WArP R&D:
Neutron to Gamma Pulse Shape Discrimination in Liquid Argon Detectors with HQE PMTs

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on behalf of
WArP R&D Group

(based on theses by R. Acciarri & P. Kryczynski)

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Outline

- Pulse Shape Discrimination in Liquid Argon
- First measurements at lower Light Yield
- New measurements at high Light Yield
- Conclusions

Scintillation light in Liquid Argon

- Liquid Argon (LAr) is used in several experiments for the Dark Matter search
- Ionizing particles interacting in LAr create electron-ion pairs (Ar^+-e^-) and excited molecular states (Ar_2^* excimer in Singlet or Triplet state)
- Both the processes lead to the formation of excited dimers wich produce VUV scintillation radiation through de-excitation processes ($Ar_2^* \rightarrow 2Ar+\gamma$)

$$\ell(\ ) = \frac{}{\tau}\exp\frac{}{\tau_S} + \frac{A_T}{\tau_T}\exp\frac{t}{\tau_T}$$

$$\tau_S\left({}^1\Sigma_U\right) = 5 \div 7 \quad ns$$

$$\tau_T\left({}^3\Sigma_U\right) = 1300 \div 1600 \quad ns$$

$$\int \ell(t)dt = A_S + A_T = 1$$

The ratio A_S/A_T depends on the ionizing particle

+ a visible intermediate component with

$\tau_\iota \sim 60$ ns

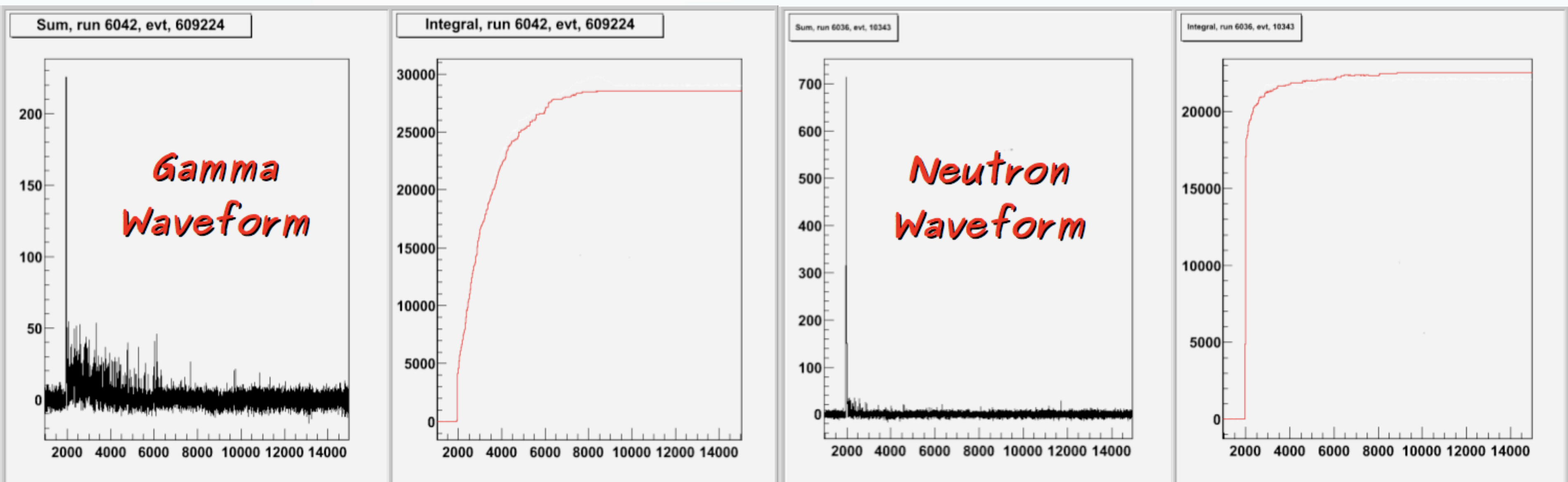
Pulse Shape Discrimination in LAr

- $A_S/A_T=1/3$ for electron recoils → "Slow" Signals

  (β and γ interactions)

- $A_S/A_T=3/1$ for nuclear recoils → "Fast" Signals

  (n and WIMP interactions)



The first test

- Within the WArP R&D phase exploratory studies have been performed with the aim of **studying** and **optimizing** of **PSD** to maximize β and γ background rejection in LAr detector:
  - Applying, developing and comparing different PSD techniques and their discrimination powers using LAr detectors/prototypes: the "**F-prompt**" method (see next slides) resulted the most appropriate among those taken into consideration
  - Optimizing the "**F-prompt**" method through analysis of real and simulated data

- A single phase LAr detector equipped with ETL PMTs and characterized by a "lower"/modest Light Yield (~1.5 *phel/keV$_{ee}$*) has been used (no electric fields)

- Signals from PMTs directly acquired by waveform digitizer (**AcqirisU1080A**)
  - 3.2×10^6 events acquired with a γ-source (^{133}Ba) for energy calibration and LY determination
  - 8.5×10^6 events acquired with an Am/Be source with 3% of neutron events

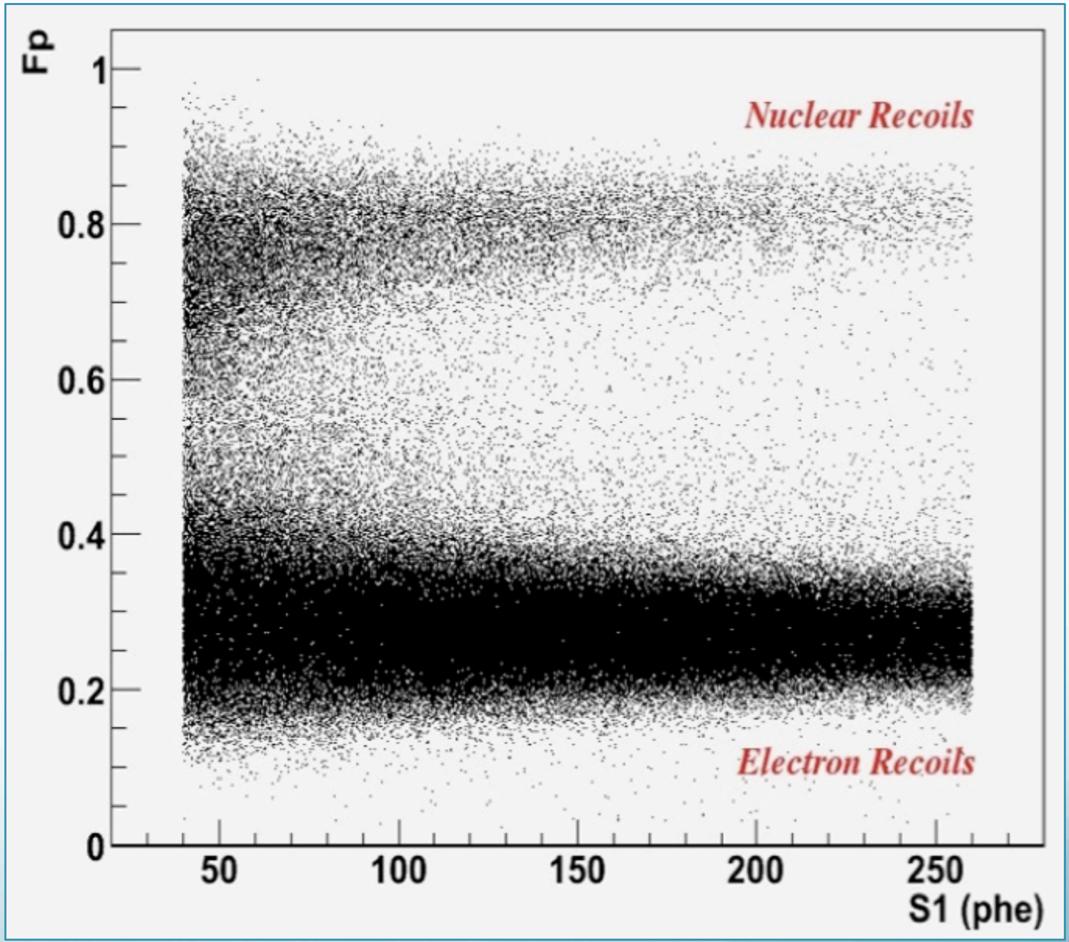
- Sensitivity and discrimination power for a DM detector based on LAr scintillation light have been estimated

