Light yield from nuclear recoils in liquid argon

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Outline

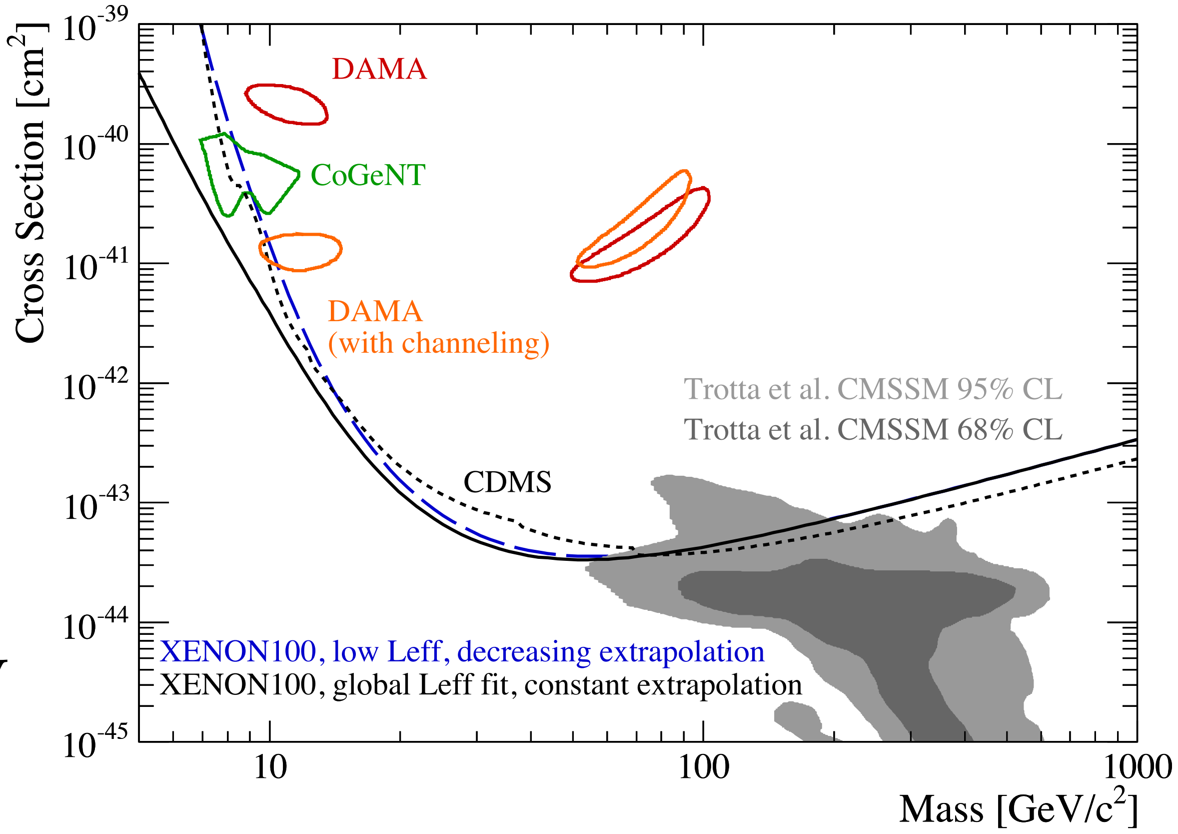
- Motivation
- Scintillation processes in LAr
- Principle of the experiment
- Data reconstruction
- Results
- Outlook

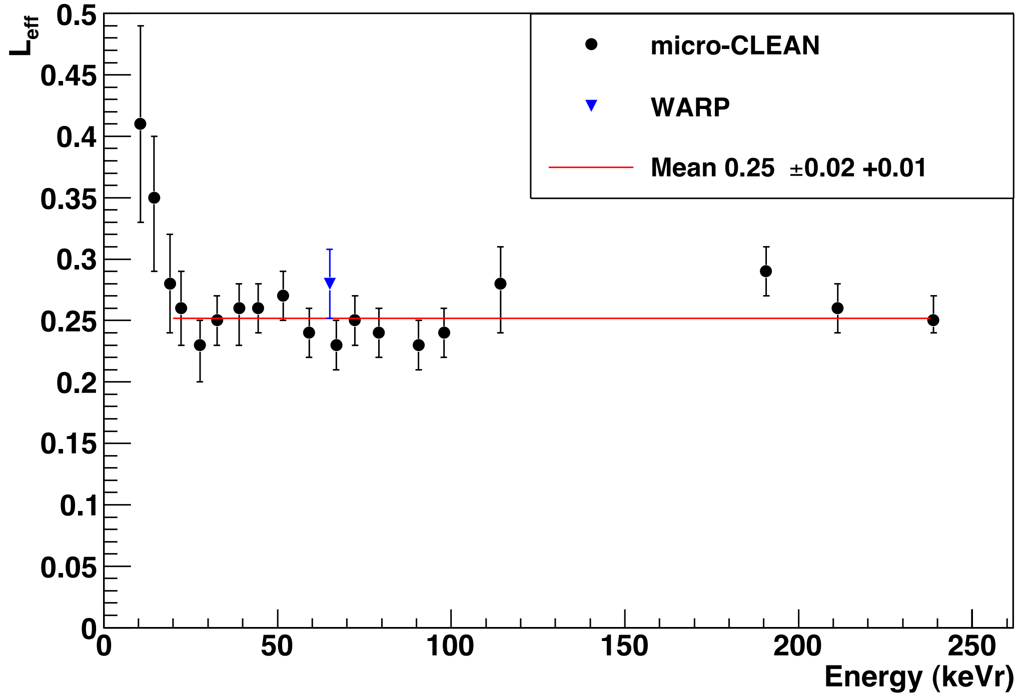
Motivation

- Measurement of relative scintillation efficiency ($\mathcal{L}_{\text{eff}}$) in LAr/LXe to quantify WIMP detection sensitivity

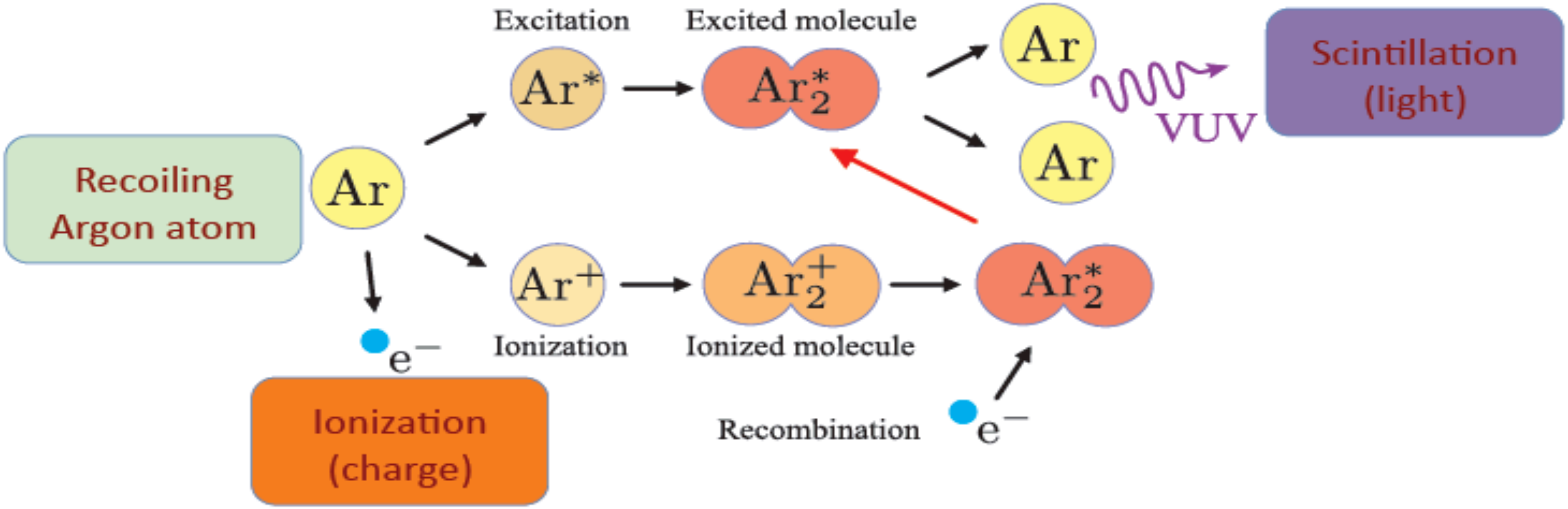
- The uncertainties in $\mathcal{L}_{\text{eff}}$ of nuclear recoils at low energy is the largest systematic uncertainties in the WIMP searches at low WIMP masses (Xenon 100)

- At low energy the $\mathcal{L}_{\text{eff}}$ should decrease according to model prediction



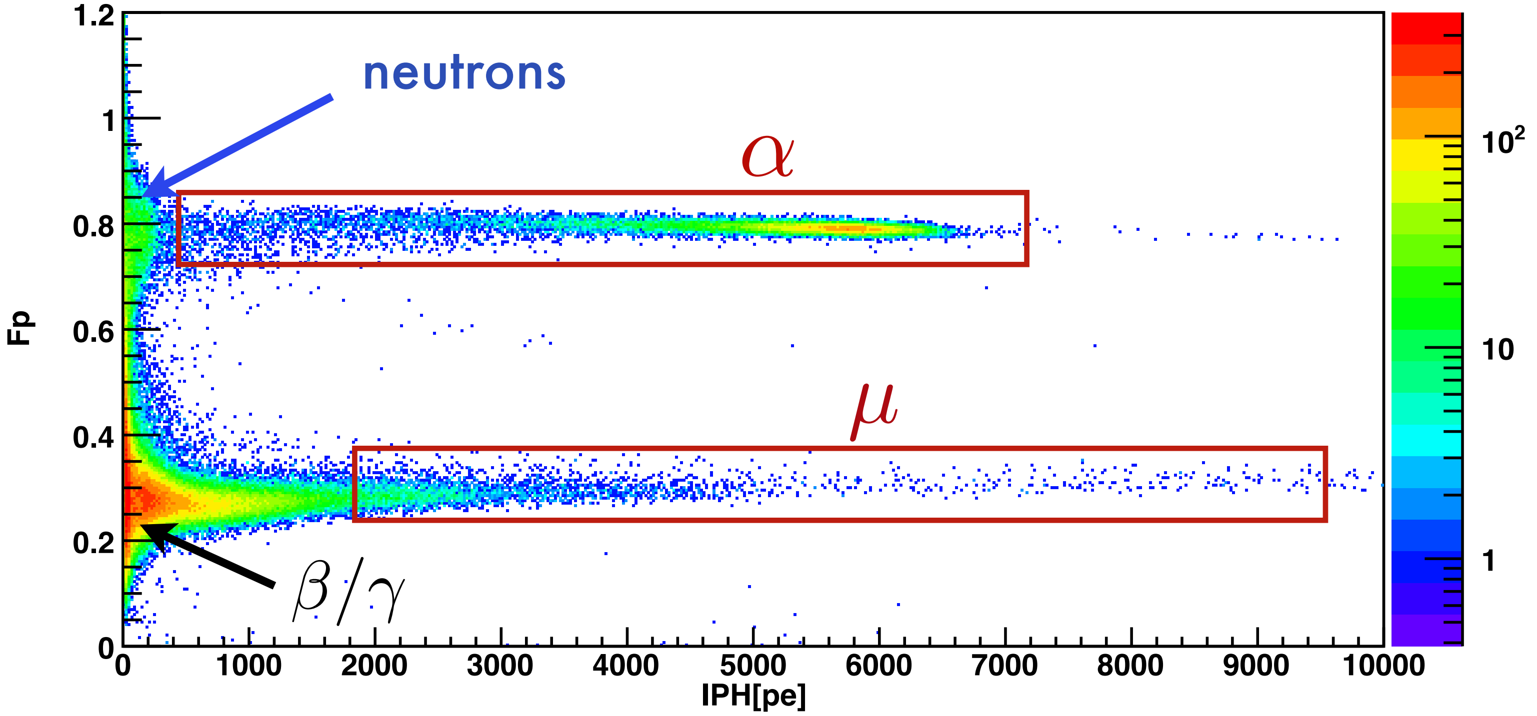


Scintillation processes in LAr



- Excitons (Ar^*) and electron-ion pairs are created along the particle track
- Free Excitons collide with ground states to form Excimers(Ar_2^*) which deexcite with emission of a VUV scintillation light
- Deexcitation in singlet states(4 ns) and a triplet state($1.6\mu s$)
- A fraction of the ionization electrons will recombine with Ar ions and produce a scintillation photon (recombination)
- Electrons that thermalize far from their parent ions may escape recombination
- Bi-Excitonic quenching $Ar^* + Ar^* \rightarrow Ar + Ar + e^-$ can reduce the scintillation light yield in very dense tracks

