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Digital Signal Processing for the EMC

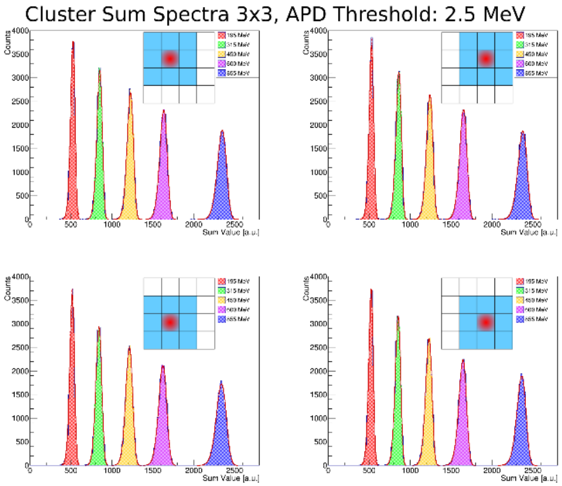
PANDA Collaboration Meeting 19/3

Contains Parts of Ph.D. Thesis

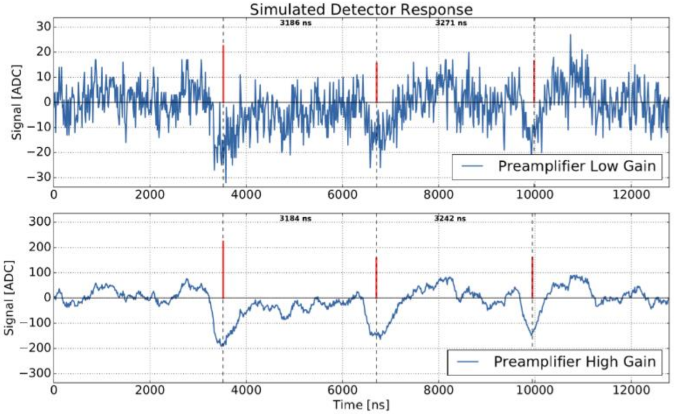
Oliver Noll

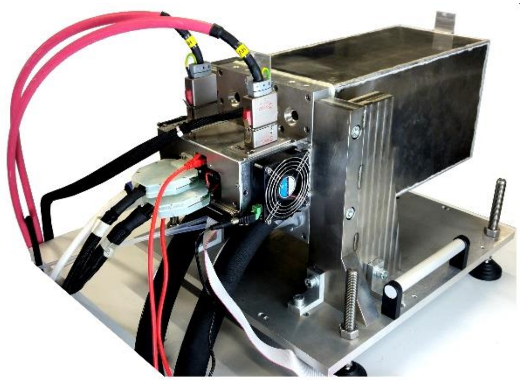
Digital Signal Processing for the EMC

Analysis



Simulations





Measurements

Outline

- Simulation Framework and Parameter Extraction
- Parameter Extraction Performance (Simulation)
- Firmware Development for the PANDA SADC
- Parameter Extraction Performance (Measurement)
- Summary and Outlook

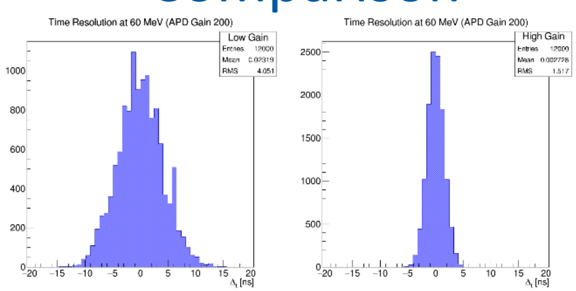
Simulation Framework

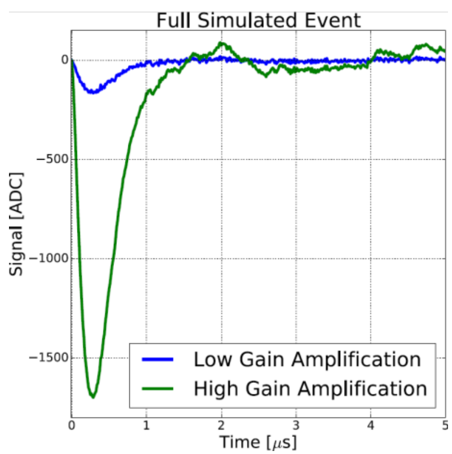
Input
- APD Gain
- Energy
- T_0
- Thresholds

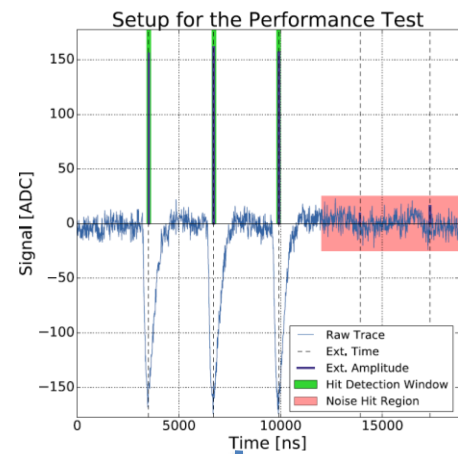
Signal Generator
- Realistic Noise
- Pulse Generator

Parameter Extraction
- Filtering
- Hit Detection
- Amplitude Extraction
- T_0 Extraction

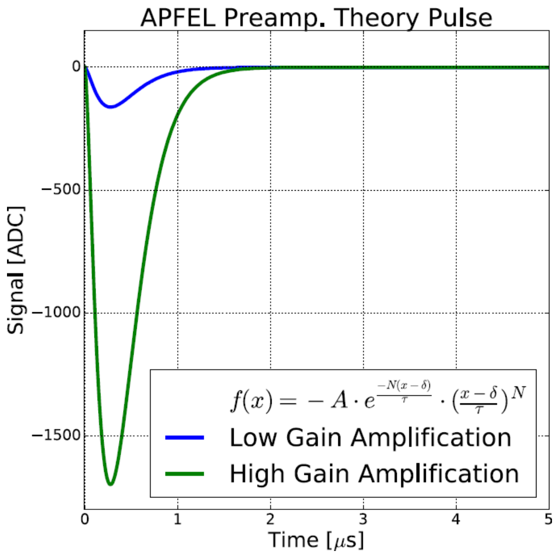
Comparison





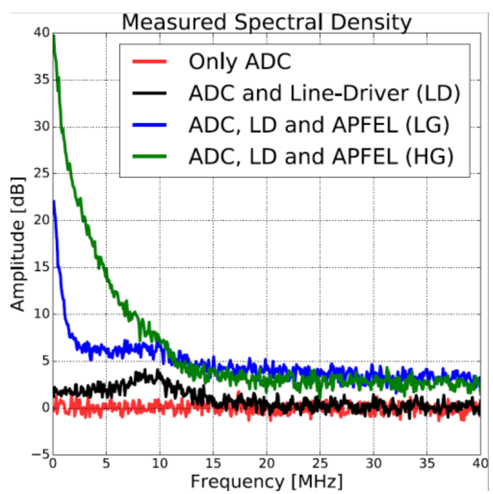


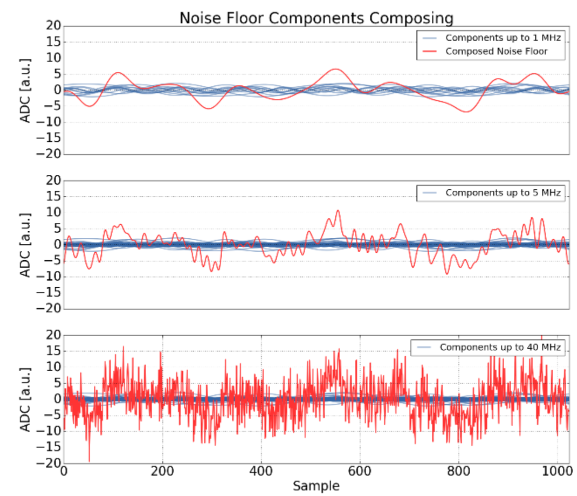
Simulation Framework
Signal Generator



Theory Pulse
- Parameter extracted from recorded waveforms
- Method which generates pulses as function of APD gain (M), Energy and T_0

Noise Generator
- Measured spectral density
- Generates noise according spectral density (IFFT)
- Assumption: Uniformly distributed phases

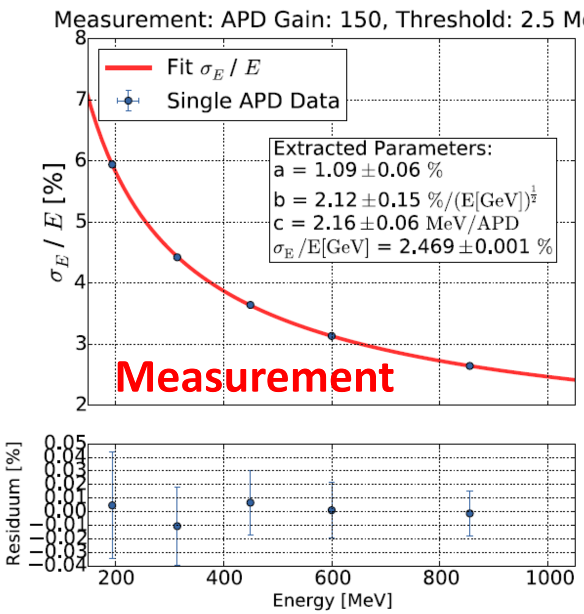


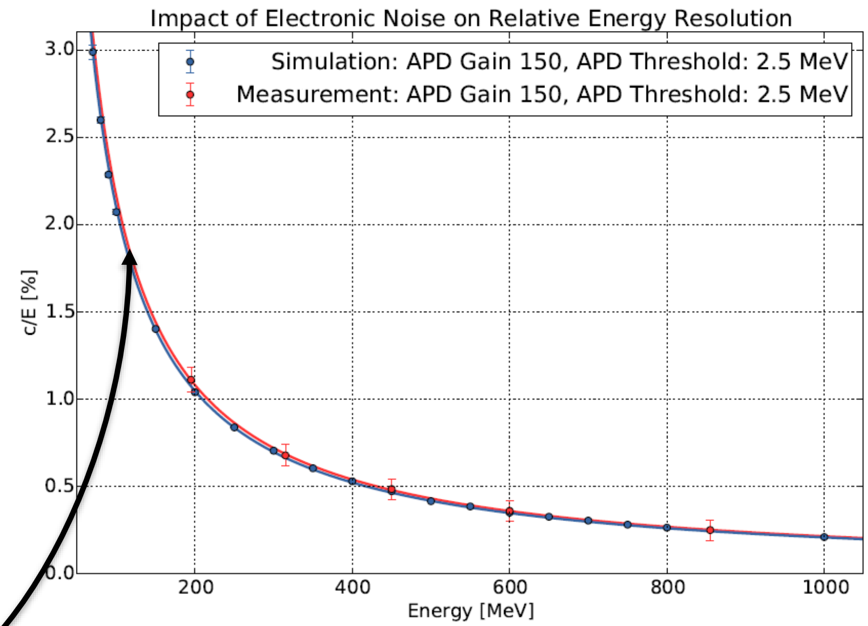


Simulation Framework

Signal Generator

Comparison between simulation and measurement





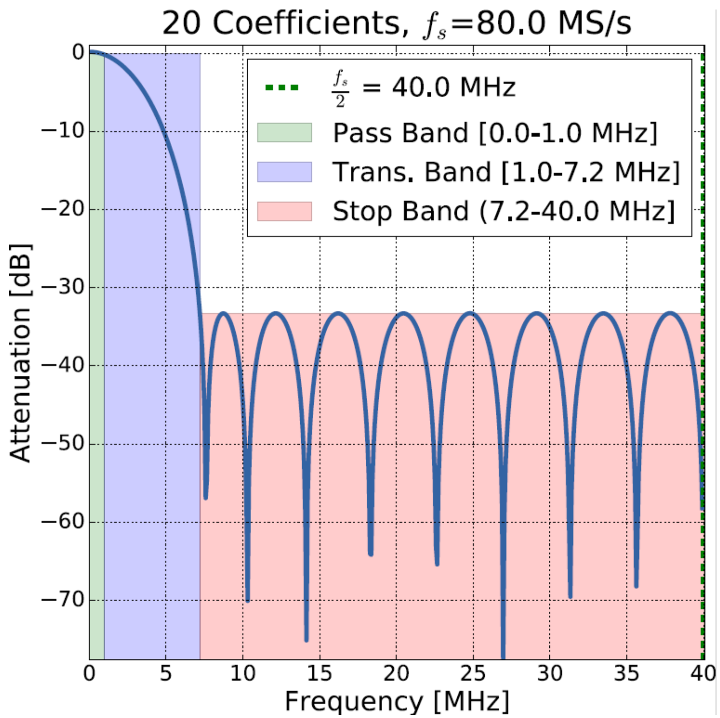
$$\frac{c}{E} = \sqrt{\left(\frac{\sigma_E}{E}\right)^2_{3\times3} - a^2 - \frac{b^2}{E}}$$

