Simulation and R&D studies for the muon spectrometer at a 10 TeV Muon Collider

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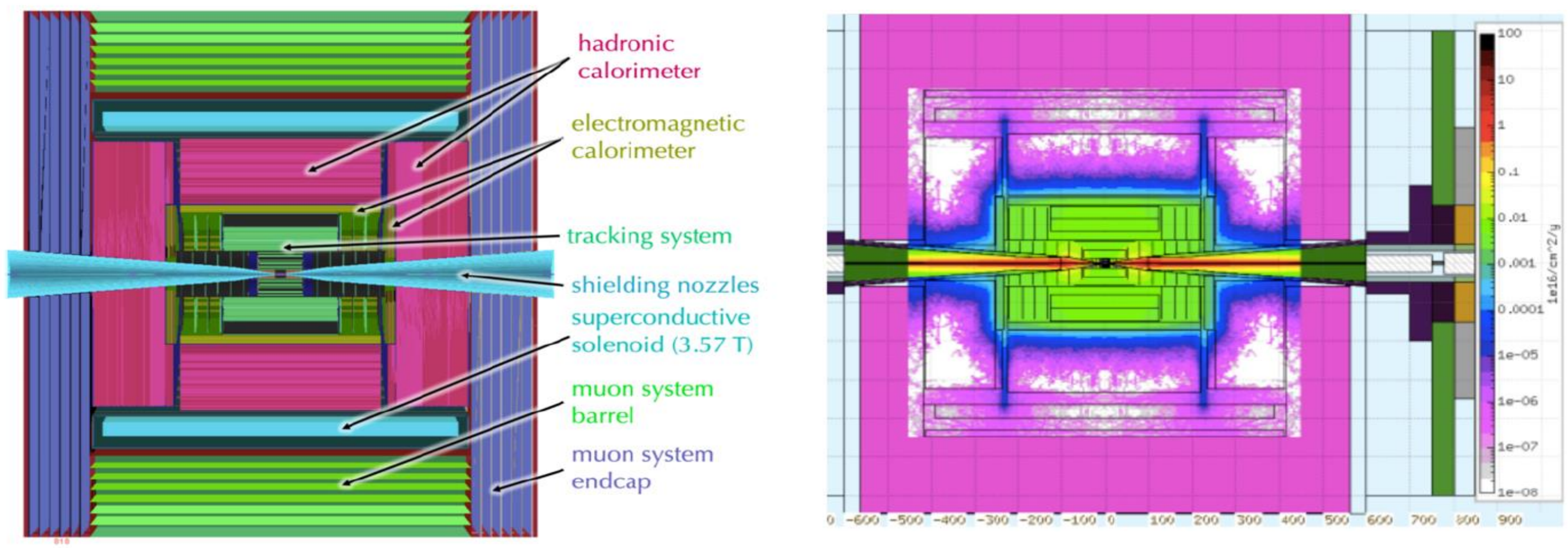

Fig. 1. Left: *initial design of the Muon Collider experiment detector. [1]* Right: *map of the 1meV-neq fluence in the detector region, shown as a function of the position along the beam axis and the radius, normalized to 1 year of operation and a collision rate of 100kHz. [2]*

Muon Collider and Beam Induced Background:

The Muon Collider is one of the most promising machines in terms of discovery potential, as it combines the advantages of both electron and hadron colliders. However, there are several challenges in its development, such as the short lifetime of muons. Muons are unstable, which leads to the so-called Beam-Induced Background (BIB). BIB consists of particles produced directly by the decay of muons and indirectly by their interaction with the detector materials.

The initial detector design is shown in Figure 1. Figure 2 is a map of the BIB fluence in the detector region, indicating that the tracking system is the most affected part of the detector, while the outermost region, which houses the muon system, is the least affected. The expected hit rate in the muon system's region closest to the beam line is ~10^4 Hz/cm^2

New muon reconstruction approach:

To cope with the high background, a new "out-to-in" reconstruction approach is being developed. In this method, muon tracks will first be reconstructed in the muon system, and then the tracks will be propagated back to the tracker. This significantly reduces the combinatorial background from the BIB. To achieve this, a fast timing detector in the muon system is necessary, with a time resolution comparable to that of the tracker (on the order of tens of picoseconds). The muon system design under test and the new approach are schematized in Figure 2. The idea is to use a new MultiPattern Gaseous Detector (MPGD) with high performance in terms of time resolution, called Picosec, as a timing layer in the first layer of the muon system endcap. Following this, there will be six layers of other tracking MPGDs with better spatial resolution, such as the Triple Gas Electron Multiplier (Triple-GEM).

