XENON1T

Energy resolution and linearity in the MeV energy range

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Introduction

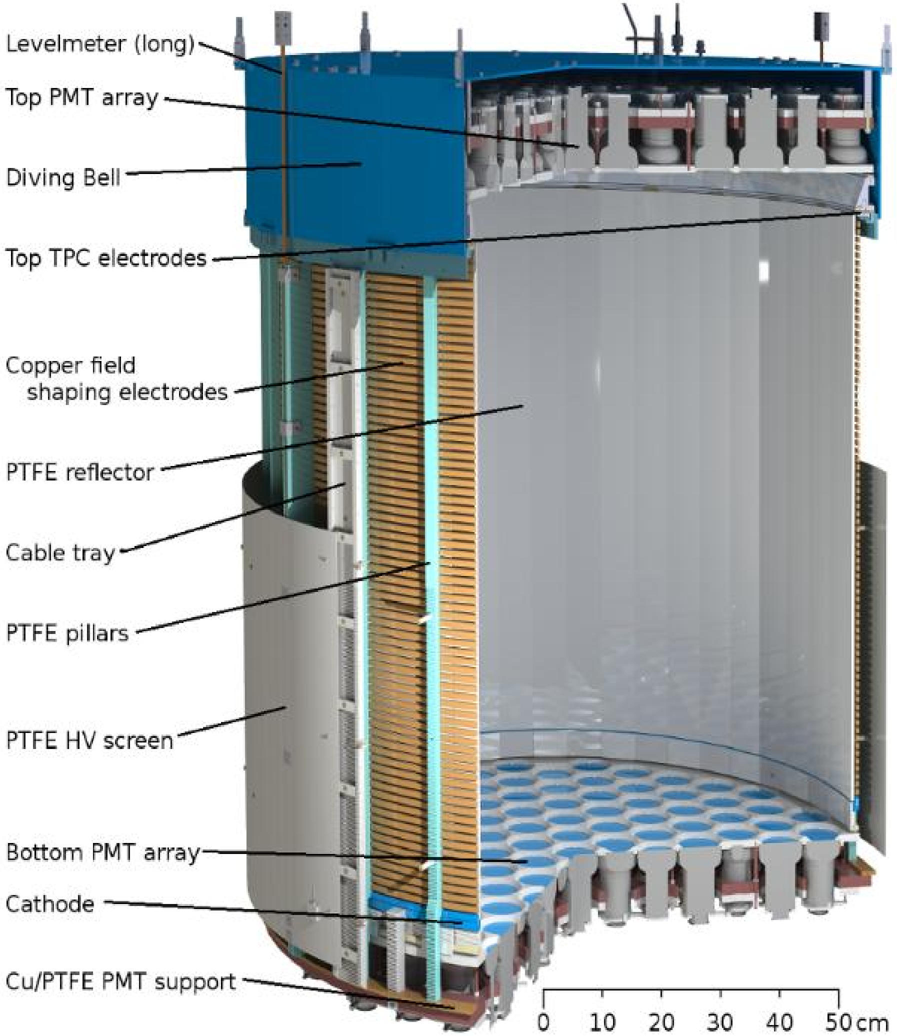
- XENON1T was mainly designed for low-energy dark matter searches.
- However, its large liquid xenon target also enables searches for rare events at MeV energies.
- In the MeV region, large S2 signals can be distorted by saturation effects.
- Correcting these distortions is essential for improving the energy resolution and extending the physics reach of LXe TPCs.

Content

- Liquid Xenon Dual Phase TPC
- Problem for MeV region
- S2 saturation correction
- Position reconstruction
- Electronic recoil energy reconstruction

