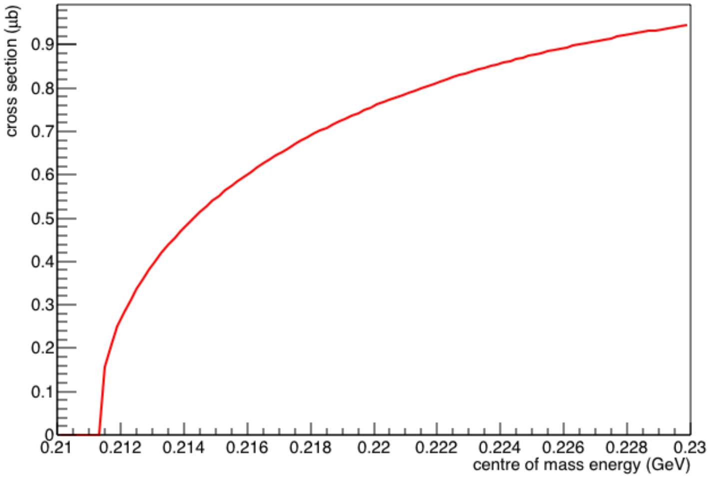
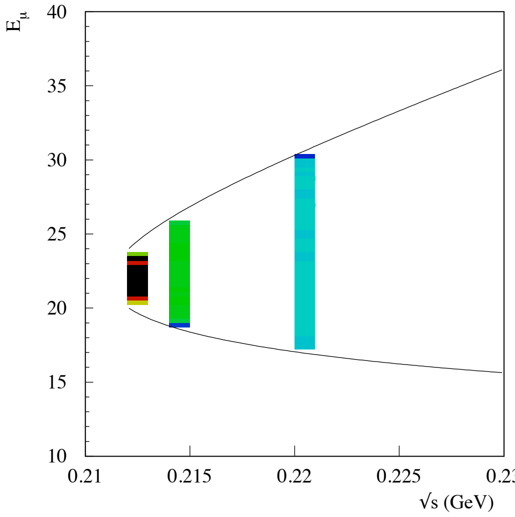
LEMMA-TB: an experiment in the CERN NA for the positron-driven muon collider

Marco Zanetti, for the LEMMA-TB team

Introduction: LEMMA

- *Low Emittance Muons Accelerator* (LEMMA): an alternative scheme to the traditional "protons-on-target" for the production of muon beams for the muon collider
  - Positrons on target, aiming at e+e- → mu+ mu-
  - Process at threshold: e+ at 45 GeV, e- at rest → high boost (~200) of the CoM system → muons preserve original e+ beam emittance
  - No cooling needed 👍, But very small cross section 👎

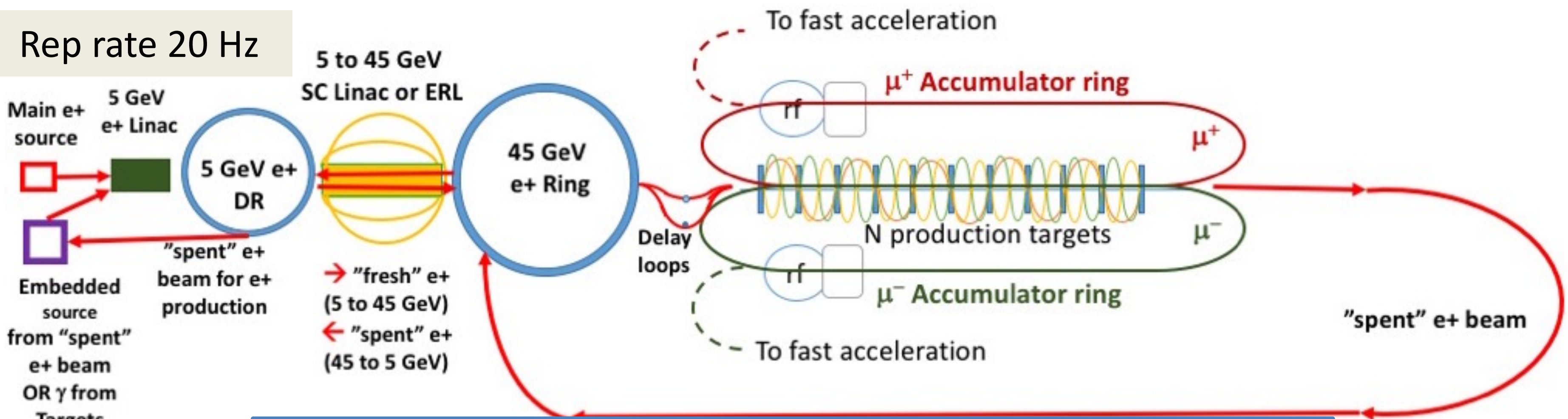




Current LEMMA scheme

- e^+ **source** @300 MeV ➔ 5 GeV Linac
- 5 GeV e^+ **Damping Ring** (damping ~10 ms)
- **SC Linac or ERL**: from 5 ➔ 45 GeV and 45 ➔ 5 GeV to cool spent e^+ beam after $\mu^\pm$ production
- **45 GeV e^+ Ring** to accumulate **1000 bunches**: **5×10^{11} e^+/bunch** for $\mu^\pm$ production and e+ spent beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- Delay loops to synchronize e^+ and $\mu^\pm$ bunches
- **One (or more) Target Lines** where e^+ beam collides with targets for direct $\mu^\pm$ production
- 2 Accumulation Rings where $\mu^\pm$ are stored until the bunch has **~10^9 μ/bunch**

