Online Monitoring of the Osiris Reactor with the Nucifer Neutrino Detector

Applied Antineutrino Physics Workshop

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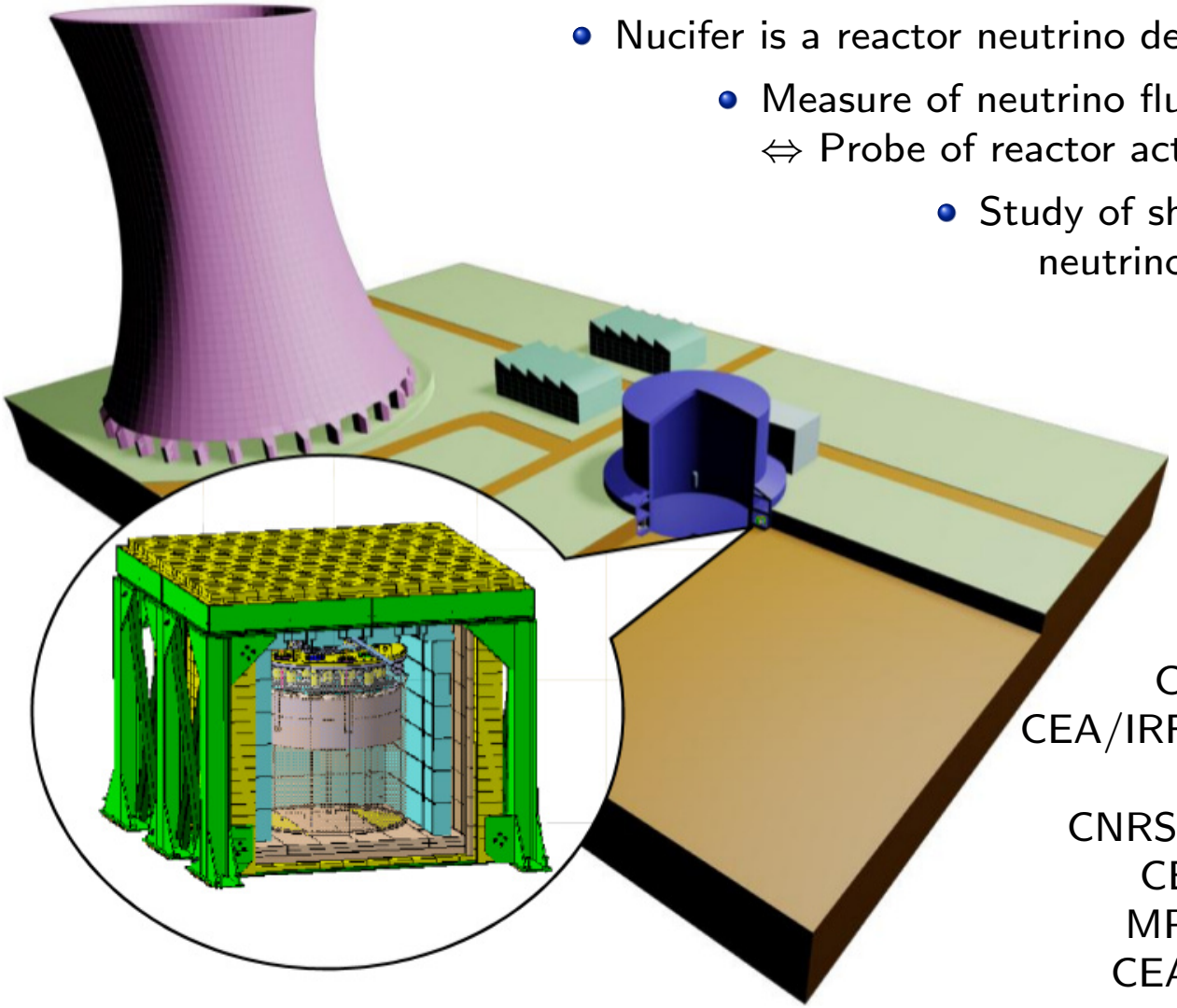
on behalf of the Nucifer collaboration

CEA / IRFU - Service de Physique des Particules

7th December 2015

Nucifer project



- Nucifer is a reactor neutrino detector project
  - Measure of neutrino flux
    $\Leftrightarrow$ Probe of reactor activity
    - Study of short baseline neutrino propagation

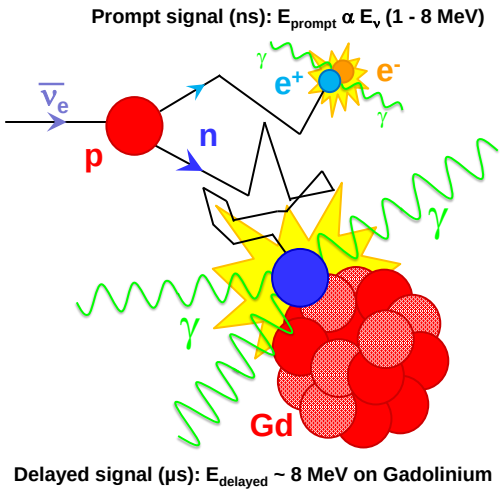
Collaboration:
CEA/IRFU: SPhN, SPP, SEDI, SIS, LENAC
CNRS/IN2P3: Subatech
CEA/DAM/DIF
MPIK Heildelberg
CEA/DEN/SERMA

and thanks to the Osiris team

Outlook

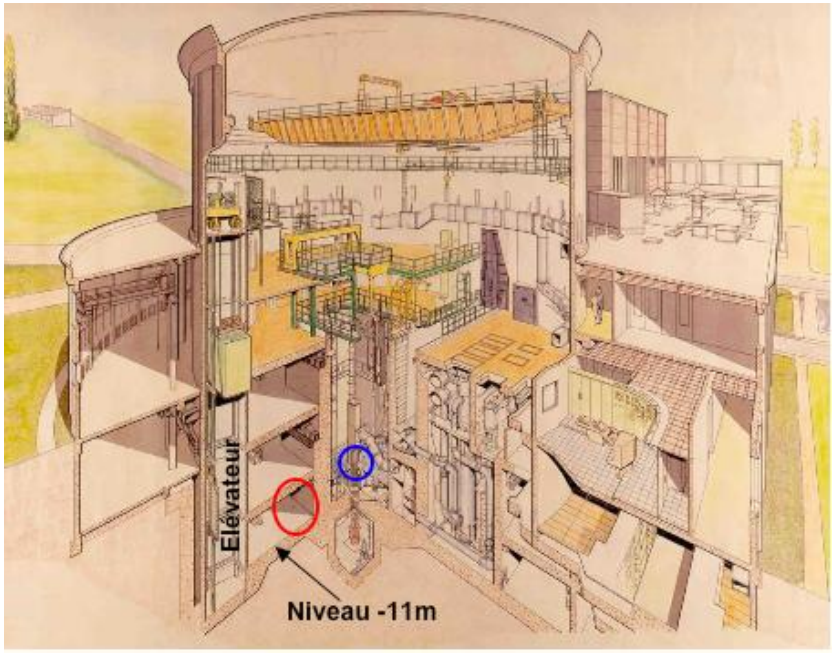
1. Detector characterization
   - Detector and site
   - Upgrades
2. Results
   - Measured neutrino count rate
   - Predicted neutrino count rate
   - Potential application: sensitivity to plutonium
3. Conclusion and perspectives

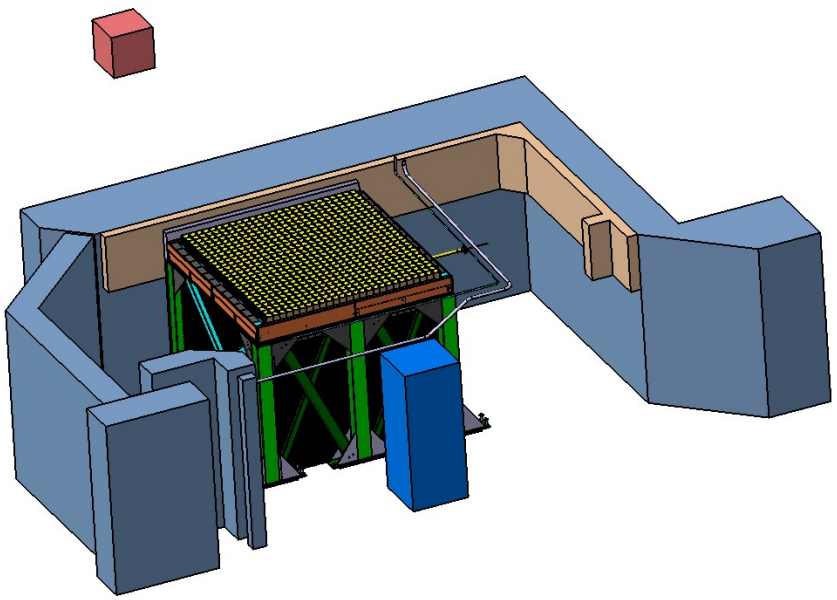
Nucifer Detector



- Inverse Beta Decay in 850 L of Gd-loaded liquid scintillator
- 16 PMTs fixed on an acrylic buffer, central calibration tube
- Designed for simplicity and reliability

Osiris site

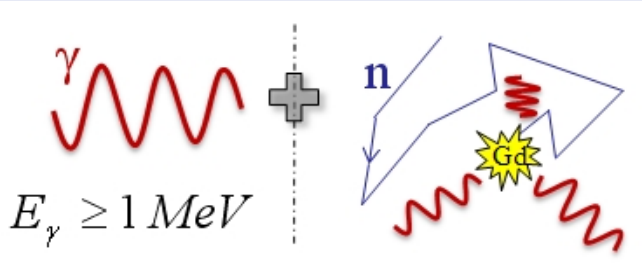




- 70 MW_{th} "pool type" research reactor, located at CEA Saclay
- ∼7 m from the reactor core, at the lowest reactor level
  ⇒ High gamma flux when reactor starts (∼50 µSv/h next to the wall)
- Low overburden, with only a muon flux attenuation of 2.7
  ⇒ High muon induced correlated background expected (fast neutrons)
- **Challenging site due to closeness with reactor and surface**

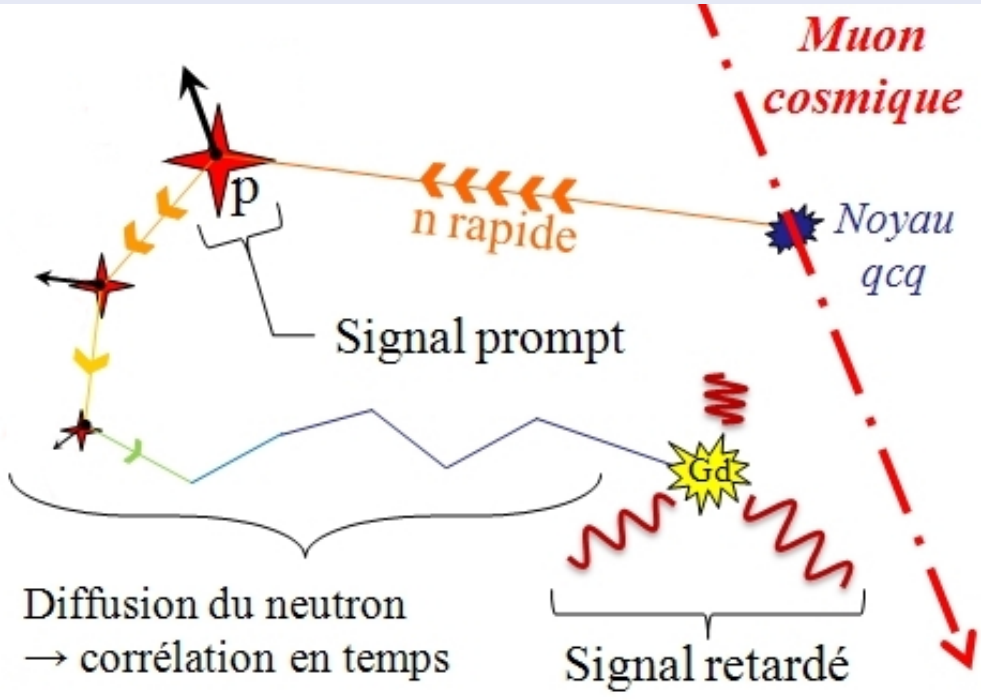
Expected backgrounds

Accidental background



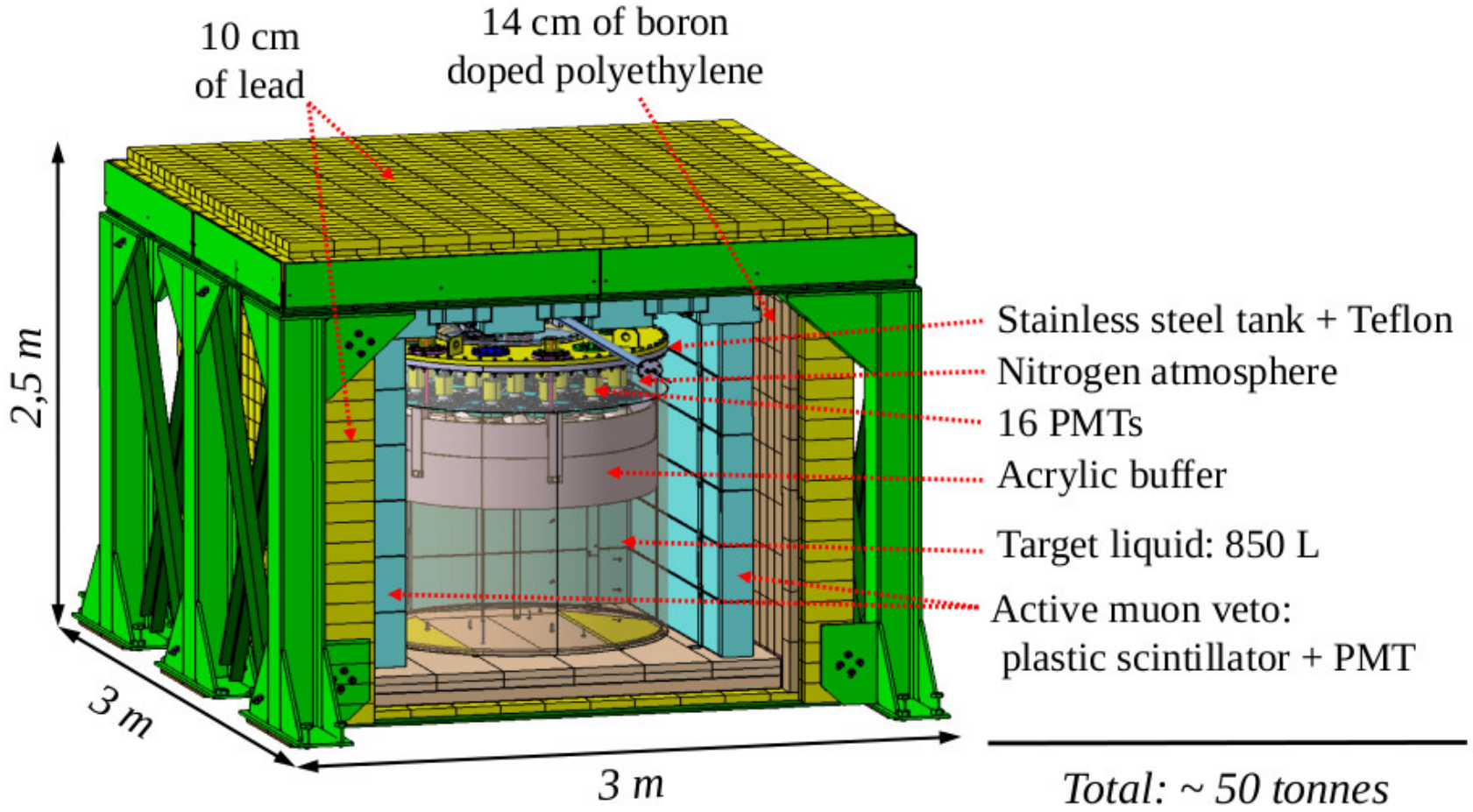
- Random coincidence
- Prompt: gamma or neutron capture with missing energy
- Delayed: high energy gamma or neutron capture
- Measured reactor ON and subtracted

Correlated background

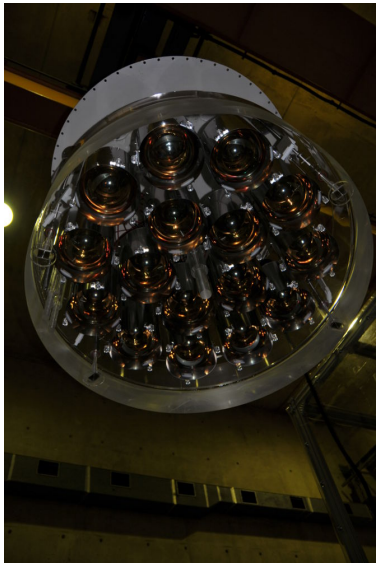


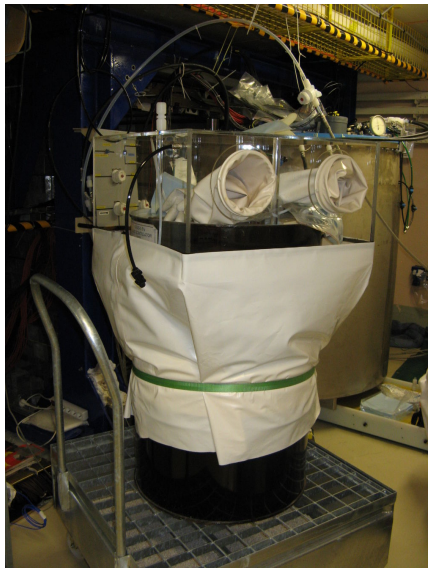
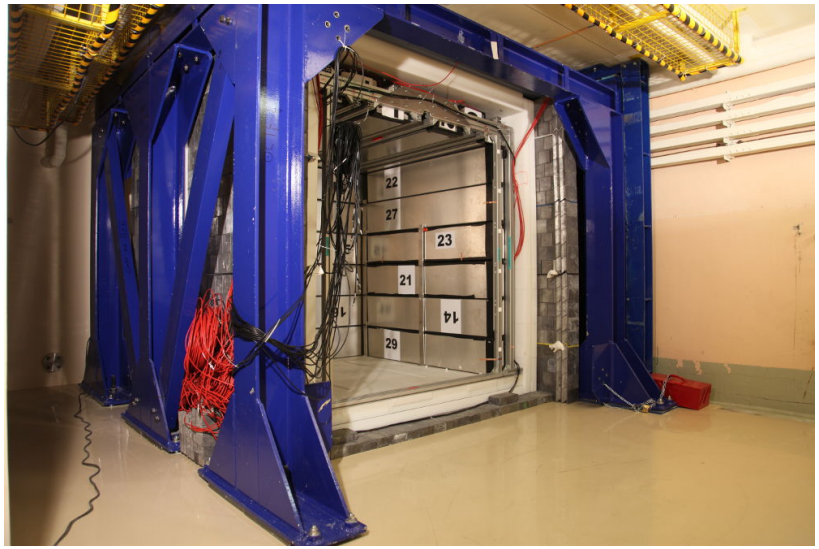
- Cosmic $\mu^{\pm} \Rightarrow$ fast ${}^{1}_{0}\mathrm{n} \Rightarrow$ correlated signal
  $\Rightarrow 2\ {}^{1}_{0}\mathrm{n}$ captures $\Rightarrow$ correlated signal
- Decreased by overburden and quenching
- Measured reactor OFF and subtracted