Particle identification in LAr



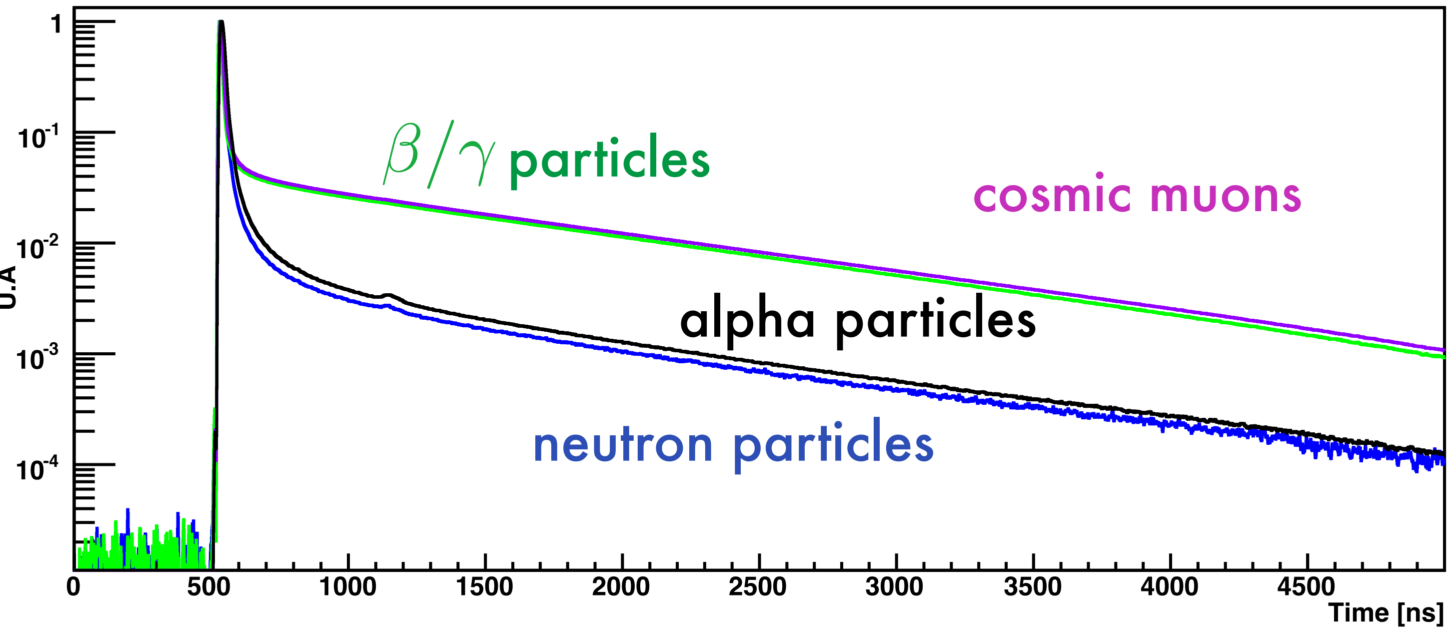
Prompt light fraction

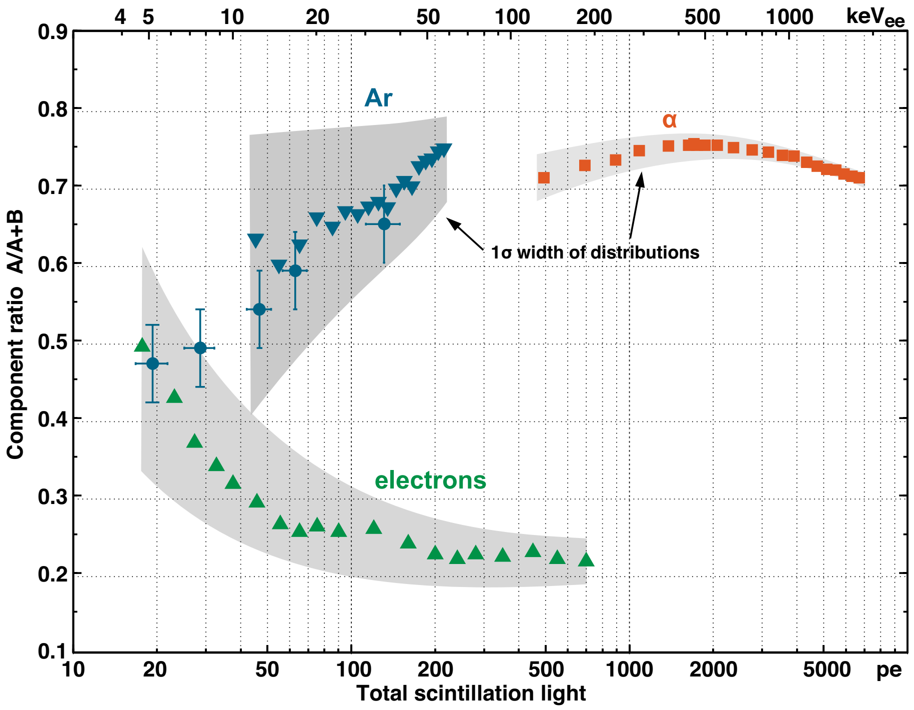
$$\mathrm{F_p} = \frac{\int_{\mathrm{t_0-20ns}}^{\mathrm{t_0+30ns}} \mathrm{U(t)dt}}{\int_{\mathrm{t_0-20ns}}^{5\mu\mathrm{s}} \mathrm{U(t)dt}} = \frac{\mathrm{IPHA}}{\mathrm{IPH}}$$

Component ratio

$$\mathcal{F} = \mathcal{G}(\mathrm{t},\sigma) \otimes \left(\mathcal{H}(\mathrm{t}-\mathrm{t_0}) \cdot \left(\frac{\mathrm{A}}{\tau_1} \cdot \mathrm{e}^{\frac{\mathrm{t}-\mathrm{t_0}}{\tau_1}} + \frac{\mathrm{B}}{\tau_2} \cdot \mathrm{e}^{\frac{\mathrm{t}-\mathrm{t_0}}{\tau_2}}\right)\right)$$

$$\mathrm{CR} = \frac{\mathrm{A}}{\mathrm{A+B}}$$





Principle of the experiment

Relative scintillation efficiency (Zero E-field) : $\mathcal{L}_{\mathrm{eff}} = \frac{\mathrm{Y_{nr}}}{\mathrm{Y_{er}}} \cdot \frac{\mathrm{S_e}}{\mathrm{S_n}} = \frac{\mathrm{N_{p.e,nr}}}{\mathrm{E_{nr}}} \cdot \frac{\mathrm{E_{ee}}}{\mathrm{N_{p.e,er}}} \cdot \frac{\mathrm{S_e}}{\mathrm{S_n}} = \boxed{\frac{\mathrm{E_{ee}}}{\mathrm{E_{nr}}} \cdot \frac{\mathrm{S_e}}{\mathrm{S_n}}}$

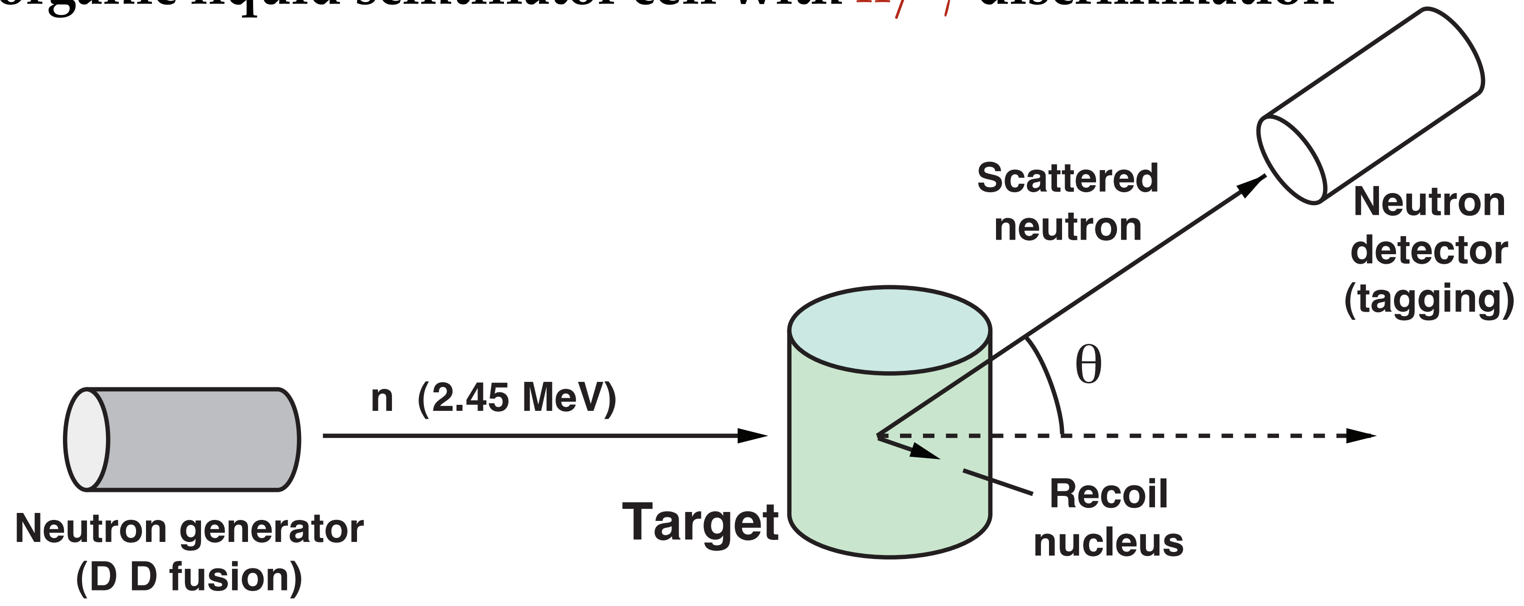
In this work $\mathrm{S_e} = \mathrm{S_n} = 1$

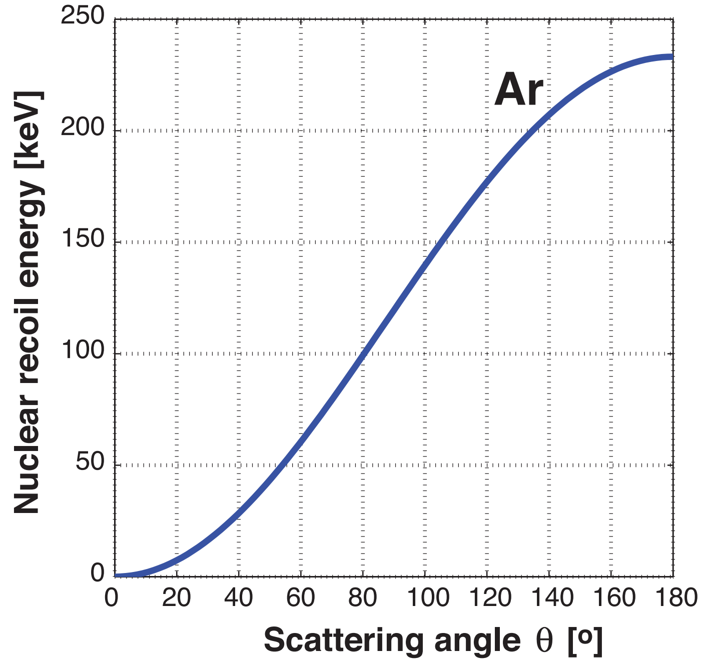
$\mathrm{E_{ee}}$ is the electron-equivalent energy expressed in keVee (nuclear recoil of visible energy ⟶ measured) calibrated using the light yield of 60 keV line γ from the Am source

$\mathrm{E_{nr}}$ is the true recoil energy expressed in keVr (energy calculated)

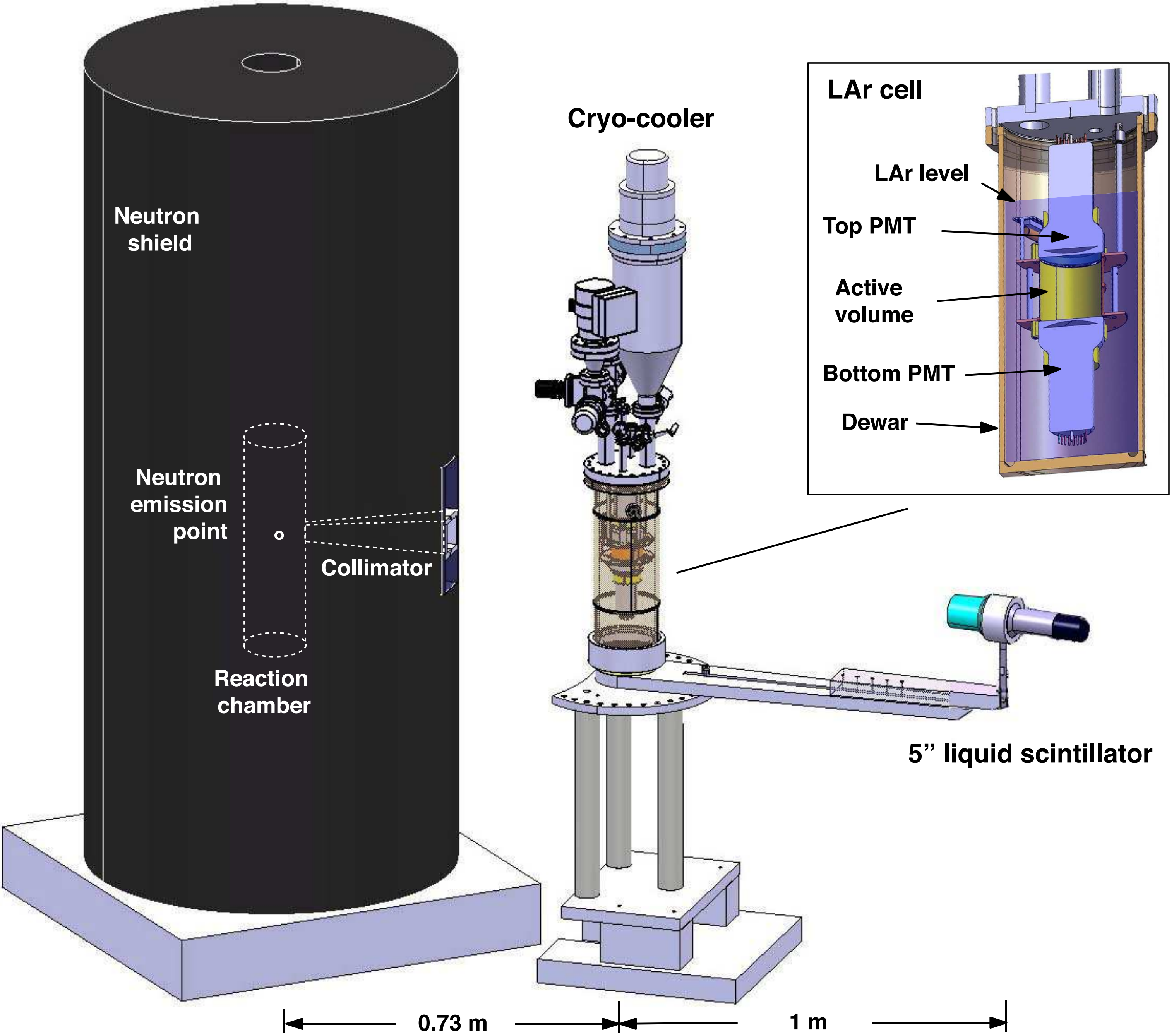
$$\boxed{\mathrm{E_{nr}} = \frac{2\mathrm{E_n}}{(\mathrm{A_{Ar}}+1)^2}\left[(1 + \mathrm{A_{Ar}} - \cos^2\theta - \cos\theta\sqrt{\mathrm{A_{Ar}^2} + \cos^2\theta - 1}\right]}$$

Measurement performed by recording fixed-angle elastic scatters in LAr of monoenergetic neutrons tagged by organic liquid scintillator cell with n/γ discrimination



