LEMMA: experimental tests

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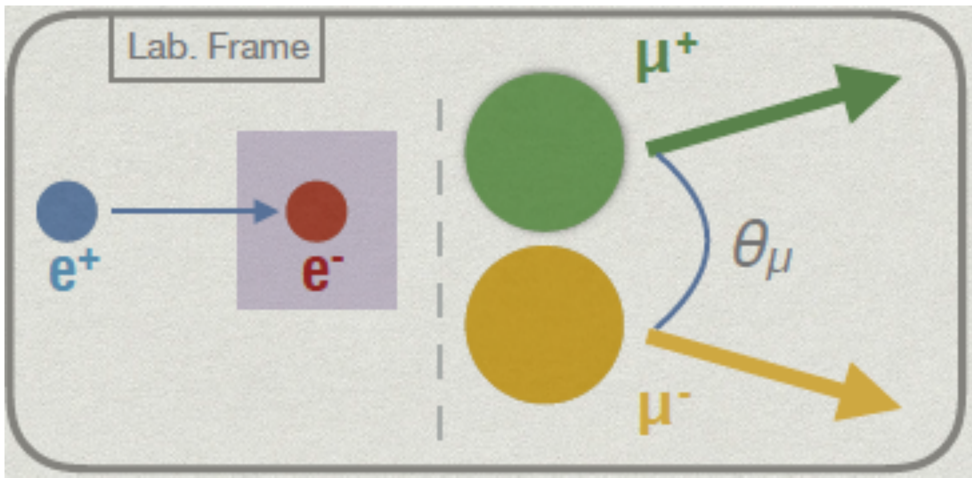
The LEMMA concept

Direct μ-pair production via $e^+e^- \to \mu^+\mu^-$ just above production threshold ($\sqrt{s}$=212 MeV), by colliding a beam of ~45 GeV e^+ on a thin target (NIM A807, 101 (2016) [*arXiv:1509.04454*])

$E(e^+) \gtrsim 44$ GeV => $E(\mu^+) \sim 22$ GeV, $\gamma(\mu) \sim 200$ => $\tau_{LAB} \sim 500\mu s$

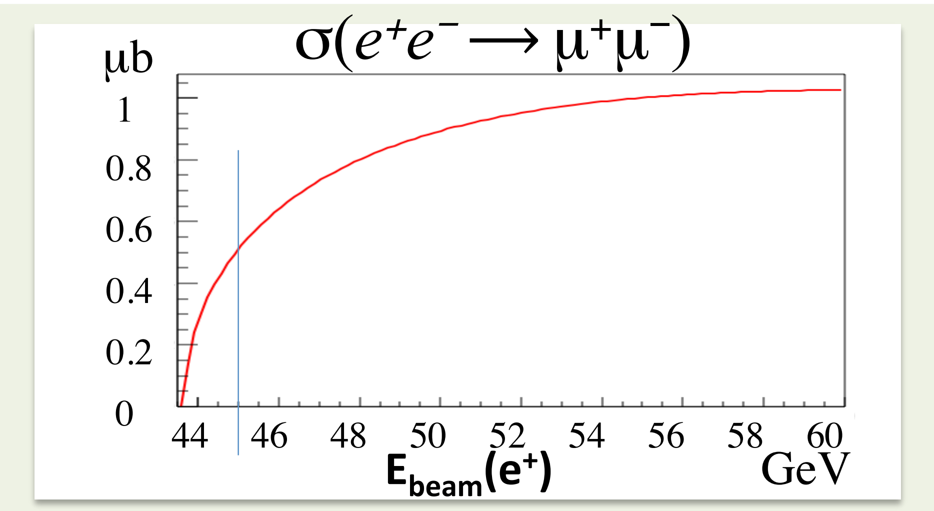


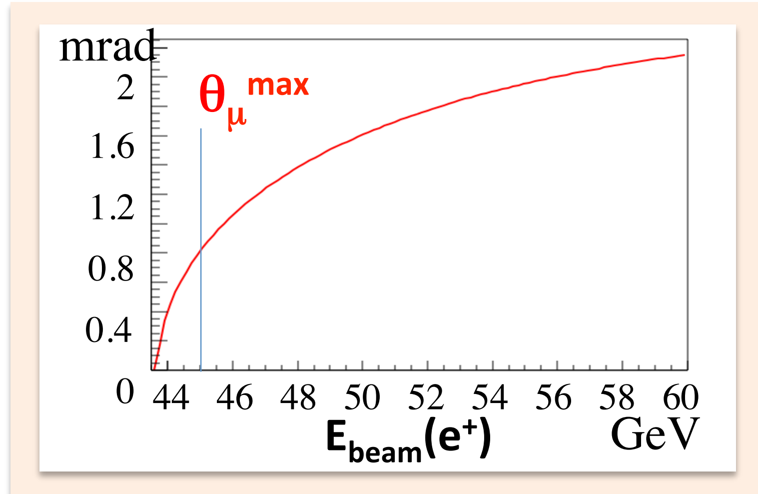
- Very small emittance is obtainable => **no cooling needed!**
- Low background
- Large boost at production => Reduced losses from muon decays
- Much smaller muon production cross section
  - ~1μb for e^+ source *vs* ~1mb for proton source

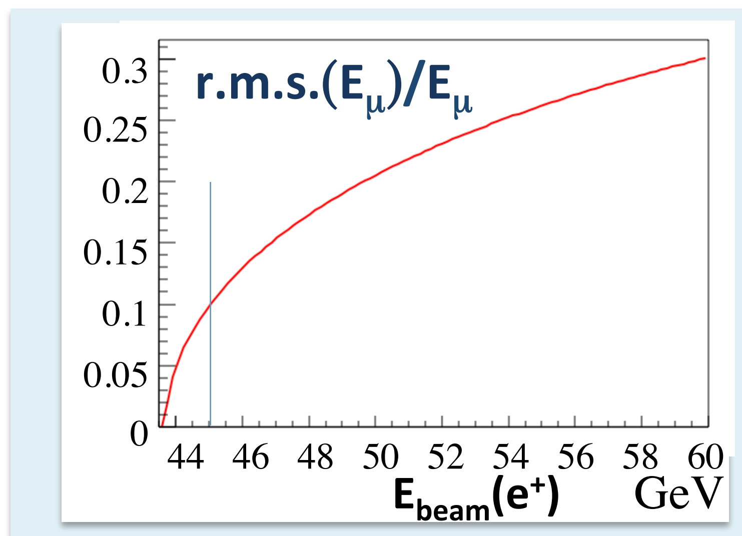
Cross-section, muons beam divergence and energy spread as a function of the e^+ beam energy

Main contributing process

- $e^+e^- \to \mu^+\mu^-$
- $e^+e^- \to e^+e^-\gamma$ (dominant)
- $e^+e^- \to \gamma\gamma$







$\sqrt{s} \simeq \sqrt{2 m_e E(e^+)}$ optimized to:

- maximize the muons production
- minimize muon beam emittance and energy spread

Working hypothesis:

$E(e^+) = 45$ GeV => $\sqrt{s} \approx 214$ MeV

Experimental tests

- Intensity and emittance of the produced muon beams depend on both positron-beam and target properties
- All these aspects should be experimentally tested, and measurements compared to theory and simulation studies

- Envisaged tests:

1. Measurement of kinematic properties of produced muon-beams
2. Study of the positron-beam degradation with different targets
   - both can be performed with a ~45 GeV positron beam at CERN SpS facility

3. Validations of the positron-ring-plus-target scheme
   - plan to perform a test at DAFNE, and extrapolate results to the working hypothesis
4. Study the target heat load and the resulting thermo-mechanical stress
   - tests can be performed in several facilities for different target options
     - HiRad Mat @CERN, FACET II @SLAC, ATF2 @KEK, CESR @CORNELL,…

Experimental tests at CERN North Area

- Measurement of kinematic properties of produced muon-beams
  - Measure emittance of outcoming muon pairs
  - Measure production rate for the provided positron beam features (momentum and energy spread)

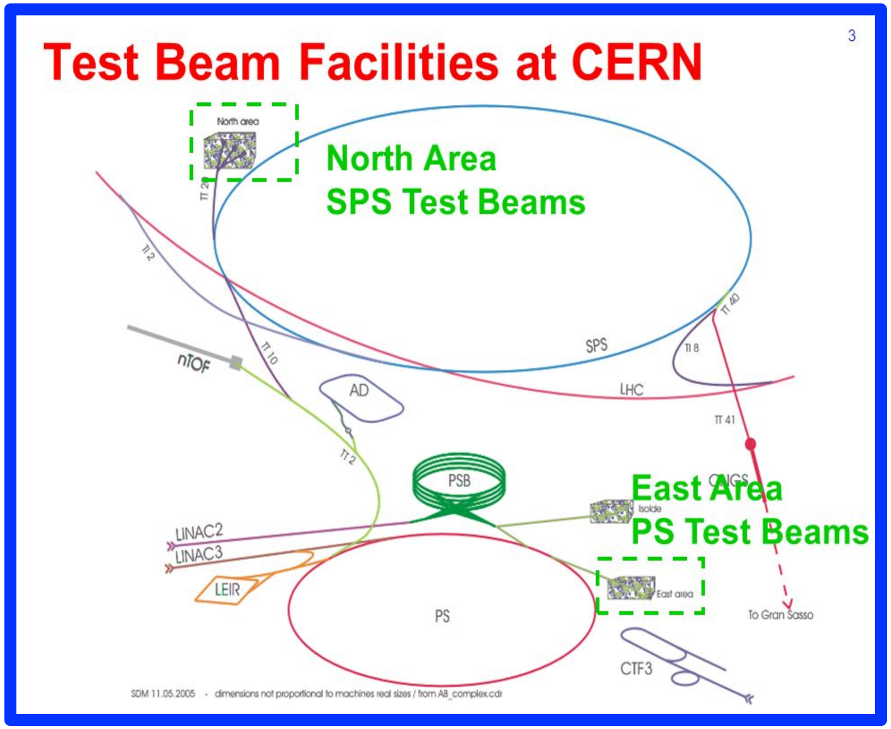
- Study of the positron-beam degradation with different targets
  - compare behavior of positron beam when passing through different targets prototypes
  - e.g. amorphous (3mm Be or C) and compare crystals in and out channeling regime
  - measure momentum spectrum and emittance of positrons
  - measure energy spectrum of radiated photons
  - use a low intensity beam ($\sim 10^3$ $e^{\pm}$/spill)
  - this test could be performed also at different test facilities with lower beam energies

Experimental tests at CERN North Area

Beams extracted from the SPS to the North Area.

Available lines with $e^{\pm}$: H2 & H4

Maximum intensity for $e^{\pm}$ @45GeV/c: a few 10^6 $e^{\pm}$/spill



- One week (over two requested) of beam time assigned at the end of July 2017, on the H4 line
  - Experimental program limited to the production rate measurements, with the maximum-intensity beam available
- One more week assigned in 2018 (August 15-22) at the H2 line
  - Continue the 2017 program with an improved experimental setup

Experimental Tests at CERN North Area

- Study muon pair production at threshold with a 45 GeV $e+$ beam on target
- First experimental verification of positron induced low emittance muon beam

