List of changes

Reviewer #1: The article "Timing performance of a micro-channel-plate photomultiplier tube" shows sound measurements of the timing performance of MCP-PMTs, if MIPs traversing the detector window. It is shown that the performance at the MCP-PMT edge is worse, mainly due to bad Cherenkov photon collection. The experimental data is presented in a compelling way and theoretical considerations are given to explain the measurements. Personally I like the analytical model and would extend it to account for multiple reflections, keeping only one fit parameter. The Monte-Carlo simulation seems to be over-fitted and a reduction of the free parameters would be good. In the introduction I suggest to include a bit more the work of other groups. Many people are using MCP-PMTs as reference detector and have studied the performance, there are as well other options for fast reference detectors.

Please consider additional comments below before publication.

Line number:

12: It could be good to mention other work achieving time resolution about 10ps, e.g. with scintillator based detectors. An example is: A. Benaglia, et.al "Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout", NIM A, 830 (2016) 30-35. There is as well the work of R. Ota, et.al "Coincidence time resolution of 30 ps FWHM using a pair of Cherenkov-radiator-integrated MCP-PMTs", Phys. Med. Biol. 64 07LT01.

> *Included the references: "There are different types of reference timing detectors providing less than 10 ps time resolution. One possible option are silicon based detectors like SiPMs that have shown a timing performance in the demanded range [3]. An other available detector technology with good timing response are MCP-PMTs. Those detectors are commonly used in various fields. One example is the use for a time-of-flight positron emission tomography (PET). Other studies have shown a coincidence time resolution (CTR) of 30ps FWHM [4]. In this work, two MCP-PMTs of type Hamamatsu R3809U-50 Micro-Channel-Plate Photomultiplier Tubes (MCP-PMT) [5] have been studied for the beam test measurement of the PICOSEC-Micromegas."*

18: "usable", typo

> *Changed to useable*

26: This statement is mathematically not true. The reference time resolution has not necessarily to be better than the detector resolution under study. If a very stable precision measurement is done, the deconvolution would work perfectly. But in view of experimental complications, especially in a beam test environment, it is indeed better to have a better reference time resolution, that's correct.

> *Changed to: "[…] it is advantageous for beam measurements to use a reference detector with time resolution significantly better than that expected for the detector under study."*

Figure 1 and Figure 2: In a black and white print these colors cannot be distinguished. As well, think about people who are color-blind.

Hatching of the figures included

57: Review this sentence, to me it does not read very nicely.

Changed to: “Figure 2 shows the schematic overlap of the photocathode with the Cherenkov light. In this example, [...]”

65: Reflexion is not really commonly used. I would suggest to write "reflection" in order to be consistent with the use of American-English (e.g. color).

Changed to: reflection

69: What is the angle of Cherenkov emssion, the cone angle? What is the angle of total internal reflection in the fused silica radiatior? What is the refractive index (n) of the fused silica window? And maybe more difficult to determine, what is the angle of total internal reflection of light created in the window going back from the photocathode. If you know all of these parameters you can as well express the reflection probabilities (Fresnel or total internal reflection). These numbers could be compared with the fit parameters obtained later on, or even better be the input for the Monte Carlos simulation.

Your comment addresses a difficulty we faced in our project: Unfortunately, we did not receive these specifications from the supplier. There is a wide range of material that can be described as fused silica, all with different n.

Changed lines 16-20 to:
“The radiator consists of a 3.2 mm thick synthetic
silica window that is integrated in the MCP-PMT. The useable
photocathode diameter is 11 mm as indicated. No further infor-
mation about the photocathode and the window is given by the
manufacturer. For the further simulation a generic Cherenkov
angle of 45 ◦ is assumed.”

Equation 1: I suggest to write direct or reflected light instead of blue and red.
Changed as suggested

Section 2.2: Please explain more in detail what is your simulation framework and what is exactly simulated an how. Then I am not sure if the title is a good one. I understood the the MC is a generalization of Equation 1 with multiple reflections. If so, I would say this in the title. In any case it is not an MC simulation but more an MC guided fitting of the data.

Reformulation of section 2.2.

85: I am quite sure that the fused silica radiator is not a crystal, as you call it later on at line 95.
Changed to: fused silica radiator

86: Photons have been randomly generated. In which direction? What was the wavelength? What were the refractive indices involved? Is all of this modeled? In which program?

