The Mu3e Experiment

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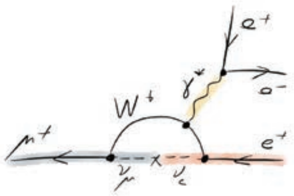
Lepton Moments 2014

Emmy Noether-Programm

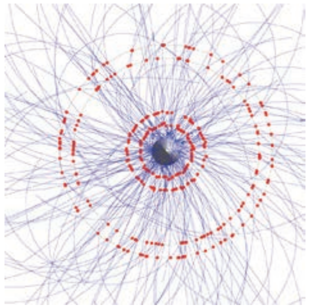
Deutsche Forschungsgemeinschaft

DFG

Overview



- The Charge:
  Can we find lepton flavour violating μ-decays?

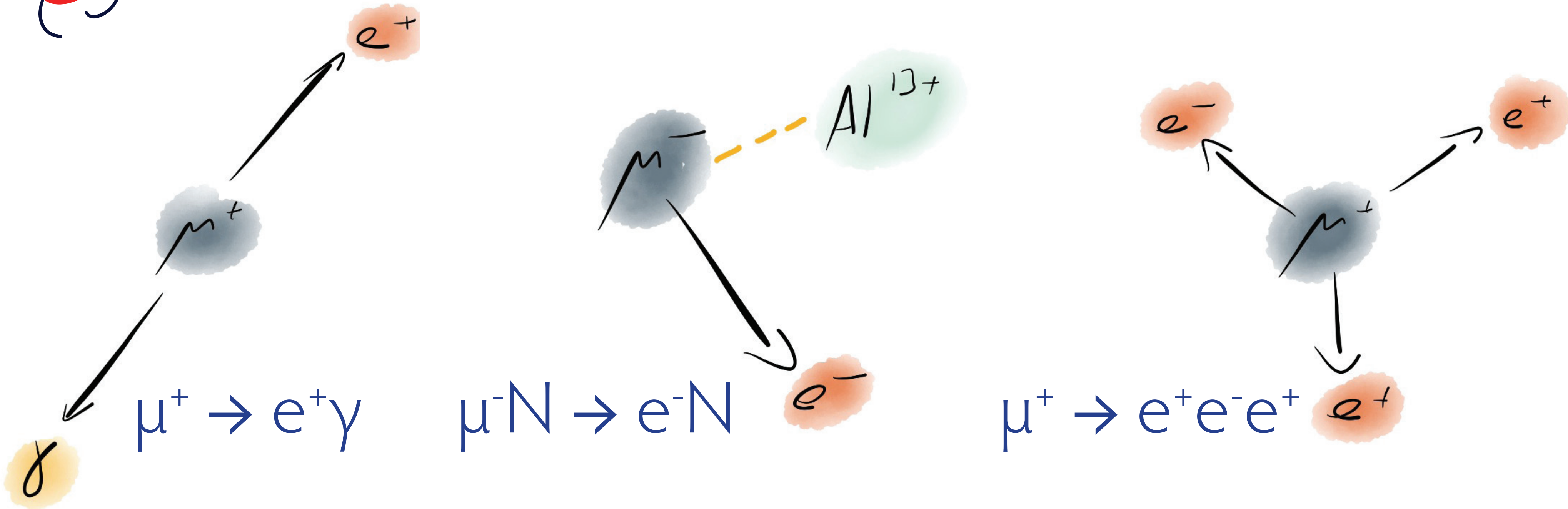


- The Challenge:
  Finding one in 10^{16} muon decays

- The Mu3e Detector:
  Minimum Material, Maximum Precision

The hunt for
charged lepton flavour violation in μ-decays

LFV Muon Decays: Experimental Situation



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

MEG (PSI)

$B(\mu^+ \rightarrow e^+\gamma) < 5.7 \cdot 10^{-13}$

(2013)

SINDRUM II (PSI)

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

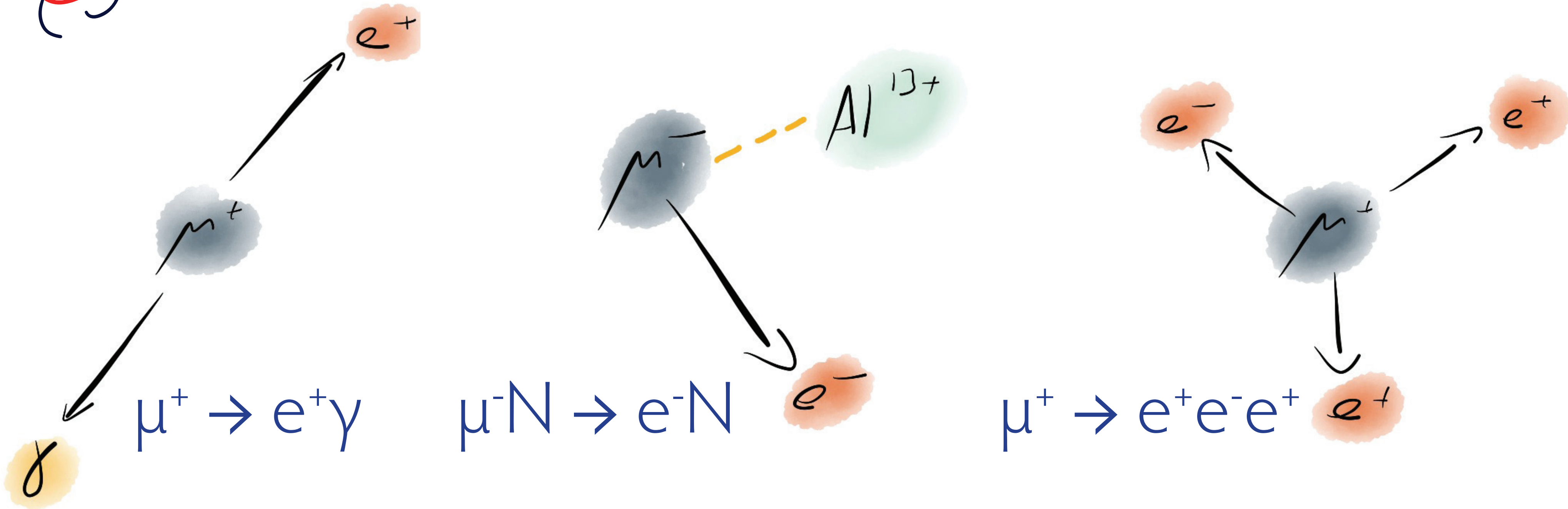
(2006)

SINDRUM (PSI)

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

(1988)

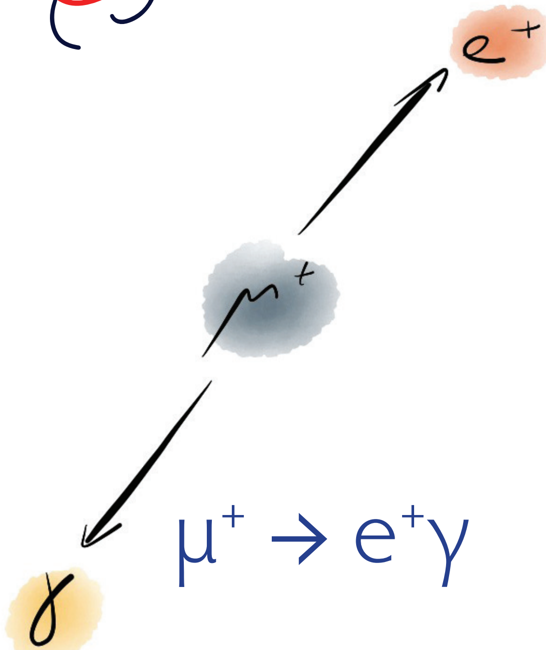
LFV Muon Decays: Experimental Situation

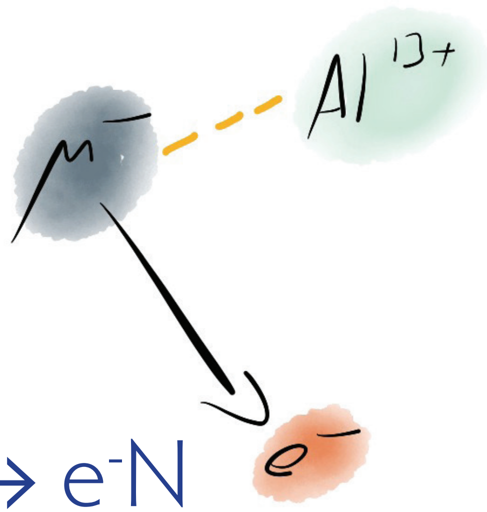


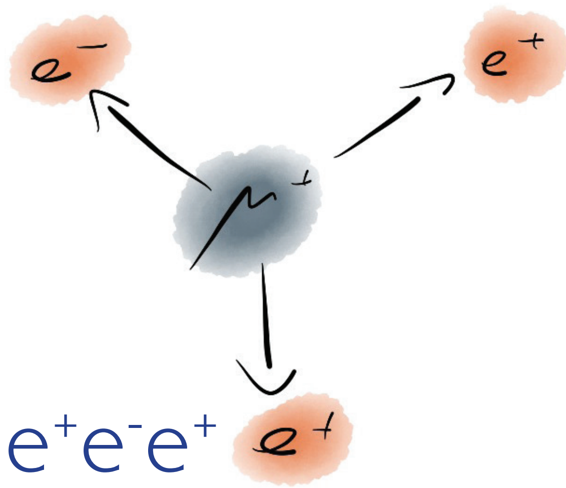
$\mu^+ \rightarrow e^+\gamma$ $\mu^-N \rightarrow e^-N$ $\mu^+ \rightarrow e^+e^-e^+$

MEG (PSI)	SINDRUM II (PSI)	SINDRUM (PSI)
$B(\mu^+ \rightarrow e^+\gamma) < 5.7 \cdot 10^{-13}$ (2013)	$B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$ (2006)	$B(\mu^+ \rightarrow e^+e^-e^+) < 1.0 \cdot 10^{-12}$ (1988)
upgrading	Mu2e/Comet	Mu3e

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

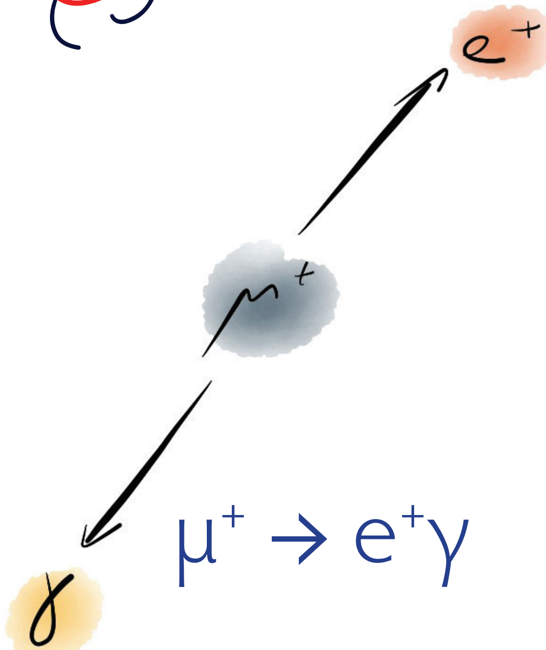
Kinematics

- 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



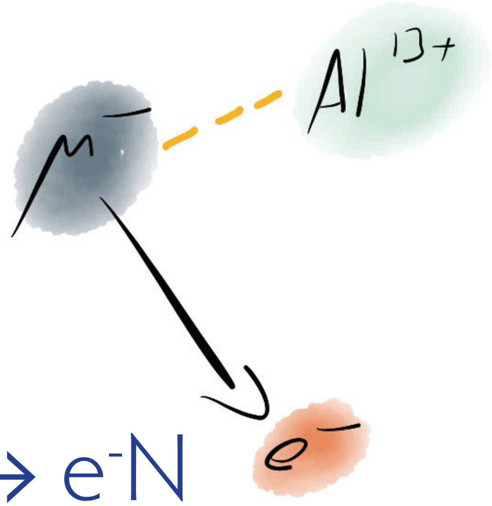
$\mu^+ \to e^+\gamma$

Kinematics

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

Background

- Accidental background



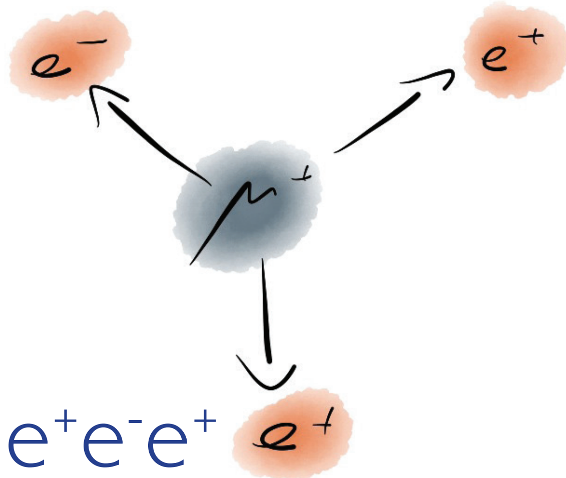
$\mu^-N \to e^-N$

Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics



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

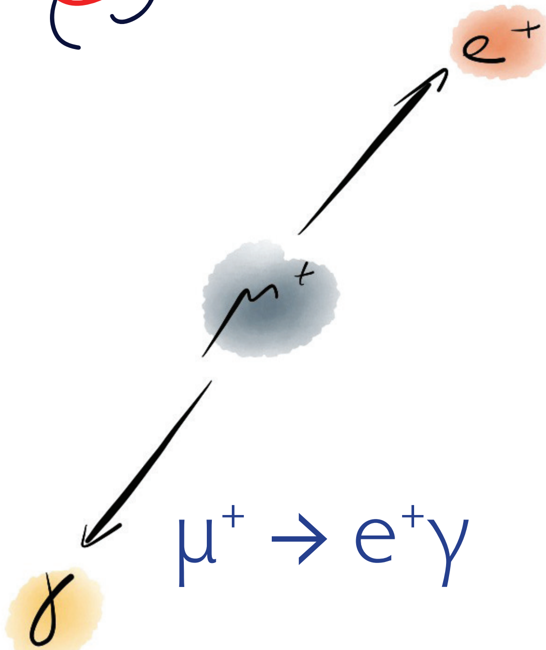
Kinematics

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

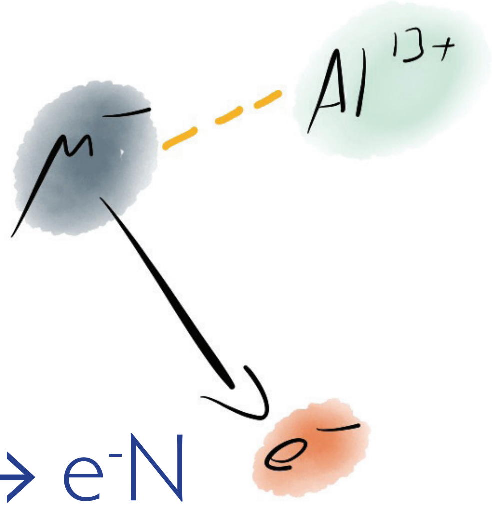
Background

- Radiative decay
- Accidental background

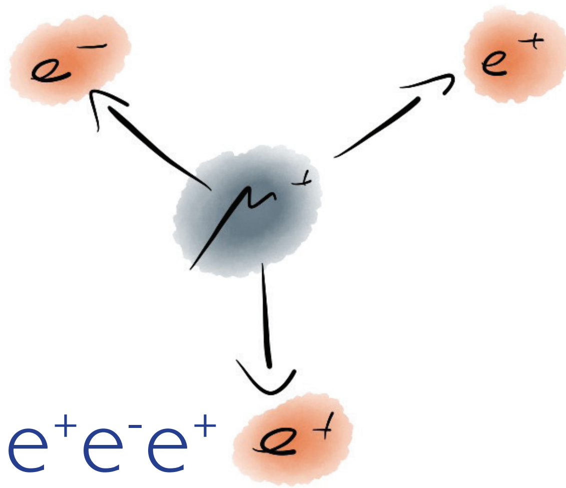
LFV Muon Decays: Experimental signatures



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



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



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

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

Backgro
- A ...al background

Continuous Beam

Kinematics
- Quasi 2-body de
- 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

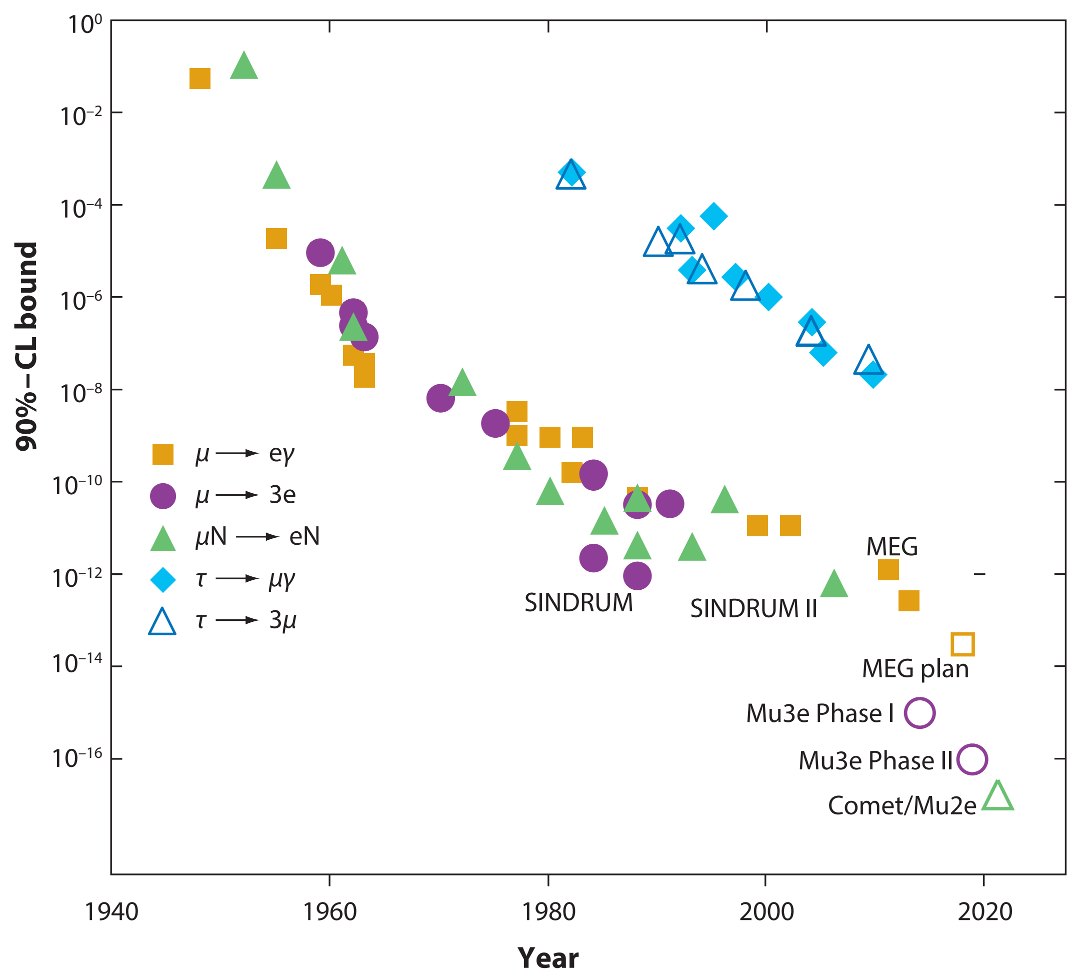
Continuous Beam

Searching for

$\mu^+ \rightarrow e^+e^-e^+$ at the 10^{-16} level

The Goal: 10^{-16}

- We want to find or exclude $\mu \rightarrow eee$ at the 10^{-16} level
- 10^{-15} in phase I (existing beamline)
- 10^{-16} in phase II (new beamline)
-
- 4 orders of magnitude over previous experiment (SINDRUM 1988)

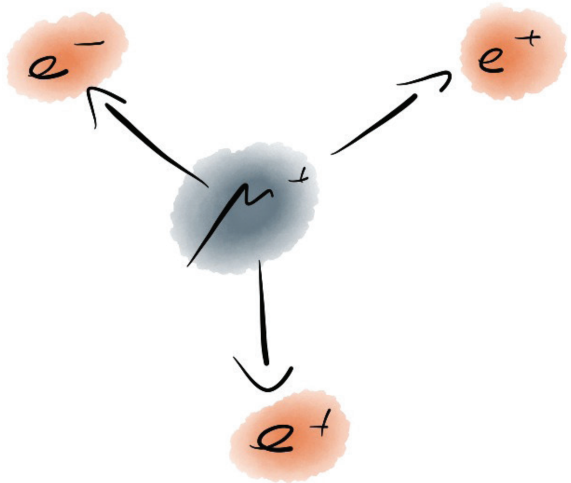


(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

The Mu3e Collaboration

- DPNC, Geneva University
- Physics Institute, Heidelberg University
- KIP, Heidelberg University
- ZITI Mannheim, Heidelberg University
- Paul Scherrer Institute
- Physics Institute, Zürich University
- Institute for Particle Physics, ETH Zürich

