# The WArP Experiment

## Report

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**Consiglio di Sezione - Pavia**

**May 30, 2012**

# Recent developments

- Following the completion of repairs and modifications that were agreed with INFN Commissione II, the detector was re-installed in the main cryostat. Immediately after the vacuum phase was started (April 20, 2011).
  - The distribution chain of the high voltage for the drift field was replaced and extensively tested;
  - optical shields on the Veto photomultipliers were installed;
  - the detector was checked in details;
  - the gas recirculation system was modified to reduce the operating costs.
- During the week of April 25$^{th}$, the helium tests for vacuum tightness were completed: the residual pressure in the detector went down to about 2.5 x $10^{-5}$ mbar, decreasing constantly. A week of vacuum pumping followed ultil a vacuum of about 1.5 x $10^{-5}$ mbar was reached. In parallel the upgrade of the Inner Detector DAQ system was completed.
- During the week of the 9$^{th}$ of May, the inner volume was “washed” with ultra-purified argon gas at room temperature. A series of six fillings up to atmospheric pressure was performed each one followed by evacuation to less than few mbars. Starting from Friday, May 13 the steady vacuum phase was restarted. The residual pressure rapidly went back to about 1.5 x $10^{-5}$ mbar and it was dominated by water (≈50%) followed by air (30%) and argon (20%).

# Recent developments

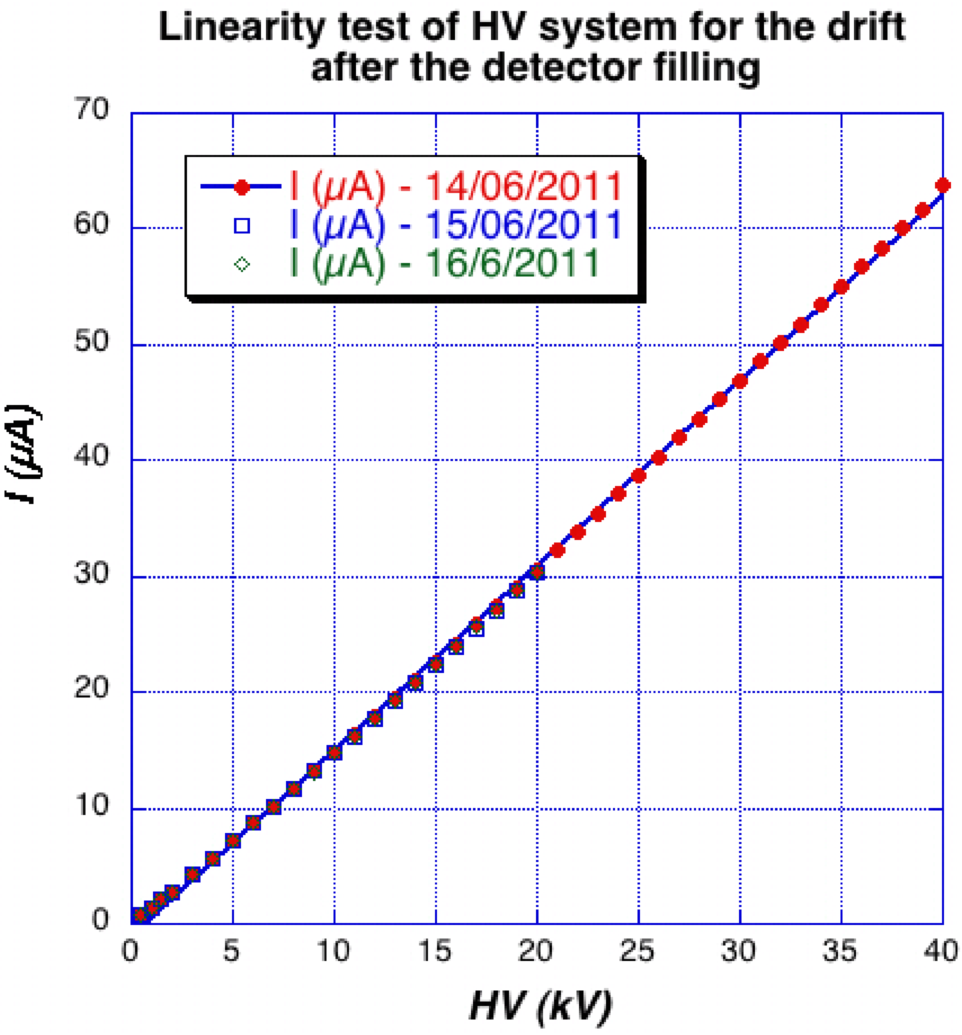
- During the following week (May 16) the detector external cabling was started. The internal detector DAQ and trigger systems were then updated and checked. In parallel, a systematic check of all photomultipliers (both of the inner detector and of the VETO). The gain at room temperature was measured. Those PMTs with anomalous dark counting rates (> 800 Hz) were identified. At the same time all the VETO readout channels have been checked; the electronics was modified and it turned out to be properly working according to the new specifications. This phase was concluded on May 24.
- The detector cooling started on May 25. As for the two previous runs initial cooling was performed by circulating liquid argon in the cooling serpentine placed inside the vacuum insulation of the main cryostat while the cryostat was kept under vacuum pumping. The cooling under vacuum lasted, with some interruption, until May 30. In the while, the LAr pre-purification system for the filling was put in operation.
- The detector filling was done between May 30 and June 1st. The argon used for the filling is “high quality” especially for the nitrogen content (contamination of $N_2 \leq 0.3$ ppm, $O_2 \leq 0.2$ ppm , $H_2O \leq 1$ ppm). The residual contamination of water and oxygen was eliminated by the pre-filter (Trigon + Zeolite) placed between the argon truck and the main transfer line, and by the main purifier (Hydrosorb + Oxysorb) placed at the main cryostat entrance.

# Recent developments

- After the cryostat filling, a thermal stabilization phase of about 10 days followed. During this period the two DAQ systems of the inner detector and the active shield have been aligned. The recirculation system in liquid phase was also put in operation.
- During the weeks of June 6 and June 13 a series of tests of the high voltage system for the drift field, with the photomultipliers turned off, have also been performed. The voltage was taken to a maximum value of -45 kV (the maximum nominal voltage is -75 kV) in a series of several power on and power off cycles. No anomalies have been detected.
- Starting from June 15, we started to turn on the photomultipliers both of the inner detector and of the active shield. A careful and long procedure was used: each day a group of 24 to 48 PMTs were brought to an initial voltage of -600 V; on the following day these phototubes were taken to -900 V and from the after after the voltage was increased by -100 V until the nominal gain (5 x $10^6$) or the maximum voltage of -1600 V are reached. All the photomultipliers that at room temperature (under vacuum) showed a high dark counting rate were left at low voltage (-600 V). During this procedure every day the gain and the rate of each phototube was recorded. The whole procedure took about one month. Starting from the end of July both the inner detector and the active shield phototubes were operating in steady conditions.
- There were 31 PMTs (out of 37) of inner detector and 280 PMTs (out of 300) of the active shield operating at nominal gain.

# First tests of the HV system for the drift field

First tests have been made the week after the detector filling up to a maximum voltage of -45 kV. The tests have been repeated in the week of May 13 up to -40 kV. No anomalies have been recorded.