Rep rate 20 Hz



M. Antonelli, M.E. Biagini, M. Boscolo, S. Guiducci, P. Raimondi, A. Variola et al.

An experiment for LEMMA

- LEMMA requirements for the e+ beam are very demanding
  - High energy, high intensity, small emittance
- Currently no machine satisfy all of them
- Still, if 45 GeV positrons are available, the production process can be studied
- The idea is then to exploit a tertiary beam in the North Area with a dedicated beam test: “LEMMA-TB”

- Note that several other tests can be conducted on the LEMMA scheme, i.e. on the targets and their thermomechanical endurance, on the optics for high momentum acceptance, etc.
  - Not discussed in this presentation

Experimental goals

- Main goal: exercise and gather experimental experience with the LEMMA production scheme

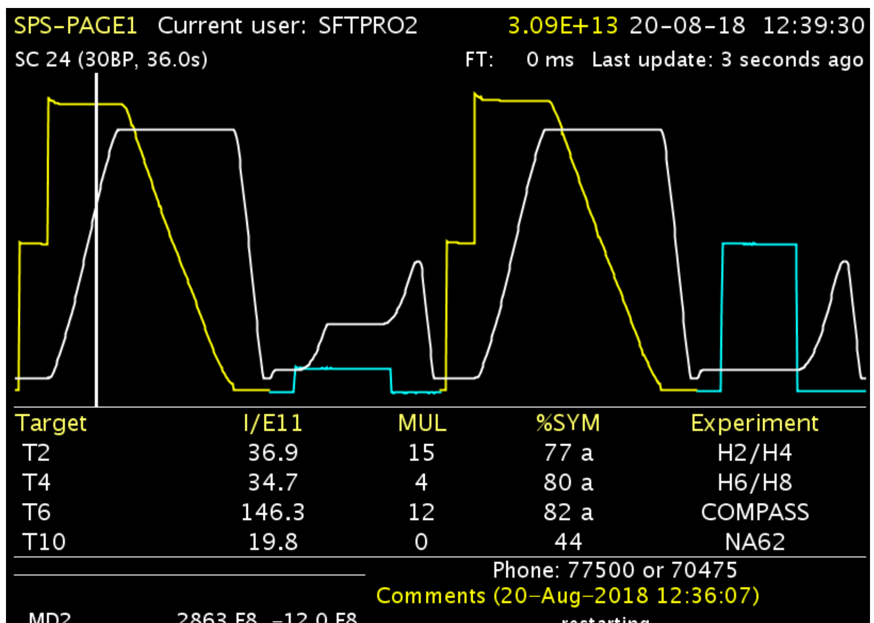
- Study the muon beam:
  - Tiny muon beam emittance, but how much exactly? How much does it depend on the properties of the e+ beam and kinematics?
  - How different target choices affect the muon beam features?
- Study the e+ spent beam:
  - Spent e+ beam needs to be recuperated and re-utilized for additional muon production: what are its properties? Can it be reused indeed?
- Physics goals
  - simple QED process, but no experimental data available at threshold!
  - Is True-muonium accessible?

Beam at the North Area

- The SPS is the only machine in the world that can currently provide a 45 GeV positron beam
- Protons on target ➔ positrons as tertiary ➔ limited beam intensity and large emittance

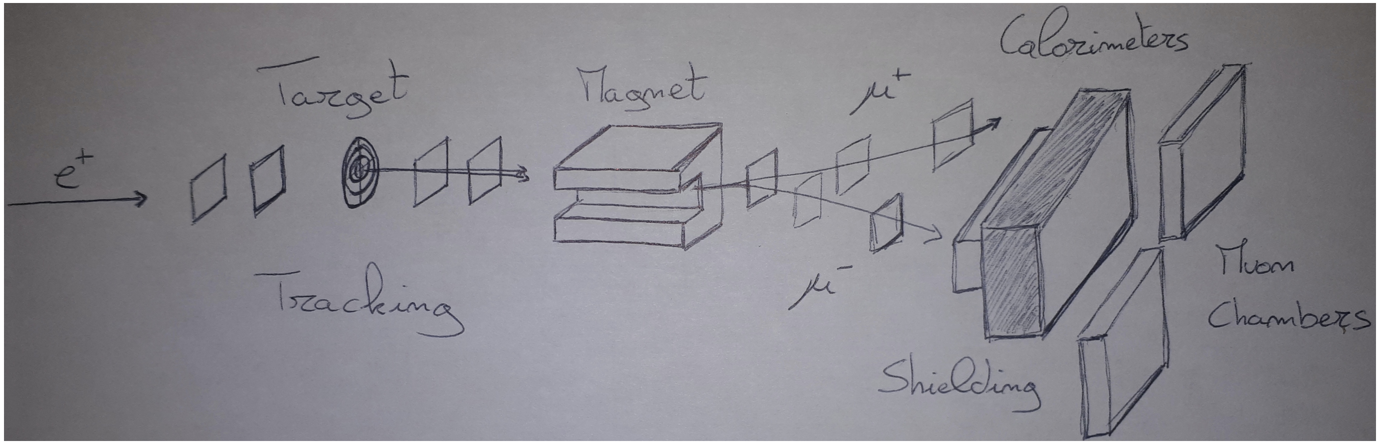
Beam at the North Area

- O (1) cm^2 spot-size on target
- About 1% energy spread at 45 GeV
- $N_{e^+} \sim 5 \cdot 10^6$ per spill (~5 sec long) ➔ ~ 1 MHz e^+ on target during the spill
  - 10^7 e+ per minute with about 2 spills per minute
- with a 0.1 X_0 thick Be target: $N_{\mu\mu} = N_{e^+} \, \sigma \, \rho \, l \sim$ 5 per spill