Nucifer shielding

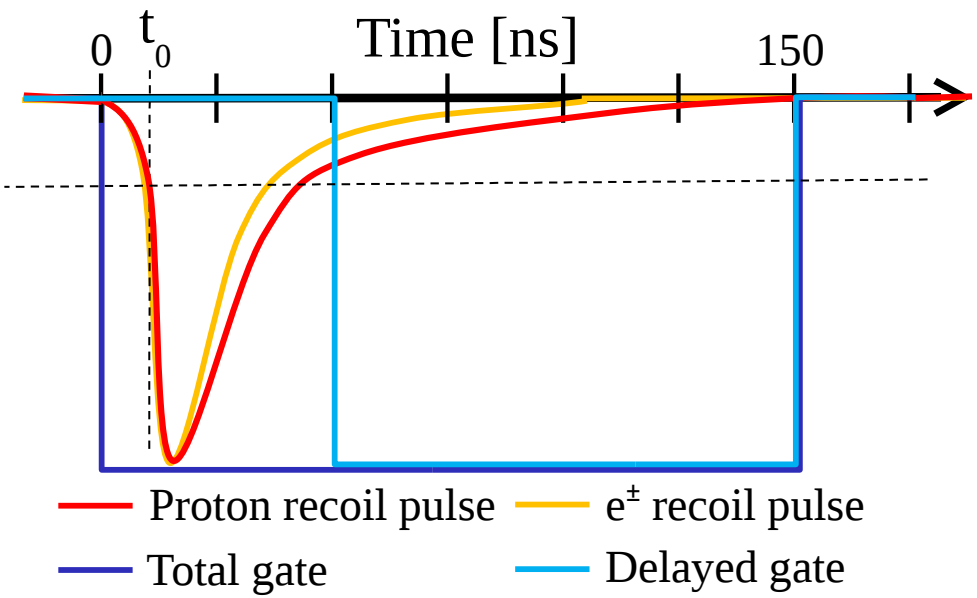


Nucifer integration

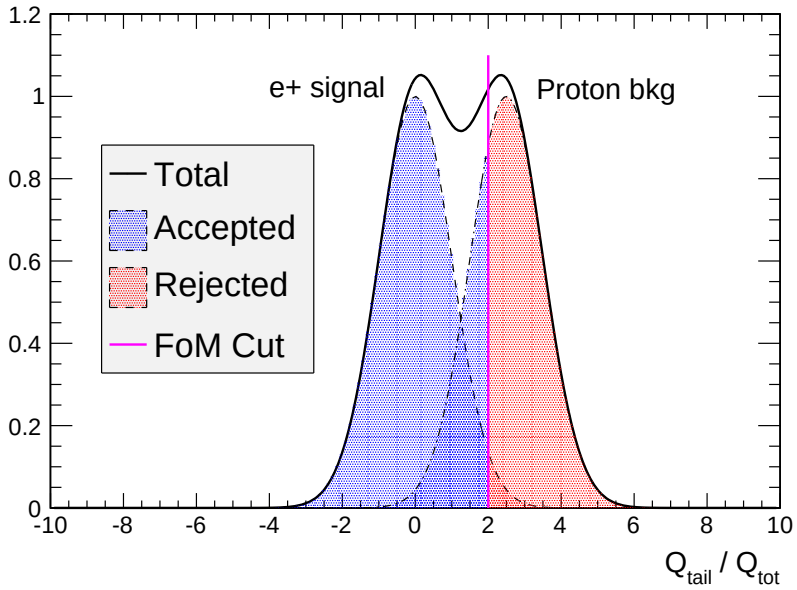


PMT pulse and fast neutron rejection



- Time t_0: needed for coincidence
- Total charge Q_{tot}: energy
- Delayed charge Q_{tail}: particle identification



- $Q_{\text{tail}}/Q_{\text{tot}}$ ratio allows (partial) identification of proton recoils
- Rejection of fast neutron induced correlated bakground

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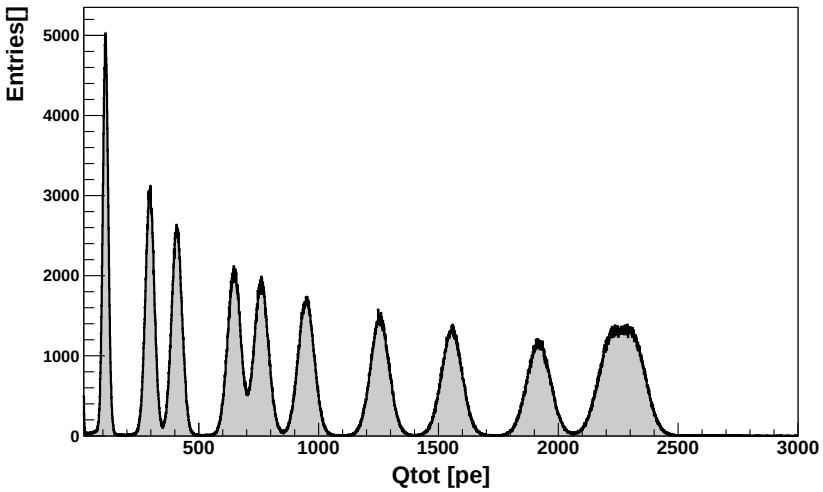
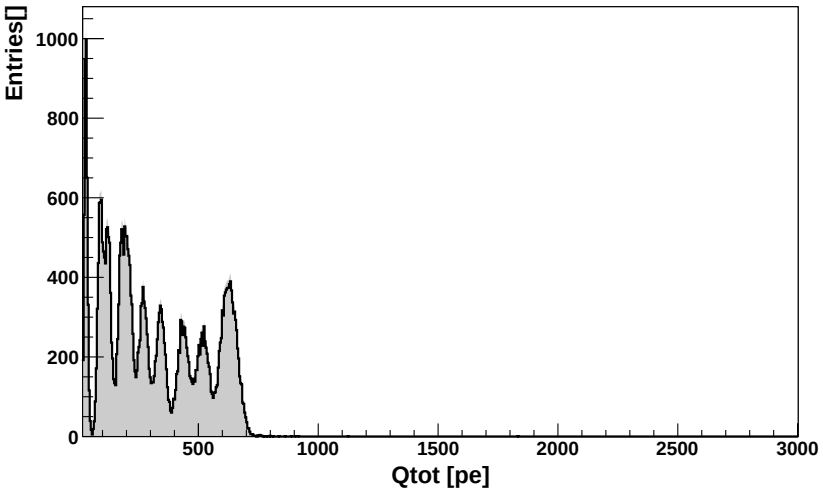
Liquid scintillator

- After long awaited agreement from safety agency (ASN), deployment was completed in Spring 2012

Response of the detector to calibration LED



Undoped test liquid
(LAB+PPO+Bis-MSB)

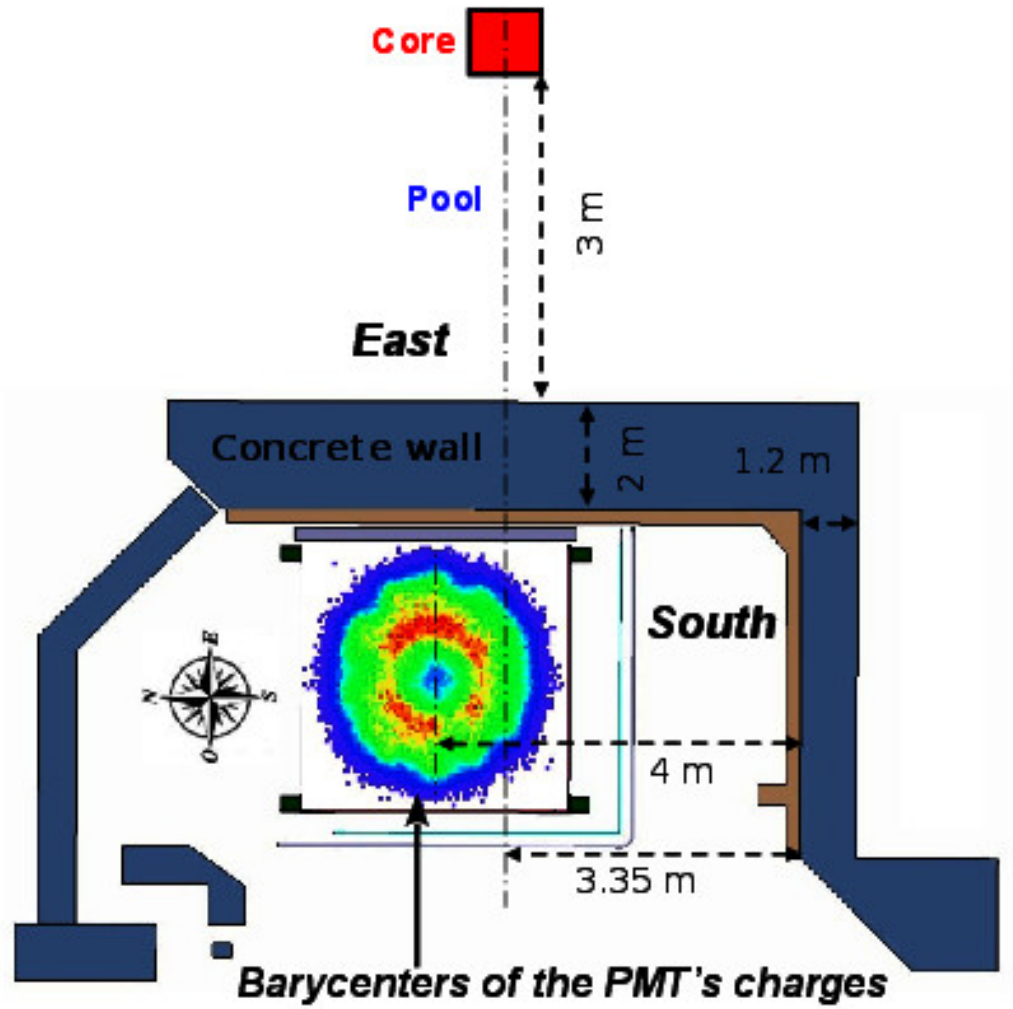


Gd-loaded commercial liquid
(EJ335)

- **Unexpected short attenuation length of liquid scintillator**
- Change liquid scintillator with a new liquid produced by the MPIK Heildelberg

Reactor induced background

- Reactor OFF background on expectation

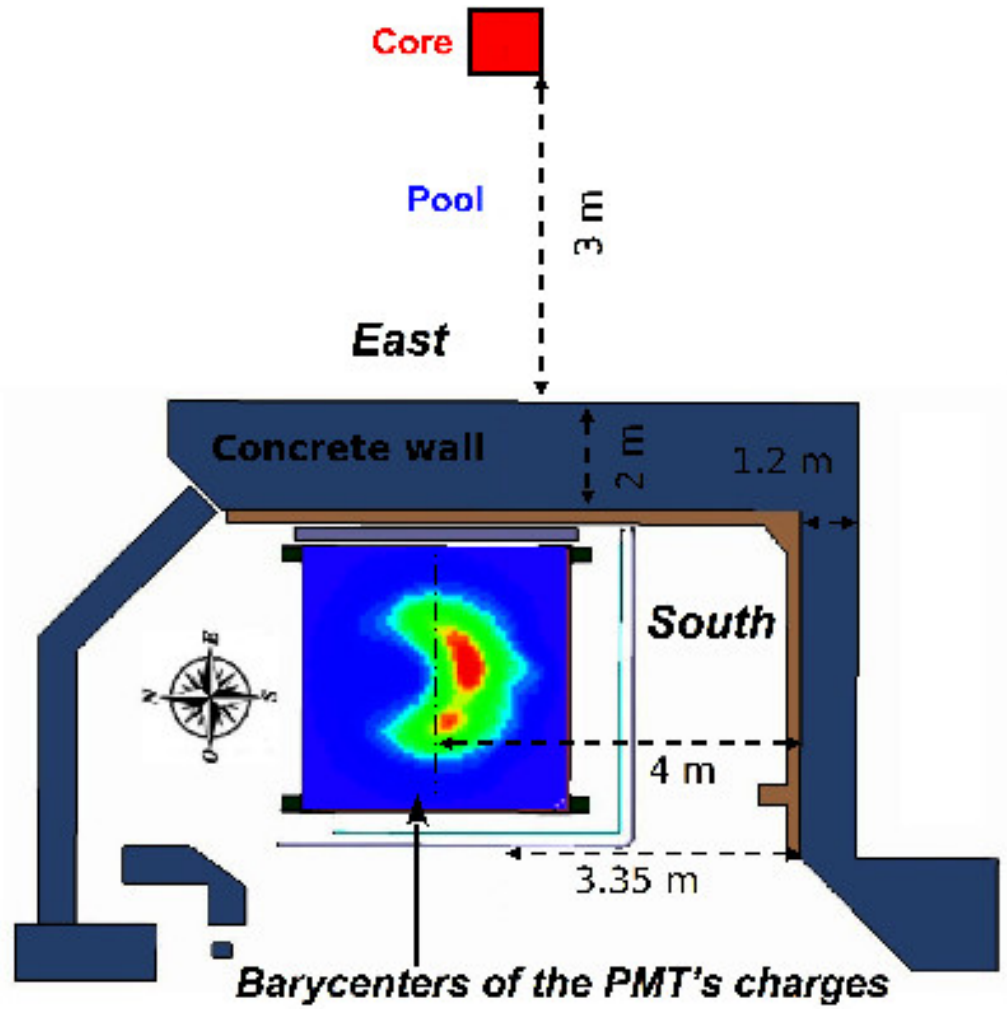


Reactor induced background

- Reactor OFF background on expectation
- Unexpected reactor induced background

  $S/B \sim 1/1000$

  - Point to South, but reactor at East



Reactor induced background

- Reactor OFF background on expectation
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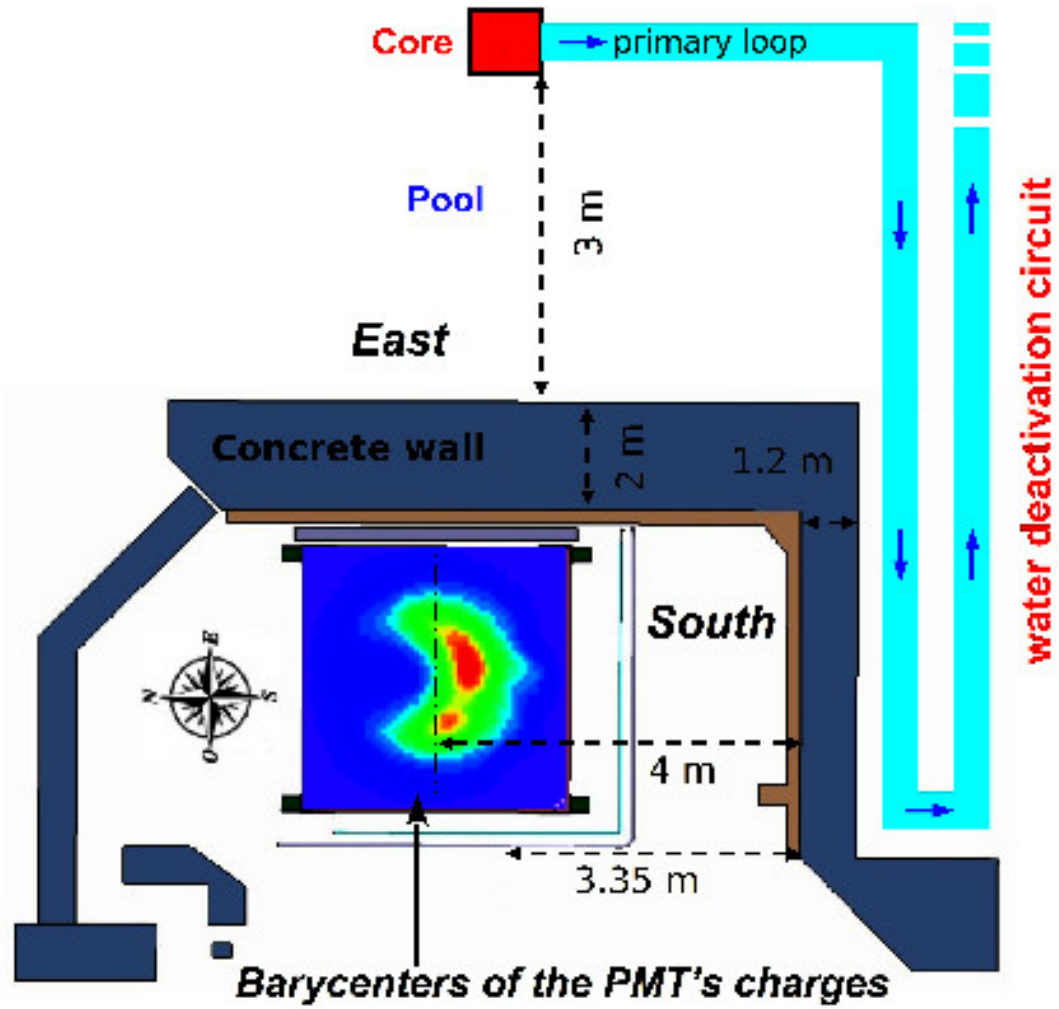
  $$S/B \sim 1/1000$$