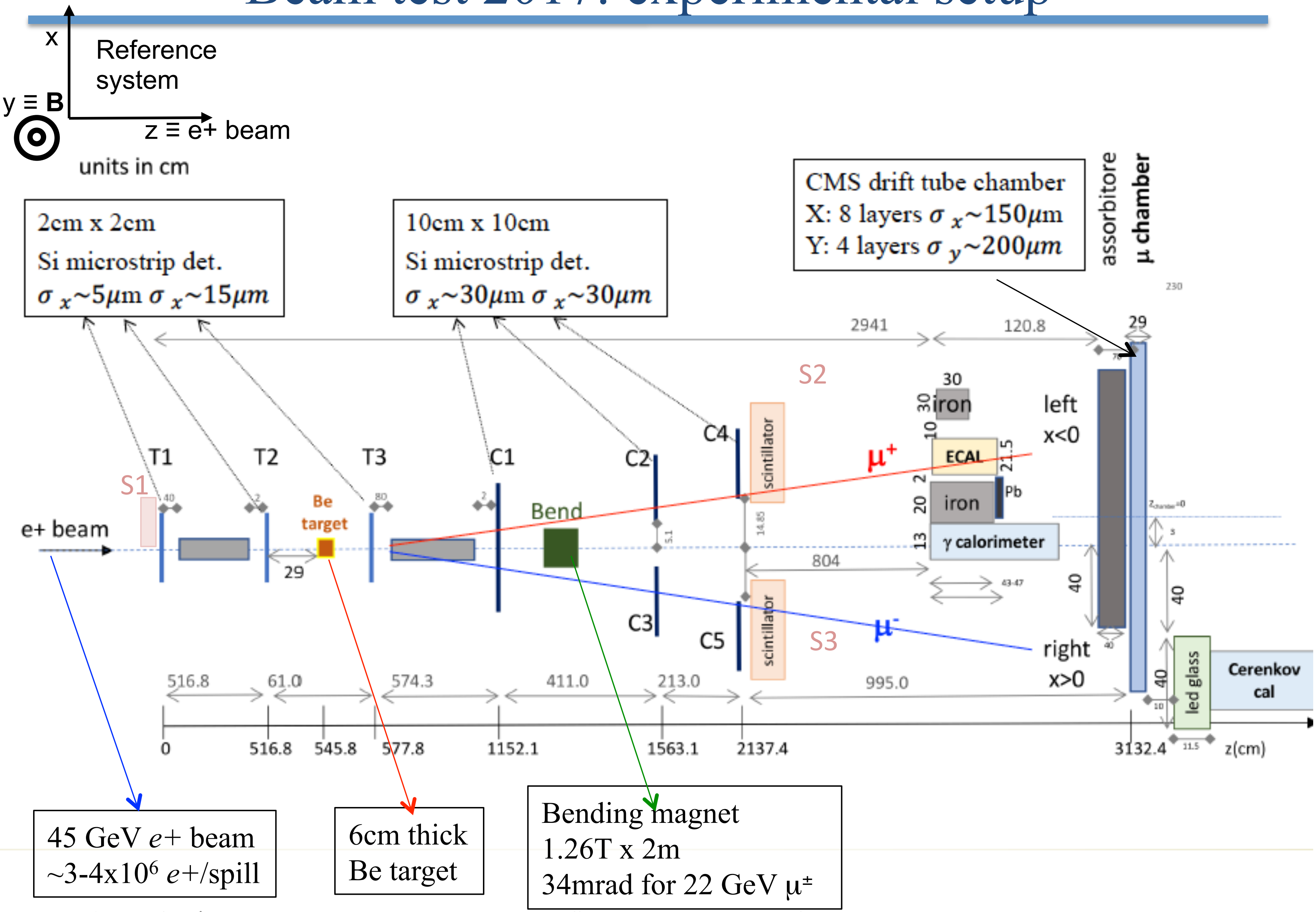
- <u>Measurements:</u>
  I. $e^+e^- \rightarrow \mu^+\mu^-$ production cross section
     - Use Bhabha events to normalize cross section
     - Interesting by itself (*e.g.* measure the Coulomb correction at threshold) and useful to tune simulation
     - A great control of acceptances and background contamination is needed for a measurement at percent level

  $$\frac{\sigma(\mu^+\mu^-)}{\sigma(e^+e^-)} = \frac{N(\mu^+\mu^-)\varepsilon(e^+e^-)}{N(e^+e^-)\varepsilon(\mu^+\mu^-)}$$

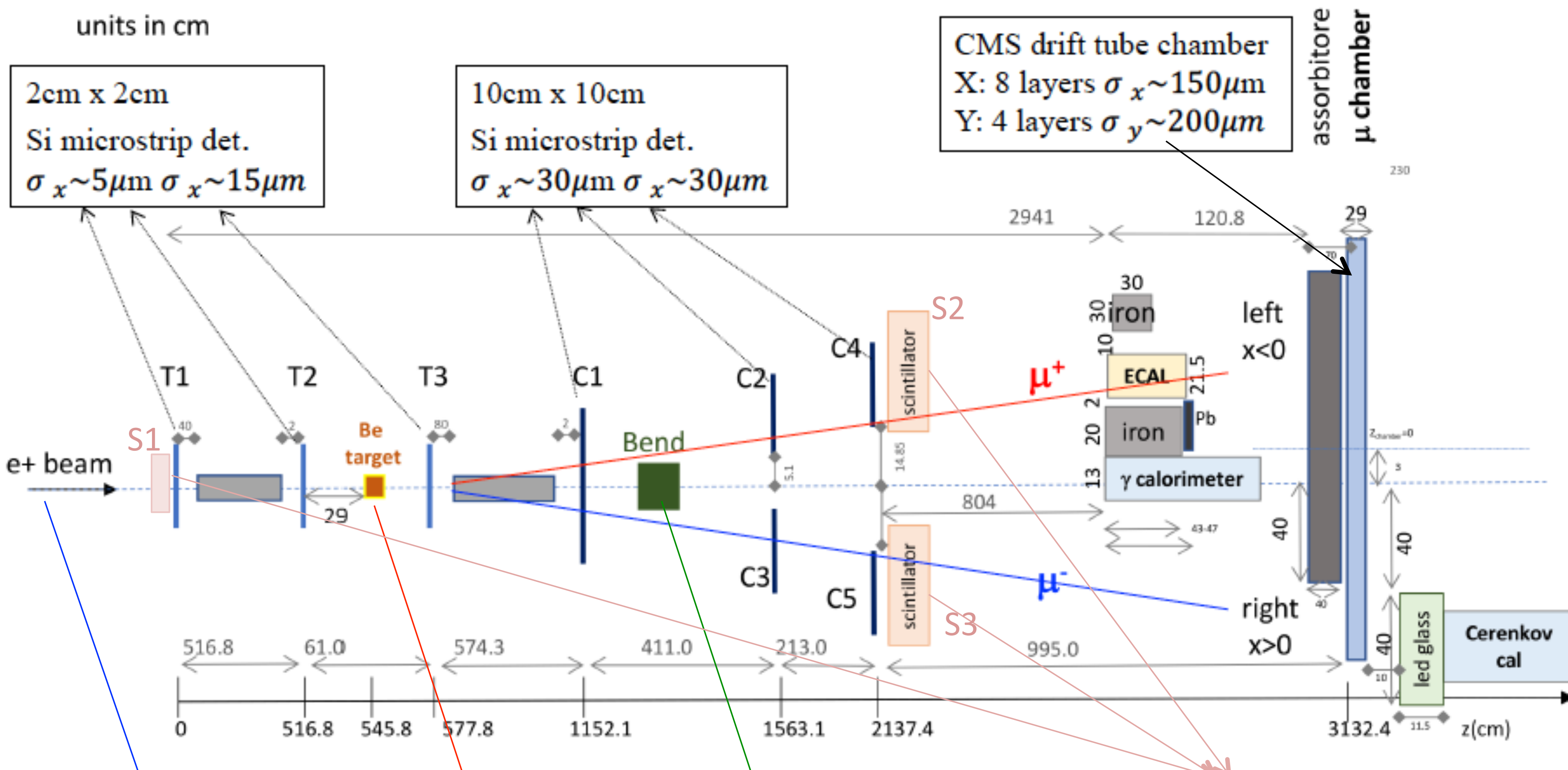
  II. Emittance of outcoming muons

- <u>Needs:</u>
  - Full tracking of charged particles
  - Detailed simulation for acceptances and efficiencies determination
  - Electron/muon identification

