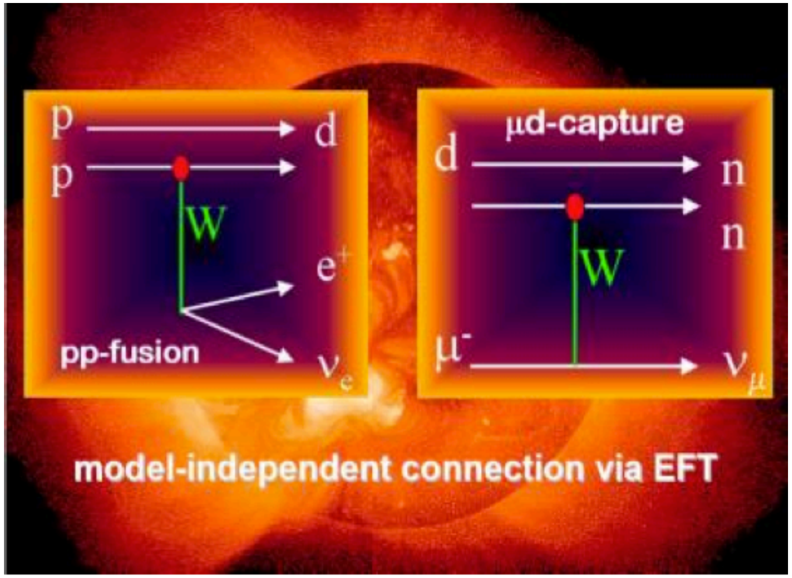
MuSun: Muon Capture on the Deuteron



NUFACT 2014

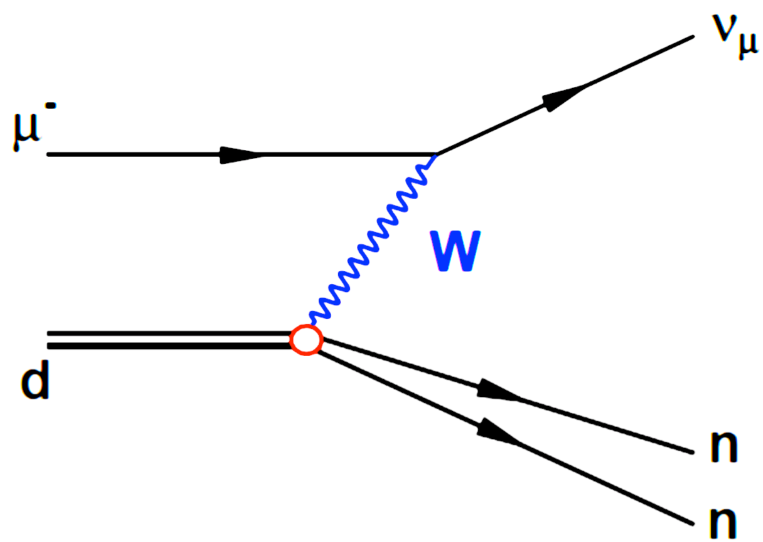
Xiao Luo (Boston University)

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.

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

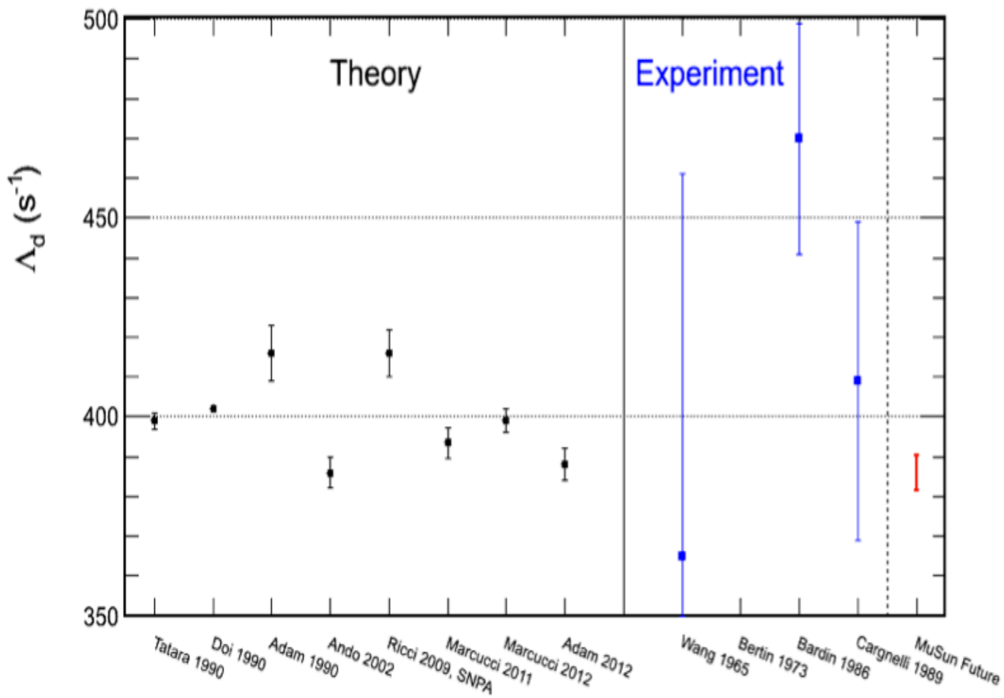


Note: Λ_d denotes the capture rate from the doublet hyperfine state of the muonic deuterium atom in its 1S ground state.

Physics Motivation

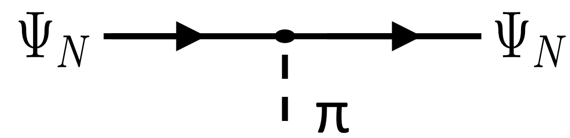
$\mu^{-} + d \rightarrow \nu_{\mu} + n + n$

- ✔ 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

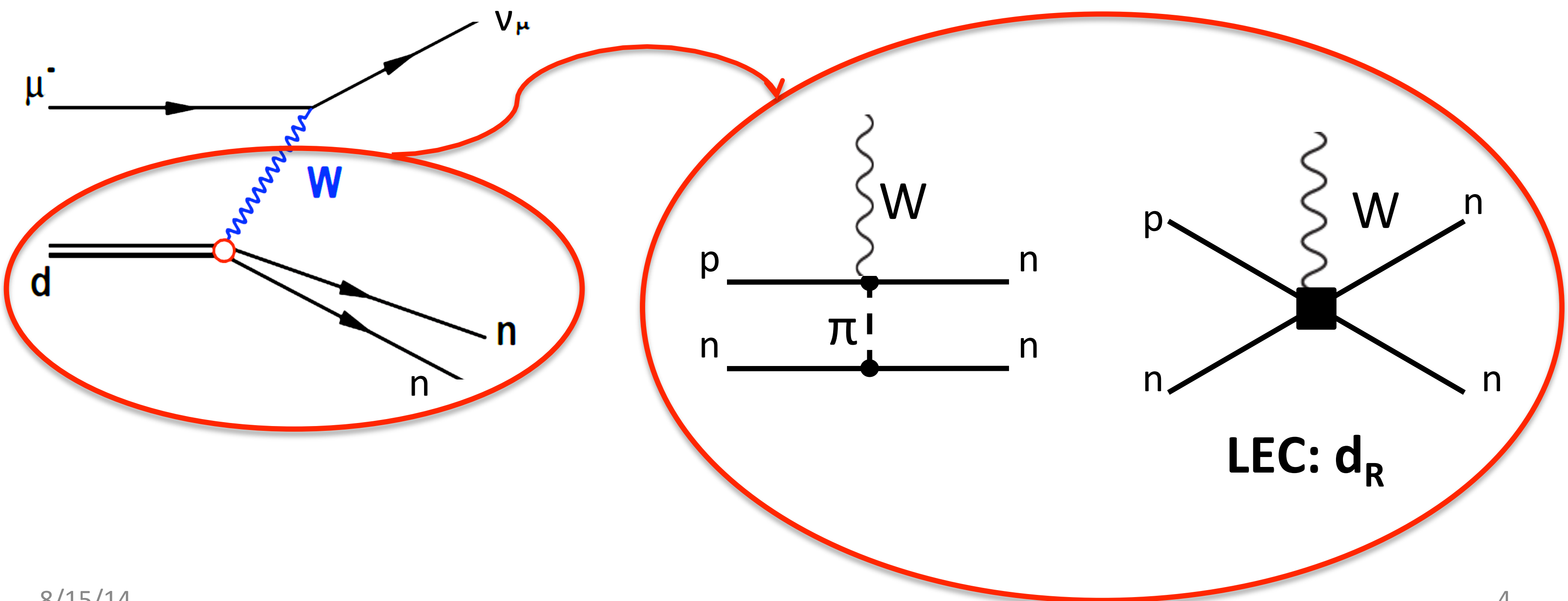
$$\mathcal{L}_{eff} = \mathcal{L}_{\pi N}^{(1)} + \mathcal{L}_{\pi N}^{(2)} + \mathcal{L}_{\pi N}^{(3)} + \ldots$$



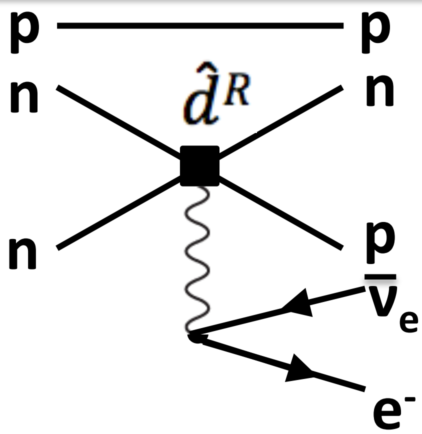
$$\mathcal{L}_{\pi N}^{(1)} = \bar{\Psi}(iD_\mu\gamma^\mu - M_N + \frac{g_A}{2}u_\mu\gamma^\mu\gamma_5)\Psi$$

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

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

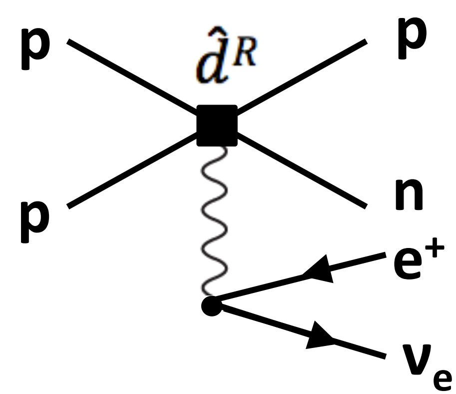


From ChPT to μ⁻d capture



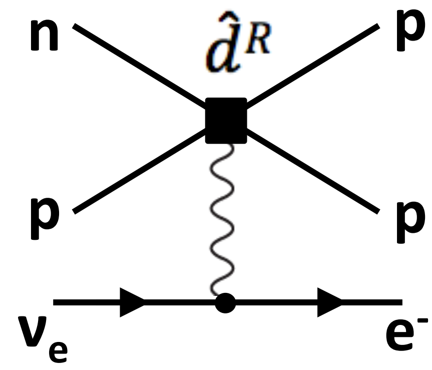
Triton β decay

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



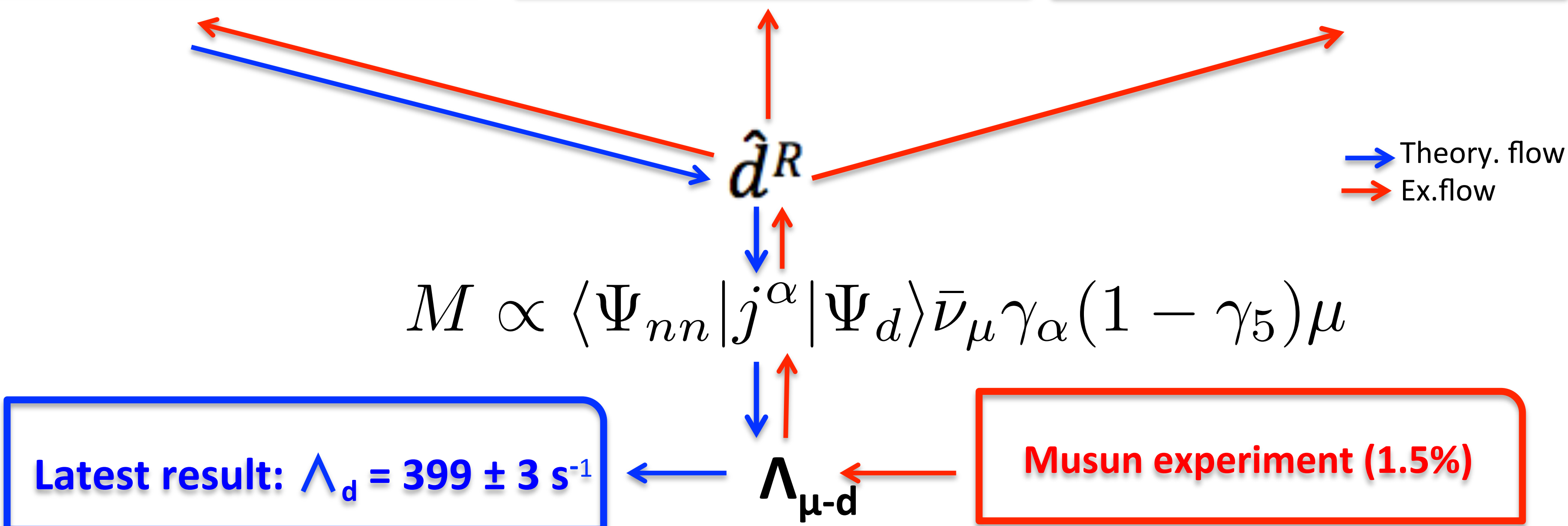
Solar pp fusion

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



SNO νd scattering

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



Experimental method: lifetime technique

Focus on sources of the muon disappearance:

Muon decay:

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

Muon capture:

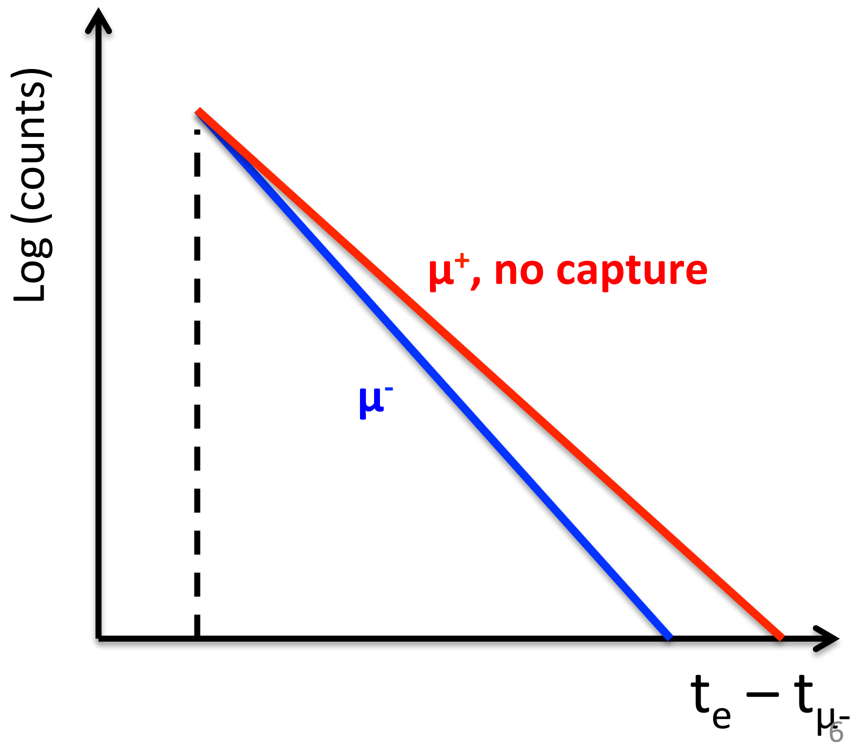
$$\mu^- + d \rightarrow \nu_\mu + n + n$$

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

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

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

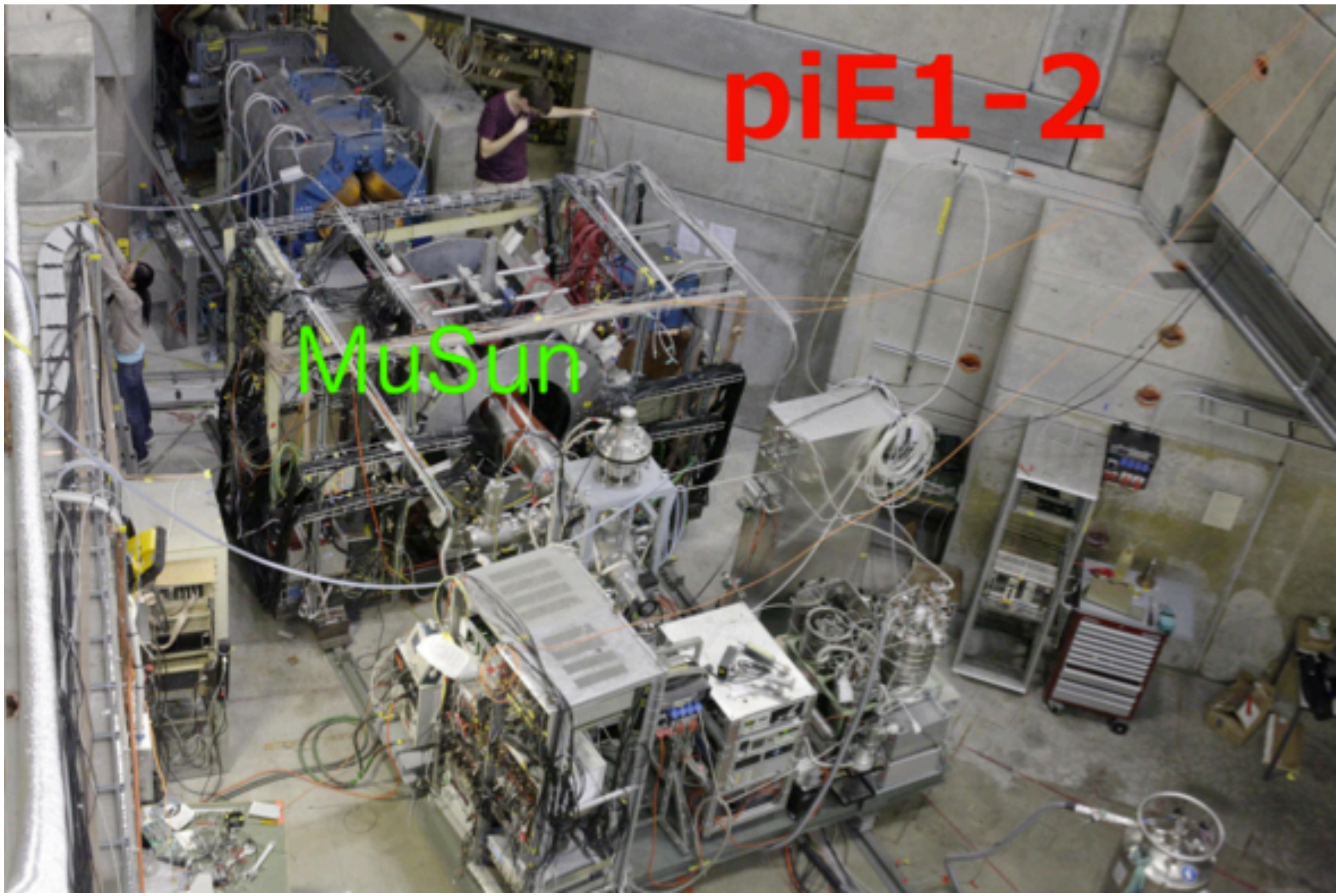
- **Determine Λ_{cap} to 1.5% level.**
- **Measure $\Lambda_{\mu-}$ to 10ppm.**
- **Require 10^{10} events.**



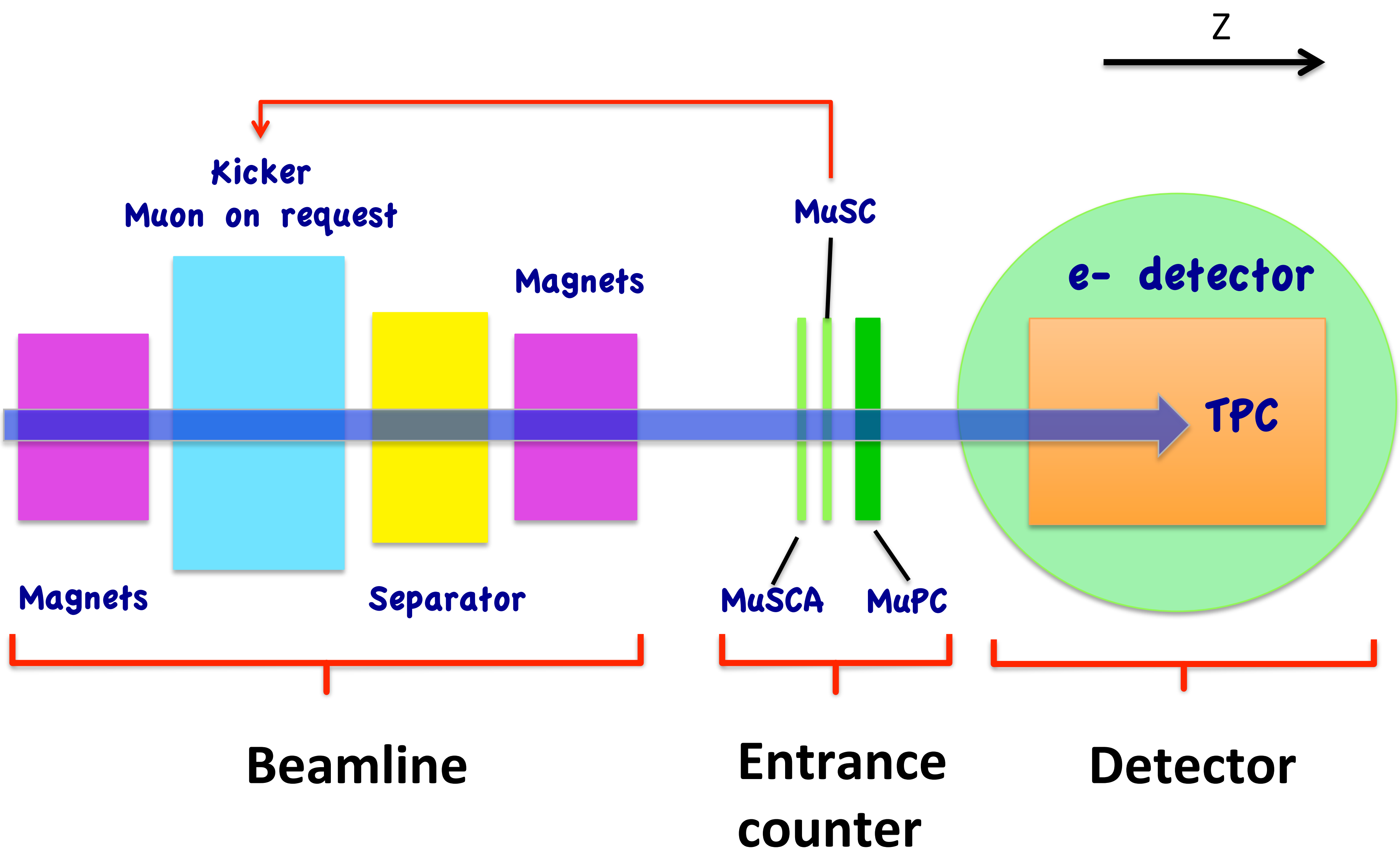
Experimental design

❖ **Intense low energy muon beam.**

Experimental setup



Experimental setup



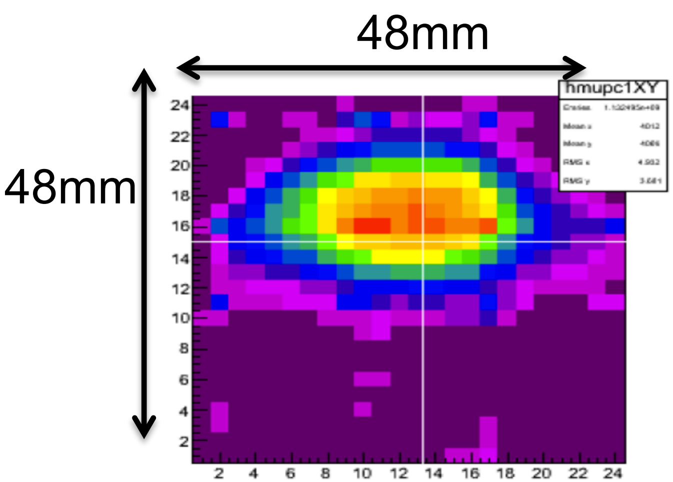
Entrance counter

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

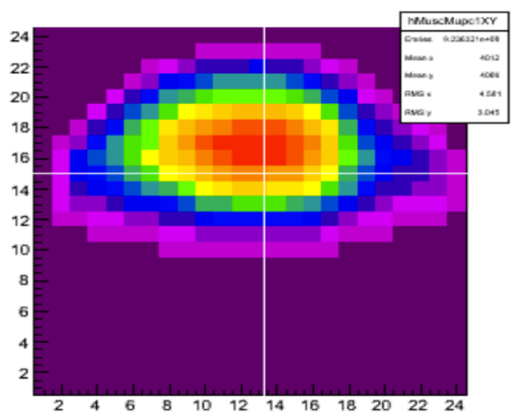
μSC	+	μPC	+	!μSCA	+	Kicker
μ entrance time t = 0 for MuSun		Position		VETO		Pile-up

