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INFN TORINO

LEMMA approach for the production of low-emittance muon beams

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Nazar Bartosik

(INFN Torino)

for the LEMMA Collaboration

Post LHC scenarios

The LHC will operate until about 2040 according to the current schedule

↳ a new machine needed to explore physics beyond the LHC reach

Current studies concentrate on two conceptually different scenarios:

1. **high energy** *(FCC-hh)*
   - + very heavy particles can be produced (~few TeV)
   - + lots of additional radiation produced in hadronic collisions
   - + kinematics of interacting partons uncertain (limited by PDF)

2. **high precision** *(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

Each of the two scenarios requires a dedicated accelerator complex

↳ can only be implemented one after another if using the same tunnel

Increased time and cost requirements for the accelerator construction

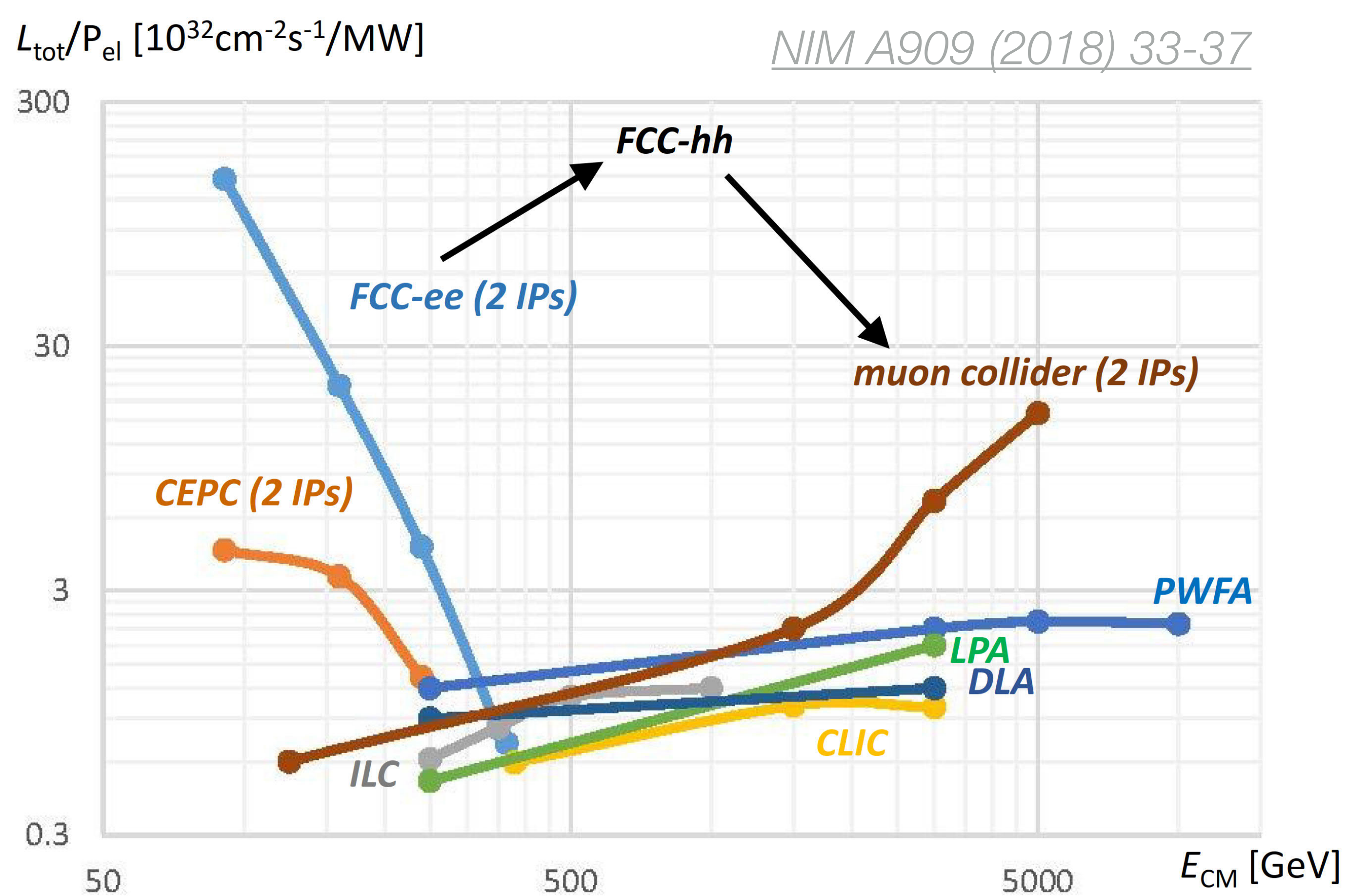
Muon collider as an alternative

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

- \+ same clean final states as in e^+e^- collisions
- \+ initial state kinematics precisely known
- \+ collisions at a multi-TeV level can be achieved
- \+ may profit from the high $\mu^+\mu^- \to H$ cross section at dedicated $\sqrt{s}$
- \+ much less synchrotron radiation
  - ↳ more compact layout
  - ↳ lower power consumption

Serious challenges to be addressed:

- accelerating and colliding muons before they decay
- suppressing background from the μ beam decay products (e^-, ν)
- **producing a low-emittance muon beam**



