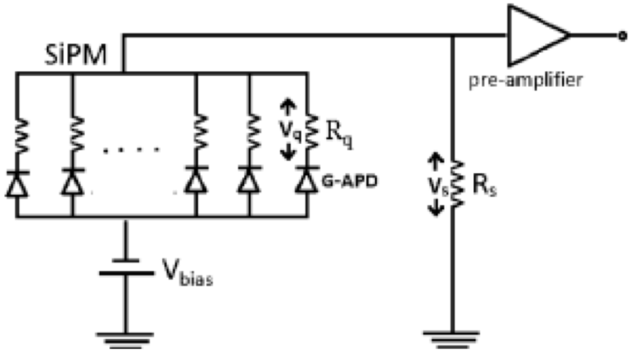
Implementation and validation of an SiPM model in GATE

BRAHIM MEHADJI, MATHIEU DUPONT, CHRISTIAN MOREL

AIX MARSEILLE UNIV, CNRS/IN2P3, CPPM, MARSEILLE, FRANCE

What to be simulated ?

- One SiPM pixel = Geiger-mode avalanche photodiodes (μCell ~ 35μm), connected in parallel

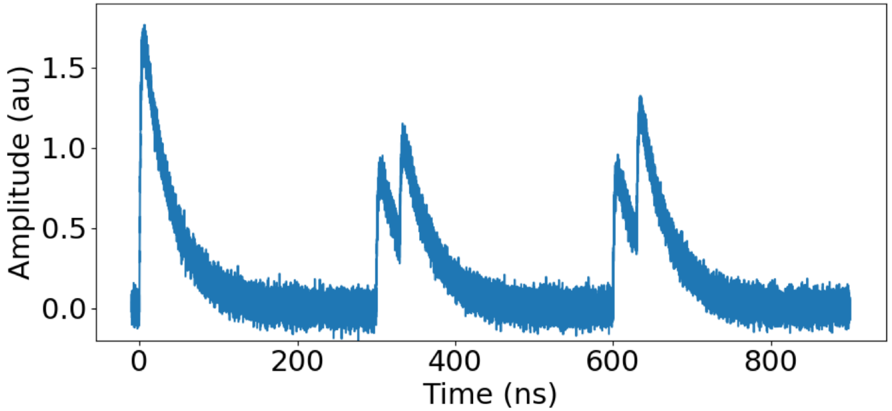


- Response of one μCell:

$$A \left[1 - \exp\left(\frac{-t}{\tau_{rise}}\right)\right] \times \exp\left(\frac{-t}{\tau_{fall}}\right)$$

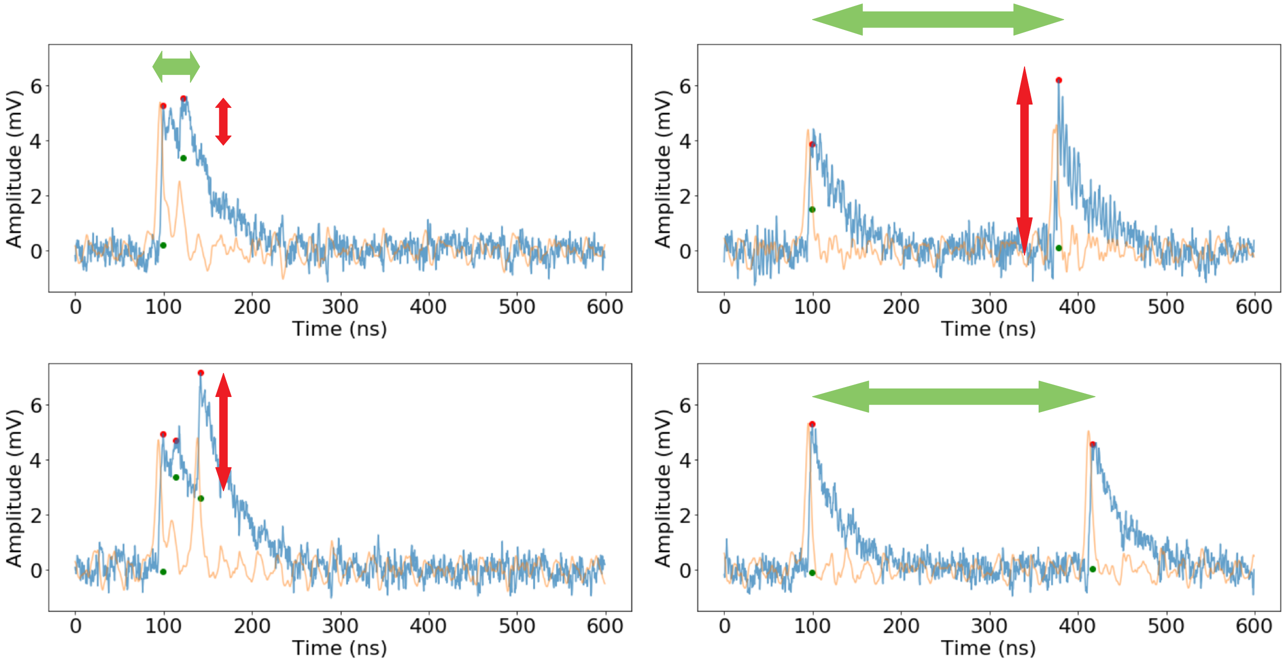
  - Signal shape: amplitude, rise time and fall time