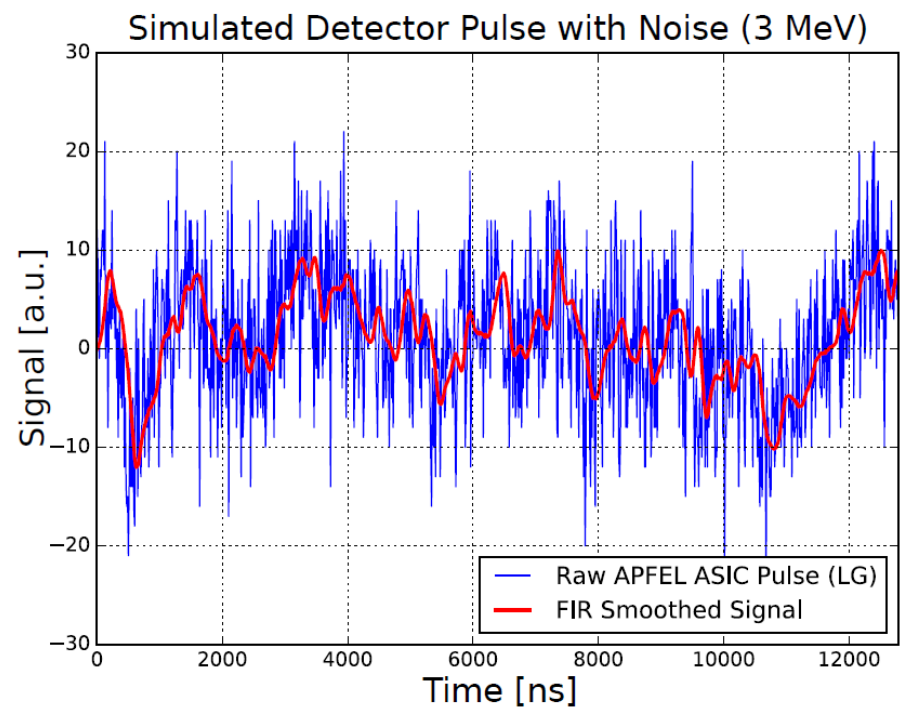
Noise term of relative energy resolution

$c_{measurement}$	2.16(6) MeV
$c_{simulation}$	2.095(6) MeV

Simulation Framework
Parameter Extraction Methods

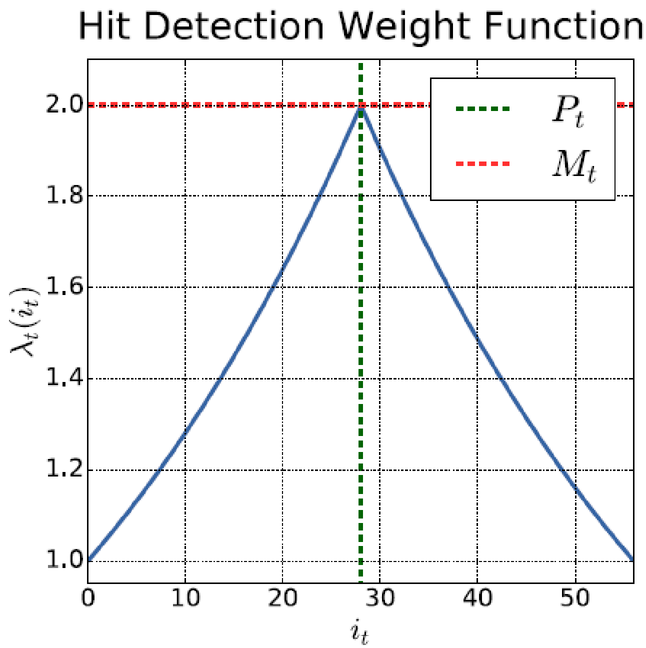
Finite Impulse Responds Filtering

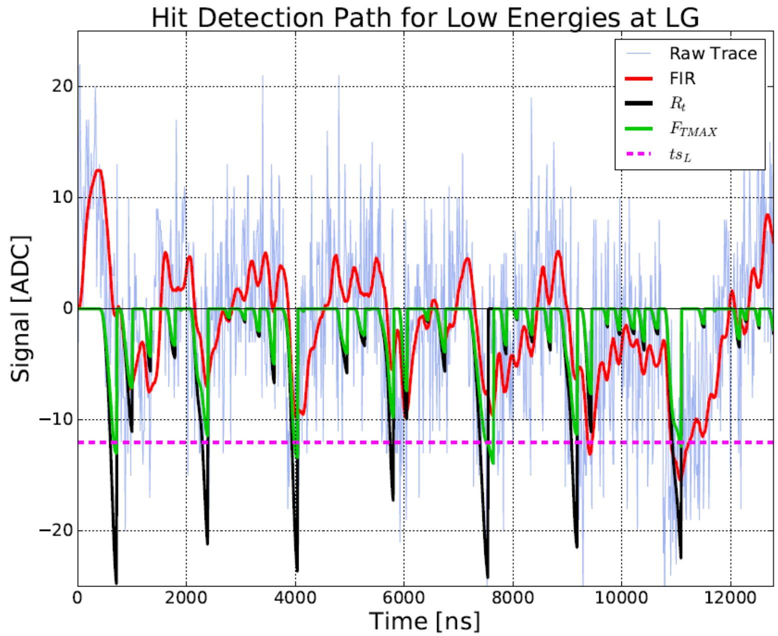




- Filter is designed to suppress high frequency noise by conserving the APFEL ASIC preamplifier pulse shape.
- The more filter coefficients the better.
- Number of coefficients limited by SADC FPGA resources.

Hit Detection





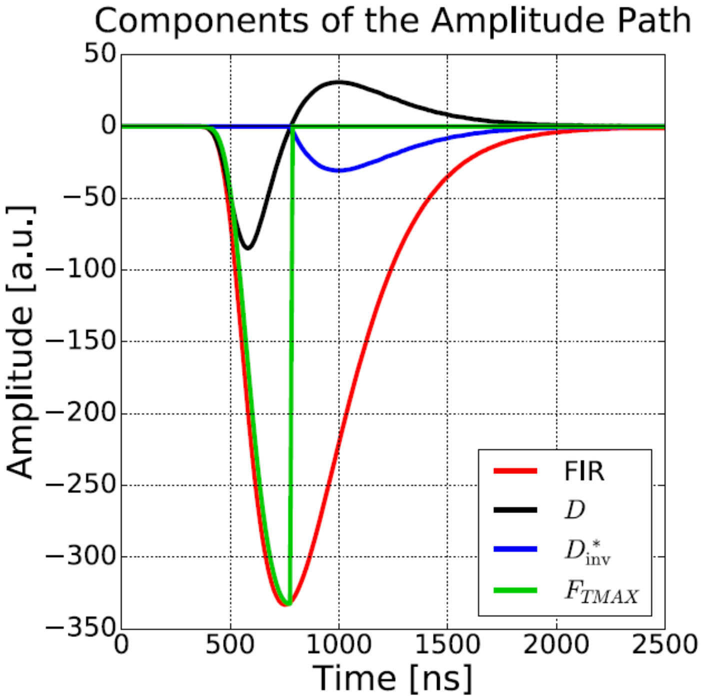
$$\lambda(i_t) \mapsto \begin{cases} e^{A_t \cdot i_t} & : i_t \leq P_t \\ M_t \cdot e^{-A_t(i_t - P_t)} & : i_t > P_t \end{cases}$$

- Weight function considers both rise time and time under zero
- Sensitive to signal structures, which are APFEL ASIC pulse-like

Simulation Framework

Parameter Extraction Methods

Amplitude Extraction



$$D[i] = T[i] - T[i-r]$$

$$D^*_{\mathrm{inv}}[i] = -\Theta(-D[i]) \cdot D[i]$$

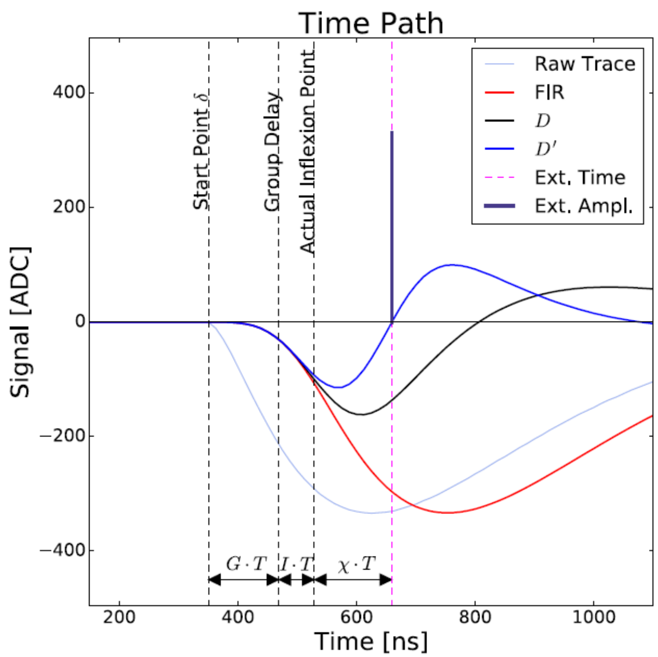
$$\Theta(x) \mapsto \begin{cases} 0: & x < 0 \\ 1: & x \geq 0 \end{cases}$$

$$D_s[i] = D[i] + D^*_{\mathrm{inv}}[i]$$

$$D_s[i] \mapsto \begin{cases} F_{TMAX}[i] = F_{TMAX}[i-1] + \frac{D_s[i]}{r} & : D_s[i] < 0 \\ F_{TMAX}[i] = 0 & : D_s[i] = 0 \end{cases}$$

- Baseline follower included by design
- Cancelling of falling edge: Important for pileup correction

T_0 Extraction



$$f(x) = -A \cdot e^{\frac{-N(x-\delta)}{\tau}} \cdot \left(\frac{x-\delta}{\tau}\right)^N$$

$$f''(x) = 0$$

$$I = \frac{\tau(\sqrt{N}-1)}{\sqrt{N}}$$

Theory inflexion point

$$T_0 = \delta + I$$

$$T_0 = i_0 + \frac{D'[i_0]}{D'[i_0] - D'[i_1]}$$

Between sample interpolation

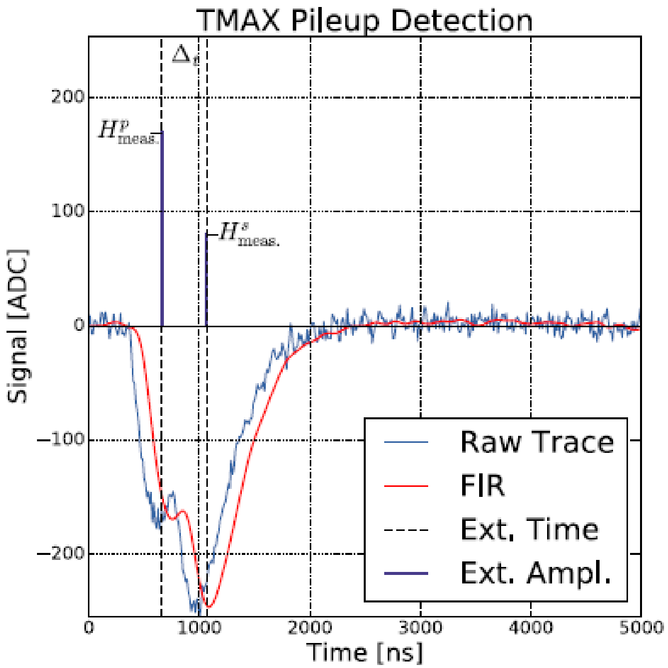
D is already the first derivative. Thus, D' is the second one

- Using inflexion point (f''(x)=0) for T_0 determination
- Interpolation between samples in order to increase time resolution

Simulation Framework

Parameter Extraction Methods

Pileup correction



$$H^s_{\mathrm{corr.}} = H^s_{\mathrm{meas.}} \cdot \Sigma(H^p_{\mathrm{meas.}}, H^s_{\mathrm{meas.}}, \Delta_t)$$

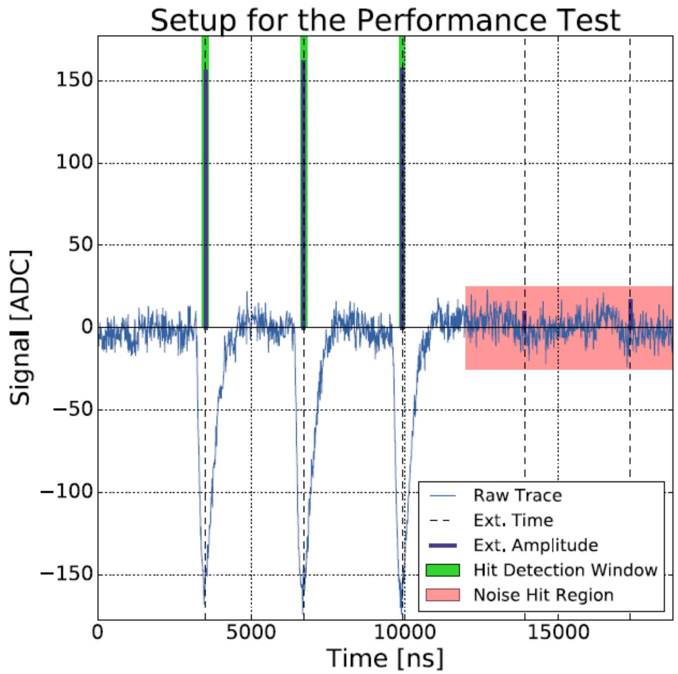
Challenge: Determination of Σ
We come back to it by using beam data in the course of this talk…

- Algorithm is capable to detect pileup on falling edge
- Amplitude correction is possible with the information of the height of the primary pulse, the height of the secondary pulse and the time difference between them.

