Two-Neutrino pile-up discrimination in bolometers for Double Beta Decay

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The problem

- It was “commonly” accepted that the only irreducible background in $0\nu\beta\beta$ search was from the tail of the $2\nu\beta\beta$ mode but...

- Bolometric detectors are
  - slow
  - not sensitive to event topology

- In Phys. Lett. B 710 (2012) 318, it was pointed out that two independent $2\nu\beta\beta$ signals can sum up to produce events in the ROI

Isotope	$T_{1/2}$ (2ν) [y]
^{82}Se	$9.2 \cdot 10^{19}$
^{100}Mo	$7.1 \cdot 10^{18}$
^{116}Cd	$2.8 \cdot 10^{19}$
^{130}Te	$7 \cdot 10^{20}$

← **worst case** (^{100}Mo)

2νββ pile-up background

- Pile up rate in the ROI = $\varepsilon \cdot (r_{2\nu})^2 \cdot \Delta t$
  - ε = fraction of events in ROI
  - $r_{2\nu}$ = 2νββ count-rate
  - Δt = resolving time

- But discrimination capability is a function of
  - Δt
  - relative amplitudes among the two pulses
  - S/N ratio

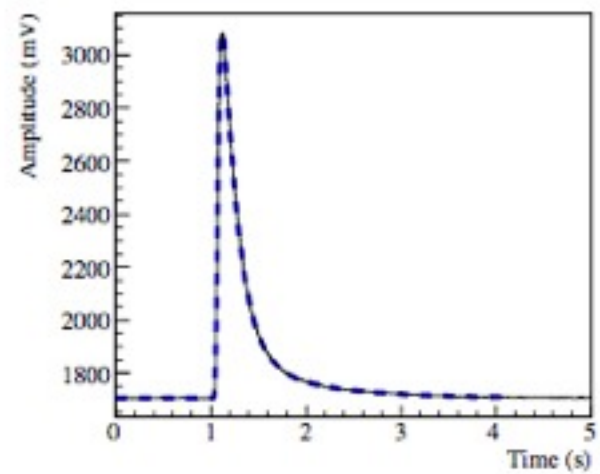
- Quantify the background induced by pile-up events in a ± 50 keV ROI for $5x5x5\ cm^3$ bolometers (ZnSe, $ZnMO_4$, TeO_2, $CdWO_4$)

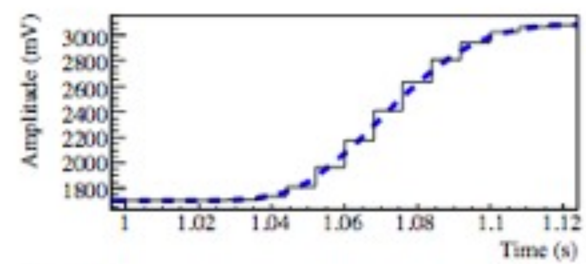
Which ΔT?

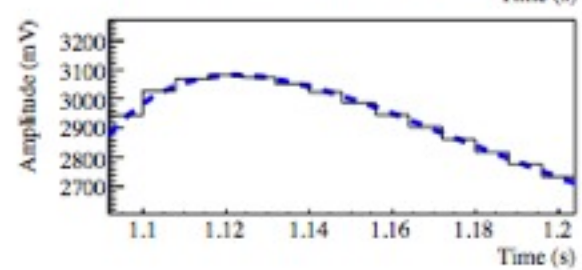
- Using the existing CUORE simulator for TeO_2 bolometers

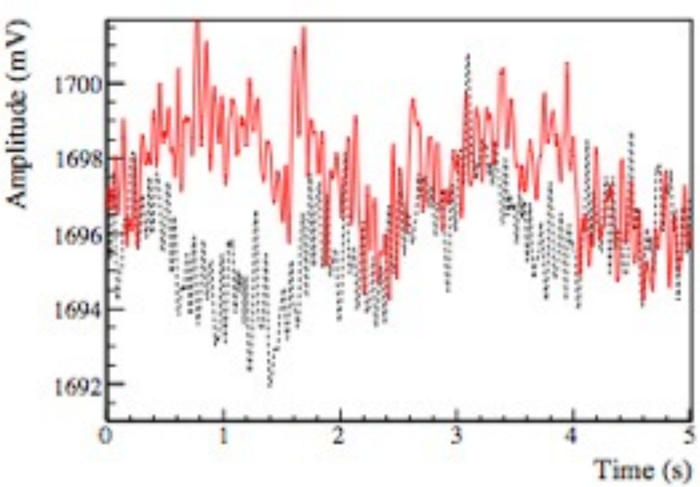
  Signal and noise simulation of CUORE bolometric detectors JINST 6(2011)P08007

