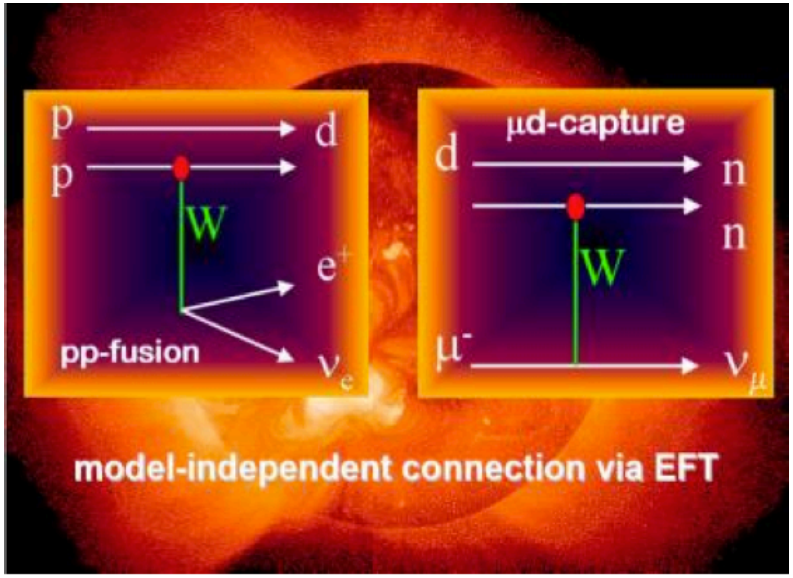
MuSun: Muon Capture on the Deuteron



ICNFP 2014 Crete

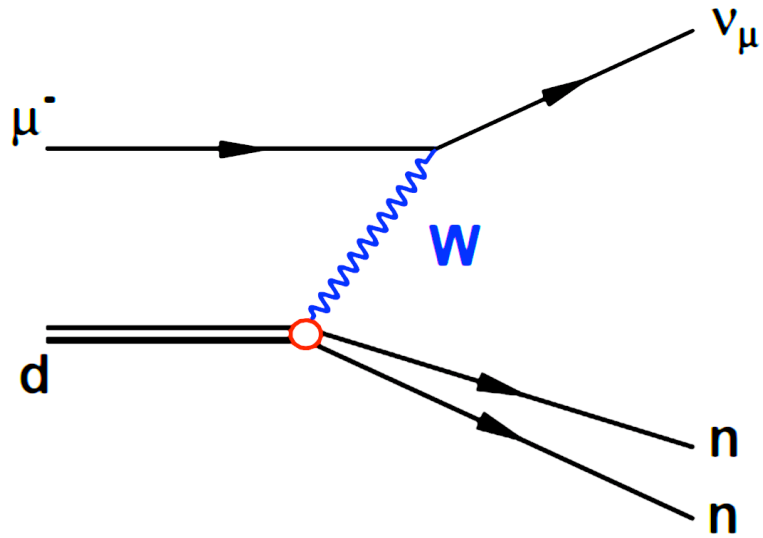
Xiao Luo (Boston University)

On behalf of the MuSun collaboration

MuSun Goal

Measure the rate Λ_d for muon capture on the deuteron to better than 1.5% precision.

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

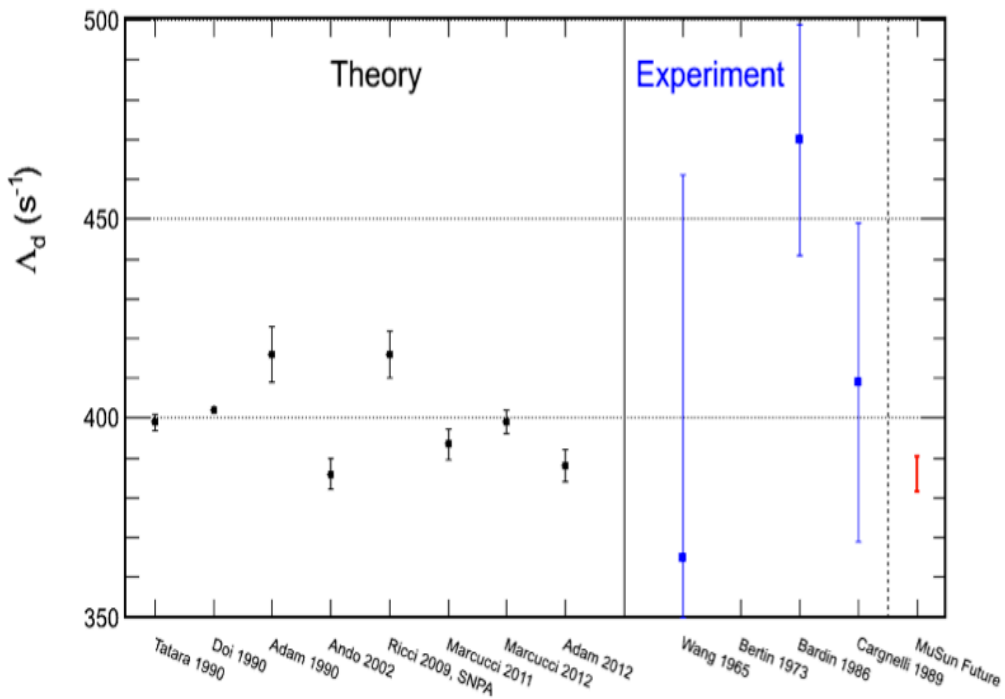


Note: Λ_d denotes the capture rate from the doublet hyperfine state of the muonic deuterium atom in its 1S ground state.

Physics Motivation

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

- ✔ Simplest process on a compound nucleus that can both be calculated and measured to a high degree of precision.
- ✔ The discrepancy between theoretical and experimental results requires better precision measurement. (2.9σ)
- ✔ Clean and accurate channel to determine the Low Energy Constant (LEC) in Effective field theory.
- ✔ Astrophysical & neutrino interests: processes such as pp fusion and neutrino deuterium scattering are closely related to mud capture.



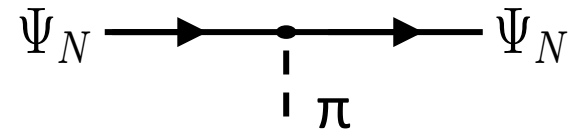
ChPT Lagrangian

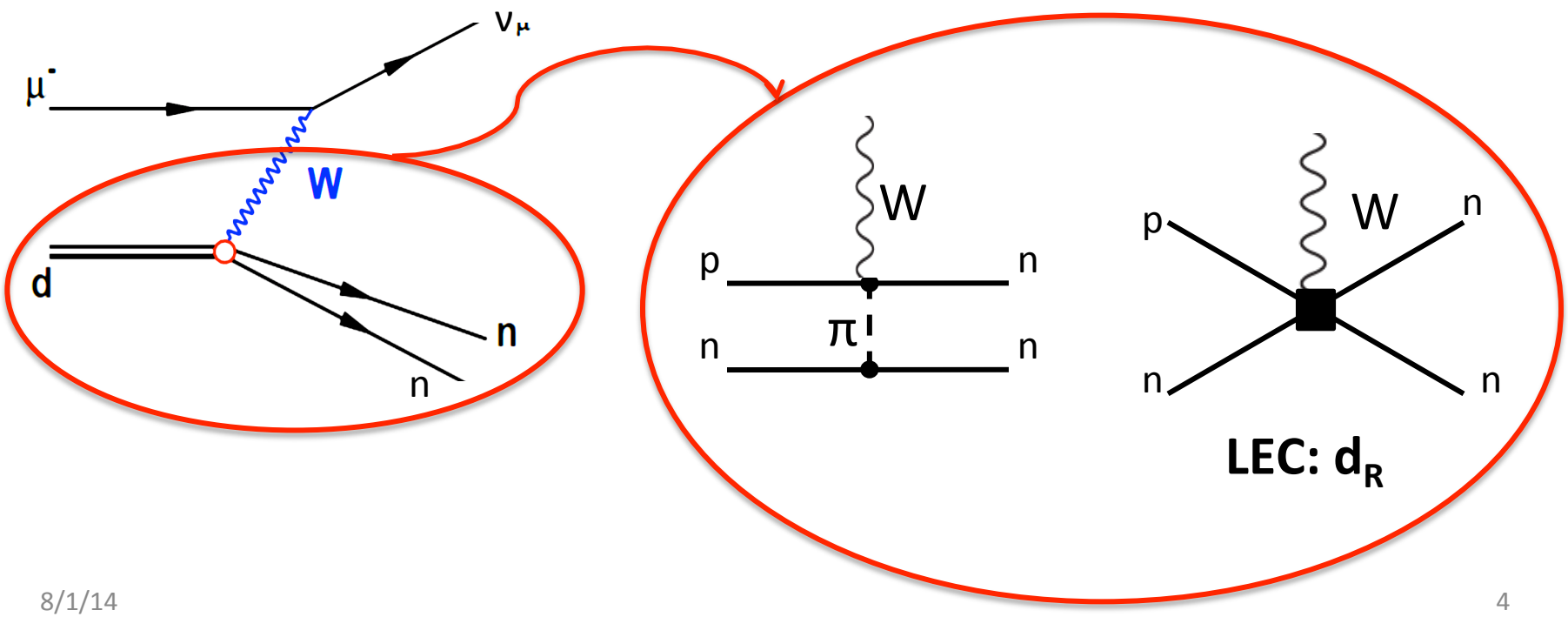
$$\mathcal{L}_{eff} = \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(3)}_{\pi N} + \ldots$$

$$\mathcal{L}^{(1)}_{\pi N} = \bar{\Psi}(iD_\mu\gamma^\mu - M_N + \frac{g_A}{2}u_\mu\gamma^\mu\gamma_5)\Psi$$

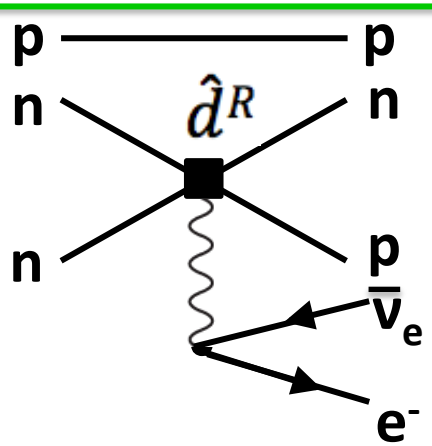
$$\mathcal{L}^{(2)}_{\pi N} = \sum_{i=1}^{7}\bar{\Psi}O^{(2)}_i\Psi$$

$$\mathcal{L}^{(3)}_{\pi N} = \sum_{i=1}^{23}\bar{\Psi}O^{(3)}_i\Psi$$



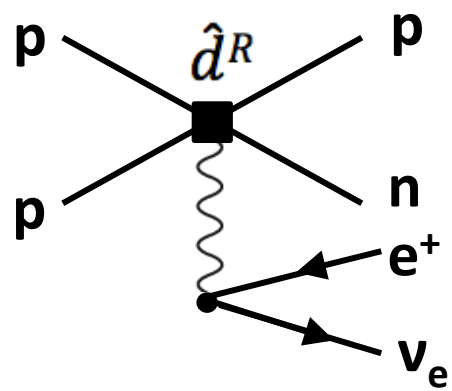


From ChPT to μ⁻d capture



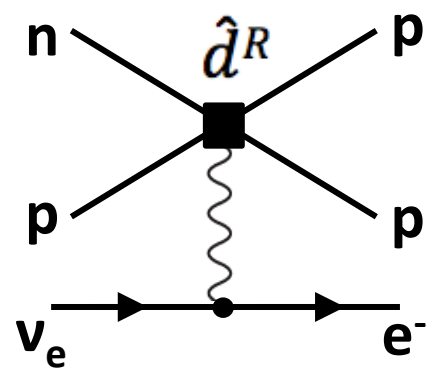
Triton β decay

$^3H \to ^3He + e^- + \bar{\nu}_e$



Solar pp fusion

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



SNO νd scattering

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

$\hat{d}^R$

Theory. flow

Ex.flow

$$M \propto \langle \Psi_{nn} | j^\alpha | \Psi_d \rangle \bar{\nu}_\mu \gamma_\alpha (1 - \gamma_5) \mu$$