Simulation Framework

Pulse Processing Validation

Simulation procedure



- Input:
  1. APD gain
  2. Event energy
  3. Hit detection threshold (LG, HG)
- Generate trace with 3 events and "noise hit region" (6750 ns)
- 4000 traces per input parameter set

In the following we will discuss the results for:

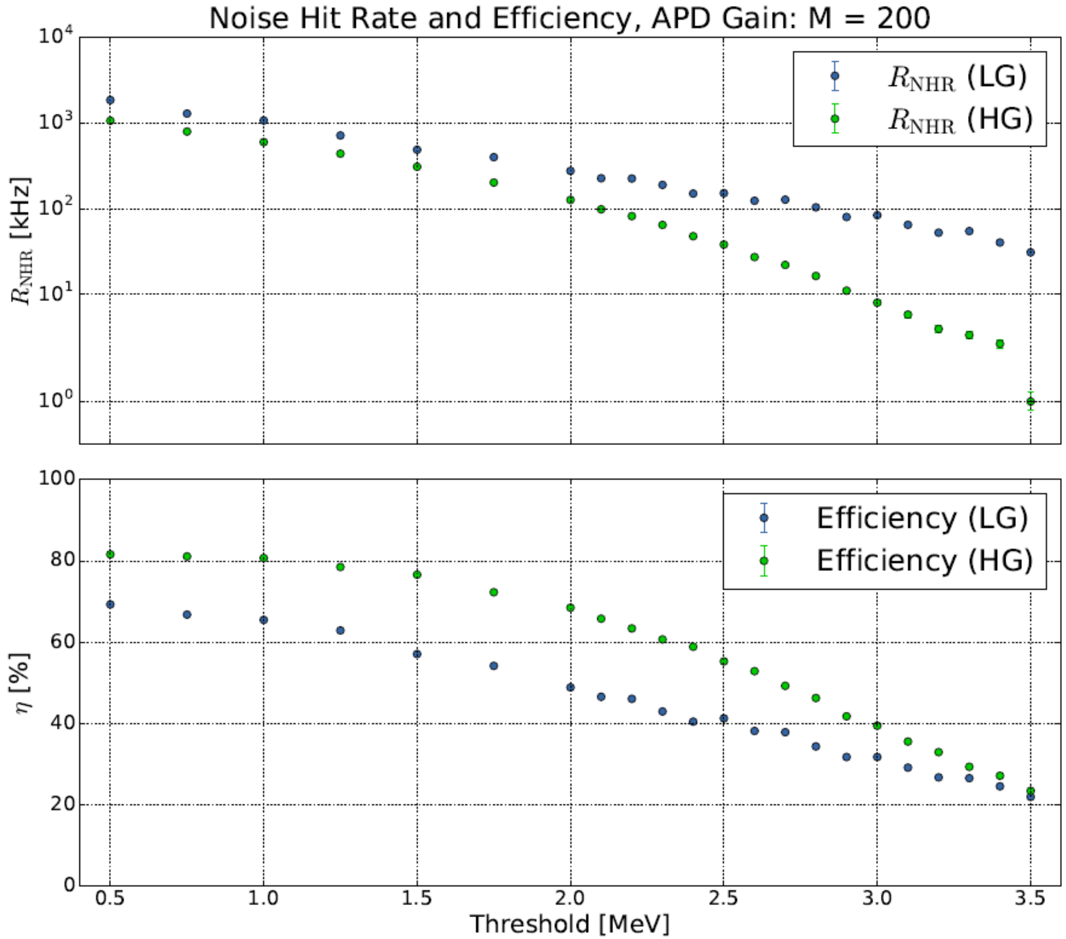
1. Noise hit rate and efficiency
2. Time resolution

for APD gain 200

Simulation Framework

Pulse Processing Validation

Noise hit rate and efficiency



- Efficiency for 3 MeV events
- Upper plot: Noise hit rate
- Lower plot: Efficiency

Example for APFEL HG:
Threshold = 1.75 MeV
Efficiency = 72.3 %
NHR = 202 kHz

DAQ limit is 558 kHz per channel at current implementation

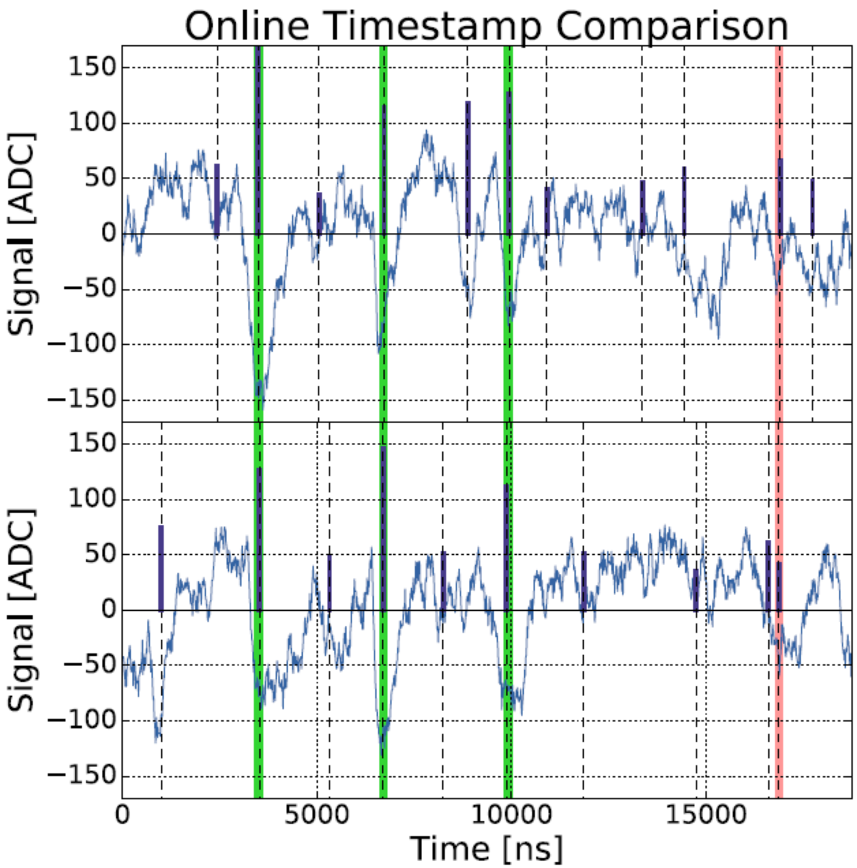
Simulation Framework

Pulse Processing Validation

Noise hit rate and efficiency

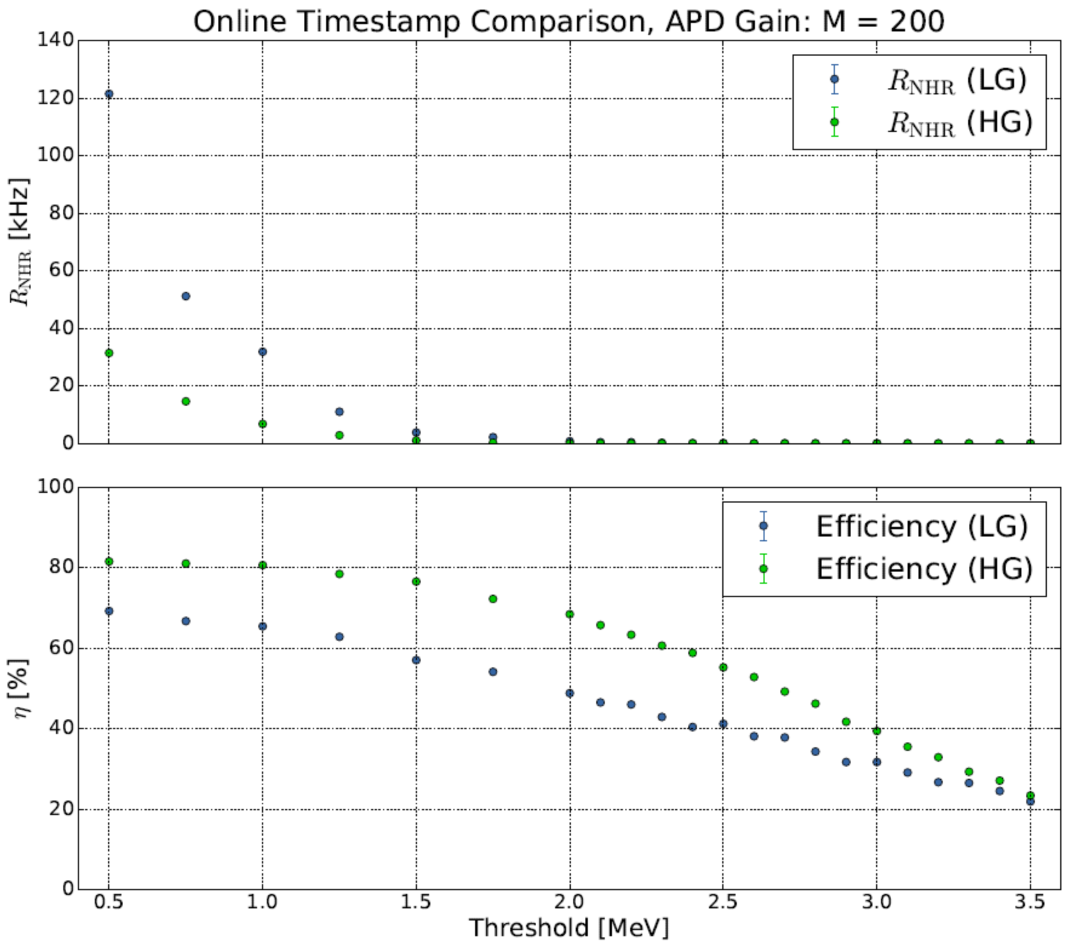
APD1

APD2



- Noise hit rate reduction by online timestamp comparison
- Events are correlated
- Noise is uncorrelated
  →Threshold lower
  →Efficiency higher

Noise hit rate and efficiency



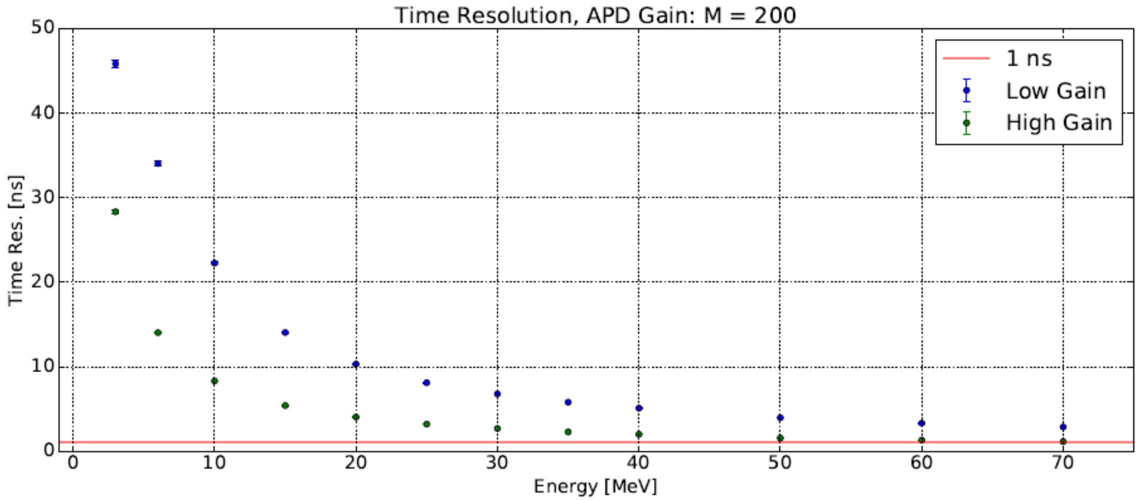
- Efficiency for 3 MeV events
- Upper plot: Noise hit rate
- Lower plot: Efficiency