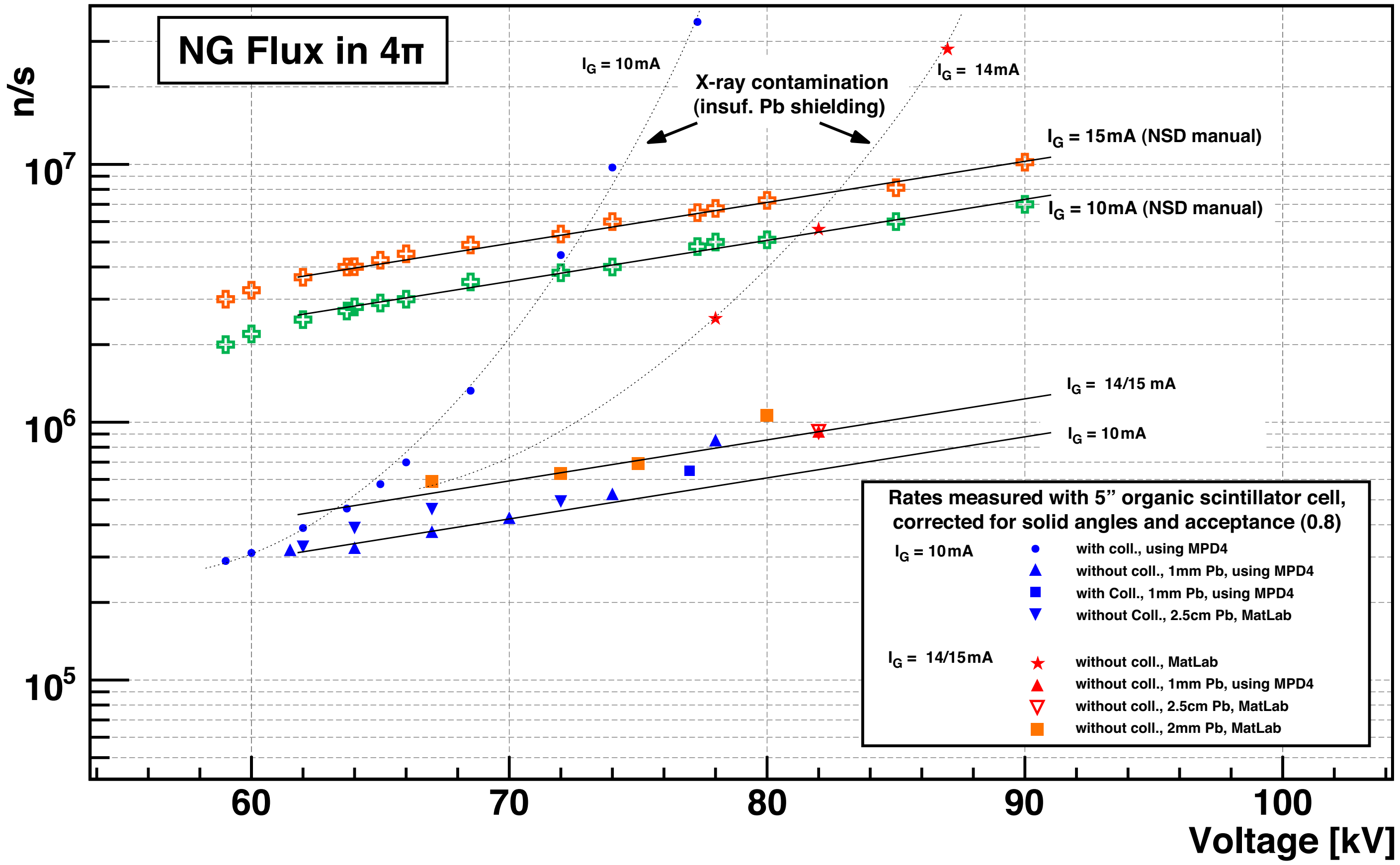


The experimental setup, LAr Cell



- Stainless steel dewar with 133 mm inner diam.
- Stainless steel thickn. 1.5mm
- Active volume surr. by 30 mm LAr
- Height of the active volume 49 mm
- 2 x R6091 3”PMT Hamamatsu, Pt underlay, QE ~15%
- Side reflector TTX,coated with TPB 1 mg/cm^2
- PMT coating : evaporated TPB, 0.08 mg/cm^2

The experimental setup, neutron generator



monoenergetic neutron
generator by DD fusion

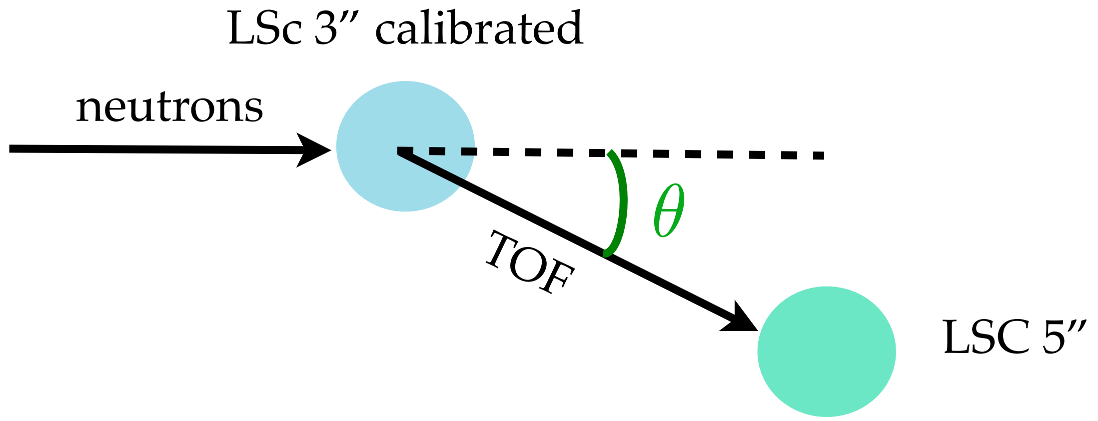
$${}_1D^2 + {}_1D^2 \rightarrow {}_2He^3(0.82\mathrm{MeV}) + {}_0n^1(2.45\mathrm{MeV})$$

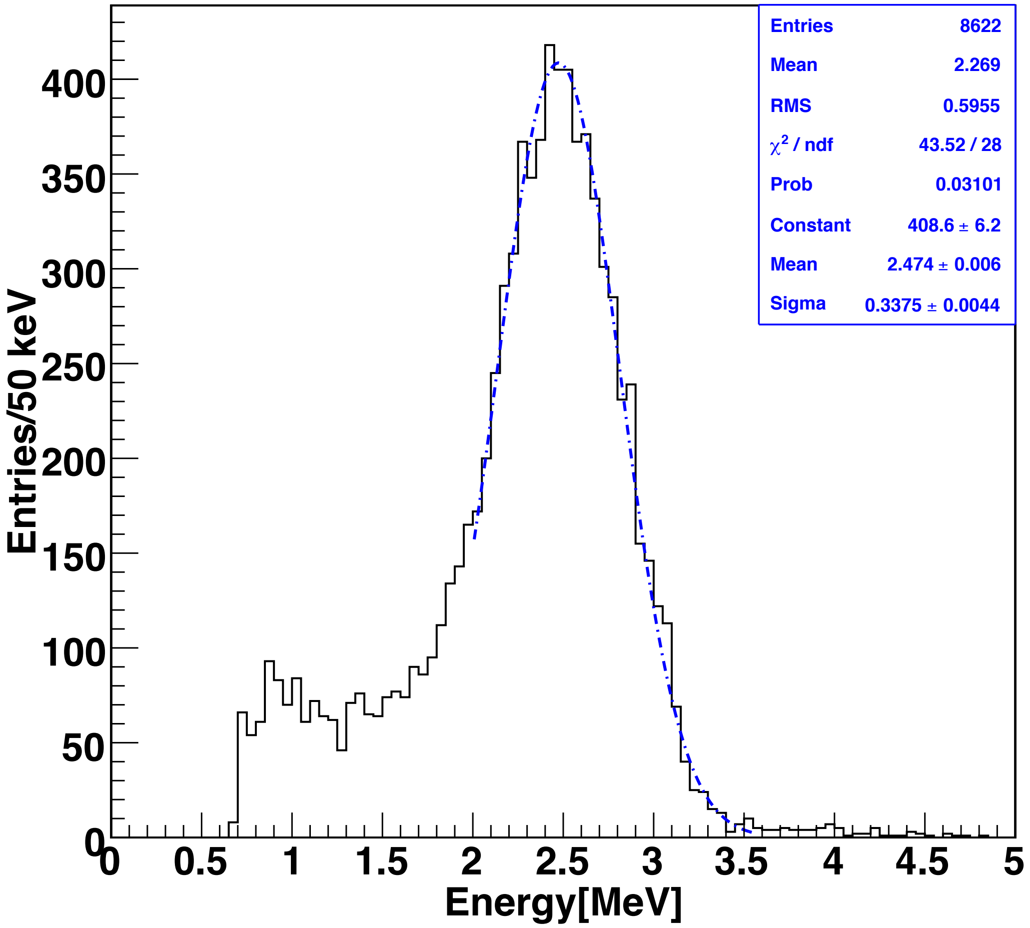
$${}_1D^2 + {}_1D^2 \rightarrow {}_1T^3(1.01\mathrm{MeV}) + {}_1p^1(3.02\mathrm{MeV})$$

NG flux measured ~1 order of magnitude less compared to the rate predicted

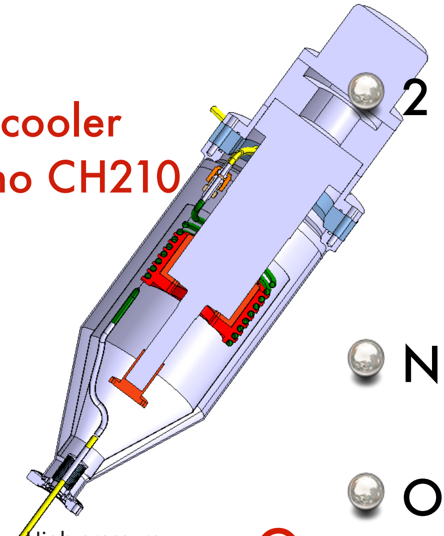
Typical operation 80 kV/10mA $\sim 6 \times 10^5$n/s in 4π

