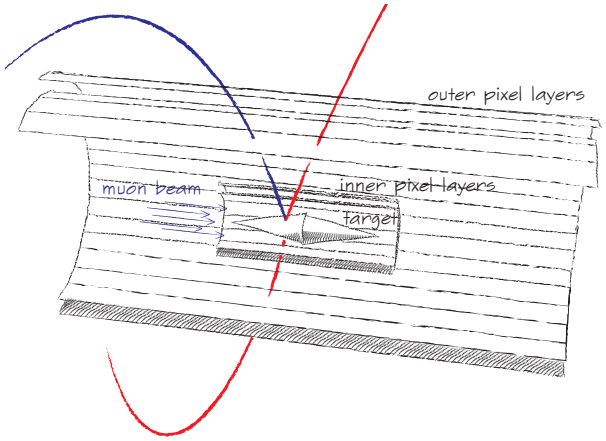
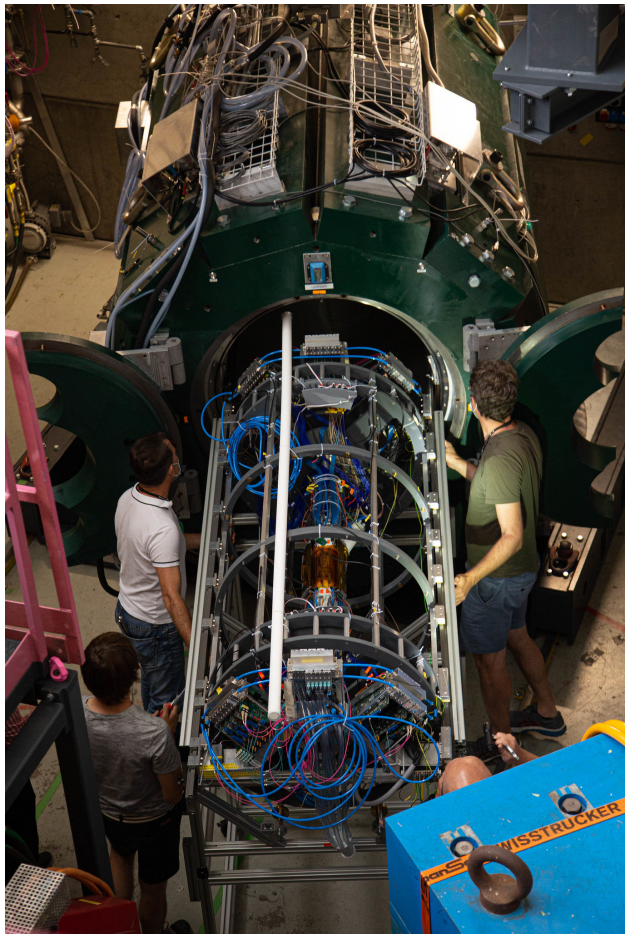
Mu3e
from idea to Experiment



Niklaus Berger

Institut für Kernphysik,
Johannes Gutenberg Universität
Mainz
MPIP München
June 2024



JG|U

DFG Deutsche Forschungsgemeinschaft

Particle Physics 2024:

- All particles in the Standard Model discovered
- Very few lab measurements in tension with SM
- SM known to be incomplete: Dark matter, baryon asymmetry, gravity, hierarchy,...

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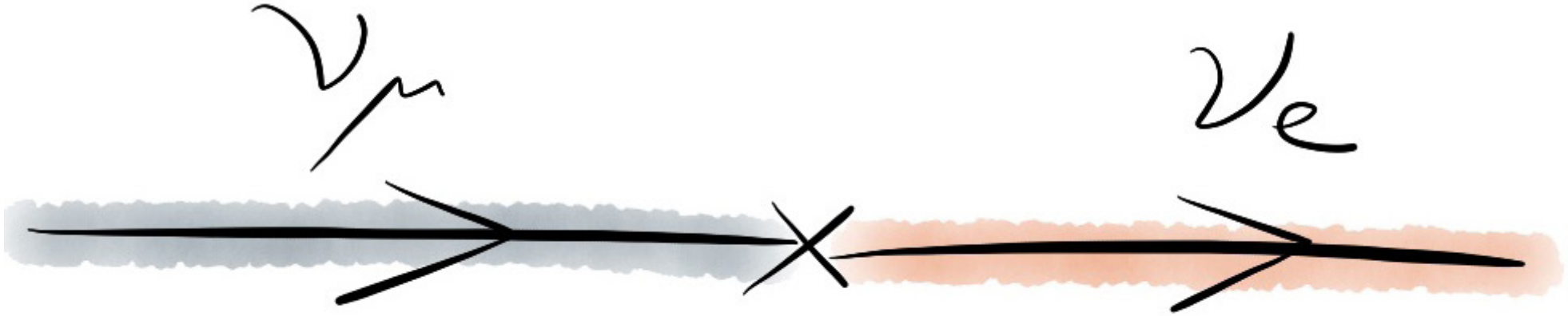
Particle Physics 2024:

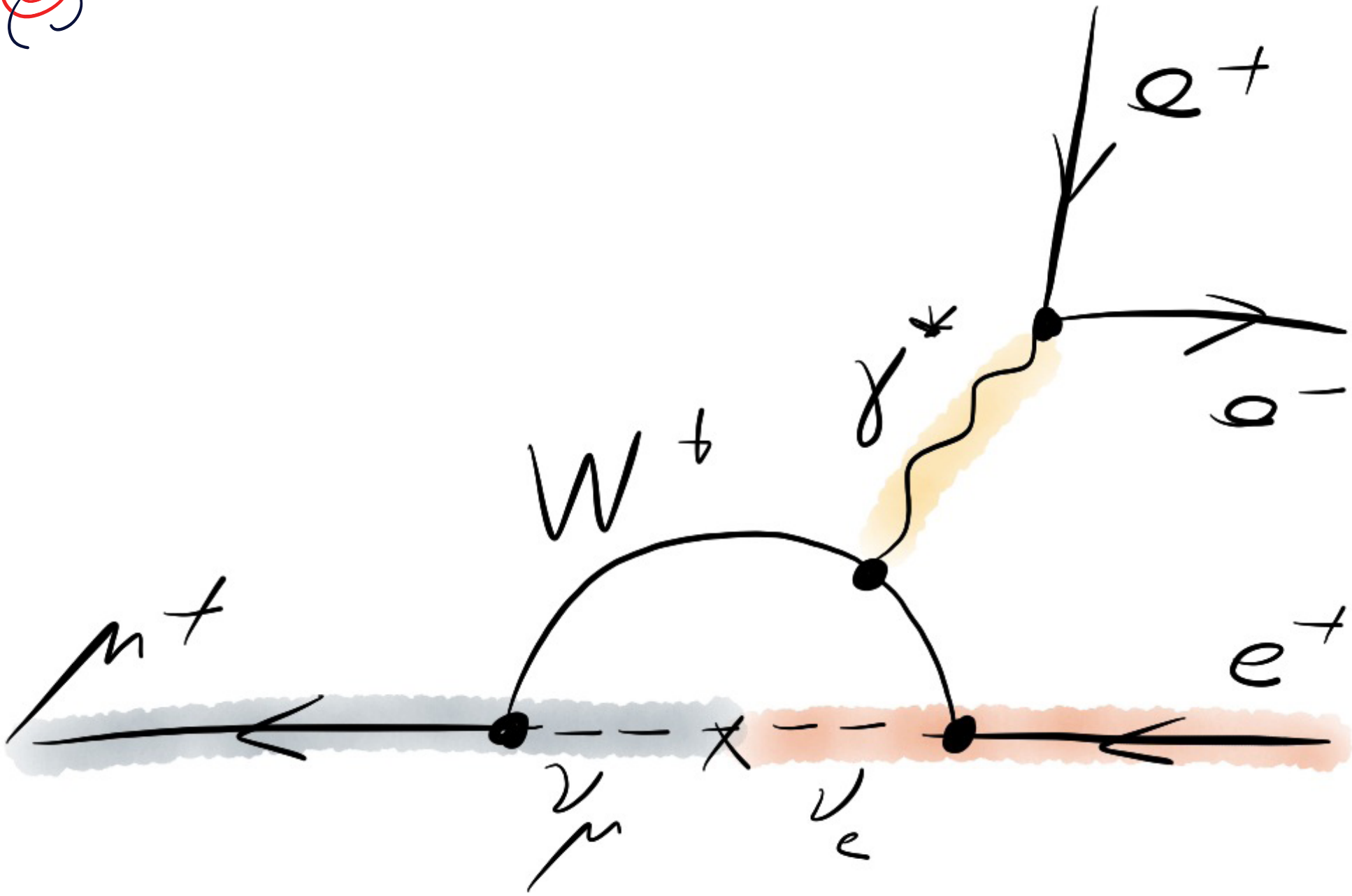
- All particles in the Standard Model discovered
- Very few lab measurements in tension with SM
- SM known to be incomplete: Dark matter, baryon asymmetry, gravity, hierarchy,...

- Where to look for new physics?
- Where do we see physics beyond the standard model already?

Lepton Flavour Violation!



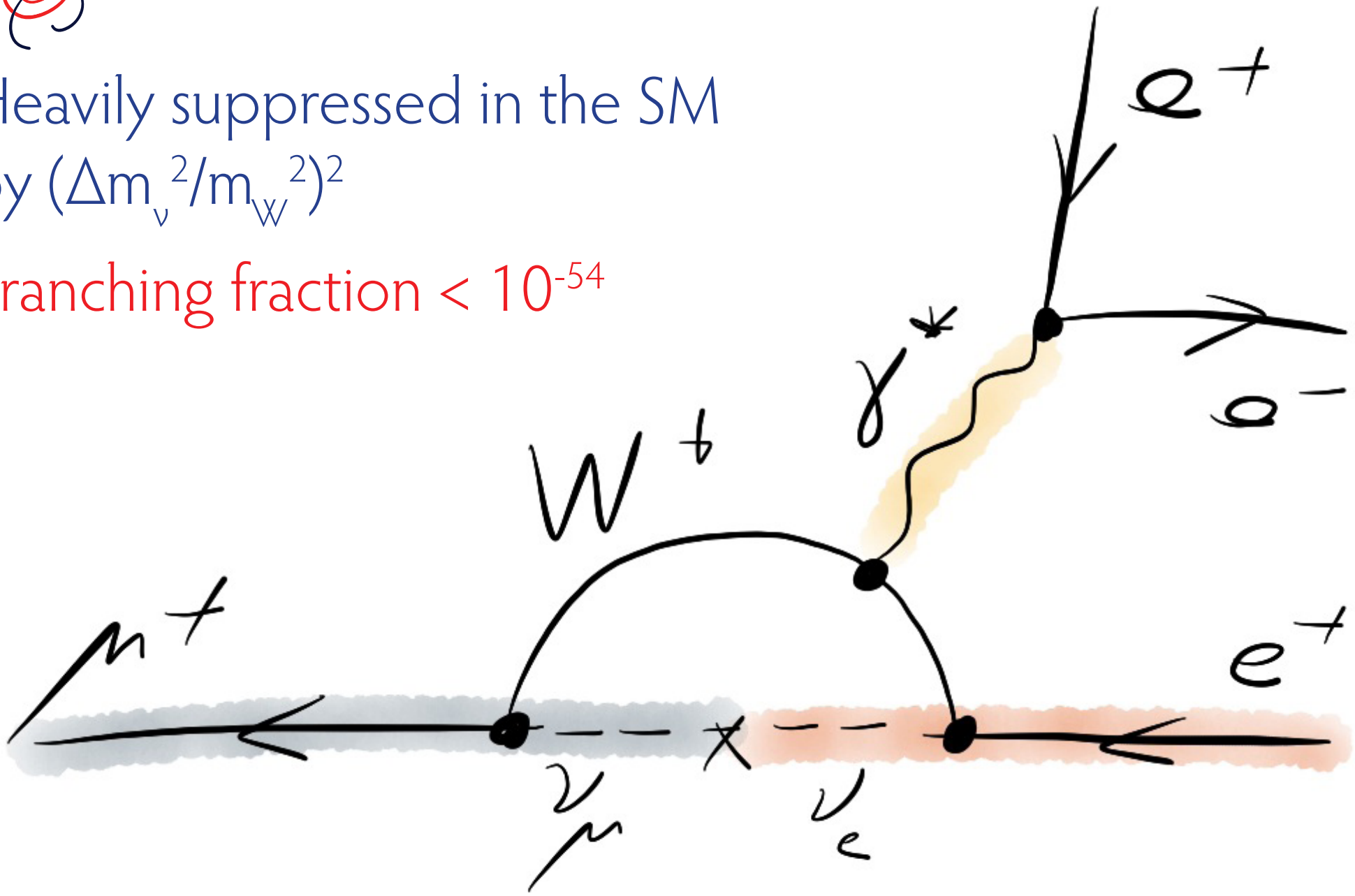
Charged Lepton Flavour Violation?



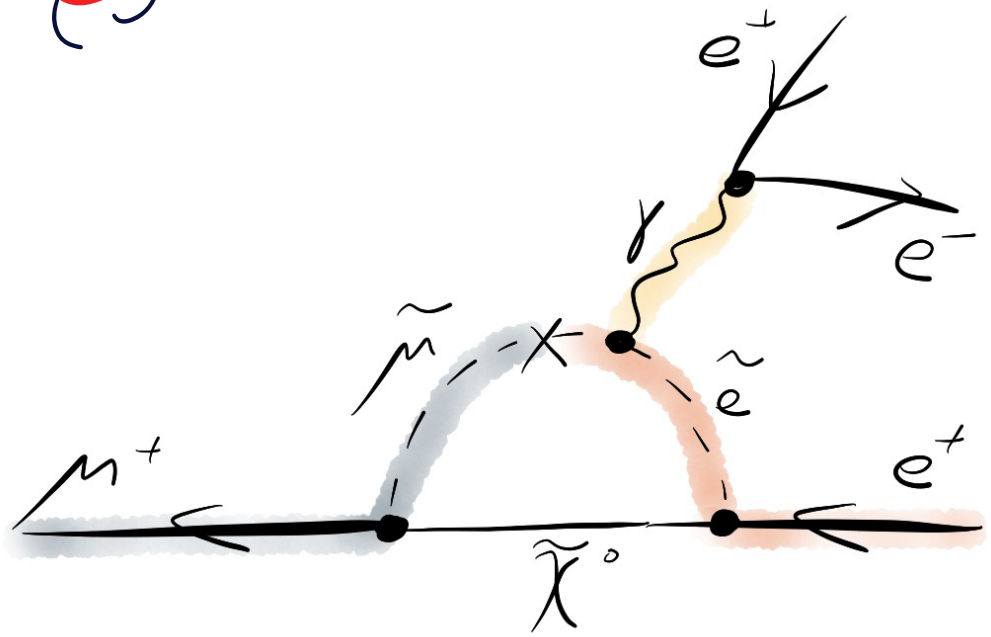
Charged Lepton Flavour Violation?

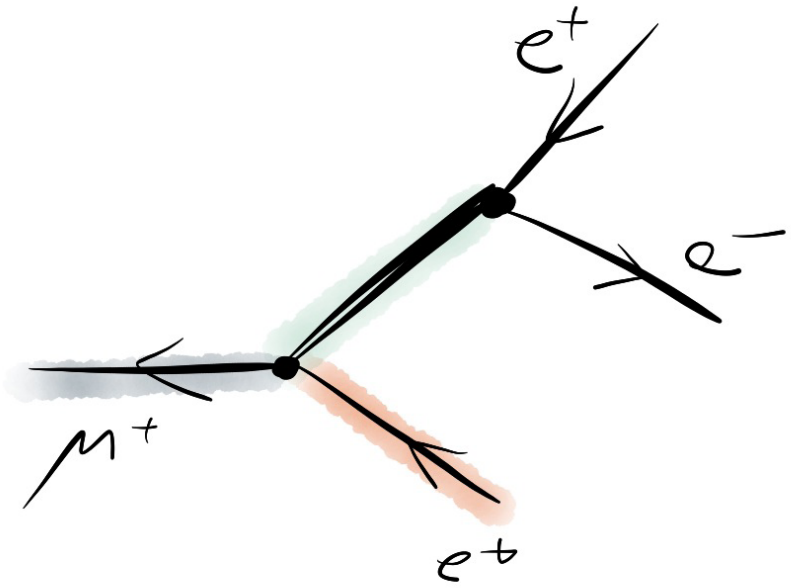
Heavily suppressed in the SM
by $(\Delta m_\nu^2/m_W^2)^2$

Branching fraction < 10^{-54}



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





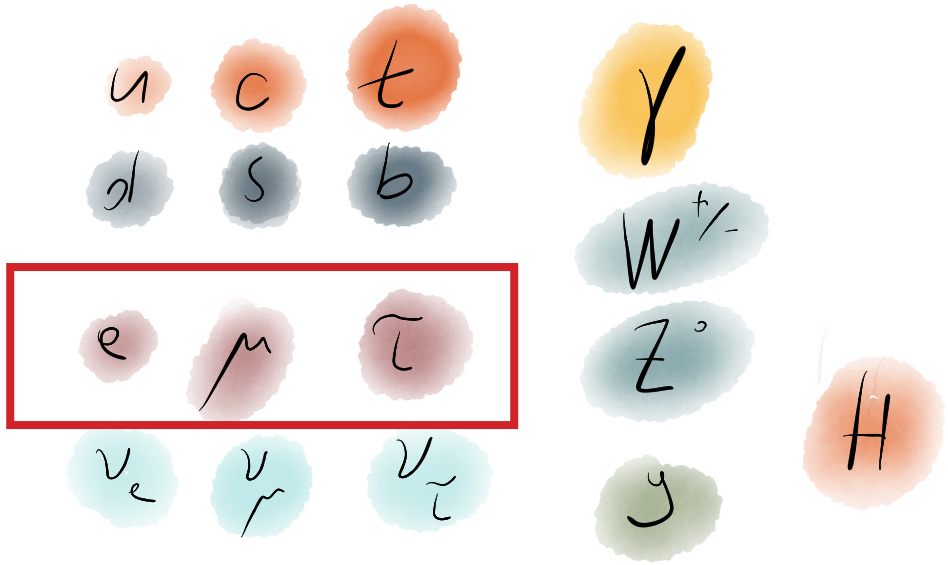
Loop diagrams

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

Tree diagrams

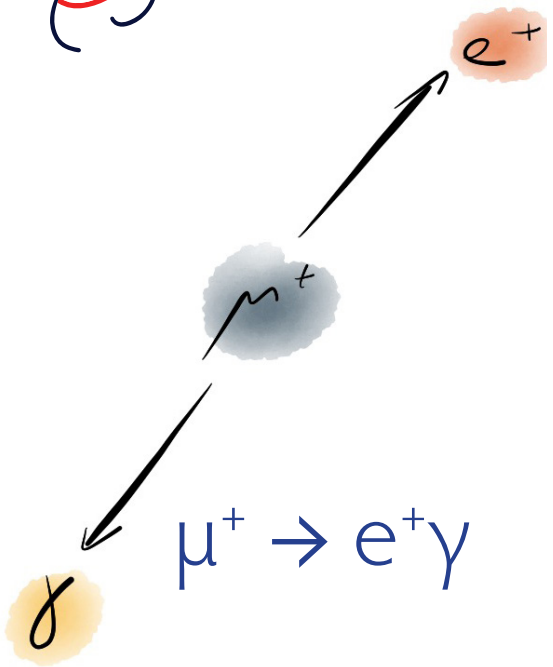
- Higgs triplet model
- Extra heavy vector bosons (Z')
- Extra dimensions (Kaluza-Klein tower)
- ...

Menu of charged Leptons

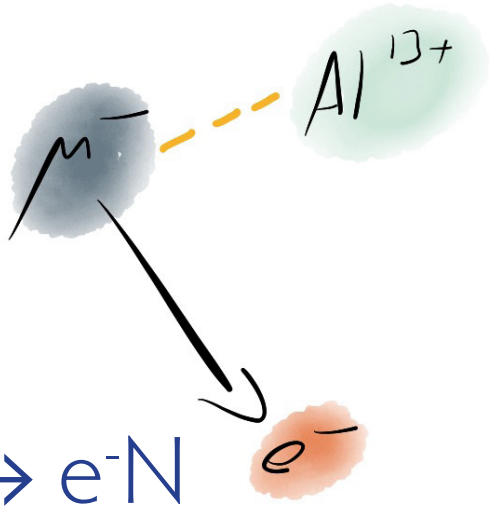


- Electrons are stable...
- New physics sensitivity (heavy new physics, very generic) scales with m_l^2
  τ's are most sensitive
- But: Can produce about as many muons per second as taus in a year
- Muons lead the search for charged Lepton Flavour Violation

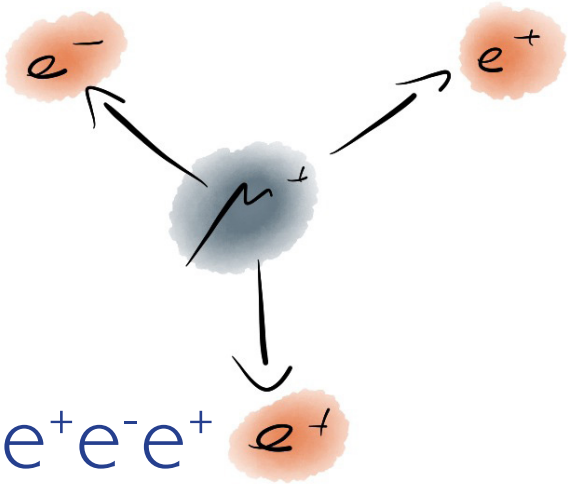
LFV Muon Decays: Experimental Situation



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



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



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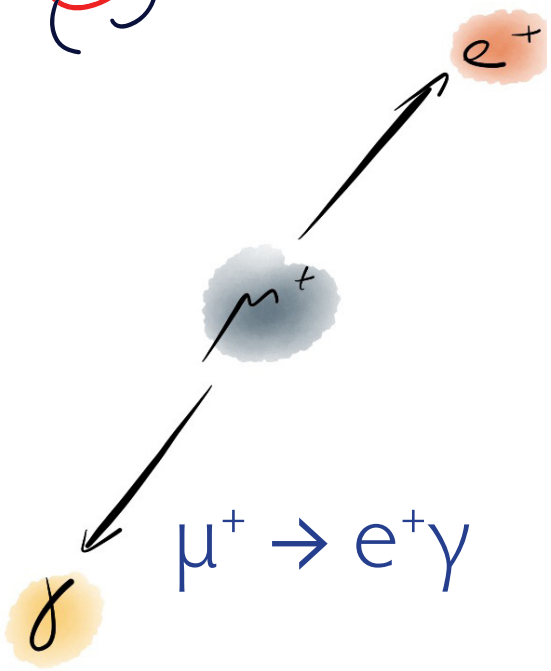

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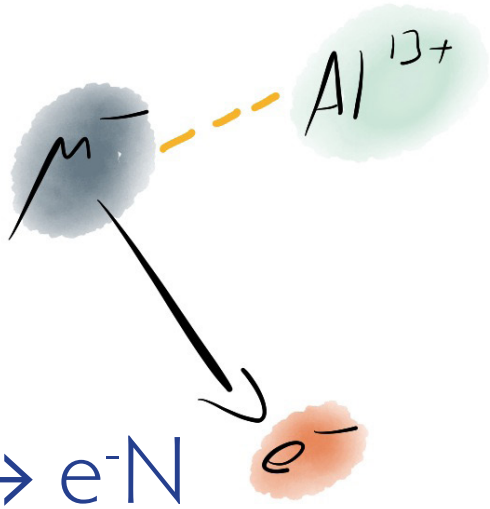

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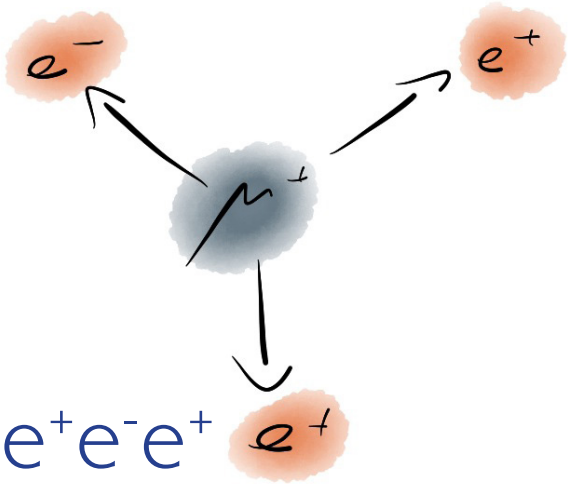

$\mu^+ \rightarrow e^+e^-e^+$

MEG/MEG II (PSI)

$B(\mu^+ \rightarrow e^+\gamma) < 3.1 \cdot 10^{-13}$

(2024)

SINDRUM II (PSI)

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

(2006)

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

(1988)

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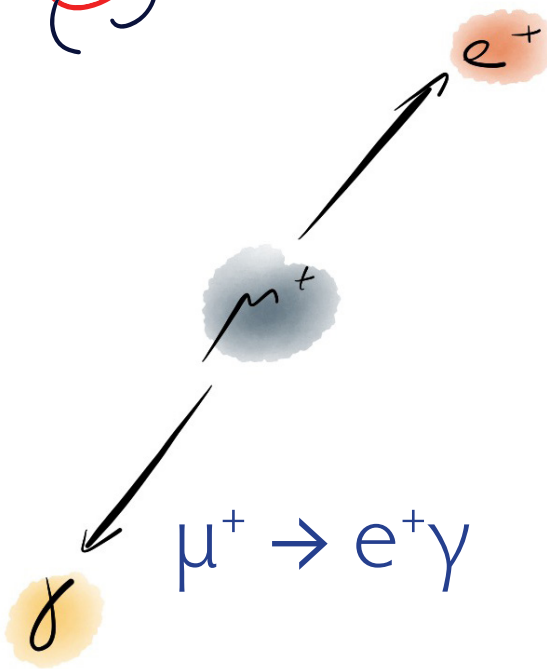

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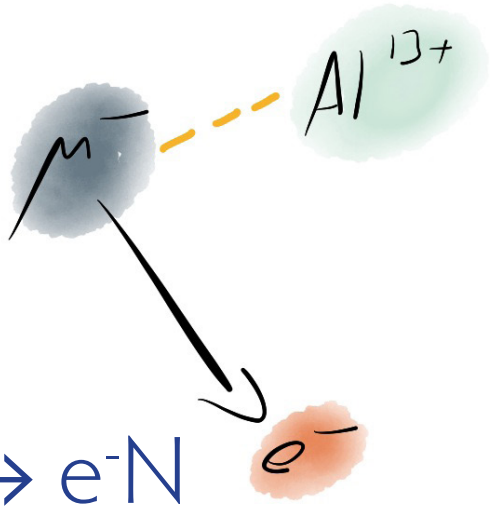

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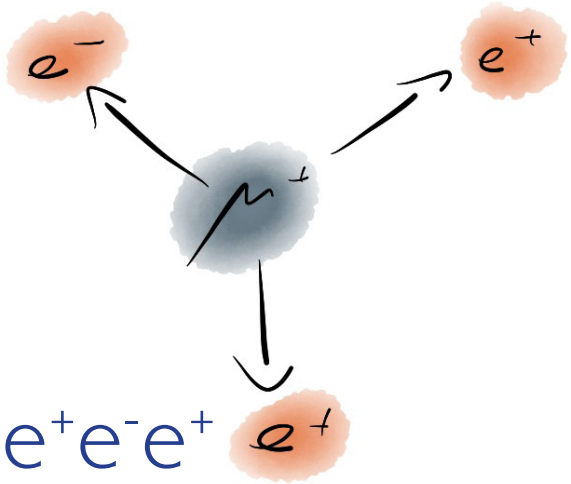

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Mu2e/Comet

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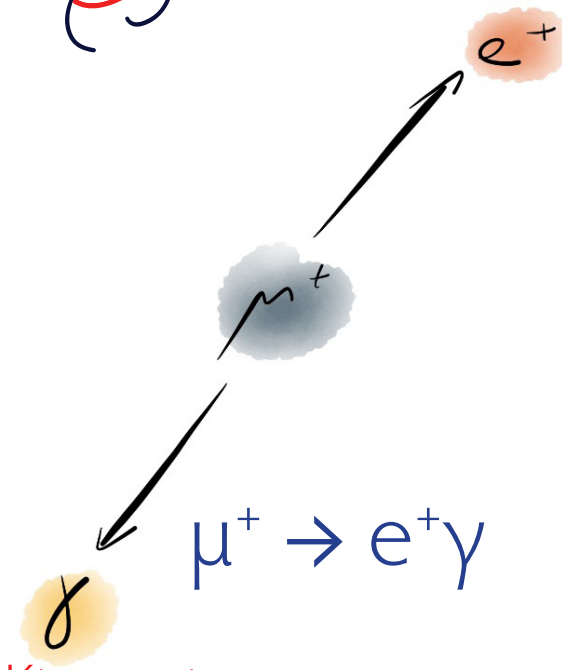
Mu3e

LFV Muon Decays: Experimental signatures



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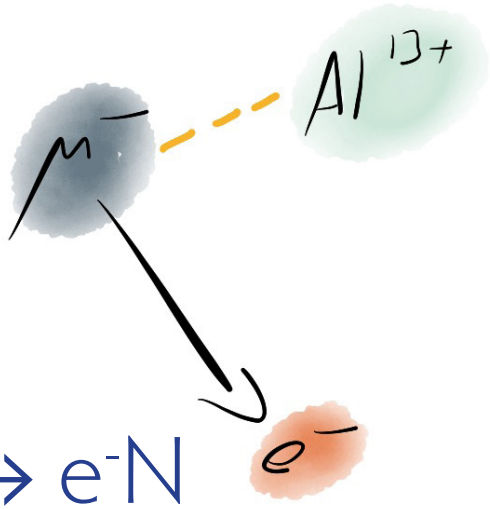

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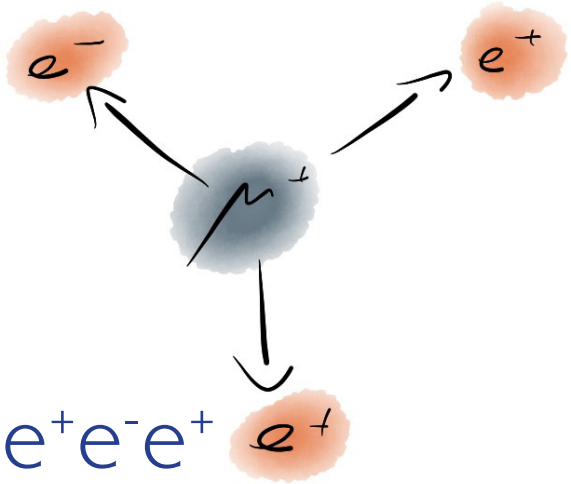


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

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

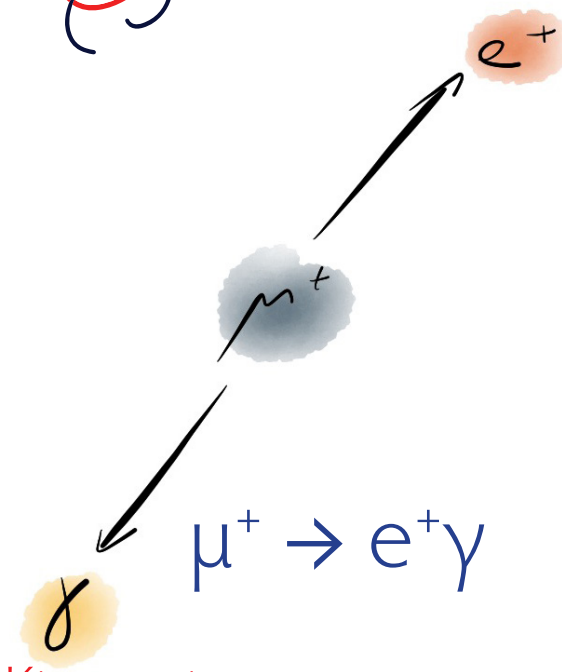
Kinematics

- 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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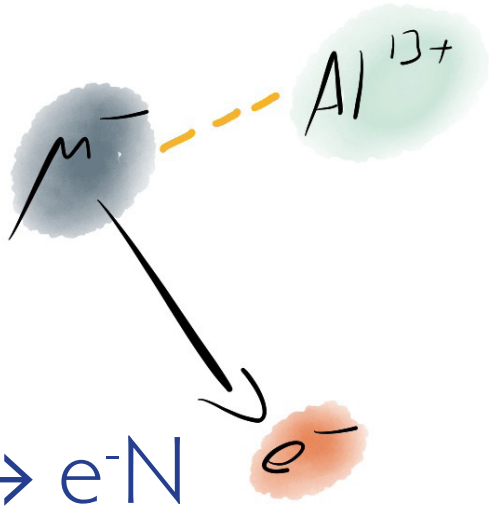

