

Charge Reconstruction and Gain Matching of the ACTAF Readout Electronics

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AMBER
Experiment

ACTAF Readout
Setup

Preamplifier Test
2025

Waveform
Processing

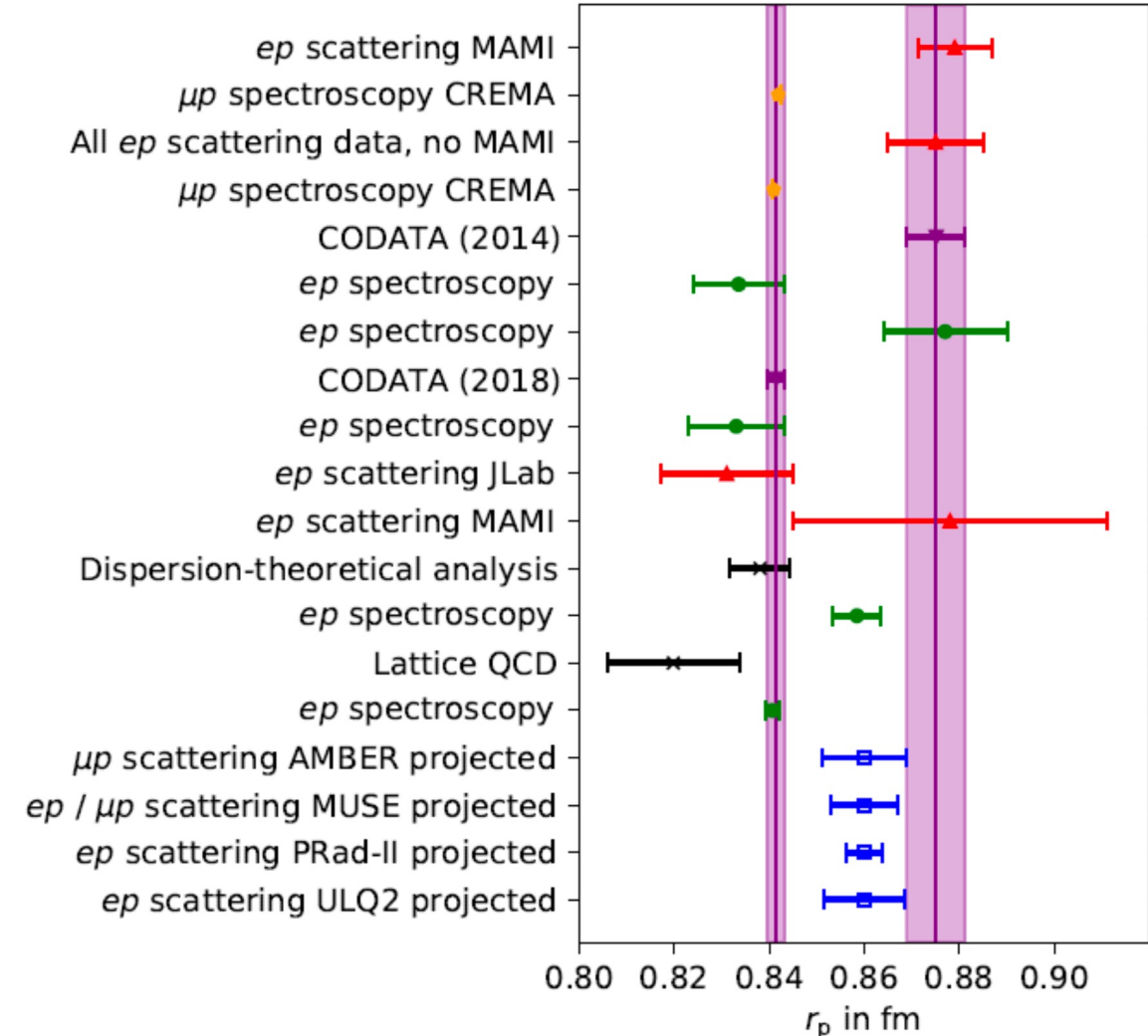
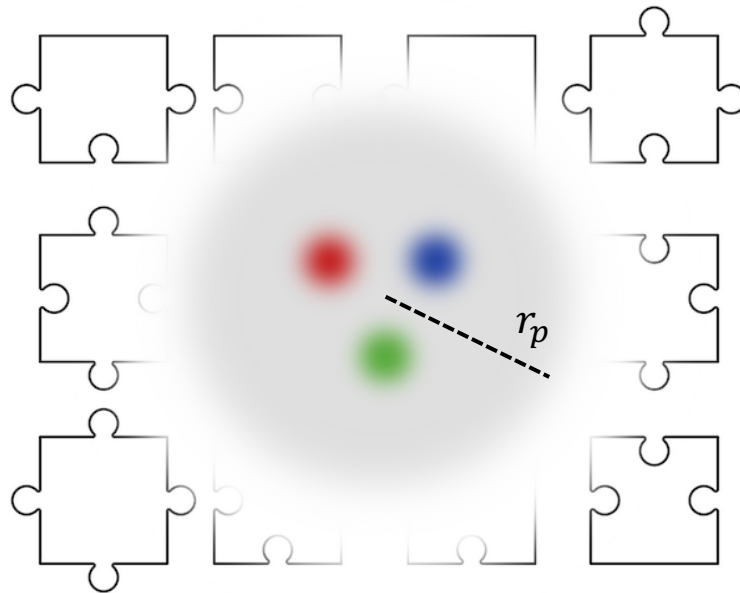
Charge
Reconstruction

Gain
Matching

Conclusions

■ Why measure the proton charge radius?

