4^{th} Joint meeting of the APS and PSJ, Oct 2014

Measurement of the dμd quartet-to-doublet fusion ratio ($\lambda_q : \lambda_d$) and the μd hyperfine rate λ_{qd} using the fusion neutrons from μ^- stops in D_2 gas.

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Experimental Goal and Motivation

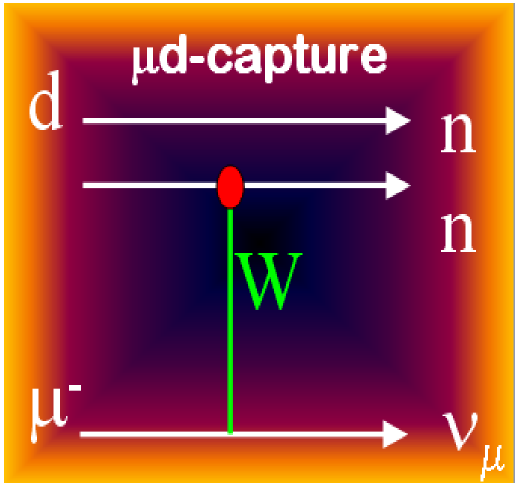
Measure muon capture rate in D_2 to a precision better than 1.5%

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

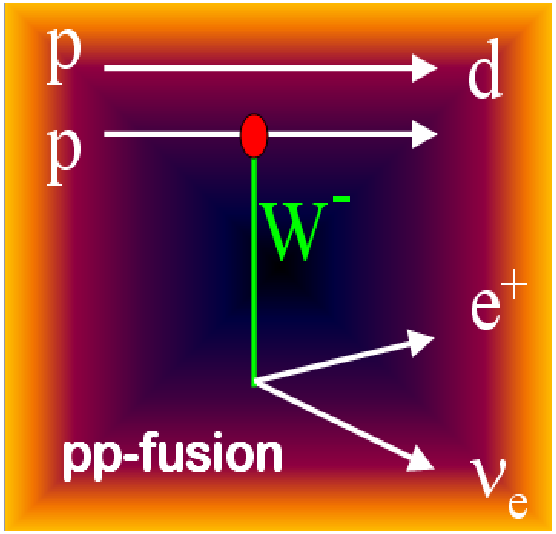
Rate Λ_d from μd ($\uparrow\downarrow$) atom

$\mu d \rightarrow$ $\uparrow\uparrow$ Quartet

$\mu d \rightarrow$ $\uparrow\downarrow$ Doublet



My Goal: To find relative populations of doublet states finally used for measuring Λ_d .



Help understand weak nuclear reactions:

Solar pp fusion: $p + p \rightarrow d + e^+ + \nu_e$

Neutrino interaction: $\nu + d \rightarrow p + p + e^-$

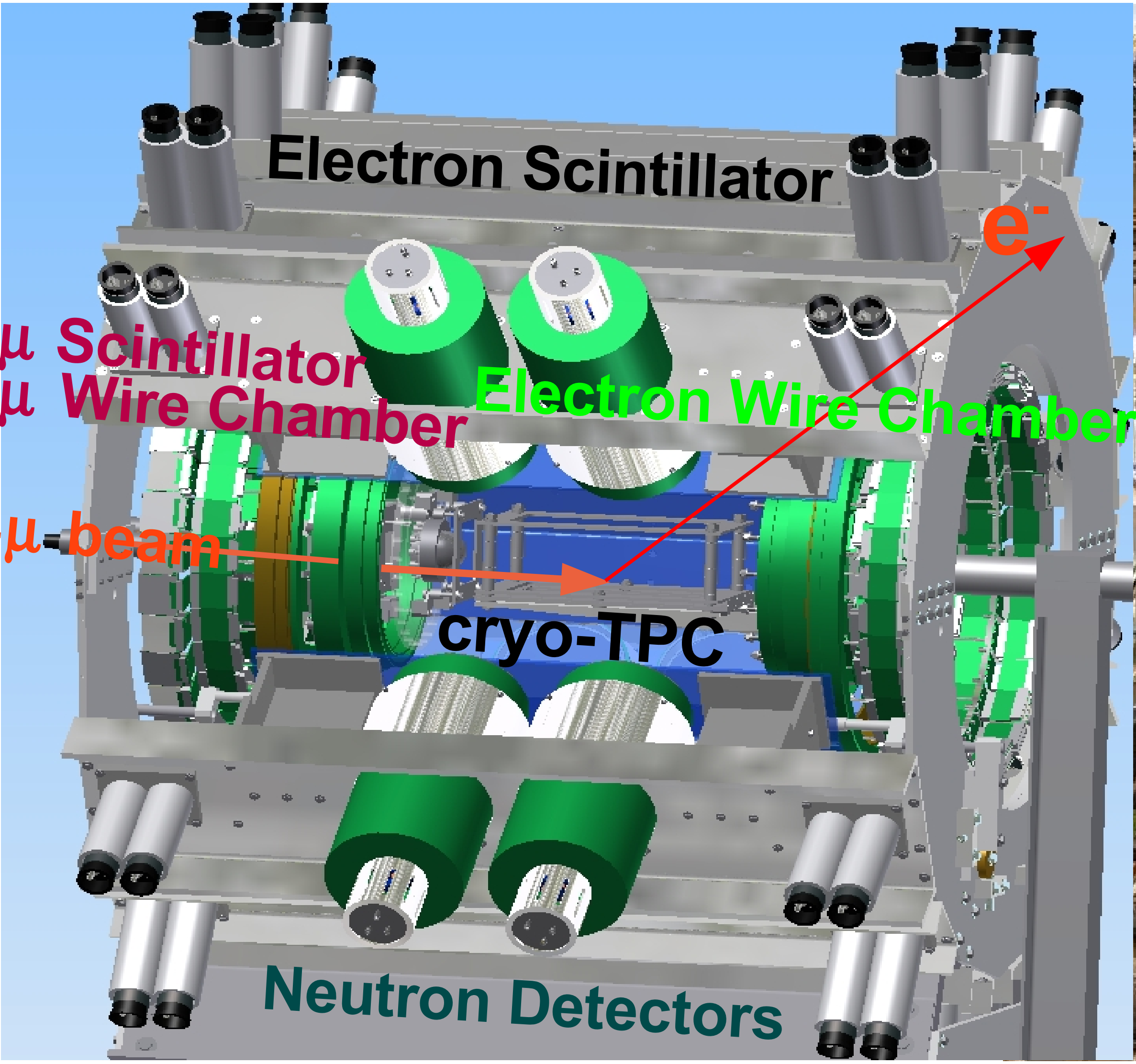
Double beta decay ...

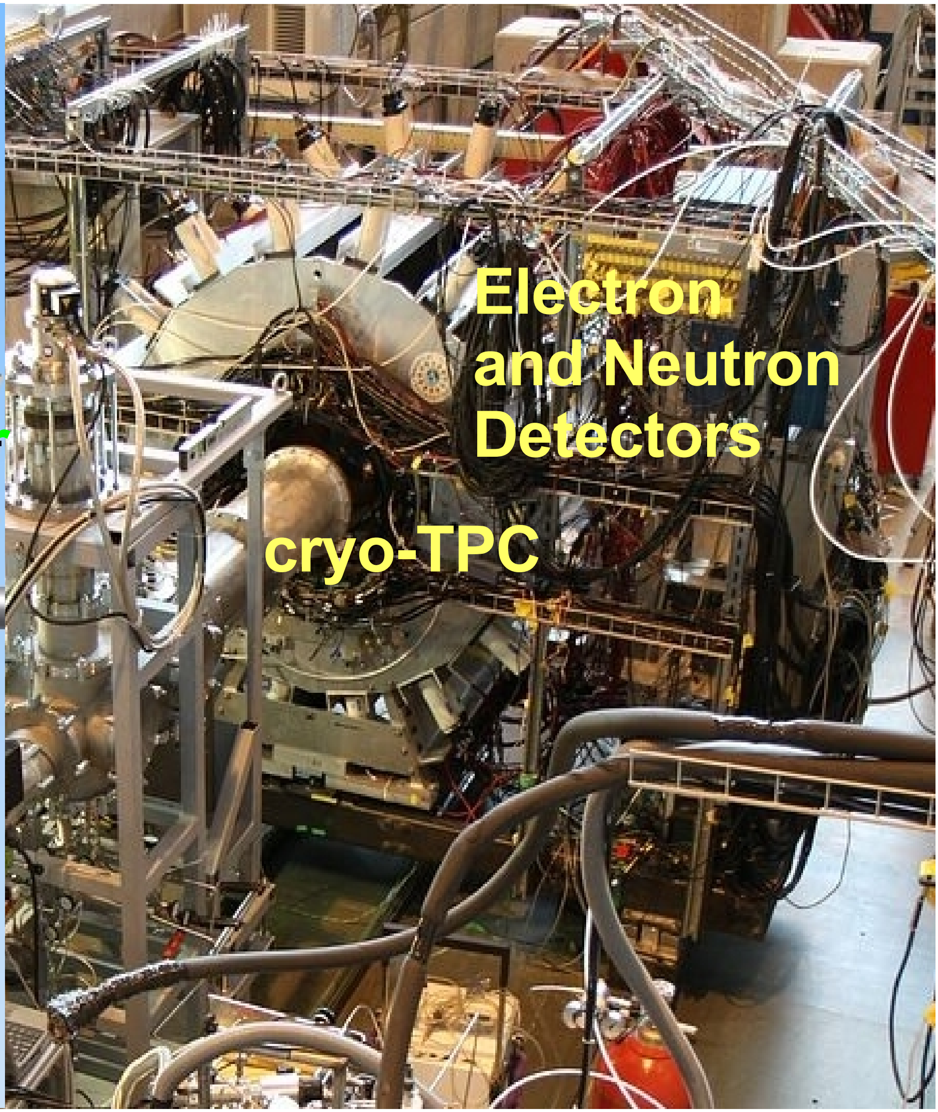
These reactions involve a poorly known two-nucleon weak axial current. The muon capture rate Λ_d determines a single LEC that parametrizes this two-nucleon weak axial current.