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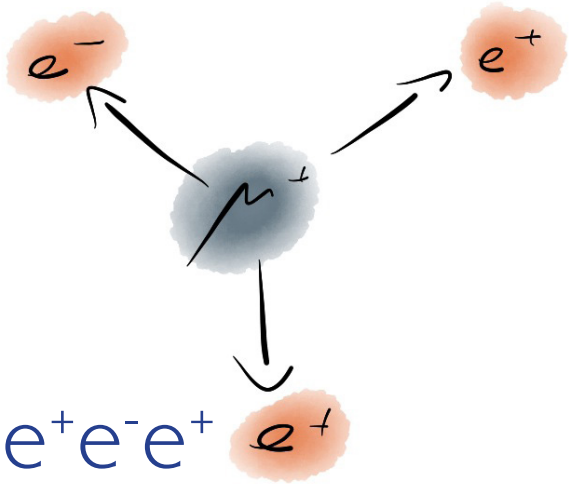


$\mu^+ \rightarrow e^+e^-e^+$

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

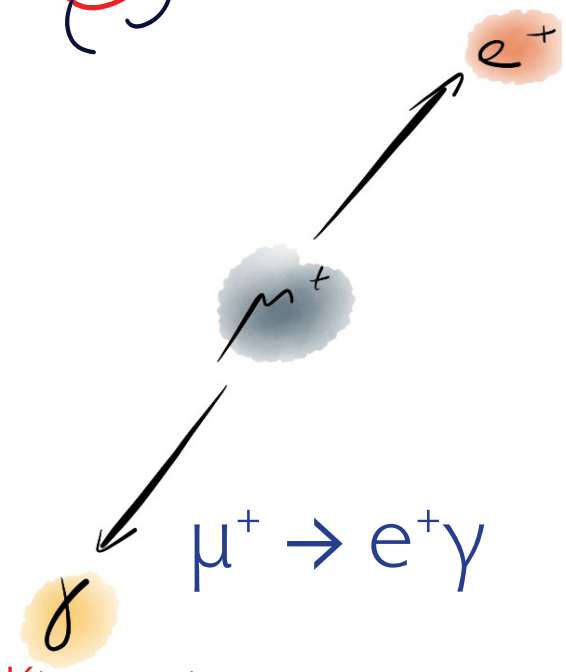
Kinematics

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

Background

- Radiative decay
- Accidental background

LFV Muon Decays: Experimental signatures



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

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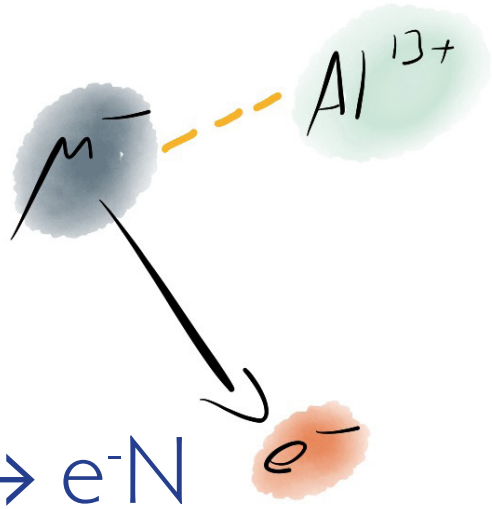
- 2-body decay
- Monoenerge
- Back-to-b

Backgro

- A al background

Continuous Beam



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

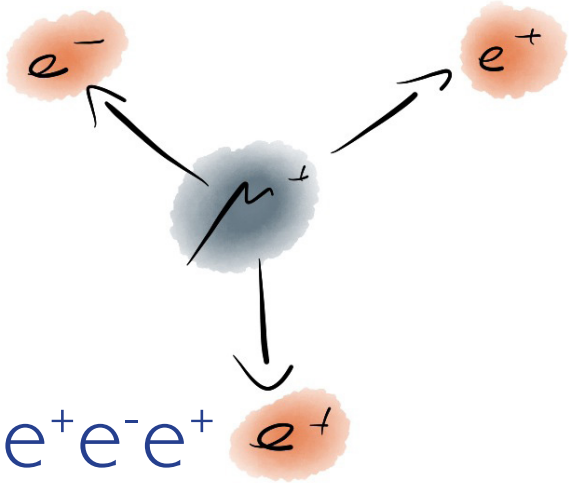
Kinematics

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

Backgro

- D orbit
- A protons, pions

Pulsed Beam



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

Kinematics

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

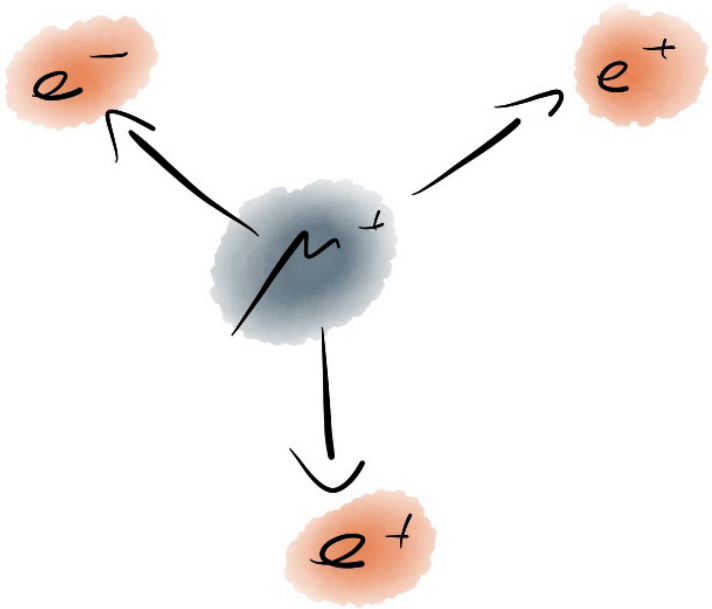
Backgro

- R decay
- Ac dental background

Continuous Beam

The $\mu^+ \rightarrow e^+ e^- e^+$ Process:
Requirements for an Experiment

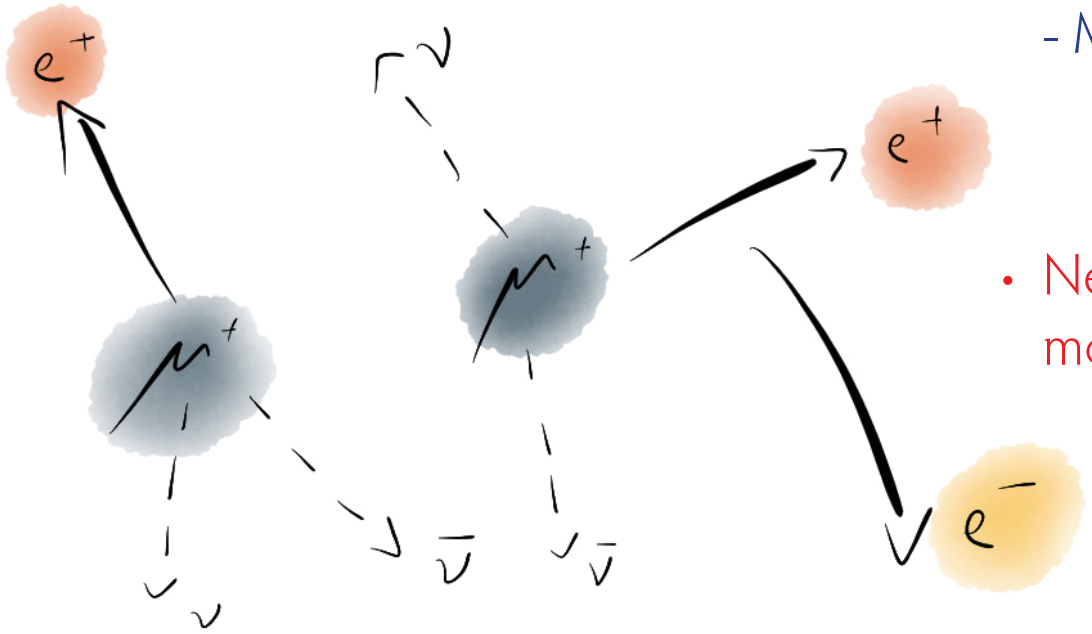
The signal



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



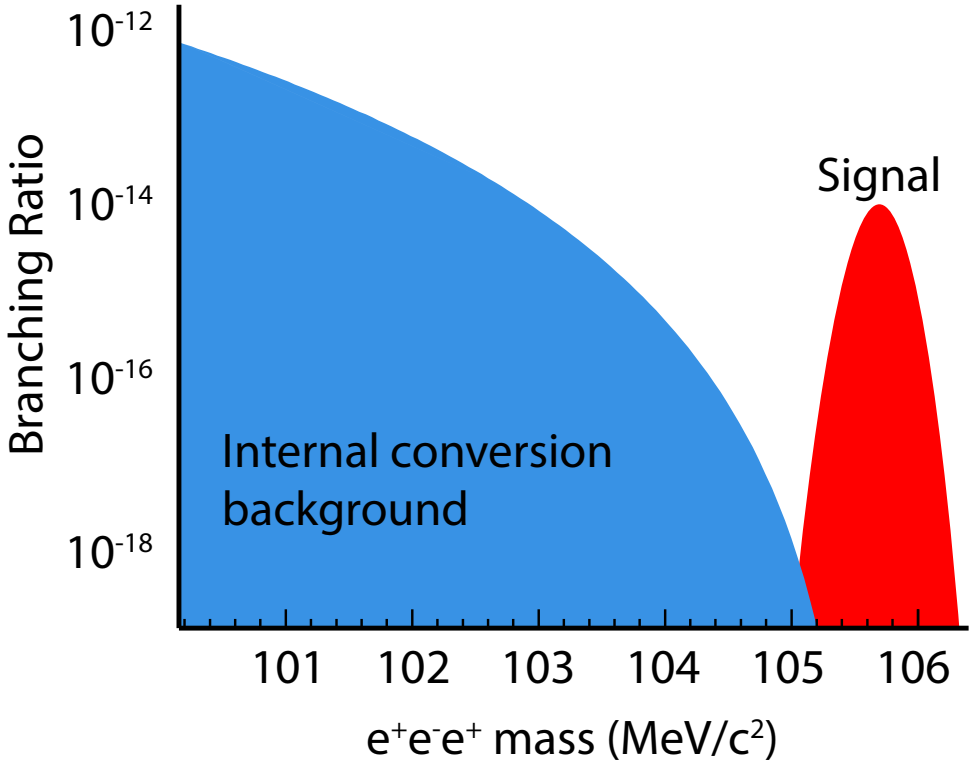
- Need very good timing, vertex and momentum resolution

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



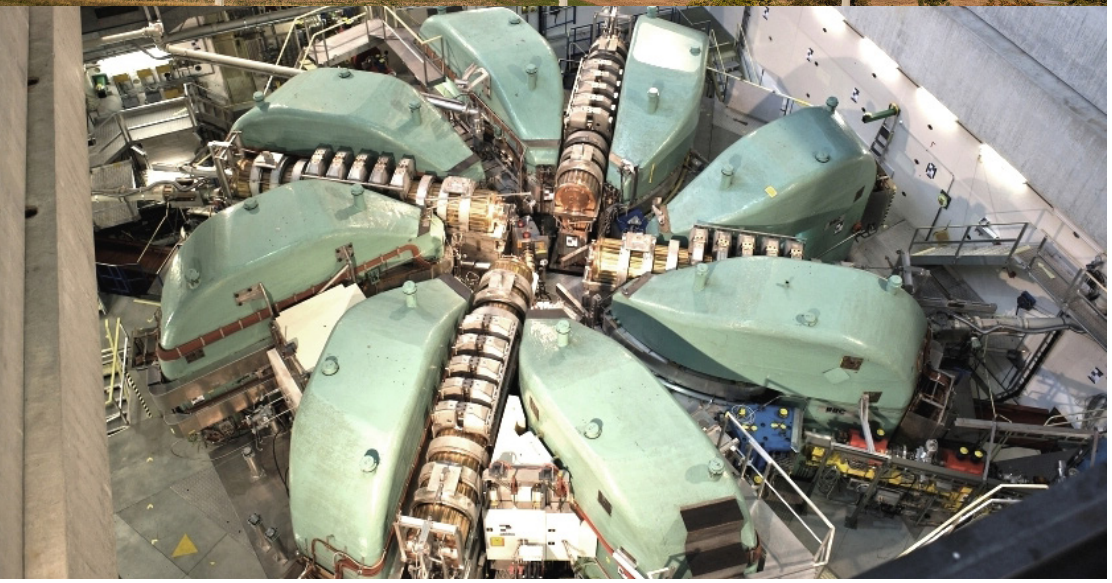
- Need excellent momentum resolution

Building the
Mu3e Experiment

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

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

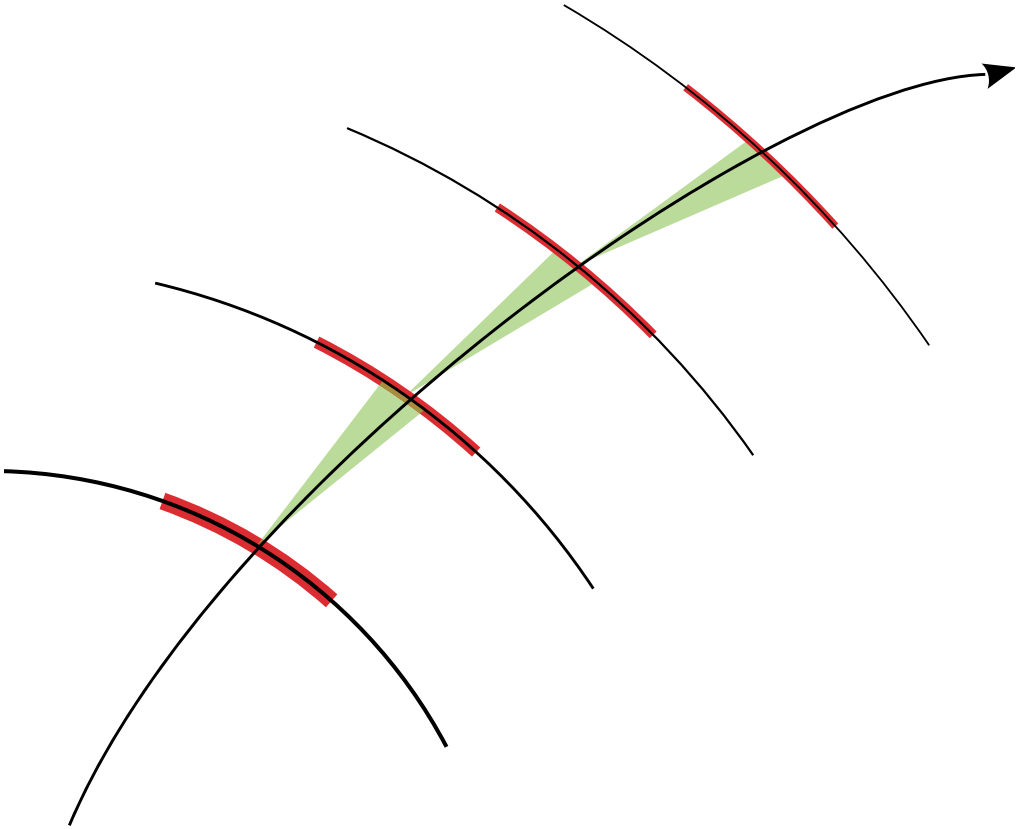
Getting Muons

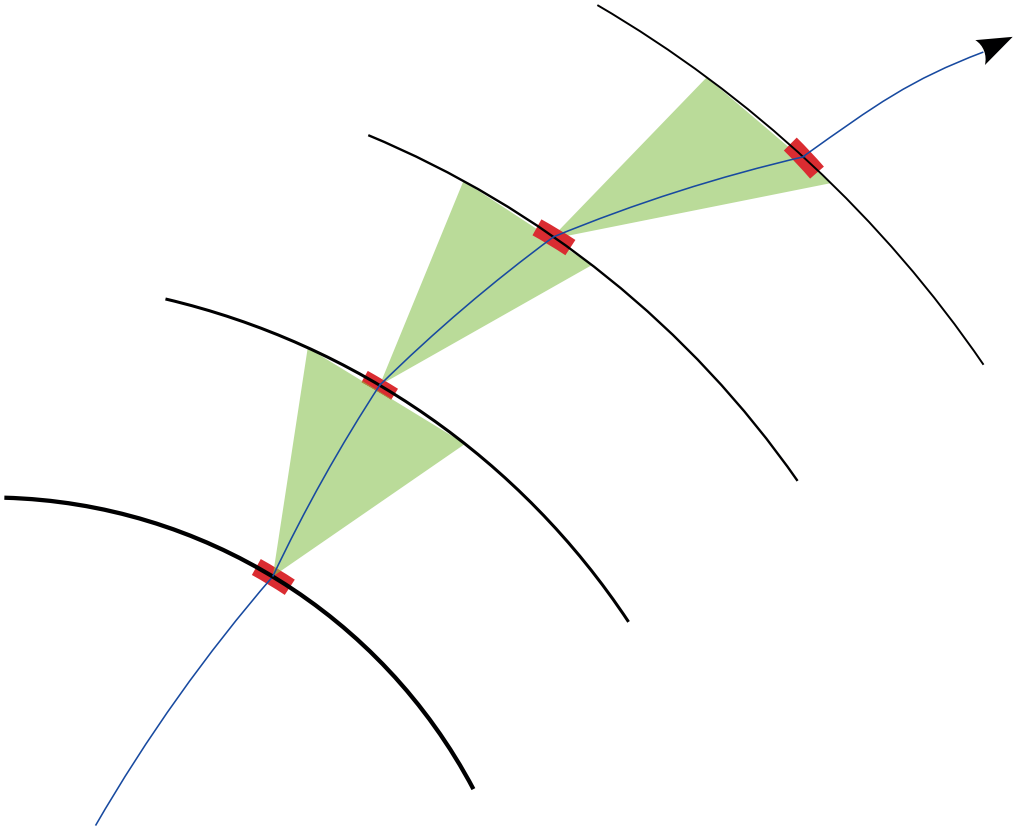


- Paul Scherrer Institute in Switzerland
- 1.4 MW, 590 MeV proton accelerator
- Carbon target, produce pions, decay to muons
- Currently: Up to 10^8 muons/s available Mu3e Phase I
- Future (2027+): High-intensity muon beamline (HIMB) with up to 10^{10} muons/s Mu3e Phase II
- Need to be able to stand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

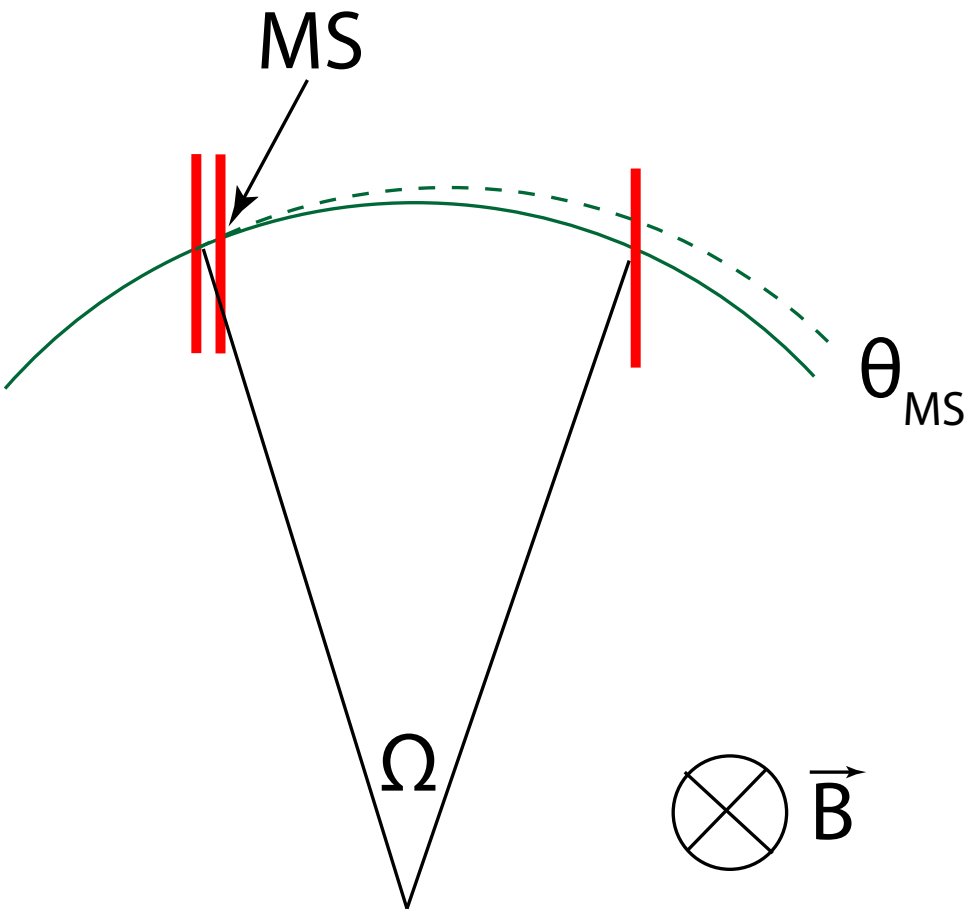
Momentum measurement

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





Momentum measurement

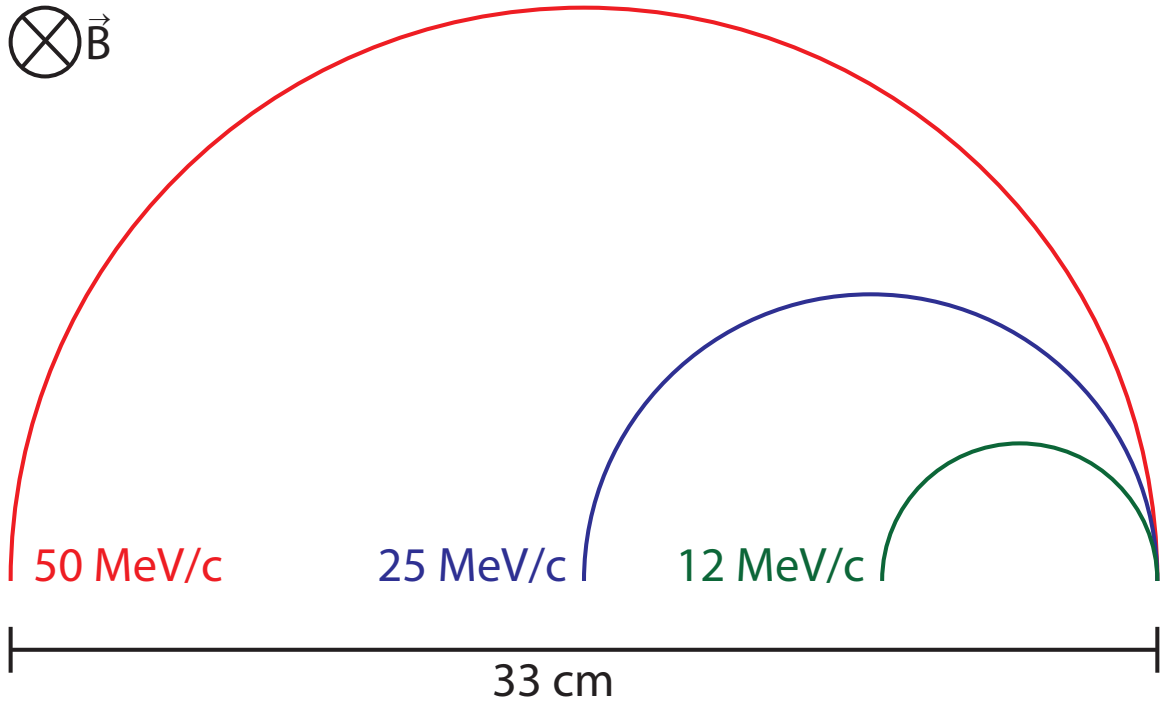


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

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

Precision vs. Acceptance



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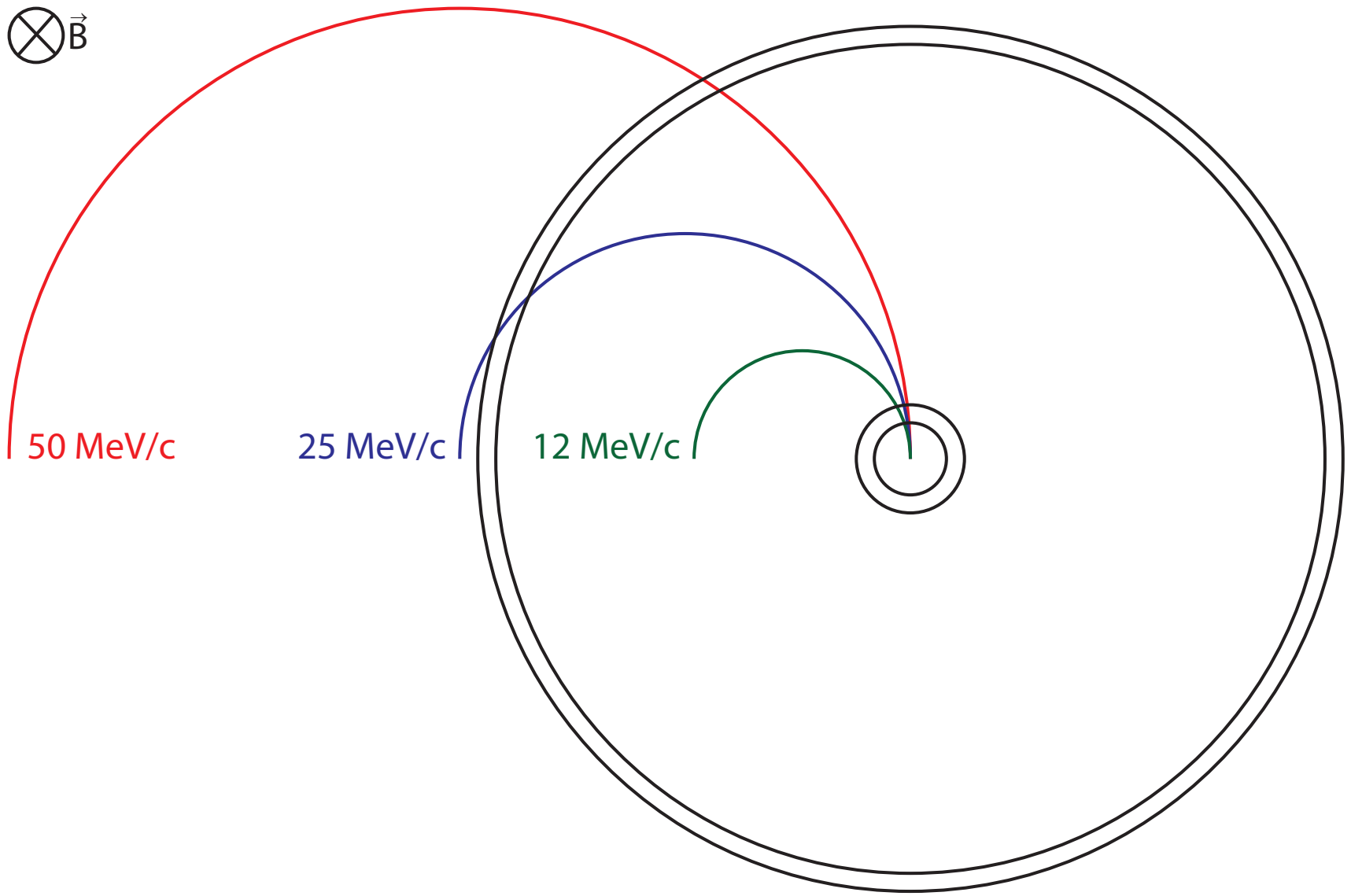

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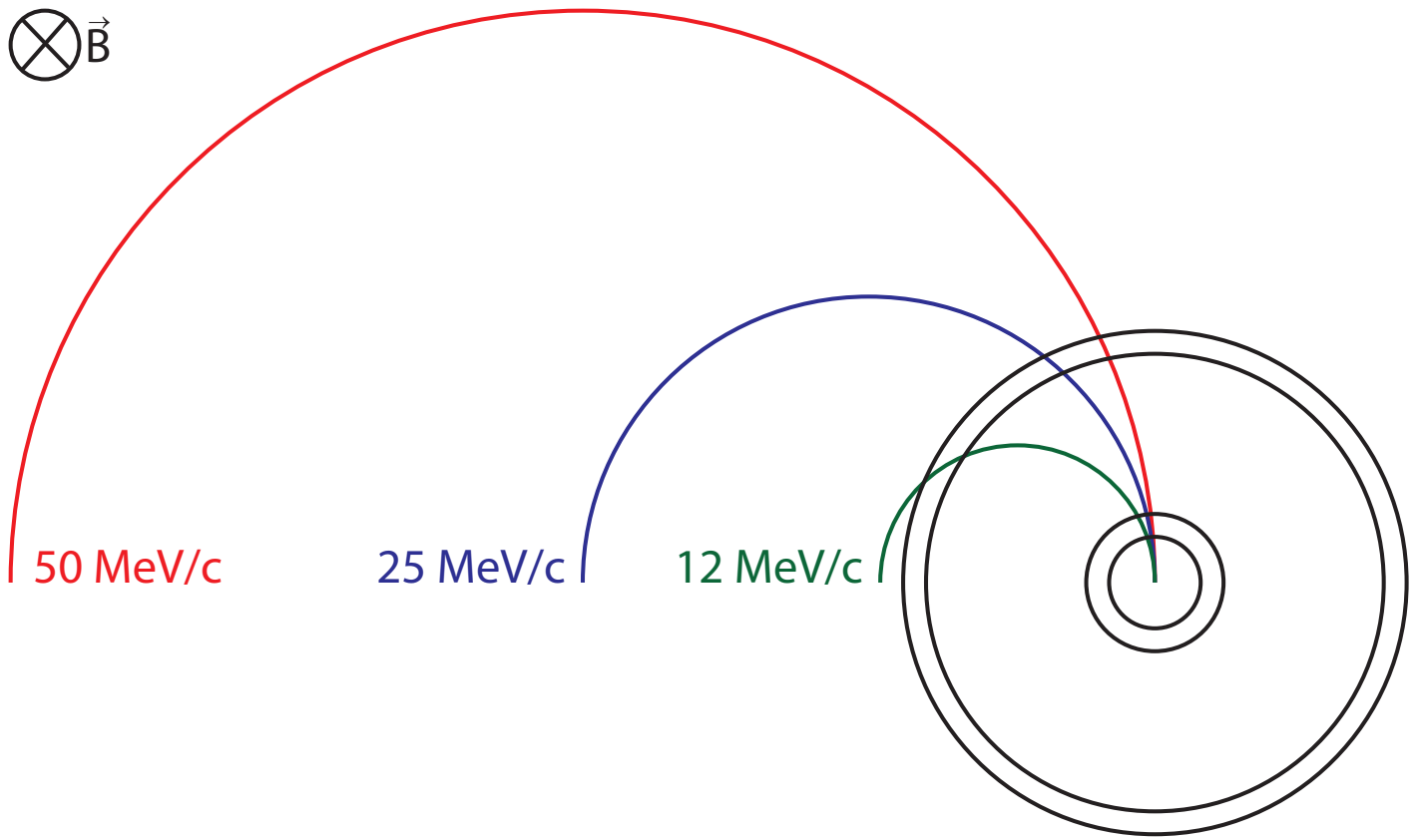

