Digitization for the Shashlyk EMC

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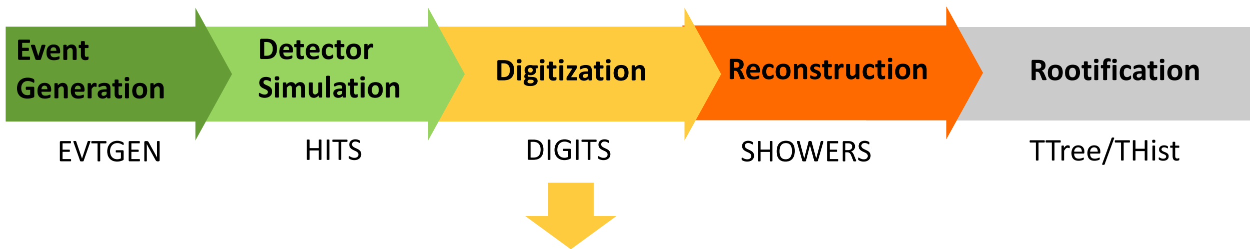
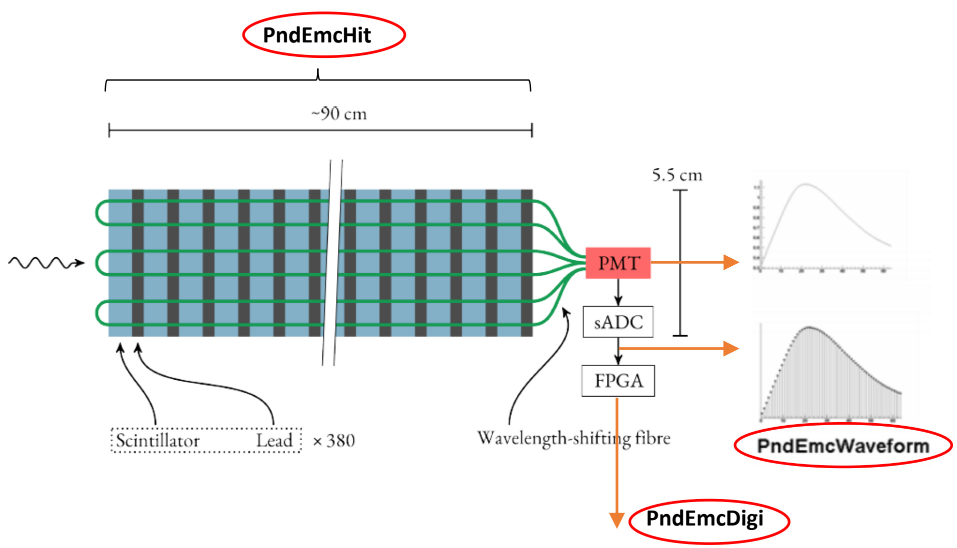
Outline

- **Introduction**
- **Shashlyk digitization in PandaRoot**
  - Signal generator
  - Feature extraction
- **Summary**

*Markus' thesis: https://panda.gsi.de/ publication/th-phd-2020-004

Digitization process in PandaRoot





Signal Generator (SG)

- **Analog waveforms creation**
- **Noises generation**
- **Digitization**
- **Pile-up waveforms creation**

Feature Extraction (FE)

- **Hit detection**
- **Amplitude/time extraction**
- **Pile-up recovery**

Time-based simulation

The Shashlyk EMC Parameters

Table 4.1: Requirements on the EMC detectors in PANDA. Data taken from [23, 48].

Property	Required values			
	Backward endcap	Barrel	Forward endcap	Shashlyk
Relative energy resolution σ_E/E	$\leq 1\% \oplus \frac{2\%}{\sqrt{E/\mathrm{GeV}}}$	$\leq 1\% \oplus \frac{2\%}{\sqrt{E/\mathrm{GeV}}}$	$\leq 1\% \oplus \frac{2\%}{\sqrt{E/\mathrm{GeV}}}$	$\leq 1\% \oplus \frac{(2-3)\%}{\sqrt{E/\mathrm{GeV}}}$
Photon-energy threshold [MeV]	10	10	10	10
Single-detector threshold [MeV]	3	3	3	3
Energy-equivalent noise [MeV]	1	1	1	1
Maximum detectable energy [MeV]	700	7300	14600	15000
Polar-angle coverage (lab frame) [°]	≥ 140	≥ 22	≥ 5	≥ 0
Solid-angle coverage (lab frame) [% 4π]	5.5	84.7	3.2	0.74
Hit rate per detector* [MHz]	0.06	0.06	0.5	~ 1
Radiation hardness [Gy y^{-1}]	10	10	125	1000

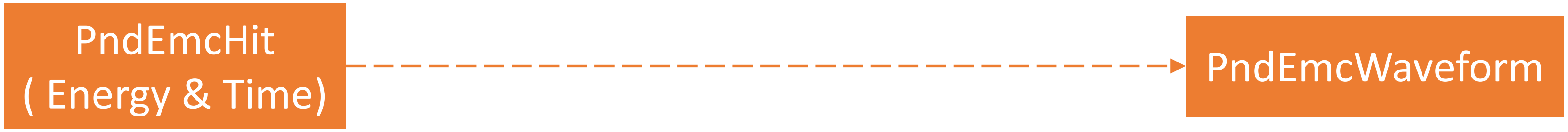
* Hit rate per individual crystal or cell.

