Recent results of the SoLid experiment

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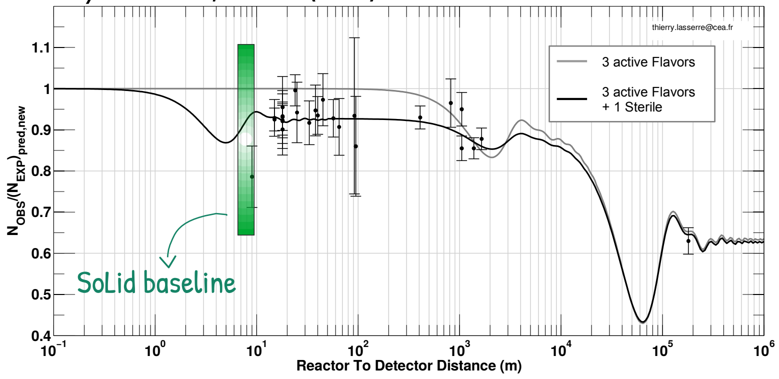
Outline

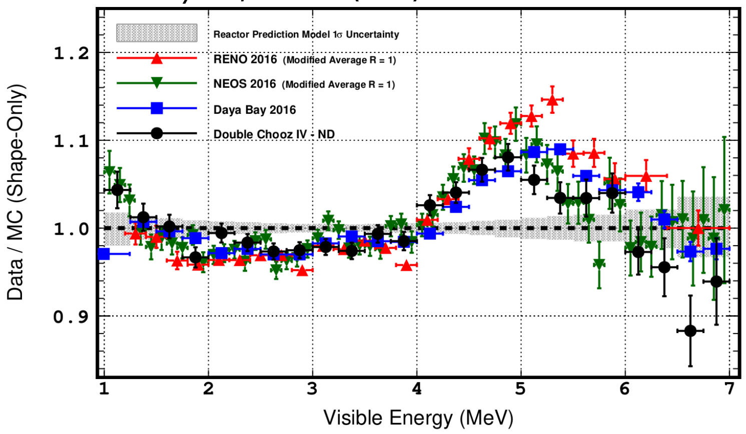
- The SoLid experiment
- Signal and backgrounds
- Energy calibration
- Antineutrino analysis
- Conclusion

Physics motivation

Phys. Rev. D 83, 073006 (2011)



Nat. Phys. 16, 558–564 (2020)



Oscillation anomalies:

- Reactor antineutrino anomaly (Short Baseline experiments)
- Gallium anomaly (GALLEX + SAGE)
- Accelerator anomaly (MiniBooNE + LSND)

The anomalies could be explaned with an oscillation into a light sterile state with an eV scale sterile neutrino.

Reactor anomalies:

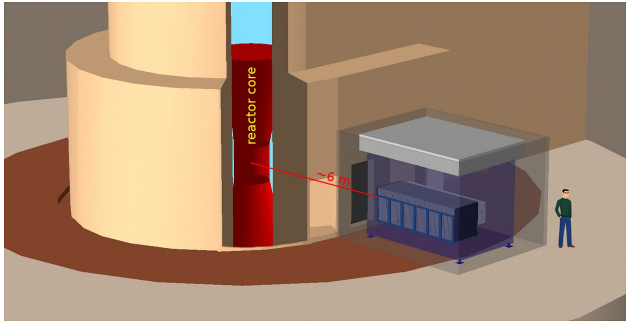
- 5 MeV Bump
- Global deficit from ^{235}U

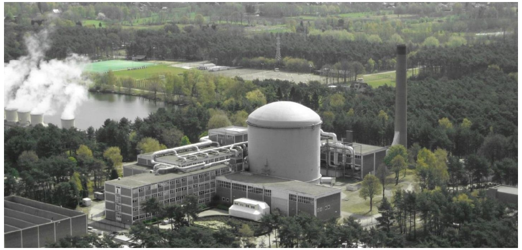
Among the 4 main Isotopes of commercial reactors, (^{235}U, ^{239}Pu, ^{238}U, ^{241}U), ^{235}U could be a candidate as the primary responsible of those anomalies.

SoLid detector at SCK CEN

Experimental site specification:

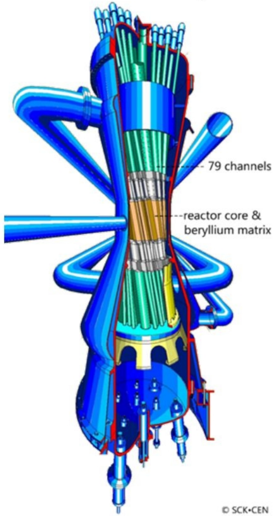
- Based at BR2 research reactor (Mol, Belgium)
- Very short baseline experiment [6.5-9] m
- Low overburden (~6-8 m.w.e)





Reactor specification:

- ^{235}U enriched reactor core (>93%)
- Compact reactor core ~50 cm
- Low background from the reactor.
- 1.5 month reactor ON/OFF (R-ON/R-OFF) cycles



SoLid detector: detection technology

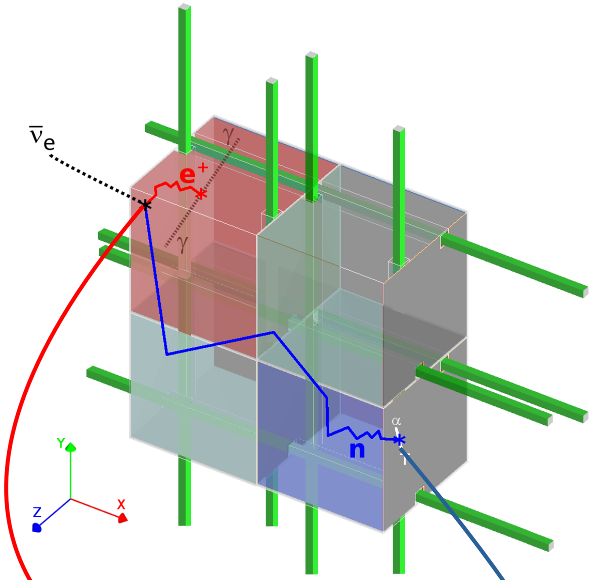
Inverse Beta Decay:

$\bar{\nu}_e + p \rightarrow e^+ + n$

Double scintillation technology:

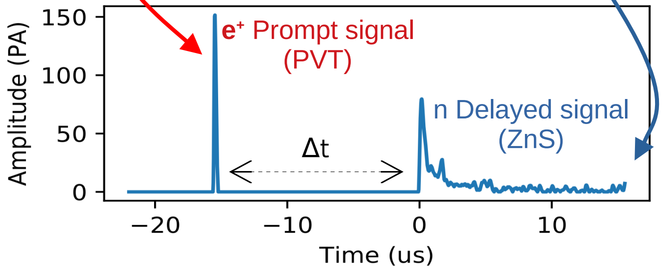
- Organic PVT as neutrino target and e^+ energy measurement
- Inorganic ^{6}LiF:ZnS(Ag) for neutron capture and detection

Time and space coincidence between **e^+** and **n** detection



High segmentation:

- 12800 5x5x5 cm^3 PVT cubes with 2 ^{6}LiF:ZnS(Ag) screens
- Each cube linked to 4 MPPCs with wavelength shifting fibres.



