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Muon collider: the Low EMittance Muon Accelerator approach

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Physics after the LHC

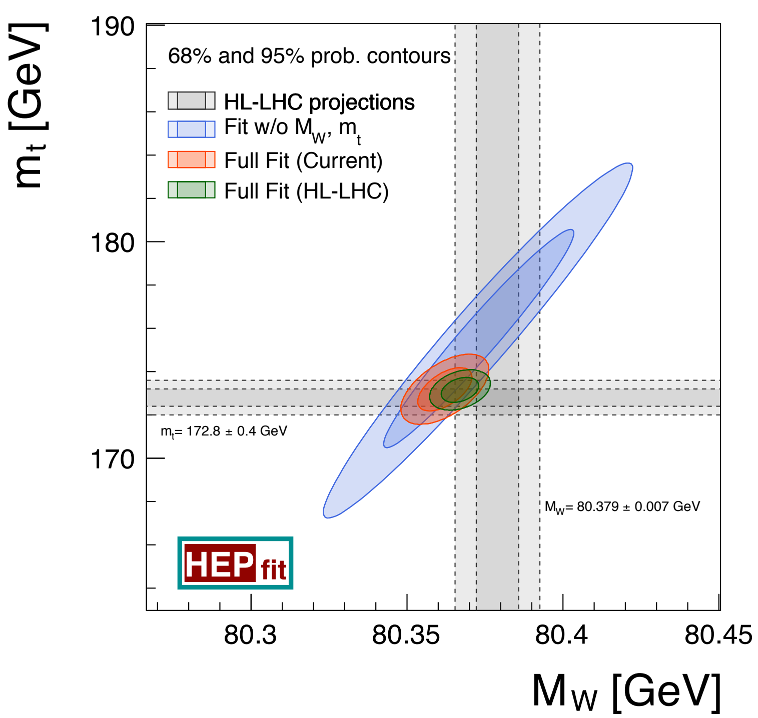
The Standard Model is incomplete and we are looking for signs of New Physics

There are two ways to search for it:

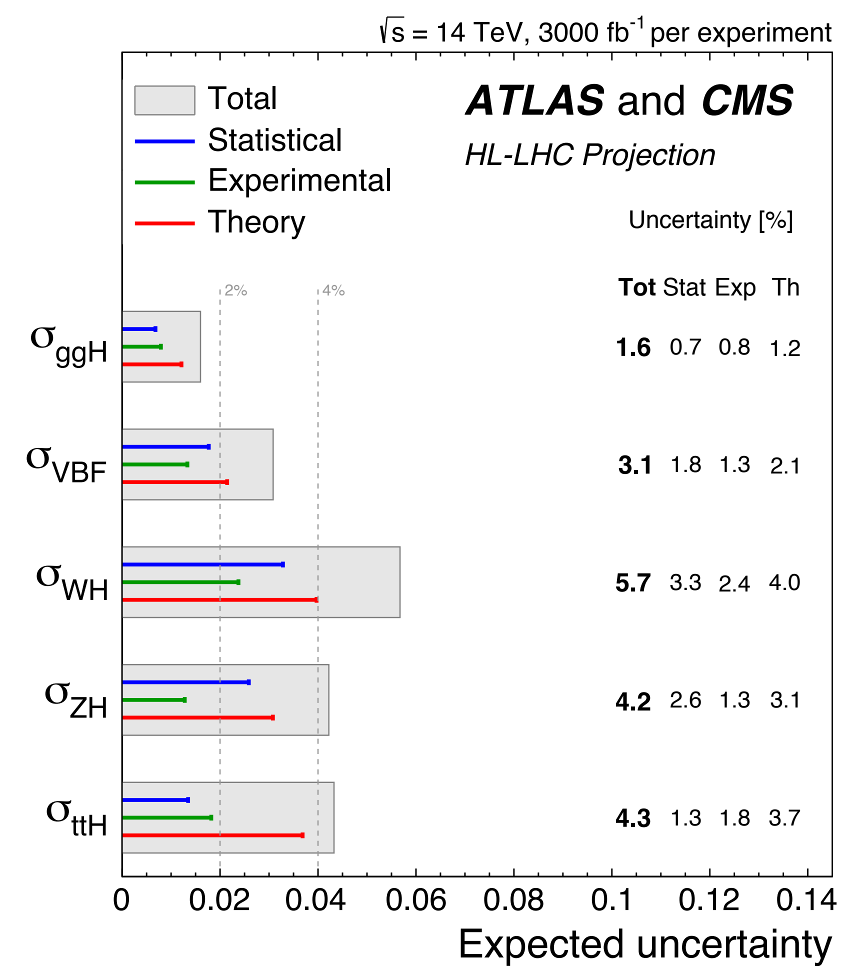
1. **direct** — observe decays of BSM particles produced in high $\sqrt{s}$ collisions
2. **indirect** — find deviations from theory in precision SM measurements

The LHC will operate until about 2040 to produce ~3000 fb^{-1} of data at $\sqrt{s}$=14 TeV

- most-notably: ~170M Higgs bosons including **~120K HH pairs → ~3σ evidence**



Experimental + theoretical uncertainties will start to limit the precision



Post LHC scenarios

Typically two classes of accelerators are considered as LHC successors:

1. ***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)*

↳ **preferable for direct searches**

2. ***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

↳ **vital for indirect searches**

Each of the two scenarios requires a dedicated accelerator complex **+ new tunnel**