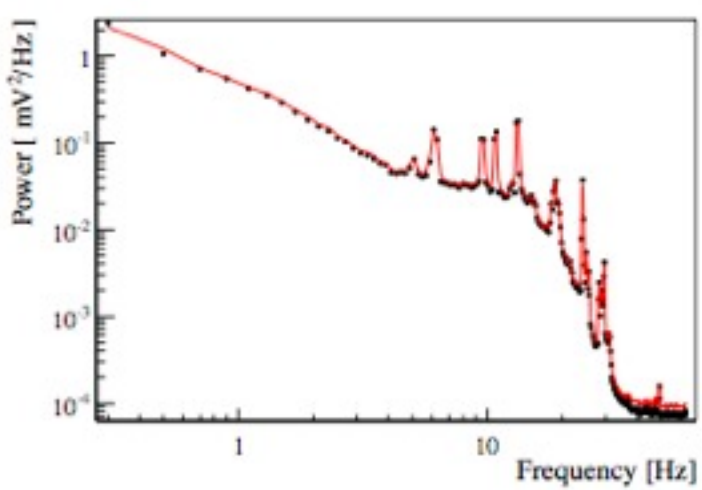
  - Signal is derived from the thermal model described in J.Appl.Phys.108 (2010) 084903
  - Noise is sampled according to measured noise power spectra of real TeO_2 detectors.
  - Effects generated by operating temperature drifts, nonlinearities and pileups are included.











Simulator input

- Custom:
  - Energy spectrum
  - Baseline distribution
  - Distribution of time arrivals between pulses

Table 1. Parameters of the signal model in Eqns. 4.15, 4.16 and 4.17.

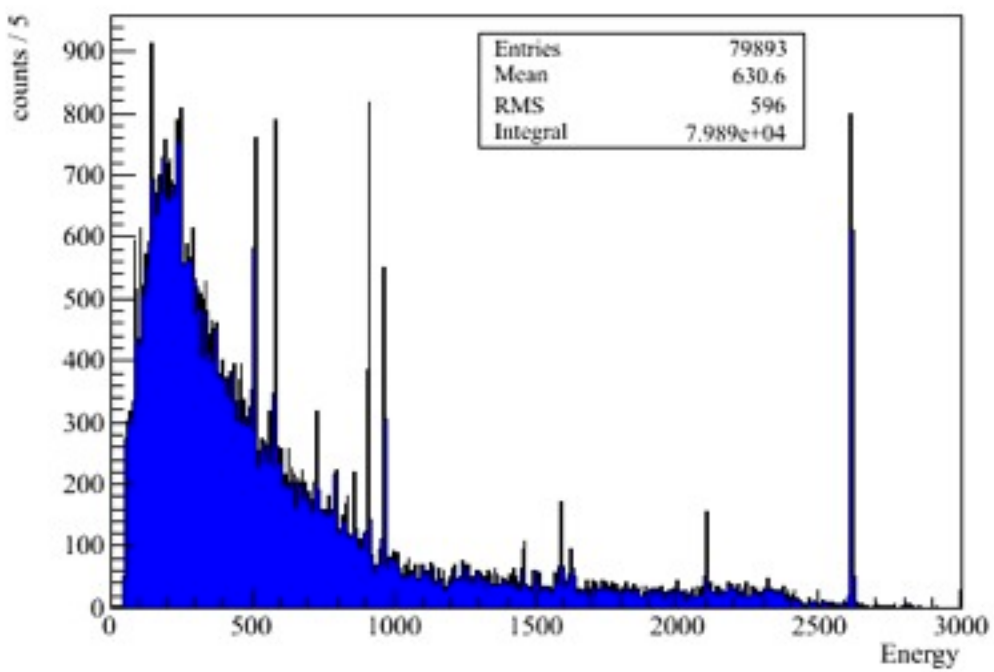
Parameter	Name	Equation	Estimation
τ_r	Thermal rise time	4.1	Fit
α	Weight of the two thermal decay constants	4.1	Fit
τ_{d1}	Fast thermal decay constant	4.1	Fit
τ_{d2}	Slow thermal decay constant	4.1	Fit
c	Energy to thermal amplitude conversion	4.10	Fit
R^B	Thermistor resistance at the pulse baseline	4.5	Measured
V_{bias}	Bias voltage	4.9	Measured
R_L	Load resistor	4.9	Measured
c_p	Parasitic capacitance	4.9	Measured
G	Electronics gain	4.11	Measured
f_b	Bessel filter cutoff frequency	4.14	Measured
V_h	Electronics offset voltage	4.16	Measured
V^B	Baseline voltage	4.17	Measured
t_0	Onset time of the pulse	4.17	Fit