The Challenges

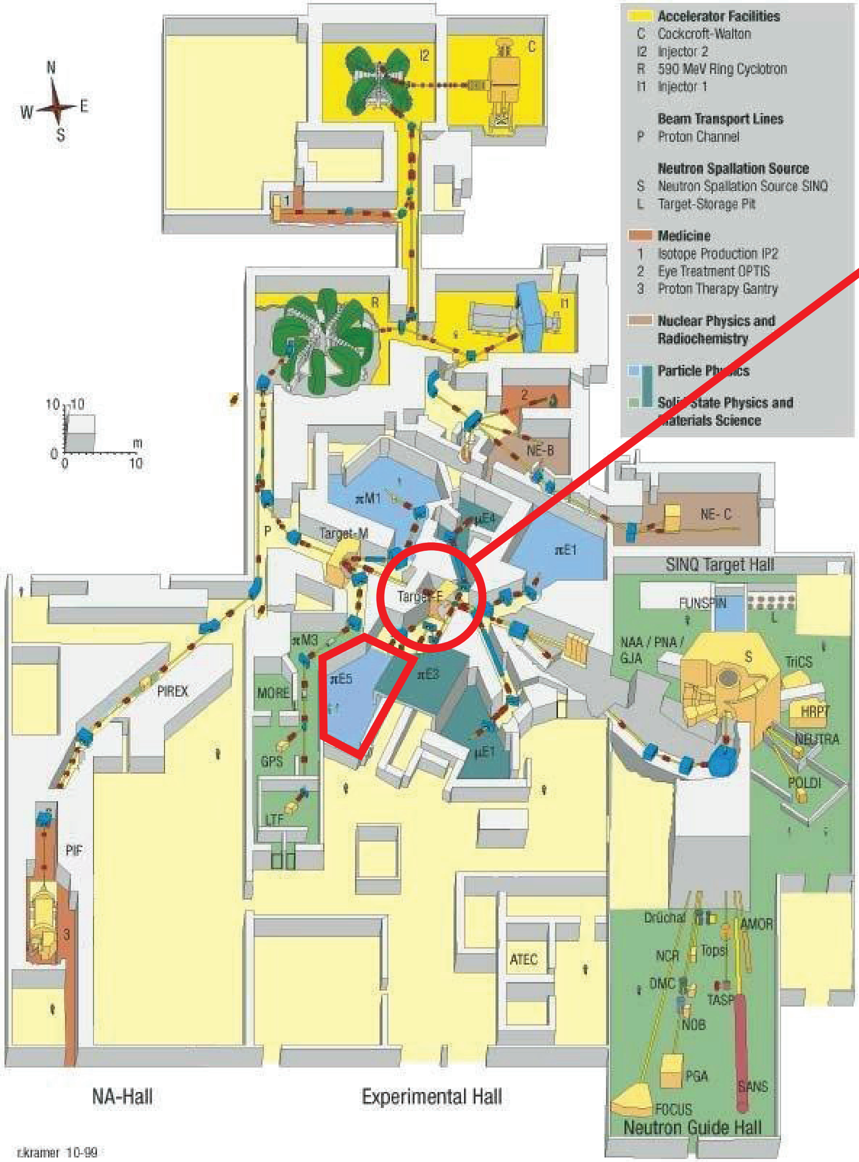


- Observe more than 10^{16} muon decays:
  2 Billion muons per second

- Suppress backgrounds by more than 16 orders of magnitude

- Be sensitive for the signal

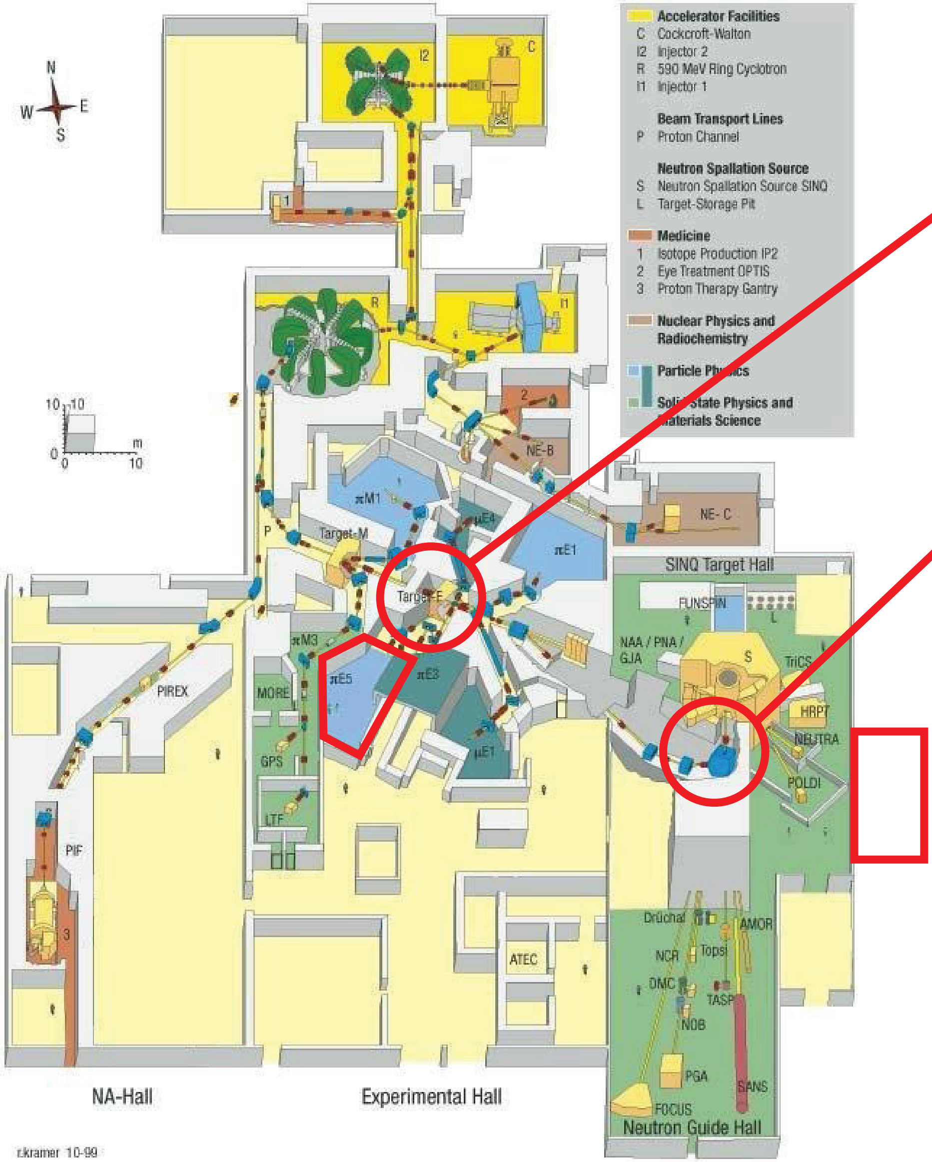
Muons from PSI



DC muon beams at PSI:

- πE5 beamline: ~ 10^8 muons/s
  (MEG experiment, Mu3e phase I)

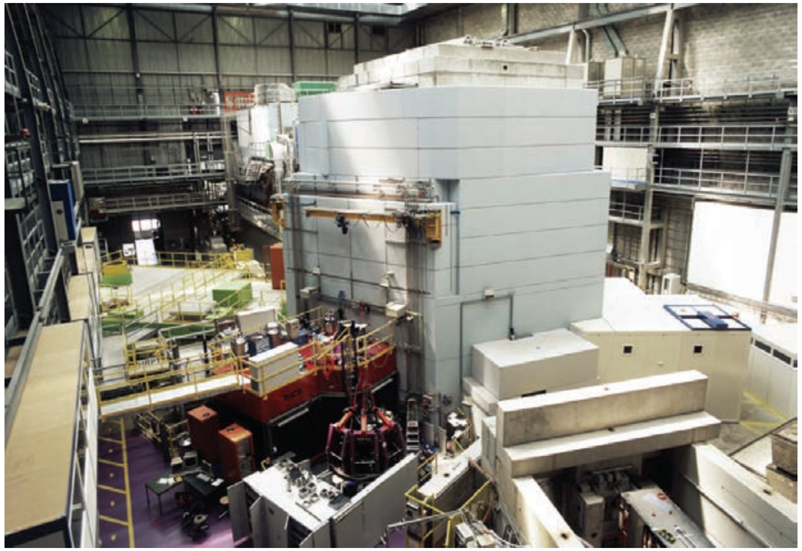
Muons from PSI



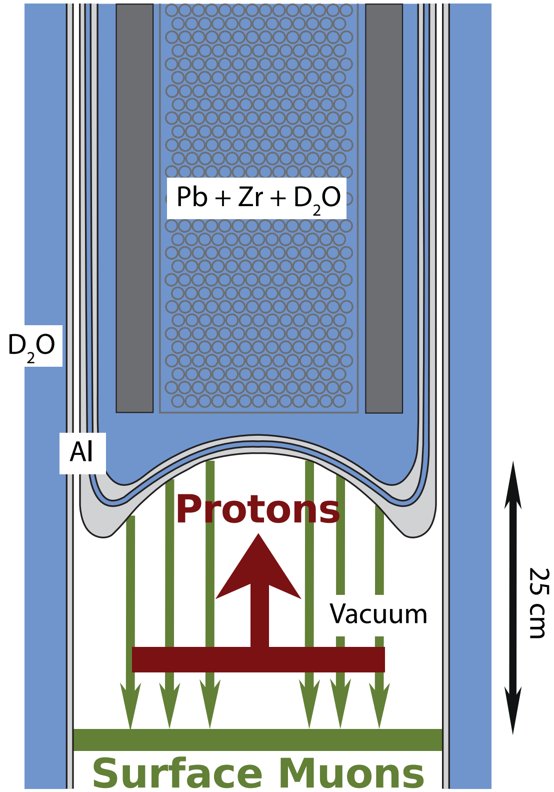
DC muon beams at PSI:

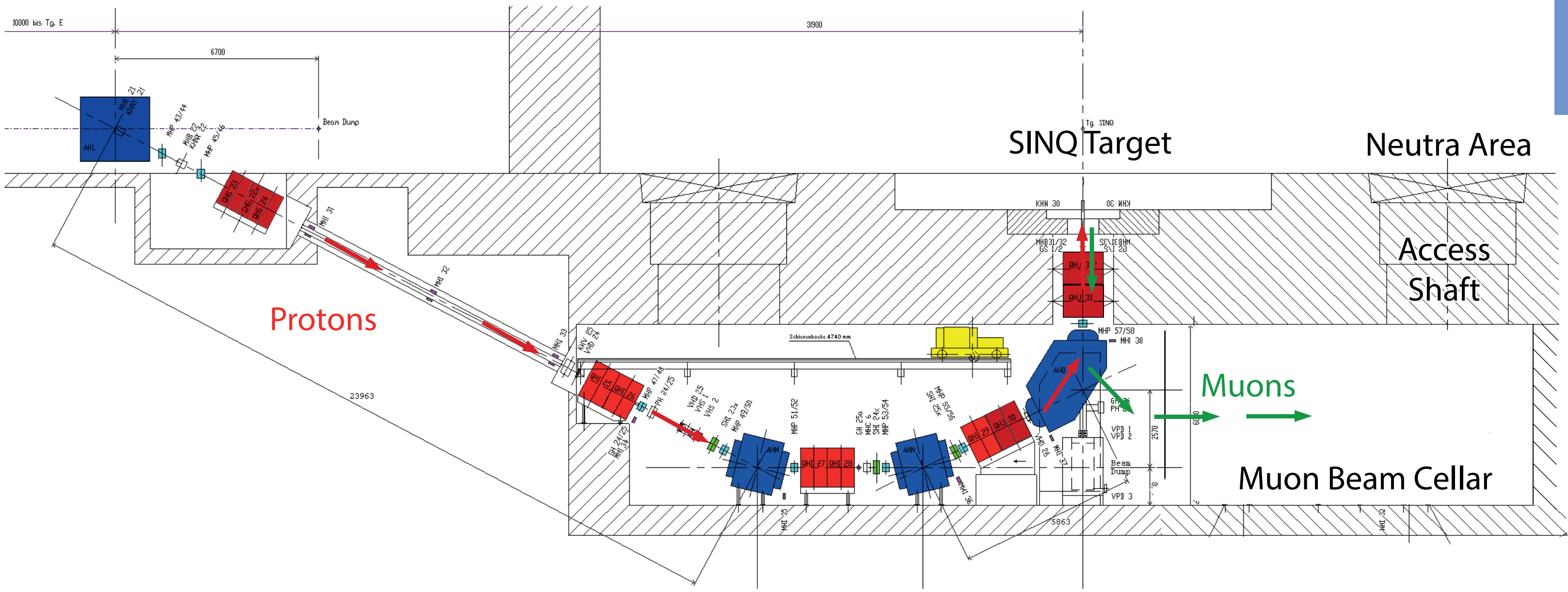
- πE5 beamline: ~ 10^8 muons/s (MEG experiment, Mu3e phase I)
- At the SINQ (spallation neutron source) more than ~ 5×10^{10} muons/s are produced
  High intensity muon beamline (HiMB) proposal
- The $\mu \to eee$ experiment (final stage) requires 2×10^9 muons/s focused and collimated on a ~2 cm spot

The High-Intensity Muon Beamline (HIMB)

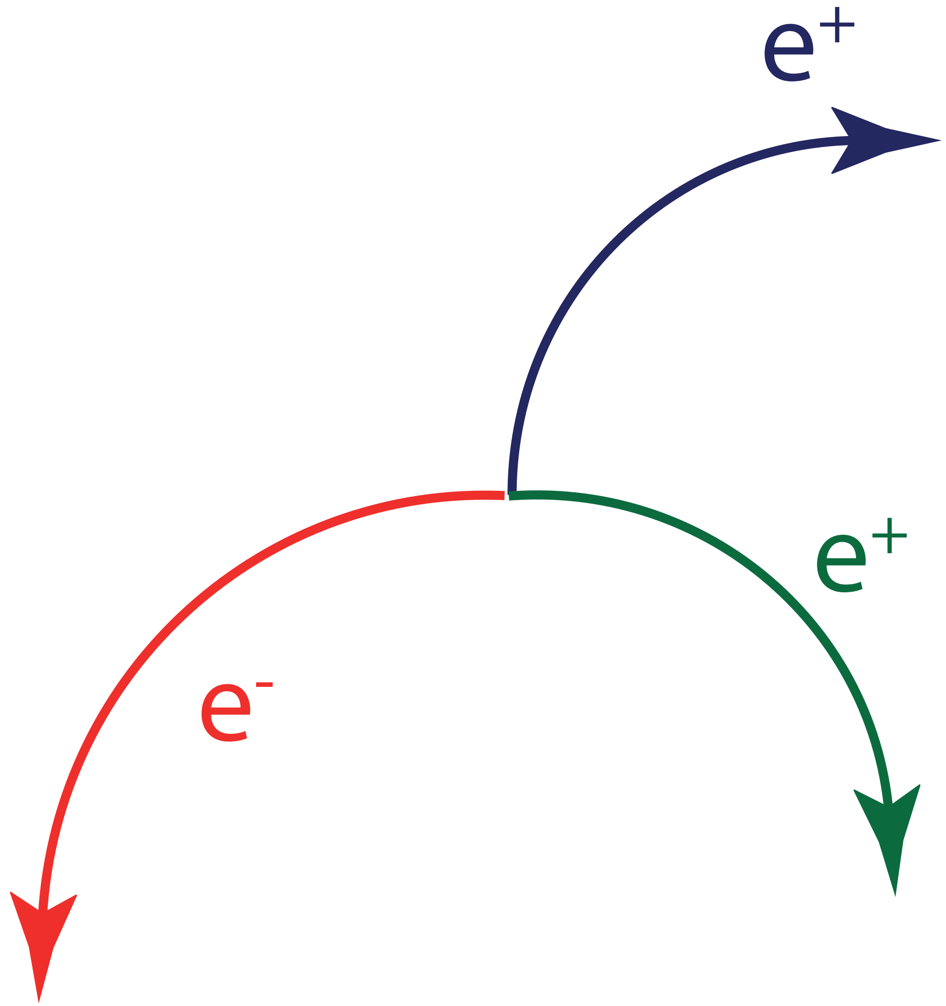


- Muon rates in excess of 10^{10}/s
- $2 \cdot 10^{9}$/s needed for $\mu \rightarrow eee$ at 10^{-16}
- Not before 2019



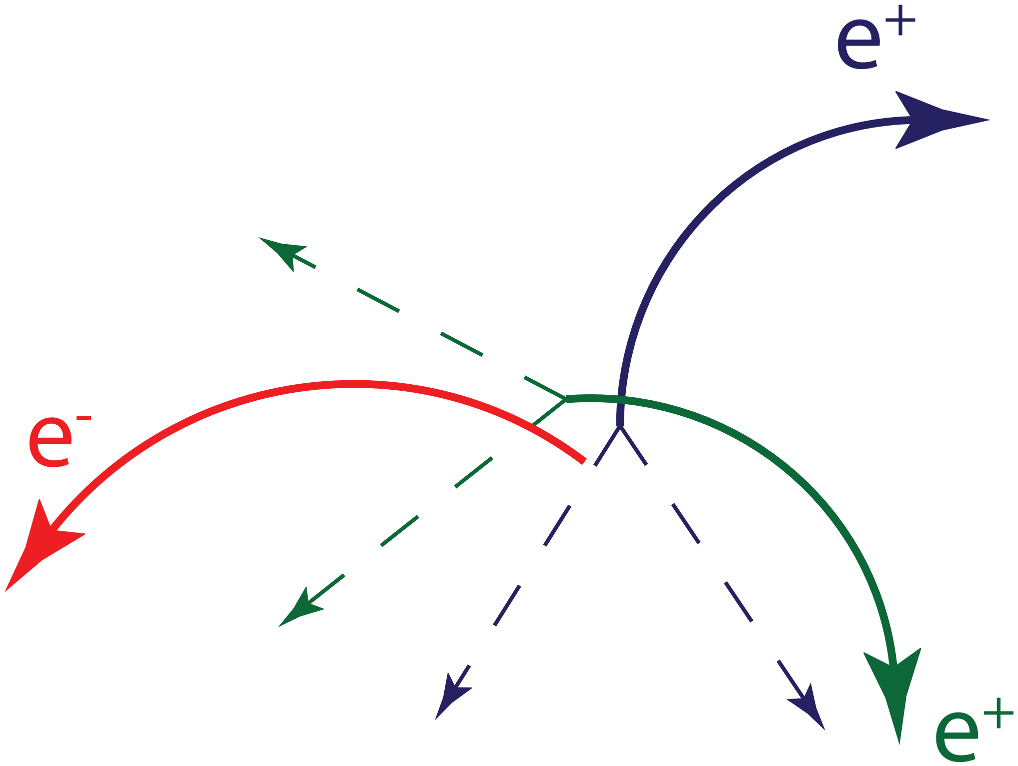


The signal



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

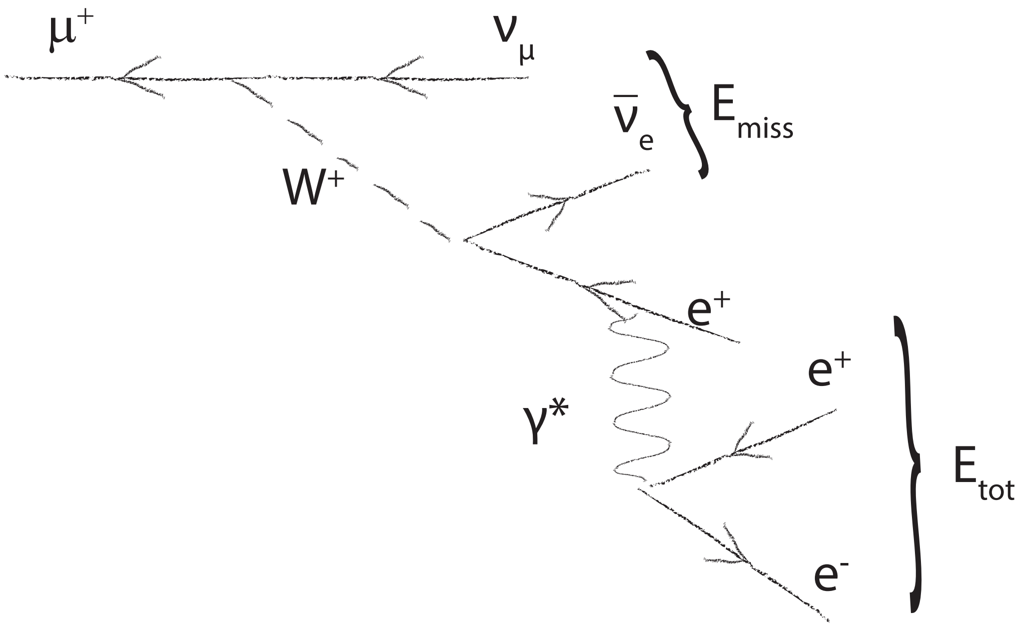
Accidental Background



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

- Need very good timing, vertex and momentum resolution

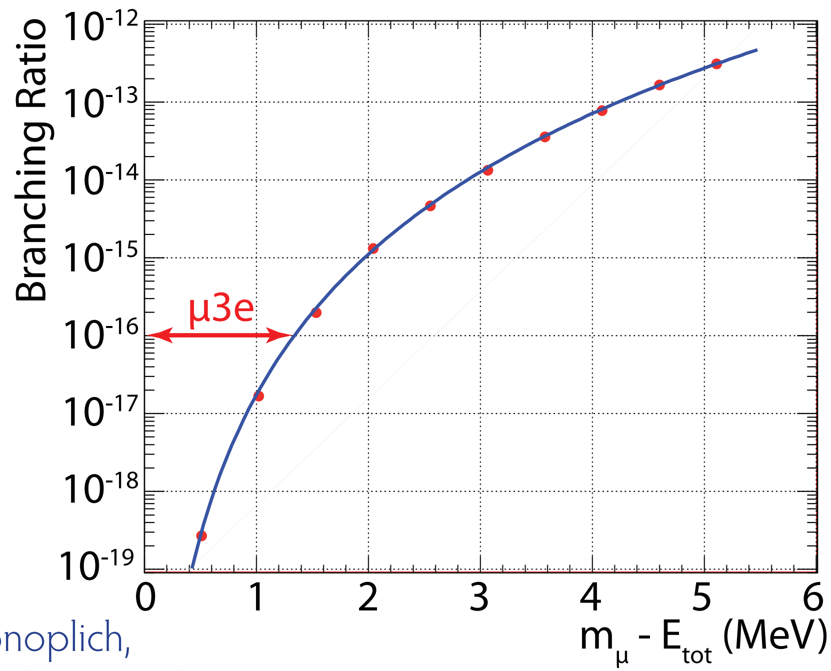
Internal conversion background



- Allowed radiative decay with internal conversion:

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

- Only distinguishing feature: Missing momentum carried by neutrinos

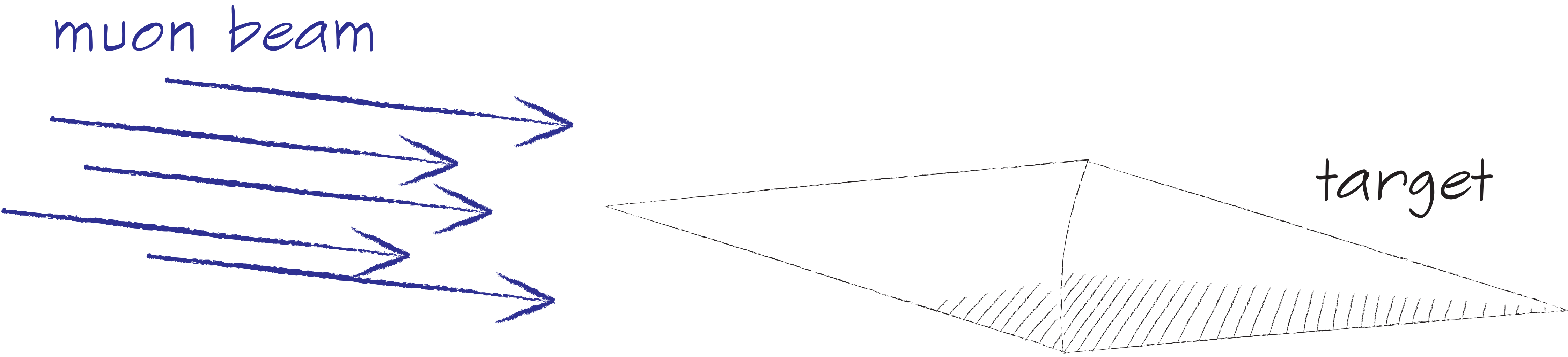


- Need excellent momentum resolution

(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

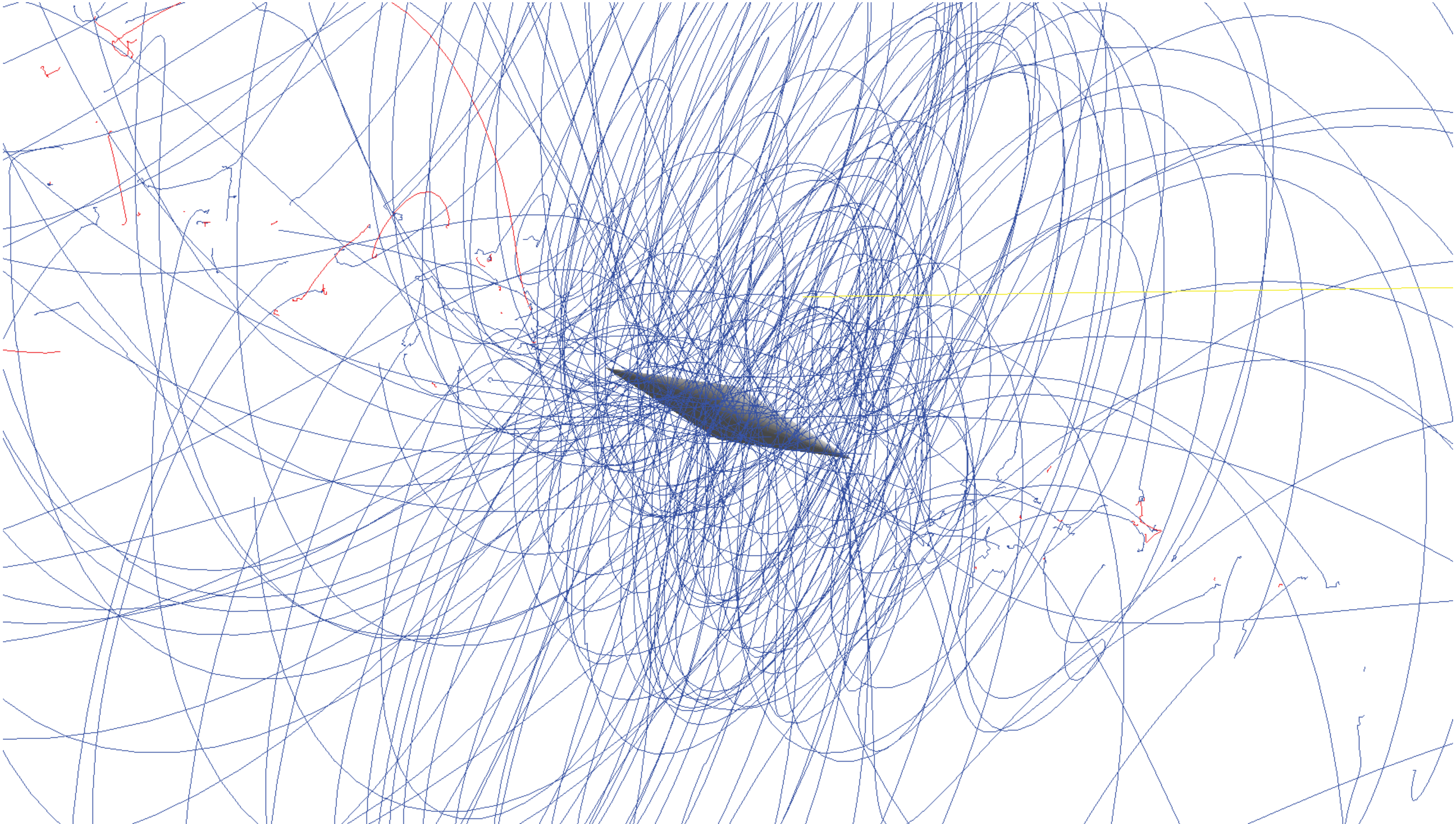
Building the Mu3e Experiment

2 Billion Muons/s



2 Billion Muon Decays/s

50 ns, 1 Tesla field

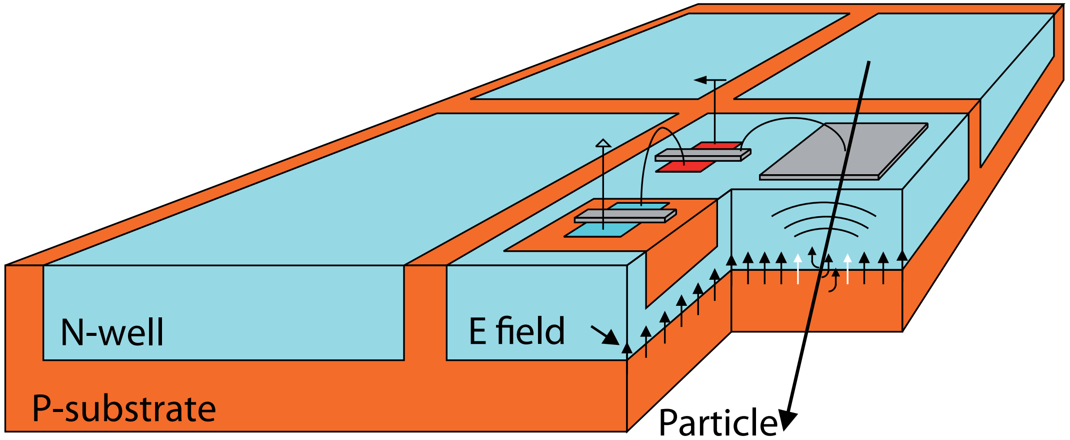


Detector Technology

- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)
- Hybrid pixels (as in LHC) do not work (material budget)

Fast and thin sensors: HV-MAPS



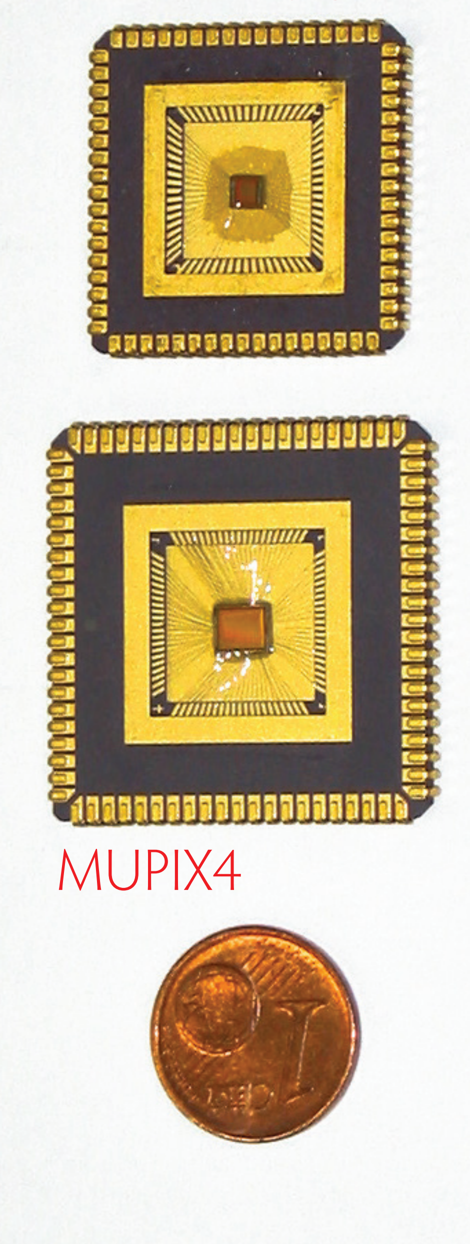
High voltage monolithic active pixel sensors

- 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
- Logic on chip: Output are zero-suppressed hit addresses and timestamps

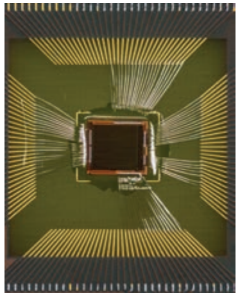
(I.Peric, P. Fischer et al., NIM A 582 (2007) 876)

The MUPIX chip prototypes

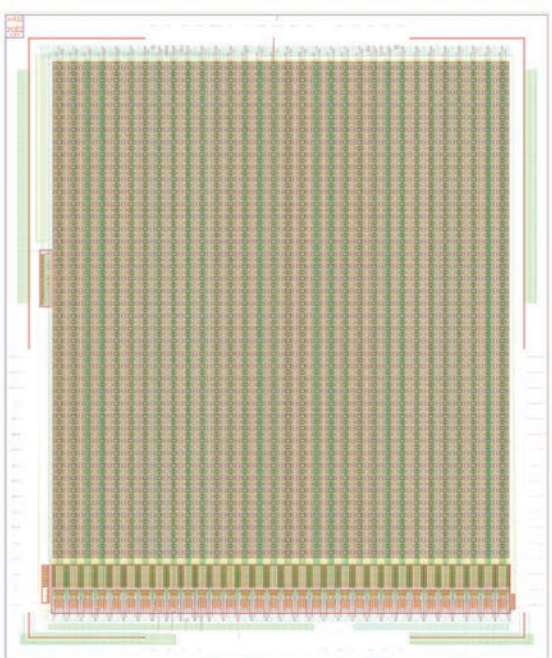
MUPIX2



MUPIX4



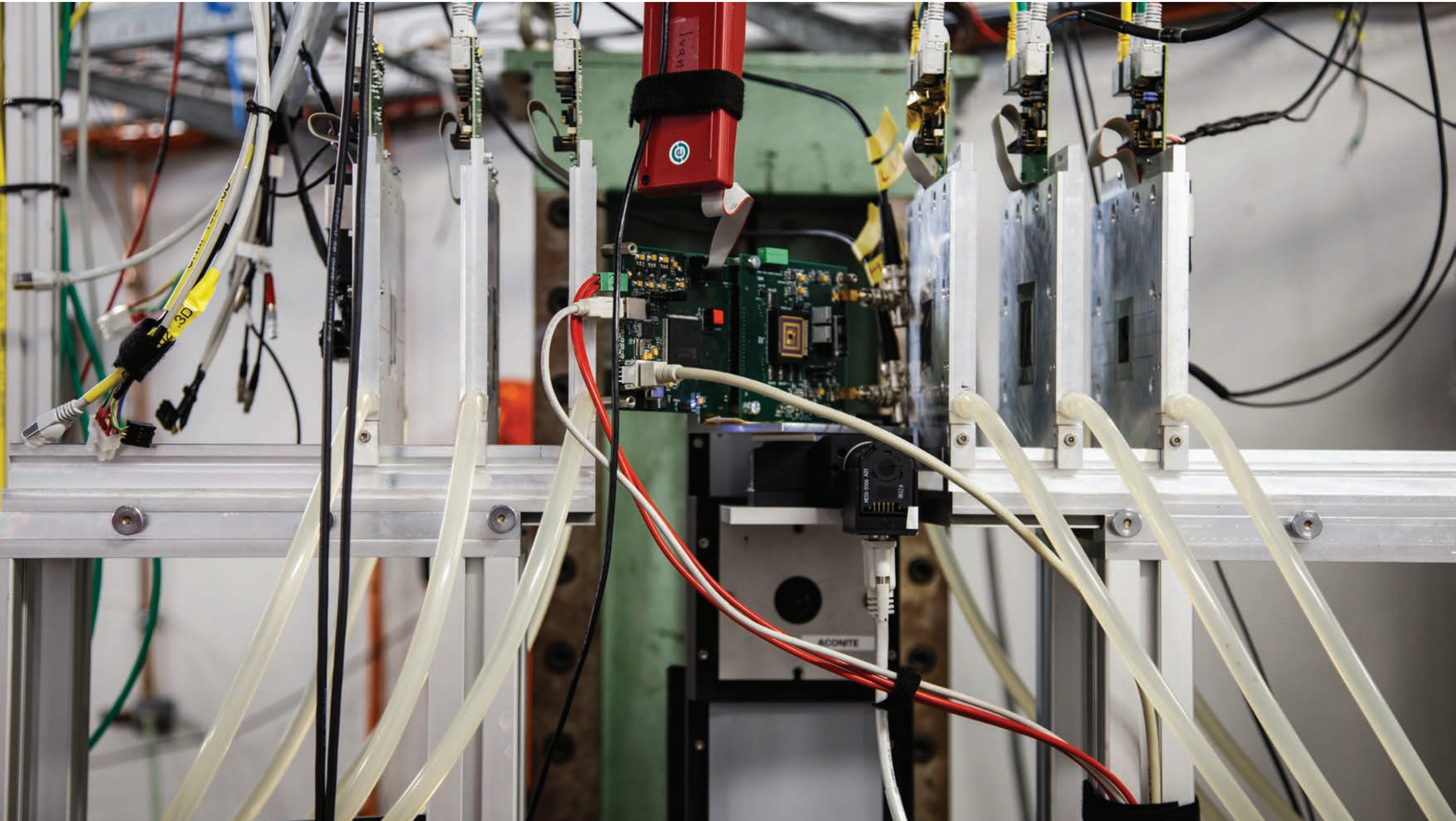
MUPIX6



HV-MAPS chips: AMS 180 nm HV-CMOS

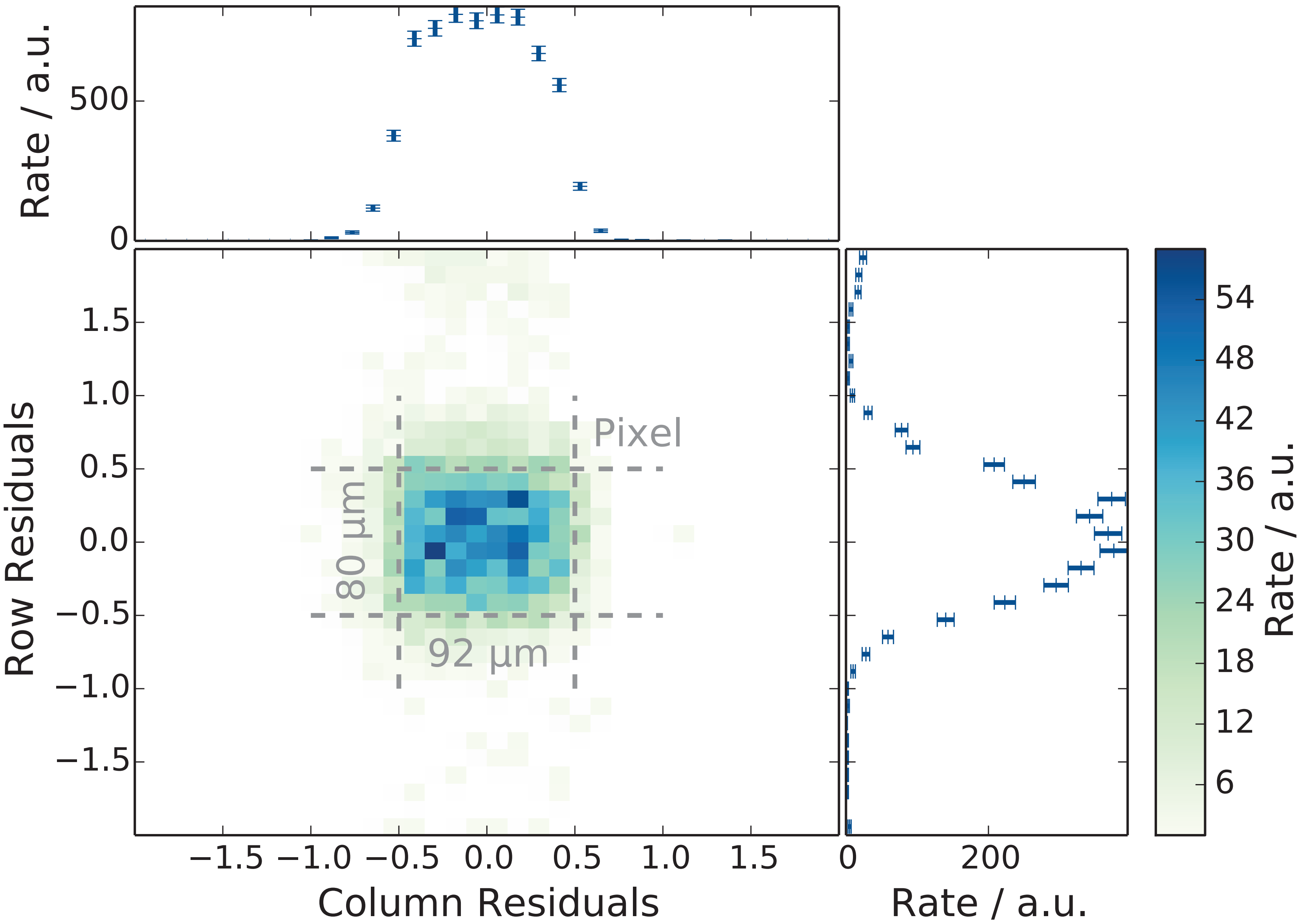
- 5 generations of prototypes
- Current generation:
  MUPIX6
  40 x 32 pixels
  80 x 103 µm pixel size
  9.4 mm^2 active area
- Test beam results with MUPIX4
- MUPIX7 (August submission) will have all features of final sensor
- Left to do: Scale to 1 x 2 and 2 x 2 cm^2

