Building the Mu3e Experiment

Niklaus Berger

Institut für Kernphysik,

Johannes Gutenberg Universität Mainz

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JG|U

DFG Deutsche Forschungsgemeinschaft

Particle Physics 2025:

- 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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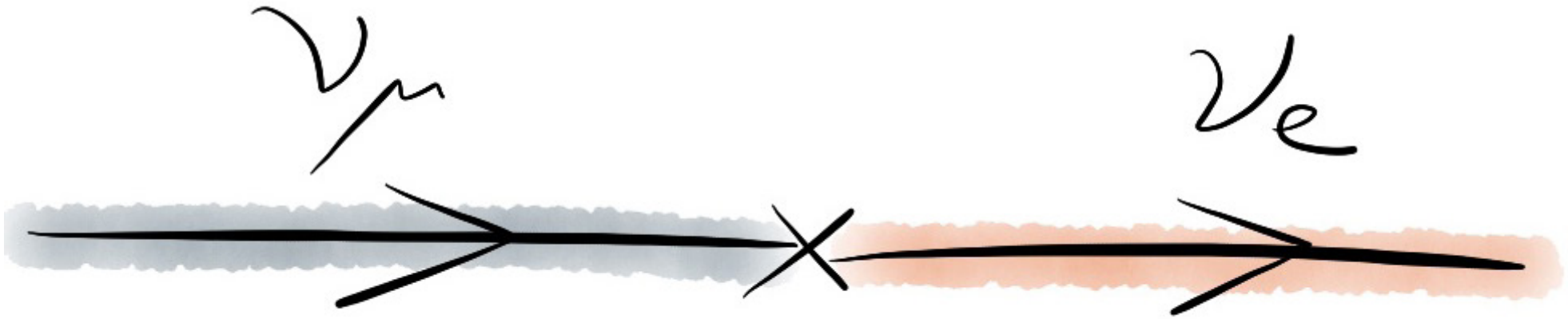
Particle Physics 2025:

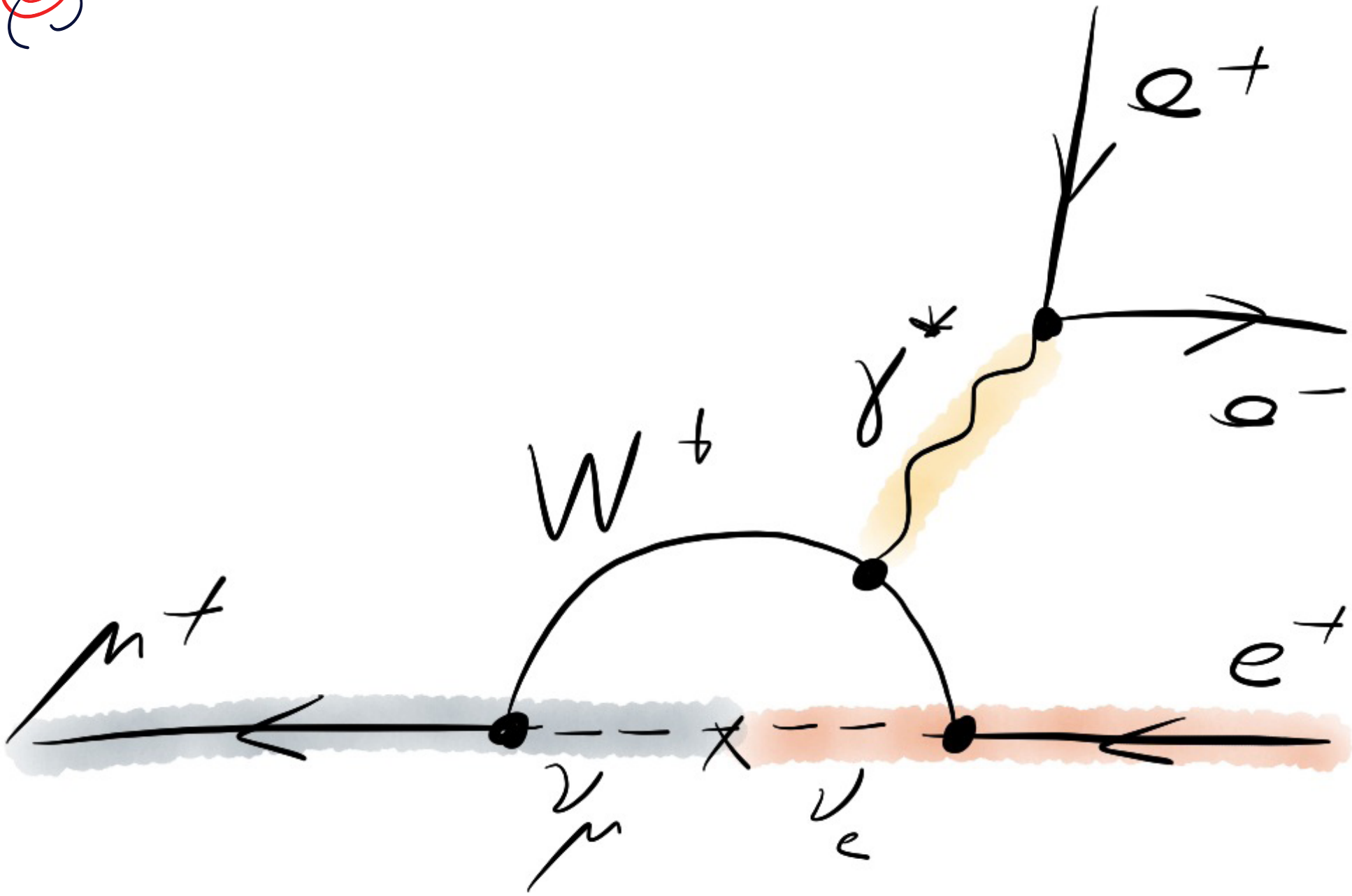
- All particles in the Standard Model discovered
- Very few lab measurements in tension with SM
- SM known to be incomplete: Dark matter, baryon asymmetry, gravity, hierarchy,...

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

Lepton Flavour Violation!



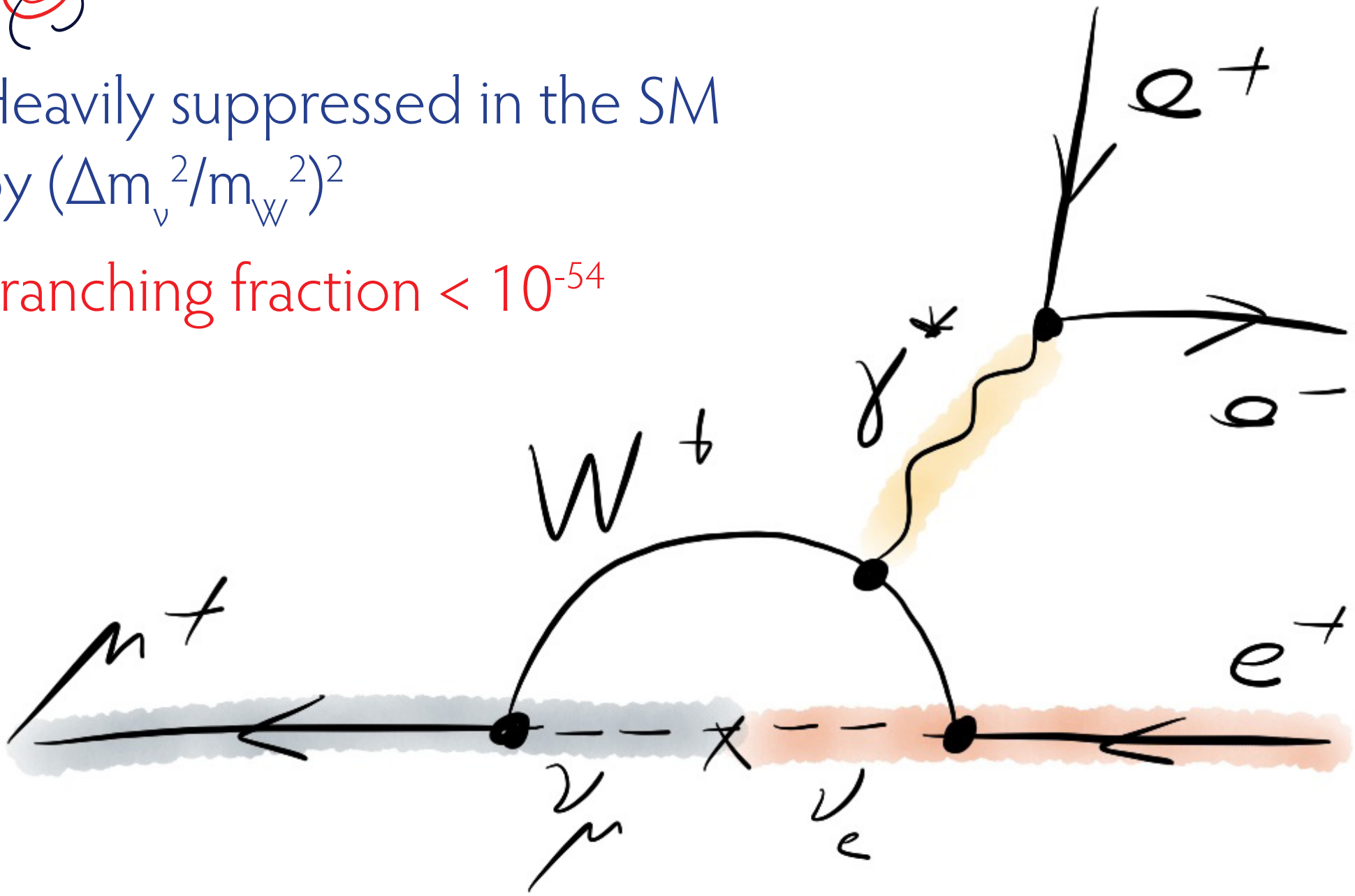
Charged Lepton Flavour Violation?



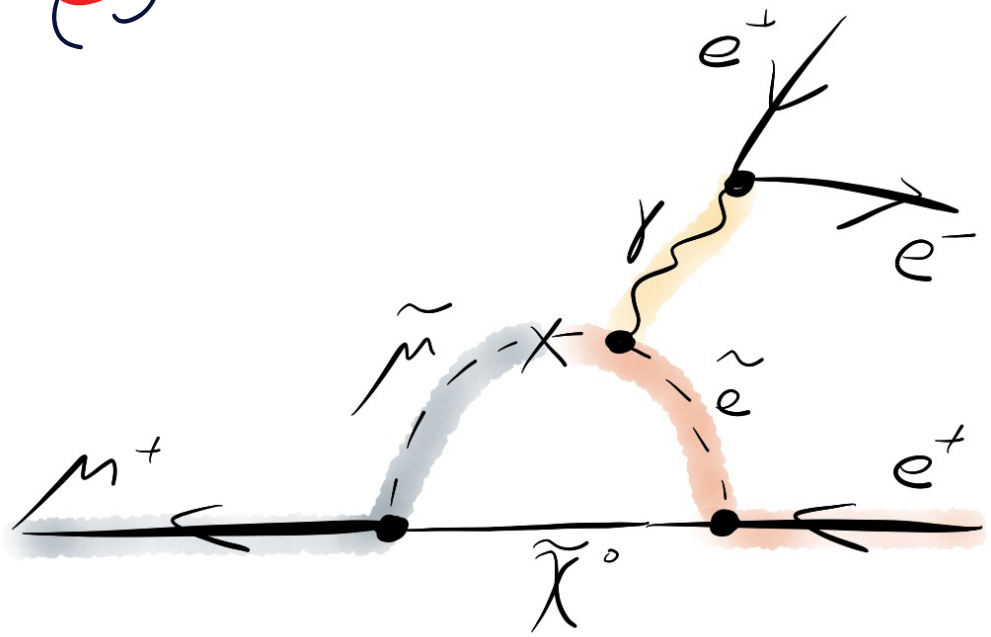
Charged Lepton Flavour Violation?

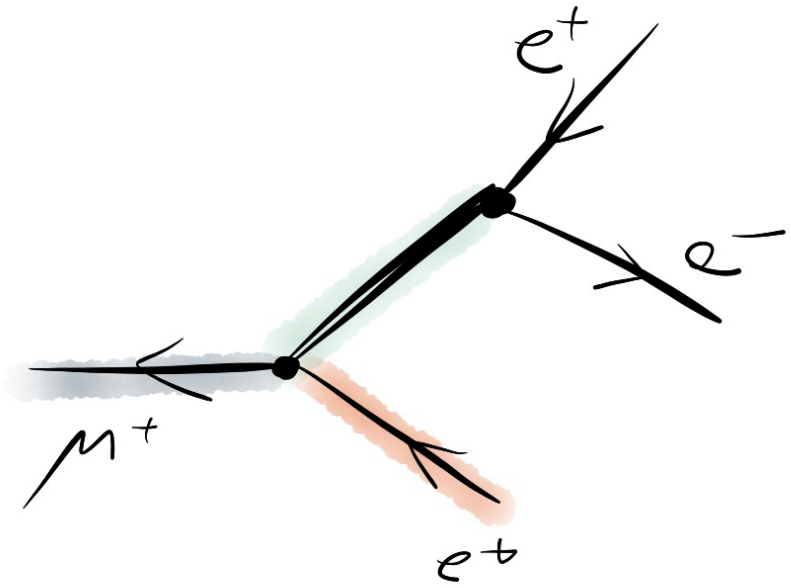
Heavily suppressed in the SM
by $(\Delta m_\nu^2/m_W^2)^2$

Branching fraction < 10^{-54}



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





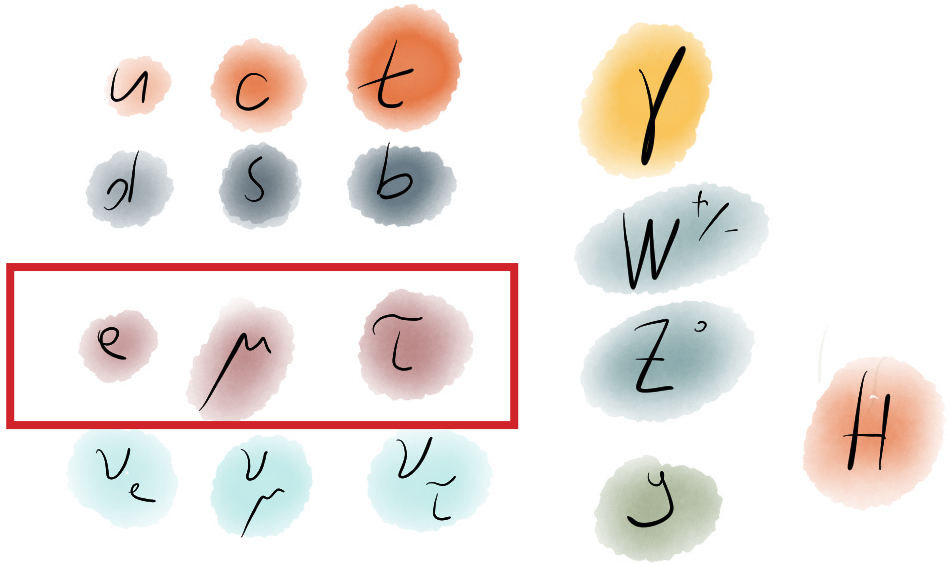
Loop diagrams

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

Tree diagrams

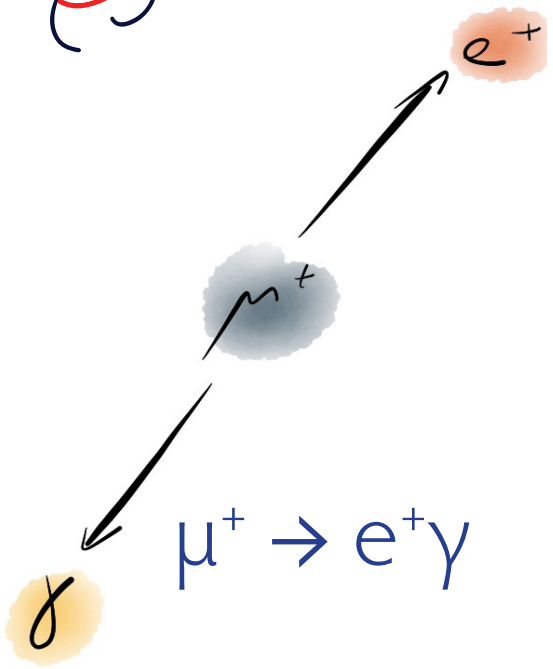
- Higgs triplet model
- Extra heavy vector bosons (Z')
- Extra dimensions (Kaluza-Klein tower)
- ...

Menu of charged Leptons

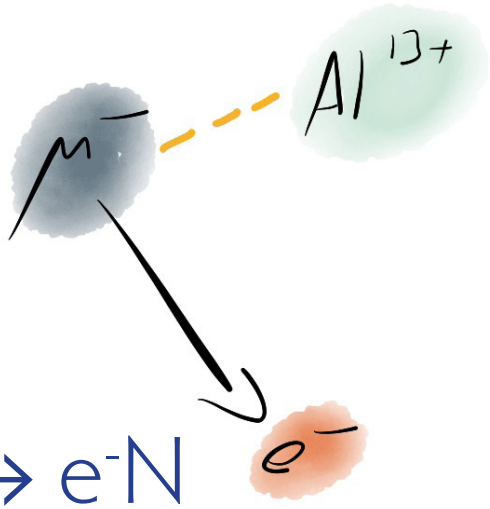


- Electrons are stable...
- New physics sensitivity (heavy new physics, very generic) scales with m_l^2
  τ's are most sensitive
- But: Can produce about as many muons per second as taus in a year
- Muons lead the search for charged Lepton Flavour Violation

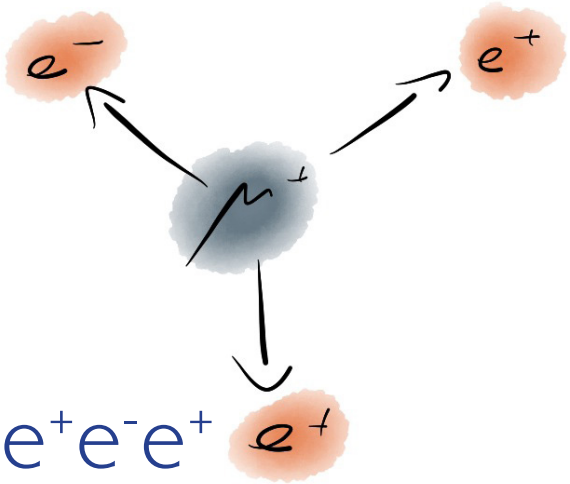
LFV Muon Decays: Experimental Situation



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



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



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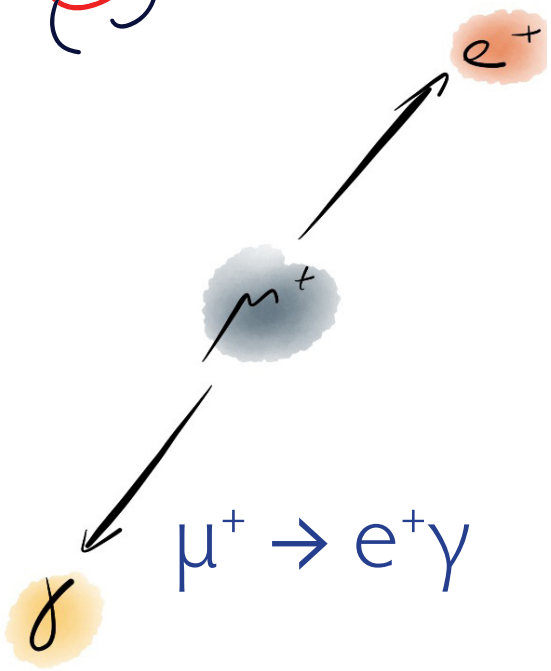

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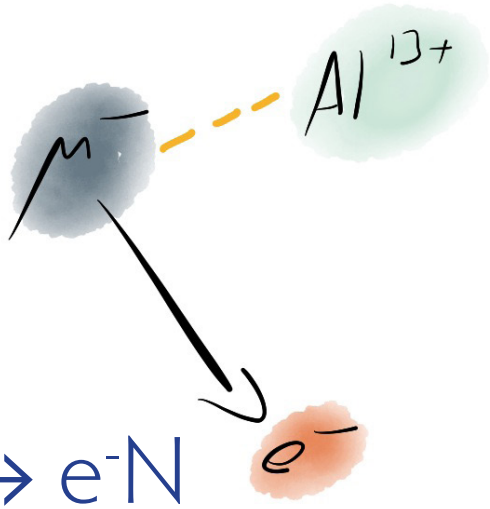

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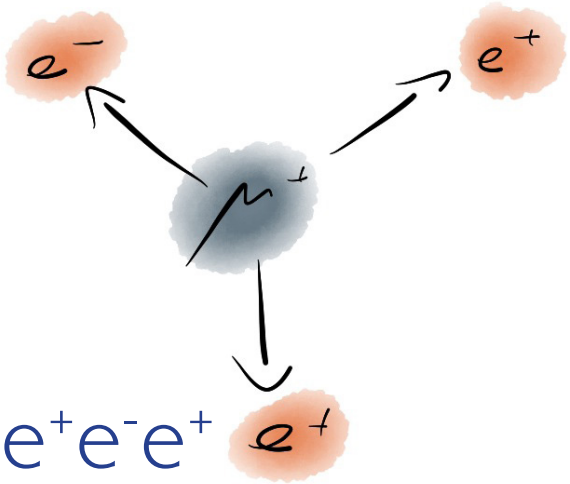

$\mu^+ \rightarrow e^+e^-e^+$

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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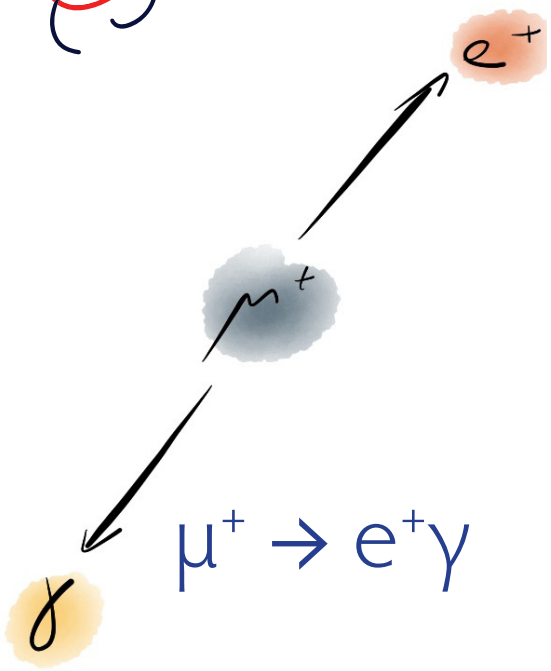

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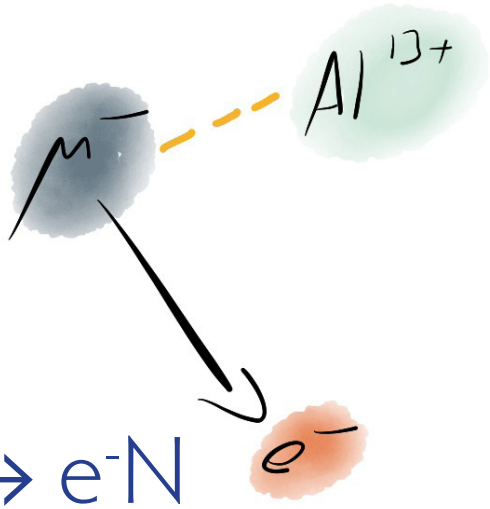

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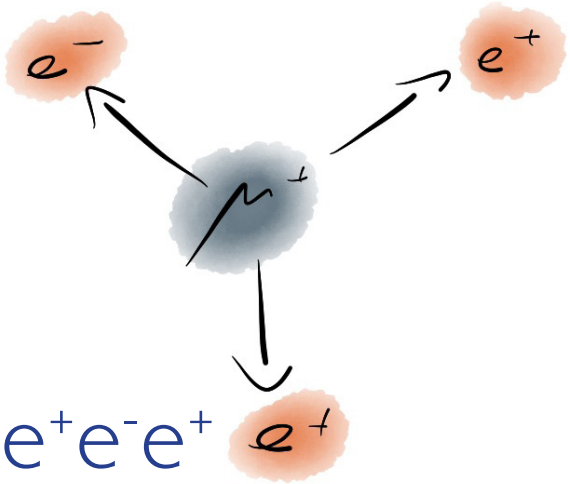

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Mu2e/Comet

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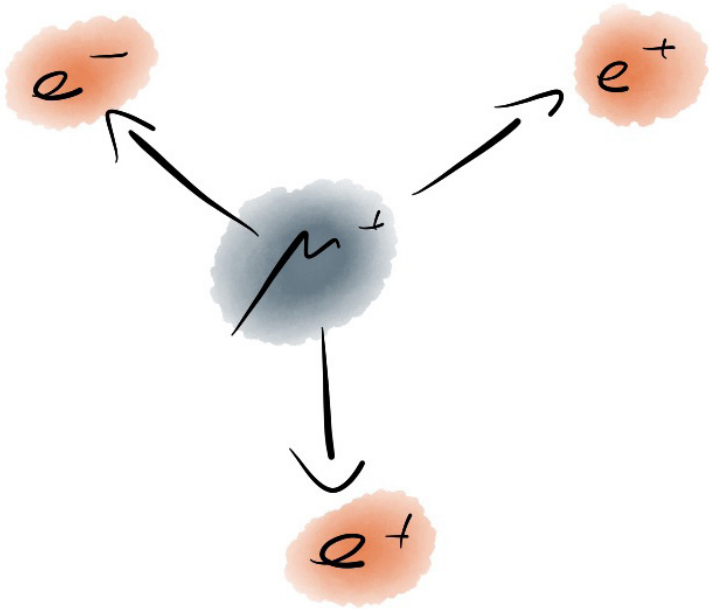
Mu3e

