Test Beam for Low EMittance Muon Accelerator

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on behalf of LEMMA collaboration

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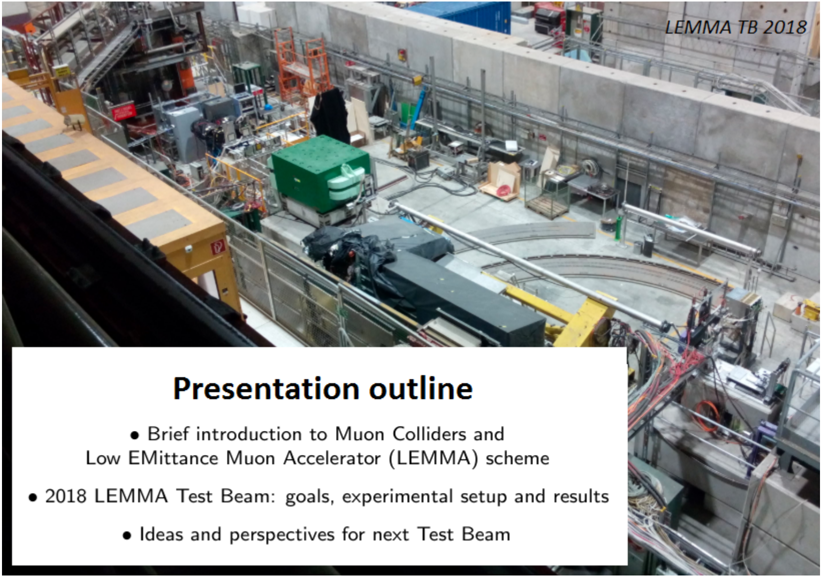
INFN
Istituto Nazionale di Fisica Nucleare



Presentation outline

- Brief introduction to Muon Colliders and Low EMittance Muon Accelerator (LEMMA) scheme
- 2018 LEMMA Test Beam: goals, experimental setup and results
- Ideas and perspectives for next Test Beam

Introduction to Muon Colliders & LEMMA

Why Muon Colliders?

Typically two classes of accelerators are considered as LHC successors:

***pp* colliders** *(FCC-hh)*

- \+ very heavy particles can be produced (~few TeV)
- \- lots of additional radiation produced in hadronic collisions
- \- kinematics of interacting partons is uncertain *(limited by PDFs)*

e^+e^- colliders *(FCC-ee, ILC, CLIC)*

- \+ extremely clean final states with minimum of additional radiation
- \+ kinematics of interacting particles known precisely
- \- limited energy reach (up to 0.5 TeV at FCC) due to synchrotron radiation

Advantages of both *pp* and e^+e^- colliders can be combined in a $\mu^+\mu^-$ collider

- \+ **initial state kinematics precisely known & clean final states**
- \+ **all energy delivered to the collision**: *multi-TeV particles can be produced*
- \+ **much less synchrotron radiation:** *compact layout + energy efficient*

Major effort towards a multi-TeV Muon Collider design made by:

- U.S. Muon Accelerator Program **(MAP)**
- International Muon Ionization Cooling Experiment **(MICE)**

Novel proposal:

- Low EMittance Muon Accelerator (**LEMMA**) main effort by INFN

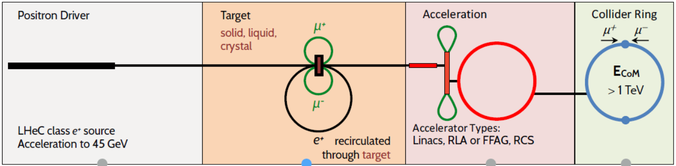
https://arxiv.org/abs/1910.11775
https://arxiv.org/pdf/1901.06150

Low EMittance Muon Accelerator

producing muons at the $e^+e^- \to \mu^+\mu^-$ threshold $(\sqrt{s} \approx 45$ GeV)

+ divergence of the $\mu^\pm$ beams very small and tunable via $\sqrt{s}$

+ long $\mu\pm$ beam lifetime (~500 μs) → reduced losses from the $\mu\pm$ decays



high-intensity positron beam (could be FCC-ee)