Test beam at DESY



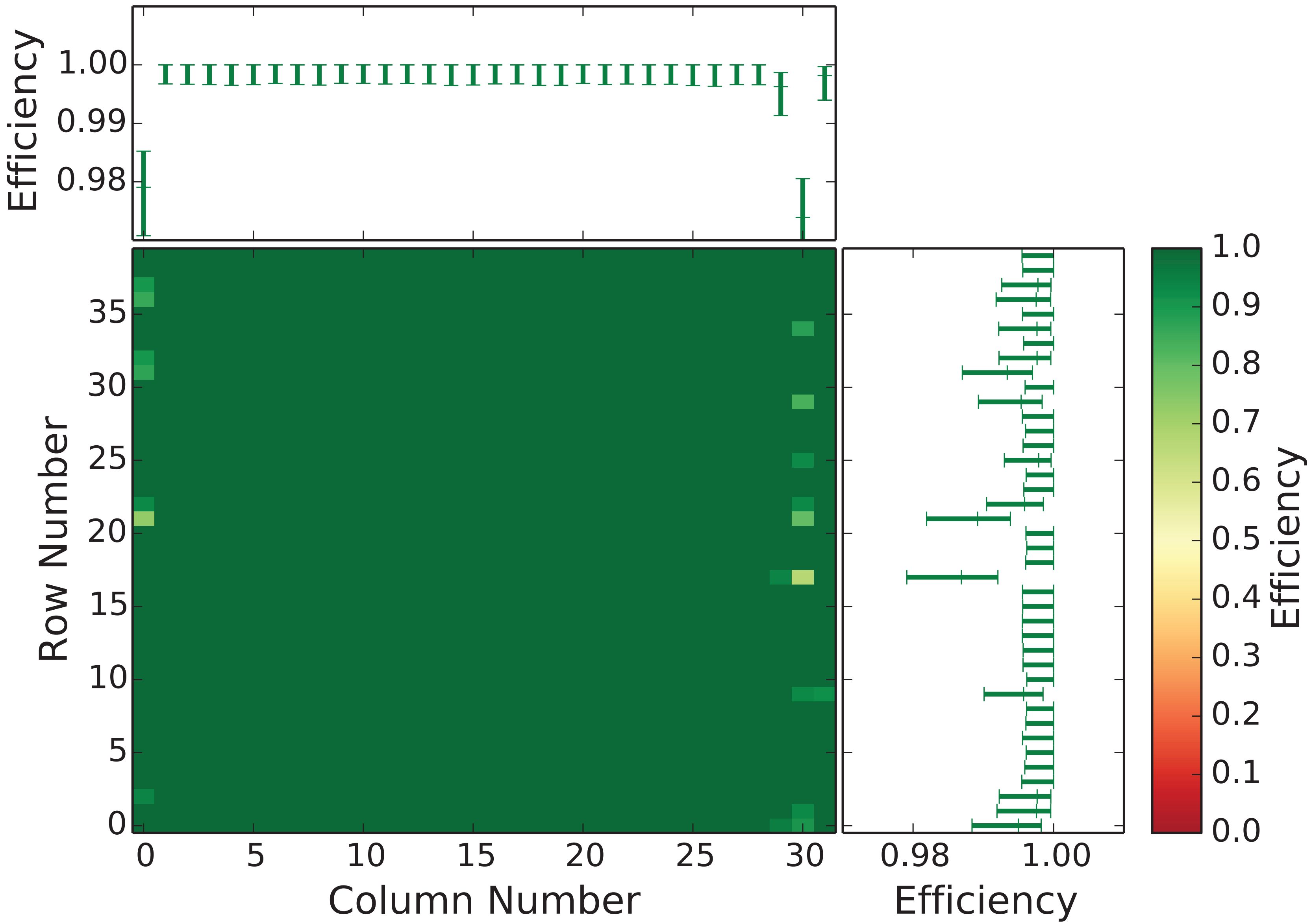
Position Resolution

Position resolution given by pixel size

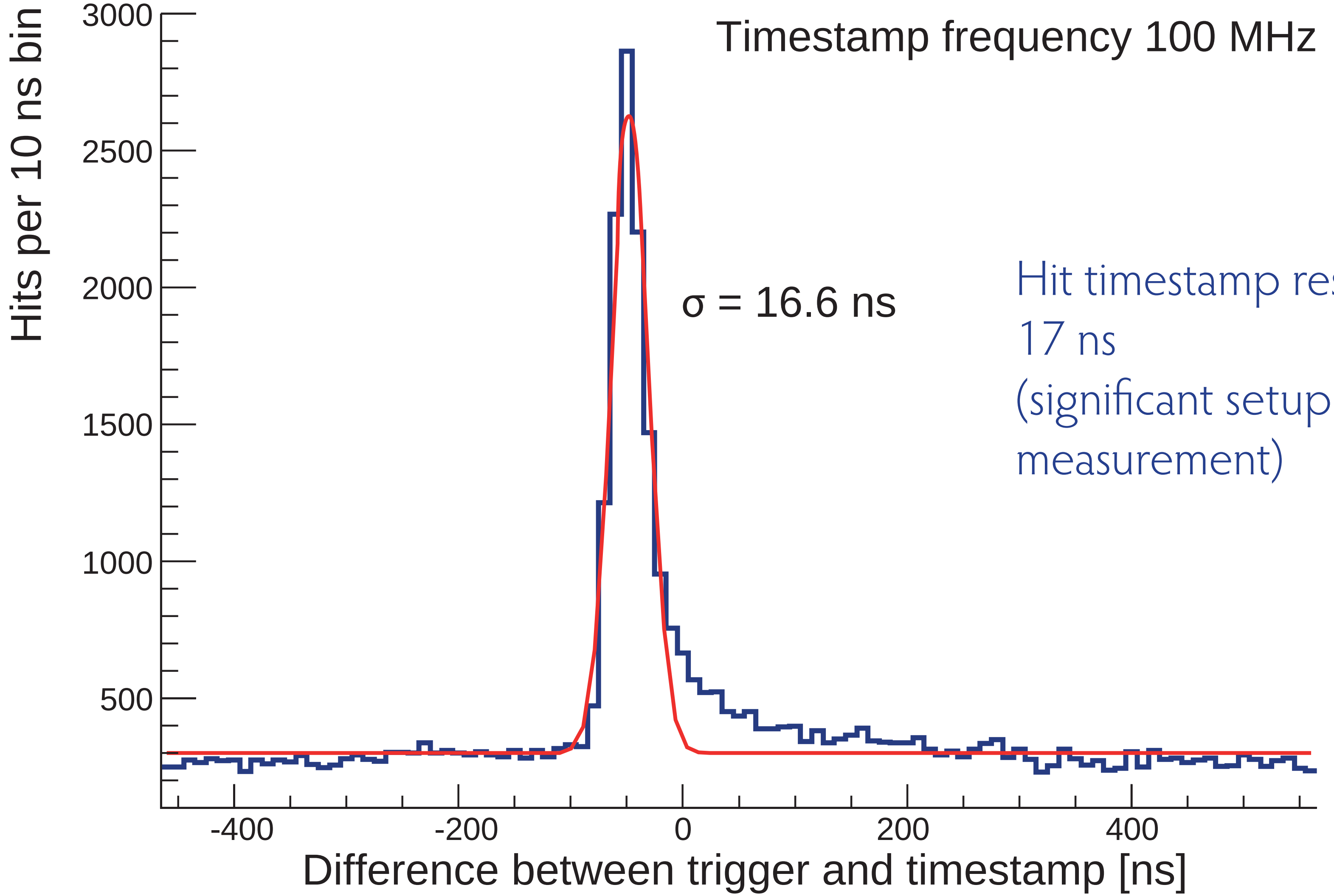


Efficiency

Hit efficiency above 99% without tuning

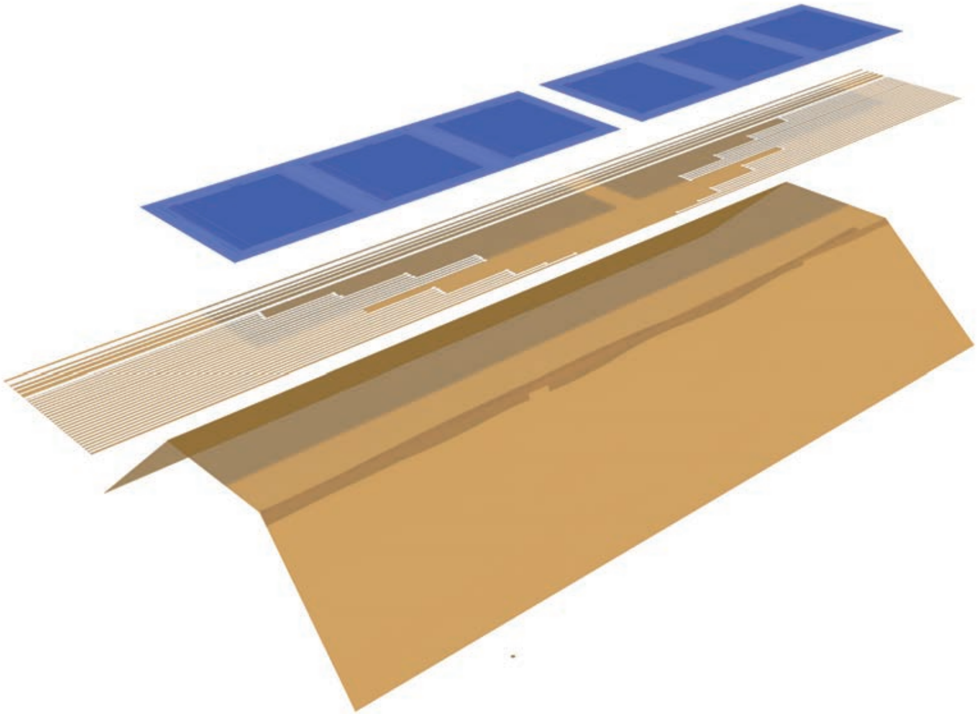


Time resolution



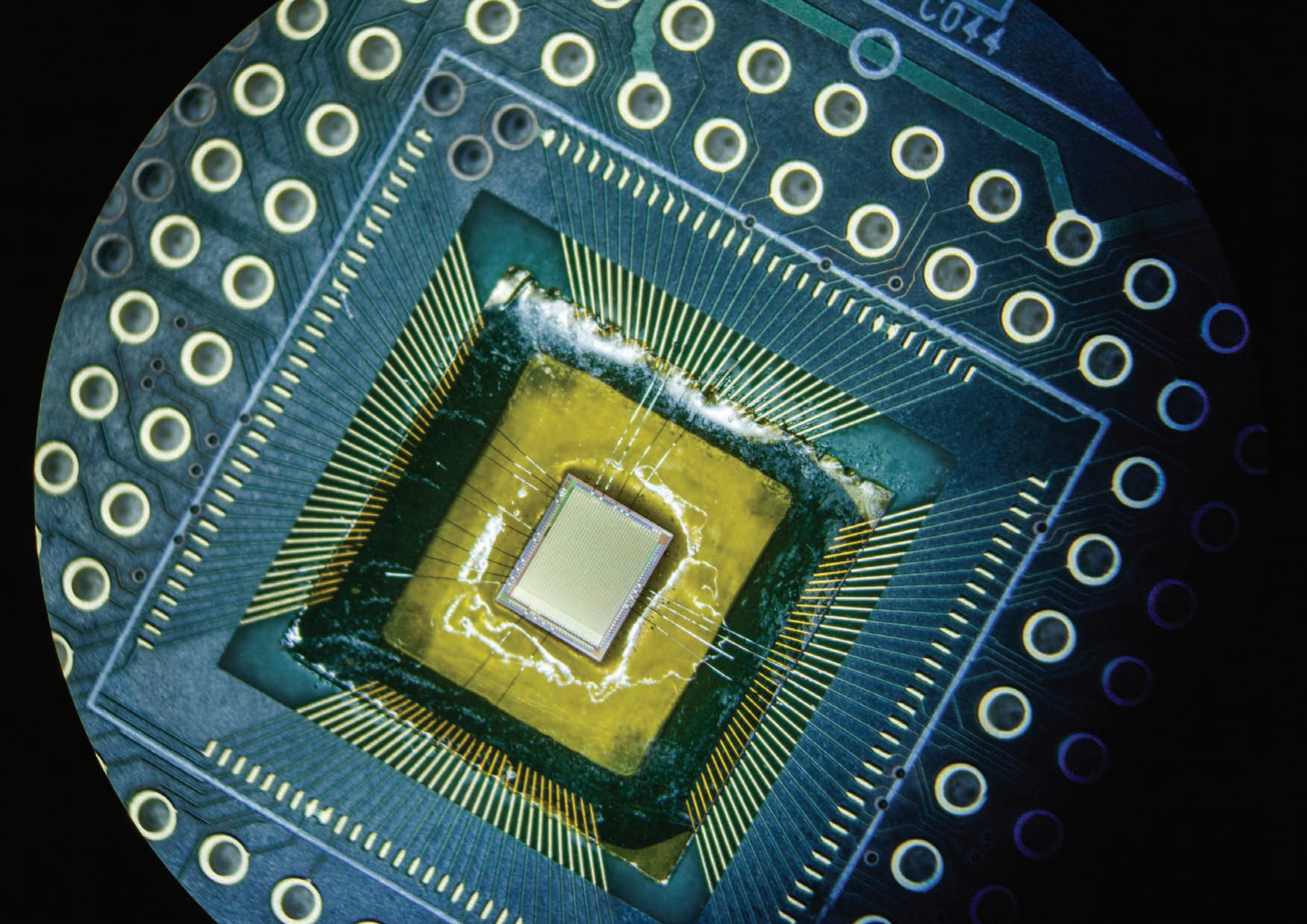
Hit timestamp resolution better than 17 ns
(significant setup contribution in the measurement)

Mechanics



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

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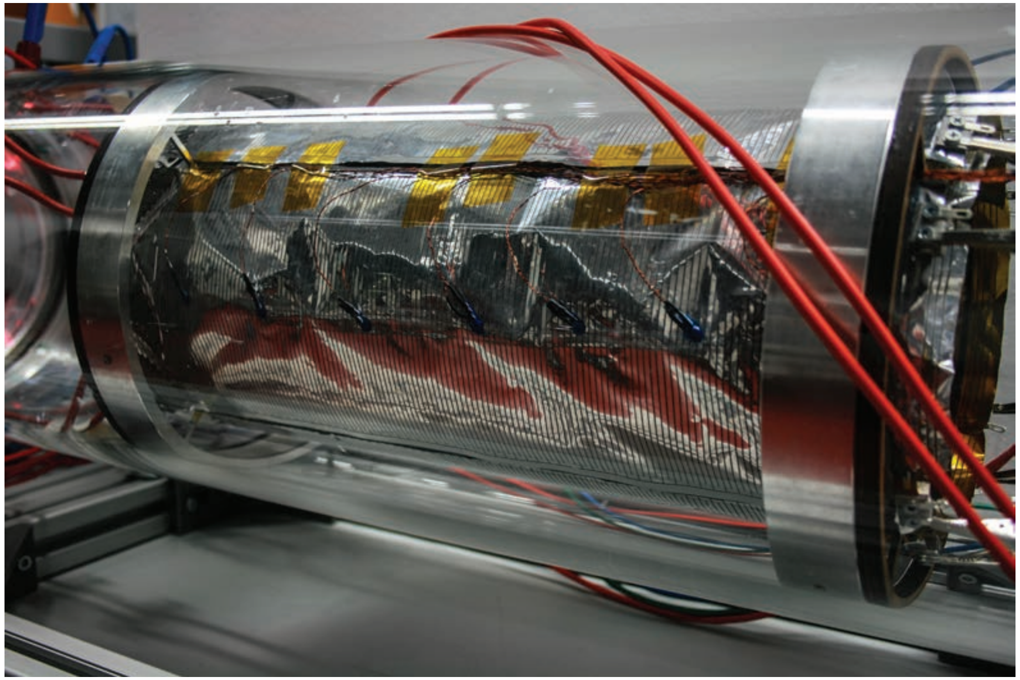
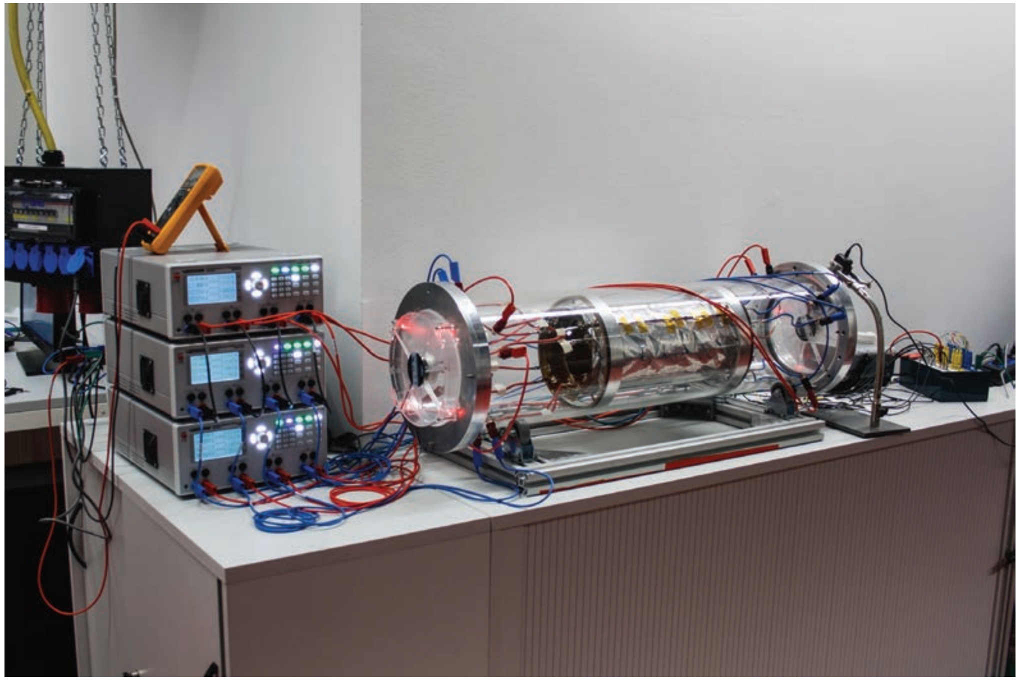
Cooling

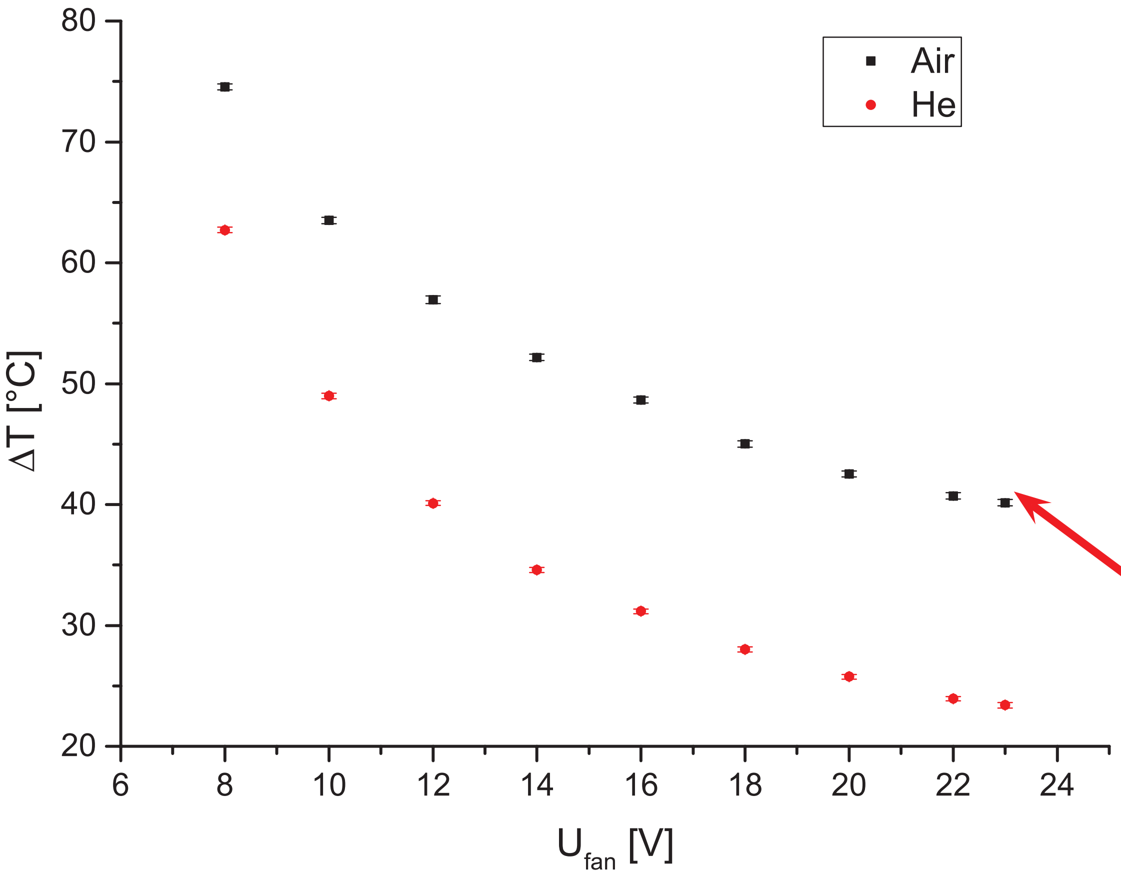
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 150 mW/cm^2 - total 2 kW
- Simulations: Need ~ several m/s flow

- Full scale heatable prototype built
- 36 cm active length
- No visible vibrations





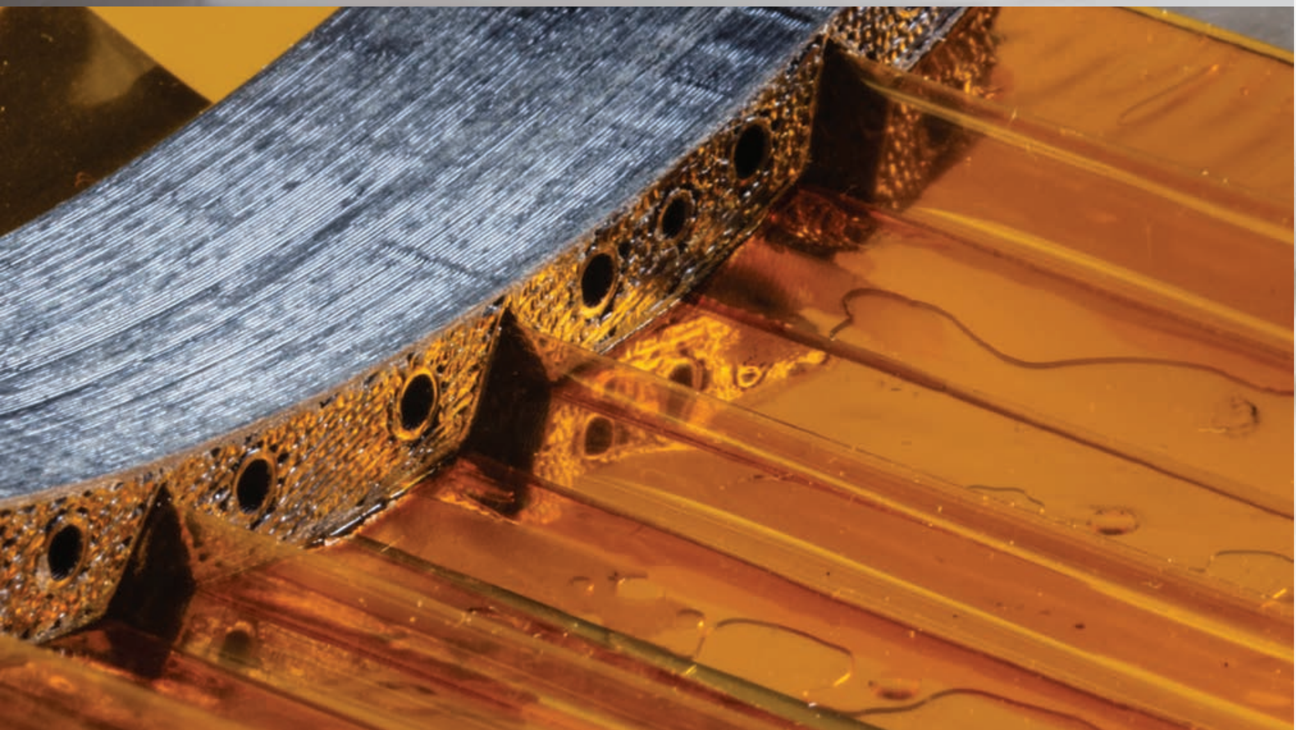
Cooling tests



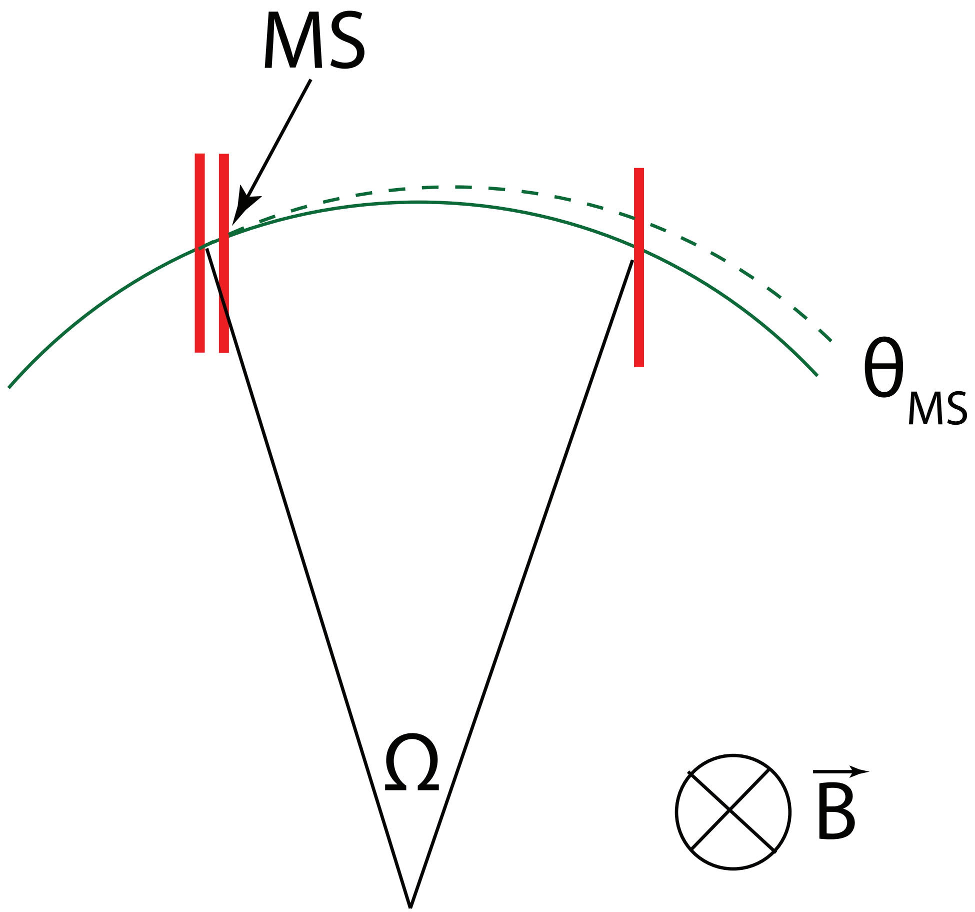
3.5 m/s in air

- Can keep gradients under 30°C over 36 cm with helium cooling
- Helium flow speed still needs to be calibrated
- Fulfilling Mu3e specs
- Can add local cooling


Ring 4
vorne



Momentum measurement

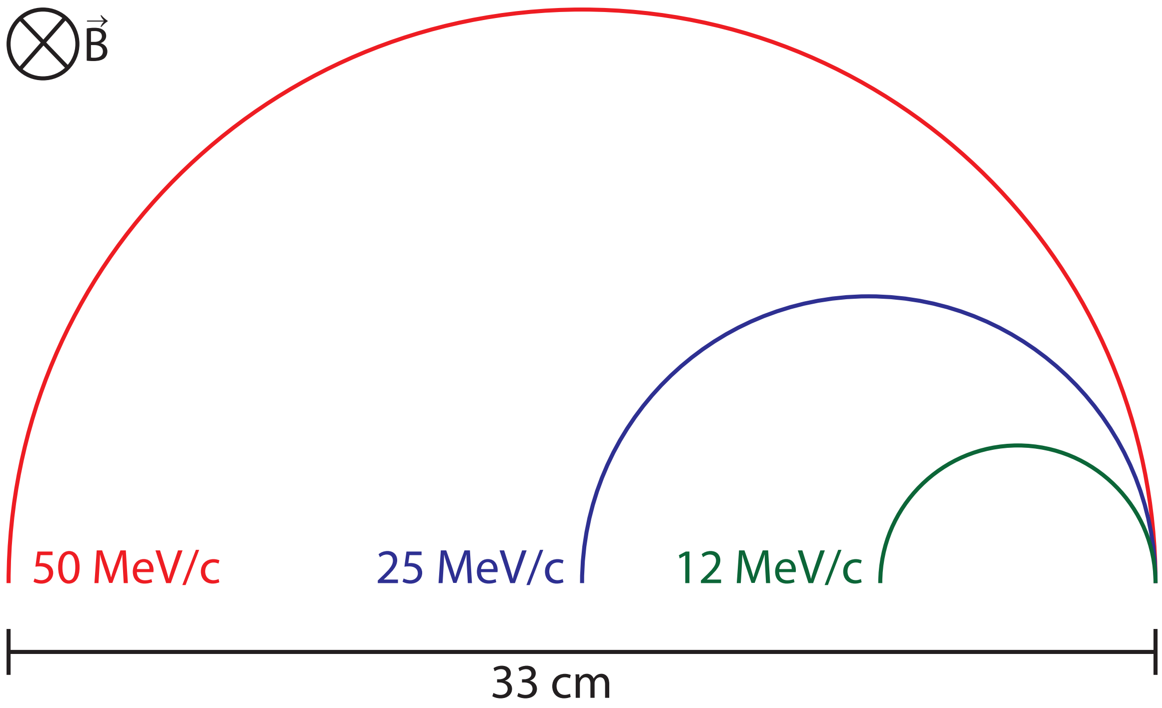


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

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

Precision vs. Acceptance



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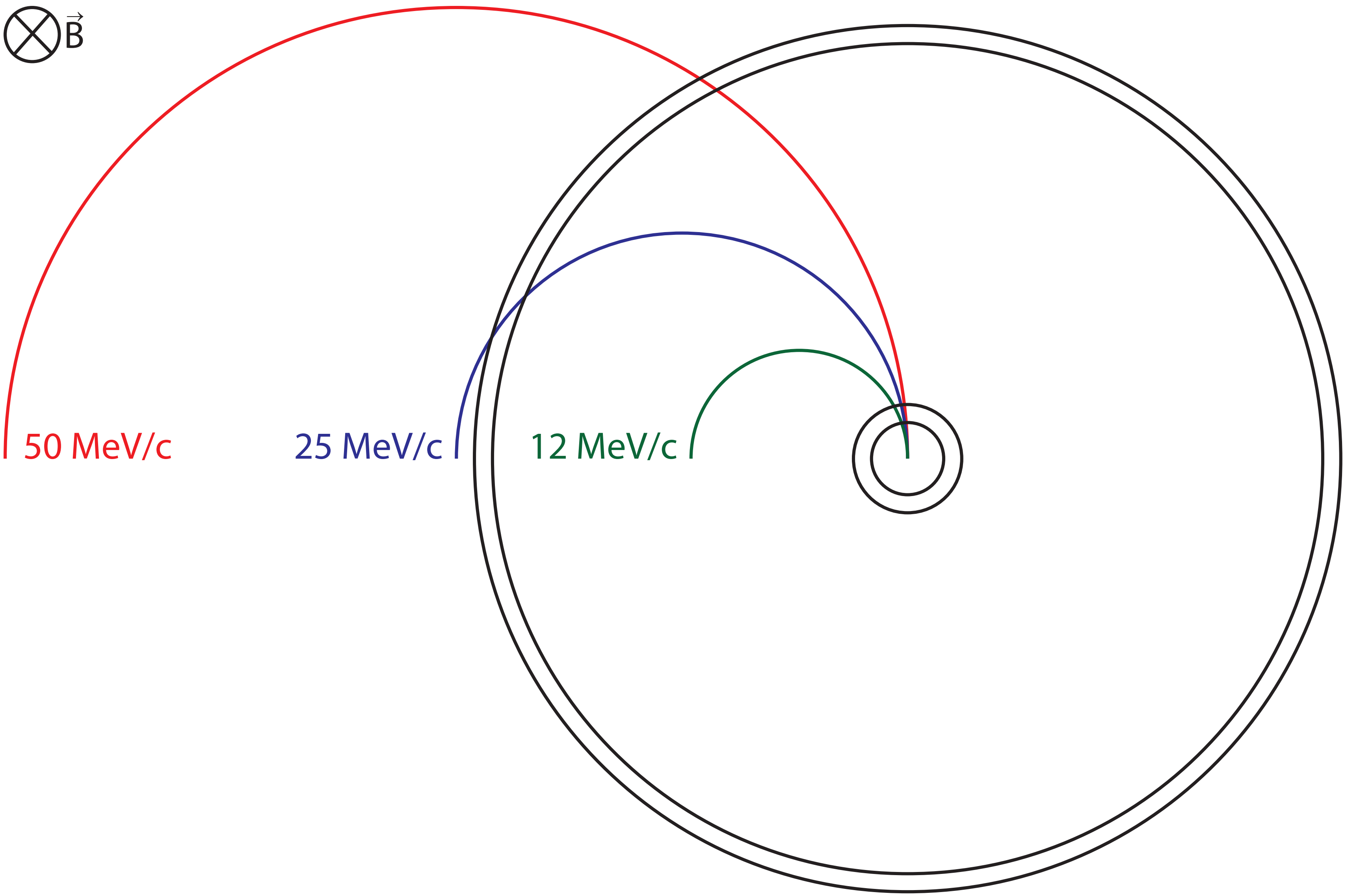