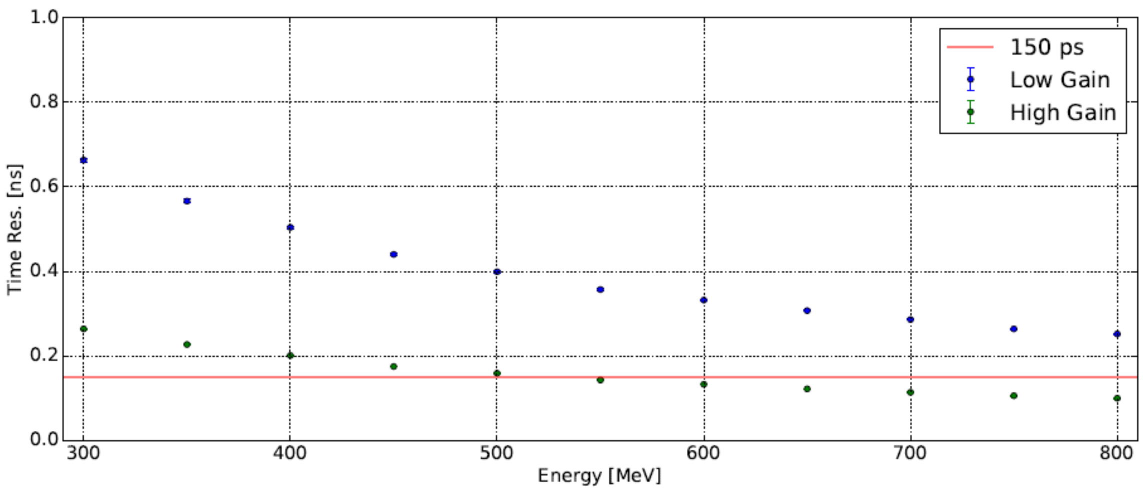
Example for APFEL HG:
Threshold = 1.0 MeV
Efficiency = 80.7 %
NHR = 6.8 kHz

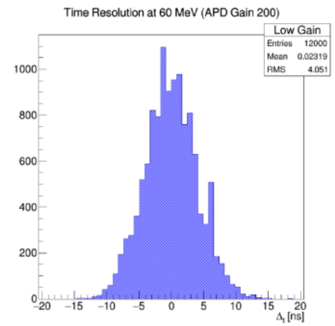
DAQ limit is 558 kHz per channel at current implementation

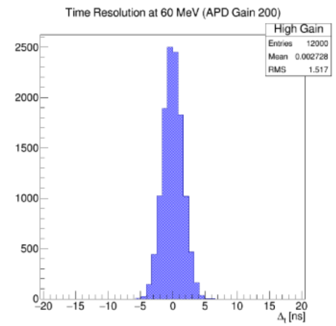
Simulation Framework
Pulse Processing Validation

Time resolution









Example time resolutions (TR) for APD gain 200:

TR(60 MeV) = 1.517(10) ns
TR(500 MeV) = 182(1) ps

Simulation Framework

Pulse Processing Validation

Summary simulations

Parameter	Achieved Value						TDR	Unit
APD Gain	150		200		250		-	-
Preamp. Gain	LG	HG	LG	HG	LG	HG	-	-
Noise Hit Rate	Threshold: 2.5 MeV							
Single	331.1(26)	160.9(20)	151.44(200)	38.07(110)	67.93(145)	5.52(45)	-	kHz
Dual ($I_{comp.} = 200$ ns)	1.27(5)	0.16(1)	0.13(1)	<0.01	<0.1	<0.01	-	kHz
Efficiency	Deposited Energy: 3 MeV							
Threshold: 2.5 MeV	39.6	50.4	41.3	55.3	42.4	58.5	-	%
Threshold: 1.5 MeV	55.9	65.9	57.1	76.6	61.5	83.9	-	%
Time Resolution								
60 MeV	5.369(35)	1.998(13)	4.051(26)	1.517(10)	3.176(21)	1.198(8)	1	ns
500 MeV	635(4)	239(2)	477(3)	182(1)	380(2)	144(1)	150	ps
Non-Linearity	Upper Limit							
Dep. Energies < 100 MeV	635.12(23)	288.24(179)	138.24(70)	134.80(7)	162.17(7)	103.66(73)	-	keV
Dep. Energies ≥ 100 MeV	64.81(3)	41.31(27)	44.90(3)	21.62(27)	44.78(3)	21.05(26)	-	keV

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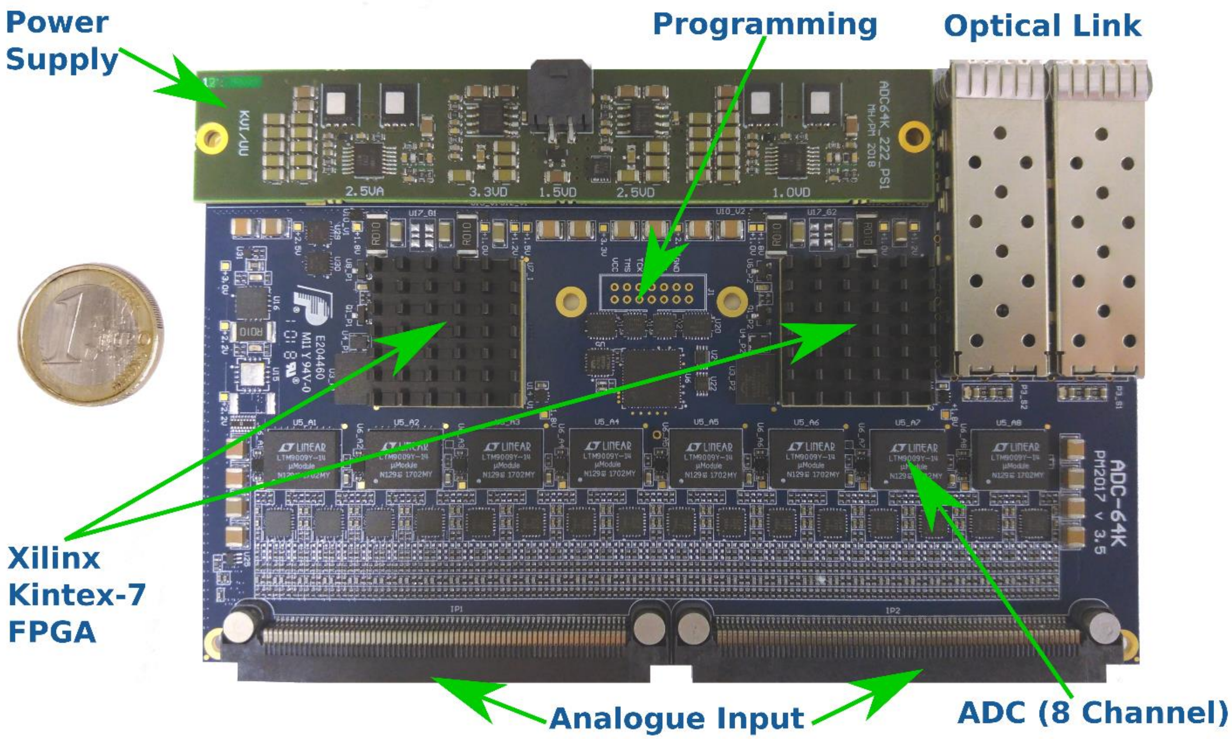
Mainz SADC Firmware

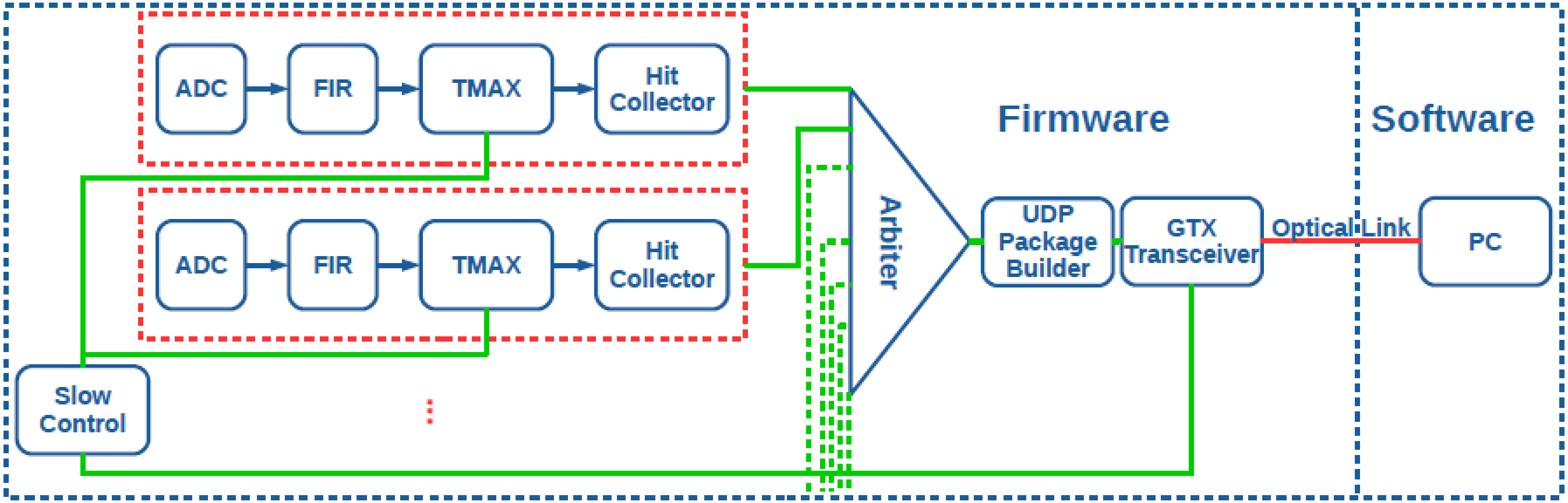


- Developed at University of Uppsala by Pawel Marciniewski
- 64 ADC channel
- 14 bit
- 80 MHz
- Two FPGA's
- Two optical links

SADC firmware was developed which includes the just discussed parameter extraction methods

Mainz SADC Firmware

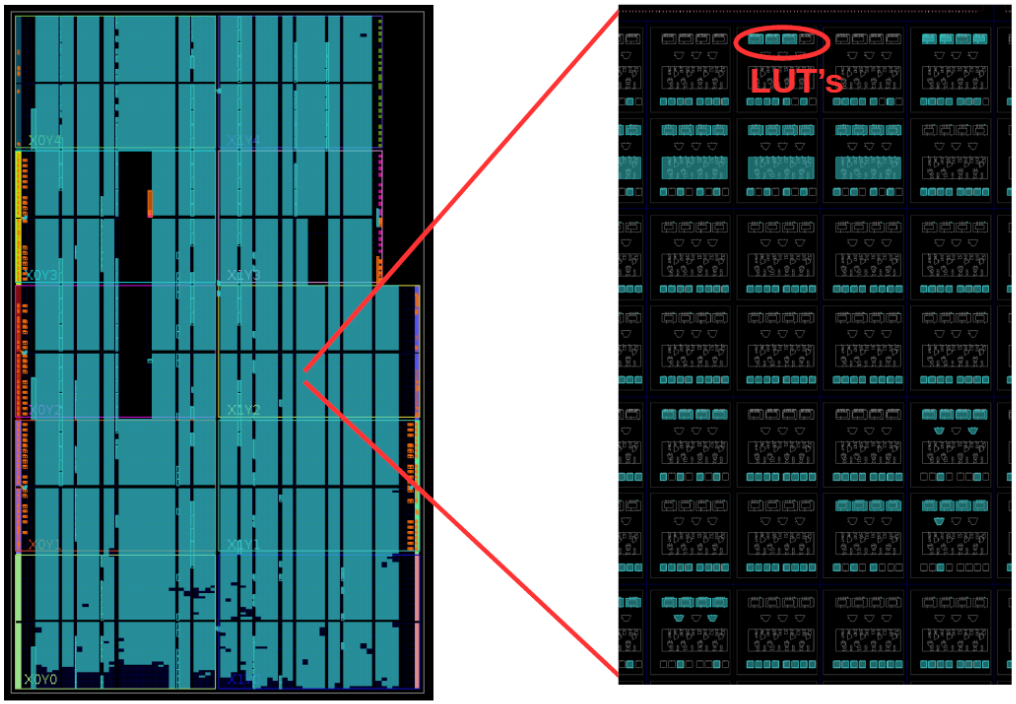
Very short overview

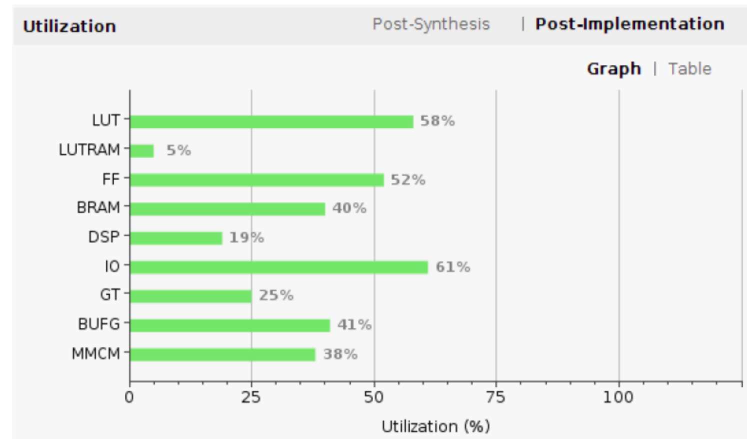


- Self-triggering approach (hit collector, arbiter)
- Efficient FIR filter implementation by using distributed arithmetic's
- Data are collected into UDP packages
- Development of receiver software
- Slow control GUI

