SADC Firmware Developments

PANDA CM 21/1 - Oliver Noll

10.03.2021

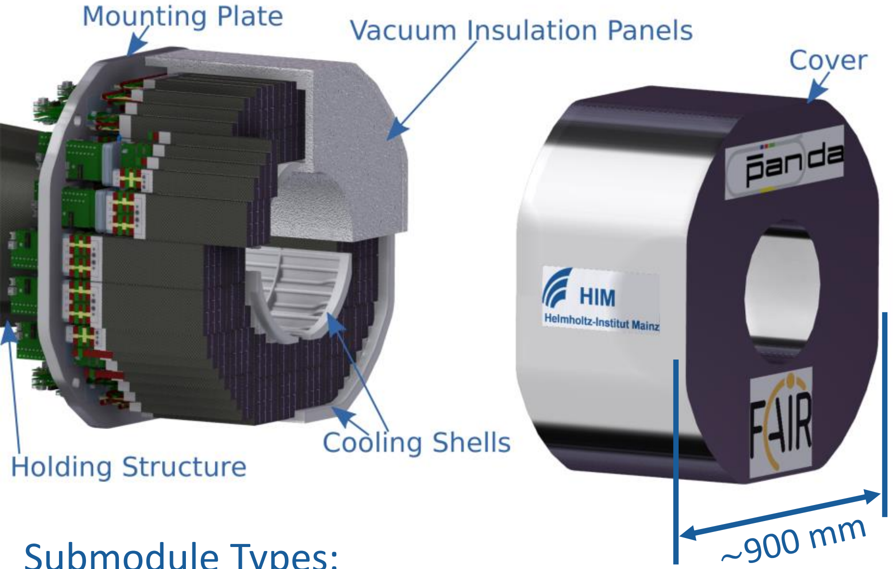
Outline

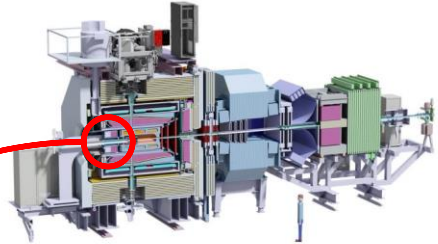
1. **Digital Signal Processing for APFEL Preamplifier Pulses**
    1. The Aim of Digital Signal Processing
    2. Short Summary of Feature Extraction Methods
    3. Achieved Performance with Beam at MAMI

2. **Update of the PANDA SADC Firmware**
    1. Full Free Streaming Data Acquisition
    2. Request System for Traces and Rates
    3. Configurable Package Sizing
    4. Trigger Synchronisation

3. **Availability of latest Developments on GitLab**

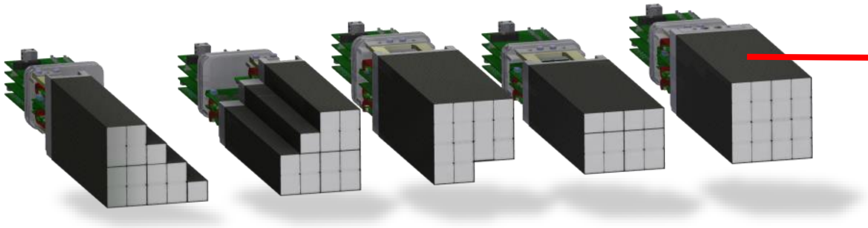
The PANDA Backward Calorimeter

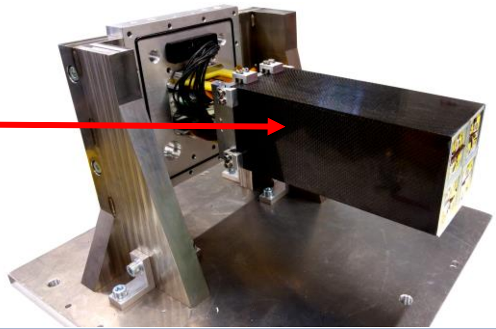


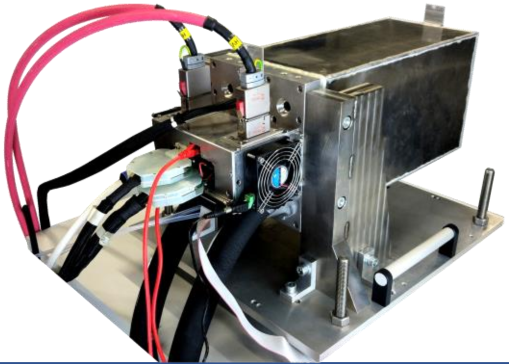


- **524** lead tungstate crystals
- Energy range: **10 MeV – 700 MeV**
- Modular design (five types of modules)
- Full functional **prototype**
- More than **500 hours** of experiments at the **Mainz Microtron** ($e^-$and γ)
- Development finished ✓

Submodule Types:







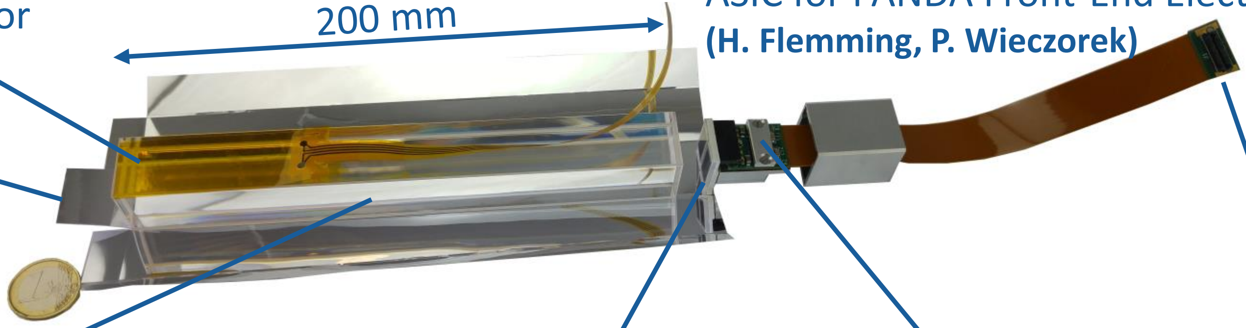
Detection Principle – Single-Crystal Unit

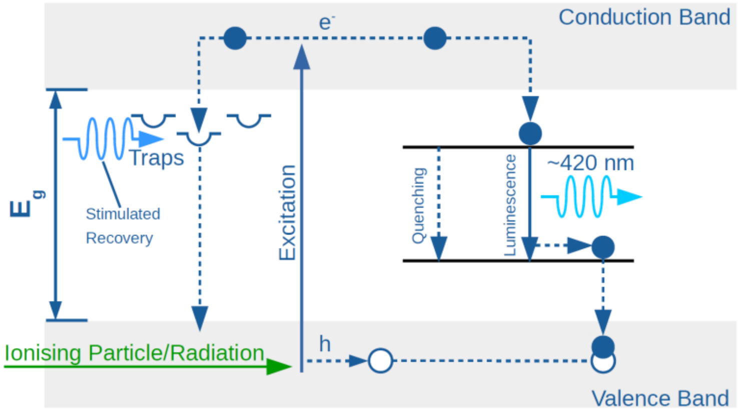
Temperature Sensor

Reflexion Foil

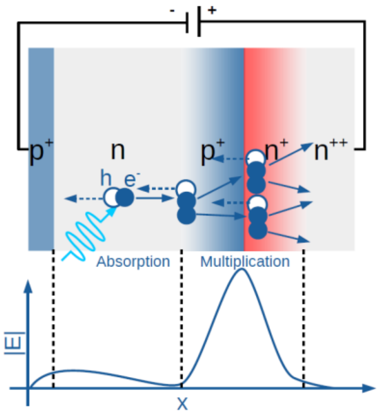
200 mm

ASIC for PANDA Front-End Electronics (APFEL)
(H. Flemming, P. Wieczorek)

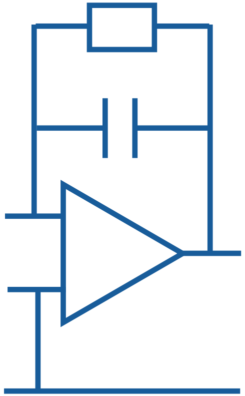




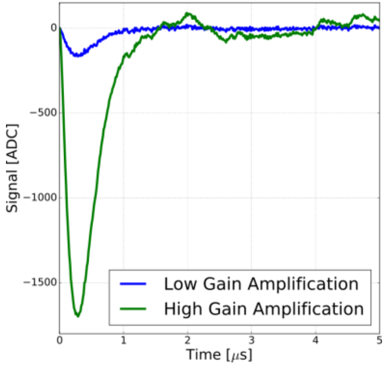
$E \propto N_{\text{photons}}$



$N_{\text{photons}} \propto Q$

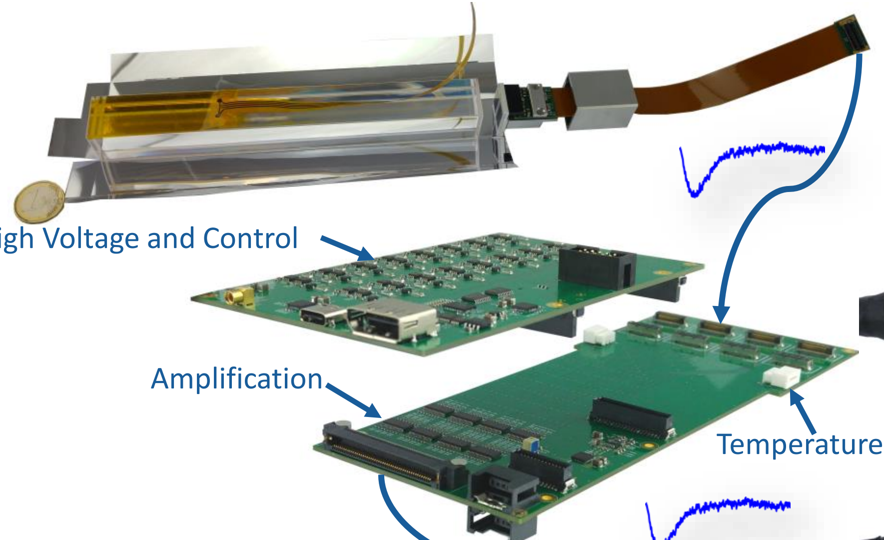


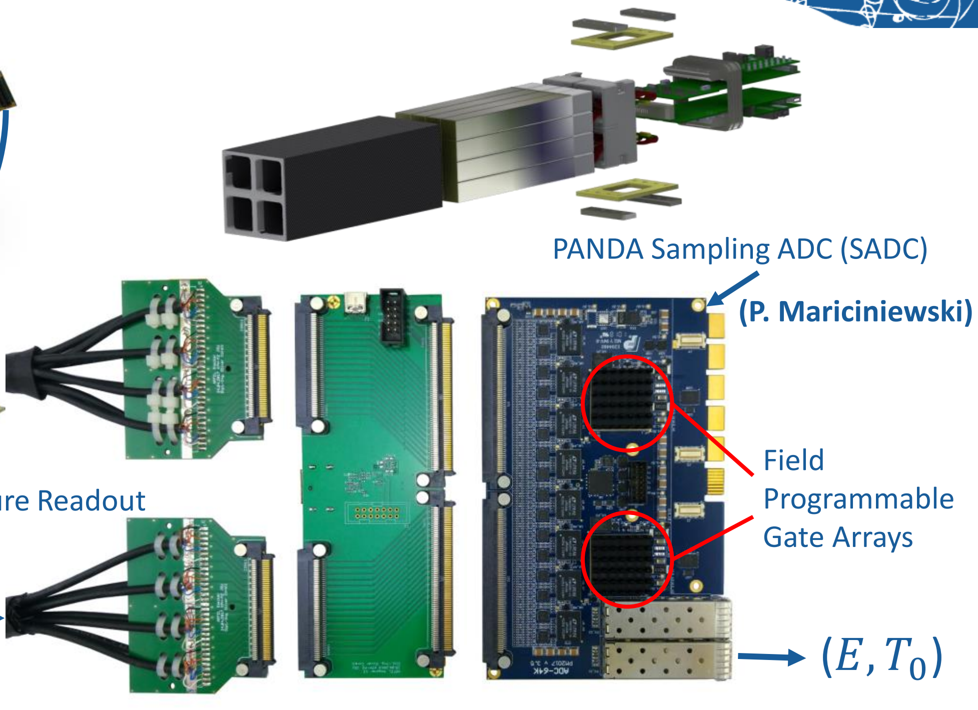
$Q \propto \text{Signal}$



$\rightarrow \text{Signal} \propto E$

Signal Digitisation and Processing





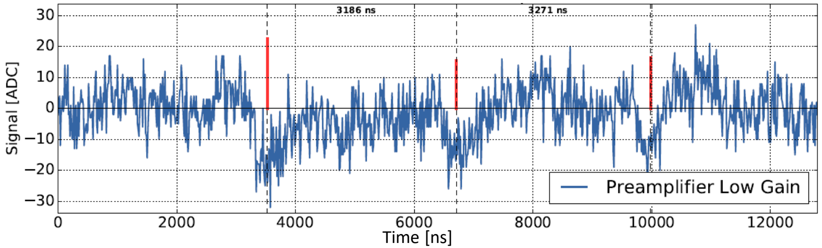
- Analogue signals from APFEL
- Transmission via Front-End electronics (green)
- Digitisation on SADC

Challenge: Compression of Information

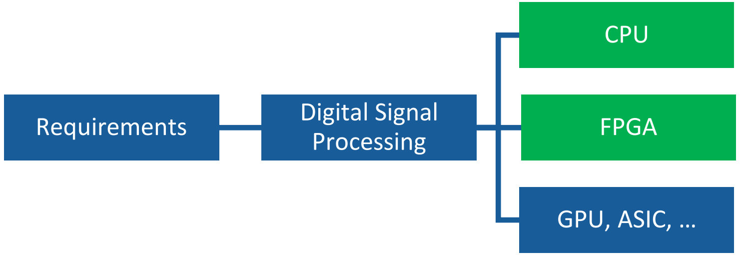
Detector → Amplification → Transmission → ADC → FPGA → Data Concentrator → Compute Nodes

Signal Digitisation and Processing

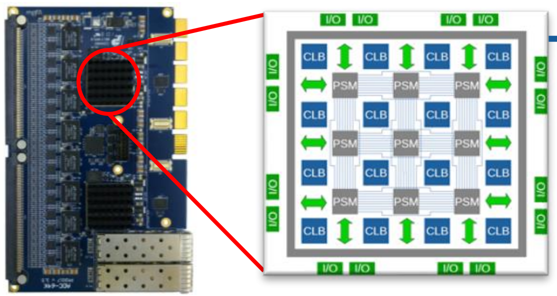
Challenge:



- Self-triggering: pulse identification
- Low detection threshold (< 3 MeV)
- Amplitude extraction (amplitude ∝ energy)
- T_0 extraction (event mapping)
- Pileup detection and correction



Field Programmable Gate Arrays (FPGAs):

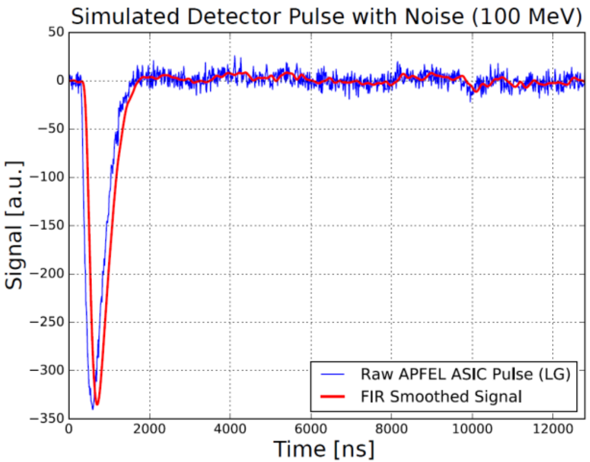


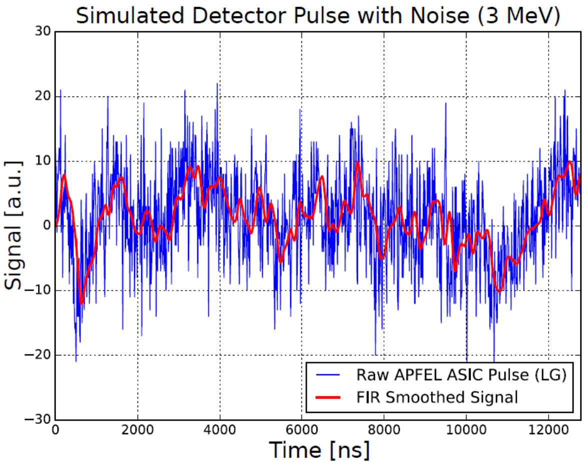
A	B	X
0	0	0
0	1	0
1	0	0
1	1	1

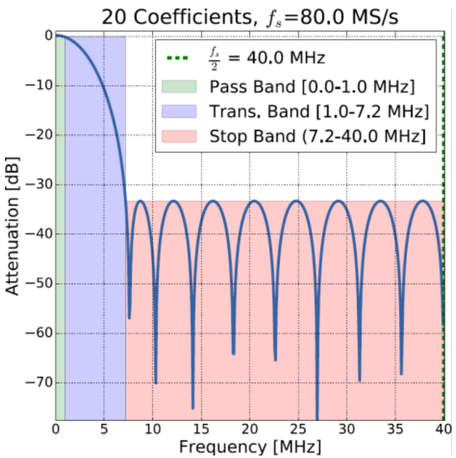
Firmware for all 64 ADC Channels:

- Self-triggering data acquisition (free streaming)
- Digital filter (sharper bands, stronger attenuation)
- Feature extraction routines
- High event rates (> 100 kHz / channel)
- Slow control (settings, thresholds, requests, …)

Signal Smoothing via Finite Impulse Response (FIR) Filtering





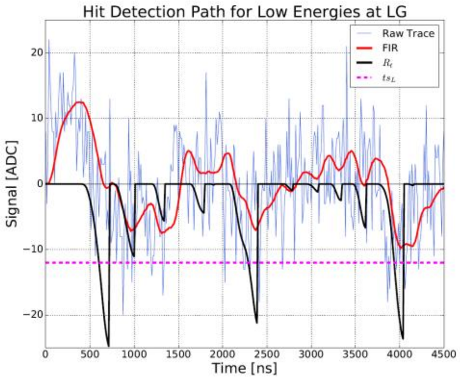


$$y[n] = \sum_{k=0}^{M} A_k x[n-k]$$

- Finite number of samples for output → no self-excitation
- Precise adoption on pulse shape
- **The more filter coefficients (A_k), the better**
- **Resource intensive on FPGA**
- Implementation via **distributed arithmetic** and/or **DSP slices**

Digital Pulse Identification and Parameter Extraction

Identification



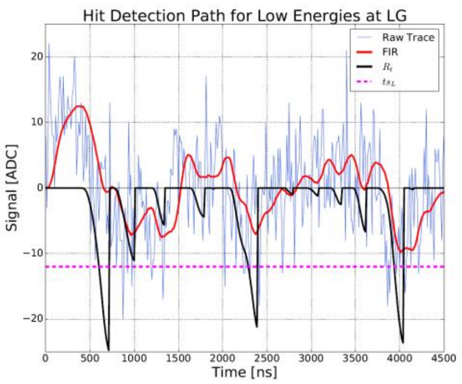
- Extraction function
- Highly sensitive on pulse shape
- Improvement of detection efficiency (small energies!)

Detailed explanations:

- **Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter, Oliver Noll PhD Thesis**
- **EMC TDR Update 2021**

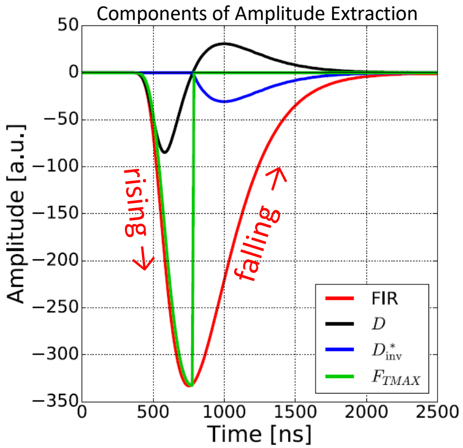
Digital Pulse Identification and Parameter Extraction

Identification



- Extraction function
- Highly sensitive on pulse shape
- Improvement of detection efficiency (small energies!)

Digital Pulse Shaping



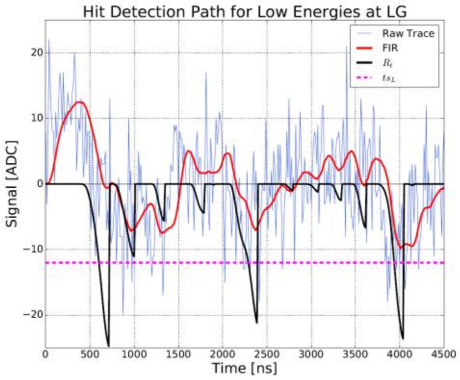
- Derivation → Integration
- Built-in baseline follower
- Elimination of falling edge
- Pileup detection and correction

Detailed explanations:

- **Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter, Oliver Noll PhD Thesis**
- **EMC TDR Update 2021**

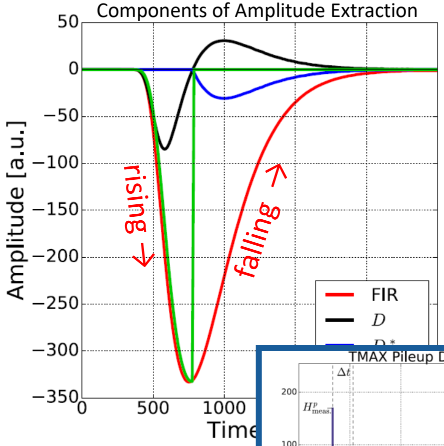
Digital Pulse Identification and Parameter Extraction

Identification

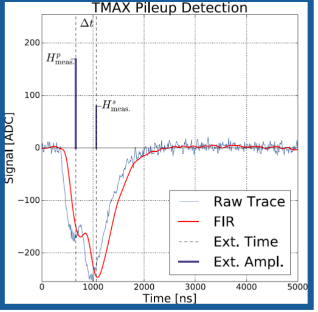


- Extraction function
- Highly sensitive on pulse shape
- Improvement of detection efficiency (small energies!)

