The Mu3e experiment
From Physics to detector design

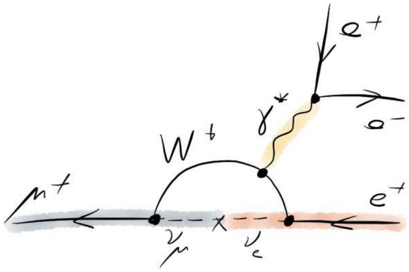
Terascale detector workshop
2/2024 Mainz

Konrad Briggl
on behalf of the Mu3e collaboration
22.02.2024

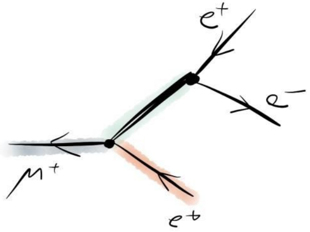
Search for Charged Lepton flavor violation

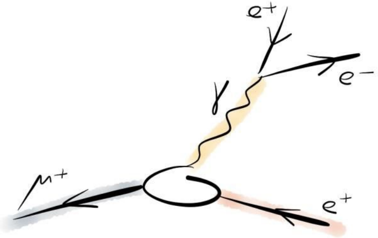
cLVF has not been observed in nature

SM - Highly suppressed Branching ratio (BR < 10^{-54})
… beyond reachable levels



Ideal probe for physics beyond SM





Search for Charged Lepton flavor violation

Channels for cLVF searches:

$\mu \rightarrow e\gamma$

Current limit: MEG ($BR_{meas} < 4.2 \times 10^{-13}$)
(MEG II: ($BR_{meas} < 5 \times 10^{-14}$))

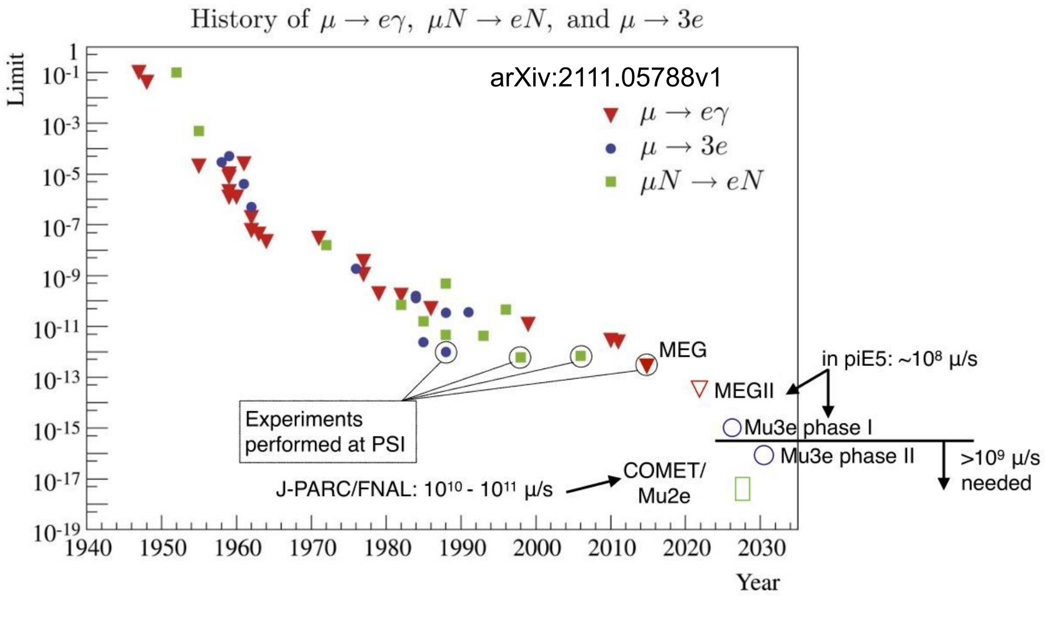
$\mu N \rightarrow eN$

Current limit: SINDRUM ($BR_{meas} < 7 \times 10^{-13}$)
(Mu2e, COMET, DeeMe ; $BR_{meas} < 10^{-16}$)

$\mu^+ \rightarrow e^+e^-e^+$

Current limit on $\mu^+ \rightarrow e^+e^-e^+$
$BR_{meas} < 10^{-12}$ (SINDRUM 1988)

<u>Future experiment (This talk): Mu3e</u>
<u>Goal:</u> $BR_{meas} < 10^{-15}$ (10^{-16} in Phase II experiment)



The search $\mu^+ \rightarrow e^+e^-e^+$

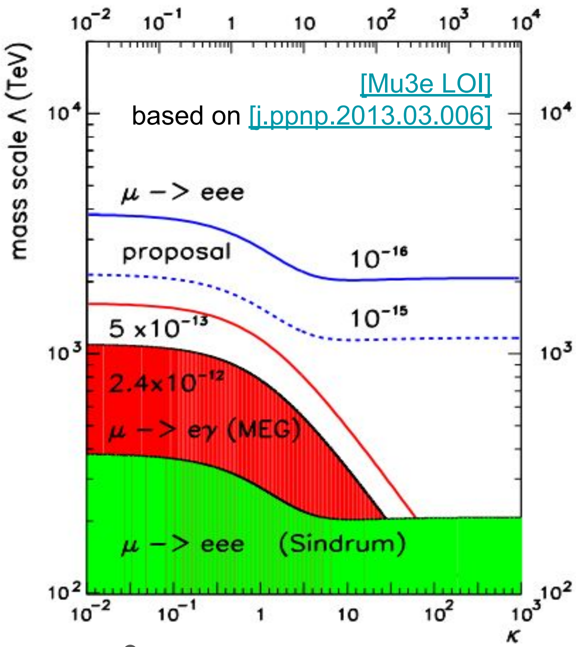
Why search for $\mu^+ \rightarrow e^+e^-e^+$?