  - Point to South, but reactor at East
- Primary loop water activation
  - High energy γ leakage from $^{16}\mathrm{N}$ decay



Reactor induced background

- Reactor OFF background on expectation
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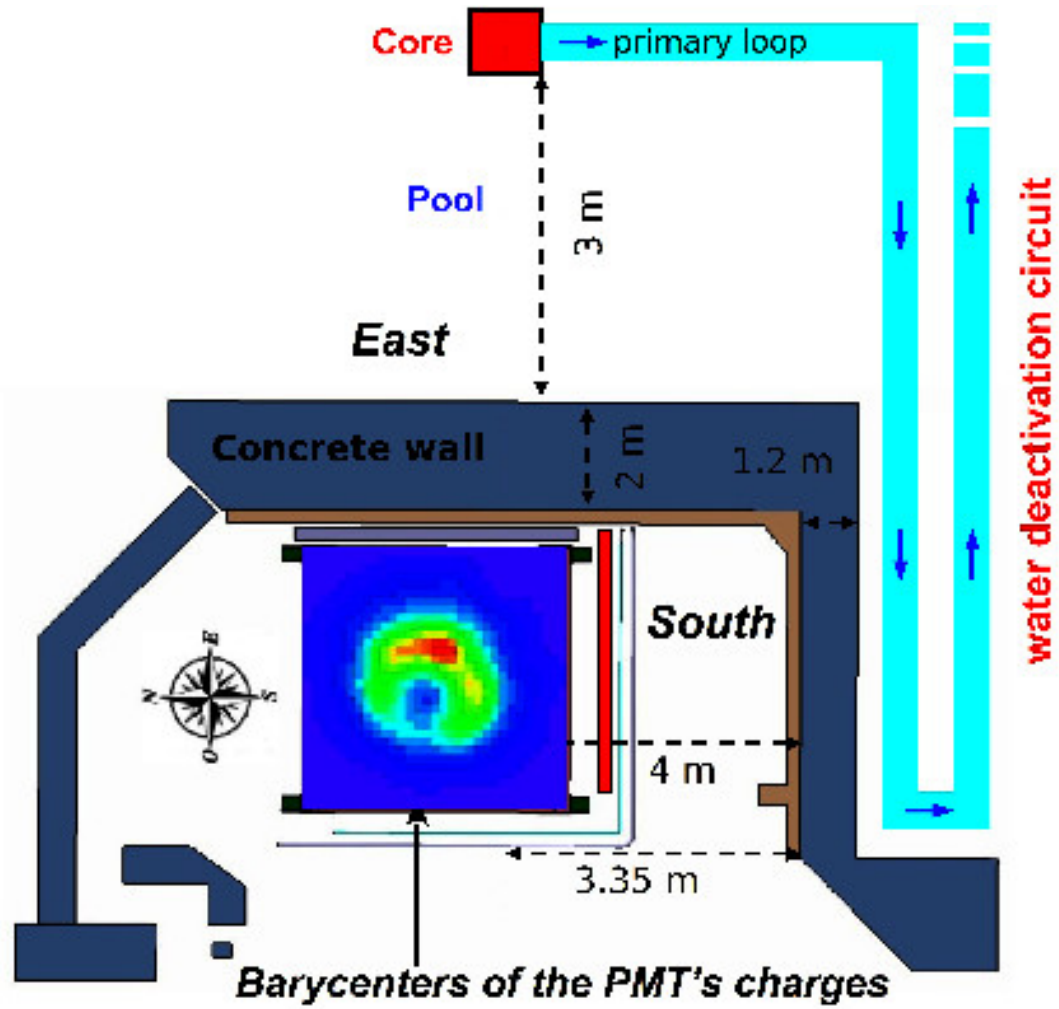
  $$S/B \sim 1/1000$$

  - Point to South, but reactor at East
- Primary loop water activation
  - High energy γ leakage from $^{16}\mathrm{N}$ decay
- New South lead wall $\Rightarrow S/B \sim 1/30$ Spring 2013

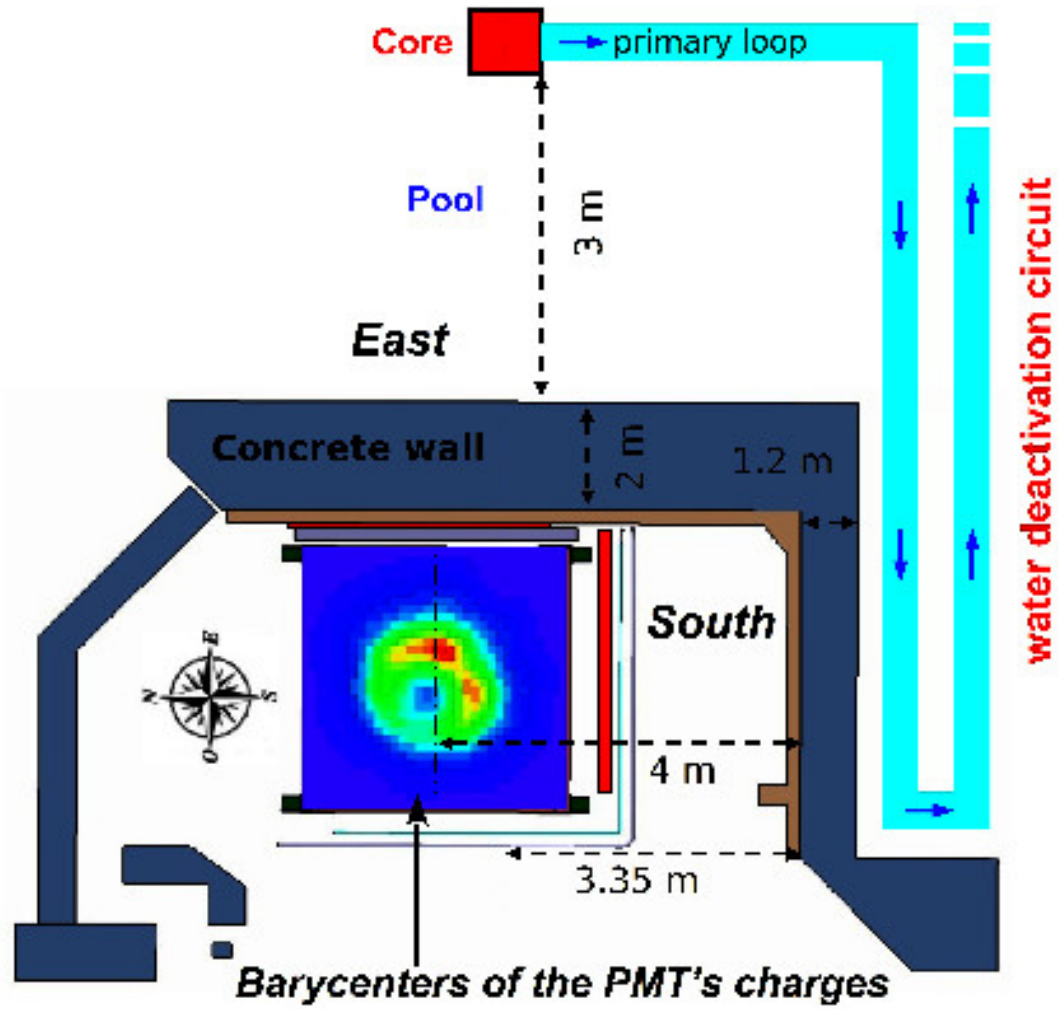


Reactor induced background

- Reactor OFF background on expectation
- Unexpected reactor induced background

  $$S/B \sim 1/1000$$

  - Point to South, but reactor at East
- Primary loop water activation
  - High energy γ leakage from $^{16}\mathrm{N}$ decay
- New South lead wall $\Rightarrow S/B \sim 1/30$ Spring 2013
- New East lead wall $\Rightarrow S/B \sim 1/10$ Spring 2014



Outlook

1. Detector characterization
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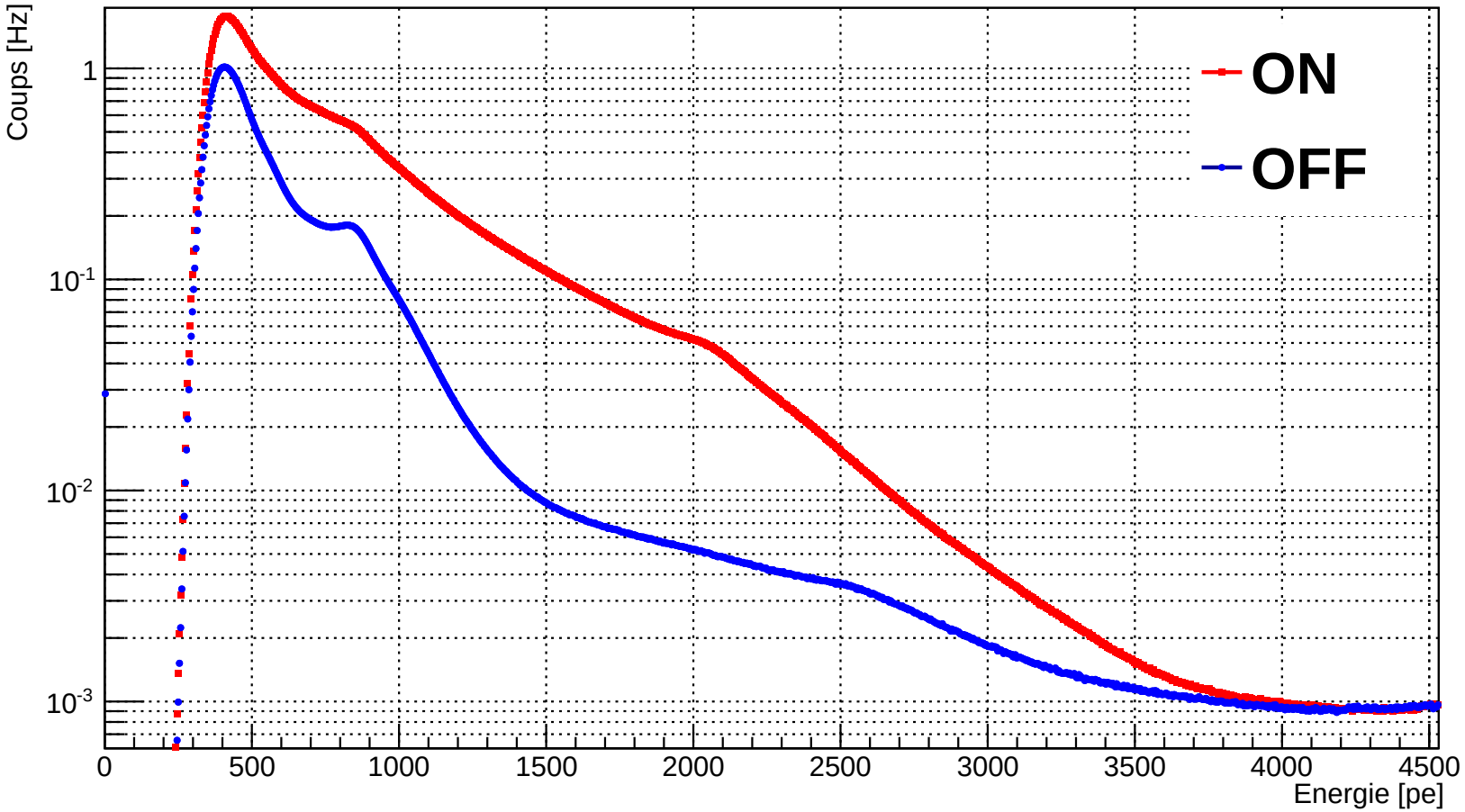
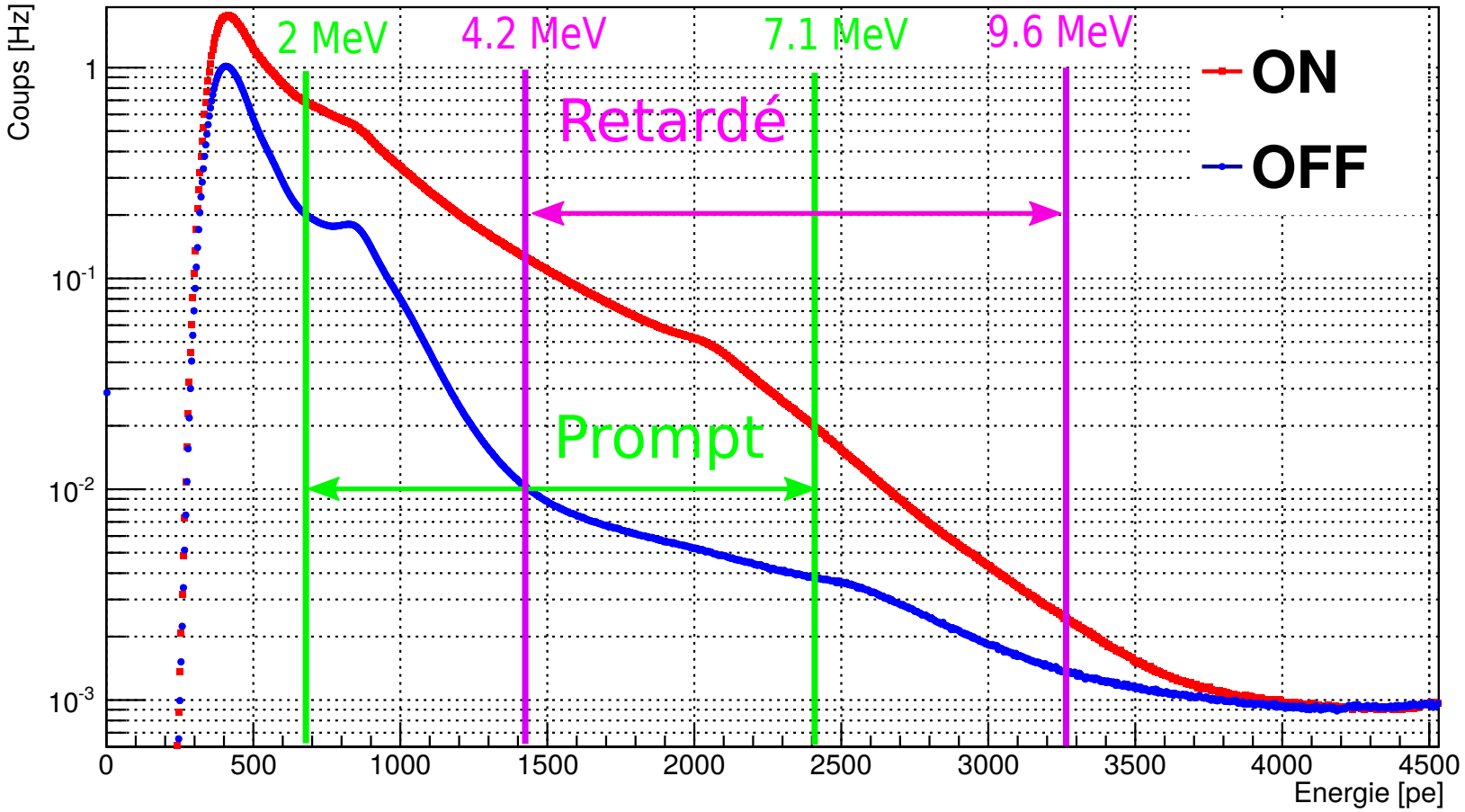
Raw spectra



- Calibration: 340 PhotoElectron(pe)/MeV
- Trigger rate: 500–600 Hz (including $\sim$ 350 Hz of muons, 70 Hz of LED)
- Physical events rate above 2 MeV threshold:
  65.7 Hz reactor OFF and 177.1 Hz reactor ON

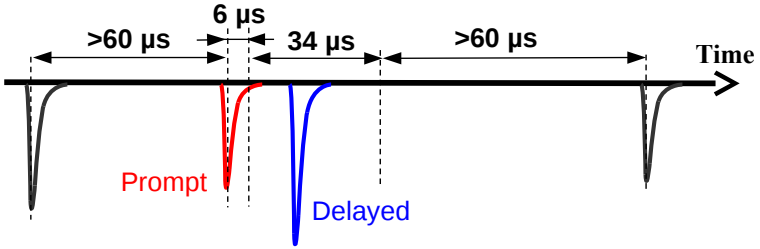
Energy cut



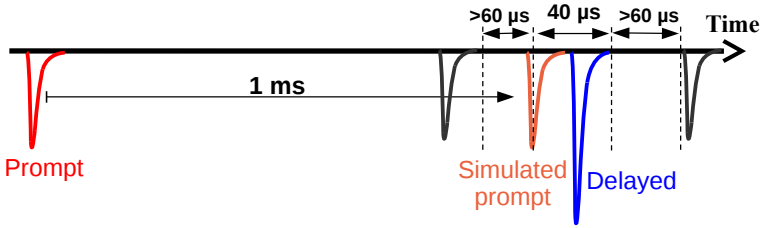
- Prompt rate: 75.4 Hz reactor ON (16.1 Hz OFF)
- Delayed rate: 15.7 Hz reactor ON (1.6 Hz OFF)