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

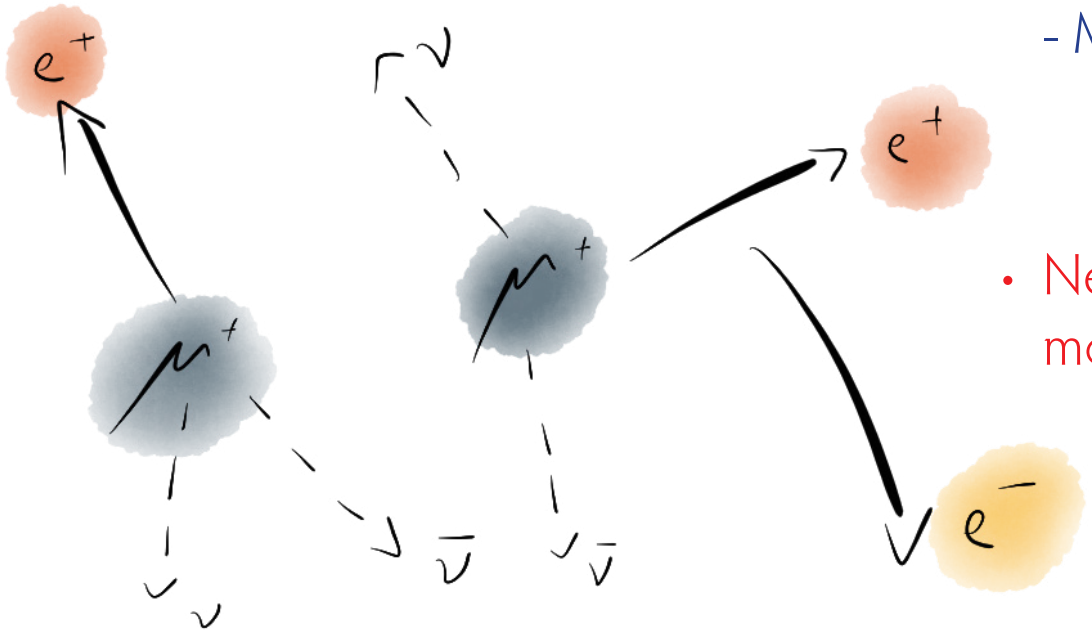
The signal



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



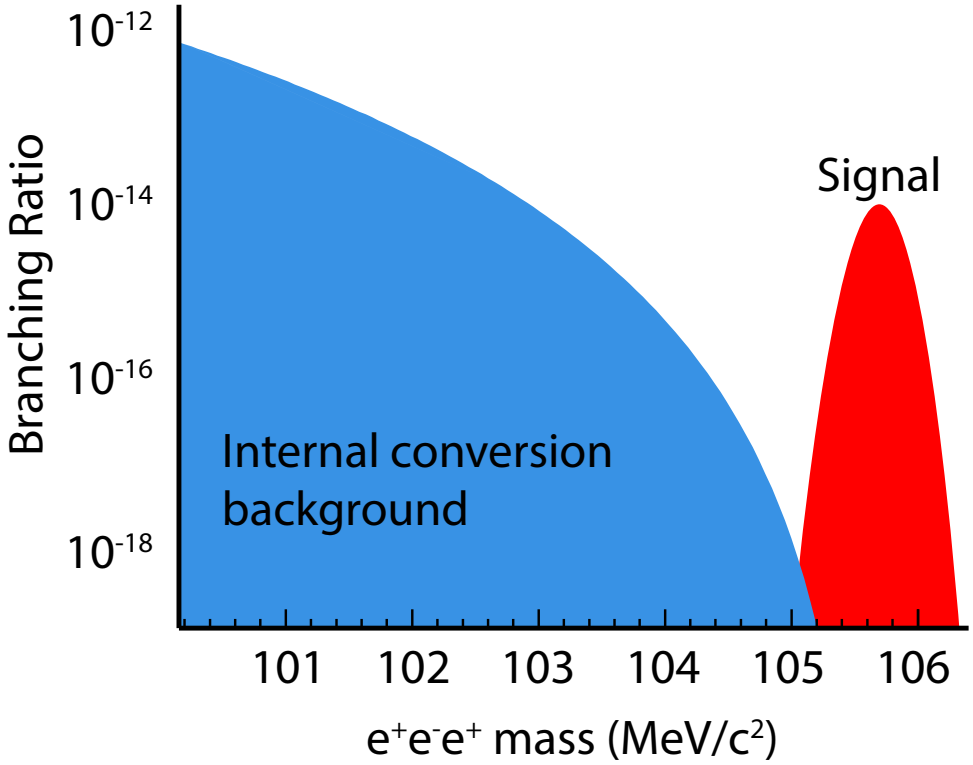
- Need very good timing, vertex and momentum resolution

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



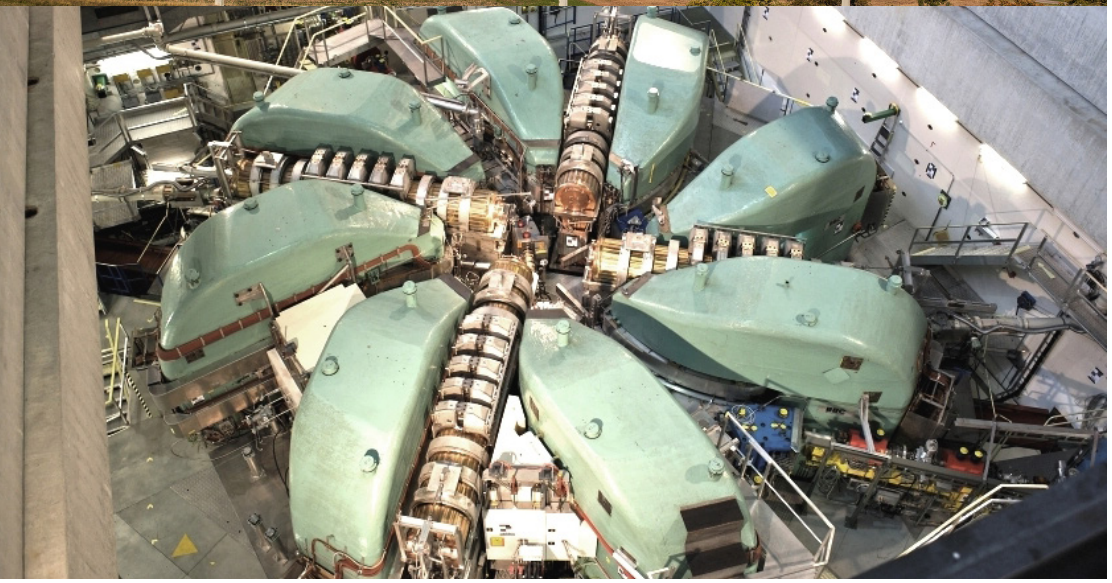
- Need excellent momentum resolution

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

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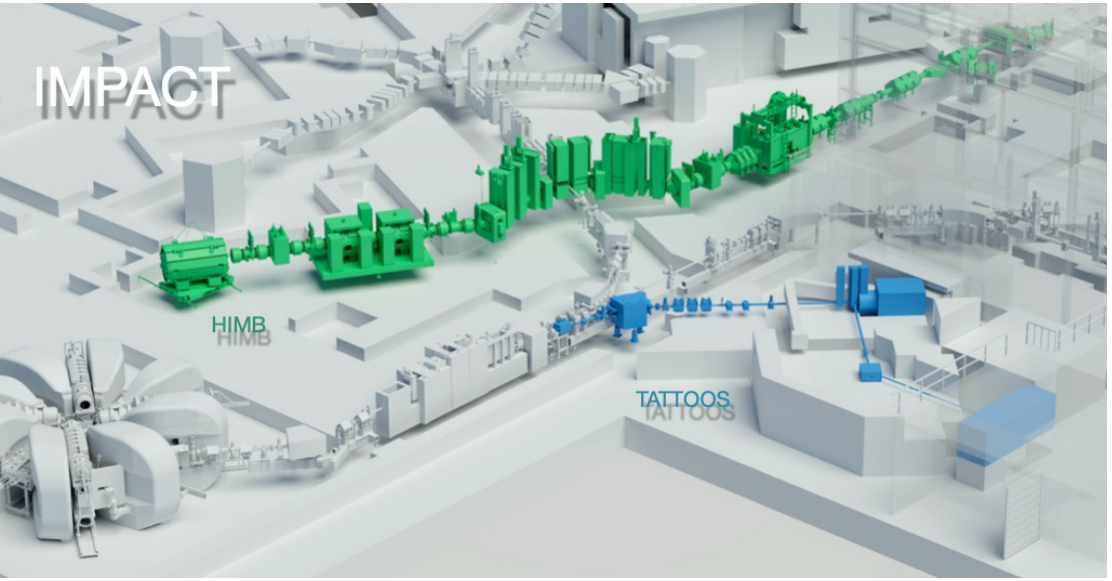
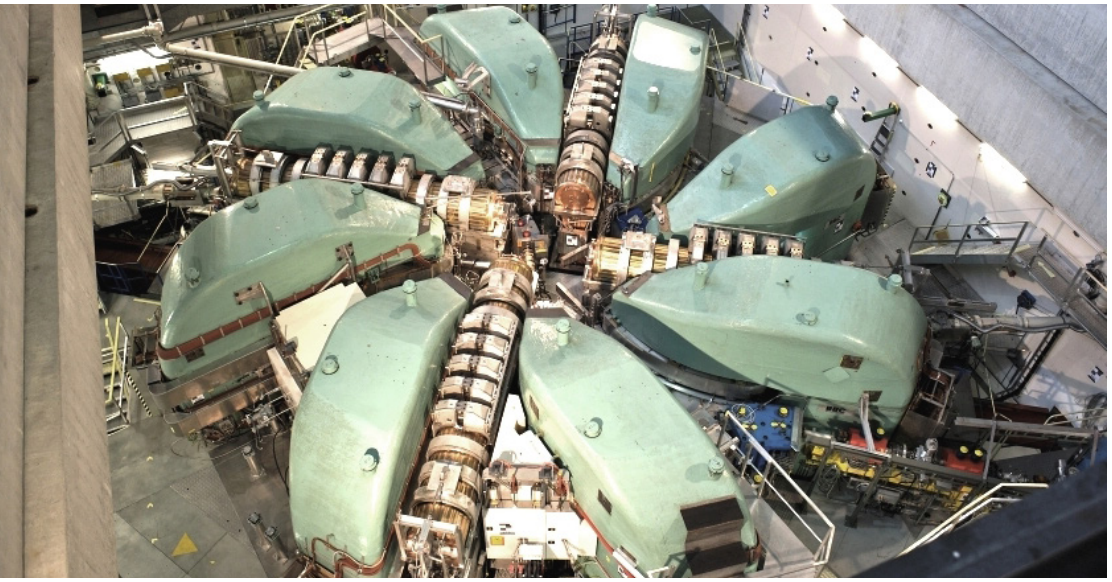




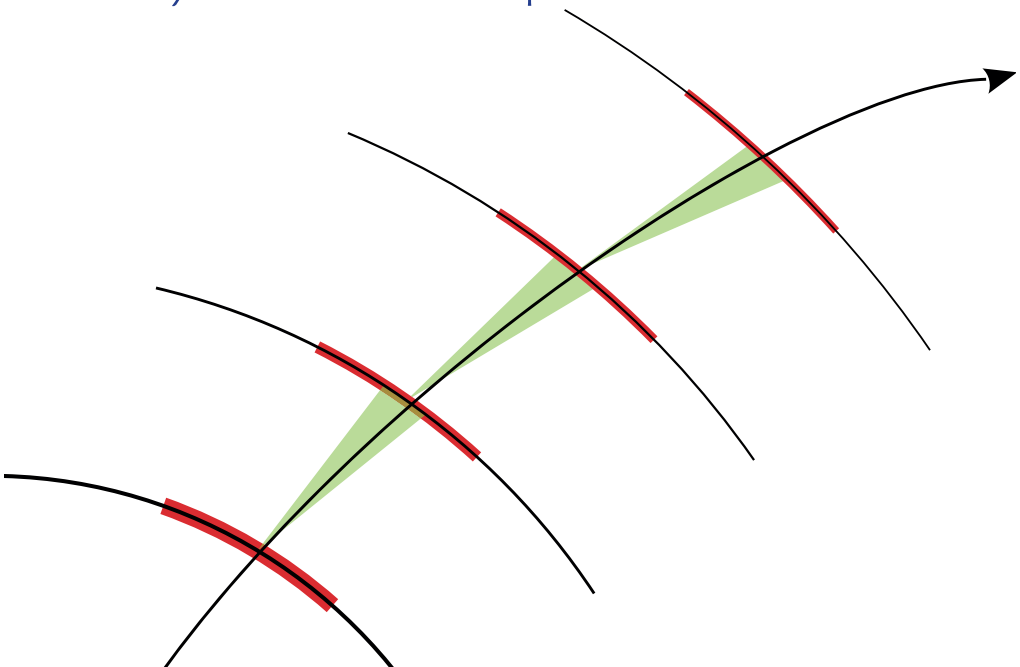
- Paul Scherrer Institute in Switzerland
- 1.4 MW, 590 MeV proton accelerator
- Carbon target, produce pions, decay to muons
- Currently: Up to 10^8 muons/s available: Mu3e Phase I
- Future (2027+): High-intensity muon beamline (HIMB) with up to 10^{10} muons/s Mu3e Phase II
- Need to be able to stand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

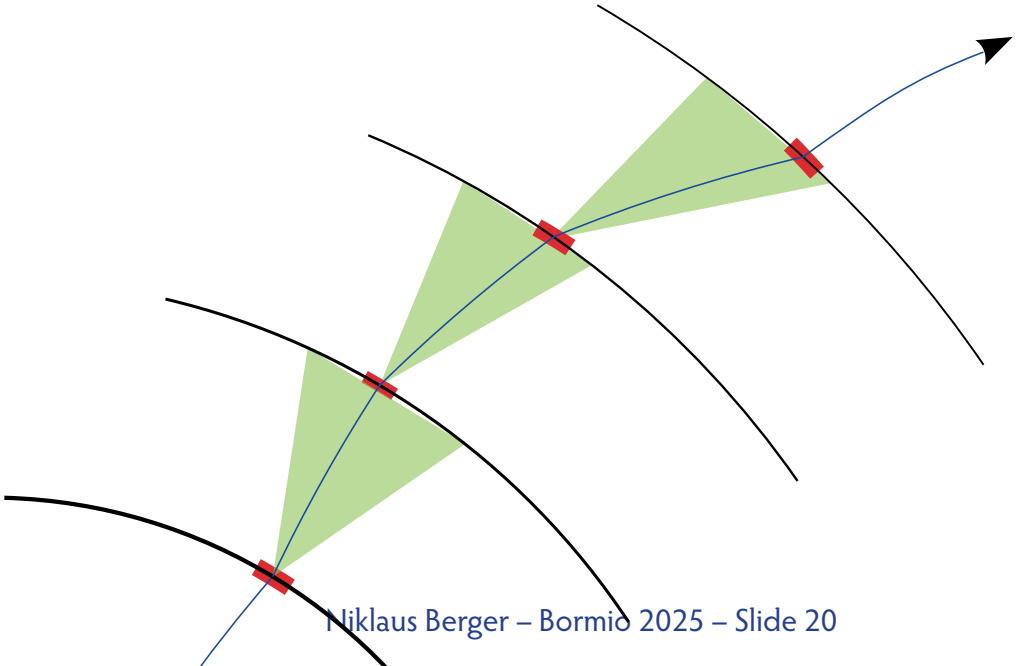
Momentum measurement in magnetic field

- Measure curvature in magnetic field
- High rates
- Want to get very close to the beam (vertexing)
- Gas detectors will not work
- Solid state detectors add material for every measurement point

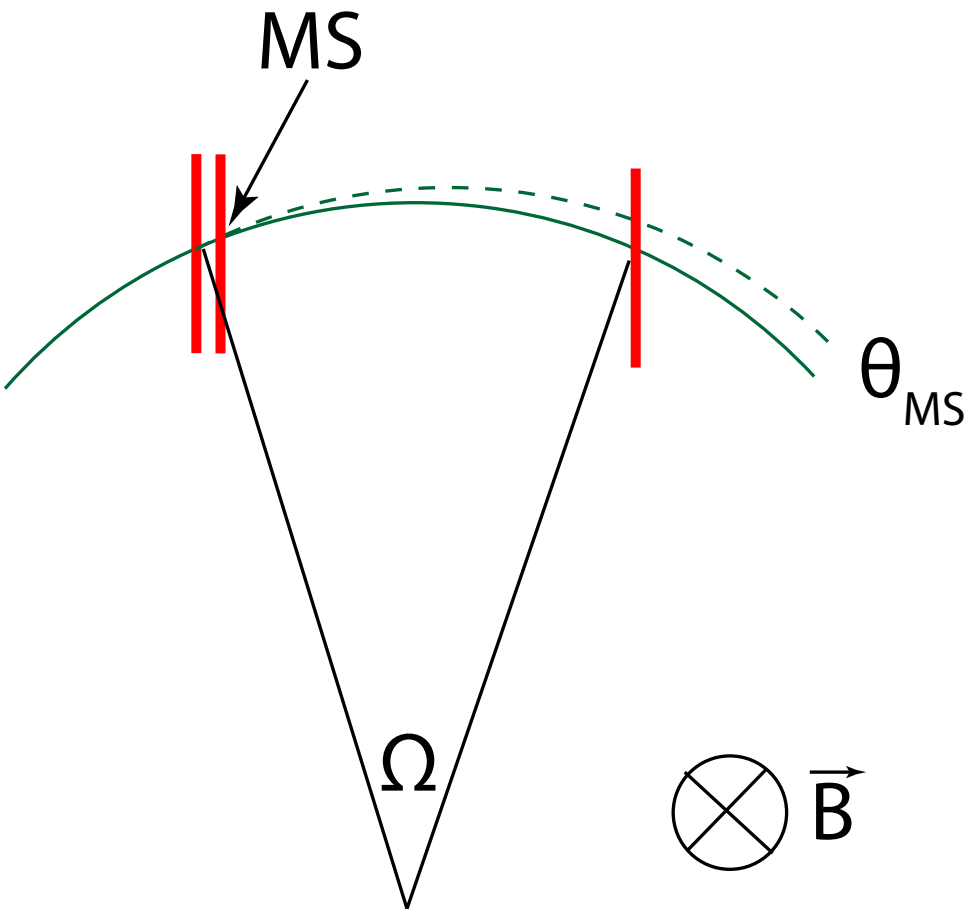
- Momenta below 53 MeV
- Resolution is completely dominated by scattering in the detector

- Want few, extremely thin layers





Momentum measurement

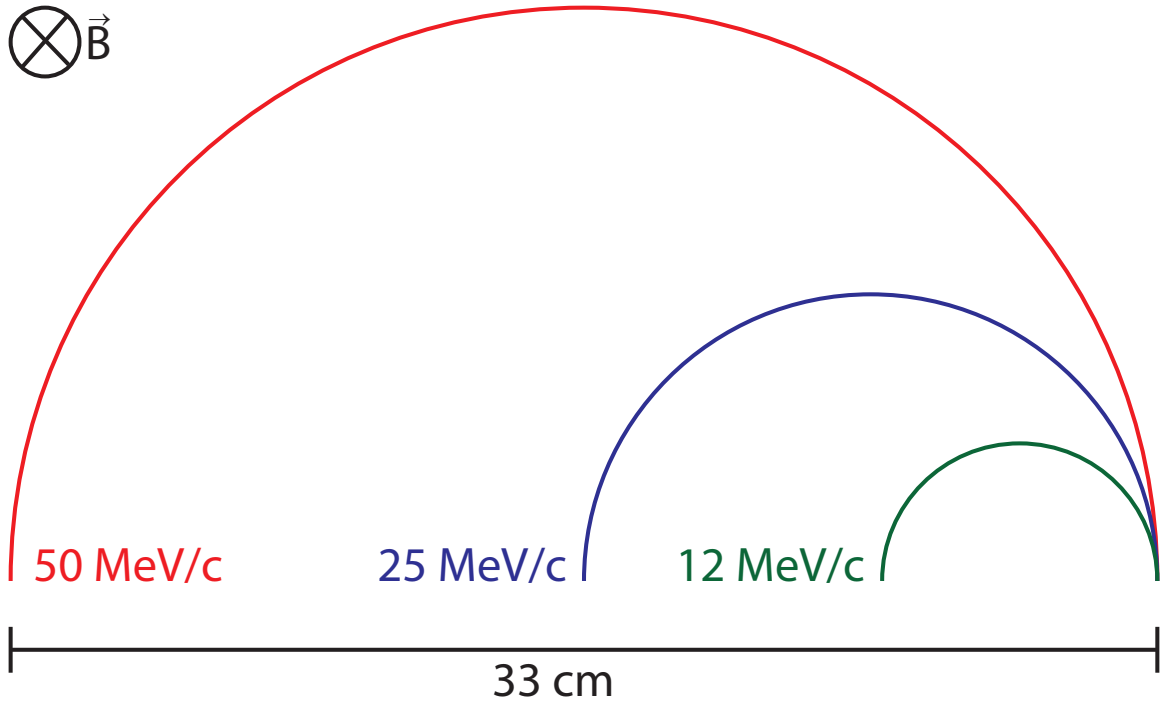


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

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

Precision vs. Acceptance



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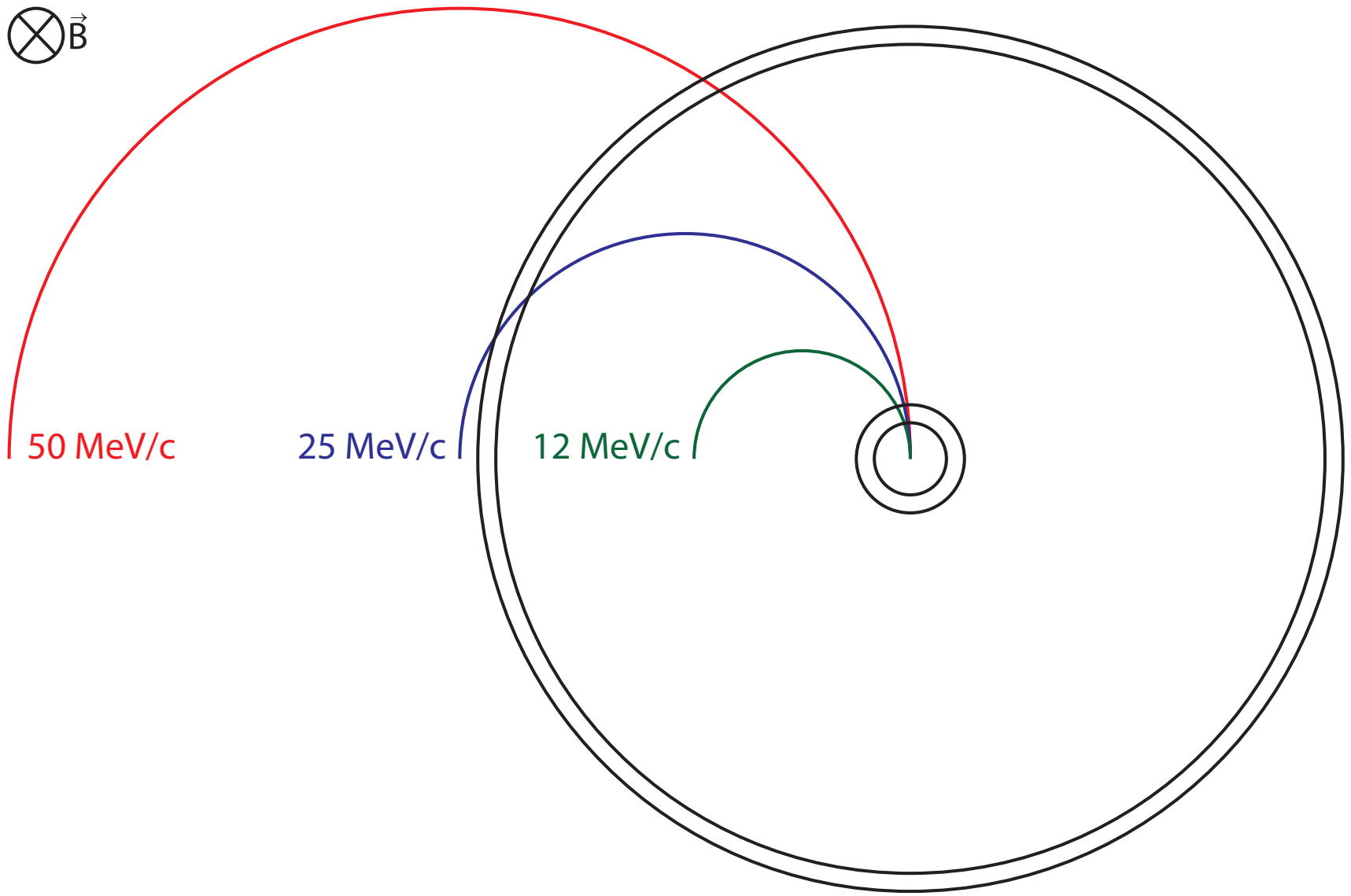

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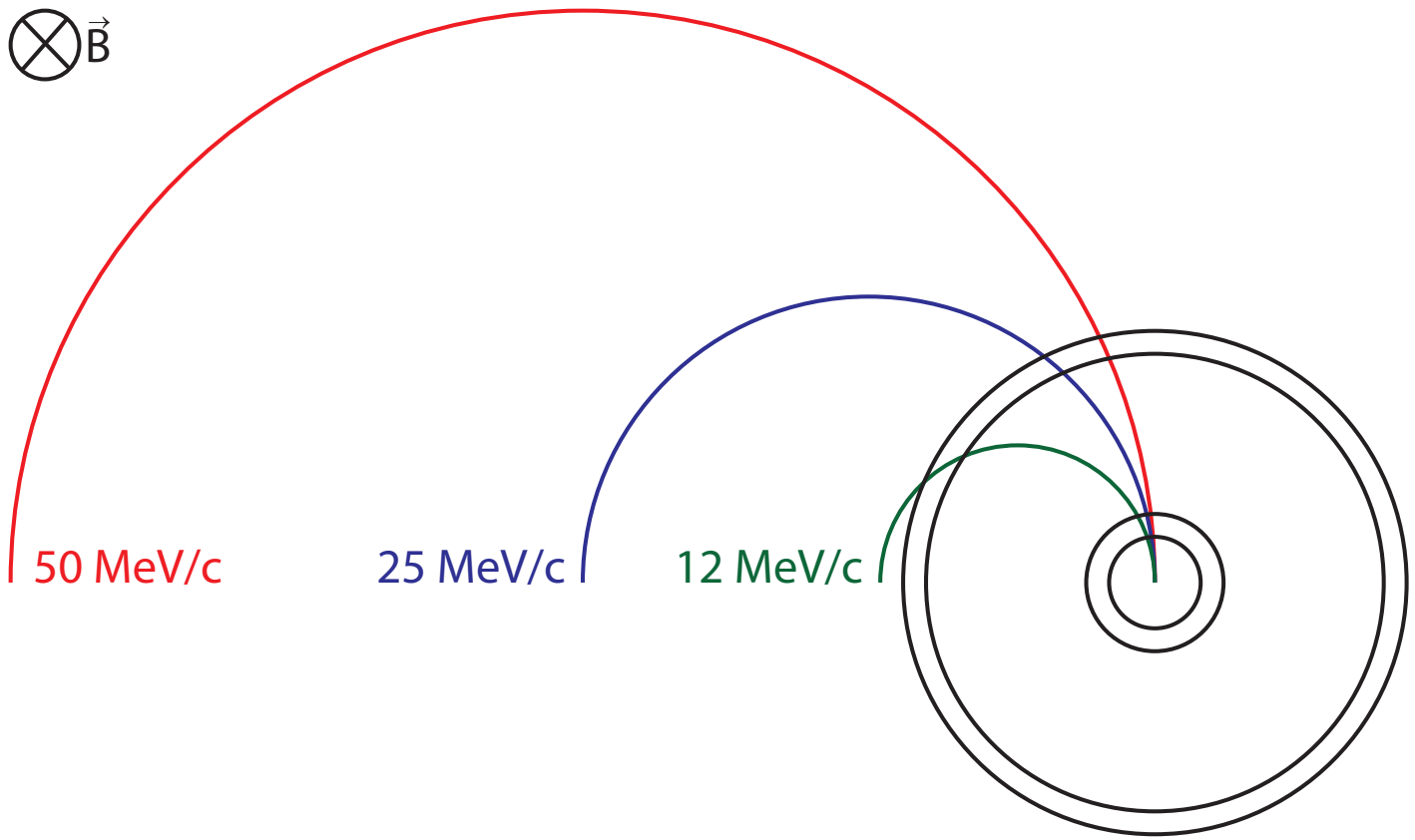