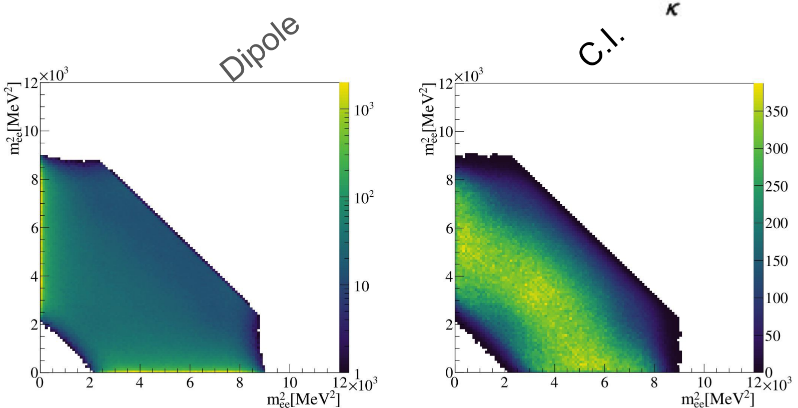
Reach for high mass scales

Complementary to other muon cLFV searches

Sensitive to new interactions on both loop and tree/contact level

Full kinematics → Operator



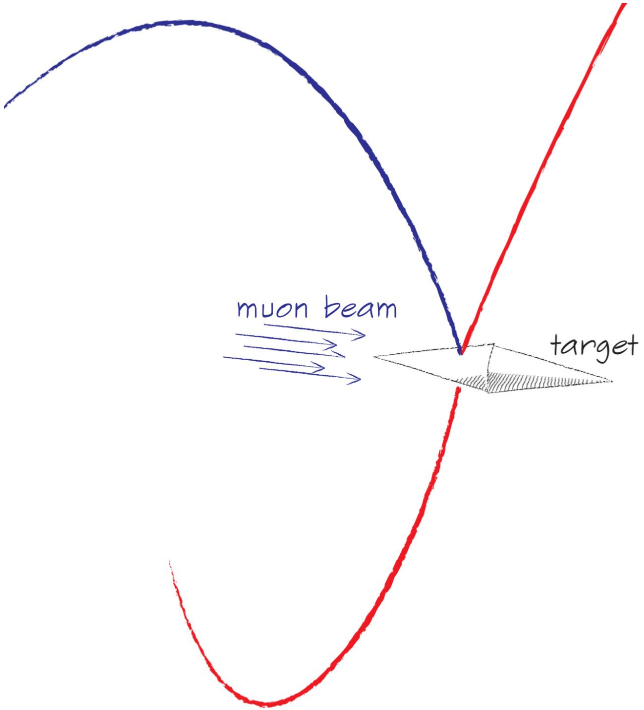


Experimental concept - The signal

High intensity muon beam
BR($\mu^+ \rightarrow e^+e^-e^+$) < 2·10^-15 (Mu3e Phase I) **10^8 μ/s**
[BR($\mu^+ \rightarrow e^+e^-e^+$) < 1·10^-16 (Mu3e Phase II) >10^9 μ/s]

Muons decay on target at rest
1T magnetic field

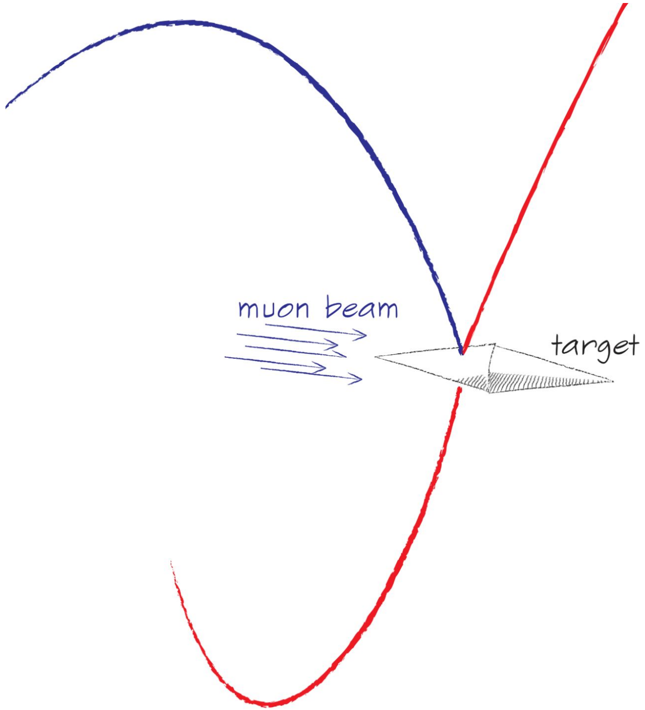
Reconstruction of 2 positrons + electron
Reconstruction of vertices on target



Experimental concept - The signal

Precise measurement of

- Common reconstructed vertex (In Space <u>and</u> Time)
- $\sum \mathbf{p}_i = 0$
- $\sum E_i = m_\mu$



Experimental concept - Backgrounds

- No SM background ($<10^{-54}$)

- $\mu^+ \rightarrow e^+ e^+ e^- \nu \bar{\nu}$

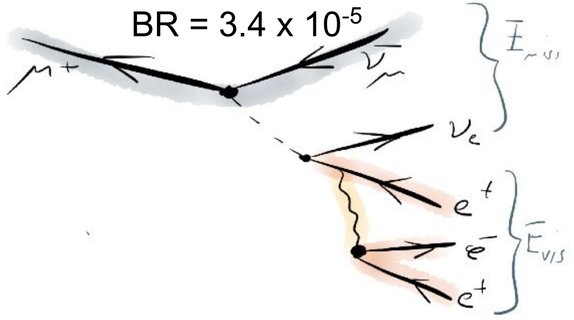
  Missing momentum & Energy

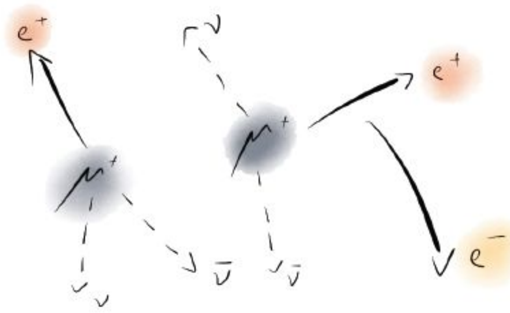
- Combinatorial background

  Missing momentum & Energy

  No common vertex

… need to be suppressed below target sensitivity





Experimental concept - Backgrounds

- No SM background ($<10^{-50}$)
- $\mu^+ \rightarrow e^+ e^+ e^- \bar{\nu}\nu$
  - Missing momentum & Energy
- Combinatorial background
  - Missing momentum & Energy
  - No common vertex

… need to be suppressed below target sensitivity

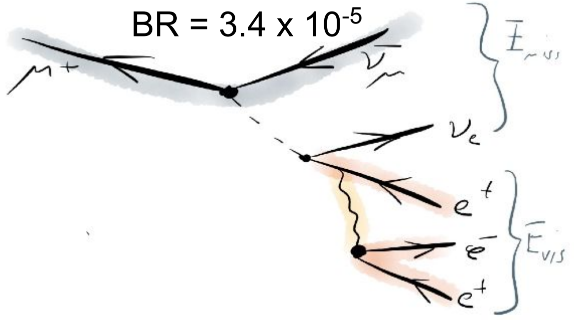
Requires excellent …

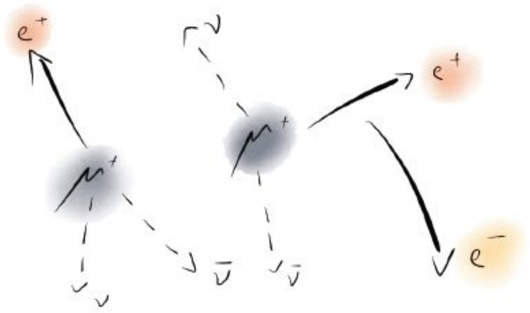
→ Vertex resolution (space & time)