Challenges to overcome:

- Novel technology to understand and qualify.
- 12 800 detection cells with several parameters to measure per cube.
- Quantify and reduce the large correlated and accidental background
- **Tag the gamma emission from e^+ annihilation.**

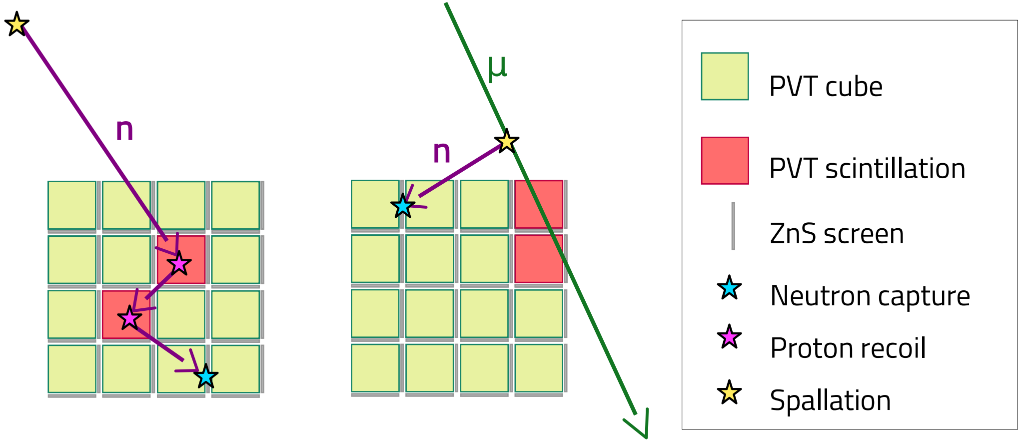
Correlated backgrounds

Atmospheric background:

Induced by **cosmic ray interaction in the atmosphere**

→ Proton recoil + neutron capture
→ Badly tagged muon + neutron capture

ΔT (Delayed-Prompt) ~ 64 μs (= ΔT_{IBD})

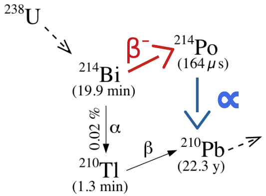


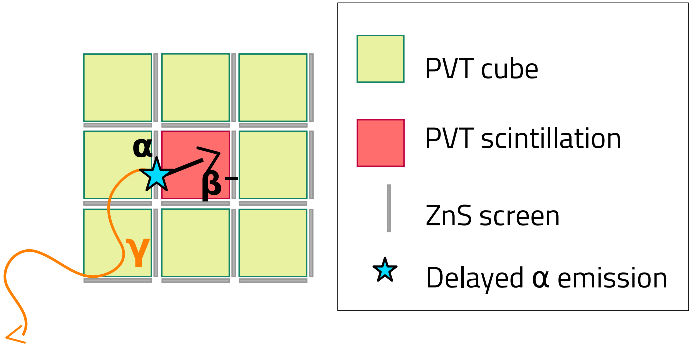
BiPo background:

Induced by **internal radioactivity from ZnS layers** unexpected contamination or **external Radon decay.**

→ β energy deposit from ^{214}Bi decay
+ delayed α from ^{210}Po decay

ΔT (Delayed-Prompt) ~ 250 μs (> ΔT_{IBD})





Signal topologies

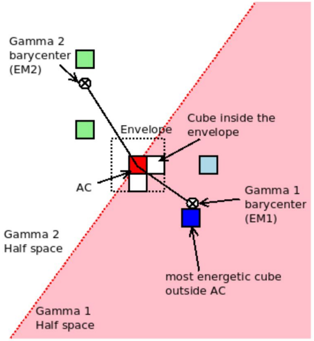
IBD expected electromagnetic signals: **e^+ energy deposit** + **2 annihilation gammas back to back**

→ **Two different strategies to classify the events:**

Spatial clusters:

→ Divide the detector in 2 hemispheres

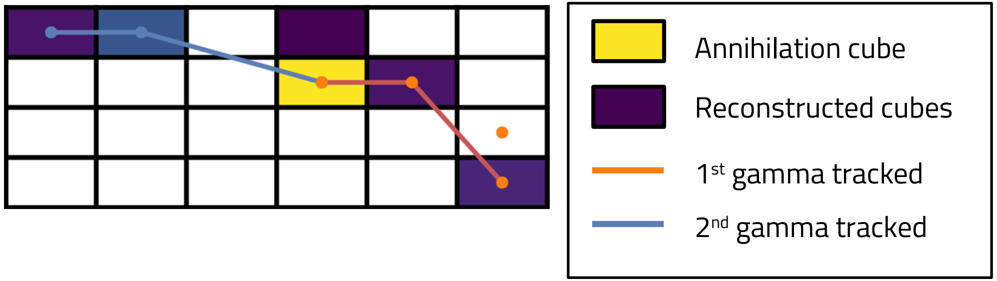
→ Build 0, 1 or 2 gamma clusters



Direct gamma tracking:

→ Track the annihilation gammas with a likelihood minimization algorithm based on x-sections

→ Build 0, 1 or 2 gamma tracks



Allow selection on the number of gamma tracks, energies of the gammas, positions…

Challenges:

→ Harder reconstruction of low energy events due to dark count rate and low efficiencies

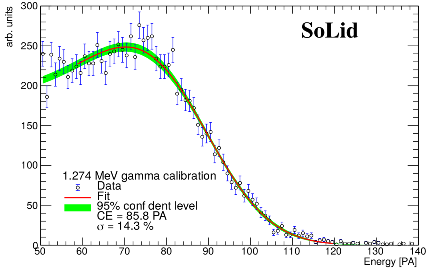
→ Have a good understanding of the energy response of the detector, especially at low energy

Energy calibration performances

Extensive energy calibration work:

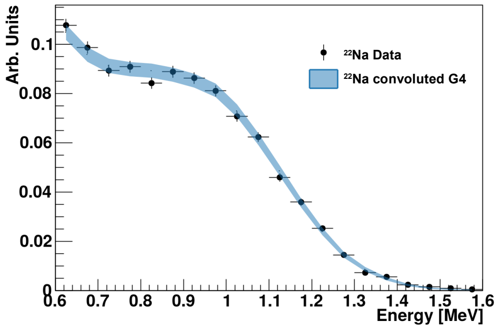
→ Gamma sources used for calibration. 2 **independent** Compton edge fit methods:

Fit with Klein Nishina x-section



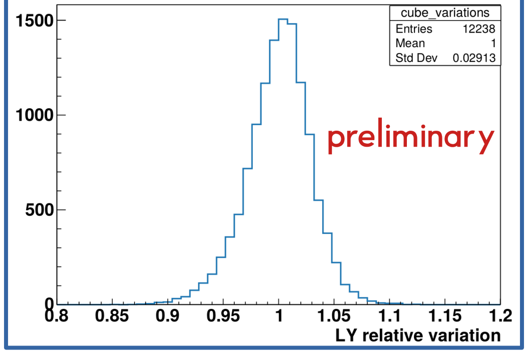
<2% agreement

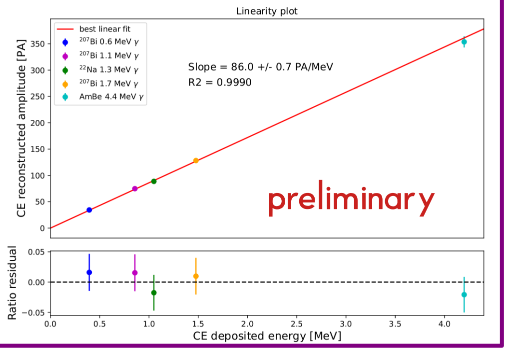
Fit between Data – Convoluted G4



→ 12800 cube light yield measured with 3% variation within a plane.

