Time resolution studies for the future LHCb ECAL

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PicoCal

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INFN
Istituto Nazionale di Fisica Nucleare

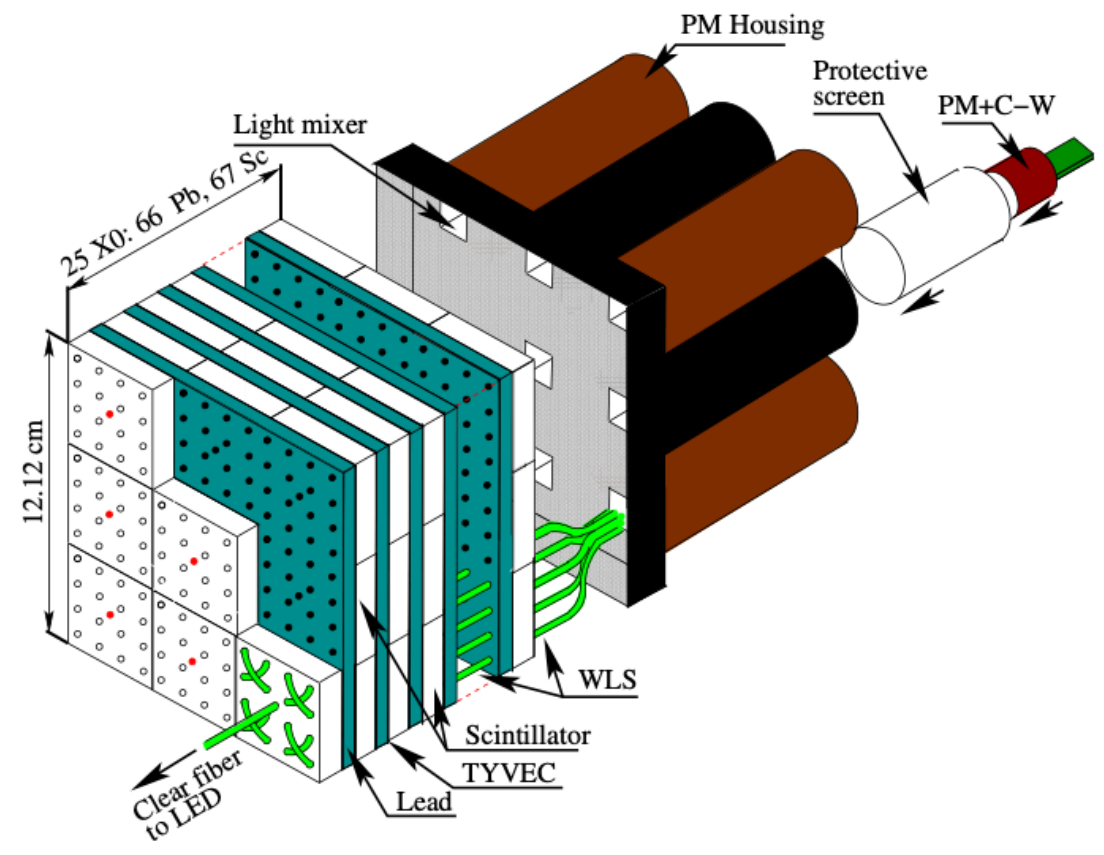
International Master
Advanced Methods
in Particle Physics

Outline

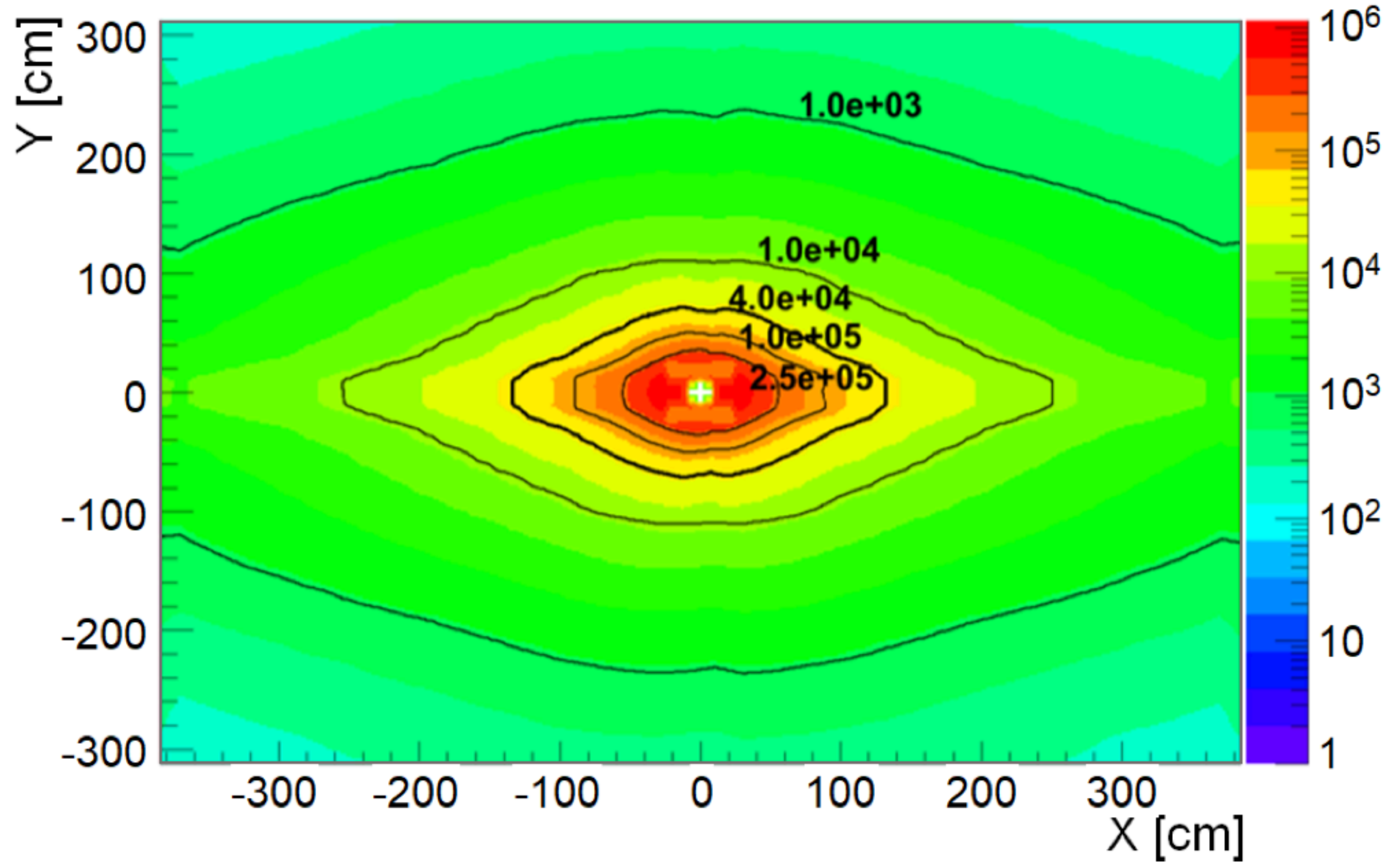
- **Introduction: the LHCb ECAL Upgrade II**
- Simulation studies of a Pb-Polystyrene module
- Analysis of testbeam data from the CERN SPS
- Conclusions

LHCb ECAL Upgrade II

- Currently: sampling ECAL composed of Shashlik modules
- Radiation doses ~ 1 MGy foreseen for Run 5 and Run 6 (innermost region)
- 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)*

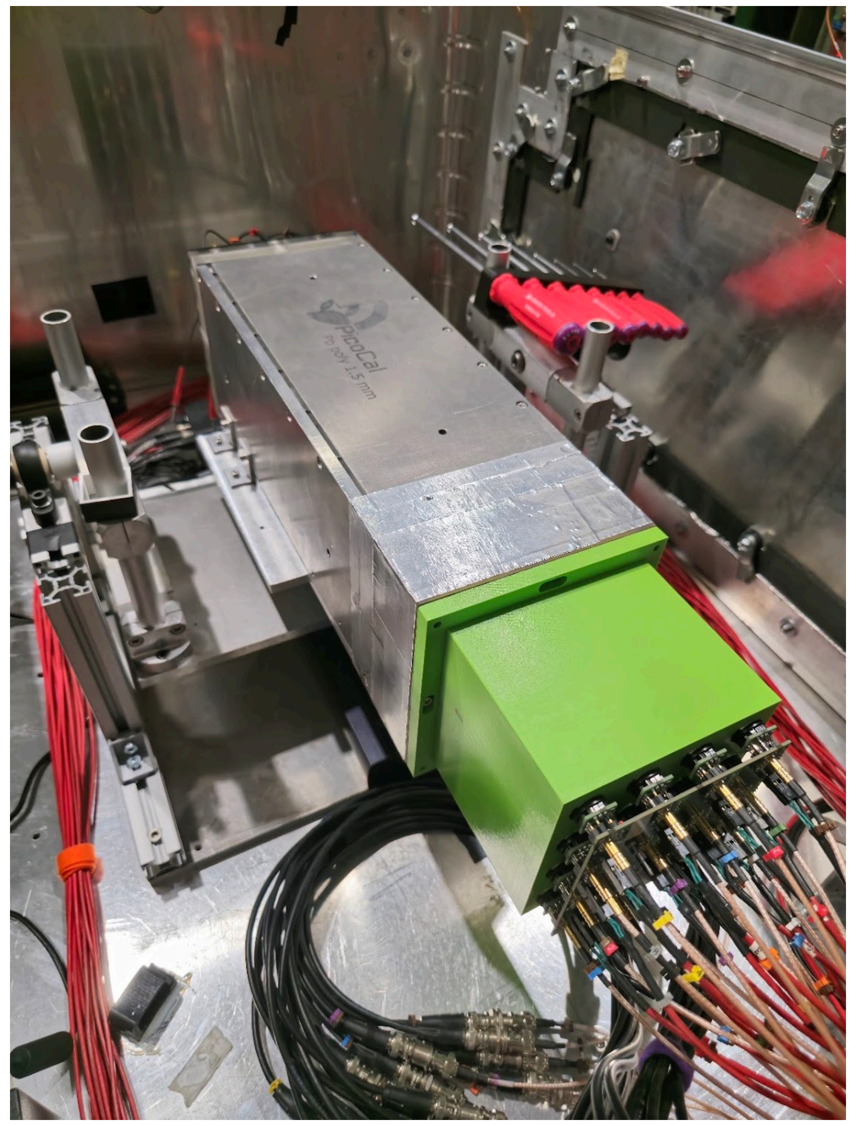


Expected radiation dose for the High Luminosity phase, in Gy *("Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era." https://inspirehep.net/literature/2707810)*

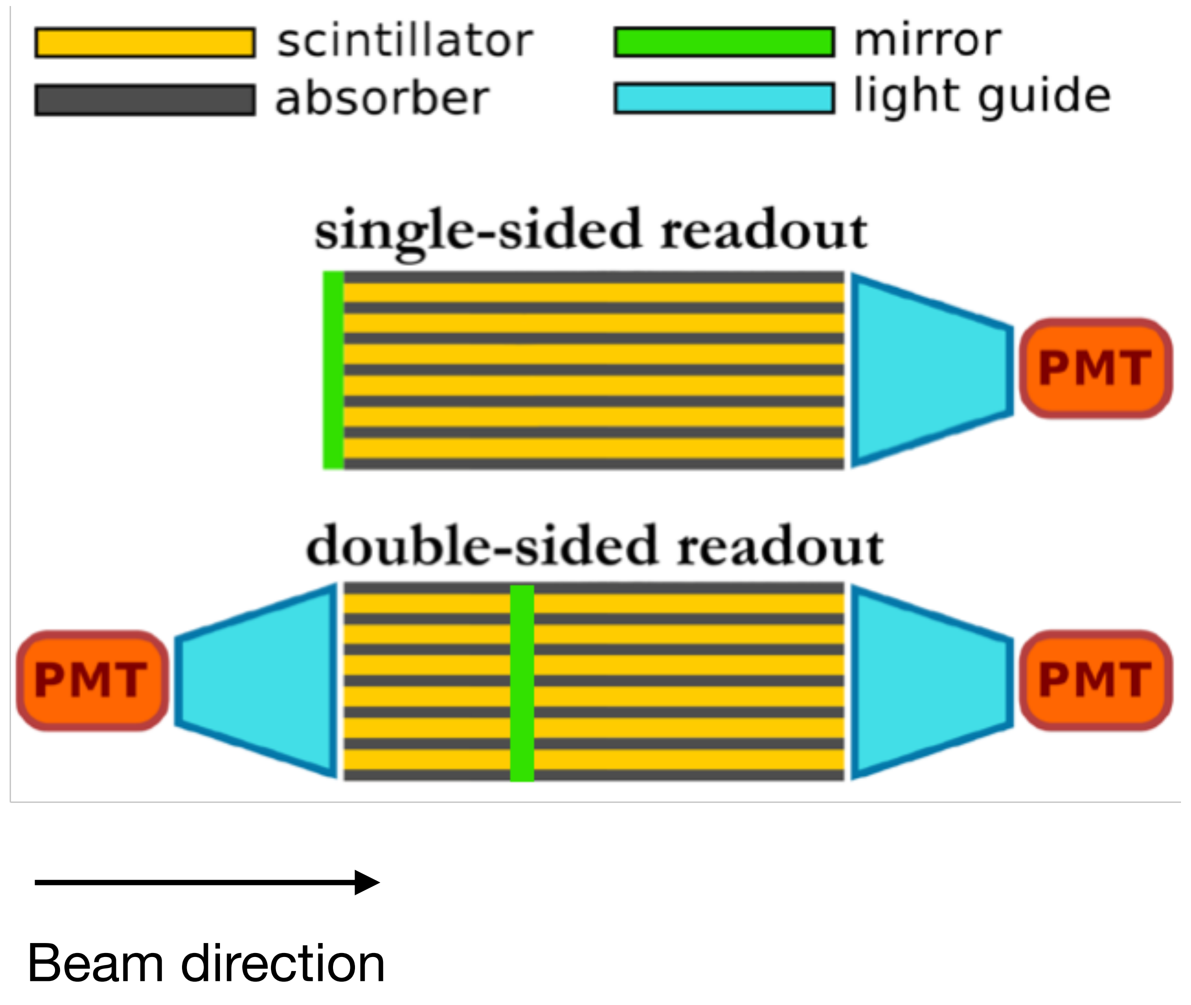
LHCb ECAL Upgrade II

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

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



➡ **Run 4:**	➡ **Run 5 & 6:**
‣ W-Poly & Pb-Poly	‣ W-Crystal and Pb-Poly
‣ Single-side readout	‣ Double-side readout
‣ No timing X	‣ Timing ✓



- If single-side readout modules perform well enough:
  - ➡ Use them for Run 5 & 6 in some regions of the ECAL
  - ➡ Reduce costs
  - ➡ Increase granularity

