High Intensity Muon Beams at PSI: the present and the future

Giovanni Dal Maso

First Annual Workshop - Intense

PAUL SCHERRER INSTITUT PSI

ETH zürich

Intense
H2020 MSCA ITN
G.A. 858199

Contents

Brief overview about beamlines used for cLFV searches at PSI in the present and in the future.

Muon production at PSI

The High Intensity Proton Accelerator (HIPA) facility

We produce the muons impinging a 590 MeV, 1.4 MW proton beam (world record) on two targets: Target M (TgM, 5 mm thick) and Target E (TgE, 40 mm thick). At the end, the beam is stopped in a spallation target to provide neutrons (SINQ).

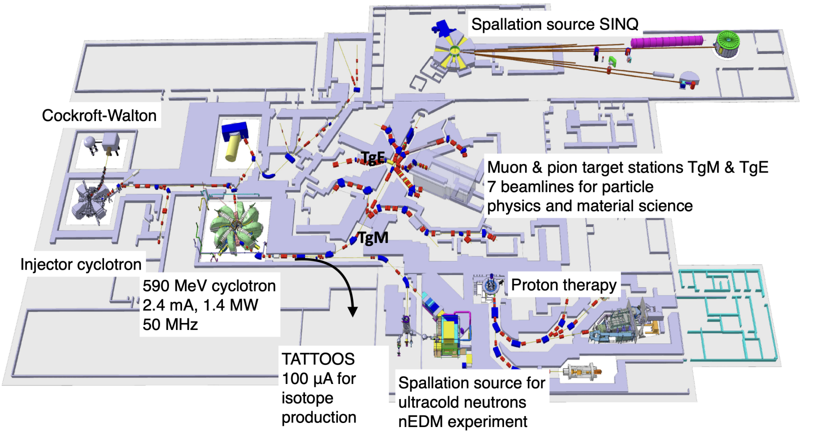
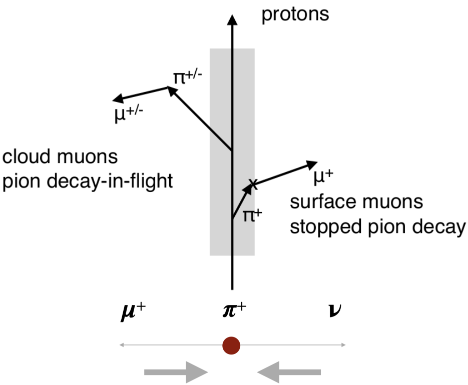


Figure: *The proton accelerator complex at PSI.*

Muons production

The protons impinge on TgM and TgE, producing pions that decay in muons. Depending on where they are created, we classify:

- Surface and sub-surface muons (5-30 MeV/c): they are created inside the target from pions at rest as a monochromatic line of 29.8 MeV/c of momentum. Therefore their energy depends only on their path inside the target. Additionally they are fully polarized.
- Cloud muons: they come from pions decay in flight.

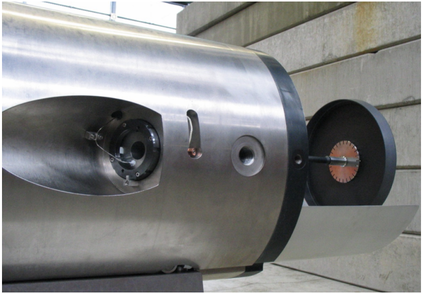


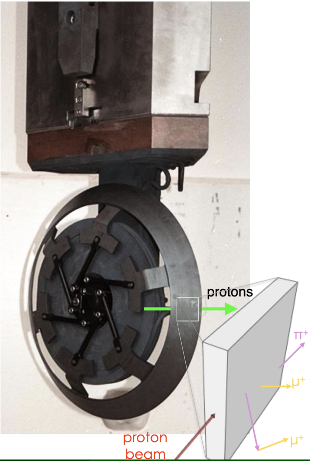
Due to the high intensity and low momentum, the most interesting muons for many experimental applications are surface muons ($\sim$ 28 MeV/c).
The produced muon beam is also DC: perfect for experiments with combinatorial backgrounds, like MEG II and Mu3e.

Target M and Target E

Currently the mesons are produced at two rotating wheels, radiation cooled, polycrystalline graphite targets.

- TgM: 5.2 mm thick, 5 kW energy deposit @2.2 mA
- TgE: 40 mm thick, 40 kW energy deposit @2.2 mA. Delivers the most intense continuous surface muon beams.