→ Linearity of the energy response tested at a couple of percent in the [.5-4 MeV] region.



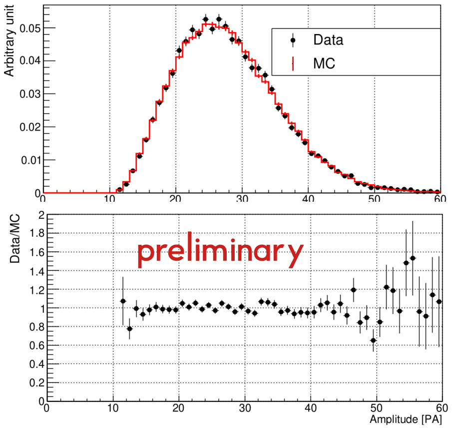


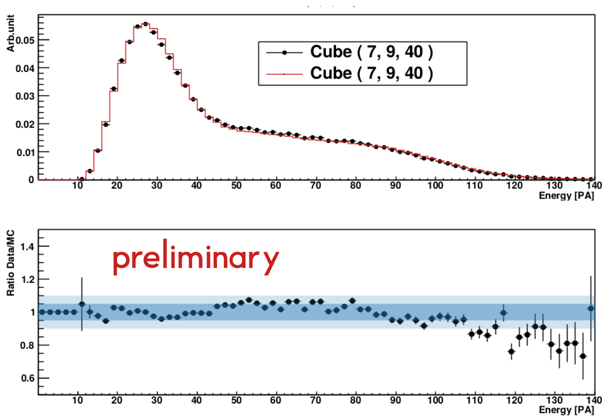
Data – Monte Carlo comparison

On ^{22}Na calibration data

→ With 1.28 MeV gamma and with 2 annihilation gammas.

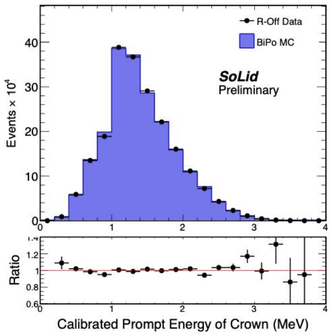
→ Good agreement within 5% between ~150 keV and 1.2 MeV.

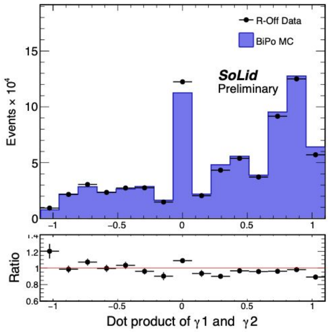




On BiPo data used as a proxy for IBD signal

With a high purity BiPo selection, the BiPo background can be used to test detector response model.





→ Prompt energy agreement at the percent level up to 3 MeV.

→ The Data-Monte Carlo comparison show a good agreement at the percent level of the reconstruction variables.

Antineutrino analysis

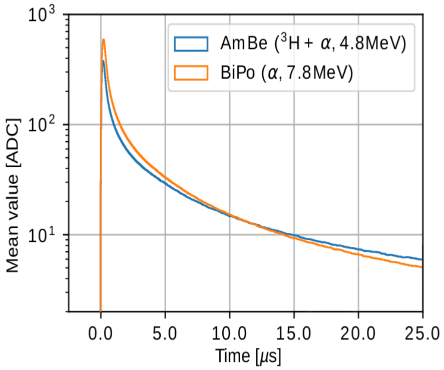
BiPo background reduction and quantification

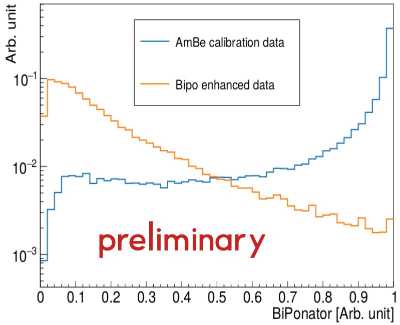
BiPonator: CNN for neutron signal identification between

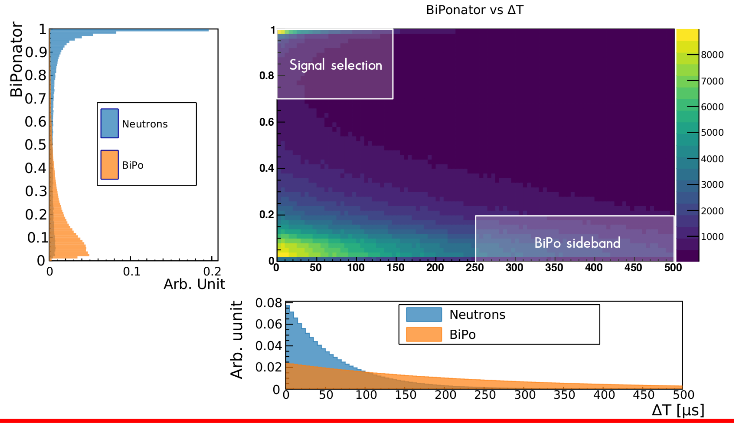
→ 4.8 MeV $^{3}H+\alpha$ from ^{6}Li breakup

→ 7.8 MeV α from BiPo.

At 80% neutron efficiency, the CNN rejects 94% of alphas







BiPonator used in combination with ΔT(delayed-prompt):

→ For BiPo rejection

→ To define BiPo sideband for quantification of the BiPo rate

Atmospheric background quantification

→ Similar capture time for neutrons from IBD and atmospheric background.

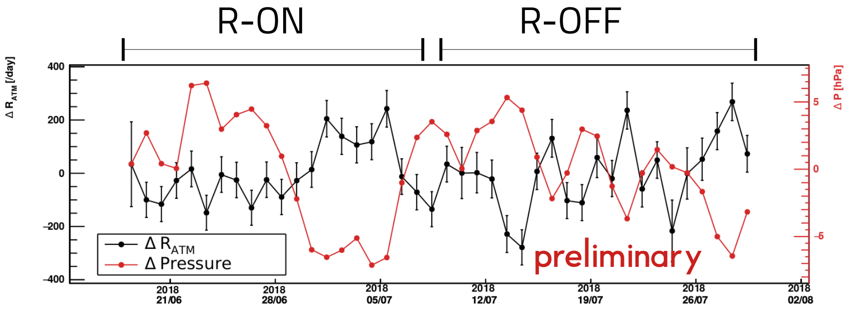
→ **No PSD** between **proton recoils** and **e⁺**.

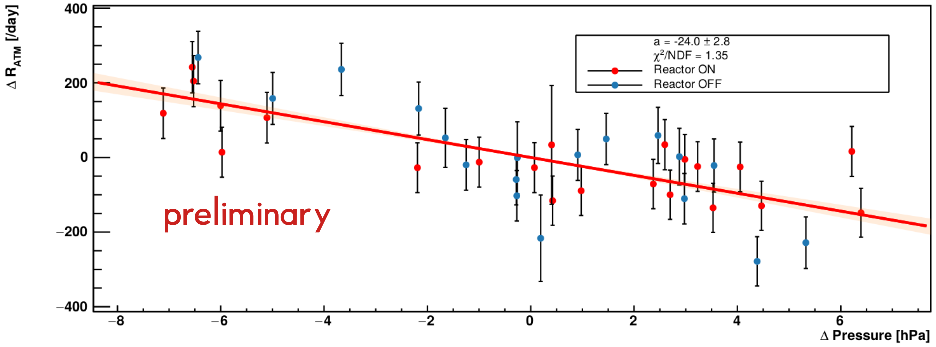
→ Energies of atmospheric background in the whole IBD energy region of interest ([1-7] MeV range).