F-prompt technique

- The F-prompt (Fp) method is the most common technique to quickly discriminate electron recoils from nuclear recoils

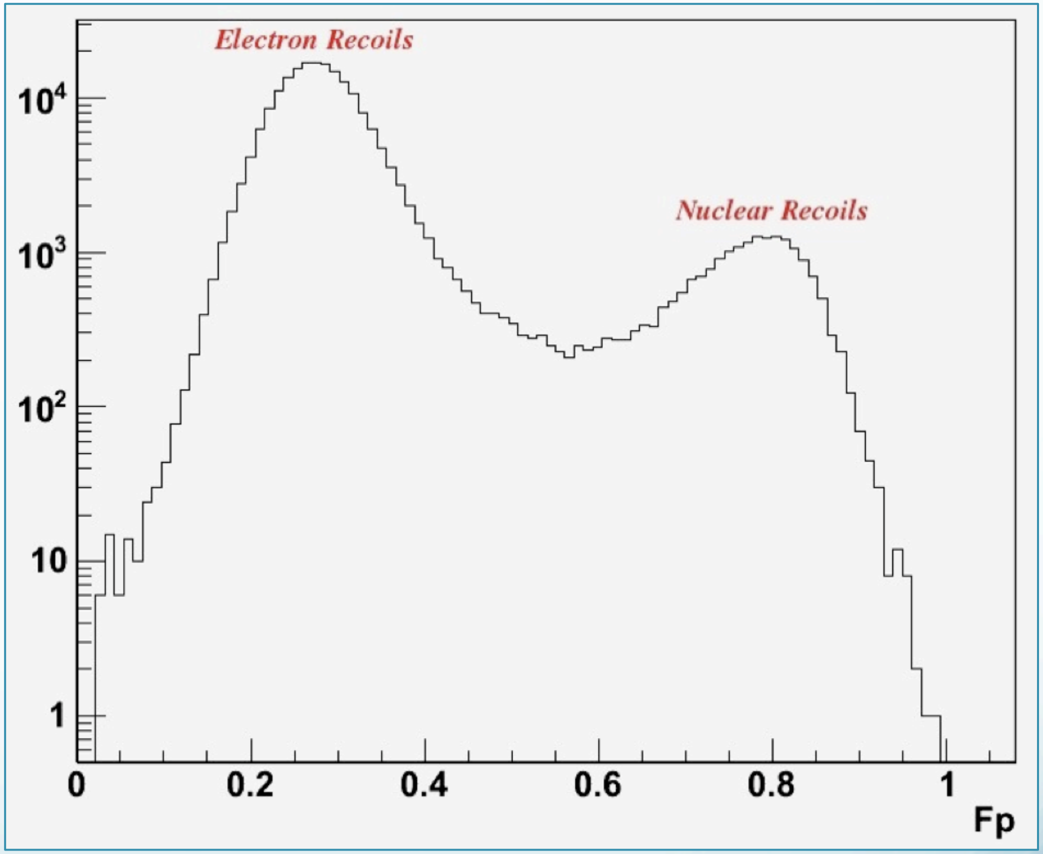
$$Fp = \frac{\int_{T_i}^{T_{Fp}} V(t)\,dt}{\int_{T_i}^{T_f} V(t)\,dt} = \frac{S_F}{S1}$$

- V(t) Signal Sum
- S_F "Fast Integral"
- S_1 "Total Integral"



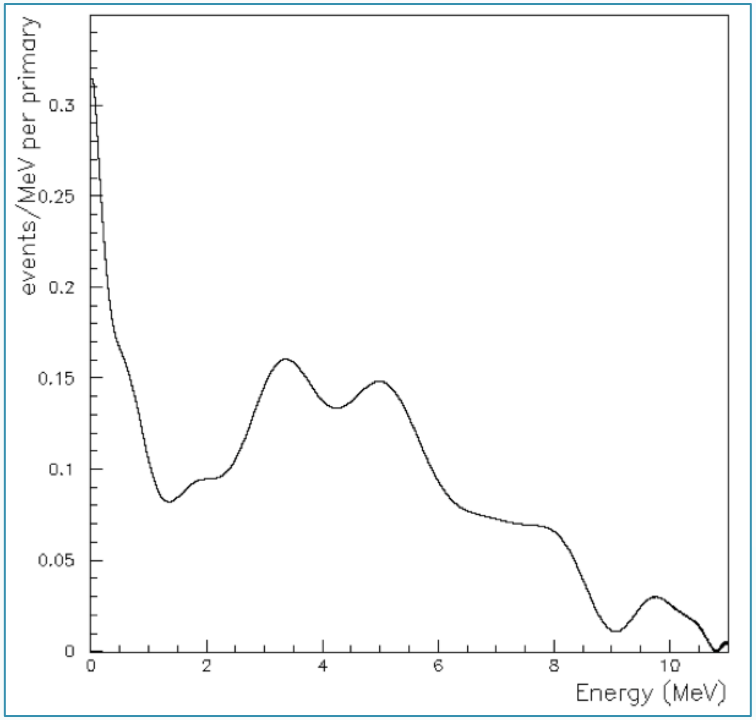
Intermediate events

- The presence of a third population of events with $Fp_{\gamma} < Fp_{i} < Fp_{n}$ has been detected
- MC simulation of the detector exposed to the Am/Be source has been performed to determine the origin of the intermediate component and to set the most appropriate Fp fitting function
- This population is ascribed to **inelastic scattering** of neutron on Ar nuclei