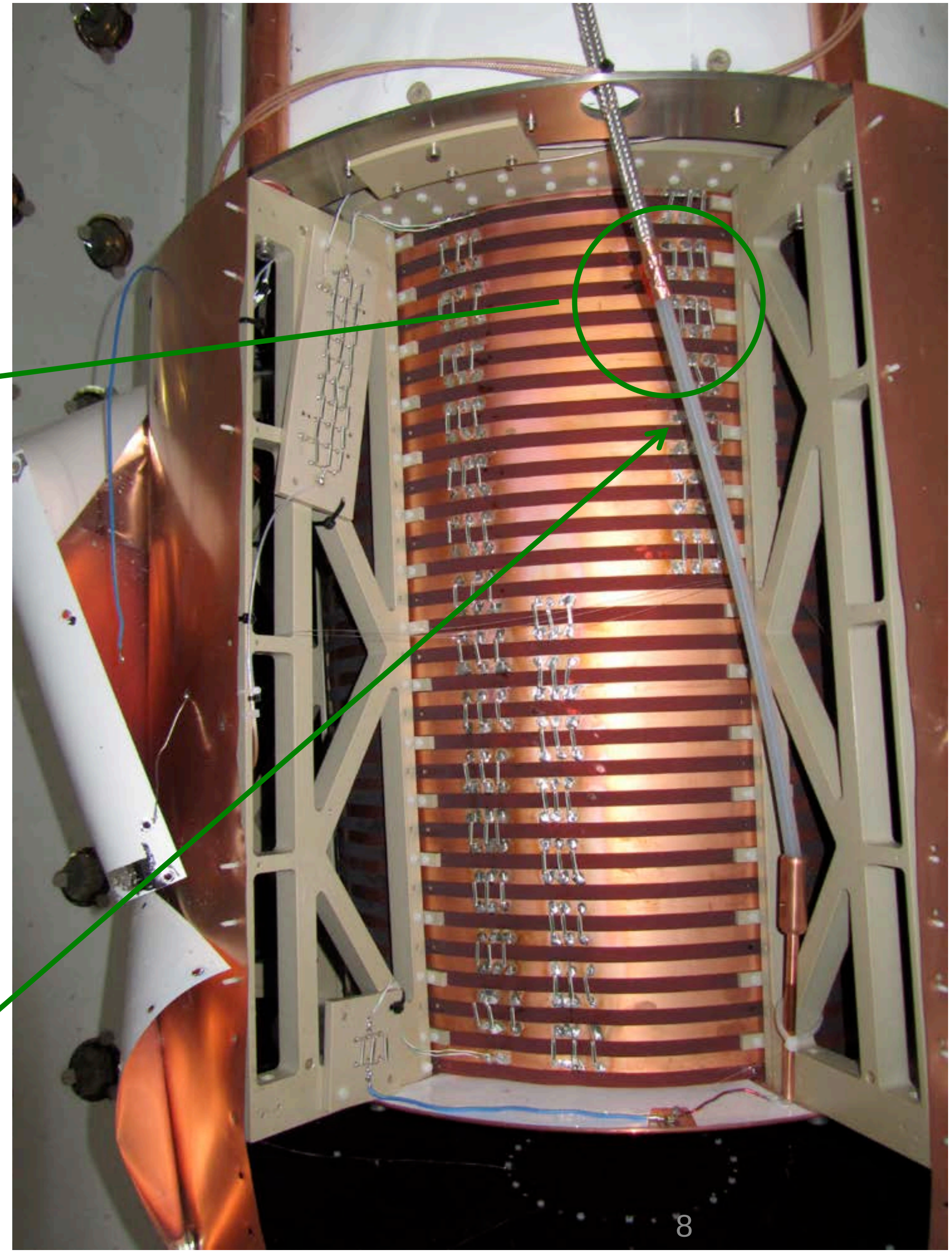
# Recent developments

- The 9th of July, 2011 another problem on the high voltage system for the drift field has shown up: during the procedure of rising up the voltage (it planned to bring the voltage to -60 kV in two days) an instability was detected after the voltage was at -20 kV since few hours. The instability has been followed by a steady over-current flow that brought the voltage to -14 kV (the current flow was 35.4 μA, due to the current limitation instead of 21 μA expected at this voltage).
- We remark that:
  - the system was tested in the previous weeks up to -45 kV and no problems were detected;
  - a “clone” of the system was previously tested in liquid nitrogen several times up to -75 kV whit no problem;
  - the HV cable and the feedthrough have been tested up to -98 kV before the installation in the 100 litres in 2010;
  - the system was brought to -80 kV during the 2010 run and no anomalous behaviour was observed.
- The instability in the current flow causes an increase in the counting rate of the active shield PMTs while no effects are seen on the inner detector PMTs.

# Recent developments

- As a first hypothesis we considered the possibility of a break in the HV cable insulation occurred in the gas phase of the main cryostat.
  - Between the end of July and the beginning of August about 2300 kg of LAr were added to increase the LAr level (≈30 cm) and the operating pressure of the cryostat (+200 mbar);
    - No significant variation in the HV instability have been observed.
  - The added argon has then been removed to reduce the consumption for the cooling (end of August).
- The analysis of the problem will be completed after inspection following the opening of the detector (planned between July and September 2012).

# HV Distribution System



First observed instability (and later confirmed):
HV=14 kV ; I=35.4 μA
R≈395 MOhm

# Recent developments

- The HV stability issue limited our capability to take data with the inner detector with the drift field active.
- However we took regularly data with the field on up to a maximum voltage of -30 kV:
  - Drift field ≈ 330 V/cm
  - Extraction/multiplication field ≈ 3000 V/cm
- We use these data to measure the free electrons lifetime and other detector functional parameters and to study our backgrounds.
- For example the free electron lifetime ranges from 700 μs, with the recirculation pump on, to 1500 μs with the recirculation pump off.
- We also took data with the field off for the measurement of the light yield and also for the study of backgrounds both with the inner detector and the active shield.
- The measured light yield for the inner detector is about 1.5 photoelectrons/keV for beta-like events with no field. This value is consistent with the one observed in the 2010 run. For the active shield we measure a light yield of about 0.5 photoelectrons/keV also consistent with the preliminary estimate from the 2010 run.

# Recent developments

- We observe an anomalous radon activity in the whole detector volume. The observed rate (0.5 ÷ 1.5 Bq/LAr ton) is uniform in the detector volume and is almost identical to the one measured in the 2010 run. We remark that in the present run, all the recirculation filters have been replaced with new ones made of different materials with respect to the ones used in 2010. The radon rate increased by about a factor three after the liquid recirculation pump was turned off. The origin of this radon excess is still under investigation.

# WARP100 3rd Run Summary

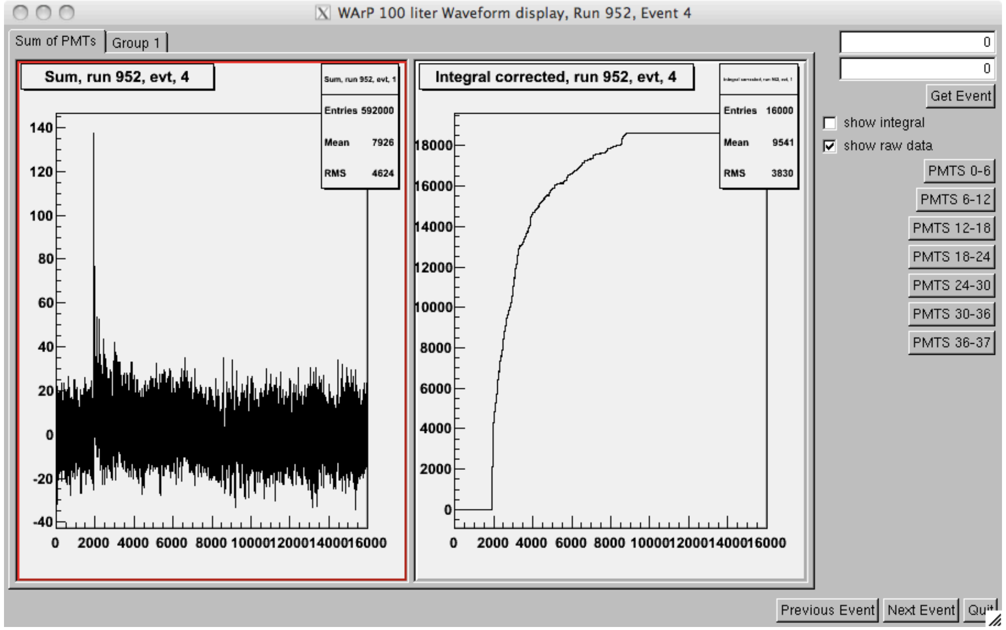
- The last WArP100 run was stopped on November 21, 2011.
- The total run duration was about 5.5 months. About two months were required, after the filling with LAr, to complete the PMTs commissioning.
- Data have been collected, after the PMTs commissioning, both at null drift field and with field (up to a maximum voltage = 30 kV).
- Data reconstruction and analysis is in progress.