Experiment Overview

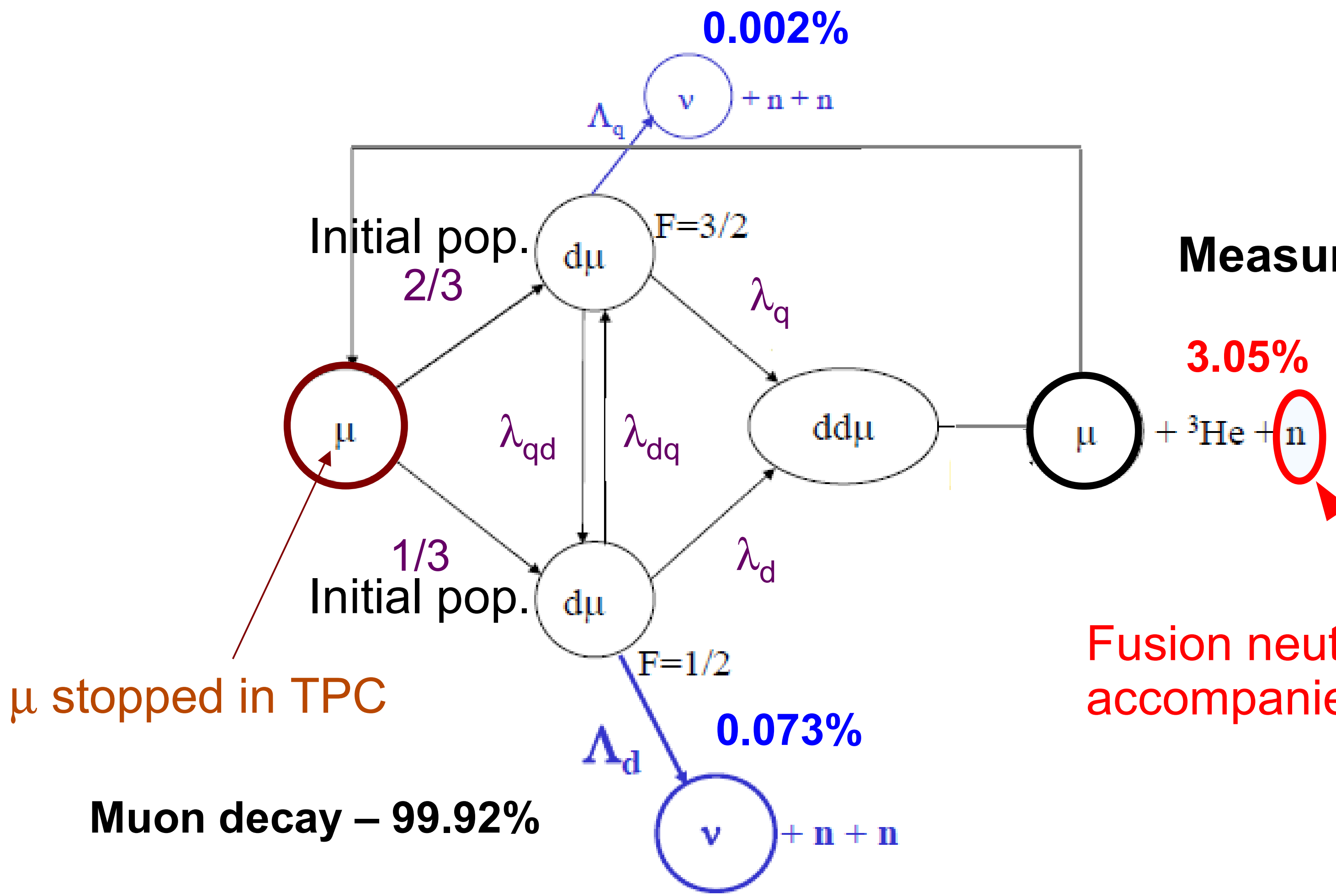
Experimental Setup:

Muons (Z - axis) enter Al vessel (~ 3 mm)– TPC (10 x 10 x 8.2 cm).
X - horizontal and Y - vertical. Target deuterium.





Muon Chemistry



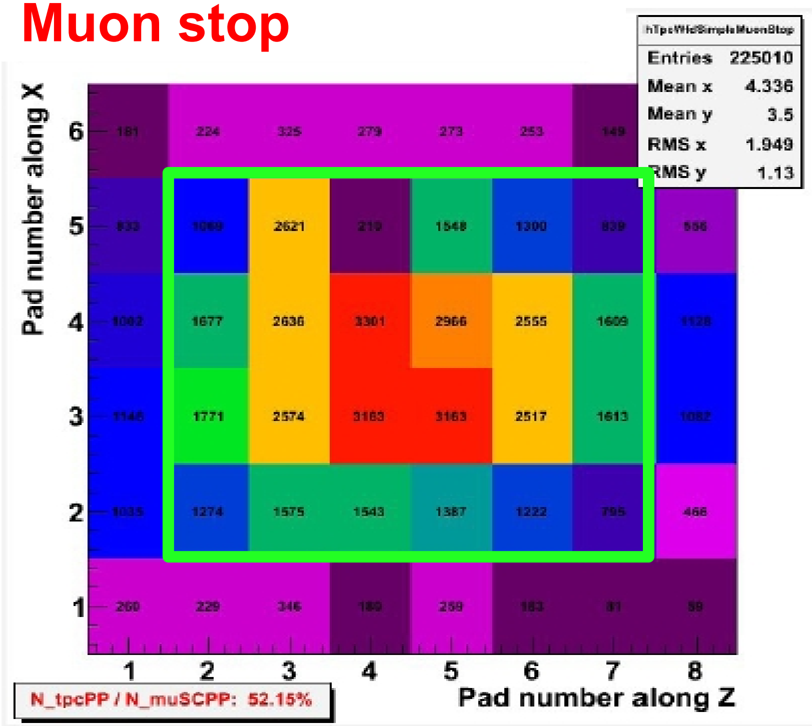
Measure λ_{qd} and $\lambda_q : \lambda_d$

