The Mu3e Experiment

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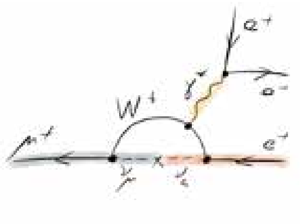
Particle Physics Seminar

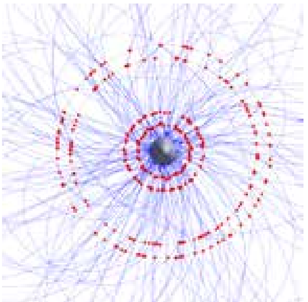
Gießen, May 2015

Overview



- The Motivation:

  New physics in lepton flavour violating μ-decays?



- The Challenge:

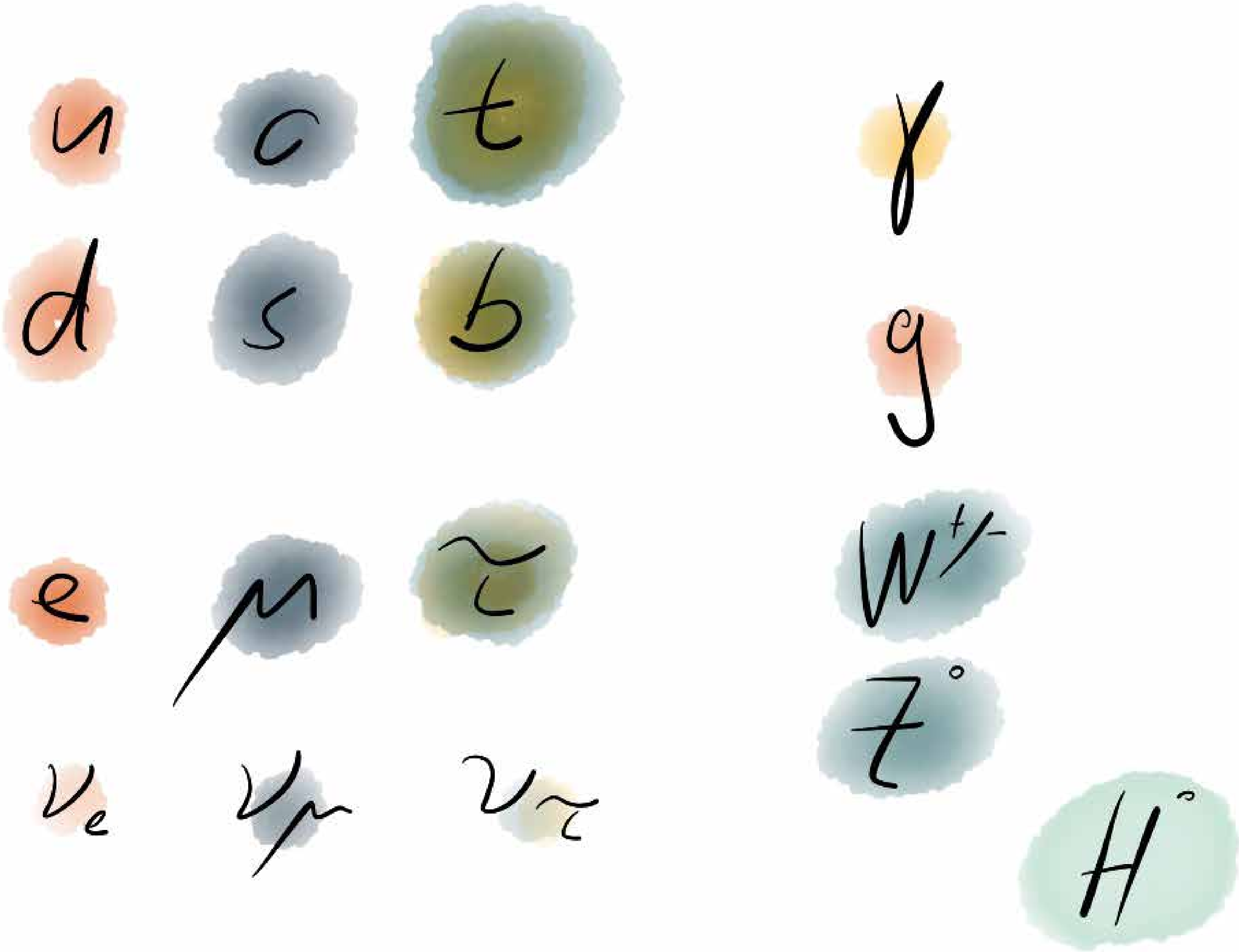
  Finding one in 10^{16} muon decays

- The Mu3e Detector:

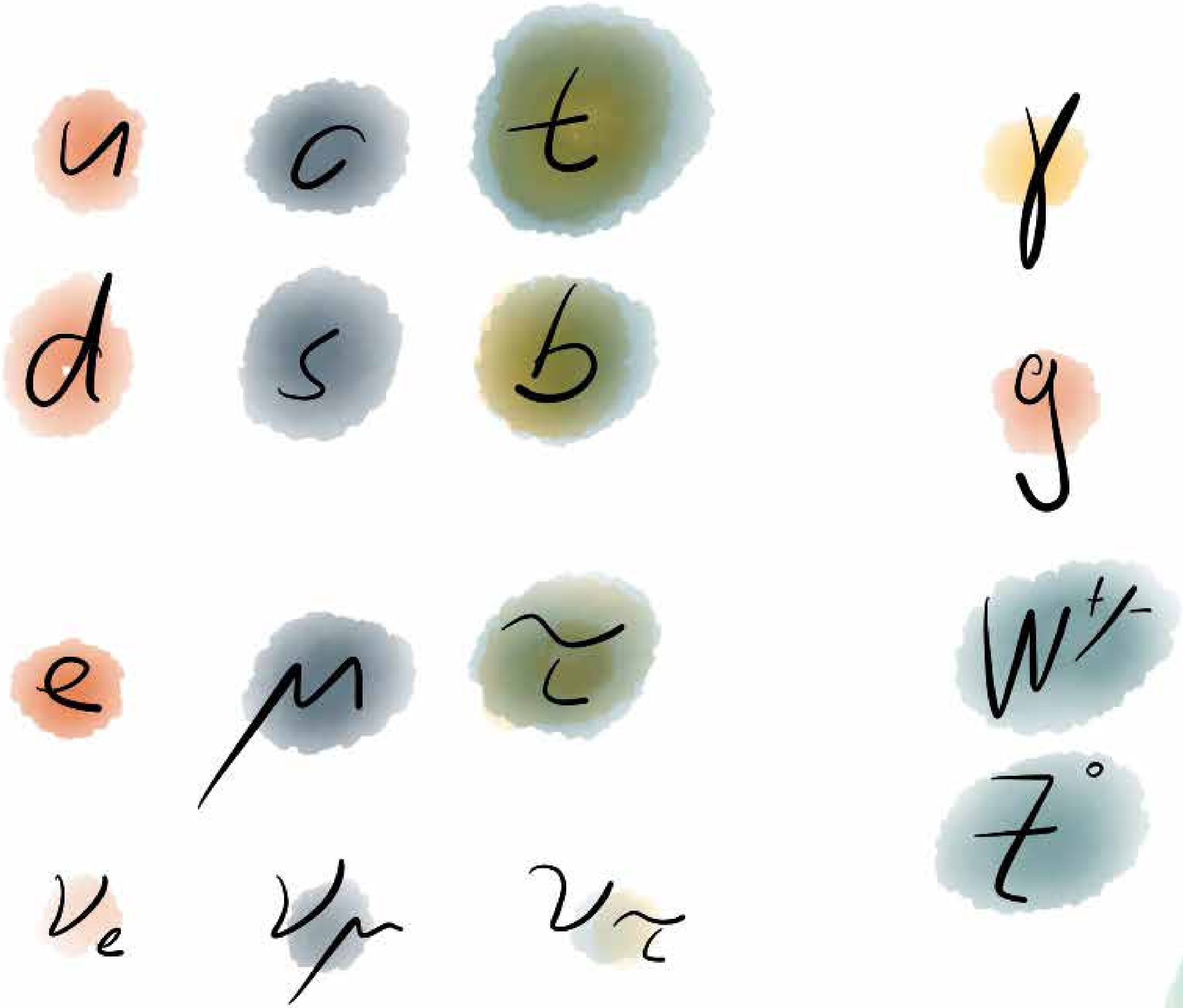
  Minimum Material, Maximum Precision

The hunt for
charged lepton flavour violation

The Standard Model of Elementary Particles



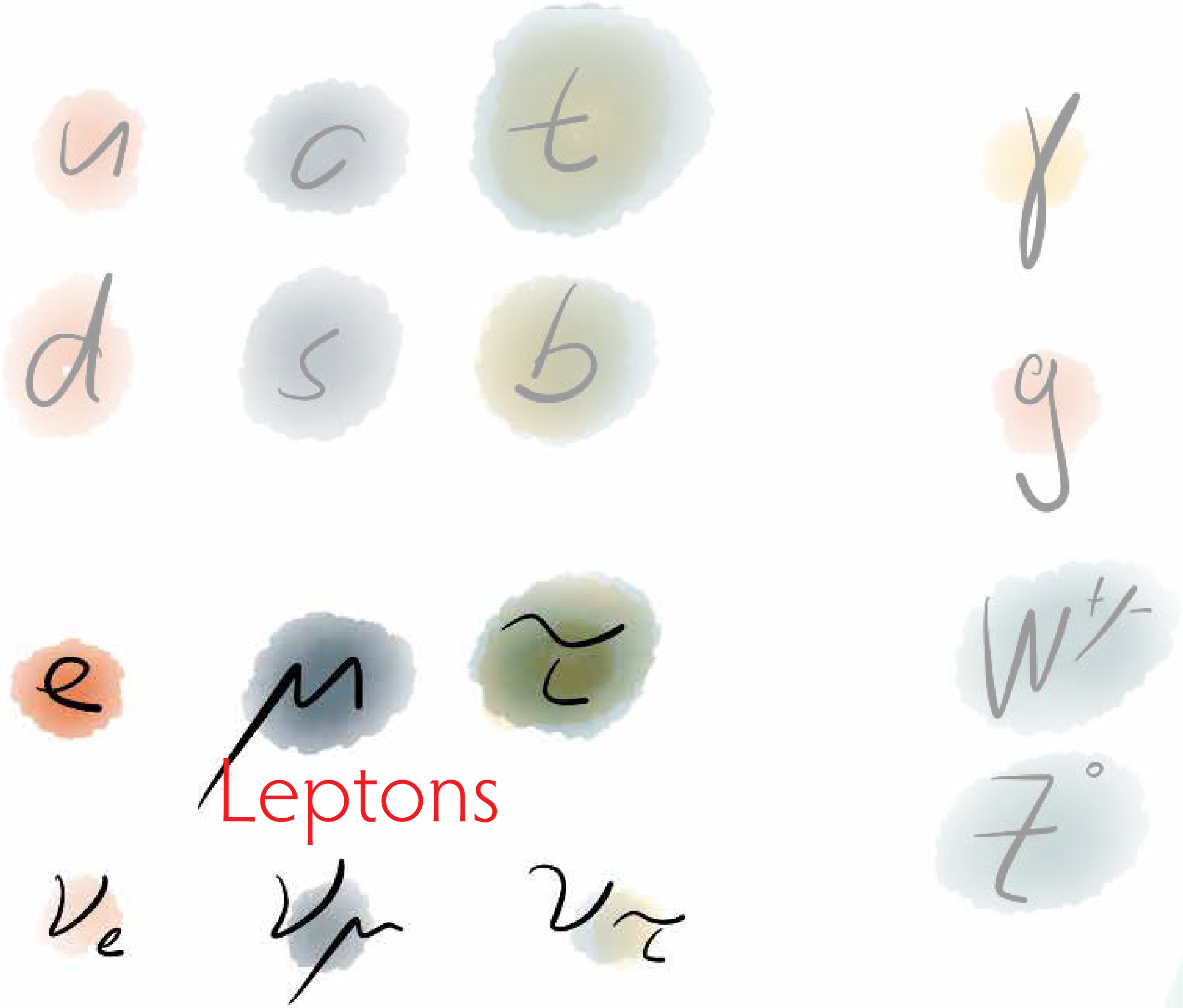
The Standard Model of Elementary Particles



All there, works beautifully, but...

- Why three generations?
- Why the mixing patterns between generations?
- Is there more to it? (the dark universe...)