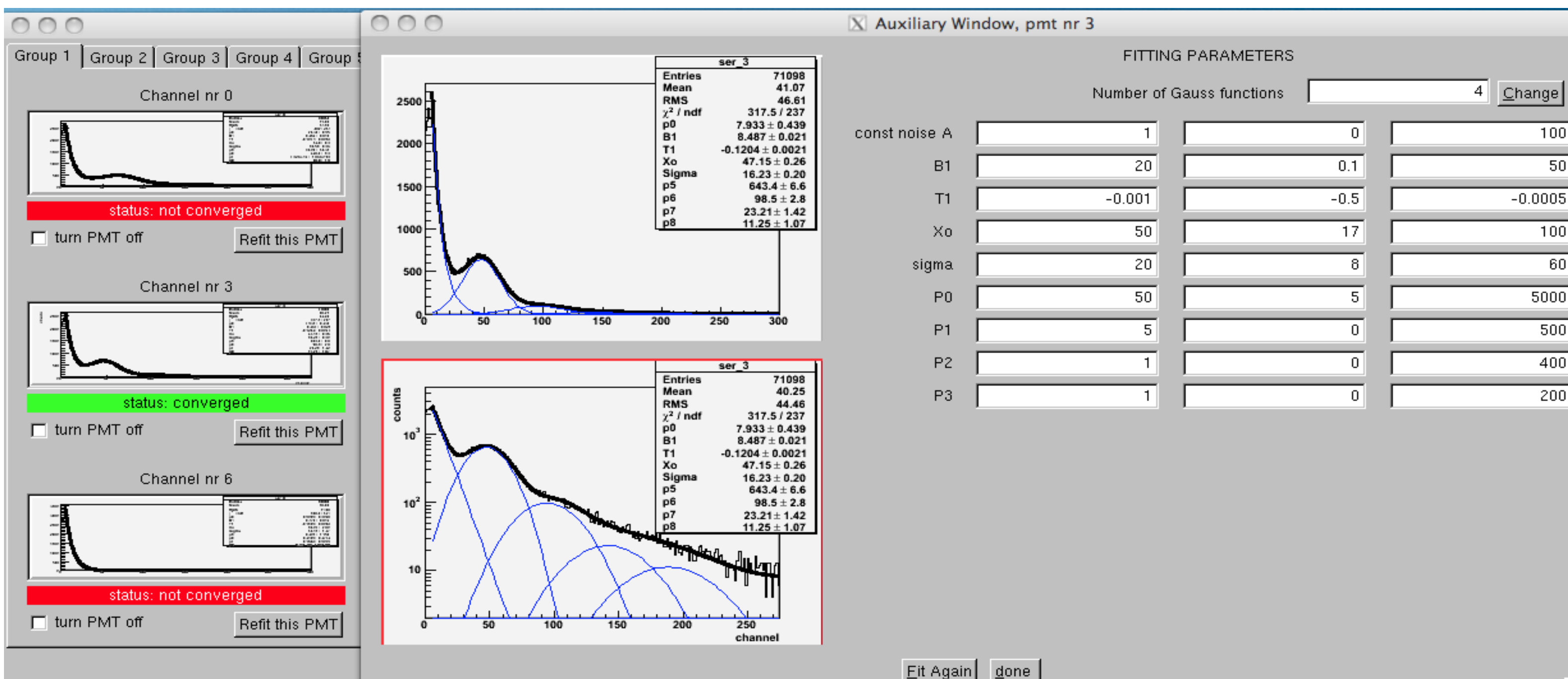
# WARP100 Data Summary

- From Jul 24 to Nov 21, 2011
  - 159 runs at null field for a total ≈ 1.6 x $10^7$ events (≈ $10^6$ s live time).
    - 9 of these runs have been taken with several calibration sources ($^{60}Co$, $^{241}Am$, $^{137}Cs$, $^{133}Ba$).
  - 64 runs with drift field (Max V from 10 kV to 30 kV) for a total ≈ $10^6$ events
    - 1.6 $10^4$ events at 10 kV (Drift field ≈ 90 V/cm)
    - 1.3 $10^5$ events at 20 kV (Drift field ≈ 210 V/cm)
    - 2 x $10^5$ events at 25 kV (Drift field ≈ 270 V/cm)
    - 8 x $10^4$ events at 27 kV (Drift field ≈ 290 V/cm)
    - 5.7 x $10^5$ events at 30 kV (Drift field ≈ 330 V/cm)
  - Most of the data were taken of both the inner detector and the active shield
  - Some runs have also been taken of the active shield operated as standalone detector.

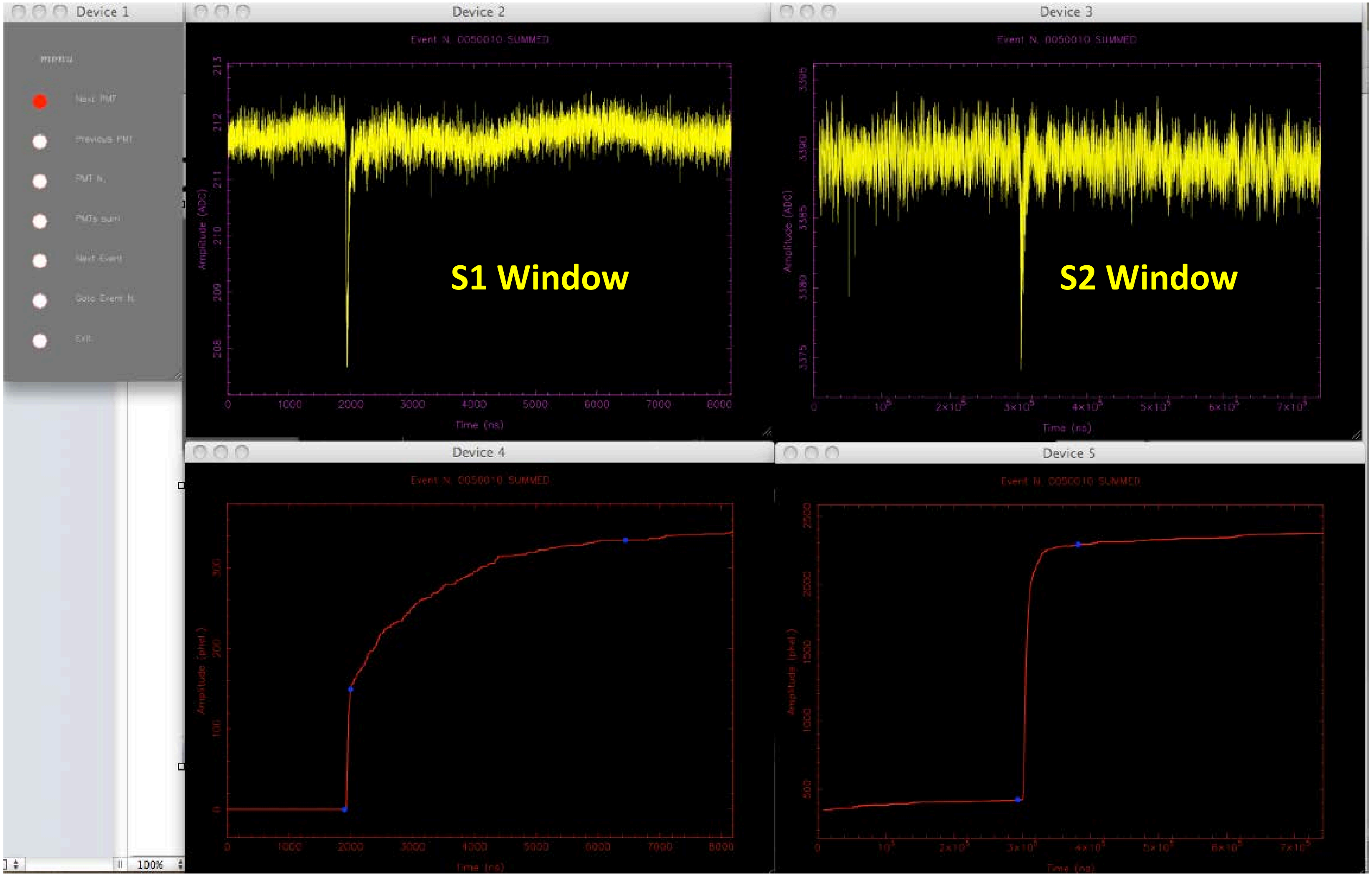
# WARP100 Inner Detector DAQ system and data analysis - II

- A completely new data analysis framework is being developed in Pavia to complete the analysis of the events acquired during the 2011 run.
- The acquired data are analyzed in three phases: the first step is the measurement of the PMT gain by the reconstruction of the Single Electron Response (SER).
- In the second phase the PMT signals are completely reconstructed to get the primary signals amplitudes, shapes and position.
- Last step is the visual inspection of a subset of the reconstructed events to check the correctness of the automatic reconstruction.


