J.-B. Mosset, A. Stoykov, M. Hildebrandt :: NUM :: Paul Scherrer Institut

Development of a 2D WLS fibre scintillation detector with SiPMs

SINE2020 WP9, PSI, Switzerland, June 2017

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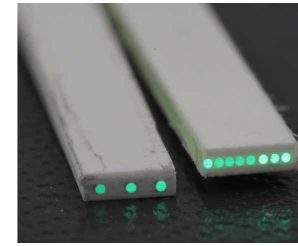
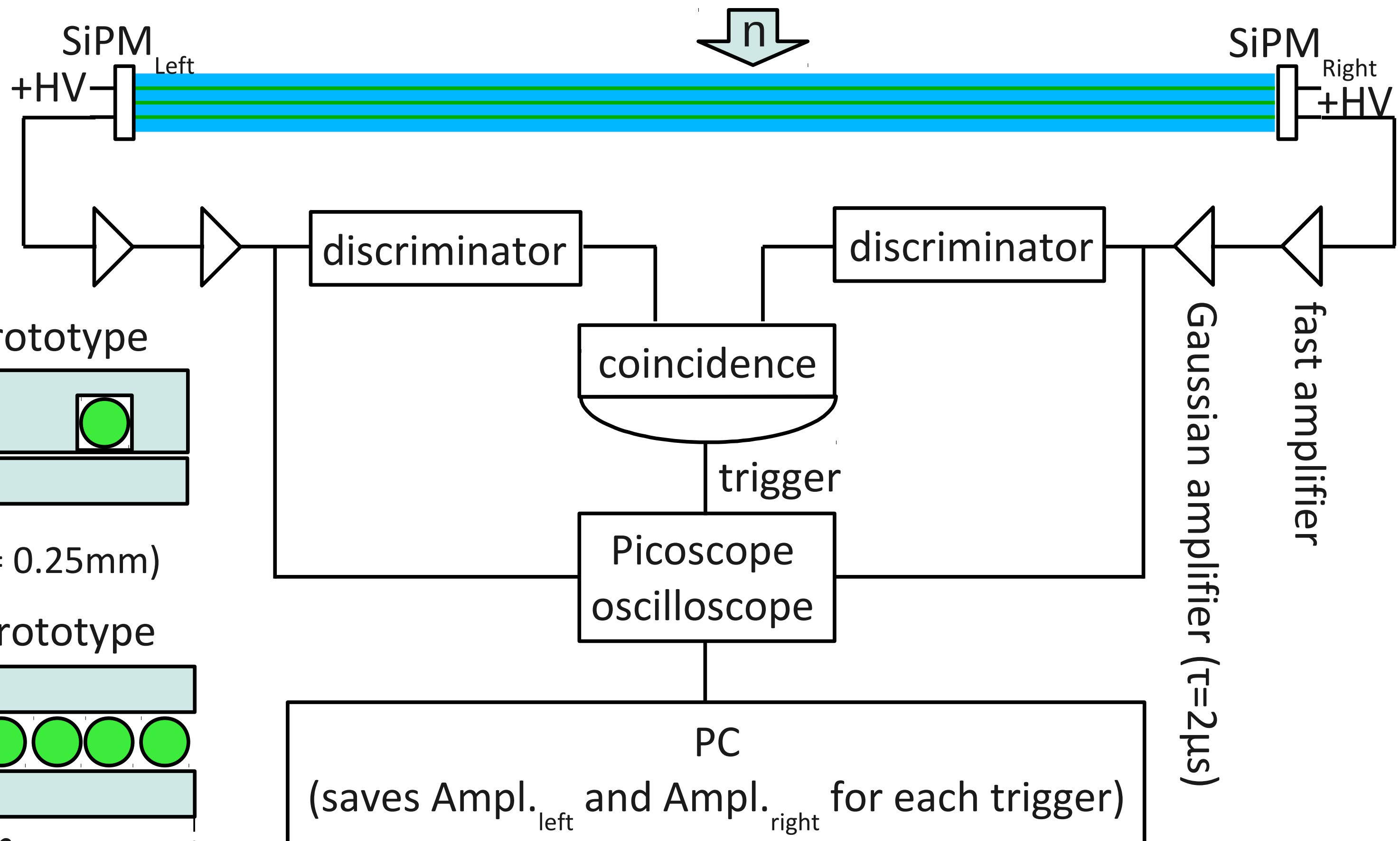
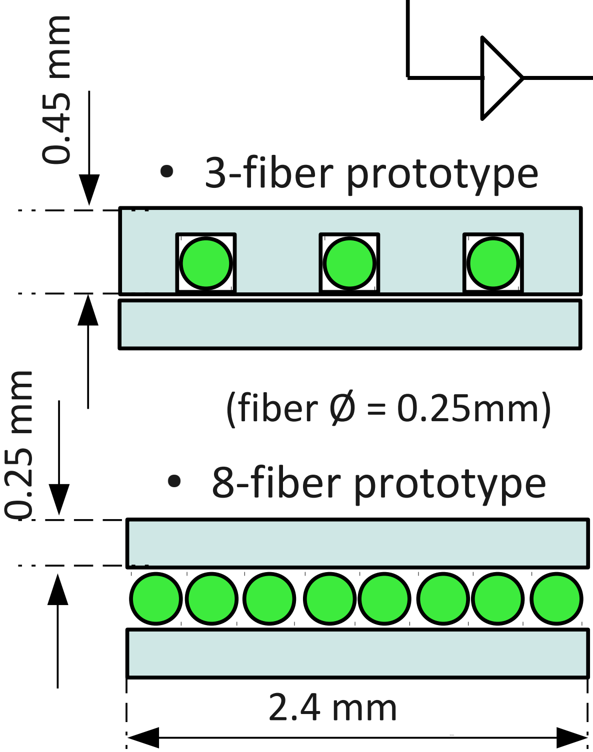
Reminder concerning the results obtained in 2016

2D detector based on light sharing

- ZnS:^{6}LiF detection unit
  - sensitive area $(2.4 \times 200)\ mm^2$
  - WLS fibers with short attenuation length (λ≈15cm) especially developed by Kuraray for this study (core doped with 2wt% PMMA)







Position reconstruction method

- Calculation of the average asymmetry measured at different positions X_i

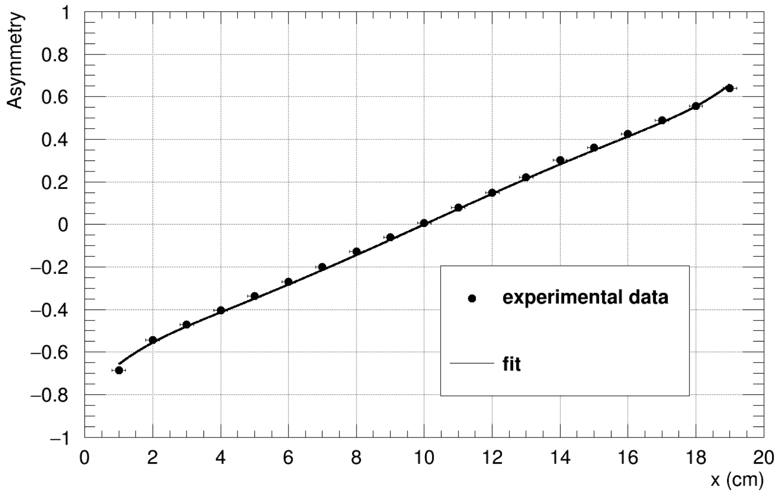
$$\langle asymmetry(x_i)\rangle = \langle \frac{A_R(x_i) - A_L(x_i)\cdot\gamma}{A_R(x_i) + A_L(x_i)\cdot\gamma} \rangle \quad \text{where} \quad \gamma = \langle \frac{A_R(L/2)}{A_L(L/2)} \rangle$$

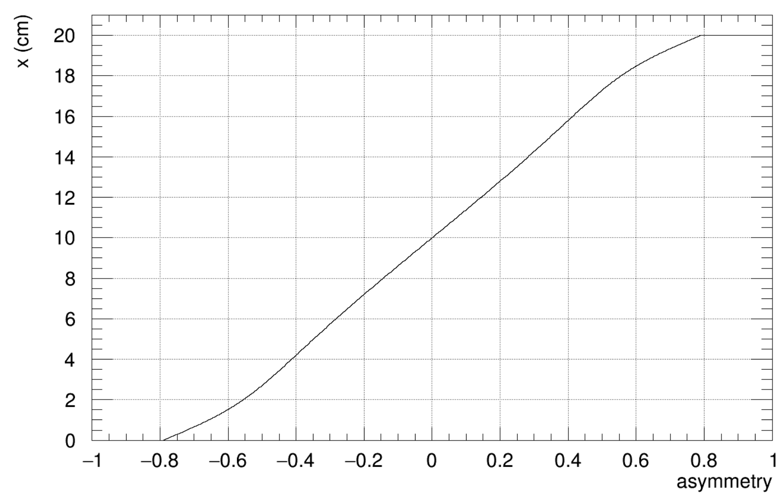
- γ factor --> corrects for possible left / right difference of the readout gain and the optical coupling
- fit of the average asymmetry curve with

$$f_{asym}(x) = \frac{att_R(x) - att_L(x)}{att_R(x) + att_L(x)}$$

where $att_L(x) = \dfrac{I_{long}\cdot e^{-x/\lambda_{long}} + I_{short}\cdot e^{-x/\lambda_{short}}}{I_{long} + I_{short}}$ (λ_{long} , λ_{short} , I_{long} and I_{short} are free parameters)

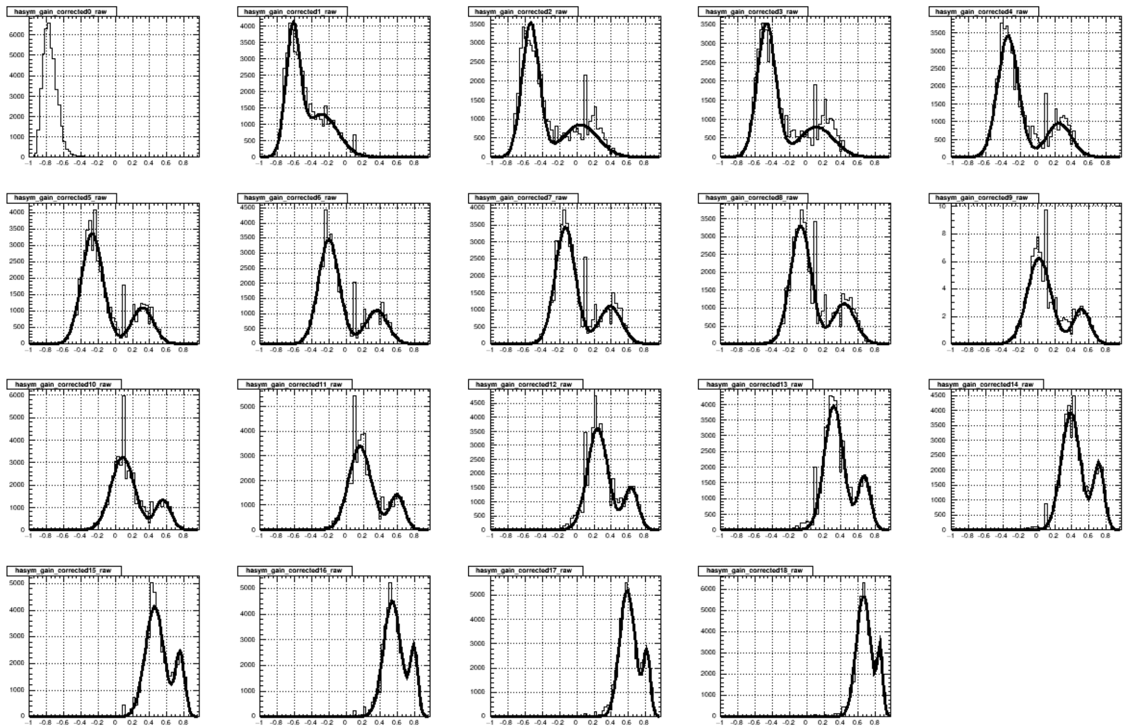
- position reconstruction of individual events with $f_{position}(asym) = f_{asym}^{-1}(x)$