Reformulation of section 2.2.

102: typo "absorbtion"

Changed to: absorption

Equation 2: Did you measure the SPTR? That would be an interesting measurement and would be important to fix or check the model parameters.

We were not able to perform a proper single photoelectron measurement. This is why we decided to substituted it with the scaling factor in Eq. 3. and we set A to the time resolution in the center.

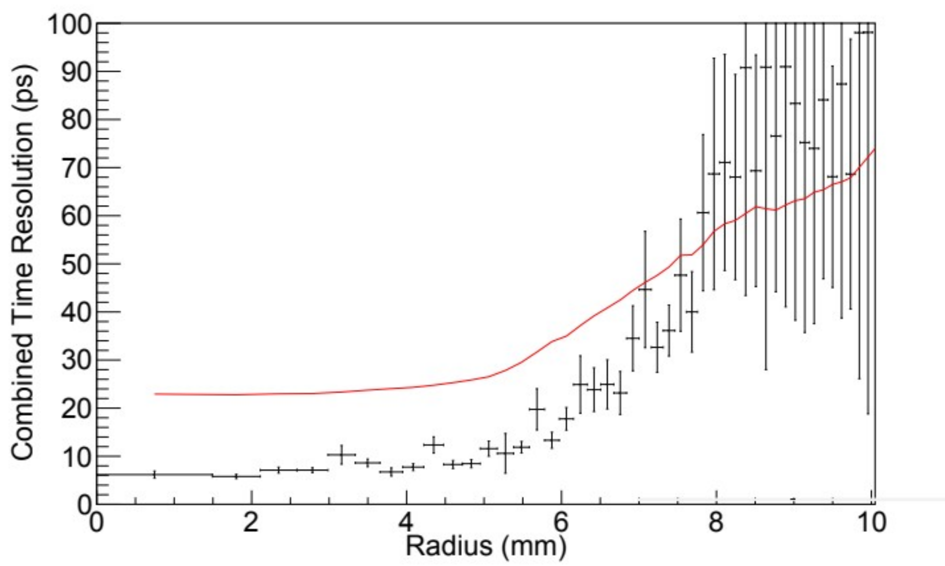
111: "We generalize this relation in the simulation ..." I do not understand this sentence, what do you mean? Can you explain this a bit more in detail?

Changed to: " This relation has been shown to be valid for MCP-PMTs, albeit without considering the spatial dependence [8]. This relation will be extended by including, spatially resolved, absorption and reflection of the Cherenkov photons at the air-radiator interface and at the photocathode."

Equation 3: To me this equation seems weird. Should the first term not be: sigma_MCP1^2*(N0/N). Thinking that the time resolution in the center is sigma_MCP1, where all N photons are detected. On the edge only N0 photons are detected, which then gives the ratio in the equation. Similar for the second term. Besides, I do not think you can just add these two terms like that. There are surely cross-correlations, which have been omitted.

This is the equation to calculate the squared time resolution of one MCP-PMT with the simulated number of photons reaching the photocathode. N0 means photons with 0 reflections and N1 are photons after one reflection circle (reflection on photocathode, reflection on air-interface, no reflection or absorbtion on photocathode). In the center of the photocathode N0→N and N1→0. The time resolution for each mcp is then calculated by sqrt((N0/N)^2(A/N0)+(N1/N)^2*(B/N1)). The combined time resolution is calculated by sqrt(sigma_mcp1^2+sigma_mcp2^2+sigma_daq^2). Please find attached the simulation with sigma_mcp1^2=(N0/N)*(A/N0)+(N1/N)*(B/N1).*

Both terms are certainly correlated. 1. they use the same N and 2. B is defined by A. While sigma_mcp1 and sigma_mcp2 are treated as two separate detectors with aligned center to each other. This means that the charge distribution is similar to both but the simulation is done separately.



Equation 4: delta_sigma should depend on N1. But what does this parameter really mean?

The radial distribution of N1 and N0 are depending on the optical properties of the window (in our case the values presented in 4.1.). delta_sigma can be interpreted as the additional jitter the reflected photons contribute to the time resolution of the detector. It is not the time delay the reflected photons arrive later at the photocathode but the additional spread these photons are giving to the signal waveform (as the rising edge of the detector signal is longer than the time delay of the reflected photons). This spread is related to the time delay of the photons and thus depending on the optical properties of the window material. By this way N0, N1 and delta_sigma are all correlated with the refractive index of the window and the reflection interfaces.