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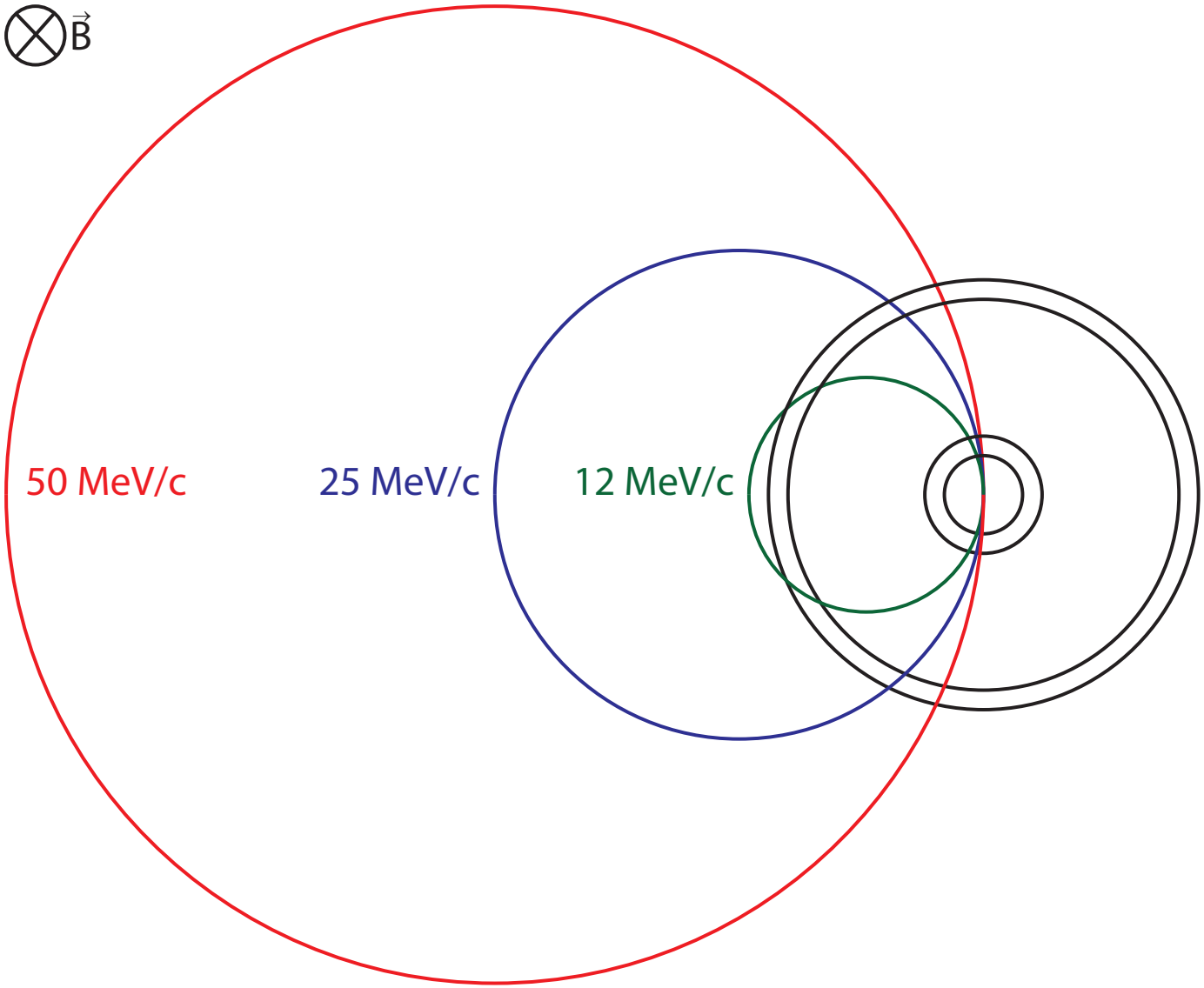

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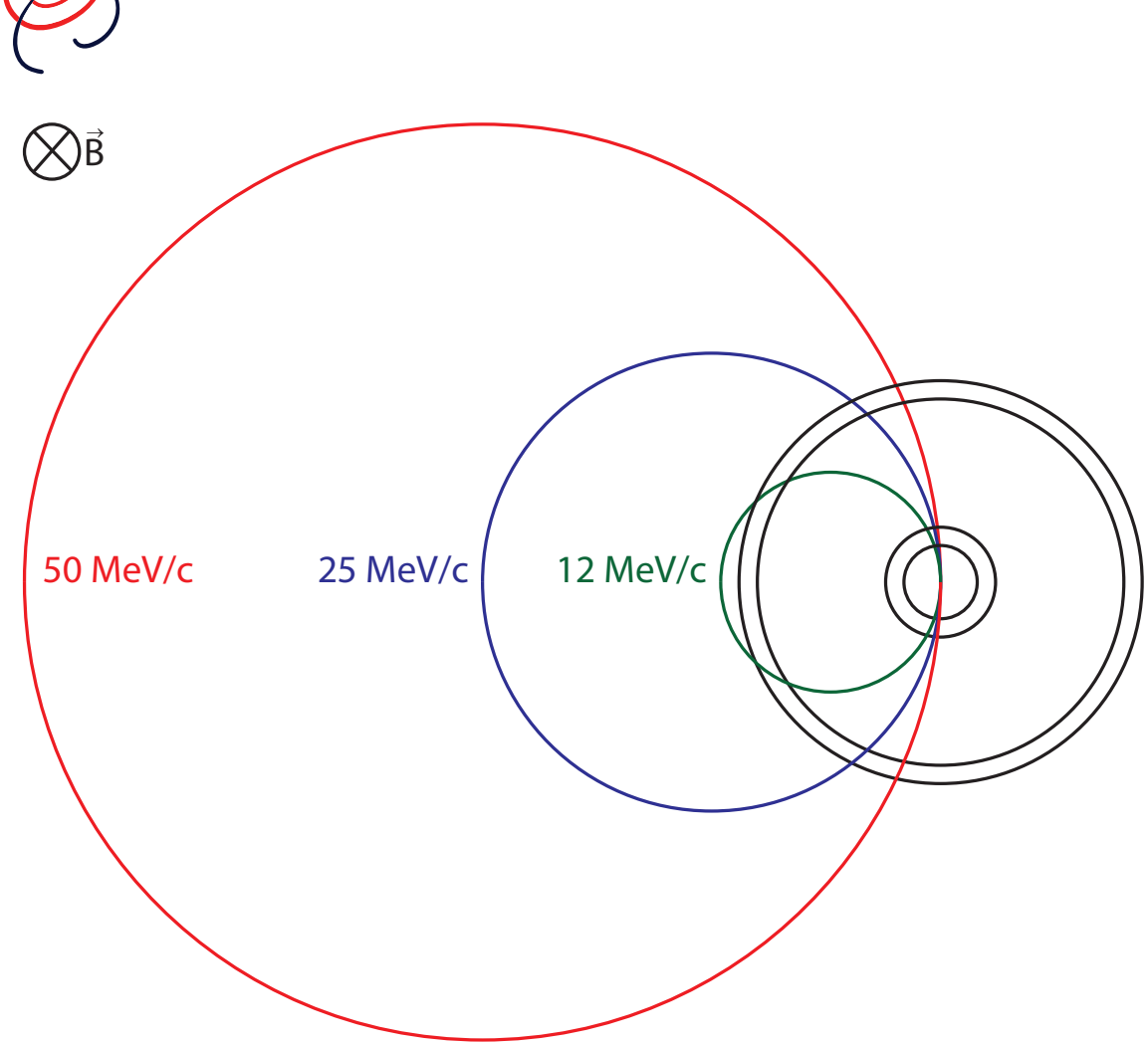
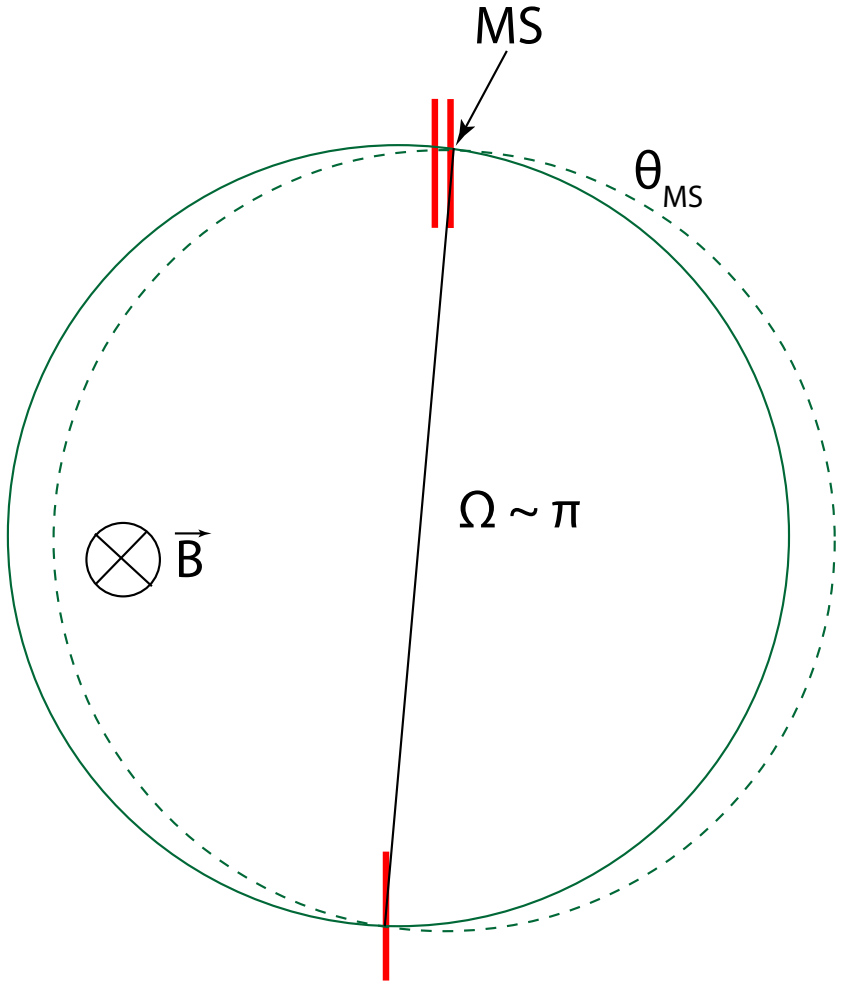
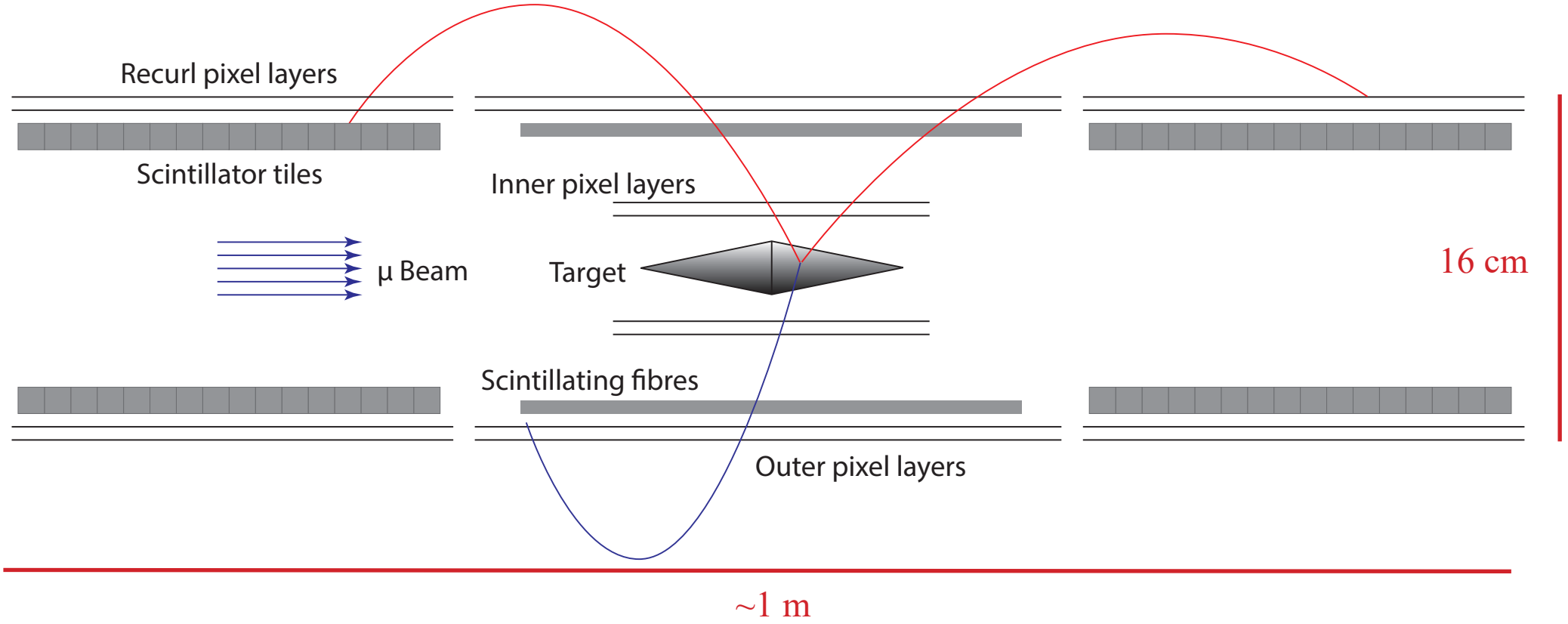


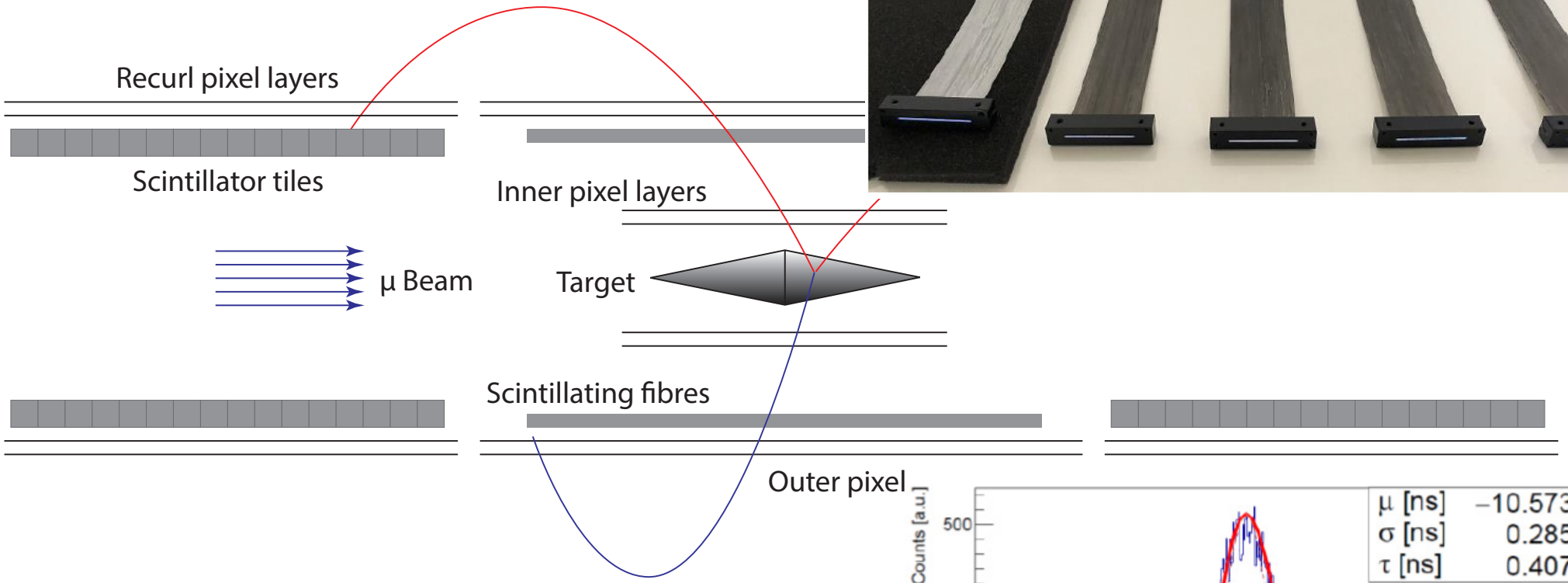


Experiment concept

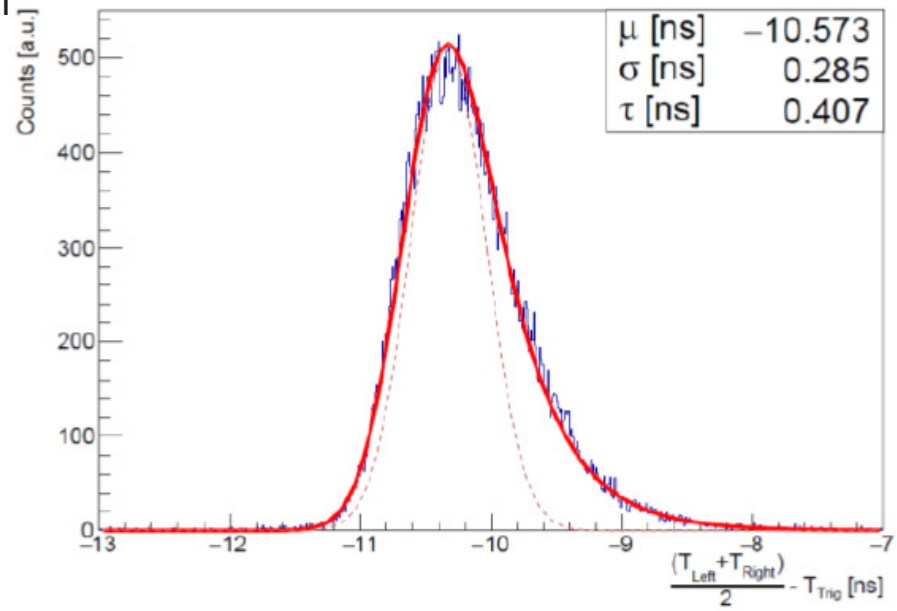


- 1 T magnetic field
- Hollow double-cone stopping target
- Pixels for momentum and vertexing
- Scintillating fibres and tiles for timing
- Measure tracks curling back in the field

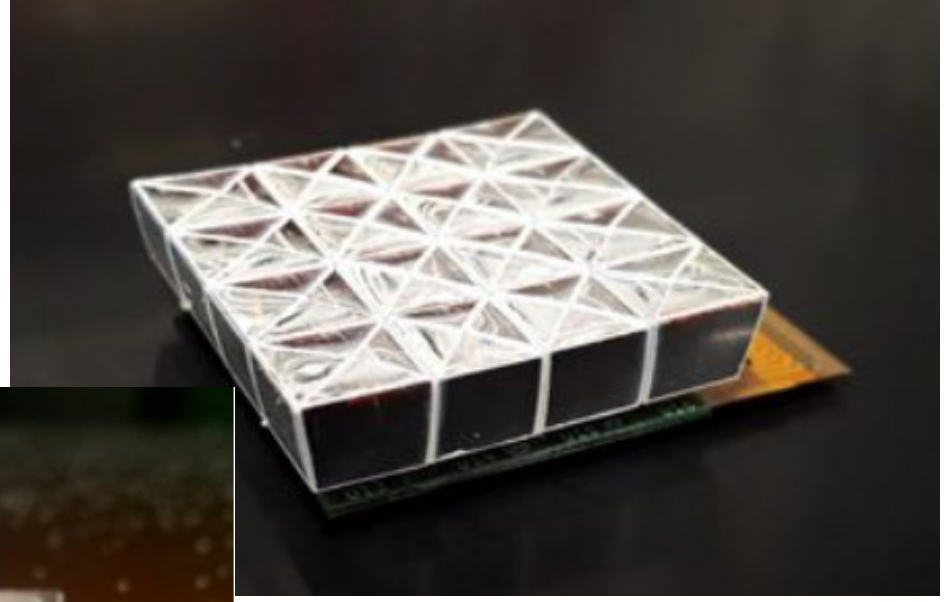
Scintillating fibres

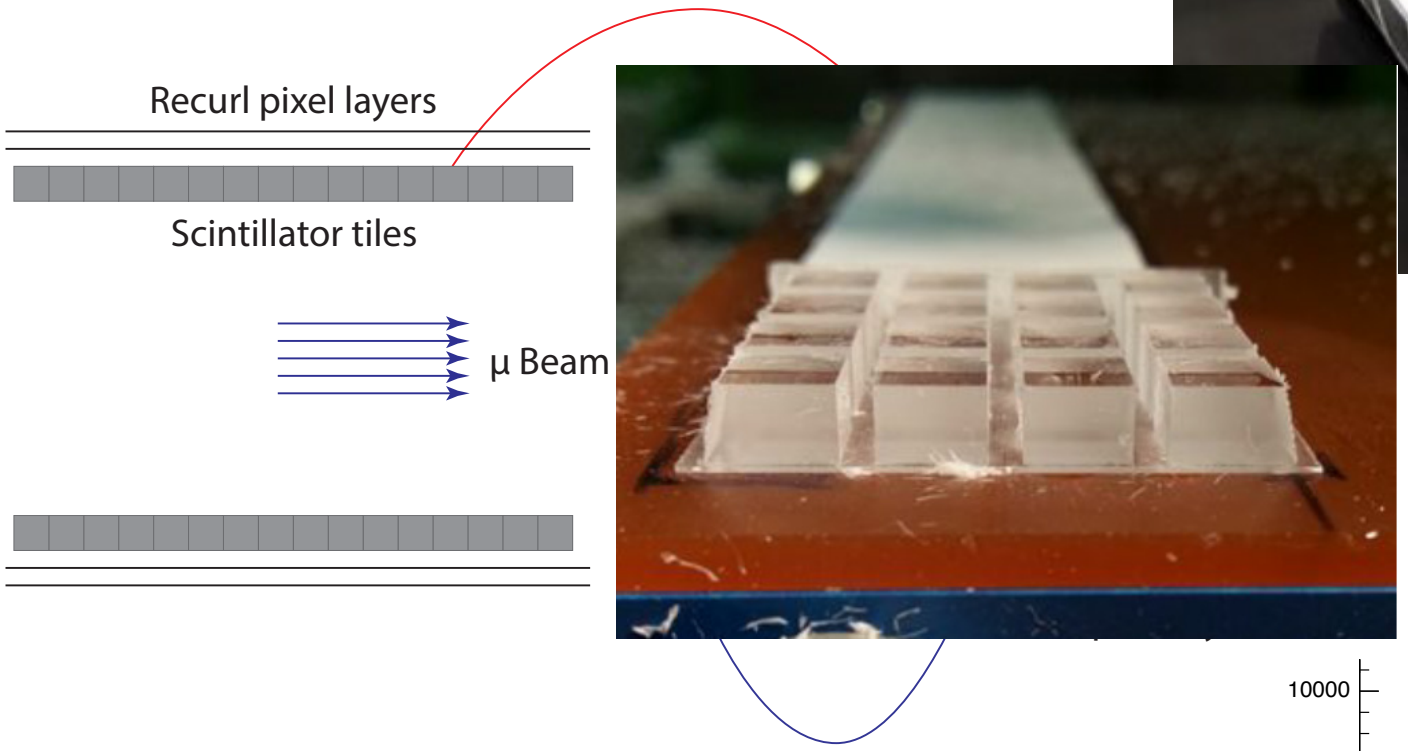


- 3 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)
- Timing resolution < 0.5 ns