$e^+e^- \to \mu^+\mu^-$
beam already cooled

$\mu^\pm$ acceleration

$\mu^+ + \mu^- \to X$

has to be experimentally proven

Novel proposal for a low emittance muon beam using positron beam on target
M. Antonelli, M. Boscolo, R. Di Nardo (Frascati), P. Raimondi (ESRF, Grenoble)
Sep 15, 2015 - 7 pages
Nucl.Instrum.Meth. A807 (2016) 101-107

POSITRON DRIVEN MUON SOURCE FOR A MUON COLLIDER *
arXiv:1905.05747v2 [physics.acc-ph] 19 May 2019

Low emittance muon accelerator studies with production from positrons on target
M. Boscolo, M. Antonelli, O. R. Blanco-García, S. Guiducci, S. Liuzzo, P. Raimondi, and F. Collamati
Phys. Rev. Accel. Beams **21**, 061005 – Published 26 June 2018
An article within the collection: IPAC 2017 Conference Edition

https://arxiv.org/abs/1803.06696
https://arxiv.org/abs/1905.05747

Test LEMMA concept

The LEMMA concept put to a test in a series of test beam campaigns in 2017 and 2018

using the CERN SPS beam line as a positron source *(5×10^6 e^+/spill)*

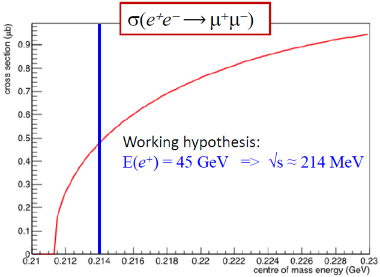
<u>The main goal of the testbeam</u>: **understand if the LEMMA approach is feasible**

$$N(\mu^+\mu^-) = N(e^+) \cdot \rho(e^-) \cdot \sigma(e^+e^- \to \mu^+\mu^-) \cdot L$$

L – target length

A number of measurements foreseen to answer this question:

- **kinematic properties of the produced muons**
  position, momenta, emittance
- **cross section of the $e^+e^- \to \mu^+\mu^-$ production**
  never measured close to threshold
- **effect of the target material/thickness**

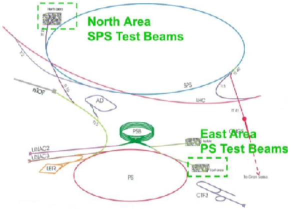


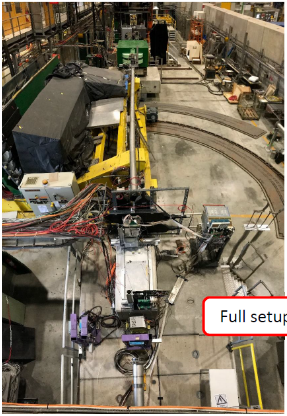
<u>Data taking performed with a number of different configurations:</u>

target materials: *Be, C*
target thickness: 2 cm, 6 cm
positron-beam energies: 45 GeV, 46.5 GeV, 49 GeV

https://arxiv.org/abs/1509.04454

LEMMA Test Beam 2018





Location: CERN North Area, SPS beam line

Test Beam Facilities at CERN

Periods and operations:

15-20 August 2018 (early stop due to SPS break down):

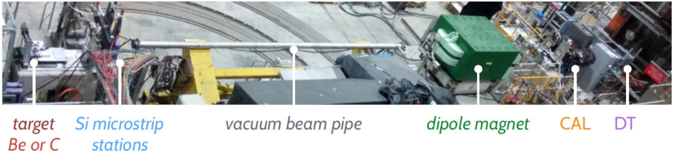
- **Calibration runs** without target using muon beam (22-32 GeV) for calorimeters and muon chambers, and positron beam (16-28 GeV) for tracking alignment
- **Physics runs** with:
  - Be target and 45 GeV e^+ beam
  - Be target and 46.5 GeV e^+ beam (only 25 min of data before SPS break down)

