Scintillation and Ionization yield of Liquid Argon

Richard Saldanha
On behalf of the SCENE collaboration

24th September 2015

Postdoc position available at UChicago

Work with Prof. Luca Grandi on Xenon1T

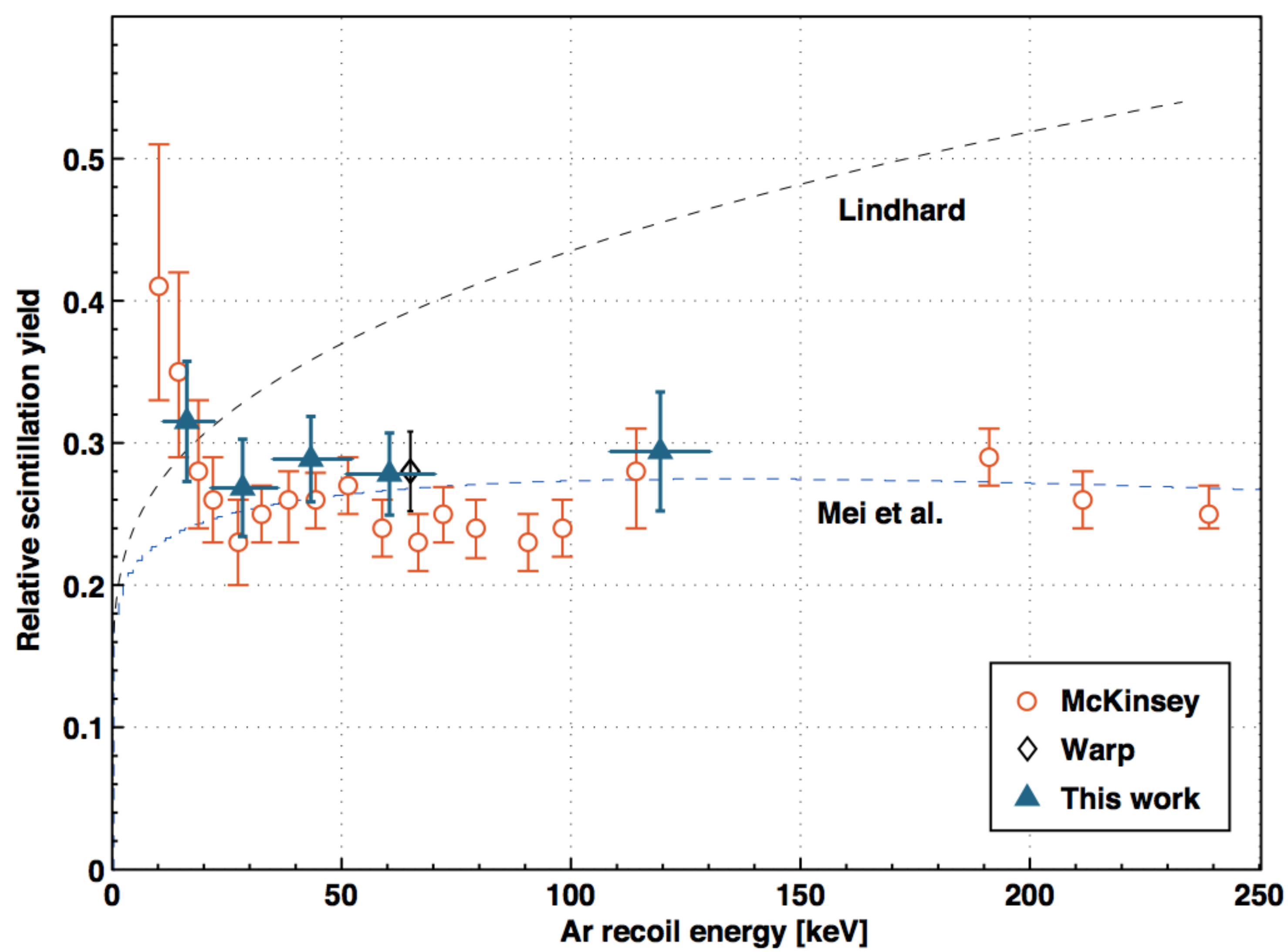
For more details please see
https://inspirehep.net/record/1389800

or talk directly to Luca !

Prior status of Ar Nuclear Recoil calibration

Few measurements of **scintillation yield** in liquid argon, especially at low (< 25 keV) energies, with no studies of the effect of the drift field

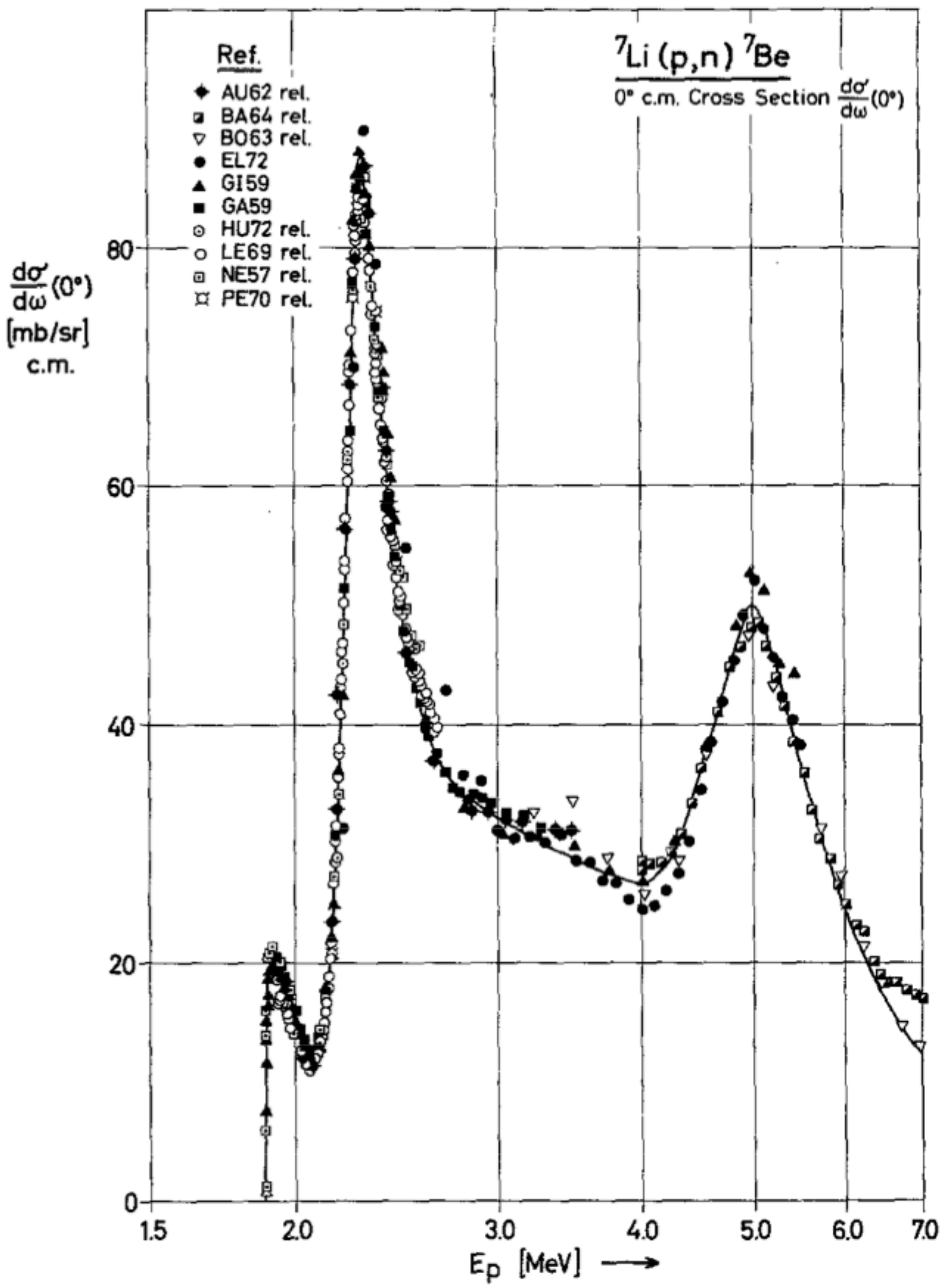
One recent measurement of **ionization yield** (Joshi, Sangiorgio et. al arXiv: 1402.2037) at 6.7 keV_r



C. Regenfus et. al., J. Phys.: Conf. Ser. 375 (2012) 012019

$^7Li(p,n)^7Be$

Produces monoenergetic (< 2 MeV) neutrons
Proton Energy Threshold: 1.881 MeV
Cross Section Peak: E_p = 2.25 MeV



ATOMIC DATA AND NUCLEAR DATA TABLES 15, 57-84 (1975)

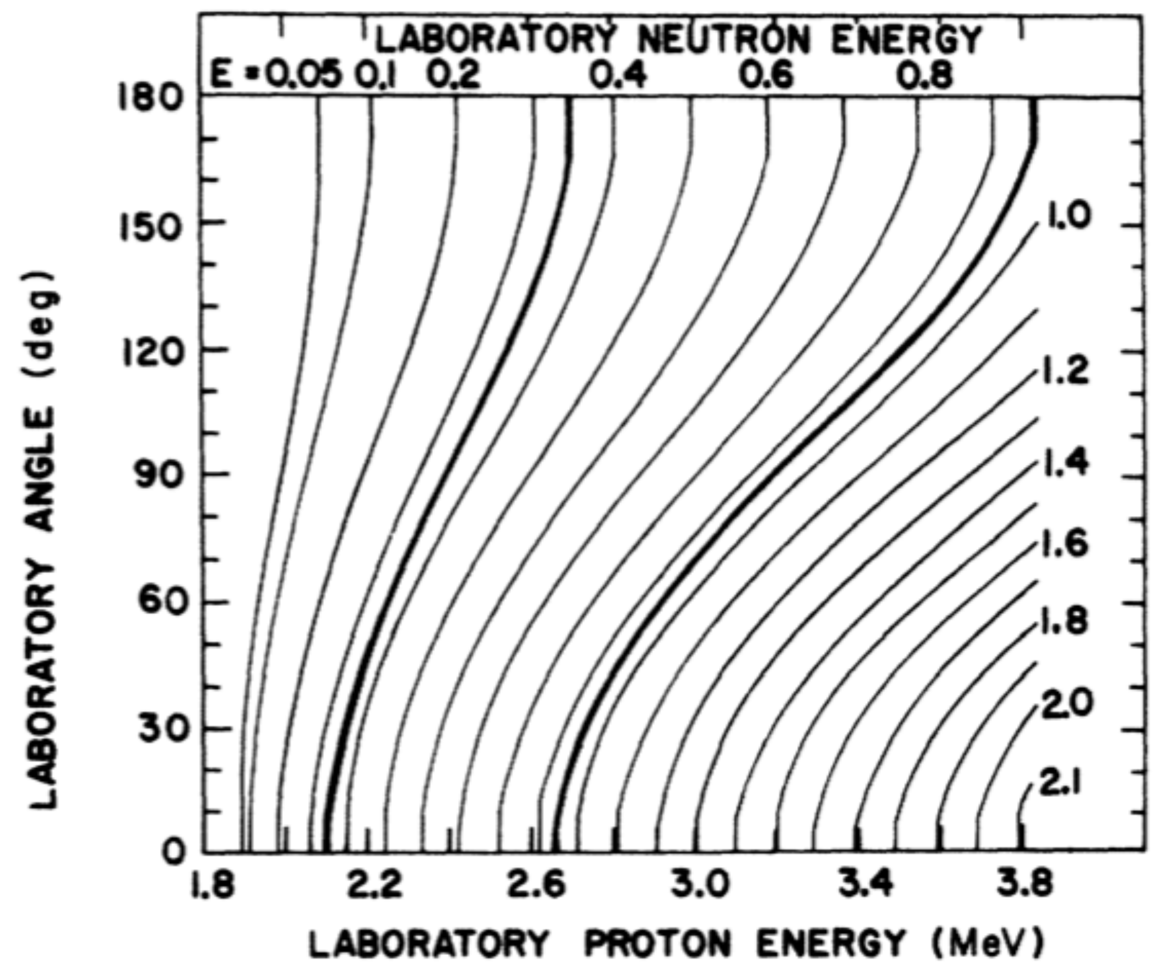
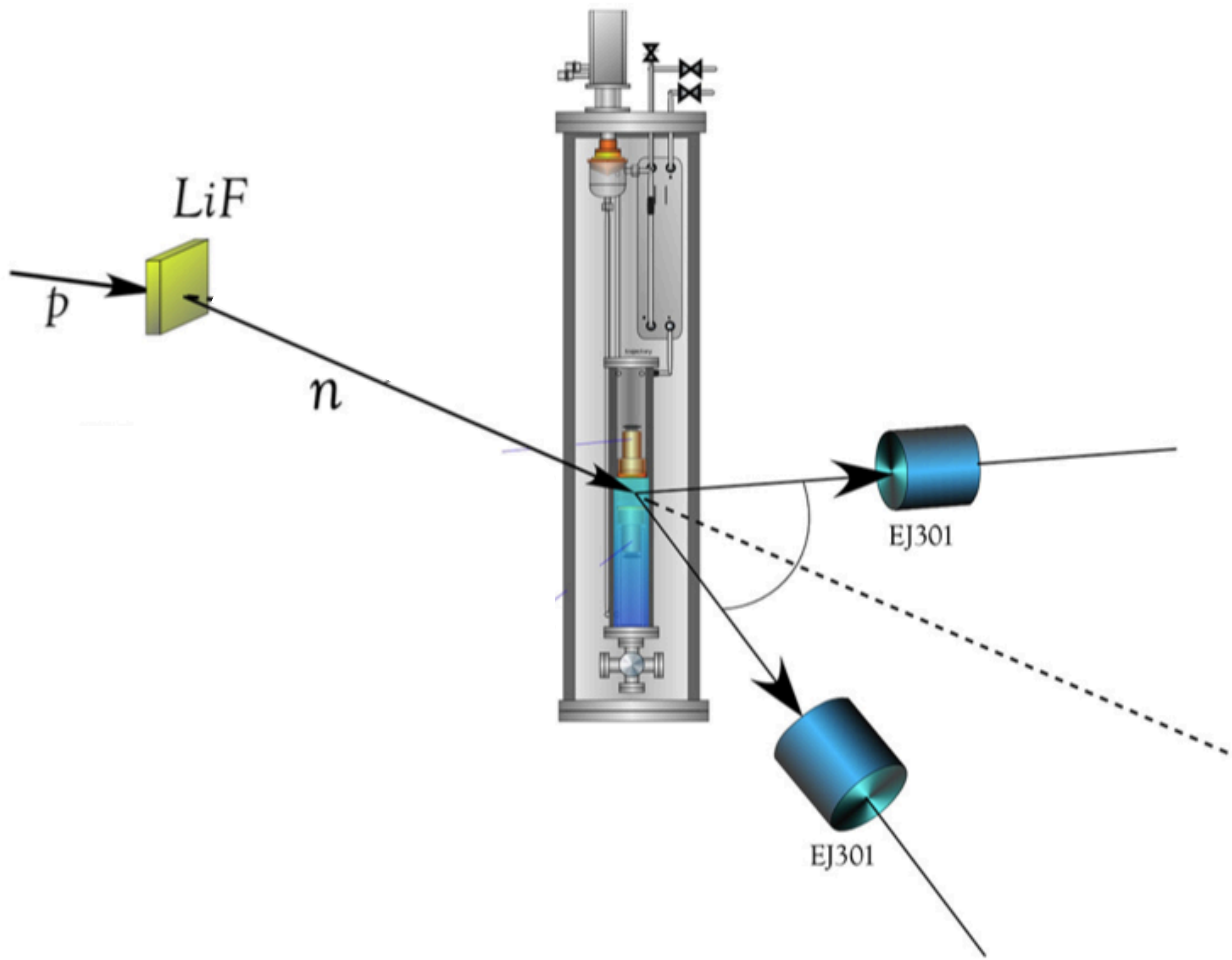


FIG. 4. Traces of constant laboratory neutron energy versus laboratory proton energy and reaction angle for $^7Li(p,n_0)^7Be$. The wide lines delimit the neutron energies for which complete angular distributions were obtained.

C.A.Burke et al., Phys. Rev. C 10, 1299 (1974)

Experimental Setup



Proton Beam

FN Tandem Van de Graaff accelerator at the University of Notre Dame

- Pulsed Beam
(Period = n x 101.5 ns)

- Beam Energy: 10 MeV max.

- Beam Energy Uncertainty
(± 1 keV mean, ± 2 keV spread)

- Beam angle at target < 0.006 deg

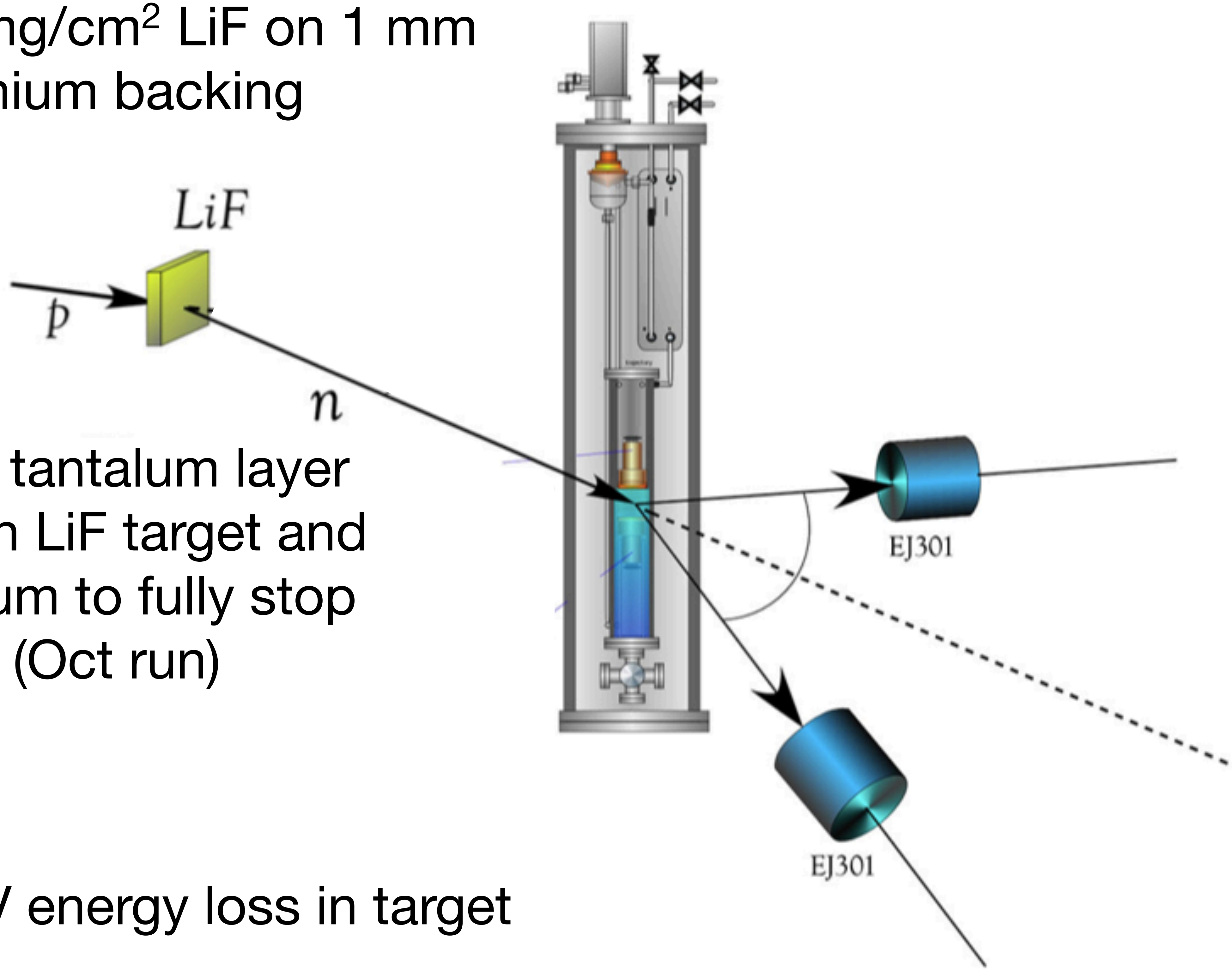
SCENE parameters
1 ns pulses
203 ns period (S1 only)
406 - 812 ns period (S2)

2.376 - 2.930 MeV

6.3 x 10^4 p/pulse
3 x 10^{-4} n/pulse (@TPC)