The Standard Model of Elementary Particles



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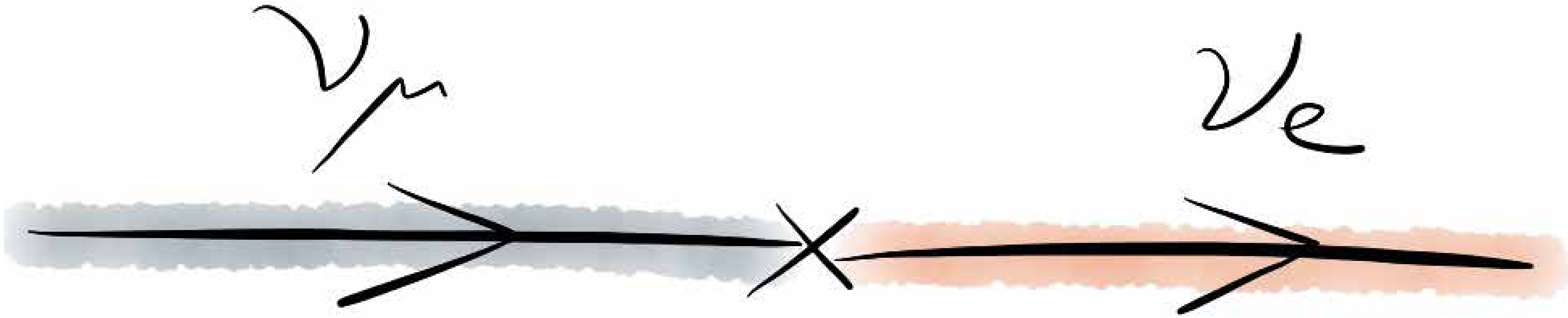
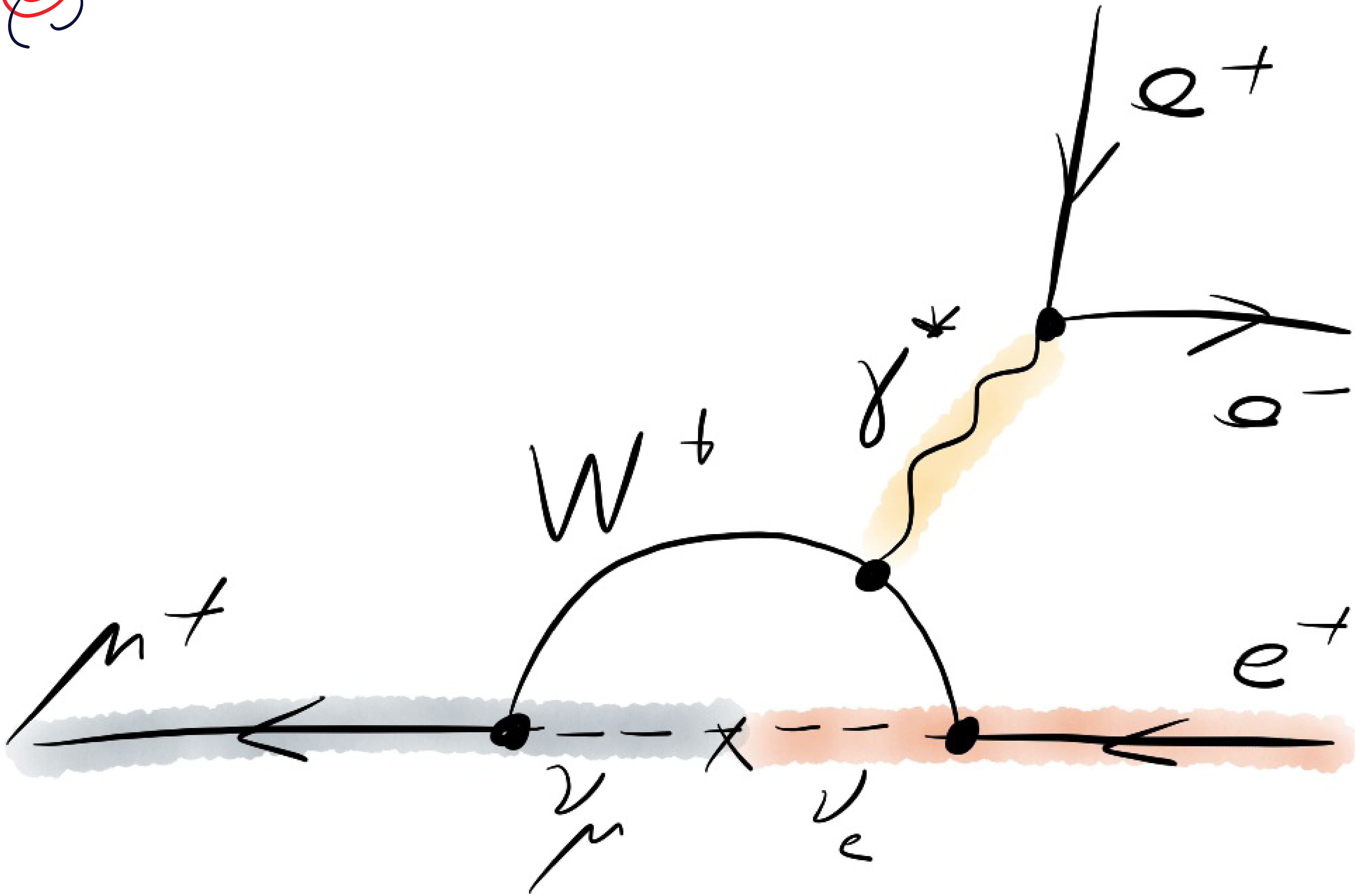
Lepton Flavour Violation!



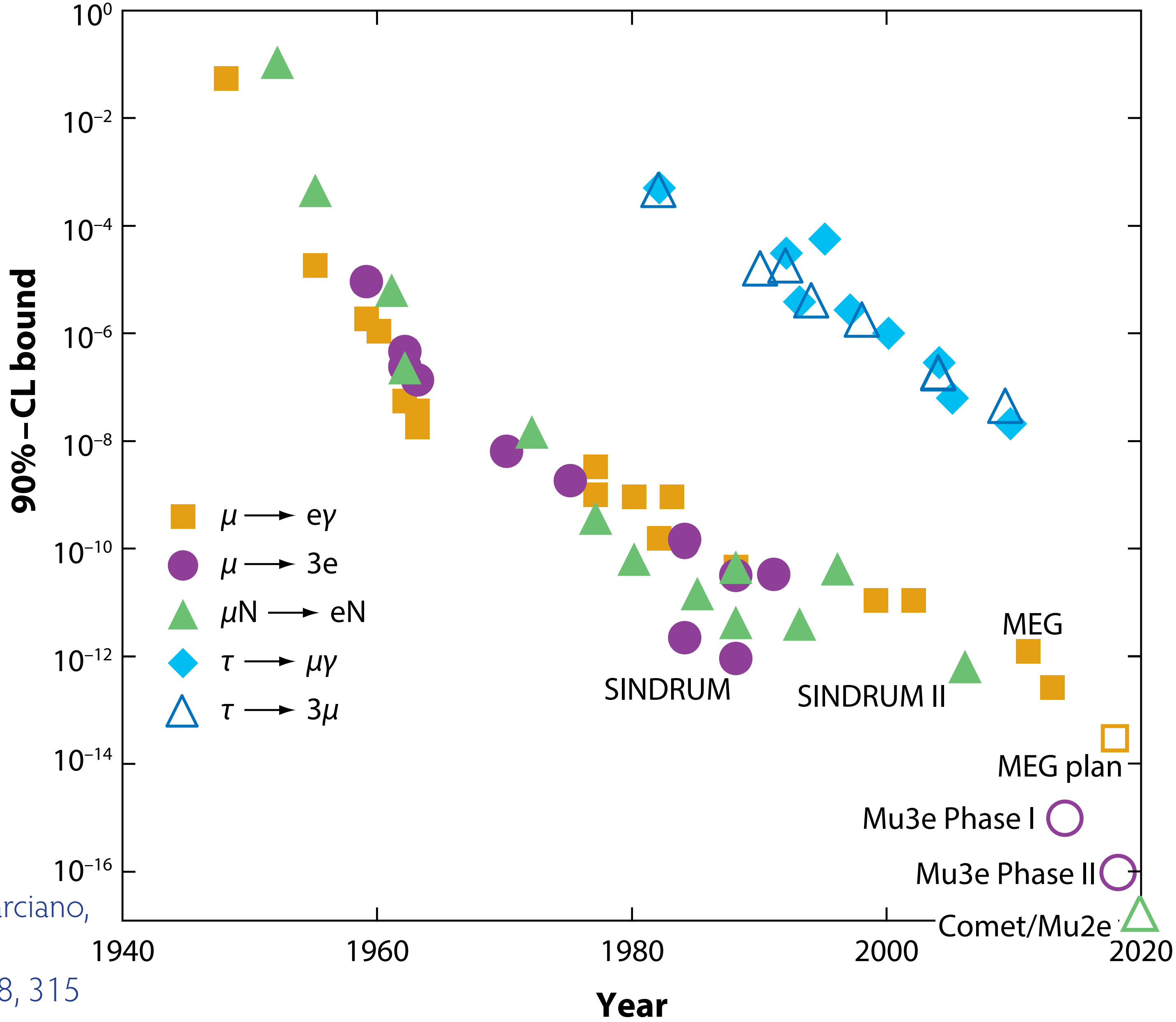
Charged Lepton Flavour Violation?