→ Momentum resolution

→ Acceptance & High Rate capability

BR = 3.4×10^{-5}





Experimental concept - Backgrounds

- No SM background ($<10^{-50}$)
- $\mu^+ \rightarrow e^+ e^+ e^- \nu \nu$
  Missing momentum & Energy
- Combinatorial background
  Missing momentum & Energy
  No common vertex

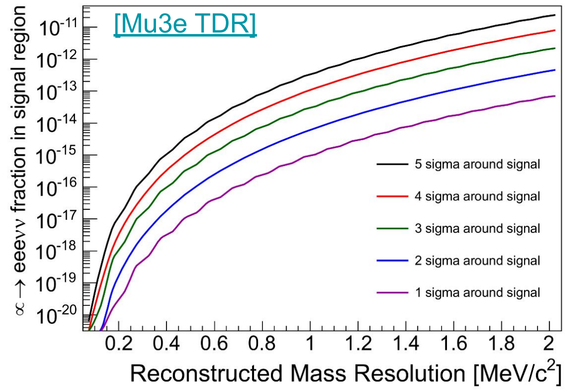
… need to be suppressed below target sensitivity

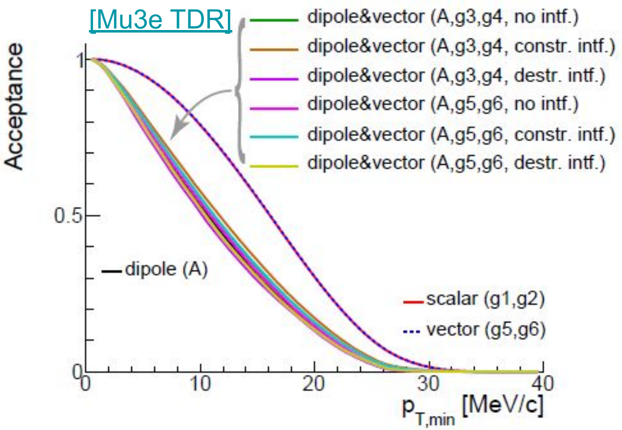
Requires excellent …

→ Vertex resolution (space & time)

→ Momentum resolution

→ Acceptance & High Rate capability





Momentum measurement - Tracking at low energies

Muons decay at rest, low energy electrons (< 53 MeV)

Measured momenta ~10 - 50 MeV/c

Magnetic field (1T) to measure momentum

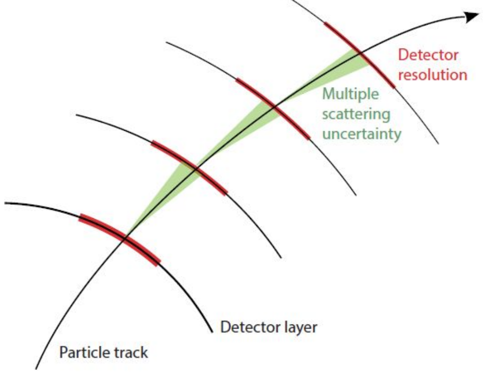
Resolution is dominated by multiple-scattering

→ Minimize material (Detector & Open volume)

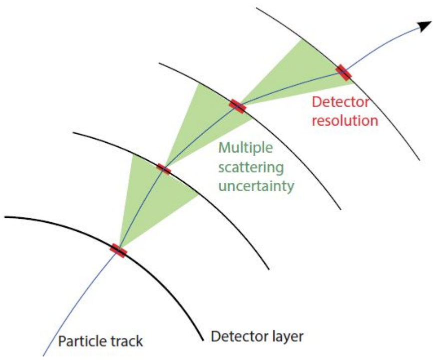
→ Recurling tracks - MS cancels at 1st order

→ Large lever arm

Detector dominated



Scattering dominated



Momentum measurement - Tracking at low energies

Muons decay at rest, low energy electrons (< 53 MeV)

Measured momenta ~10 - 50 MeV/c

Magnetic field (1T) to measure momentum

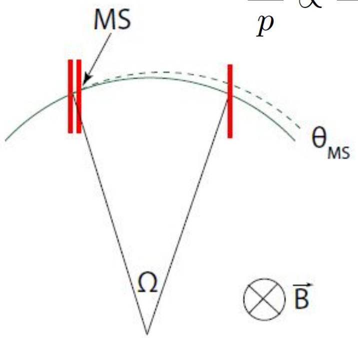
Resolution is dominated by multiple-scattering

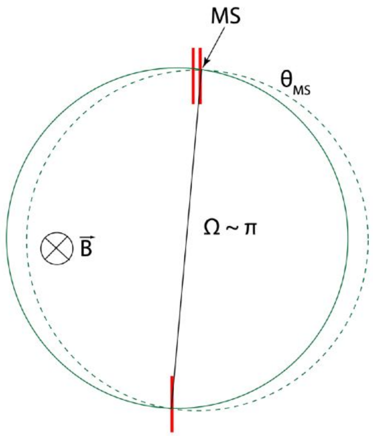
→ Minimize material (Detector & Open volume)

