The Mu3e Experiment

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Sheffield (unfortunately only virtually)
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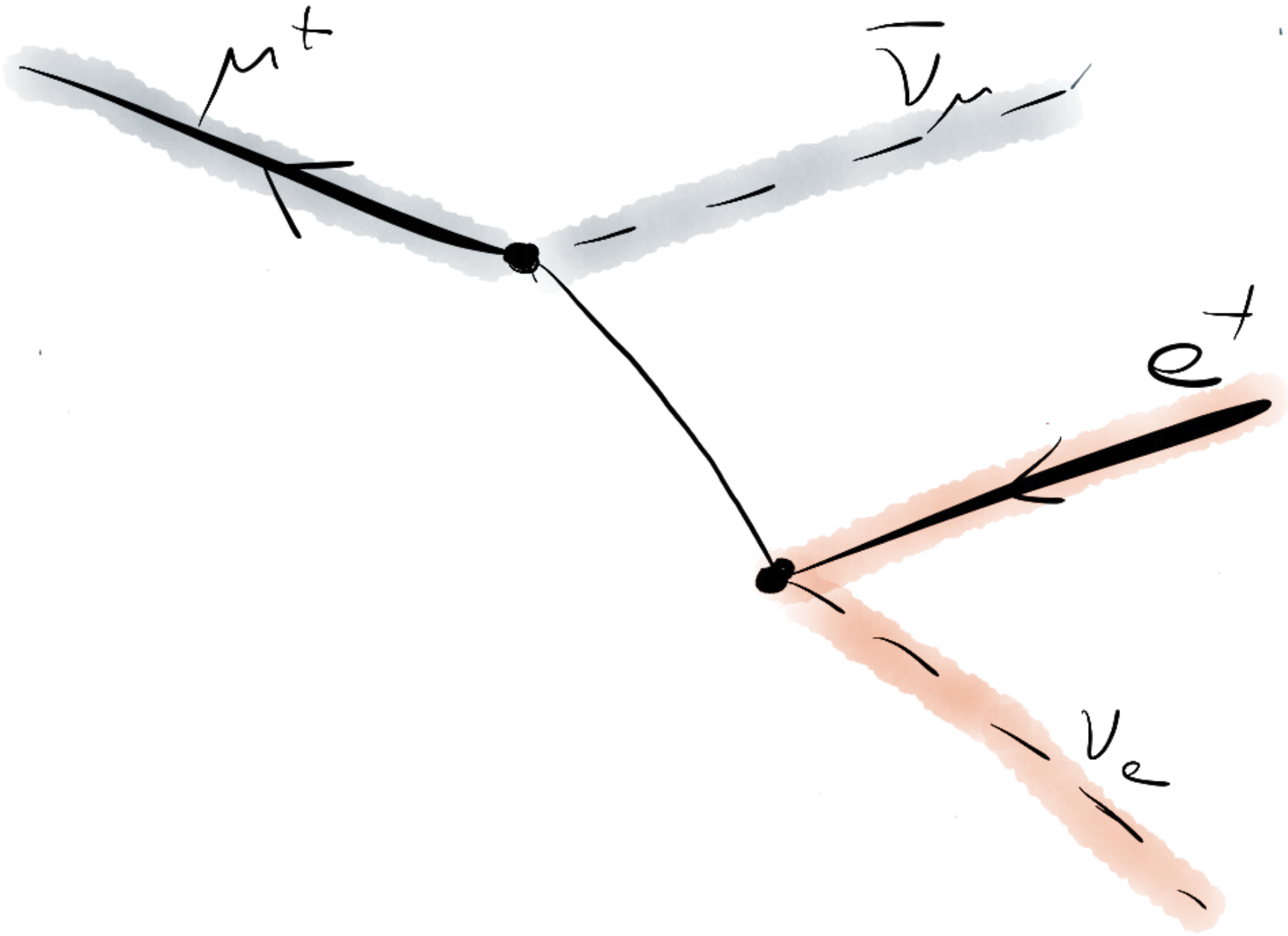
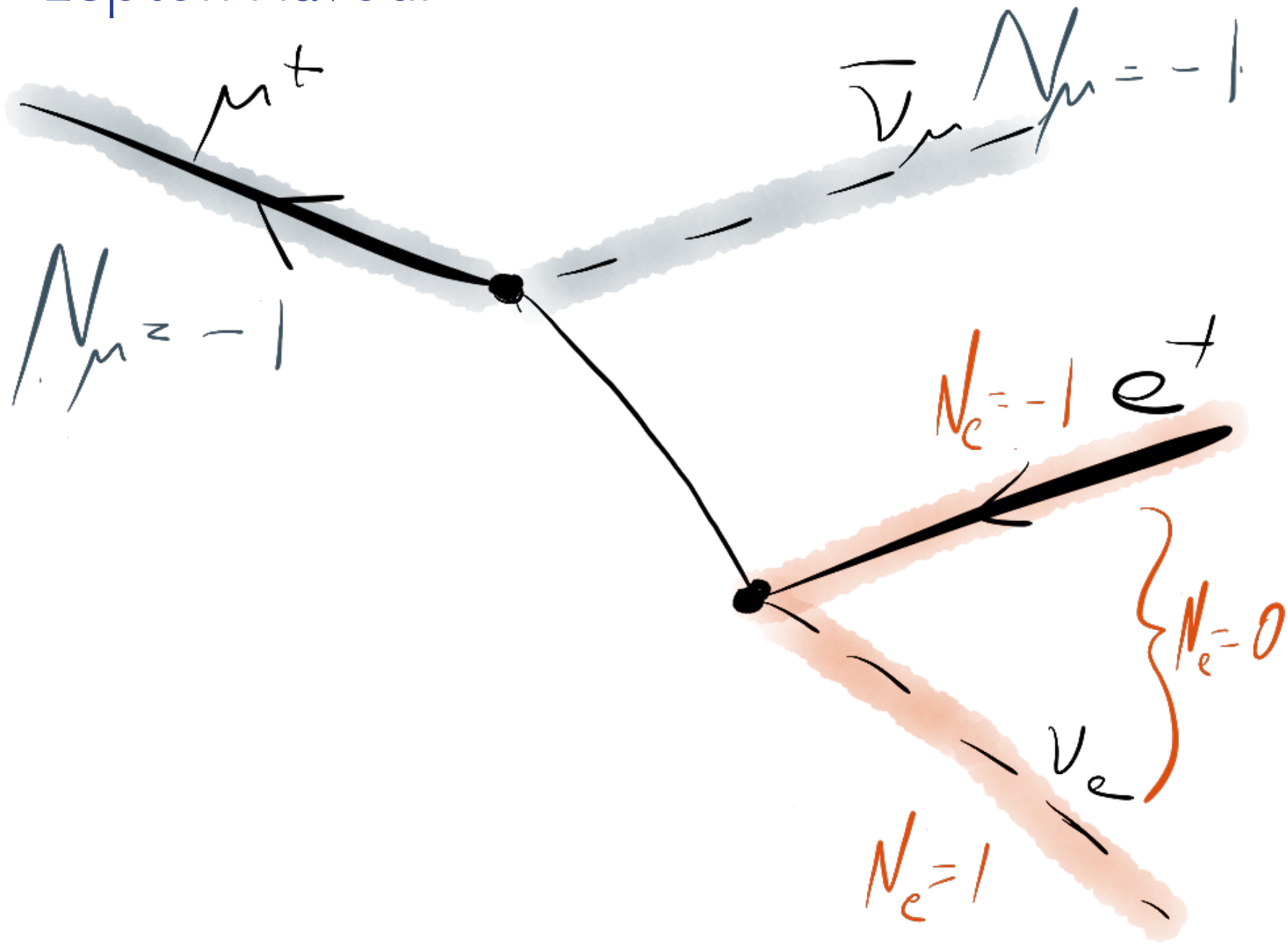
Overview

- Lepton Flavour Violation in Muon Decay
- The $\mu^+ \rightarrow e^+e^-e^+$ Process
- Searching for $\mu^+ \rightarrow e^+e^-e^+$ with Mu3e
- High-Voltage Monolithic Active Pixel Sensors
- Timing detectors
- Simulation
- Integration
- DAQ
- Status and Plans

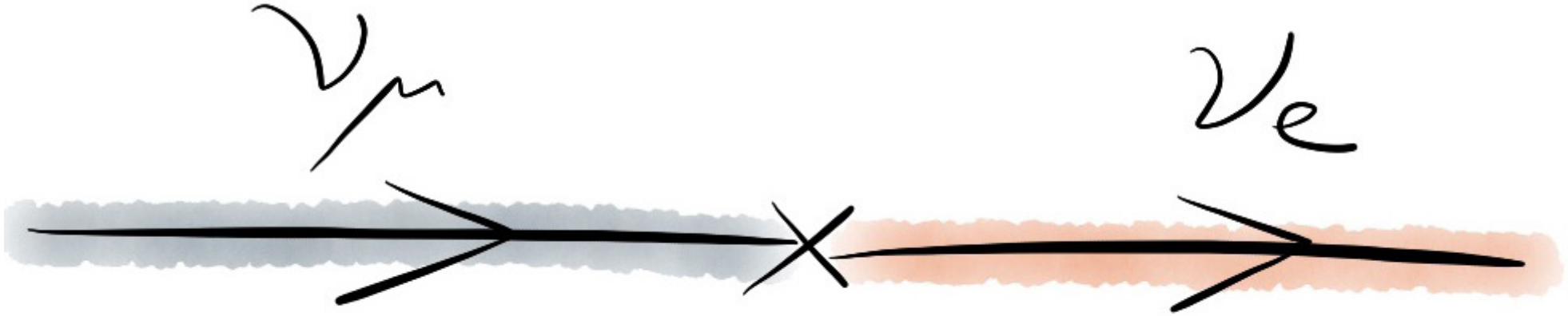
Lepton Flavour



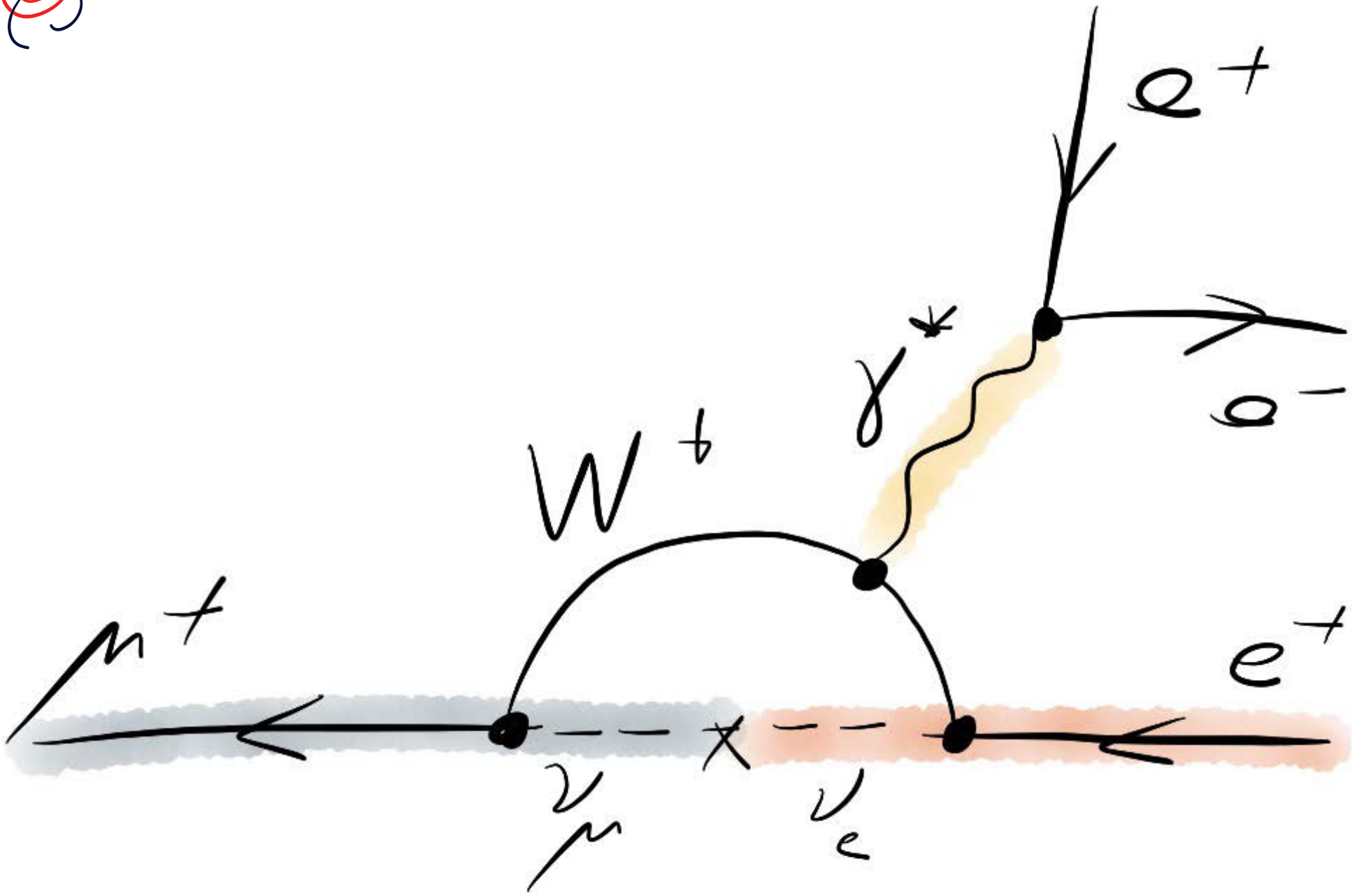
Lepton Flavour



Lepton Flavour Violation!



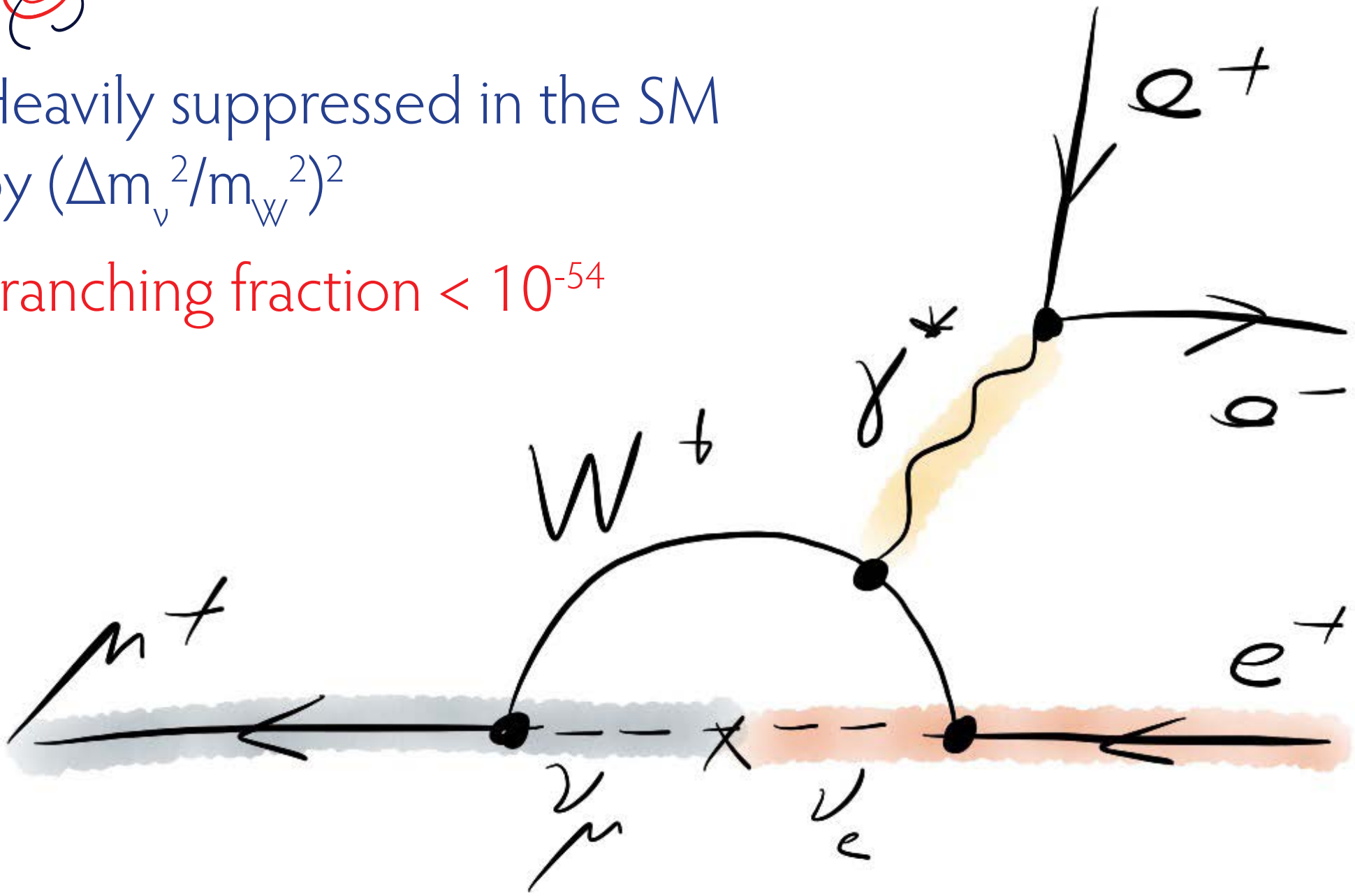
Charged Lepton Flavour Violation?



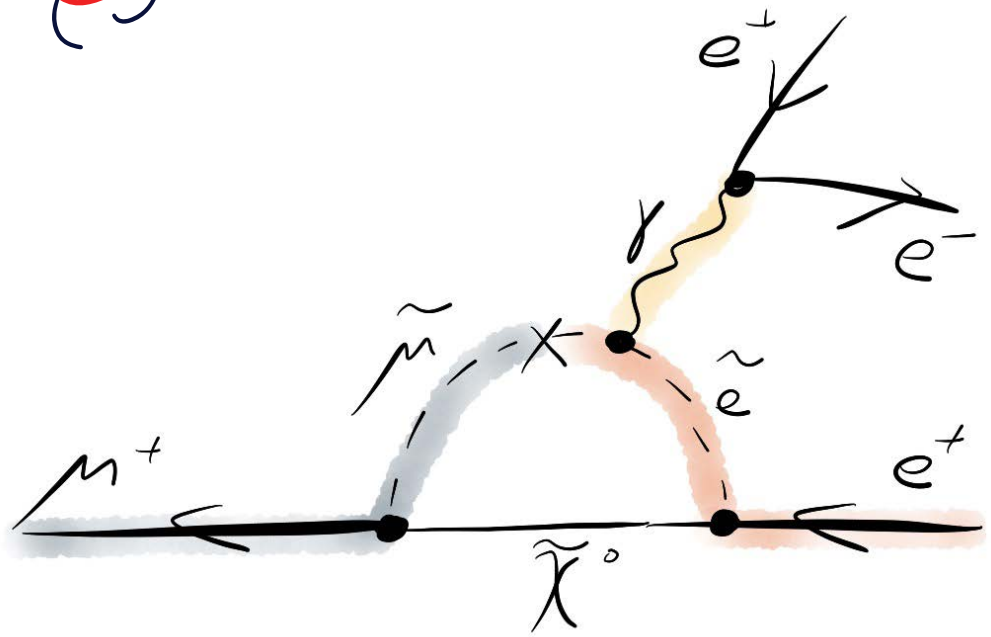
Charged Lepton Flavour Violation?

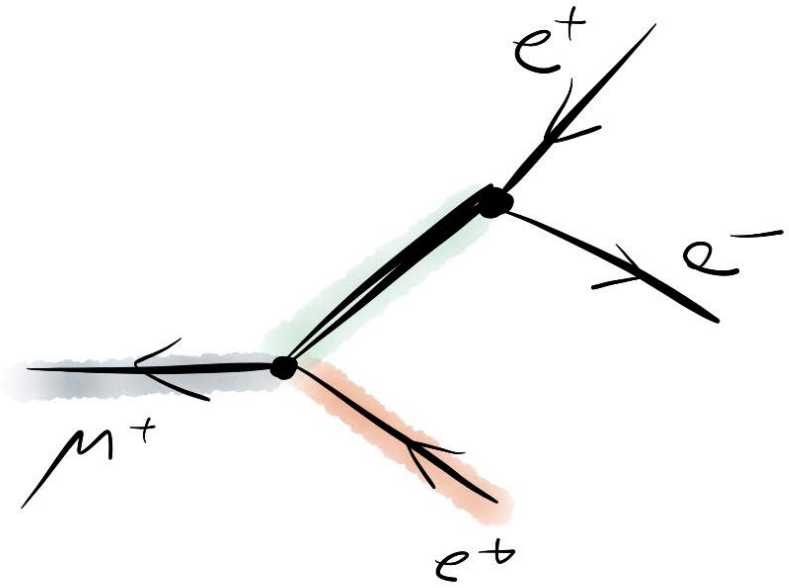
Heavily suppressed in the SM
by $(\Delta m_\nu^2/m_W^2)^2$

Branching fraction < 10^{-54}



New physics in $\mu^+ \to e^+e^-e^+$





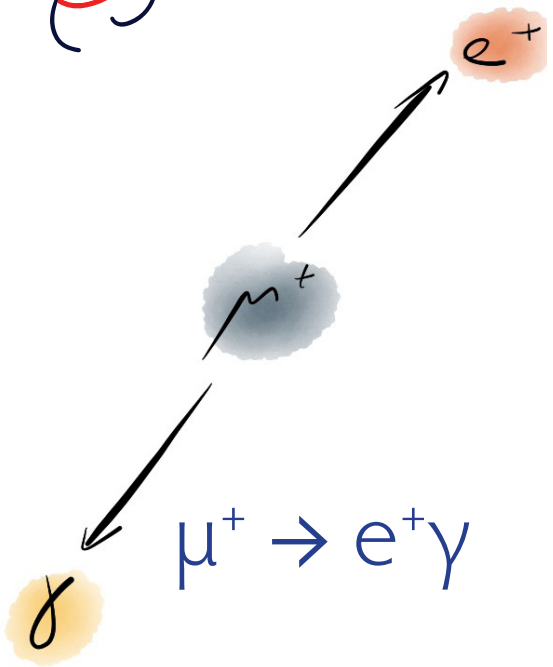
Loop diagrams

- Supersymmetry
- Little Higgs models
- Seesaw models
- GUT models (leptoquarks)
- and much more...

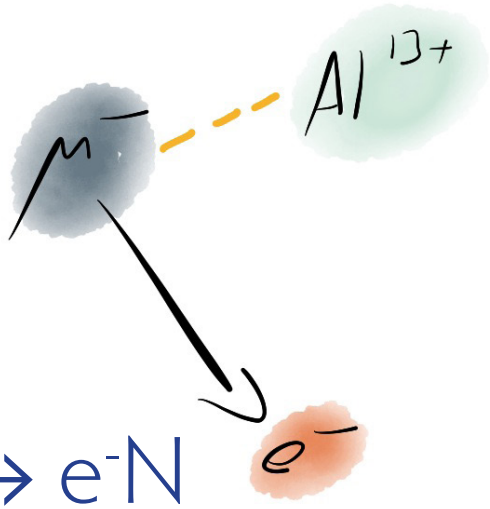
Tree diagrams

- Higgs triplet model
- Extra heavy vector bosons (Z')
- Extra dimensions (Kaluza-Klein tower)

LFV Muon Decays: Experimental Situation



$\mu^+ \rightarrow e^+\gamma$



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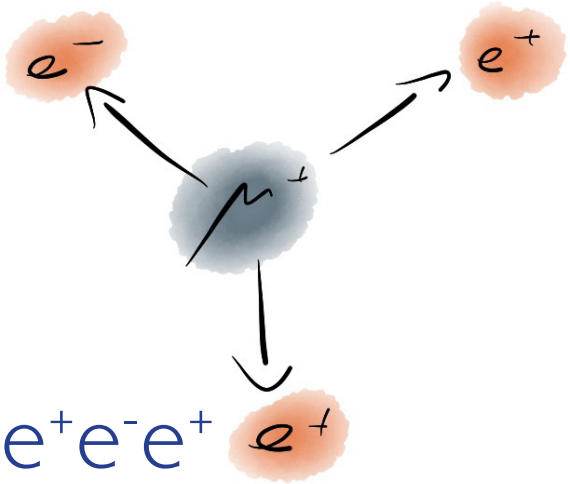

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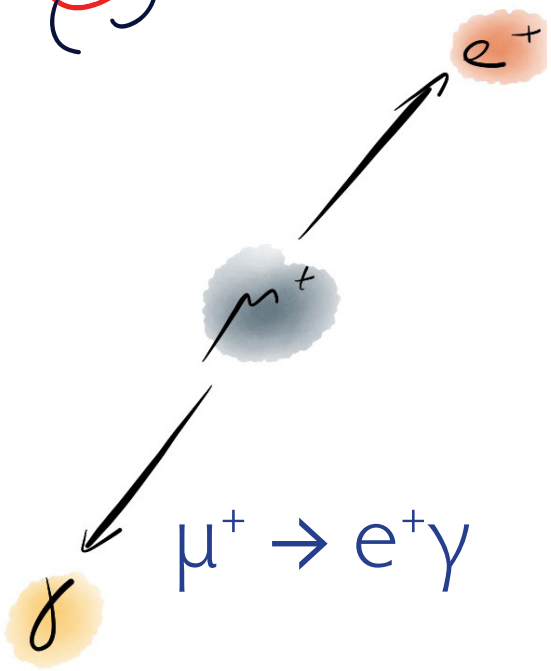

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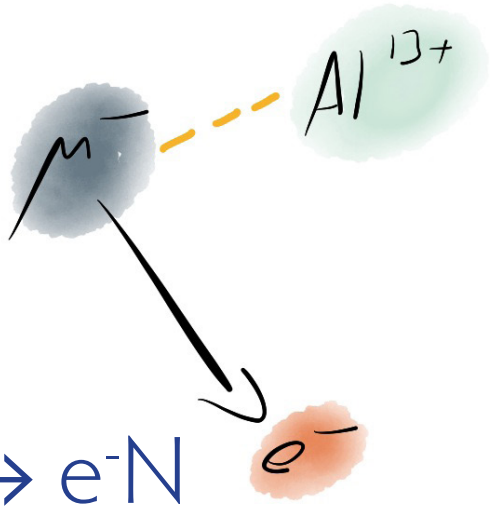

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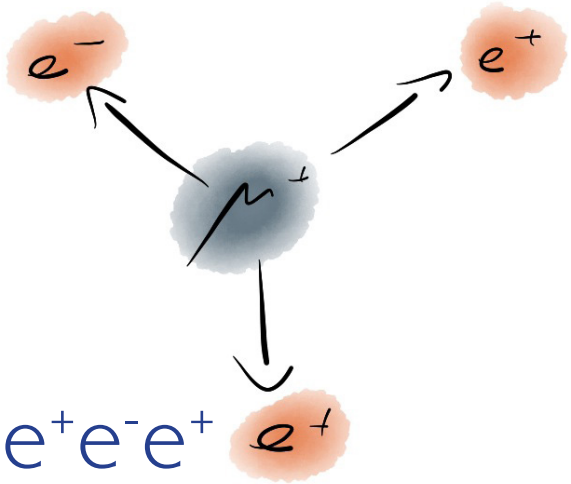

$\mu^+ \rightarrow e^+e^-e^+$

MEG (PSI)

$B(\mu^+ \rightarrow e^+\gamma) < 4.2 \cdot 10^{-13}$

(2016)

SINDRUM II (PSI)

$B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$

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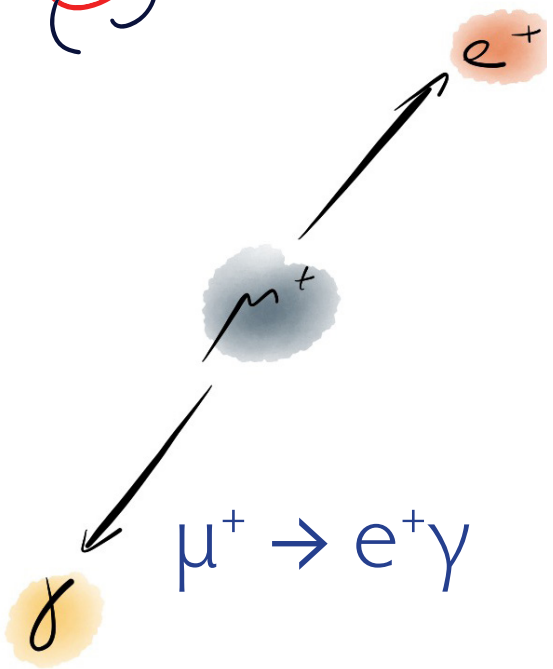

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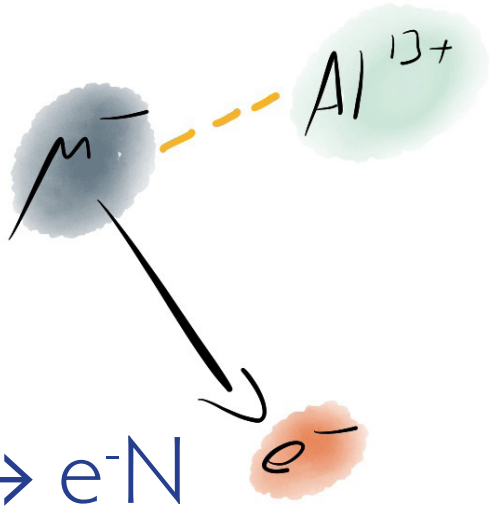

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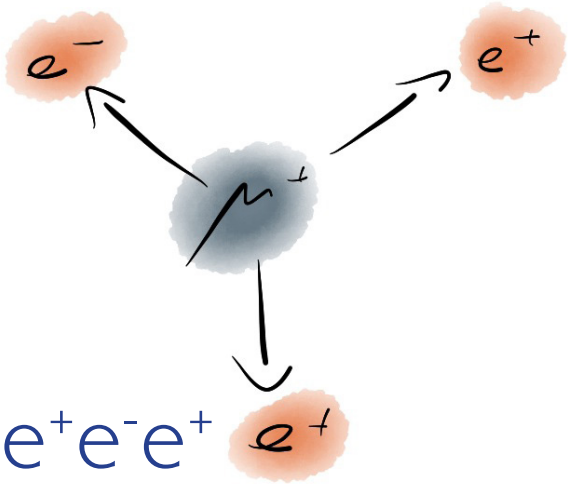