Digital Pulse Shaping



- Derivation → Int
- Built-in baseline
- Elimination of fa
- Pileup detection

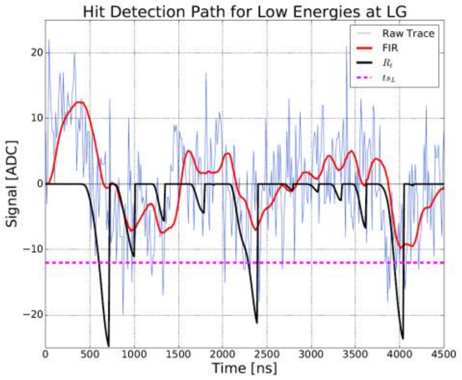


Detailed explanations:

- **Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter, Oliver Noll PhD Thesis**
- **EMC TDR Update 2021**

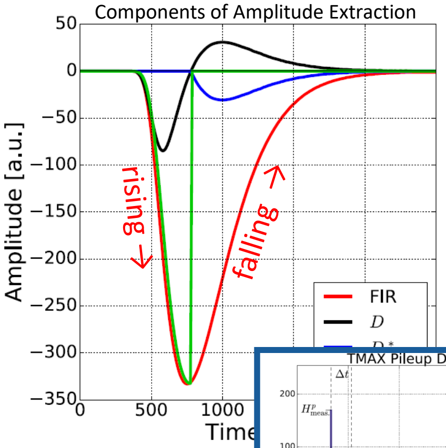
Digital Pulse Identification and Parameter Extraction

Identification

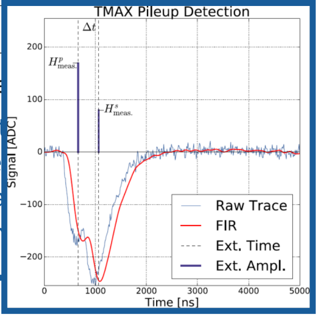


- Extraction function
- Highly sensitive on pulse shape
- Improvement of detection efficiency (small energies!)

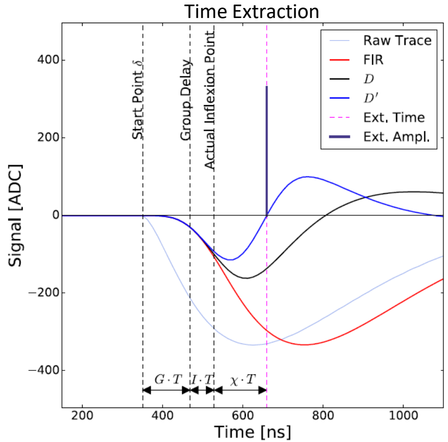
Digital Pulse Shaping



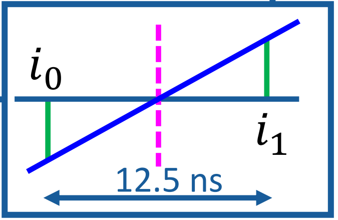
- Derivation → Int
- Built-in baseline
- Elimination of fa
- Pileup detection



Time



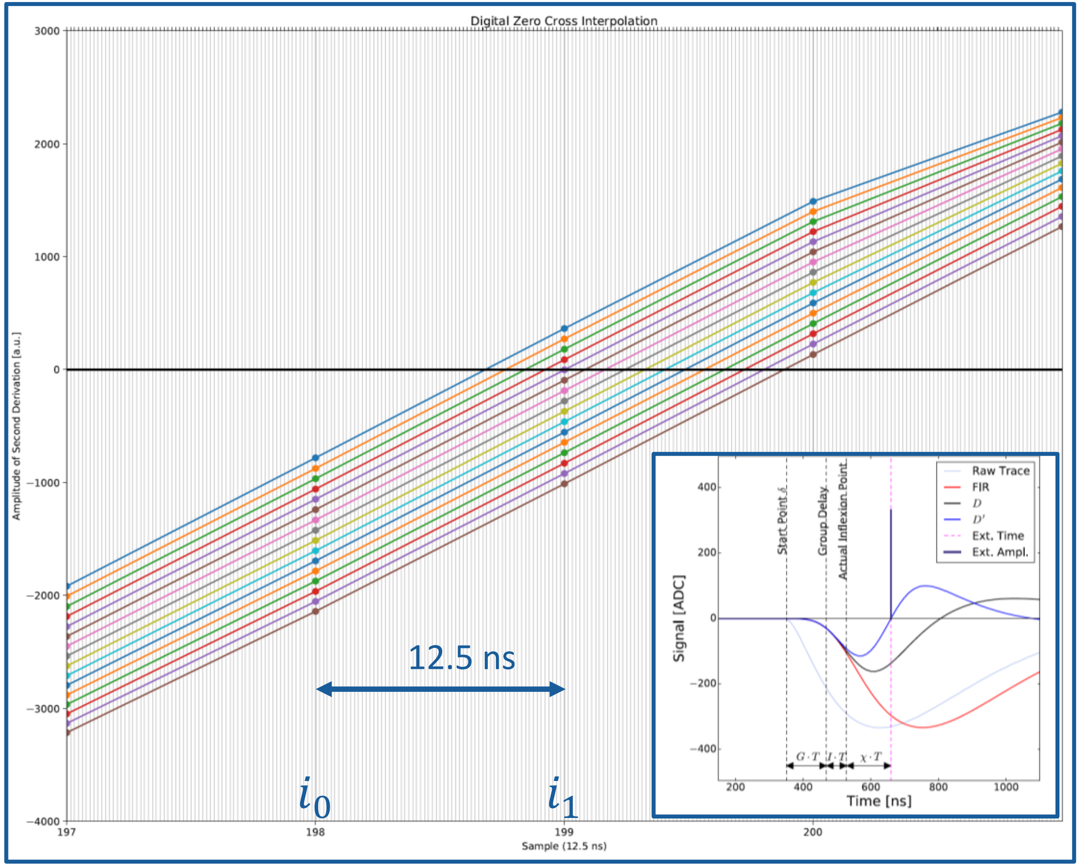
- T_0 at inflexion point ($f''(x) = 0$)
- Discrete derivation → Interpolation



Detailed explanations:

- **Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter, Oliver Noll PhD Thesis**
- **EMC TDR Update 2021**

Digital Zero Cross Interpolation for T0-Determination

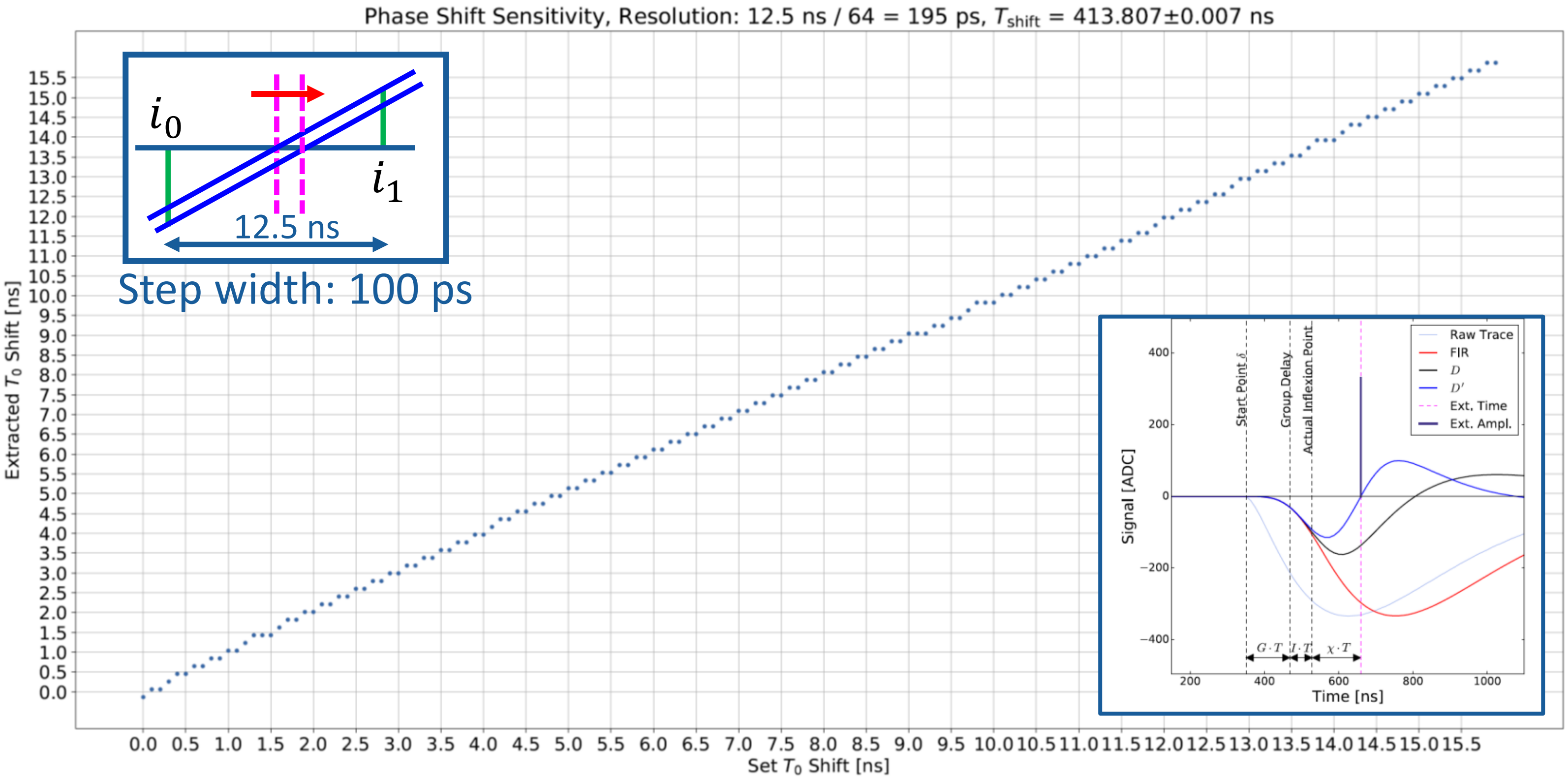


$$T_0 = i_0 + \frac{D'[i_0]}{D'[i_0] - D'[i_1]}$$

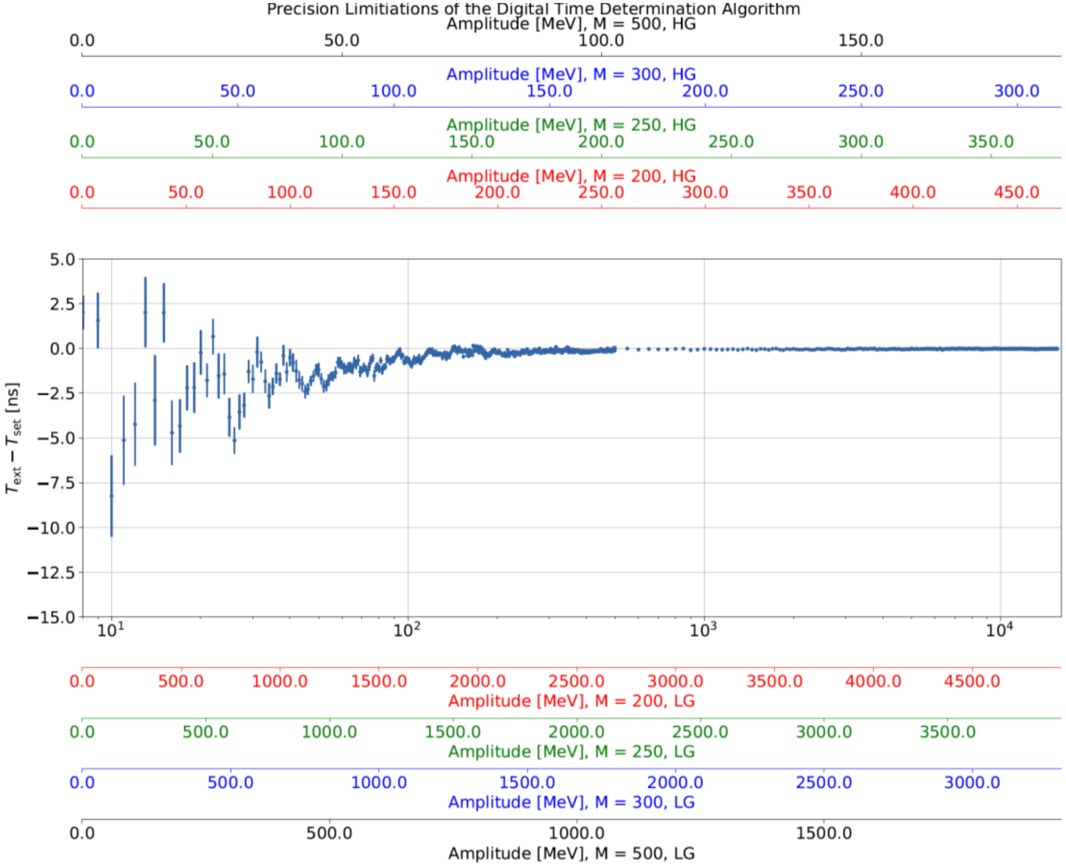
D' is second derivative, since D is the first one

- Fragmentation of time between samples: **12.5 ns / 64 = 195 ps**
- Precision is a function of scaling
- Impact on FPGA resources
- As always: **good compromise between FPGA resources and precision**

T0-Determination: Pulse Transportation along Time Axis



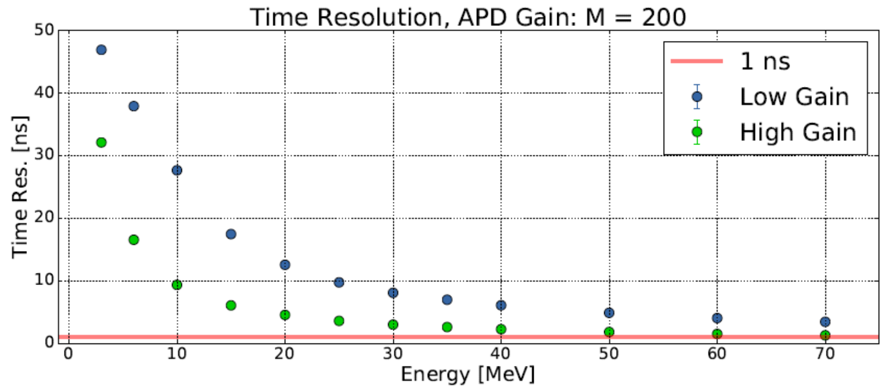
T0-Determination: Pulse Transportation along Time Axis

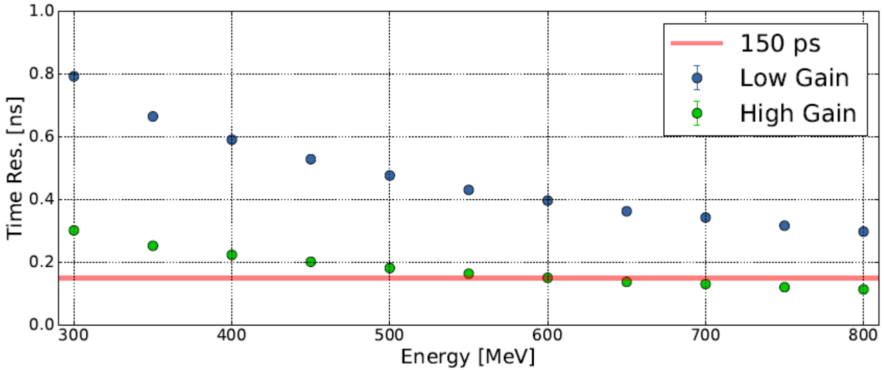


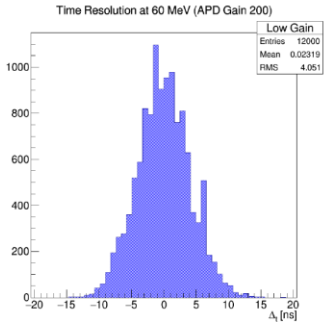
$$T_0 = i_0 + \frac{D'[i_0]}{D'[i_0] - D'[i_1]}$$

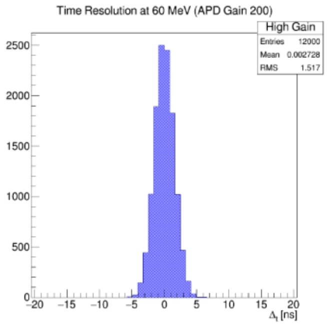
- **Technical precision limitation**
- **Can be improved if necessary**
  - **Impact on other parts of the implementation**
  - **Larger word widths**
  - **More cycles at the division**

T0-Determination: Time Resolution (Simulation with Realistic Noise)







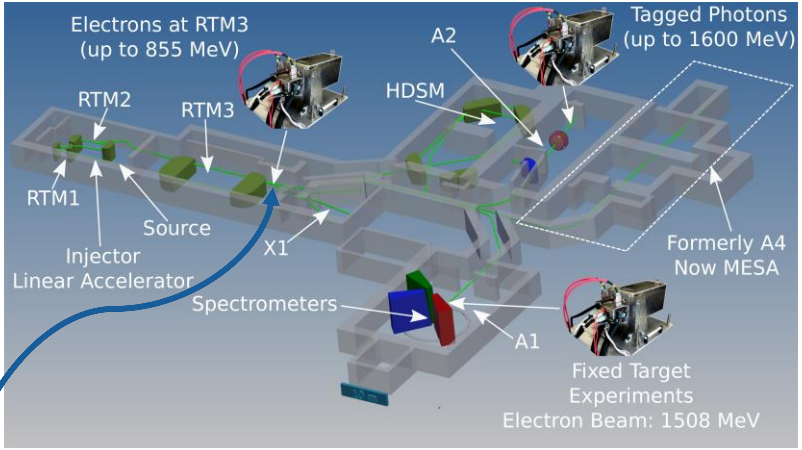


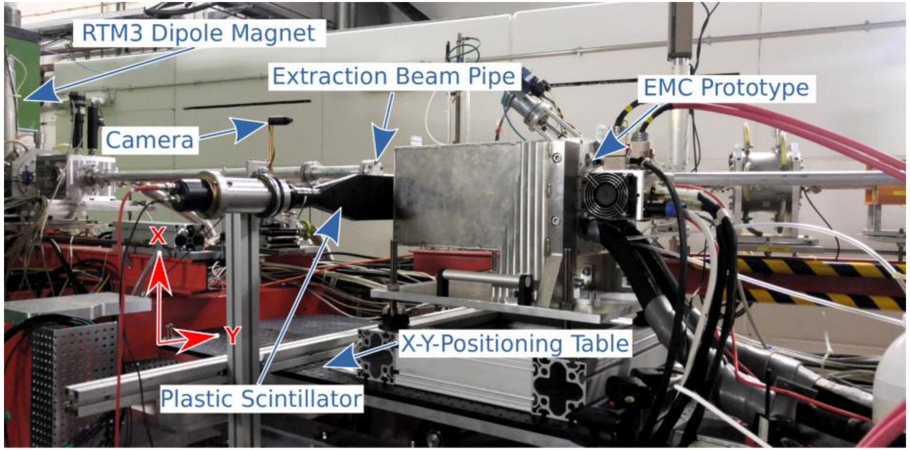
Example: APD gain 200:

TR(60 MeV) = 1.517(10) ns

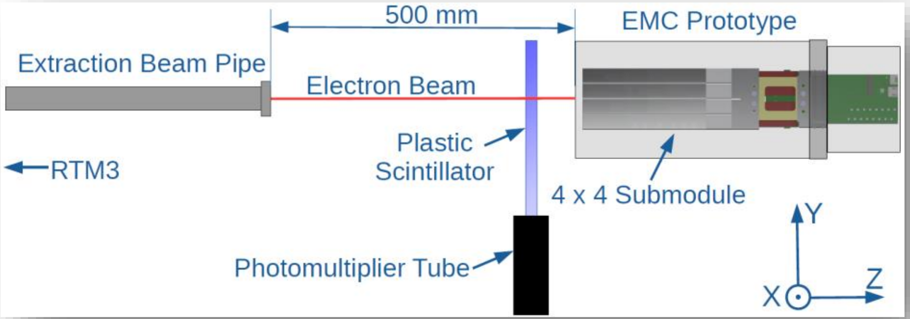
TR(500 MeV) = 182(1) ps

Test Measurements at the Mainz Microtron MAMI





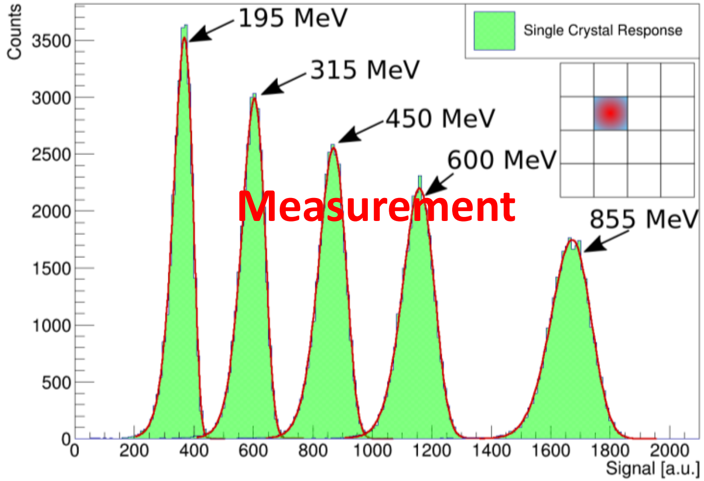
- Electron machine (also photons by conversion)
- Four race track microtron accelerator stages
- Energies from 195 MeV to 1600 MeV
- Continuous wave beam



- Beam extraction behind RTM3 (X1)
- Energies: 195 MeV – 855 MeV
- Excellent beam properties:
  - Energy stability: 13 keV (1σ)
  - Beam spot width: ~1mm