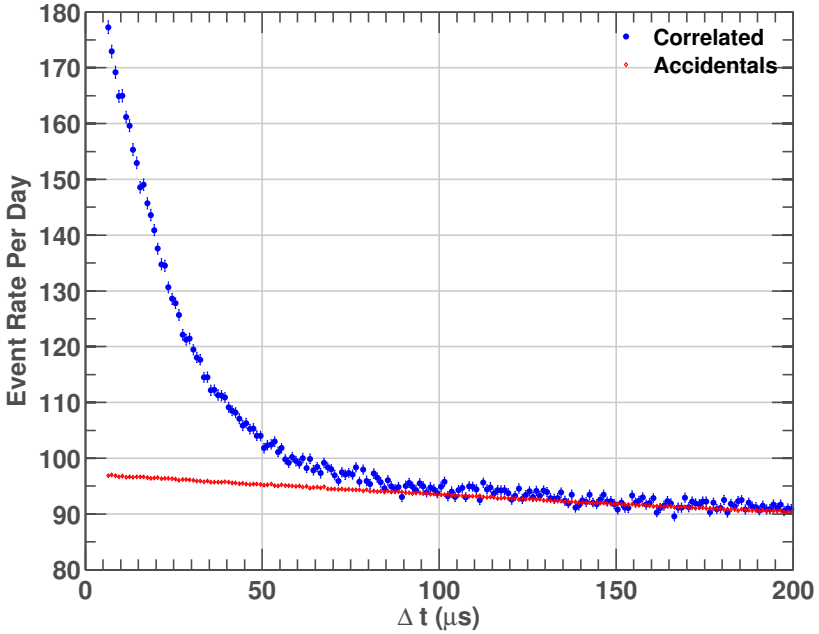
Time cut

Correlated events



Accidental background measurement

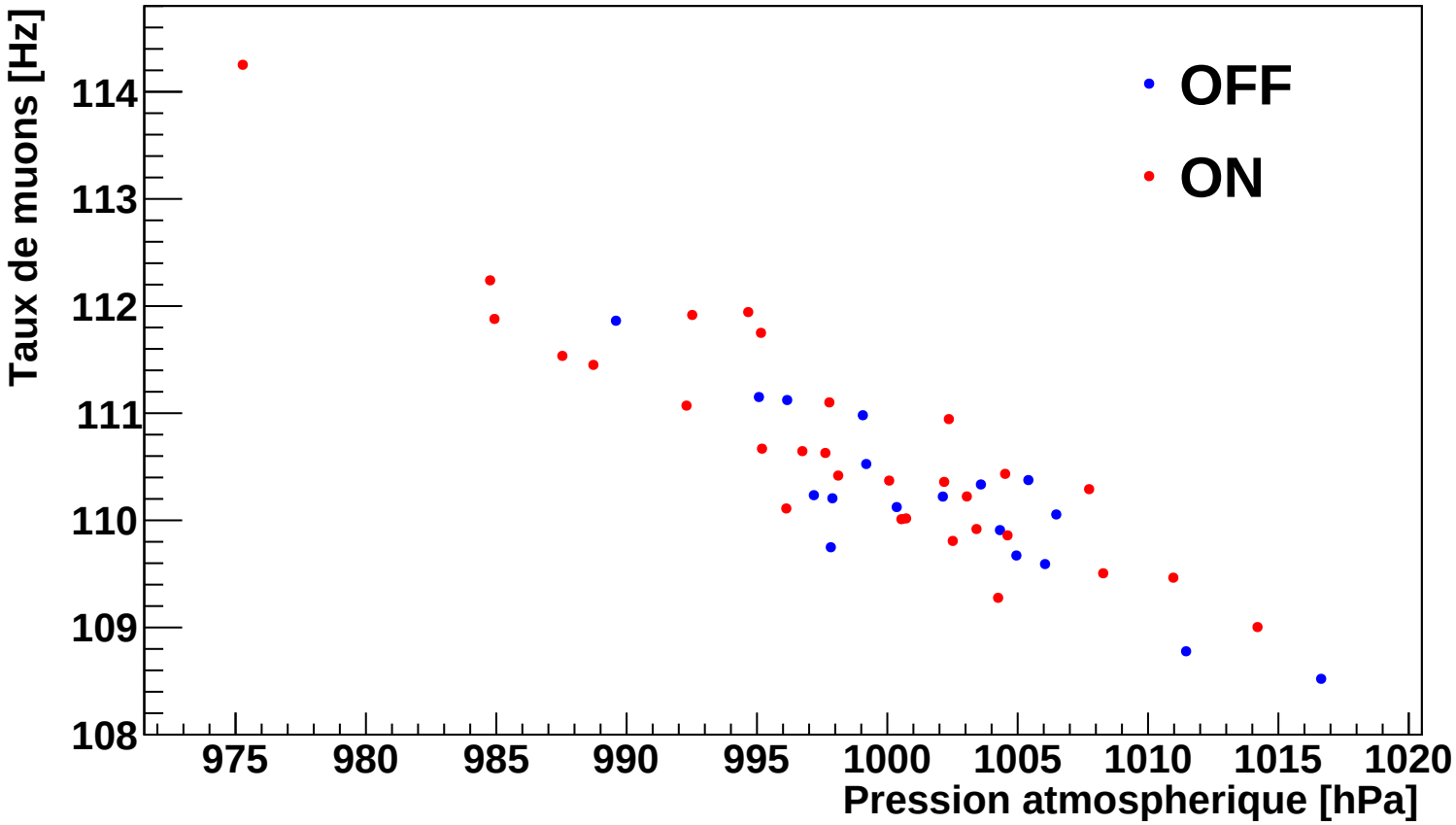




- Correlated pairs:
  - Time between prompt and delayed events: $6\,\mu s < \Delta t < 40\,\mu s$
  - Muon veto: $100\,\mu s$, plus correction factors for muons between a pair
  - Multiplicity cut: no event $60\,\mu s$ before prompt and $100\,\mu s$ after, impact on efficiency measured with LED triggers
- Accidental background measured online with 100 shifted prompt events
- **4733.1 ± 5.7 correlated/day and 3332.8 ± 0.5 accidental/day reactor ON**

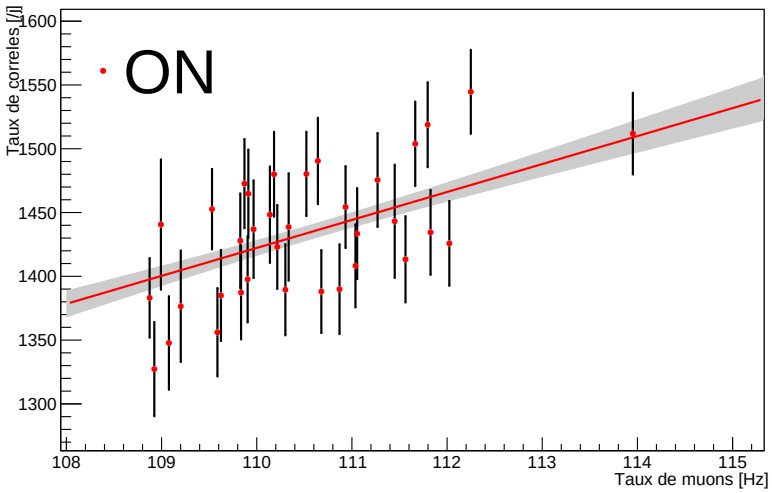
Reactor OFF correlated background (1)

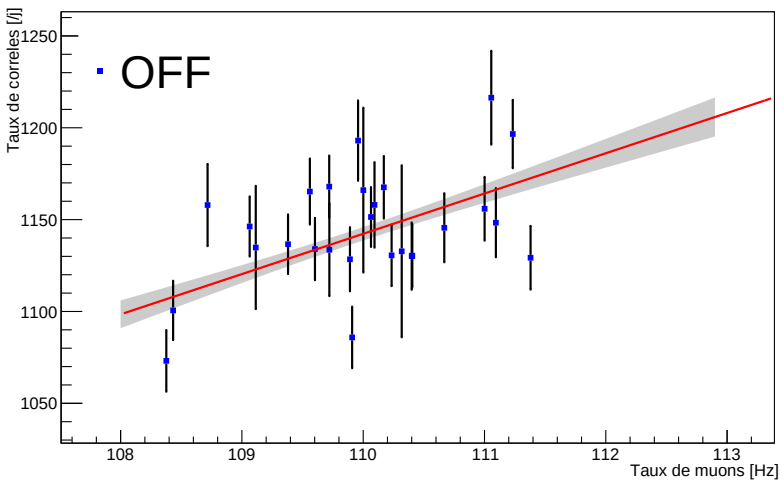
- Mean correlated event rate with reactor OFF: 1202.4 ± 3.4 pairs/day (PSD not stable enough at month scale to be used, would reject $\sim 3/4$)
- But the muon rate depends on the atmosphere, mostly on pressure



Reactor OFF correlated background (2)

- Linear modelling of correlated event rate with muon rate





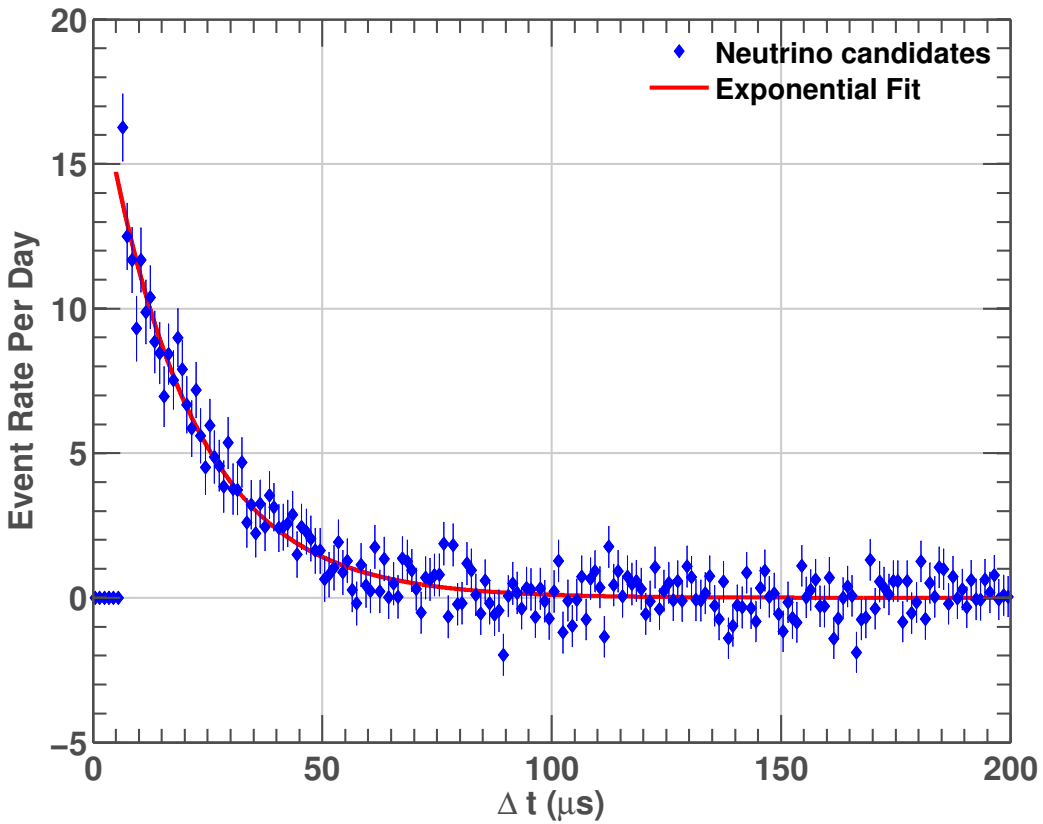
$$\tau_{\mathrm{corr}}^{\mathrm{ON}}(\tau_\mu) = 22,76 \times \tau_\mu - 1082$$

$$\tau_{\mathrm{corr}}^{\mathrm{OFF}}(\tau_\mu) = 22,76 \times \tau_\mu - 1361$$

- Same slope reactor ON and reactor OFF $\Rightarrow$ correct $\tau_{\mathrm{corr}}^{\mathrm{OFF}}$ with τ_μ^{ON}

Neutrino rate

$$\tau_{\overline{\nu_e}}^{ON} = \tau_{corr}^{ON} - \tau_{acc}^{ON} - \left(\tau_{corr}^{OFF}(\tau_{\mu}^{ON}) - \tau_{acc}^{OFF}\right)$$

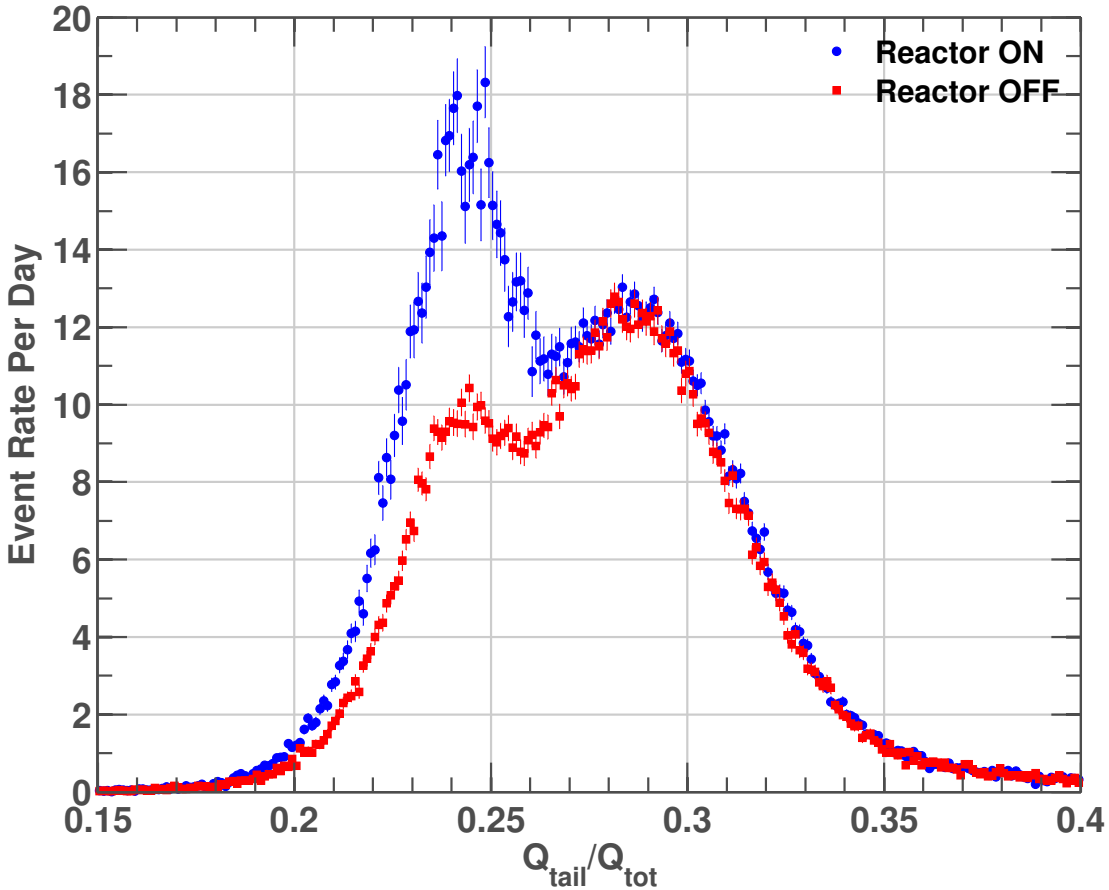


- Characteristic time: $19.7 \pm 0.8\,\mu s$, constant compatible with zero: 0.01 ± 0.08
- $0.1\,\%$ on accidental background $\Rightarrow$ control of the subtraction

$281.1 \pm 7.1\,\overline{\nu_e}$/day detected in Nucifer

Could it be a reactor correlated background ?