No clear discrimination or selection variables to build a pure sideband in the energy range.

Dependent on the atmosphere density → Pressure model to quantify the rate variation of the atmospheric background

To test it, selection on **above 7 MeV** energy deposits.





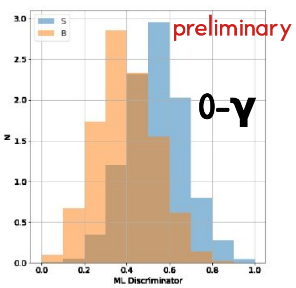
R – R_{ref}(RON/ROFF) as a function of P – P_{ref} for both reactor ON and OFF

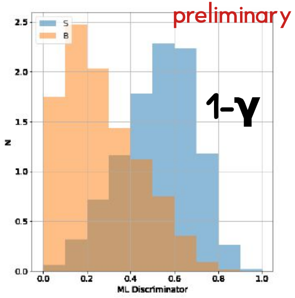
Variation of the neutron like signals induced by cosmic induced background variations.

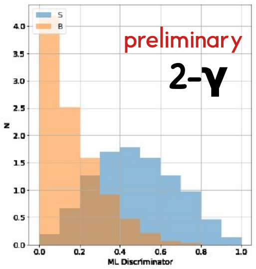
IBD analysis: multivariate analyses

Uniform BDT (uBDT)
+ Spatial gamma clustering

→ Ensures flatness of the efficiency on given parameters

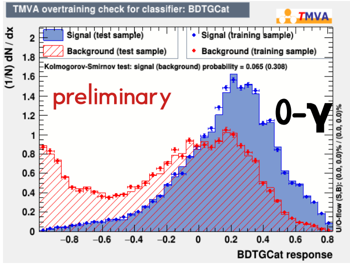


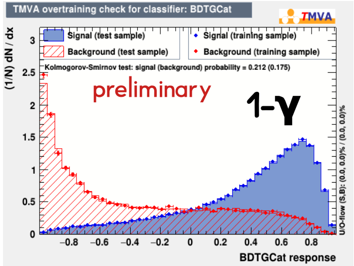


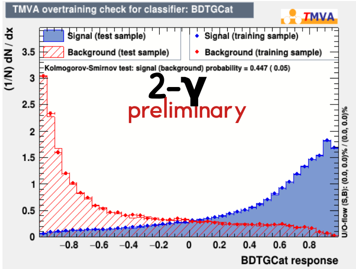


TMVA Gradient BDT (GBDT)
+ gamma tracking

→ BDT based on gradient descent algorithm

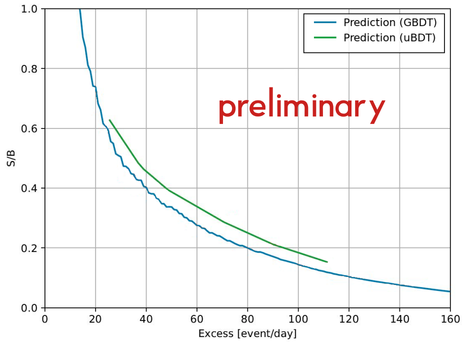






Performances prediction obtained with IBD simulation and R-OFF data.

→ Similar performances for both analyses



Extraction of antineutrino signal: Open dataset (~1 month R-ON)

Subtraction:

1

→ Select the signal ΔT vs Biponator neutron window

→ Subtract accidental component with false neutron triggers

→ Subtract BiPo component with the BiPo sideband

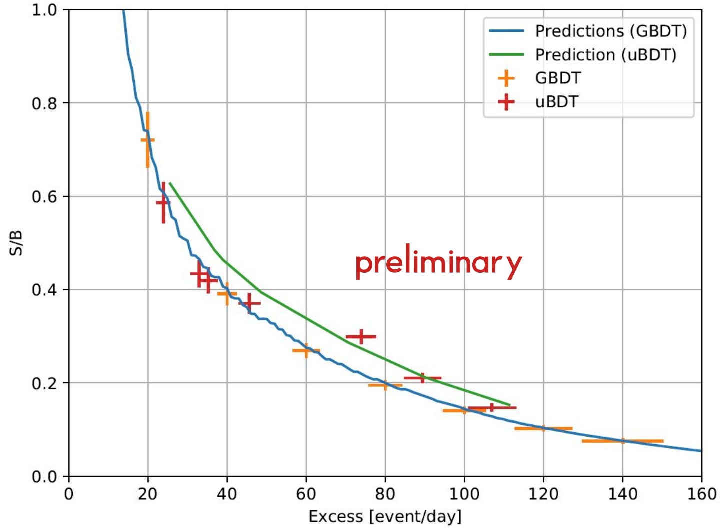
Left in the samples:

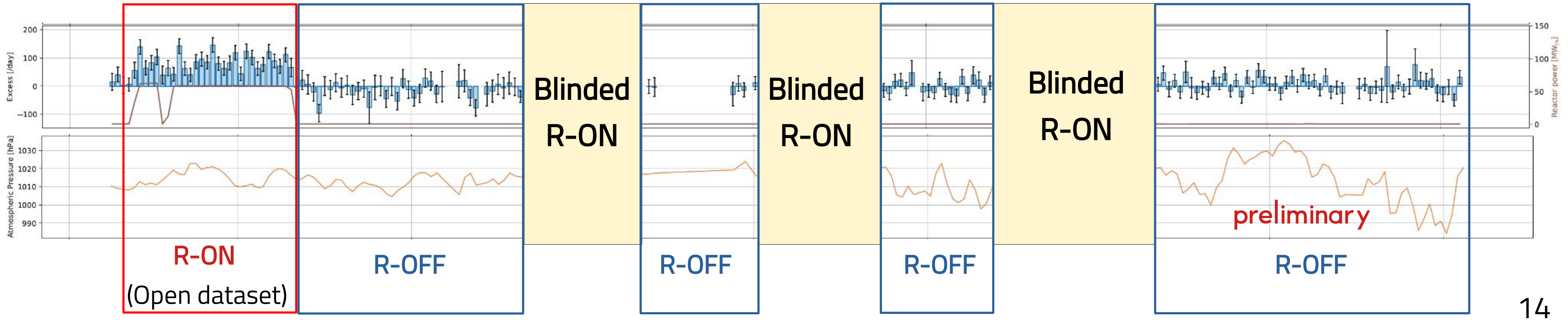
2

→ R-ON: Atmospherics + IBDs

→ R-OFF: Atmospherics

Compute the pressure model with both R-ON and R-OFF





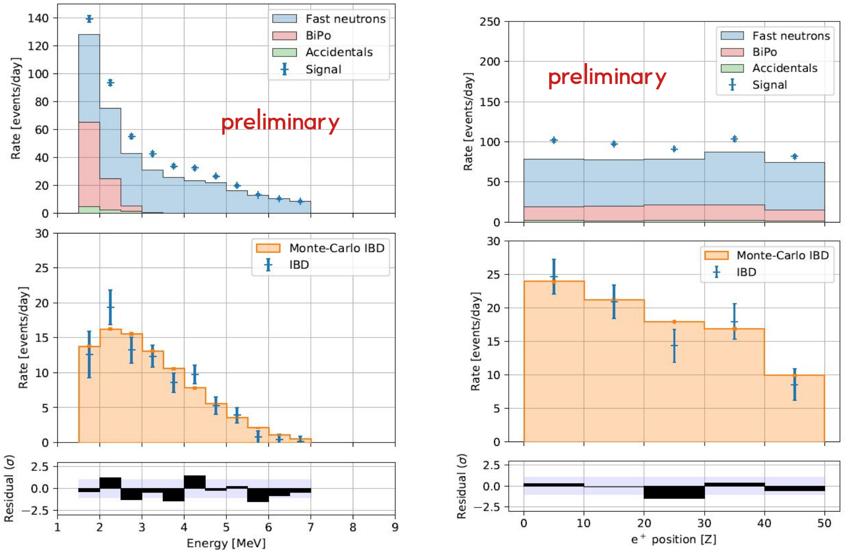
Energy and distance distributions

→ Use the R-OFF to extract each background shape.