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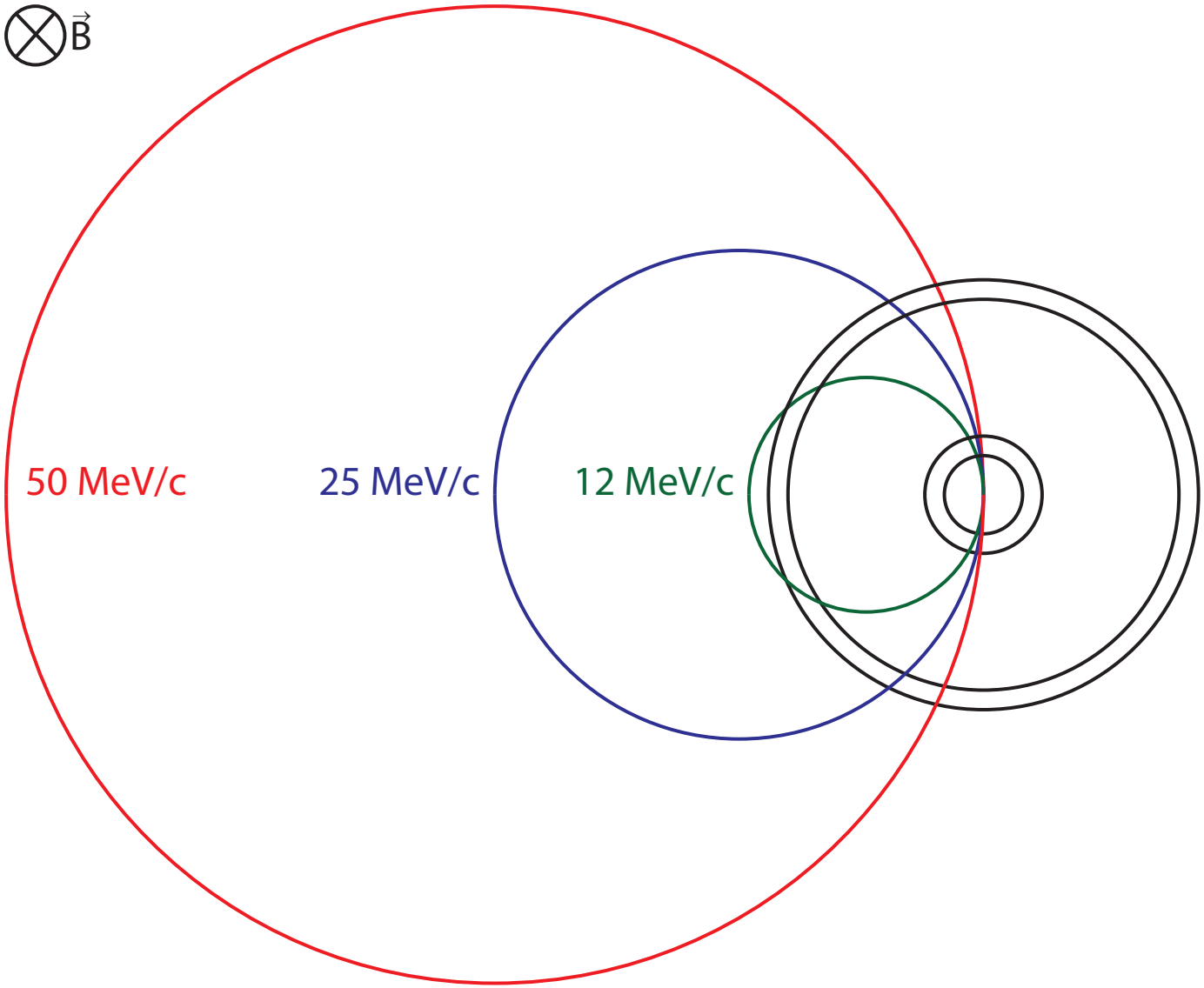

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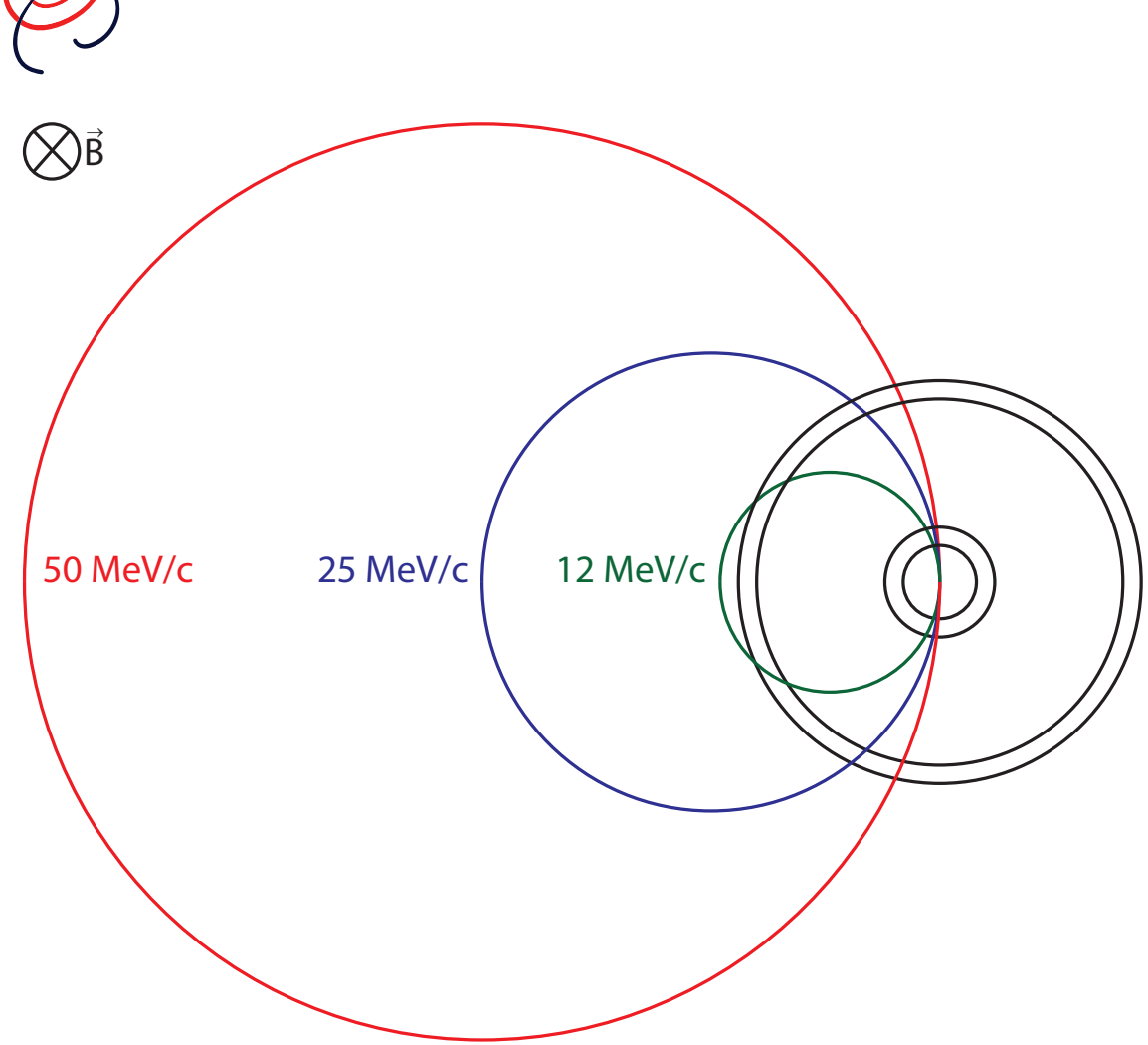

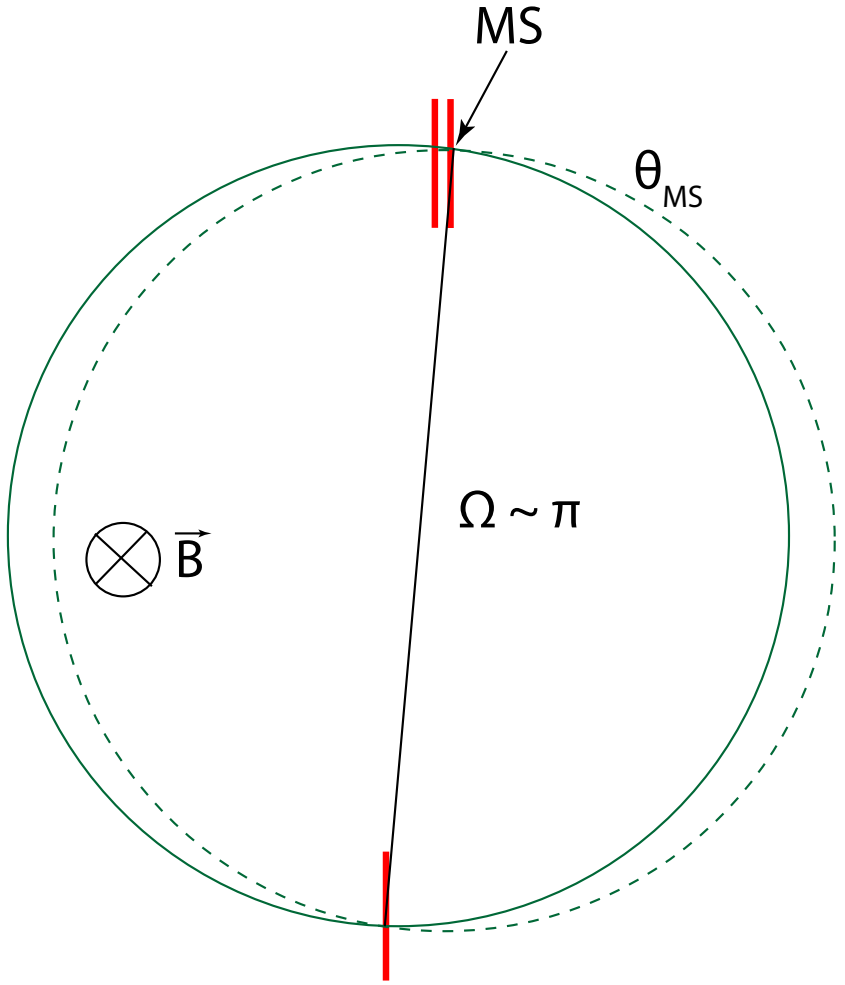

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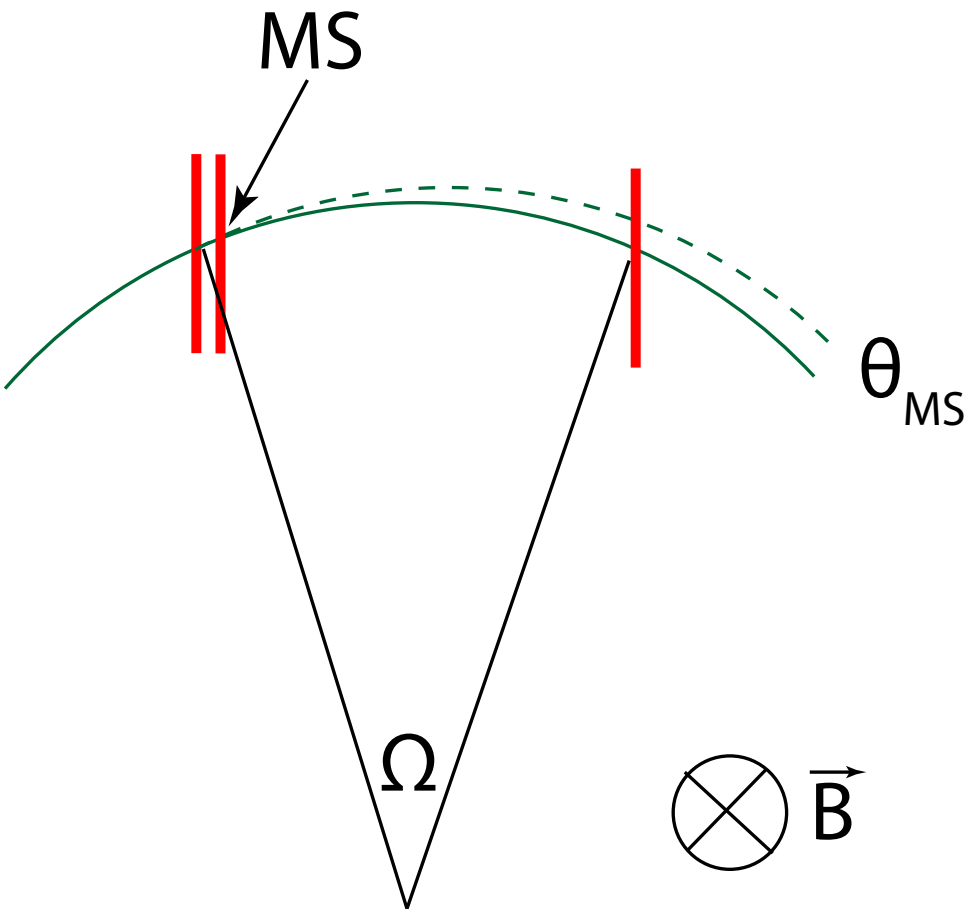

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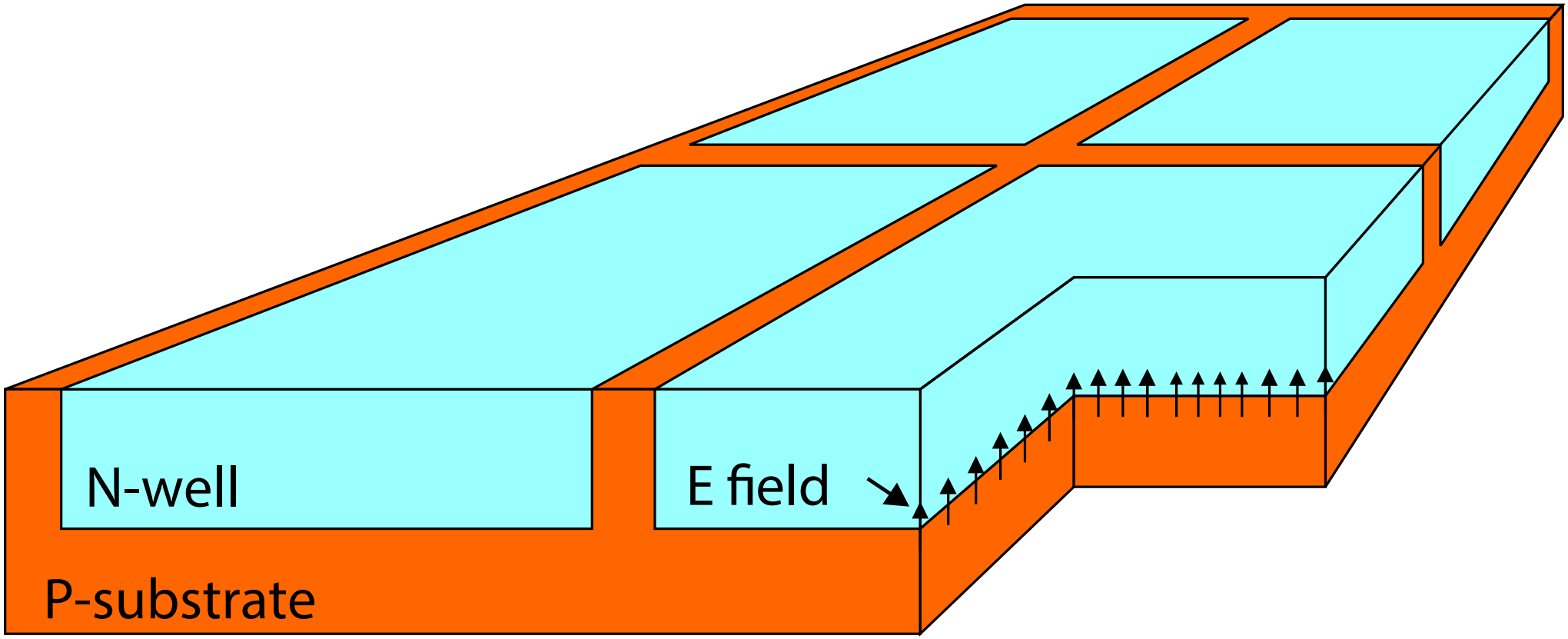
Very thin and fast silicon pixel sensors: HV-MAPS

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)



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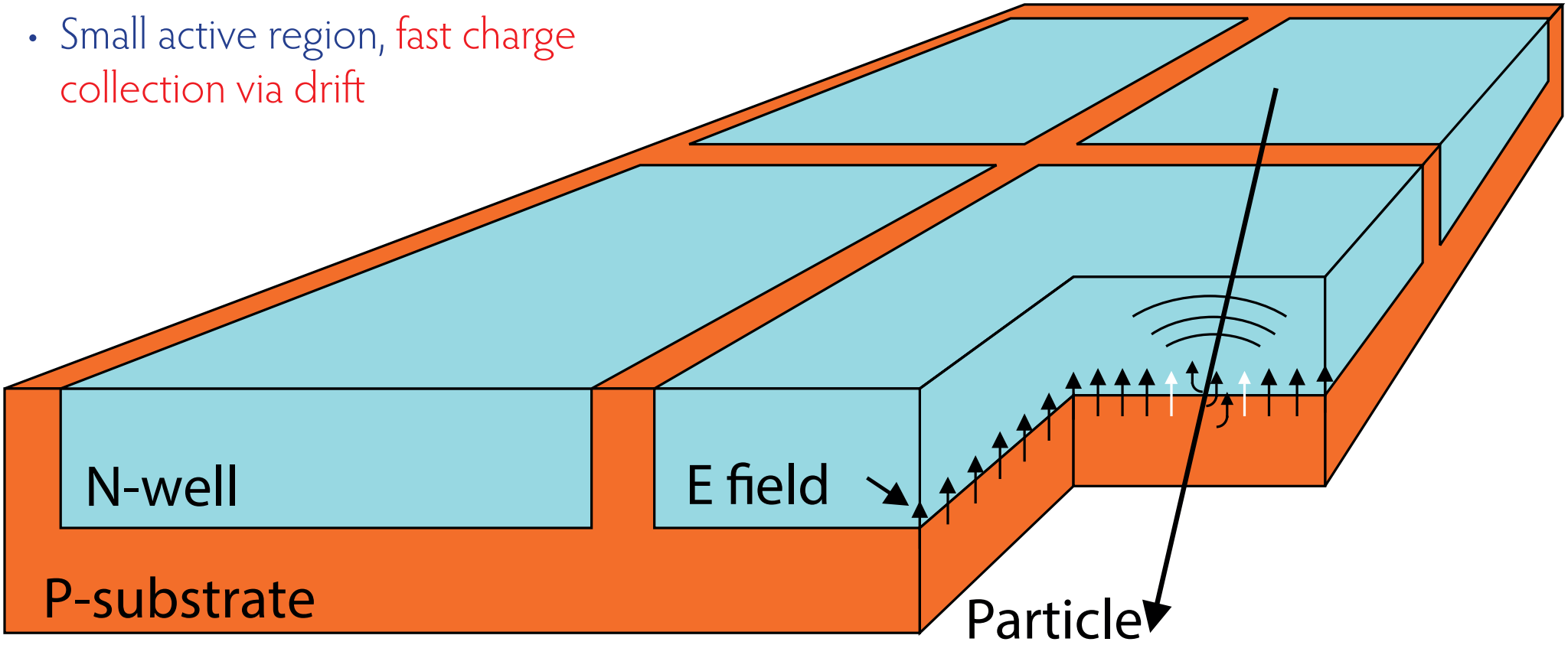

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

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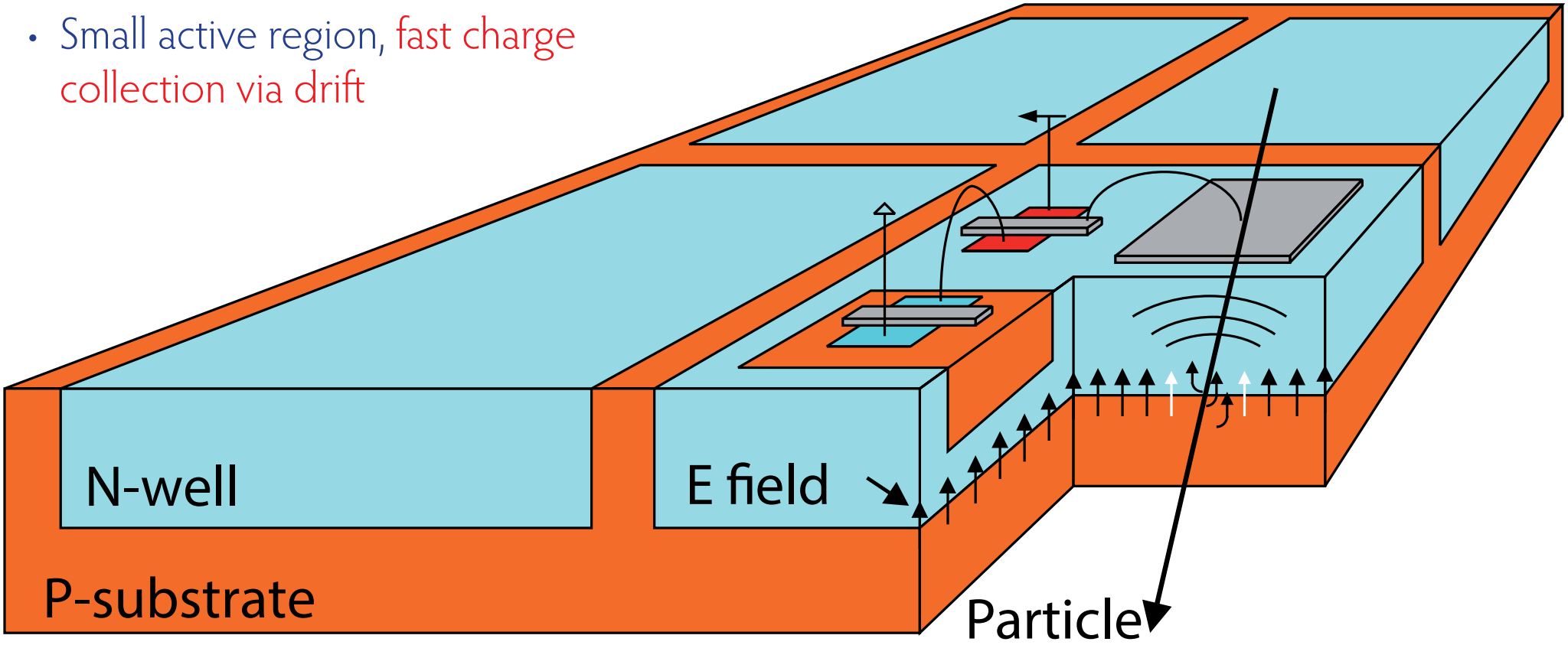
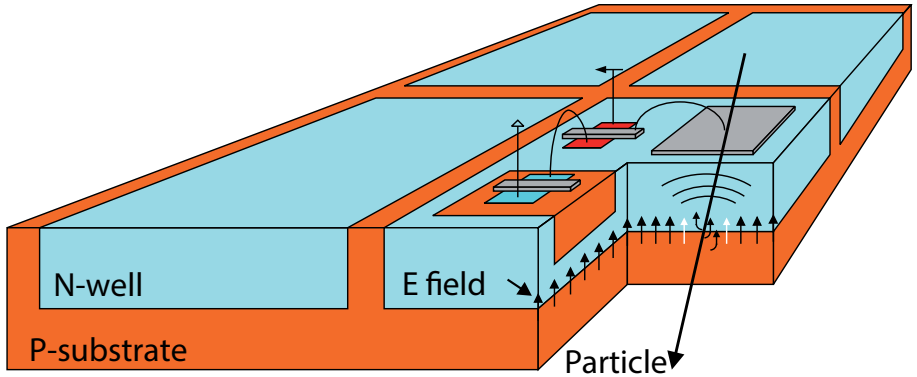
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to ~ 50 µm

(I.Perić, NIM A 582 (2007) 876)

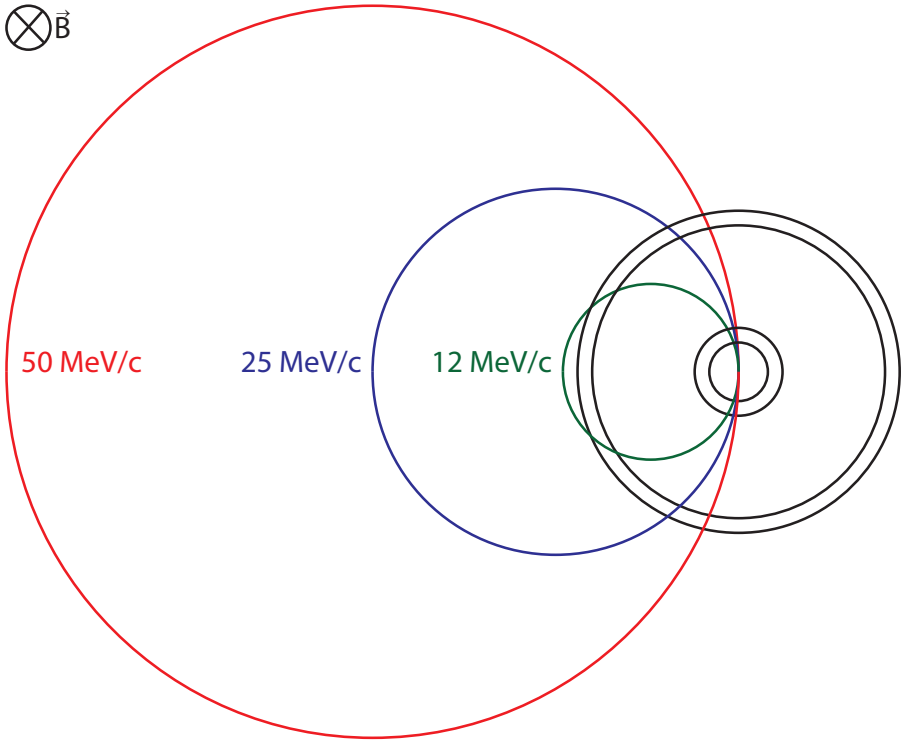


Mu3e concept

- HV-MAPS: Thin, fast pixel sensors



- Recurler tracking: Bending in field happens mainly outside of the tracker



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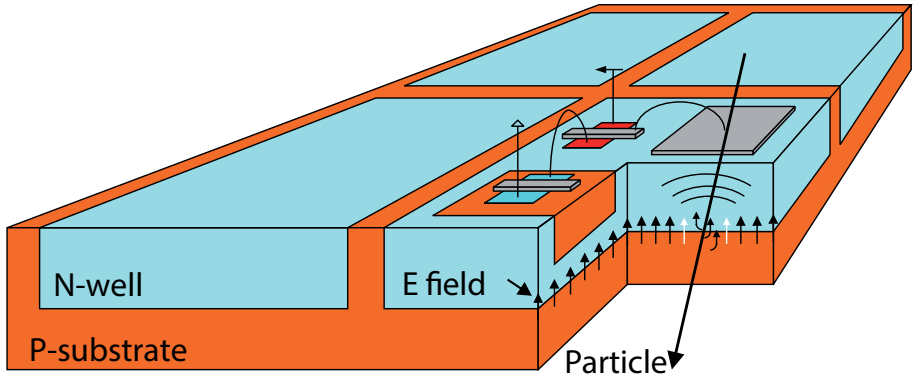
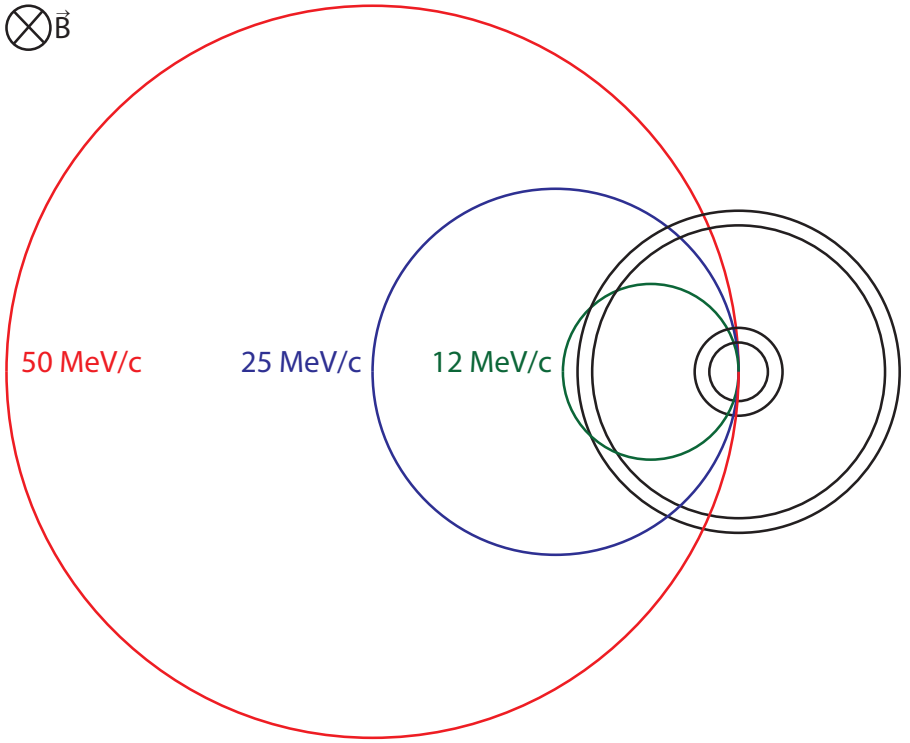
- HV-MAPS: Thin, fast pixel sensors



- Recurler tracking: Bending in field happens mainly outside of the tracker



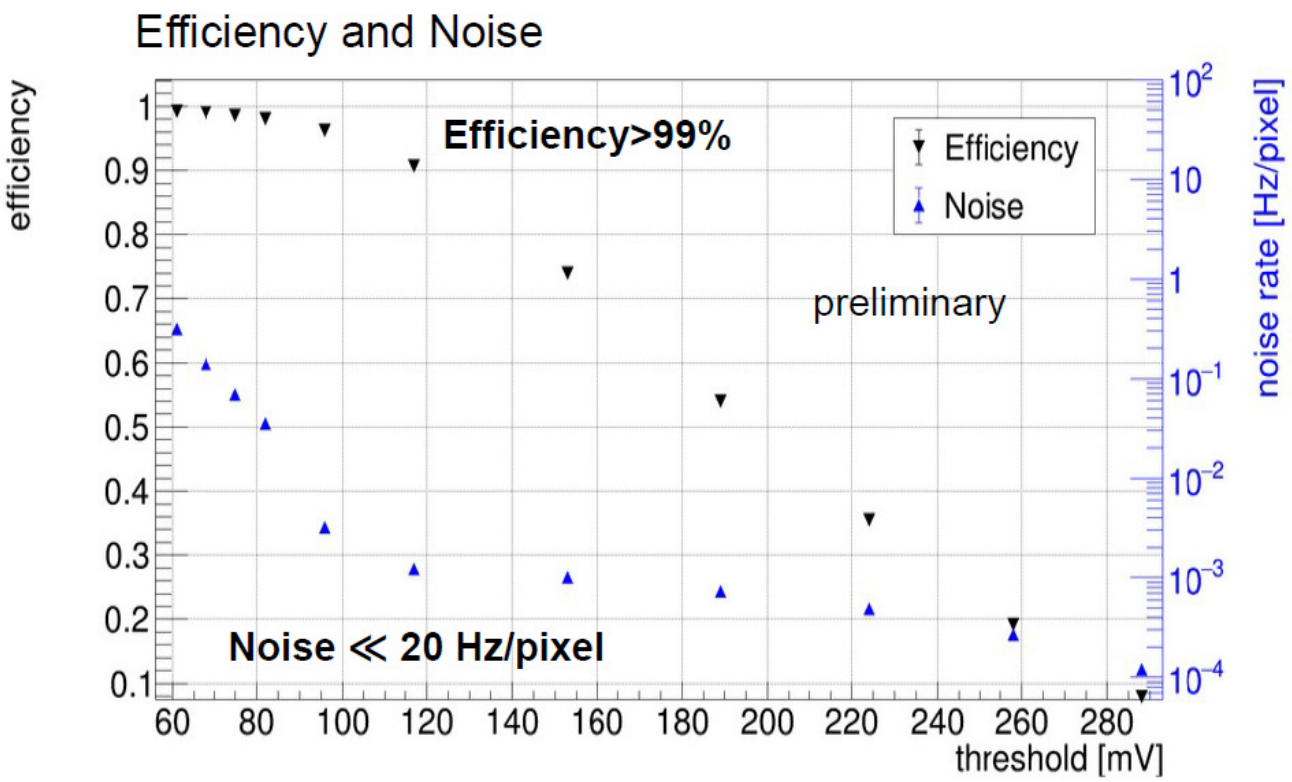
- We knew that more than 10 years ago - experiment is taking shape now - what happened in the meantime?