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Mu2e/Comet

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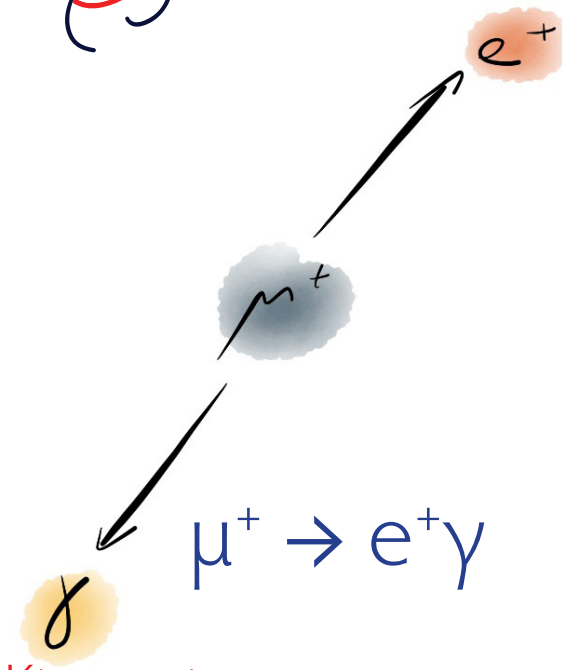
(1988)

Mu3e

LFV Muon Decays: Experimental signatures



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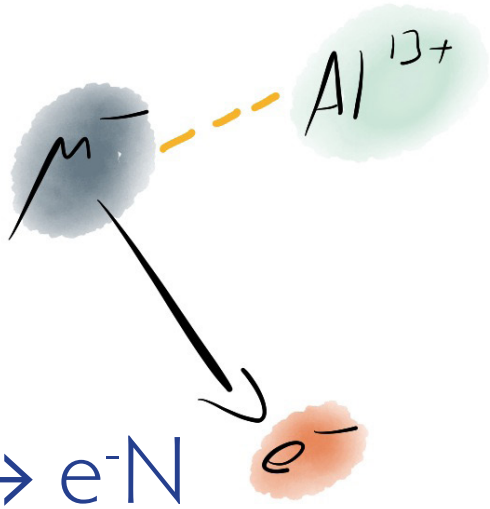

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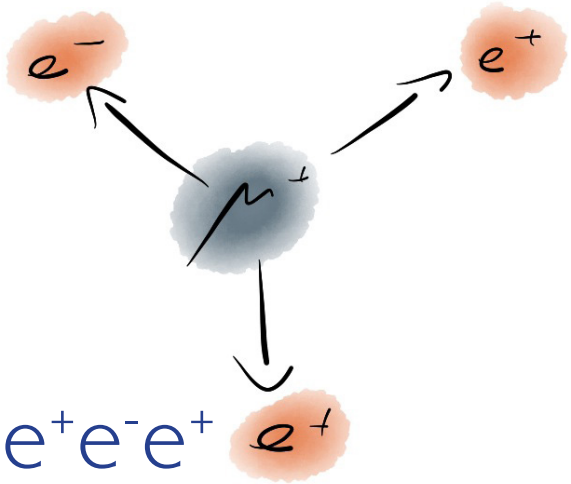


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

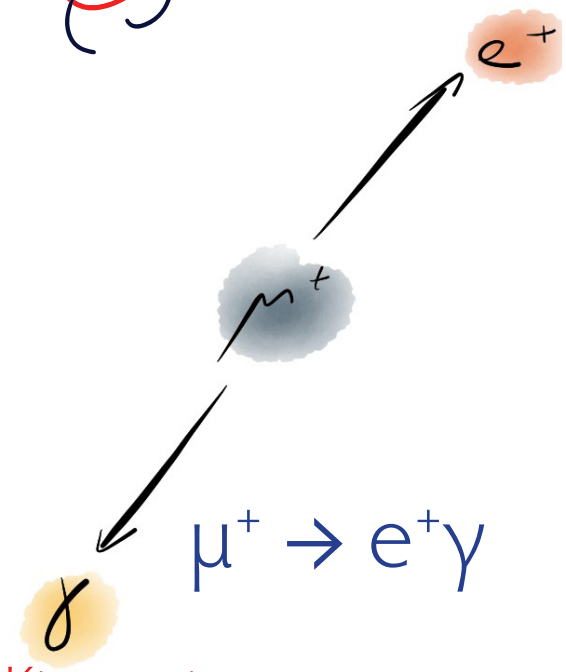
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

LFV Muon Decays: Experimental signatures



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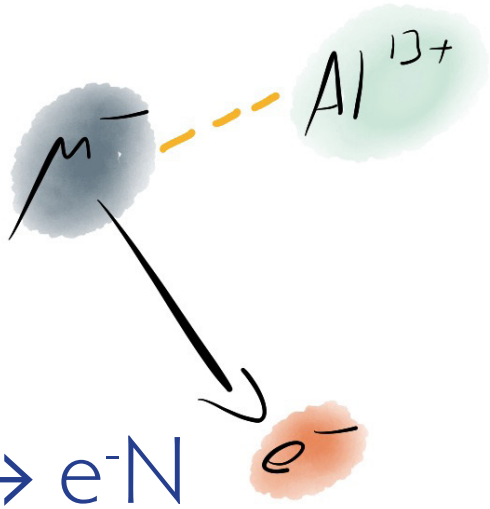

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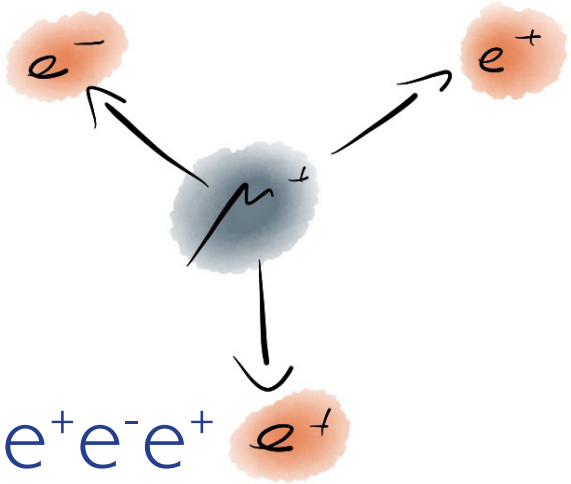


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions, cosmics

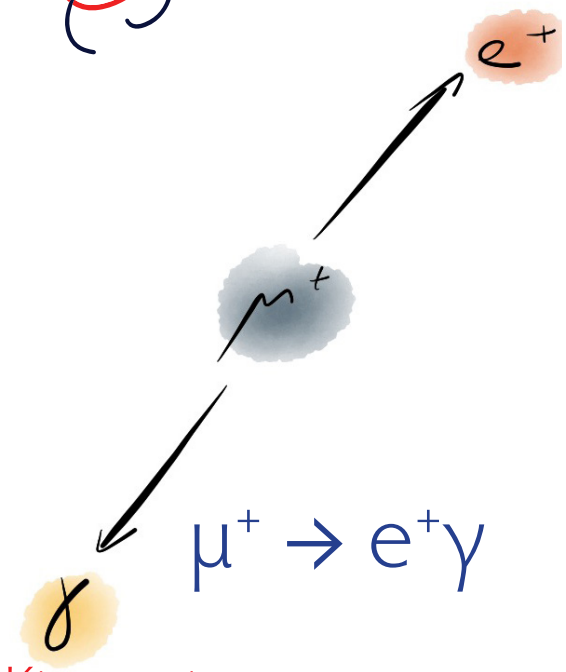
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

Background

- Radiative decay
- Accidental background

LFV Muon Decays: Experimental signatures



$\mu^+ \rightarrow e^+\gamma$

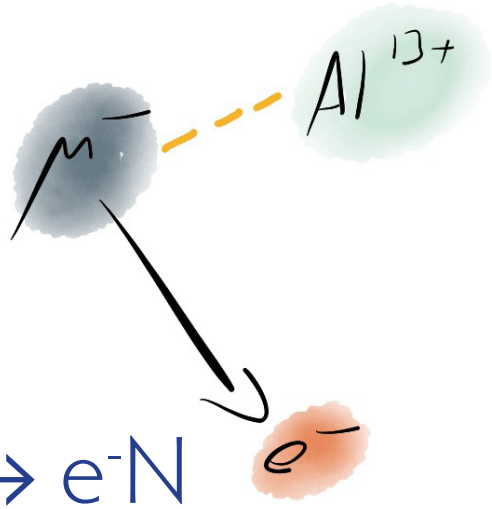
Kinematics

- 2-body decay
- Monoenerge
- Back-to-b

Backgro

- A al background

Continuous Beam



$\mu^-N \rightarrow e^-N$

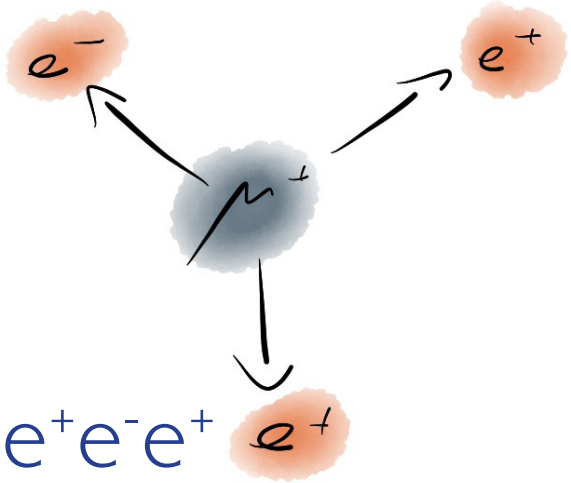
Kinematics

- Quasi 2-body d
- Monoenerge
- Single p etected

Backgro

- D orbit
- A protons, pions

Pulsed Beam



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Kinematics

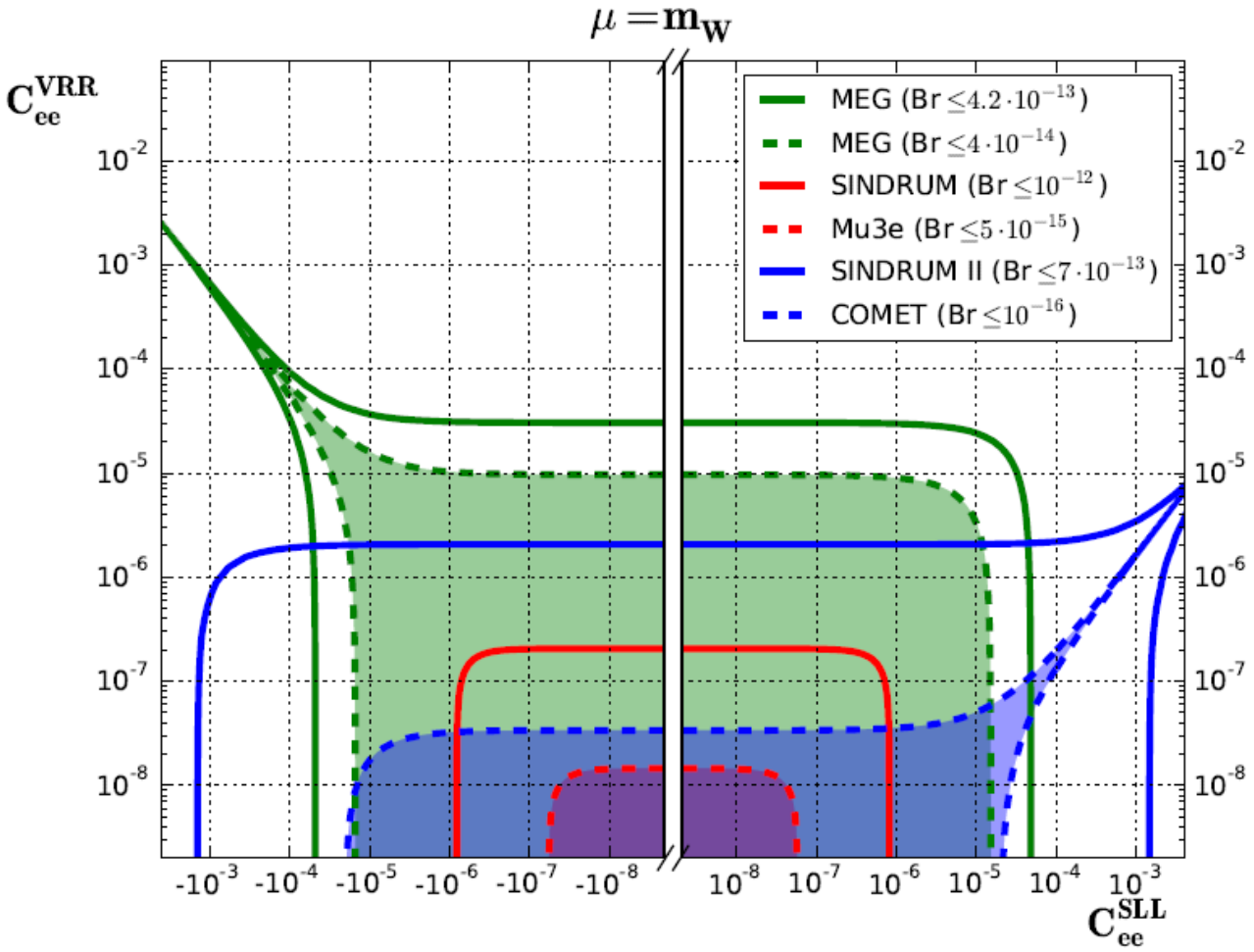
- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro

- R decay
- Ac ental background

Continuous Beam

LFV Muon Decay in Effective Field Theory

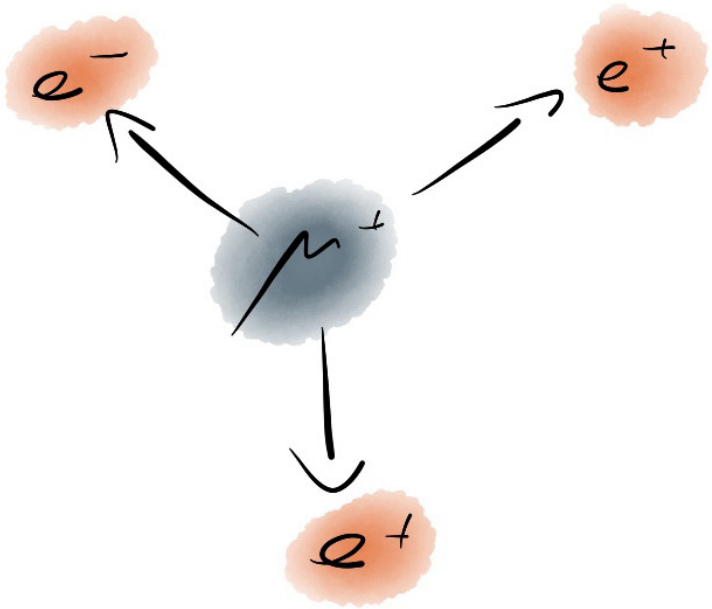


- Effective field theory approach with renormalisation group running
- Experiments put complementary constraints on Wilson coefficients

Renormalisation-group improved analysis of μ→e processes in a systematic effective-field-theory approach
A. Crivellin, S. Davidson, G. M. Pruna, A. Signer
e-Print: 1702.03020 [hep-ph] JHEP 05 (2017), 117

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

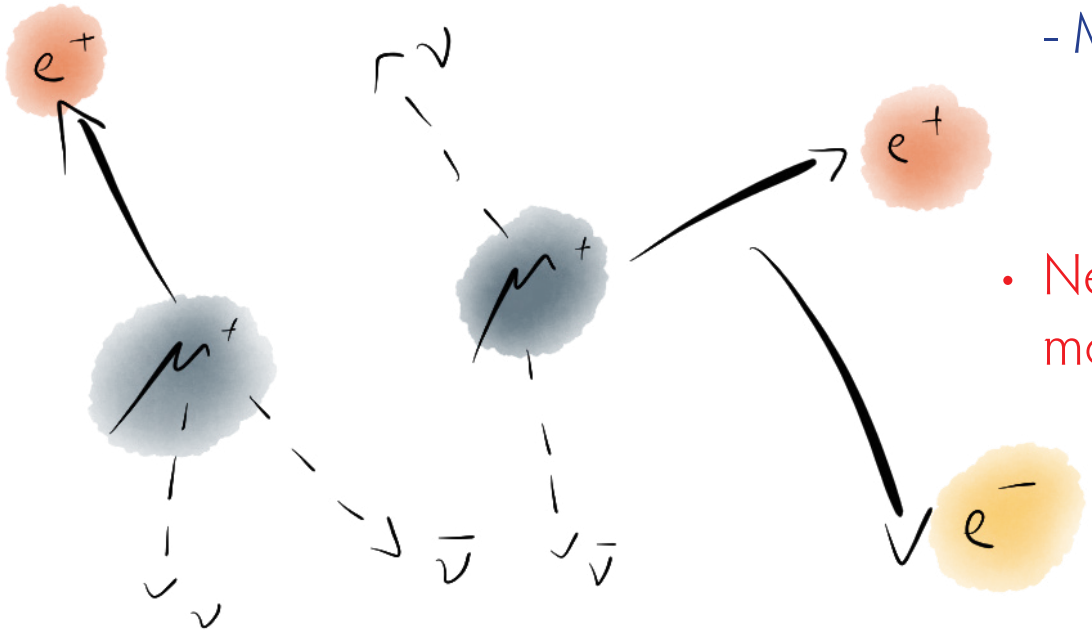
The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: ½ m_μ = 53 MeV/c

Accidental Background

- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha scattering,
  - Mis-reconstruction



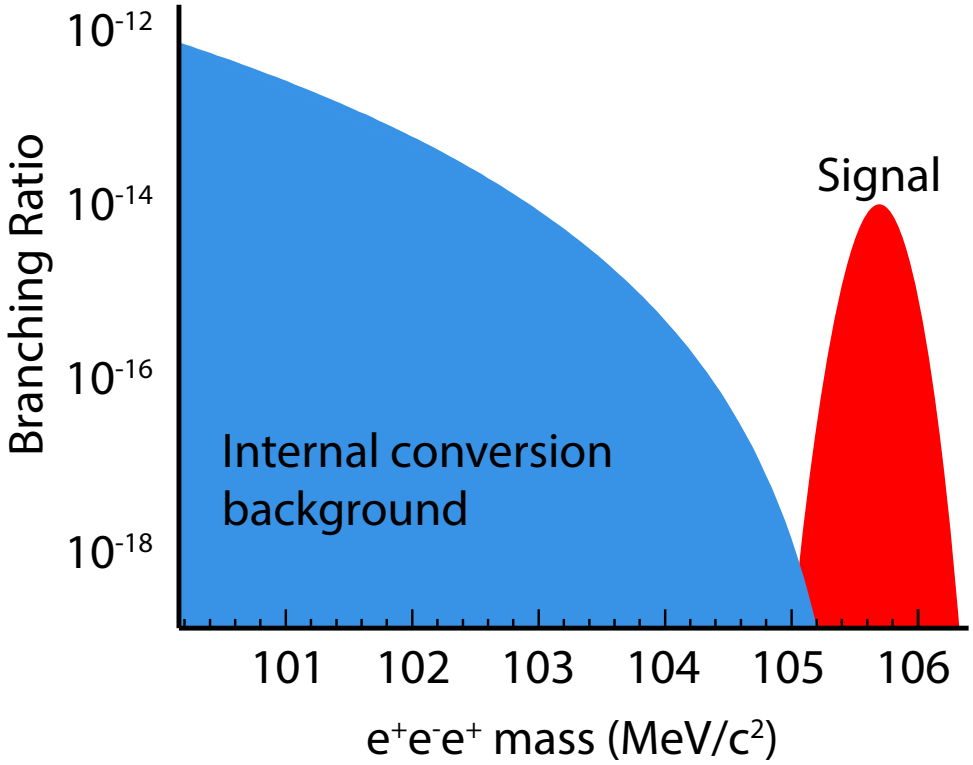
- Need very good timing, vertex and momentum resolution

Internal conversion background

- Allowed radiative decay with internal conversion:

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

- Only distinguishing feature: Missing momentum carried by neutrinos



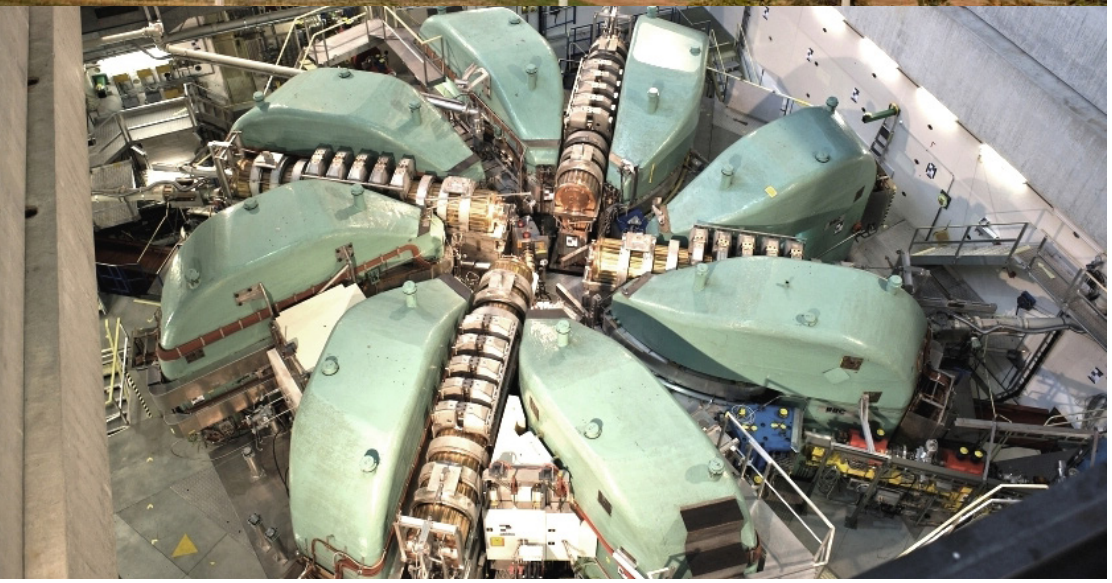
- Need excellent momentum resolution

Building the
Mu3e Experiment

aiming for a branching ratio sensitivity of 10^{-16}

(few 10^{-15} for the current first phase)

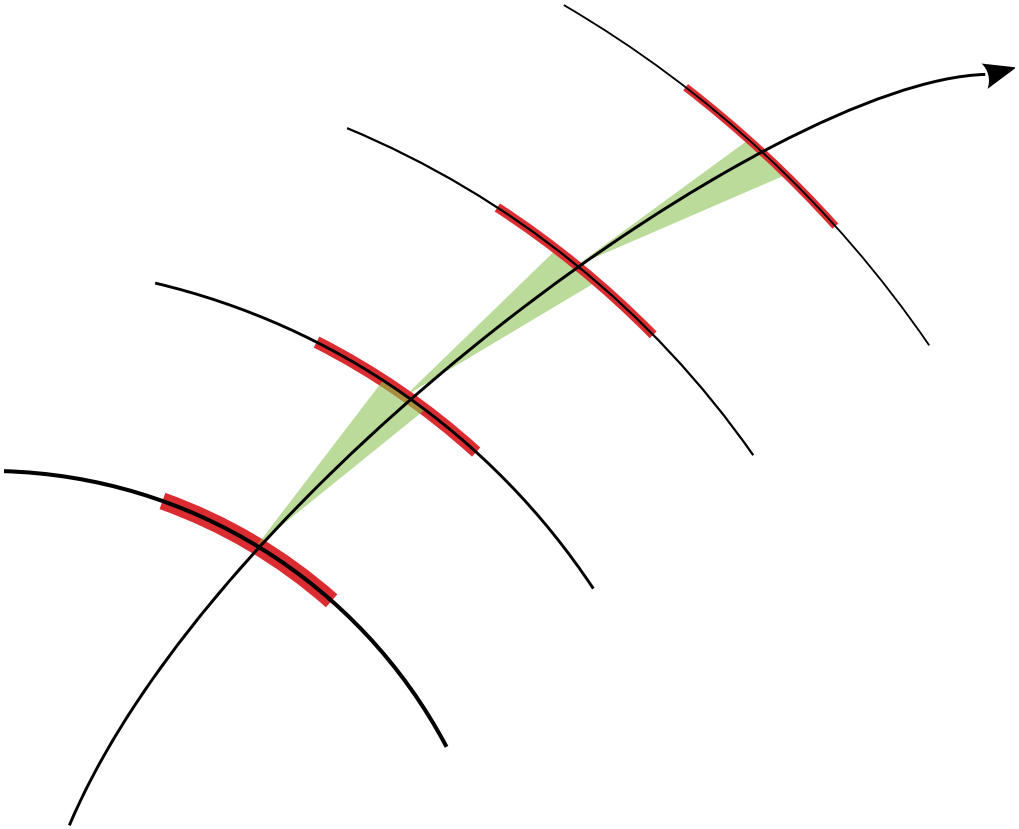
Getting Muons

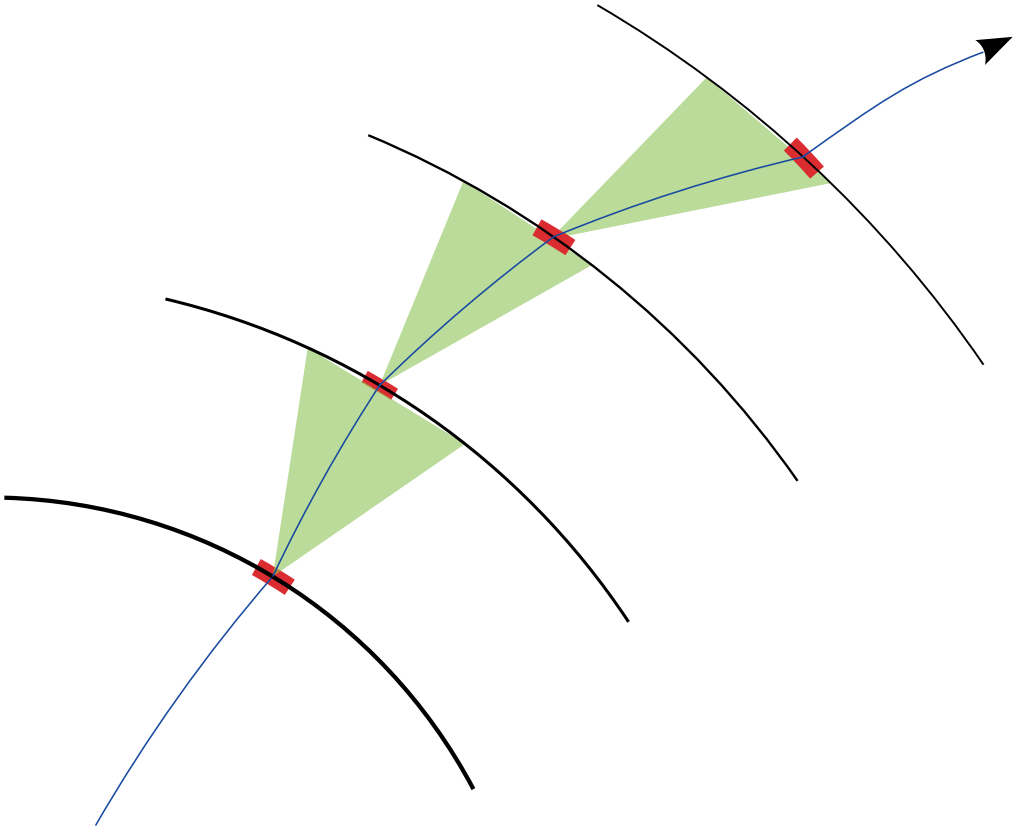


- Paul Scherrer Institute in Switzerland
- 1.4 MW, 590 MeV proton accelerator
- Carbon target, produce pions, decay to muons
- Currently: Up to 10^8 muons/s available Mu3e Phase I
- Future (2027+): High-intensity muon beamline (HIMB) with up to 10^{10} muons/s Mu3e Phase II
- Rest of the presentation: Phase I

Momentum measurement

- Apply magnetic field (e.g. 1 Tesla)
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector