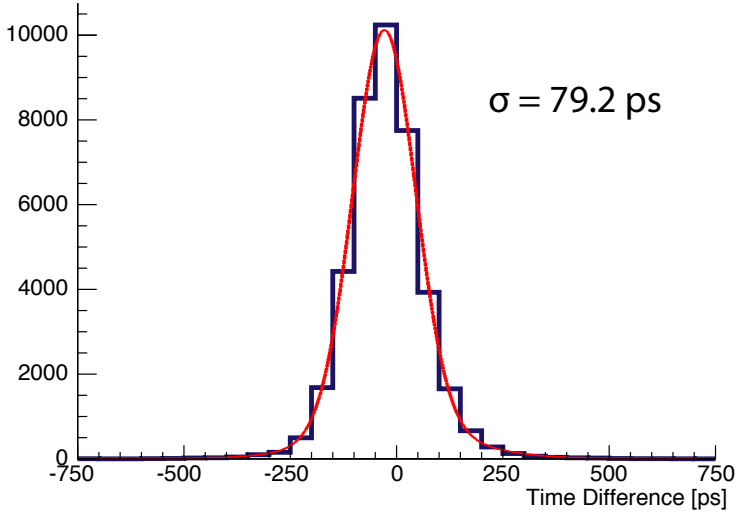


Scintillating tiles





- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution ~ 80 ps

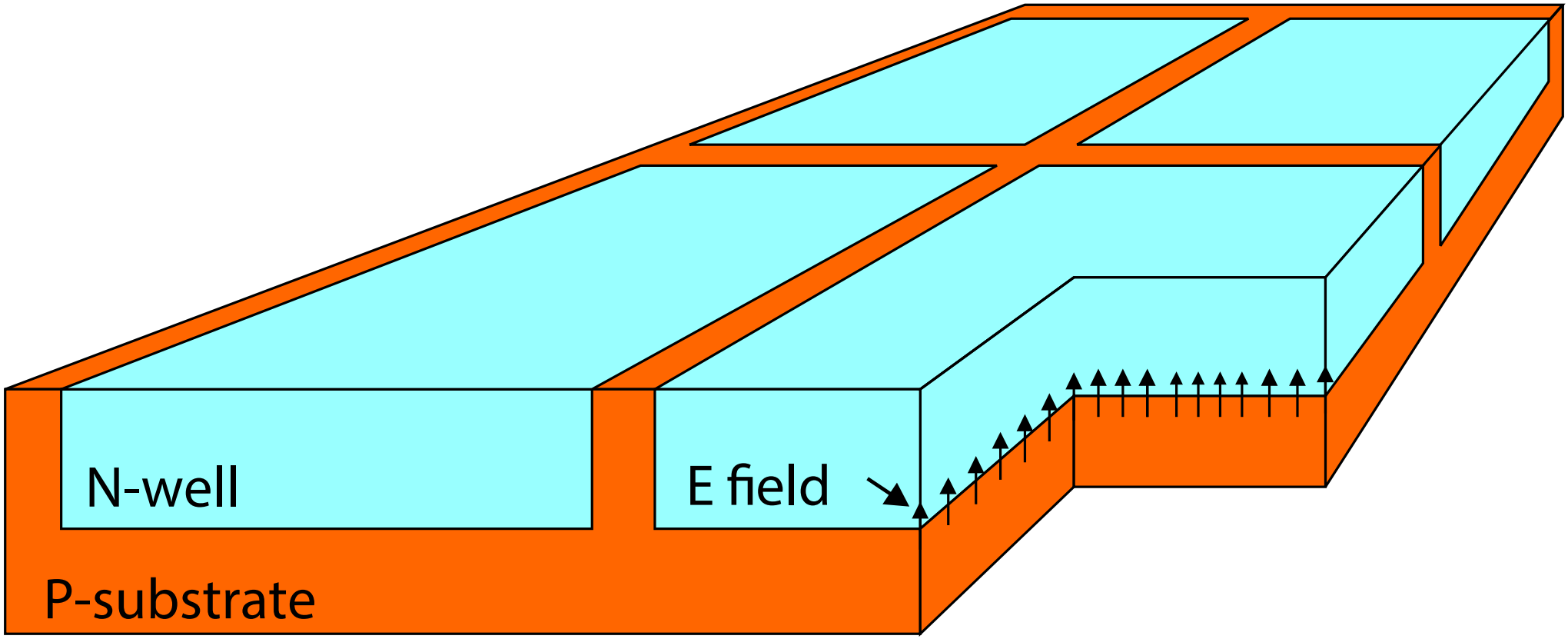


Very thin and fast silicon pixel sensors: HV-MAPS

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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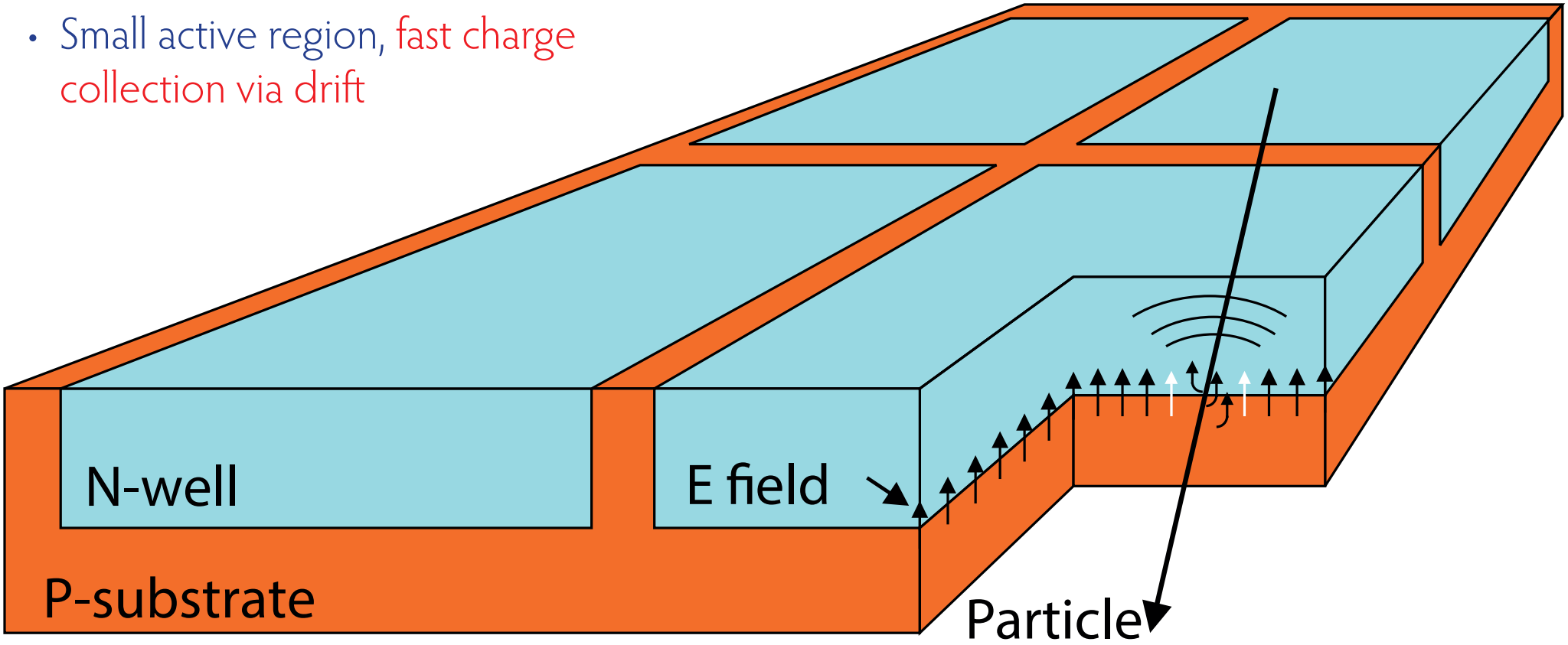

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
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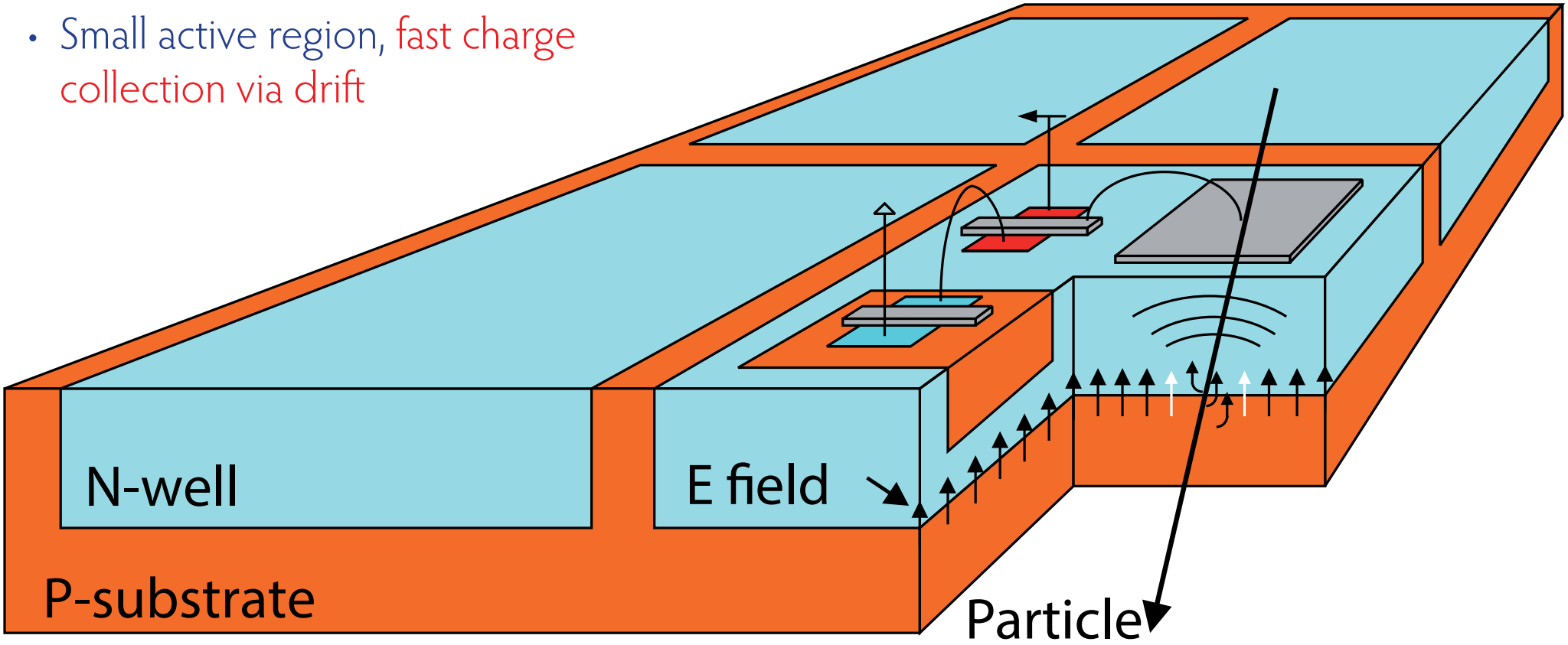
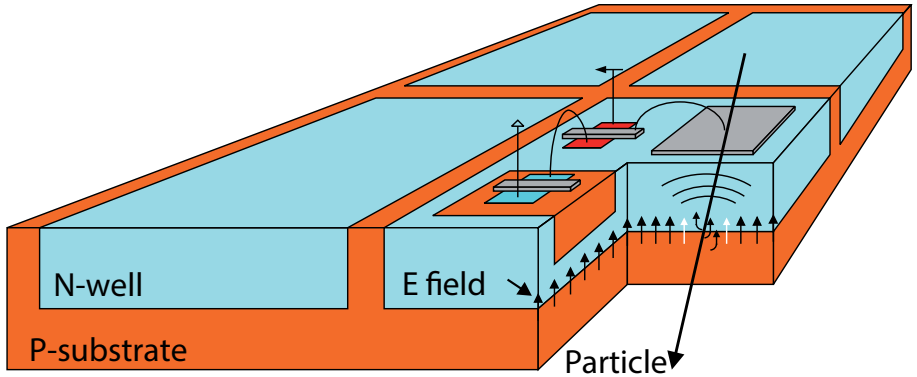
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to ~ 50 µm

(I.Perić, NIM A 582 (2007) 876)

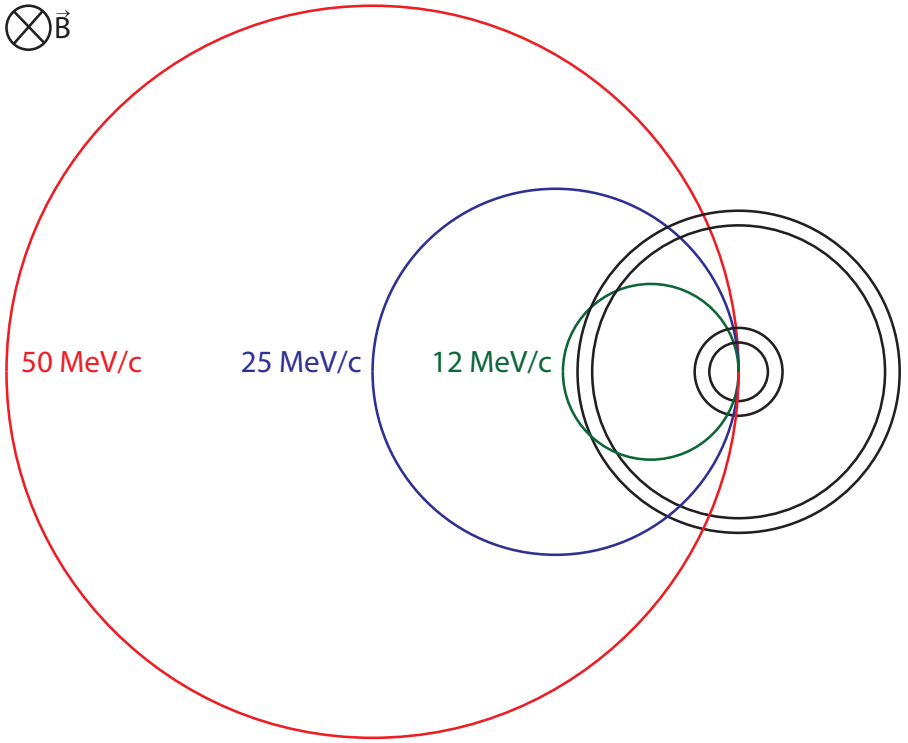


Mu3e concept

- HV-MAPS: Thin, fast pixel sensors

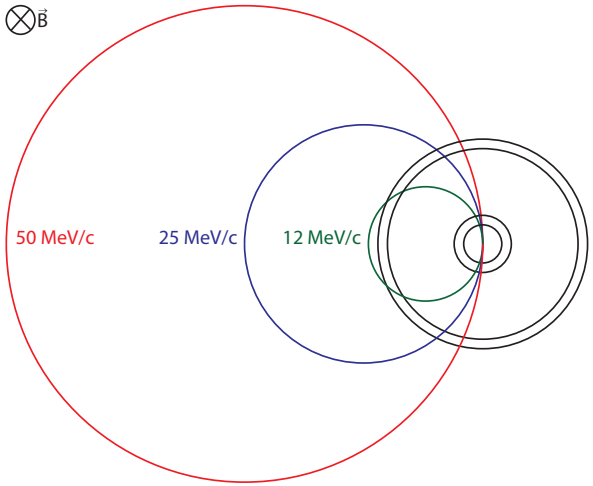


- Recurler tracking: Bending in field happens mainly outside of the tracker

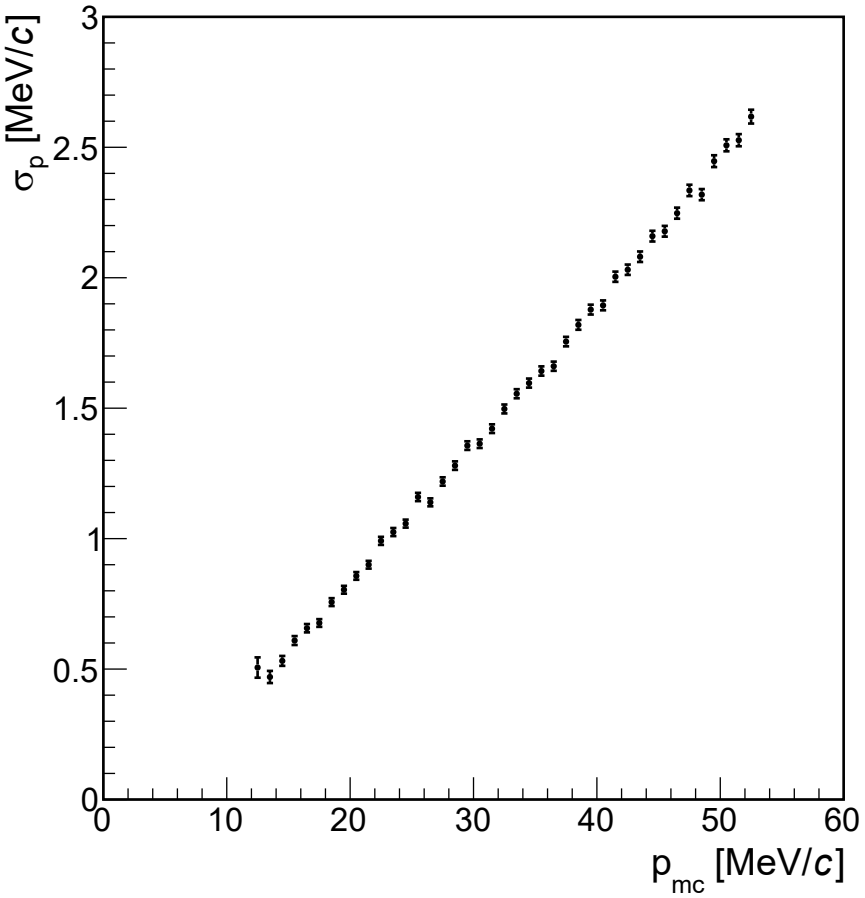


Performance simulation

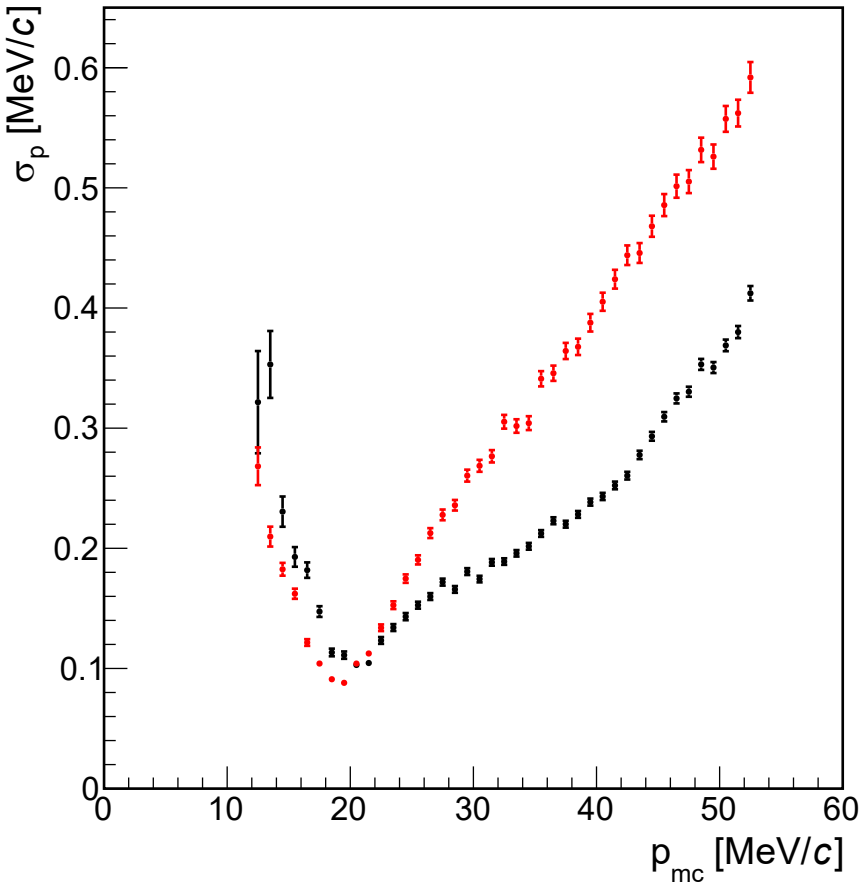
Momentum resolution



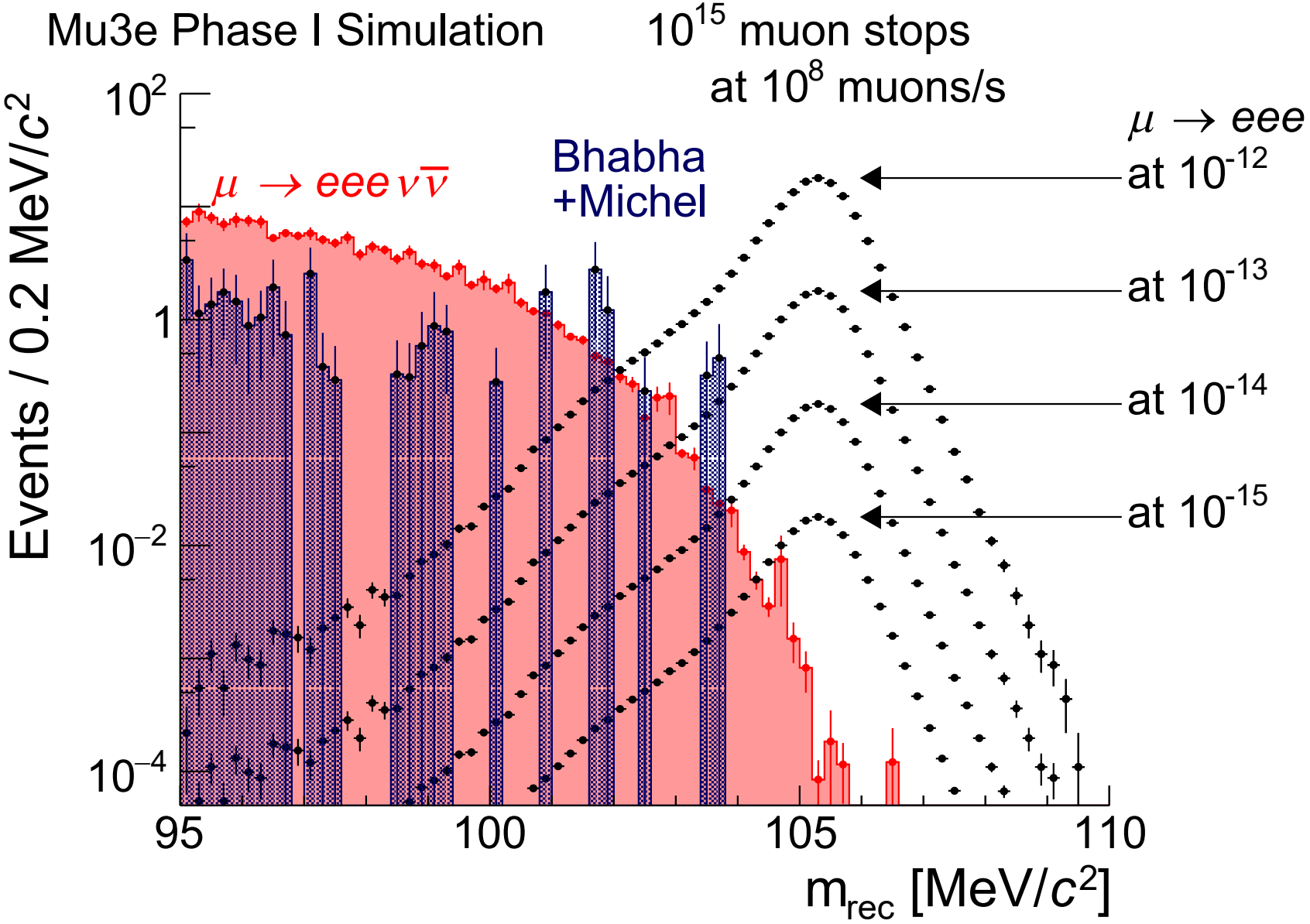
Outgoing part of tracks only



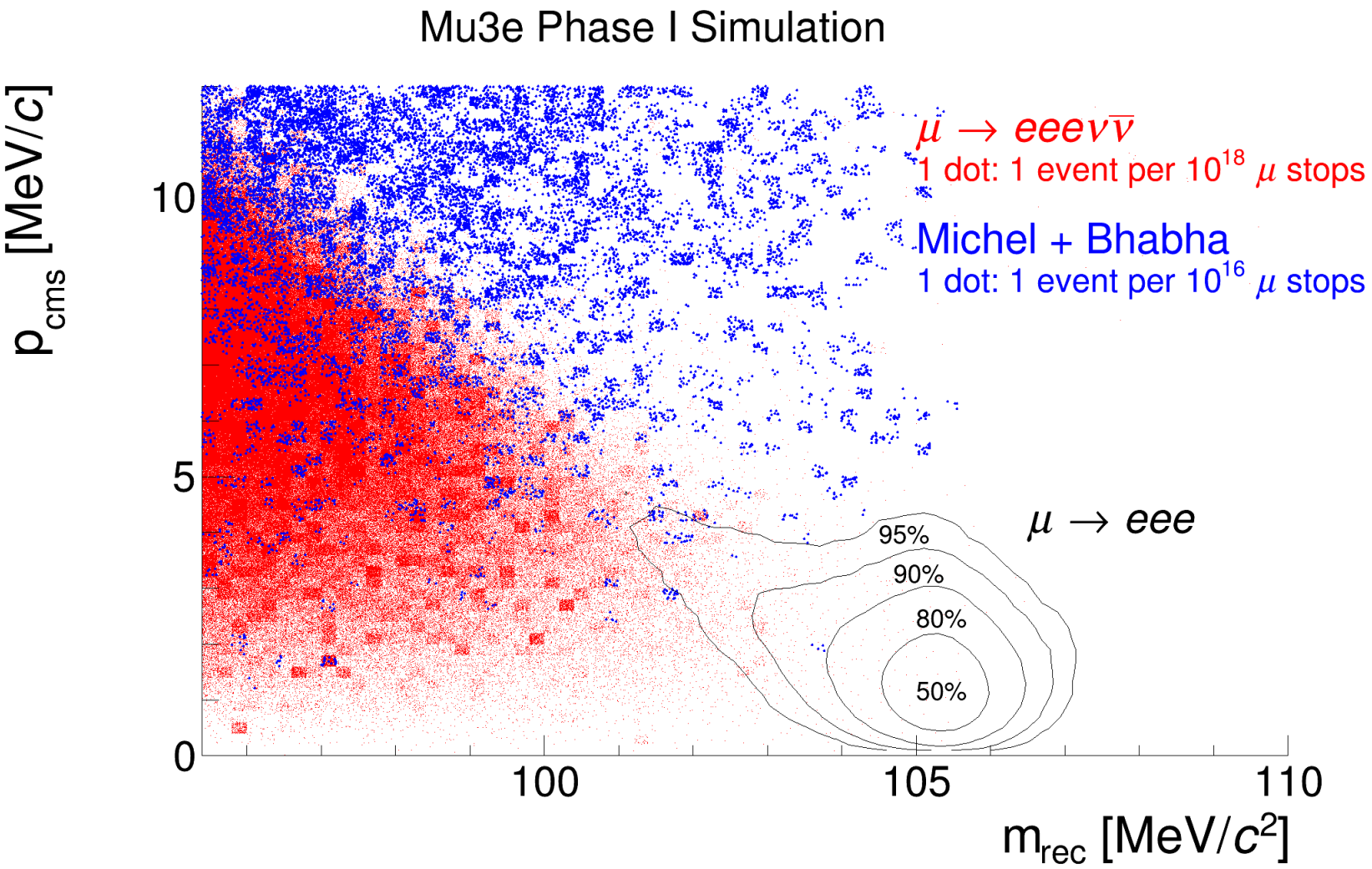
Recurling tracks



Mass distribution



Mass/Momentum distribution



Mu3e concept

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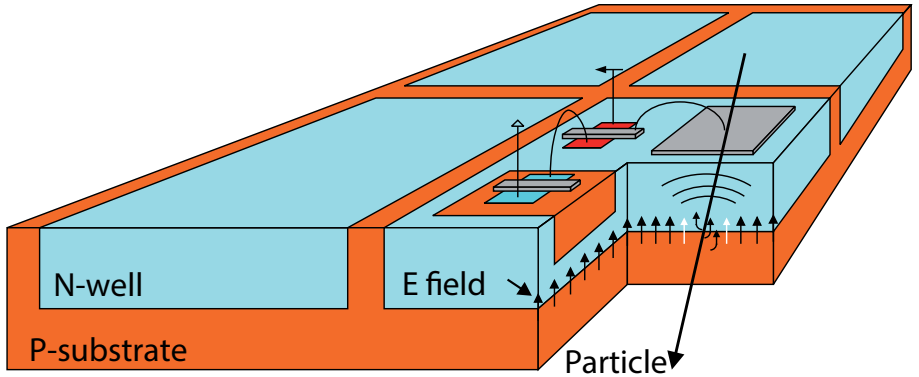
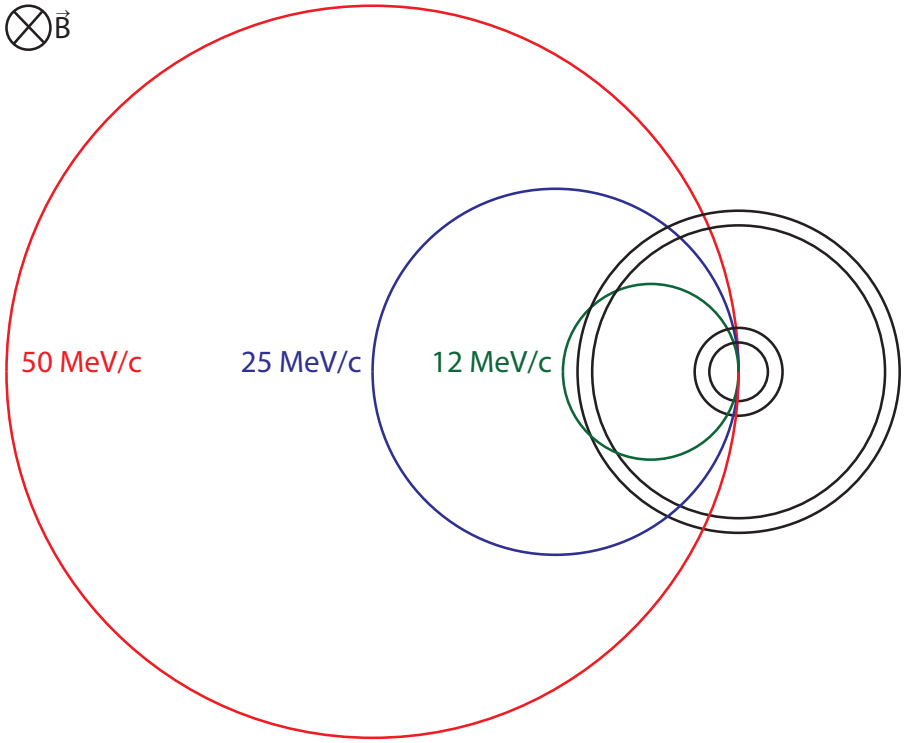


