Search for LFV with Mu3e experiment

NUFACT 2021.09.07

Alexandr Kozlinskiy (JGU Mainz, Institut für Kernphysik)

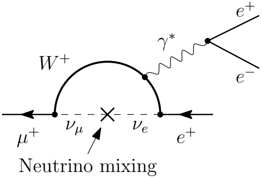
on behalf of the Mu3e Collaboration

Mu3e Experiment

Search for Lepton Flavor Violation (LFV)

- Searching for a decay $\mu^+ \to e^+e^+e^-$
- This decay is not observable in the Standard Model (Br $< 10^{-54}$)
- *Any observed decay will point to New Physics*

SM $\mu^+ \to e^+e^+e^-$



Mu3e Experiment

Current experimental status:

- SINDRUM (1988) *Nucl.Phys.B299(1988)1*
- Br < 10^{-12} at 90% c.l

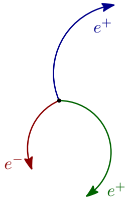
Mu3e aims for Single Event Sensitivity (SES) of $2 \cdot 10^{-15}$

- Use existing beam line (πE5, $10^8 \mu$/s) at Paul Scherrer Institute
- Factor 10^3 improvement compared to SINDRUM result
- At Phase II aim for 10^{-16} sensititivy
  - New High Intensity Muon Beamline (HIMB) at PSI
  - See "The HIMB project at PSI" talk on Thursday by Andreas Knecht

Signal

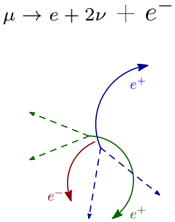
Signal ($\mu \to 3e$):

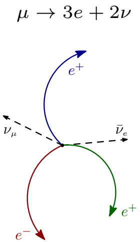
- Three tracks (two positrons and one electron)
- Muon decays at rest
  - $\sum \mathbf{p}_e = 0 \to$ need good momentum resolution
  - Invariant mass: $M_{e^+e^+e^-} = m_\mu$
  - $|\mathbf{p}_e| < 53$ MeV/c $\to$ large Multiple Scattering (MS) $\to$ need to reduce material
- Common vertex & time $\to$ need good vertex resolution

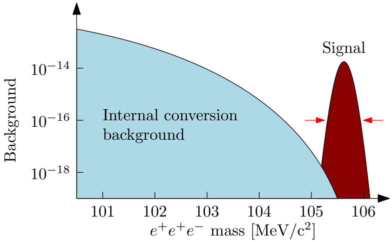


Background:

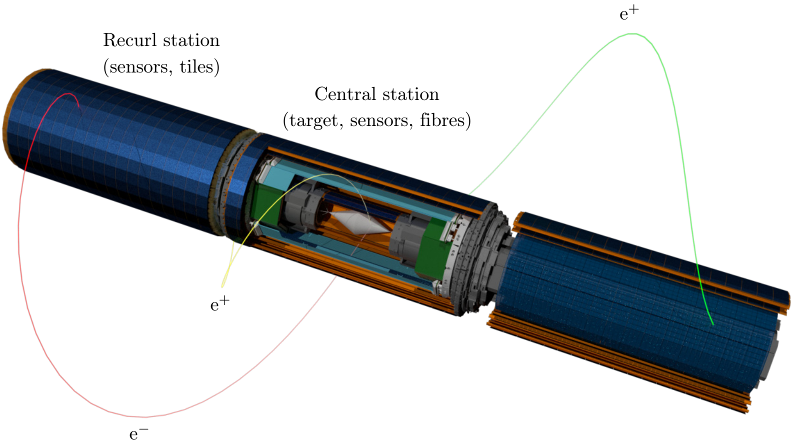
- Random combinations:
  - Overlap of $\mu^+ \to e^+ + 2\nu$, $e^\pm$ scattering
  - *Fake* tracks
  - Not same vertex, time, etc.
- Internal conversion:
  - $\mu^+ \to e^+e^+e^- + 2\nu$
  - Missing momentum & energy