→ Quantify each background rate on R-ON data.

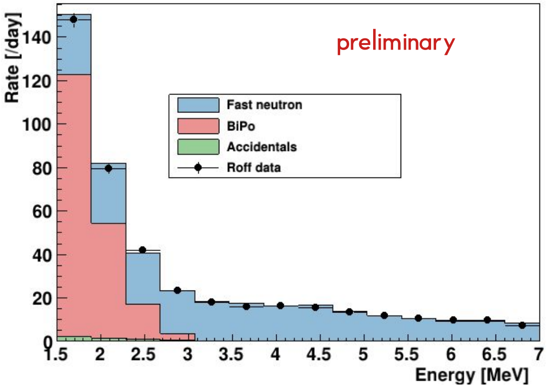
Subtraction of R-ON by the weighted sum of the background shapes.

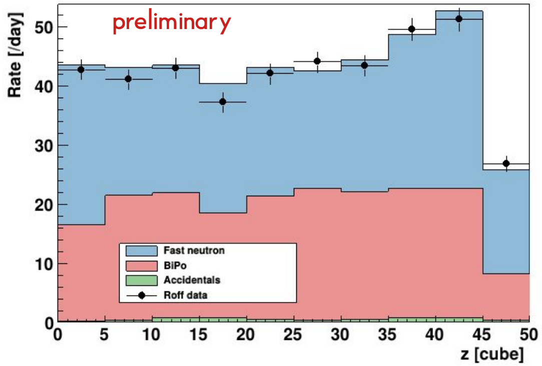
R-ON - R-OFF subtraction



uBDT: Signal excess (90 event/day, S/B =0.21)

R-OFF breakdown





Available dataset

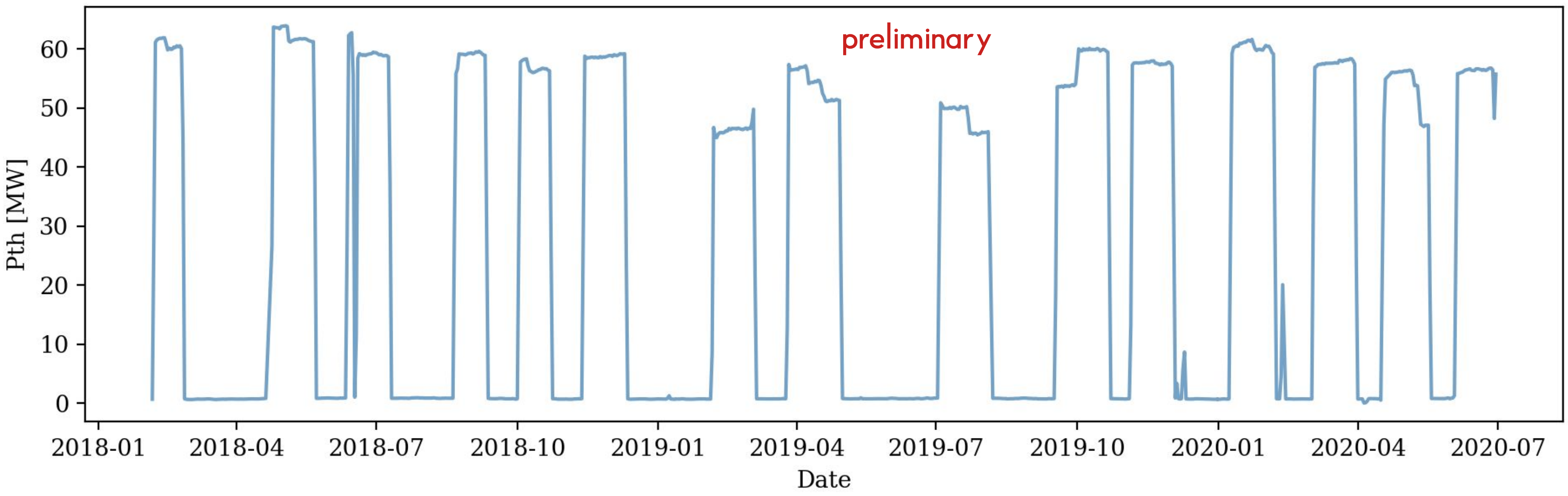
Data on tape:

→ Two years of data (April 2018 – July 2020)

→ 14 R-ON cycles during this time

→ Data selection with stable environmental conditions

→ Selected respectively ~300 days and ~180 days of R-ON and R-OFF data for an oscillation analysis

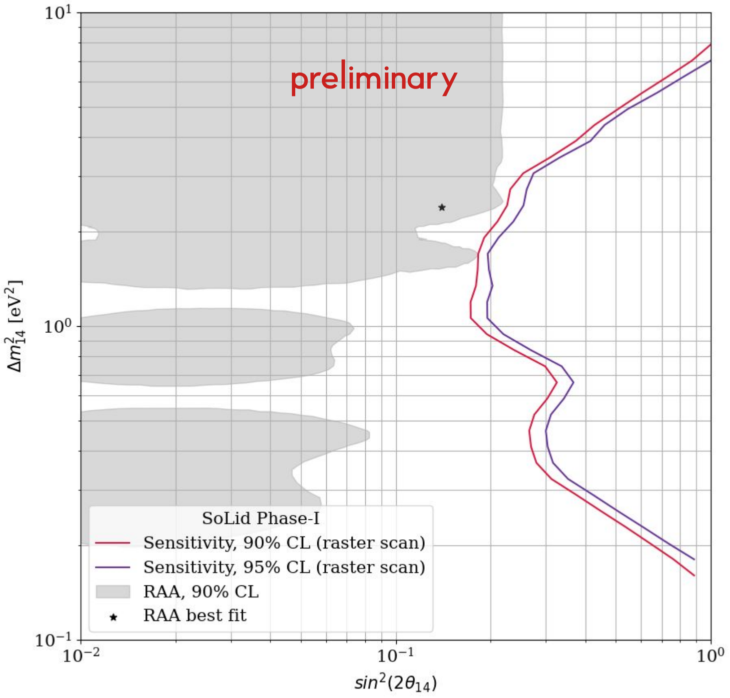


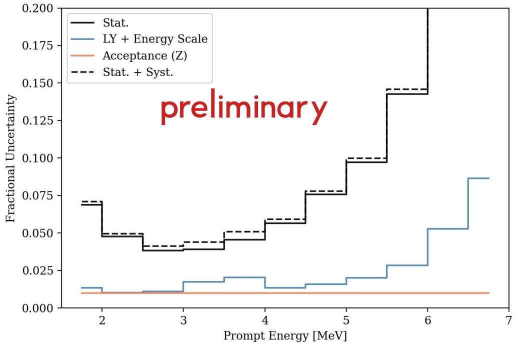
SoLid oscillation sensitivity

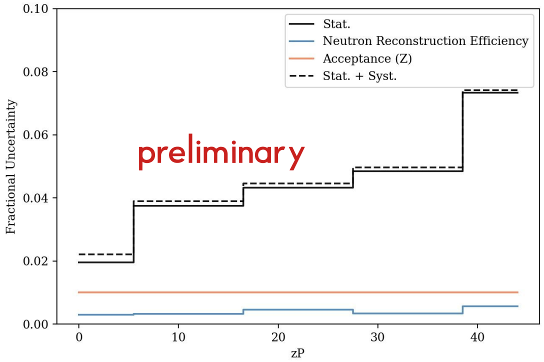
→ Rejection zones derived with Feldman-Cousins prescription.