↳ increased time and cost requirements for the accelerator construction

There is an alternative: Muon Collider

Muon Collider: benefits

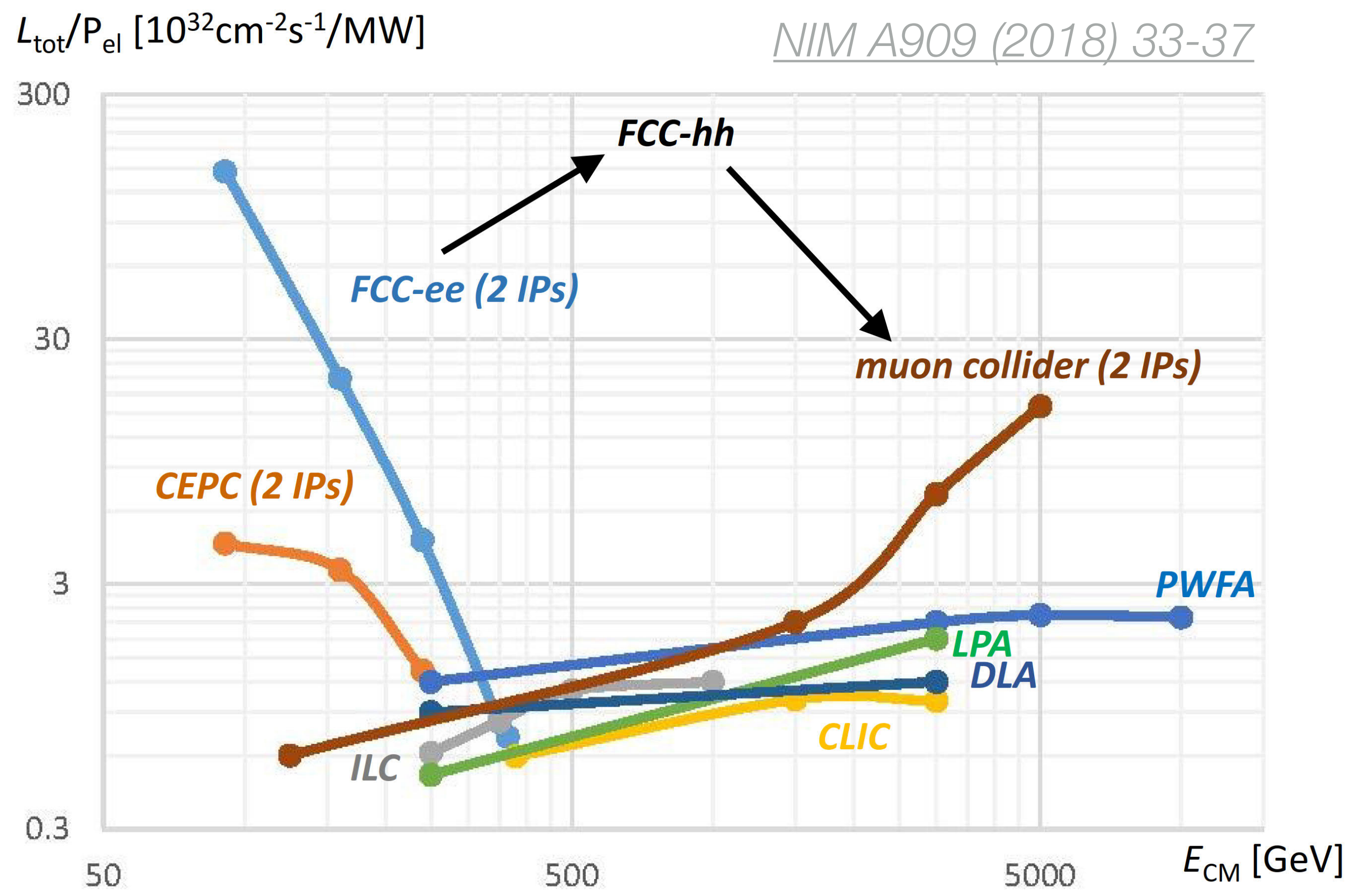
Advantages of both *pp* and e^+e^- colliders can be combined in a $\mu^+\mu^-$ collider

+ **same clean final states as in e^+e^- collisions**
+ **initial state kinematics precisely known**
+ **all energy delivered to the collision**: *multi-TeV particles can be produced*
+ **much less synchrotron radiation:** *compact layout + energy efficient*
  ↳ **$\sqrt{s}$ = 14 TeV collider** can be fit in the existing LHC tunnel ≈100 TeV ***pp*** collider

Serious challenges to be addressed:

- accelerating and colliding muons before they decay
- suppressing background from the $\mu^\pm$ beam decay products ($e^\pm$, ν)
- **producing a low-emittance muon beam** to the accelerator