- Noises:
  - Pulse generation:
    - Dark noise: rate
    - Crosstalks: probability multiplicity
    - Afterpulse: recovery time, decay time
    - Delayed-crosstalks: recovery time, decay time
  - Electronic Noise: sigma



Parameters Measurement (1/2)

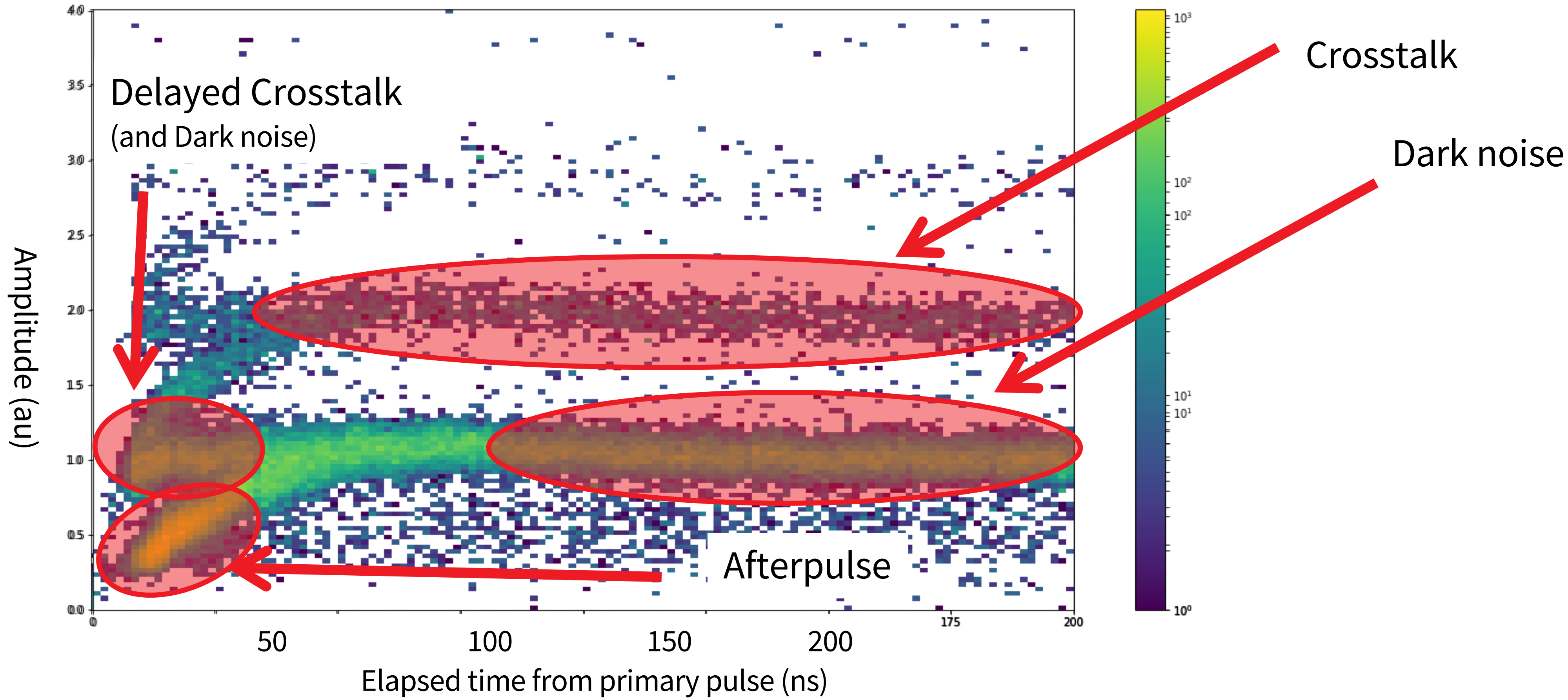
Simply record SiPM response in dark condition