→ Systematic uncertainties here related to the energy scale, neutron capture efficiency and detector acceptance. Dominated by statistical uncertainties for now.

→ Ongoing effort to assess impact of remaining systematics.







Future prospects

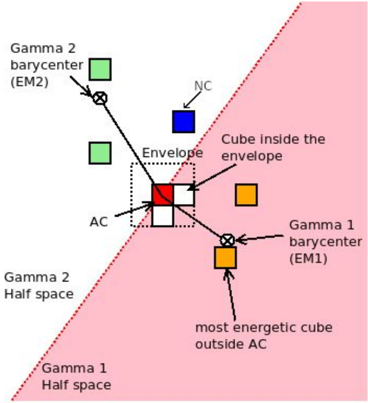
Future development: topological selection on only two gammas.

Based on the Spatial clusters topologies:

→ New analysis based on two gamma topology.

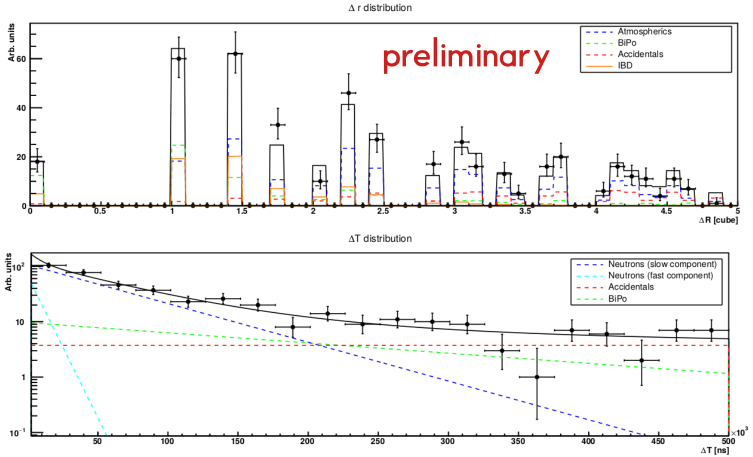
→ Uses a better reconstruction that takes into account calibration effects.

→ Multivariate analysis to remove each background component.

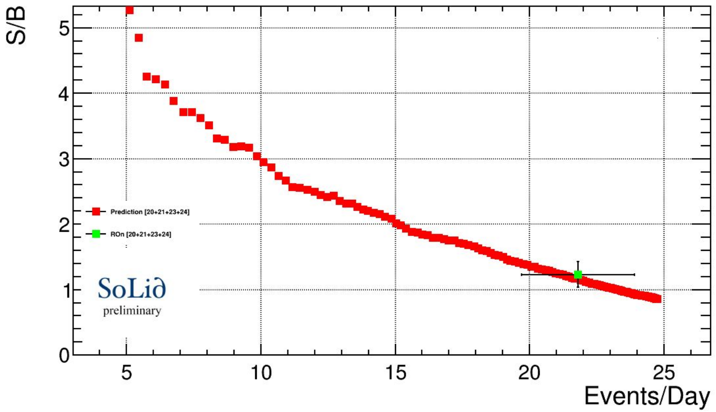


Each R-ON component yield is obtained with a multi-dimensional **ΔT (Delayed-prompt)** , **ΔR (Delayed-prompt)** simultaneous fit.

→ **Good agreement between excess and predicted excess, with S/B larger than one:**



$$N(\overline{\nu}/\text{day}) = 21.8 \pm 2.1\ (\text{stat}) \pm 1.5\ (\text{syst}).$$



Future development: SoLid Phase-II upgrade

During summer 2020, upgrade of the detector with new MPPCs:

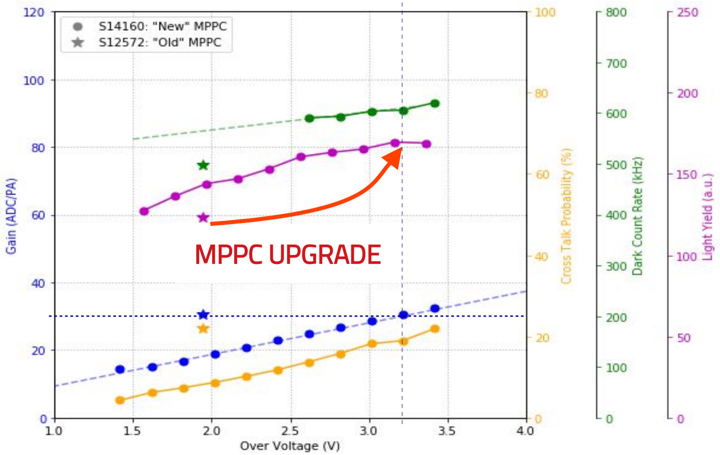
→ New MPPCs with **lower x-talk for similar Over Voltage** (OV)

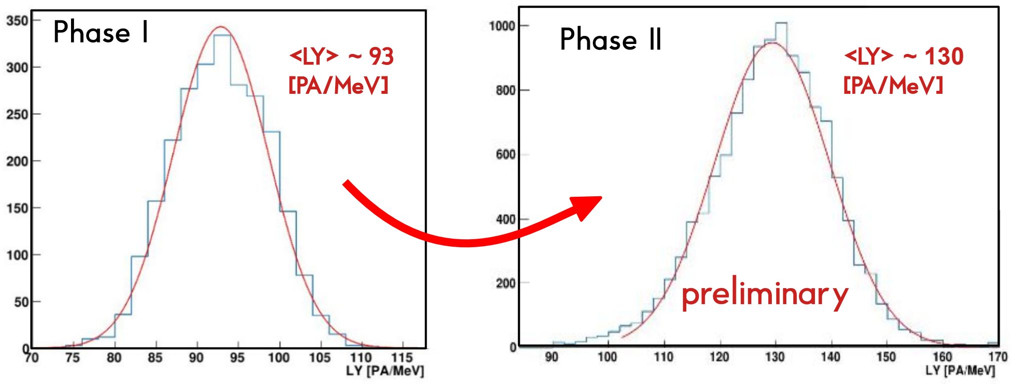
→ Allows to operates at a larger OV → **40% light yield increase in the same conditions**

→ Improved **energy resolution**

→ Expected improvement of the **annihilation gamma** reconstruction

Taking data with Phase-II detector since late 2020





Conclusion

- Detector technology to answer to the reactor antineutrinos anomaly.

- **Highly segmented plastic scintillator detector** (16x16x50 detection cells).