This
(charged lepton flavour violation)
has never been seen

and not because we have not looked

History of LFV experiments

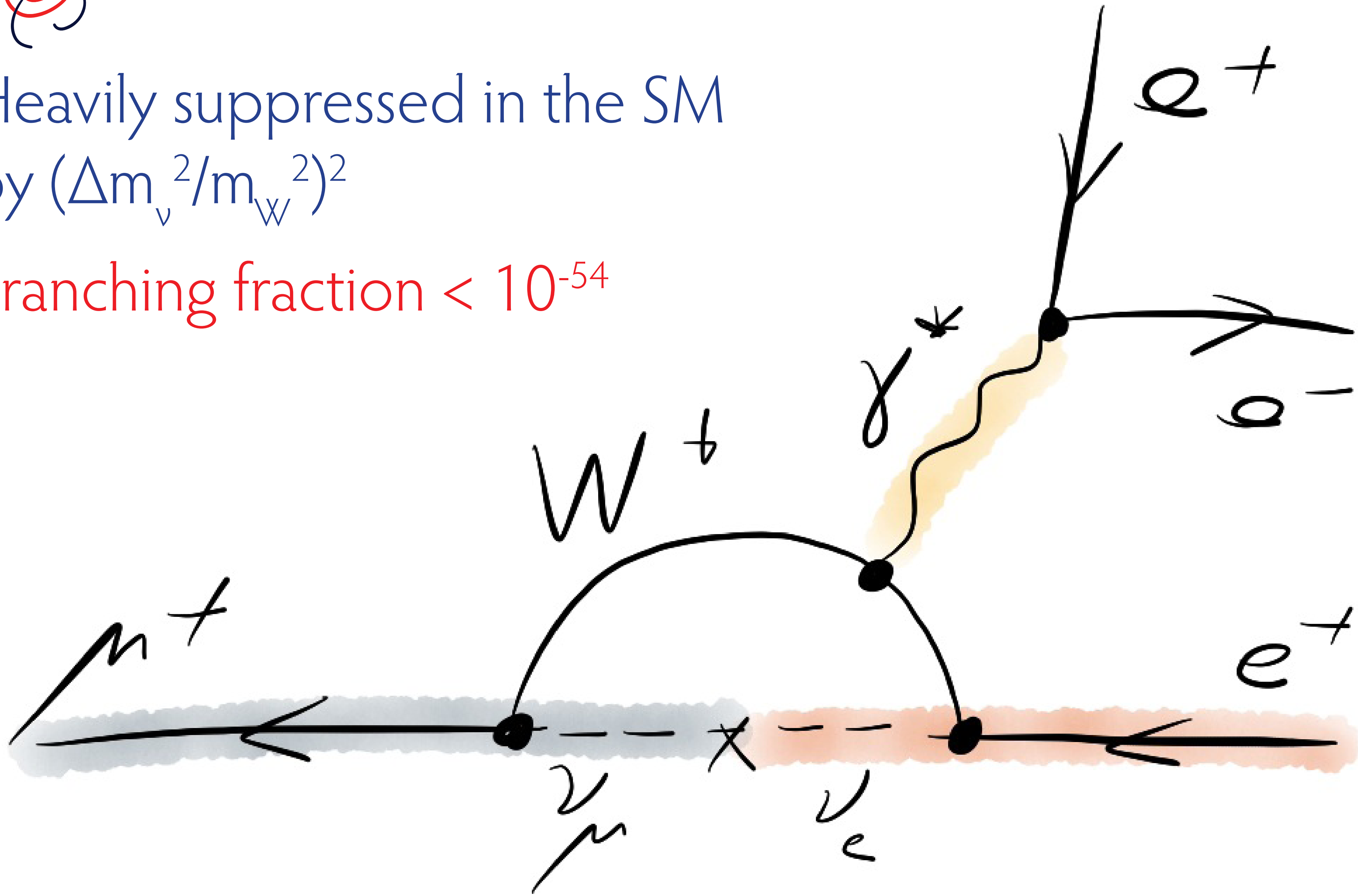


(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

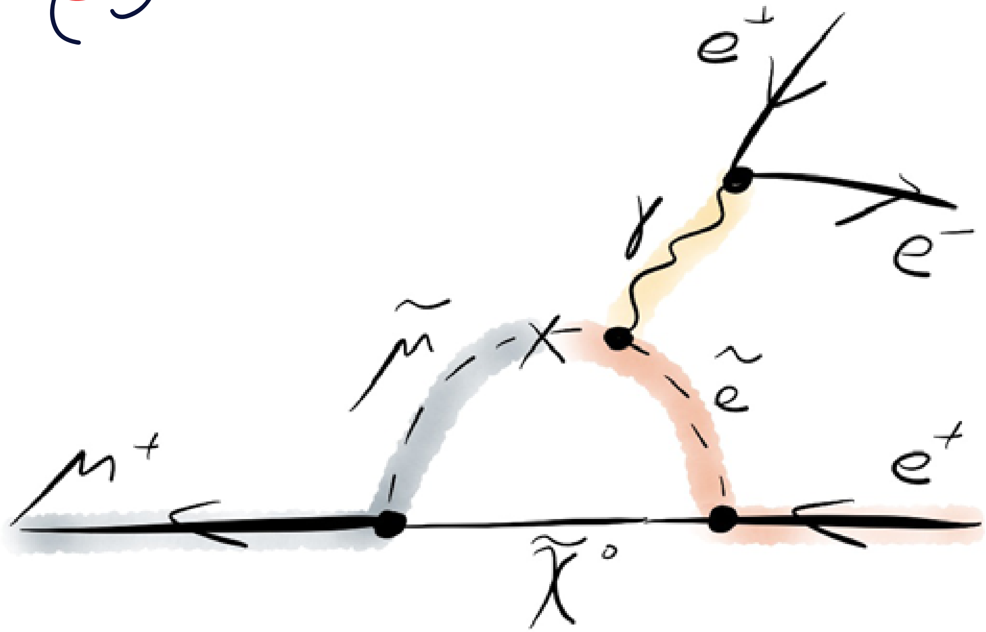
Heavily suppressed in the SM

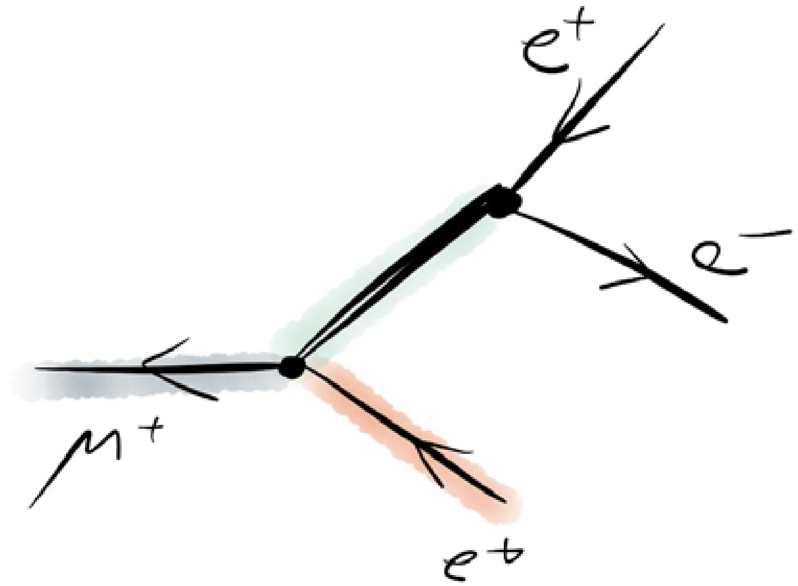
by $(\Delta m_\nu{}^2/m_W{}^2)^2$

Branching fraction < 10^{-54}



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