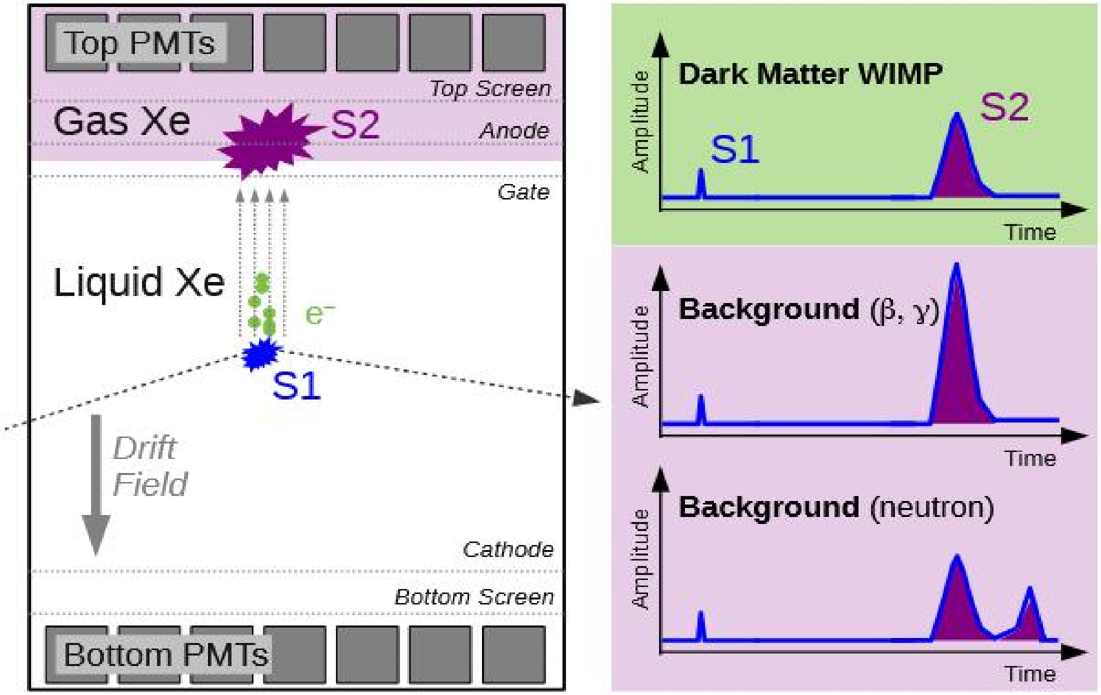
XENON1T Detector

- Located underground in Hall B of the Laboratori Nazionali del Gran Sasso (LNGS), Italy, at a depth of 3600 meter water equivalent.
- The XENON dark matter project aims at the detection of WIMP dark matter(keV) with dual-phase time projection chambers filled with a liquid xenon (LXe) target.
- XENON1T contains 3.2 tonnes of liquid xenon, with about 2.0 tonnes forming the active target of the dual-phase TPC.

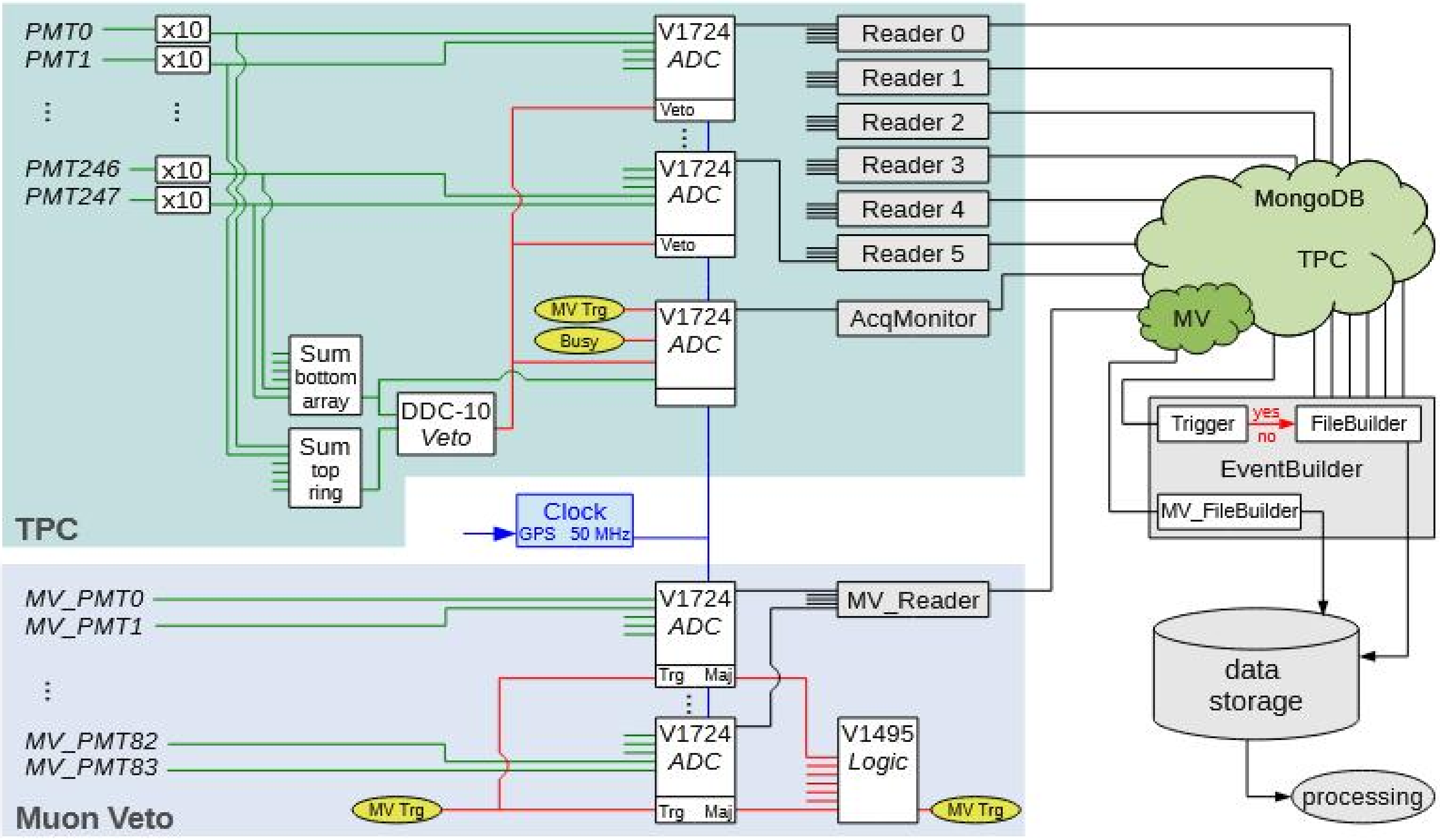


XENON1T Detector

- Particle interacting with liquid xenon produces prompt scintillation light, S1, and ionization electrons.
- Under an electric field, the electrons drift toward the gas phase and generate proportional scintillation light, S2.
- The S1 waveform is produced by prompt scintillation light in liquid xenon
- S2 is broadened by longitudinal electron diffusion during drift, leading to a Gaussian-like waveform.