↓

Good μ Entrance

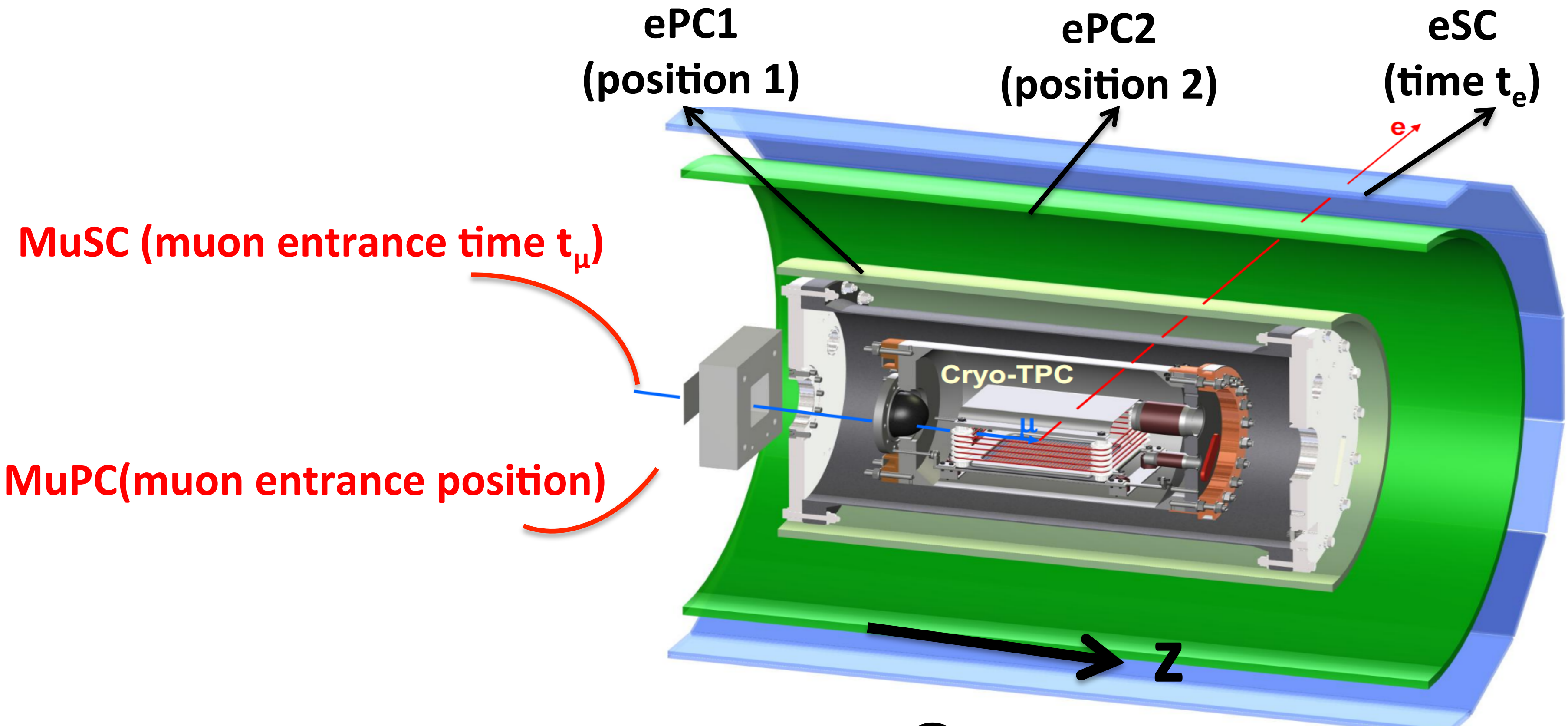


Raw μPC

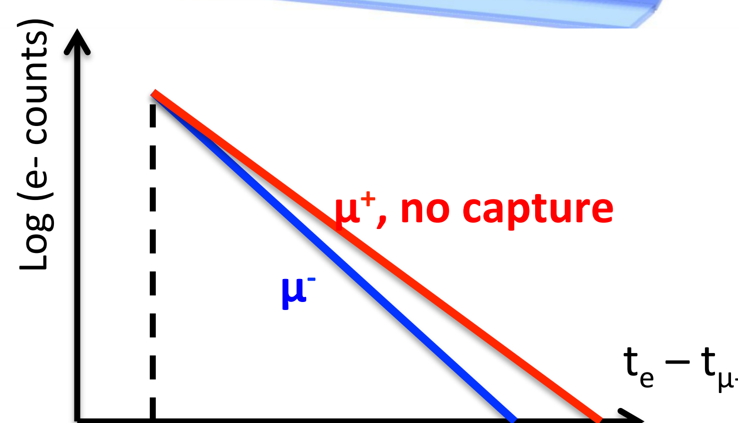


μPC && μSC

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.



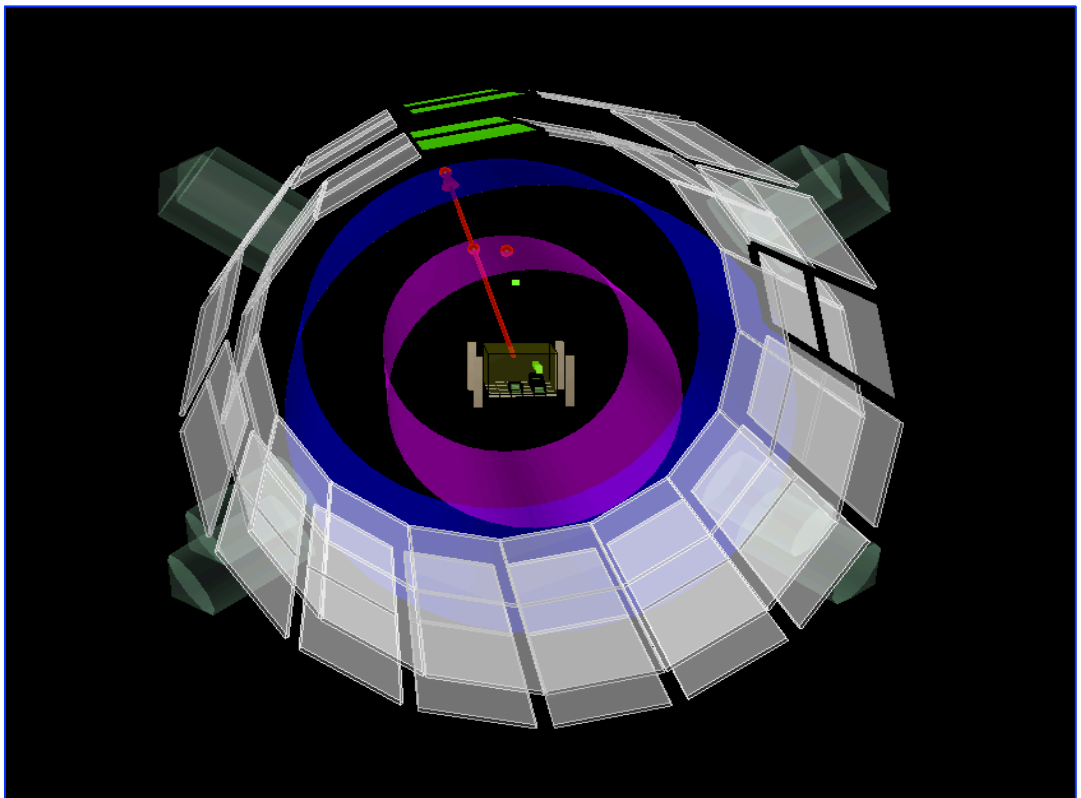
Electron detector

Goal: Identify electron tracks from muon decay

eSC + ePC1 + ePC2

e time — Position — Position

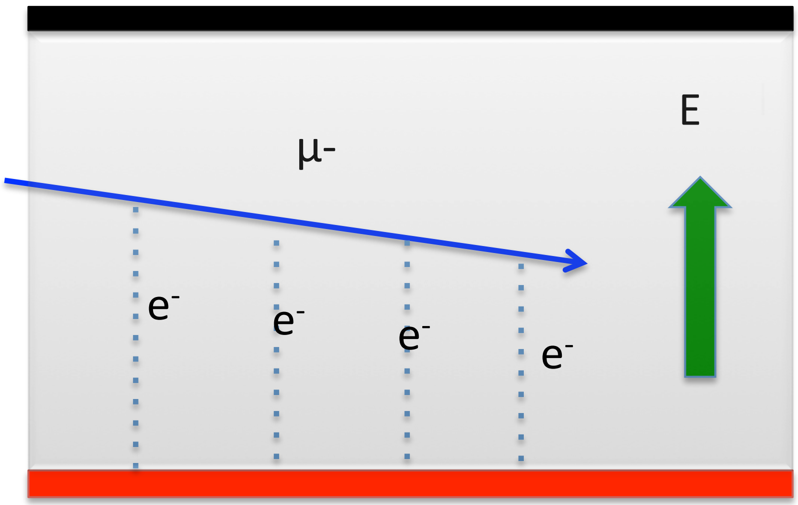
→ Good e track



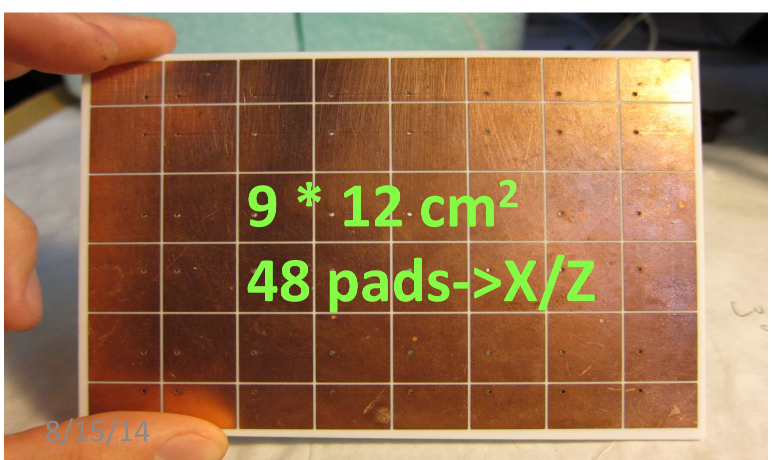
Cryo TPC- target & cut box

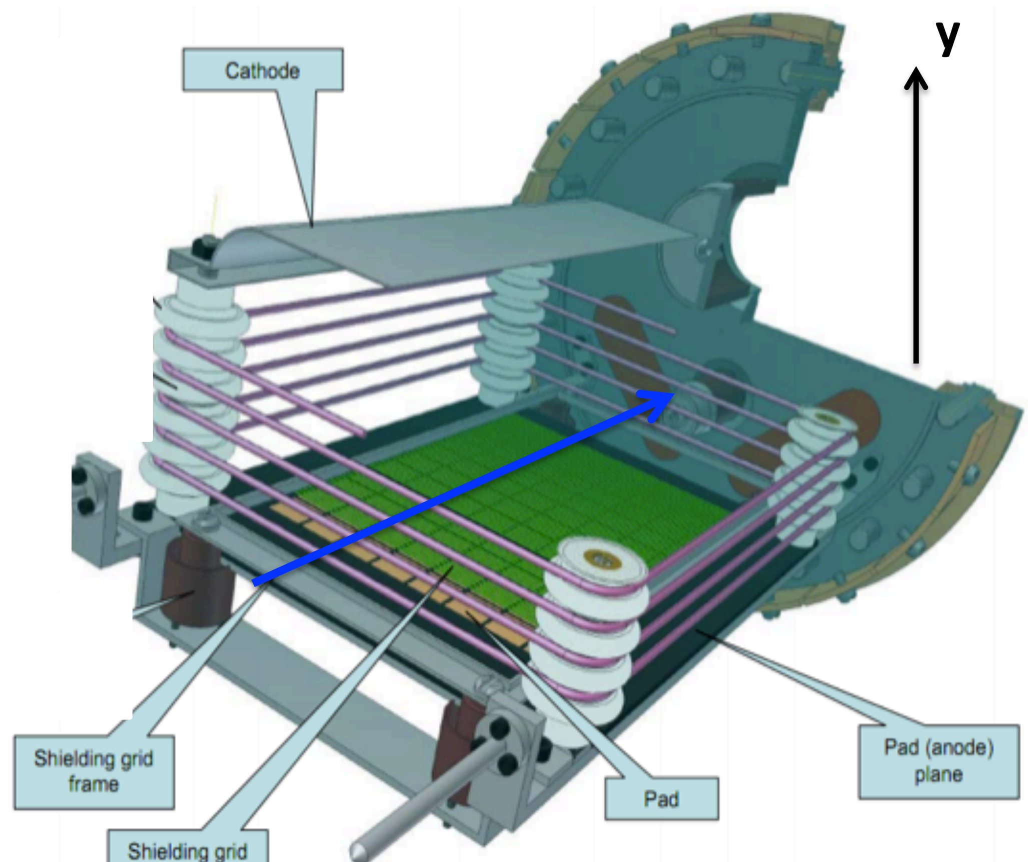
- **Ultrapure Deuterium target to stop the muons**
- **Ionization chamber: drift electrons 0.4cm/μs.**
- **Reconstruct 3D muon track, make cuts on data to define good muon stops.**