LiF target

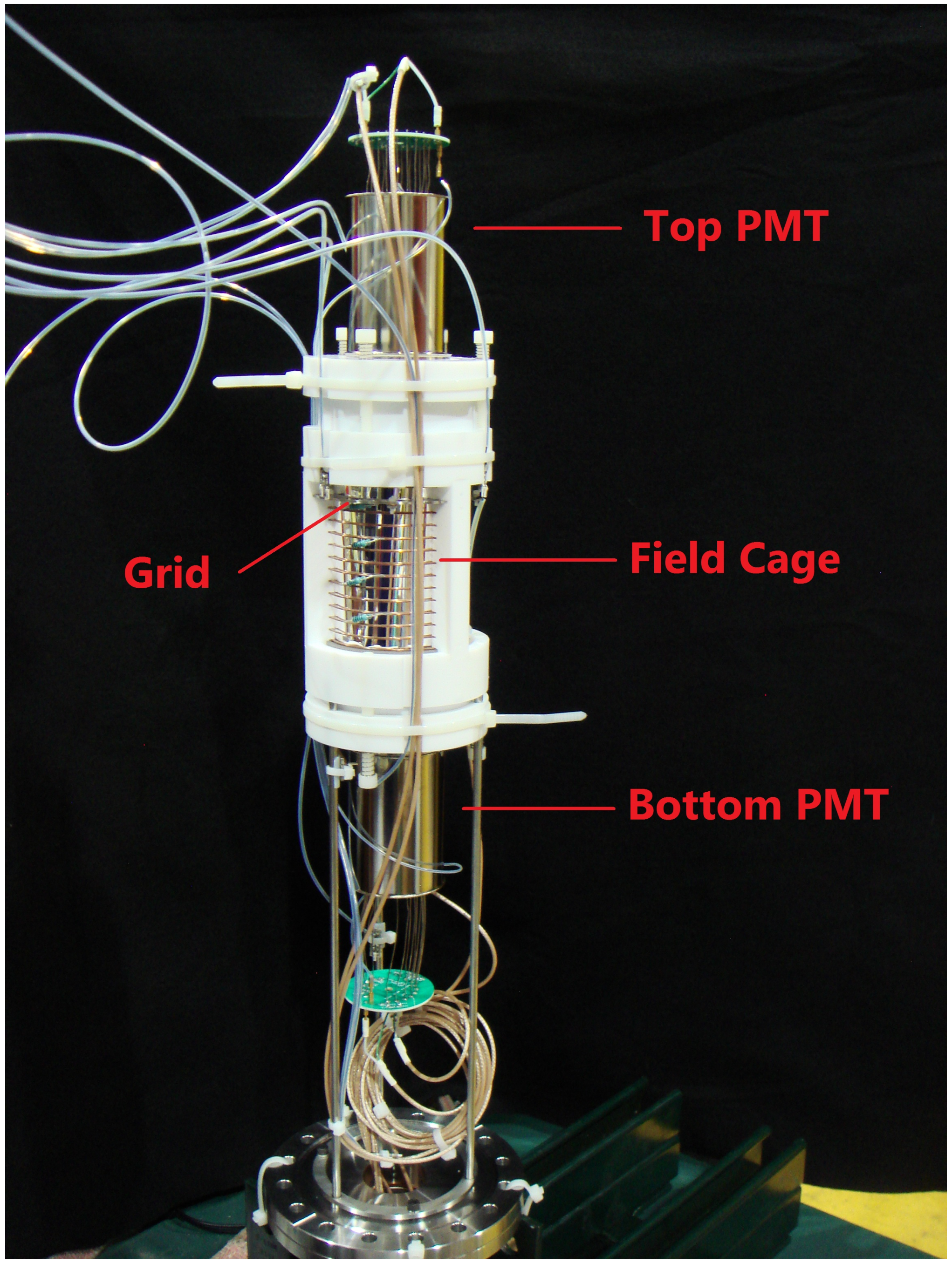
0.20 mg/cm^2 LiF on 1 mm aluminium backing

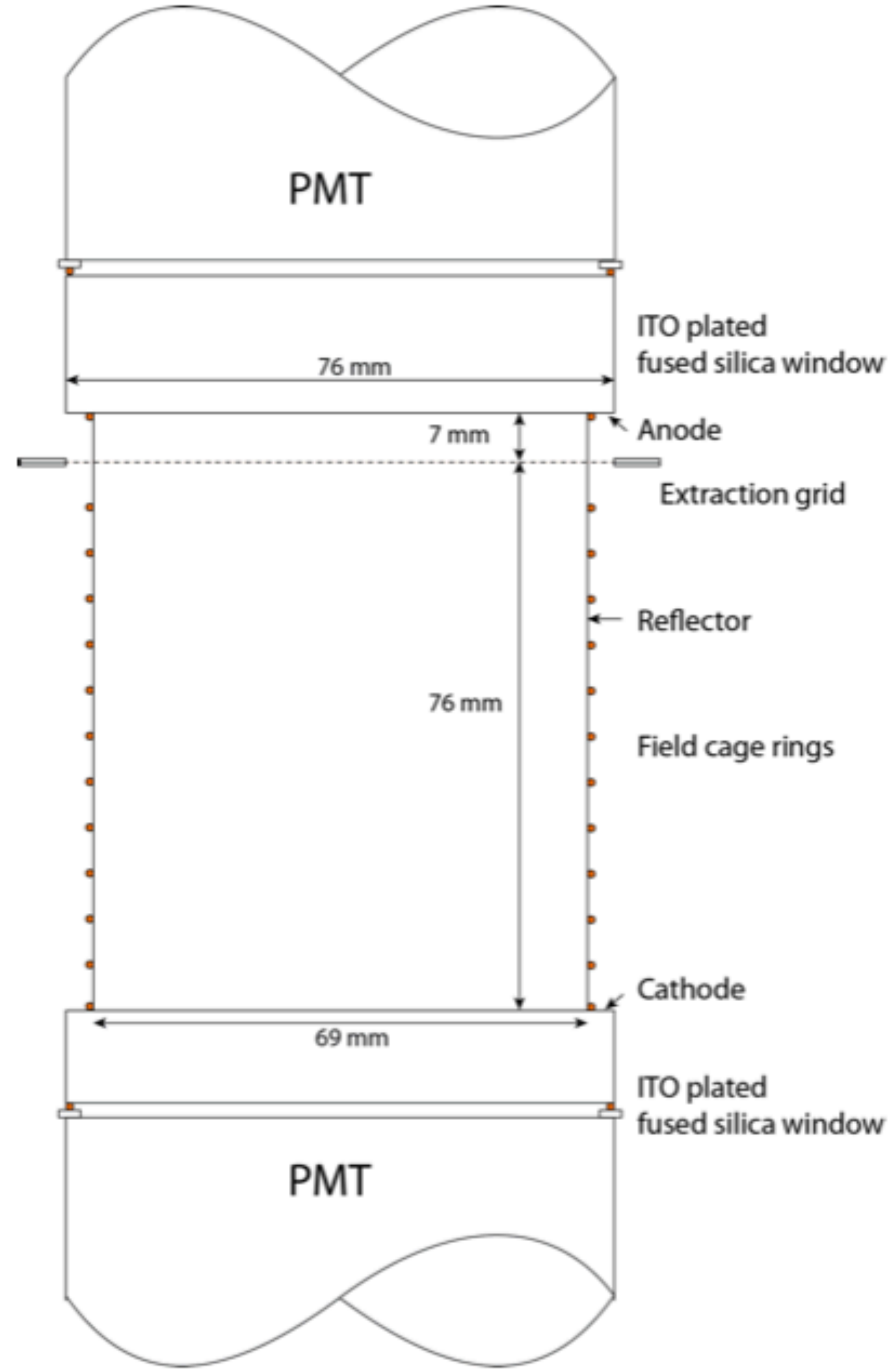


0.1 mm tantalum layer between LiF target and aluminium to fully stop protons (Oct run)

~ 20 keV energy loss in target

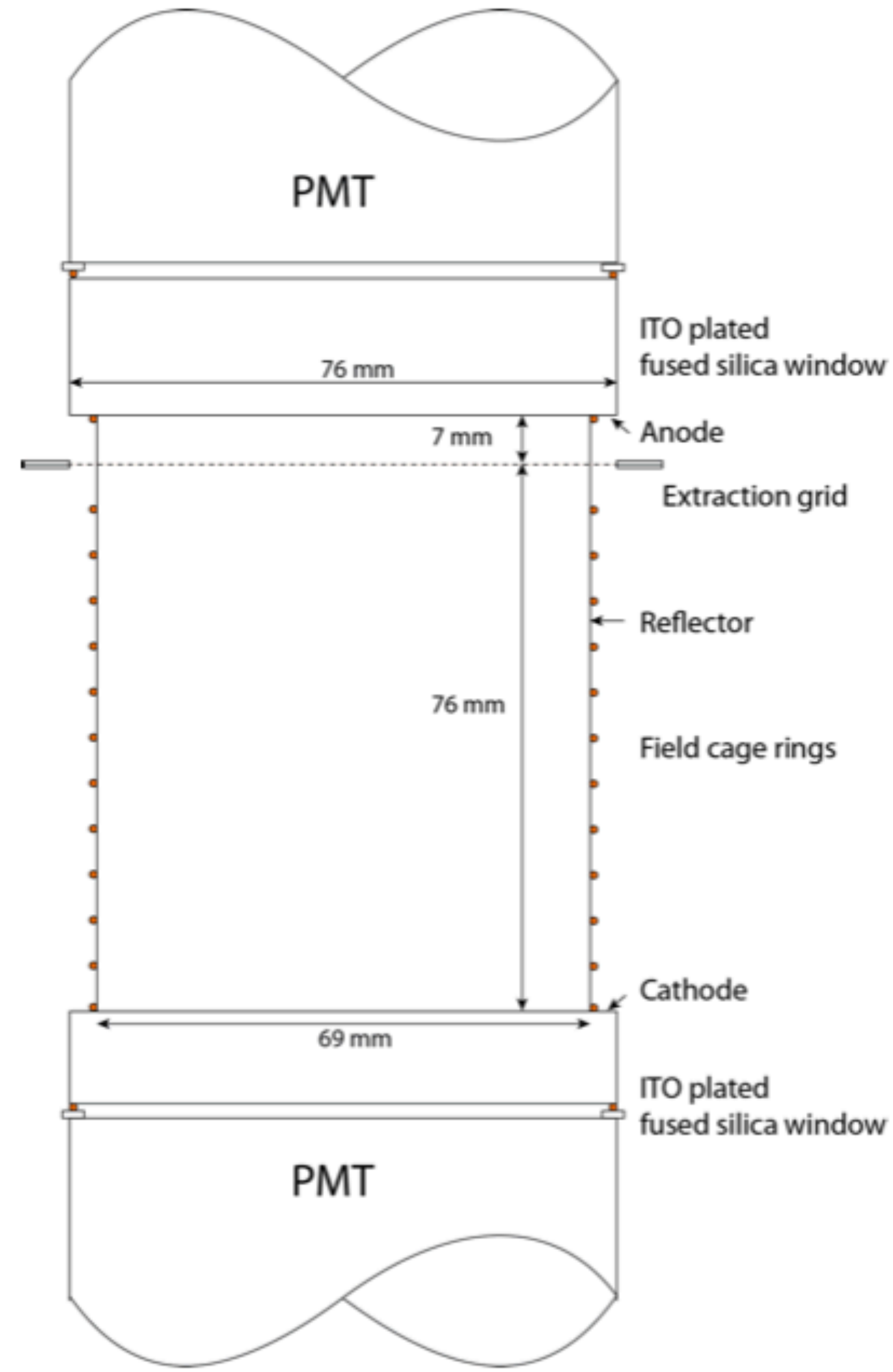
Two-phase liquid argon TPC





2 x 3” R11065 PMTs top and bottom
3M foil reflector
ITO-coated fused silica windows

Two-phase liquid argon TPC

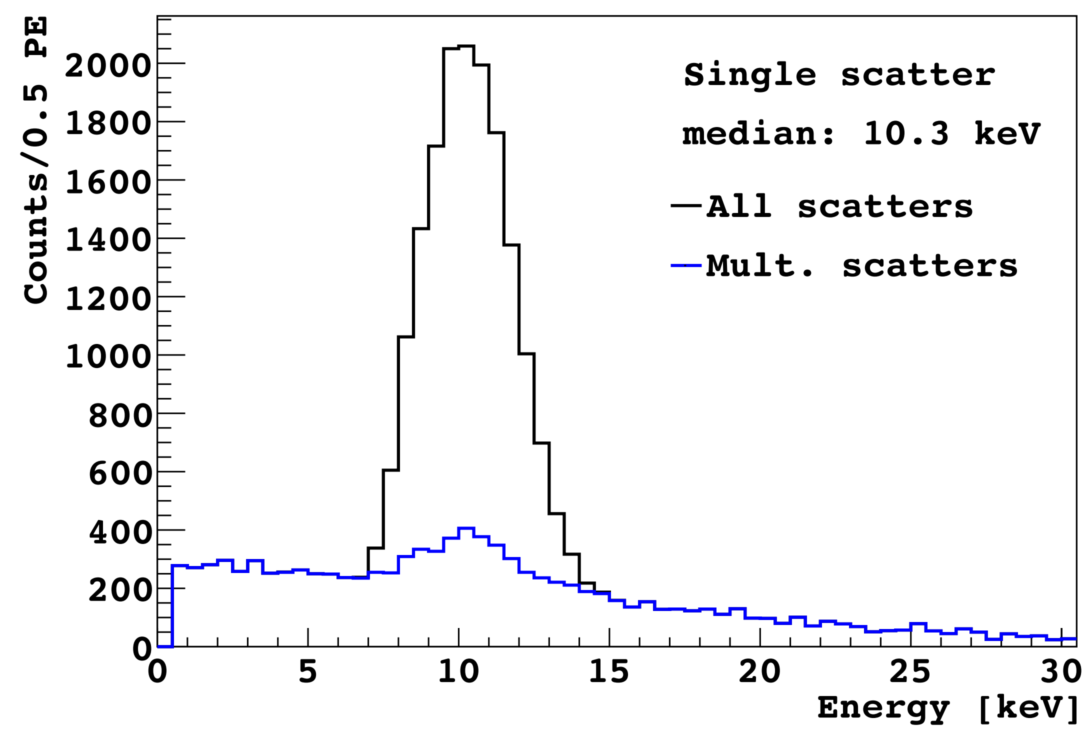


2 x 3" R11065 PMTs top and bottom
3M foil reflector
ITO-coated fused silica windows

Two-phase liquid argon TPC

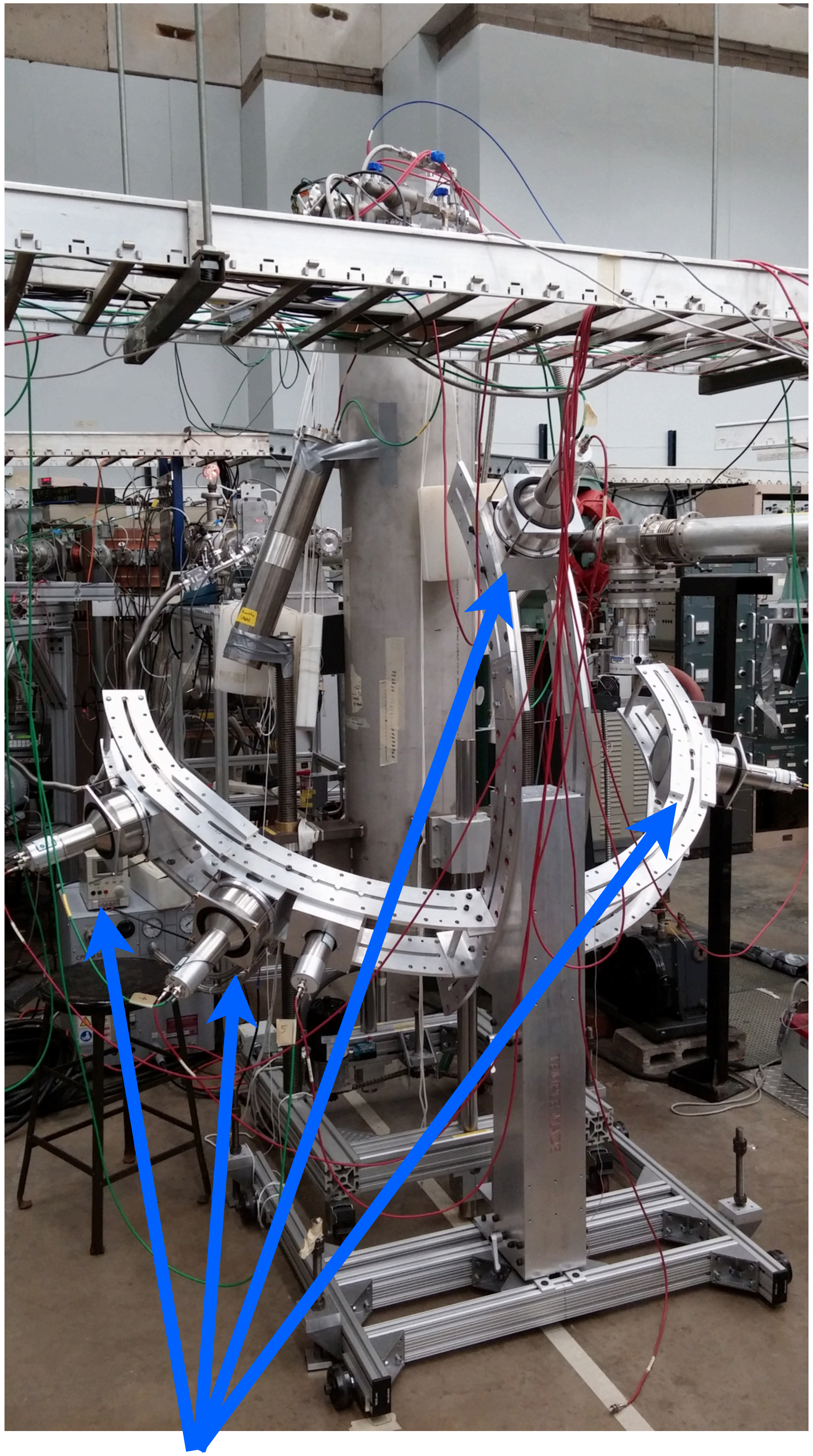
Designed to minimize neutron scatters outside active volume

Geant4 simulations of neutron beam predict a clear single scatter peak (after coincidence cuts) above the multiple scatter background



Nominal E Field [V/cm]	Neutron-weighted median field [V/cm]	68% coverage field range
50	49.5	45.5 - 53.5
100	96.4	92.5 - 108
200	193	189 - 212
300	293	285 - 322
500	486	476 - 536
1000	970	954 - 1073

Simulations of electric field uniformity indicate a ~ 8-10% variation of electric field in the neutron interaction region