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

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

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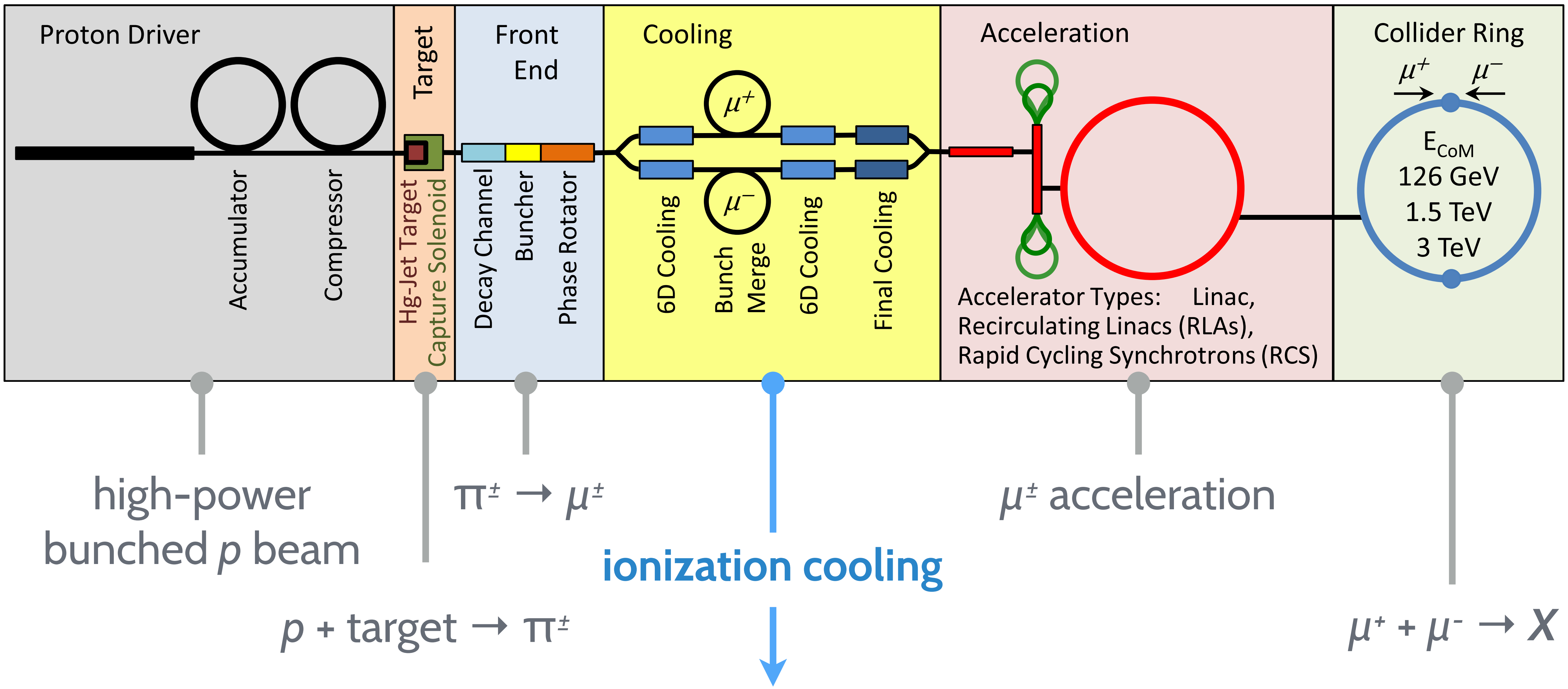
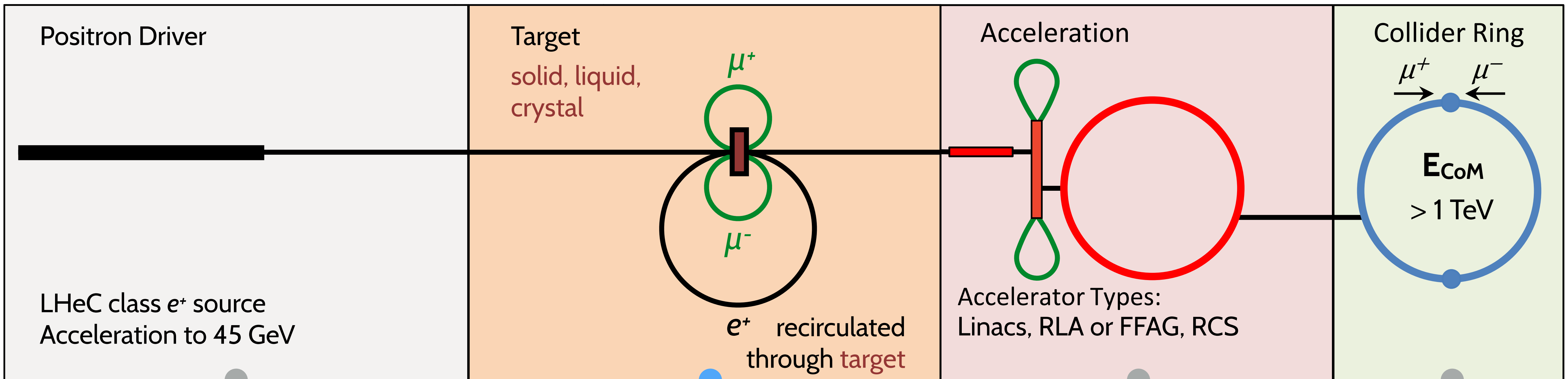


A series of RF cavities + solenoid coils to reduce the transverse beam divergence