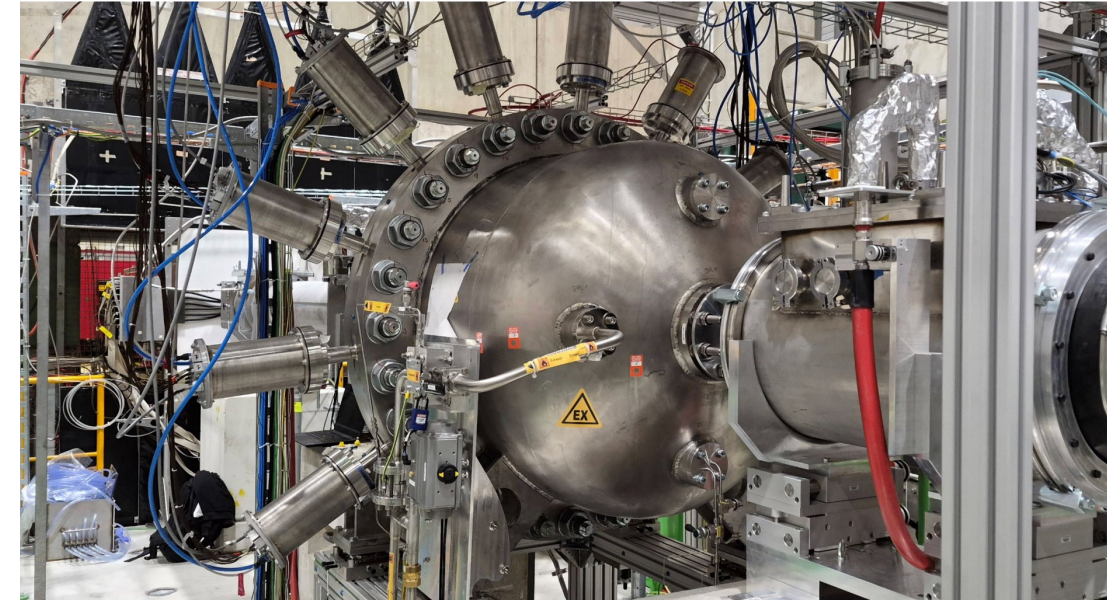
- $r_p = \sqrt{\langle r^2 \rangle_{\text{charge}}}$: fundamental property
- Significant disagreement with previous results:
„proton radius puzzle”



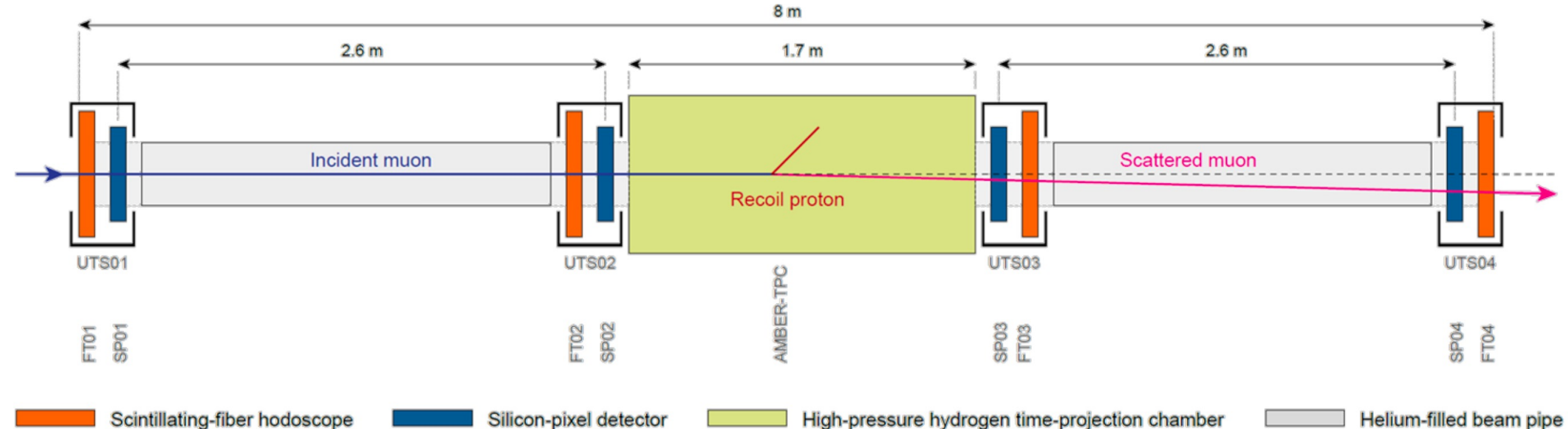
- Why measure the proton charge radius?
 - $r_p = \sqrt{\langle r^2 \rangle_{\text{charge}}}$: fundamental property
 - Significant disagreement with previous results:
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- How does AMBER measure it?

high-energy elastic μ -p scattering (100 GeV/c)



Recoil proton
↓
Ionization charge
↓
Energy

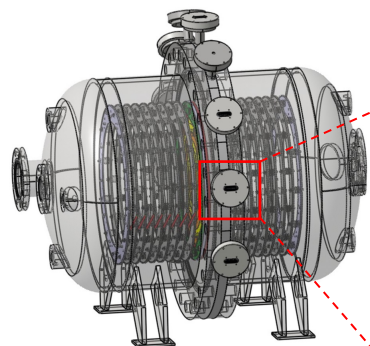


ACTAF Readout Setup = Active Target for EAIR

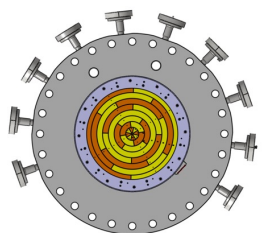
R^3B = Reactions with
Relativistic Radioactive
Beams



ACTAF TPC (gas-filled, high-pressure H_2)

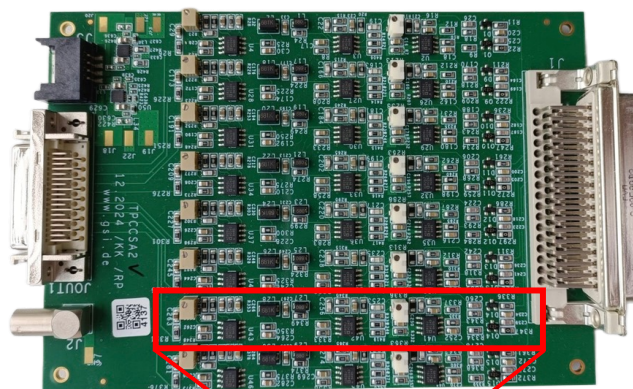


Anode plane (detail)



2 anode planes,
64 pads per plane

Preamplifier module (16 channels)



One channel

Charge generation and drift (in TPC)
Charge collection (on pads)
Signal transport (Feedthroughs)



Signal amplification and shaping:
Individual pad charges correspond
to a few fC



Mounting of the preamplifiers @ CERN – 22.04.2026
Photo: B.Ketzer

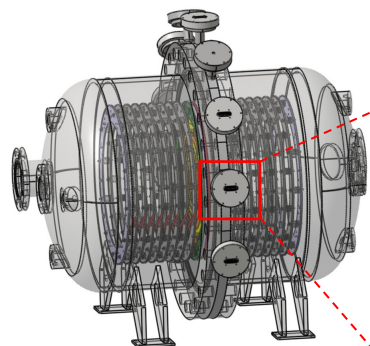
ACTAF Readout Setup = Active Target for FAIR

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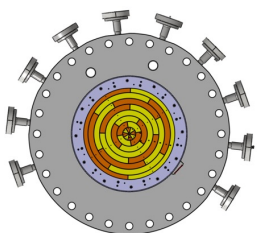