→ Recurling tracks - MS cancels at 1st order

→ Large lever arm

$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$

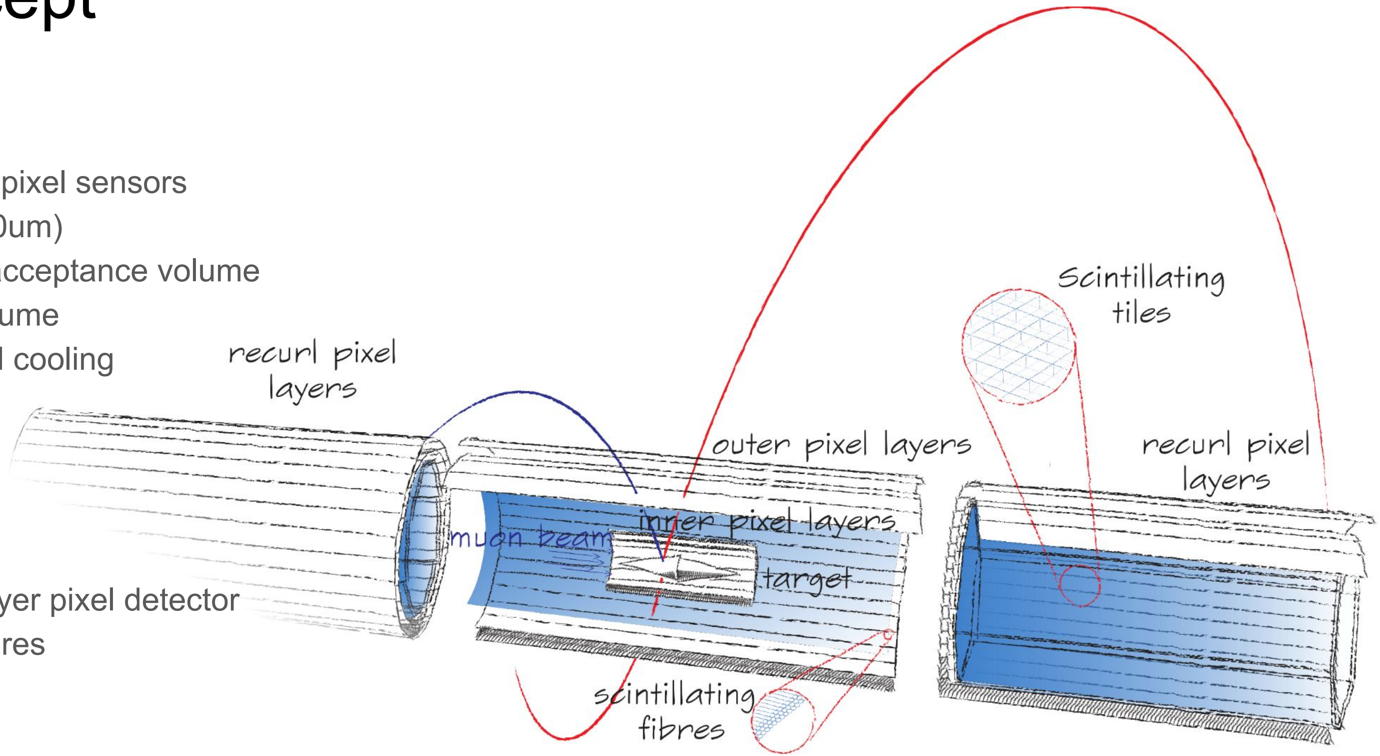




Detector concept

Minimize material

- Thin monolithic active pixel sensors
  (HV MAPS ; 50um / 70um)
- "No infrastructure" in acceptance volume
- Helium in Tracking volume
  He Flow used for Pixel cooling



Central detector

- Tracking & Vertex 4 layer pixel detector
- Timing: Scintillating fibres

Recurl stations

- Improve tracking
- Improved timing: scintillating tiles

Detector concept

Minimize material

- Thin monolithic active pixel sensors
  (HV MAPS ; 50um / 70um)
- “No infrastructure” in acceptance volume
- Helium in Tracking volume
  He Flow used for Pixel cooling