Generic experiment layout

- A "thick" (w.r.t LEMMA scheme) target, e.g. 3 cm Be target to gain on event statistic
- Precision tracking around the target (see later)
- Dipole to separate μ^+ - μ^- , μ^+ (~20 GeV) vs e^+ (<45 GeV)
- Calorimeters to measure spent beam, Bhabha and $\gamma\gamma$ events
- Absorbers in front of muon chambers to tag the $\mu^+\mu^-$ pair



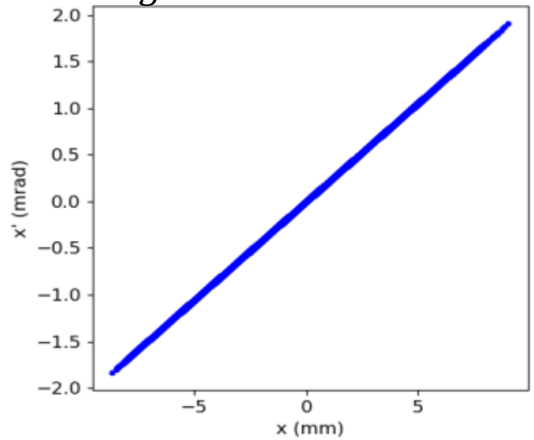
The challenge (I)

- The issue with the emittance:
  - Emittance of e+ beam in the NA is very large (several order of magnitudes larger than in the LEMMA scheme)
  - Intrinsic emittance due to muon kinematics and interaction with the target is tiny!
- Aim at measuring the “intrinsic” muon emittance by correcting event-by-event for the incoming e+ kinematics:

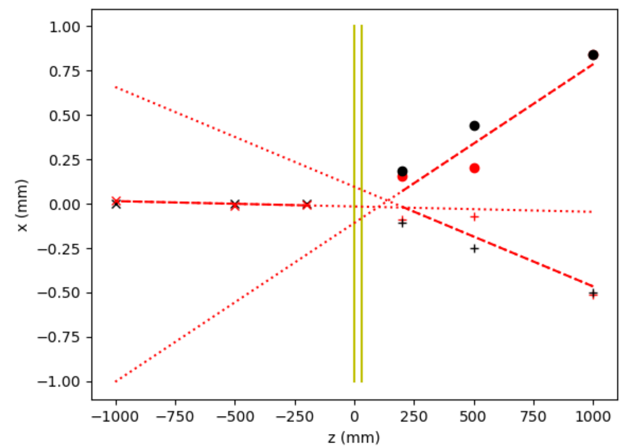
$$x = x(\mu) - x(e^+)$$
$$x' = x'(\mu) - x'(e^+)$$

- Requires extremely good tracking resolution before and after the target

$\varepsilon_{geo} = 3.8$ nm rad



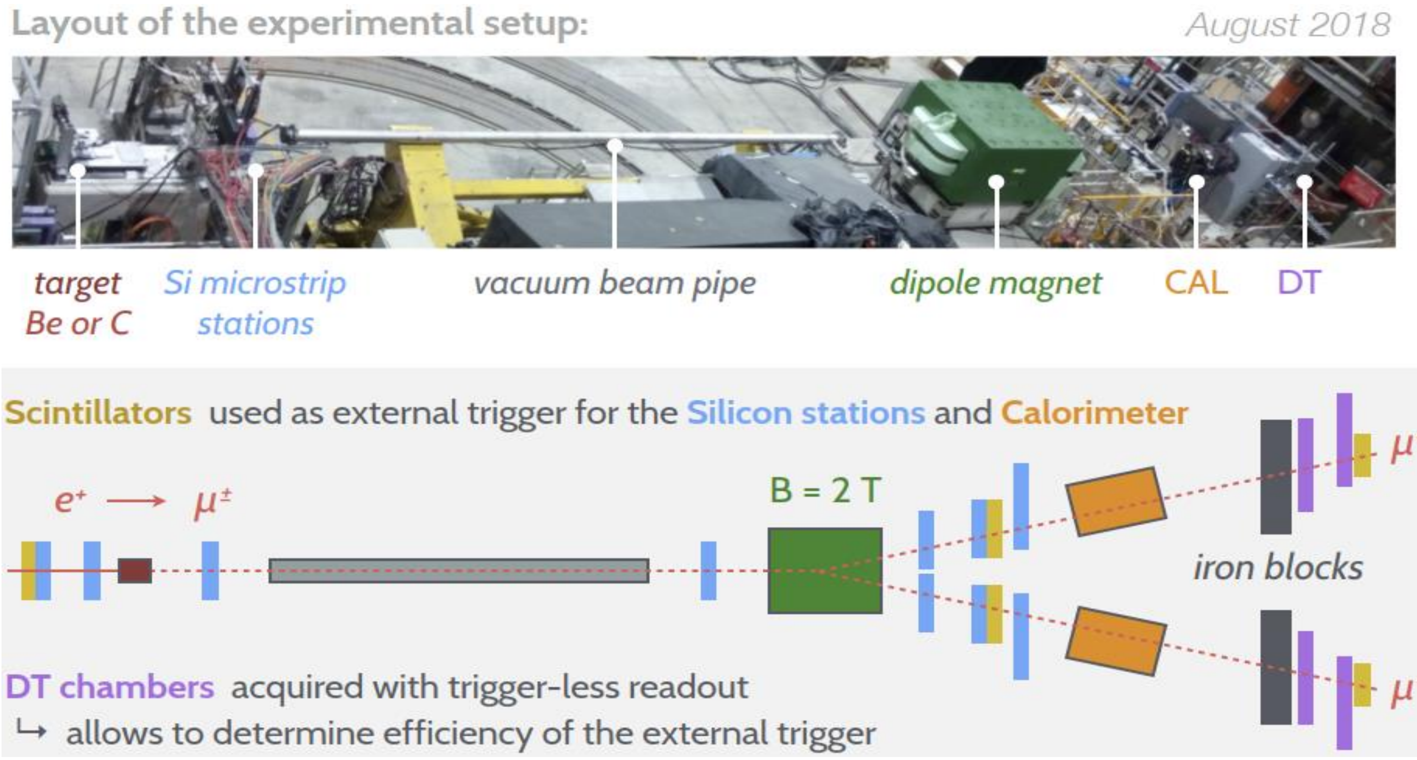
intrinsic true μ^- emittance



The challenge (II)