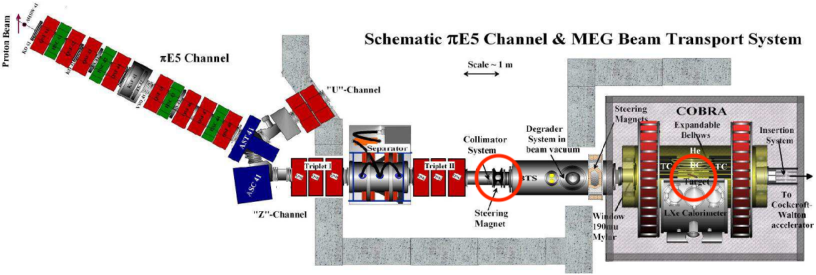


The πE5 area

MEG II beamline

After the collimator the Beam Transport Solenoid (BTS) delivers the beam inside the COBRA (Constant Bending Radius) magnet.
We have two measuring points for beam tuning:

- at collimator
- at COBRA center



Collimator: Pill detector

Measurements at collimator are performed using the MEG pill detector: phototube coupled to scintillator. The scan is performed using a robotic arm able to move along two directions: vertical and horizontal in the plane perpendicular to the muon beam centerline.

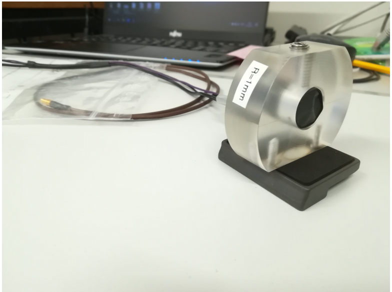


Figure: *Pill detector.*

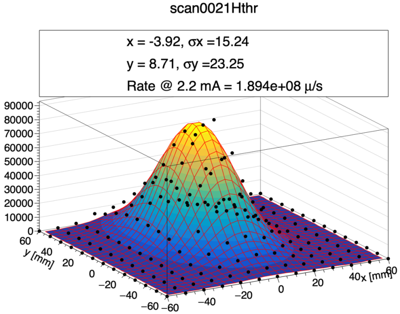


Figure: *Pill detector profile.*

Collimator: SciFi detector

The Scintillating Fibers (SciFi) detector is a grid of scintillating fibers coupled to SiPMs. During 2022 we are going to build and implement the final version of the detector, that will be permanently installed along the beamline, together with a motor to insert it or remove it on demand.

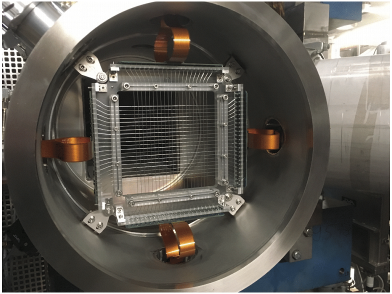


Figure: *SciFi detector.*

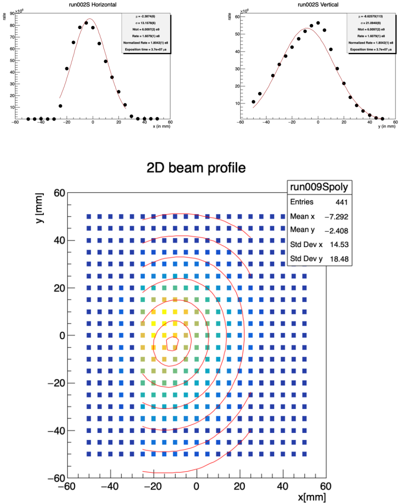


Figure: *SciFi detector profile.*

Collimator: MatriX detector

The MatriX detector is a matrix of plastic scintillators coupled to SiPMs.
The current prototype has been successfully tested at collimator.