- Recurler tracking: Bending in field happens mainly outside of the tracker

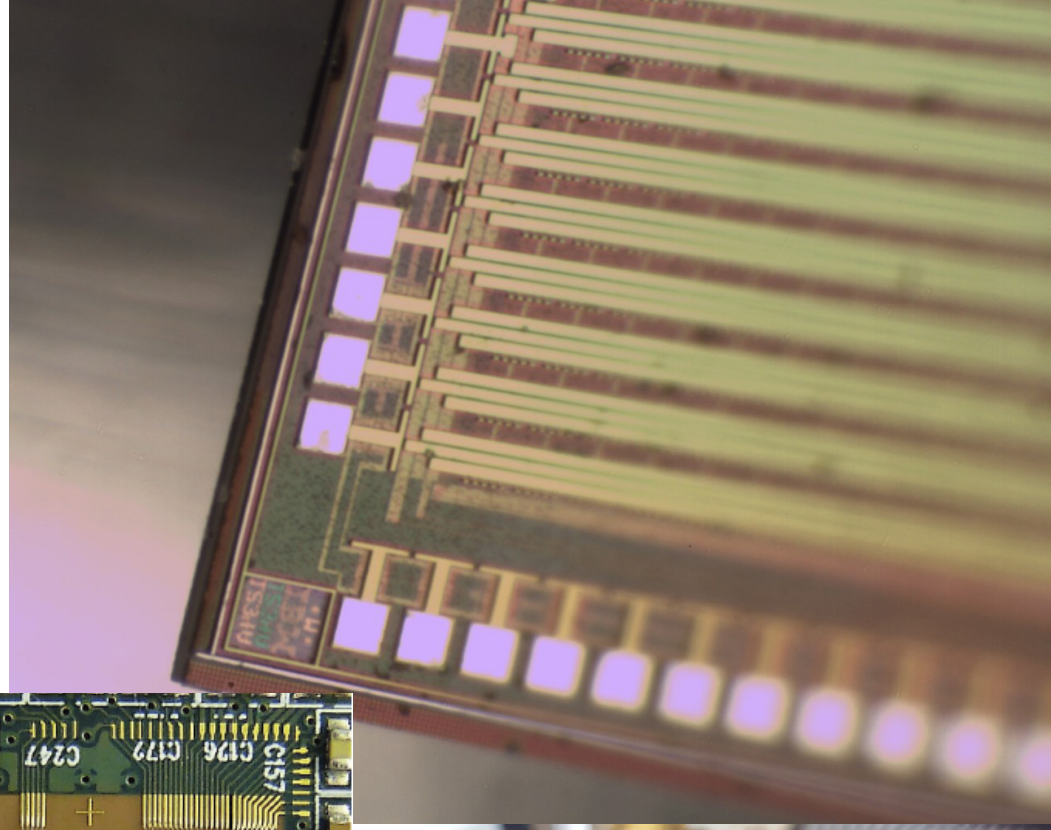


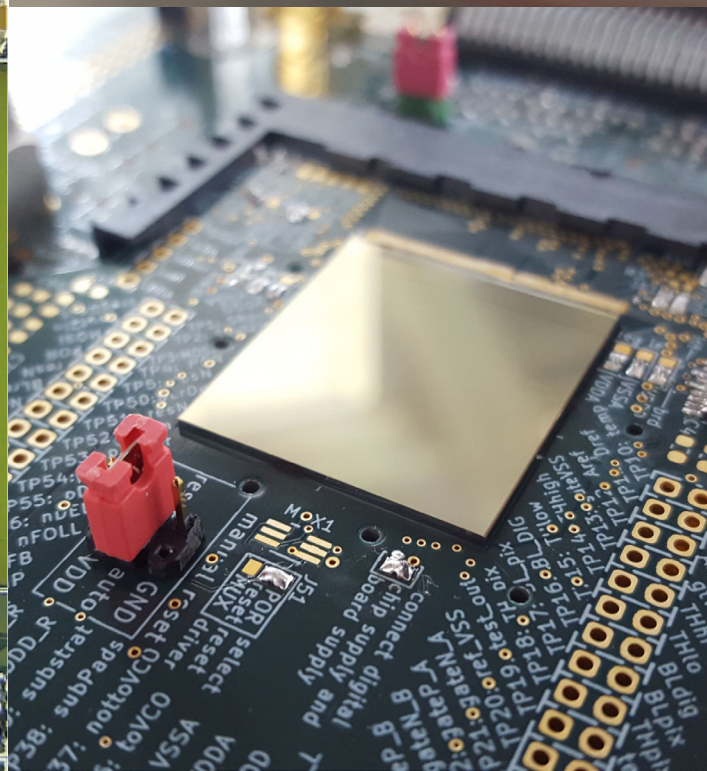
- Concept is 10 years old, experiment is being assembled now - what happened in the meantime?

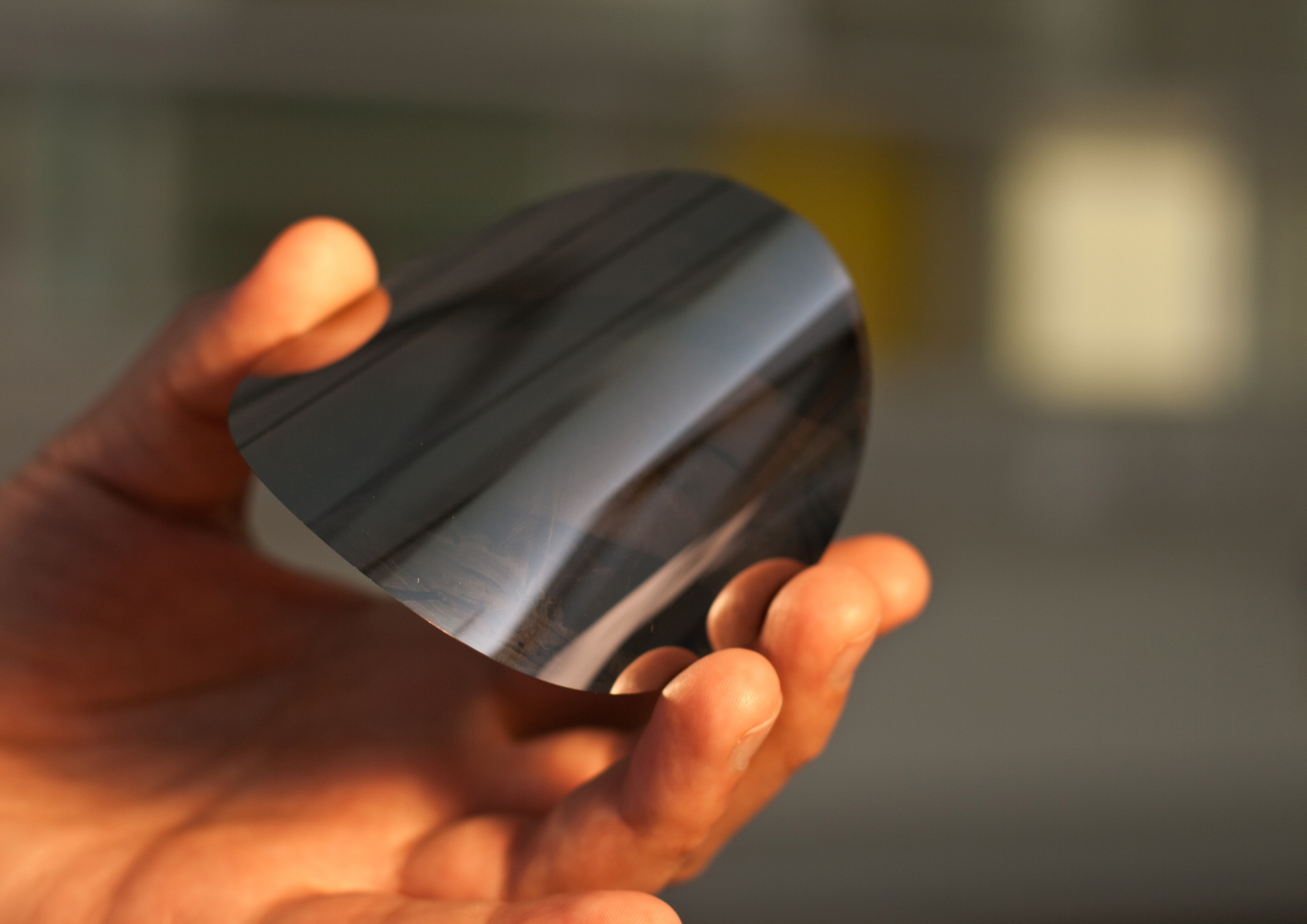
The MuPix Prototypes

Series of HV-MAPS prototypes

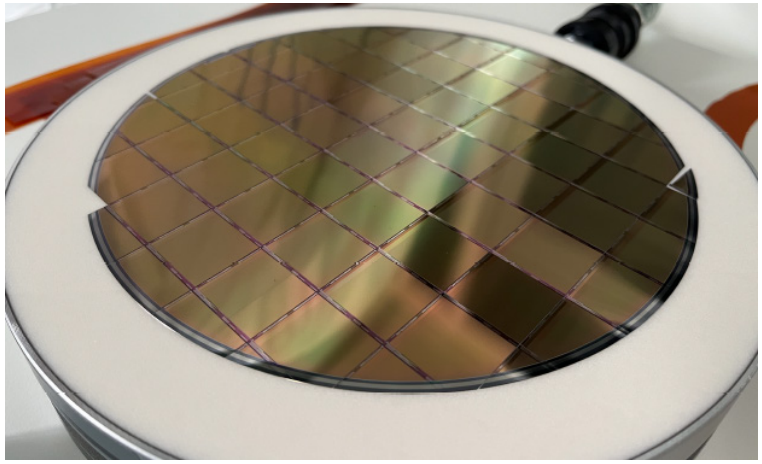
- Goal: Detection and signal processing with just 50 µm silicon
- 10 prototypes over a decade, adding features, fixing bugs
- MuPix11, 2 x 2 cm^2, production chip, now available
- Efficiency > 99.9%
- Less than 1 Hz noise per pixel
- < 20 ns time resolution
- 200 mW/cm^2 power consumption

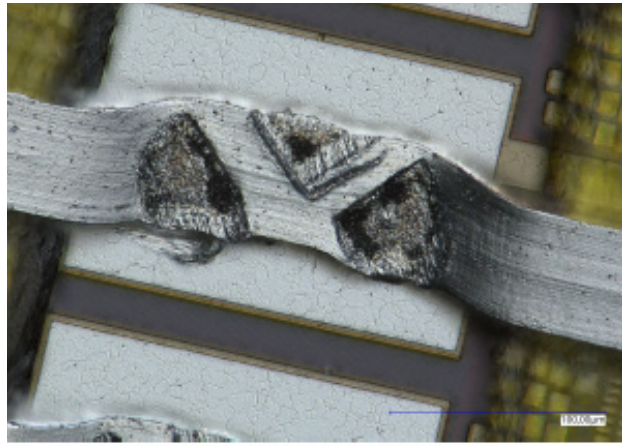




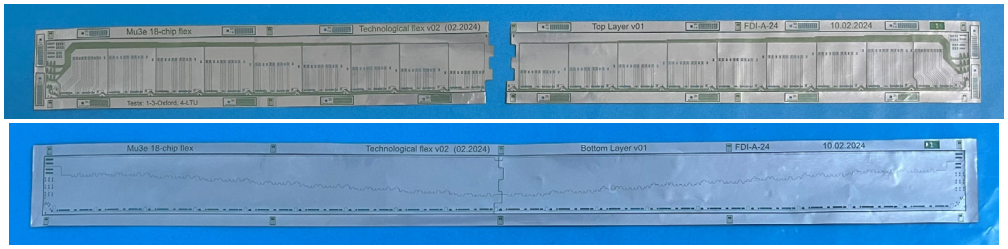


Mechanics and Connections

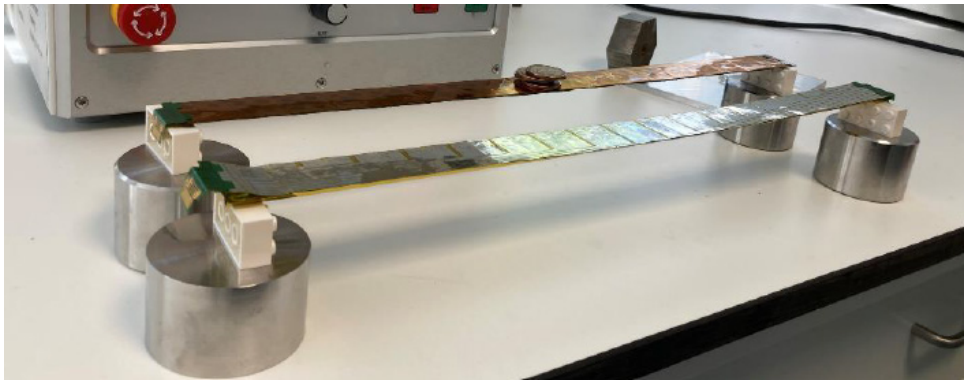




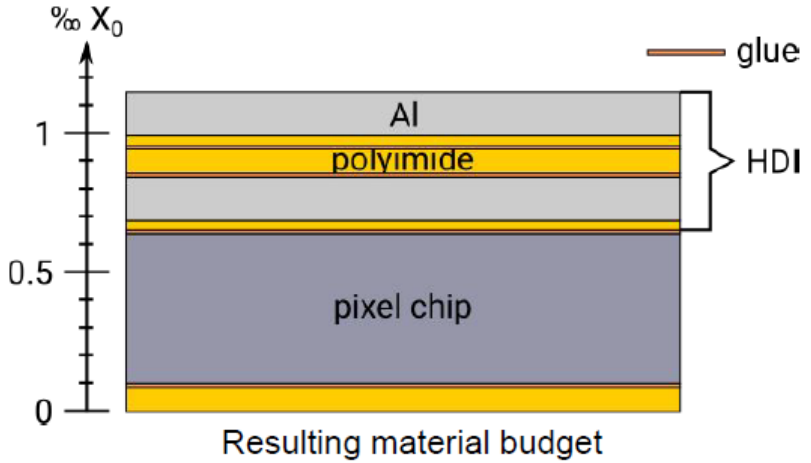
- 50 μm silicon



- 25 μm Kapton™ flexprint with aluminium traces (manufactured by LTU, Kharkiv, Ukraine)
  SpTAB bonds for connections



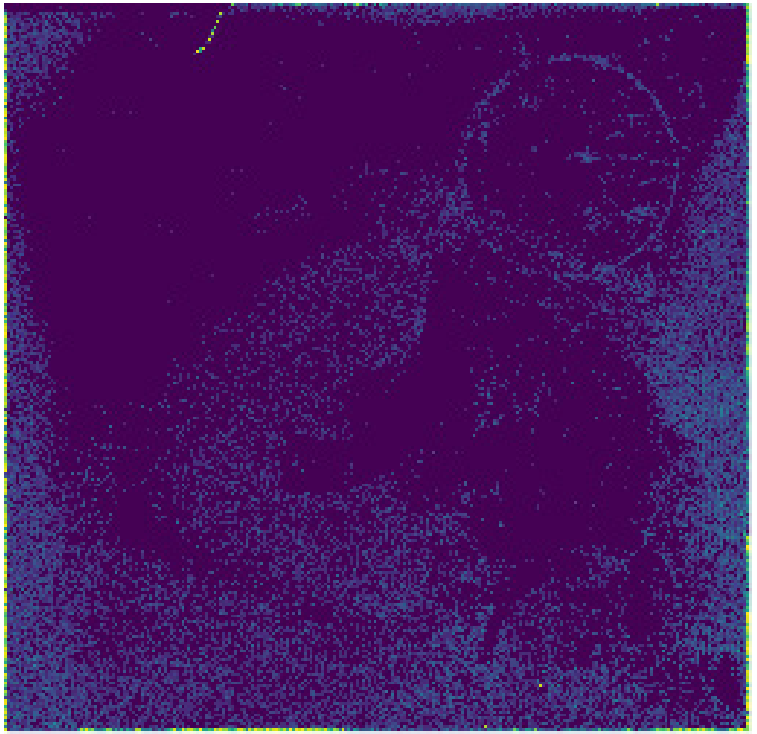
- Kapton™ or unidirectional carbon fibre supports