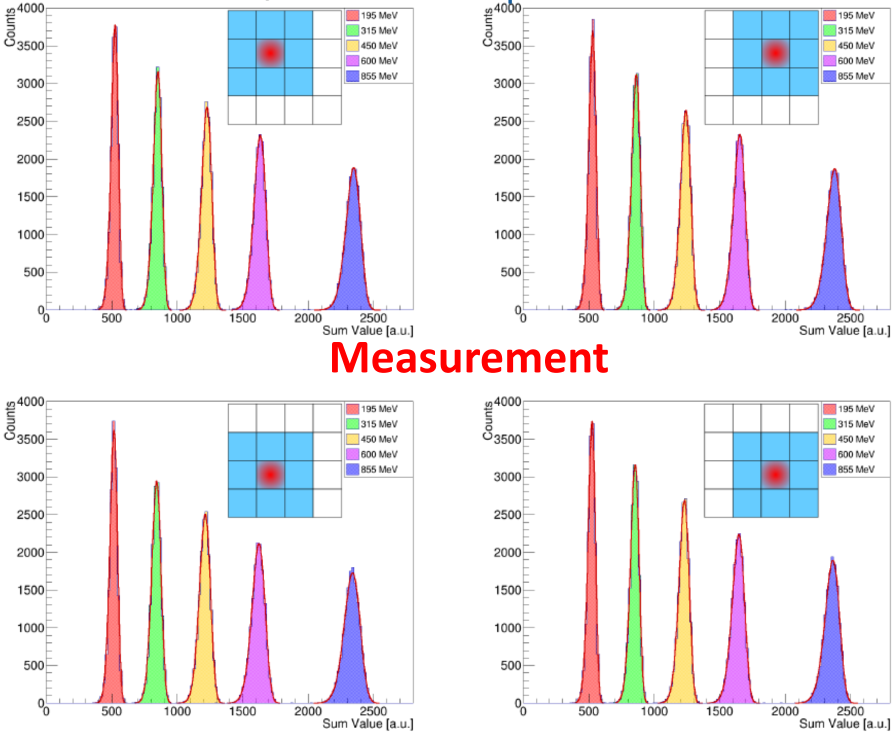
Energy Calibration and Sum Spectra

Single Crystal Energy Calibration



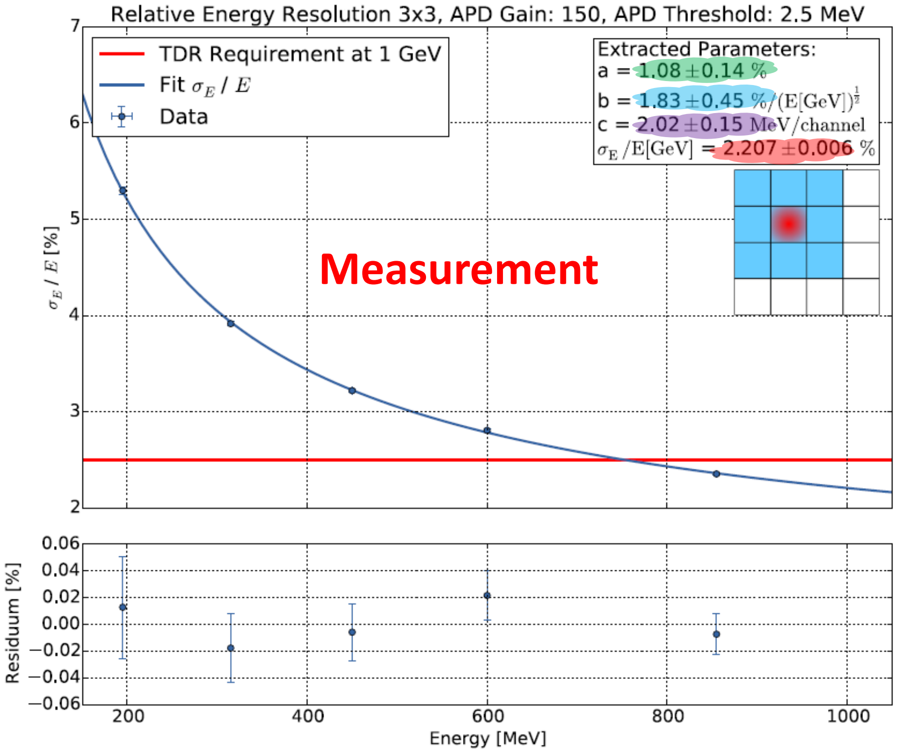
- Differences in single-crystal unit responses
- Geant4 simulation: Expected deposited energy
- Energy calibration → normalisation

3x3 Sum Spectra



- APD Gain: 150, threshold: 2.5 MeV
- Position ∝ E, Width ∝ $\sigma_E \rightarrow \sigma_E/E$

The Relative Energy Resolution



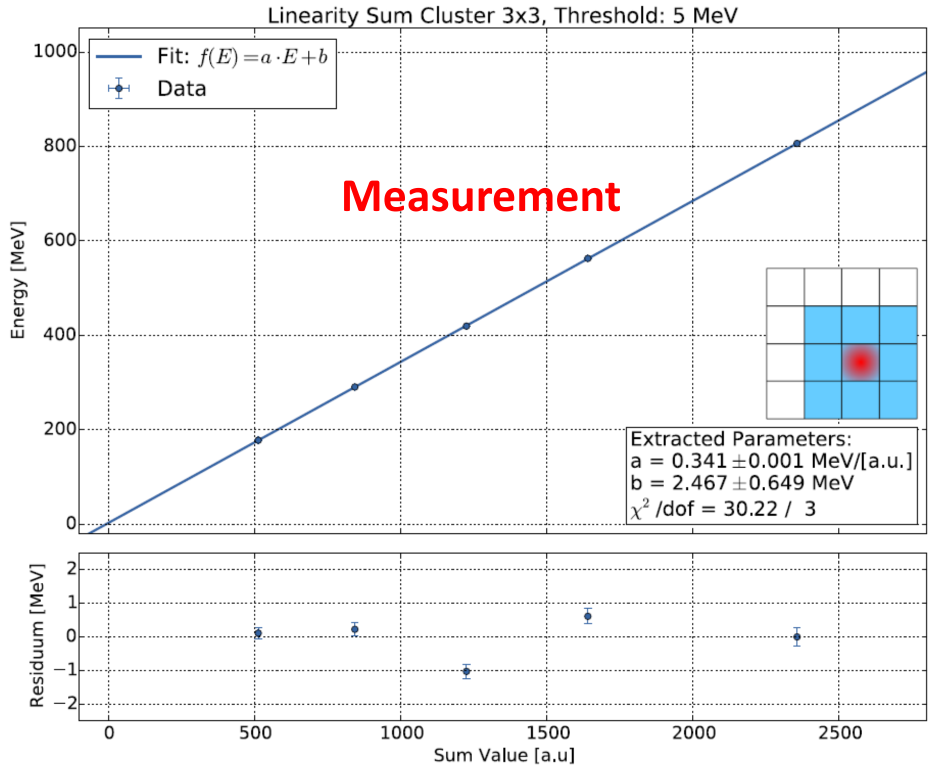
- Most important characterisation of a calorimeter
- Distinguishability of nearby energies

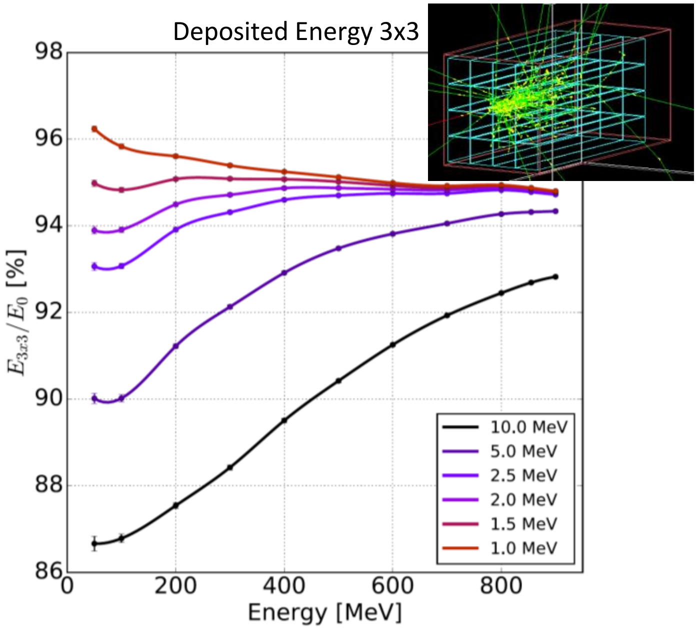
$$\frac{\sigma_E}{E} = \underbrace{a}_{\text{Constant}} \oplus \underbrace{\frac{b}{\sqrt{E}}}_{\text{Stochastic}} \oplus \underbrace{\frac{c}{E}}_{\text{Noise}} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Technical Design Report (TDR) requirements:

- $a_{\mathrm{TDR}} \leq 1\%$ ✓
- $b_{\mathrm{TDR}} \leq 2 \frac{\%}{\sqrt{\mathrm{GeV}}}$ ✓
- $c_{\mathrm{TDR}} \leq 3\ \mathrm{MeV}$ ✓
- $\sigma_E/E(1\ \mathrm{GeV})_{\mathrm{TDR}} \leq 2.5\%$ ✓

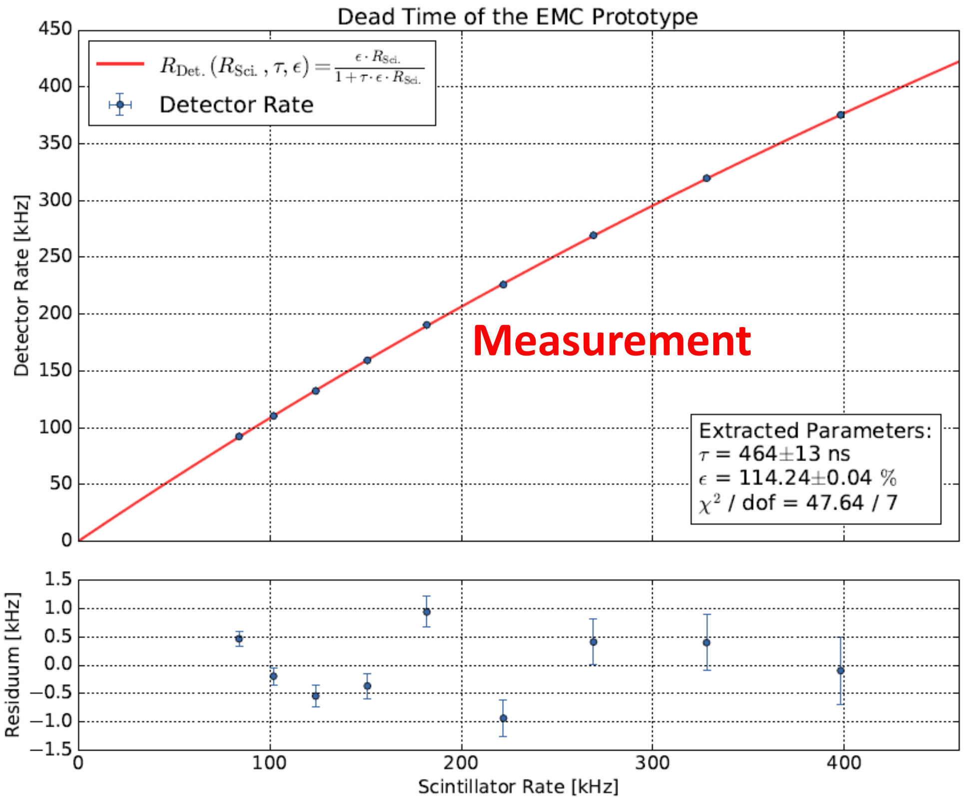
The Detector Response as a Function of the Deposited Energy

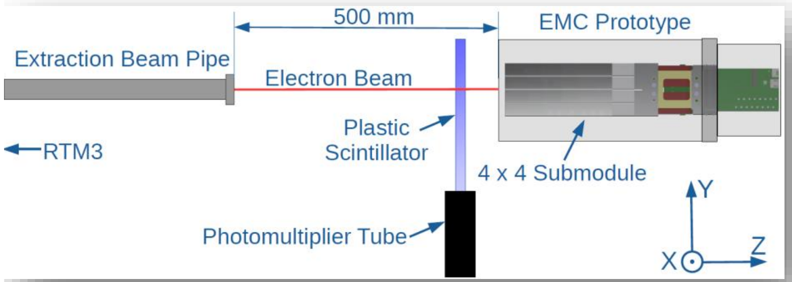




- Leakage energies considered by Geant4 simulation
- Nonlinearity ~ **1 MeV, $\boldsymbol{O}$(‰)**

High-Rate Measurements (PANDA Rate ~ 100 kHz + R_{NHR})

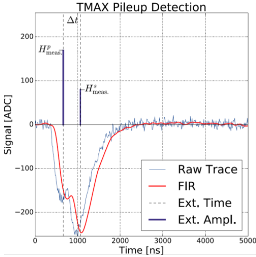




$P_{100\mathrm{kHz}}$: Pileup probability at 100 kHz

Dead time τ	$P_{100\mathrm{kHz}}$ uncorrected	$P_{100\mathrm{kHz}}$ corrected	$P_{100\mathrm{kHz}}$ TDR
464(13) ns	**13.9 %**	**4.53(12) %**	**1 %**

- Pileup **detection on FPGA** and pileup **correction on CPU**
- Reduction of effective pileup probability

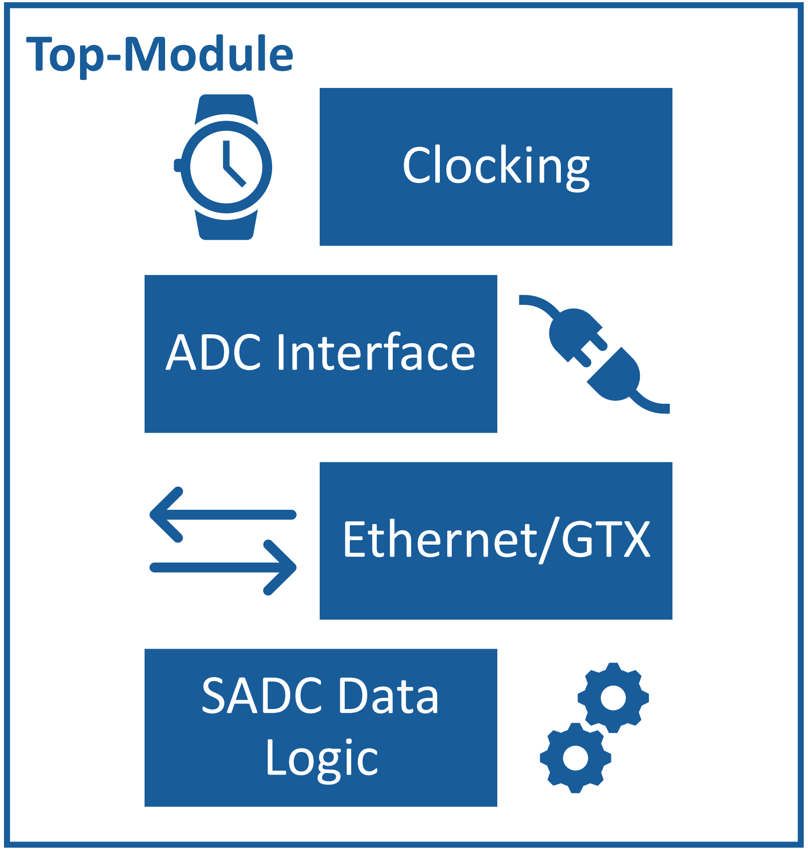


Latest Firmware Developments for the PANDA SADC

- SADC v 2.0
- Modification of "Bonn Firmware"
  Kindly supported by Johannes Müllers
- First self-triggering DAQ implementation in 2018
- Successfully tested with beam

- SADC v 3.5
- Final SADC for PANDA
- Also used for FAIR Phase-0 in Mainz
- Update and restructuring of firmware
  - Full free streaming approach
  - Request system for traces and rates
  - Configurable package sizing

Latest Firmware Developments: New Hierarchy



Latest Firmware Developments: New Hierarchy

Top-Module

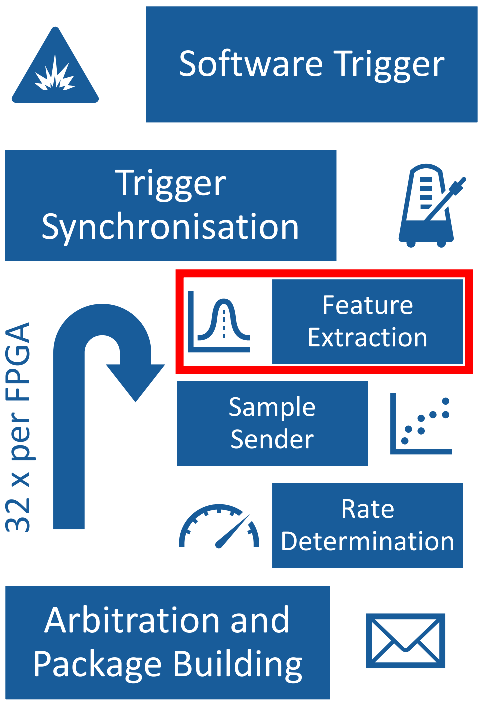
- Clocking
- ADC Interface
- Ethernet/GTX
- SADC Data Logic

SADC Data Logic

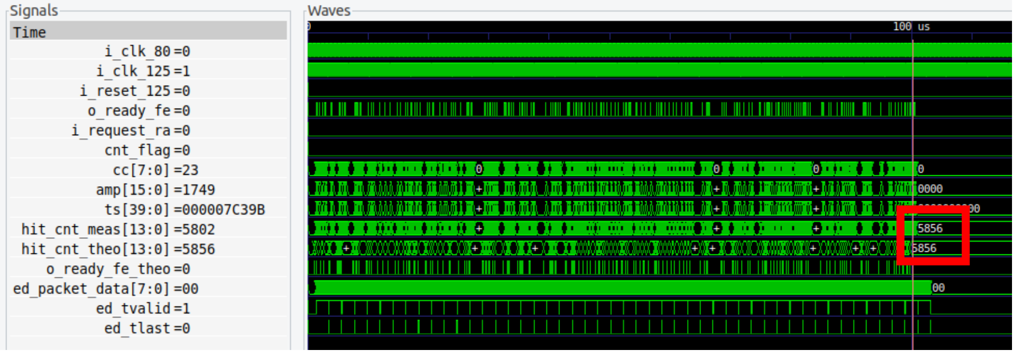
- Software Trigger
- Trigger Synchronisation
- 32 x per FPGA:
  - Feature Extraction
  - Sample Sender
  - Rate Determination
- Arbitration and Package Building

Latest Firmware Developments: High-Rate Capability

SADC Data Logic

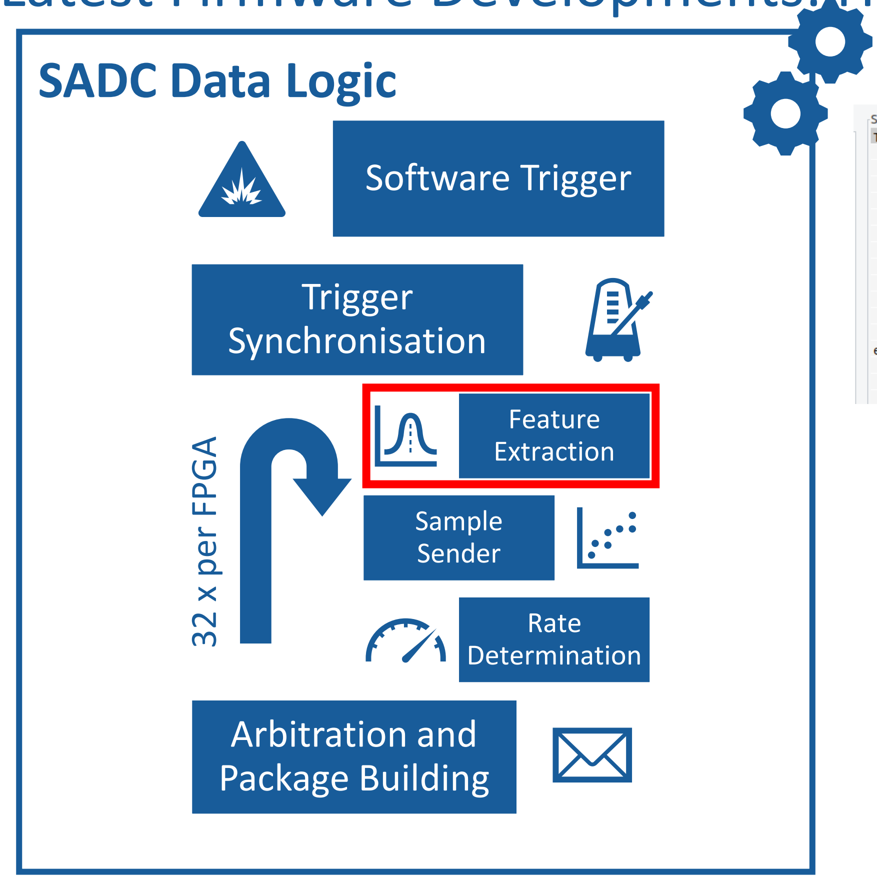


Simulation: 2 MHz Hit Rate per Channel

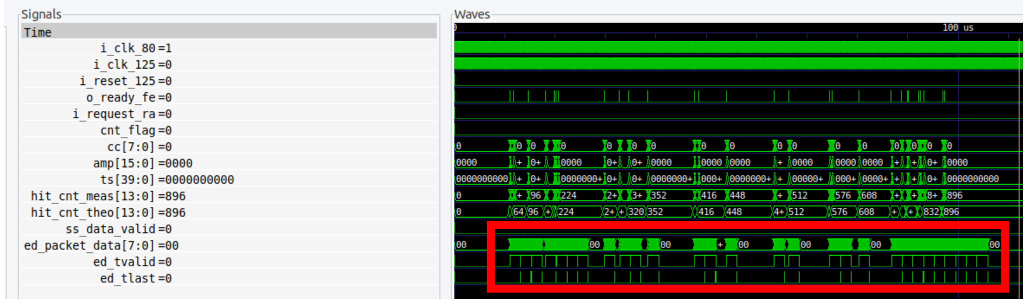


- **SADC Data Logic** manages easily **2 MHz** hit rate per channel
- Poison distributed events
- Bottleneck:
  - “Slow” calorimeter signals
  - 1 Gbit/s interface (**ed_packet_data**)

