Development, Calibration & Experiment

Active Polarized Proton Target

M. Biroth for the A2-Collaboration
Institut für Kernphysik, Mainz, Germany

A2

MAMI MAINZER MIKROTRON

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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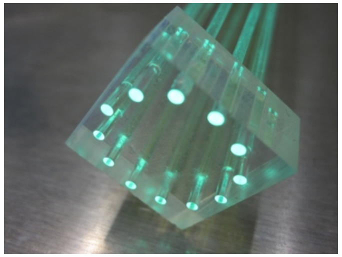
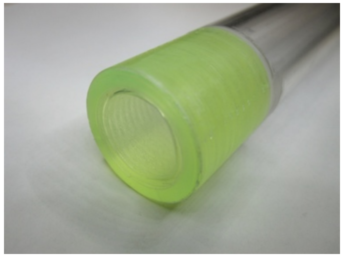
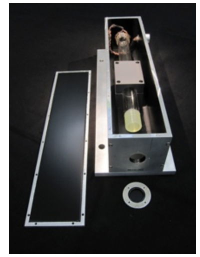
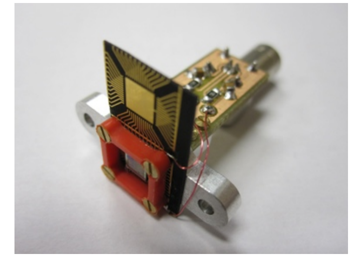
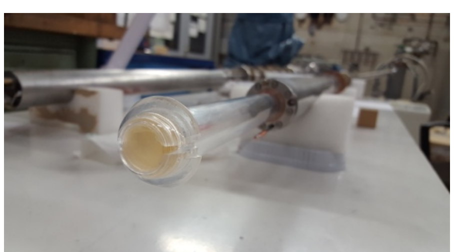




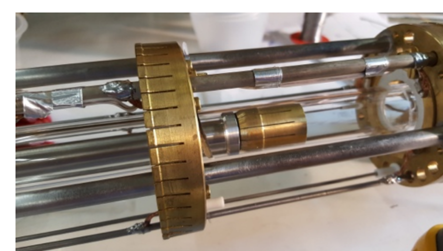



First Active Target Experiment 2016

5 years of development to match the requirements

- Photo detectors: SiPM at cryogenic temperatures
  successful operation at 4K 2014
  NIM A 787 (2015) 68-71
- Electronics: low-noise SiPM amplifiers working
  some meters away from the detectors
  NIM A 787 (2015) 185-188
- Prototypes: research in light guides and target geometry

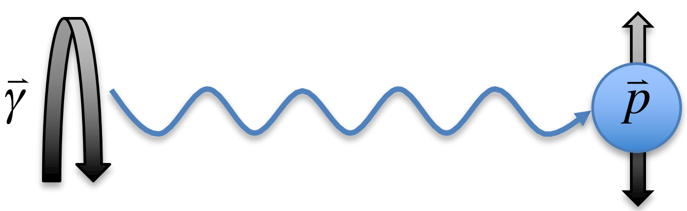


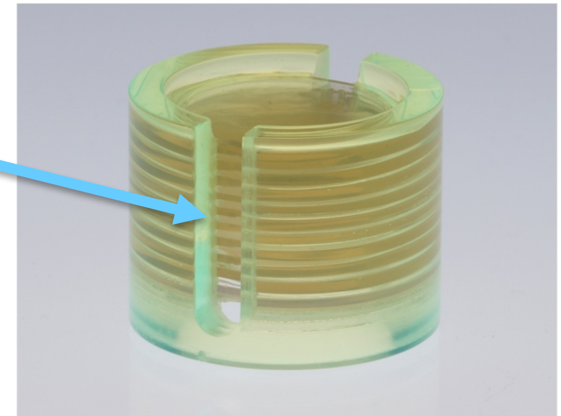
Experiment Parameters

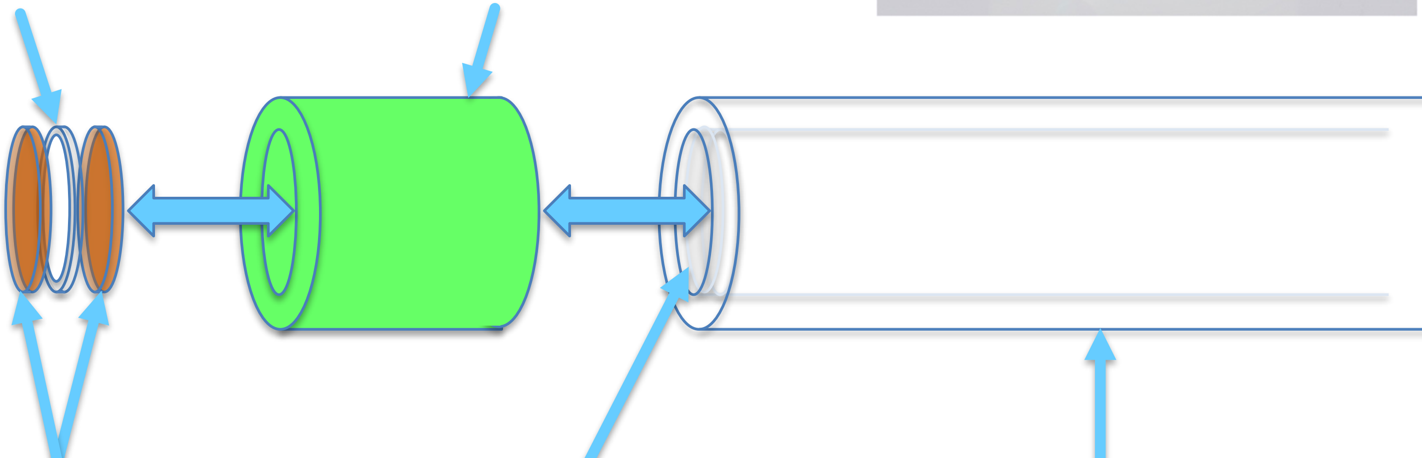
- Beam: 450MeV, polarized
- Radiator: Møller, ⌀1.5mm collimator
- Holding-coil: 437.5mT, transverse
- Cryostat temperature: 45mK
- Trigger: CB Energy-sum
- Detectors: CB, TAPS, PID, MPWC, Cherenkov

Beam Current	Energy Sum High	Active Tagger Channels
5nA	60-80MeV	325
20nA	30-40MeV	200



Final Active Target Design



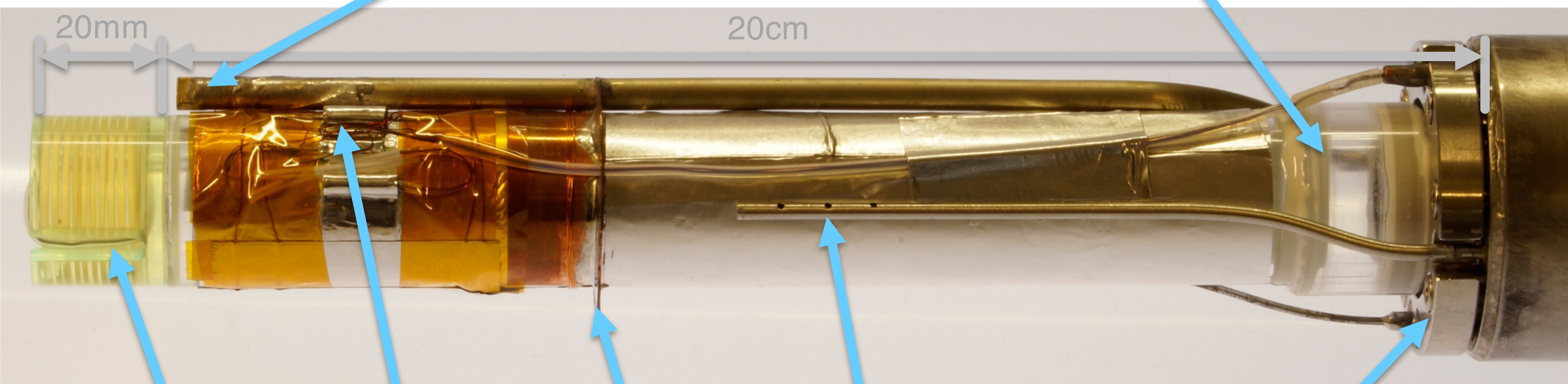


Maik Biroth, Institut für Kernphysik, Mainz, Germany mbiroth@uni-mainz.de

Final Cryostat Insert with the Active Target

μWave guide with UHF tuner and outlet port for DNP

He-vacuum feedthrough for the light guide tube



Temperature probes

Outlet nozzle of the ^{4}He pre-cooling line

He-vacuum feedthrough for cabling, μWave and pre-cooling

Target head with cooling slit and transverse NMR coil

μWave radiation shield

Developed by Mainz & Dubna

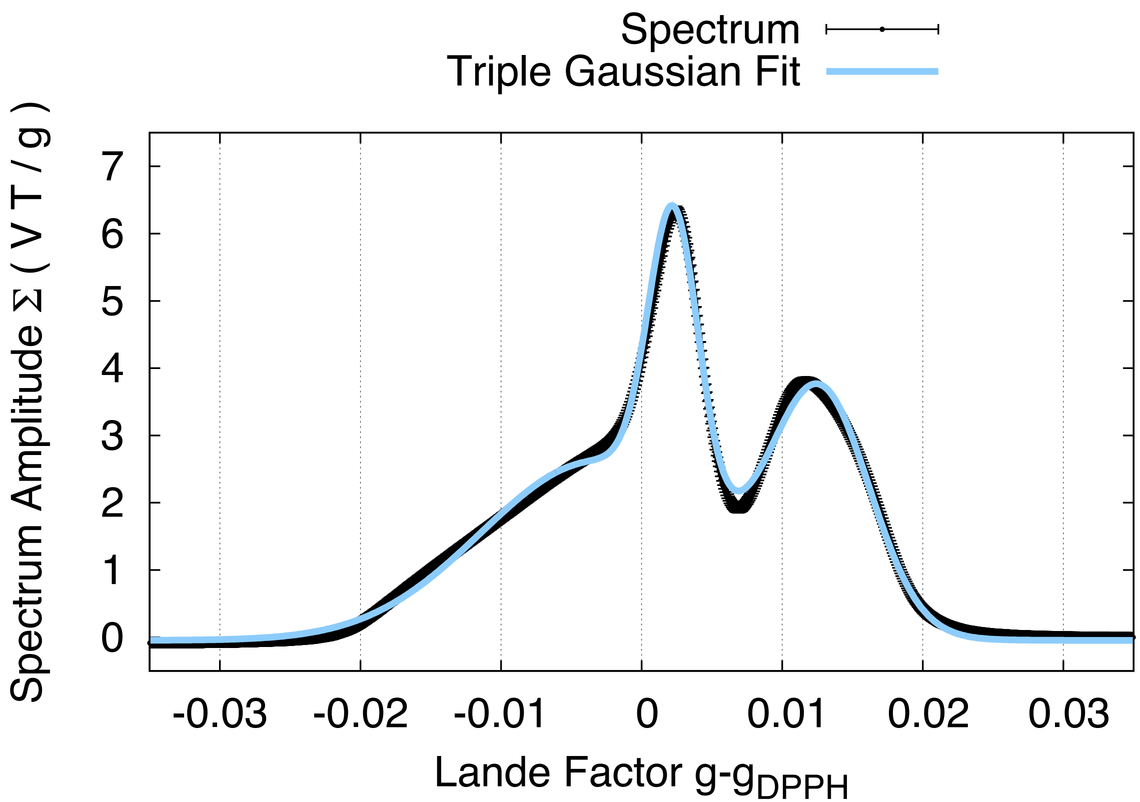
Maik Biroth, Institut für Kernphysik, Mainz, Germany

mbiroth@uni-mainz.de

ESR Spectrum of the Scintillator 4-Oxo TEMPO in Polystyrene

For all ESR measurements the magnetic field was varied under a constant µWave frequency ν_{RF} = 9.363 GHz at room temperature
DPPH is used as reference sample at B_{DPPH} = 334.587(1) mT

Electron spins are coupled with proton spins and enable Dynamic Nuclear Polarization