DAQ System



PMT → **Amplifier** → **Digitizer** → **Processor**

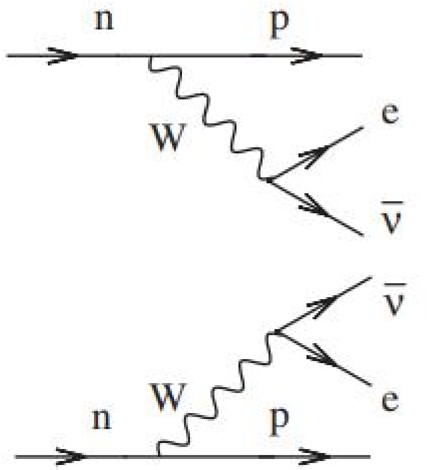
Neutrinoless double beta decay

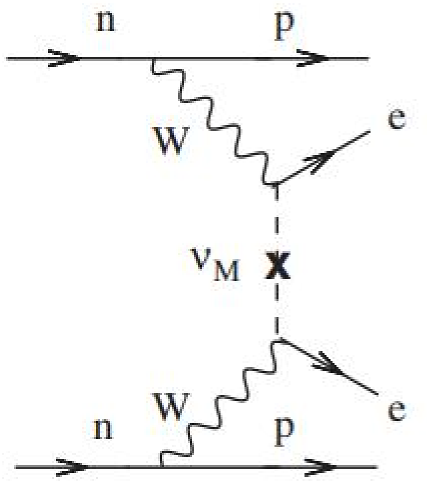
$$2\nu\beta\beta:\quad n+n\to p+p+e^-+e^-+\bar{\nu}_e+\bar{\nu}_e$$

$$\nu=\bar{\nu}$$

$$0\nu\beta\beta:\quad n+n\to p+p+e^-+e^-$$

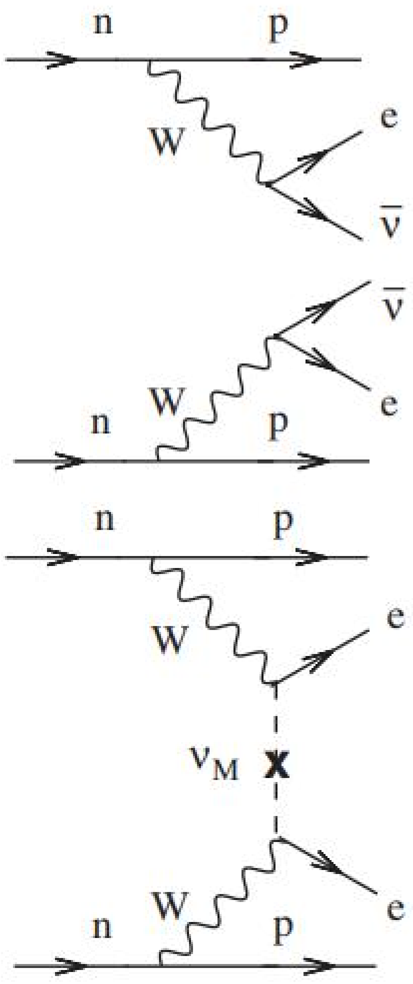
A detection of 0νββ would establish the Majorana nature of neutrinos and demonstrate lepton number violation by two units.





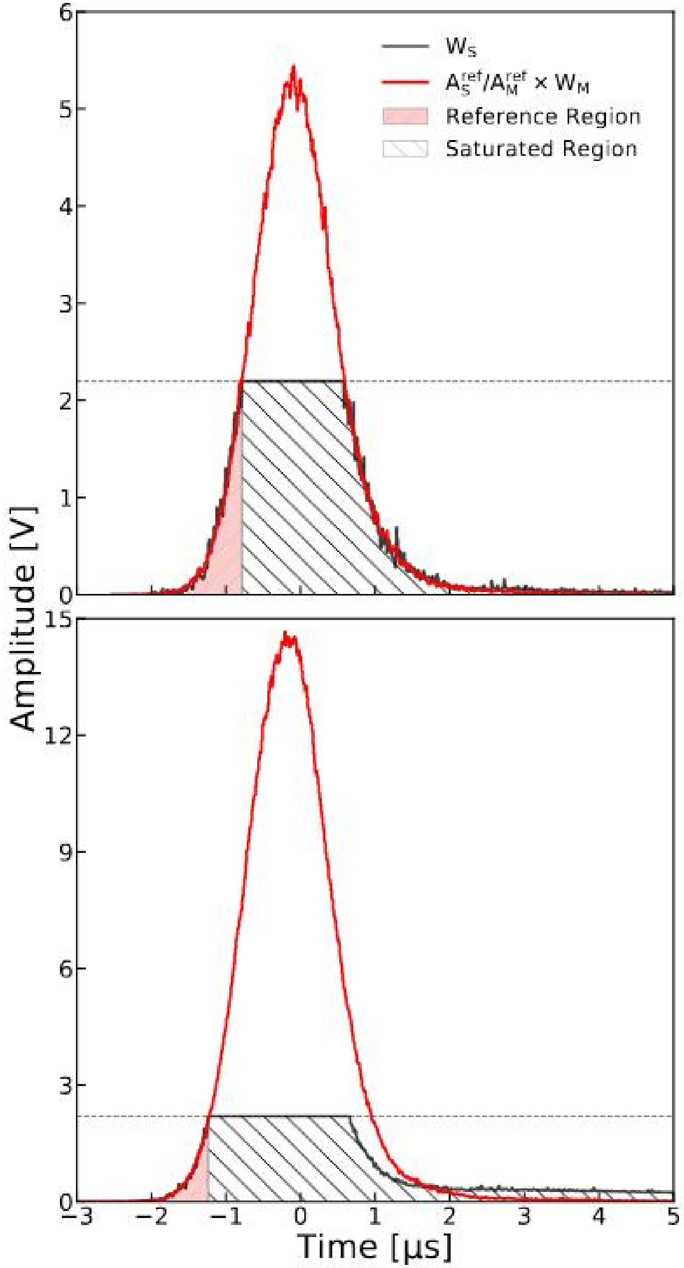
Problem:Extended to the MeV energy range

