Study of the simulations of the readout for the future LHCb Electromagnetic Calorimeter and characterization of photomultipliers

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International Master
Advanced Methods
in Particle Physics

Outline

- Introduction: the LHCb ECAL Upgrade II
- Simulation studies of a Pb-Polystyrene module
- Analysis of testbeam data from the CERN SPS
- Ageing campaign of the PMT Hamamatsu R14755U-100
- Conclusions

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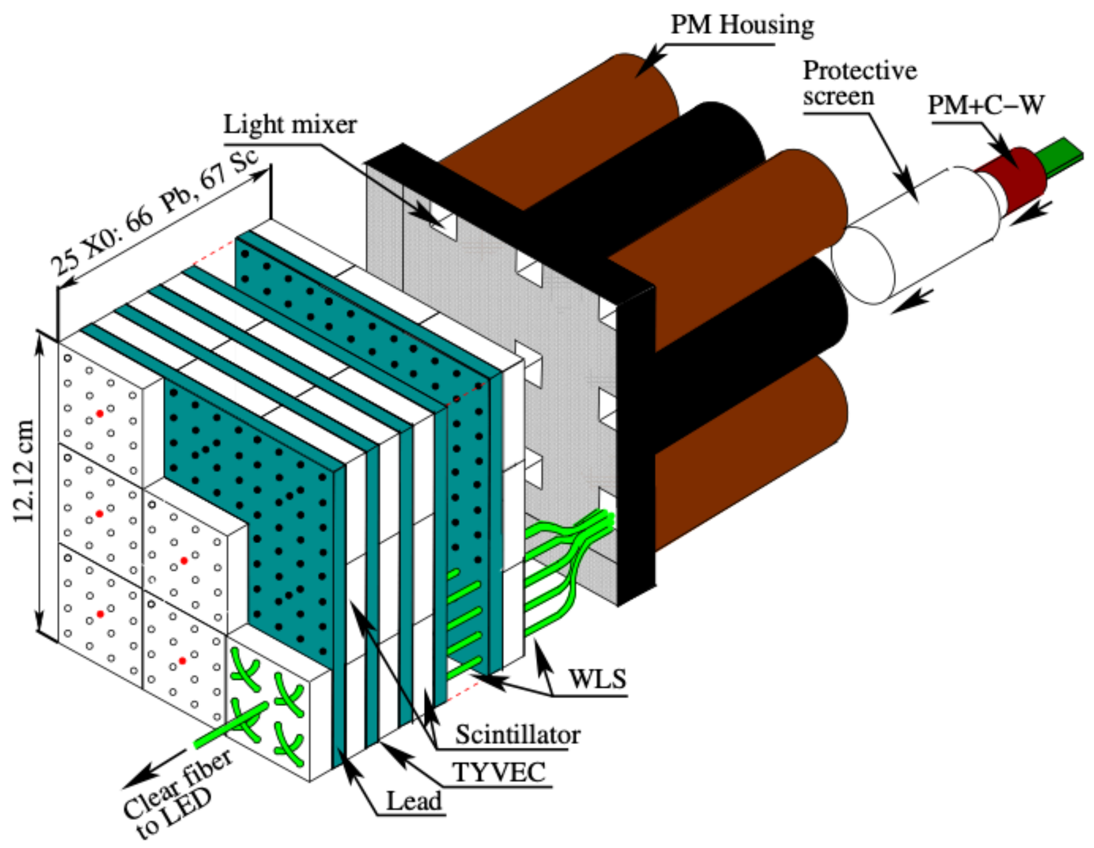
Working principle of a sampling ECAL

(Scintillator-based)

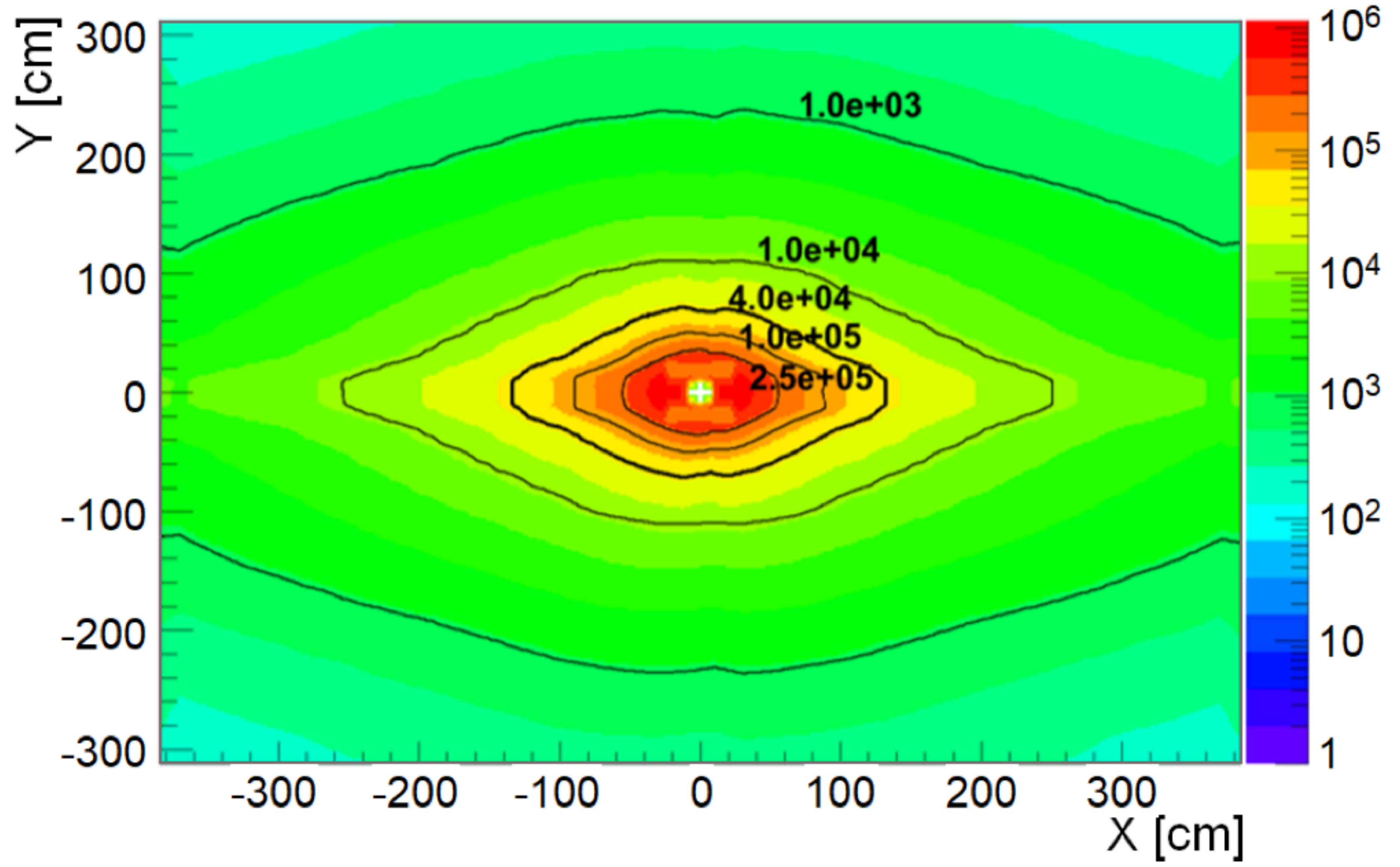
- Electromagnetic Calorimeters (**ECALs**) measure the incident particles' energy ($e^{\pm}$, π^0) providing position information, too
- Two main materials involved:
  - **Scintillator** (active): converts the incident particles' energy into **light**
  - **Absorber** (passive): generates the **electromagnetic shower** and absorbs the energy
- The produced light has to be propagated to the photodetectors
- Finally, the photodetectors (e.g. **PMTs**) create the signals

LHCb ECAL Upgrade II

- Currently: sampling ECAL composed of Shashlik modules
- Radiation doses ~ 1 MGy foreseen for Run 5 and Run 6
- Luminosity up to 1.5 x 10^{34} cm^{-2} s^{-1}
- The high luminosity environment will require:
    - **Time resolution ~ few tens of picoseconds**
    - **Radiation hardness**
    - Energy resolution at the level of the current one (10% sampling term, 1% constant term)



Scheme of a currently-used Shashlik module *(Irina Machikhiliyan and LHCb calorimeter group. https://iopscience.iop.org/article/10.1088/1742-6596/160/1/012047)*



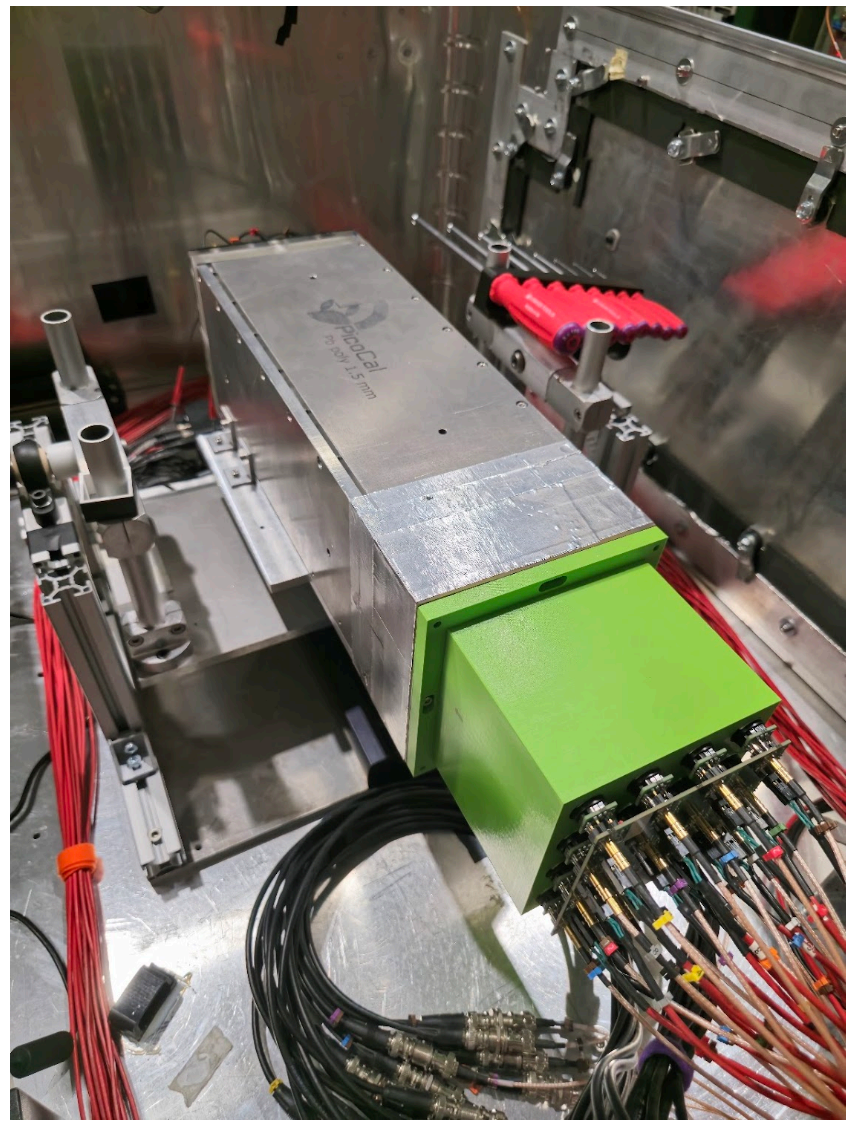
Expected radiation dose for the High Luminosity phase, in Gy *("Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era." https://inspirehep.net/literature/2707810)*

LHCb ECAL Upgrade II

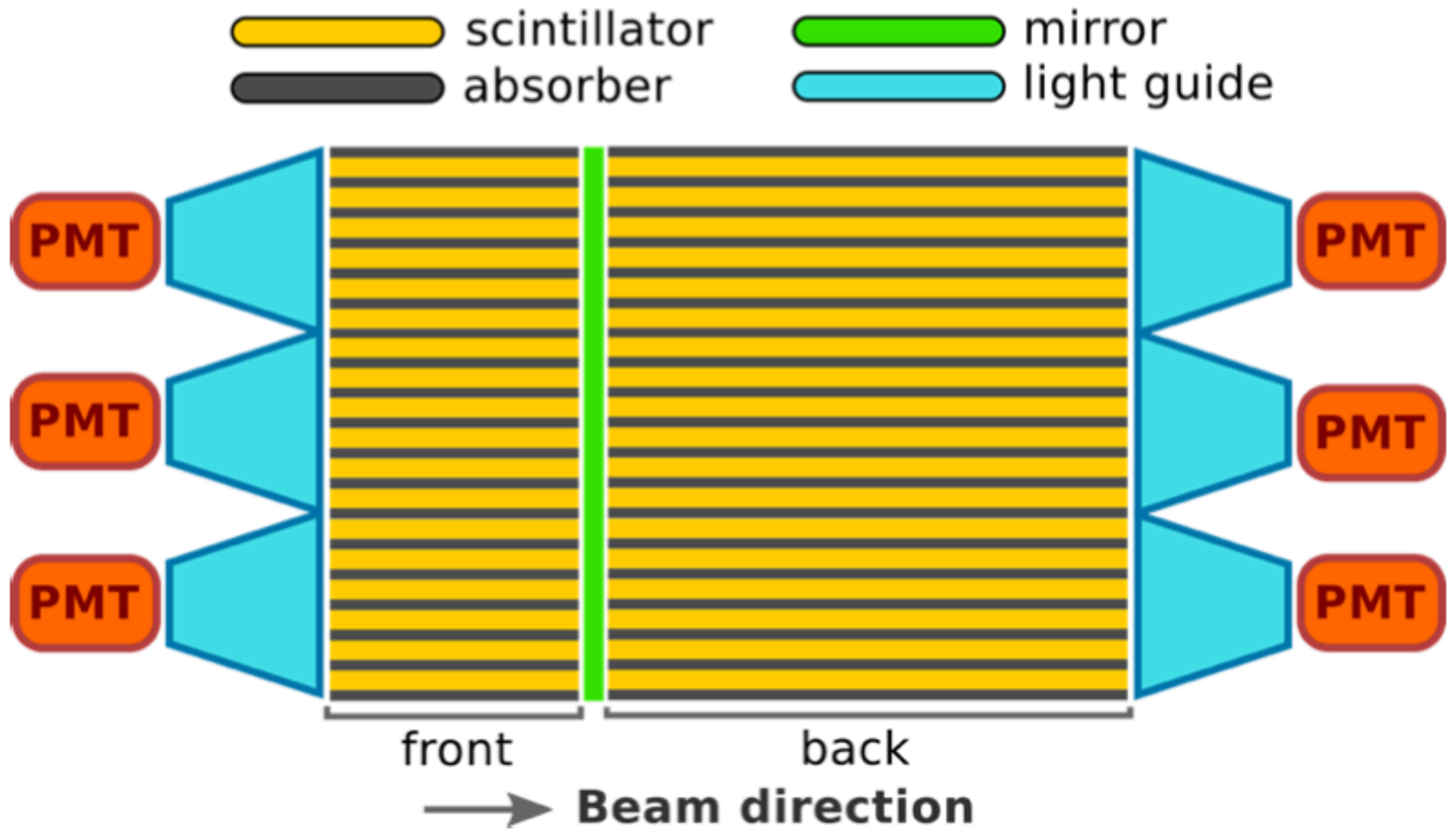
- Future: **Spaghetti Calorimeter** (SpaCal)
- Scintillating fibres inserted into a dense passive absorber
  - Fibres: **polystyrene** / **garnet crystal**
  - Absorber: **lead (Pb)** / **tungsten (W)**

➡ **Run 4:**
- W-Poly
- Single-side readout

➡ **Run 5 & 6:**
- W-Crystal and Pb-Poly
- Double-side readout



Picture of a Pb-polystyrene prototype in a test-beam setup



Scheme of a SPACAL module featuring a double-side readout
("Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era." https://inspirehep.net/literature/2707810)

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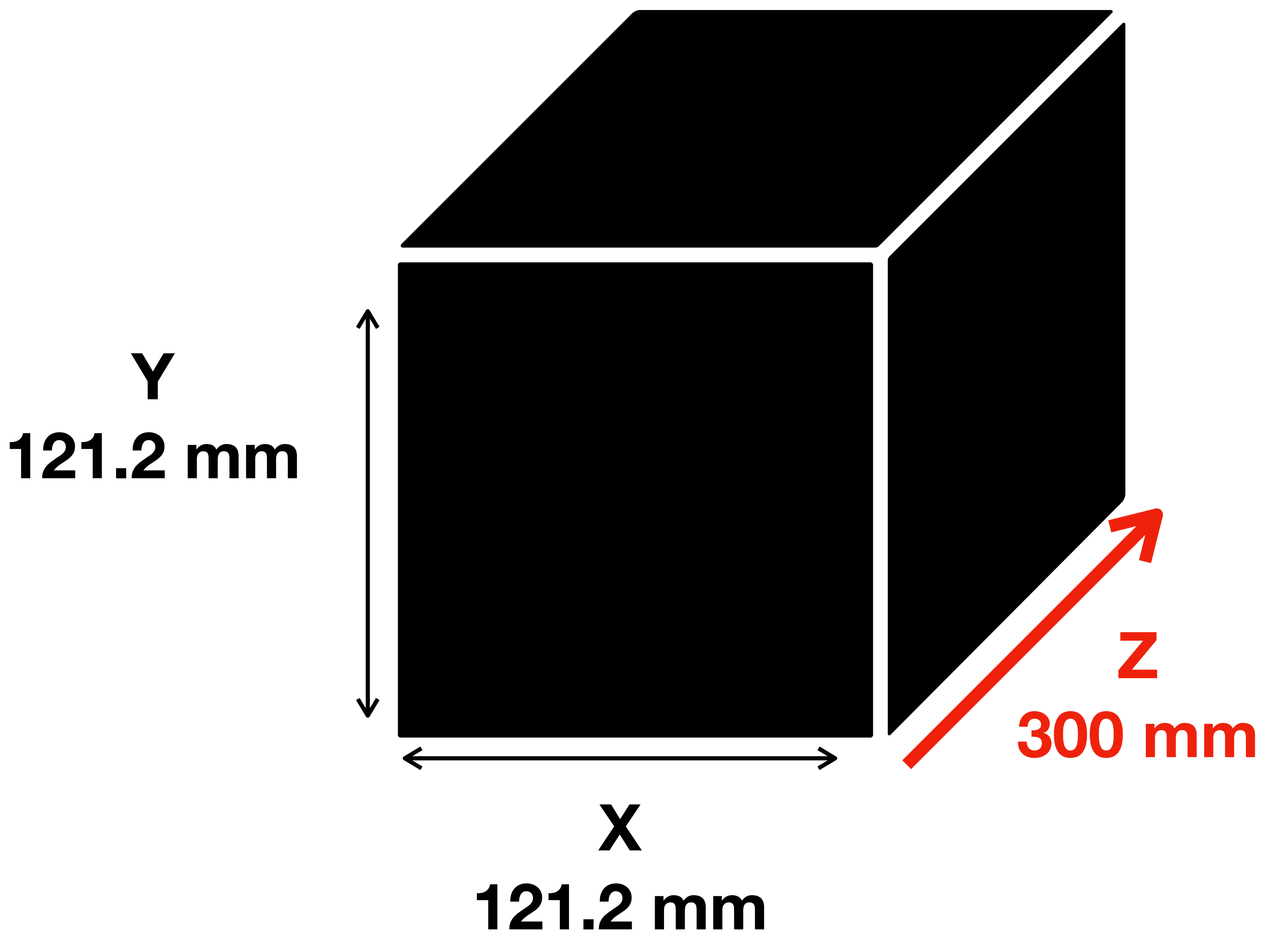
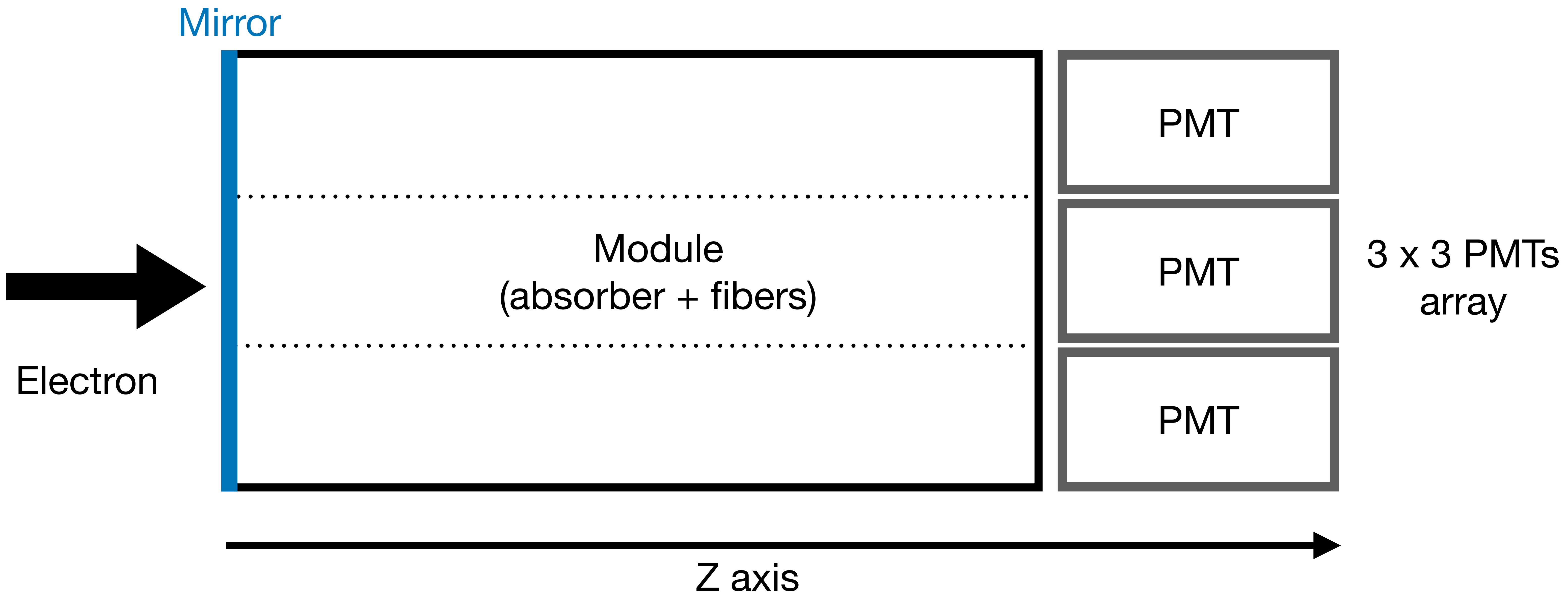
- **Goal**: study the **time resolution** of a simulated module using GEANT4
- 1000 incident *e*$^-$ at 1 GeV and 10 GeV
- 3°/3° angles (w.r.t. *x* and *y* axes)
- Module under study: **Pb + Polystyrene**
- **Single side readout** (back)
- 3 x 3 cells, each one read out by a PMT



Y
121.2 mm

X
121.2 mm

Z
300 mm



Mirror

Module
(absorber + fibers)

PMT

PMT

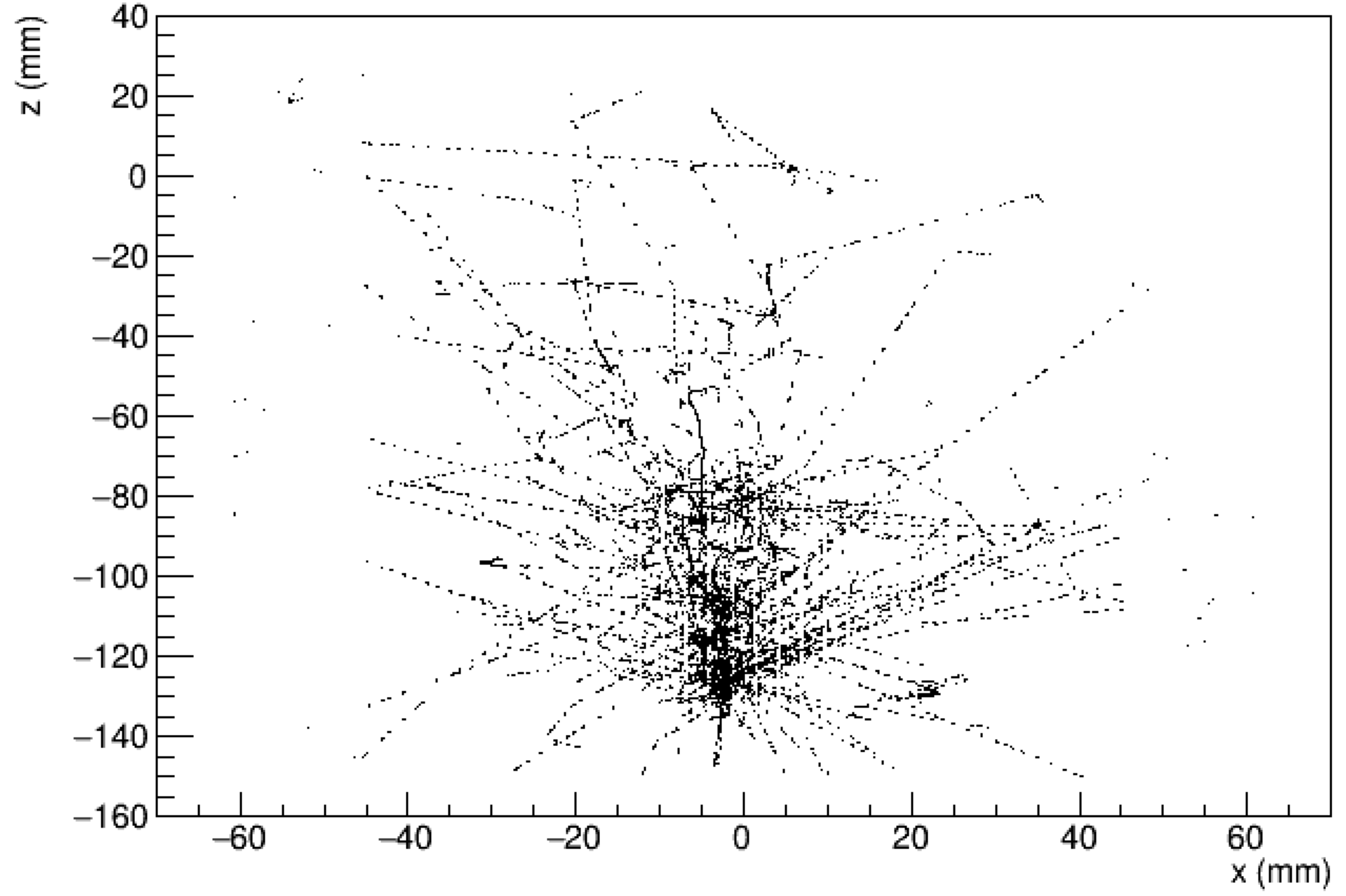
PMT

3 x 3 PMTs
array

Electron

Z axis

Energy depositions (1 GeV)



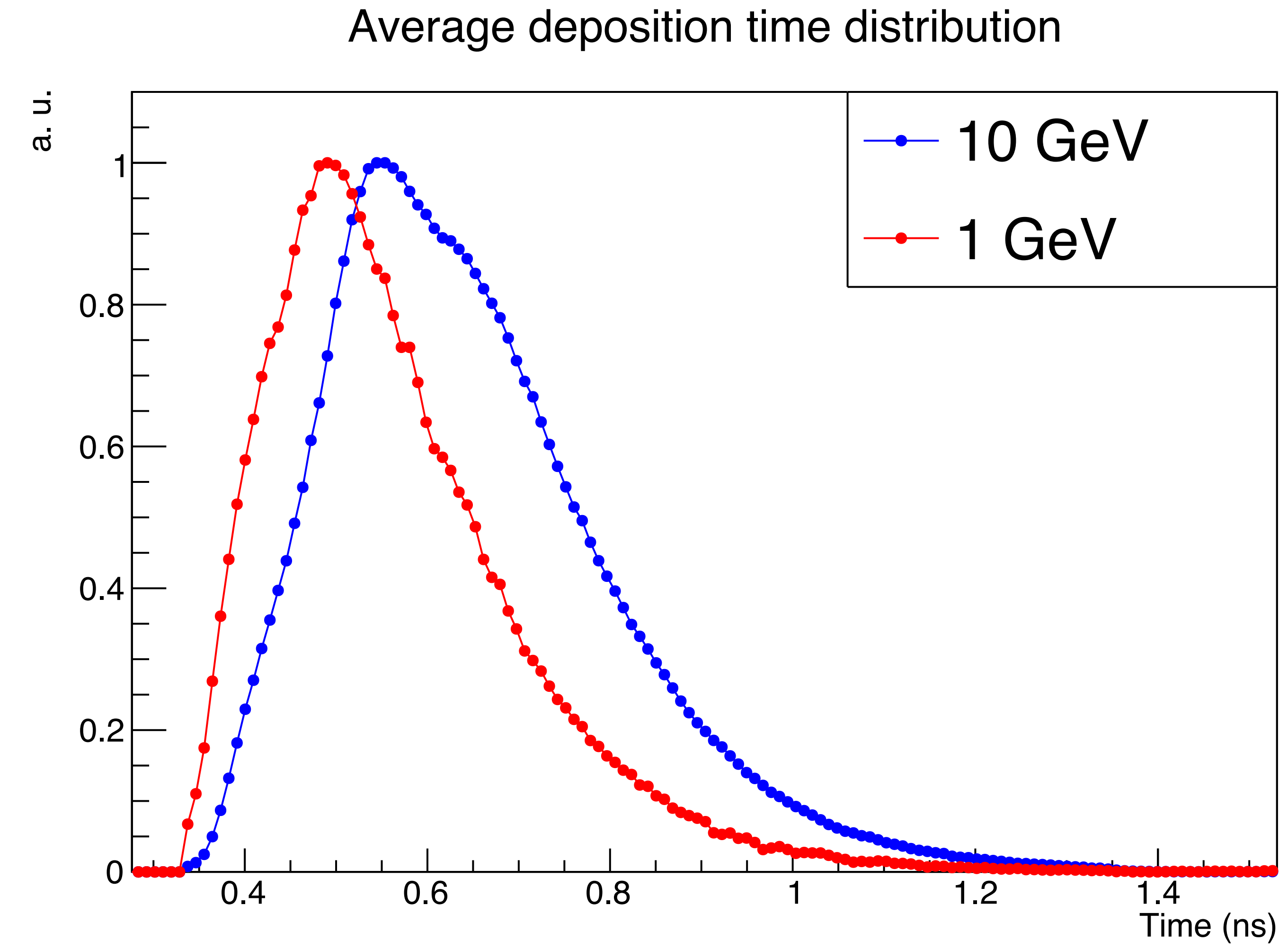
Simulation of the photons

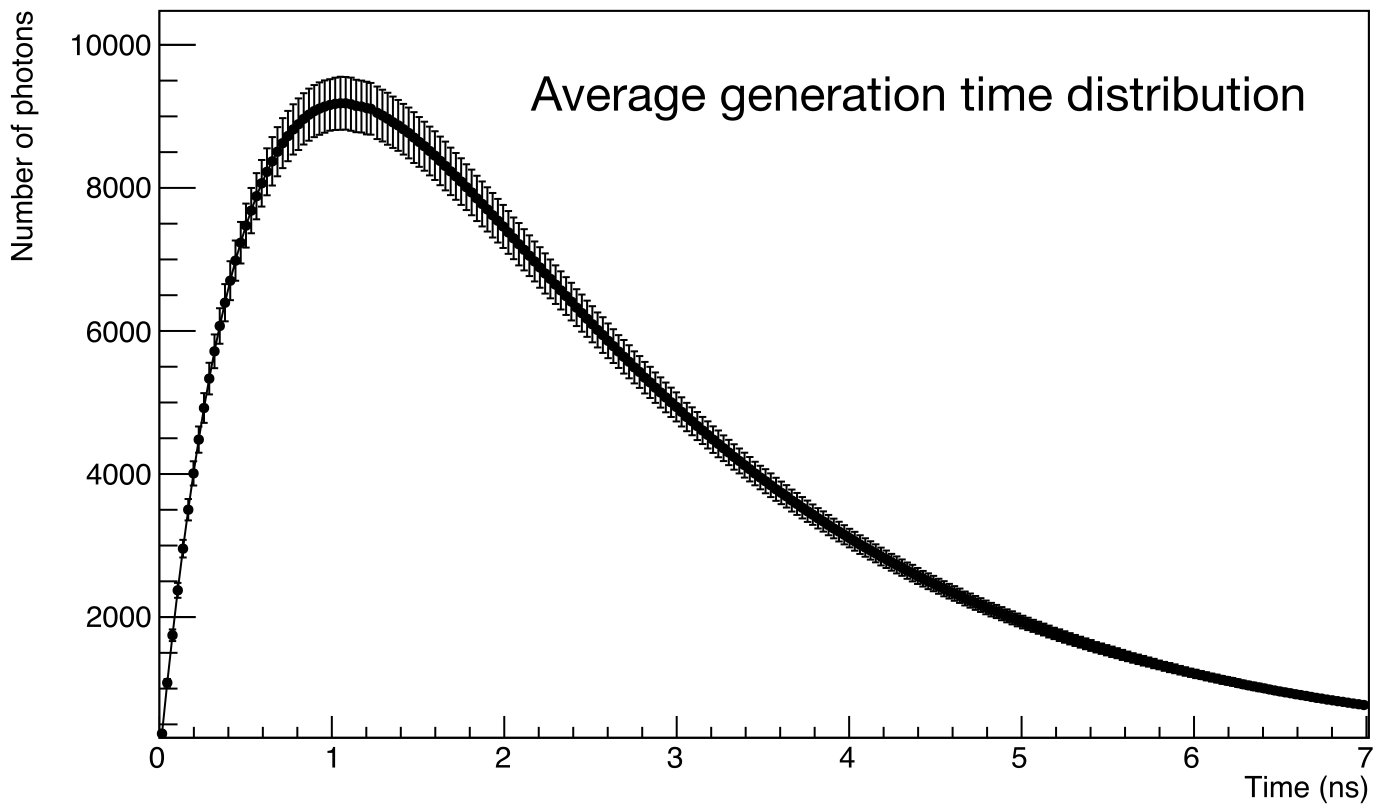
Each optical photon has:

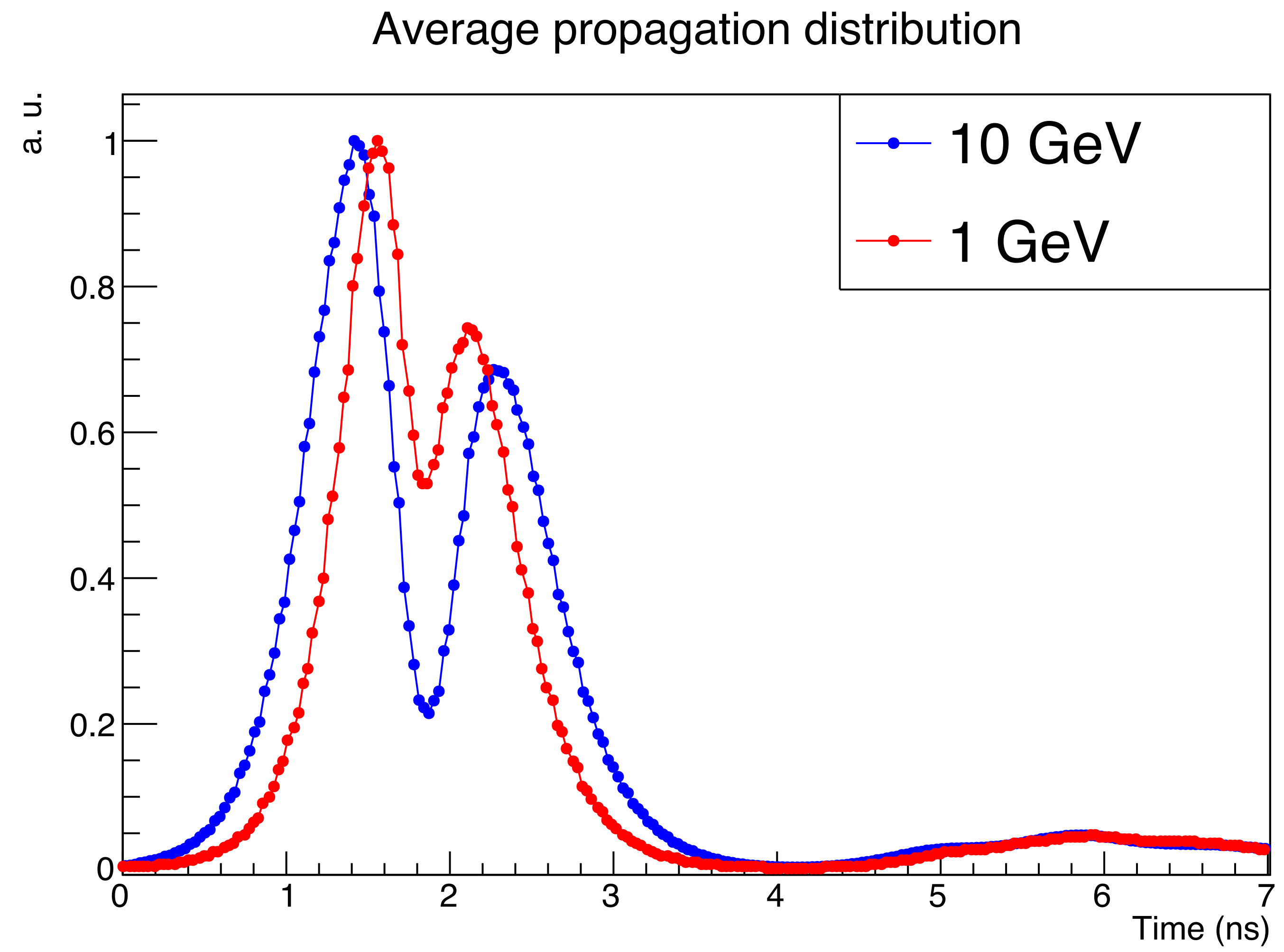
- **Deposition time** = time stamp of the single energy deposition which triggers the scintillation
- **Generation time** = time required by the scintillation process to generate the photon
- **Propagation time** = time to reach the PMT window

$$t_{total} = t_{deposition} + t_{generation} + t_{propagation}$$

(where the incident electron is created at t = 0)