Latest Firmware Developments: High-Rate Capability

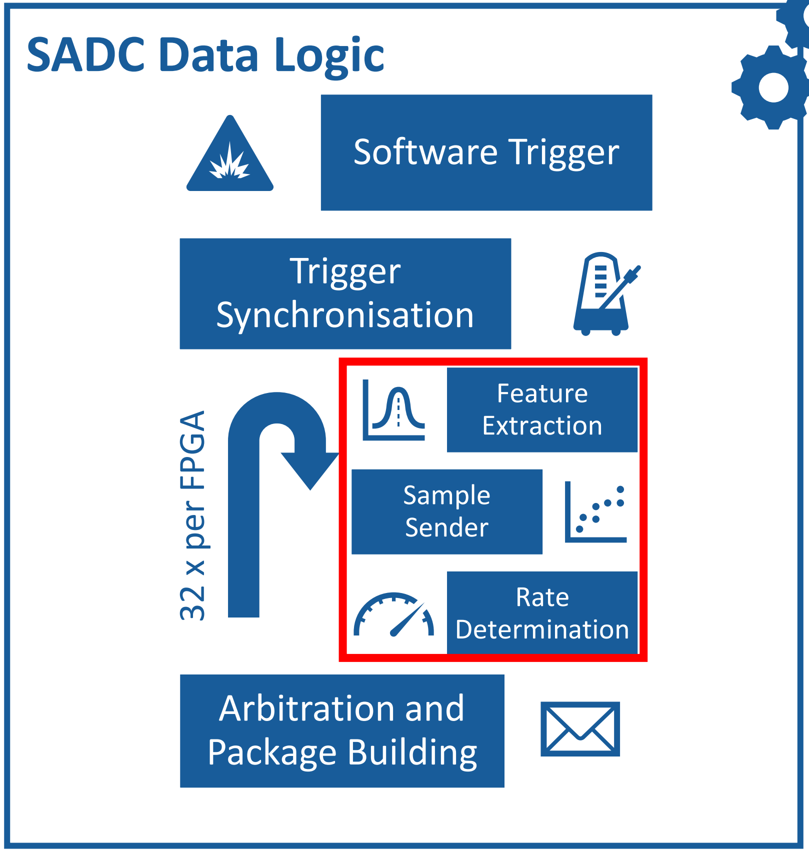


Simulation: 200 kHz Hit Rate per Channel

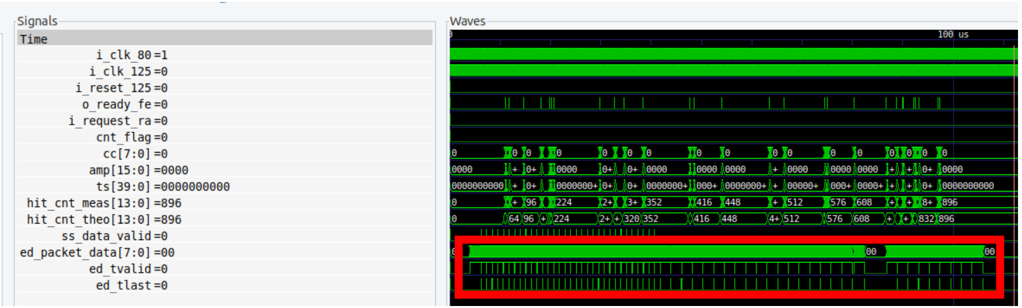


- **SADC Data Logic** manages easily **2 MHz** hit rate per channel
- Poison distributed events
- Bottleneck:
  - “Slow” calorimeter signals
  - 1 Gbit/s interface (**ed_packet_data**)
- PANDA maximum hit rate: **200 kHz / channel**
  - Event rate: 100 kHz / channel
  - Noise hits: 100 kHz / channel (very conservative)

Latest Firmware Developments: Free Streaming Mixed Readout

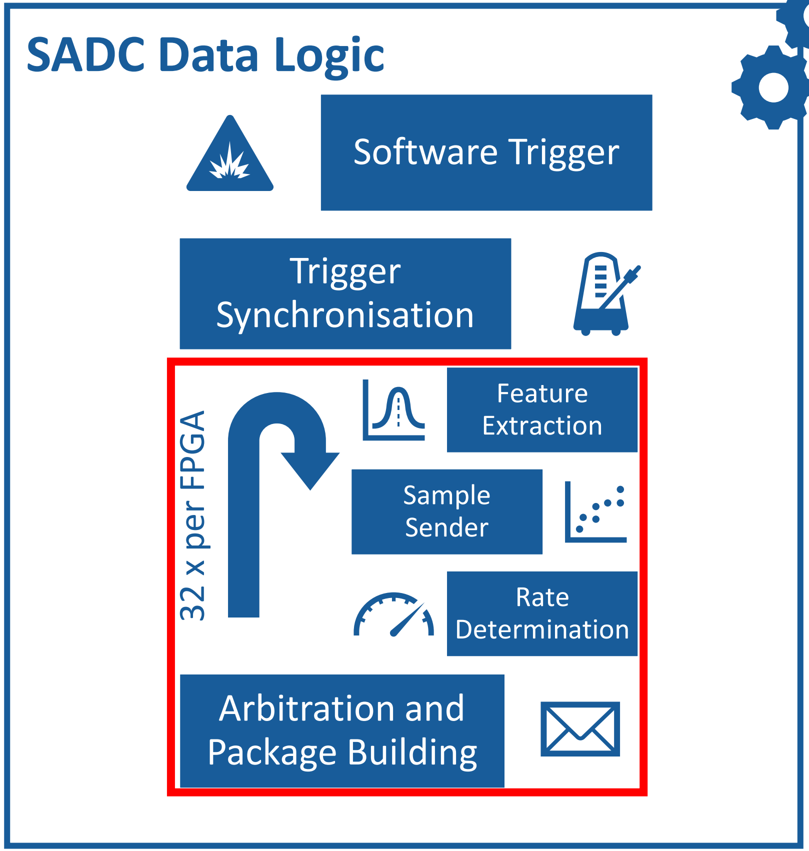


Simulation: 200 kHz Hit Rate per Channel

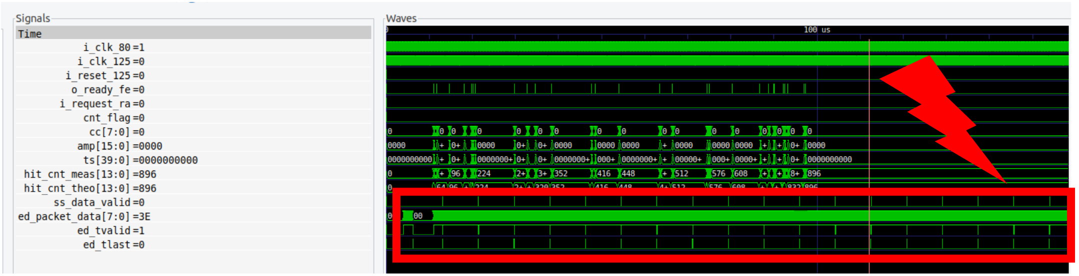


- **200 kHz / channel**
- Free streaming mixed readout
    - Different data frames appear to arbitrary times
    - Request system
- Rate request (one small package)
- Sample request (**64 samples / channel**)
- Still, plenty of headroom

Latest Firmware Developments: Free Streaming Mixed Readout



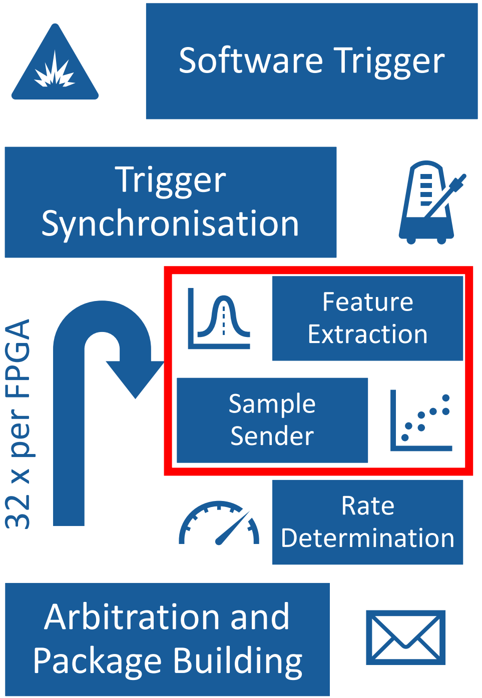
Simulation: 200 kHz Hit Rate per Channel



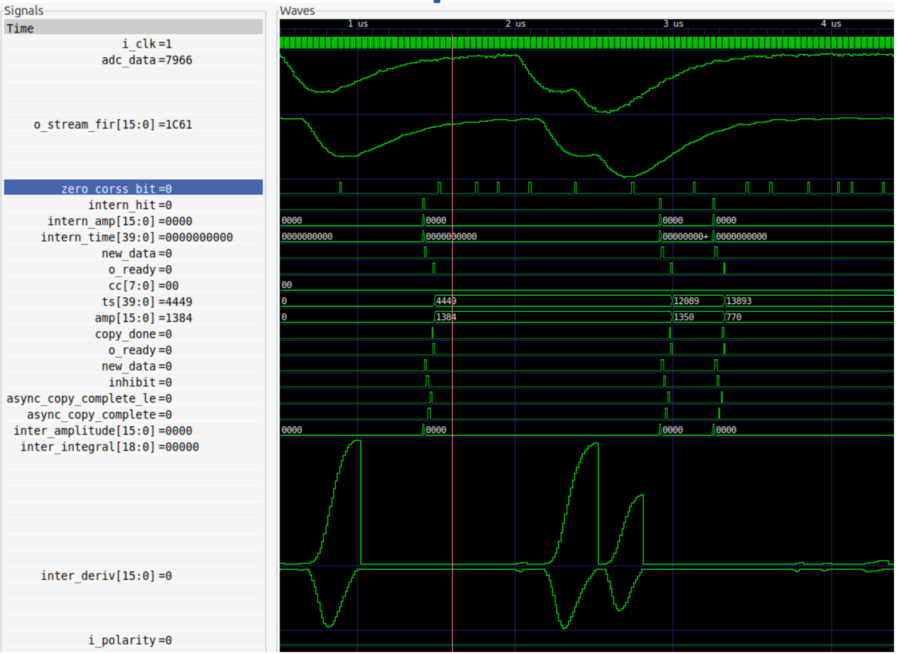
- **200 kHz / channel**
- Rate request (one small package)
- Sample request (**512 samples / channel**)
- More FIFO depth, more resources… not necessary
- **Configurable package sizing:**
    - Long traces for detector adjustments (>512 samples)
    - Shorter traces for pileup events (≈128 samples)
    - Very short trace for monitoring (≈64 samples)

Latest Firmware Developments: Pileup

SADC Data Logic

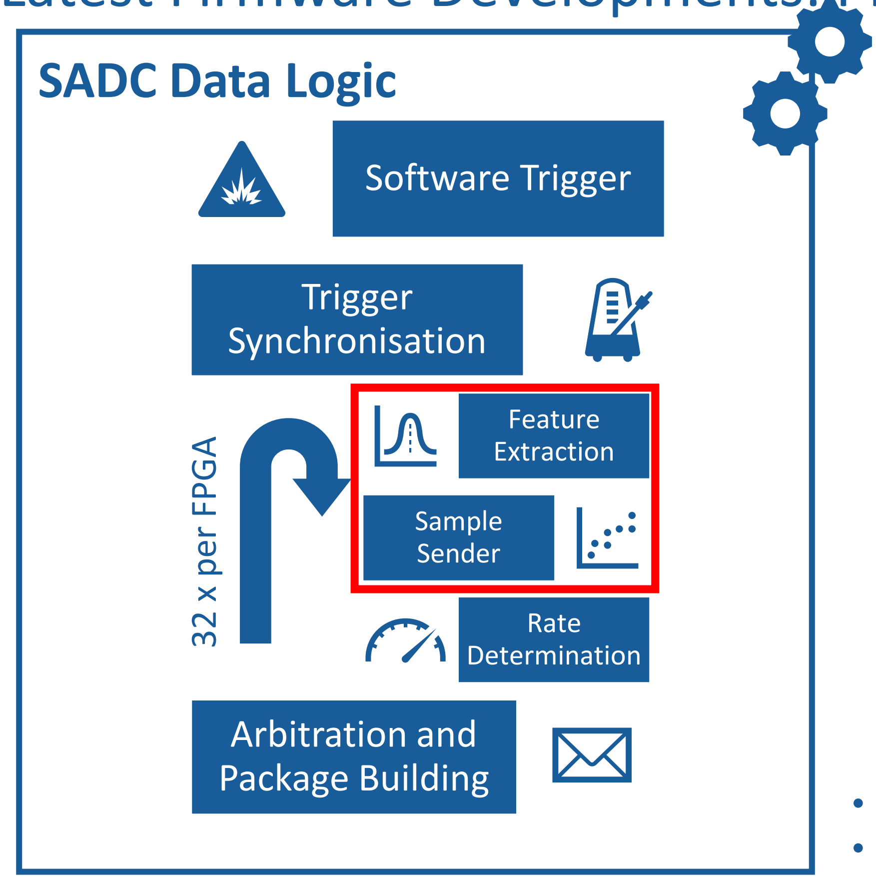


Simulation: Pulse to pulse distance ≥ 350 ns

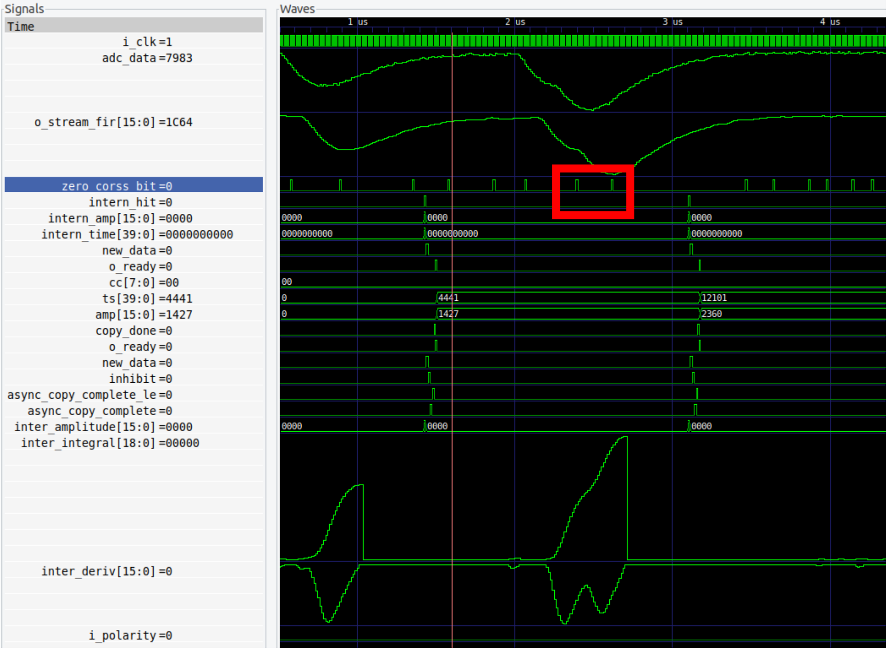


- Feature extraction is capable to distinguish pulses
- Software amplitude recovery

Latest Firmware Developments: Pileup



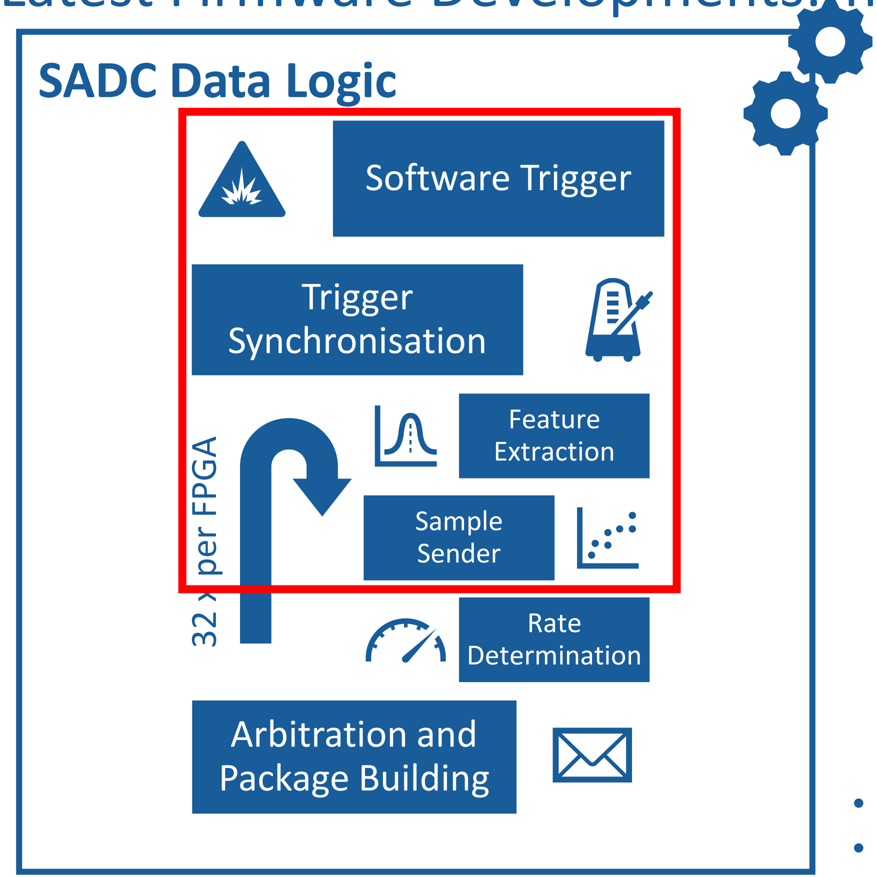
Simulation: Pulse to pulse distance $\leq$ 350 ns



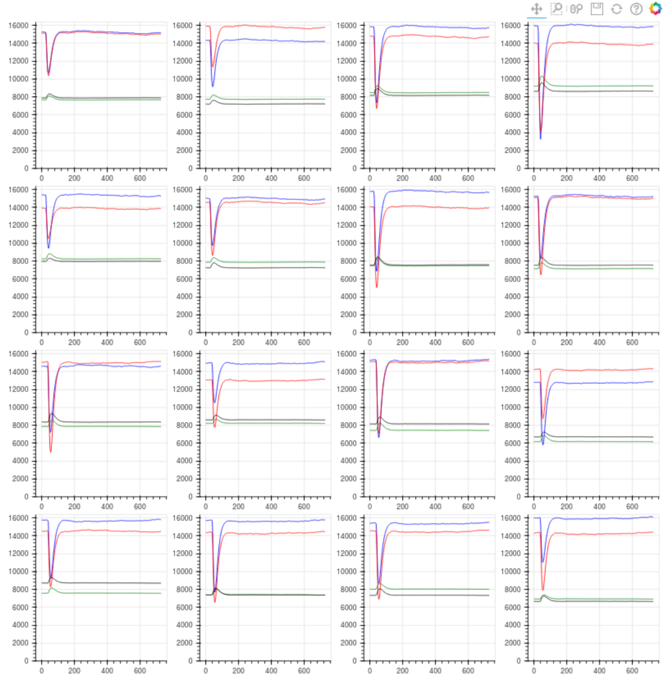
- Feature extraction is not anymore capable to distinguish pulses
- Activation of sample sender for specific channel
- More sophisticated recovery on CPU

Latest Firmware Developments: Trigger Synchronisation

SADC Data Logic



First version of new detector monitor



- Synchronisation of sample request trigger and feature extraction
- Configurable trace length before pulse start
- Arbitrary total trace length

Latest Firmware Developments: Availability of Source

Development

"SADC Data Logic"

- Generators
- Simulations
- Testbenches
- Documentation

SADC V. 3.5 Firmware

- Vivado Project
- "build.tcl"
- Control software

https://gitlab.rlp.net/emp/sadc_data_logic

https://gitlab.rlp.net/emp/sadc_v_3_5

Summary and Next Steps

Summary

- Digital signal processing optimised for APFEL preamplifier signals
- Successfully tested with beam
- SADC firmware which supports trigger-less readout concept of PANDA
- Firmware Update:
  SADC v. 2.0 → SADC v. 3.5
  - Restructuring of hierarchy
  - Full free streaming concept
  - Request system (traces, rates)
  - Configurable package sizing
  - Trigger synchronisation
- Source is available

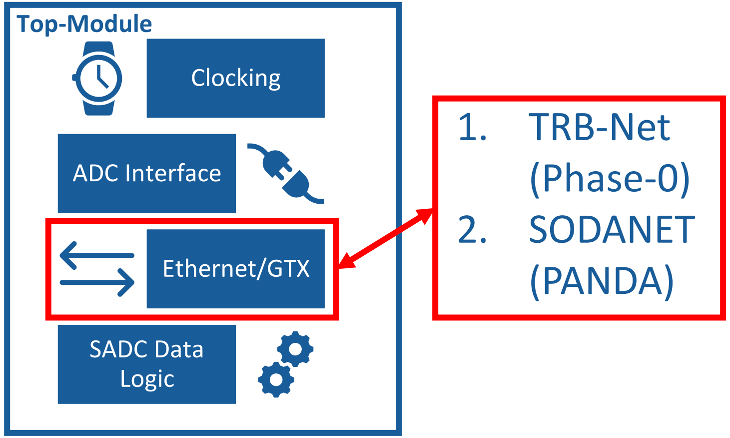
Summary and Next Steps

Summary

- Digital signal processing optimised for APFEL preamplifier signals
- Successfully tested with beam
- SADC firmware which supports trigger-less readout concept of PANDA
- Firmware Update:
  SADC v. 2.0 → SADC v. 3.5
  - Restructuring of hierarchy
  - Full free streaming concept
  - Request system (traces, rates)
  - Configurable package sizing
  - Trigger synchronisation
- Source is available

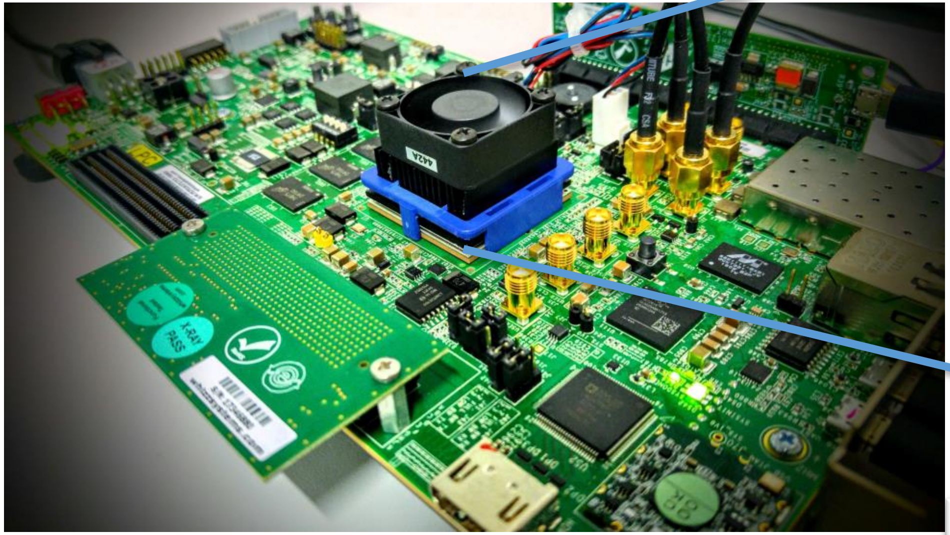
Next Steps

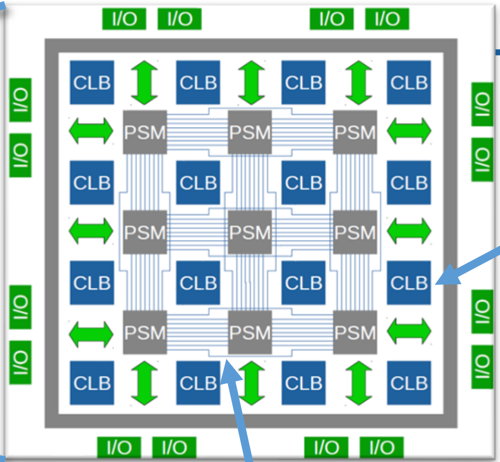
- Current firmware will be used for detector component tests
- Submodule calibration (FAIR Phase-0)
- Preparations for Phase-0 and PANDA

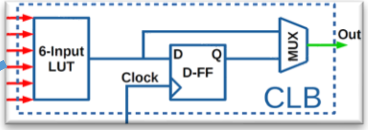


Digital Signal Processing

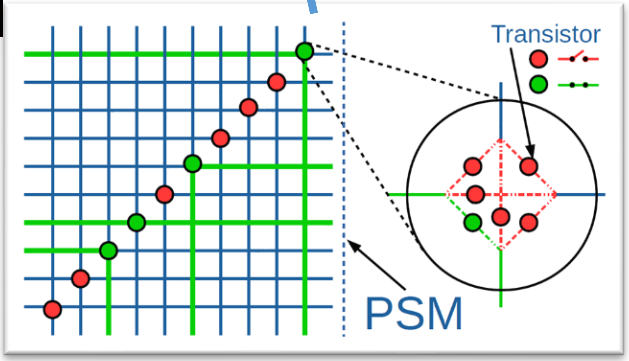
Field Programmable Gate Arrays







Configurable Logic Blocks



Programmable Switch Matrix

Why so "fast"?