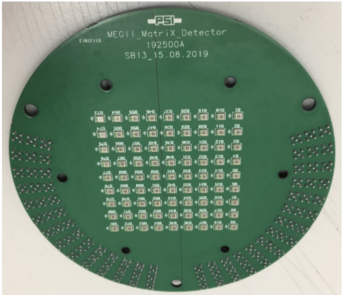


Figure: *MatriX detector.*

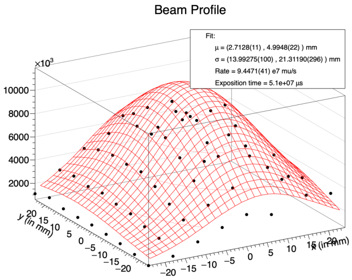
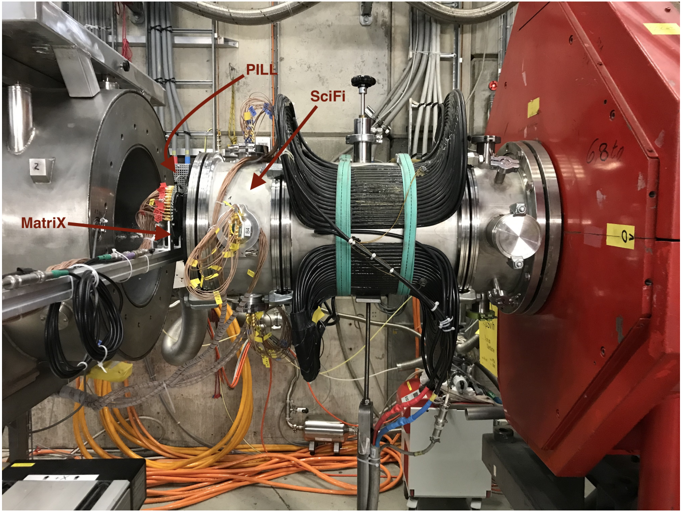


Figure: *MatriX detector profile.*

Collimator: setup



COBRA center: APD

Measurements at COBRA center are performed using an Avalanche Photo Diode (APD). The scan is performed using a robotic arm able to move along two directions: vertical and horizontal in the plane perpendicular to the muon beam centerline.

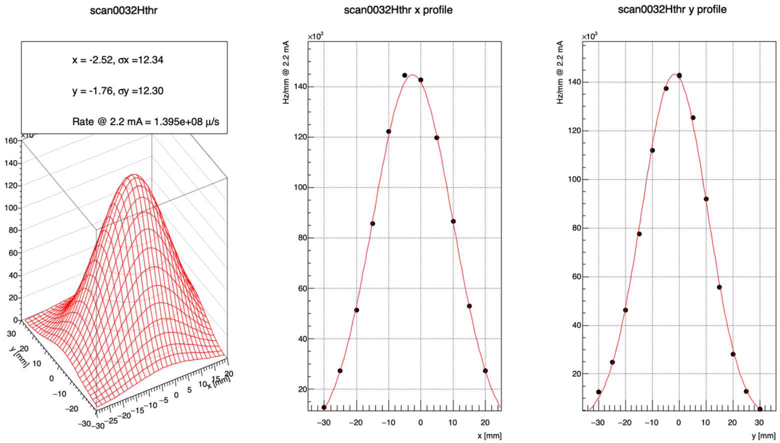


Figure: *Grid scan at COBRA center.*

COBRA center: MatriX

This year we tested different combinations of thinner scintillators on top of plexiglass cubes to increase separation and screen SiPMs from radiation. During 2022 we foresee to build an updated version of the detector to be used at COBRA center.

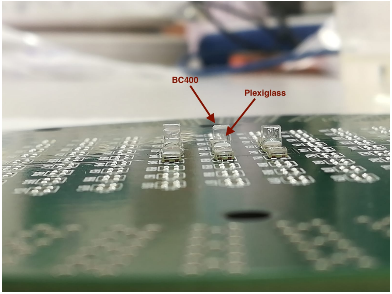
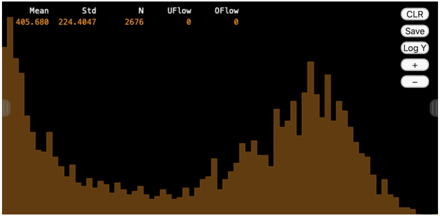
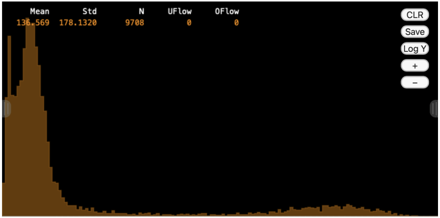