- Measure:
  - SiPM : MPPC S1330-3050VE
  - C12332-01 evaluation board (Gain = 21)
  - Lecroy oscilloscope, 2.5 GHz
  - Dark room
  - Temp: 25°C
- Compute:
  - White noise sigma
  - Rise and fall time of the signal

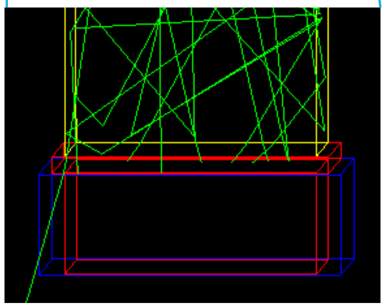
→Make 2D histogram amplitude peaks vs elapsed time from primary pulse

Parameters Determination (2/2)



The GATE simulation

Detected photons (time)



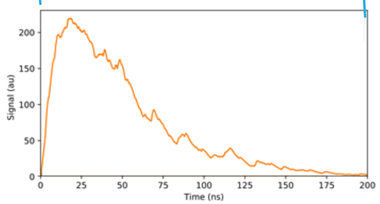
Potential pulses (time)

Time (ns)	ų-cell
0 ns	20
10 ns	1654

Generation of pulses due to the noise and their amplitudes by taking account for the recovery time

Time (ns)	ų-cell	Amplitude
0	20	1
5	20	0.2
10	1654	1
10	1655	1

Generating and summing the signal for each pulse



```
<?xml version="1.0" encoding="utf-8" ?>
- <sipms>
 - <sipm name="hamamatsucross">
  - <propertiestable>
   - <!--
        <property name="tauRise" value="1" unit="nanosecond"/>
                        <property name="tauFall" value="100" unit="nanosecond"/>
     -->
     <property name="durationPulse" value="300" unit="nanosecond" />
     <property name="deadTime" value="0." unit="nanosecond" />
     <property name="tauRecovery" value="28.5" unit="nanosecond" />
     <property name="tauBuilk" value="11.26" unit="nanosecond" />
     <property name="Cap" value="0.07" />
     <property name="Cct" value="0.00779" />
     <property name="histRes" value="11." unit="nanosecond" />
     <property name="t0" value="0." unit="nanosecond" />
     <property name="a" value="-1." />
     <property name="b" value="-0.5" />
     <property name="signalDeconvolvedAmplitude" value="0.00048" unit="volt" />
     <property name="signalDeconvolvedAmplitudeSigma" value="0.0000025" unit="volt" />
     <property name="whiteNoiseSigma" value="3.77E-05" unit="volt" />
     <property name="darkNoise" value="496" unit="kilohertz" />
   - <propertyvector name="DIMENTIONS" unit="micrometer">
       <ve value="50." />
       <ve value="50." />
     </propertyvector>
   - <propertyvector name="CROSSTALK">
       <ve value="9.32349329e-01" />
       <ve value="6.16959618e-02" />
       <ve value="5.38537476e-03" />
       <ve value="5.13045742e-04" />
       <ve value="5.06332074e-05" />
       <ve value="5.09200439e-06" />
       <ve value="5.12085052e-07" />
       <ve value="5.14986007e-08" />
     </propertyvector>
   - <propertyvector name="CROSSTALK_DISPERTION">
       <ve value="9.32349329e-01" />
       <ve value="6.16959618e-02" />
       <ve value="5.38537476e-03" />
       <ve value="5.13045742e-04" />
       <ve value="5.06332074e-05" />
       <ve value="5.09200439e-06" />
       <ve value="5.12085052e-07" />
       <ve value="5.14986007e-08" />
     </propertyvector>
   - <propertyvector name="PULSE" unit="nanosecond">
       <ve time="0.0" value="0.011675983255021347" />
       <ve time="0.050000000066756627" value="0.014392492543427967" />
       <ve time="0.10000000133514675" value="0.01854140934527878" />
```