WArP 100 liter Waveform display, Run 952, Event 4
Sum of PMTs
Group 1
Sum, run 952, evt, 4
Entries 592000
Mean 7926
RMS 4624
Integral corrected, run 952, evt, 4
Entries 16000
Mean 9541
RMS 3830
Get Event
show integral
show raw data
PMTS 0-6
PMTS 6-12
PMTS 12-18
PMTS 18-24
PMTS 24-30
PMTS 30-36
PMTS 36-37
Previous Event
Next Event

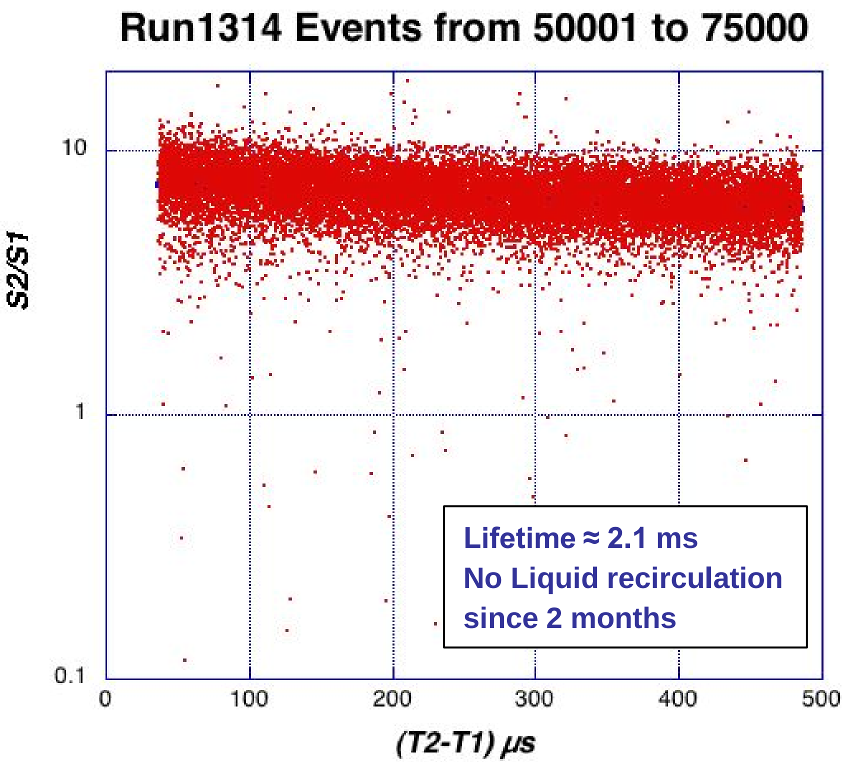

Group 1
Group 2
Group 3
Group 4
Channel nr 0
status: not converged
turn PMT off
Refit this PMT
Channel nr 3
status: converged
turn PMT off
Refit this PMT
Channel nr 6
status: not converged
turn PMT off
Refit this PMT
Auxiliary Window, pmt nr 3
ser_3
Entries 71098
Mean 41.07
RMS 46.61
χ² / ndf 317.5 / 237
p0 7.933 ± 0.439
B1 8.487 ± 0.021
T1 -0.1204 ± 0.0021
Xo 47.15 ± 0.26
Sigma 16.23 ± 0.20
p5 643.4 ± 6.6
p6 98.5 ± 2.8
p7 23.21 ± 1.42
p8 11.25 ± 1.07
ser_3
Entries 71098
Mean 40.25
RMS 44.46
counts
channel
FITTING PARAMETERS
Number of Gauss functions 4
Change
const noise A 1 0 100
B1 20 0.1 50
T1 -0.001 -0.5 -0.0005
Xo 50 17 100
sigma 20 8 60
P0 50 5 5000
P1 5 0 500
P2 1 0 400
P3 1 0 200
Fit Again
done

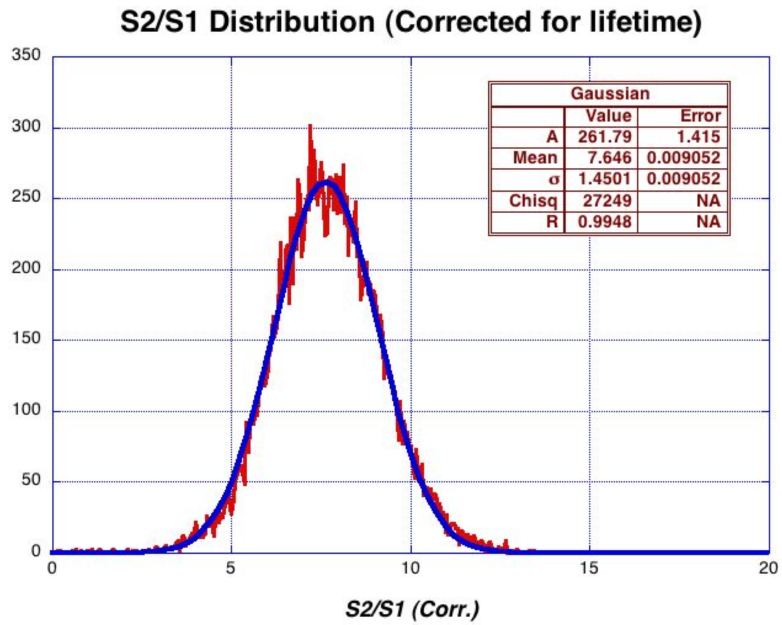
# Data reconstruction and analysis tools