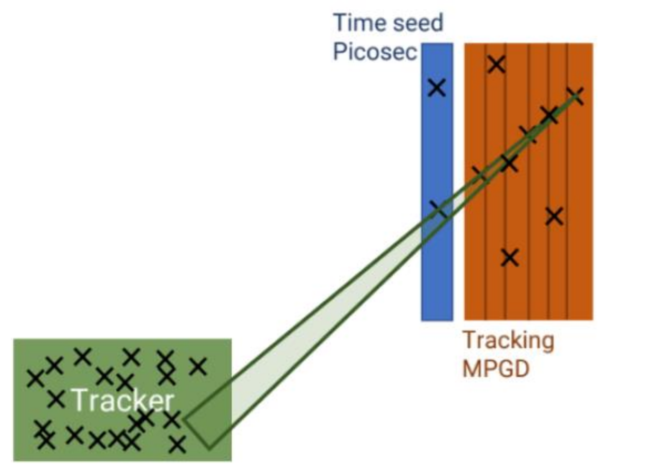

Fig. 2. *Schematization of the out-to-in approach for the proposed muon system. [3]*

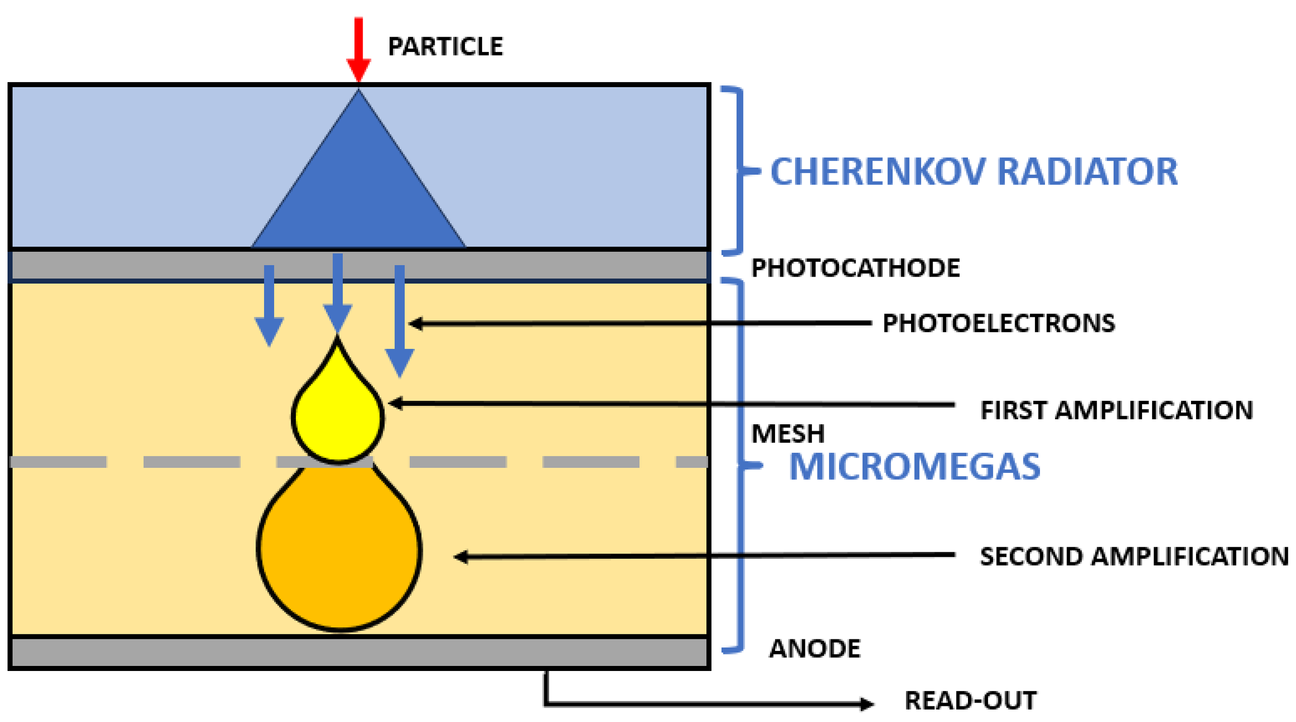

Fig. 3. *Particle detection with Picosec: the incoming radiation emits Cherenkov light prompt in the radiator. Then, the photocathode converts part of the γ produced above in electrons that undergo two stages of avalanche amplification. The resulting signal is induced on the anode. [4]*

