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LEMMA-TB: an experiment to measure the production of a low emittance muon beam

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Introduction

Colliding muon beams at high energies represent a fascinating opportunity to probe the microscopic scale beyond the current reach of the LHC. Such beams could originate as tertiary products of a high intensity proton beam impinging on a target or, alternatively, exploiting very asymmetric collisions between positrons and electrons yielding directly muon pairs. The former production scheme requires a very effective phase-space cooling; a dedicated R&D program has been carried out addressing this issue both in the US and by the MICE collaboration [2] [3]. The latter scheme, also known as LEMMA (Low Emittance MuonS Accelerator [1]), grants instead prompt muons with long lifetime, which gather into a beam with a very small emittance and thus ready to be further accelerated. In order to achieve that, a high brightness positron beam needs to be shot

*The member of CERN personnel having contributed to the study, does not take position nor responsibility towards the required approval processes, as established by the organization onto a target, producing collisions with the electrons of the target's material at a center of mass energy only slightly above twice the mass of the muon; this corresponds to a positrons energy of about 45 GeV.

Although studies can be performed on data generated by simulation programs, it is of paramount importance to accurately measure all the key parameters of this process, in particular the emittance of the emerging muon beams, the differential cross section of the production process and the properties of the spent positron beam. No experimental data is available in the literature concerning those aspects. The CERN North Area is the only facility in the world that currently can provide a 45 GeV positron beam in a controlled, flexible and spacey environment; even though the delivered intensity is far from what required for a muon collider, with the slow extraction of 4.8 seconds an event-by-event reconstruction can be performed, allowing a thorough study of the production process.

Beam tests have been conducted with limited resources and for short periods in 2017 and 2018 (one week at the time). On the basis of the experience gathered then, a dedicated experiment, LEMMA-TB, has been designed to achieve the aforementioned physics goals.

The experimental setup and a possible solution for its deployment along the H4 line are described in this proposal, which seeks the recommendation of the SPS and PS Experiments Committee. In the following the expected results and the strategy to obtain them will be discussed.

Physics program

A precise measurement of the $\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-$ cross section in the proximity of the production threshold has never been performed: at that energy the Sommerfield-Schwinger-Sakharov enhancement factor [5] becomes important and can be directly assessed; furthermore, the $\mu^+\mu^-$ bound state (also known as true-muonium) is also produced and could be revealed with an appropriate instrumentation. Such measurements are therefore interesting per se, probing a previously unmeasured phase space region.

The main goal however is the study of the produced muon properties and their dependence on the parameters of the actual production process. Ultimately both the number of produced muons and the beam emittance need to be optimized, although that would imply several trade-offs in the choices of the experimental configuration. That is why it is critical to assess the dependence of the production cross section and the kinematic properties of the muon pairs on the center-of-mass energy (i.e. the positron beam energy) and the target characteristics (composition, thickness, etc.). The physics program of LEMMA-TB includes primarily those measurements.

The North Area is the only facility in the world that can currently provide positrons with high enough momentum. The H4 and H2 beam lines can provide rates of positrons per spill above 10^6, with small spot size and beam divergence. Considering a production cross section of at most $1\,\mu$b and a light material (e.g. Beryllium) target about $0.1\,\mathrm{X}_0$ thick, a production rate of a few events per spill is expected under these conditions. Although such rate is very limited, a two weeks continuous data taking campaign would yield a signal dataset with enough statistical precision (better than 1% on the cross section measurement).

The measurement of the intrinsic emittance of the muon beams produced via $e^+e^- \to \mu^+\mu^-$ is affected by several experimental effects, which must be disentangled by experimental procedures and accurate simulation of the experimental apparatus. In particular, the contribution of the positron-beam emittance can be corrected on an event-by-event basis by the coordinates in the phase space of the incoming positrons. As discussed later, this will require a very accurate particle tracking both before and after the target.

The LEMMA scheme foresees the positron beam recovery after the target interaction in order to significantly reduce the request on the positron production rate. It is therefore one of the goals of the experiment to measure the positron beam parameters downstream of the target both in amorphous and channeling regimes. The latter, due to the suppression of nuclei effects, is predicted to reduce the beam degradation caused by the interaction with the target. Both the transverse emittance and the energy spectrum of positrons exiting the target will be measured. In addition, a measurement of the energy distribution of produced photons can be used to investigate the possibility of positrons production within the same target complex. This part of the experimental program requires a low-intensity beam ($\sim 10^3\, e^+$/spill) and the study of targets of different structure and materials. It will be one of the primary subjects of the experiment in the future years, while it is at low priority in 2021.