EJ-301's mounted on two-axis goniometric stand

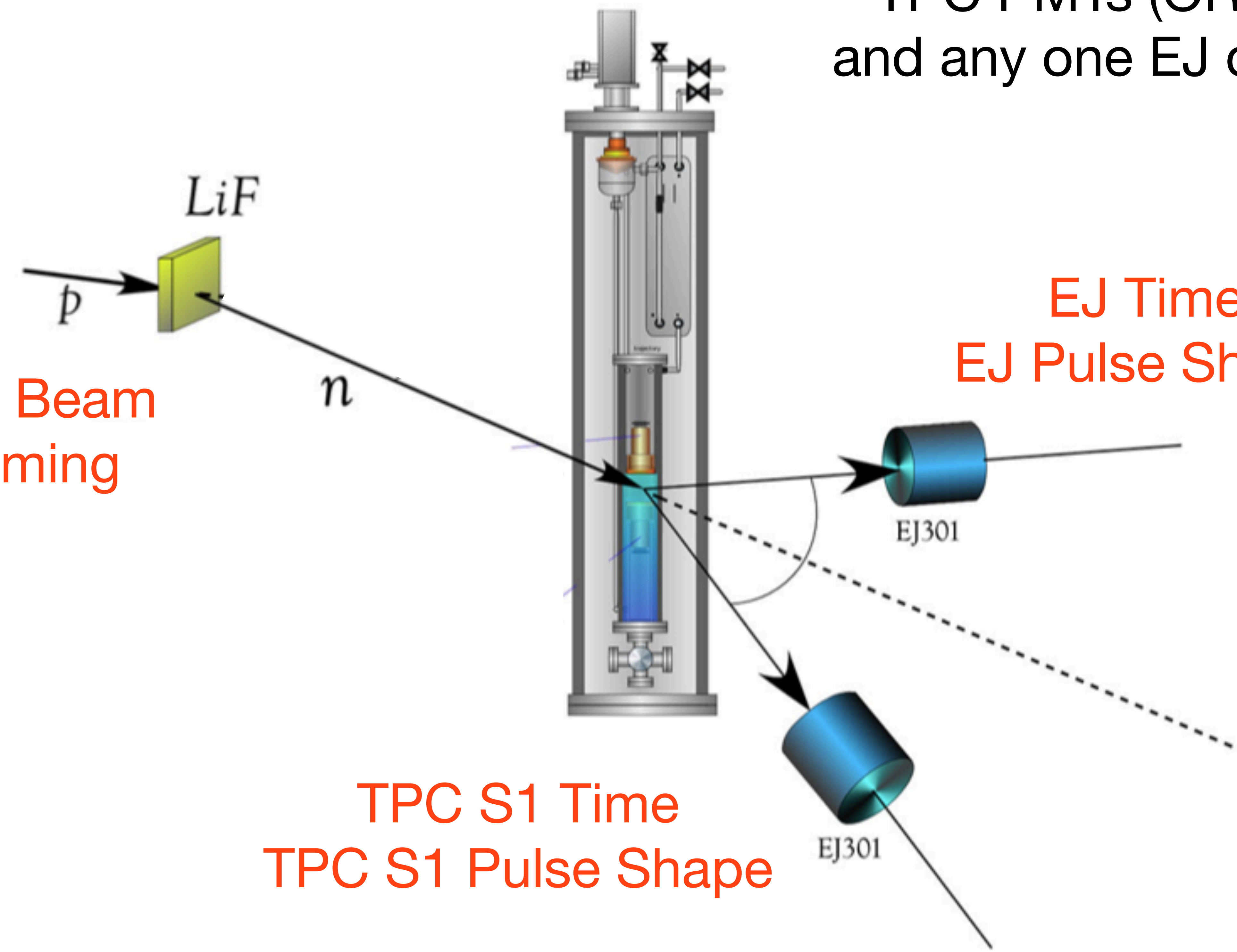
Neutron Detectors

EJ-301 Organic Liquid Scintillator
5" x 5" coupled to PMT

Provides both timing and
γ/n pulse shape discrimination

Background Discrimination

Triggered on coincidence of
TPC PMTs (OR/AND)
and any one EJ detector



Proton Beam
RF Timing

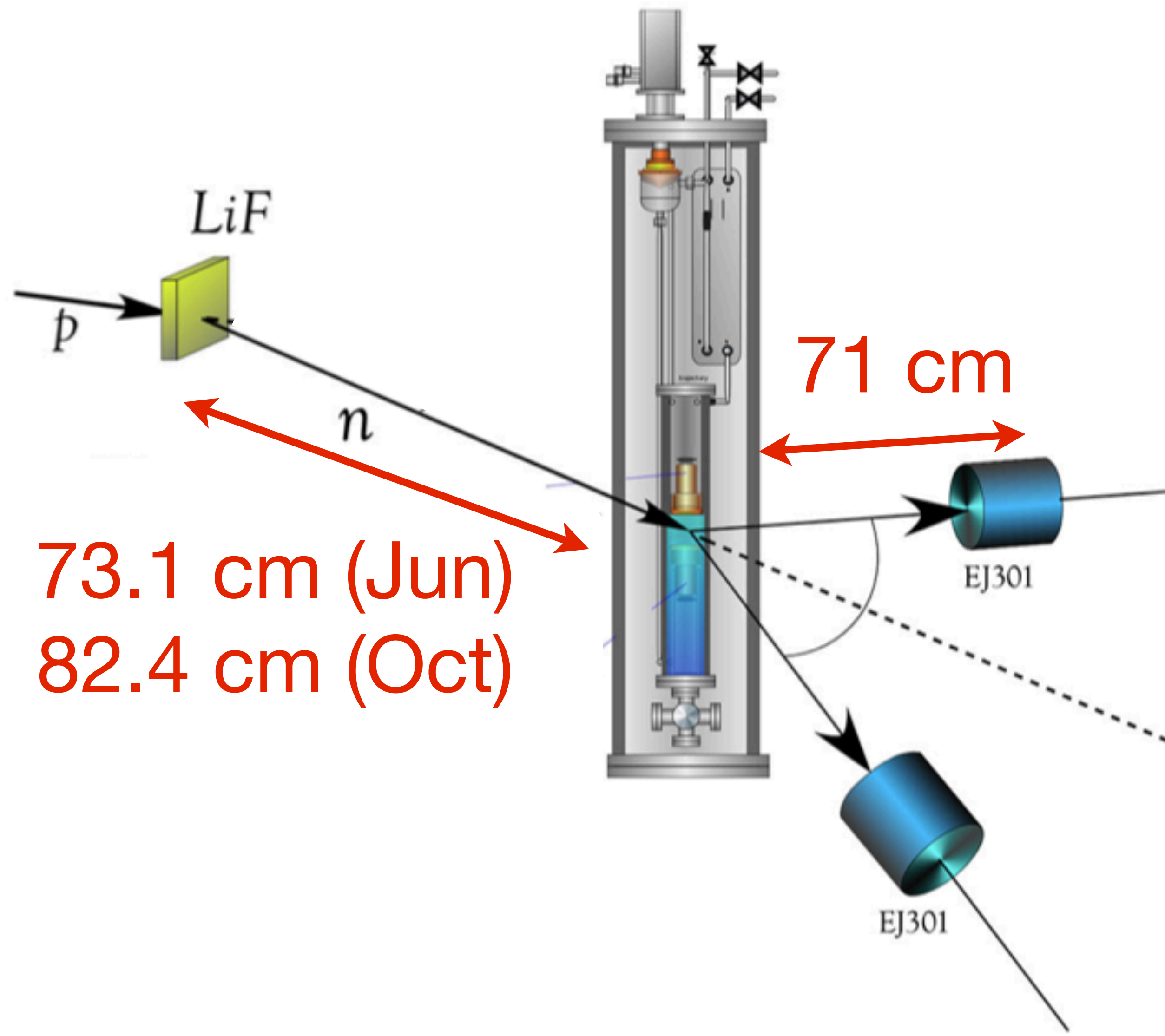
EJ Time
EJ Pulse Shape

TPC S1 Time
TPC S1 Pulse Shape

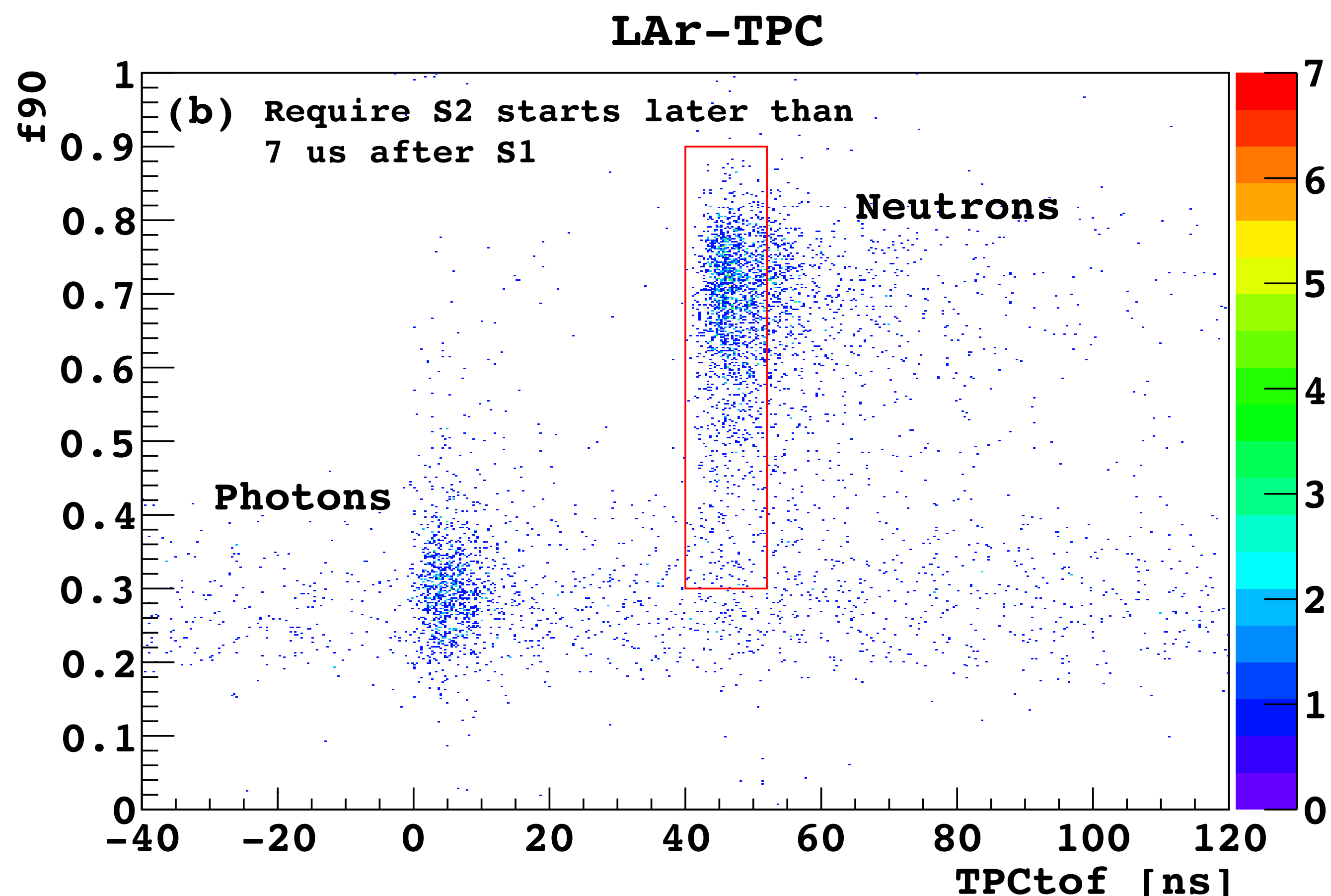
Experimental Setup

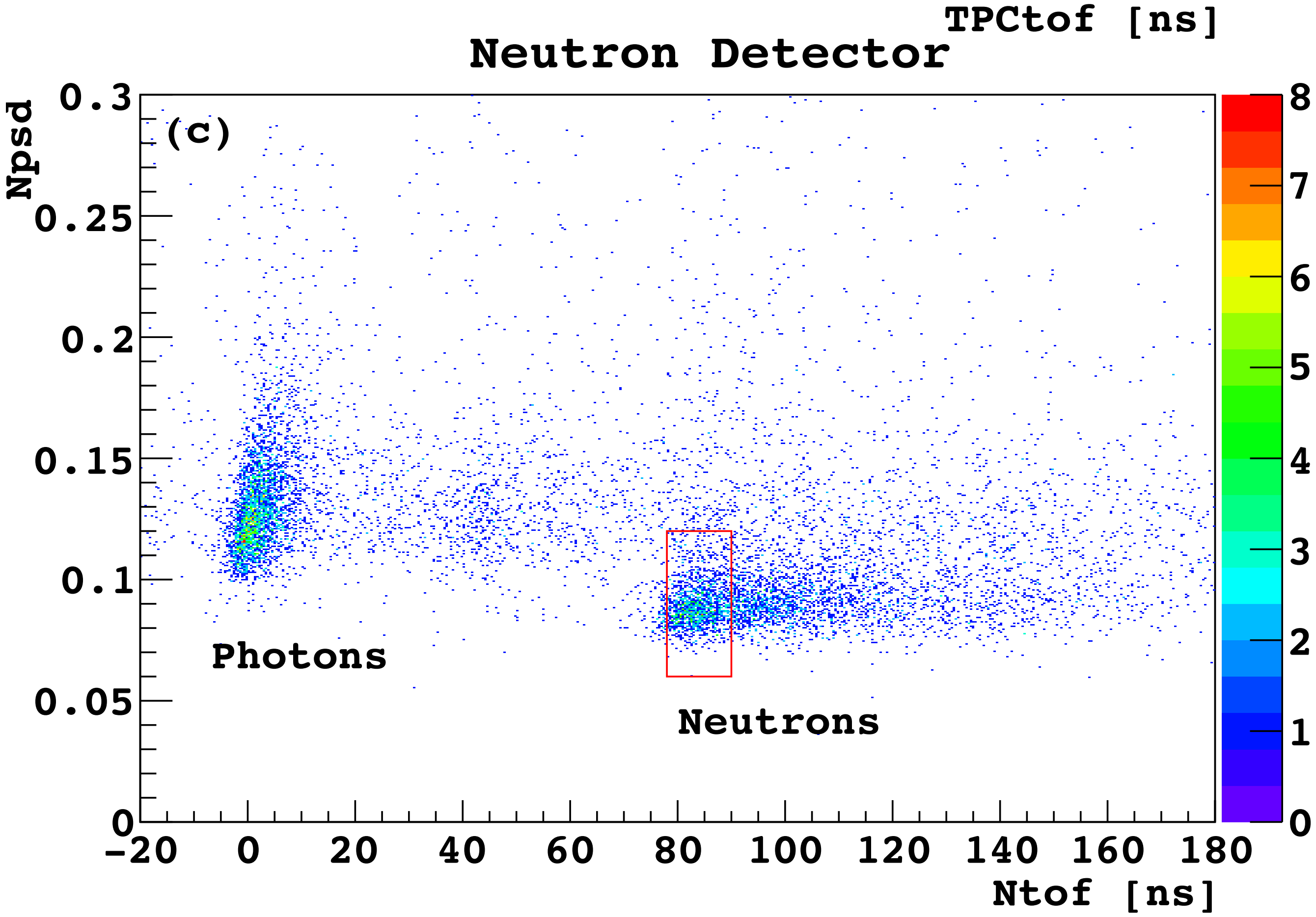
	Proton Energy [MeV]	Neutron Energy [MeV]	Scattering Angle [°]	Nuclear Recoil Energy [keV]	Geometric Energy [keV]
Jun 2013	2.376	0.604	49.9	$10.3^{+1.5}_{-1.4}$	10.8
	2.930	1.168	42.2	$14.8^{+2.7}_{-2.6}$	15.2
	2.930	1.168	49.9	$20.5^{+3.0}_{-2.8}$	20.8
	2.930	1.168	59.9	$28.7^{+2.8}_{-2.8}$	29.0
	2.930	1.168	82.2	$49.7^{+3.4}_{-3.4}$	49.9
Oct 2013	2.316	0.510	69.7	$16.9^{+1.5}_{-1.5}$	16.5
	3.607	1.773	45.0	$*25.4^{+3.2}_{-2.9}$	26.1
	2.930	1.119	69.7	$*36.1^{+3.1}_{-3.1}$	36.3
	3.607	1.773	69.7	$*57.3^{+5.0}_{-4.9}$	57.6

S1 [V/cm]	S2 [V/cm]
0	0
49.5	
96.4	96.4
193	193
293	293
486	486
970	



Selection Cuts

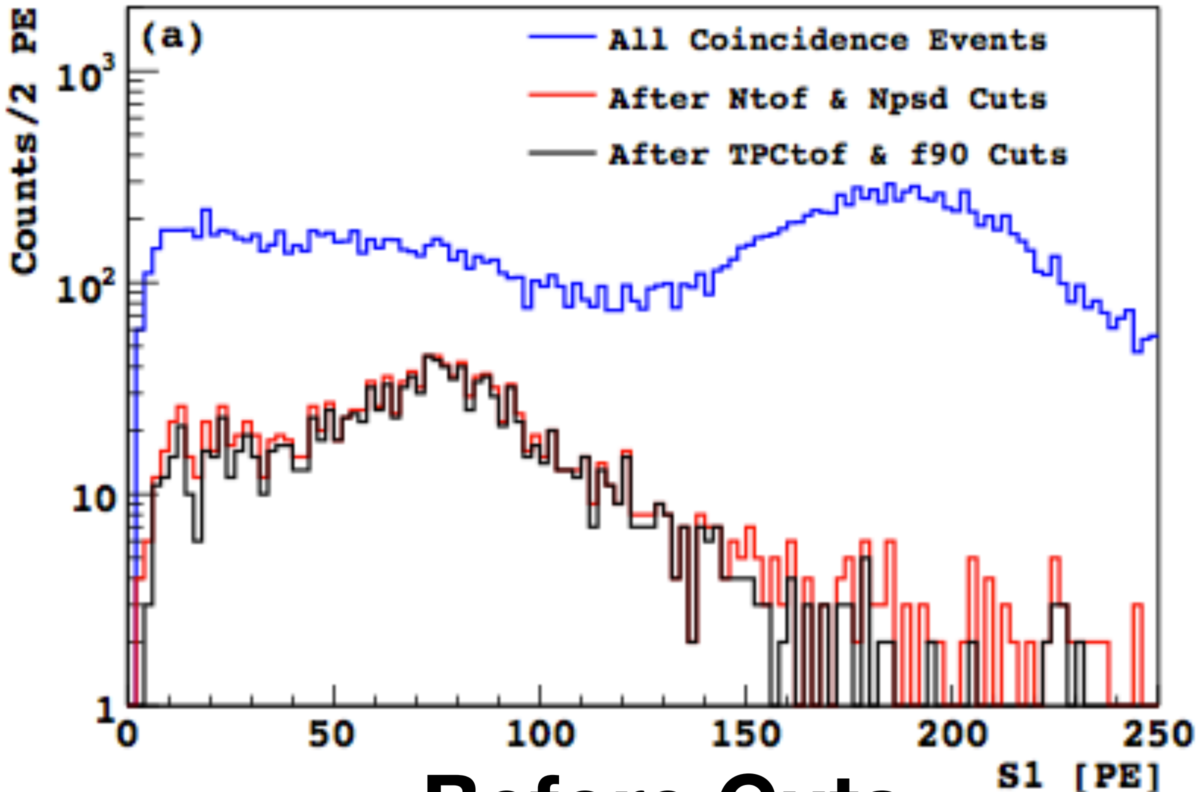




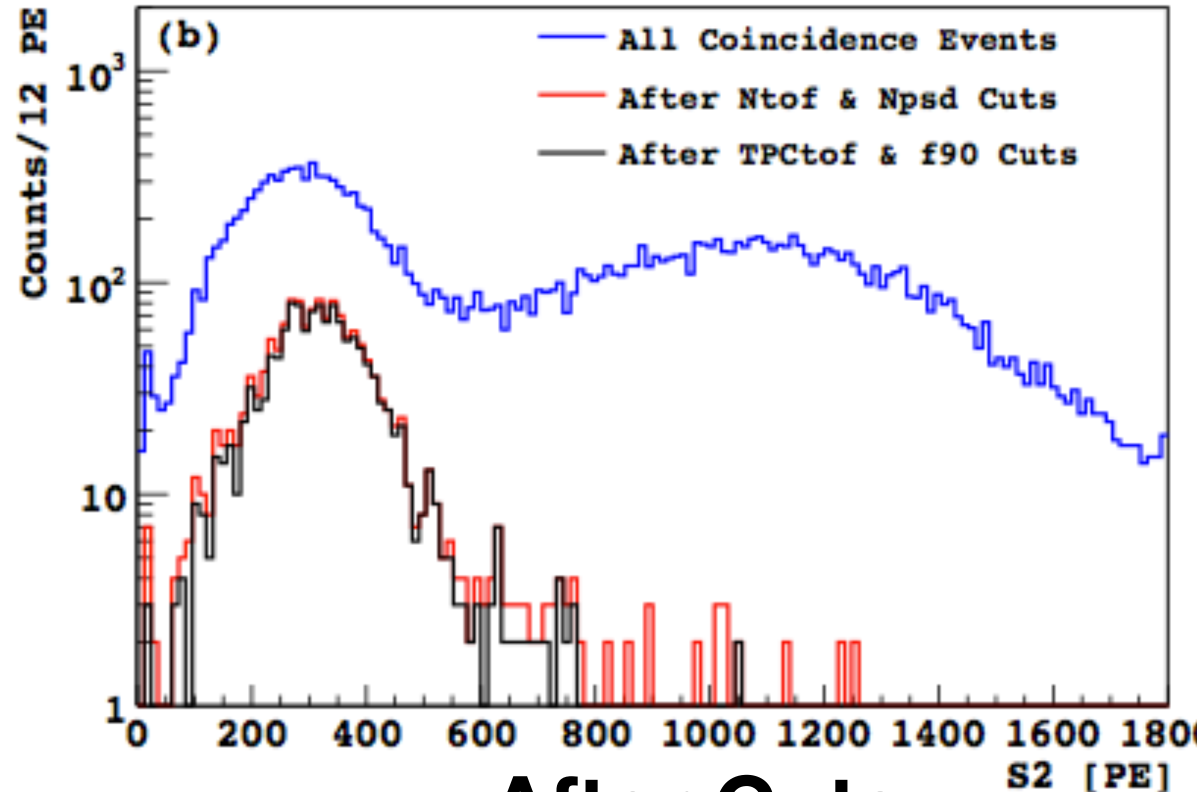
Application of
2 TOF and 2 pulse shape cuts
allows for extremely clean
sample of data