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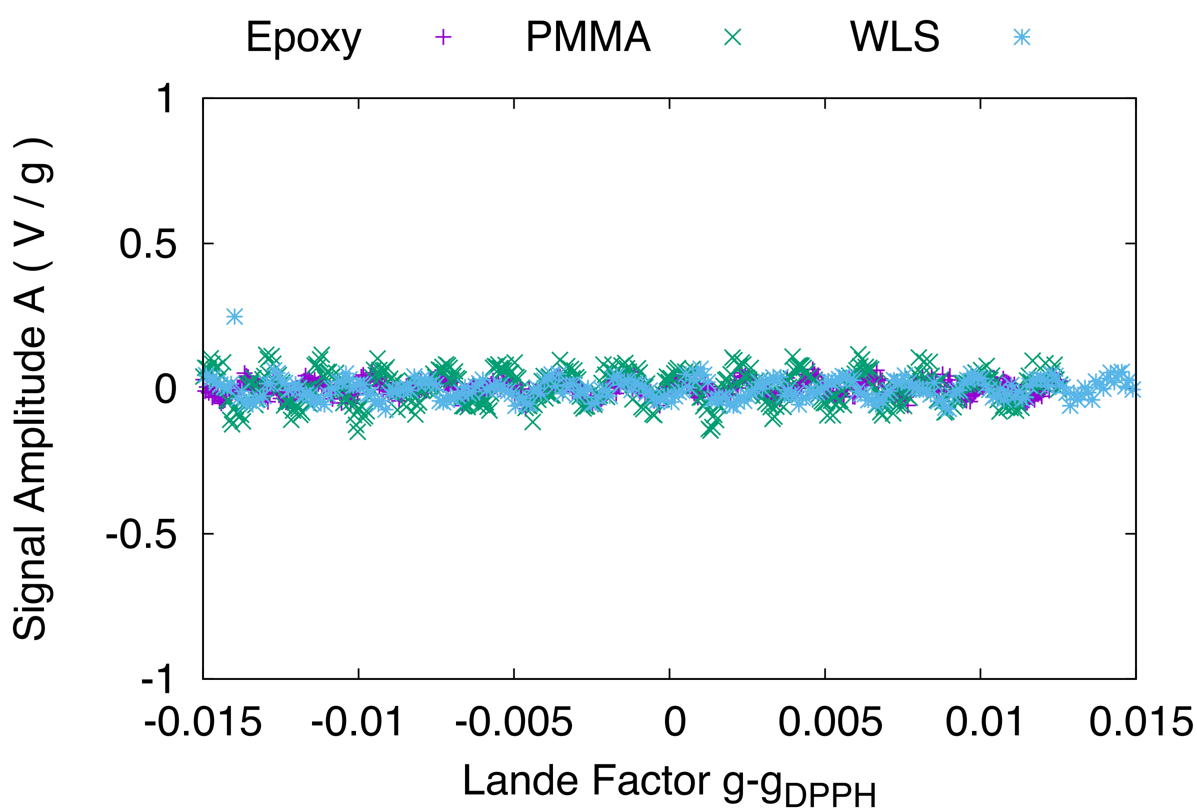
Proof the Density of Free Electron Spins in the Passive Target Materials

Epoxy, PMMA spacers and wave length-shifting material
do not include any unpaired electron spins

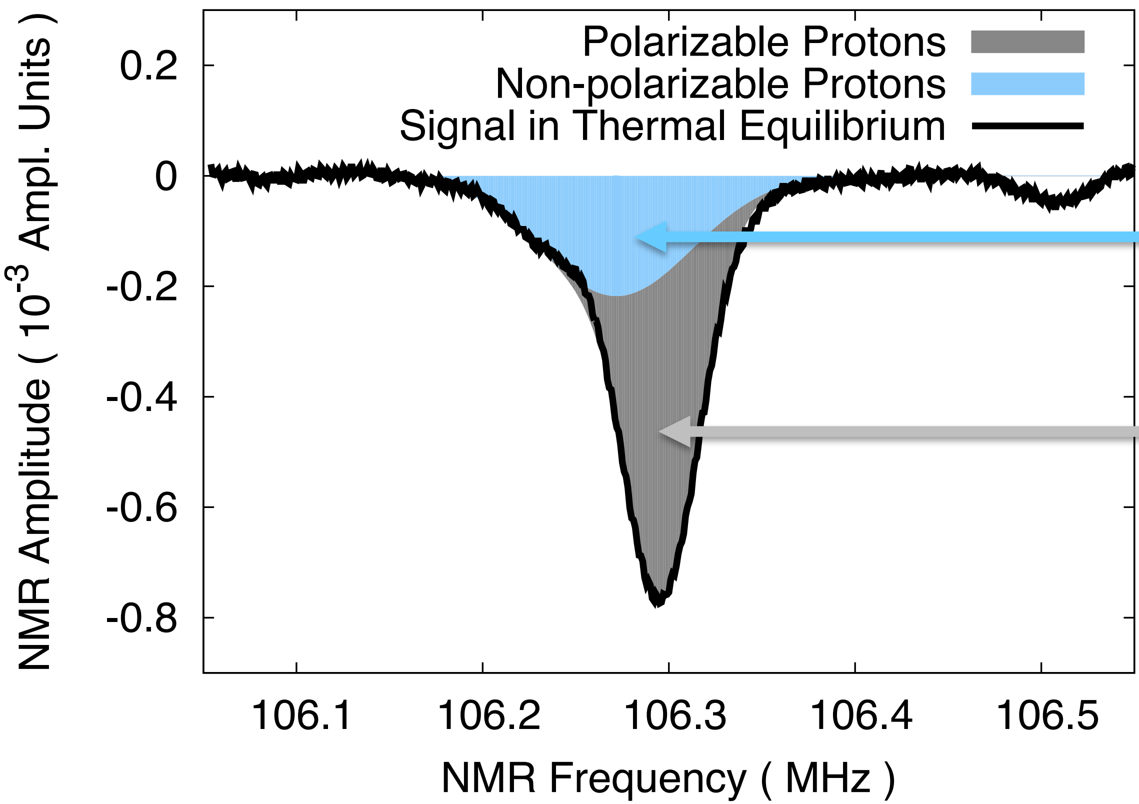


Thanks to
Gerhard Reicherz

Polarization Calibration at the Thermal Equilibrium with NMR

At T=1K spins relax to the thermal equilibrium state where polarization is calculable

$$P_{TE} = \left.\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right|_{T_{TE}} = \tanh\left(\frac{h\nu_L}{k_B T_{TE}}\right)$$

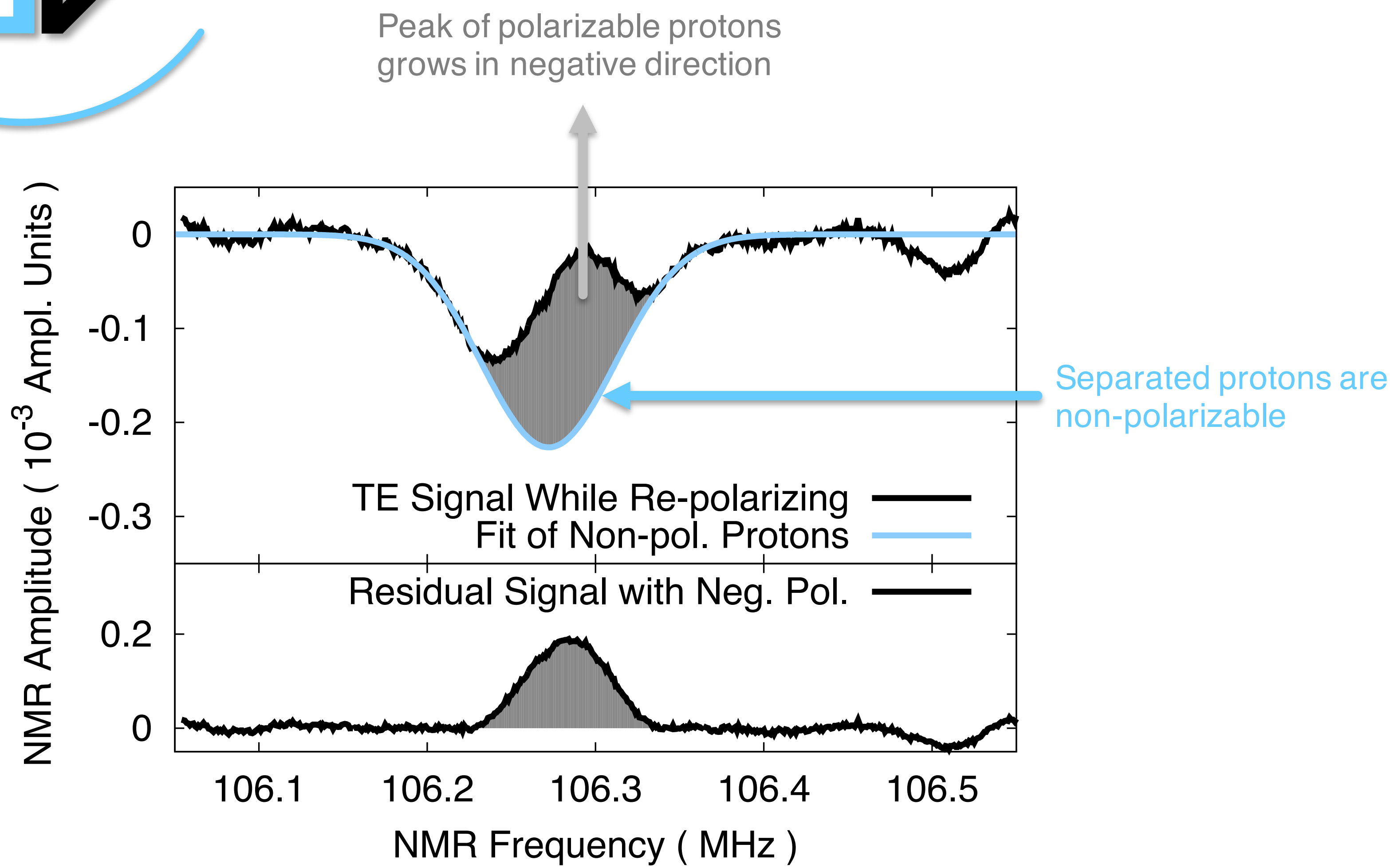


Separated protons in epoxy, PMMA and WLS

A_{TE} – area below TE-signal of the polarizable protons in the scintillator

$$P(T,t) = \frac{P_{TE}}{A_{TE}} \cdot A(T,t)$$

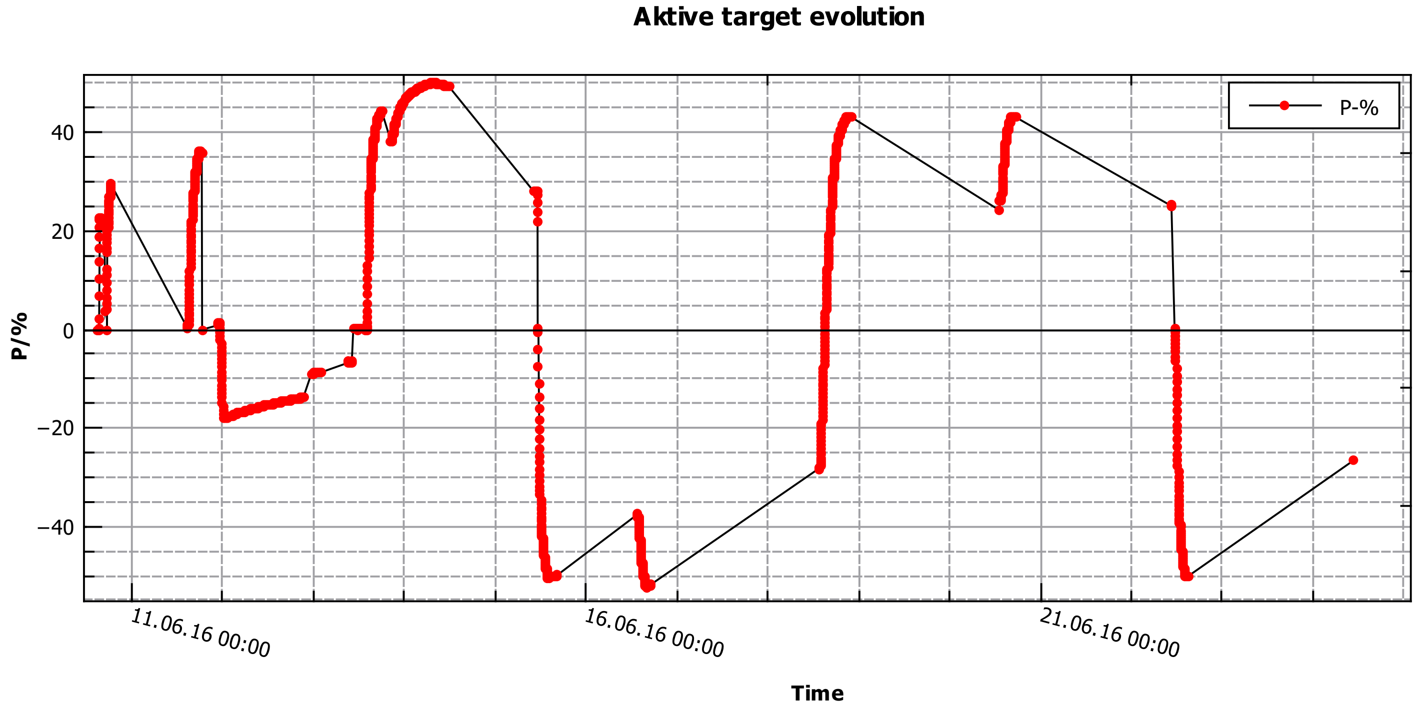
Application of μWaves to the Thermal Equilibrium Signal



Polarization during the Beamtime

Holding coil 437.5mT, temperature 45mK

Spin setting	Max. Polarization	Max. Relaxation Time
Positive	(46±1)%	78.3h
Negative	(49±1)%	74.1h