Past beam tests

Data-taking campaigns have been conducted in the past, in 2017 and 2018, along the H4 and H2 beam lines, respectively. The results of the latter are reported on Ref. [4], where the possibility was proved of clearly identify and measure $e^+e^- \to \mu^+\mu^-$ events; in particular signal events were discriminated from $e^+e^- \to e^+e^-\gamma^*$, with $\gamma^* \to \mu^+\mu^-$, thanks to a precise measurement of the muon momenta and reconstruction of the $\mu^+\mu^-$ invariant mass. The plots in Fig 1 show the reconstructed total momentum and invariant mass of the selected muon pairs, which peak respectively at about $45\,\mathrm{GeV}/c$ and $214\,\mathrm{MeV}/c^2$, as expected, displaying good agreement with simulated data.

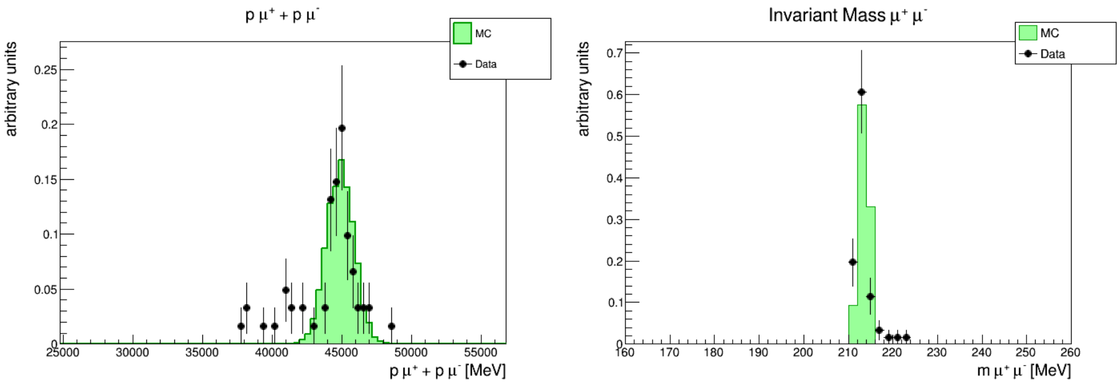

Figure 1: Reconstructed total momentum (left) and invariant mass (right) of the muon pair. Data (points with error bars), are compared to MC (filled histogram).

Those experiments have been extremely useful as preliminary tests exposing the challenges of the planned physics measurements and helped formulating possible improvements. In particular, the background due to the spent positron beam and other electroweak processes has not been straightforward to cope with, dominating the signal events by several orders of magnitudes and causing high occupancy in the detectors. A limited total trigger rate and a sub-optimal trigger strategy led to a rather inefficient data acquisition and thus to a small signal dataset. Furthermore, correcting on an event-by-event basis the muon beam properties taking into account the direction and position of the incoming positron tracks required the knowledge of the latter with an accuracy exceeding the one of the employed tracking devices, based on silicon strips.

The complexity of the experimental setup (conceptually similar to that proposed for 2021 shown in Fig. 2) required quite an effort to be fully installed and an amount of time which in the end consisted in a sizable fraction of the overall available time budget. The installation was then followed by long sessions of detector alignment and calibrations, by making use of special runs with muon and electron beams at different energies and intensities. The effective time remained for the actual data taking was therefore limited to less than four days, not sufficient to complete the set of measurements the collaboration aimed at; in particular no dedicated studies for background characterization could have been performed.

In the next two sections the experimental apparatus foreseen for the proposed experiment and a proposal for its deployment in the H4 beam line are reported.

The apparatus

A schematic view of the LEMMA-TB experiment proposed for 2021 is shown in Fig. 2; even though the layout is similar to the one exploited in 2018, several key components will be considerably improved. In particular, the microstrip detectors in the target region are replaced by more performing silicon pixel detectors, with a much higher number of active channels and an increased number of layers to reduce detection inefficiencies and to improve tracking accuracy.