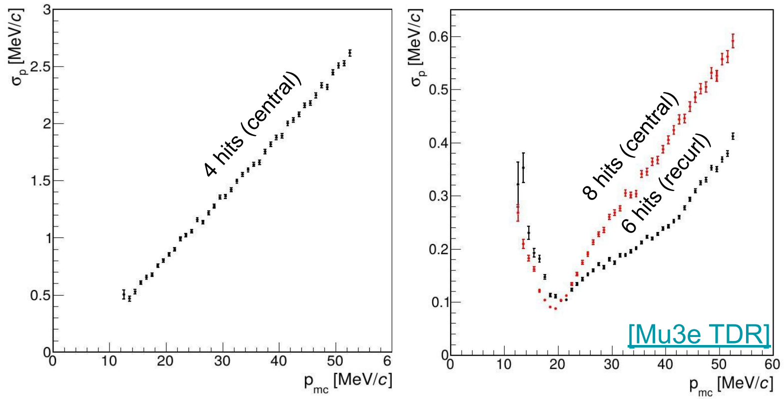
Central detector

- Tracking & Vertex 4 layer pixel detector
- Timing: Scintillating fibres

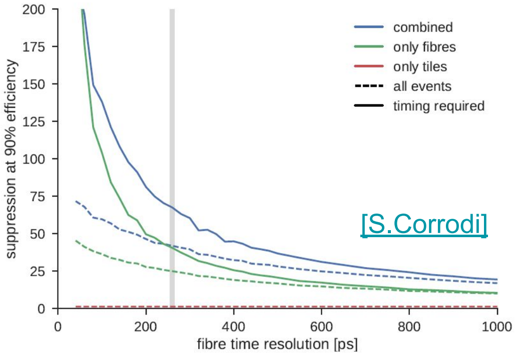
Recurl stations

- Improve tracking
- Improved timing: scintillating tiles

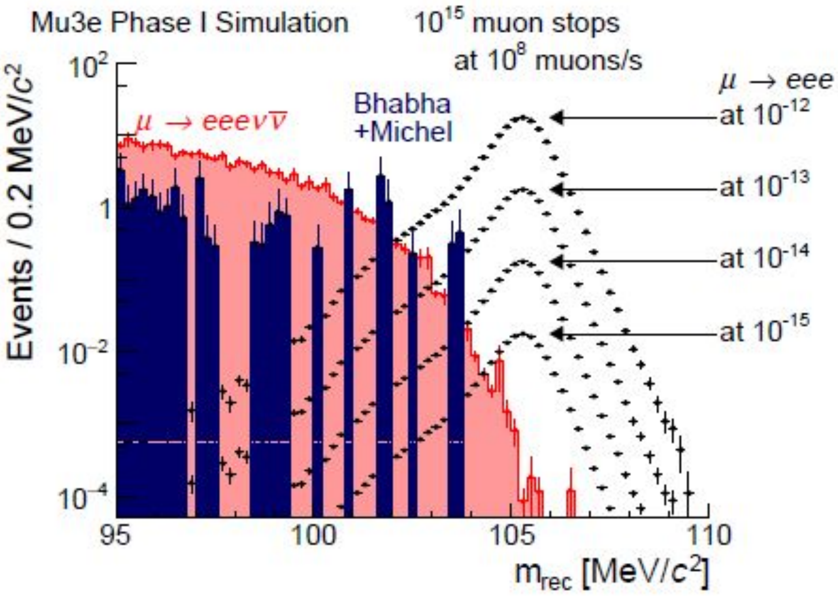
Momentum resolution

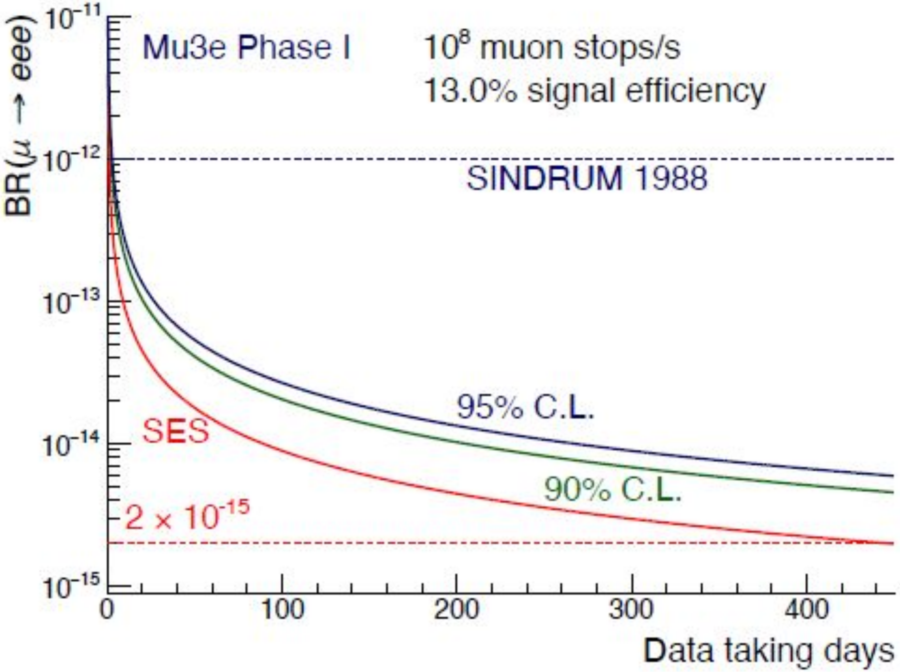


Suppression from timing detectors



Experimental concept - Simulated performance





PSI PiE5 - The Beamline

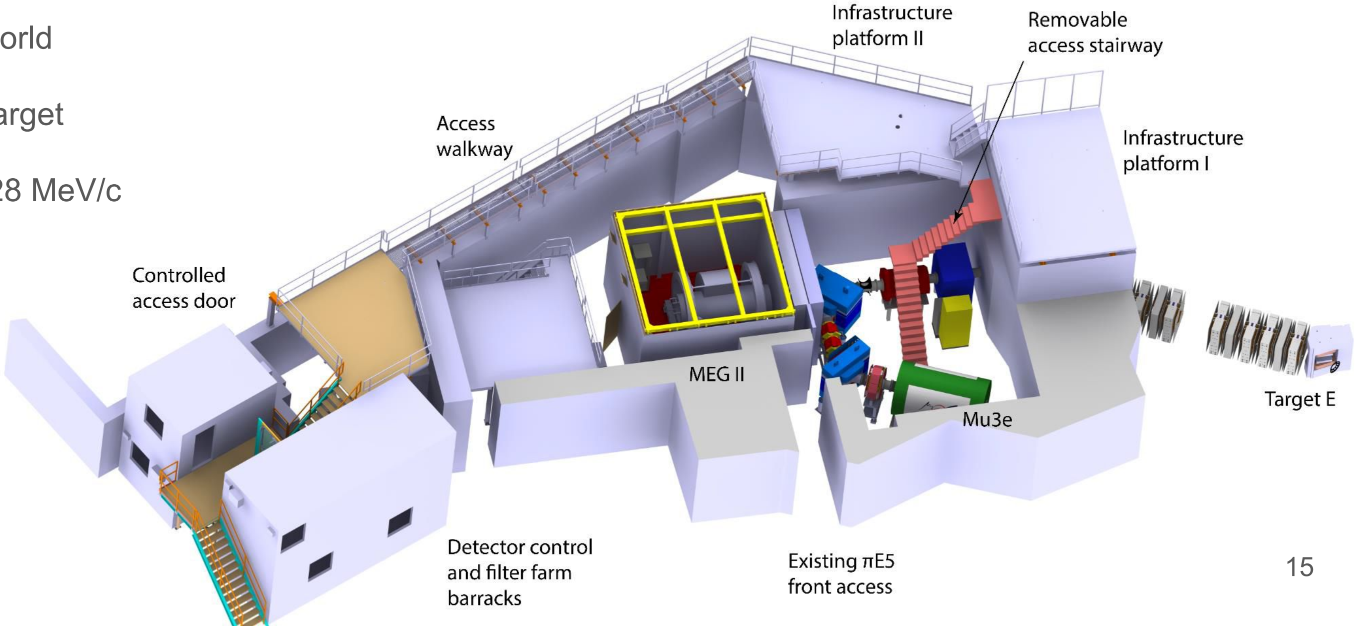
HIPA accelerator at Paul Scherrer Institute (PSI) in Switzerland

2.2 mA protons at 590 MeV (1.5 MW)

πE5 beamline: shared between MEG II and Mu3e experiments

Most intense muon beam in the world

- 10^8 μ/s stopped on Mu3e target
- Low momentum muons: ~28 MeV/c



PSI PiE5 - The Beamline

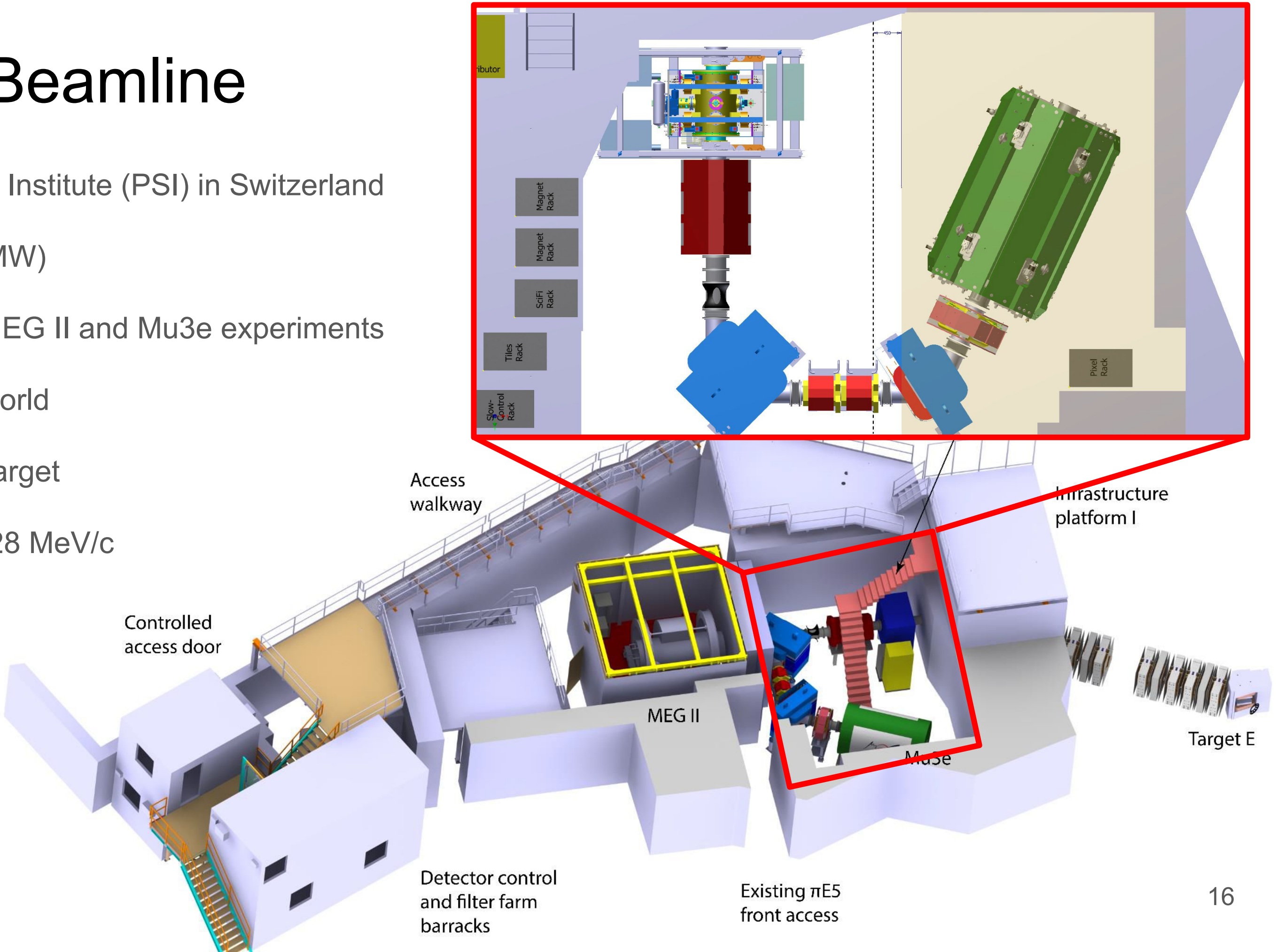
HIPA accelerator at Paul Scherrer Institute (PSI) in Switzerland