- Each muon –and corresponding e^+ – needs to be tracked individually ➔ need to resolve in time the structure of the NA spill (~1 MHz)
- ➔ Fast and dead-time-less trigger and DAQ systems
- Very large background to fight to isolate (eventually steer) the signal muons
  - Emerging positrons have a continuous energy spectrum, swept in a large direction range by the magnet
- Cross section measurement requires full control on trigger efficiency and detector acceptance
  - Luminosity normalization shall require reference to other physics process, e.g. $\gamma\gamma$ production ➔ dedicated calorimeter

Past experiences



- Two beam tests in the CERN NA in the past (2017 and 2018)
  - Along H4 in 2017 and H2 in 2018
  - done with essentially ~0 budget, reusing equipment from other experiments
    - Most severe limitation: low resolution, high dead-time tracking devices
  - About 10 days of beam time in total…

Preliminary results

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Study of muon pair production from positron annihilation at threshold energy

N. Amapane,[a,b] M. Antonelli,[c] F. Anulli,[d] G. Ballerini,[e,f] L. Bandiera,[g] N. Bartosik,[b] M. Bauce,[d] A. Bertolin,[h,1] C. Biino,[b] O.R. Blanco-Garcia,[c] M. Boscolo,[c] C. Brizzolari,[e,f] A. Cappati,[a,b] M. Casarsa,[i] G. Cavoto,[j,d] F. Collamati,[d] G. Cotto,[a,b] C. Curatolo,[h] R. Di Nardo,[k] F. Gonella,[h] S. Hoh,[l,h] M. Iafrati,[c] F. Iacoangeli,[d] B. Kiani,[b] D. Lucchesi,[l,h] V. Mascagna,[e,f] A. Paccagnella,[l,h] N. Pastrone,[b] J. Pazzini,[l,h] M. Pelliccioni,[b] B. Ponzio,[c] M. Prest,[e,f] M. Ricci,[c] R. Rossin,[l,h] M. Rotondo,[c] O. Sans Planell,[a,b] L. Sestini,[h] M. Soldani,[e,f] A. Triossi,[m] E. Vallazza,[f] S. Ventura[h] and M. Zanetti[l,h]

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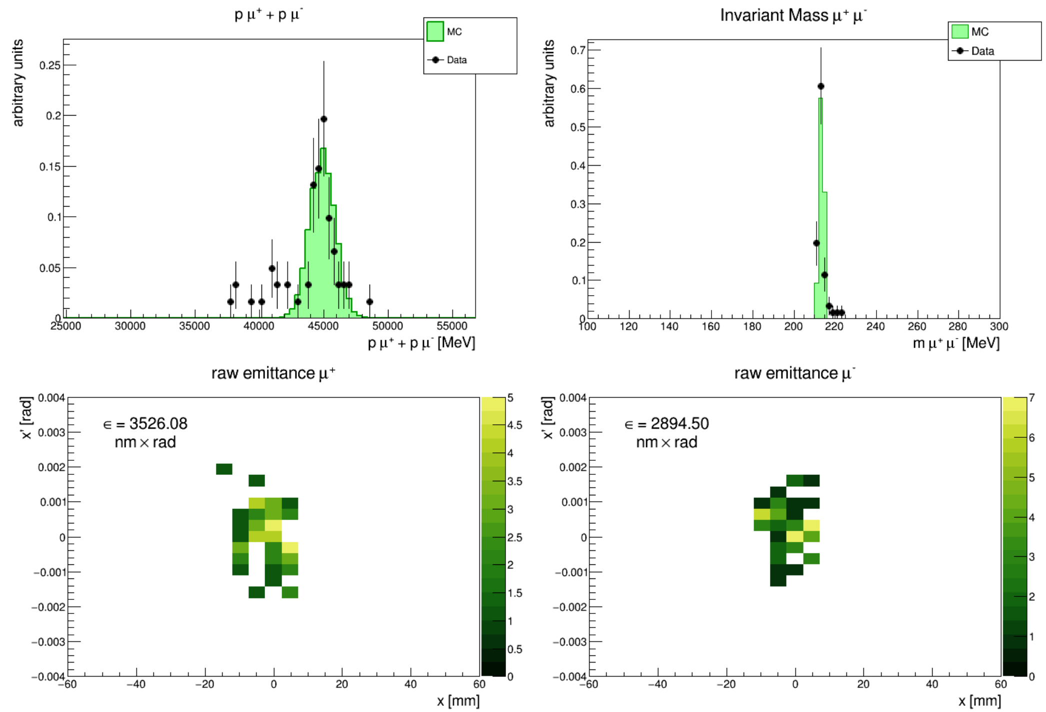
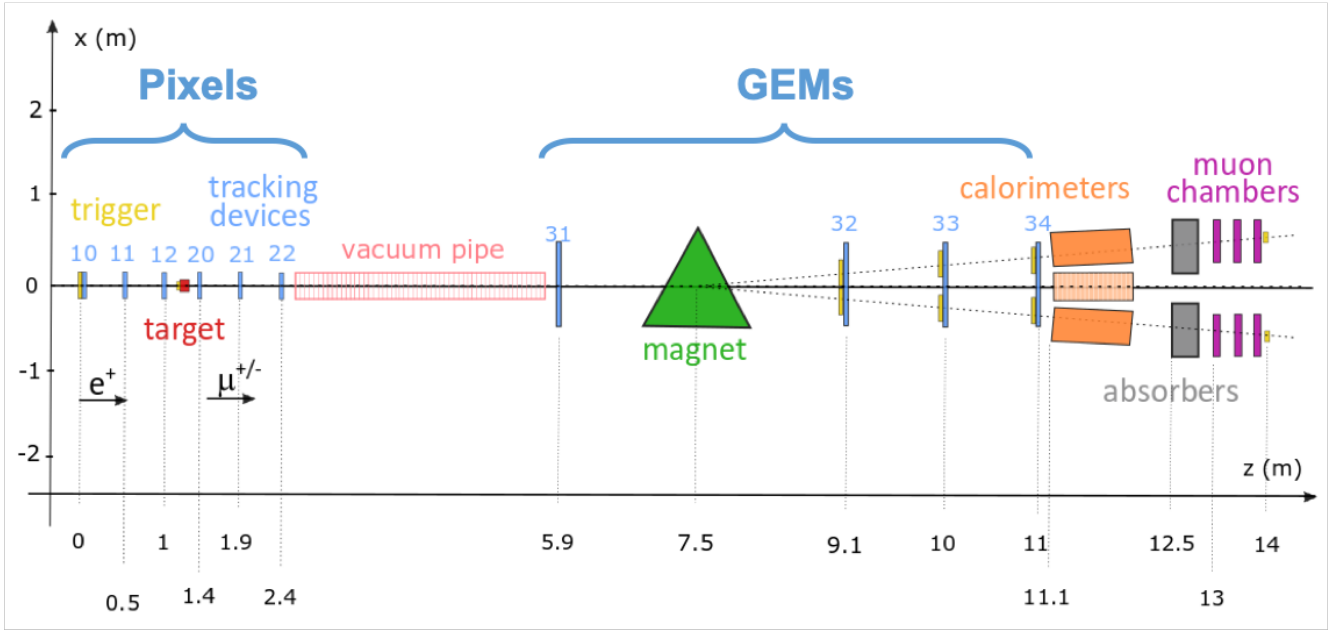