19-25 September 2018

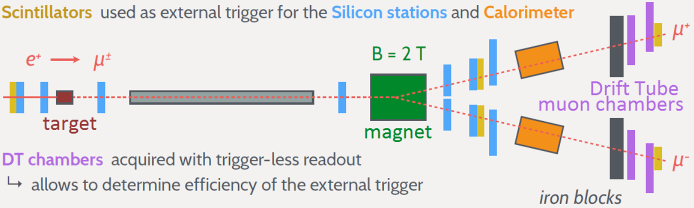
- **Calibration runs** without target using muon beam (22-32 GeV) for calorimeters and muon chambers, and positron beam (16-28 GeV) for tracking alignment
- **Physics runs** with:
  - Be target and 45 GeV e^+ beam
  - Be target and 49 GeV e^+ beam
  - Be target and 46.5 GeV e^+ beam
  - C target (6cm) and 45 GeV e^+ beam
  - C target (2cm) and 45 GeV e^+ beam

A combination of detectors used to measure the $\mu^{\pm}$ trajectories and momenta

Layout of the experimental setup: *August 2018*



Scintillators used as external trigger for the **Silicon stations** and **Calorimeter**

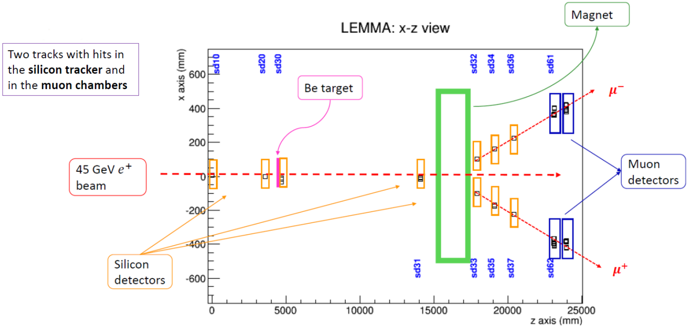


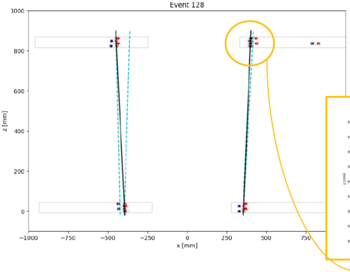
DT chambers acquired with trigger-less readout

↳ allows to determine efficiency of the external trigger

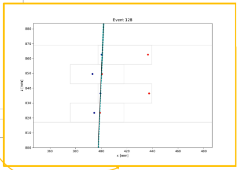
Several calibration runs were performed without a target:

- **μ^- beam:** for alignment of the Calorimeters and DT muon chambers
- **e^+ beam:** for alignment of the Silicon stations + calibration of the Calorimeters

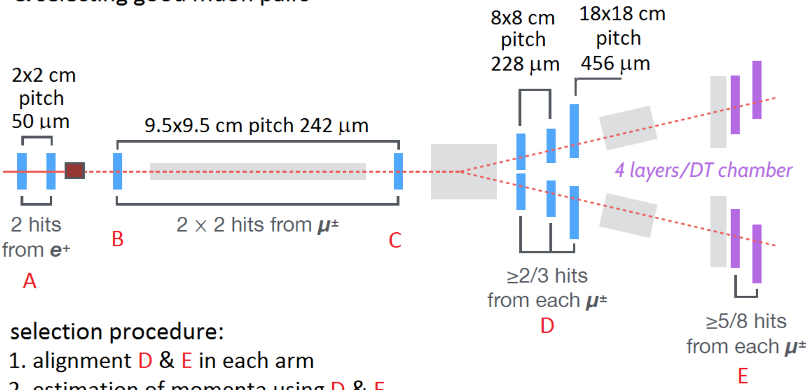




DT muon chambers
built in Legnaro (Padova)