Thanks to
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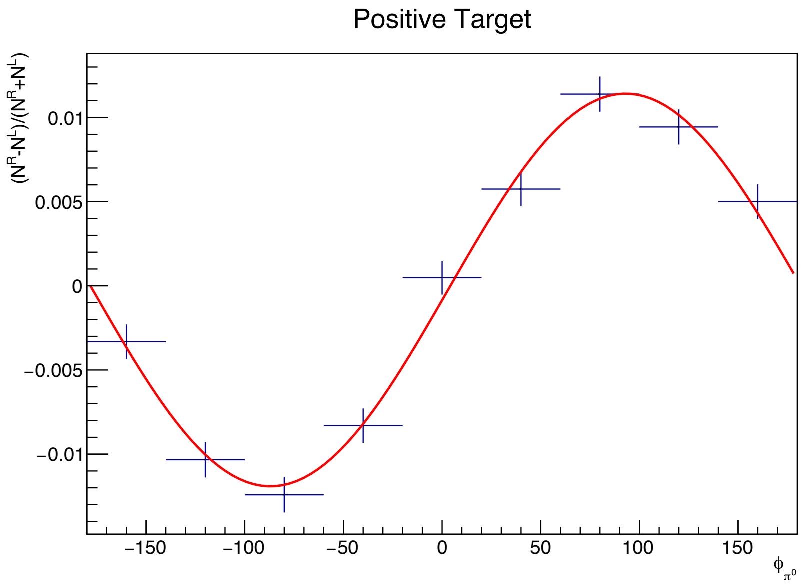
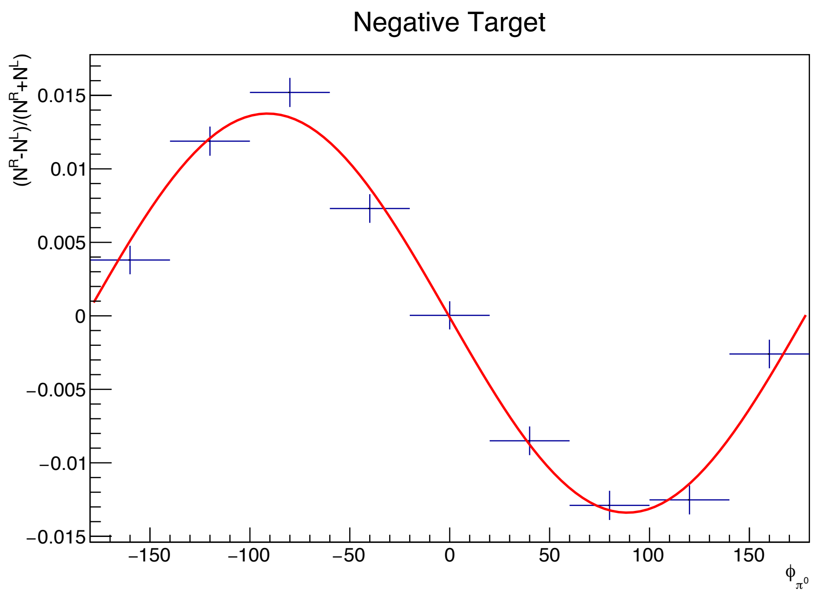
Maik Biroth, Institut für Kernphysik, Mainz, Germany
mbiroth@uni-mainz.de

Angular Distribution of the π^0 Asymmetry

Target asymmetry of the helicity states flips sign with the polarization

$$A = \frac{N^R - N^L}{N^R + N^L}$$

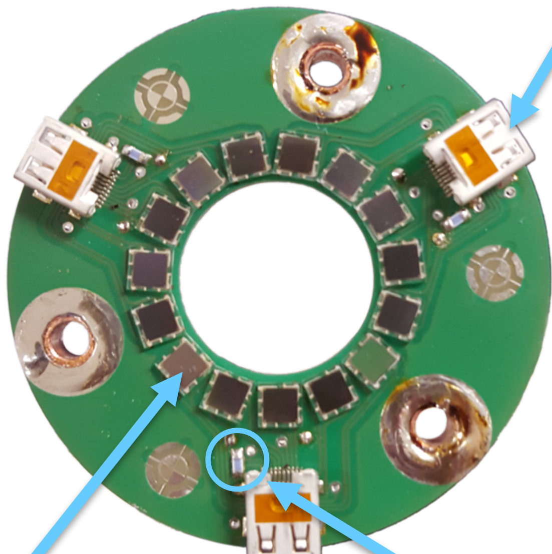


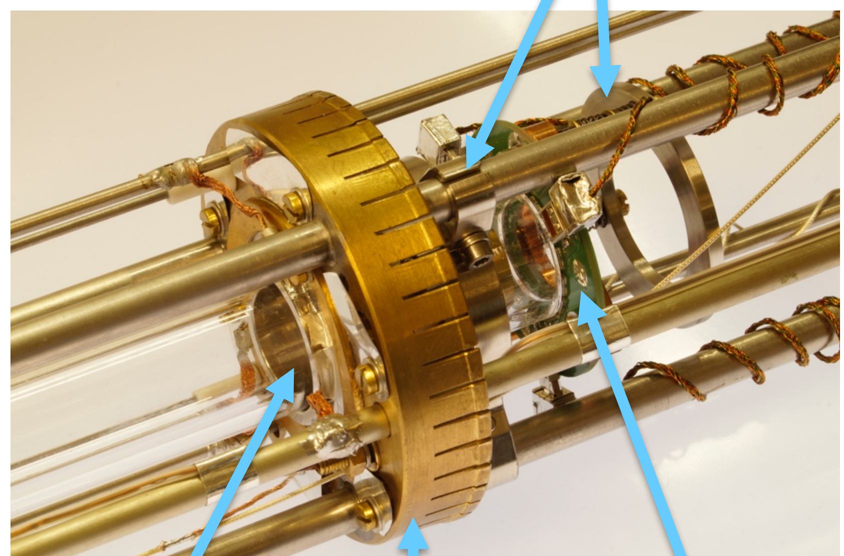


Thanks to Phil Martel

Maik Biroth, Institut für Kernphysik, Mainz, Germany
mbiroth@uni-mainz.de

Scintillation Light Read Out





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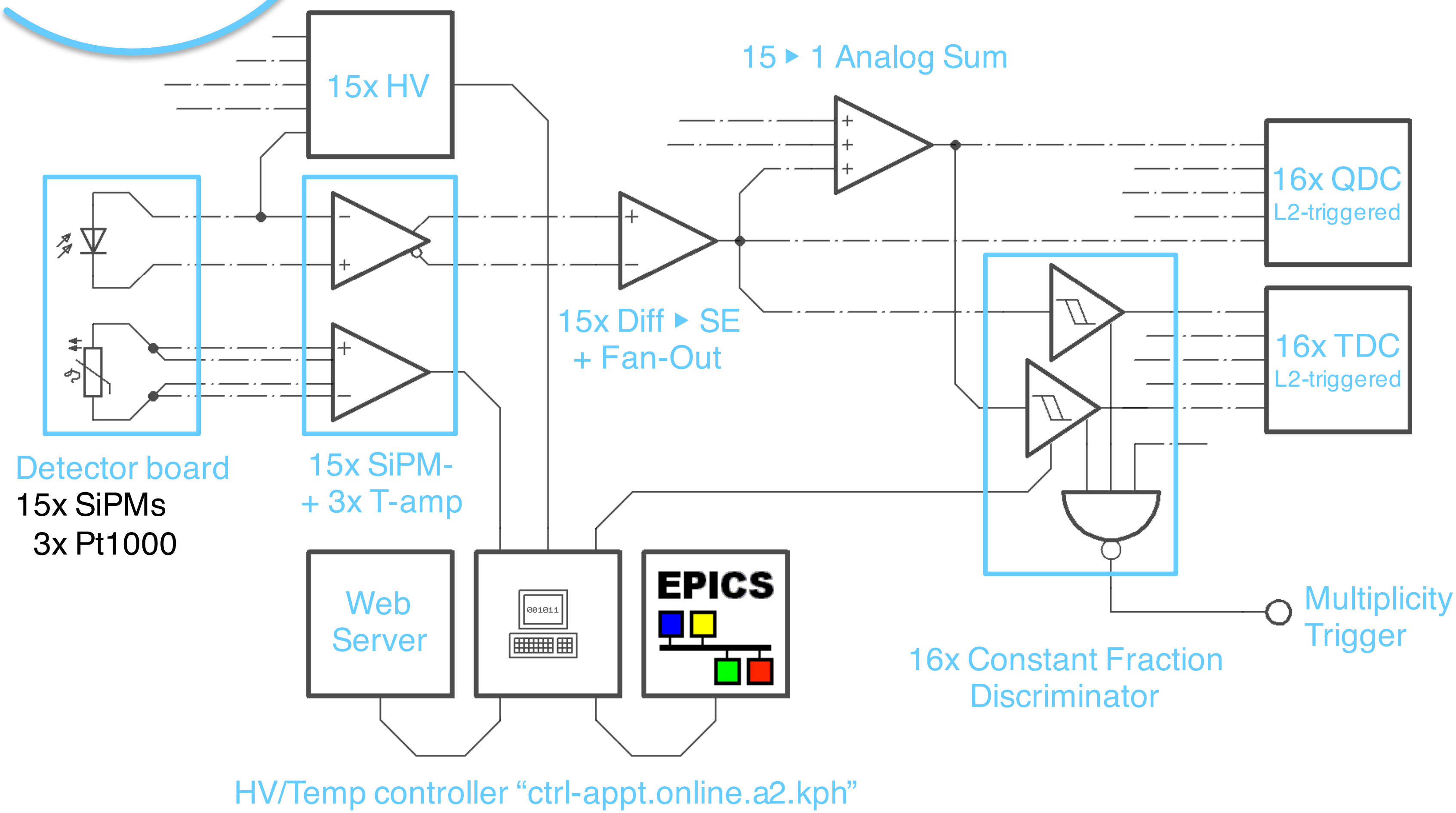
mbiroth@uni-mainz.de

Schematic of the Read-out Chain and HV Control Feedback Loop



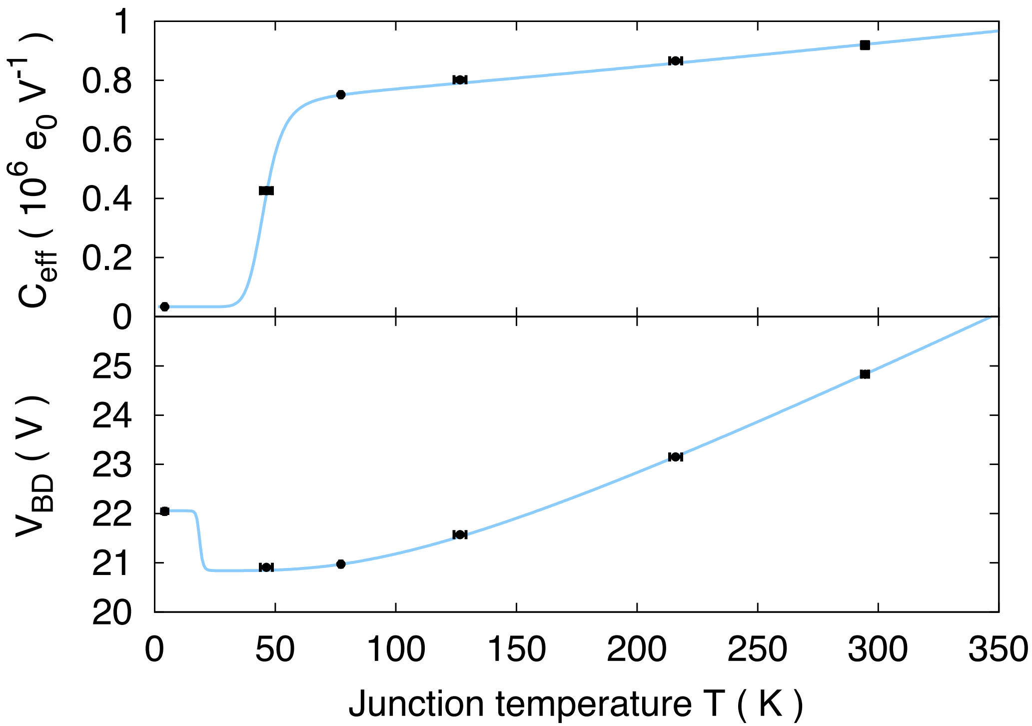
Maik Biroth, Institut für Kernphysik, Mainz, Germany
mbiroth@uni-mainz.de

SiPM Operational Parameters in Temperature Dependence

T-dependence of single pixel gain G was investigated
It can be parameterized by the following formula:

$$G[V,T] = C_{\mathrm{eff}}[T] \times (V - V_{\mathrm{BD}}[T])$$

Loss of single pixel capacity for T→0 because of freeze-out of the quenching resistor



Increasing breakdown voltage with temperature $V_{BD} \propto T$ because of thermal excitation of phonon modes