ACTAF TPC

(gas-filled, high-pressure H_2)

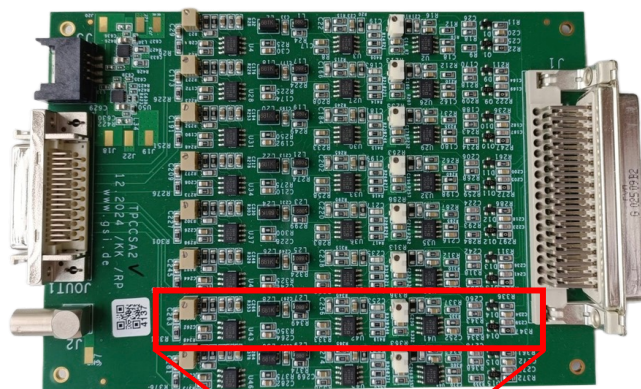


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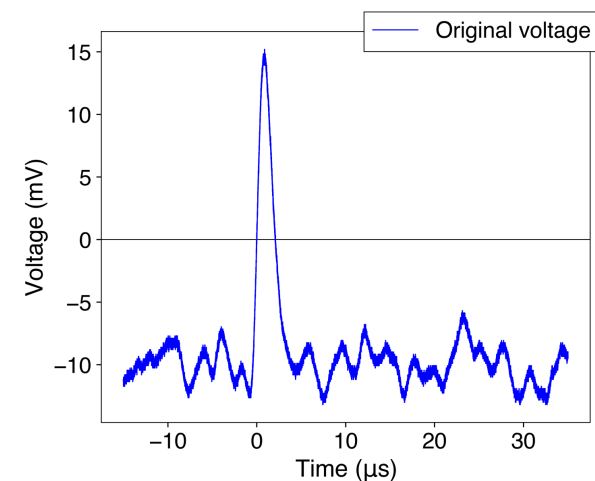


One channel

FADC SIS3316 (Flash Analog-to-Digital Converter)



Digitized raw waveform



ADC Channel $\Rightarrow$ Voltage
Sample $\Rightarrow$ Time

Charge generation and drift (in TPC)
Charge collection (on pads)
Signal transport (Feedthroughs)

Signal amplification and shaping:
Individual pad charges correspond
to a few fC

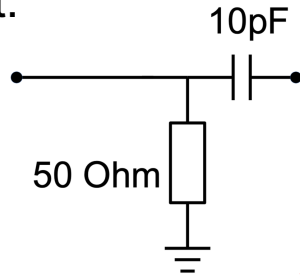
Digitization

ACTAF data analysis

Preamplifier Test 2025

- Preamplifier calibration setup @ Mainz University

- GSI-style circuit:



- Known charges were injected to each channel:

$$Q_{in}[\text{fC}] = 70[\text{mV}] \cdot 10^{-\text{dB}/20} \cdot 10[\text{pF}]$$

where dB is the attenuation introduced by the attenuator

- Q_{in} is shaped through a 5th-order Bessel function

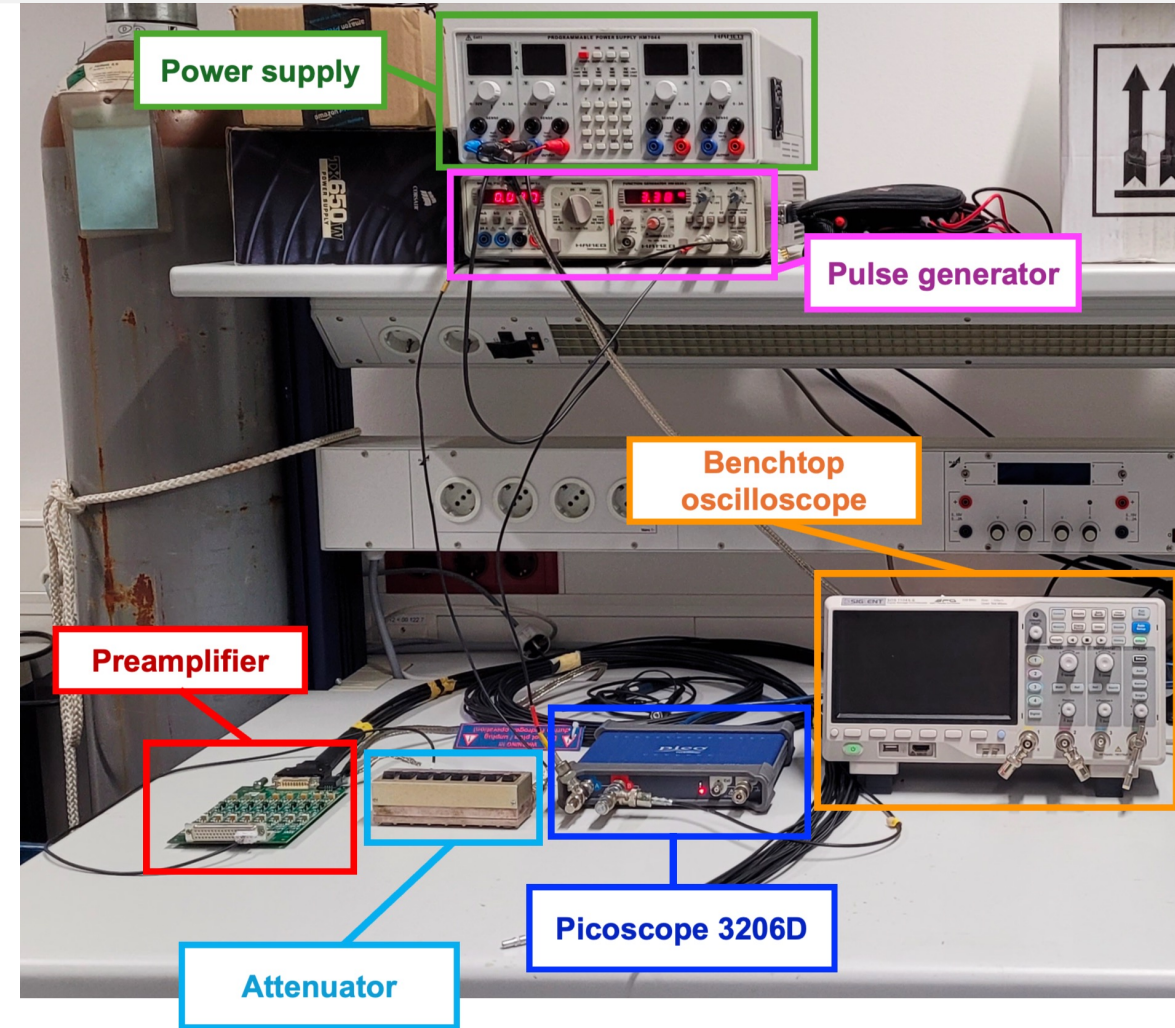
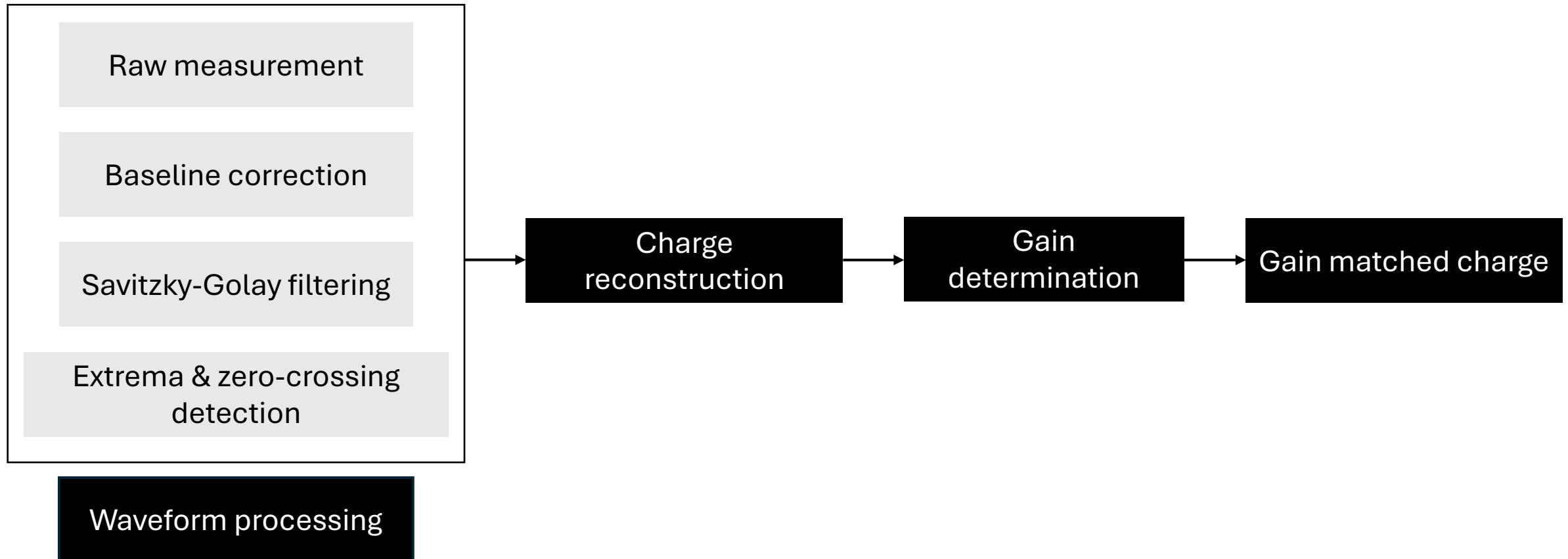