Average deposition time distribution


Average generation time distribution


Average propagation distribution

Simulation of the photons

Each optical photon has:

- **Deposition time** = time stamp of the single energy deposition which triggers the scintillation
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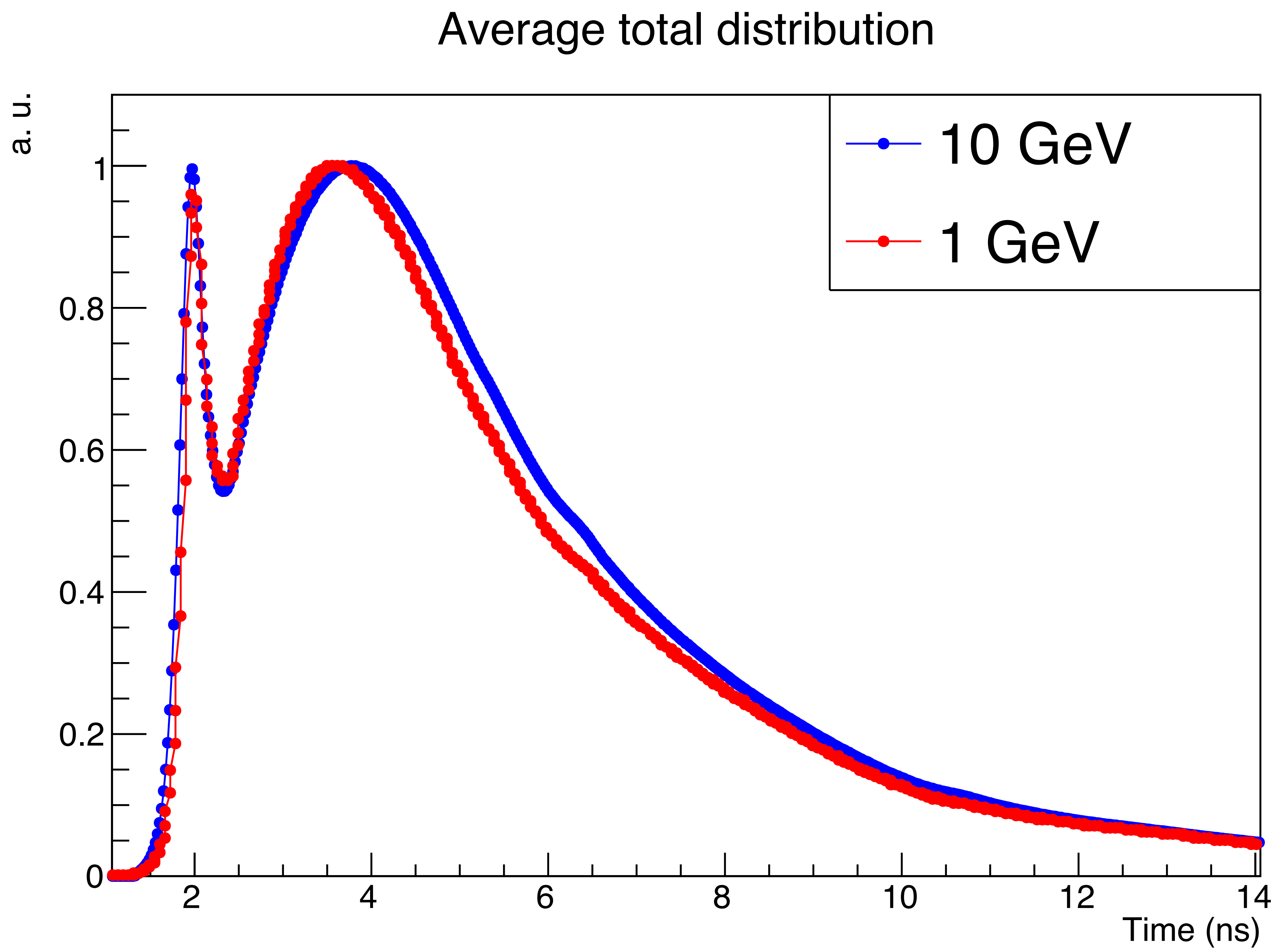
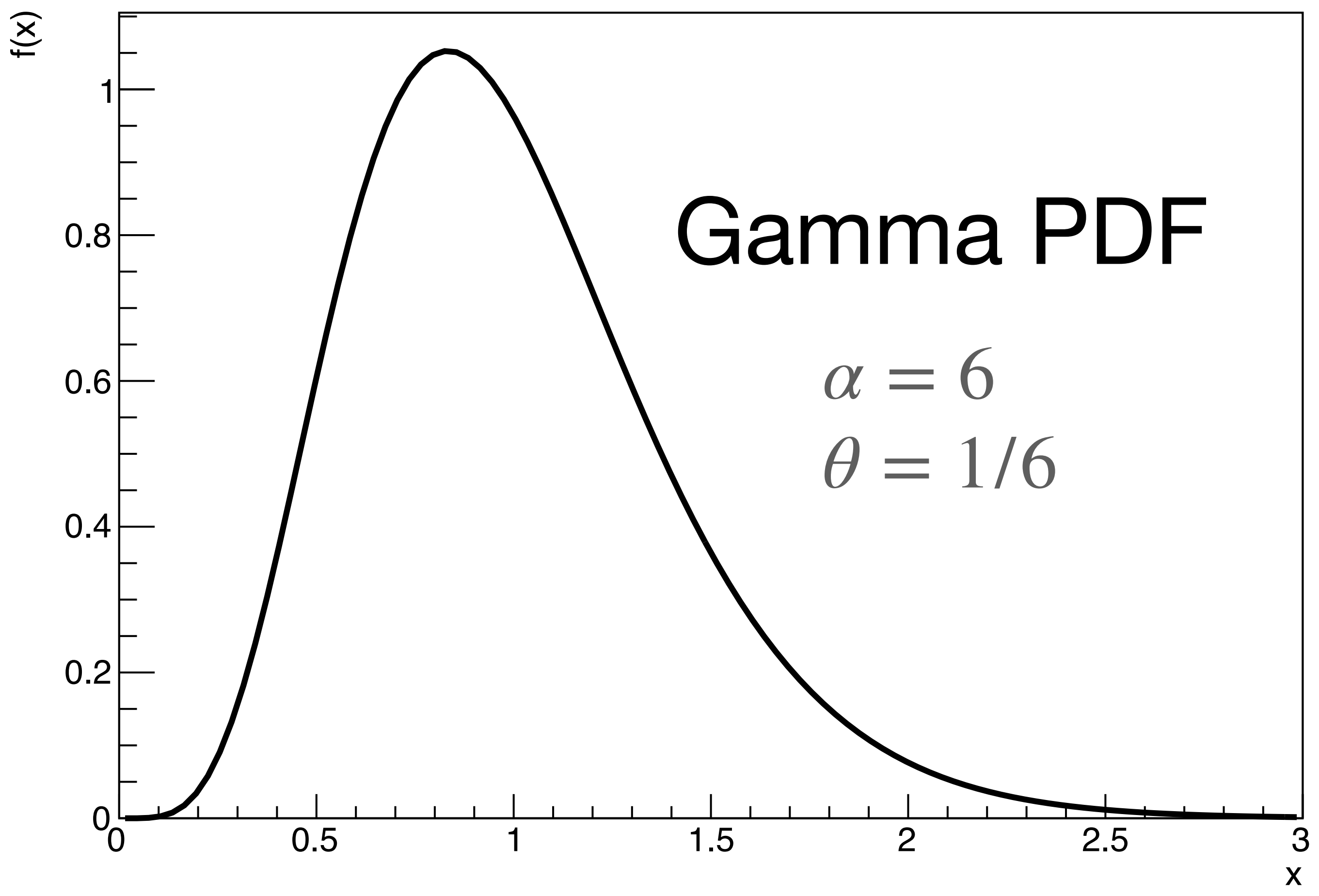


PMTs simulations



- 1024 samples in 204.8 ns time window $\longrightarrow$ $\Delta t = 200$ ps
- SPTR (or TTS, Transit Time Spread)
- Amplitude fluctuations following a Gamma pdf: $p(x) = \frac{1}{\Gamma(\alpha) \cdot \theta^{\alpha}} x^{\alpha - 1} e^{-x/\theta}$

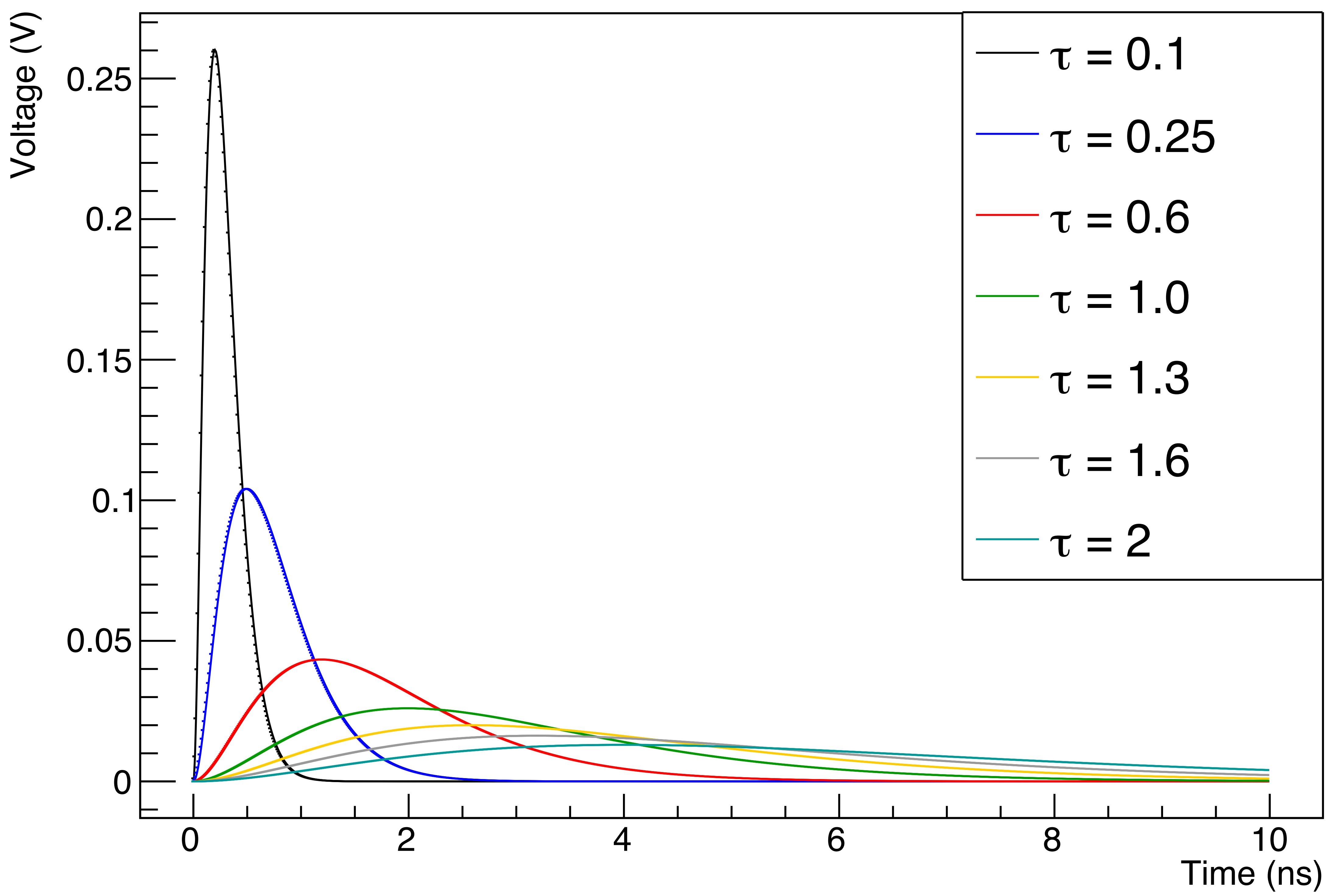
Single photoelectron pulse:

$$\boxed{f(t) = A \cdot t^2 \cdot e^{-t/\tau} \quad \Big| \quad A = \frac{R \cdot \text{gain} \cdot q_e}{\tau^3} \cdot 10^9}$$

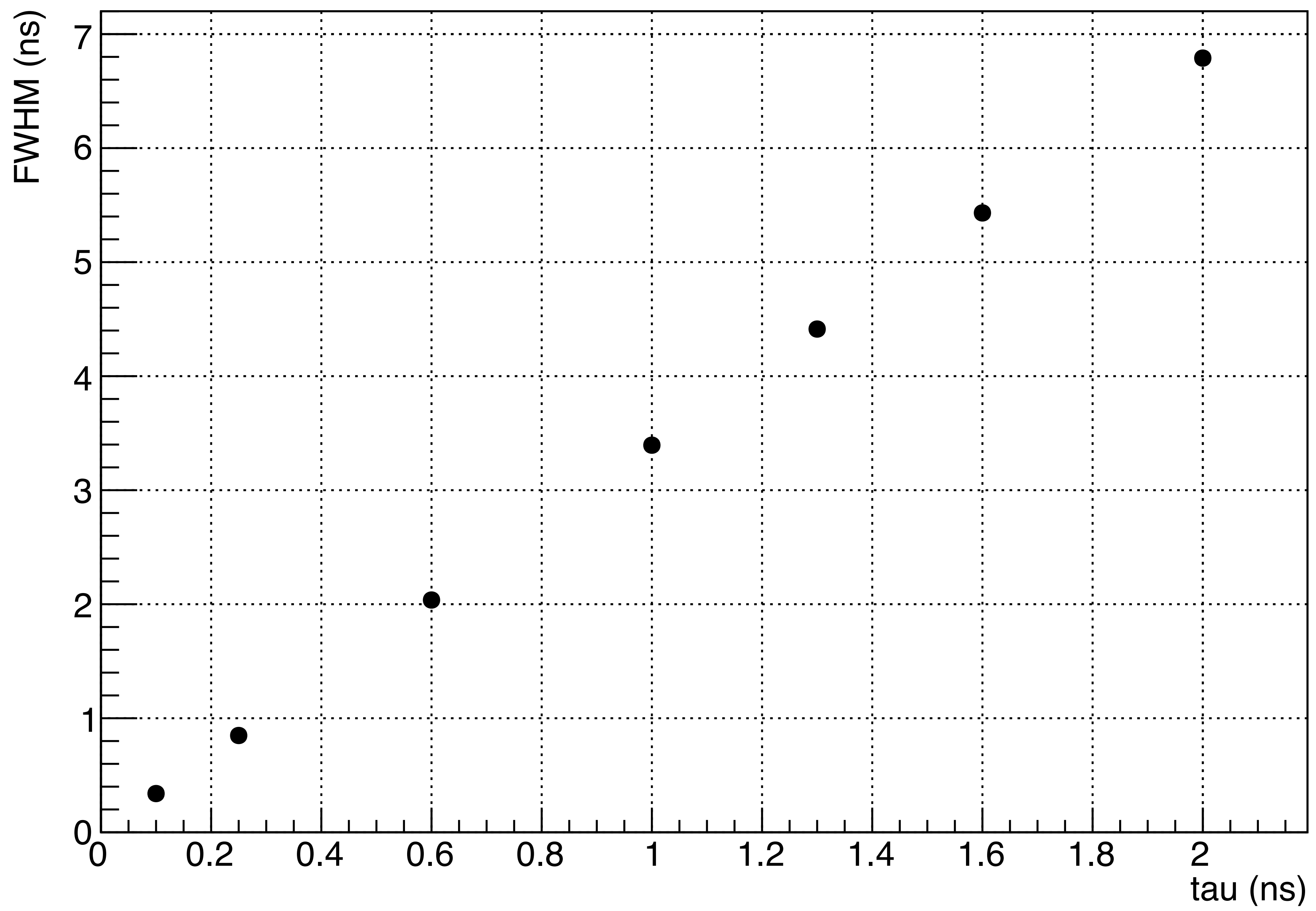
(FWHM proportional to tau)

Single p.h.e. pulses

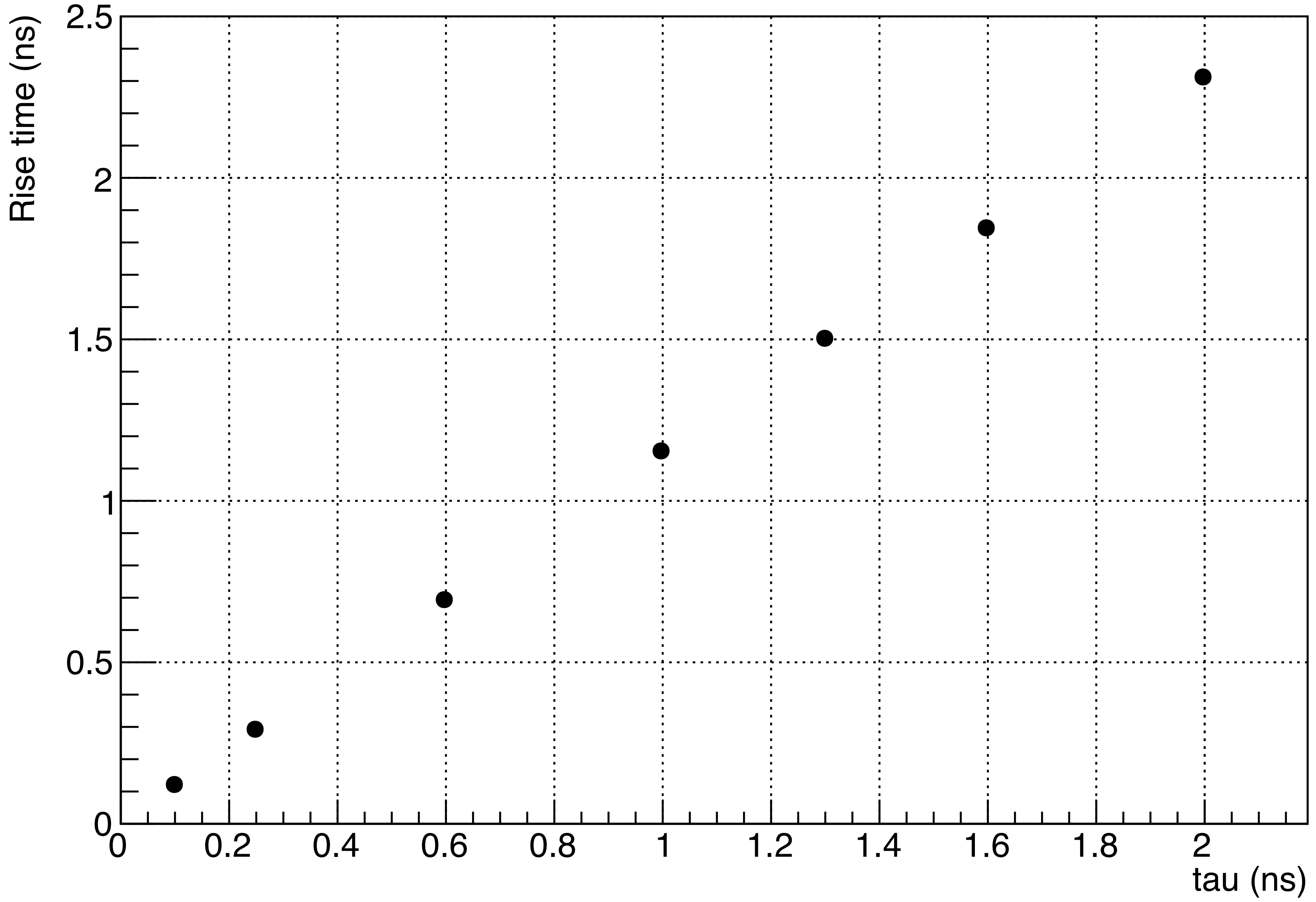
FWHM, rise time and increase linearly with tau



Single phe pulses



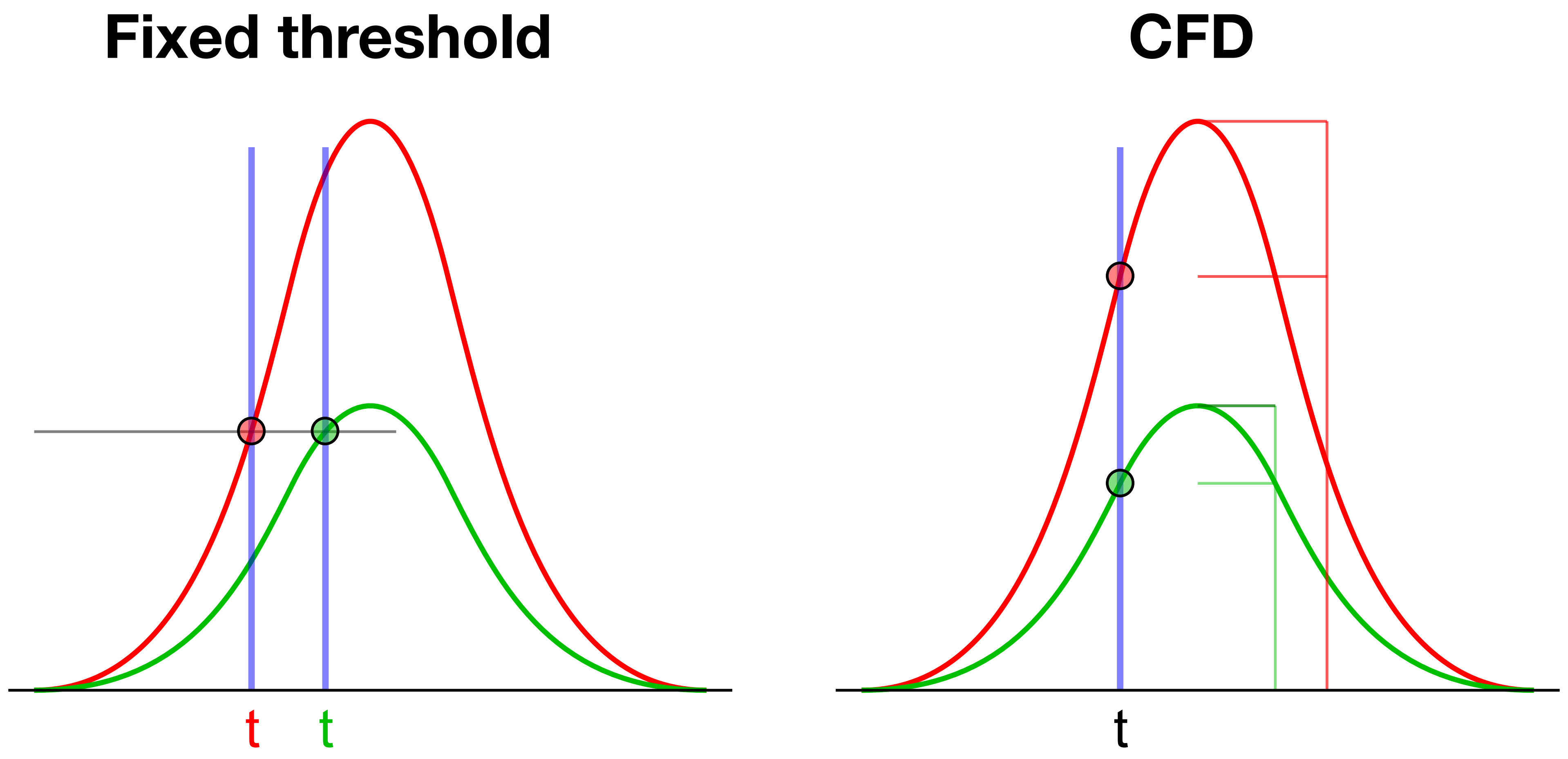
FWHM vs tau



Rise time

What is the “time stamp” of a signal?

- Time stamp computed with the “**C**onstant **F**raction **D**iscriminator” (**CFD**) algorithm
- **Time stamp** = time at which the signal exceeds a defined fraction of the pulse’s amplitude
- The “best” fraction must be properly chosen in order to optimize the time resolution
- **Time resolution** = std. dev. of the time stamps sample



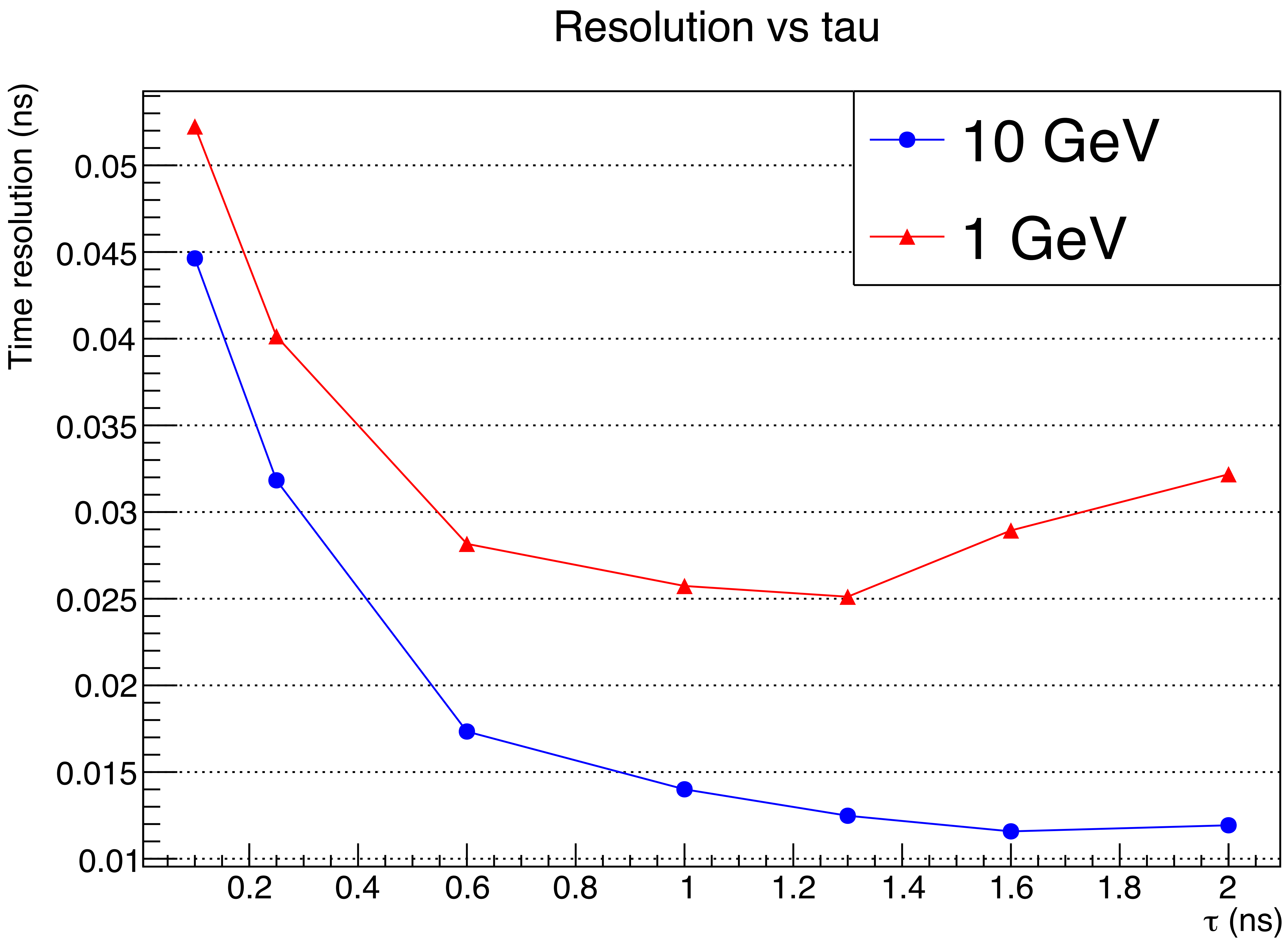
https://en.wikipedia.org/wiki/Constant_fraction_discriminator

First results

- As expected, better resolution at higher energies (photostatistics contribution)
- Slow PMTs perform better

Why?

➡ Slow PMTs are less affected by the longitudinal fluctuations of the showers



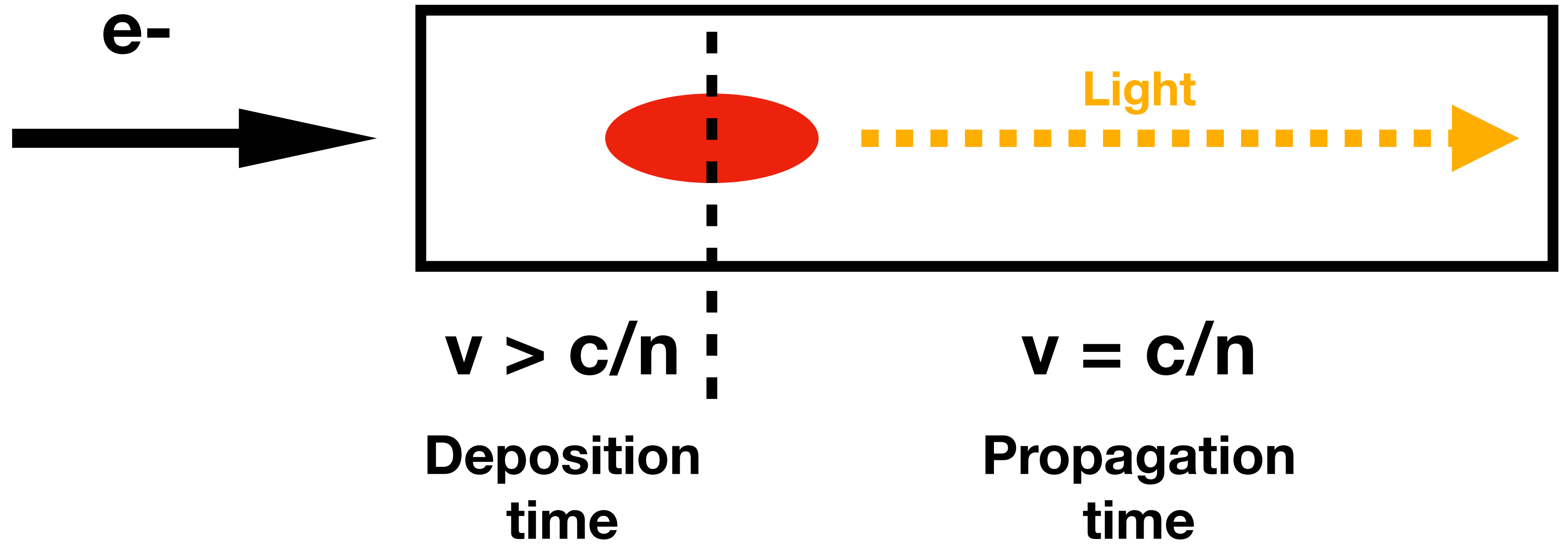
More info in backup slides

Why are slower PMTs better ?

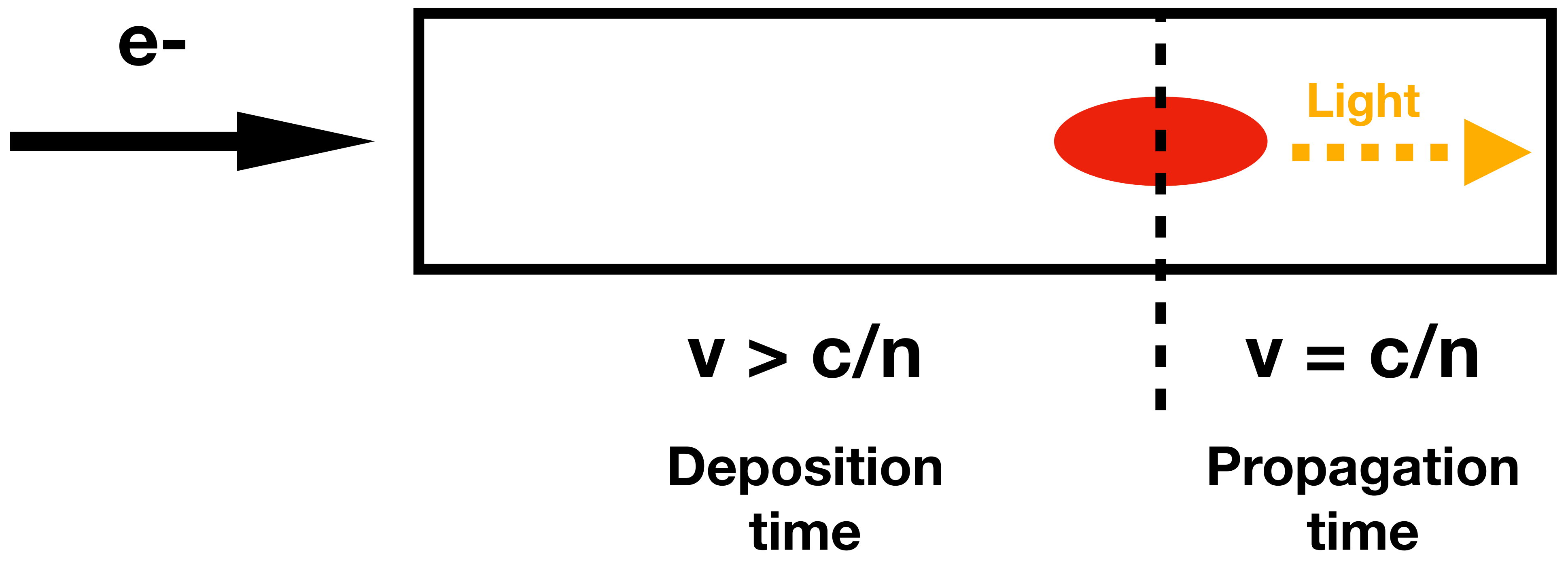
- Shower depth and time stamp are correlated. For **deeper showers**:
  - **Direct photons arrive earlier** to the PMT —> Negative correlation

- *Barycenter of the energy depositions*
- *Direct photons*

“Surface” event



“Deep” event



More info in backup slides

Why are slower PMTs better ?