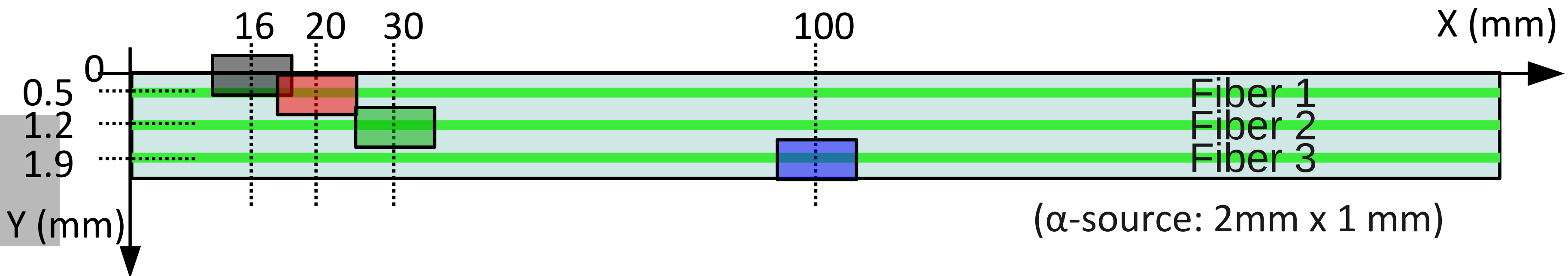
Anomaly observed with the 3-fiber prototype

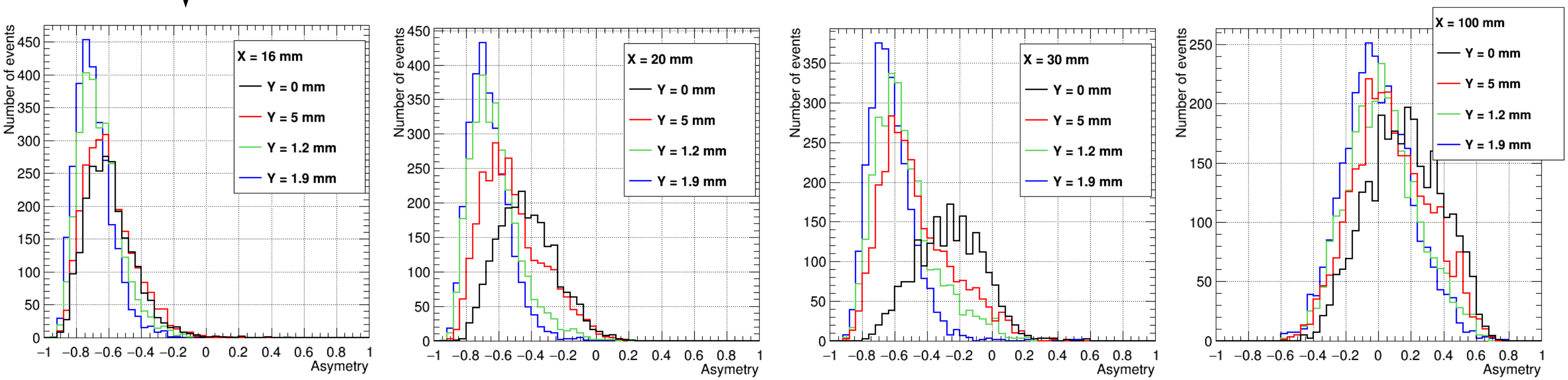
Asymmetry distribution measured at diff. positions (1, 2, .., 19cm)



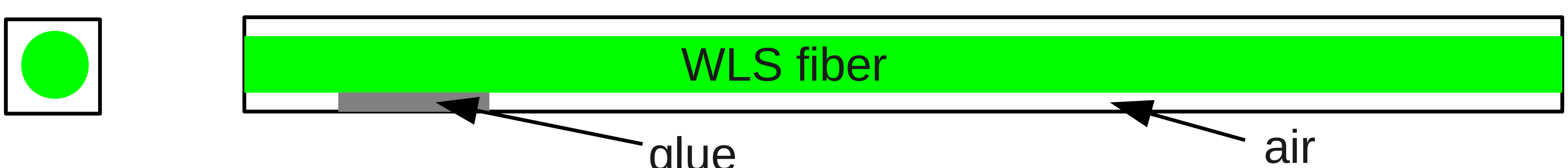
- we suspected that ''something wrong happens with one fiber''
- **only events with an asymmetry in the left peak are selected**

Lateral scans of the bar with a collimated α-source



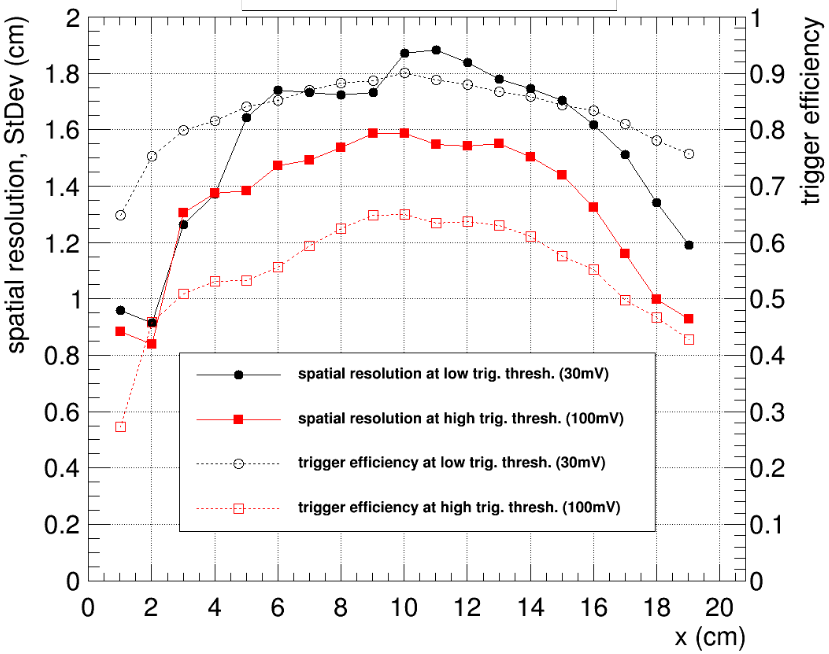


- the asymmetry is the same at all lateral positions except at Y=0, where fiber 1 collects most of the light ---> "something wrong happens with the fiber 1"
  - an optical defect (initial thought) or
  - non uniform index of refraction around the fibers (bad gluing)

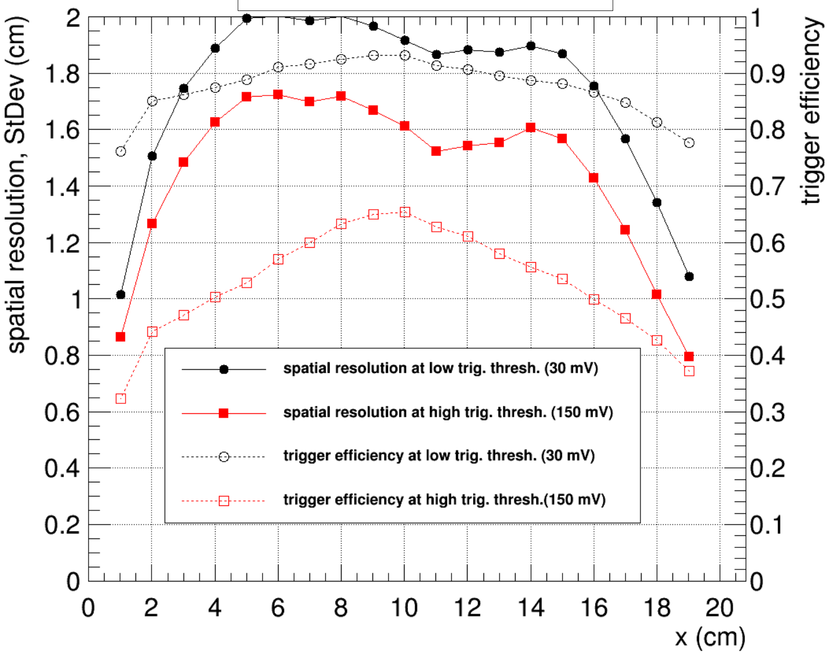


Results

3-fiber prototype



8-fiber prototype



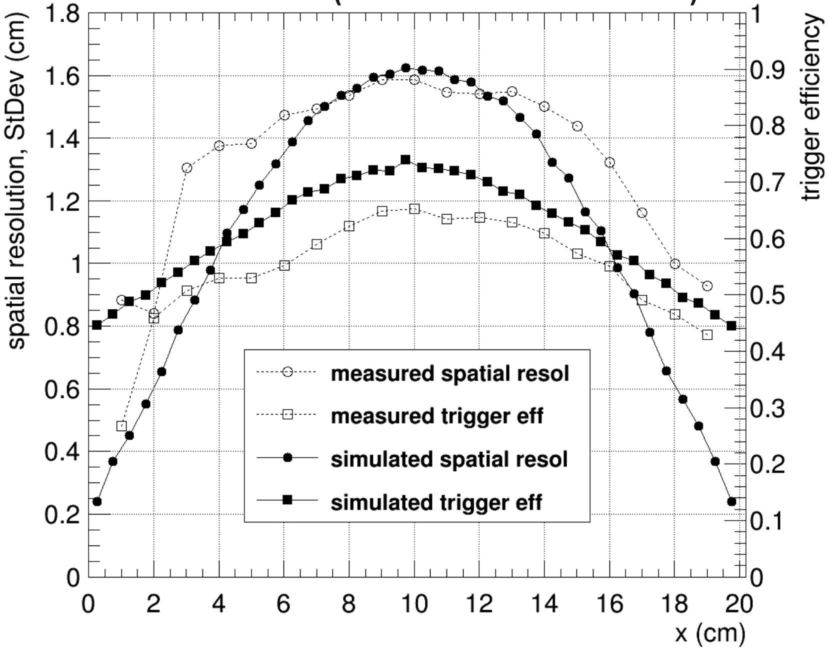
<spatial resolution> ≈ 1.3 cm
@trigger efficiency ≈ 55%

<spatial resolution> ≈ 1.4 cm
@trigger efficiency ≈ 55%

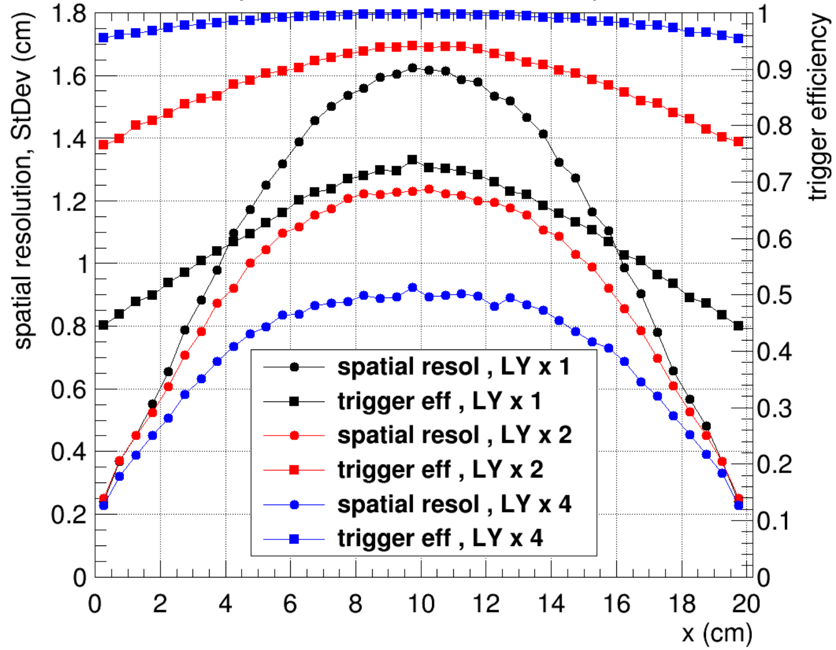
- the 8-fiber prototype has:
  - a LY 40% higher than the 3-fiber prototype
  - a worst spatial resolution than the 3-fiber prototype
  - a spatial resolution that is spoiled because of the non uniform refraction index around the fibers (bad gluing)

Simulation of the 3-fiber prototype

(Threshold = 100 mV)



(Threshold = 100 mV)