At T≃0 charge carrier freeze-out leads to saturation of both

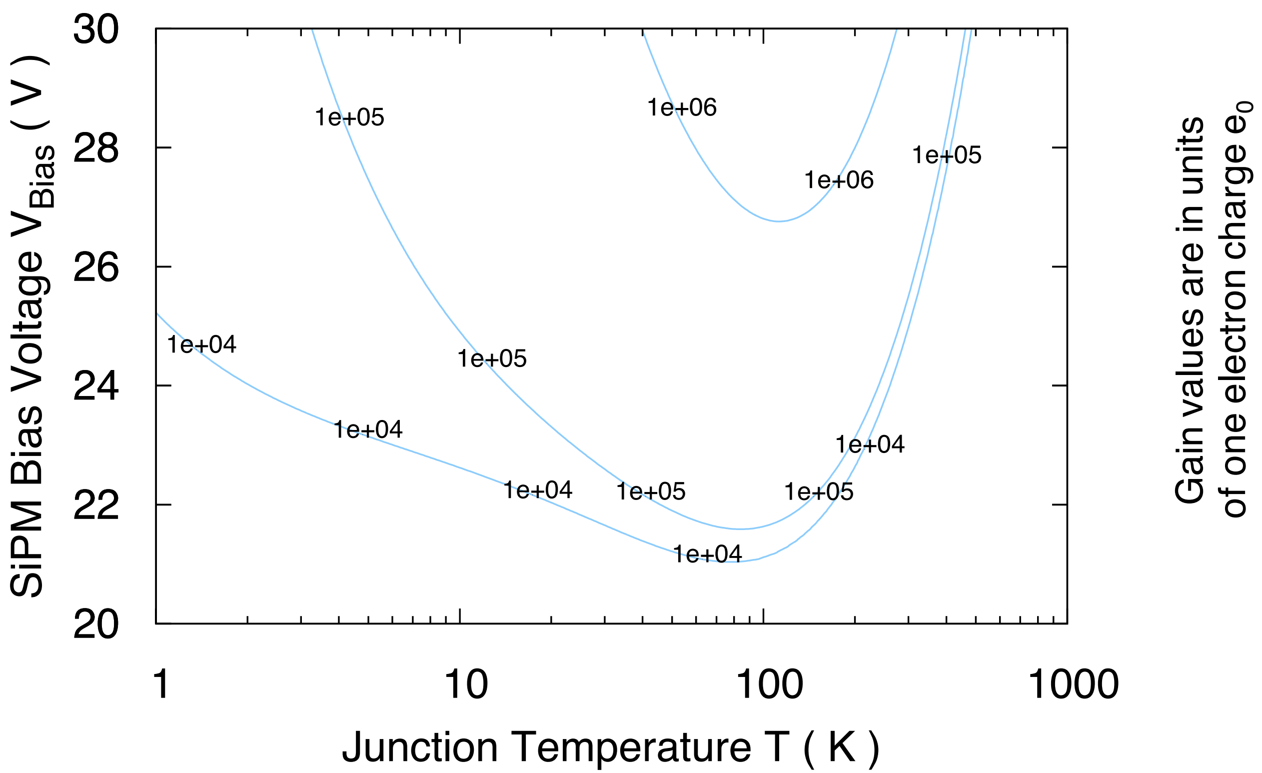
Maik Biroth, Institut für Kernphysik, Mainz, Germany
mbiroth@uni-mainz.de

Model for Automatic SiPM Bias Control

Constant gain G over temperature T by controlling the bias voltage V_{Bias}

$$V_{\mathrm{Bias}}[G,T] = V_{\mathrm{BD}}[T] + \frac{G}{C_{\mathrm{eff}}[T]}$$

Algorithm based on data from SiPM tests was implemented in the HV/temperature controller



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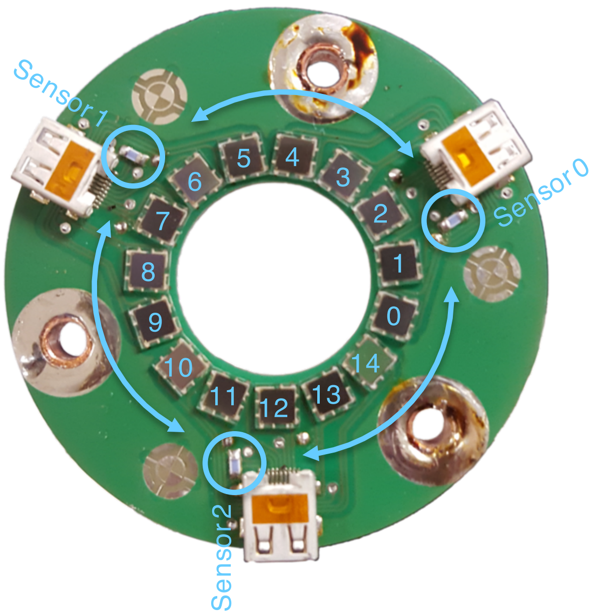
mbiroth@uni-mainz.de

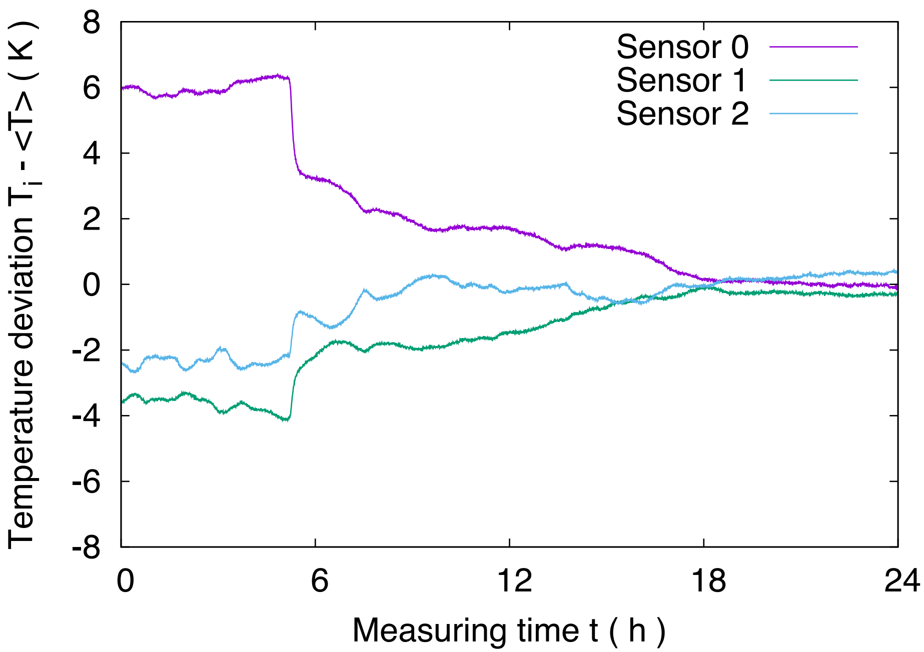
Circular Interpolation of the SiPM Junction Temperatures

SiPMs gain depends strongly from the temperature ~1% K^{-1}. Therefore it is necessary to control the bias voltage some ~10mV K^{-1}. The individual junction temperatures of the SiPMs have been calculated by a circular interpolation between the 3 temperature probes.

Sketchy formula:

$$T_n = T_{Sensor(i)} + \frac{\measuredangle(SiPM, Sensor) + n \cdot \measuredangle(SiPM, SiPM)}{\measuredangle(Sensor, Sensor)} \cdot (T_{Sensor(i+1)} - T_{Sensor(i)})$$





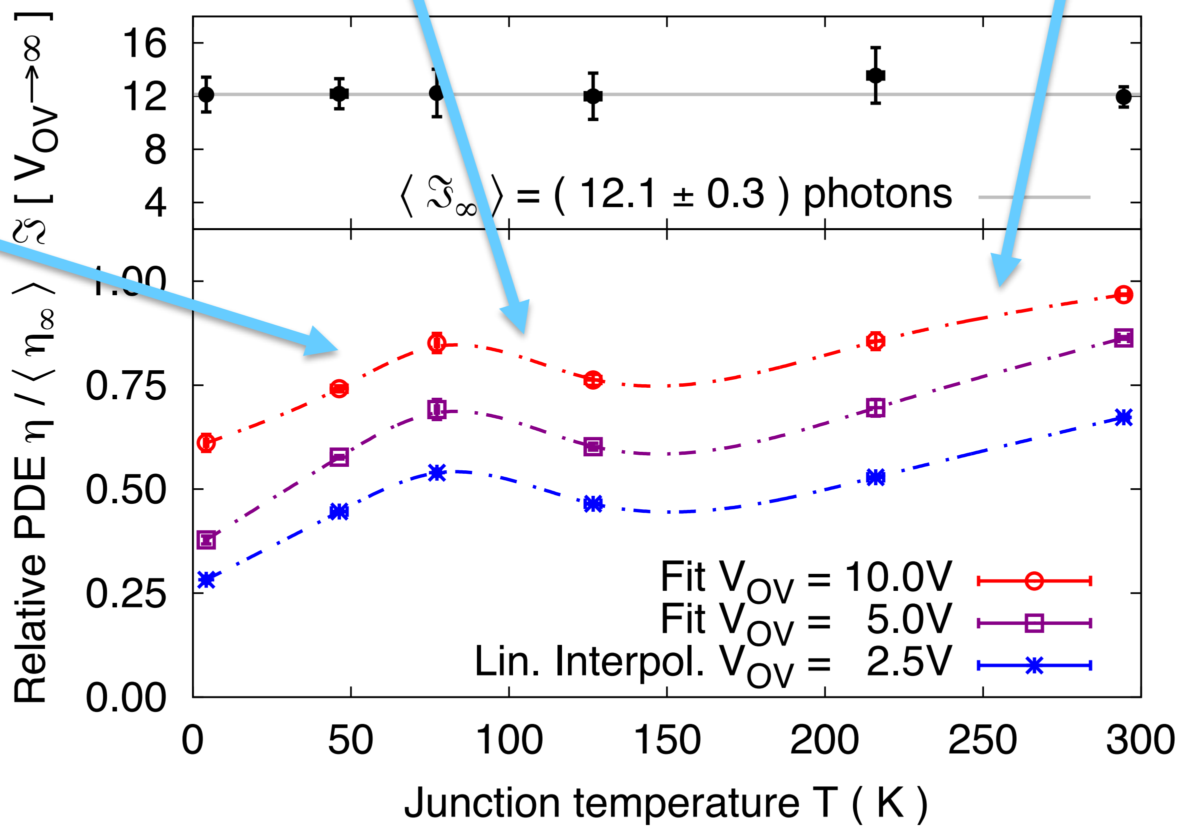
Maik Biroth, Institut für Kernphysik, Mainz, Germany
mbiroth@uni-mainz.de

SiPM PDE with Decreasing Temperature

Increase because of the charge carrier mobility

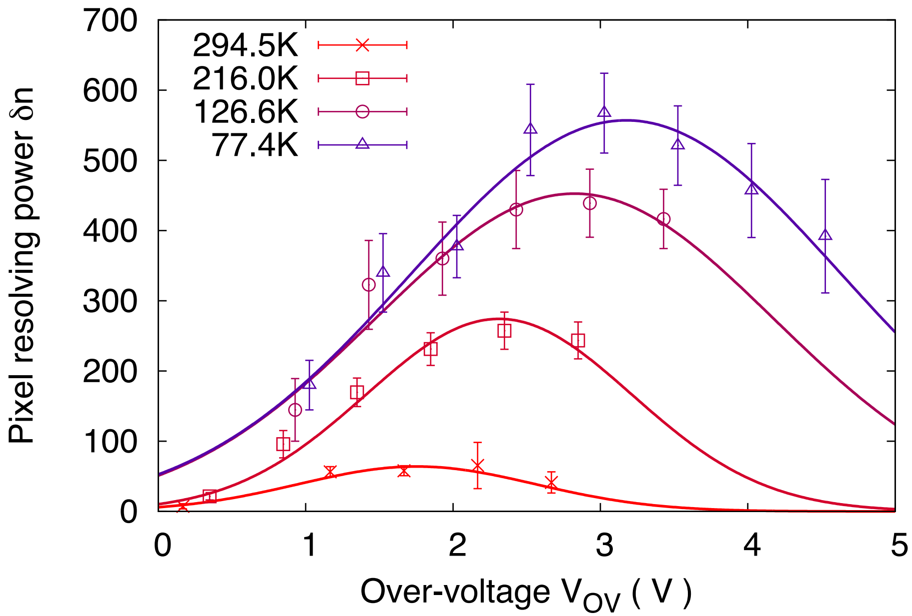
PDE decreases with temperature because of acoustical phonon freeze-out