- Detector response well understood and modeled with extensive calibration work.
- IBD analysis based on MVA algorithms to reduce correlated background on open dataset (~1 month R-ON) → **~90 event/day, S/B =0.21**

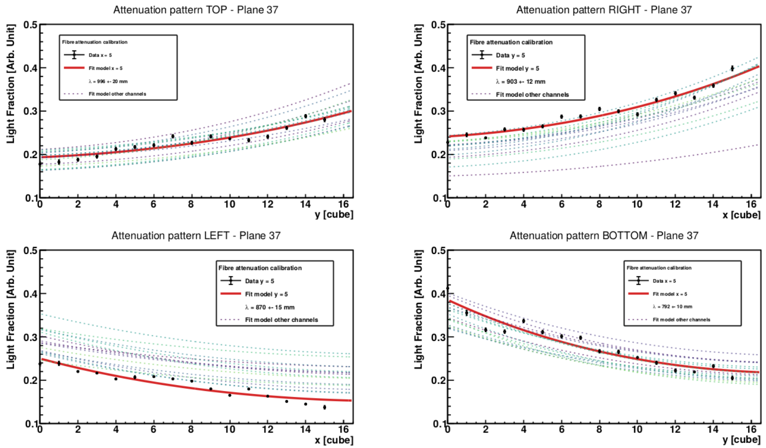
- Unblinding and analysis on 2 years data with an exclusion contour for Phase I dataset coming soon.

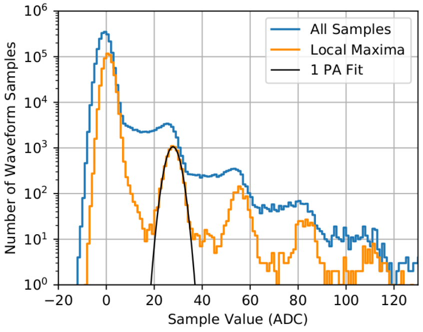
- Analysis based on pure signal 2-gamma events.

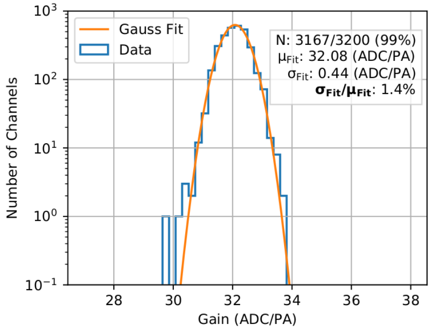
- Upgrade of the detector in summer 2020, currently taking data with 40% increased light yield.