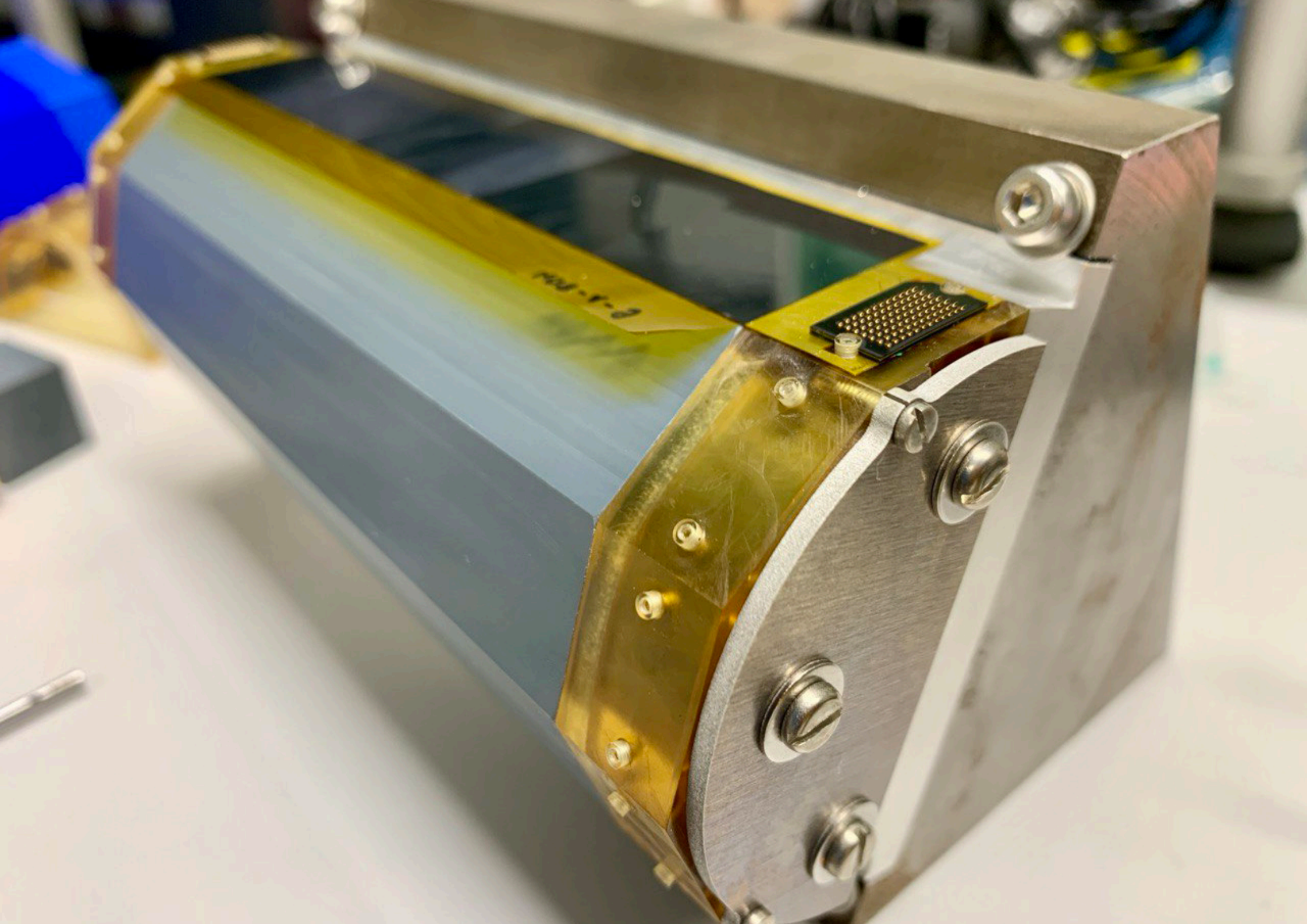
Resulting material budget

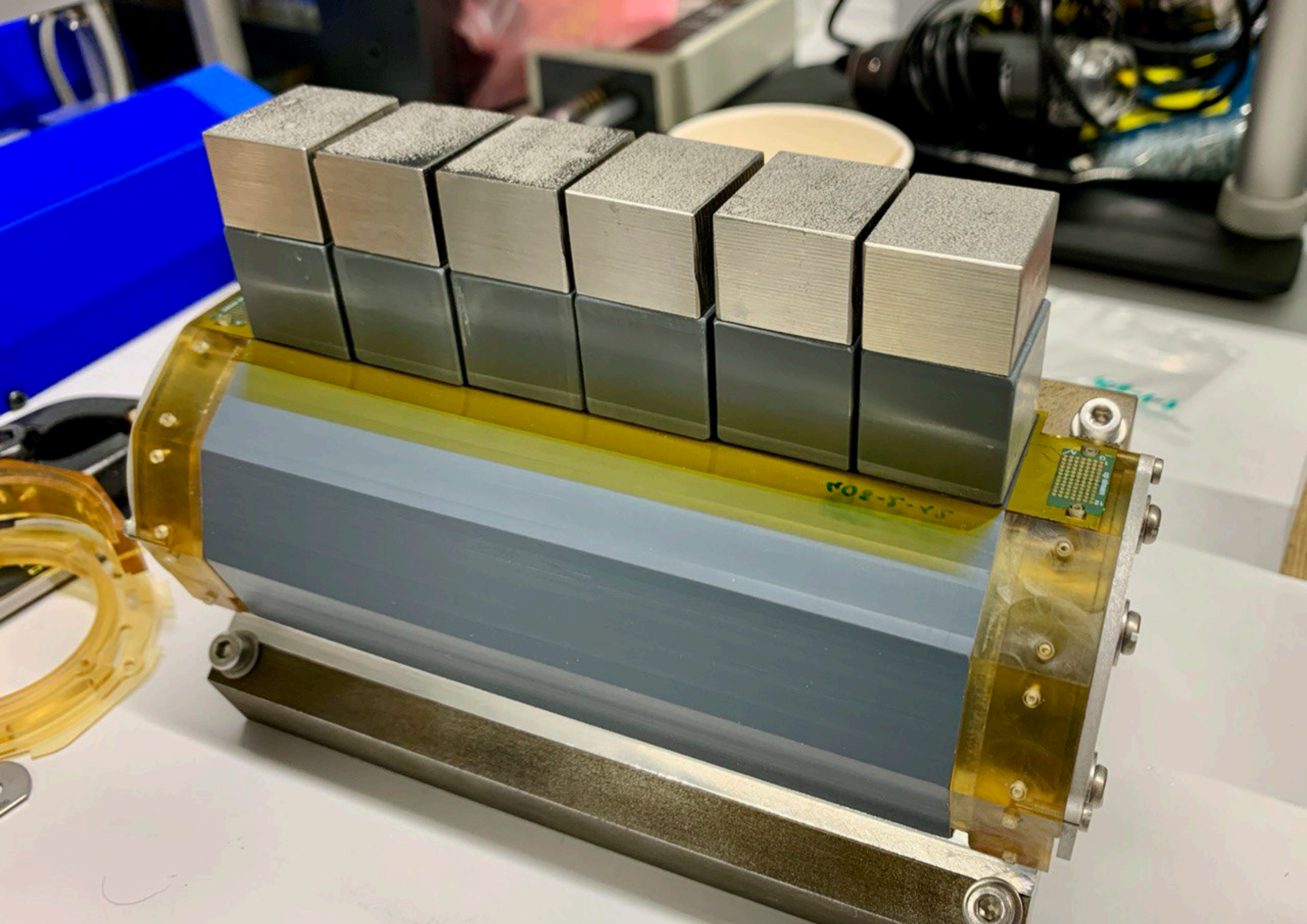
Handling

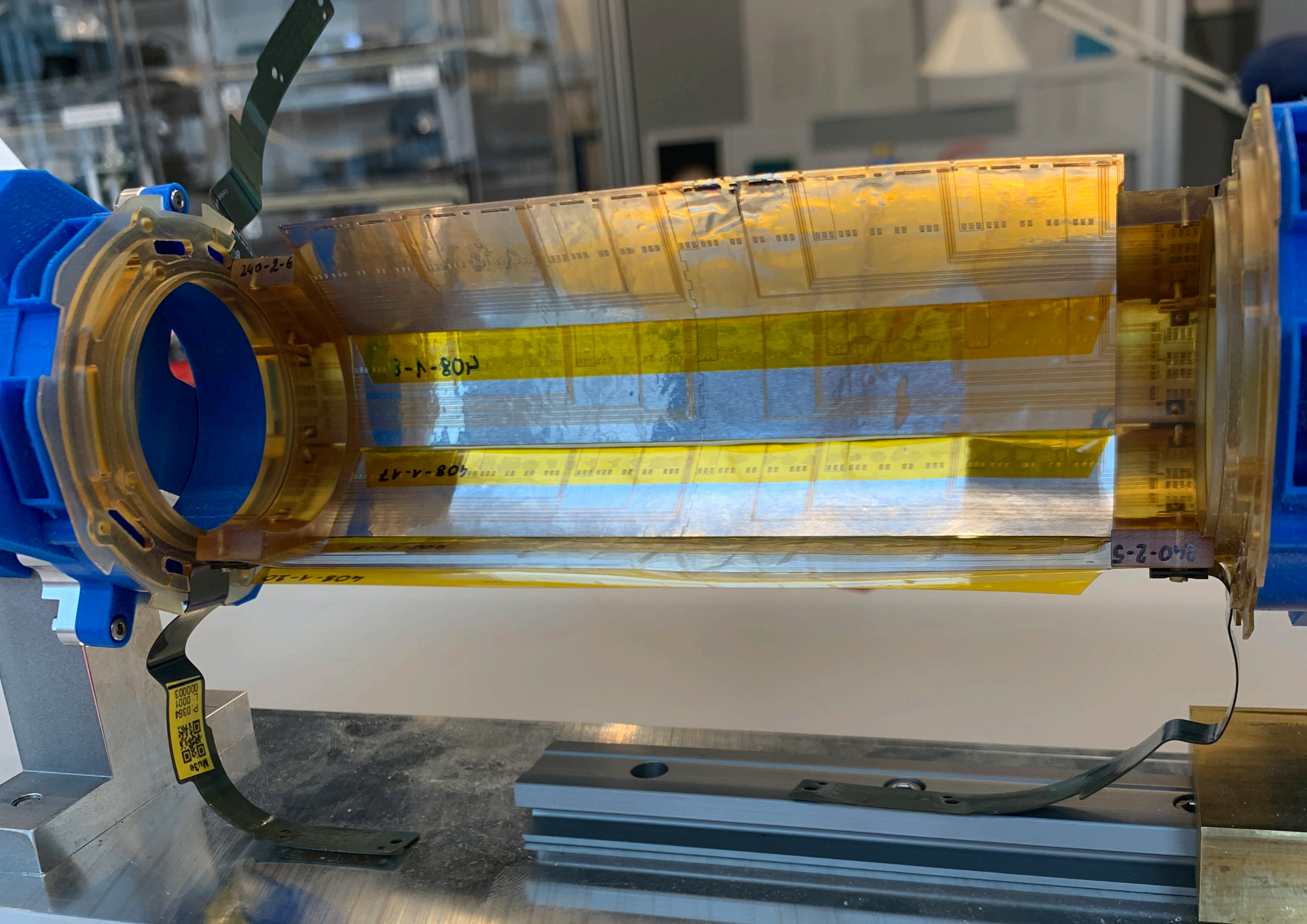
- 50 µm chips are super fragile
- Every step needs to be qualified: Establish procedures and train people



- Chips "remember" mechanical mistreatment: Here - noise map shows pick-up tool and glue

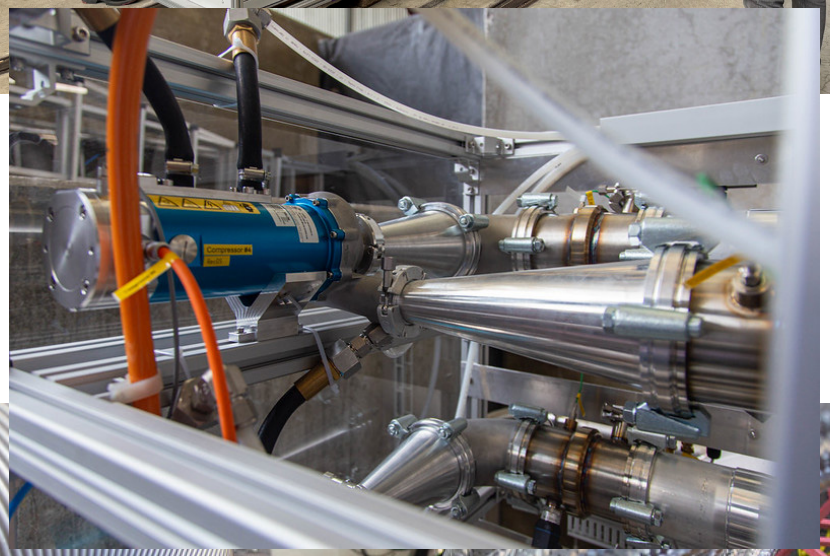


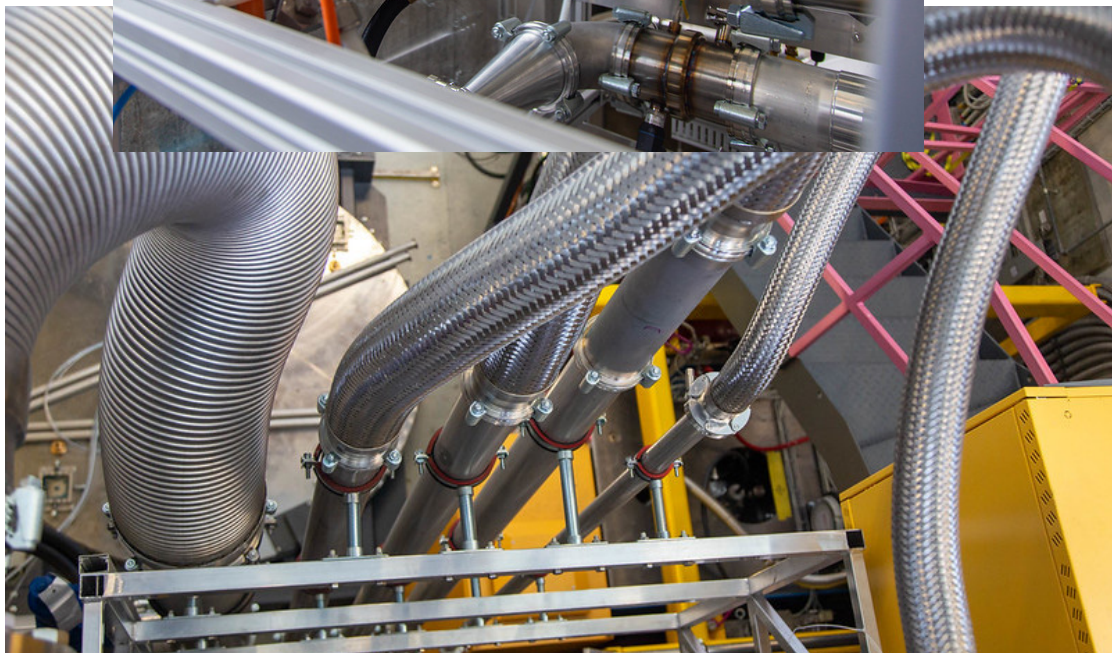



240-2-6
240-2-5
408-1-17

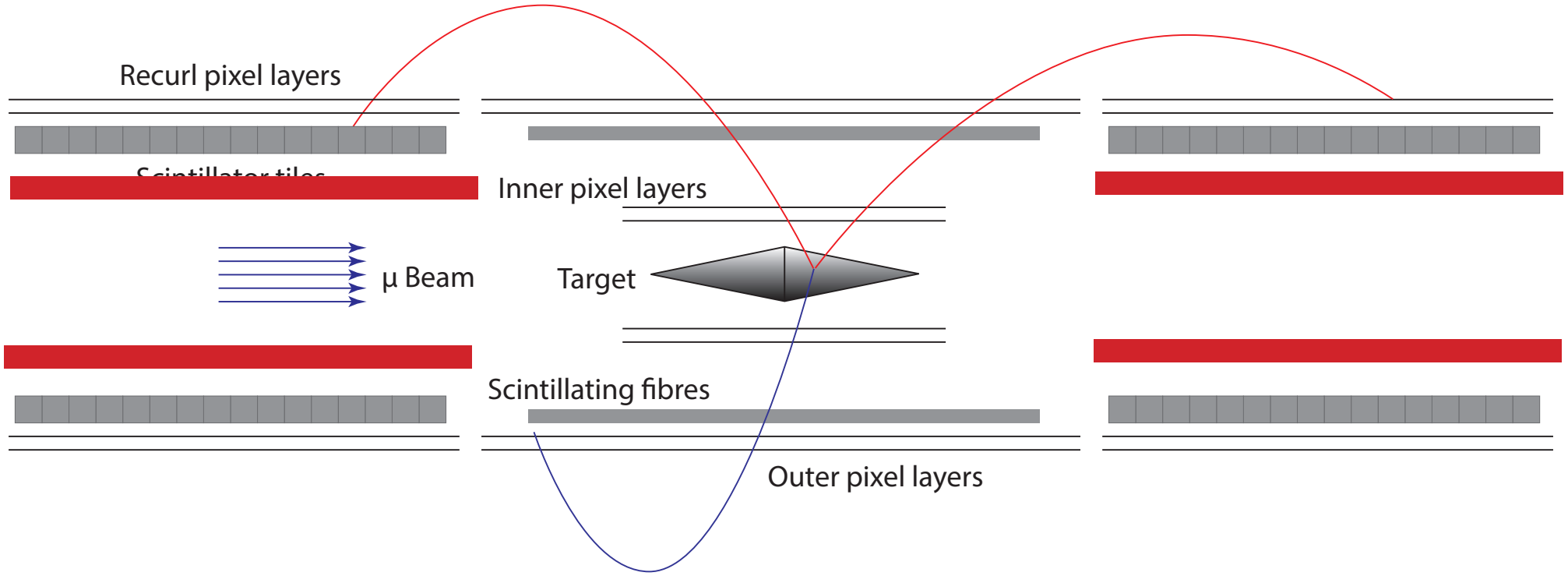
Cooling

- ~ 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 liters/s at STP...)
- Helium is difficult to pump...
- Very nice little turbocompressors available
- Cooling plant is an engineering project of its own

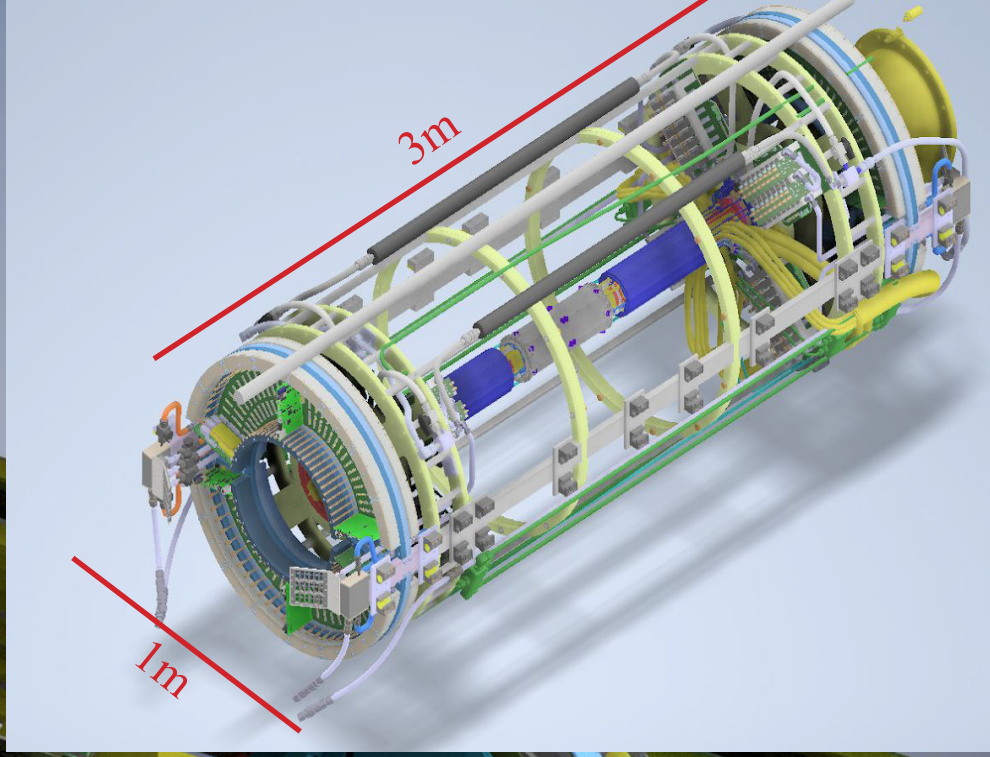




Putting all of this together, making connections

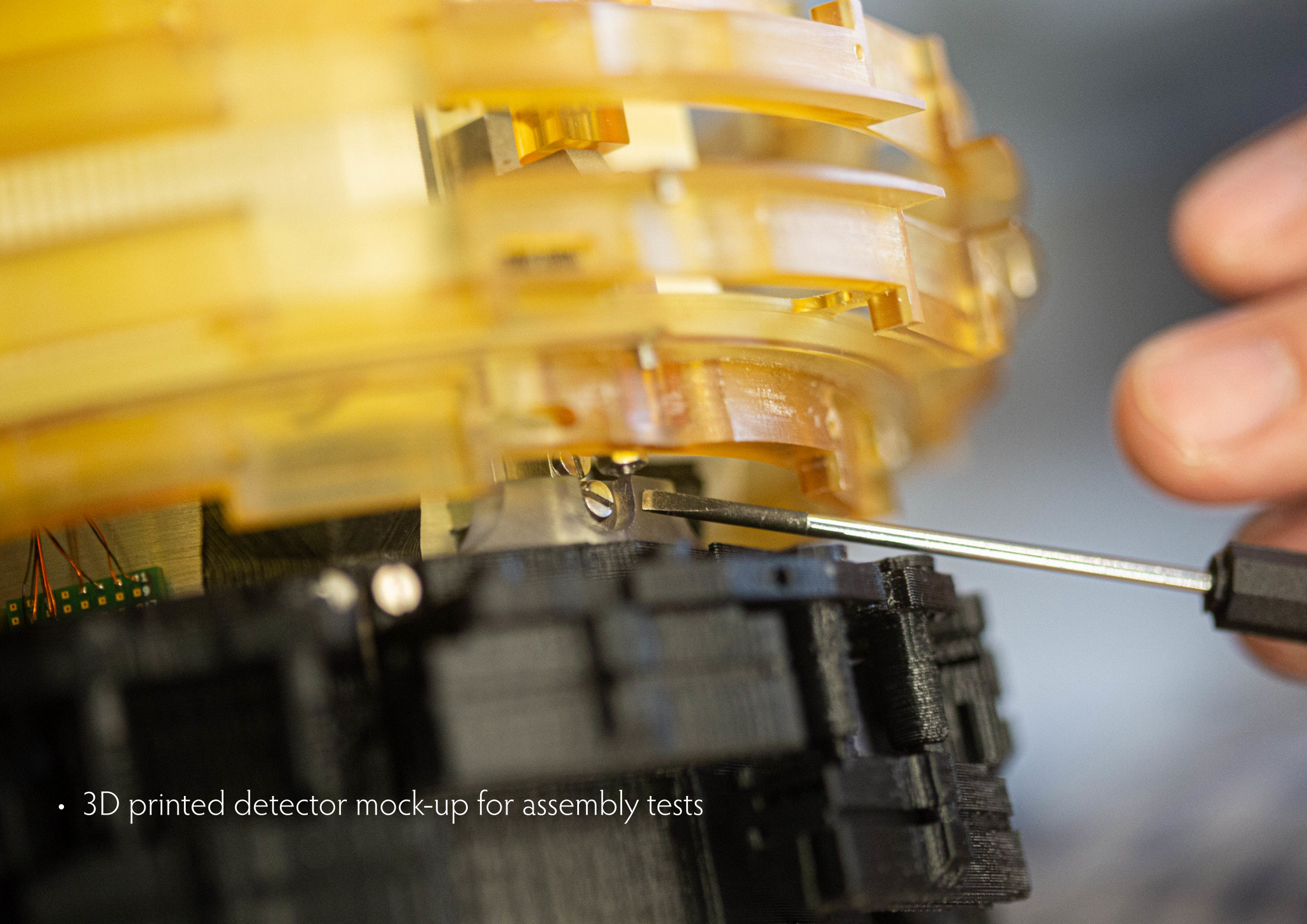


Detector Design

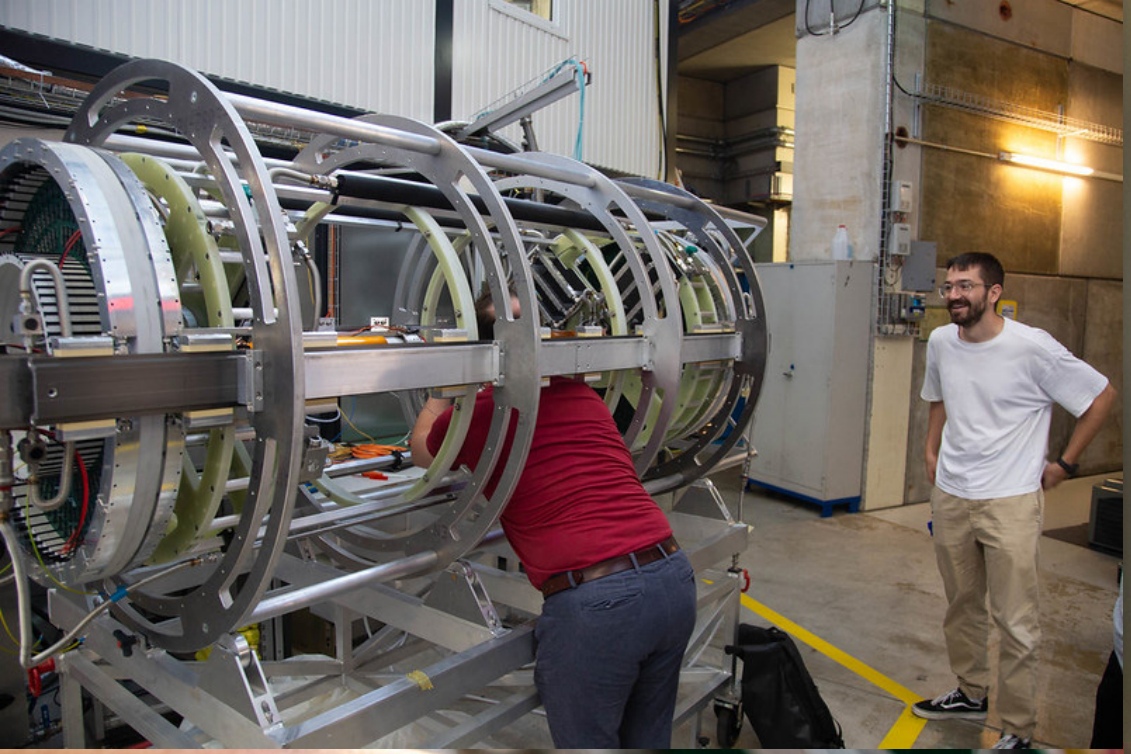


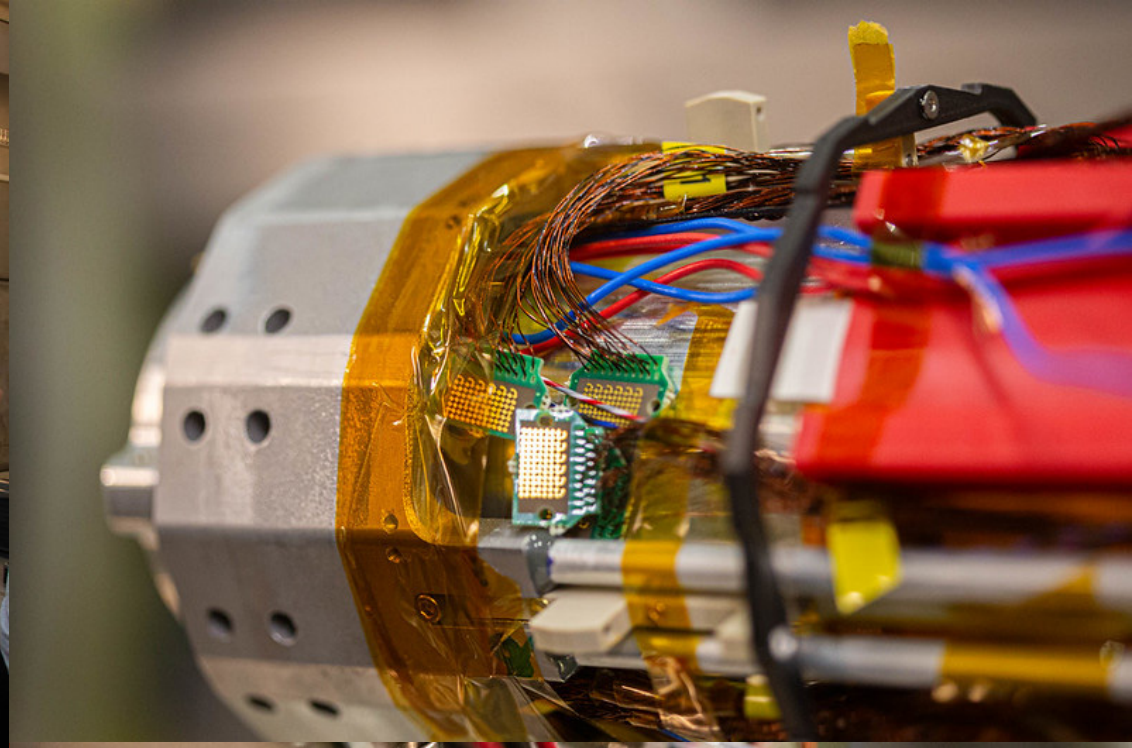
10 cm

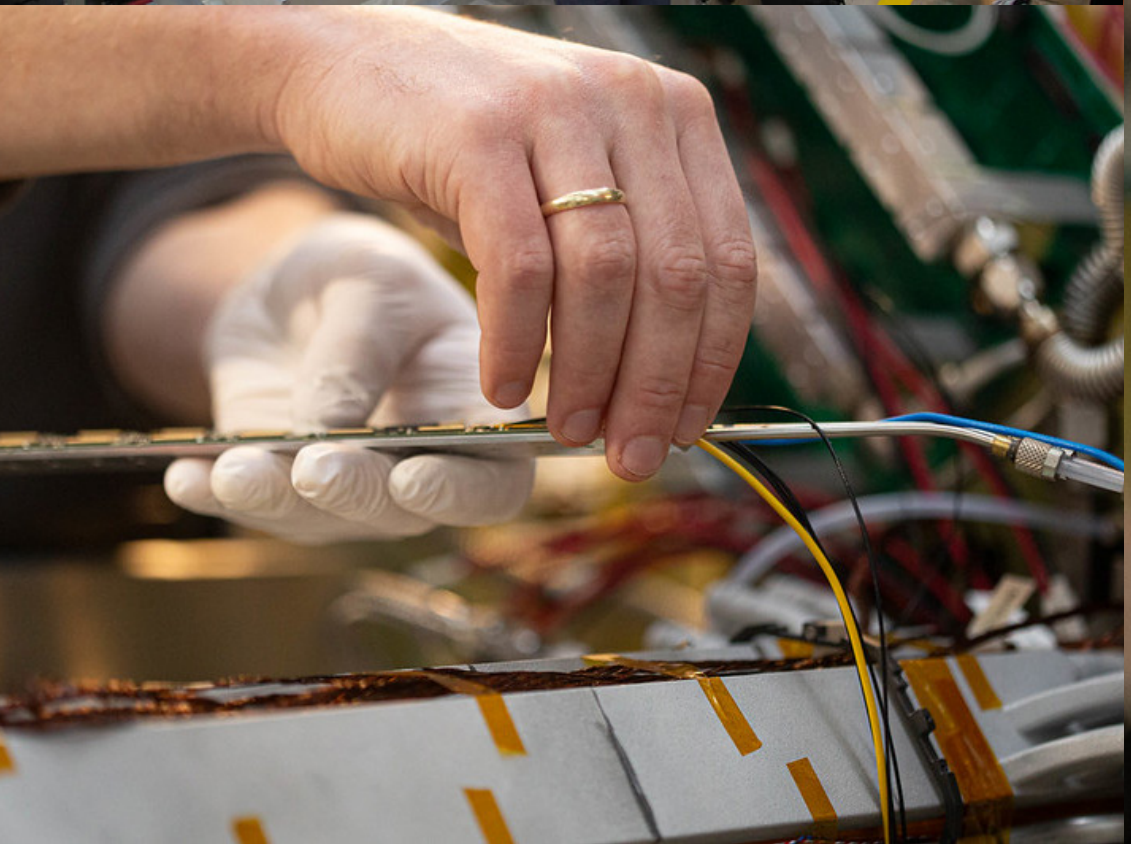
- Full CAD with wires and pipes
- Space is very tight