- Results confirmed by 2 independent codes, both validated on simulation
- (γ,n) neutrons are not energetic enough (E_n <3 MeV + quenching $\Rightarrow$ signal < 1 MeV)
- **The excess is only made of $e^{\pm}$ recoil** $\Rightarrow$ no fast neutrons from core



- **Accidental rate divided by 3 with last shielding wall but neutrino rate constant**

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Neutrino propagation from reactor to detector

Detection rate:

$$\tau_{\overline{\nu_e}}(t) = \frac{P_{\mathrm{th}}(t)}{\sum_k \alpha_k(t) E_k} \rho_p \sum_k \alpha_k(t) \int_0^\infty S_k(E)\, \sigma_{\overline{\nu_e}}(E)\; l_{\mathrm{eff}}\, \mathrm{d}E$$

with $k \in \{^{235}\mathrm{U}, ^{238}\mathrm{U}, ^{239}\mathrm{Pu}, ^{241}\mathrm{Pu}\}$

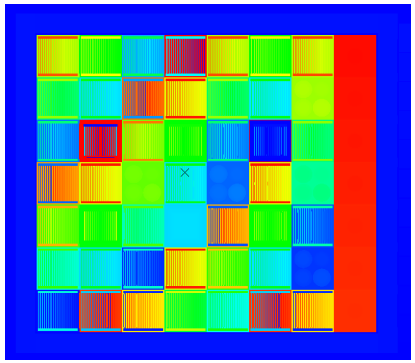
$$l_{\mathrm{eff}} = \iiint_{\mathscr{V}_\mathrm{c}} \Psi_{\mathrm{f},k}(t, \overrightarrow{r_\mathrm{c}})) \iiint_{\mathscr{V}_\mathrm{d}} \frac{\varepsilon(E, \overrightarrow{r_\mathrm{d}})}{4\pi \left(\overrightarrow{r_\mathrm{d}} - \overrightarrow{r_\mathrm{c}}\right)^2} \mathrm{d}^3\overrightarrow{r_\mathrm{d}}\, \mathrm{d}^3\overrightarrow{r_\mathrm{c}} \sim \frac{\varepsilon\, \mathscr{V}_\mathrm{d}}{4\pi L^2}$$

experimental data — published data — simulated data

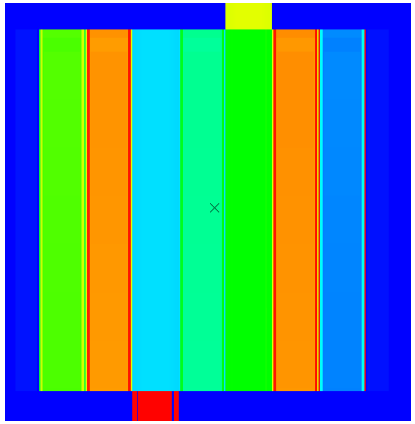
Full Monte Carlo simulation scheme:

- Reactor simulation to get $\alpha_k(t)$ and $\Psi_{\mathrm{f},k}(t, \overrightarrow{r_\mathrm{c}})$ $\Rightarrow$ TRIPOLI-4®
- Propagation simulation to get l_{eff} $\Rightarrow$ NuMC (Neutrino Monte Carlo)
- Detector simulation to get $\varepsilon(E)$ $\Rightarrow$ Geant4

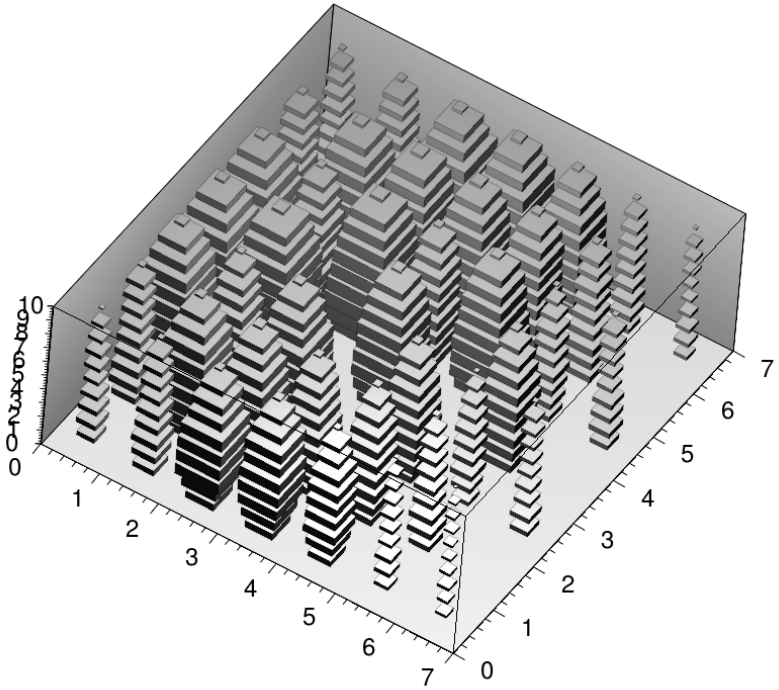
TRIPOLI-4® simulation of the core



XY cut of Osiris in TRIPOLI-4®

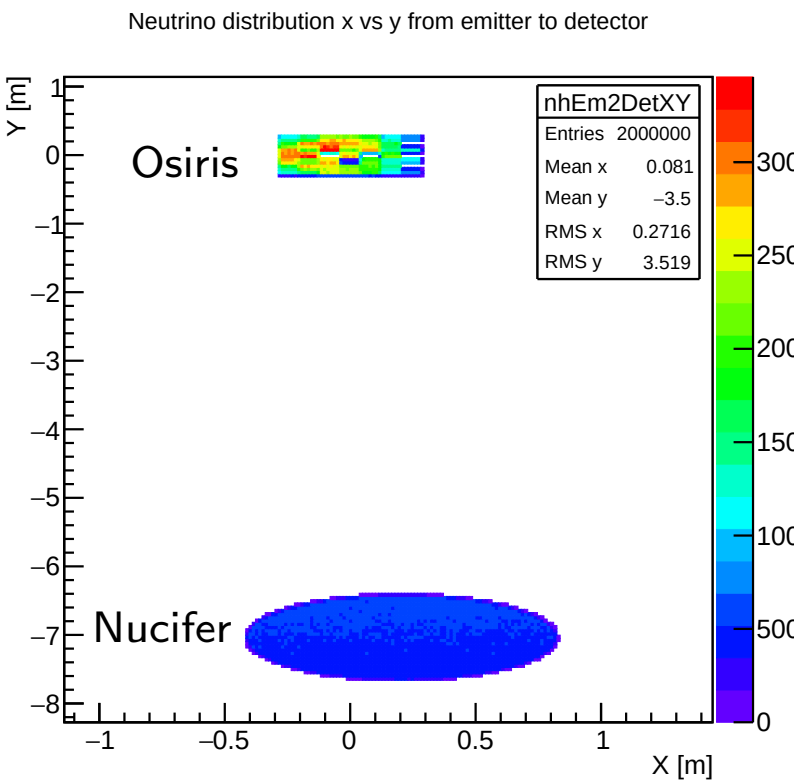


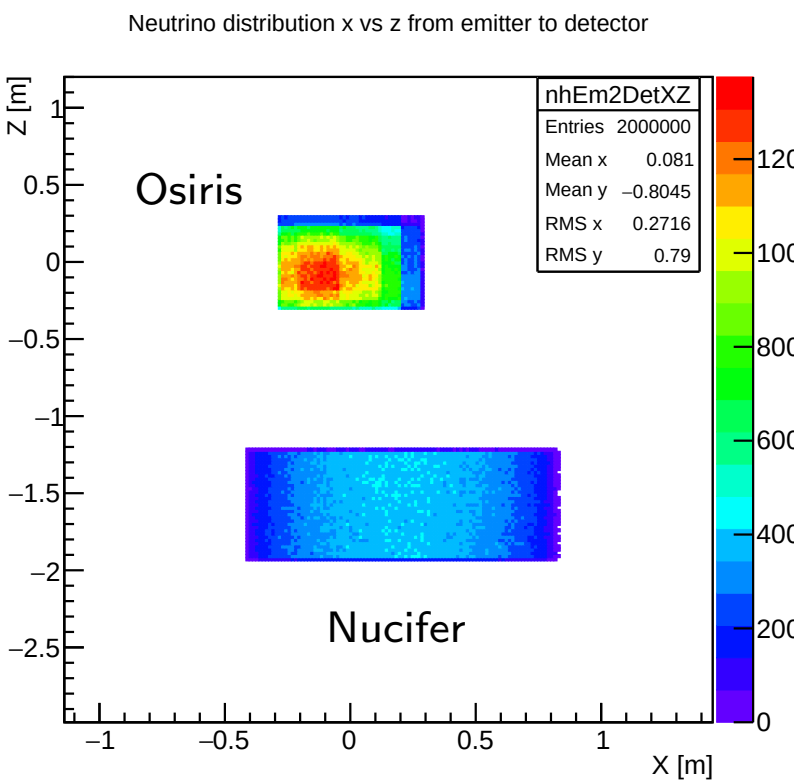
XZ cut of Osiris in TRIPOLI-4®



3D distribution of ^{235}U fission in Osiris

NuMC propagation

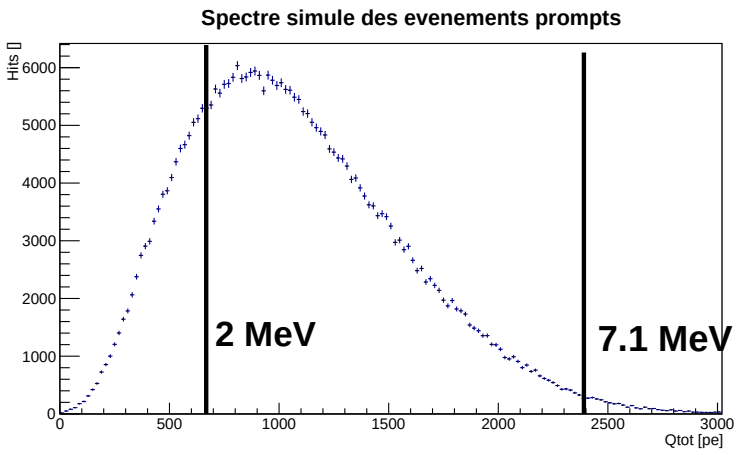


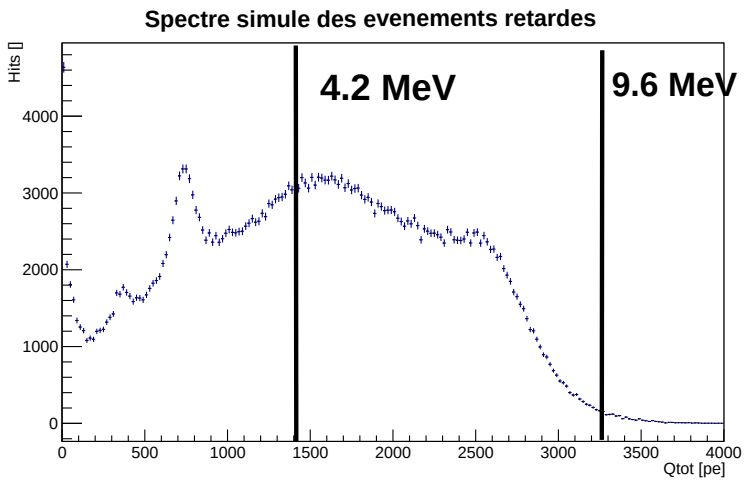


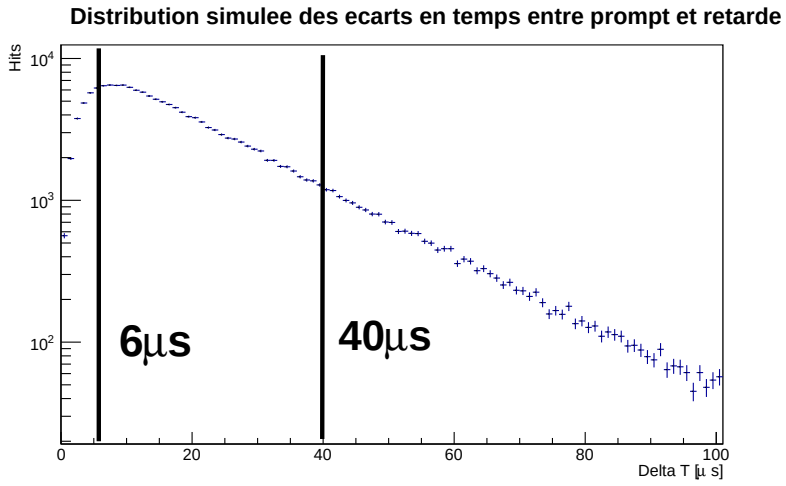
- $\overline{\nu_e}$ shot in the core according to TRIPOLI-4® fission distributions
- Isotropic propagation, measurement of the length of the path crossing Nucifer
- Generation of e^+/neutron pairs according to double differential cross-section

Geant4 simulation of efficiency

- $e^+ / {}^1_0\mathrm{n}$ generated according to fission distribution and precise IBD kinematic:





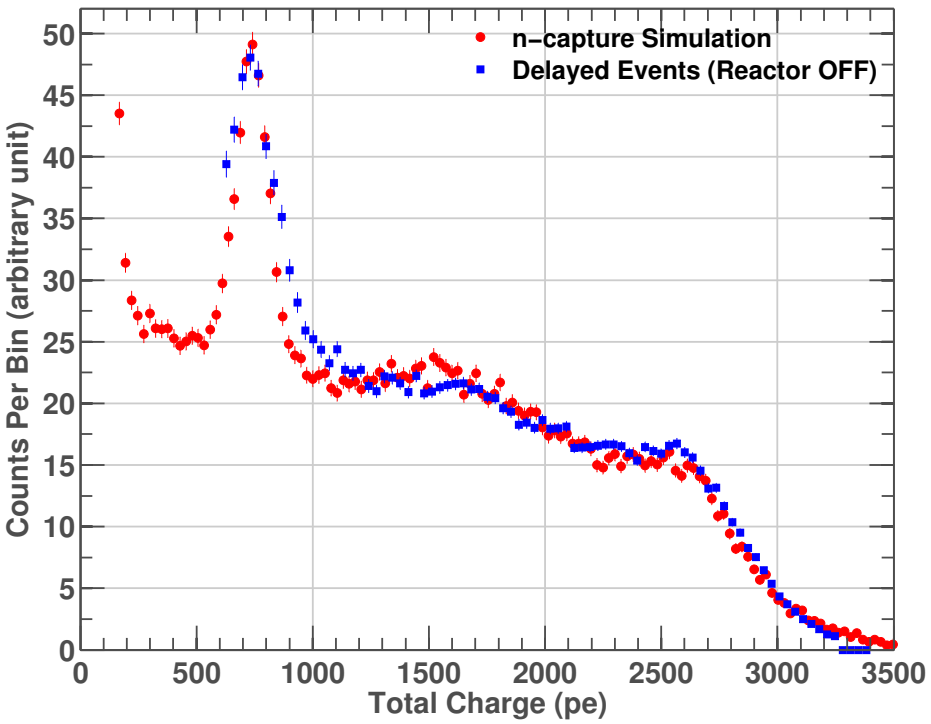


Selection cut	Efficiency (%)
$6\,\mu\mathrm{s} < \Delta t < 40\,\mu\mathrm{s}$	75.1
Energy cuts	41.6
$\varepsilon_{\mathrm{det}}$	30.3

- Time and energy cuts are *not* independent, efficiency is evaluated at once running data analysis on MC

+ neutron capture time corrected with TRIPOLI-4®

Energy scale uncertainty



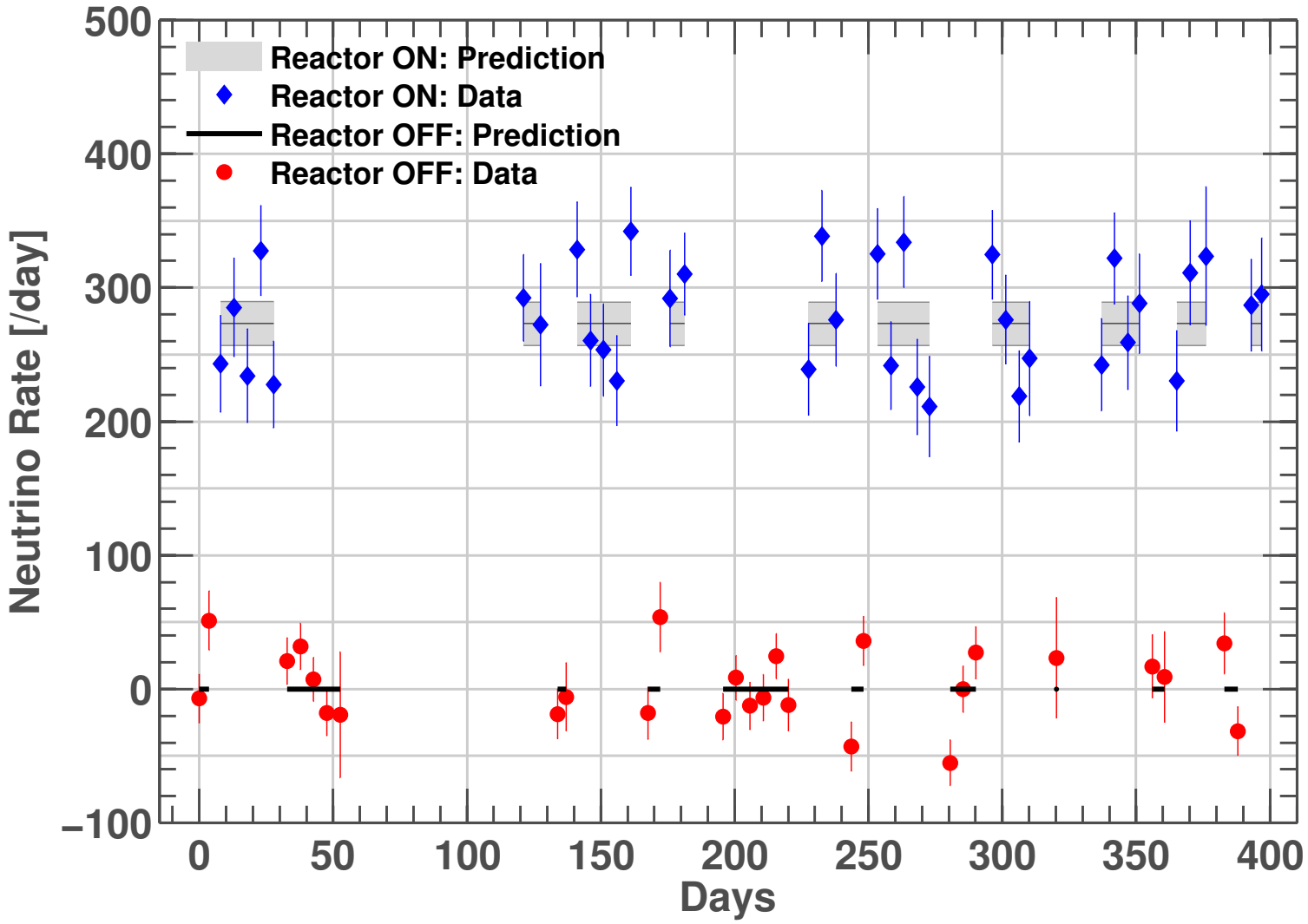
- Uncertainty on energy scale given by comparison with the simulation
- Comparison between neutrons shot uniformly inside the shielding and delayed events reactor OFF
- Maximum shift between simulation and data: 2.5 %
- Uncertainty on efficiency induced by energy scale: $\varepsilon = 30.3 \pm 2.1\,\%$
  $\Rightarrow$ **6.3 % uncertainty on neutrino count rate**

Other uncertainties and expected rate

Source	Relative uncertainty (%)
Baseline	3.1
Fission cross-section	2.2
Thermal power	2.0
Fission fractions	1.0
Number of protons	1.2
Sub-total	4.6
Efficiency	6.3
Total	7.8

- Expected neutrino count rate in Nucifer: $280 \pm 20\,\overline{\nu_e}$/day
- Total uncertainty of 7.8 %, dominated by energy scale
- Good agreement with measurement: $281.1 \pm 7.1\,\overline{\nu_e}$/day
- The anomaly would decrease this expected rate by 6–7 %
- Uncertainties too large to conclude about anomaly