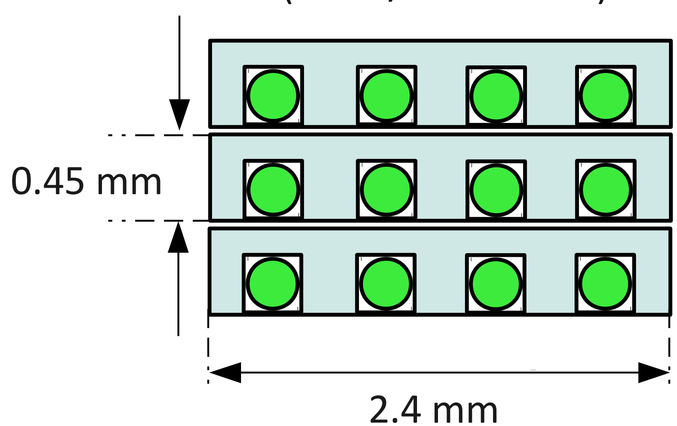
- High LY is crucial for :
  - Spatial resolution
  - Trigger efficiency

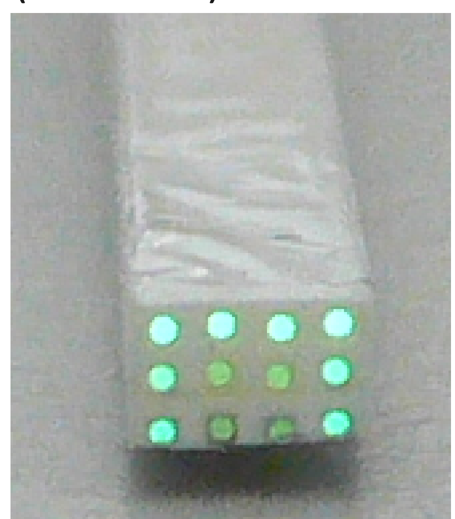
What has been realized in 2017

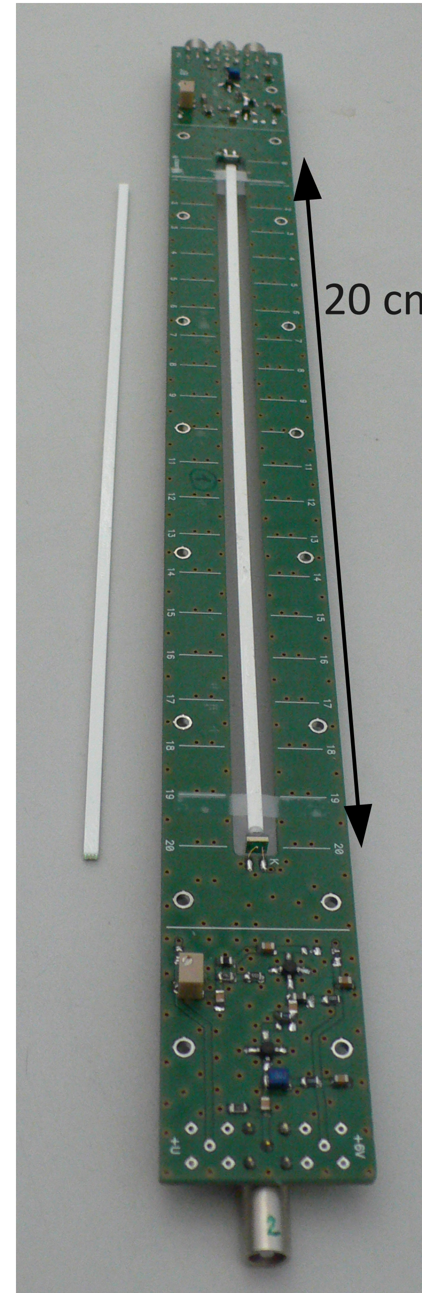
- Preparation of two batches of 15 ''good'' fibers having:
  - a uniform light attenuation over their length
  - similar attenuation lengths

- Production of two prototypes with a new structure
  - fiber grooves entirely filled with optical glue during fiber gluing --> uniform index of refraction around the fibers
  - expected LY at least twice higher than for the 3-fiber prototype
  - 1 proto with the “old” neutron screen ND2:1 (<2016, Scintacor)
  - 1 proto with a new neutron screen ND2:1 (Scintacor)

(fiber Ø = 0.25mm)

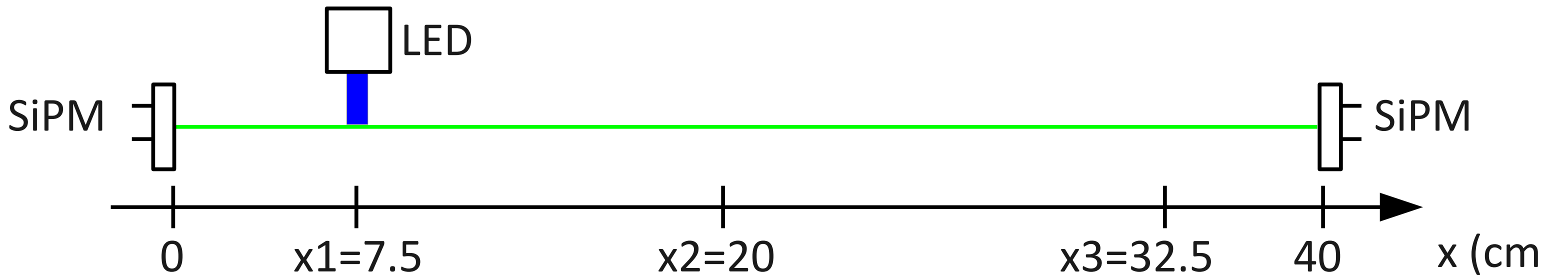






Selection of good fibers

Initial procedure



- Measurement of the asymmetry at 3 positions
- attenuation length determined by fitting the asymmetry curve with:

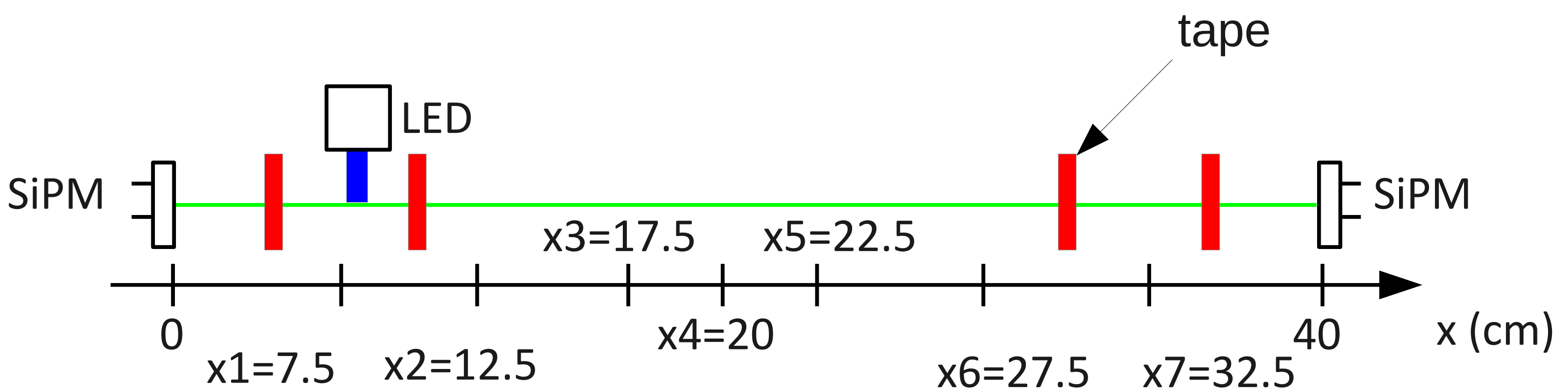
$$f_{asym}(x) = \frac{att_R(x) - att_L(x)}{att_R(x) + att_L(x)}$$

where

$$att_L(x) = \mathrm{e}^{-x/\lambda}$$

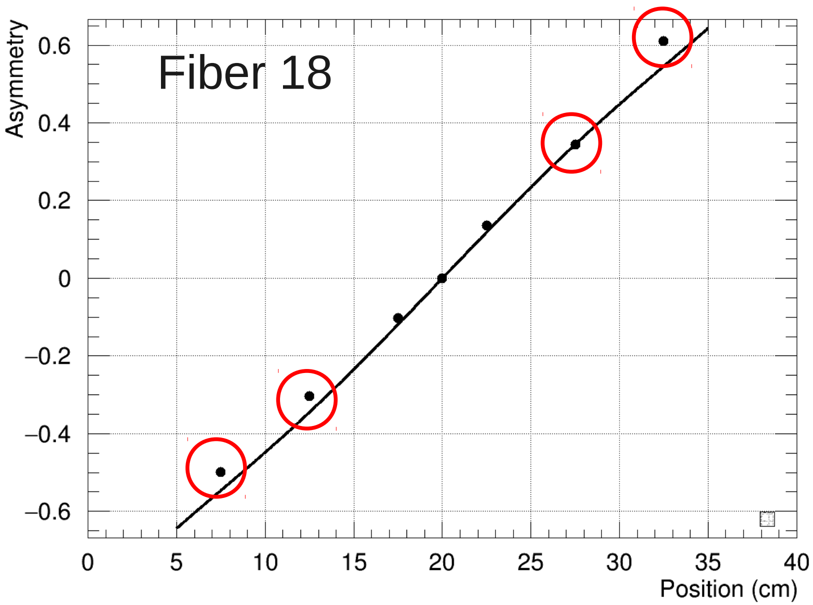
$$att_R(x) = \mathrm{e}^{-(L-x)/\lambda}$$

