$\mu \rightarrow eee$
Experimental Aspects

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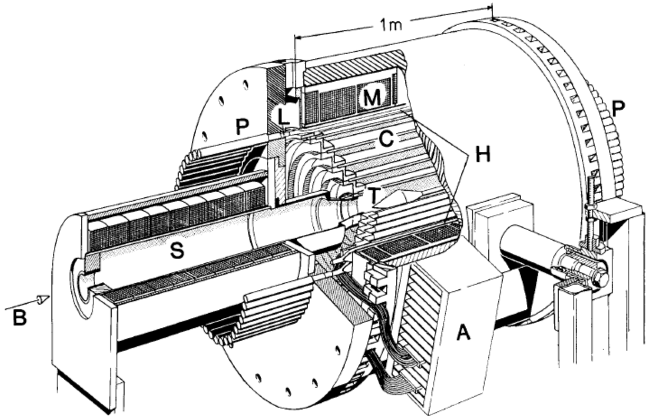
RF5: CLFV
July 2020

JG|U

PRISMA+

Overview

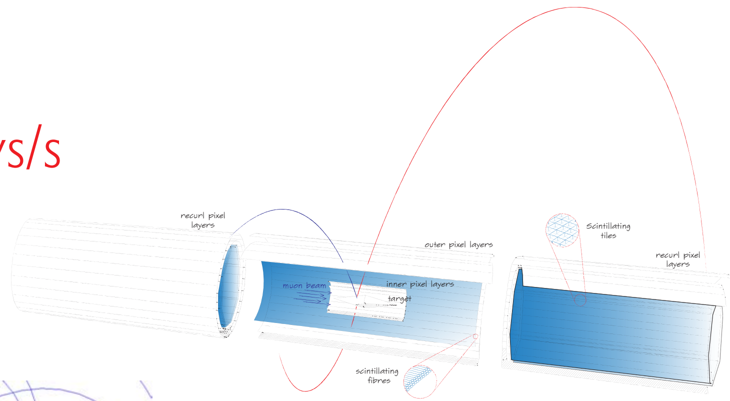


A look back:

- The SINDRUM experiment

The Mu3e experiment:

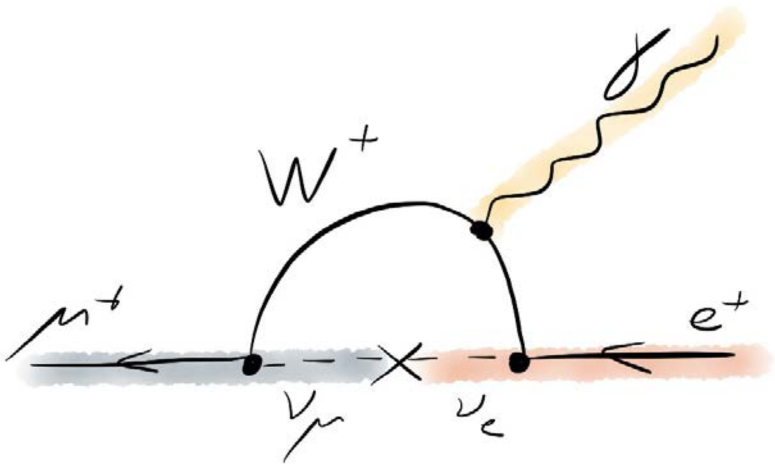
- A fast, thin, high resolution detector for > 10^8 muon decays/s



Beyond Mu3e:

- Technological challenges

Muon lepton flavour violation experiments



Standard Model branching fractions of

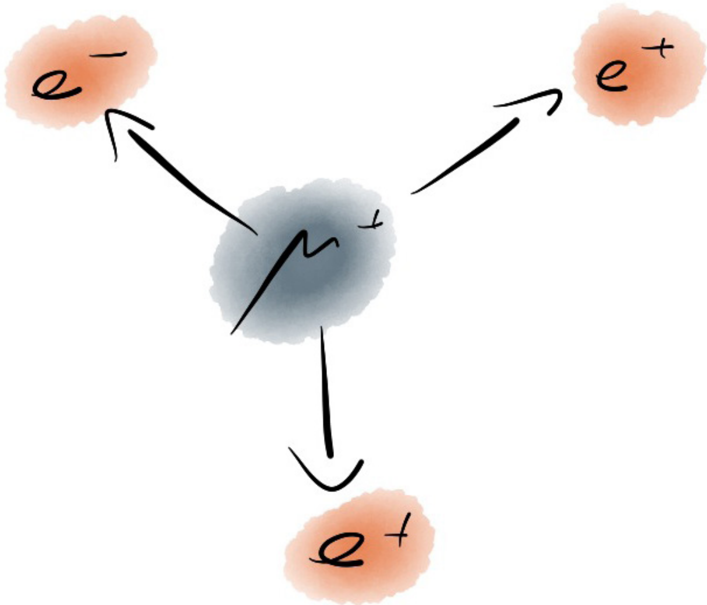
$10^{-50\text{ish}}$

Only limited by number of muons and background suppression:

Experimental/technical challenge

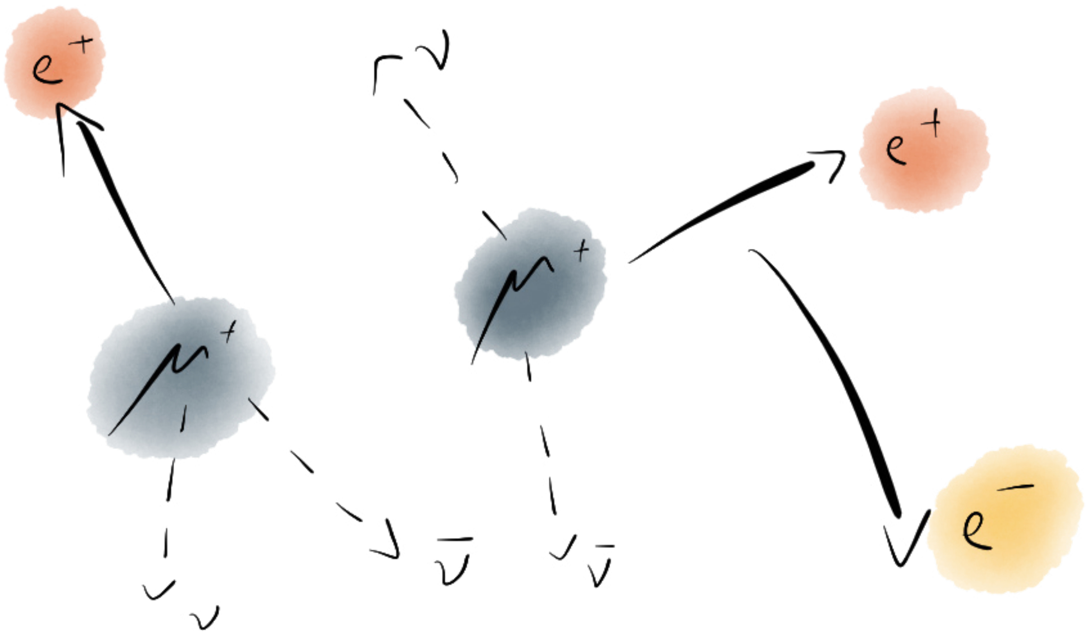
Searching for $\mu^+ \rightarrow e^+e^-e^+$

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma p_e = m_\mu$
- Maximum momentum: ½ m_μ = 53 MeV/c

Accidental Background



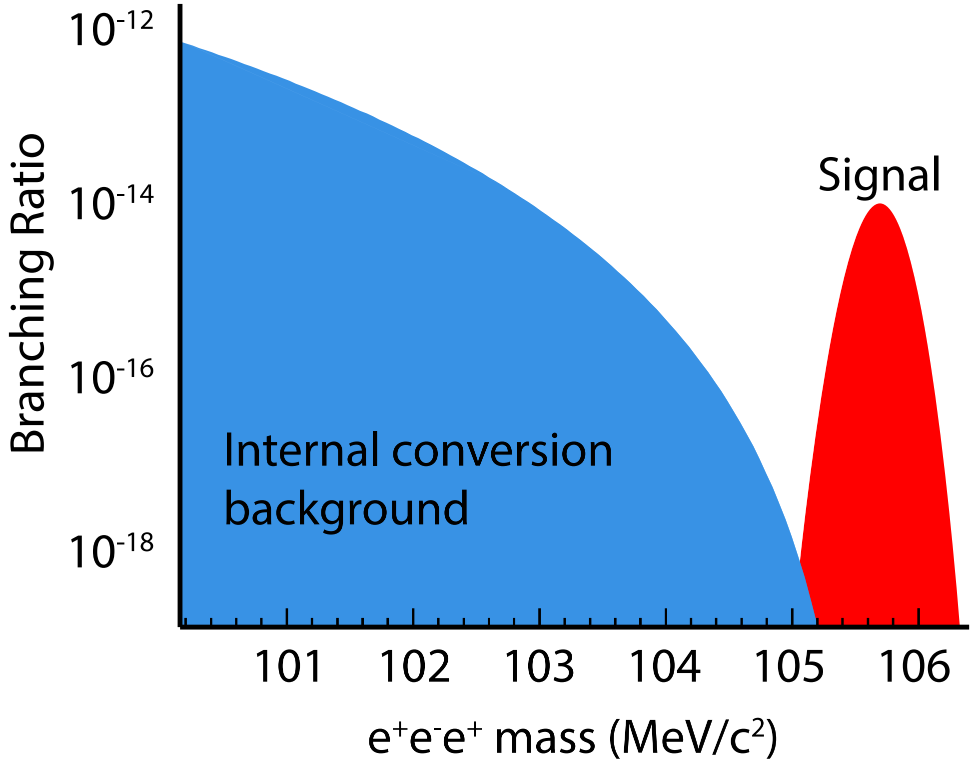
- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha (electron-positron) scattering,
  - Mis-reconstruction
- Need very good timing, vertex and momentum resolution
- Need a continuous beam (PSI...)

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

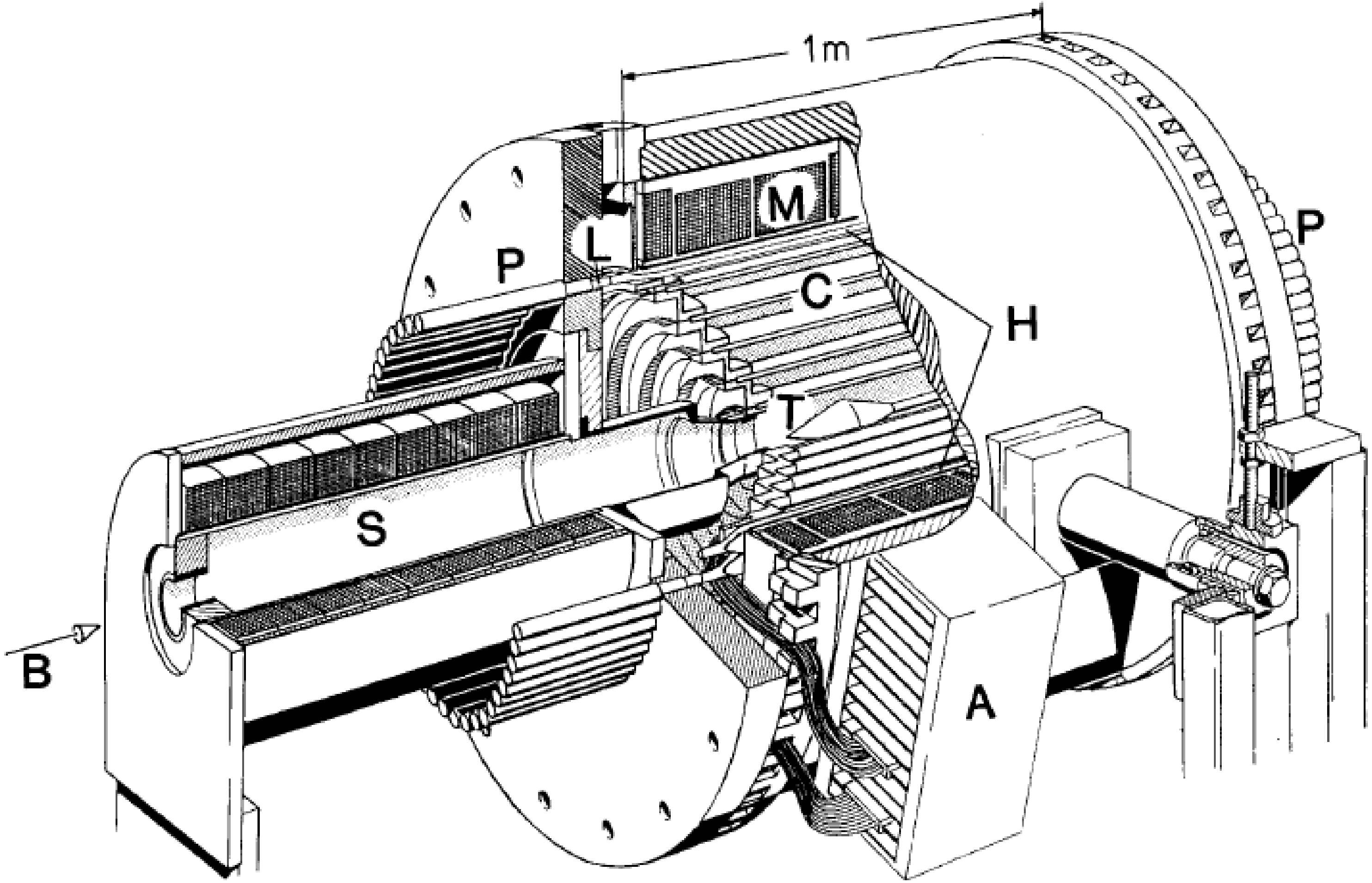


- Need excellent momentum resolution

Searching for $\mu^+ \rightarrow e^+e^-e^+$:

SINDRUM

SINDRUM



B: Muon Beam

S: Focusing Solenoid

T: Target

C: Five cylindircal multiwire proportional chambers

H: Scintillator hodoscope

L: Light-guides

P: Photomultipliers

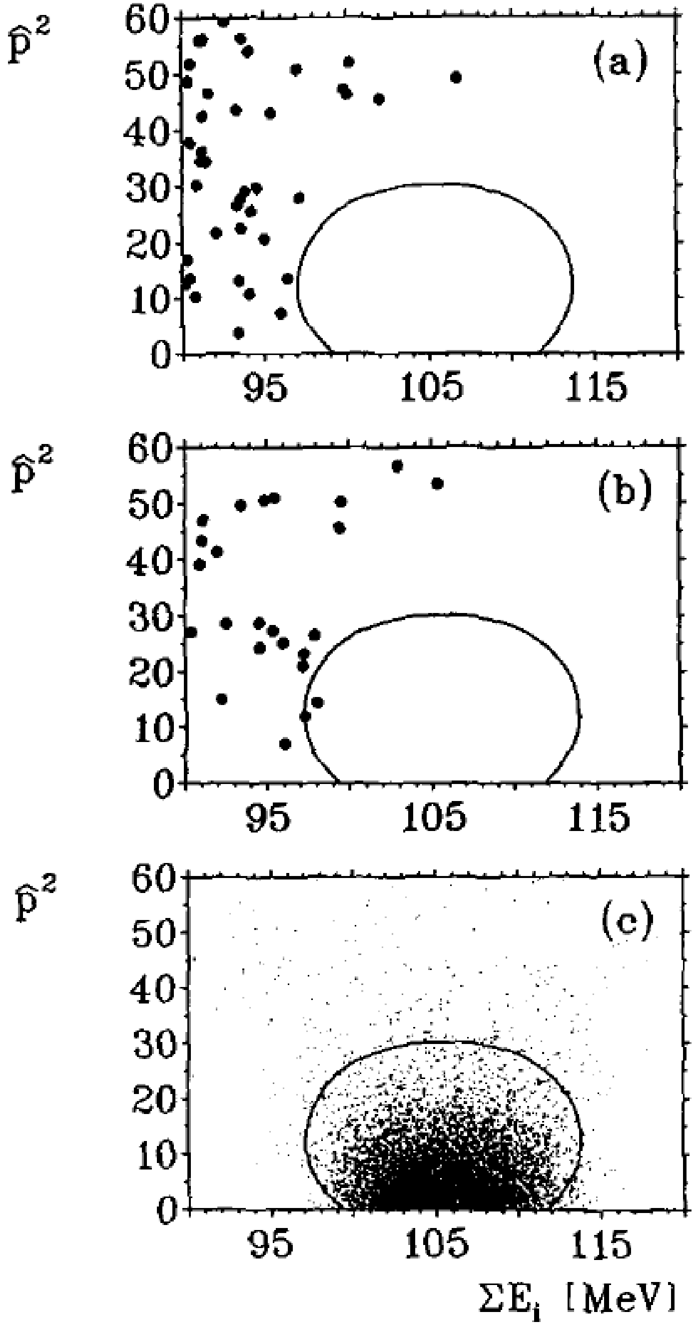
A: Preamplifiers

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

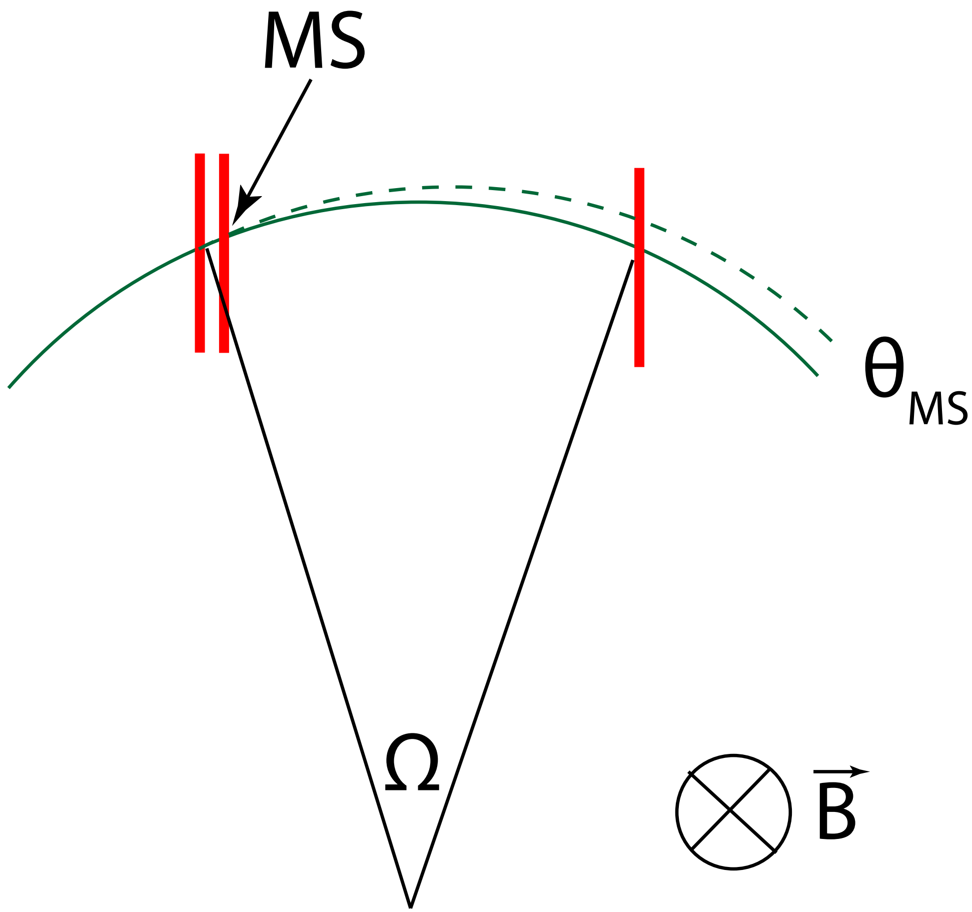
No events in signal area seen:

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

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

How to get excellent momentum resolution for very low momentum electrons

Momentum measurement

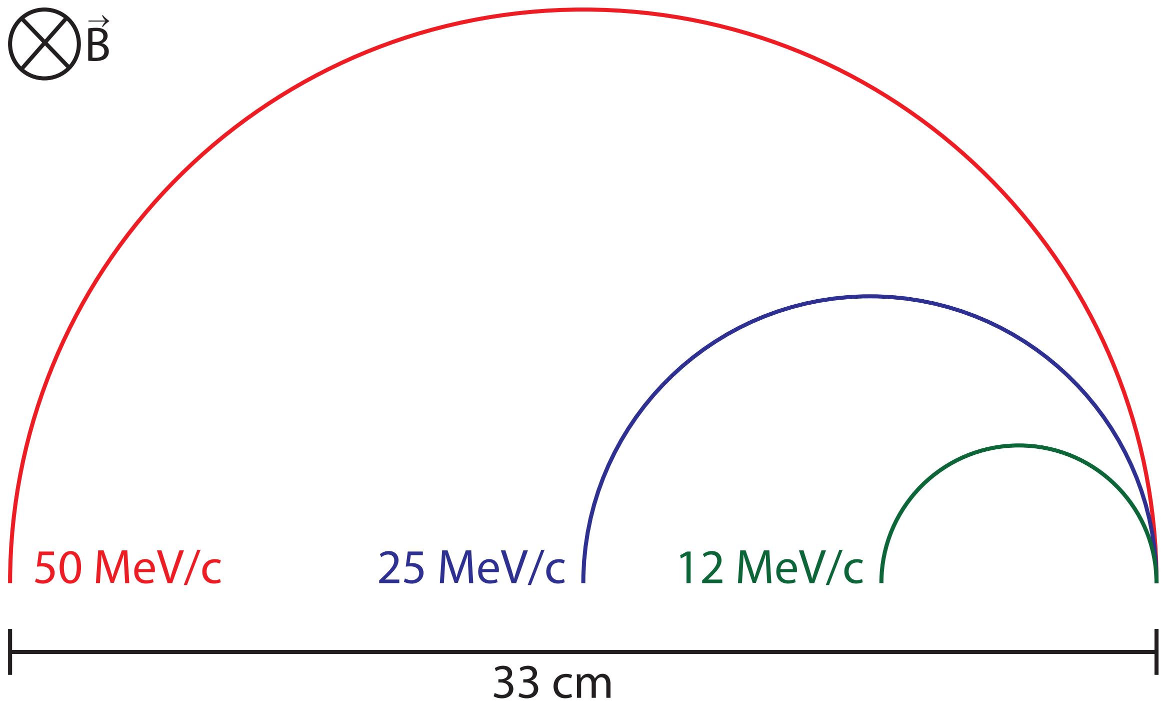


- Low momentum electrons/positrons
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

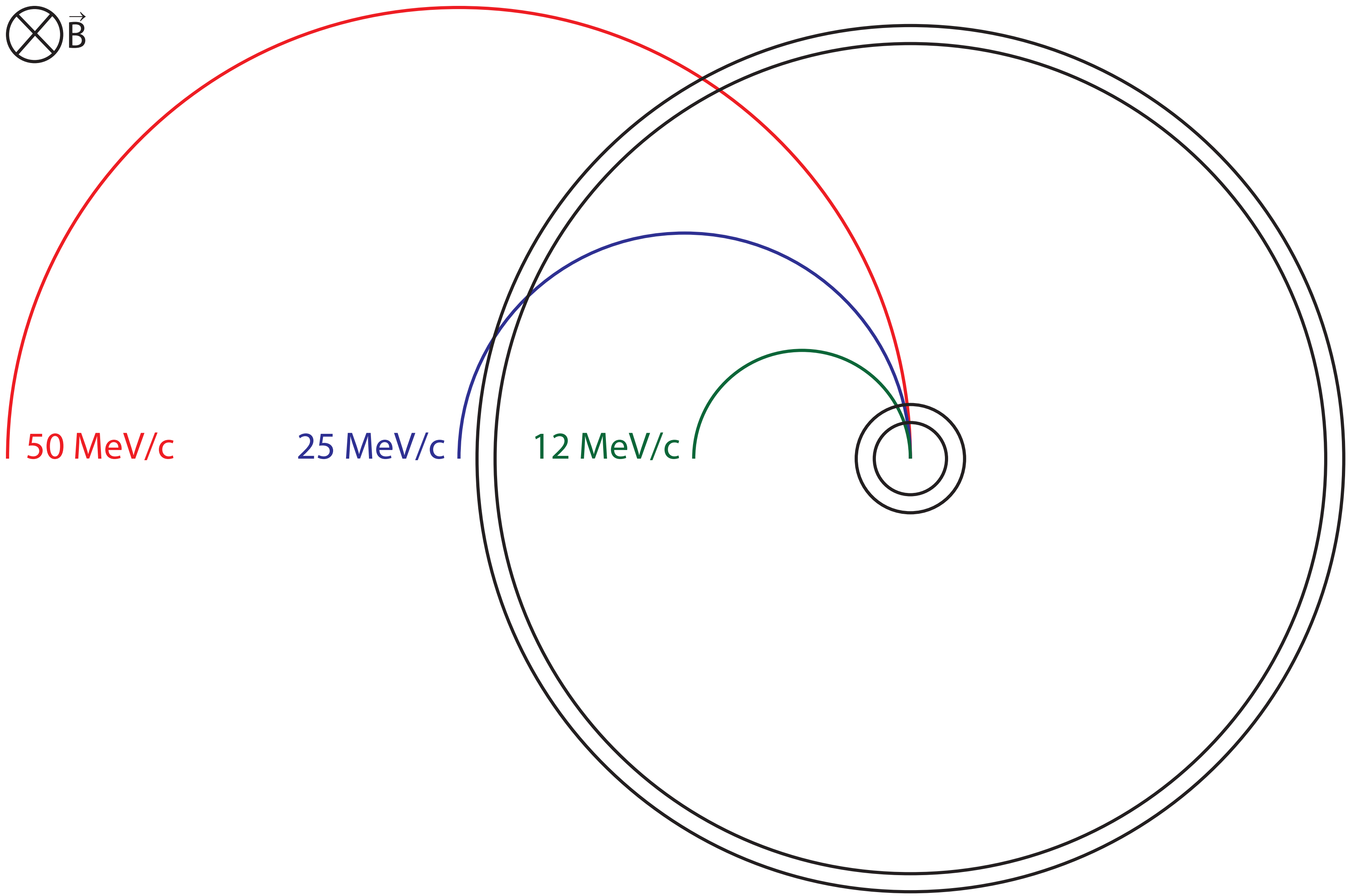
$$\sigma_P/_P \sim \theta_{MS}/_\Omega$$

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

Precision vs. Acceptance



Precision vs. Acceptance



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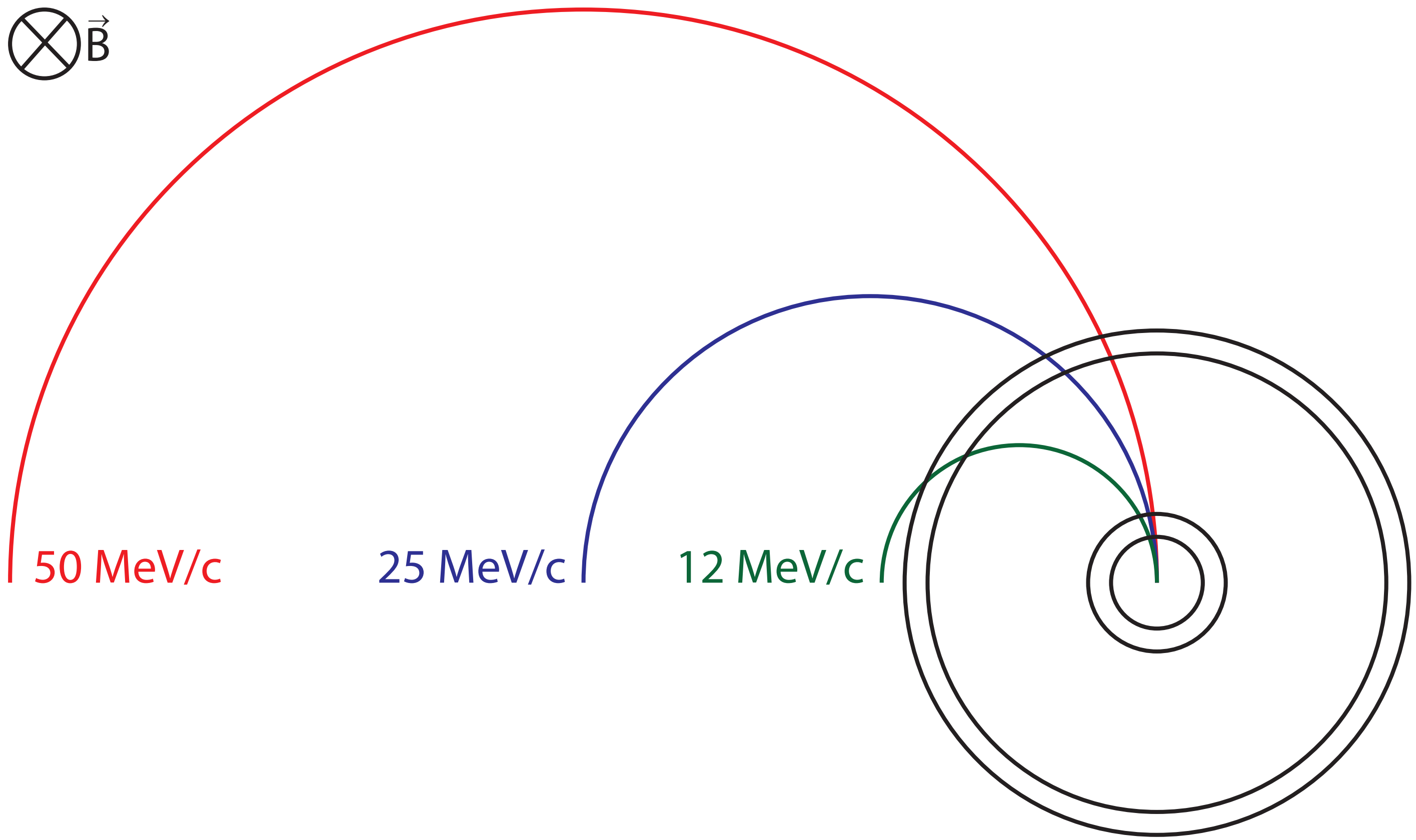
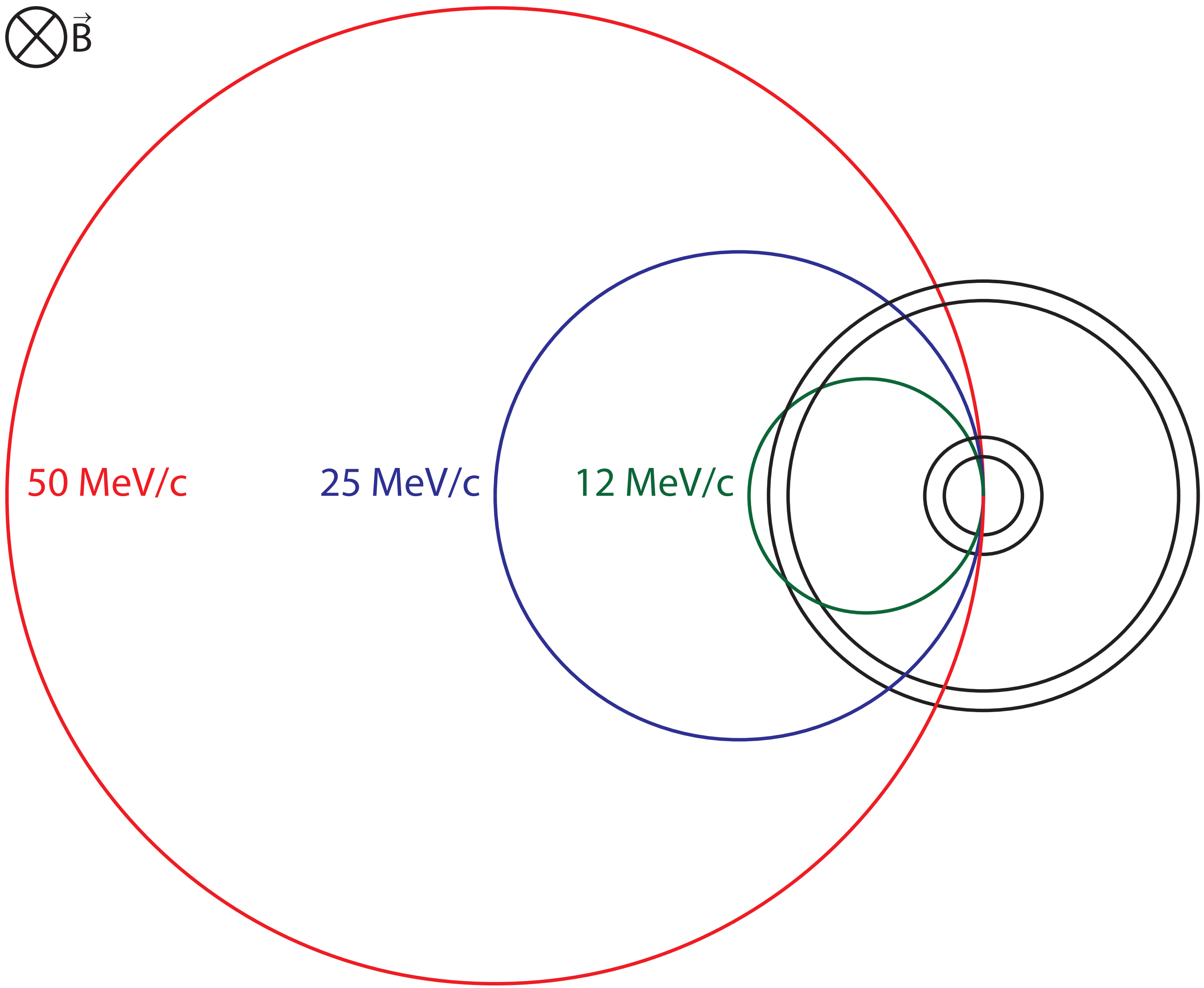
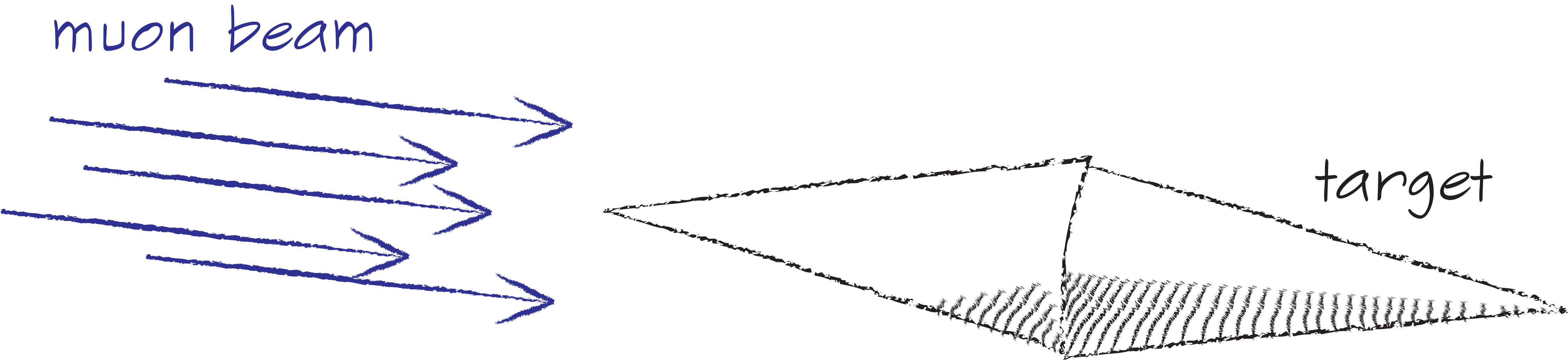