New scheme: LEMMA

A new approach has been proposed recently: Low Emittance Muon Accelerator producing muons at the **$e^+e^- \rightarrow \mu^+\mu^-$** 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)*

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

$\mu^\pm$ acceleration

$\mu^+ + \mu^- \rightarrow X$

Very elegant and technically simpler design → has to be experimentally proven

The LEMMA concept put to a test in a series of testbeam campaigns in 2017/2018

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

The main goal of the testbeam: **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** (emittance, momentum, ...)
- **cross section of the $e^+e^- \to \mu^+\mu^-$ production** *(depends on the e^+ energy)*
- **effect of the target material/thickness**

Data taking performed with a number of different configurations:

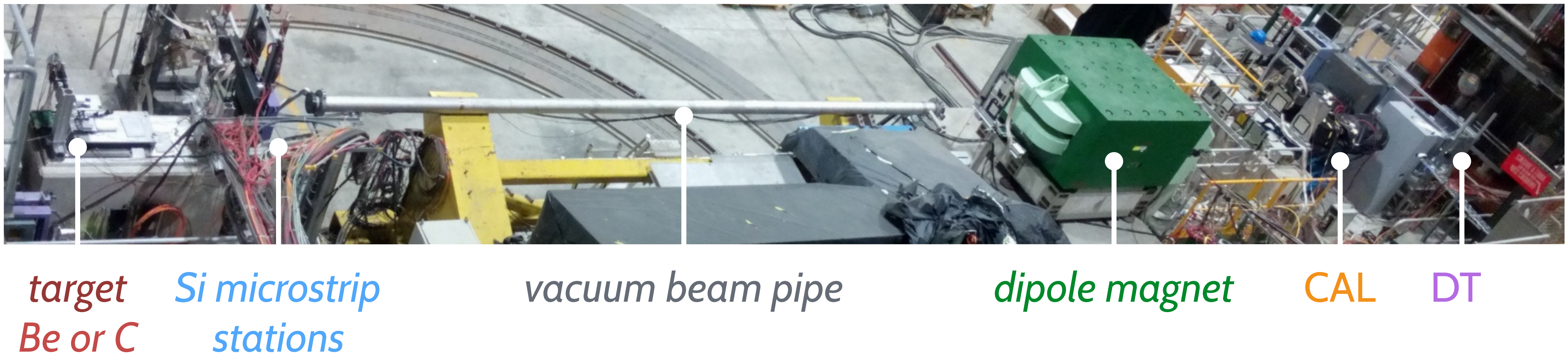
- **target materials:** *Be*, *C*
- **Target thickness:** 2 cm, 6 cm
- **positron-beam energies:** 45 GeV, 46.5 GeV, 49 GeV

LEMMA testbeam: layout

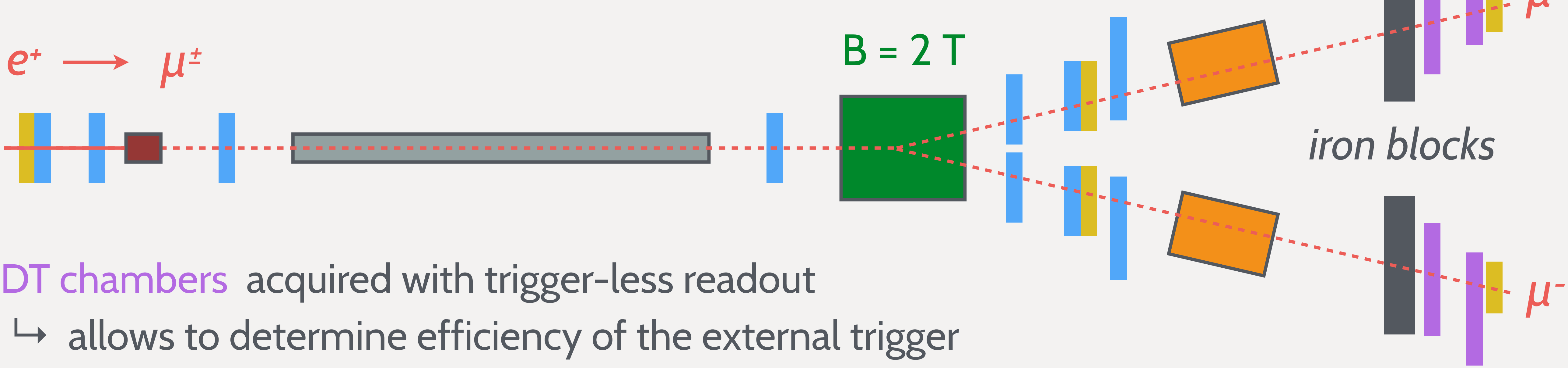
A combination of detectors used to measure the $\mu^{\pm}$ trajectories and energies

Experimental setup:

August 2018



Scintillators used as external trigger for the Silicon stations and Calorimeter



DT chambers acquired with trigger-less readout

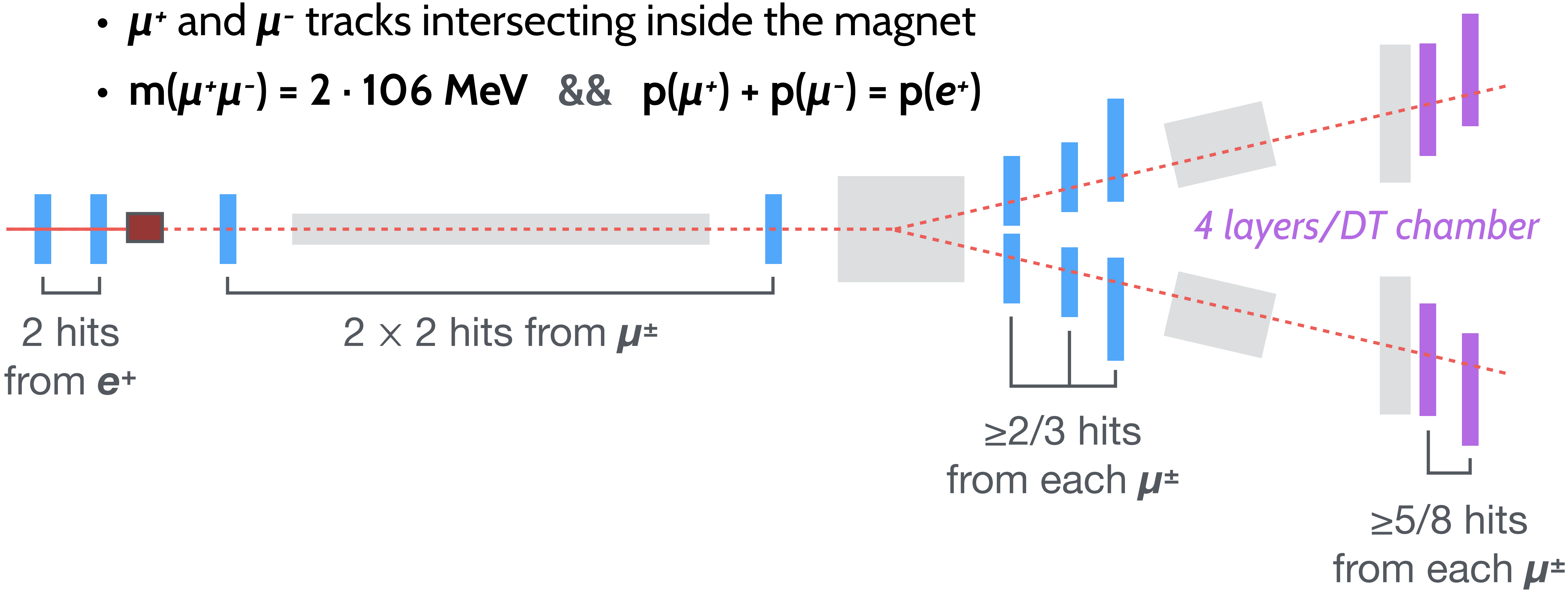
↳ allows to determine efficiency of the external trigger

Several calibration runs were performed without a target:

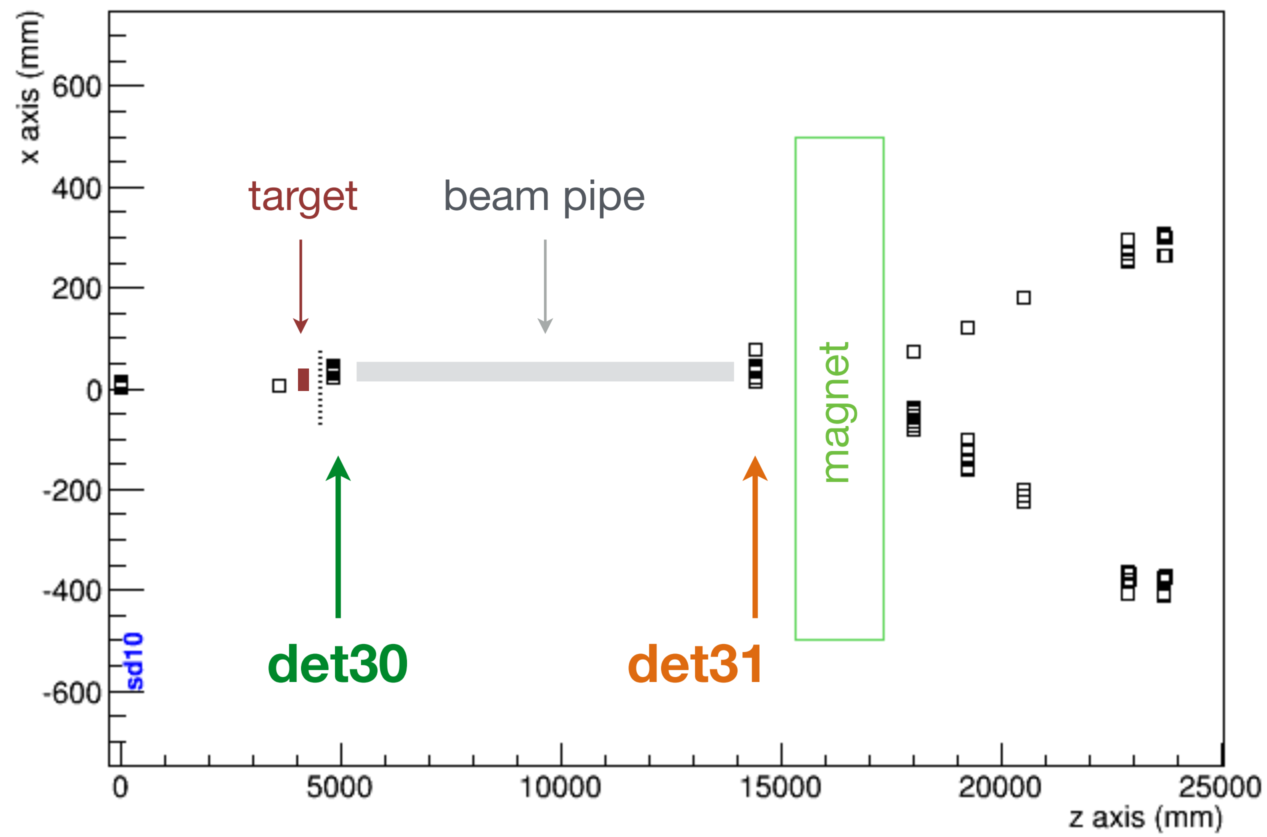
- **μ^- beam:** for alignment of the Calorimeters and DT muon chambers
- **e^+ beam:** for alignment of the Silicon stations + calibration of the Calorimeters