focus of this talk



Classical scheme: MAP

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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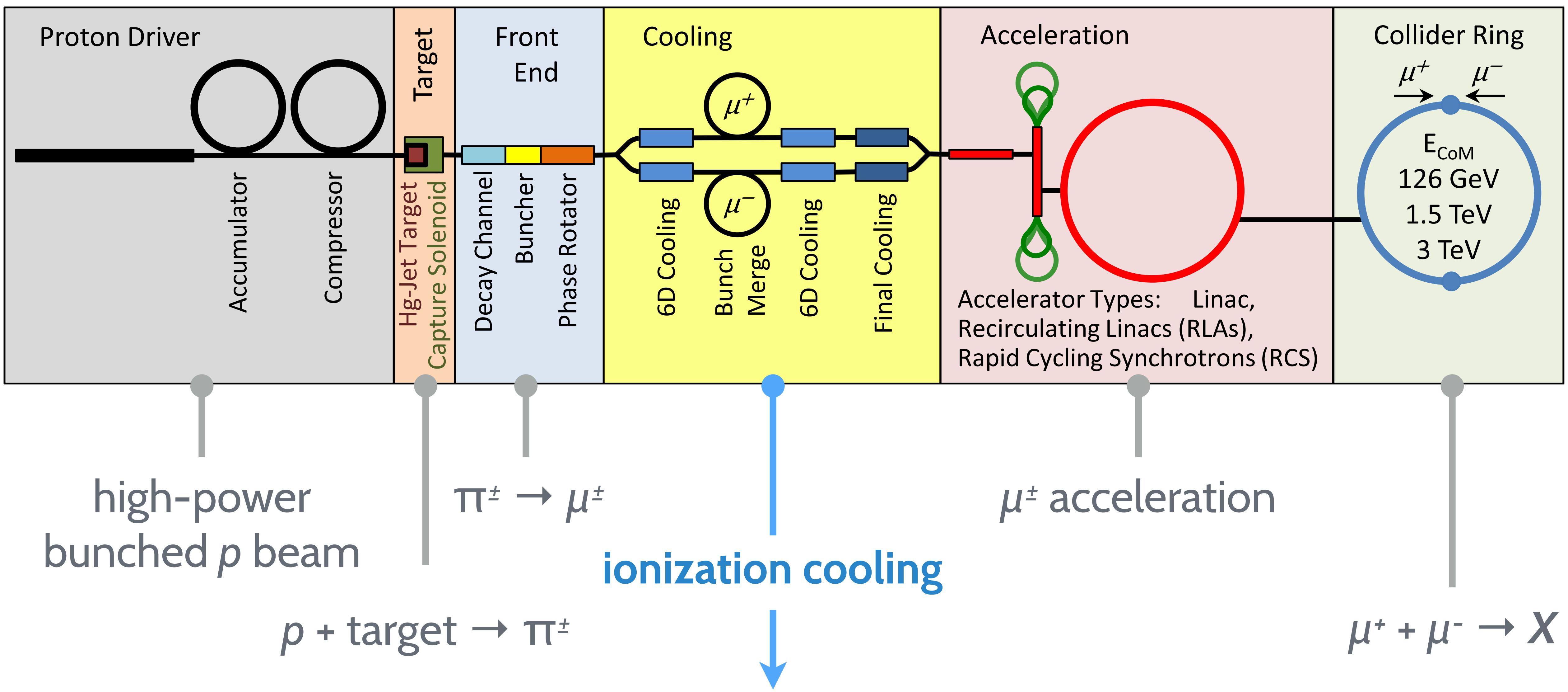
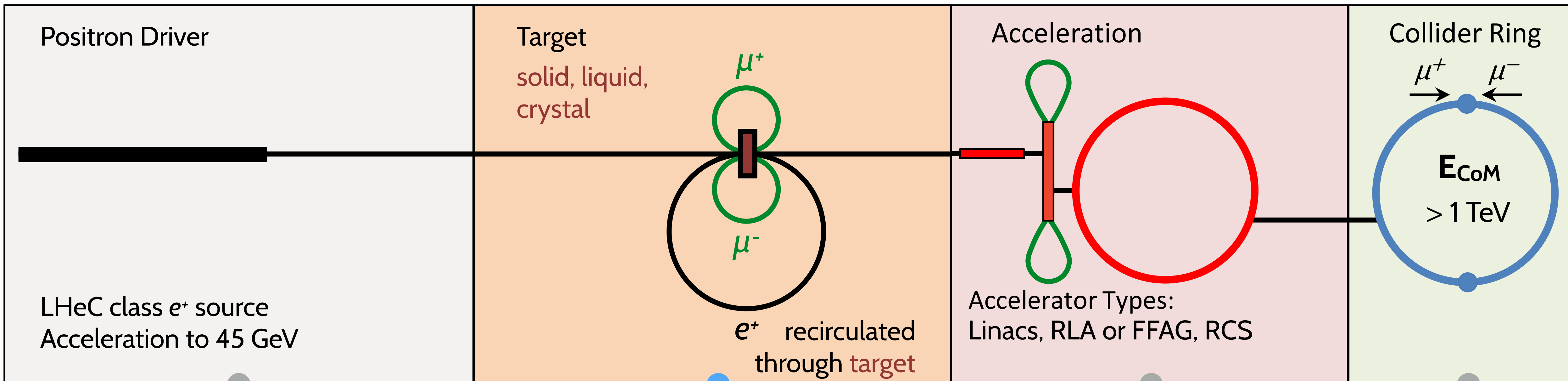


A series of RF cavities + solenoid coils to reduce the transverse beam divergence

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

LEMMA testbeam: goals

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)*

<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** (emittance, momentum, …)
- **cross section of the $e^+e^- \to \mu^+\mu^-$ production** *(depends on the e^+ energy)*
- **effect of the target material/thickness**

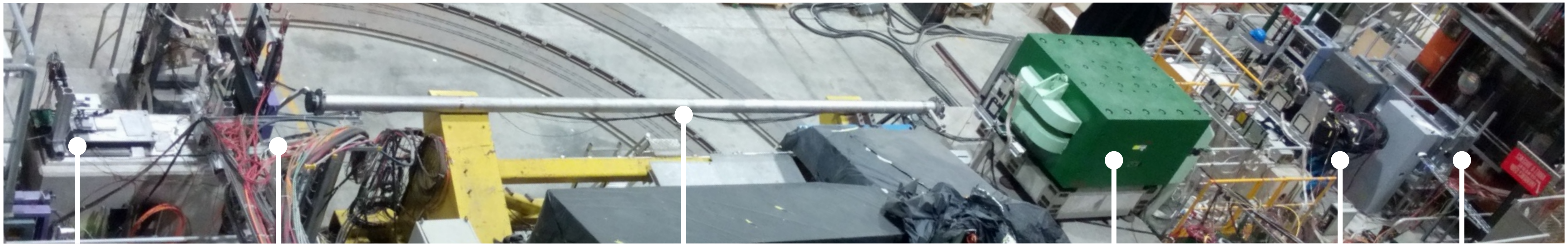
<u>Data taking performed with a number of different configurations:</u>