Selection Cuts (57.3 keV, 193 V/cm)

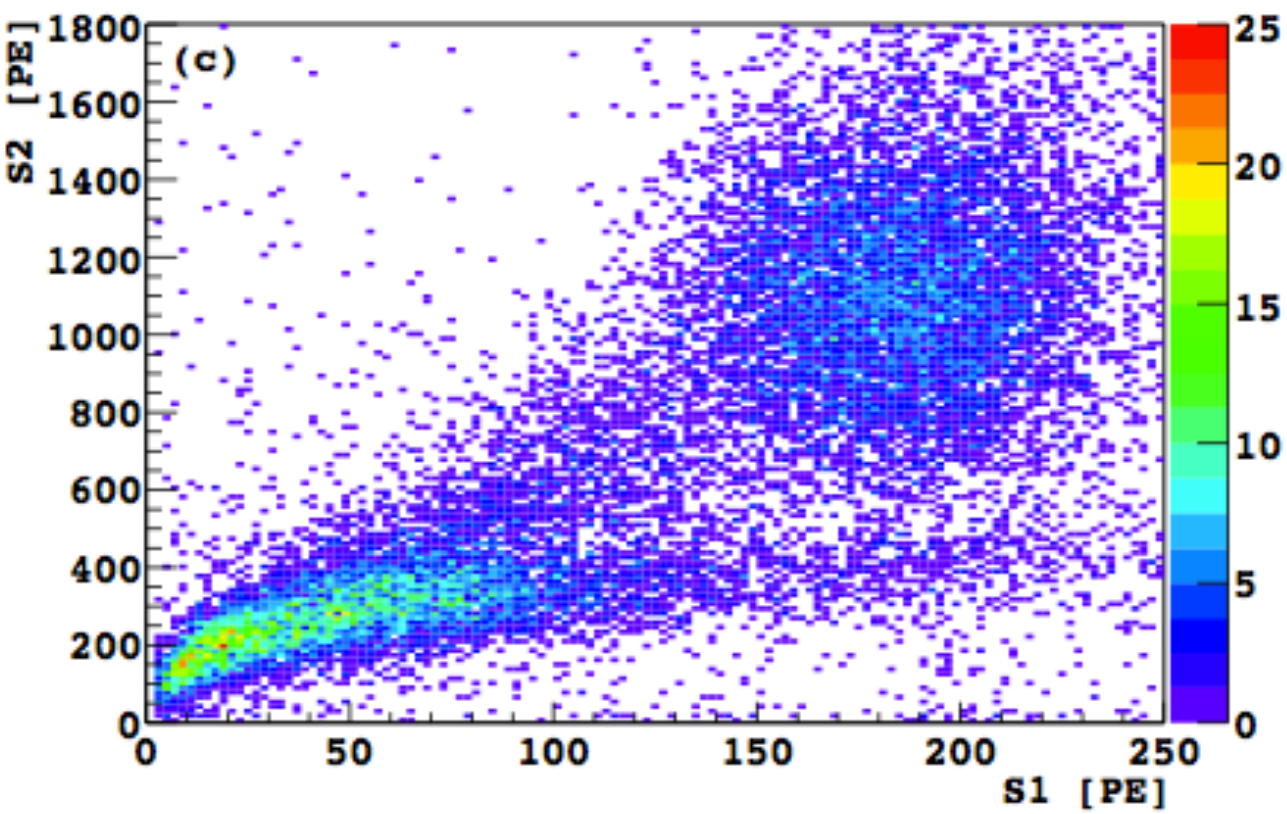
S1



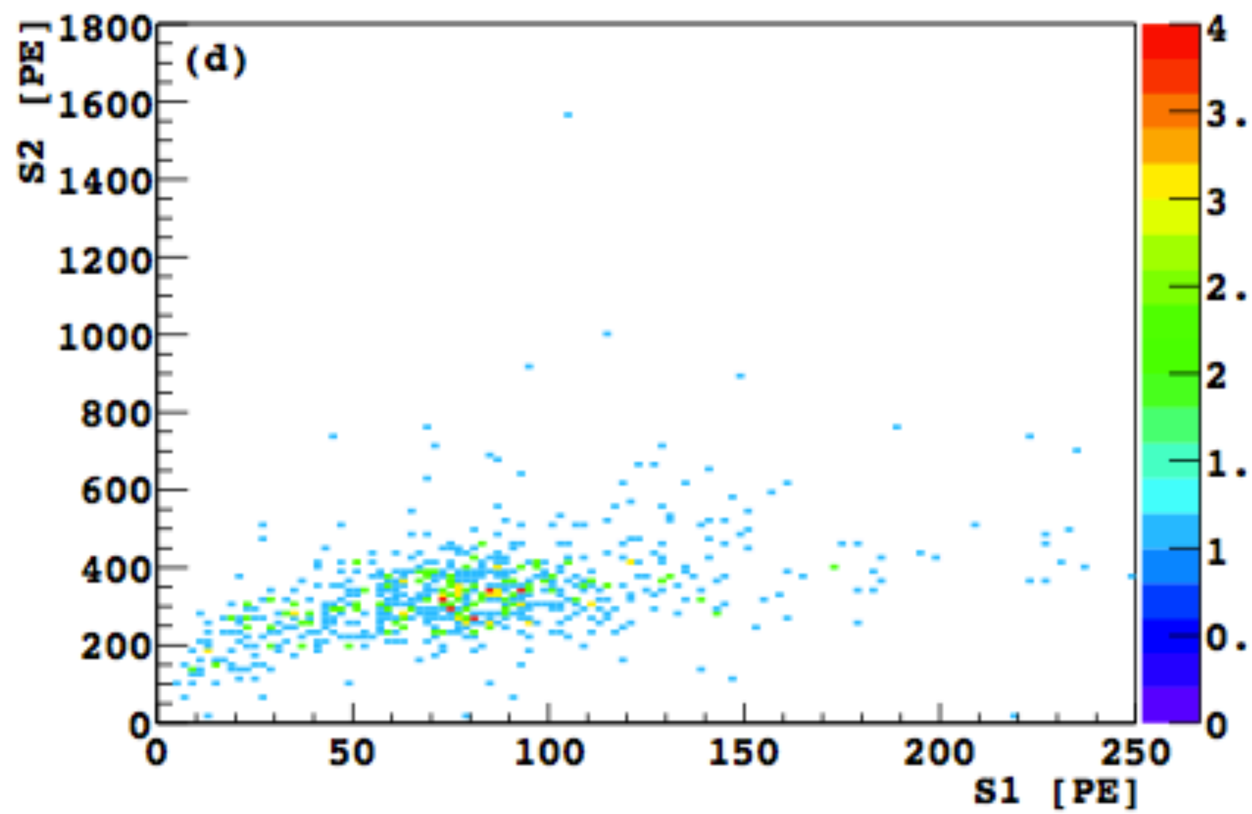
S2



Before Cuts



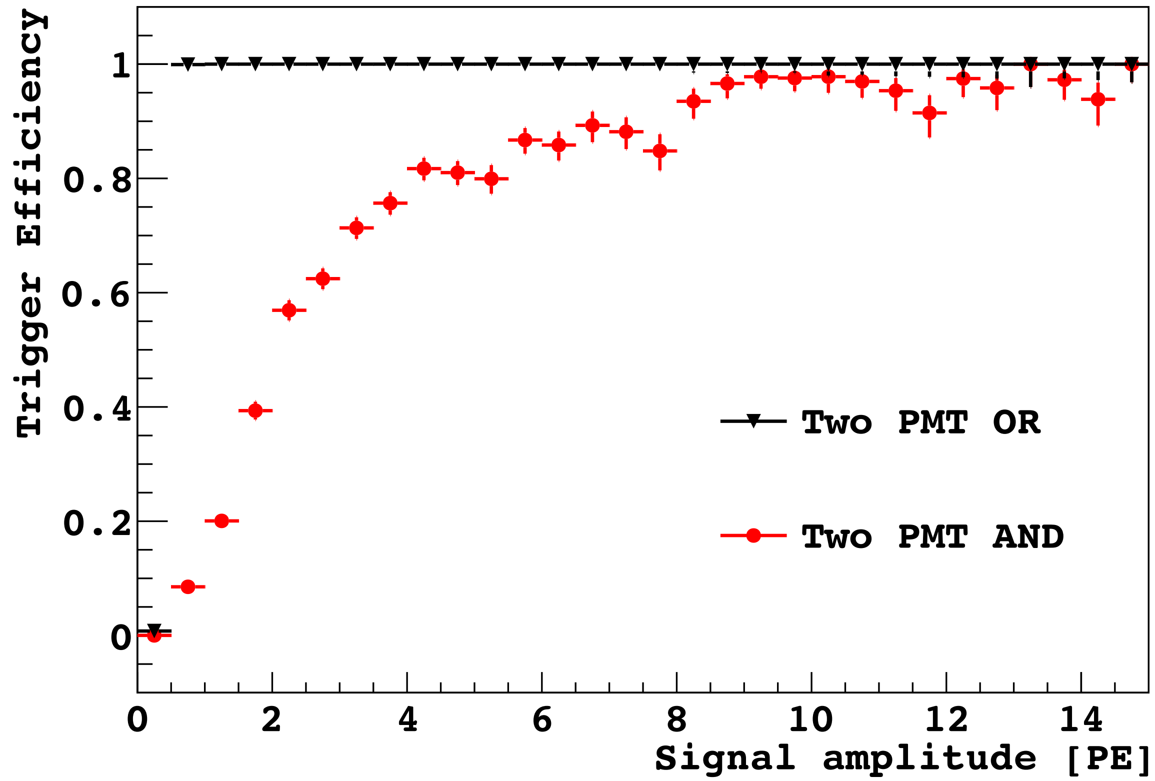
After Cuts



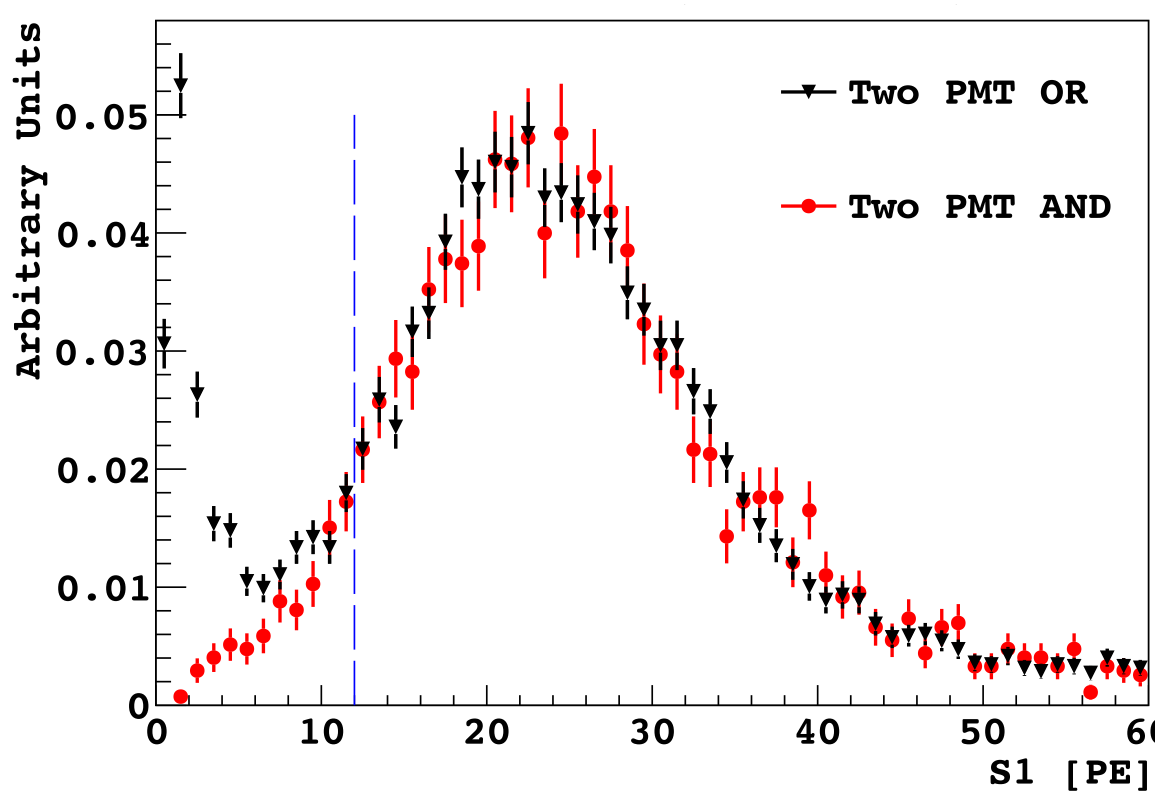
S1 Trigger Efficiency

Two methods used to measure trigger efficiency

Simultaneously digitize signal and trigger logic, while triggering on ^{22}Na source with external coincidence detector
(Plante et. al. Phys. Rev. C 84, 045805)



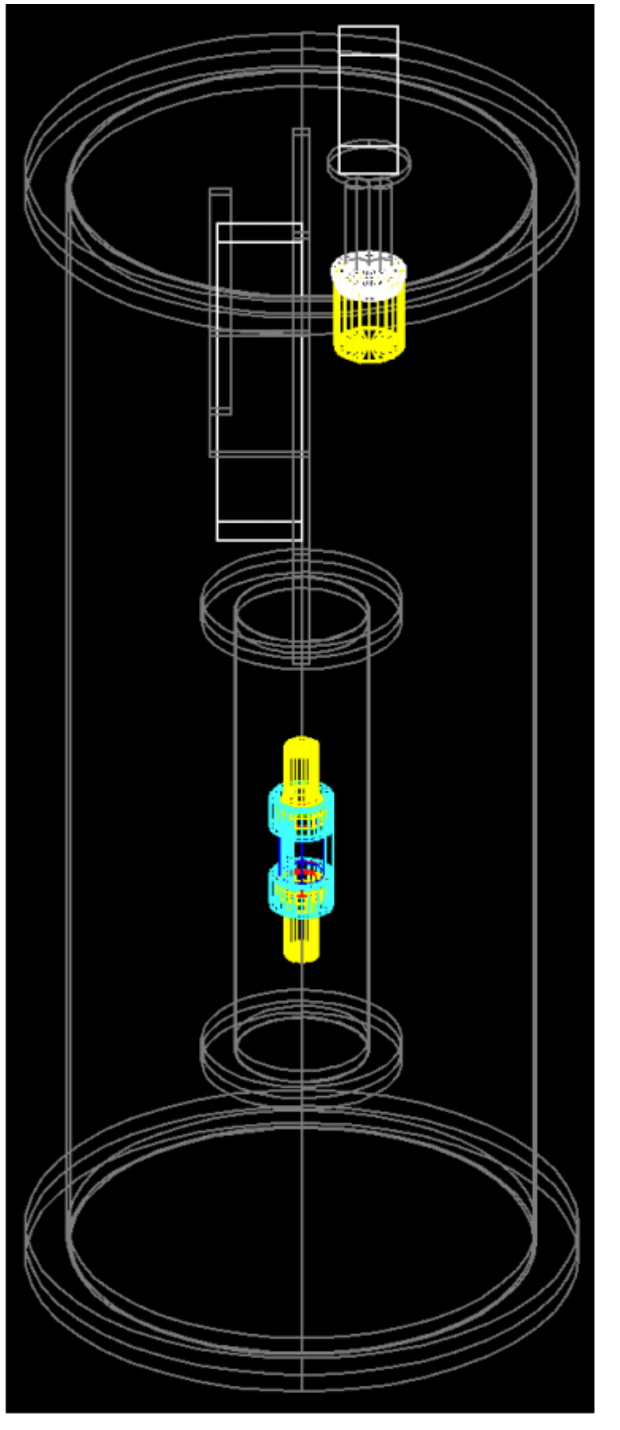
Nuclear recoils at 20.5 keV and 970 V/cm were acquired using both OR and AND trigger



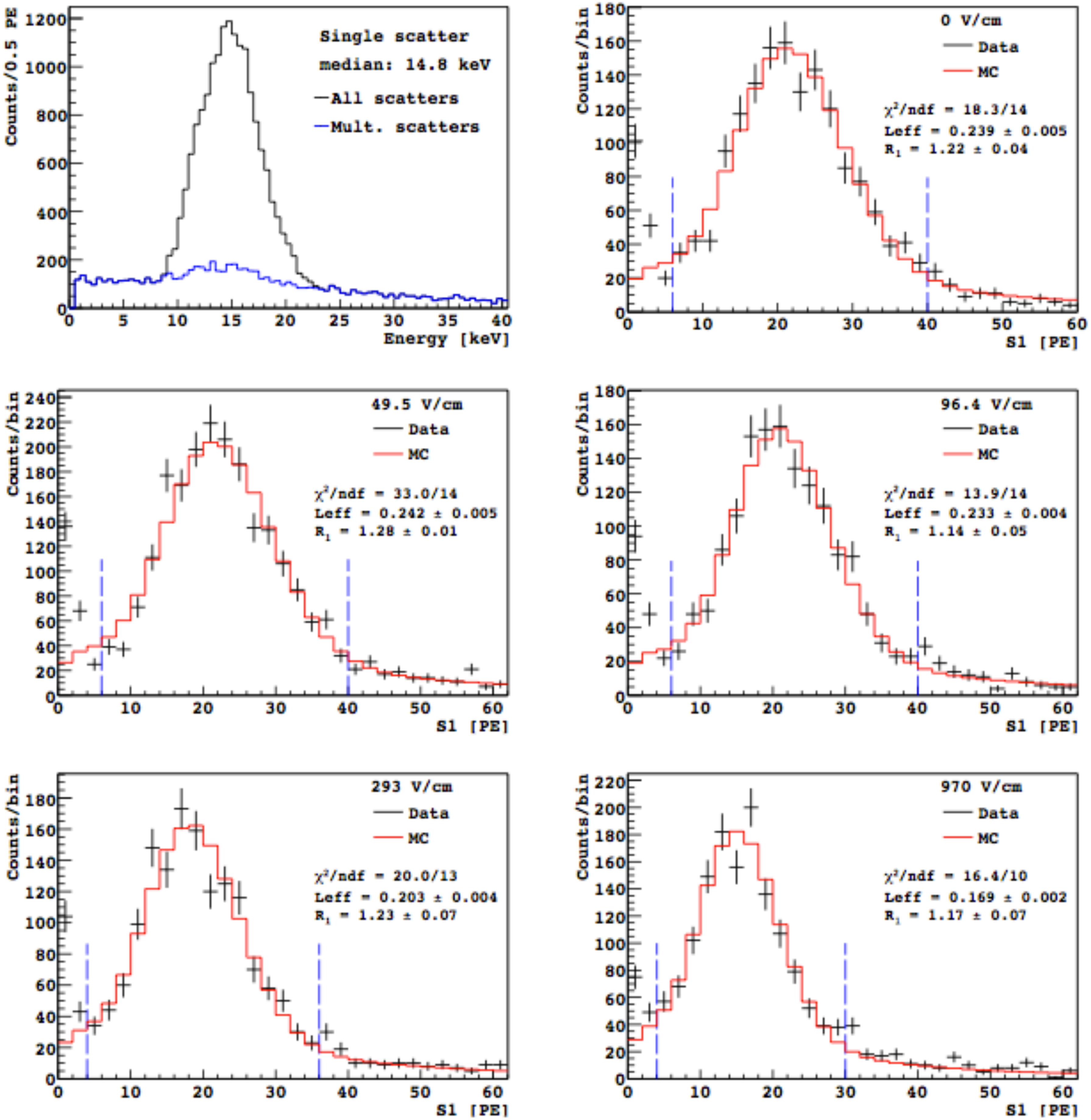
S1 OR Analysis Threshold: 4 PE
S1 AND Analysis Threshold: 12 PE

Fitting S1 Spectra

- To determine the scintillation yield, the S1 spectra are fit with a Monte Carlo generated recoil spectrum.
- Starting from the neutron production, the entire geometry of the TPC and neutron detectors is simulated
- The same coincidence and timing cuts as used in the analysis are implemented in the simulation to obtain the final sample of nuclear recoils
- The data were then fit to the MC spectra using an independent fixed L_{eff} and resolution for each geometrical setup