Latest result: Λ_d = 399 ± 3 s⁻¹

$\Lambda_{\mu\text{-}d}$

Musun experiment (1.5%)

Experimental method: lifetime technique

Focus on sources of the muon disappearance:

Muon decay:

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

Muon capture:

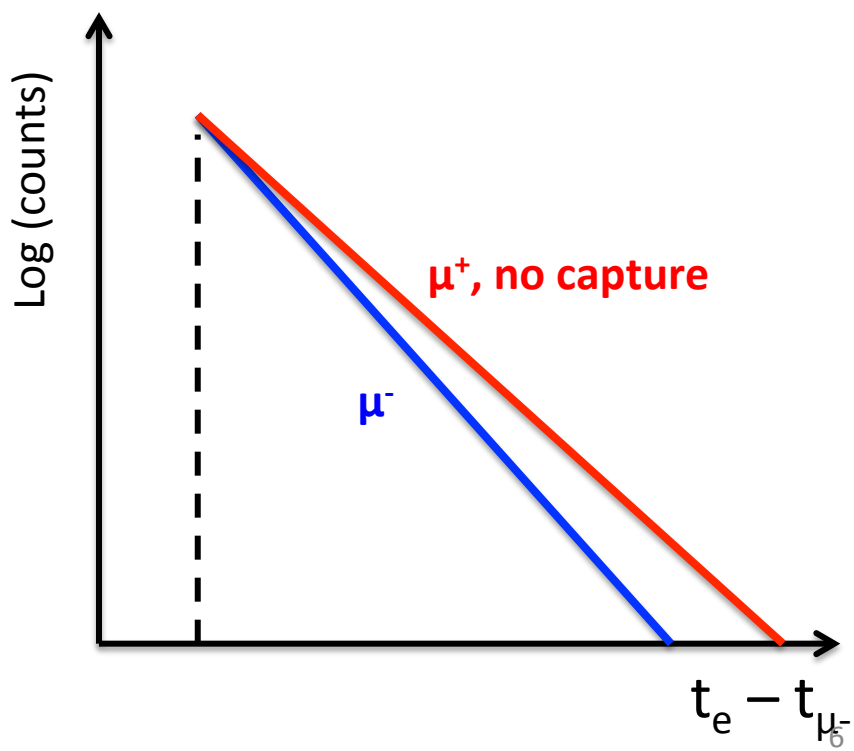
$$\mu^- + d \rightarrow \nu_\mu + n + n$$

$\Lambda_{\mu^-} = \Lambda_{cap} + \Lambda_{dec}$

$\Lambda_{\mu^+} = \Lambda_{dec}$ ~ 455kHz

$\Lambda_{cap} = \Lambda_{\mu^-} - \Lambda_{\mu^+}$ ~ 400Hz ± 6Hz

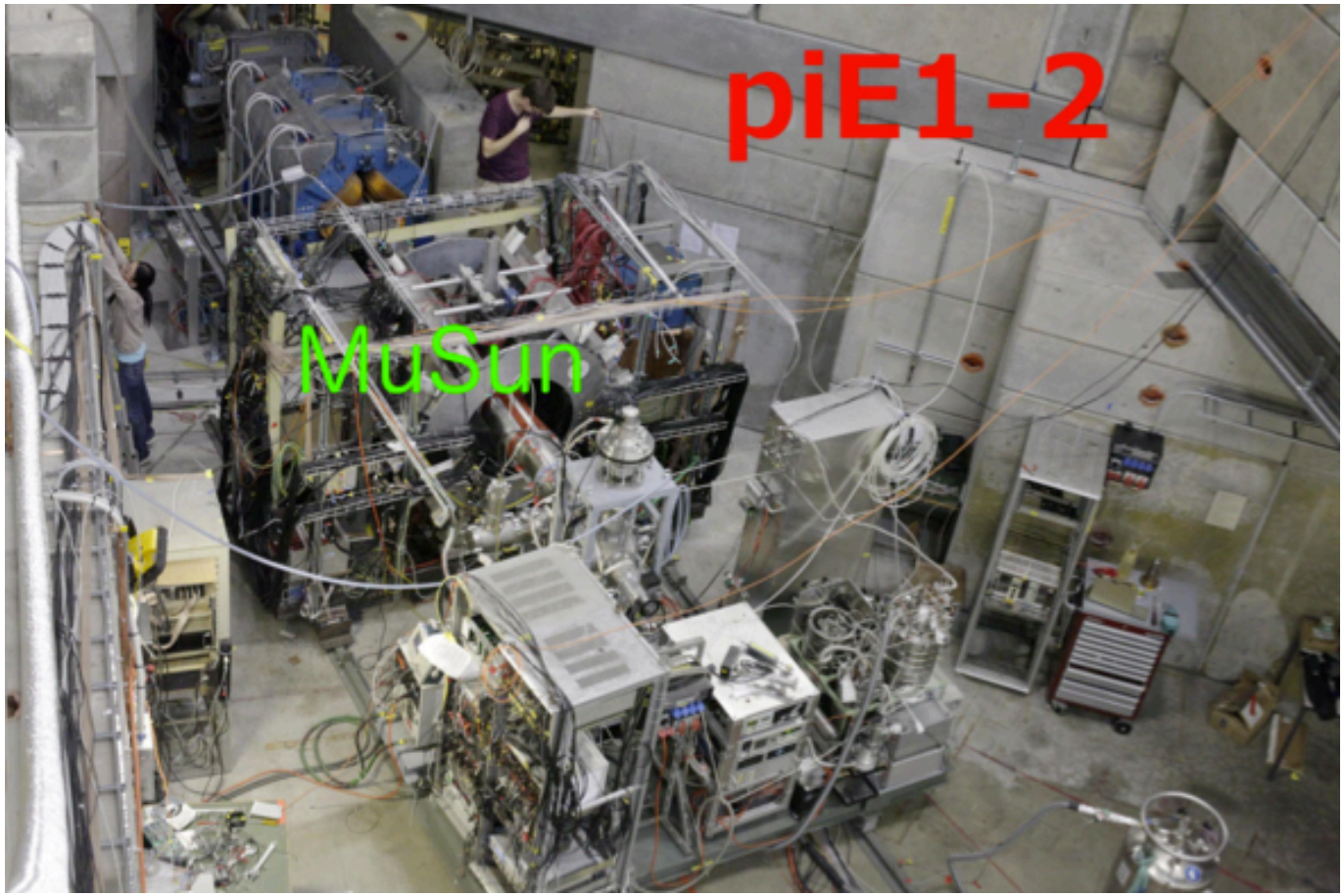
- Determine Λ_{cap} to 1.5% level.
- Measure Λ_{μ^-} to 10ppm.
- Require 10^{10} events.