For Shashlyk EMC:

- Larger energy resolution (sampling detector, larger cell size)
- Polar angle coverage: 0-5 deg vertically, 0-10 deg horizontally
- The same single-detector threshold starting at 3 MeV 🡐 Require fine digitization

Signal Generator

Signal generator



Photon statistics

PndEmcHit
(Energy & Time)

Scaled by *Energy* & *Q.E.*

$N_{p.e.}$

PndEmcWaveform

Photon statistics in PMT:

Importing the photon statistics by smearing the energy*:

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{E}} \times \sqrt{\frac{F}{N_{p.e.}}}$$

(*Q.E.* = 0.15, *F* = 1.3)

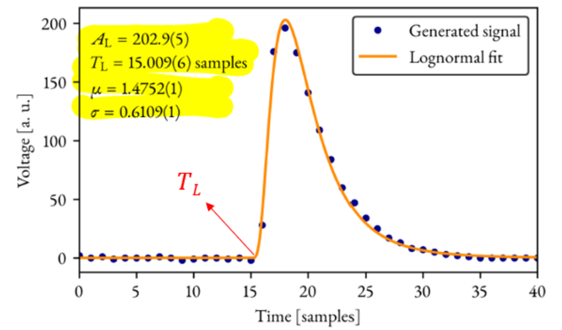
* EMC TDR

Idea pulse

Idea pulse generation by sampling:

$$f_L(t) = \begin{cases} \frac{A_L \exp(\mu - 0.5\sigma^2)}{t - T_L} \exp\left[\frac{[\log(t-T_L)-\mu]^2}{2\sigma^2}\right], & \text{if } t > T_L \\ 0, & \text{otherwise,} \end{cases}$$

PndEmcHit
(Energy & Time)



PndEmcWaveform

Scaled by *Energy* & *Q.E.*

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($Q.E.$ = 0.15, F = 1.3)

$N_{p.e.}$

* EMC TDR

Real pulse

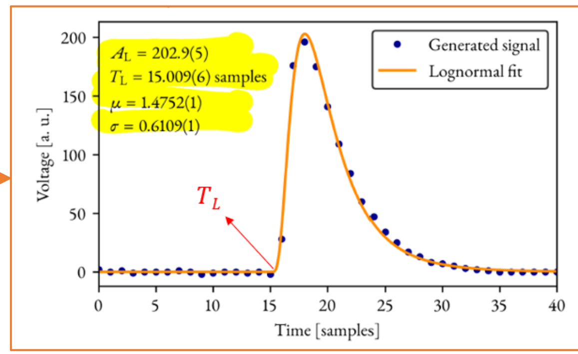
Idea pulse generation by sampling:

$$f_L(t) = \begin{cases} \frac{A_L \exp(\mu - 0.5\sigma^2)}{t - T_L} \exp\left[\frac{[\log(t-T_L)-\mu]^2}{2\sigma^2}\right], & \text{if } t > T_L \\ 0, & \text{otherwise,} \end{cases}$$

ADC pulse generation:

- Adding electronics noise: 1 ADC
- Digitizing: 125 MHz

PndEmcHit
(Energy & Time)



PndEmcWaveform

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Pulses in simulation

Idea pulse generation by sampling:

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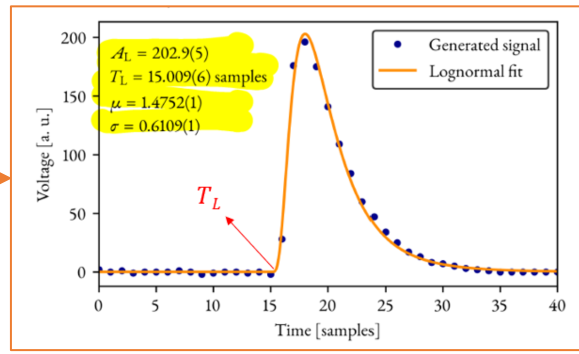
(Energy & Time)