- Infrastructure adapted on problem
- True parallelism

Efficient Implementation on FPGA

$$y[n] = \sum_{k=0}^{M} A_k x[n-k] \qquad x[k] = \sum_{l=0}^{N-1} b_{kl} 2^l$$

1 or 0

$$y[n] = \sum_{l=0}^{N-1} \left[\sum_{k=0}^{M} A_k b_{(n-k)l} \right] 2^l$$

Lookup Table (LUT)

Possible result	Binary signature	Value
1	000	$A_0 \cdot 0 + A_1 \cdot 0 + A_2 \cdot 0 = V_0$
2	001	$A_0 \cdot 0 + A_1 \cdot 0 + A_2 \cdot 1 = V_1$
3	010	$A_0 \cdot 0 + A_1 \cdot 1 + A_2 \cdot 0 = V_2$
4	011	$A_0 \cdot 0 + A_1 \cdot 1 + A_2 \cdot 1 = V_3$
5	100	$A_0 \cdot 1 + A_1 \cdot 0 + A_2 \cdot 0 = V_4$
6	101	$A_0 \cdot 1 + A_1 \cdot 0 + A_2 \cdot 1 = V_5$
7	110	$A_0 \cdot 1 + A_1 \cdot 1 + A_2 \cdot 0 = V_6$
8	111	$A_0 \cdot 1 + A_1 \cdot 1 + A_2 \cdot 1 = V_7$

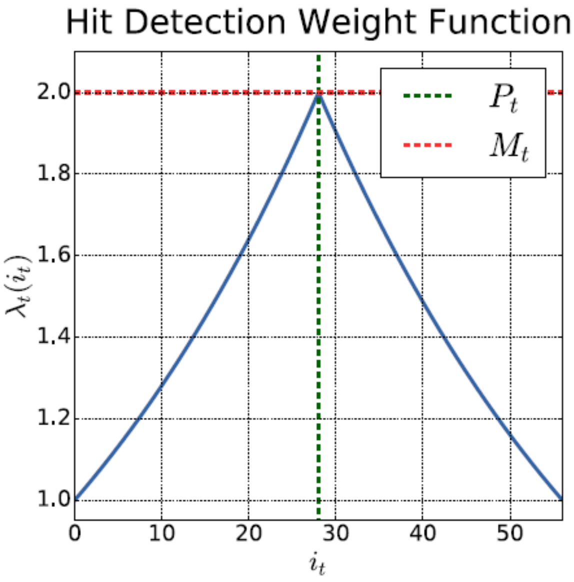
Example: $M = 2, k \in [0,1,2], 2^{M+1} = 8$

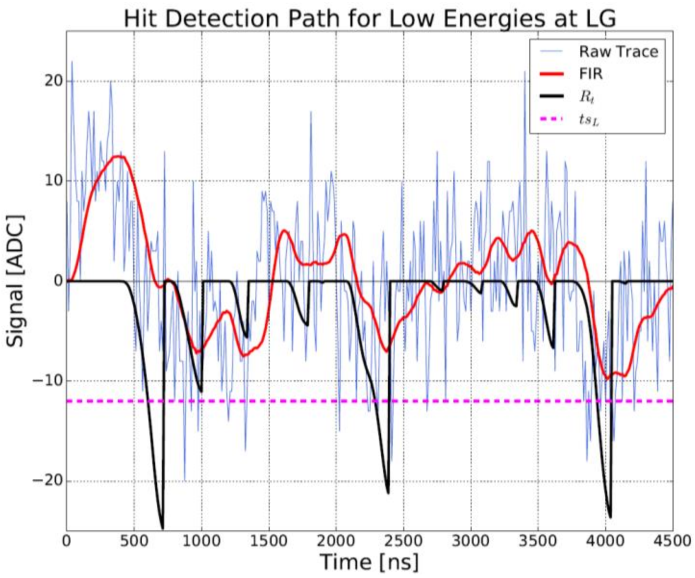
Sampe	2^{N-1}	2^{N-2}	...	2^4	2^3	2^2	2^1	2^0
x_0	0	1	...	1	1	0	0	0
x_1	0	0	...	1	1	1	1	1
x_2	0	1	...	0	1	0	0	1
output	V_0	V_5	...	V_6	V_7	V_2	V_2	V_3

Implemented on FPGA: $M = 19, k \in [0,1,\dots,19]$

- Only sums and bit shift operations
- Avoiding limited multiplication networks
- High order (20 coefficients) filter for all channels

Hit Detection

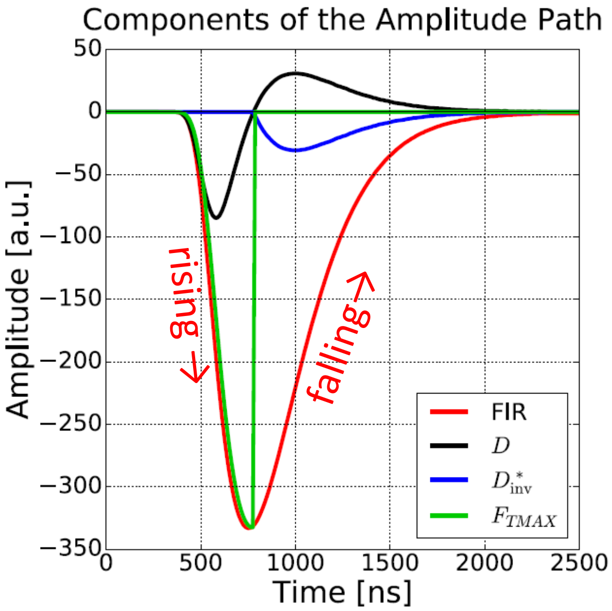




$$\lambda(i_t) = \begin{cases} e^{A_t \cdot i_t} & : i_t \leq P_t \\ M_t \cdot e^{-A_t(i_t - P_t)} & : i_t > P_t \end{cases}$$

- Sensetive on pulse shape
- Ingrease of detection efficiency

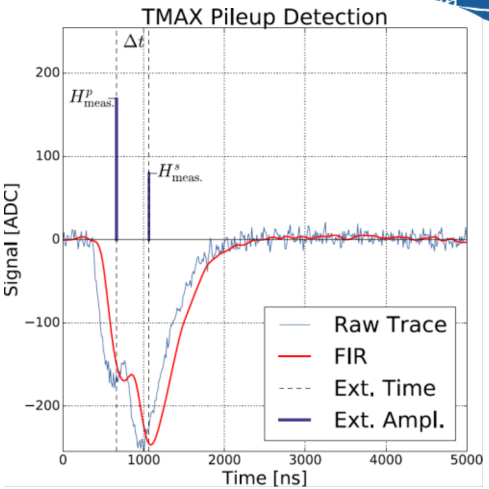
Amplitude Extraction



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

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

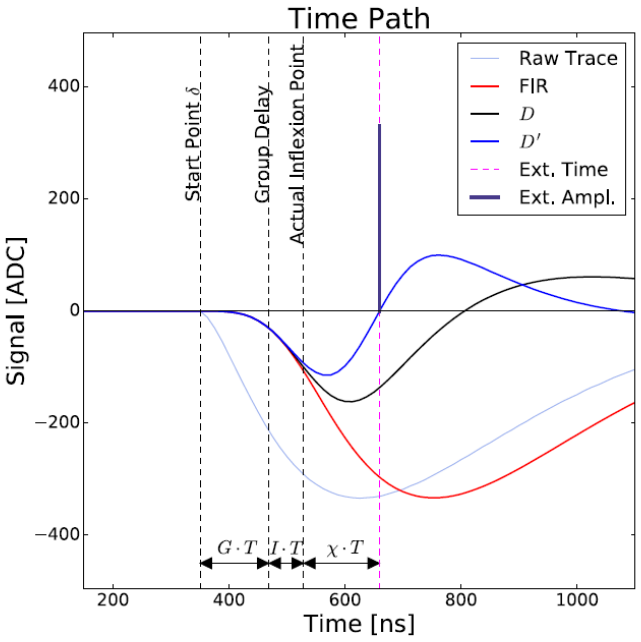
$$D_s[i] = D[i] + D^*_{inv}[i]$$



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

- Derivation → Integration
- Build in baseline follower
- Elimination of falling edge
- Pileup detection and correction

Time (T_0) Extraction



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

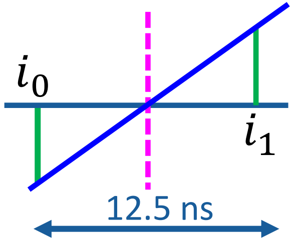
$$I = \frac{\tau(\sqrt{N} - 1)}{\sqrt{N}} \qquad T_0 = \delta + I$$

T_0 determination at inflexion point $f''(x) = 0$

$$\mathrm{T}_0 = \mathrm{i}_0 + \frac{D'[i_0]}{D'[i_0] - D'[i_1]}$$

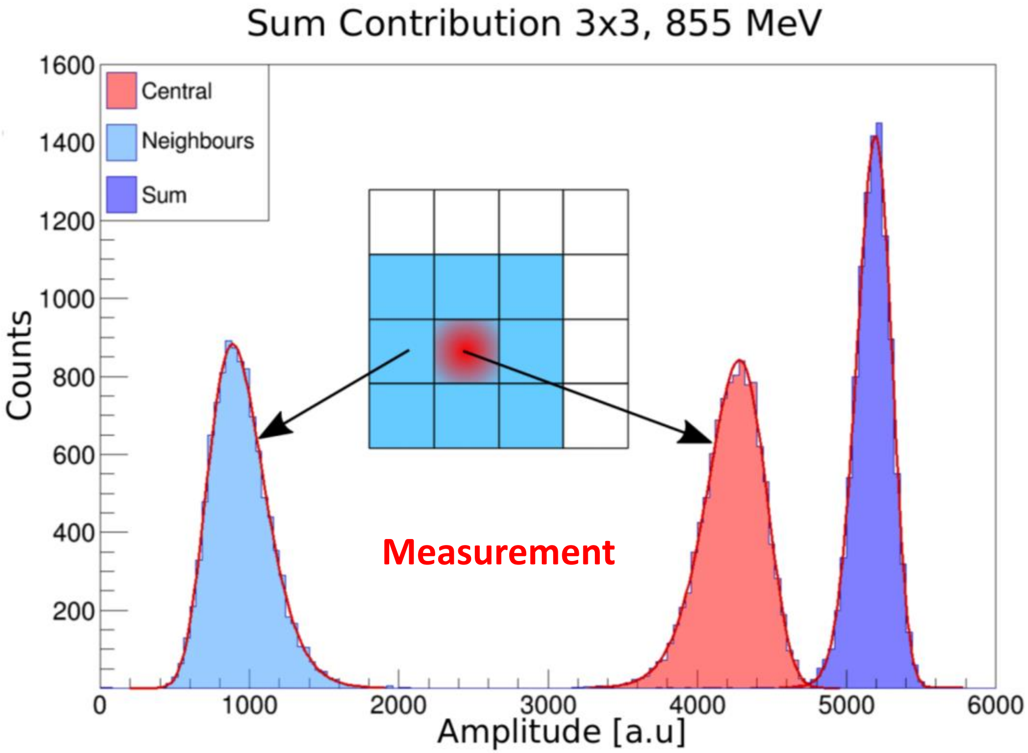
Discrete derivative →interpolation

D' is second derivative, since D is the first one

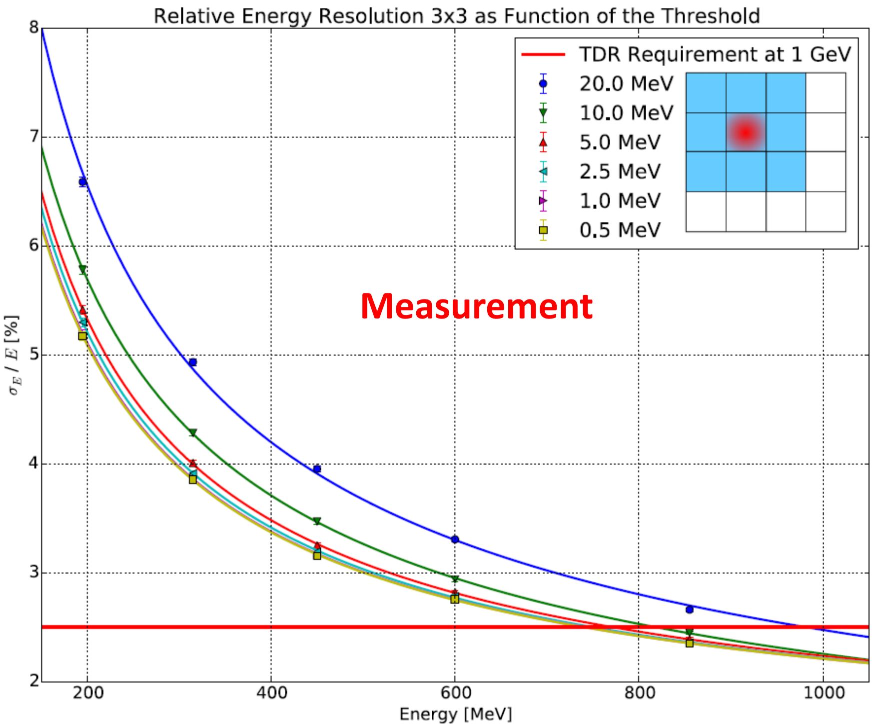


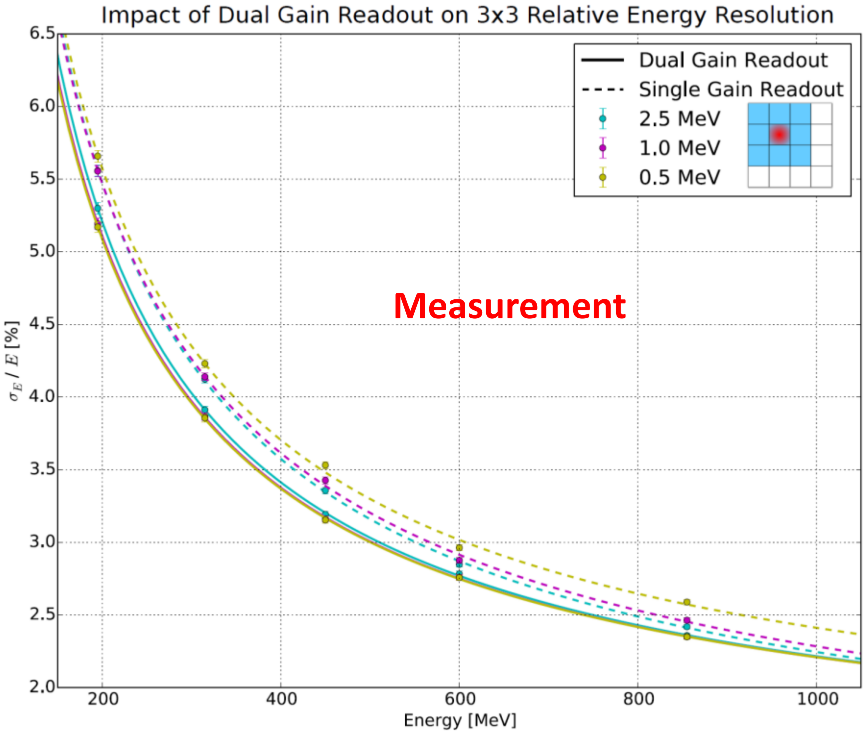
Measurements

Sum Contribution 3x3, 855 MeV

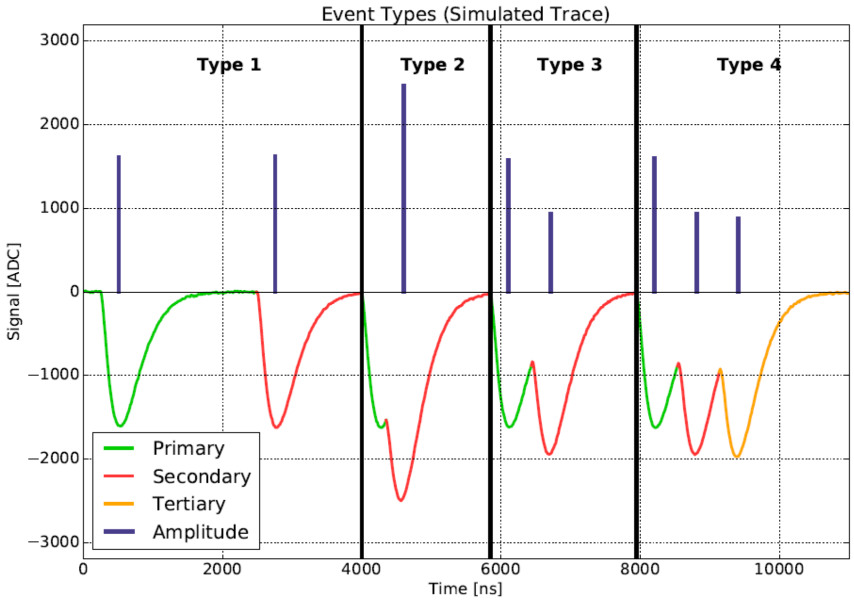


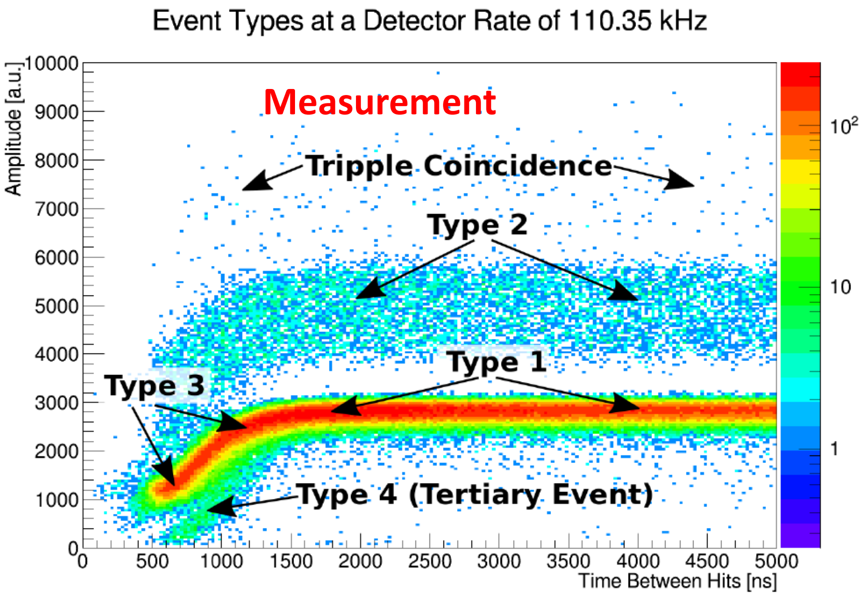
Threshold Scan and Dual Gain Readout





Pileup Detection and Correction





Type	ΔT	k	$\lambda = \Delta T \cdot 100\,\text{kHz}$	$P_{100\,\text{kHz}}$
1	≥ 1500 ns	0	0.150	86.1 %
2	≤ 450 ns	1	0.045	4.3 %
3	≥ 450 ns $\wedge \leq 1500$ ns	1	0.105	9.5 %
4	≤ 1500 ns	≥ 2	0.150	1.0 %