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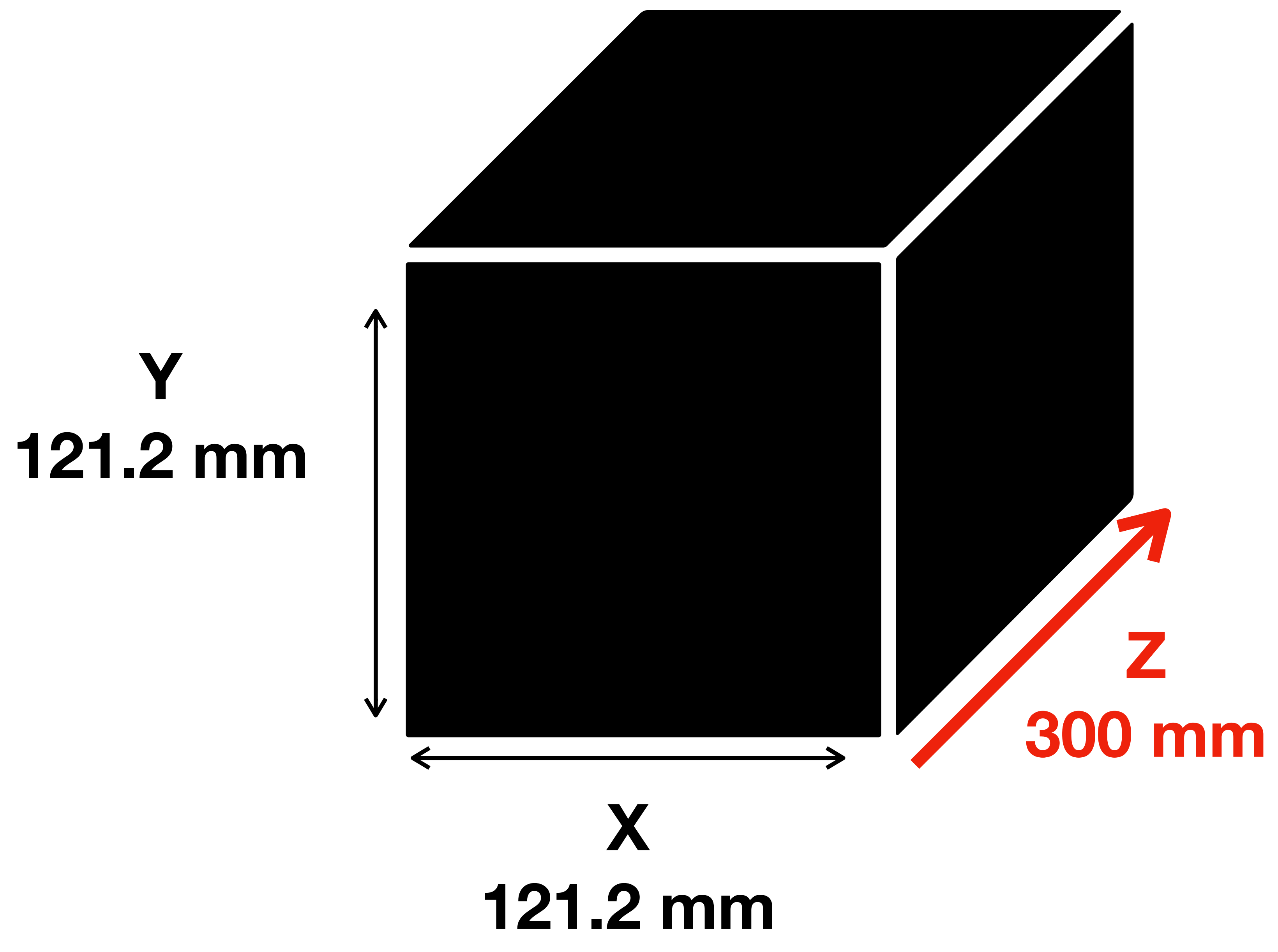
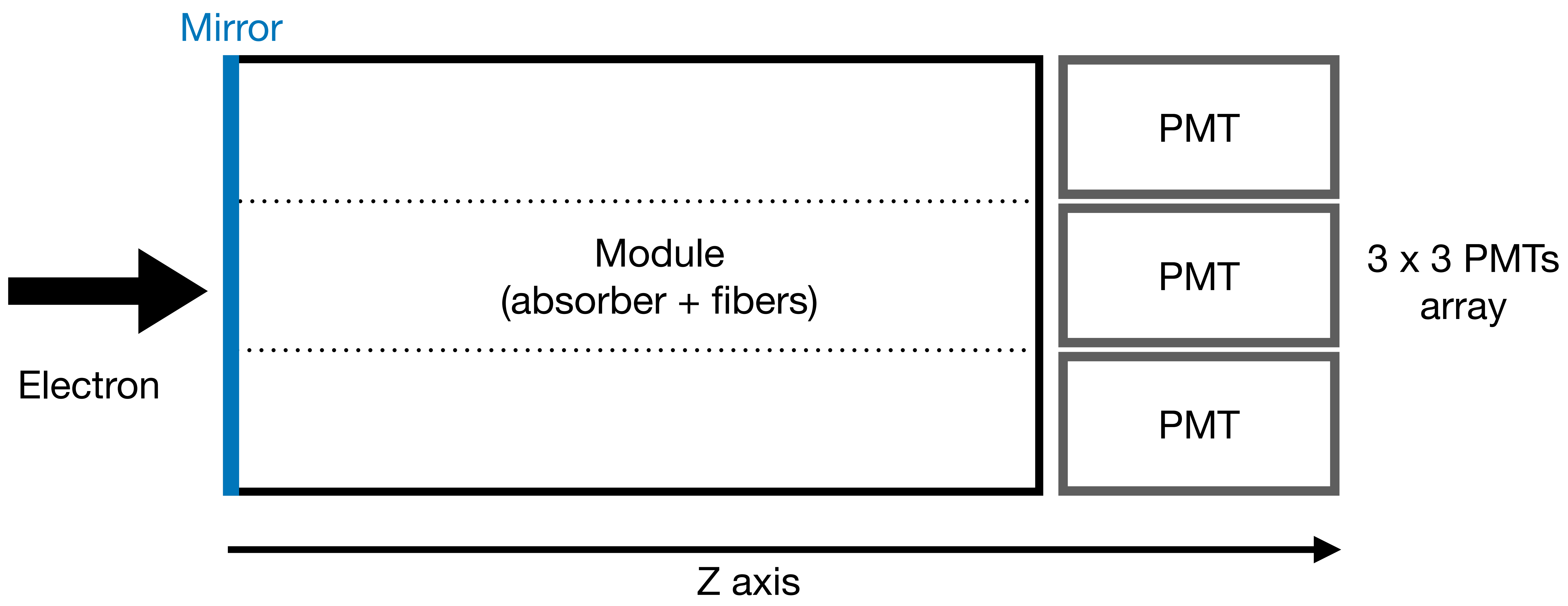
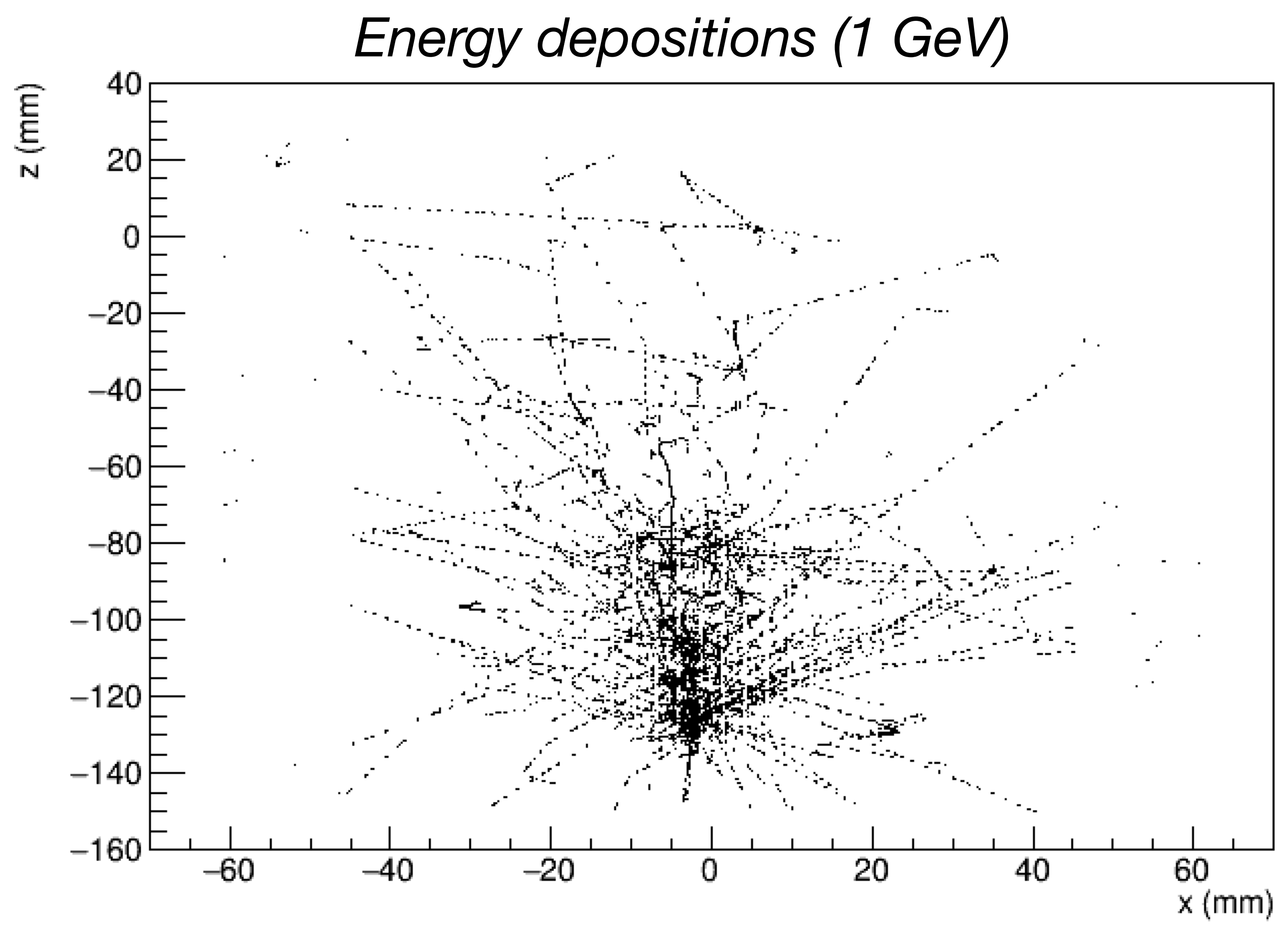
- **Goal**: study the **time resolution** of a simulated module
- Incident e^- at 1 GeV and 10 GeV
- Module under study: **Pb + Polystyrene**
- **Single-side readout** (back)



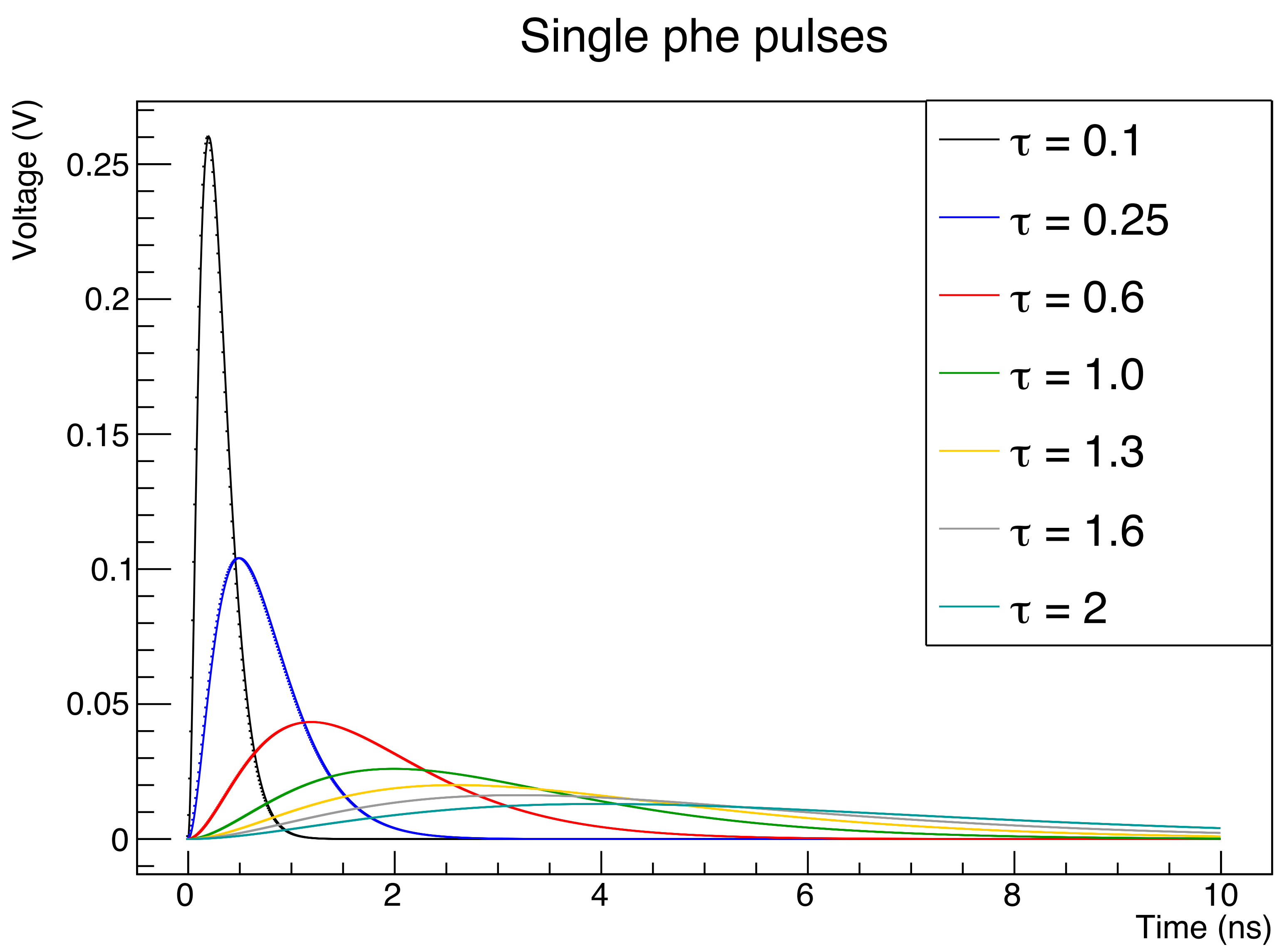


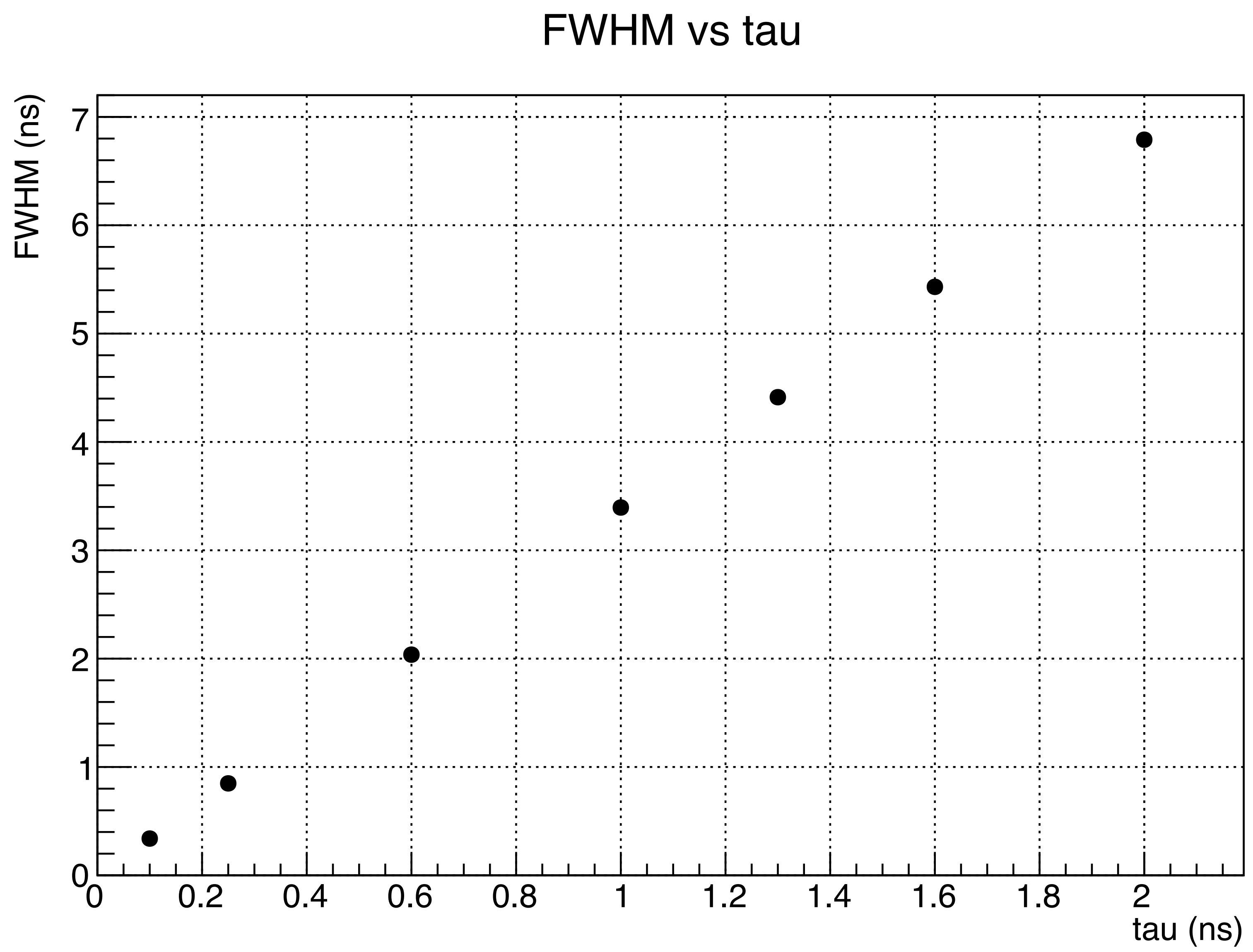


PMTs simulations

Single photoelectron pulse:

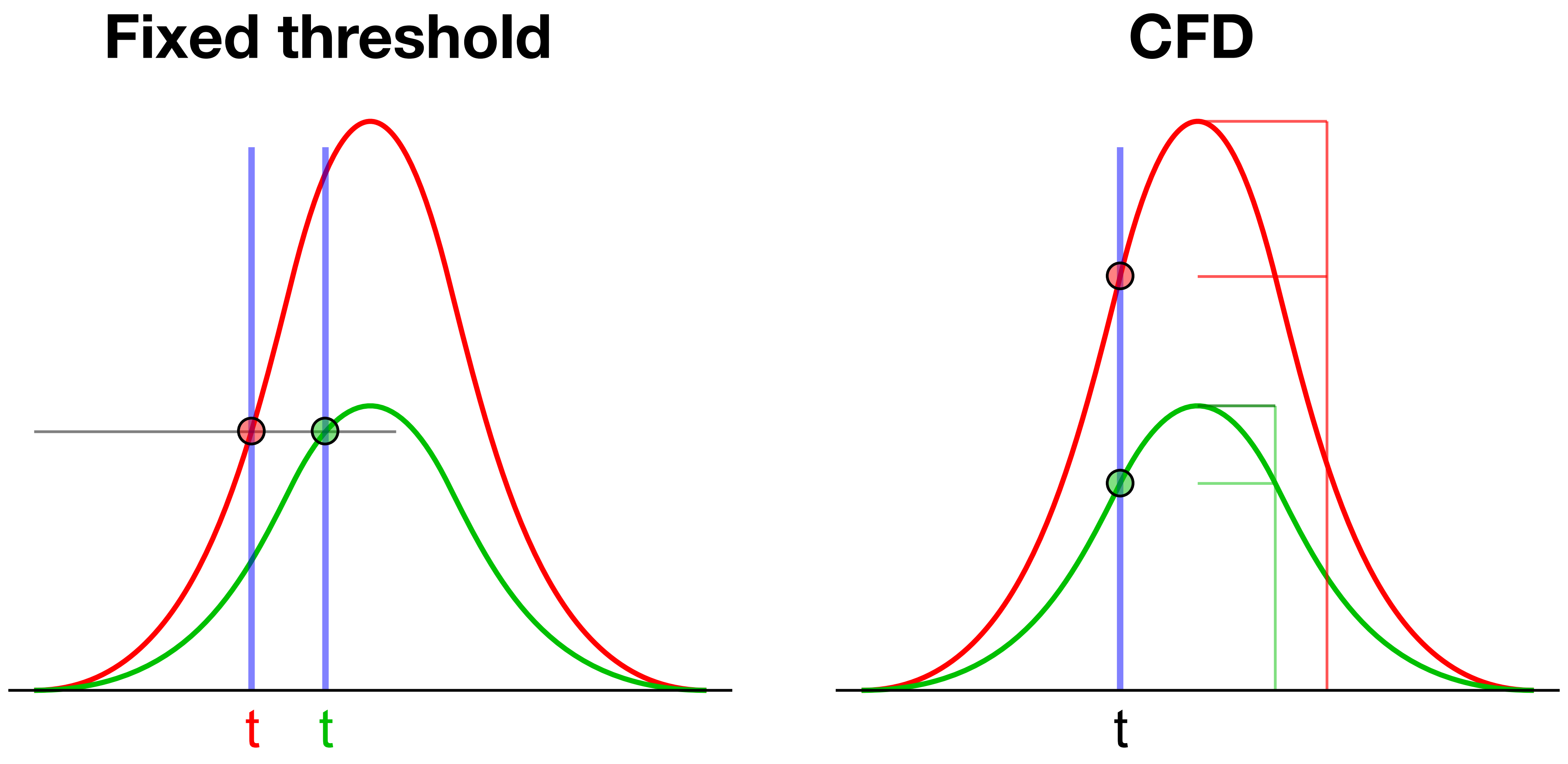
$$f(t) = A \cdot t^2 \cdot e^{-t/\tau} \qquad A = \frac{R \cdot \text{gain} \cdot q_e}{\tau^3} \cdot 10^9$$





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



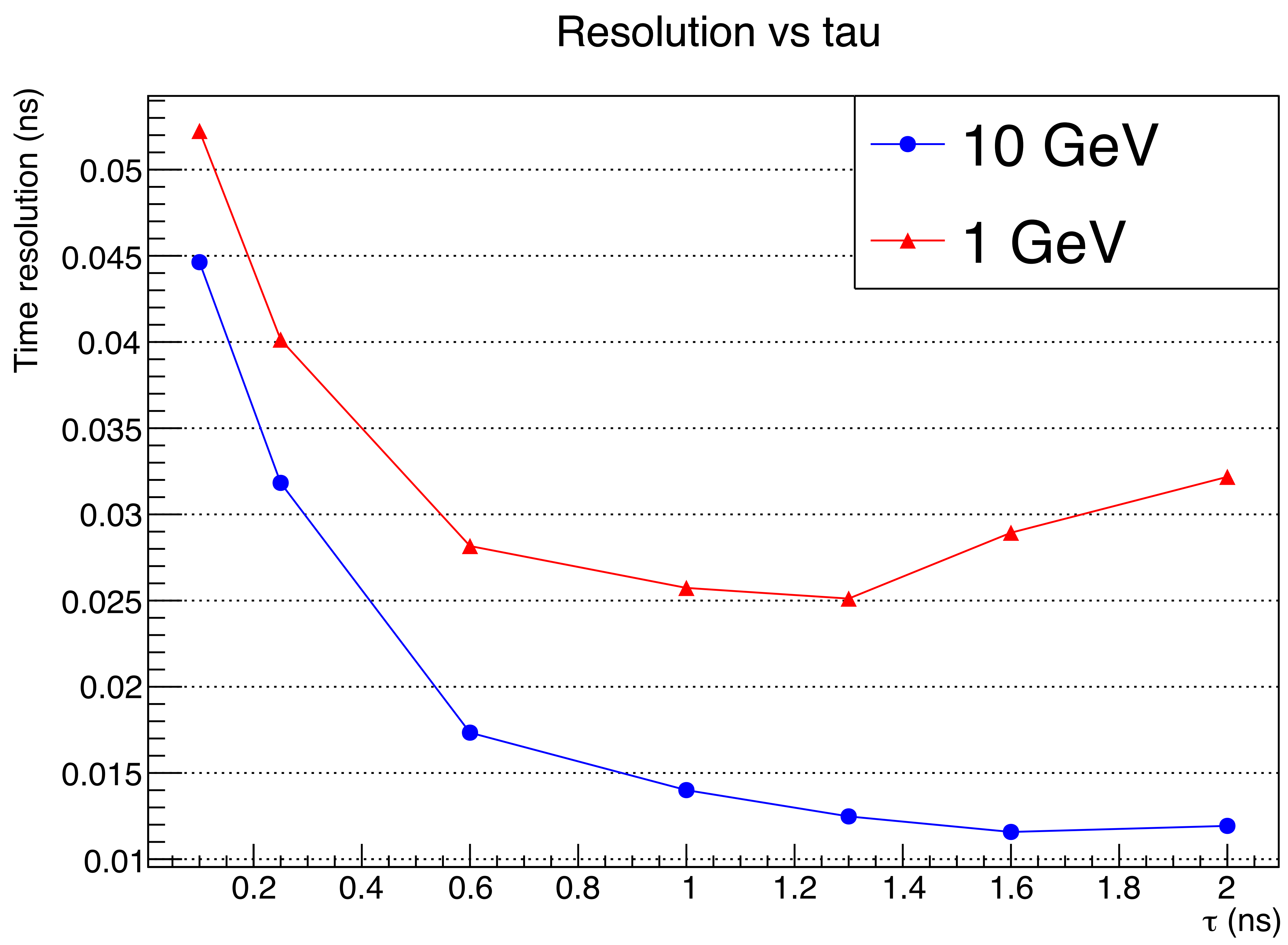
https://en.wikipedia.org/wiki/Constant_fraction_discriminator

