamps

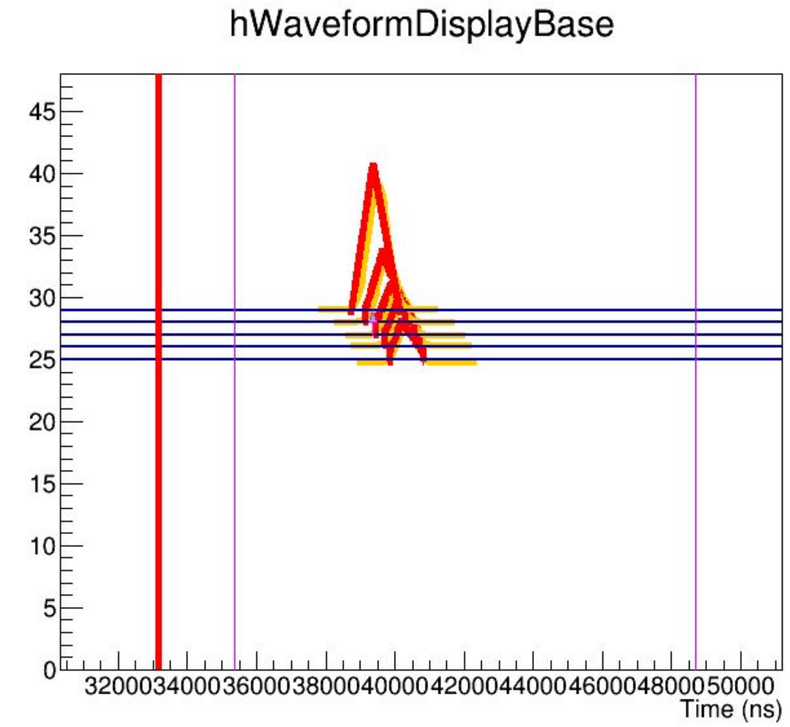




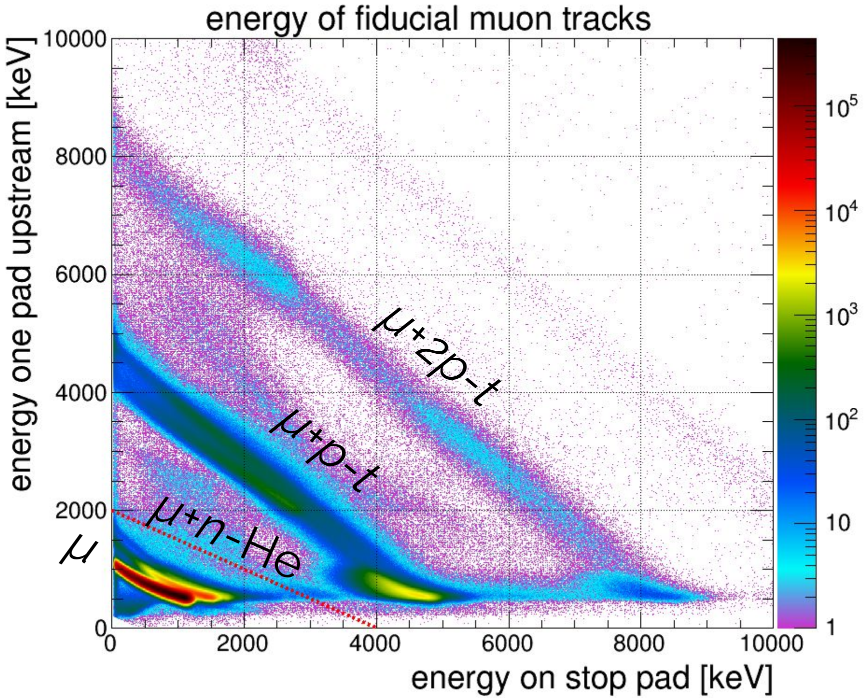


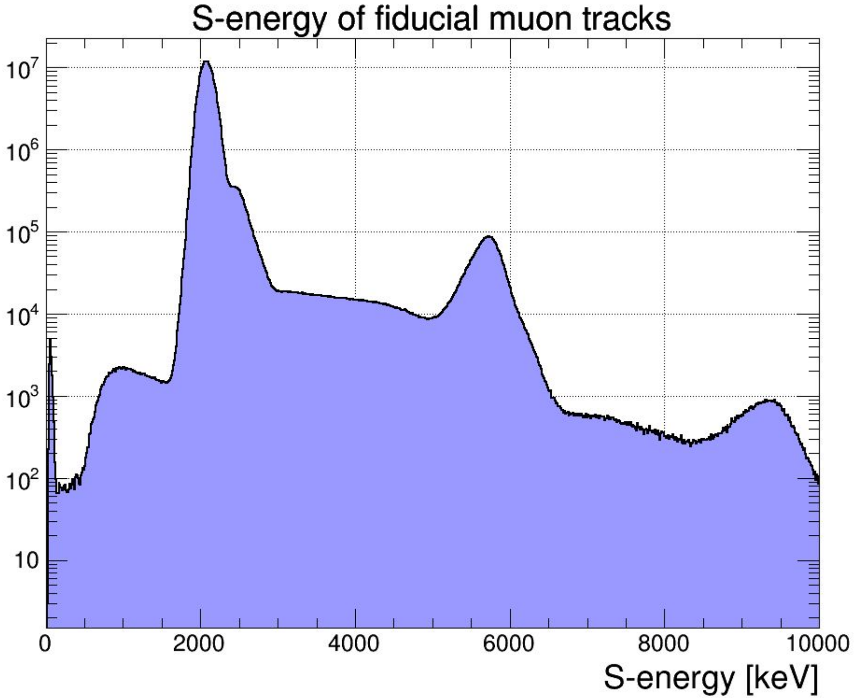
Tracking muons



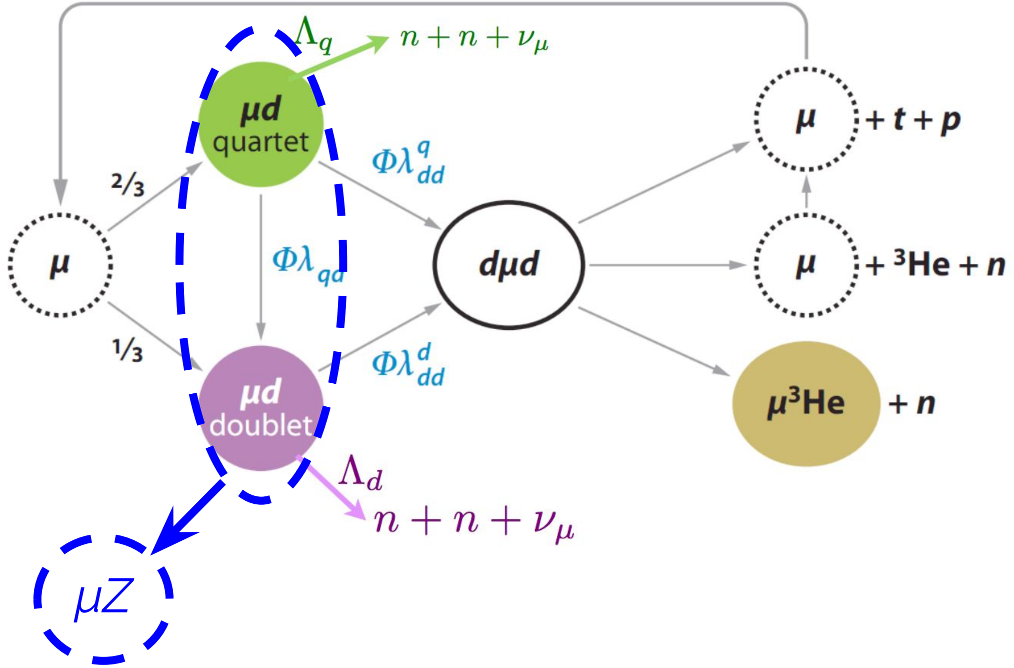


Events in the TPC