2.2 mA protons at 590 MeV (1.5 MW)

πE5 beamline: shared between MEG II and Mu3e experiments

Most intense muon beam in the world

- 10^8 μ/s stopped on Mu3e target
- Low momentum muons: ~28 MeV/c



Magnet & Target

Solenoid produced by Cryogenic Ltd.

Magnetic field up to 2.6T

Very homogeneous field in a large volume (> 2 m³)

$\Delta B/B < 2 \cdot 10^{-4}$

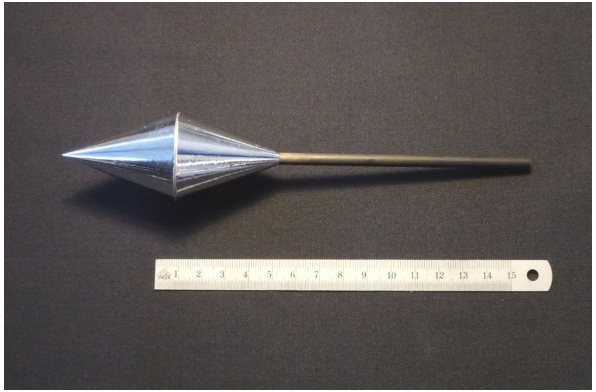
Delivered to PSI & operational

Target

Optimized shape (accidental background, stopping eff.)

Thin mylar double cone (hollow)

70μm thick, 100mm long, 19mm radius



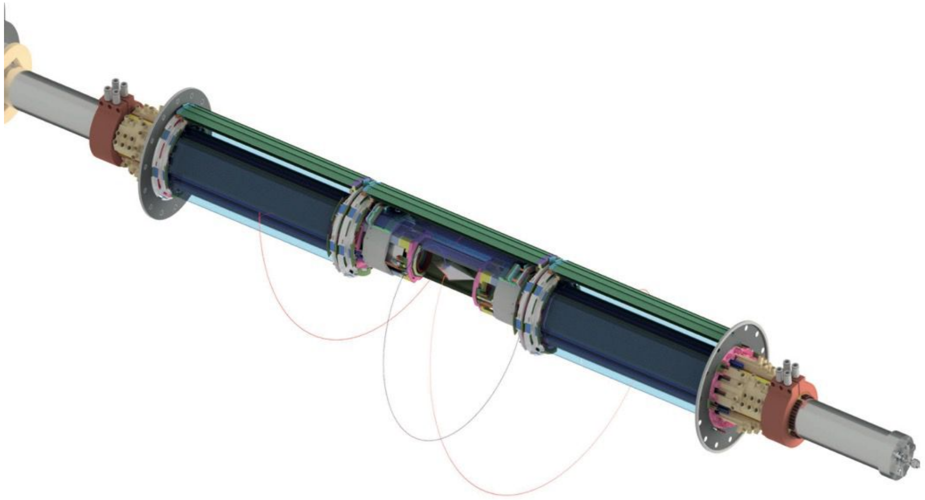
Tracking detector

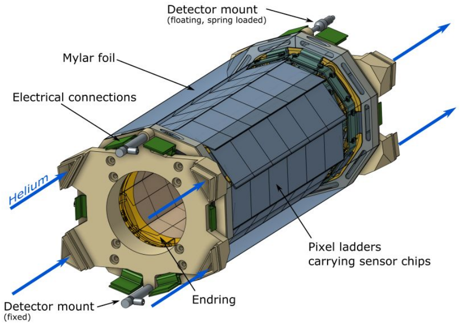
Low-Material tracker from Mupix Sensors
2 Vertex detector layers (central detector)
2 Outer tracking layers (central & recurl stations)
… close to 3000 pixel chips
… more than 1m² sensitive area
… 3.8Tbit/second integrated bandwidth

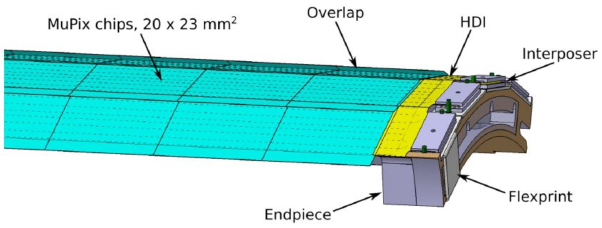
50-75um Silicon ; 25um Aluminum/Kapton flex ; 25um Kapton
→ 0.1% X/X_0 per layer

Novel gaseous Helium cooling

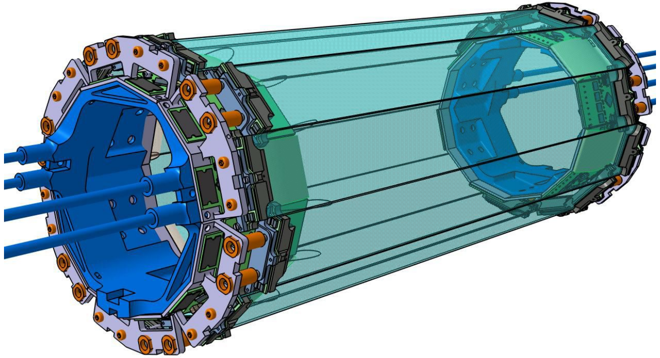
→ Talk by Thomas Rudzki yesterday





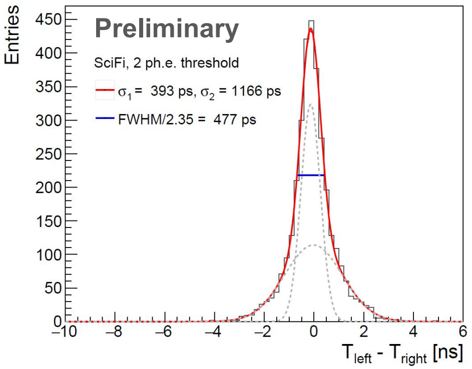


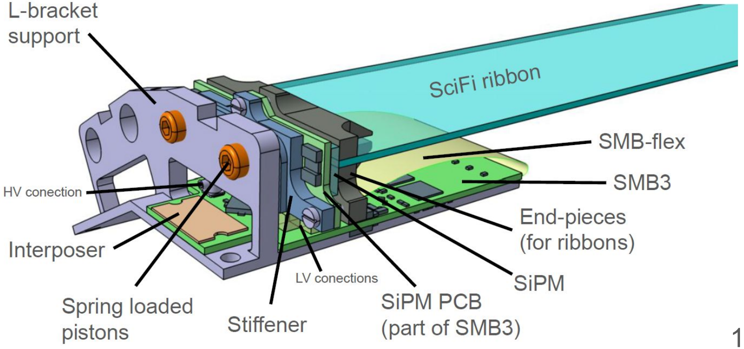
Timing detectors - Scintillating Fibres



Timing detector in central station
Minimize material: X/X_0 ~ 0.2%
Very compact design