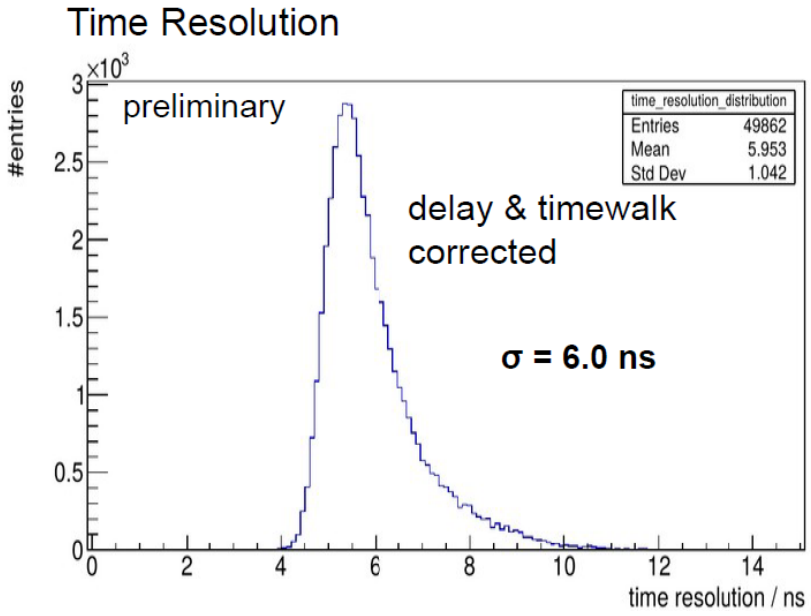
HV-MAPS: Sensor to system

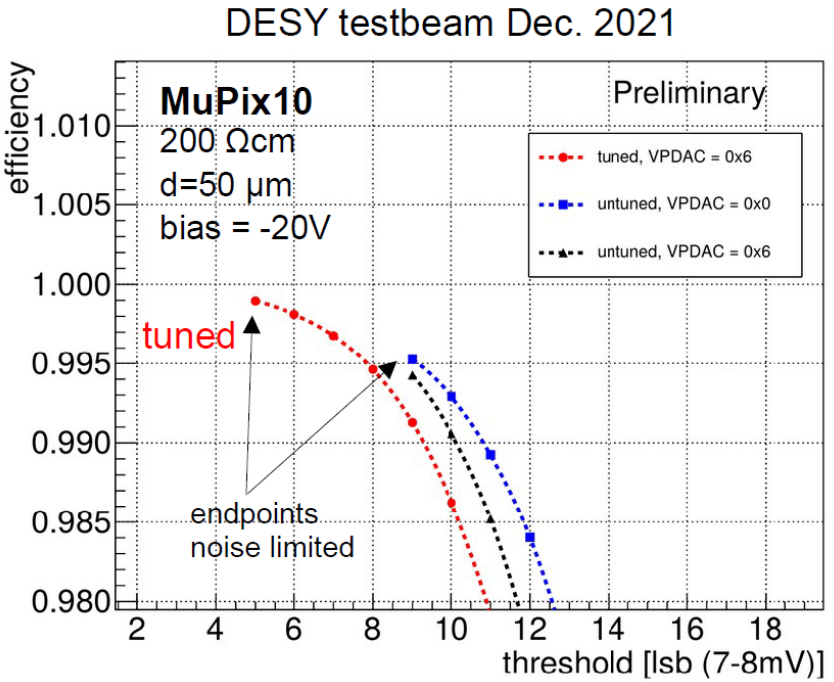
The MuPix chips

Pixel cell

- 80 x 80 μm^2
- High efficiency
- Low noise
- Good time resolution
- Low power consumption
  ~ 200 mW/cm^2 achieved

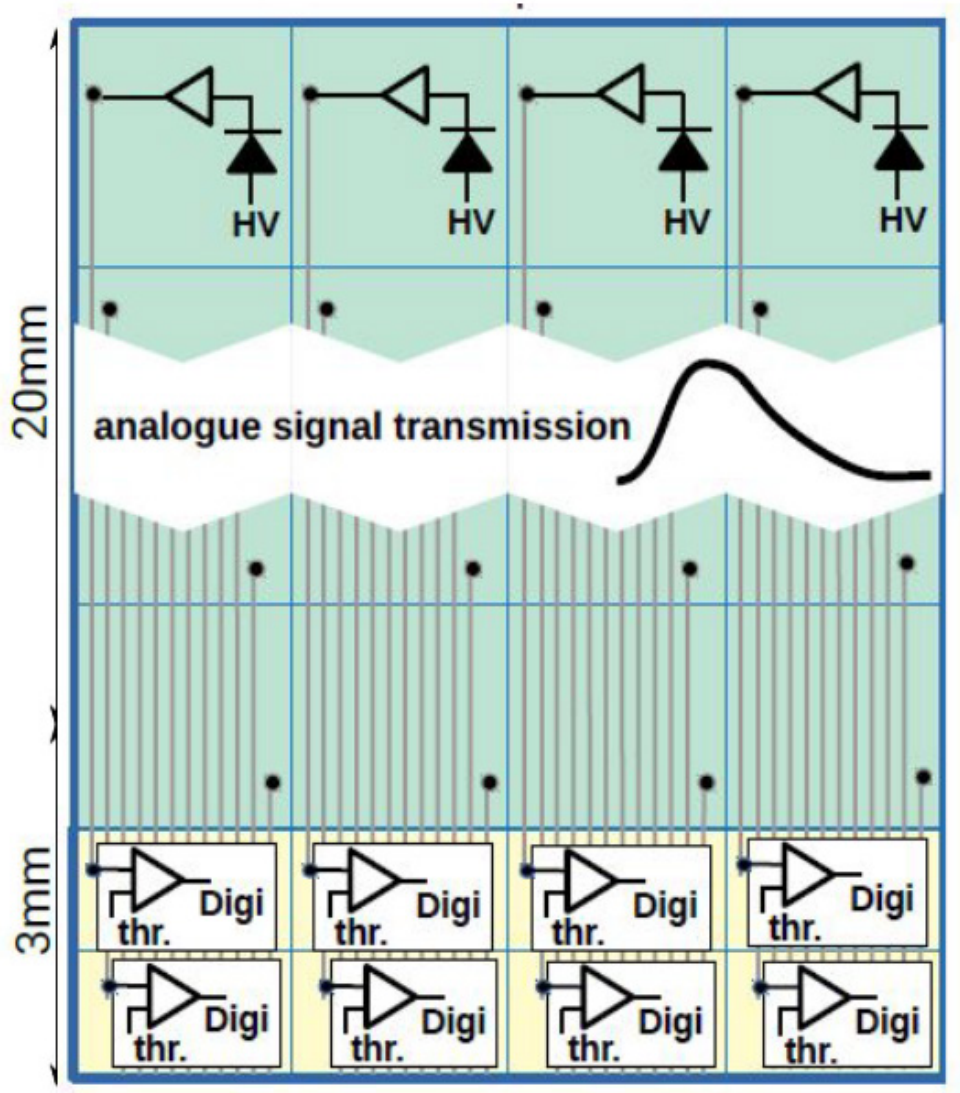






Readout architecture

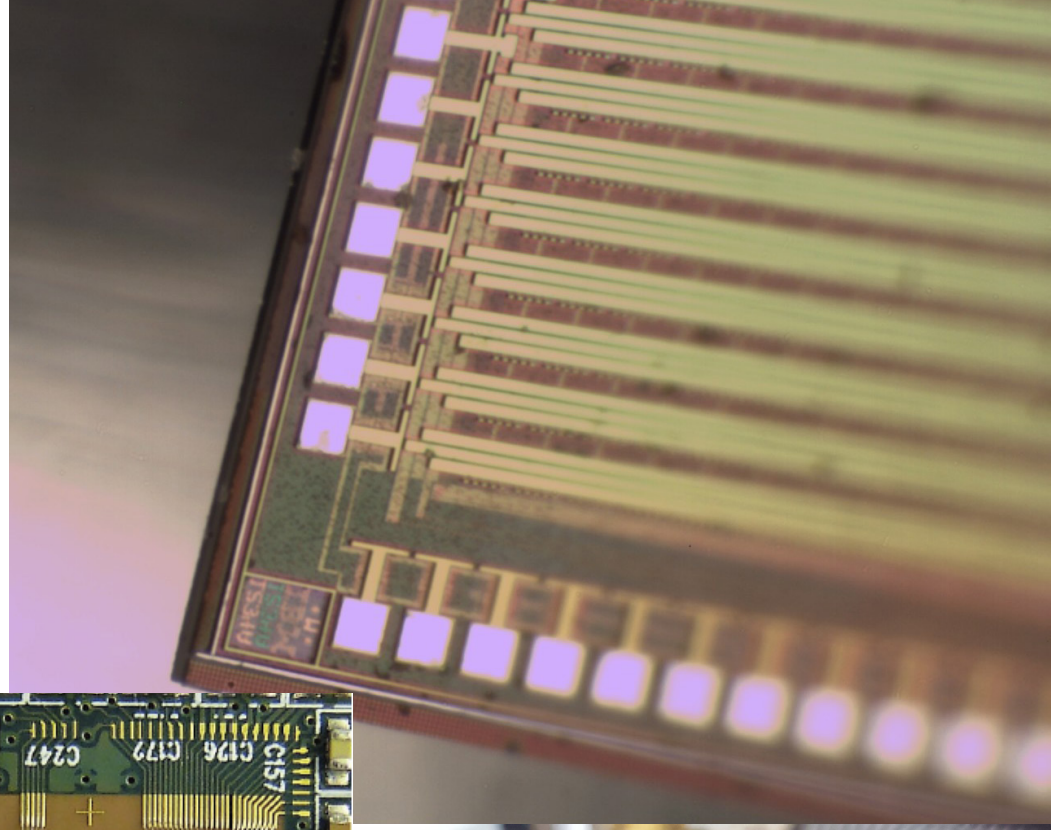
- Amplifier in pixel
- Comparator, hit latching and time-stamping in the periphery
- Streaming column-drain readout controlled by on-chip state machine
- Three 1.25 Gbit/s LVDS links for data output

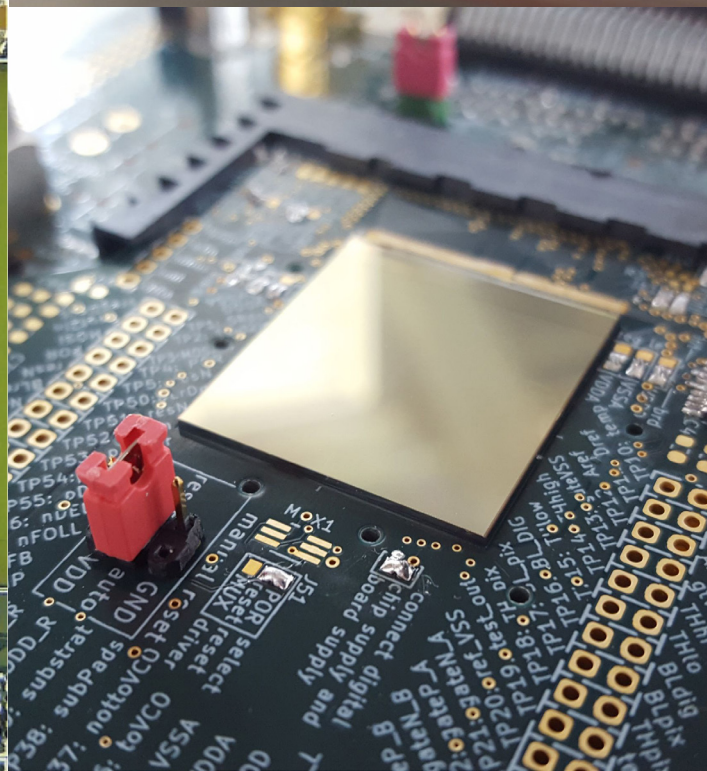


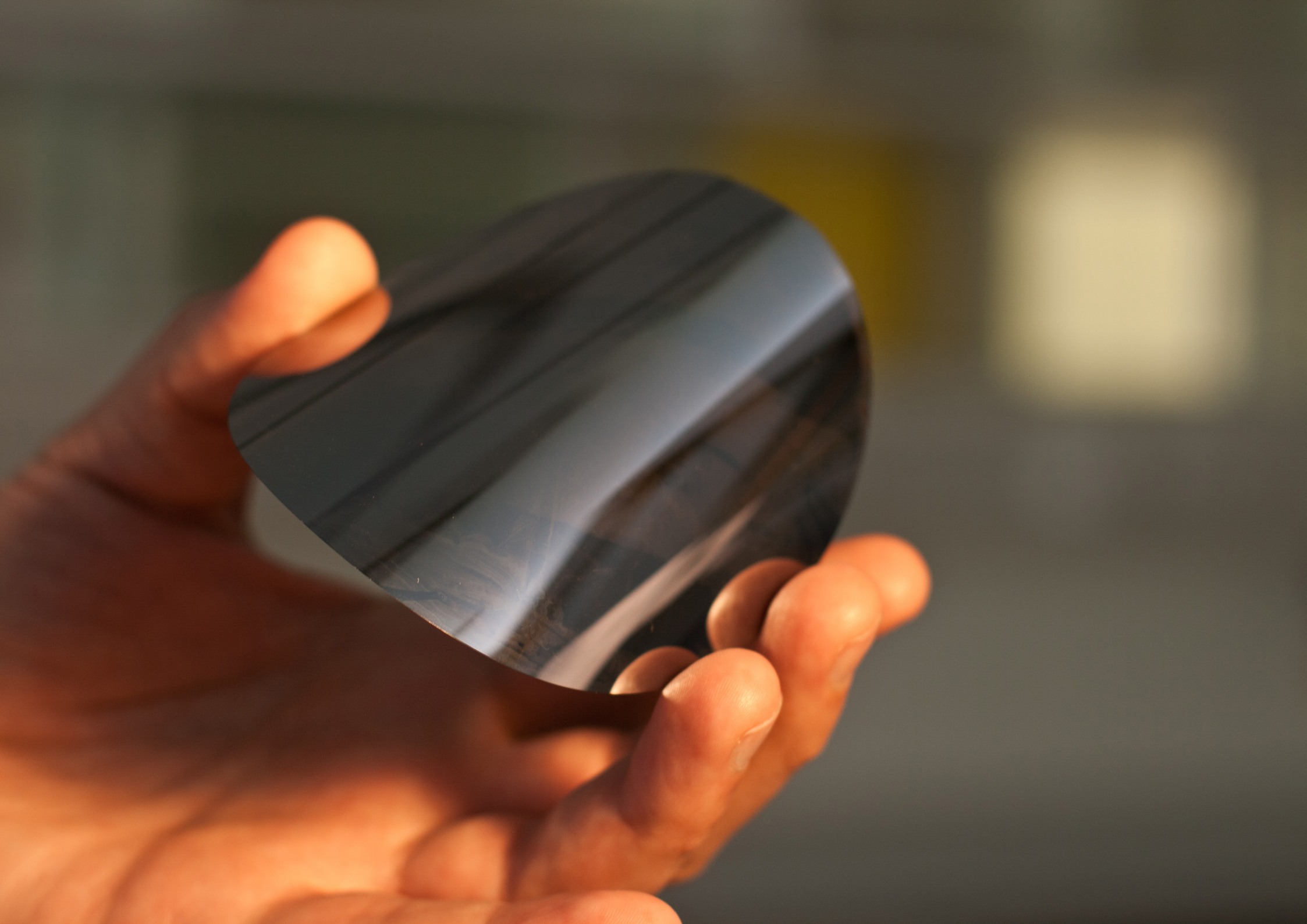
The MuPix Prototypes

Series of HV-MAPS prototypes

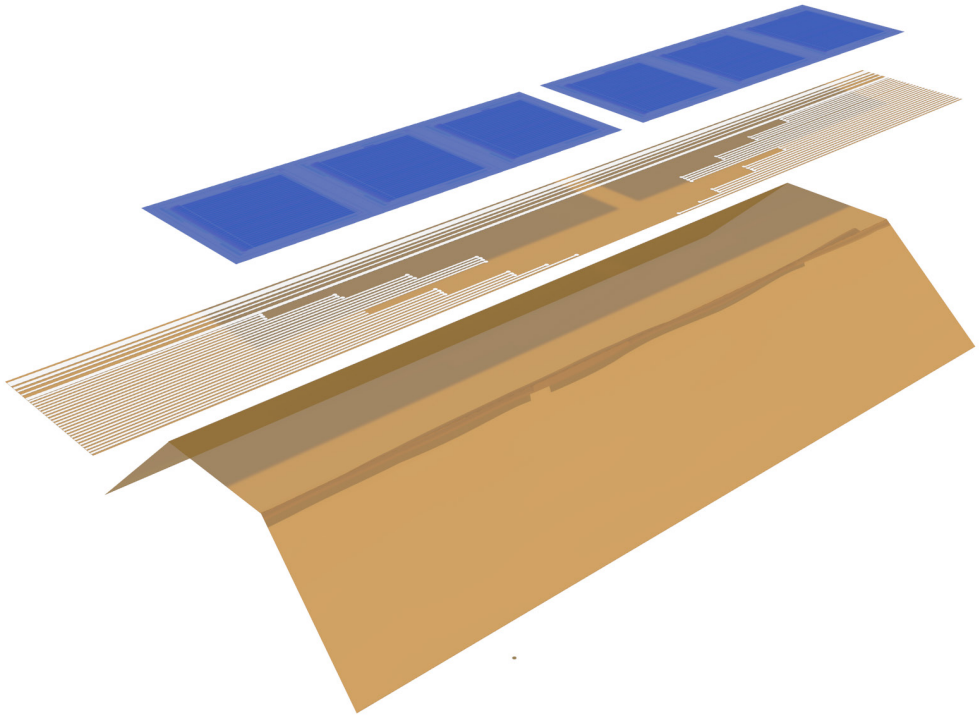
- Goal: Detection and signal processing with just 50 µm silicon
- 6th chip, MuPix7, was the first full system-on-a-chip
- Going "big" 2 x 1 cm^2 MuPix8 with 80 by 80 µm pixels also working nicely - some growing pains fixed
- MuPix10, 2 x 2 cm^2, almost final
- MuPix11, 2 x 2 cm^2, production chip, now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





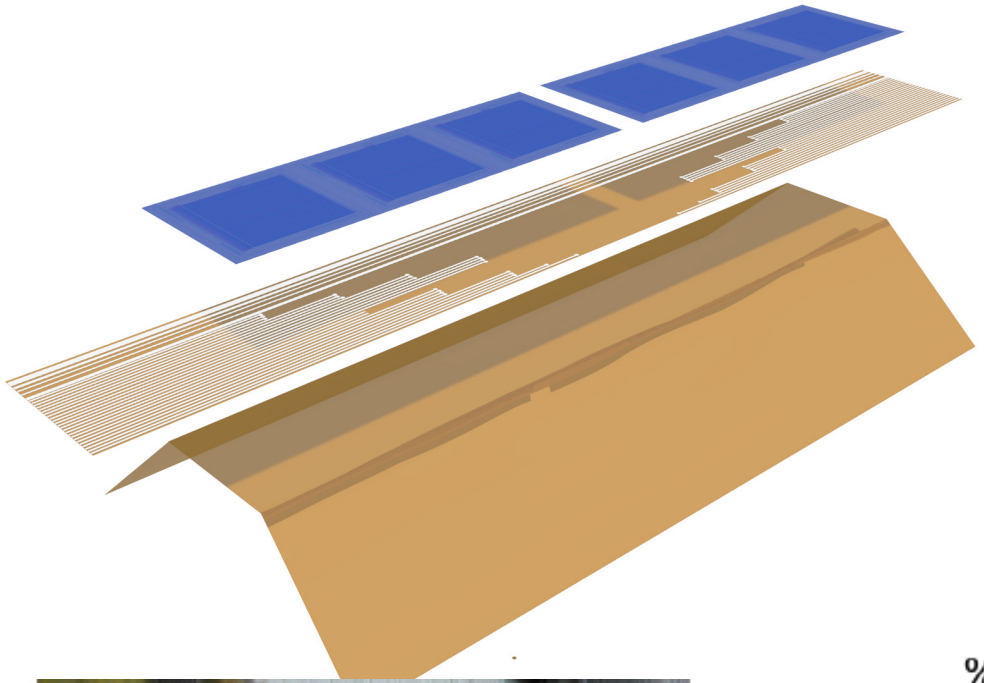


Mechanics and Connections

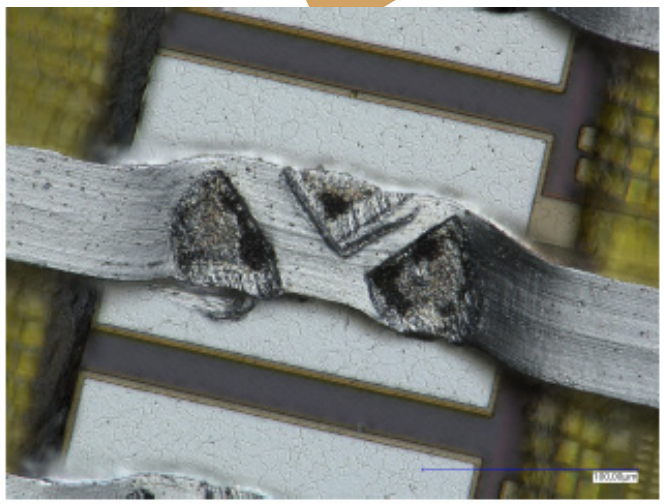


- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- Kapton™ or unidirectional carbon fibre supports

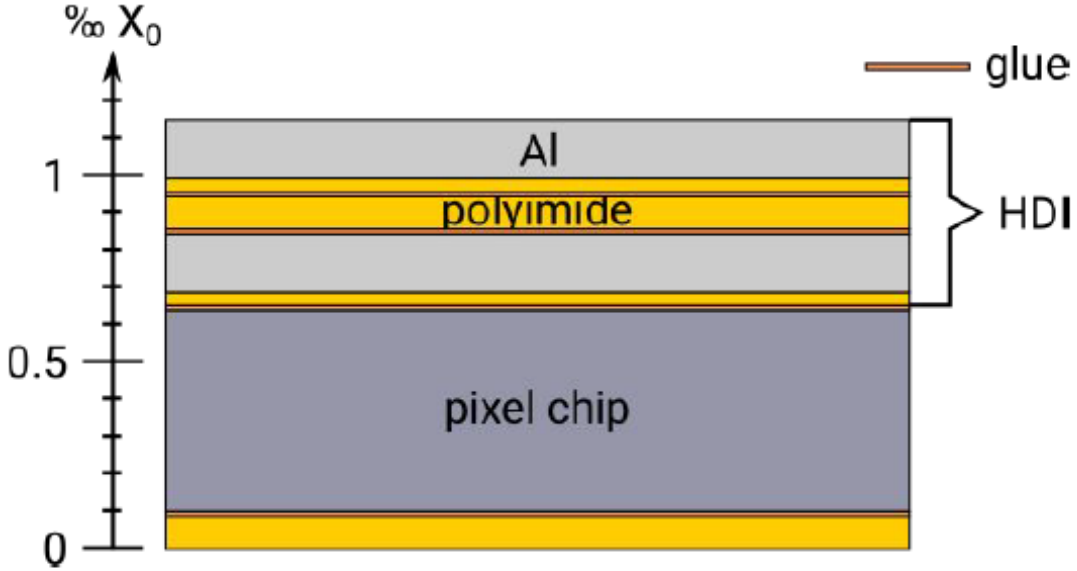
Mechanics and Connections



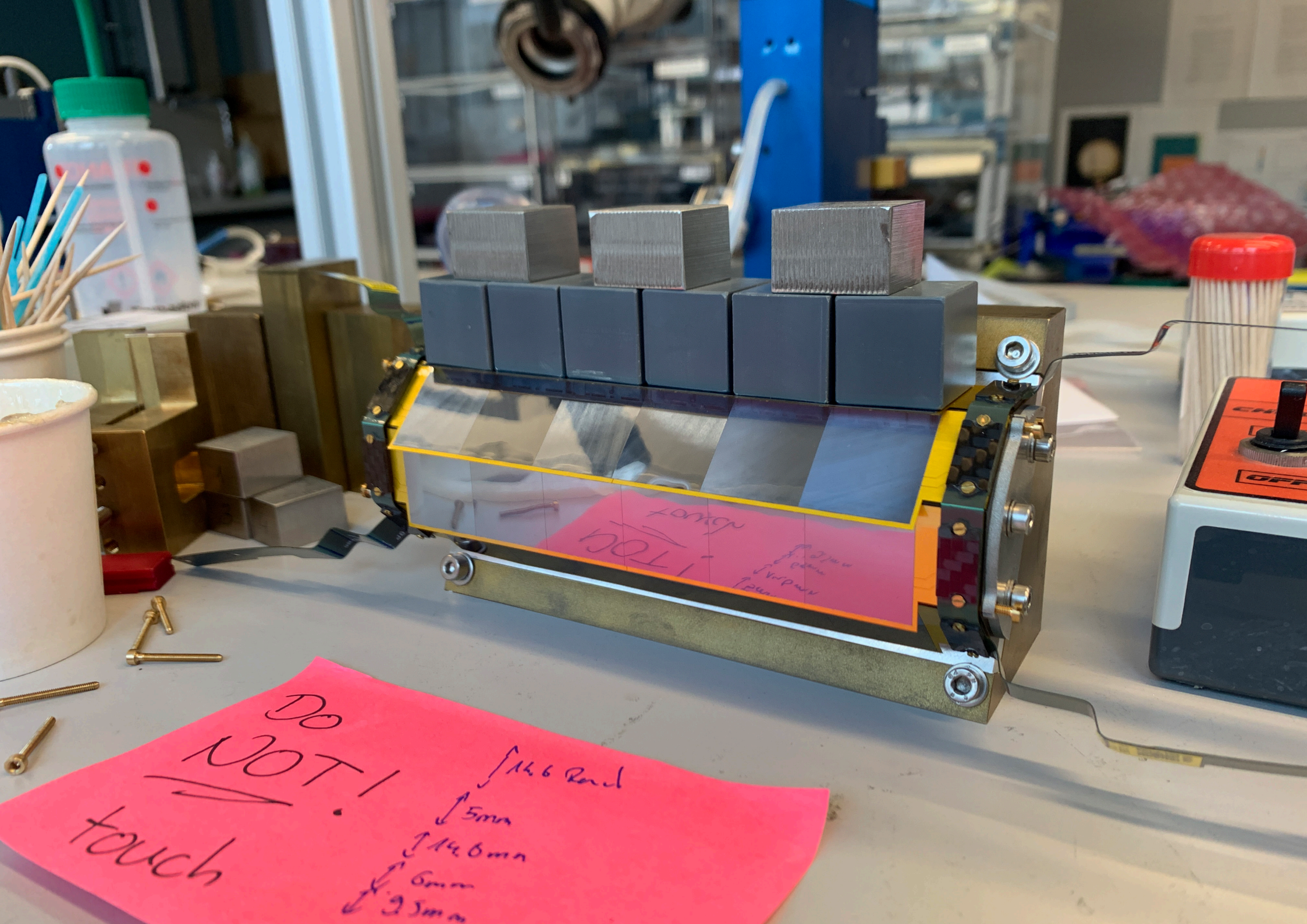
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- Kapton™ or unidirectional carbon fibre supports
- About 1‰ of a radiation length per layer
- Large traces: few lines possible
- No decoupling capacitors...

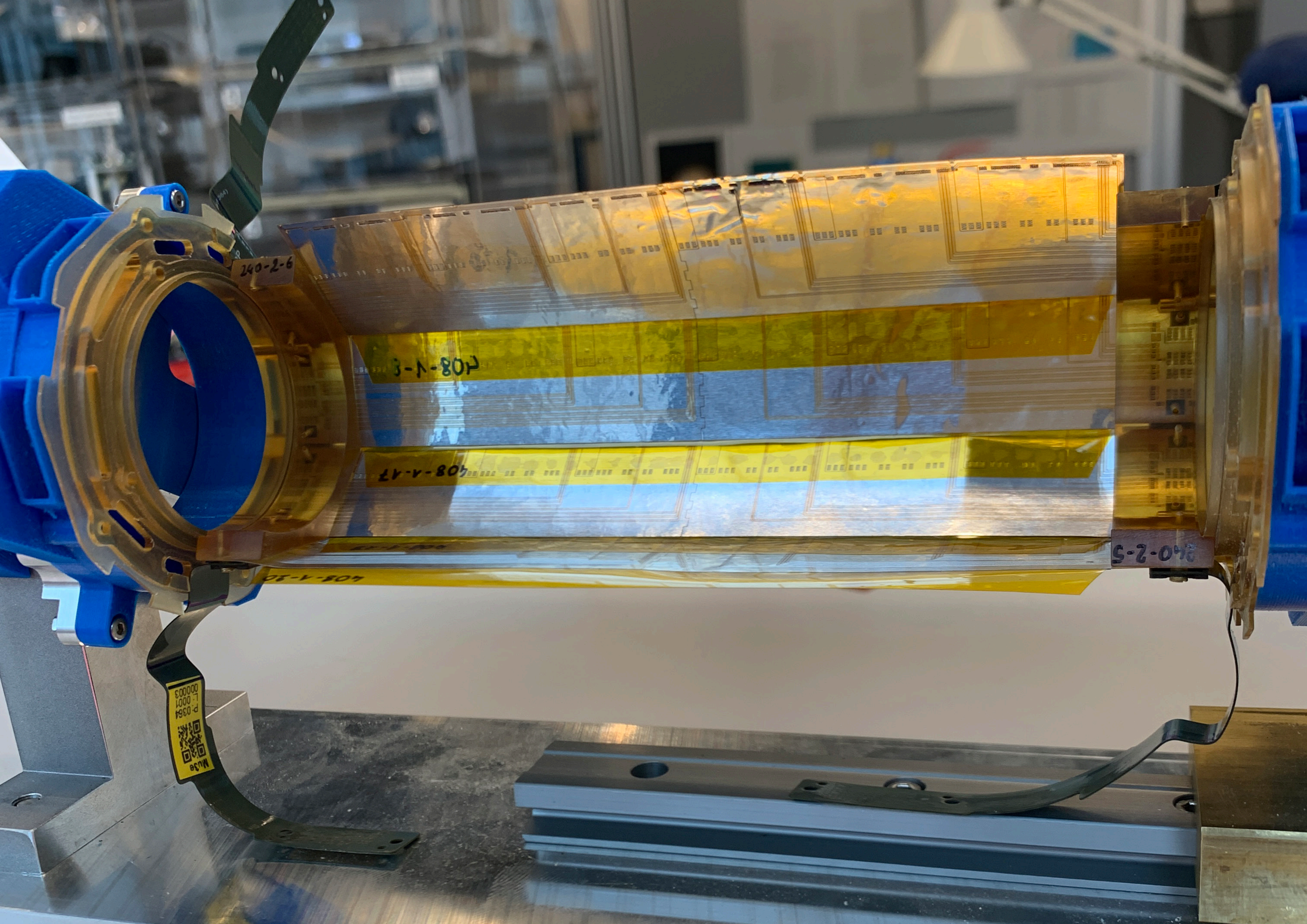


spTAB connection



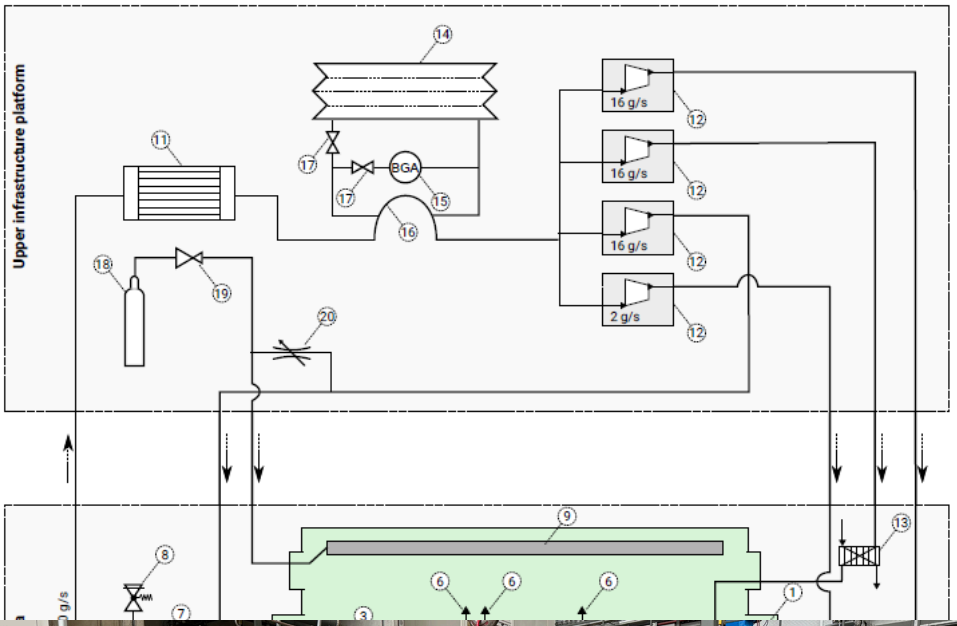
Resulting material budget


DO
NOT!
touch
14,6 Rand
5mm
14,6mm
6mm
3,5mm


240-2-6
408-1-17
240-2-5

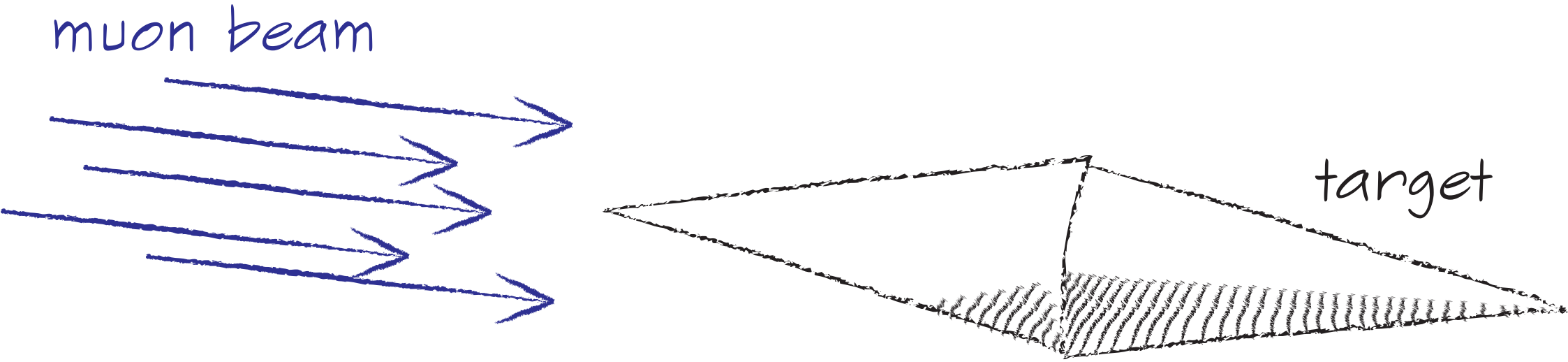
Cooling

- ~ 200 mW/cm^2 - about 2 KW for the complete pixel detector
- Add as little material as possible: Gaseous helium at ~ 0°C
- Need around 50 g/s (~280 liter/s at STP...)
- Helium is difficult to pump...
- Very nice little turbocompressors available
- Cooling plant is an engineering project of its own