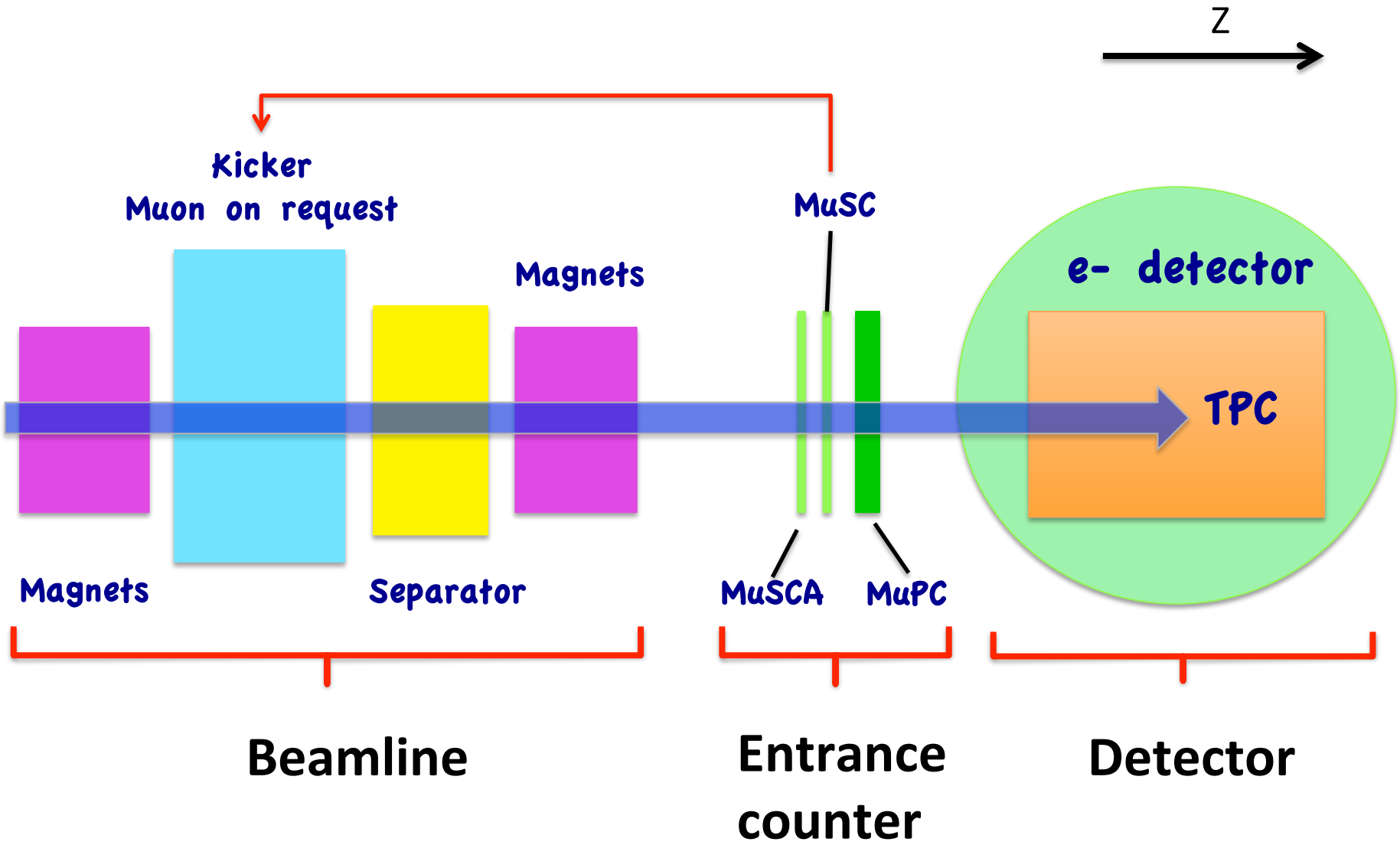
Experimental design

❖ **Intense low energy muon beam.**

Experimental setup



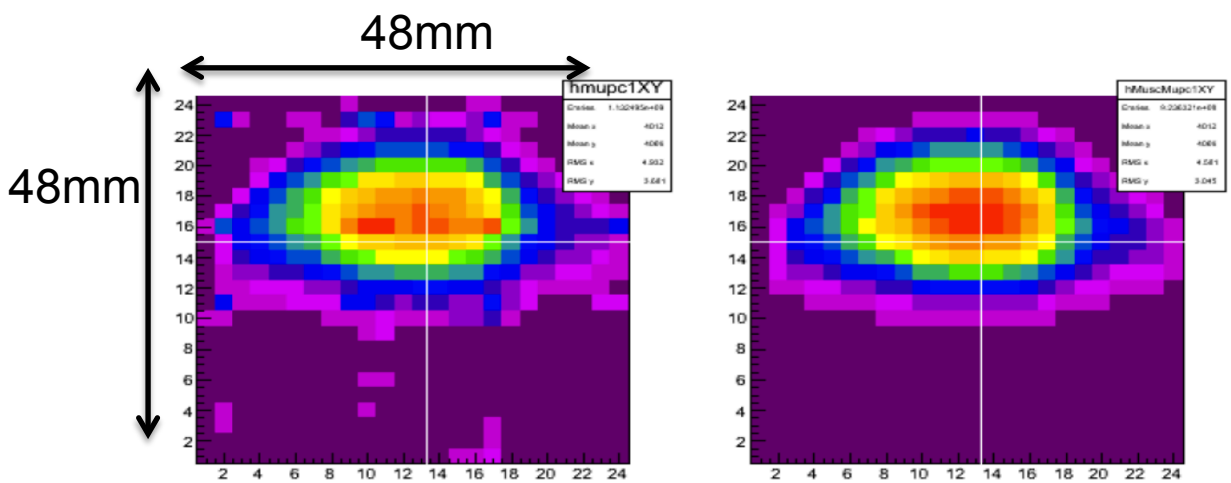
Experimental setup



Entrance counter

Goal: Identify good muon entrances and avoid pile-up. **t=0 for the experiment!**

μSC	+	μPC	+	!μSCA	+	Kicker
μ entrance time t = 0 for MuSun		Position		VETO		Pile-up

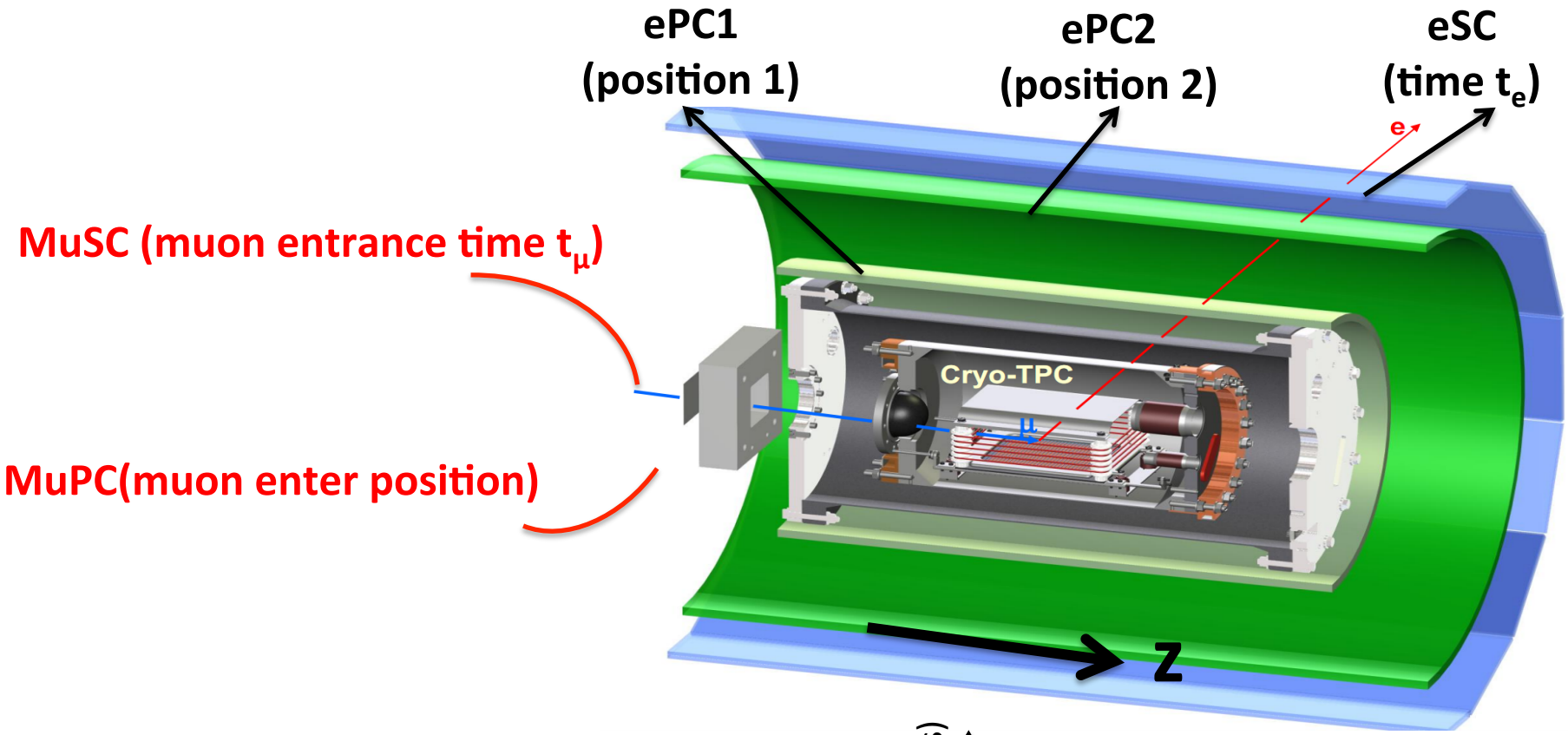


Raw μPC

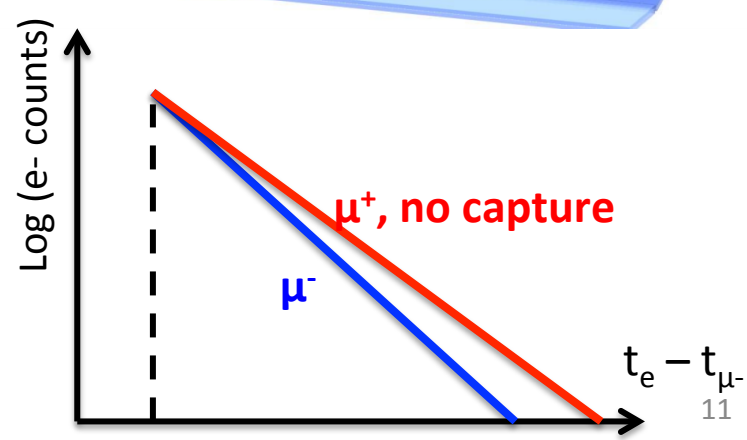
μPC && μSC

Good μ Entrance

Muon and Electron detector



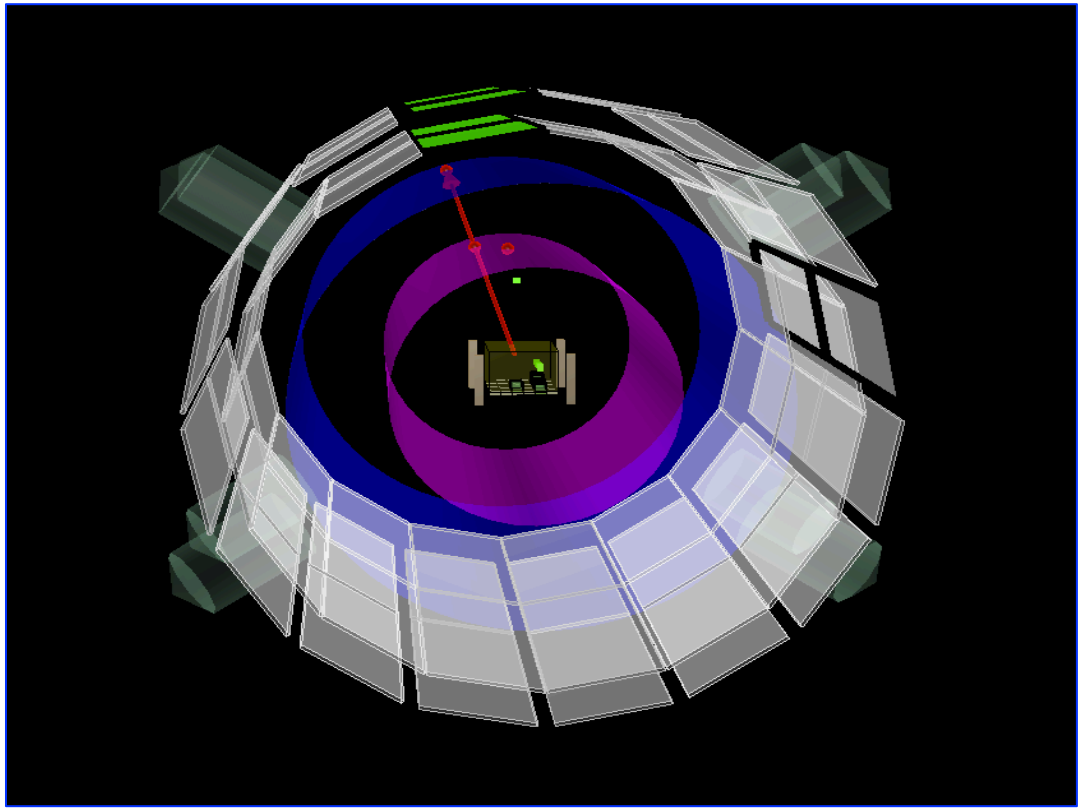
- ePC1 & ePC2: Wire chambers to get (r, Φ, Z), extrapolate decay e- track.
- eSC: 16 Scintillators segments, to determine the electron time.
- Lifetime technique: get t_e-t_μ , select "good" data to fill in lifetime histogram.