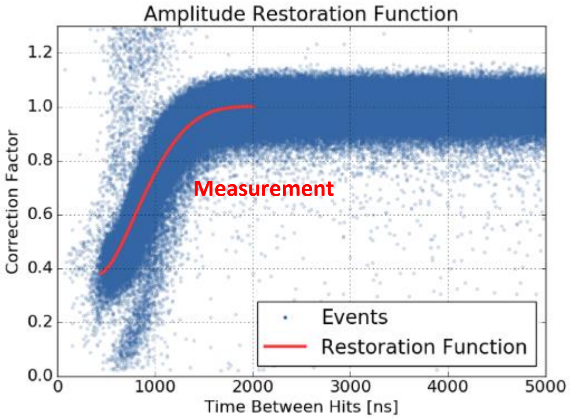
$$P_\lambda(k) = \frac{\lambda^k}{k!} \cdot e^{-\lambda}$$

Rate

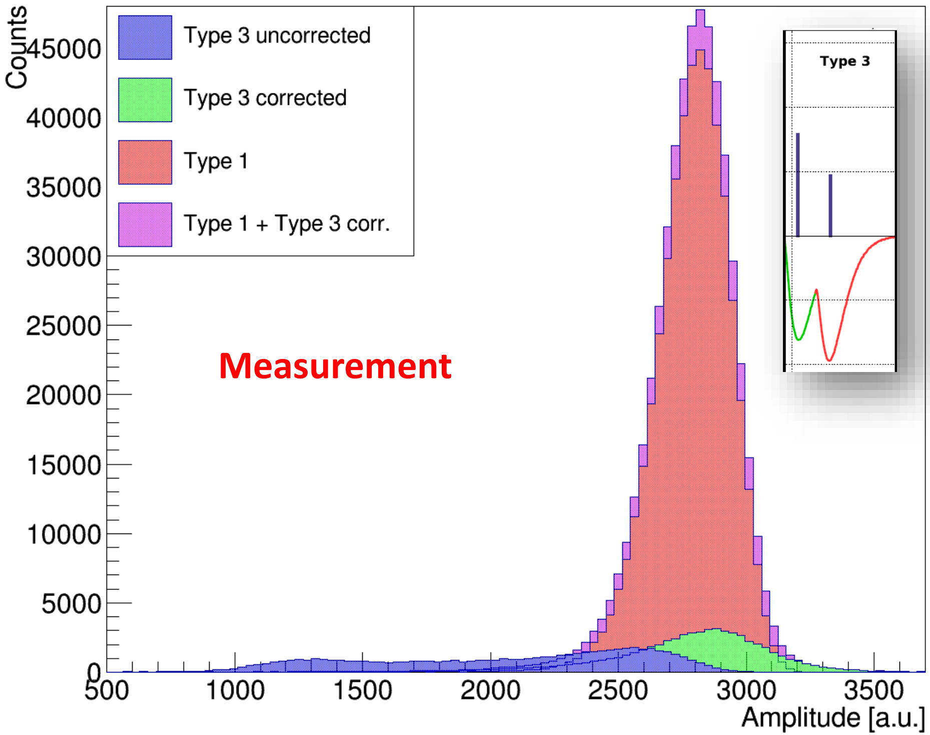
$$\lambda = \Delta T \cdot R$$

Pileup Detection and Correction

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



- Type 3 events (second pulse within falling edge of first pulse) are correctable
- Monochromatic electron beam
- Proof of principle
- To do: Map out Σ with simulations



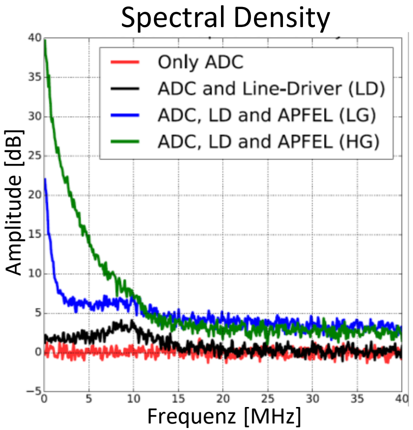
Beam Test with the EMC Prototype : Results

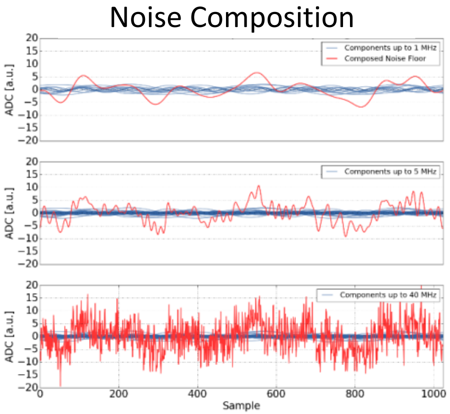
Parameter	Achieved Value			TDR	Unit
	Worst	Typical	Best		
Rel. En. Res.					
σ_E/E at 1 GeV	2.440(14)	2.207(6)	2.190(2)	≤2.5	%
Constant a	1.23(21)	1.08(14)	0.95(61)	≤1	%
Statistics b	2.02(65)	1.83(45)	1.78(30)	≤2	$\frac{\%}{\sqrt{E[\mathrm{GeV}]}}$
Noise/Ch. c	2.14(9)	2.02(15)	1.92(60)	≤3	MeV
Non-Linearity					
Maximum	2.22(36)	1.26(24)	1.21(19)	-	‰
Timing					
Dead Time τ	-	464(13)	-	-	ns
Pileup $P_{100\,\mathrm{kHz}}$	13.9 (w/o corr.)	4.53(12)	-	1	%
Highest Event Rate	-	-	375.4(6)	100	kHz

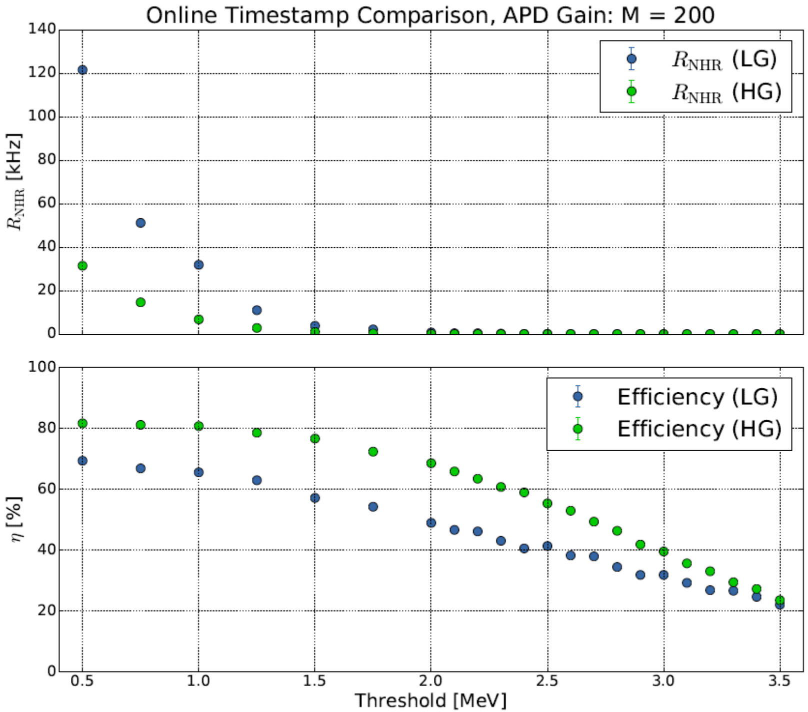
Simulations

Simulations for the Study of Digital Signal Processing Methods

- Defined testing environment
- Realistic detector signals (pulse shape + noise)
- Optimisation of filter parameters
- Performance tests: **detection efficiency, noise hit rate, linearity, time resolution, …**





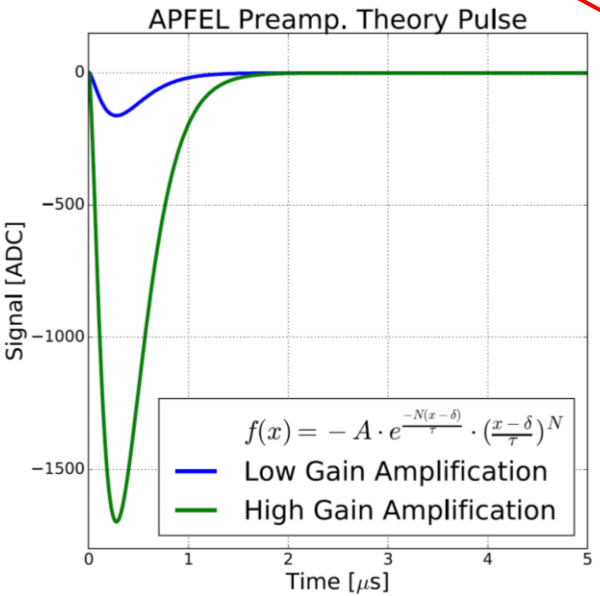


Example:

- Noise hit rate (R_{NHR})
- Detection efficiency (η) for 3 MeV events

Generation of Realistic Detector Signals

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



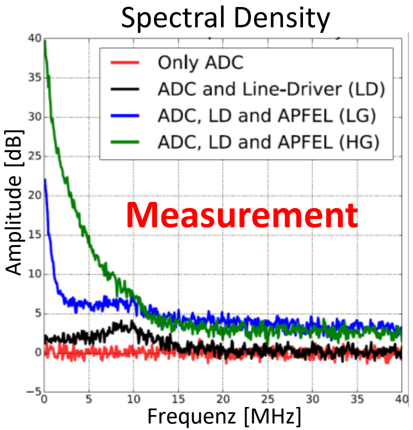
$$\alpha = \frac{q}{M \cdot LY_{-25°C} \cdot A_{eff} \cdot Q_{eff} \cdot e \cdot G_{ASIC}} \text{ [MeV/channel]}$$

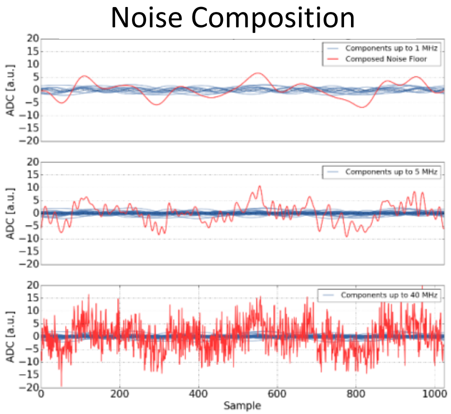
Parameter	Value	Unit	Source
q	0.122	mV/channel	[Cor18]
M	≥ 1	-	-
$LY_{-25\,°C}$	500	$n_{photo.}$/MeV	[TDR08]
$A_{eff.}$	16	%	[HAM09]
$Q_{eff.}$	0.70	$n_{elec.}/n_{photo.}$	[HAM09]
e	$1.602\,176\,634 \times 10^{-19}$	C	[NT19a]
G_{ASIC}	0.22×10^{15}	mV C^{-1}	[Wie19]

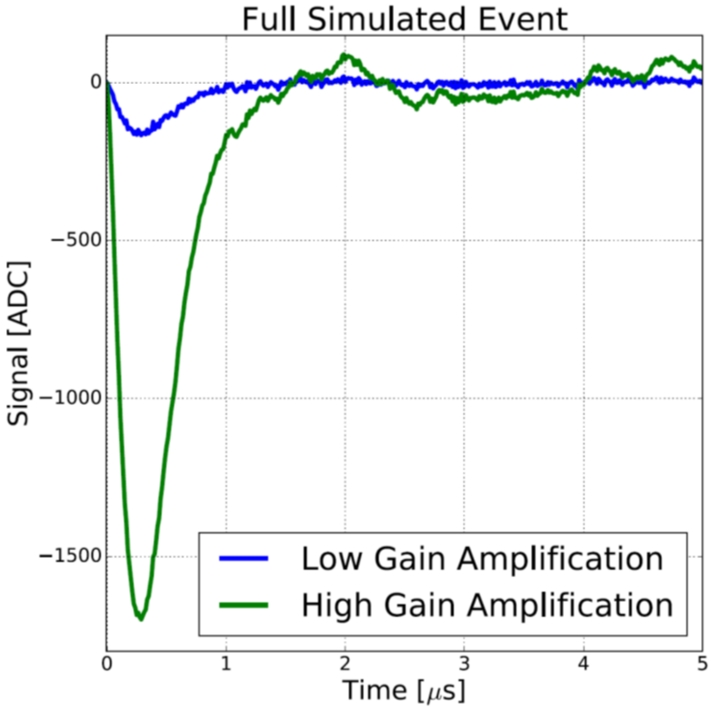
$$H = \frac{E \text{ [MeV]}}{\alpha(M) \text{ [MeV/channel]}} \text{ [channel]}$$

$$A = E[\text{MeV}] \cdot \alpha(M)^{-1} \cdot e^N$$

Generation of Realistic Detector Signals



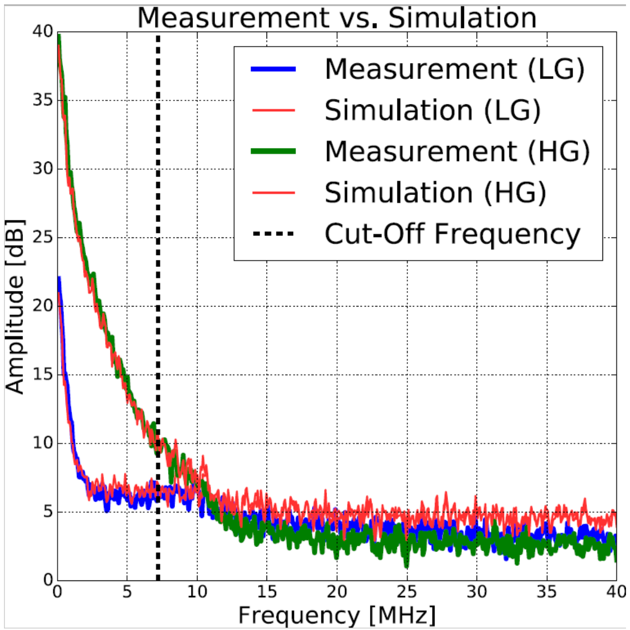


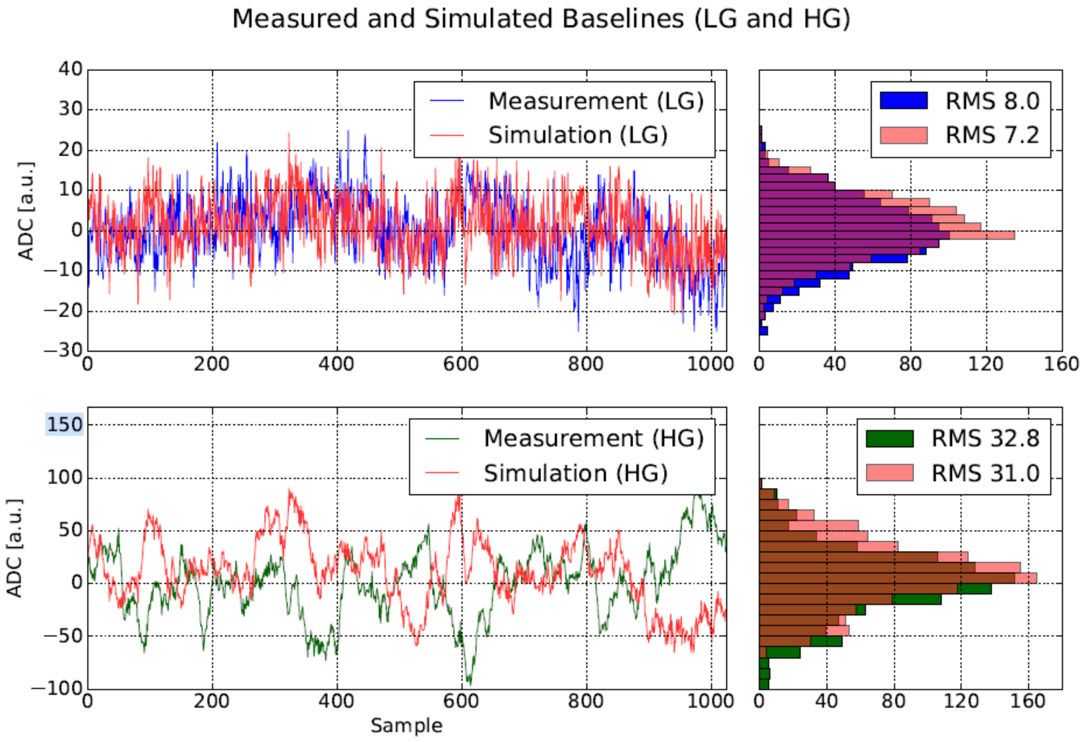


$$C(I_i) = \cos_{I_i}(x + \phi) \cdot 10^{\frac{P(I_i)[dB]}{20}}$$

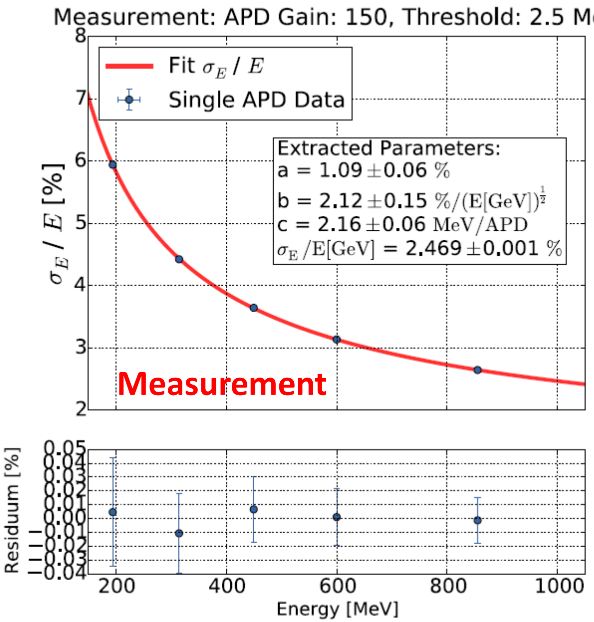
$$T_{\text{noise}} = \sum_{i=1}^{N\_I} C(I_i)$$

Comparison between Simulation and Measurement

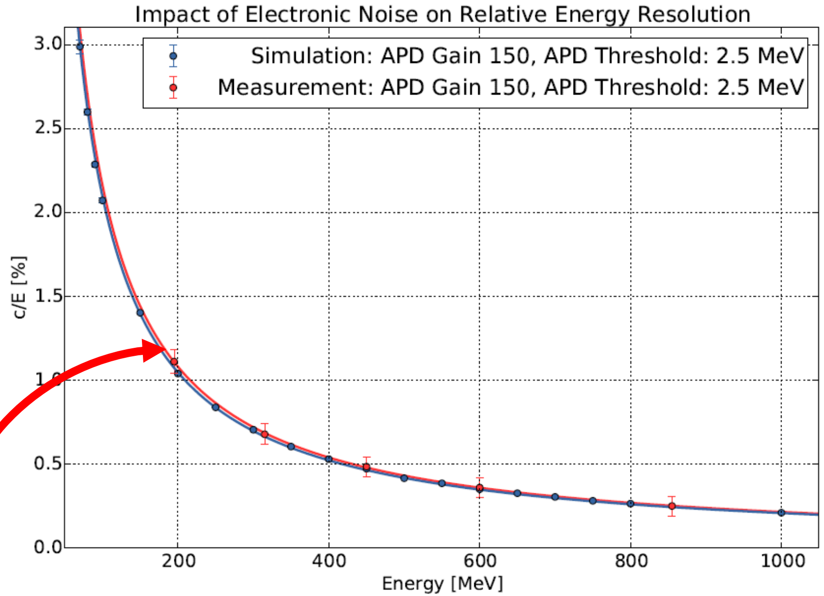




Comparison between Simulation and Measurement



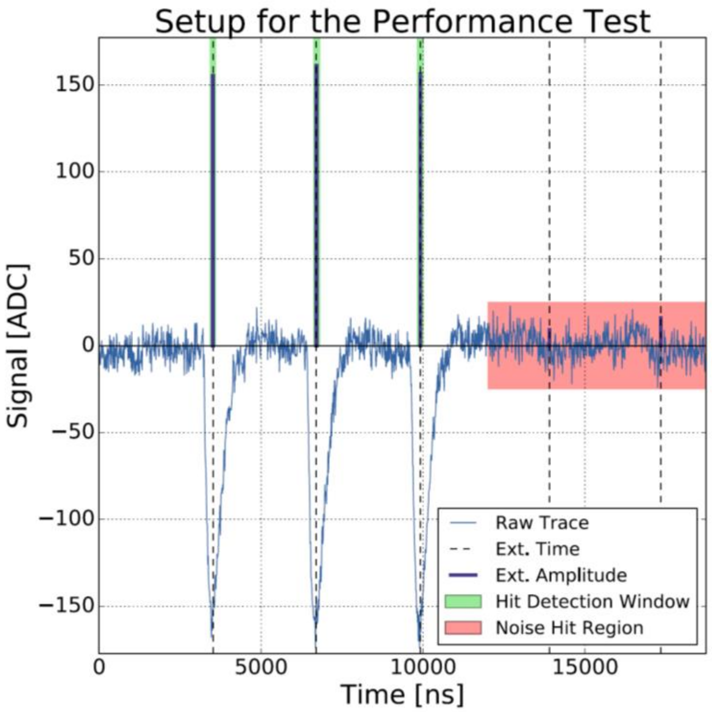
$$\frac{c}{E} = \sqrt{\left(\frac{\sigma_E}{E}\right)^2_{3\times3} - a^2 - \frac{b^2}{E}}$$