Beam test 2017: experimental setup



Beam test 2017: experimental setup

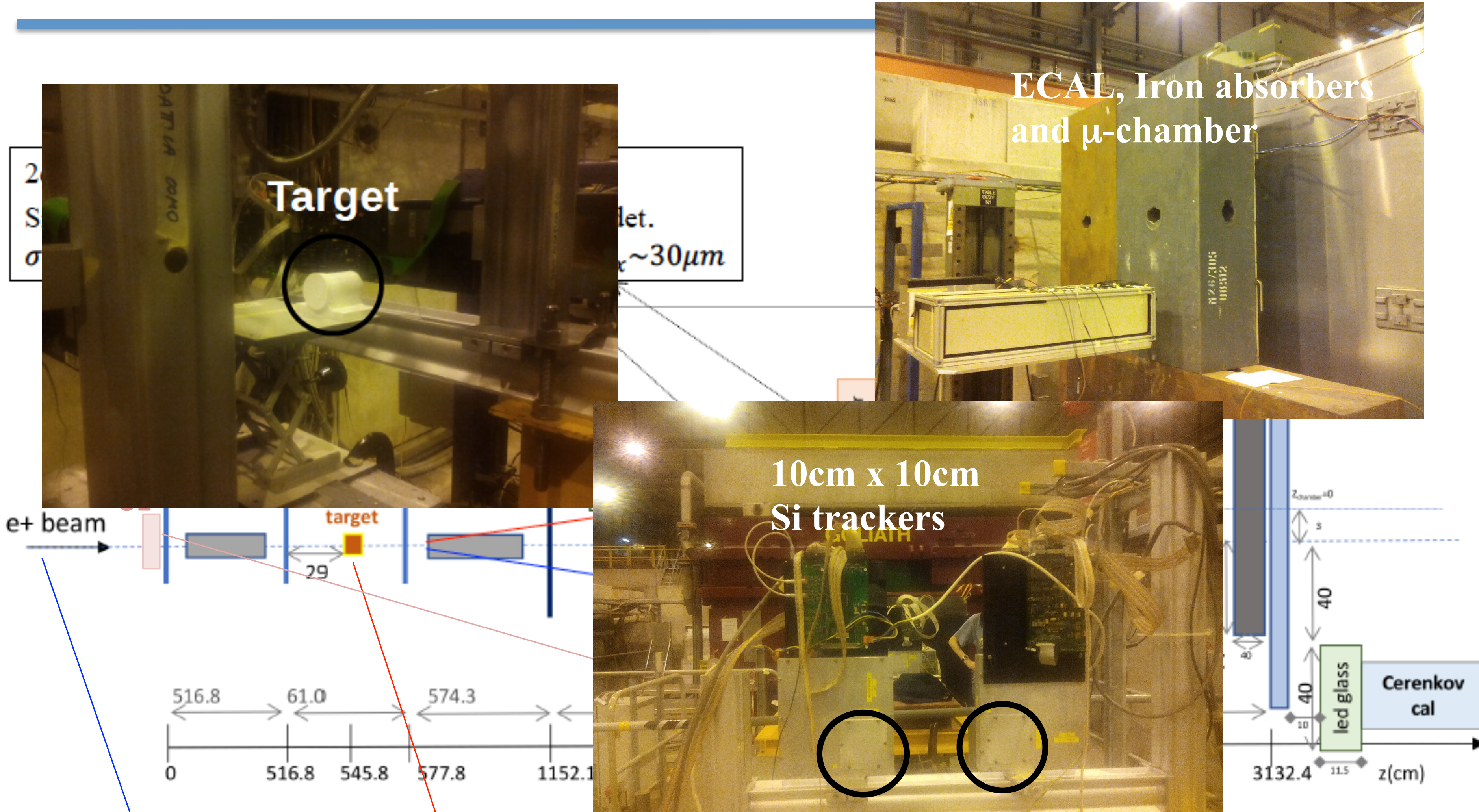


45 GeV $e+$ beam
~4x10^{6} $e+$/spill

6cm thick
Be target

Bending magnet
1.26T x 2m
34mrad for 22 GeV $\mu^{\pm}$

Trigger
2-track events triggered by
coincidence of the 3 Scintillators



2… S… σ…

…det. …$_x$~30μm

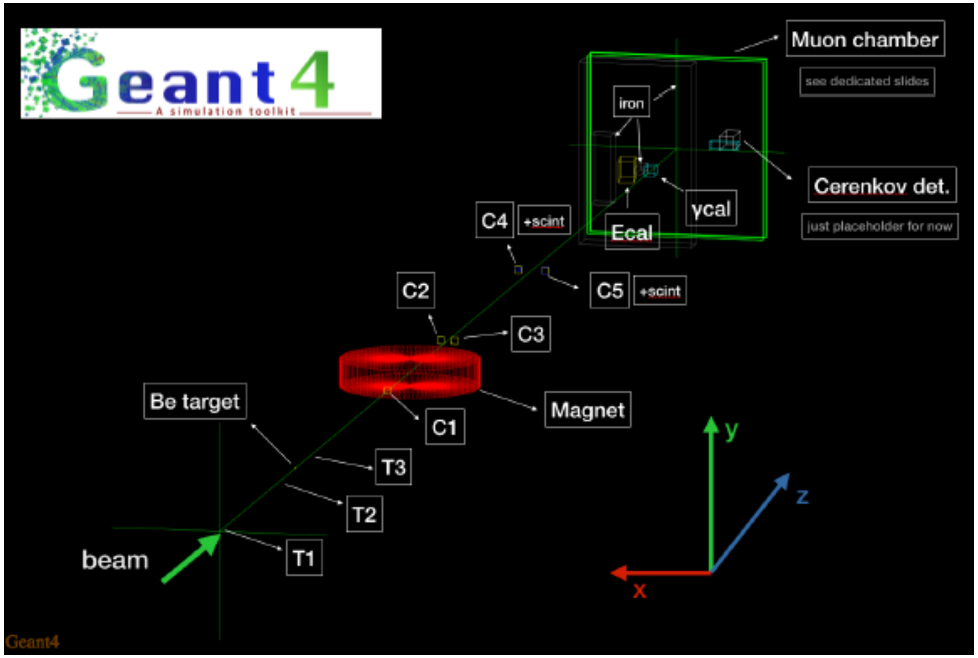
45 GeV $e+$ beam
~4x10^6 $e+$/spill

6cm thick
Be target

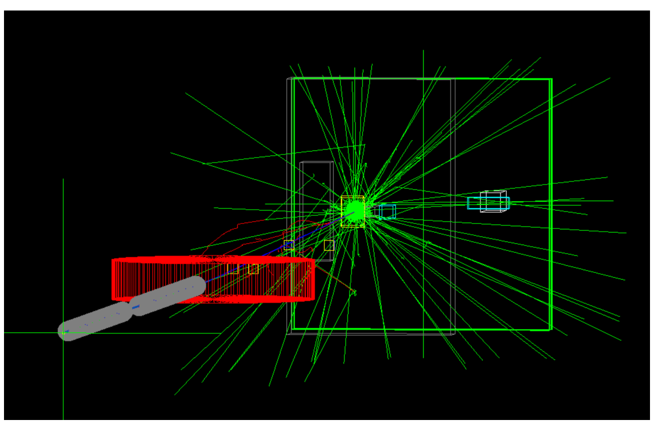
…1.261 x 2m
34mrad for 22 GeV μ±

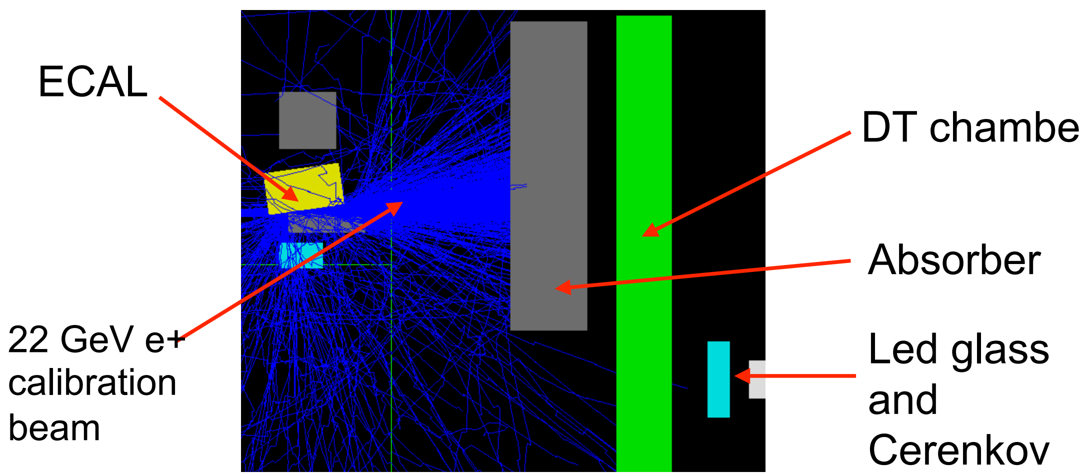
…gered by
coincidence of the 3 Scintillators

Simulation



- Performed with Geant4.
- Important to validate the reconstruction and identification techniques.
- Necessary to estimate the muons/ electrons acceptances and selection efficiencies.





Test Beam schedule

- Because of the very low **$e^+e^- \to \mu^+\mu^-$** cross section (~0.4μb for a 45 GeV e^+) we used a positron beam of the highest possible intensity, and a thick target

- Features of delivered beam:
  - E = 45 GeV; ΔE/E <2%; spot size: ~1x1cm^2 (~flat)
  - ~3-4x10^6 e+/spill (homogeneous in time); beam purity: ~99%
  - spill duration ~4s => 1 e+/μs during spill
- Target: 6 cm-thick Be

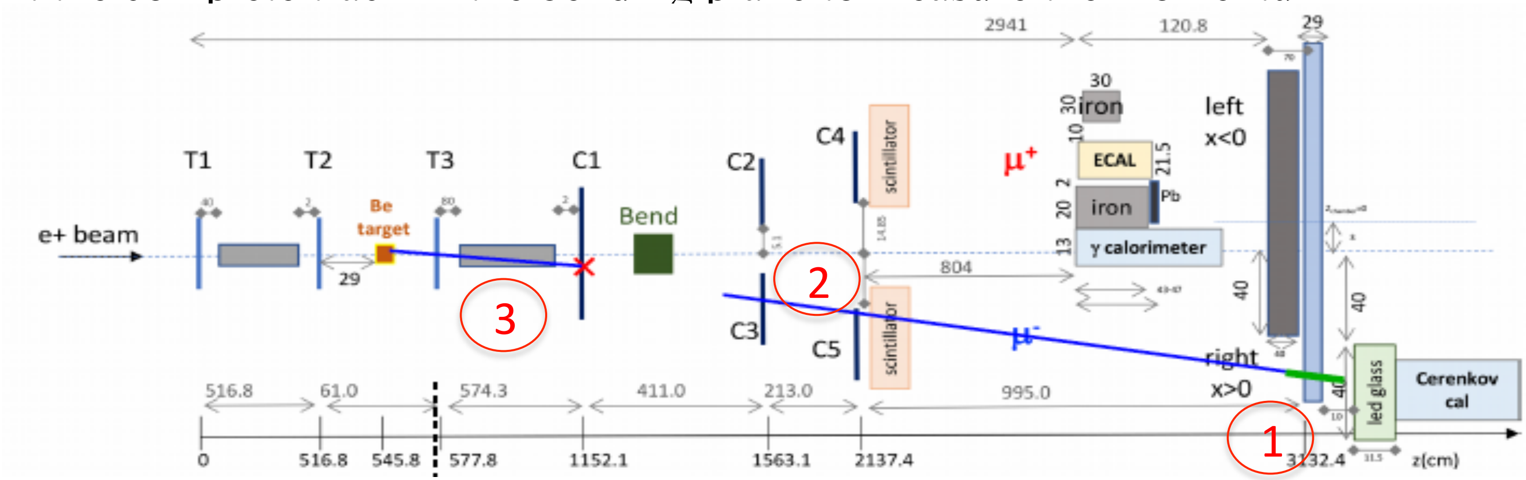
➔ Under these conditions a few **$e^+e^- \to \mu^+\mu^-$** events/spill were expected

- For calibration and alignment purposes, we used also
  - $\mu^\pm$ beams with an energy up to 30 GeV,
  - $e\pm$ at low intensity (~10^3 e+/spill) and lower energy (between 18 and 26 GeV)
  - running without the target to test the calorimeters' response to MIPs and electrons, and to align the tracking detectors

Tracking and event selection

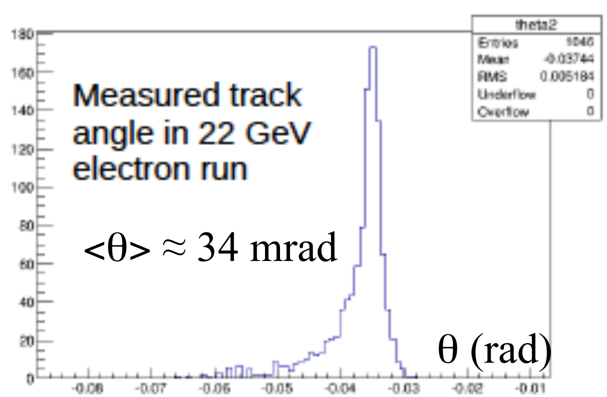
Tracking algorithm, based on a backward track reconstruction starting from the μ-chamber (DT):

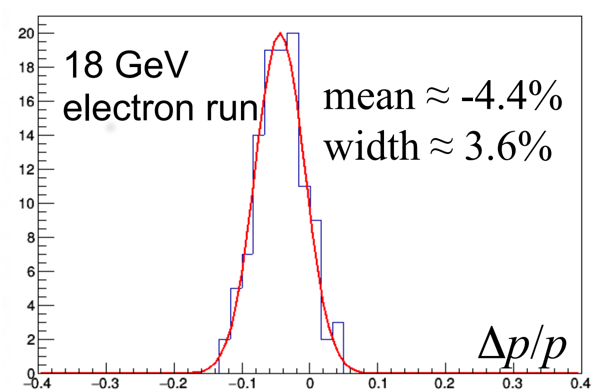
1. reconstruct a track segment in the DT in both x and y view
2. hits in Si detectors after bending added with linear fits
3. extrapolate the rough track to the Si detector T3 and C1, and add closest hits to the track
4. refit the complete track in the bending plane to measure the momentum



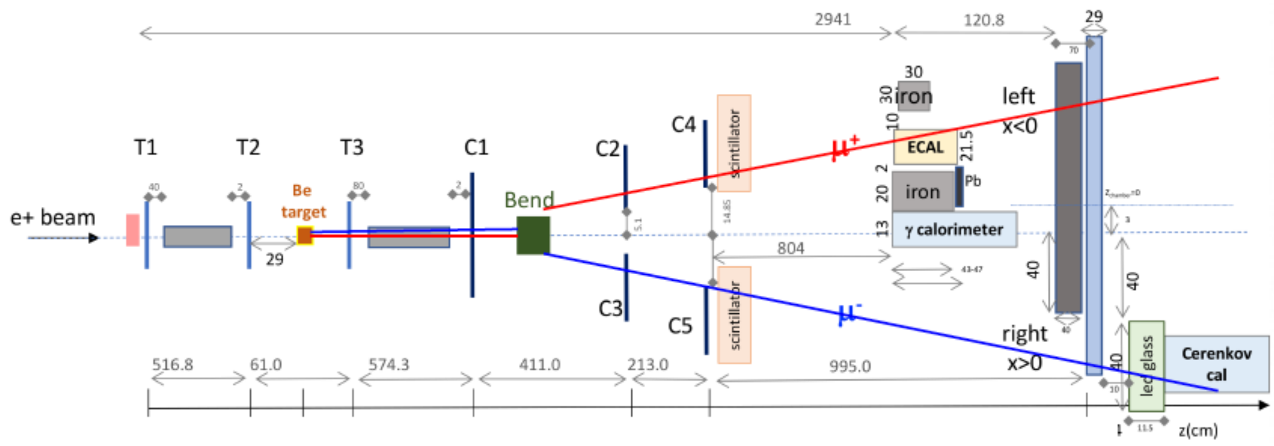
The tracking algorithm has been tested with calibration runs:

- $e^{\pm}$ of E = 18, 22, 26 GeV, and target removed



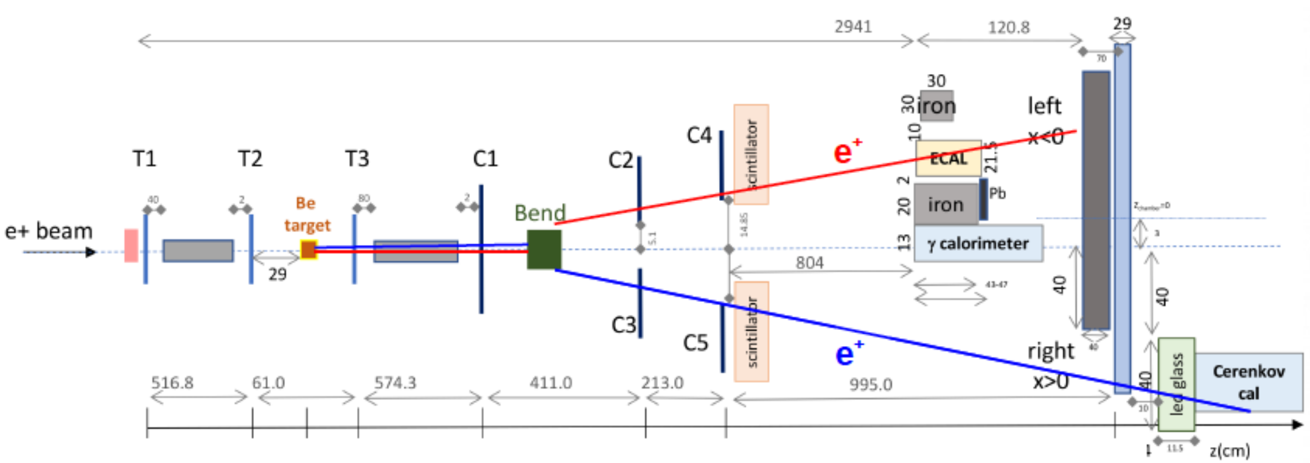


Event topologies



e+e- → μ+μ−

Two tracks on opposite sides of the μ-chamber

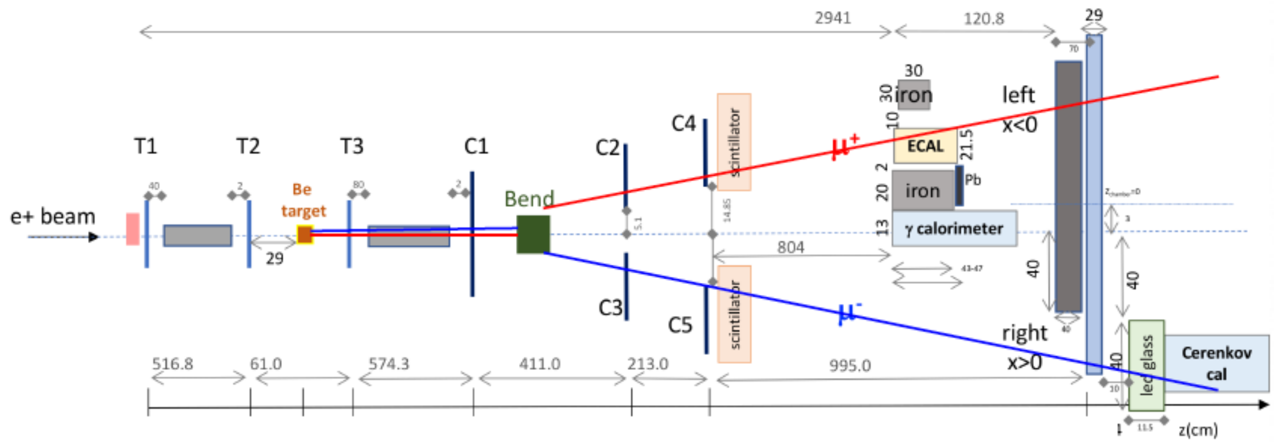


e+e- → e+e-

Only the e^- produces a good track in the μ-chamber.
The e^+ is stopped by the calorimeters and the absorbers