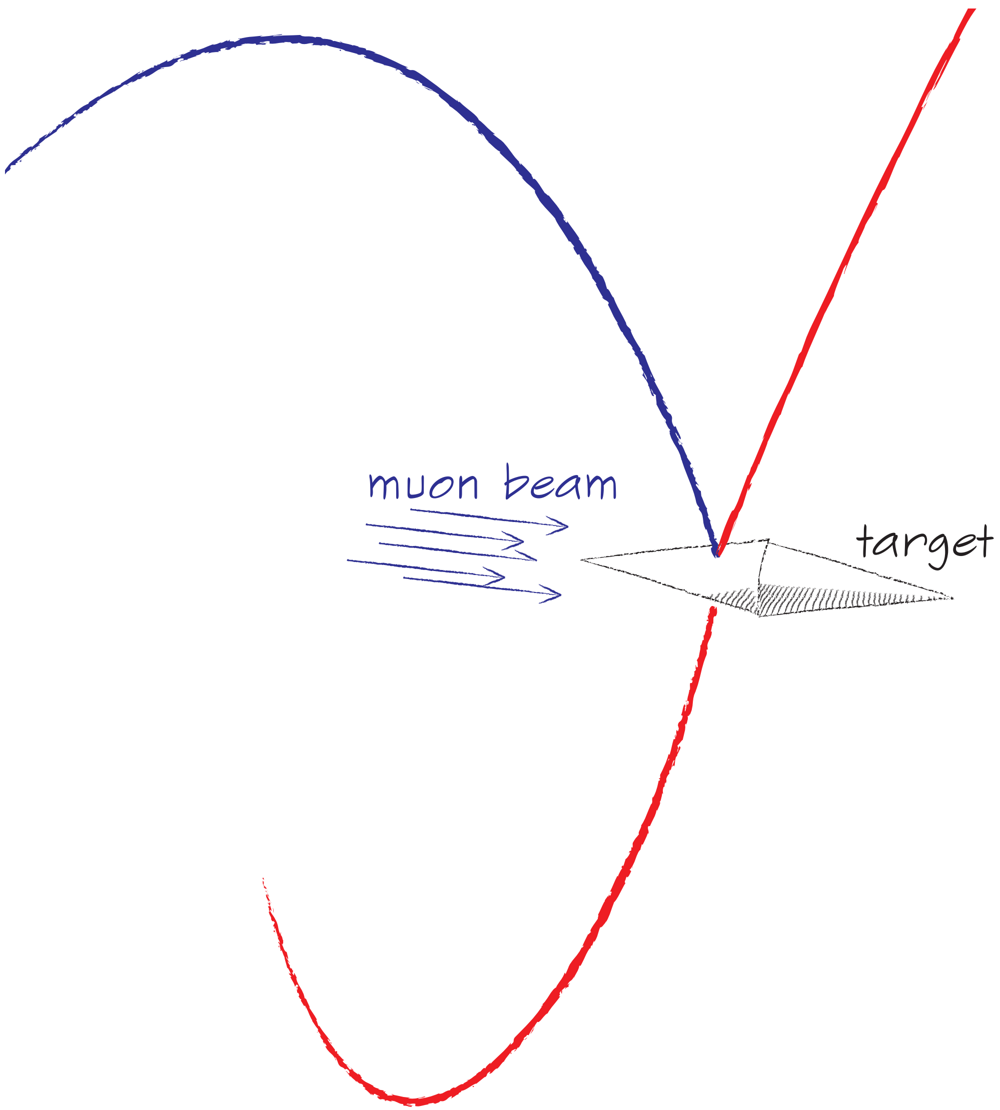
Precision vs. Acceptance



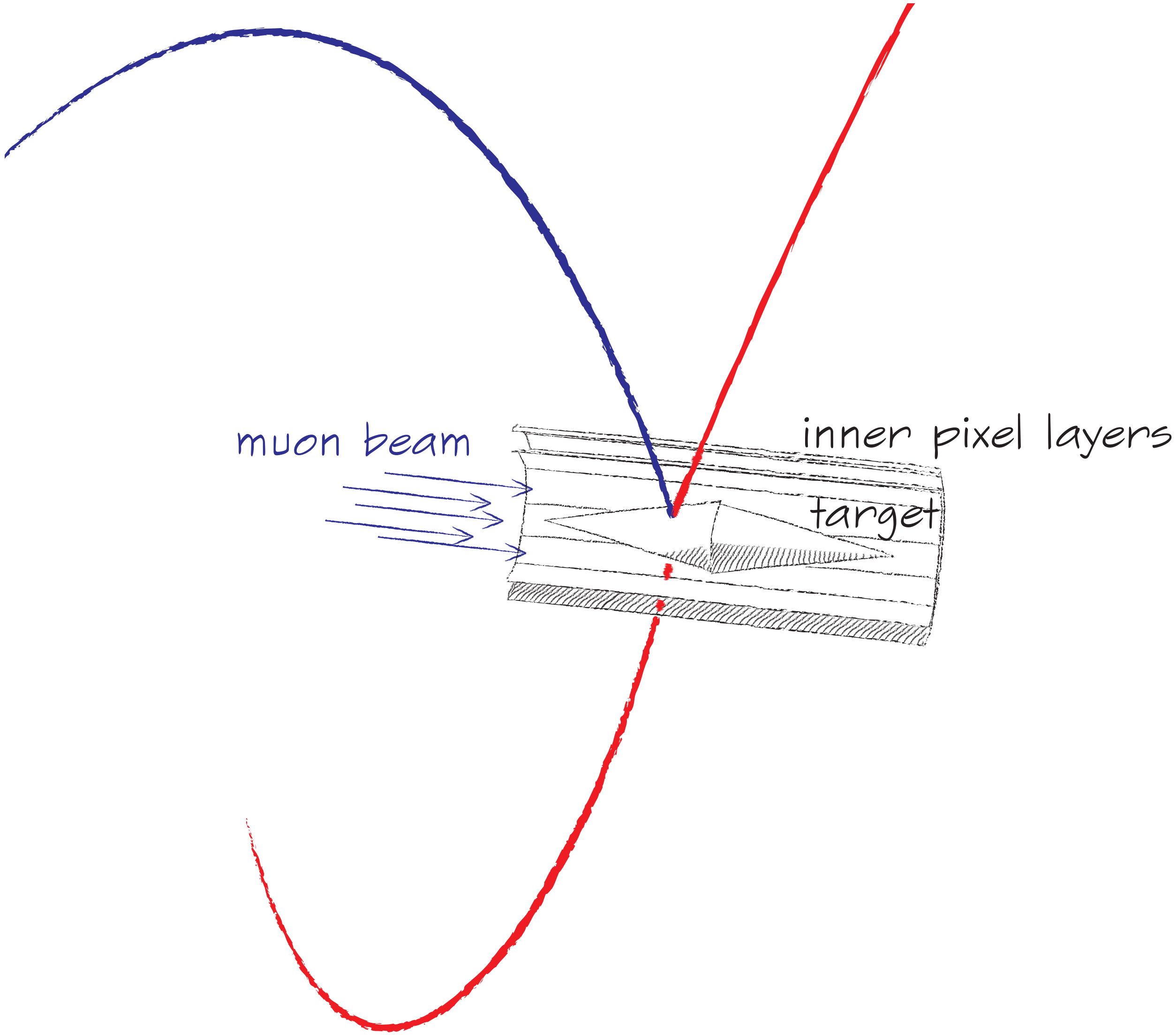
Detector Design



Detector Design



Detector Design



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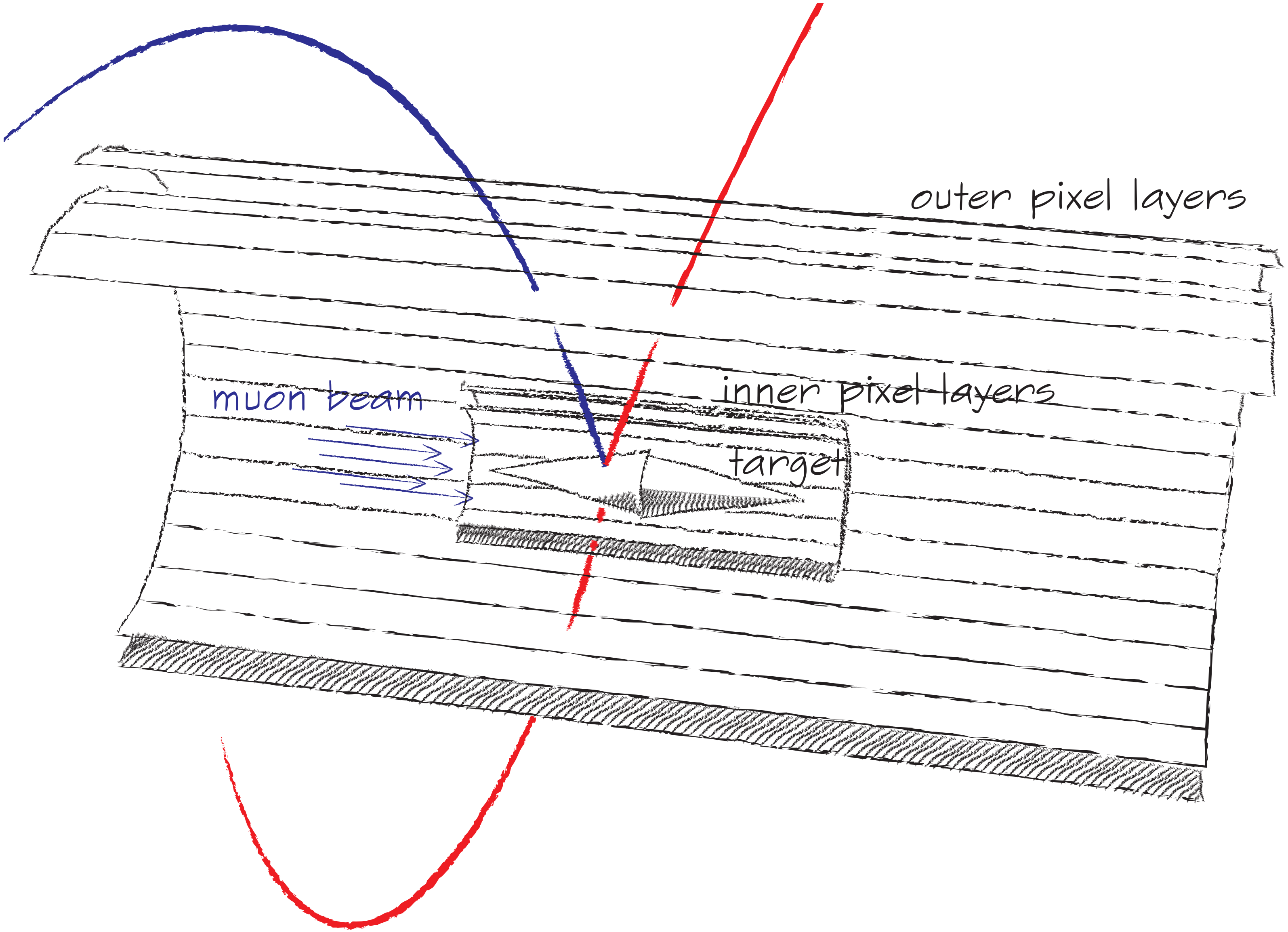
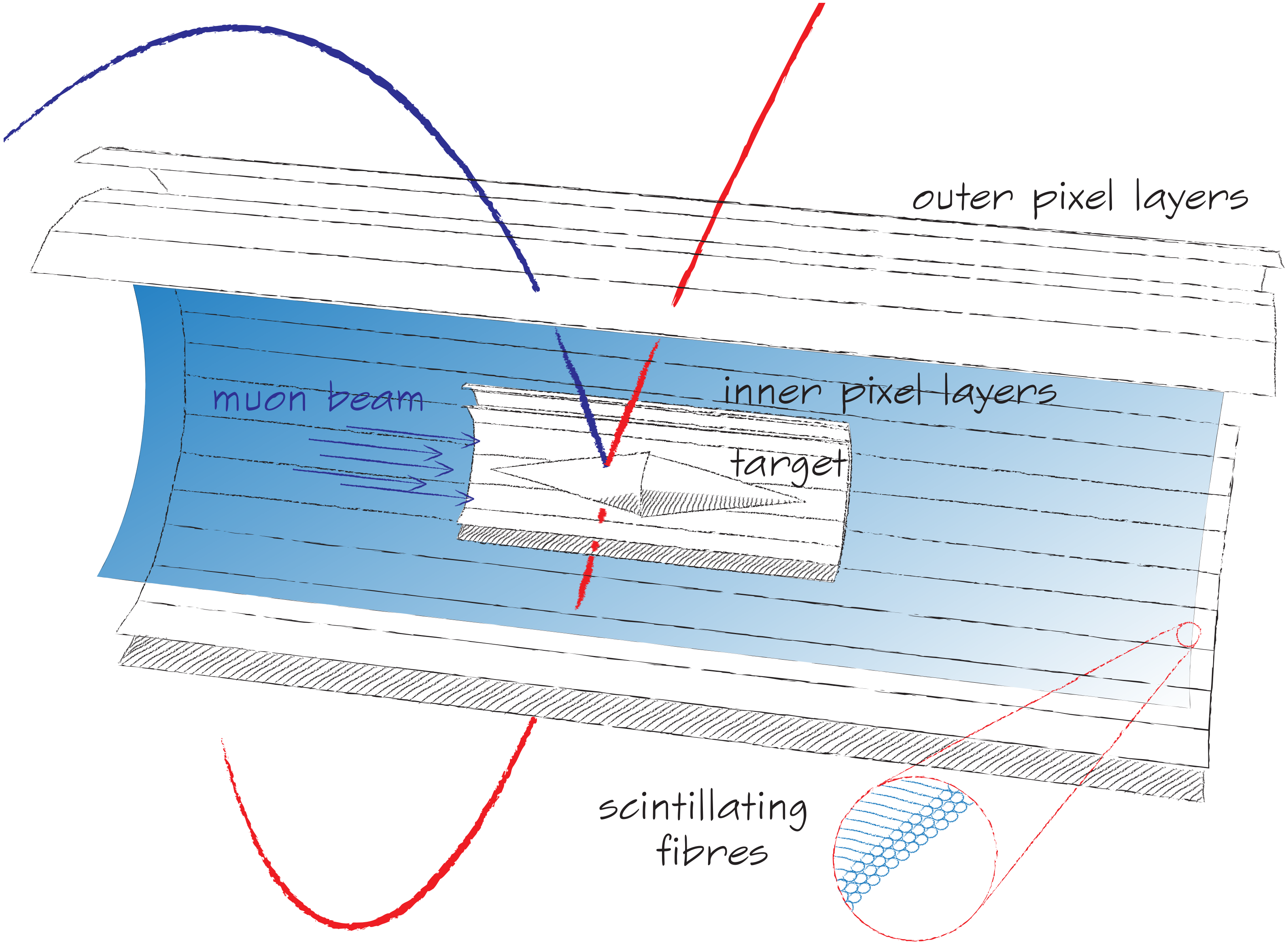
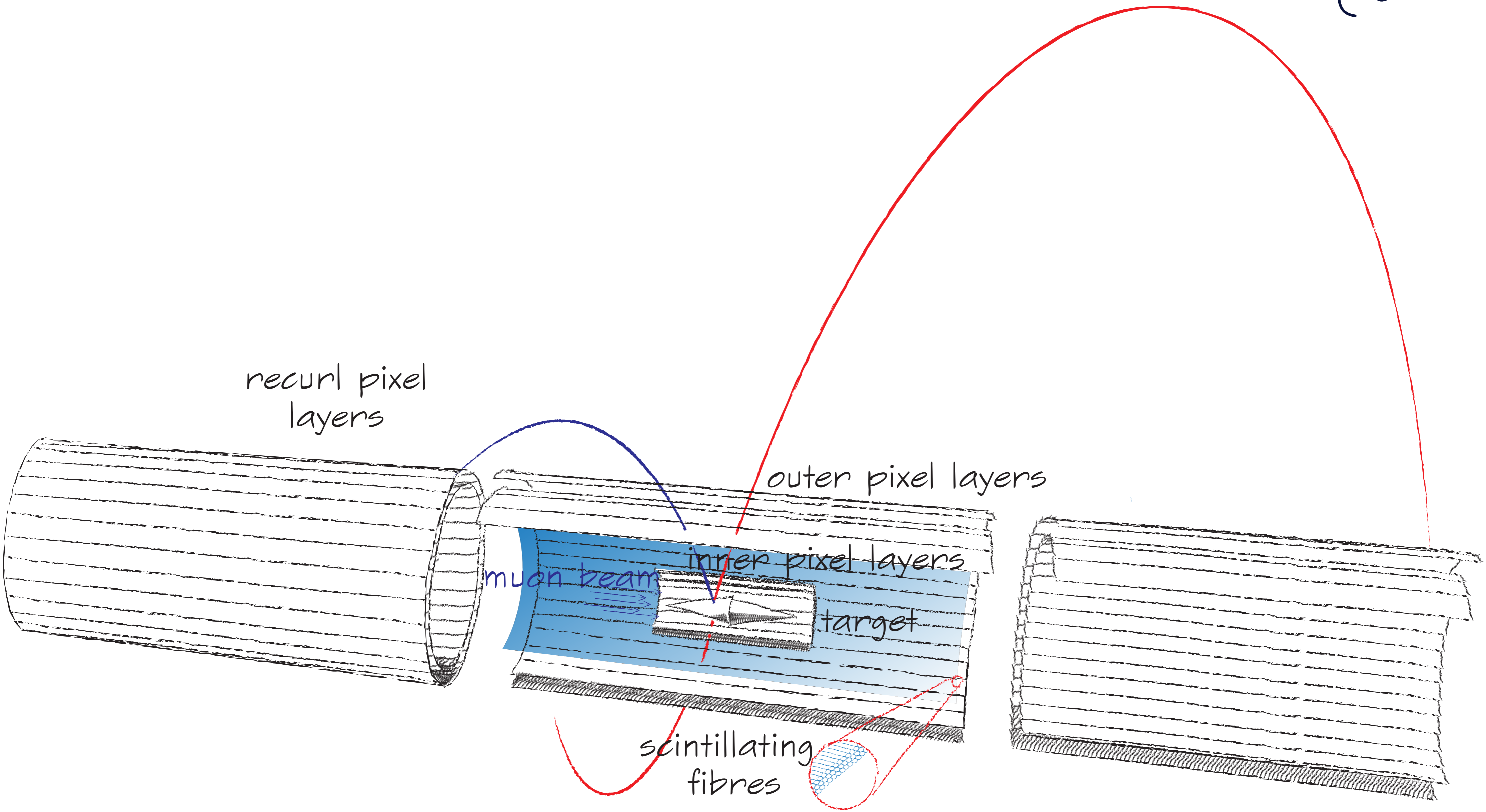