165: Please describe in one sentence how this CFD was done offline.

Inserted: "The rising edge of each signal has been fitted with a generalized logistic function and the time value for 40 % of the amplitude has been calculated for the CFD analysis."

180: Does this power divider change the signal amplitude or slope?

No, a 18 GHz power divider has been used and we could not observe any change of the signal

216: Here w is 8%. This seems reasonable. Nevertheless, one should check with the TIR and Cherenkov cone angles. That could be subject for a discussion.

We strongly agree in this point. However, such a discussion would in our view go beyond the scope of this publication. For that reason, we included in lines 229-231: "More refined models with precise knowledge on the MCP-PMT materials and including signal formation processes might yield different results."

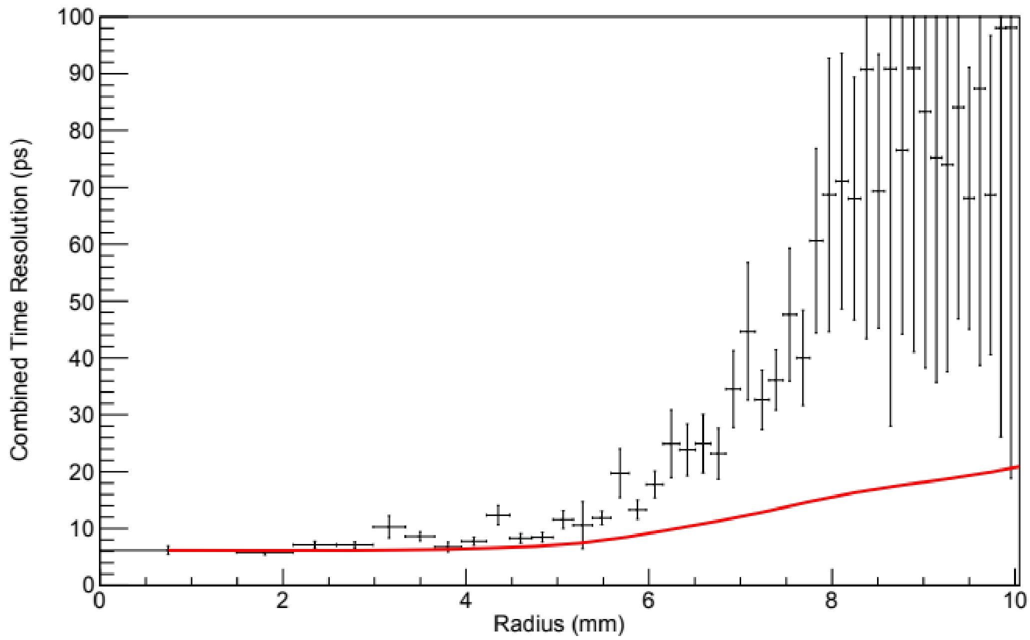
220 ff: Here the parameters seem to be very different. Which is a bit disturbing. Do these parameters reflect a physical meaning. That is easy to check with simple back on the envelope calculations. Subject for discussion? This would be interesting for the understanding, because it is clear that the fits in Figure 3 get much better with 3 open parameters instead of only one. Although, all these 3 parameters would actually be defined by the material properties, hence, not really subject to a fit.

1. We agree that a comparison to material information would be beneficial, but the company was not willing to provide those information.
2. To reach a first order reflection a photon has to: Get reflected at the photocathode (0.2), then get reflected at the air-radiator interface (0.8) and not get reflected again at the photocathode nor get absorbed (1-0.2-0.4).
*=> 0.2*0.8*(1-0.2-0.4)=0.064 which is not far off from 0.08.*

I would suggest to try an extended analytical model, taking into account multiple reflections with only one parameter w.

Figure 5: Out of curiosity, can you plot as well the relation sigma_mcp(r=0)*sqrt(normalized mean charge of figure 3)? Just to compare this really simple relation to the complex equation with the additional time jitter of 7.5ps.

See attached plot in this document


Combined Time Resolution (ps)
Radius (mm)
0
2
4
6
8
10
10
20
30
40
50
60
70
80
90
100