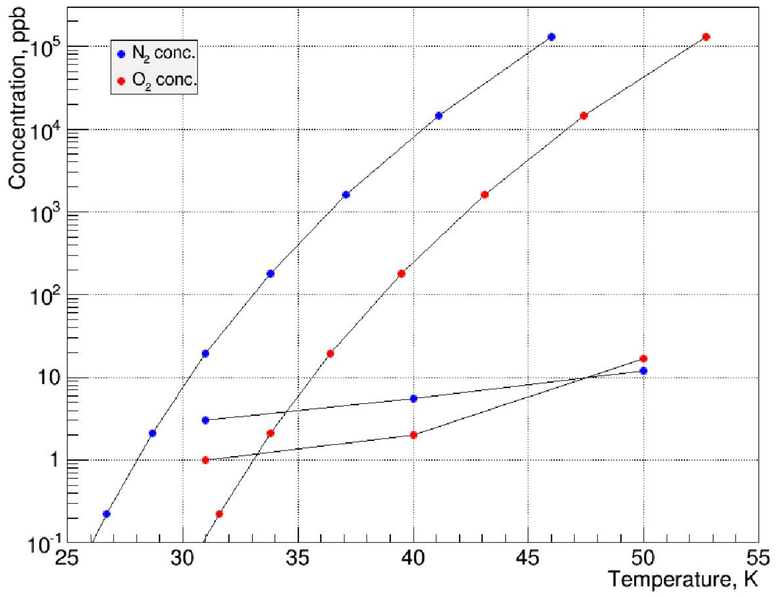




Target purity

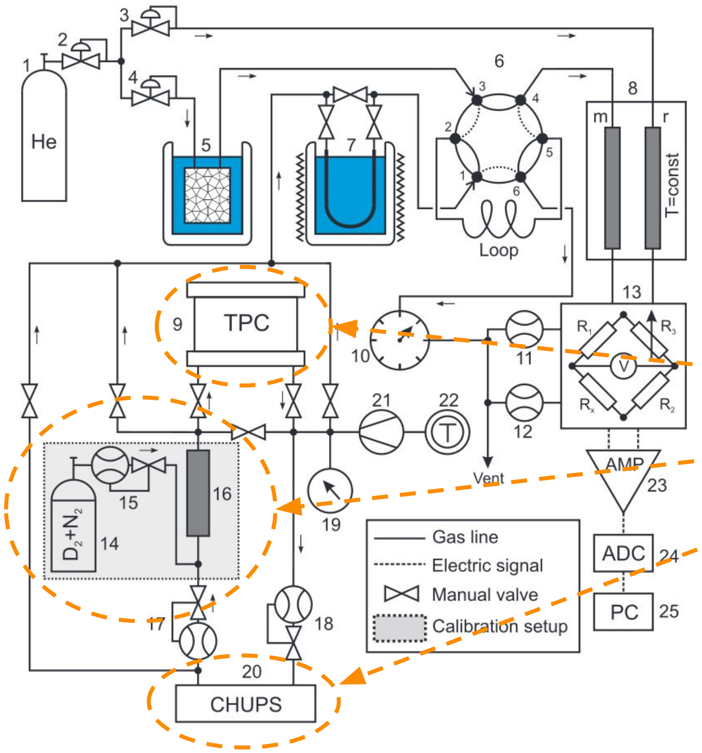


1 ppb N_2 ⇒ $\Delta\Lambda_d$~3 s^{-1}



CHUPS and gas chromatography

Chromatography



cryo-distillation