In the macro file:

```
/gate/digitizer/Singles/insert  sipm
/gate/digitizer/Singles/sipm/setVolume SiPM_macropixels
/gate/digitizer/Singles/sipm/type hamamatsucross
/gate/digitizer/Singles/sipm/setStartSignal 0 ns
/gate/digitizer/Singles/sipm/setDurationSignal 0.01 s
/gate/digitizer/Singles/sipm/setStepSignal .1 ns
/gate/digitizer/Singles/sipm/surface YZ
```

Dark count amplitude: $$DC(t) = A_{DC}\left[1 - \exp\left(-\frac{t}{\tau_{rise}}\right)\right]\exp\left(-\frac{t}{\tau_{fall}}\right)$$

Afterpulse recovery: $$A(t) = A_{DC}\,\theta(t)\left[1 - \exp\left(-\frac{t}{\tau_{rec}}\right)\right]$$

Afterpulse distribution: $$f_{AP}(t) = \frac{C_{AP}}{t}\exp\left(-\frac{t}{\tau_{bulk}}\right)\frac{\mathrm{A(t)}}{\mathrm{A_{DC}}}$$

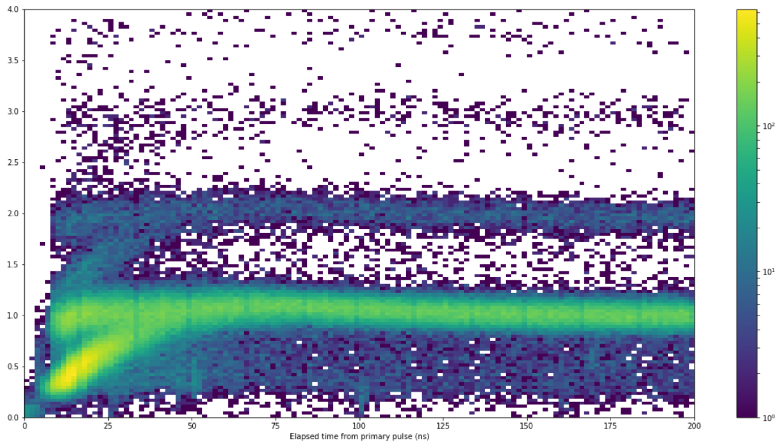
Delayed-crosstalk distribution: $$f_{\mathrm{CT}}(t) = \frac{C_{\mathrm{CT}}}{\sqrt{t}}\exp\left(-\frac{t}{\tau_{bulk}}\right)$$