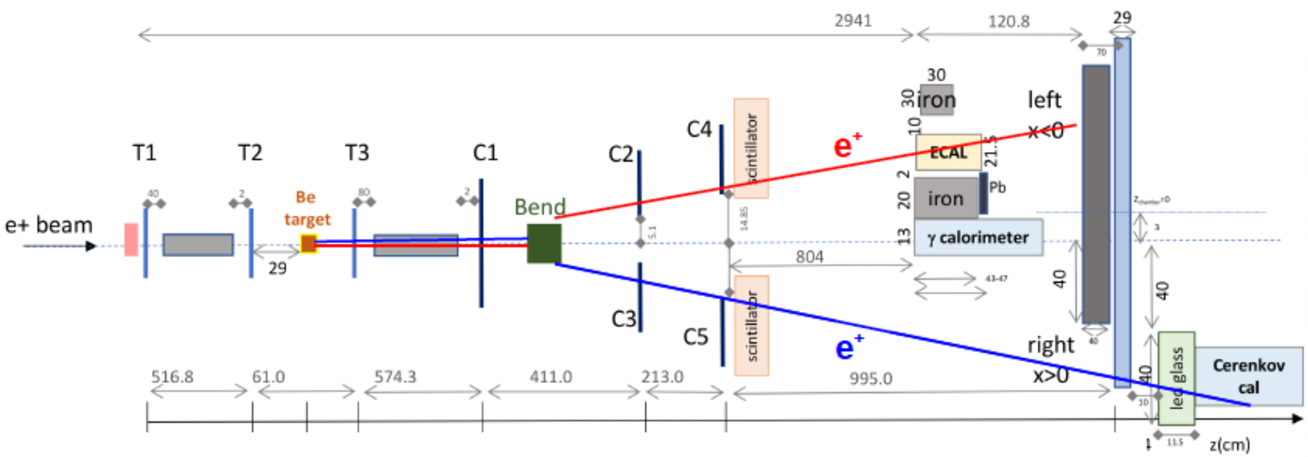
X5 e+e- events w.r.t. μ+μ− events in the same momentum range, that is within tracking system acceptance

Event topologies



e+e- → μ+μ−

Two tracks on opposite sides of the μ-chamber

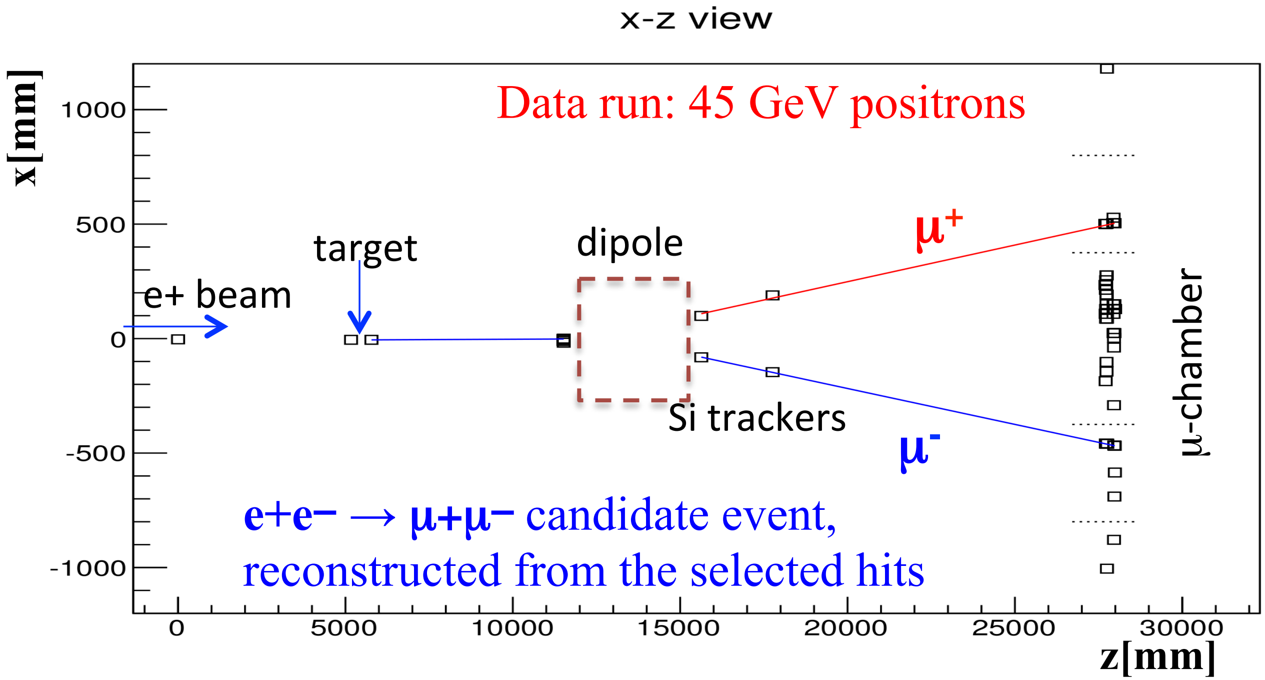


e+e- → e+e-

Only the e^- produces a good track in the μ-chamber.
The e^+ is stopped by the calorimeters and the absorbers

Data analysis

- We analyzed the runs with the final trigger configuration, ~1.5 days of data taking
- 620k collected events
- **27 μ+μ- candidates are selected**

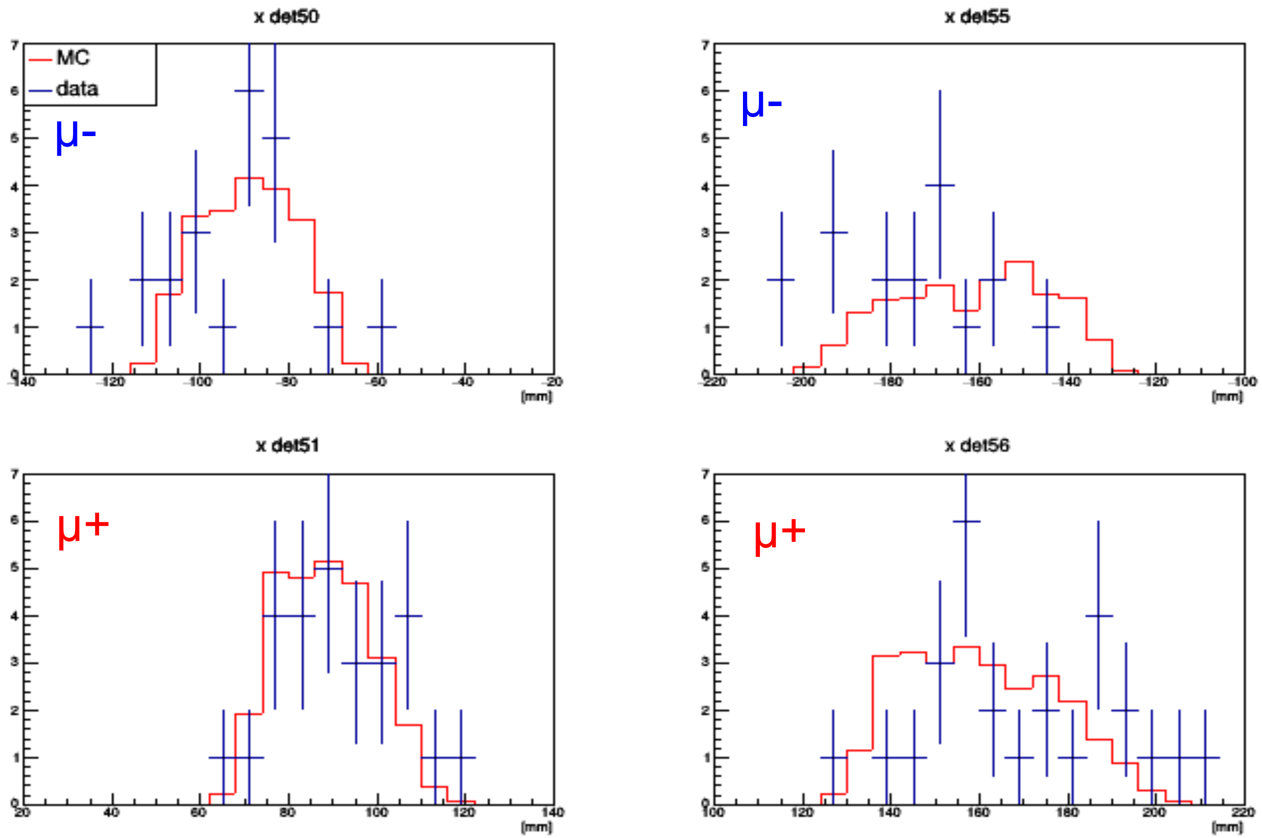


- High level of noise in the muon chamber drift tubes limits the signal yield
- Contamination from Bhabha events negligible
  - None of the positrons of the 22-GeV calibration run produce a valid track in the DT chamber after the iron absorber

Data-MC comparison

27 e+e- → μ+μ− events selected

- Horizontal position of hits associated to the reconstructed tracks, in the two pairs of Si detectors after the dipole magnet
- MC resolution corrected for the value measured in calibration runs