- XENON1T was originally optimized for keV-scale dark matter signals, but MeV-scale rare events are also important.
- The search for neutrinoless double beta decay of ^{136}Xe focuses on a monoenergetic peak near $Q_{\beta\beta} \approx 2458$ keV.
- In the high-energy region, dual-phase liquid xenon TPCs can suffer from S2 saturation and nonlinearity, which degrade the performance of conventional energy reconstruction.



S2 saturation

- The digitizer saturation occurs at energies above ~ 200 keV, such signals exceed the 2.25 V dynamic range of the digitizers and result in truncated waveforms (WFs).
- Non-linear responses of the PMT voltage divider circuits and the amplifiers are expected to occur at a higher energy of ~ 1 MeV, corresponding to an S2 signal on the order of 106 PE.



S2 saturation correction

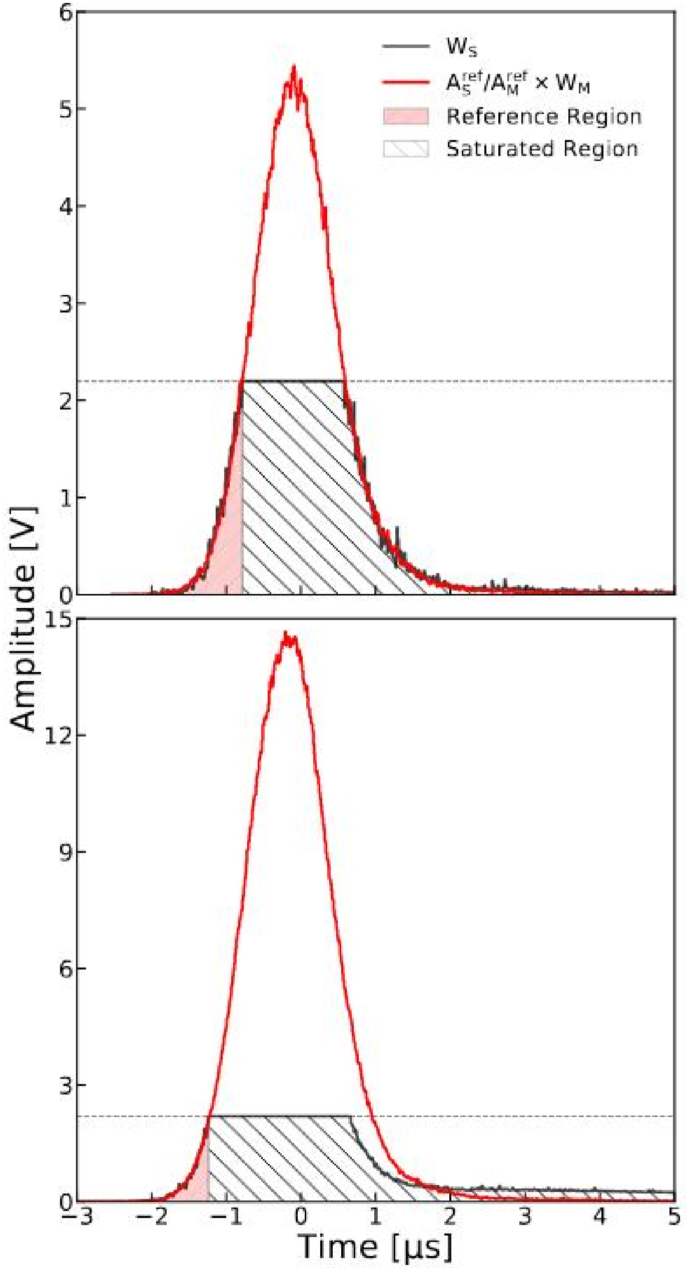
1.Sorting all S2 WFs into two classes: saturated and nonsaturated

2.All non-saturated WFs are summed together to get a WF model denoted as WM.

3.For each saturated WF denoted as WS, the region before the first saturated sample is used as a reference region. We denote the integral of WS and of WM over the reference region as A_S and A_M , respectively.