J. Rosado and S. Hidalgo, 2015 *JINST* **10** P10031

Construction des histogrammes 2D

Experimental

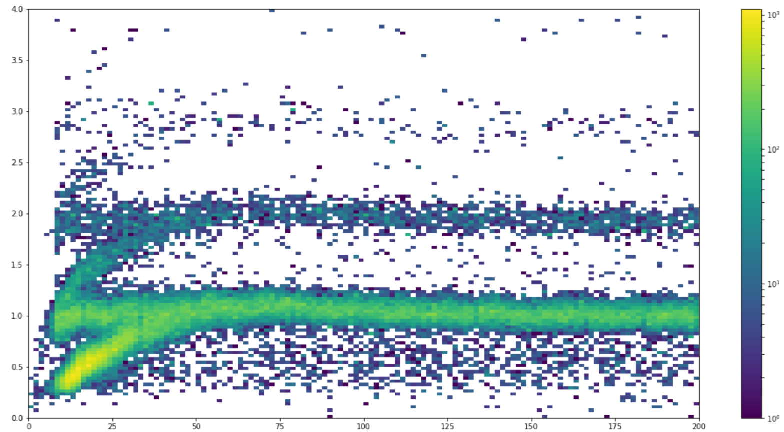
Amplitude



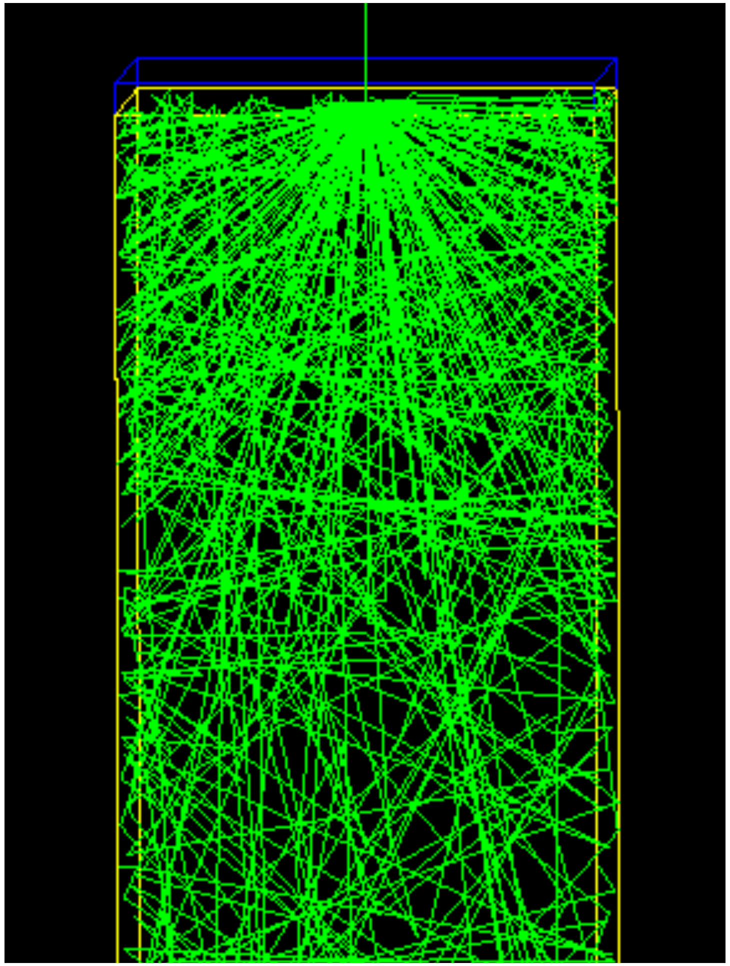
Temps écoulé (ns)

Simulation GATE

Amplitude



Temps écoulé (ns)