Electron detector

Goal: Identify electron tracks from muon decay

eSC	+	ePC1	+	ePC2
e time		Position		Position

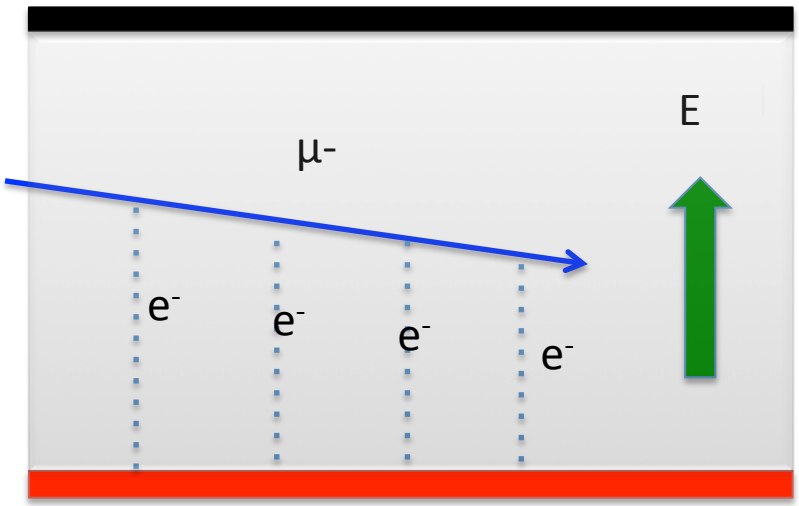


Good e track

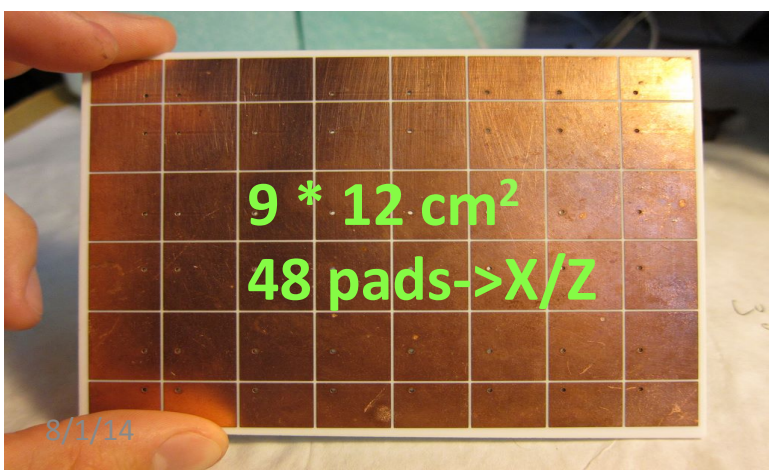
Cryo TPC- target & cut box

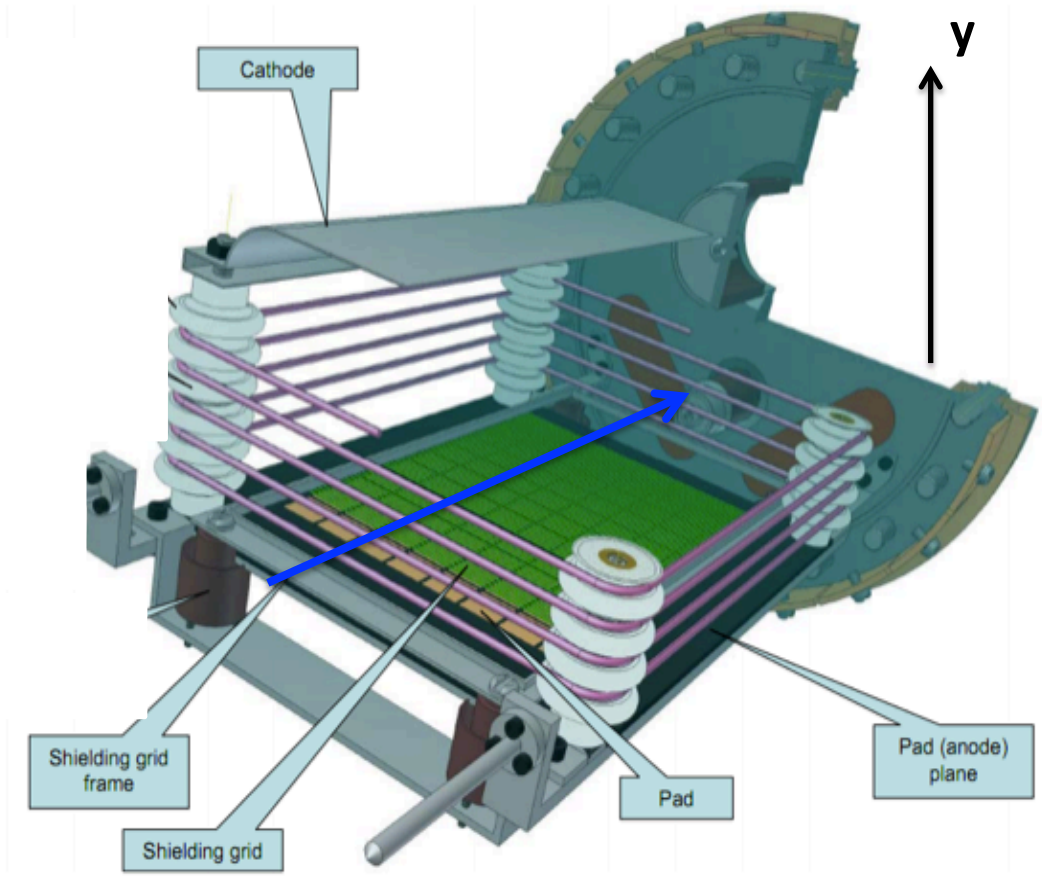
- **Ultrapure Deuterium target to stop the muons**
- **Ionization chamber: drift electrons 0.4cm/µs.**
- **Reconstruct 3D muon track, make cuts of data to define good muon stops.**