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

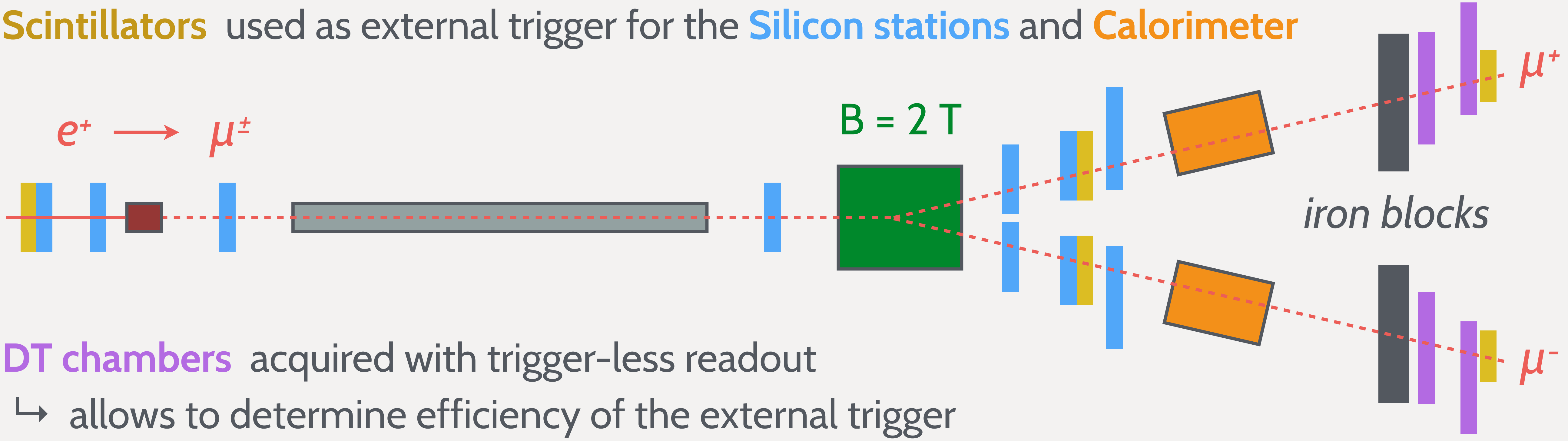
LEMMA testbeam: layout

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

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

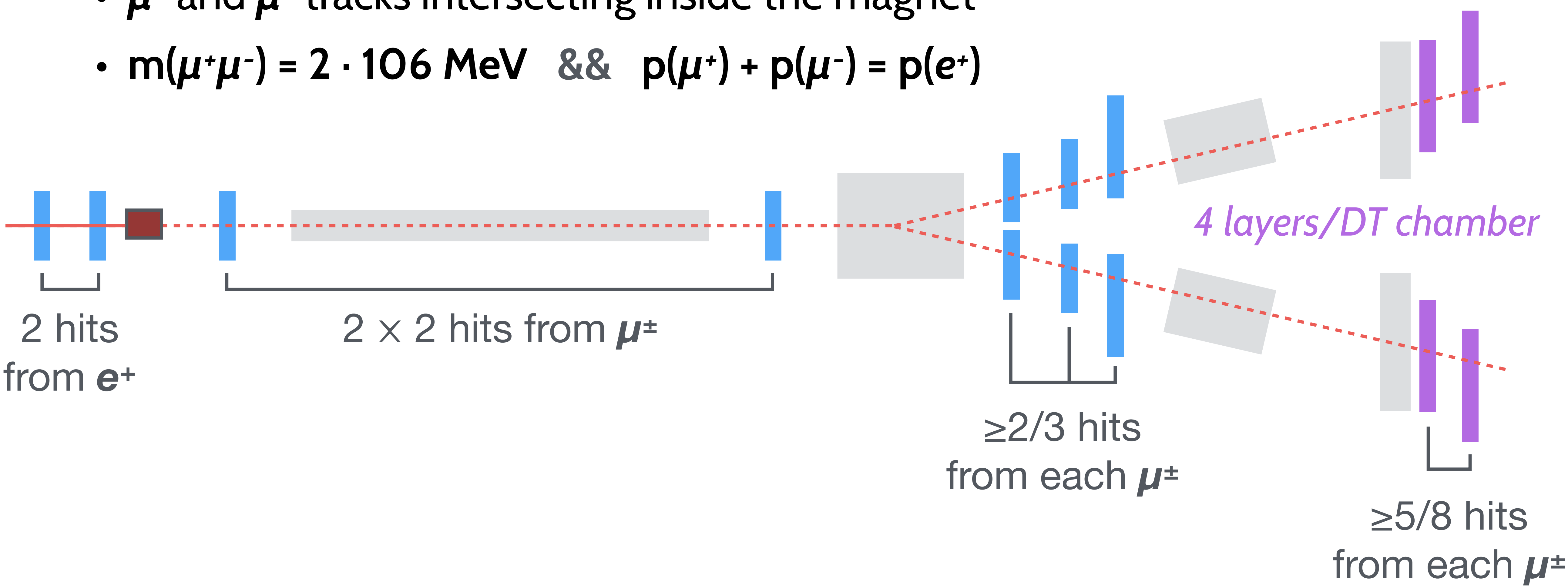
LEMMA testbeam: analysis progress

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

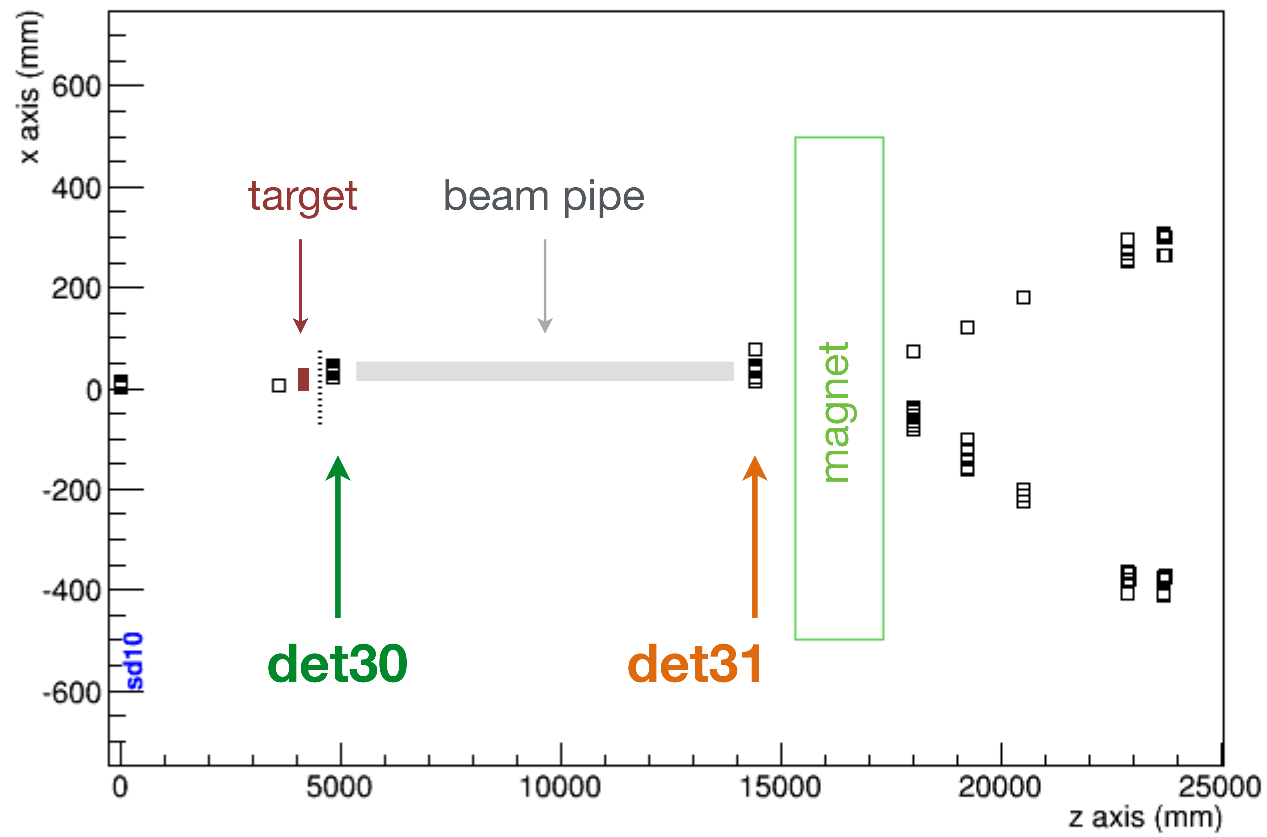
First version of muon analysis performed: *calorimeter information not considered*