Mainz SADC Firmware

Very short overview

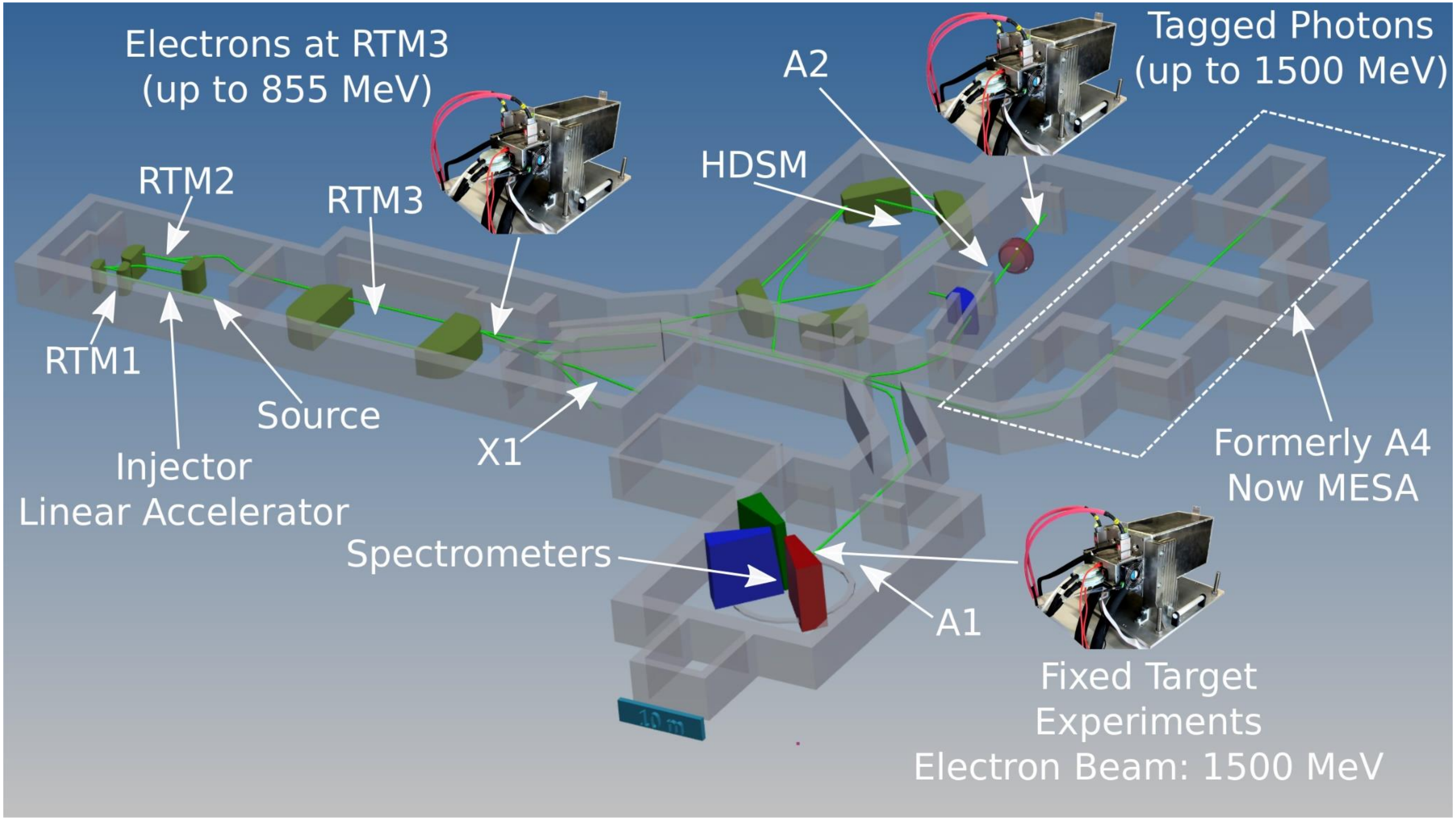




- FIR filter implementation by using distributed arithmetic's saves DSP slices for other operations
- About 50 % of FPGA resources occupied

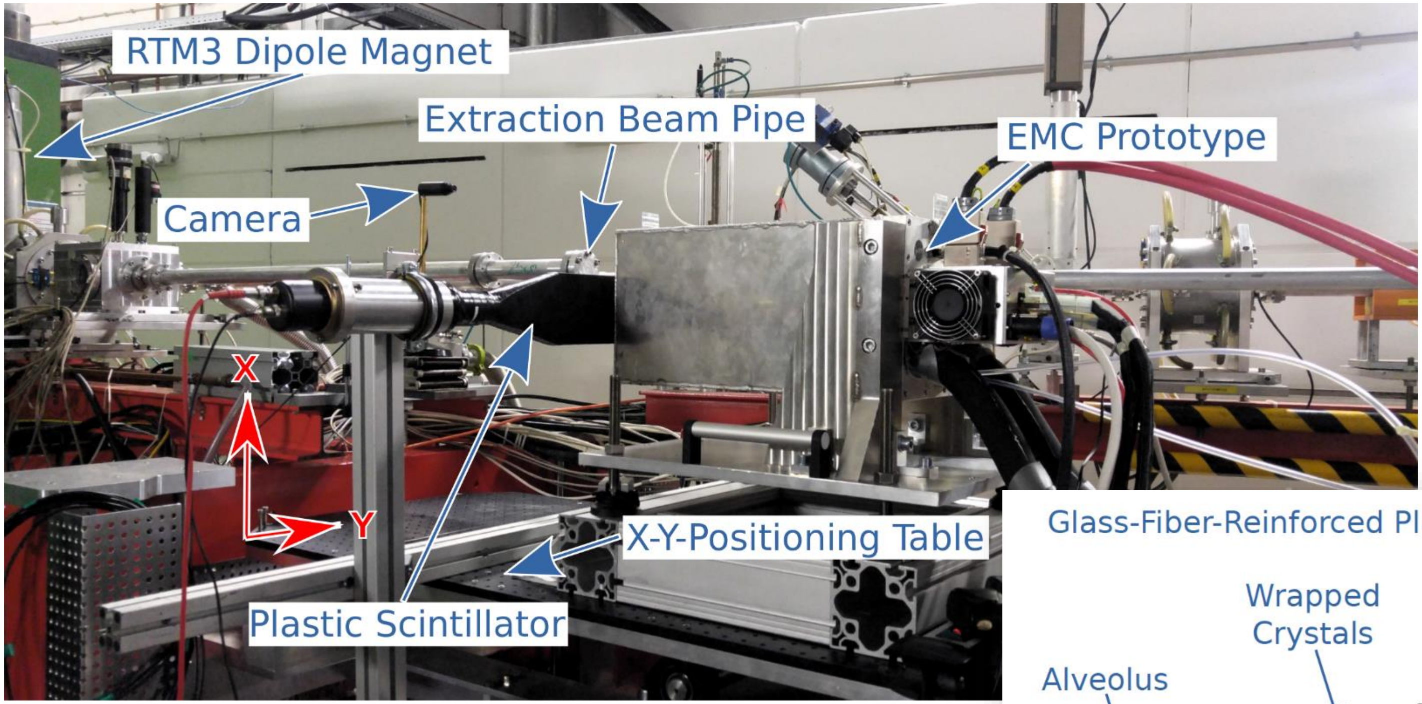
Beam Tests with the EMC Prototype

Mainz Microtron (MAMI)

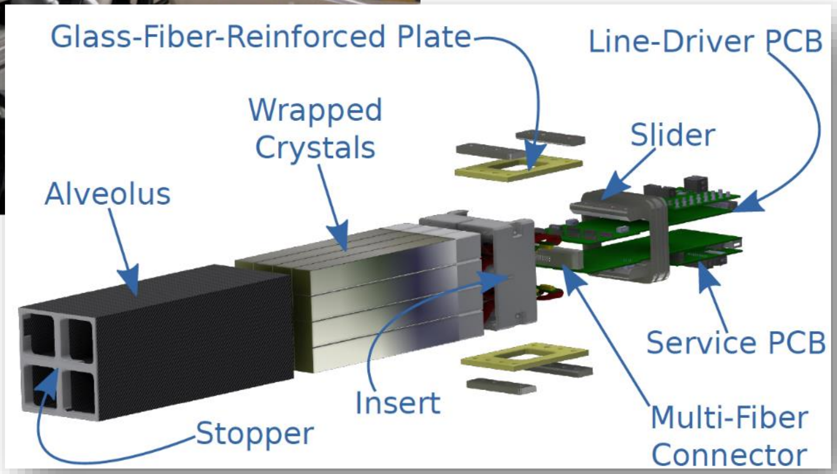


Beam Tests with the EMC Prototype

X1 electron beam extraction



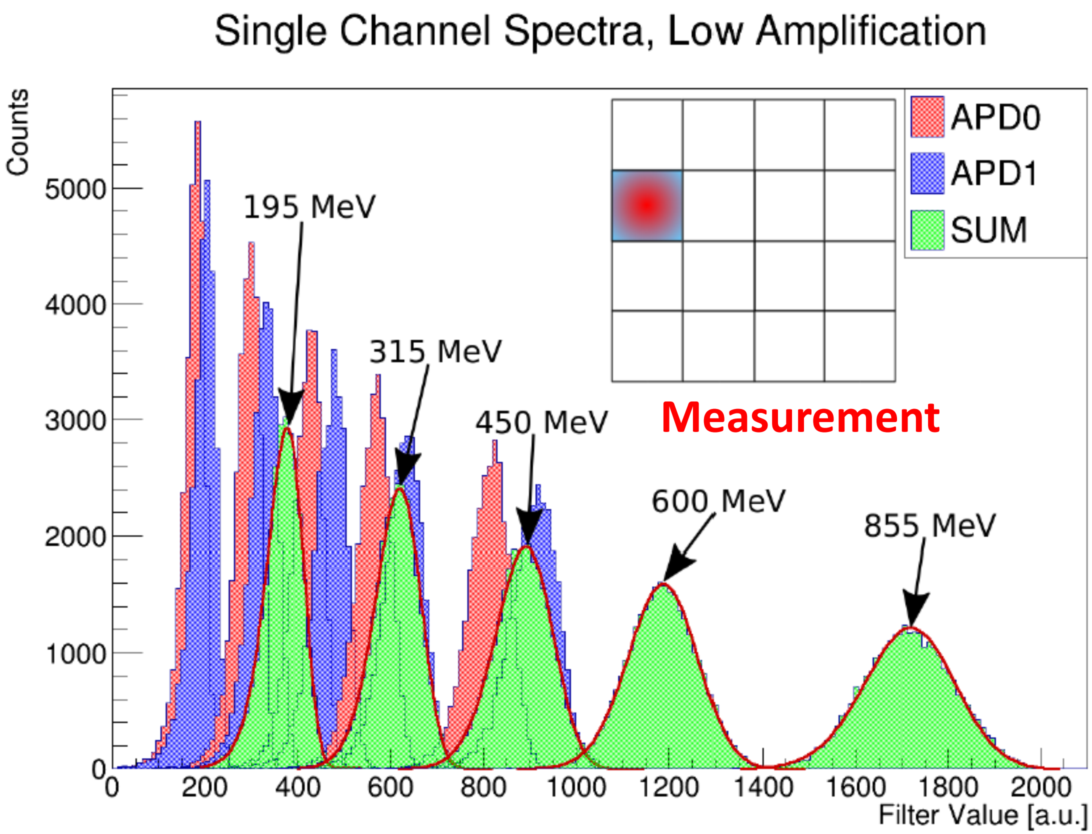
Electrons with energies between 195 MeV and 855 MeV



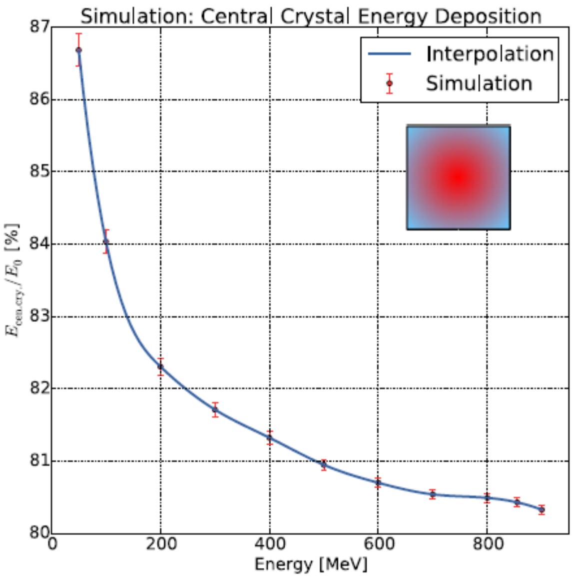
- EMC prototype = 4 x 4 BWEC submodule
- Full slow control
- Full readout chain