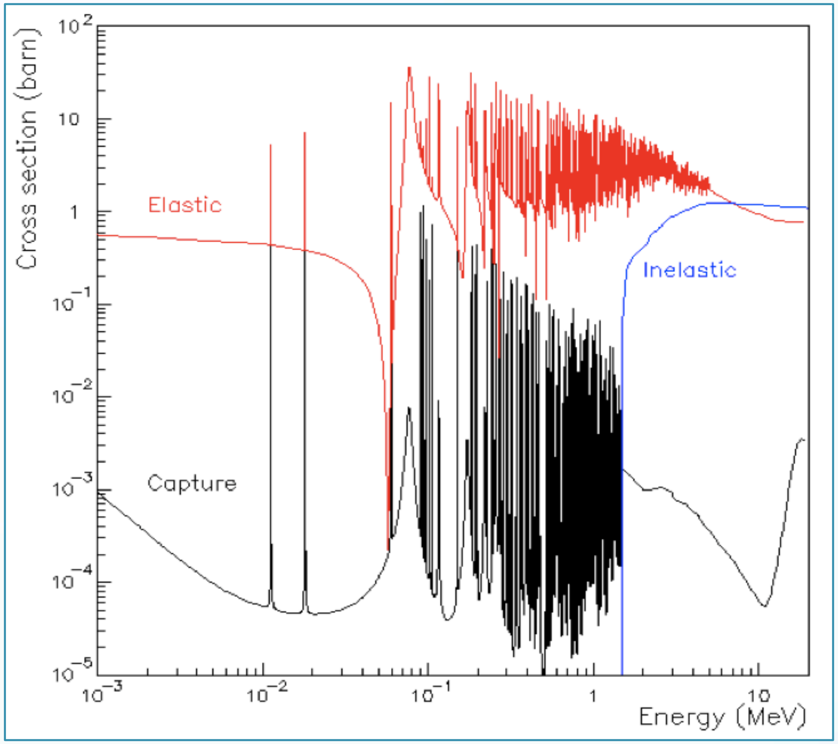


Raw Fp distribution from Am/Be source exposure

Neutron spectrum and cross section



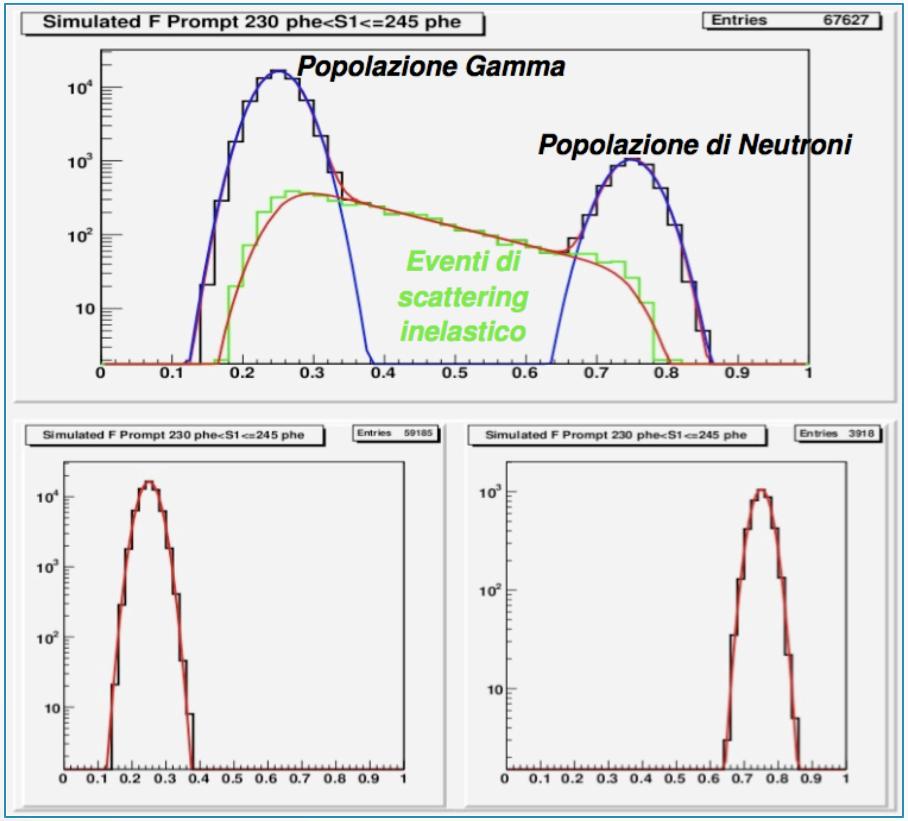
Primary Am/Be spectrum

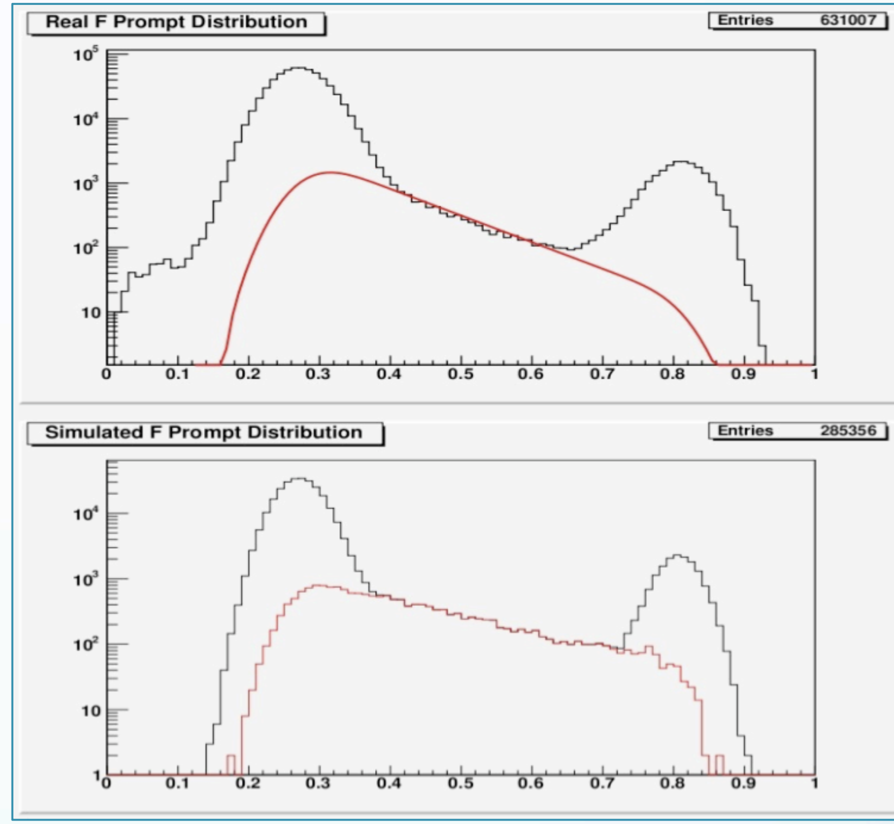


Neutron cross section on ^{40}Ar

	Mean free path in LAr (cm)	Total cross section (barn)	Elastic cross section (barn)	(n,n'γ) cross section (barn)	(n,X) cross section (barn)
2.4 MeV	8.5	5.56	4.98	0.58	-
5.0 MeV	14.5	3.29	1.81	1.48	-
14.2 MeV	20.8	2.28	0.79	0.64	0.85 (n,2n)

MonteCarlo simulations

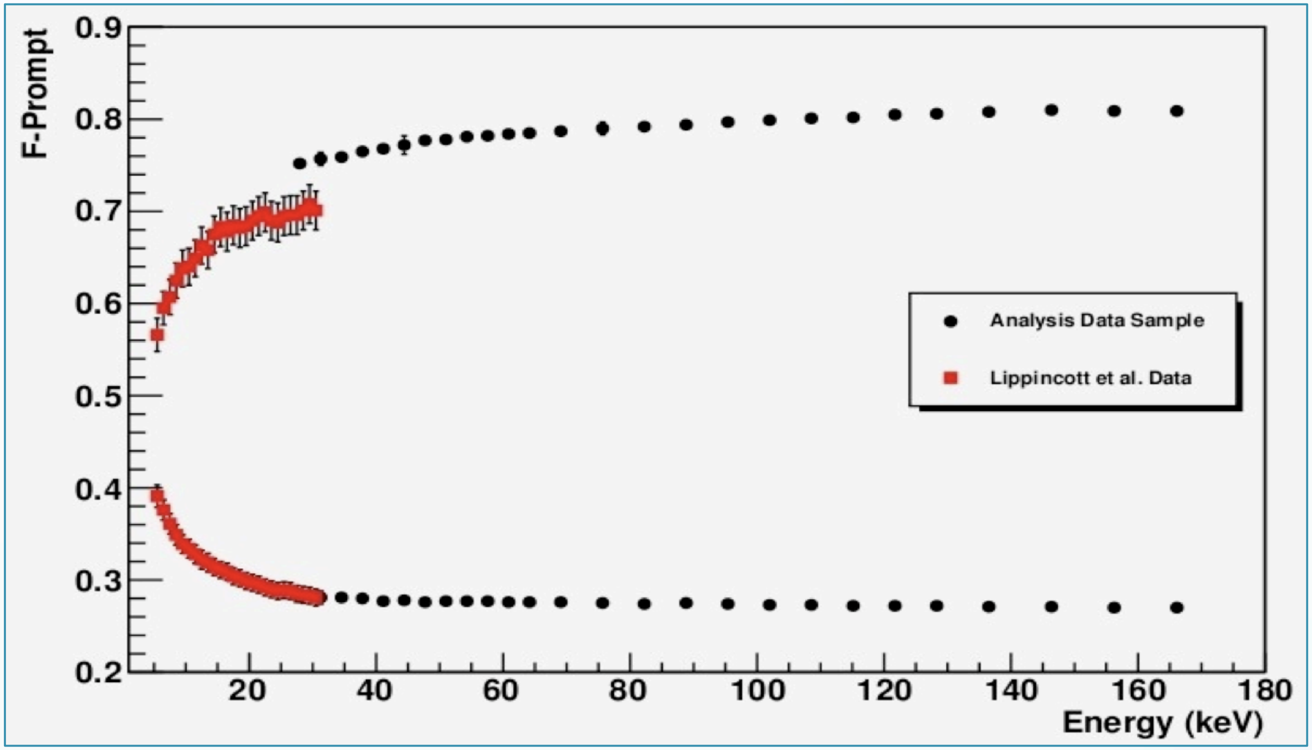




- Intermediate populations of events originated by inelastic scattering of neutrons on Argon nuclei
- The suitable fitting function able to reproduce the total Fp distribution is given by: $F_{tot}(t)=G_{\gamma} + G_{n} + (Exp \times G)_{int}$