Figure: *MatriX detector.*



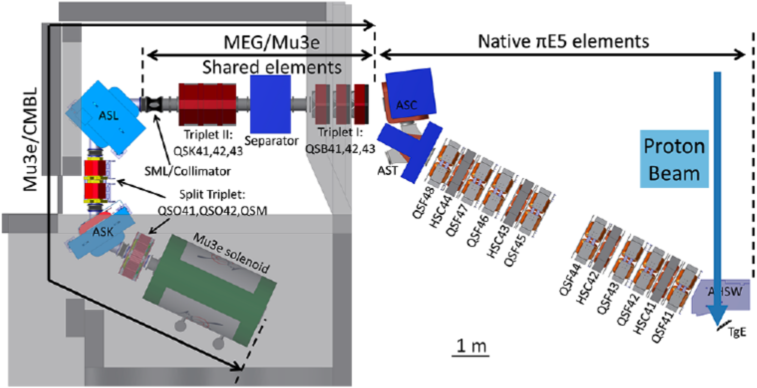
(a) only μ^+



(b) $e^+ + \mu^+$

Figure: *Positron - muon separation.*

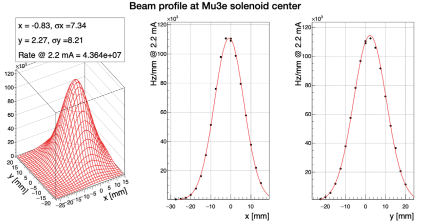
Mu3e beamline



CMBL: commissioning

The full Compact Muon Beam Line together with the Mu3e solenoid was assembled in πE5 for the first time during the 2021 Mu3e integration run and successfully operated.

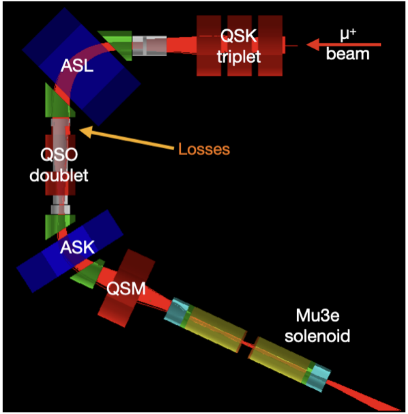
- We were able to propagate the beam through the CMBL to the Mu3e solenoid center
- We found the working point of the separator SEP41 to have optimal separation between μ^+ and e^+
- A maximum rate of 4 10^7 μ^+/s @ 2.2 mA was obtained at solenoid center after tuning the beam line



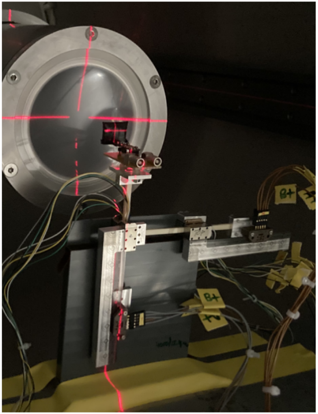
Mu3e beamline: foreseen improvements

Based on phase space reconstruction and beam profiles the current settings don't allow optimal transmission, and a big fraction of beam is lost along the QSO section:

- We will assemble the beam line in steps to increase transmission between the different sections: we expect to improve the maximum rate by 40∼50 %
- We aim at improving the new beam monitor based on piezo-electric motors



2021 settings beam simulation



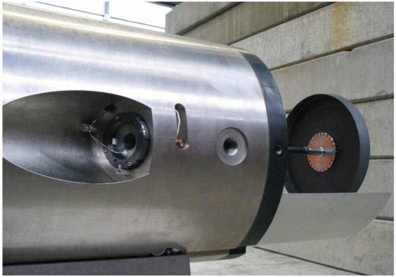
beam monitor inside Mu3e solenoid

The High Intensity Muon Beam project

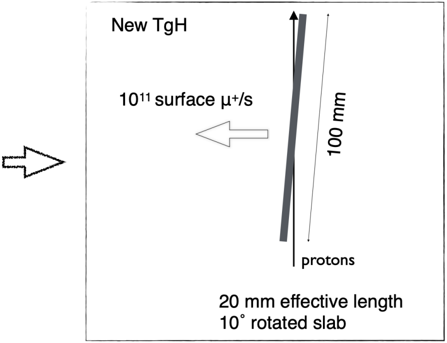
Target H

The plan is to substitute the existing Target M station with a High intensity one using a slanted target geometry:

- 5 mm TgM $\rightarrow$ 20 mm TgH
- 10 deg rotation angle w.r.t. the proton beam, as efficient (surface μ) as a standard 40 mm TgE
- muon collection sideways
- Slanted geometry tested at TgE to significantly enhance the surface muon yield