- Good consistency between data and simulation

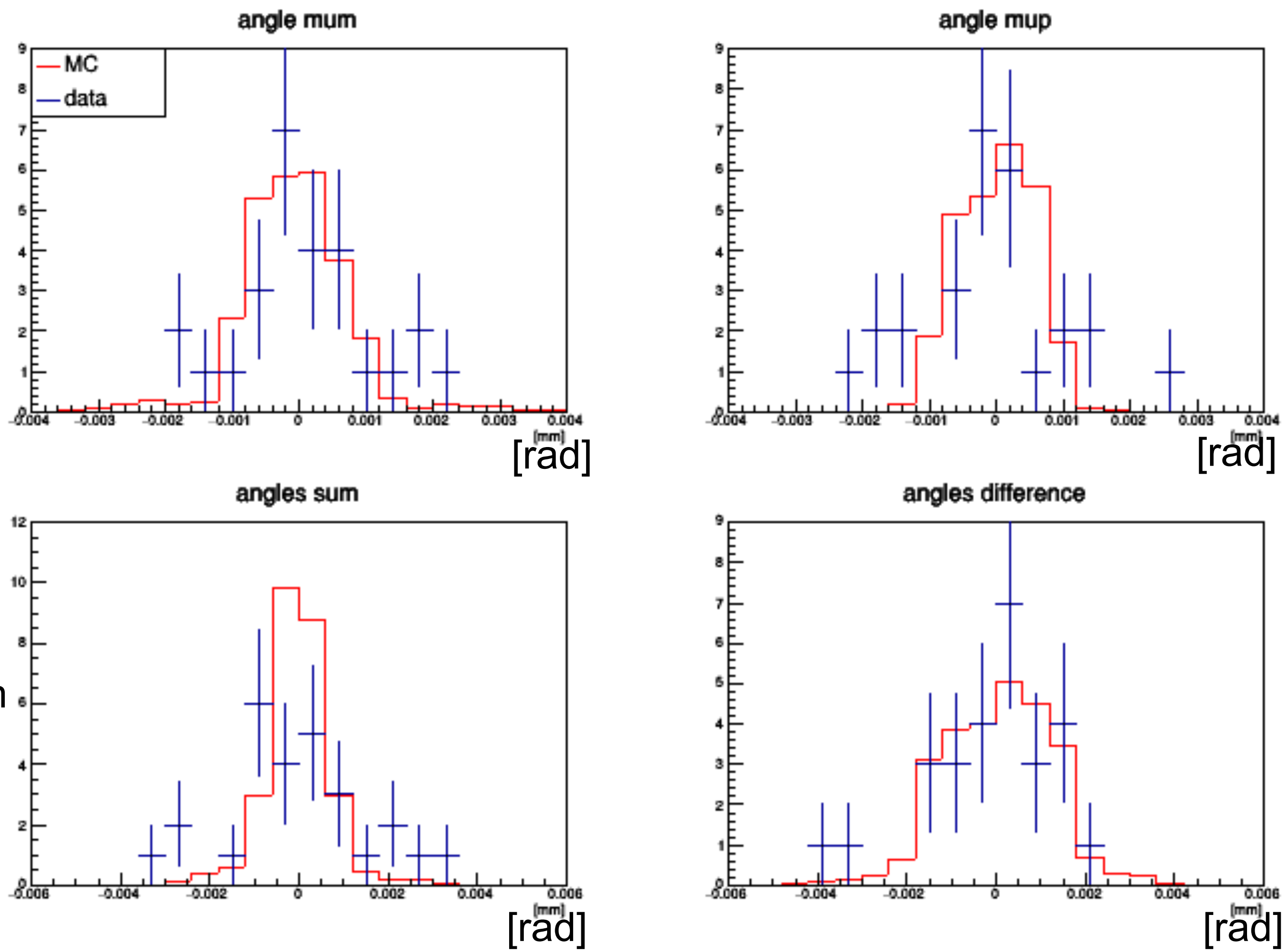
Reconstructed production angles

μ- production angle wrt beam axis

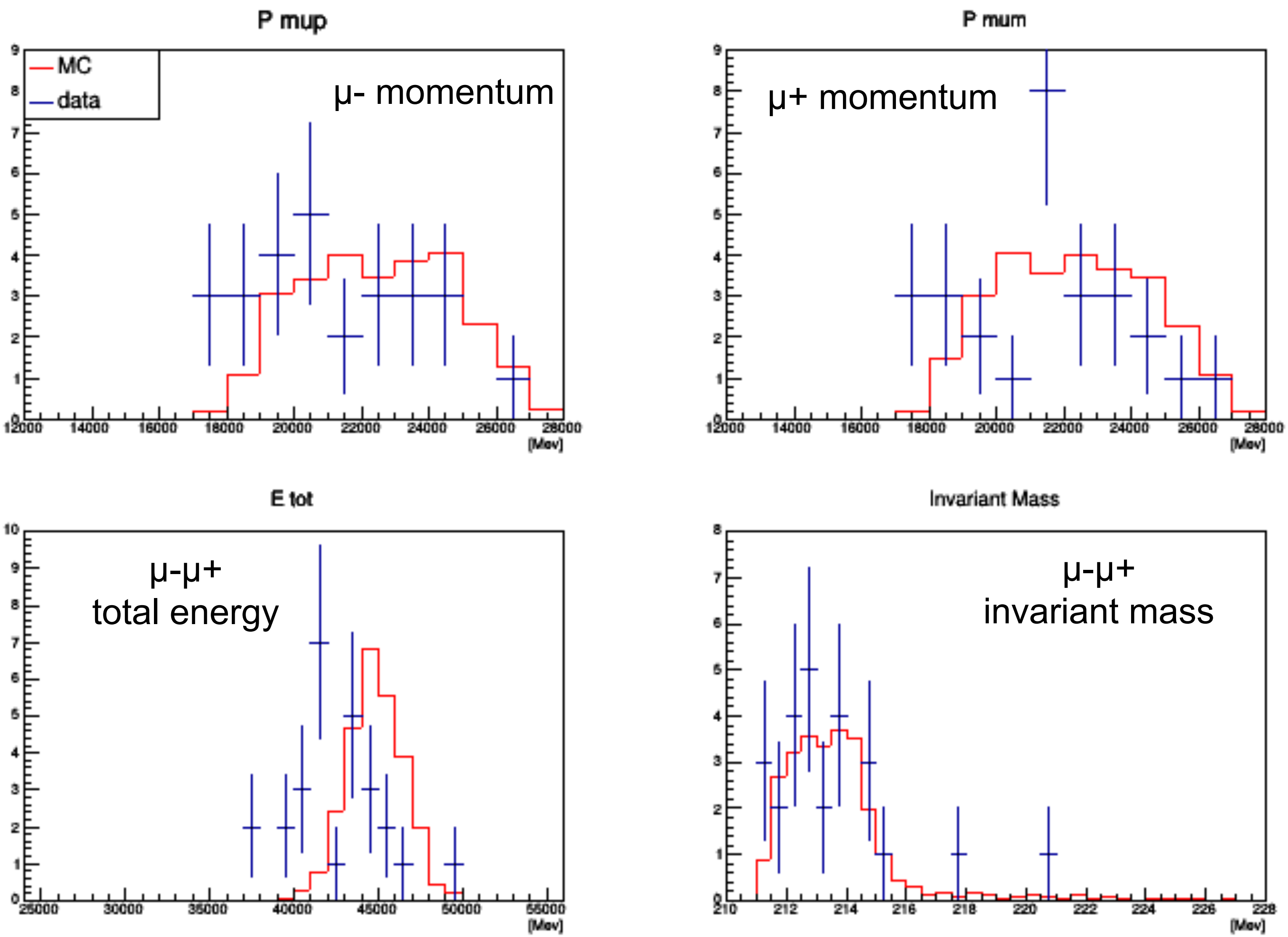
μ+ production angle wrt beam axis

μ-μ+ production angles sum

μ-μ+ production angles difference



Measured invariant mass

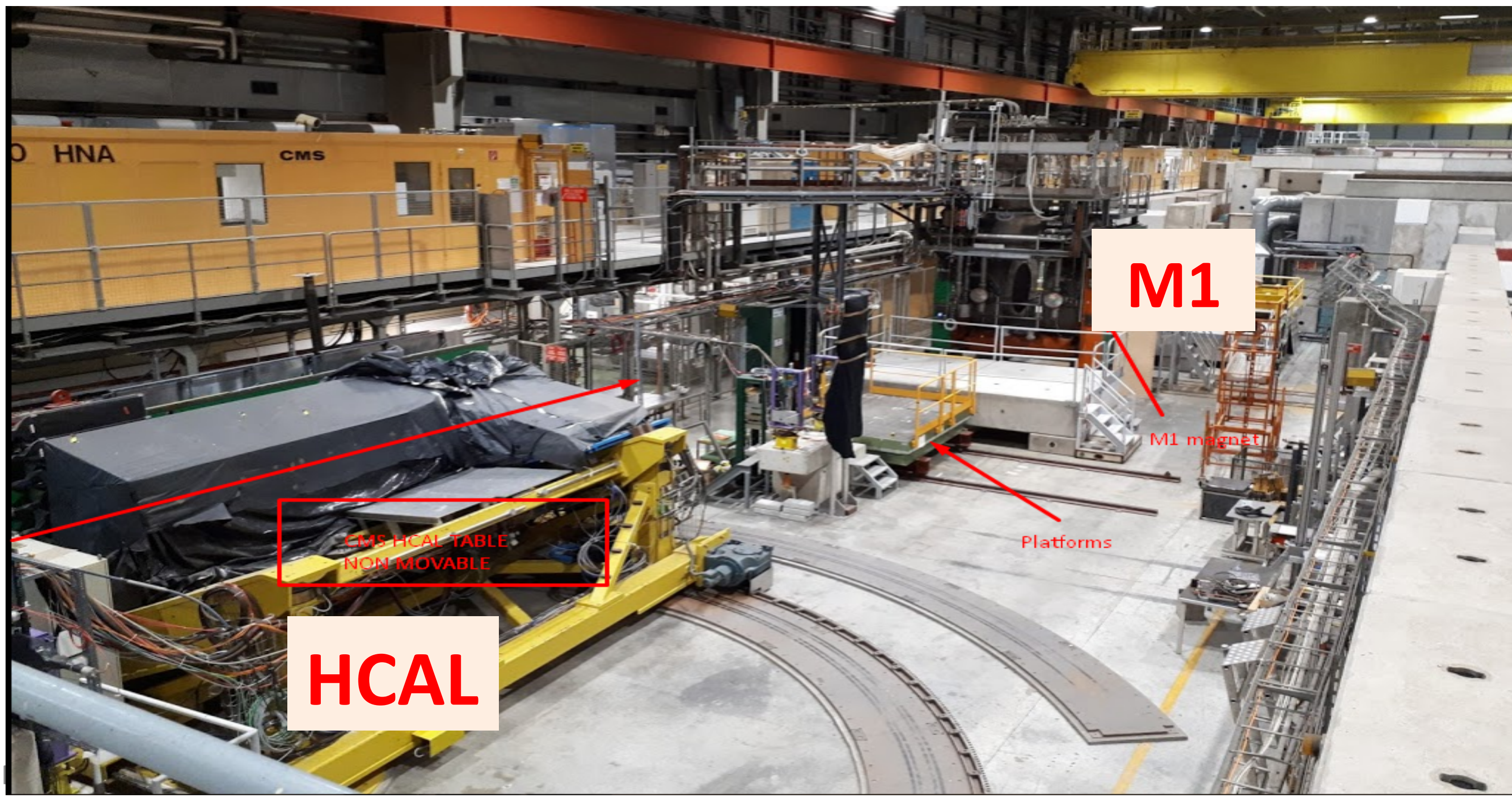


2017 TB summary

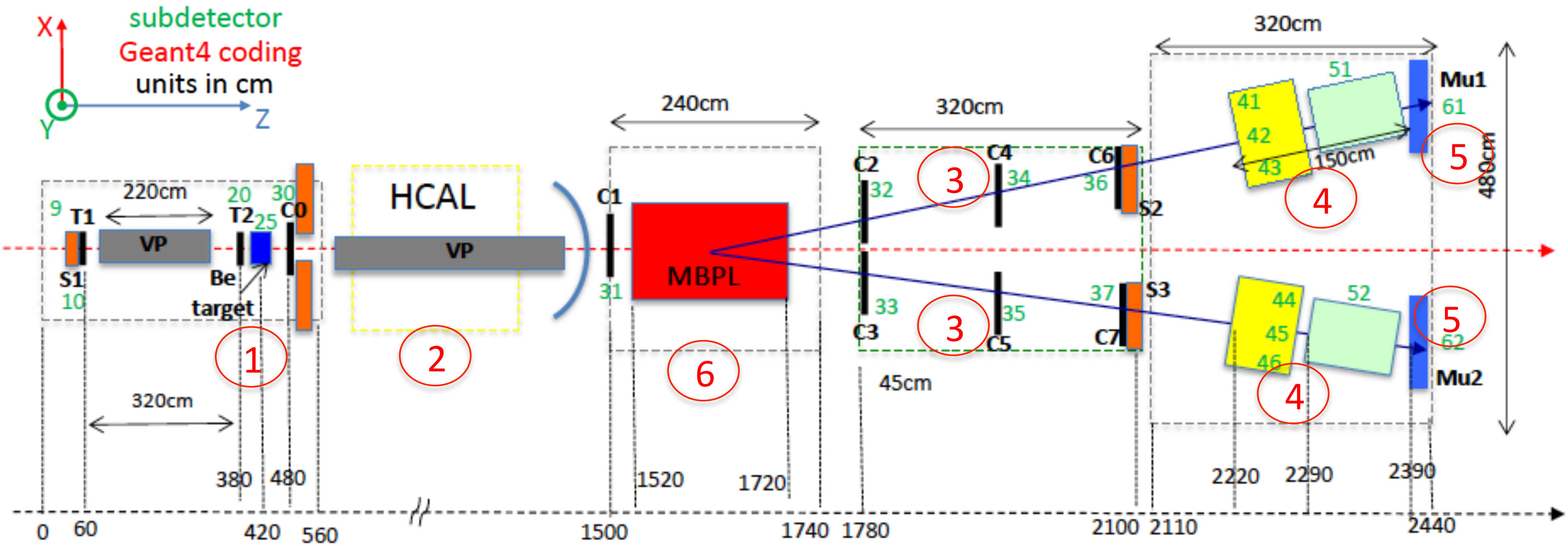
- The accumulated statistics is too low to make any significant measurements
  - hardware problems, occupancy in the muon chamber, alignment issues, beams availability, limited the number of selected and fully identified muon pairs to a few tens
- We proved to be able to reconstruct a pure sample of $e^+e^- \rightarrow \mu^+\mu^-$ events
- The foreseen 2018 test beam will profit of the experience gained with the running of the experiment and of the tools developed for event reconstruction and data analysis
- The analysis of the collected events is continuing, though with a lower priority w.r.t. the preparation for the 2018 TB, to extract the maximum information

Notes on the 2018 Beam Test (August 15-22)

- Goal: repeat the 2017 experiment, with an improved detector setup
- H4 not available => experiment moved to H2
  - H2 hall significantly different from H4
  - Experiment layout strongly affected by the presence of the HCAL calorimeter and the M1 magnet



LEMMA 2018 setup



Main features and differences w.r.t. 2017 setup

1. Same target (6-cm thick beryllium)
2. The two trackers between target and magnet MBPL separated by ~10m => better measurement of production angle for emittance determination
3. Three (w.r.t. two) Si tracking stations after the dipole
4. New calorimeters (Lead-glass + fully equipped cherenkov calorimeters)
5. New μ-chambers (two separate 70x70cm^2 DT chambers for μ+ and μ−)
6. Higher B field to increase separation of signal and primary beam contamination