Cathode



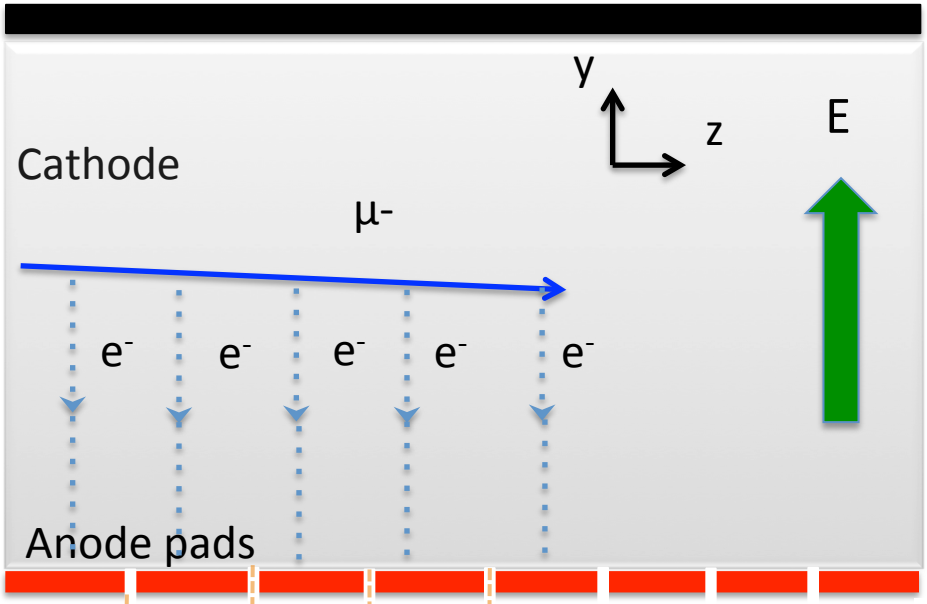
Anode pads

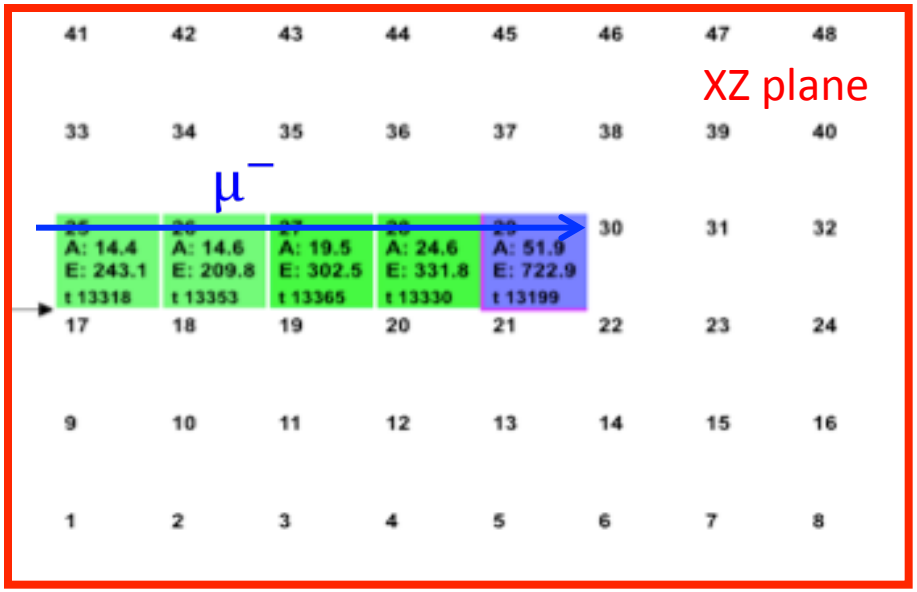


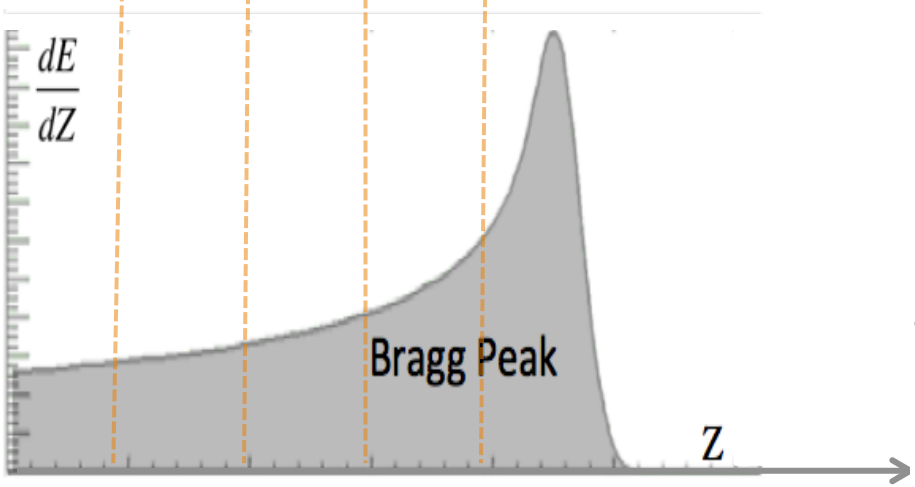


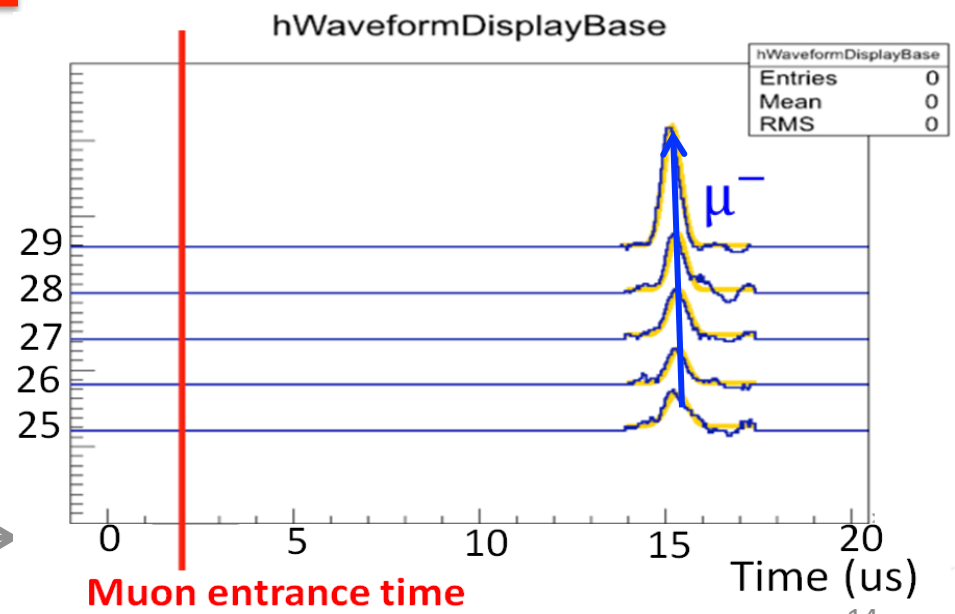
Muon track reconstruction

TPC

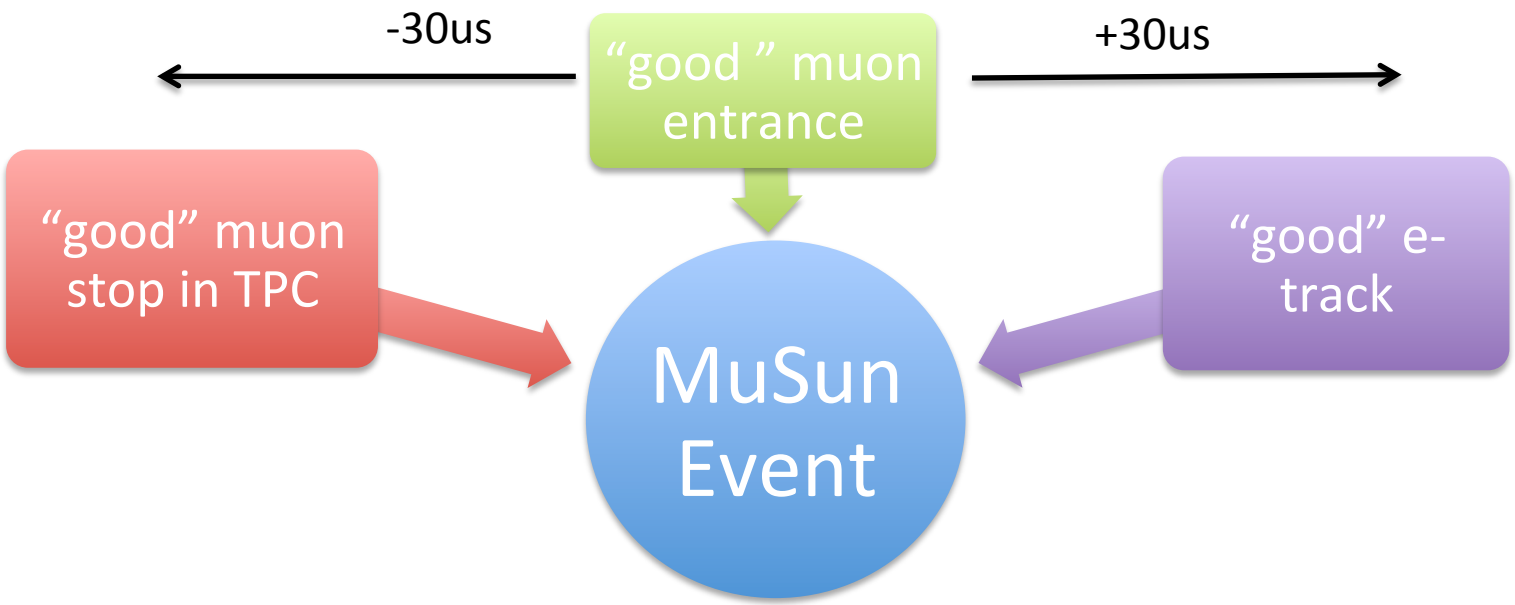




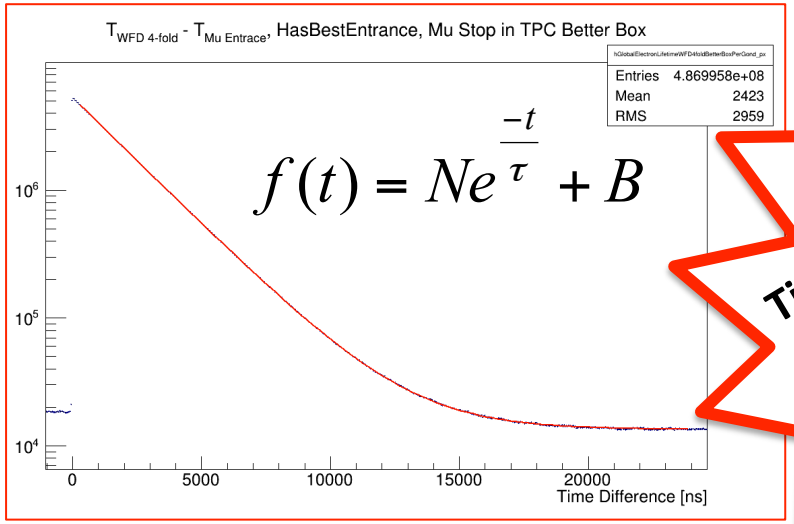




MuSun event

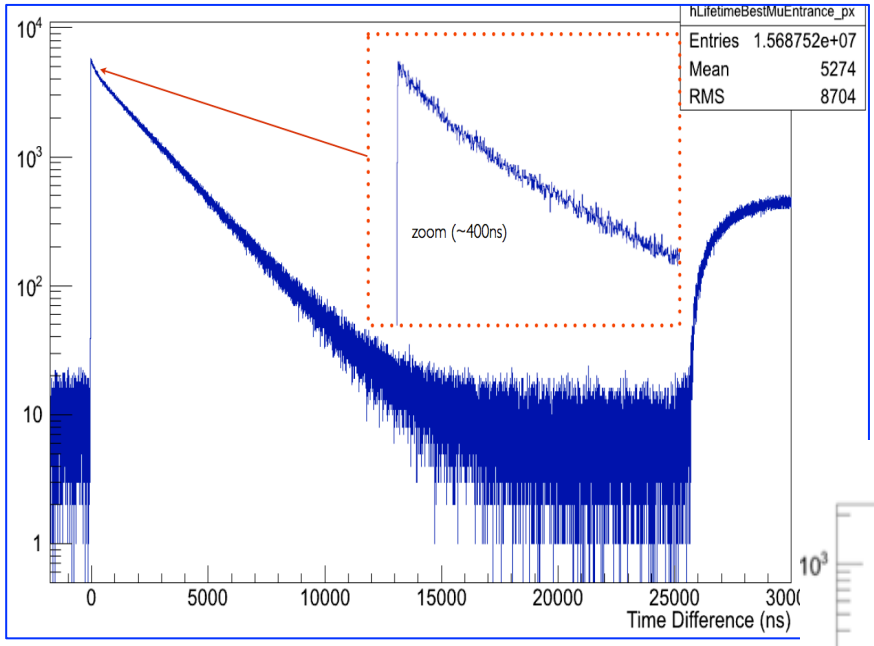


- **3 parameters expo fit to extract the slope as the muon disappearance rate.**
- **Tricky to define "good" in each level**



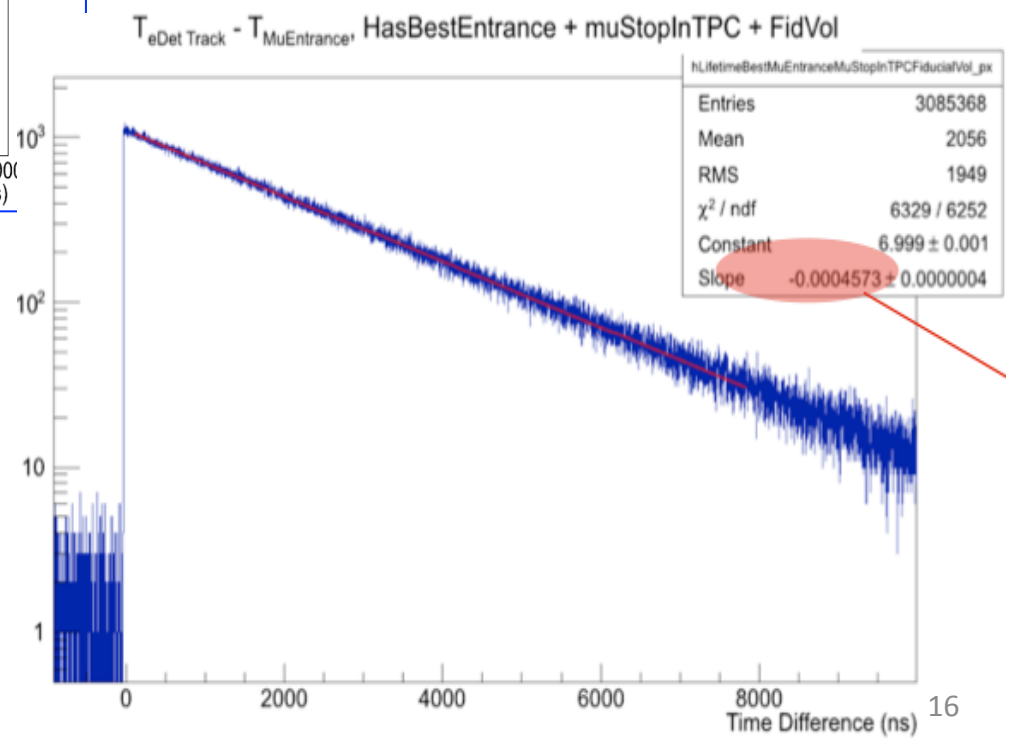
DANGEROUS
Time dependent cuts introduce systematic error.