- Despite the tiny investment, some physics results obtained out of those data takings
- Most importantly, experience was gathered on what are the critical issues and how to tackle them

Experiment from 2022 on



- Fast and high-resolution pixel-based telescopes in the target region
- Fast GEM detectors beyond the magnet
- Combination of several Calorimeters
- 4+2 Muon chambers
- Improved (integrated, low dead time) DAQ system
- Improved trigger system

Experiment in 2021 (->2022)

Submitted to SPSC

CERN-SPSC-2020-004 / SPSC-P-364
07/03/2020

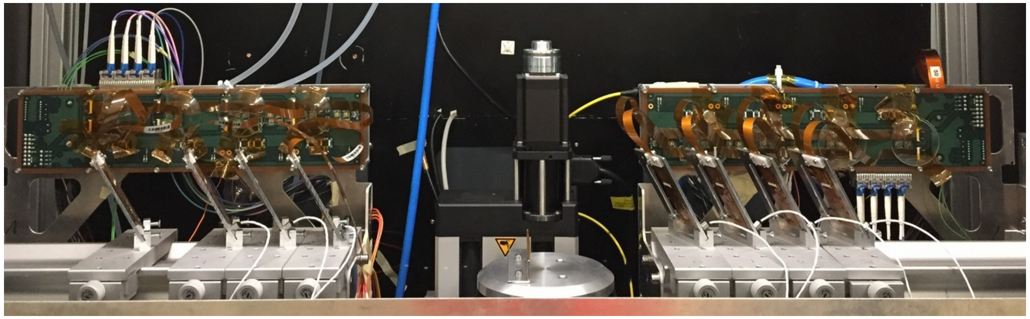
LEMMA-TB: an experiment to measure the production of a low emittance muon beam

N. Amapane[a,b], M. Antonelli[c], F. Anulli[d], N. Bacchetta[h], N. Bartosik[b], M. Bauce[d], A. Bertolin[h], M. Bianco[m], C. Biino[b], O. R. Blanco-Garcia[c], M. Boscolo[c], A. Braghieri[q], A. Cappati[a,b], F. Casaburo[l,d], M. Casarsa[i], G. Cavoto[l,d], N. Charitonidis[*m], A. Colaleo[p], F. Collamati[d], G. Cotto[a,b], D.Creanza[p], C. Curatolo[h], N. Deelen[t], F. Gonella[h], S. Hoh[n,h], M. Iafrati[c], F. Iacoangeli[d], B. Kiani[b], D. Lucchesi[n,h], V. Mascagna[e,f], S. Mersi[m], A. Paccagnella[n,h], N. Pastrone[b], J. Pazzini[n,h], M. Pelliccioni[b], B. Ponzio[c], M. Prest[e,f], C. Riccardi[q,r], M. Ricci[c], R. Rossin[n,h], M. Rotondo[c], P. Salvini[q], O. Sans Planell[a,b], L. Sestini[h], L. Silvestris[p], A. Triossi[o], I. Vai[q,s], E. Vallazza[f], R.Venditti[p], S. Ventura[h], P. Verwilligen[p], P. Vitulo[q,r], and M. Zanetti.[n,h]