Picosec as a new fast-timing MPGD:

Picosec is a new fast-timing MPGD based on the MICro MEsh GAseous Structure (MICROMEGAS) developed by the Picosec Micromegas Collaboration. The most significant limitation of the time resolution achievable by a standard MPGD is due to the fluctuation of the ionization position along the drift gap. Picosec achieves extraordinary performance in time resolution by exploiting the Cherenkov effect and a two-stage amplification process. In the upper part of the detector, there is a radiator where charged particles produce Cherenkov light. These photons are then converted into electrons by a photocathode. The drift gap is reduced to a size of ~100 micrometers instead of a few millimeters. This setup allows the charges produced to be amplified twice, initiating the avalanche as soon as possible, thus improving the time resolution to tens of picoseconds. Figure 3 shows a schematic view of the detector and of the detecting process.

R&D aimed at Picosec optimization:

Since Picosec technology is new, fundamental R&D work aimed at its optimization is needed to make it suitable for experiments at future colliders like the Muon Collider. The components analyzed here are the photocathode, the gas mixture, and the radiator.

Regarding the photocathode, the standard material is cesium iodide (CsI), which is very efficient at converting photons. However, its principal drawback is its durability, as CsI is hygroscopic and severely affected by ion backflow. Alternatives such as Diamond-Like Carbon (DLC) and Boron Carbide (B_4C) are being considered. The results, shown in Figure 4, indicate that DLC could be a good candidate for a robust photocathode.

The standard gas mixture, inherited from the COMPASS experiment, consists of neon (Ne), ethane (C_2H_6), and CF_4 in an 80/10/10 ratio. This mixture is very expensive and has a high Global Warming Potential (GWP) of approximately 740. New mixtures composed of Ne and isobutane (iC_4H_{10}), with a GWP lower than 1, are being tested as replacements. Results shown in Figure 5 suggest that a mixture of 94% Ne and 6% isobutane could be a viable alternative.

Regarding the radiator, the standard material is magnesium fluoride (MgF_2), which is expensive and difficult to produce in large areas. Quartz has been tested as a potential alternative. The results, shown in Figure 6, suggest that the standard MgF_2 remains preferable over the tested quartz. Figure 6 shows the preliminary results from the latest test beam conducted in April 2024. The focus of these tests was the gas mixture, and the plots display interesting results obtained with different concentrations of Ne and isobutane. However, these results need to be validated, and further tests are required to determine the precise concentration of the mixture inside the detector.