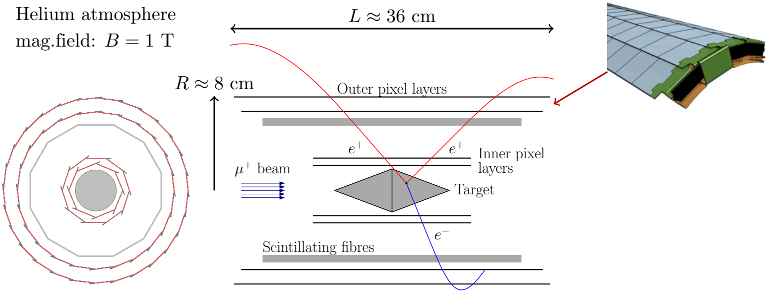




Mu3e Detector



Detector - central station



Double cone hollow target:

- Muons stop on target and decay at rest
- Vertices are distributed over surface of the target for better vertex separation

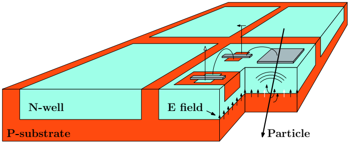
4 pixel layers:

- Provide hits for track reconstruction
- HV-MAPS technology (minimize material budget to reduce Multiple Scattering)

High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

- Commercially available (HV-CMOS) process (AMS & TSI 180 nm)
- Combination of matrix + readout, in-pixel electronic
- Large area (2×2 cm^2)
- High granularity (pixel size 80×80 µm^2)
- High efficiency ($> 99\%$)
- Fast charge collection via drift (HV, $\sigma_t < 15$ ns)
- Can be thinned to 50 µm

- See "HV-MAPS" talk on Wednesday by Andre Schöning



I.Peric, NIM A582(2007)876

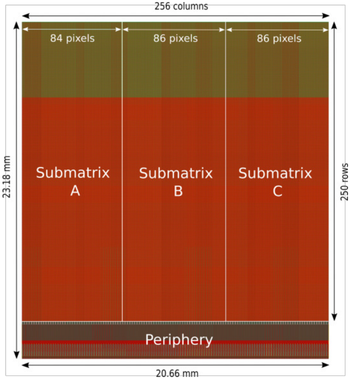
MuPiX 10

Design:

- Substrate: 20, 200 $\Omega\ cm$
- Thickness: 50-70, 100, 650 μm
- Matrix: 256 $\times$ 250
- Pixes size: 80 $\times$ 80 μm^2
- Active area: 20.48 $\times$ 20 mm^2

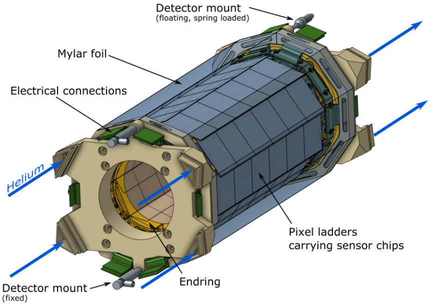
Performance:

- Efficiency $> 99\%$
- Noise rate < 2 Hz/Pixel
- Power consumption $< 350\ \mathrm{mW/cm^2}$
- Time resolution O(13) ns

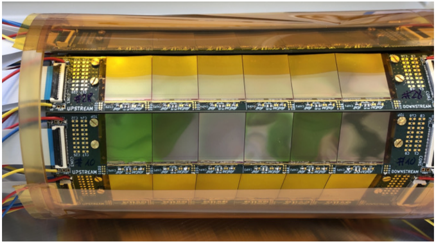


Inner/vertex tracker

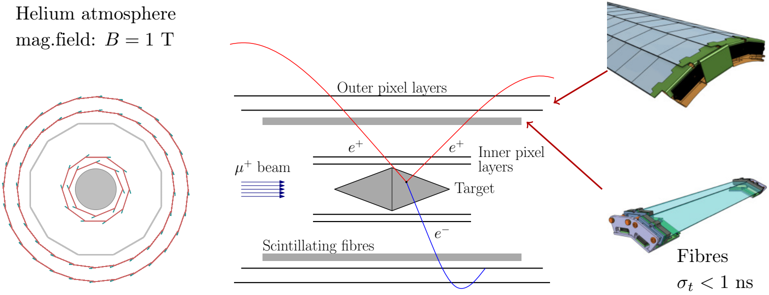
- Sensors are mounted on High Density Interconnect (polyimide substrate with aluminum traces)
- First Layer - 8 ladders (placed close to target), second layer - 10 ladders (about 1 cm distance from first layer)
- Each ladder made of 6 sensors (12 cm length)