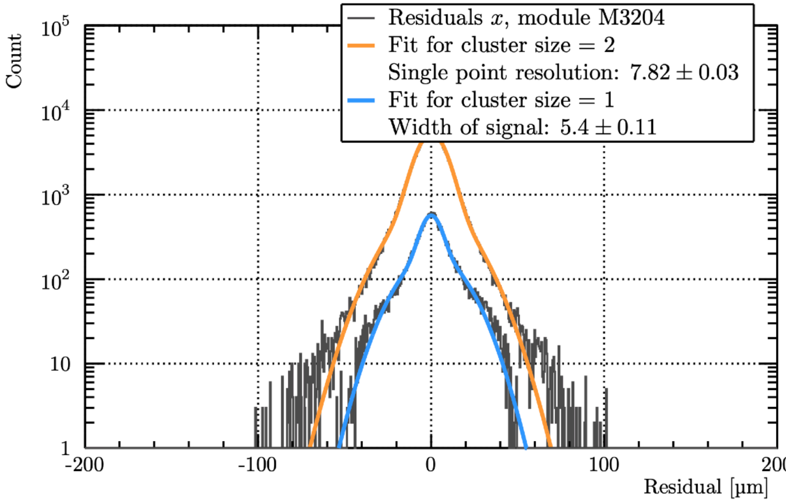
http://cds.cern.ch/record/2712394

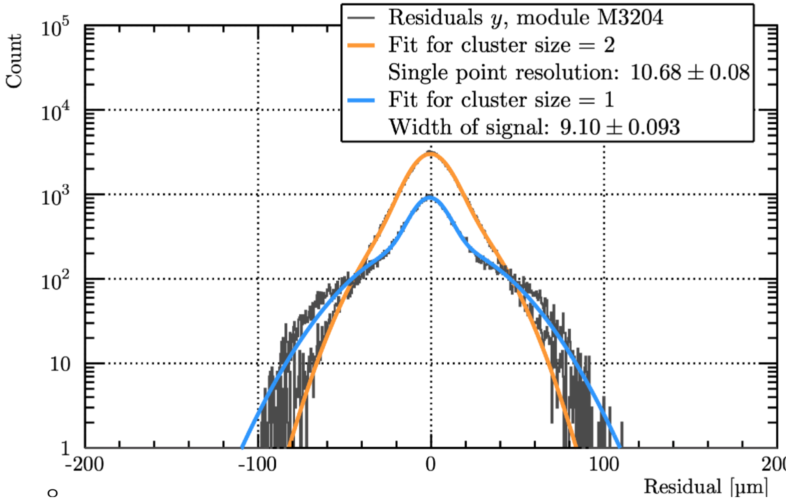
Initially aiming at 2021, but pandemic has stopped hardware preparation at CERN and other labs

Pixels



- CMS modules deployed as beam telescopes by the CHROMIE collaboration
- Fast readout (>100 KHz) and high point resolution (~10 μm)
- Will use 12 modules arranged in 3+3 pairs
  - 4x7 cm^2 active area

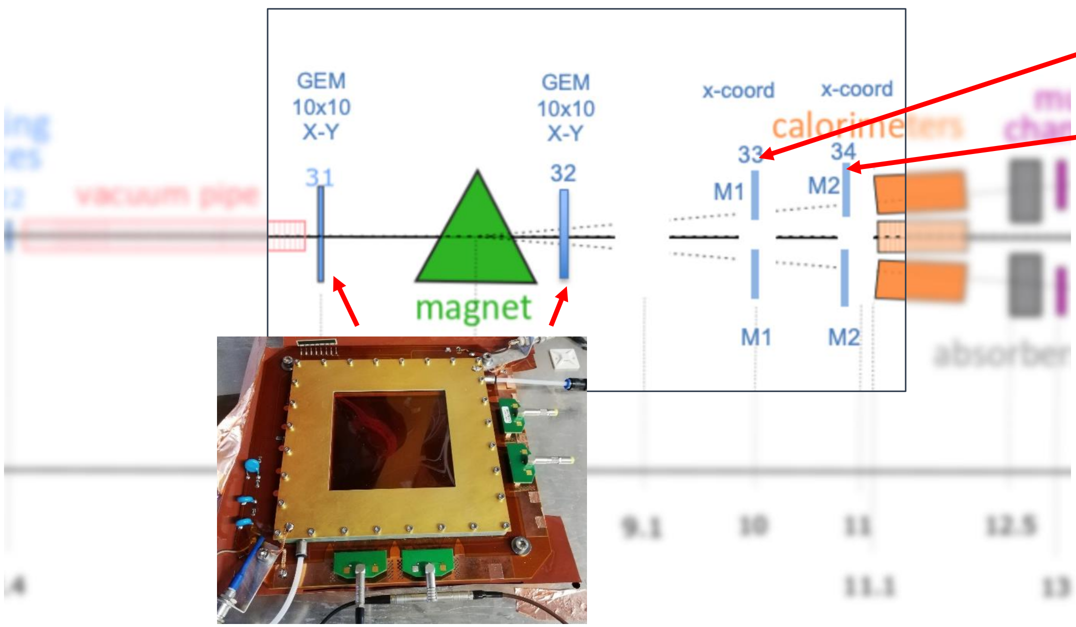


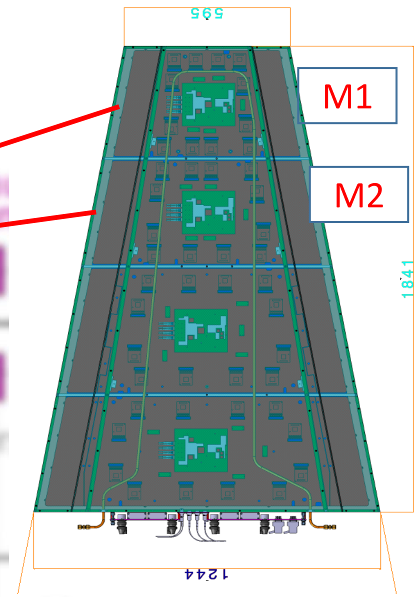


N. Deelen, N. Bacchetta

GEM

- 2 Dedicated hi-res 10x10 triple-GEM
  - X-Y, 260 um pitch (75 um resolution)
- Standard CMS modules in muon arms
  - Trapezoidal, 360-600 um resolution
- Fast read-out (possibly continuous)