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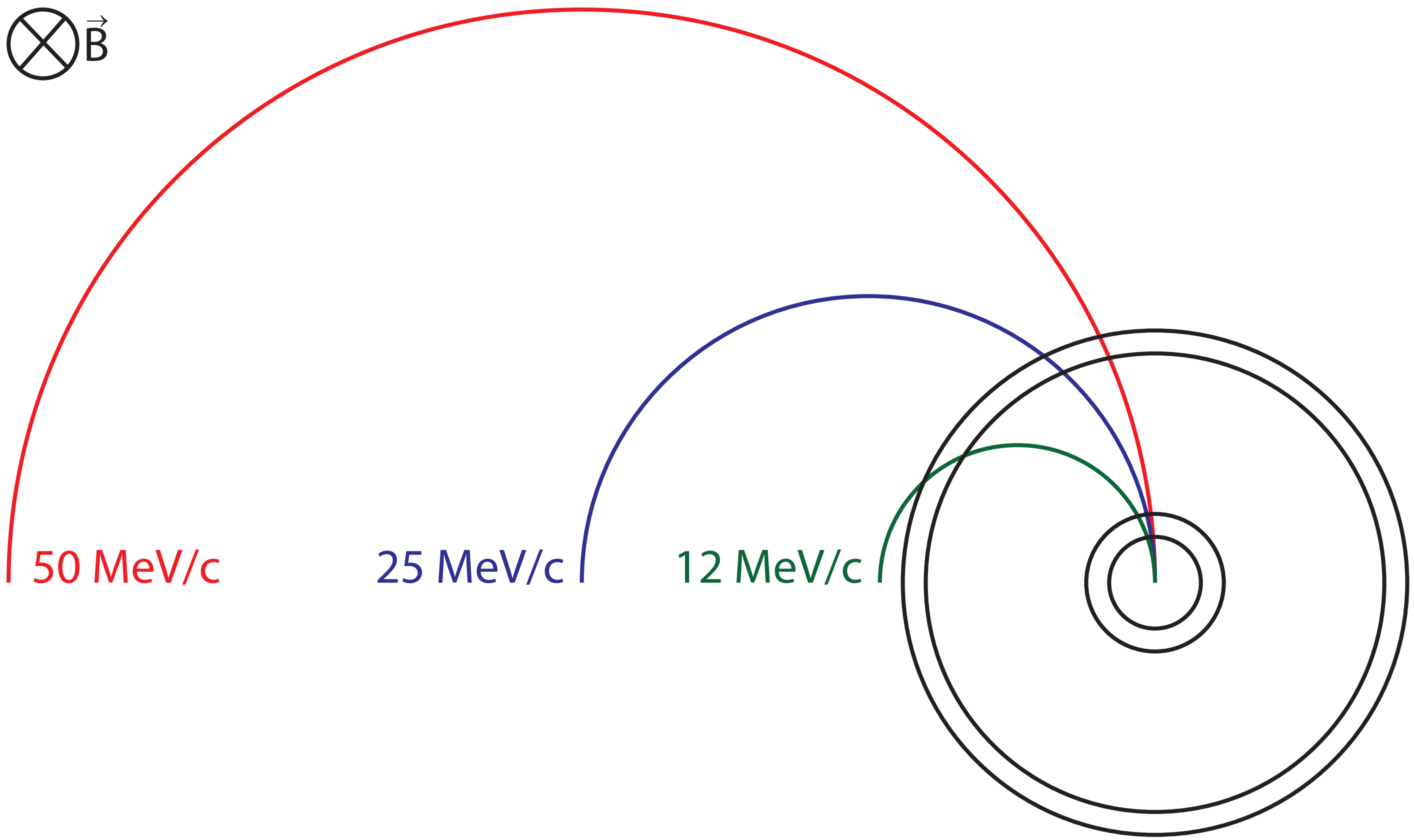

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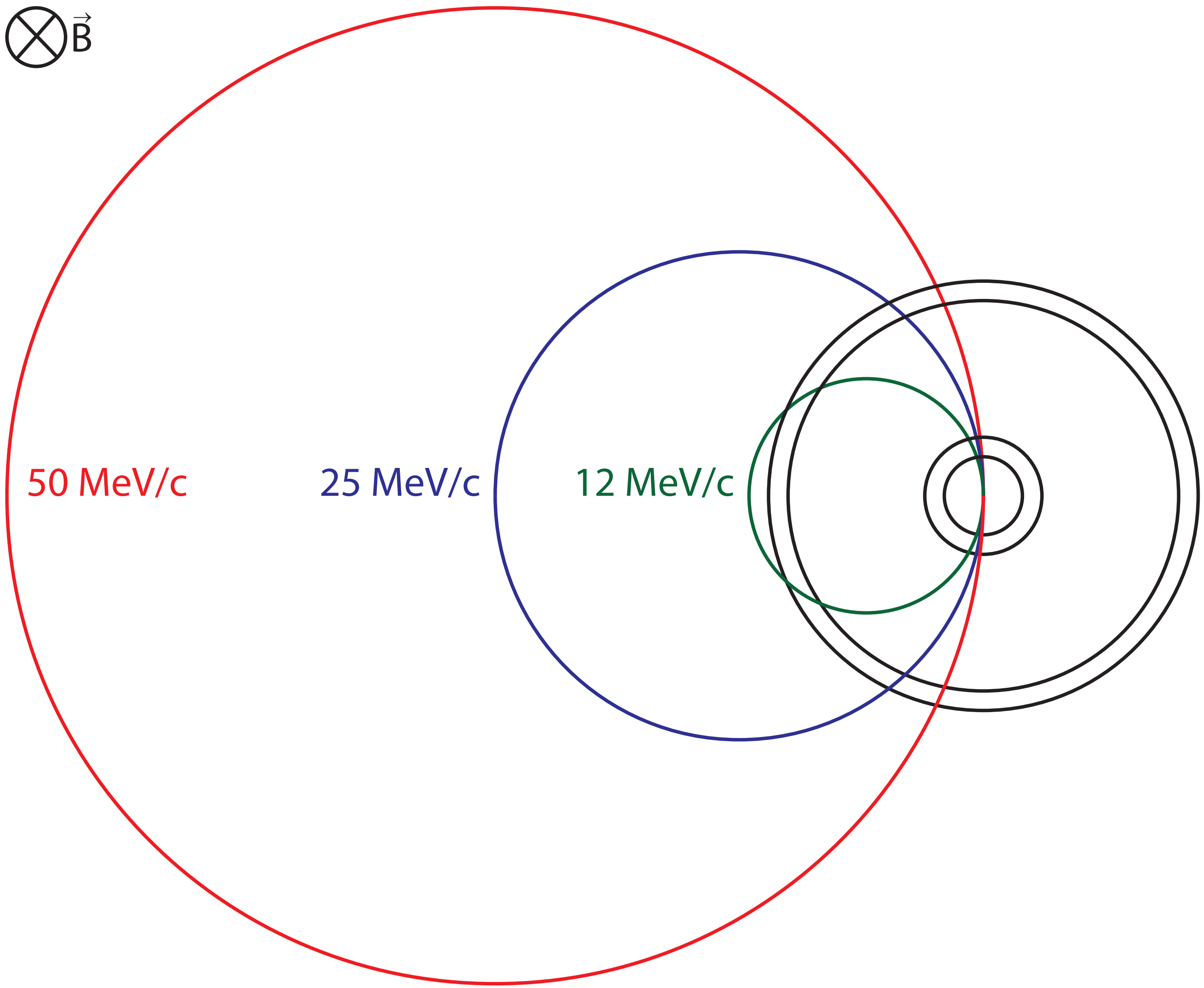

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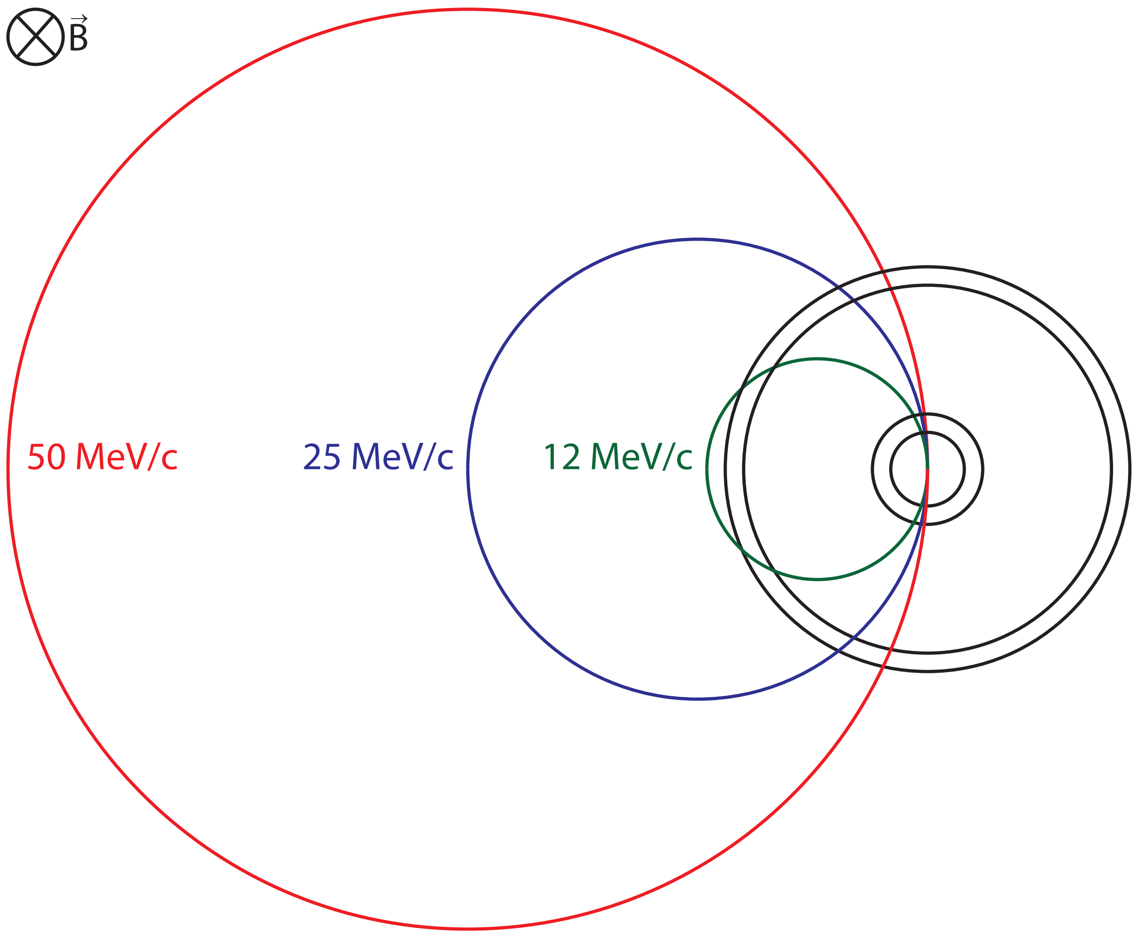
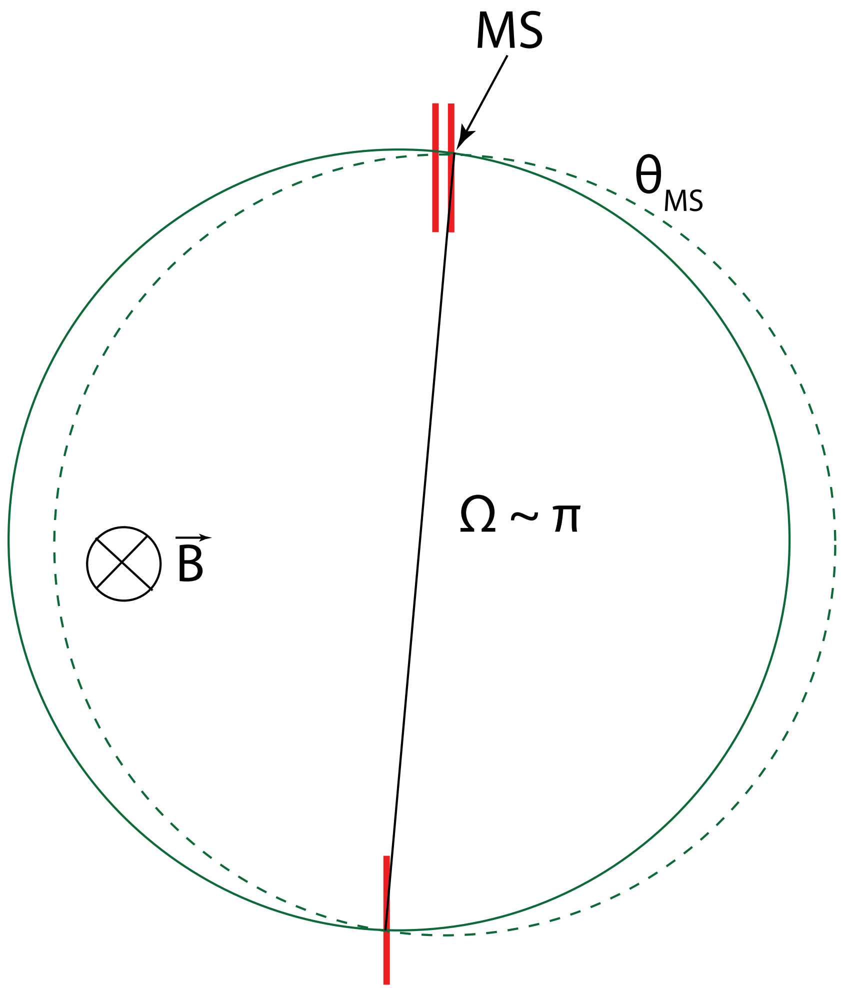
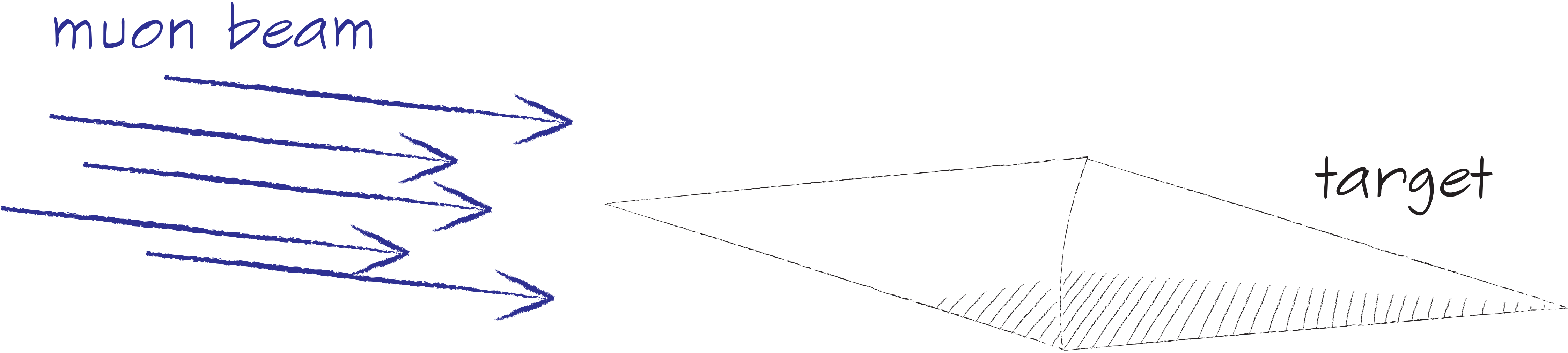




Detector Design



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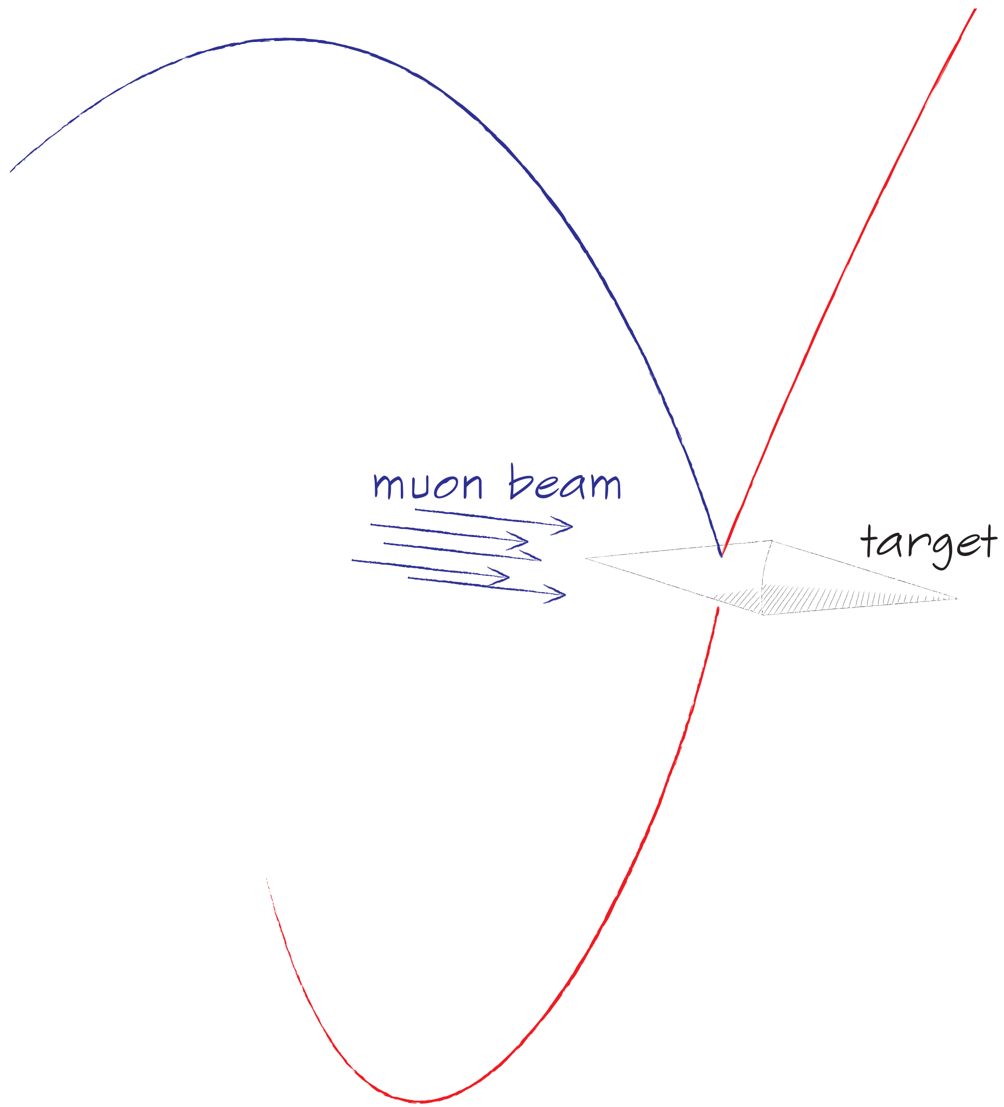