Beam Tests with the EMC Prototype

Single channel energy calibration

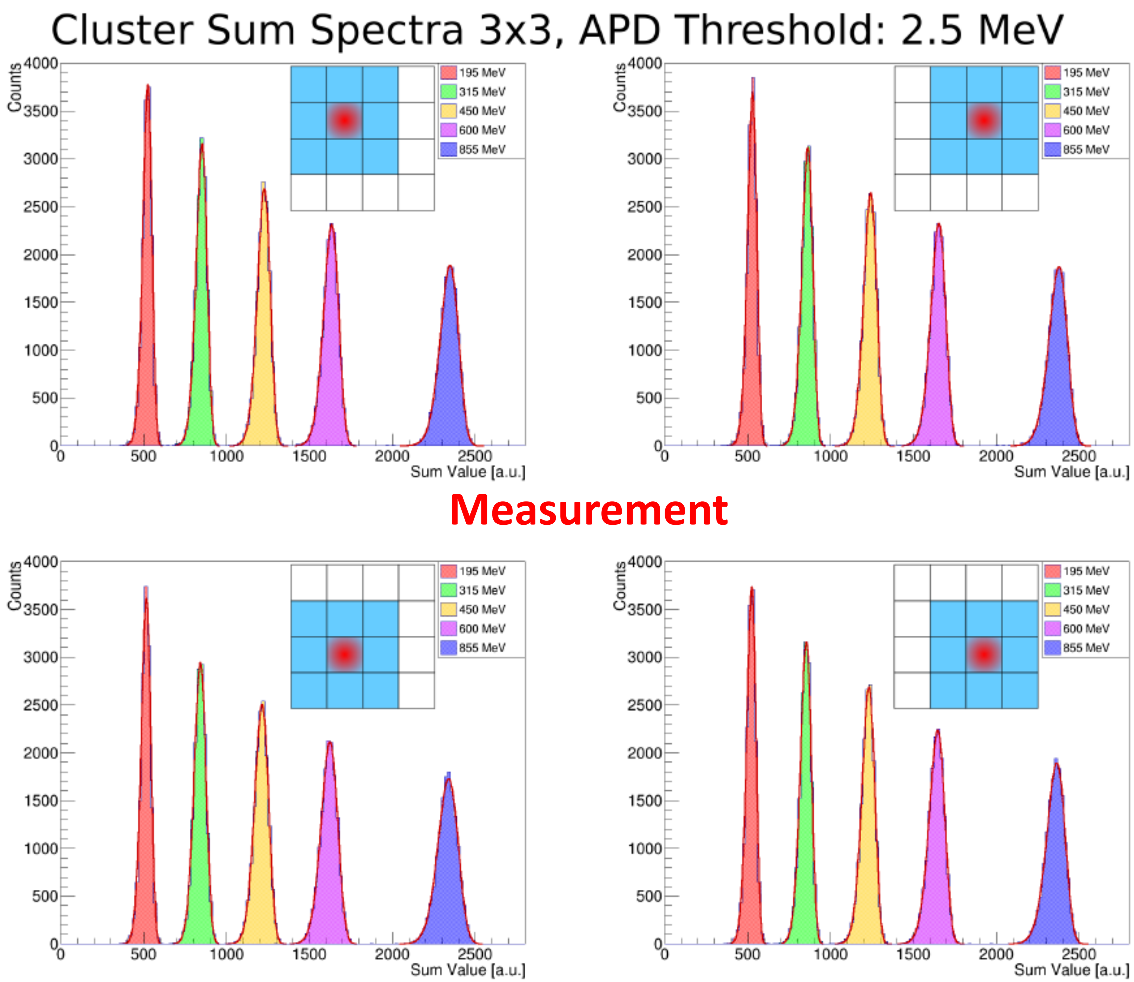


- Energy calibration
- Correction by Geant4 simulation



Beam Tests with the EMC Prototype

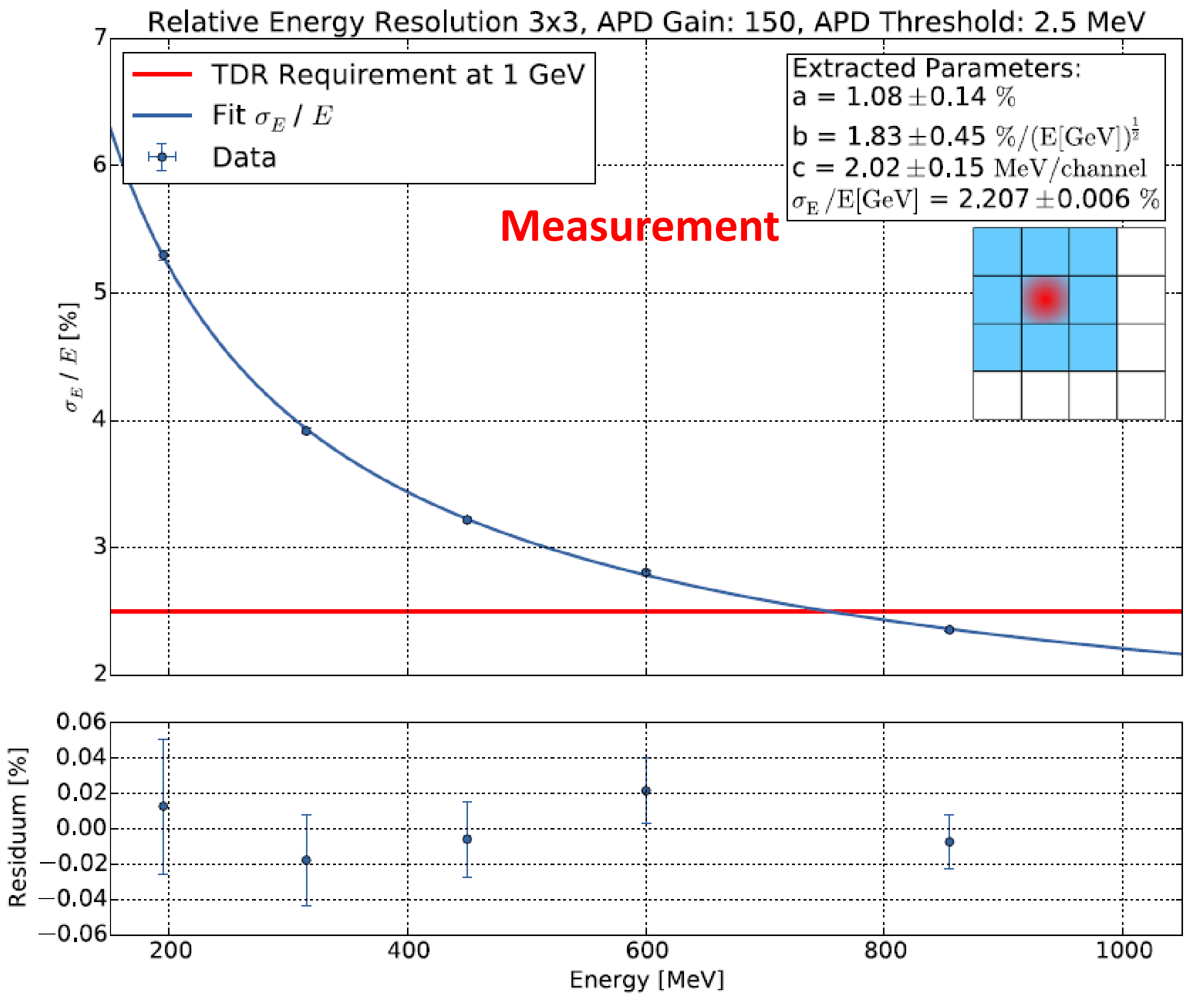
Sum spectra



- Sum spectra for APD gain 150
- Threshold = 2.5 MeV (LG and HG)