**Data reconstruction and analysis tools are being rewritten from scratch.**

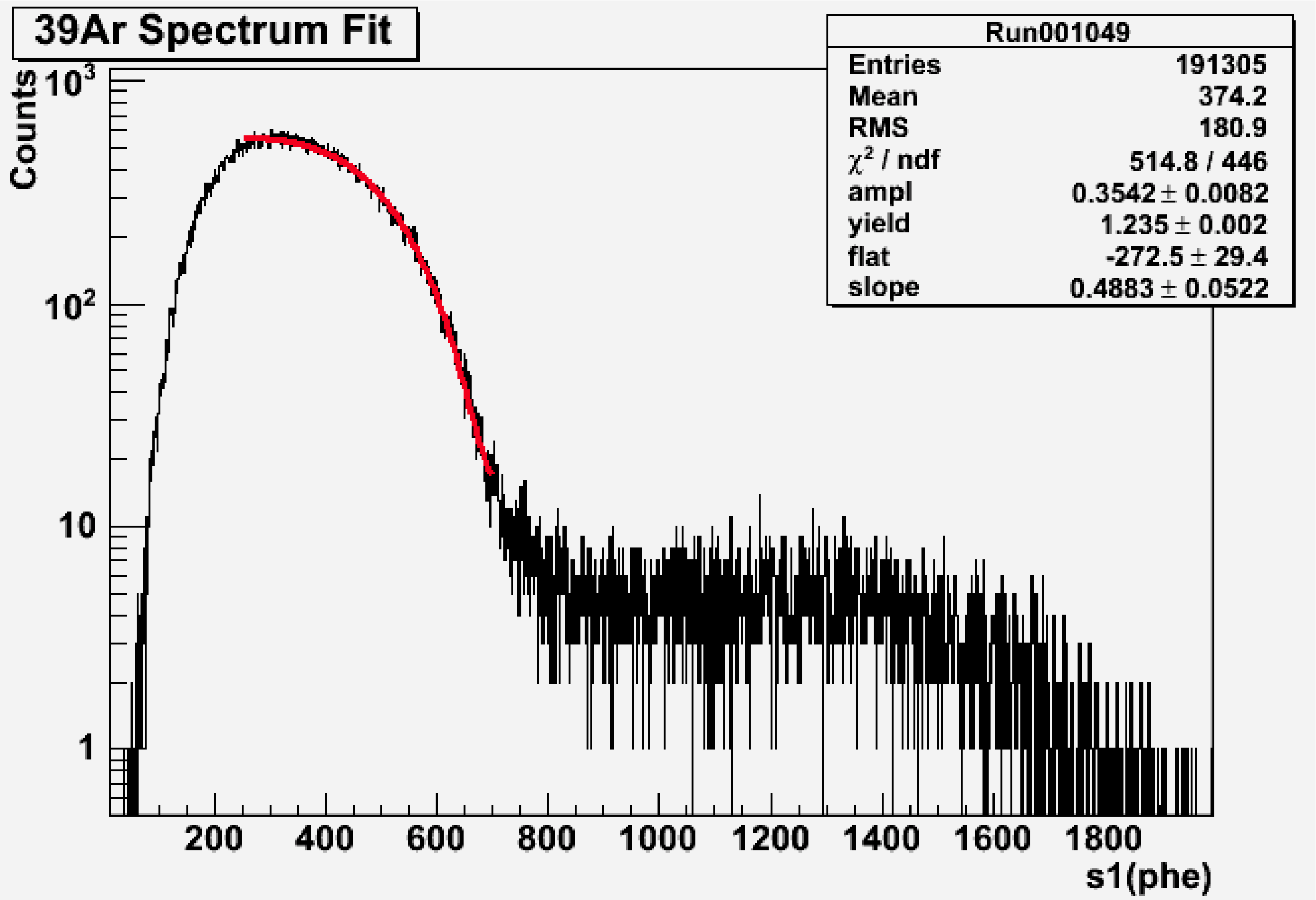
# Some Preliminary Results




**Good Free Electron Lifetime (> 2 ms)**
**Similar to the one in ICARUS T600**
**but without liquid recirculation**

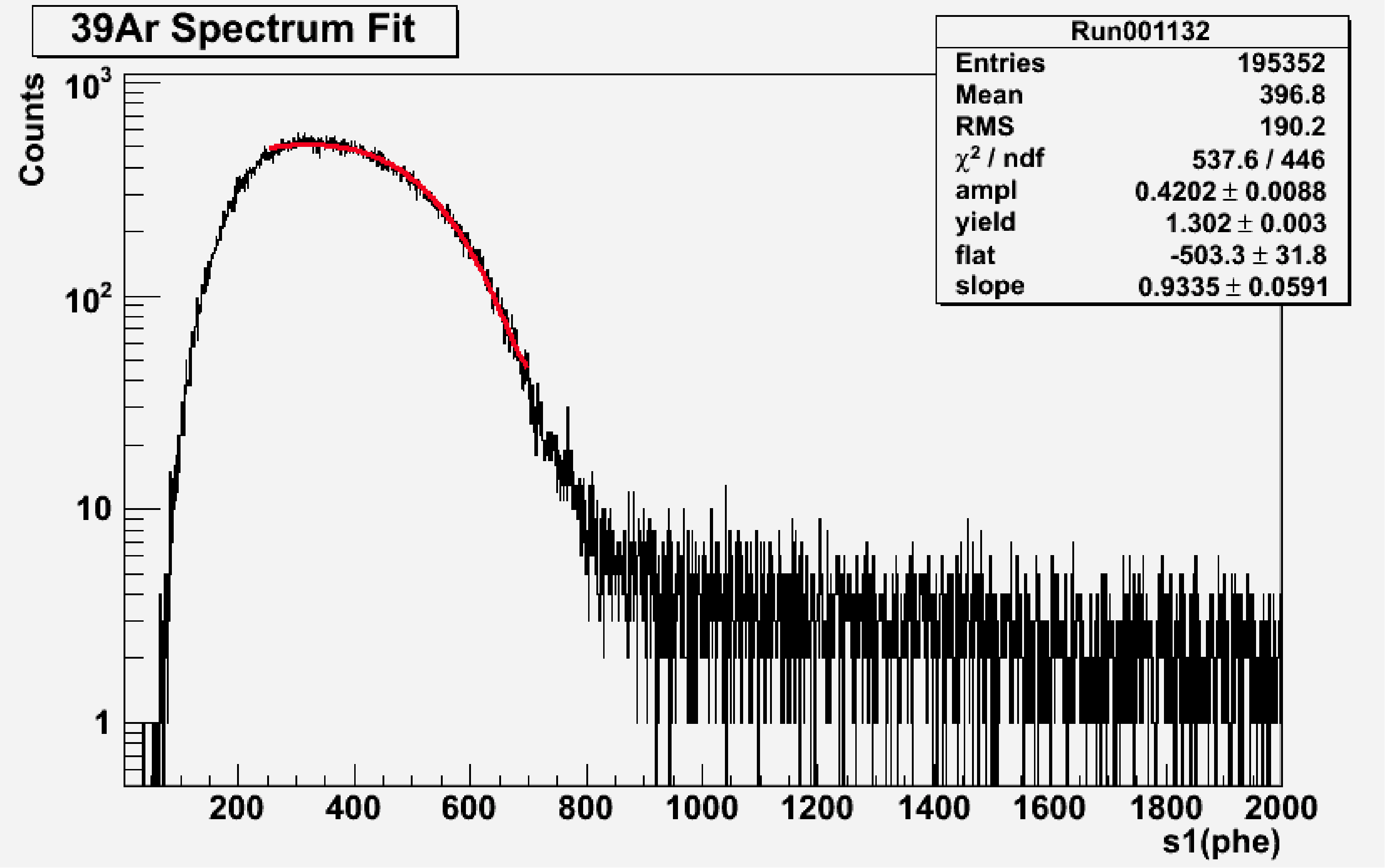
**S2/S1 Distribution Nicely Represented by a Gaussian. Only 7 Events over 25000 are Reconstructed in the Nuclear Recoils Region.**
**Rejection Efficiency from S2/S1 ≤ 3 x $10^{-4}$**
**To be compared with $10^{-2}$ Rejection from other experiments.**




Selection: s1 > 0; 1800ns < t1 < 1950ns; ovfl = 0; ns2 = 0 (fit between 250 and 700 phe).

Data taken with the recirculation pump ON, with 31 PMTs out of 37.

Light Yield: LY = 1.47 phe/keV

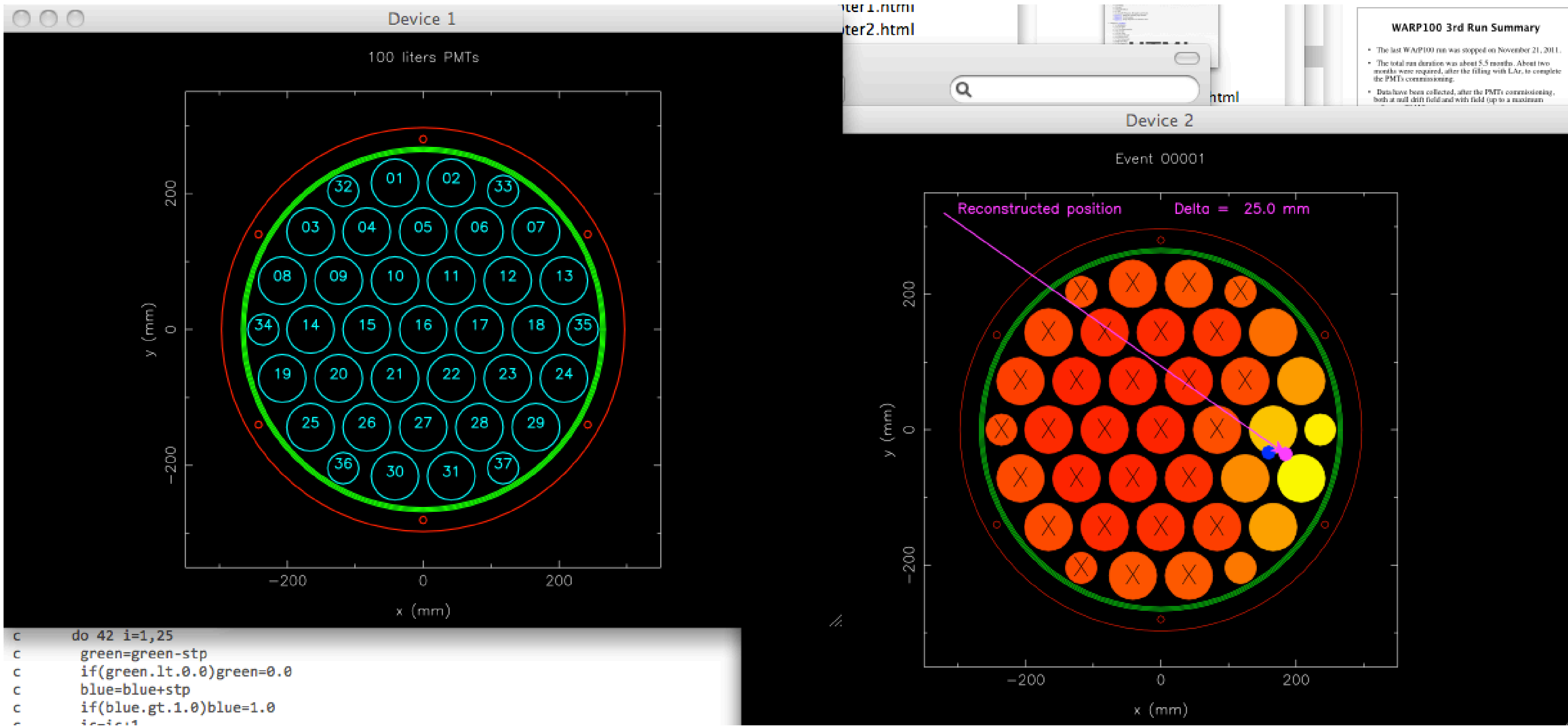



Selection: s1 > 0; 1800ns < t1 < 1950ns; ovfl = 0; ns2 = 0 (fit between 250 phe and 700 phe).

Data taken with the recirculation pump OFF, with 31 PMTs out of 37.