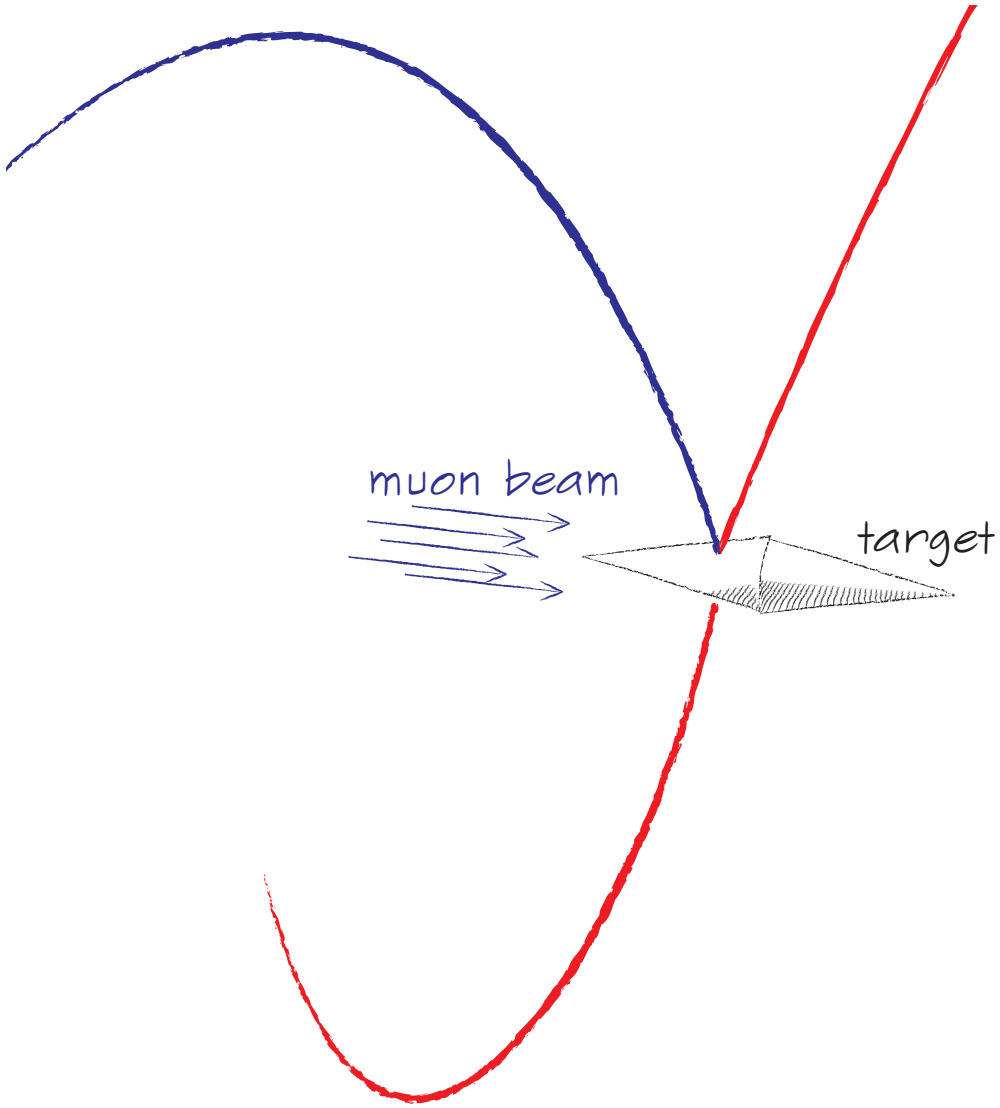


Assemble this to an experiment...

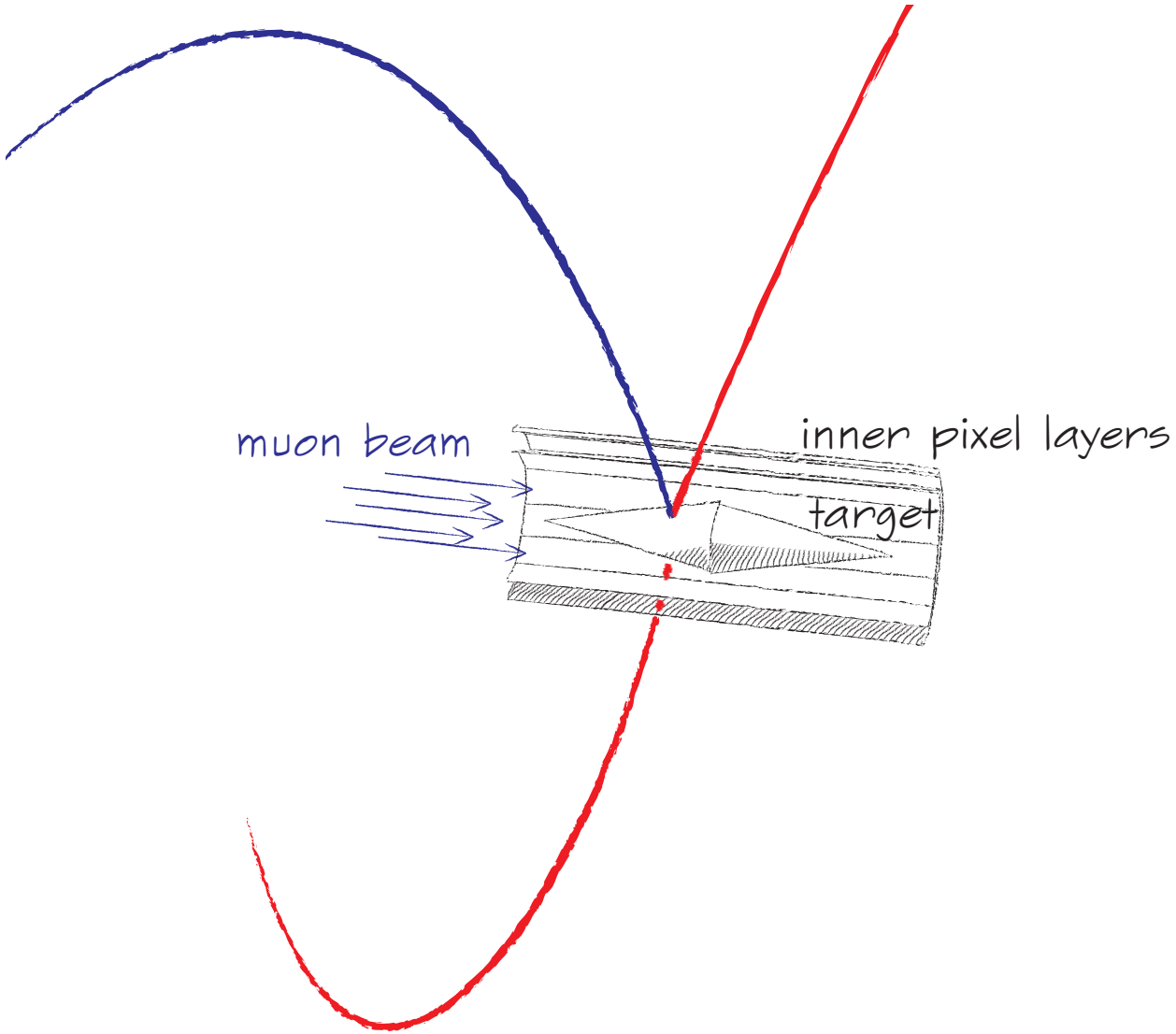
Detector Design



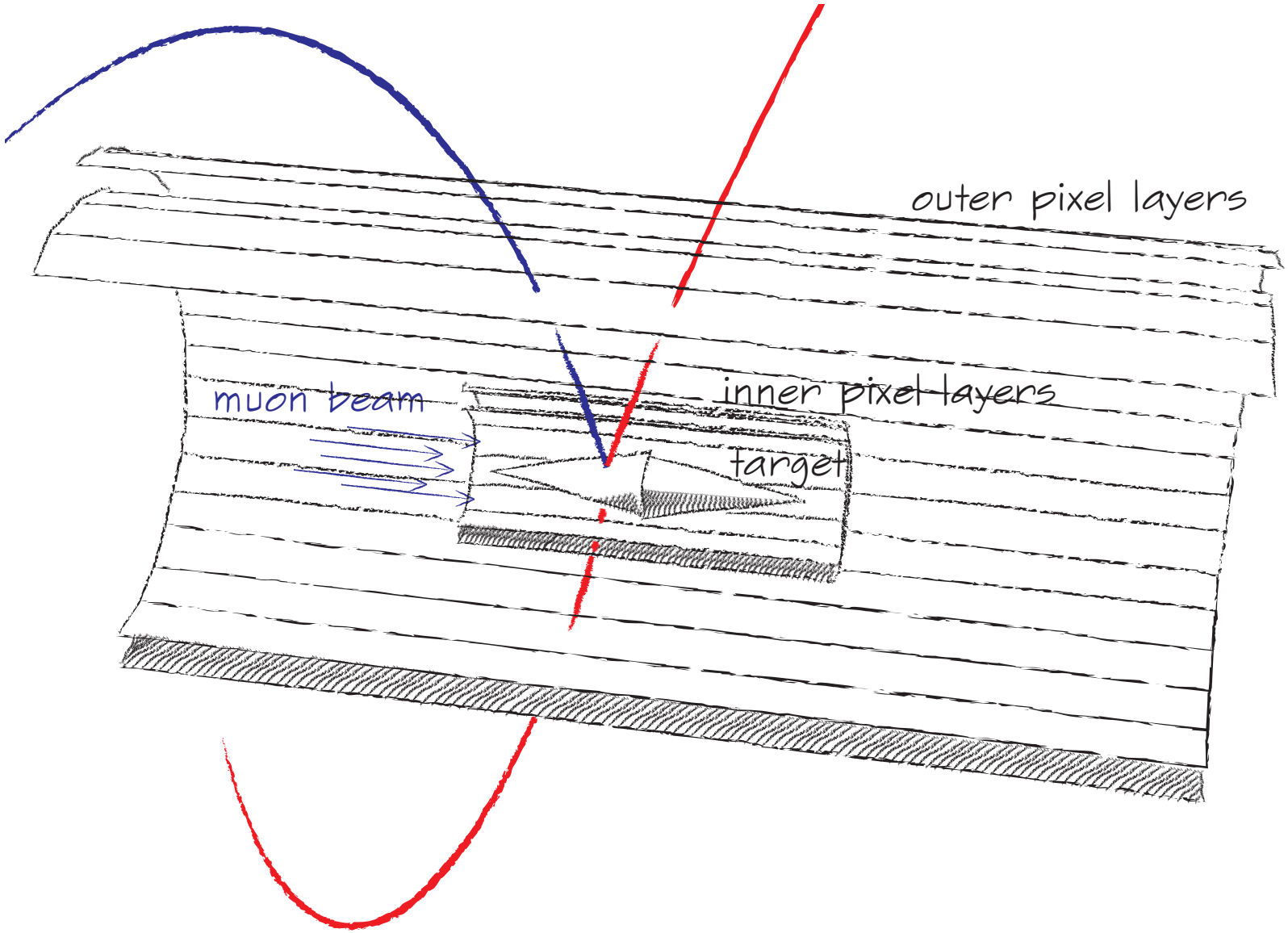
Detector Design



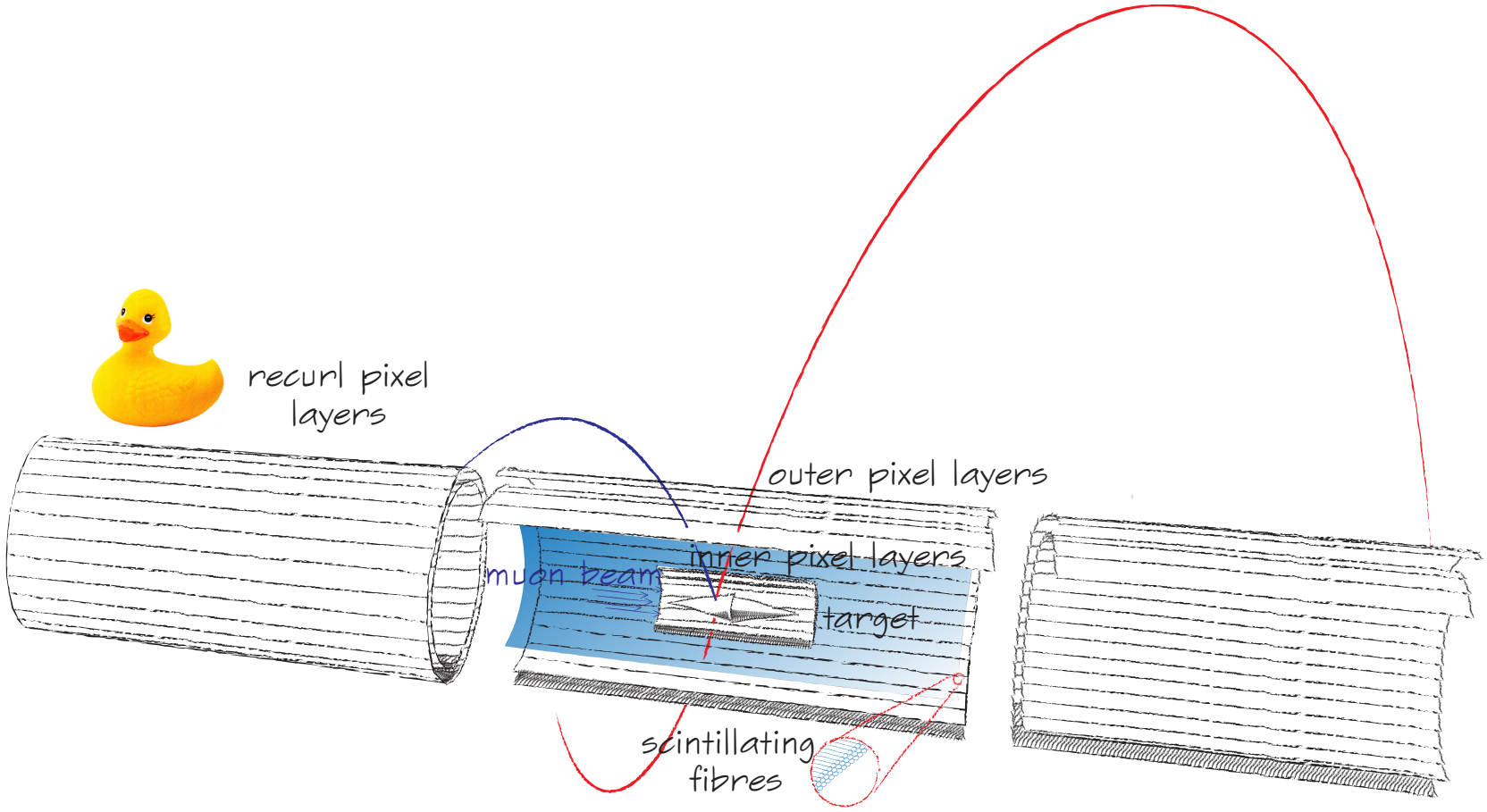
Detector Design



Detector Design



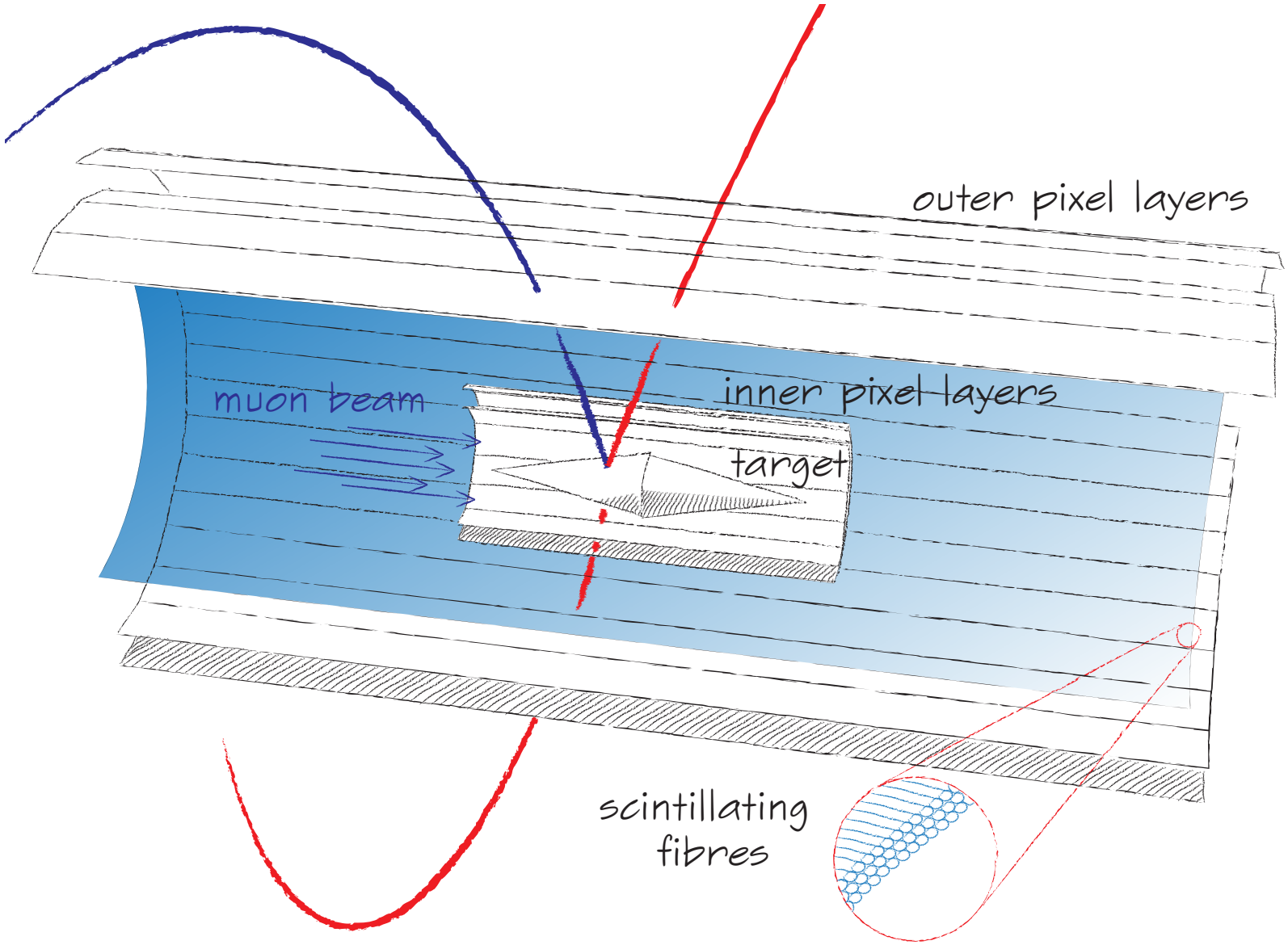
Detector Design



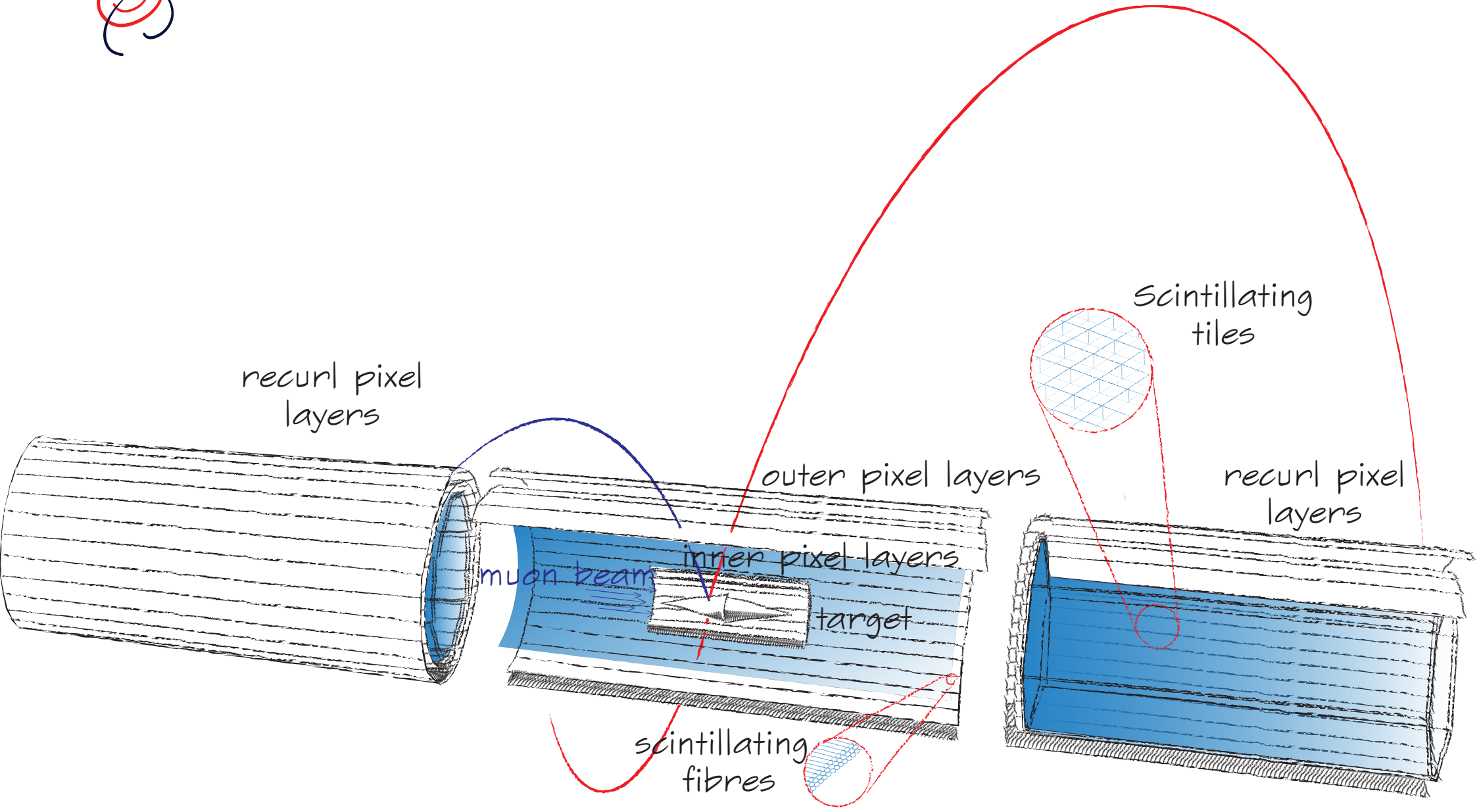
Need further suppression of accidental background:

Timing

Detector Design

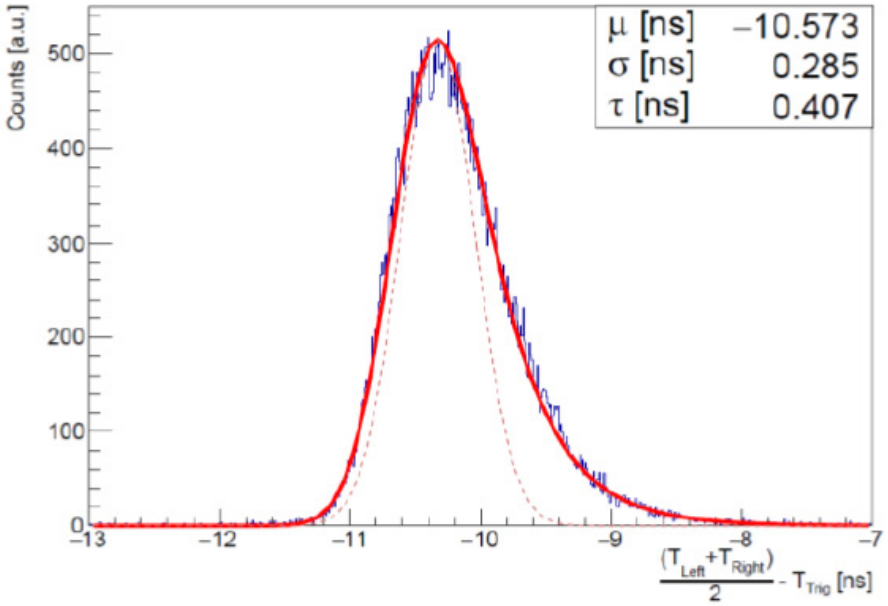


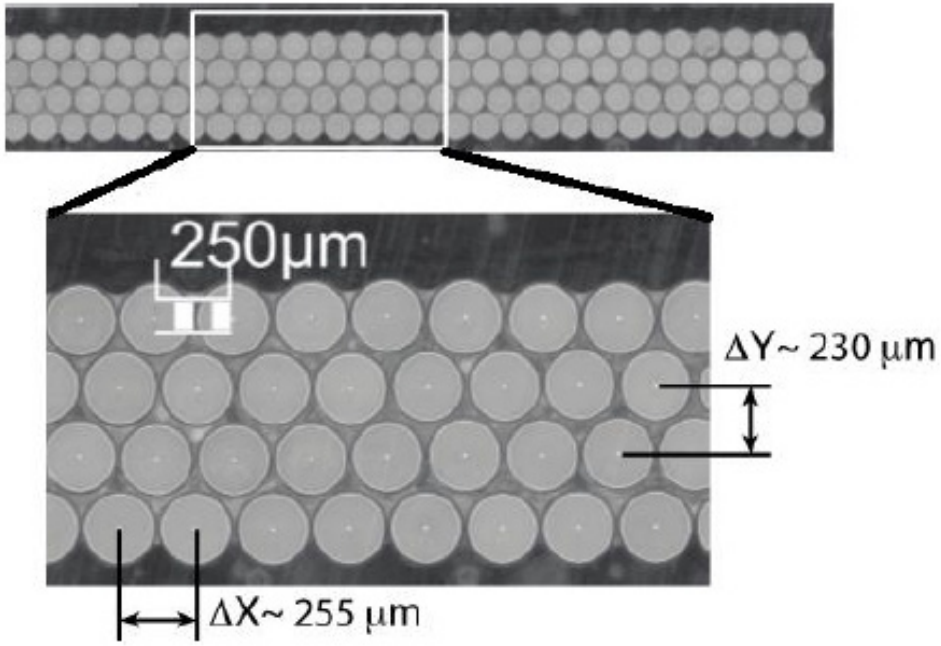
Detector Design



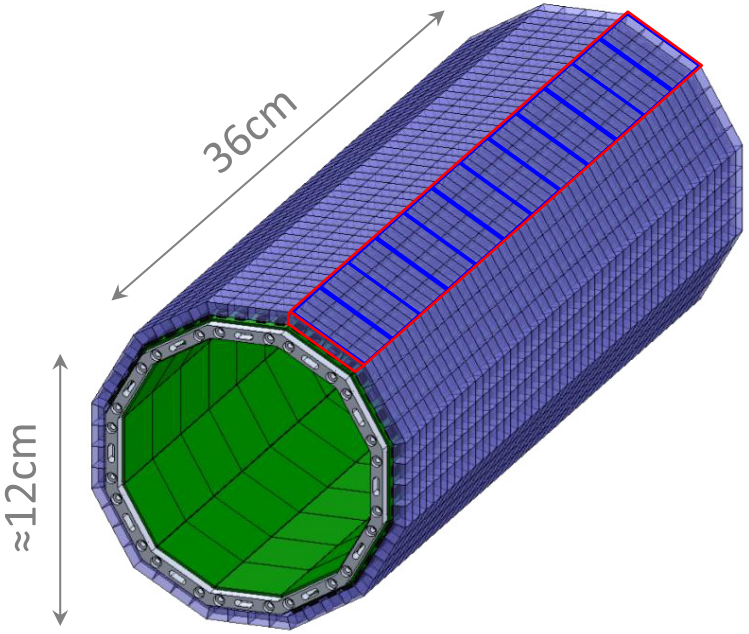
Timing Detector: Scintillating Fibres

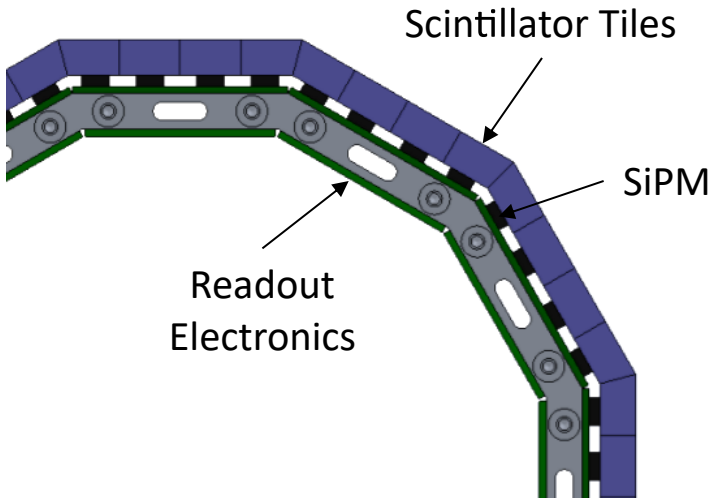
- 3 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)
- Timing resolution < 0.5 ns