Inner tracker prototype



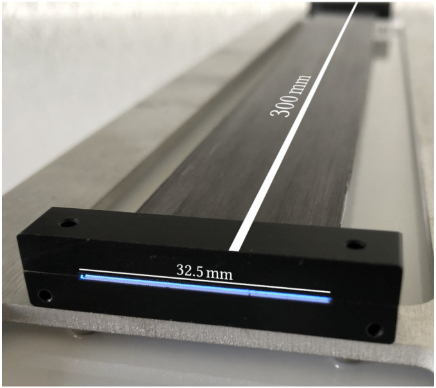
Detector - central station



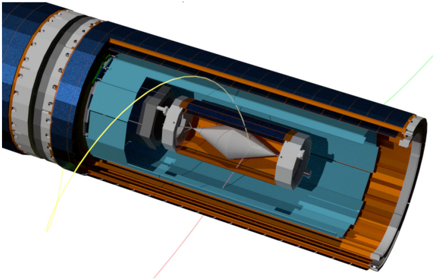
Scintillating fibres:

- Time measurement to reduce combinatorial background
- Required resolution of better than 1 ns
- Placed just before outer layers

Scintillating fibres

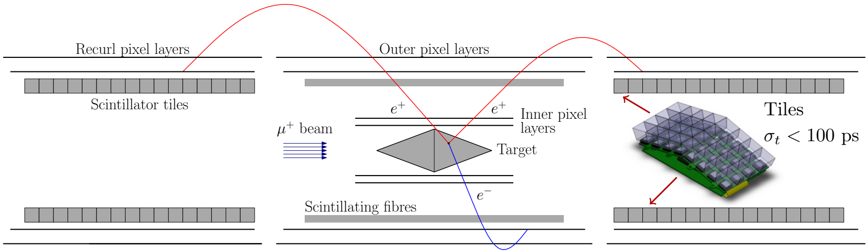


- 3 layers of fibres (Kuraray SCSF-78MJ, diameter 250 μm)
- $X/X_0 \approx 0.2\%$



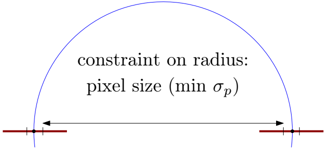
- 12 fibre ribbons coupled at both end to SiPM arrays (Hamamatsu S13552-HRQ)
- The SiPM arrays are read out by MuTRIG ASIC
- Prototype time resolution of 250 ps

Detector - recurl stations



Particles bend back in magnetic field:

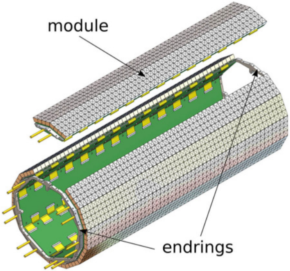
- Dedicated 'recurl' stations
- Improve momentum resolution (factor 5-10 improvement)



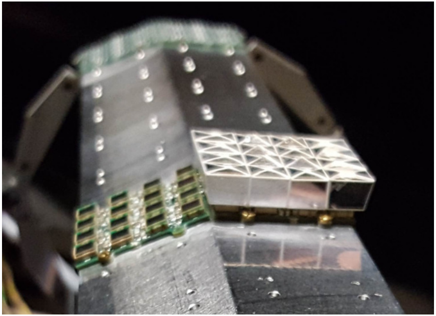
Two recurl stations:

- Two pixel layers (same as outer layers of central station)
- + scintillating tiles
  - $\sigma_t < 100$ ps
  - Suppress accidentals

Scintillating tiles



- Tile detector station: 7 modules
- Module:
  - 13 sub-modules
  - Read out by 13 MuTRIG ASICs

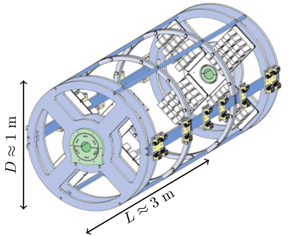


- Sub-module: 32 scintillator tiles
- Protoype performance (DESY testbeam):
  - Efficiency above 99%
  - Single channel (tile) resolution ≈ 45 ps

Magnet

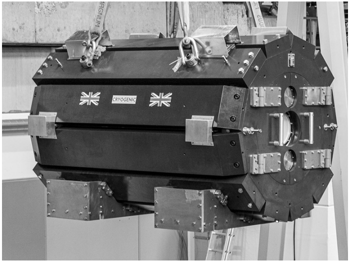
The detector is assembled on a beam pipe within the rigid cage:

- Allows for easy mounting and extraction from the magnet by use of rail system
- Supports additional infrastructure, such as power converters, front-end boards, cables, etc.