Reconstructed NG spectrum
Edep_LSc3" + E_TOF



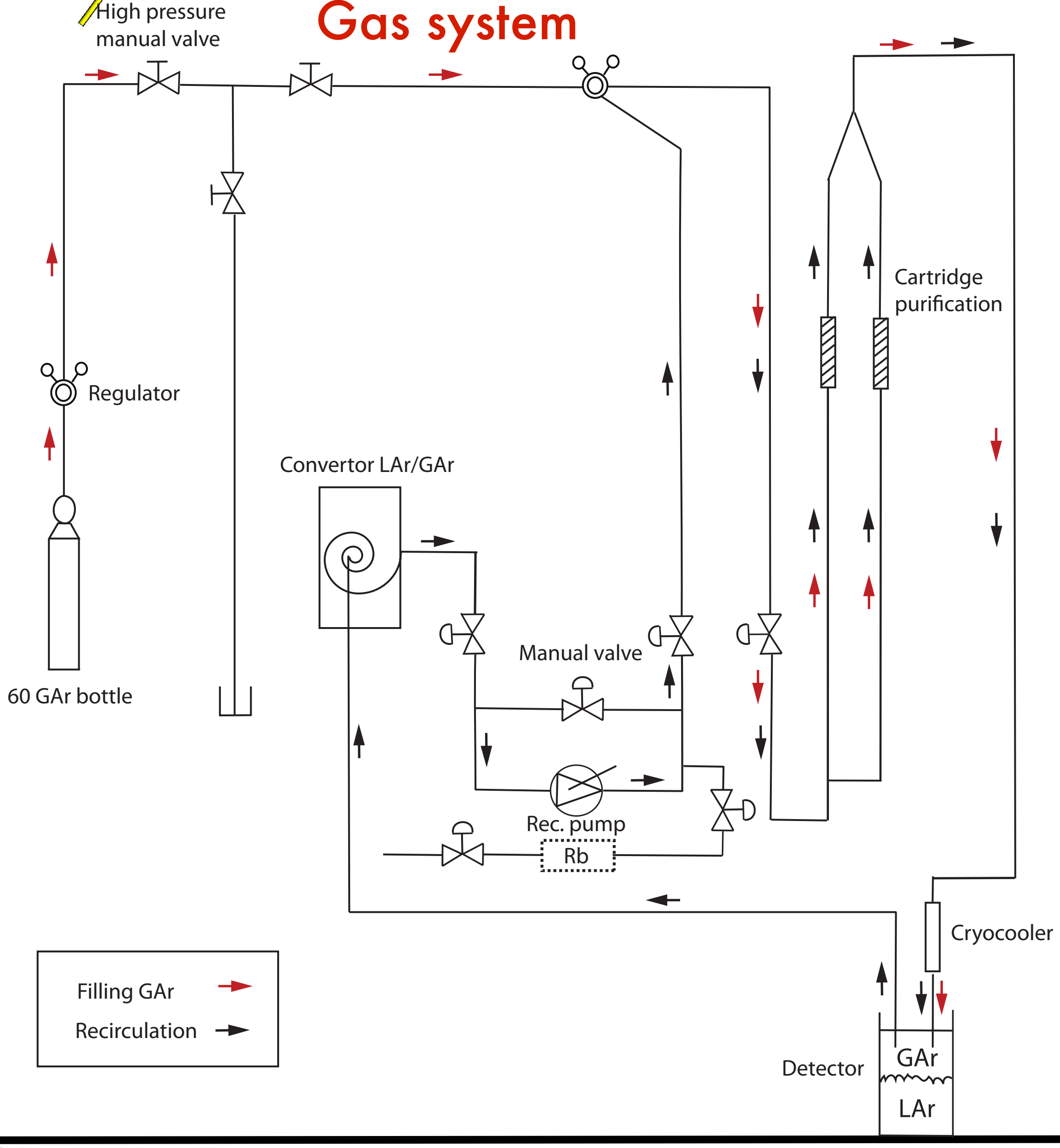


The experimental setup, auxiliary systems

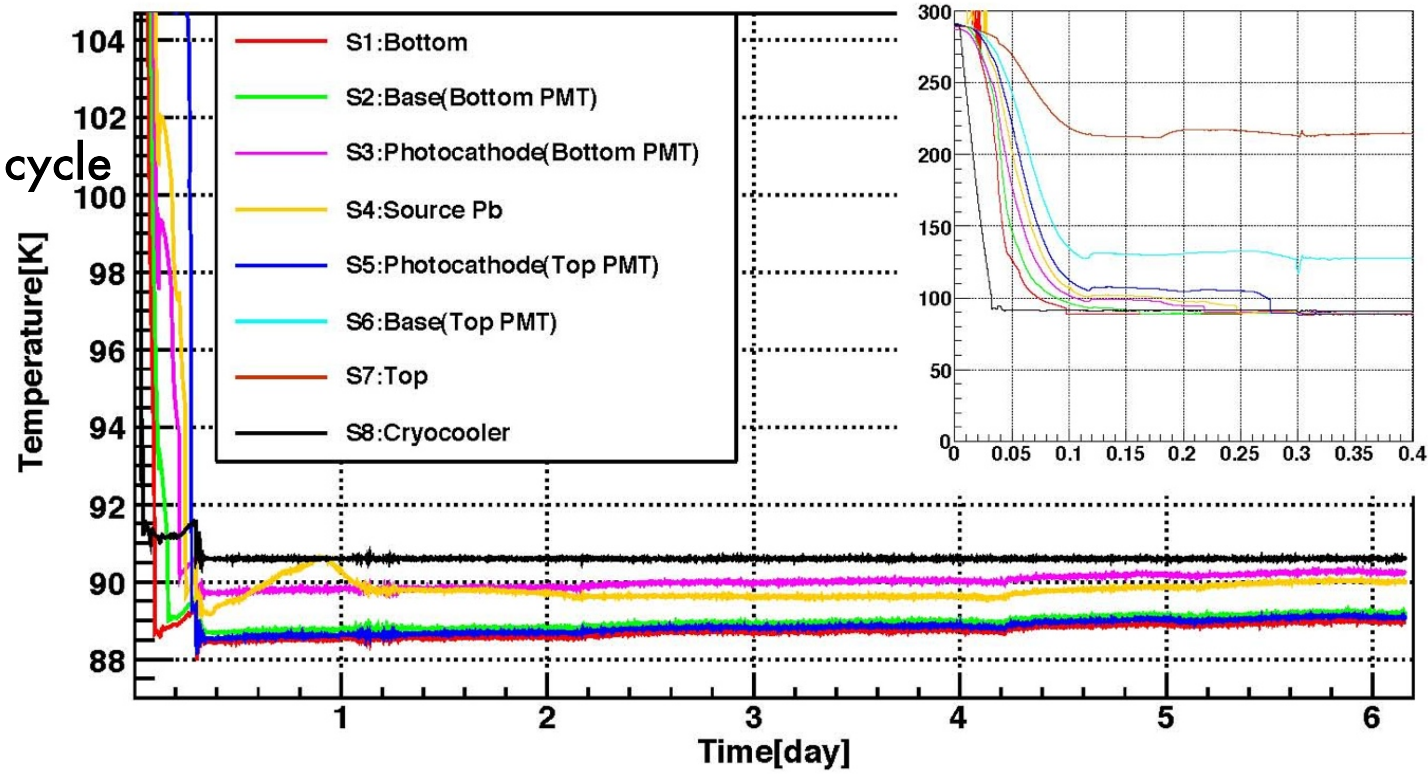


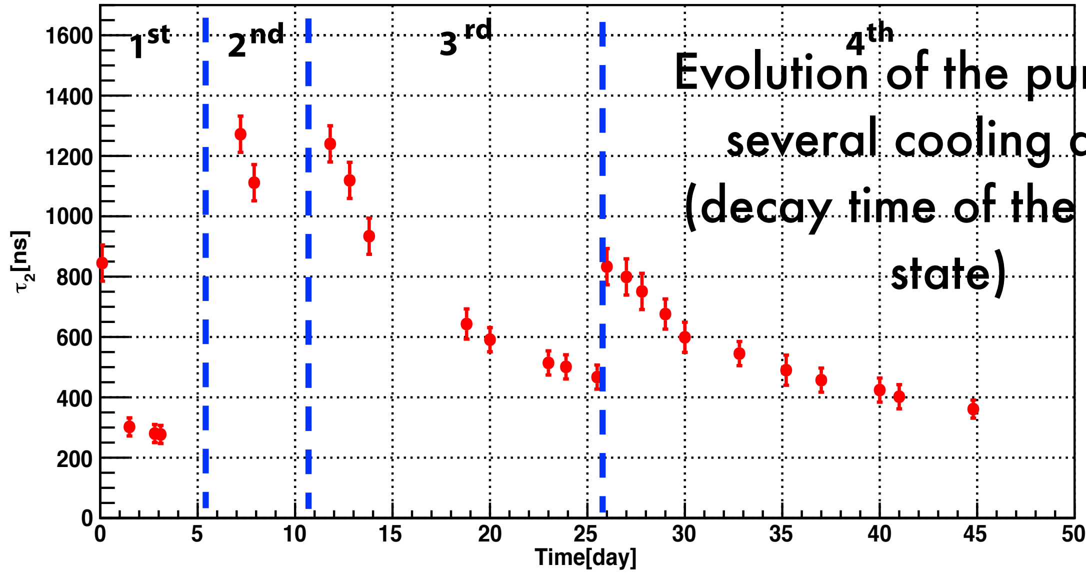
- 2 stages refrigerator:
  - first stage 110 W at 77K
  - second stage 6 W at 20K
- Nominal cooling power 80 W
- Operates on the GM refrigerator cycle

Gas system



- Heaters were placed on the first stage to maintain the boiling point of Ar (88K)
- Good stability of the cryostat (fluctuation ~10mK)



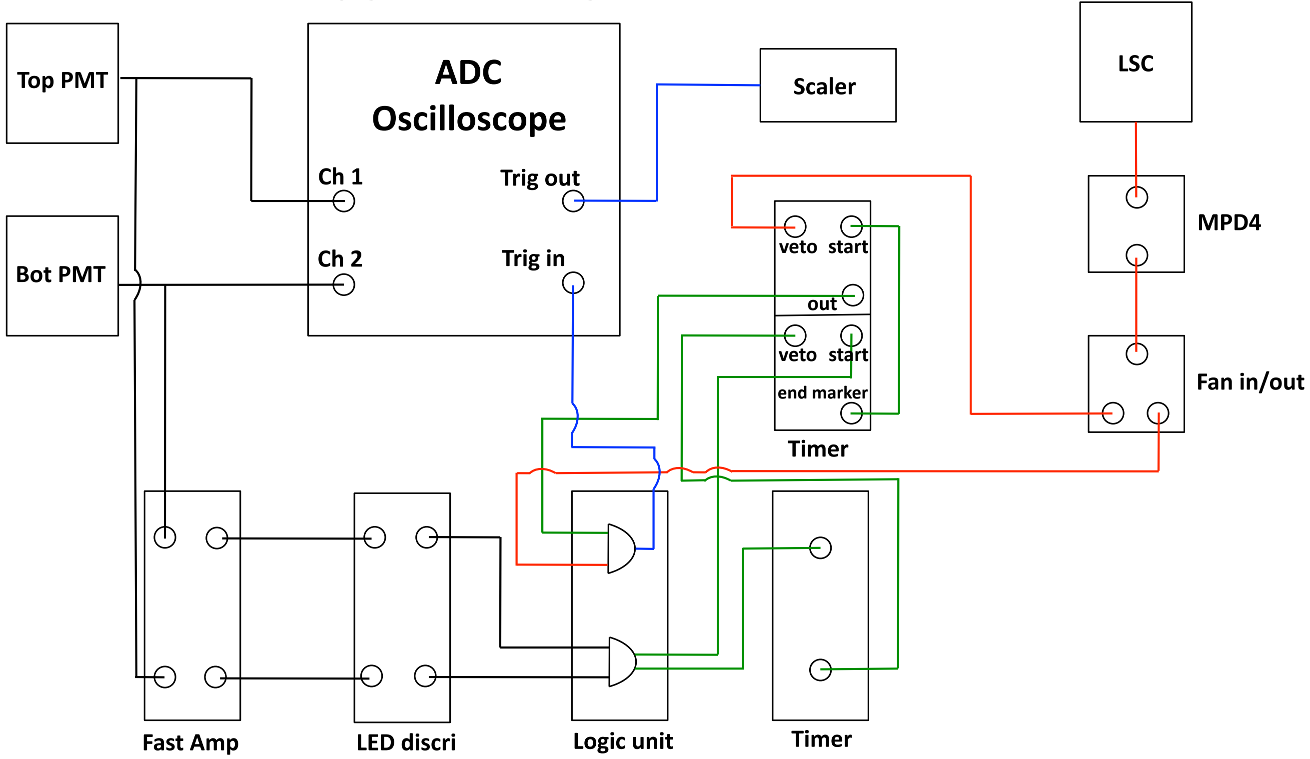


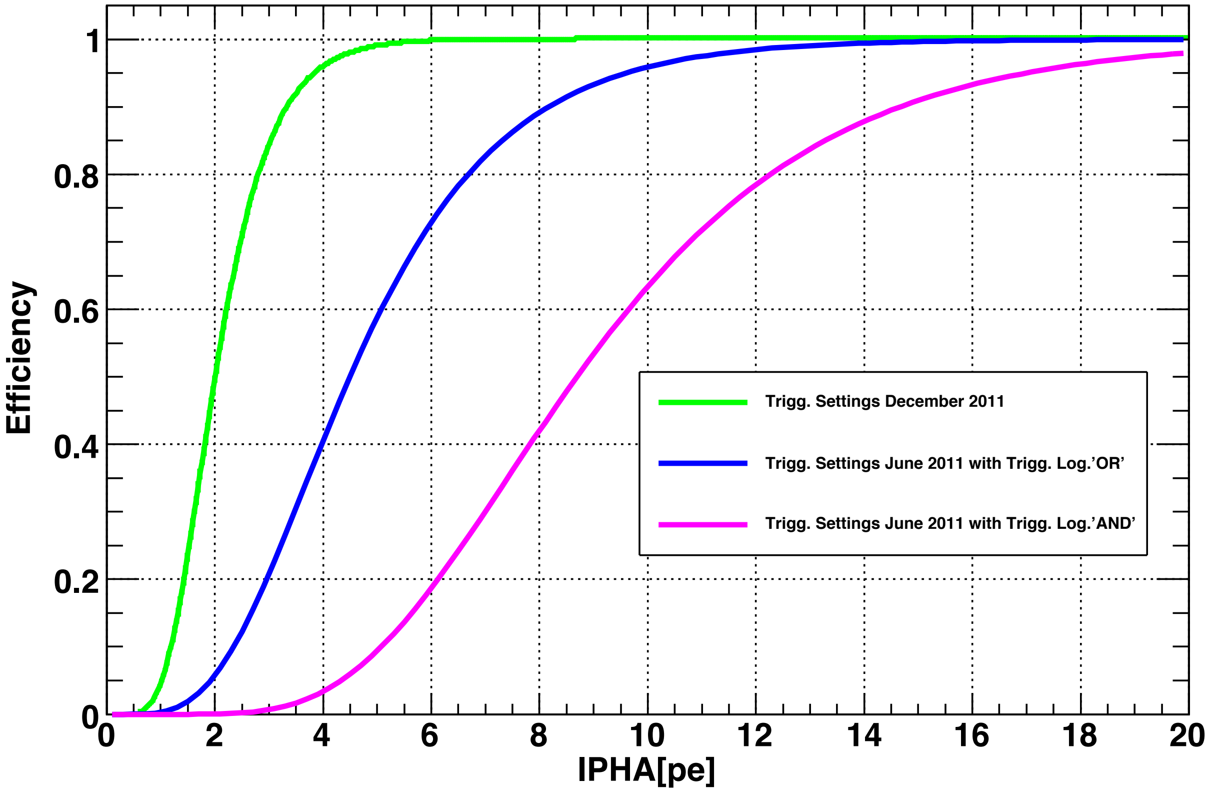
Evolution of the purity for several cooling down (decay time of the triplet state)

DAQ system and trigger

- LeCroy oscilloscope WavePro 35Zi DSO 4 x 1Gs/s 8bit
- Analogue signal split (passive)
- Data recorded with 5000 samples at 1Gs/s
- Trigg. Cond. between PMt's in LAr "OR" or "AND" (only "AND" for december 2011)
- Events accepted if there is a Coinc. signal in LAr "AND" a signal in LSC within a time window <200 ns
- Signal of neutrons in LSC are directly selected by the module MPD4
- MPD4 suitable for a TOF measurement
- In Jul-Aug 2011 trigg. settings was performed using a programable logic trigg. for the signals coincidence
- Trigger efficiency measurement as a function of the integrated pulse height of the prompt light (Scintillation of the singlet states IPHA)