Fusion neutrons (2.45 MeV) accompanied by e^-

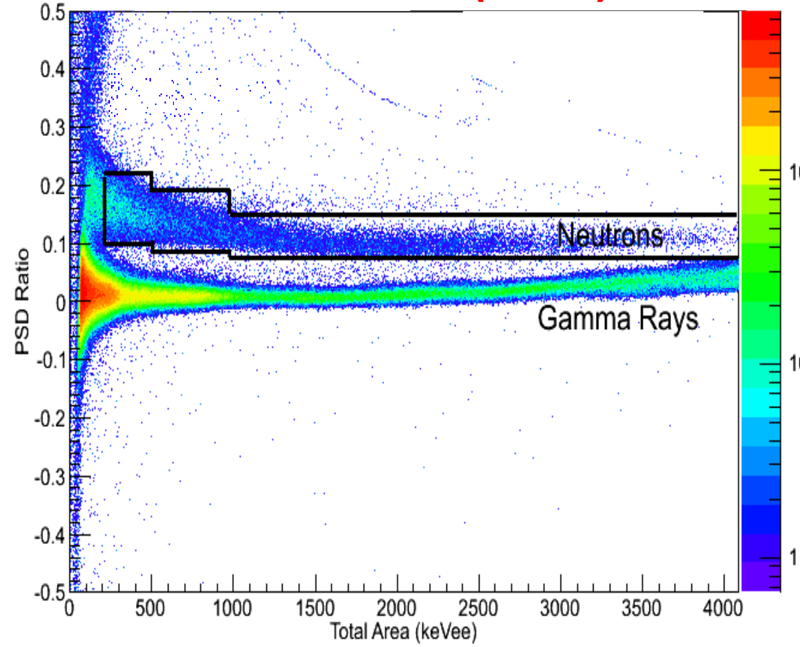
Muon decay – 99.92%

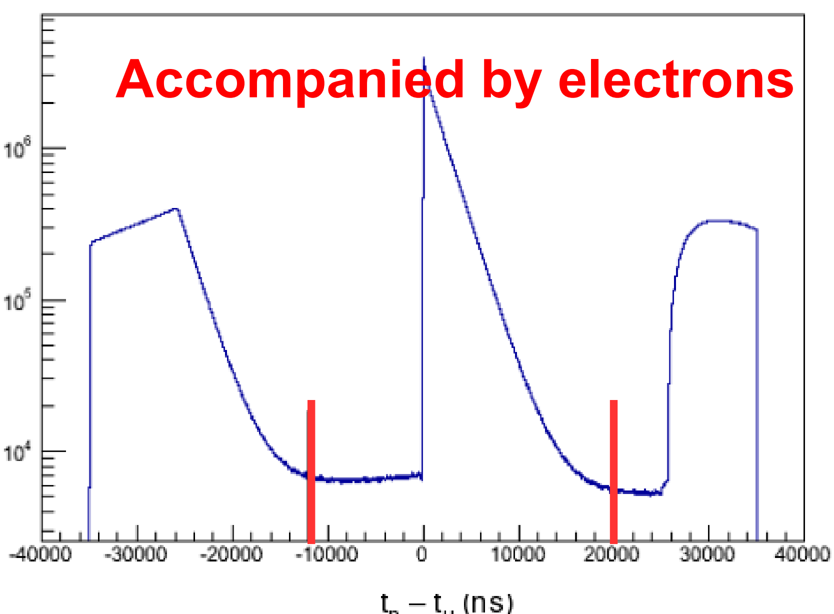
Fusion Neutron definition:

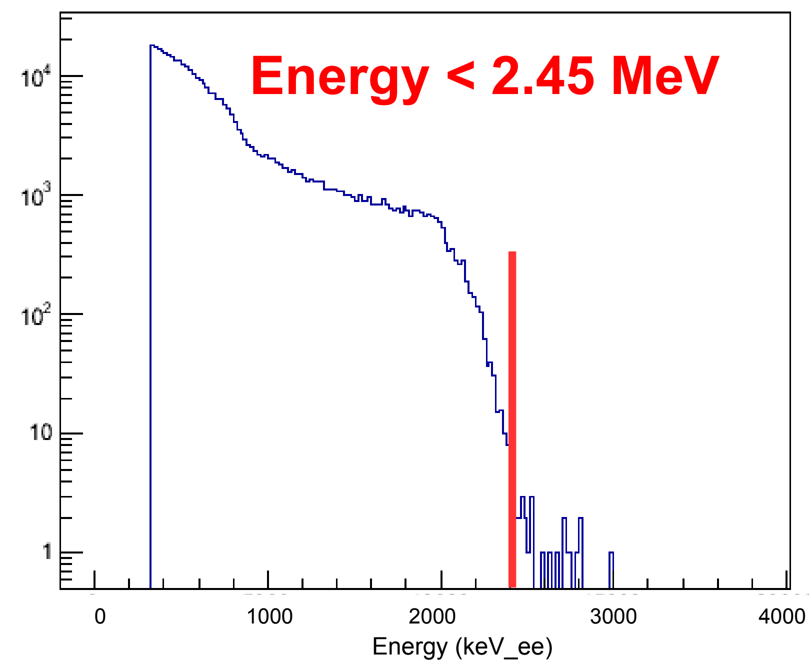
Muon stop



Neutron cut (PSD)

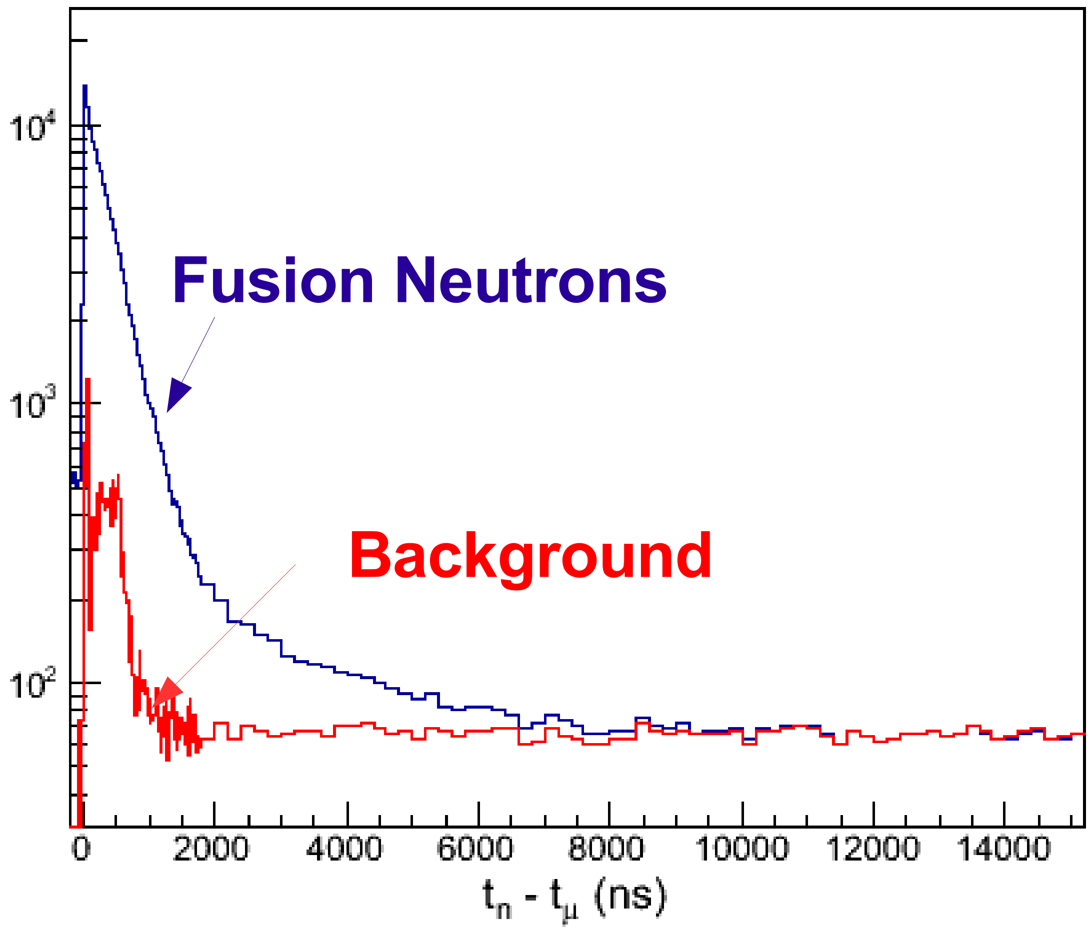






Fusion Neutron Time Distribution

Time distribution: Time of neutron relative to the muon entrance time.
All **fusion neutron** cuts applied gives time distribution in blue
Contains accidental **background** from accelerator and beamline neutrons.
Subtracted background histogram and fitted it.



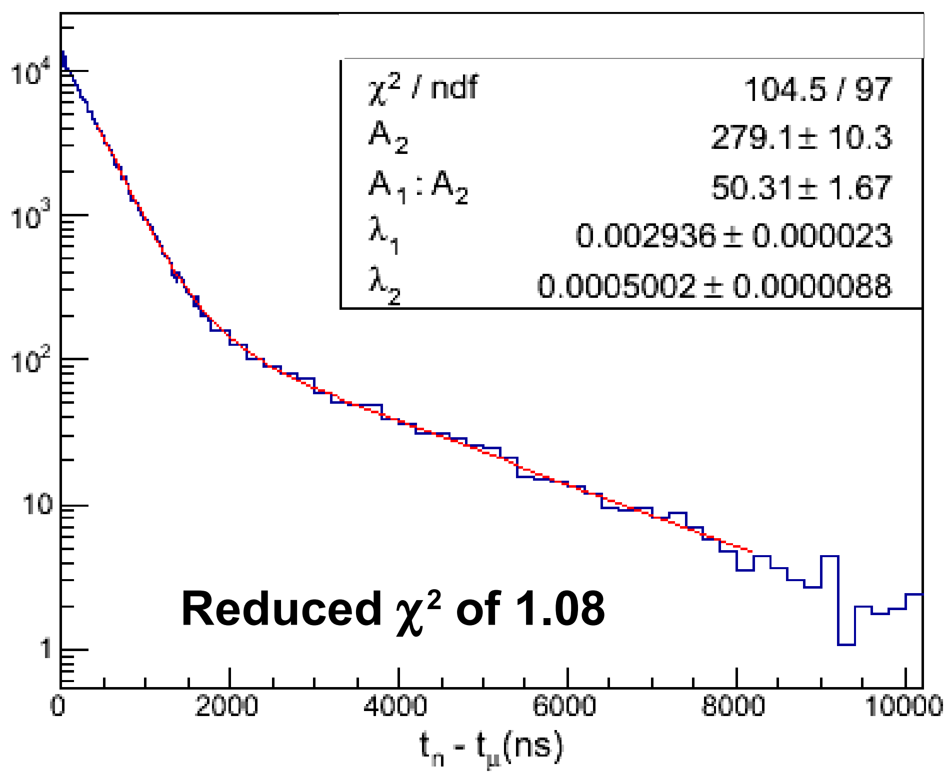
Lifetime Fit of Fusion time distribution