Photo: Preamplifier Test 2025 @ Mainz University

- From raw data to preamplifier channel calibration: **THIS WORK**



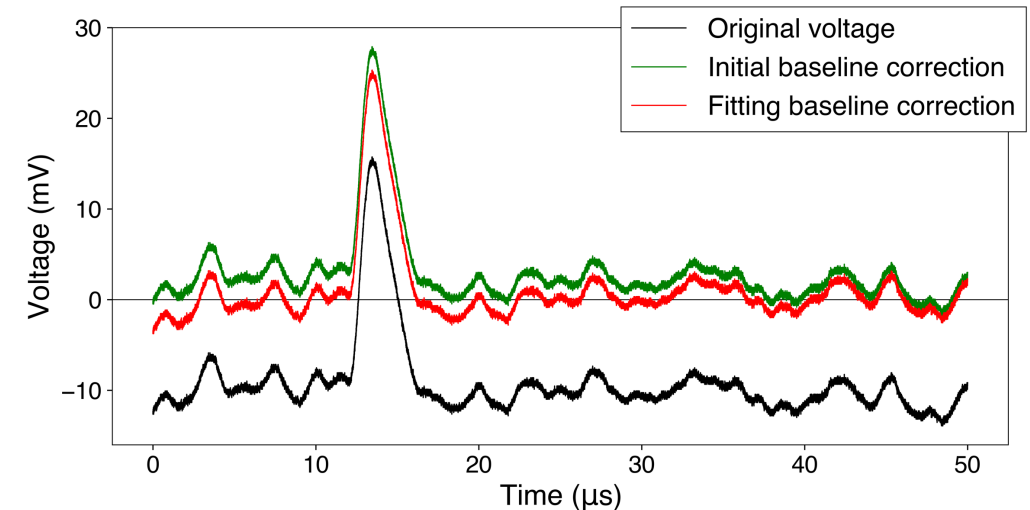
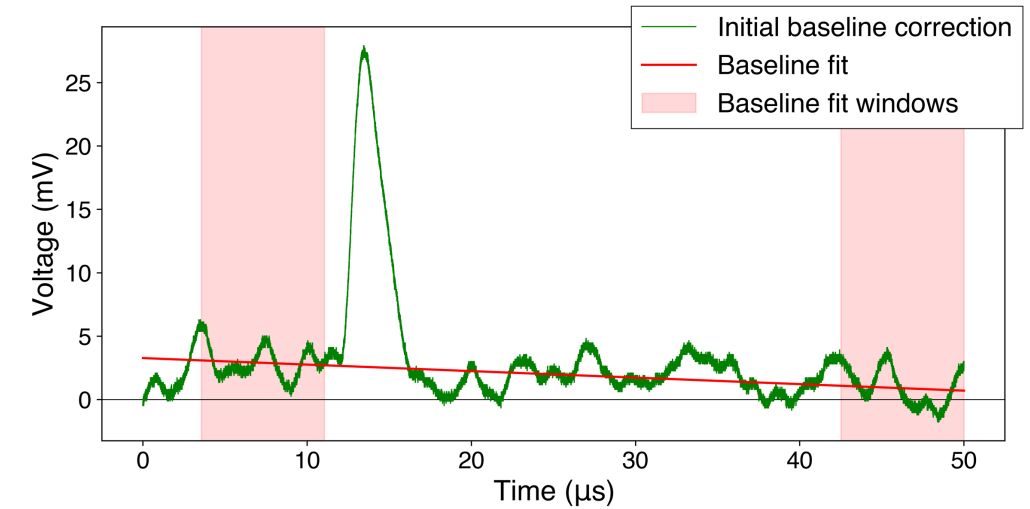
Raw measurement