Trigger settings in December 2011



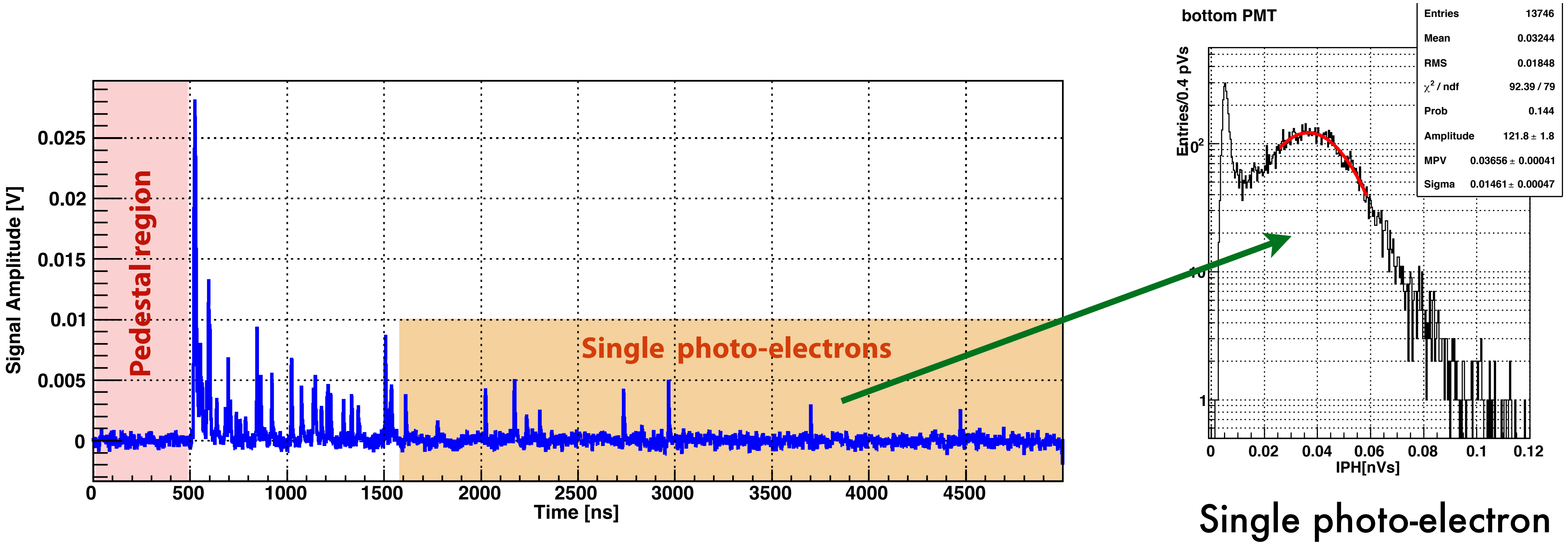


Data reconstruction, SPR

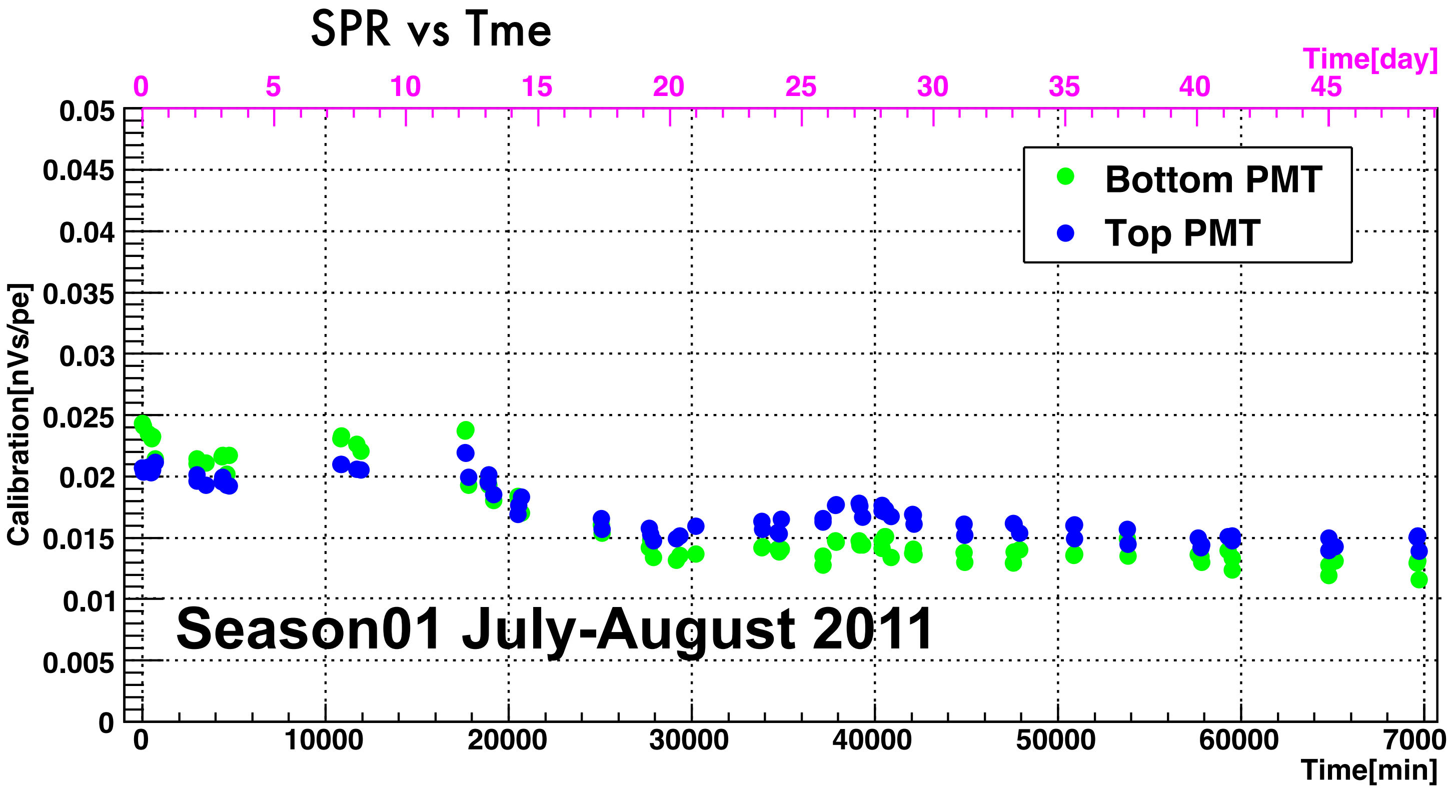
Calibration of Single photo-electron response using a peak finder algorithm on the tail of the signal

MPV of the single photo-elec. response corrected to obtain the mean of the spectrum

The single photo-elec. response during 1month and 1/2 of data taking

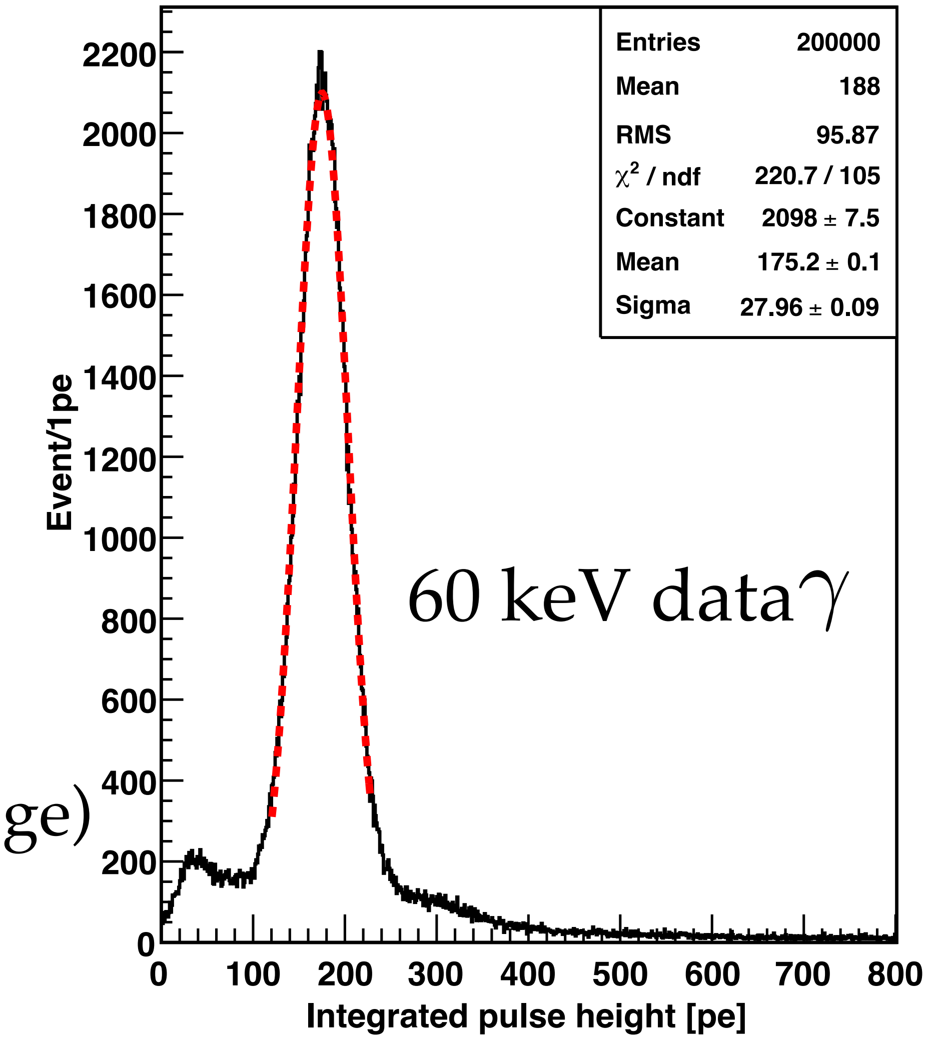


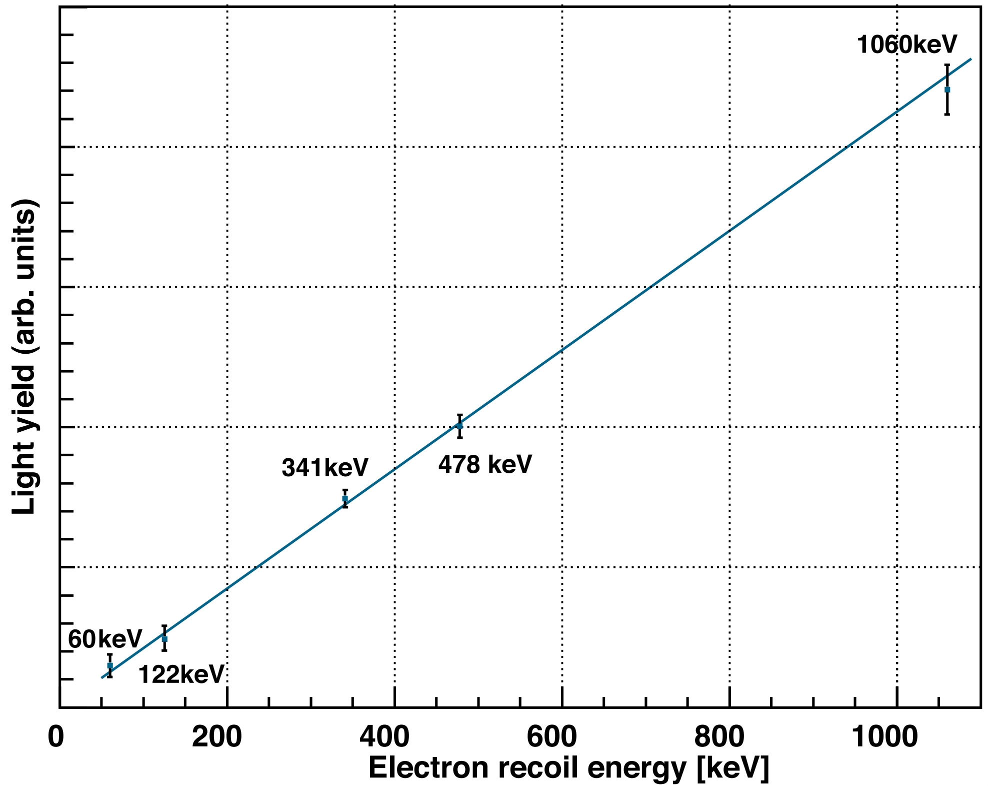
Single photo-electron response distribution

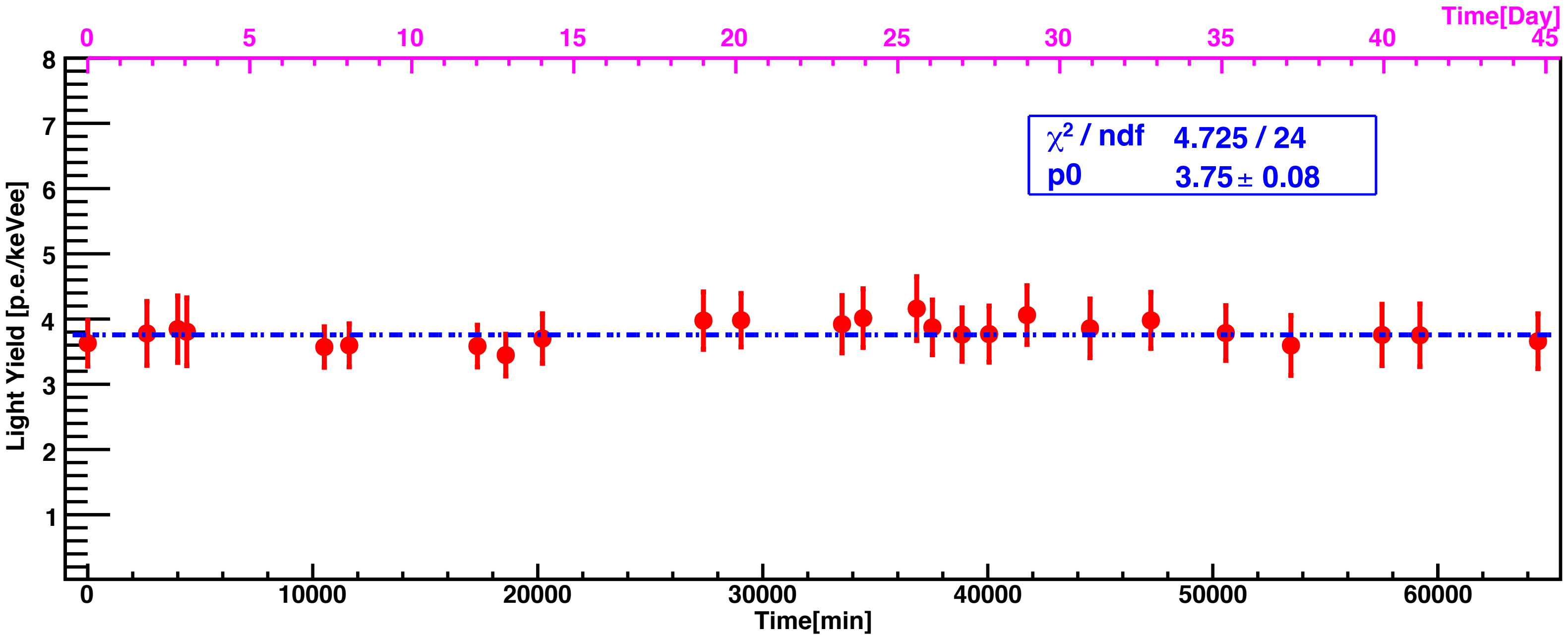


Data reconstruction, Energy calibration

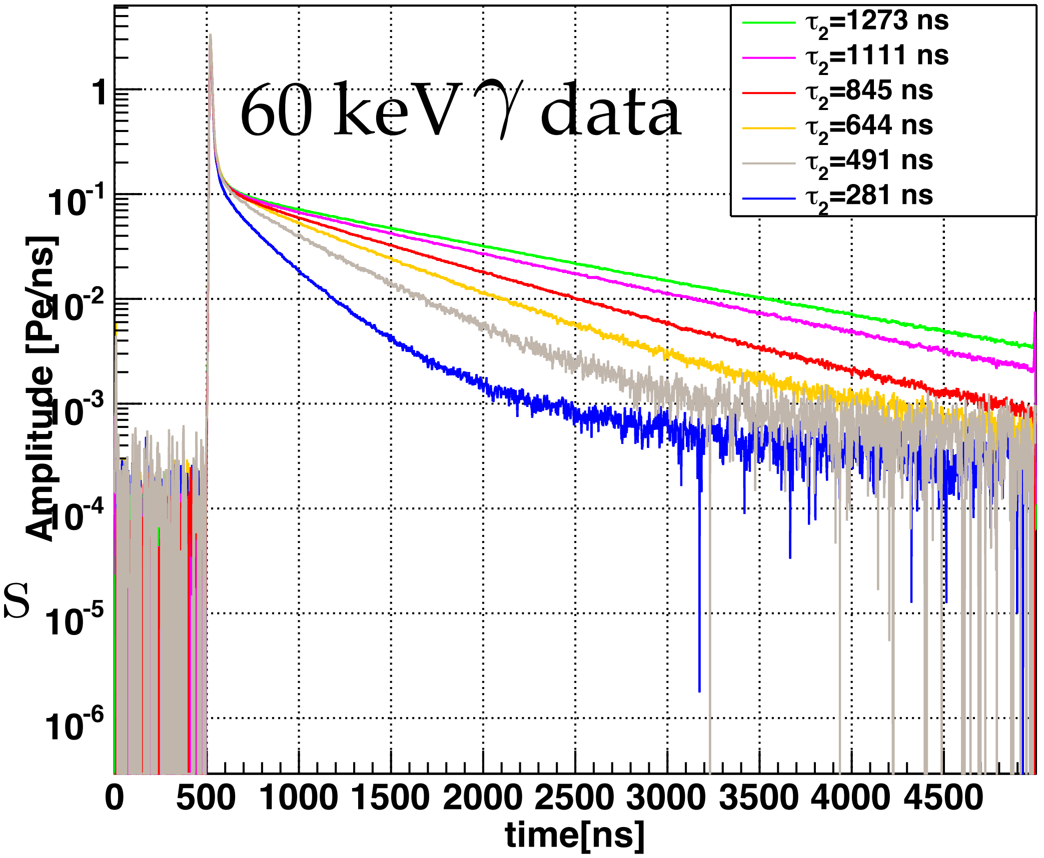
- Energy calibration based on the 60 keV line from the $^{241}\mathrm{Am}$ source
- The Light Yield was corrected for the finite integral and for the scintillation losses caused by the impurities
- L.Y measurement performed periodically
- L.Y estimated at 3.75 p.e./keVee
- Other external sources were employed to check the linearity; $^{57}\mathrm{Co}$ (122 kev photopeak), $^{22}\mathrm{Na}$ (511 and 1275 keV Compton edge) and $^{137}\mathrm{Cs}$ (662 keV Compton edge)