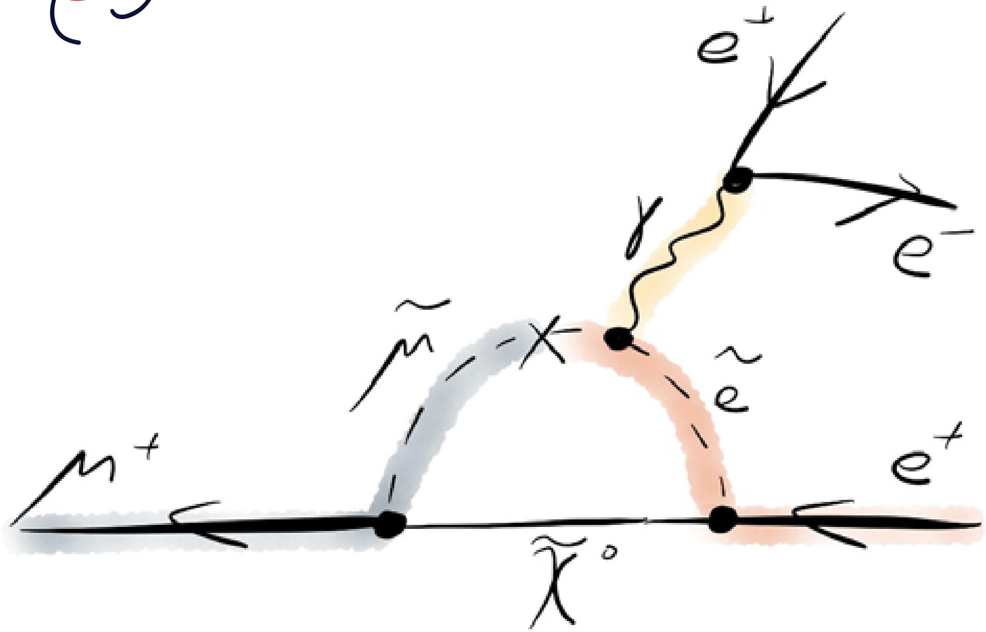
Loop diagrams

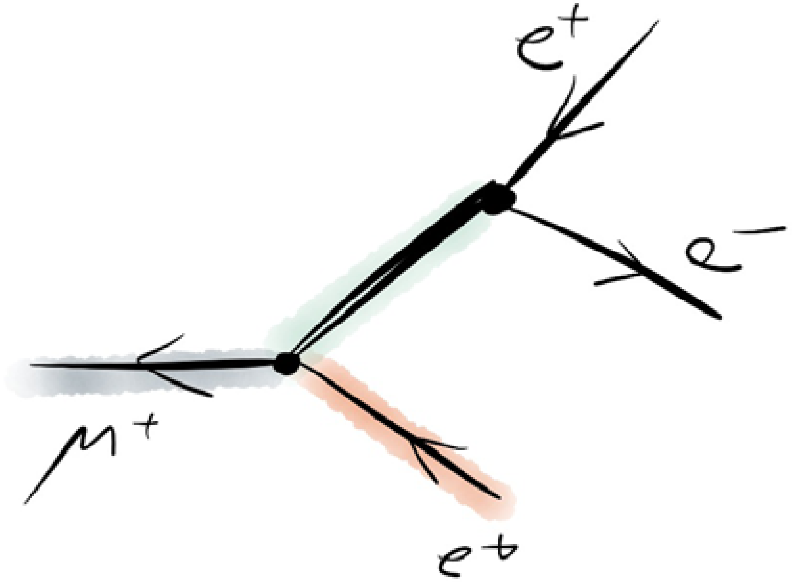
- Supersymmetry
- Little Higgs models
- Seesaw models
- GUT models (leptoquarks)
- and much more...

Tree diagrams

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

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

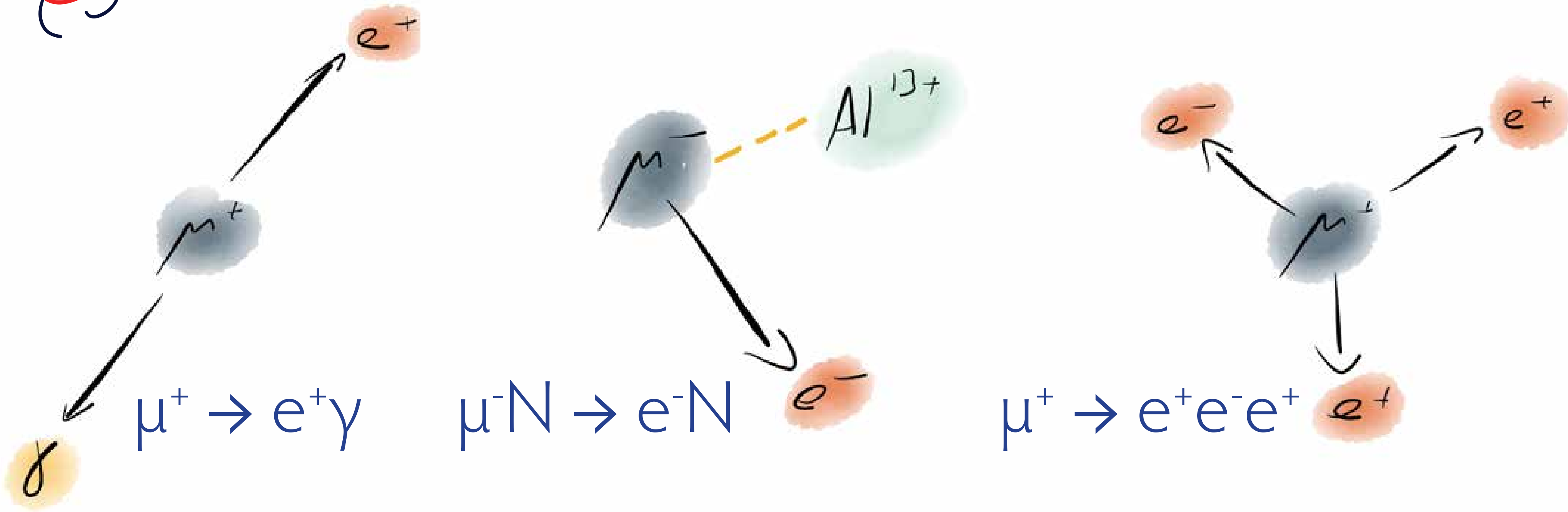




Muon decays sensitive to new physics at $\mathcal{O}$(1000 TeV) scale for $\mathcal{O}$(1) couplings!