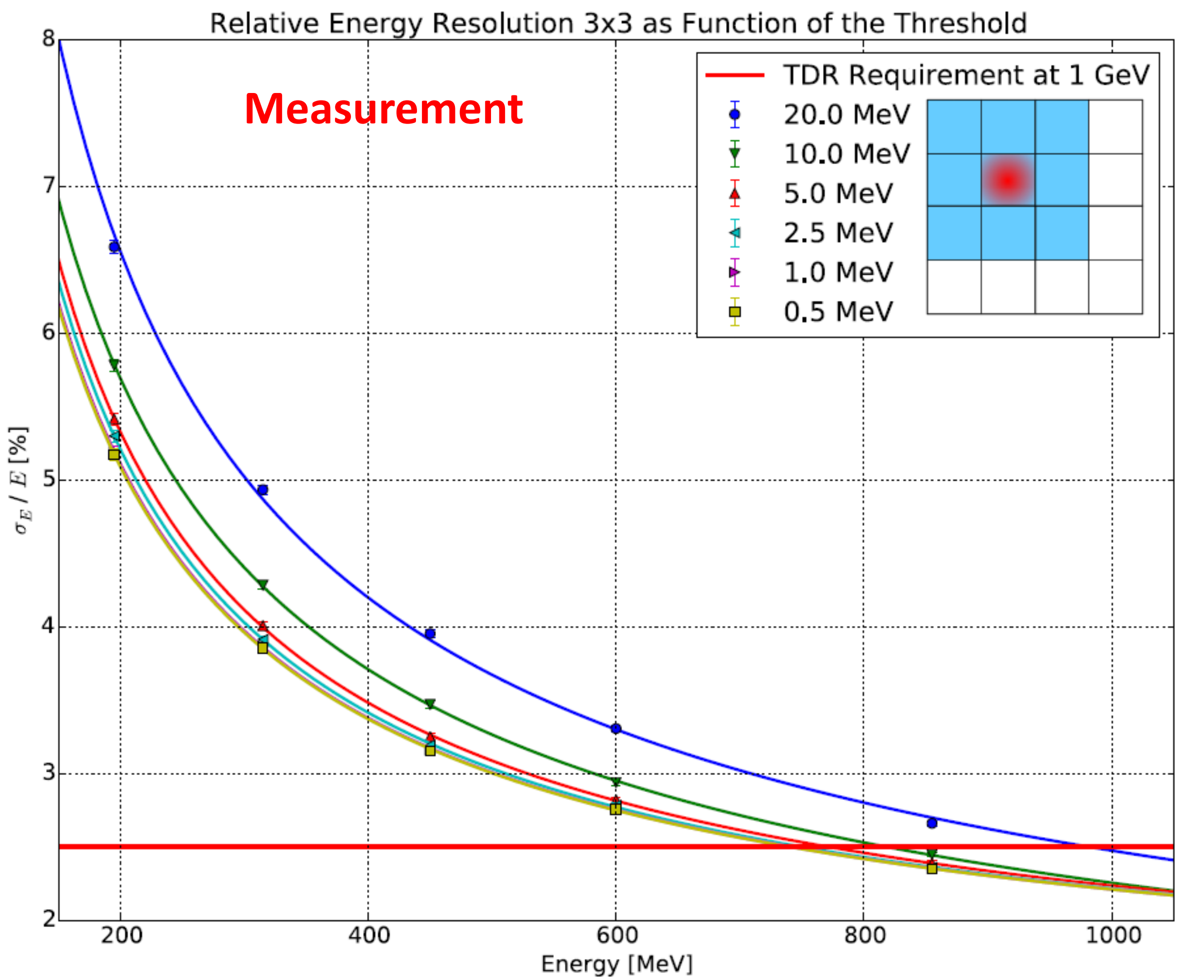
Beam Tests with the EMC Prototype

Relative energy resolution



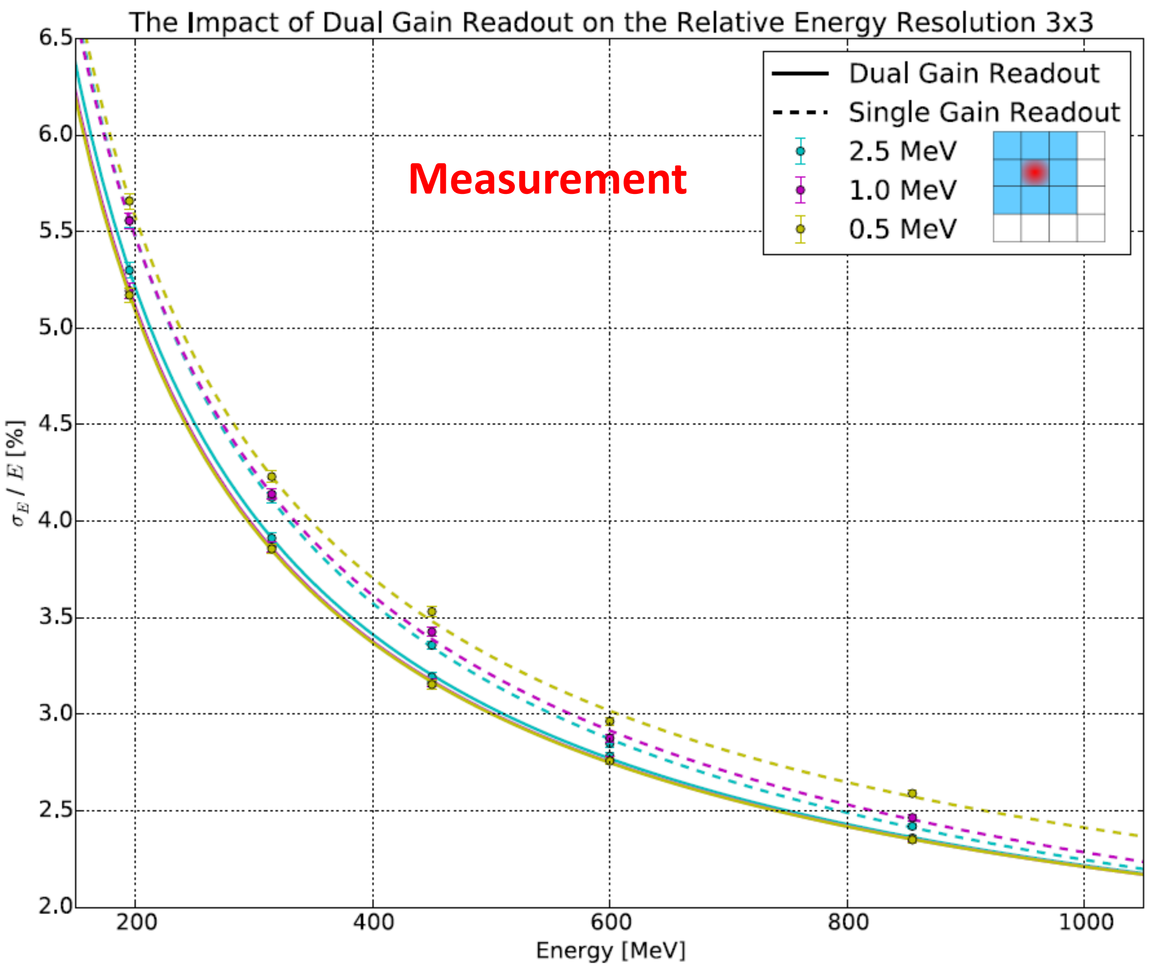
Beam Tests with the EMC Prototype

Relative energy resolution as function of the threshold



Beam Tests with the EMC Prototype

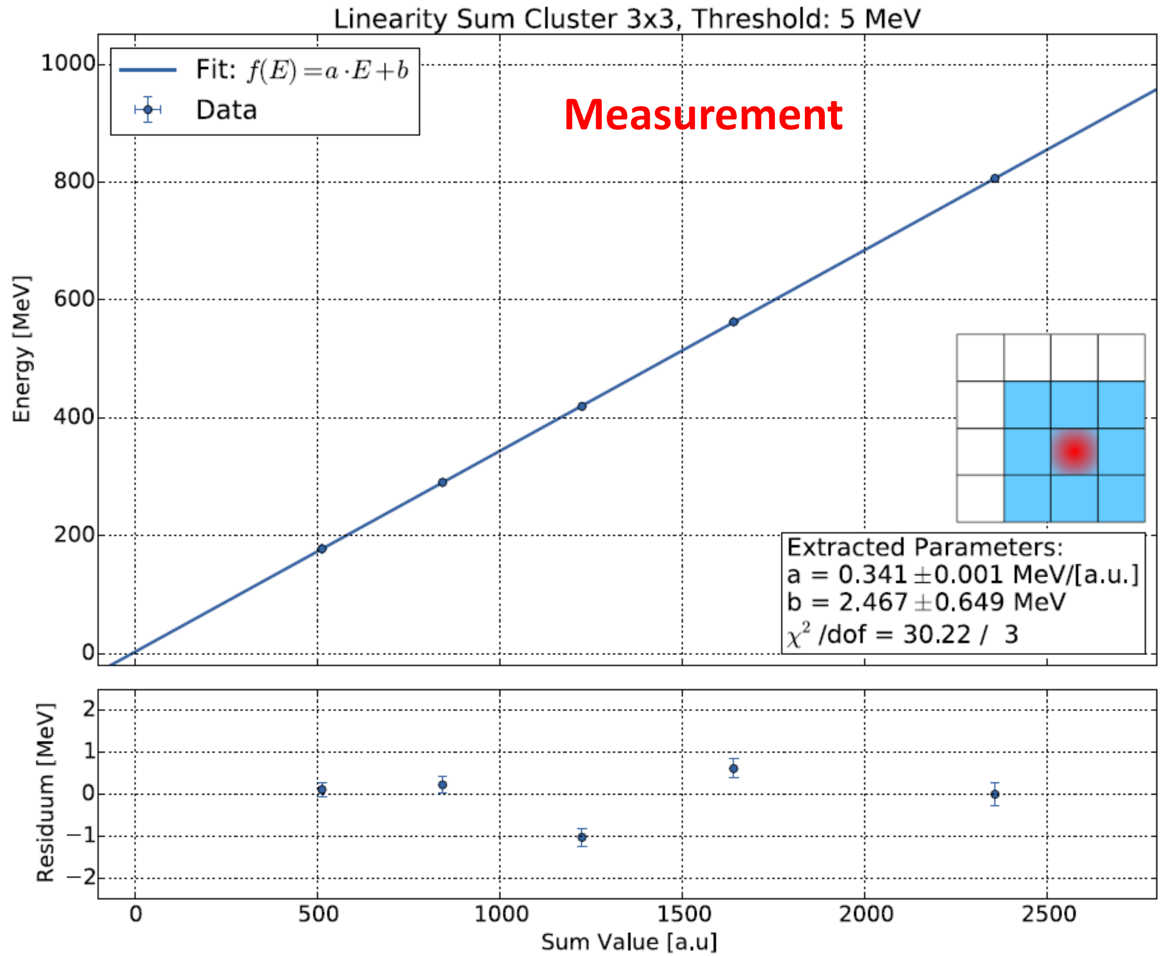
Relative energy resolution: Impact of dual gain readout

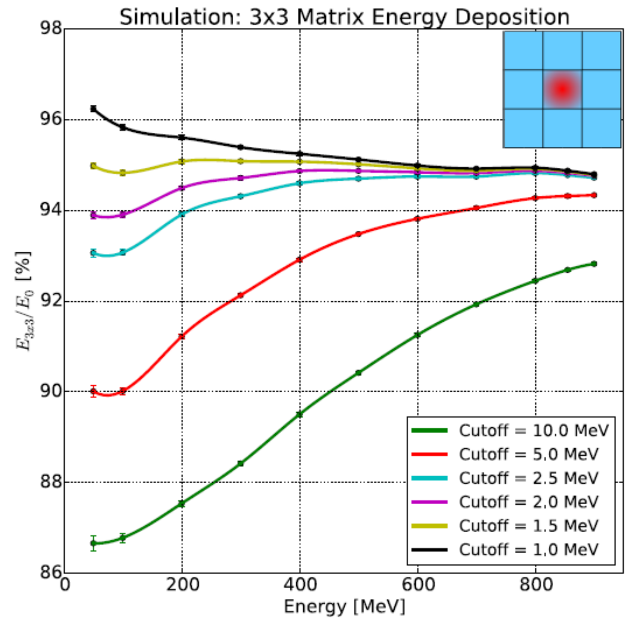


Relative energy resolution always benefits from dual gain (APFEL HG + LG) readout.

Beam Tests with the EMC Prototype

Linearity

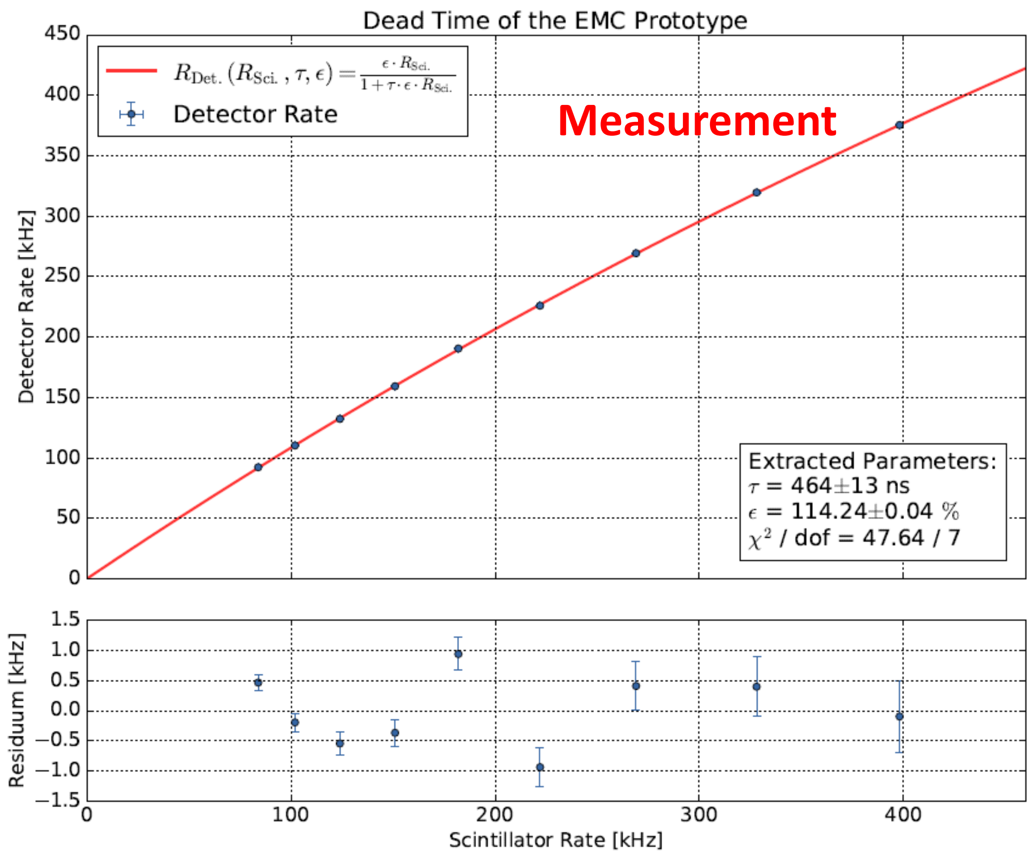




- Correction by Geant4 simulation
- Non-linearity in the order of 1 MeV

Beam Tests with the EMC Prototype

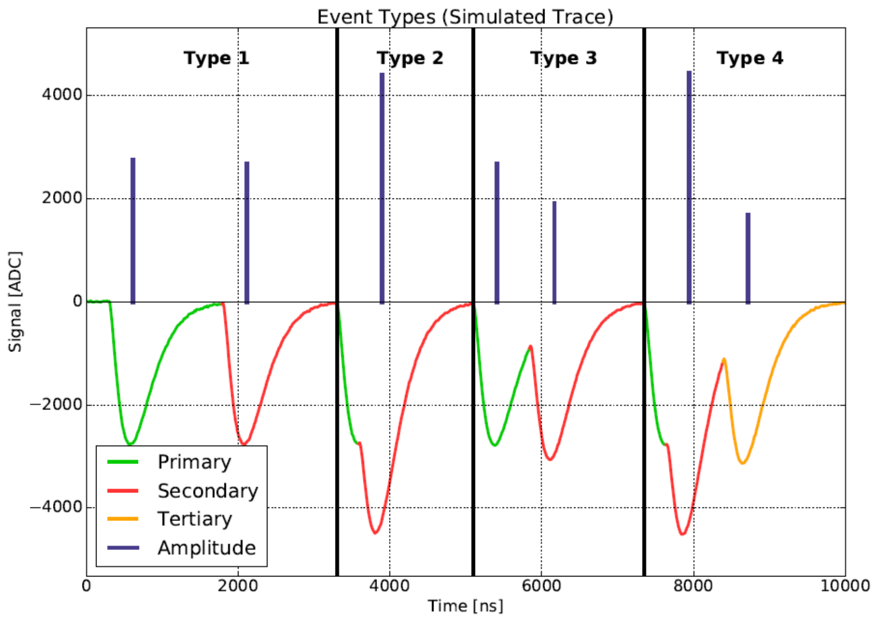
High rate measurements



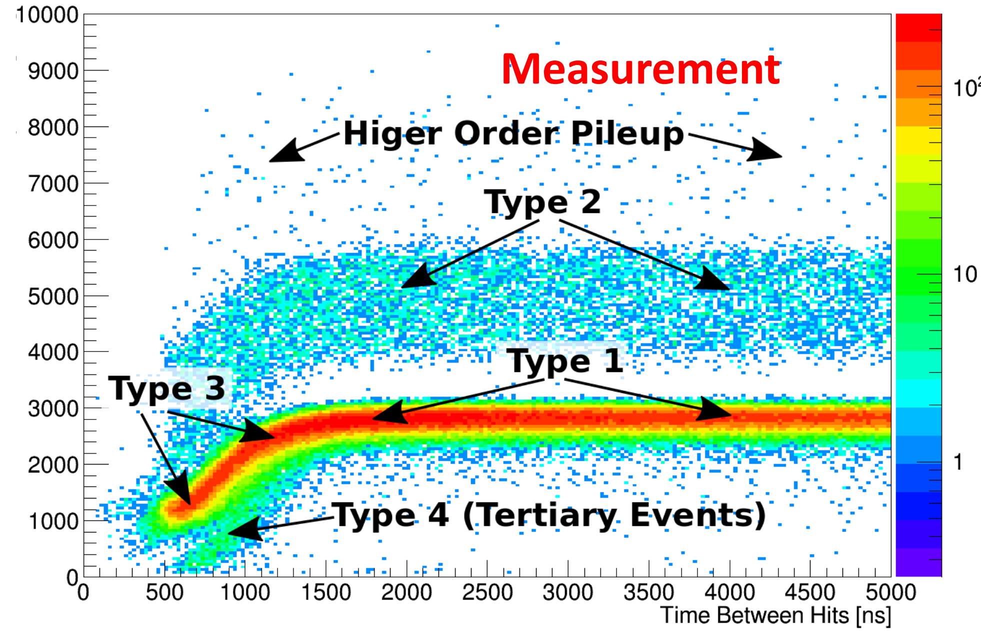
- Plastic scintillator with PMT readout as reference
- Dead time of the EMC prototype:
  τ = 464(13) ns
- Pileup probability at 100 kHz:
  $\mathbf{P_{100kHz} = 4.43(12)\ \%}$
- Amplitudes?