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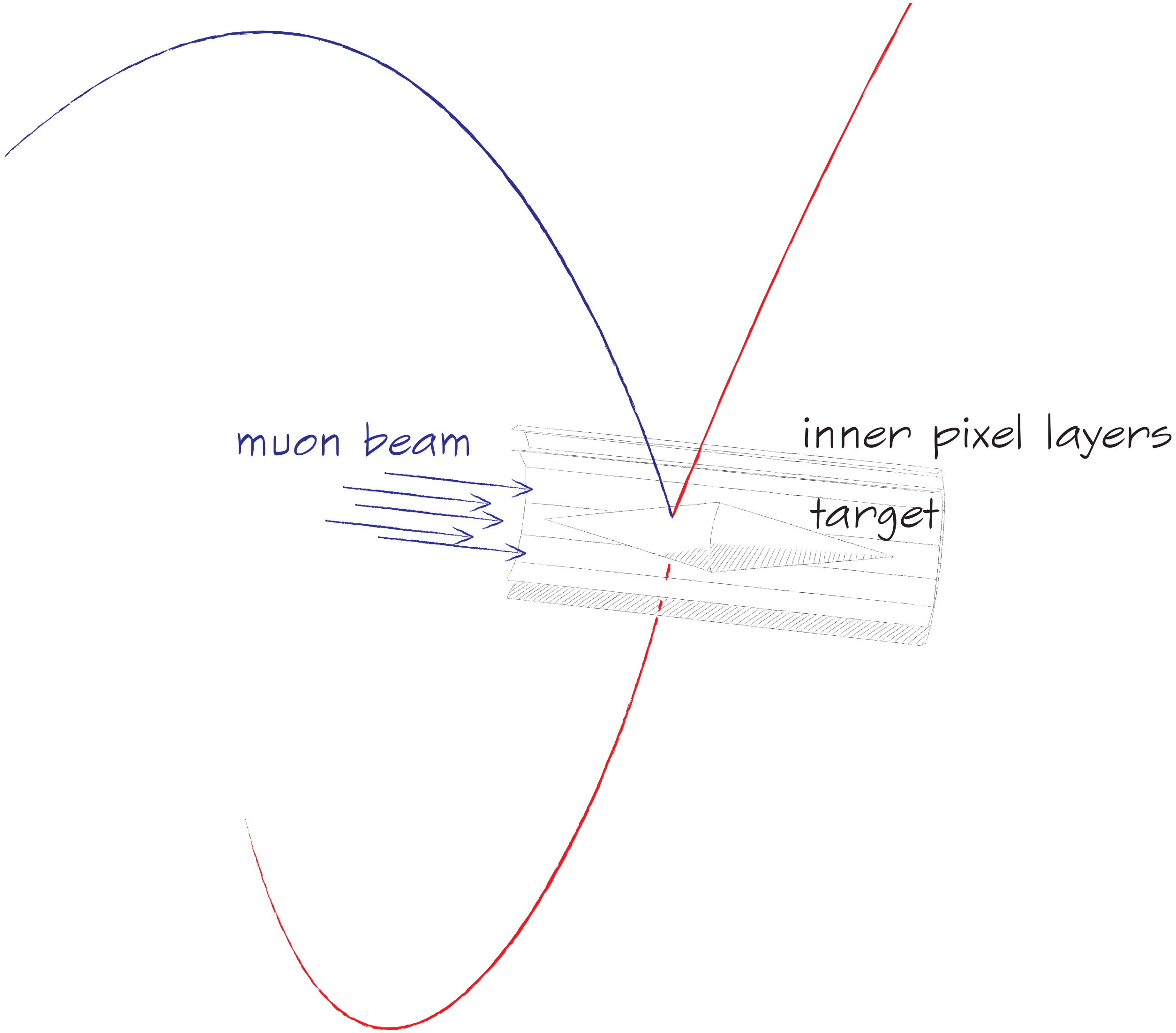

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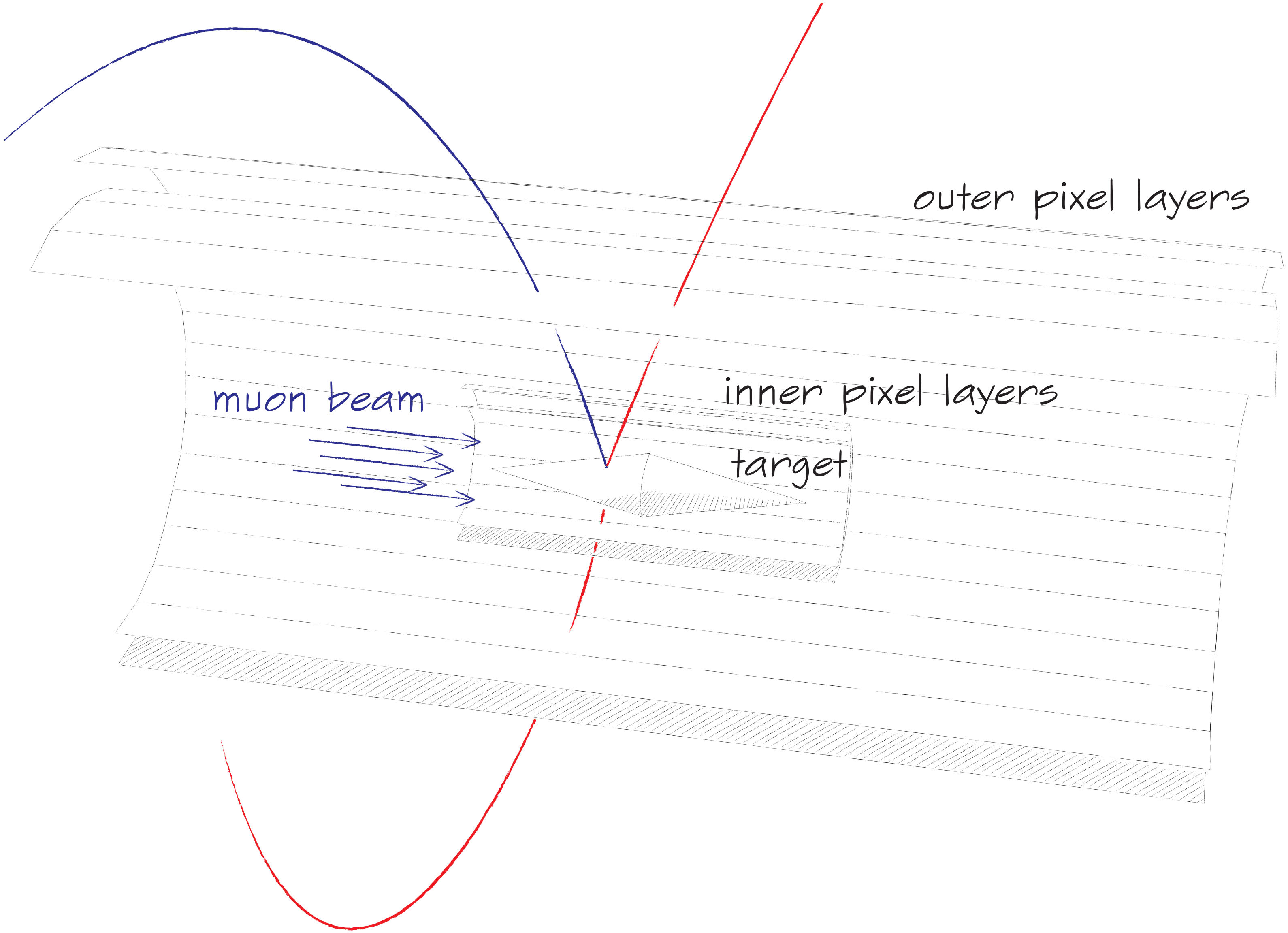

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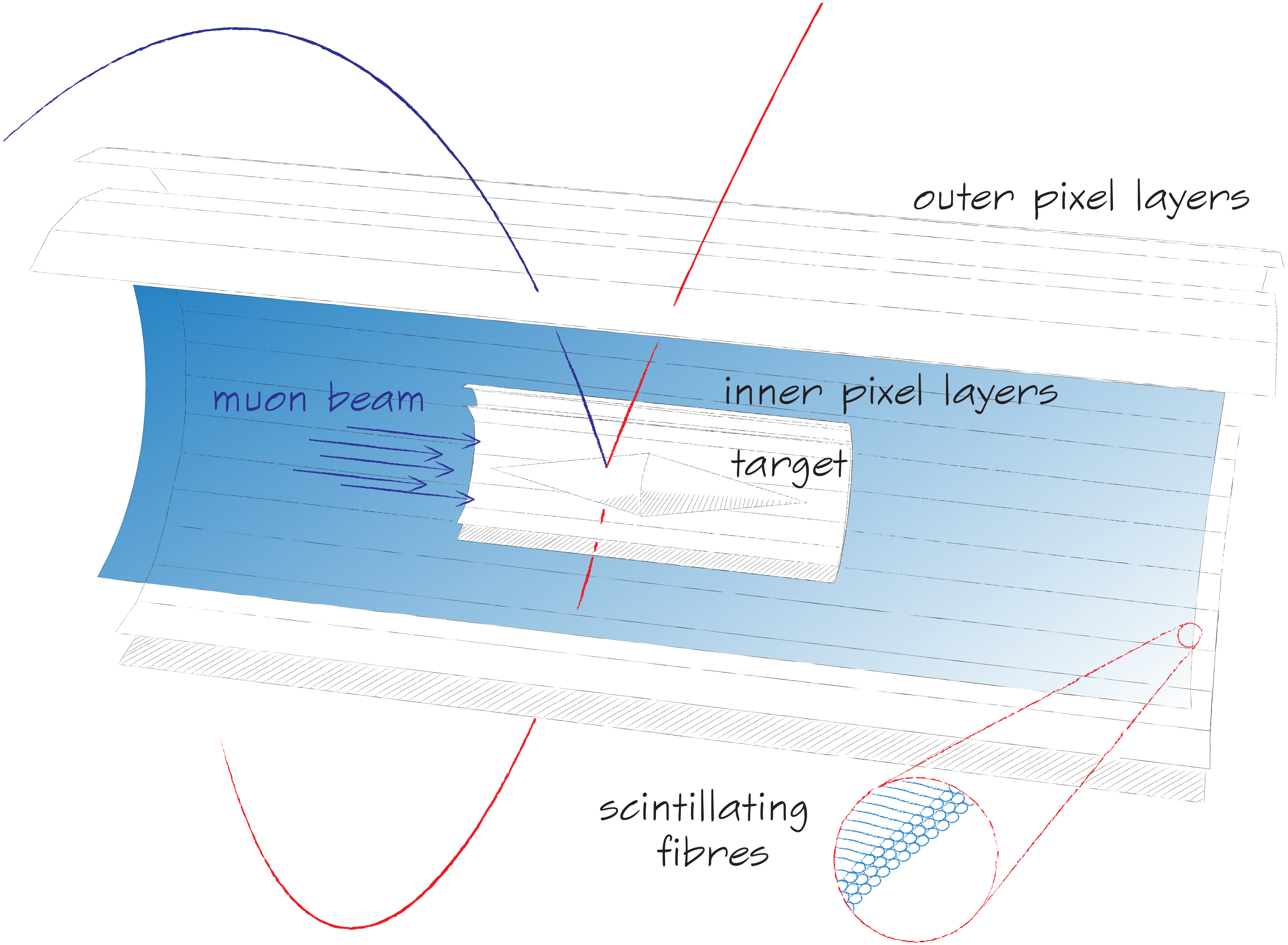

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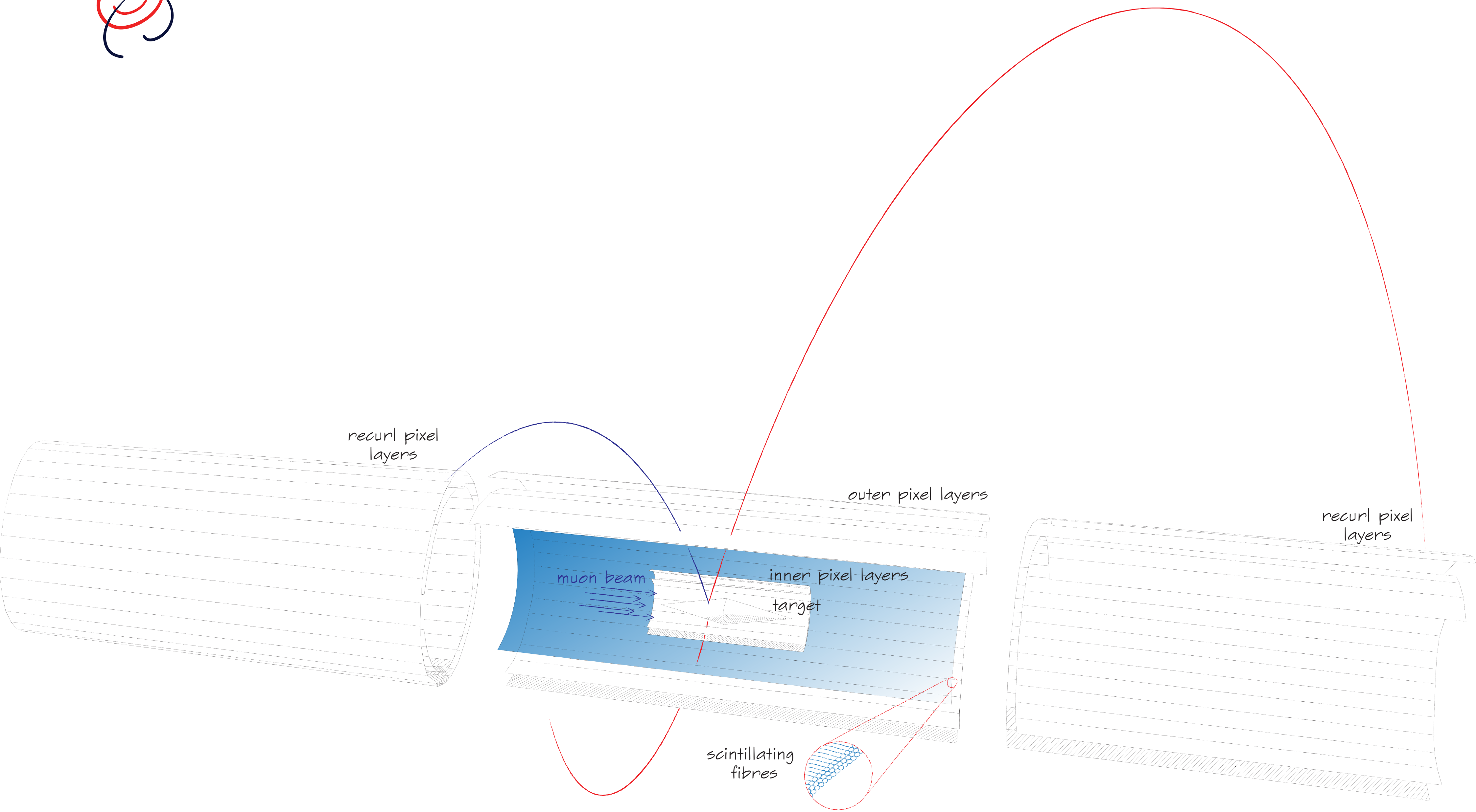

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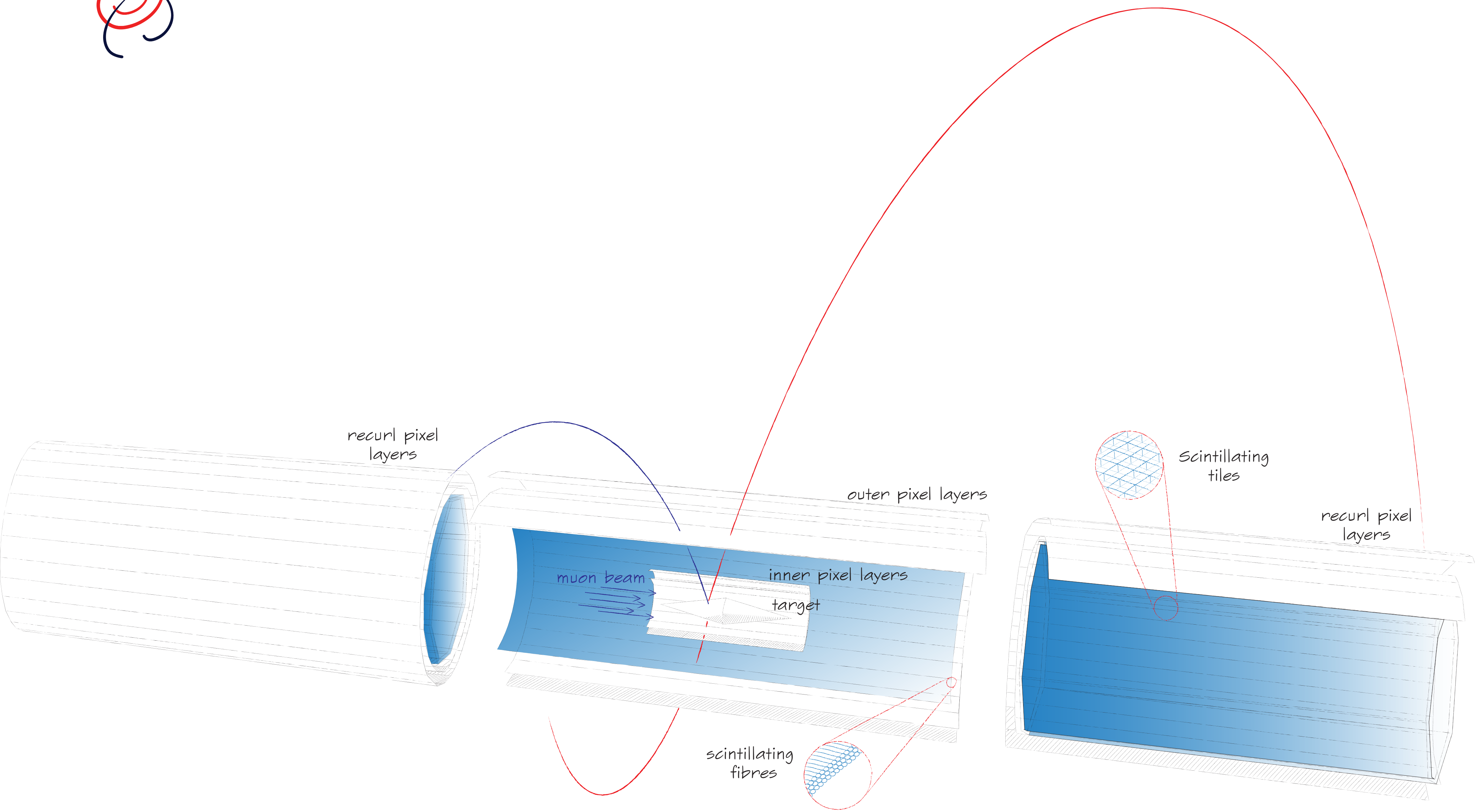
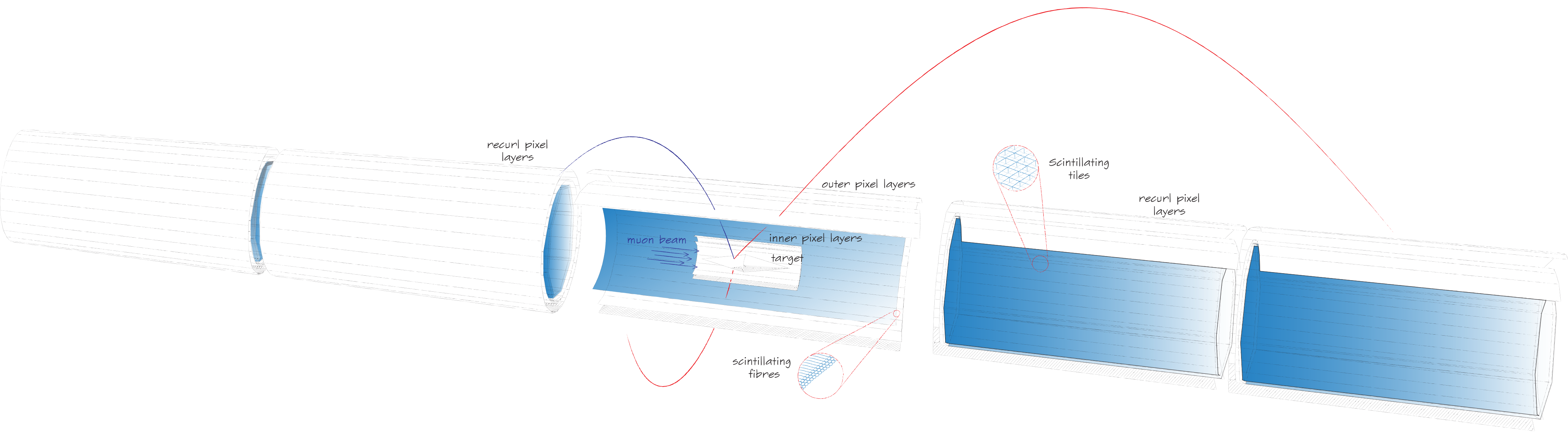
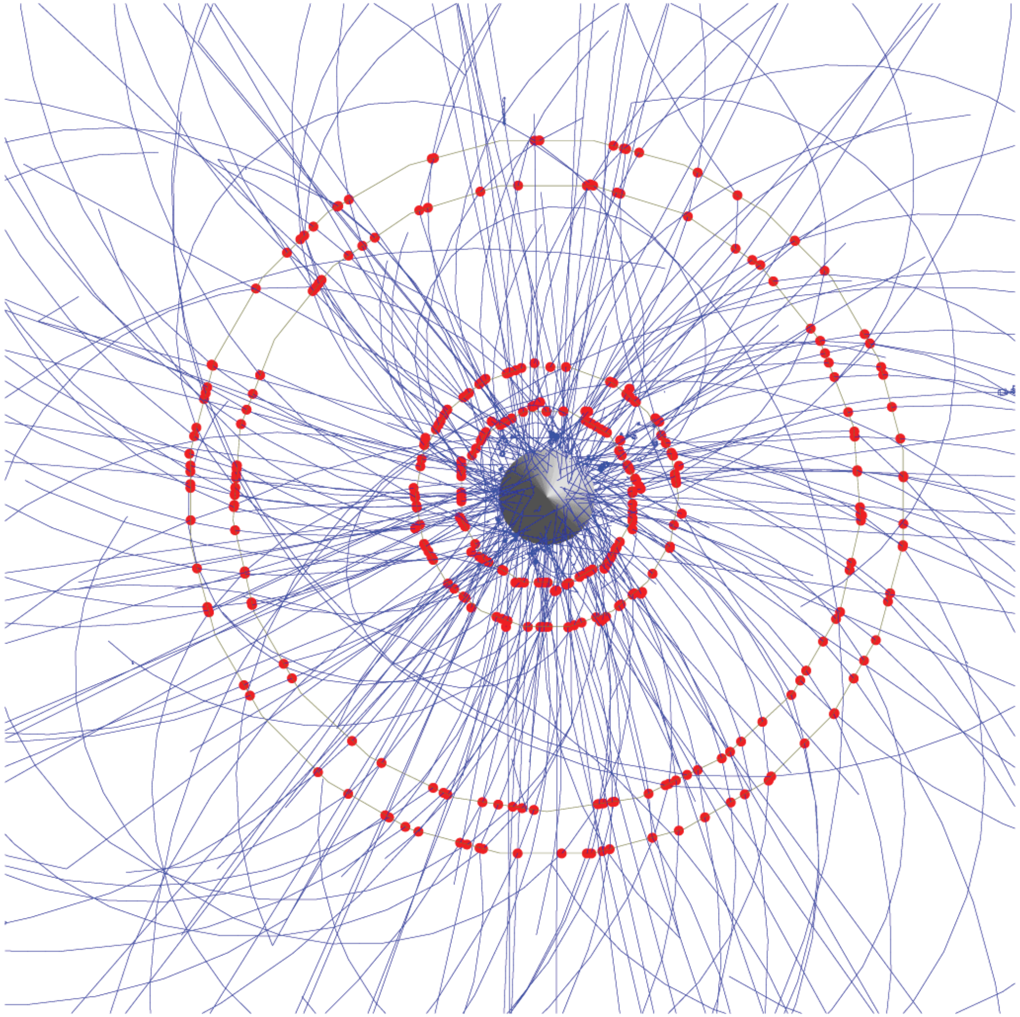