- Scintillating fibres: Kuraray SCSF-78MJ (multi-clad)
- 30 cm long ribbons (3 layers of 250 μm thin fibers)
- SiPM Array: Hamamatsu S13552-HRQ @ -10°C
  (liquid cooling w. silicon oil)
- Dedicated SiPM readout ASIC: MUTRiG
- Efficiency > 95%, Time resolution <500ps

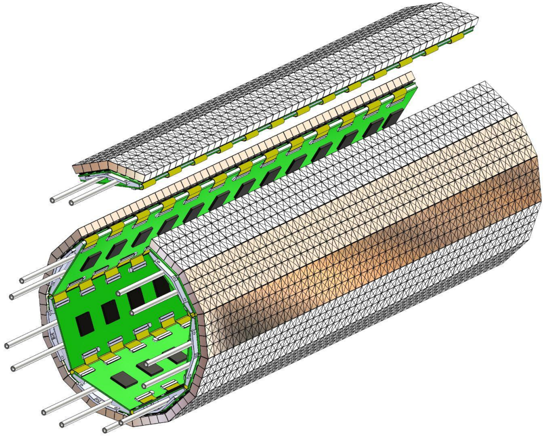


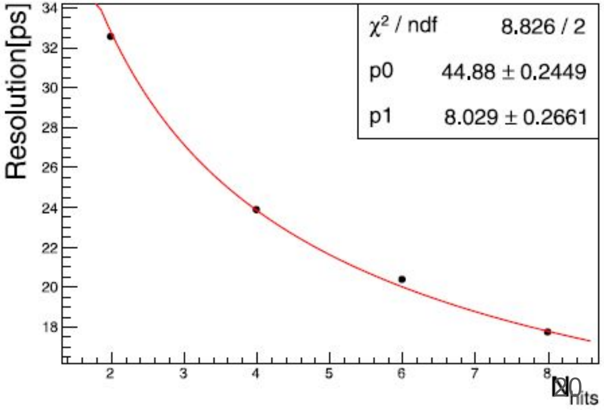


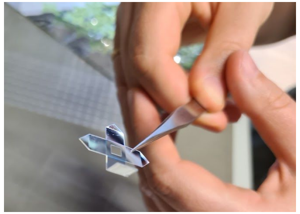
Timing detectors - Scintillating Tiles

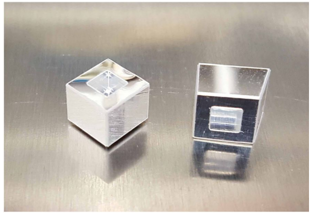
Timing detector in recurl stations
No tight material limitation on Detector volume → “Thick” detector
Highly segmented in ~6k tiles
Very compact design

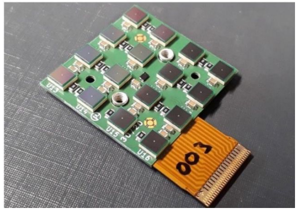
- Tiles from fast Ej-228 plastic scintillator (6 x 6 x 5 mm^3)
- Individually wrapped in ESR foil - Minimize crosstalk
- Coupled to Hamamatsu SiPMs read out by Mutrig ASIC (S13360-3050VE @ -10°C, Silicon oil cooling)
- Efficiency > 99%, single-channel time resolution ~40 ps

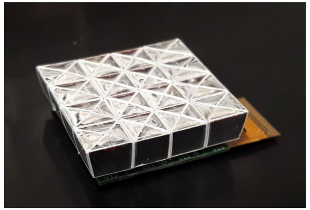








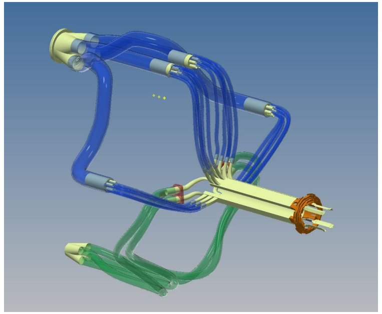




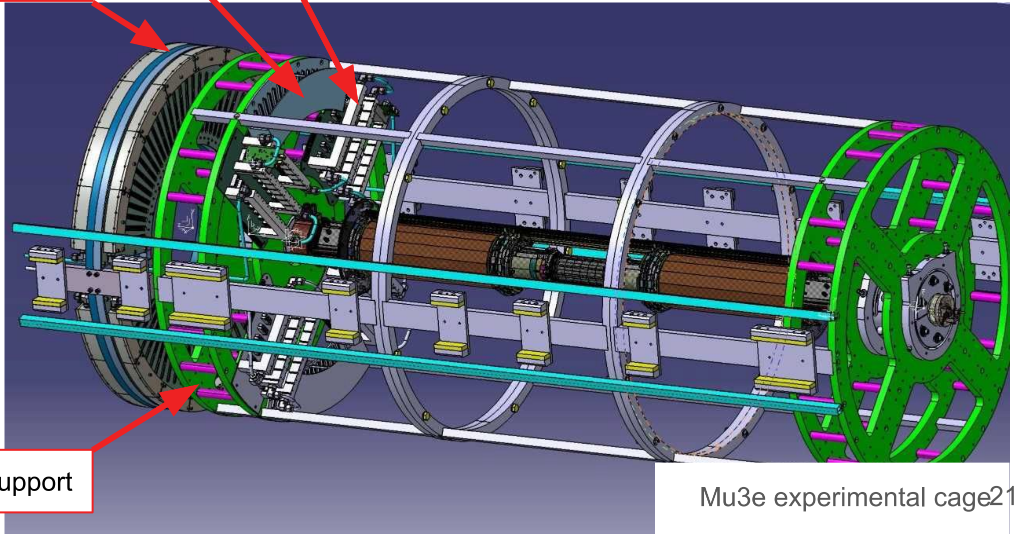
Mu3e - Experimental cage & Beam pipe

Mu3e is a **dense detector design**
Front-end power supplies, FPGAs
.. inside magnet, outside sensitive volume