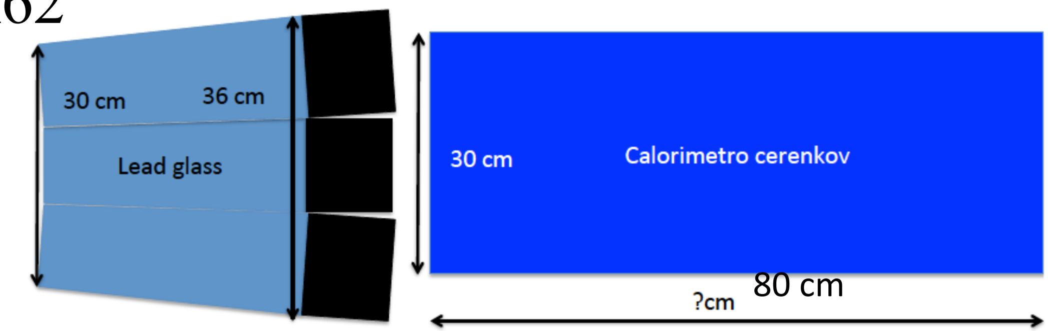
Preparation to the data taking

- Test beam to be started in about 6 weeks
- Still many things to do, but no serious issues foreseen
- Layout basically defined.
  - For a few issues needs help by H2-line and NA managers (e.g. vacuum pipe above HCAL, dipole positioning and alignment, B-field measurements, detectors alignment, and other services)
- Production/refurbishing of detectors proceedings at various INFN sites
- The design of mechanical supports for the detectors is being worked out
- DAQ integration (calo's, μ-chambers, silicon trackers) is in progress
- The new experimental setup is already in GEANT4. Simulation to be completed for:
  - defining the final layout geometry (for maximize acceptances)
  - studying background and estimating signal efficiencies and acceptances
- Analysis strategy based on 2017 experience
  - A monitoring system needed to validate data soon after a run is finished

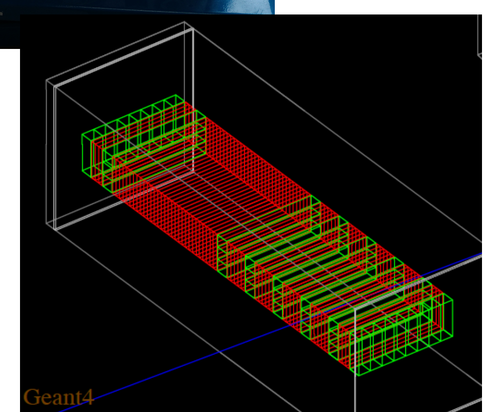
Hardware status: Calorimeters

- Technolgies: a combination of **lead glass + smart absorber**
  - same configuration on both "muon lines"

- Lead-glass from OPAL/NA62
  - section10cmx10cm
  - available in Frascati
  - needs refurbishing

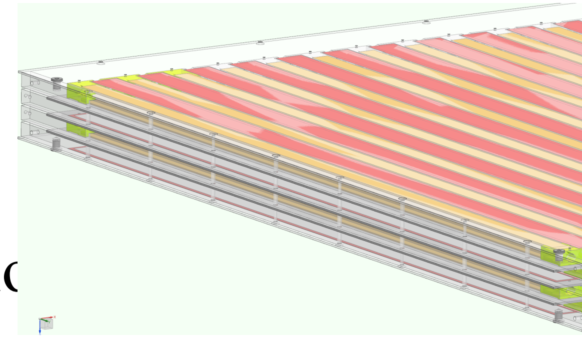


- "Smart Absorber" from CRYSBEAM
  - alternating layers of **tungsten and fused silica** (Cherenkov) radiators.
  - a simplified version already used in 2017
  - final configuration: 8 quartz layers read by PMTs
  - The first detector ready
  - The material for the second one has been ordered



Hardware status: the Mini-DT μ-chambers

- A rescaled and refurbished version of the CMS Drift Tubes chamber used for the 2017 test beam
  - Overall transverse dimensions: ~70x70 cm^2
  - Rather light, can be carried "by hand"



- Same cell geometry and electrodes configuratio
- Same "superlayer" (quadruplet) configuration
  - Layers are staggered to allow mean-timer application
- Reutilization of several spare CMS components
  - Aluminum plates, electrodes, front-end electronics, HV boards
- Several new components too
  - Rationalizations of mechanics
  - Better grounding than 2017 TB
- Assembling of 4 quadruplets is ongoing
- Final configuration:
  - 2 "chambers" made of 2 quadruplets, both measuring the bending coordinate

Summary and perspectives

- The CERN SpS beam facility can provide 45-GeV positron beams with features suitable for studying several aspects of the muon production in terms of beam characteristics and target options

- A preliminary test beam has been carried out in Summer 2017, with a quite complex detector layout
  - several problems met, so limited number of good muon pairs accumulated
  - however, we have shown the capability of the system to select **$e^+e^- \to \mu^+\mu^-$** events with no contamination from Bahbha or bremsstrahlung events with converted photons

- A new one-week-long test beam is planned for Augut 2018
  - improved experimental setup to continue the 2017 experiment
  - preparation is proceedings timely

BACKUP slides

Test at DAΦNE

- **Beam dynamics studies of the ring-plus-target scheme:**
  - transverse beam size
  - current
  - lifetime
- **Measurements on target:**
  - temperature (heat load)
  - thermo-mechanical stress

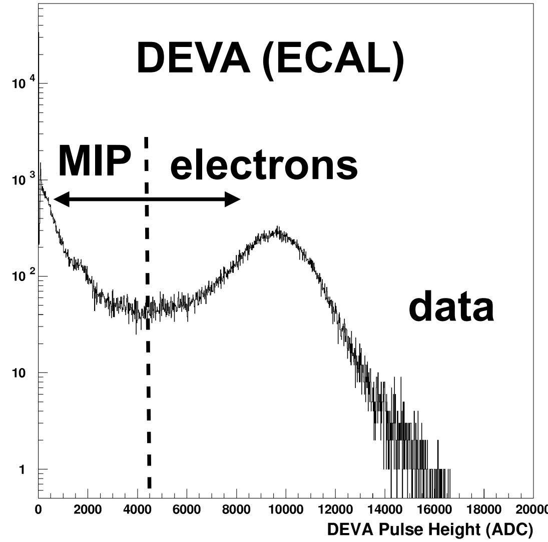
Table 8: DAFNE parameters for the test with thin target at IP.

Parameter	Units	
Energy	GeV	0.51
Circumference	m	97.422
Coupling(full current)	%	1
Emittance x	m	0.28×10^{-6}
Emittance y	m	0.21×10^{-8}
Bunch length	mm	15
Beam current	mA	5
Number of bunches	#	1
RF frequency	MHz	368.366
RF voltage	kV	150
N. particles/bunch	#	1×10^{10}
Horizontal Transverse damping time	ms/turns	42 / 120000
Vertical Transverse damping time	ms/turns	37 / 110000
Longitudinal damping time	ms/turns	17.5 / 57000
Energy loss/turn	keV	9
Momentum compaction		1.9×10^{-2}
RF acceptance	%	± 1

- The SIDDHARTA-2 experiment run will end on 2019 => our tests in 2020
- The target will be inserted at the IP:
  - To minimize modifications of the existing configuration
  - low-β and D_x=0 is needed
- First studies with the SIDDHARTA optics and target placed at the IP ongoing
- Limited energy acceptance of the ring (~1%) => we plan to insert light targets (Be, C) with thickness in the range 10-100μm.
- Crystal targets can be foreseen too, modified Geant4 tool needed for simulation

electron/muon discrimination

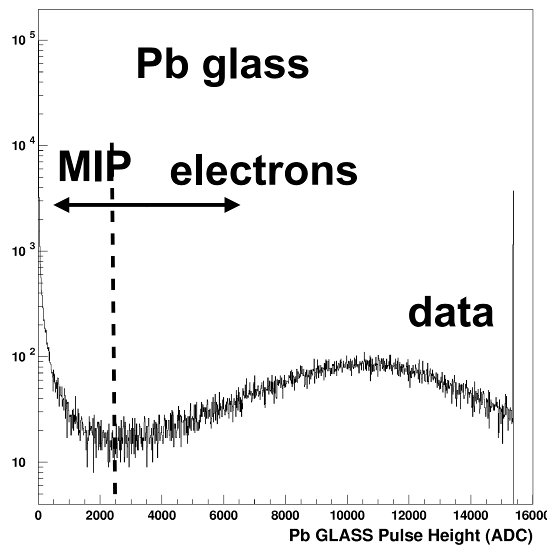
μ^+e^+ line

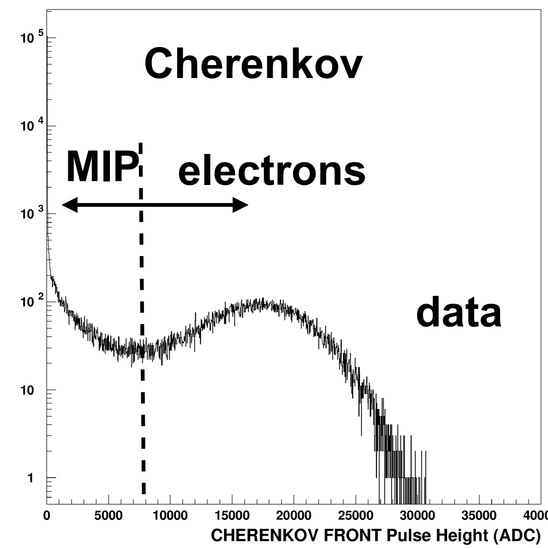


Work is ongoing to define criteria for MIP/ electrons identification

Not used in the current reconstruction

μ^+e^+ line

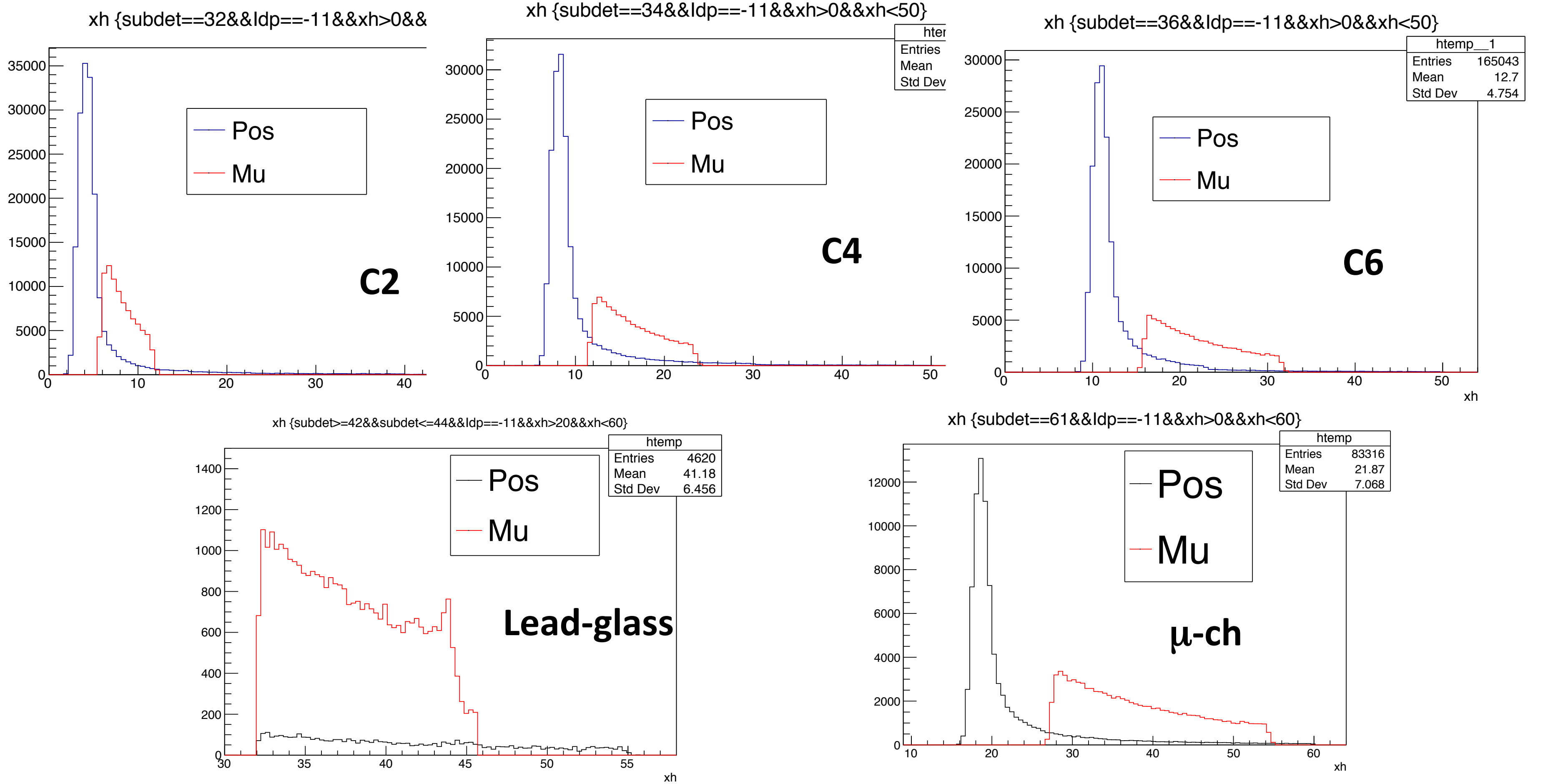




Preliminary studies for 2018 TB

- μ^+ beam: $15 < p < 30$ GeV/c, flat (we expect $18 \lesssim p_{\mu\pm} \lesssim 26$ GeV/c)
- e^+ beam: interacting with 6cm Be-target, nominal p (45 GeV with 2% gaussian spread)
- $\boldsymbol{Bl}$ **= 3.7 Tm**