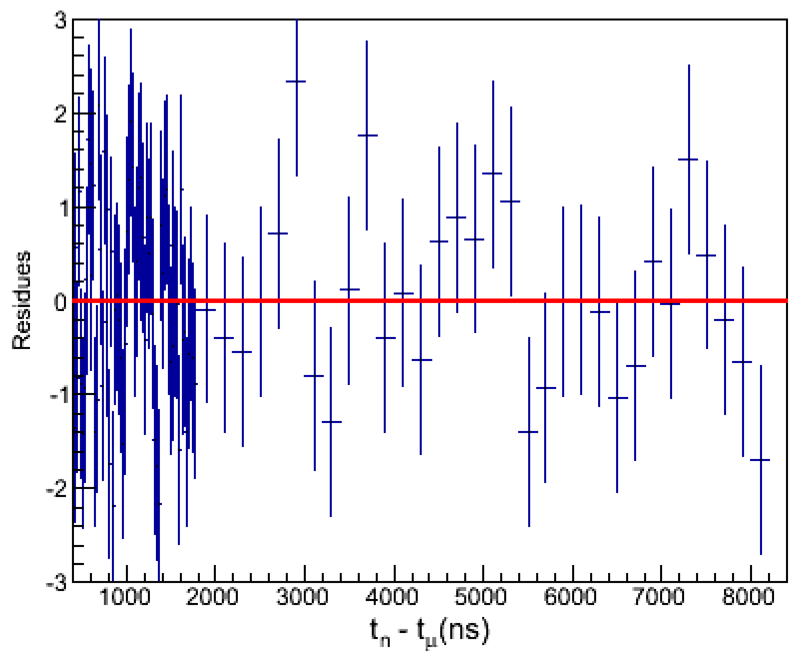
Lifetime fit: A two lifetime (λ_1 and λ_2) fit function from the general solution of muon chemistry gives the fusion time distribution as,

$$n(t) = A_1\, e^{-\lambda_1 t} + A_2\, e^{-\lambda_2 t}$$

Fitted the background subtracted histogram with above fit function on a flat background = 0. Fit parameters A_1:A_2, prompt lifetime rate λ_1 and and slow rate λ_2, A_2 – Initial population.

$$\text{Residue} = \frac{y(t) - y_i}{\sigma}$$





Results from Analytical Solutions

Differential equations of the population of states derived from the muon chemistry were solved to find kinematic parameters λ_{qd} and λ_q : λ_d from the fit results.

$$\lambda_1 \sim \phi\, (\lambda_{qd} - \lambda_\mu) \qquad \lambda_2 \sim \phi\, \lambda_\mu$$

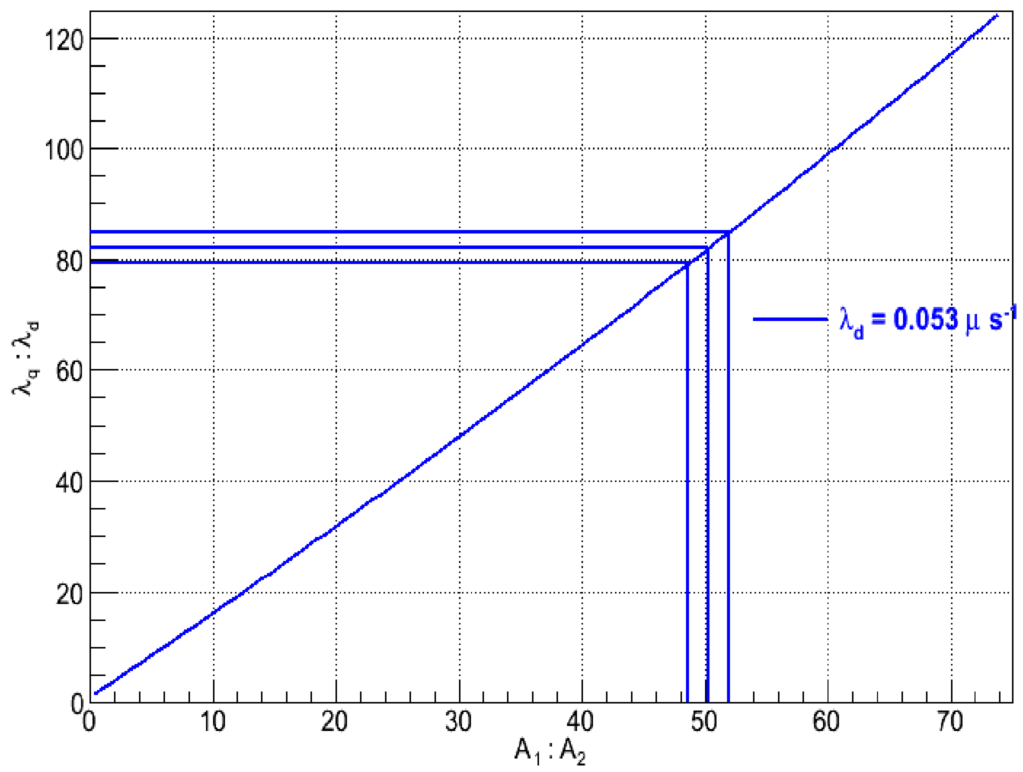
$$\lambda_{qd} \sim (\lambda_2 - \lambda_1) / \phi$$

Thus the difference in $\lambda_2 - \lambda_1$ gave

λ_{qd} = 39.67 (0.4)

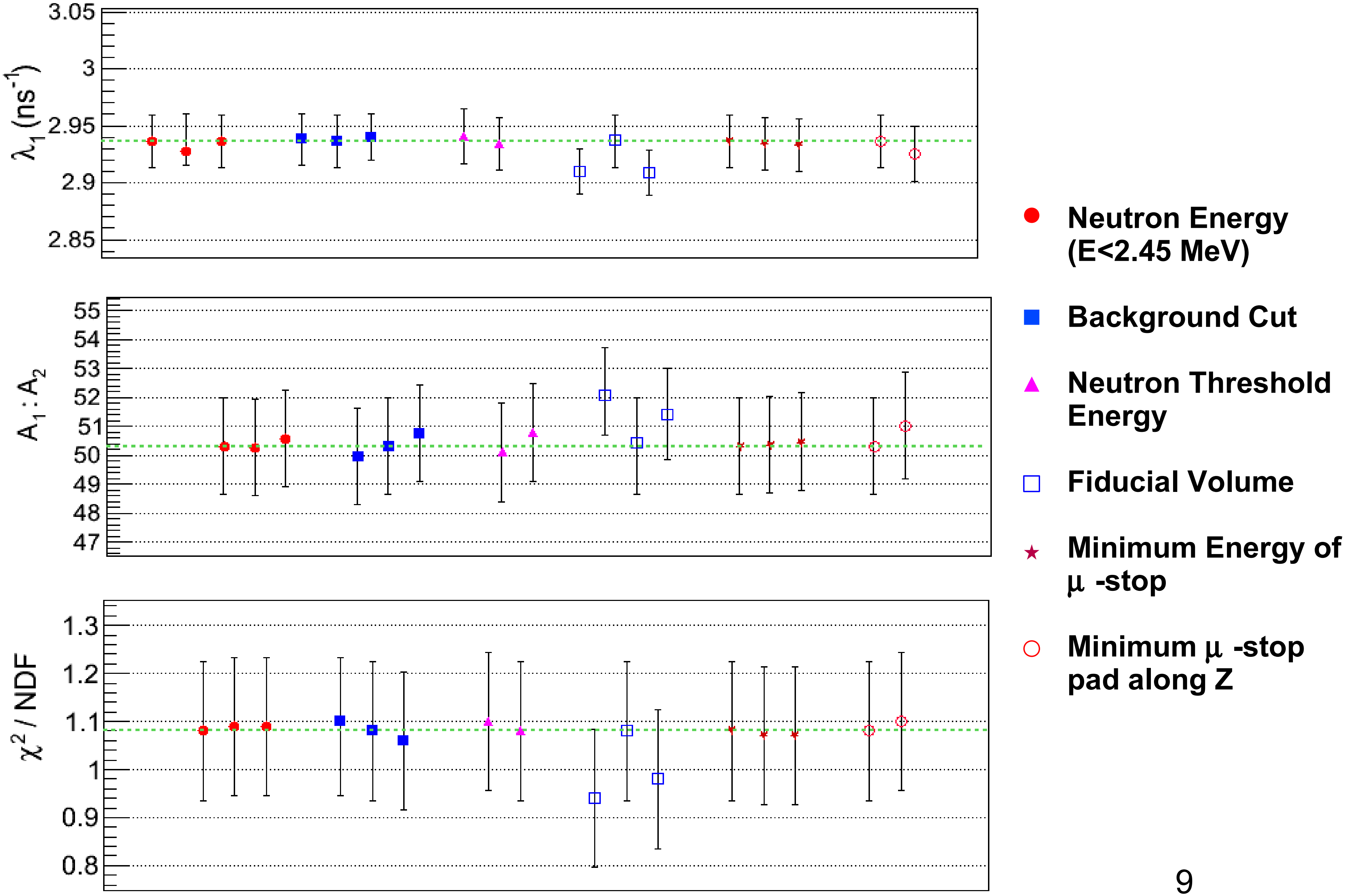
Amplitude ratio $A_1 : A_2 = f\,(\lambda_q : \lambda_d)$