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

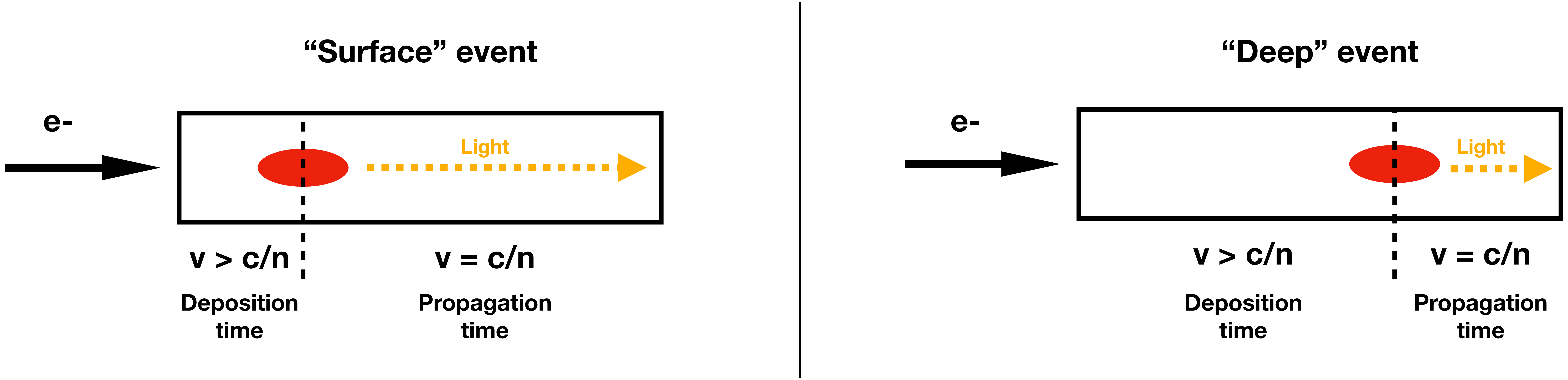


Results with no electronic noise, no amplitude fluctuations of the single ph.e. pulses, no light guides/optical coupling

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*



Why are slower PMTs better ?

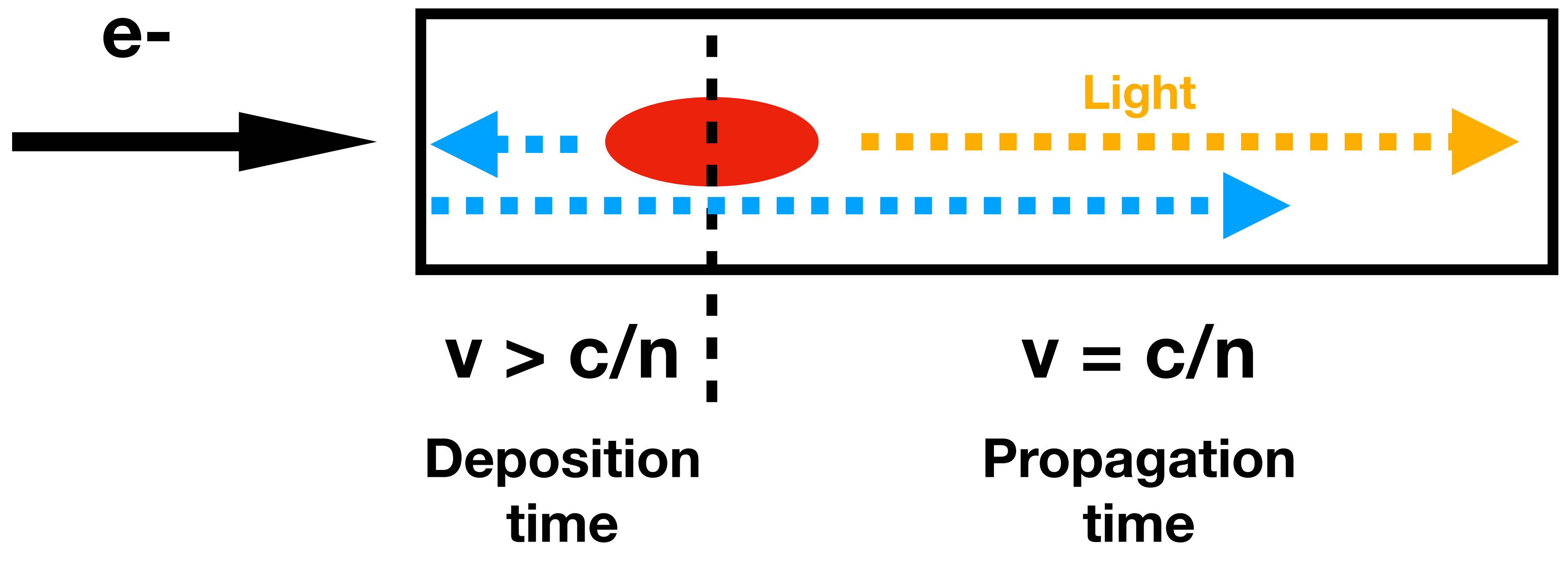
- Shower depth and time stamp are correlated. For **deeper showers**:
  - **Direct photons arrive earlier** to the PMT —> Negative correlation
  - **Reflected photons arrive later** —> Positive correlation

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

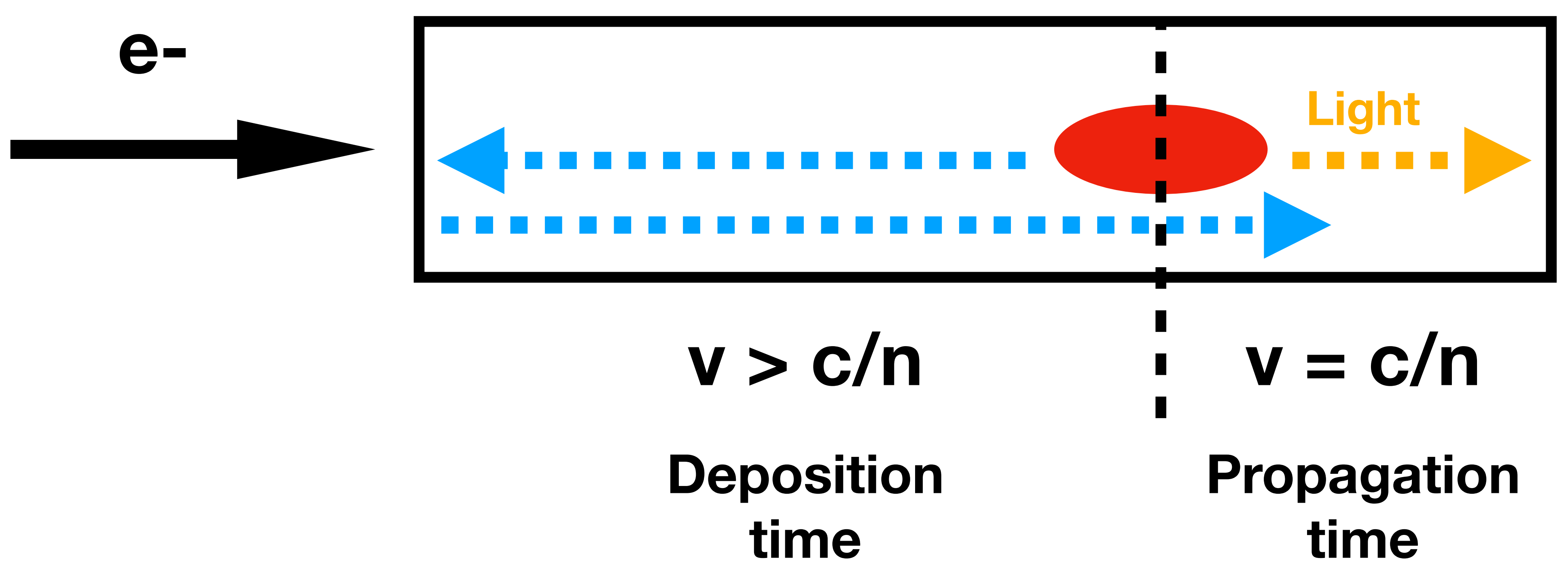
➡ **This bias worsens the time resolution**

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

“Surface” event



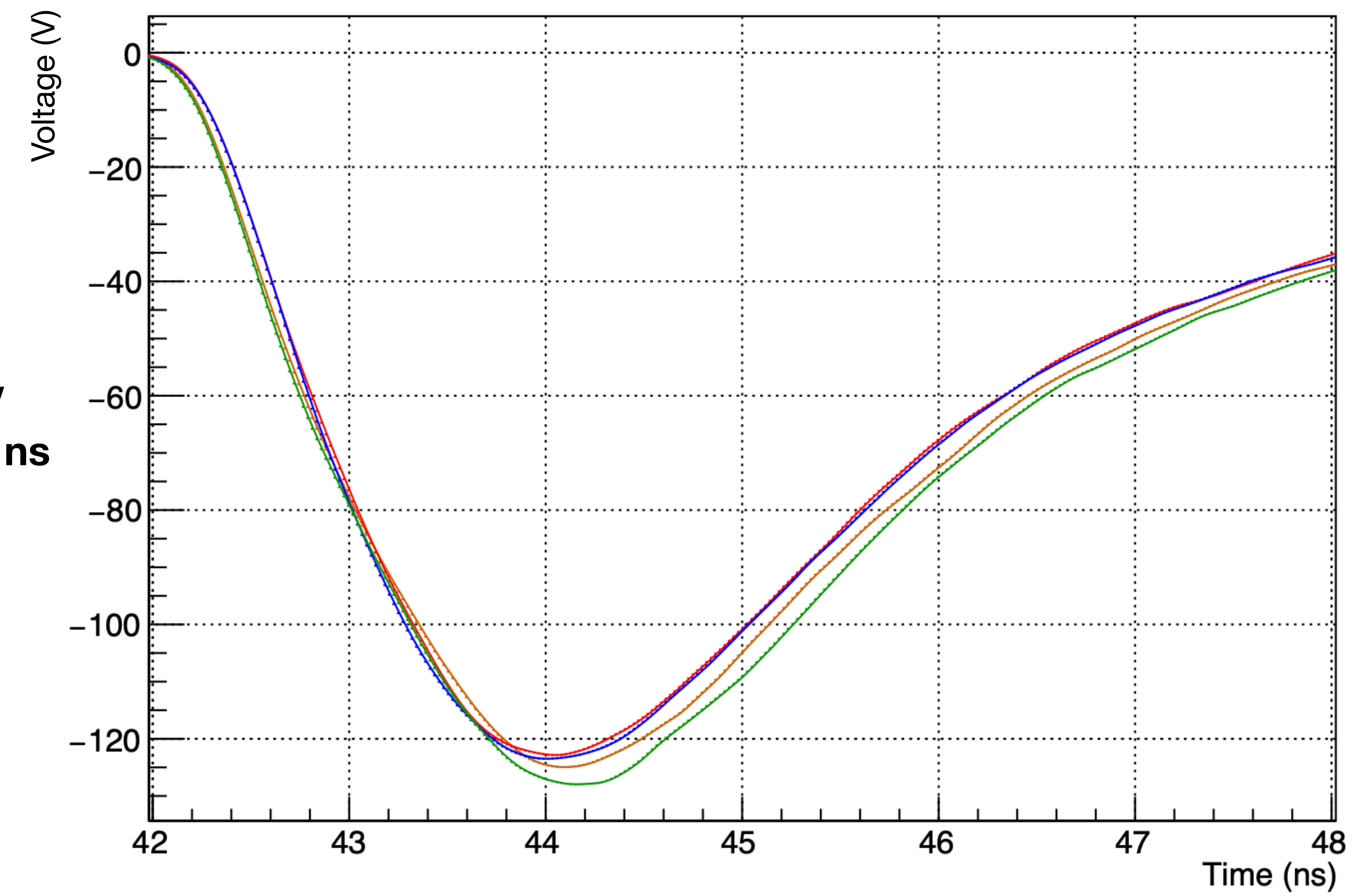
“Deep” event

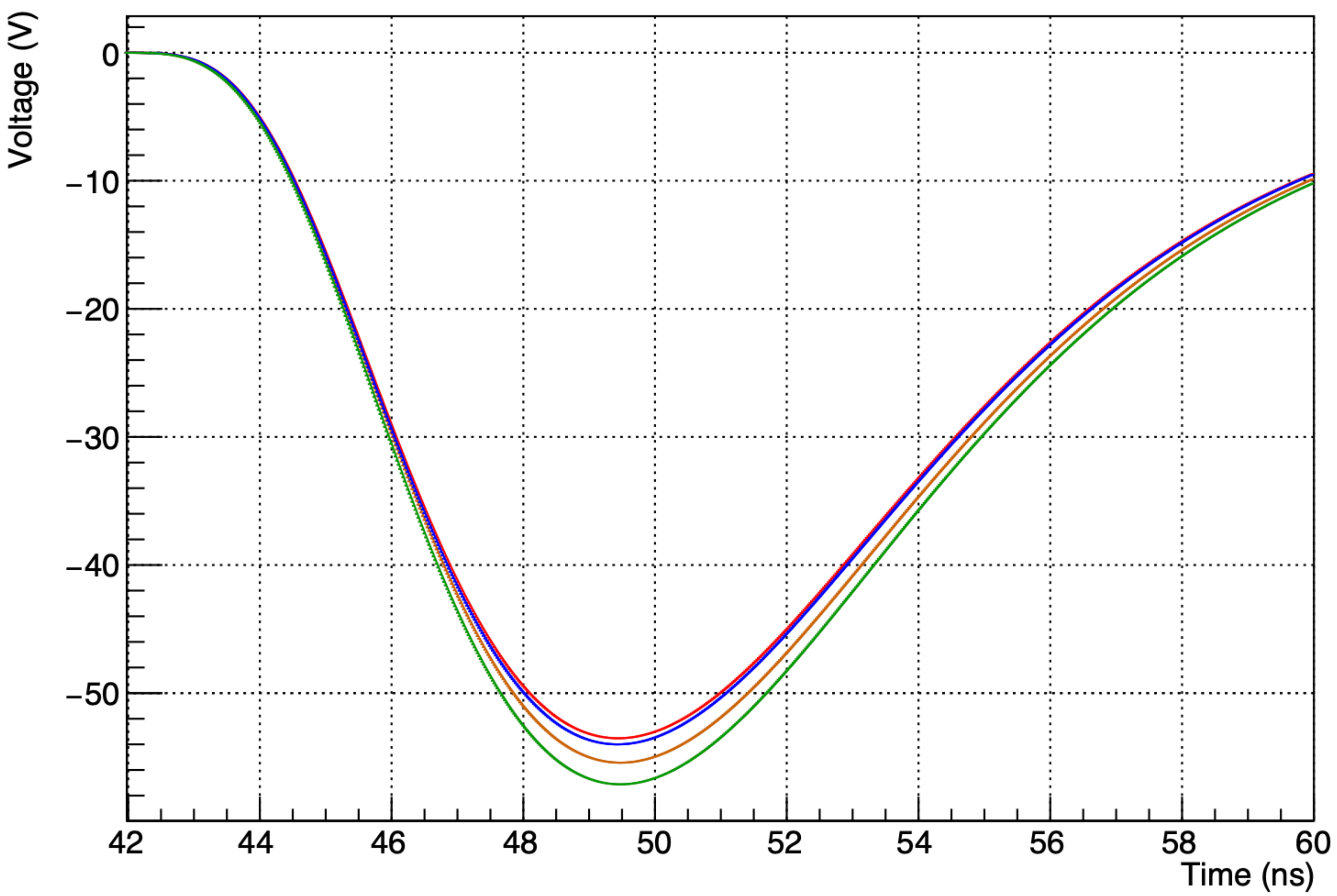


Why are slower PMTs better ?