- 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 && $p(\mu^+) + p(\mu^-) = p(e^+)$



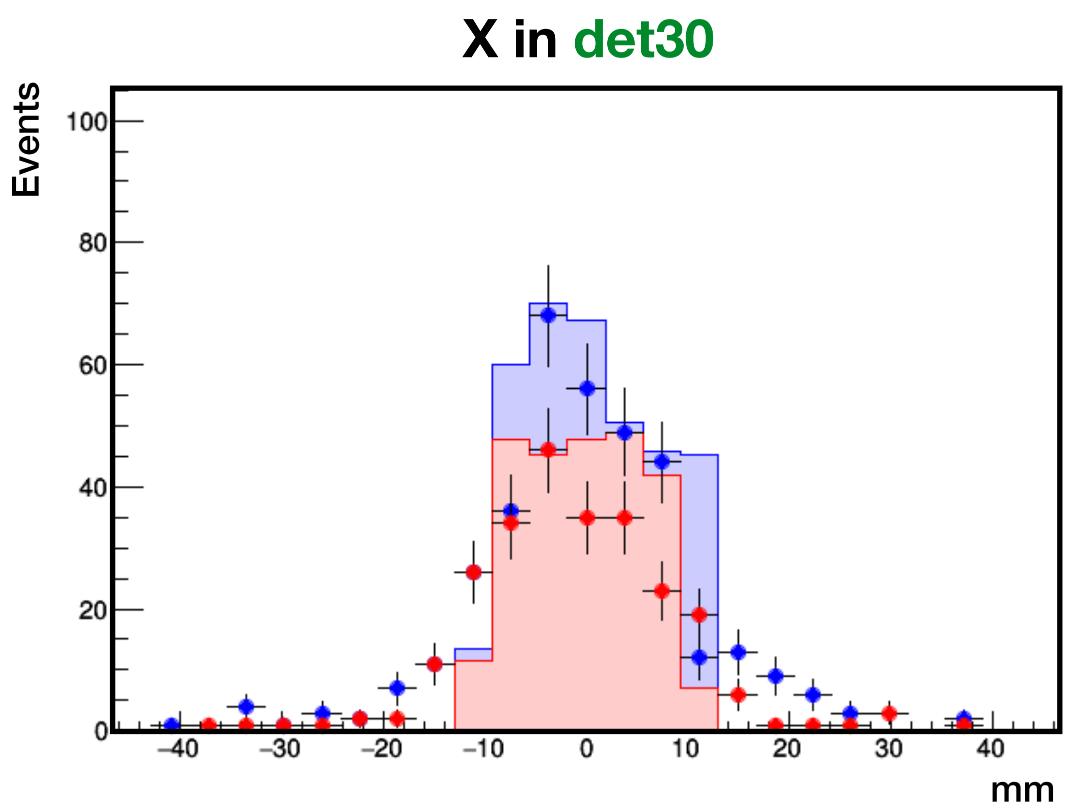
LEMMA testbeam: preliminary results

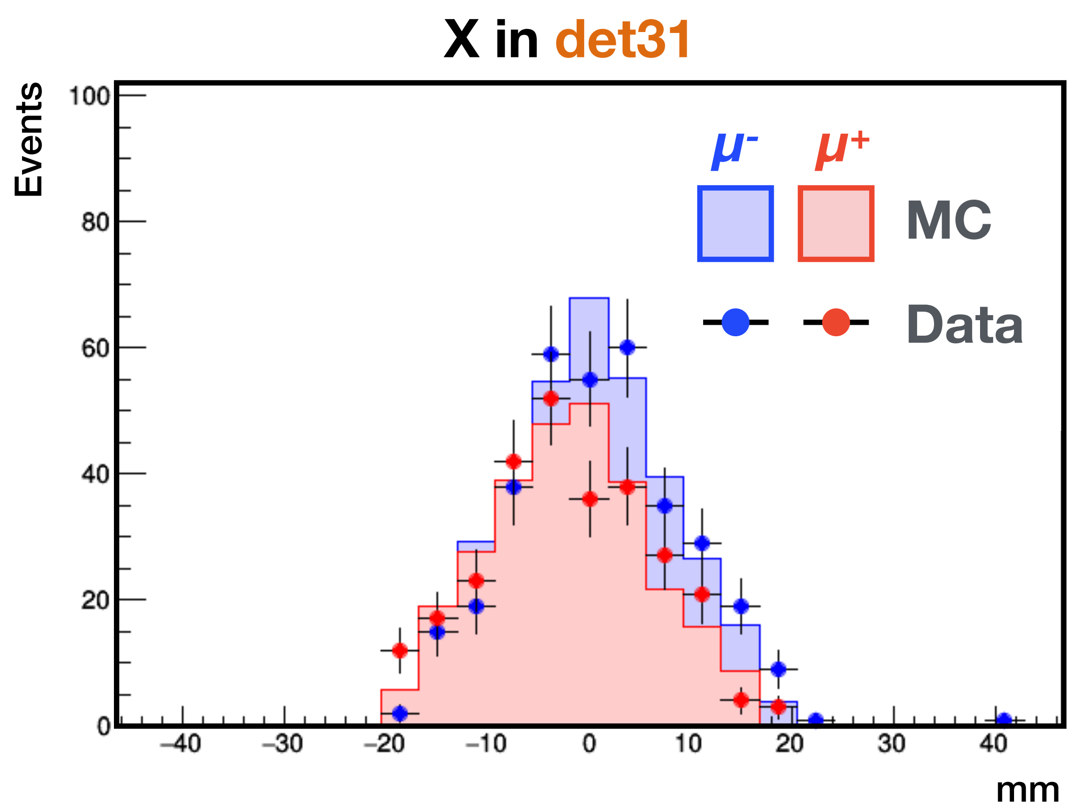
Reconstructed hits from Silicon stations and DT chambers in a signal event →
(August 19th, 2018)