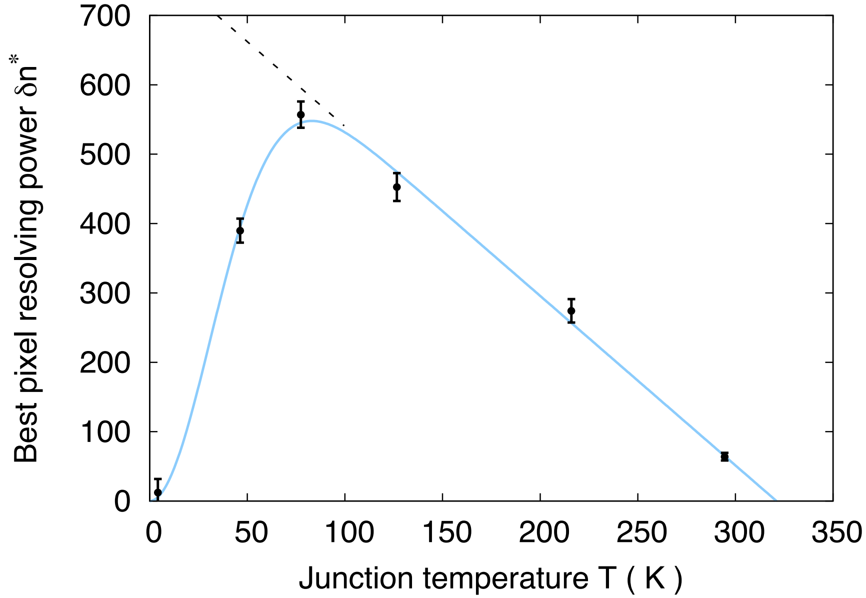
Decrease because of charge carrier freeze-out



Optimum of Single-pixel Resolution

Peaking of the single-pixel resolution around liquid nitrogen temperatures

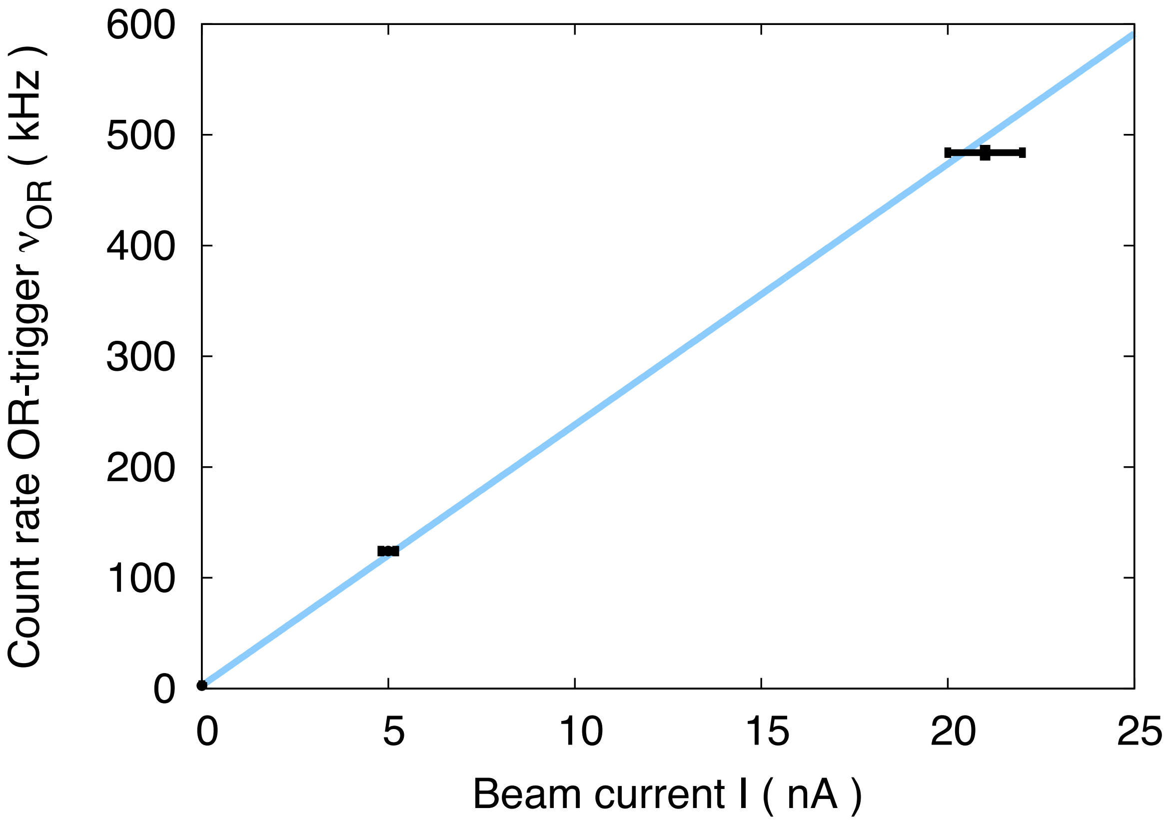




Maik Biroth, Institut für Kernphysik, Mainz, Germany
mbiroth@uni-mainz.de

Self-triggered Rate Test

Rate was measured for different beam currents.
The single-detector dead-time was 250ns.



5nA	21nA
(121±2)kHz	(481±5)kHz
(24±1)kHz nA^{-1}	(23±1)kHz nA^{-1}

- virtually no saturation effects

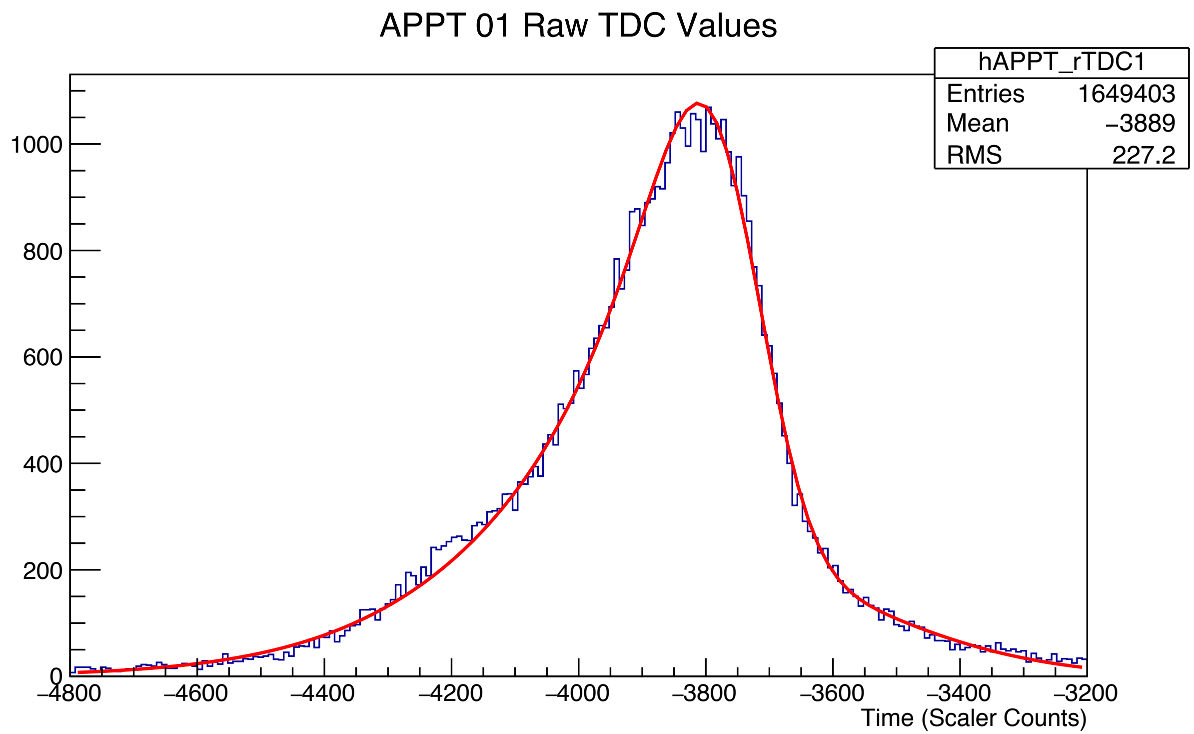
TDC Calibration – Fit of Raw Spectra

Convolution of exponential distribution with arrival time τ

$$\propto exp\left[-\frac{t}{\tau}\right]$$

and Gaussian distribution with resolution σ

$$\propto exp\left[-\frac{1}{2}\left(\frac{t}{\sigma}\right)^2\right]$$



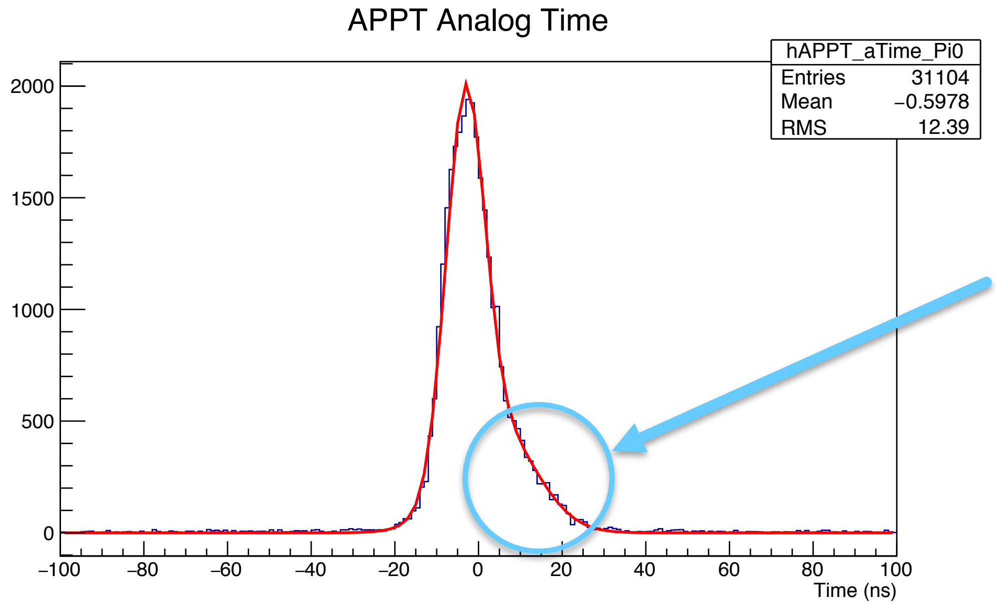
$$N[t] = E[t] * G[t] = \frac{1}{2\tau} \cdot exp\left[\frac{\sigma}{\tau} \cdot \left(\frac{\sigma}{2\tau} - \frac{t-t_0}{\sigma}\right)\right] \cdot \left(1 - erf\left[\frac{1}{\sqrt{2}} \cdot \left(\frac{\sigma}{\tau} - \frac{t-t_0}{\sigma}\right)\right]\right)$$

Maik Biroth, Institut für Kernphysik, Mainz, Germany mbiroth@uni-mainz.de

TDC Calibration – Target Event Time

Options for extracting the target event time

- Use only TDC channel of analog sum
  $\Rightarrow$ Problem of unmatched delays

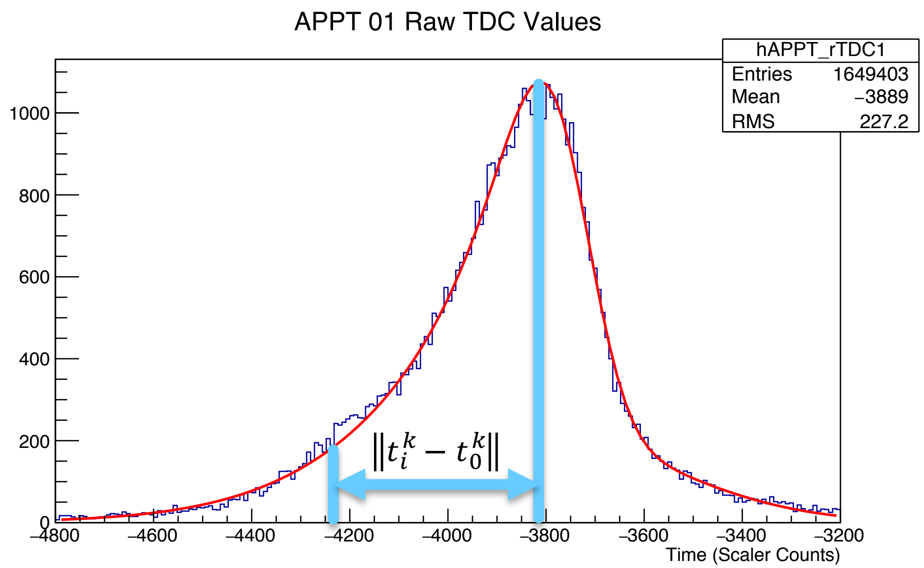


Reference to π^0 time shows up second distribution

- Use additional information contained in the 15 single TDC channels

TDC Calibration – Minimum Algorithm

Minimum algorithm selects for each event the channel with the best timing



For each event i search in all channels k for the individual channel with minimum time gap (t_i-t_0) to its fit parameter t_0

$$\Delta t_i = \left(t_i^{min} - t_0^{min}\right) \Big| \forall k \in \{1 \cdots 15\}: \left\|t_i^{min} - t_0^{min}\right\| \leq \left\|t_i^k - t_0^k\right\|$$