Output

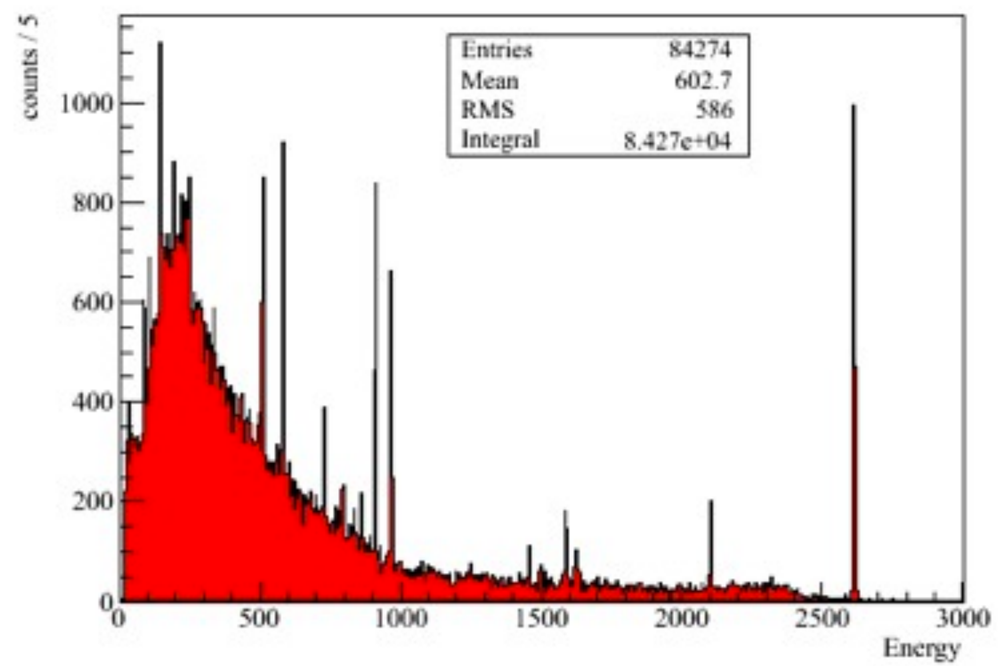
Signal and heater pulses + pure noise waveforms

MC Example and Validation

- A ^{232}Th calibration was simulated using as input a real calibration from a CUORE crystal validation run (CCVR1, 7 channels)