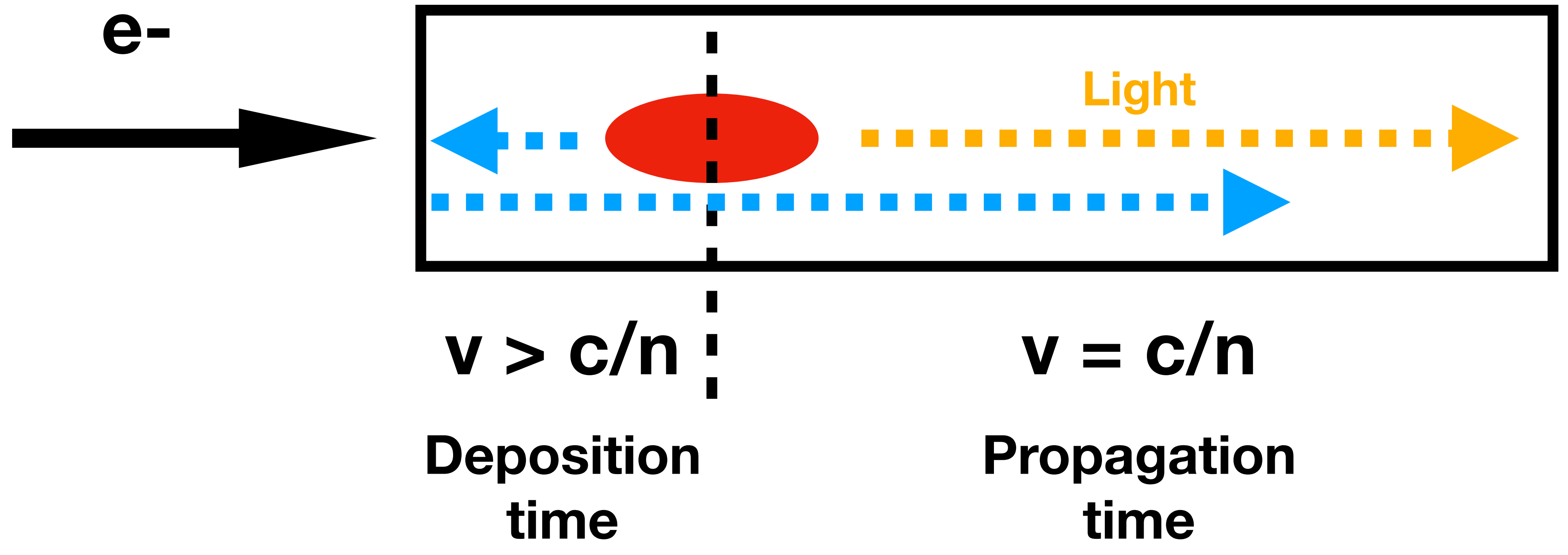
- Shower depth and time stamp are correlated. For **deeper showers**:
  - **Direct photons arrive earlier** to the PMT —> Negative correlation
  - **Reflected photons arrive later** —> Positive correlation

➡ **The CFD time stamp is biased by the shower depth**

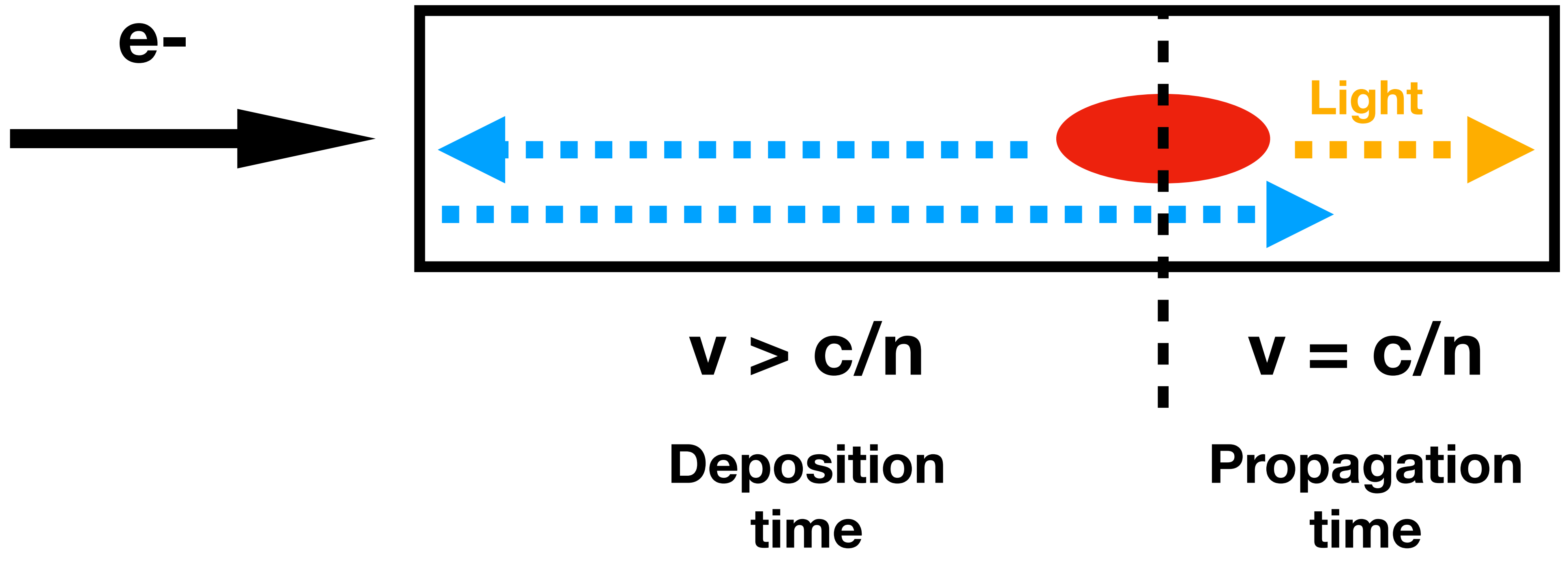
➡ **This bias worsens the time resolution**

- ● *Barycenter of the energy depositions*
- ● *Reflected photons*
- ● *Direct photons*

"Surface" event



"Deep" event

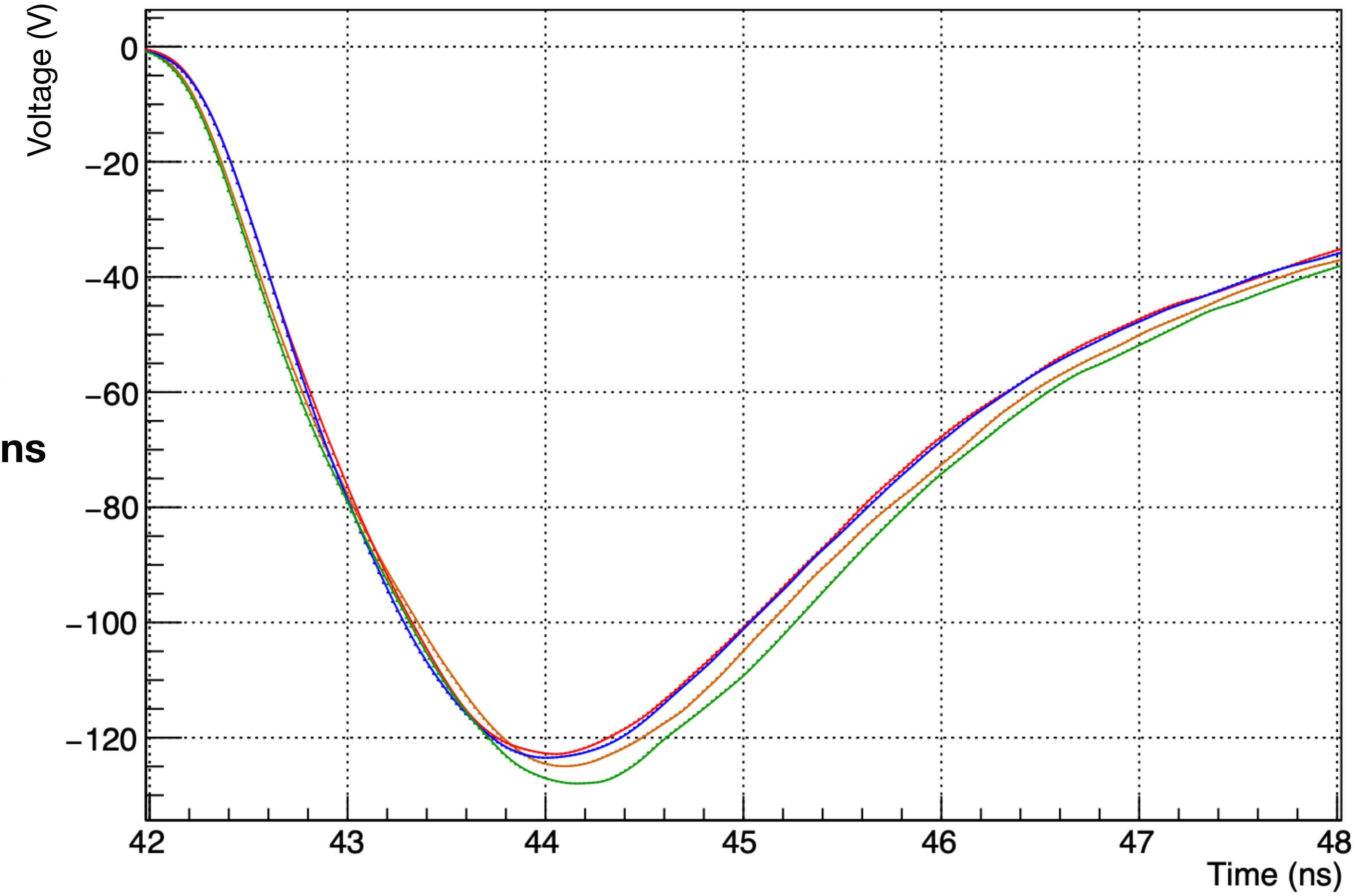


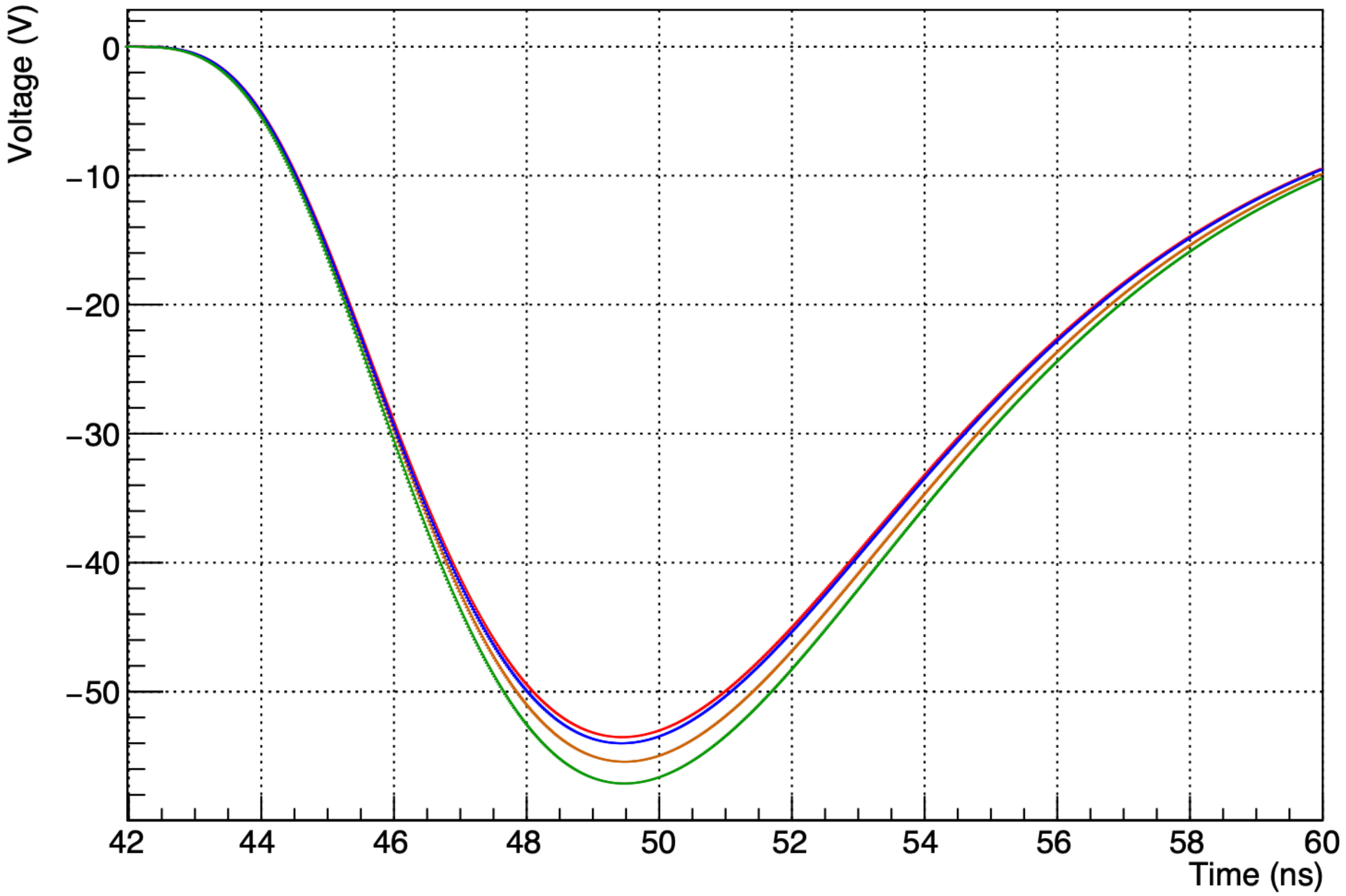
More info in backup slides

Why are slower PMTs better ?

- This effect is **more relevant for fast PMTs** (they better distinguish between direct and reflected photons)
- It **affects the shape of the PMTs signals** —> The CFD method can’t take it into account
- It **depends on the CFD threshold**
    - Low thresholds mostly detect direct photons
    - For some thresholds the two correlations partially cancel out each other, removing the overall bias

10 GeV
Tau = 0.1 ns
“Fast”

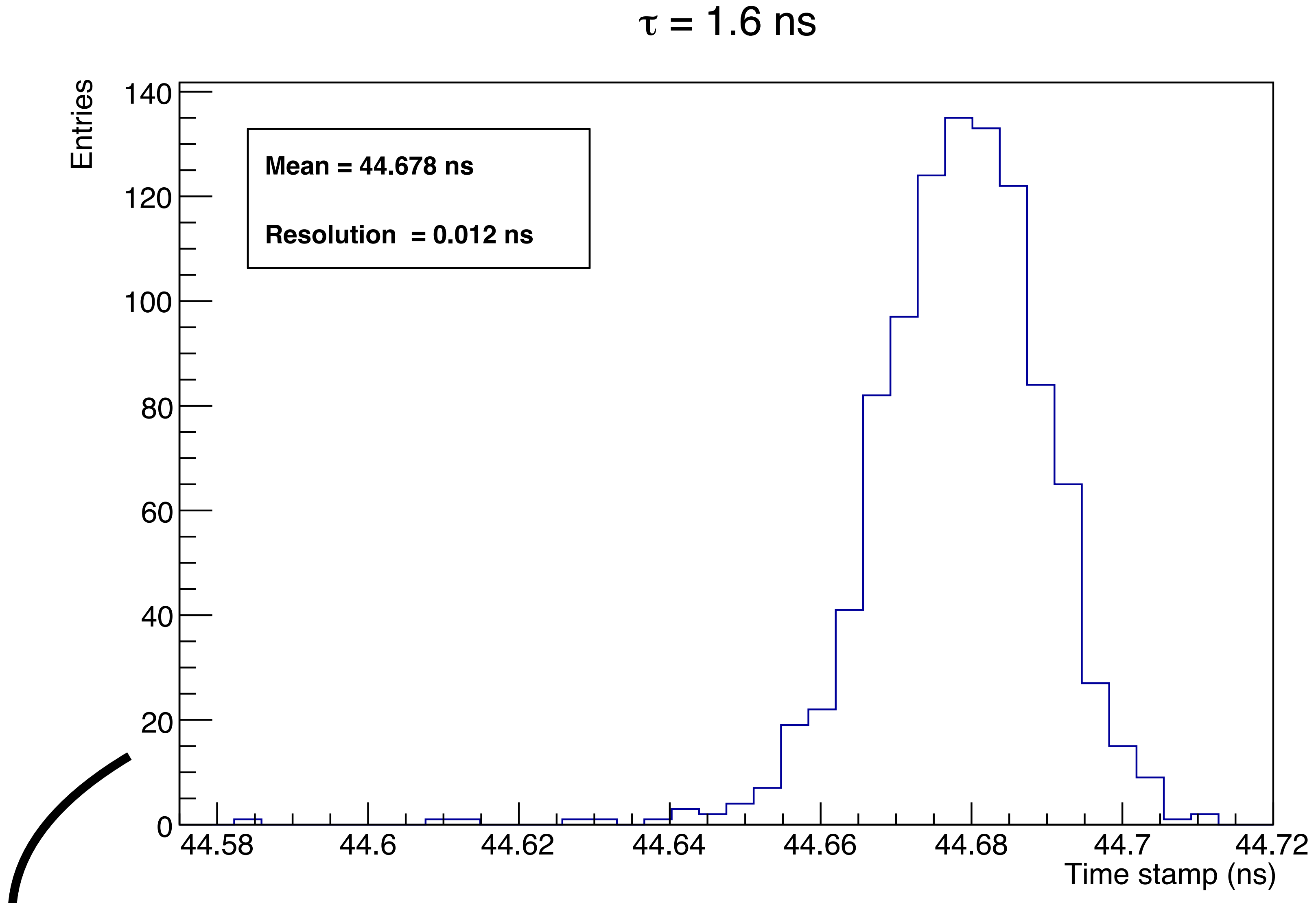


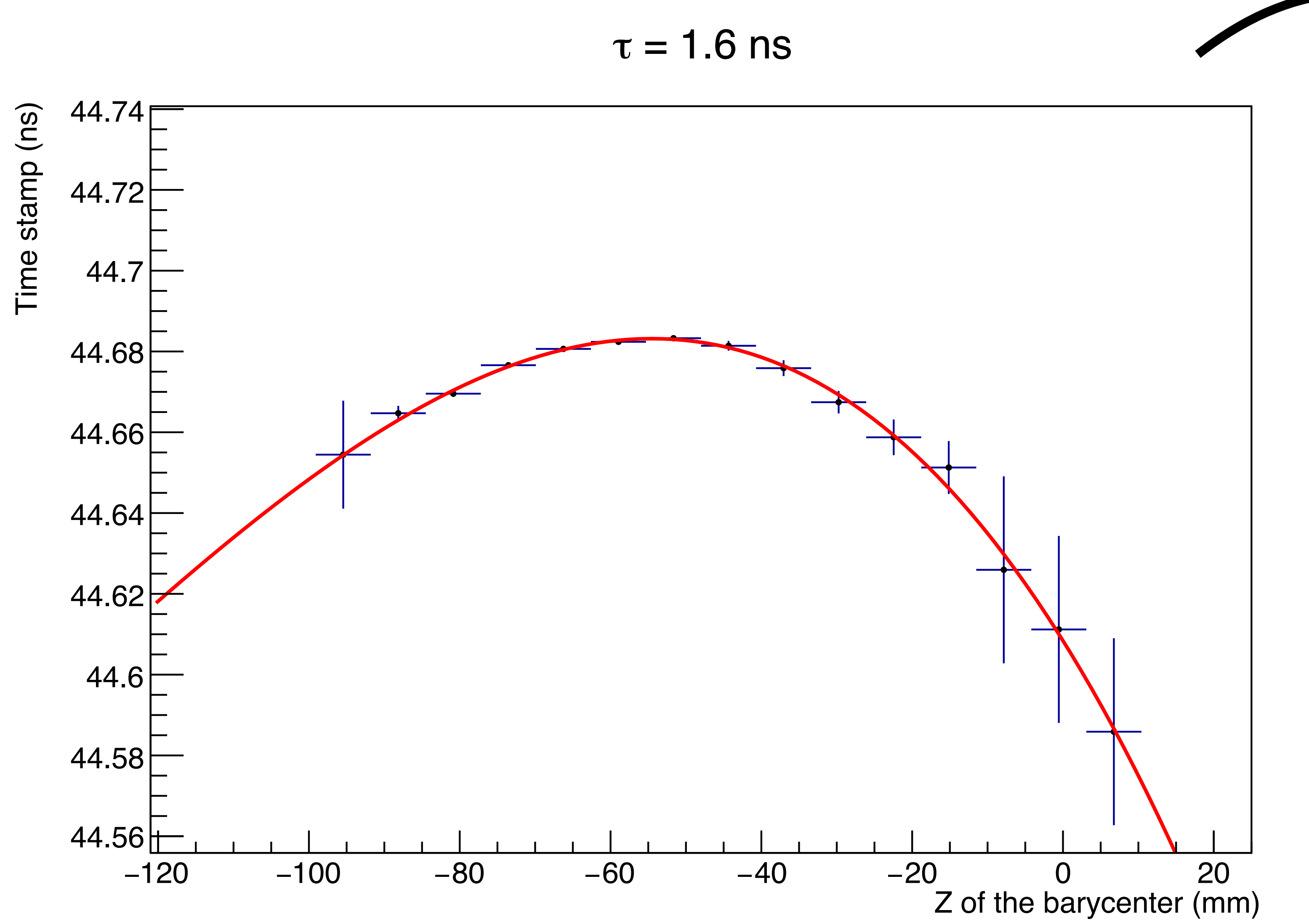


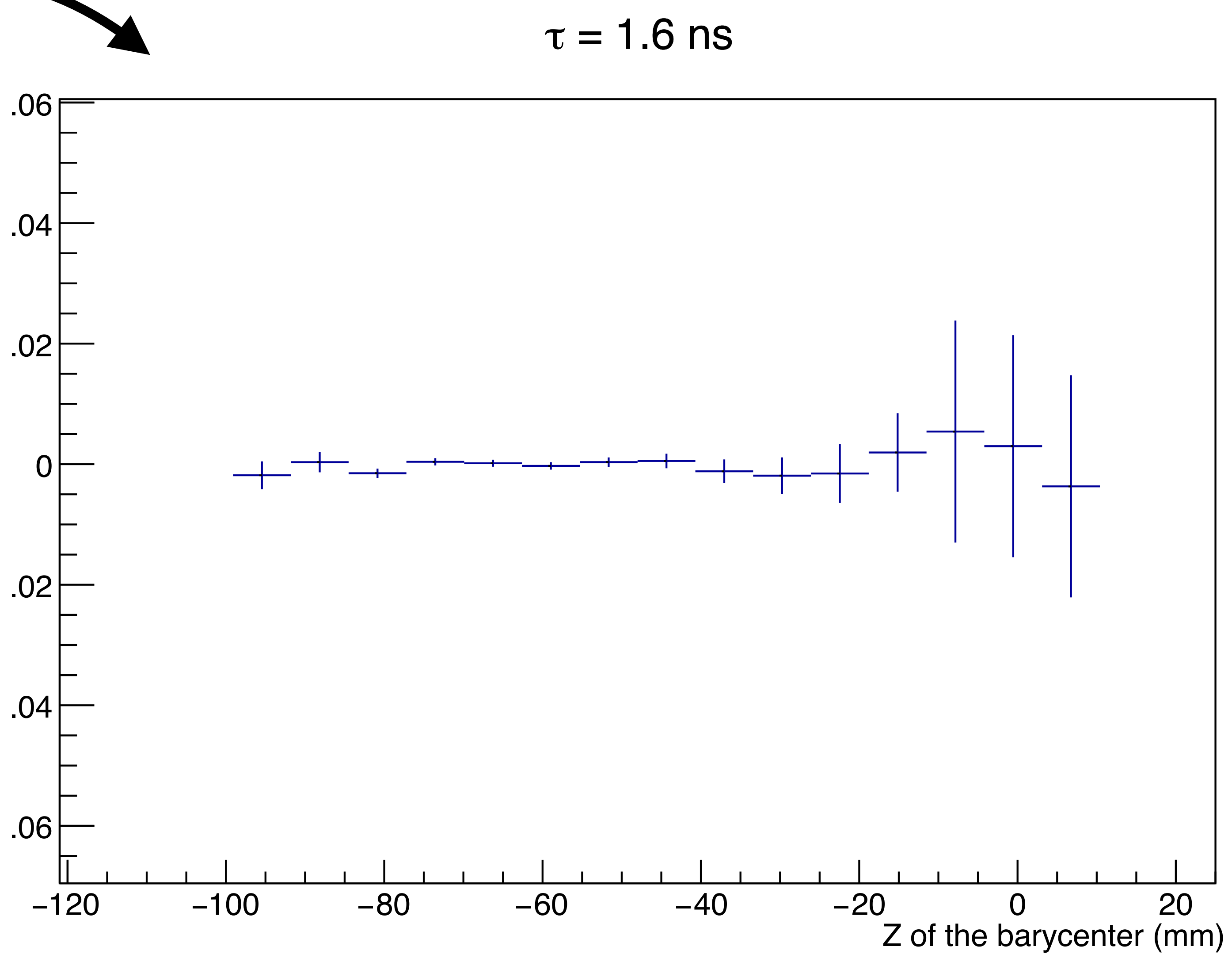
10 GeV
Tau = 2.0 ns
“Slow”

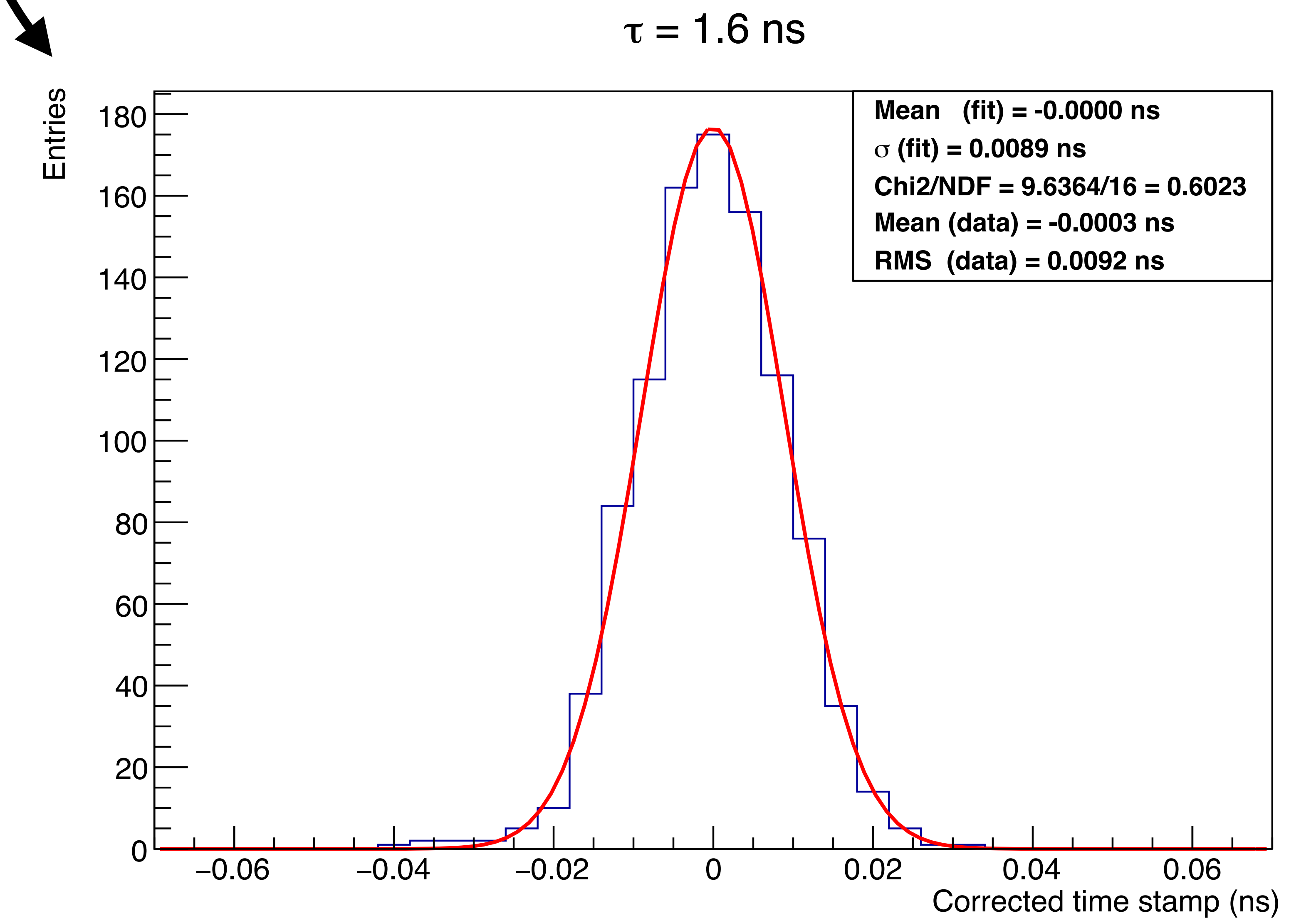
Correction procedure

- Polynomial fit to the profiled scatter plot of time stamp t vs shower depth of each event
    - ➡ Find the correction curve f
- **Corrected time stamp** for the j^{th} event defined as: $\hat{t}_j = t_j - f_j$
- The best CFD threshold after the bias correction may be different







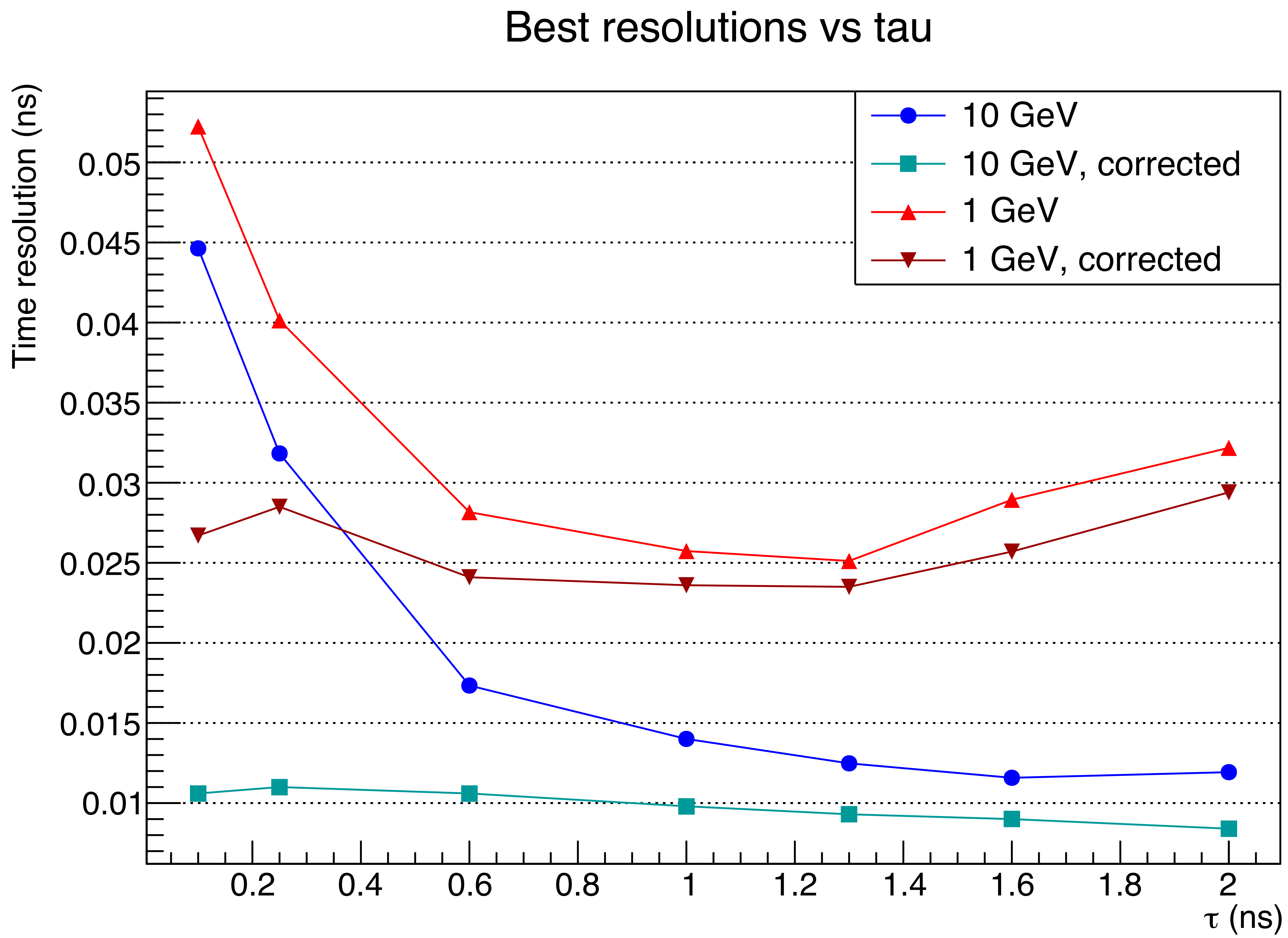


Results

- **Corrected resolution** = std. dev. of the unbiased time stamps $\hat{t}$

- **Faster PMTs (lower τ) undergo wider corrections**

- The best CFD threshold after the correction is **always ~ 10% or ~ 90%**
    - At these levels: correlation between time stamp and shower depth is maximum
    - Highest corrections



Here, the best CFD threshold is the optimal one for each point (different before/after the correction)

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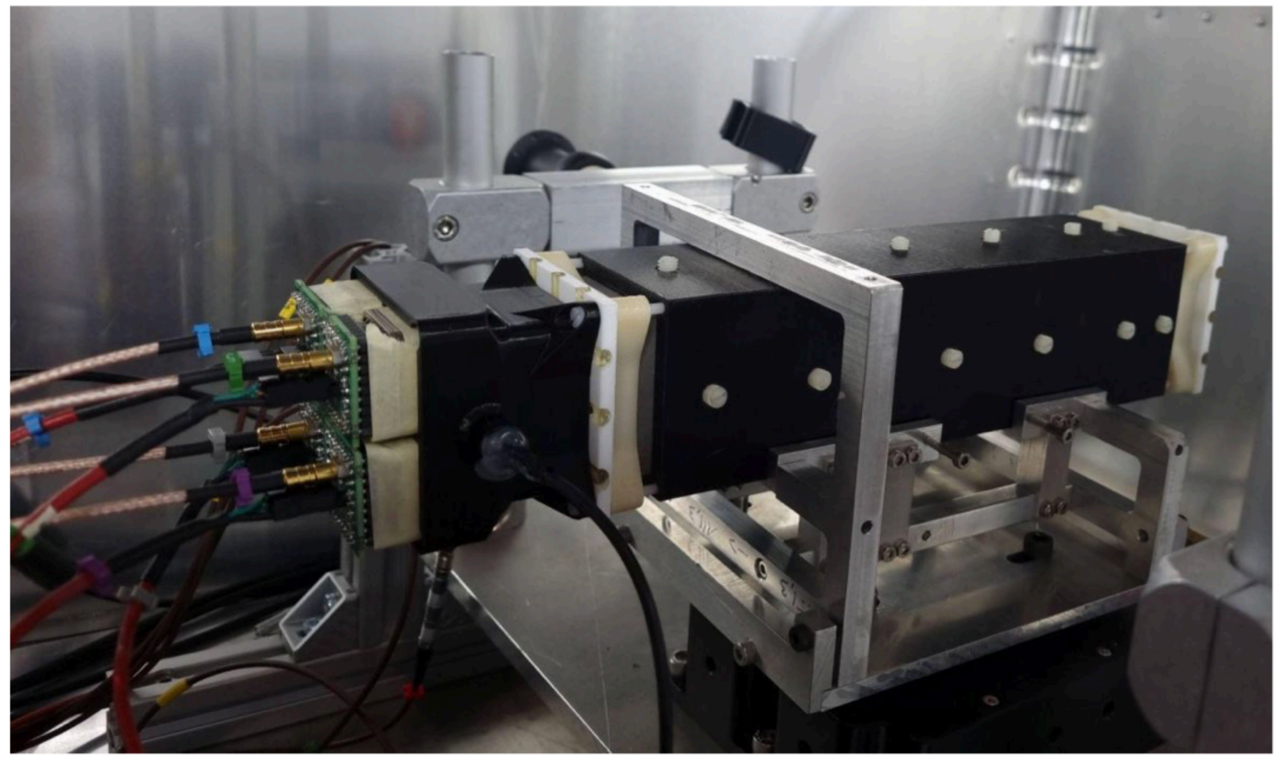
Prototypes