Cathode

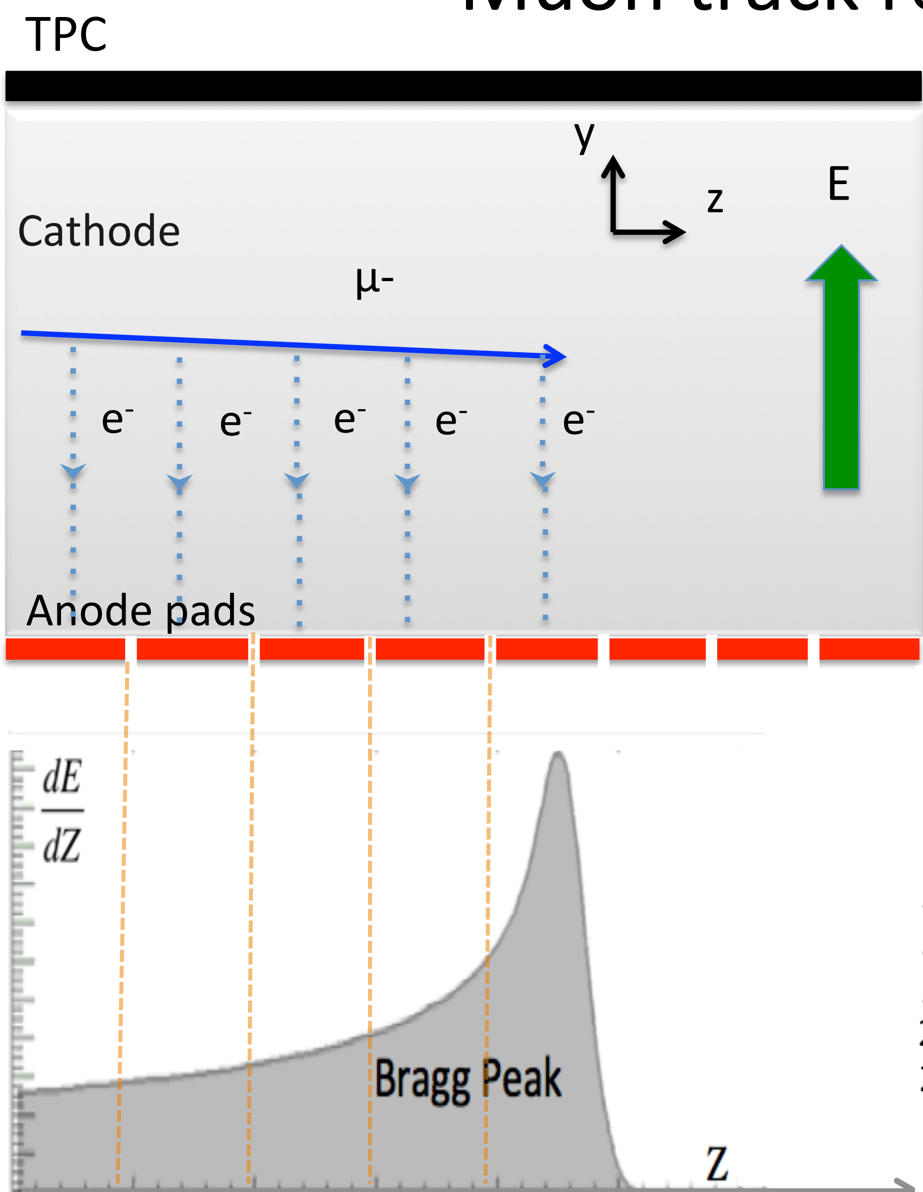


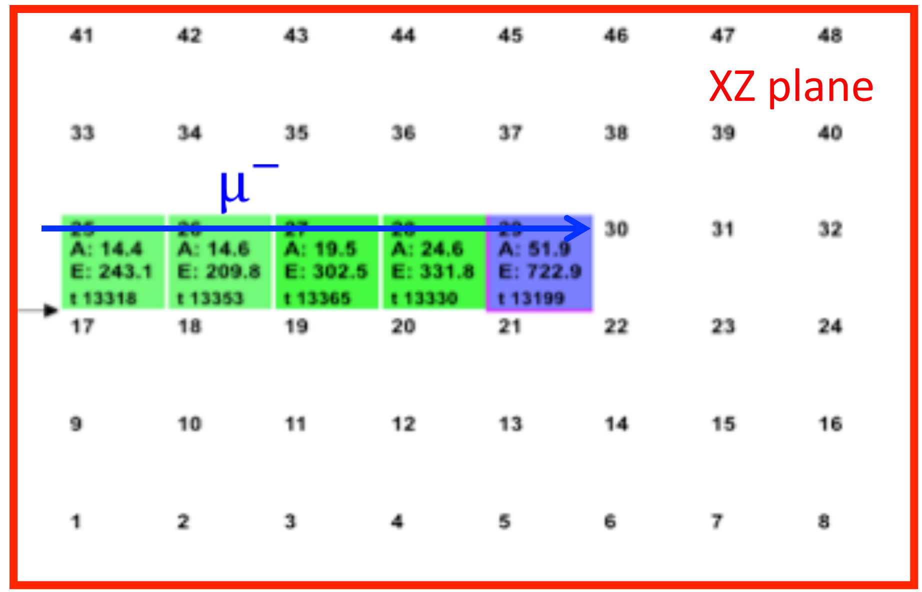
Anode pads

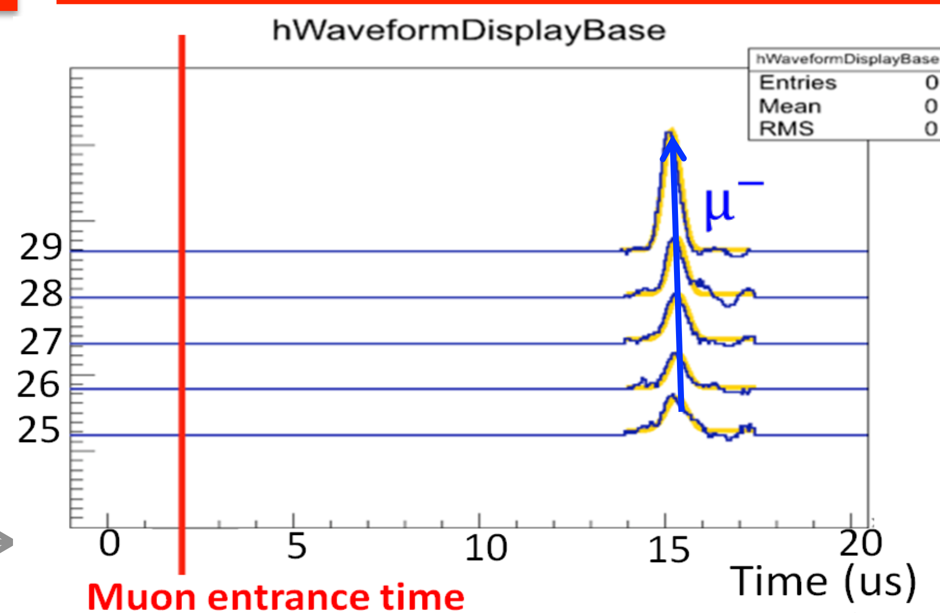




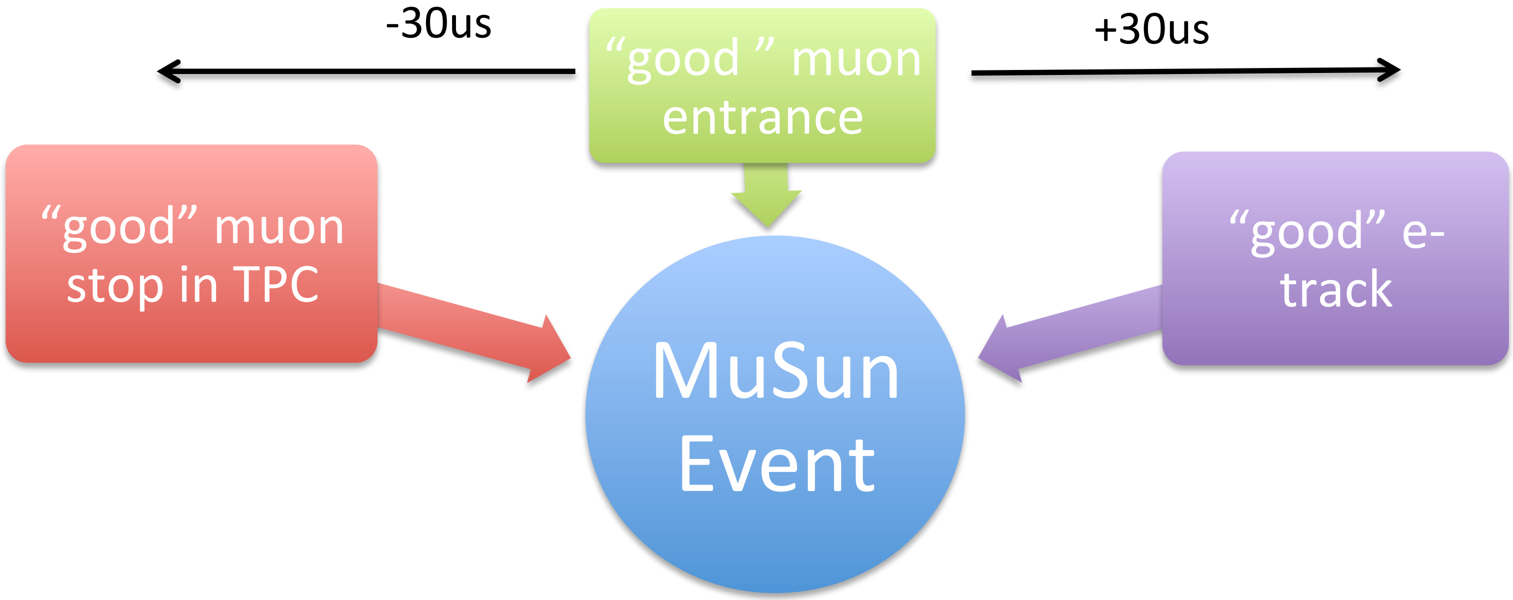
Muon track reconstruction



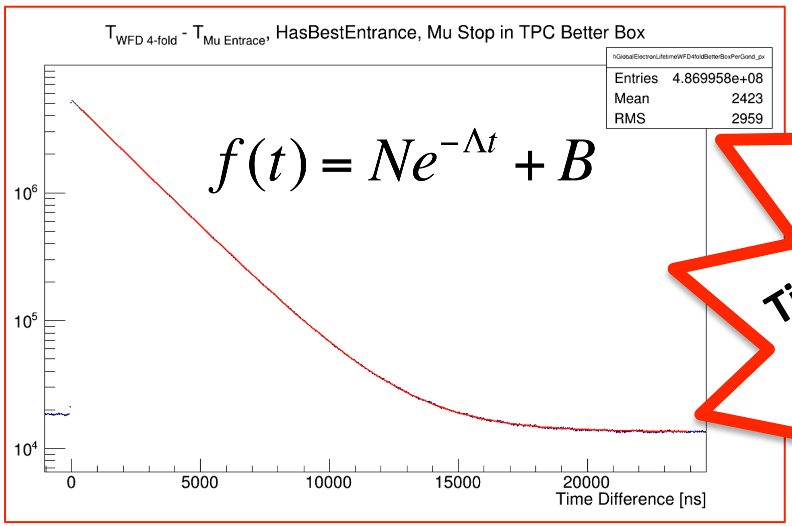




MuSun event



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



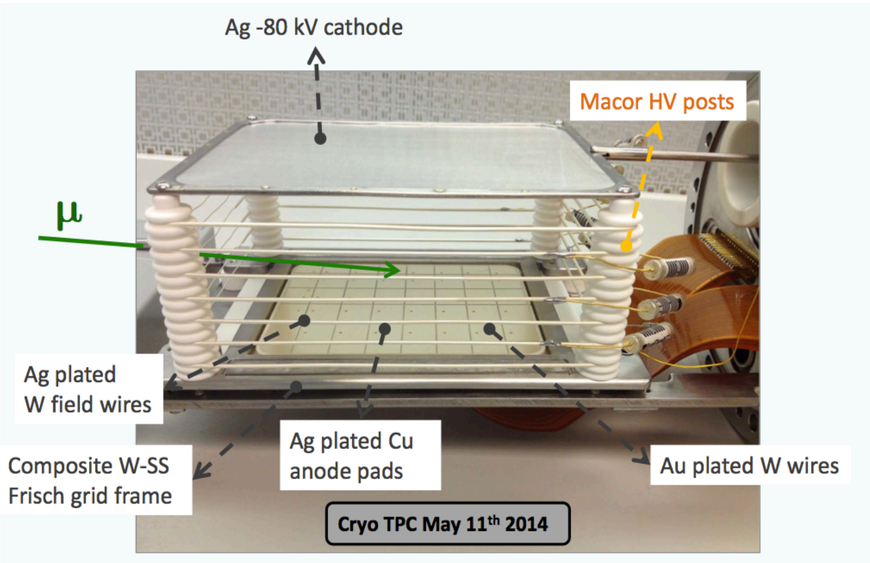
DANGEROUS
Time dependent cuts introduce systematic error.