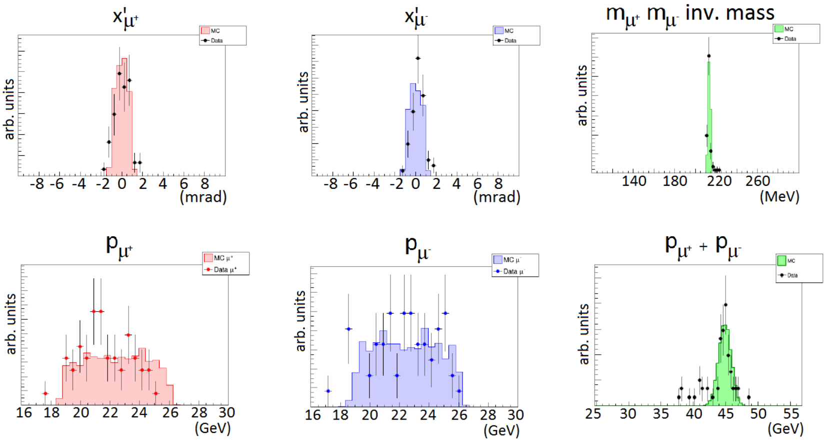
Muon analysis performed *(calorimeter infos not considered)*
reconstructing positrons and muons trajectories
& selecting good muon pairs



selection procedure:

1. alignment D & E in each arm
2. estimation of momenta using D & E
3. position extrapolation backward and check with C
4. global fit up to B
5. global fit including A and constraining e^+ μ^+ μ^- tracks to a common vertex

Features of 61 reconstructed muon pairs for 45 GeV positron beam on 6 cm Be target: experimental data against Geant4 simulation at the muon pairs production vertex

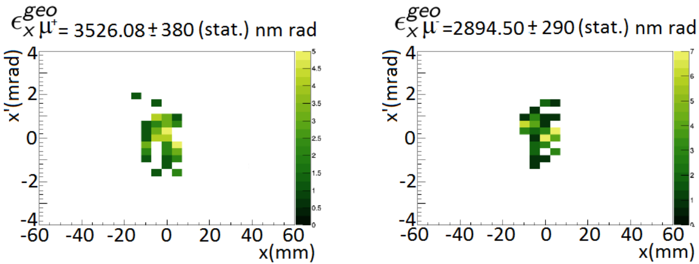


https://arxiv.org/pdf/1909.13716v2

Experimental results for geometrical transverse emittance

$$\epsilon_x^{geo} = \sqrt{(\langle x^2 \rangle - \langle x \rangle^2)(\langle x'^2 \rangle - \langle x' \rangle^2) - (\langle x \rangle \langle x' \rangle - \langle xx' \rangle)^2}$$

Raw values: no corrections for incoming positron beam spread
Measured at target exit

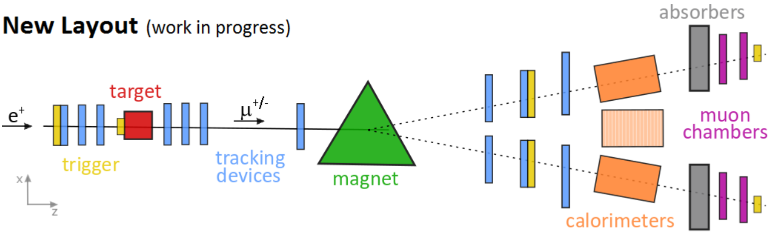


Geant4 simulated value: 2760 ± 150 (modelling) nm rad
`EEMUMU` (ad-hoc code) simulated value: 3221 nm rad

`https://arxiv.org/pdf/1909.13716v2`

Next LEMMA Test Beam preparation

New Layout (work in progress)



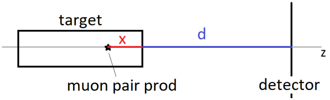
- trigger: fast scintillators, one just before target to count number of incoming positrons for total cross section calculation
- target: Be 6 cm, C 2 and 6 cm
- tracking devices:

- 2/3 before target to track positrons, silicon pixel detectors resolution $\sim 20\ \mu$m
- 3+1 after target before magnet to track muons, silicon pixel det res $\sim 20\ \mu$m
- 3 on each arm to track muons, silicon pixel det res $\sim 250\ \mu$m
- simulations to determine exact positions for ones before magnet: `EEMUMU` home made code (Geant4 full simulation in progress)