- 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"

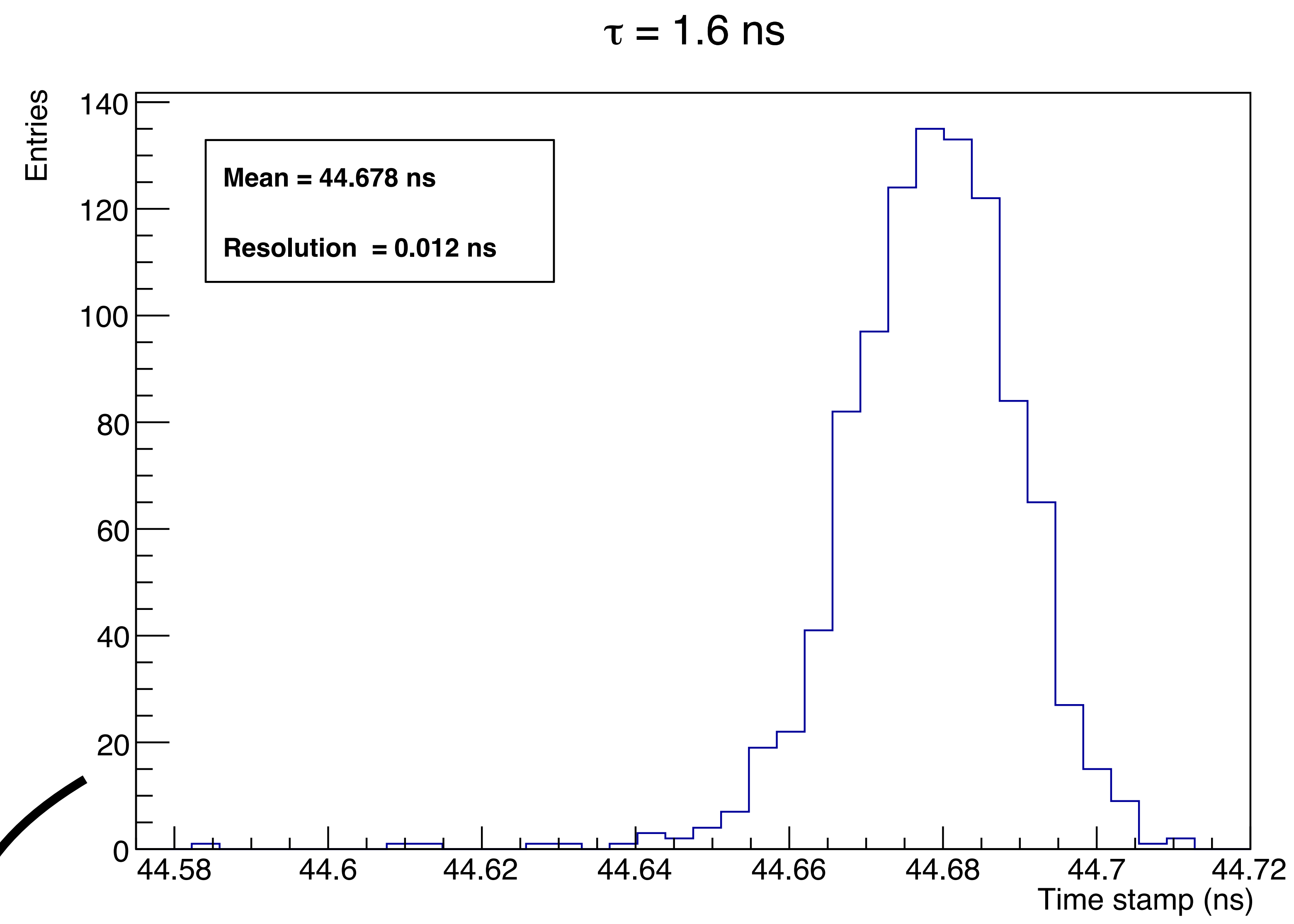


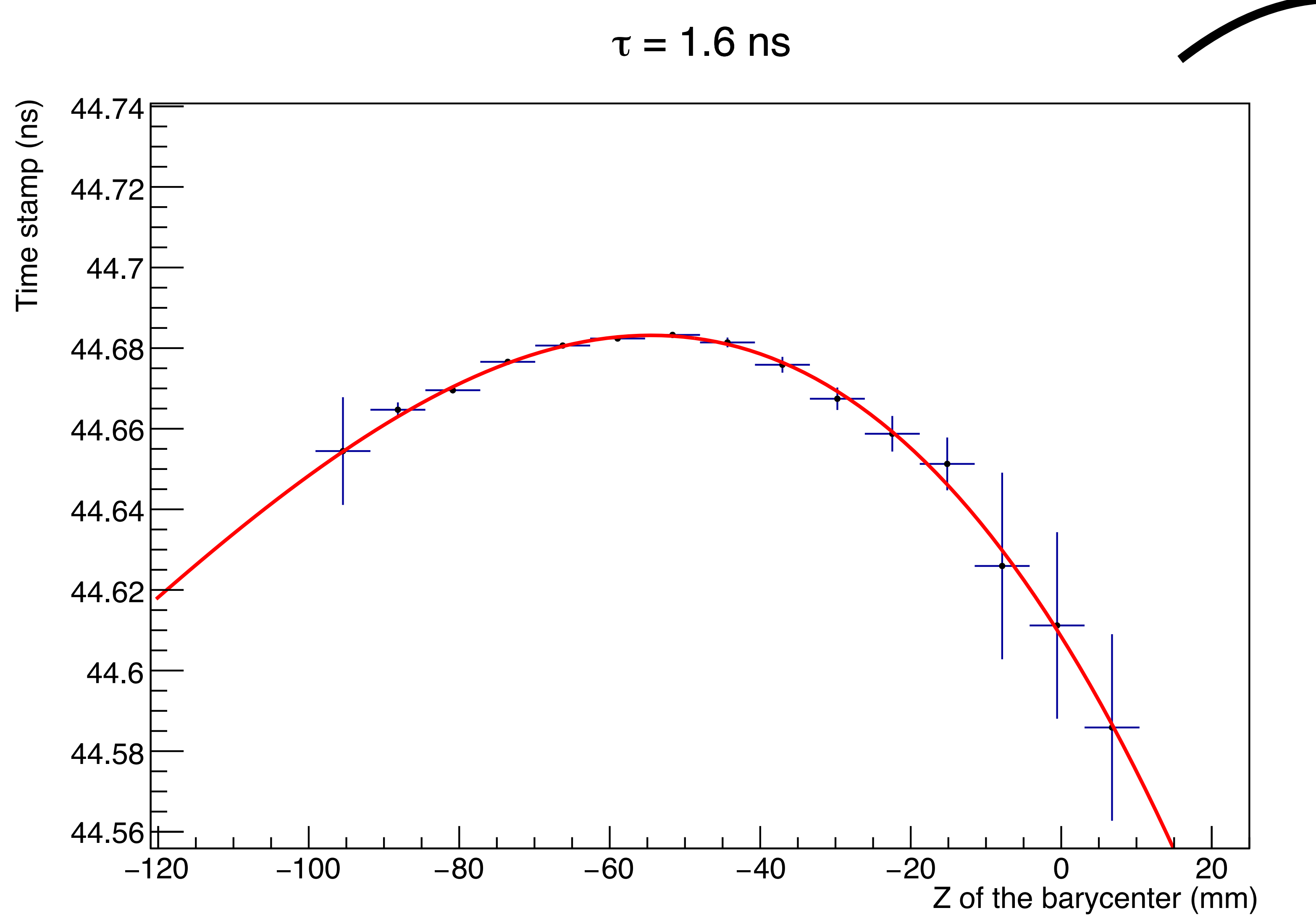


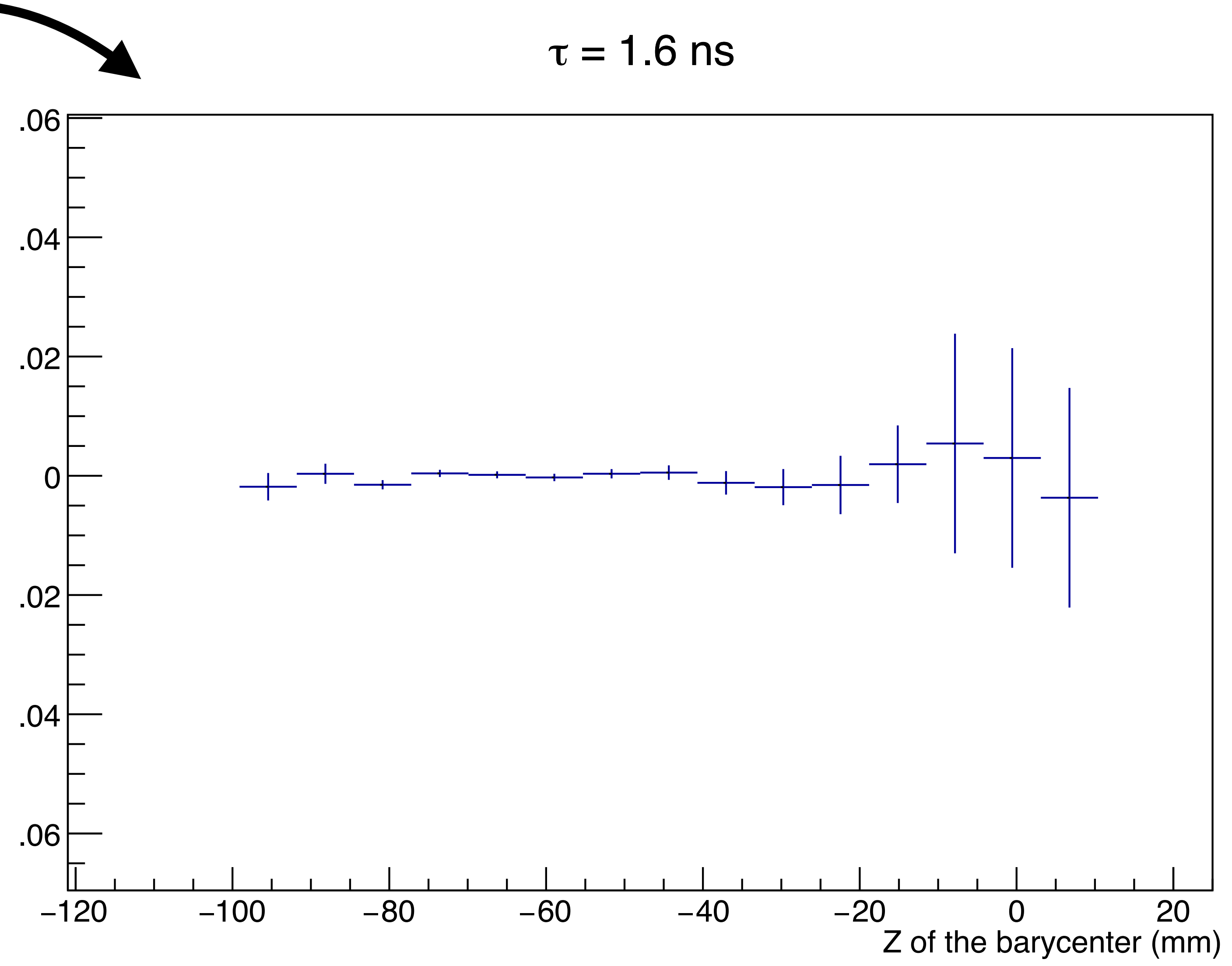
10 GeV
Tau = 2.0 ns
"Slow"

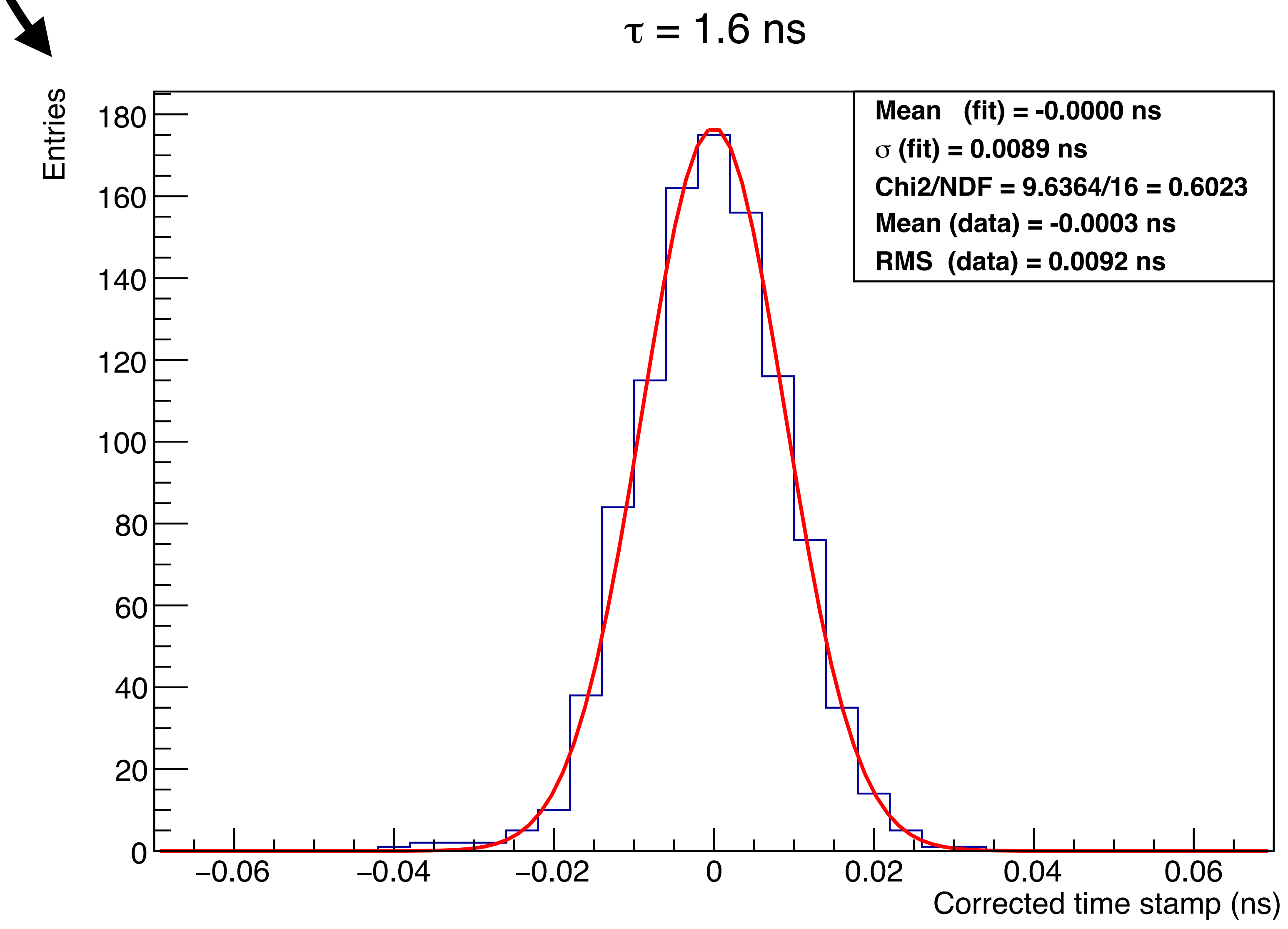
Correction procedure

- 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







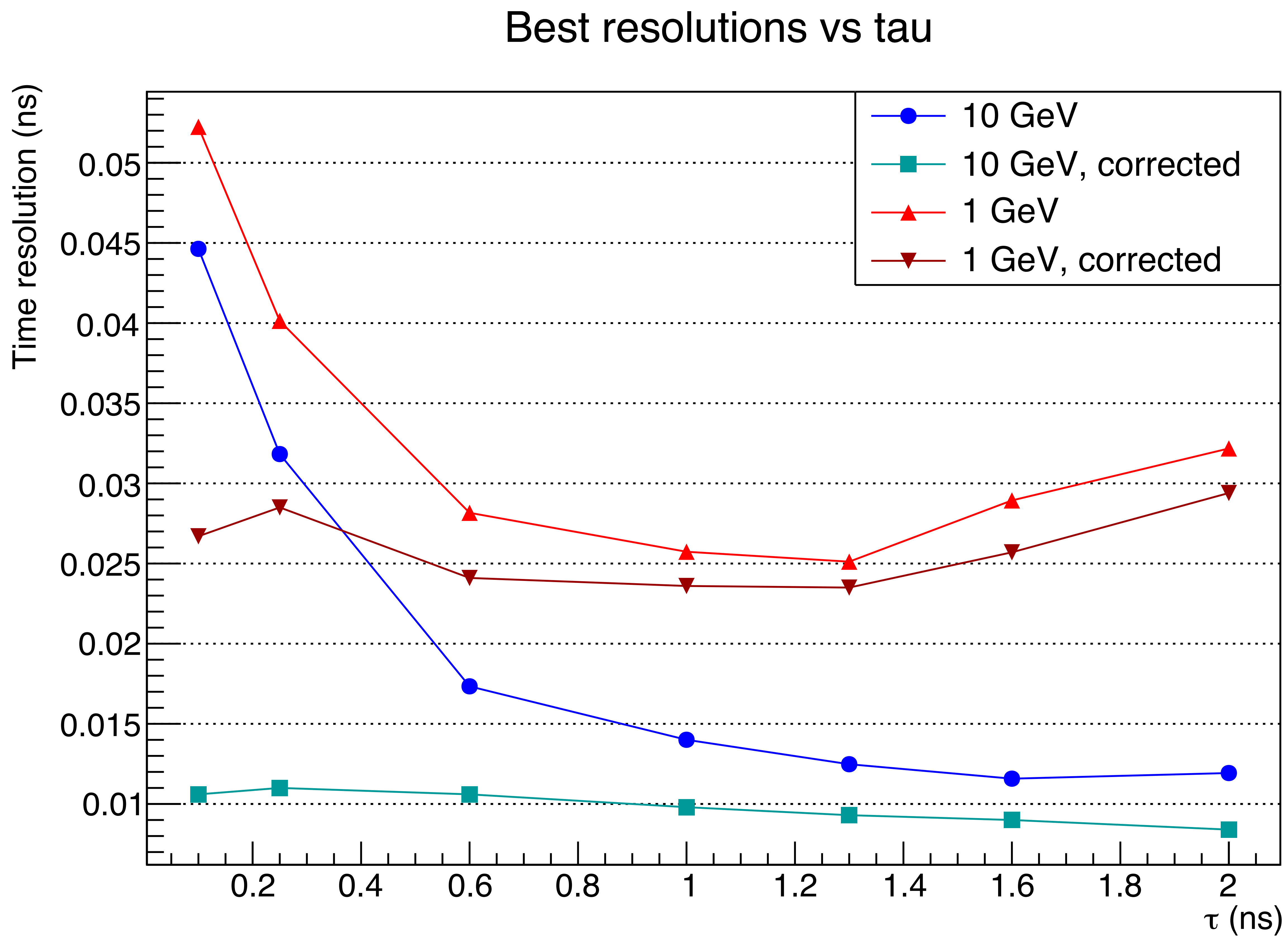


Results

- **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



Results with no electronic noise, no amplitude fluctuations of the single ph.e. pulses, no light guides/optical coupling

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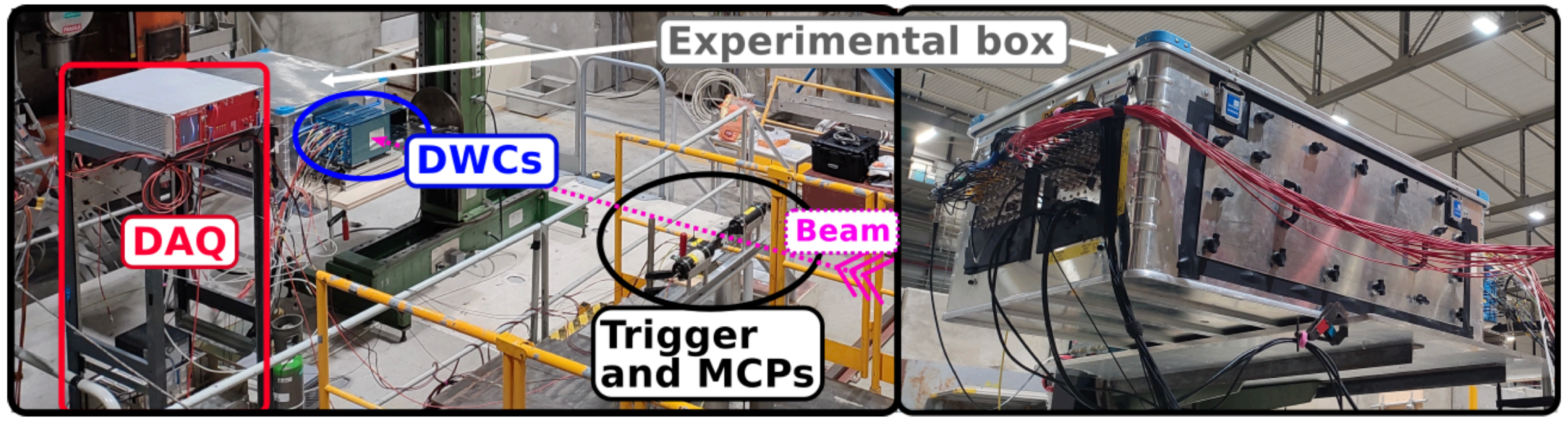
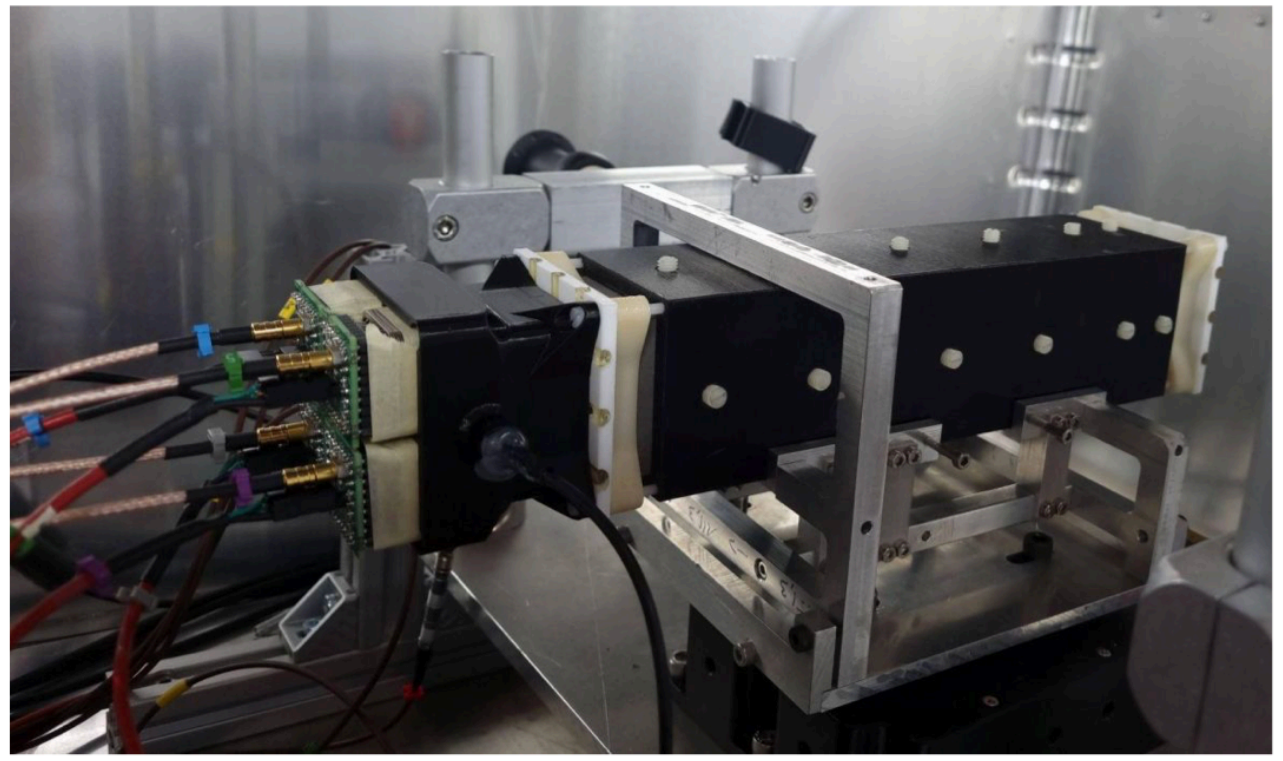
Setup