Data reconstruction, Impurity correction



The decay time of the triplet τ_2 decreases with the impurities

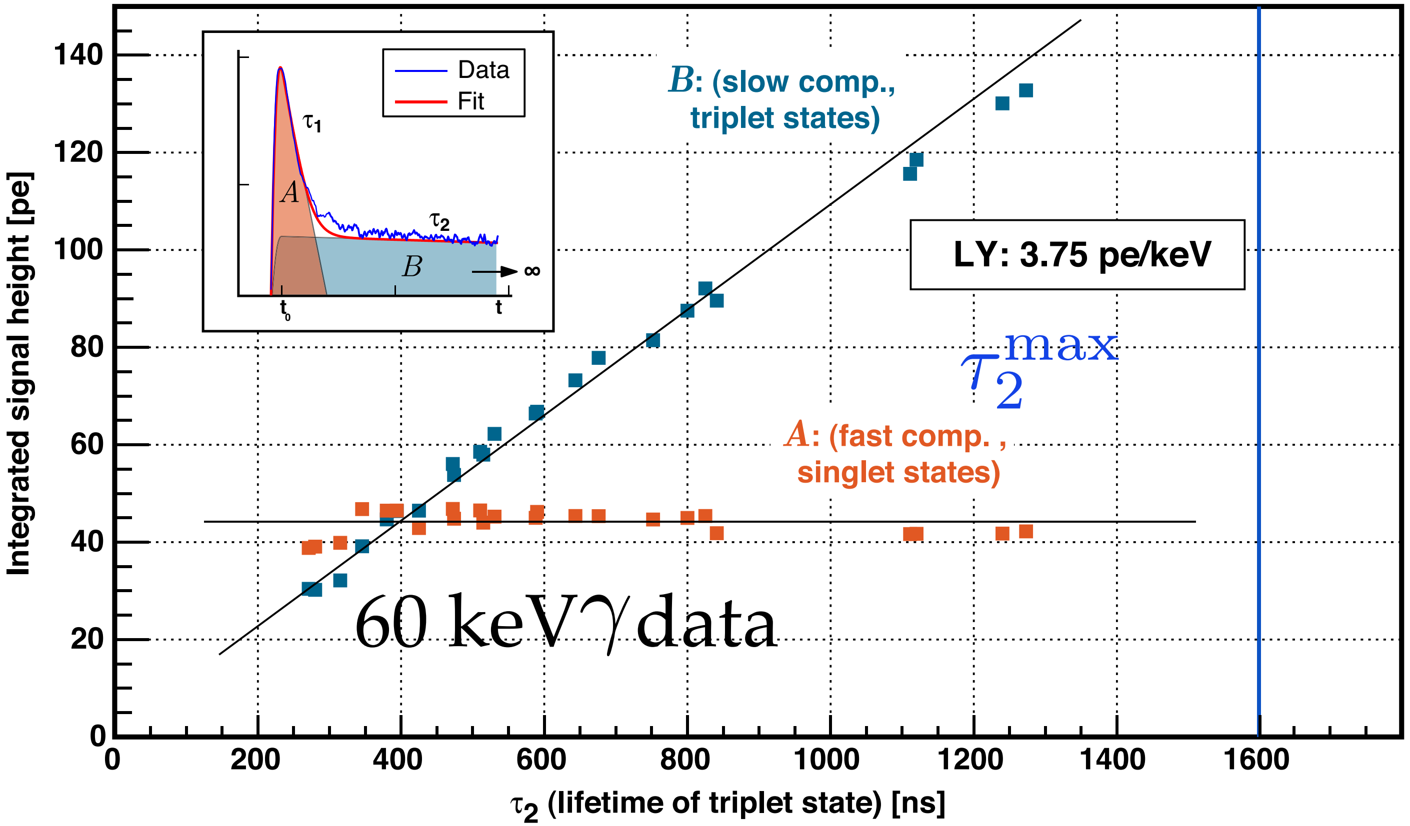
The singlet state A remains unaffected for $\tau_2 \geq 400\text{ns}$

Light yield correction

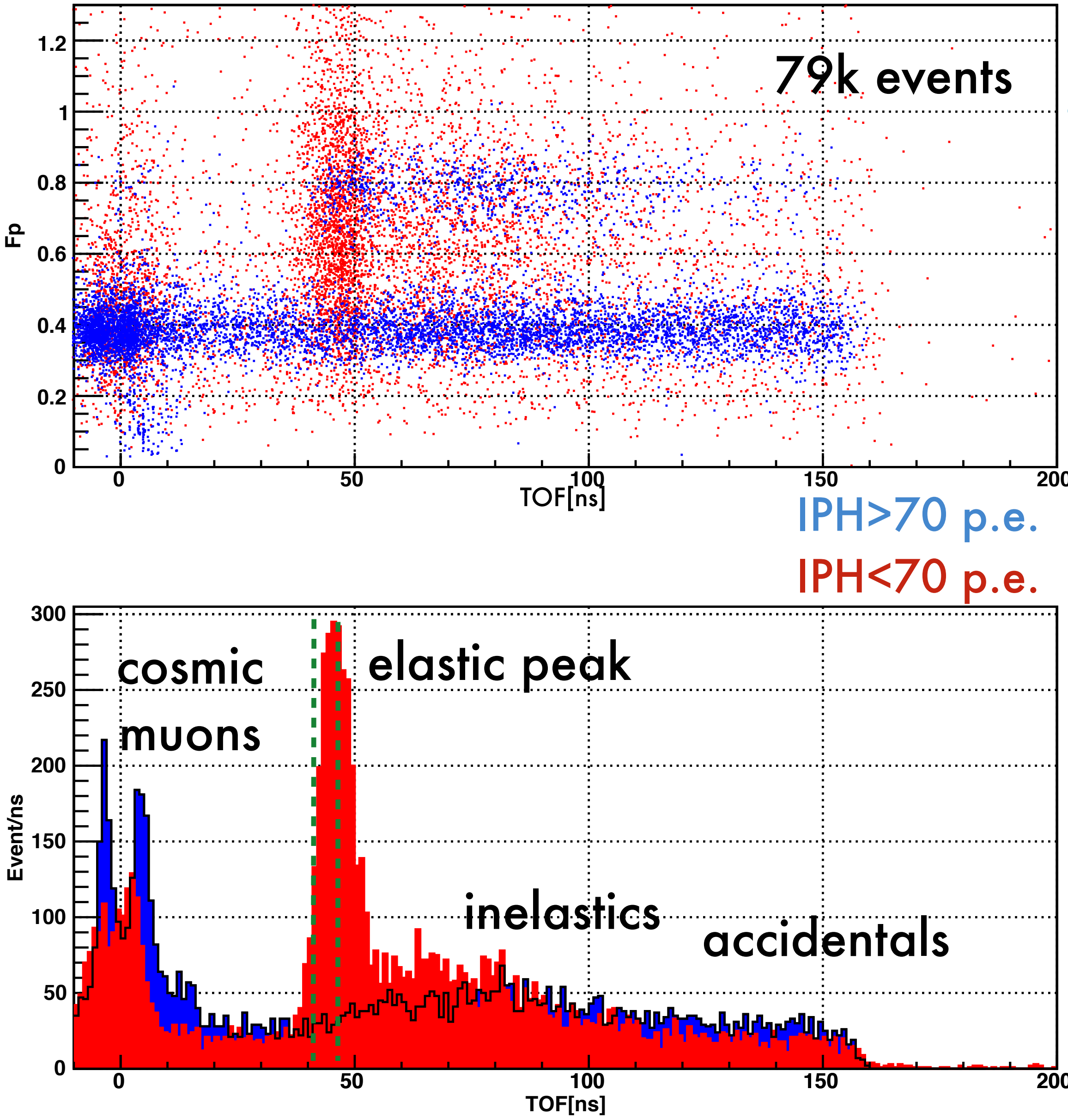
$$Y_{cor} = A + B_{cor} = A + \frac{B}{\tau_2} \cdot \tau_2^{max}$$

From the fit of the average pulse (meantrace) we correct the component ratio and the light from the integral of the singlet state (A≈IPHA) for N-Scatt. Exp.

$$CR_{cor} = \frac{A}{A+B_{cor}} \qquad Y_{cor} = \frac{A}{CR_{cor}}$$



Results



Example at 40 deg (28.49 keVr)

2 main cuts on the analysis:

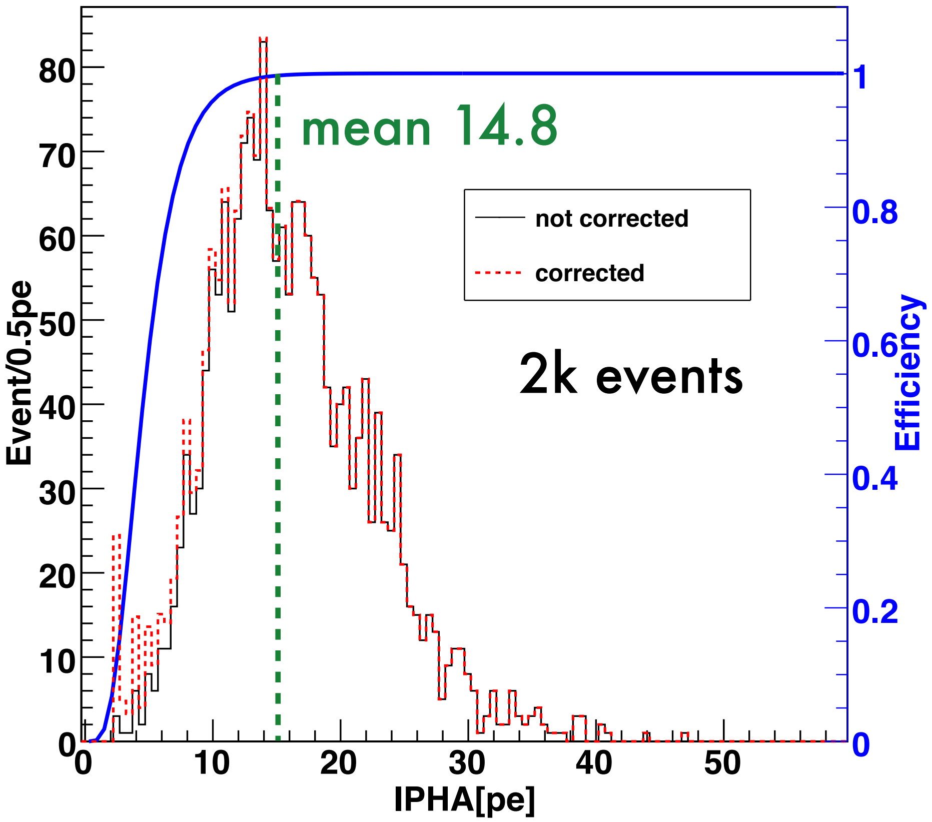
- TOF cut : time window acceptance 5ns around 46ns
- Energy cut: IPH<70 p.e