First version of muon analysis performed: *calorimeter information not considered*

- reconstructing e^+ and $\mu^\pm$ trajectories and selecting good $\mu^+\mu^-$ candidate events
  - μ^+ and μ^- tracks intersecting inside the magnet
  - $m(\mu^+\mu^-) = 2 \cdot 106$ MeV && $p(\mu^+) + p(\mu^-) = p(e^+)$

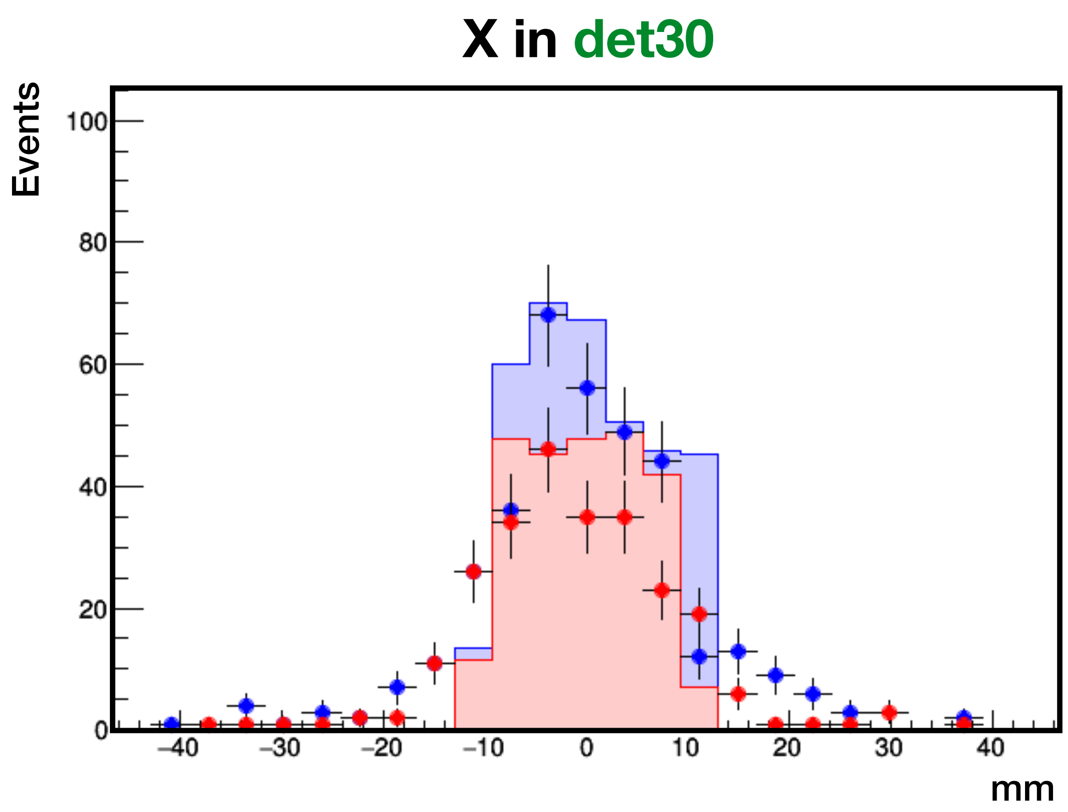


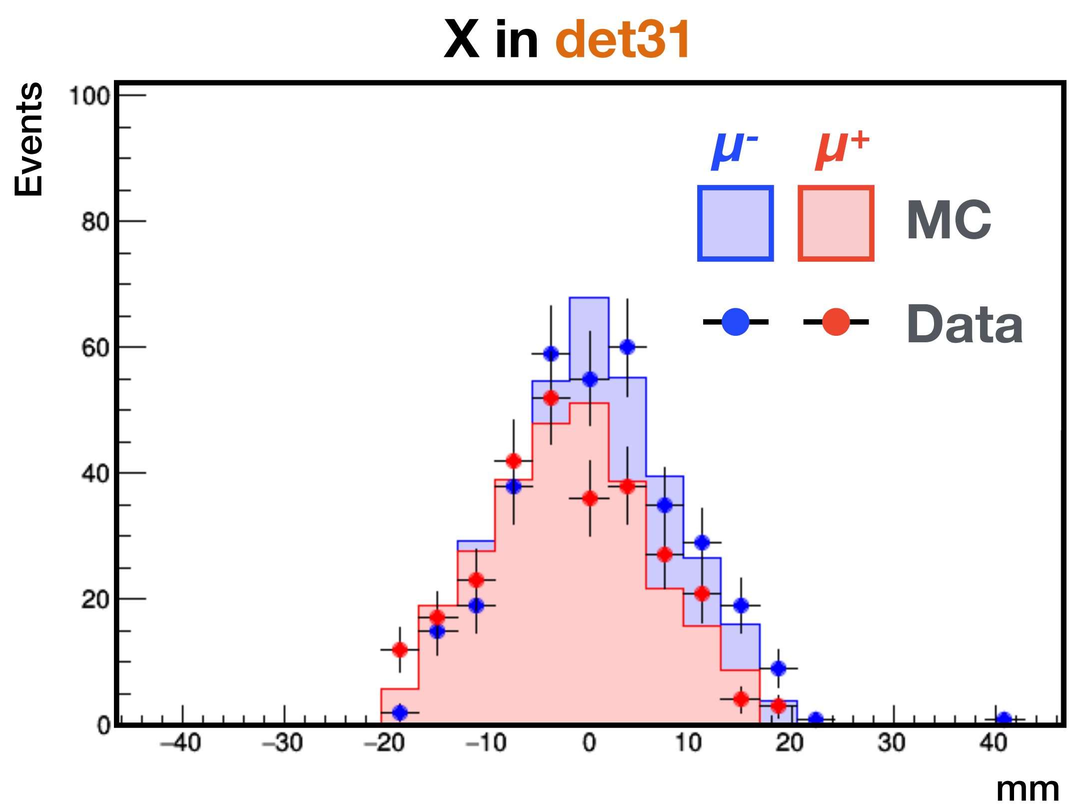