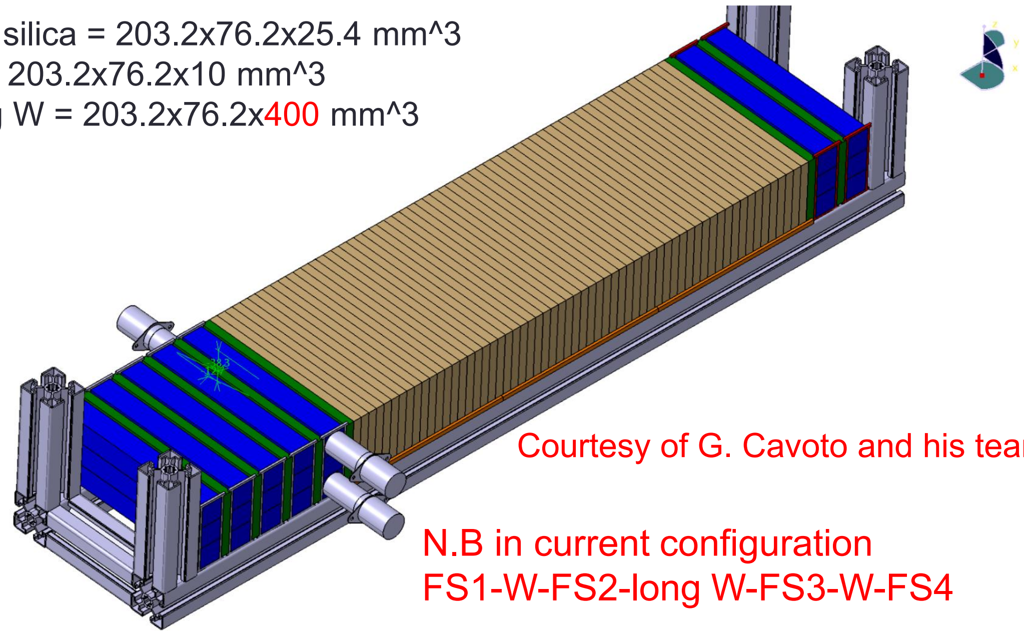
Horizontal distributions of the beams at the longitudinal positions corresponding to the various detectors input. Studies for tracking layout optimization



Smart absorber

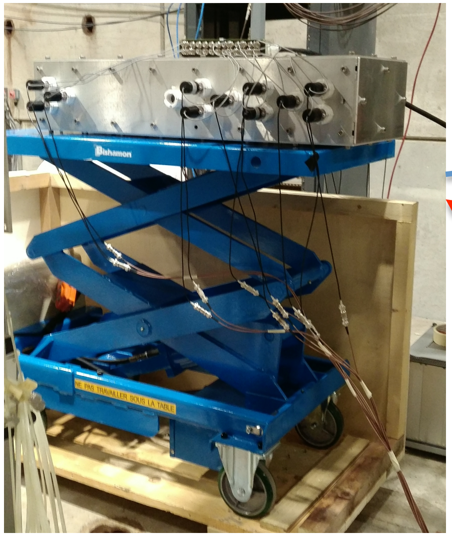
G. Cavoto

Blue – fused silica = 203.2x76.2x25.4 mm^3
Green – W = 203.2x76.2x10 mm^3
Yellow – long W = 203.2x76.2x400 mm^3

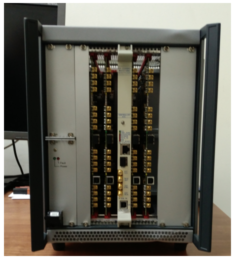


Courtesy of G. Cavoto and his team

N.B in current configuration
FS1-W-FS2-long W-FS3-W-FS4



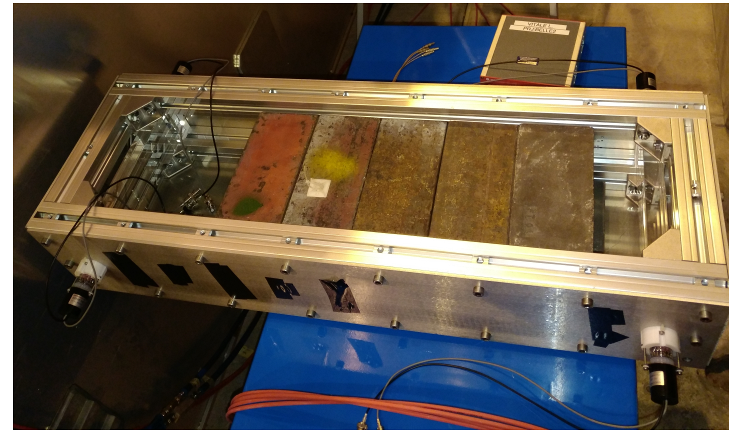
64Ch WaveCatcher readout

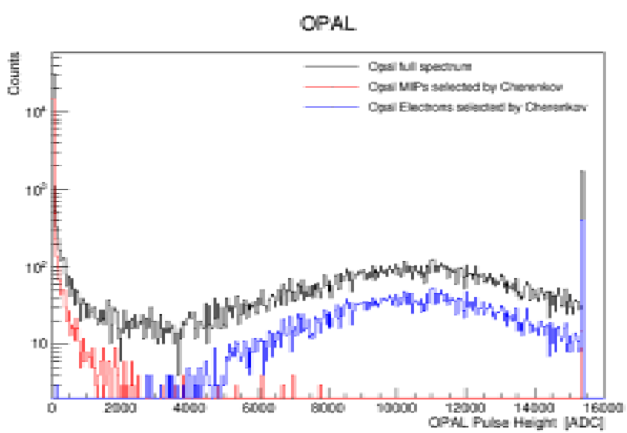


Multichannel Power Supply System

The smart-absorber in the Lemma test beam (2017)

- only 2 layers of fused silica ,(the first and the last one) and 50 cm of iron absorber (~30 radiation length ,~ 3 pion interaction length)
- Used as veto to separate μ and e
- Only 4 channels (2 front and 2 back) readout by 8-channels WaveCatcher



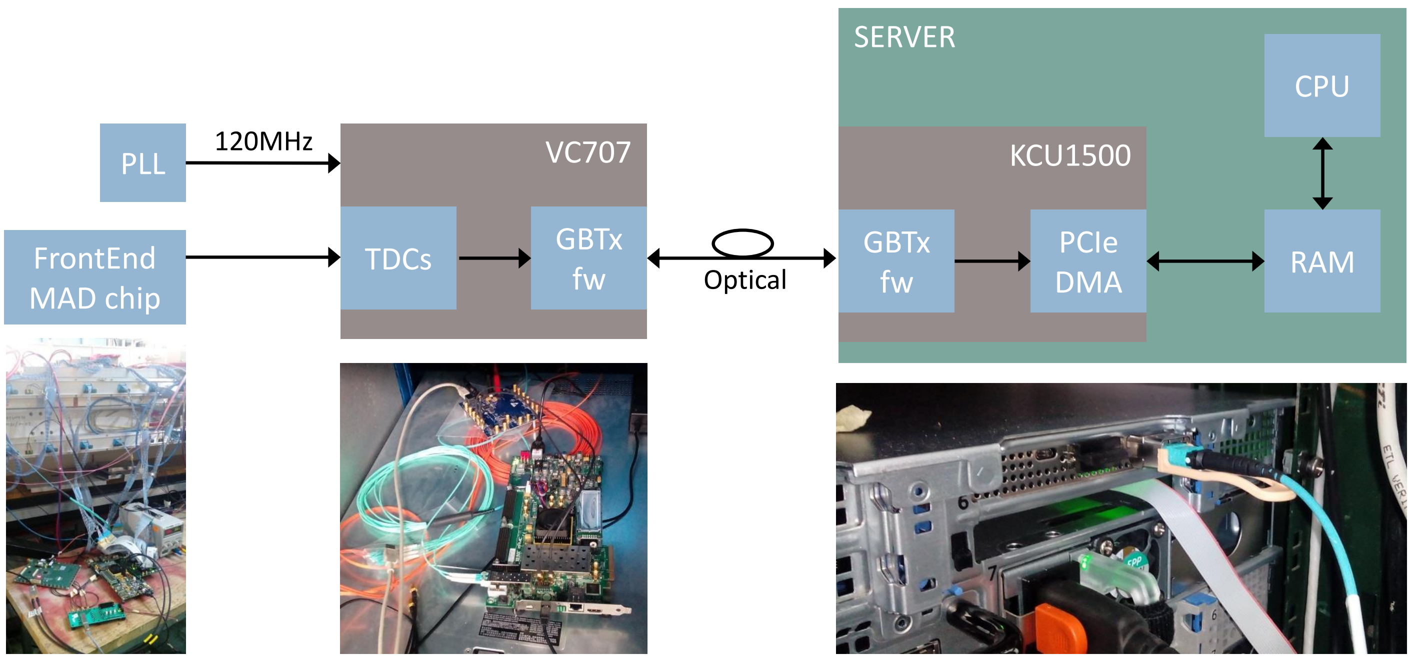


Amplidute spectrum of lead glass calorimeter with end without veto

- Data was integrated on LEMMA DAQ and used for offline analysis
- Preliminary analysis shows the Smart Absorber can used to cut Bahbah events

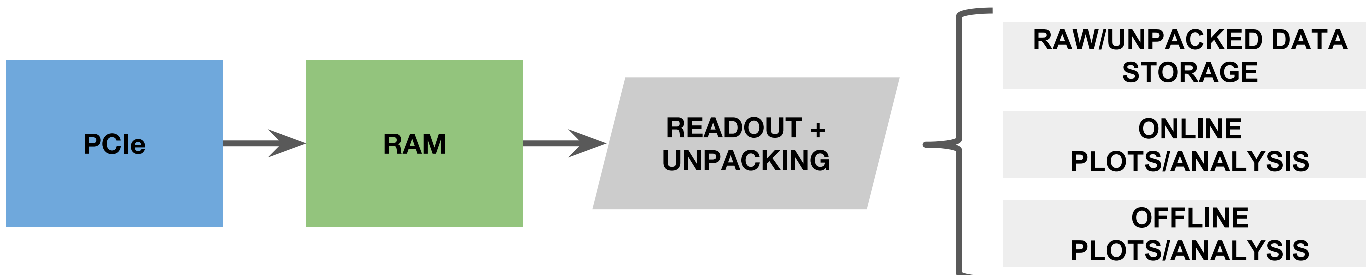
DT Read-out and trigger(less)

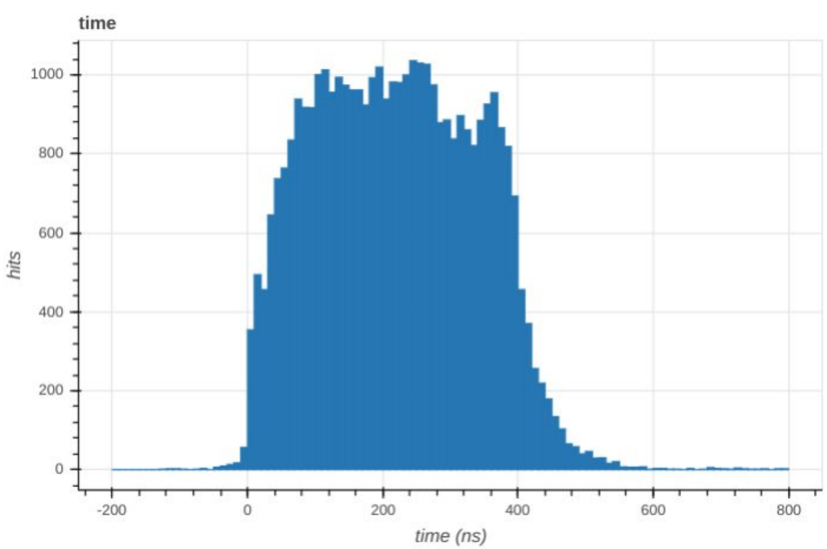
- Same front-end but completely new read-out system
- Trigger-less readout at 40 MHz:
  - Raw TDC data needs to processed to reconstruct muon stubs
- Successfully deployed and tested at CERN
- Being installed on DT chambers in LNL today!