The hunt for
charged lepton flavour violation in μ-decays

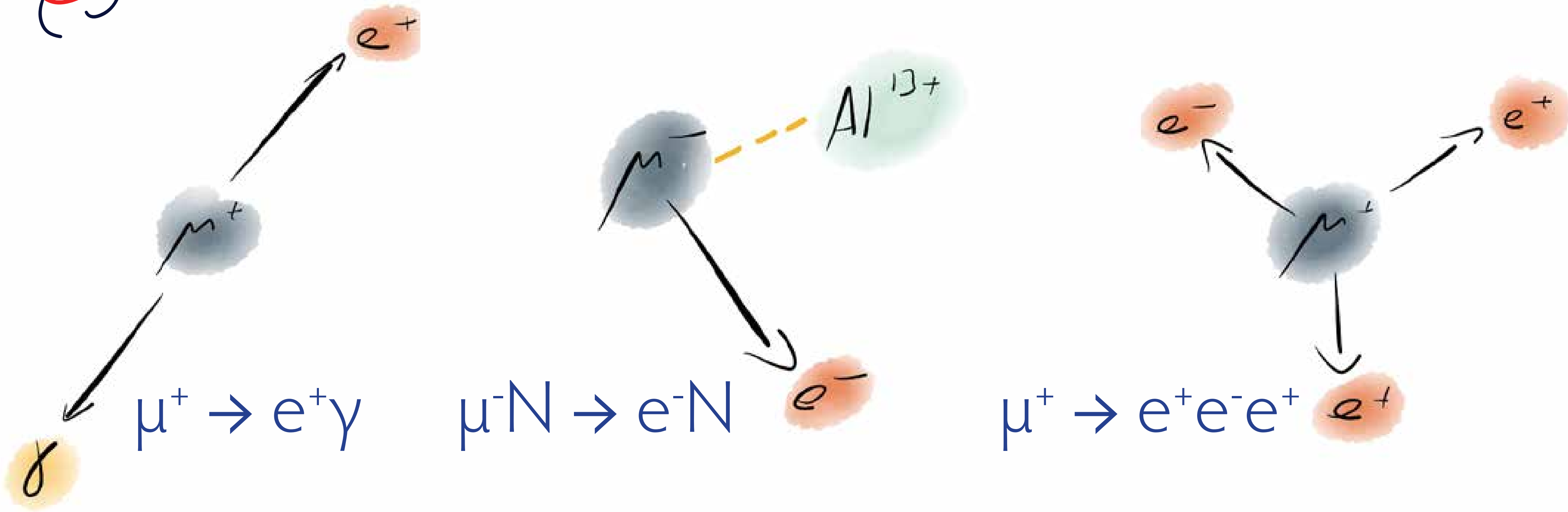
LFV Muon Decays: Experimental Situation



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

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

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)

upgrading

SINDRUM II (PSI)

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

(2006)

Mu2e/Comet

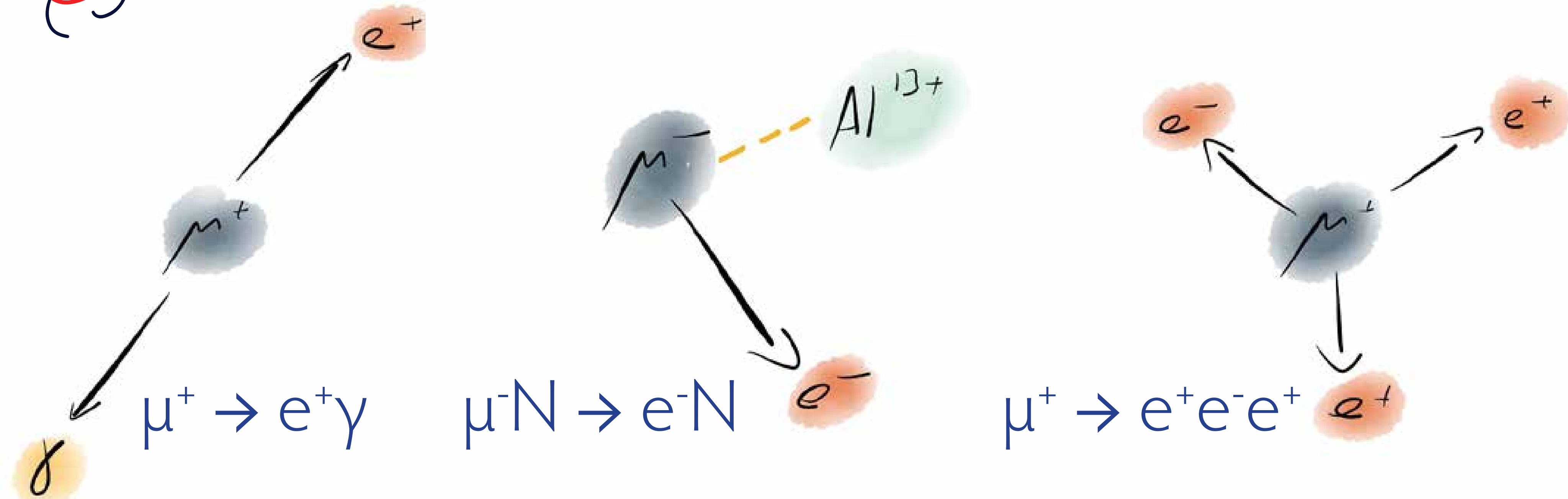
SINDRUM (PSI)

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

(1988)

Mu3e

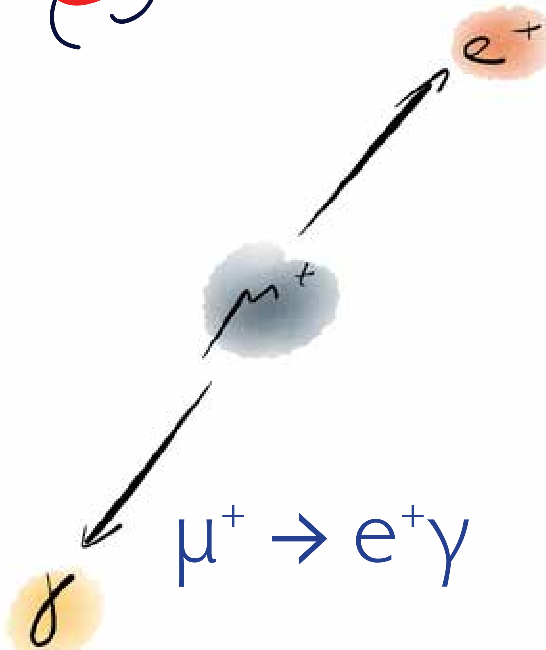
LFV Muon Decays: Experimental signatures



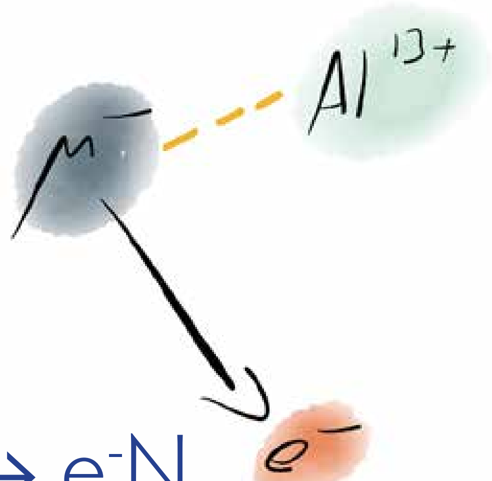
$\mu^+ \to e^+\gamma$ $\mu^-N \to e^-N$ $\mu^+ \to e^+e^-e^+$