TDC Calibration – Consequences on the Time Spectrum

Non-linear operation ⇒ Time peak is not Gaussian distributed

Convolution of exponential distribution with arrival time τ

$$\propto exp\left[-\frac{t}{\tau}\right]$$

and Cauchy distribution with FWHM Γ

$$\propto \frac{1}{1+4\left(\frac{t}{\Gamma}\right)^2}$$

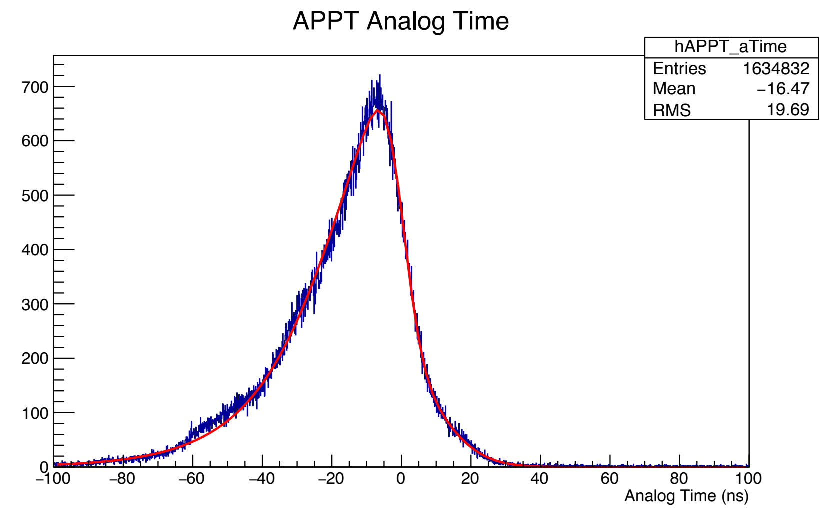
Convolution can be approximated by a linear combination with weight κ

$$N[t] = E[t] * C[t]$$

$$\cong \frac{4}{\pi(1+\kappa)\cdot\Gamma + 4(1-\kappa)\cdot\tau} \cdot \left((\Theta[t_0 - t] + \kappa \cdot \Theta[t - t_0]) \Big/ \left\{ 1 + 4\left(\frac{t - t_0}{\Gamma}\right)^2 \right\} + \cdots \right.$$

$$\left. \cdots + (1-\kappa)\cdot\Theta[t - t_0] \cdot exp\left[-\frac{t - t_0}{\tau}\right] \right)$$

TDC Calibration – Comparison of the Analog and Calculated Spectra



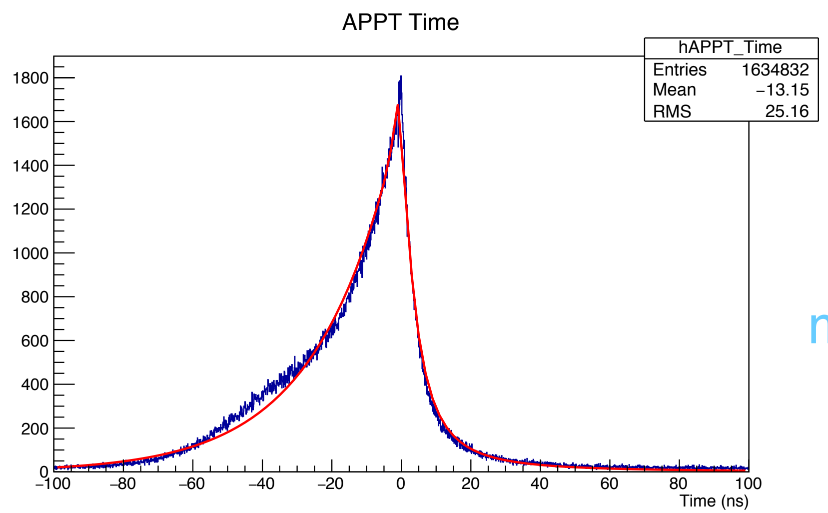
Time spectrum of the analog sum

$\sigma = 4.4ns$

$FWHM = 10.3ns$

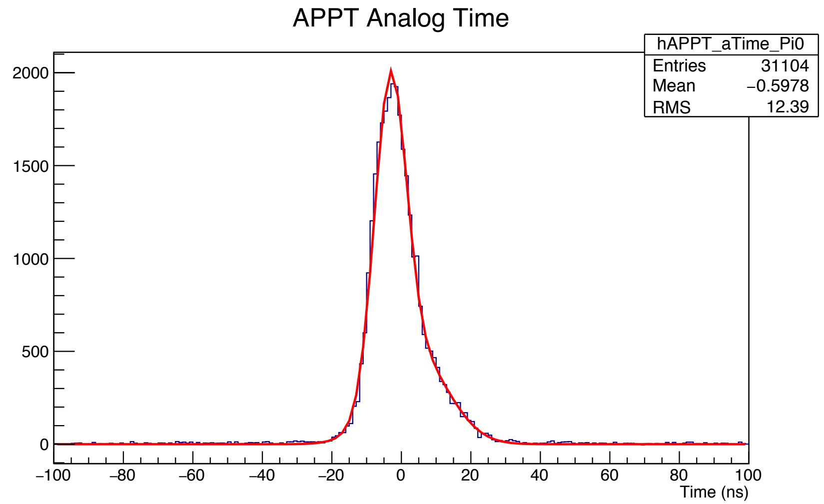
Time resolution similar

$\Gamma = 9.0ns$



Time spectrum by the minimum algorithm

TDC Calibration – Tim Spectra Referenced to π^0

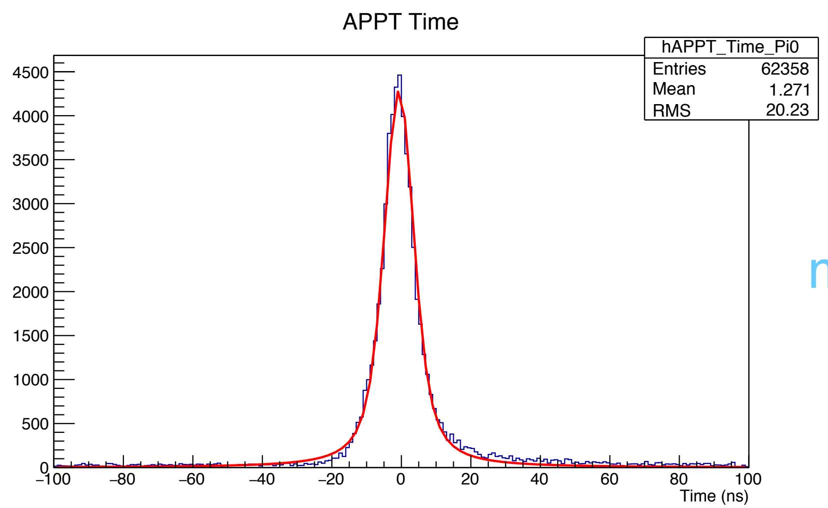


$\sigma = 4.5ns$

$FWHM = 10.7ns$

Time spectrum of the analog sum fitted with two Gaussian distributions

Time resolution equal, but spectrum symmetrical



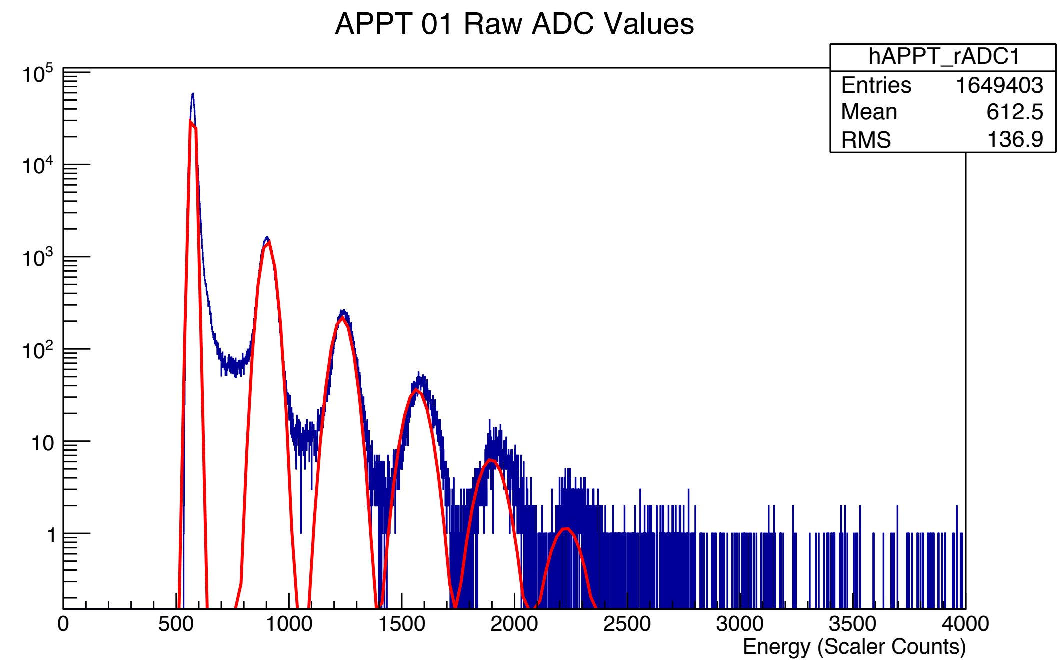
$\sigma = 2.9ns$

$\Gamma = 5.8ns$

$FWHM = 10.4ns$

Time spectrum by the minimum algorithm fitted with Voigt profile

ADC Calibration – Fit of Raw Spectra



Peaks in SiPM spectra are Gaussian distributed

$$\propto exp\left[-\frac{1}{2}\frac{\{Q-(Q_0+n\,G_{SP})\}^2}{\sigma_0^2+n\,\sigma_{SP}^2}\right]$$

Pedestal position Q0

Pedestal width σ_0

Single-pixel gain G_{SP}

Single-pixel variation σ_{SP}

Energy resolution $\frac{\Delta E}{E} \cong \frac{1}{\sqrt{n}} \cdot \frac{\sigma_{SP}}{G_{SP}} = \frac{8\%}{\sqrt{n}}$

Pixel resolution $\hat{n} \cong \left(\frac{G_{SP}}{\sigma_{SP}}\right)^2 = 156px$

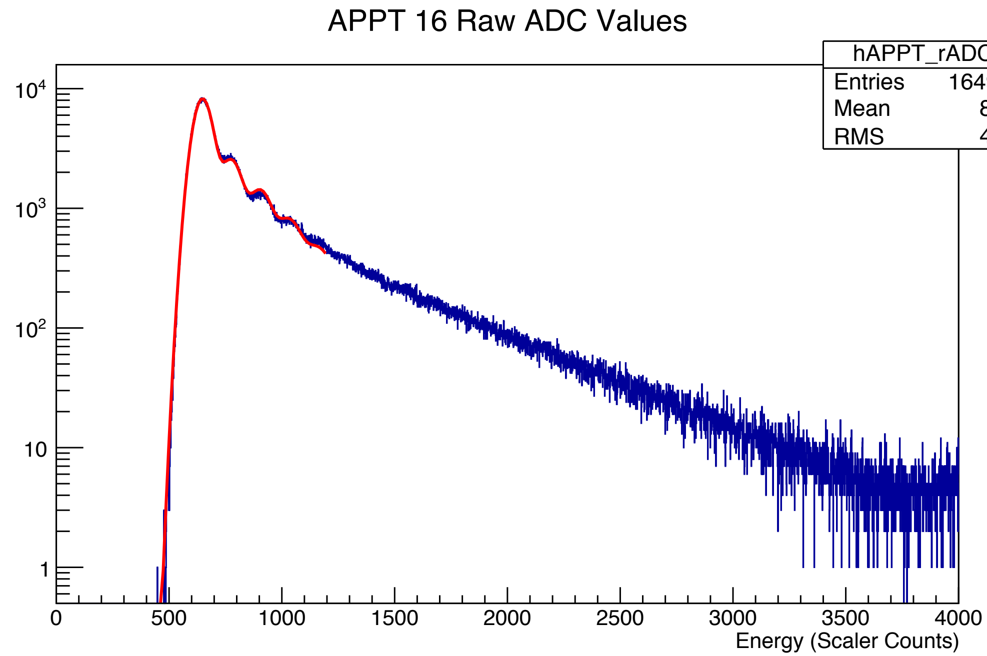
Maik Biroth, Institut für Kernphysik, Mainz, Germany mbiroth@uni-mainz.de

ADC Calibration – Fit of Analog Sum

If single-detector gains are well aligned

$$\sigma_{eff} = \sqrt{15\,\sigma_0^2 + n\,\sigma_{SP}^2}$$

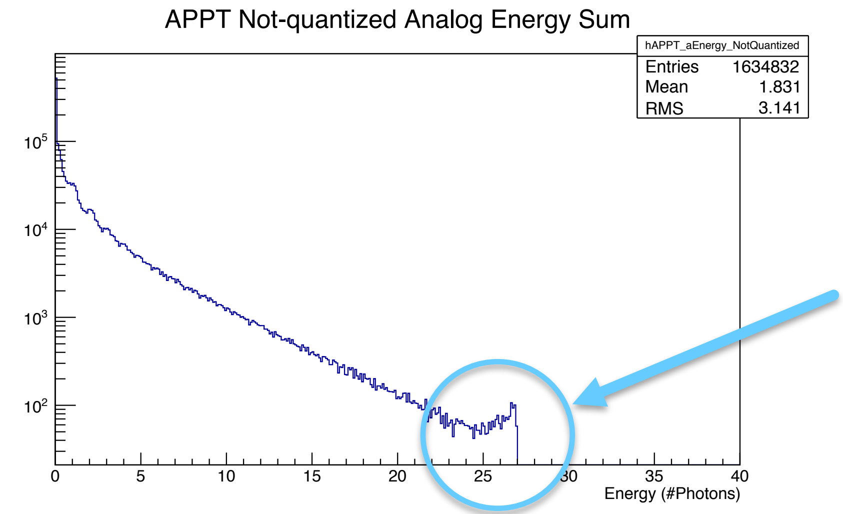
If not, spectrum is washed out



→ Use information contained in the 15 single ADC channels, calibrate them and sum up