MC



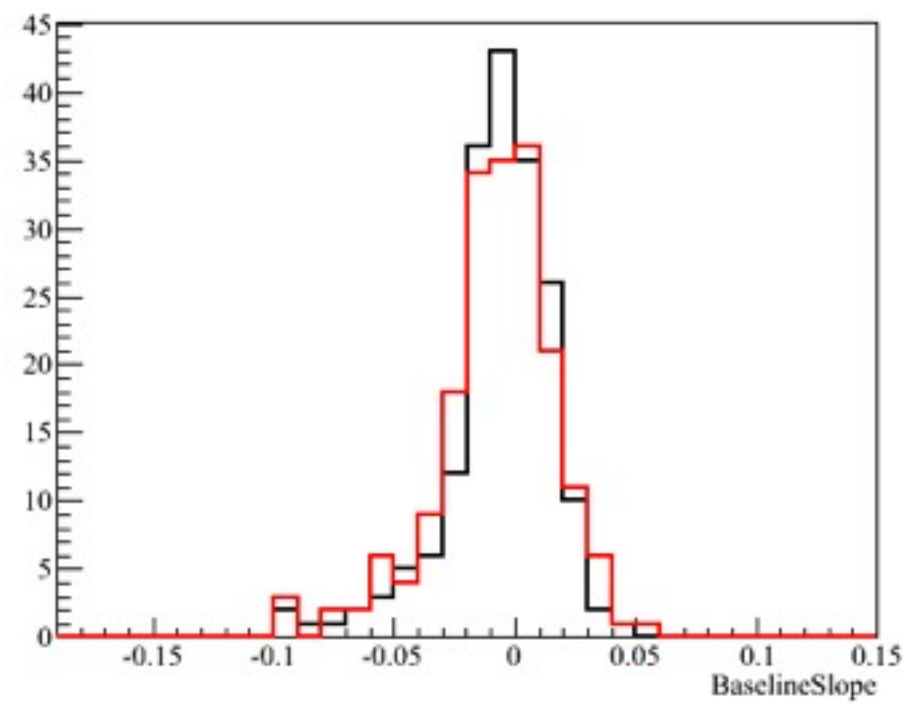
data

Validation

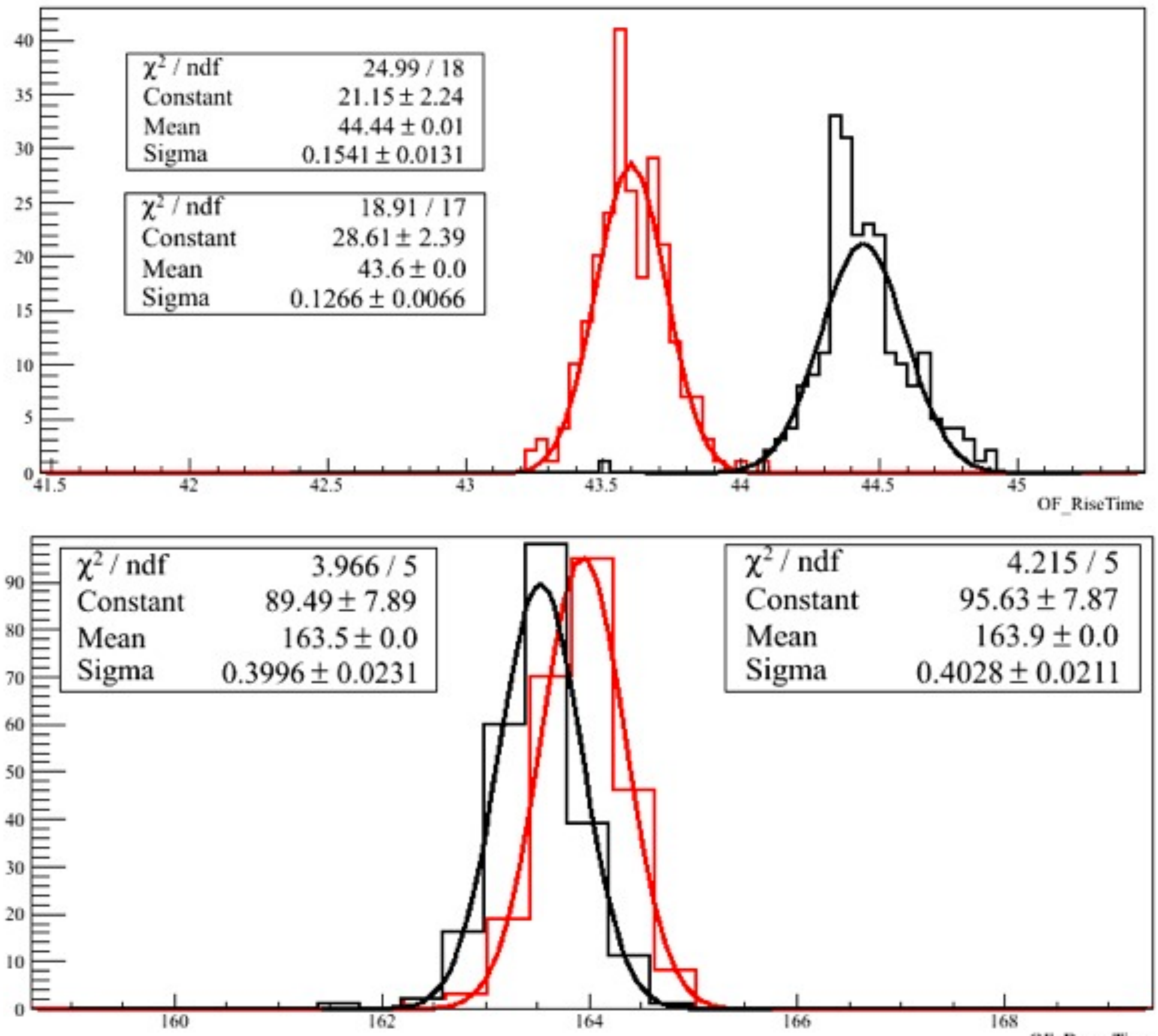
- MC and data processed with the same analysis chain
- Average pulse done on 2615 keV line
- Comparison of several distribution (for pulses @ 2615)
- CAVEAT: we expect some discrepancies in the width of RiseTime distribution due to the fact that the simulator assigns to each pulse exactly the same trigger position (ADC sample), while for real pulses this is not always true.