PndEmcWaveform

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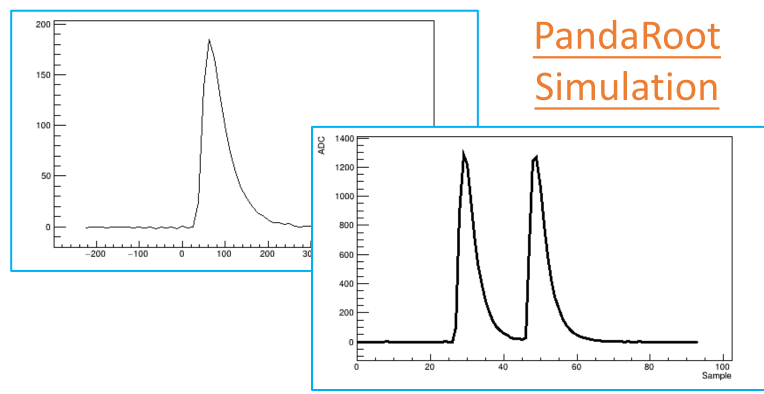
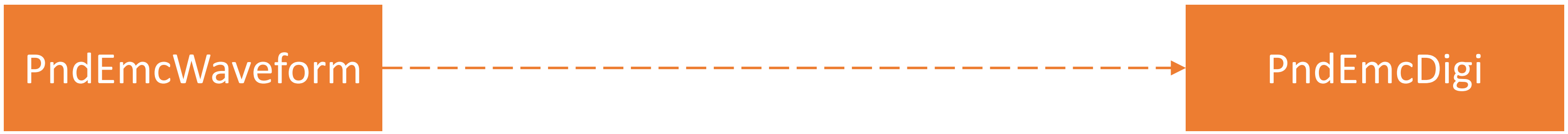


PandaRoot Simulation

* EMC TDR

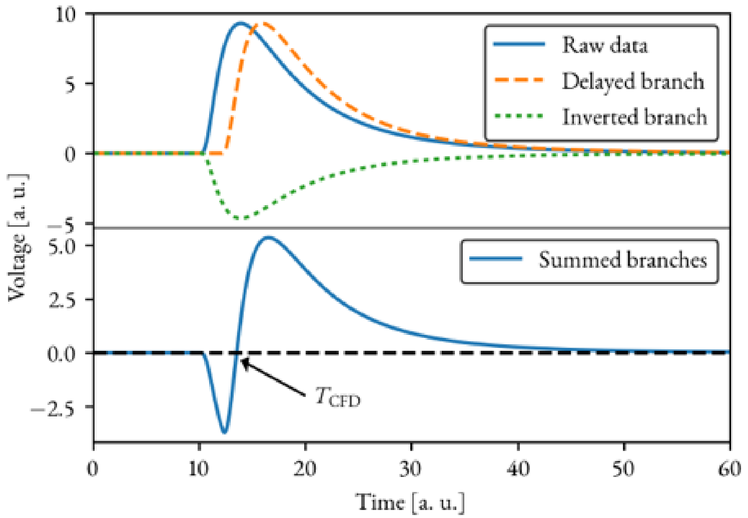
Feature Extraction

Feature Extraction



Time determination: CFD

PndEmcWaveform —CFD→ T0 PndEmcDigi



Constant Fraction Discriminator (CFD)

- Extract time at a fixed fraction of the maximum height
- To reduce the time-walk

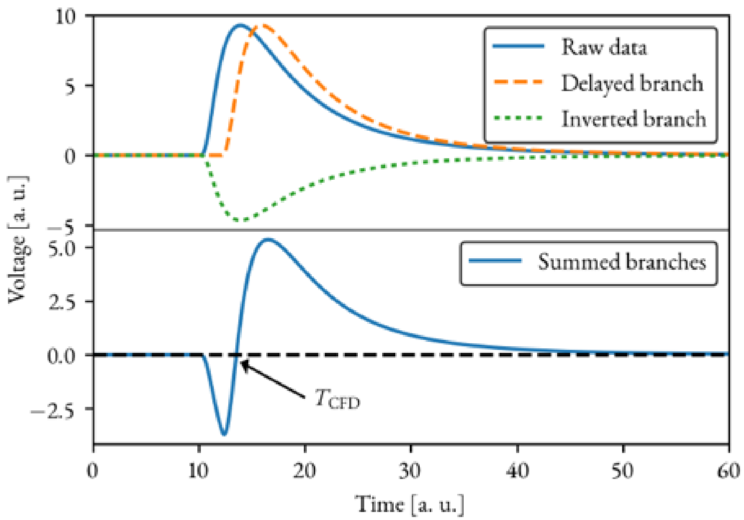
$$V_{CFD}(t) = (V(t - t_d) - V_0(t - t_d)) - f(V(t) - V_0(t))$$