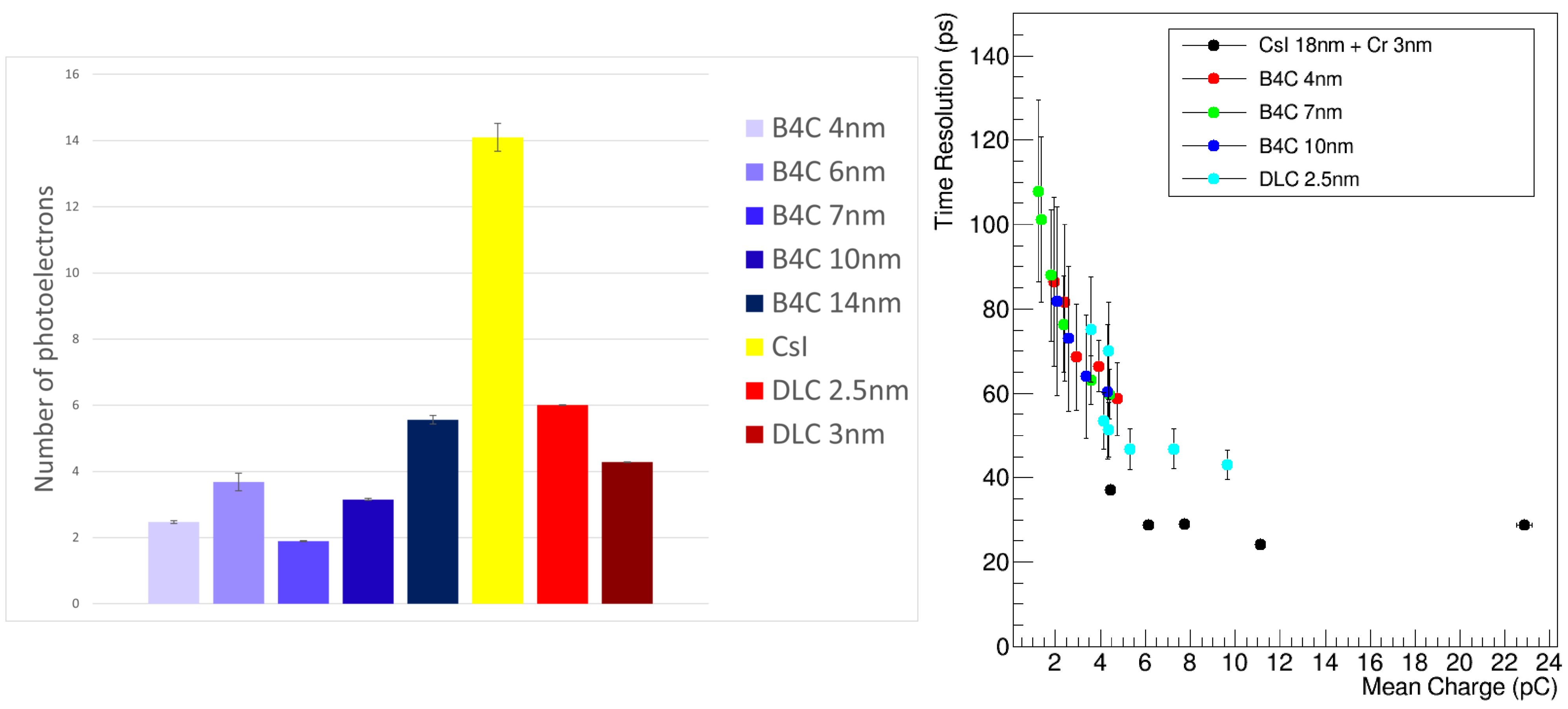

Fig. 4. Left*: comparison of the experimental results obtained by the tested photocathodes concerning the mean number of photoelectrons emitted per MIP. [3]* Right*: comparison between the photocathodes' performance in terms of time resolution as a function of signal mean charge. The gas mixture used is the standard one and the Micromegas was resistive (380 kΩ). [3]*