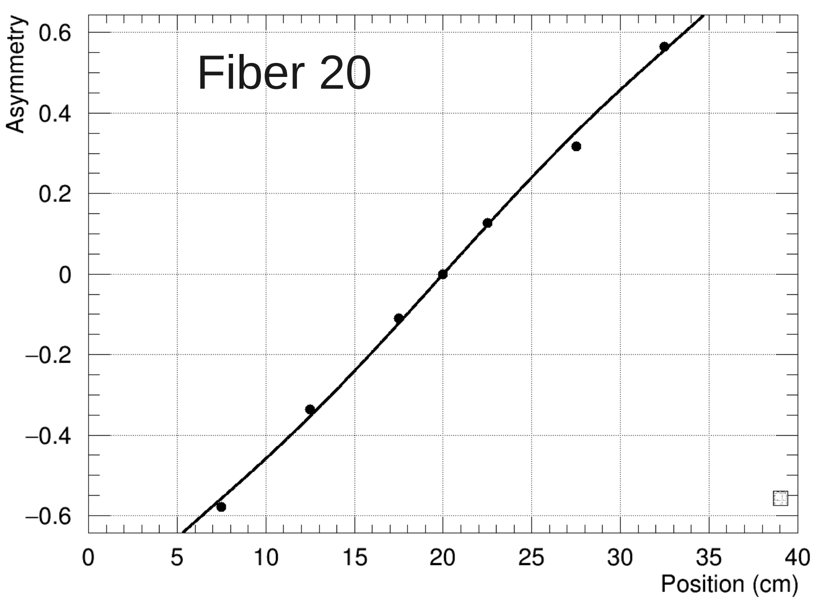
New procedure

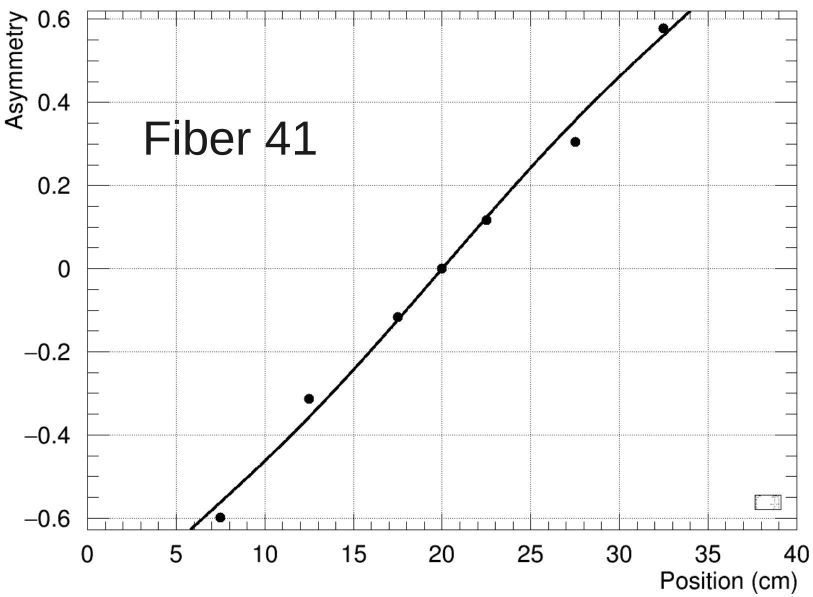


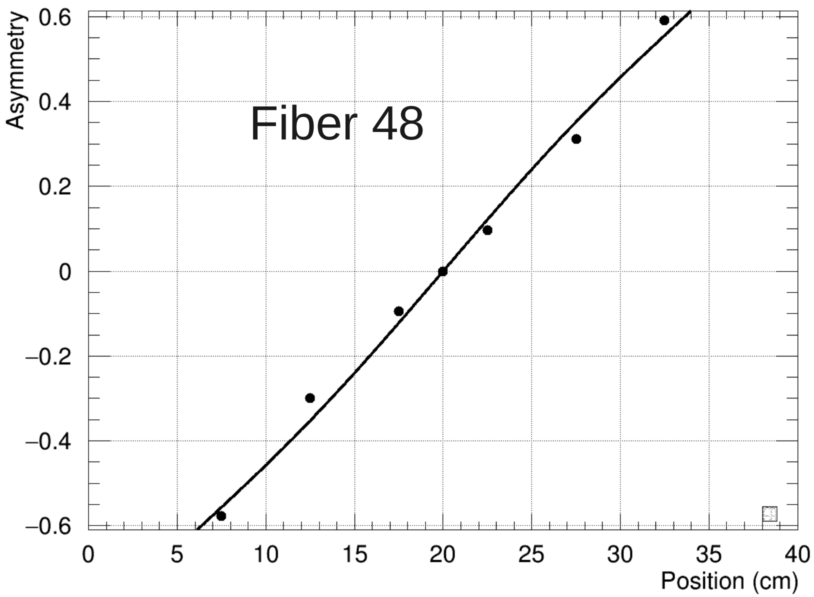
- the 20 fibers tested with the initial procedure are tested again with the new procedure
- in total, 50 fibers have been tested
- the last 21 fibers were labeled following the order in which they were cut
- measurement of the asymmetry at 7 positions

Typical asymmetry curves

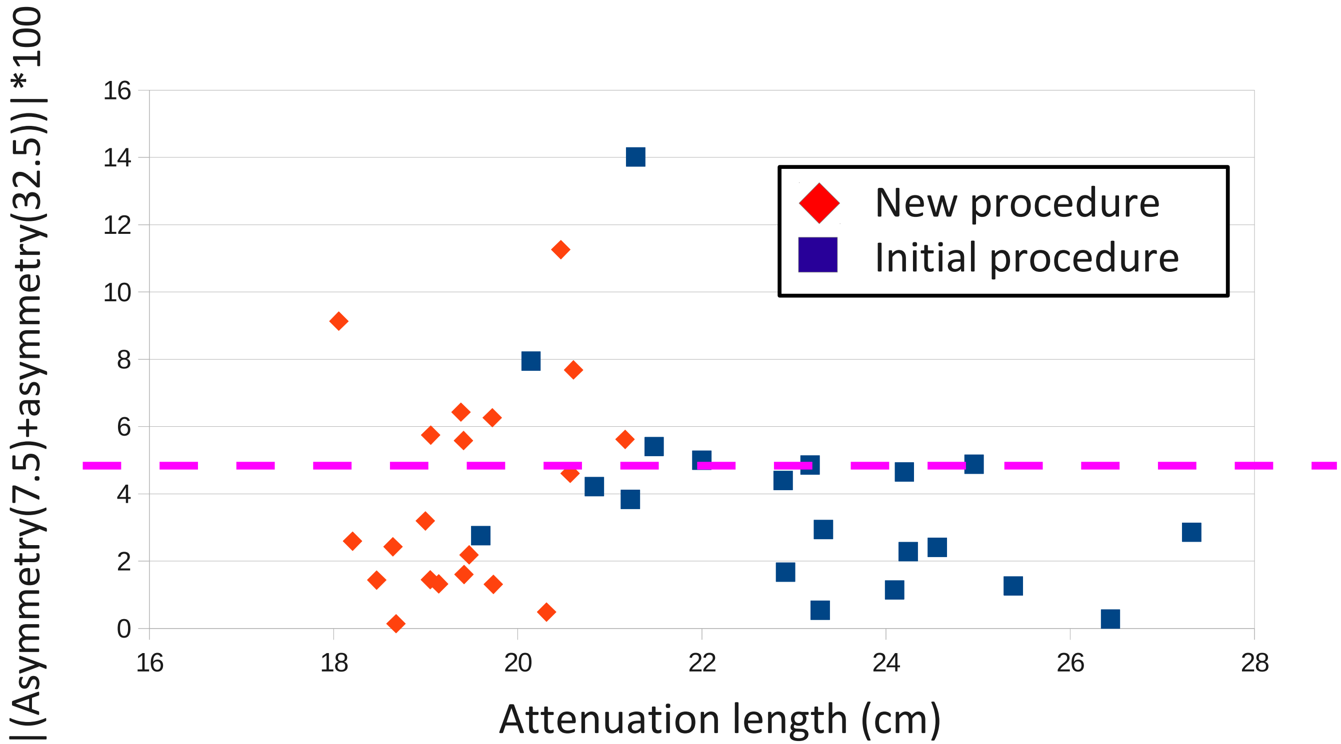






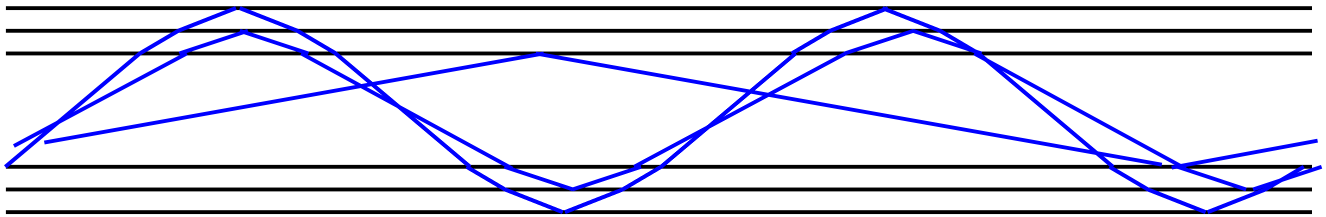


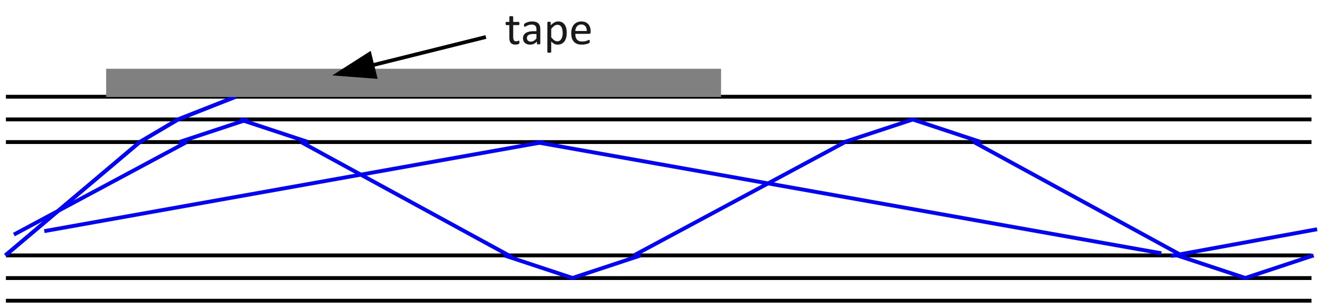
Comparison of the results obtained with the two procedures



- acceptance criteria: |((Asymmetry(7.5)+asymmetry(32.5))|*100 < 5.
- With the tape (new procedure), the measured attenuation length is significantly lower. (propagation modes with a large inclination are suppressed)

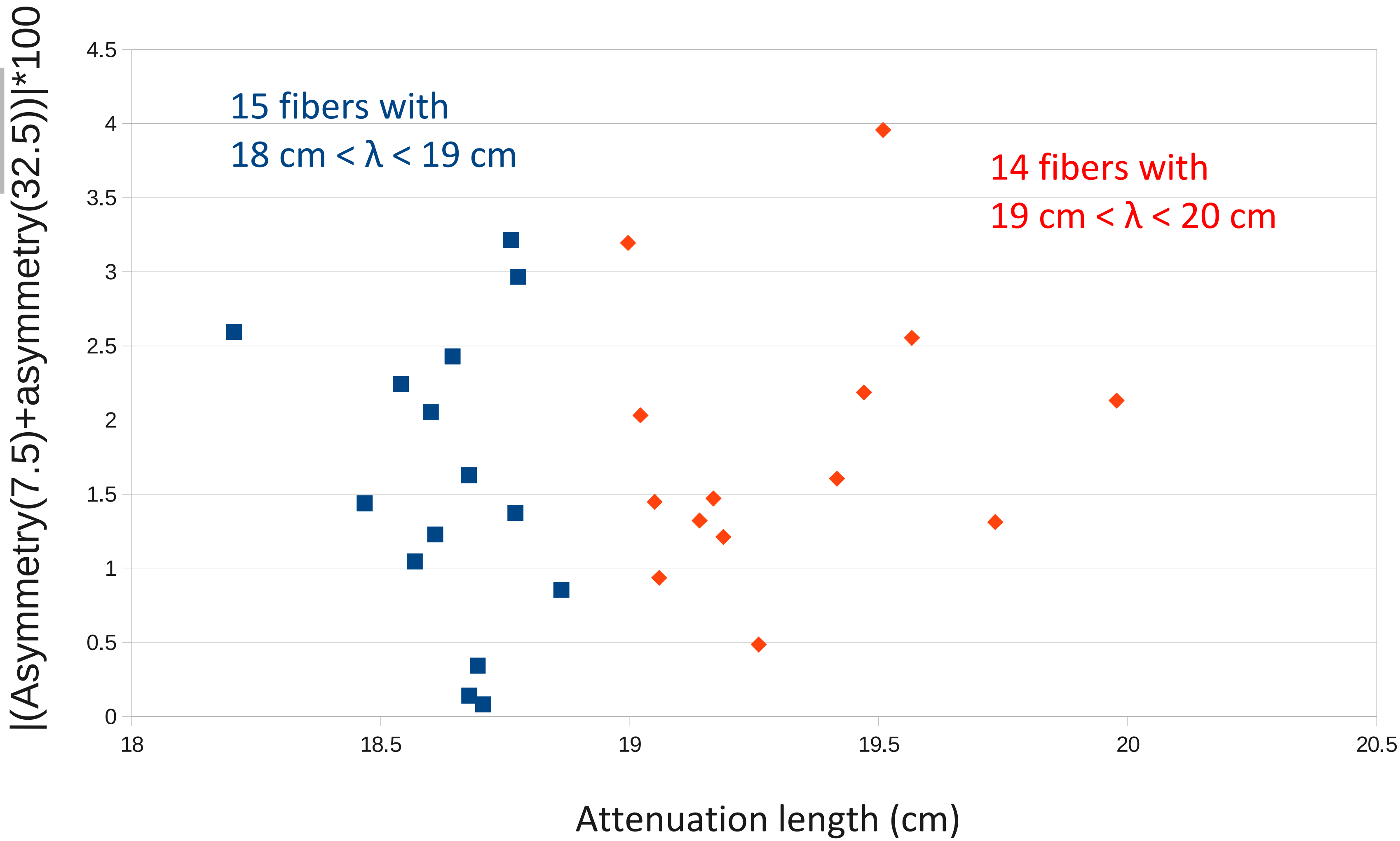
Effect of the tape on the different propagation modes