Fitting S1 Spectra



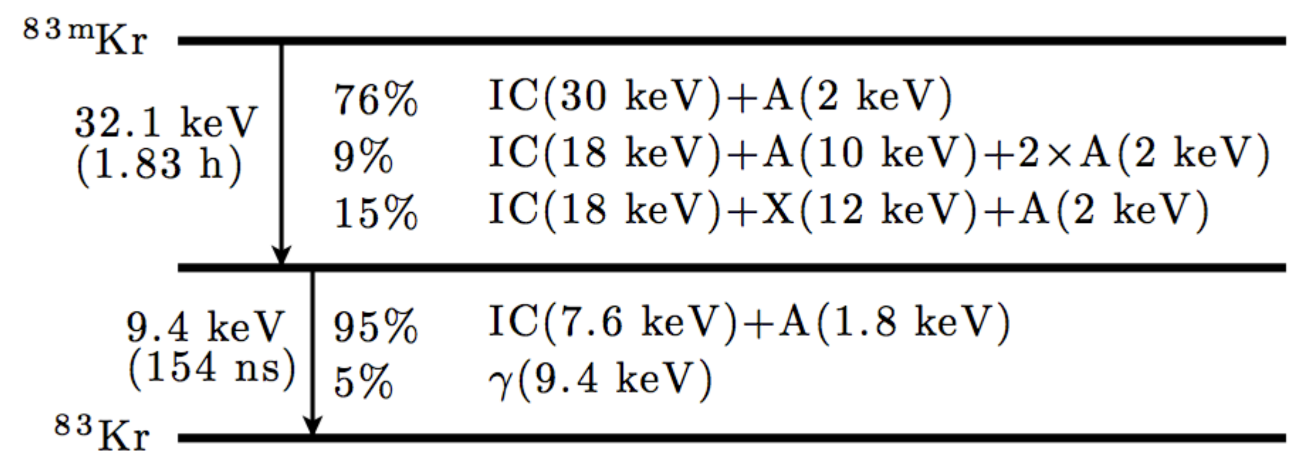
Example of fits to 14.8 keV nuclear recoils

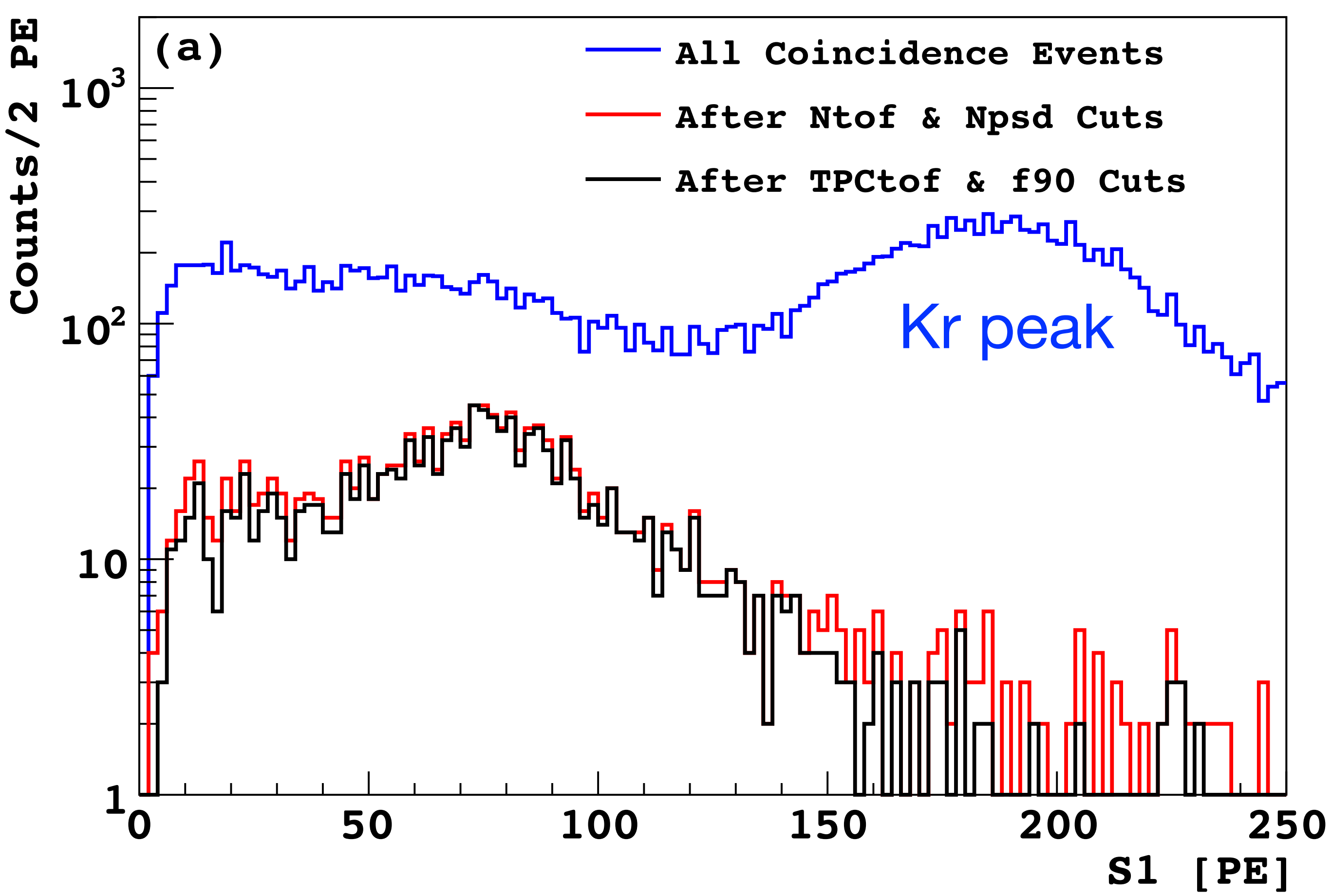
Kr Reference

L_{eff} measurements are usually made with respect to electron recoils at null field

$$\mathcal{L}_{\mathrm{eff},\,^{83m}\mathrm{Kr}}\left(E_{\mathrm{nr}},\mathcal{E}_{\mathrm{d}}\right)=\frac{S1_{\mathrm{nr}}\left(E_{\mathrm{nr}},\mathcal{E}_{\mathrm{d}}\right)/E_{\mathrm{nr}}}{S1_{\mathrm{Kr}}\left(\mathcal{E}_{\mathrm{d}}=0\right)/E_{\mathrm{Kr}}}$$

^{83m}Kr is extremely useful as a reference calibration since it can easily injected, distributes within the active volume, and decays to a stable isotope within a few hours





^{83m}Kr was continuously injected into the detector to monitor the light yield stability during the beam runs

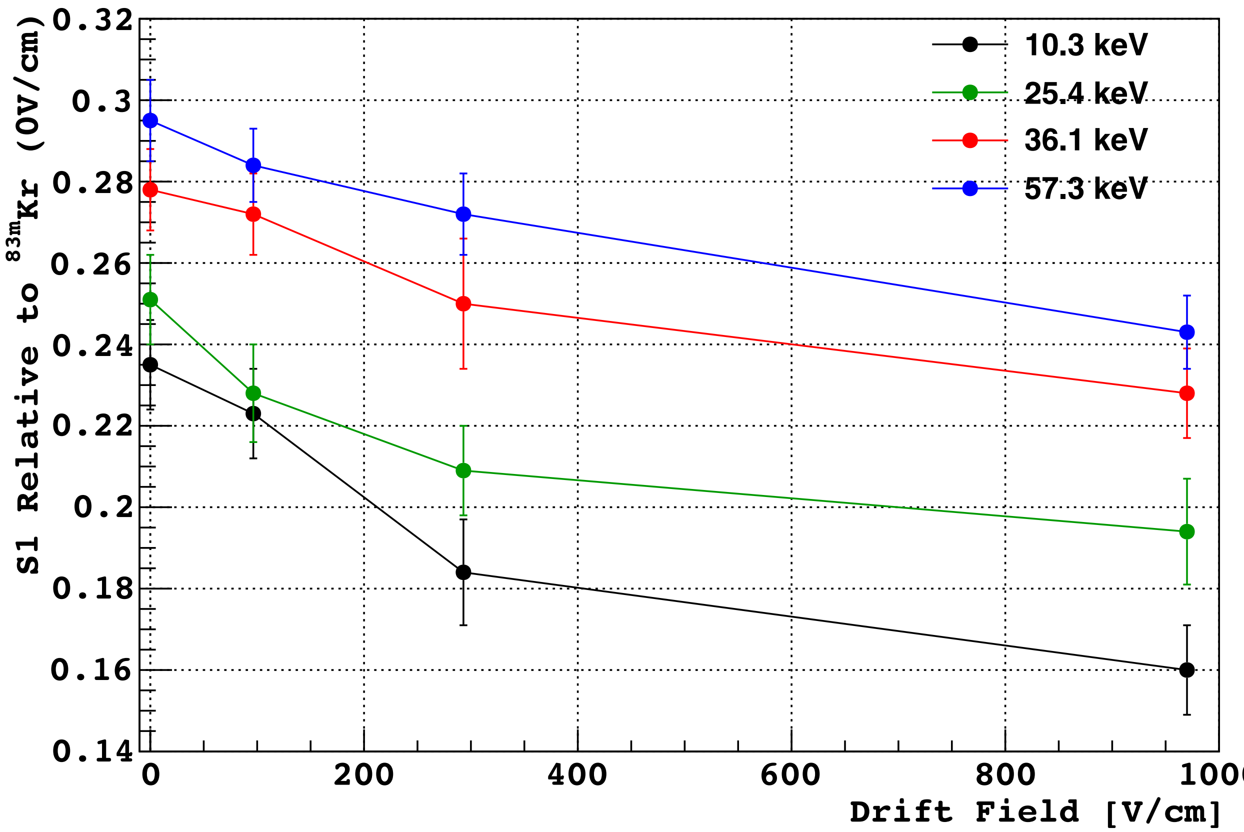
Null Field LY:

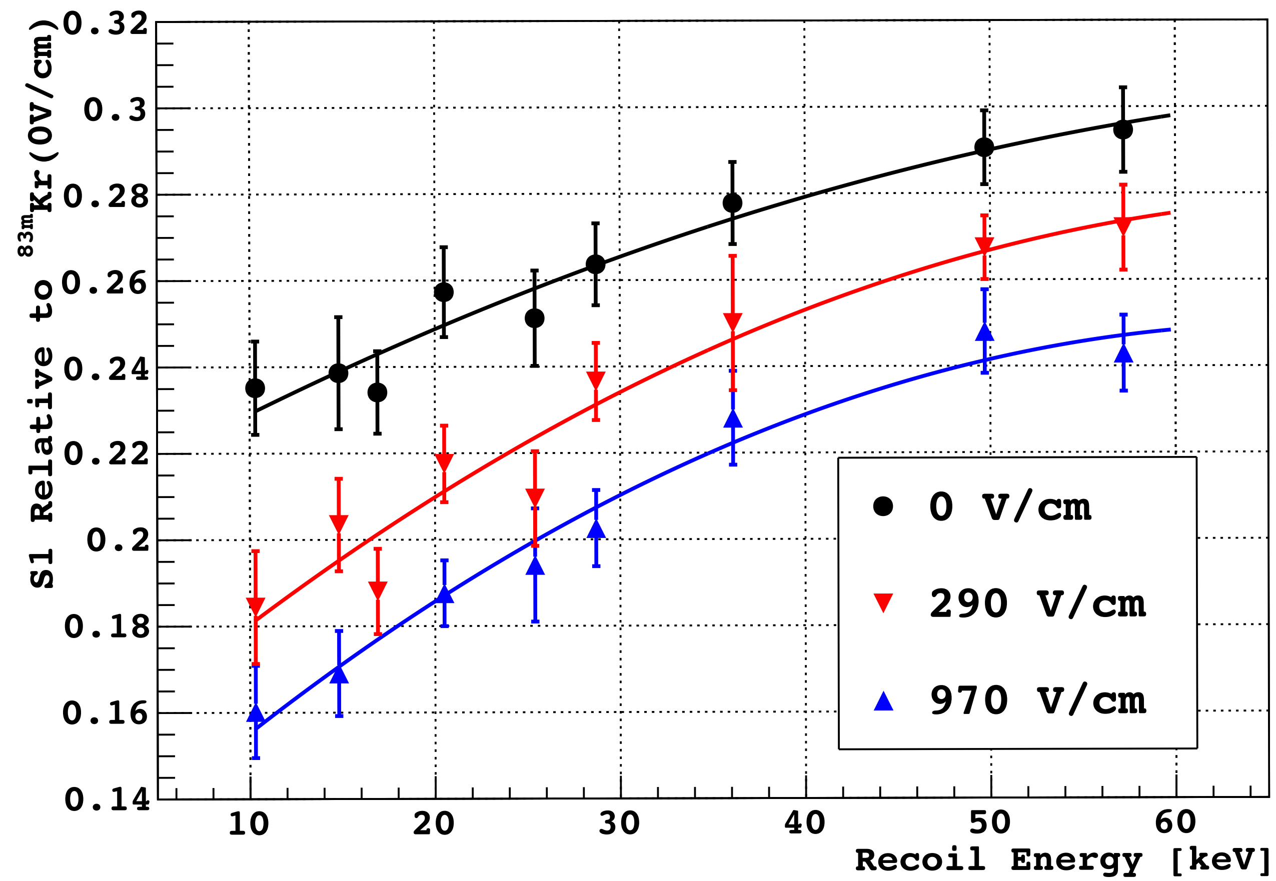
6.3 ± 0.3 PE/keV (June)

4.8 ± 0.2 PE/keV (Oct)

L_{eff} Results

Previously believed that the scintillation yield of nuclear recoils is **unaffected by external fields** due to the dense nature of the track





SCENE measurements show lower scintillation yield at high fields

Advantageous to run liquid argon TPCs at low fields to improve pulse shape discrimination

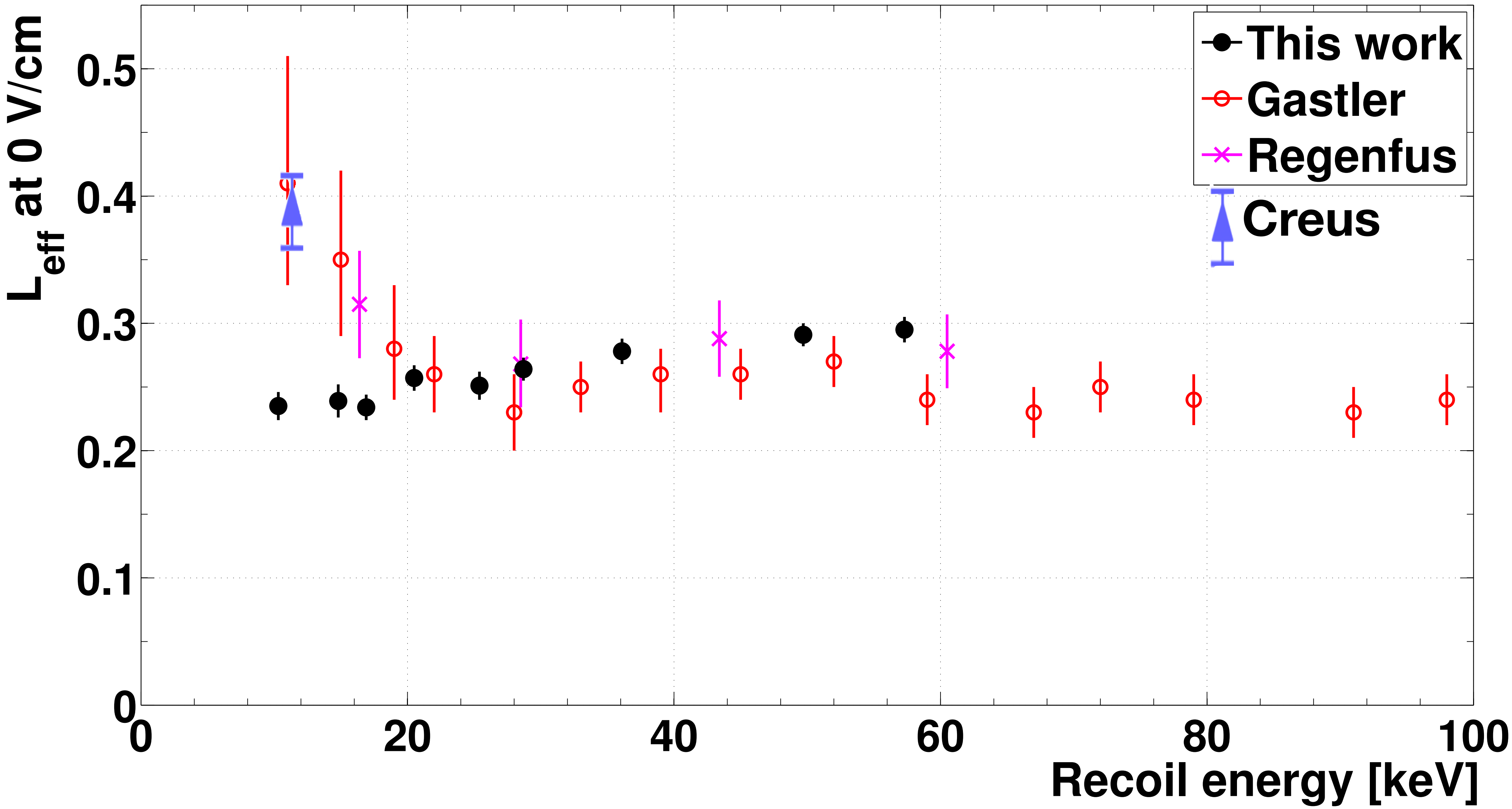
L_{eff} Systematics

Example of systematics studied at null field

Recoil Energy [keV]	10.3	14.8	16.9	20.5	25.4	28.7	36.1	49.7	57.3
$\mathcal{L}_{\mathrm{eff},{}^{83\mathrm{m}}\mathrm{Kr}}$	0.235	0.239	0.234	0.257	0.251	0.264	0.278	0.291	0.295
Statistical error	0.003	0.005	0.004	0.001	0.005	0.004	0.003	0.005	0.004
Systematic error source									
Fit method	0.001	0.000	0.004	0.004	0.002	0.001	0.003	0.001	0.002
Fit range	0.000	0.002	0.000	0.001	0.002	0.000	0.001	0.000	0.000
TPCtof cut	0.002	0.003	0.003	0.001	0.002	0.001	0.001	0.001	0.001
Ntof cut	0.004	0.002	0.001	0.001	0.002	0.004	0.001	0.003	0.001
f90 cut	0.004	0.004	0.003	0.001	0.000	0.001	0.000	0.000	0.000
^{83m}Kr light yield	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.006	0.006
Recoil energy									
TPC position	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
EJ301 position	0.007	0.010	0.005	0.008	0.008	0.005	0.006	0.003	0.006
Combined error total	0.011	0.013	0.010	0.010	0.011	0.009	0.010	0.009	0.010

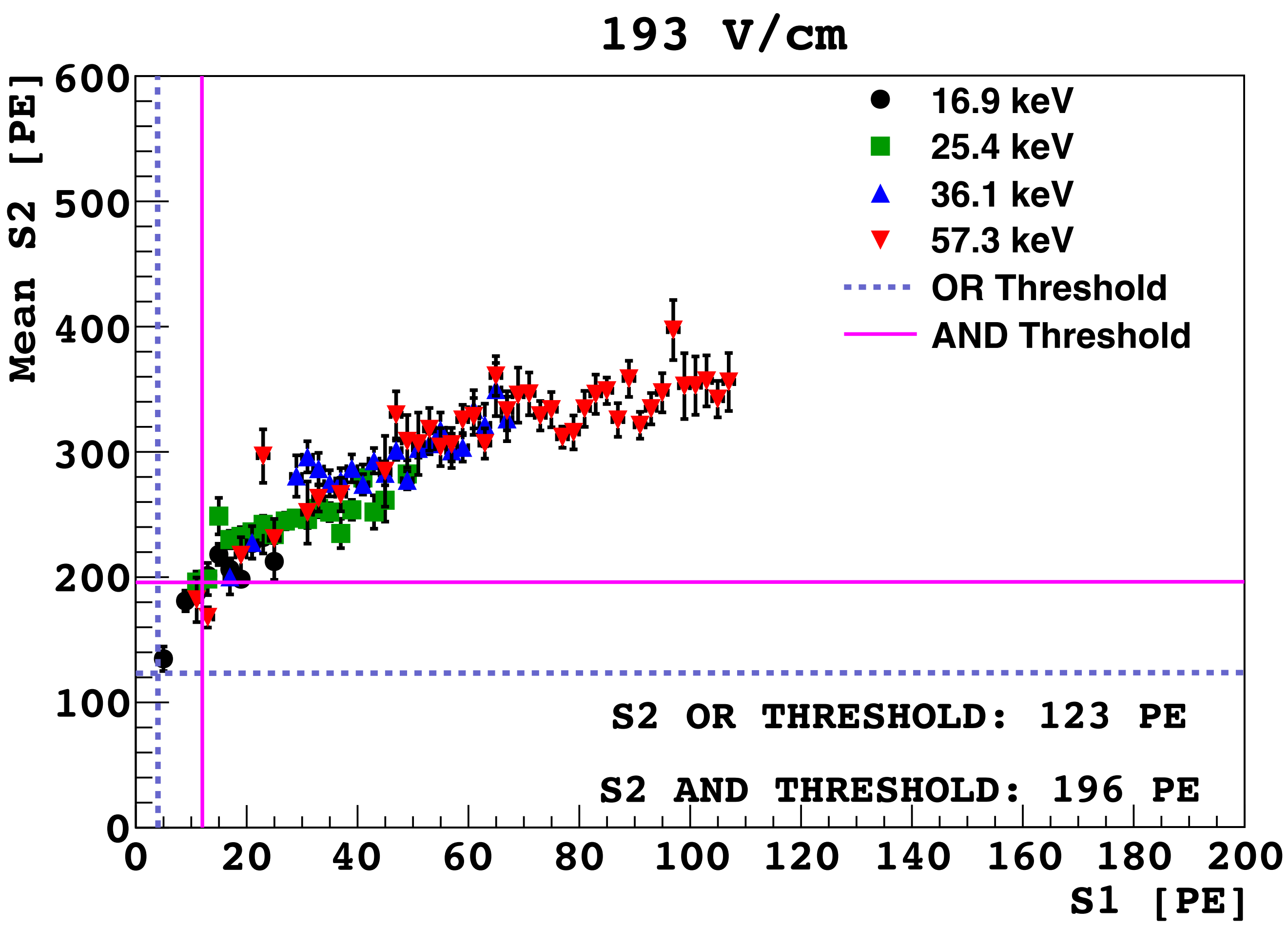
TABLE IV. Summary of error contributions to individual $\mathcal{L}_{\mathrm{eff},{}^{83\mathrm{m}}\mathrm{Kr}}$ measurements at $\mathcal{E}_{\mathrm{d}} = 0$. Only minor variations in the magnitude of systematic errors were observed across the range of drift field explored. The combined error for each measurement is shown Fig. 9.