for <100 ppb H_2

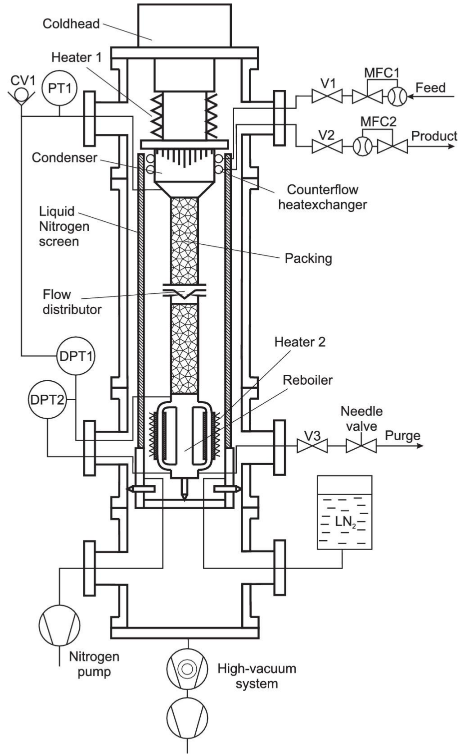
5 l/min continuous flow

impurity injection for calib.

zeolite filtration

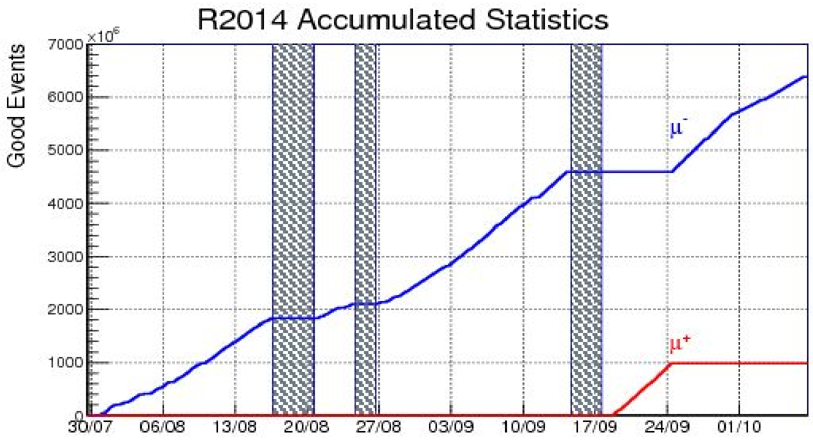
~1 ppb purity and measurement sensitivity!