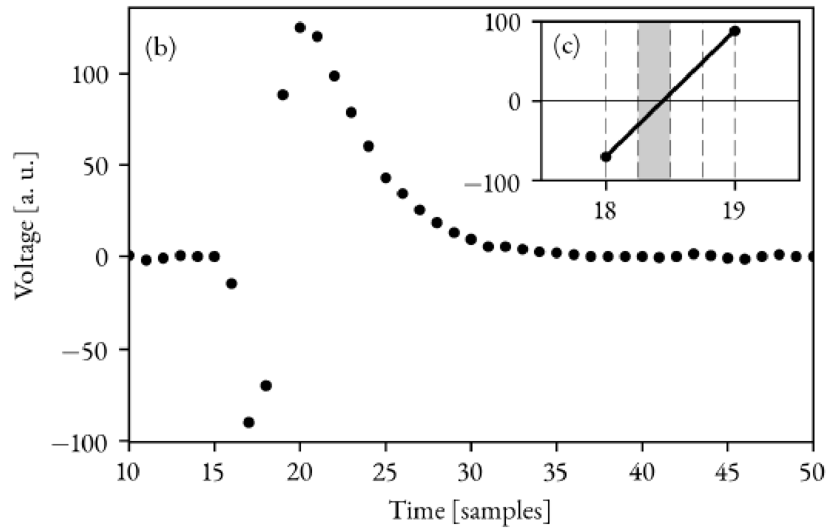
CFD parameters: $t_d = 2$, $f = 0.5$

Time determination: Binary-CFD

PndEmcWaveform → (CFD) → T0

PndEmcDigi





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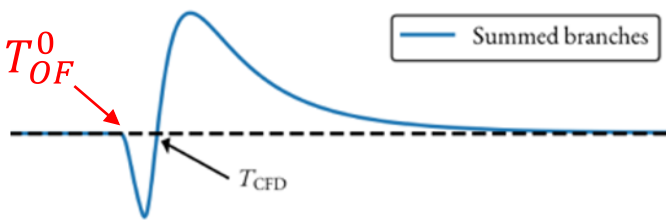
Binary-Search CFD

- Binary search the zero-crossing quarter-sample wide window
- $T_{B\text{-}CFD}$: Center of the window
- Arithmetic:
  - One-bit shift: (V(1) – V(0))/2
  - Much faster than division

Time determination: Correction

Time correction: Correction from the zero-crossing to the actual waveform start time



$$T^0_{\mathrm{OF},\,i} = T_{\text{B-CFD},\,i} - \langle T_{\text{B-CFD}} - T_{\mathrm{L}} \rangle.$$

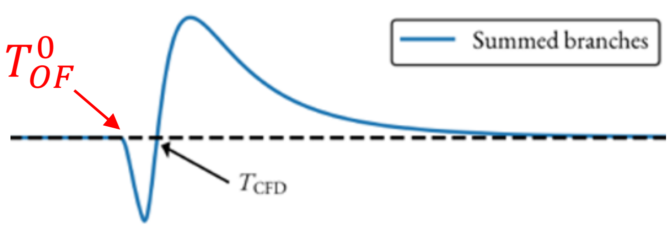
B-CFD window	$\langle T_{\text{B-CFD}} - T_{\mathrm{L}} \rangle$ [samples]
1	3.454
2	3.460
3	3.417
4	3.413

Time determination: Simulation

PndEmcWaveform → CFD → T0

PndEmcDigi

Time correction: Correction from the zero-crossing to the actual waveform start time



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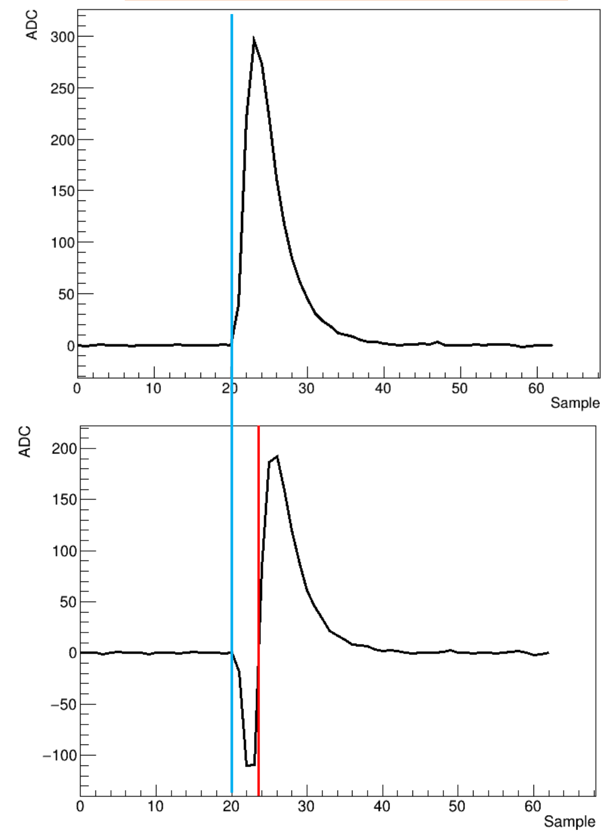
PandaRoot Simulation