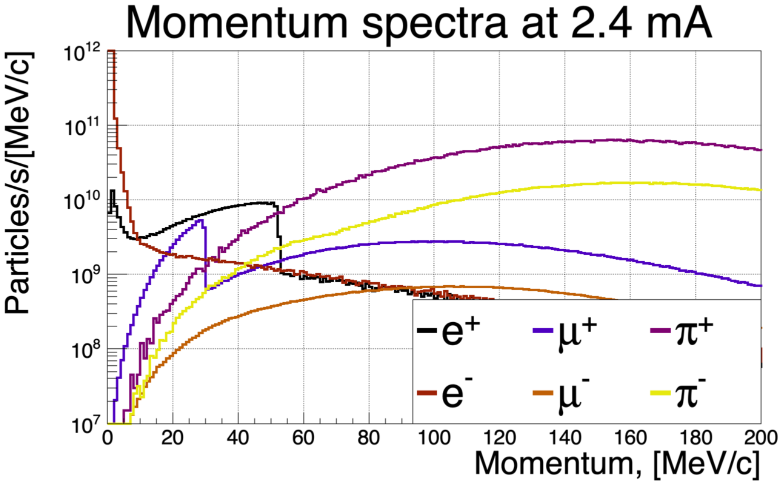


Existing TgM



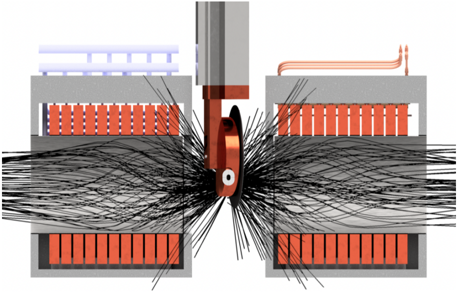
Particle production at TgH

We don't produce only muons of course!



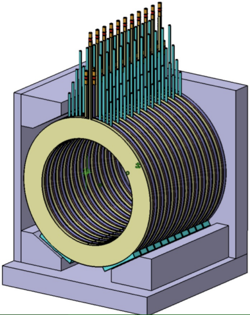
The plan is to design dipoles up to 80 MeV/c.

Split capture solenoids



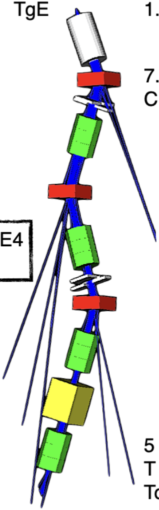
We can't surround our target with a unique solenoid (SINQ) $\rightarrow$ let's split it:

- Two normal conducting, radiation-hard solenoids close to the target for capture (very similar to the ones used in the existing μE4 beamline at PSI)
- Central field $\sim$ 0.4 T



Solenoid-based beamlines

TgE

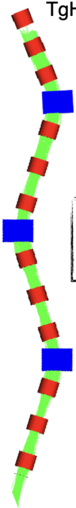


Existing μE4 beamline

Existing μE4 beamline		Solenoid-based beamline
1.2×10^{11} μ+/s	Source	1.3×10^{11} μ+/s
7.2×10^{9} μ+/s C ~ 6%	Capture	3.4×10^{10} μ+/s C ~ 26%
5×10^{8} μ+/s T ~ 7% Total ~ 0.4%	Transmission	1.3×10^{10} μ+/s T ~ 40% Total ~ 10%

⇨ Gain due to high capture and transmission efficiency

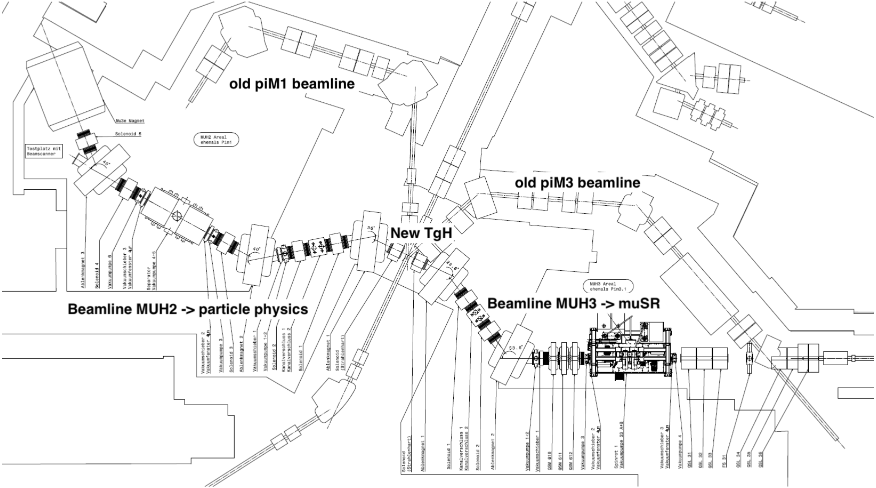
TgH



Solenoid-based beamline

Beamline layout

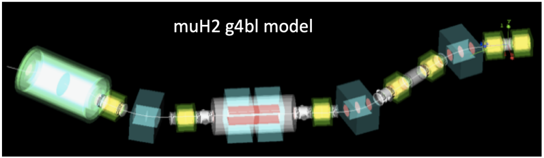
Two new high intensity muon beamlines at 90 deg angle w.r.t. the proton beam. We have started with the single element position optimization.