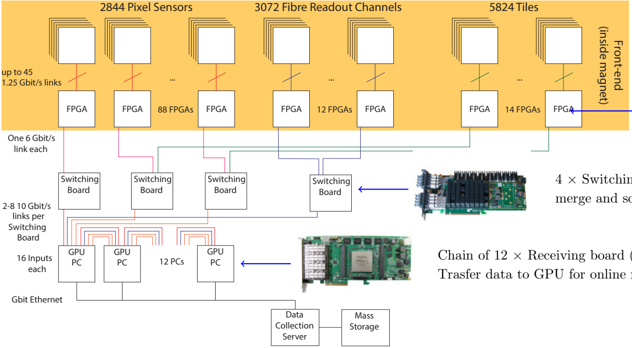


The cage is inserted inside the magnet:

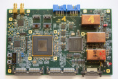
- Magnetic field: $B = 1$ T
- Inhomogenity below 10^{-3} and stability better than 10^{-4} over 100 days
- Produced by Cryogenic and delivered to PSI in summer 2020



Readout



114 × Front-End Board (Arria V)
readout for pixels, fibres and tiles
lvds to optical links

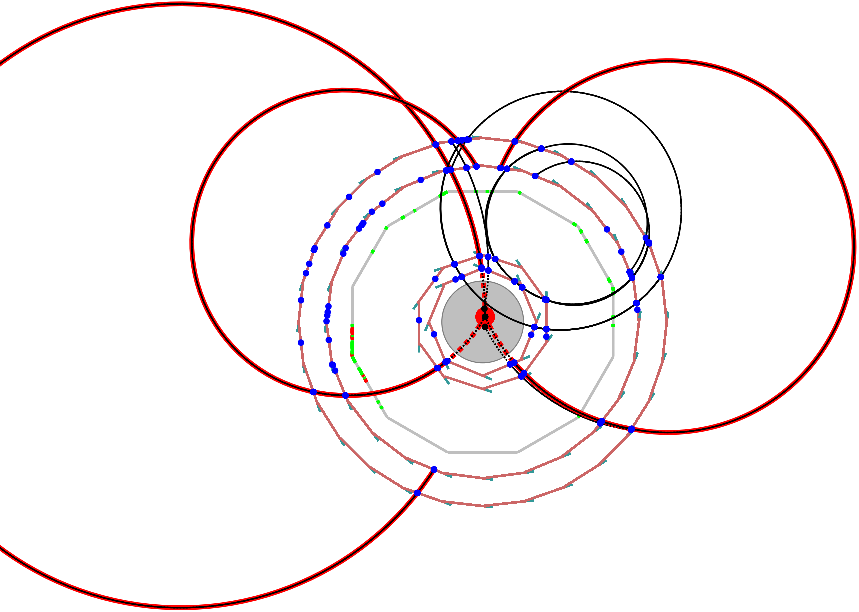


4 × Switching board (LHCb PCIe40, Arria 10)
merge and sort data streams

Chain of 12 × Receiving board (DE5a NET, Arria 10)
Trasfer data to GPU for online reconstruction

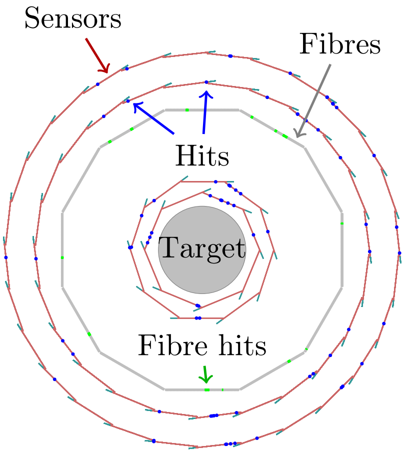
Large data rate:

- 10^8 Hz muon stopping rate
- Pixel sensors: up to 740 Mbit/s per link at inner layer (occupancy of 1.3 MHz/cm^2)
- Fibre detector average hit rate of 620 kHz per channel $\rightarrow$ 700 Mbit/s per link + noise



$10^8 \mu/s$ stop and decay on target

- Hit rate of 10^9 per second + fibre and & tile hits
- Due to limitted storage need fast online reconstruction to reduce rate by factor 100
- Continuous readout (DC beam), no trigger
- Data divided into 64 ns time slices



Reconstruction:

- Fast (triplet) fit for MS dominated environment
- Use same algorithms online and offline

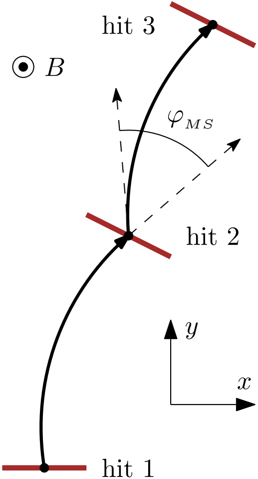
Triplet fit

Track in magnetic field:

- Described by helical trajectory
- Require minimum 3 hits to reconstruct track (triplet)

Tripet - trajectory with Multiple Scattering (MS) in middle point

- No pixel uncertainty and no energy loss
- Only one parameter - curvature r (momentum p)
- Triplet fit: minimize MS angle
  - No analytical solution
  - Small MS angles → linearization



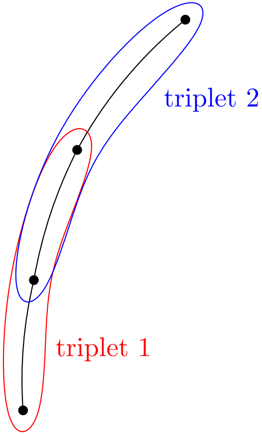
NIM A844(2017)135

Track fit

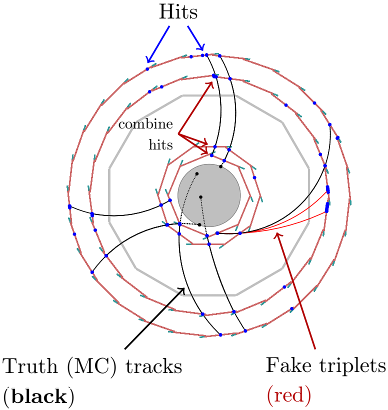
Track:

- Sequence of triplets (2 consecutive triplets share pair of hits)
- Minimize combined χ^2
  - r = weighted average of individual triplet solutions

Offline reconstruction includes effects of pixel size and energy loss



Reconstruction: from triplets to short tracks

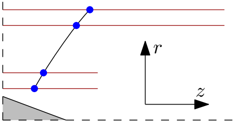


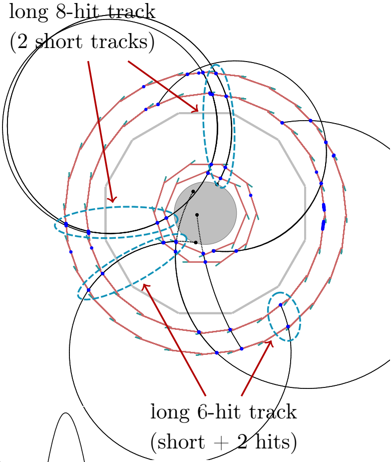
Triplet (3 hits) seeds:

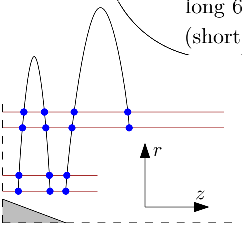
- Combine hits from first 3 layers
- 10-20 hits per layer per 64 ns time slice, O(1K) combinations
- Total 10^9 triplet fits each second
- Fake rate ≈ 1 (1 per truth track)

Short (4 hits) tracks:

- Combination of triplet and hit in outer layer
- Fake rate $\approx 1.0\%$







Long 6-hit tracks:

- Combine short track with pair of hits in outer layers

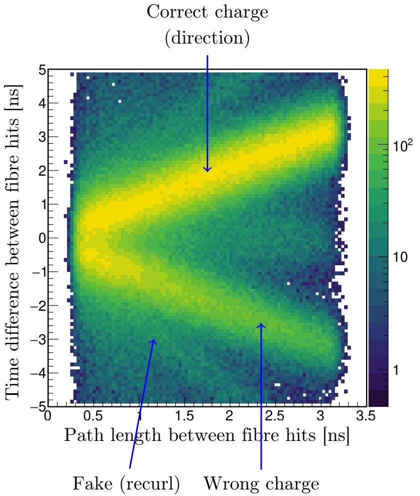
Long 8-hit tracks:

- Combine 2 short tracks with opposite curvature
- Ambiguity in direction (charge)
- Fake rate ≈ 3.7% - combination of short tracks from wrong turns

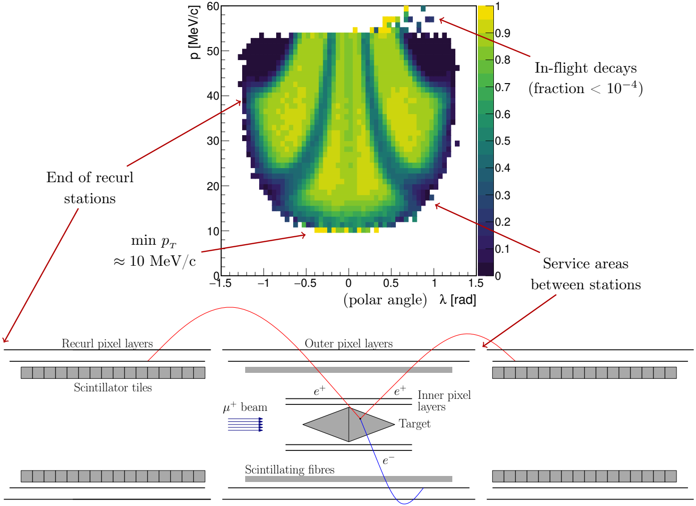
Timing

Time information from fibres and tiles:

- Link fibre and tile clusters to reconstructed tracks
- Use time difference between two fibre hits to identify track charge
- Reconstruct time at first layer that is used to reduce number of wrong combinations during vertex fit



Acceptance and efficiency



- Acceptance: $\epsilon_{acc} \approx 70\%$ (1 hit per layer, min p_T, etc.)
- Short tracks: $\varepsilon_{short} \approx 90\% \cdot \varepsilon_{acc}$ (χ^2 cut)
- Long tracks: $\varepsilon_{long} \approx 70\% \cdot \varepsilon_{short}$ (gaps, etc.) → analysis

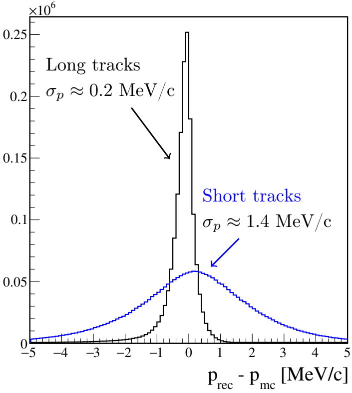
Momentum resolution

Short tracks (4 hits)

- $\langle\sigma_p\rangle \approx 1.4$ MeV/c
- Depends linearly on momentum

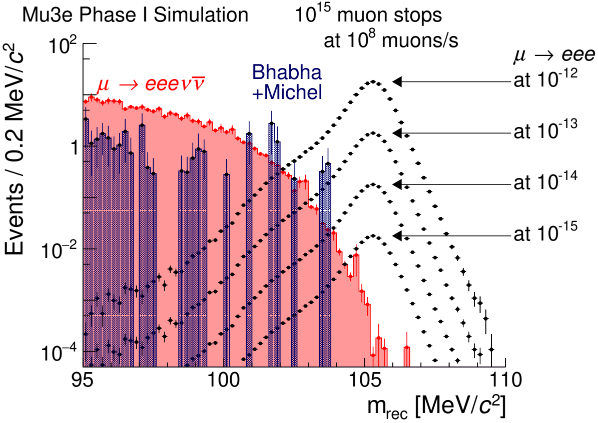
Long tracks (6 and 8 hits)