T_{OF}^{0} T_{B-CFD}

Optimal Filter: Fine time/amplitude determination

Optimal Filter (OF)

- The process of OF is equivalent to fitting the incoming data with a linearized version of the known pulse shape in a χ^2 fit

$$\chi^2 = \sum_{i=1}^{M} \sum_{j=1}^{M} (S_i - Ag(t_i - \tau)V_{ij}(S_j - Ag(t_j - \tau))$$

g(t): Pulse function
A: Amplitude
τ: Time difference to T_{OF}^{0}
S: Waveform content

- By solving this linear problem, the ***A*** and ***Aτ*** can be written in the following form, which are two FIR filters:

$$\alpha_1 \equiv A = \sum_{i=1}^{M} a_i S_i$$

$$\alpha_2 \equiv A\tau = \sum_{i=1}^{M} b_i S_i$$

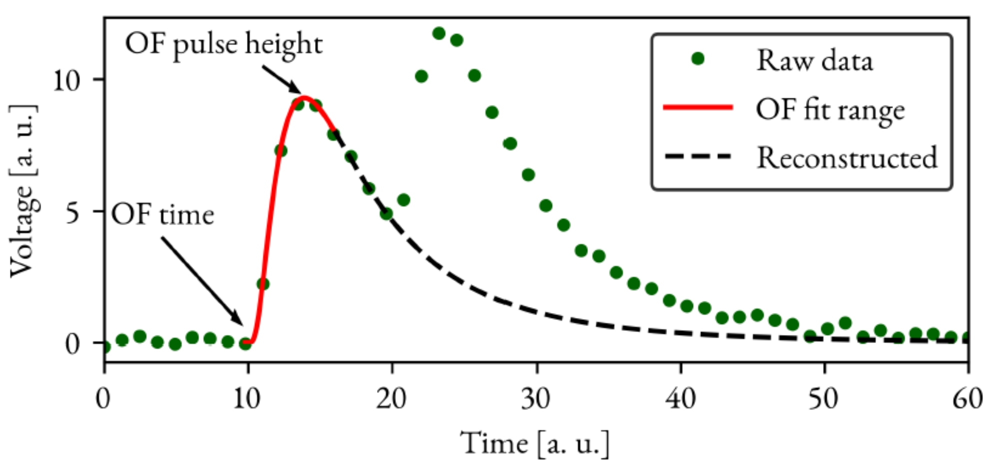
- The coefficients a and b can be analytically solved, which gives the ***A*** and ***τ***
- The OF can provide an amplitude and a more accurate time as it used more information of the waveform

Optimal Filter: Pile-up recovery

PndEmcWaveform → (CFD) → T0 → (OF) → T/A → PndEmcDigi

Pileup recovery:

- To reduce the contamination from upcoming pile-up waveforms, a truncated pulse shape are used in the OF (B0, B0+M)
- The previous detected pulse are subtracted as the baseline
- Perform the CFD + OF for the remaining waveform