A case of study

$3 \times 3\ mm^2$ MPPC s13360-3050VE

$3 \times 3 \times 5\ mm^3$ LYSO crystal

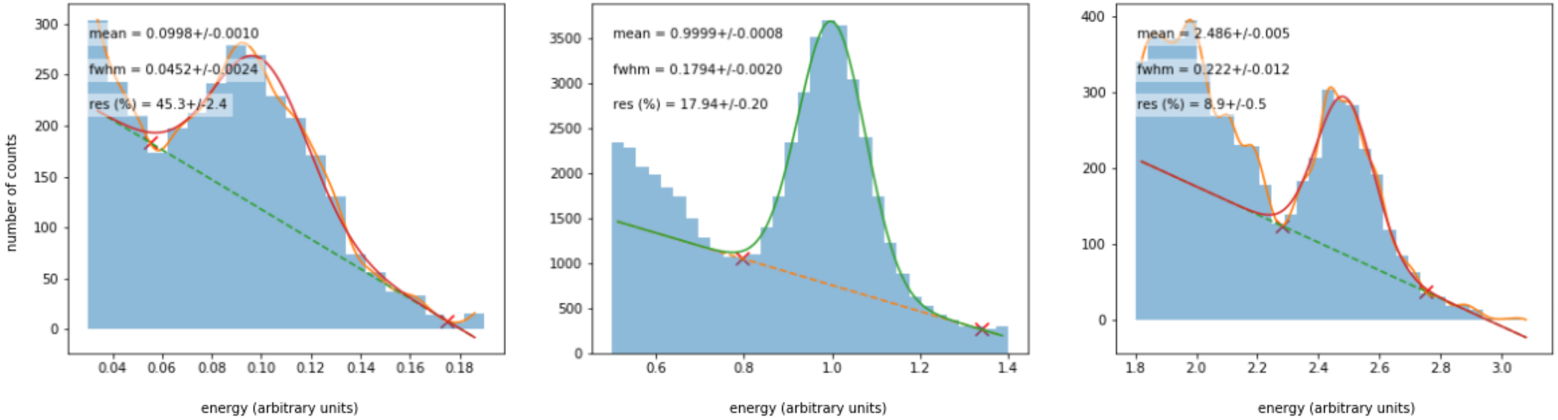
No wrapping

No amplifier

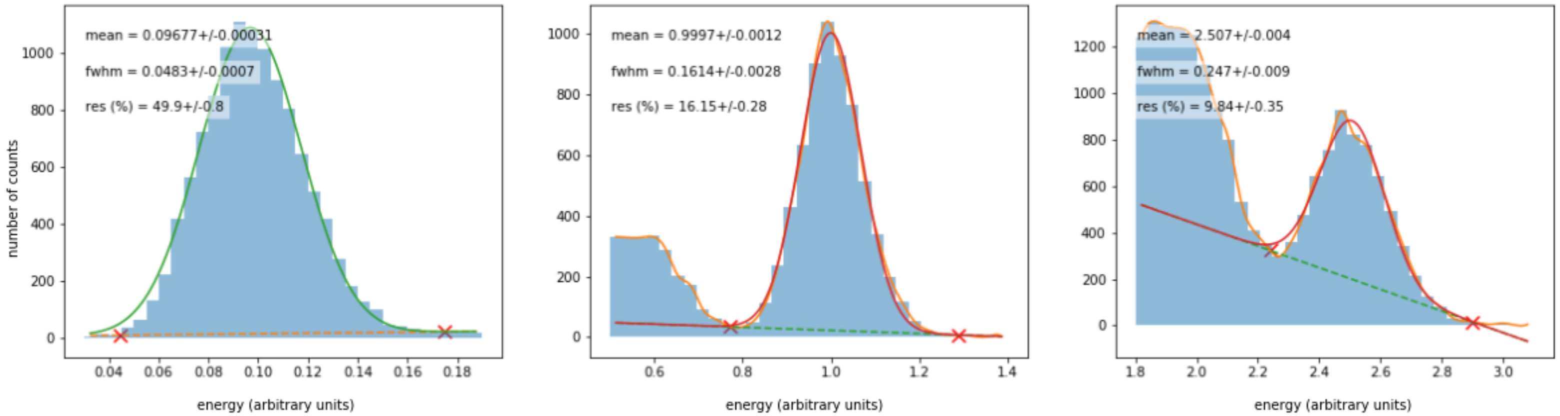
Measurements with a ^{22}Na and ^{241}Am source

-> crystal parameters determined by using the ET9125SWB photomultiplier and transposed to the SiPM simulation