- calorimeters: 2/3, central one for Bhabha
- DT muon chambers: 2/3 per arm

EEMUMU code

- simulates $e^+ + e^- \to \mu^+ + \mu^-$ in target: realistic positron beam, flat random longitudinal distribution of muon pairs production within target, multiple scattering effect of target material on positrons and muons
- propagation of emitted muon pairs up to plans perpendicular to z axis (schematic detectors) considering multiple scattering in air
- for each muon angle and transverse position given by sum of production, propagation and multiple scattering in materials contributions



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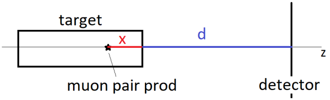
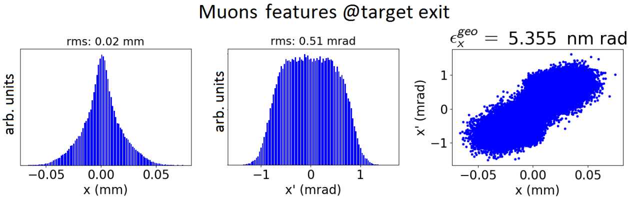
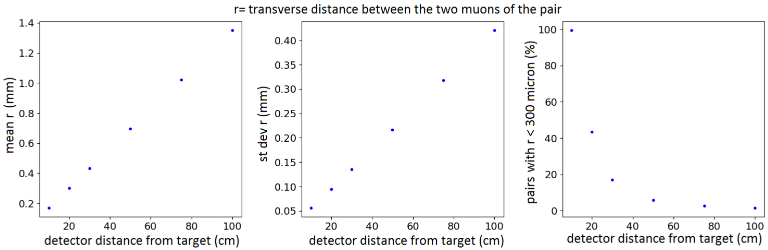


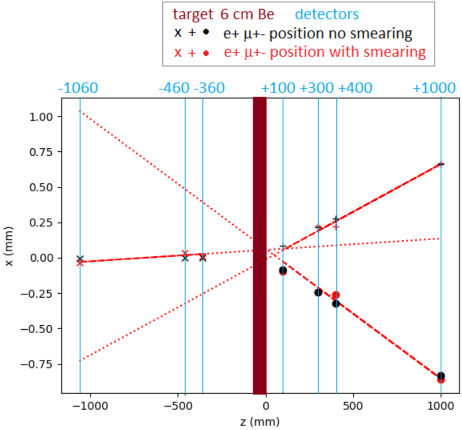
- Ex: Ideal incoming positron beam $\sigma_x^{e+} = 1\ \mu$m, $\sigma_{x'}^{e+} = 0$ and 6 cm Be target



- Detectors are set at some distances before and after the target in air
- On each detector we introduce a shift on e^+ position given by experimental uncertanty: Gaussian smearing with 20 μm rms
- On each detector a shift on μ^+ and μ^- positions given by experimental uncertanty:
-if the distance (in x, y) of the two muons in the pair is > 300 μm: Gaussian smearing of 20 μm rms on each muon position
-otherwise the mean position of the two muons is taken with Gaussian smearing with 100 μm rms (same position value)
- Linear fit applied to the shifted positions of positron and muons to retreive the muon beams emittance value (the same for μ^+ and μ^- beams)
- Many configurations are been tested considering the percentage of not resolved pairs (μ^+ μ^- distance < 300 μm). For the example above:

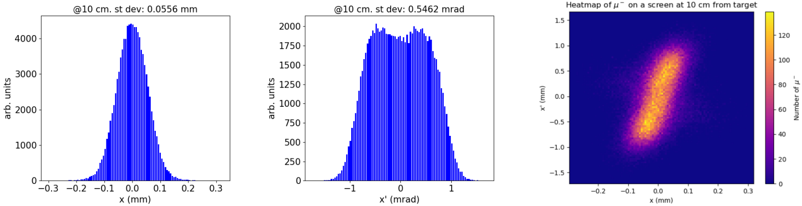


A good configuration (preliminary, we consider the emittance corrected for the positron position but we don't force tracks to a common vertex yet):