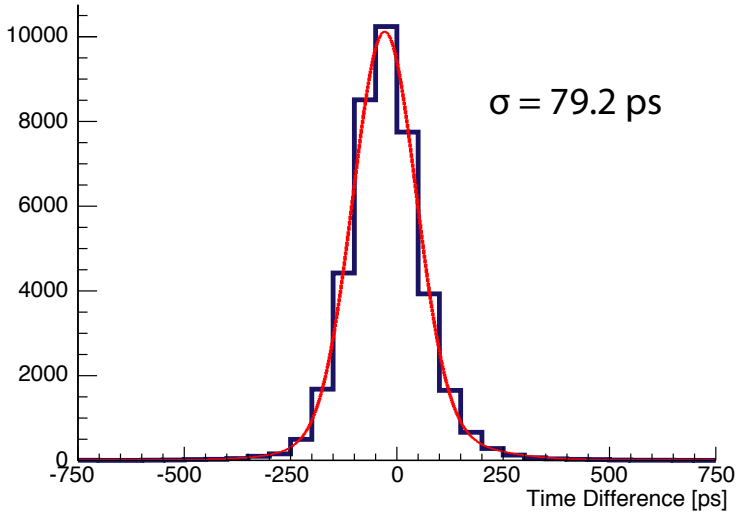


Timing Detector: Scintillating tiles



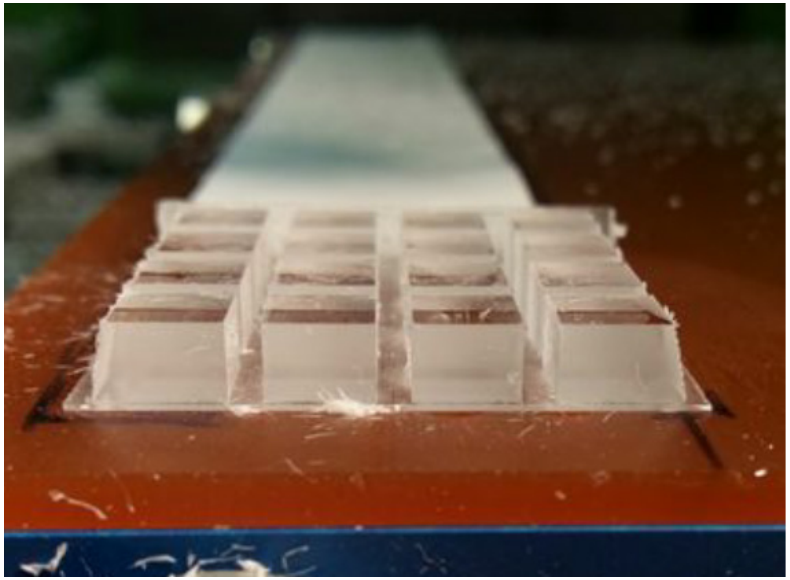


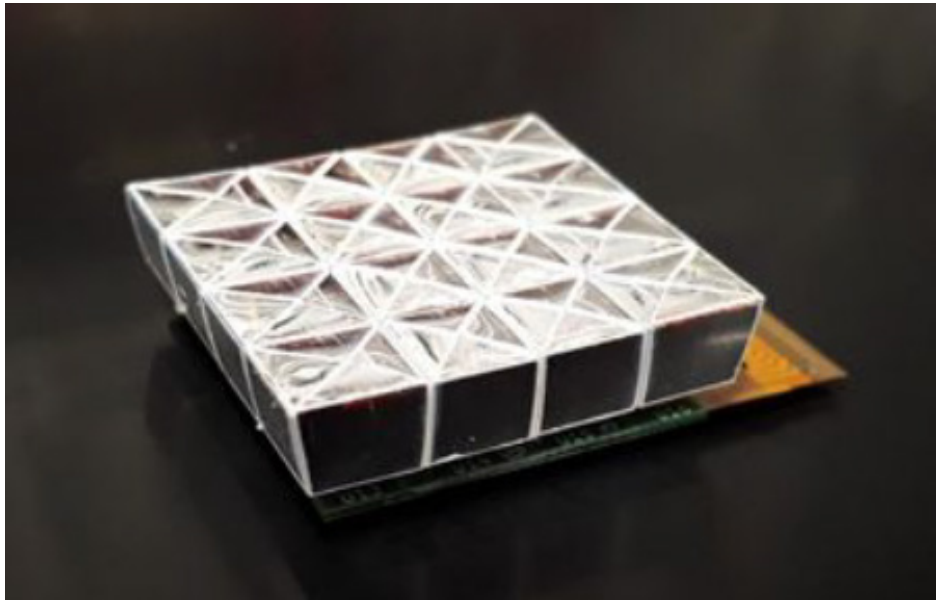
- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)

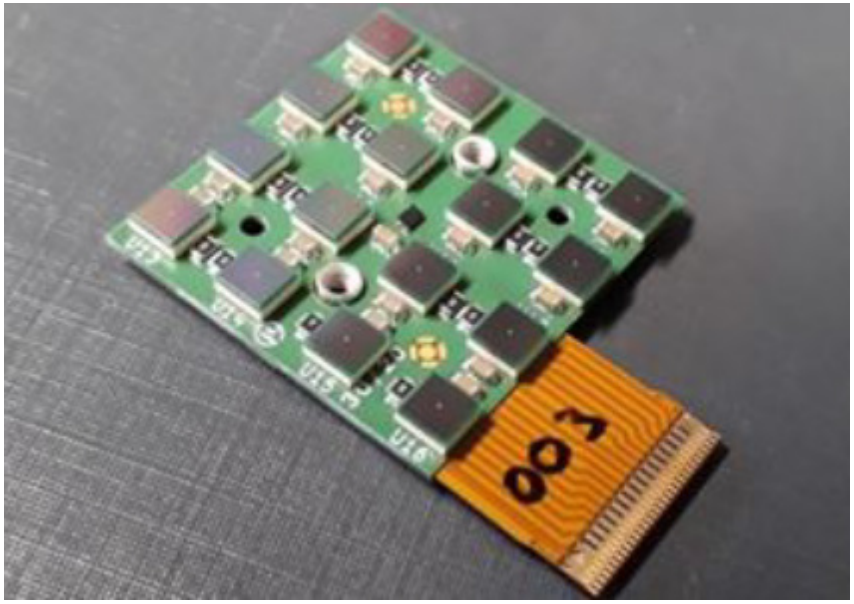


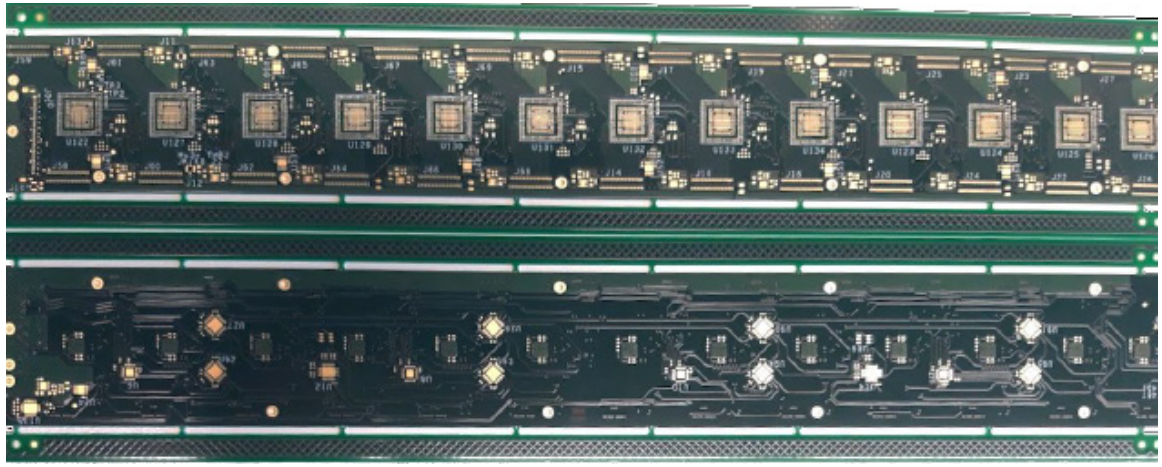
- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps

Timing Detector: Scintillating tiles



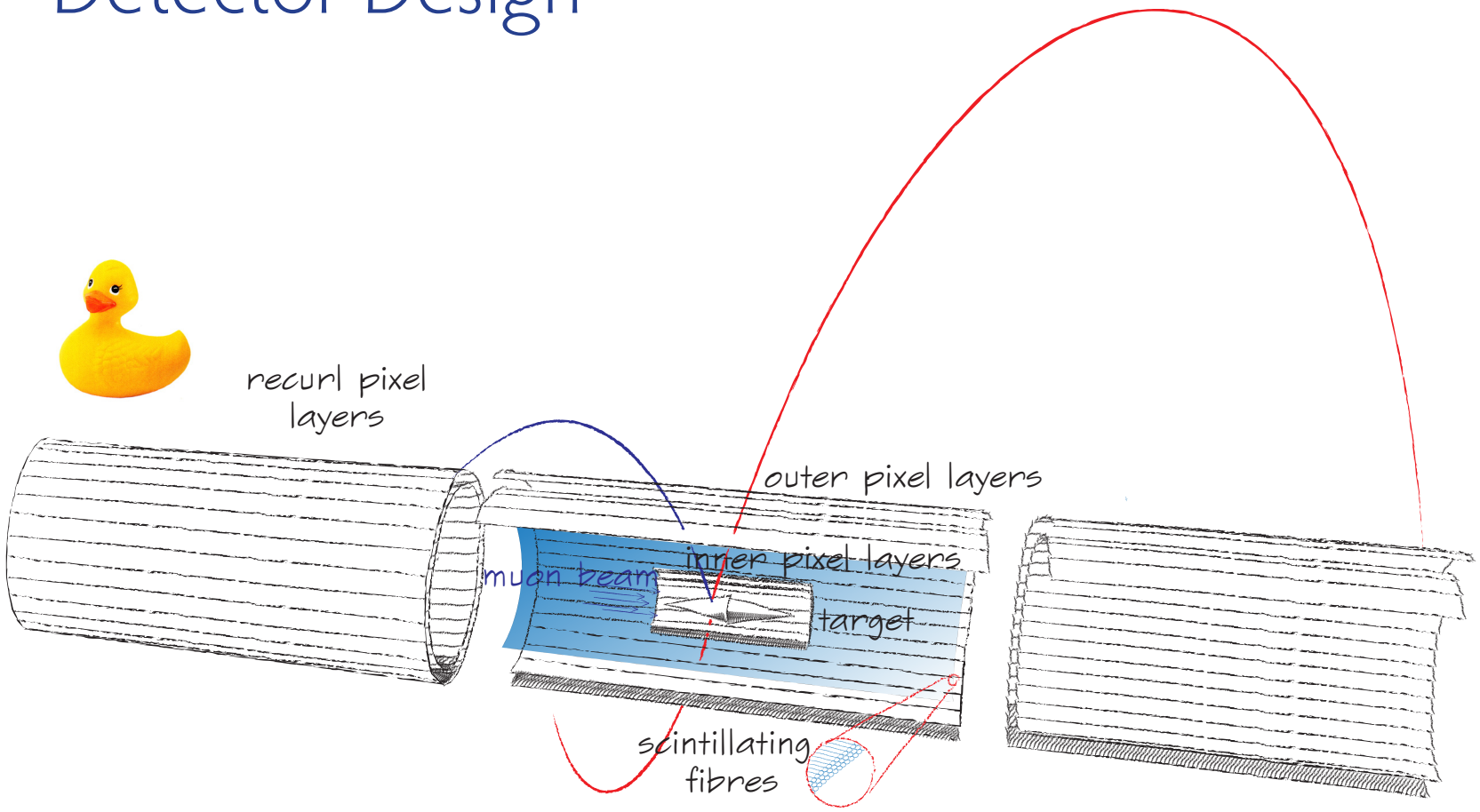






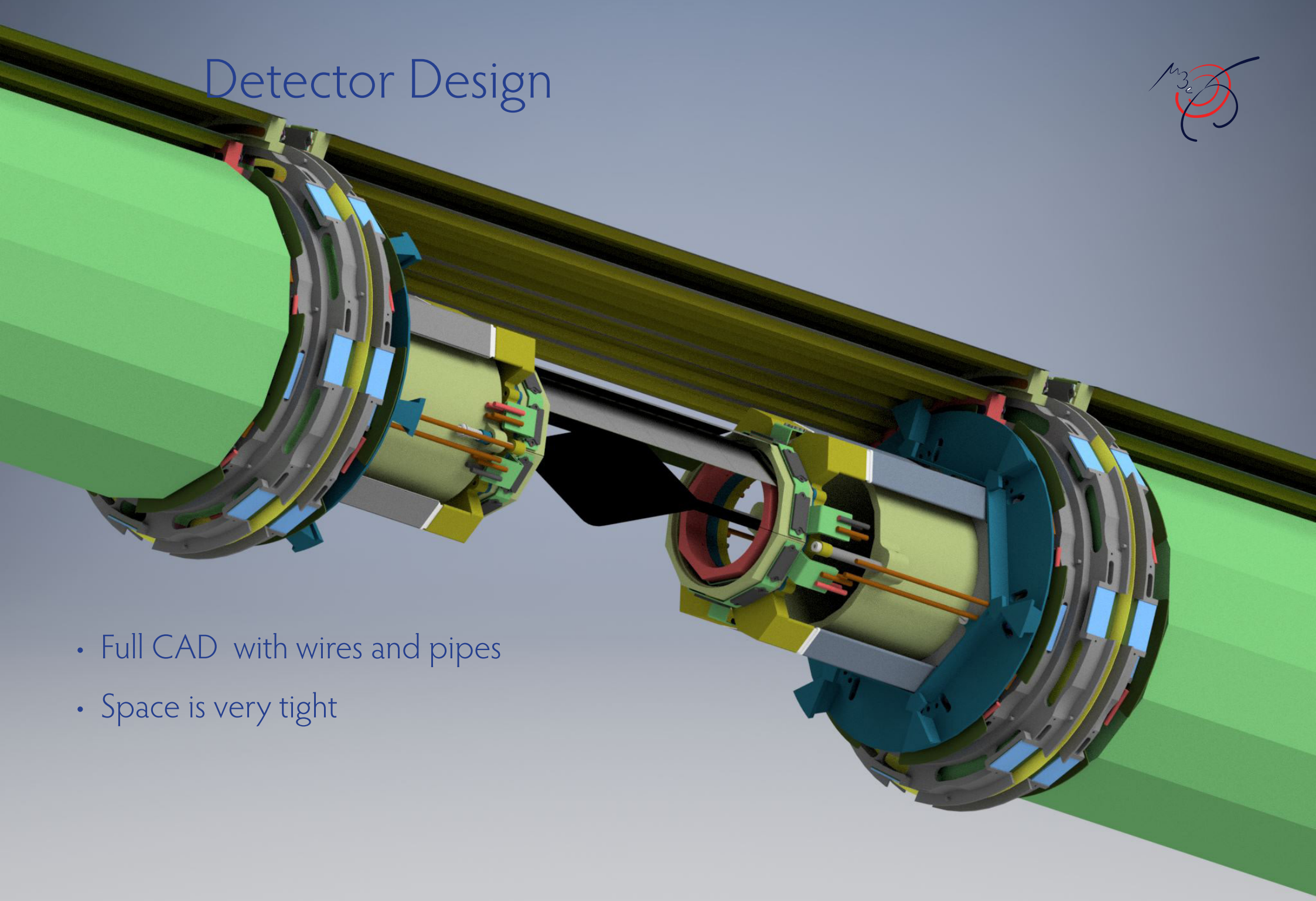
Long thin tube detector: Integration challenges

Detector Design

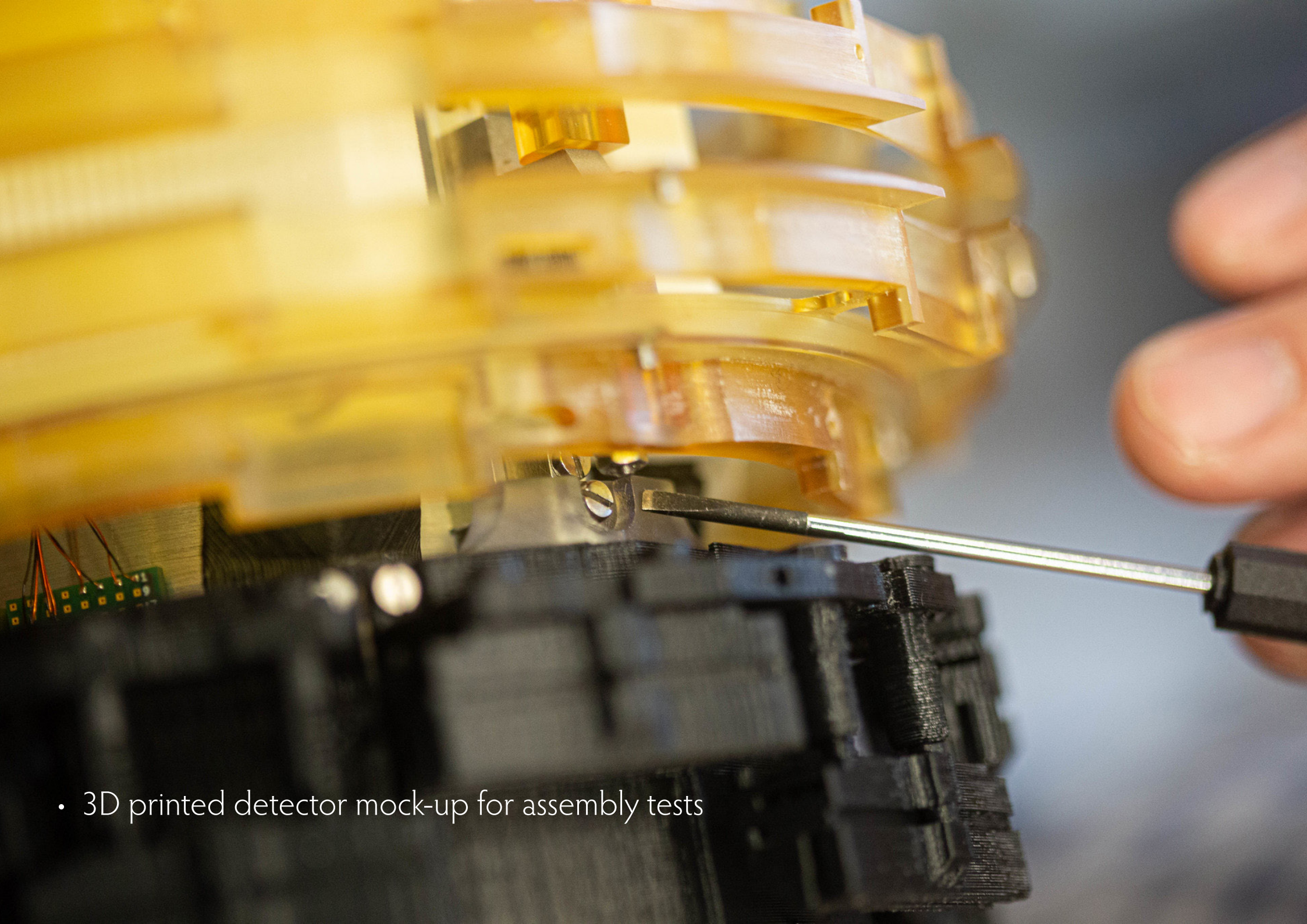


All services for all subdetectors around the beam pipe in the recurl stations

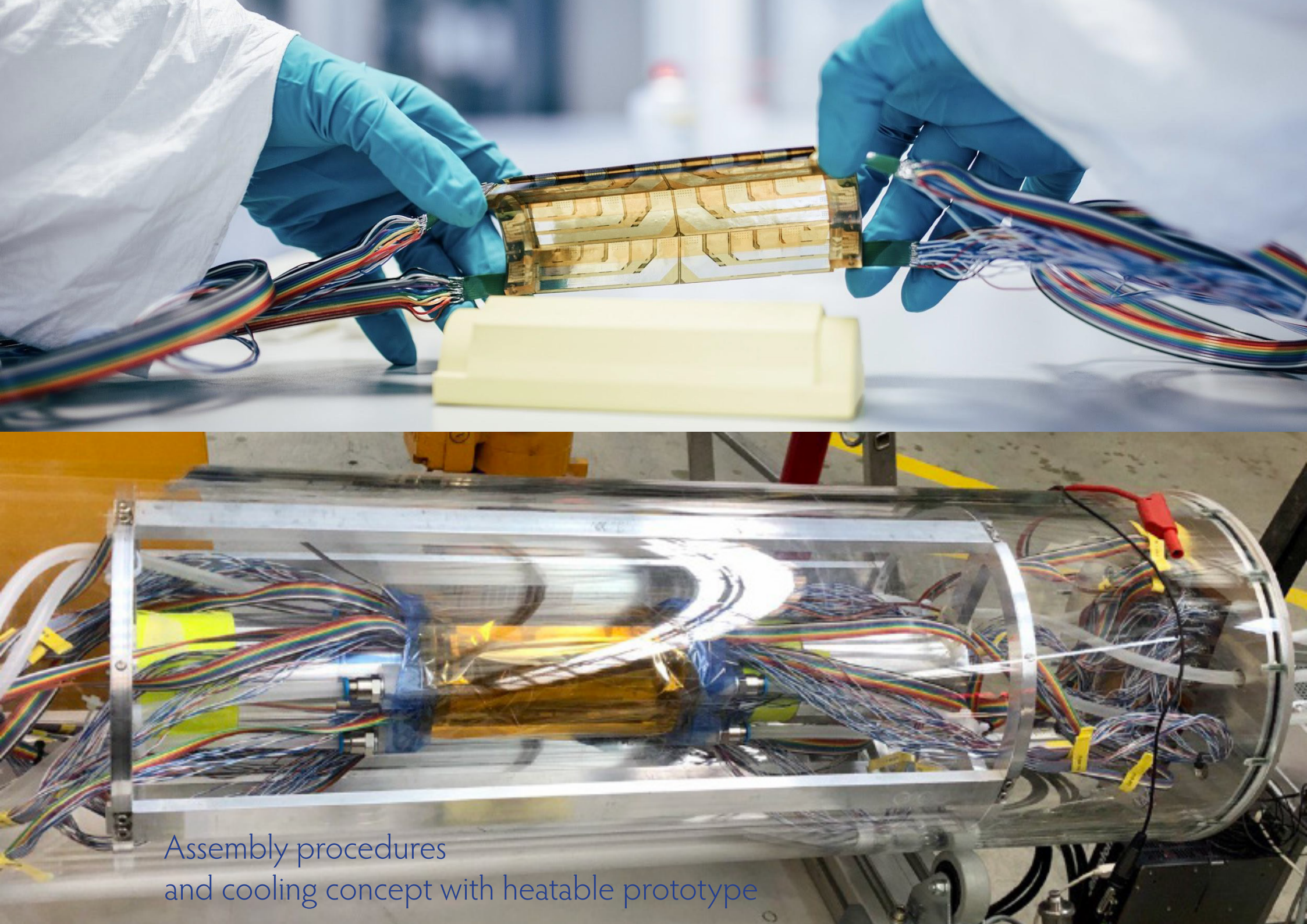
Detector Design



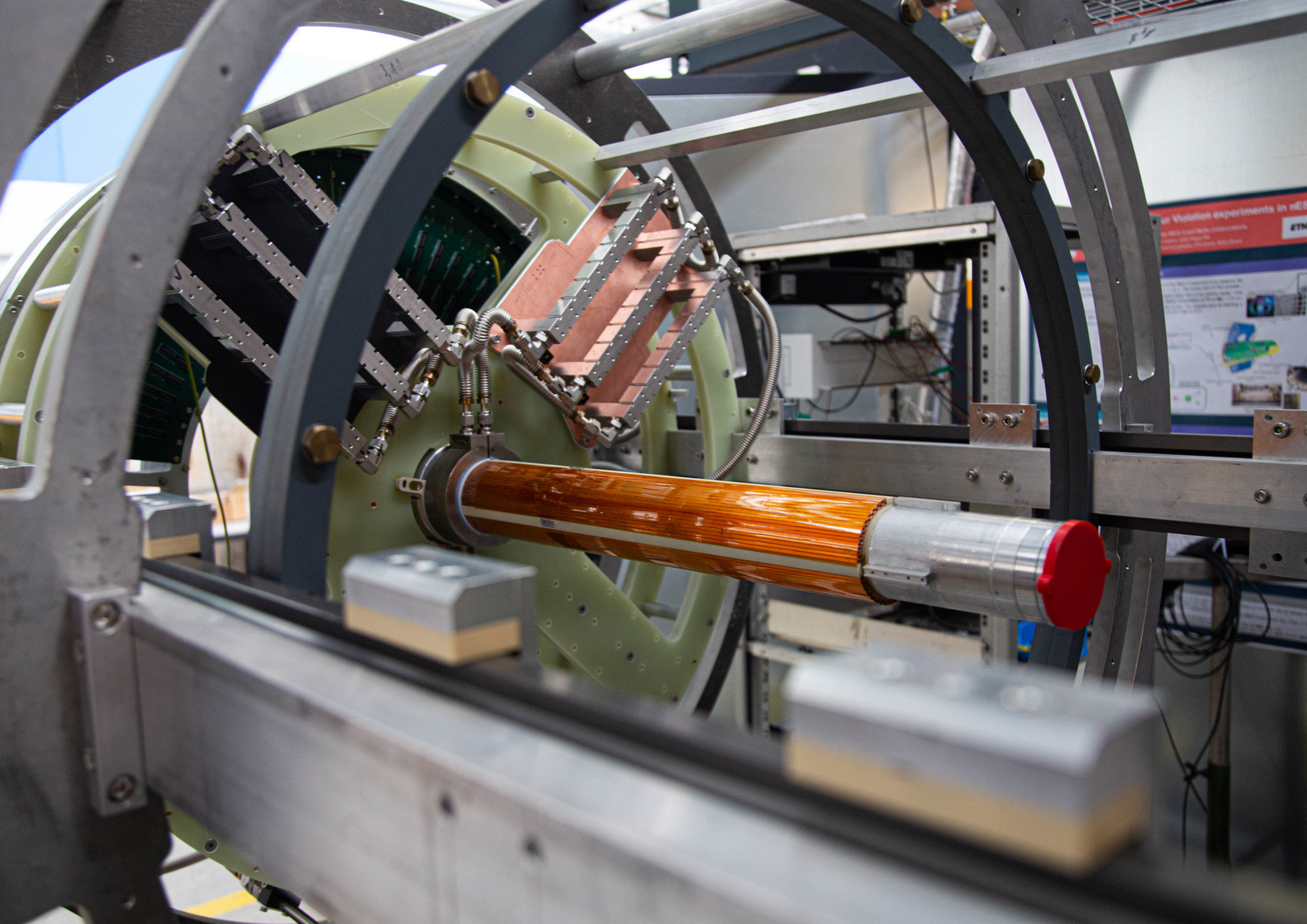
- Full CAD with wires and pipes
- Space is very tight

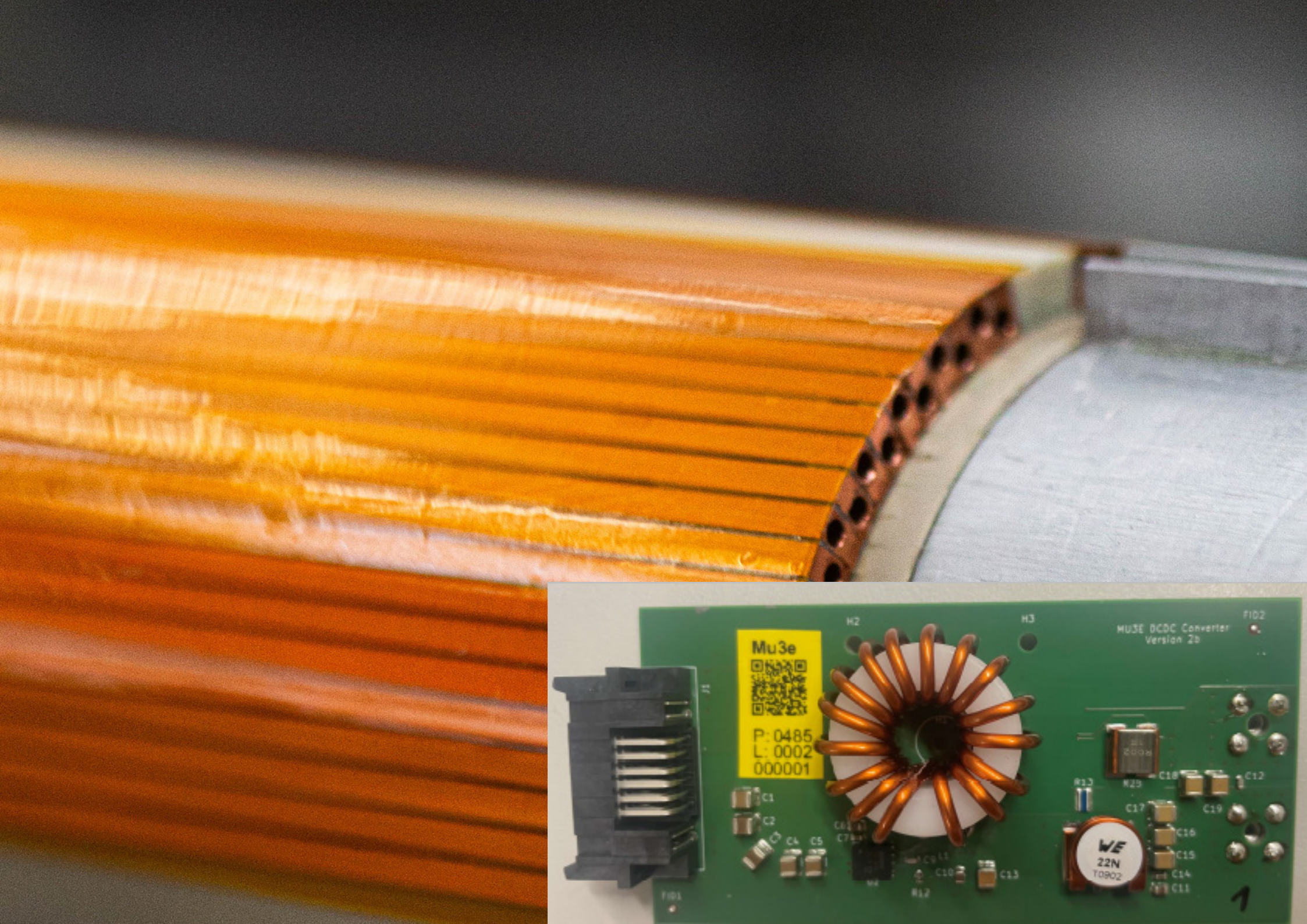


- 3D printed detector mock-up for assembly tests



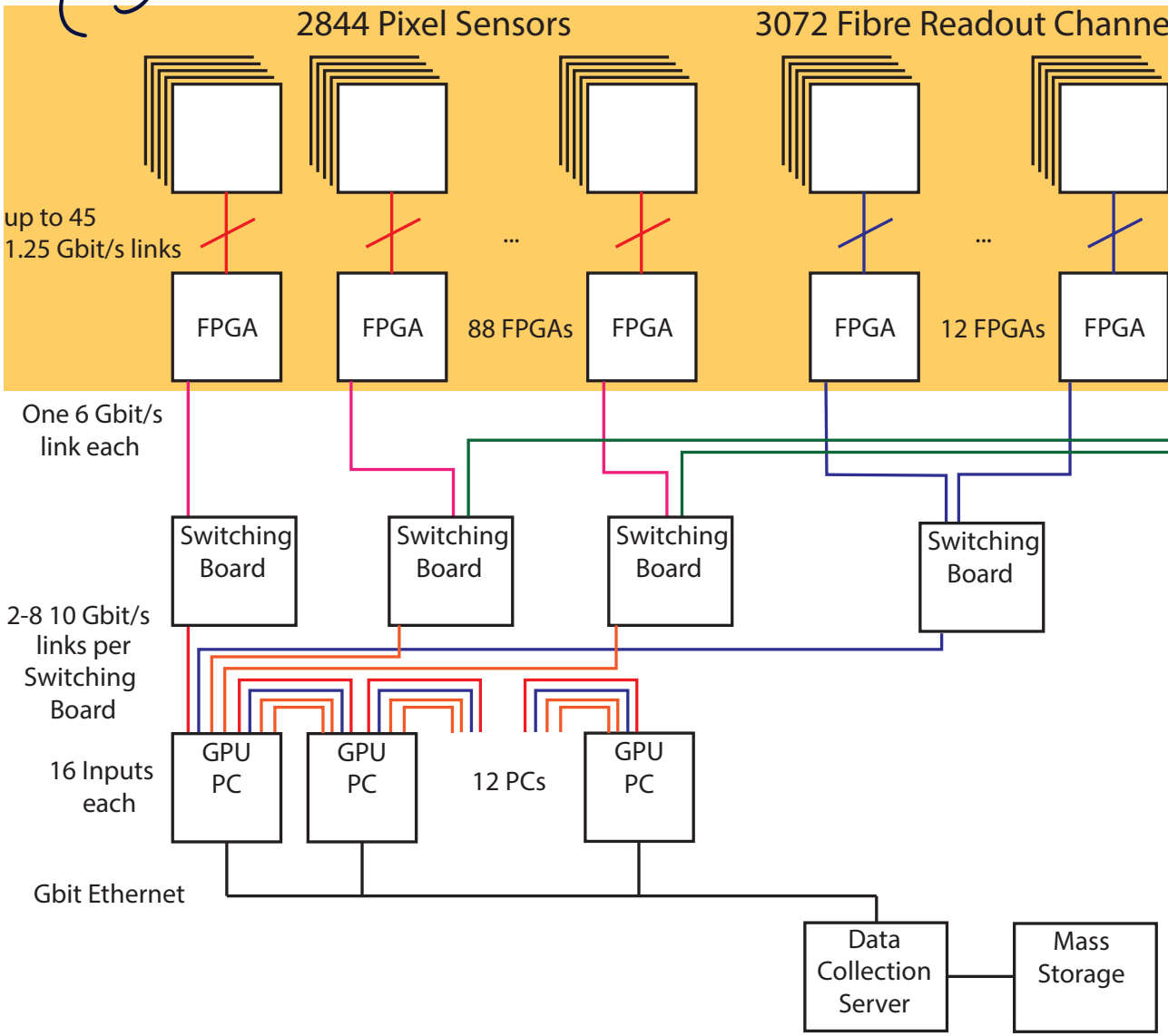
Assembly procedures
and cooling concept with heatable prototype