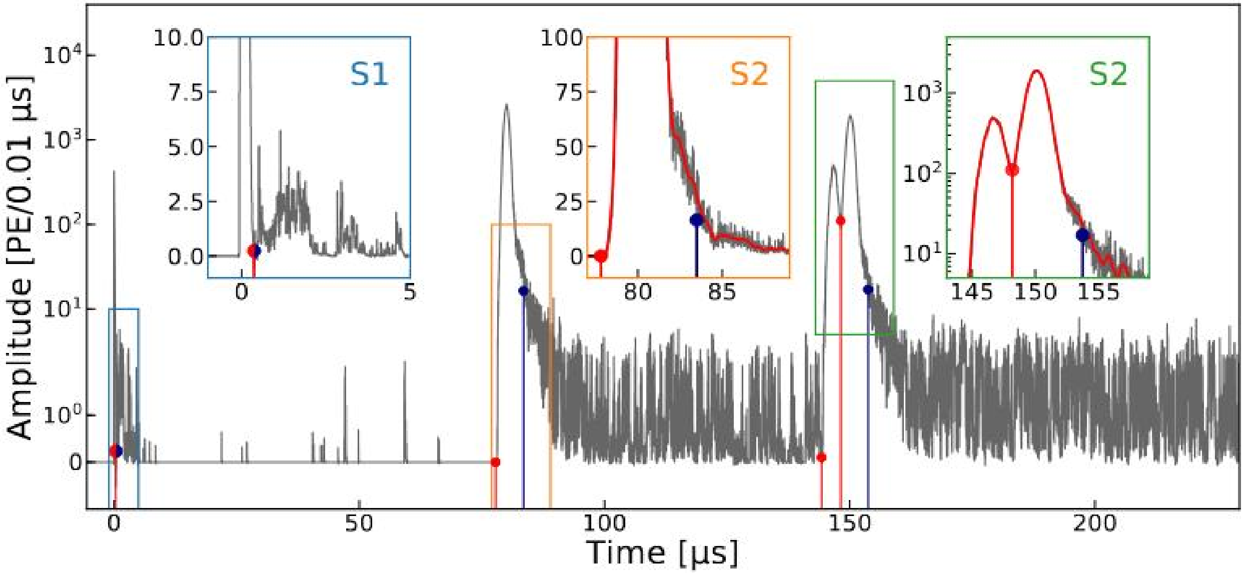
4.Each saturated WF is corrected as A_S /A_M × WM after the reference region.

5.The correction is applied to the region: from WFs start to 1 μs after the WFs fall below the channel-specific trigger thresholds.



Secondary signals correction

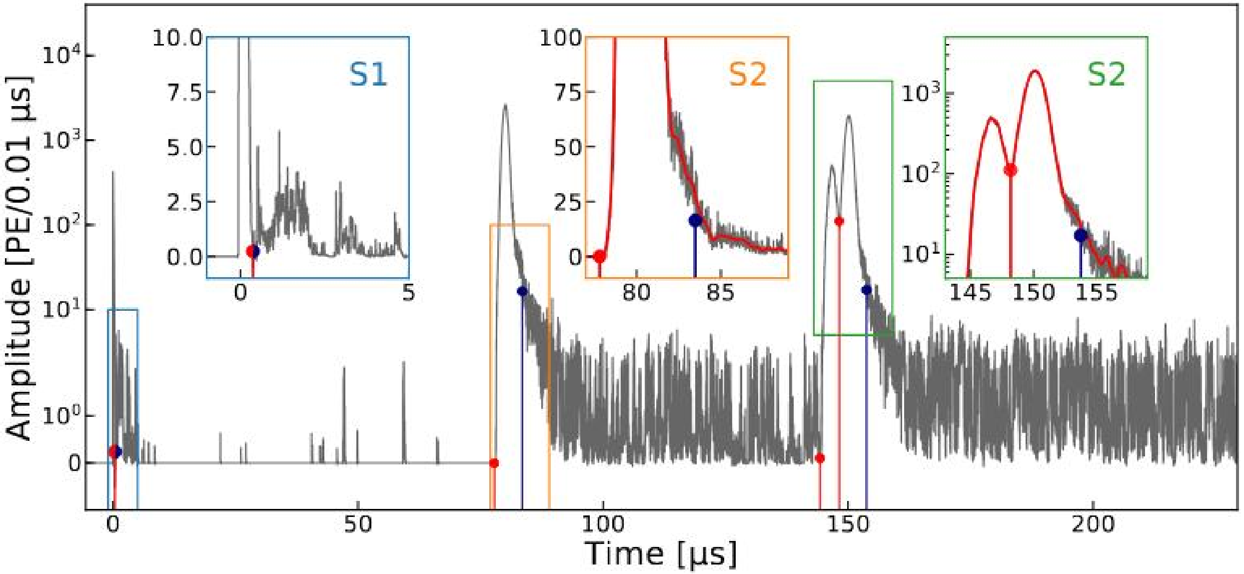
- Secondary signals are defined as signals not directly caused by particle interactions in the LXe.
- Gas present in PMTs can be ionized by accelerated electrons between the photocathode and the first dynode, producing after-pulse (AP) signals.
- Both photodetachment of electronegative impurities and the photoelectric effect at the metal surfaces of the gate electrode produce electrons within the LXe, that we call photoionization (PI) signals.
- both AP and PI signals start to appear shortly (1 μs) after the primary S1 or S2, they have significant effects on finding the peak boundaries.