At least three stages of pixel detectors upstream the target intercept the incoming positrons and measures their track parameters. In addition, a set of three or four pixels stations followed by a 2D microstrip detector track the charged particles emerging from the target. Accurate simulation studies have been conducted to define the requirements on the spacial resolution of the tracking devices at the various stages along the beam line. Hit resolutions in the range of $10-20\,\mu$m should

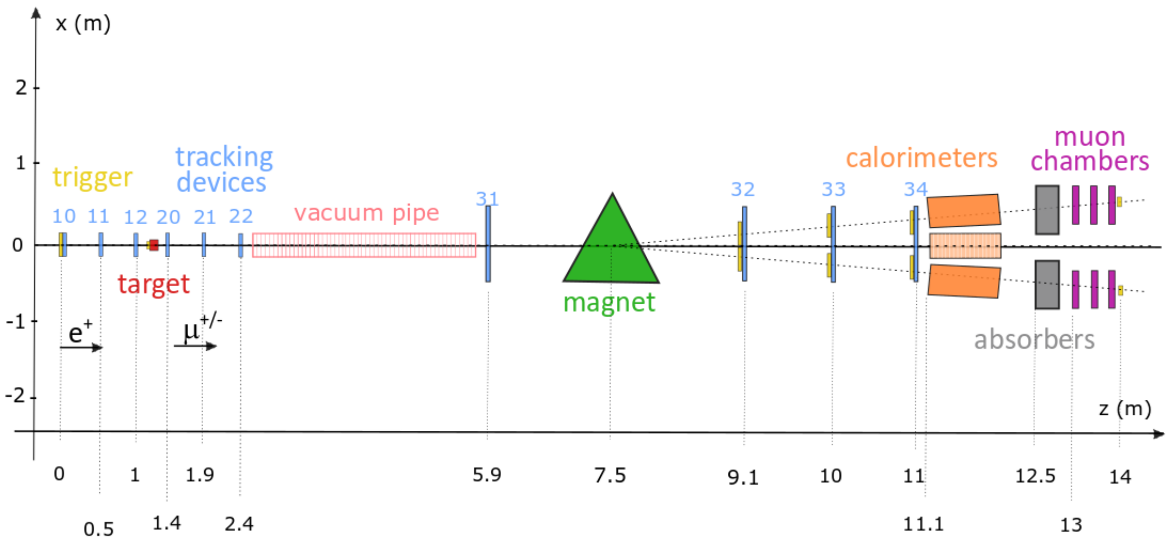

Figure 2: Experiment setup in 2021.

be sufficient to nail down the effect of production process kinematic and of the multiple scattering within the target on the muon beam emittance, independently from the emittance of the incoming positron beam. Several options are being considered for such tracking detectors, among which the pixel sensors used for the vertex detection at CMS during the first LHC run. All those options will feature in addition a very fast response time, which will allow reading them out at high rate, i.e. at about 100 kHz. This in turn will relax the requirements on an ultra-pure trigger selection.

The plots in Fig.3 shows a typical signal event as it would be reconstructed by the pixel sensors close to the target (left) and the reconstructed emittance as obtained by correcting the estimated muon trajectories by the direction of the incoming positron (right).

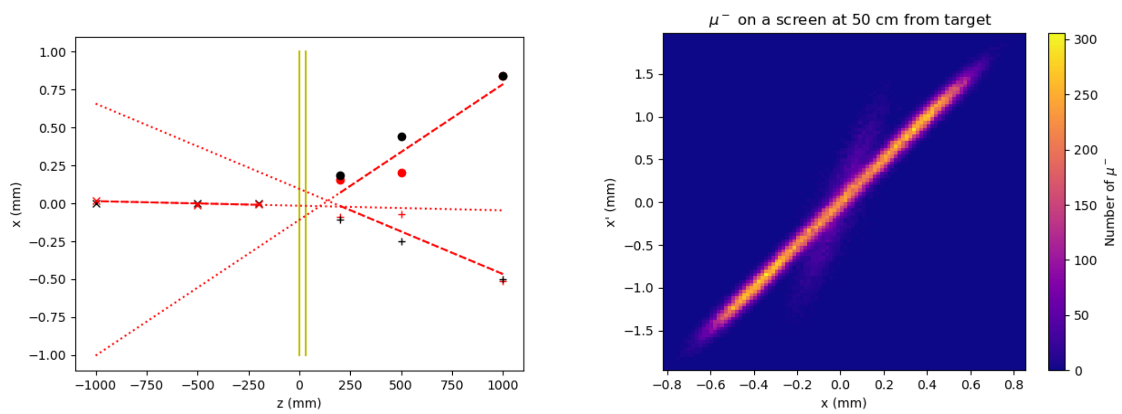

Figure 3: Left graph: hits left by an incoming positron and by the two outgoing muons in the tracking devices nearby the target: simulated event in black, simulated event with detector smearing in red, fit of the red measures in dashed red line. Right graph: trace space for x dimension of the muon beam as estimated from the tracking measurements.