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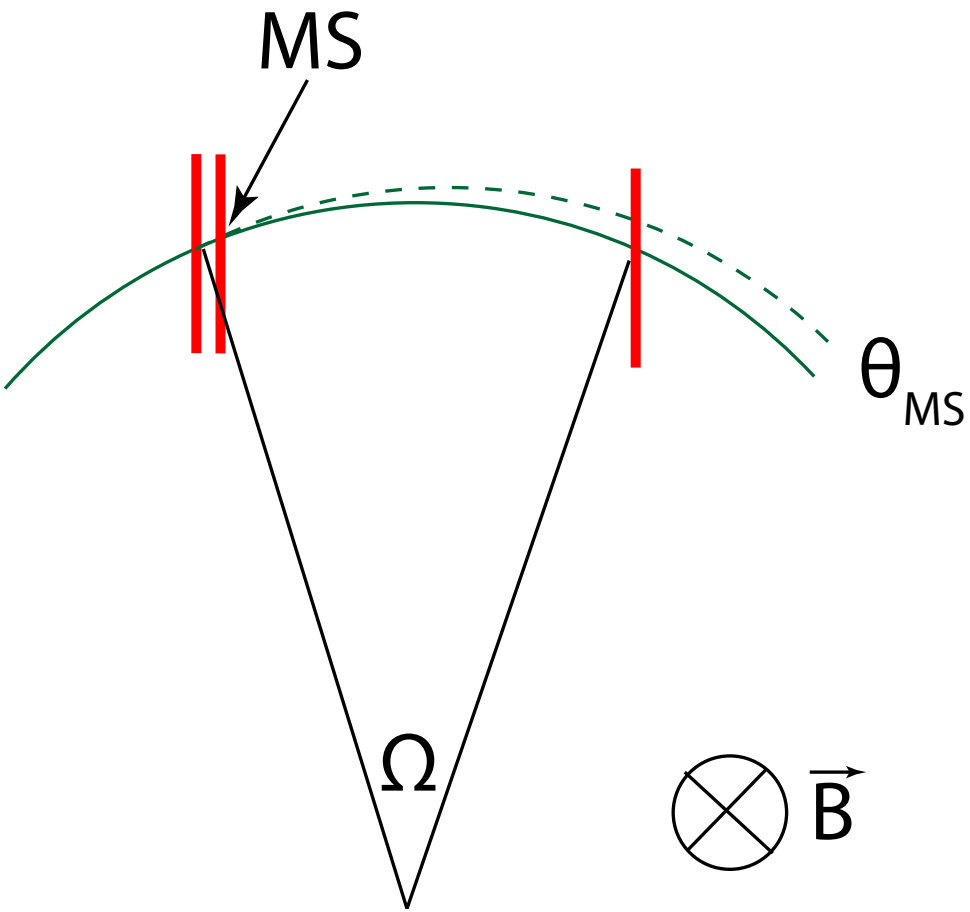
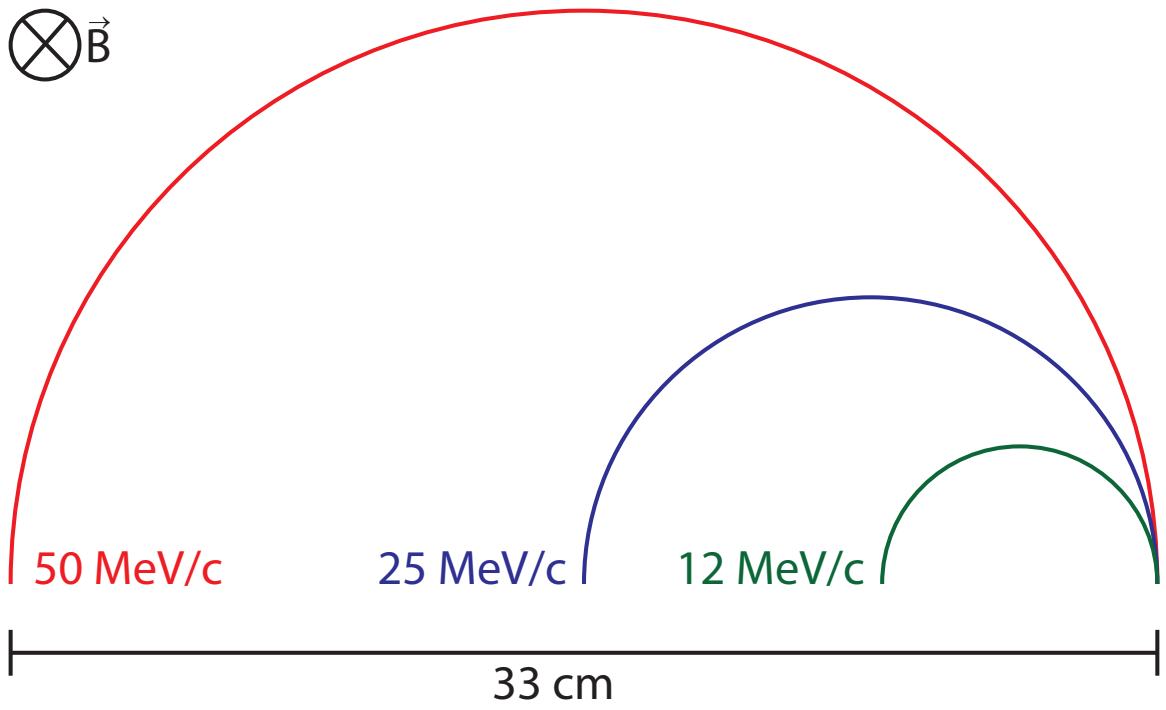


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}

Precision vs. Acceptance



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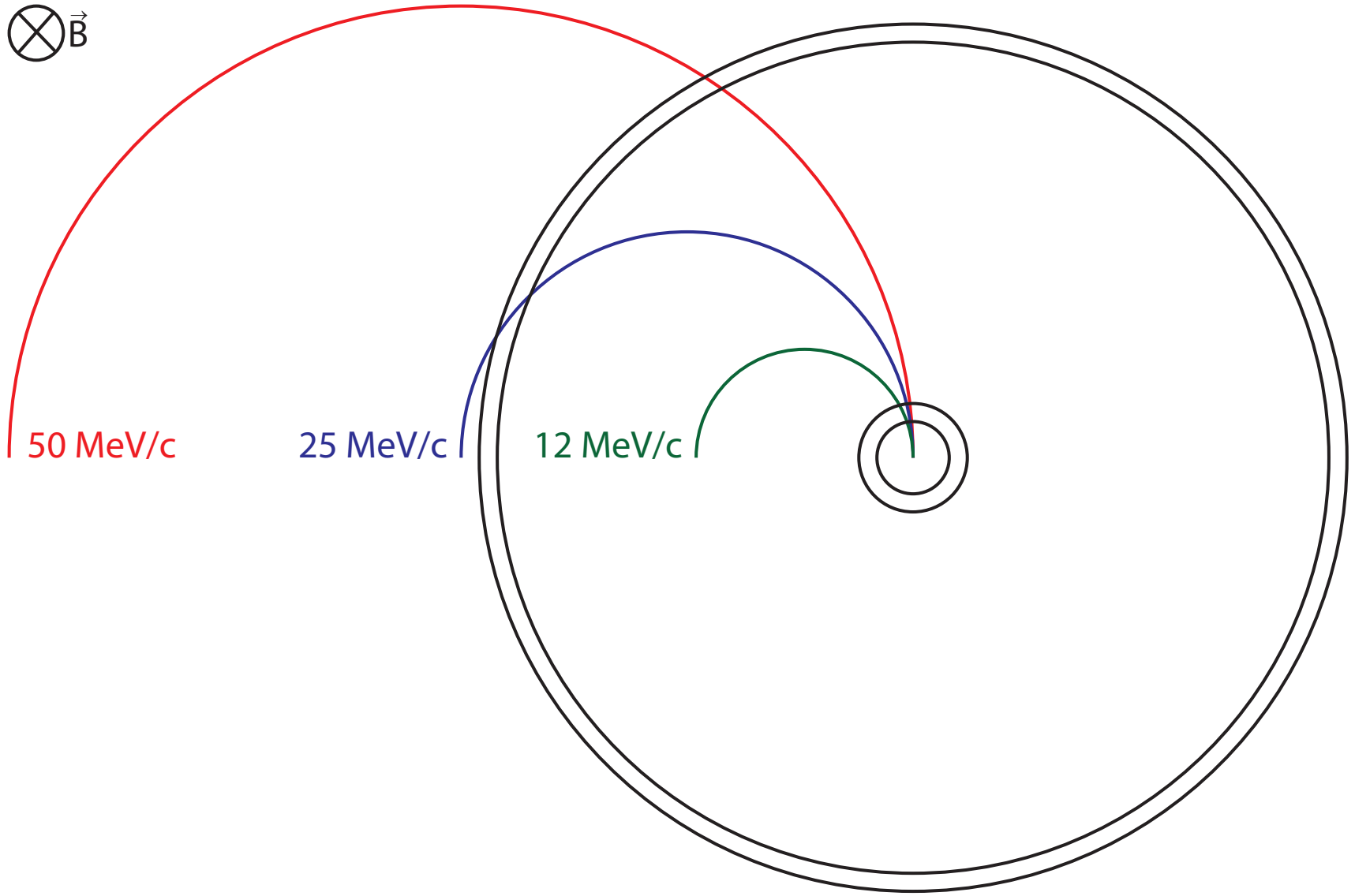

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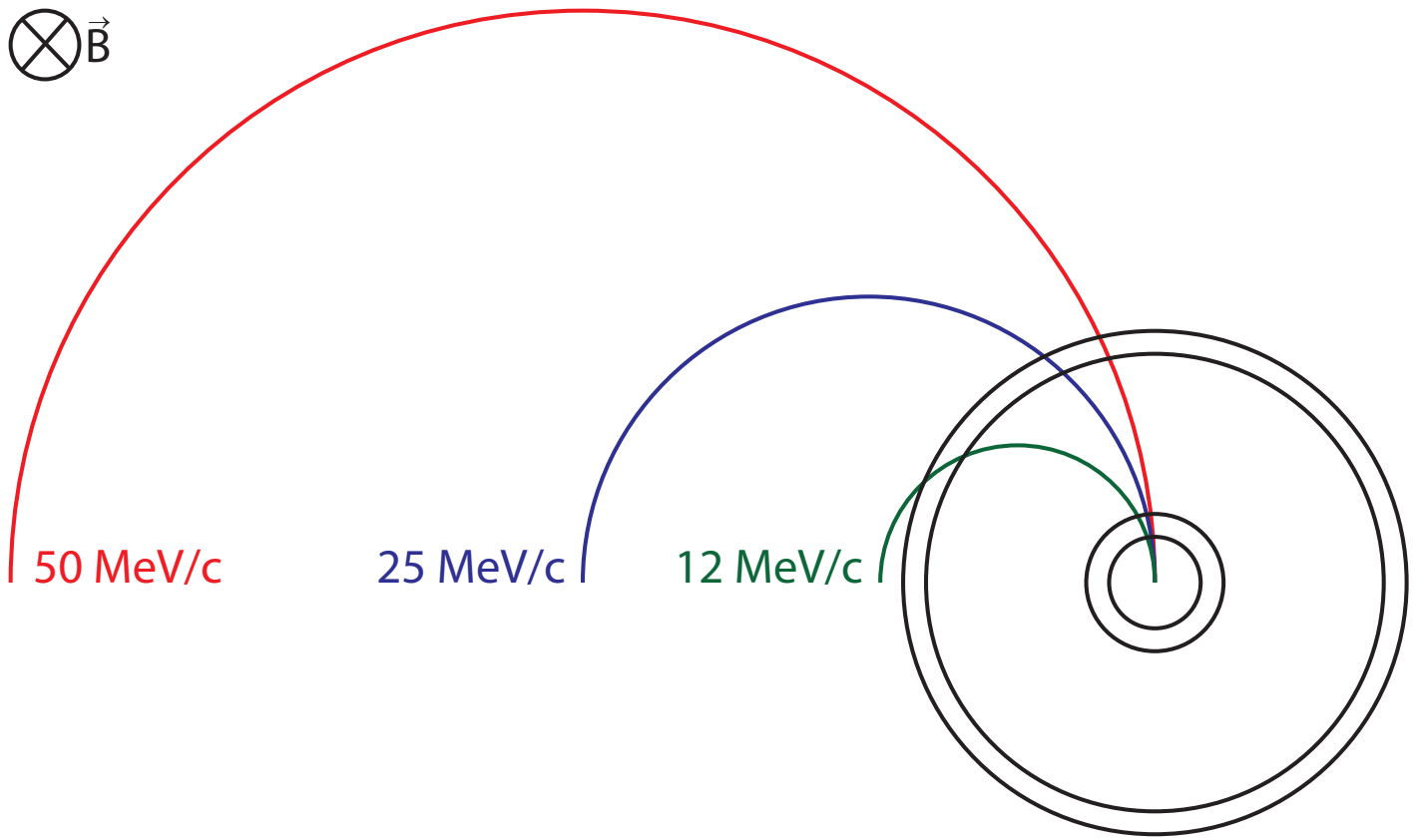

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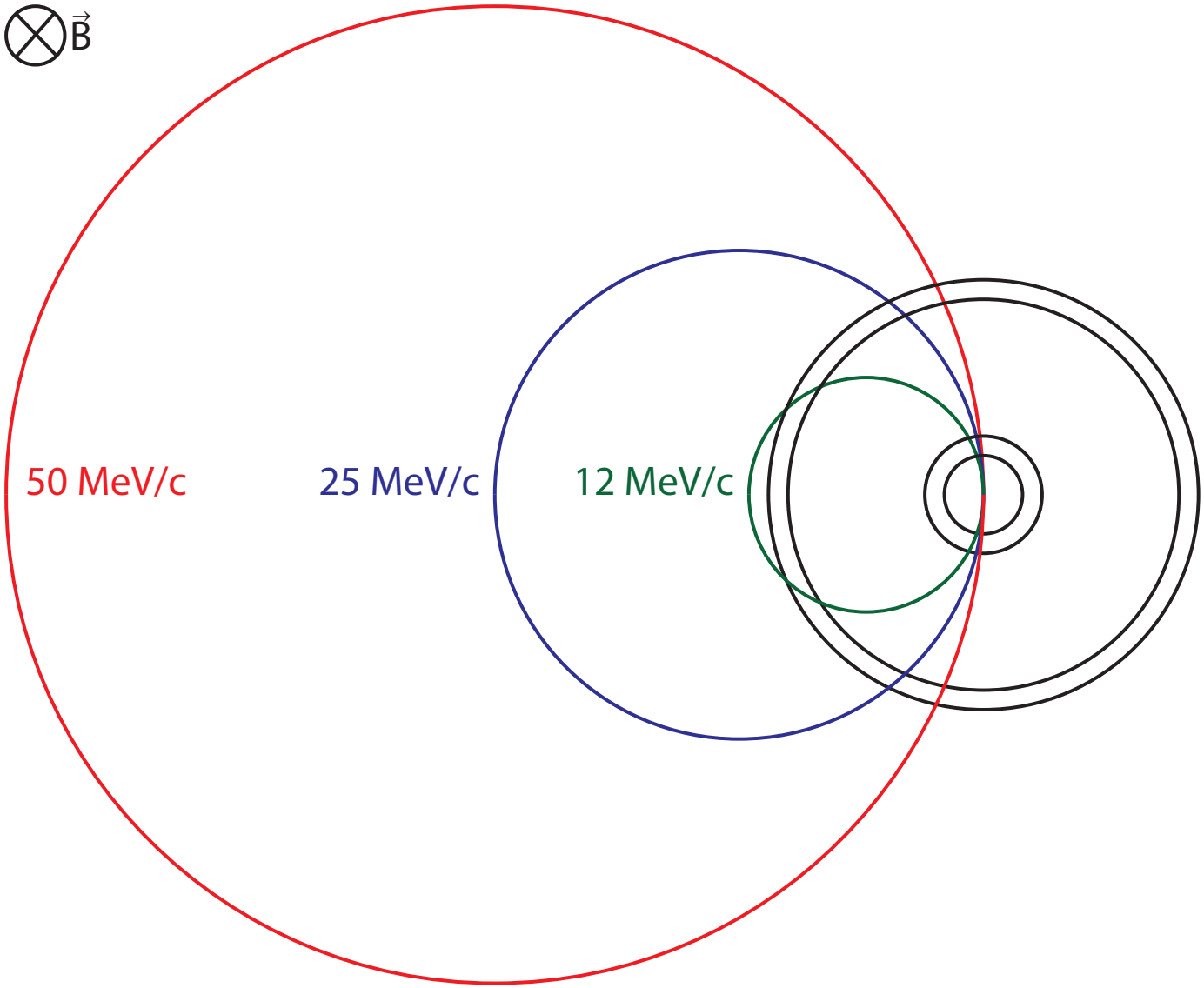

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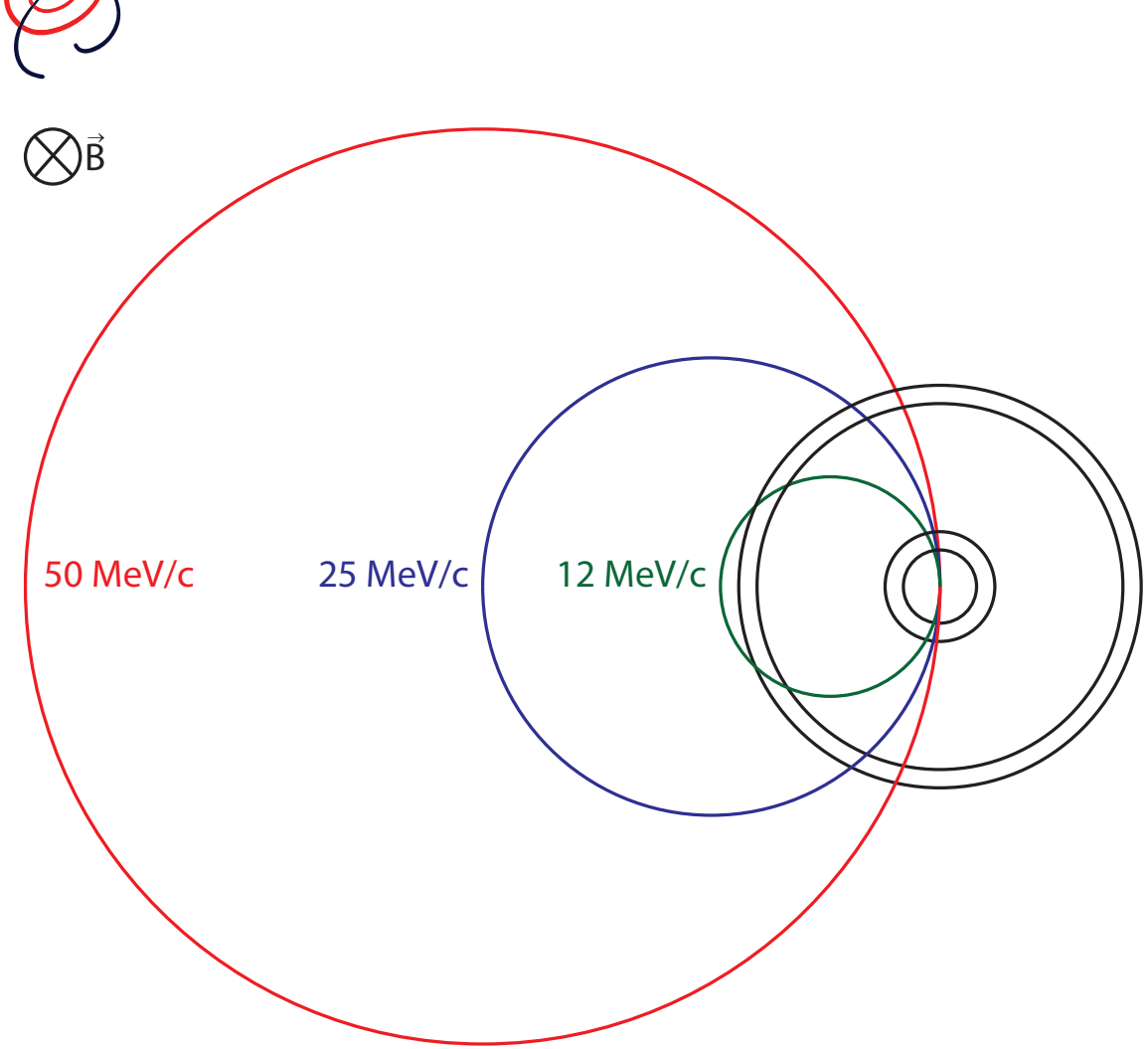

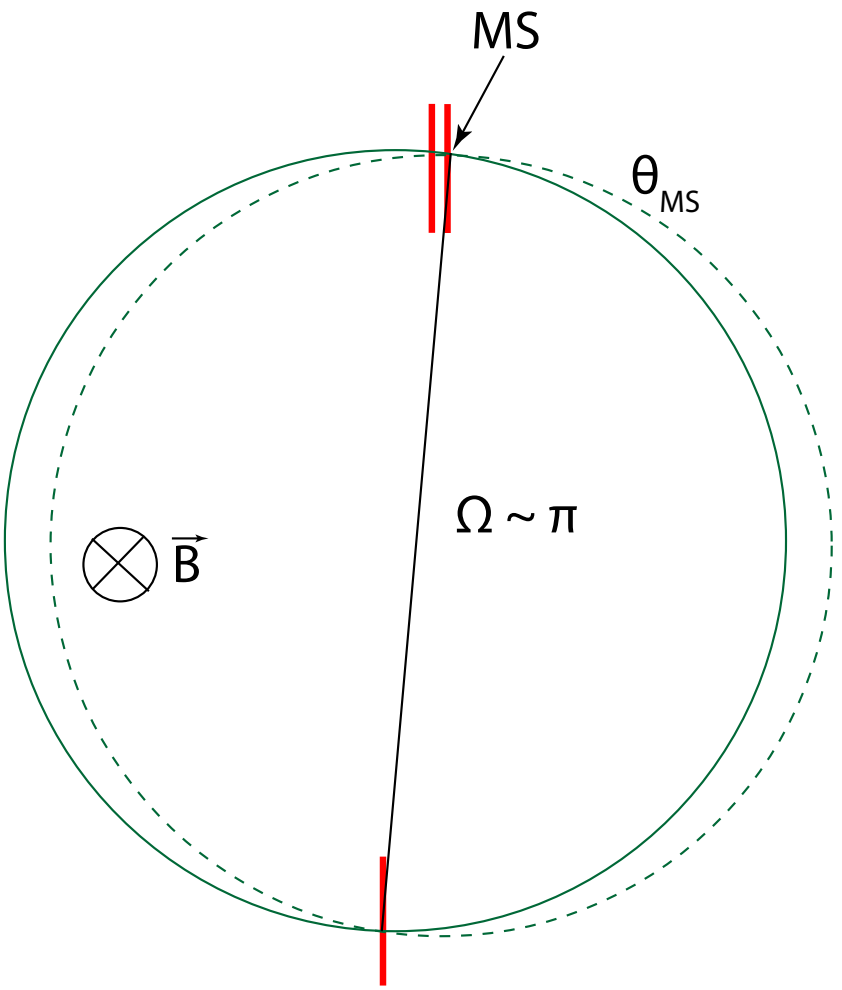

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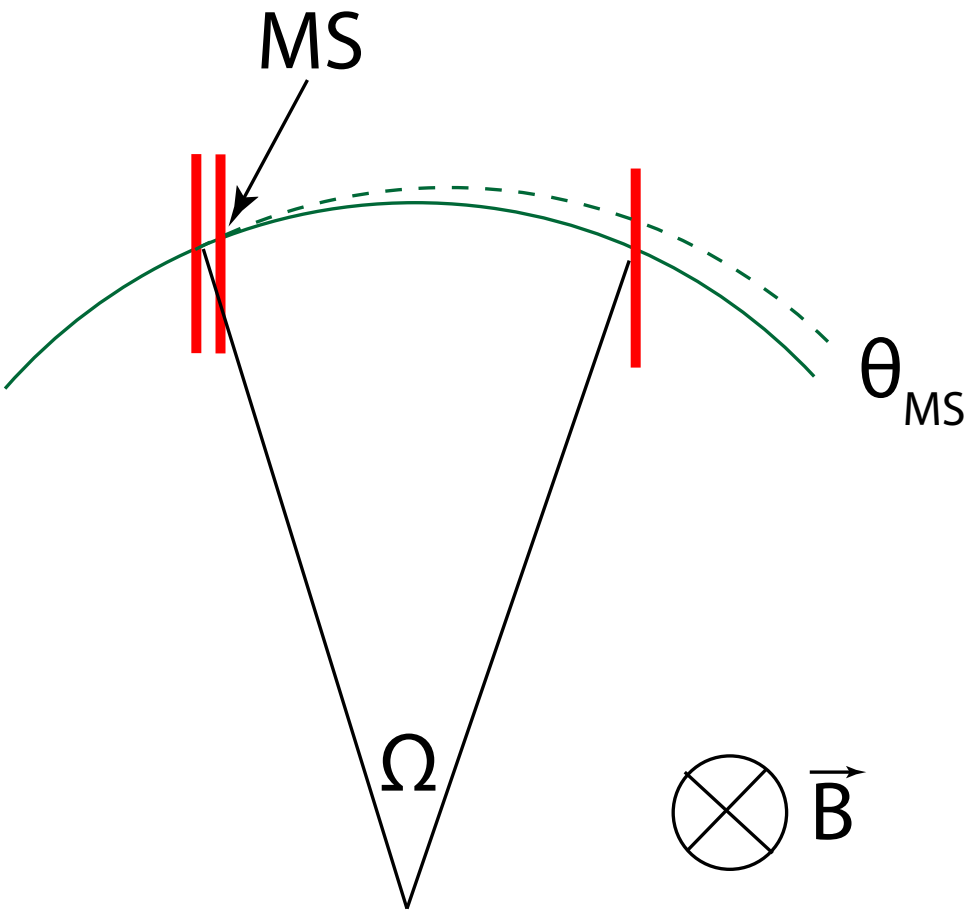

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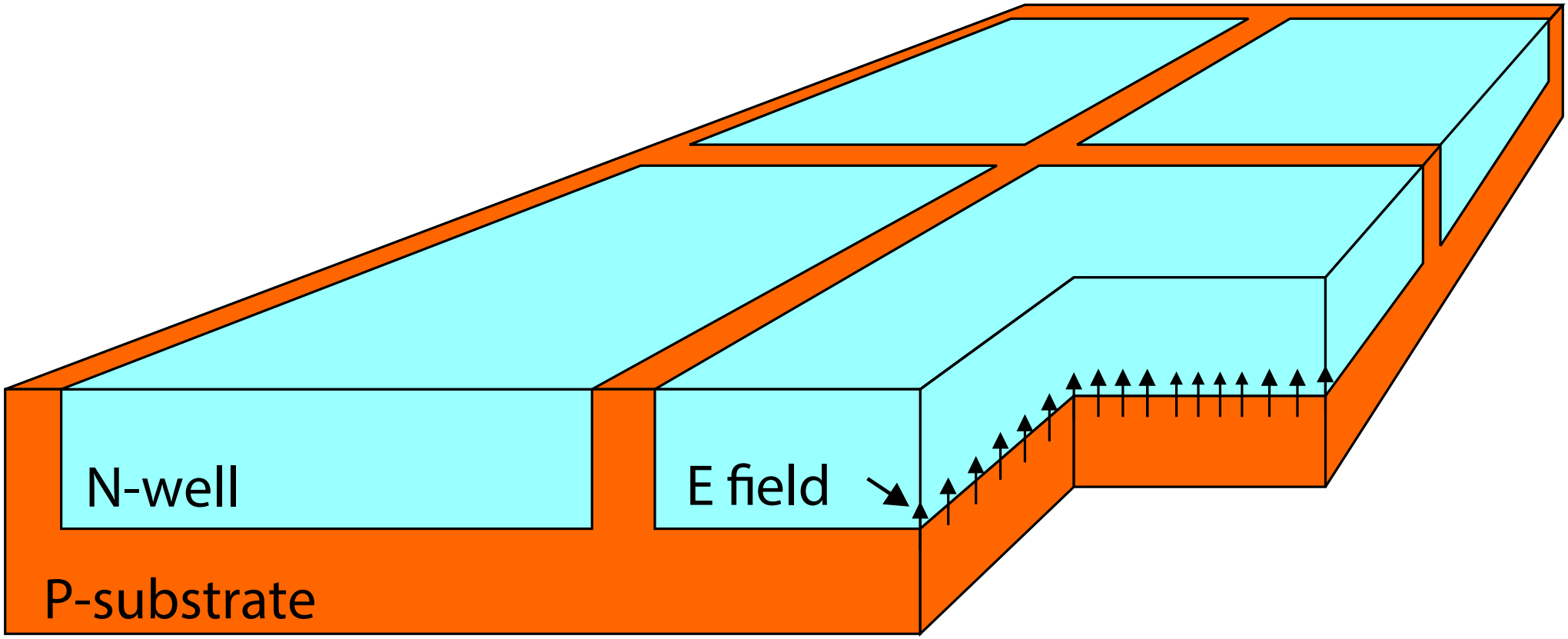
Very thin and fast silicon pixel sensors: HV-MAPS

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)



Fast and thin sensors: HV-MAPS

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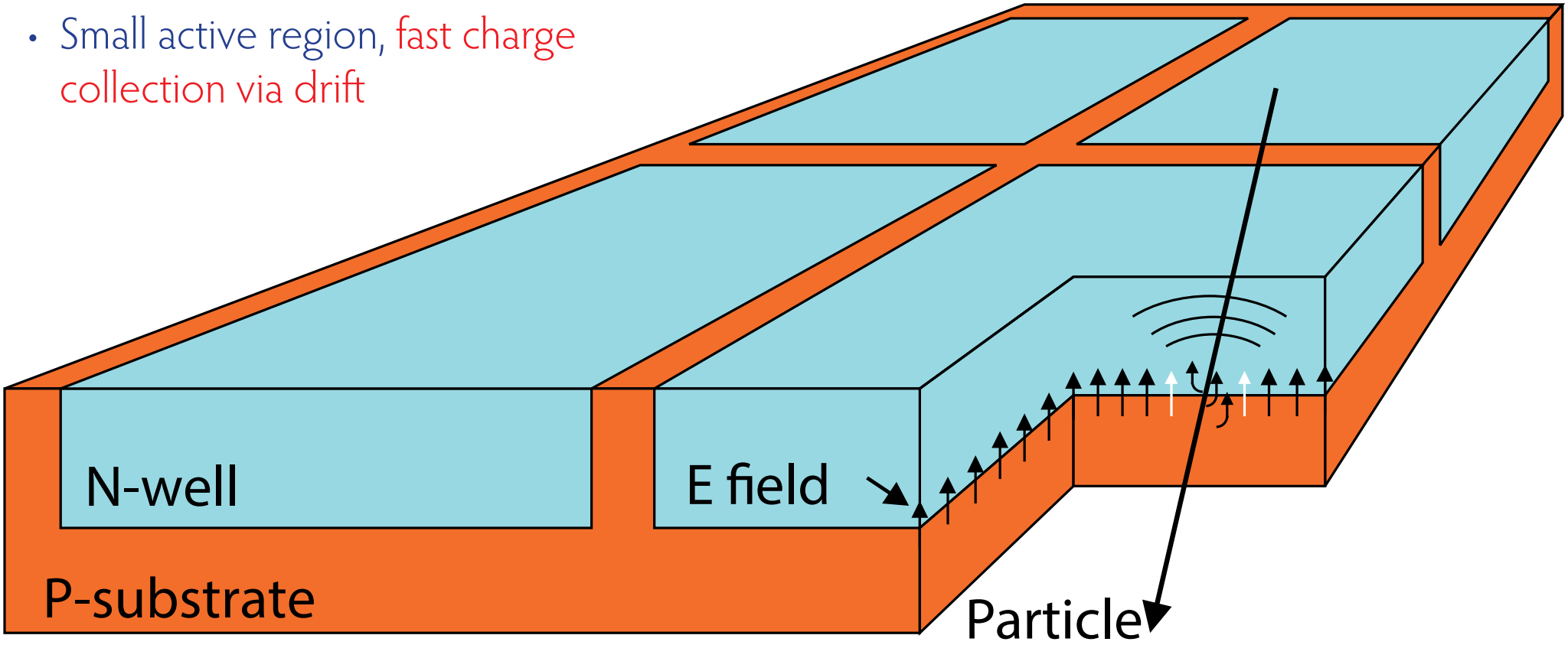