Systematics: Non-Deuterium capture

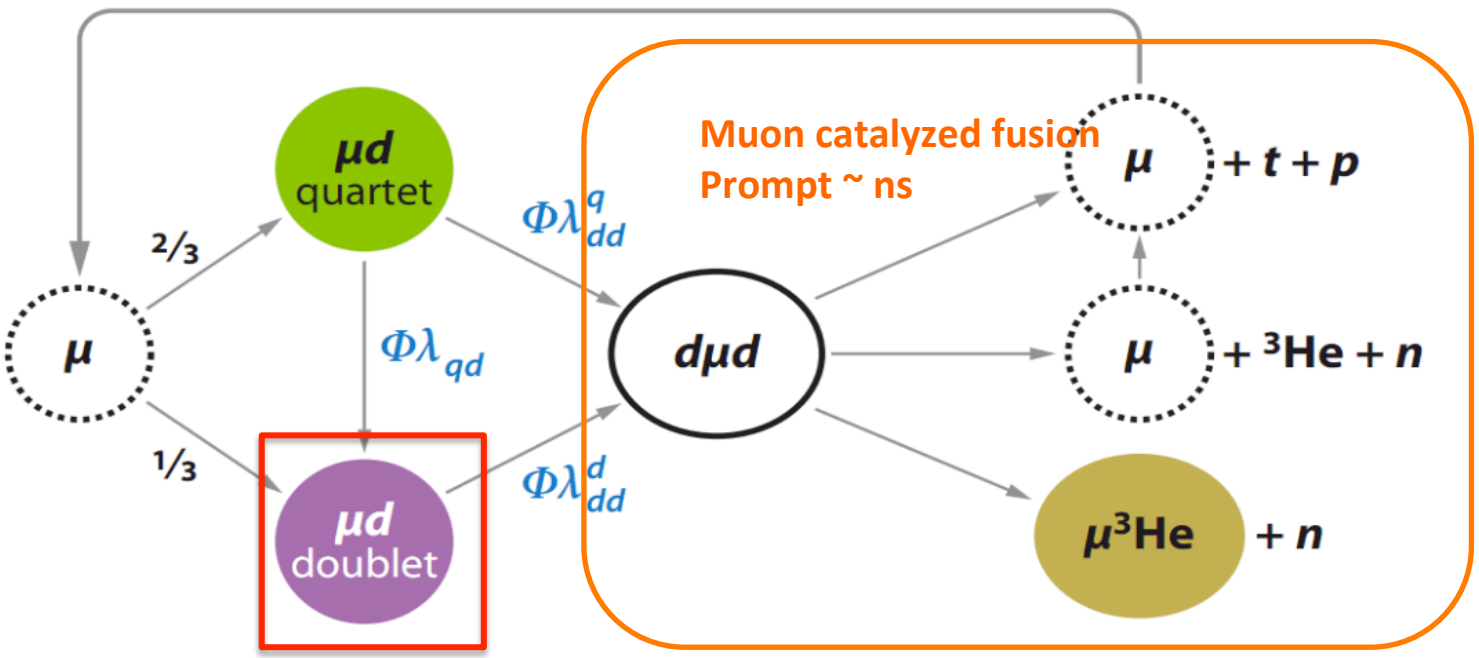


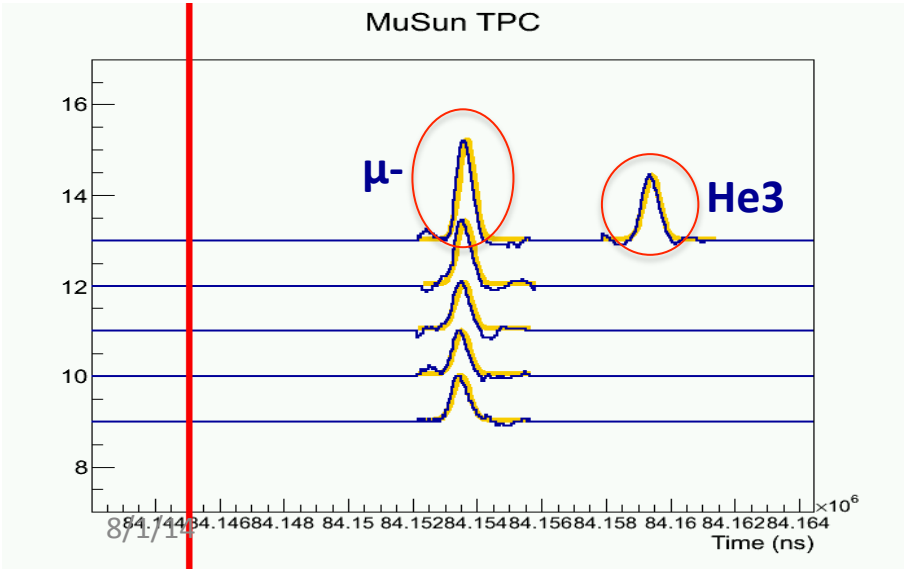
- **D2 gas is surrounded by the High Z material**
  - Apply Fiducial Volume Cut
  - Delay the fit window
- **Impurities in the gas, Medium Z N2, and O2**
  - 1ppb N2->2Hz correction
  - Low temperature to freeze out the impurities
  - Gas chromatography and Xray tagging

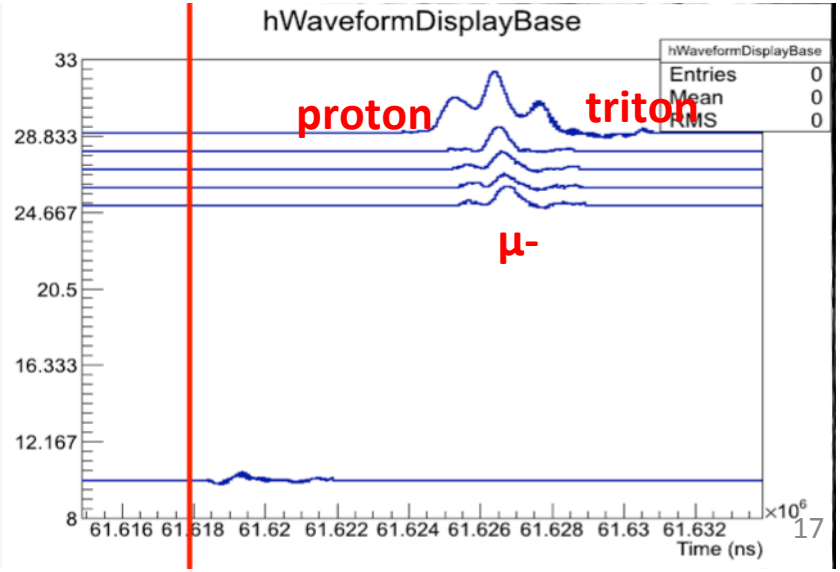
element	μ capture rate (Hz)	life (ns)
D	~400	2194
N	65 10^3	1930
O	98 10^3	1810
Si	850 10^3	760
Fe	4400 10^3	207
Au	12 000 10^3	74