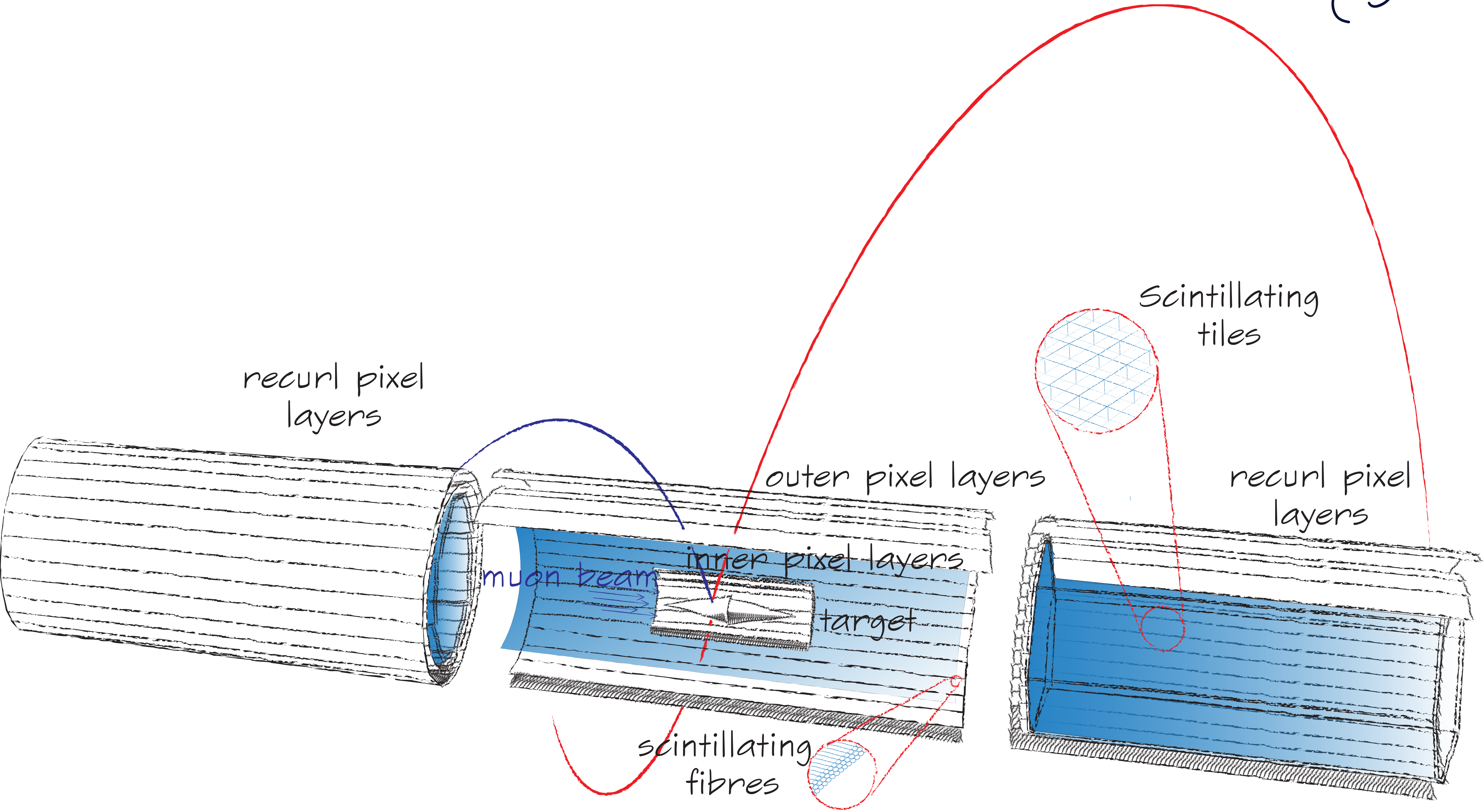
Detector Design



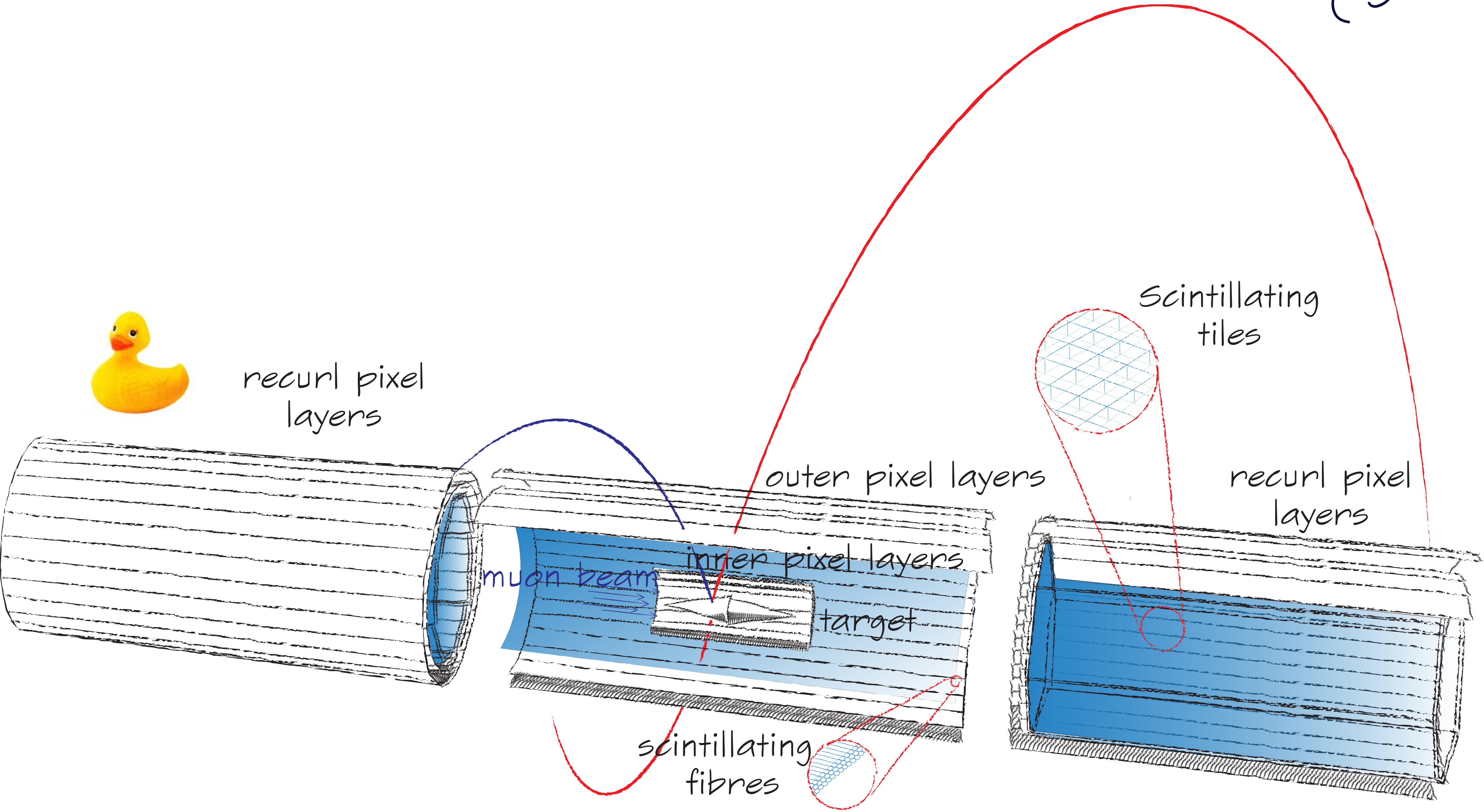
Detector Design



Detector Design



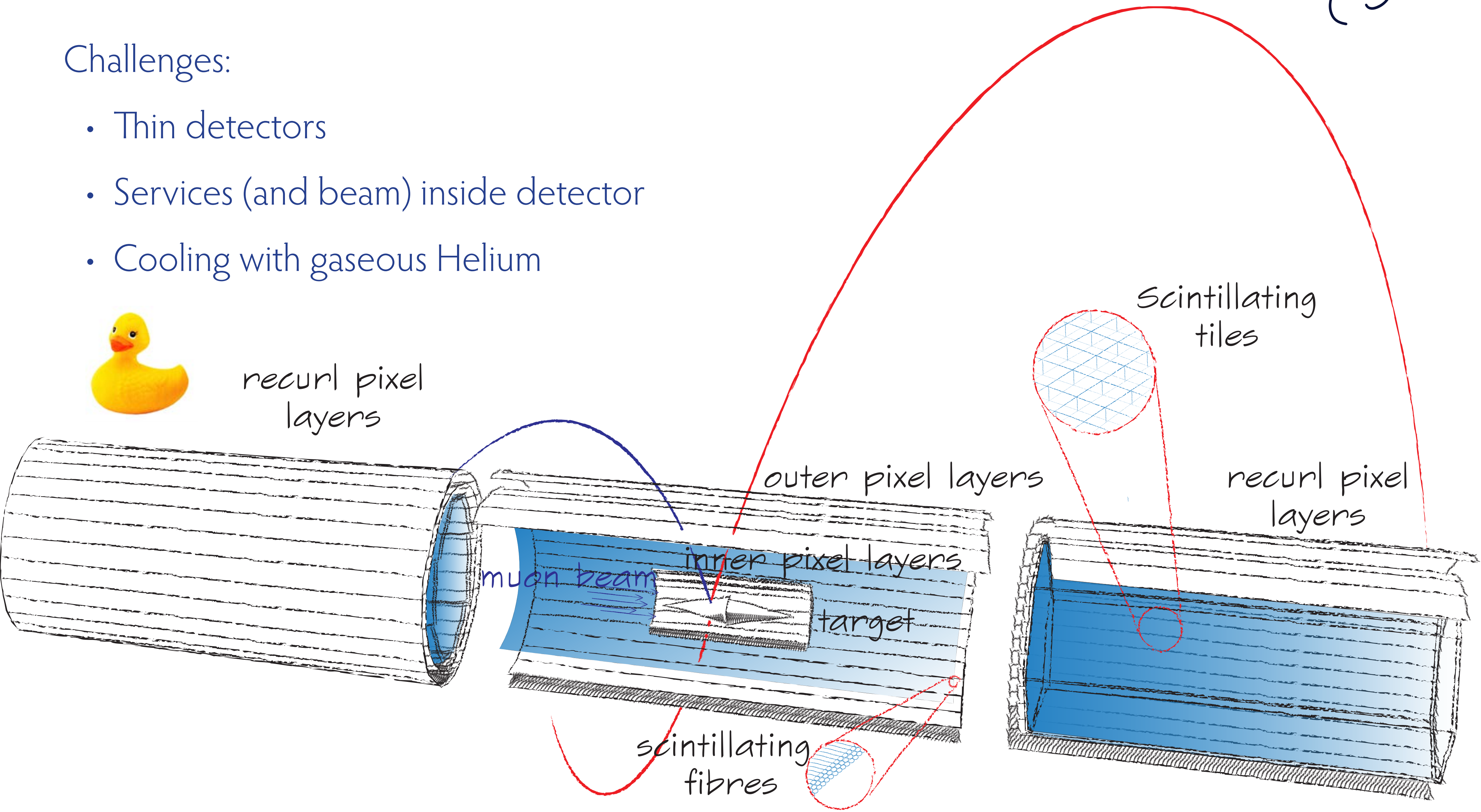
Detector Design



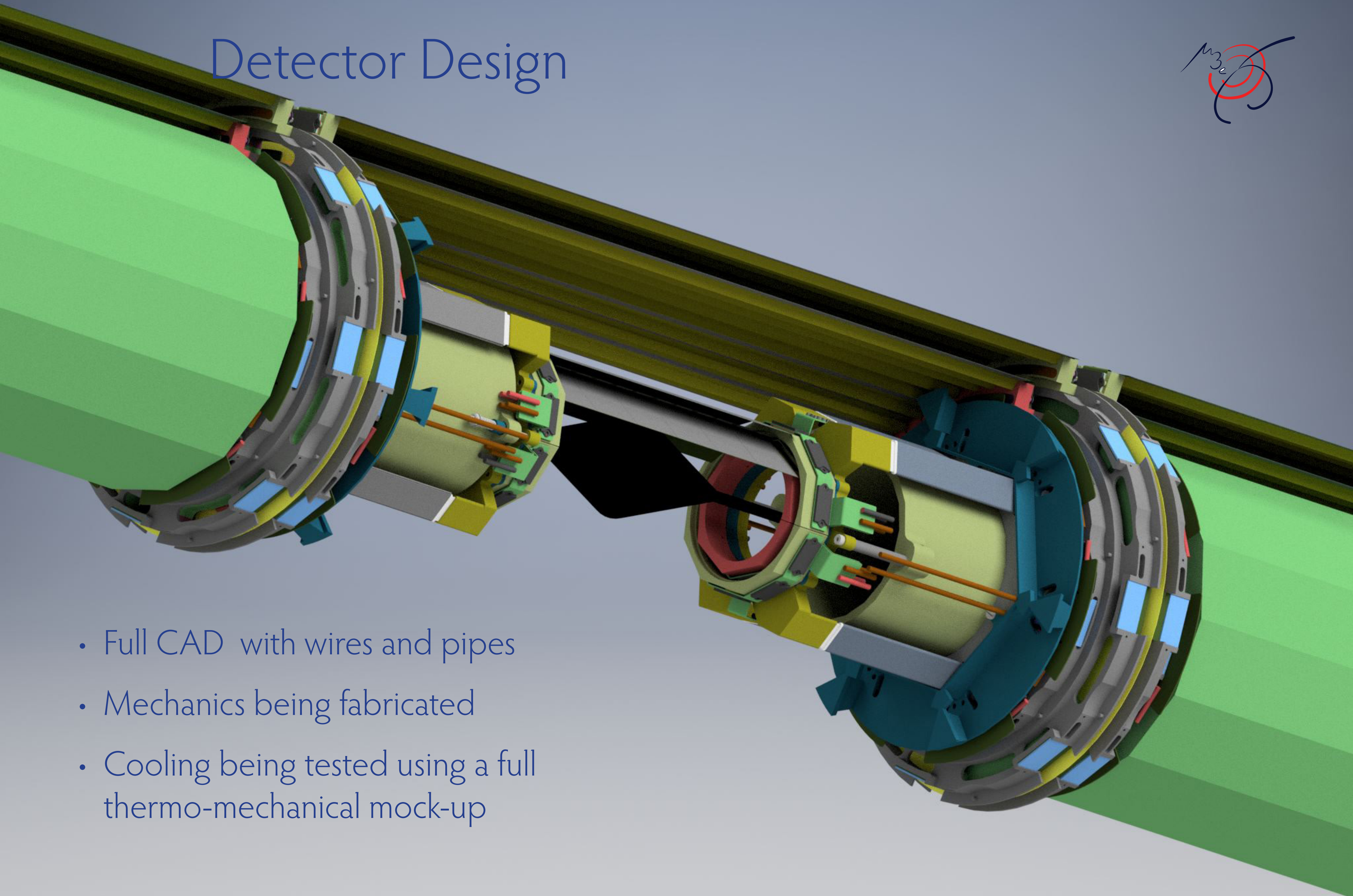
Detector Design

Challenges:

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



Detector Design



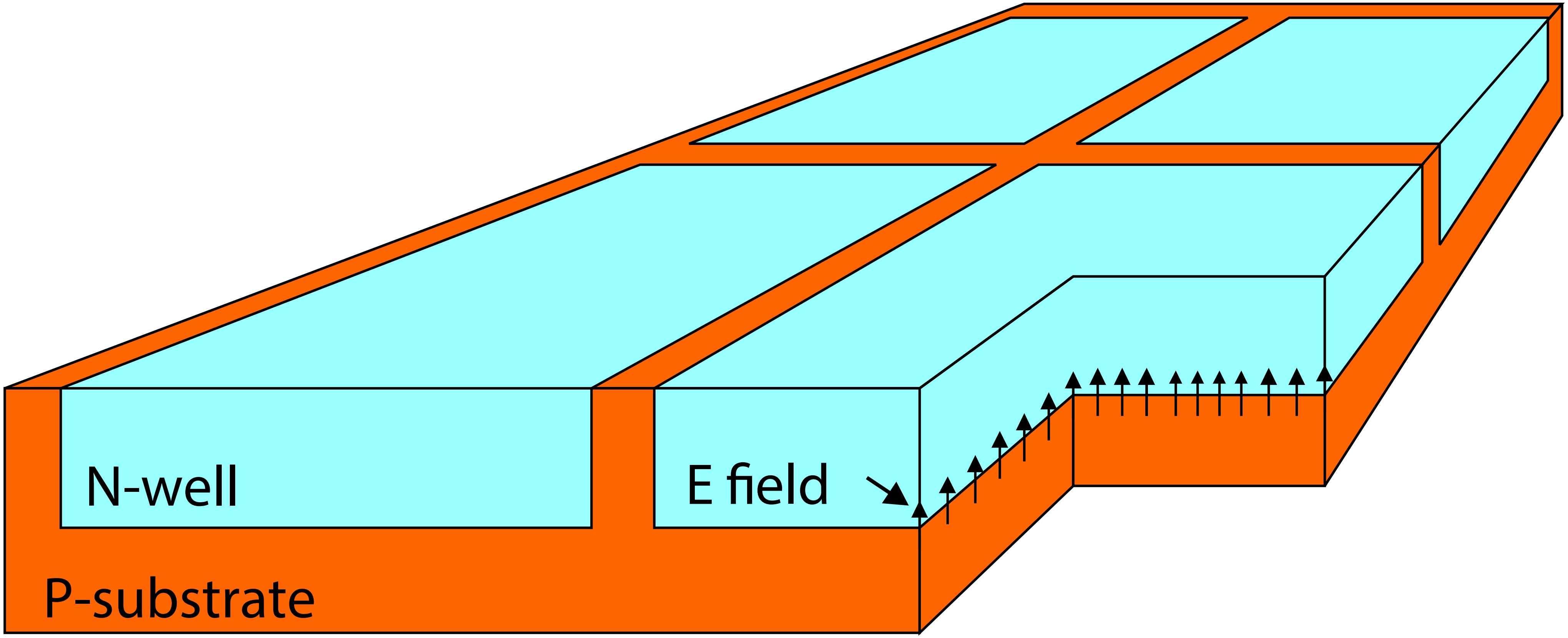
- Full CAD with wires and pipes
- Mechanics being fabricated
- Cooling being tested using a full thermo-mechanical mock-up

Very thin and fast silicon pixel sensors: HV-MAPS

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

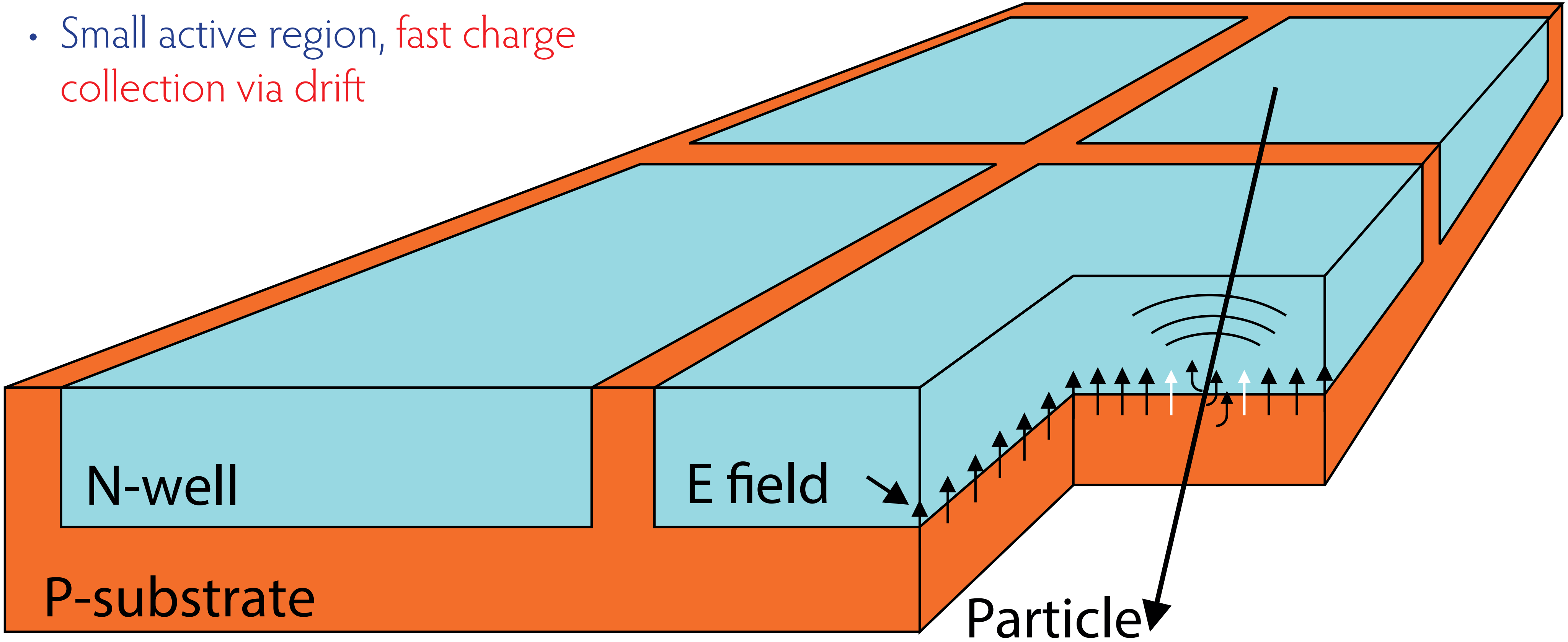
- Use a high voltage commercial process (automotive industry)



Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

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



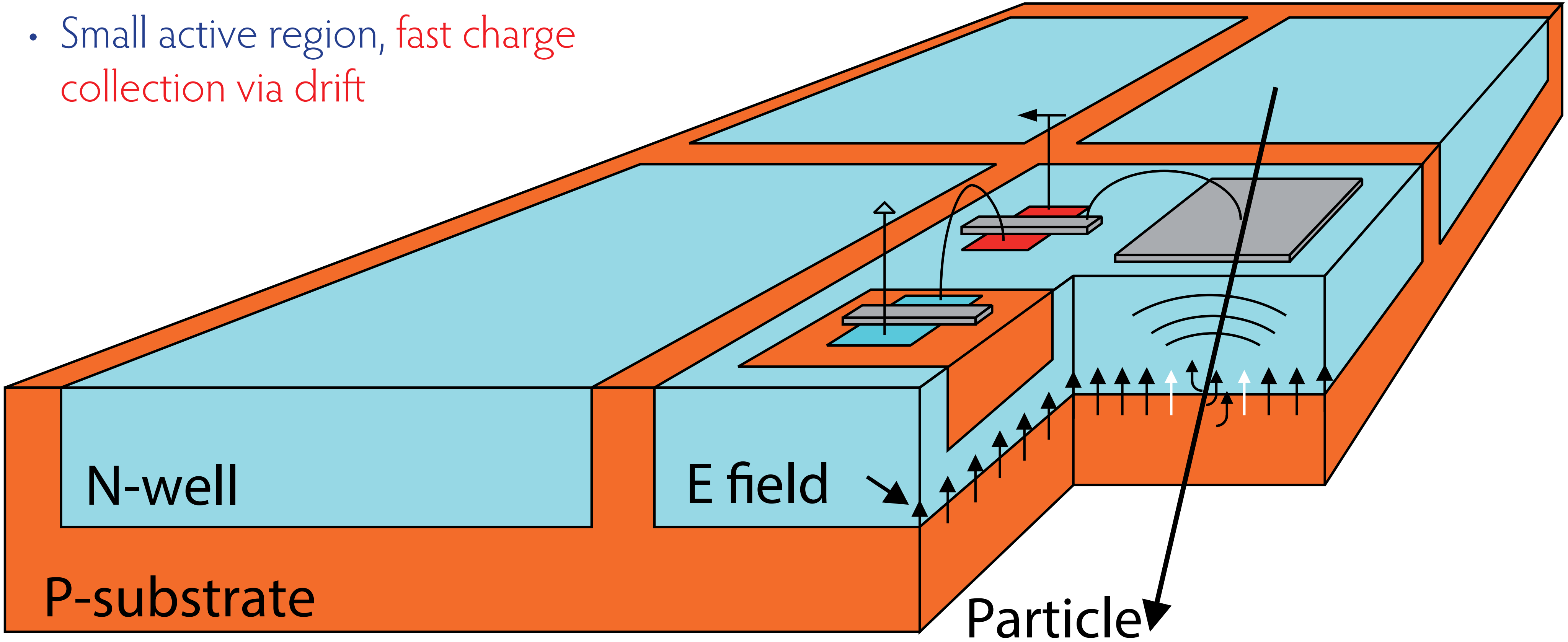
Fast and thin sensors: HV-MAPS

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

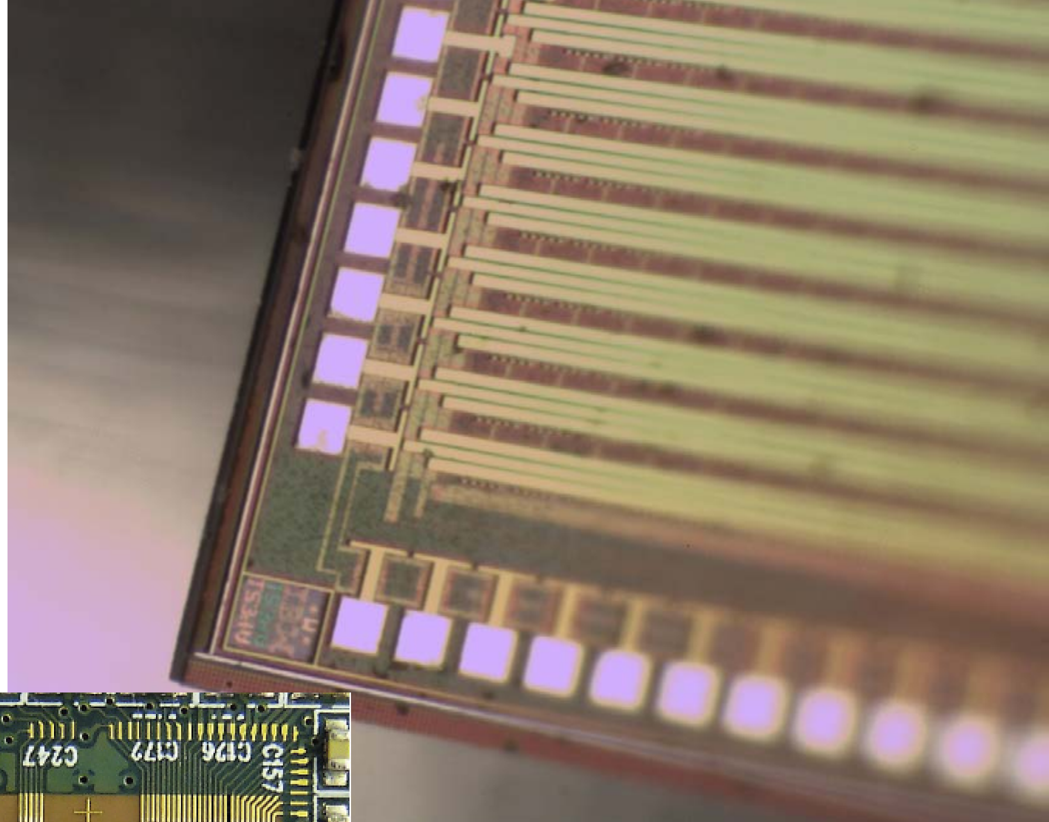
Developed a series of HV-MAPS prototypes