Systematics

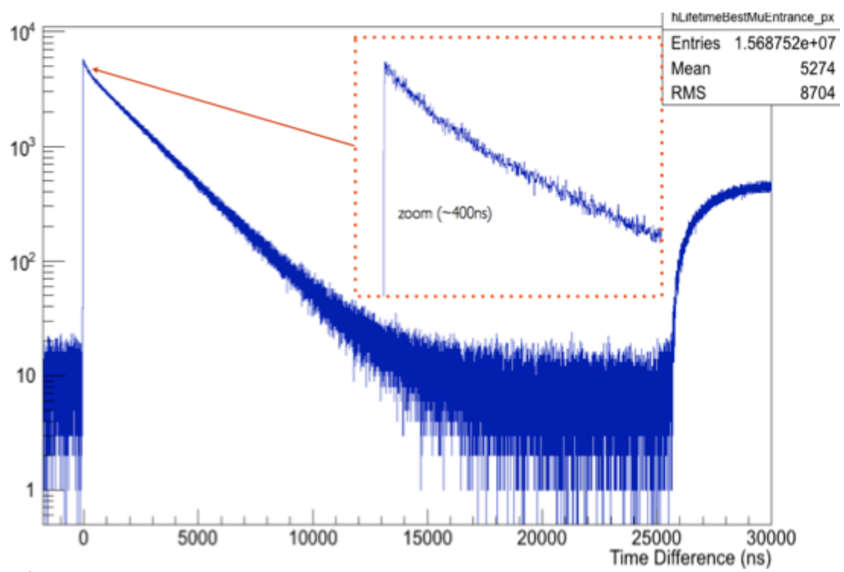
- **Non-deuterium capture**
  - High Z Capture: W, Ag, Stainless steel, etc
  - Medium Z capture: N_2 and O_2 impurities in the gas

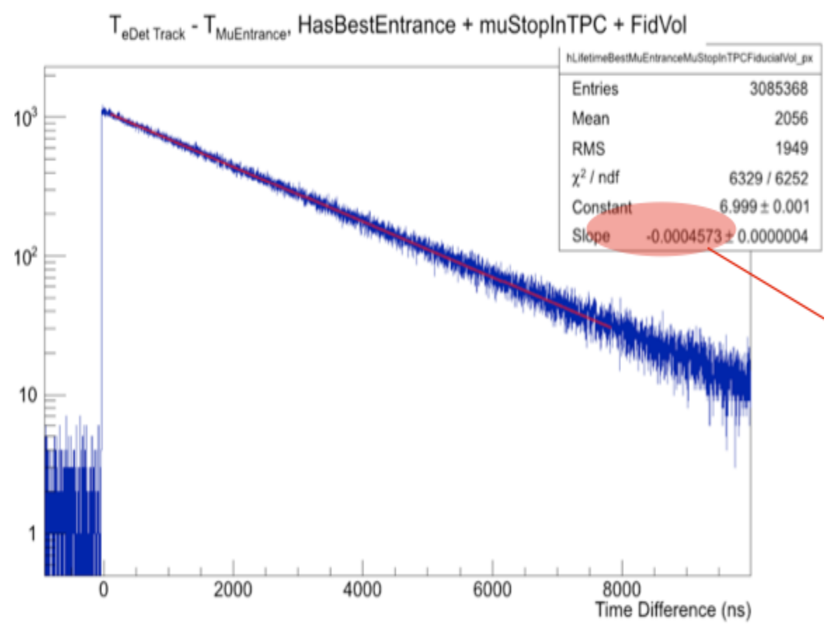
- **Fusion interference**

Systematics I: High Z capture



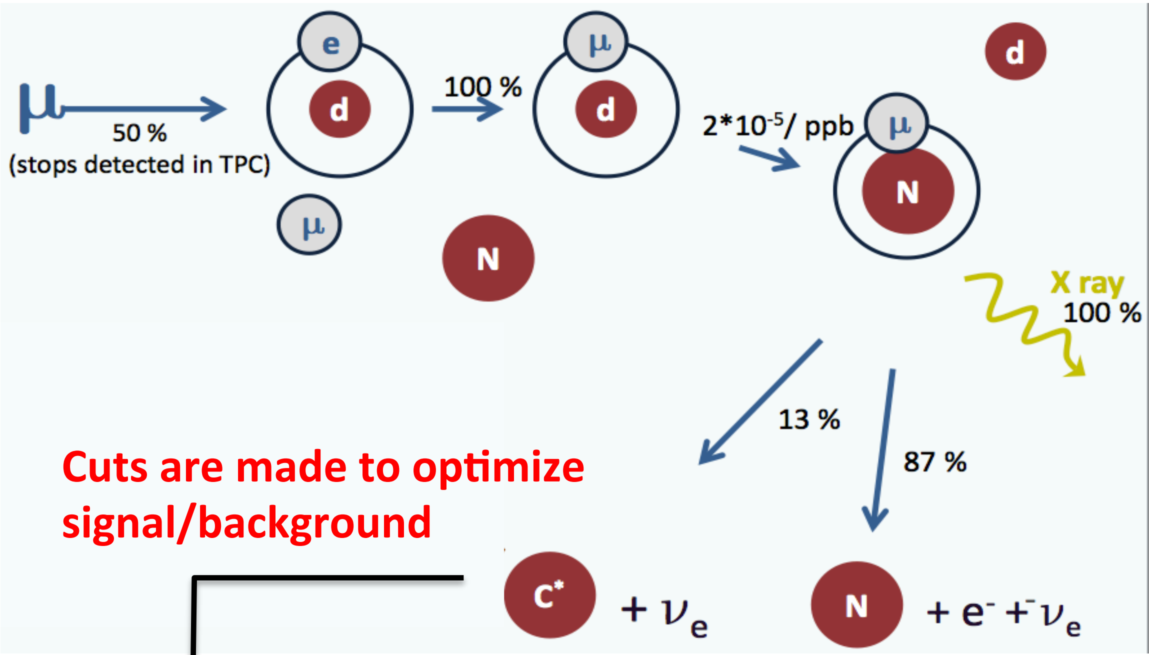
- D2 gas is surrounded by high Z material: W, Ag,etc
- Observe fast capture component
- Apply Fiducial Volume Cut to veto High Z capture events.
- Delay the fit window to avoid the early time bend.

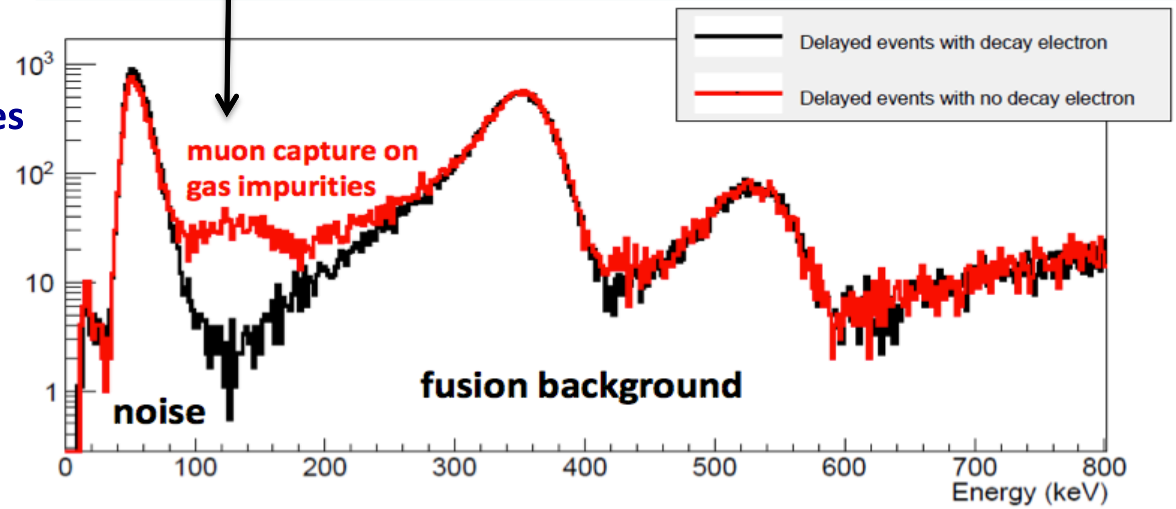




Chemical impurities II - Medium Z capture

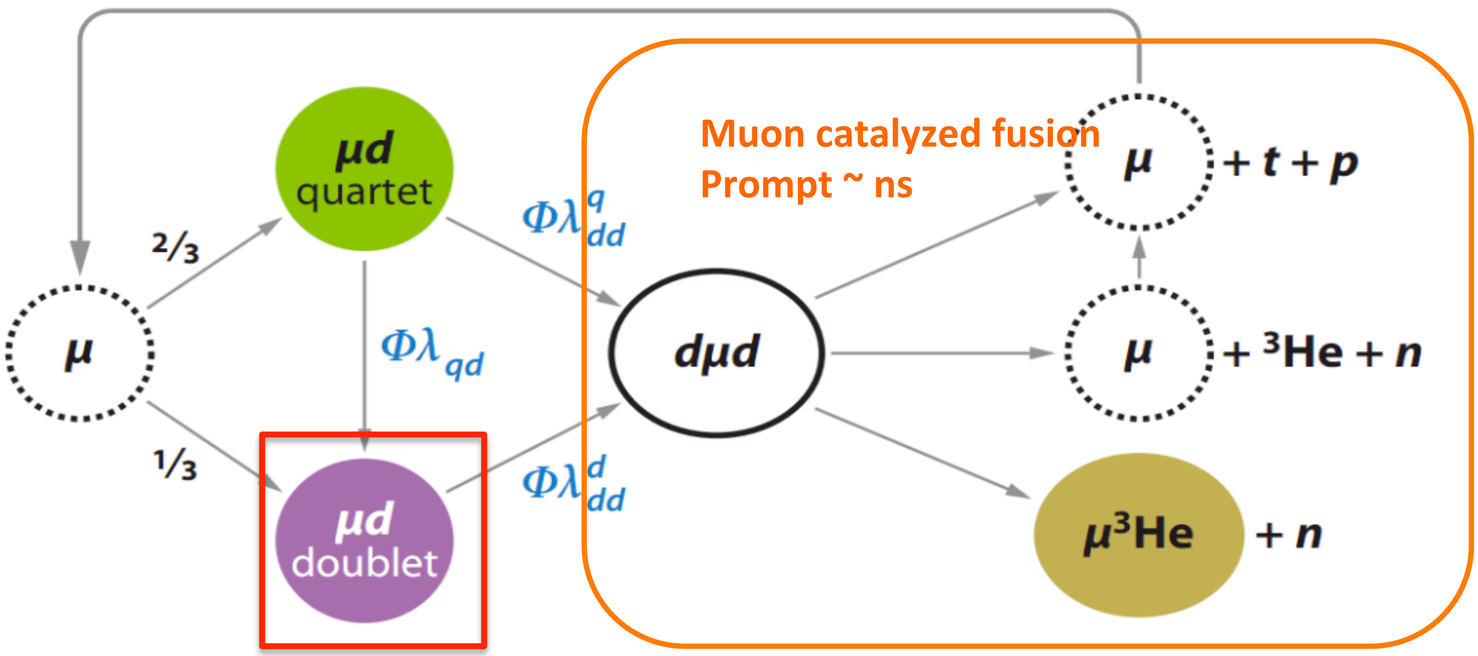
element	μ capture rate (Hz)	life (ns)
D	~400	2194
N	65 10^3	1930
O	98 10^3	1810
Si	850 10^3	760
Fe	4400 10^3	207
Au	12 000 10^3	74

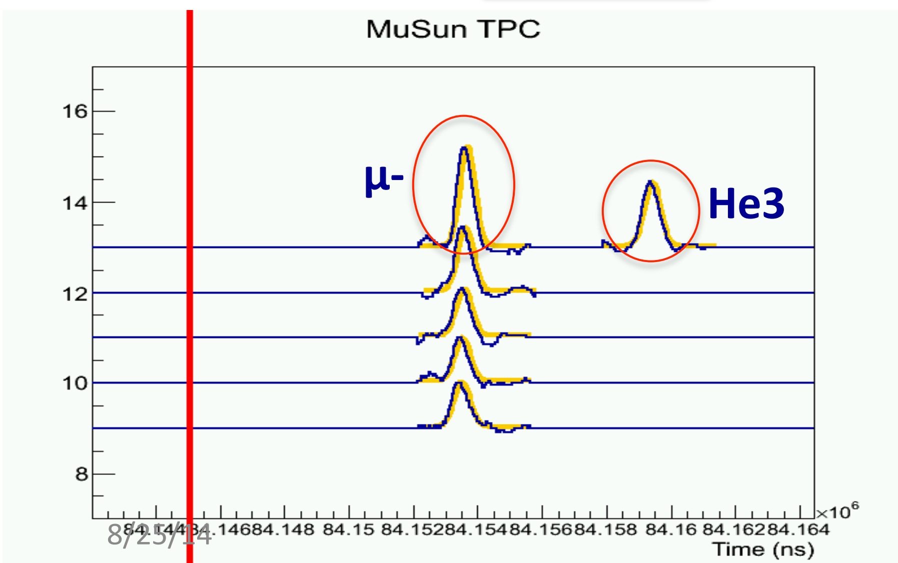


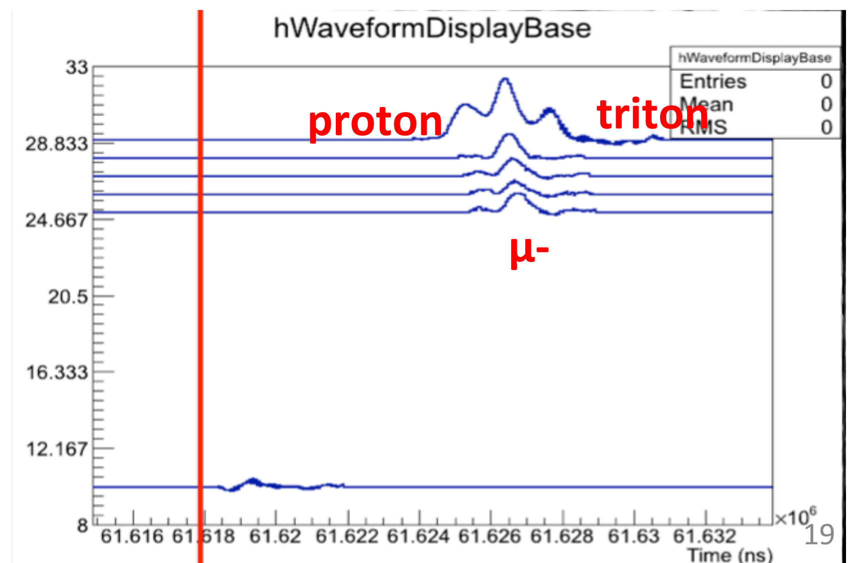


- Impurities in the gas: N2, and O2
- 1ppb N2->2Hz correction
- Cryogenic TPC freezes out impurities low vapor pressure at 30K)
- CHUPS purifies and the isotopically clean D2 produced on site
- Gas chromatography and direct detection to monitor the impurity concentration.