A. Colaleo et al.

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Year 1

- Deployment of the full experimental setup
  - Integration of sub-detectors, time-synchronization, calibration
    - Would profit a lot from 2021 tests
  - Alignment of pixel modules, check its stability over time
  - Prove pixel modules combined spatial resolution and hits disambiguation (for modules between target and magnet)
- Goal: first accurate assessment of the properties $e^+e^- \rightarrow \mu^+\mu^-$ process at threshold
  - Differential cross section measurement
  - Intrinsic muon emittance measurement
- Desiderata:
  - High intensity (>5x10^6) and high purity (H4 line) e+ beam
  - 3 consecutive weeks

Year 2

- Gather large dataset to improve precision on Year 1 goals
  - Chase *true muonium* as well? (to check first if possible on simulation)
- Test several target options
  - Different length of Be targets
  - Other light materials
  - Crystals (to study possibilities of channelling exploitation)
- Study of the spent e+ beam
  - Positron energy and angular distribution after target for different target solutions (both in amorphous and channeling regime)
- Desiderata:
  - same as Year 1 for $e^+e^- \rightarrow \mu^+\mu^-$ studies
  - reduced e+ beam intensity for spent beam studies

Year 3

- Resume what left from Year 2
- Other goal: Measurement of the energy spectrum of the photons produced in the target (to study the possibility of using them for an additional positron source in the LEMMA scheme)
  - Additional dedicated calorimeter to be deployed

An improved e^+ source?

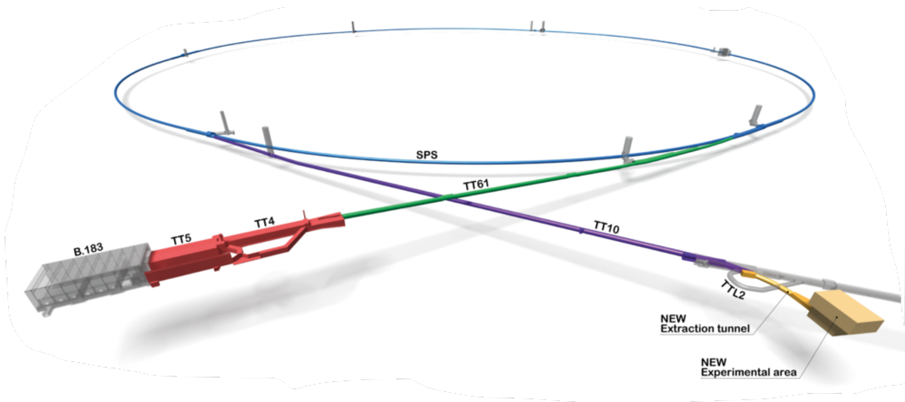
- Multipass scheme proposed in 2015 paper by Antonelli et al. (*Nucl.Instrum.Meth.A* 807 (2016) 101-107) proposed figures for a 6 km ring, in particular:
  - I = 240 mA (100 x 3e11 e+) ➔ 140 MW at E= 45 GeV
- That beam intensity was meant for the SPS, aiming at the actual source for a high luminosity Muon Collider (assuming an outdated, unrealistic scheme)
- A demonstrator would require way less than that

eSPS as an option?

arXiv:2009.06938v4 [physics.acc-ph] 21 Dec 2020

A primary electron beam facility at CERN — eSPS

Conceptual design report



Corresponding editors:

Torsten Åkesson, Lund University

Steinar Stapnes, CERN

LEMMA is explicitly discussed as item under the list of "Accelerator facility research and development"

eSPS as an option?

Quoting from paragraph 6.6, “Potential upgrade: positron related research and development ”

- Phase 1: eSPS tests of positron production and targets, and injector studies for LEMMA;
- Phase 2: LEP3 where 45 GeV positrons would be available in the LEP/LHC tunnel providing a test ground for muon production with positrons;
- Phase 3: A final booster and storage ring for muons which could be the SPS or a larger tunnel adapted to the physics requirements pertaining.

A key issue of the LEMMA scheme is the stress in the muon production target due to the impinging positron beam. Different technologies could be considered to overcome this. They range from conventional targets from robust materials to crystals or liquid targets. Experimental studies of these targets are of great importance in order to establish whether they are practical for a muon collider.

Another challenge that has to be faced is the control of the positron and muon beam emittance. The beams pass through the muon production target repeatedly, each time increasing emittance by multiple scattering. Experimental studies of the scattering of positrons (and also electrons) will improve the reliability of the predictions of the emittances of the produced muon beams. It will also allow the testing of specific target shapes and materials that promise improved performances.