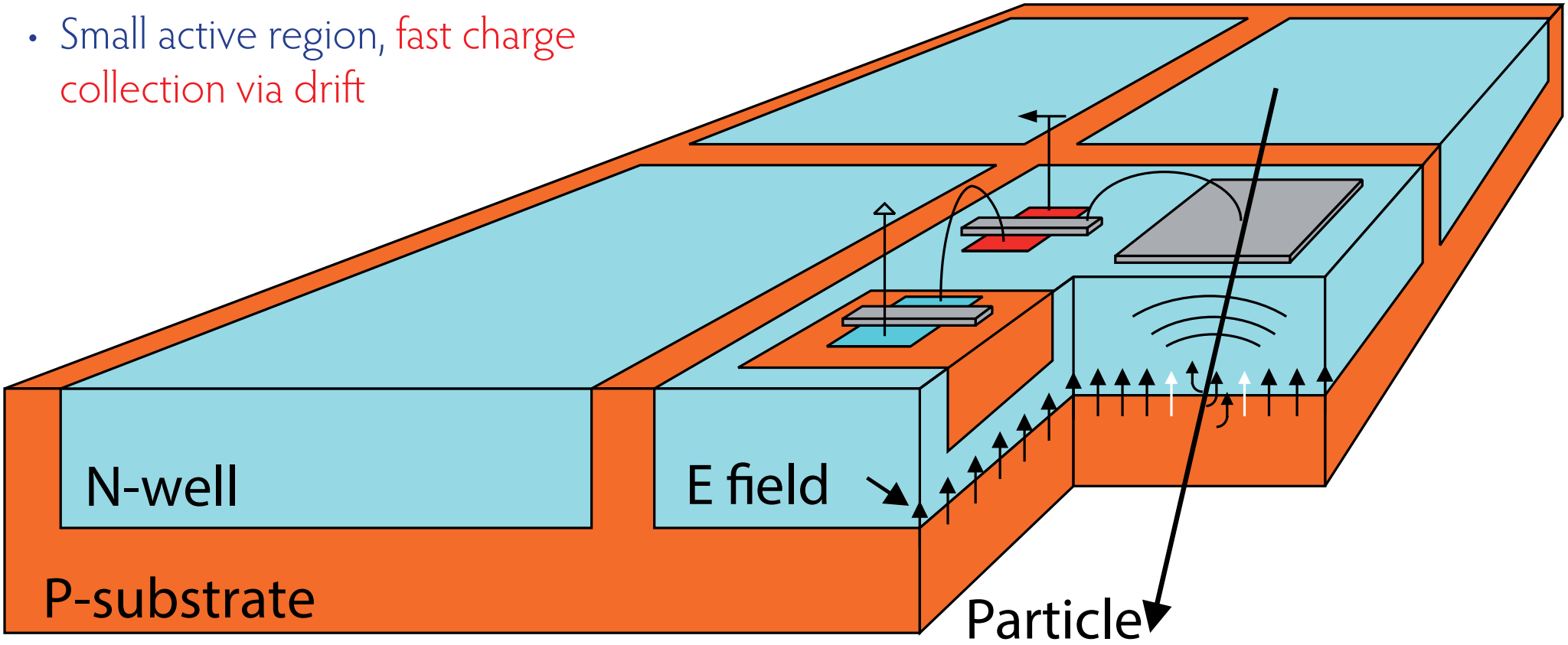
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift

- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 µm

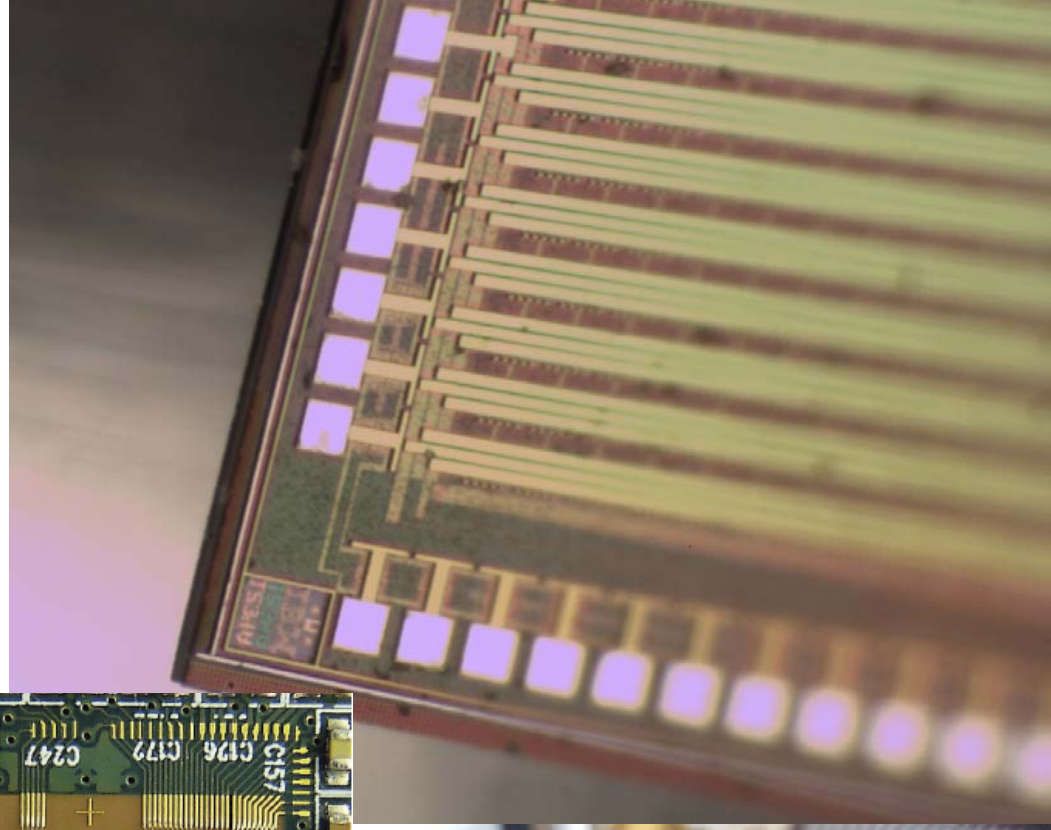
(I.Perić, NIM A 582 (2007) 876)

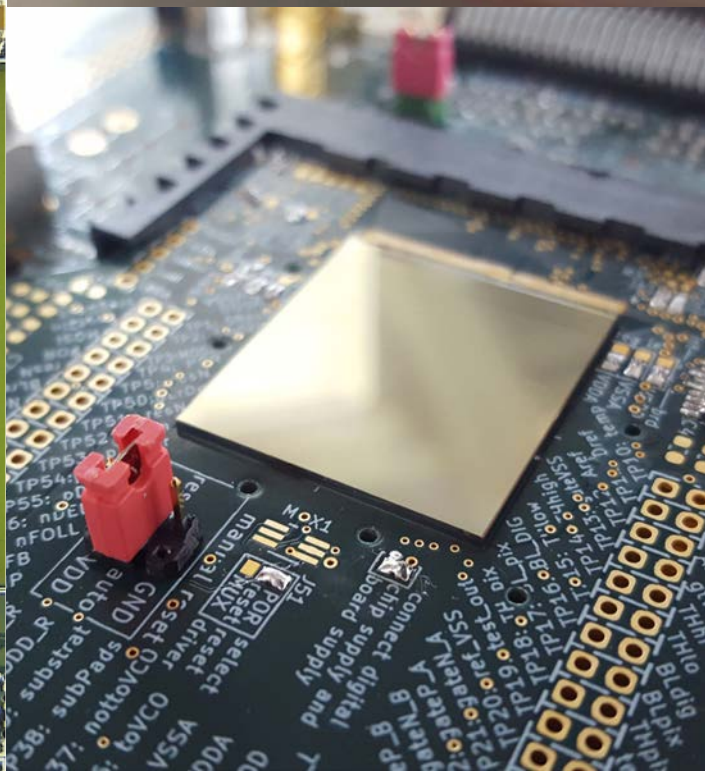


The MuPix Prototypes

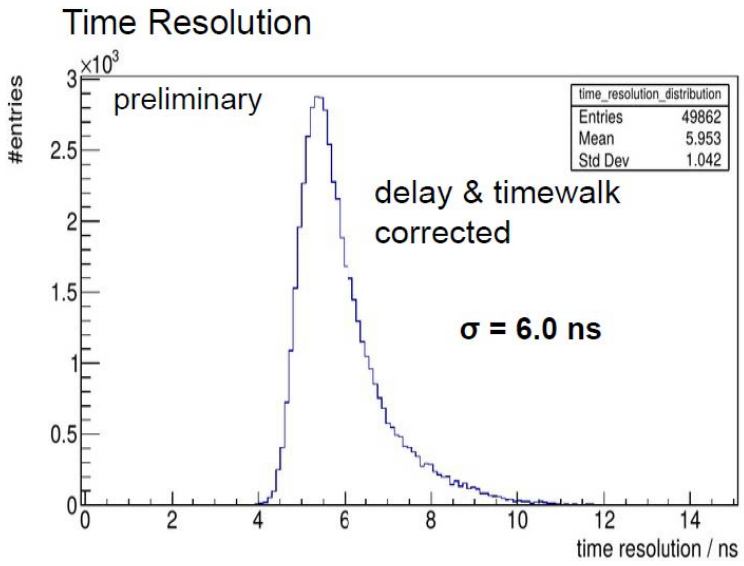
Developed a series of HV-MAPS prototypes

- Goal: Detection and signal processing with just 50 µm silicon
- 6th chip, MuPix7, was the first full system-on-a-chip
- Going "big" 2 x 1 cm^2 MuPix8 with 80 by 80 µm pixels also working nicely - some growing pains fixed
- MuPix10, 2 x 2 cm^2, almost final
- MuPix11, 2 x 2 cm^2, production chip, submitted, expected this summer

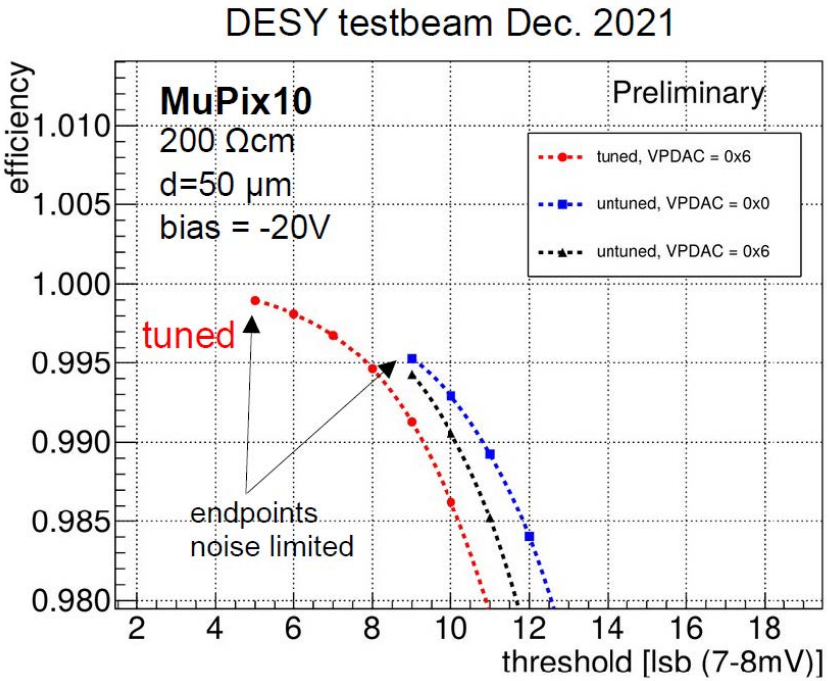


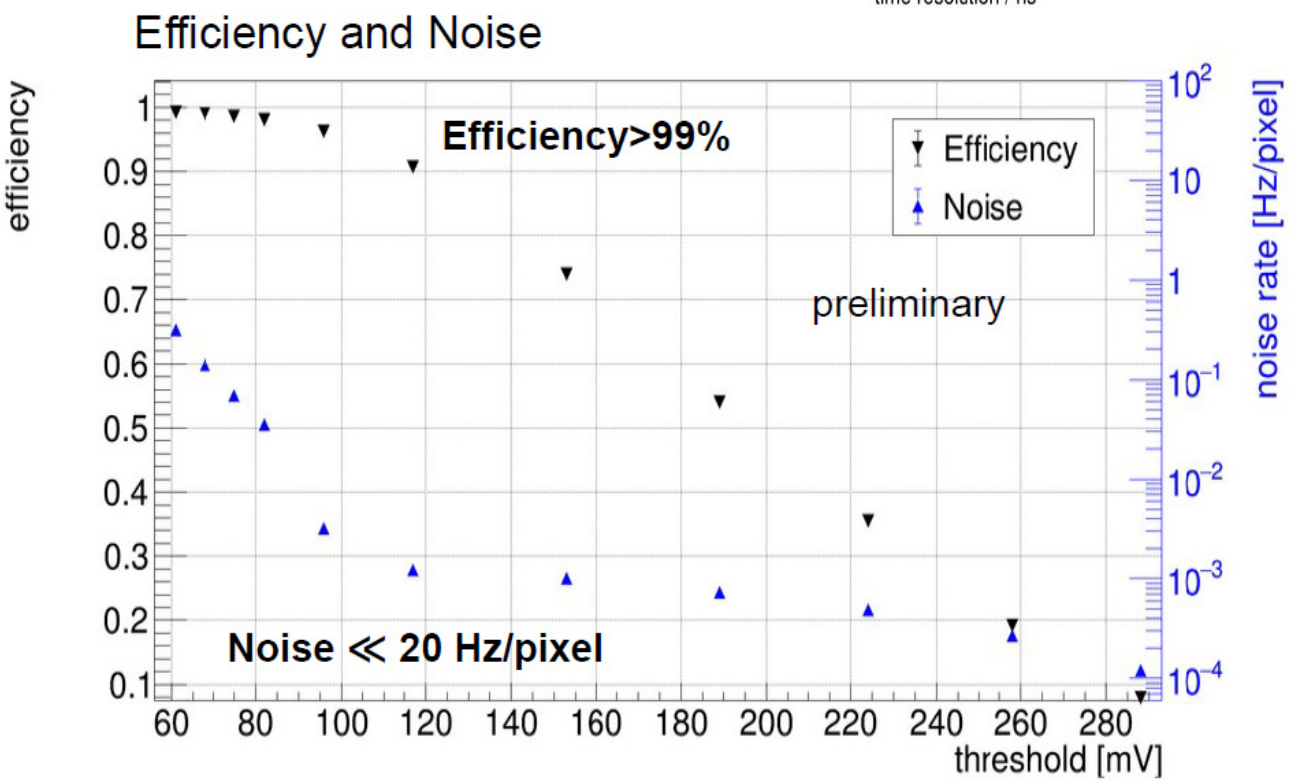


MuPix10: Results

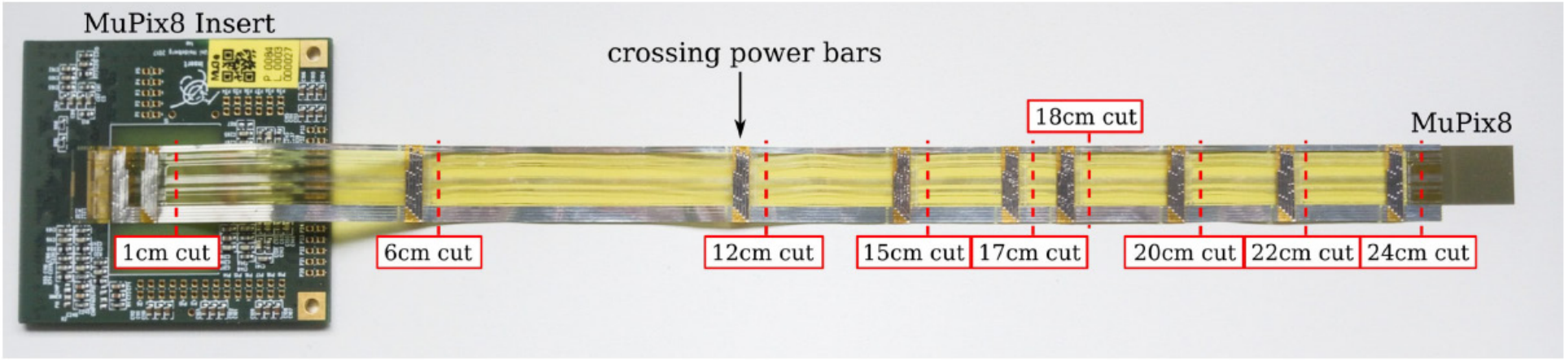


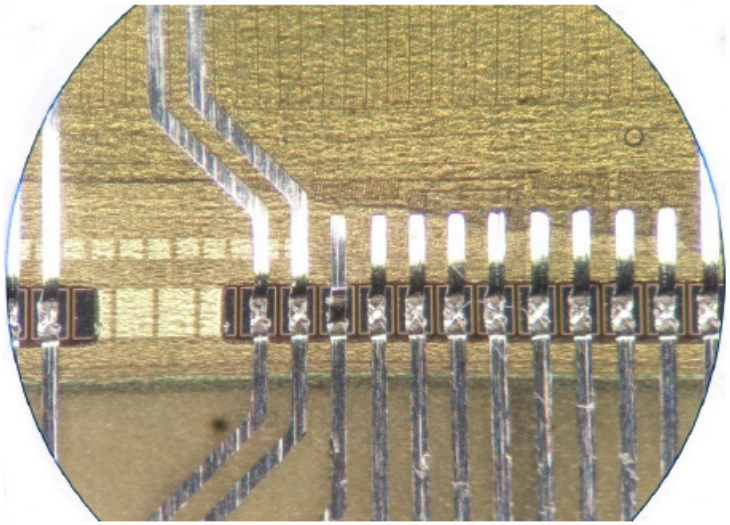
Specs of the experiment fulfilled





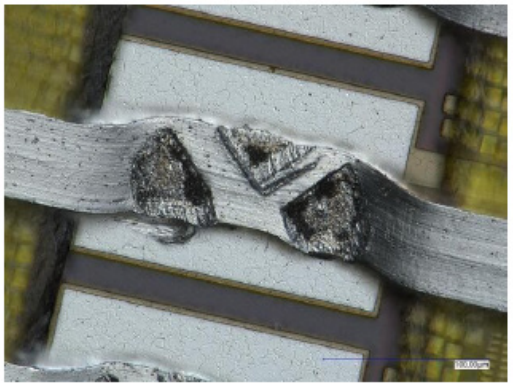
Integration with Flexprint



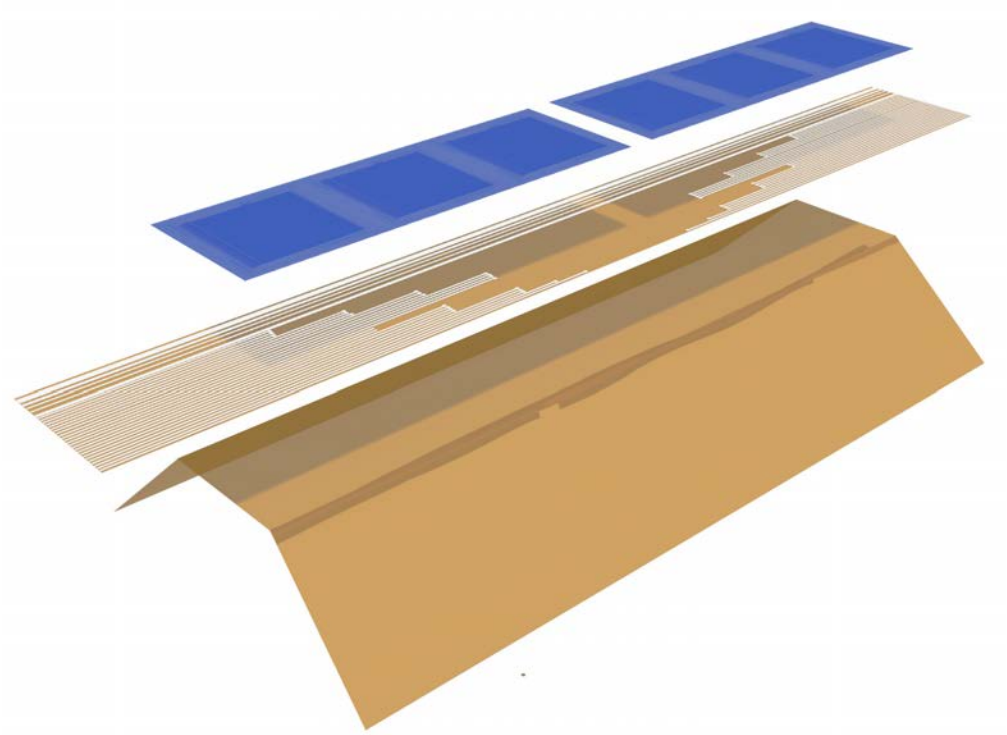


Operate MuPix on an aluminium-kapton flexprint without decoupling capacitors

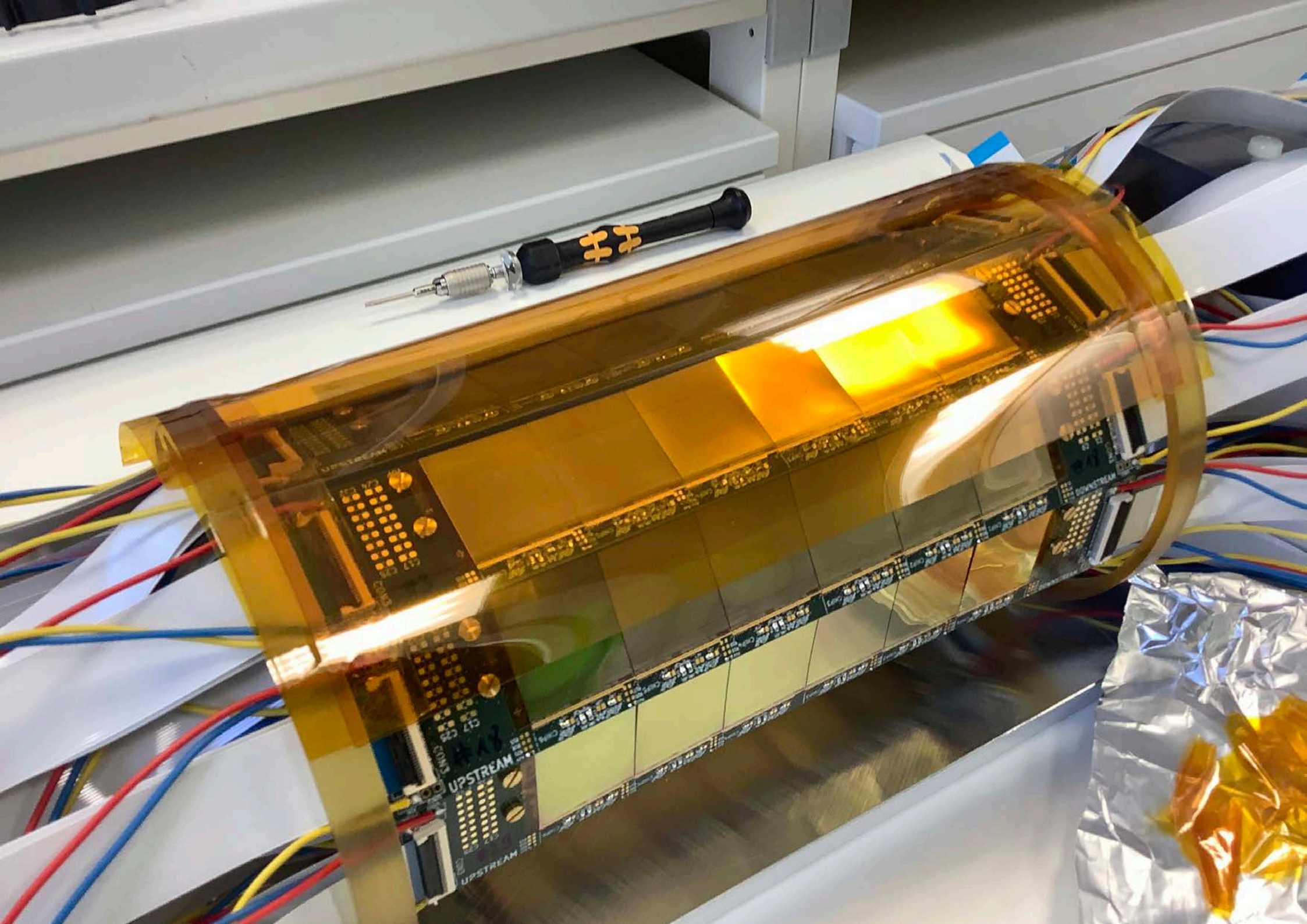
- Low noise
- No transmission errors
- Longer than needed for Mu3e



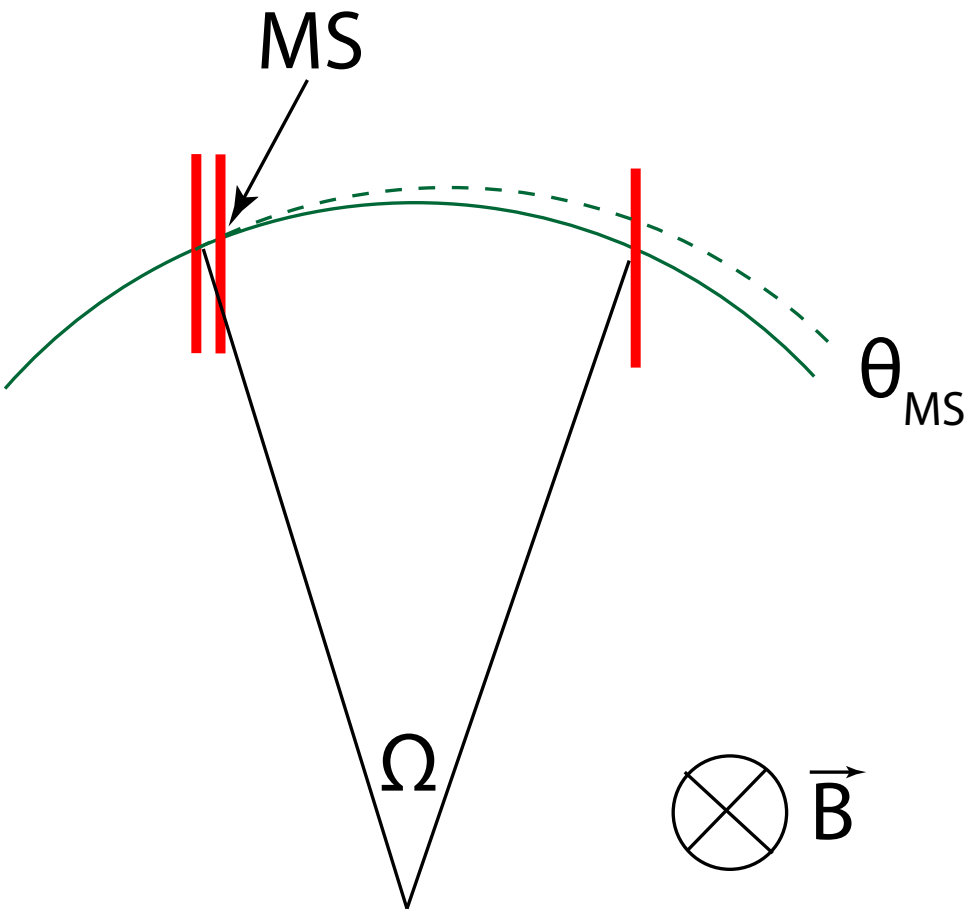
Mechanics



- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- About 1‰ of a radiation length per layer