Neutron to gamma separation

Improvement of the separation is achieved through:



- Optimization of the integration time T_{Fp} (parameter of the Fp definition)
- Taking account of the intermediate population via the Fp distribution fitting function

Our first set of data was limited at the low energies by the modest LY characterizing our detector (ETL PMTs)

The new test

As part of the experimental test with the 4 lt chamber at LNGS equipped with HQE PMTs (**Hamamatsu R11065**) – [reported in **E. Segreto's talk**] (High Light Yield - LY):

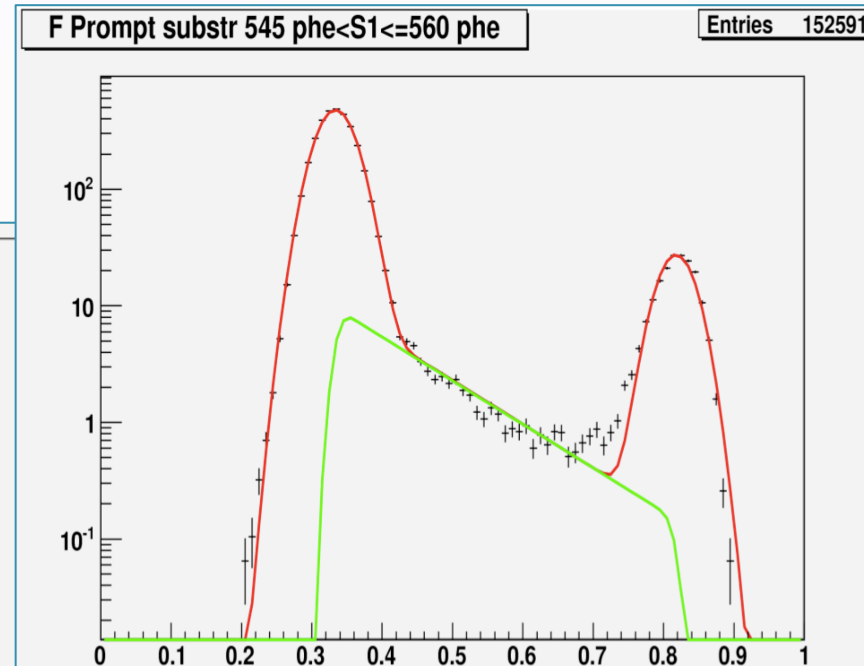
- The chamber was again radiated with an Am/Be source to test the signal-to-background separation capability obtainable in particular at lower recoil energies
- Due to the new DAQ set-up and high LY (in the 6 *phel/keV*$_{ee}$ *range*) [**E. Segreto** & **A. Szelc** presentations] the analysis is extended (compared to our previous tests) into a much wider energy range
- Sensitivity and precision of the measurement **improved** when compared to the first test.

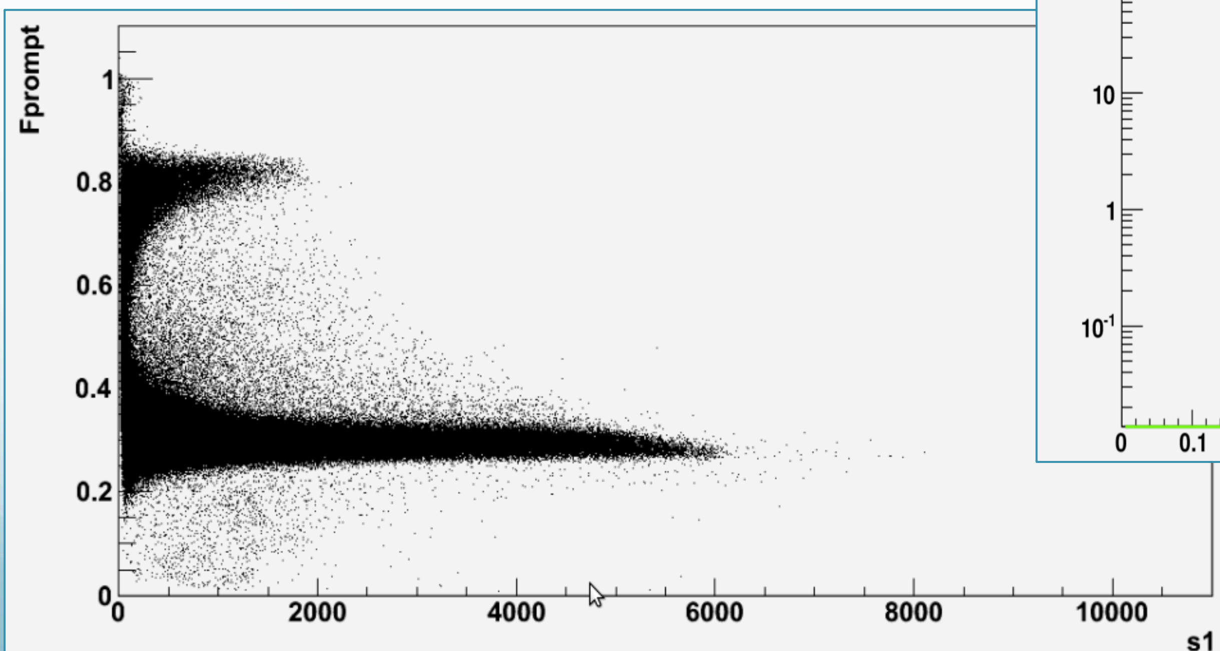
New data sample

- No electric field applied to the LAr active volume (same LAr volume as before - about 4 lt)
- Much Higher Light Yield (6.35 phel/KeV_{ee} – [E. Segreto's talk])
- Signals from the 4 PMTs directly acquired by means a new fast waveform digitizer (**CAEN V1751**) [A. Szelc talk]
- Much higher statistics: 30 milion triggers (Am/Be events) acquired with ~7% of neutrons compared to ~3.5 % in previous work (due to low energy n-events and optimized n-source positioning)
- Improved background subtraction with the new DAQ system
- Data taken in a relatively short period (~1.5 days)

First results with the new set-up

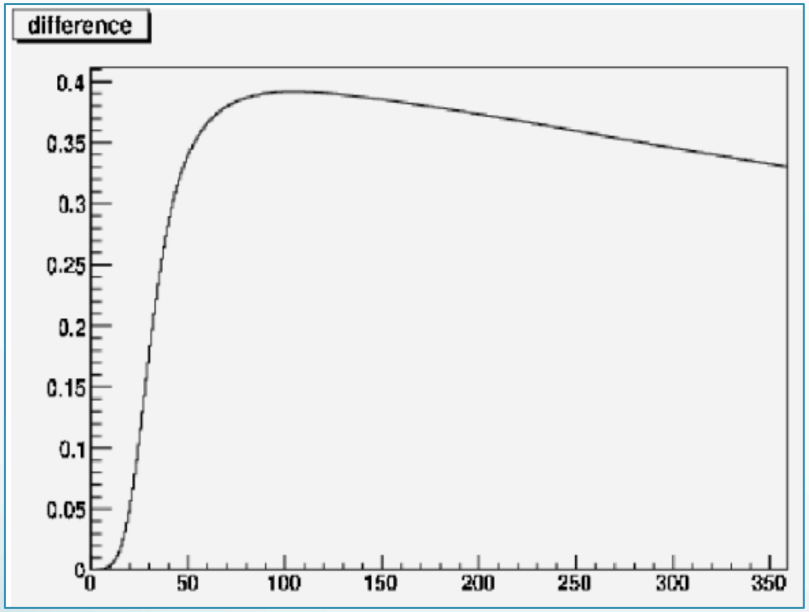
- 20 milion Am/Be events have been considered in the data analysis
- Intermediate population still present (well contained within the extended dynamic range of the new CAEN wfm recorder in use with this test)
- Neutrons go up to 2000 *phel*