The magnetic dipole will separate the produced muons according to their charge in the two arms of the spectrometer, where additional tracking detectors will precisely measure the track momenta. The intensity of the magnetic field is such to provide a bending power of the order of a few Tm, but the final choice, as well as the dimensions of the entire apparatus, will be determined by the space available in the assigned experimental hall.

Combinations of plastic scintillators will be employed along the experiment to generate the trigger signal for selecting both di-muon events and Bhabha candidates. A dedicated scintillator of appropriate size will be placed in front of the target, to filter only those events where the positron beam impacted on the active volume of the target itself and allowing furthermore the measurement of the positron flux. More sophisticated trigger selections could be implemented, relying on the measurements of "Gas Electron Multiplier" chambers, which eventually will be installed at the end of the positive and negative muon arms. At that position, the experiment will feature six muon chambers, properly screened by a pair of thick iron blocks. Those are drift tubes chambers with a layout similar to those installed in the barrel of the CMS experiment but with a smaller footprint; they provide excellent muon identification capabilities and accurate position measurements for a redundant tracking in 4D. As in 2018, those chambers will be read-out continuously at 40 MHz, providing an handle to estimate the trigger efficiency.

Prior to the iron shielding, Electromagnetic calorimeters will be installed, to support the identification of minimum ionizing particles, to tag Bhabha events and to suppress background, in particular radiative Bhabha events.

Choice of the North Area beam line

As already stated, the dimensions and the actual layout of the apparatus can be adjusted accordingly to the space available, in particular the LEMMA-TB setup can be designed to fit longitudinally in less than 15 meters, with a transverse size between 2.5 and 4 meters, depending on the chosen bending power of the dipole magnet. The proposed setup could therefore be hosted in several experimental areas of the North Area, in beam lines that are capable of providing a high-intensity, and very high purity and quality electron beam, given the precision measurement we are aiming to perform. Our preference goes for the H4 line as it provides the highest possible electron intensity of about 10^7 electrons per spill, with minimal material upstream. The line used in the 2018, H2, although still suitable for our purposes, is considered not optimal: the permanently installed NA61/SHINE experiment upstream includes material that cannot be removed from the beam line, thus limiting the number of electrons and introducing low-energy tails that cannot be cleaned.

The experimental zone PPE-134 would perfectly fit our needs, the area beyond the GOLIATH magnet in fact is wide enough and would ease one of the most critical aspect for the measurement of the muon emittance, i.e. the alignment of the tracking system in the target area.

Summary

A muon collider represents one of the most intriguing and challenging options for the long-term strategy in HEP. Several options for the production of intense muon beams suitable for $\mu^+\mu^-$ collisions have been proposed, all presenting strong challenges. The proposed experiment is conceived as a series of independent beam tests, to be performed in the next few years, aiming at shedding light on several aspects of the production of low-emittance muon beams with the positrons-on-target scheme of Ref. [1]. The main goal of the 2021 experiment will be the measurement of the μ-pair production rate and emittance as a function of several parameters, such as beam energy and target thickness. It would also be the first systematic study of $\mathrm{e^+e^-}$ interactions at the $\mu^+\mu^-$ production threshold.

In summary, our proposal requires three weeks of beam time. Given the complexity of the proposed experiment, the first week will be devoted to the installation and commissioning of the apparatus, including calibration sessions to align the detectors, characterize and quantify the various background sources, and the testing of the different trigger options and the data acquisition system. The other two weeks of beam time are considered the amount of time sufficient to achieve our physics goals.

The positron beam should satisfy the following requirements:

- energy around 45 GeV with $< 1\%$ energy spread;
- intensity above $5 \times 10^6\, e^+$/spill;
- spot size of the order of 1 cm^2

For calibration purposes, $e^\pm$ beams with different energy settings between 15 and 40 GeV, as well as muon beams at similar energies, are needed.

This project is part of the INFN research program on future accelerators. Sufficient funds have been allocated (and partly already spent) for the procurement of the hardware and its development in the electronic and mechanical workshops. The team grew in number with respect to past beam tests, including experts from CERN and other institutes.

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