Reconstructed hits from Silicon stations and DT chambers in a signal event →
(August 19th, 2018)



Reconstructed hit positions in silicon stations before and after the beam pipe

- good agreement with the MC simulation

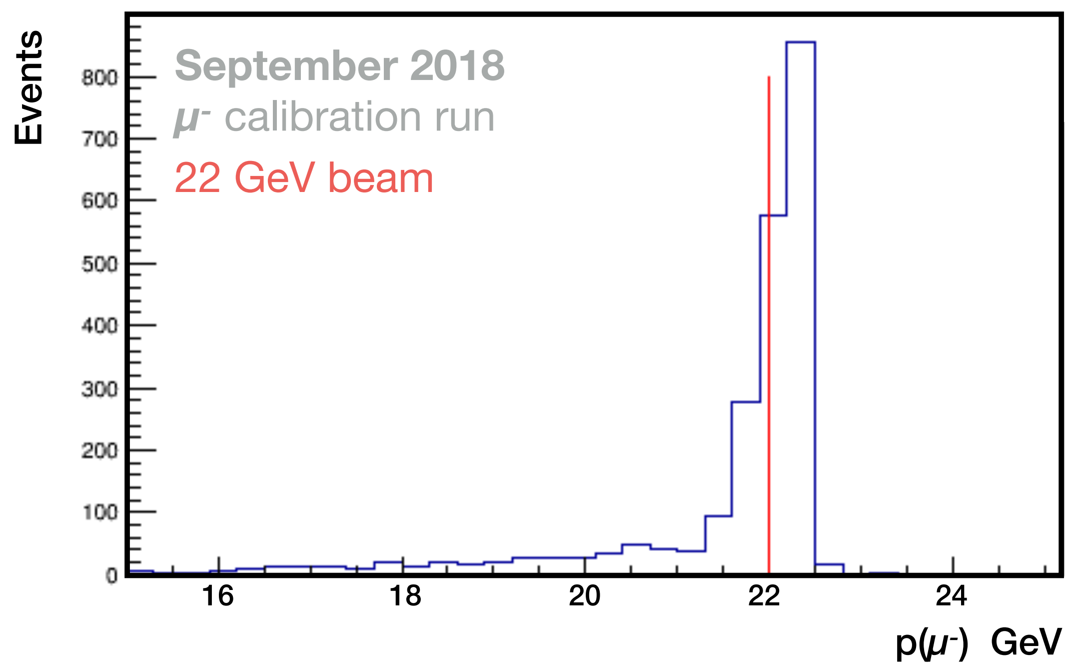




LEMMA testbeam: preliminary results

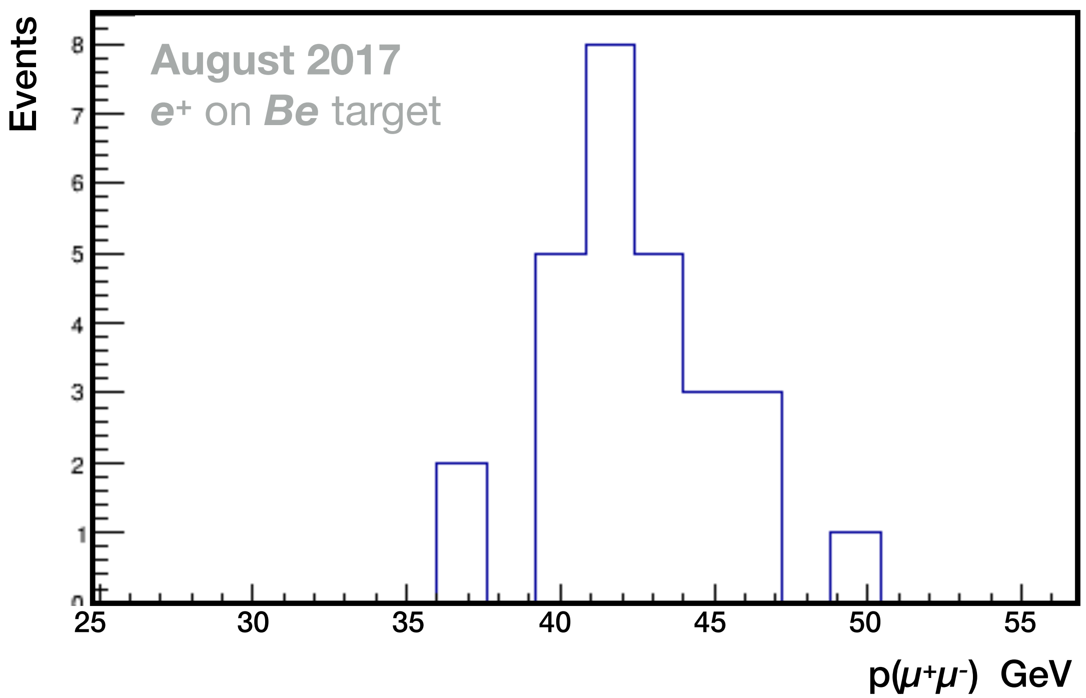
Silicon stations and DT chambers used for the muon track reconstruction