CRcorr =0.49±0.05 $(\tau_2 \sim 700\text{ns})$

$$A = \text{IPHA} - 7\% \cdot \text{IPHB}$$

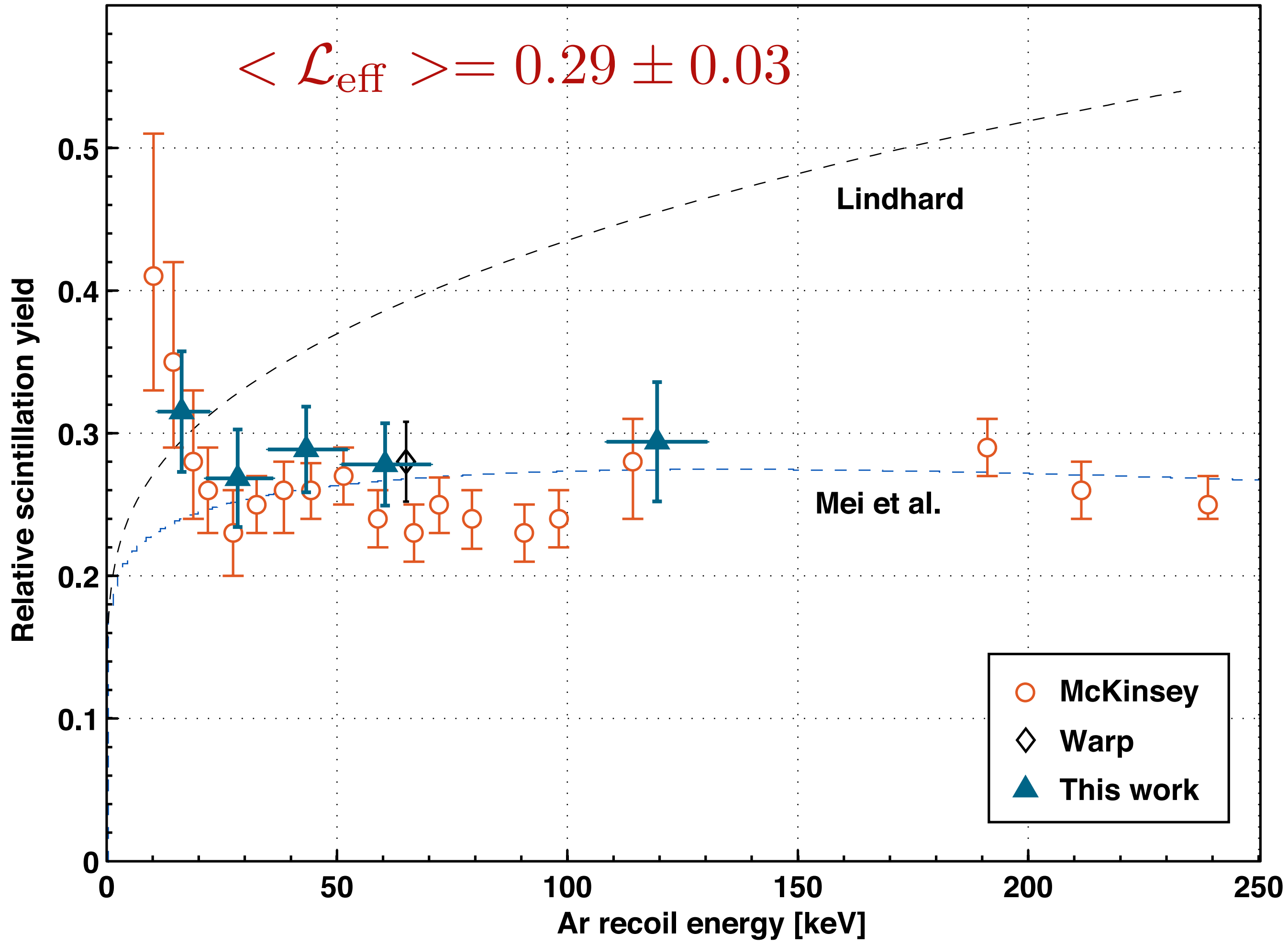
$$Y_{\text{corr}} = \frac{A}{\text{CR}_{\text{corr}}}$$

$\mathcal{L}_{\text{eff}}$= 0.272±0.030



The error of $\mathcal{L}_{\text{eff}}$ is estimated from the reconstruction of A, CR and LY and calculated by the standard propagation law

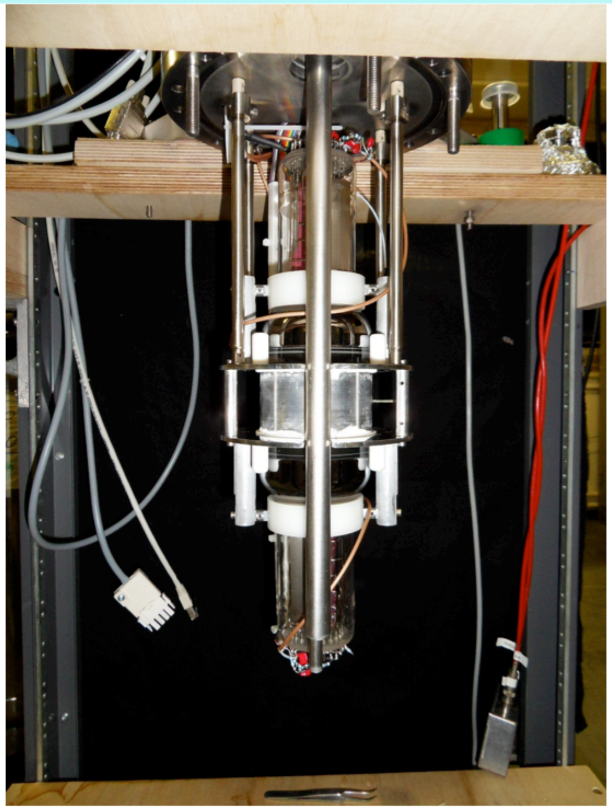
Results

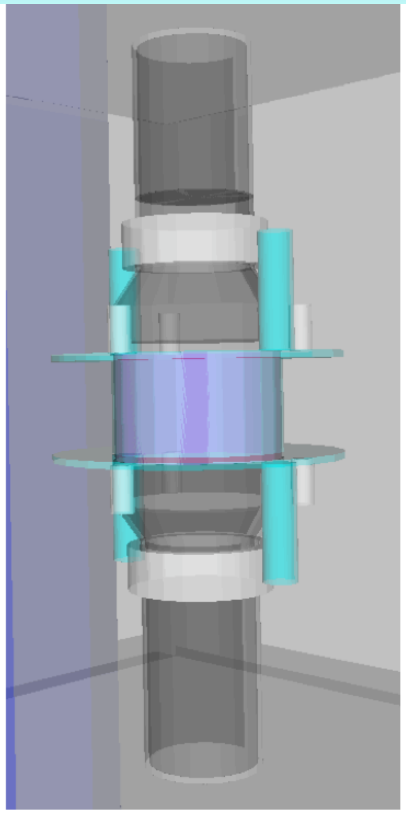


Angle [deg]	Energy [KeVr]	$\mathcal{L}_{\rm eff}$
30	16.36	0.318±0.041
40	28.49	0.272±0.030
50	43.37	0.290±0.022
60	60.50	0.279±0.020
90	119.51	0.295±0.042

In agreement with McKinsey results

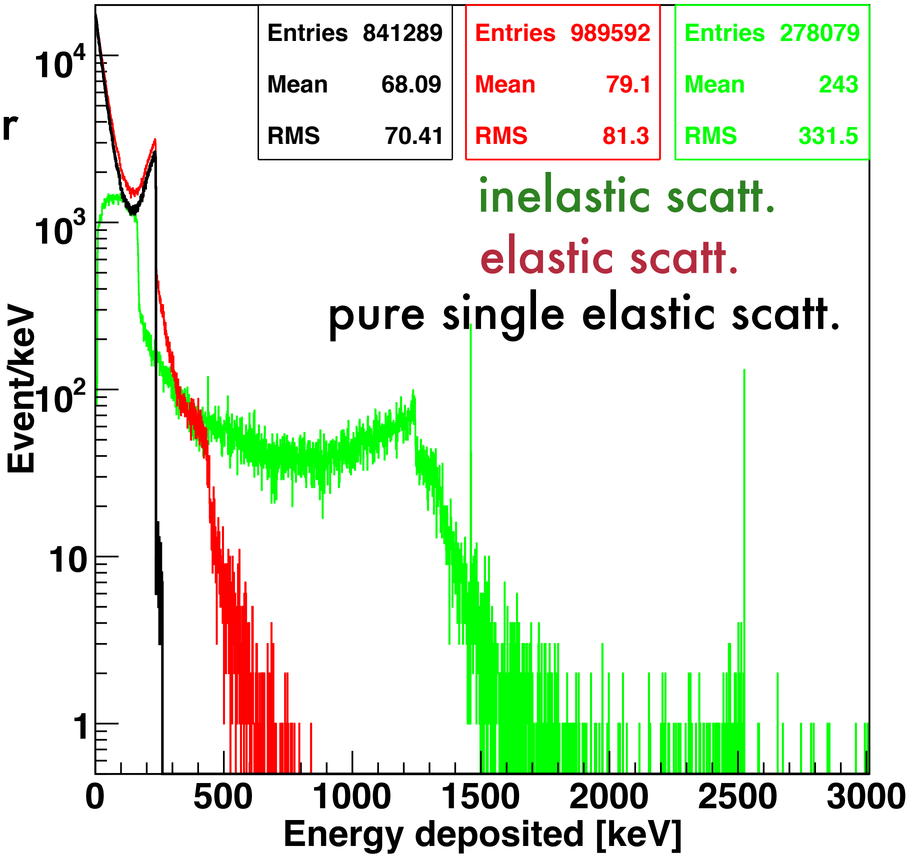
MC Geant 4

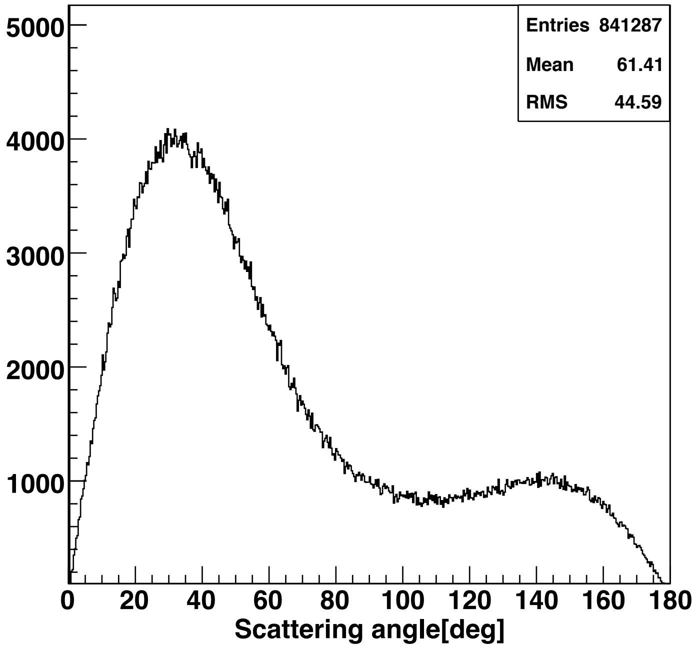




Energy deposited in LAr

28% inelastic
85% pure single elastic
among the total elastic
scatt. events

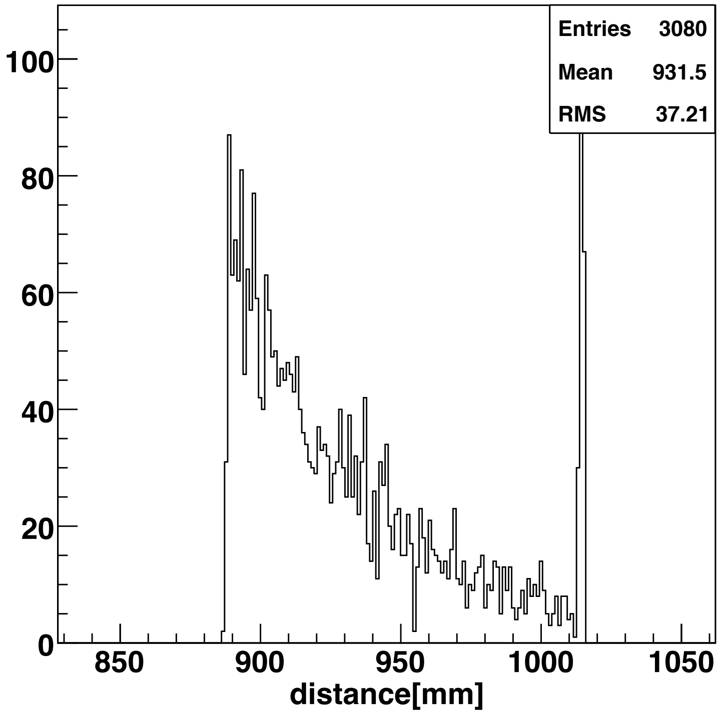




distance between the middle of
the LAr cell and the first vertex
in LSc

mean free path theo. in LSc ~ 4.38 cm
mean free path MC in LSc ~ 5.38 cm

Y.Allkofer+A.Davide Ferella



Outlook

- Finish to apply a better data reconstruction event by event for NR data
- MC/Data comparison
- Upgrade of the set up using 3″ PMTs with 30% QE

Back up slides

Model prediction

- A recoiling nucleus loses energy through inelastic interactions with electrons in the medium (electronic stopping) and elastic collisions with nuclei (nuclear stopping)

$$(\frac{dE}{dx})_{\text{tot}} = \boxed{(\frac{dE}{dx})_{\text{elec}}} + \boxed{(\frac{dE}{dx})_{\text{nucl}}}$$

Ionization
Excitation

Heat
(Thermal motion)

Production of scintillation light

Energy not detectable

f_n: Ionization reduction factor from Lindhard's theory

$$f_n(E_R) = \frac{\int_0^{E_R} (dE/dx)_{\text{elec}} dE}{\int_0^{E_R} ((dE/dx)_{\text{elec}} + (dE/dx)_{\text{nucl}}) dE}$$

- Lindhard's theory describes the ionization for semi-conductors and organic scintillators but not for noble liquid