Secondary signals split

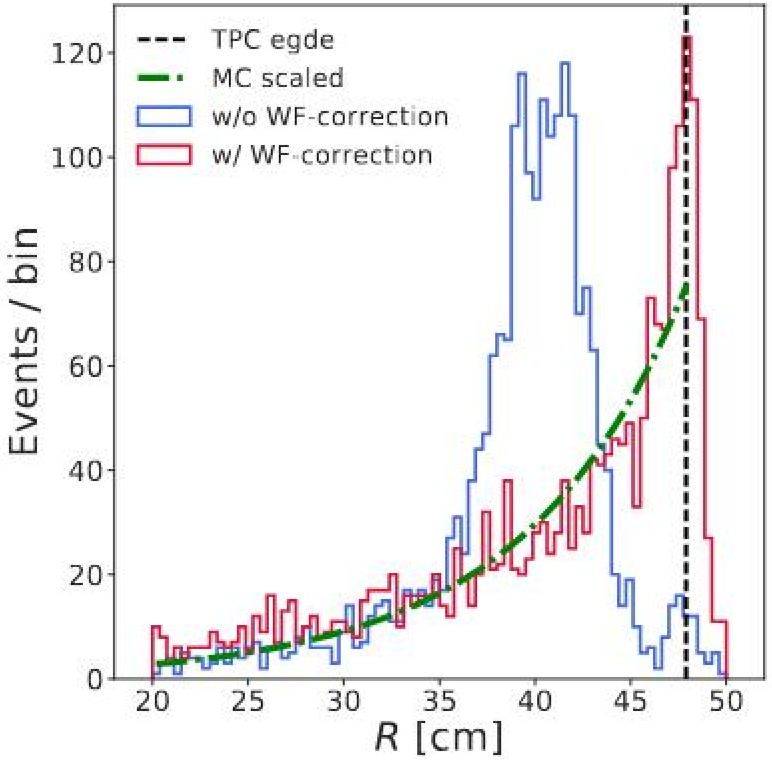
- the summed WF (grey lines) is smoothed (red lines). Local minima are used to define peak boundaries marked as red points.

- A cutoff on the amplitude is set for each peak to define the extent of its falling edge. The cutoff threshold is placed at the value of a Gaussian function 3-σ away from its center.



Position reconstruction

- Used calibration data from an external 228Th source(2614.5 keV gamma) to check the improvement
- The calibration source is placed at the side of the detector, close to the top of the TPC, which increases the number of saturated events and avoids the field distortion effect.



Single and multi-site interactions

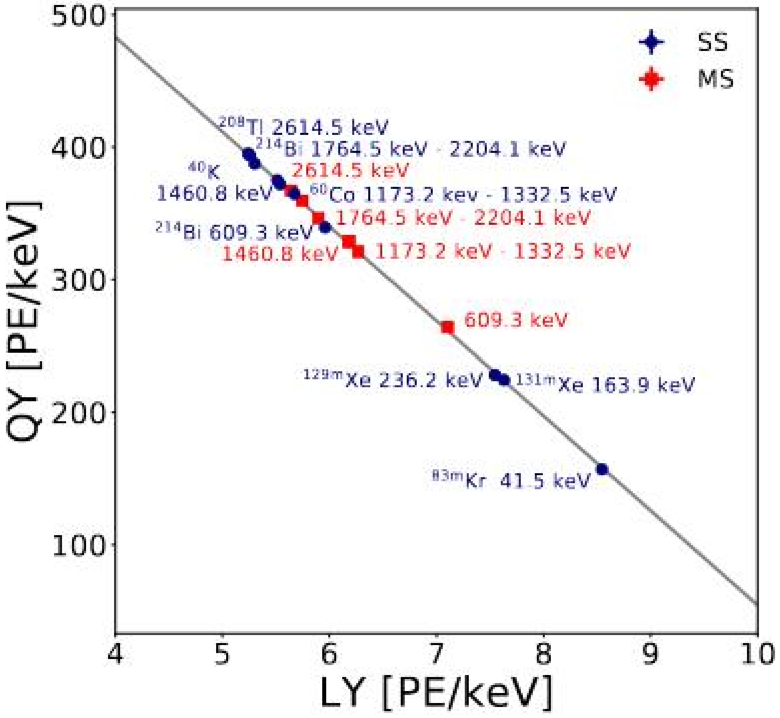
- SS events are signal-like events for rare processes, including dark matter, 0νββ, and 2νββ decays.
- MS events mainly come from gamma-ray multiple Compton scatters or coincident gamma rays.
- For 0νββ and 2νββ, the two betas are emitted from the same vertex.
- Since their range in LXe is less than 3 mm, they cannot be spatially resolved in XENON1T.
- Thus, ββ decays are reconstructed as single-scatter events.