L_{eff} Results

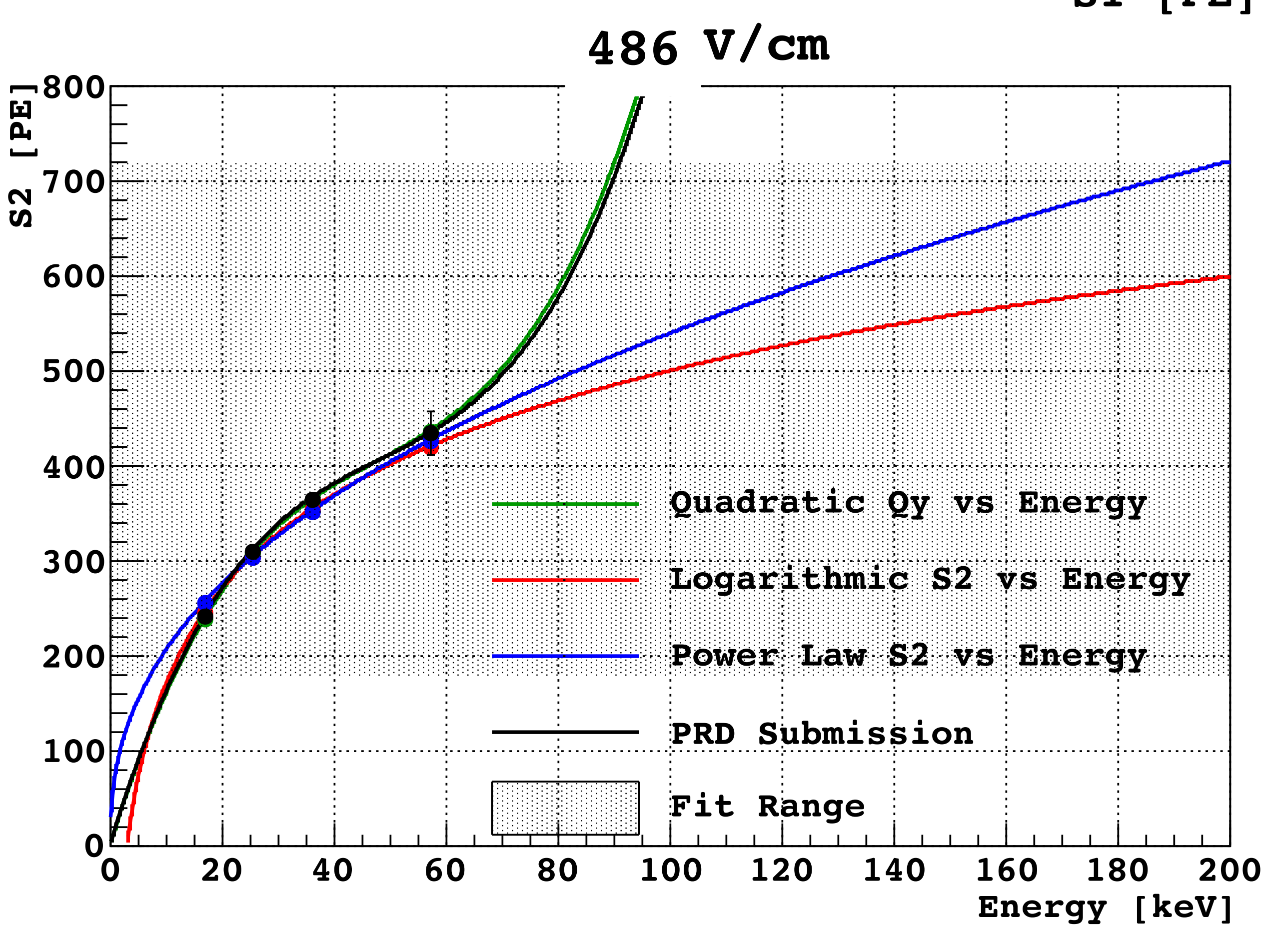


Gastler et. al. Phys. Rev. C 85, 065811 (2012)
Regenfus et. al. J. Phys.: Conf. Ser. 375, 012019 (2012)
Creus et. al arXiv:1504.07878v2

S2 fitting



Threshold for S2 fitting set by translating S1 threshold using data at each drift field setting



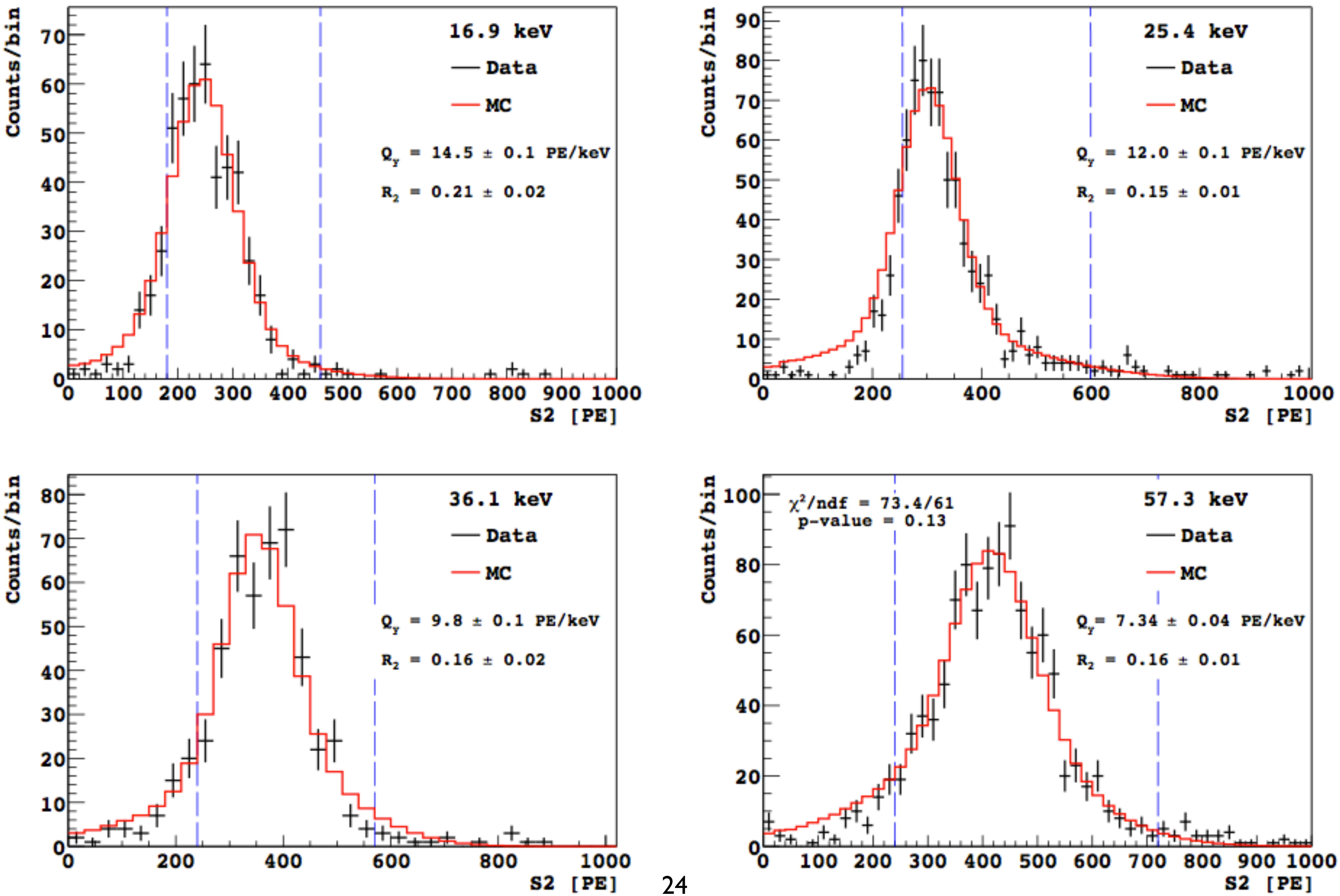
S2 yield can vary rapidly with energy, significantly even within a given geometrical setup

Data was fit using several different global functions:

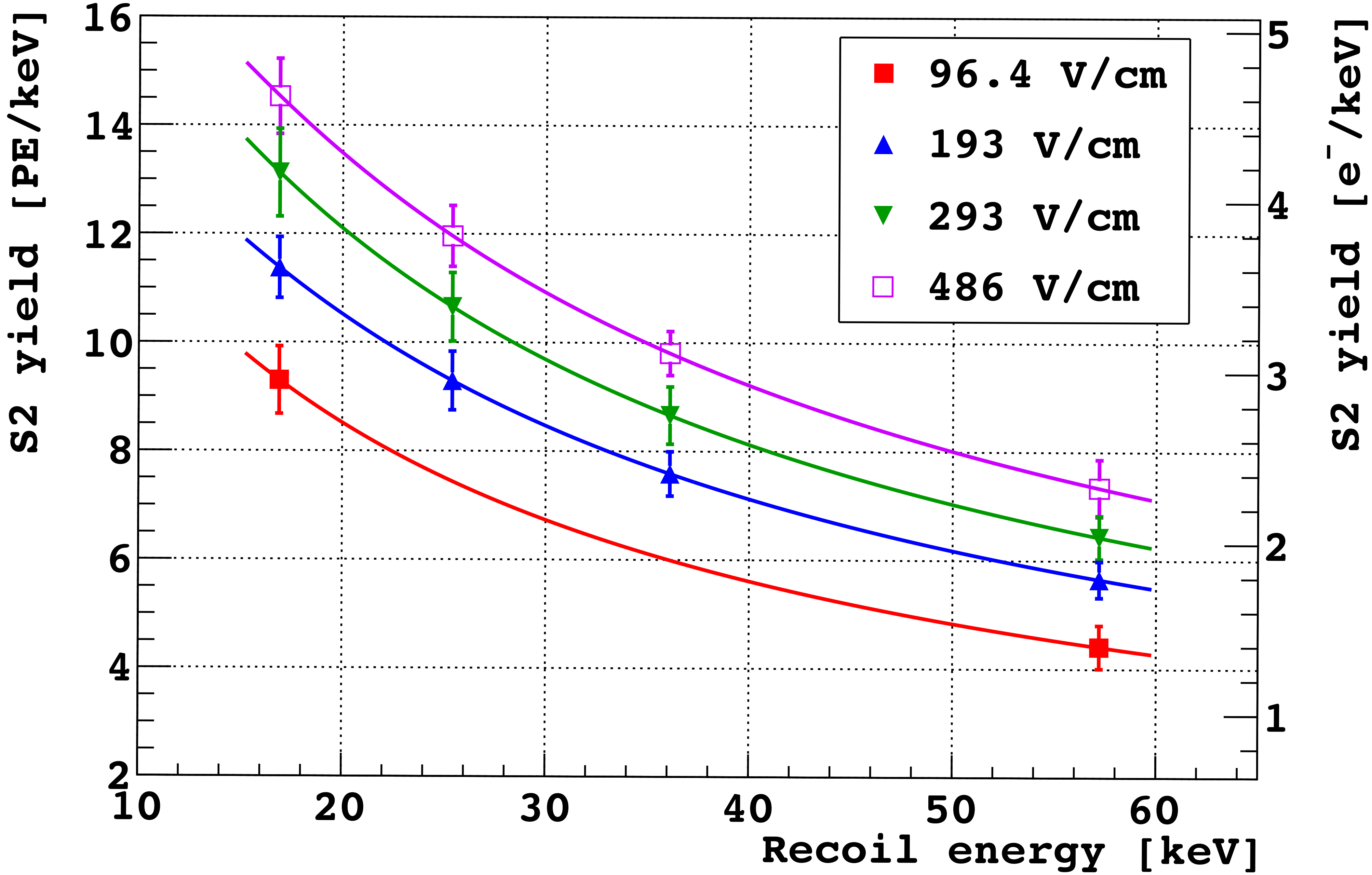
Quadratic, Logarithmic, Power Law

S2 fitting

Results for data acquired at 486 V/cm



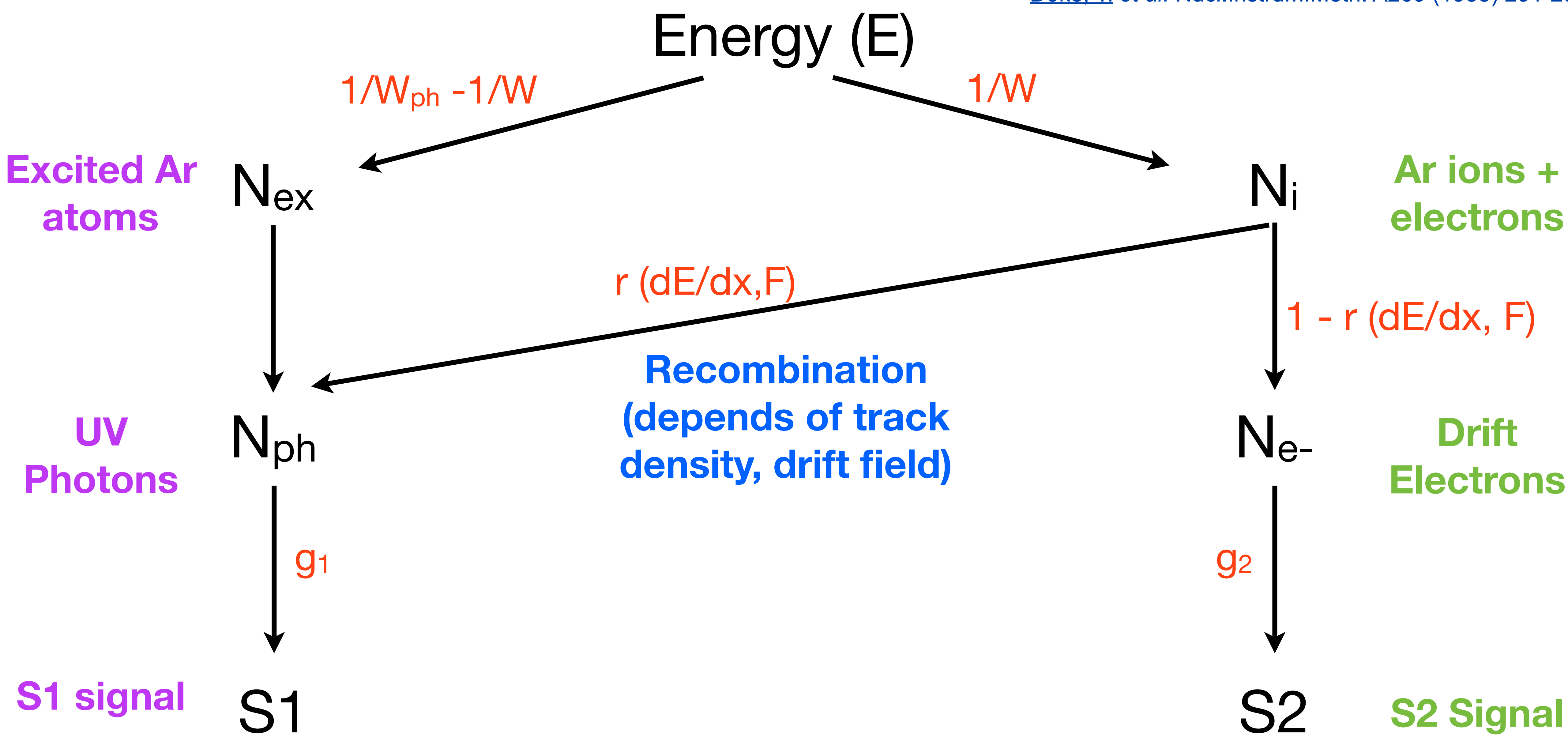
Q_y results



S2 yield [PE/keV]
16
14
12
10
8
6
4
2
10
20
30
40
50
60
Recoil energy [keV]
S2 yield [e$^-$/keV]
5
4
3
2
1
96.4 V/cm
193 V/cm
293 V/cm
486 V/cm

Model of energy deposition for electron recoils

[LET Dependence of Scintillation Yields in Liquid Argon](#)
Doke, T. *et al.* Nucl.Instrum.Meth. A269 (1988) 291-296



W : Energy required to produce electron-ion pair

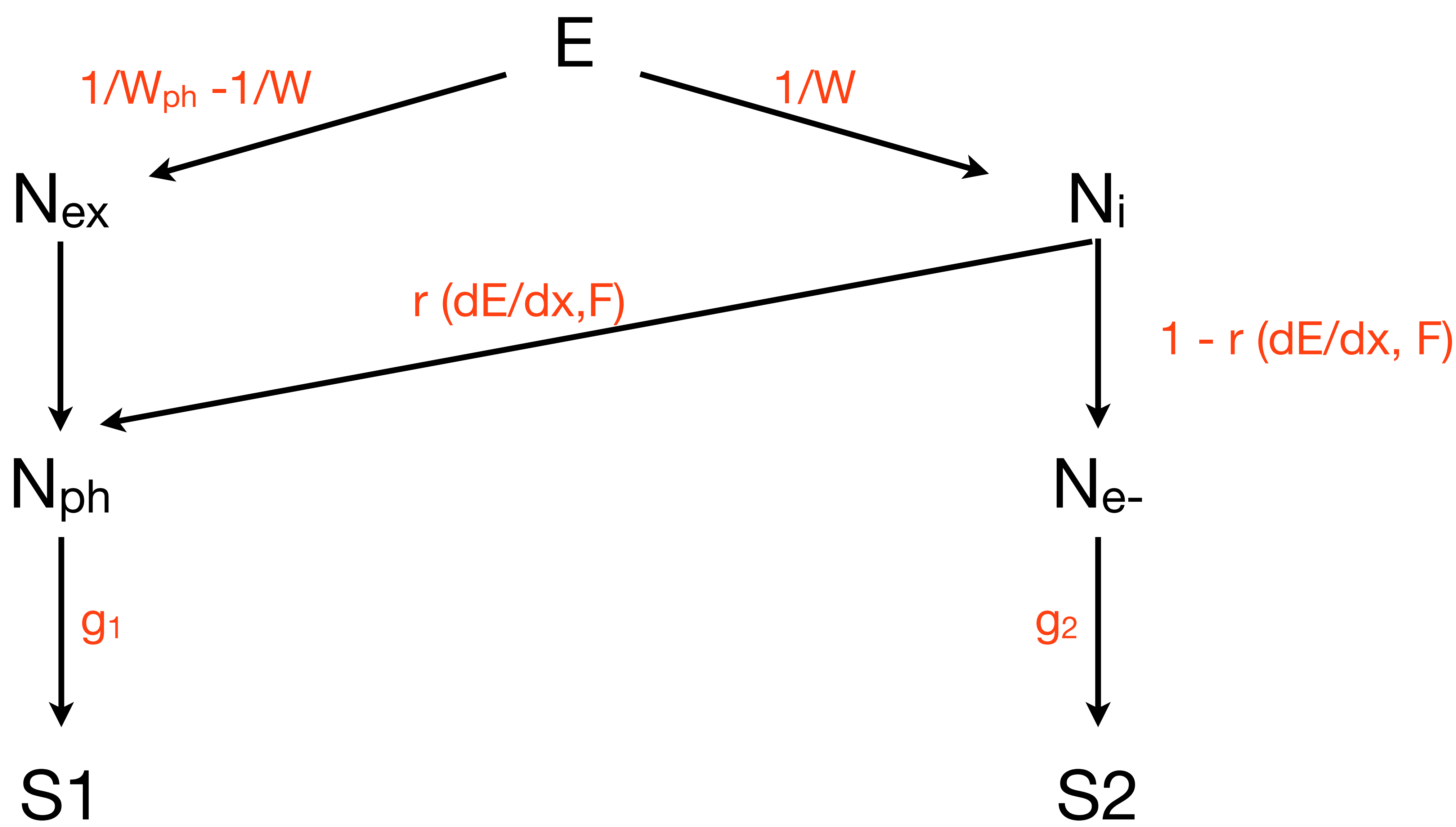
W_{ph} : Energy required per quanta (N_{ex} + Ni)