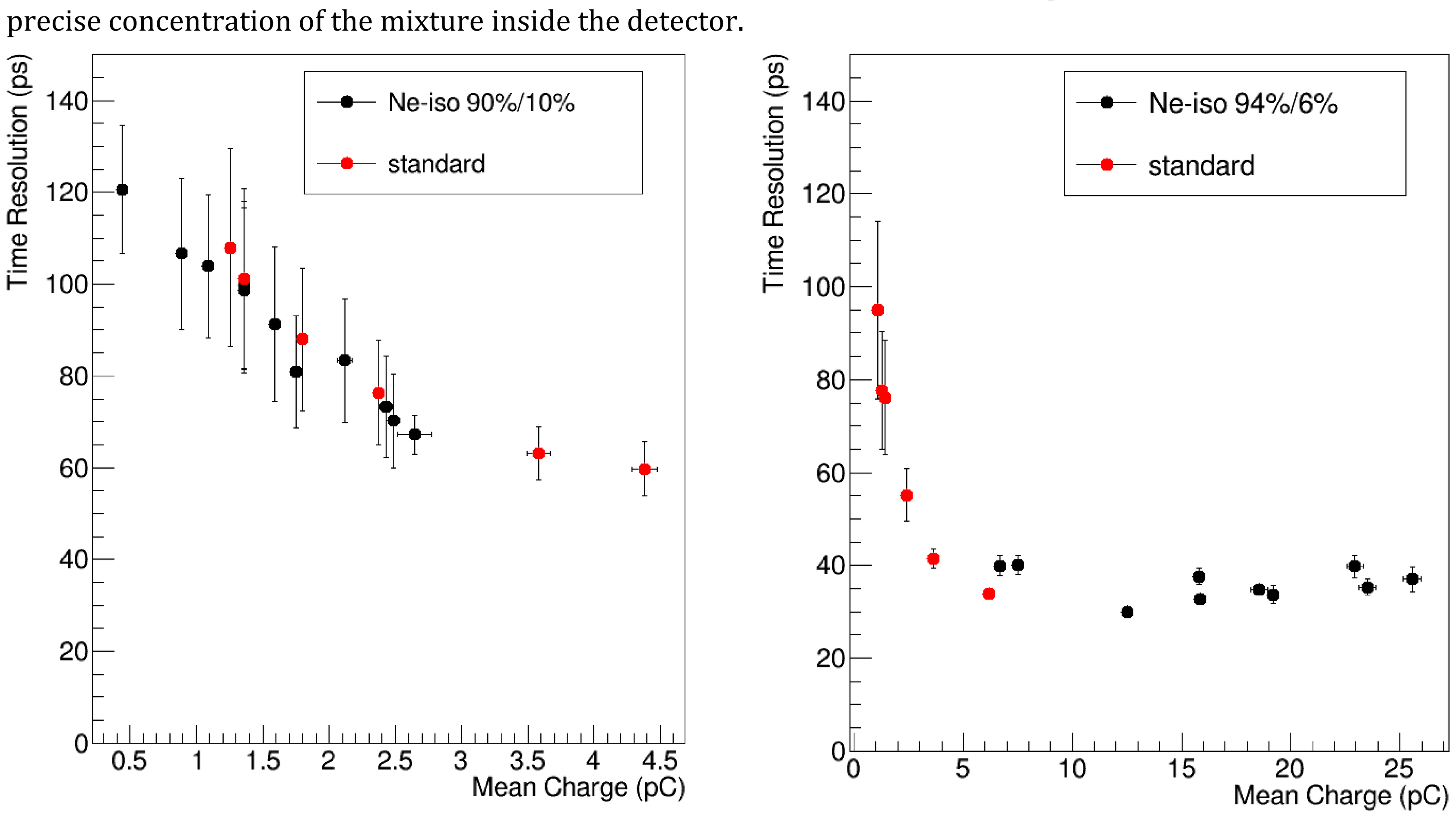

Fig. 5. Left: *comparison between the standard mixture and the Ne/iC_4H_{10} 90%/10% one in terms of time resolution as a function of the signal charge. The photocathode used was the B4C 7 nm thick. The Micromegas used was resistive (380 kΩ). [3]* Right: *Comparison between the standard mixture and the Ne/iC4H10 94%/6% one in terms of time resolution as a function of the signal charge. The photocathode used was the CsI 18 nm thick with a 3 nm chromium layer. The Micromegas used was resistive (82 MΩ). [3]*