A plot of amplitude ratio versus $\lambda_q : \lambda_d$ gave $\lambda_q : \lambda_d$ = 82.05 (2.89)



Systematic Errors

Shows stable fit results. The horizontal green line shows original values (before changing the cuts)



Preliminary Results

The transition rate of muonic deuterium from quartet to double state at a temperature 34 K and density 6.12% LH_2

$\lambda_{qd} = 39.67 \pm 0.402_{stat} \pm 0.032_{sys}\ \mu s^{-1}$

The dμd formation rate from quartet state to double state
$\lambda_q / \lambda_d = 82.05 \pm 2.89_{stat} \pm 2.78_{sys}$

Experiment	Year	λ_{qd} (μs^{-1})	$\lambda_q : \lambda_d$	Density	Temp (K)
SIN [1]	1983	$37.0^{+1.3}_{-1.7}$	79.5(8.0)	4.8 %	34.7
PSI [2]	1987	36.89 (0.8)	80.17(7.8)	4.83 %	40
Dubna [3]	1991	37.84 (21)	65.51(0.59)	4.9 %	53
PSI [4]	2009	37.1 (3)	80.98(1.59)	5.14 %	32.2
This work	2014	39.67 (0.4)	82.05(4.01)	6.12 %	34

Conclusion

We obtain quite stable results which would help us find the relative populations of μd in quartet and doublet states under our experimental conditions. The relative population of the doublet state from this analysis will be further used by MuSun to ultimately find Λ_d

Thank You !

References

1. First observation of muonic hyperfine effects in pure deuterium -
   P. Kammel et al. Phys.Rev. A28 2611-2622 (1983)

2. Muon Catalysed dd fusion b/w 25 to 150 K: Experiment
   J. Zmeskal et. al. Phy. Rev. Vol. 42, # 3. 1987

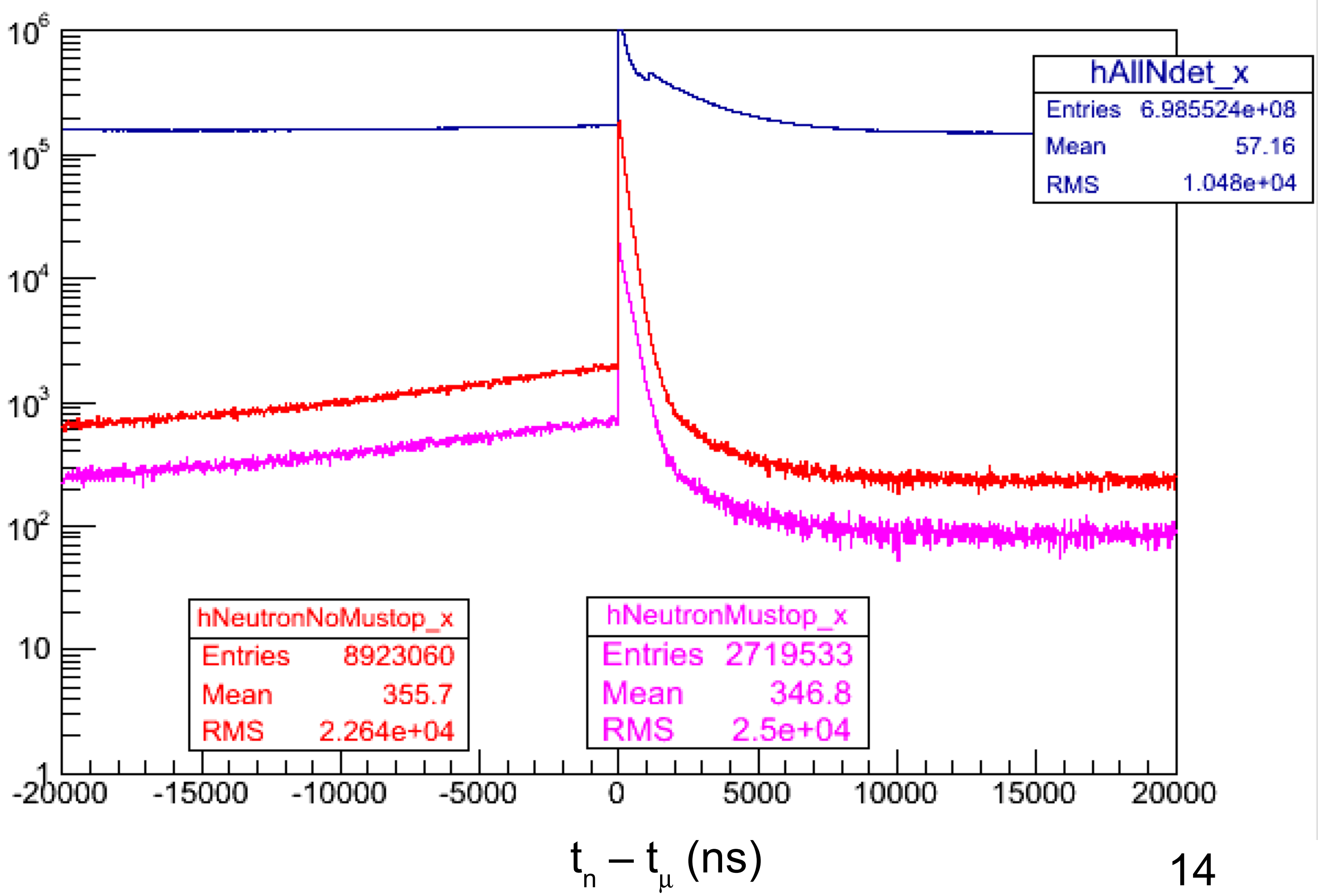
3. D. V. Balin et al., Muon Catalyzed Fusion 5/6, 163(1990/1991).