= Energy required to produce a photon when $r = 1$

r : Recombination fraction

g_1: Scintillation detection efficiency [PE/UV photon]

g_2: Electron detection efficiency [PE/electron]



Only recombination (r) depends on the drift field (F)

S1 and S2 are linearly anti-correlated, independent of drift field

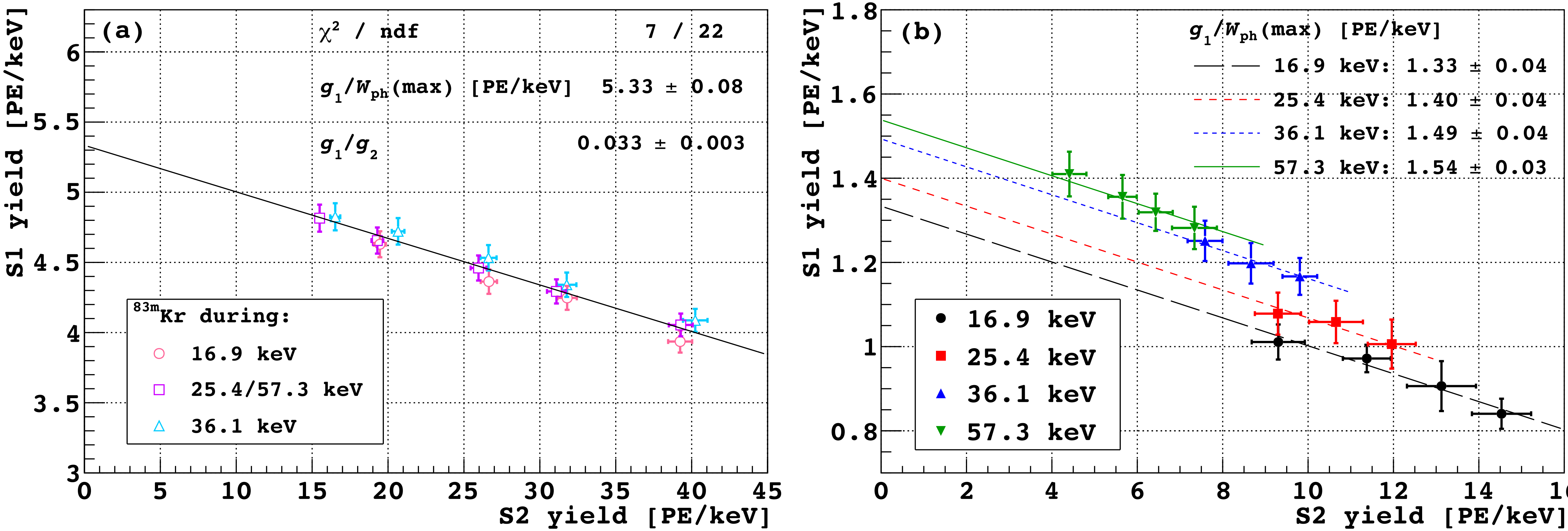
$$\frac{S1}{E} = -\frac{g_1}{g_2} \cdot \frac{S2}{E} + \frac{g_1}{W_{ph}}$$

Is this also true for nuclear recoils ?

S2 vs S1

$$\frac{S1}{E} = -\frac{g_1}{g_2} \cdot \frac{S2}{E} + \frac{g_1}{W_{ph}}$$

Krypton　　　　　　　　Nuclear Recoils



Both electron and nuclear display an S1-S2 anti-correlation, with the **same slope** ($-g_1/g_2$)

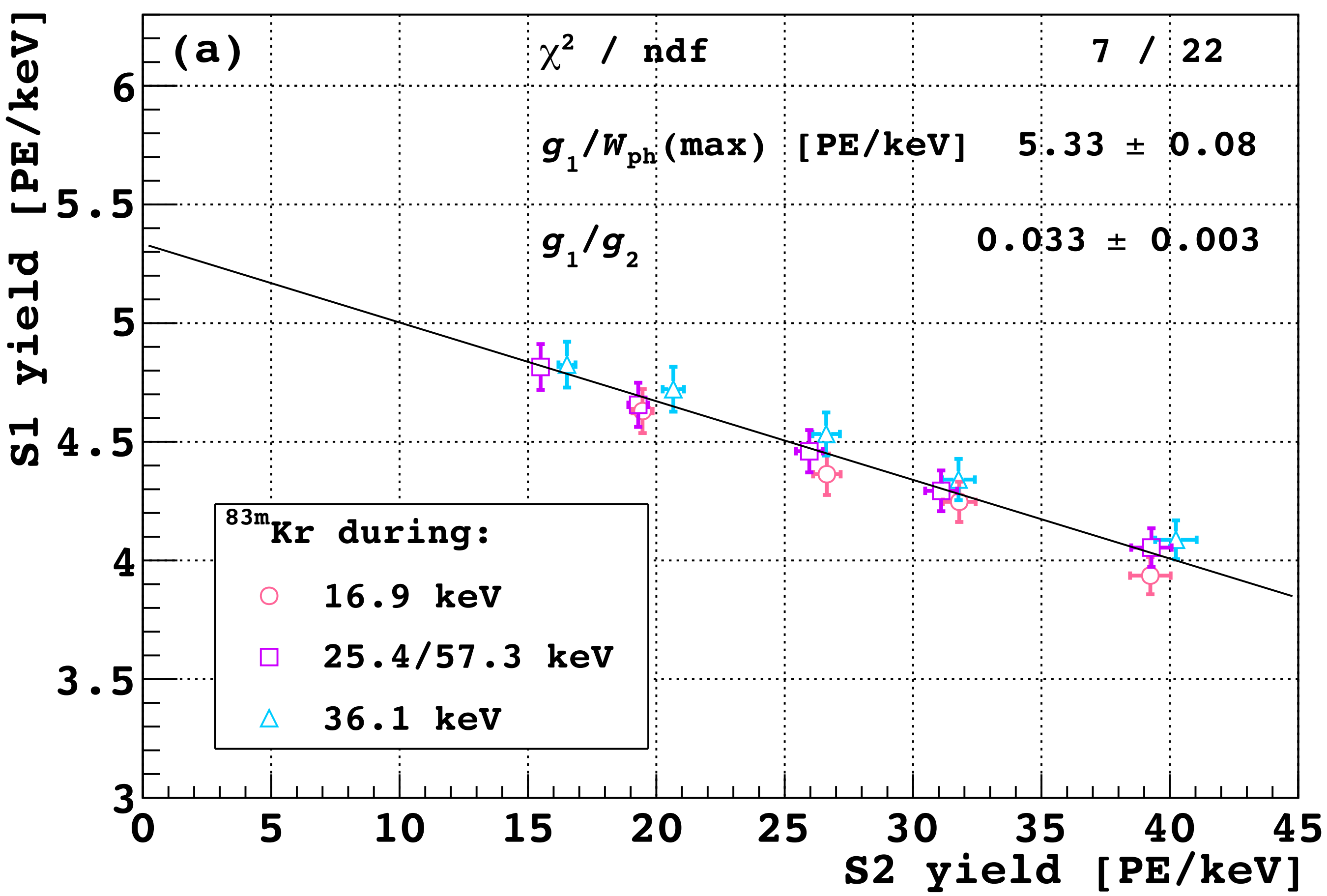
g_1: 0.104 ± 0.006 PE/photon　　　　g_2: 3.1 ± 0.3 PE/e^-

Assuming W_{ph}(Kr) = 19.5 ± 0.1 eV

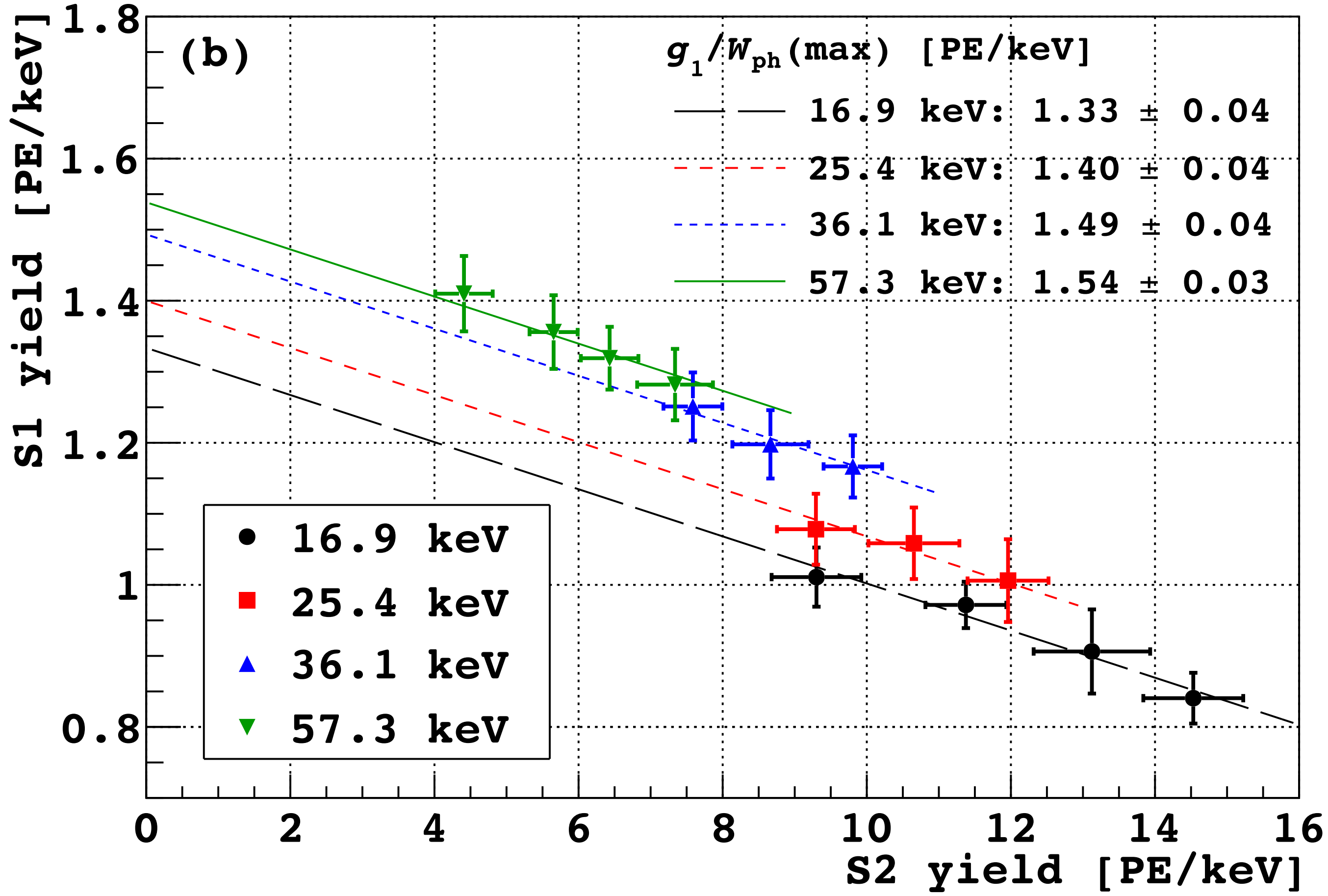
S2 vs S1

$$\frac{S1}{E} = -\frac{g_1}{g_2} \cdot \frac{S2}{E} + \frac{g_1}{W_{ph}}$$

Krypton



Nuclear Recoils



Intercept (g_1/W_{ph}) changes with energy for nuclear recoils

Total Quenching

Nuclear Recoil Energy (E_{nr})

$\eta\ (E_{nr})$

Electron Recoil Energy (E)

$1/W_{ph} - 1/W$

$1/W$

N_{ex}

N_i

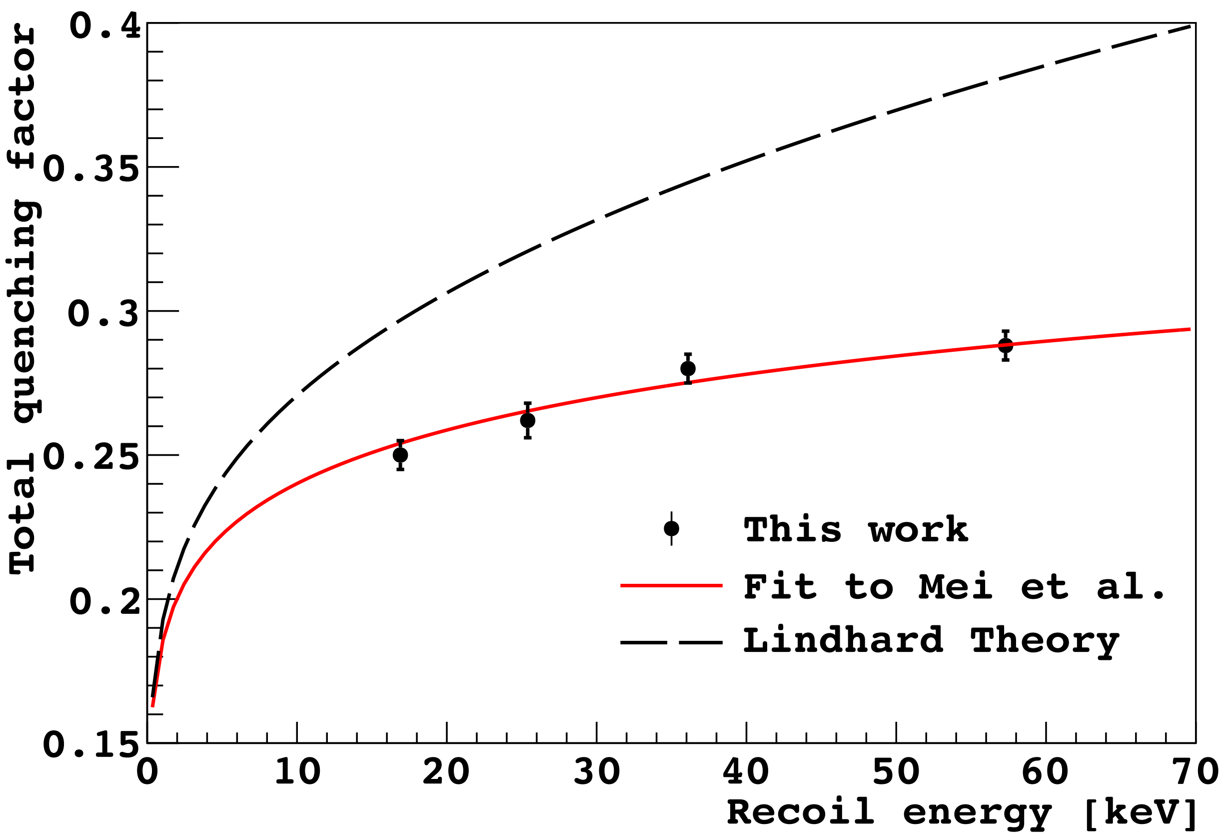
r (dE/dx,F)

1 - r (dE/dx, F)

N_{ph}

N_{e-}

Some nuclear recoil energy is lost to atomic motion



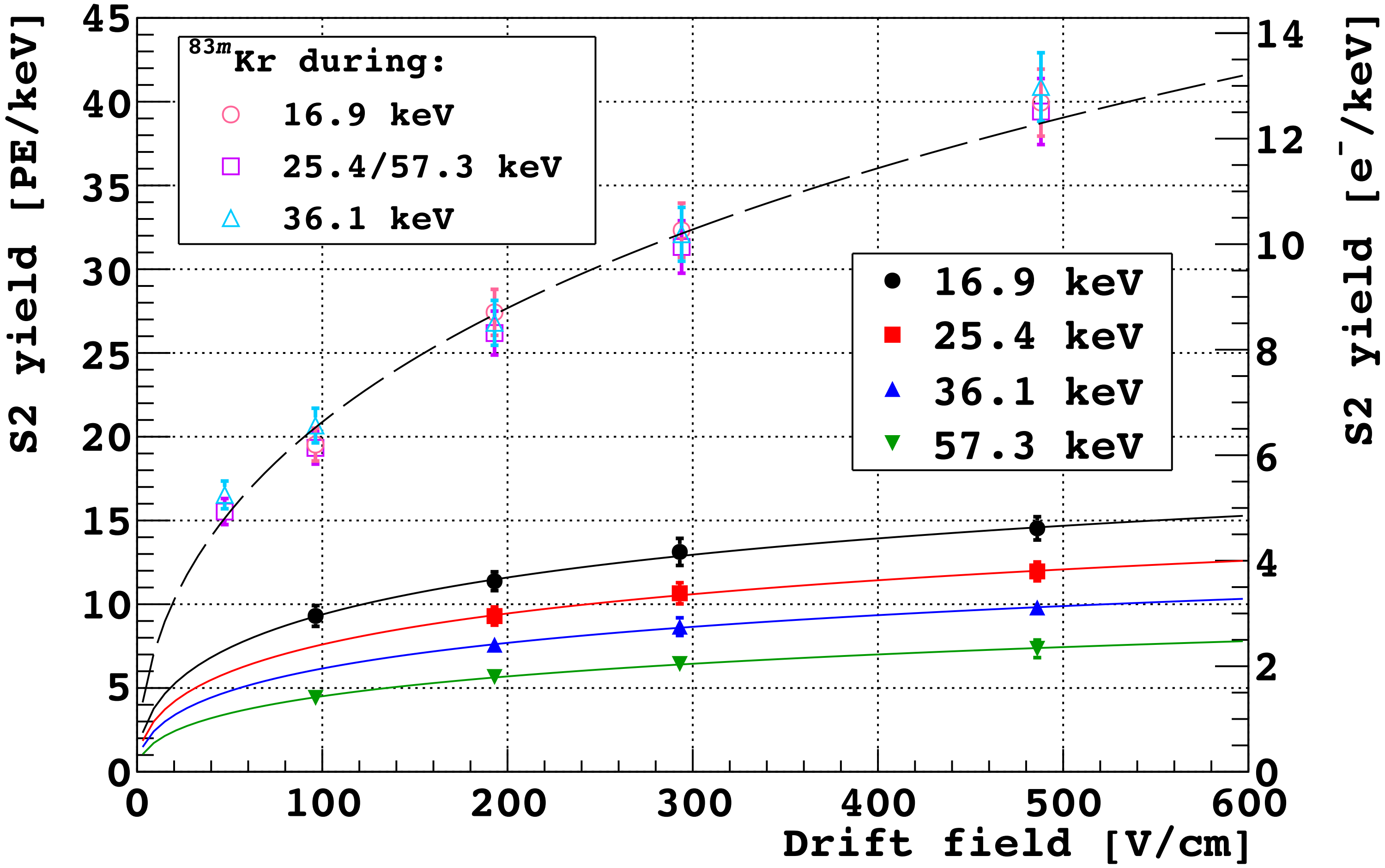
Lindhard Theory: Quenching attributed to loss of energy to atomic motion

Mei et. al: Quenching attributed to Lindhard + Birk's quenching ($kB = 5.0 \pm 0.2 \times 10^{-4}$ MeV/g/cm^2)

Recombination Model

Number of ions can also be determined using a recombination model

Modified Thomas-Imel Box Model (arXiv: 1402.2037)



$$Q_y = g_2 \frac{N_i}{E\xi} \ln(1+\xi), \ \xi = \frac{N_i C}{\mathcal{E}_d^B}$$

B: Constant - same for all species, energies (0.61 ± 0.03)