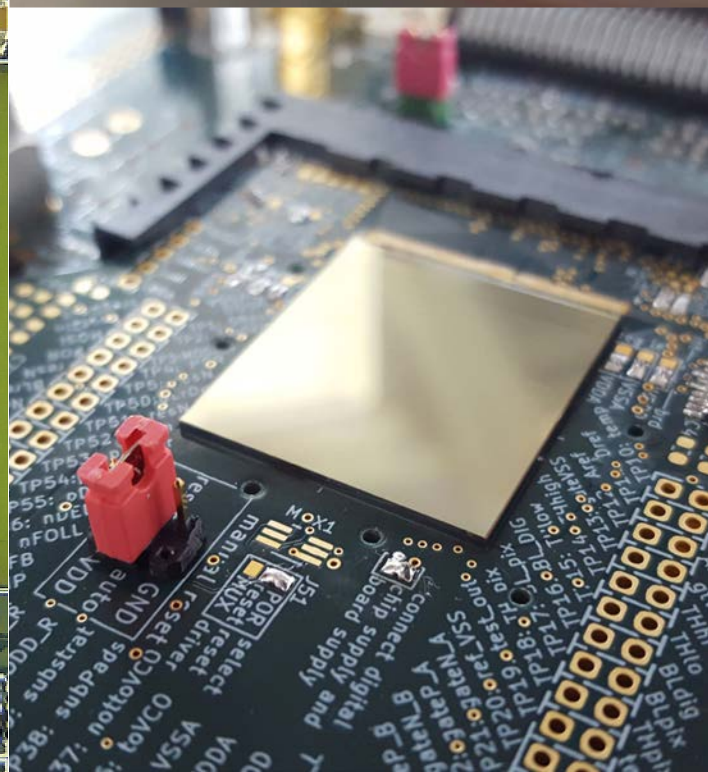
- Goal: Detection and signal processing with just 50 µm silicon

- 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

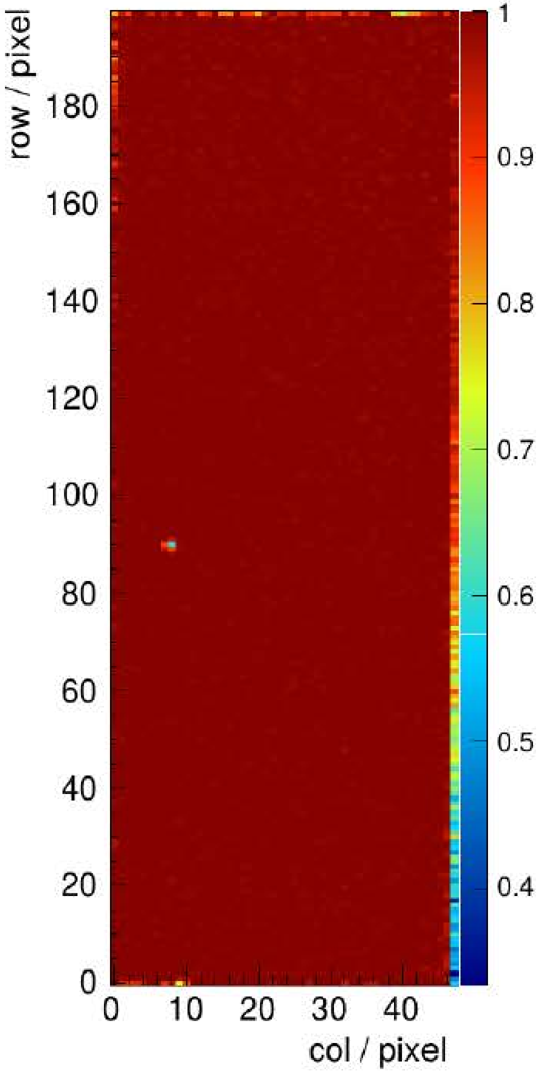
- Now: MuPix10, 2 x 2 cm^2, integration ready - under test



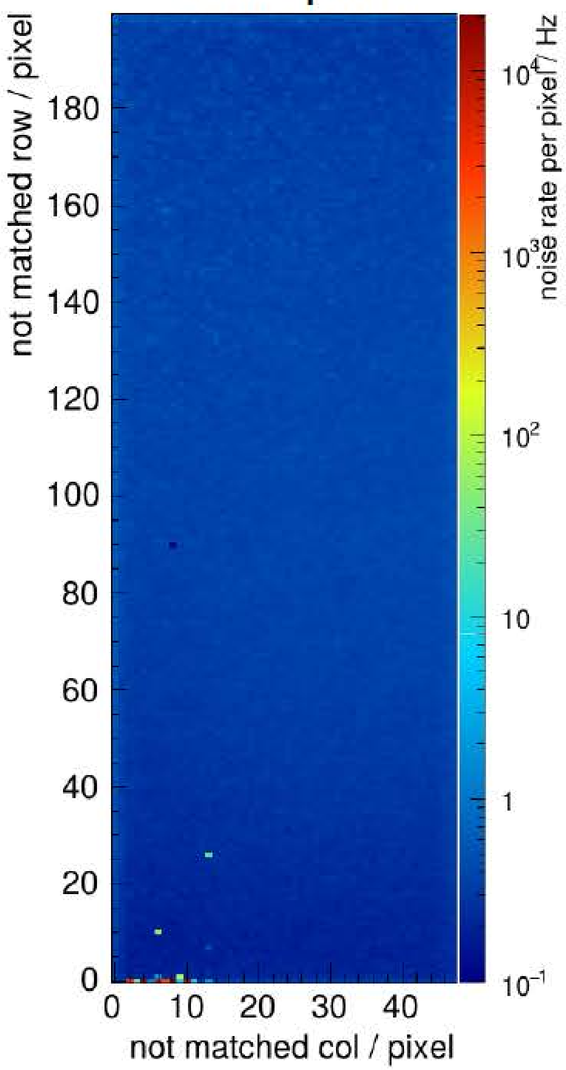


MuPix8: Results

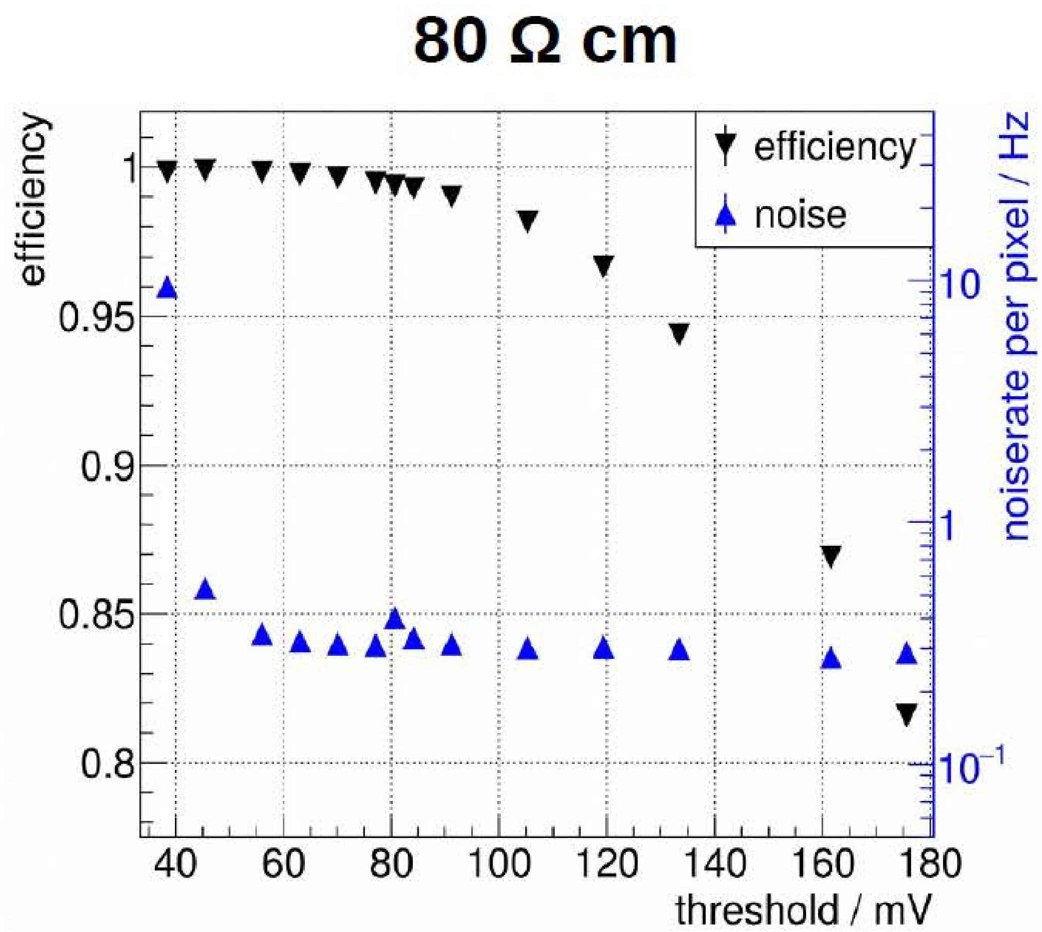
efficiency
~99.9%



noise
~1Hz/pixel

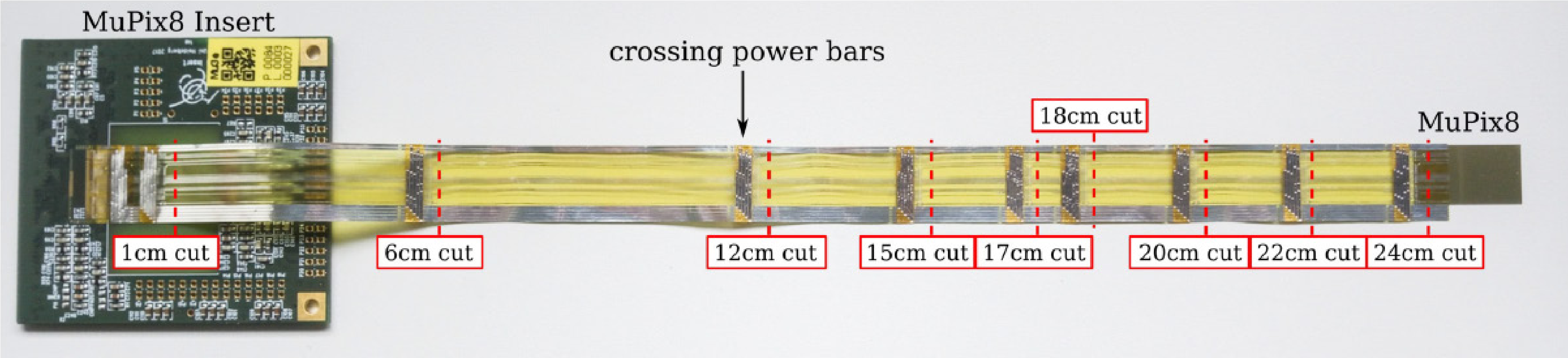


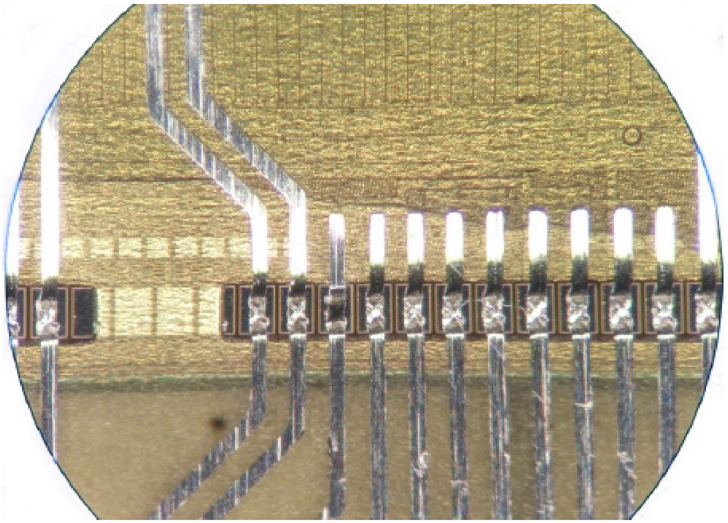
Time resolution of < 6 ns σ reached



100mV ~ 1300 e-

Integration with Flexprint





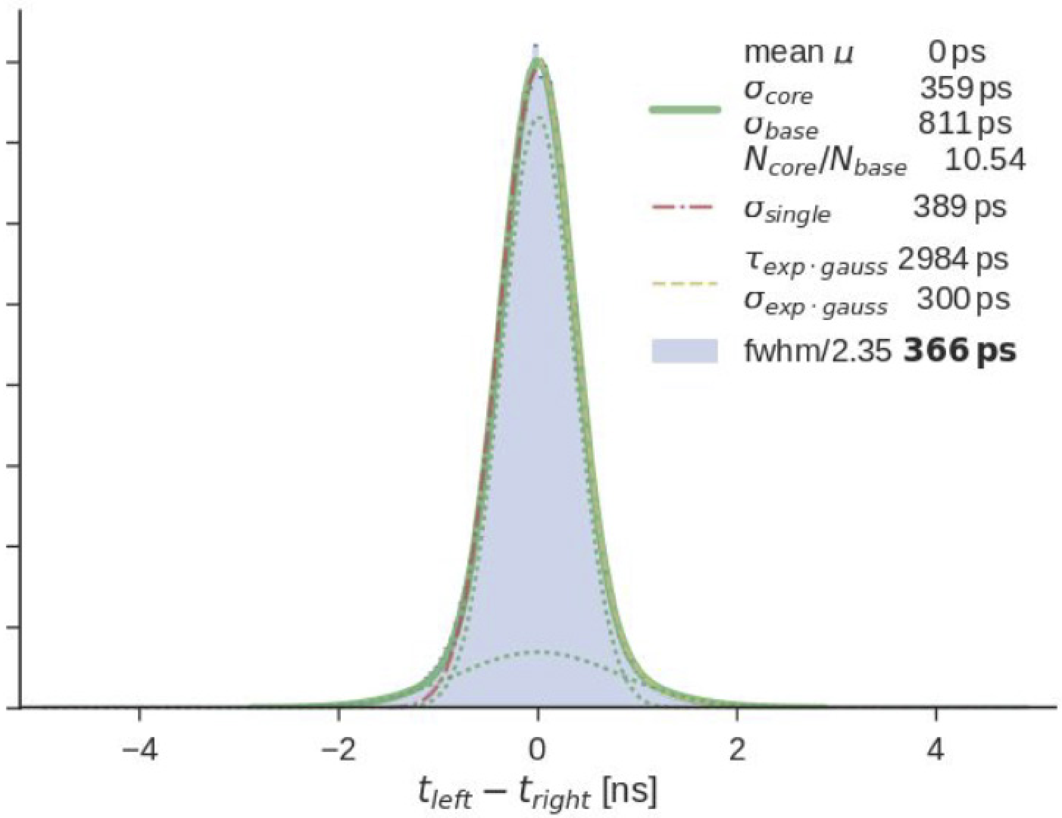
Operate MuPix on an aluminium-kapton flexprint without decoupling capacitors

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

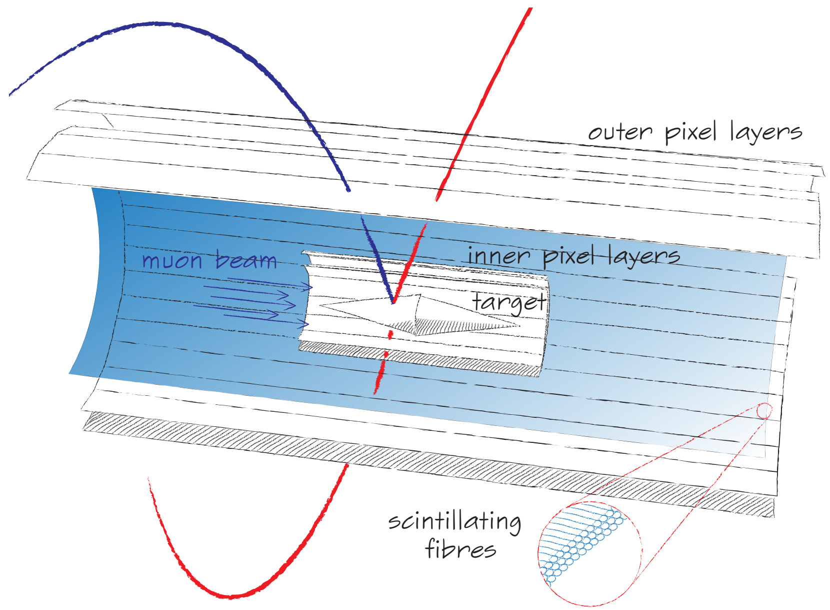
Better timing:
Scintillating fibres and tiles

Timing Detector: Scintillating Fibres

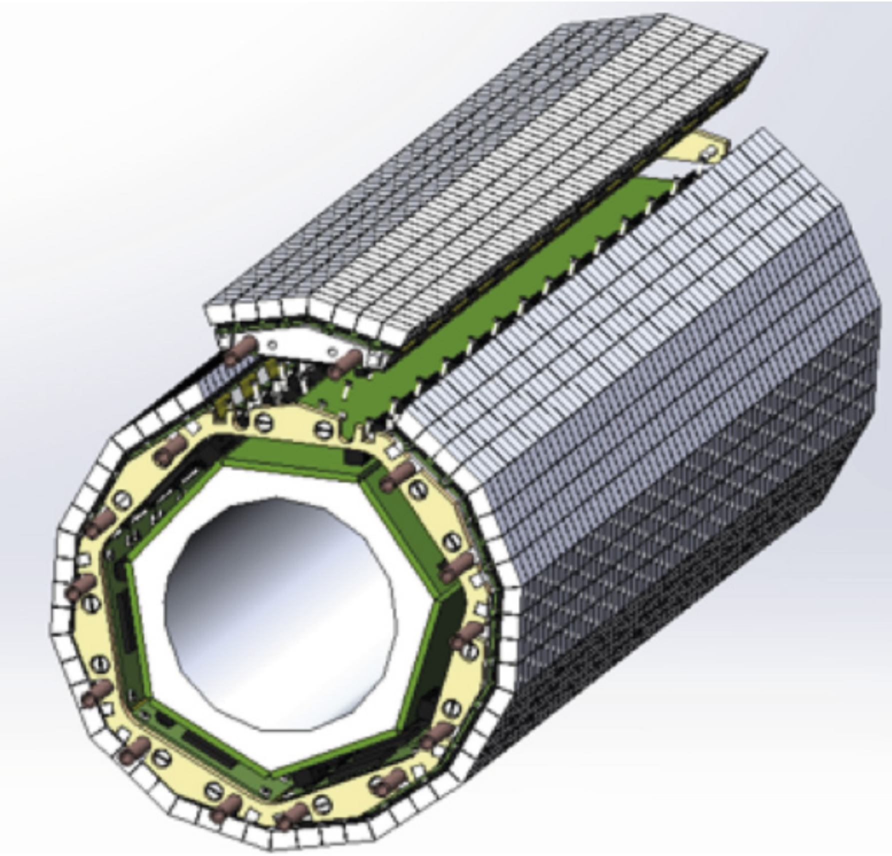
- 3 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)