- Testbeam campaign at the CERN SPS in June 2024
- Full characterization of SpaCal and Shashlik modules
- For time resolution measurements: e^- beams (20 GeV - 100 GeV)



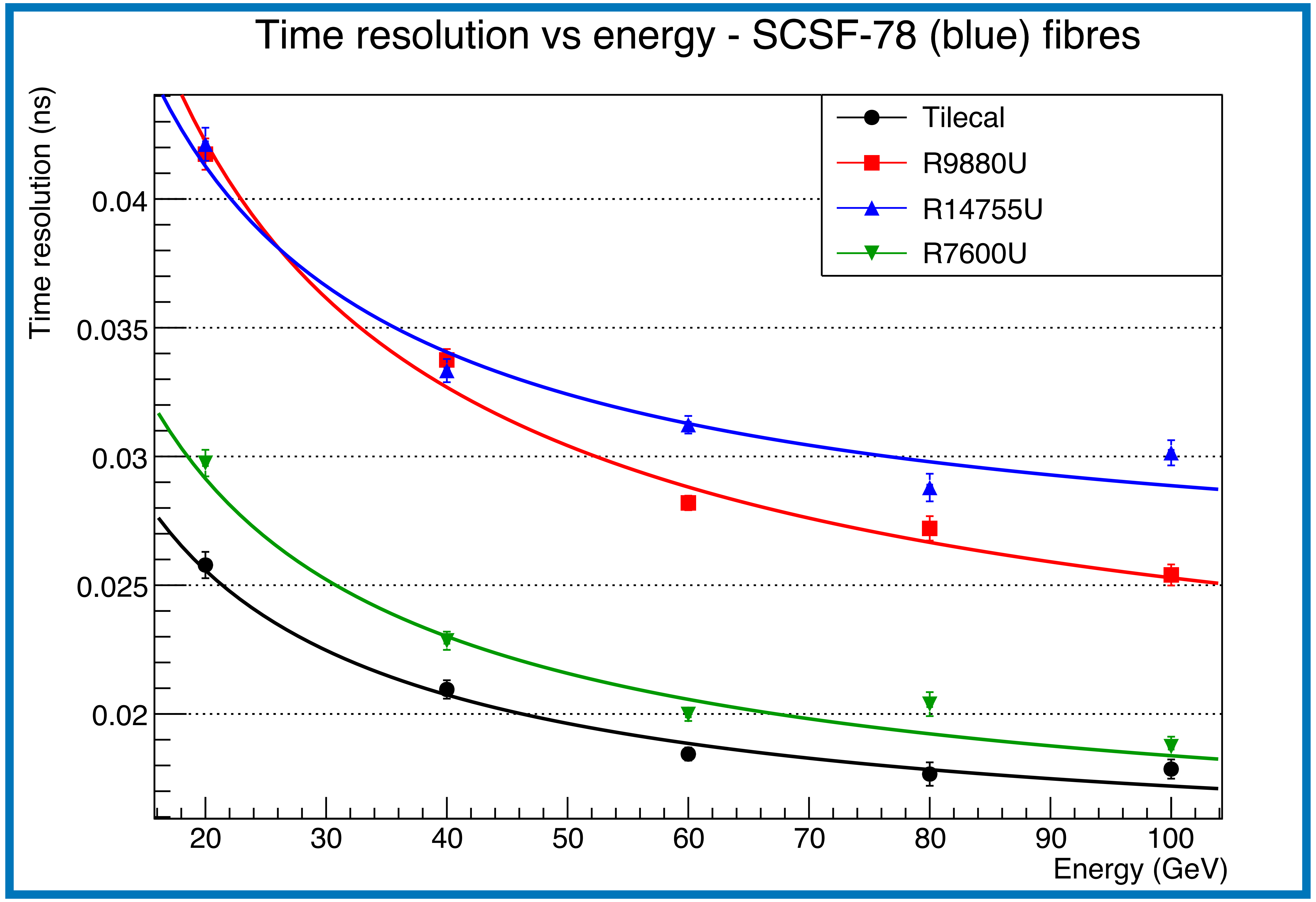
"Small module"

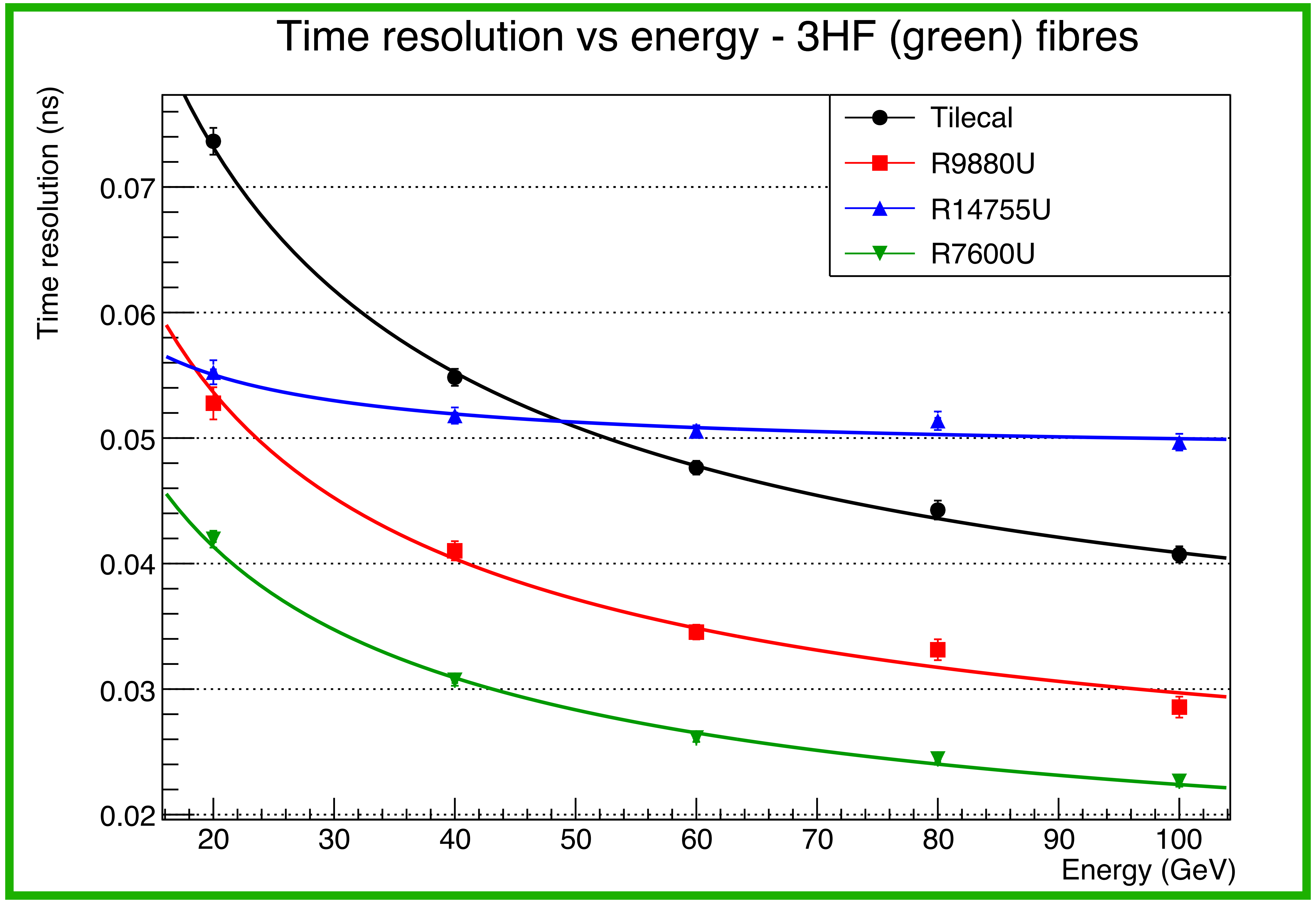
- SpaCal **W-Polystyrene**
- 4 cells only (4.5 x 4.5 cm^2)
- Kuraray SCSF-78 (blue) or 3HF (green) fibres
- Readout with 4 different PMTs:
  - R7600U, R9880U, R14755U, R11187 (a.k.a. Tilecal)



Time resolution results - Small module

$$\sigma_T(E) = \frac{sampl.}{\sqrt{E}} \oplus const.$$



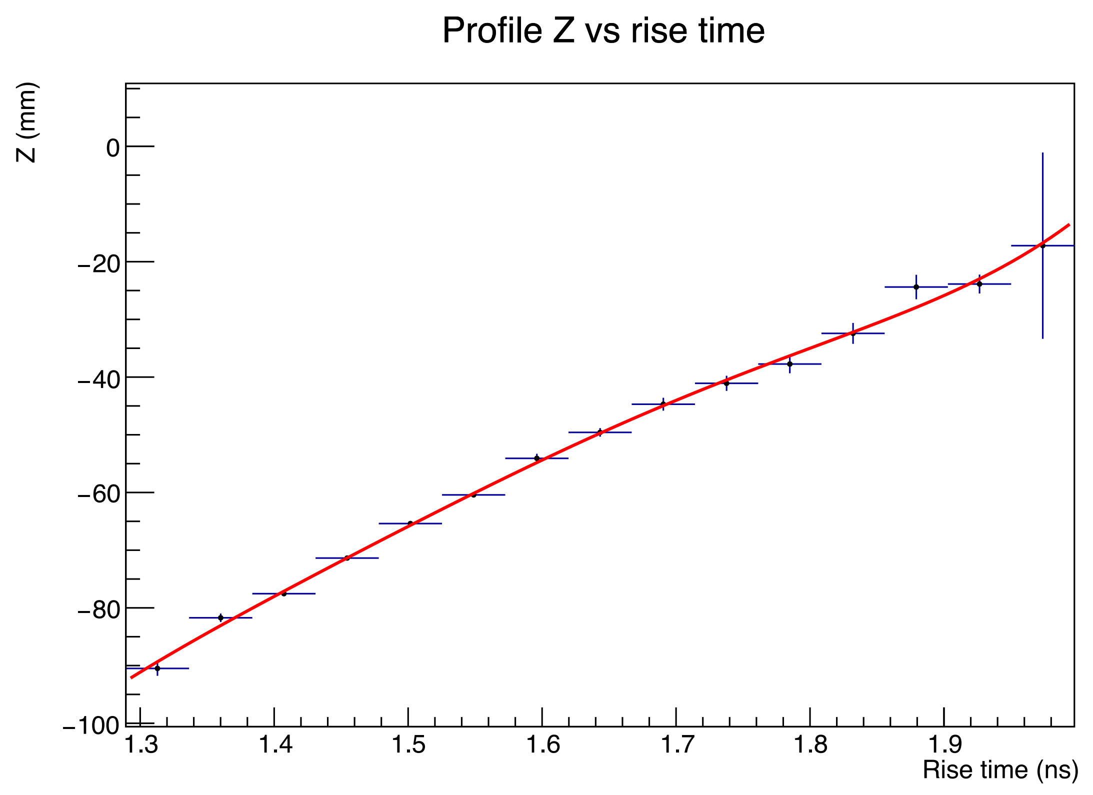


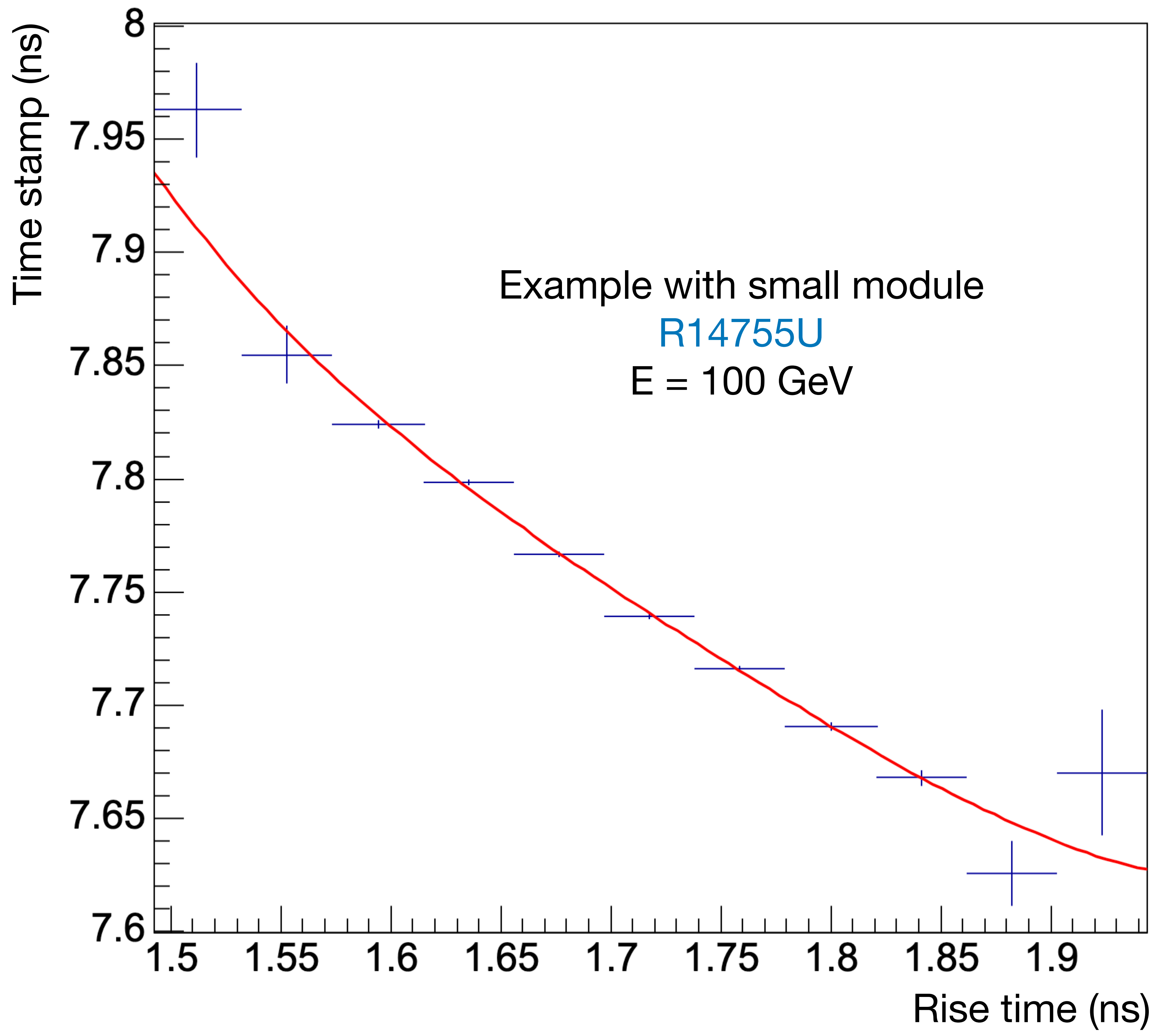
- SCSF-78 results are systematically better due to faster decay time of the fibres
- SCSF-78 fibres: slow PMTs (R7600U and Tilecal) perform better —> Less biased by shower depth
- 3HF fibres: best results for PMTs with **E**xtended **R**ed **M**ulti **A**lkali (**ERMA**) photocathode

Correction to the time stamp

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

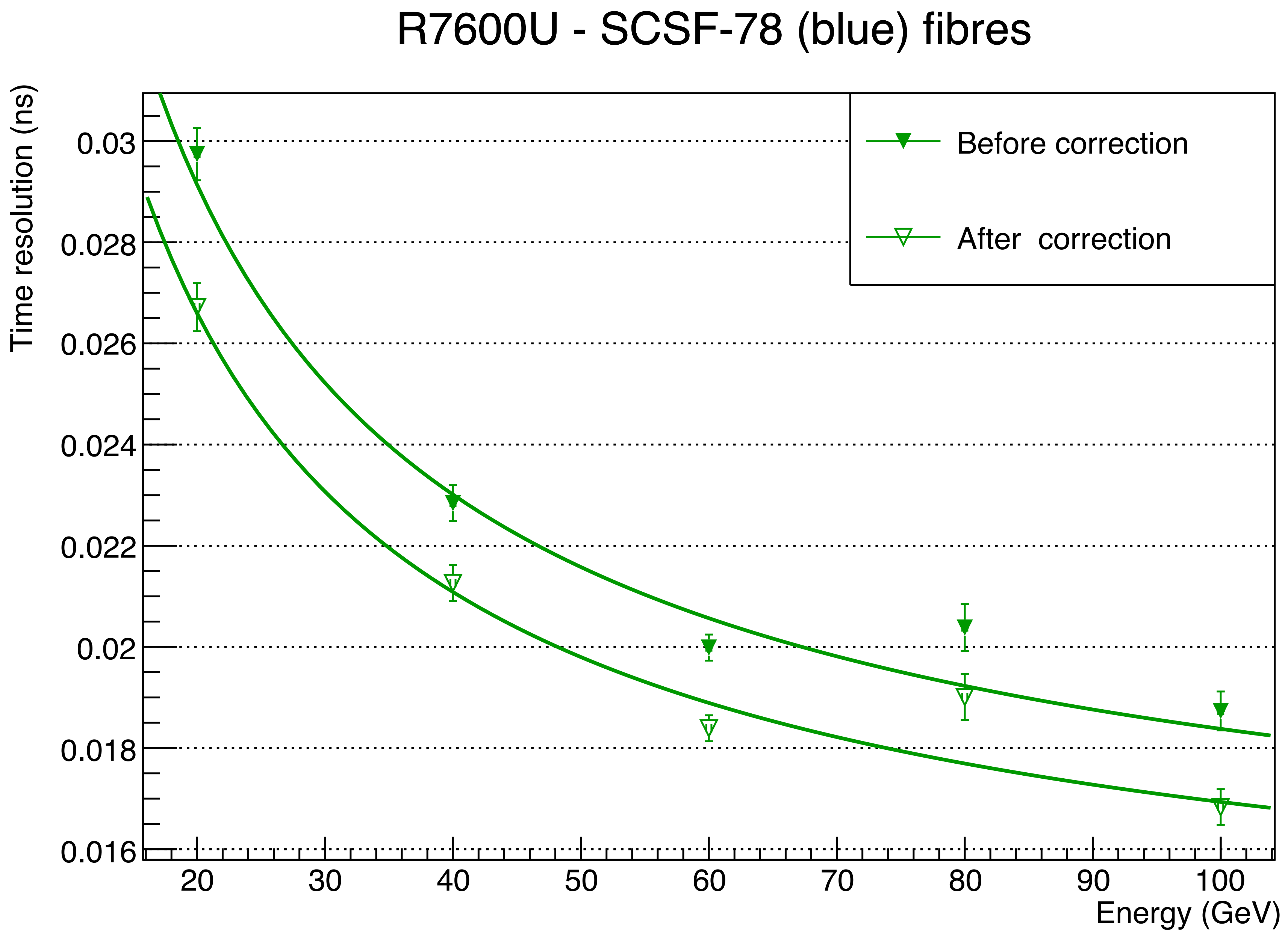
➡ **Idea: exploit the rise time to remove the bias**