- $\langle\sigma_p\rangle \approx \mathbf{0.2}$ MeV/c
  - ($\times 10$ better than short tracks)
- **min** $\sigma_p \approx 100$ KeV/c



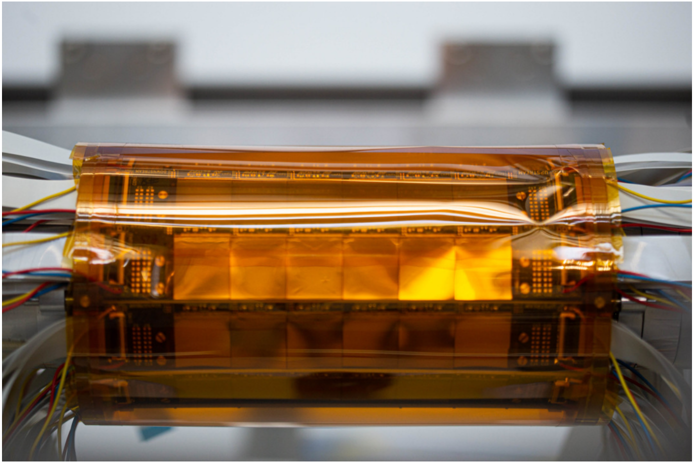
Sensitivity

- Combine 3 long tracks
- Fit vertex and apply cut on vertex time
- + other cuts to suppress Bhabha background

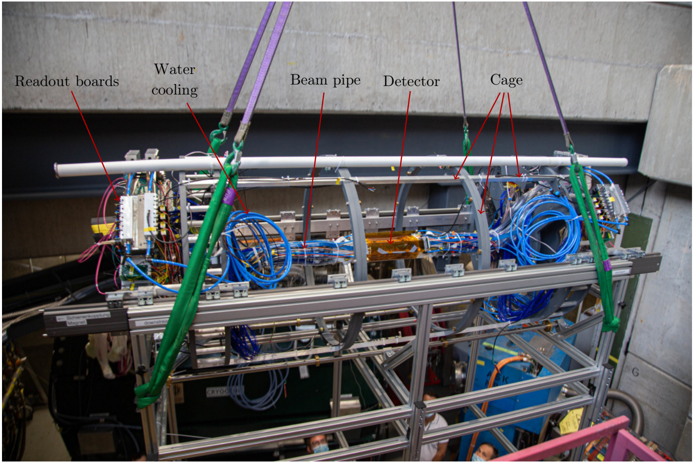


Integration run

Successfull integration run campaign from May to July 2021
with reduced detector: 2 pixel layers + fibre detector

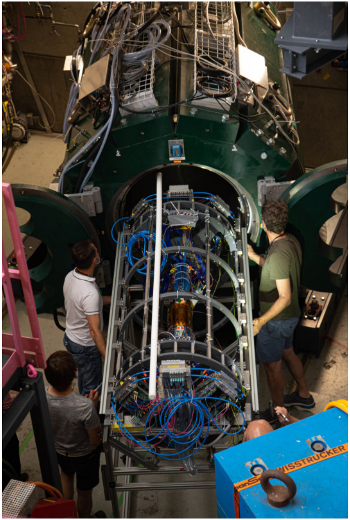


Mounted in a cage with all the readout electronics, services (cooling pipes), power converters, etc.



Integration run

- Inserted into magnet
- Run with helium cooling, in magnetic field and with a muon beam
- Almost full data readout chain
  - From detectors to front-end boards
  - Then optically from inside the magnet to switching boards in the counting room
  - Finally transfer data to PC and store to disk
- See "Mu3e Integration Run 2021" poster by Marius Köppel