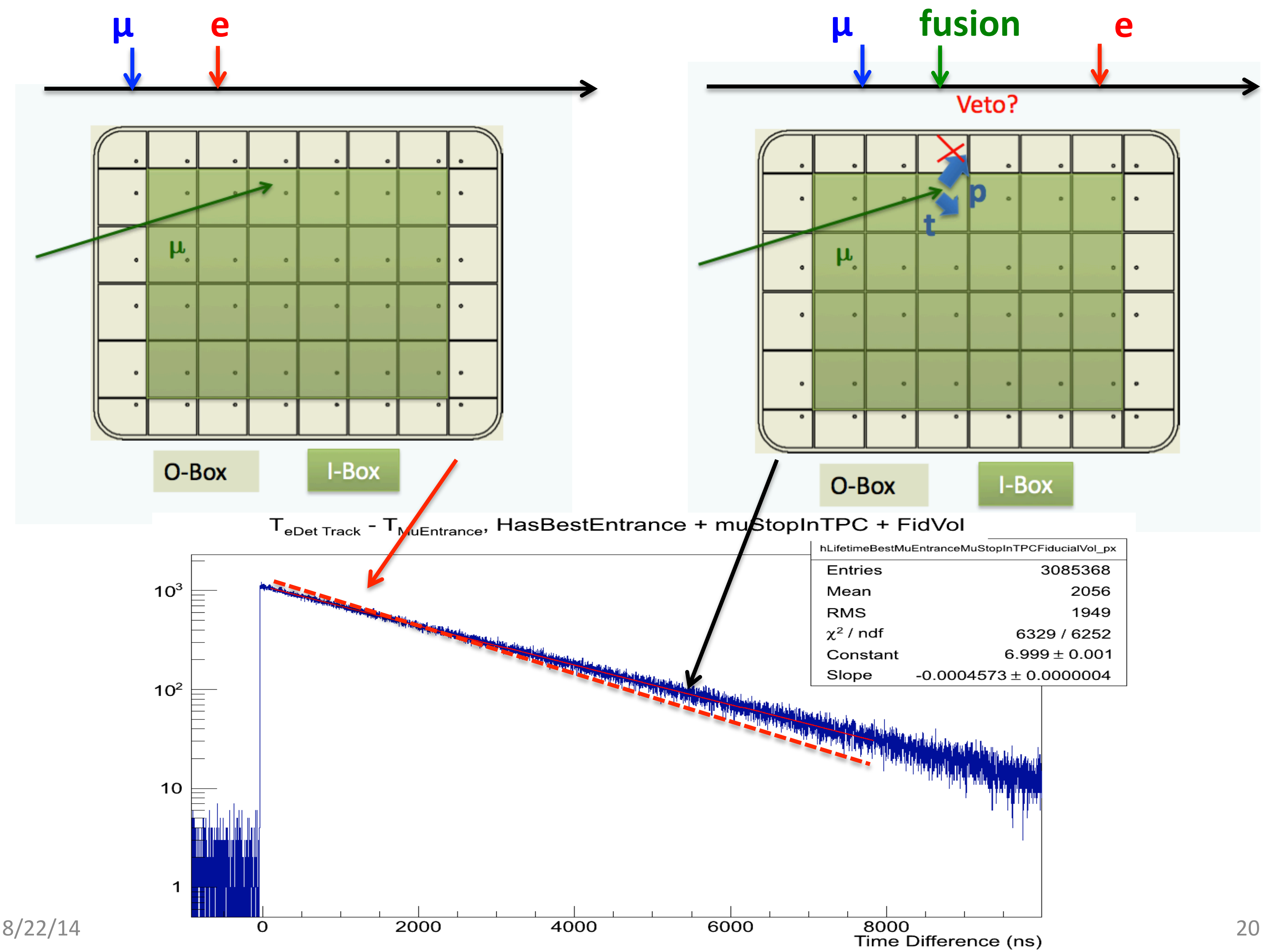
Systematics III -muon catalyzed fusion







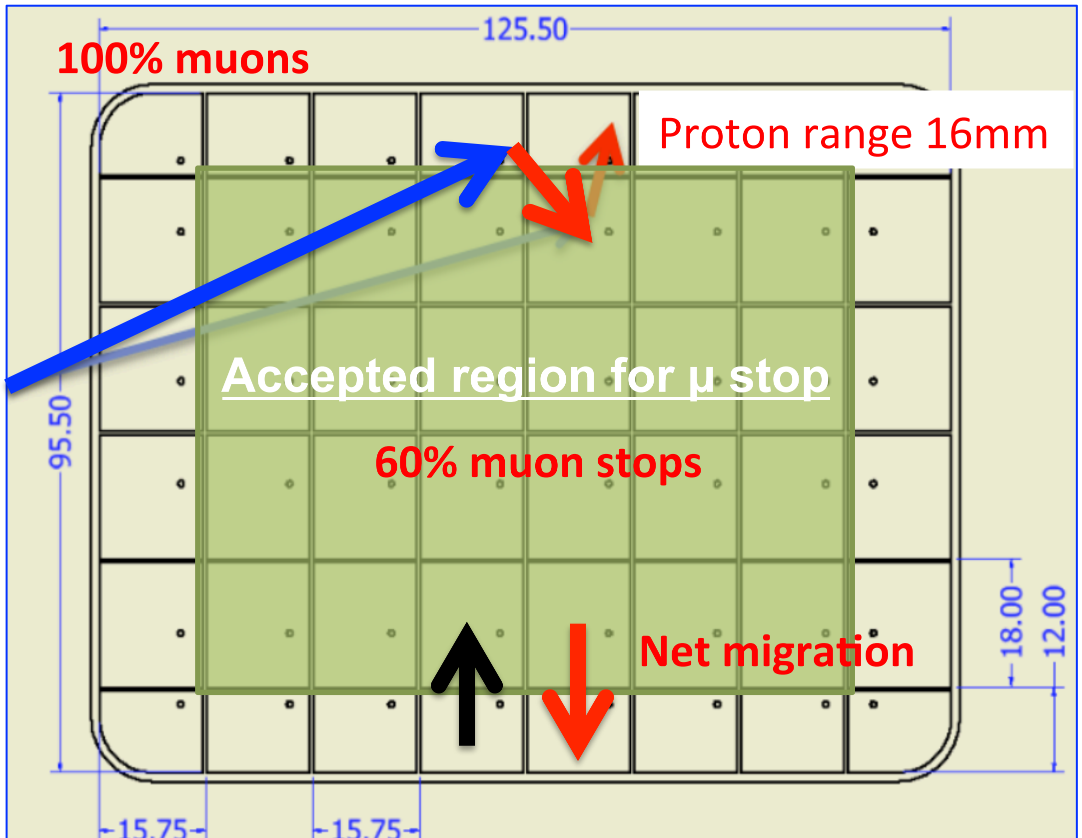
Fusion time dependent interference



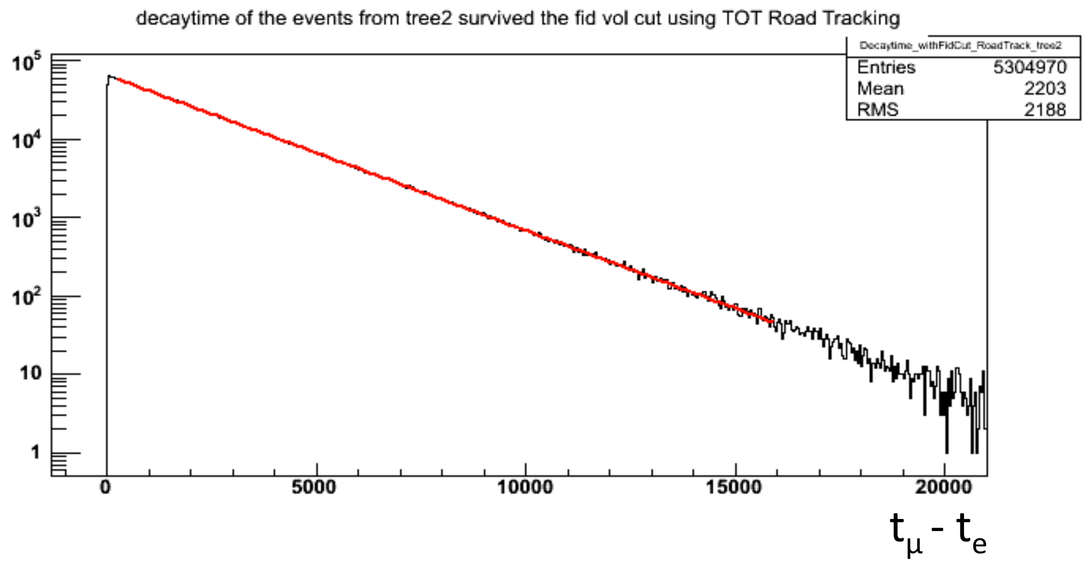
Systematics – fusion interference

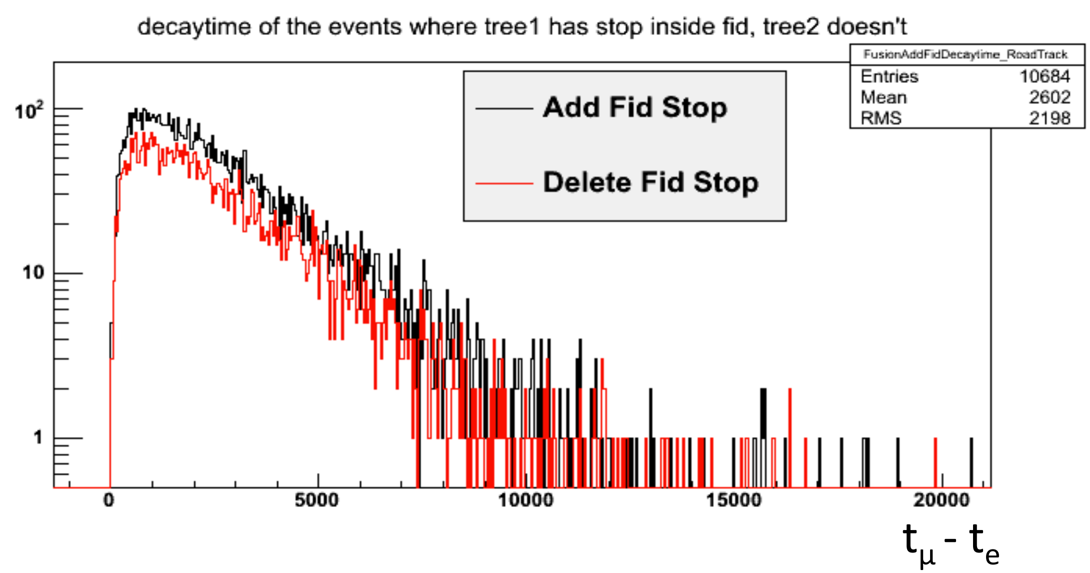
100% muon stops in TPC → ~60% stops in FidVol → ~5% stops are PT → ~1.2% of PT cause net migration

~400ppm all muons are PT-caused migration events at the Fiducial volume cut.



Systematics – fusion interference (simulation)





- **Lifetime of the fusion-caused migration events are longer than muon lifetime.**
- **In current tracking algorithm, fusions tend to pull muon stop into the Fiducial volume.**
- **According to the Monte Carlo, net migration in the current tracking algorithm decreases the disappearance rate by ~50Hz.**
- **This correction mainly depends on the muon stop tracking algorithm and the balance of the net migration.(Ongoing work)**

Other Systematics

- Electron interference
- Electron track definition
- Muon scattering -> High Z Capture
- Mu+ spin rotation.
- Isotope contamination
- μd quartet capture
- μ-p diffusion, μ-d diffusion
- Fiducial volume cut
- Pileup veto inefficiency

Status

- Data collected 2011: 6e9 good events
- Data collection in 2013: 2e9 good events
- Smooth taking data 2014 for 11 weeks
- Various systematics (impurities, fusion interference, pile-up, etc.) ongoing, expect first result in 2015.