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

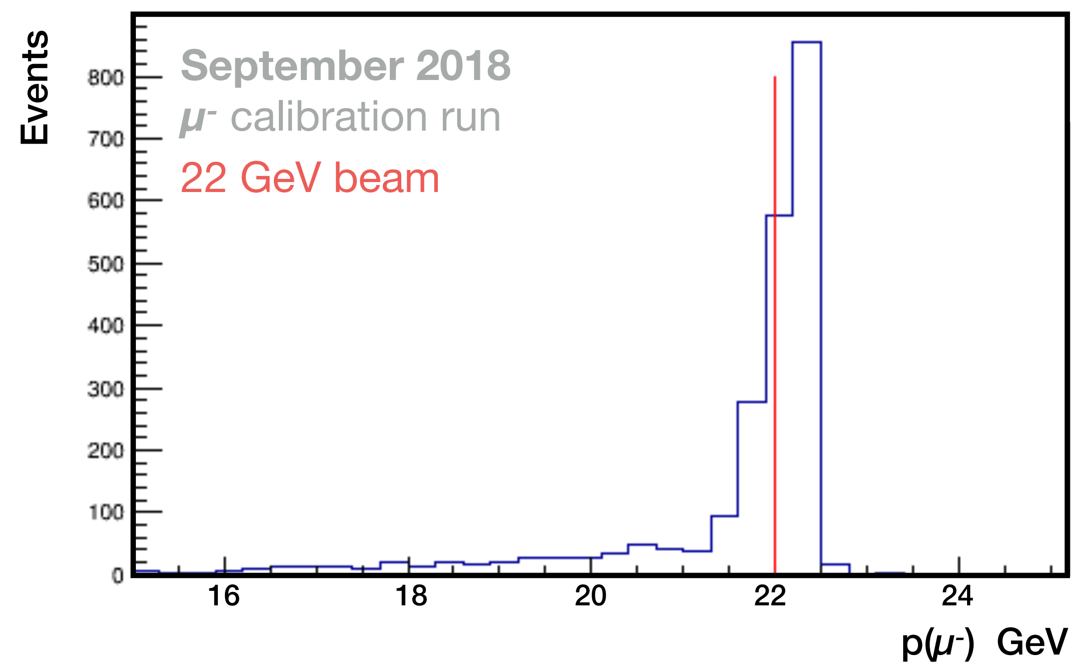
- good agreement with the MC simulation





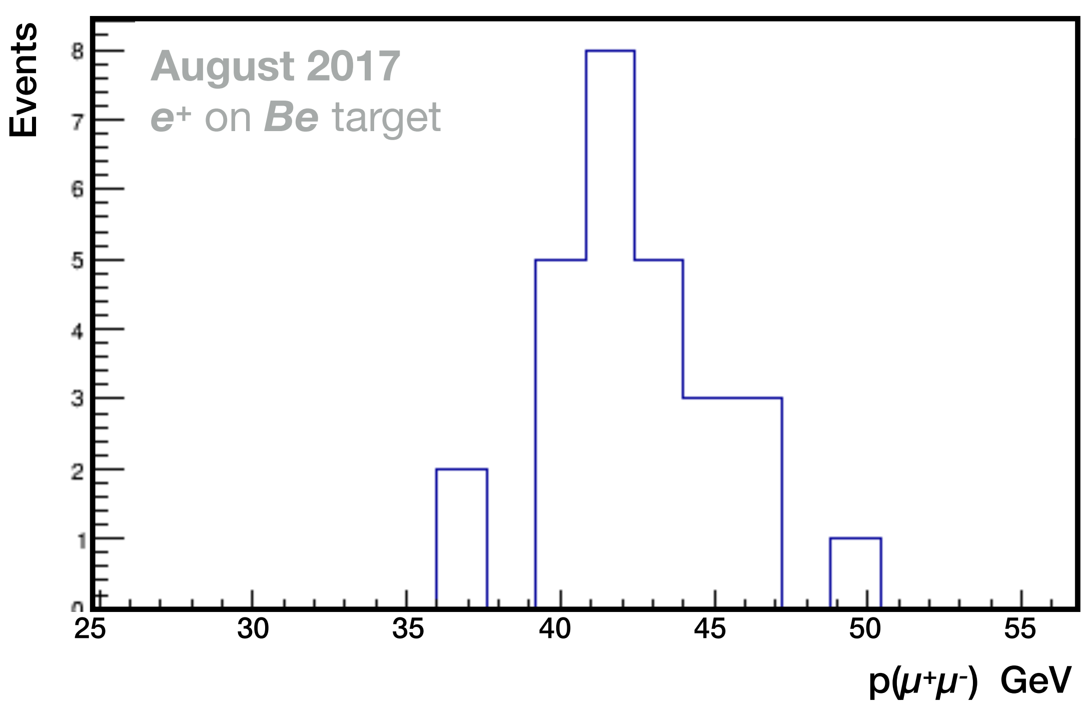
Silicon stations and DT chambers used for the muon track reconstruction