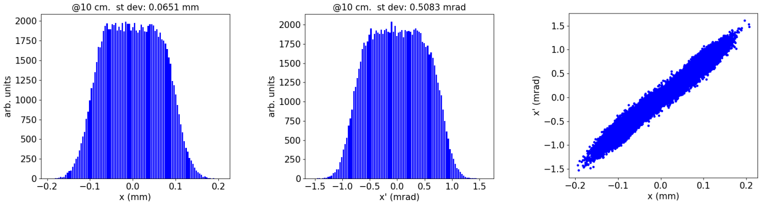


On a plane ⊥ to z @ 10 cm from target exit

incident positron correction, measurement errors, ms air contribution ε_{geo}= 25.949952 nm rad

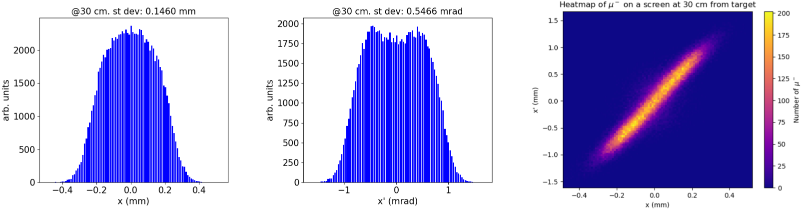


only ms air contribution ε_{geo}= 5.384992 nm rad

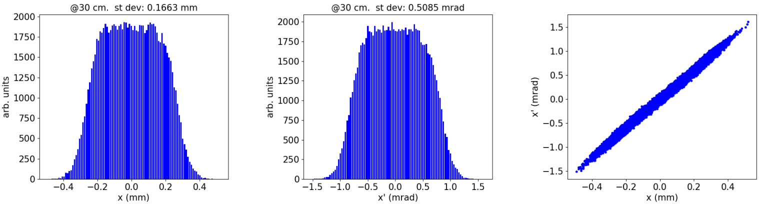


On a plane ⊥ to z @ 30 cm from target exit

incident positron correction, measurement errors, ms air contribution ε_{geo}= 25.955286 nm rad

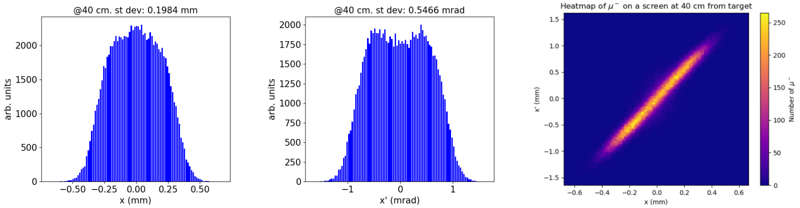


only ms air contribution ε_{geo}= 5.989111 nm rad

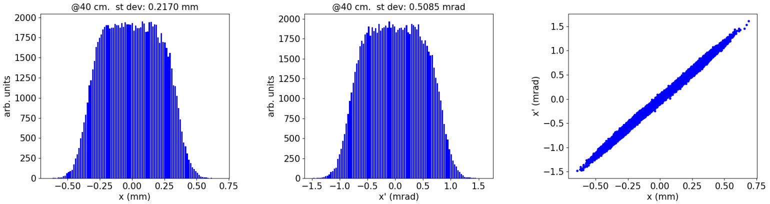


On a plane ⊥ to z @ 40 cm from target exit

incident positron correction, measurement errors, ms air contribution ε_{geo}= 25.961071 nm rad