Count rate evolution

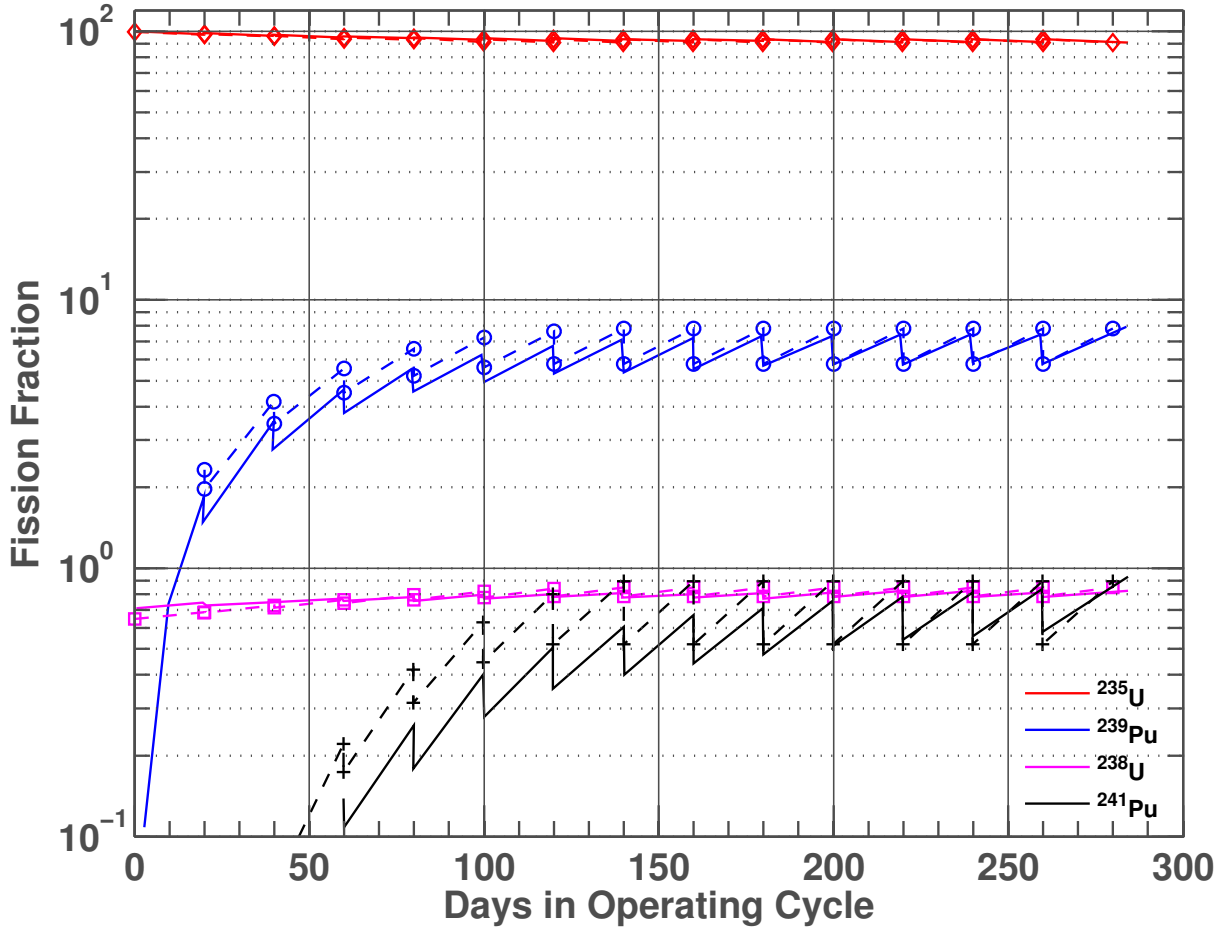


Outlook

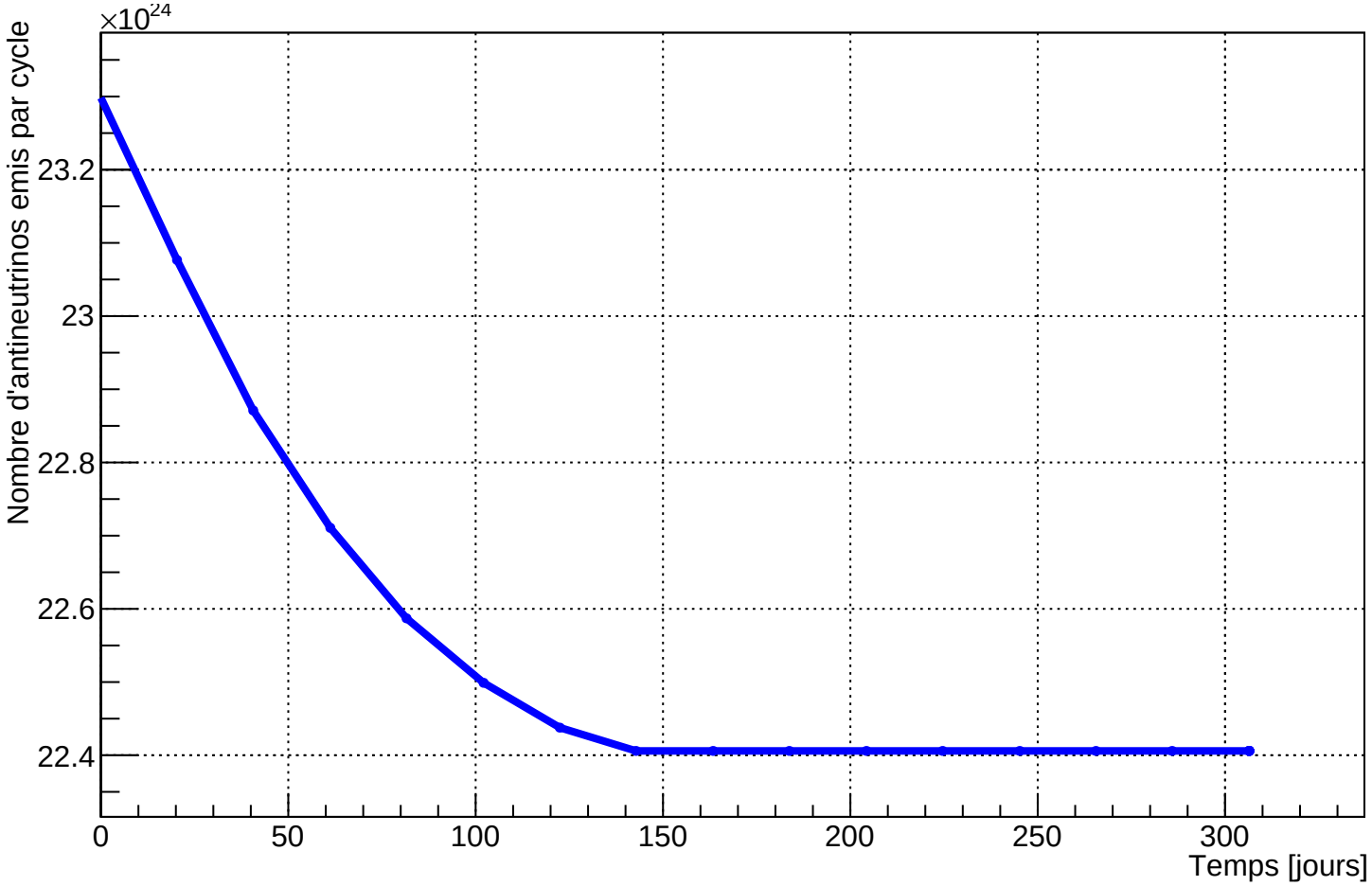
1. Detector characterization
   - Detector and site
   - Upgrades
2. Results
   - Measured neutrino count rate
   - Predicted neutrino count rate
   - Potential application: sensitivity to plutonium
3. Conclusion and perspectives

Simplified evolution of Osiris fuel

- Simplified simulation with the FIASCO code (written at IRFU-SPhN)
- Start with 82 kg of ^{238}U and 20 kg of ^{235}U
- Reloading by $1/7^{\mathrm{th}}$ of core each 20 days until stable composition is reached



Simplified evolution of neutrino rate

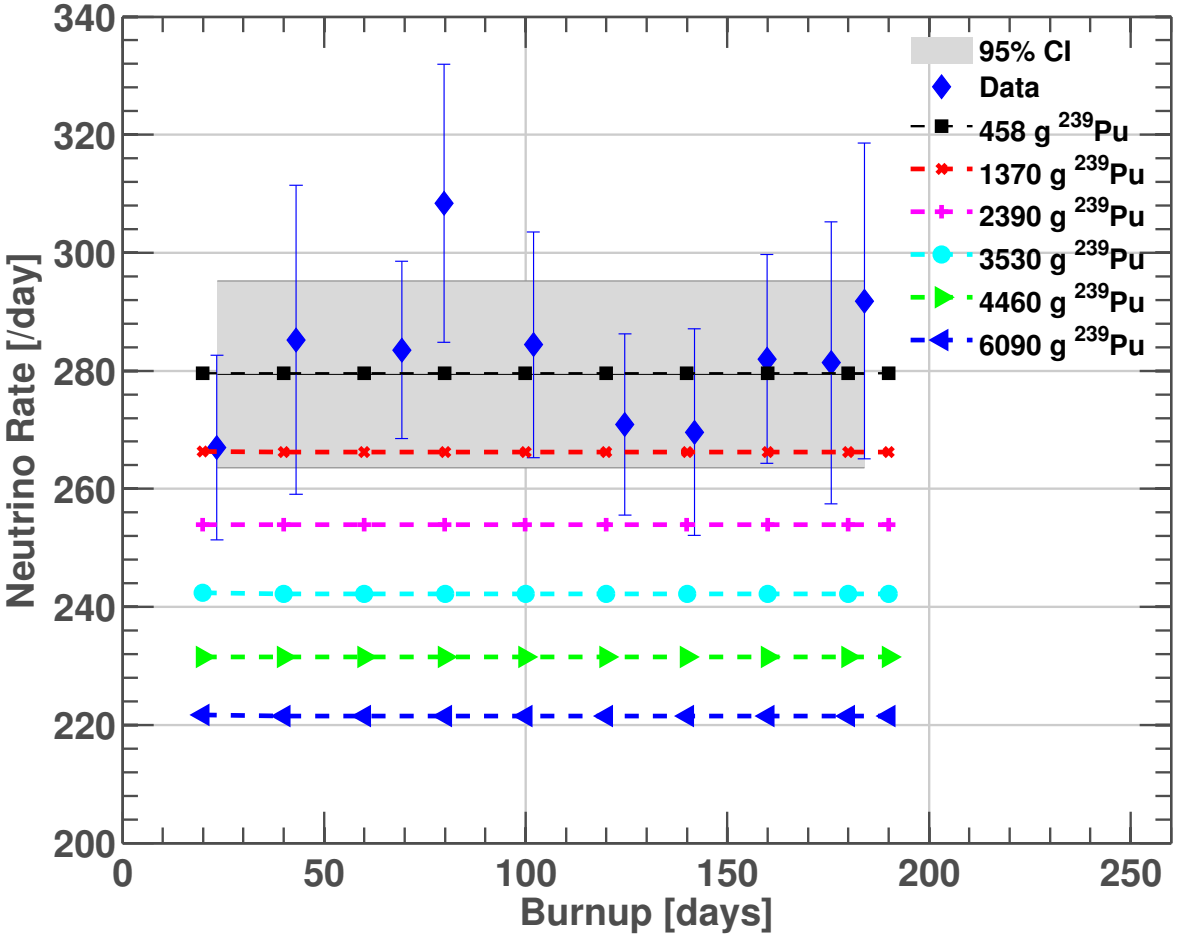


- Neutrino rate only 3.5 % lower with fuel at equilibrium compared to fresh fuel
  ⇒ **No sensitivity to diversion of fuel** (undeclared retrieval of Pu)

Sensitivity to plutonium content

- Other idea: application to control of military Pu destruction by irradiation
- Restart core evolution replacing ^{235}U by ^{239}Pu

Sensitivity to 1.55 kg of Pu @ 95 % CL



Conclusion and perspectives

Conclusion

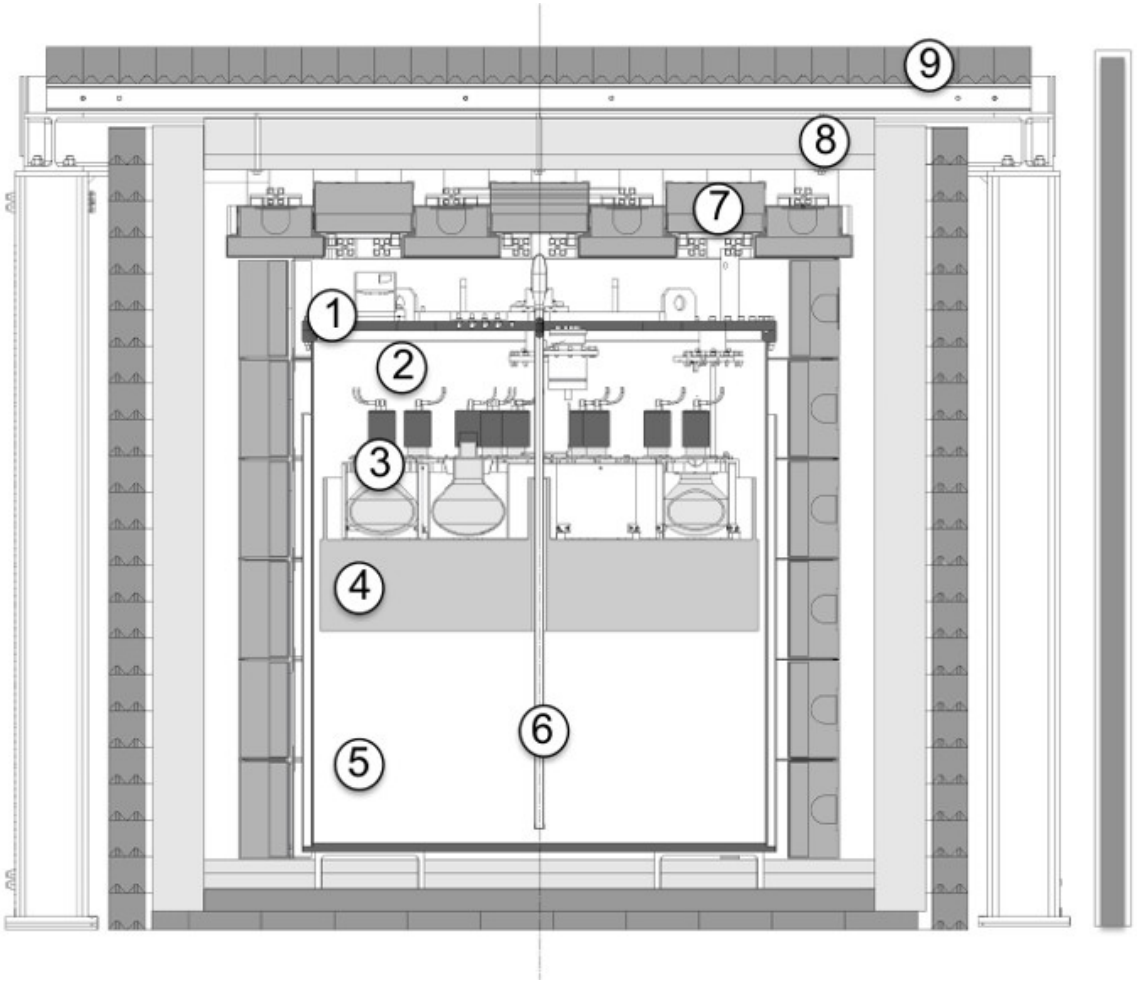
- Nucifer submitted its first paper, reporting neutrino detection at Saclay [1]: $281.1 \pm 7.1\,\overline{\nu_e}$/day measured for $280 \pm 20\,\overline{\nu_e}$/day expected
- High accidental background from the core and the deactivation circuit, even after 2 new lead walls (S/B $\sim$ 1/10)
- Correlated background fluctuating with pressure (S/B $\sim$ 1/3)
- Sensitivity to 1.5 kg of ^{239}Pu if Osiris fuel was made of ^{239}Pu and ^{238}U

Perspectives

- Osiris will definitively stops at the end of 2015
- New analysis ongoing: Geant4 tuning, re-evaluation of systematics, inclusion of latest data
- Deployment on a power plant under study: at 20 m, $490\,\overline{\nu_e}$/day/GW_{th} expected, no accidental background $\Rightarrow$ no passive shielding to deploy and enhanced sensitivity

Back-up

Detector design



① Stainless steel tank Teflon coated

② Nitrogen atmosphere

③ 16 PMTs

④ Acrylic buffer

⑤ Target Liquid (0.8 m^3)