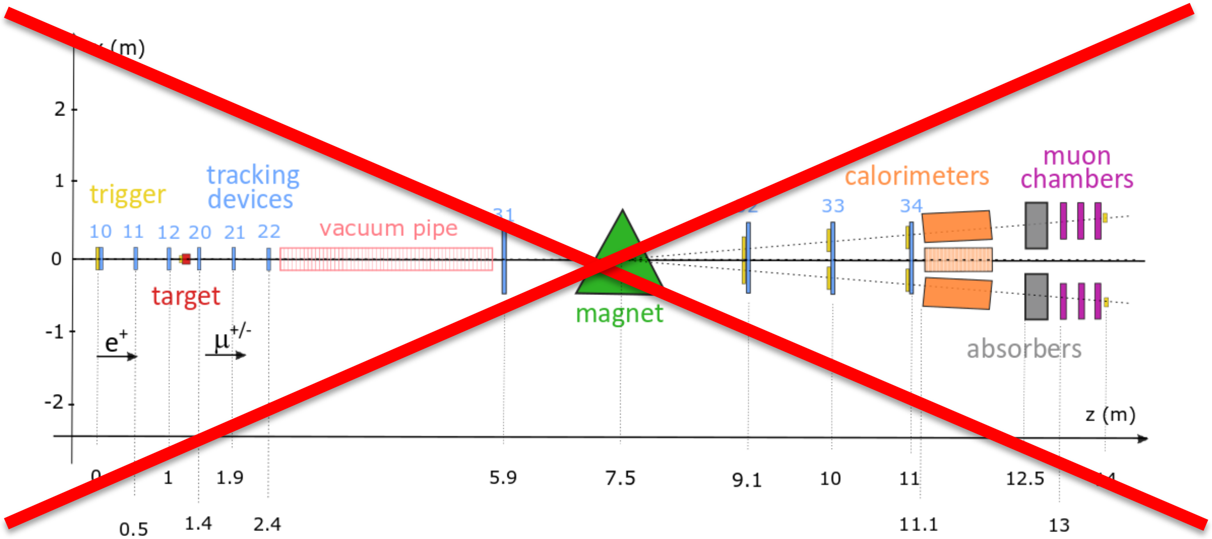
General considerations

- If eSPS will make a convincing physics case, a LEMMA demonstrator can be part of the program
- Do not need figures close to those needed for an actual muon collider; such a facility will allow experimenting the key concepts of the LEMMA scheme and prove (or not) its feasibility
- A suitable experimental setup could be designed on the basis of what learned in the incoming NA tests

BACKUP

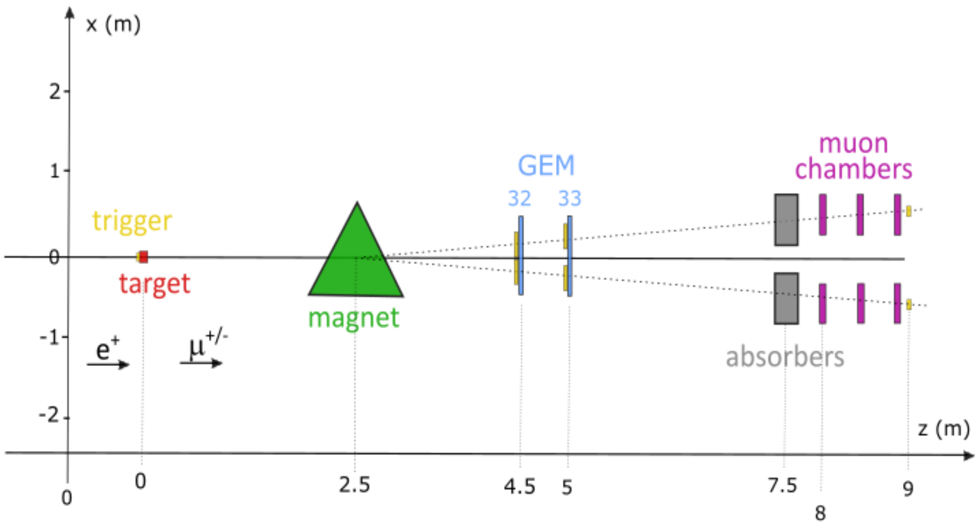
Status

- Brand new apparatus compared to past beam tests
- Due to the pandemic we accumulated delays on several fronts
  - In particular the pixels modules are being delivered at CERN only now (6 months delay).
  - Similar situation for the GEMs (less affected though)
  - Not clear when we'll be allowed to get to CERN to work on detectors testing and integration
- The experimental campaigns cannot start as planned on 2021.
- Still, even a limited amount of beam time could be useful for setting up things



2021 (Year 0)

- GEM will be tested as part of the RD51 program, a reduced setup could be deployed right afterword:
  - Be target, 2 GEM stations and muon chambers
    - i.e. almost complete setup beyond dipole magnet
- Goals (more details later):
  - Integration of GEM and Drift Tubes
  - Test of trigger schemes
  - Validation of geometry and assessment of background fluxes
- Requirements:
  - One week of beam time
  - Standard e+ beam, muon beam for calibration and alignment
  - <10 meters along H2 or H4



Details about 2021 program

- The DAQ/trigger system was what limited the most the physics performances in past beam tests
- We aim at deploying a continuous, deadtimeless ("triggerless") 40 MHz acquisition for Drift Tubes and GEM
- A trigger is anyhow needed for pixel modules and for increasing the purity of the recorded dataset. Critical requirements:
  - The trigger selection must be fully efficient for signal events and at the same time reduce background rate to << 100 kHz
  - The trigger efficiency needs to be assessed very accurately to allow a precise cross section measurement
- Beam induced showers (interactions with magnet, absorbers, supports, etc.) can increase dramatically detectors occupancy ➔ validating Geant studies and figuring out in situ an optimal components disposition is critical