Mu3e
P: 0485
L: 0002
000001
MU3E DCDC Converter
Version 2b
H2
H3
FID2
FID1
J1
C1
C2
C3
C4
C5
C10
C13
R12
R23
R25
C18
C12
C17
C19
C16
C15
C14
C11
WE
22N
T0902

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

GPU reconstruction

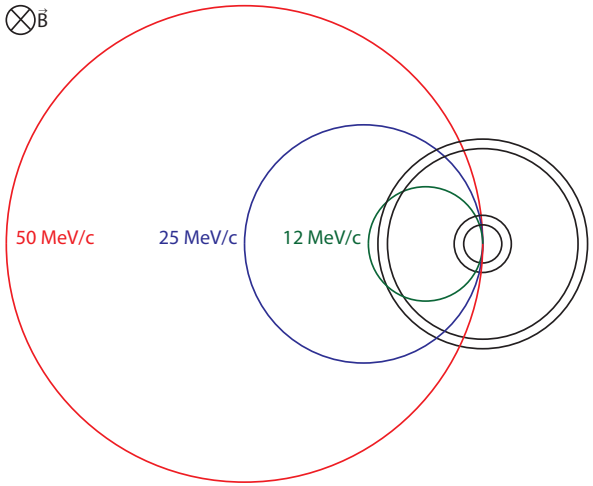
- GPU reconstruction on gaming cards
- Have achieved > 10^9 track fits/s per GPUs (Nvidia GTX 980)
- Twelve GTX 1080Ti are sufficient for dealing with 10^8 muon decays/s

  ~ 8 years pass

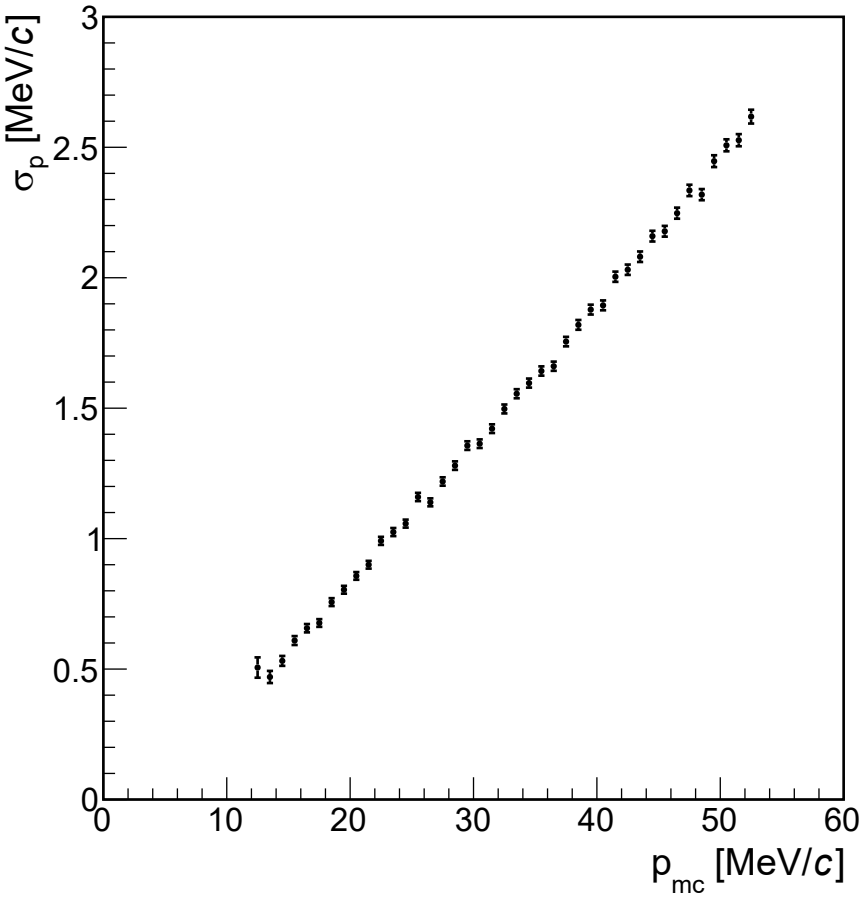
- Just four RTX 4090 can handle Mu3e phase I...

Performance simulation

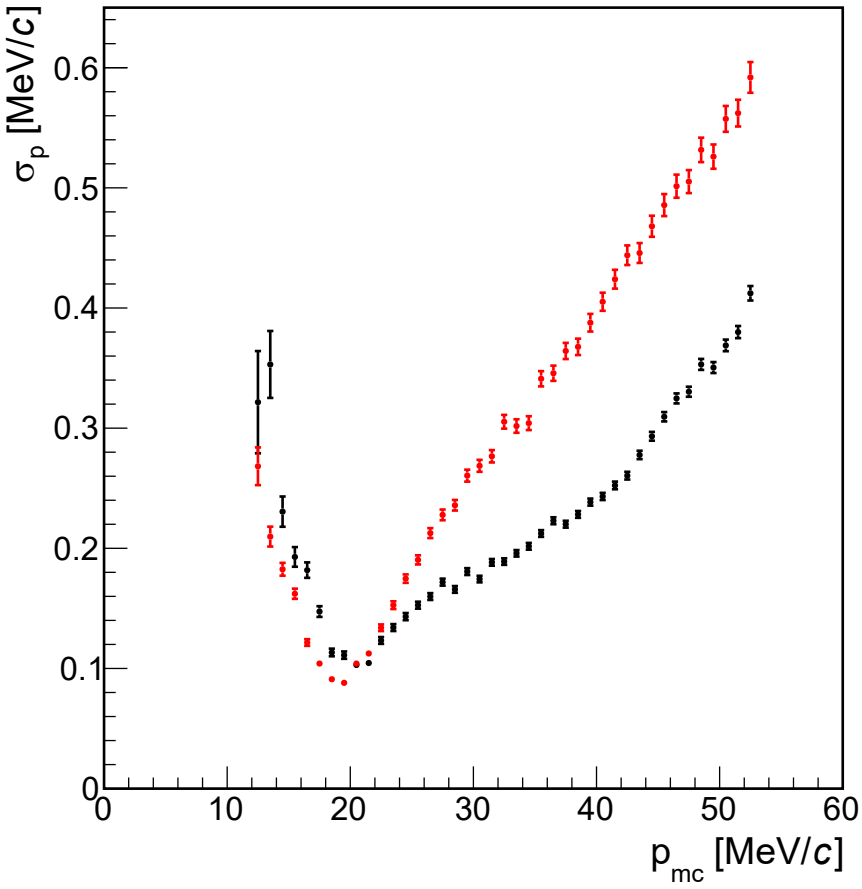
Momentum resolution



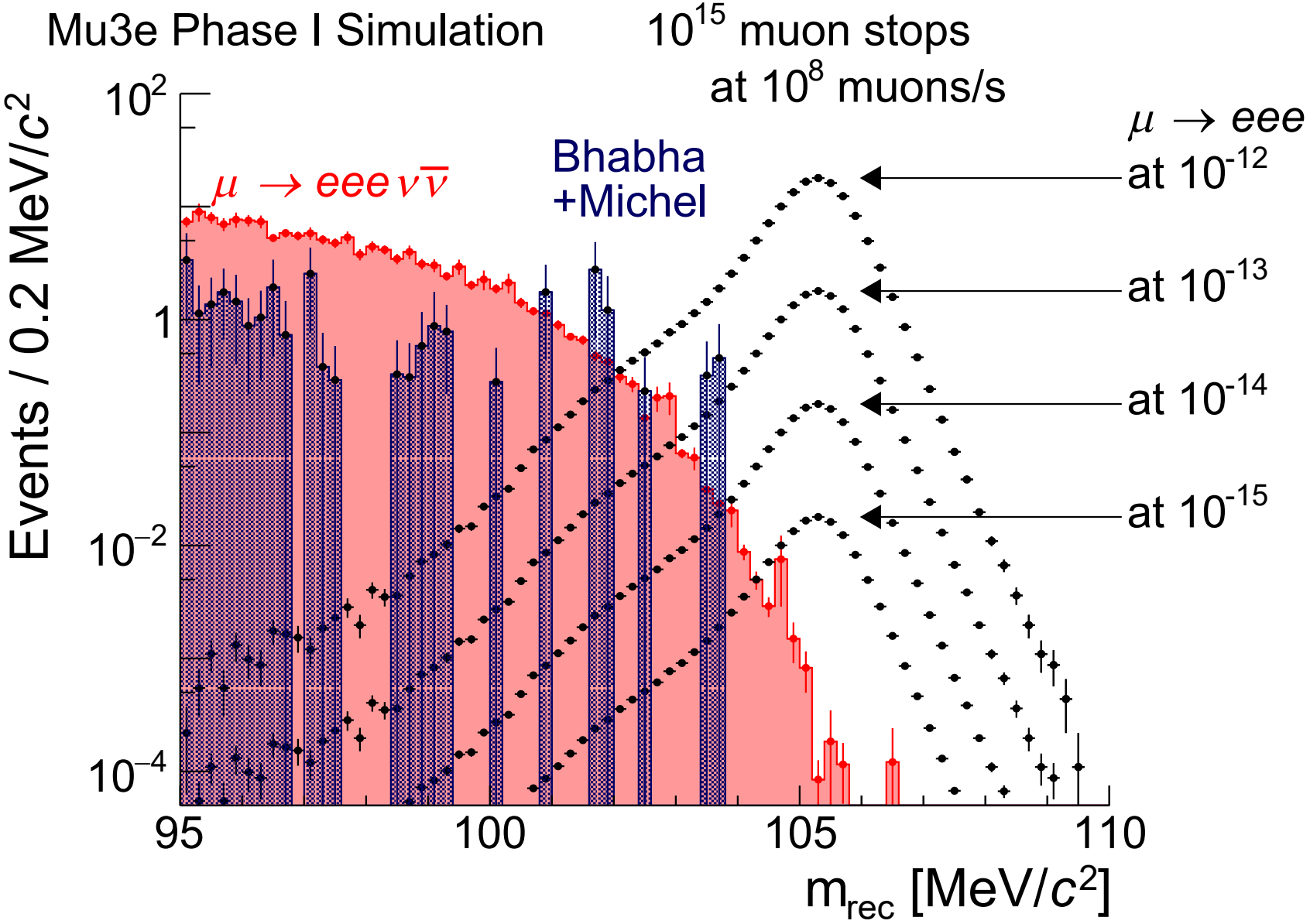
Outgoing part of tracks only



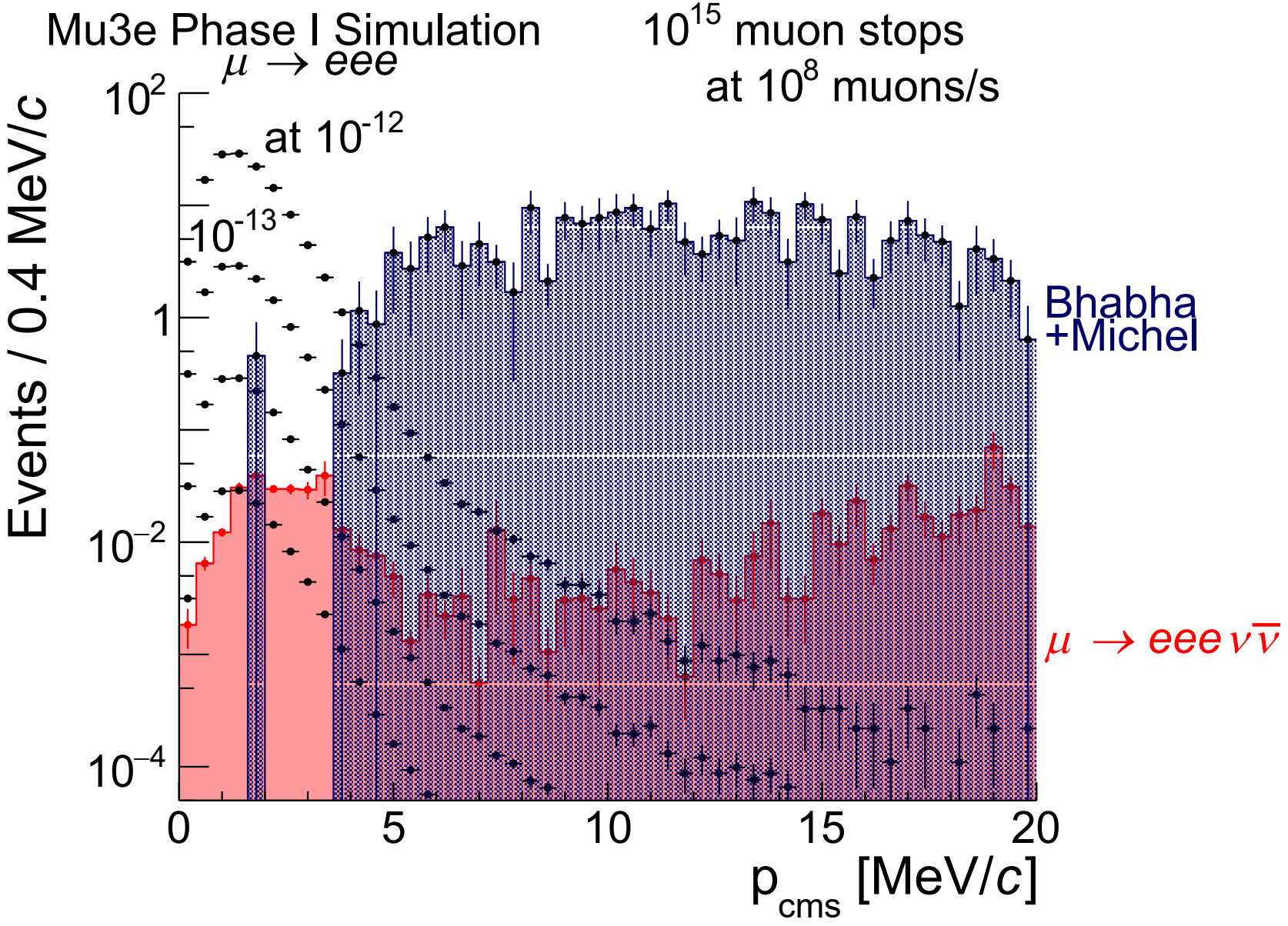
Recurling tracks



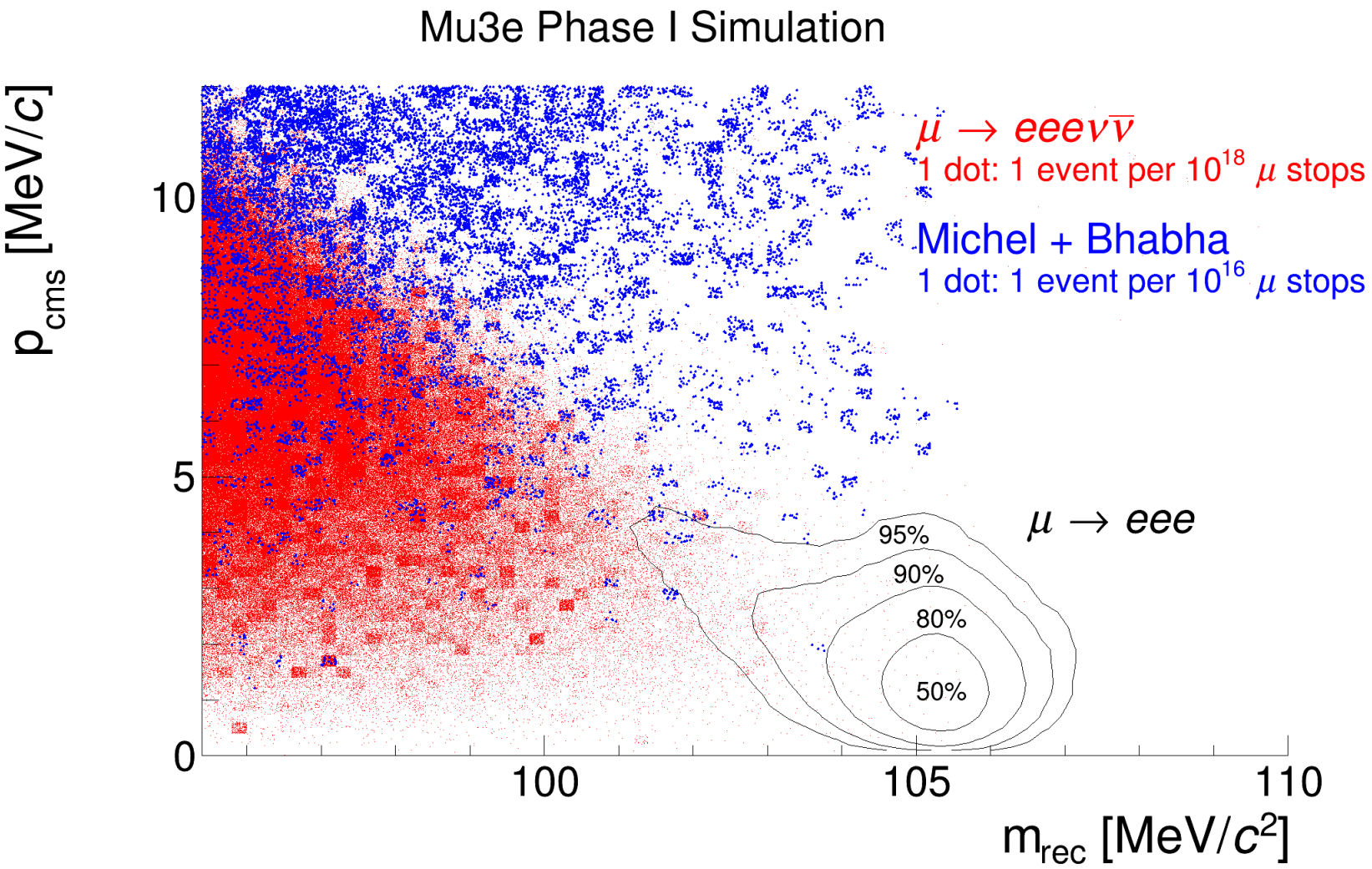
Mass distribution



Momentum distribution

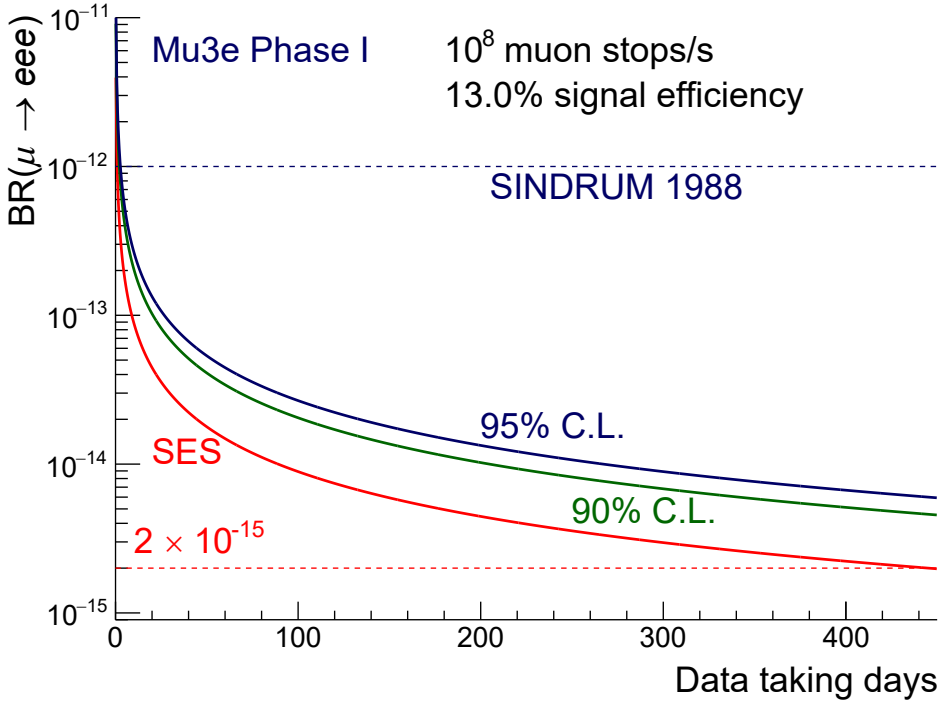


Mass/Momentum distribution



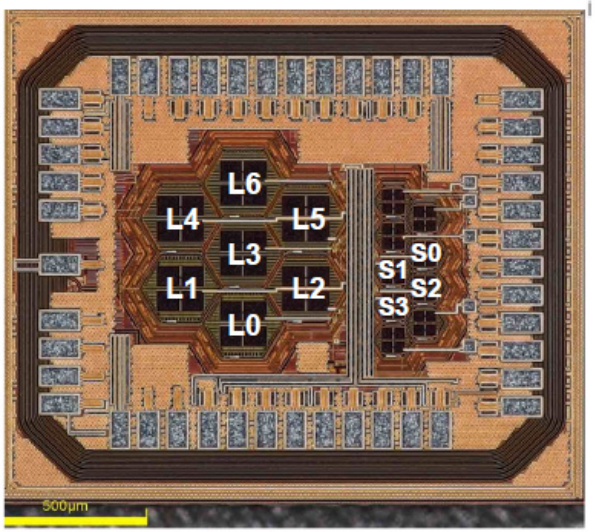
Sensitivity

- Phase I expected SES is a few 10^{-15}
- Upgrade to high-intensity muon beam line likely in 2027
- 20 times more beam:
  A lot of new challenges
- Gradual transition to Phase II



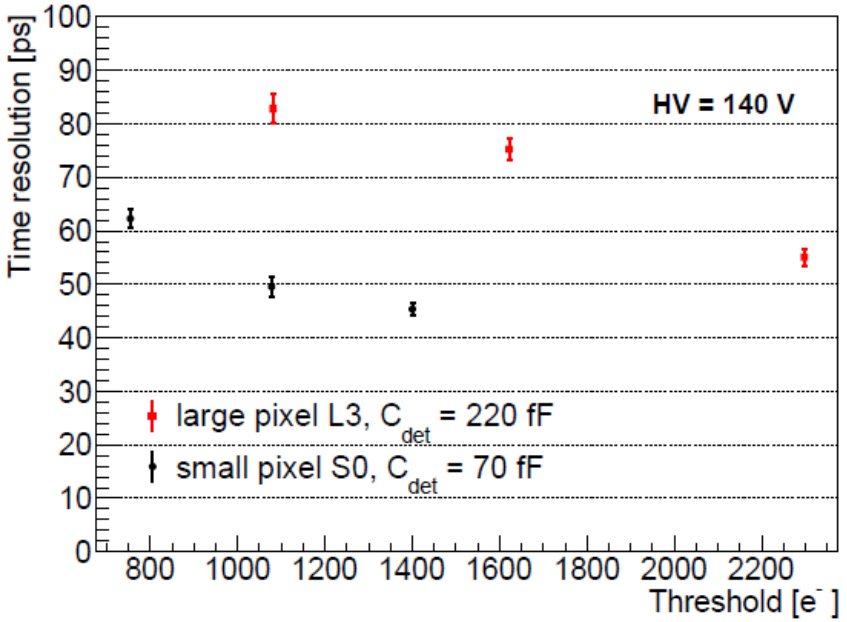
Phase II requirements and ideas

G. Iacobucciet al. 2019
JINST 14 P11008



Better timing:

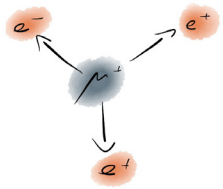
- Replace scintillating fibres by super-fast pixel detector O(100 ps)
  (SiGe, gain layer,...)
- Push HV-MAPS timing to O(1 ns)

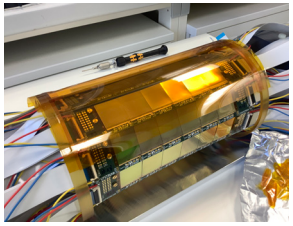


More acceptance, less material:

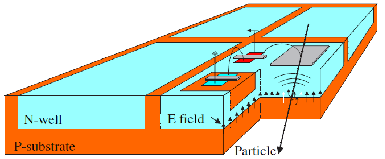
- Longer pixel modules
- Carbon fibre supports
- Serial powering
- Chip-to-chip communication
- ...

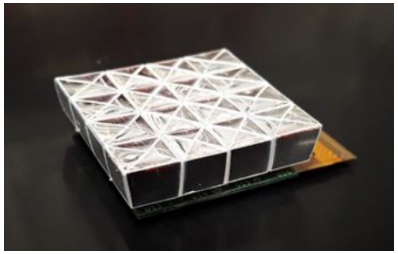
Conclusion

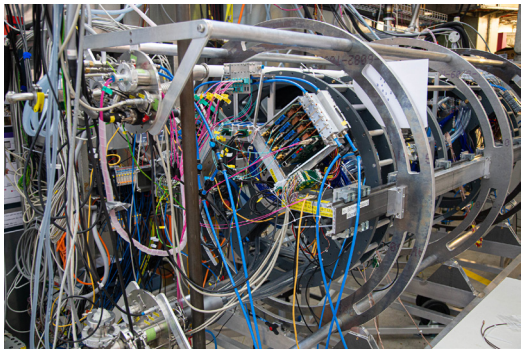


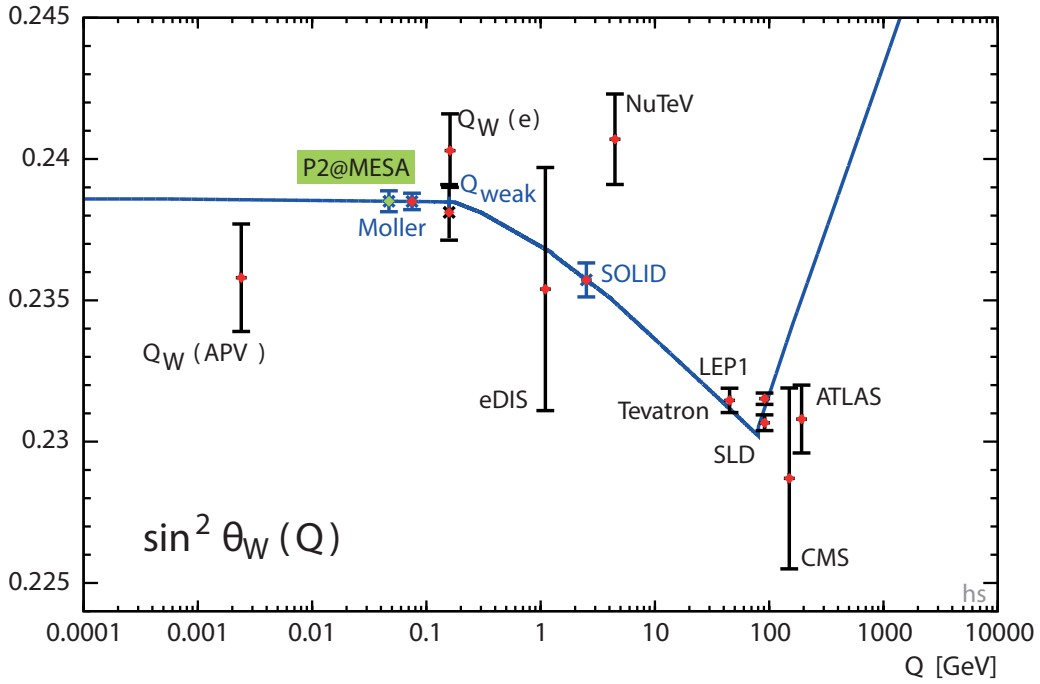


- Mu3e aims for μ → eee at the 10^{-16} level
- First large scale use of HV-MAPS
- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct >10^8 tracks/s in ~100 Gbit/s on ~4 GPUs
- Integration and commissioning 2024/25
- … and then finally data!