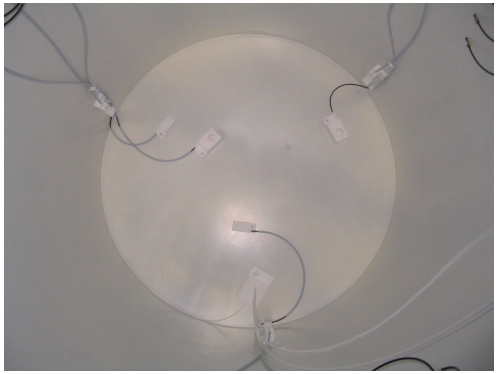
⑥ Calibration tube

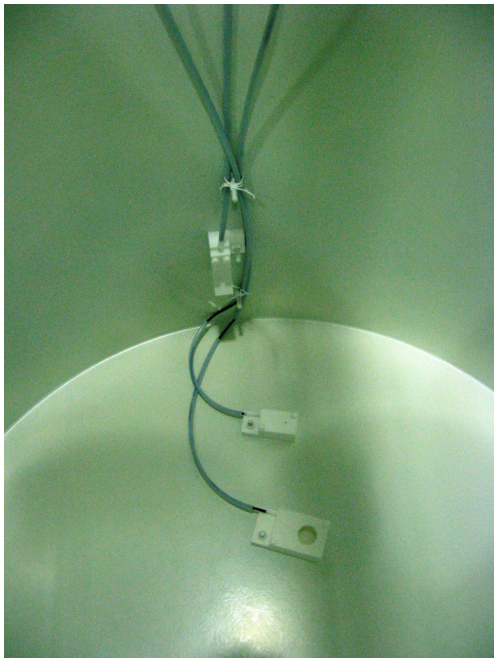
⑦ Cosmic ray veto

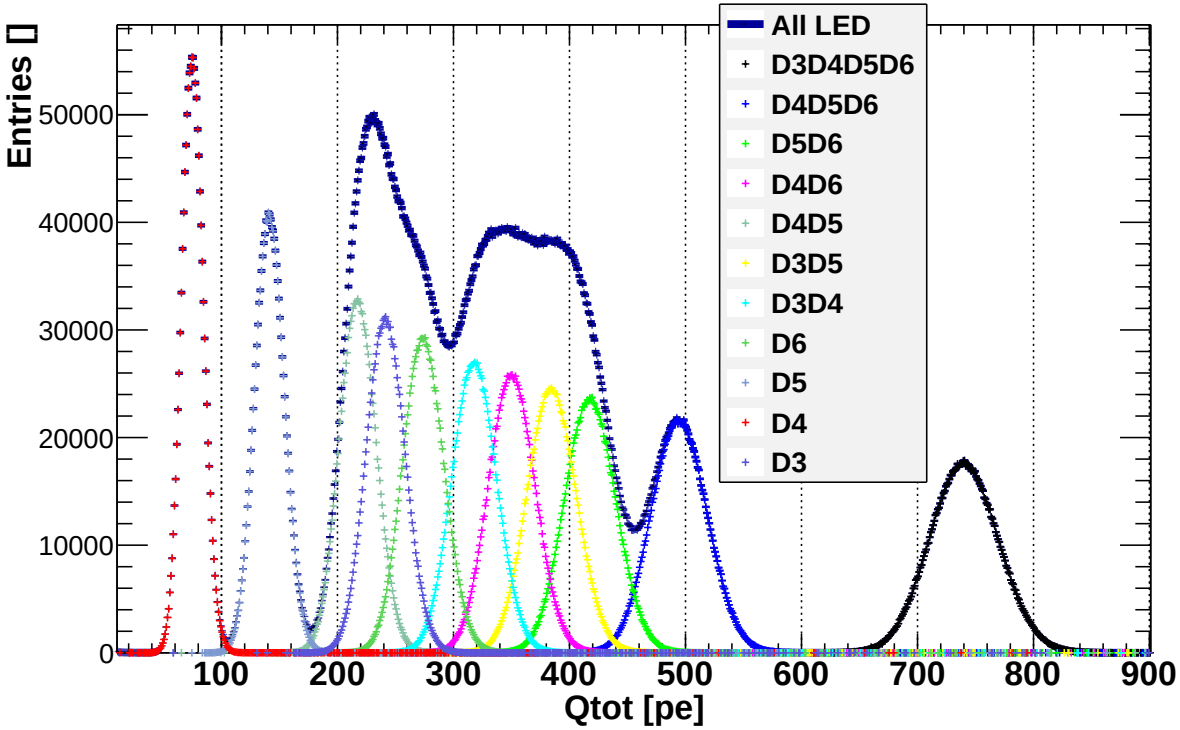
⑧ 15 cm B-doped polyethylene

⑨ 10 cm Lead

LED, optic fibers and diffusers

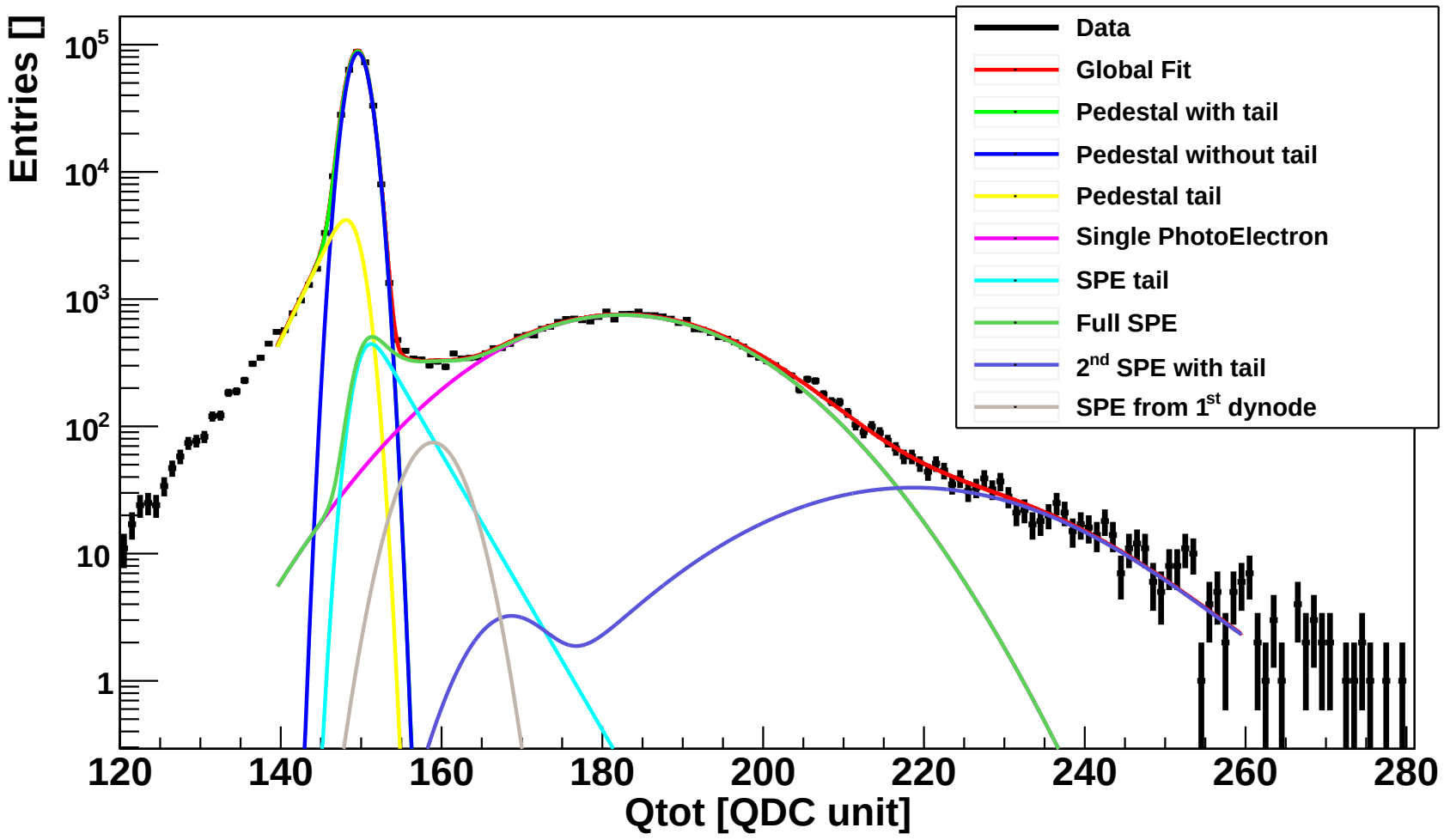






- Several optics fibers link LEDs to diffusers at the bottom of Nucifer
- 4 linearity and liquid stability LED
- 1 single photo electron LED

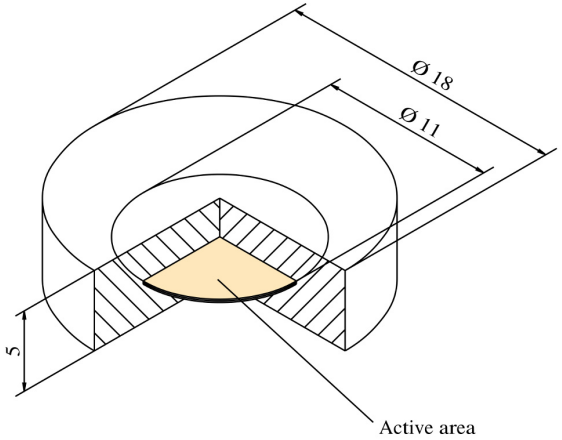
Time and charge auto-calibration

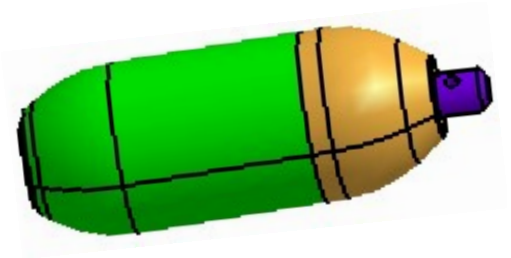


Automatic fit of pedestal and gain for each channel: charge calibration in PhotoElectron (pe)

Energy calibration with radioactive sources

Source	Reaction	Observable	Energy (MeV)
^{137}Cs	β^-	1 γ	0.661
^{60}Co	β^-	2 γ	1.15 + 1.35
^{22}Na	β^+	2+1 γ	$2 \times 0.511 + 1.25$
AmBe	(α, n)	$\gamma + {}^1_0 n$	4.4 + some MeV





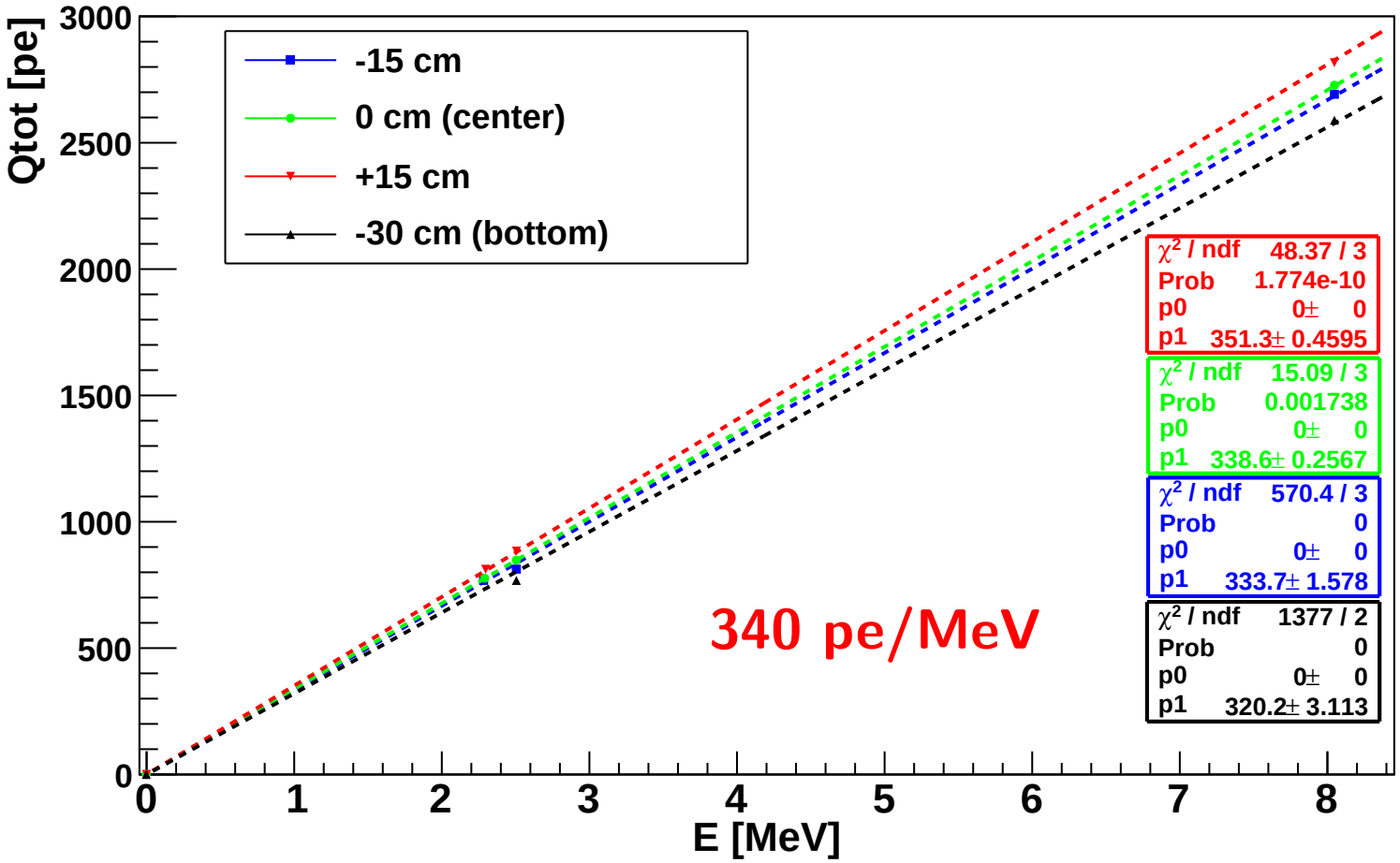
Source holder

Radioactive sources

Source	Period (year)	Reaction	Observable	Energy (MeV)
$^{137}\mathrm{Cs}$	30,1	$^{137}_{55}\mathrm{Cs} \xrightarrow{\beta^-} {}^{137}_{56}\mathrm{Ba} + e^- + \overline{\nu_e} + \gamma$	1 γ	0,611
$^{60}\mathrm{Co}$	5,27	$^{60}_{27}\mathrm{Co} \xrightarrow{\beta^-} {}^{60}_{28}\mathrm{Ni} + e^- + \overline{\nu_e} + \gamma$	2 γ	1,15 and 1,35
$^{22}\mathrm{Na}$	2,60	(a) $^{22}_{11}\mathrm{Na} \xrightarrow{\beta^+} {}^{22}_{10}\mathrm{Ne} + e^+ + \nu_e + \gamma$ (b) $e^+ + e^- \rightarrow 2\gamma$	2+1 γ	2 $\times$ 0,511 and 1,25
AmBe	432	(a) $^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\alpha$ (b) ${}^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{13}_{6}\mathrm{C}^*$ (c) ${}^{13}_{6}\mathrm{C}^* \rightarrow {}^{12}_{6}\mathrm{C}^* + {}^{1}_{0}\mathrm{n}$ (d) ${}^{12}_{6}\mathrm{C}^* \rightarrow {}^{12}_{6}\mathrm{C} + \gamma$	γ and ${}^{1}_{0}n$	4,4 and some MeV

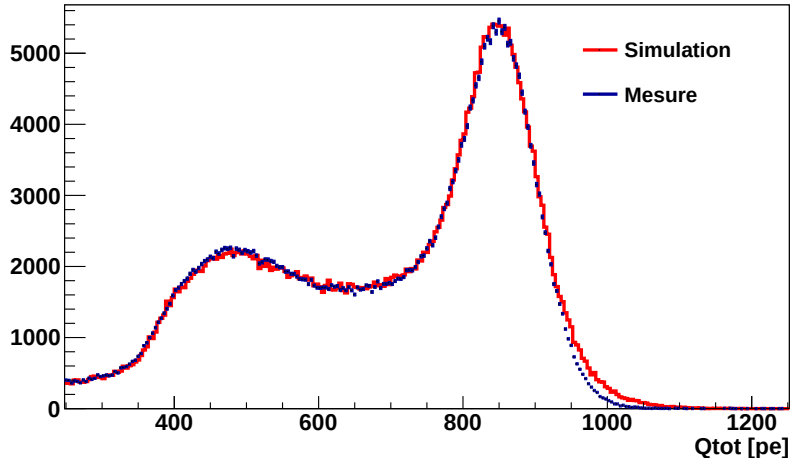
Calibration of the new liquid

- Detector response linear and uniform, light yield 340 pe/MeV

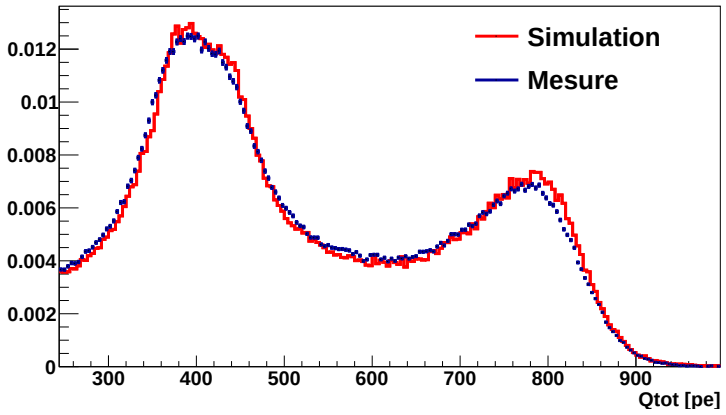


Energy calibration and comparison with Geant4

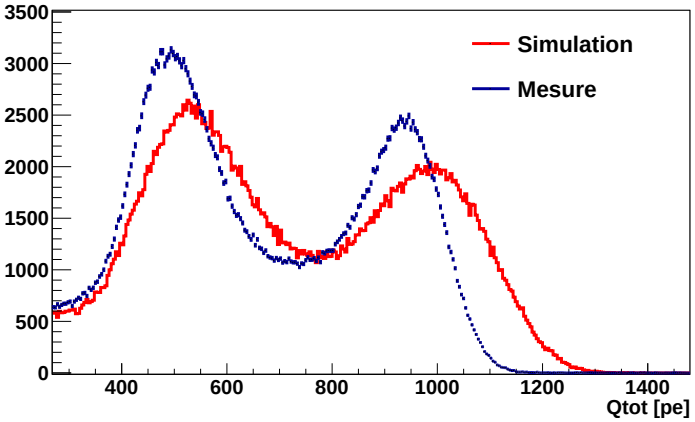
^{60}Co source, middle of the liquid



^{60}Co source, bottom of the liquid



^{60}Co source, top of the liquid



- Good agreement at the center and the bottom but discrepancy near the PMTs

Corrections to rate

$$\tau_{\text{corr}} = \frac{N_{\text{corr}}}{t_{\text{live}}} \qquad \tau_{\text{acc}} = \frac{N_{\text{acc}}}{100\ t_{\text{live}}} \frac{F_\mu}{\epsilon_{\text{LED}}} \qquad \tau_{\text{diff}} = \frac{\tau_{\text{corr}} - \tau_{\text{acc}}}{\epsilon_{\text{LED}}}$$

$$\delta\tau_{\text{corr}} = \frac{\sqrt{N_{\text{corr}}}}{t_{\text{live}}} \qquad \delta\tau_{\text{acc}} = \frac{\sqrt{N_{\text{acc}}}}{100\ t_{\text{live}}} \sqrt{\frac{1}{N_{\text{acc}}} + \left(\frac{\delta F_\mu}{F_\mu}\right)^2 + \left(\frac{\delta\epsilon_{\text{LED}}}{\epsilon_{\text{LED}}}\right)^2}$$