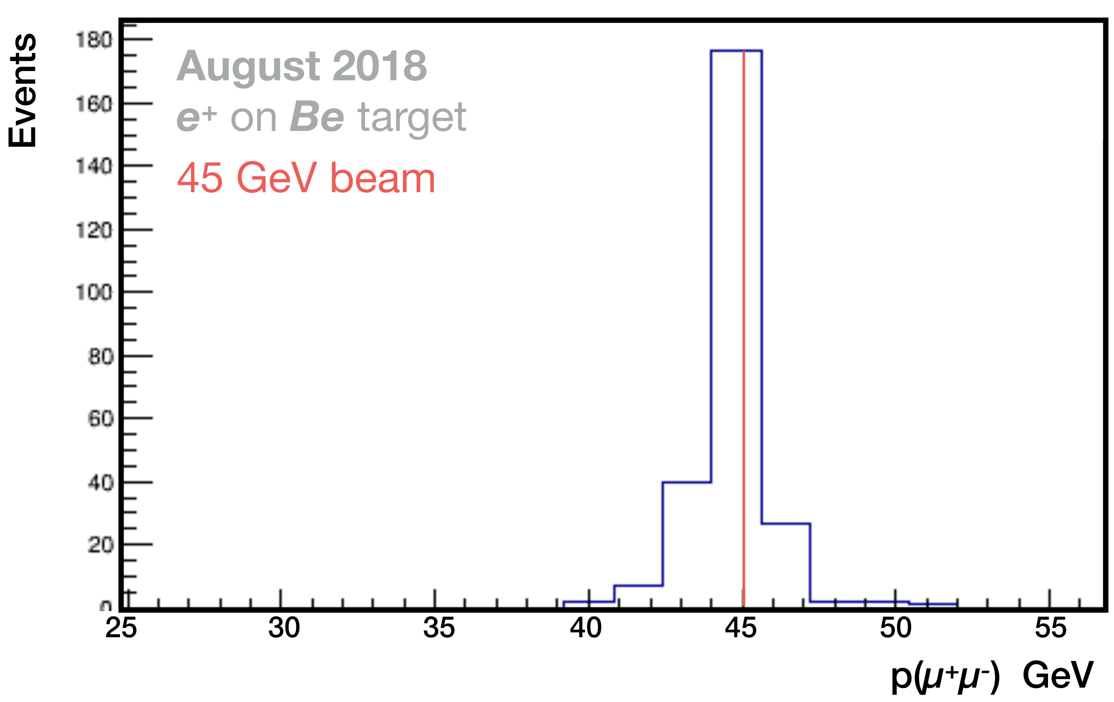
- providing ~6% momentum resolution



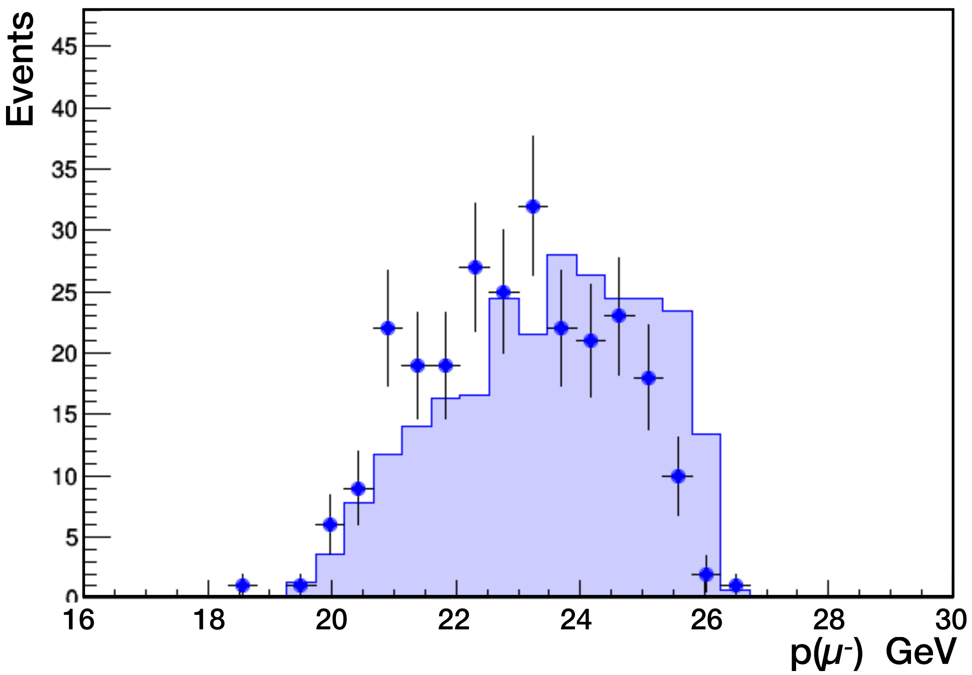
Significant improvement in 2018 compared to 2017

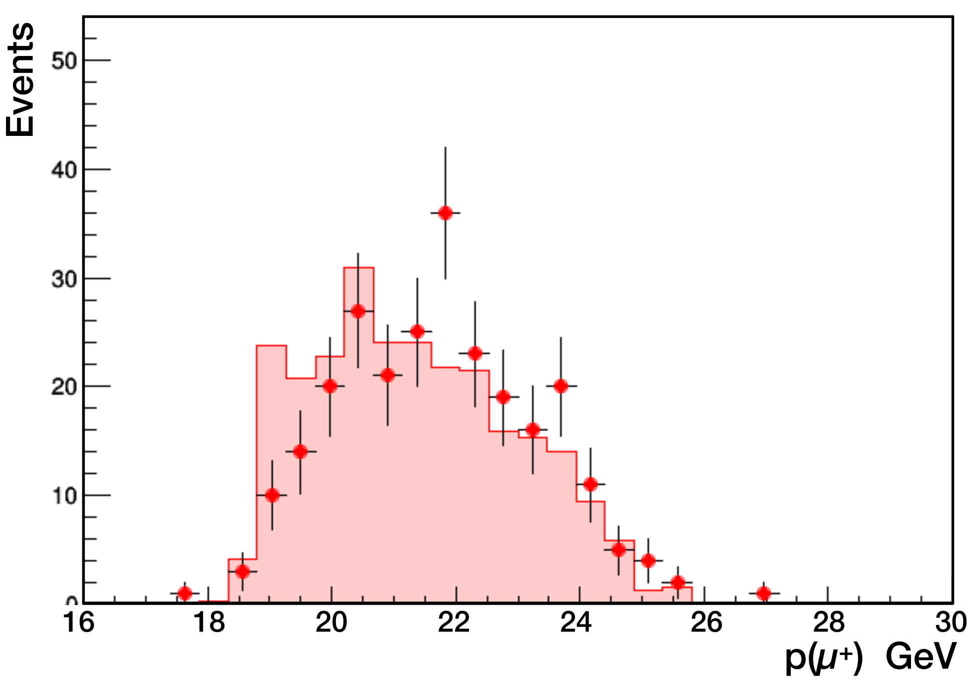
- low statistics due to hardware problems in 2017