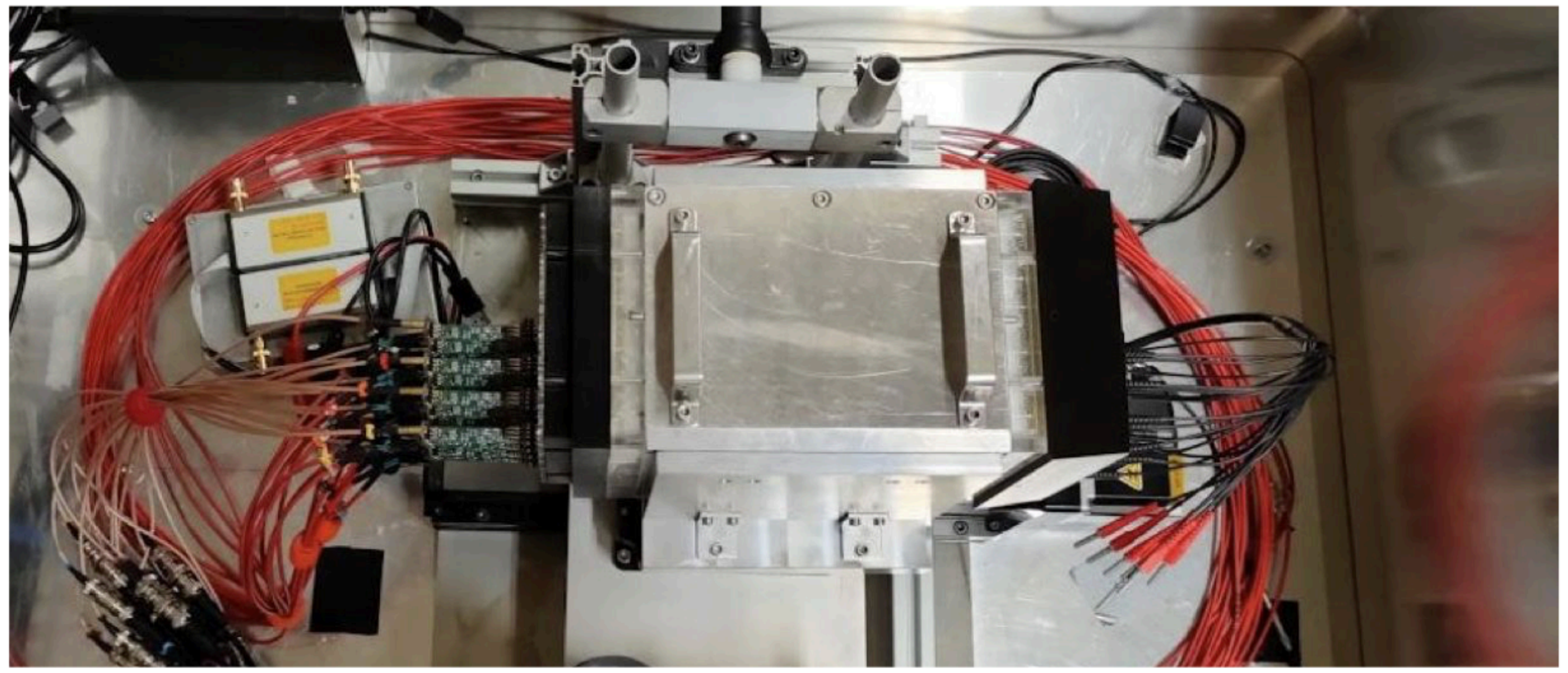
“Small module”

- SpaCal **W-Polystyrene**
- 4 cells only (4.5 x 4.5 cm^2)
- 5 cm - square to octagon light guides
- Kuraray SCSF-78 (blue) or 3HF (green) fibres
- Readout with 4 different PMTs:
  - R7600U, R9880U, R14755U, R11187 (a.k.a. Tilecal)



“Module 0”

- SpaCal **W-Polystyrene**
- Full-size module: 16 cells (12.1 x 12.1 cm^2)
- 10 cm - square to octagon light guides
- Kuraray SCSF-78 (blue) fibres
- Readout with R9880U PMT



Time resolution model

- The time resolution as a function of the number of photons impinging the PMTs is well described by

$$\sigma_T(N_{ph}) = \boxed{\frac{a}{N_{ph}}} \oplus \boxed{\frac{b}{\sqrt{N_{ph}}}} \oplus \boxed{c}$$

- Noise term
- Sampling term
- Constant term

- Assuming linearity: $N_{ph} \propto E$ (energy of the incident e^-)

$$\sigma_T(E) = \frac{a'}{E} \oplus \frac{b'}{\sqrt{E}} \oplus c'$$

Time resolution model

- **Noise term:** caused by the electronic noise fluctuations
- Faster PMTs (quicker rise time) lead to smaller noise terms
- When exploiting the CFD algorithm, it can be estimated as

$$\sigma_{T_{noise}} = \sqrt{\frac{2}{3}} \frac{\sigma_n}{dA/dt}$$

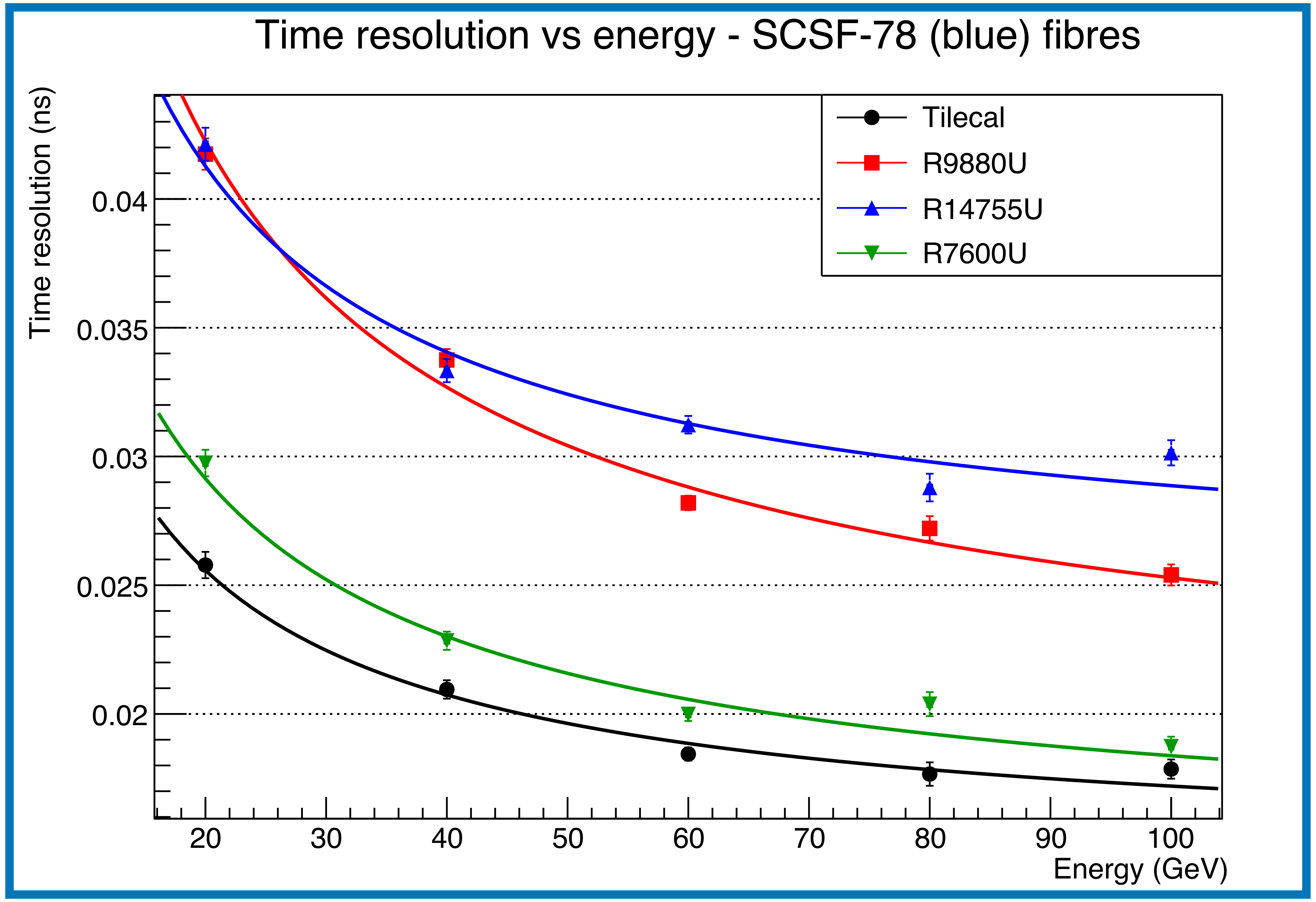
- σ_n = std. dev. of the electronic noise
- A = pulse's amplitude

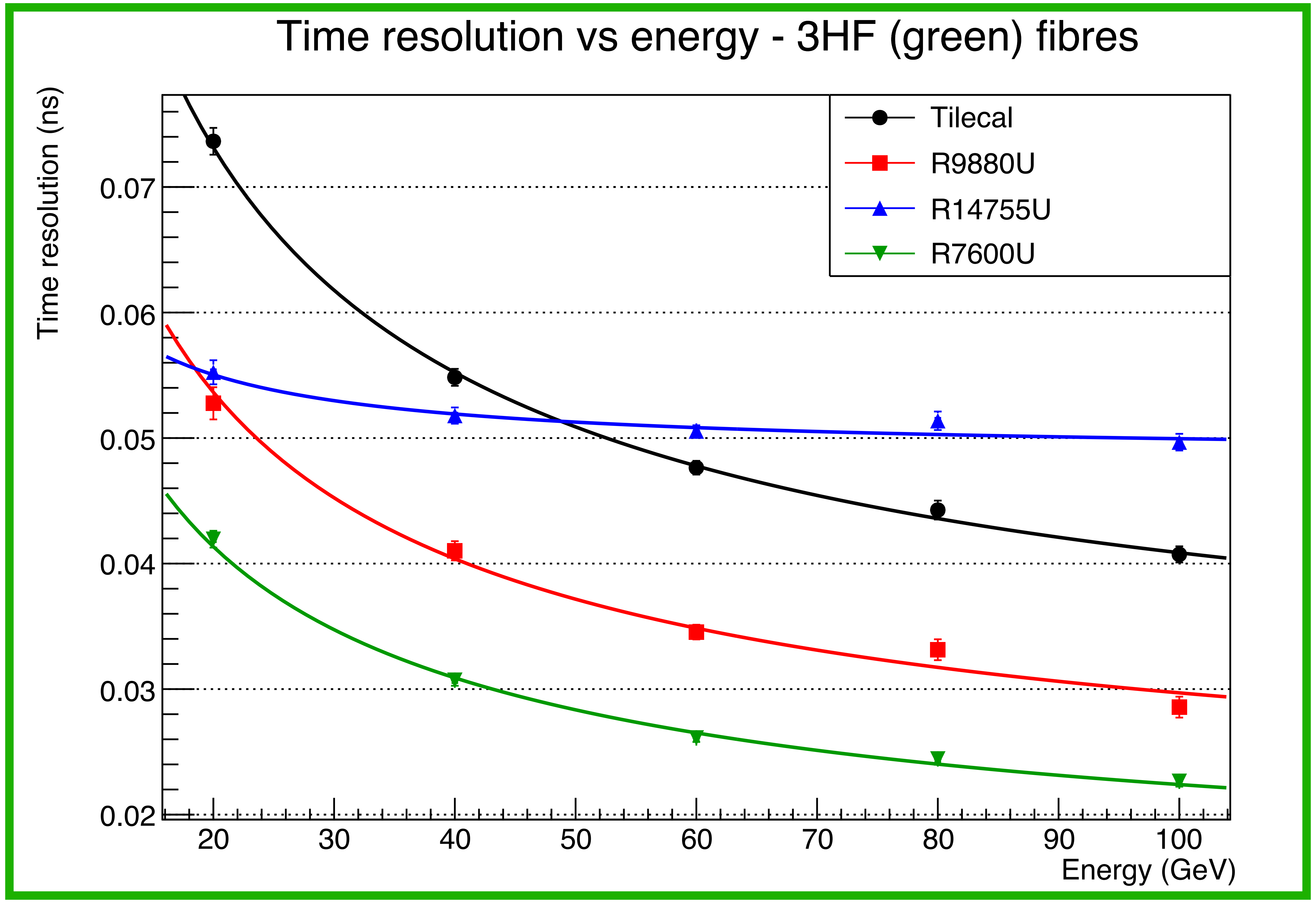
- If it is subtracted in quadrature, the resolution as a function of the energy becomes

$$\boxed{\sigma_T(E) = \frac{b'}{\sqrt{E}} \oplus c'}$$

Ref: Eric Delagnes, June 2016, "*What is the theoretical time precision achievable using a dCFD algorithm?*"

Time resolution results - Small module





- SCSF-78 results are systematically better due to faster decay time of the fibres
- SCSF-78 fibres: slow PMTs (R7600U and Tilecal) perform better —> Less biased by shower depth
- 3HF fibres: best results for PMTs with **E**xtended **R**ed **M**ulti **A**lkali (**ERMA**) photocathode

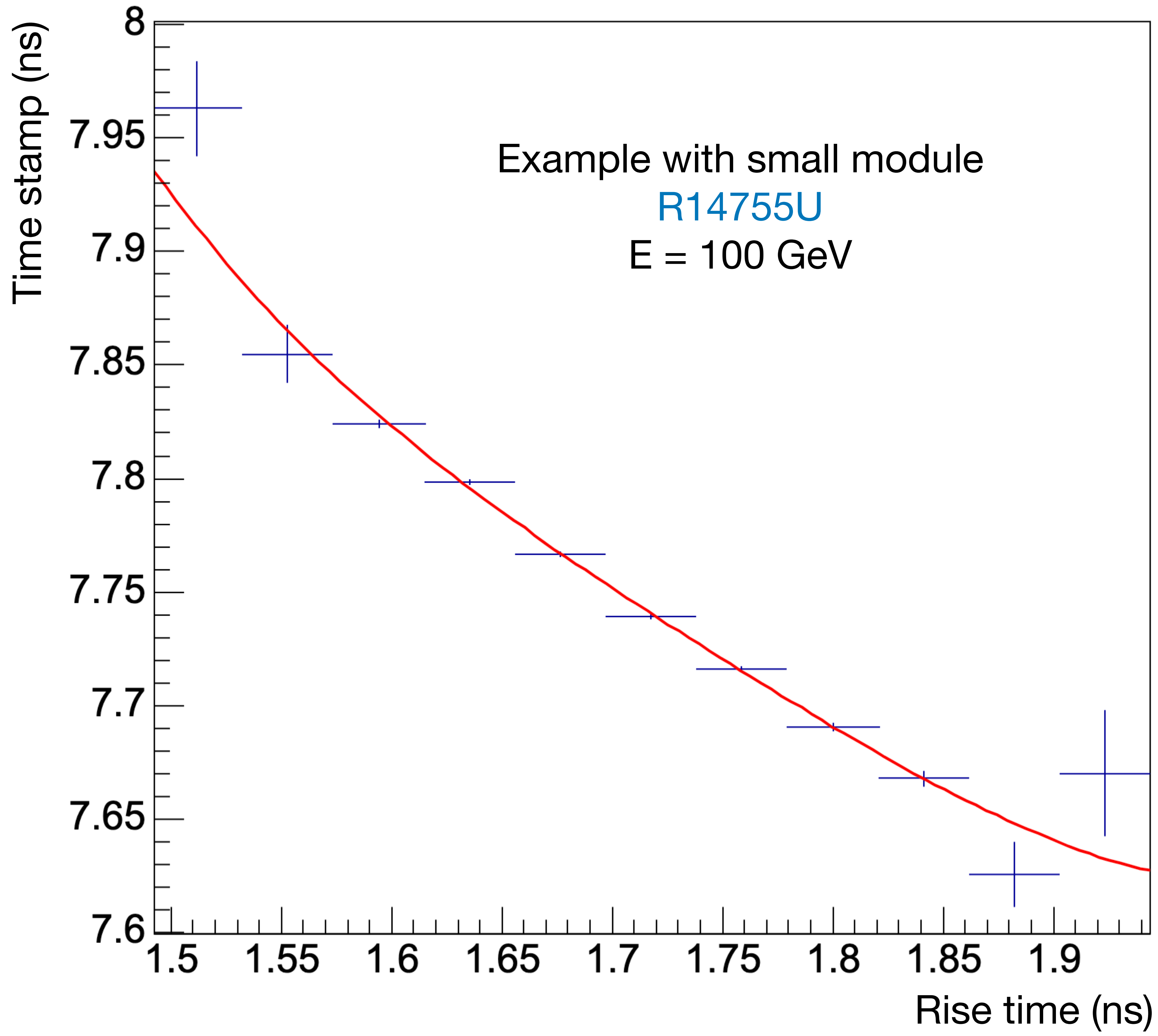
Correction to the time stamp

More info in backup slides

Simulations show that the rise time is highly correlated to the shower depth

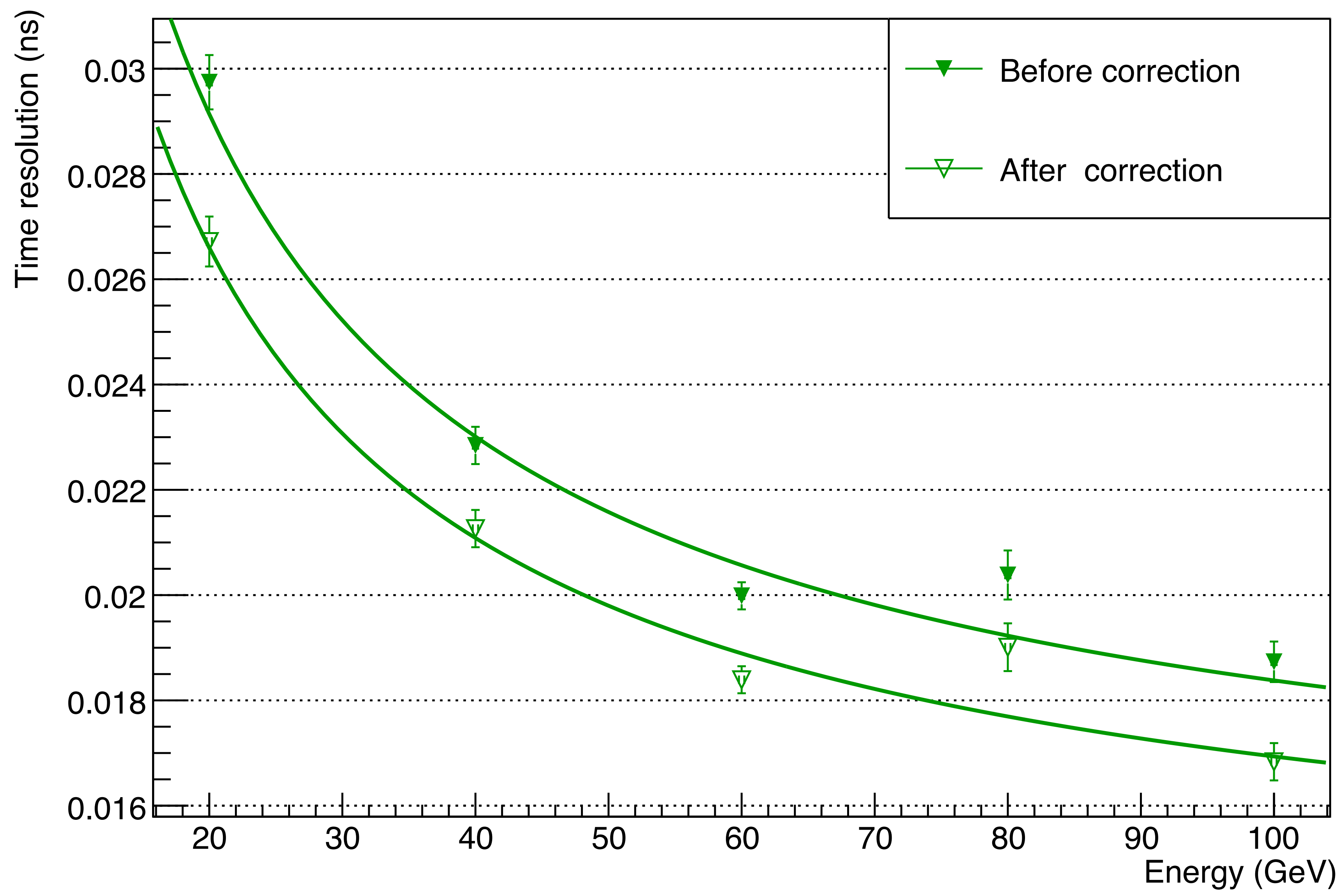
➡ **Idea: exploit the rise time to remove the bias**

- Polynomial fit to the profiled scatter plot of time stamp t vs rise time of each signal —> Find the correction curve f
- **Corrected time stamp** for the j^{th} event defined as: $\hat{t}_j = t_j - f_j$
- The corrected time resolution is the standard deviation of $\hat{t}$