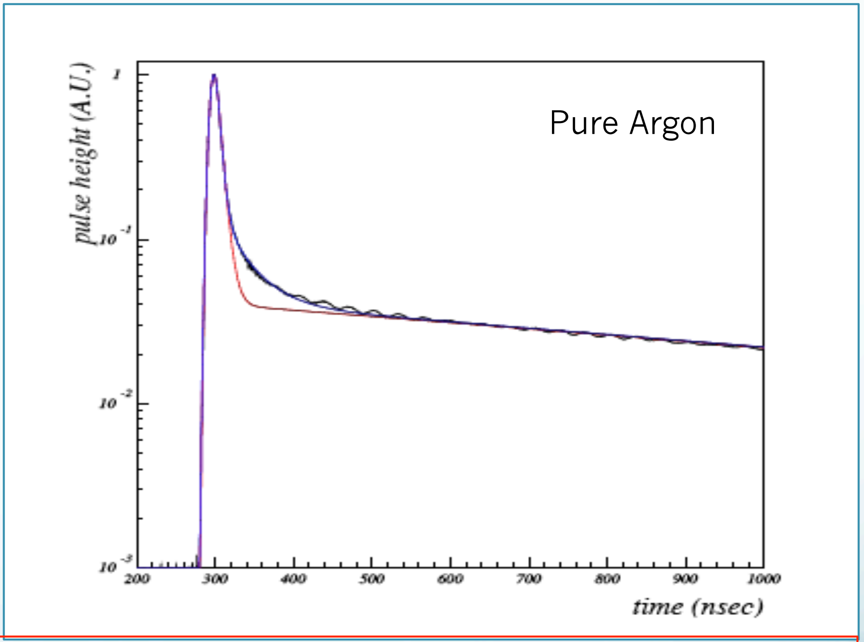




Optimization of T_{Fp}

- T_{Fp} chosen at maximum difference between average neutron and gamma waveforms
- Value confirmed independently by comparing the separation of the neutron and gamma peaks in each energy bin for different values of T_{Fp}





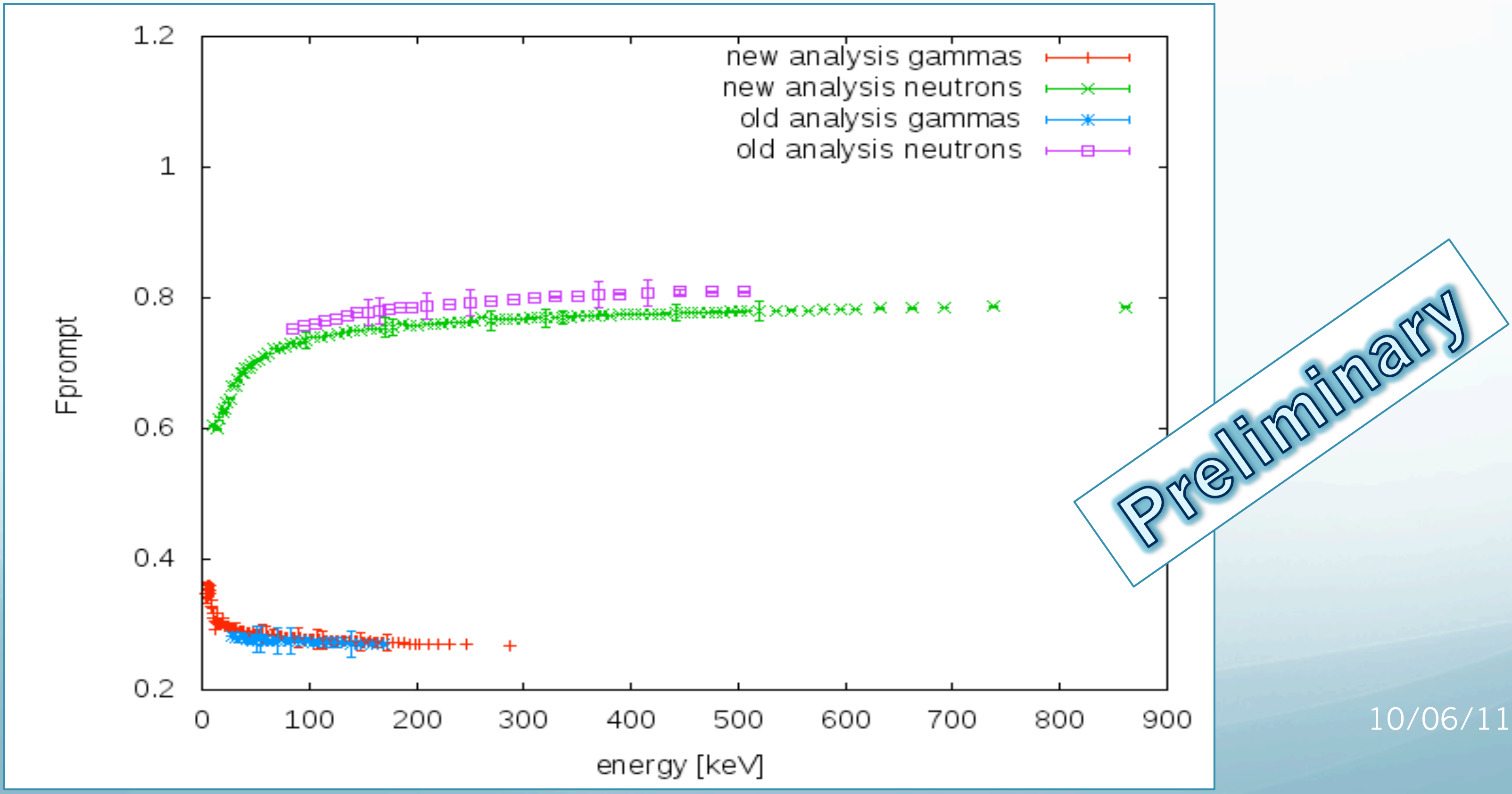
Optimal value considered T_{Fp}: 100 ns

T_{Fp}~100 ns instead of expected tens of ns ascribed to the presence of an intermediate component in the LAr scintillation light signals