- the tape eliminates the propagation modes with large angles

Two batches of fibers have been prepared



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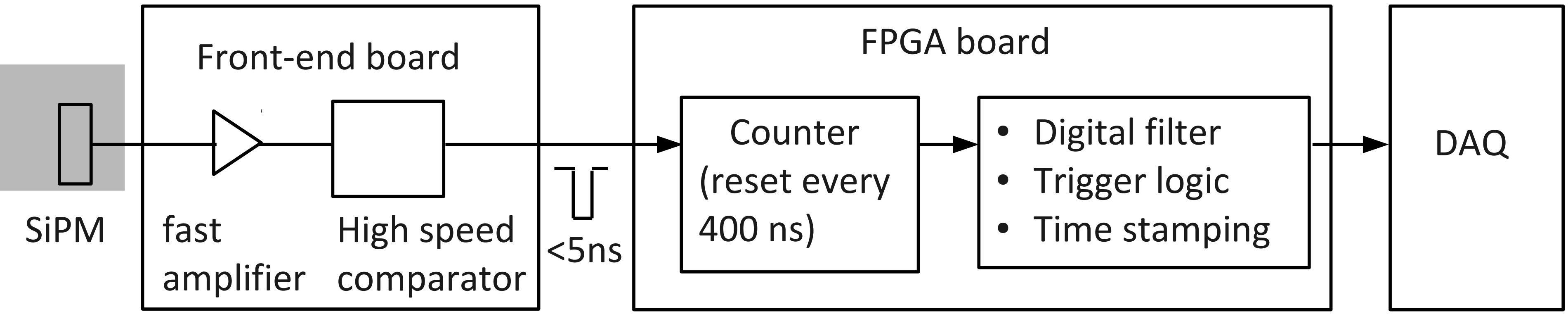
Next steps for 2017

- Characterization of the two new prototypes
  - longitudinal spatial resolution
  - trigger efficiency
  - Impact of the count rate on the spatial resolution
  - measurements with different shaping times (2µs, 1µs, 0.5µs)
- Development of a low cost readout electronics and DAQ system for large detectors (e.g. Heimdal)
  - front end board
  - FPGA firmware

Principle of a low cost readout system



- photon counting approach
- Sampling of the density of SiPM counts every 400 ns
- Digital filtering of the sampled signal
- Trigger logic
  - Channel is ready
  - Filter output is maximum (time tagging)
  - Filter output is larger than the trigger threshold

Implementation of the readout system

For a large number of channels

Can handle 20'000 ch (or more) with a global time averaged rate of 10 Mevent/s)

SiPM → **Front-end board**: MAR amplifer → High speed comparator LMH7220 (LVDS output) → **V2495 board (CAEN)** → **VME crate** → PC

V2495 board (CAEN)
- 64 LVDS input channels
- Possibility to install up to 3 mezzanines with 32 LVDS inputs.

(up to 160 LVDS input ch.)

VME crate

Can host up to 20 V2495 boards

VME crates provide:
- Powering
- Power dissipation (fan)

For a small number of channels (from 64 channels up to maybe 160 channels)

SiPM → **Front-end board**: MAR amplifer → High speed comparator LMH7220 (LVDS output) → **Standalone V2495 board** → PC (USB)

Standalone V2495 board
- 64 LVDS input channels
- Possibility to install up to 3 mezzanines with 32 LVDS inputs.

(up to 160 LVDS input ch.)

V2495 board (CAEN)

mezzanines

Summary

- Advantages of the readout system
  - Suitable for prototypes and for large detectors
  - Low cost: 28 – 50 euro / ch (depends on the FPGA firmware optimization)
  - High flexibility (1 photo-electron threshold, shaping time, trigger threshold, blocking time)
  - No hardware development

- We have one V2495 board (CAEN)
- We will start the development of the FPGA firmware (starting from free firmware demos provided by CAEN)

Is there anyone interested in this readout system ?

Thank you for your attention !

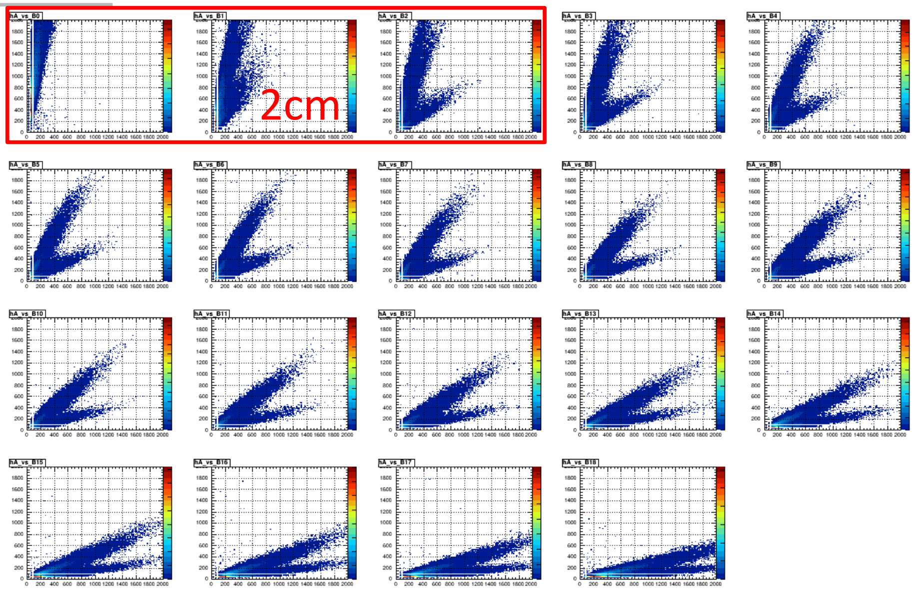
Estimation cost of a readout for 20'000 channels
(after the front-end board)

- The maximum number of channels per FPGA board will depend on the firmware optimization.

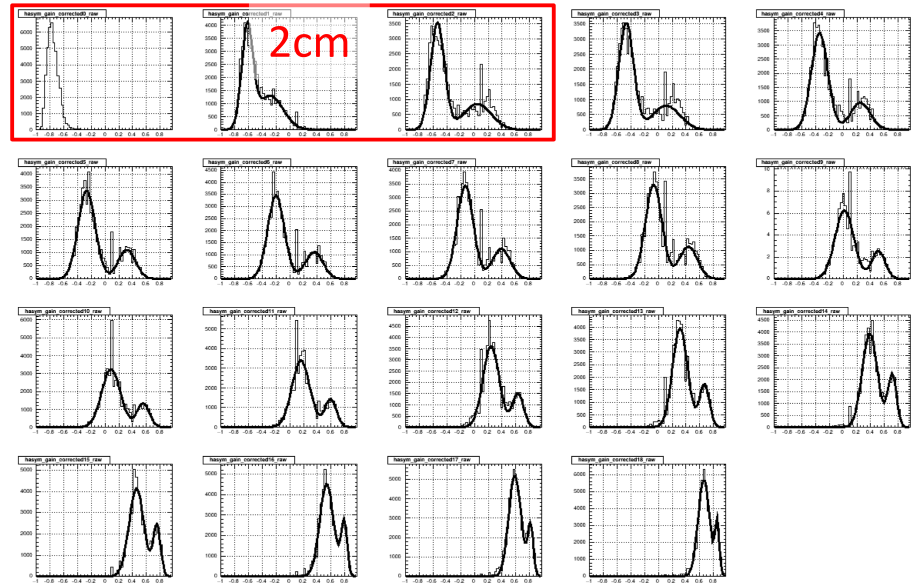
Conservative scenario	**moderate scenario**	**optimistic scenario**
64 ch / board	96 ch / board	160 ch / board
16 x 4950 (VME create)	11 x 4950 (VME create)	7 x 4950 (VME create)
+ 313 x 2980 (V2495)	+ 209 x 2980 (V2495)	+ 125 x 2980 (V2495)
+ 3320 (controler + PCIe)	+ 209 x 390 (mezzanines)	+ 3 x 125 x 390 (mezzanines)
+ 2000 (PC)	+ 3320 (controler + PCIe)	+ 3320 (controler + PCIe)
	+ 2000 (PC)	+ 2000 (PC)
1'017'000 euro	765'000 euro	560'000 euro
50 euro / ch	**39 euro /ch**	**28 euro /ch**

Anomaly observed with the 3-fiber prototype

A_{left} vs A_{right} at diff. positions (1, 2, .., 19cm)



Asymmetry at diff. positions (1, 2, .., 19cm)



- "Something happens with one fiber at x ≈ 2 cm"
  (confirmed with lateral scans of the bar with a collimated α-source)
- **only events with an asymmetry in the left peak are selected**

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Determination of the γ factors in case of a multichannel detector

1. Measure the attenuation functions $att_L(x)$ and $att_R(x)$ for one channel

2. Irradiate uniformly each position sensitive channels (plexiglas bloc in the beam)

3. Determine for each channel (i=1, ..., n) the average ratio between right and left amplitudes

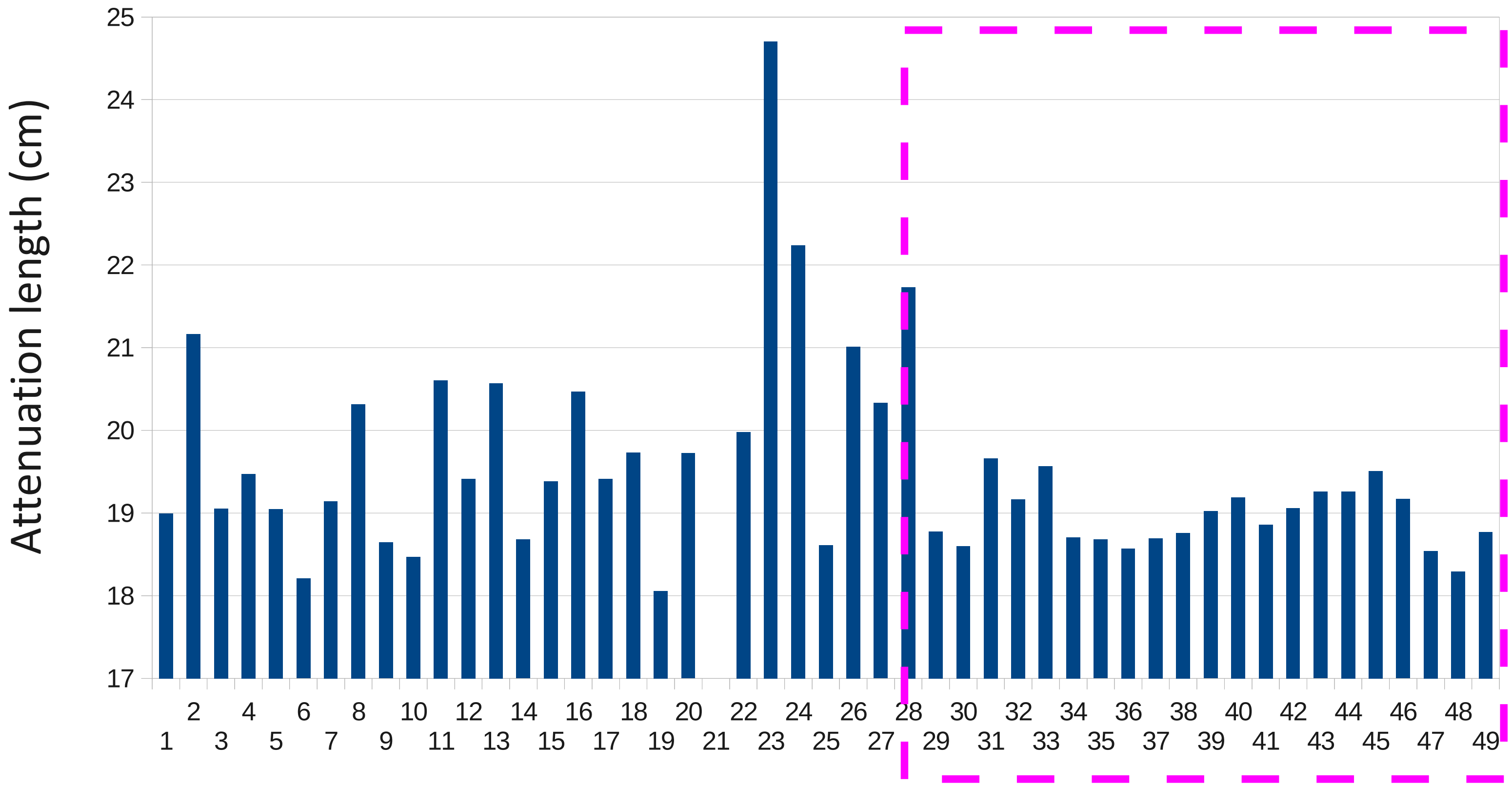
$$R_i = \langle \frac{A_R}{A_L} \rangle$$

4. The γ factor of the different channels is given by

$$\gamma_i = \frac{R_i}{\frac{1}{L}\int_0^L dx \frac{att_L(x)}{att_R(x)}}$$

Remark: the baselines of all channels have to be measured. If they are different from 0, the amplitudes have to be baseline subtracted.