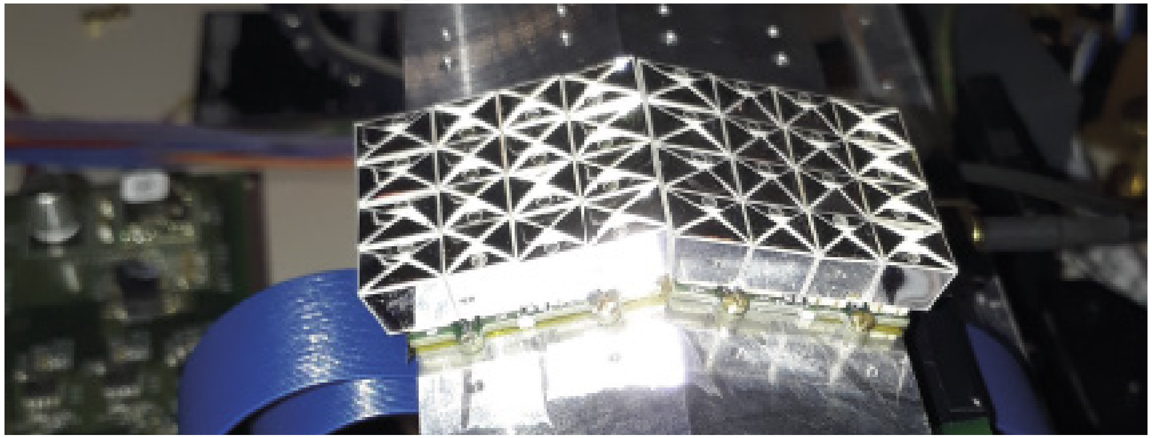


Timing resolution < 400 ps including ASIC

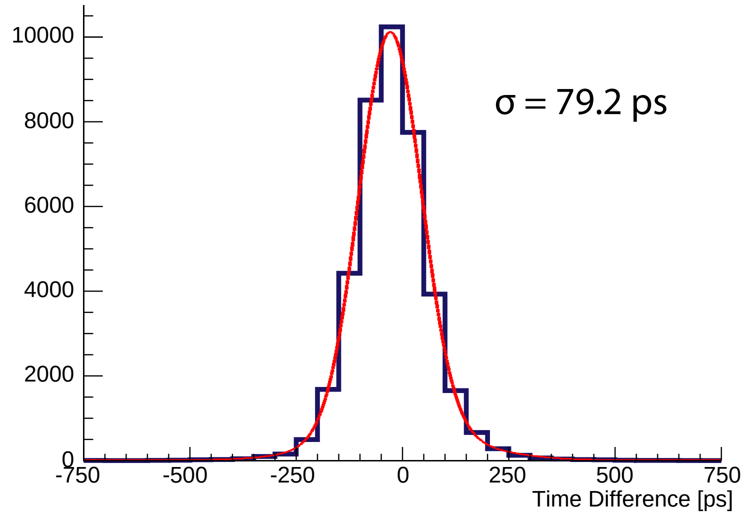


Timing Detector: Scintillating tiles





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

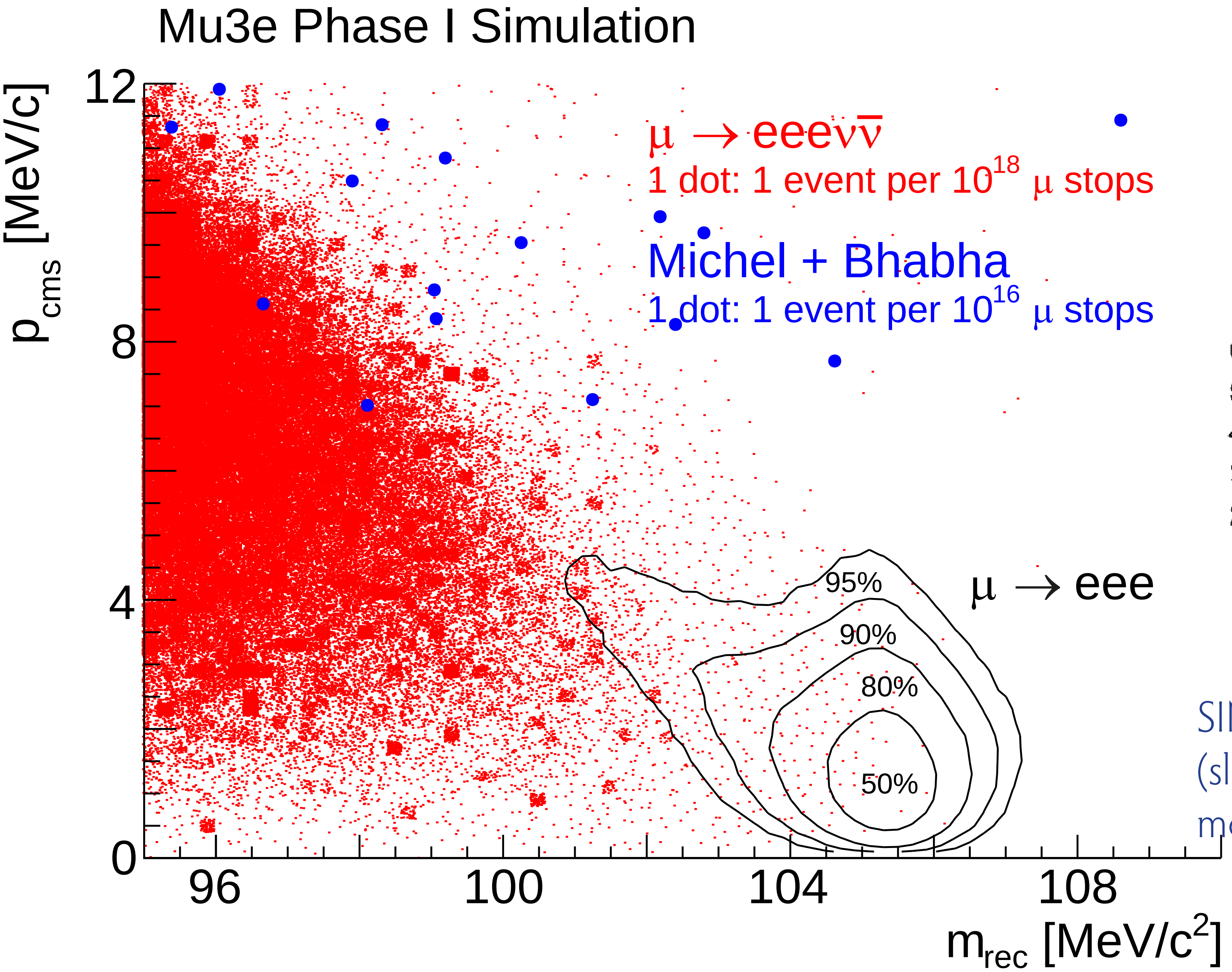


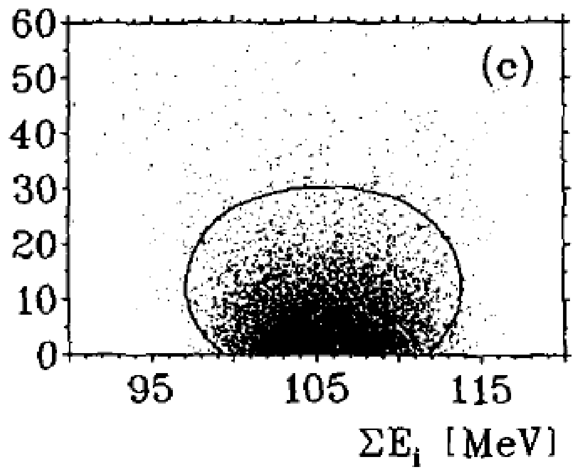
- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution better 80 ps

Phased experiment:

Phase I uses the existing PiE5 beam line at PSI, shared with MEG II, 10^8 muons/s

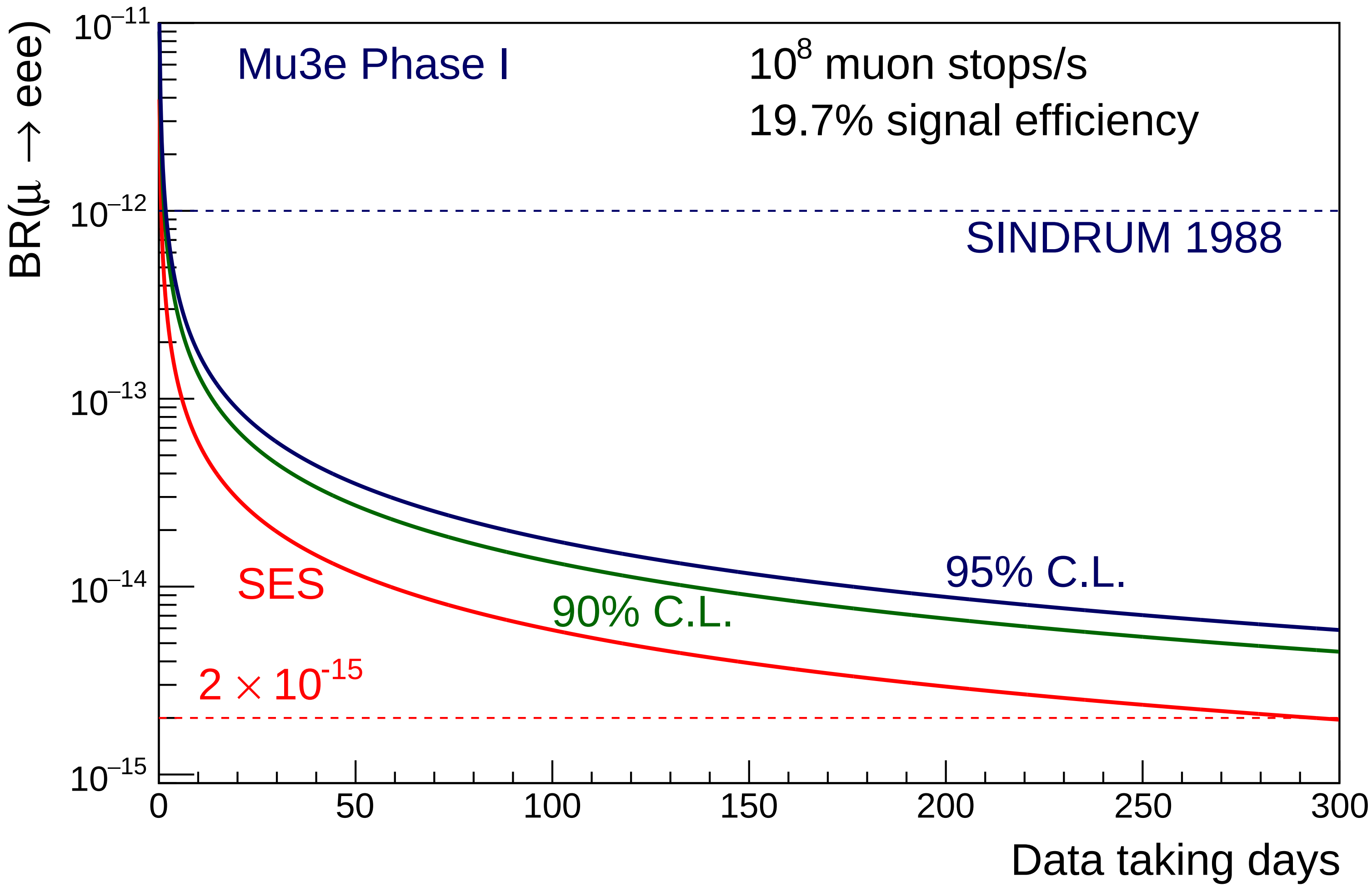
Phase II requires a High Intensity Muon Beamline (HiMB, $> 2 \cdot 10^9$ muons/s)





SINDRUM simulation (slightly different momentum variable)

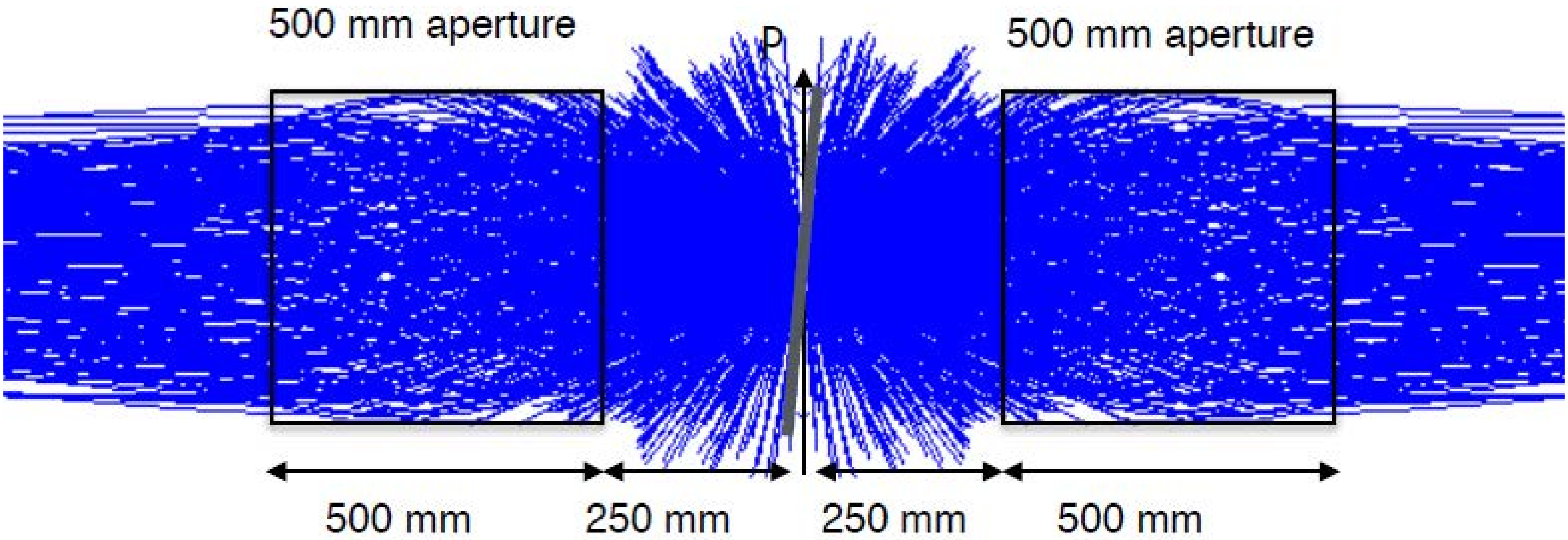
Sensitivity - Mu3e Phase I



- Magnet arrives at PSI in autumn, integration tests
- Construction in 2021
- Data taking 2022++

Mu3e Phase II

Mu3e Phase II - High Intensity Muon Beamline

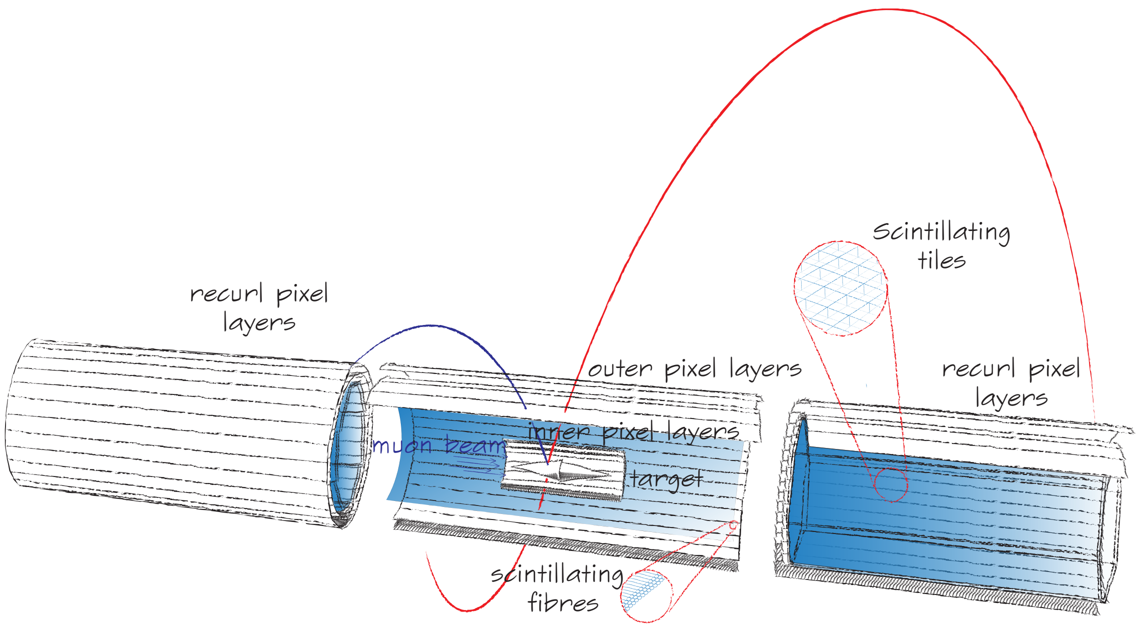


- Ongoing study at PSI
- Same proton accelerator, keep E target (MEG/Mu3e I) and spallation neutron source
- Replace M target (MUSE)
- Optimized target geometry (successfully tested in 2019)
- Solenoidal capture, one channel for particle physics one for µSR (solid state)
- $> 10^{10}$ surface muons/s

Detector improvements

- Aim for 2×10^9 μ-stops/s:
  10^{-16} single event sensitivity
- Smaller target radius:
  Better vertex resolution
- Longer pixel modules:
  Better geometric acceptance
- Need to replace scintillating fibres:
  Occupancy approaching 100%,
  SiPM radiation hardness

Silicon detectors with sub ns timing resolution (LGAD and derived) - how to power, how to cool - R&D started



Beyond Mu3e

Better momentum resolution!

- 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}

- Geometry close to optimal
- Thinner layers: Now at ~ 1.1‰ X_0

  Push silicon from 50 µm → 35 µm

  Reduce interconnect thickness by chip-to-chip connections (wafer postprocessing)

  0.7 ‰ X_0 maybe possible,
  not very much gain ($\theta_{MS} \sim\sqrt{X/X_0}$)

- Think different, go to high-energy decay in-flight (NA-62 like)
  Very, very long decay tube…

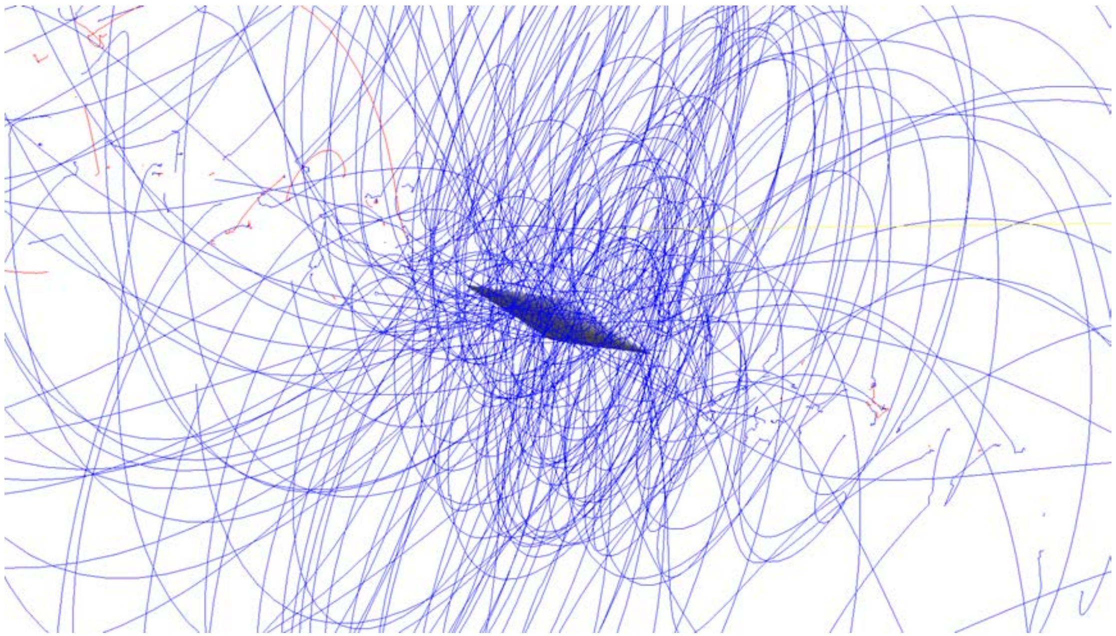
Better timing resolution!