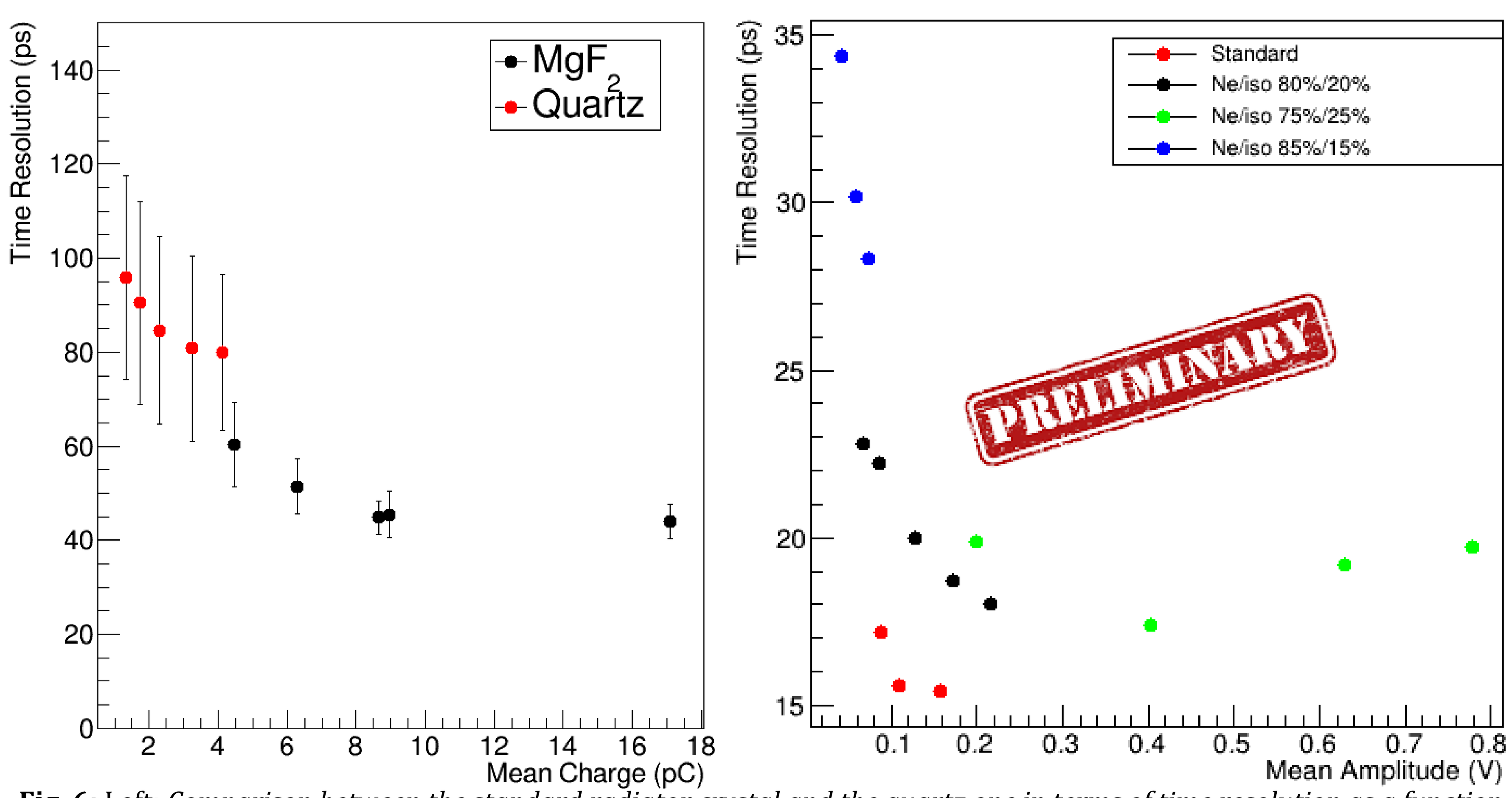

Fig. 6: Left: *Comparison between the standard radiator crystal and the quartz one in terms of time resolution as a function of the signal charge. The photocathode used was the CsI 18 nm thick with a 3 nm chromium layer. [3]* Right: *comparison between the standard mixture and the Ne/iC_4H_{10} mixtures with different ratios in terms of time resolution as a function of the amplitude of the signal. The photocathode used was CsI, and the Micromegas was non-resistive. Errors contained in the markers. Results are preliminary.*

Conclusion and future perspectives:

For the future, the R&D work will mainly focus on two aspects: the gas mixture and the scalability of the technology. The first is crucial as regulations for high greenhouse gases are becoming increasingly strict, making their supply more difficult. Thus, a good alternative mixture with a lower Global Warming Potential (GWP) is needed. Scalability is essential for the application of this technology in large experiments, which is challenging since it is difficult to create a large-area detector while maintaining the necessary planarity for proper functionality.

In conclusion, Picosec is a fast-timing MPGD capable of achieving excellent performance in terms of time resolution, making it suitable for future experiments such as those at the Muon Collider. Further R&D is required to enhance the robustness of this technology and reduce the environmental impact of the gas mixture. However, interesting and encouraging results have already been obtained. Moreover, Picosec could represent a turning point in track reconstruction in the presence of high BIB, as its time resolution is sufficient to function as a timing layer for background rejection using an out-to-in reconstruction approach.

Bibliography:

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