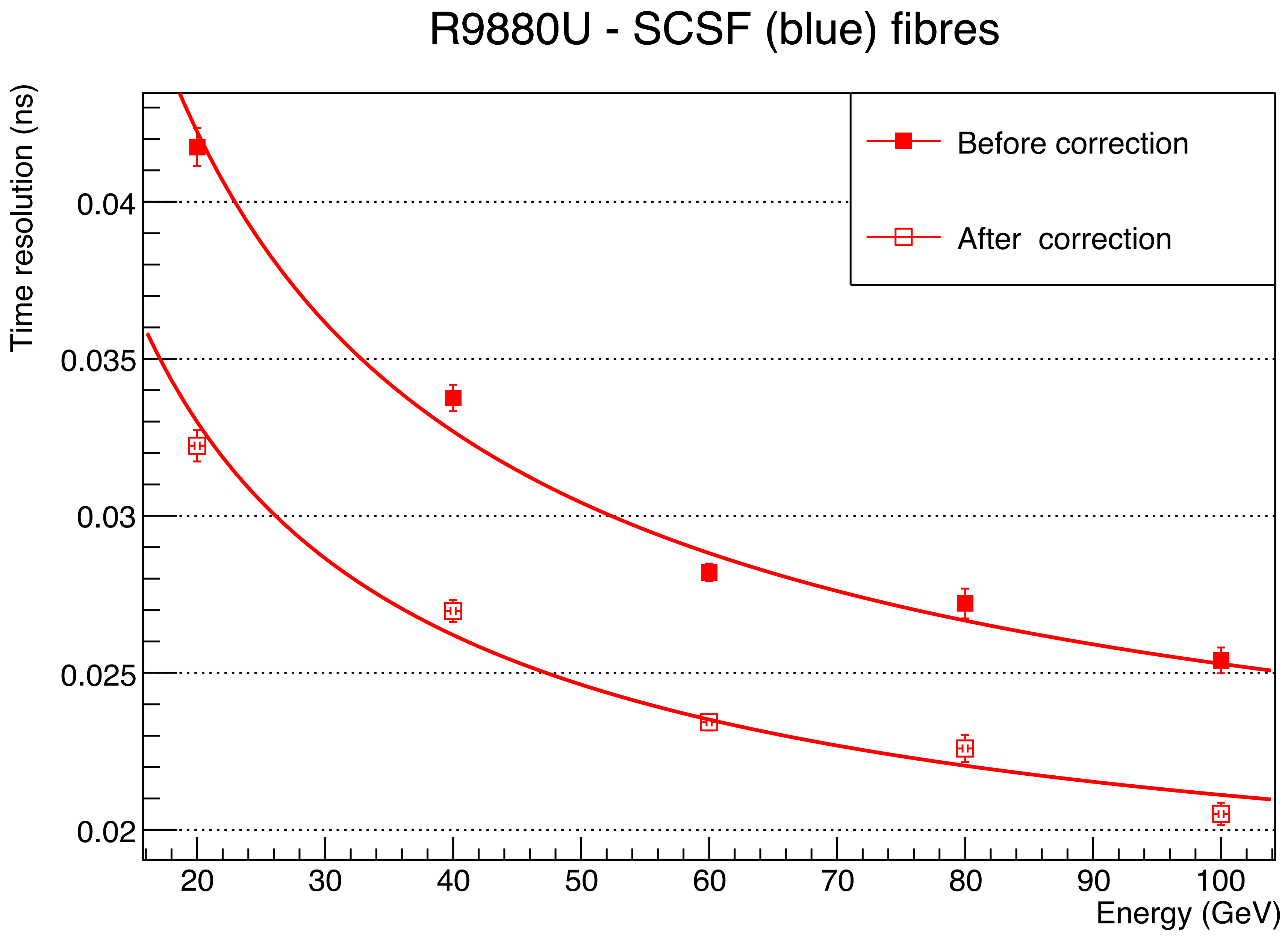


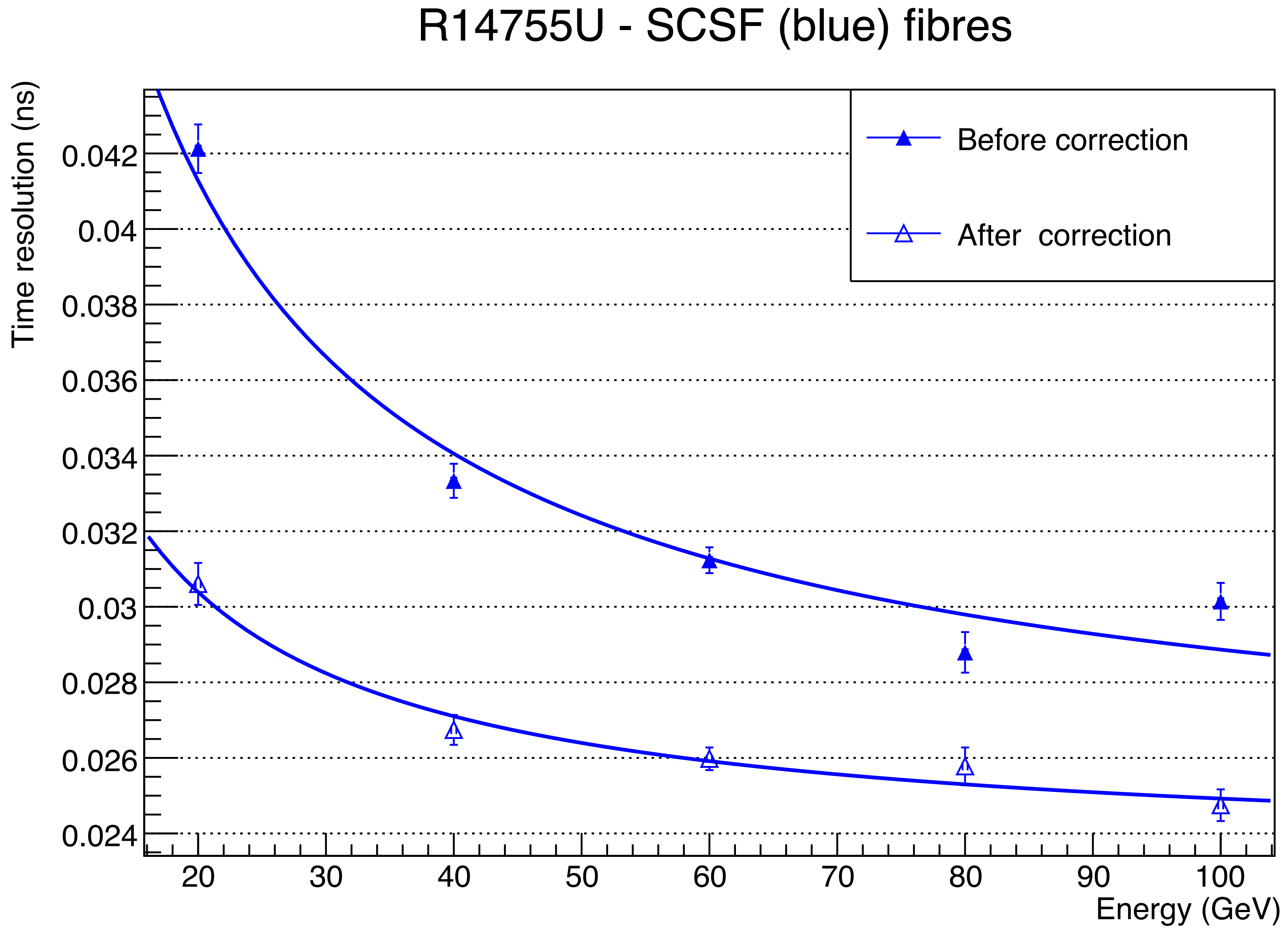


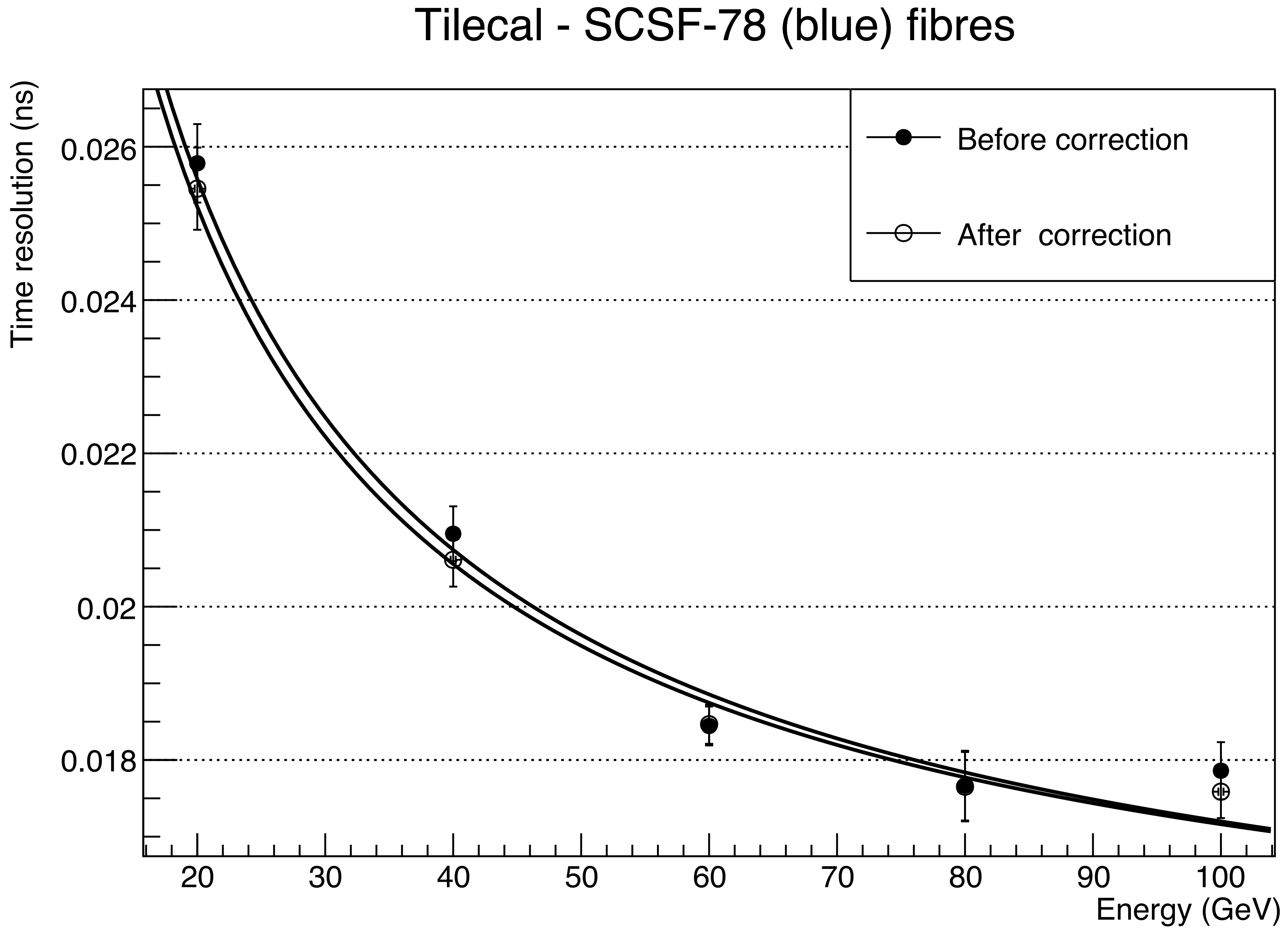
- Polynomial fit to the profiled scatter plot of time stamp t vs rise time of each signal —> Find the correction curve f
- **Corrected time stamp** for the j^{th} event defined as: $\hat{t}_j = t_j - f_j$
- The corrected time resolution is the standard deviation of $\hat{t}$