Baseline correction

Savitzky-Golay filtering

Extrema & zero-crossing detection

- Initially, baseline was estimated from the mean of the first 100 samples
- Implementation of a baseline slope correction:
 - Preliminary pulse start t_{10} at 10% of the peak amplitude
 - Baseline fit windows of 15% of the waveform duration:
 - 1st ends 1 μ s before t_{10}
 - 2nd ends with the acquisition window
 - Both windows are fitted with a linear function



Raw measurement

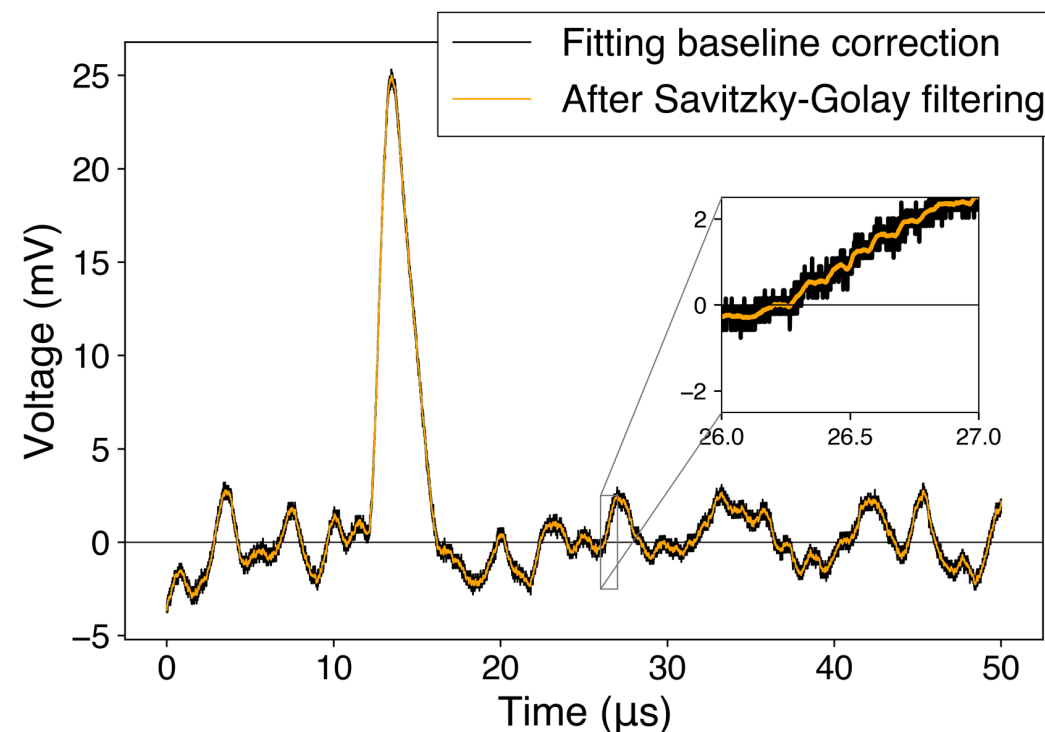
Baseline correction

Savitzky-Golay filtering

Extrema & zero-crossing detection

- Smoothing filter already implemented in the existing data processing chain:
 - Savitzky-Golay : 51-sample window, 3rd-order polynomial
- Used to suppress high-frequency fluctuations while preserving the pulse shape
- Filter optimization was **outside the scope** of this work

The filtering method and its parameters should be further evaluated



Raw measurement

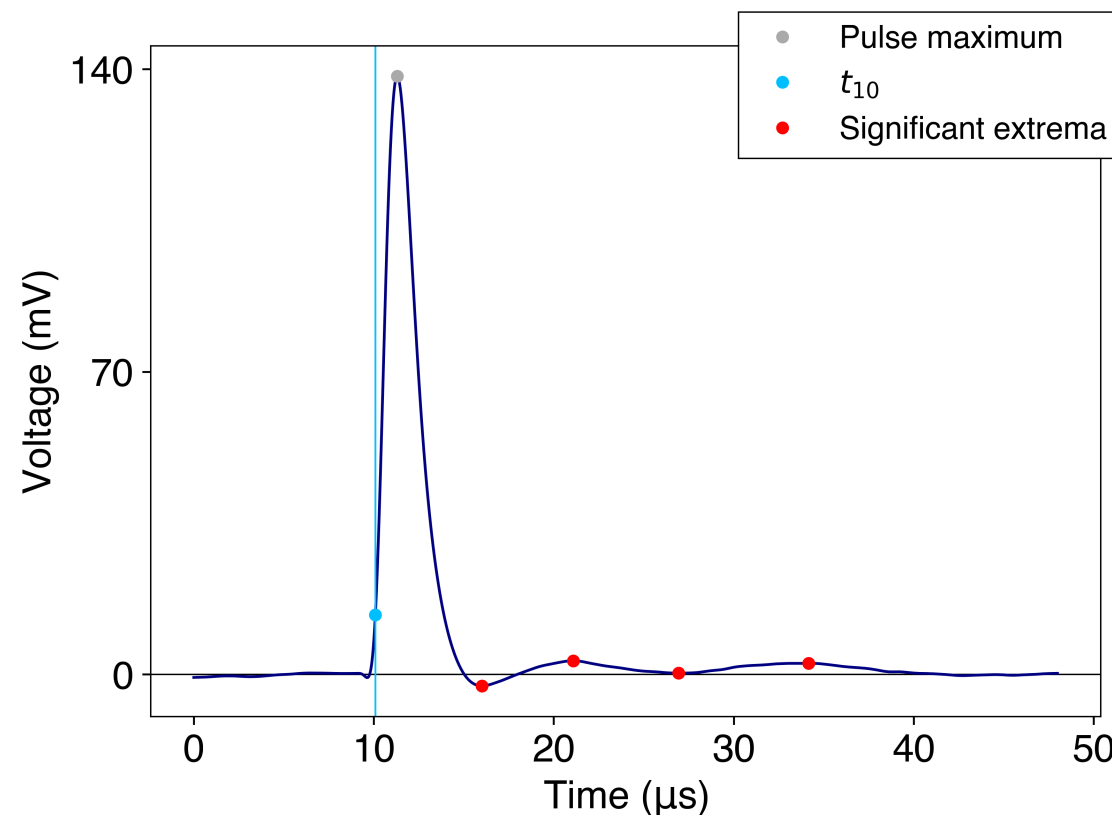
Baseline correction

Savitzky-Golay filtering

Extrema & zero-crossing detection

■ Pulse features

- Average 100 raw waveforms $\Rightarrow$ Baseline correction $\Rightarrow$ Savitzky-Golay filter
- t_{10} is refined from the pulse peak through a backward search
- Extrema are extracted with `scipy.signal.find_peaks`
 - Initially: fixed prominence threshold
 - Implementation: prominence of 1% of the peak amplitude, scales with signal size