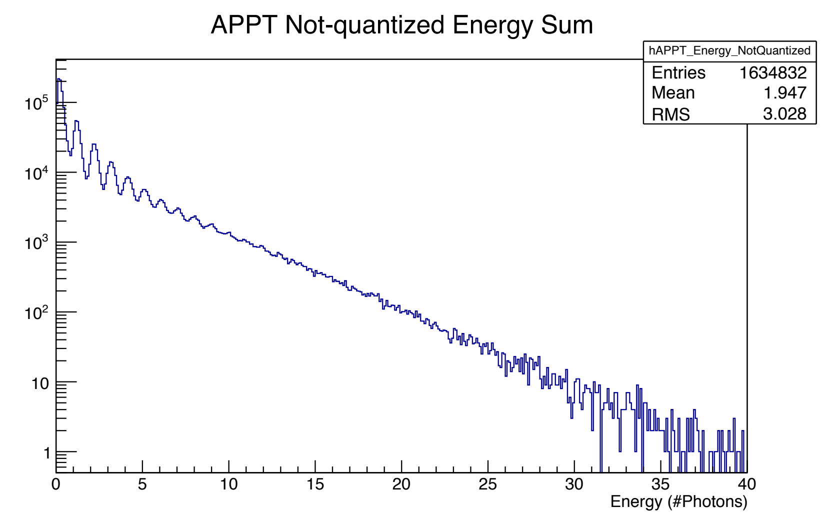
ADC Calibration – Calculate the Energy Sum

Analog Energy Sum



Washed out spectrum and saturation for high gains and intensities

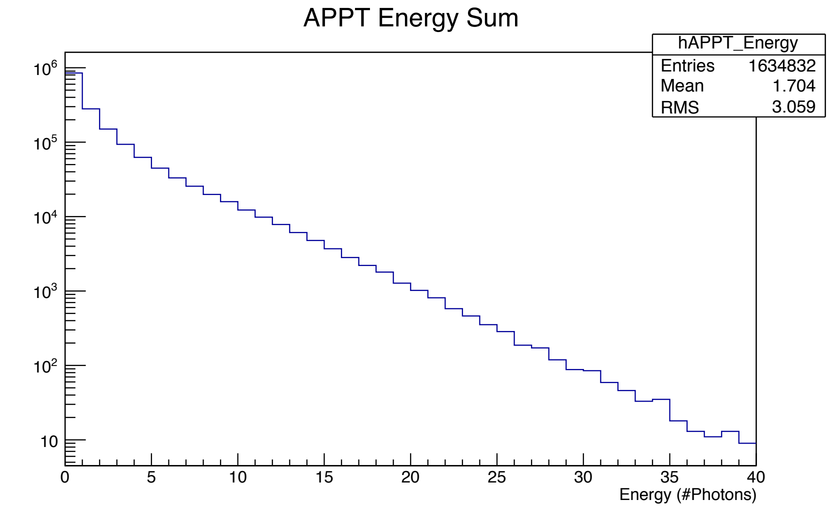
Energy Sum out of the single spectra



Better single-pixel resolution and dynamic range

ADC Calibration – Improve the Energy Sum

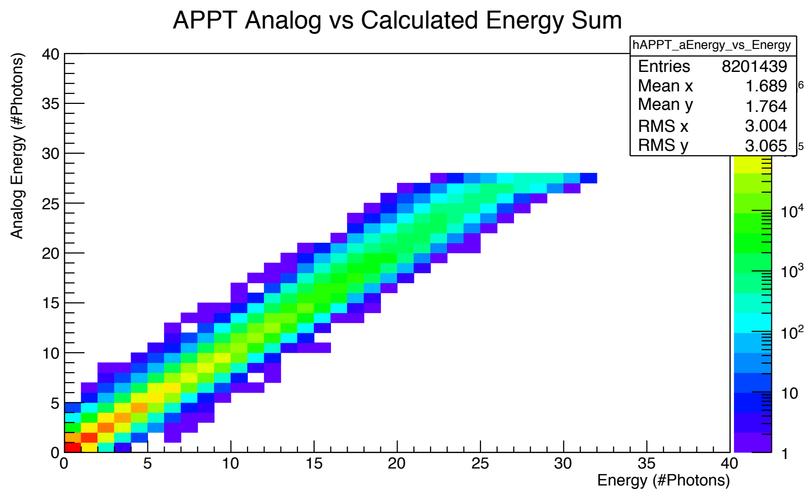
Calculated discrete energy sum



Quantize energy in the single channels before summing up

$$\sigma_{eff} \propto \sqrt{n}$$

Proof of correlation between analog and calculated energy sum

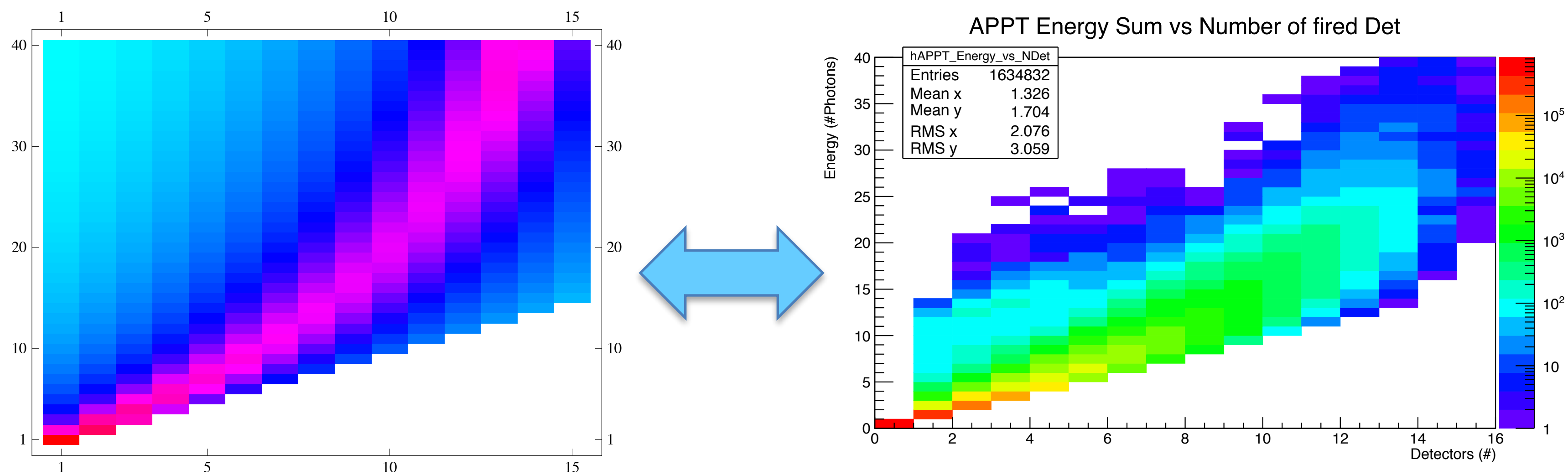


Detectors Multiplicity – Total Energy

Distribution of detector multiplicity is given by Binomial distribution using Jordan term

$$P_{n,\lambda} = \sum_{i=0}^{n} (-1)^i \binom{N}{n} \binom{n}{i} \left(\frac{n-i}{N}\right)^{\lambda}$$

Involving intensity distribution and crosstalk effects leads to the measured spectrum



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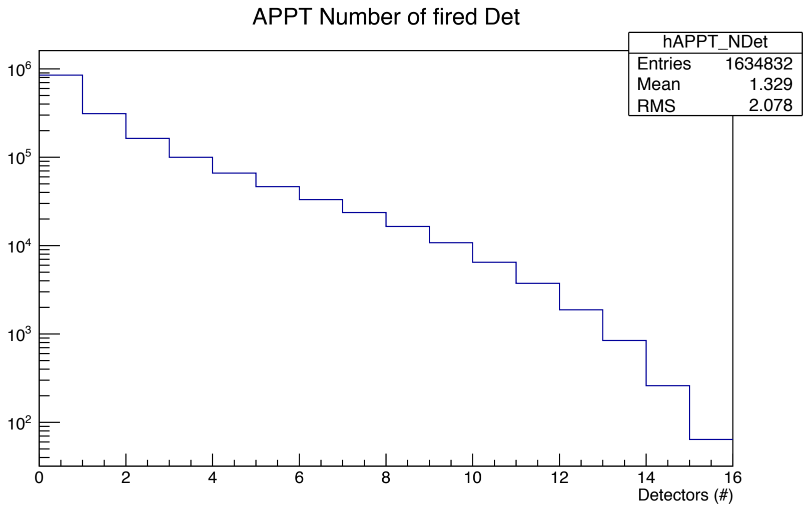
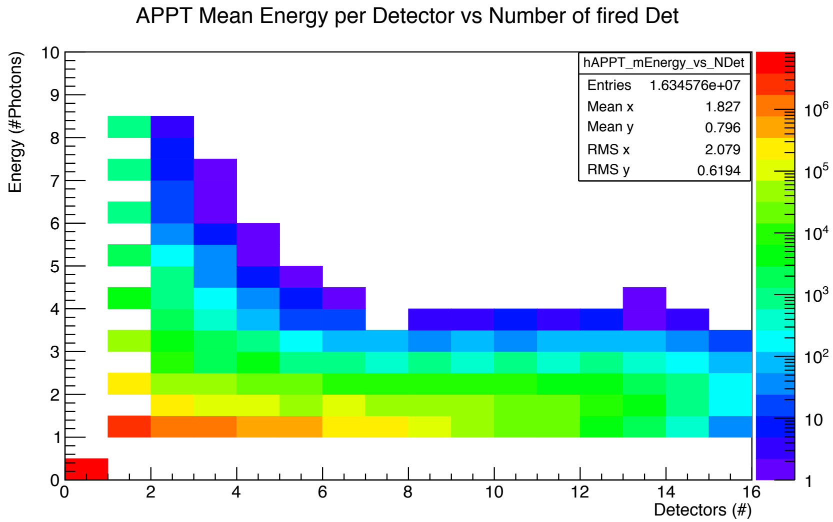
mbiroth@uni-mainz.de

Detectors Multiplicity – Mean Energy

Mean energy deposition per detector is 1-3 photons

Maximum energy is limited





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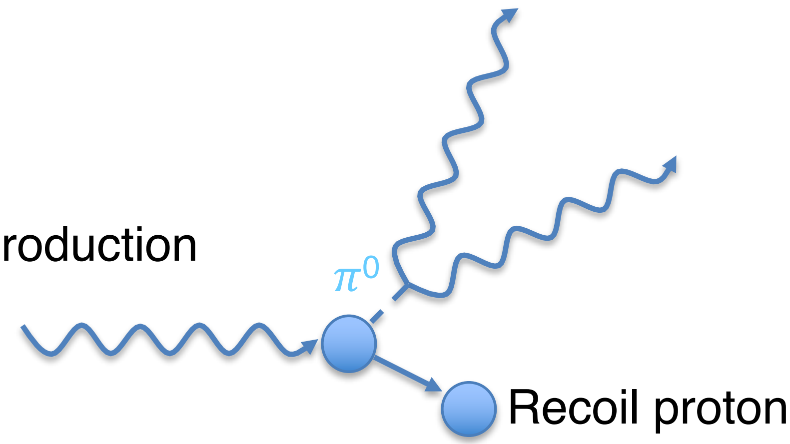
mbiroth@uni-mainz.de

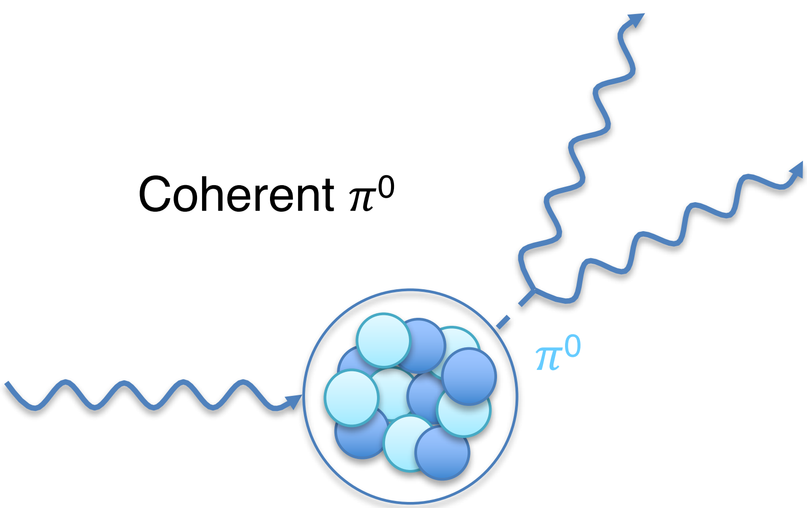
Analysis π^0 – Background Reactions of γ,p → π^0,p