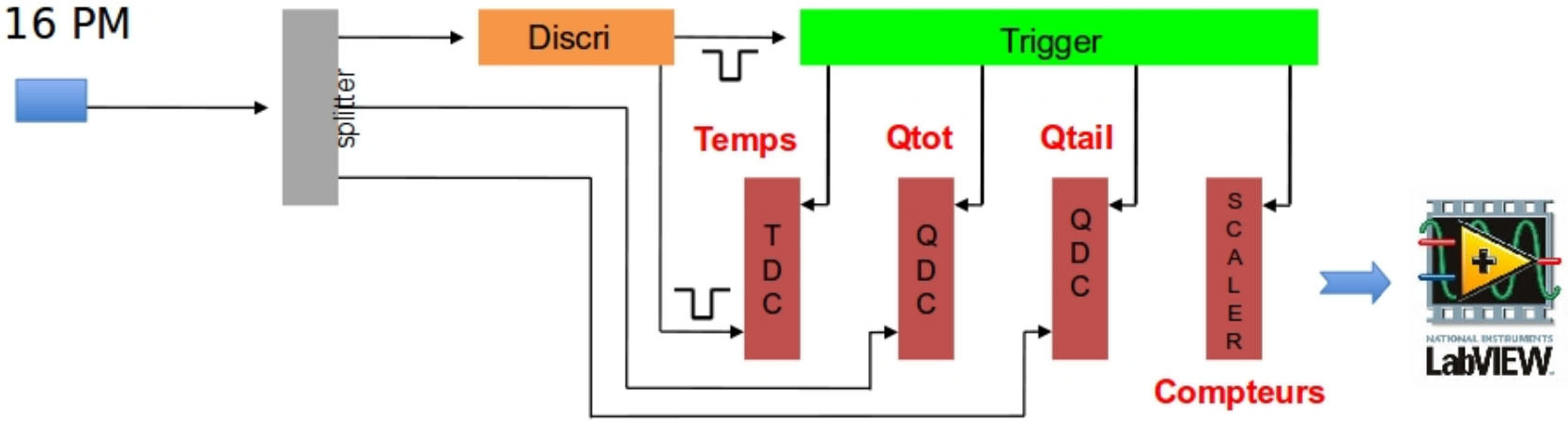
$$\delta\tau_{\text{diff}} = \frac{\tau_{\text{corr}} - \tau_{\text{acc}}}{\epsilon_{\text{LED}}} \sqrt{\left(\frac{\delta\tau_{\text{corr}}}{\tau_{\text{corr}}}\right)^2 + \left(\frac{\delta\tau_{\text{acc}}}{\tau_{\text{acc}}}\right)^2 + \left(\frac{\delta\epsilon_{\text{LED}}}{\epsilon_{\text{LED}}}\right)^2}$$

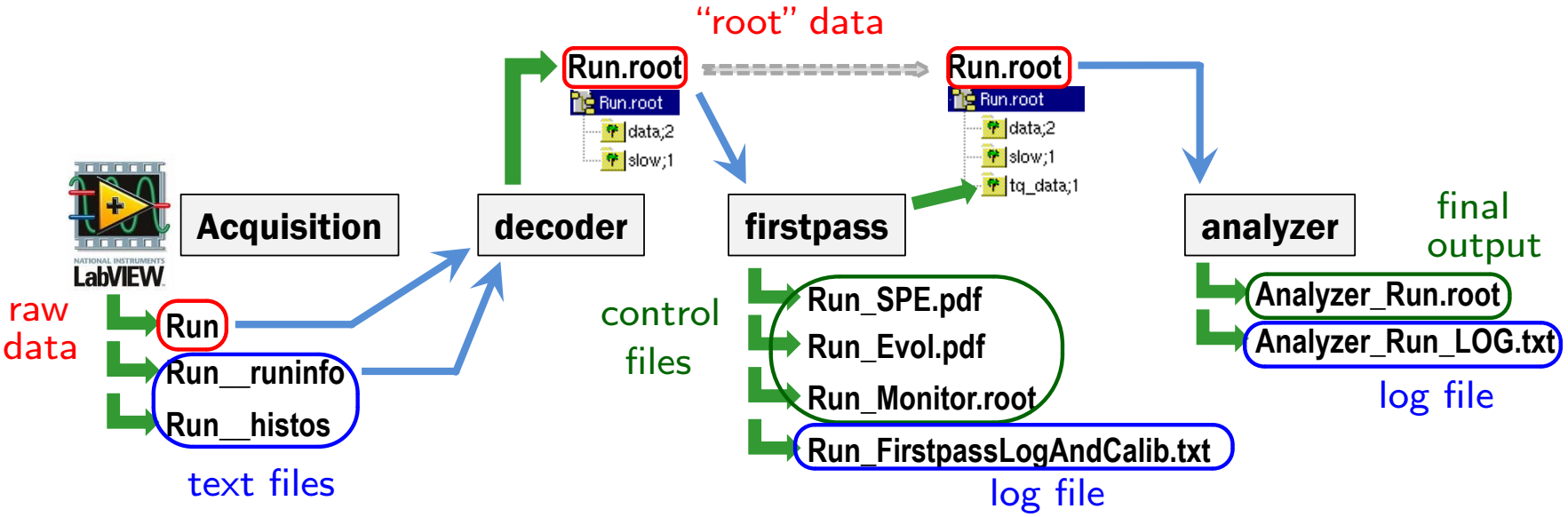
$$F_\mu = \frac{\exp((T_v - T_e)\tau_\mu) - \exp((T_v - T_c)\tau_\mu)}{\tau_\mu (T_c - T_e)}$$

$$\delta F_\mu = \left| \frac{\delta\tau_\mu}{\tau_\mu} \left(\frac{(T_v - T_e)e^{(T_v - T_e)\tau_\mu} - (T_v - T_c)e^{(T_v - T_c)\tau_\mu}}{T_c - T_e} - F_\mu \right) \right|$$

$T_e = 6\,\mu$s: electronic gate, $T_c = 40\,\mu$s: coincidence gate, $T_v = 100\,\mu$s: veto gate

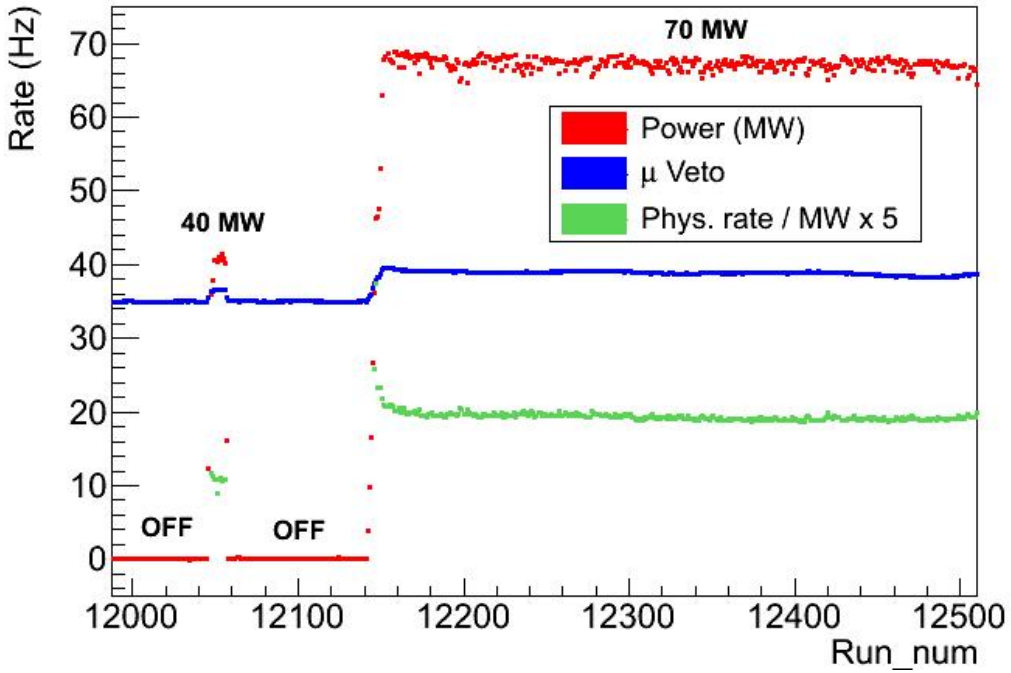
Acquisition and analysis scheme



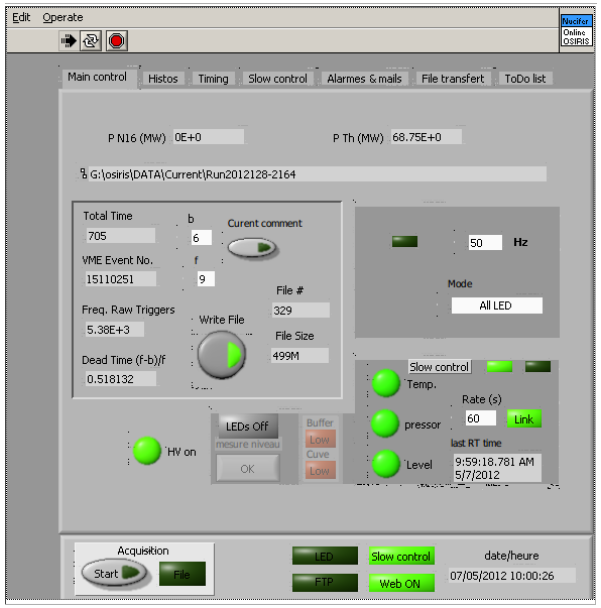


Remote data taking

- Full remote control, including slow control, automatic data transfer and alarm report

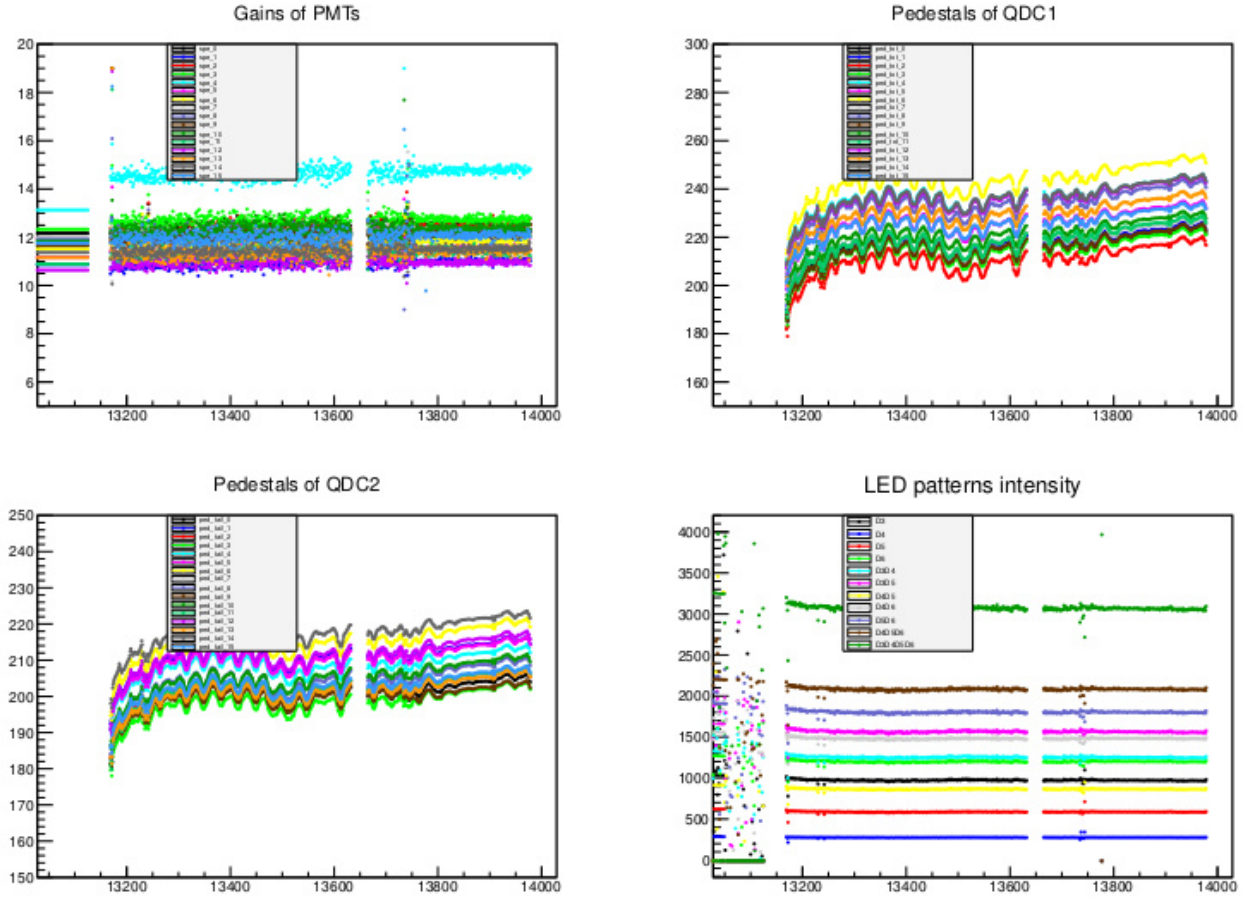


Beginning of 2013, March cycle



Remote control window

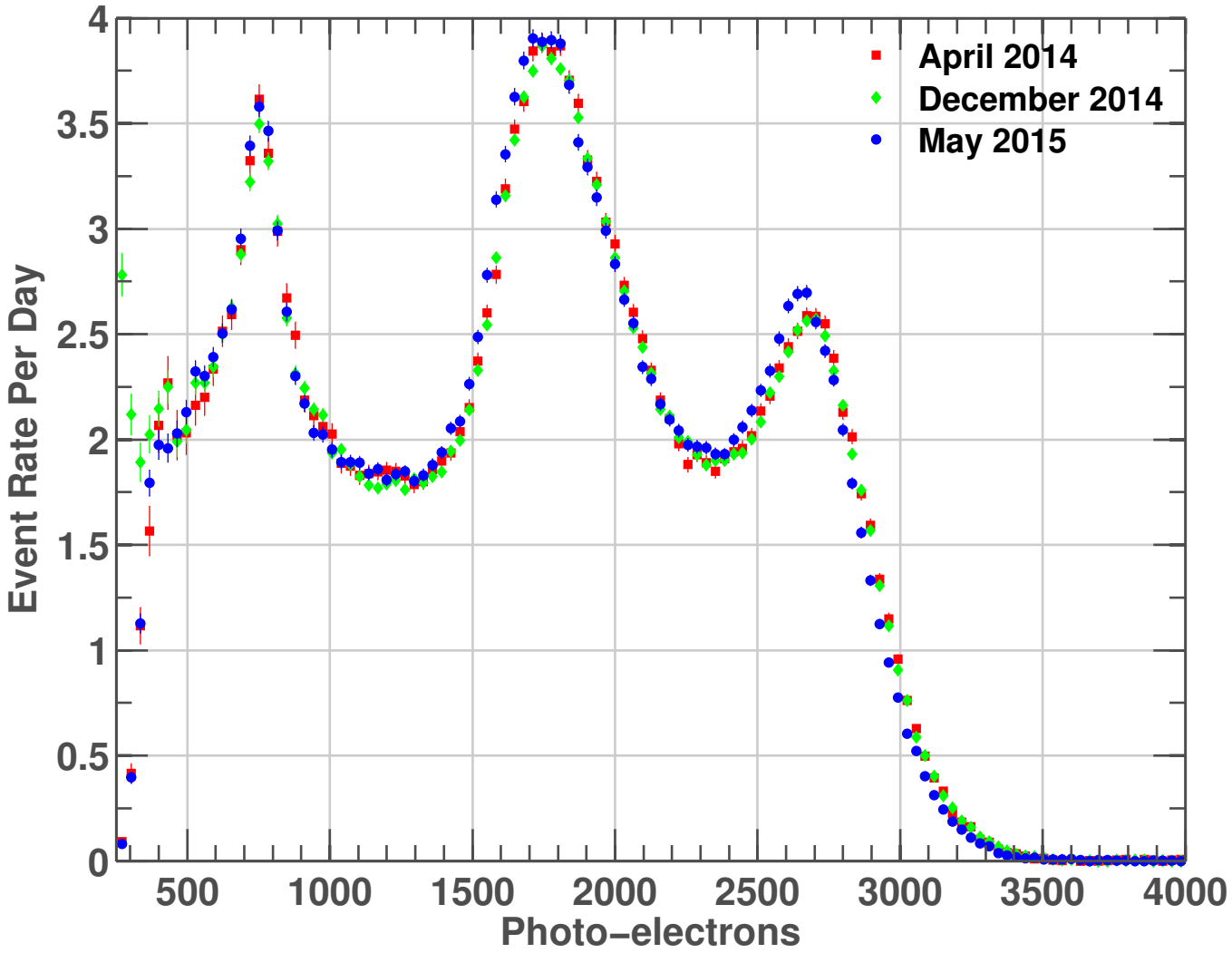
Stability



- Accurate monitoring of gains ($\pm 2.5\,\%$) and pedestals ($< \pm 1\,\%$)
- Pedestal correlation with temperature (including day/night oscillations)
- Controlled drifts over several months

Liquid stability

- Liquid stable over several month



References I

[1] G. Boireau et al.
Online Monitoring of the Osiris Reactor with the Nucifer Neutrino Detector.
2015.