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	• $\Sigma p_i = 0$

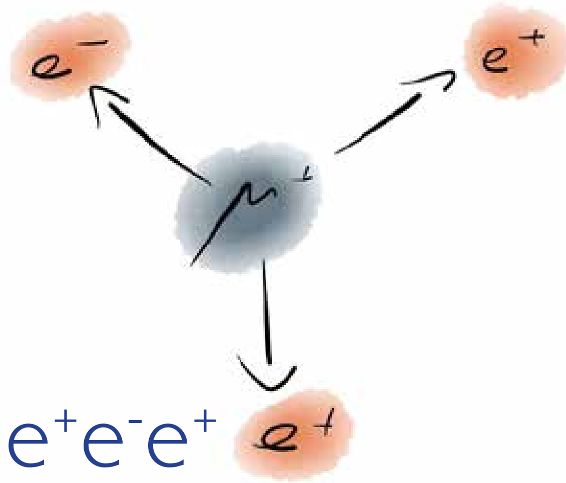
LFV Muon Decays: Experimental signatures



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



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



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

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

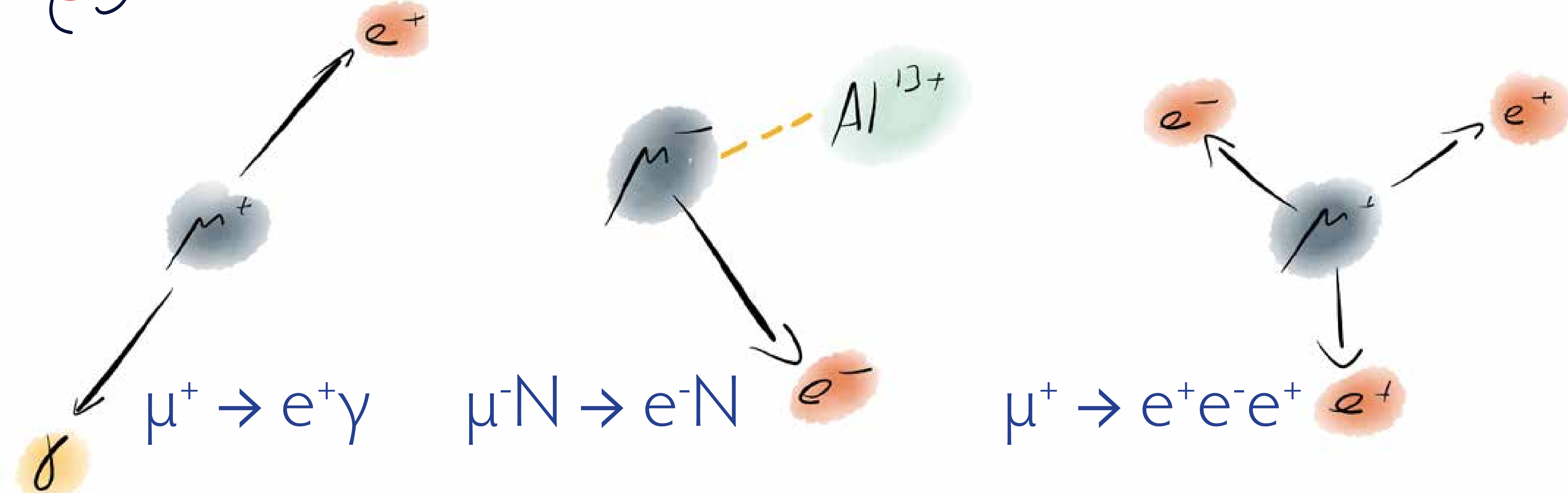
Kinematics

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

Background

- Radiative decay
- Accidental background

LFV Muon Decays: Experimental signatures



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

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

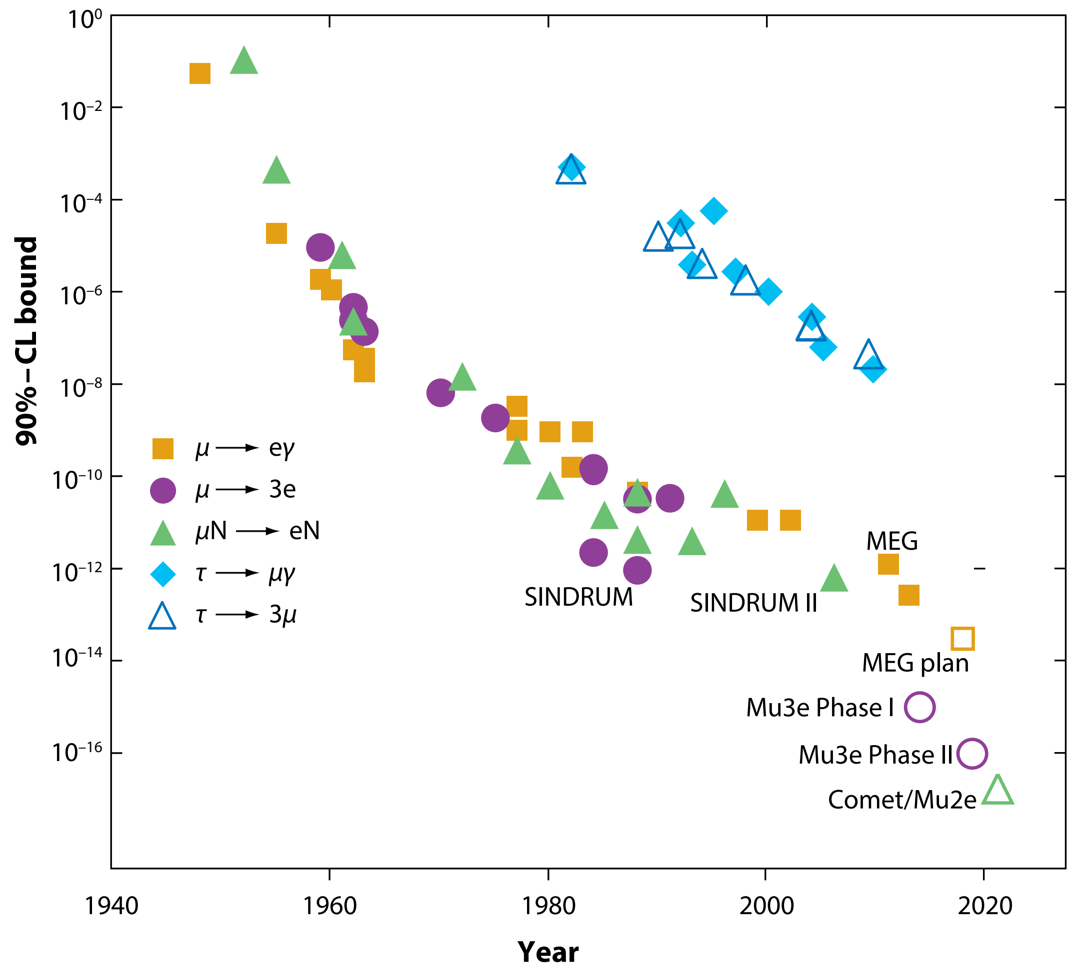
Kinematics
- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro
- R decay
- Ac dental background

Continuous Beam

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)

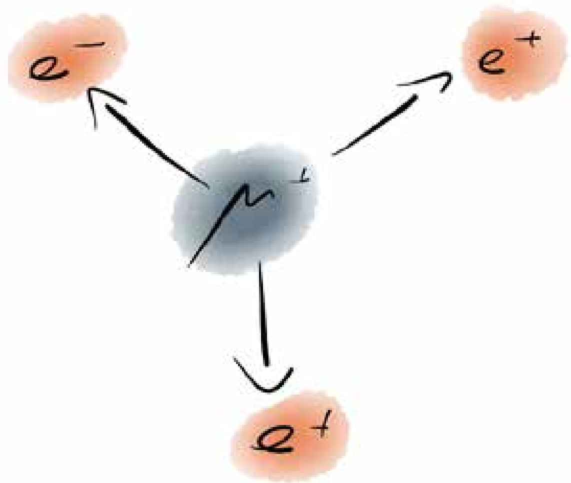
- 4 orders of magnitude over previous experiment (SINDRUM 1988)