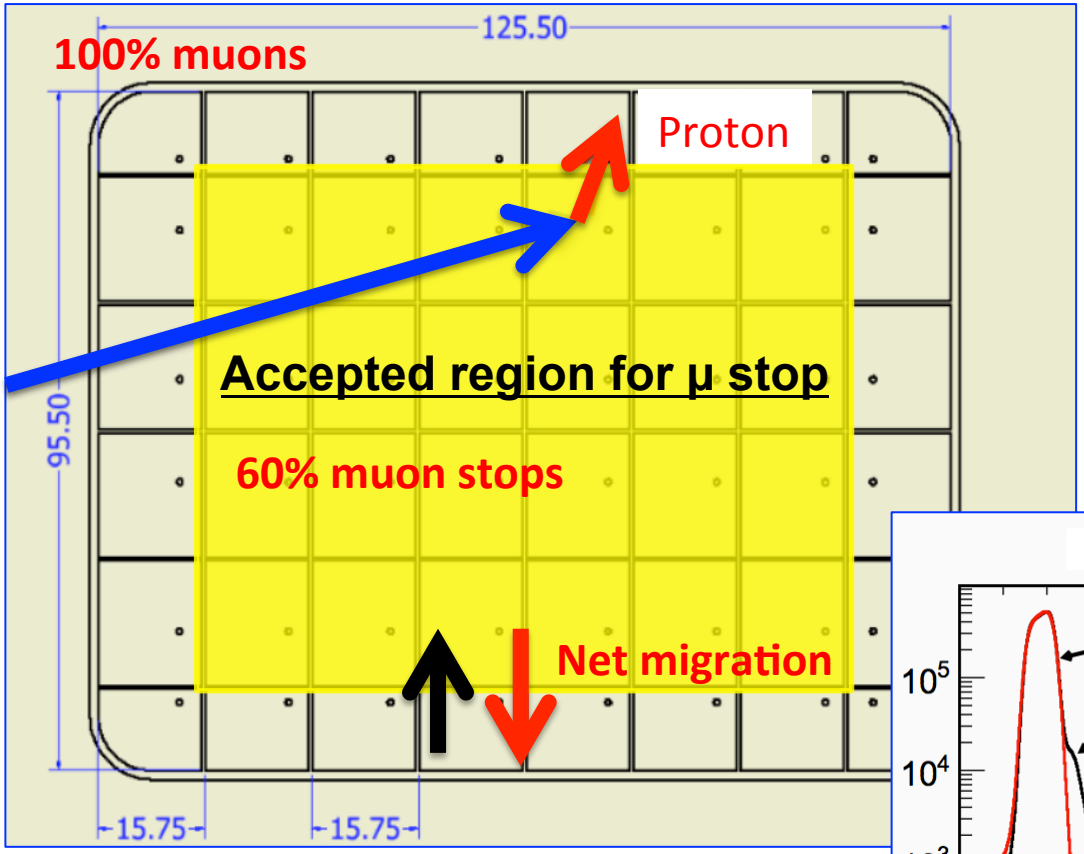
Systematics-muon catalyzed fusion





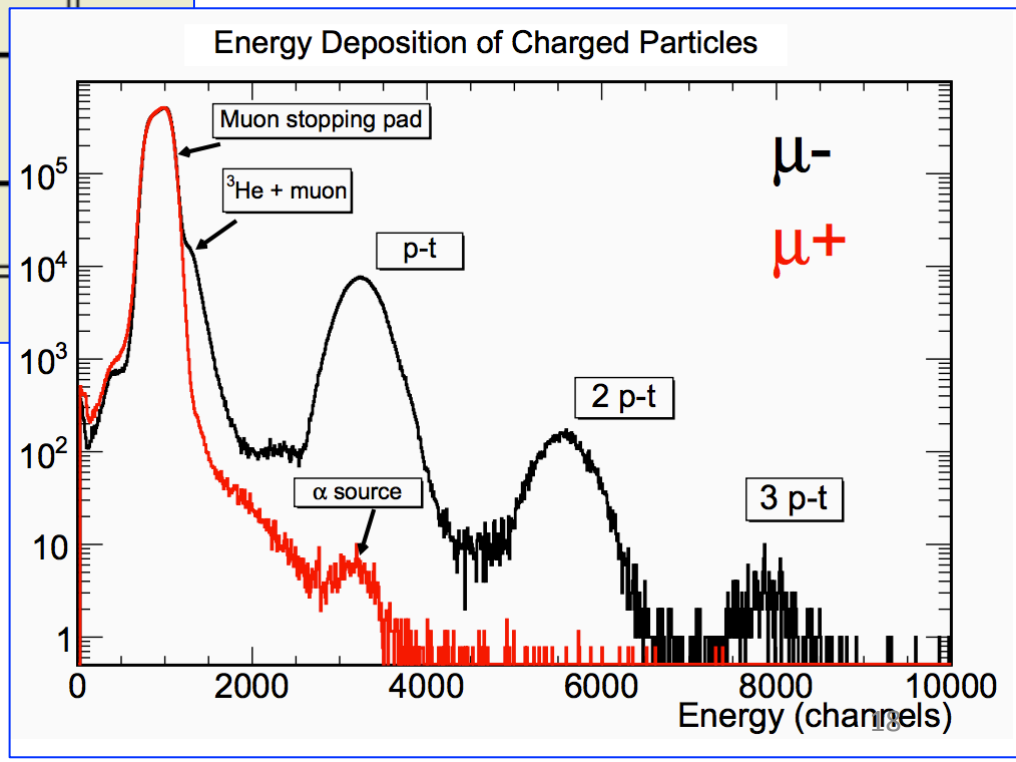


Systematics – fusion interference



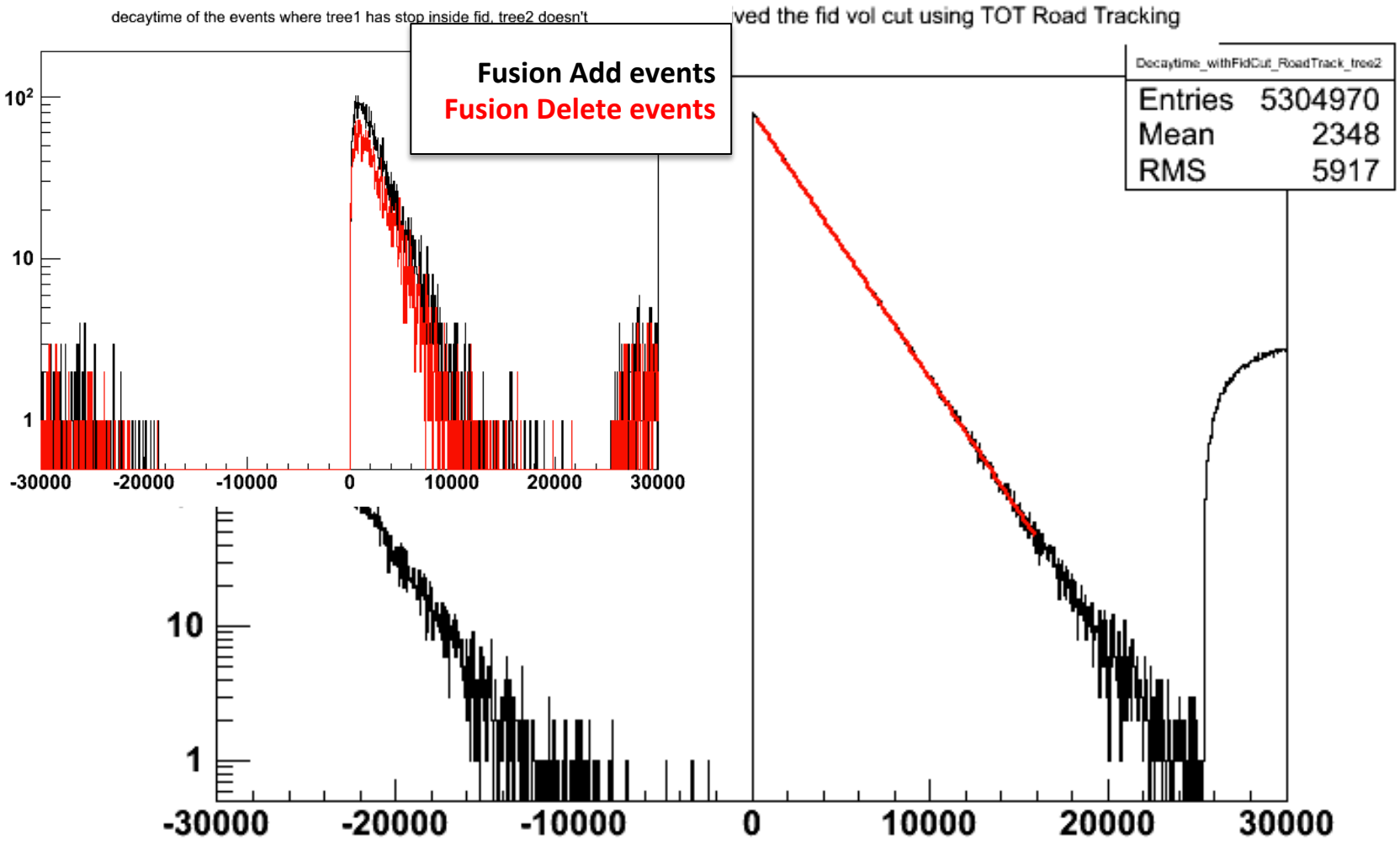
Proton + triton fusion happens ~5% of all muon stops (3% inside FidVol)

Net migration caused by fusion is 1.5% of fusion events ->450ppm of all stops.



Proton travels about 16mm, confuses the tracking algorithm as to whether or not the muon stopped within Fiducial Volume.

Systematics – fusion interference (simulation)



According to the Monte Carlo simulation, fusion interference causes a ~50Hz systematic error. (Ongoing work)

Other Systematics

- Electron interference
- Muon scattering->High Z Capture
- Electron track definition
- Mu+ spin rotation.
- Isotope contamination

Statistics	**3.4**
Chemical Impurities	2
Estimated Error in Analysis	2
μ + p hard scattering	1
μ pileup veto inefficiency	1
μd diffusion	.5
^{1}H contamination	~ 0
Fusion Processes	1
Muon Kinetics (quartet, ^{3}He, etc.)	.5
Total Systematic Error	3.3
Total Error	4.7

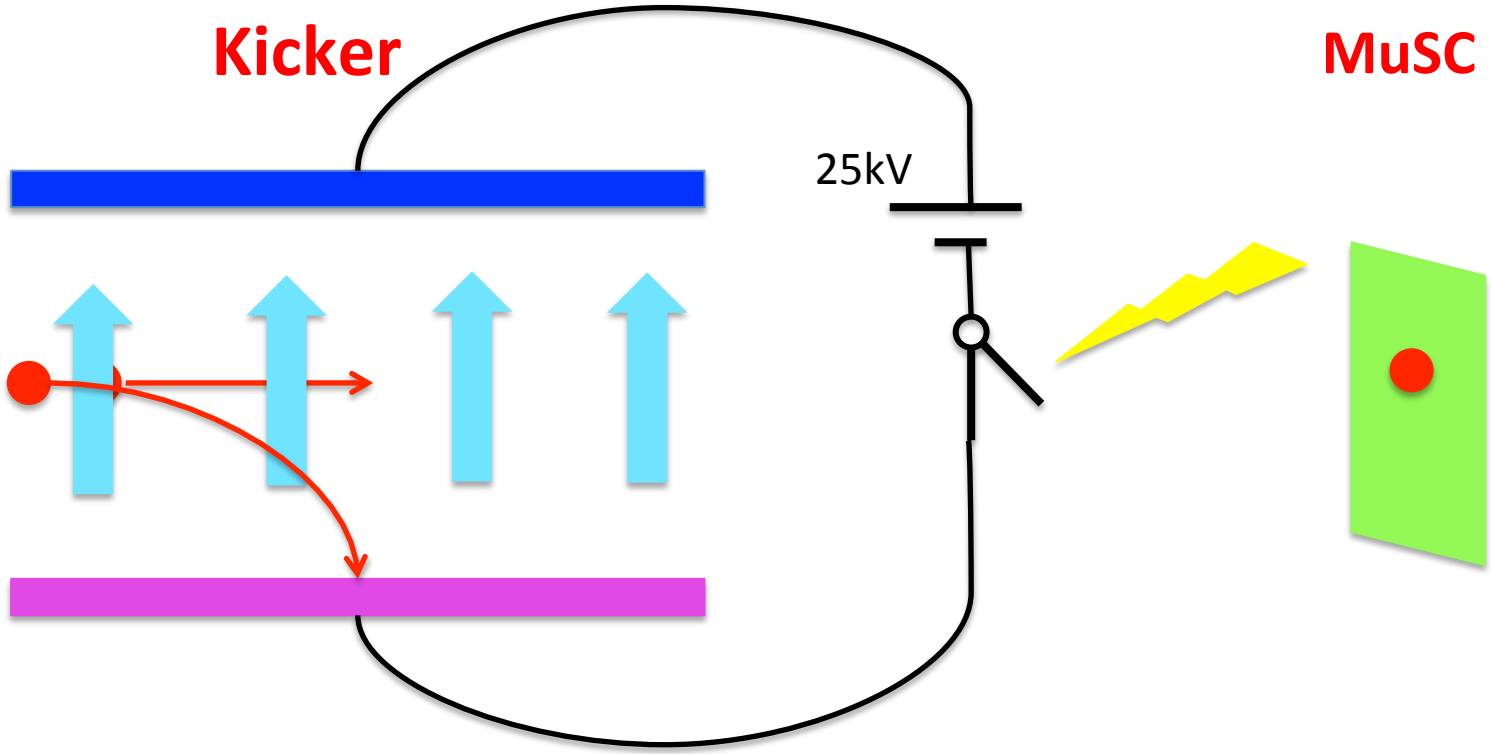
status

- Data collected 2011: 5e9
- Data collection in 2013: 2e9
- Taking data 2014 for 3 weeks
- Ongoing various systematics on the impurity, fusion interference, pile-up, etc. expect preliminary result in 2015.

Collaboration:

Thanks!

Beamline-kicker (muon on request, backup)



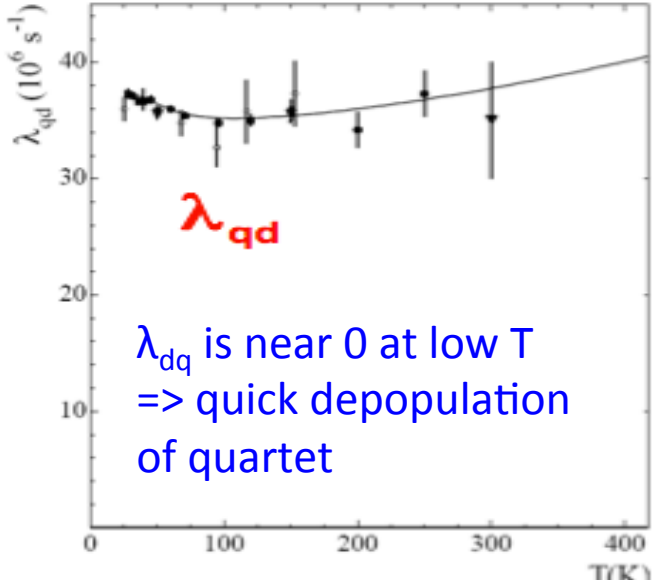
Pile up protection: Kicker is active for 25µs, to make sure there is only one muon in the TPC.