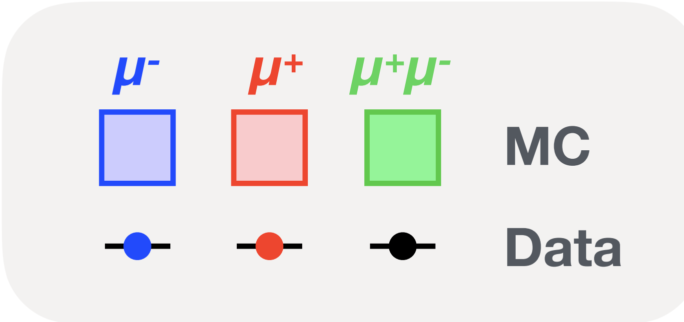


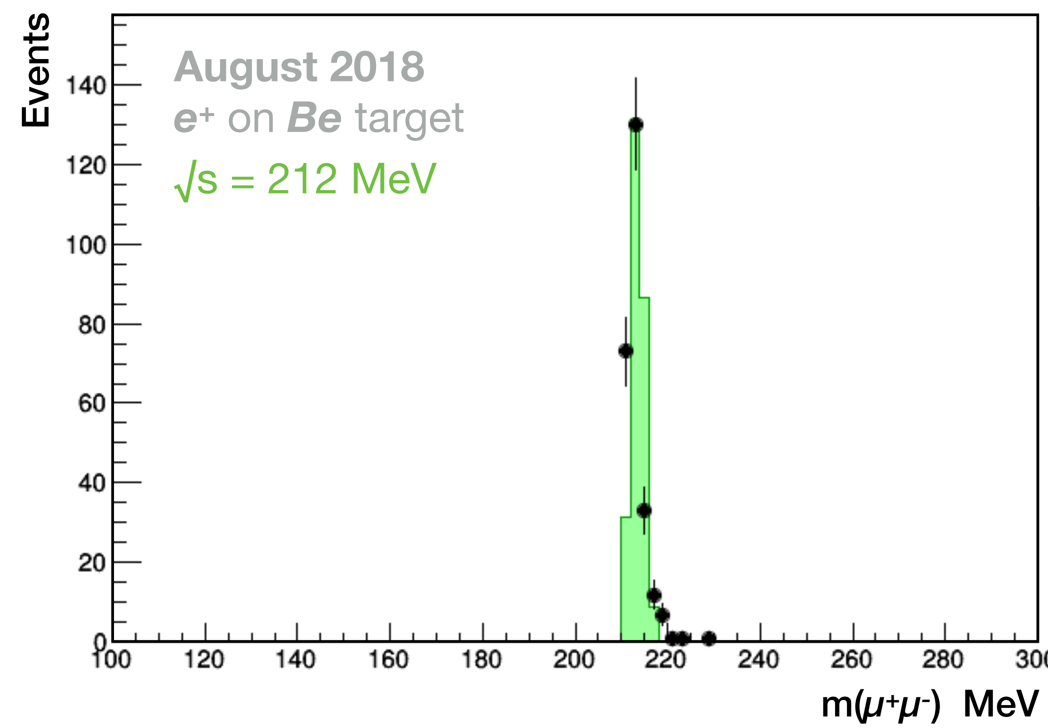


Reconstructed muon kinematics in a good agreement with the MC simulation









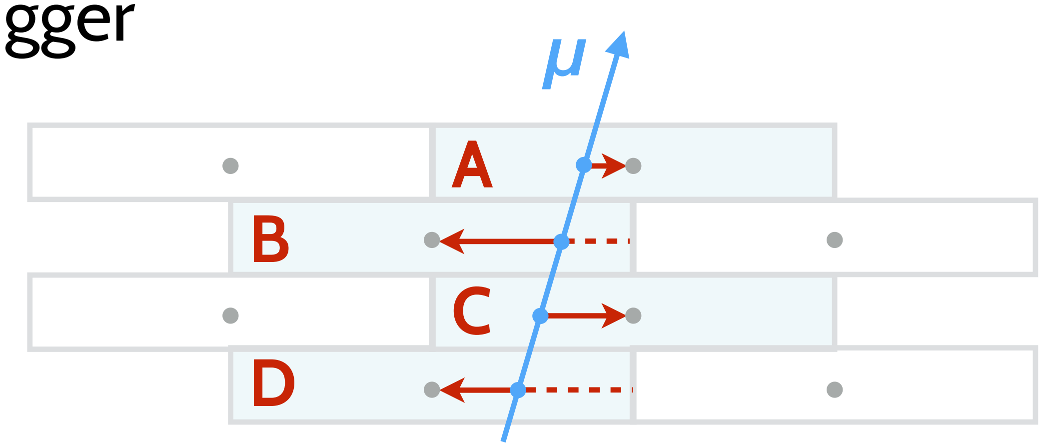
Not all setup features implemented in MC yet

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



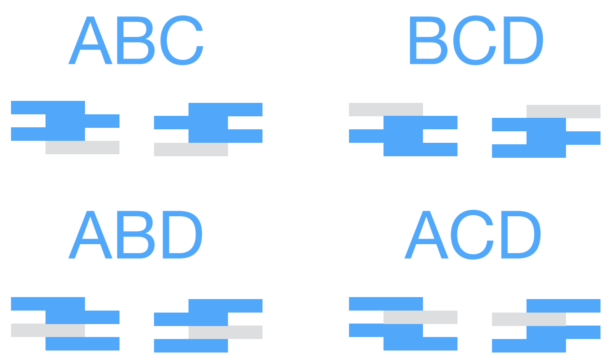
Each of the 4 chambers contains 64 cells arranged in 4 layers

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: ~10K events **preliminary**

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

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

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 $\mu^\pm$ 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 on the emittance?

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