Combined energy from S1 and S2

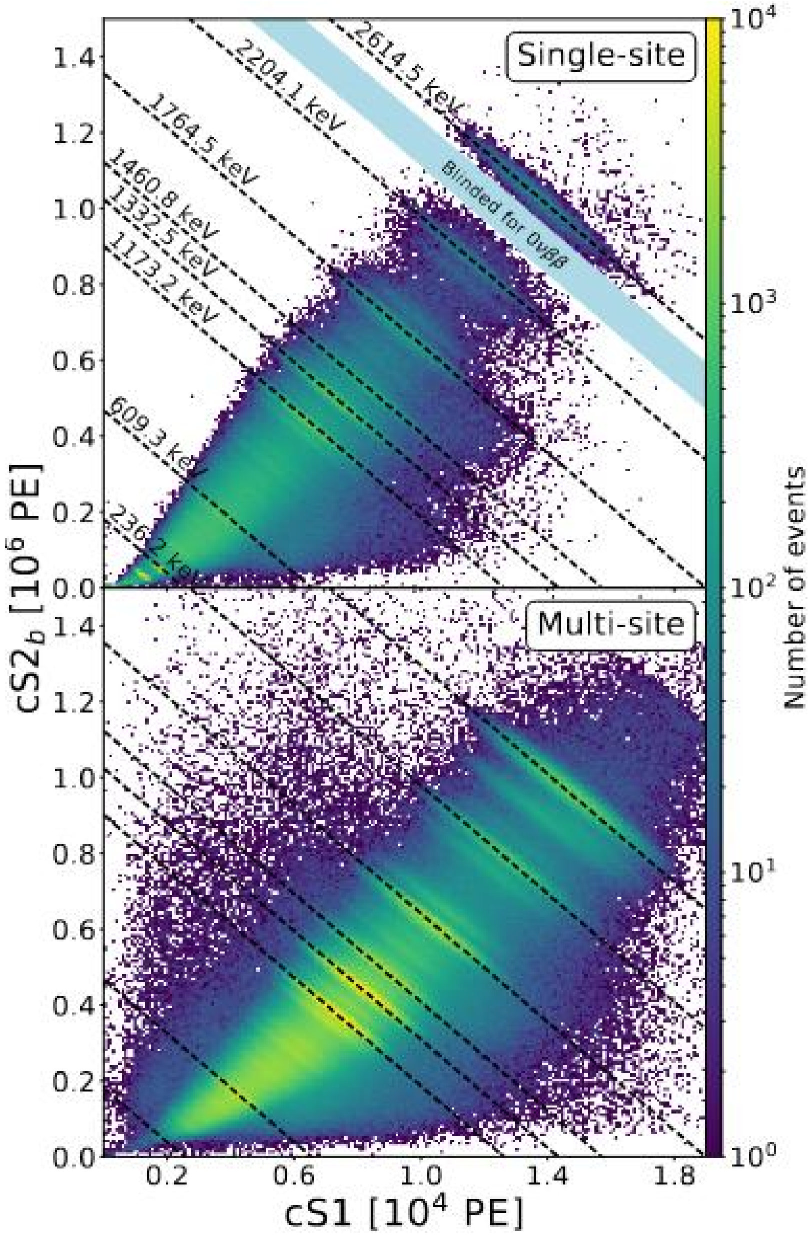
$$E = (n_{\mathrm{ph}} + n_{\mathrm{e}}) \cdot W = \left(\frac{\mathrm{S1}}{g_1} + \frac{\mathrm{S2}}{g_2}\right) \cdot W \ ,$$