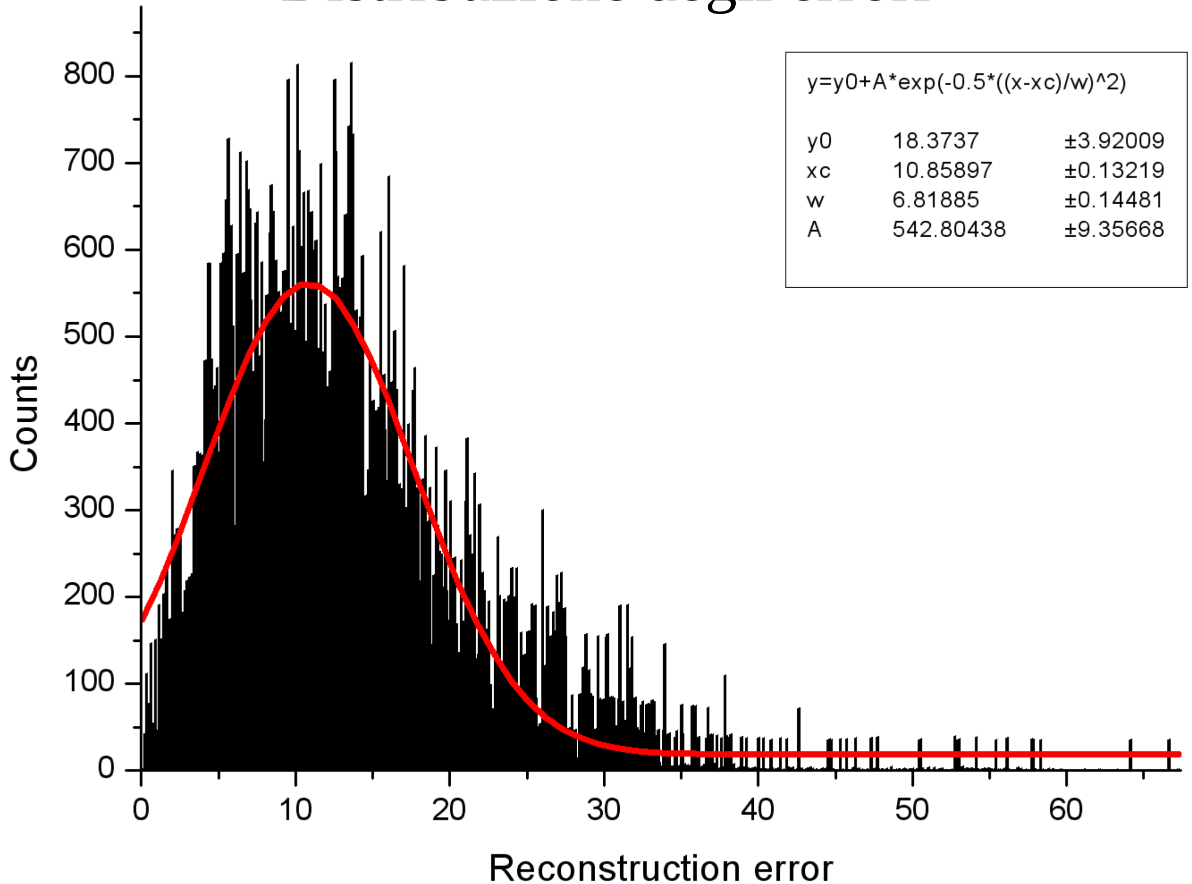
Light Yield: LY = 1.55 phe/keV

# Barycentre Reconstruction



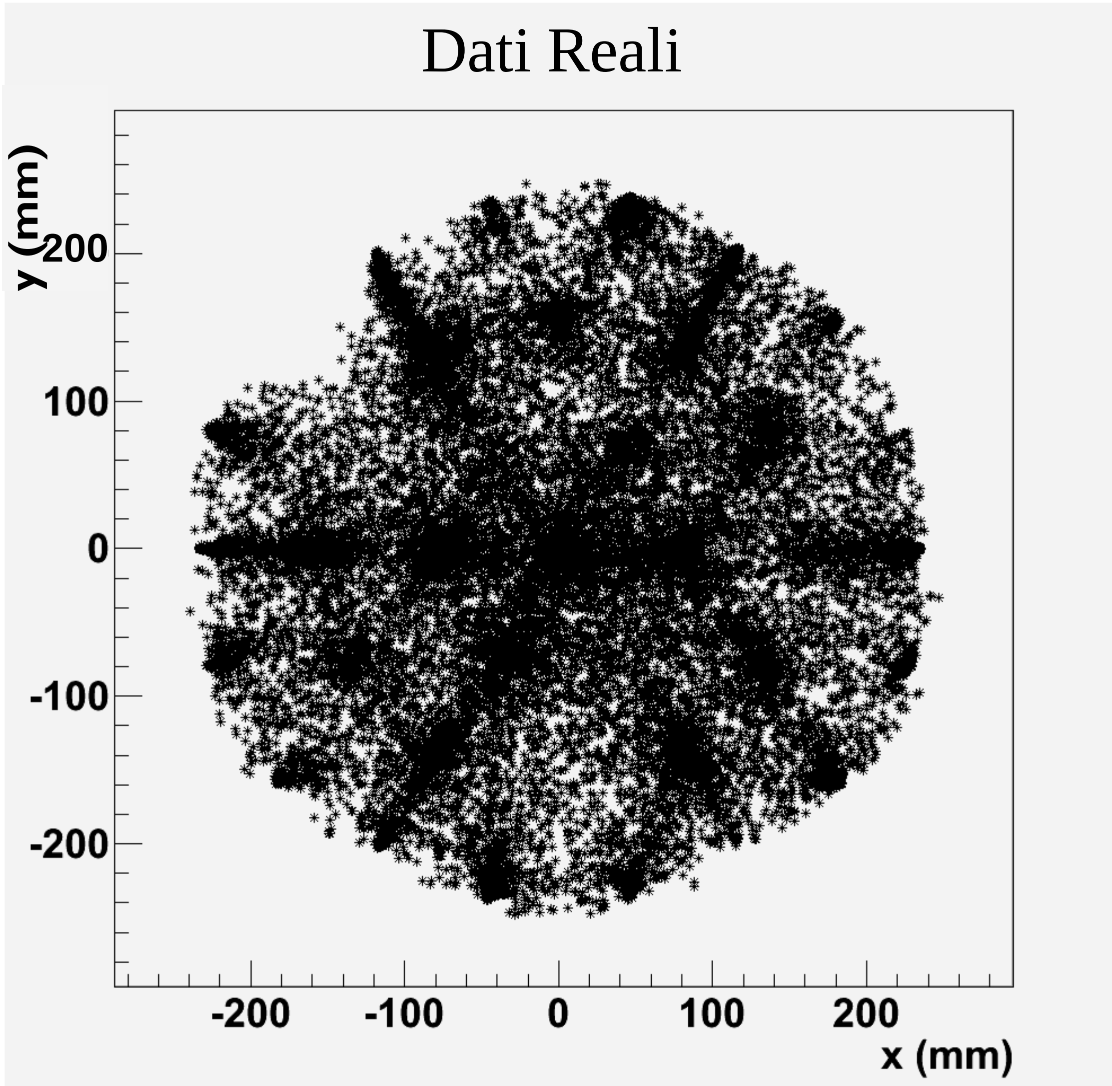

**Program exercised with Montecarlo data.**

# Distribuzione degli errori



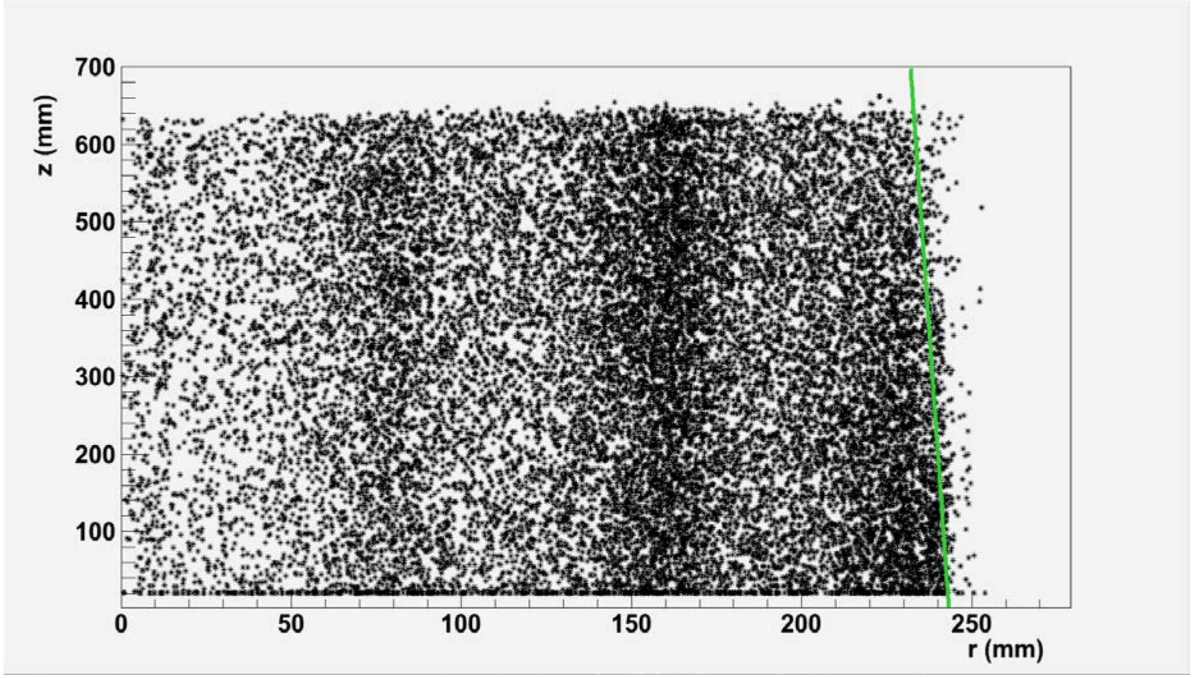

Errore medio = 10. 86 mm ± 0.13 mm

σ = 6.82 mm ± 0.14 mm




La forma è adesso un esagono con i lati arrotondati. A causa della contrazione termica del riflettore, il volume efficace del rivelatore non avrà più forma circolare: poiché il riflettore è fissato in 6 punti la forma si avvicinerà a quella esagonale.