Good agreement for all channels

BaselineSlope



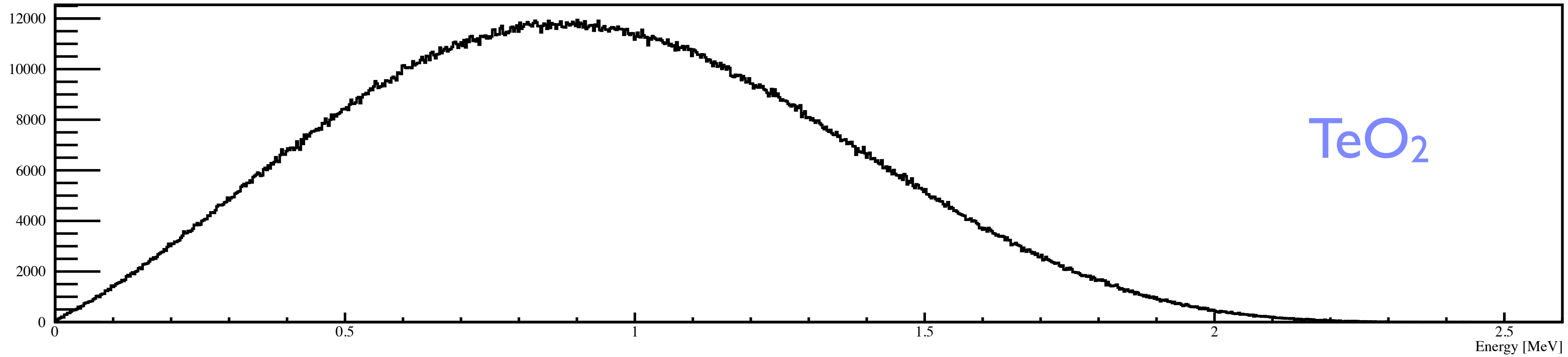
Validation



MC
Data

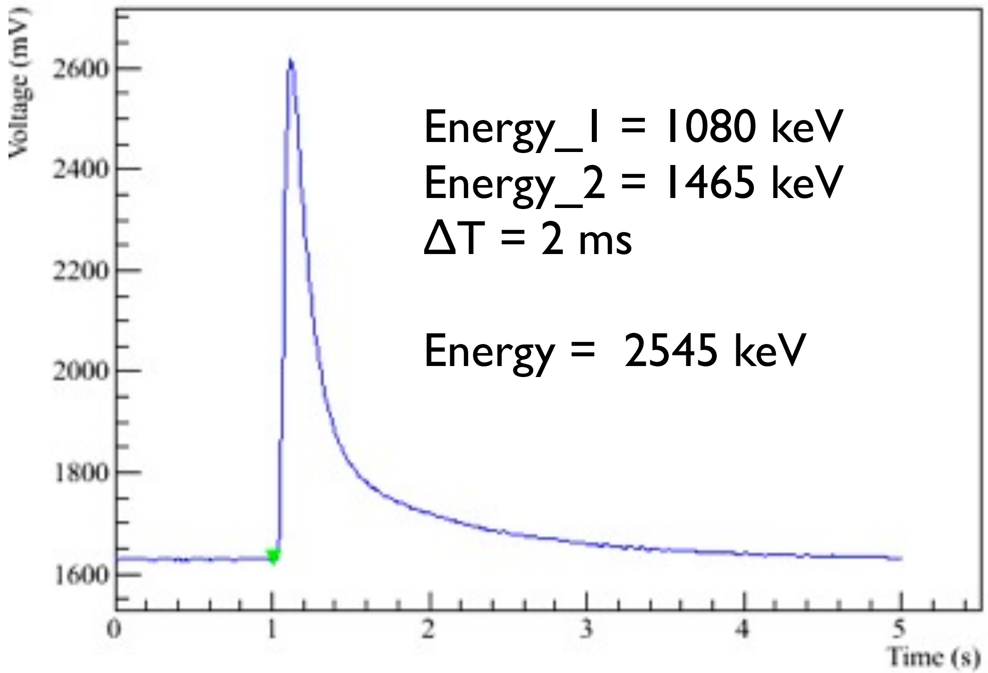
Simulation Input

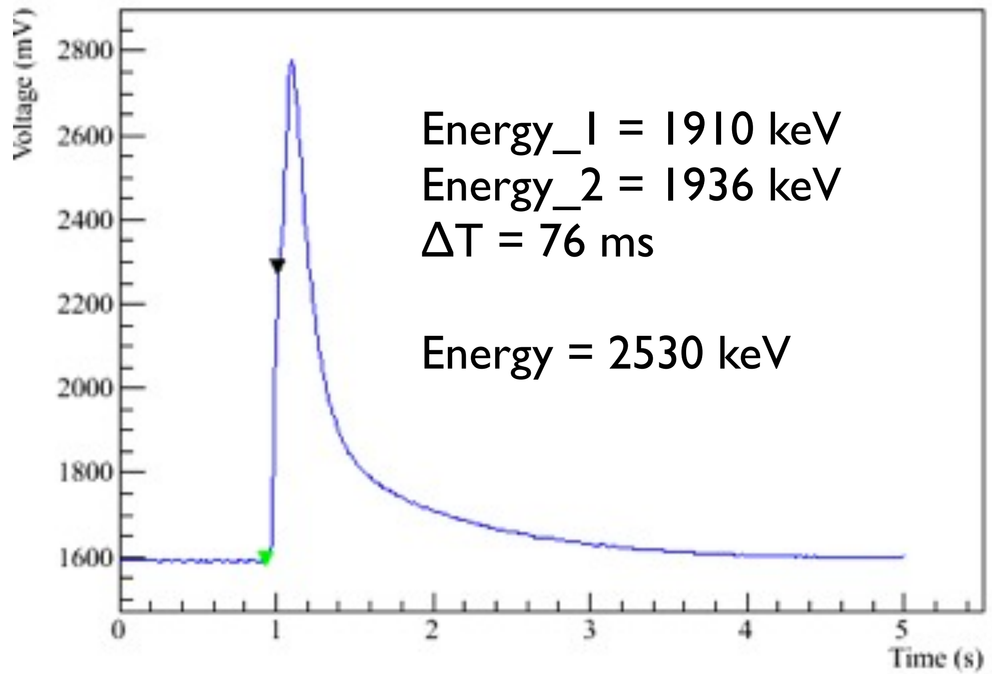
- Energy distribution:
  - 0νββ: for comparison with single pulse events at Q value
  - 2νββ: usual distribution see Zuber's Book "Neutrino Physics"
- Single energy distribution eq 7.27 $$\frac{dN}{dT_e} \approx (T_e+1)^2(Q-T_e)^6[(Q-T_e)^2+8(Q-T_e)+28]$$
- Sum energy distribution eq 7.28 $$\frac{dN}{dK} \approx K(Q-K)^5\left(1+2K+\frac{4K^2}{3}+\frac{K^3}{3}+\frac{K^4}{30}\right)$$