UPSTREAM
UPSTREAM

Momentum measurement

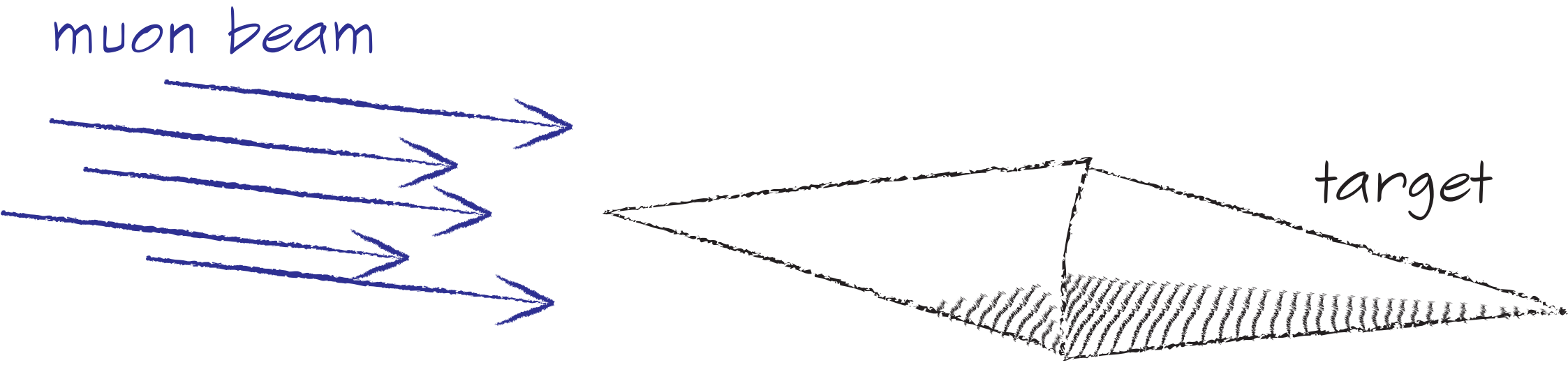


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

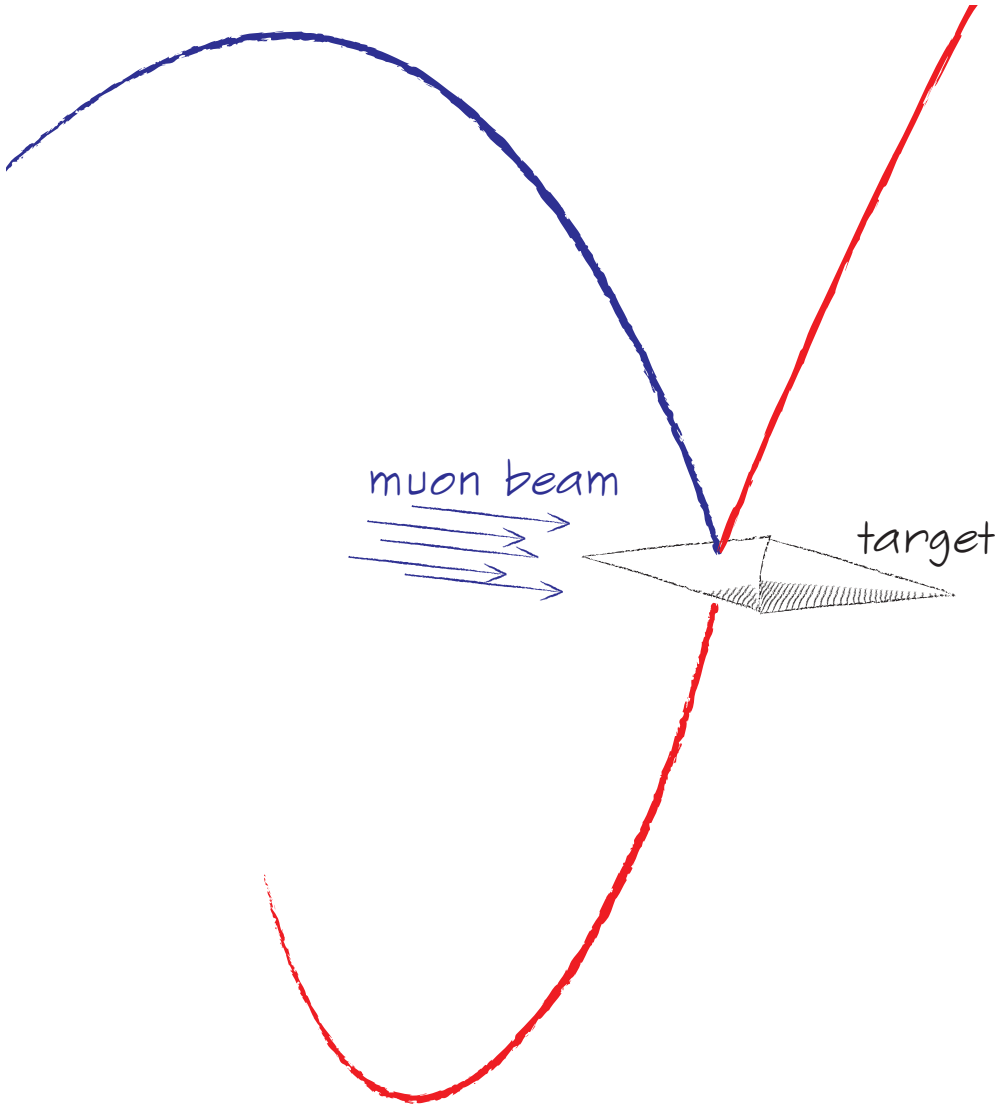
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}

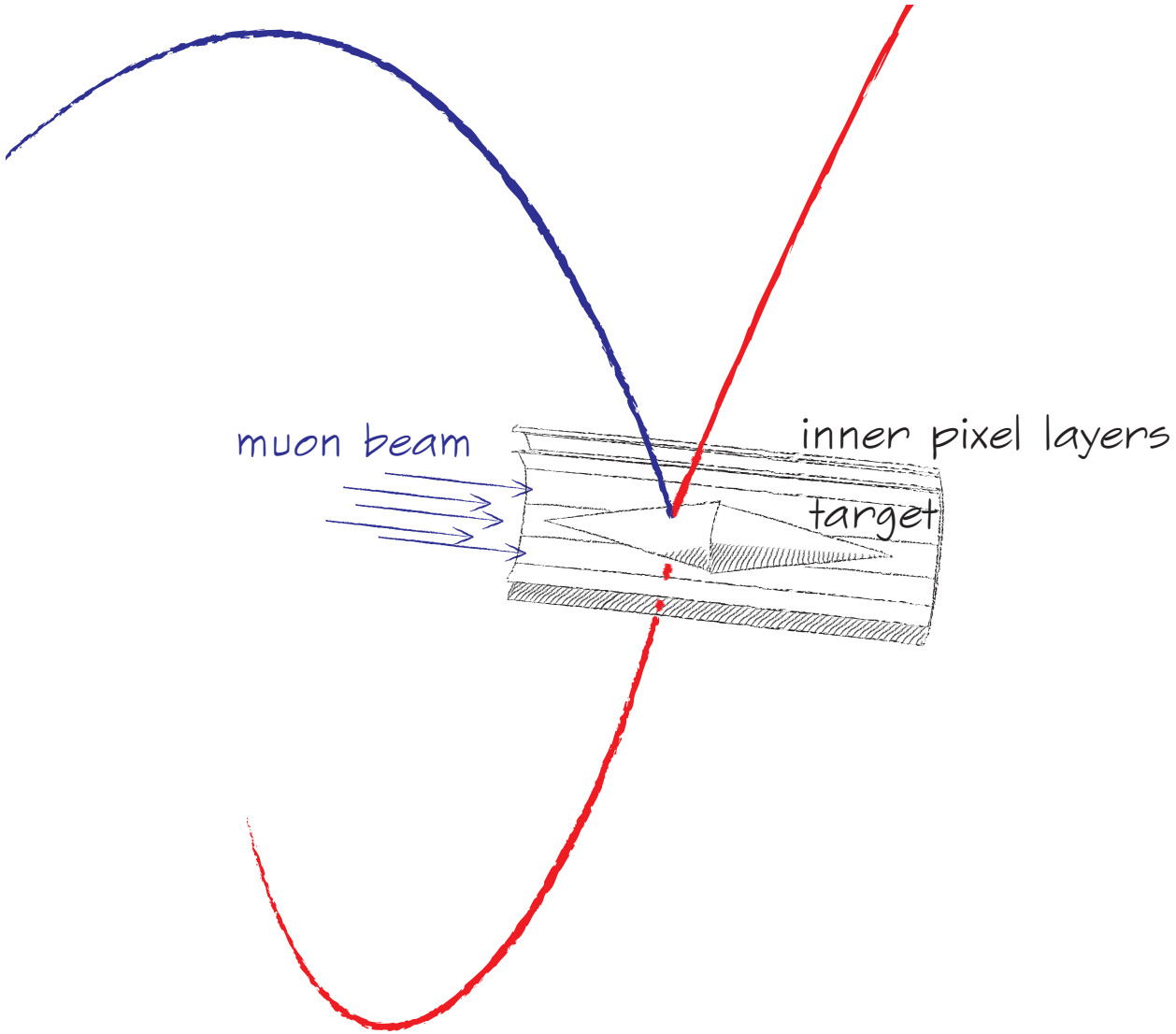
Detector Design



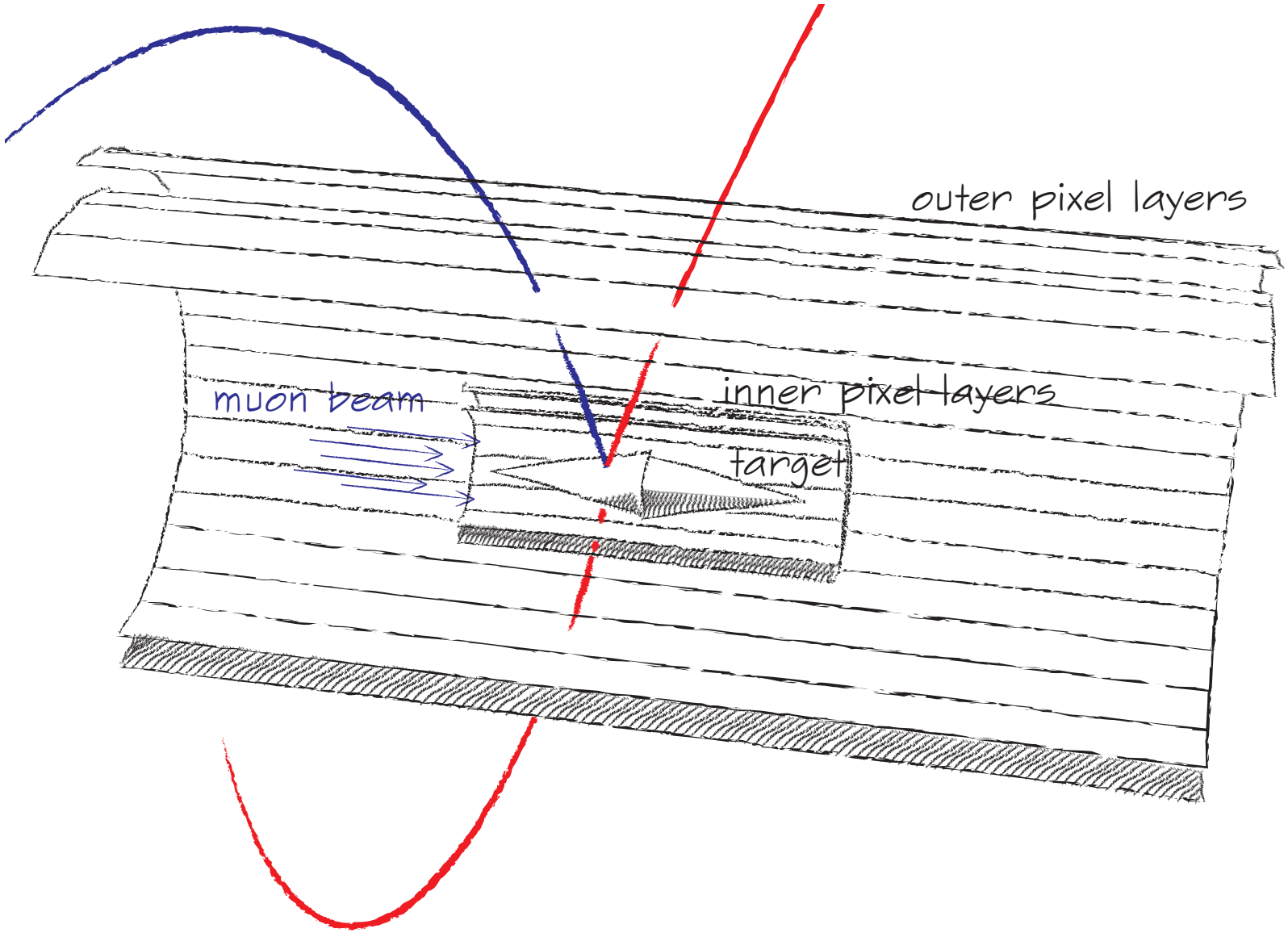
Detector Design



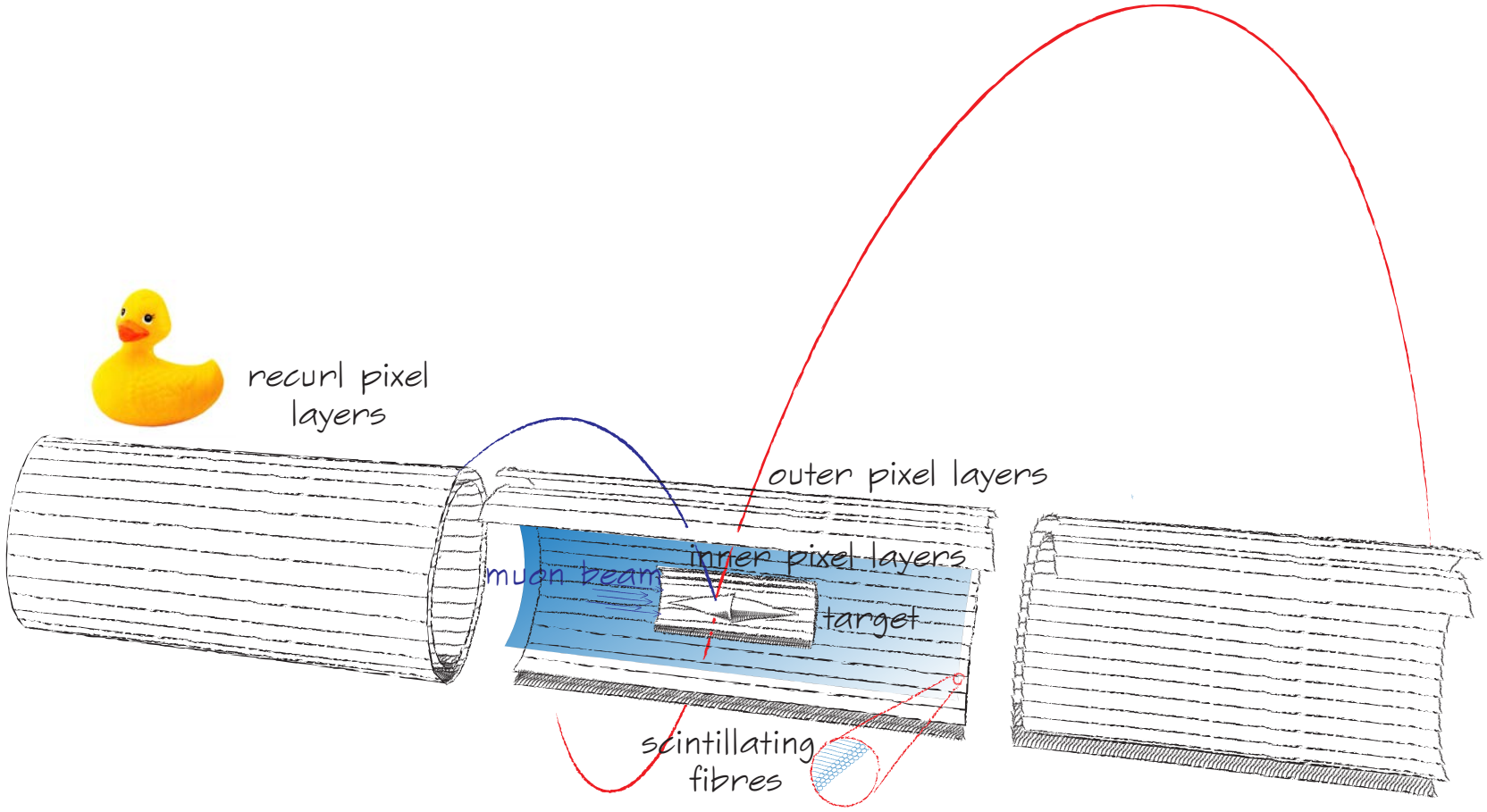
Detector Design



Detector Design



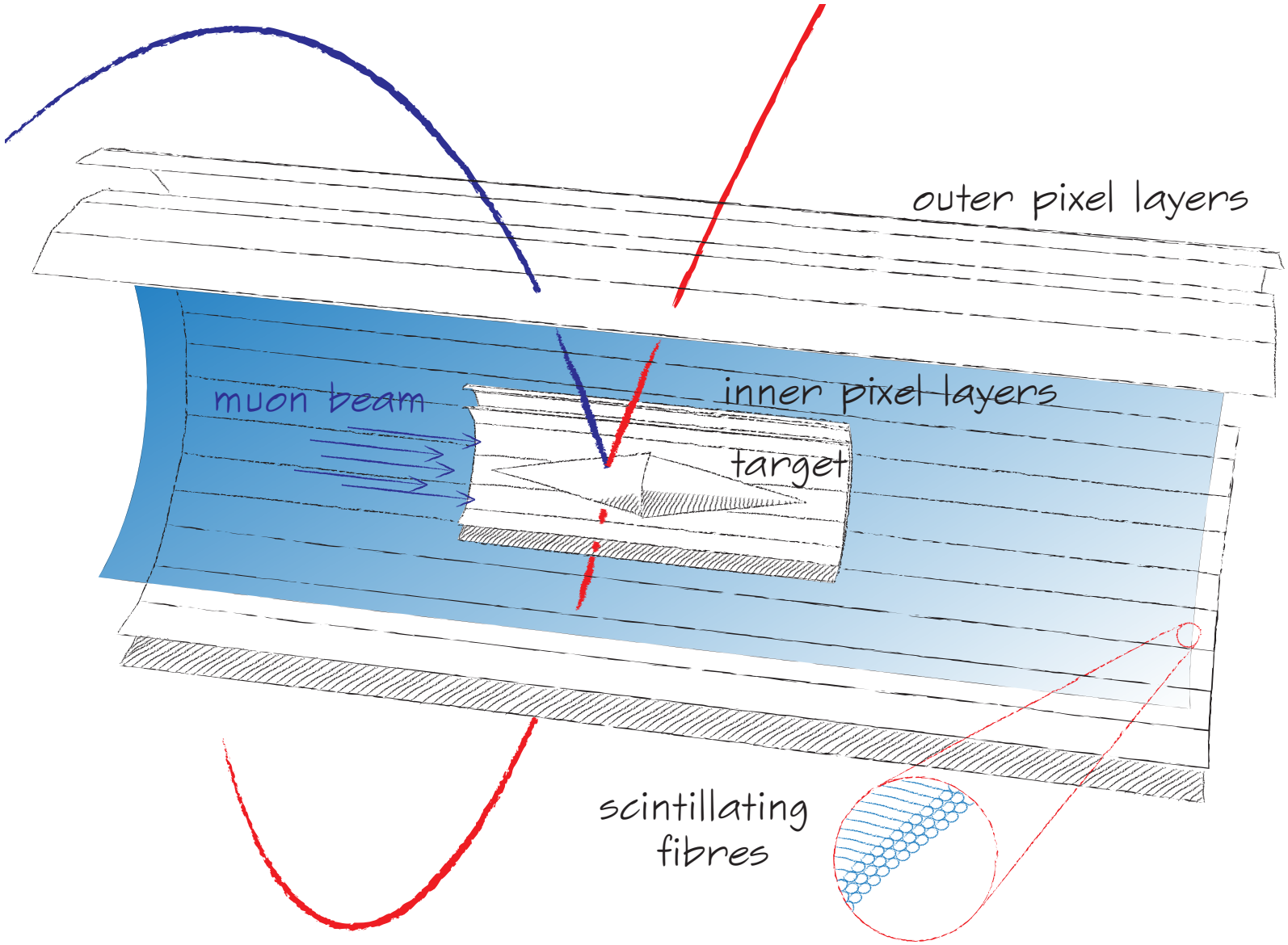
Detector Design



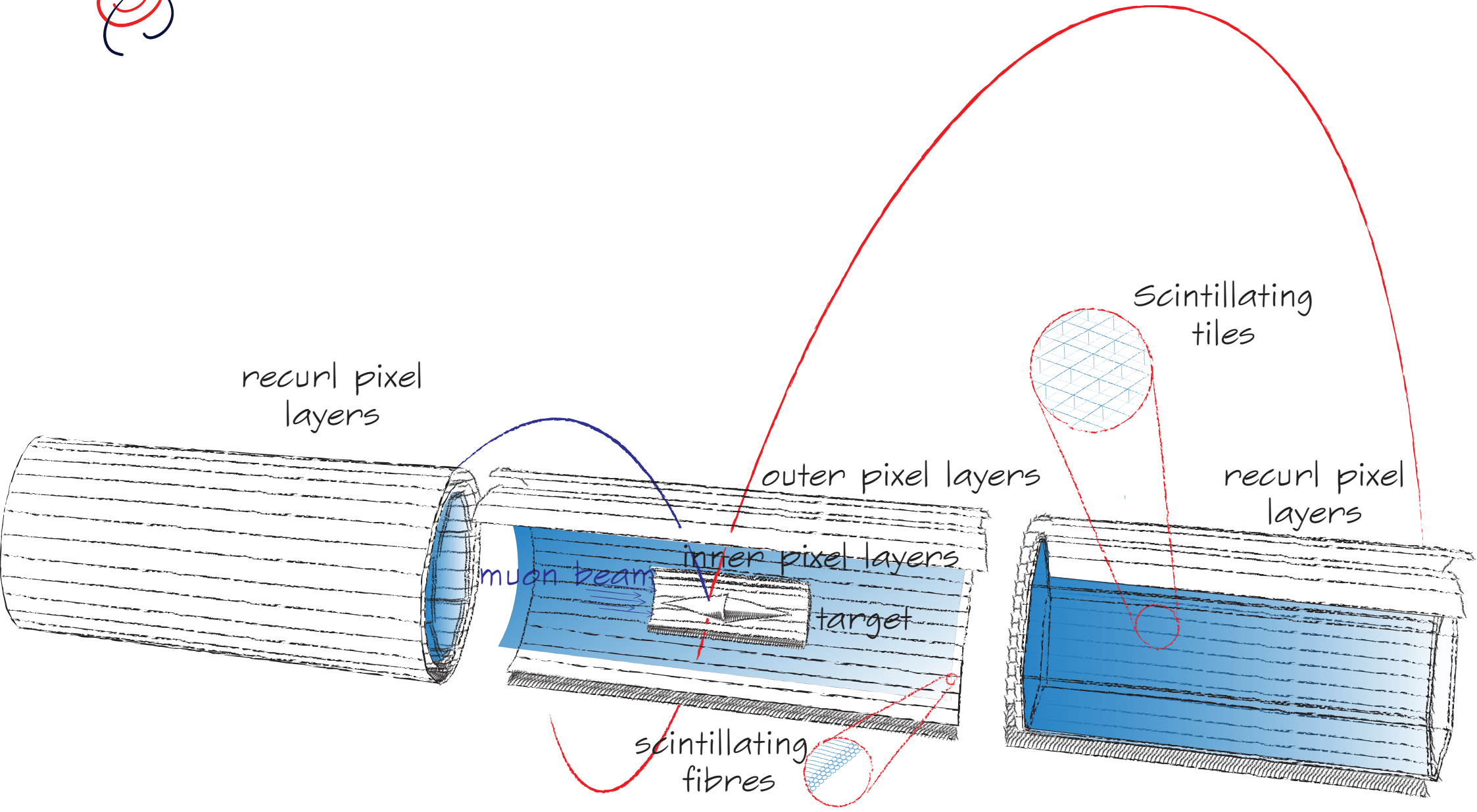
Need suppression of accidental background:

Timing

Detector Design

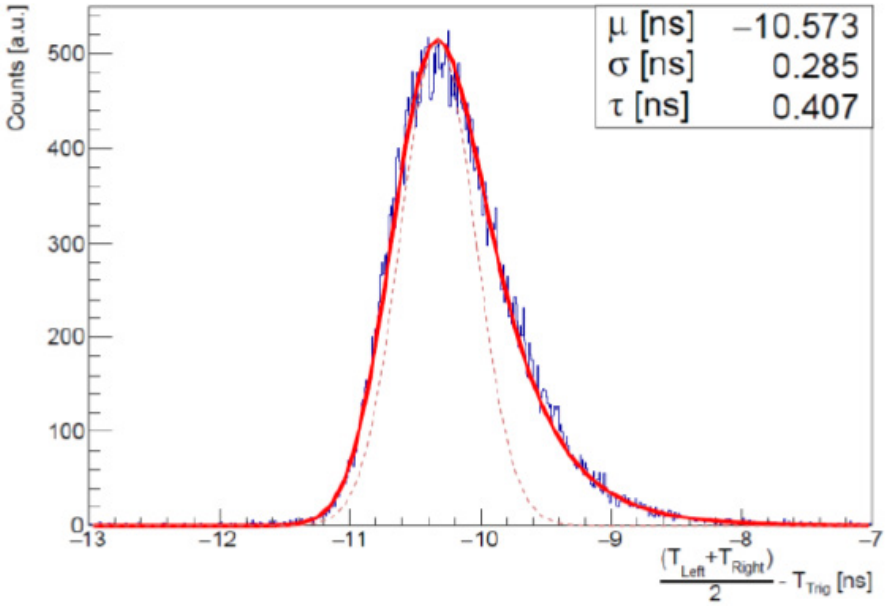


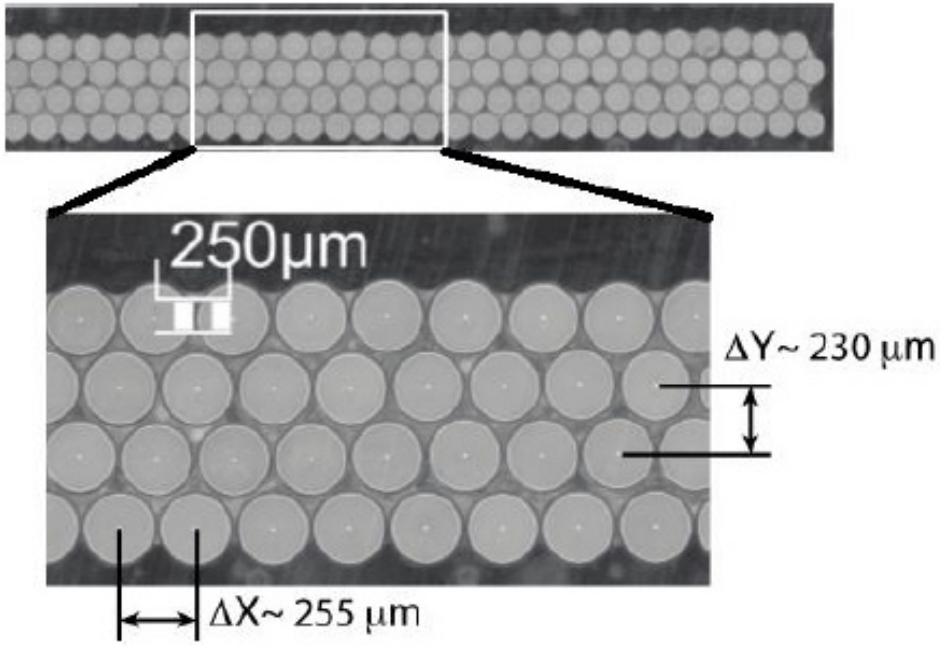
Detector Design



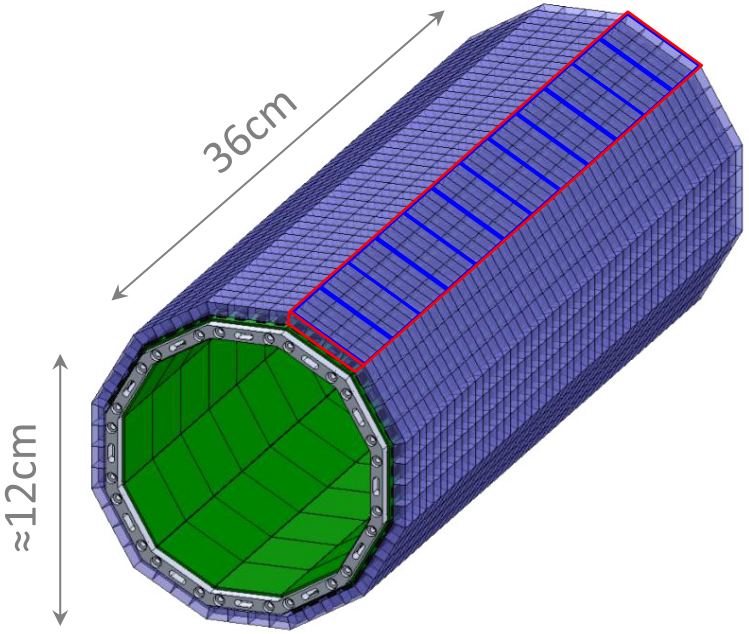
Timing Detector: Scintillating Fibres

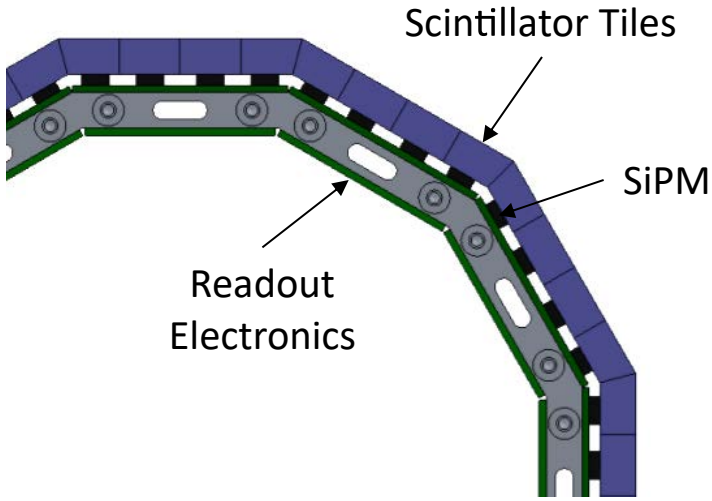
- 3 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)
- Timing resolution < 0.5 ns