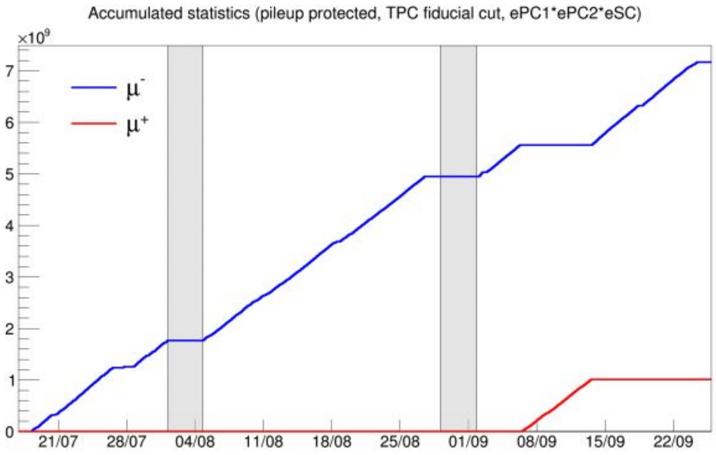
Isotope separation



Production runs and statistics

- Production runs in 2014 & 2015
- ~3 kHz fid. vol μ^- ⇒ ~10^9 evt/week
- Have 10^{10} candidate events in hand!
- μ^+ useful for systematic checks

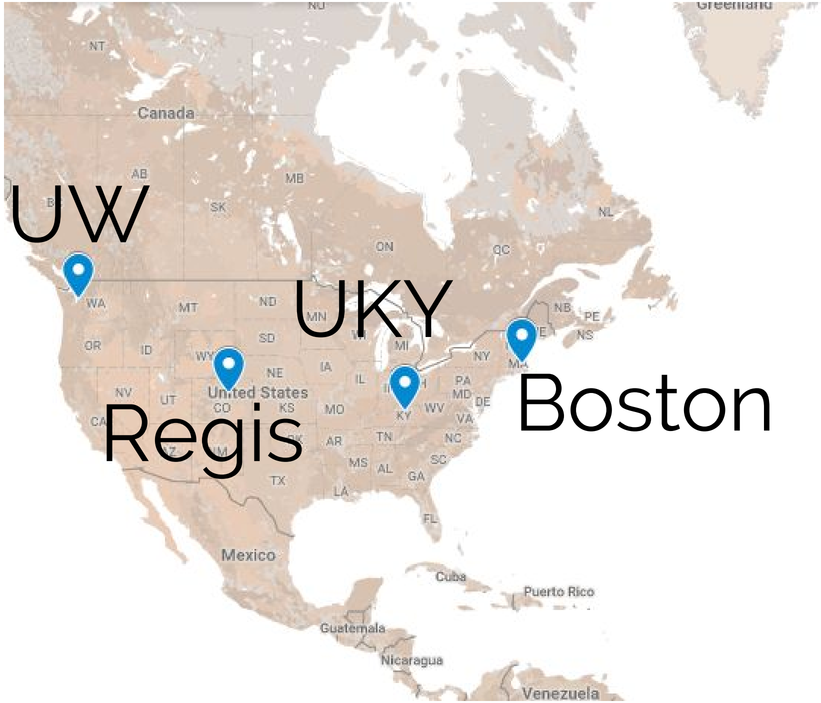




Outlook

- MuSun offers a unique glimpse into the nucleus
  - first determination of d^R in the two-nucleon system, leading to robust understanding of solar fusion and CC *v-d* cross section
- with a unique experiment comes unique challenges
  - developed techniques to understand muon kinetic/fusion effects
  - path forward on constraining backgrounds, wall stops, impurities
- $\sim 12 \cdot 10^9$ events in the bag
  - potential prelim. result from 2014 soon, 2015 analysis underway

MuSunnies



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