- Push timing resolution of silicon pixels

  Keep power/cooling and material budget in mind

- Absolutely needed for reconstruction: Combinatorics, confusion, fakes

- Better scintillator time resolution only helps if tracker is also better (matching problem)

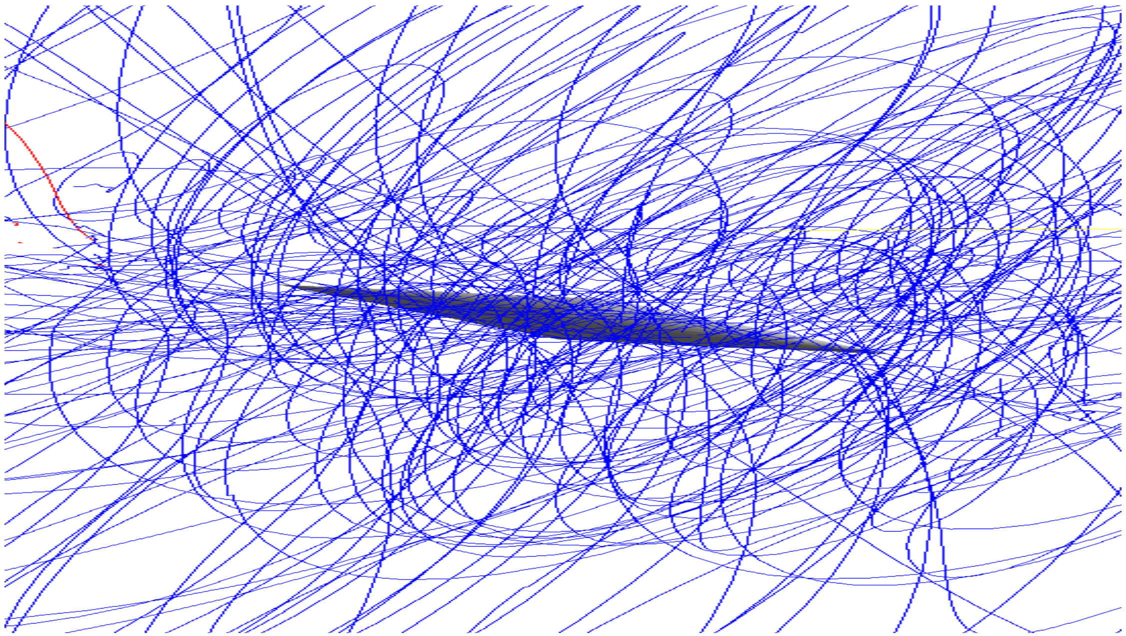


Better vertex separation!

- Smaller pixels in innermost layer
  (this is the only place where this helps)

- Smaller radius of innermost layer
  (less extrapolation)

- Longer target
  (more spread, less material in
  transverse direction,
  but beam divergence...)



Summary

- SINDRUM:
  Still best limit: BR < 10^{-12}

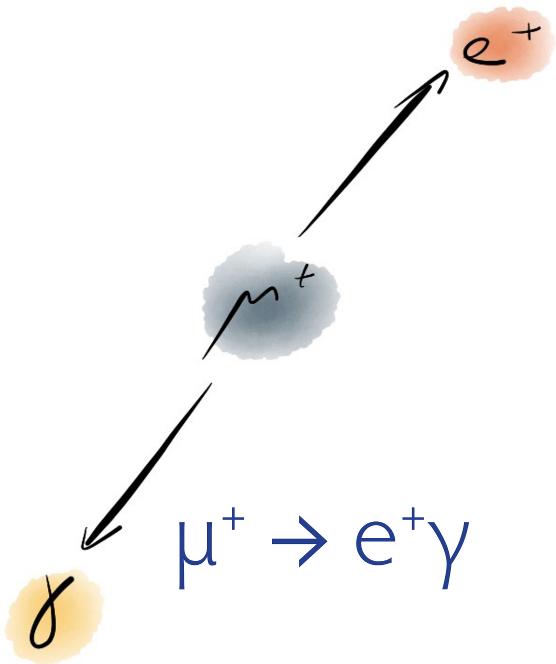
- Mu3e Phase I:
  Search for $\mu \rightarrow eee$ with a sensitivity of $2 \cdot 10^{-15}$ - starting to put detector together

- Mu3e Phase II:
  Challenging path to 10^{-16} - technologies existing

- Beyond 10^{-16}:
  Will need new technologies, new ideas

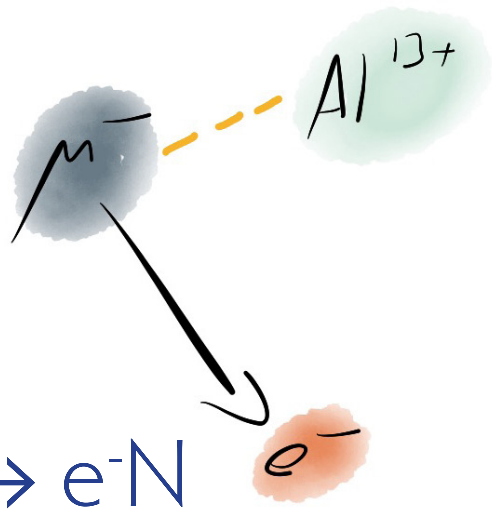
Backup

LFV Muon Decays

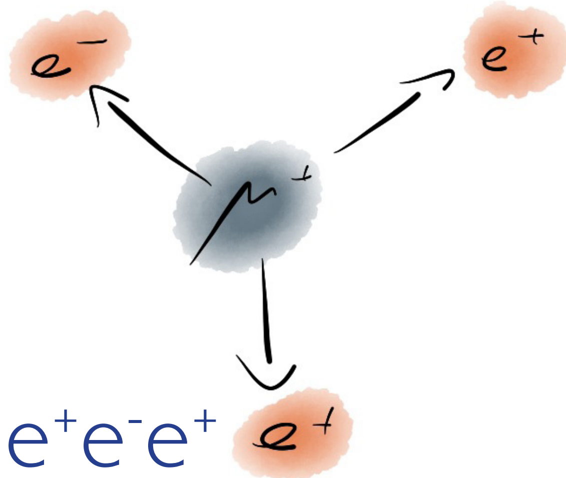


$\mu^+ \rightarrow e^+\gamma$

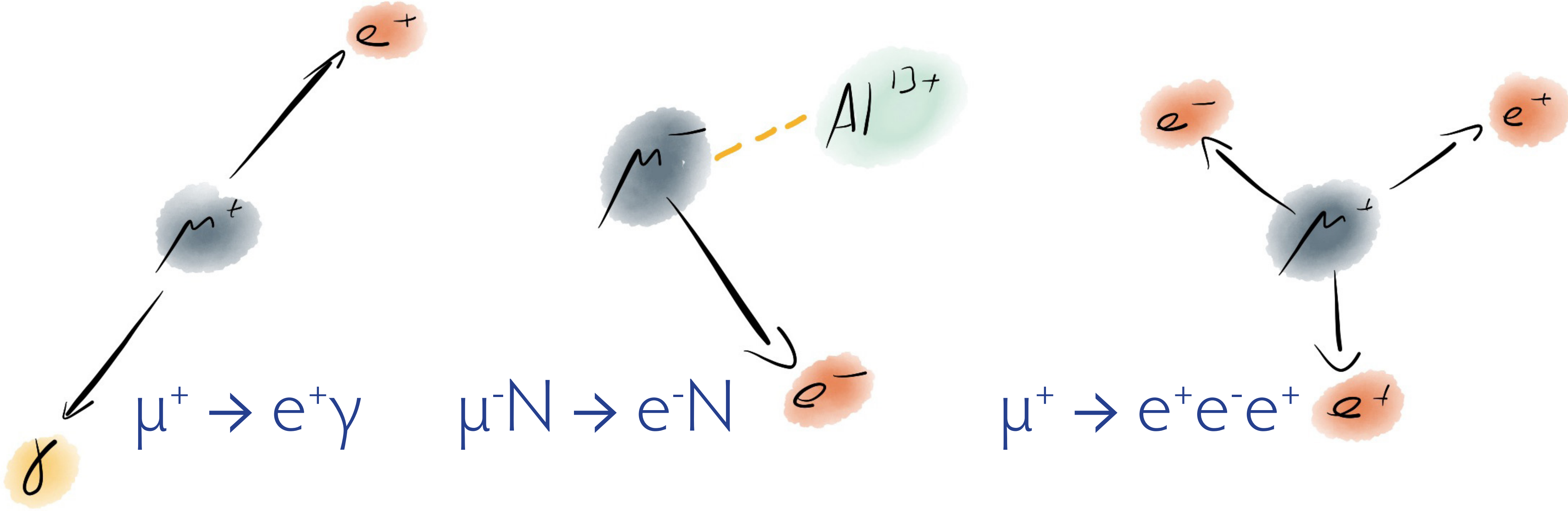
$\mu^-N \rightarrow e^-N$



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

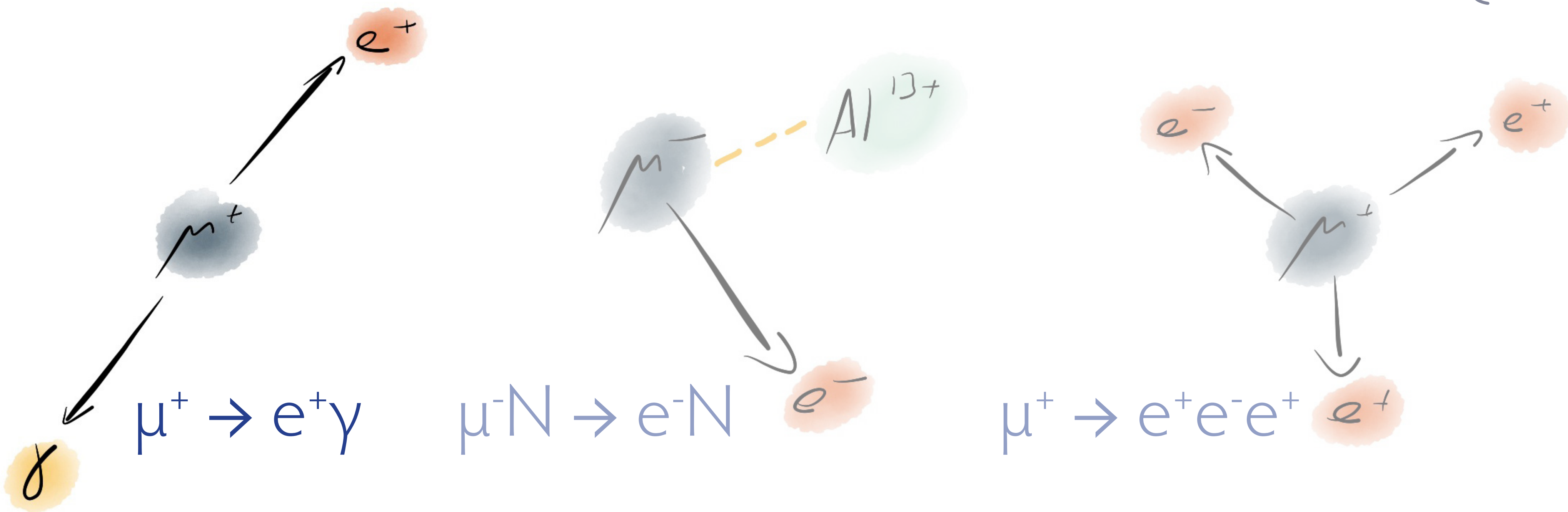


LFV Muon Decays: Experimental Situation



MEG (PSI)	SINDRUM II (PSI)	SINDRUM (PSI)
$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$	$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$	$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(2016)	(2006)	(1988)
	relative to nuclear capture	

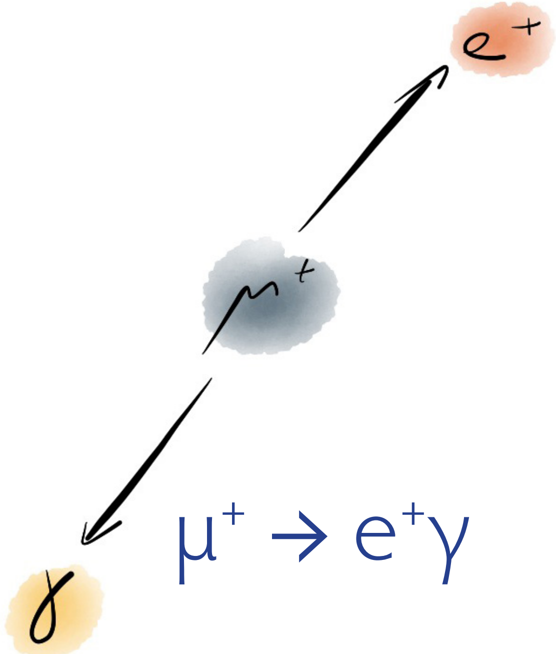
LFV Muon Decays: Experimental signatures



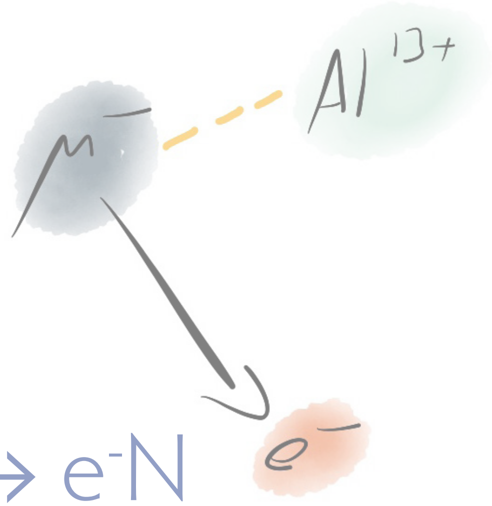
Kinematics

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

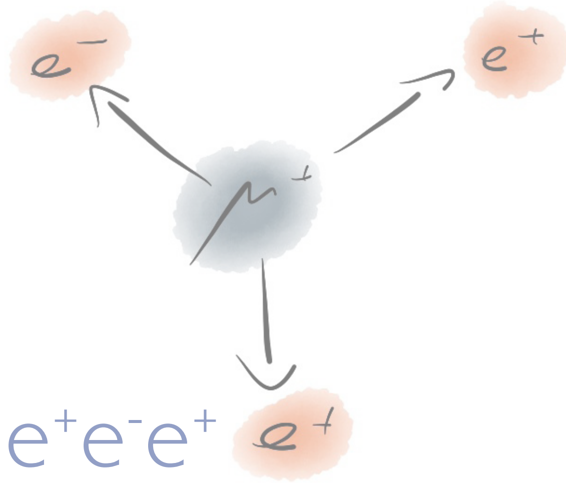
LFV Muon Decays: Experimental signatures



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



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



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

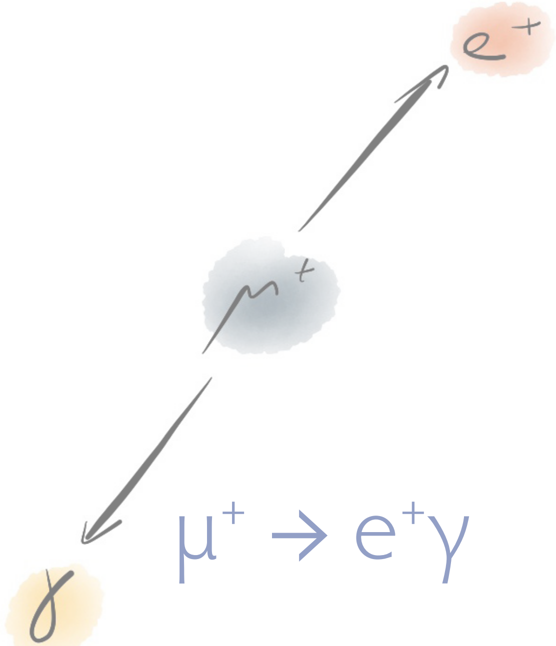
Kinematics

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

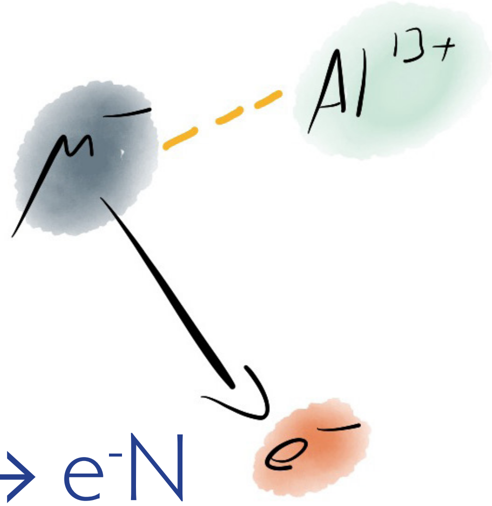
Background

- Accidental background
- Radiative decay

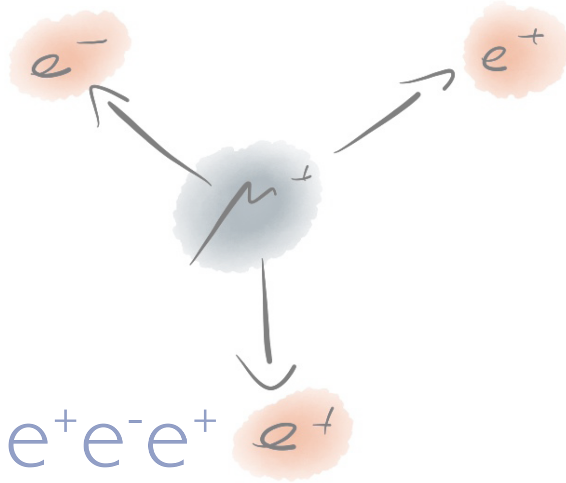
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