Comparison with First Test

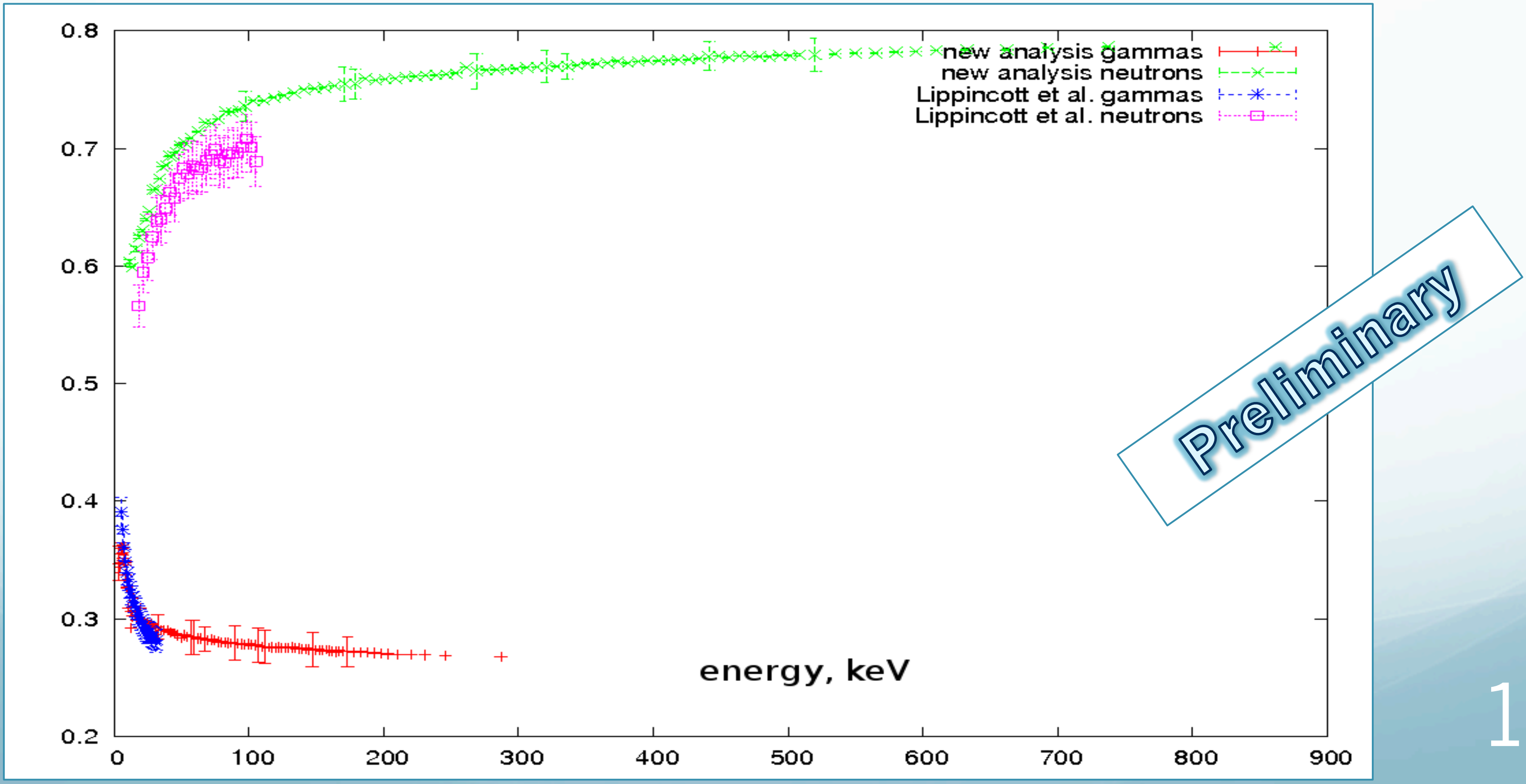
The second test setup is equivalent in size and photo-cathodic coverage to the first but characterized by a higher LY value

- Better energy range, but slightly worse neutron-to-gamma separation achieved with the new set-up, possibly due to N_2 contamination [see E. Segreto's talk] – work in progress
- The nearing of neutron and gamma populations observed (as in Lippincott et al.)
- Assuming Quenching Factor of 0.3



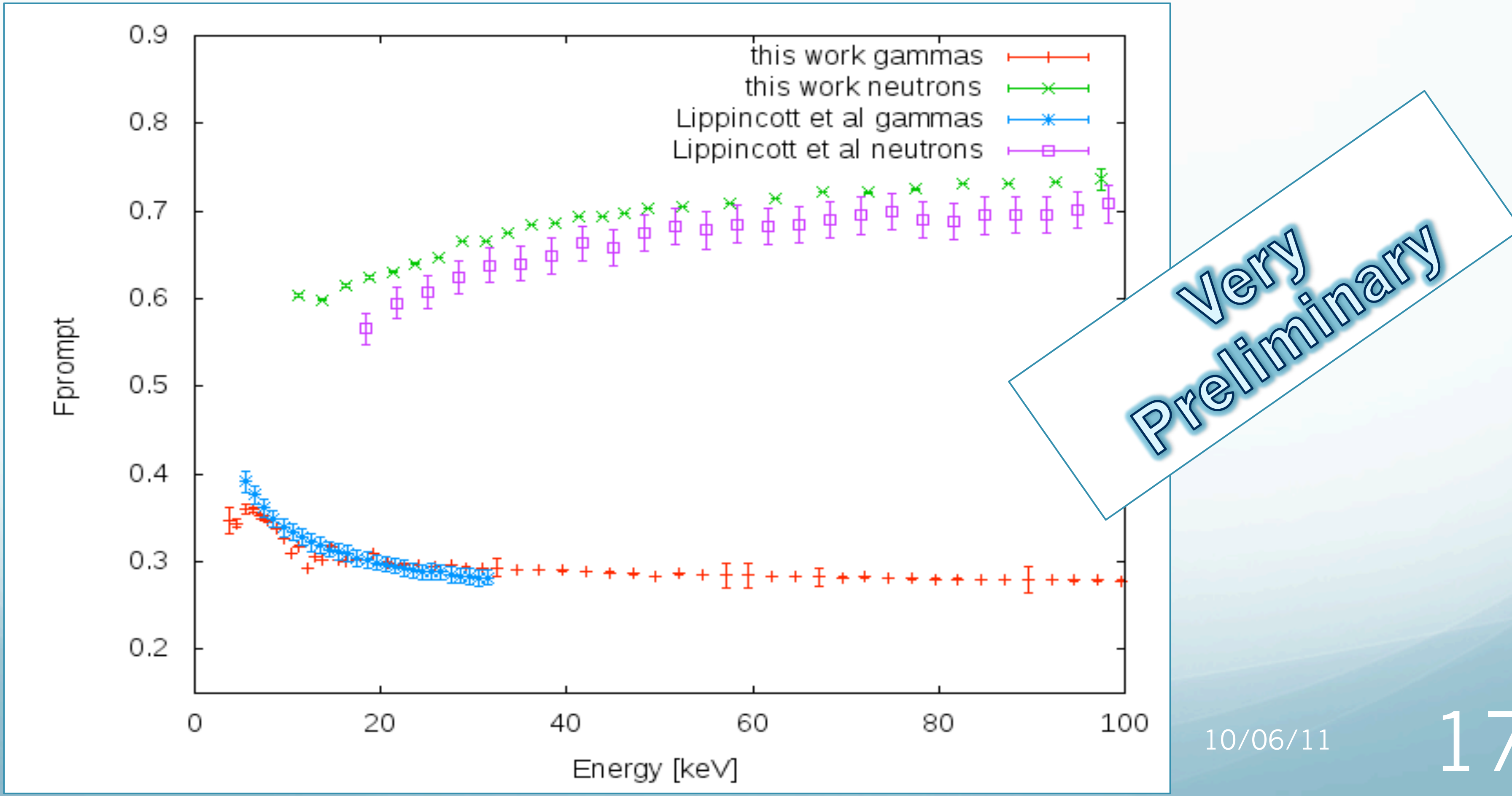
Comparison with published results

- The wider neutron-gamma separation found should lead to higher sensitivity for searches of DM signals with Argon based detectors
- Systematic errors are still under investigation
- MC to check discrepancy in development