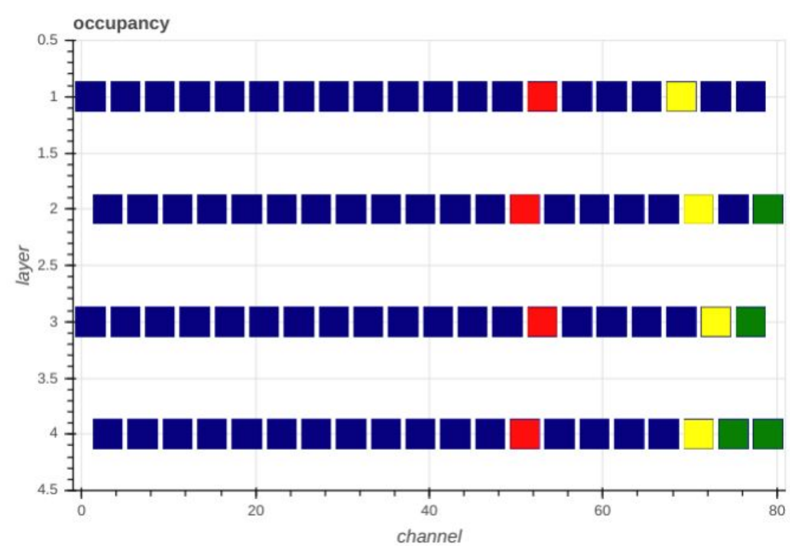


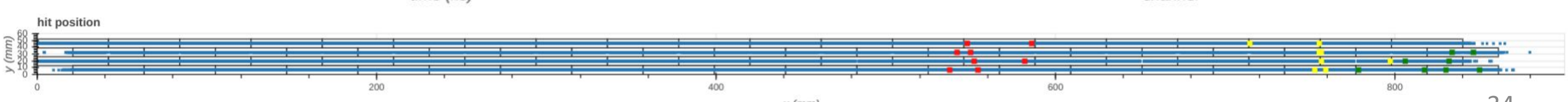
Software

- Entire software chain (from raw data to track fit and monitoring) is in place
- Needs to be expanded to multiple quadruplets



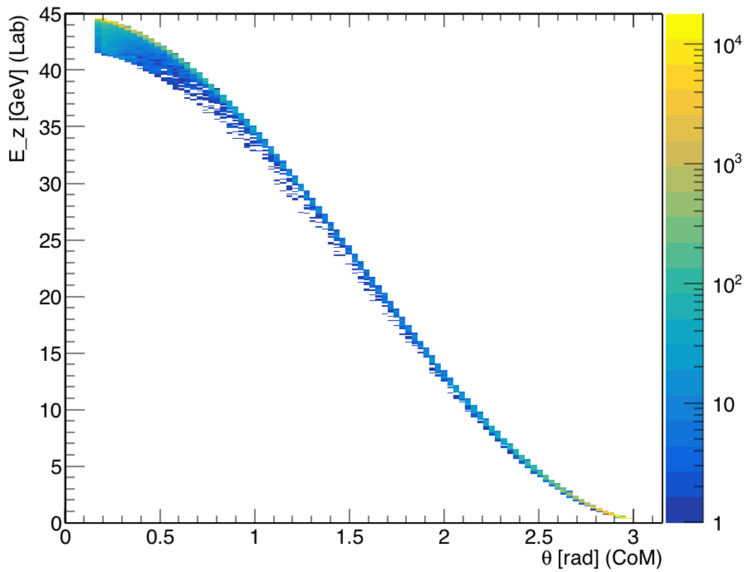


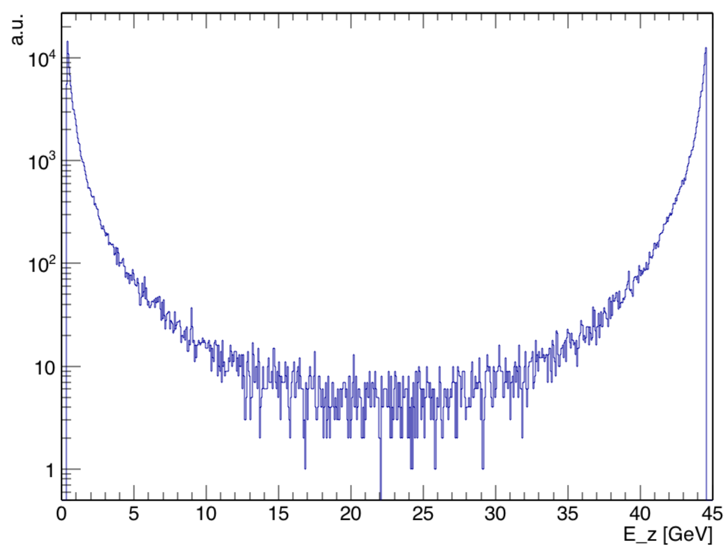


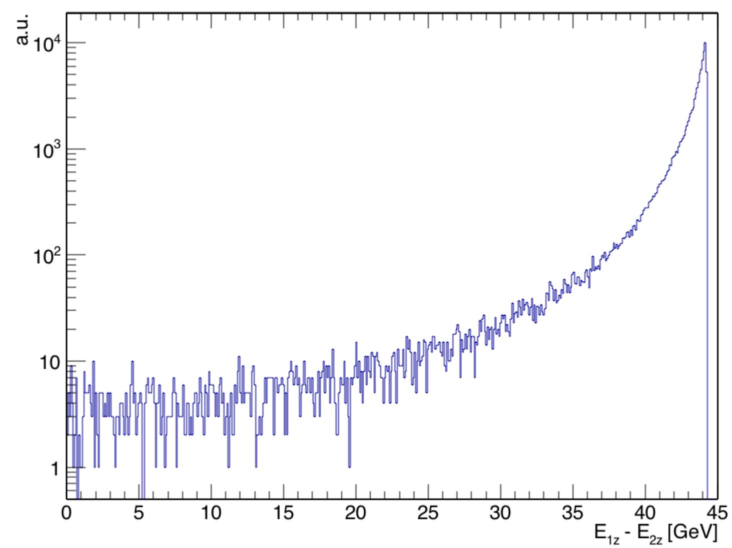


Bhabha

- Bhabha cross section diverges at null scattering angle
- Longitudinal momentum and angle fully correlated
- Bulk of events are completely asymmetric in E_z

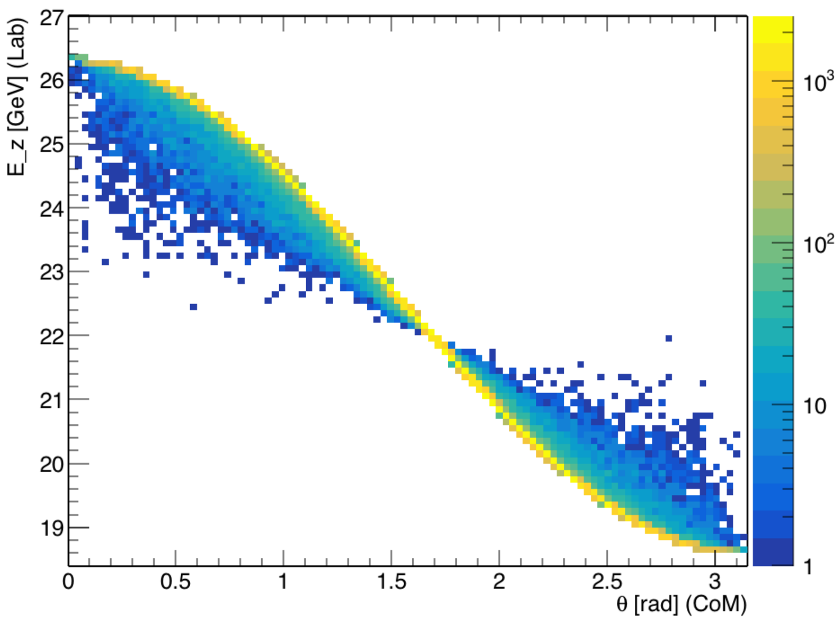


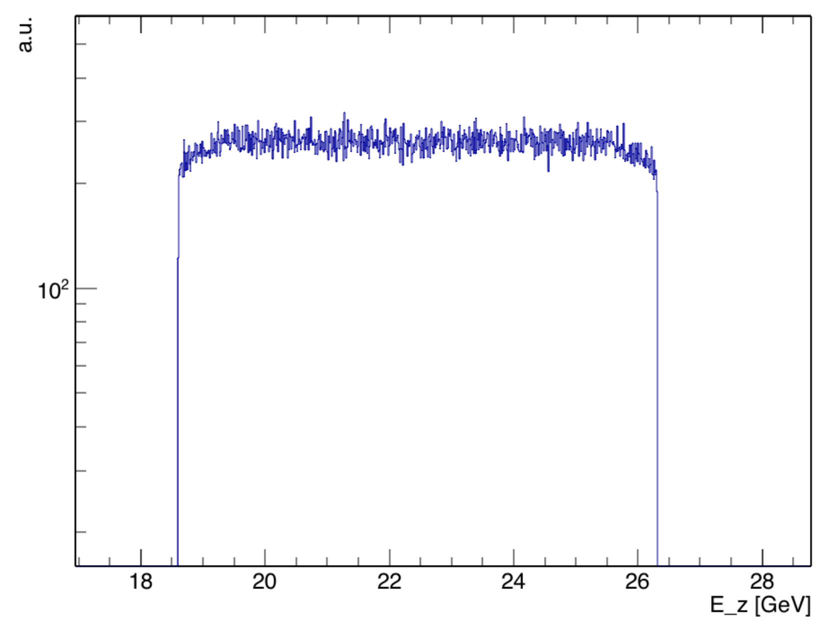




$\mu^+\mu^-$ production

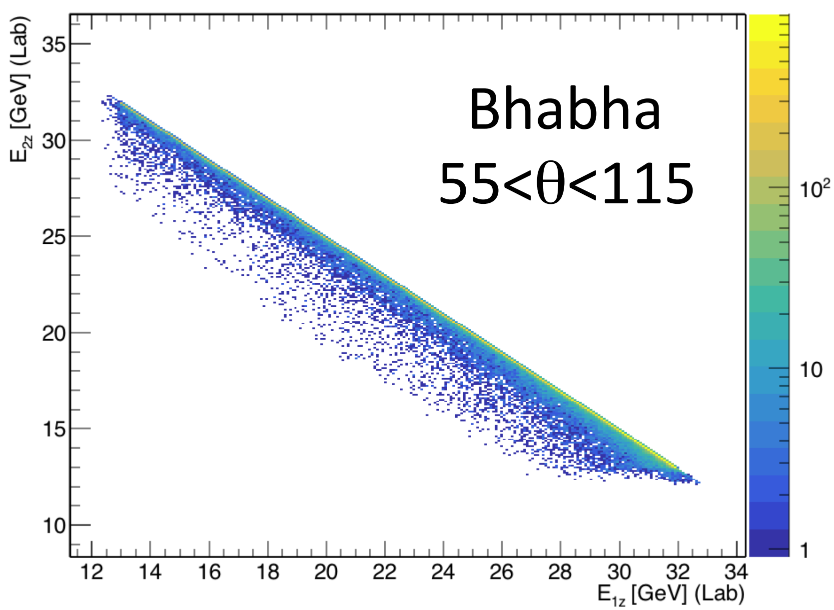
- Same E_z-θ correlation as Bhabha
- Production at threshold ➔ Events kinematically constrained in a flat E_z window a few GeV wide
  - ~8 GeV at $\sqrt{s}$=0.2145 GeV (45 Gev e^+ beam)

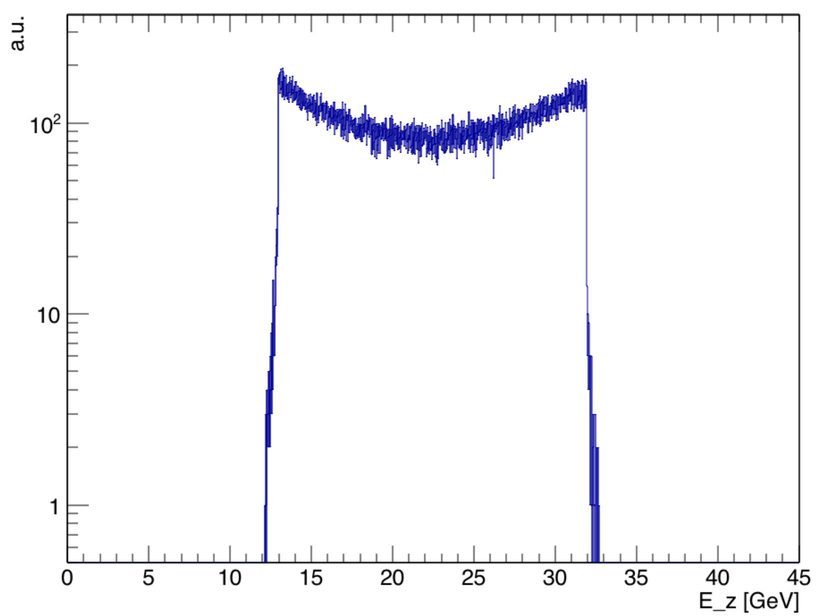




Cross sections comparison

- Estimate Bhabha cross section for events kinematically similar to $\mu^+\mu^-$ from a sample restricted to high scattering angle
  - $\sigma(e^+e^- \rightarrow e^+e^-)$=1.88 μb
  - Those events should be there in Geant too
- To be compared with $\sigma(e^+e^- \rightarrow \mu^+\mu^-)(\sqrt{s}=0.2145)$ = 0.41 μb





Rate Normalization

- Can we use ee→gg to normalize our event rate?
- Preliminary studies indicates it will be hard
  - Signal overwhelmed by background photons
  - ➔ To be further studied