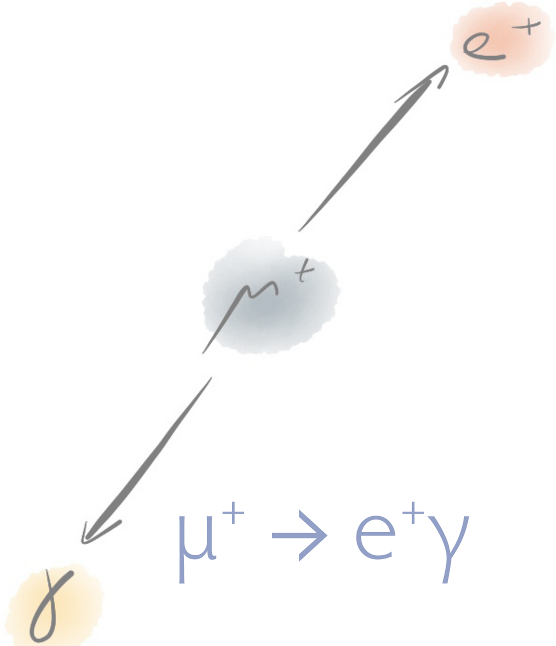
Background

- Accidental background
- Radiative decay

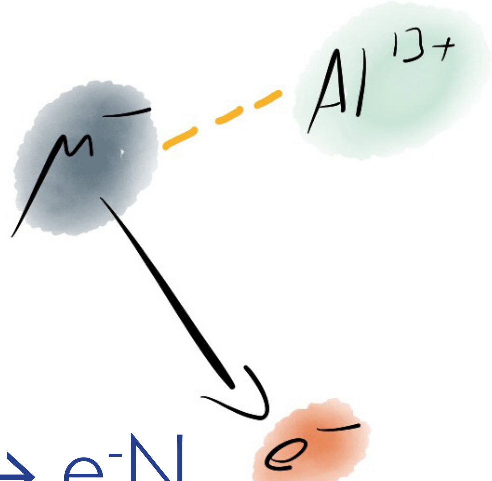
Kinematics

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

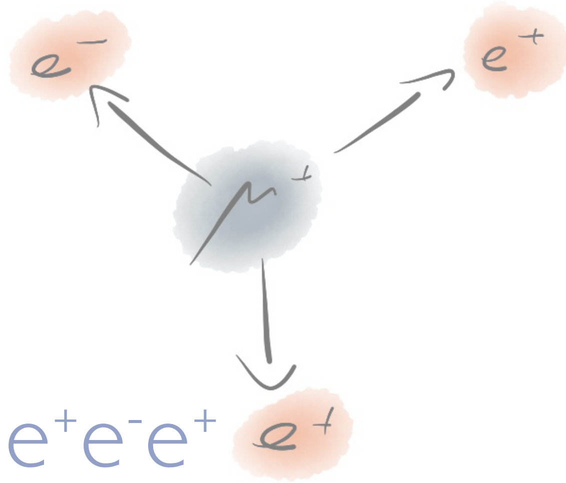
LFV Muon Decays: Experimental signatures



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



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



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

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

Kinematics

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

Background

- Accidental background
- Radiative decay

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

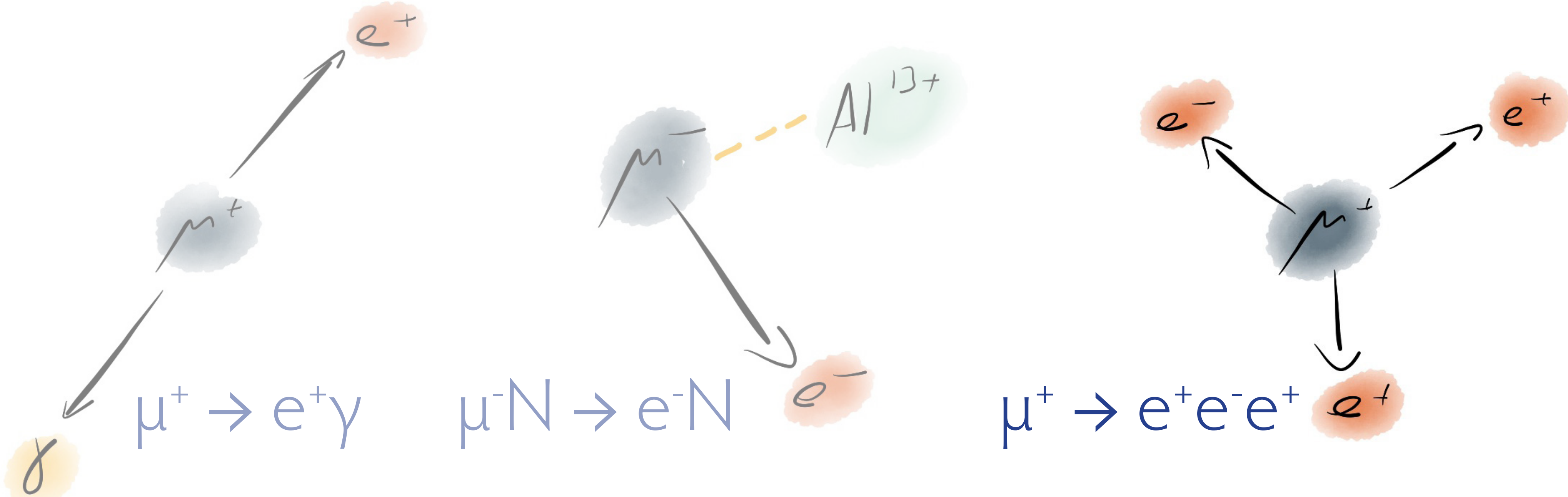
Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics

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
- Radiative decay

Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics

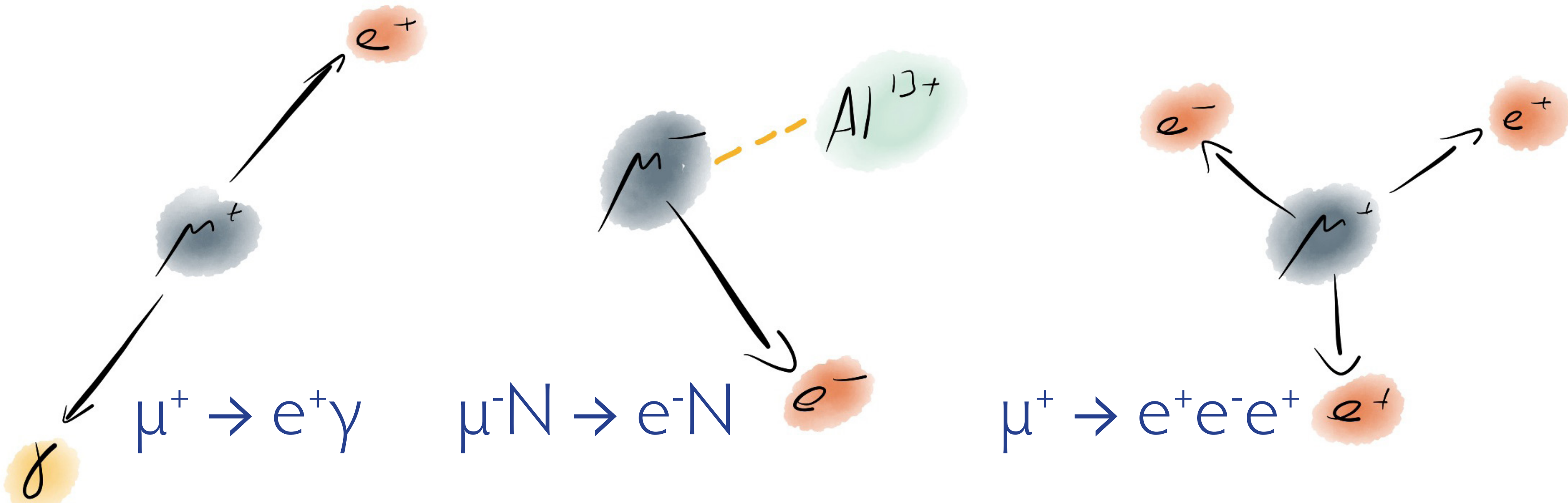
Kinematics

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

Background

- Internal conversion decay
- Accidental background

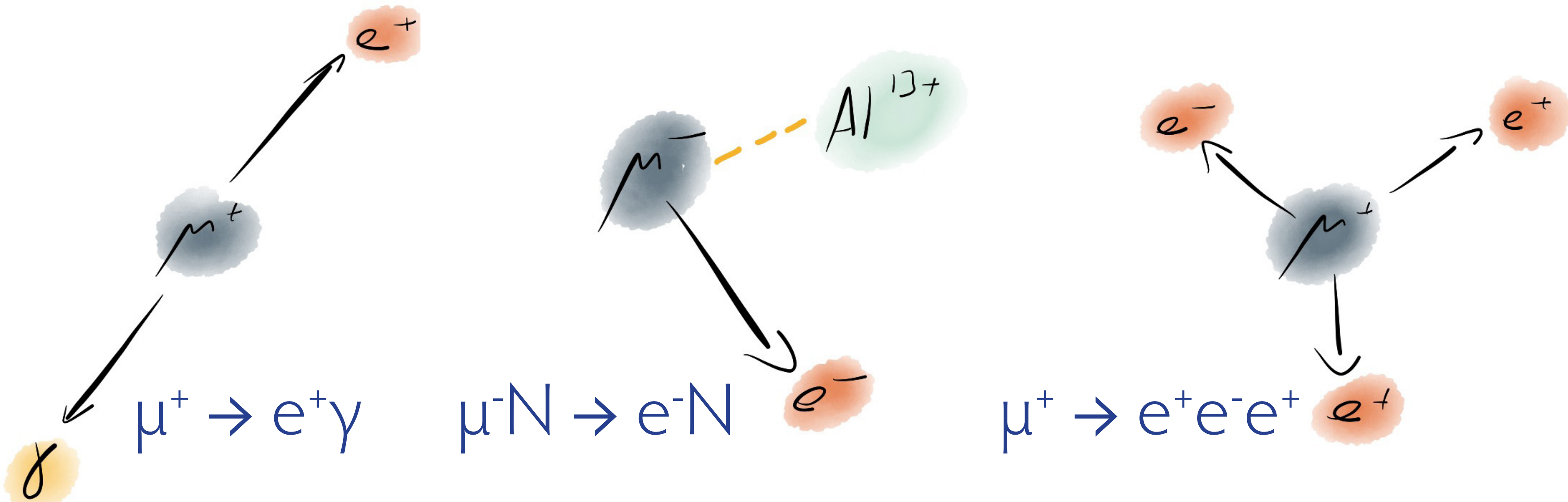
LFV Muon Decays: Experimental signatures



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

Kinematics	Kinematics	Kinematics
• 2-body decay	• Quasi 2-body decay	• 3-body decay
• Monoenergetic e^+, γ	• Monoenergetic e^-	• Invariant mass constraint
• Back-to-back	• Single particle detected	• $\Sigma p_i = 0$
Background	Background	Background
• Accidental background	• Decay in orbit	• Internal conversion decay
• Radiative decay	• Antiprotons, pions, cosmics	• Accidental background

LFV Muon Decays: Experimental signatures



Kinematics

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

Backgro

- A …al background

Continuous Beam

Kinematics

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

Backgro

- D… …orbit
- A… protons, pions

Pulsed Beam

Kinematics

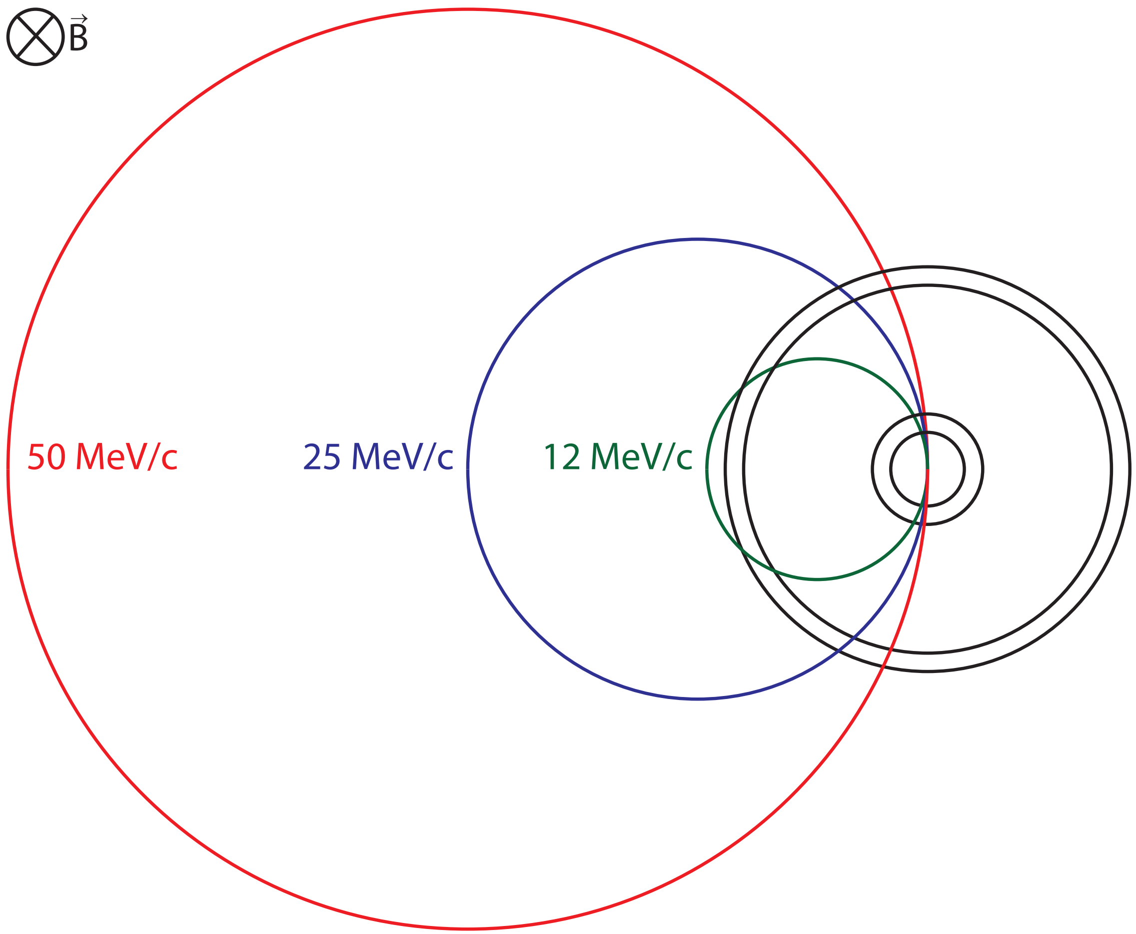
- 3-body decay
- Invariant mas… …aint
- $\Sigma p_i = 0$

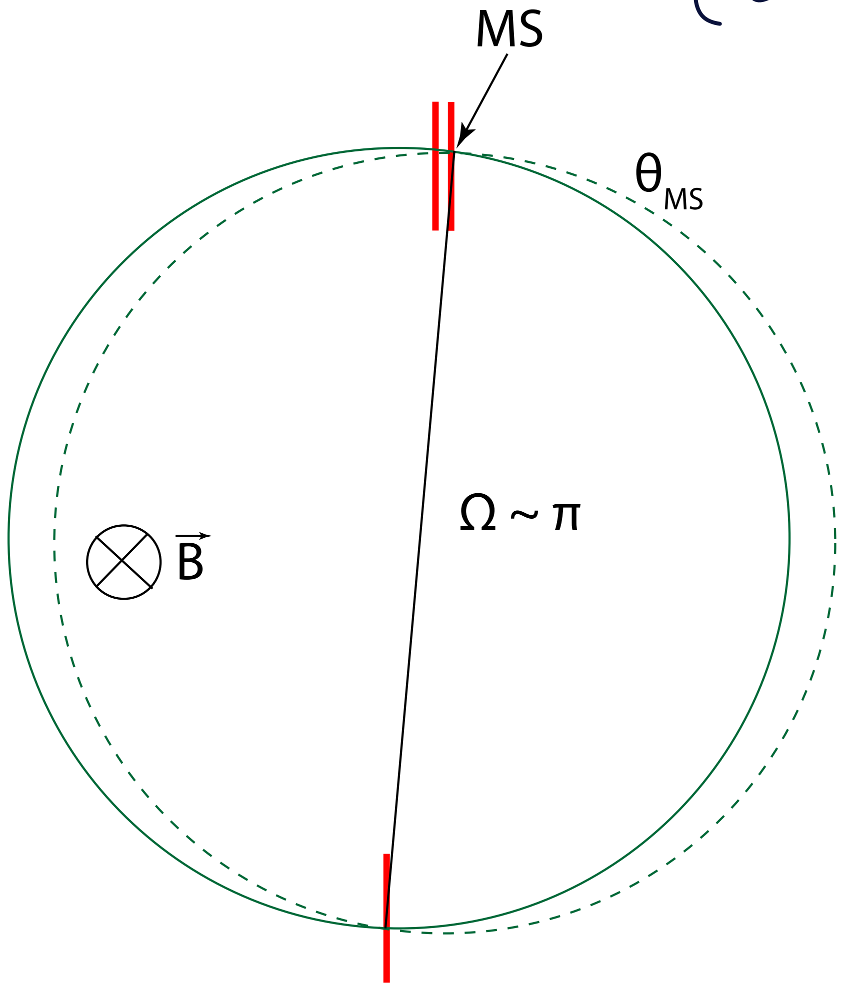
Backgro

- R… …decay
- Ac… …dental background

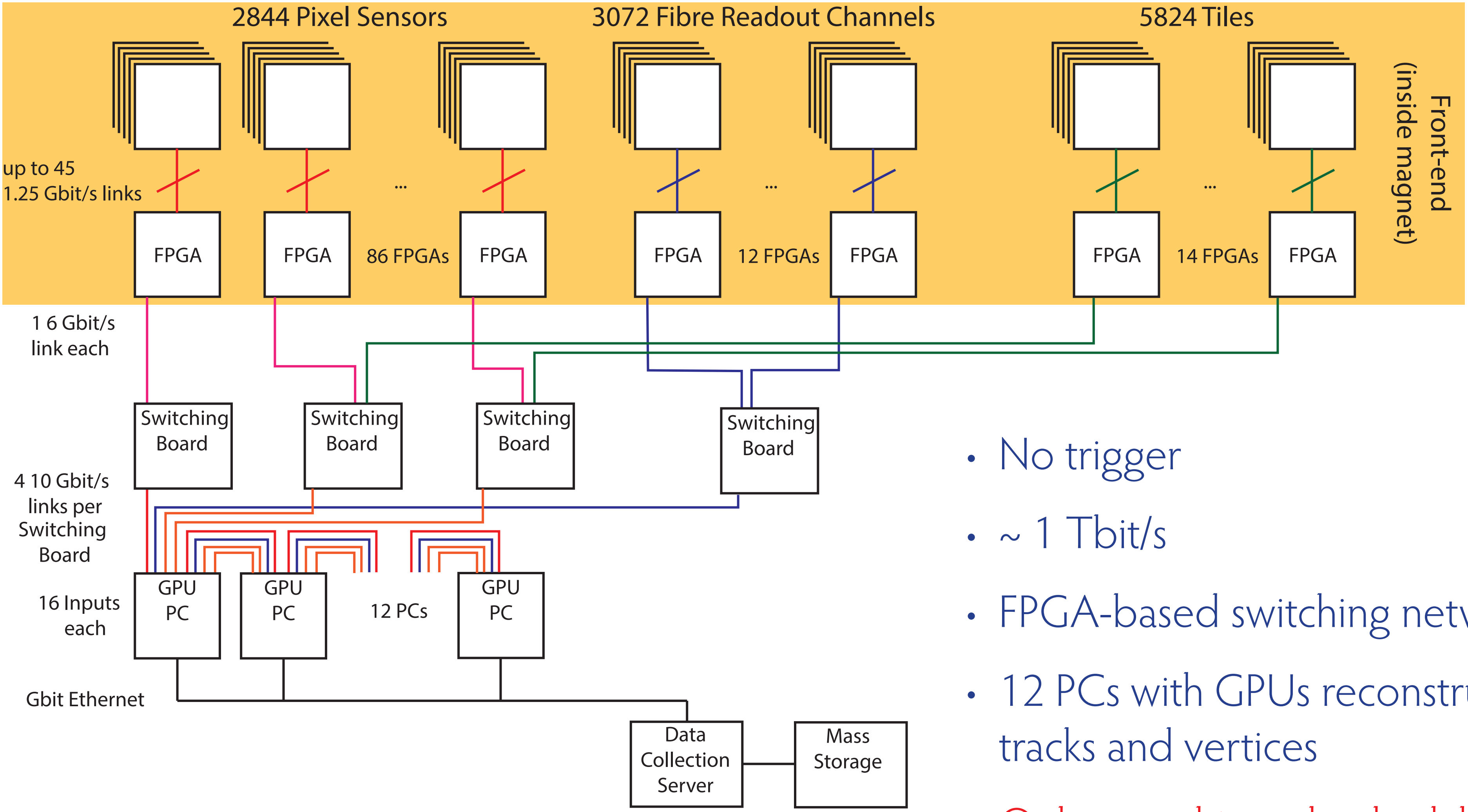
Continuous Beam

Precision vs. Acceptance





Phase I Data Acquisition and Filter Farm



- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- 12 PCs with GPUs reconstruct tracks and vertices
- Only save things that look like $\mu^+ \rightarrow e^+e^-e^+$