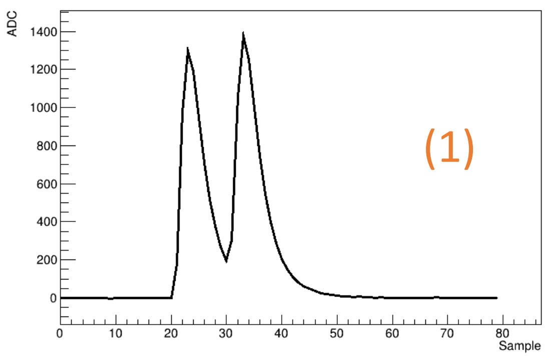


B0 = -3
M = 4

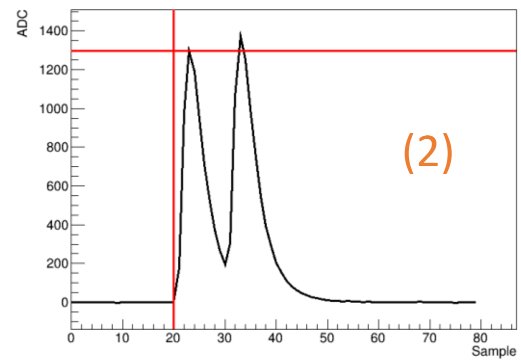
PandaRoot simulation

PndEmcWaveform —CFD→ T0 —OF→ T/A → PndEmcDigi

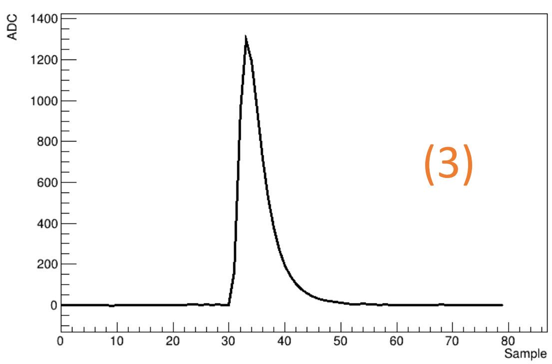
PandaRoot Simulation



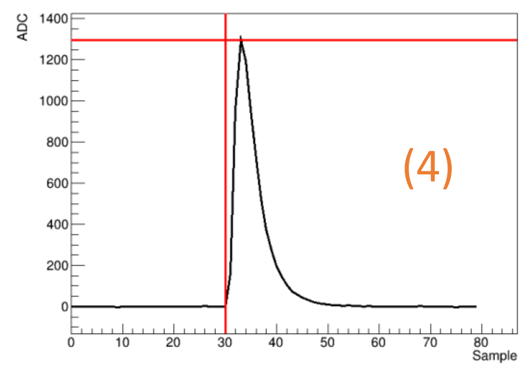
(1) A pile-up waveform



(2) First waveform detected