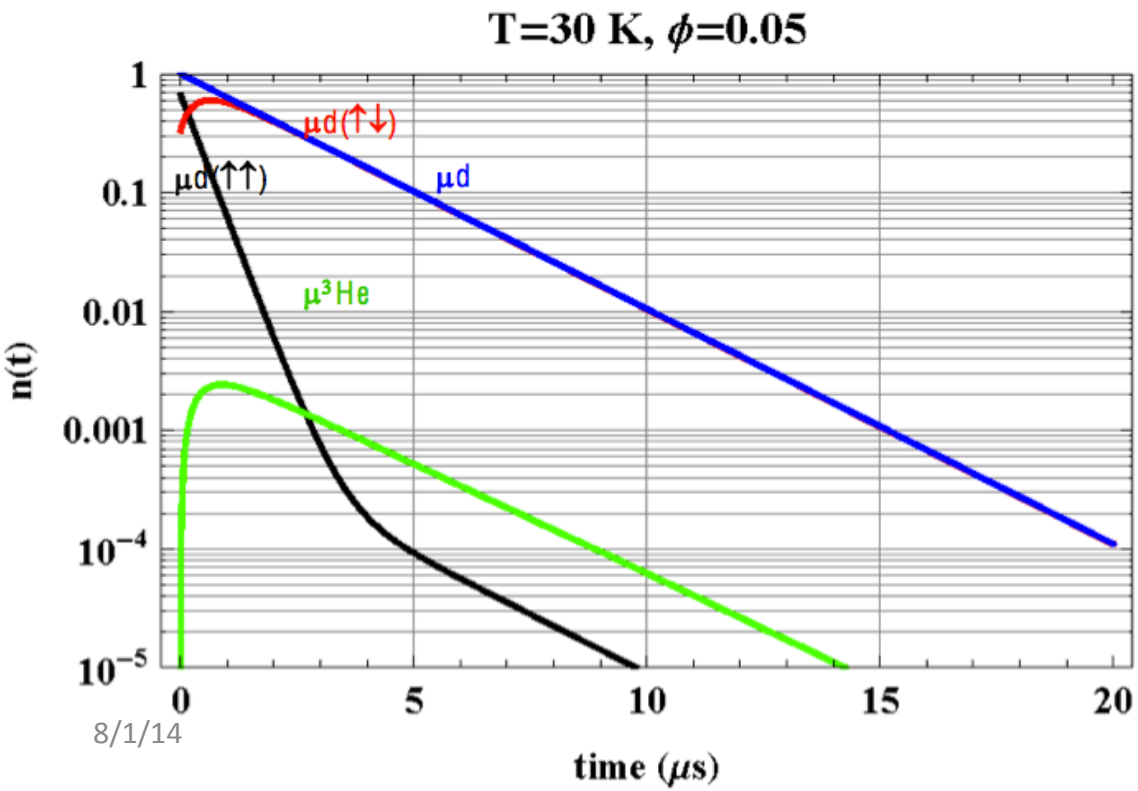
TPC conditions

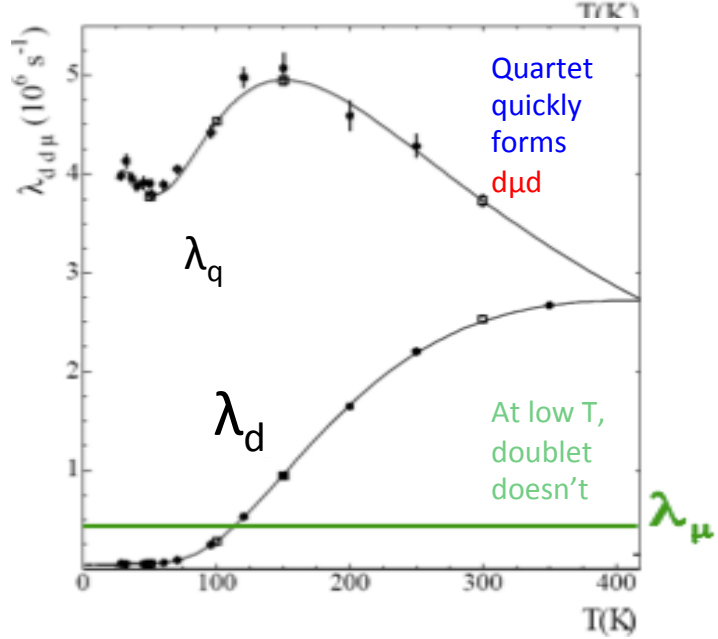
Goal: Maximize the population of μd doublet.

Temperature T = 33K

Density of deuterium gas ϕ = 6% of liquid H_2.

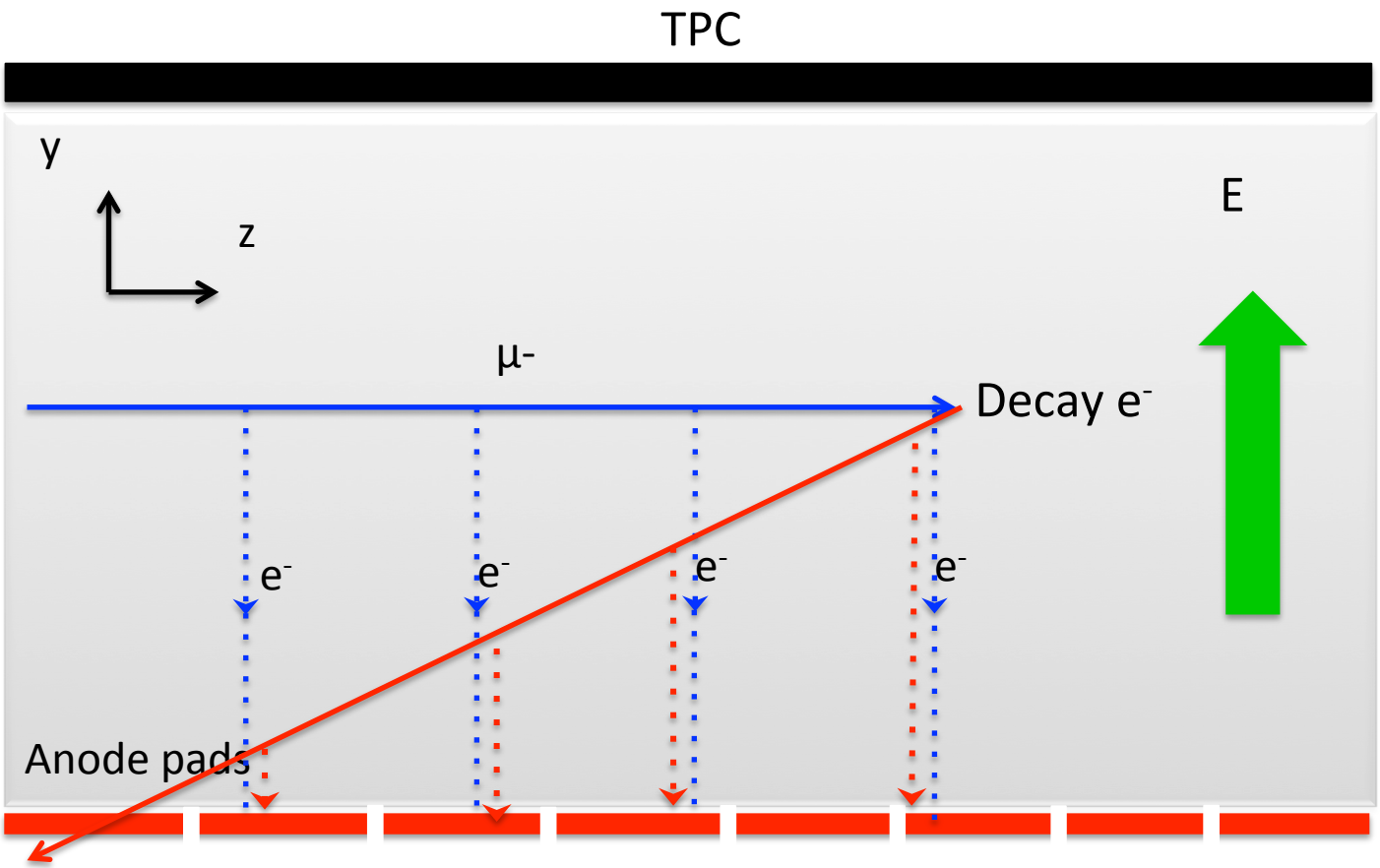




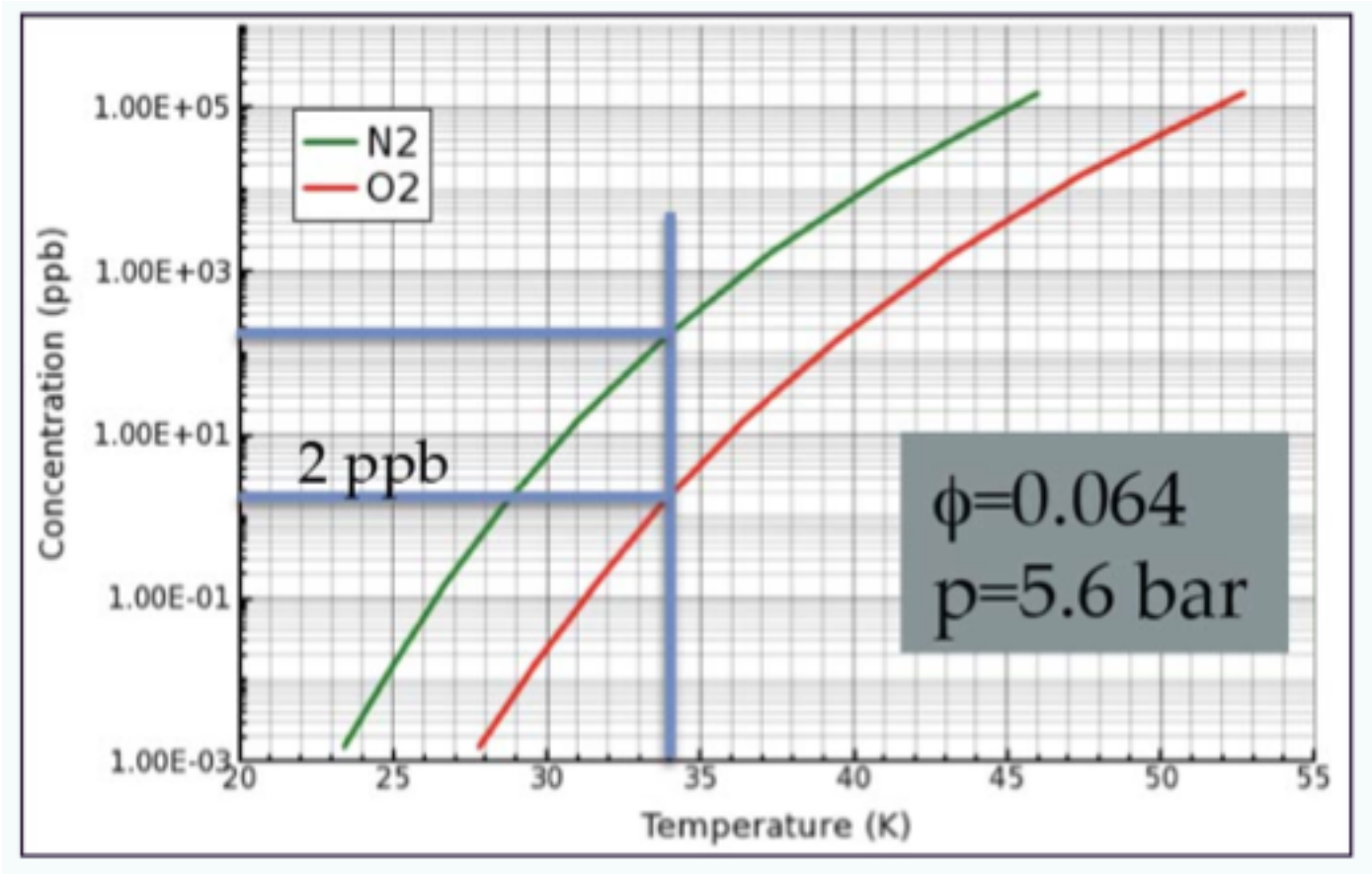


Electron interference

Problem: **energy deposition by the electron track, if interfere with the muon track, could lead to a time-dependent muon stop acceptance.**



Impurity – vapor pressure



Impurity-software