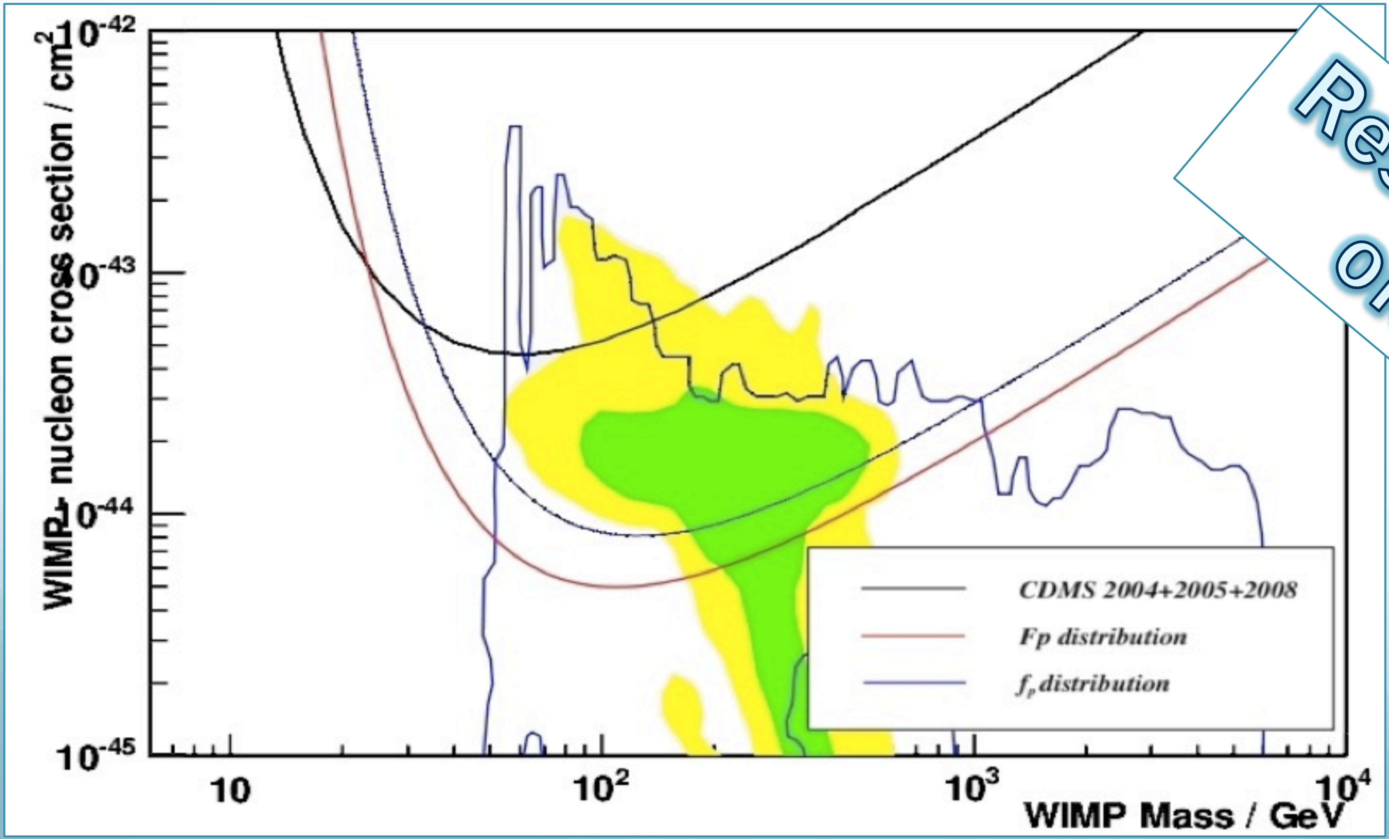
Comparison at low energies

- Gamma and neutron averaged waveforms for different energy bins been taken into account
- Lowest 6 energy bins still under study to optimize reconstruction efficiency



Predicted sensitivity calculation (preliminary)

- Assuming LY of 1.6 *phel/keV* and requesting no background from ^{39}Ar (first test data)
- Will be **much better** with the **higher LY**
- **Work is still in progress** (once we figure out the systematics we will be able to show the new sensitivity plot)



Results of the old test

Conclusions

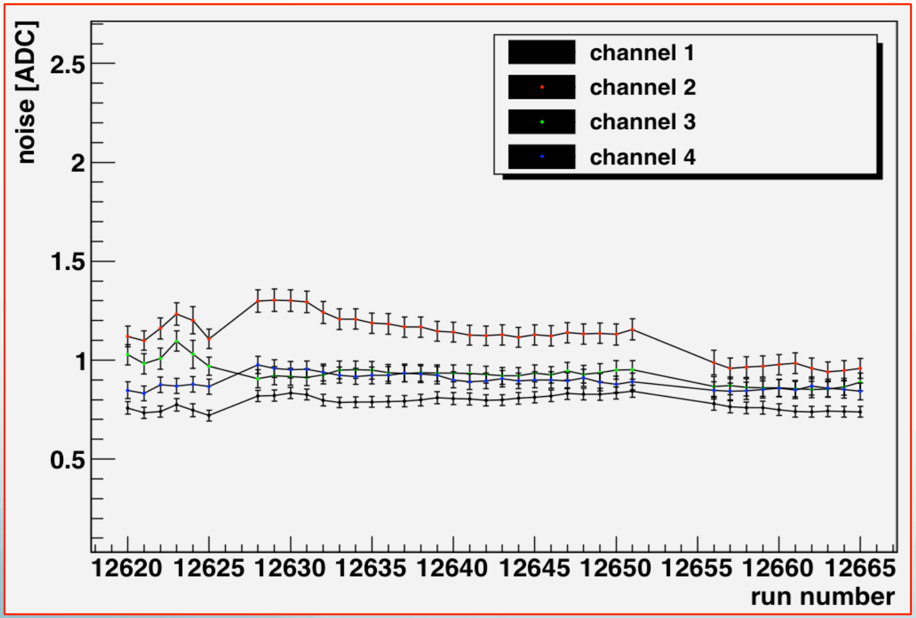
- Two separate tests have been performed to estimate the PSD in Liquid Argon using an Am/Be source
- The first test with ~1.5 *phel/keV*, the second with *6.3 phel/keV*
- Calibrating with a standard neutron source one should take into account the inelastic events
- Due to a high LY, we were able to study the PSD separation with more precision
- Stay tuned for final results on predicted sensitivity and lowest energy events

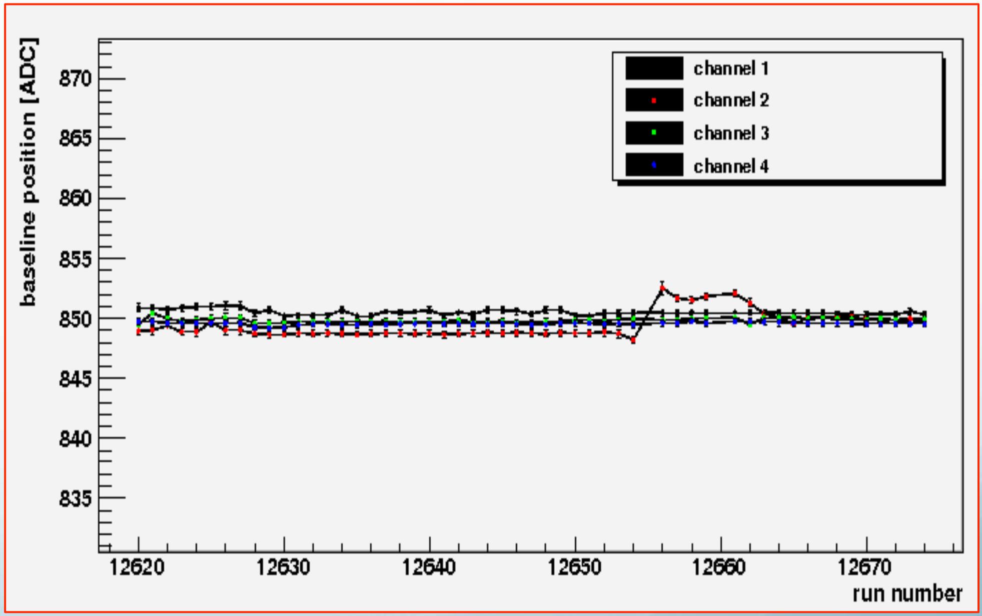
- The present talk is widely based on the theses of Pawel Kryczynski and Roberto Acciarri