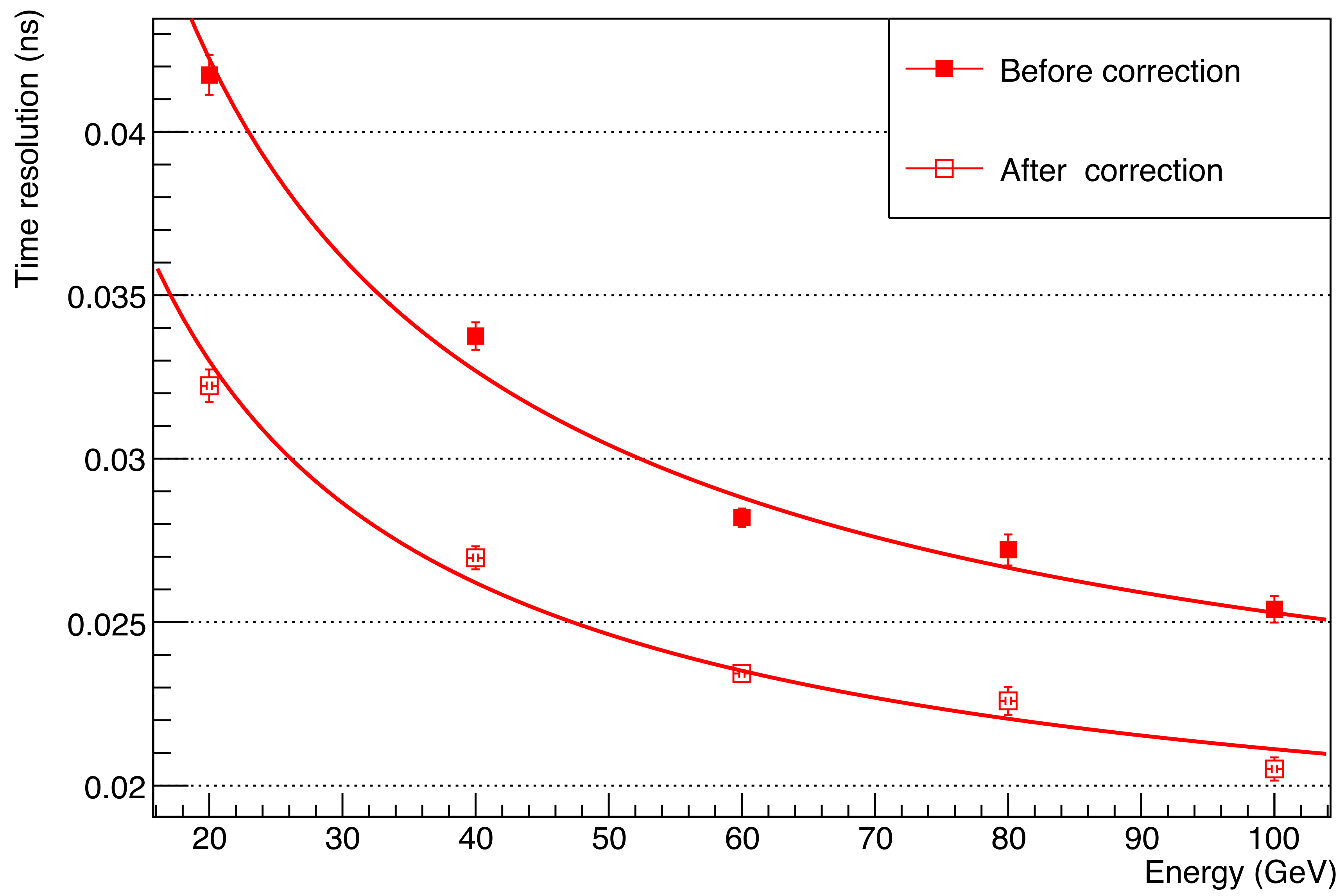


Corrected resolution - Small module with SCSF-78 fibres

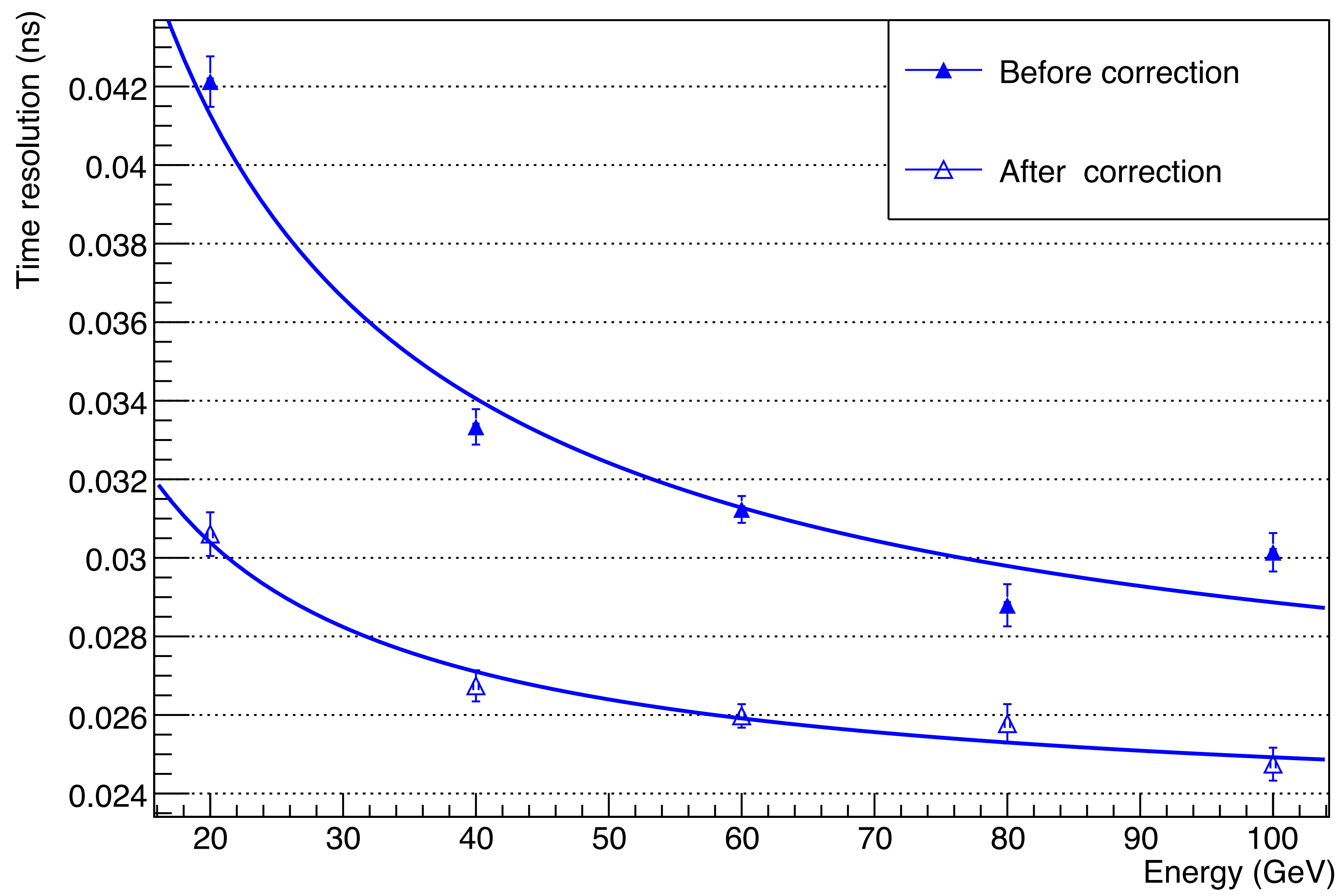
R7600U - SCSF-78 (blue) fibres



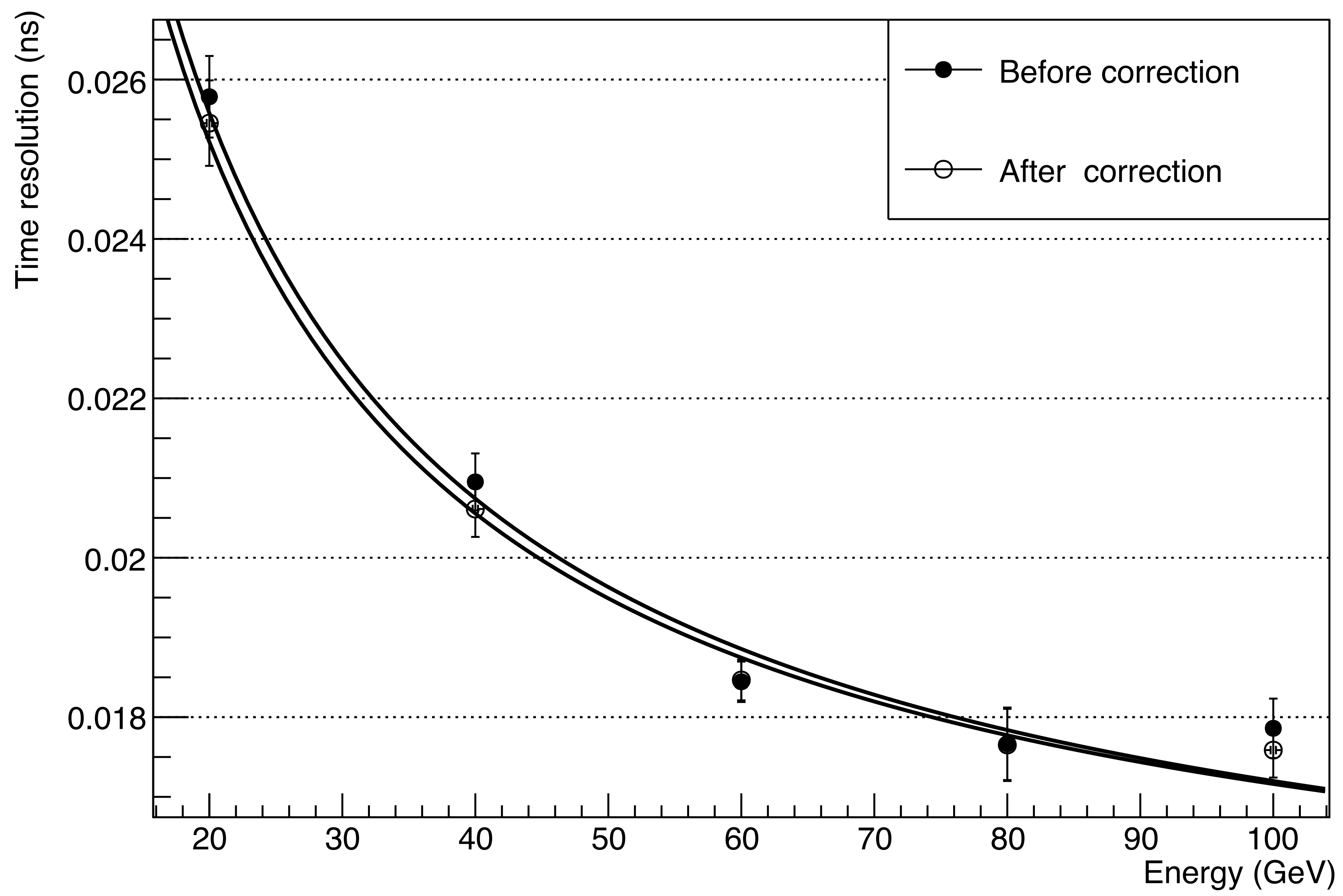
R9880U - SCSF (blue) fibres



R14755U - SCSF (blue) fibres

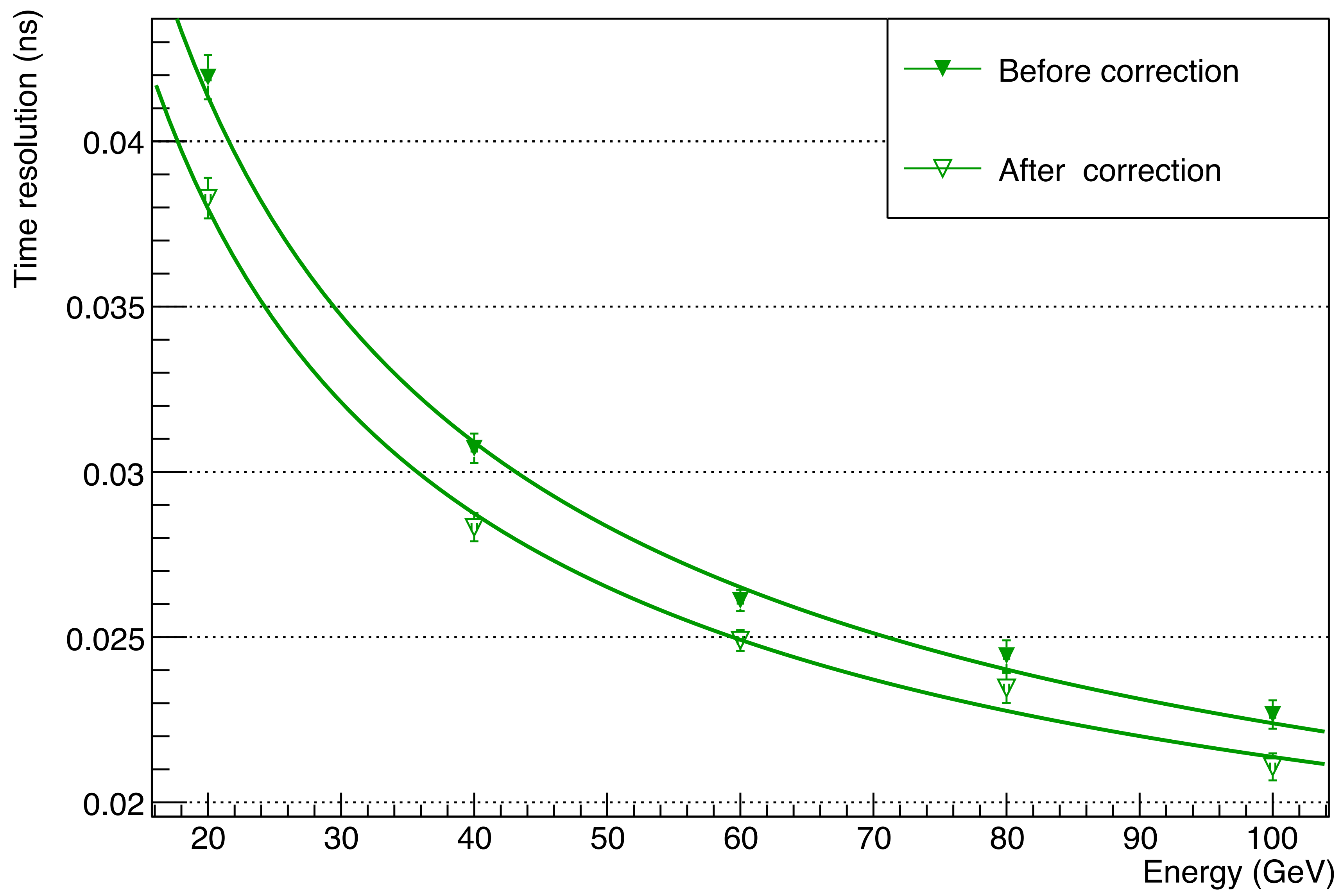


Tilecal - SCSF-78 (blue) fibres

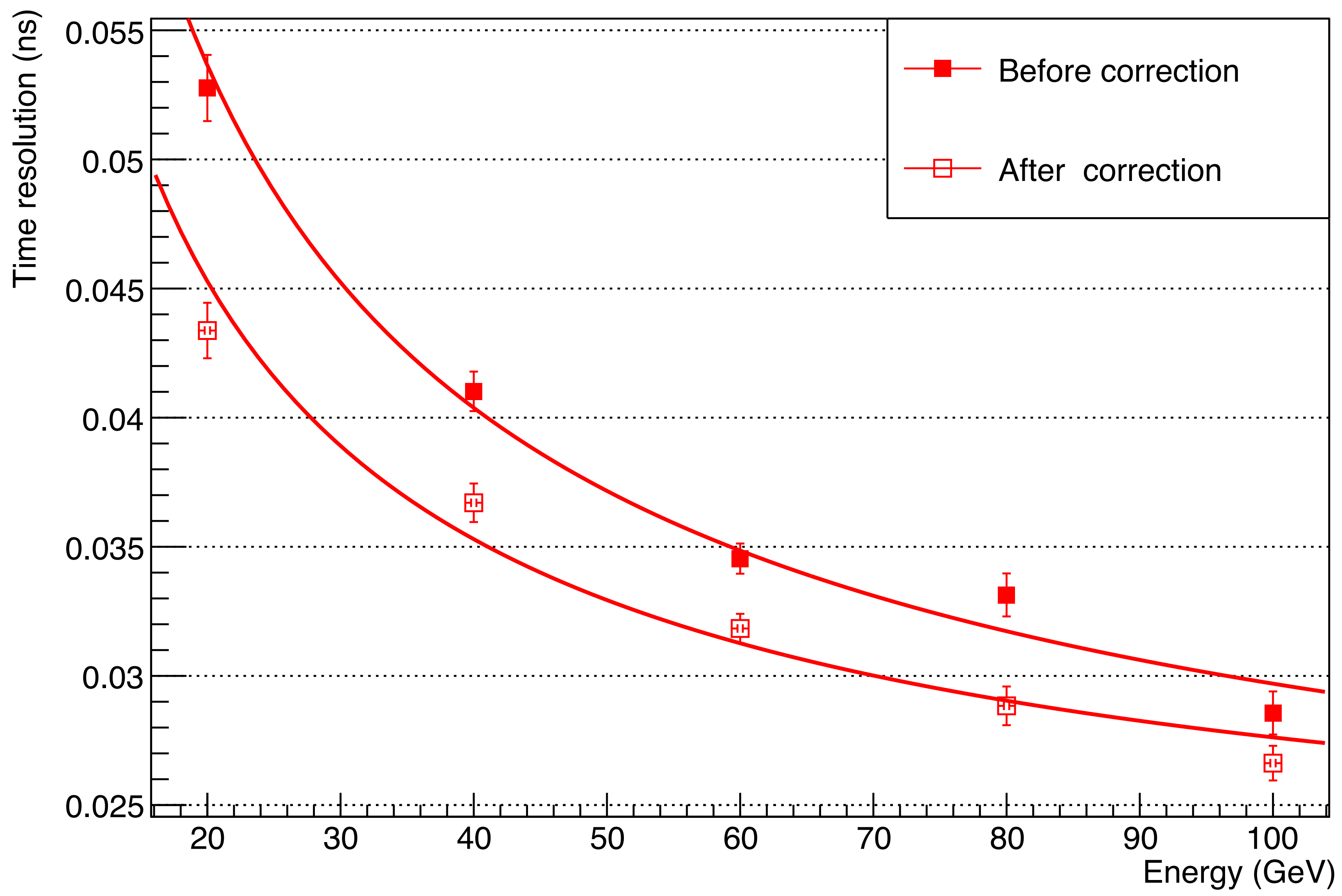


Corrected resolution - Small module with 3HF fibres

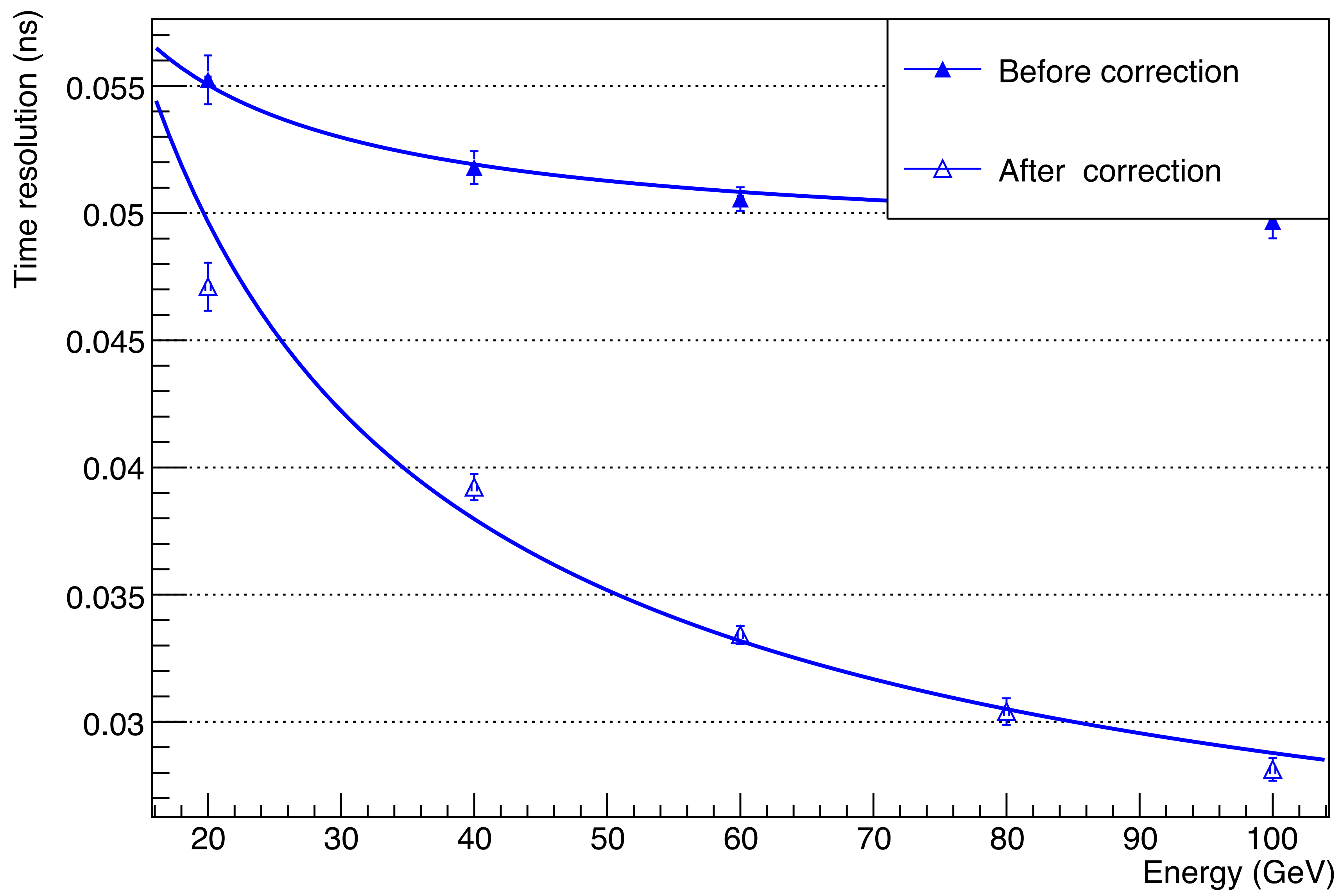
R7600U - 3HF (green) fibres



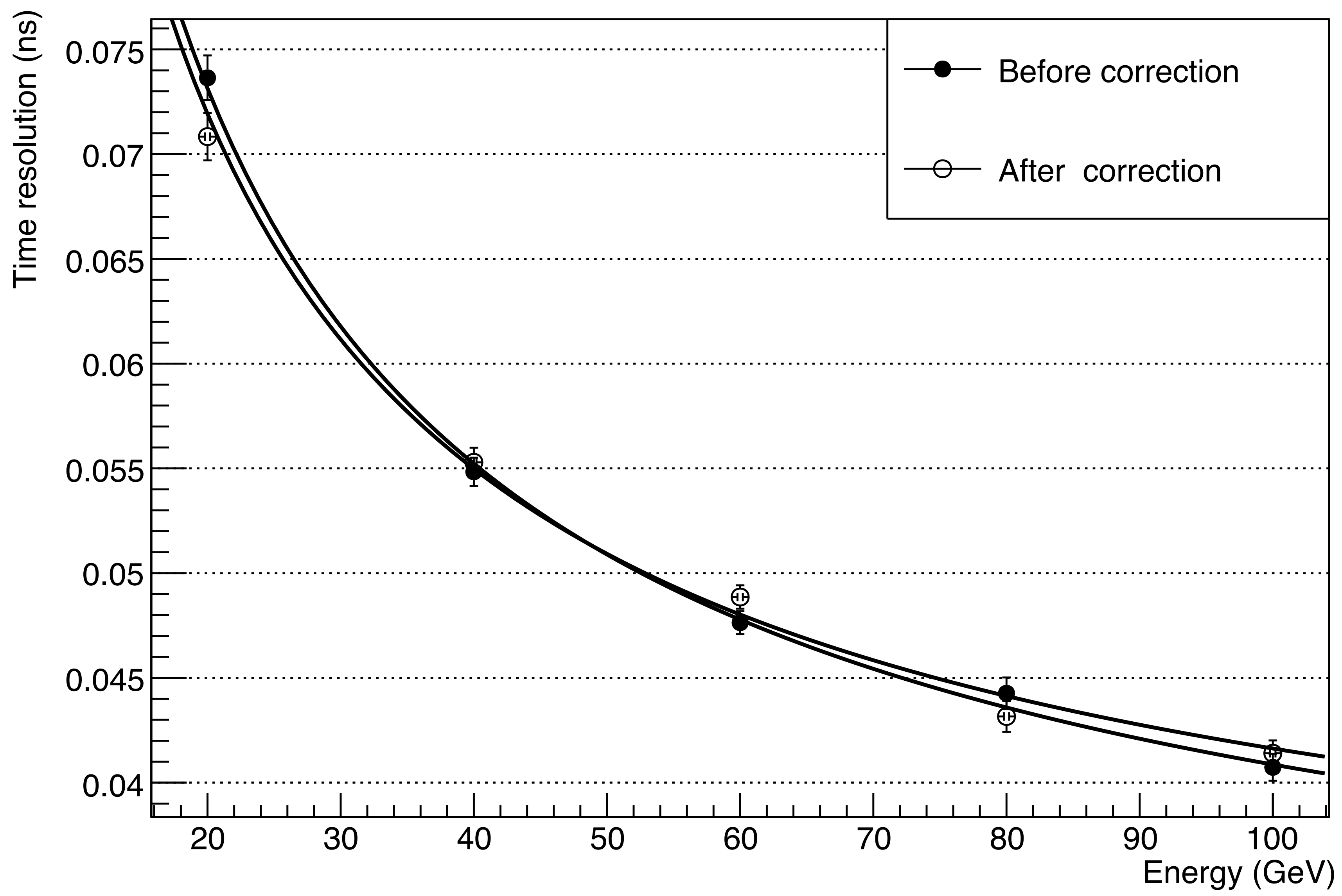
R9880U - 3HF (green) fibres



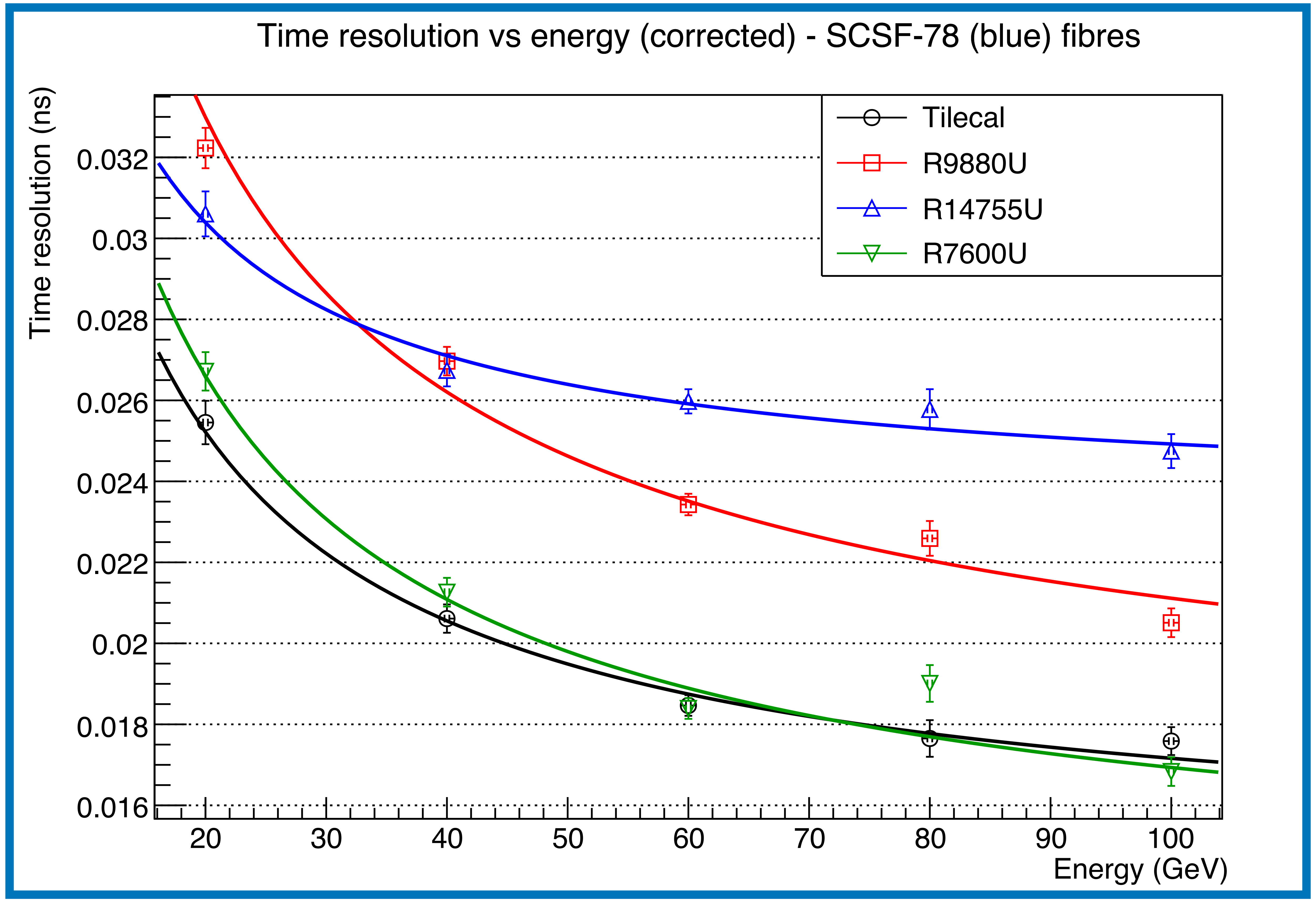
R14755U - 3HF (green) fibres

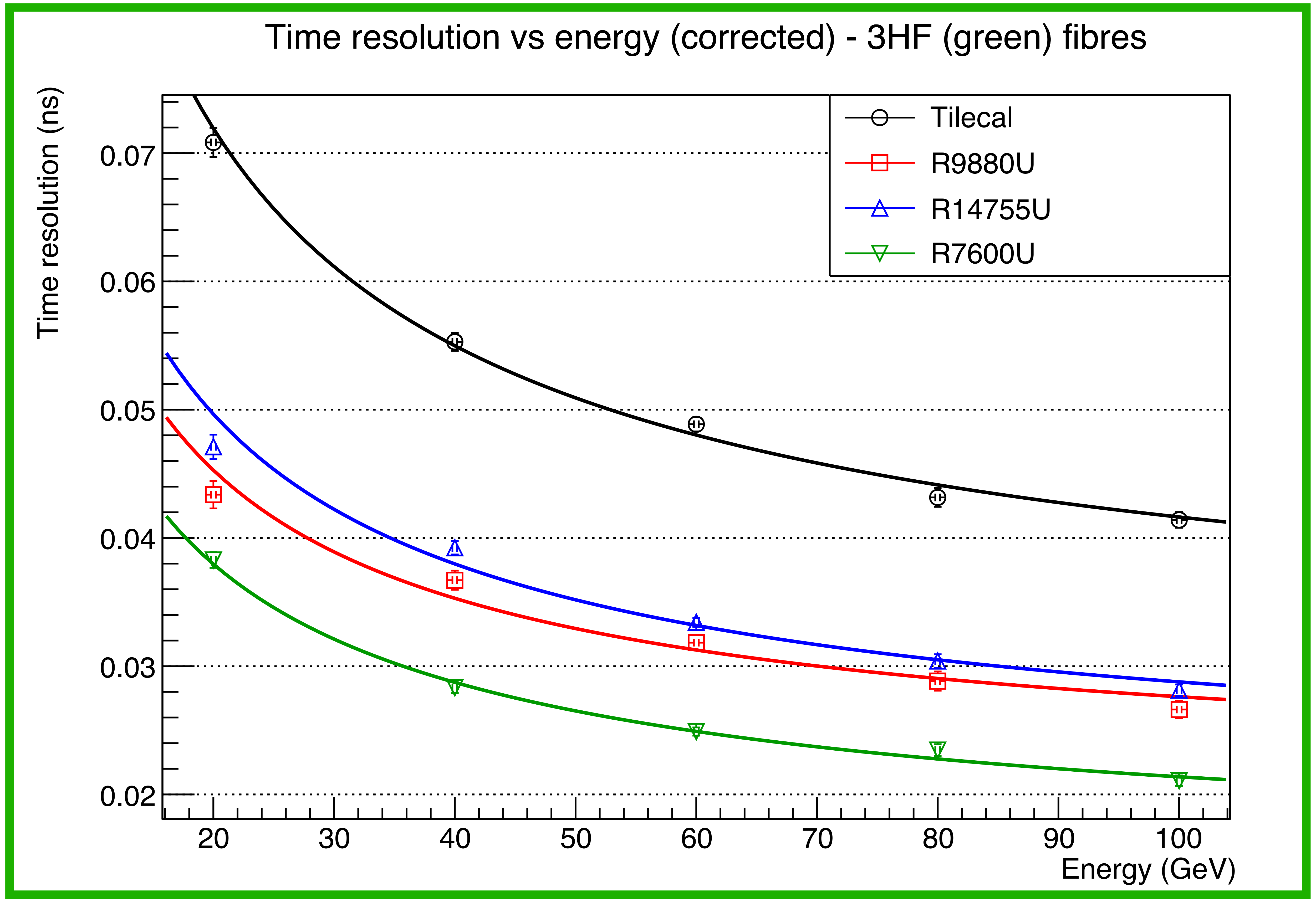


Tilecal - 3HF (green) fibres



Corrected resolution - Small module





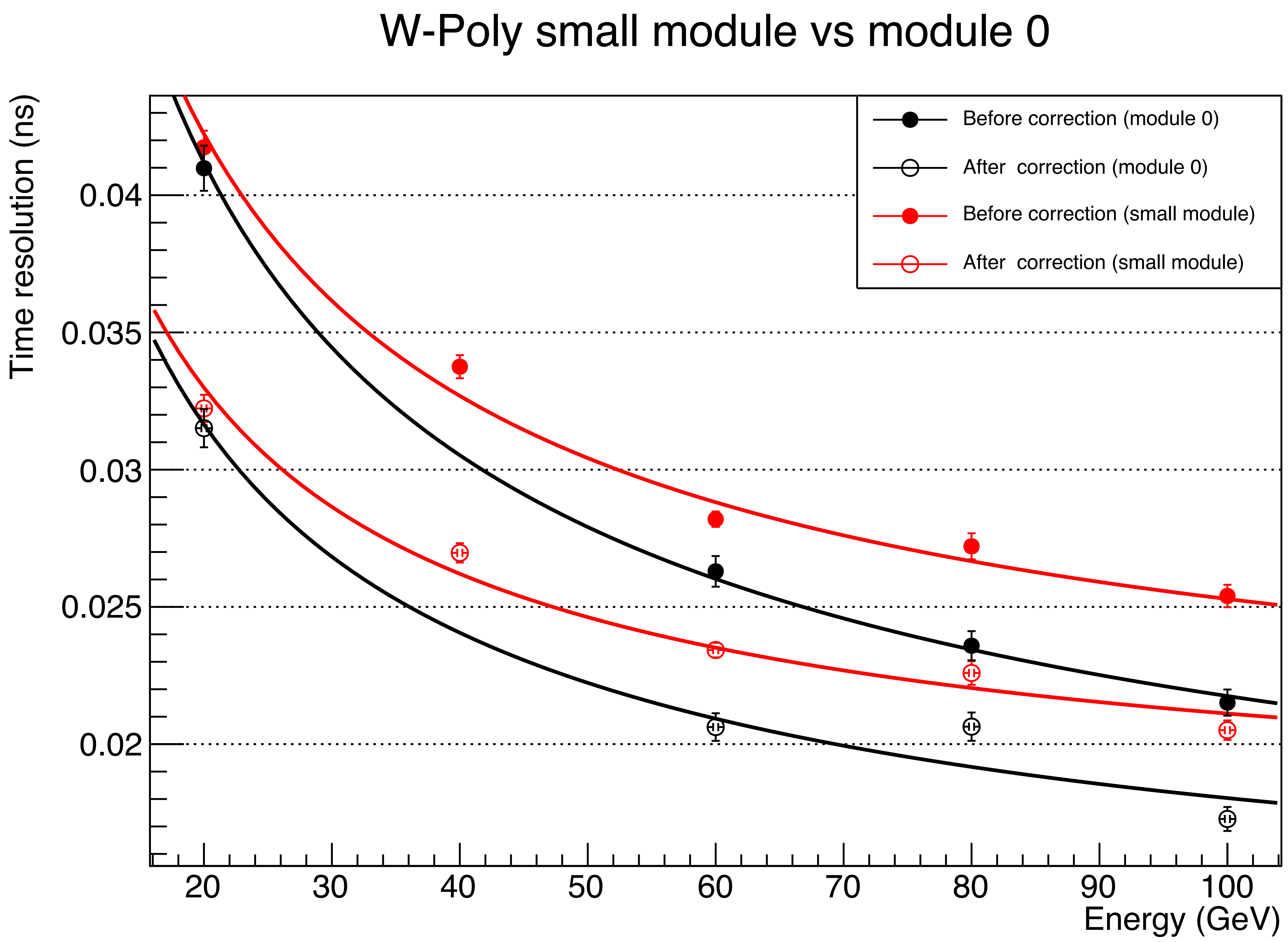
- As expected, **fast PMTs** (R9880U and R14755U) **undergo wider corrections**
- Still not enough for the fast PMTs to do better than R7600U
- The best threshold is always ~ 10% or 90%

“Module 0” vs “Small module”

- Both equipped with SCSF-78 fibres and R9880U PMT

- **Module 0 performs better**
    - Down to 17 ps at 100 GeV

- Differences probably caused by **different light guide length**
    - 10 cm (module 0) vs 5 cm (small module)
    - Different photons loss



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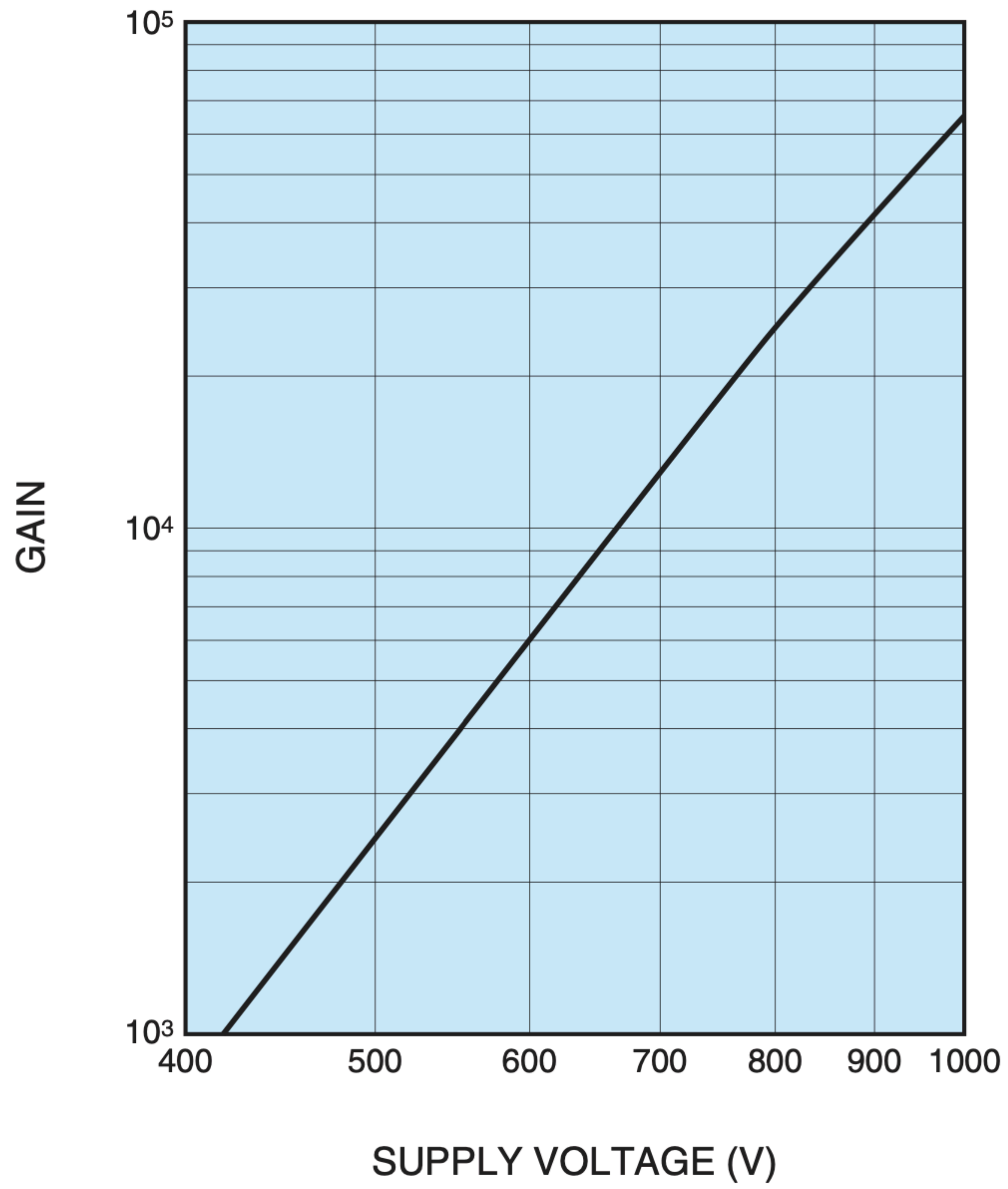
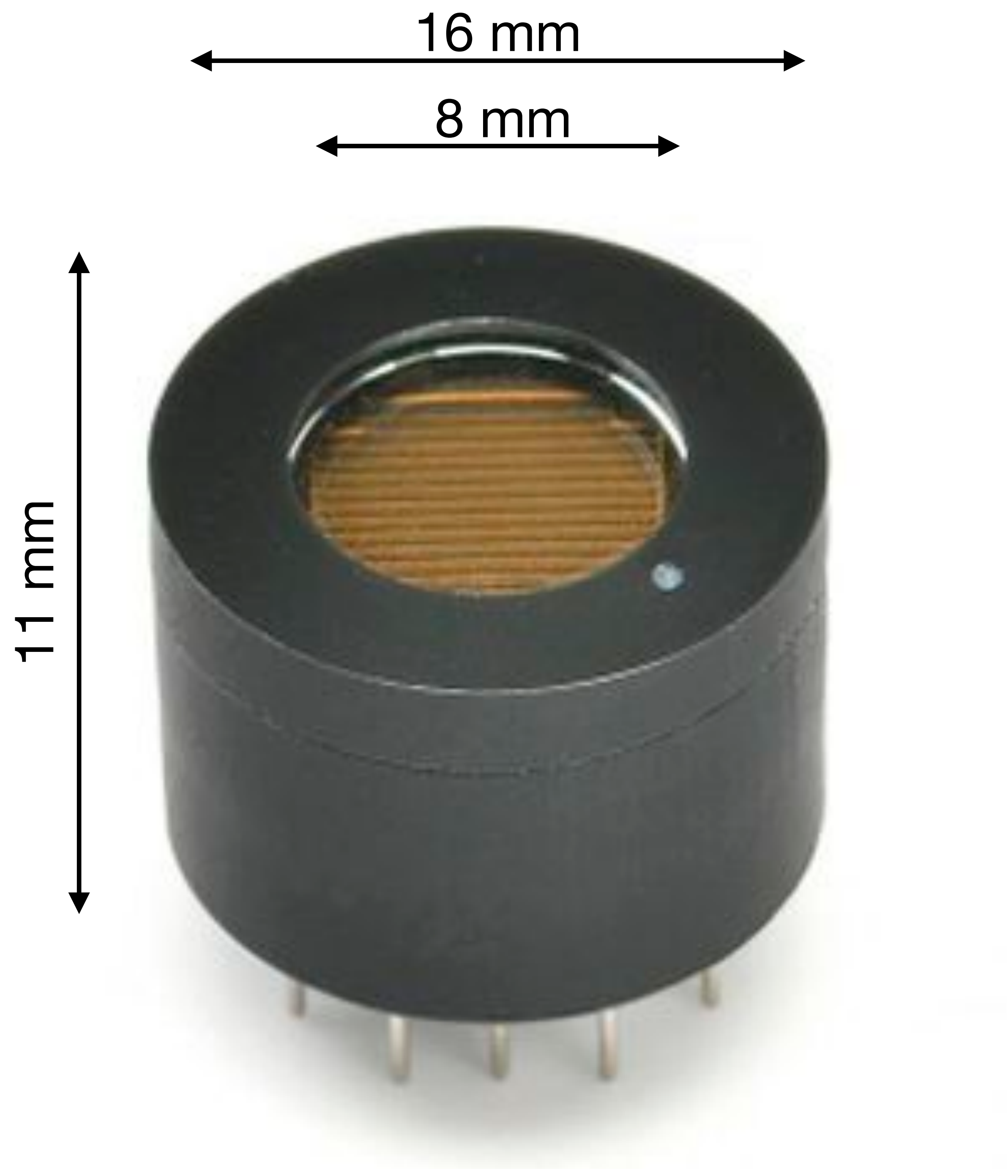
The Hamamatsu R14755U-100 PMT

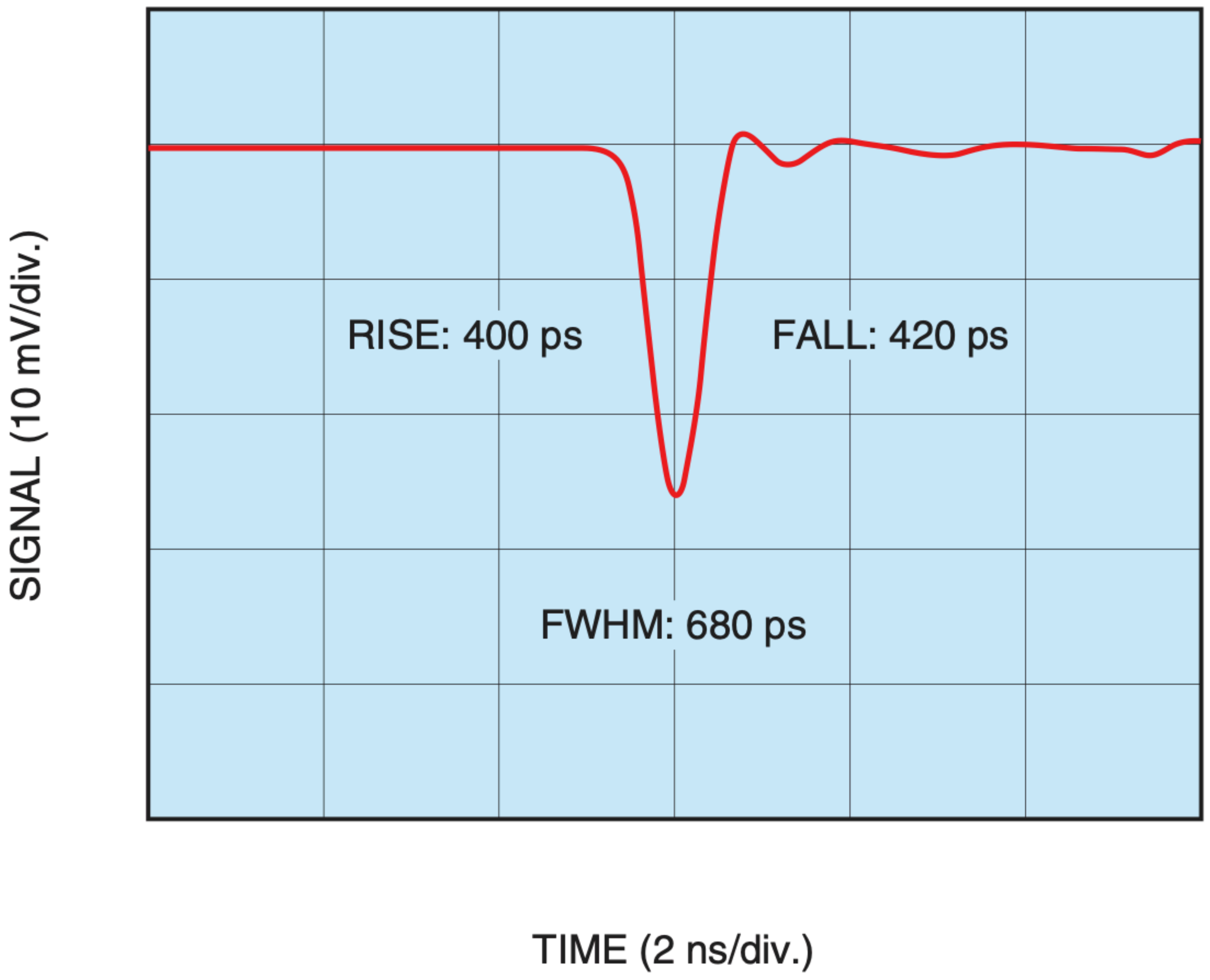
- Candidate PMT for the future LHCb ECAL thanks to its fast response
- Low gain, 6 dynode stages

Figures from the Hamamatsu data sheet
(https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/R14755U-100_TPMH1380E.pdf)