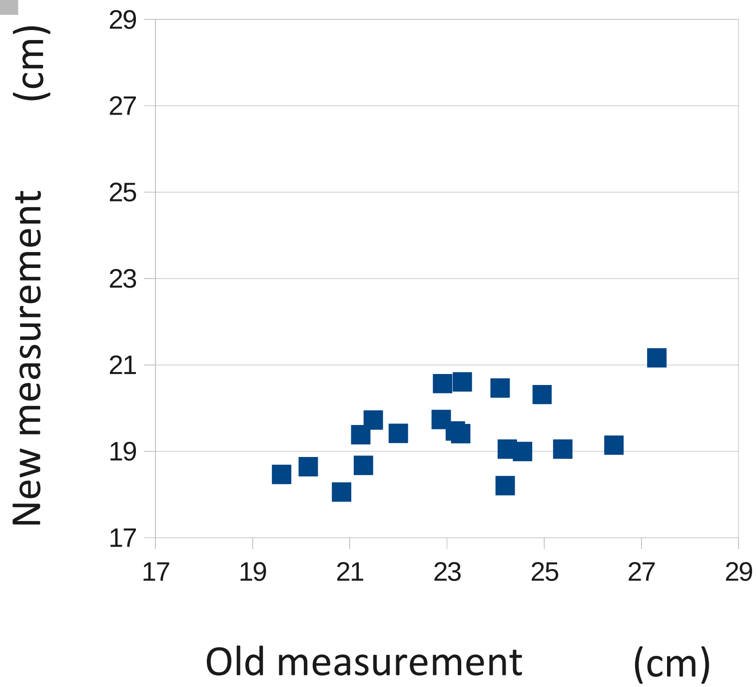
Distribution of the attenuation length



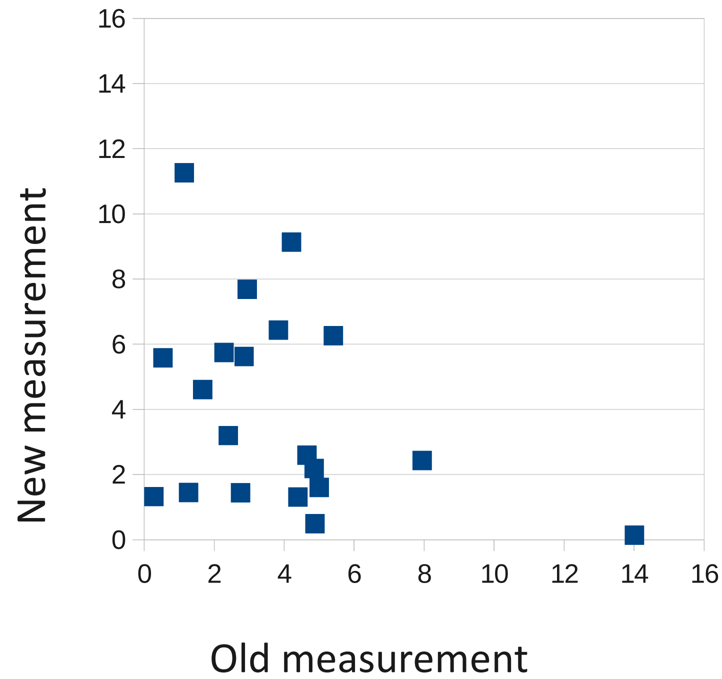
- The last 21 fibers were labeled following the order in which they were cut.
- The attenuation length change rather smoothly --> the measurement precision is sufficient.
- higher yield for the last fibers:
  - 62% of accepted fibers over the first 32 fibers
  - 88% of accepted fibers over the last 17 fibers

Comparison of the results obtained with the two procedures

Attenuation length



|((Asymmetry(7.5)+asymmetry(32.5))|*100

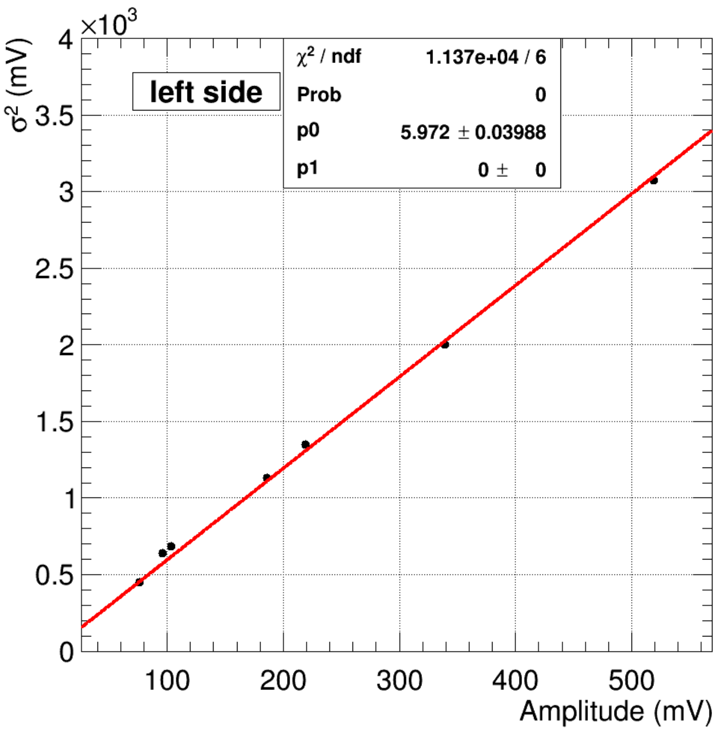


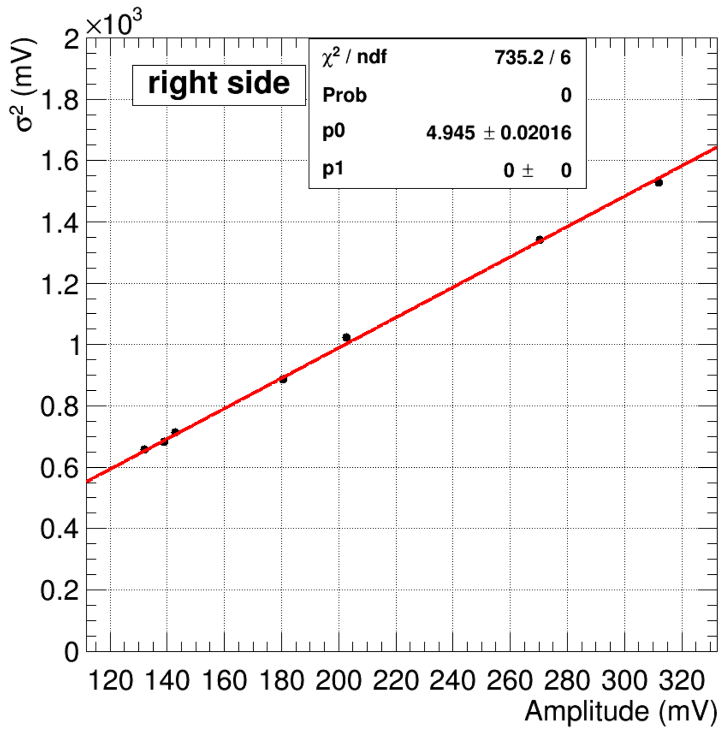
Annex: Measure of the readout gain

For a stable light injection system, the number of photons detected by a SiPM follows a Poisson statistics (SiPM crosstalk (~4%), SiPM afterpulse (~2%), and dark counts are neglected). So, $\langle Npe \rangle = \langle \sigma_{Npe} \rangle^2$

We also have, $\langle A \rangle = \langle Npe \rangle G$ and $\langle \sigma_A \rangle = \sigma_{Npe} G$

$$\boxed{G = (\sigma_A)^2 / \langle A \rangle \quad ([gain]=mv / pe)}$$





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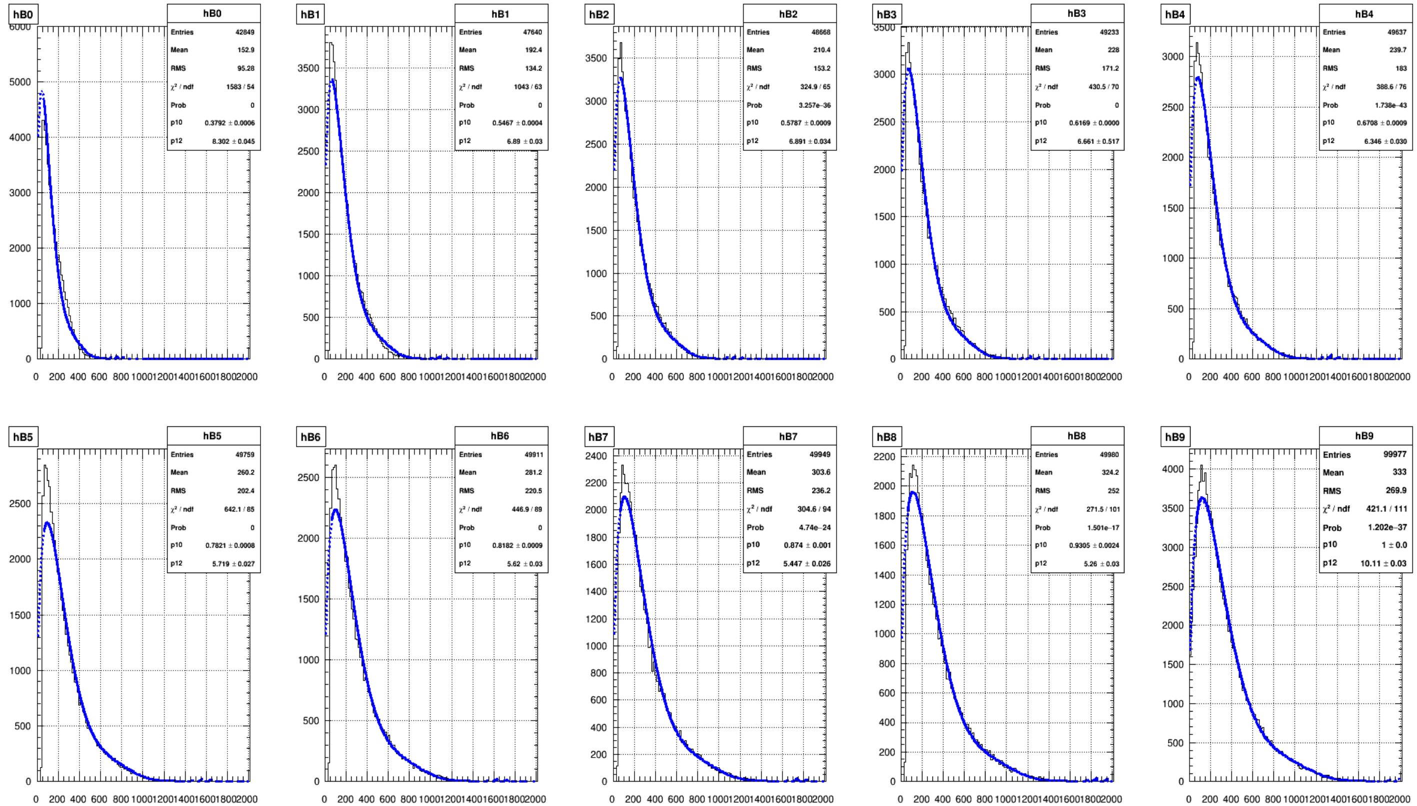
Annex: Absolute trigger efficiency estimation

(amplitude unit is mV)