Back-up Slides

DAQ parameters

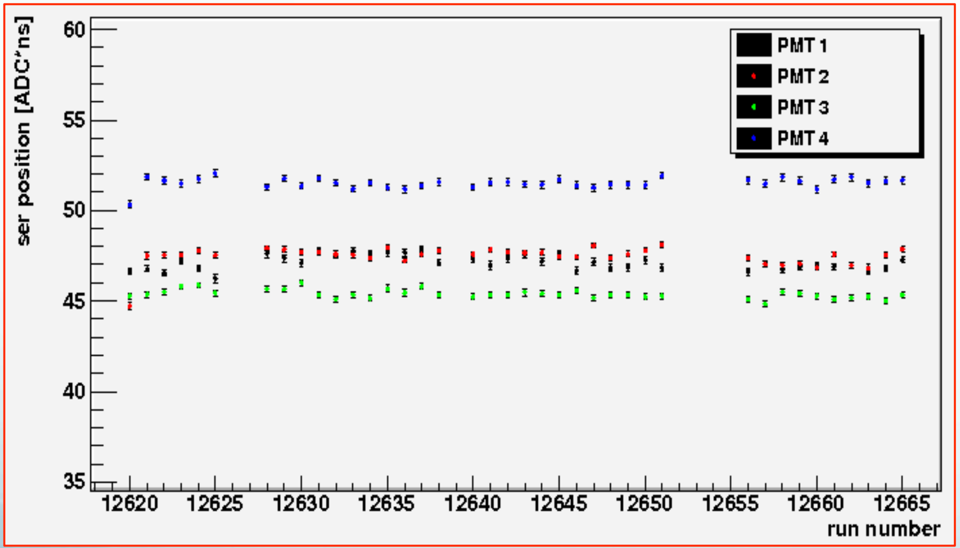
- Trigger on majority of 3 PMTs; each triggering on a fraction of single *phel* (5 ADC)
- Noise and baseline stable
- Reconstruction+trigger set an efficiency curve which starts below 20 *phel*

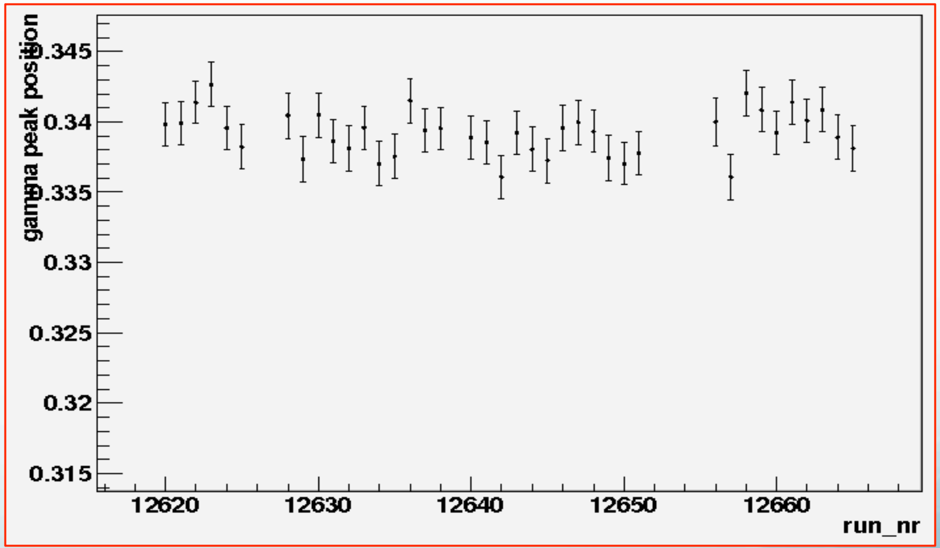




SER and γ-peak position stability

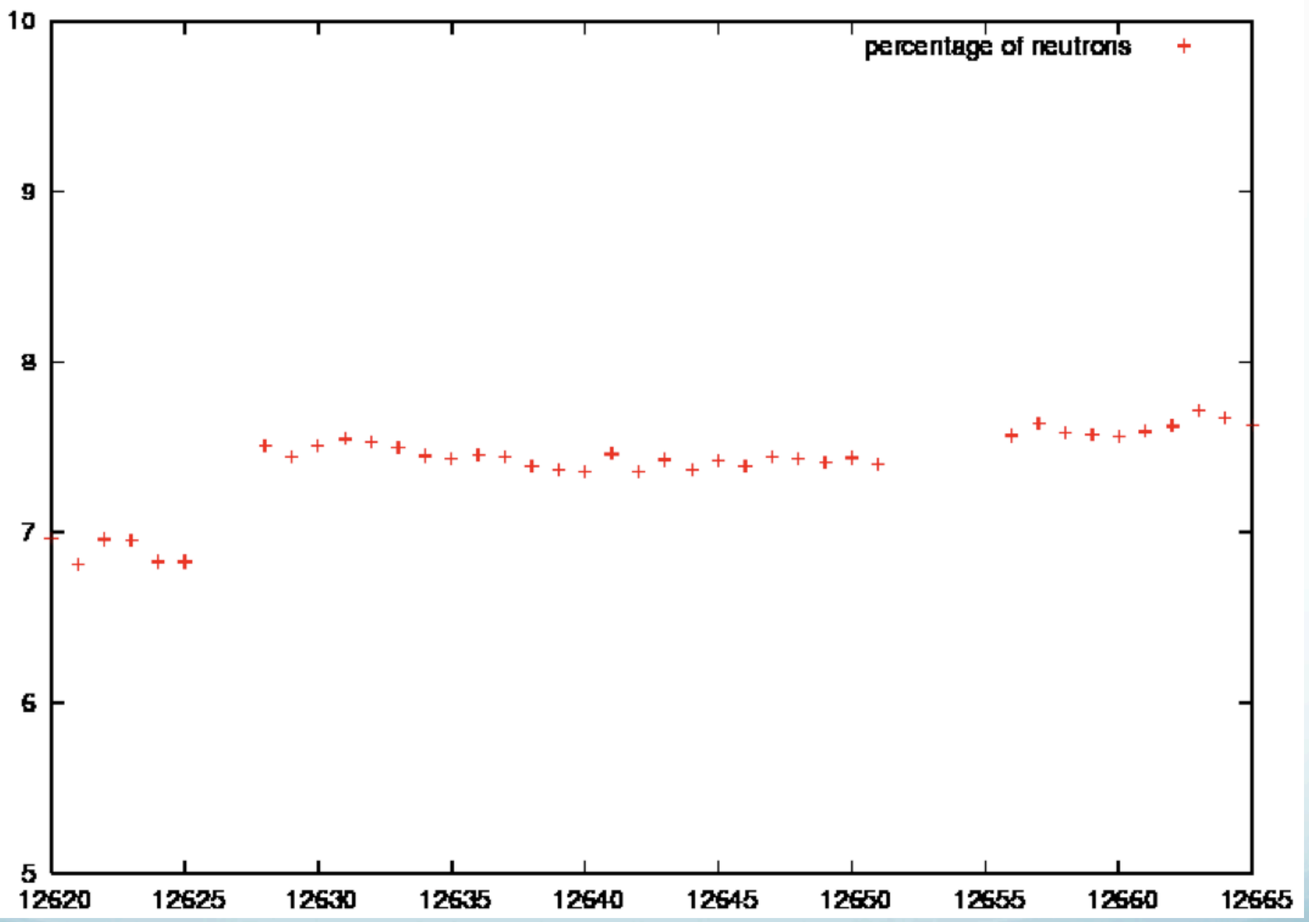
- PMT Single Electron Response positions stable during the whole of the run
- Gamma peak relatively stable during the acquisition run (important when adding runs together)





Neutron percentage

- Up to 7 percent of good neutron events in the data (compared to ~3.5 % in previous work)



Cuts applied

- Basic cuts
  - arrival time window about 50 ns
  - no saturation
  - no secondaries
- Noise cut removes events with F-prompt ~1
- F-prompt cut removes misreconstructed double events