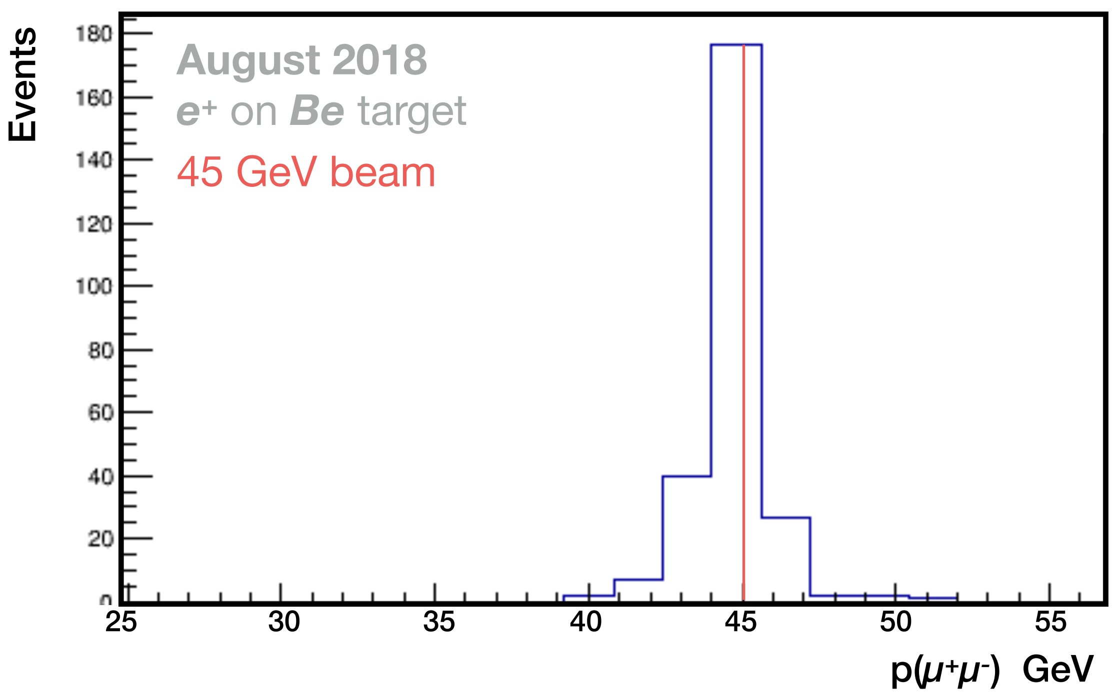
- providing ~6% momentum resolution



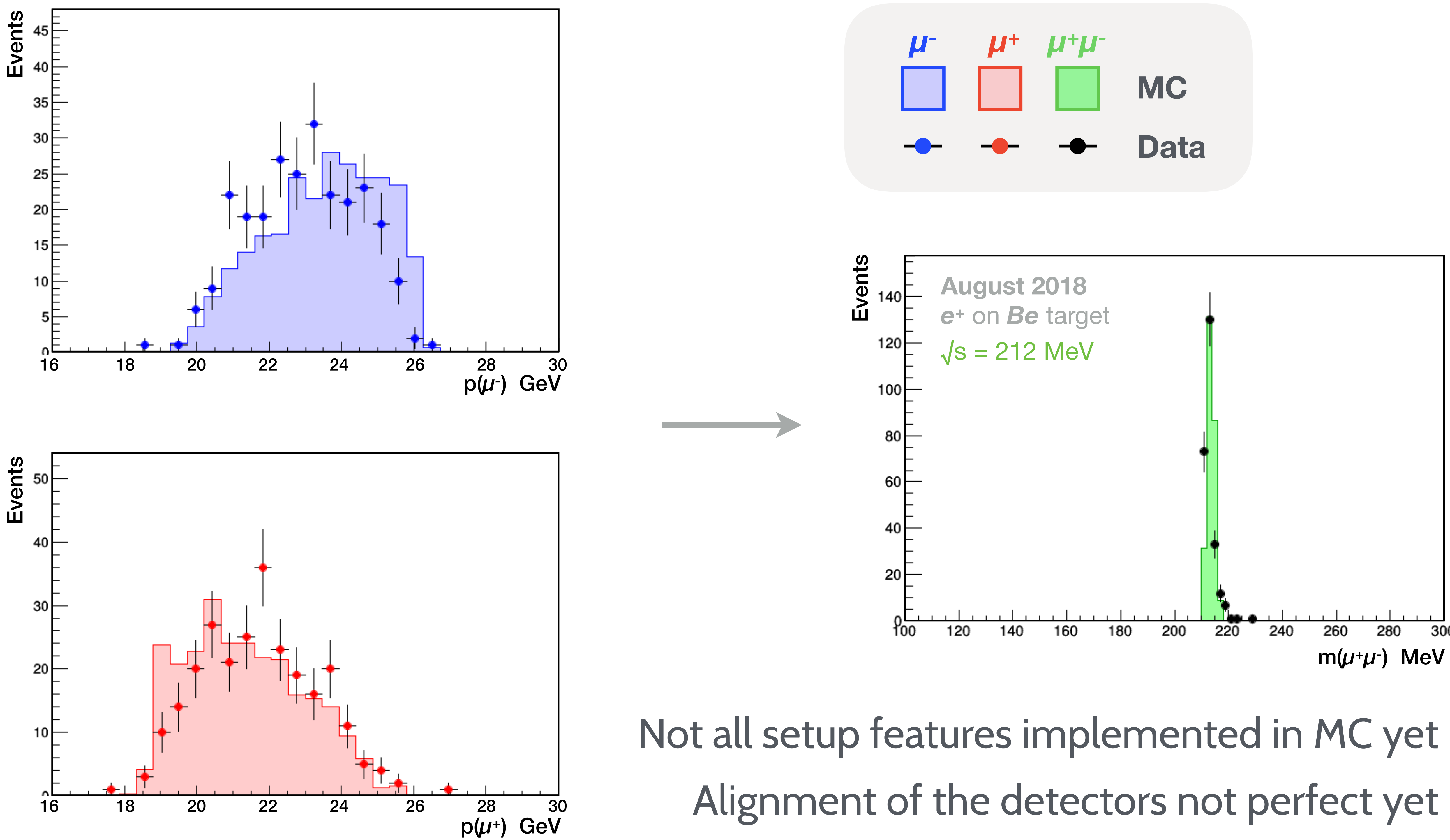
Significant improvement in 2018 compared to 2017

- low statistics due to hardware problems in 2017





Reconstructed muon kinematics in a good agreement with the MC simulation



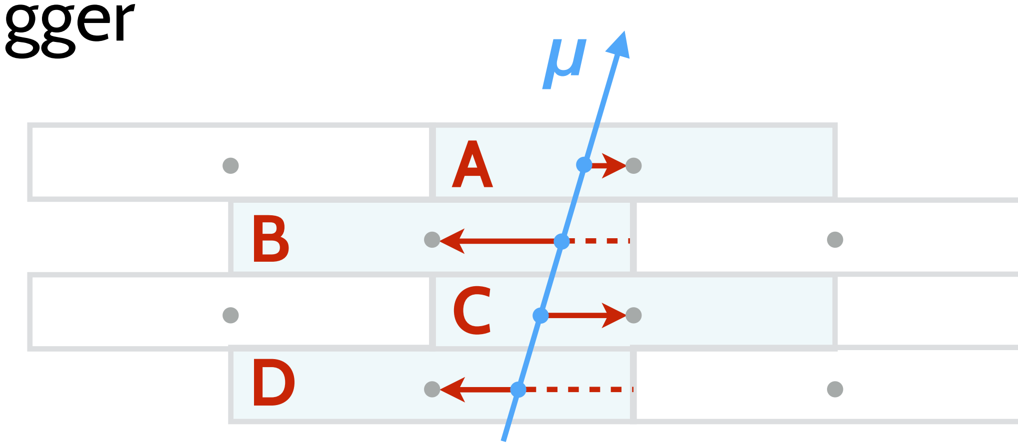
Not all setup features implemented in MC yet

Alignment of the detectors not perfect yet

LEMMA testbeam: trigger efficiency

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



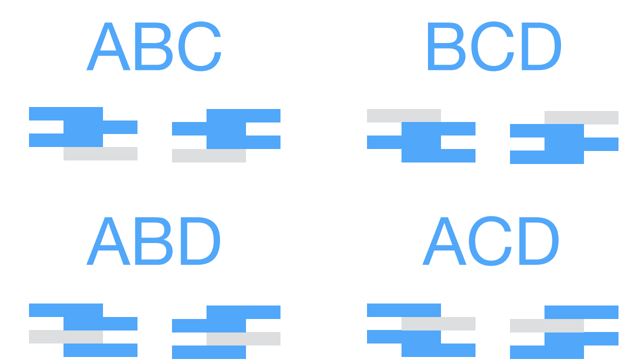
Each of the 4 chambers contains 64 cells arranged in 4 layers

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: ~10000

- trigger efficiency: ~2-20% *(preliminary estimate)*

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

Summary

A Muon Collider is a promising project that could replace or complement the rather well studied e^+e^- and *pp* collider options

LEMMA is an elegant solution for producing low-emittance muon beams

The LEMMA scheme has been implemented using the e^+ beam at CERN

A number of open questions remain:

1. Can the desired μ production rate of ~10^{11} be achieved?
2. What is the actual luminosity vs emittance dependence?
3. What is the effect of the target material and length?

The obtained testbeam data is the first step in providing the answers

A lot of work has already been done: experimental setup + data analysis

Main ingredients of the analysis chain already in place

↳ **conclusive numerical results are a matter of time** + our devoted work