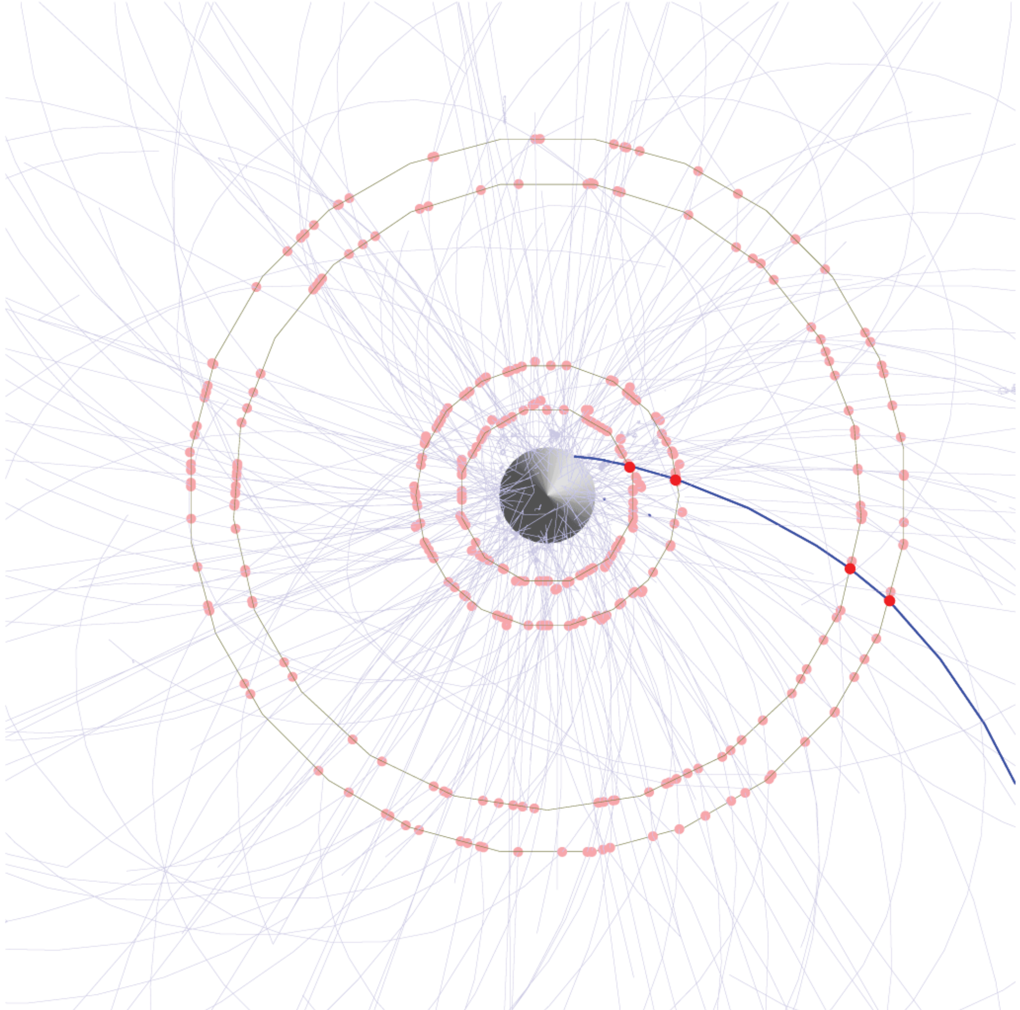
Detector Design



Timing measurements

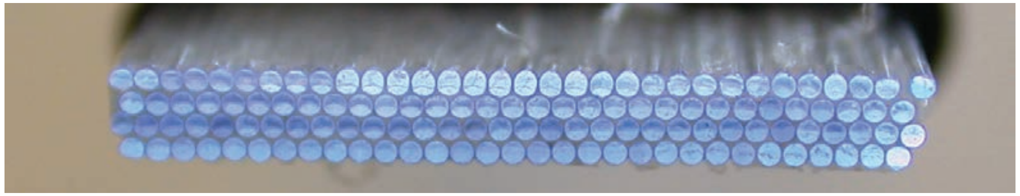


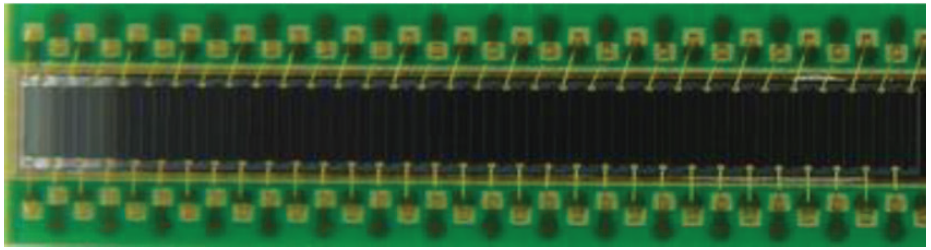
Pixels: O(50 ns)



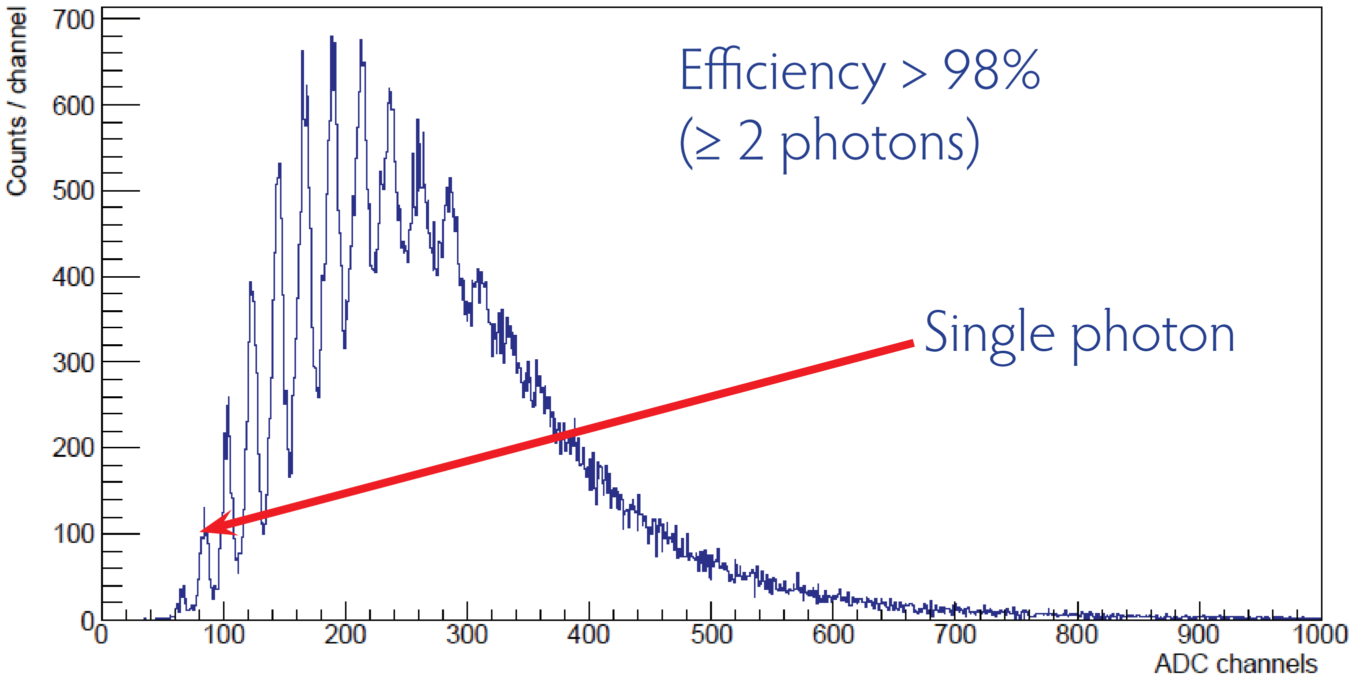
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

Timing Detector: Scintillating Fibres

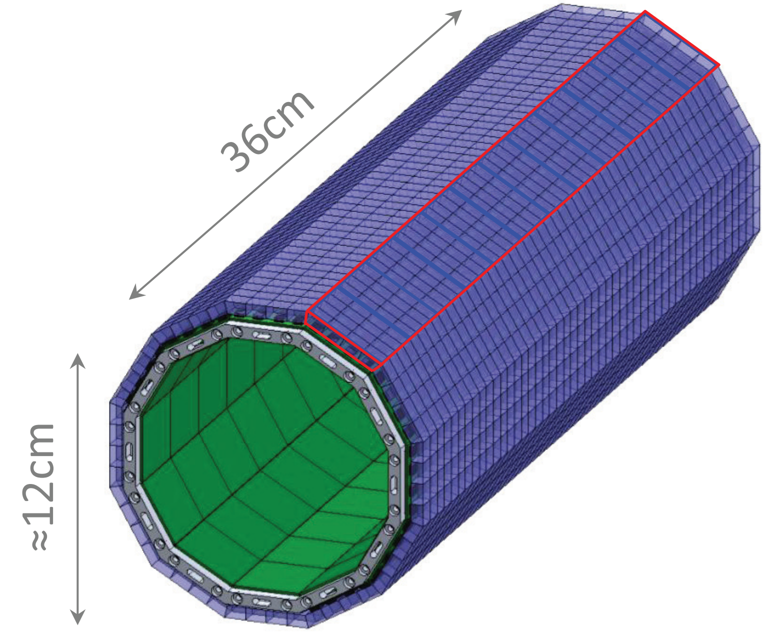


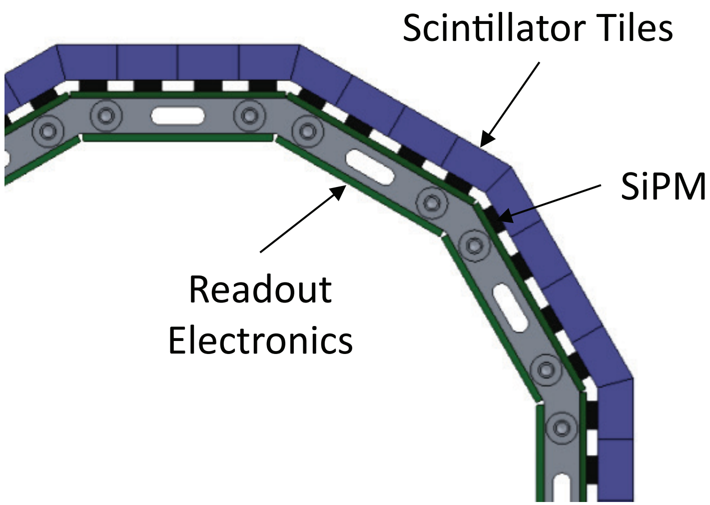


- 3-5 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution $\mathcal{O}$(1 ns) (measured with sodium source)



Timing Detector: Scintillating tiles

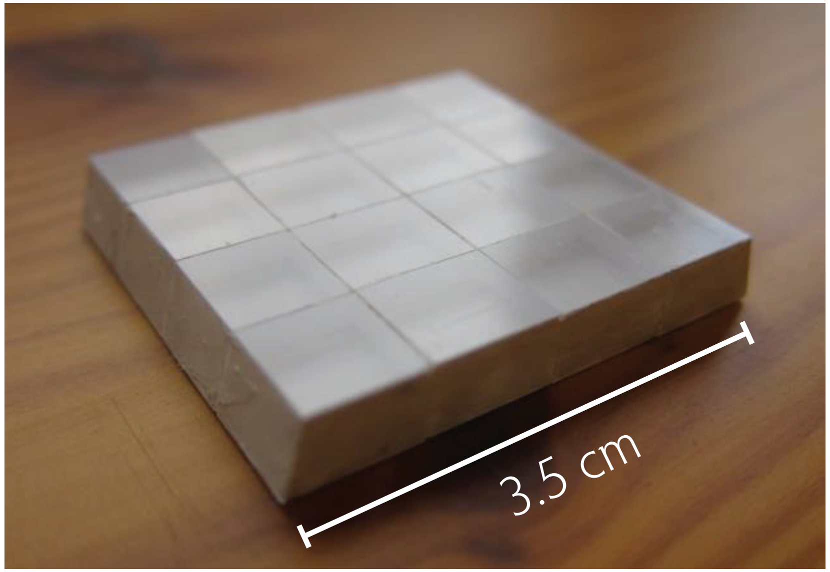




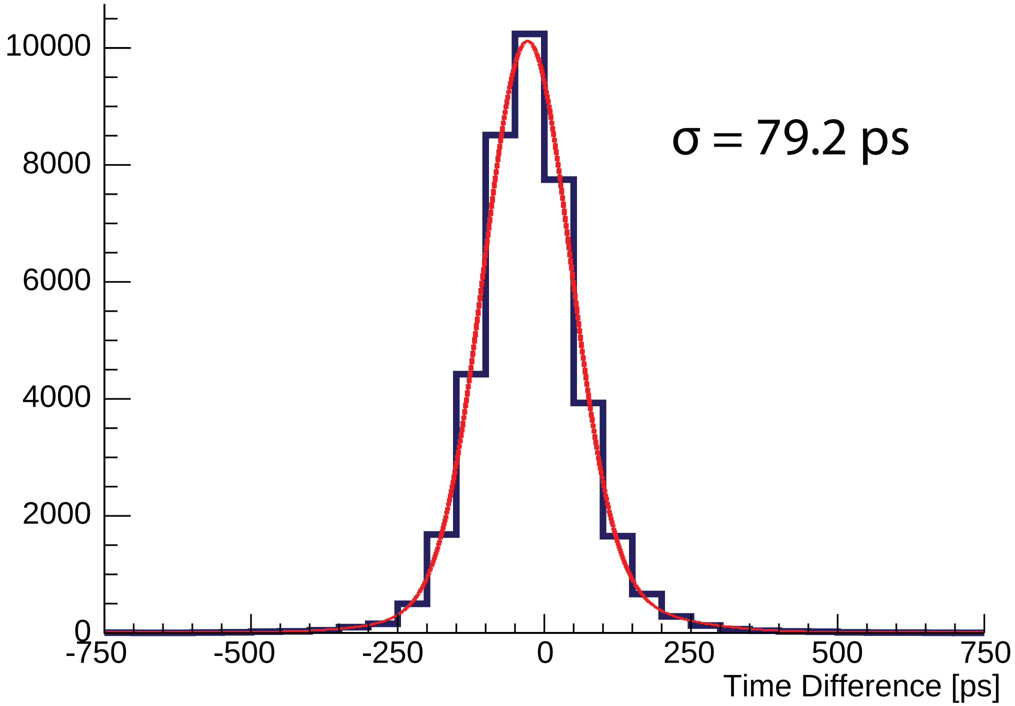
- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)

Timing Detector: Scintillating tiles

Front

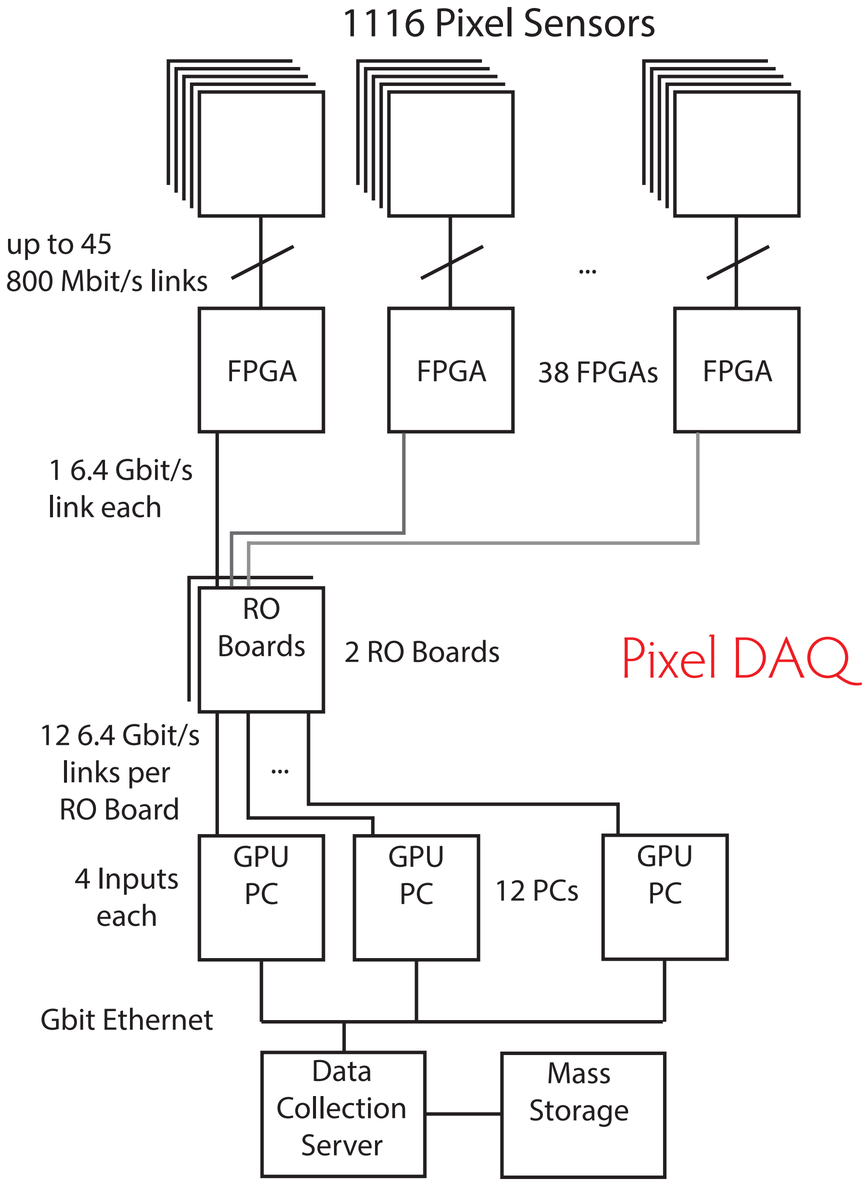


Back



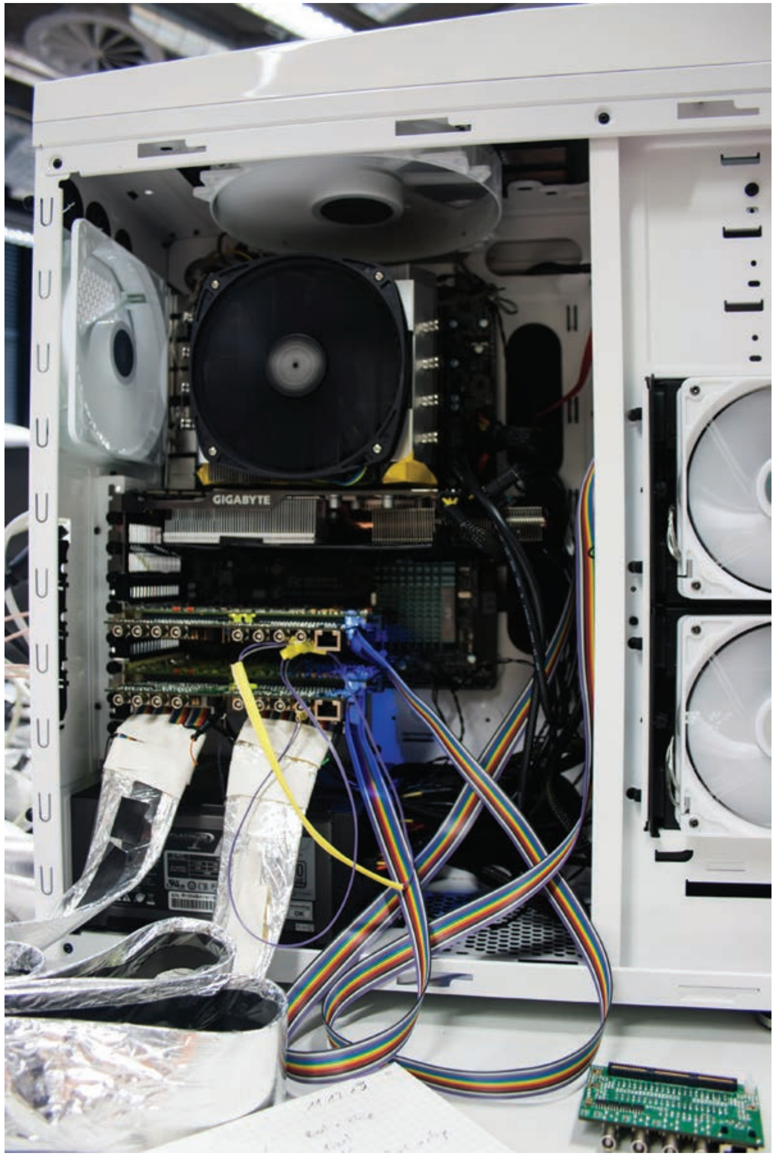
- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps

Data Acquisition



- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(50) PCs with GPUs

Online filter farm

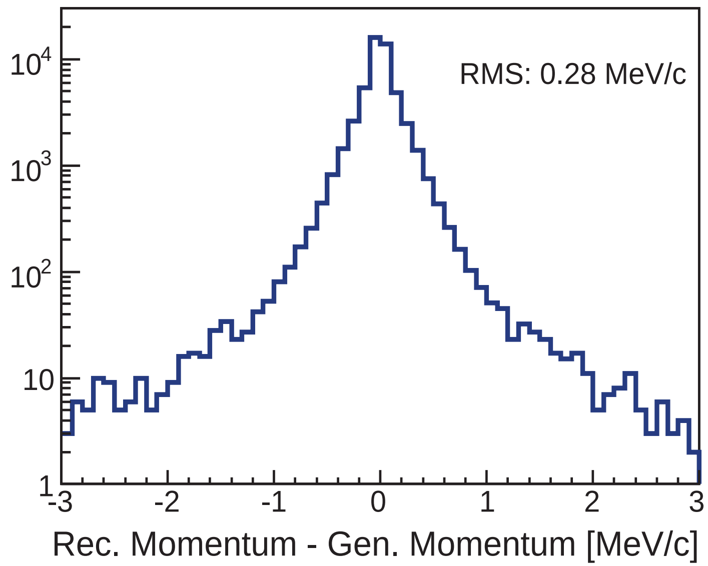


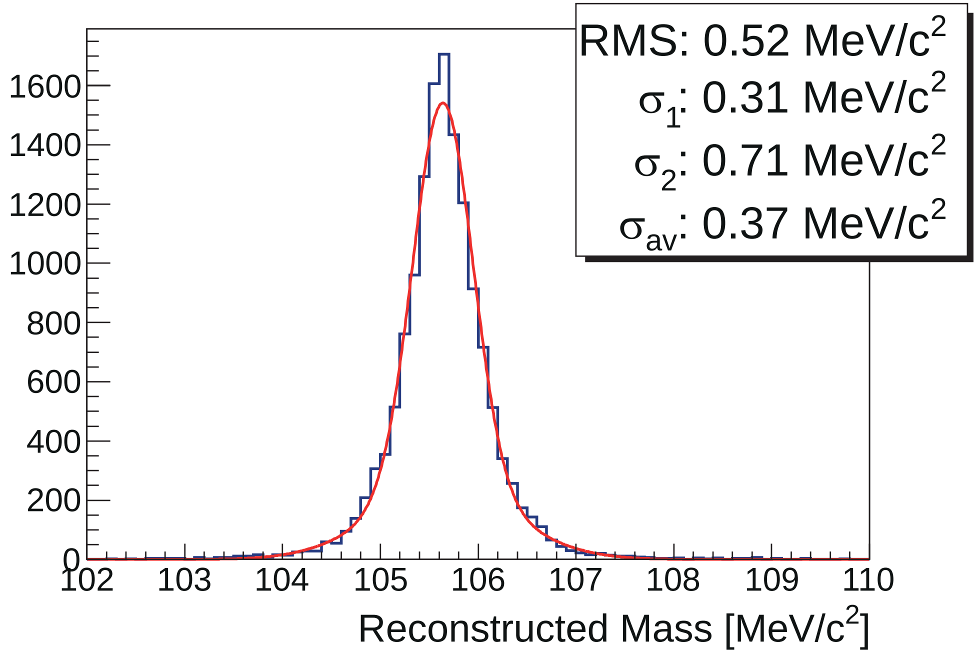
Online software filter farm

- Continuous front-end readout (no trigger)
- ~ 1 Tbit/s
- PCs with FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