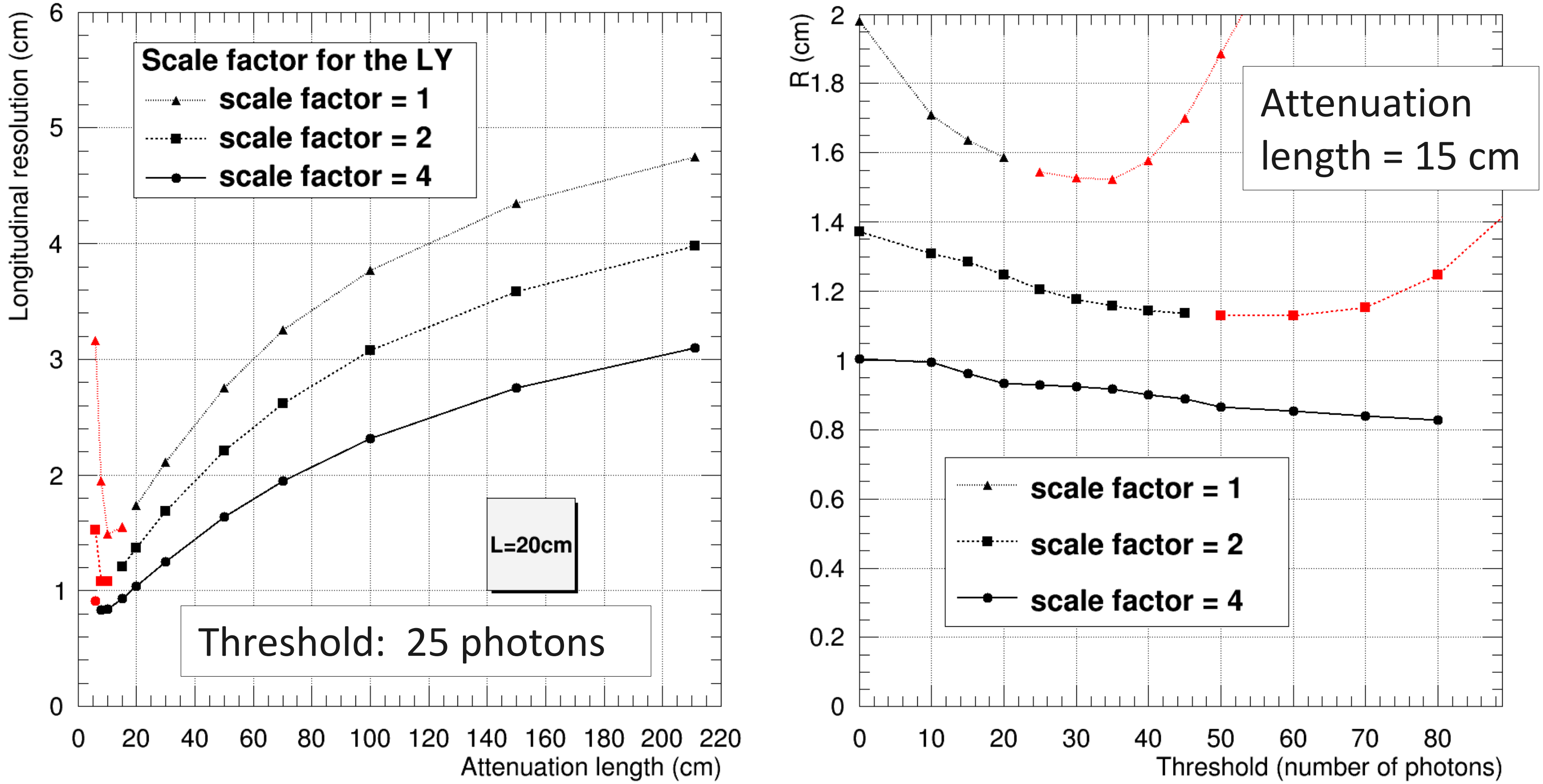
- At the central position, the first bins of the amplitude spectrum (before the discrimination threshold) are filled according to a linear extrapolation of the distribution.
- A polynomial function convoluted with a poisson distribution is fitted on this spectrum.
- All other spectra are fitted with the same function. Only an horizontal scale factor and a normalisation factor for the area are kept free.
- The trigger efficiency is calculated as :

$$trig.\ eff. = \frac{\int_{threshold}^{2000} f_{extrapolation}(A)\,dA}{\int_{0}^{2000} f_{extrapolation}(A)\,dA}$$

Annex: Explanations about the simulation

- Input parameters
  - distribution I_0 of the number of photons trapped in the WLS fibers which propagate toward one extremity of the fibers
  - parameters of the light attenuation in the fibers: λ_{long} , λ_{short} , I_{long} , I_{short}
  - photon detection efficiency (PDE) of the SiPM
- Output parameters
  - Number of photons detected on the left and right sides for each event
- Simulations steps and assumptions
  - For each event, the value of I_0 is randomized accordingly to its distribution
  - We assume that the process of photon trapping follow a Poisson distribution. So, $I_{left} = \text{Poisson}(I_0)$, $I_{right} = \text{Poisson}(I_0)$
  - We assume that the distribution of the number of detected photons follows a binomial statistic. It is well approximated by a gaussian distribution of mean, $\langle Npe_{left} \rangle = I_{left} \cdot att_{left}(x) \cdot PDE$ and variance, $\sigma_{Npeleft} = I_{left} \cdot (att_{left}(x) \cdot PDE) \cdot (1 - att_{left}(x) \cdot PDE)$

Annex: Simulation of a 20 cm long detection bar



Remarks:

- In this model, the trigger condition is (A_{left} > thr.) || (A_{right} > thr.)
- When the average trigger efficiency along the strip is higher than 80% and when the maximum relative difference of the trigger efficiency along the fiber is lower than 10%, the markers are black. Otherwise, they are red.

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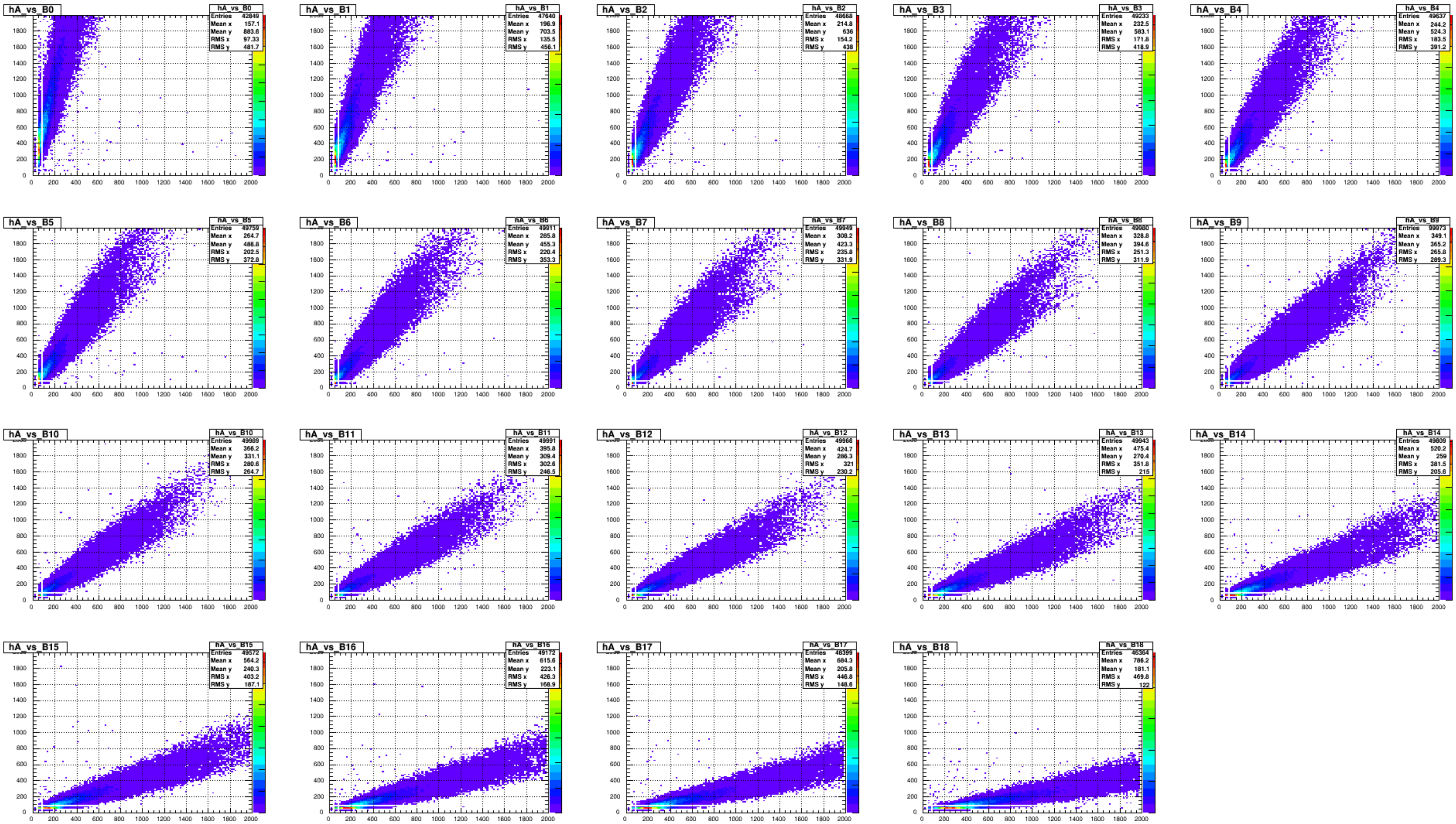
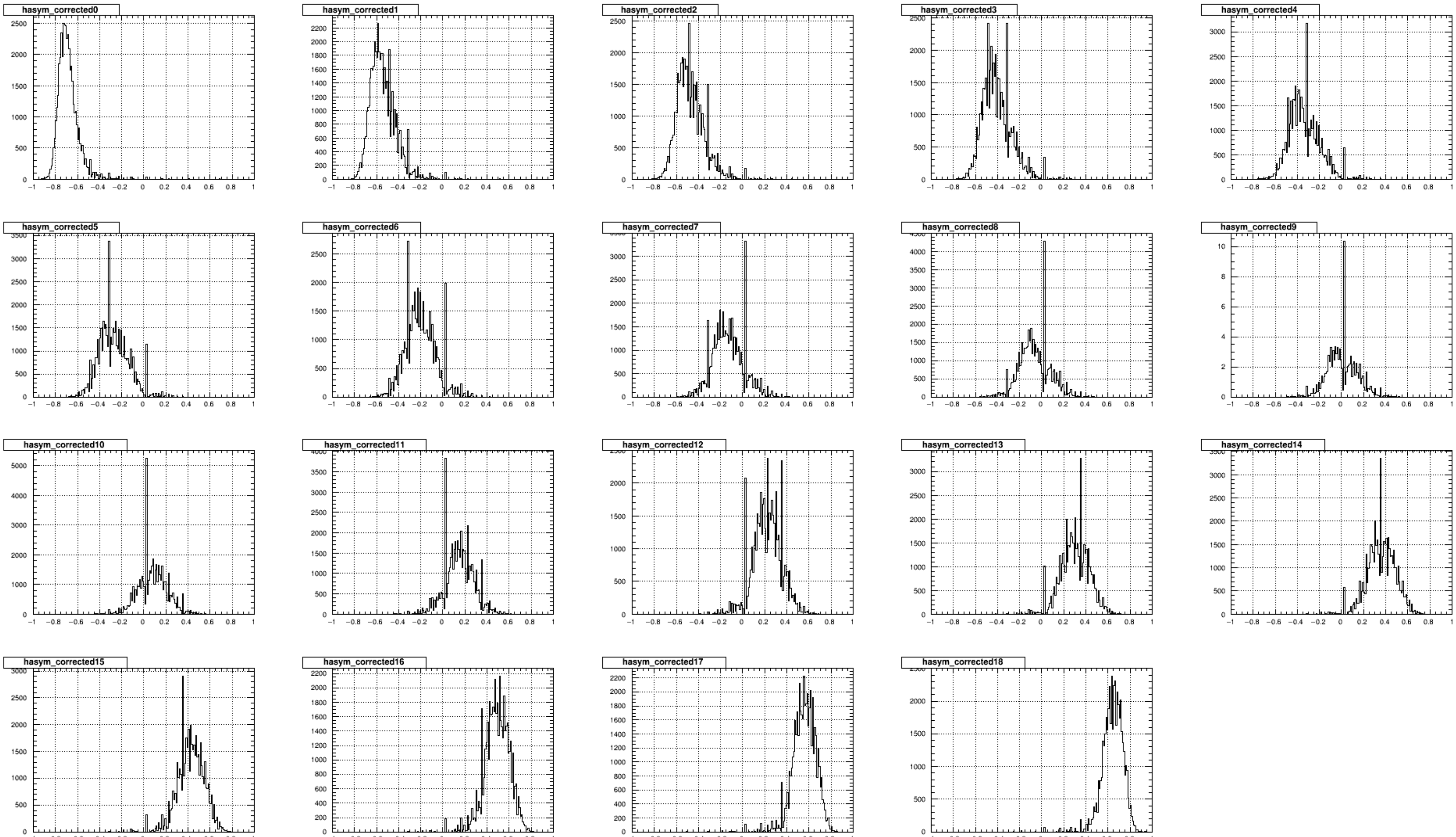
Annex: 8-fiber prototype, correlection plot