4. HIGH PRECISION STUDY OF MUON CATALYZED FUSION IN D2 AND HD GAS
   D. V. Balin et al.

Back up Slides

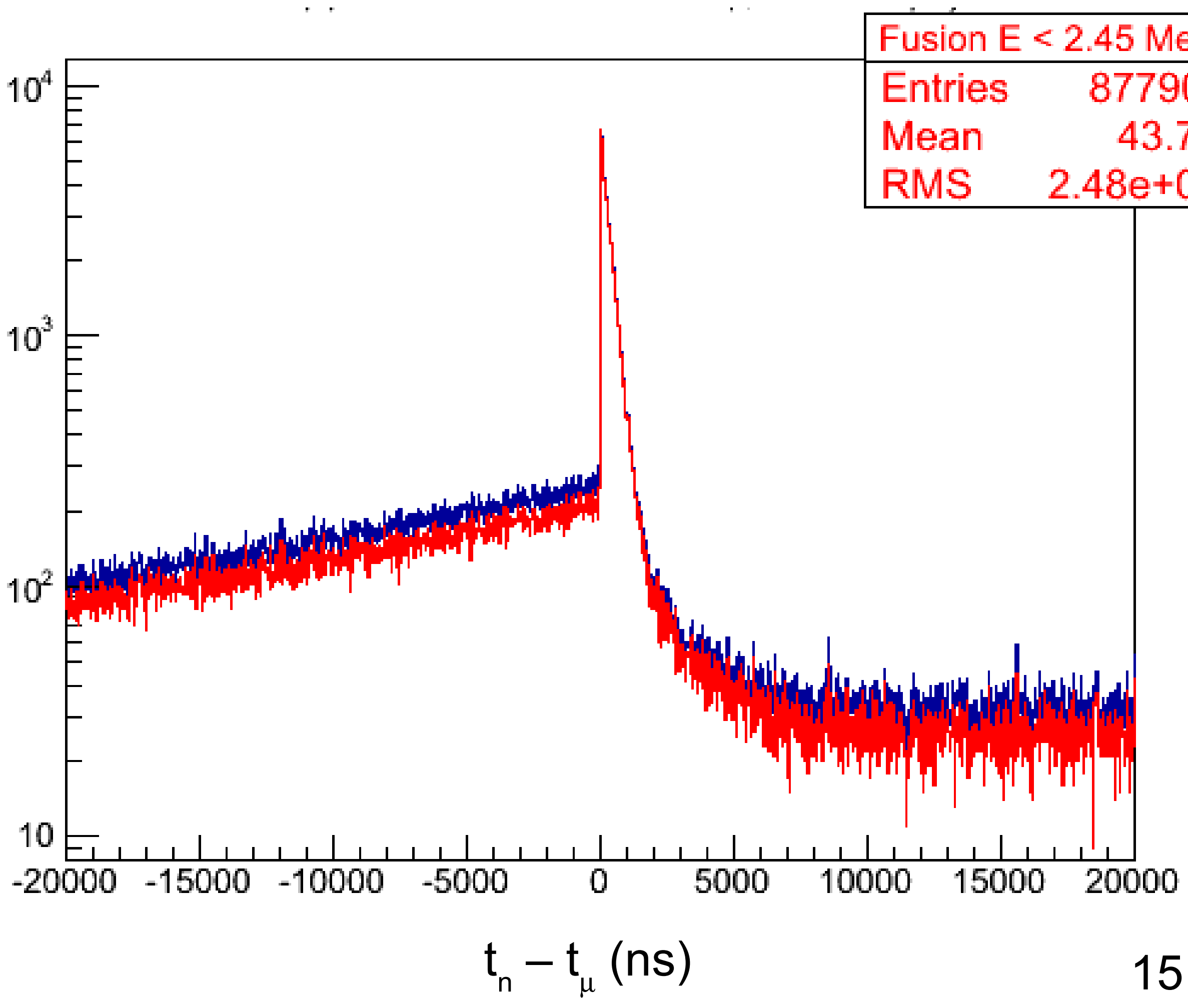
Neutron Time Spectrum

Pile up protection of muons (one muon enters the TPC in a specific time window $\pm$ 40 μs) - **Blue spectrum** – all pulses seen by the counters (neutrons, gamma rays etc.) - Kinck due to after pulses.
Neutron time spectrum after applying PSD (gamma rays excluded) – **Red Spectrum**
Applied a muon stop condition in the TPC. Includes capture and fusion neutrons – **Magenta Spectrum**. This analysis is for ds_211 (around 1000 midas runs)



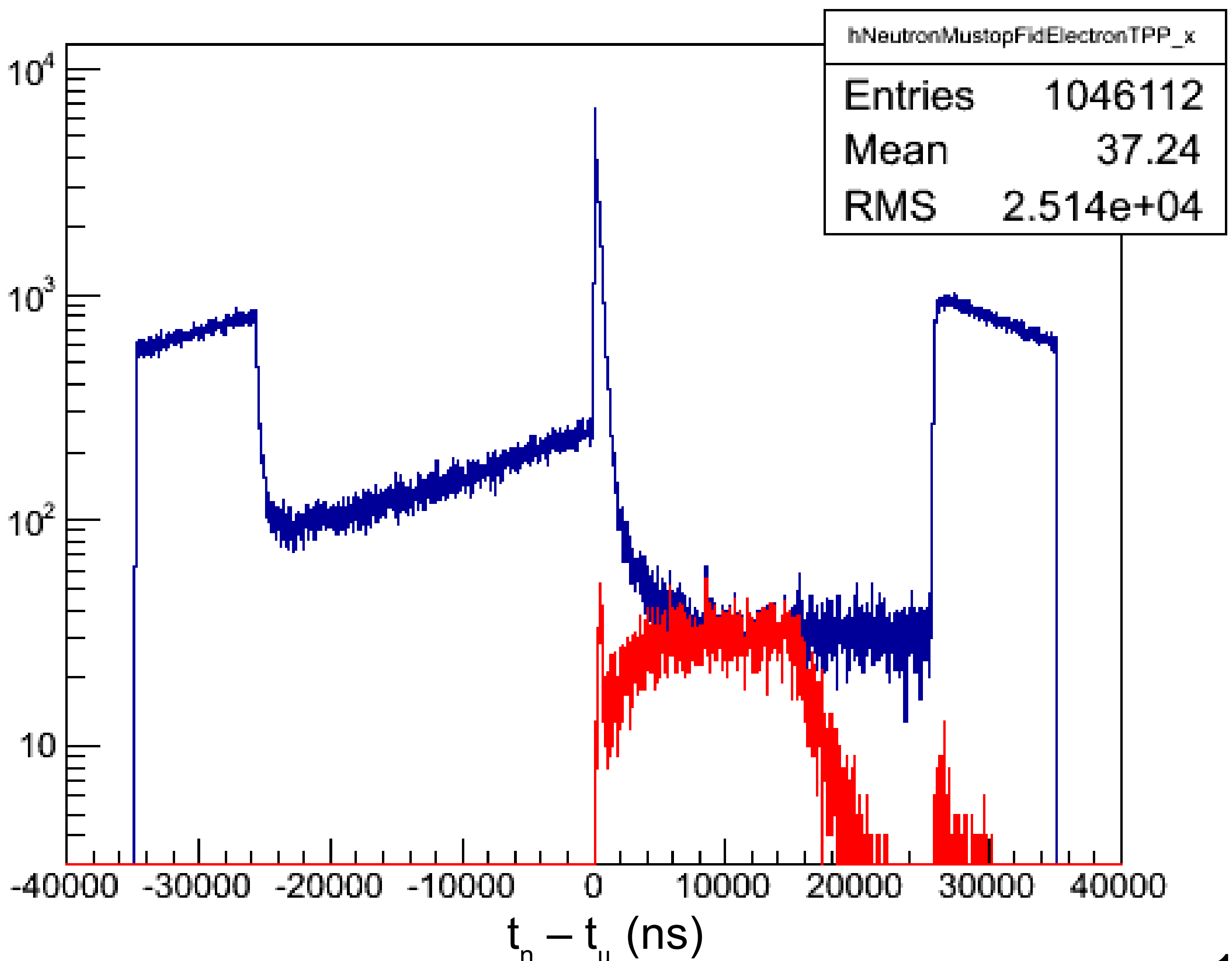
Fusion Neutron Time Spectrum

Fusions accompanied by electrons. An electron coincidence with e from fiducial volume of the TPC applied – **Blue Spectrum**
Fusion Neutron are monoenergetic – applied energy cut < 2.45 MeV – **Red spectrum**