Experimental



Simulation



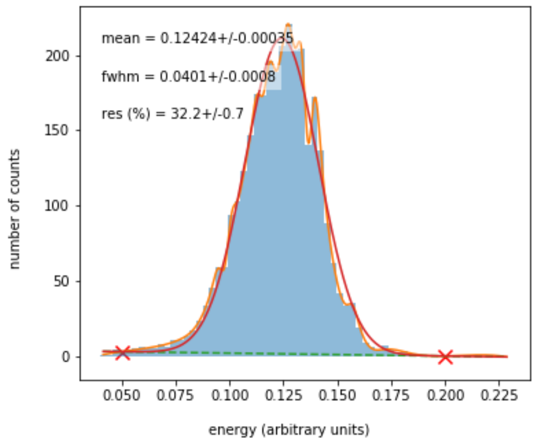
60 keV **511 keV** **1275 keV**

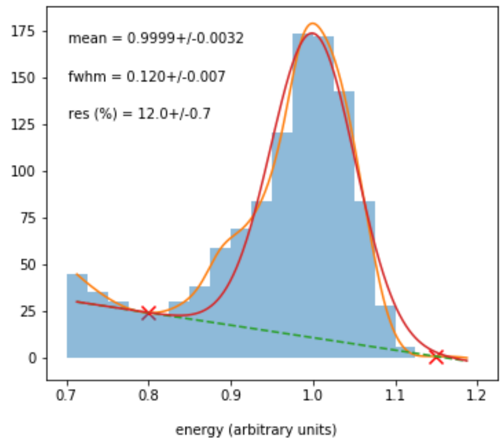
PM

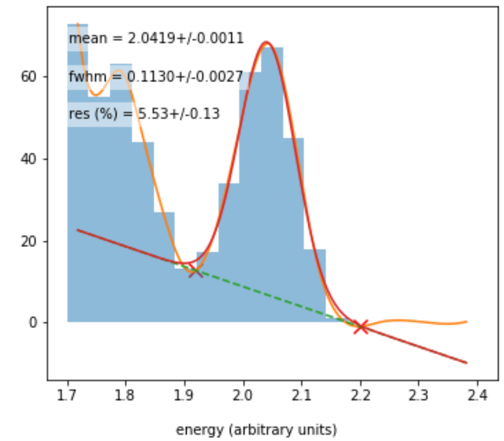
ET9125SWB

At 60 keV, the crystal emit 20 % less photons per keV than at 511 and 1275 keV

Experimental



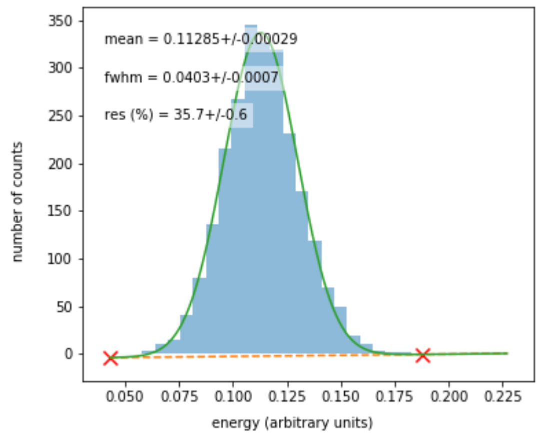


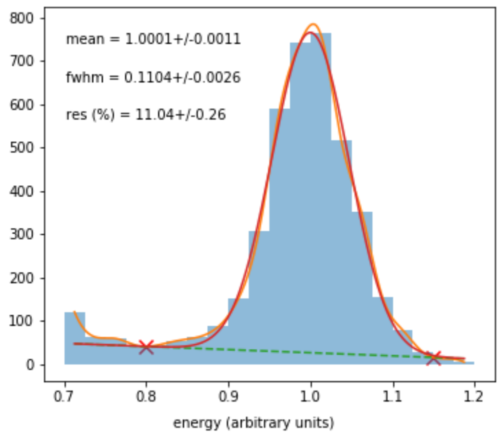


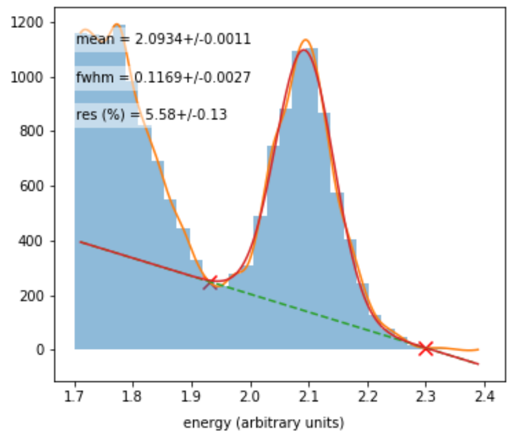
SiPM

MPPC s13360-3050VE

Simulation

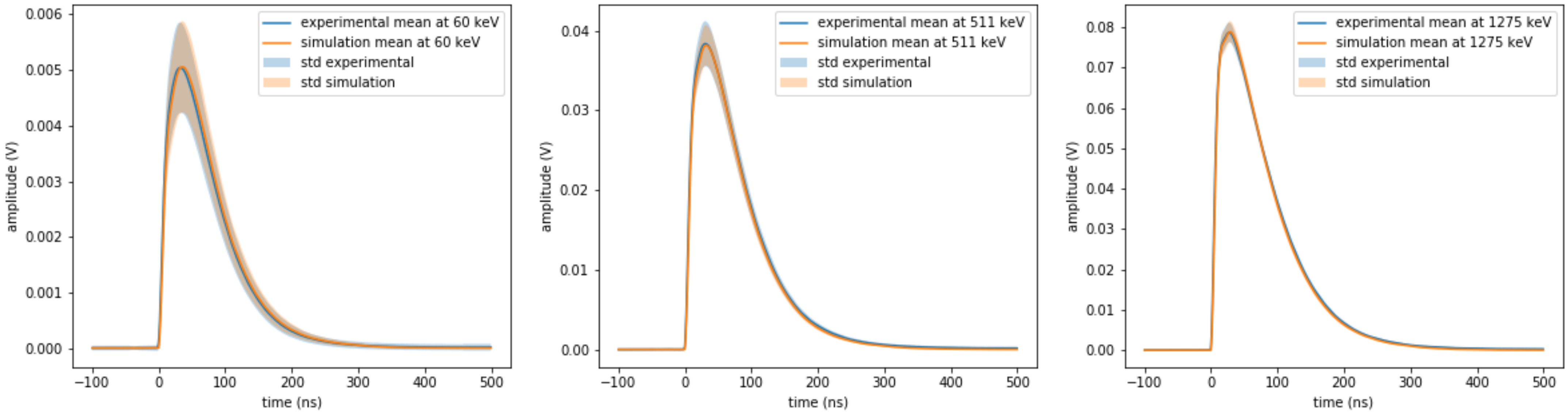






60 keV **511 keV** **1275 keV**

Signals comparison



Signal shape of the photoelectric peaks while using an SiPM in experimental and simulation

Simulating without noises ...