Beam Tests with the EMC Prototype

Amplitude Restoration



Event Types at a Detector Rate of 110.35 kHz

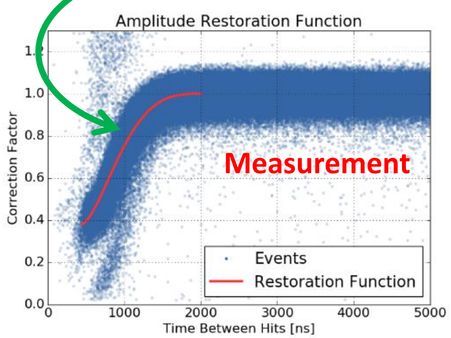


Type	Description	Δ_t [ns]	$P_{100\,\mathrm{kHz}}$ [%]
1	Secondary pulse after decay time of primary pulse	≥ 1500	86.07
2	Secondary pulse within rising edge of primary pulse	< 450	4.30
3	Secondary pulse within falling edge of primary pulse	> 450	9.45
4	Tertiary pulse on type 2 or type 3	-	0.97

Beam Tests with the EMC Prototype

Amplitude Restoration

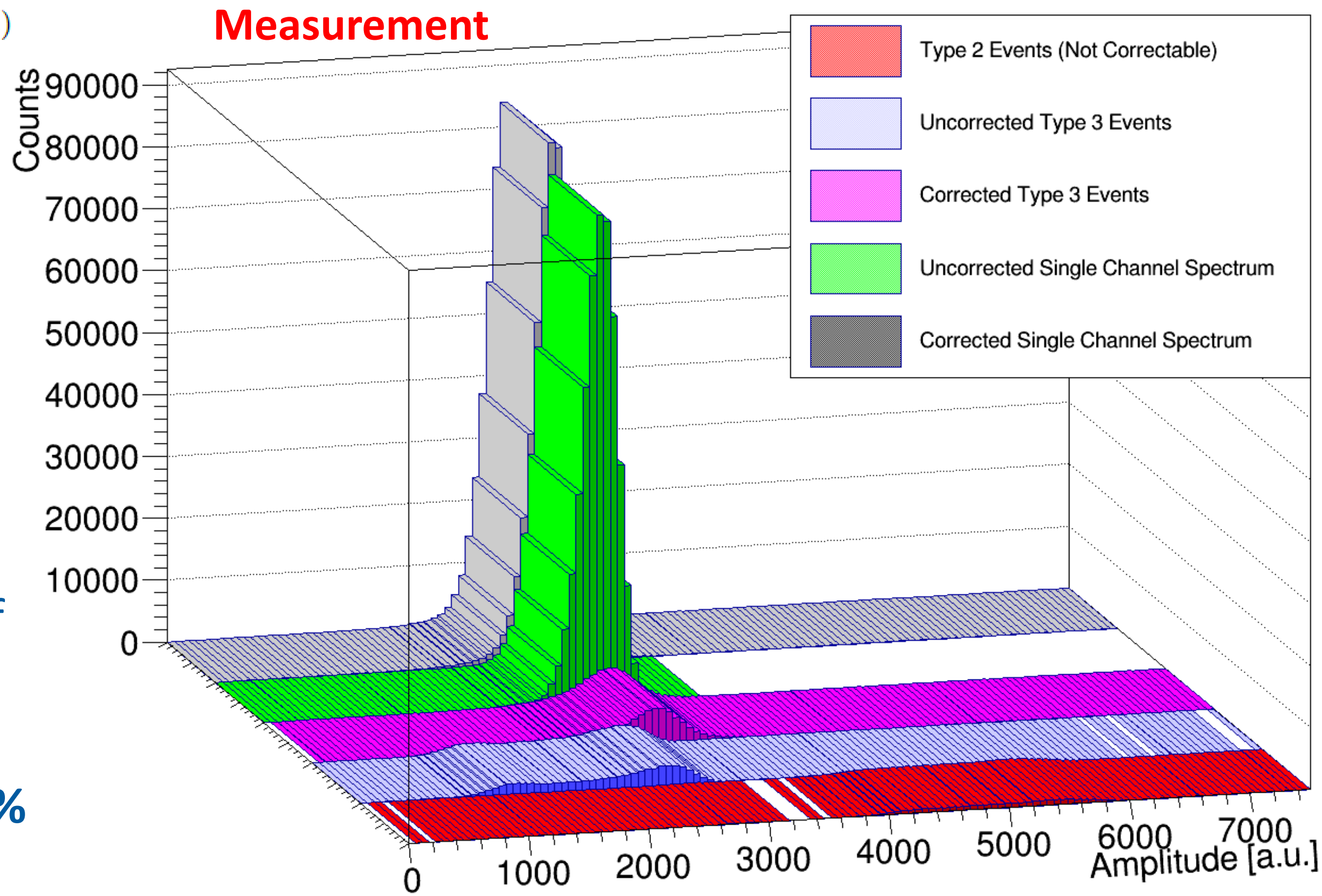
$$H^s_{\text{corr.}} = H^s_{\text{meas.}} \cdot \Sigma(H^p_{\text{meas.}}, H^s_{\text{meas.}}, \Delta_t)$$



Type 3 events (secondary pulse within falling edge of primary pulse) are already correctable

→ $\mathbf{P_{100kHz} = 4.43(12)\ \%}$

Amplitude Restoration at a Detector Rate of 110.35 kHz



Beam Tests with the EMC Prototype

Summary measurements

Parameter	Achieved Value			TDR	Unit
	Worst	Typical	Best		
Rel. En. Res.					
σ_E/E at 1 GeV	2.440(14)	2.207(6)	2.190(2)	$\leq$2.5	%
Constant a	1.23(21)	1.08(14)	0.95(61)	$\leq$1	%
Statistic b	2.02(65)	1.83(45)	1.78(30)	$\leq$2	$\frac{\%}{\sqrt{E[\mathrm{GeV}]}}$
Noise/Ch. c	2.14(9)	2.02(15)	1.92(60)	$\leq$3	MeV
Non-Linearity					
Maximum	2.22(36)	1.26(24)	1.21(19)	-	‰
Timing					
Dead Time τ	-	464(13)	-	-	ns
Pileup $P_{100\,\mathrm{kHz}}$	12.9 (w/o corr.)	4.43(12)	-	$\sim$1	%
Highest Rate	-	-	375.4(6)	100	kHz

Contains Parts of Ph.D. Thesis

Without this work

Summary and Outlook

<u>Summary:</u>

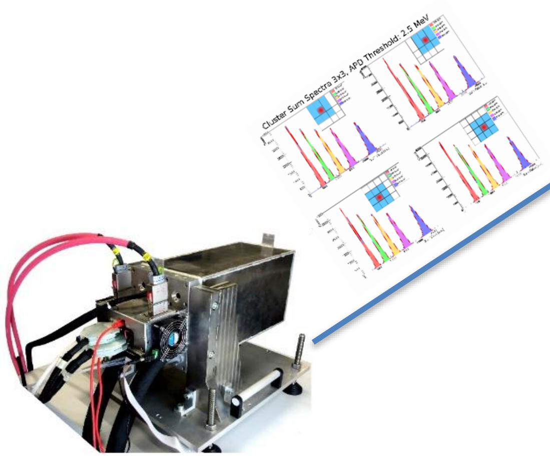
- APFEL ASIC preamplifier pulse parameter extraction
  - FIR
  - Hit detection
  - Amplitude extraction
  - Timestamp
  - Pileup correction
- Extensive studies by using simulations
  - Simulation framework generates realistic baselines and pulses
  - Defined conditions for parameter extraction validation
  - Noise hit rate, efficiency, time resolution, linearity
- Firmware development for the PANDA SADC
- Extensive studies by performing beam tests
  - Relative energy resolution
  - Linearity
  - High rate measurements → pileup correction

Summary and Outlook

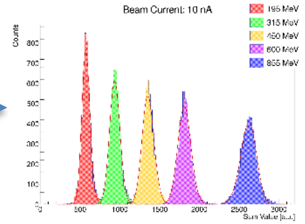
Outlook:

- Using results from "clean" X1 measurements as input for simulation framework
- Add background from Phase-0 test measurements
- Determination of relative energy resolution as function of the beam current for Phase-0

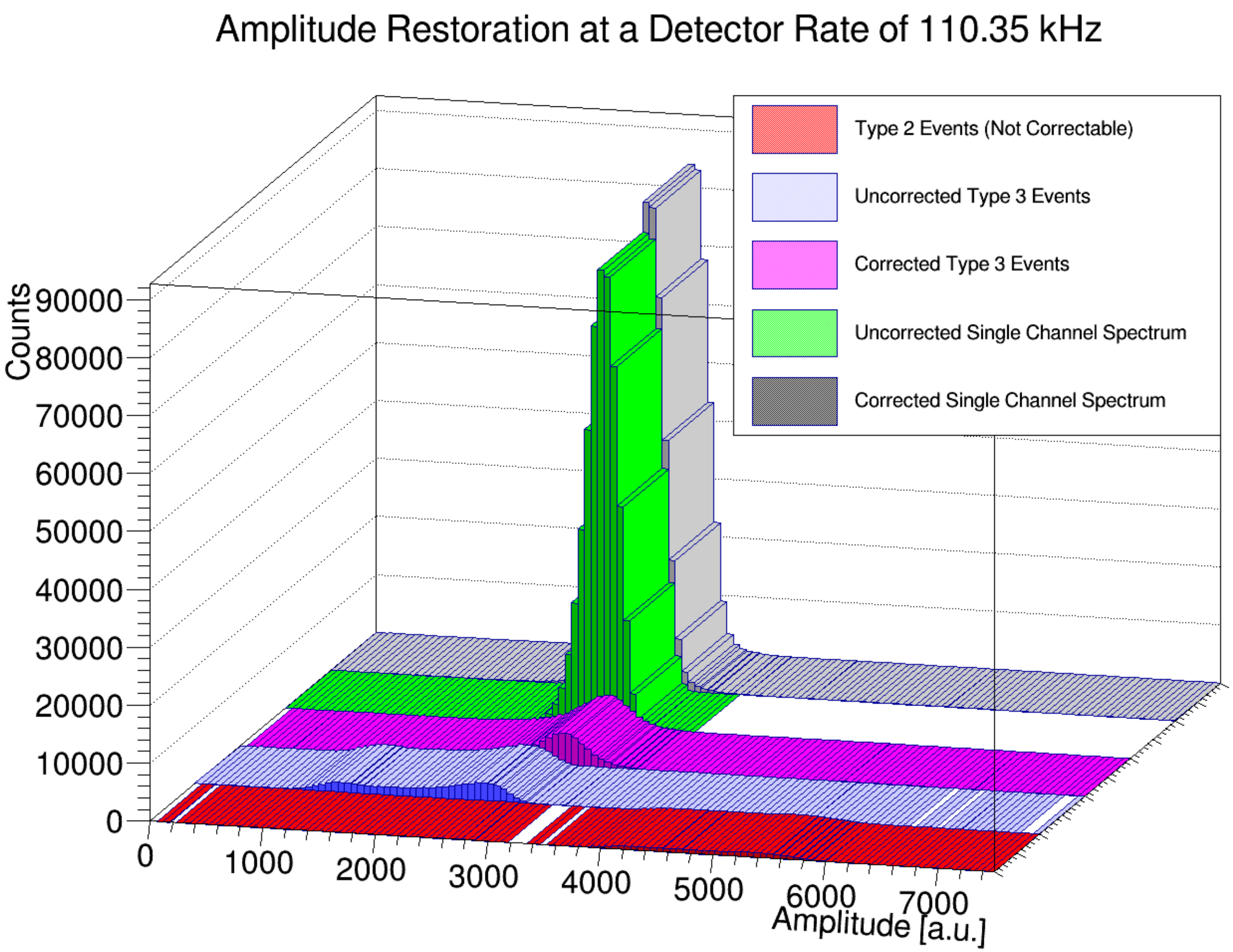
Background Function



Simulation Framework



Backup



Amplitude Restoration at a Detector Rate of 110.35 kHz
Type 2 Events (Not Correctable)
Uncorrected Type 3 Events
Corrected Type 3 Events
Uncorrected Single Channel Spectrum
Corrected Single Channel Spectrum
Counts
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0
1000
2000
3000
4000
5000
6000
7000
Amplitude [a.u.]