Può essere fatta un'altra prova della bontà della ricostruzione, vedendo se i dati ricostruiti formano un tronco di cono, cioè la forma 3D del rivelatore.




Il modo migliore per verificarlo consiste nel plottare z vs. r.
Dalle dimensioni del rivelatore si ricava che

pendenza vera = 62

Dal fit otteniamo

pendenza ricostruita = 61.9 ± 1.4

# WArP 100 Veto

# Veto electronic read out

- The signals of the 280 PMTs that observe the LAr volume of the veto are plugged into 40 ***N914 CAEN*** boards;

- Each board has ***8 channels*** with charge preamplifiers (sensitivity = -8.3 mV/pC) and integrators (*decay time = 7 µs*);

- *The multiplexed (analog sum) signals of 8 PMTS* from each N914 board are sent to 5 ***CAEN V1724*** that digitize the waveforms with a sampling frequency of *100 MHz* and a resolution *of 14 bit*;

- Two different “trigger mode” are available for the veto:
  - *Standard mode* -> PMTs signals are acquired in coincidence with a trigger of the internal volume;
  - *Self trigger mode* -> a simple trigger system based uniquely on the signals of the veto PMTs -> veto is acquired in a stand alone way.

# Veto self trigger system

- N914 boards offer the possibility to discriminate the signals of the eight PMTs with a common threshold (fixed in our case @ 5 mV ~ 1.5 phel) giving as output a Majority Signal – analog sum of steps with 40 mV amplitude and 2 μs width for each PMT above threshold;

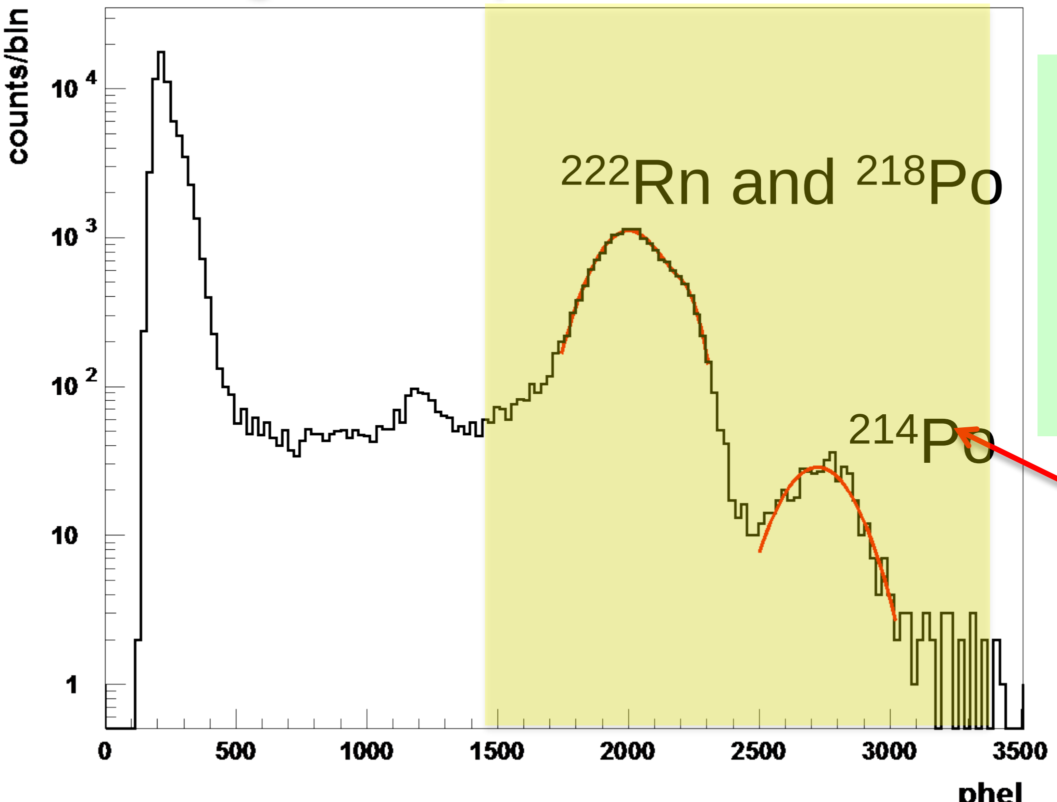
- The Majority signals from all 40 CAEN N914 boards are *summed and discriminated at a level equivalent to about 100 phel*;

- ***Summed step signals above threshold*** trigger the acquisition of the PMTs in the veto.

Example of a triggered signal

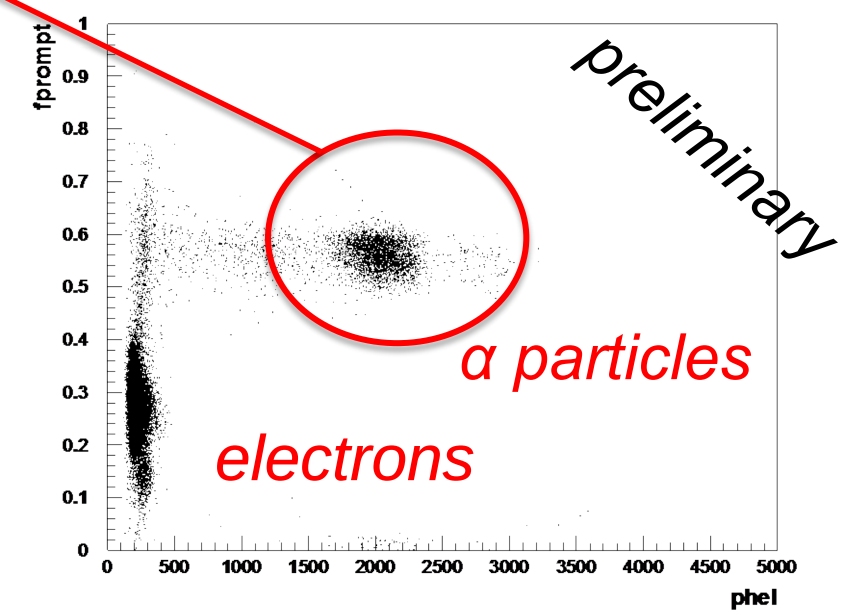
Sum signal

# Background spectrum




*Cuts:*

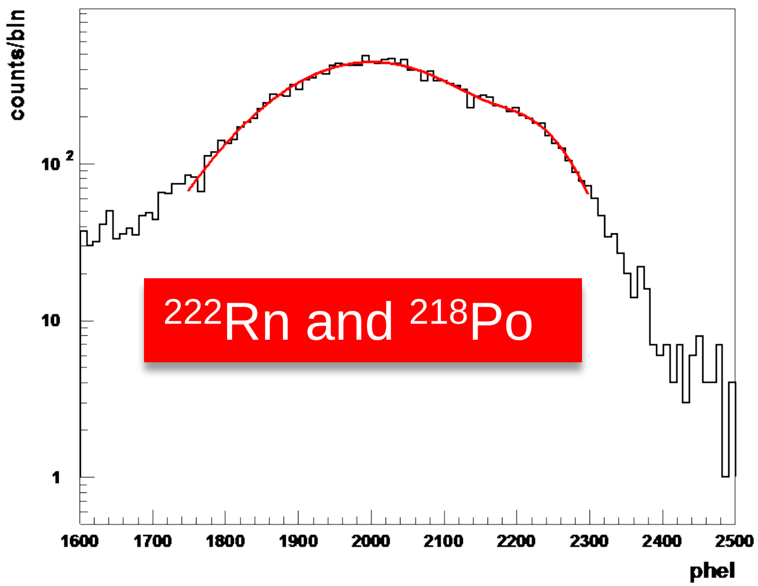
- *Each channel must have a clear baseline;*
- *Signal maximum in a 4 μsec window after trigger;*
- *Maxima summed together to obtain the full spectrum.*