Distribution of Helium for Pixel-Cooling
Other services & Cabling
Beam transportation
→ Volume-intensive



Helium distribution to detectors



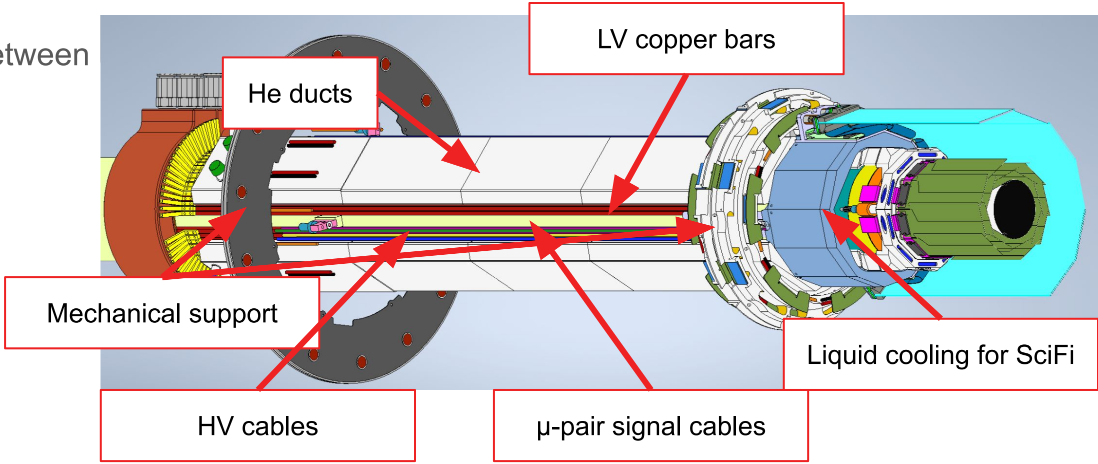
Mu3e experimental cage

Mu3e - Experimental cage & Beam pipe

… but also: A long, narrow tube

Many services need to fit under Recurl stations
- LV power - Directly integrated in beampipe
- HV & Signal cables
- Pipes and helium ducts for cooling
- Beam pipe
- Connection area gets equally dense and shared between detectors

→ Easily causing interferences between detector components & Services
→ Requires many iterations



Mu3e DAQ Chain & Filter

Search for mu3e does not allow for on-detector trigger

Instead: Online filter using GPUs

3 Layers in DAQ chain:

- Hit Data sorting & Concentration
- Assembly of time slices
- Distribute & filter on GPUs:
    - Track reconstruction in central pixel detector
    - vertex finding
    - O(100) reduction
- (Write candidate events to disk)

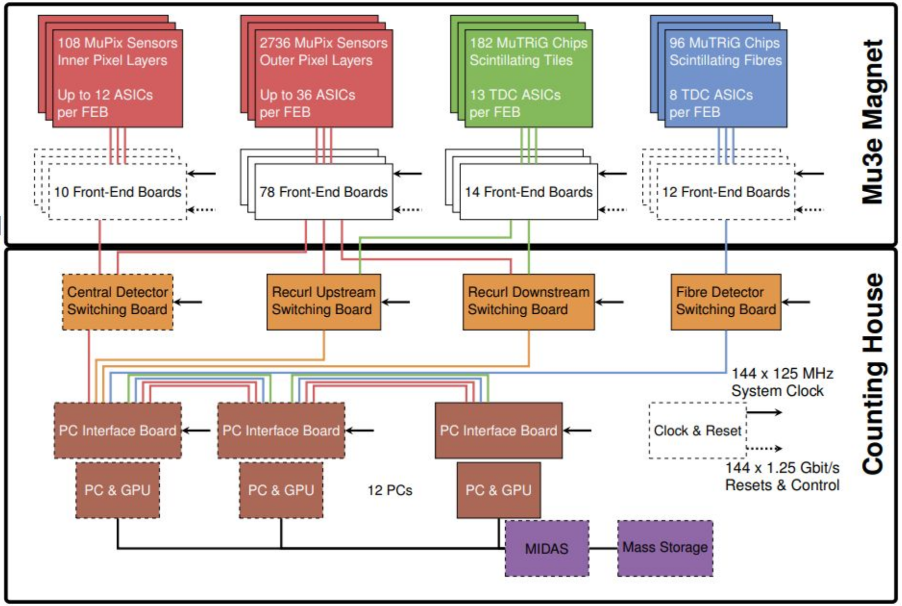
up to 3 x $1.25\,\mathrm{Gbit/s}$ LVDS links per ASIC

1-2 x $6.25\,\mathrm{Gbit/s}$ optical link per board

2-8 x $10\,\mathrm{Gbit/s}$ optical links per board

16 inputs per Farm FPGA

Gbit Ethernet

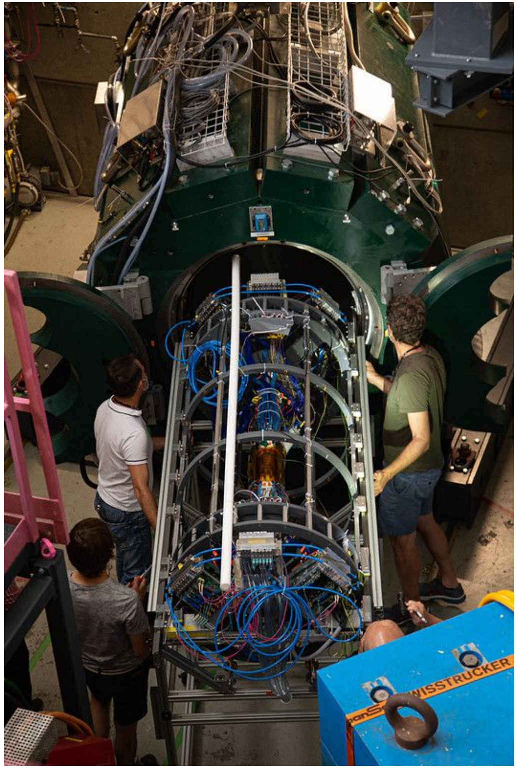


Status of the experiment

- Runs with prototype modules conducted 2021-2022
- Finalized ASICs and detector components
- 2023: Transition to production phase
  - QA of modules & components
  - Production of final detector modules

- Currently ongoing: Assembly & Integration of infrastructure
  - On-detector services
  - Helium cooling plant
  - Electrical connections

- Installation of first detectors planned in second half of 2024
  - Vertex detector
  - SciFi & Tiles
  - Outer pixel modules available in 2025



Conclusions

- Mu3e is searching for the CLFV Decay mu→eee
- Seeks to improve the current limit by 3-4 orders of magnitude

Challenging detector concept

- Dense environment
- Minimal material
- High hit rates in detectors
- No trigger - High data rates transmitted off-detector
- Many first, often pushing boundaries

After more than a decade in development, we are producing final detector components!

Experiment will be commissioned in 2025