- Pile-up for 2νββ simulated for with 0<ΔT<100 ms

Example of pile-up events in ROI

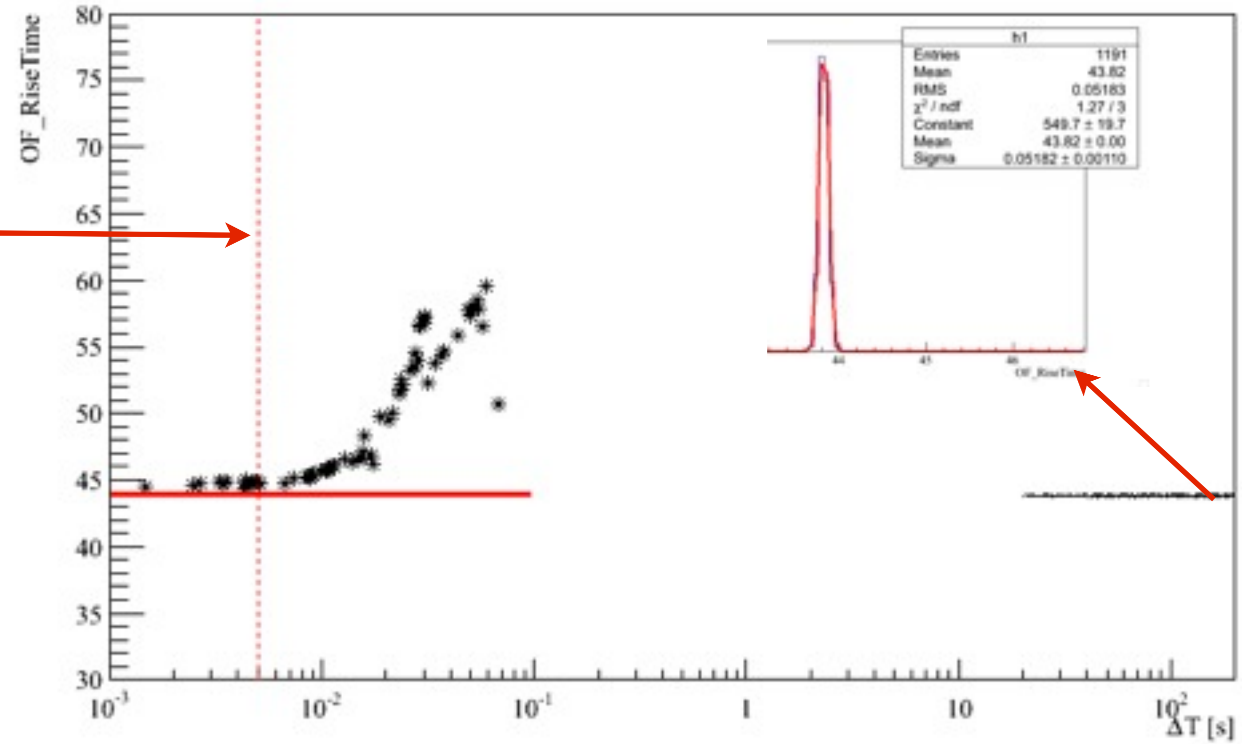


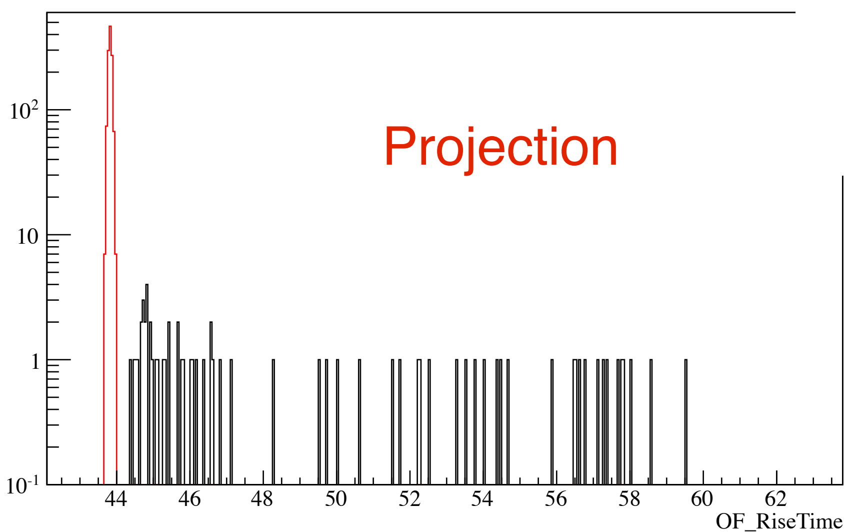


ΔT

- Scatter plots of rise time vs. ΔT between the pulses that pile-up (from MC truth)