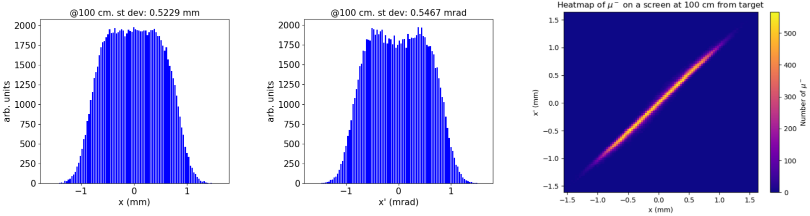


only ms air contribution ε_{geo}= 6.741723 nm rad

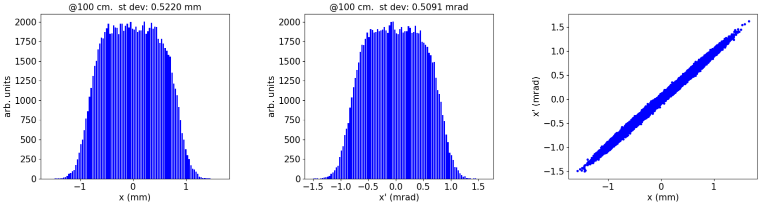


On a plane ⊥ to z @ 100 cm from target exit

incident positron correction, measurement errors, ms air contribution ε_{geo}= 26.033206 nm rad



only ms air contribution ε_{geo}= 17.360924 nm rad



Summary

- LEMMA muon production scheme has been investigated using SPS positron beam at CERN in 2017 and 2018
- 2018 test beam: big improvement with respect to 2017, very good agreement with simulations but number of data to be increased. A lot of work on experimental setup and data analysis already been done
- New layout for the next test beam is under devolpement: better trigger, more resolution and better positioning for silicon detectors and more beam time are needed. Looking forward for the next test beam at CERN in 2021, if approved!

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Thank you for your attention!

Many thanks from the LEMMA collaboration to SPS staff and Large Scale Metrology group, in particular Henrik Wilkens and Nikolaos Charitonidis, for their support during test beam installation and data taking. Many thanks from myself to N. Bartosik, A. Bertolin and A. Cappati.

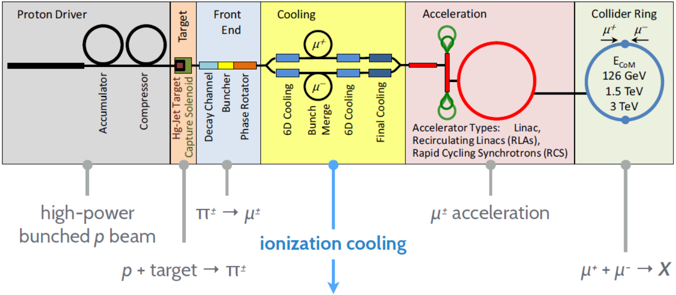
Backup slides

Muon Accelerator Program

Major effort towards a multi-TeV Muon Collider design made by:

- U.S. Muon Accelerator Program **(MAP)**
- International Muon Ionization Cooling Experiment **(MICE)**

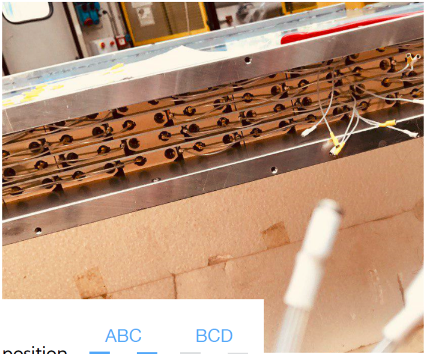
FERMILAB-CONF-13-307-APC



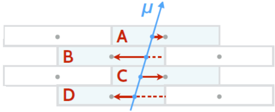
more studies on cooling are needed

DT muon chambers have a trigger-less readout:
all channels acquired every 25ns

- can detect $\mu^+\mu^-$ events without the external trigger
- similar design considered by the LHCb/CMS/ATLAS for HL-LHC



Each of the 4 chambers contains 64 cells arranged in 4 layers



Measuring time of a charge carrier reaching the wire
↳ reference time t_0 needed to convert time to a hit position

A triplet of hits sufficient to determine t_0 *(meantimer method)*
↳ separate equation for each type of pattern

The determined t_0 found to be more precise than the external trigger
due to a ~3 ns jitter in the trigger electronics

The number of events identified with DT data: ~10K events preliminary

- trigger efficiency: 2% *(hardware problems)* → 20% *(problems solved)*

$$\varepsilon_{trg} = \frac{N_{trg}}{N_{DT}}$$