Typical single photoelectron signal

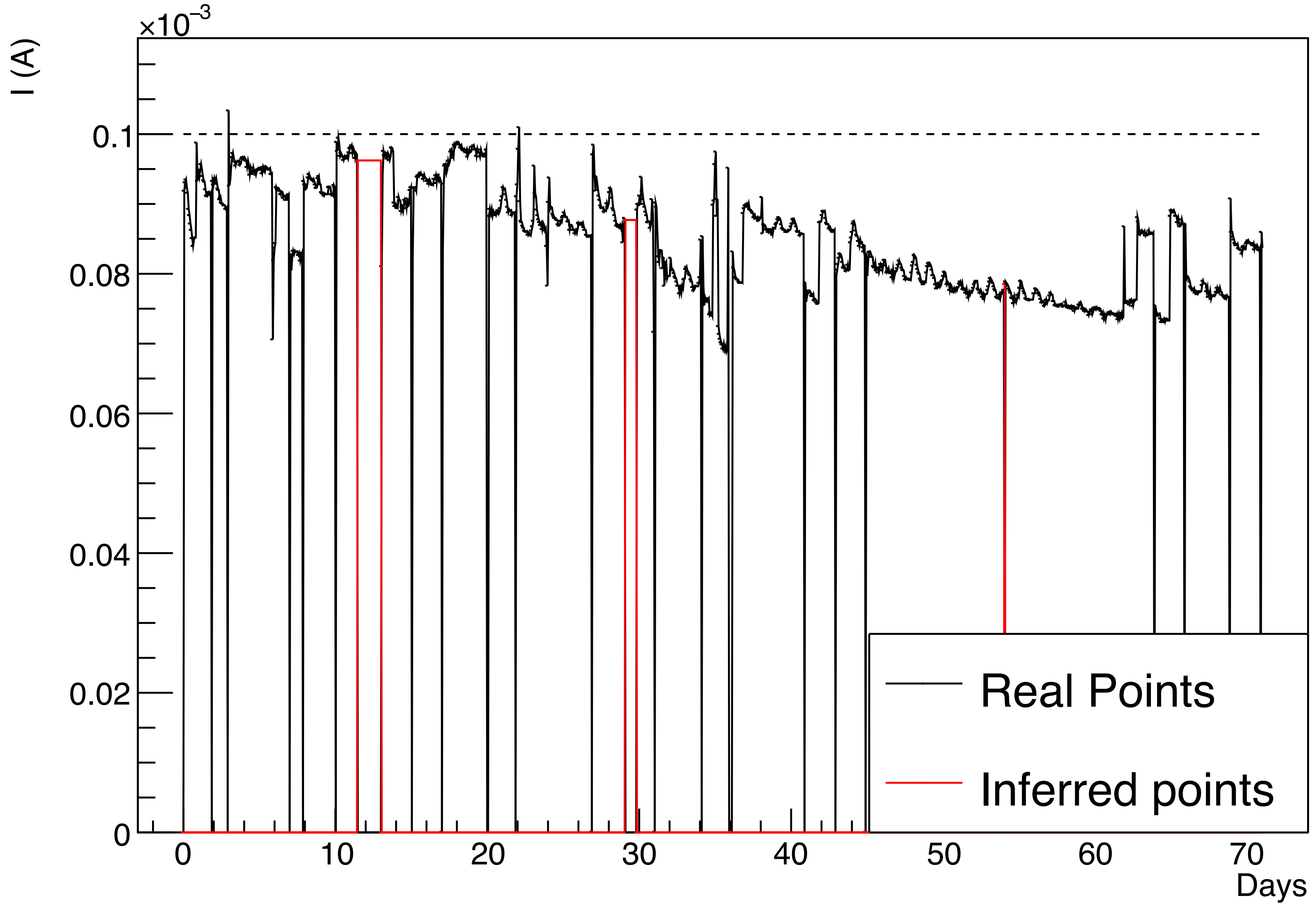


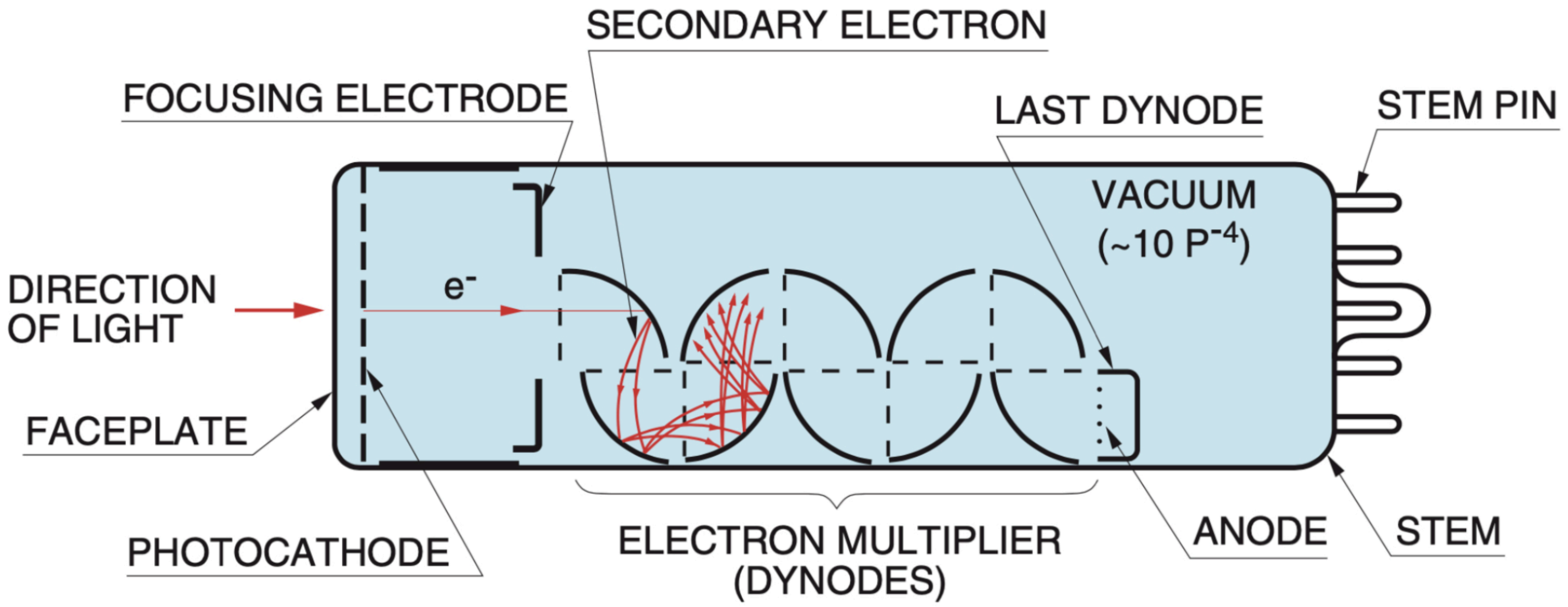
Ageing campaign & experimental setup

- Ageing affects the PMT performances:
  - Wear of the dynode system
  - Increase of the dark current
  - Decrease of the photocathode efficiency

- **Goal:** study the variation of the PMT gain up to 500 C of integrated charge

- Order of 10'000 C expected for new ECAL readout PMTs





$$\text{Gain} \doteq \frac{I_{anode}}{I_{cathode}}$$

Experimental setup & method

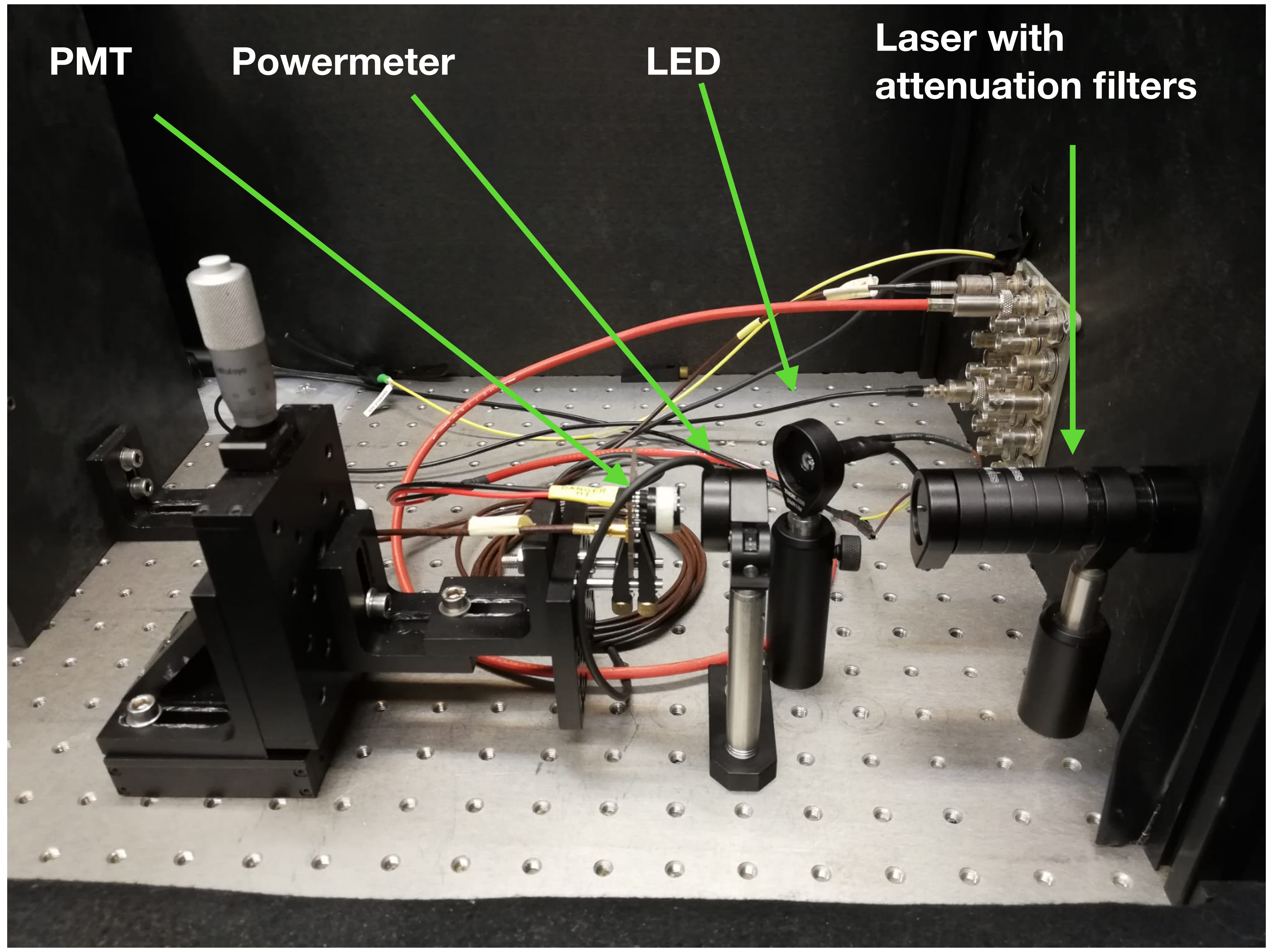
- **Ageing** performed with a white LED light continuously impinging the PMT
- **Gain measurements:** using a laser light ($\lambda = 405$ nm), temporarily switching off the LED
- Measure the power (*P*) of the laser
  - ➡ get the number of photons per second impinging the PMT window:

$$P = n_\gamma \cdot \frac{hc}{\lambda}$$

- By measuring the anodic and dark current, we get the gain:

$$G = \frac{n_e}{\mathrm{Q}_E \cdot n_\gamma} = \frac{hc}{\mathrm{Q}_E \cdot P \cdot \lambda} \cdot \frac{(I_{anode} - I_{dark})}{q_{e^-}}$$

- Procedure validated by measuring the gain of another PMT also with another method (compatibility within 12%)



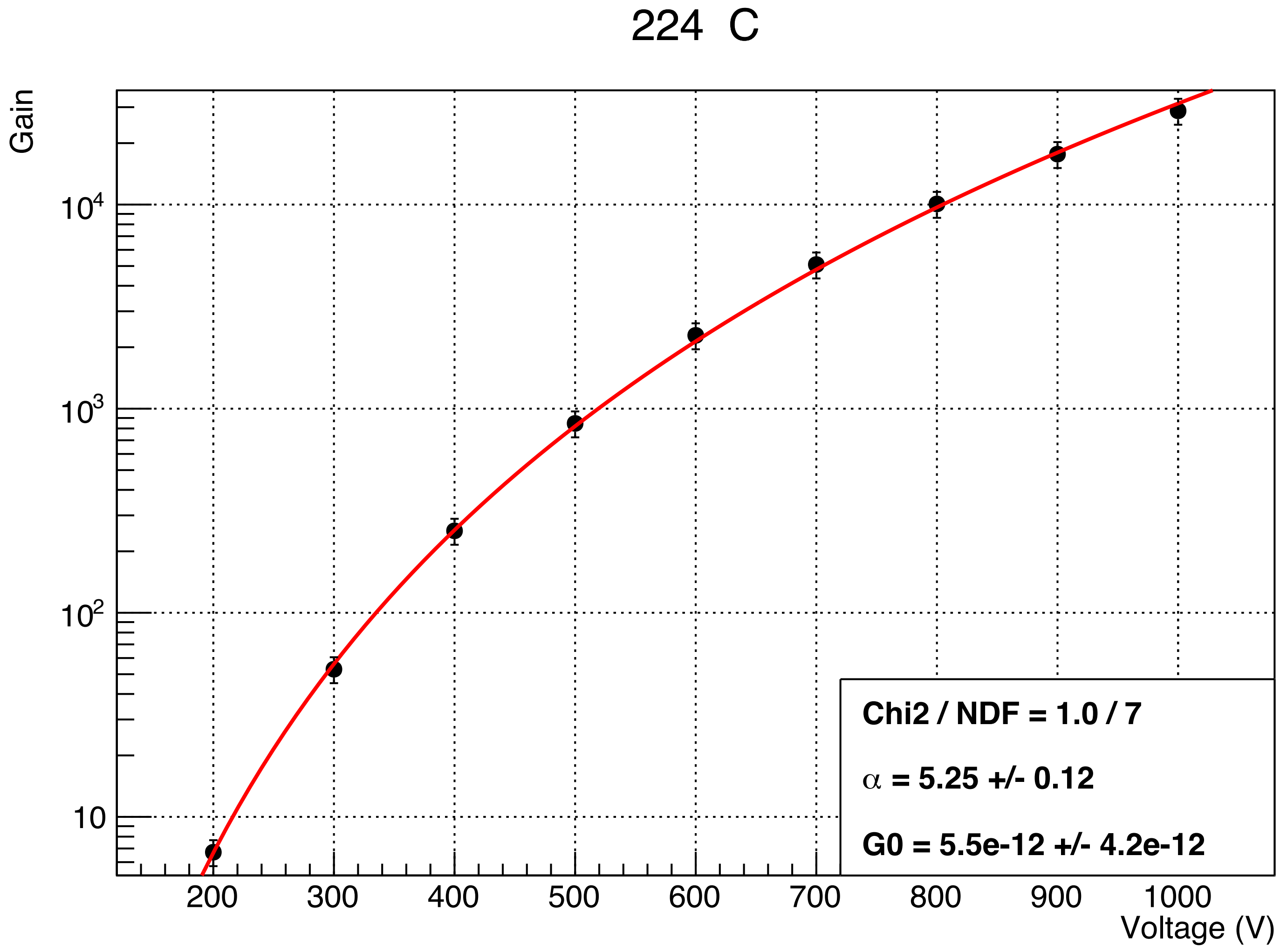
Gain and HV

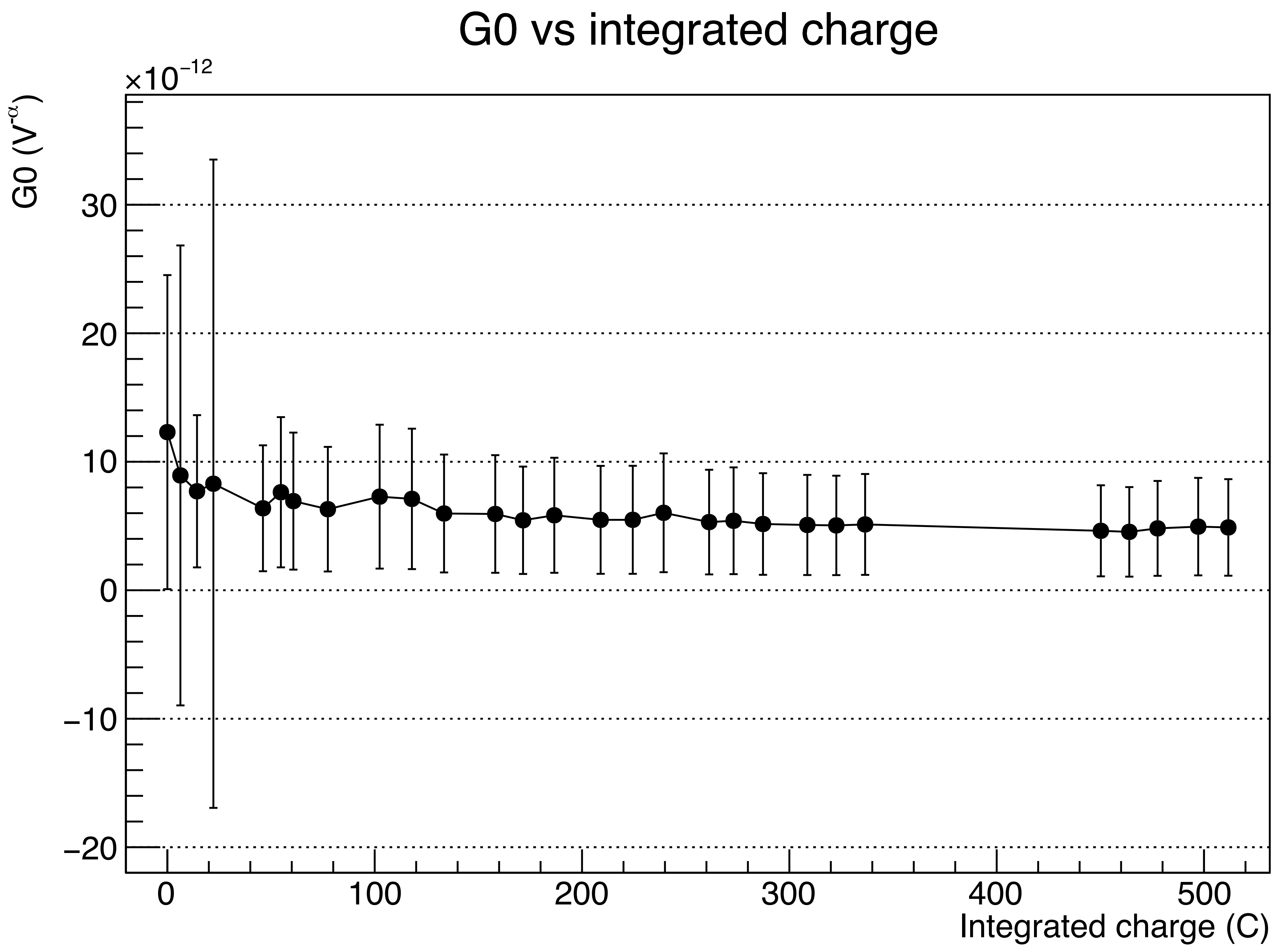
- The PMT gain grows with the applied voltage following:

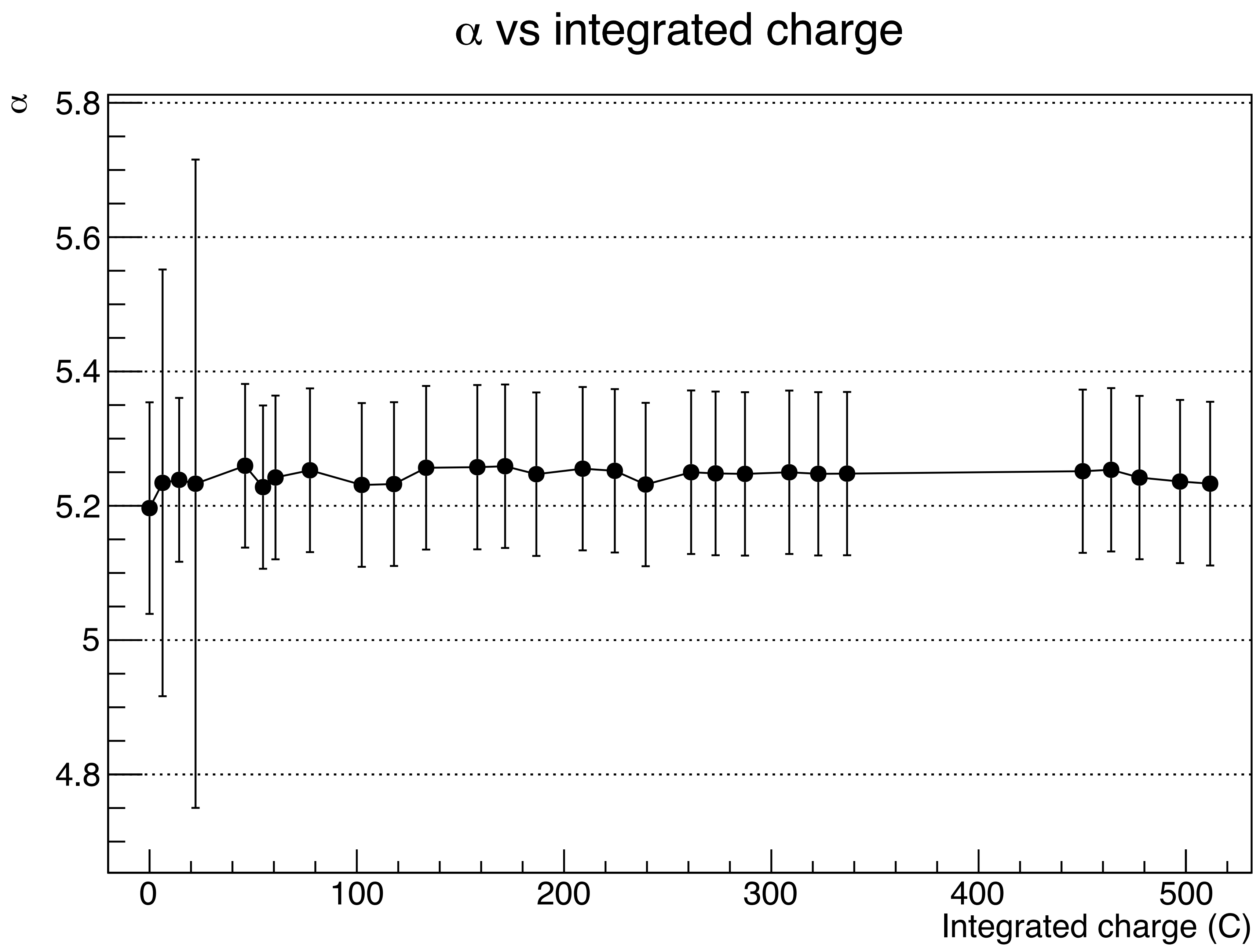
$$G = G_0 \cdot V^{\alpha}$$

- Each time, the gain has been measured from 200 V to 1000 V (with 100 V steps)
- Power-law fit to the data to get α and G_0

Example of a power-law fit

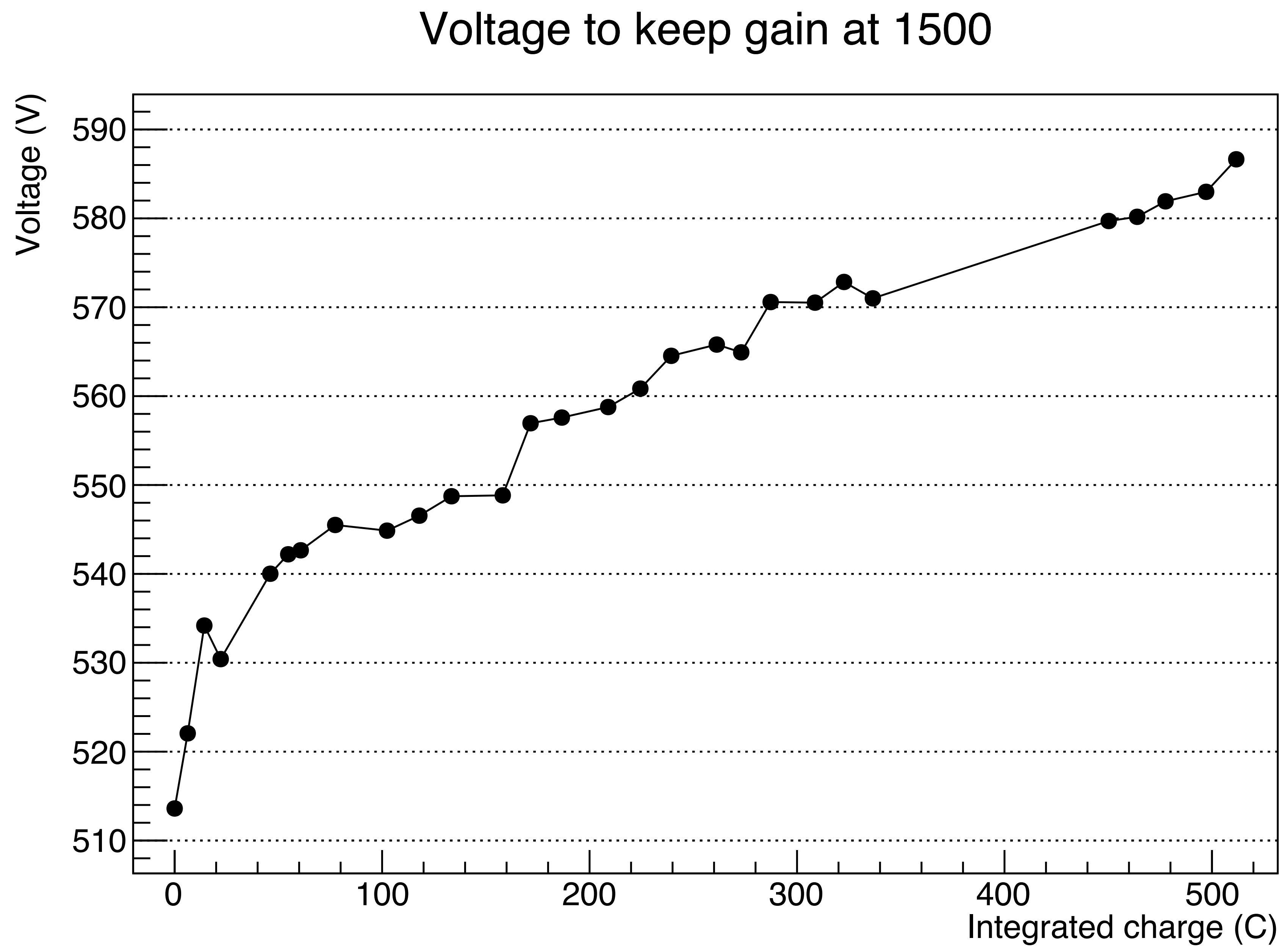


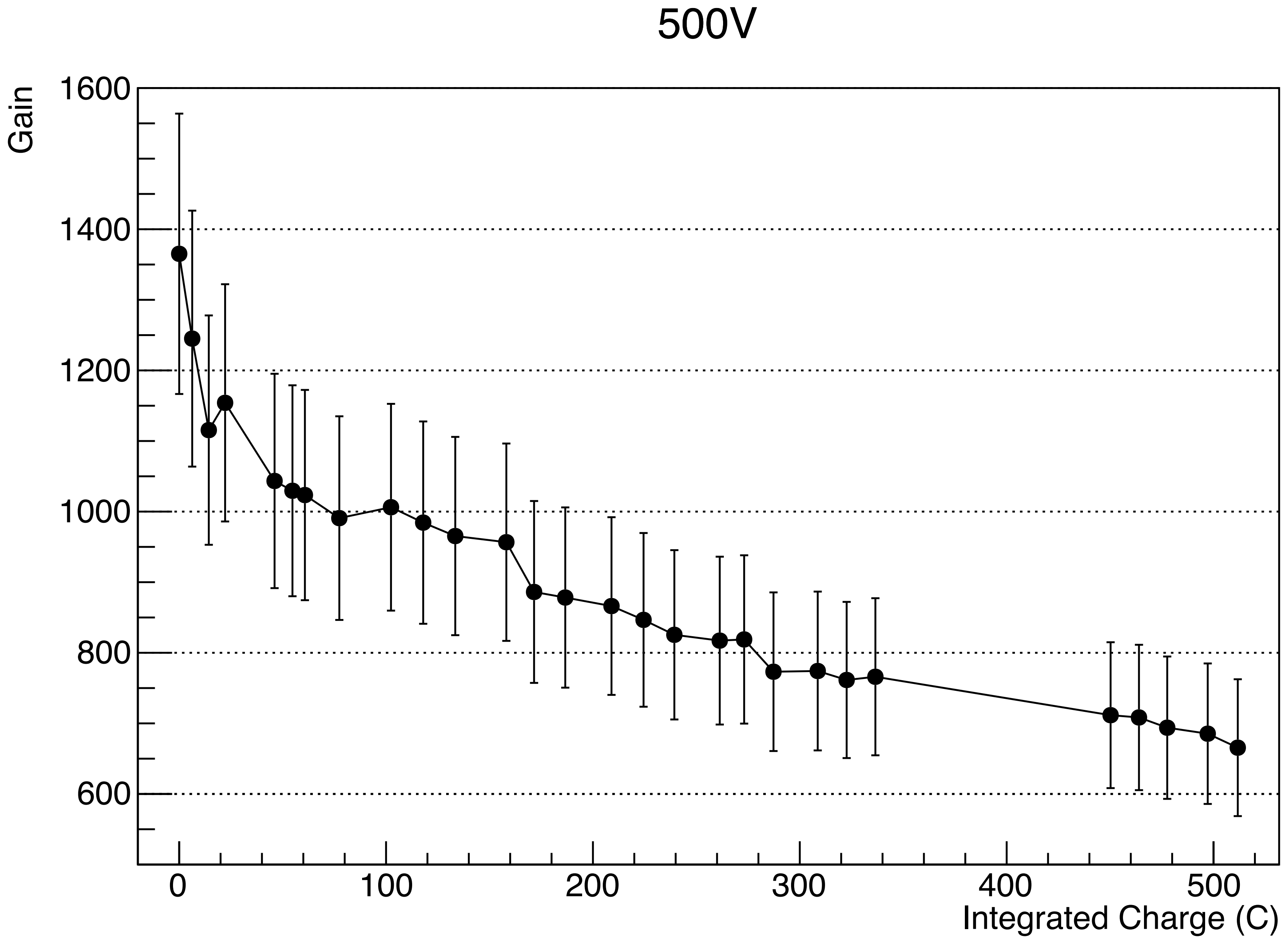


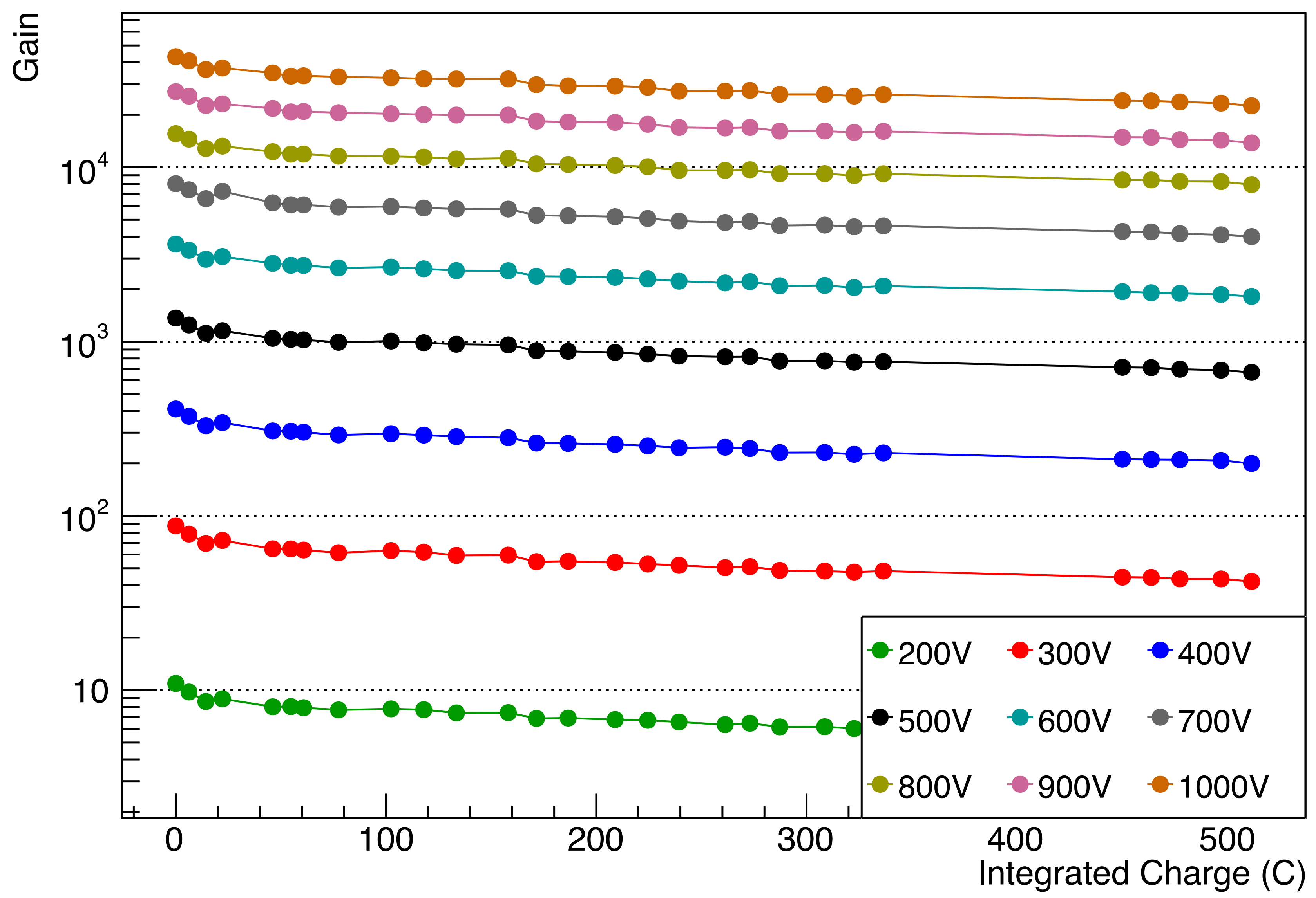


Results

- Quick drop in the first 50 C
- Then, stable and slow decrease up to 500 C
- Overall decrease by a factor 2
- Same behaviour at all the applied voltages







Outline

- Introduction: the LHCb ECAL Upgrade II
- Simulation studies of a Pb-Polystyrene module
- Analysis of testbeam data from the CERN SPS
- Ageing campaign of the PMT Hamamatsu R14755U-100
- **Conclusions**

Conclusions - Time resolution

Simulation studies

- The signal formation inside the single-side readout SpaCal modules has been studied by means of GEANT4 simulations
- The time resolution is worsened by the longitudinal fluctuations of the showers affecting the pulses’ shape

  ➡ **The CFD algorithm can’t take this into account**
- A procedure aiming at removing the shower depth bias has been developed and applied to testbeam data, exploiting the signals’ rise time

Conclusions - Time resolution

Simulation studies

- The signal formation inside the single-side readout SpaCal modules has been studied by means of GEANT4 simulations
- The time resolution is worsened by the longitudinal fluctuations of the showers affecting the pulses' shape

  ➡ **The CFD algorithm can't take this into account**
- A procedure aiming at removing the shower depth bias has been developed and applied to testbeam data, exploiting the signals' rise time

SPS Testbeam data

- A comparison among 4 PMT models and 2 types of fibres has been performed for two SpaCal W-Polystyrene modules
- Resolutions below 20 ps obtained at high energies

  ➡ **Good timing capabilities of the SpaCal even in single-side readout mode**

Open questions & Outlook

- What is the physical origin of the sampling and constant terms of the time resolution?