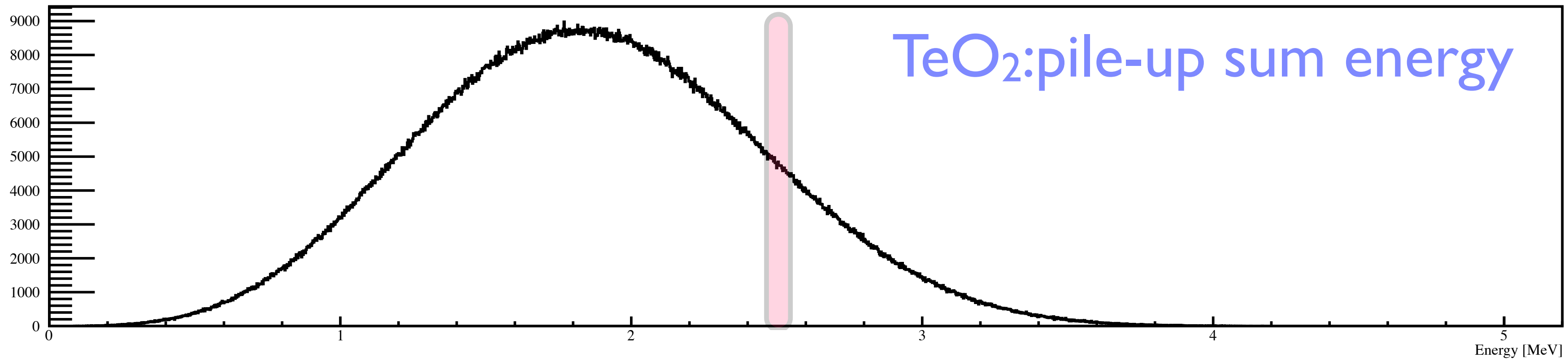
5 sigma limit based on the fit
performed on 0v events
(no pile-up)

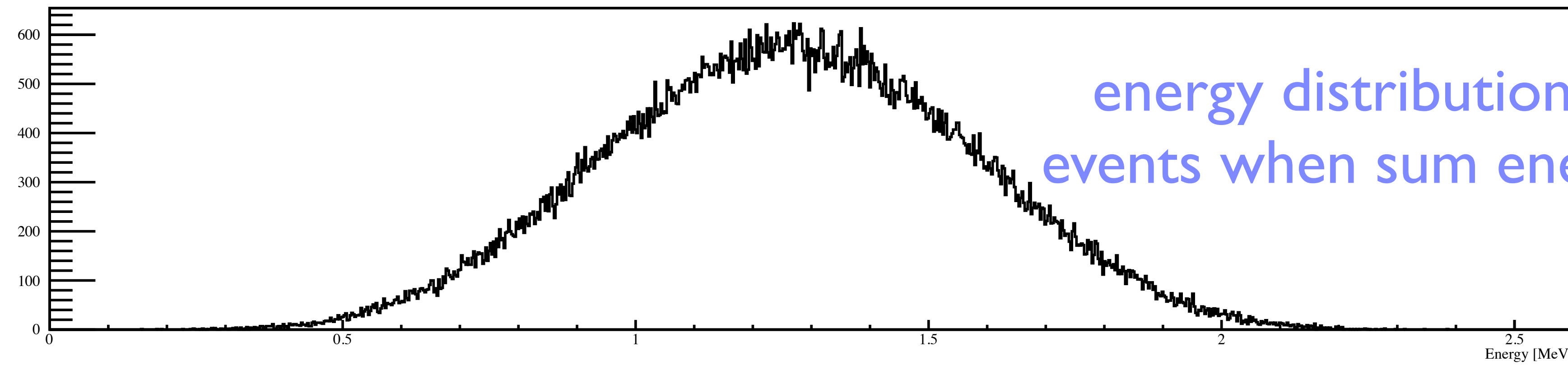




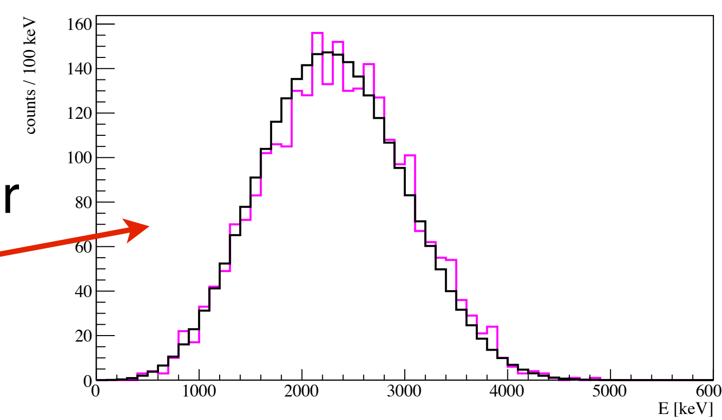
- With these cuts and Δt ≥ 5ms ALL pile-up events in ROI are discriminated