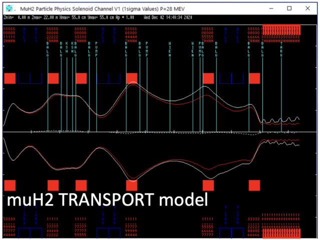


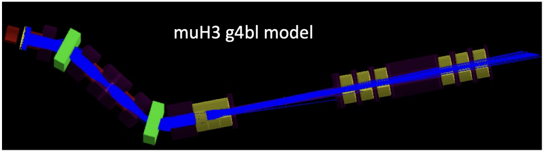
Simulation tools

To do so, we have simulation and optimization tools:

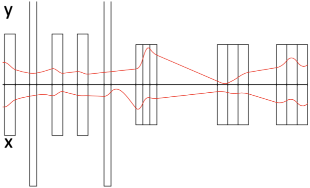
- Simulation:
    - TRANSPORT, COSY INFINITY: optical model programs
    - g4bl: single particle tracking based on Geant4, with in-house parametrised cross sections for pion production, tested with the results in μE4 design and 2019 TgE test
- Optimization: grid searches and hyperparameter searches





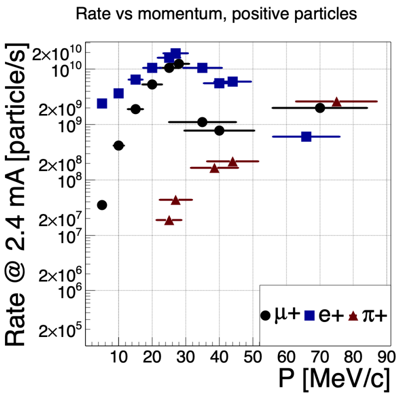


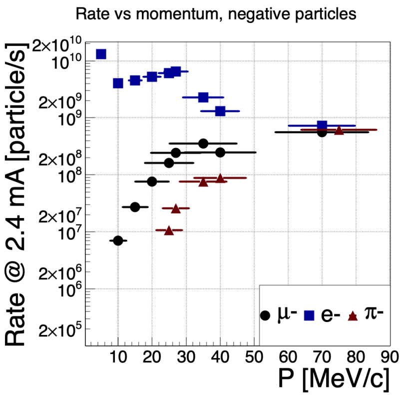
muH3 COSY INFINITY model



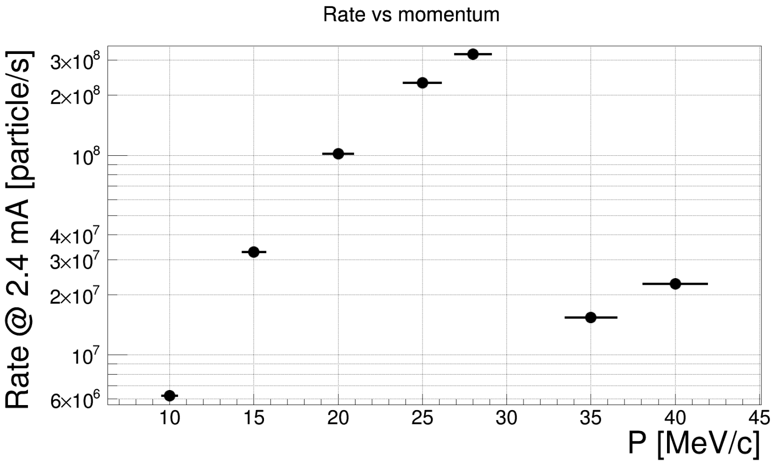
MUH2 beam rates

Expected rates in MUH2 for the particles produced @TgH.