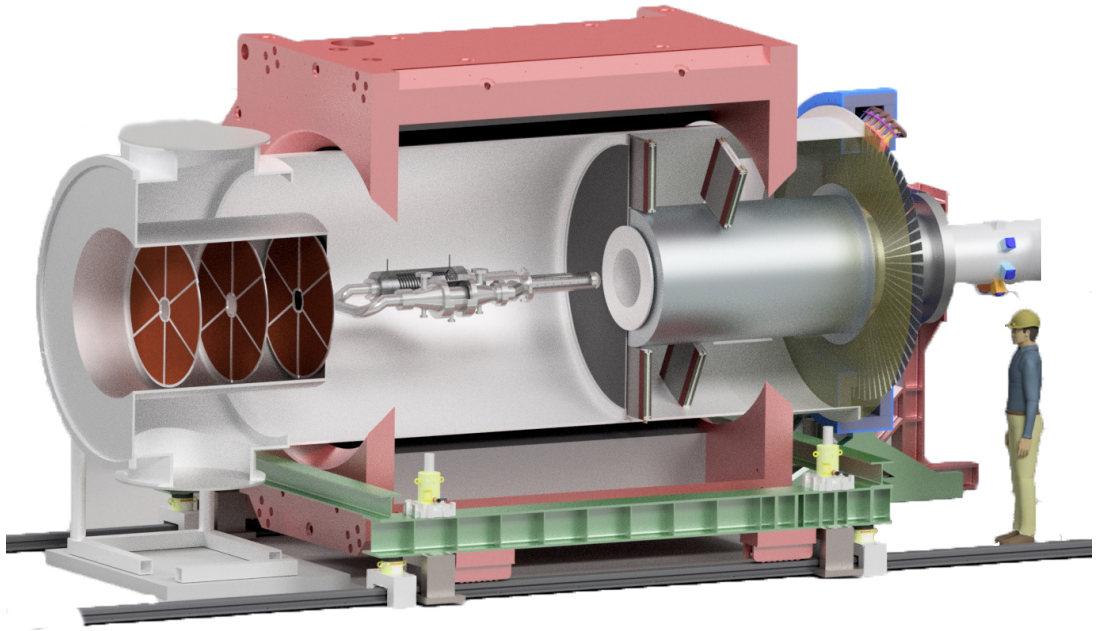


P2 @ MESA

- Low-energy, high current Mainz Energy-Recovery Superconducting Accelerator MESA
- P2 aims to measure the weak mixing angle in parity violating electron scattering

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}(Q_W - F(Q^2))$$

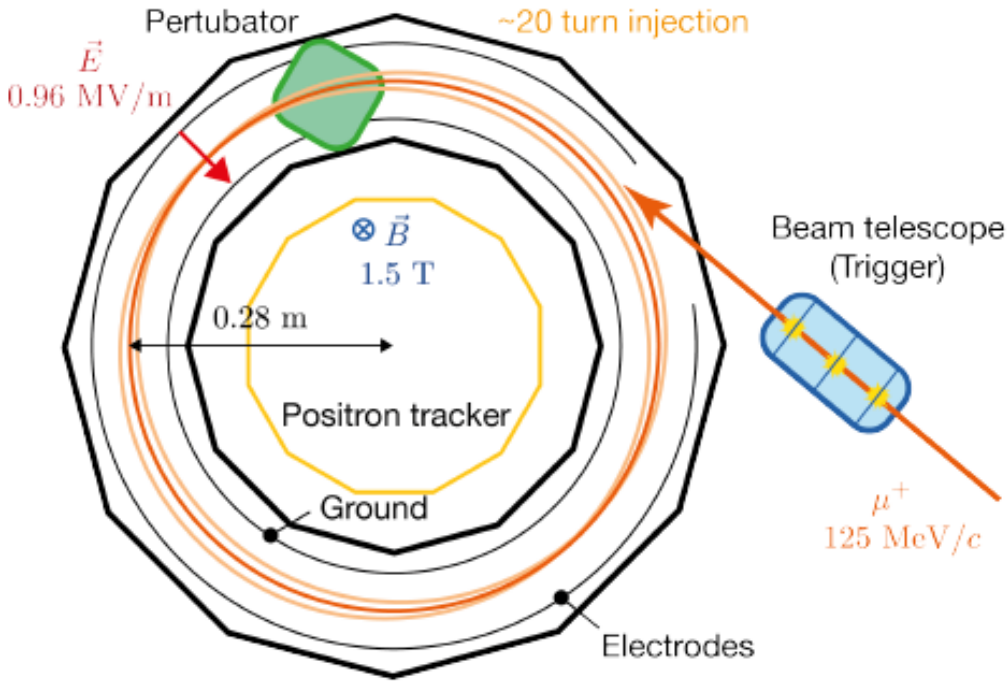
$$\sin^2\theta_W = \frac{1 - Q_W}{4}$$



- Tracking detector for Q^2 measurement

More experiments/ideas

- Muon electric dipole moment using frozen spin technique



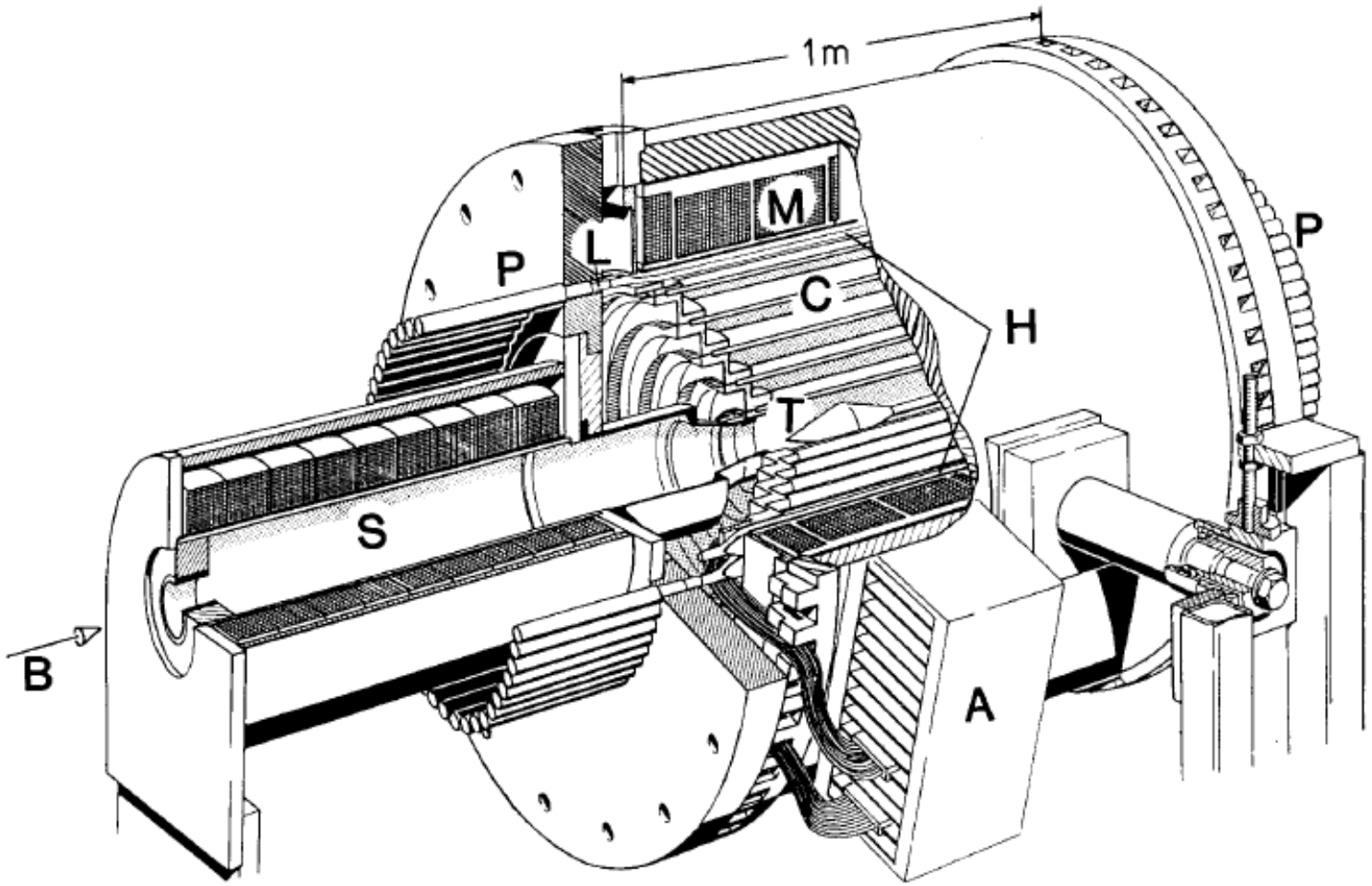
- Parity violation in muonic atoms
- μ → eγ with photon conversion

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

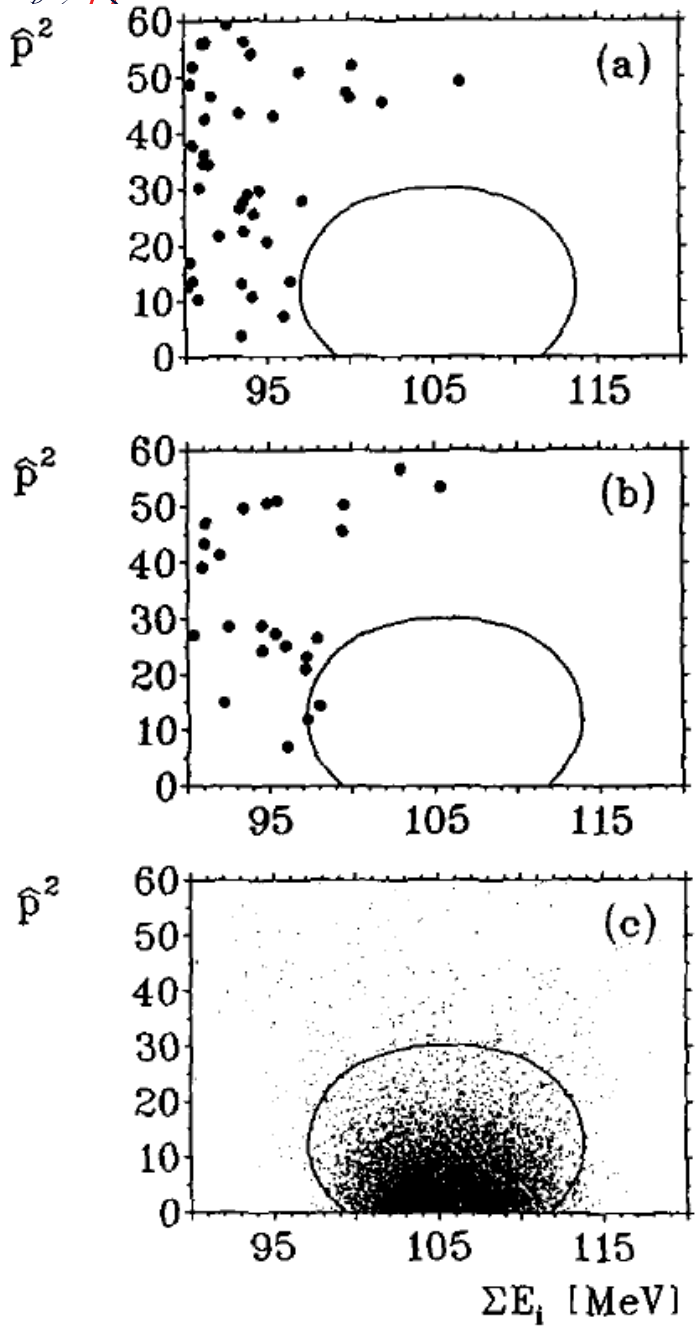
A: Preamplifiers

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

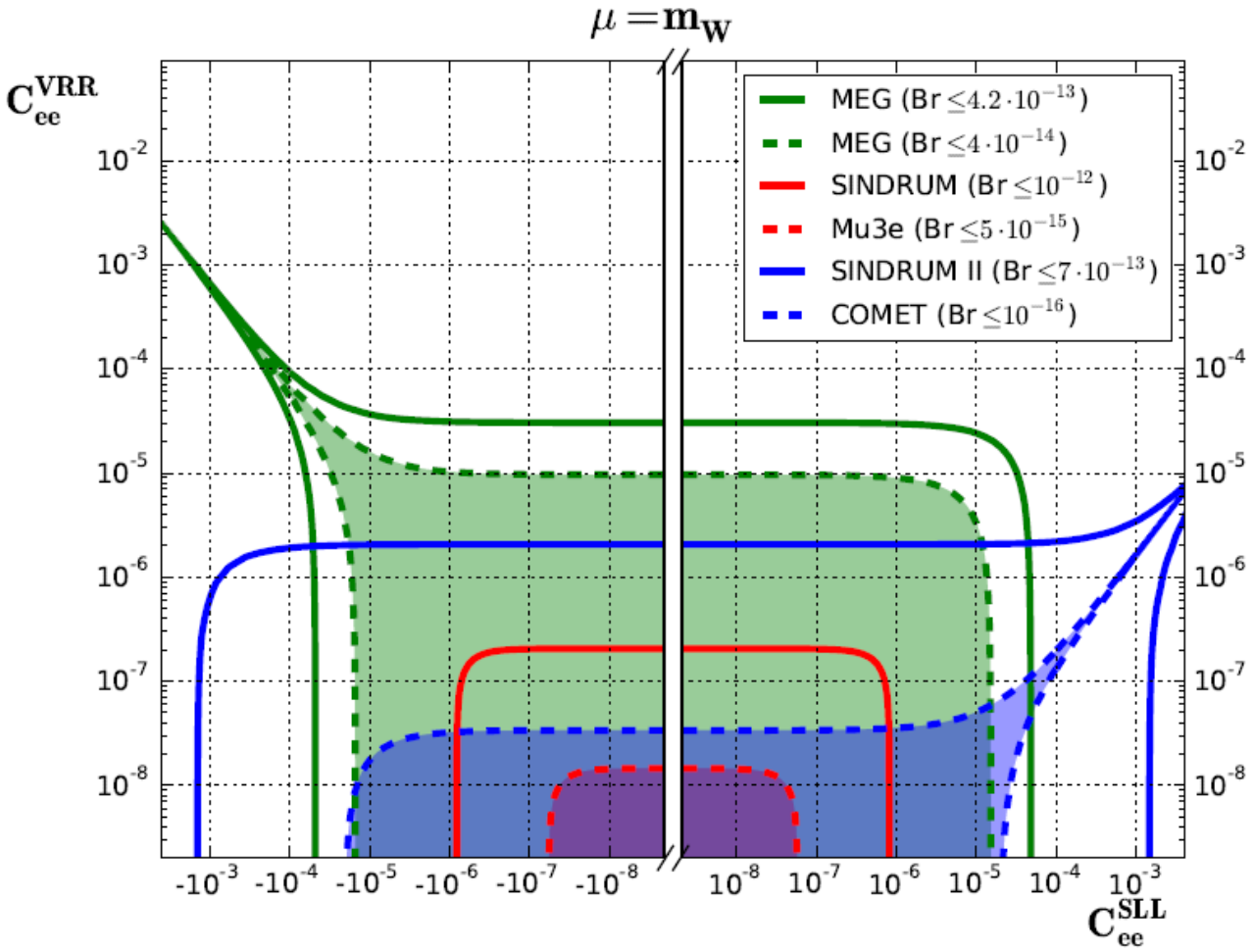
(c) Signal MC with 95% contour

No events in signal area seen:

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

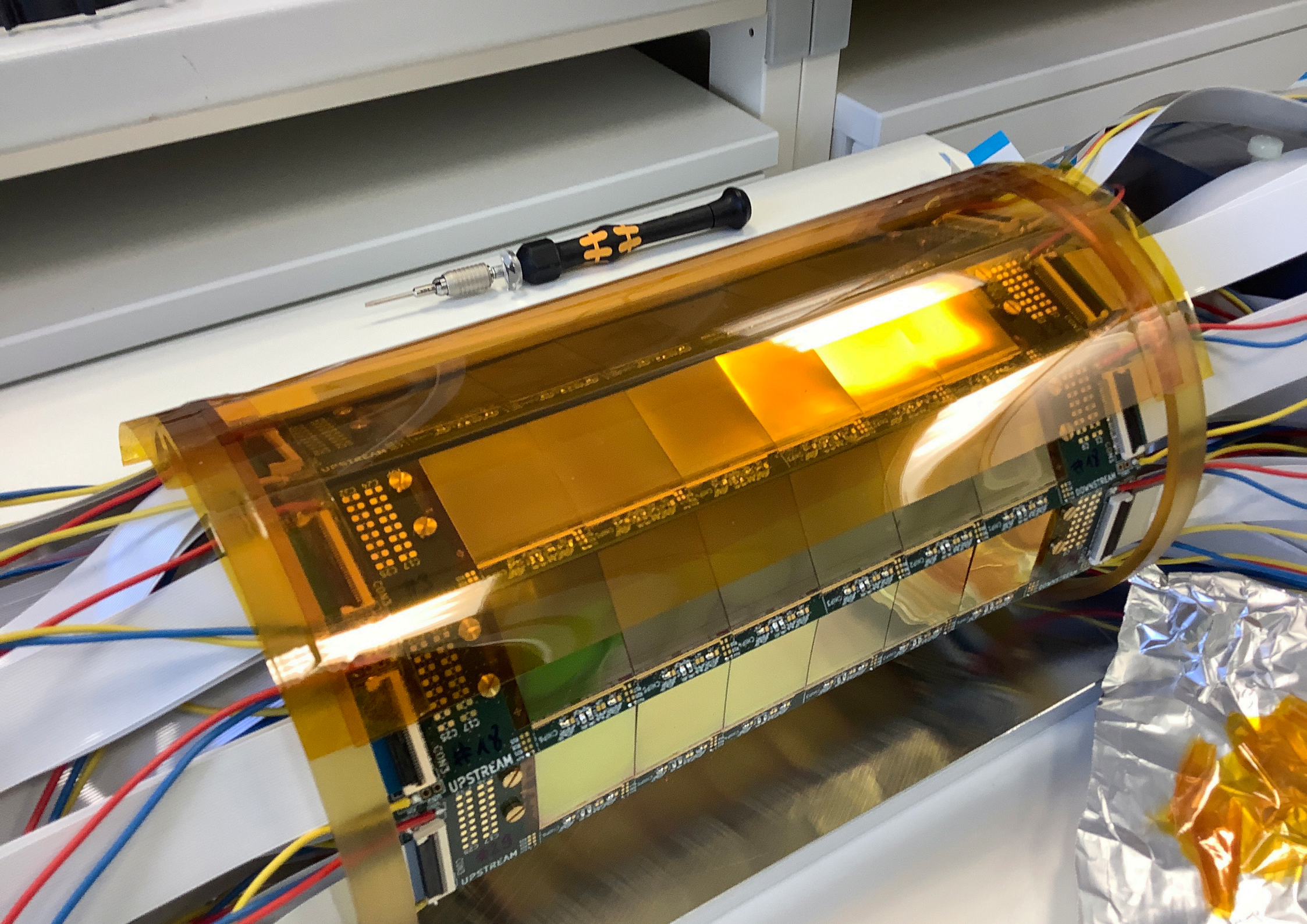
Probably some more potential in the apparatus, ultimately limited by rate capability and momentum resolution

LFV Muon Decay in Effective Field Theory



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

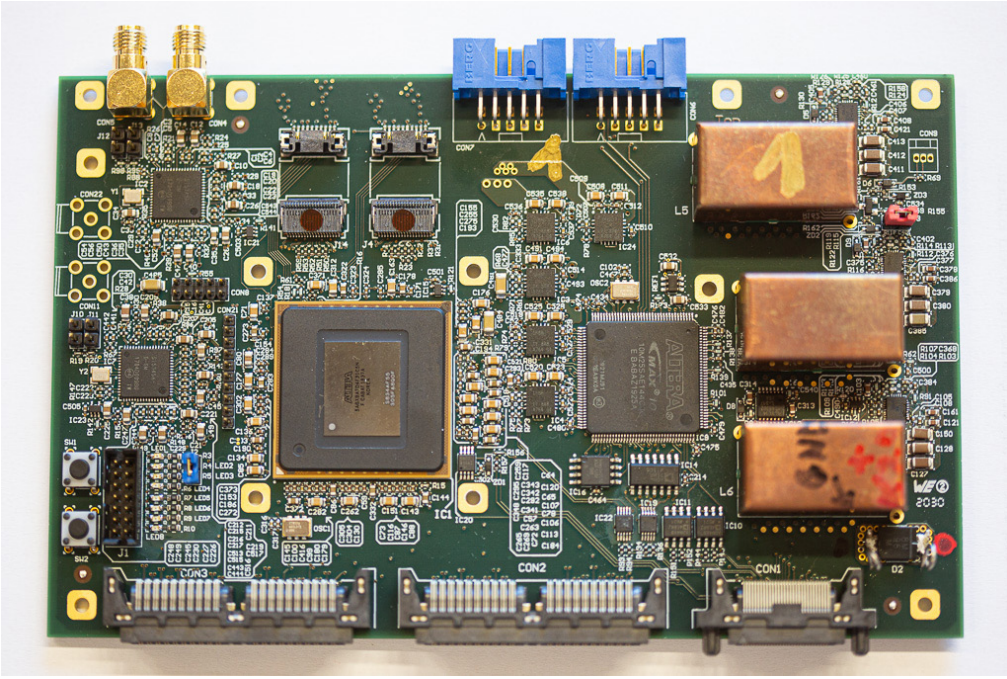
Renormalisation-group improved analysis of μ→e processes in a systematic effective-field-theory approach
A. Crivellin, S. Davidson, G. M. Pruna, A. Signer
e-Print: 1702.03020 [hep-ph] JHEP 05 (2017), 117

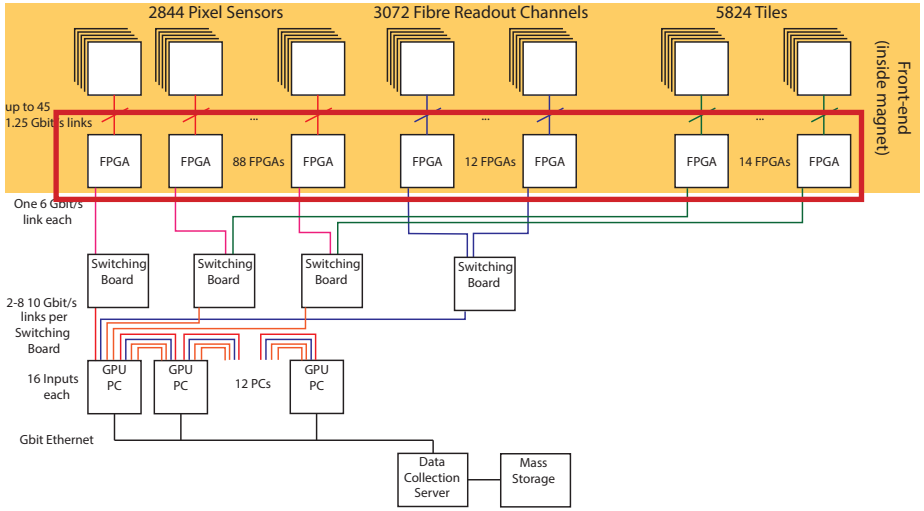

UPSTREAM
UPSTREAM

More on DAQ

Front-end board

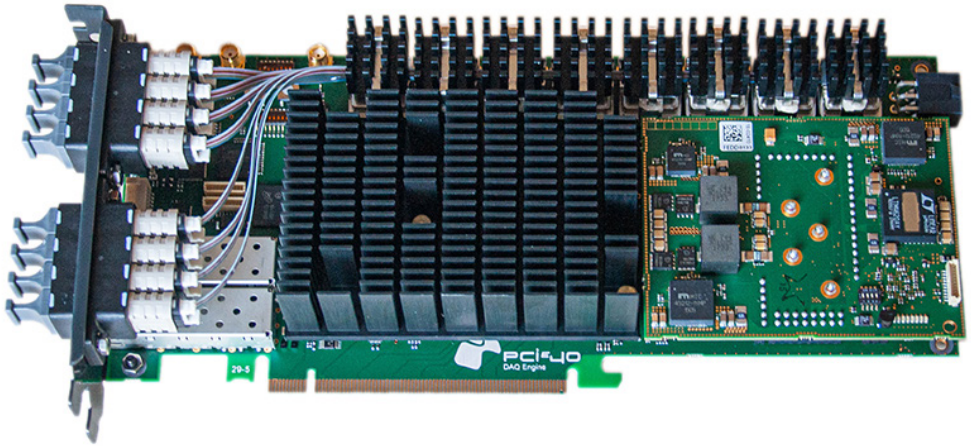
- Operates in magnet and helium atmosphere, space is tight
- Up to 45 1.25 GBit/s LVDS inputs from detector ASICs
- Intel Arria V A7 FPGA for time-sorting and clustering of hits
- Output to a 6 Gbit/s optical link on a Samtec Firefly Transceiver
- Intel MAX10 FPGA for configuration and monitoring
- Air-coil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

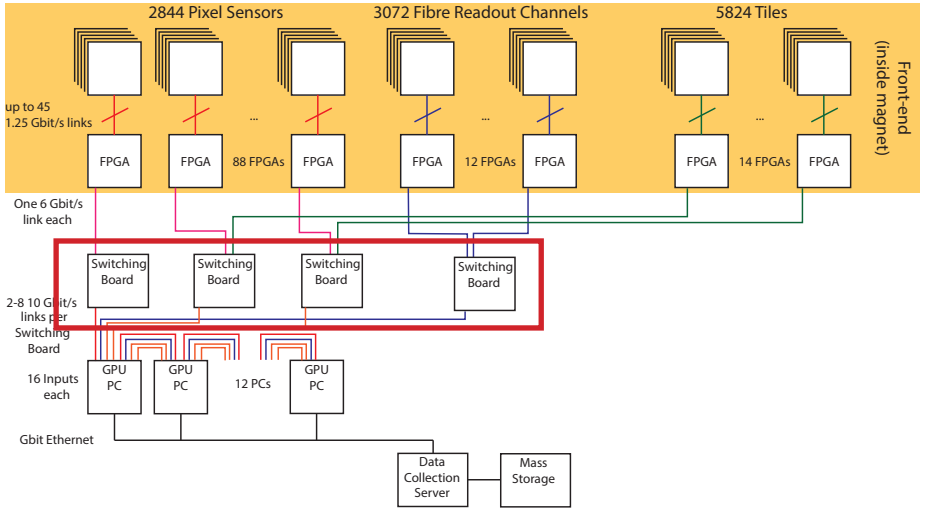




Switching board

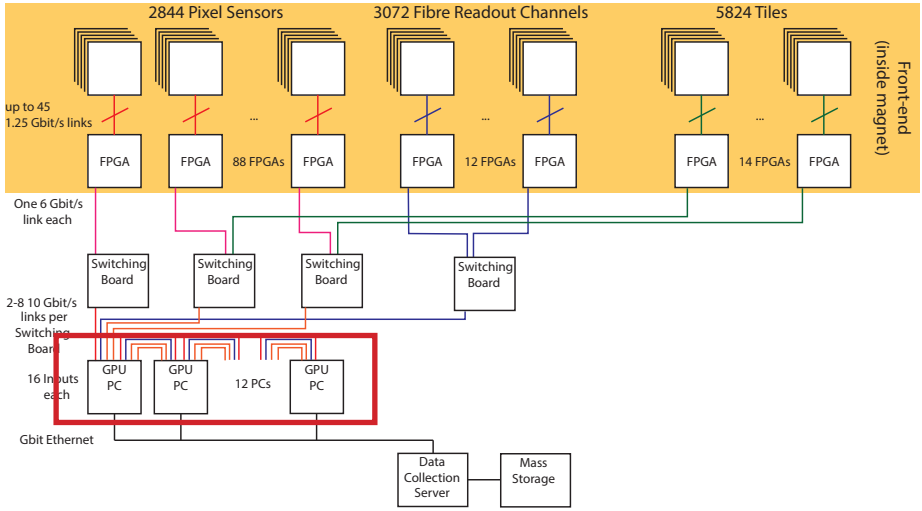
- Operates in a PC case
- Up to 37 front-end board inputs (and control lines)
- Up to eight 10 Gbit/s outputs to filter farm
- Use PCIe40 board developed in Marseilles for LHCb and ALICE upgrades
- Intel Arria 10 - 115 FPGA
- Avago MiniPod Transmitters and Receivers
- Two 8-lane PCIe 3.0 interfaces (used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



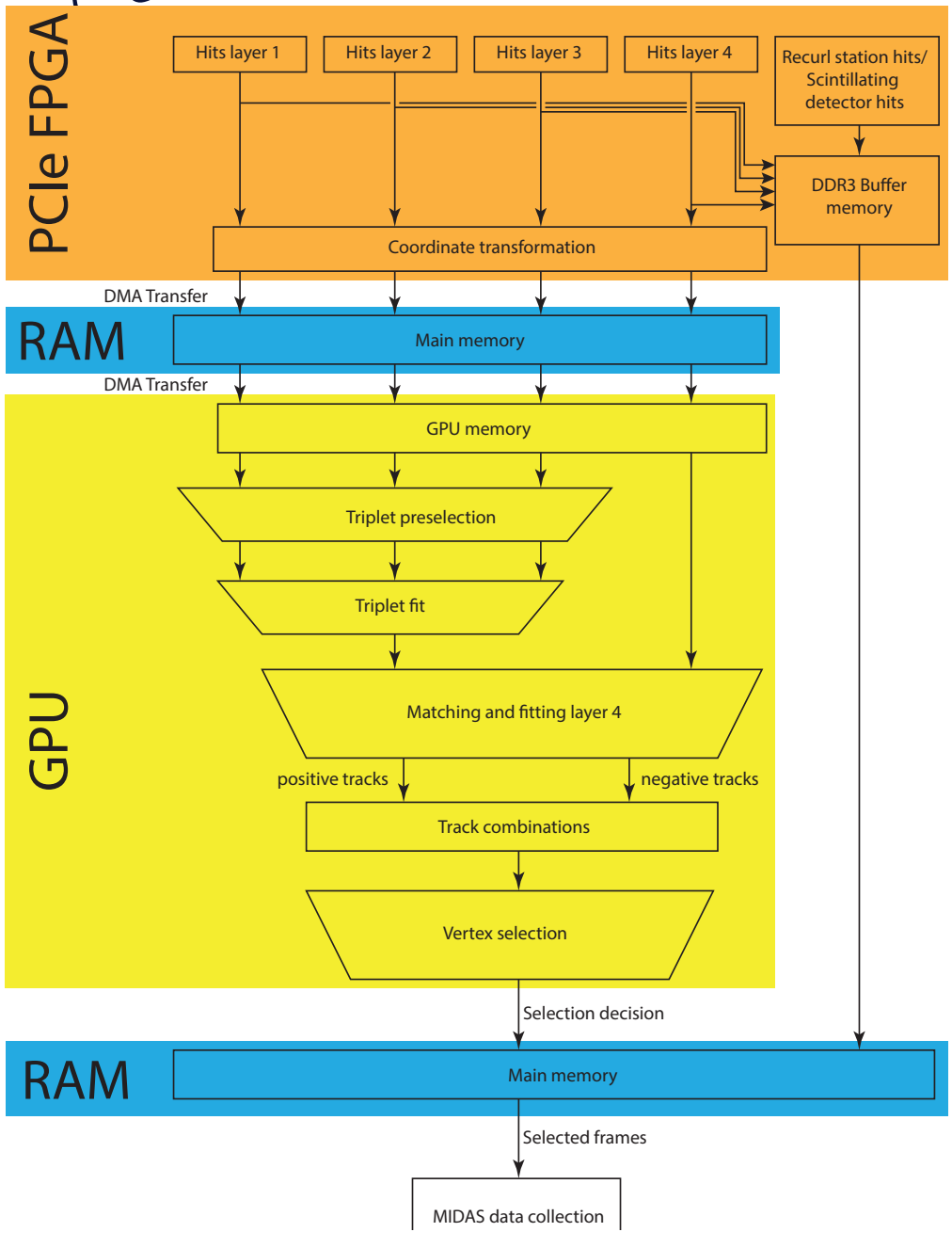


Receiving board

- 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



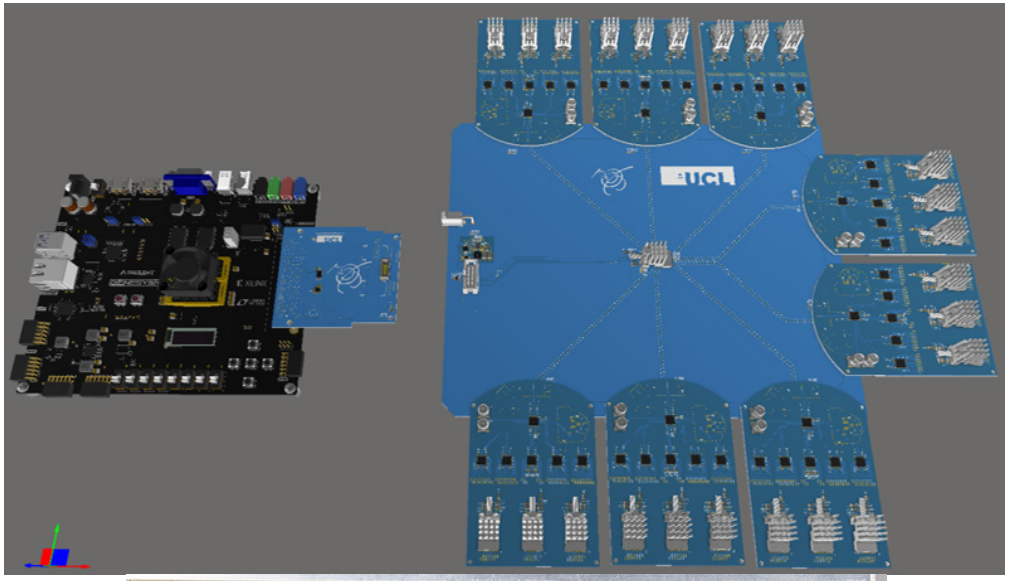
Farm data flow

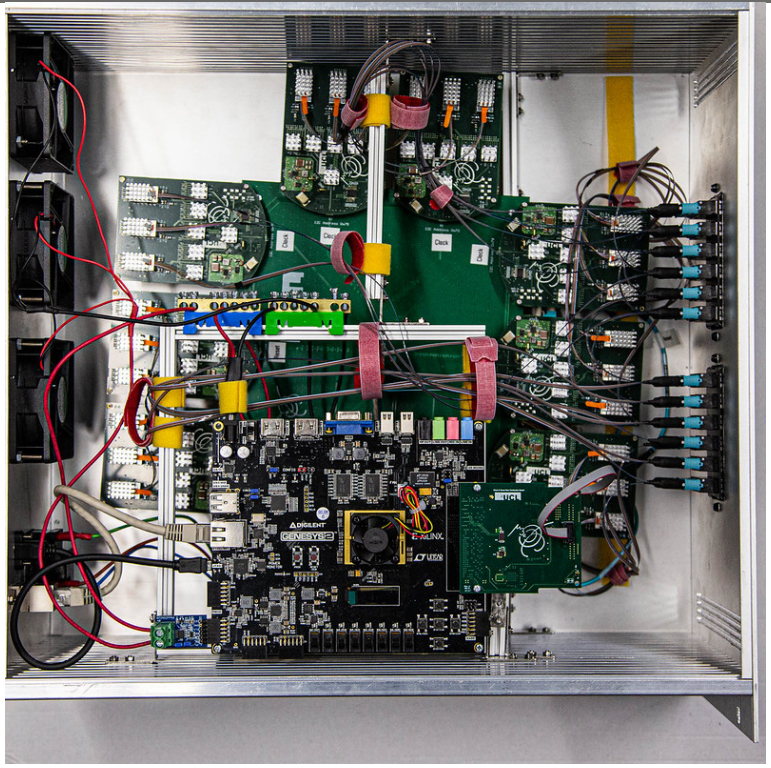


- Buffer all incoming data in DDR memory
- Use subset from central detector for track and vertex finding on a GPU
- If interesting: Get full data from buffer, send to PC
- Up to 38 Gbit/s PCIe DMA transfers using custom firmware and driver
- After full reconstruction: Send off to mass storage
- Use the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

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