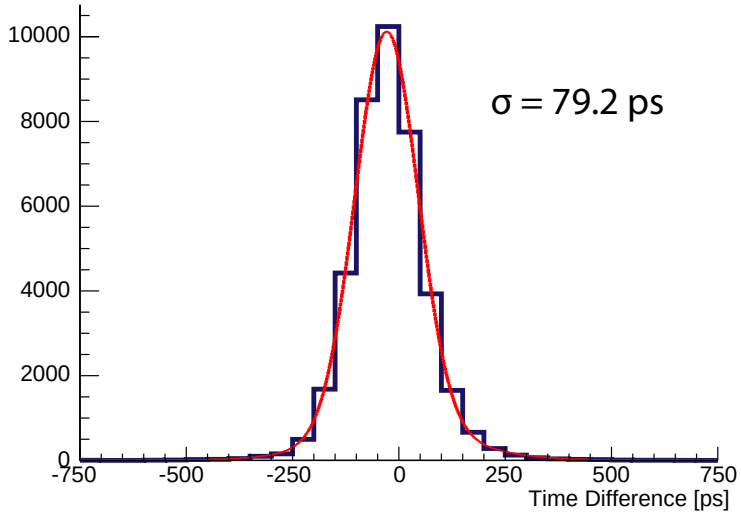


Timing Detector: Scintillating tiles



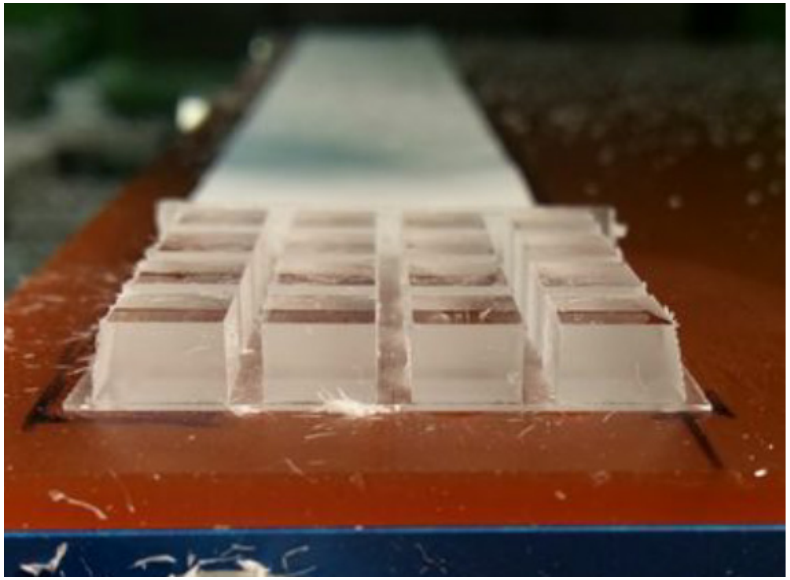


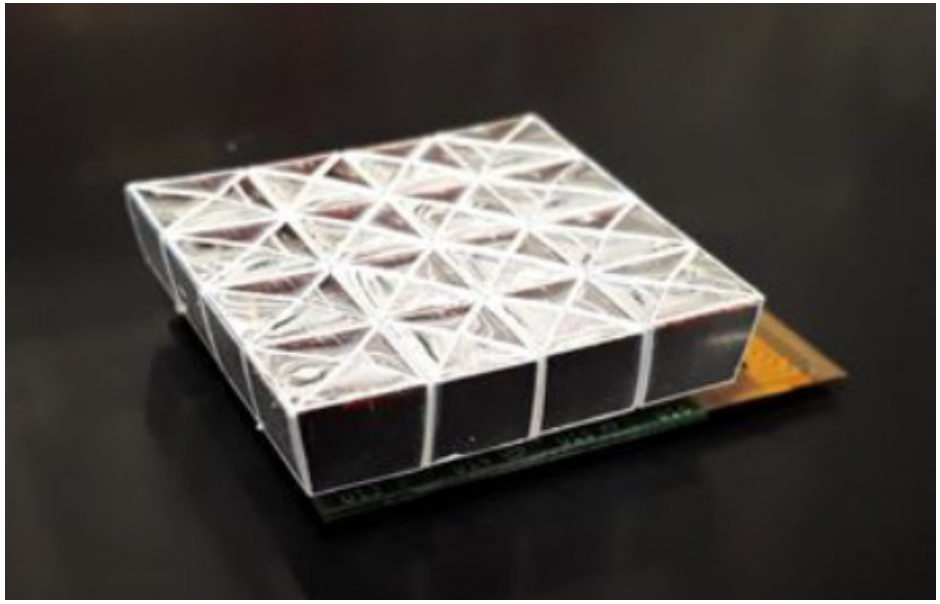
- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)

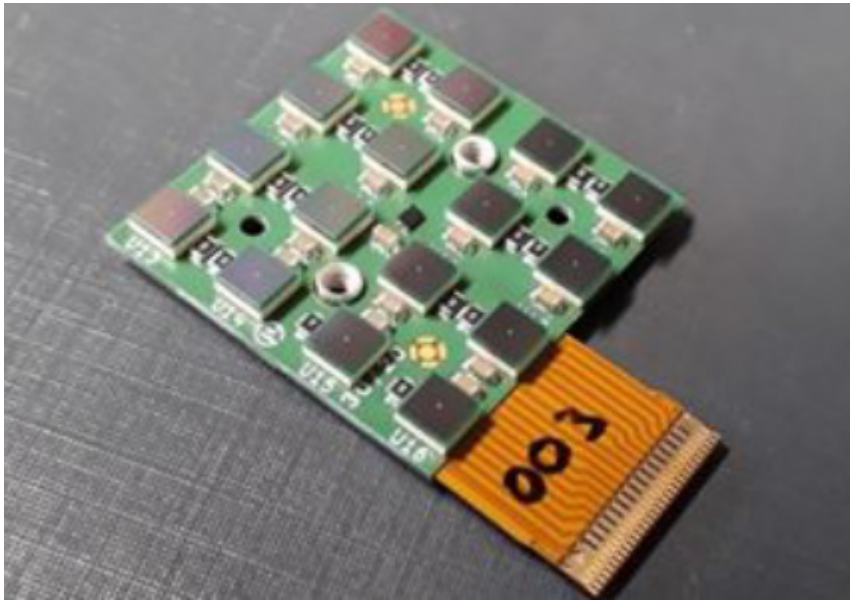


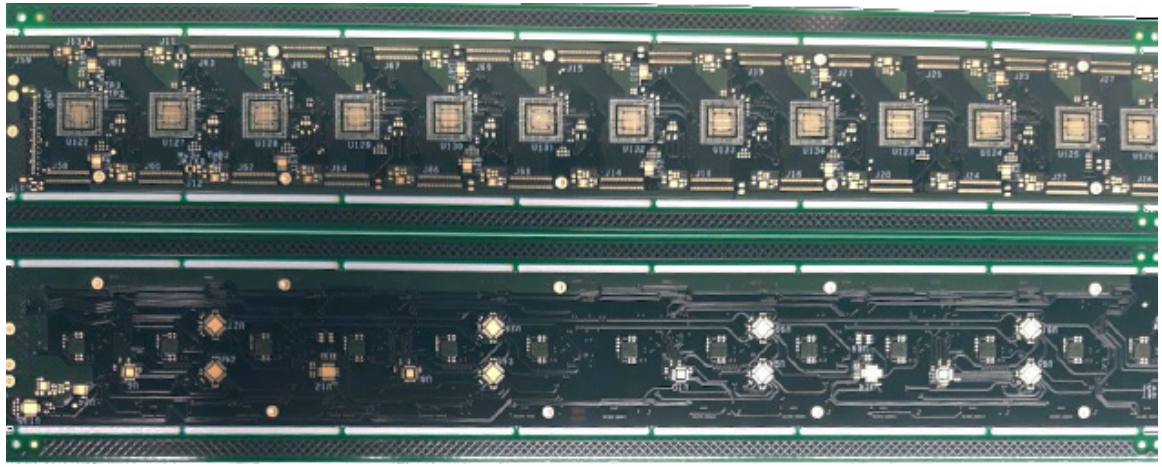
- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps

Timing Detector: Scintillating tiles



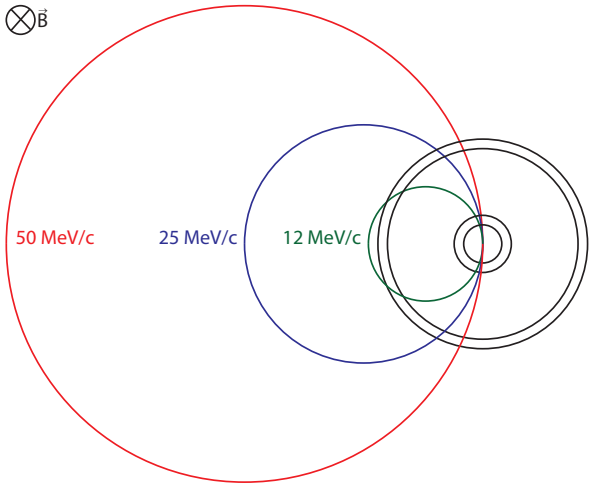




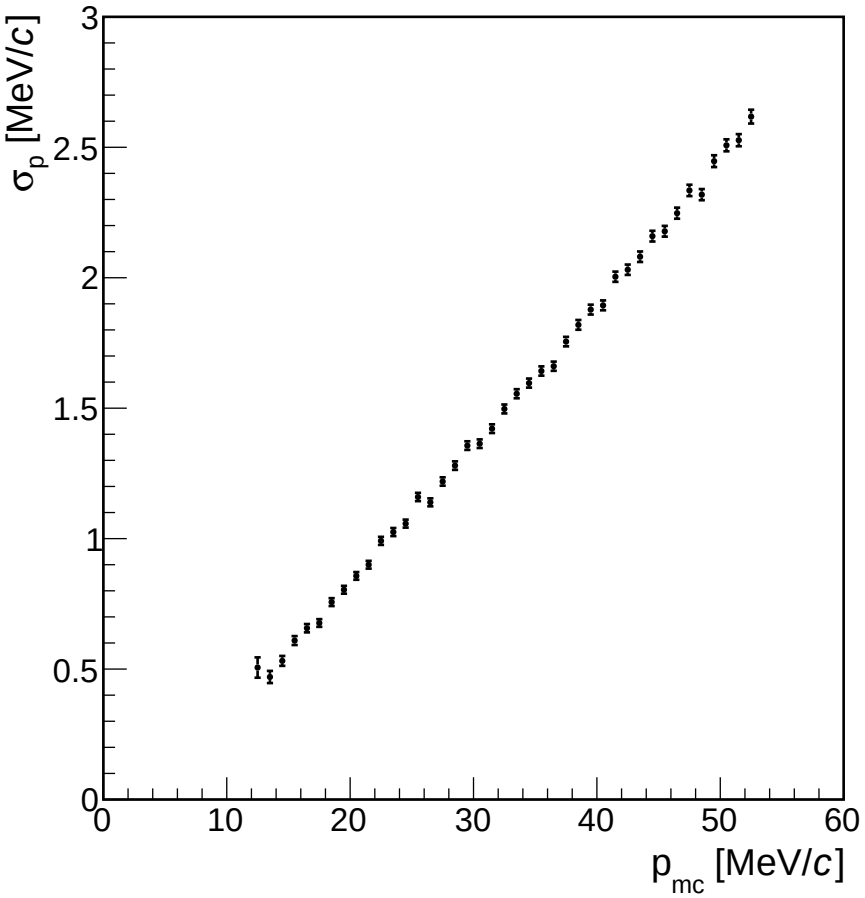


Putting things together: Simulation

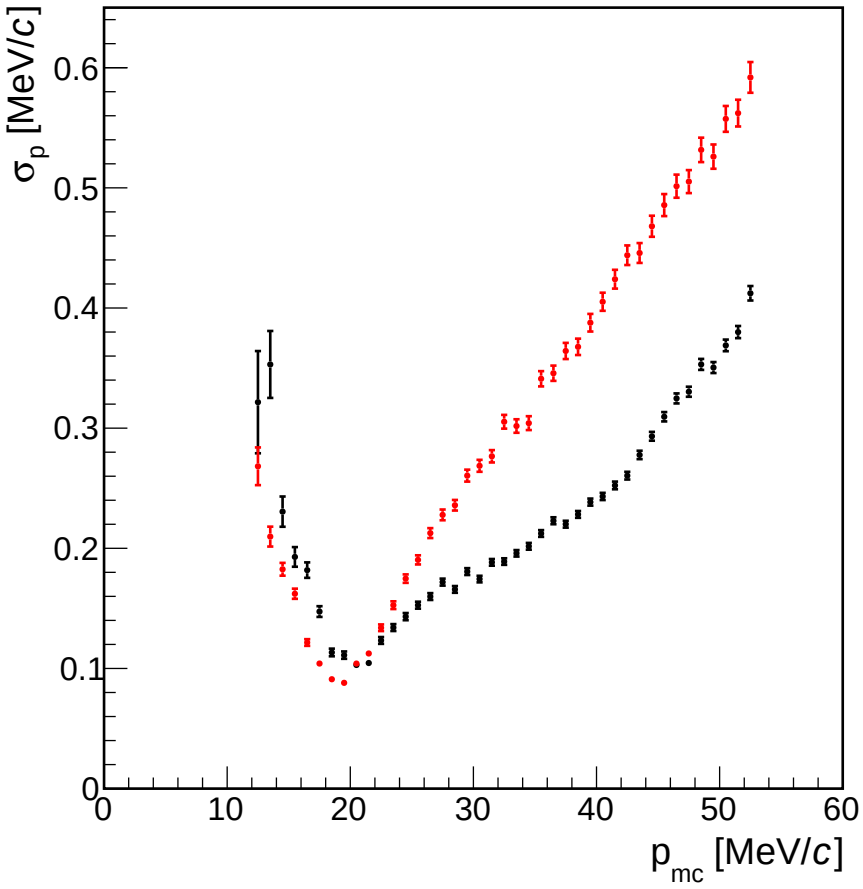
Momentum resolution



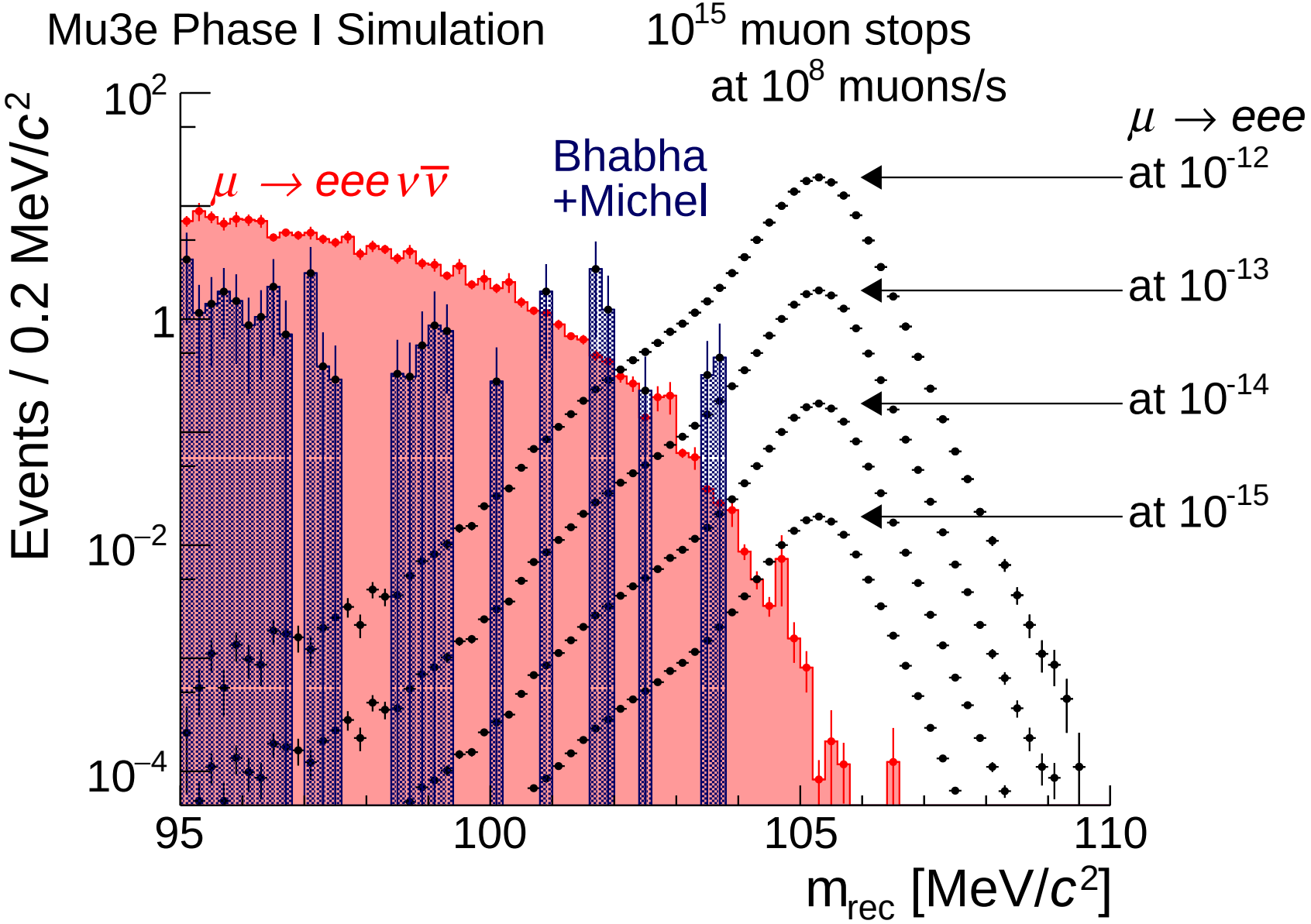
Outgoing part of tracks only



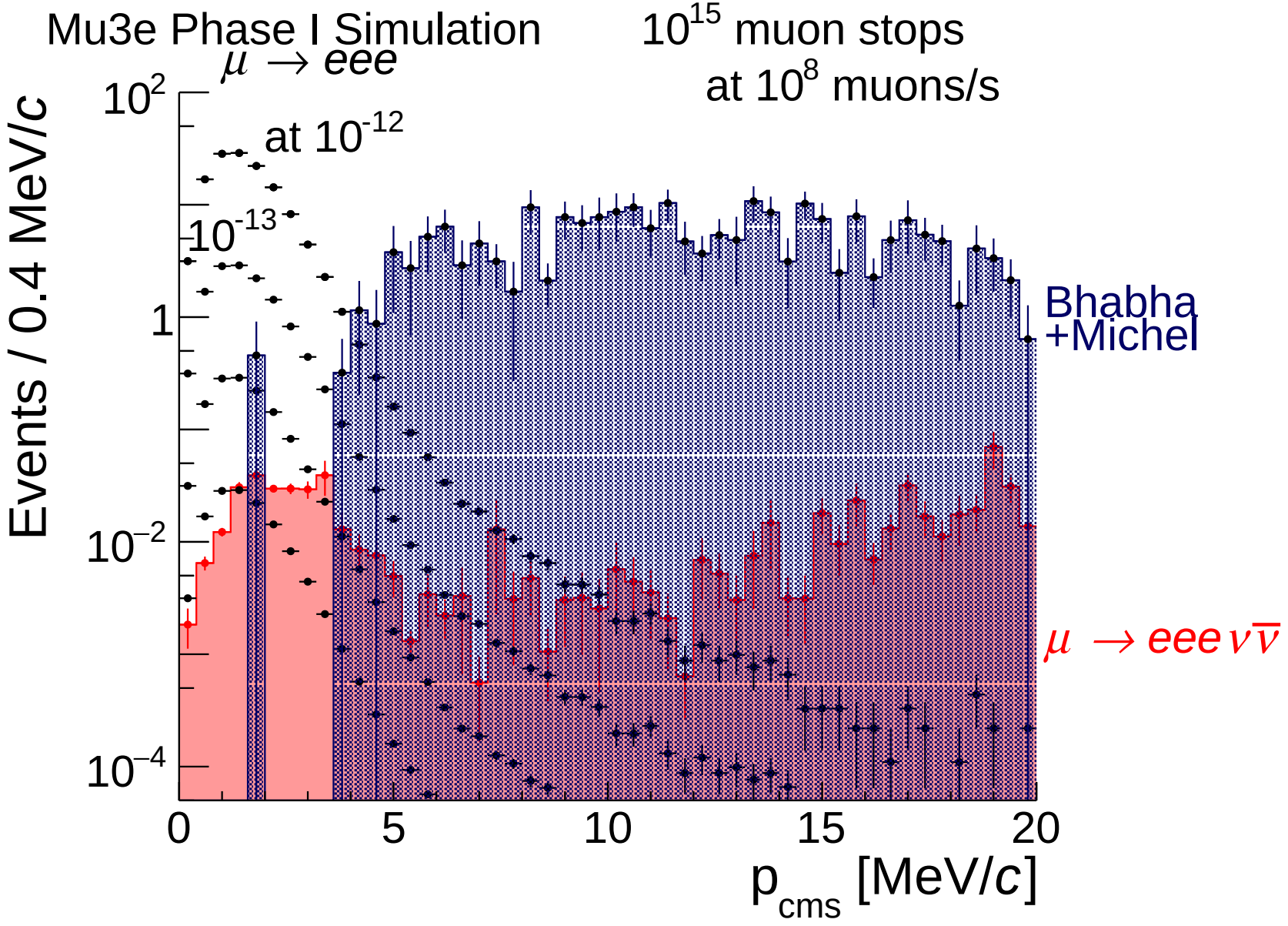
Recurling tracks



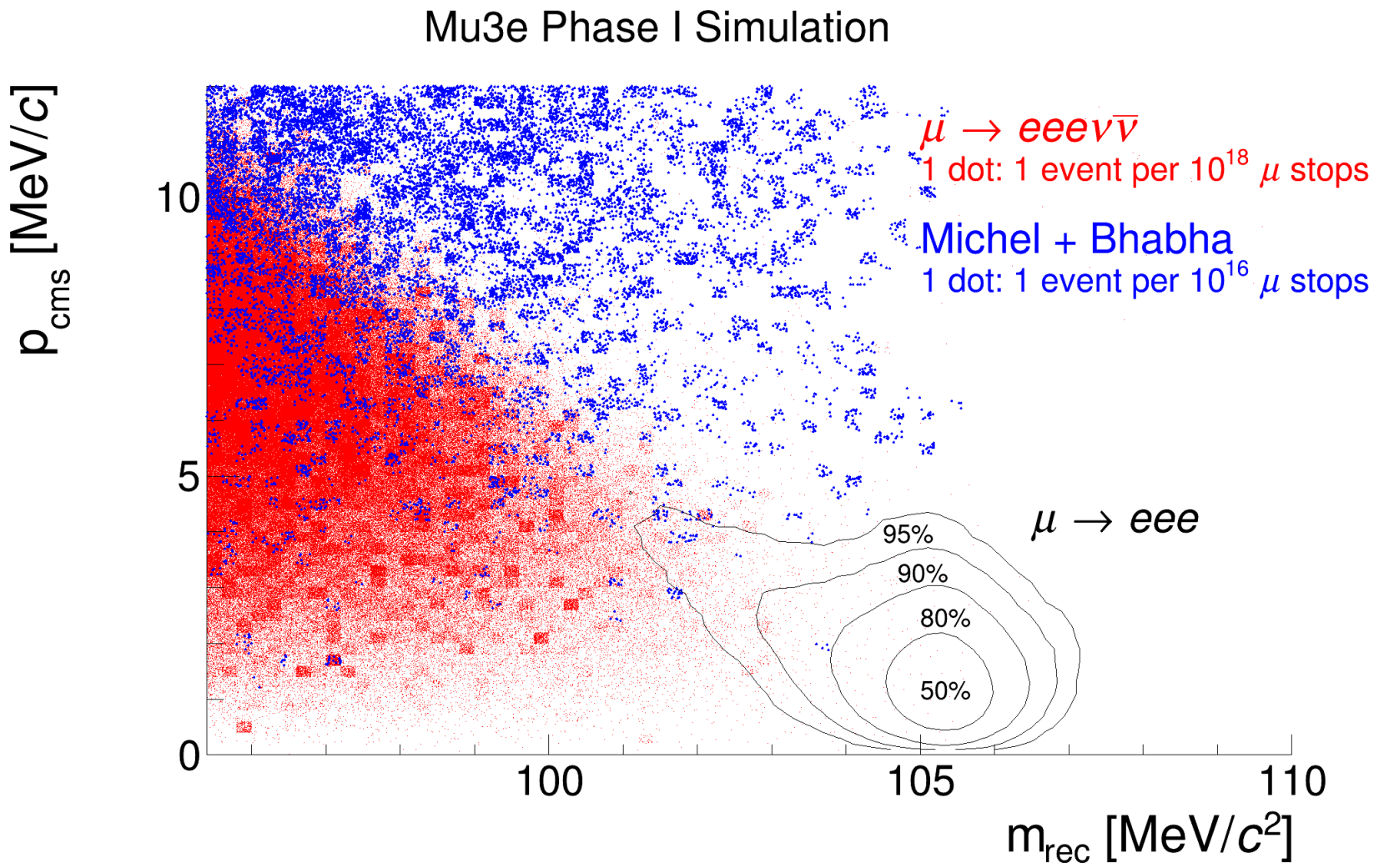
Mass distribution



Momentum distribution



Mass/Momentum distribution



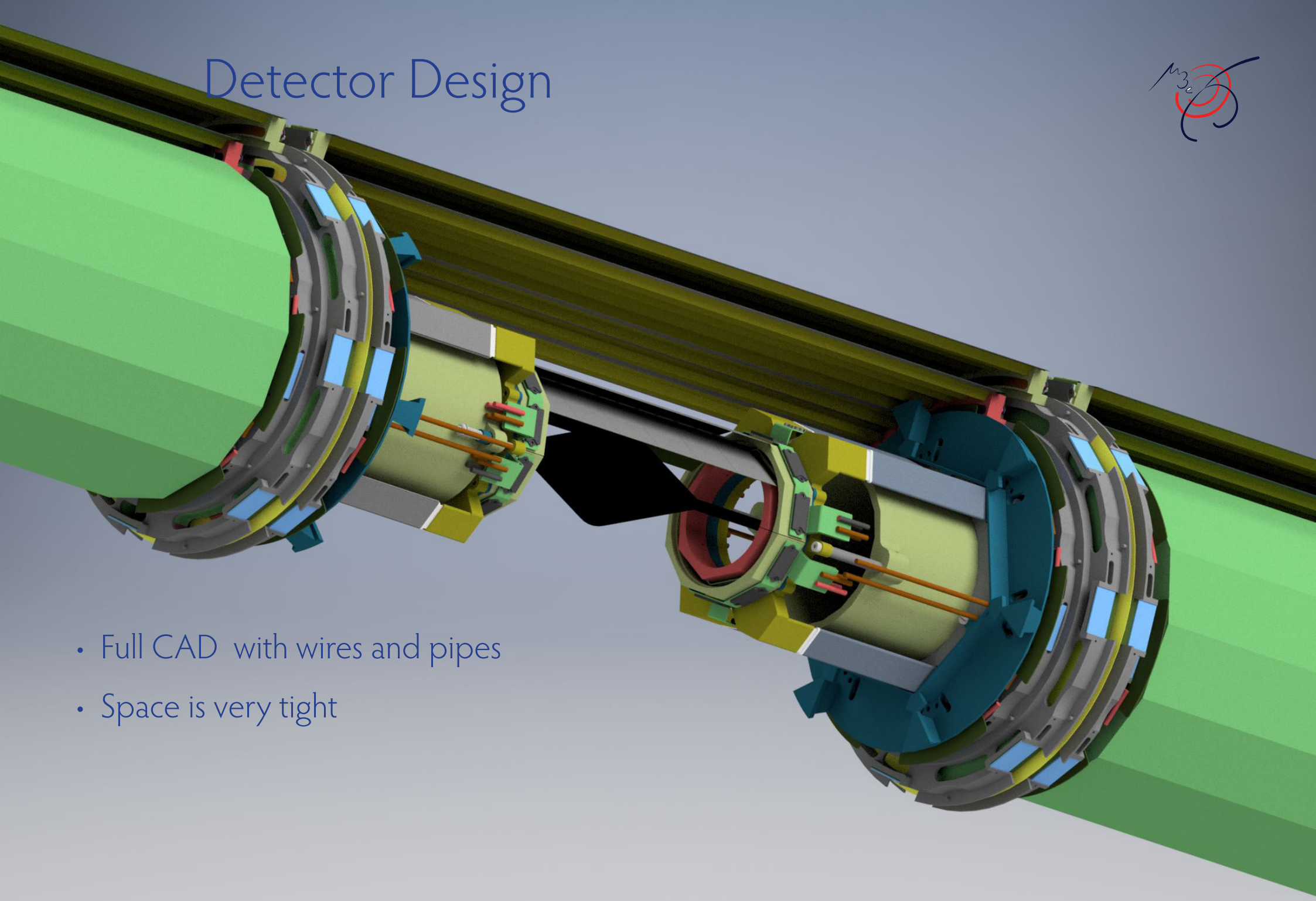
Putting things together: Reality

Detector Design

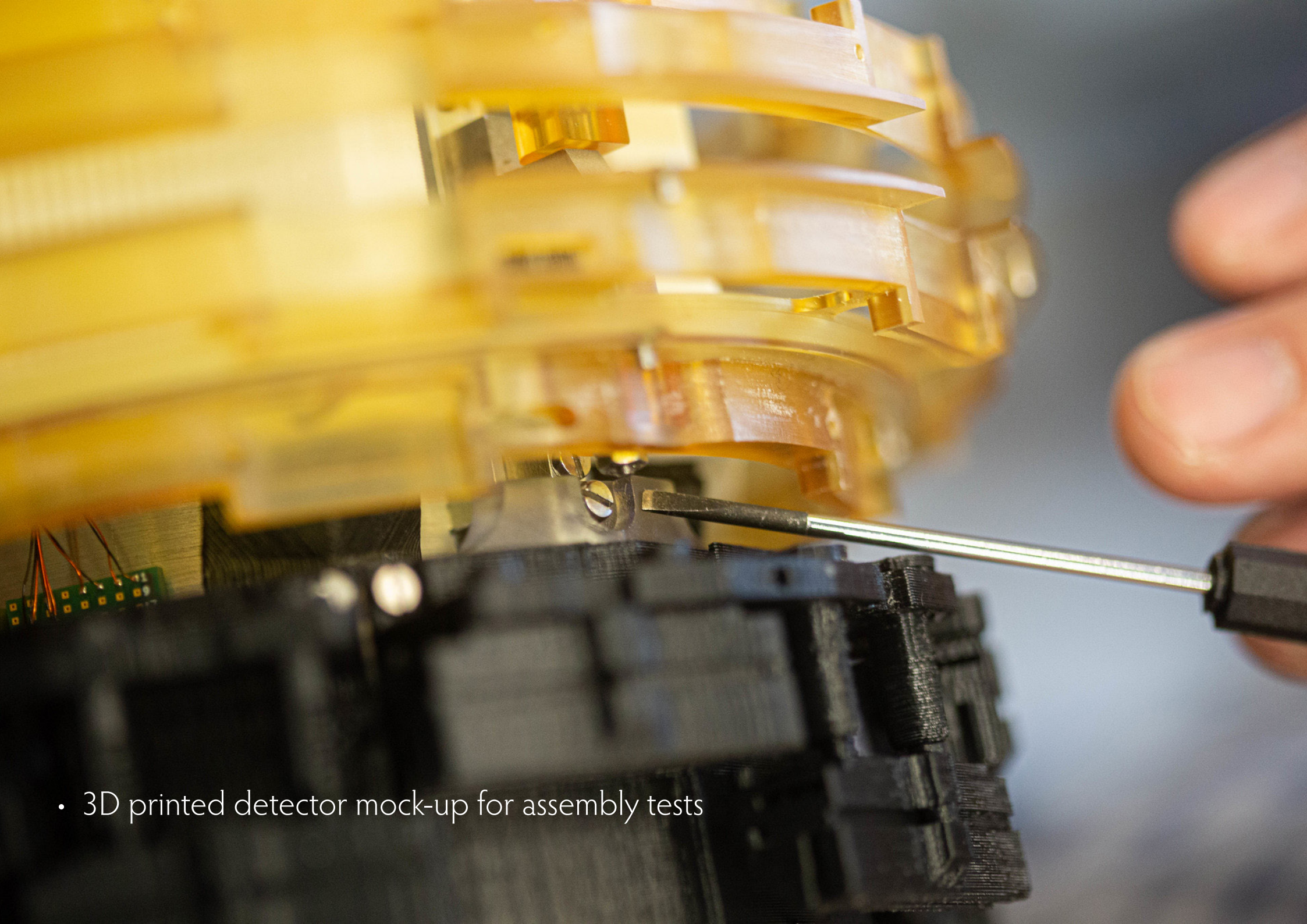
Challenges:

- Thin detectors
- Services (and beam) inside detector
- Cooling with gaseous Helium

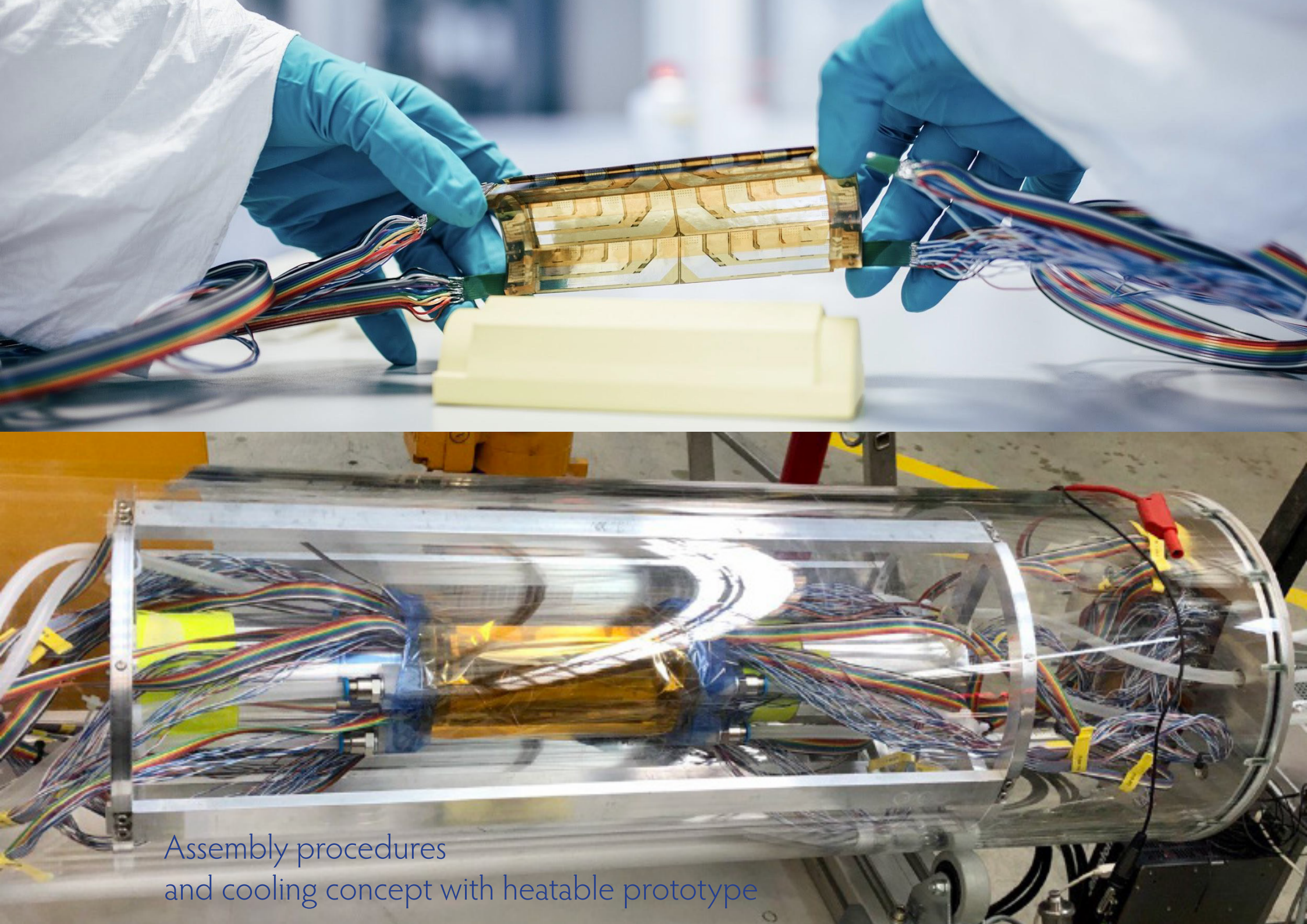
Detector Design



- Full CAD with wires and pipes
- Space is very tight



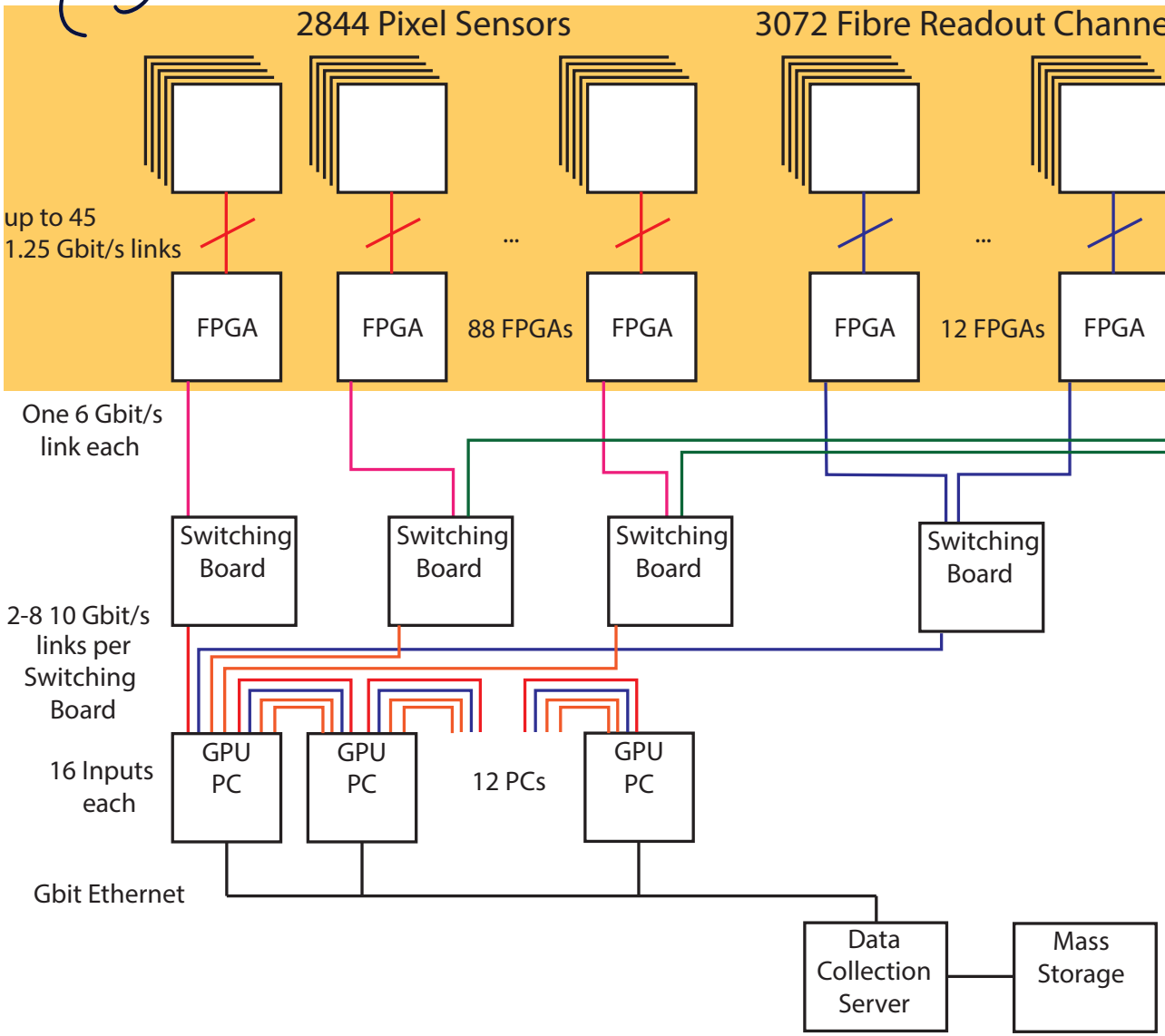
- 3D printed detector mock-up for assembly tests



Assembly procedures and cooling concept with heatable prototype

Data Acquisition

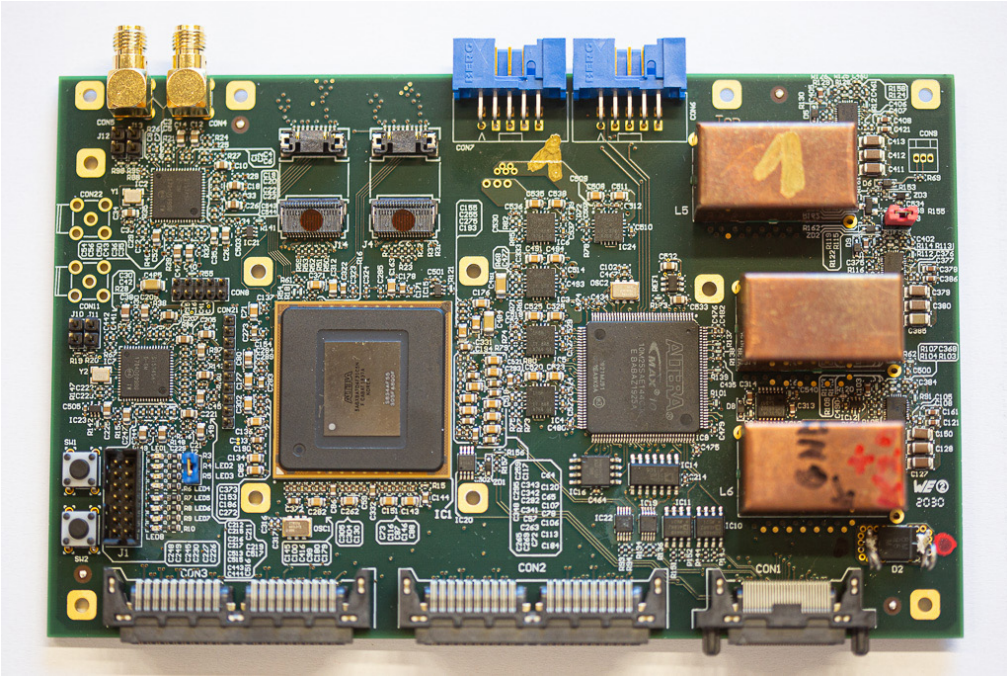
DAQ Design

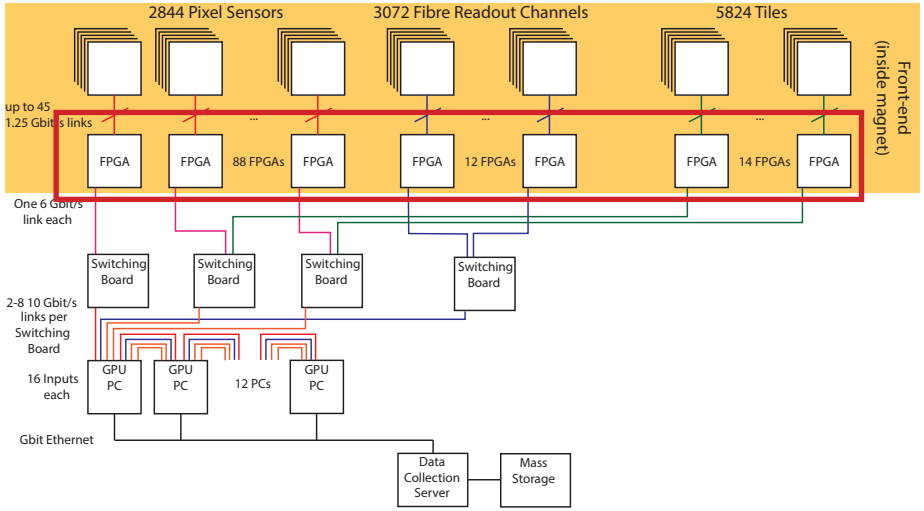


- Fully streaming DAQ
- Network of FPGAs and optical links
- Collect all data of a time slice on one PC
- Reconstruct tracks, then vertices on a GPU
- Write interesting events to disk

Front-end board

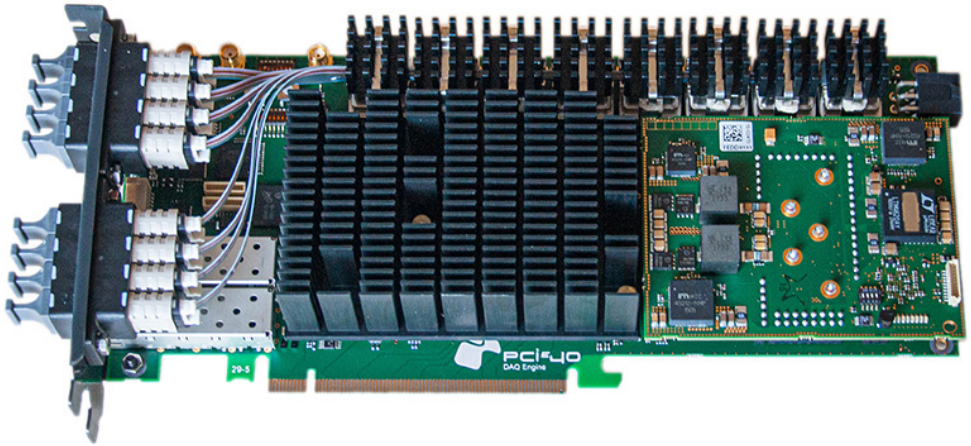
- Operates in magnet and helium atmosphere, space is tight
- Up to 45 1.25 GBit/s LVDS inputs from detector ASICs
- Intel Arria V A7 FPGA for time-sorting and clustering of hits
- Output to a 6 Gbit/s optical link on a Samtec Firefly Transceiver
- Intel MAX10 FPGA for configuration and monitoring
- Air-coil DC/DC converters for powering

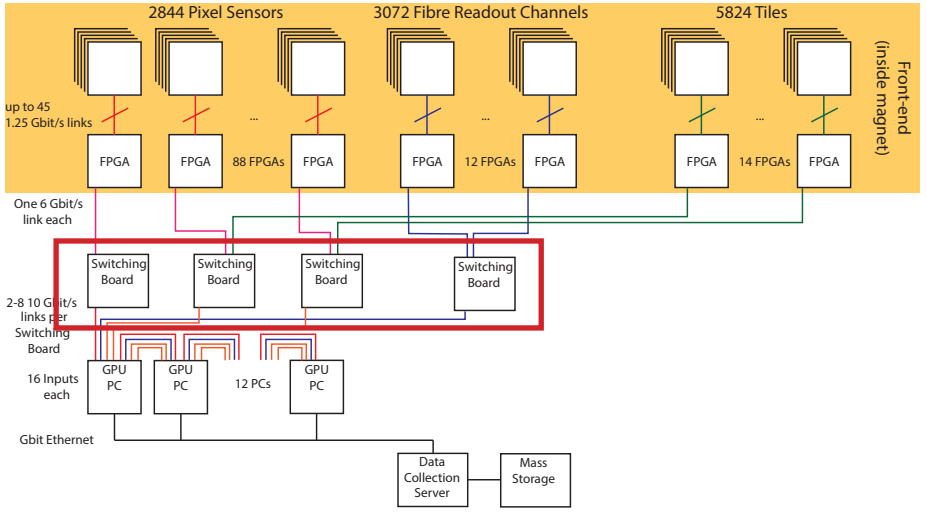




Switching board

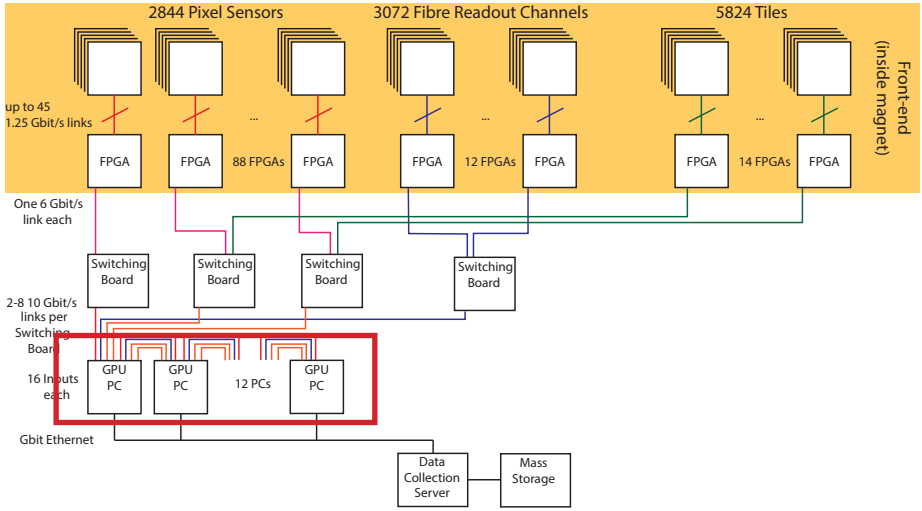
- Operates in a PC case
- Up to 37 front-end board inputs (and control lines)
- Up to eight 10 Gbit/s outputs to filter farm
- Use PCIe40 board developed in Marseilles for LHCb and ALICE upgrades
- Intel Arria 10 - 115 FPGA
- Avago MiniPod Transmitters and Receivers
- Two 8-lane PCIe 3.0 interfaces (used for control and monitoring data)



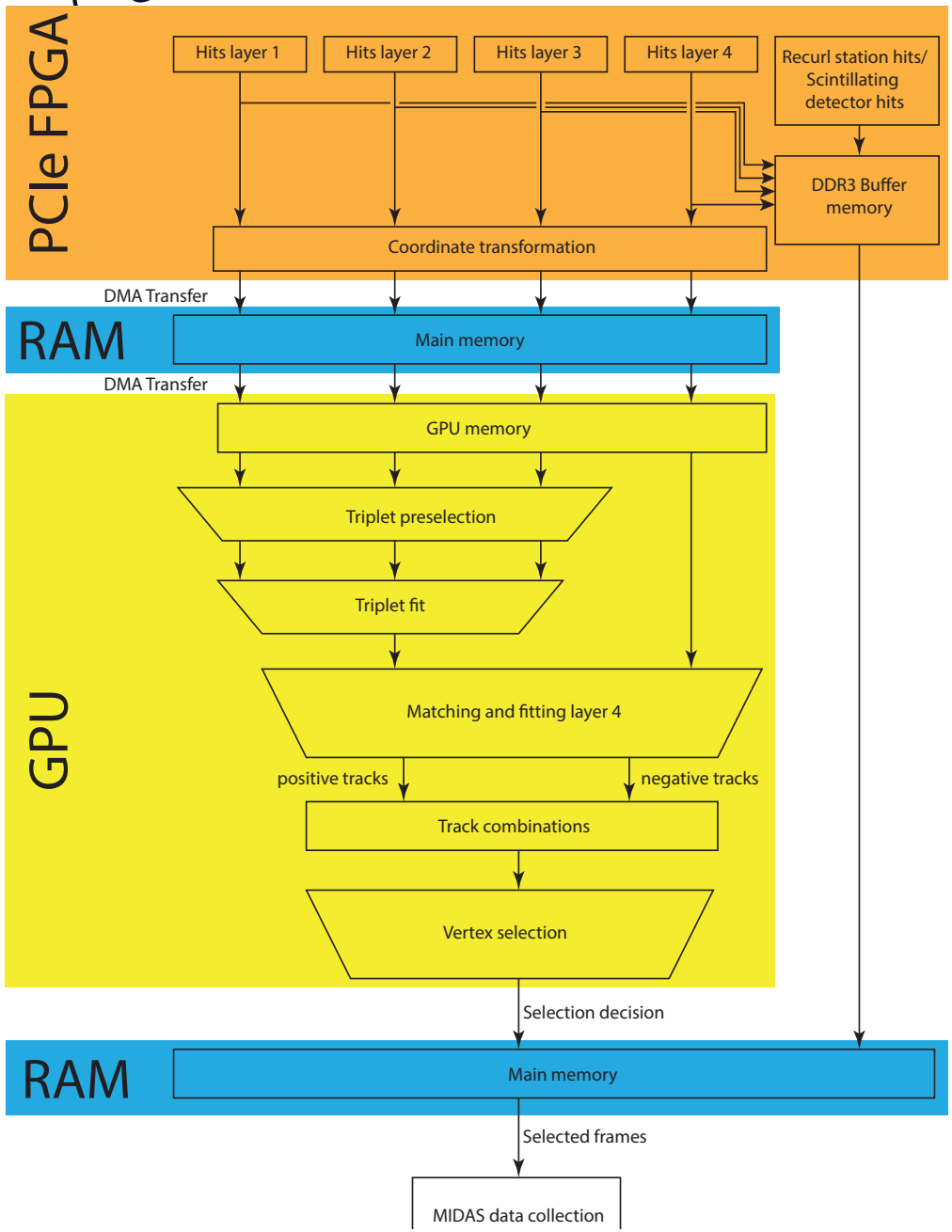


Receiving board

- Operates in a PC case, together with a GPU
- 16 10 Gbit/s inputs and outputs (daisy chain)
- Use commercial DE5A NET board from Terasic Inc.
- Intel Arria 10 - 115 FPGA
- DDR 4 memory for buffering
- QSFP Transmitters and Receivers
- 8-lane PCIe 3.0 interface



Farm data flow



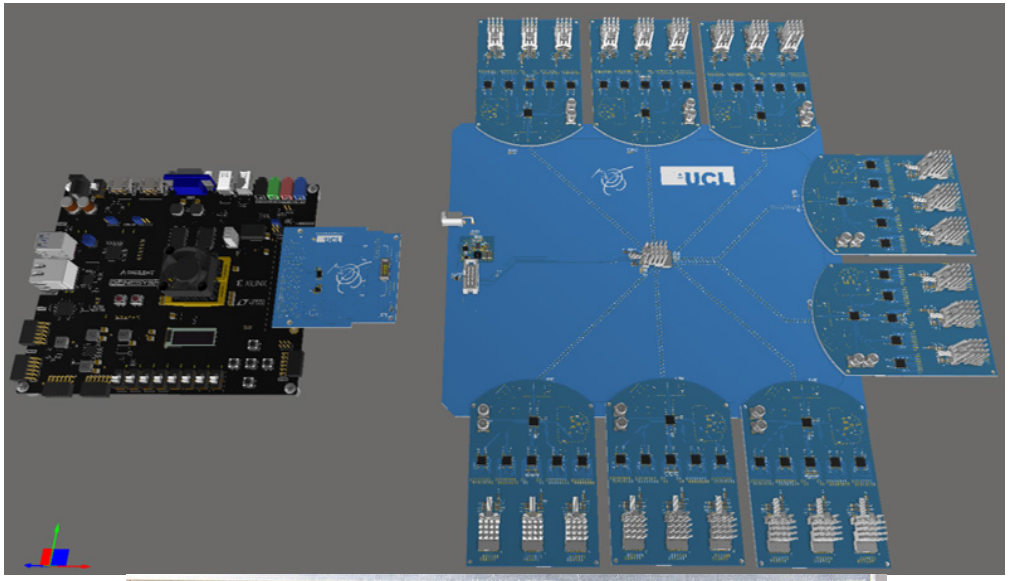
- Buffer all incoming data in DDR memory
- Use subset from central detector for track and vertex finding on a GPU
- If interesting: Get full data from buffer, send to PC
- Up to 38 Gbit/s PCIe DMA transfers using custom firmware and driver
- After full reconstruction: Send off to mass storage
- Use the MIDAS software for data collection, detector control and monitoring etc.

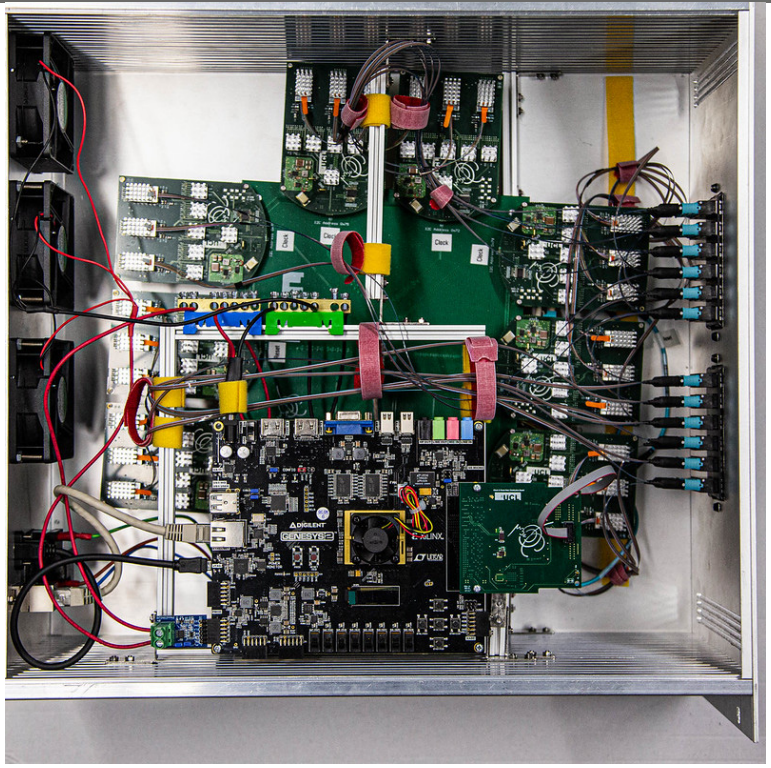
GPU reconstruction

- GPU reconstruction on gaming cards
- Have achieved > 10^9 track fits/s per GPUs (Nvidia GTX 980)
- Twelve GTX 1080Ti are sufficient for dealing with 10^8 muon decays/s
- Excited about the possibilities with the latest cards...