Proton π^0 photo production

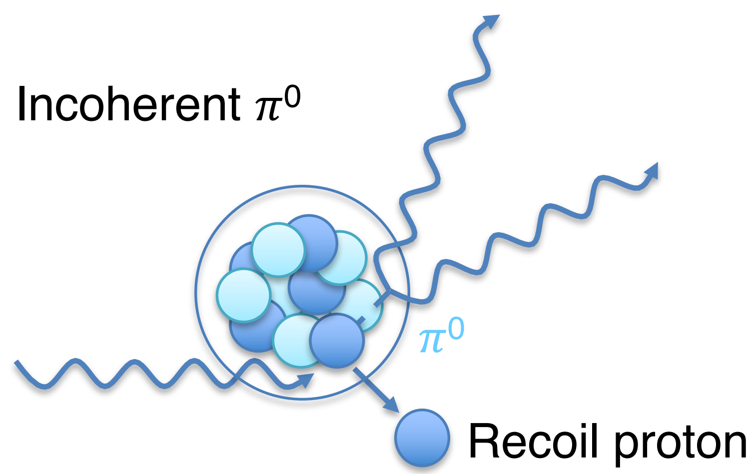


Background reactions by scattering on ^{12}C or heavy nuclei

Coherent π^0



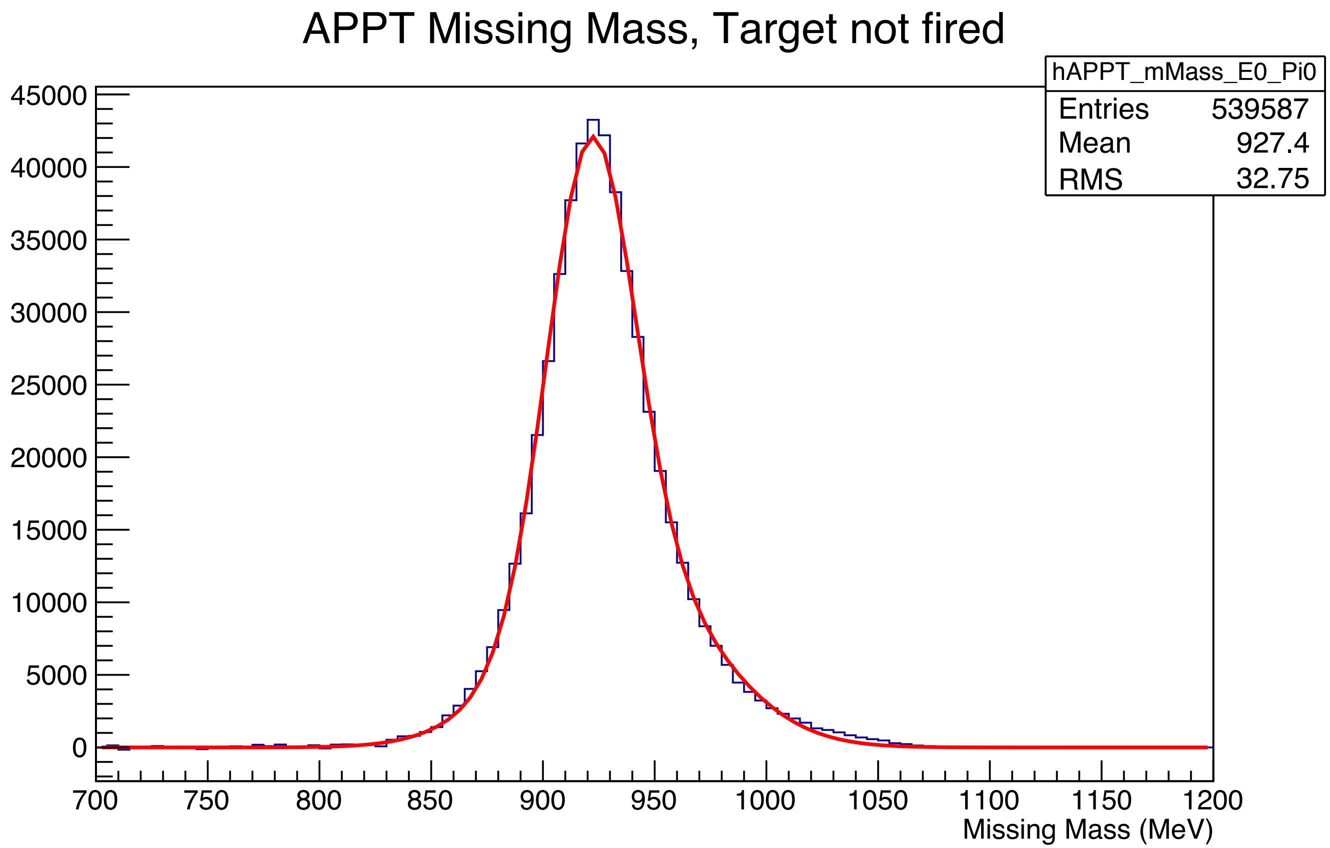
Incoherent π^0



Maik Biroth, Institut für Kernphysik, Mainz, Germany mbiroth@uni-mainz.de

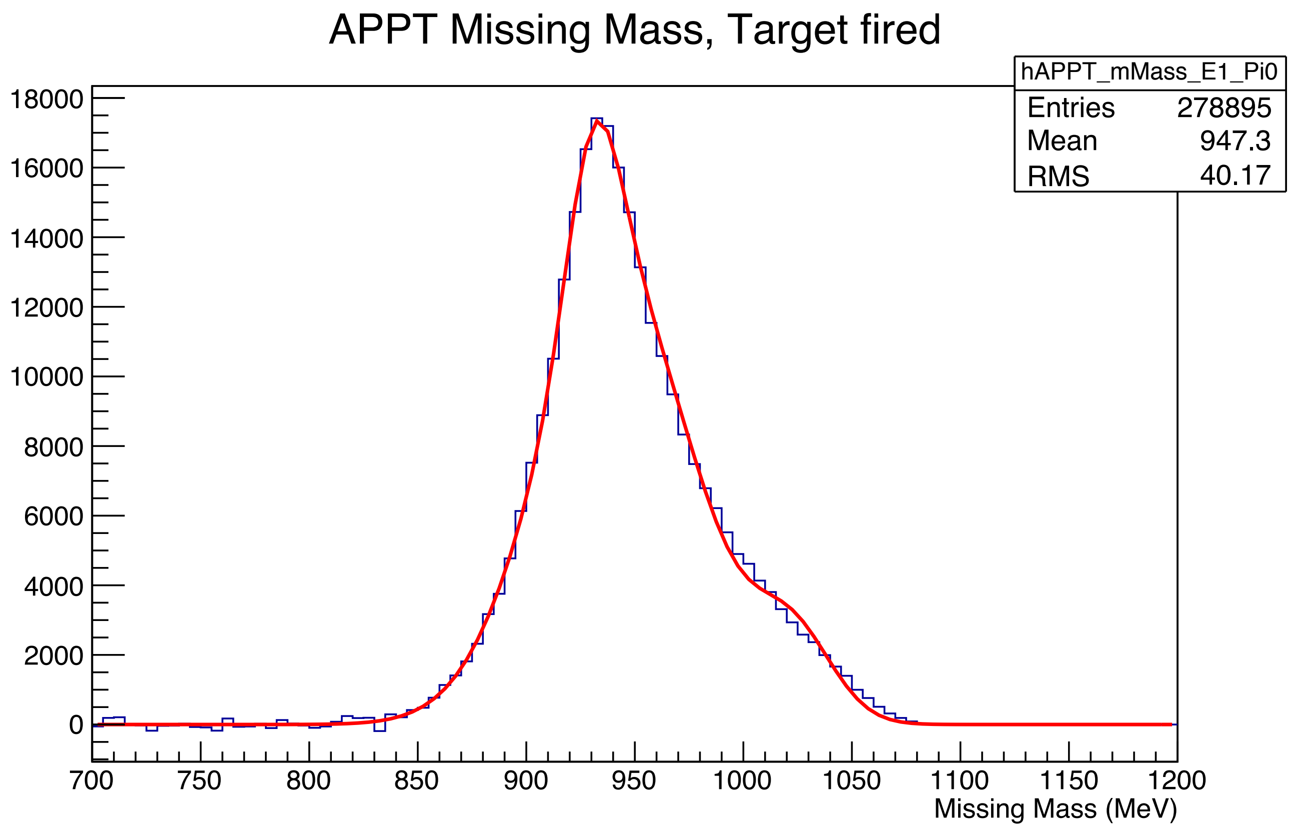
Analysis π^0 – Proton Detection Efficiency from Missing Mass Spectrum

Target did not fire, Two distributions:
Coherent scattering at 921 MeV and
undetected recoil protons at 935 MeV



Analysis π^0 – Proton Detection Efficiency from Missing Mass Spectrum

Target fired, Two distributions:
Recoil protons from scattering on H and
a broad distribution from incoherent scattering on ^{12}C



Analysis π^0 – Proton Detection Efficiency from Missing Mass Spectrum

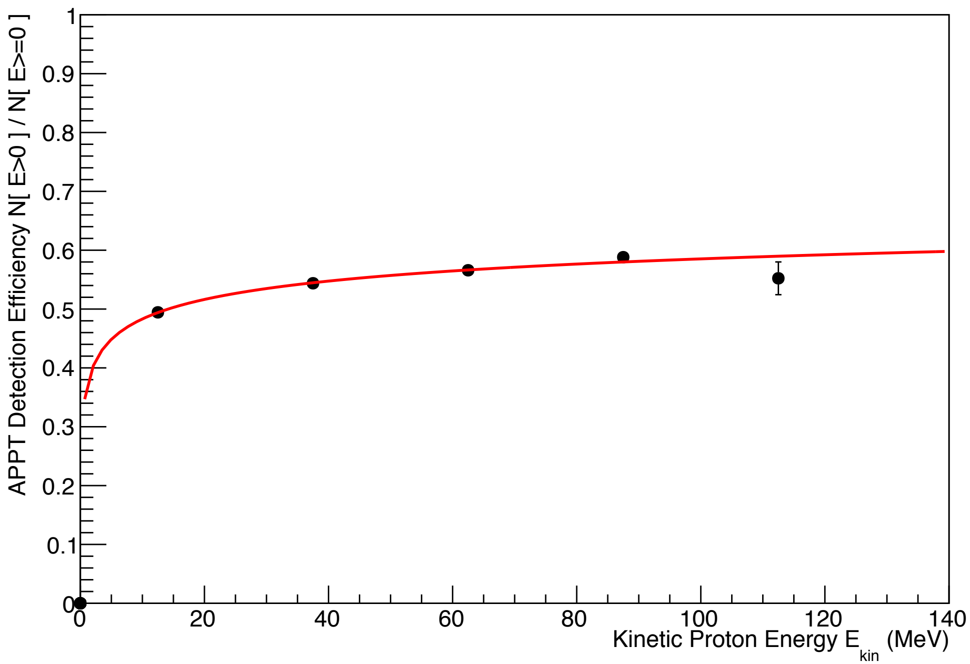
Ratios were extracted from the number of entries in the Missing Mass spectra

Scattering	Missing Mass	Ratio
Coherent	921 MeV	36.3%
Incoherent, not det.	935 MeV	29.5%
Incoherent, detected	-	34.2%

$$\langle \varepsilon \rangle = 54\%$$

Analysis π^0 – The Forbidden Protons

Select π^0 events where recoil proton was detected outside → Check target energy λ



Exponential fit

$$\varepsilon[E_{kin}] = \frac{\int_1^\infty d\lambda \cdot N}{\int_0^\infty d\lambda \cdot N}$$

$$= \varepsilon_\infty \cdot \left(1 - \exp\left[-\frac{E_{kin}}{E_{kin,0}}\right]\right)$$

Maik Biroth, Institut für Kernphysik, Mainz, Germany mbiroth@uni-mainz.de

Efficiency from fit

$$E_{kin}^{10\%} = (0.8 \pm 0.2) MeV$$

$$\varepsilon_{\infty} = (55 \pm 1)\%$$

Efficiency from all events 0-200MeV

$$\langle\varepsilon\rangle = \frac{\int dE_{kin} \int_1^{\infty} d\lambda \cdot N}{\int dE_{kin} \int_0^{\infty} d\lambda \cdot N} = (54 \pm 2)\%$$

Outlook and Conclusion

Tanks to anybody who helped to realize this project!

- ✓ The first forward active target was operated successfully down to 45mK
- ✓ 2 weeks of data taking at high polarization up to ±50%
- ✓ small error on polarization measurement: protons from surrounding material are separable by NMR
- ✓ high-sensitive and low-noise electronic was developed which was integrated in the EPICS slow-control system
- ✓ Calibration of the detectors successful
- ✓ Proton detection efficiency of more than 50% achieved
- ▪ Compton analysis is ongoing