Collaboration

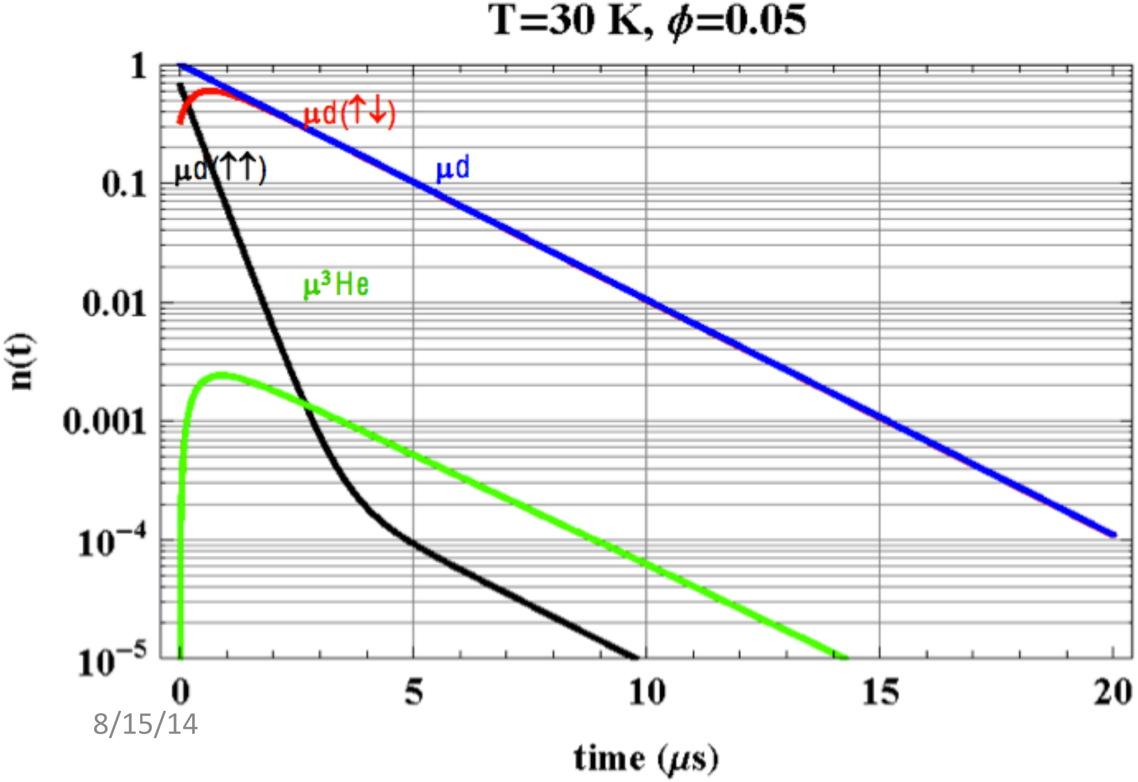
Thanks!

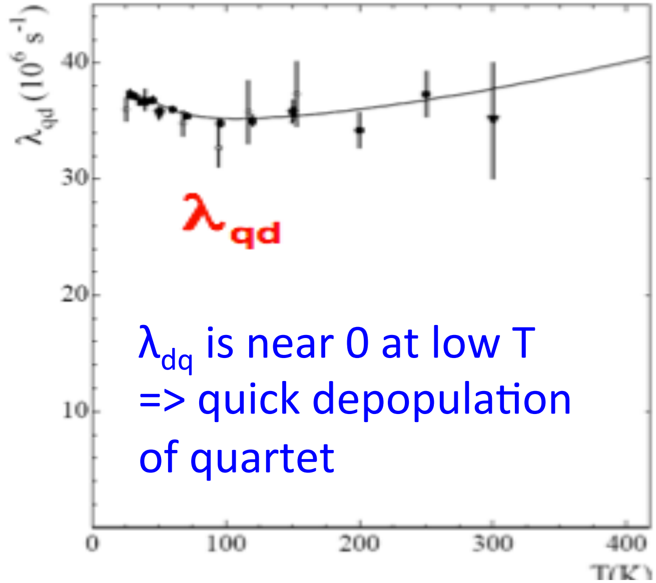
TPC conditions (back up)

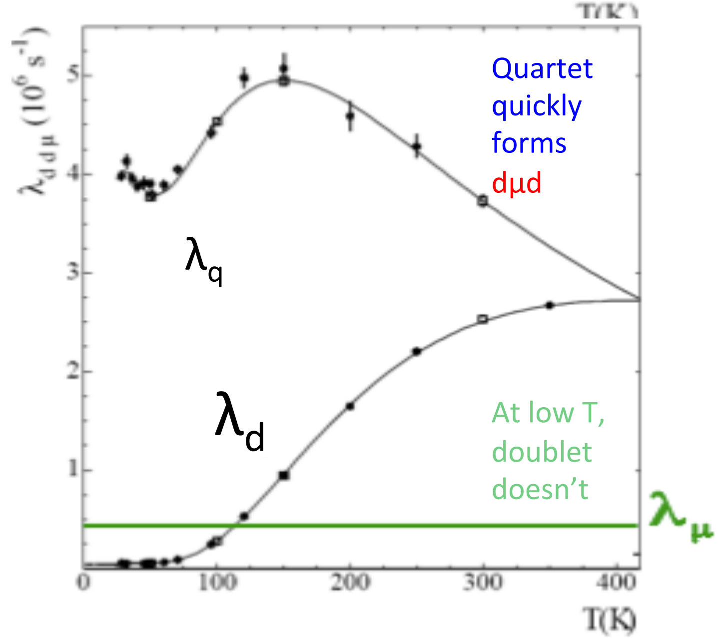
Goal: Maximize the population of μd doublet.