C, N_i: Constant - different for each energy

Recoil Energy [keV]	C [(V/cm)^B/e^-]	N_i/E[keV]
16.9	0.58±0.17	8.2±1.9
25.4	0.50±0.23	7.0±2.5
36.1	0.45±0.19	5.9±2.0
57.3	0.42±0.16	4.8 ± 1.8

Summary

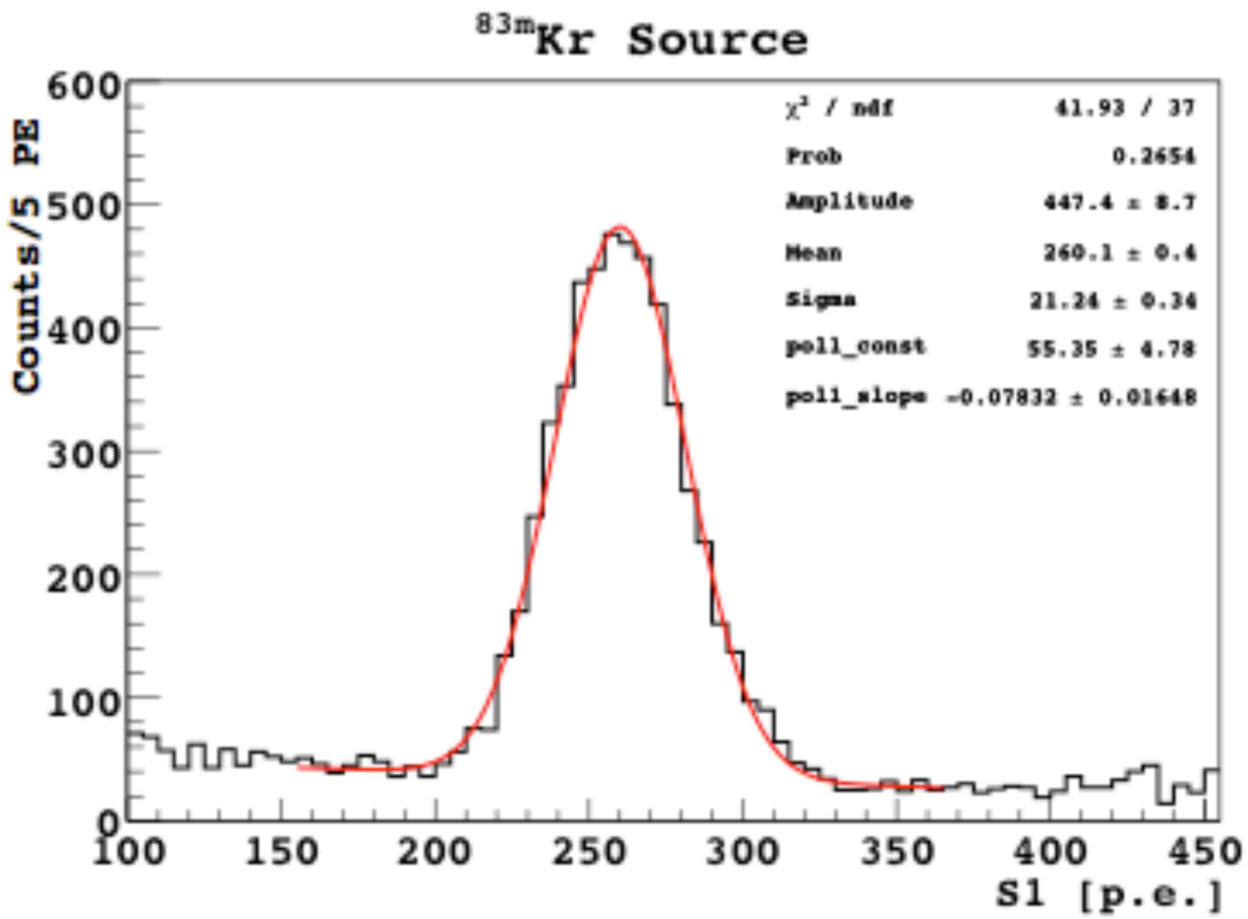
- We have performed a measurement of the scintillation and ionization yield of liquid argon
- Measurement spans energy ranges from 10 - 57 keV recoils with drift fields from 0 - 970 kV/cm
- Simultaneous measurement of the S1 and S2 signals allows for a comparison with quenching and recombination models
- For additional details, including measurements of pulse shape discrimination and directionality, please see publications:

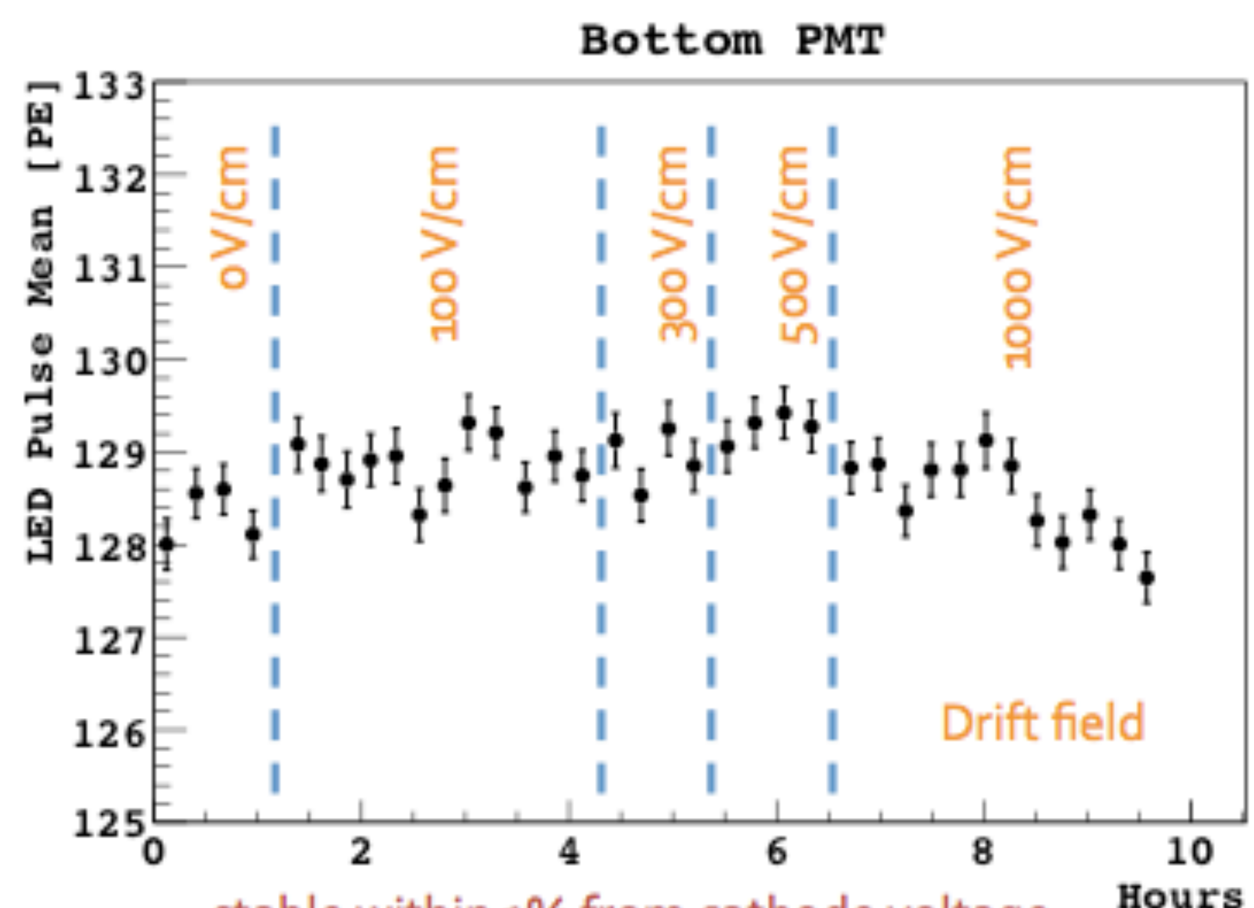
Observation of the dependence on drift field of scintillation from nuclear recoils in liquid argon
T. Alexander et. al. (SCENE Collaboration) Phys.Rev. D88 (2013) 9, 092006

Measurement of Scintillation and Ionization Yield and Scintillation Pulse Shape from Nuclear Recoils in Liquid Argon
Cao et. al. (SCENE Collaboration) Phys. Rev. D 91, 092007 (2015)

Thank you

Light Yield Monitors: ^{83m}Kr Source + LED





stable within 1% from cathode voltage changes

^{83m}Kr: LY and electron lifetime calibration

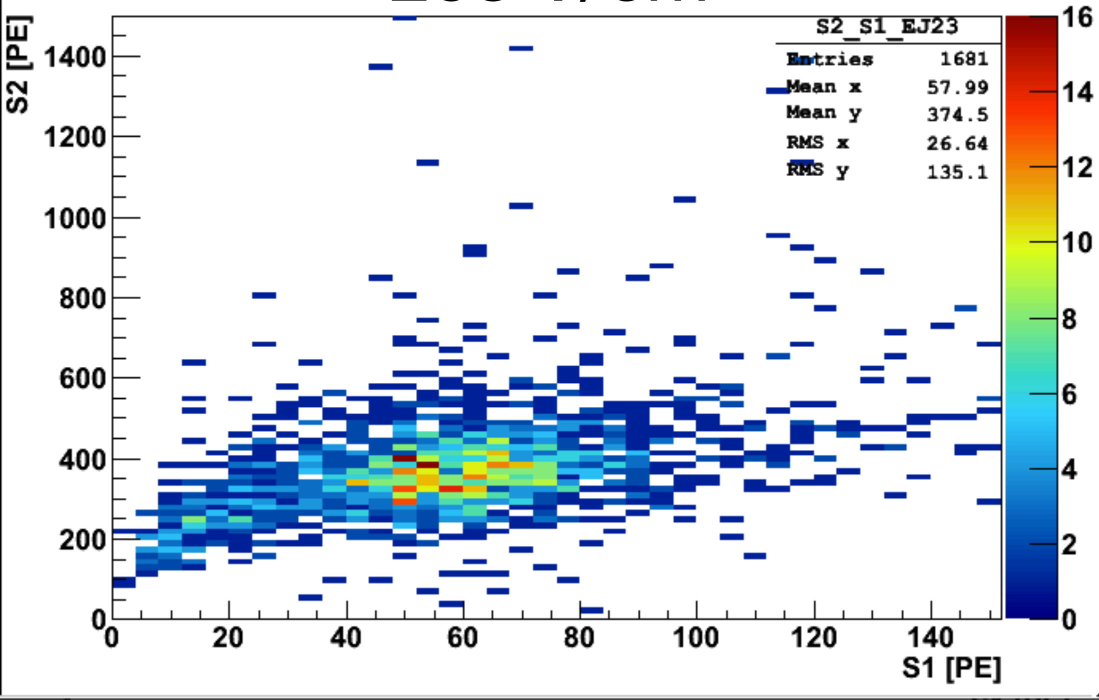
Continuous recirculation during the beam run for maintaining ^{83m}Kr activity (1.2 kBq in Jun, 0.5 kBq in Oct) and LAr purity

LED Pulse (added for Oct Run):
PMT efficiency monitoring
Continuously recorded at 1 Hz

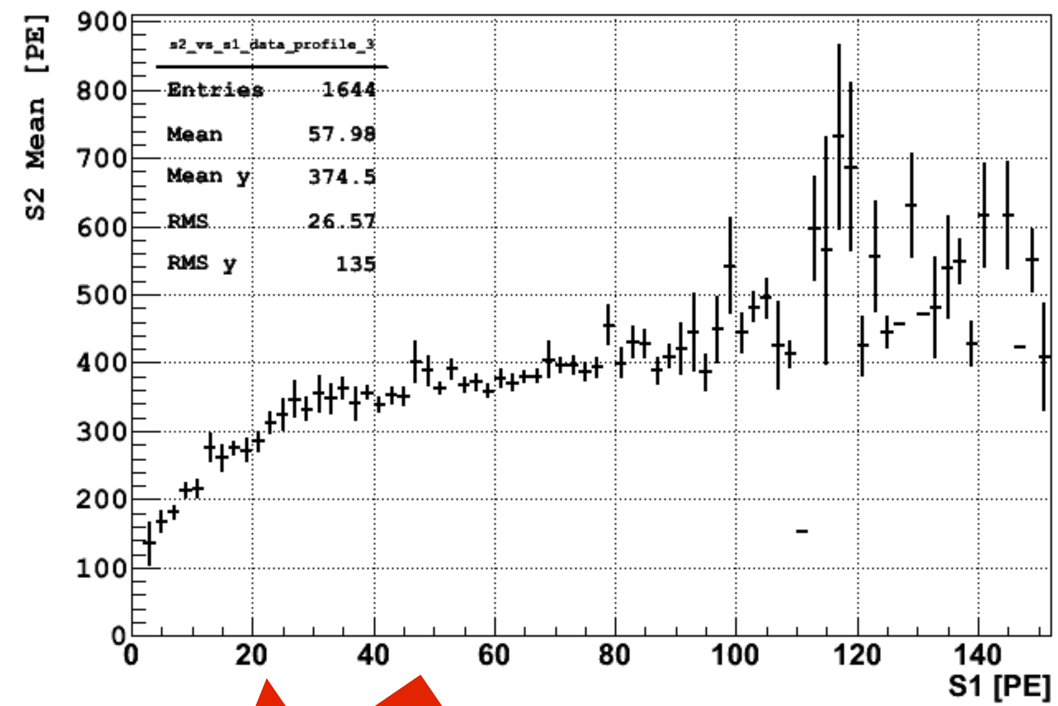
Top PMT efficiency was affected by S2. LED pulse provided calibration.

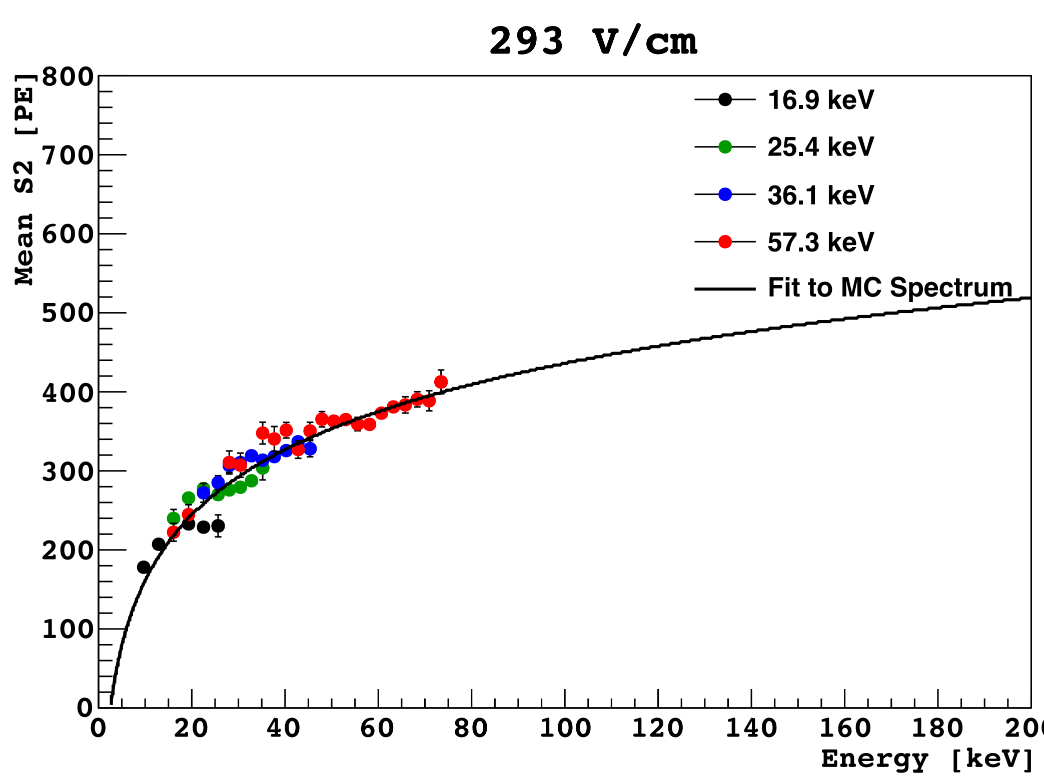
S1-S2 Consistency Check

293 V/cm



Take profile of means in each S1 slice

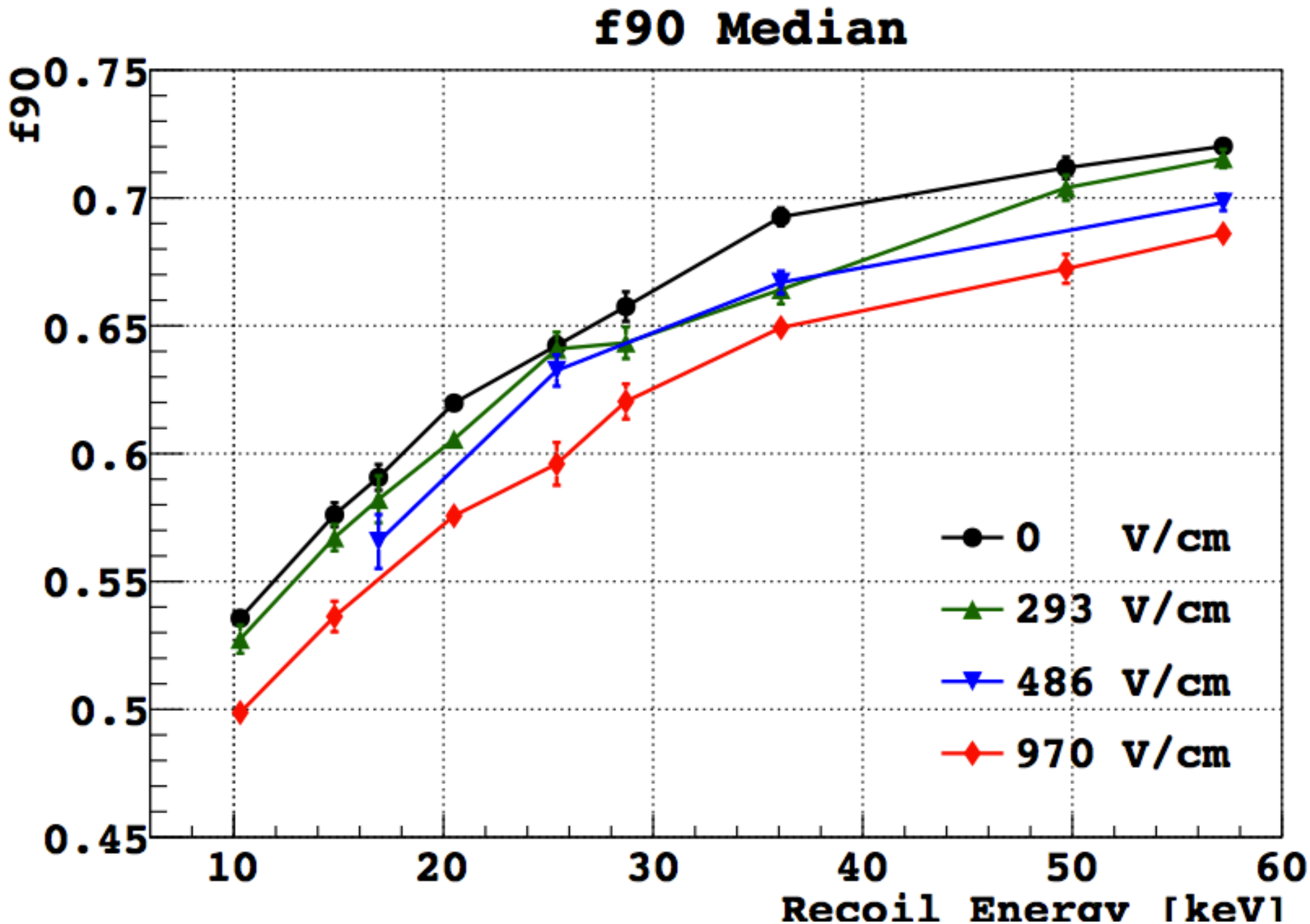




Assume all events after cuts are single scatter nuclear recoils in TPC

Convert S1 axis to energy using Leff measurement:

S1 = E x LYx Leff



f90 Median
f90
0.75
0.7
0.65
0.6
0.55
0.5
0.45
10
20
30
40
50
60
Recoil Energy [keV]
0 V/cm
293 V/cm
486 V/cm
970 V/cm