MUH3 beam rates



Research 2021

- MEG II:
  - πE5 beam tuning
  - new beam monitor developments
  - detector calibrations
  - X17 set-up preparation
- Mu3e:
  - CMBL commissioning
  - new beam monitor developments
- HIMB:
  - studies of particle production at target H
  - MUH2 and MUH3 optimization for non-surface muon beams
  - MUH2 beams time structure

Research plans

2022:

- X17 data taking with MEG II
- MEG II & Mu3e Beam monitors
- Mu3e beamline commissioning
- HIMB simulations

2023:

- Beam monitoring upgrade for HiMB
- Full Mu3e detector commissioning
- HIMB simulations

University duties 2021

Courses:

- autumn 2021:
  - "Learning to Teach": this course imparted a variety of teaching skills that help Doctoral Teaching Assistants with their teaching tasks
  - "Astronomical Observations and Instrumentations": : course focused on the main and recent astronomical observations and description of the most relevant employed instrumentations
- spring 2022:
  - Joint Universities Accelerator School, COURSE 2: technology and applications of particle accelerators

Teaching:

- autumn 2021: Physics 1 exercise class for Medicine and Health Sciences students
- spring 2022: Physics 2 exercise class for Medicine and Health Sciences students

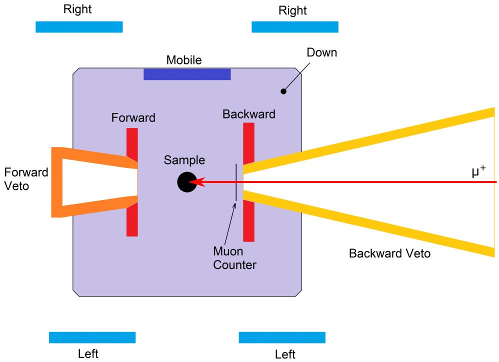
Backup

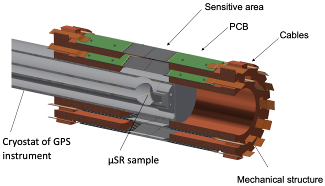
μSR

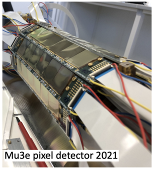
μSR

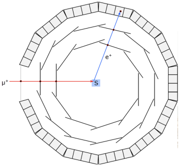
With μSR measurements it is possible to probe the magnetic properties of a material: with a fully polarized muon beam you can measure the polarization resulting from the interaction with the sample. The energy of the muons define the depth in the sample.

For surface muons, the limit in rate is due to the apparatus: one muon at a time inside the sample $\rightarrow$ max O(30 kHz). Under development: multiple μ measurements. The detectors development aims at switching to a vertexing approach









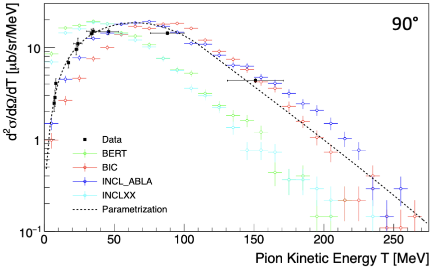
π cross section

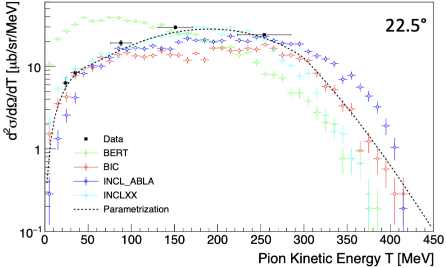
π cross section

The models distributed with Geant4, perform poorly or they are valid only on specific proton energies and scattering angles.

Therefore we implemented a data-based parametrization valid for protons up to $<$ 1000 MeV kinetic energy, at all scattering angles and materials.

$\rightarrow$ Reliable at 10 % level.