Temperature T = 33K

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

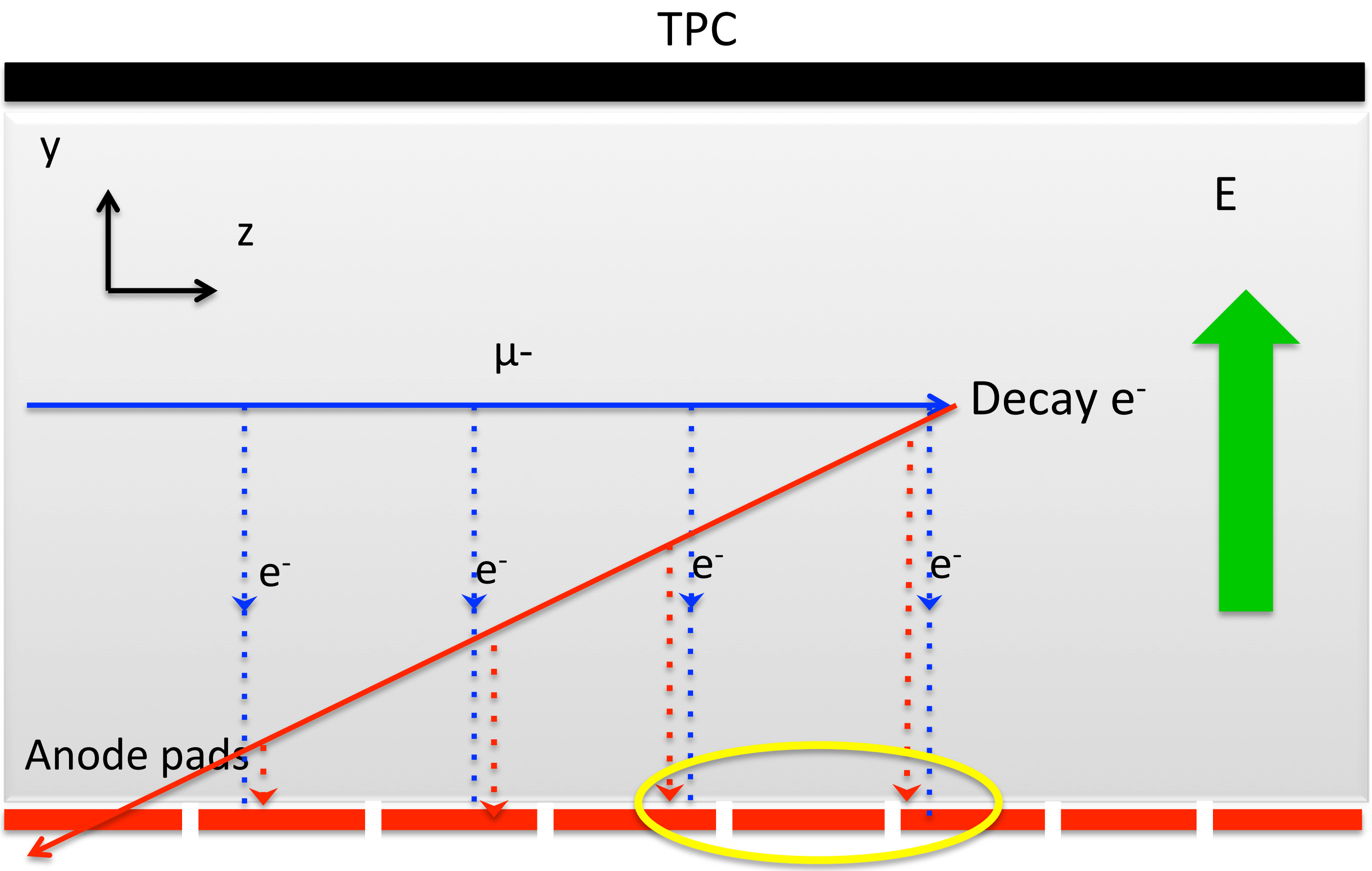




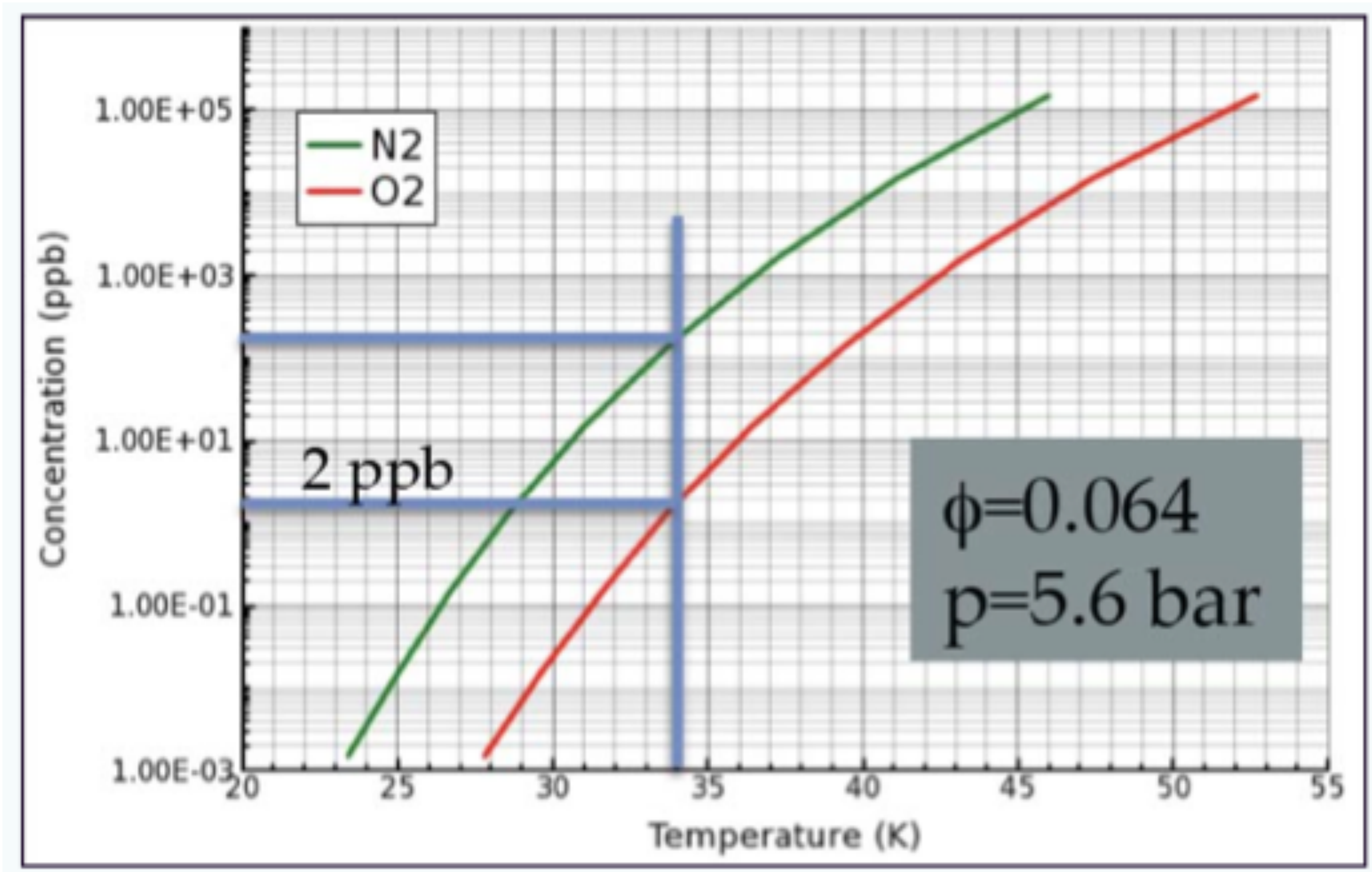


Electron interference

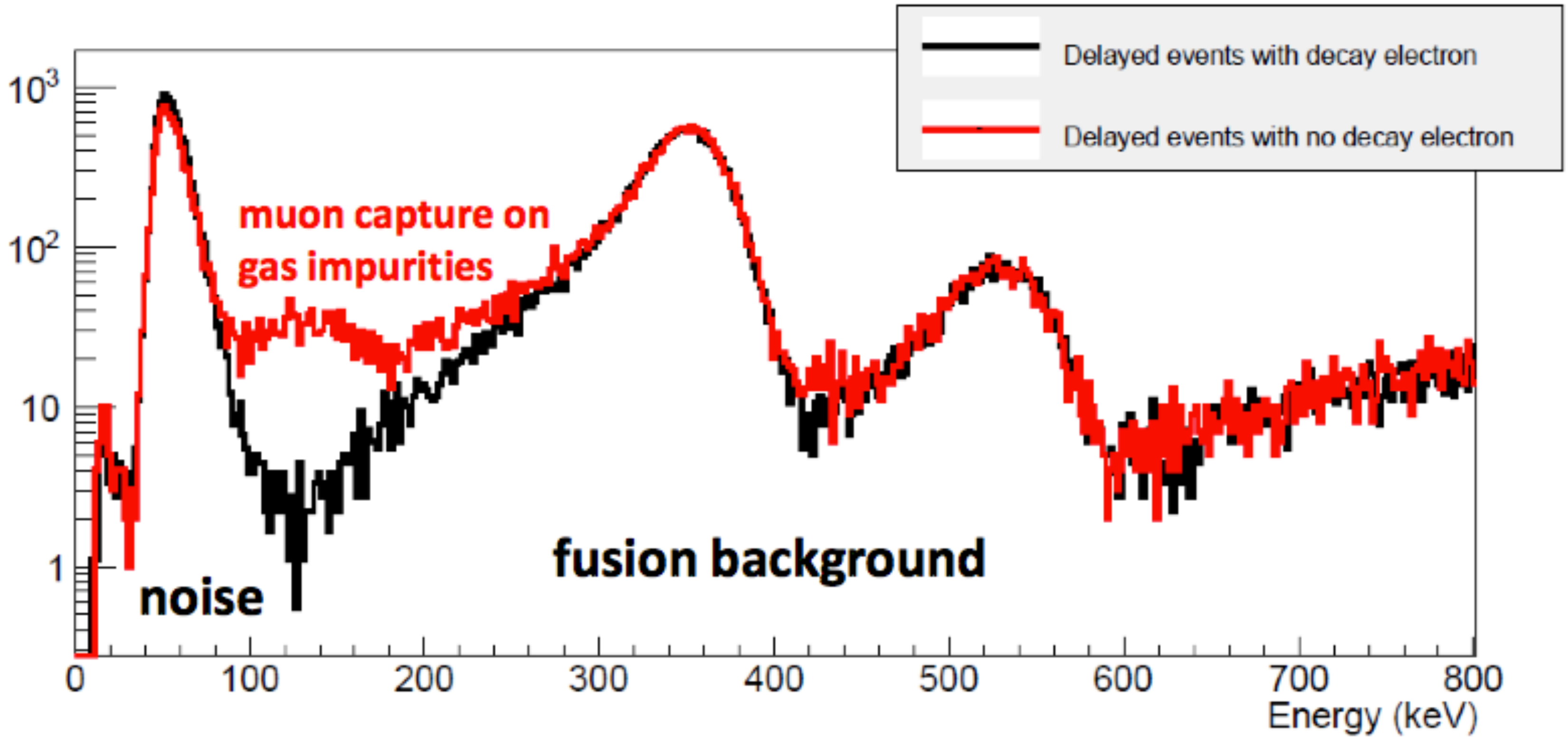
Problem: **energy deposition by the electron track, if interfere with the muon track, could lead to a time-dependent muon stop acceptance.**



Impurity – vapor pressure



Impurity-software



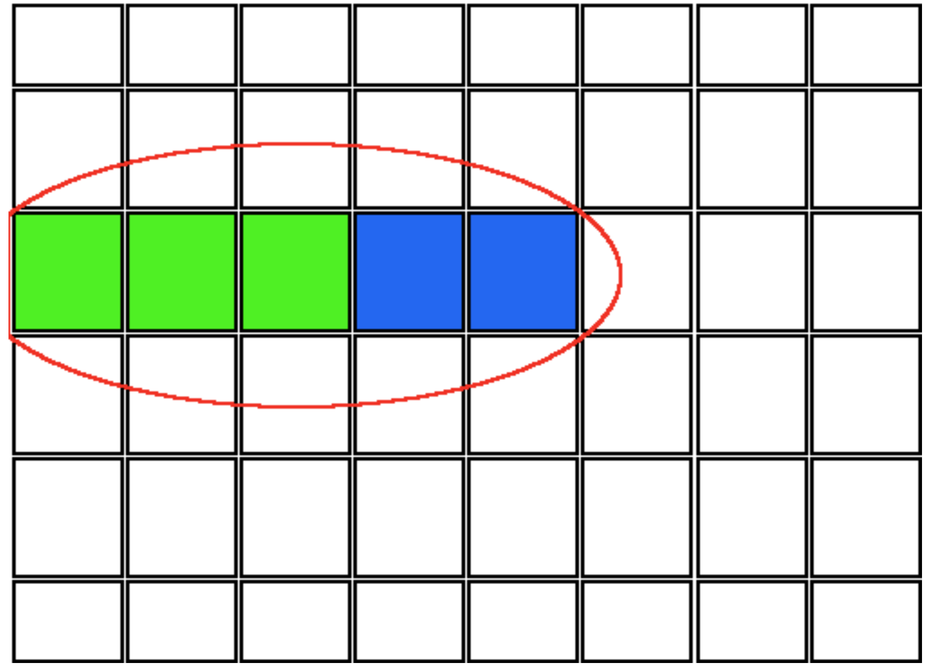
TPC Basic Cluster Tracking

Form **clusters** from TTPCMiniPulses (or other pulses)

1. Distance to nearby pulses
   - $\Delta X \leq 1$ pad
   - $\Delta Z \leq 2$ pads (one gap allowed)
   - $\Delta Y \leq 2\mu s$ (= 1cm)

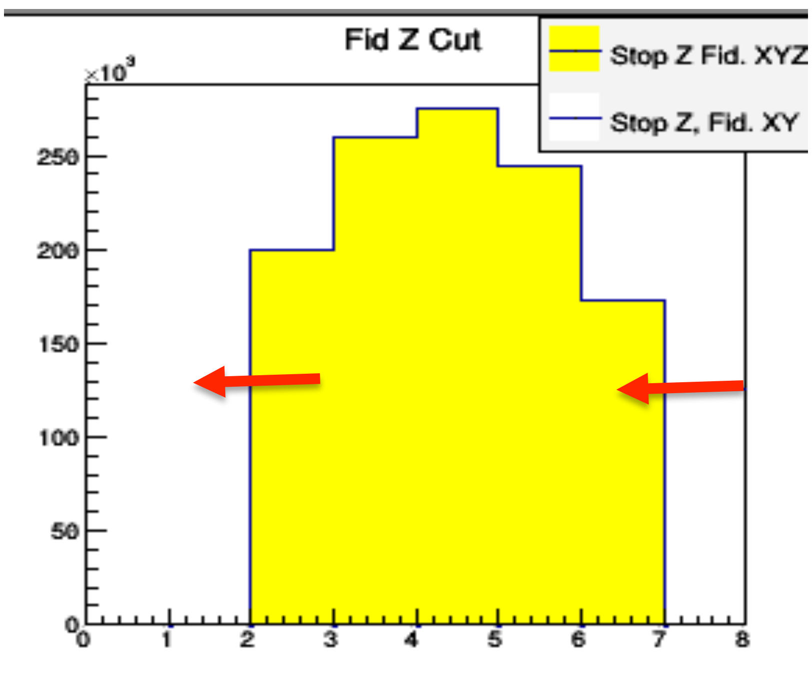
2. S-Energy > 440 keV

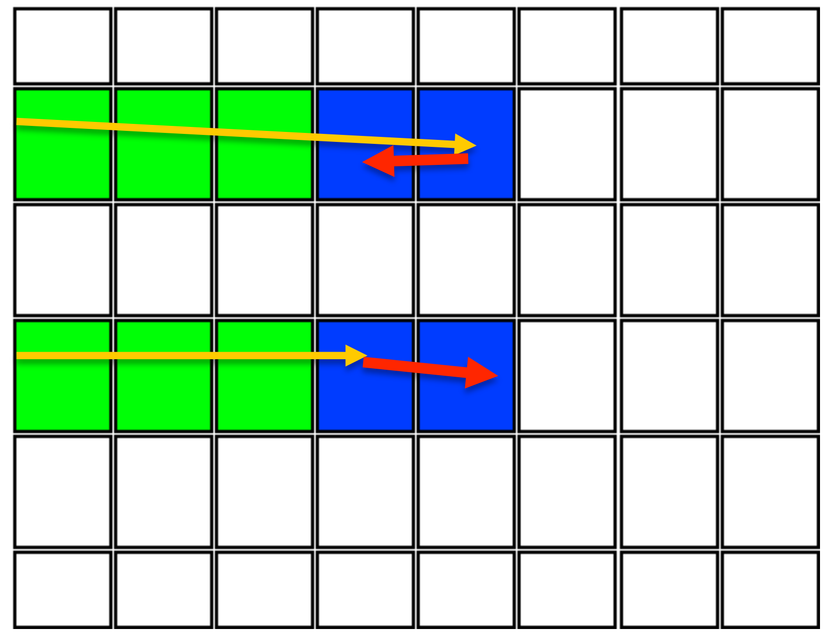
3. Length >= 3 pads



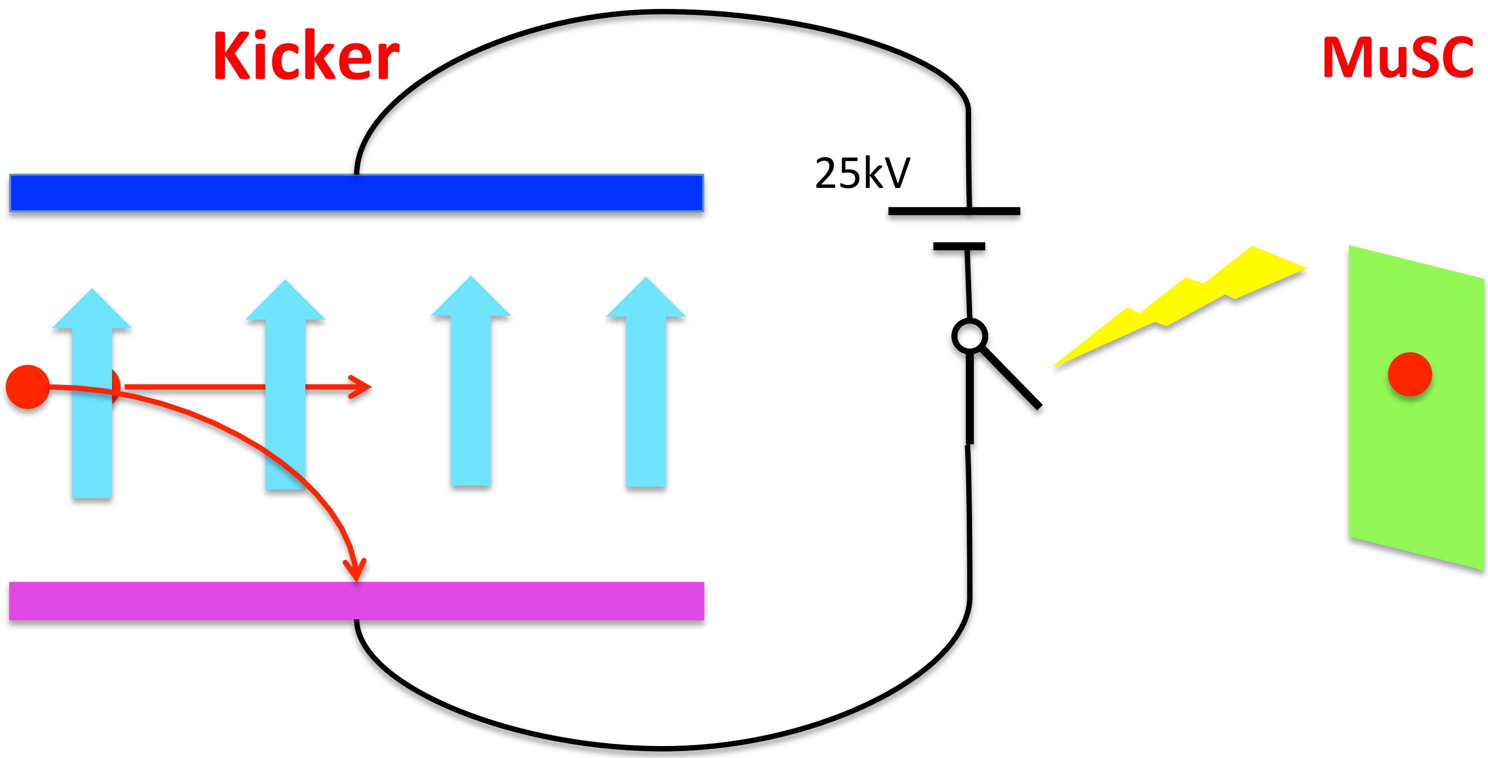
TPC Advanced Tracking

By managing the populations of events, we can balance the number of stops that migrate in and out of the fid. vol.





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.