Noise term of relative energy resolution

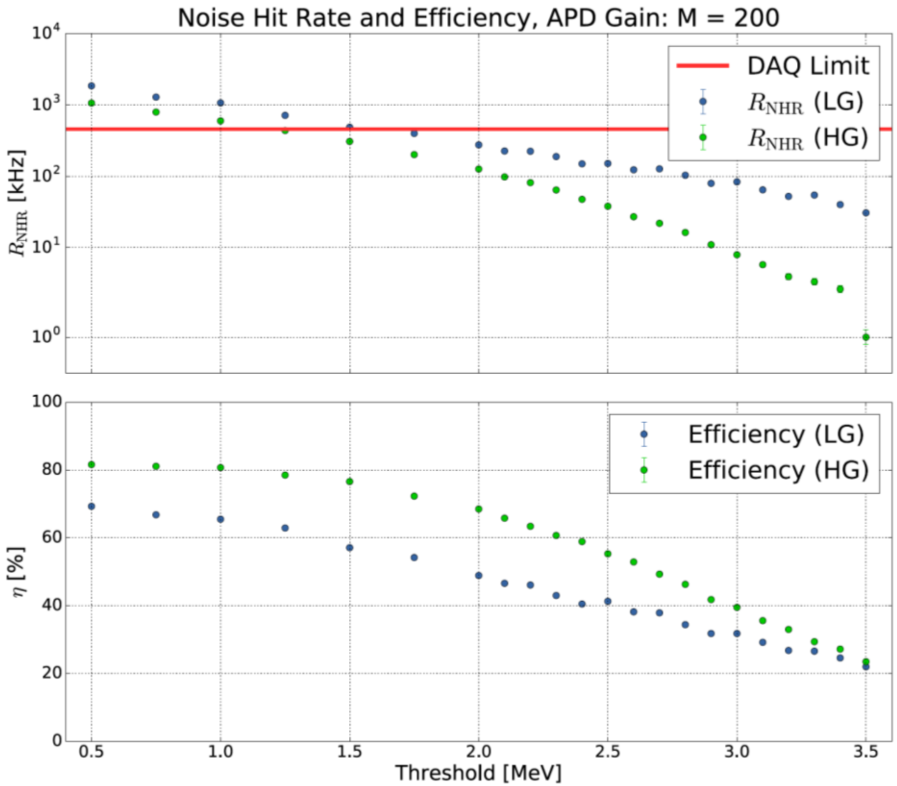
$c_{measurement}$	2.16(6) MeV
$c_{simulation}$	2.095(6) MeV

Performance Tests with the Simulation Framework



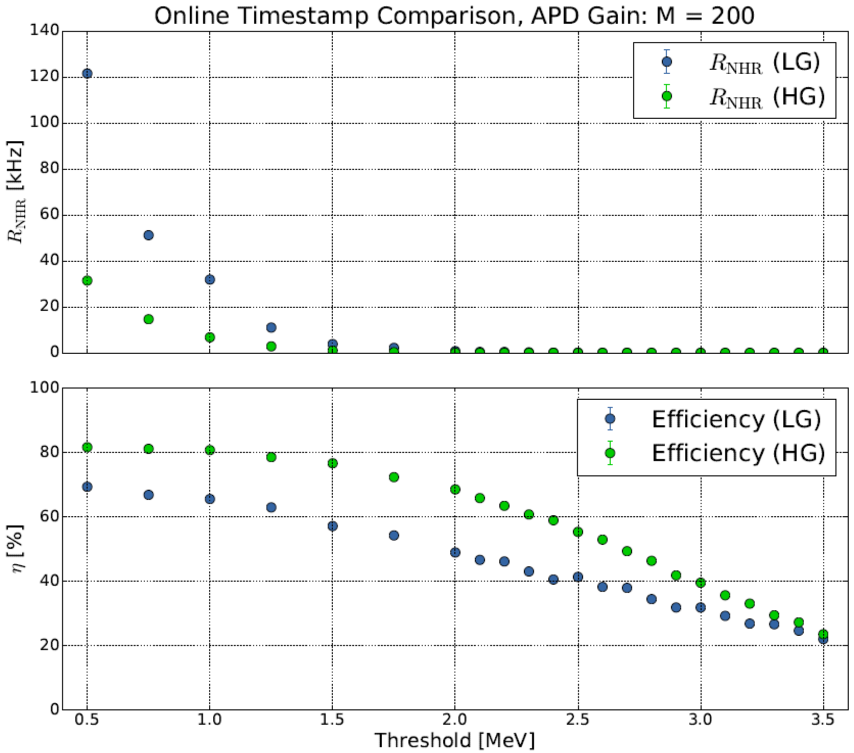
- Generate trace for low gain and high gain
- Defined pulse appearance times
- Noise hit region
- Vary amplitudes (energies) and thresholds

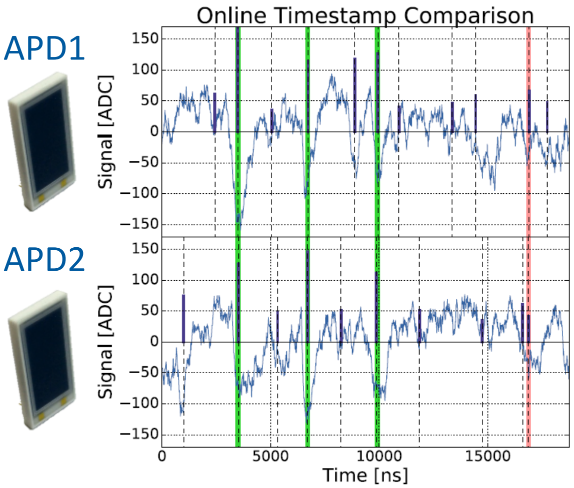
Performance Tests with the Simulation Framework: Noise Hit Rate



- DAQ Limit = 558 kHz – 100 kHz (true events)

Performance Tests with the Simulation Framework: Noise Hit Rate





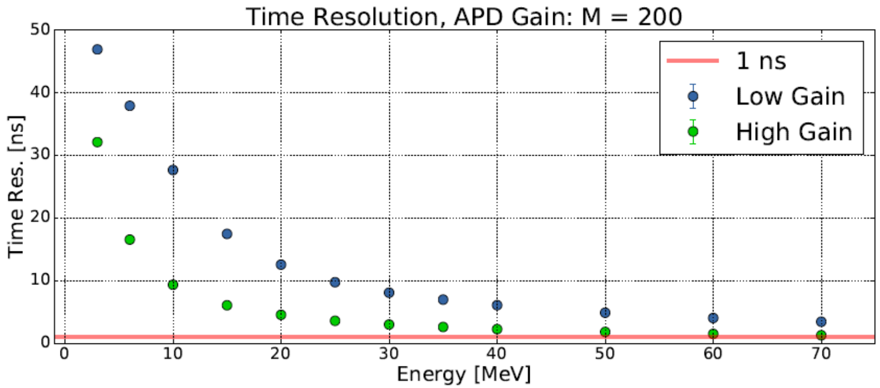
Example

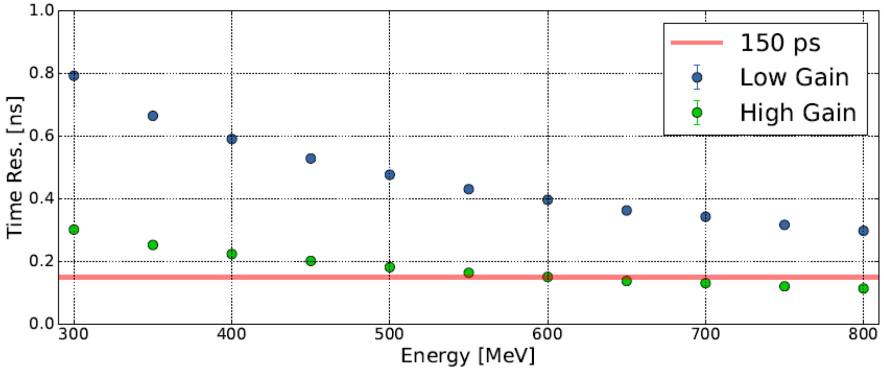
Threshold = 1.0 MeV

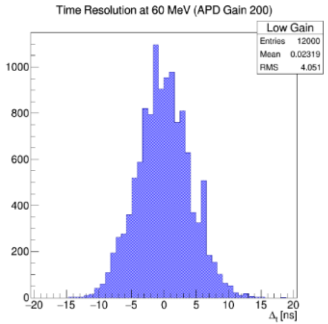
Efficiency = 80.7 % (3 MeV events)

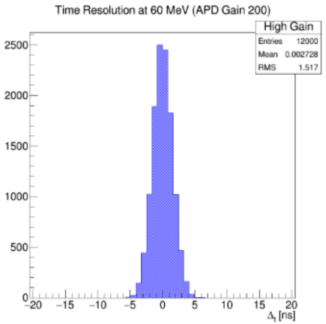
NHR = 6.8 kHz

Performance Tests with the Simulation Framework: Time Resolution







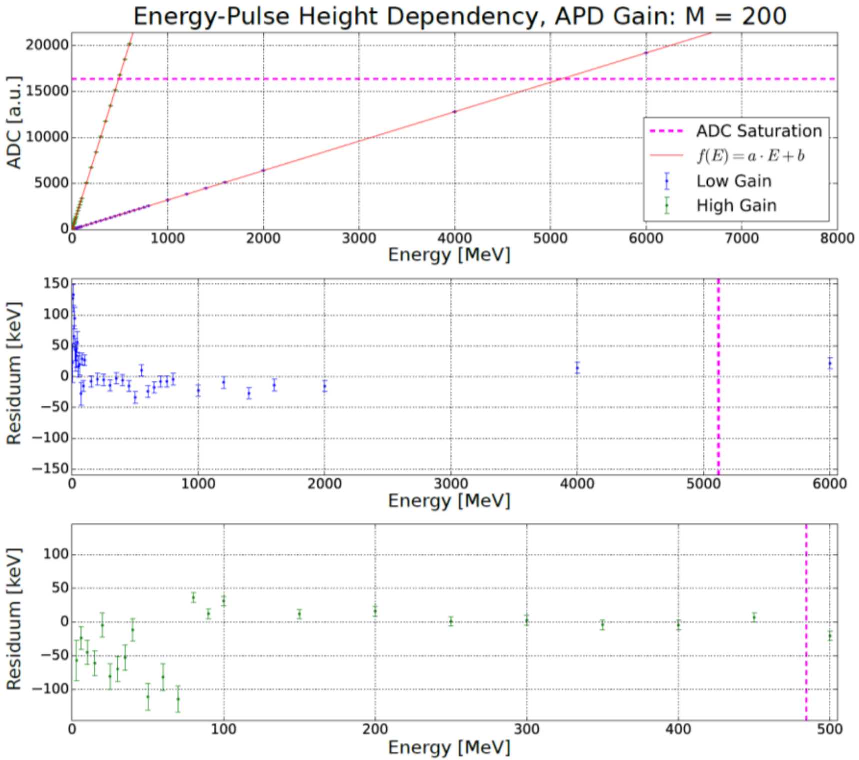


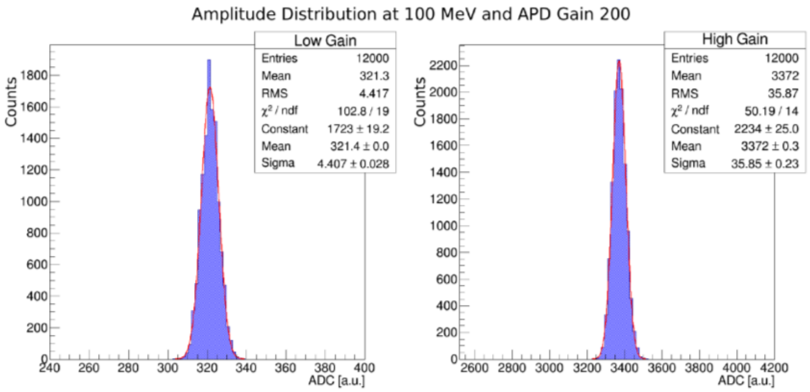
Example: APD gain 200:

TR(60 MeV) = 1.517(10) ns

TR(500 MeV) = 182(1) ps

Performance Tests with the Simulation Framework: Linearity





Example: APD gain 200:

Always smaller than **160 keV**
Above 100 MeV smaller than **50 keV**
Single crystal threshold: **3 MeV**

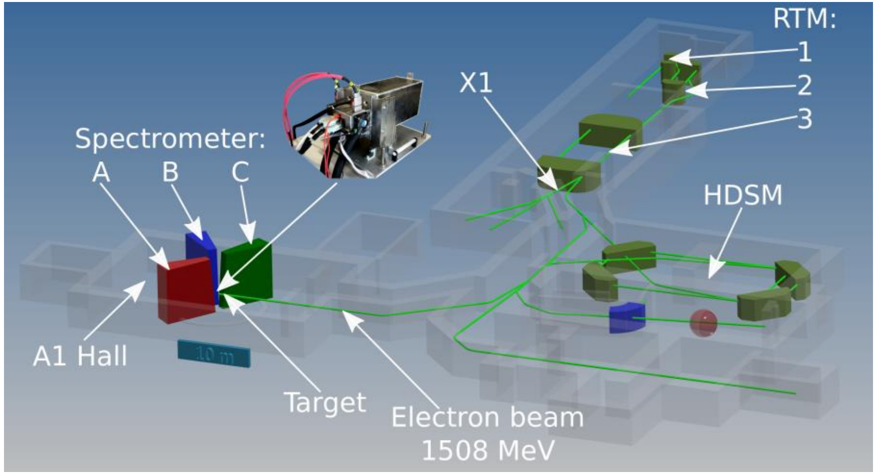
Performance Tests with the Simulation Framework: Results

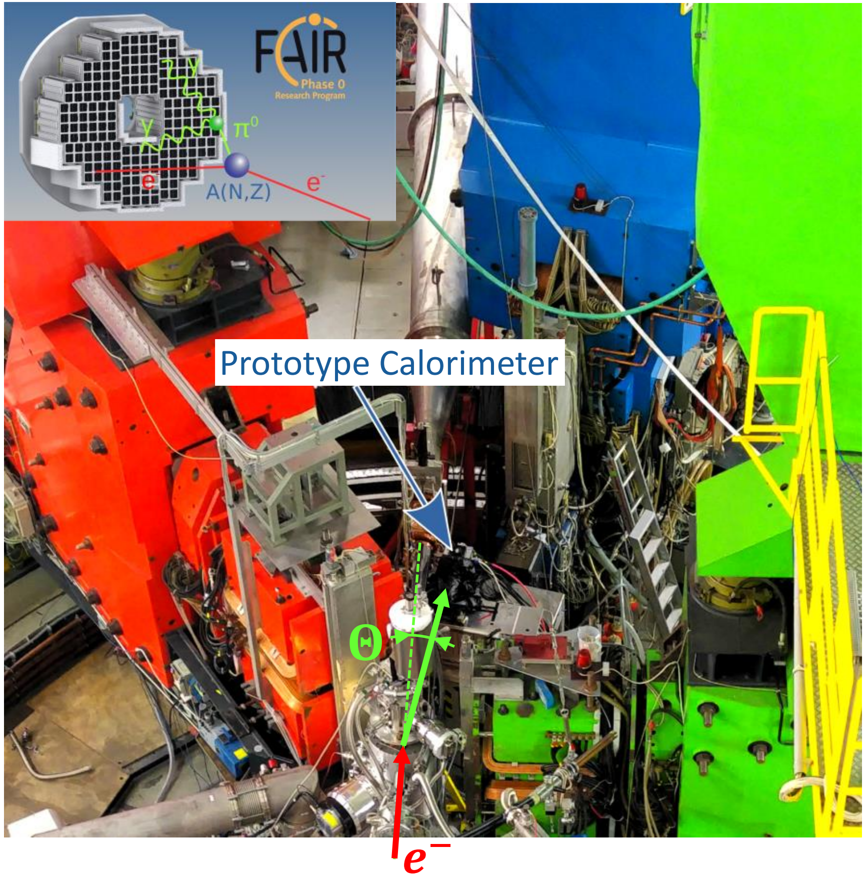
Parameter	Achieved Value						TDR	Unit
APD Gain	150		200		250		-	-
Preamp. Gain	LG	HG	LG	HG	LG	HG	-	-
Noise Hit Rate	Threshold: 2.5 MeV							
Single	331.1(26)	160.9(20)	151.44(200)	38.07(110)	67.93(145)	5.52(45)	-	kHz
Dual ($I_{comp.} = 200\,ns$)	1.27(5)	0.16(1)	0.13(1)	<0.01	<0.1	<0.01	-	kHz
Efficiency	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

Table 5.3: The table summarises the results of the parameter extraction performance simulation.

Phase-0

Exploratory Measurements and Simulations for FAIR Phase-0

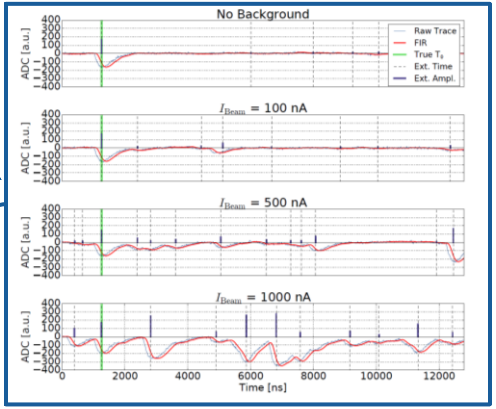




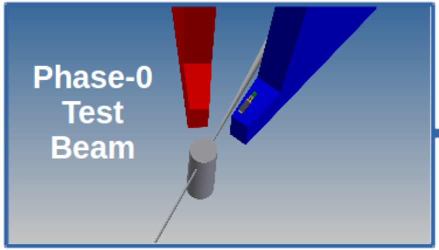
- Determination of $\pi^0\gamma\gamma$ transition form factor
  → hadronic light-by-light contribution to $g_\mu - 2$
- Version of PANDA backward calorimeter
- Electron scattering at heavy nucleus (**Tantalum, Z=73**)
- Measurement in **forward direction**
- Strong low energy electromagnetic background
- **Relative energy resolution at small scattering angles?**

Signal Generator for Low Energetic Background

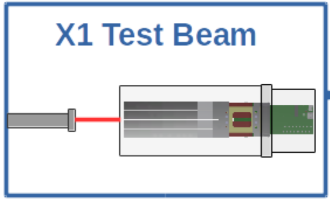
Simulation at the trace level!

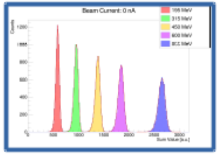


Superposition of useful pulses and low energy background pulses

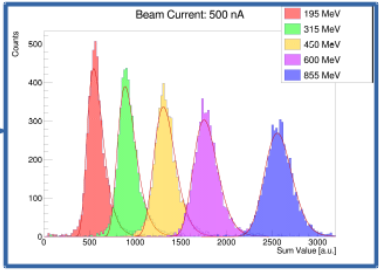


Background Function





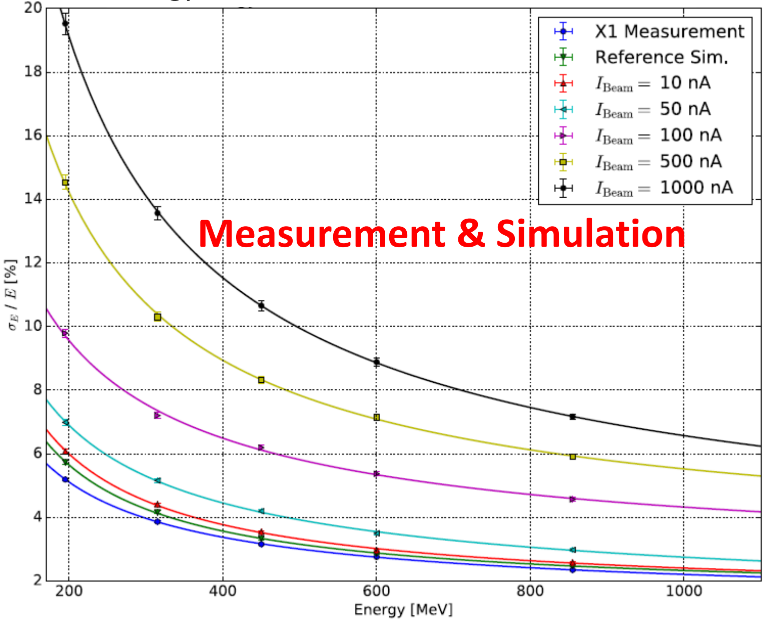
Simulation Framework



- Energy resolution
- Linearity
- High rates
- …

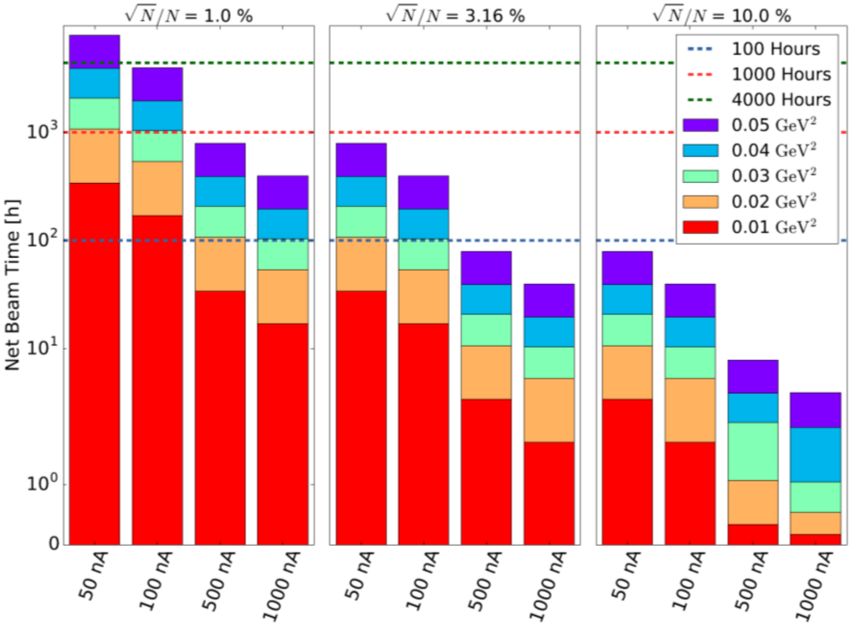
Relative Energy Resolution (3x3) as a Function of the Luminosity

Relative Energy Resolution as a Function of the Beam Current



$$L = \dot{N}_{\text{Beam}} \cdot n_{\text{Target}} \cdot d_{\text{Target}}$$

Net Beam Time as a Function of the Beam Current



$$R = L \cdot \sigma^*_{\text{eff}}$$

*Measurement of the Electromagnetic Transition Form Factor of the π^0 in the Space-Like Region via Primakoff Electroproduction. Letter of Intent, 2020

The Anomalous Magnetic Moment of the Muon

Dirac Theory:

Dirac equation with EM-field:

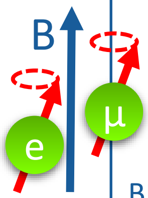
$$(i\gamma^\mu \partial_\mu - e\gamma^\mu A_\mu - m)\psi = 0$$