Raw measurement

Baseline correction

Savitzky-Golay filtering

Extrema & zero-crossing detection

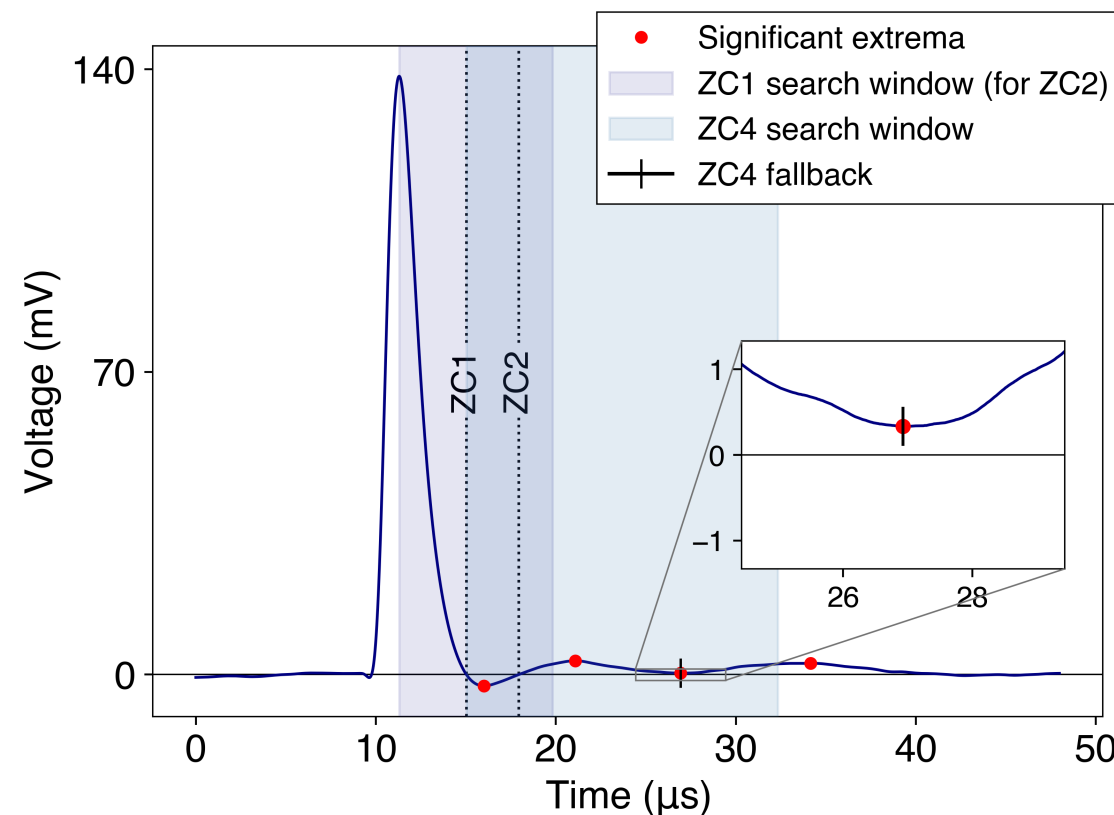
Zero-crossings

- ZC2 and ZC4 are validated within pulse dependent search windows, Δt

Endpoint	Δt	Validation window
ZC2	$7(t_{\text{peak}} - t_{10})$	$[t_{\text{peak}}, t_{\text{peak}} + \Delta t]$
ZC4	$3.5(t_{\text{ZC1}} - t_{10})$	$[t_{\text{ZC1}}, t_{\text{ZC1}} + \Delta t]$

provide suitable search windows for the expected ZC in the analyzed dataset

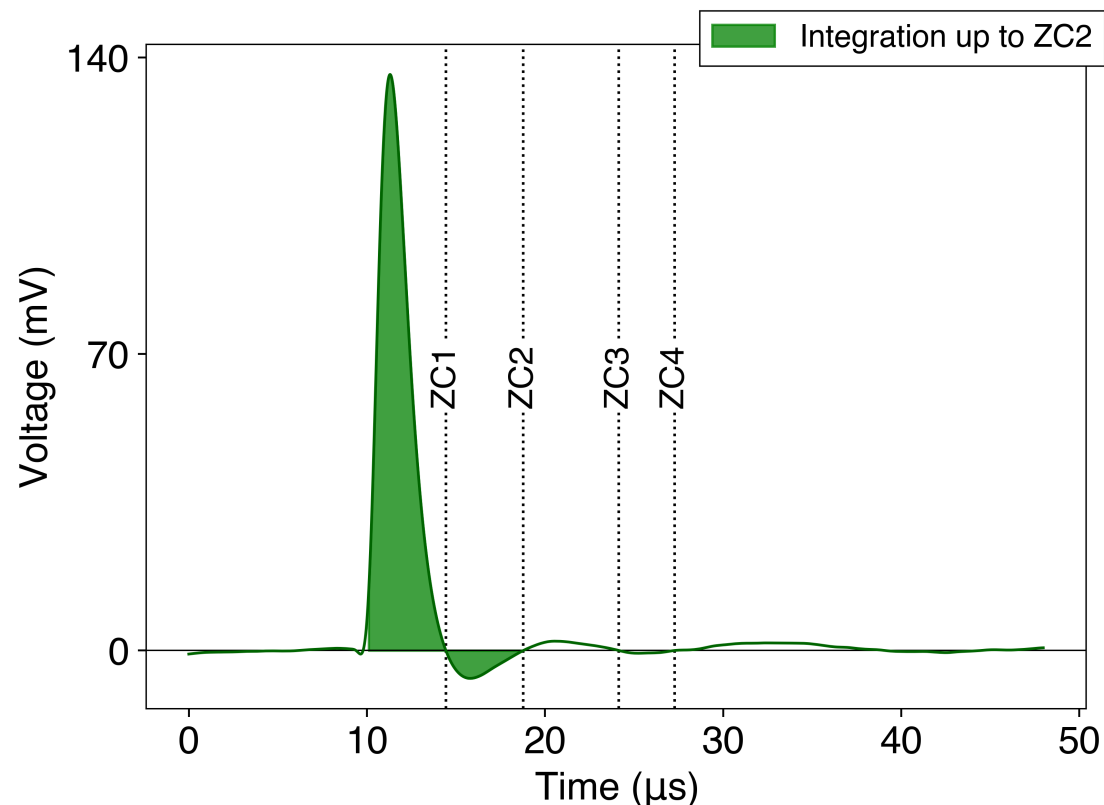
- If the expected ZC is not found, a significant minimum is used as a fallback