Find ε in ± 50 keV ROI





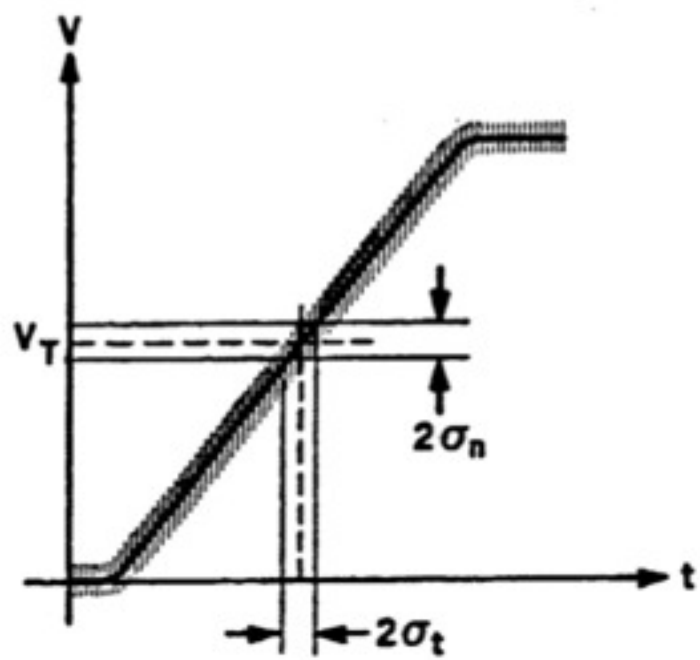
- ε≈3.5% for TeO_2
  ≈ 3.4% for $CdWO_4$,≈3.2% for ZnSe, $ZnMO_4$
- Caveat: the above distribution simply sum the two ener irrespectively of their time difference
  - true for ΔT<5 ms



Time Resolution

- In timing measurements the quantity to optimize is not S/N but slope/noise
  - t_r = rise time
  - rise time matters but noise also

$$\sigma_t = \frac{\sigma_n}{(dS/dt)_{S_T}} \approx \frac{t_r}{S/N},$$



Helmuth Spieler - *Radiation Detectors and Signal Processing*

$$\sigma_t = \frac{\sigma_n}{\left.\frac{dV}{dt}\right|_{V_T}}$$

Comparison in heat bolometers

- R=rejection power
- $R/R_{TeO2} = \tau_{TeO2}/\tau \cdot [(S/N)_{TeO2} /(S/N)]$

Detector	rise time(ms)	S/N	R/R_{TeO2}
ZnSe	7	700	2
$CdWO_4$	20	?	
$ZnMoO_4$	10	1700	3
TeO2	50	2600	1

Background estimate

Isotope	Detector	Crystal Mass [g]	a.i. [%]	$N_{\beta\beta}$ 2v	$T_{1/2}$ 2v [y]	Rate 2v [Hz]	Rate pile-up [Hz]	counts/kg keV y in ROI	counts/kg keV y in ROI scaled by R
^{82}Se	ZnSe	659	90	2.50E+24	9.20E+19	5.90E-04	1.70E-09	2.70E-05	1.30E-05
^{100}Mo	$ZnMoO_4$	537	90	1.30E+24	7.10E+18	4.00E-03	8.80E-08	1.50E-03	5.00E-04
^{116}Cd	$CdWO_4$	887	90	1.50E+24	2.80E+19	1.20E-03	6.80E-09	7.40E-05	7.4E-05?
^{130}Te	TeO_2	750	90	2.50E+24	7.00E+20	8.20E-05	3.40E-11	5.00E-07	5.00E-07

- Can we gain something by exploiting the faster time response of light detectors?

S/N ratio in light detector

- We assume $\sigma \simeq$ 150 eV for the light detector, rise time ~10 ms
- S= light emitted @ 2.6 MeV

Detector	LY @2615 keV	S/N	R_L/R_{TeO2}
ZnSe	7 keV/MeV	120	0.22
$CdWO_4$	17 keV/MeV	330	0.53
$ZnMoO_4$	1.4keV/MeV	20	0.04

- The worst case is $ZnMo_4$ which is also the bolometer for which we expect the highest background contribution

Comparison with EPJ(2012)72:1989

- Simulation of light detector
- Signal and noise pulse from real detector faced to a small $ZnMO_4$ crystal
- S/N fixed at 30, rise time ~3 ms
- Flat ΔT in 0-10 ms
- Energy of two decays summed
- time resolution of 1 ms