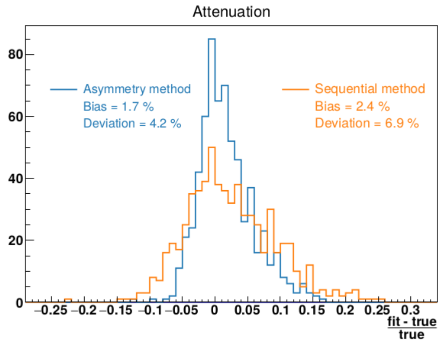
Backup

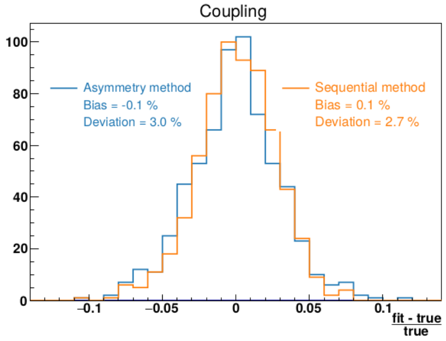
Fibre calibration



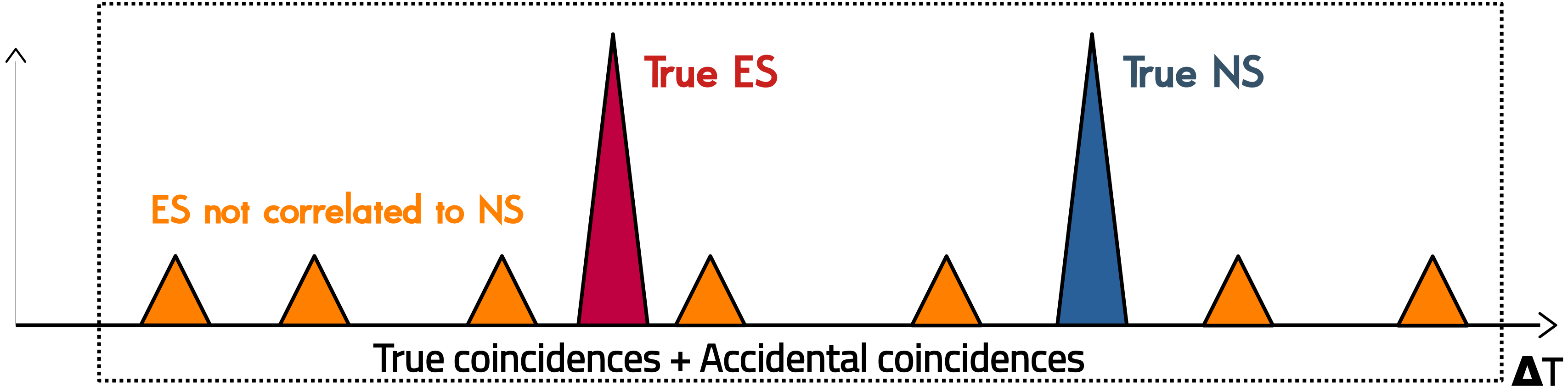


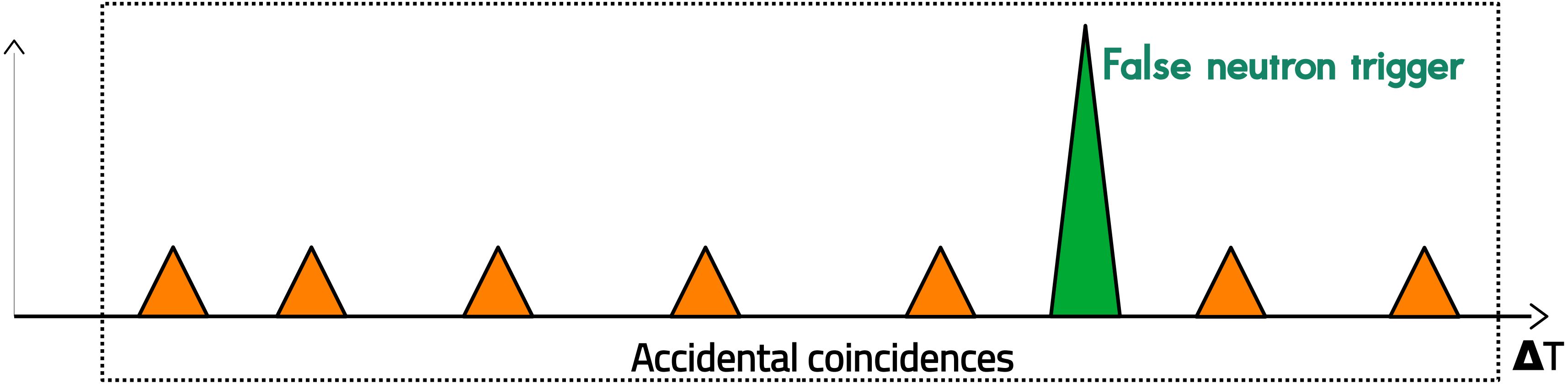


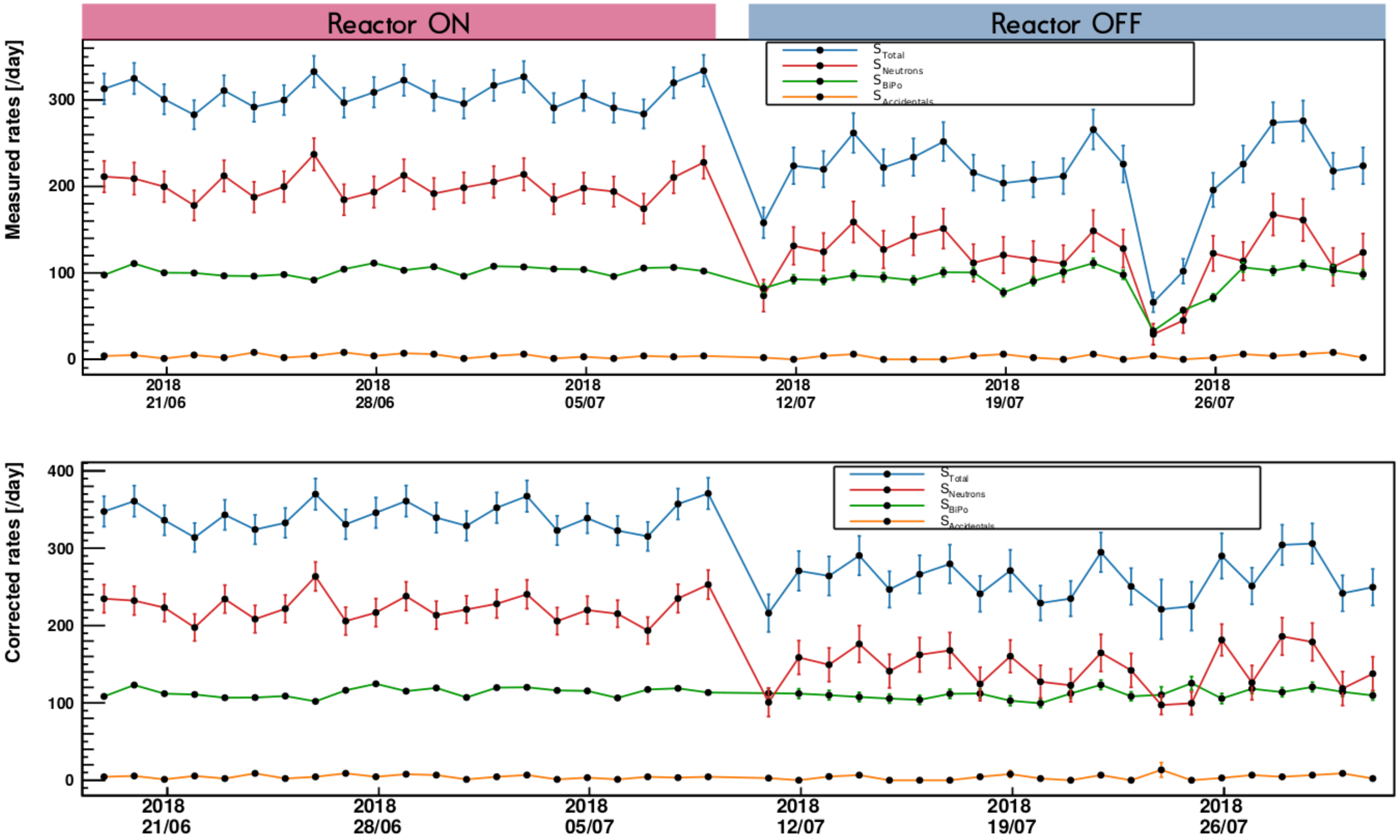




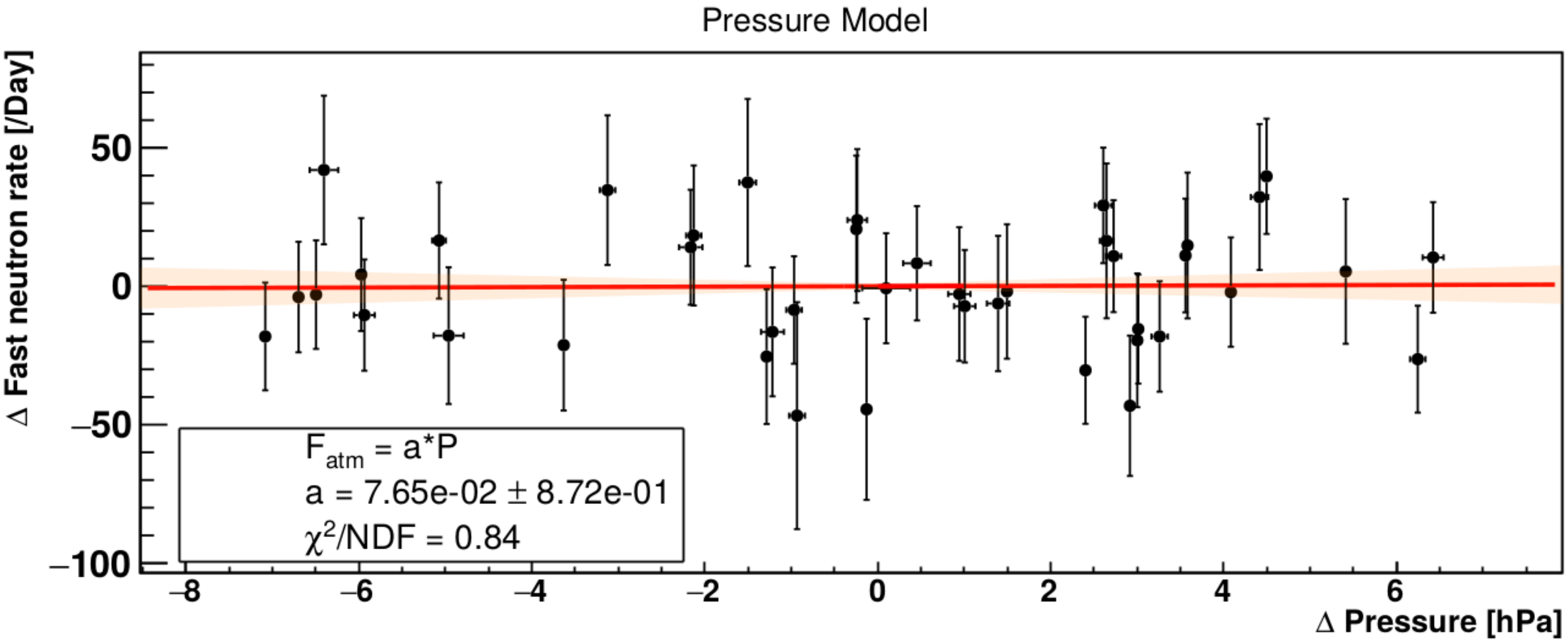
False neutron trigger for accidentals







Reactor ON
Reactor OFF
Measured rates [/day]
300
200
100
0
S_{Total}
$S_{Neutrons}$
S_{BiPo}
$S_{Accidentals}$
2018 21/06
2018 28/06
2018 05/07
2018 12/07
2018 19/07
2018 26/07
Corrected rates [/day]
400
300
200
100
0
S_{Total}
$S_{Neutrons}$
S_{BiPo}
$S_{Accidentals}$
2018 21/06
2018 28/06
2018 05/07
2018 12/07
2018 19/07
2018 26/07


Pressure Model
Δ Fast neutron rate [/Day]
50
0
−50
−100
−8
−6
−4
−2
0
2
4
6
Δ Pressure [hPa]
F_{atm} = a*P
a = 7.65e-02 ± 8.72e-01
χ^2/NDF = 0.84