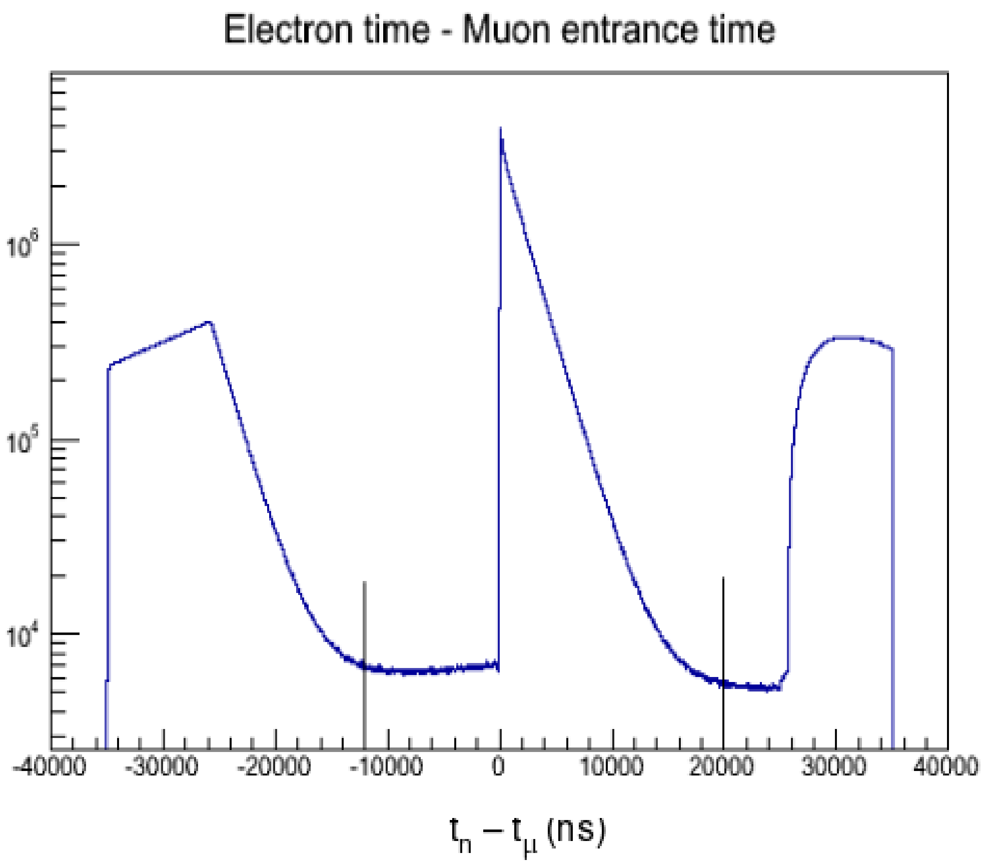
Background Spectrum

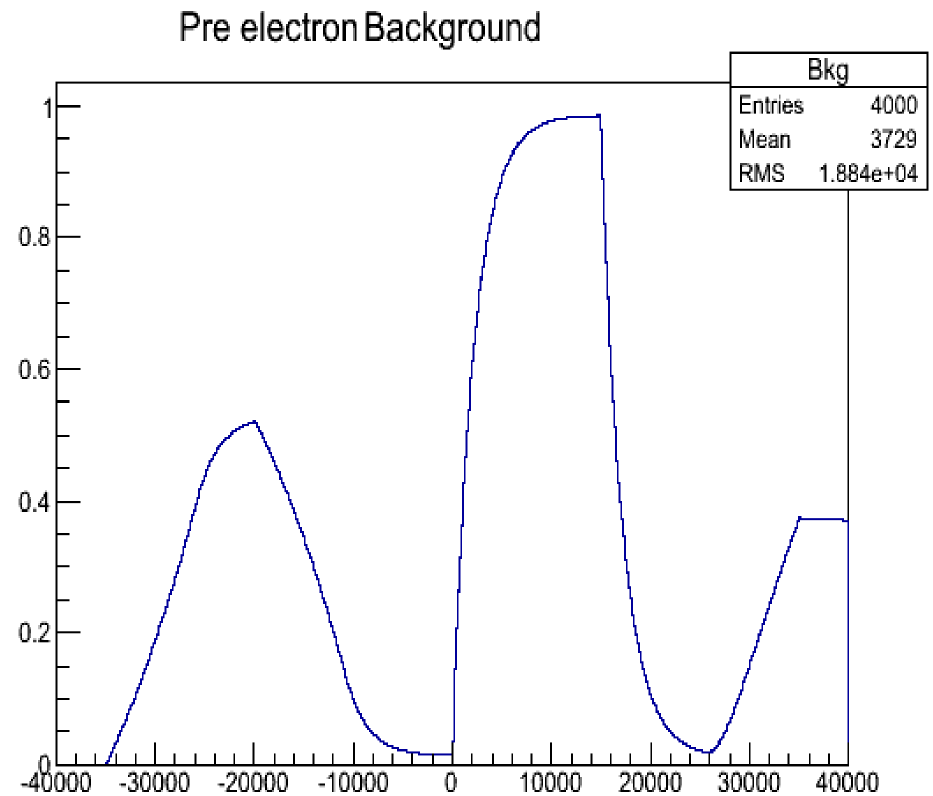
Background – from pre electron condition – electrons before the neutrons are generated   in a window of -100 to -15000 ns time of electron time wrt to neutron time **Red spectrum.**



Background Spectrum

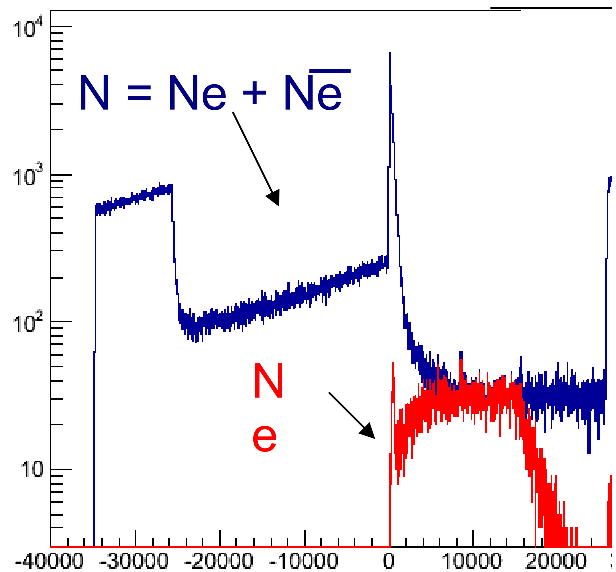
Electron association window is shown in the left panel. Probability for electrons to leak in the background window is found by shifting the pre electron window over every bin of the neutron spectrum divided by the area shown in the left (which is the sample space). Output of this in the right figure is the efficiency function.

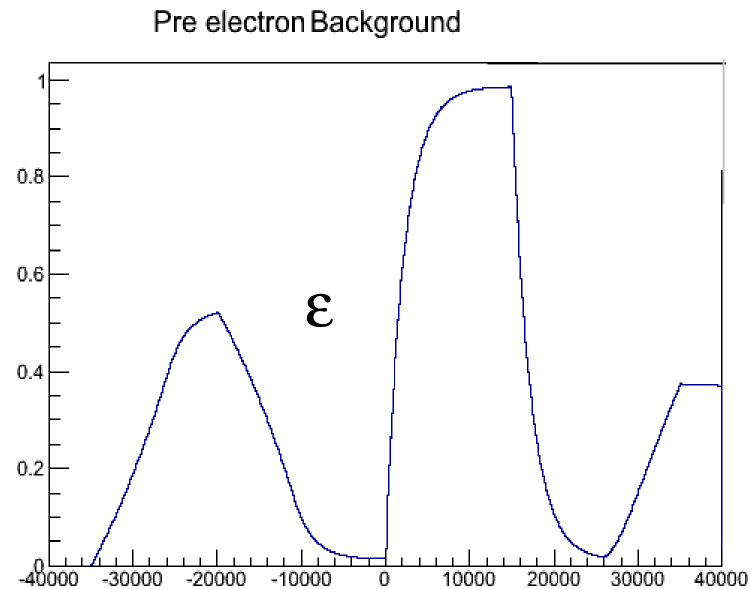




Error Propagation – Lifetime fit

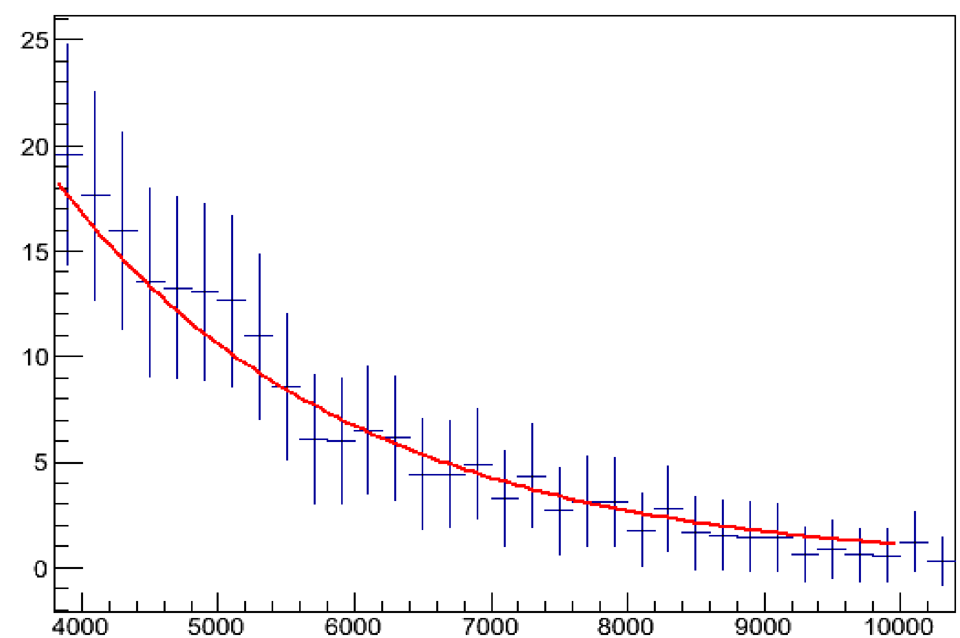
Blue spectrum = pre electron and no pre electron – used two uncorrelated components
Red – only pre electron
Right spectrum efficiency ε