Corrected resolution - Small module with SCSF-78 fibres

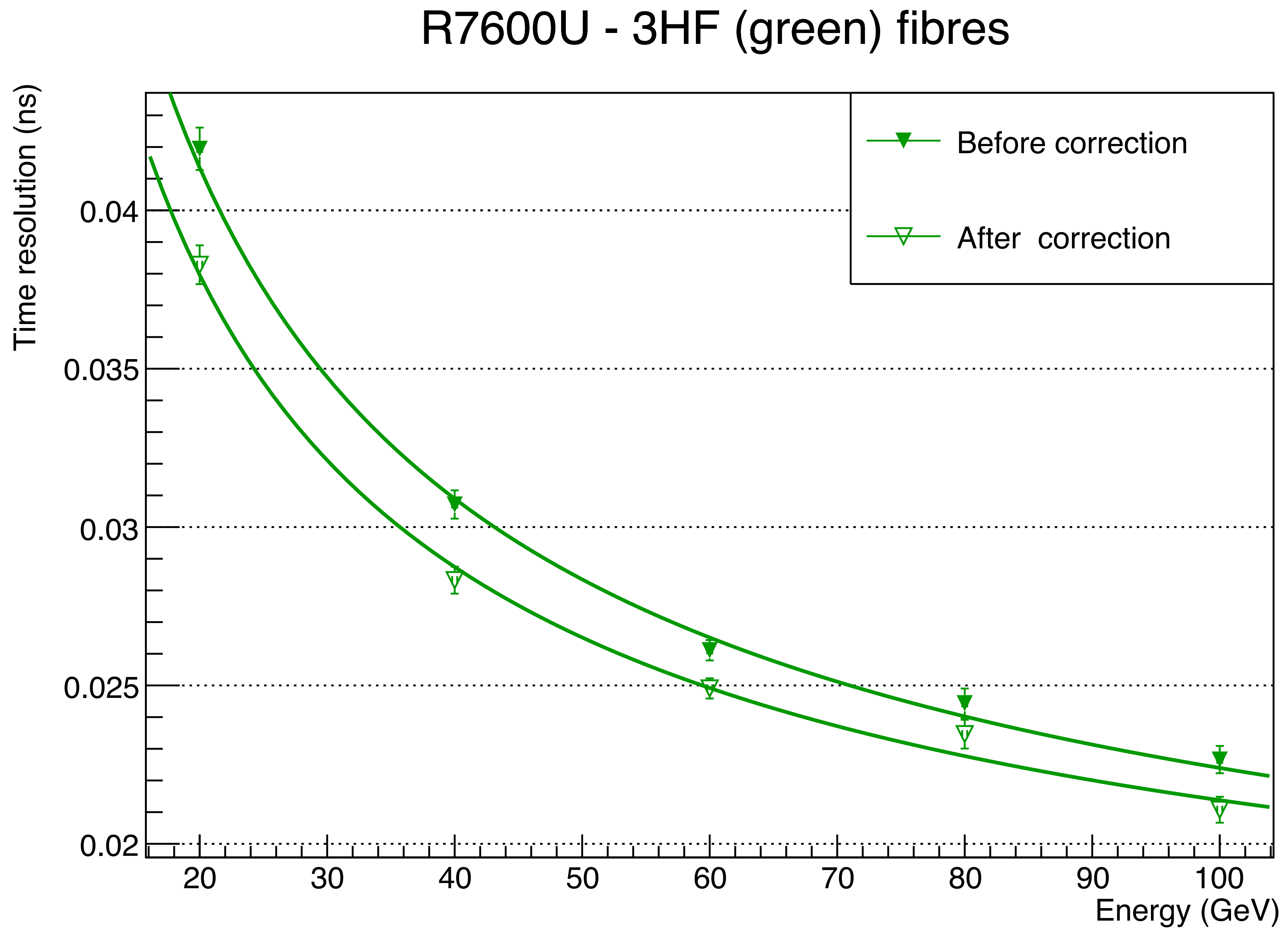


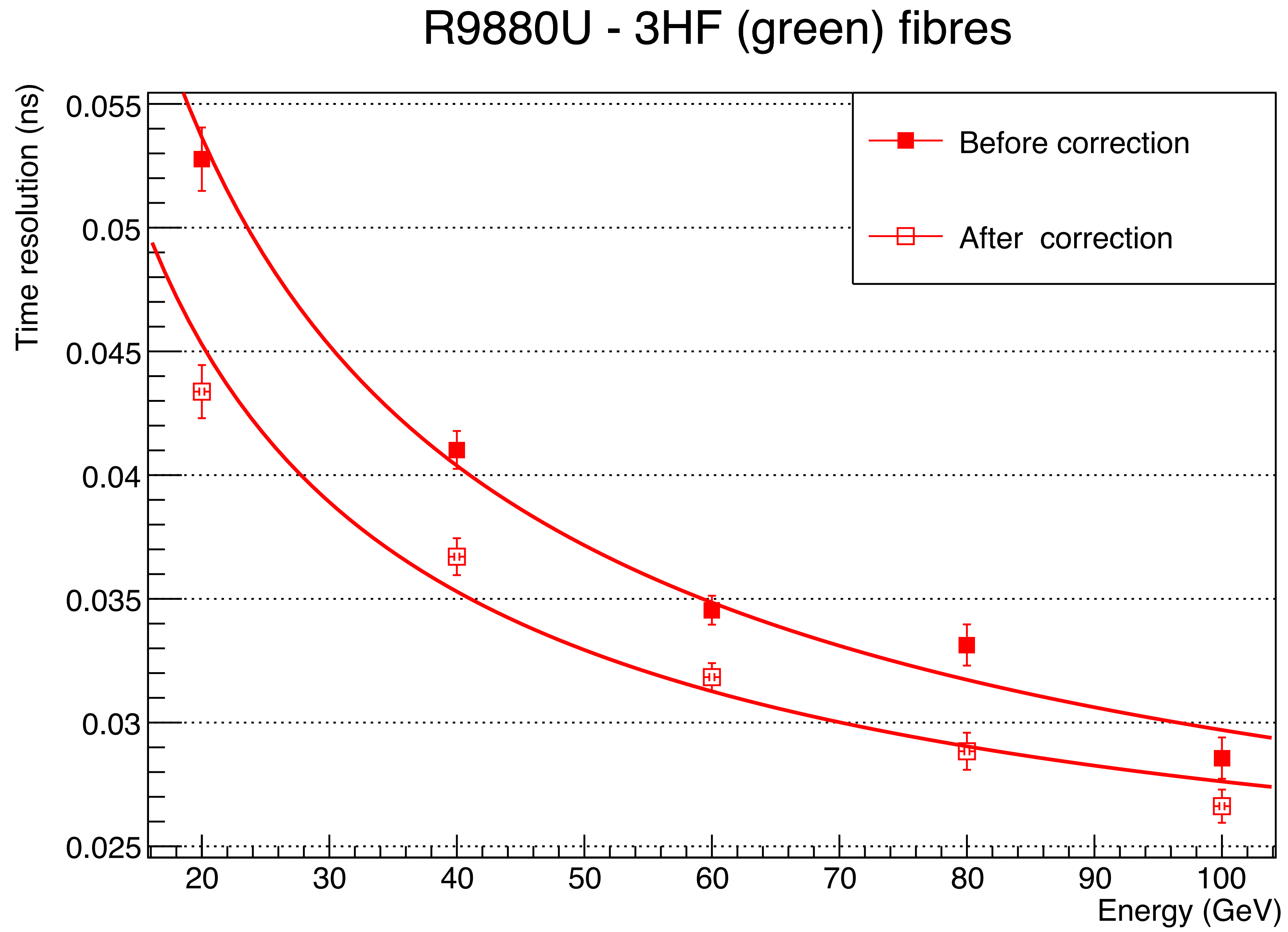


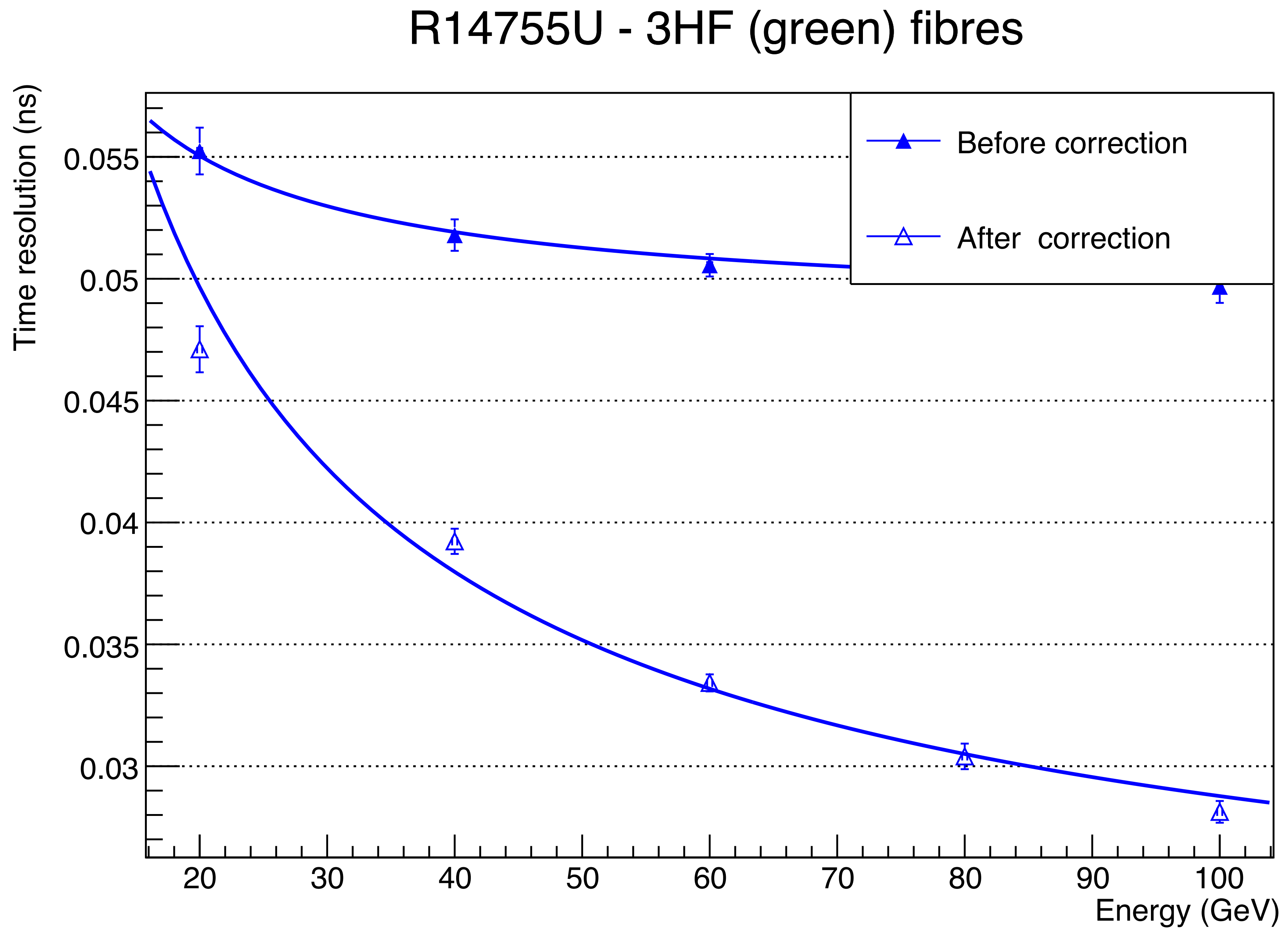


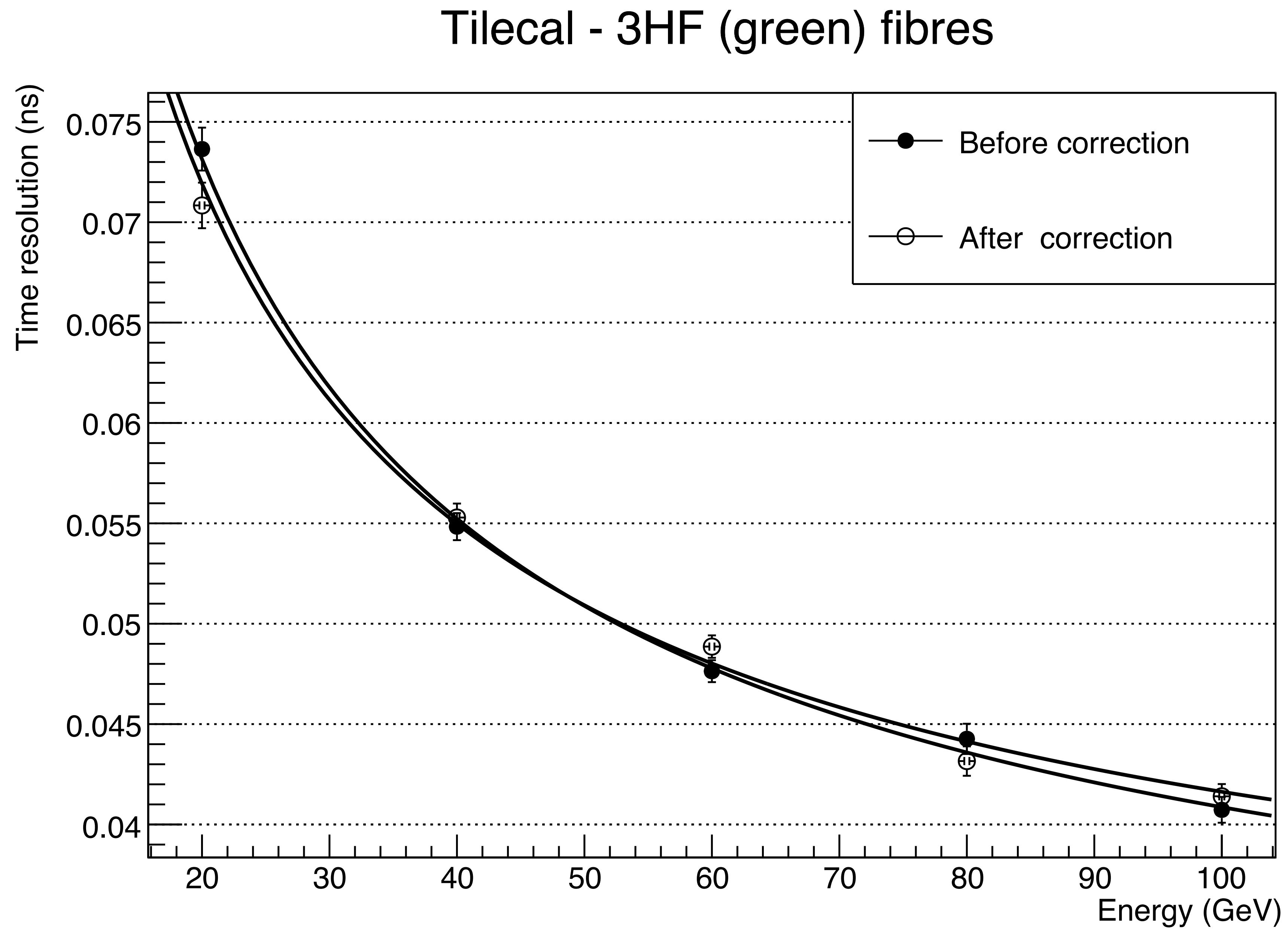


Corrected resolution - Small module with 3HF fibres



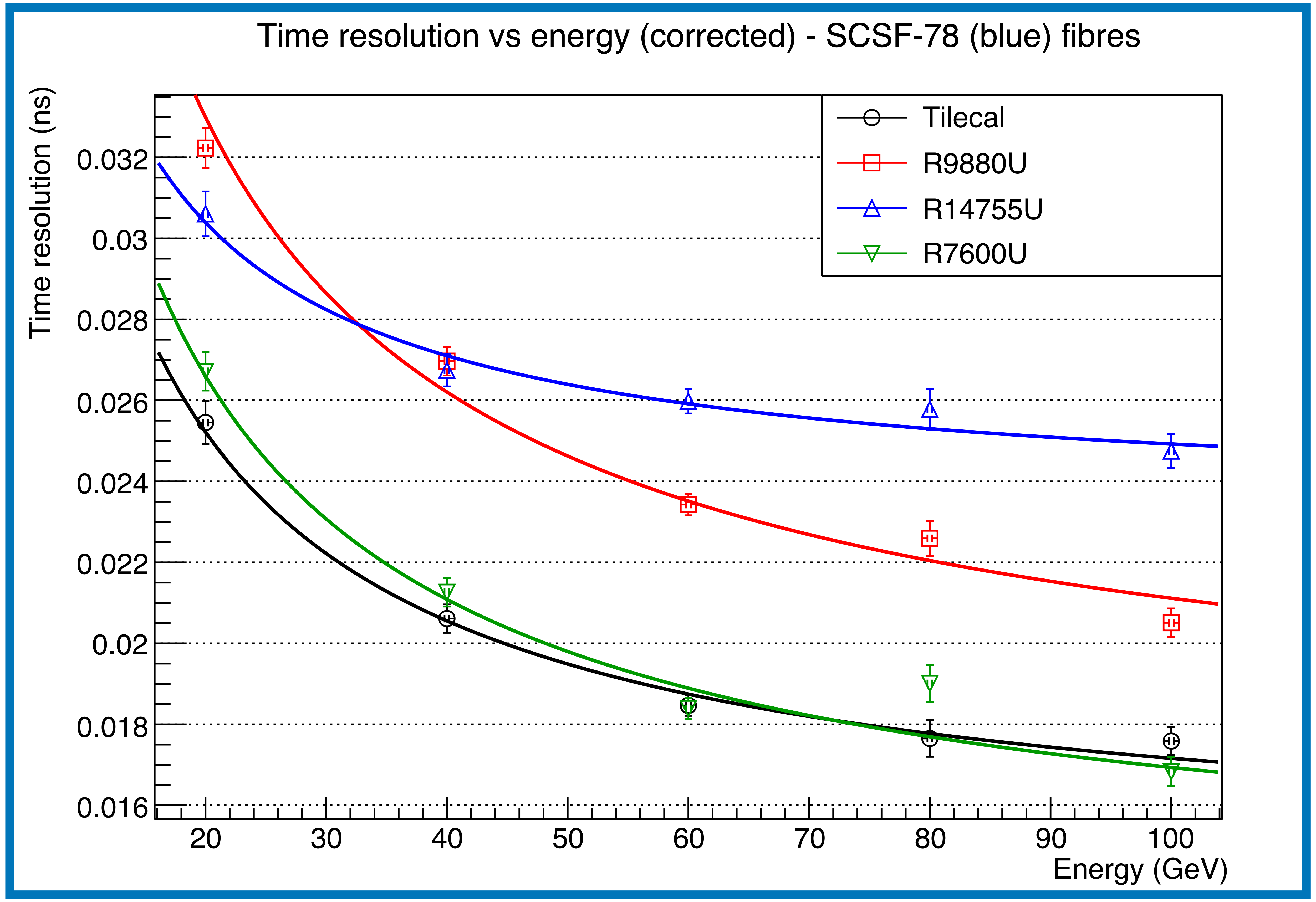


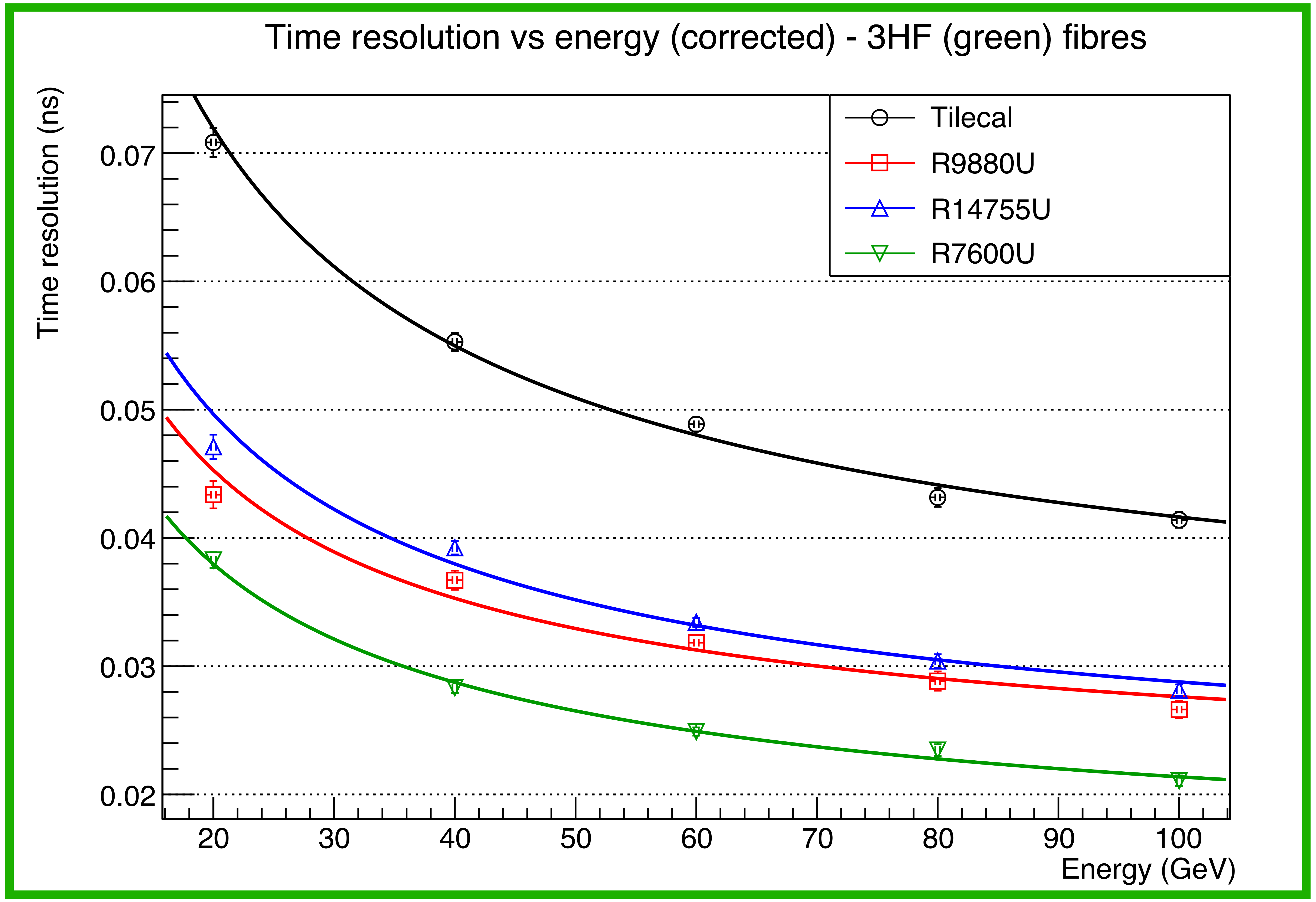




Corrected resolution - Small module

$$\sigma_T(E) = \frac{sampl.}{\sqrt{E}} \oplus const.$$





- 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%

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Conclusions

- 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

- Resolutions below 20 ps obtained at high energies with testbeam data

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

Conclusions

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- Resolutions below 20 ps obtained at high energies with testbeam data

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

Is there a better way to define the time stamps?

Thank you for your attention

PicoCal

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International Master
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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

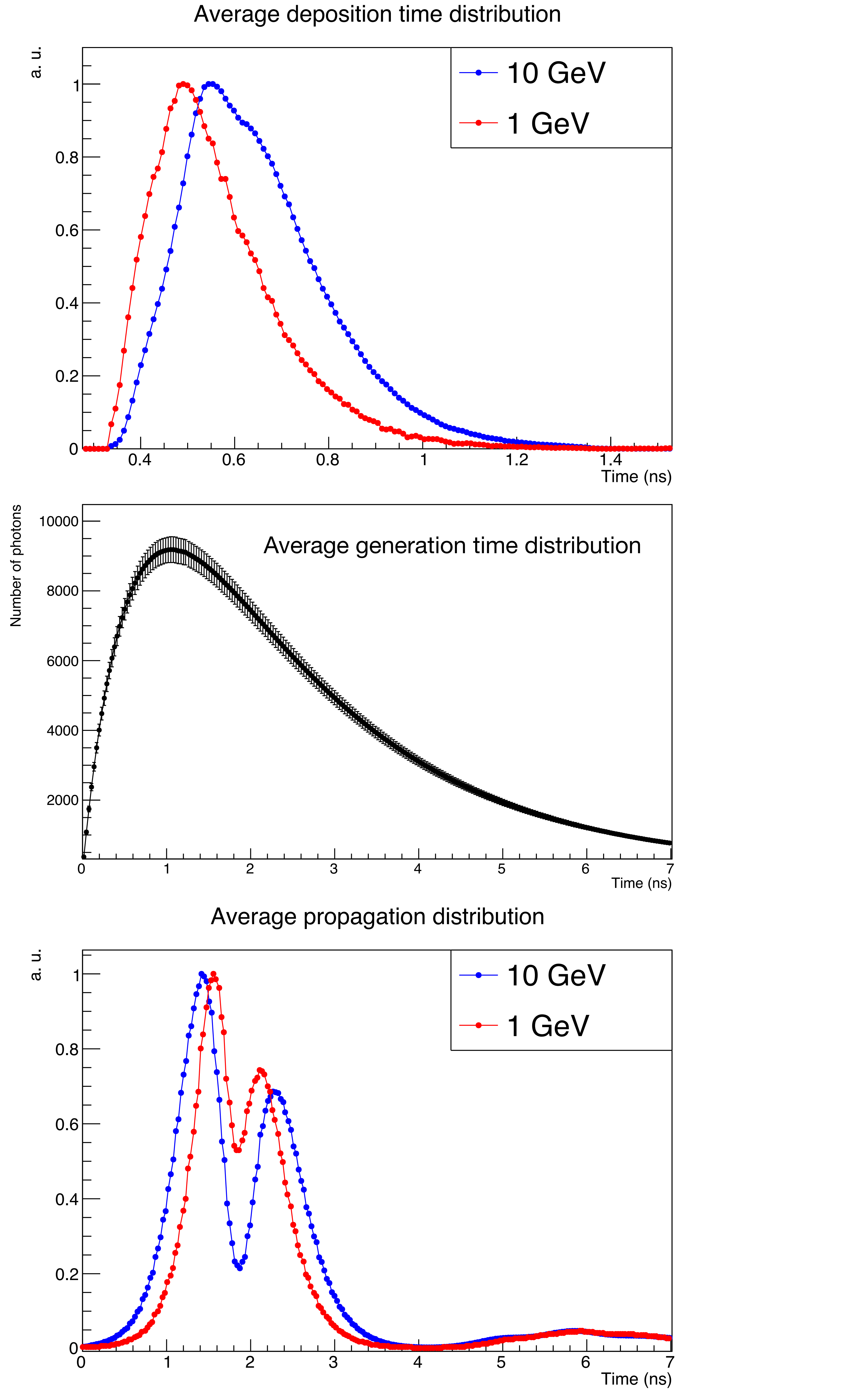
Simulation of the photons

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)