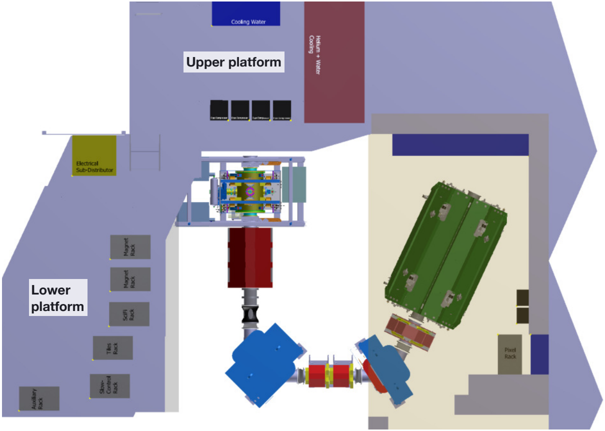
Summary

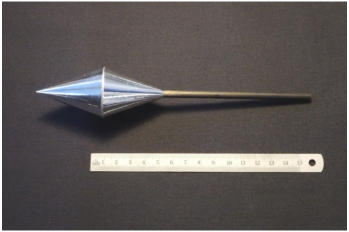
- Search for $\mu^+ \to e^+ e^+ e^-$ decay (LFV)
- Single event sensitivity of $2 \cdot 10^{-15}$
- Successfull integration run this summer (2 pixel layers, fibres, magnet, beam)
- TDR published in NIM A <https://doi.org/10.1016/j.nima.2021.165679>
- Construction and commissioning is under way

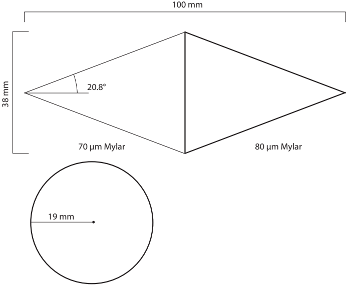
Backup

- "The HIMB project at PSI" talk on Thursday by Andreas Knecht
- "HV-MAPS" talk on Wednesday by Andre Schöning
- "Mu3e Integration Run 2021" poster by Marius Köppel
- "The Power Distribution System for the Mu3e Experiment" poster by Sophie Gagneur

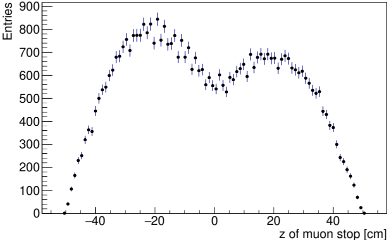
Experimental area





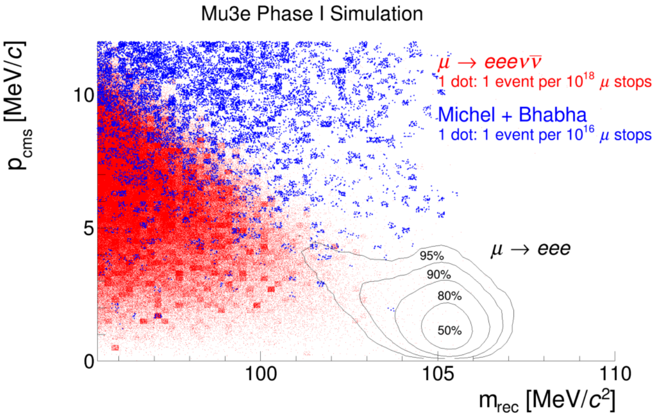


Muon stopping rate distribution:



Simulation performance

	Efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	38.1%	38.1%
Geometrical acceptance, long tracks	68.0%	25.9%
Long track reconstruction	67.2%	17.4%
Recurler rejection/Vertex fit convergence	99.4%	17.3%
Vertex fit $\chi^2 < 15$	91.3%	15.8%
CMS momentum $< 4\,\mathrm{MeV/c}$	95.6%	15.1%
$m_{ee,low} < 5\,\mathrm{MeV/c^2}$ or $> 10\,\mathrm{MeV/c^2}$	98.0%	14.9%
$103\,\mathrm{MeV/c^2} < m_{rec} < 110\,\mathrm{MeV/c^2}$	97.0%	14.4%
Timing	90.0%	13.0%


Mu3e Phase I Simulation
$\mu \to eee\nu\bar{\nu}$
1 dot: 1 event per 10^{18} μ stops
Michel + Bhabha
1 dot: 1 event per 10^{16} μ stops
$\mu \to eee$
95%
90%
80%
50%
p_{cms} [MeV/c]
m_{rec} [MeV/c^2]
0
5
10
100
105
110

Sensitivity