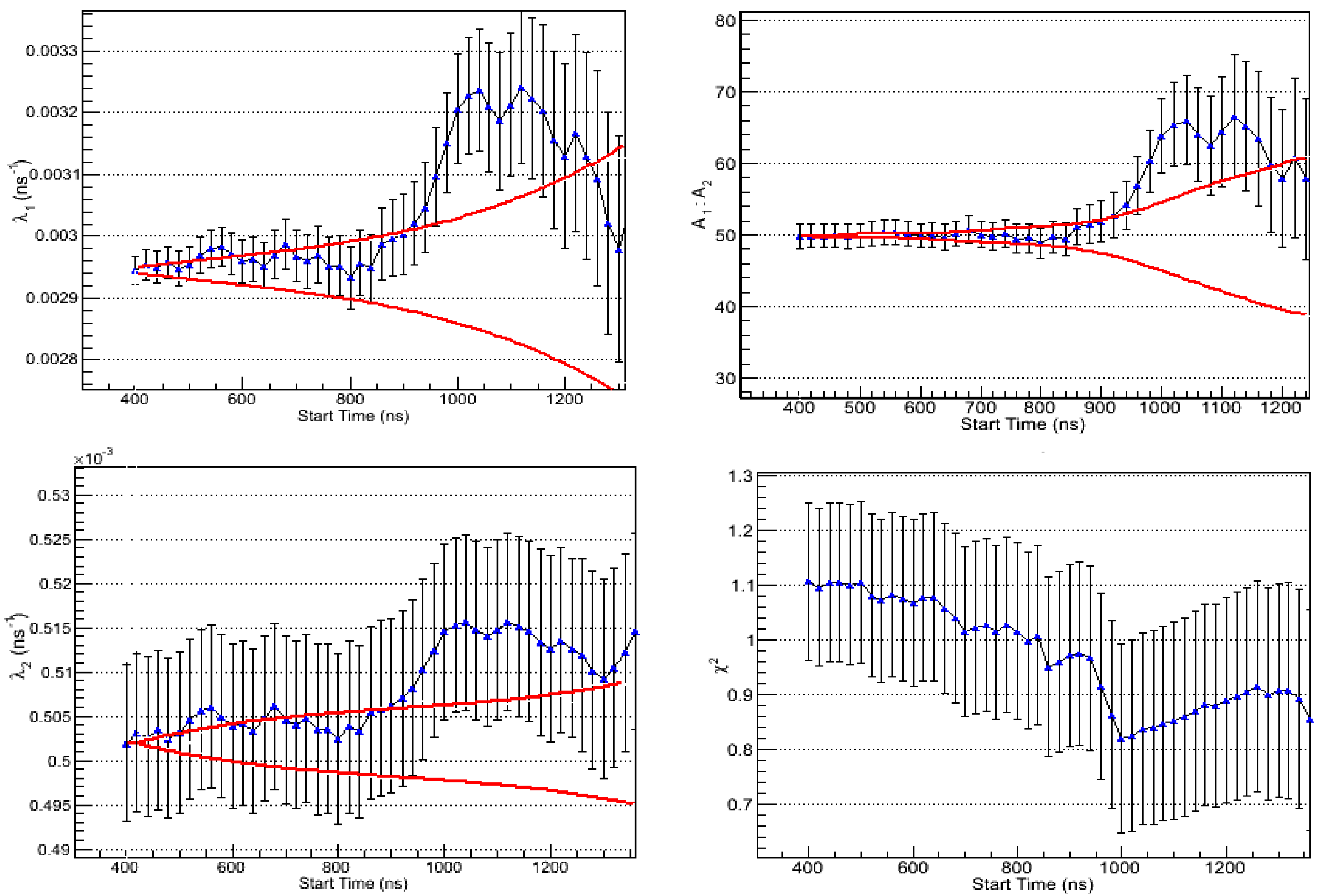
Final fusion spectrum

Nf = Ne + $\overline{\text{Ne}}$ – Ne/ε

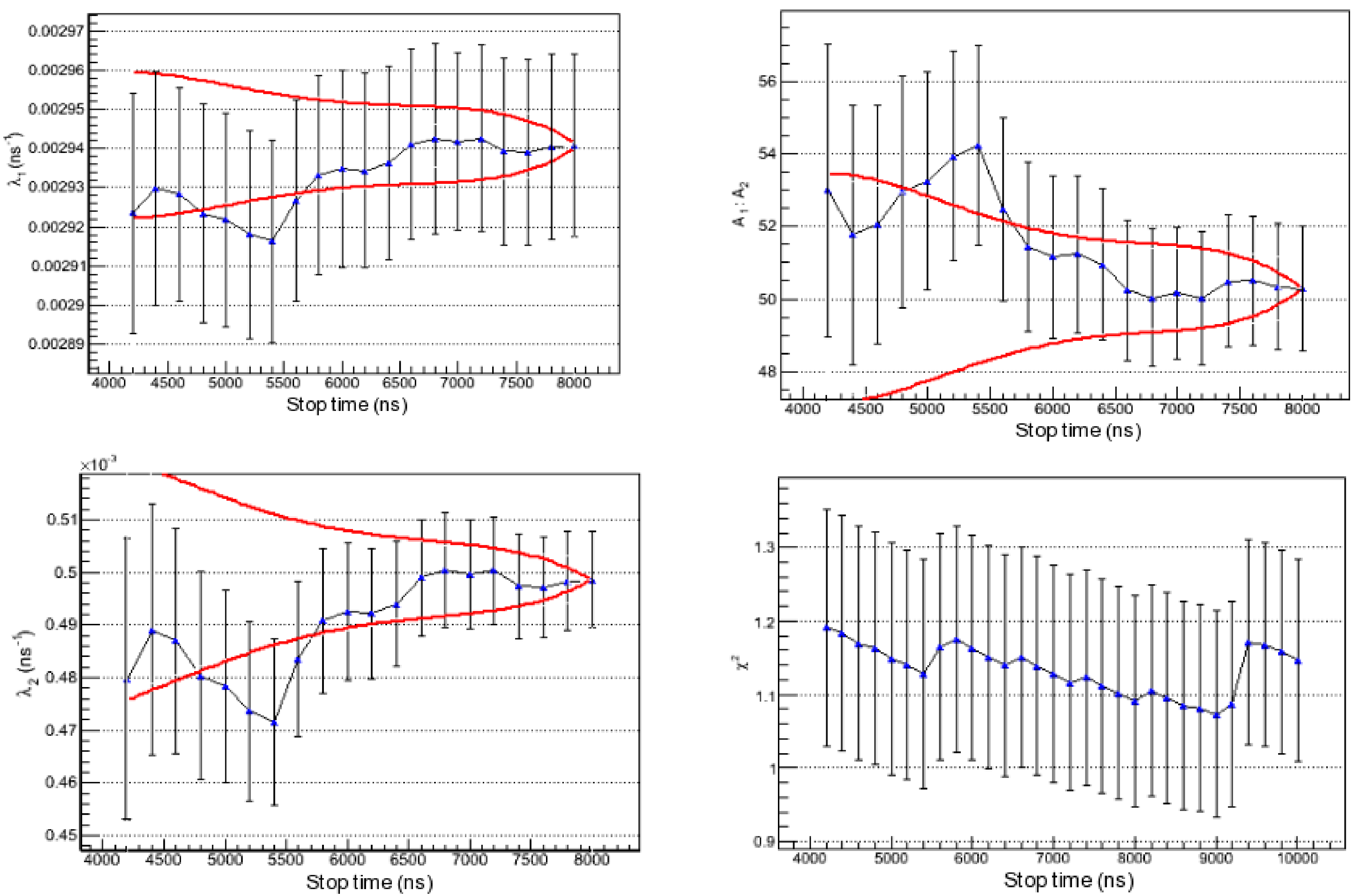


Errors were evaluated based on the above equation after rebinning each spectra 10 from ~ 2000 ns. Results for a small range shown in the right plot. Previous slide has full spectrum errors (in log scale)

Start Time Scan for Fit Range



Stop Time Scan for Fit Range



Systematic Errors - Sources

In a previous analysis I completed a set of systematic error analysis – to near completion for this method. The fit results were extremely stable, and sources of these errors were found to be due to:

✧An imperfect pile up protection – accidental external muons in coincidence with the muon in consideration
✧Fiducial volume and other backgrounds in the muon stop definition
✧Misidentified muon stops like a fusion causing confusion
✧Misidentified electrons due to imperfect pile up protection and accidental electrons
✧Electrons not emanating from the fiducial volume of the TPC to eSC, but rather in opposite direction
✧Background spectrum being sensitive to electron Bremsstrahlung, afterpulses in neutron detectors, misidentified gamma rays etc.

Meticulous cuts were made to minimize these effects and all cuts corresponding to these effects were varied to investigate the effects