- Absolute output charge is reconstructed as:

$$Q_{\text{out}} = \frac{1}{R} \int_{t_{10}}^{t_{\text{end}}} |V(t)| dt$$

- Input impedance of the FADC: $R = 50 \Omega$
 - Processed waveform: $V(t)$
 - Integration start t_{10}
 - Integration endpoint t_{end} : same criterion required for all waveforms. Initially set at ZC1
- **ZC2 vs ZC4 investigated as possible endpoints**
 - ZC4: failed in ~10% of the waveforms and frequently required the fallback minimum
 - **ZC2: more reliable → selected as t_{end}**



Integration beyond ZC1 includes the negative undershoot of the shaped pulse

■ Gain determination

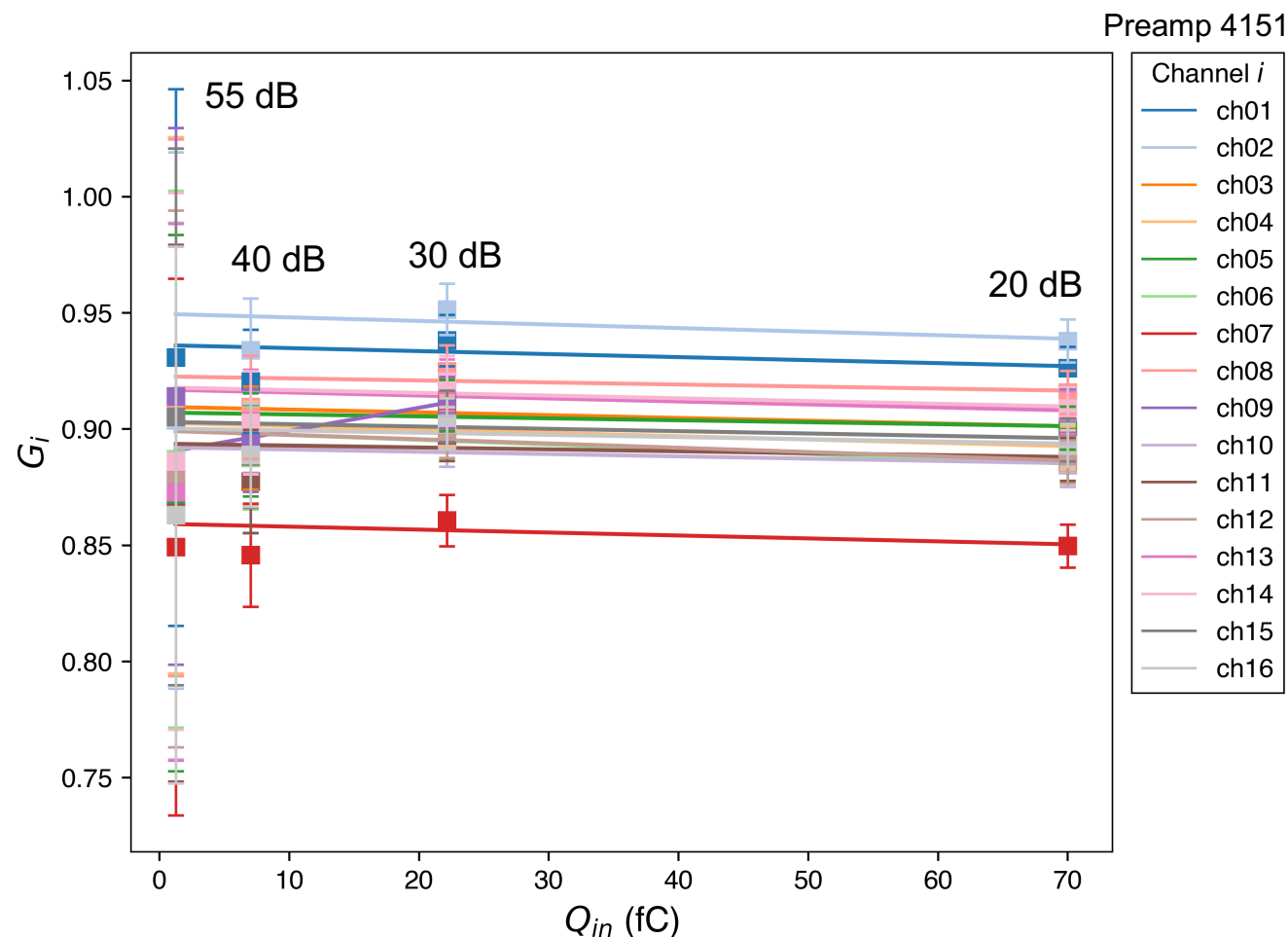
- The absolute gain of each channel i is calculated as:

$$G_i = \frac{Q_{\text{out},i}}{Q_{\text{in}}}$$

- Instead of the expected constant gain, a small dependence on Q_{in} has been found. This was described by a weighted linear fit:

$$G_i(Q_{\text{in}}) = a_i Q_{\text{in}} + b_i$$

- Gain differences between channels must be corrected to ensure the same response to the same input charge across the detector



Errors were obtained by propagating Q_{in} and Q_{out}

■ Gain matching factors

- Common reference for all preamplifiers: *4151 channel 03*

- Matching factor of each channel:

$$M_i(Q_{in}) = \frac{G_{ref}(Q_{in})}{G_i(Q_{in})}$$

- It is applied to the reconstructed charge as:

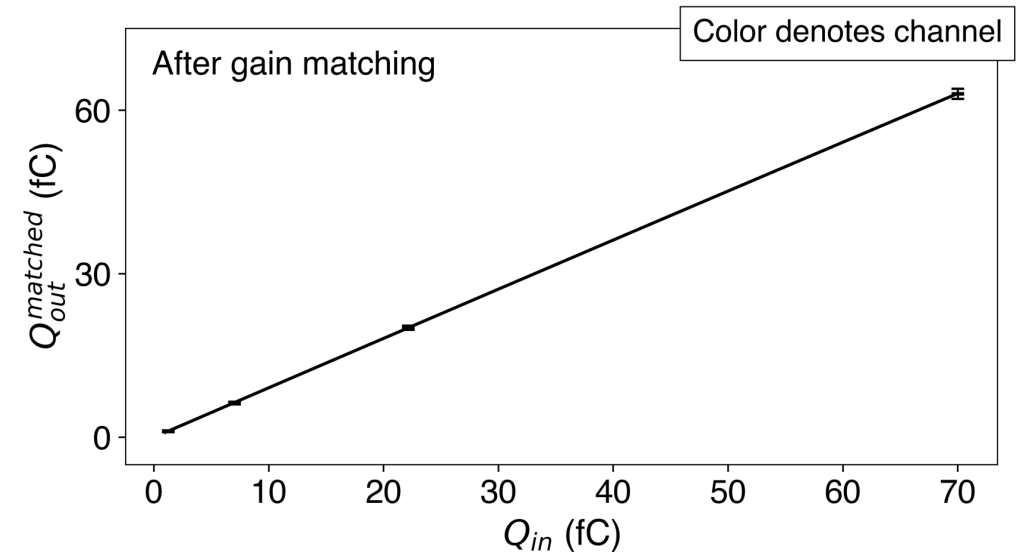
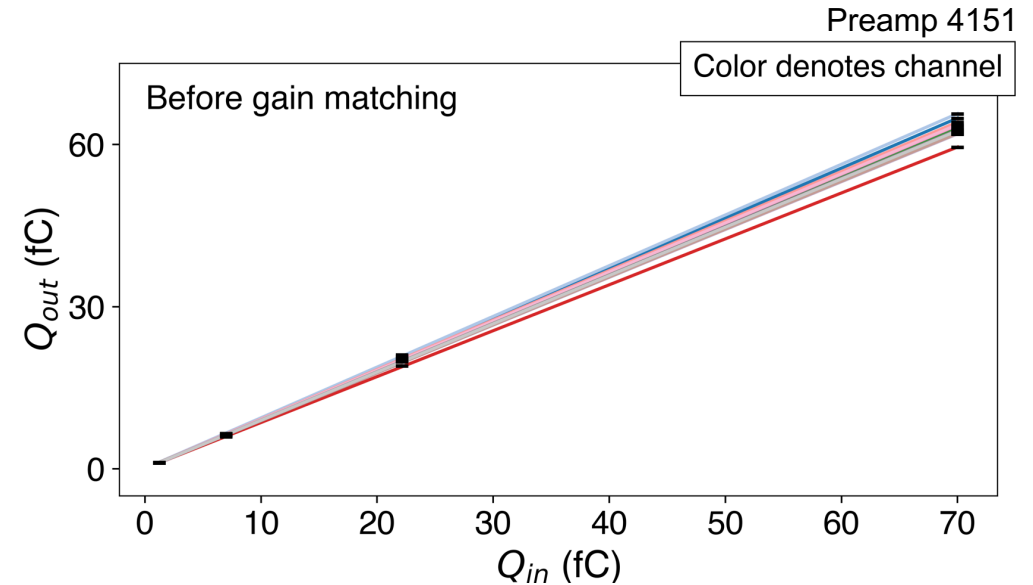
$$Q_{out,i}^{matched} = M_i \cdot Q_{out,i}$$

Residual deviations

$$\frac{Q_{out,i}^{matched} - Q_{out,ref}}{Q_{out,ref}} \cdot 100 < 1\%$$

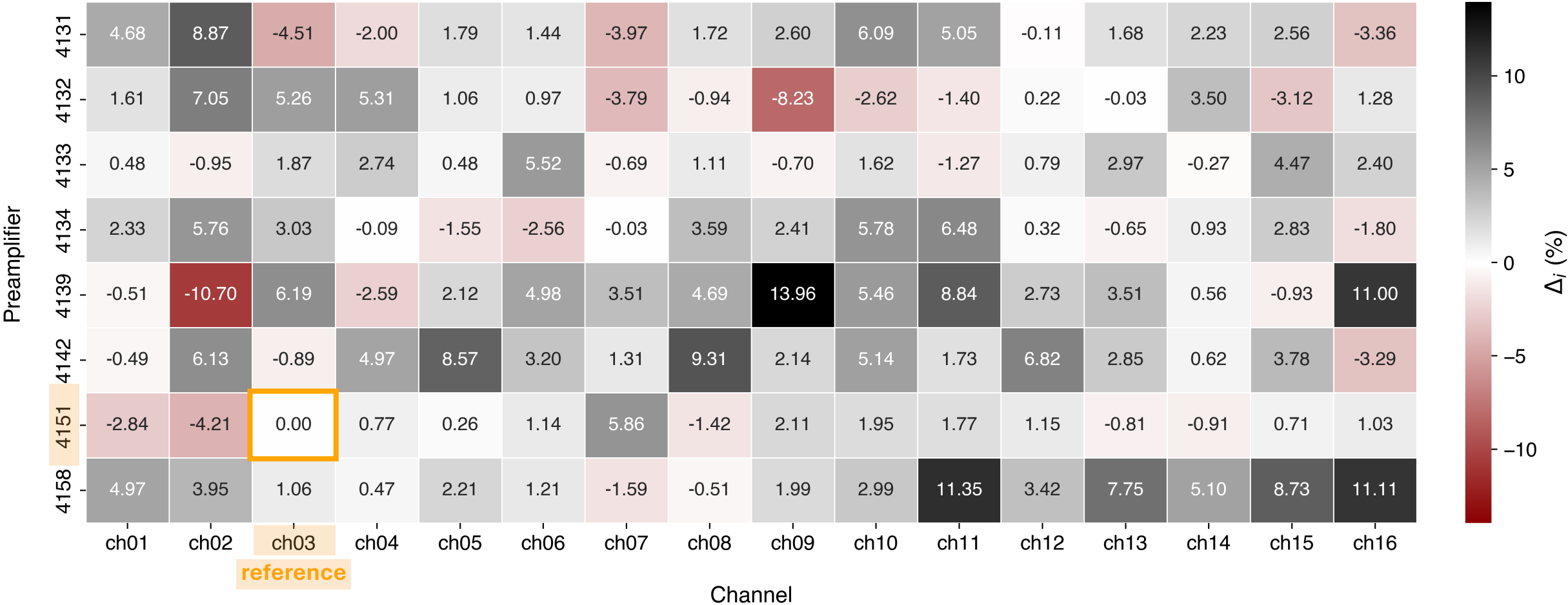
Larger signals meet
the target deviation

Up to 3-4% for
smaller signals



■ Extension to all preamplifiers: 55 dB attenuation

Relative correction:
 $\Delta_i [\%] = (M_i - 1) \cdot 100$



- **Charge reconstruction and gain calibration procedure** for ACTAF readout electronics
- **Waveform processing refined**
 - Baseline correction accounting for its slope
 - Adaptive zero crossing identification
 - ZC2 selected as a reliable integration endpoint
- **Channel-dependent gain characterized** from the reconstructed charge
- **Gain matching factors derived** with respect to a common reference
- **Electronics-response differences reduced**
 - $< 1\%$ target deviation reached for larger signals
 - Consistent response required for proper track reconstruction

❀❀ Thank you ❀❀

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