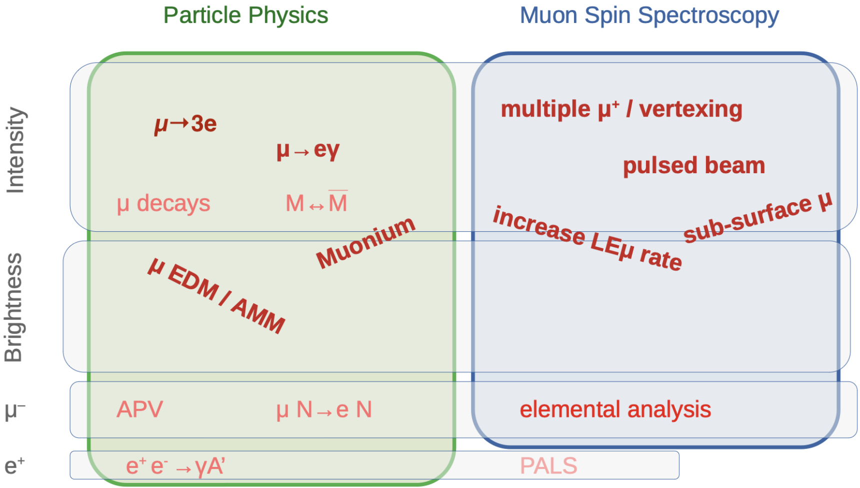




What to do with HIMB? Motivations

Science Case Workshop

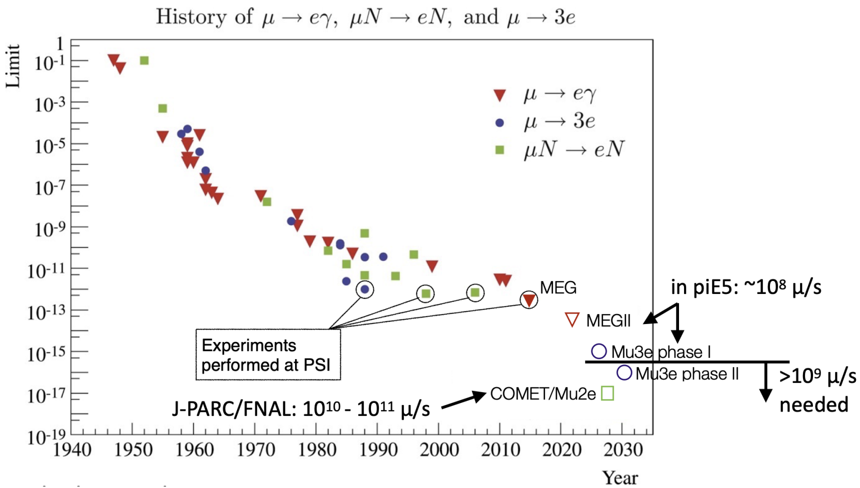
We had a science case workshop between 6-9 April 2021.



https://indico.psi.ch/e/himbws

Charged Lepton Flavor Violation

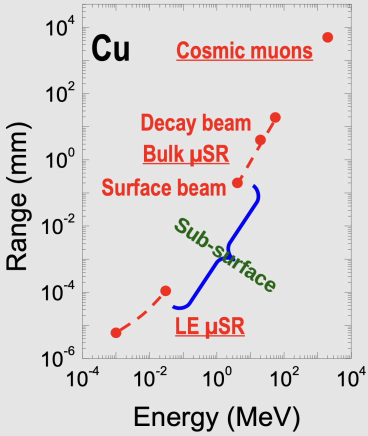
For $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ it is very important to have DC beams and intensity-frontier machines, such as HIPA.



μSR

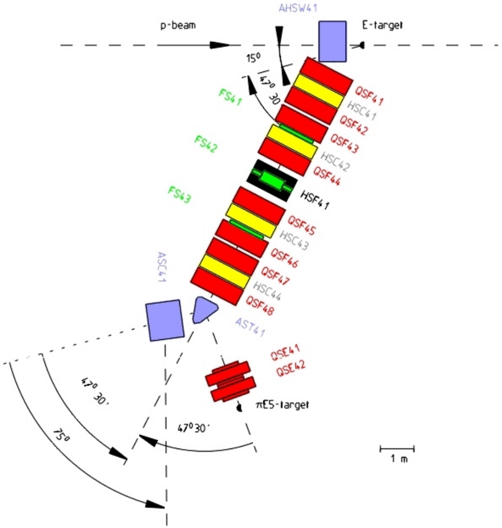
With μSR measurements it is possible to probe the magnetic properties of a material, and the energy of the muons define the depth in the sample. HIMB would allow to:

- Increase the Low Energy muons ($<$ 30 keV) rate by > 10: currently $\sim$ 4.5 10^3 μ/s, because they are degraded surface muons
- Allow to explore the sub-surface gap in depth: the surface muons peak is sharp



π**E5 channel**

πE5 channel



Length	10.4 m
Solide angle	150 msr
Momentum acceptance (FWHM)	10 %
Momentum resolution (FWHM)	2 %
Spot size (FWHM)	15 mm horizontal
	20 mm vertical
Angular divergence (FWHM)	450 mrad horizontal
	120 mrad vertical

$$10^8\,\mu^+/\mathrm{s}$$