Nonrelativistic limit ($E \approx m$):

$$\frac{1}{2m}\left|\vec{p} - e\vec{A}\right|^2 \psi - \underbrace{\frac{e}{m}}_{\mu_s}\vec{S}\cdot\vec{B}\psi = 0$$

$$g = \frac{\mu_s}{\mu_L} = 2 \qquad a_l = \frac{g_l - 2}{2} = 0$$

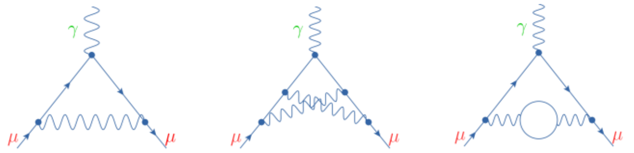
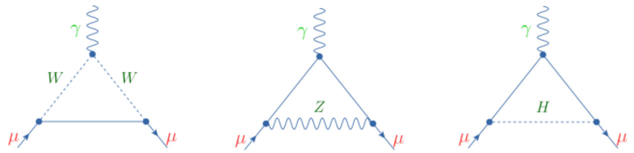
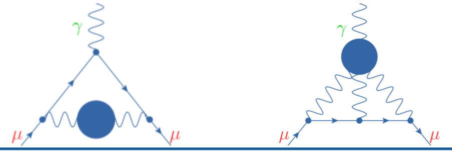
Messung:



$$\omega_L = \frac{g}{2}\cdot\frac{eB}{m} \qquad \omega_c = \frac{eB}{m}$$

$$a_\mu^{\text{Exp.}} = 0.00116592089(63)$$

BNL (E821) 2006

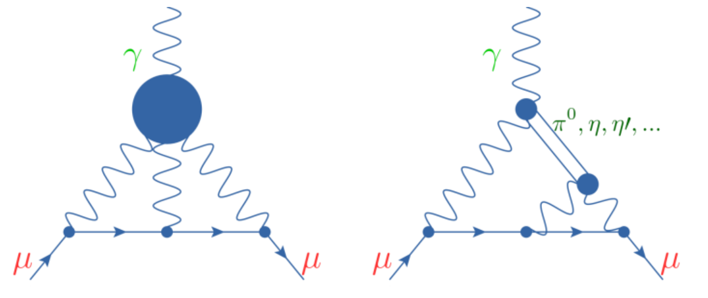
$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{QCD}}$	Δa_μ^{SM}
 …	0.01×10^{-10} T. Aoyama et al. 2012
 …	0.10×10^{-10} C. Gnendiger et al. 2013
	Each: $\sim 3 \times 10^{-10}$ F. Jegerlehner 2019

$$a_\mu^{\text{SM}} = 0.00116591782(43)$$
$$a_\mu^{\text{Exp.}} = 0.00116592089(63)$$

4σ

Reduction of the Uncertainty on a_μ^{SM} by a Data-Driven Approach

Hadronic Light-by-Light Scattering



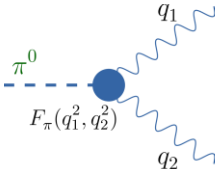
Light Pseudo Scalar Mesons, PS = π^0, η, η'

Data-Driven Approach

Integral over Transition Form Factors (TFF) $F_{PS\gamma^*\gamma^*}(Q_1^2, Q_2^2)$ with virtual space-like momenta $Q_{1,2}^2$:

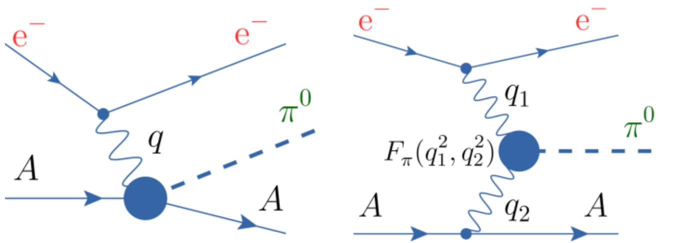
$$a_\mu^{HLbL,PS} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau\, w(Q_1, Q_2, \tau) F_{PS\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) F_{PS\gamma^*\gamma^*}(-Q_2^2, 0)$$

Numerically greatest contribution : $F_{\pi^0\gamma^*\gamma^*}$

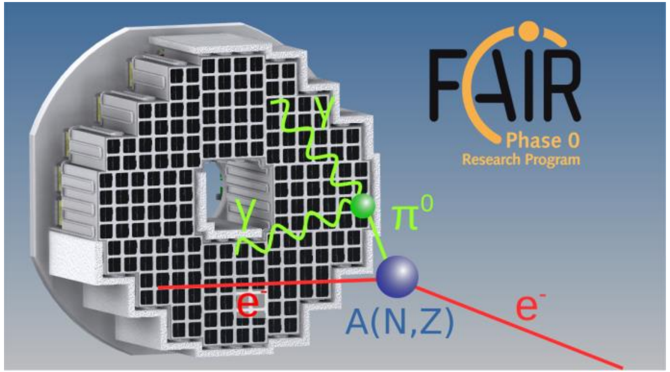


V. Pauk, M. Vanderhaeghen 2014, M. Hoferichter 2018

Primakoff π^0 Electroproduction

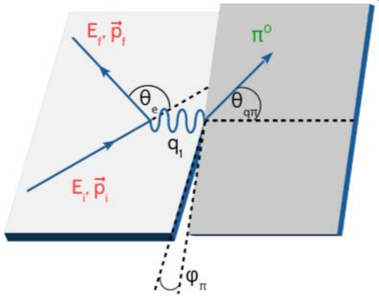


Contribution to coherent nuclear pion production



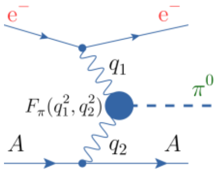
- Full developed FAIR detectors in stand-alone experiments
- PANDA backward calorimeter for FAIR Phase-0 at MAMI

The Primakoff π^0 Electroproduction



$$\left(\frac{d^5\sigma}{dE_f d\Omega_f d\Omega_\pi}\right)^{EP} = \frac{\boldsymbol{\lambda(q_1^2, q_2^2)}}{8\pi^3 v_i}\alpha^2 \boldsymbol{Z^2} |\vec{p}_\pi| \frac{E_f}{E_i}\frac{1}{q_1^4 \vec{q}_2^4} \cdot \left[2(\vec{p}_i\vec{r})(\vec{p}_f\vec{r}) + \frac{1}{2}r^2 q_1^2\right] \cdot |F_{em}(\vec{q}_2^2)|^2$$

$$\boldsymbol{\lambda(q_1^2, q_2^2) \propto |F_\pi(q_1^2, q_2^2)|^2}$$



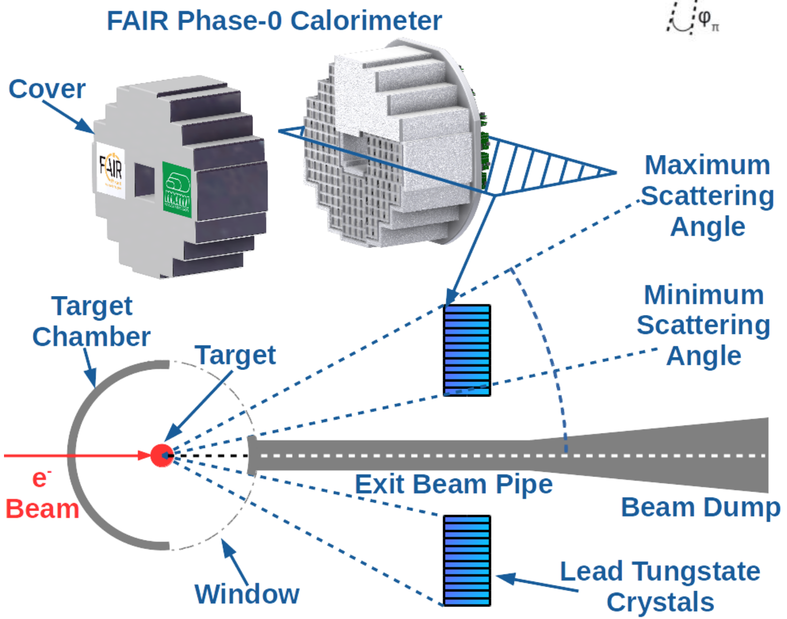
Kinematics: Minimizing of $\vec{q}_2$

1. E_π maximized
   1. $E_\pi \cong E_i - E_f$
   2. $E_i \sim 1200$ MeV
   3. $E_f \sim 300$ MeV $- 700$ MeV
2. $Q^2 = 2E_iE_f(1-\cos(\Theta_e))$ small
   1. Θ_e small
   2. Θ_{q_1} small
3. $\Theta_{q\pi}$ within a few degree
4. Lorentz boost of photons

→ **Measurement at small forward angles**

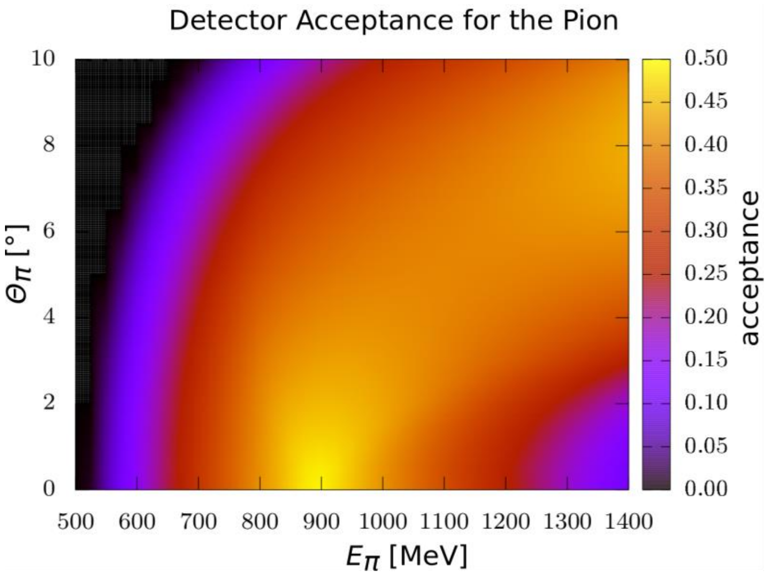
→ $\boldsymbol{-q_1^2 = Q^2 = [0.01, 0.05]\ \mathrm{GeV}^2}$

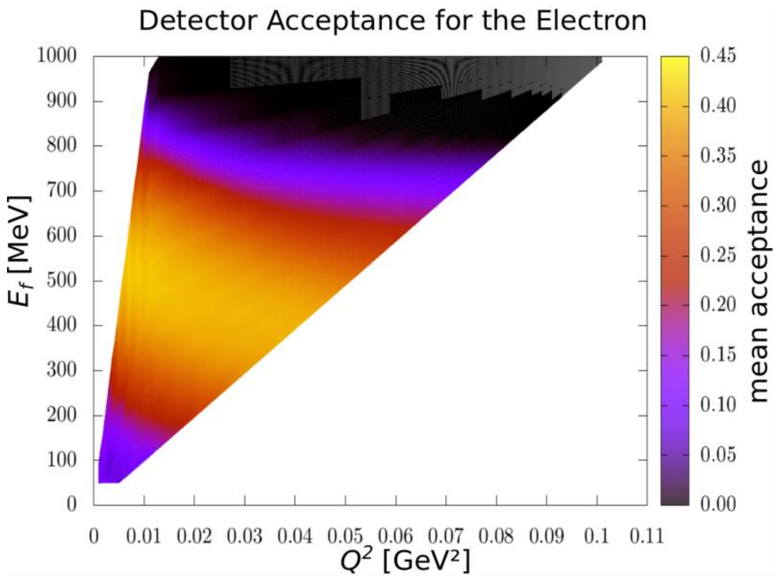
→ $\boldsymbol{\Theta = 5° - 15°}$



Measurement of the Electromagnetic Transition Form Factor of the π^0 in the Space-Like Region via Primakoff Electroproduction. Letter of Intent, 2020

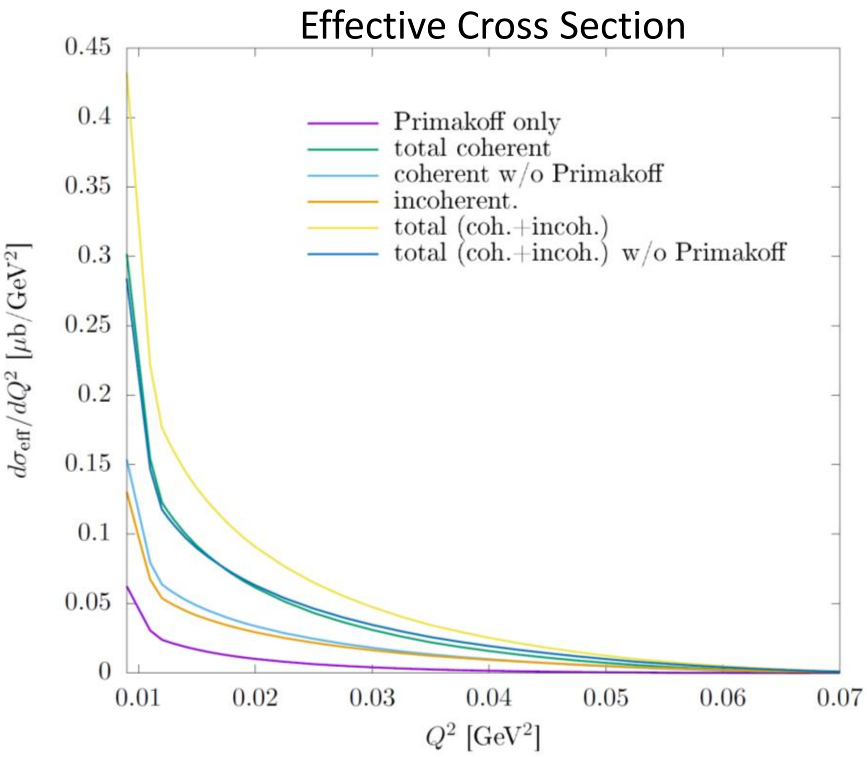
The Primakoff π^0 Electroproduction

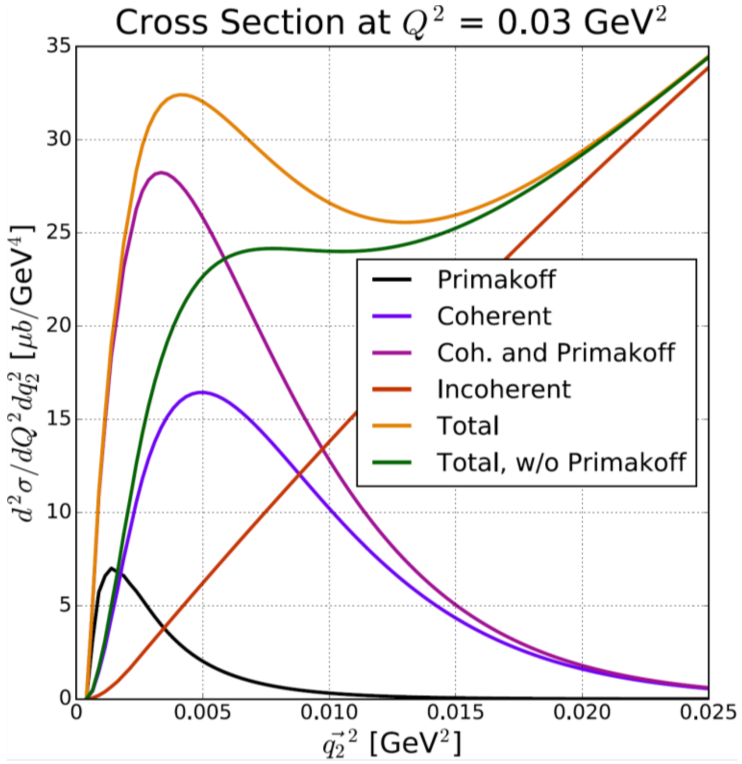




Measurement of the Electromagnetic Transition Form Factor of the π^0 in the Space-Like Region via Primakoff Electroproduction. Letter of Intent, 2020

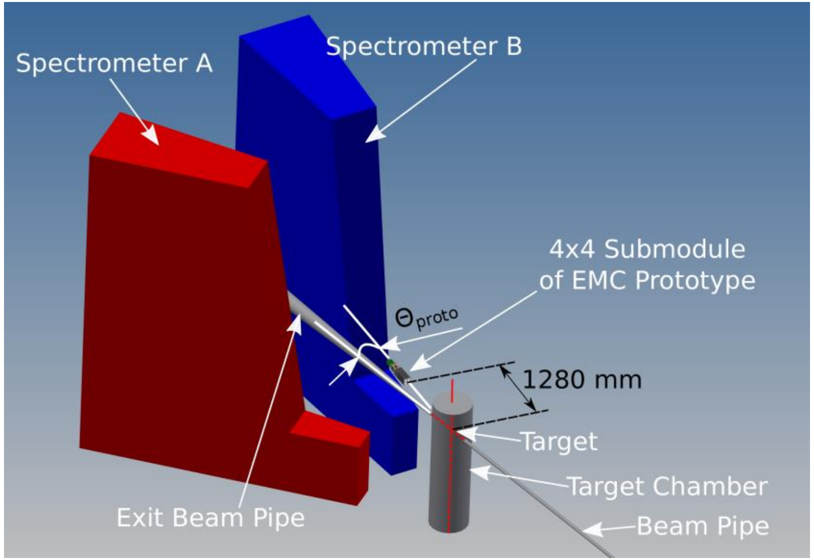
The Primakoff π^0 Electroproduction

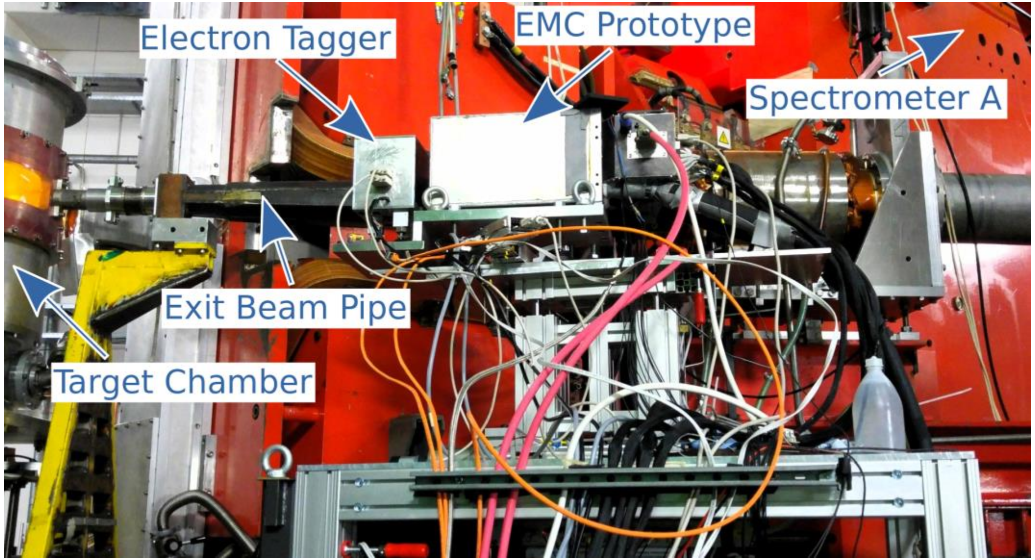




Measurement of the Electromagnetic Transition Form Factor of the π^0 in the Space-Like Region via Primakoff Electroproduction. Letter of Intent, 2020

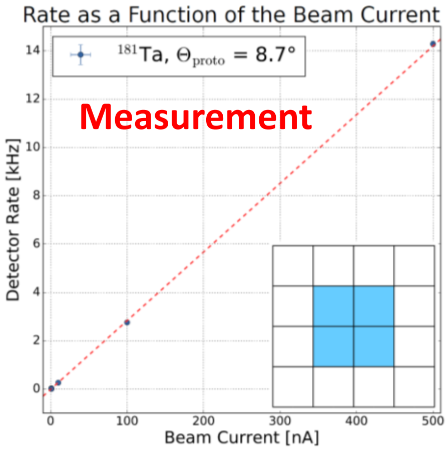
FAIR Phase-0 Test Beam at MAMI

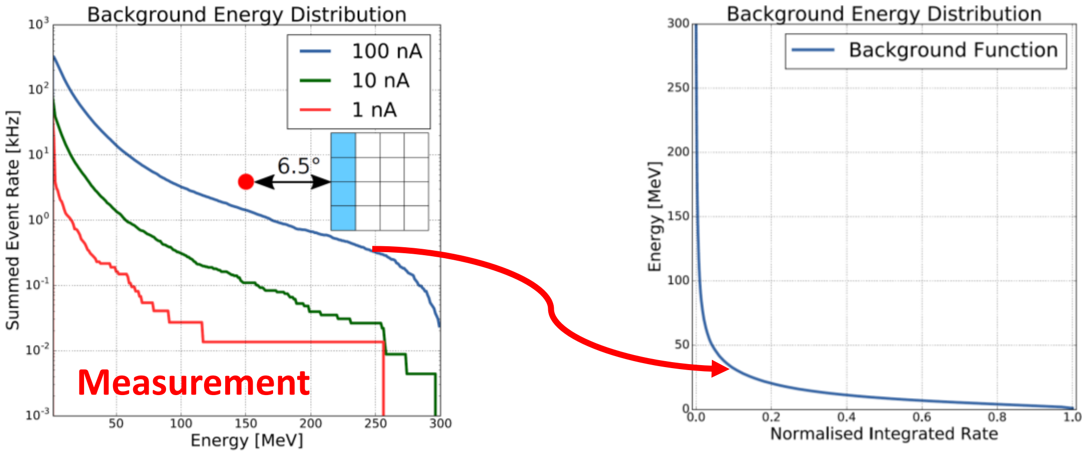




- Polyethene $[-\mathrm{CH}_2 - \mathrm{CH}_2]_n$ → elastic electron proton scattering on H nuclei
  - Coincidence with spectrometer A (proton) and prototype (electron)
  - Energy calibration
- Quasi-elastic scattering on ${}^{12}_{6}\mathrm{C}$
- Rate and background determination on ${}^{181}_{73}\mathrm{Ta}$
- Electron tagger test (electron-photon separation)

FAIR Phase-0 Test Beam: Background





<u>Signal Generator:</u>

1. Number of hits on trace by Poisson random generator: $R(I_{Beam}) = \frac{R_{100nA}}{100\ nA} \cdot I_{Beam}$
2. Time of occurrence by uniform random generator
3. Energy amplitudes via background energy distribution by using a uniform random generator (0,1)