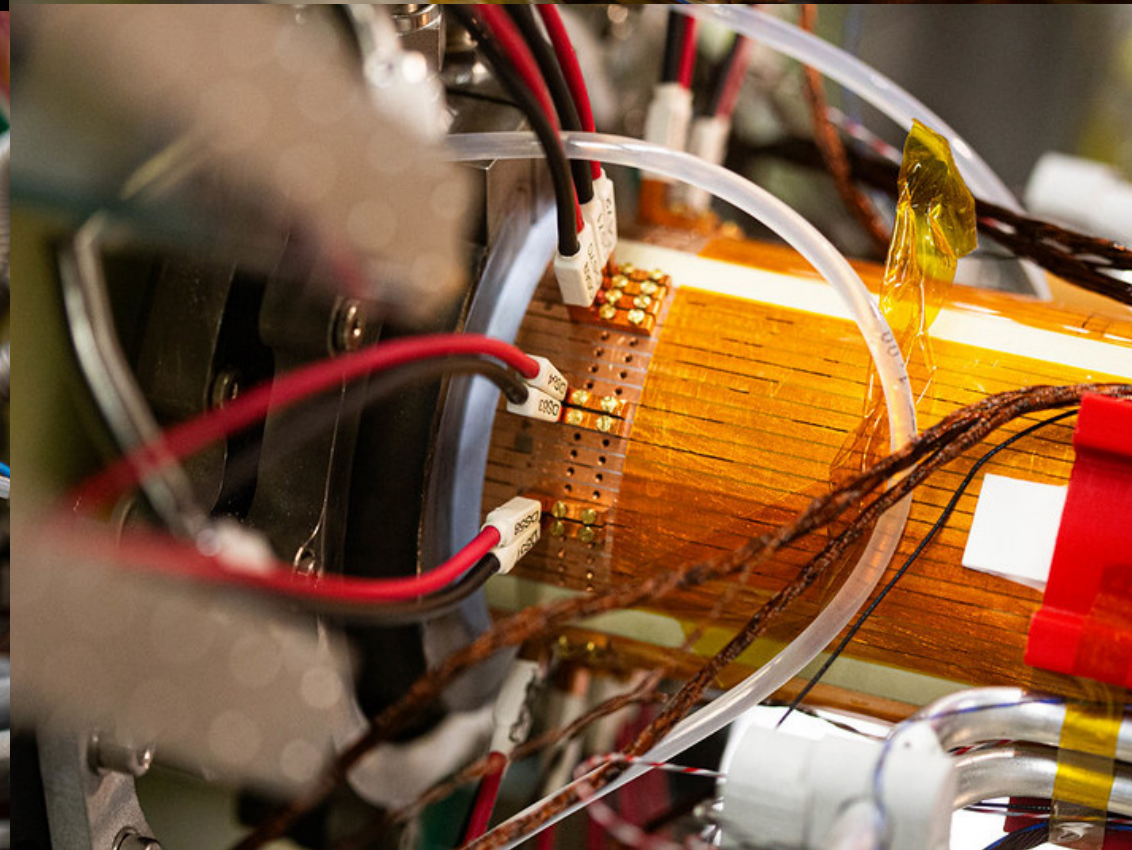


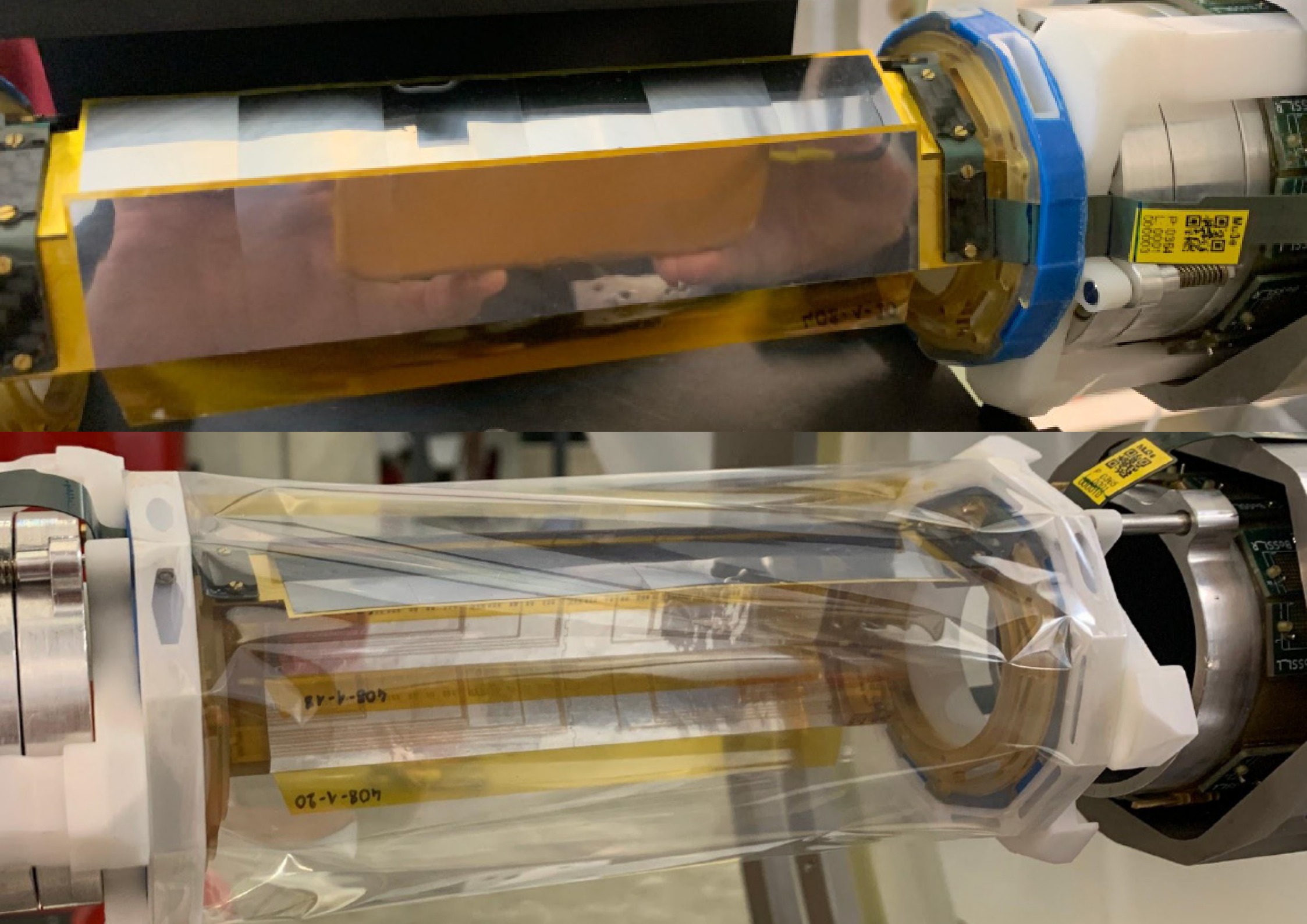
- 3D printed detector mock-up for assembly tests



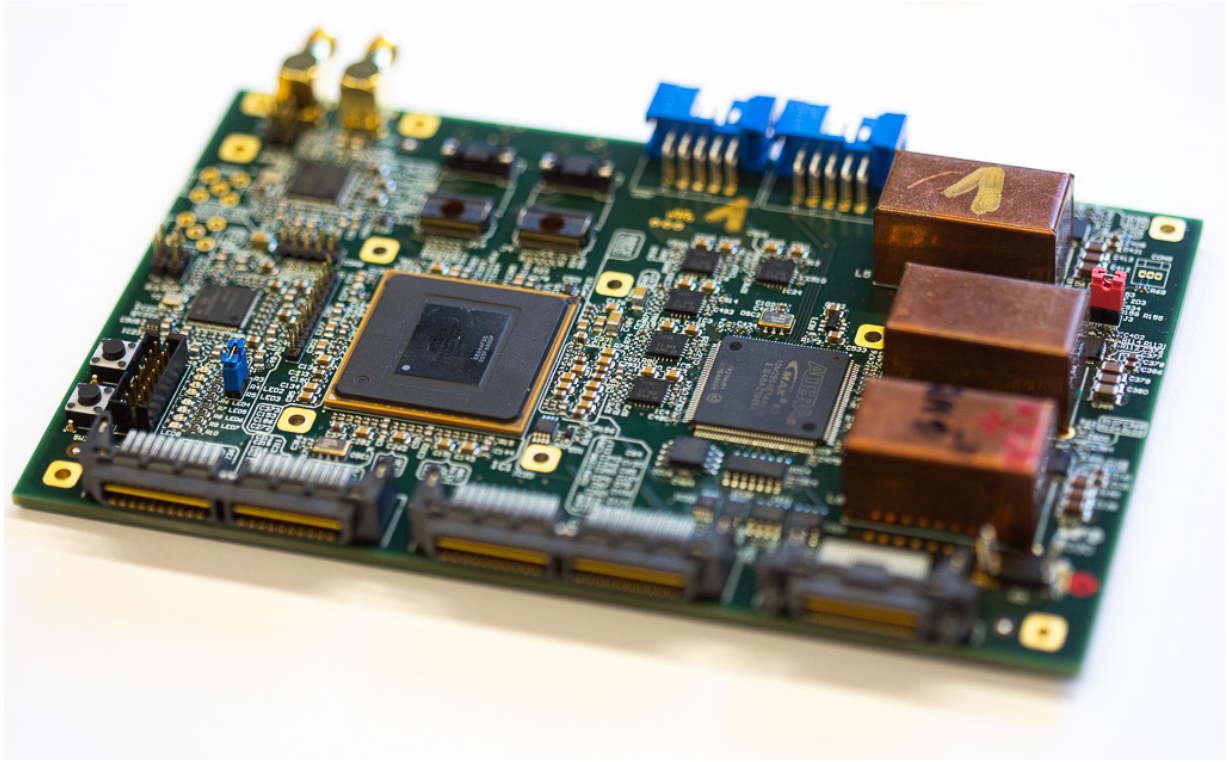




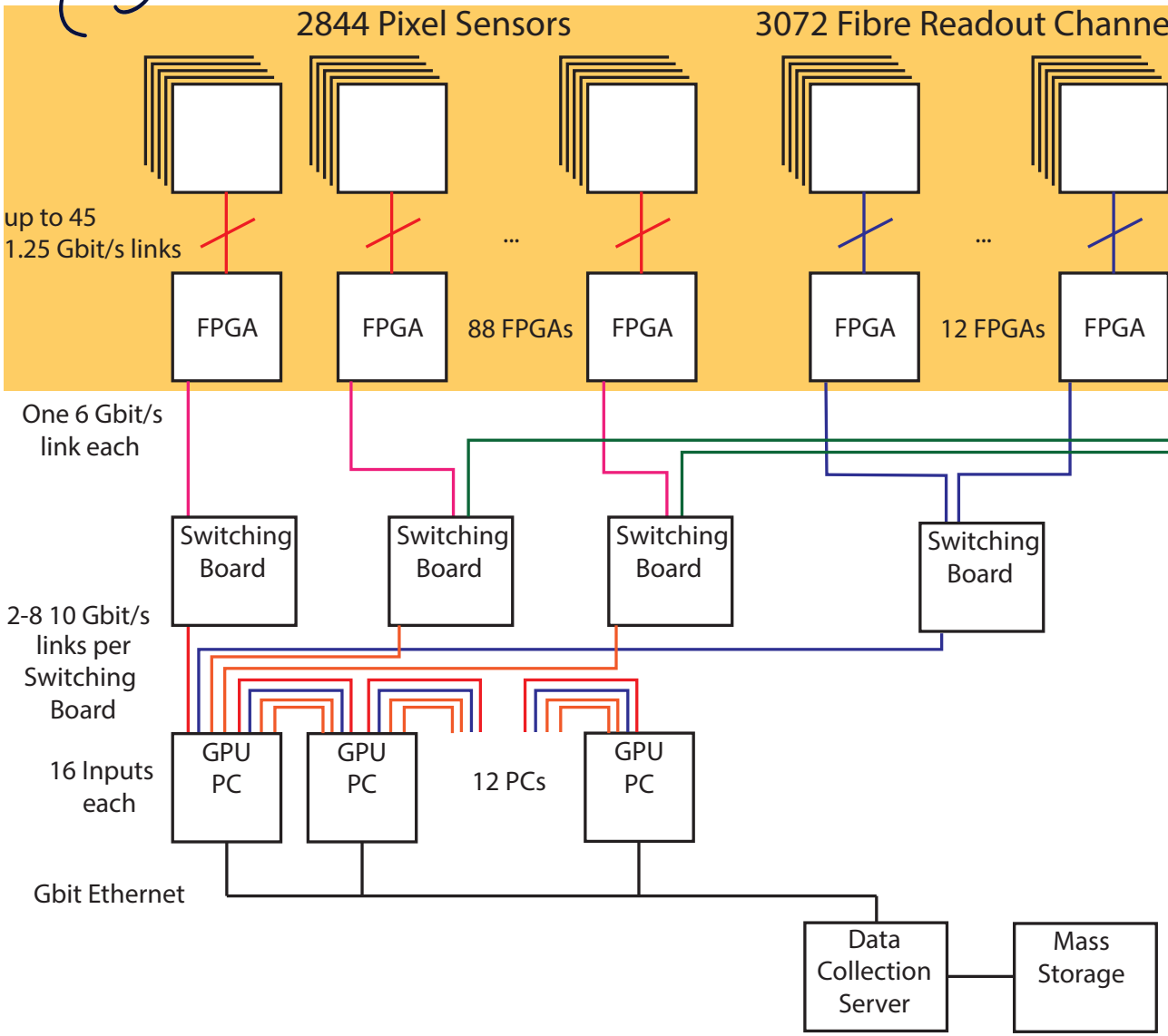



408-A-20
408-A-18

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

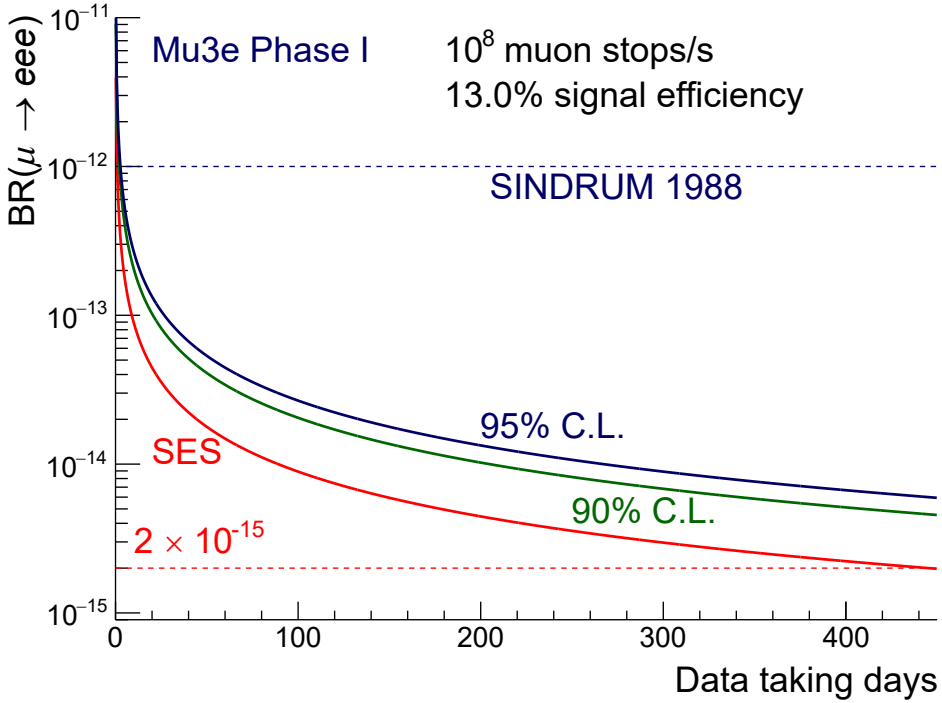
- GPU reconstruction on gaming cards
- Have achieved > 10^9 track fits/s per GPUs (Nvidia GTX 980)
- Twelve GTX 1080Ti are sufficient for dealing with 10^8 muon decays/s

  ~ 8 years pass

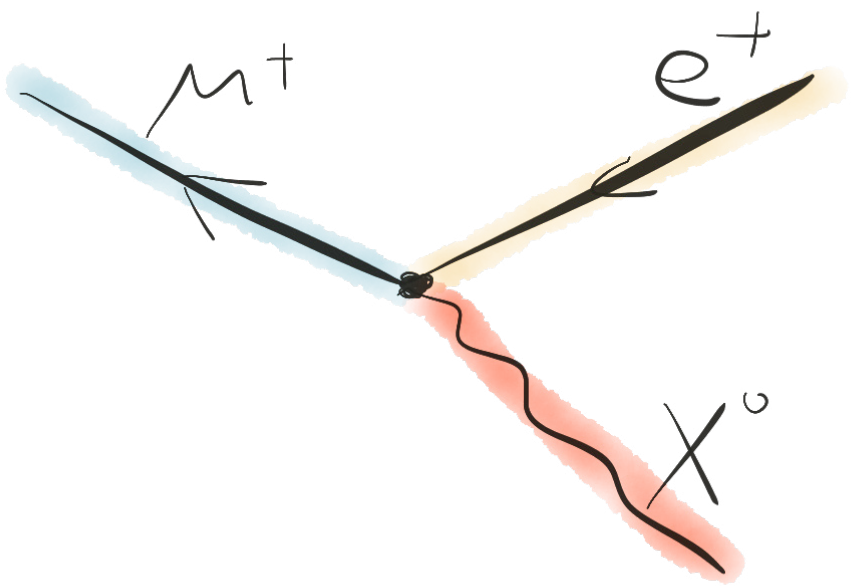
- Just four RTX 4090 can handle Mu3e phase I...

Status and plans

- Assembly now, test run in 2025
- First physics data taking in 2026
- 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



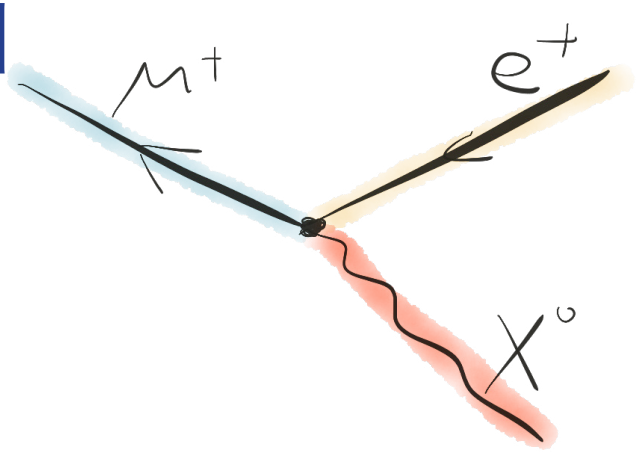
Familons in Mu3e



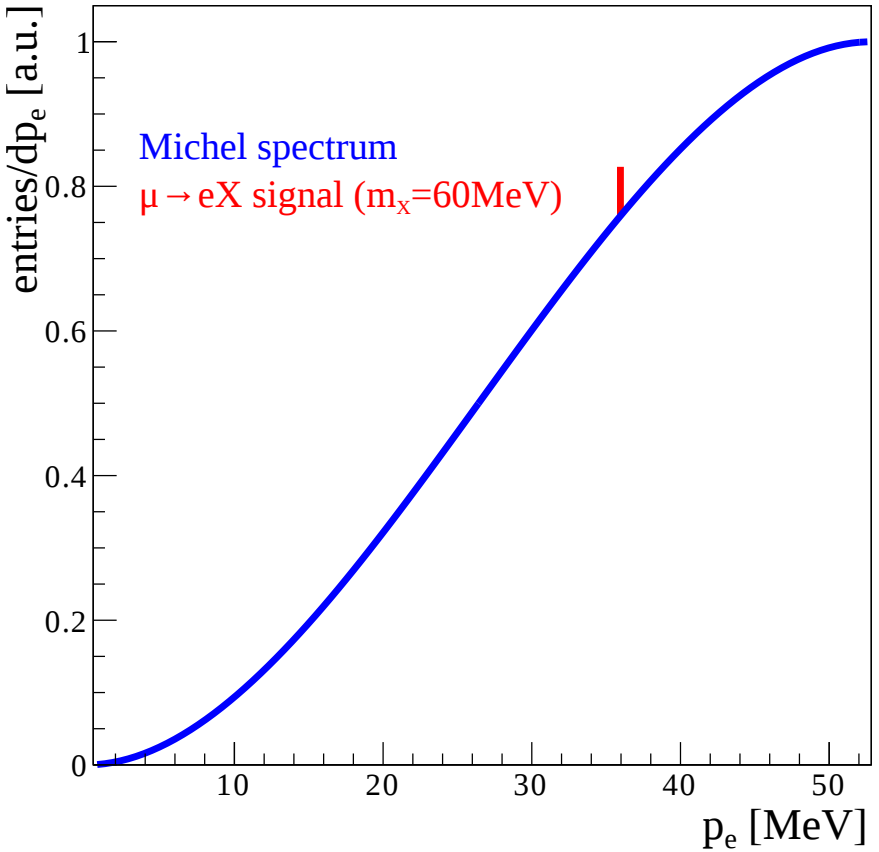
- Spontaneously broken flavour symmetry: Goldstone boson(s) called familons
- Can be a light dark matter candidate
- Lead to μ → eX, where X a familon

- μ → eX can also show up in other models, search for it with the large muon decay data set at Mu3e

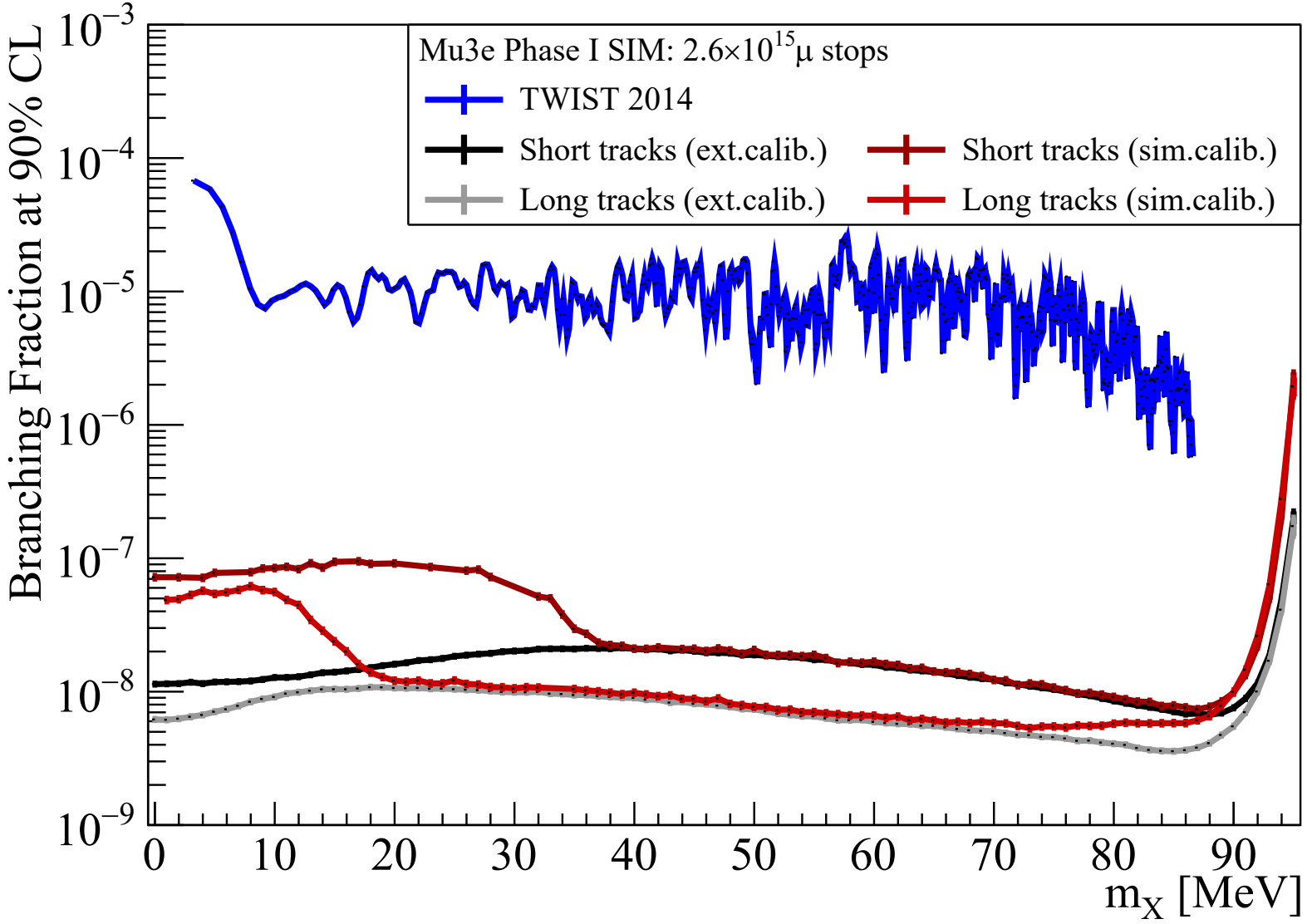
Signature and Background



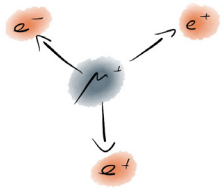
- Signal: Two-body decay:
  Monoenergetic positron
- Background: All other positrons,
  dominated by Michel decay,
  smooth momentum distribution
- Bump hunt on the positron spectrum
  (all tracks - needs to run online)

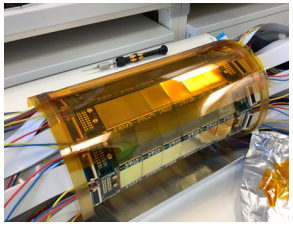


Projections

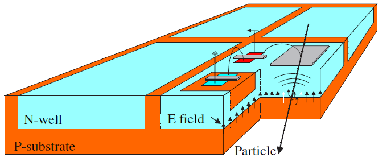


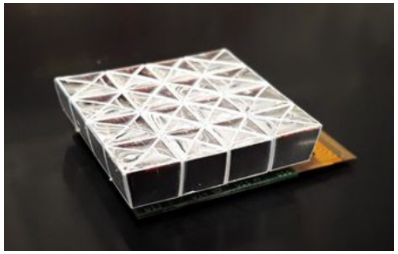
Conclusion

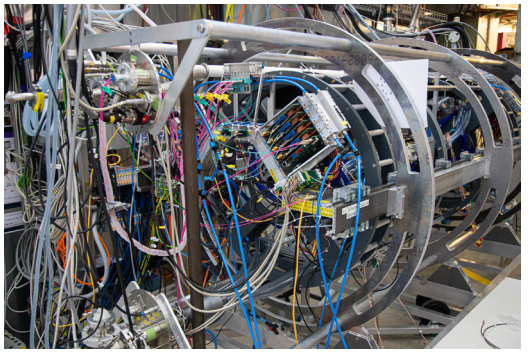




- Mu3e aims for μ → eee at the 10^{-16} level
- First large scale use of HV-MAPS
- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct >10^8 tracks/s in ~100 Gbit/s on ~4 GPUs
- Integration and commissioning 2024/25
- … and then finally data!