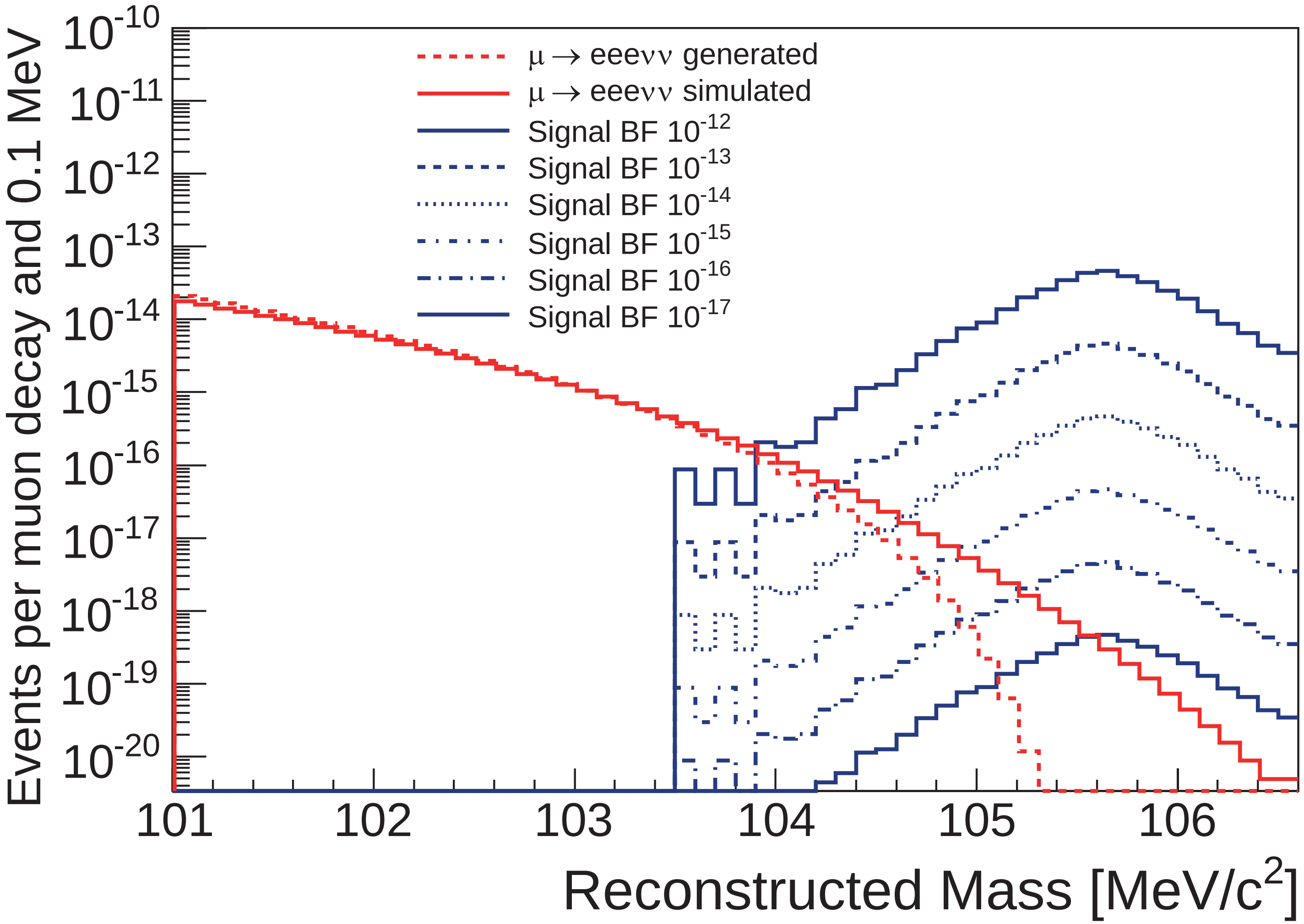
Simulated Performance

- 3D multiple scattering track fit
- Simulation results:
  280 keV single track momentum
  520 keV total mass resolution

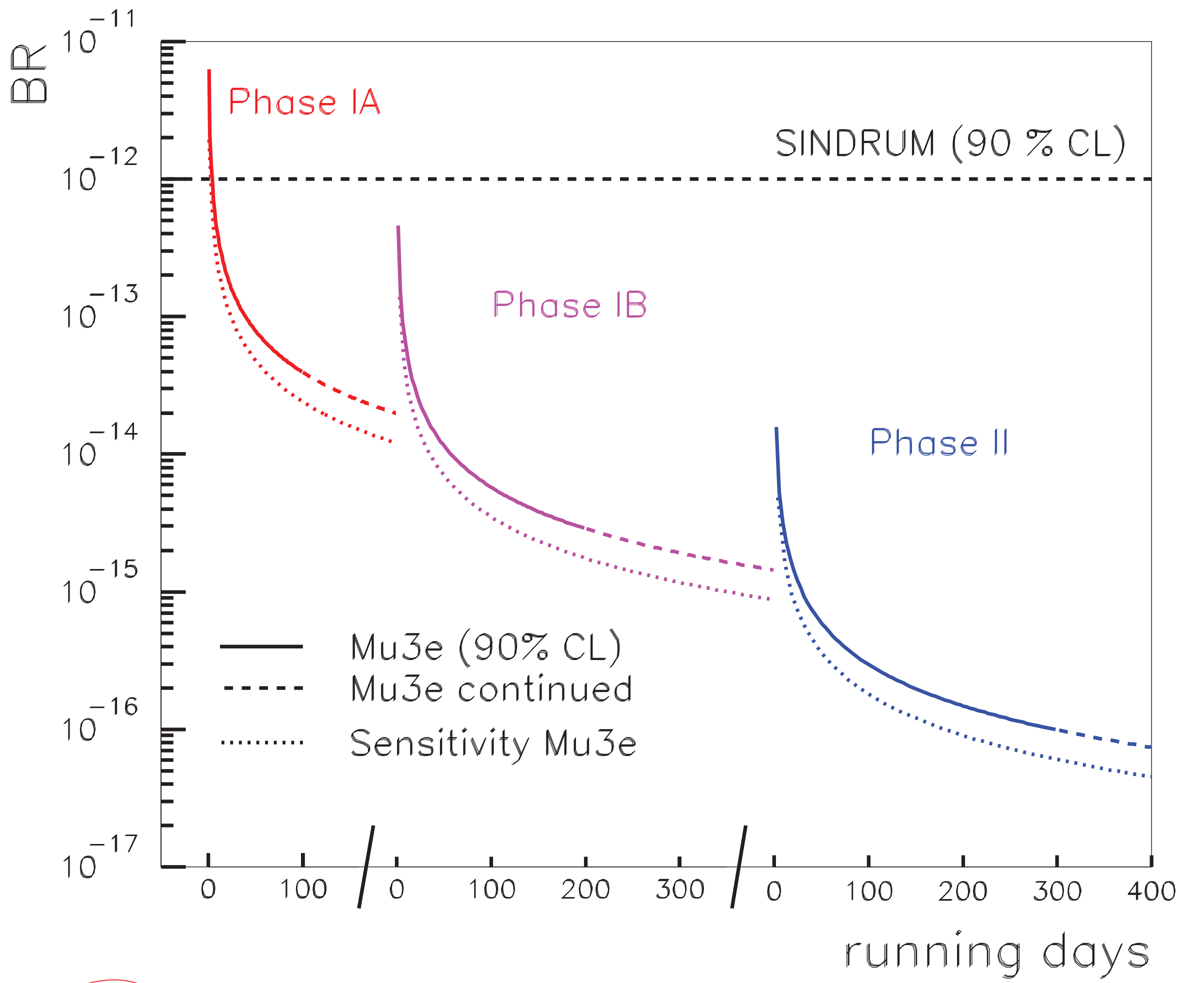


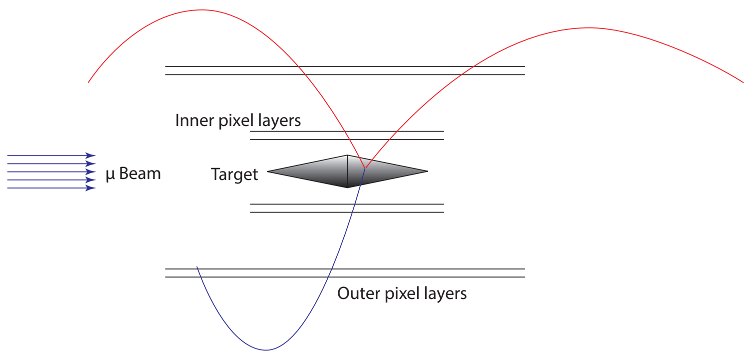


Simulated Performance



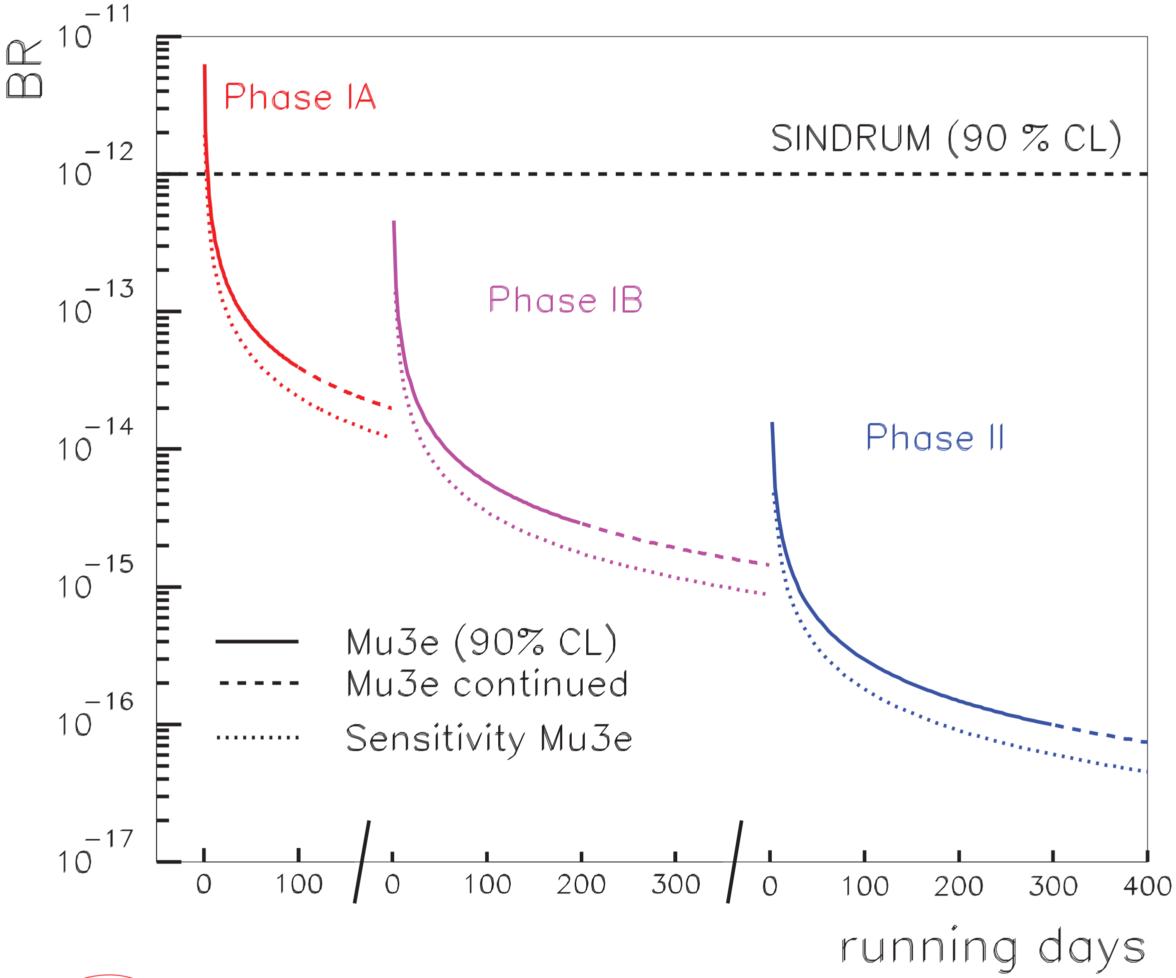
Sensitivity

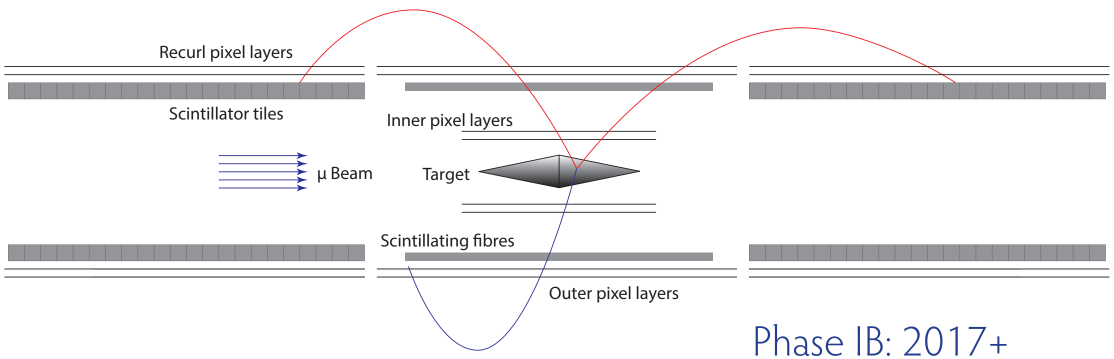




Phase IA: Starting 2016
$2 \cdot 10^7$ μ/s

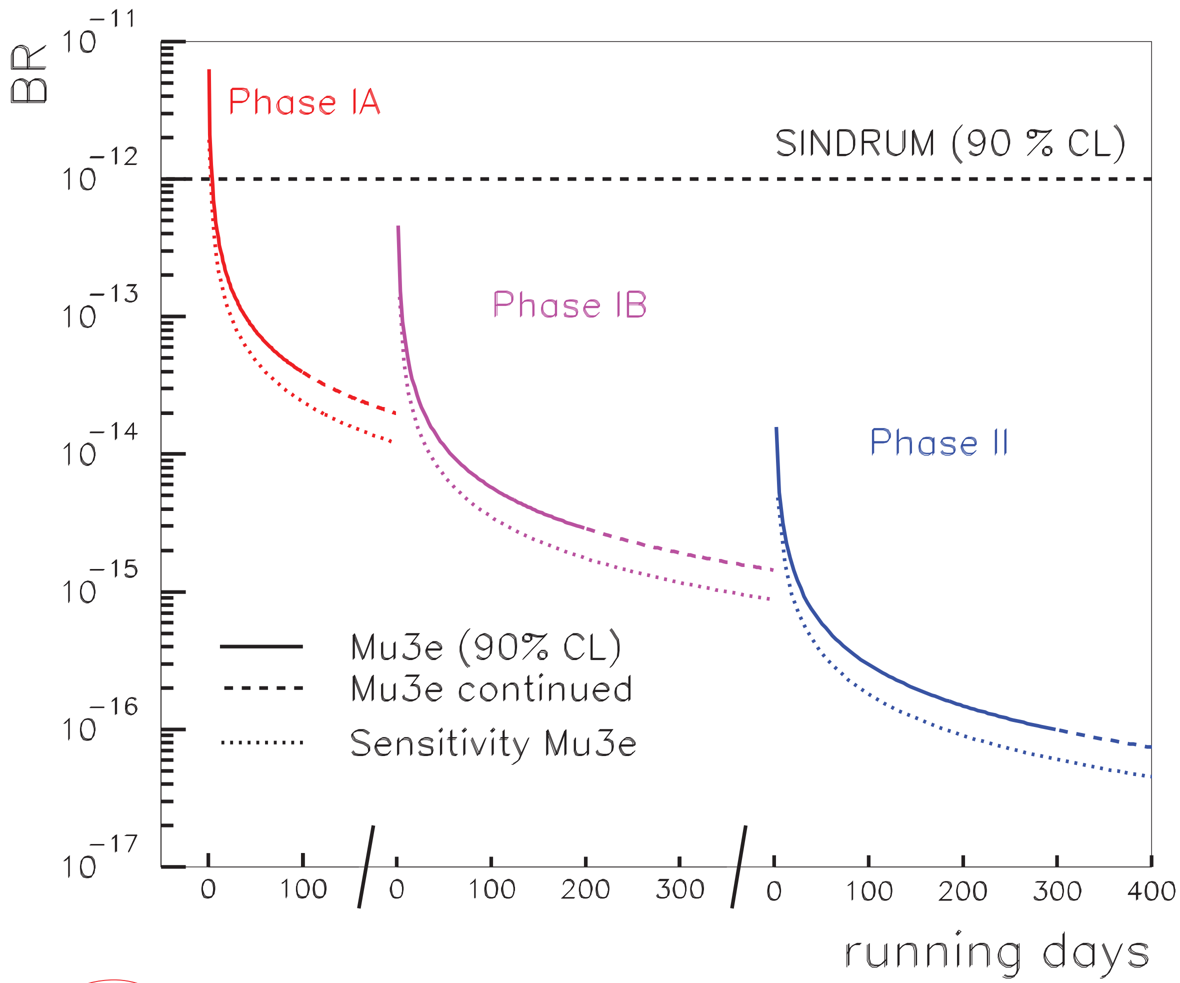
Sensitivity

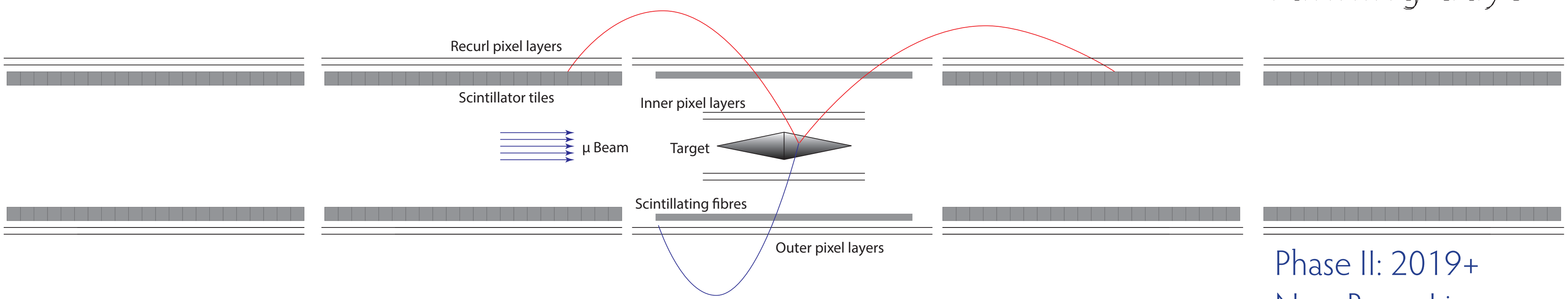




Phase IB: 2017+
$1 \cdot 10^{8}$ μ/s

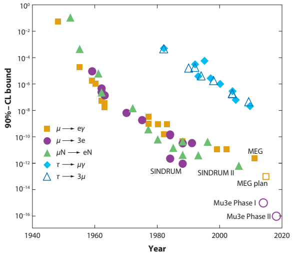
Sensitivity



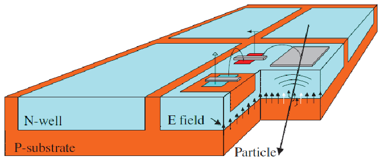


Phase II: 2019+
New Beam Line
$2 \cdot 10^9$ μ/s

Conclusion



- Mu3e aims for $\mu \to eee$ at the 10^{-16} level



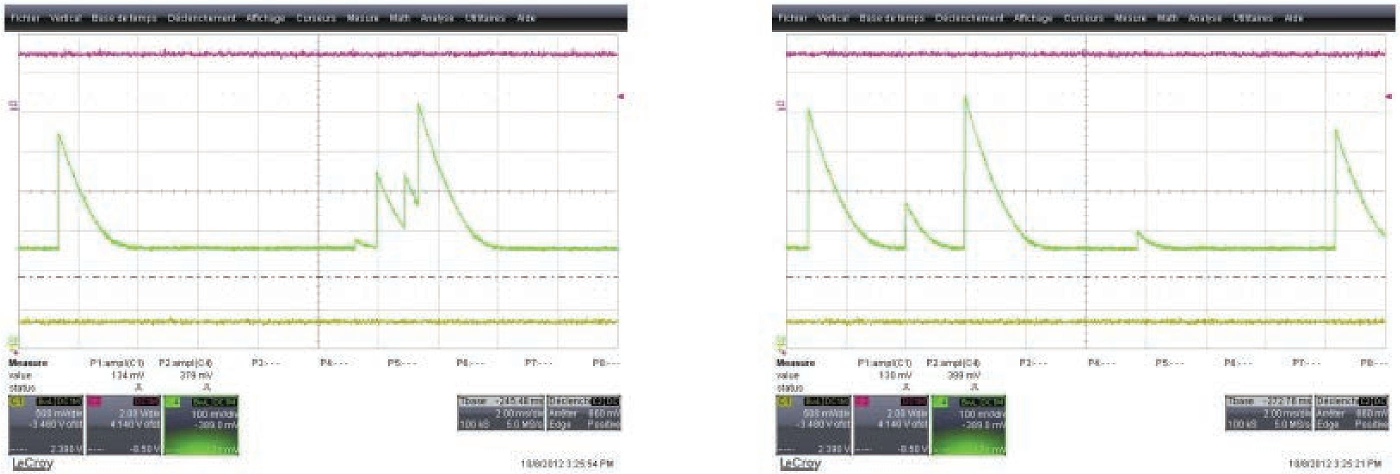
- First large scale use of HV-MAPS
- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs

- Start data taking in 2016
- 2 billion muons/s not before 2019

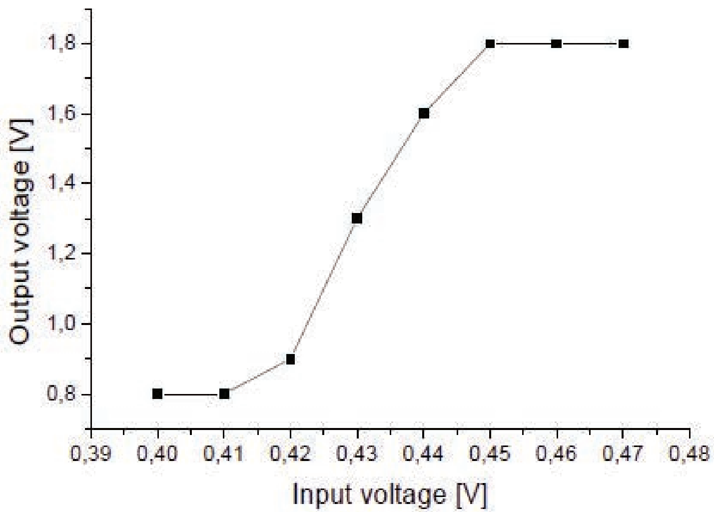
Backup Material

Radiation Hardness

- Requirements not as strict as at LHC



The chip works, particles are measured when the chip is in the beam: Output of the amplifier



Comparator characteristics.

- Irradiation at PS
- After 380 MRad (8×10^{15} n_{eq}/cm^2)
- Chip still working

(Courtesy Ivan Perić, RESMDD 2012)

MUPIX electronics