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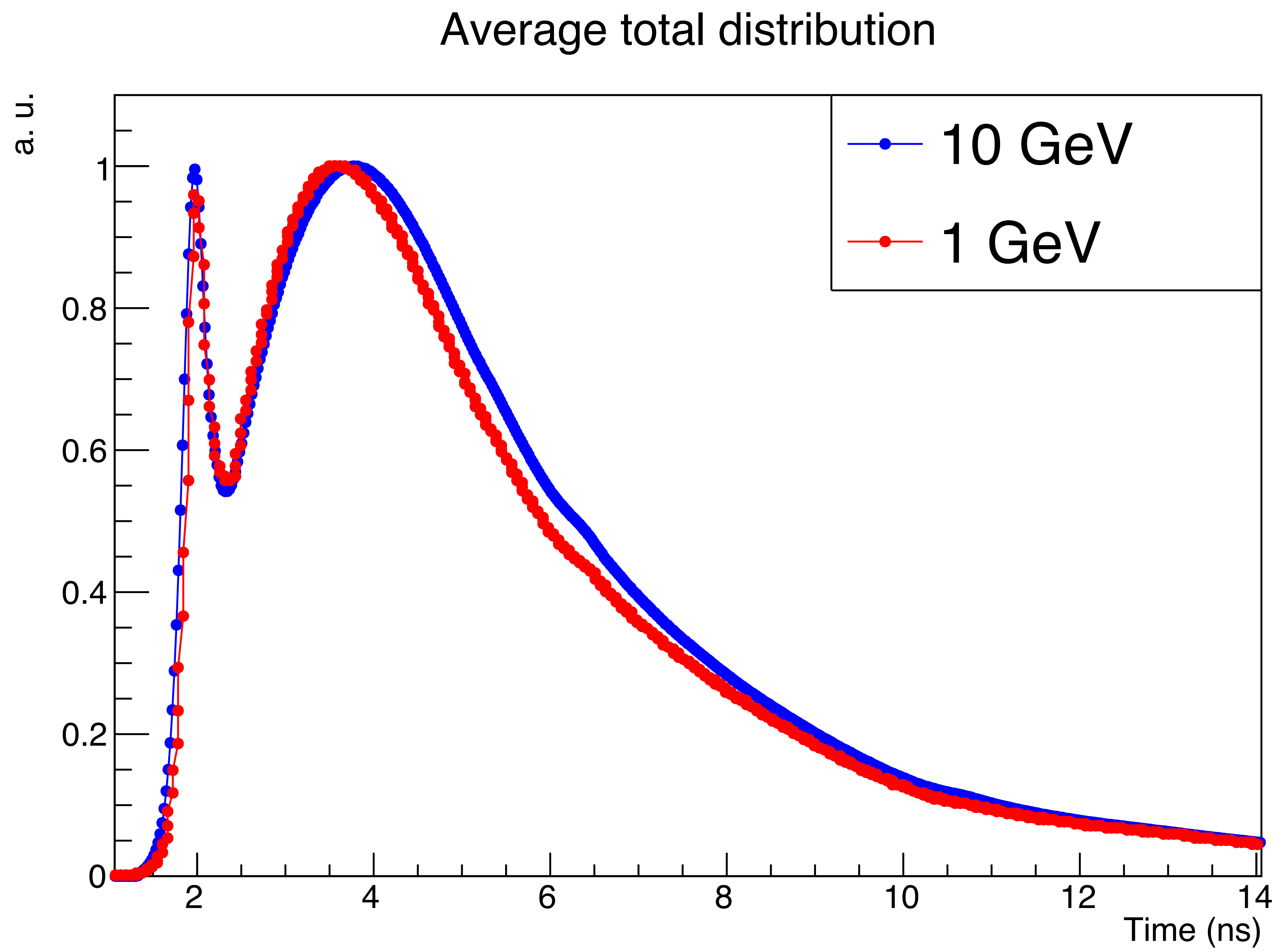
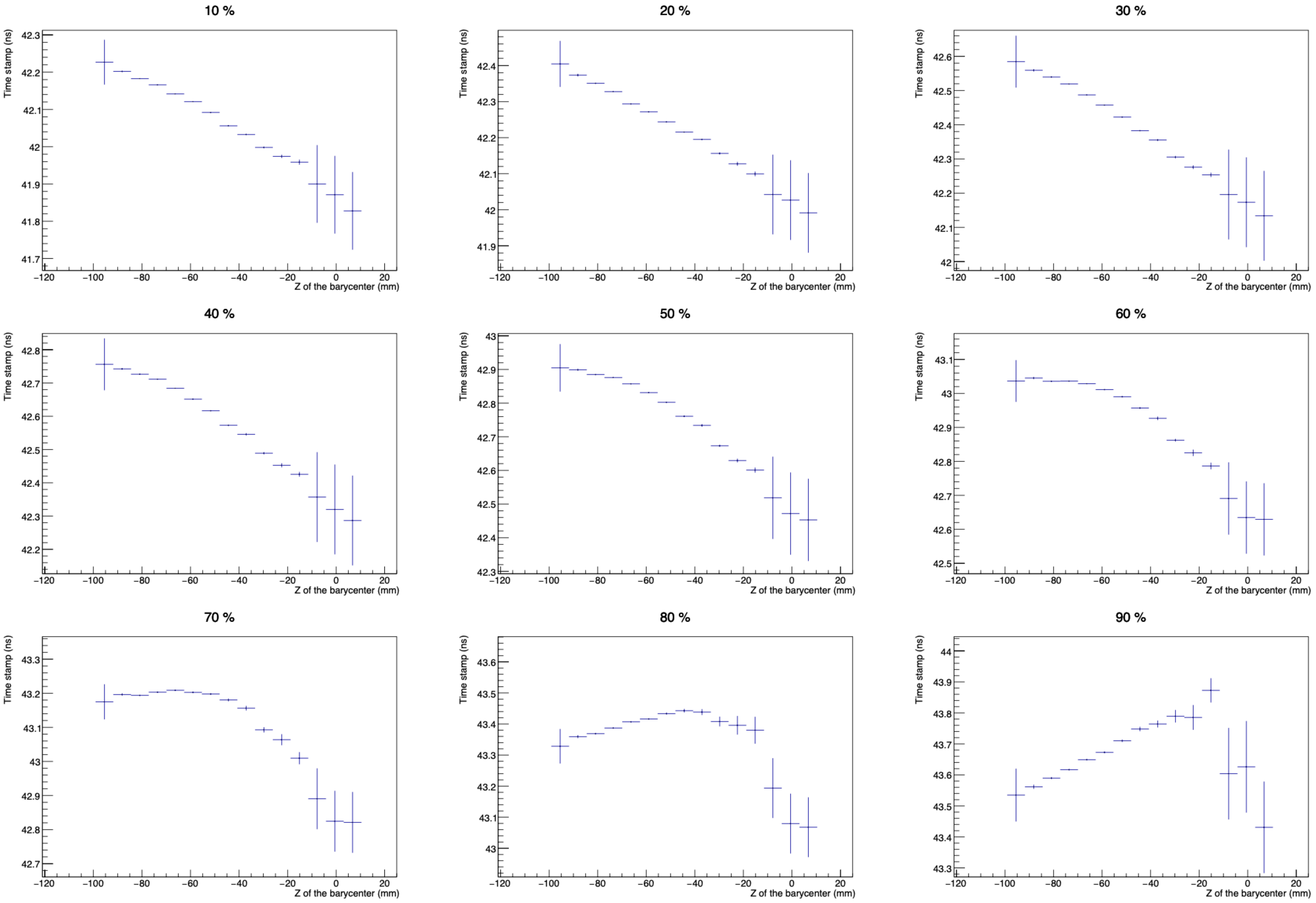
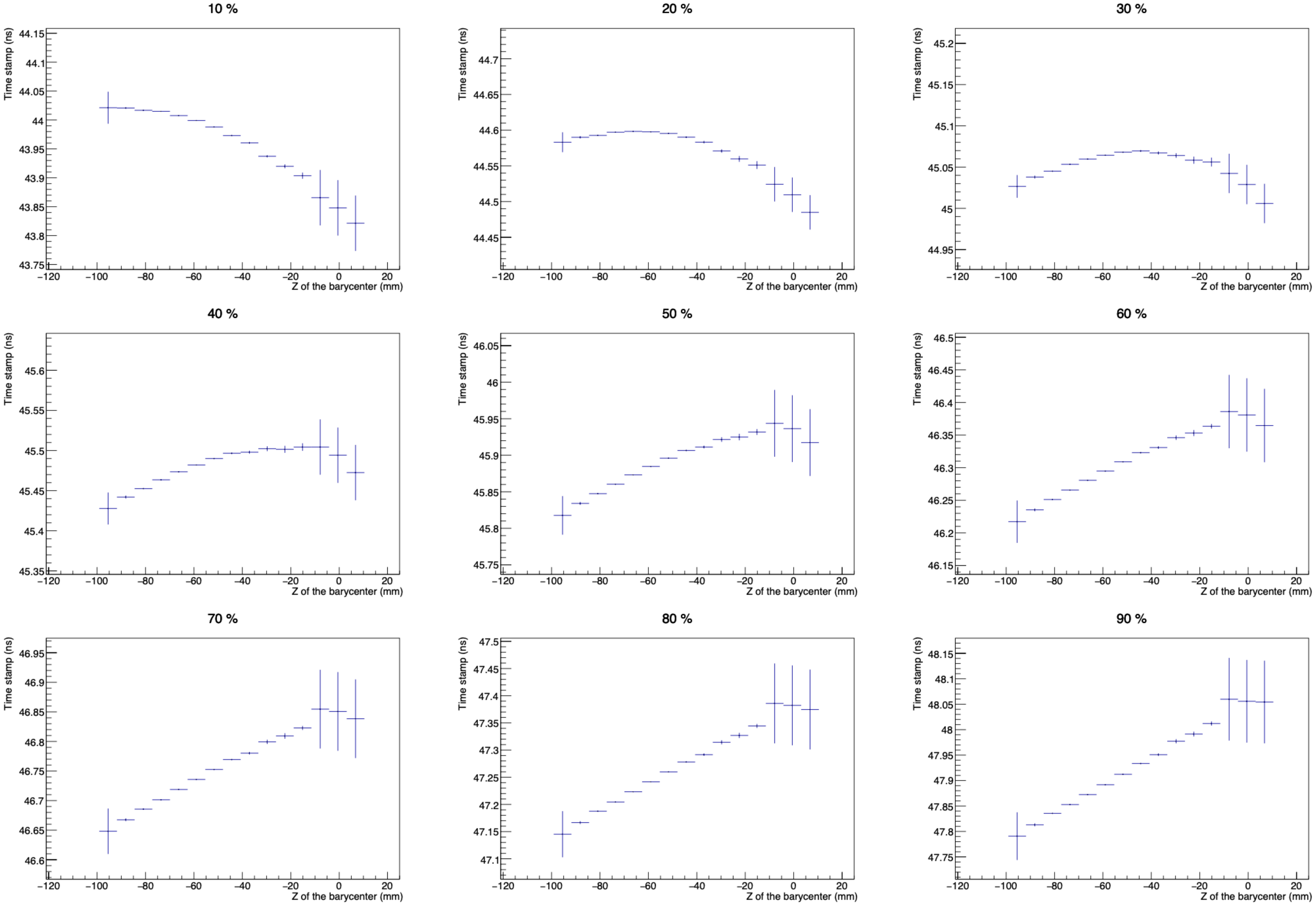


Tau = 0.1 ns
(FWHM = 0.35 ns)

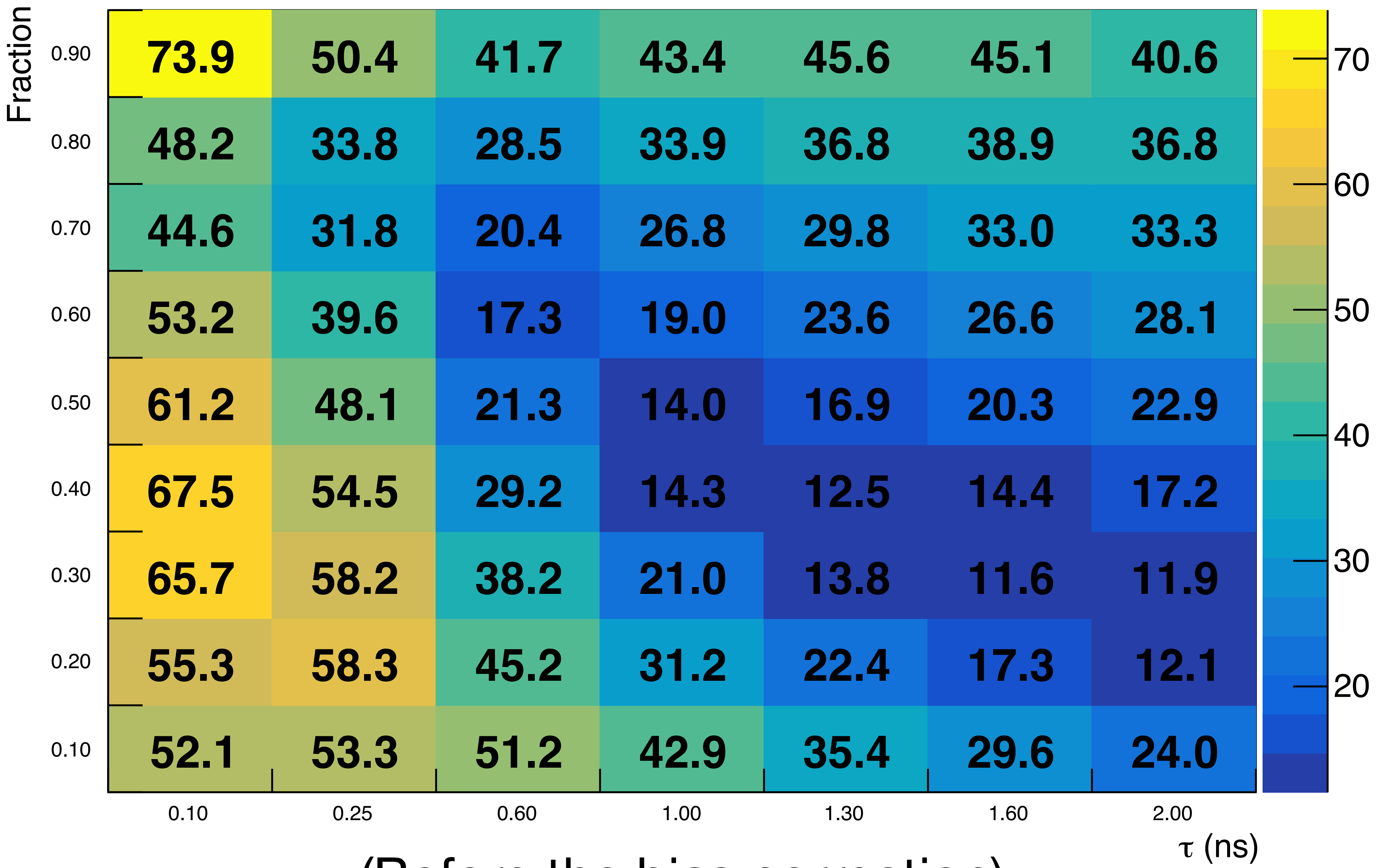


Tau = 2.0 ns
(FWHM = 7 ns)



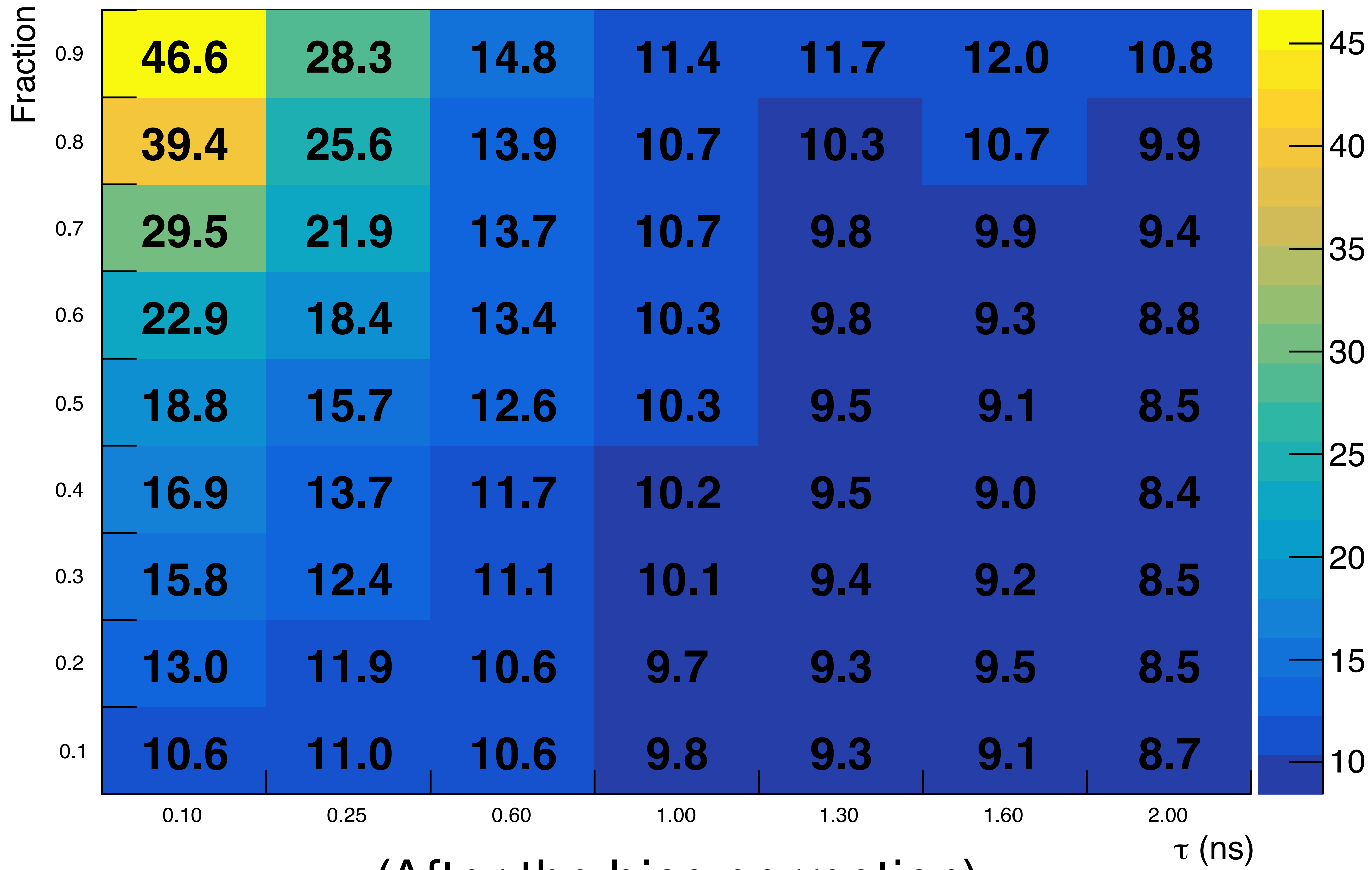
Some results (10 GeV)

Resolution (ps)



(Before the bias correction)

Corrected resolution (ps)



(After the bias correction)

- **Slow PMTs give a better resolution**
- This effect is caused by the double peak of the propagation time distribution

Time resolution model

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

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

- 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

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

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