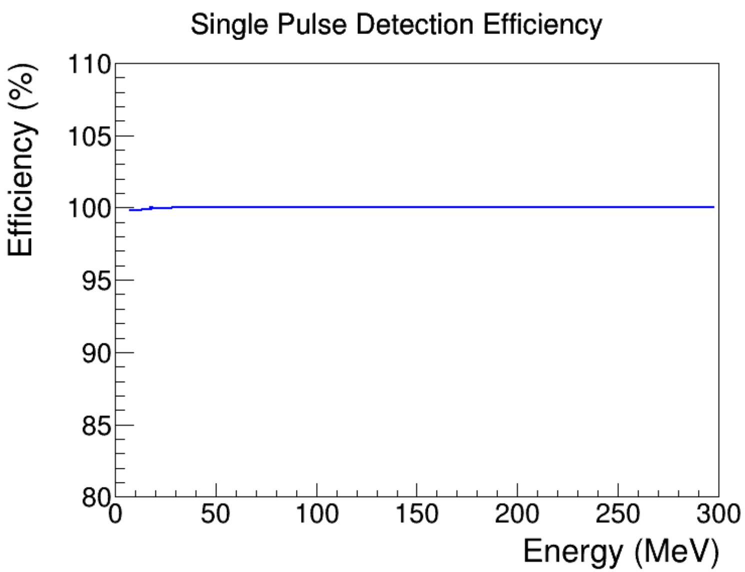


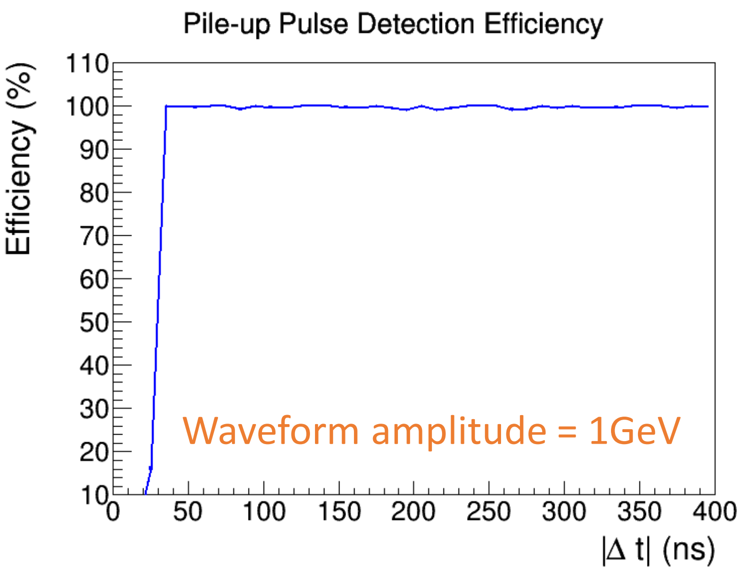
(3) Baseline subtracted



(4) Second waveform detected

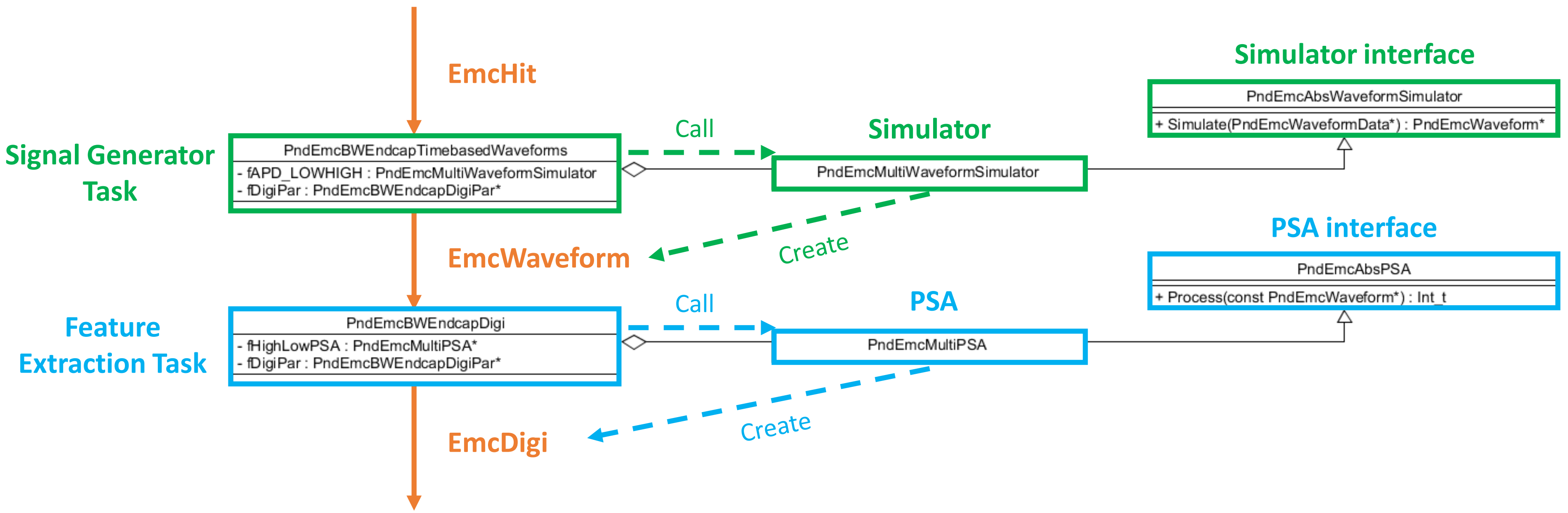
Waveform detection efficiency in simulation





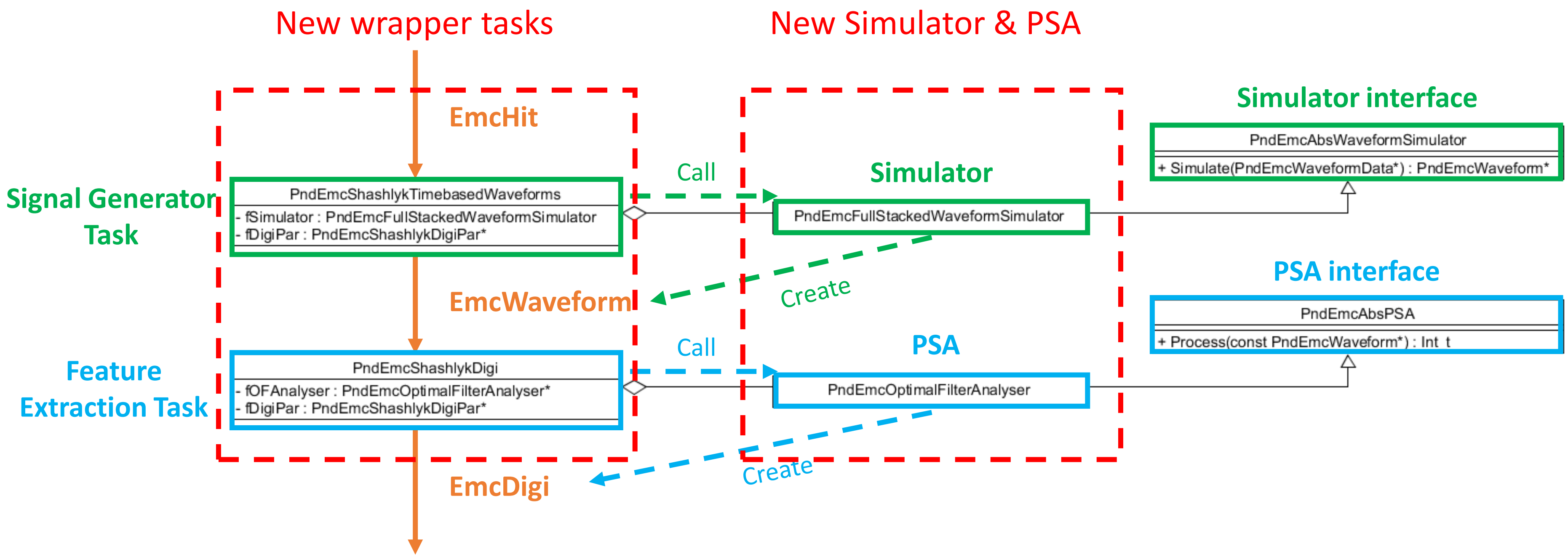
Reasonable pulse detection efficiencies

Code Structure (BWEC)