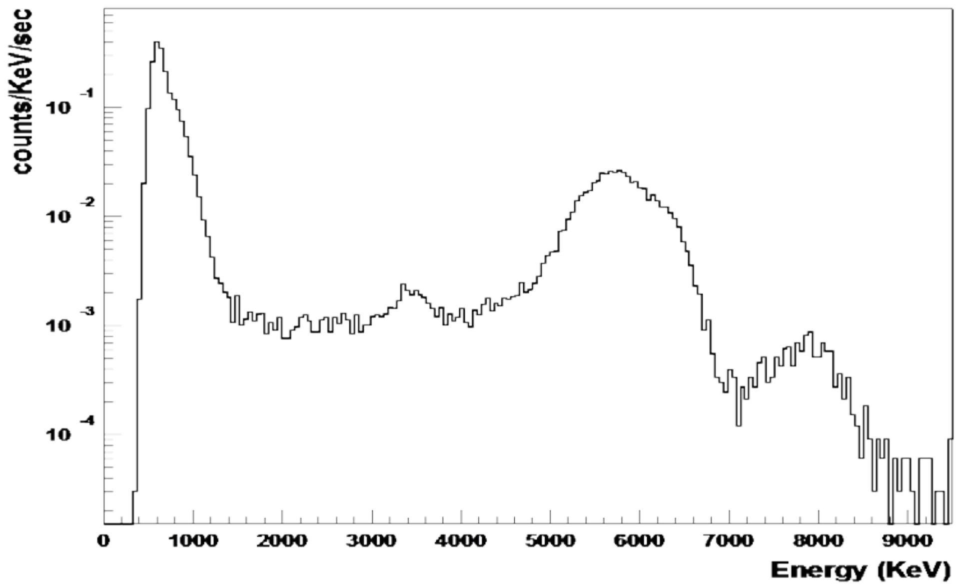



- High energy part of the spectrum ***dominated by α particles*** (*fprompt distribution vs. energy*);
- Approximate activity of 222Rn chain: 11 Bq (1.4 Bq/LAr ton);
- According to our experience (2.3l chamber) the peaks can be attributed to ***$^{222}$Rn***, ***$^{218}$Po*** and ***$^{214}$Po*** with energies of ***5.59 MeV***, ***6.11 MeV*** and ***7.83 MeV*** respectively.

FPROMPT = fast light component/total light

# Light yield estimation with α peaks



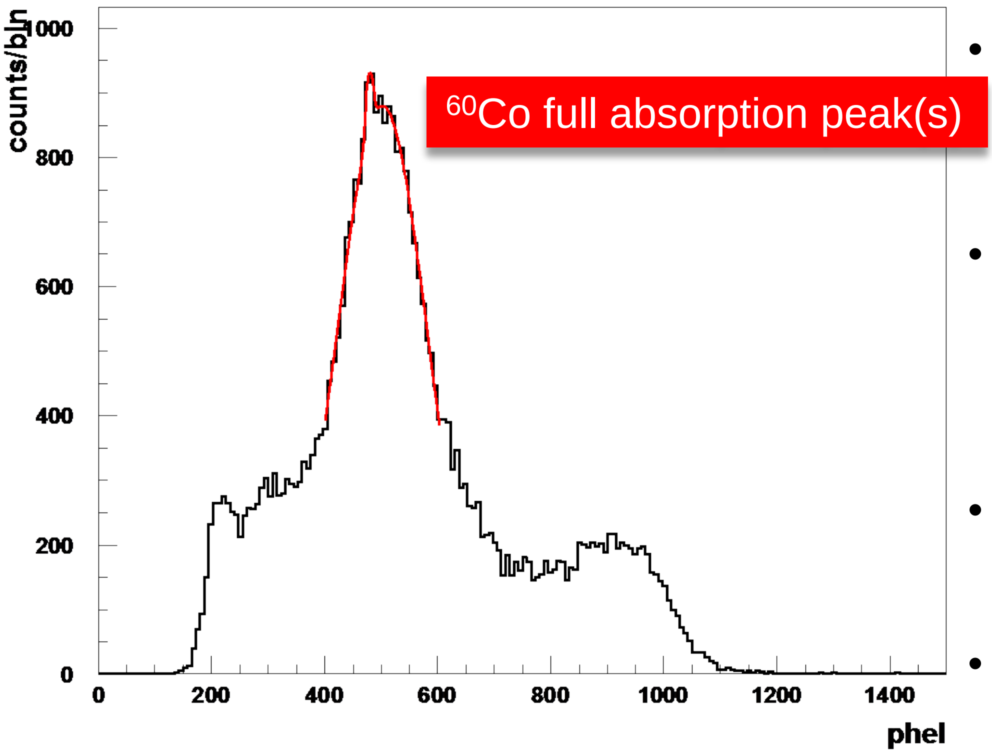

- The $^{222}$Rn and $^{218}$Po peaks are found at *2000 phel and 2225 phel (from fit)* and the $^{214}$Po peak is found at *2725 phel (from fit)*;
- These three peaks allow to estimate a light yield of ***0.36 phel/KeV for α particles***.
- For α particles about 45% of the light is emitted in the slow part of the signal ($\tau_{slow}$ = 1.5 μs) and 55% in the fast (6 ns);
- Since the preamplifier has an integration time of 7 μs -> *35% of the slow signal is lost* and only **85% of the total light is integrated**;
- **The quenching factor for α particles (with respect to electrons) ~ 0.8**;
- ***The electronic light yield at 0 field can be estimated as 0.36/0.8/0.85 phel/KeV = 0.53 phel/KeV***

# Gamma calibration

- The WArP 100 detector allows the insertion of gamma calibration sources deep inside the veto volume (and close to the inner one) through an insulated tube with a diameter of 28 mm;

- *A first calibration run* has been performed with a ***$^{60}$Co*** (~ 3 KBq) -> two gamma lines (*1.17 MeV and 1.33 MeV*) ;

- The peak is clearly visible at *501 phel* (from gaussian fit) -> not enough resolution to discriminate the two gammas;




- Assuming an average energy of 1.25 MeV for photons, ***an electronic light yield of 0.4 phel/KeV is found;***

- Electrons produce slower signals than α, with 75% of the light in the slow component -> **Integrated light by preamplifier ~ 75% of the total light**;

- ***We can estimate an electronic light yield of 0.4/0.75 phel/KeV = 0.53 phel/KeV***

- *This value is perfectly compatible with the one found with α particles.*

# WARP Run 3 & Consequences

- Results of WARP Run 3 discussed at INFN CSN2 meeting of September 2011
- Cristiano Galbiati charged by INFN President in October 2011 with the task of WARP Spokesperson, mandate to boost the collaboration, restart experiment, unify LAr searches at LNGS

# Developments

- Series of discussion within WARP collaboration Nov-Dec 2011
- Meeting with INFN President, CSN2 President, LNGS Director Nov 2011
- Meeting of WARP and DarkSide Italian PIs Dec 2011

# Conclusions

- WARP-100 not fit to produce a timely result
  - HHV
  - Rn contamination
- Immediate unification of LAr DM community at LNGS - DarkSide & WARP - to optimize use of limited resources

# 3-Prong Proposal

1. Complete and commission DS-50 as proof of principle of technology at G1 stage
2. Study of ionization and scintillation response of liquid argon to low-energy nuclear recoils
3. Completion of WARP (papers, analysis of 2011 failure). Study of the feasibility of adapting the WARP shield for a possible multi-ton (G2) argon detector at LNGS

# Decisions

A. Princeton University and Naples
   - Committed to all three steps.
B. LNGS/AQ
   - Expresses strong interest and declaration of availability to all steps. Decision to be taken following possible INFN approval, and definition of contracts.
C. Padova
   - Theoretically interested in all three steps. However, full commitment to ICARUS and CMS and lack of additional resources makes its involvement impractical. At this moment, no contribution can be guaranteed.
D. Pavia
   - Fully focused on ICARUS program, expected to transition to CERN at end of 2013. Committed to understanding reasons of failure of 2011 campaign, completion of data analysis and production of papers on detector and 2011 data.

# Present Status and Future activities

- Following its January 2012 meeting, INFN CSN2 recommended the closure of the WARP experiment.

- It was also recommended that a small queue of activities take place in 2012 at LNGS to determine the cause of the malfunction of the HHV connection in the 2011 run. Additionally, the WARP members also part of DarkSide expressed interests towards the possible use of the WARP infrastructure for a future second generation experiment, and the INFN CSN2 recommended that this idea be re-submitted in a future meeting.

- Analysis of data from the 2011 run is ongoing and the collaboration expects to finalize it within the beginning of 2013.