- Why do fast PMTs still do worse than R7600U after the correction procedure?
  - Corrections are never ideal
  - CFD + polynomial fit may not be the best approach

- **The CFD algorithm may not be the best one**

  ➡ **Is there a better way to define the time stamps?**
  - A Machine Learning method will be tested in the near future

Conclusions - Ageing campaign

- An ageing campaign of the Hamamatsu R14755U-100 PMT has been carried out up to 500 C
- The gain has been measured at applied voltages between 200 V and 1000 V
  - **Stable decrease** (up to 500 C)
  - Same behaviour at all the applied voltages
- The PMT showed a very good (slow) aging behaviour

➡ **Good candidate for the future LHCb ECAL in terms of ageing**

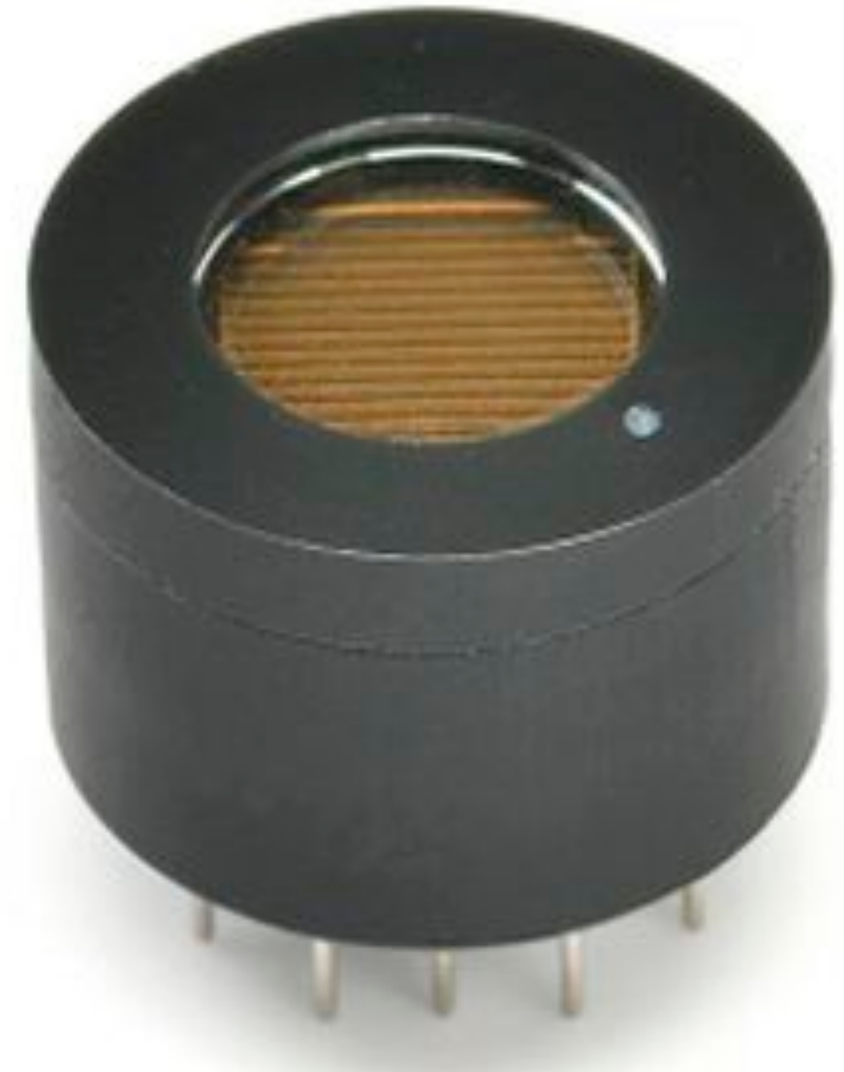
Thank you for your attention

International Master
Advanced Methods
in Particle Physics

Backup slides

To get an idea:

Hamamatsu R7600U-00-M4
FWHM ~ 2.1 ns
Tau ~ 0.6 ns

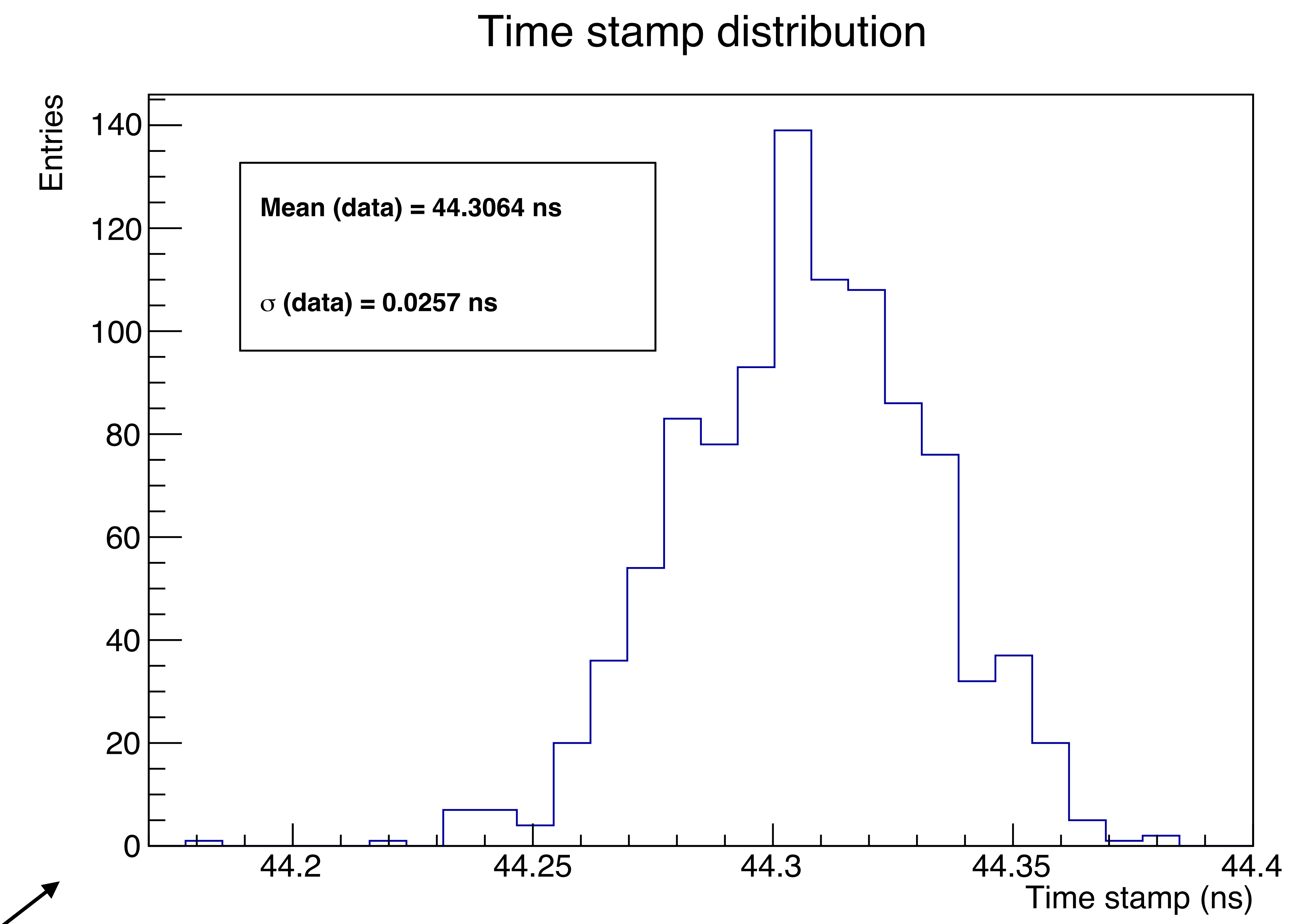


Hamamatsu R14755U-100
FWHM ~ 0.68 ns
Tau ~ 0.2 ns

- Only the central PMT is considered
- **Time resolution = std. dev.** of the time stamps sample
- **Rise time:** time between the 10% and 90% of the pulse's amplitude
- In general the shapes are not gaussian
- Presence of outliers

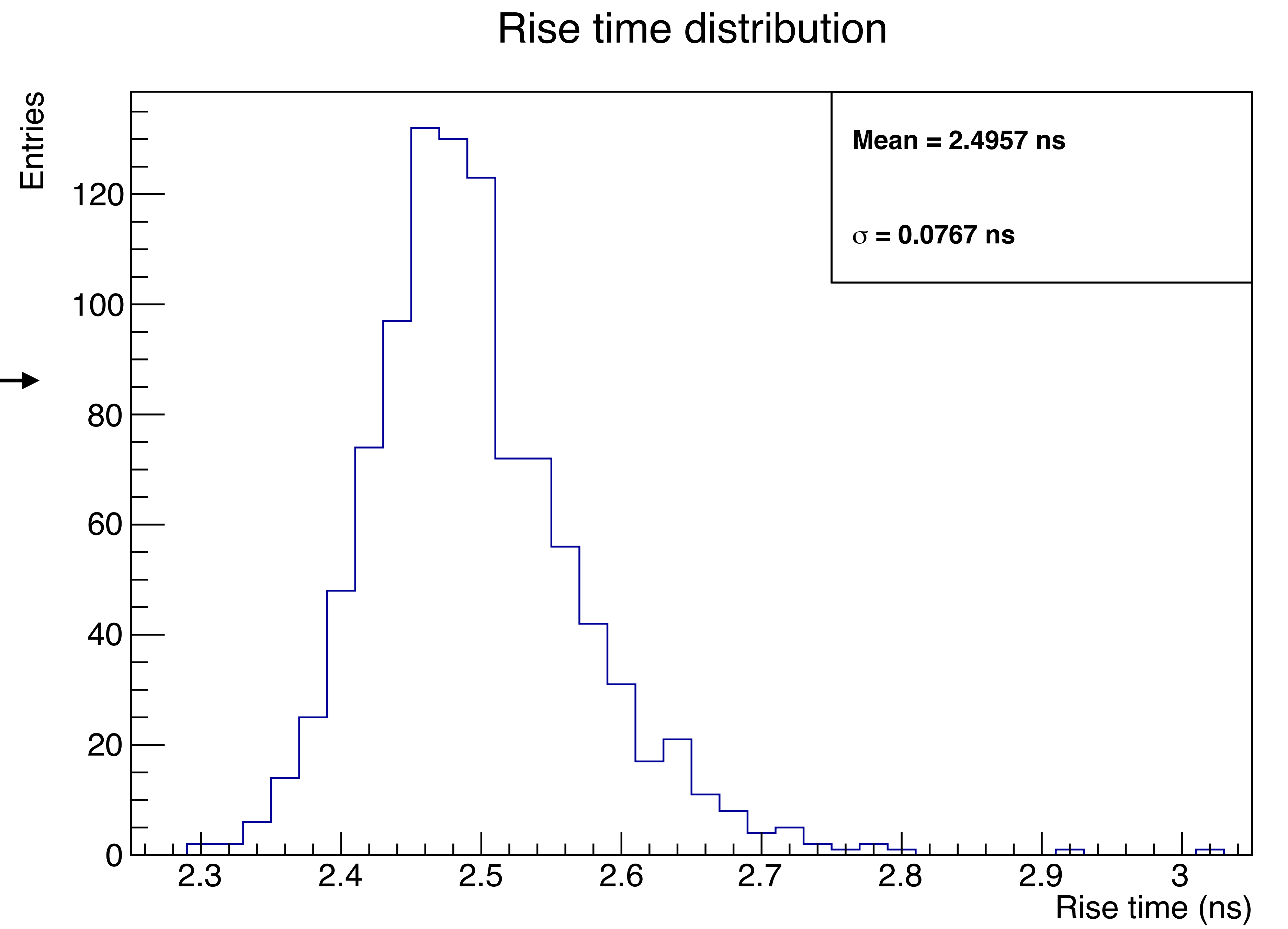
Example here:

- Tau = 1.0 ns (FWHM = 3.4 ns)
- CFD fraction = 40%


Time stamp distribution

Mean (data) = 44.3064 ns

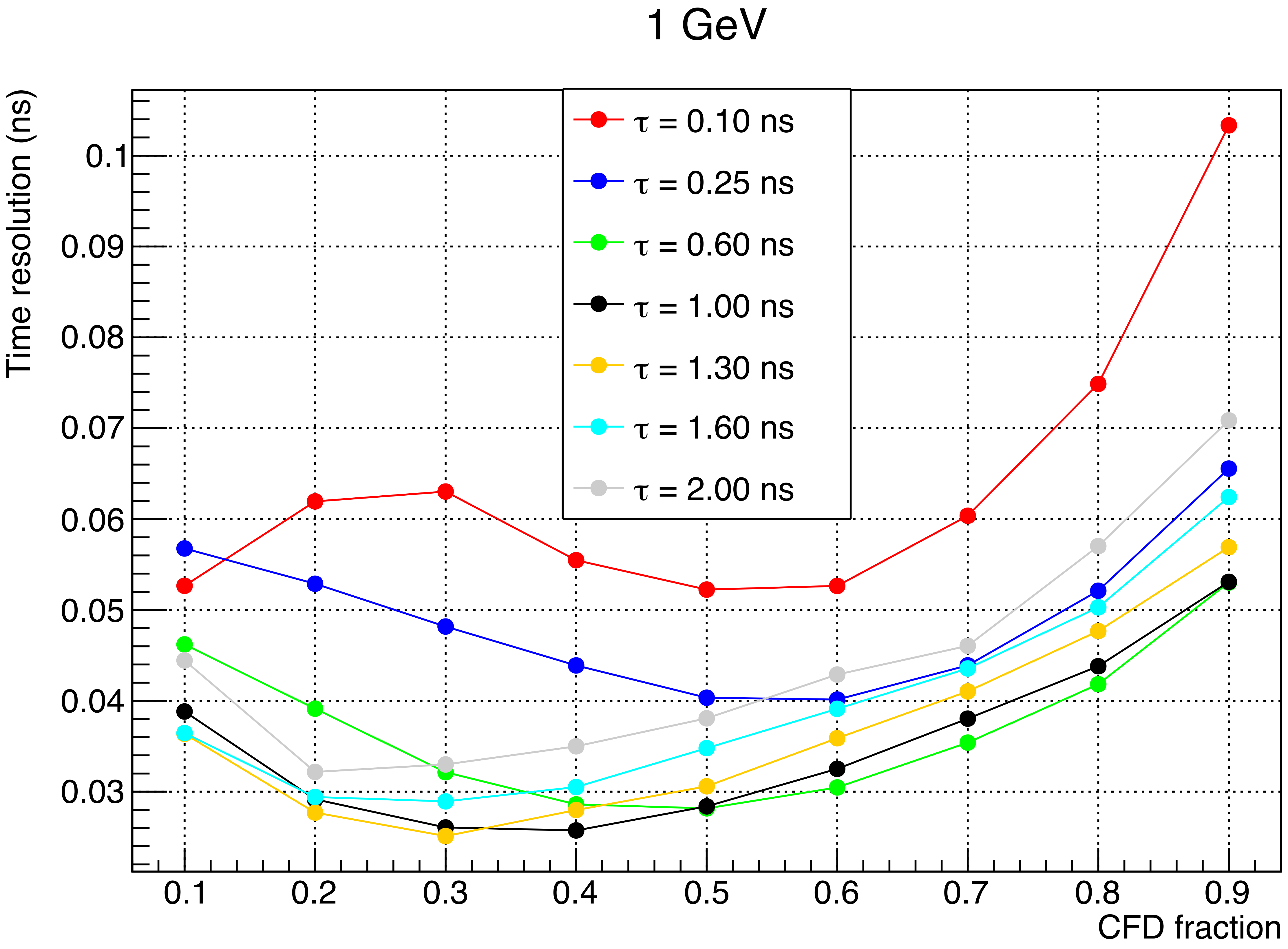
σ (data) = 0.0257 ns

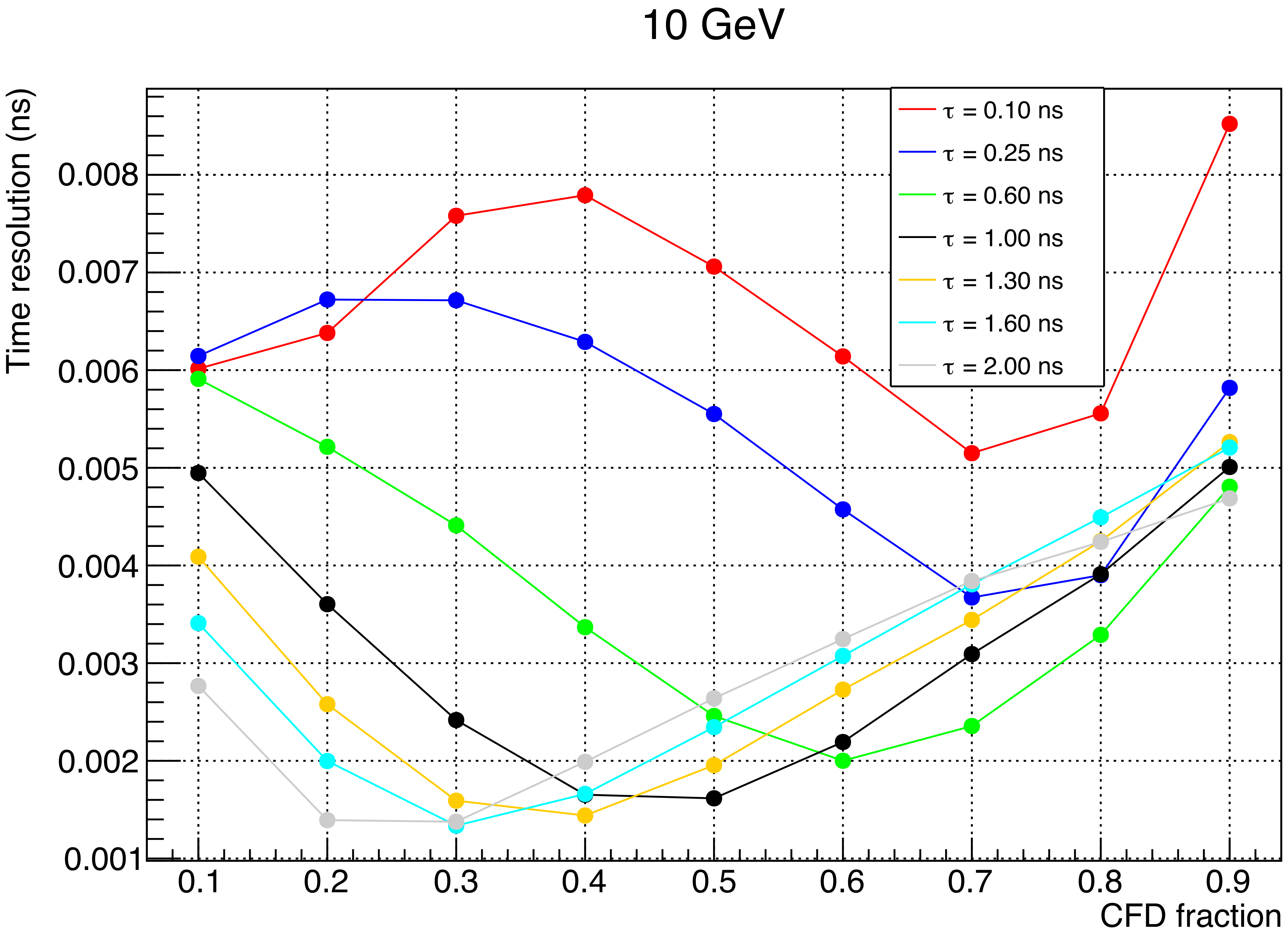

Rise time distribution

Mean = 2.4957 ns

σ = 0.0767 ns

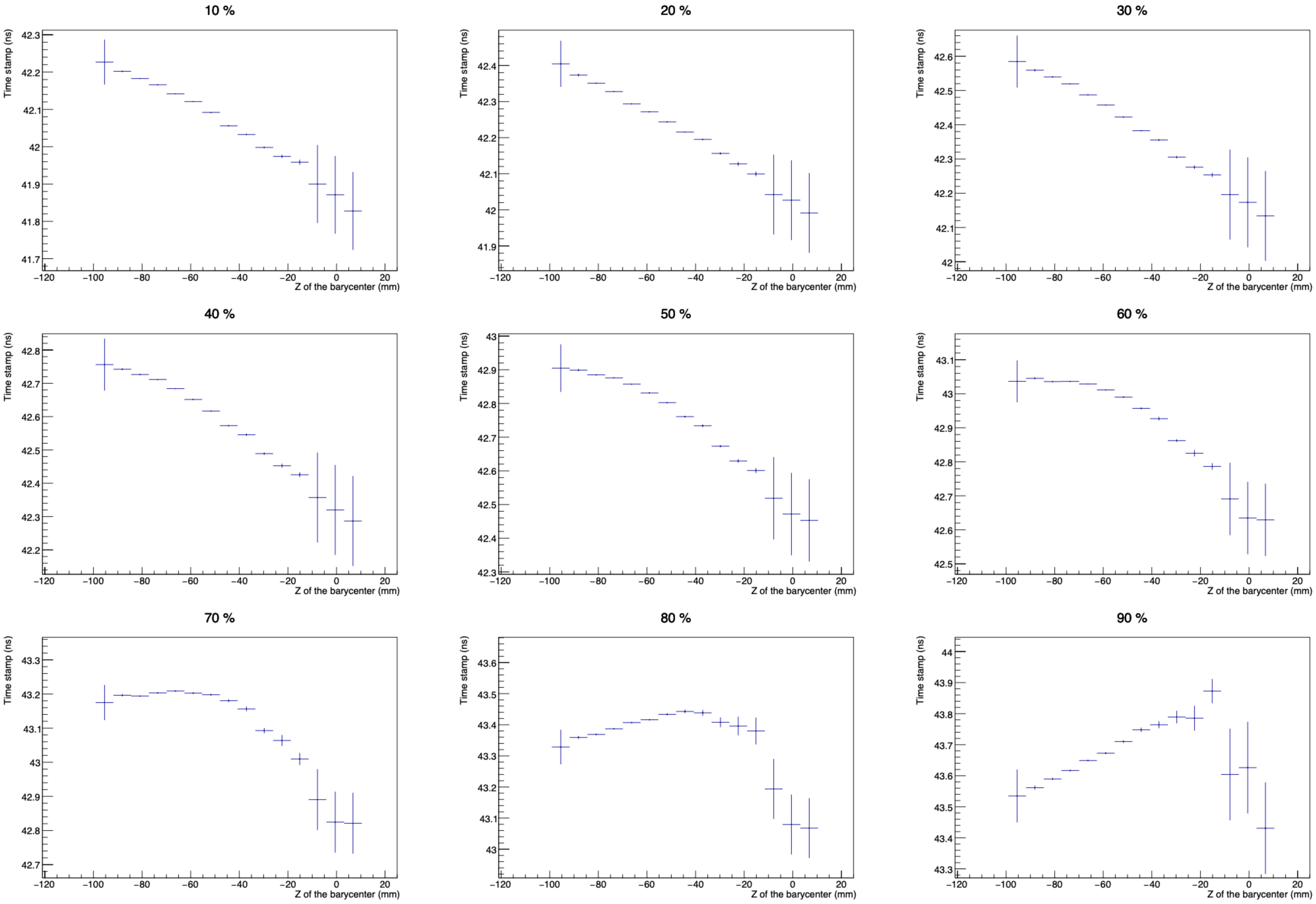
CFD fraction scan



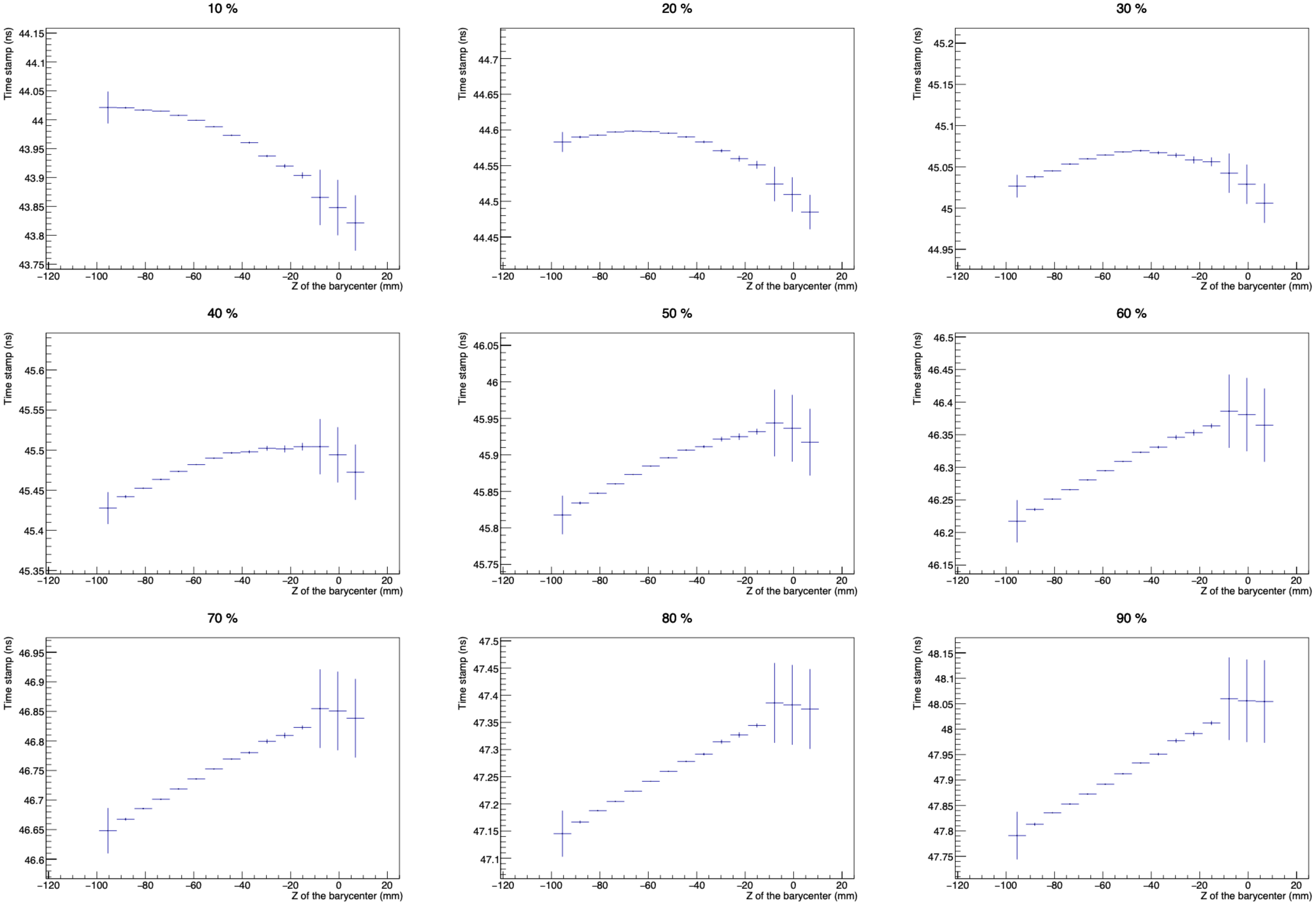


- The best CFD threshold tends to decrease for slower PMTs
- Best values always between 20% and 70%

Tau = 0.1 ns
(FWHM = 0.35 ns)



Tau = 2.0 ns
(FWHM = 7 ns)

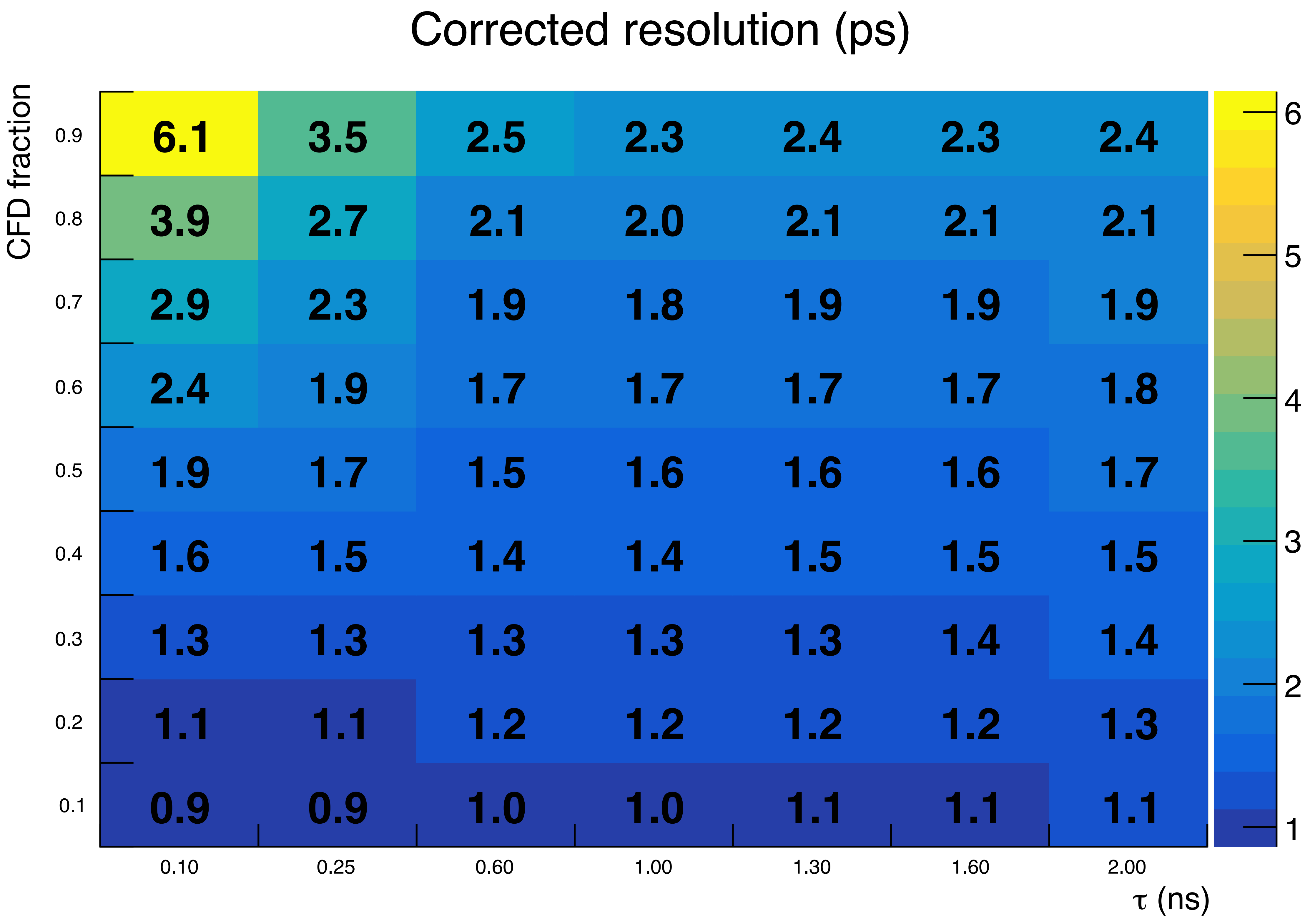


Why are slower PMTs better ?

- Arrival time to the PMT window: $t_{total} = t_{generation}$
- Corrections to the time resolution are negligible

Resolution (ps)

CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.9	6.2	3.5	2.5	2.3	2.4	2.3	2.4
0.8	3.9	2.7	2.1	2.0	2.1	2.1	2.1
0.7	2.9	2.3	1.9	1.8	1.9	1.9	1.9
0.6	2.4	1.9	1.7	1.7	1.7	1.8	1.8
0.5	1.9	1.7	1.6	1.6	1.6	1.6	1.7
0.4	1.6	1.5	1.4	1.4	1.5	1.5	1.5
0.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4
0.2	1.1	1.1	1.2	1.2	1.2	1.2	1.3
0.1	0.9	0.9	1.0	1.0	1.1	1.1	1.1

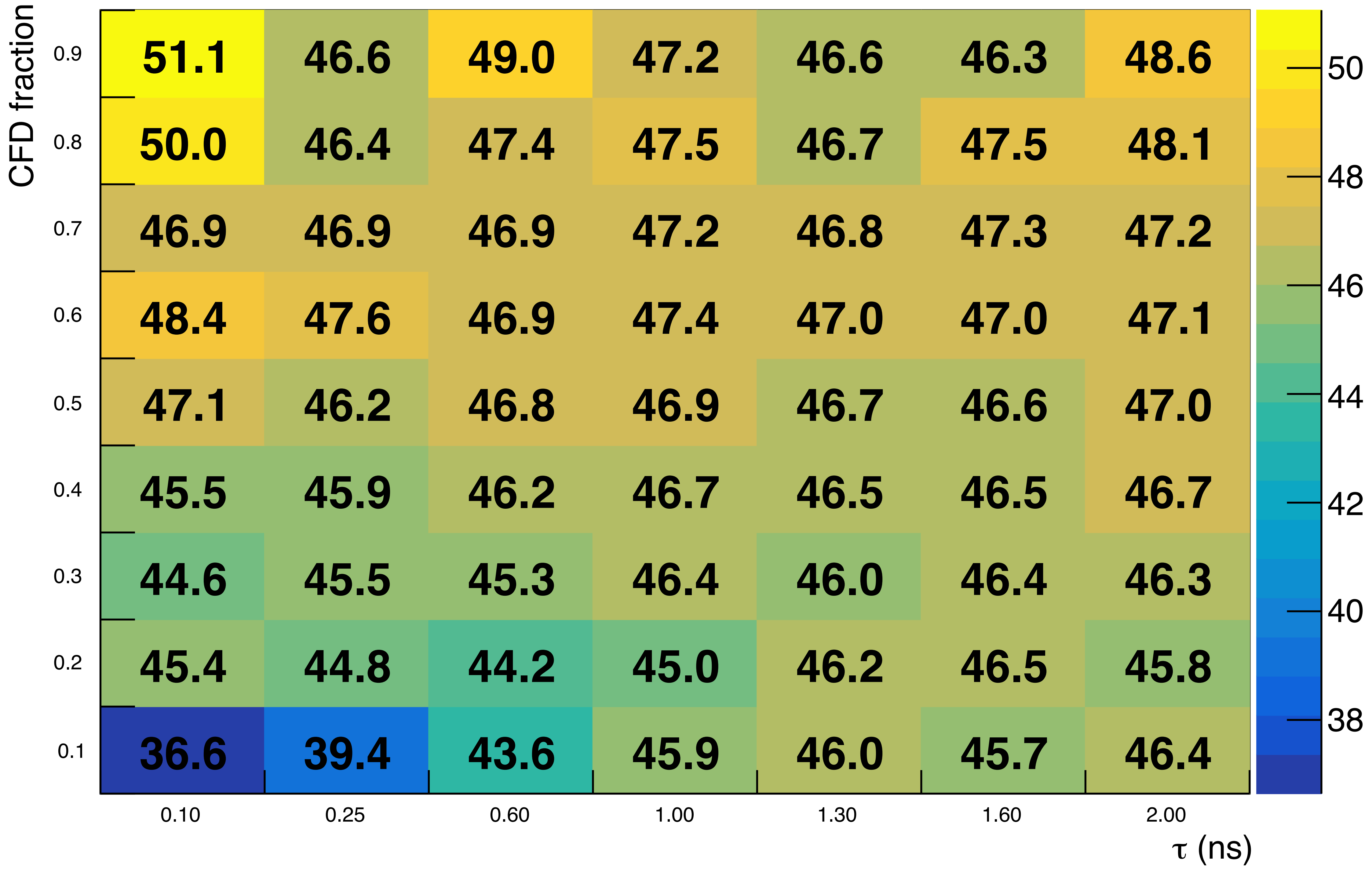


Corrected resolution (ps)

CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.9	6.1	3.5	2.5	2.3	2.4	2.3	2.4
0.8	3.9	2.7	2.1	2.0	2.1	2.1	2.1
0.7	2.9	2.3	1.9	1.8	1.9	1.9	1.9
0.6	2.4	1.9	1.7	1.7	1.7	1.7	1.8
0.5	1.9	1.7	1.5	1.6	1.6	1.6	1.7
0.4	1.6	1.5	1.4	1.4	1.5	1.5	1.5
0.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4
0.2	1.1	1.1	1.2	1.2	1.2	1.2	1.3
0.1	0.9	0.9	1.0	1.0	1.1	1.1	1.1

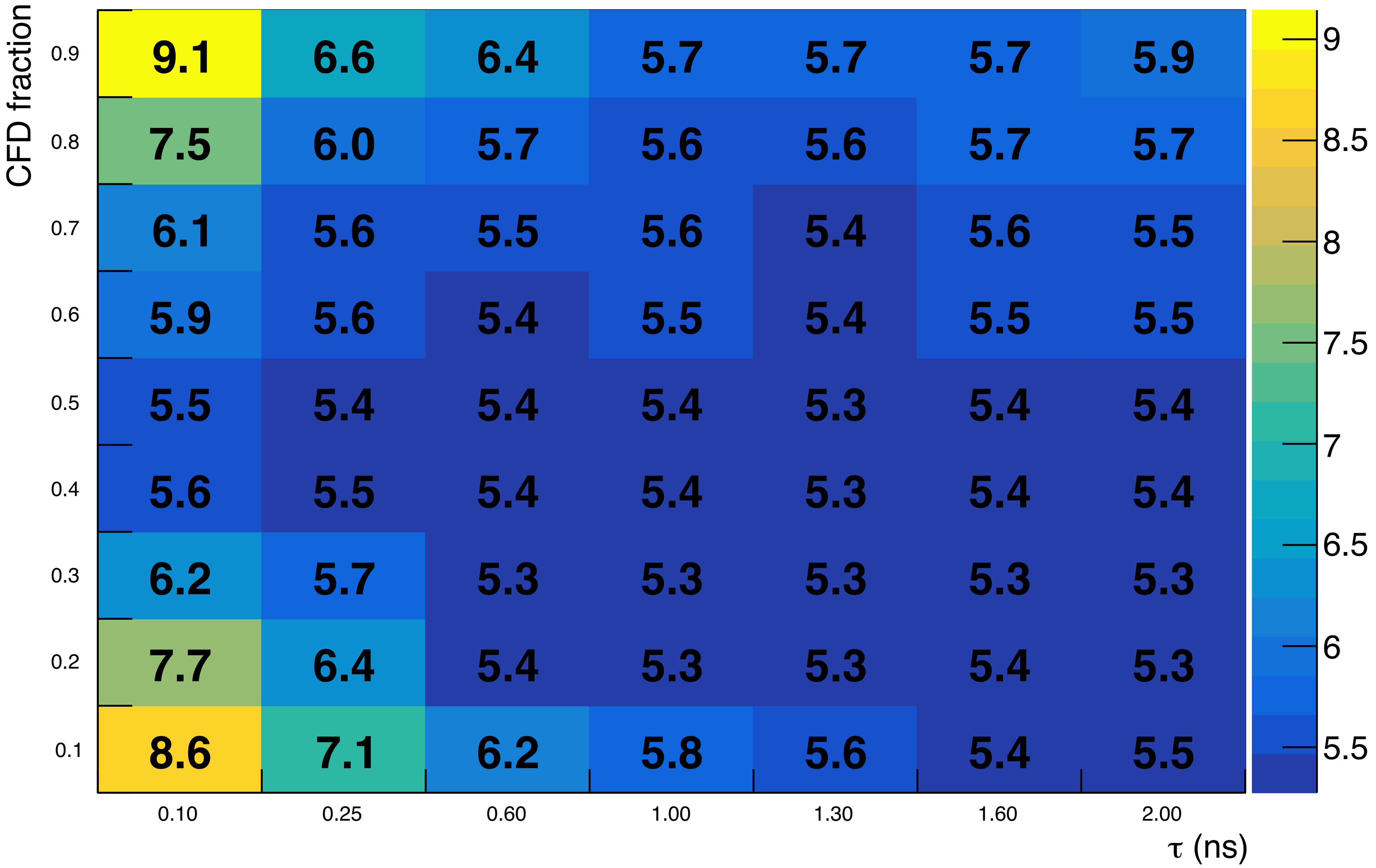
Why are slower PMTs better ?