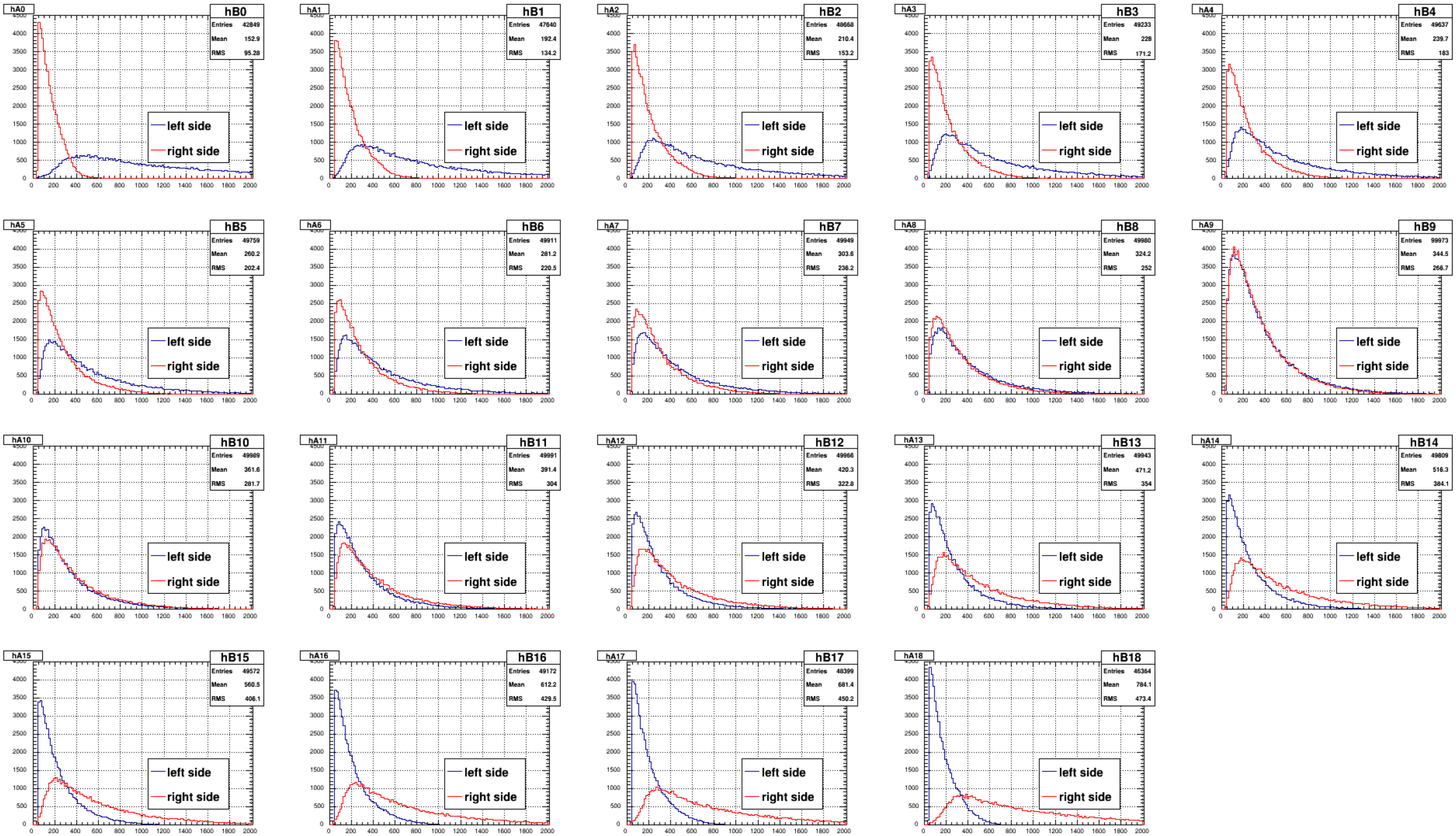


Annex: 8-fiber prototype, asymmetry spectra

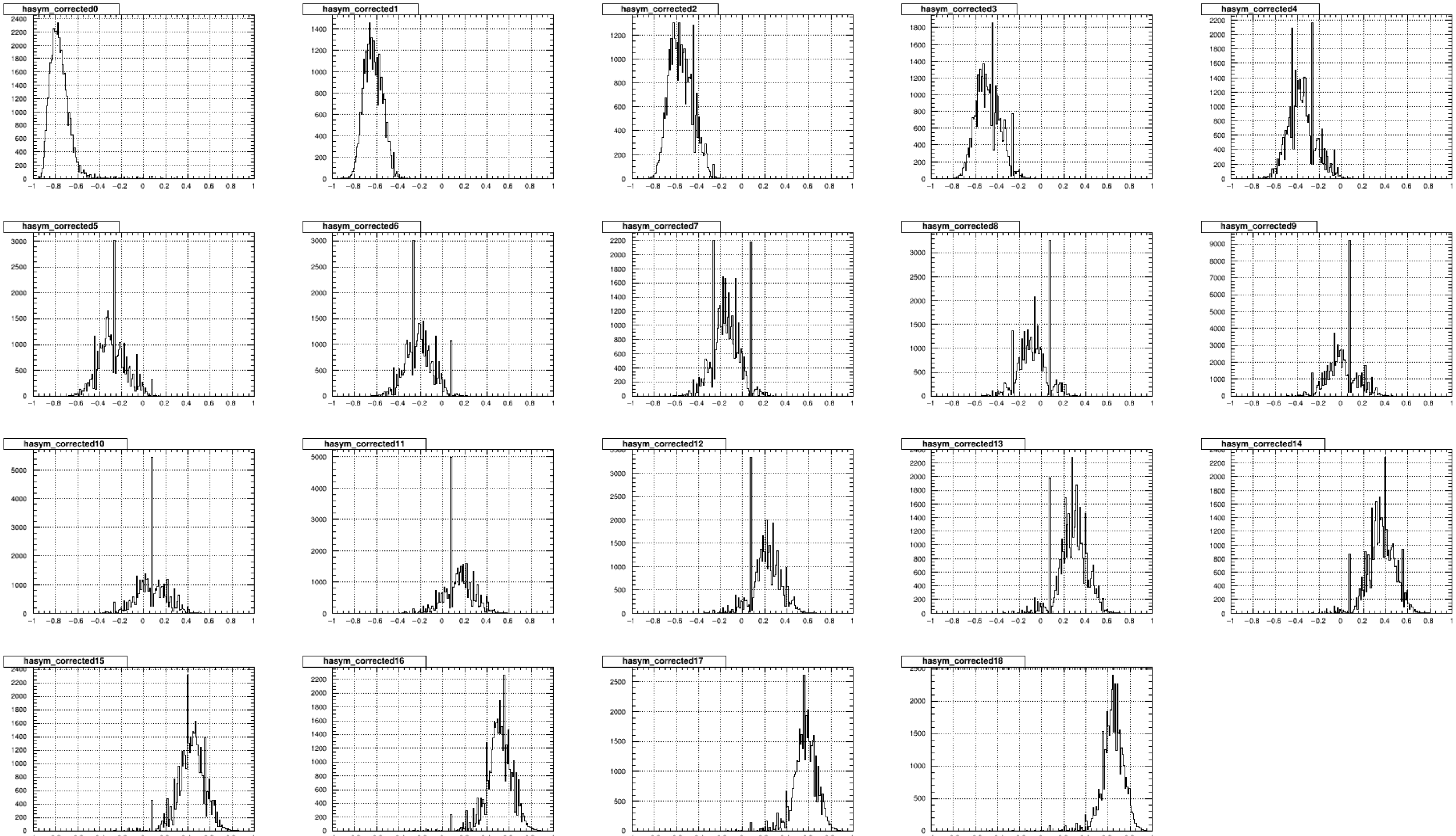


Annex: 8-fiber prototype, amplitude spectra

(readout gain ~ 5mV/photon)



Annex: 3-fiber prototype, asymmetry spectra (clean data)



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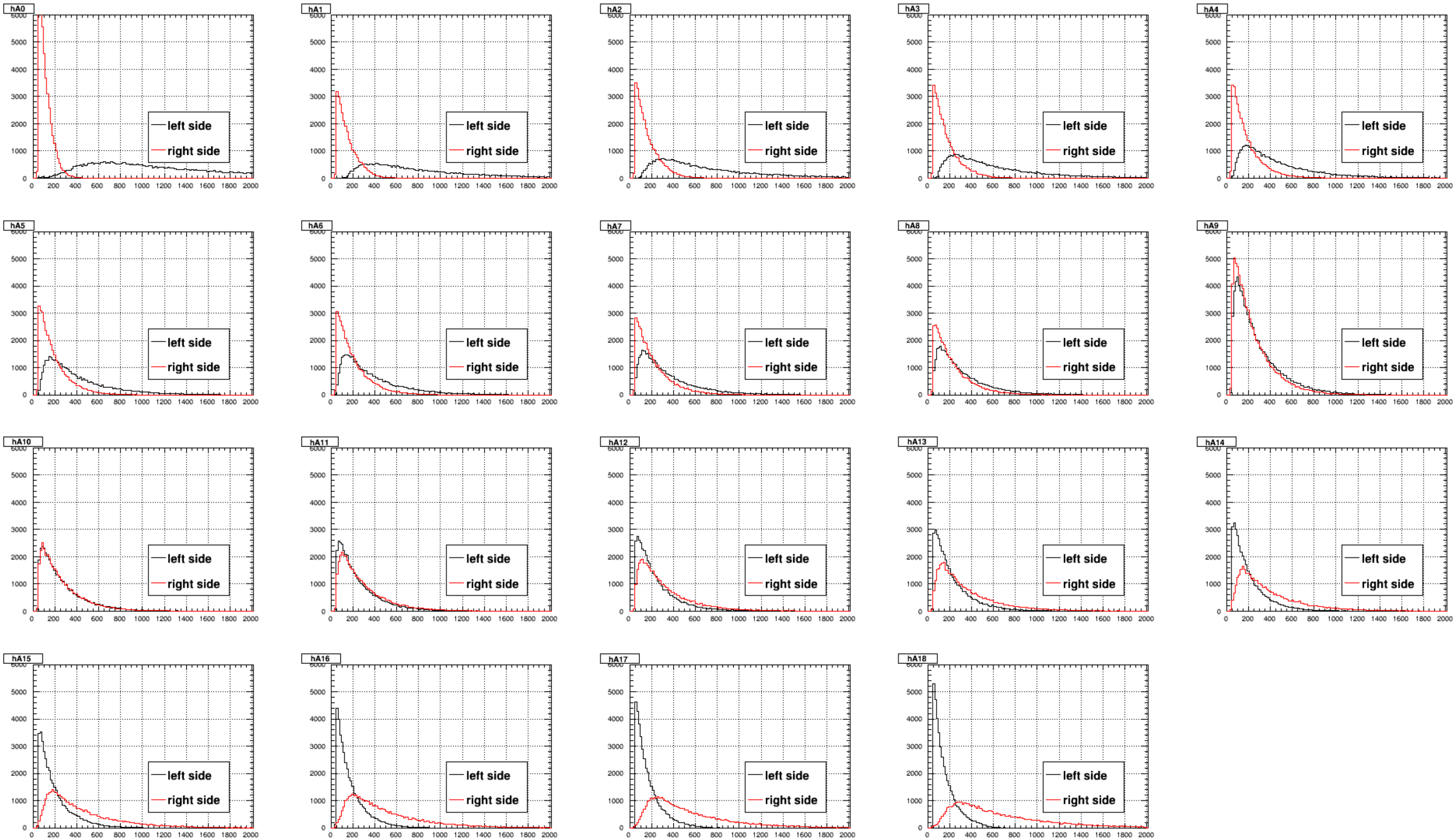
Annex: 3-fiber prototype, amplitude spectra
(readout gain ~ 5mV/photon, clean data)



Annex: 3-fiber prototype, asymmetry curve