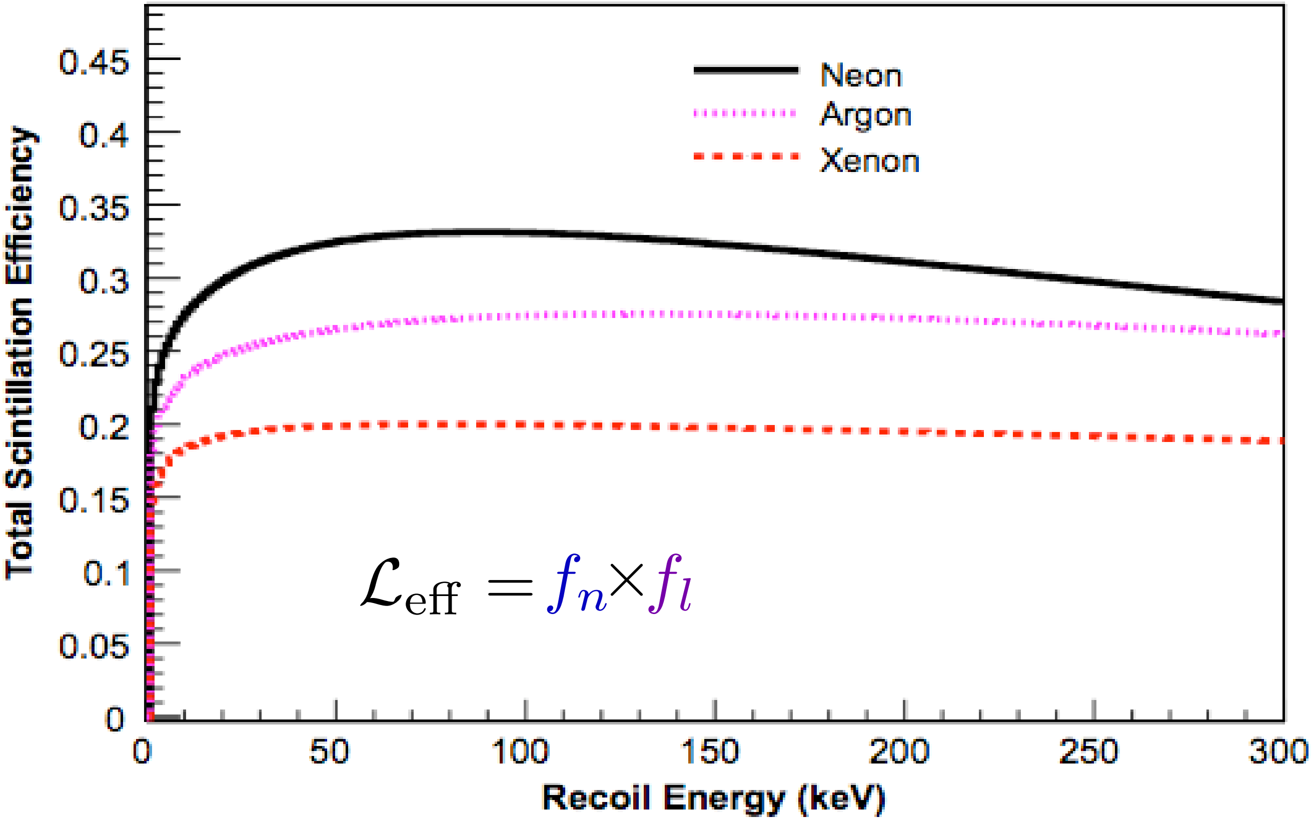
- Hitachi model explaining the reduced scintillation yield due to high Ionization density :
  a charged particle crossing a medium left a track behind core (high ionization density zone) and penumbra (low ionization density)
  - Bi-Excitonic collision ➞ $\text{Ar}^* + \text{Ar}^* \to \text{Ar}^+ + \text{Ar} + \text{e}^-$
  - Penning process ➞ $\text{Ar}_2^* + \text{Ar}_2^* \to 2\text{Ar} + \text{Ar}_2^+ + \text{e}^-$

f_l: Electronic quenching factor

$$f_l = \frac{1}{1 + kB\frac{dE}{dx}}$$

k: collision probability in the core

$B\frac{dE}{dx}$: local concentration of the core proportional to the ionization density

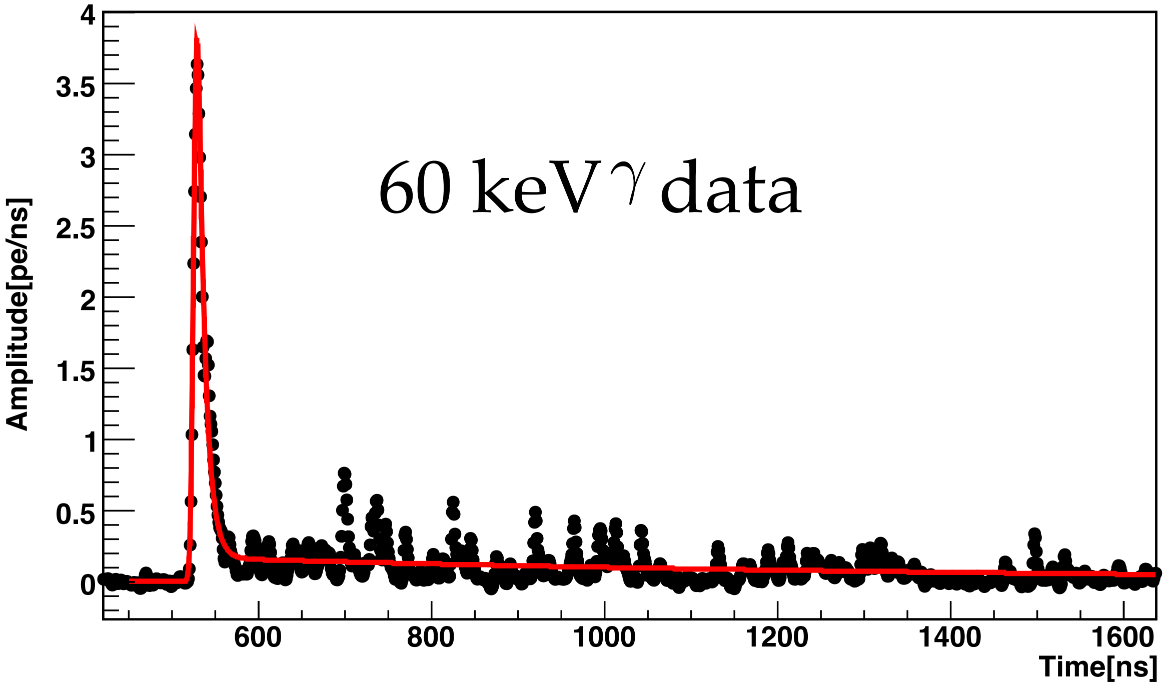


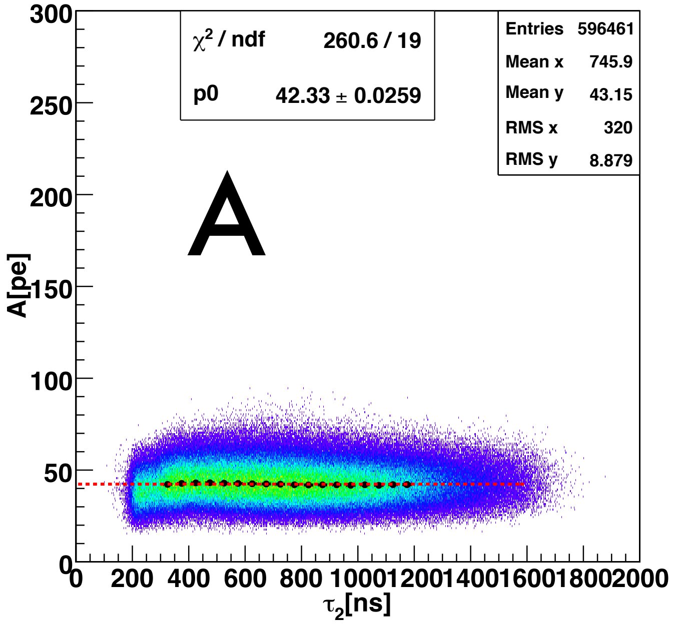
$$\mathcal{L}_{\text{eff}} = f_n \times f_l$$

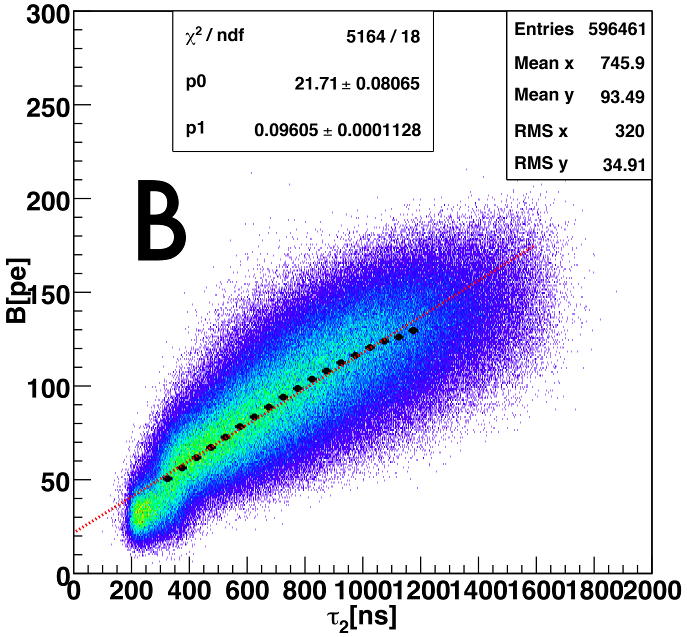
Data reconstruction, Impurity correction

Other technics were investigated to correct the impurity event by event

LL fit on the pulse shape event by event







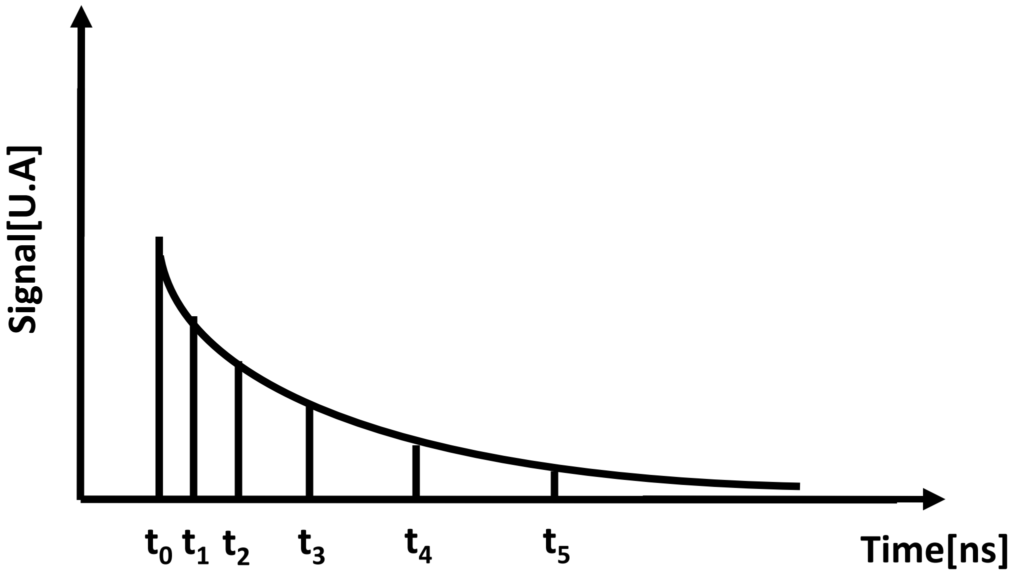
Data reconstruction, Impurity correction

LogBinning method event by event

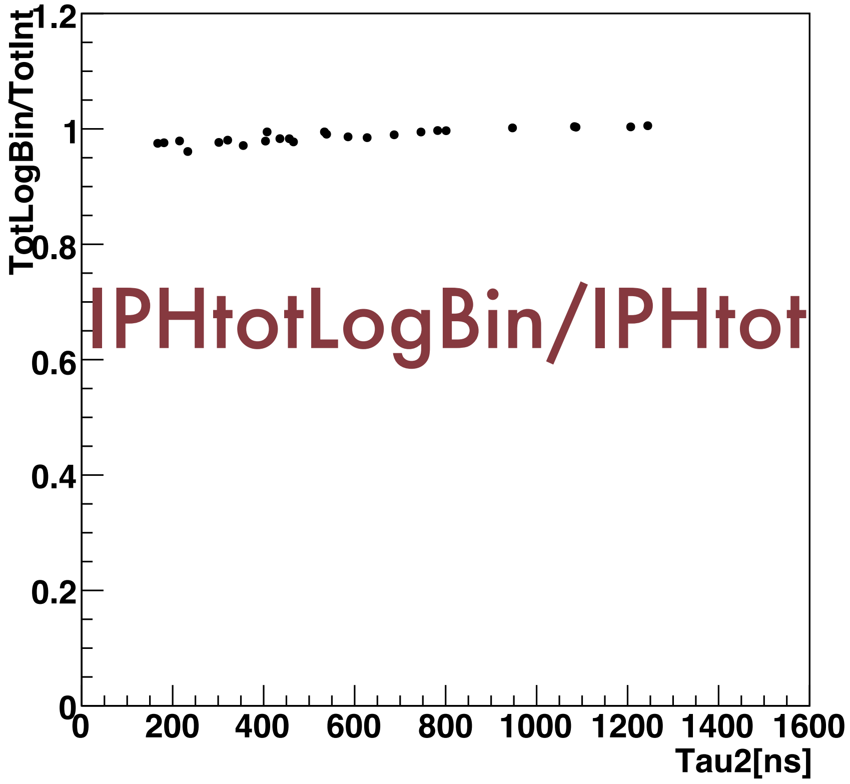
$$t_i = \tau_2 \times Ln\left(\frac{N}{N-i}\right)$$

i: Bin number

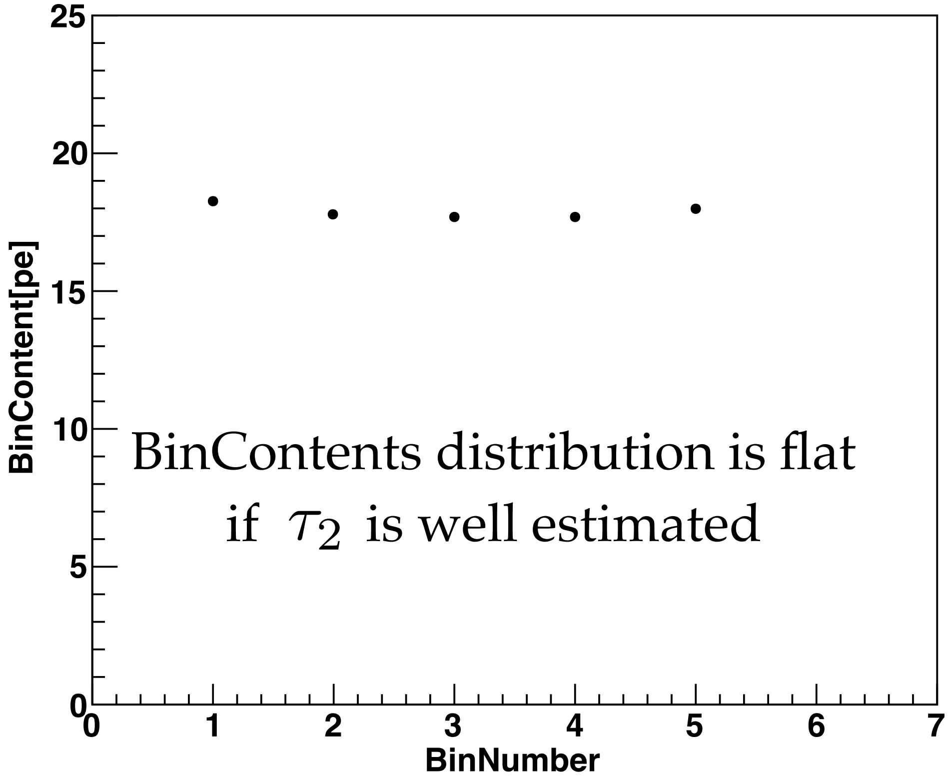
Depends on 3 parameters
N: total number of Bins
t_0: starting time integration
τ_2: life time of triplet states



$$B = \mathrm{Mean}_{\mathrm{BinContents}} \times N$$



IPHtotLogBin/IPHtot



BinContents distribution is flat if τ_2 is well estimated