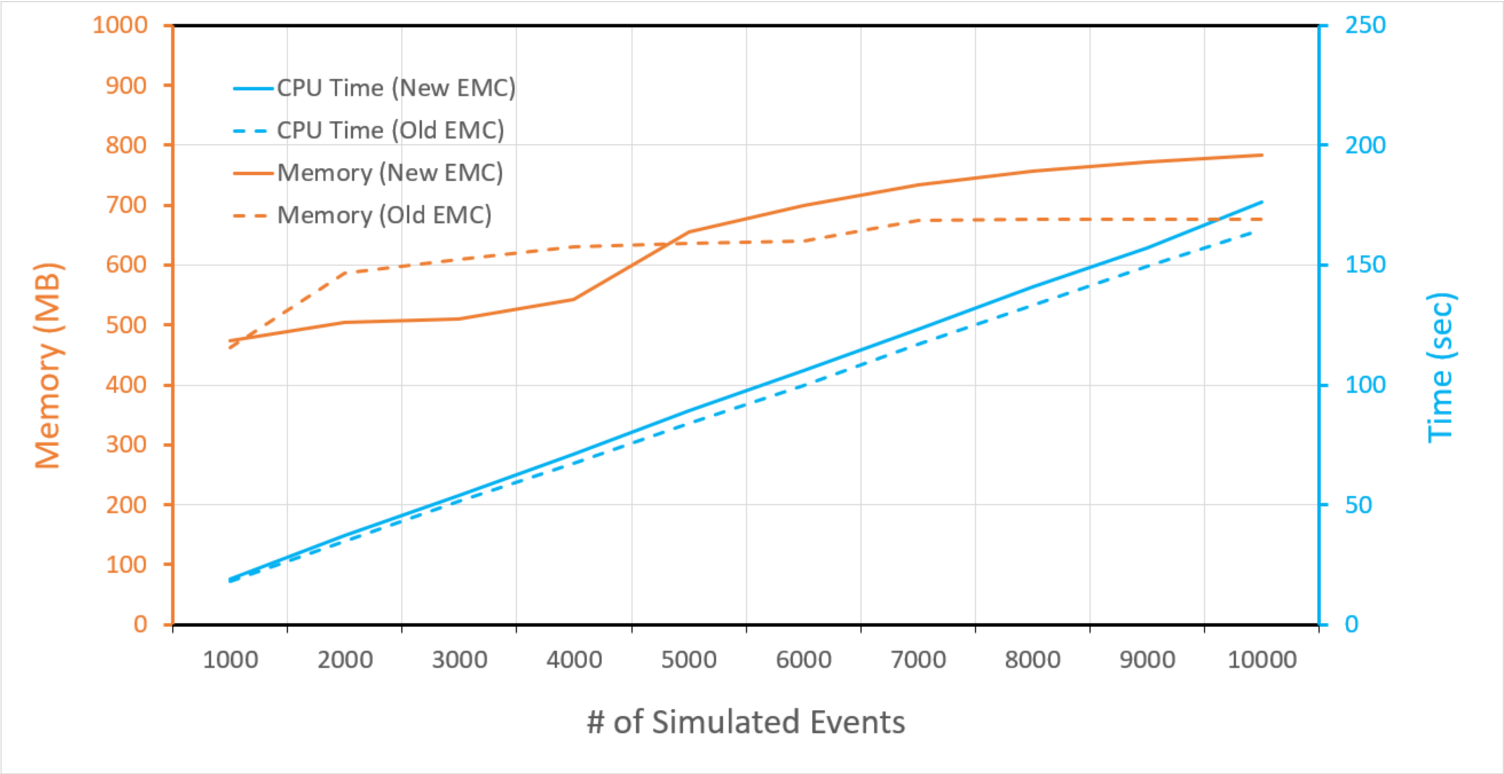
- Two tasks for signal generator and feature extraction respectively
- Simulator and Pulse Shape Analyzer (PSA) as the “algorithms”
- The algorithms inherit from the “interfaces”

Code Structure (Shashlyk)



- Easy to modify from the bwec package by plugging in two new “algorithms”
- An entirely new Simulator and PSA are implemented for the shashlyk EMC (core algorithms)
- New wrapper tasks (only simple modifications)

Performance Test



We can obtain quite similar computing performance compared to the old PandaRoot algorithm

Summary

- **Have implemented Markus' work in PandaRoot, including**
  - Pulse generation using a shape template
  - Feature extraction using CFD+OF filters

- **Code is most ready**
  - Using the same framework as the bwec/barrel digitization
  - Key functions are modularized. Can be easy to migrate to the framework that are currently being developed by Ben
  - Need some final checks before checking in

Thank you!