System synchronization

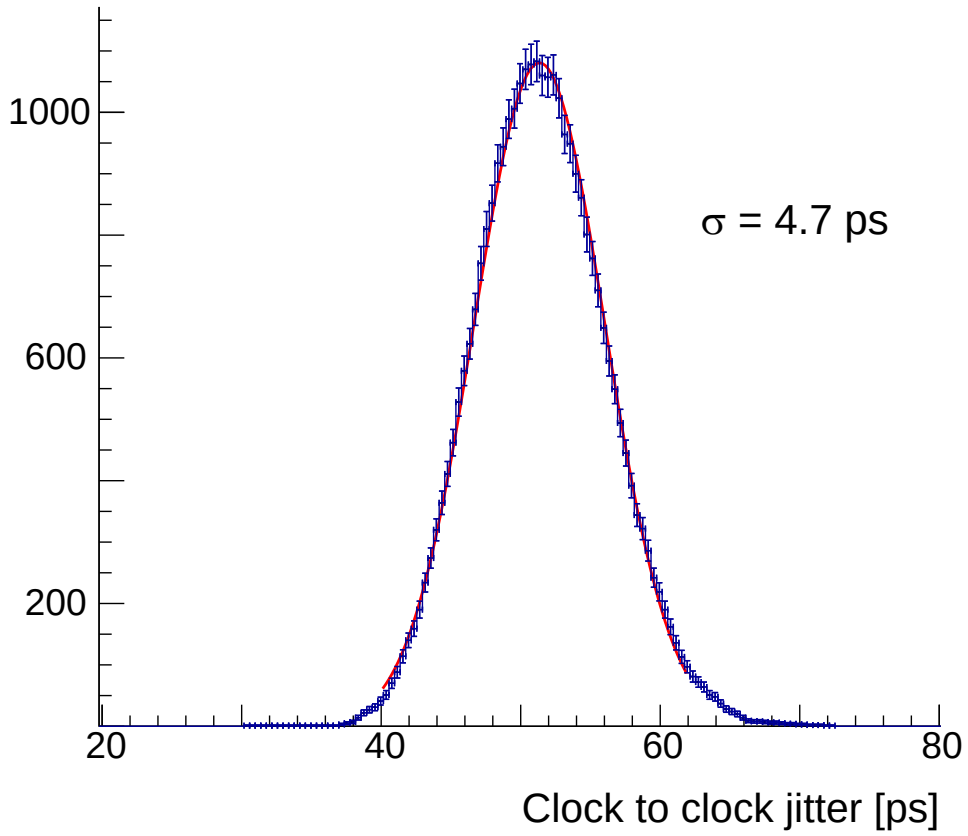
- Produce 144 copies of the 125 MHz system clock
- Produce 144 copies of the 1.25 Gbit/s, 8bit/10bit encoded reset and state transition signal
- Digilent Genesys FPGA board
- Samtec Firefly optical transmitters





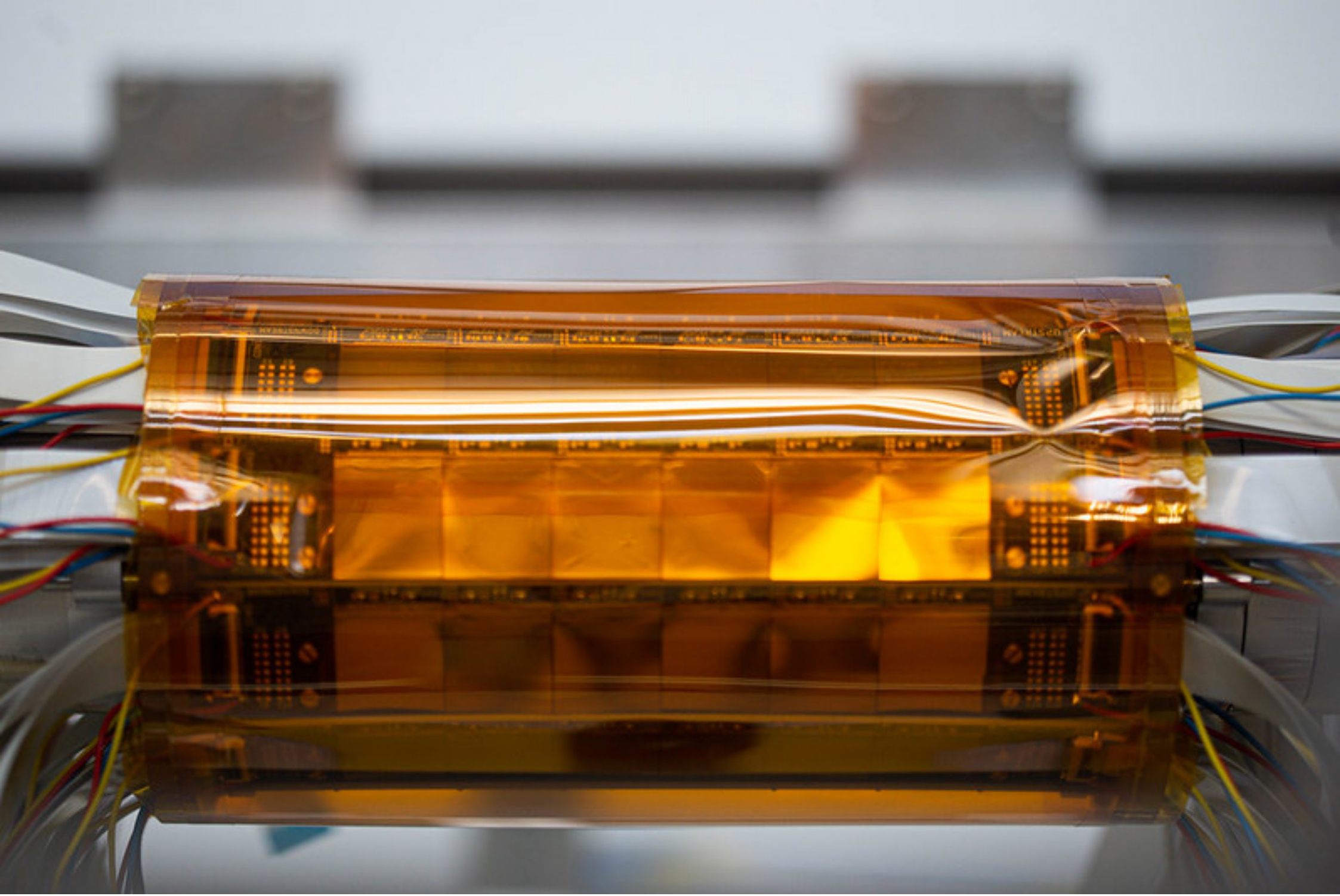
System synchronization

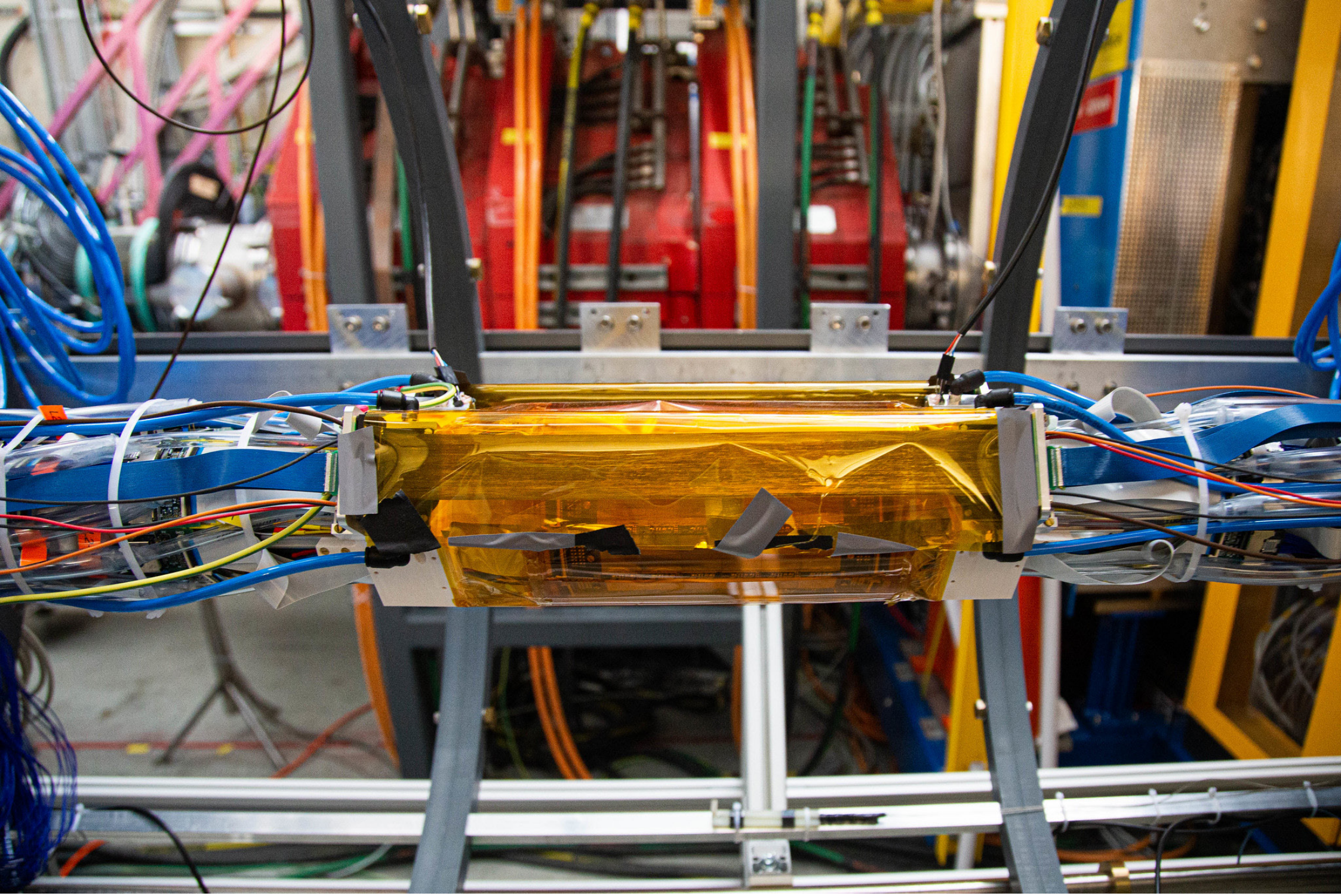
- Produce 144 copies of the 125 MHz system clock
- Produce 144 copies of the 1.25 Gbit/s, 8bit/10bit encoded reset and state transition signal
- Digilent Genesys FPGA board
- Samtec Firefly optical transmitters
- Less than 10 ps clock-to-clock jitter

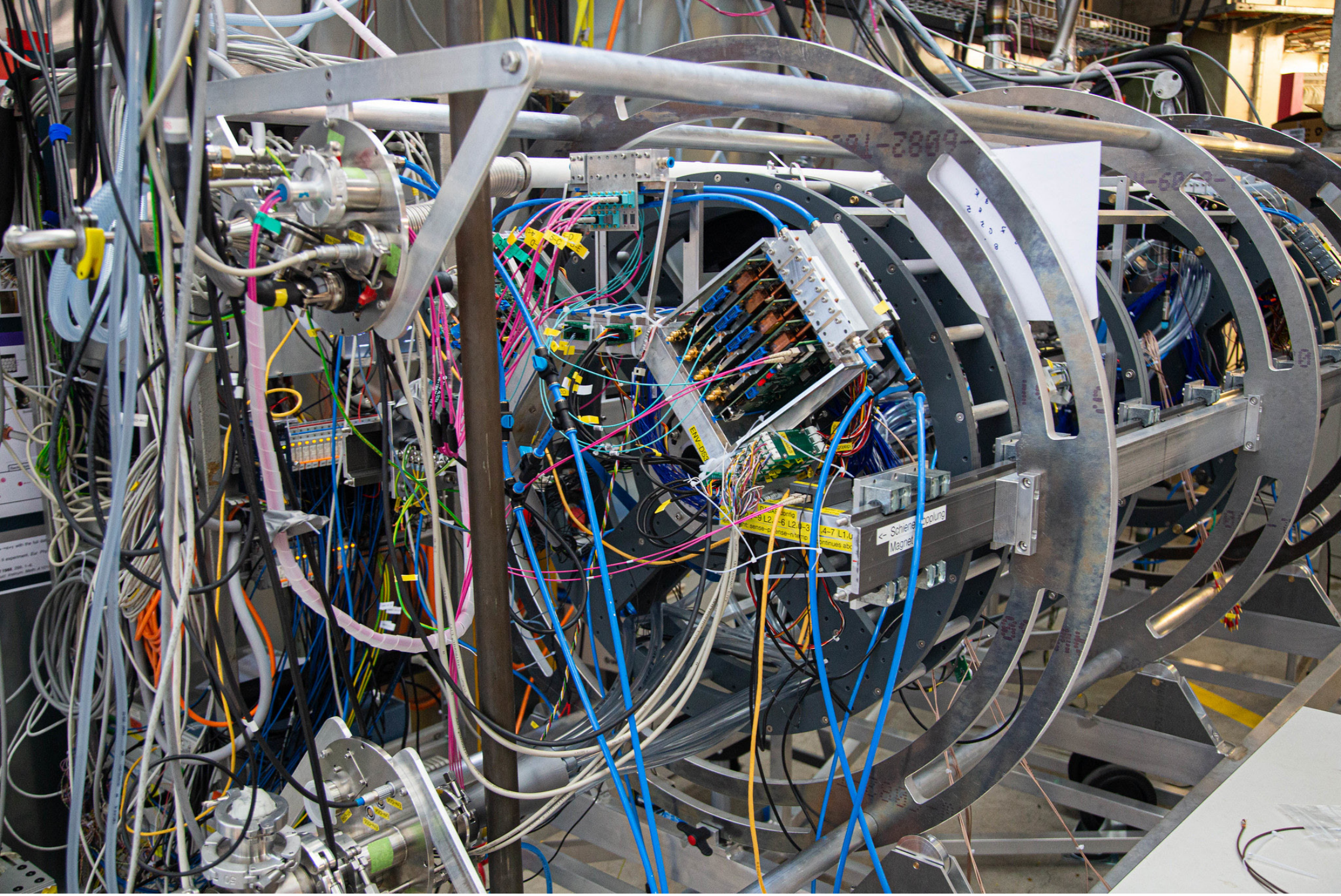


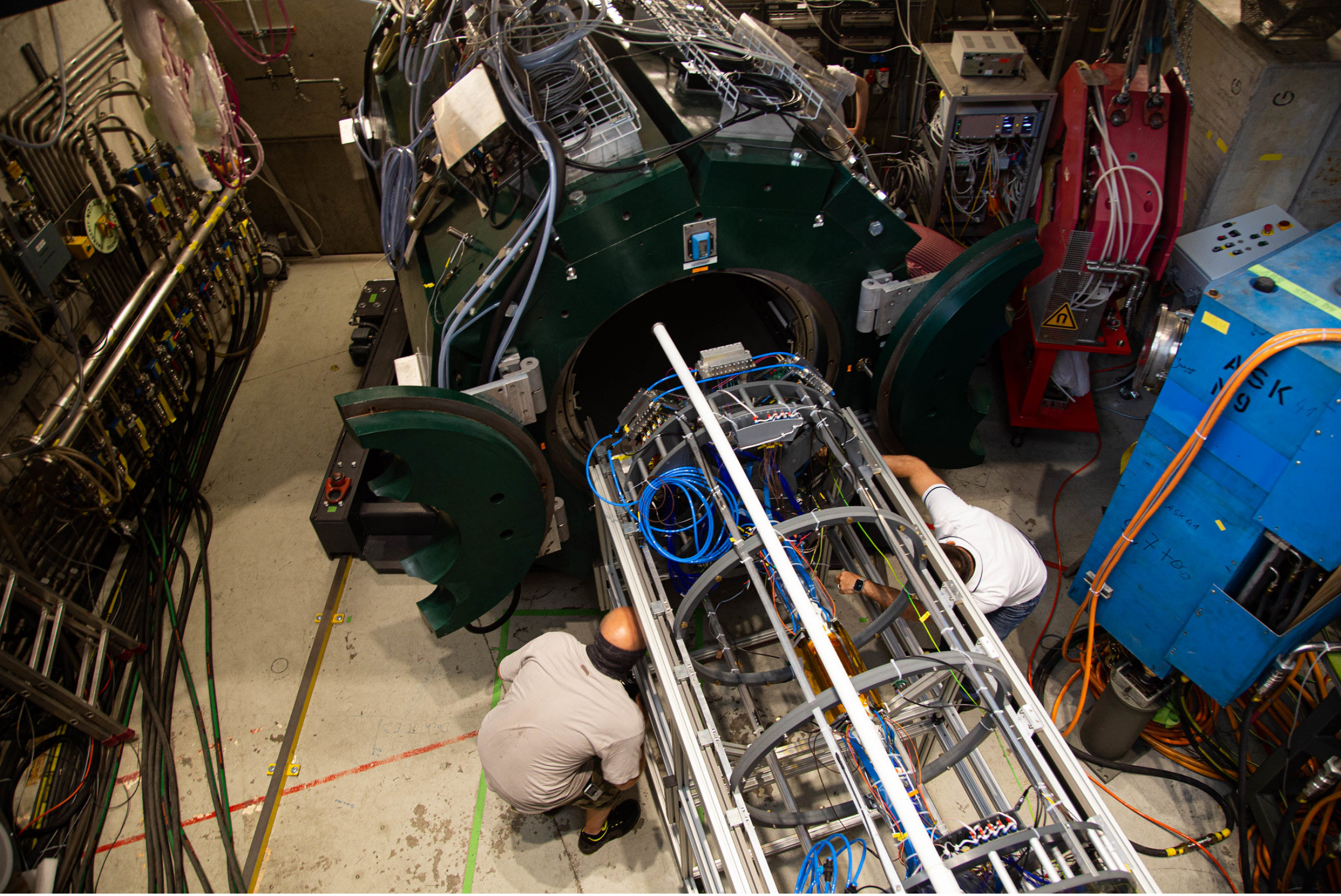
Status and Plans

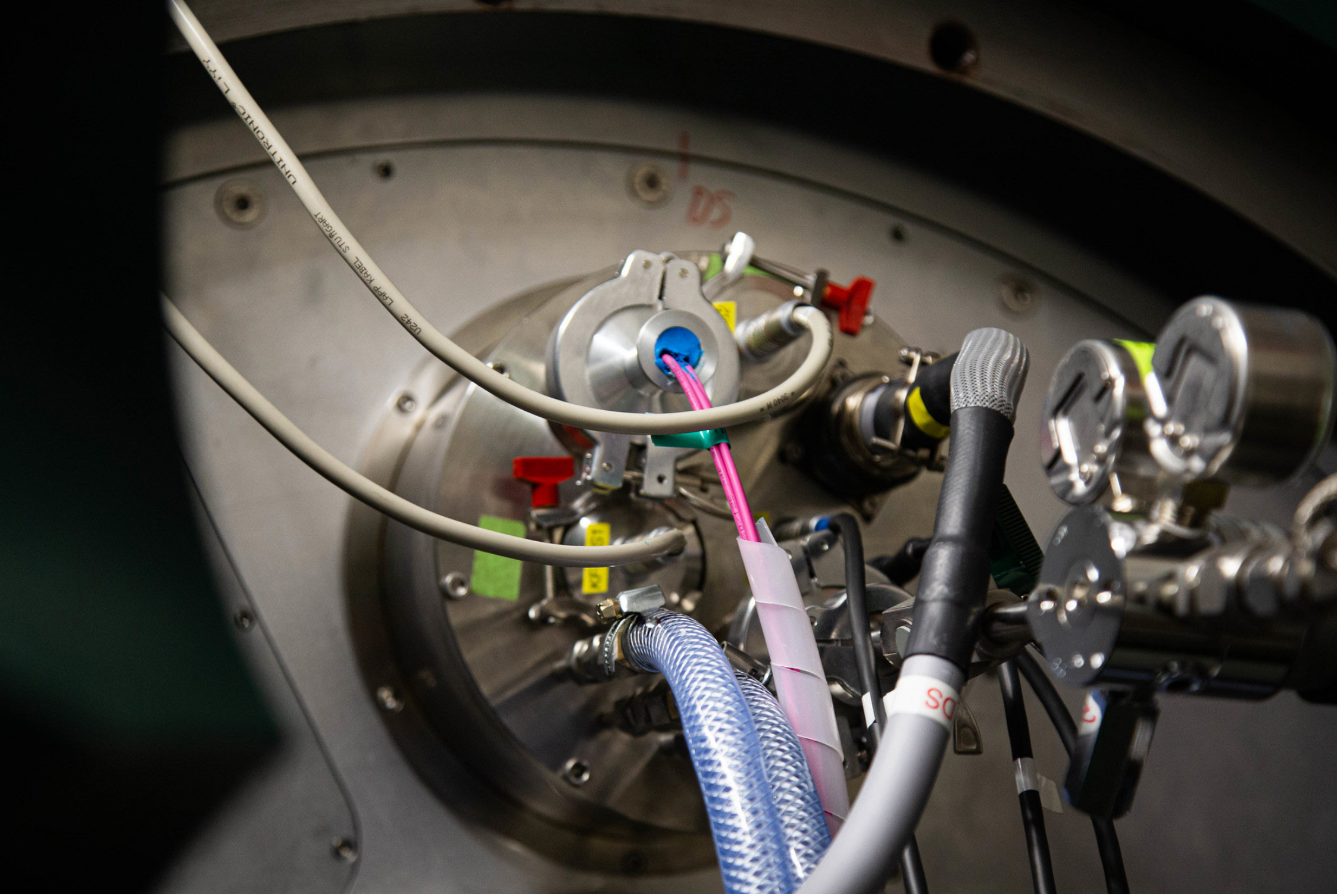

CRYOGENIC



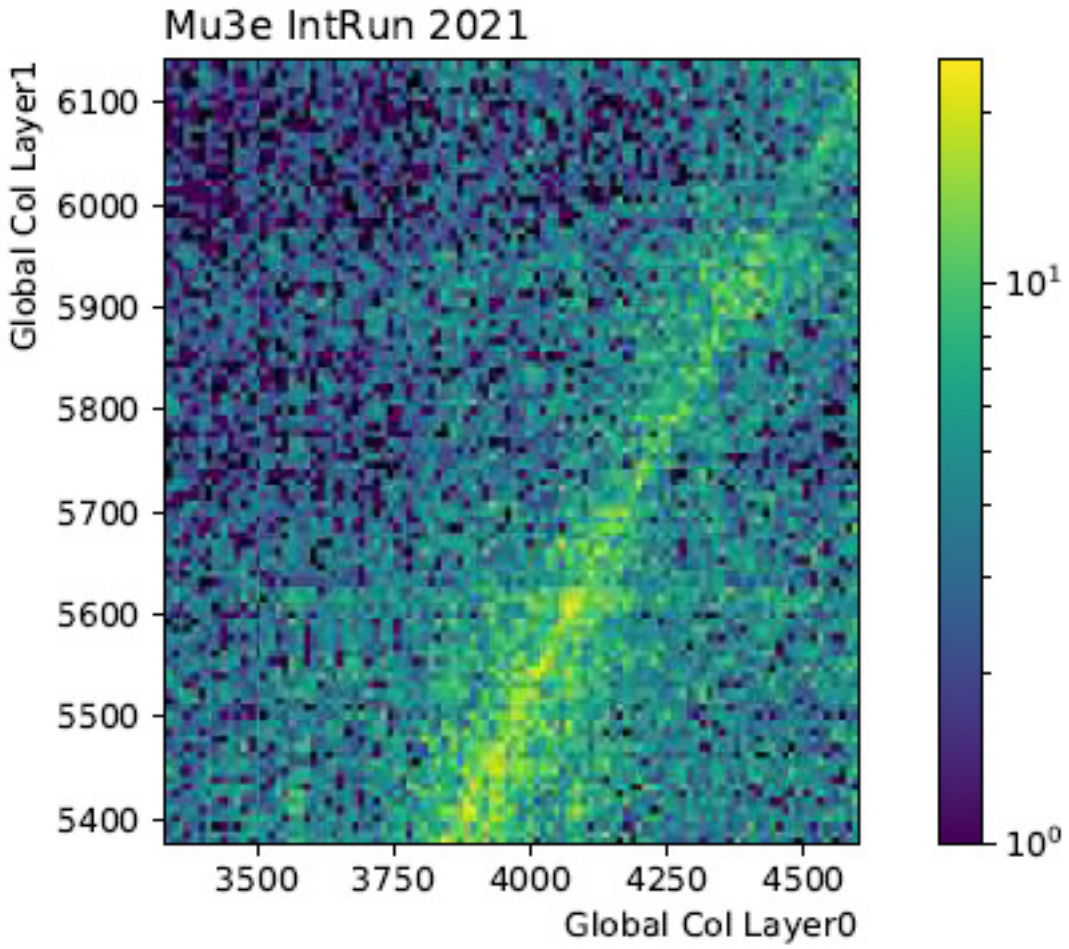



Magnet




LAPP KABEL STUTTGART
SQ

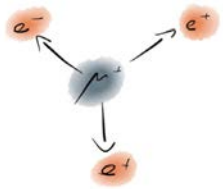
Run results

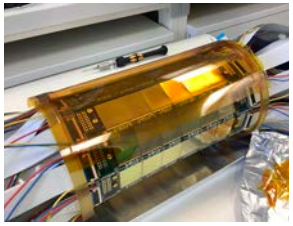


- Detectors work in magnet and helium, with beam
- Helium cooling works
- We can read data
- We see correlations between sensors

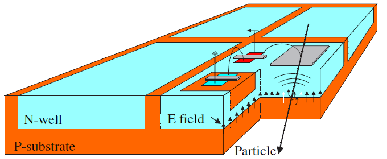
- Second run (cosmics only) just starting
- Might have first tracks next week

Conclusion

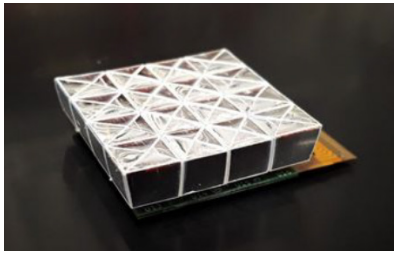




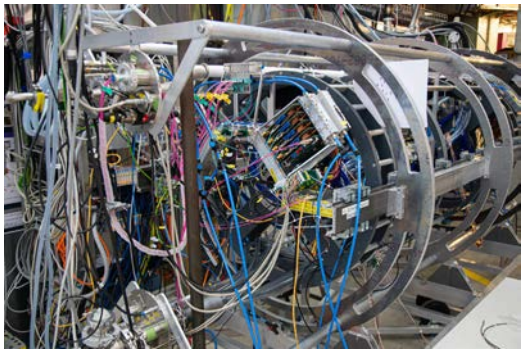
- Mu3e aims for μ → eee at the 10^{-16} level
- First large scale use of HV-MAPS



- Build detector layers thinner than a hair



- Timing at the 100 ps level
- Reconstruct >10^8 tracks/s in ~100 Gbit/s on ~12 GPUs
- Integration and commissioning ongoing



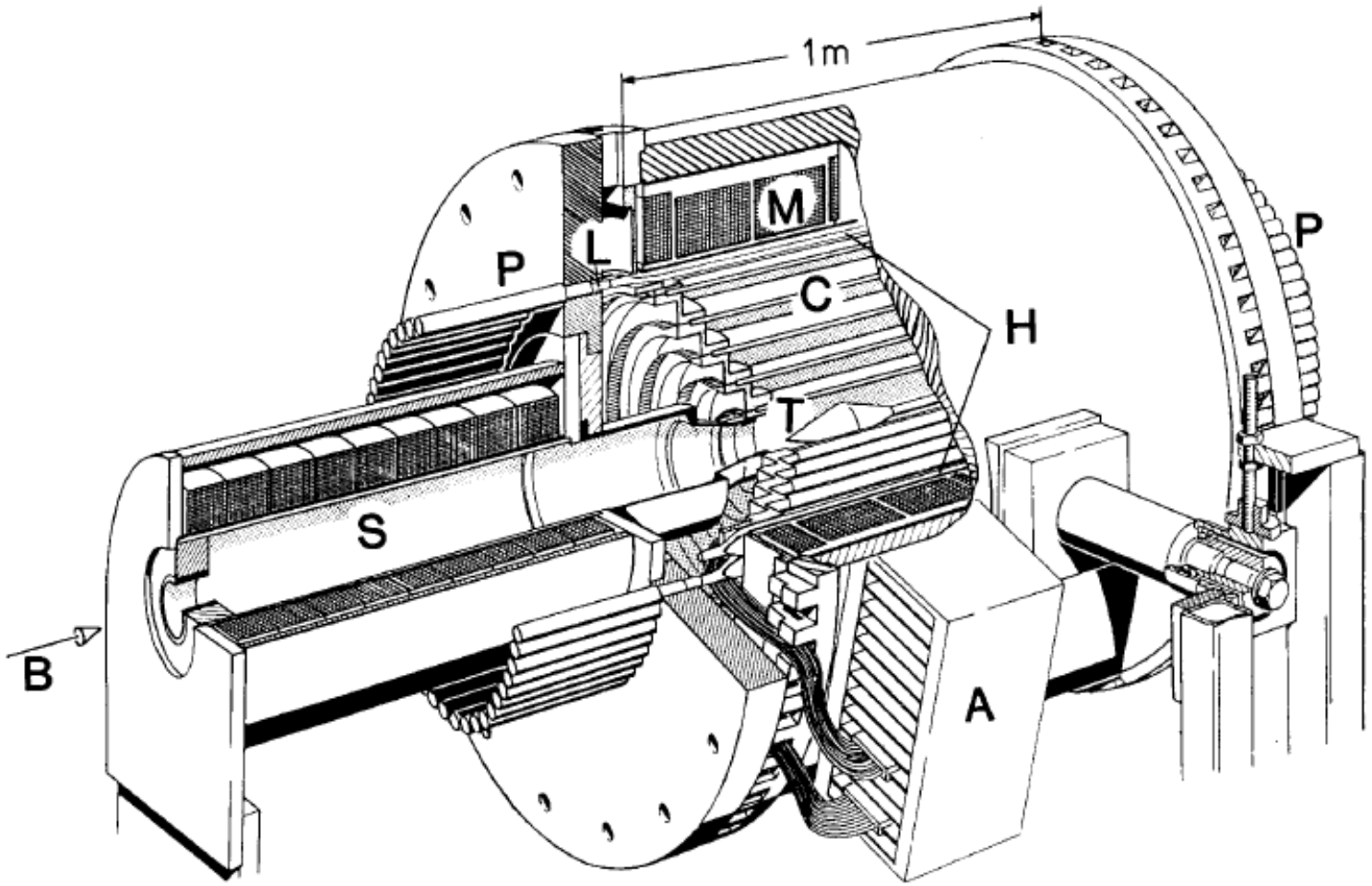
- First data taking 2024

Backup

Searching for $\mu^+ \rightarrow e^+e^-e^+$ in the past:

SINDRUM

SINDRUM



B: Muon Beam

S: Focusing Solenoid

T: Target

C: Five cylindircal multiwire proportional chambers

H: Scintillator hodoscope

L: Light-guides

P: Photomultipliers

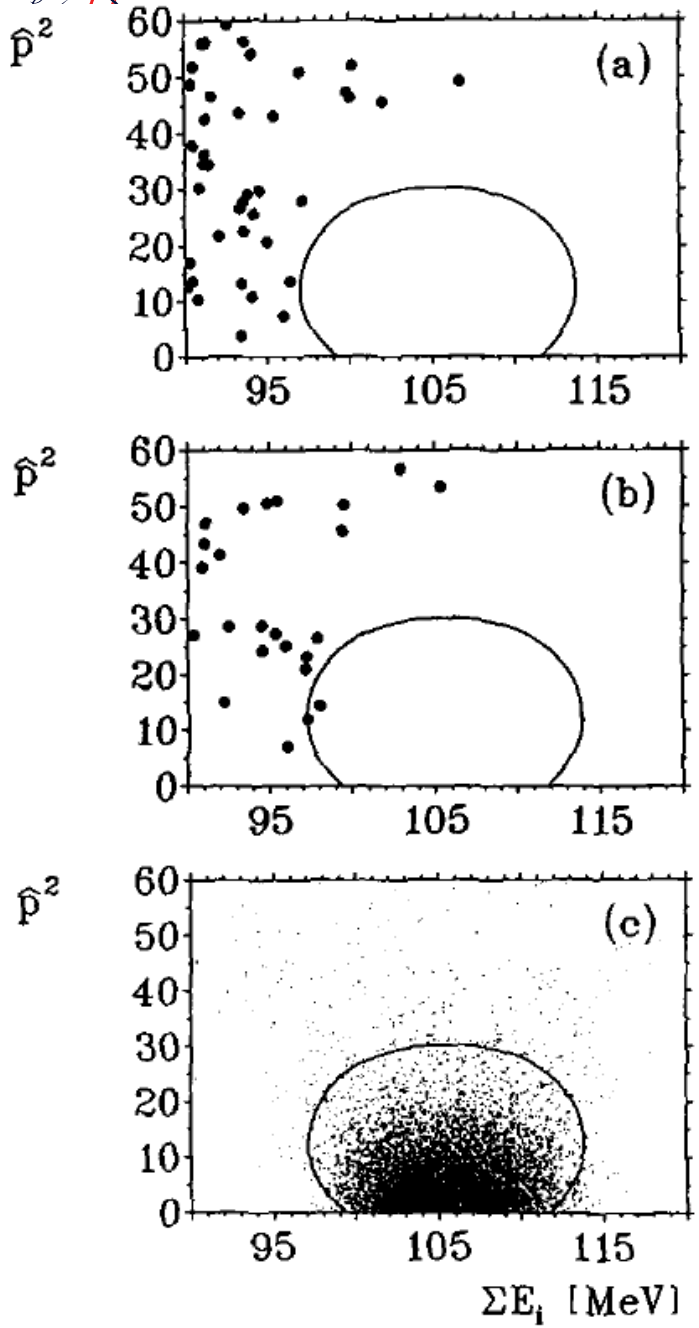
A: Preamplifiers

M: Magnet coil (normal conducting, 0.6 T)

Data taking 1983 - 1986
Up to 5×10^6 μ stops/s

Nuclear Physics B260 (1985) 1–31

SINDRUM



Nuclear Physics B299 (1988) 1–6

Results:
(Resolution weighted momentum of the CMS system vs. sum of the three electron energies)

(a) Coincident events - 60% accidentals,
40% internal conversion
(b) Accidentals

(c) Signal MC with 95% contour

No events in signal area seen:

$$B(\mu^+ \rightarrow e^+e^-e^+) < 1.0 \cdot 10^{-12}$$

Probably some more potential in the apparatus, ultimately limited by rate capability and momentum resolution