	With noises		No afterpulsing		No Crosstalks		No darknoise		No noise	
	mean	FWHM	mean	FWHM	mean	FWHM	mean	FWHM	mean	FWHM
60 keV	0.11	35.7±0.6	0.11	31.3±1.3	0.11	31.6±1.0	0.11	31.3±1.3	0.11	30.5±1.3
511 keV	1.00	11.0±0.3	1.00	10.9±0.6	1.00	10.2±0.6	1.00	10.3±0.6	1.00	10.3±0.5
1275 keV	2.09	5.6±0.1	2.10	5.3±0.4	2.13	5.3±0.3	2.09	5.5±0.3	2.14	5.2±0.6

Photo-peaks mean and FWHM while simulating the SiPM by removing some sources of noise

- **The SiPM behaviour is well enough reproduced into GATE so has to get realistic results**
- **Adding noises makes simulation closer to experimental**

Simulating and summing pulses is sufficient

Detected photons (time)

Potential pulses (time)

Generation of pulses due to the noise and their amplitudes by taking account for the recovery time

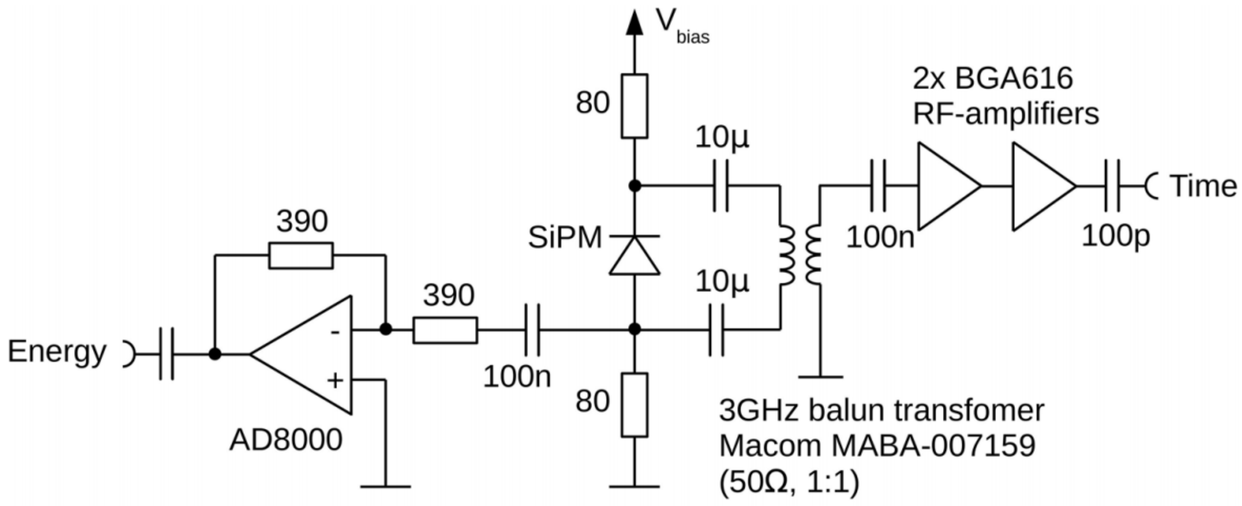
~~Generating and summing the signal for each pulse~~

Summing pulses amplitude

Energy (keV)	SiPM simulation		SiPM simulation summing pulses	
	Mean	FWHM (%)	mean	FWHM(%)
60	0.11	35.7	0.11	35.7
511	1	11.0	1	11.0
1275	2.09	5.6	2.09	5.6

Prospective

To validate GATE for simulating timing performances



S. Gundacker et al., "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET", Phys. Med. Biol. 64 (2019) 055012.

Thank you for you attention

B. Mehadji, M. Dupont, <u>C. Morel</u>
mehadji@cppm.in2p3.fr

Centre de Physique des Particules
de Marseille (CPPM)

Aix-Marseille Univ' and CNRS/IN2P3