QY = S2/E and LY = S1/E

$$\mathrm{QY} = -\frac{g_2}{g_1}\mathrm{LY} + \frac{g_2}{W} \ ,$$



g1 = (0.147 ± 0.001) PE/photon
g2 = (10.53 ± 0.04) PE/electron



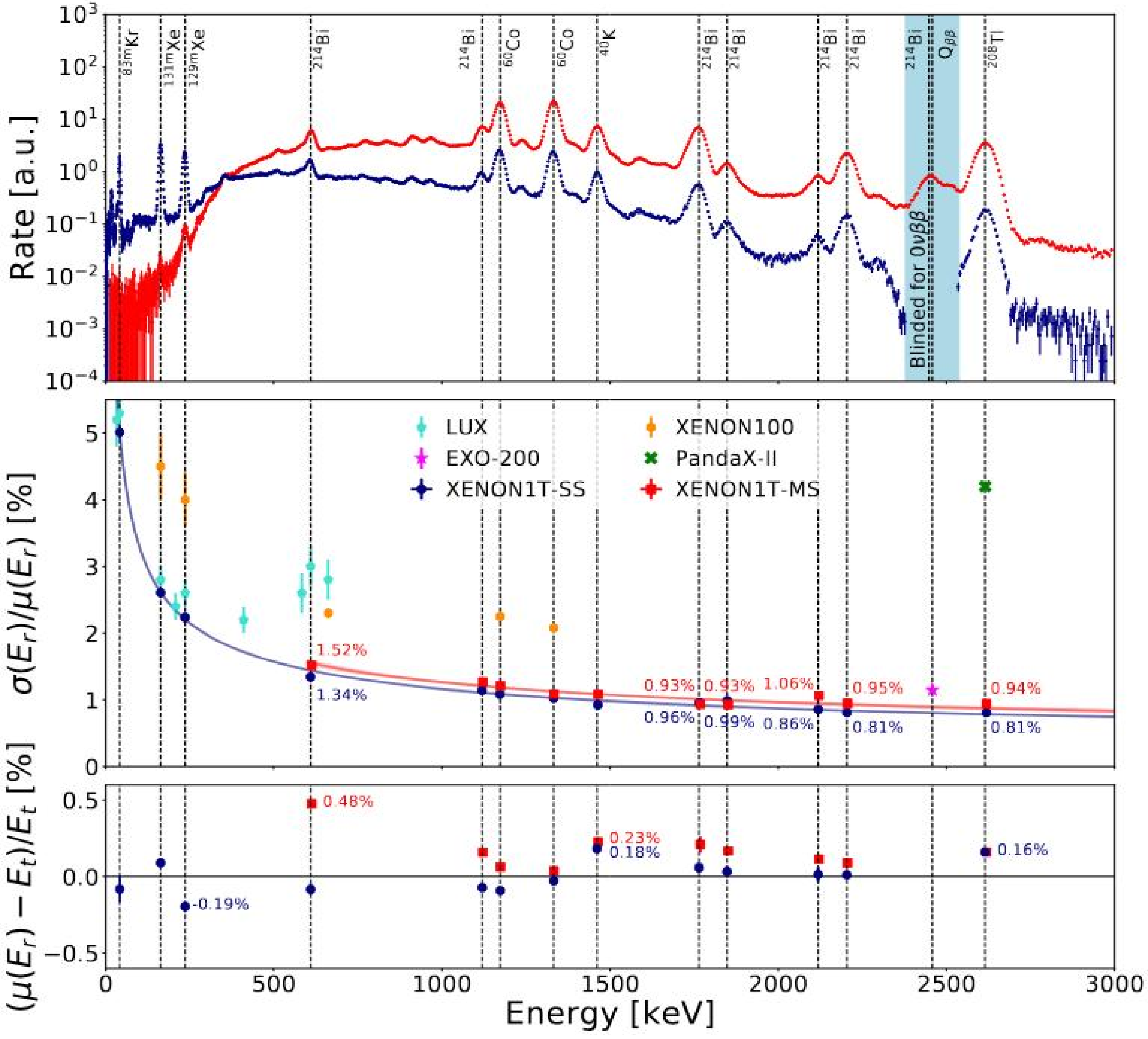
Linearity and resolution

- σ (Er)/μ(Er):the resolution of the reconstructed energy

- (μ(Er) − Et)/Et:shift from the nominal value,

- Energy resolution of SS:(0.80±0.02) %

- Energy resolution of MS:(0.90 ± 0.03)%



Conclusion

- S2 saturation was corrected for digitizer limitations and non-linear PMT/electronics responses.
- After correction, XENON1T achieved $\sigma/\mu = (0.80 \pm 0.02)\%$ at 2.46 MeV.
- The energy scale remains highly linear, with deviations below 0.4%.
- These results support the use of LXe TPCs in MeV-scale rare-event searches, such as $0\nu\beta\beta$ decay of ^{136}Xe.

Reference

E. Aprile et al. (XENON Collaboration), Energy resolution and linearity of XENON1T in the MeV energy range, European Physical Journal C 80, 785 (2020). https://doi.org/10.1140/epjc/s10052-020-8284-0

E. Aprile et al. (XENON Collaboration), The XENON1T Dark Matter Experiment, European Physical Journal C 77, 881 (2017). https://doi.org/10.1140/epjc/s10052-017-5326-3

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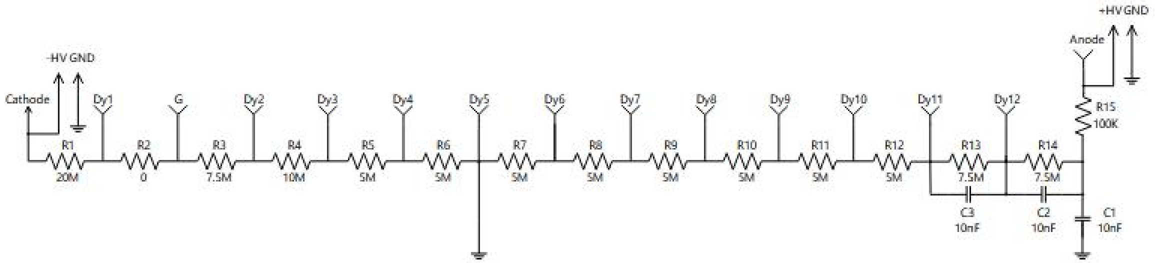
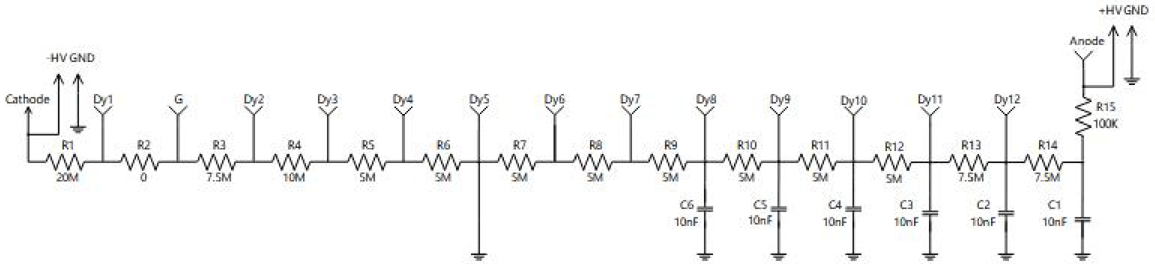
PMT waveform saturation and suppression

- In PandaX-4T, the PMT waveform saturation and suppression were attributed to the high-voltage divider base. Large pulses disturb the voltage distribution between dynode stages, especially in the later dynodes. This reduces the multiplication gain and leads to a non-linear PMT response.



(a) The original PMT base with three capacitors



(b) The improved PMT base with six capacitors

L. Luo et al., Improvement on the Linearity Response of PandaX-4T with new Photomultiplier Tube Bases, arXiv:2401.00373.

Problem

S1没有correction的原因：饱和的数量比较少，因为S1没有气相放大

S2波形尾巴符合的不好：论文认为主要是次级信号影响，而且信号前面的参考区域足够做缩放，不符合的区域论文认为对能量重建影响不大