- Arrival time to the PMT window: $t_{total} = t_{generation} + t_{deposition}$
- ~45 ps worsening of the biased resolution
- ~40 ps corrections, homogeneous behaviour in the parameter space



Resolution (ps)

CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.9	51.1	46.6	49.0	47.2	46.6	46.3	48.6
0.8	50.0	46.4	47.4	47.5	46.7	47.5	48.1
0.7	46.9	46.9	46.9	47.2	46.8	47.3	47.2
0.6	48.4	47.6	46.9	47.4	47.0	47.0	47.1
0.5	47.1	46.2	46.8	46.9	46.7	46.6	47.0
0.4	45.5	45.9	46.2	46.7	46.5	46.5	46.7
0.3	44.6	45.5	45.3	46.4	46.0	46.4	46.3
0.2	45.4	44.8	44.2	45.0	46.2	46.5	45.8
0.1	36.6	39.4	43.6	45.9	46.0	45.7	46.4

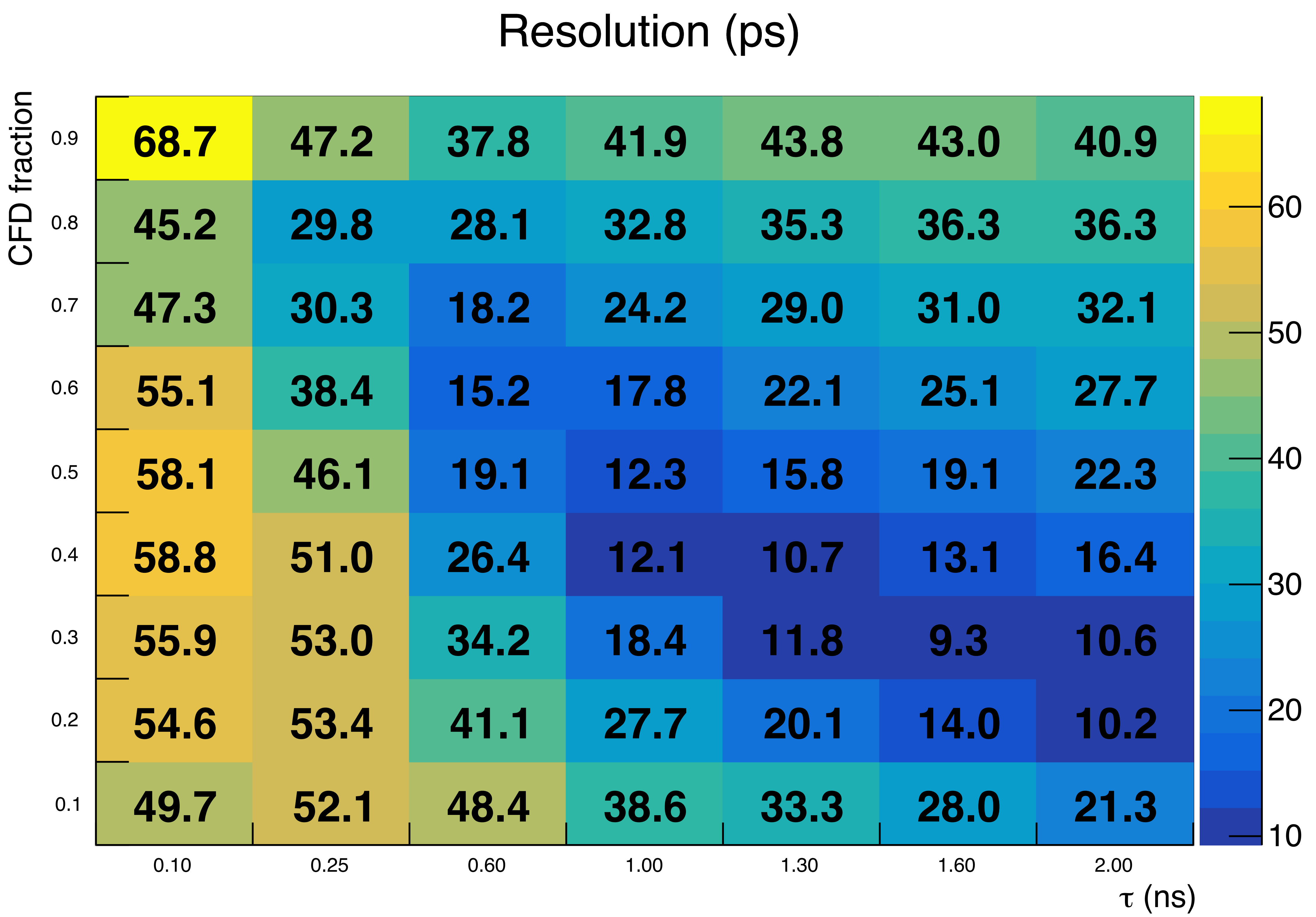


Corrected resolution (ps)

CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.9	9.1	6.6	6.4	5.7	5.7	5.7	5.9
0.8	7.5	6.0	5.7	5.6	5.6	5.7	5.7
0.7	6.1	5.6	5.5	5.6	5.4	5.6	5.5
0.6	5.9	5.6	5.4	5.5	5.4	5.5	5.5
0.5	5.5	5.4	5.4	5.4	5.3	5.4	5.4
0.4	5.6	5.5	5.4	5.4	5.3	5.4	5.4
0.3	6.2	5.7	5.3	5.3	5.3	5.3	5.3
0.2	7.7	6.4	5.4	5.3	5.3	5.4	5.3
0.1	8.6	7.1	6.2	5.8	5.6	5.4	5.5

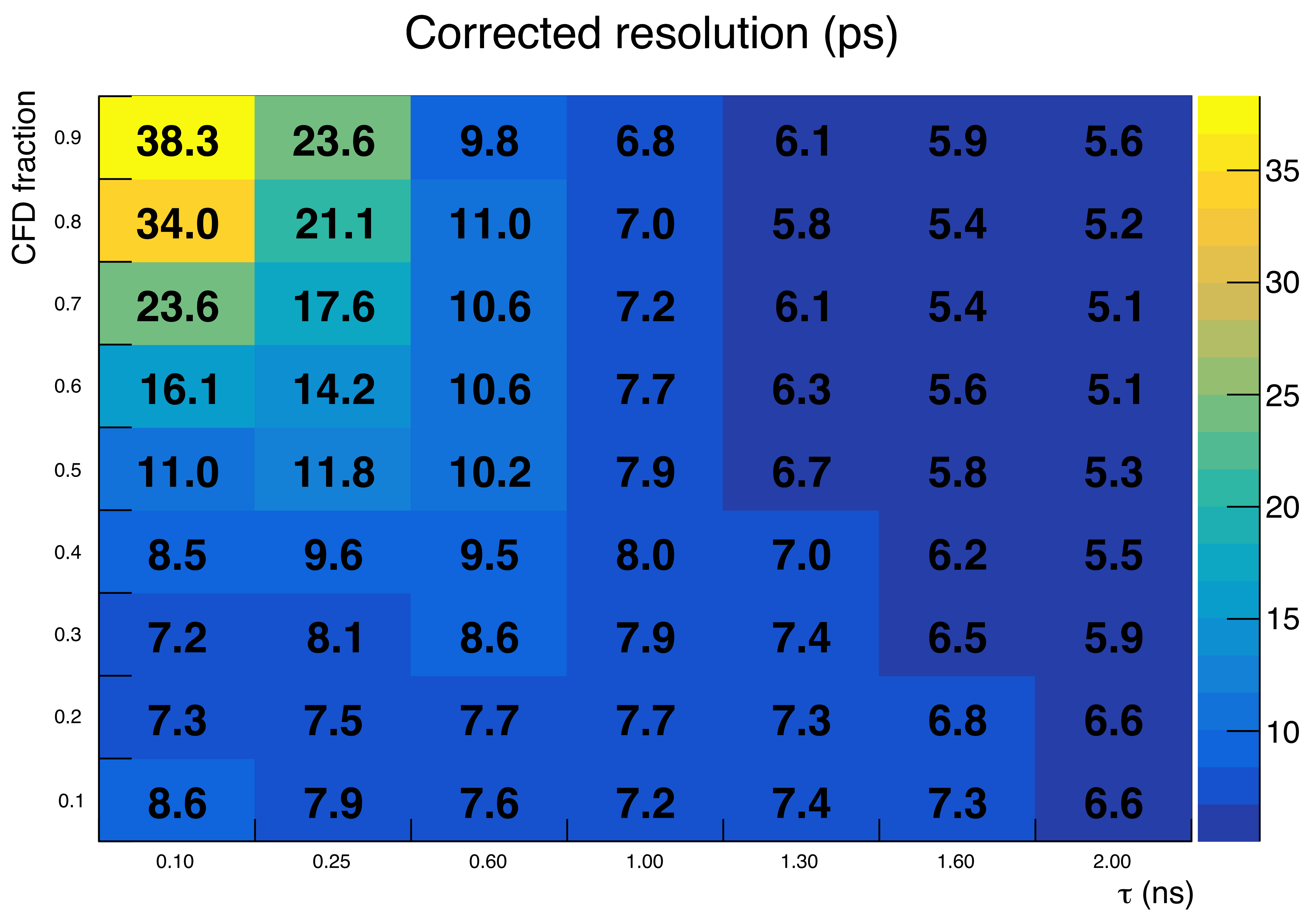
Why are slower PMTs better ?

- Arrival time to the PMT window: $t_{total} = t_{generation} + t_{deposition} + t_{propagation}$
- Best resolutions: when the two correlations (reflected/direct photons) cancel out each other
- After correction: more homogeneous behaviour in the parameter space



Resolution (ps)

CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.9	68.7	47.2	37.8	41.9	43.8	43.0	40.9
0.8	45.2	29.8	28.1	32.8	35.3	36.3	36.3
0.7	47.3	30.3	18.2	24.2	29.0	31.0	32.1
0.6	55.1	38.4	15.2	17.8	22.1	25.1	27.7
0.5	58.1	46.1	19.1	12.3	15.8	19.1	22.3
0.4	58.8	51.0	26.4	12.1	10.7	13.1	16.4
0.3	55.9	53.0	34.2	18.4	11.8	9.3	10.6
0.2	54.6	53.4	41.1	27.7	20.1	14.0	10.2
0.1	49.7	52.1	48.4	38.6	33.3	28.0	21.3



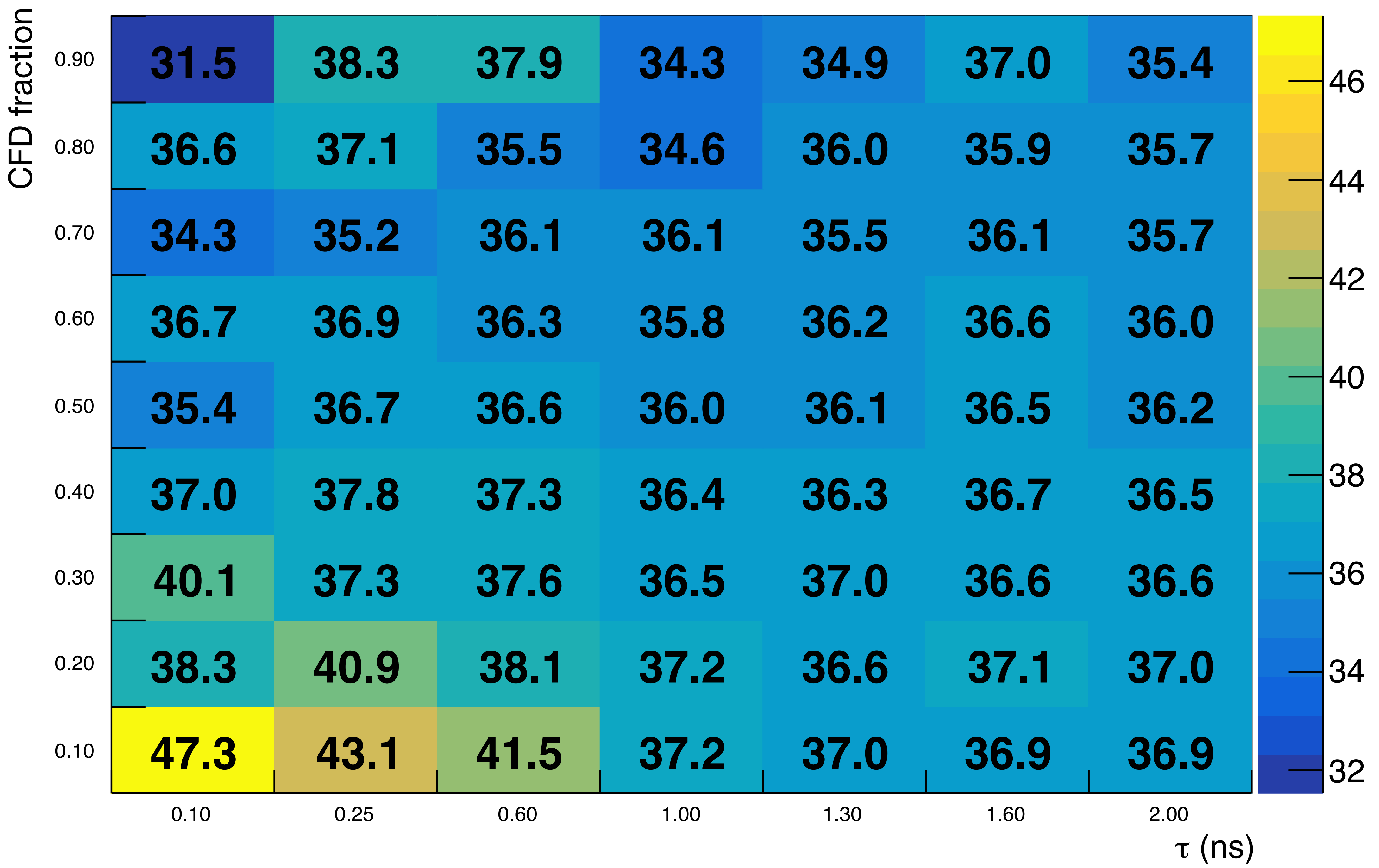
Corrected resolution (ps)

CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.9	38.3	23.6	9.8	6.8	6.1	5.9	5.6
0.8	34.0	21.1	11.0	7.0	5.8	5.4	5.2
0.7	23.6	17.6	10.6	7.2	6.1	5.4	5.1
0.6	16.1	14.2	10.6	7.7	6.3	5.6	5.1
0.5	11.0	11.8	10.2	7.9	6.7	5.8	5.3
0.4	8.5	9.6	9.5	8.0	7.0	6.2	5.5
0.3	7.2	8.1	8.6	7.9	7.4	6.5	5.9
0.2	7.3	7.5	7.7	7.7	7.3	6.8	6.6
0.1	8.6	7.9	7.6	7.2	7.4	7.3	6.6

Why are slower PMTs better ?

- Arrival time to the PMT window: $t_{total} = t_{generation} + t_{deposition} + t_{propagation}$
- **Only direct photons considered**
- Homogeneous behaviour in both cases

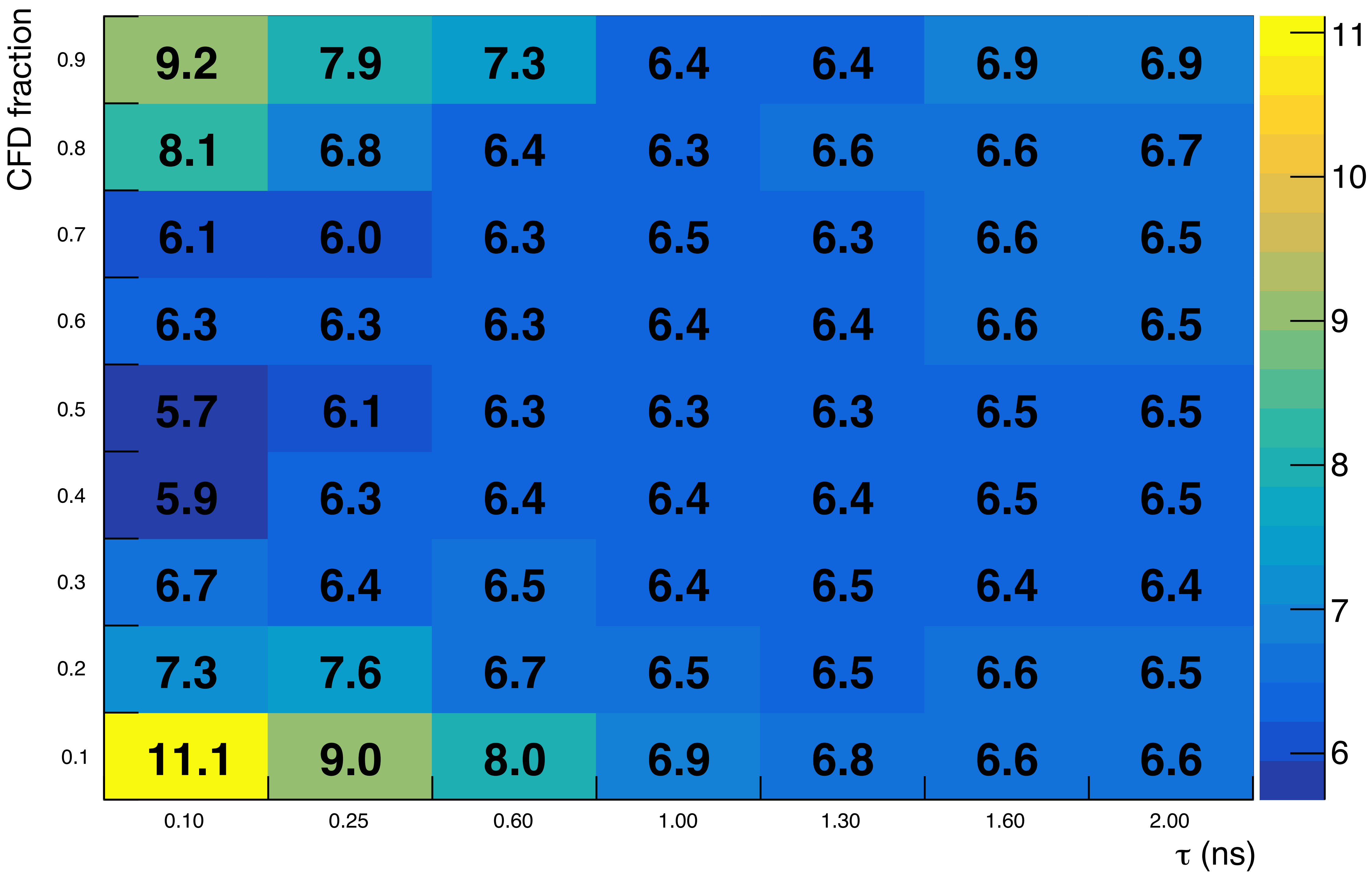
Resolution (ps)



CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.90	31.5	38.3	37.9	34.3	34.9	37.0	35.4
0.80	36.6	37.1	35.5	34.6	36.0	35.9	35.7
0.70	34.3	35.2	36.1	36.1	35.5	36.1	35.7
0.60	36.7	36.9	36.3	35.8	36.2	36.6	36.0
0.50	35.4	36.7	36.6	36.0	36.1	36.5	36.2
0.40	37.0	37.8	37.3	36.4	36.3	36.7	36.5
0.30	40.1	37.3	37.6	36.5	37.0	36.6	36.6
0.20	38.3	40.9	38.1	37.2	36.6	37.1	37.0
0.10	47.3	43.1	41.5	37.2	37.0	36.9	36.9

τ (ns)

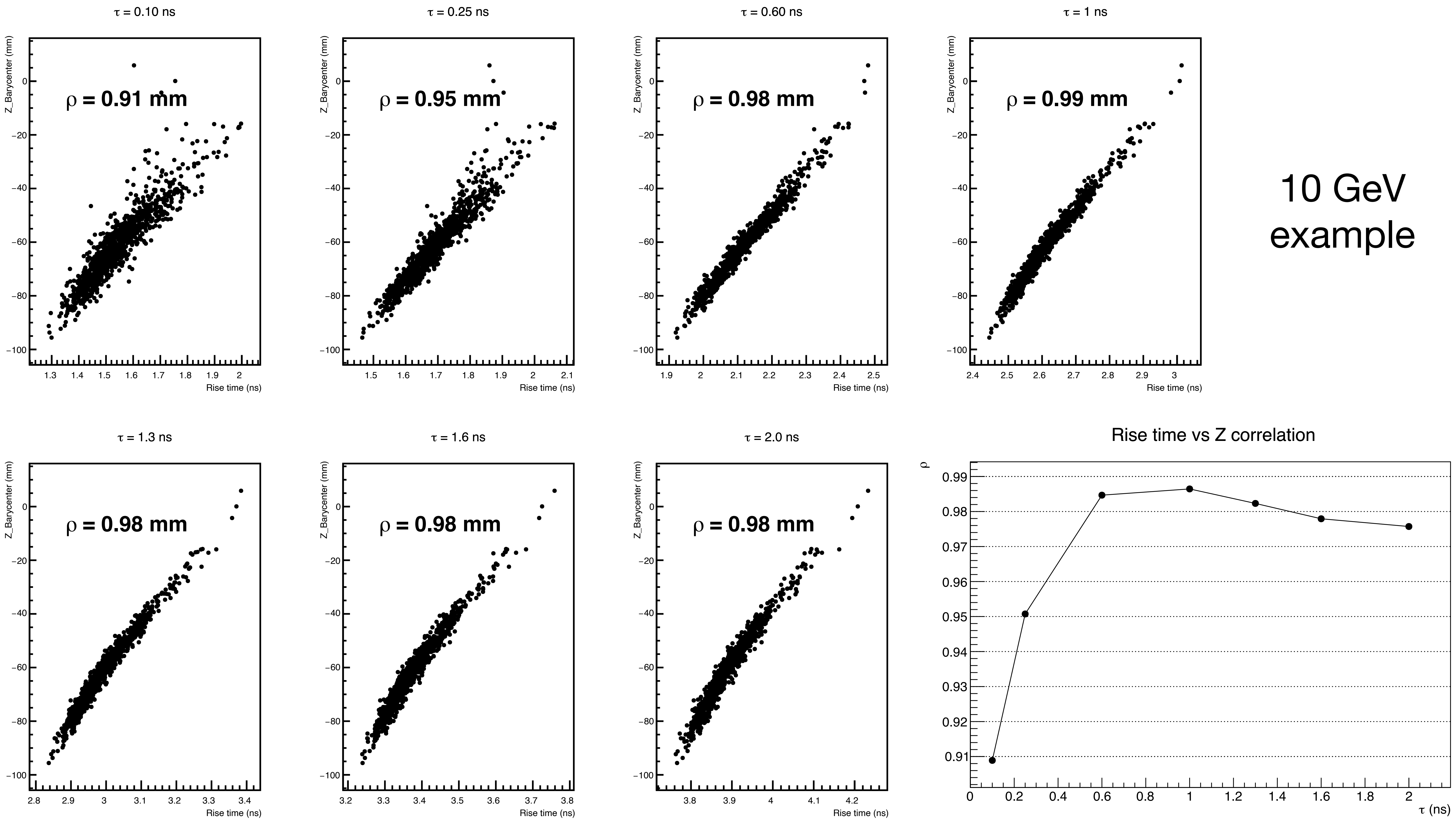
Corrected resolution (ps)



CFD fraction	0.10	0.25	0.60	1.00	1.30	1.60	2.00
0.9	9.2	7.9	7.3	6.4	6.4	6.9	6.9
0.8	8.1	6.8	6.4	6.3	6.6	6.6	6.7
0.7	6.1	6.0	6.3	6.5	6.3	6.6	6.5
0.6	6.3	6.3	6.3	6.4	6.4	6.6	6.5
0.5	5.7	6.1	6.3	6.3	6.3	6.5	6.5
0.4	5.9	6.3	6.4	6.4	6.4	6.5	6.5
0.3	6.7	6.4	6.5	6.4	6.5	6.4	6.4
0.2	7.3	7.6	6.7	6.5	6.5	6.6	6.5
0.1	11.1	9.0	8.0	6.9	6.8	6.6	6.6

τ (ns)

Shower depth vs rise time



10 GeV example

- High correlation between shower depth and rise time:
  - Deeper showers present a **higher spread** in the Z direction
  - Deeper showers feature **more separated peaks in the propagation time distribution** of the photons

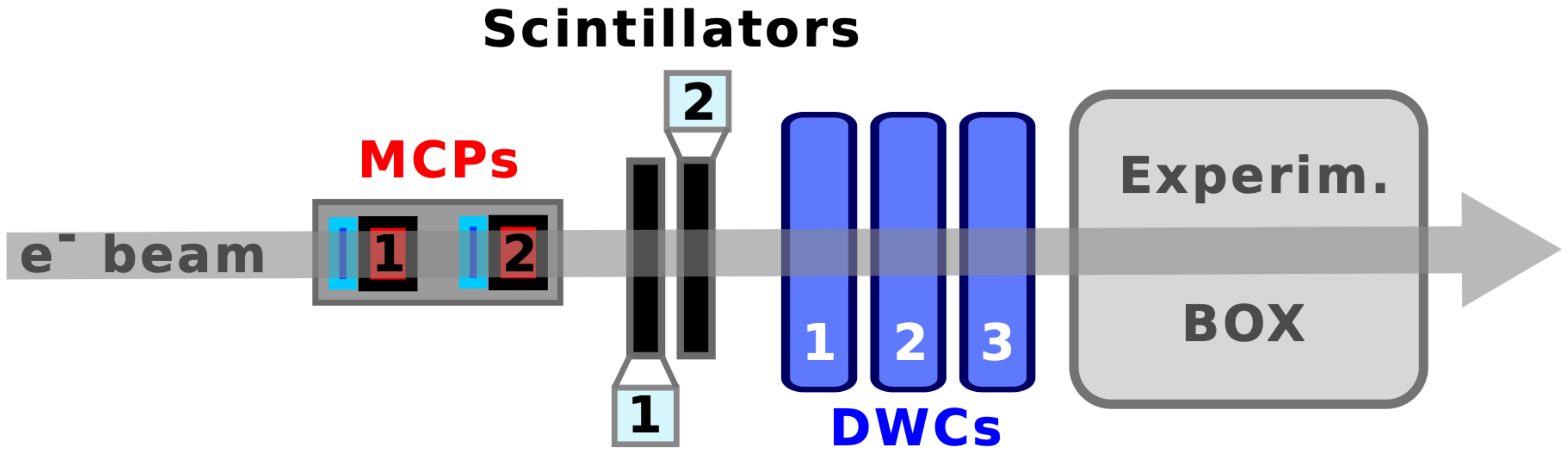
SPS testbeam setup

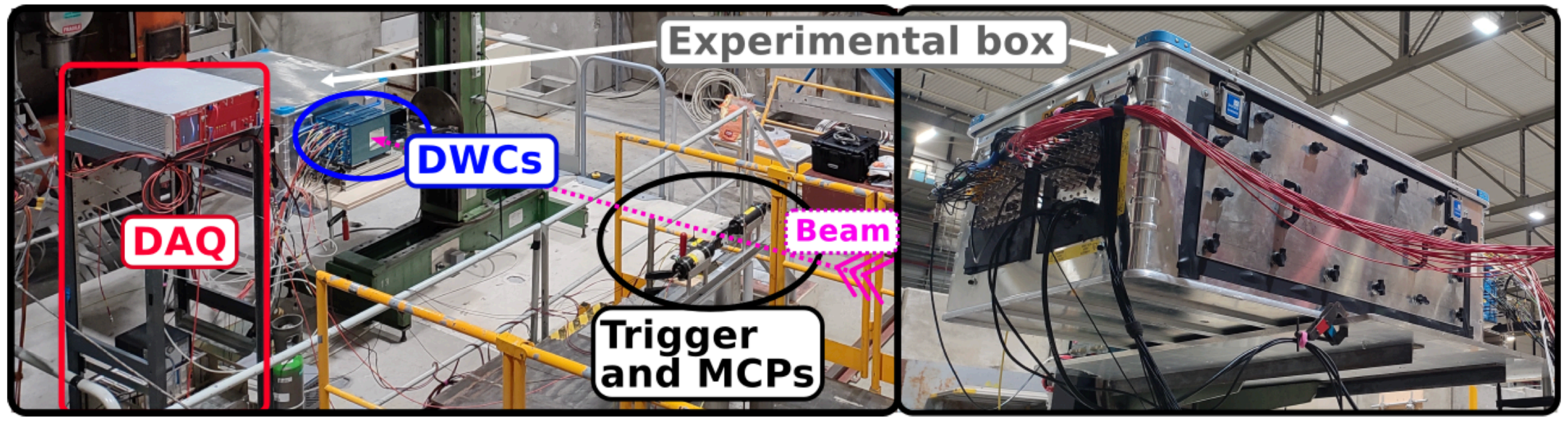
- June 2024 at the CERN Super Proton Synchrotron (SPS)
- ~ 2 weeks of data-taking

- Characterization of SpaCal and Shashlik prototypes
- e^- and hadrons beams (20 GeV - 100 GeV)

Experimental setup

- **Trigger:** scintillators + PMTs
- **Timing reference:** MCPs ($\sigma \simeq 15$ ps)
- **Tracking:** DWCs ($\sigma_{xy} \simeq 200\ \mu$m)
- Prototype inside a thin and dark experimental box
- **Digitizer:** 5×10^9 Hz (200 ps sampling period)





Few technical details

- Spatial selection: 10x10 mm^2 around the centre of one cell
- **R7600U** and **R9880U** feature **E**xtended **R**ed **M**ulti **A**lkali (**ERMA**) photocathodes
- **R9880U** and **R14755U** are the **fastest ones**

Quantum efficiency

	SCSF-78	3HF
R7600U	12%	12%
R9880U	15%	18%
R14755U	26%	10%
Tilecal	/	/

(Taken from data sheet)

Single photoelectron pulse

	FWHM (ns)	Rise time (ns)
R7600U	3.2	1.6
R9880U	1.25	0.57
R14755U	0.68	0.4
Tilecal	/	/

(Taken from data sheet)

Small module - fit parameters

SCSF-78 fibres

Before correction	Sampling term (ps x $\text{GeV}^{1/2}$)	Constant term (ps)
R7600U	113 ± 3	14.5 ± 0.5
R9880U	169 ± 4	18.8 ± 0.6
R14755U	148 ± 5	24.8 ± 0.6
Tilecal	95 ± 4	14.4 ± 0.5

After correction	Sampling term (ps x $\text{GeV}^{1/2}$)	Constant term (ps)
R7600U	103 ± 3	13.5 ± 0.4
R9880U	127 ± 3	16.9 ± 0.5
R14755U	87 ± 5	23.4 ± 0.4
Tilecal	92 ± 4	14.5 ± 0.5

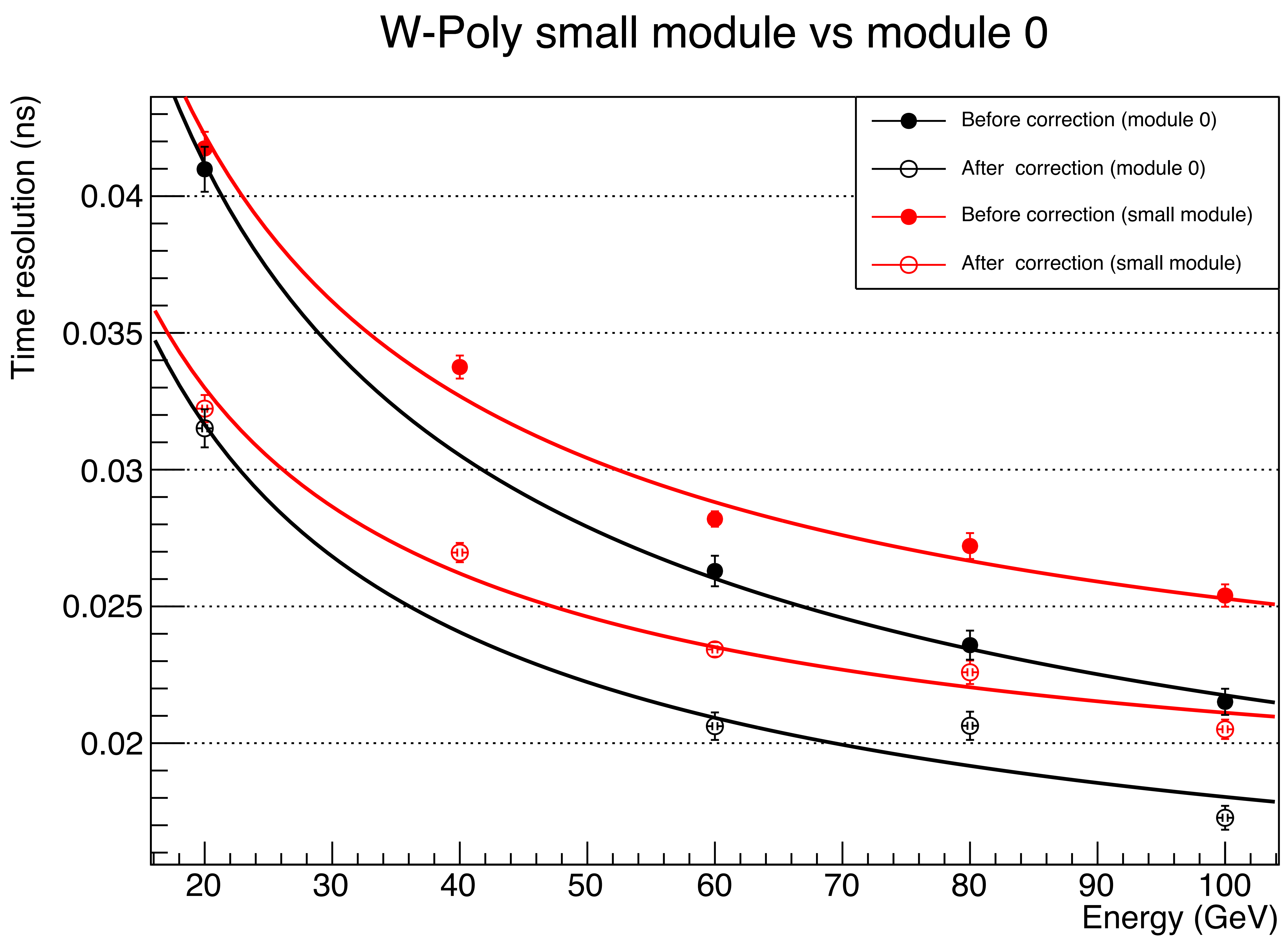
3HF fibres

Before correction	Sampling term (ps x $\text{GeV}^{1/2}$)	Constant term (ps)
R7600U	174 ± 3	14.1 ± 0.8
R9880U	223 ± 7	19.6 ± 1.4
R14755U	116 ± 12	48.6 ± 0.6
Tilecal	303 ± 6	27.4 ± 1.2

After correction	Sampling term (ps x $\text{GeV}^{1/2}$)	Constant term (ps)
R7600U	157 ± 4	14.5 ± 0.7
R9880U	179 ± 7	21.0 ± 1.0
R14755U	202 ± 5	20.5 ± 0.9
Tilecal	293 ± 6	29.5 ± 1.1

Small module vs module 0 - fit parameters

	Sampling term (ps x GeV$^{1/2}$)	Constant term (ps)
Small module	169 ± 4	18.8 ± 0.6
Small module (corrected)	127 ± 3	16.9 ± 0.5
Module 0	175 ± 5	12.9 ± 1.1
Module 0 (corrected)	130 ± 5	12.5 ± 0.8



Uncertainties

- Several sources of uncertainties
    - Quantum efficiency not precisely known (taken from producer's data sheet)
    - Laser instability affecting the measurements
    - General electronic noise

Physical quantity	Uncertainty	Type
Power	0.05 nW	absolute
Dark current	10%	relative
Anodic current	1%	relative
Quantum efficiency	0.05	absolute

- Fluctuations presenting a long period (~ 1 minute) when measuring I_{anode}

N.B. *These are not precision measurements and these uncertainty values are preliminary*