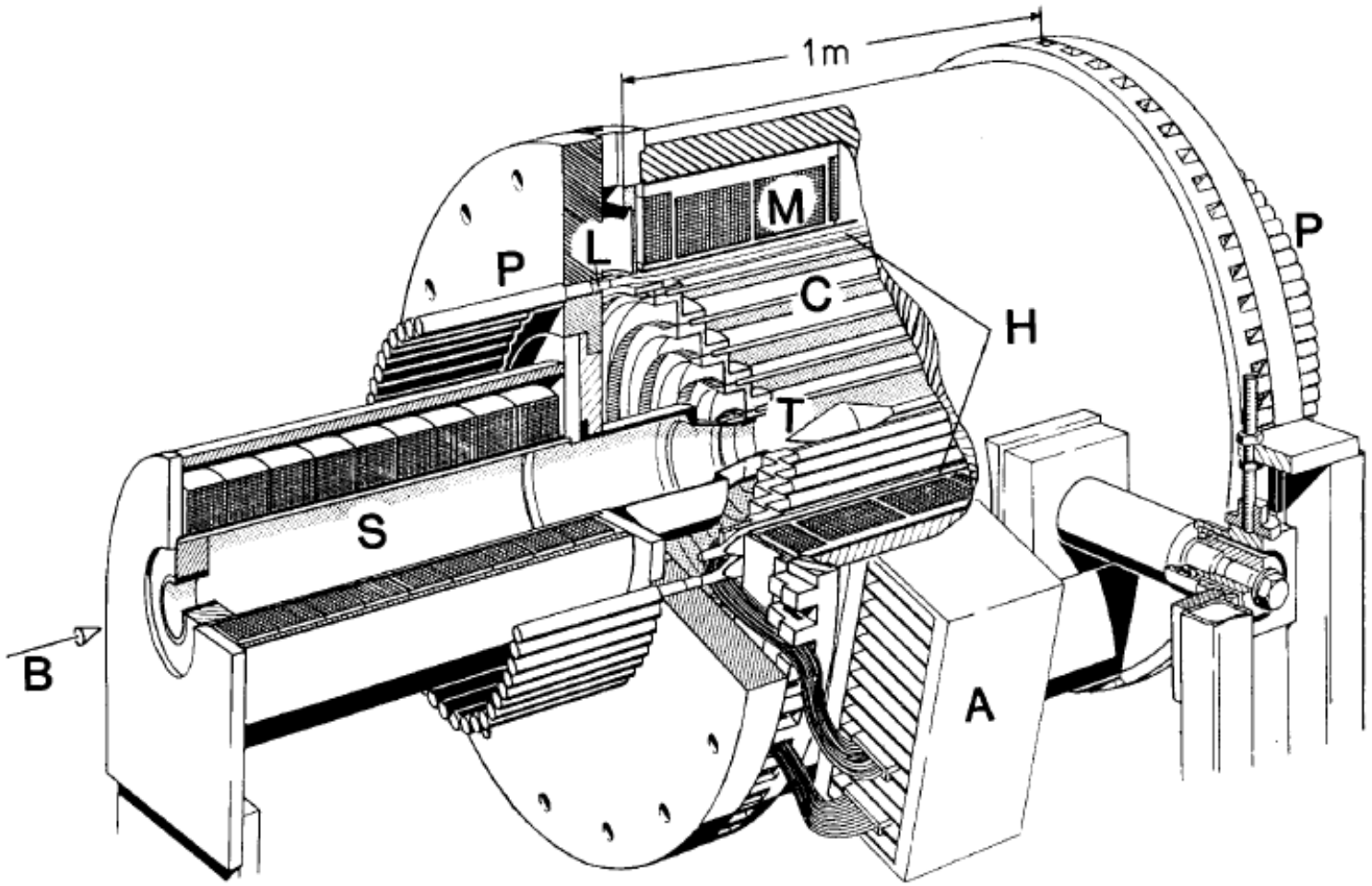


Backup

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

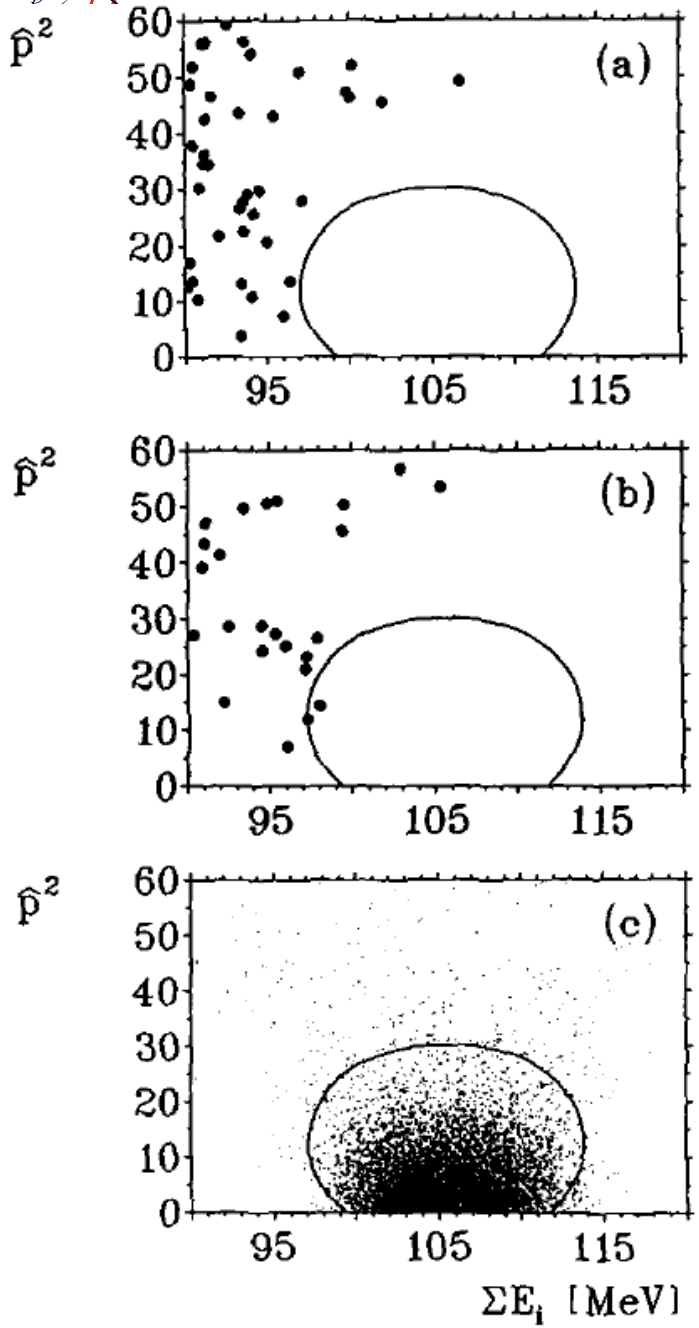
A: Preamplifiers

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

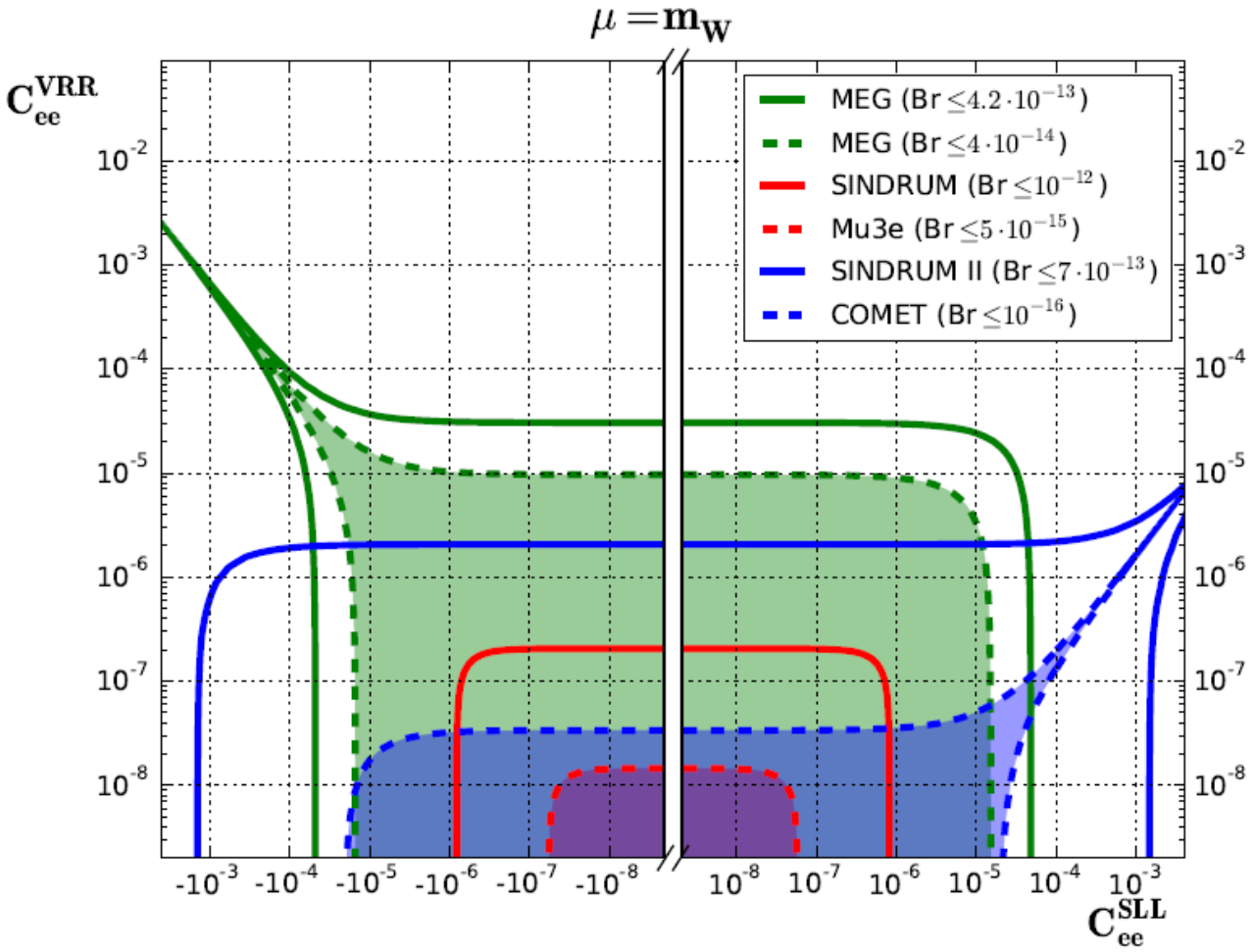
(c) Signal MC with 95% contour

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

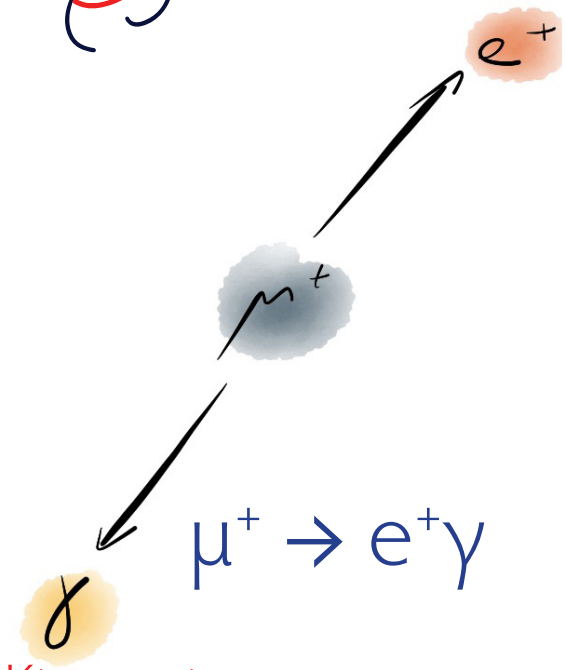
LFV Muon Decay in Effective Field Theory



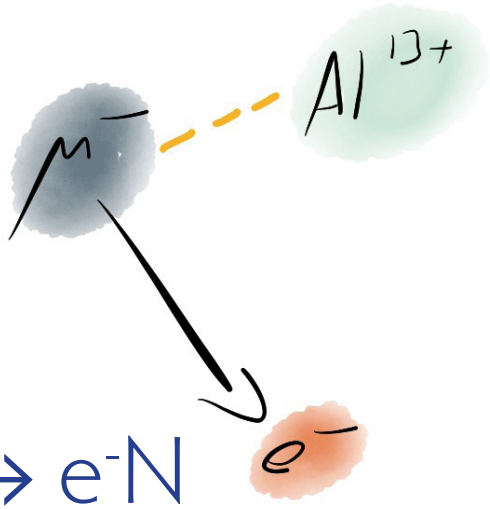
- Effective field theory approach with renormalisation group running
- Experiments put complementary constraints on Wilson coefficients

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

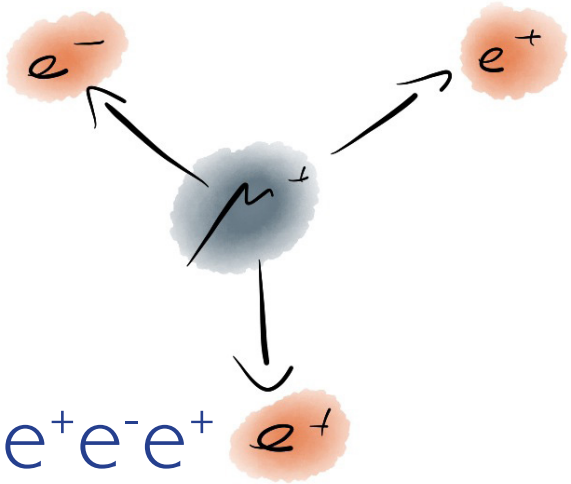
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

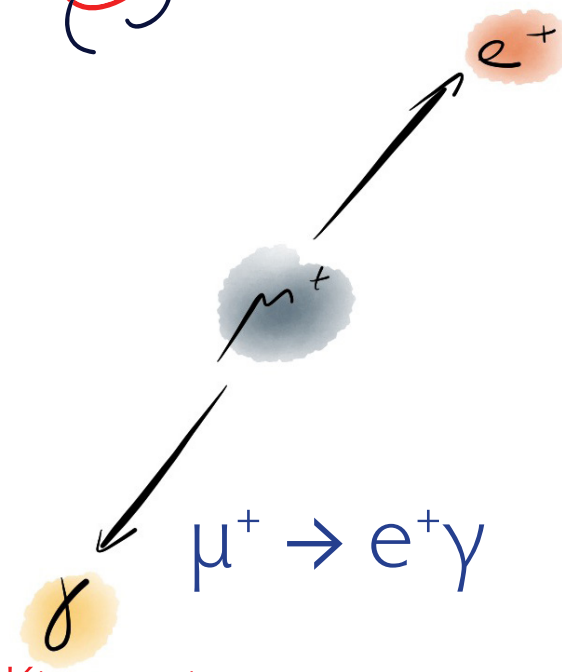
Kinematics

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

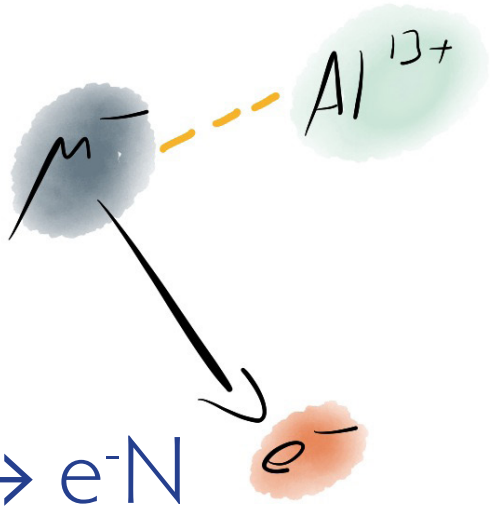
Kinematics

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

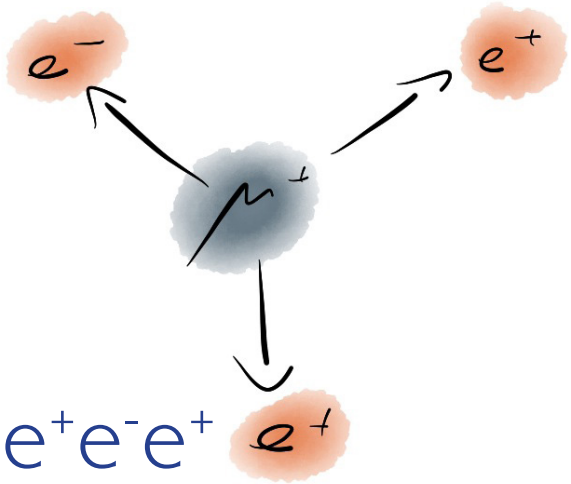
LFV Muon Decays: Experimental signatures



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



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



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

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

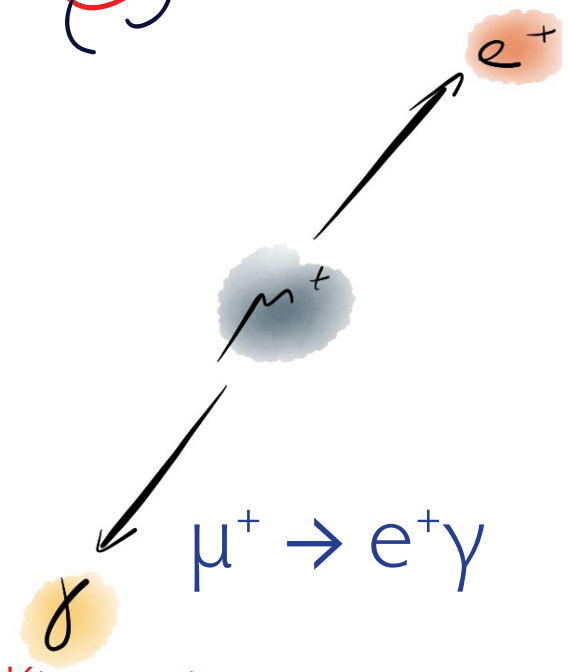
Kinematics

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

Background

- Radiative decay
- Accidental background

LFV Muon Decays: Experimental signatures



$\mu^+ \to e^+\gamma$

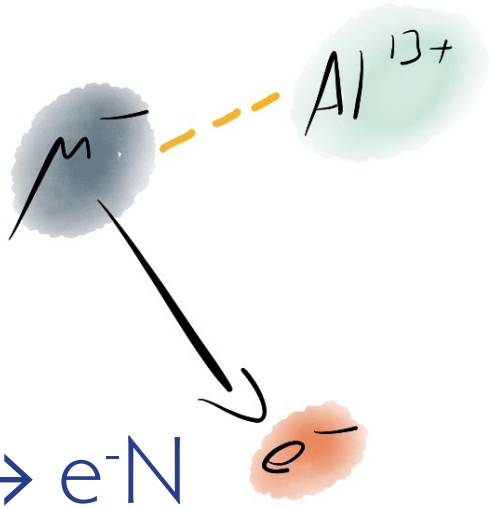
Kinematics

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

Backgro

- A al background

Continuous Beam



$\mu^-N \to e^-N$

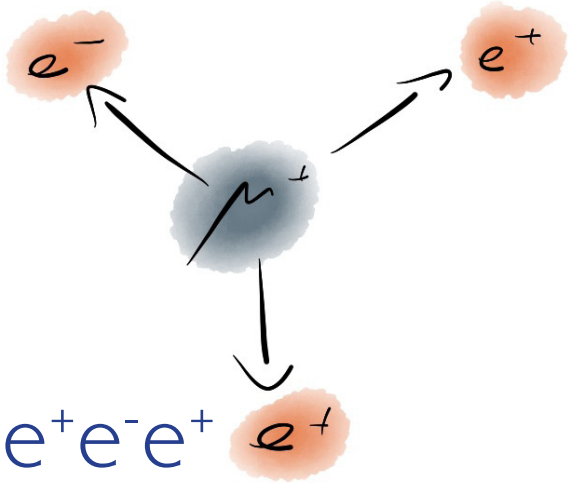
Kinematics

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

Backgro

- D orbit
- A protons, pions

Pulsed Beam



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

Kinematics

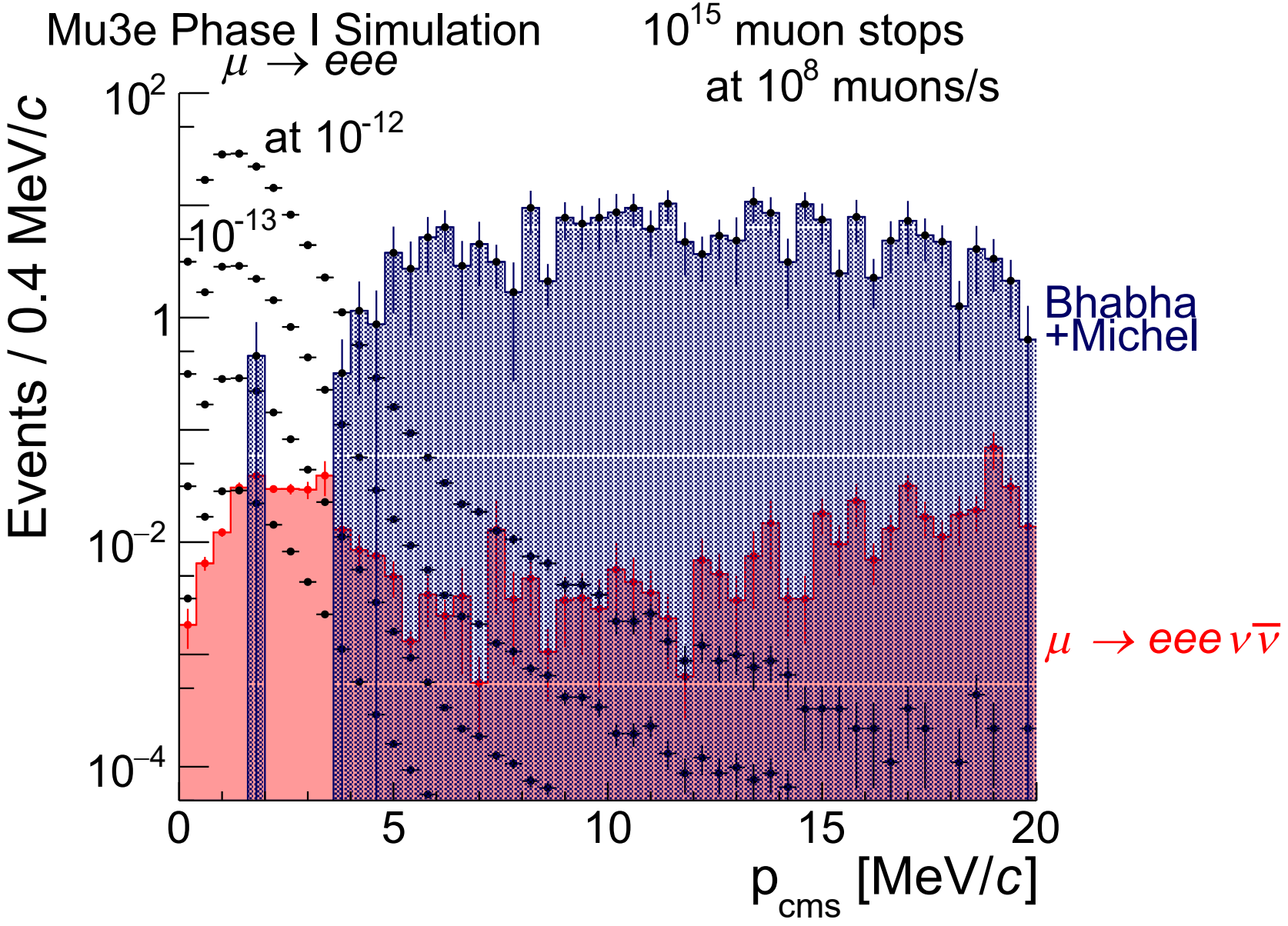
- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro

- R decay
- Ac ental background

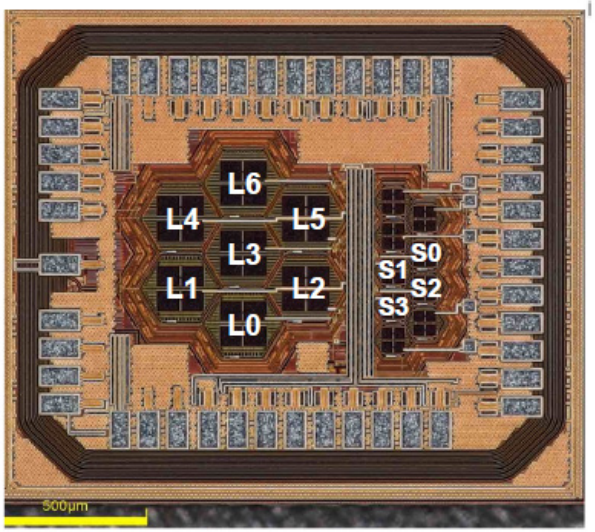
Continuous Beam

Momentum distribution



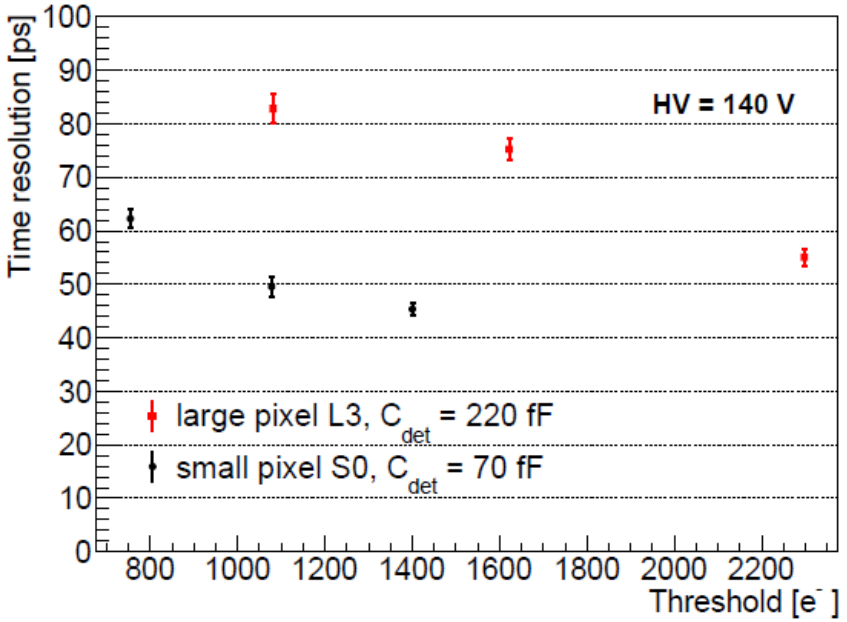
Phase II requirements and ideas

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
- ...