(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
- IPE, Karlsruhe Institute of Technology
- Paul Scherrer Institute
- Physics Institute, Zürich University
- Institute for Particle Physics, ETH Zürich
- Institute for Nuclear Physics, JGU Mainz

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

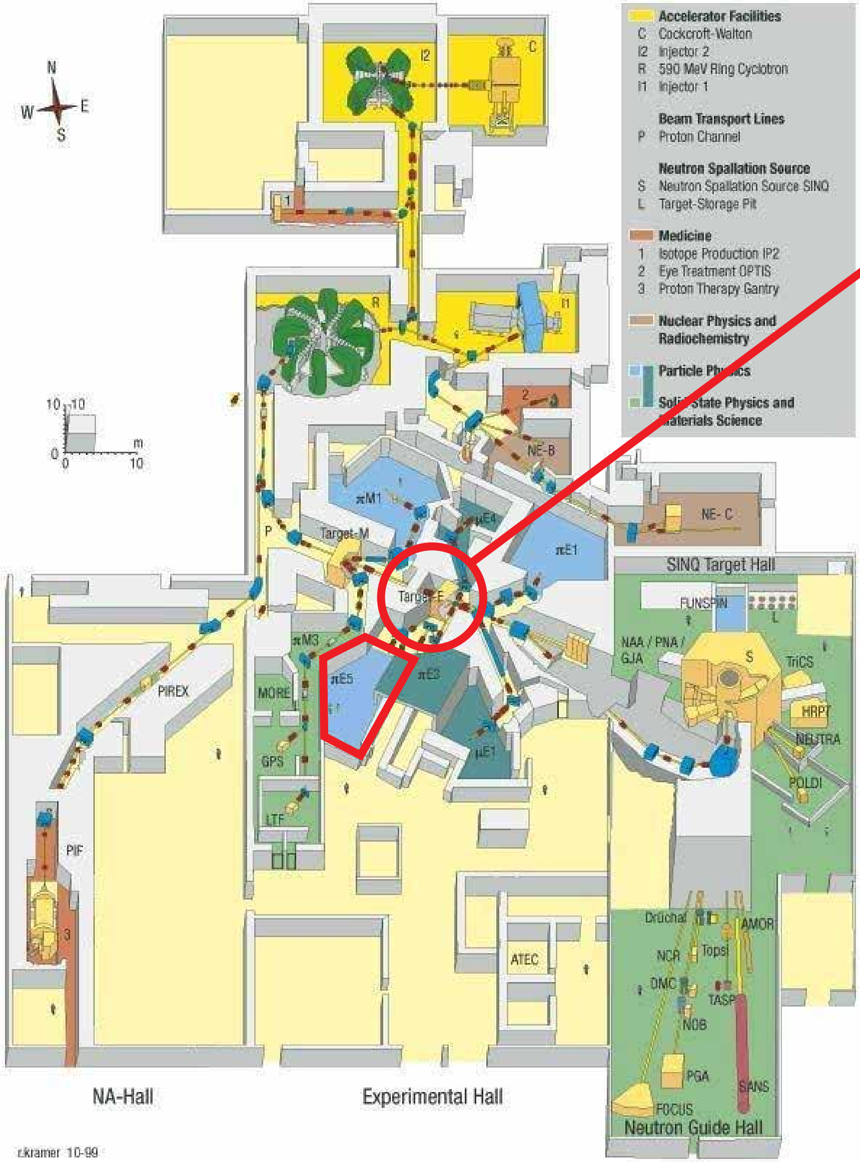
Paul Scherrer Institute in Villigen, Switzerland

Muons from PSI

Paul Scherrer Institute in Villigen, Switzerland

World's most intensive proton beam
2.2 mA at 590 MeV: 1.3 MW of beam power

Muons from PSI

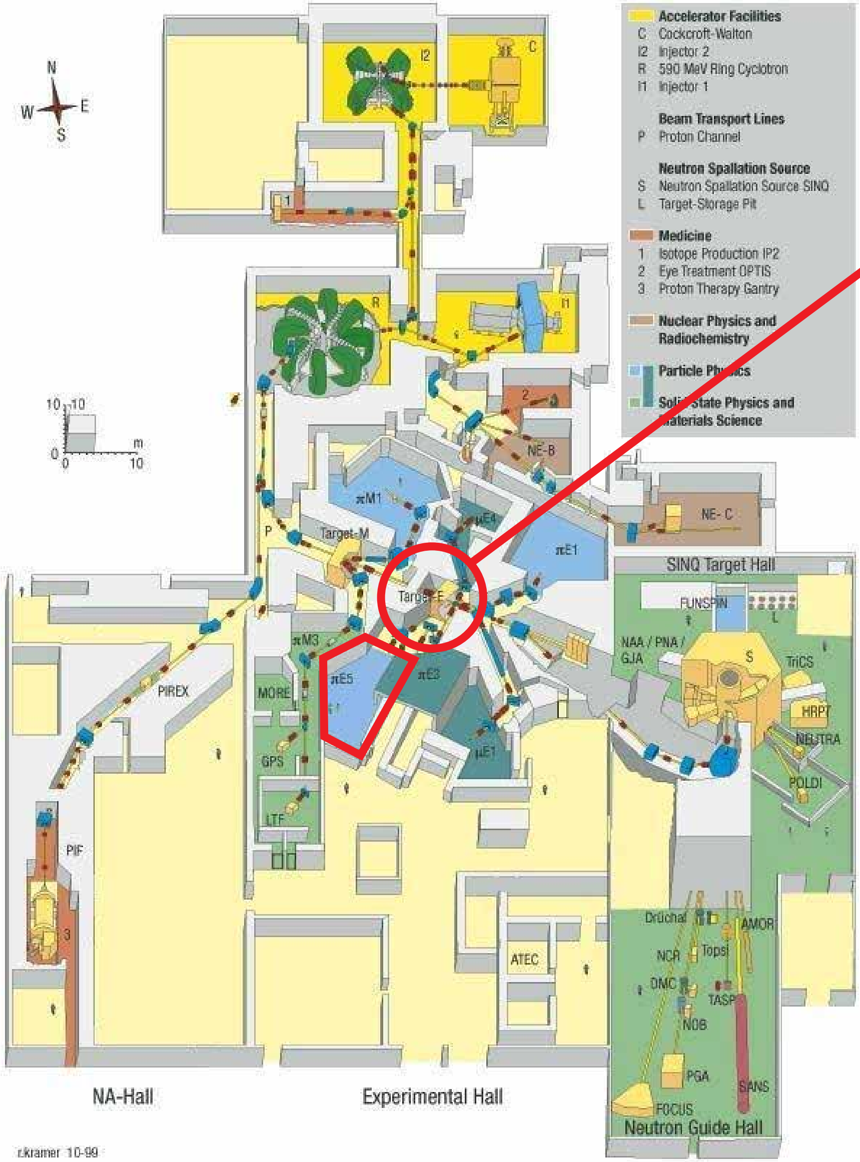


DC muon beams at PSI:

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

- Surface muons, p = 29.7 MeV/c
  Stopped in < 1 mm of plastic

Muons from PSI



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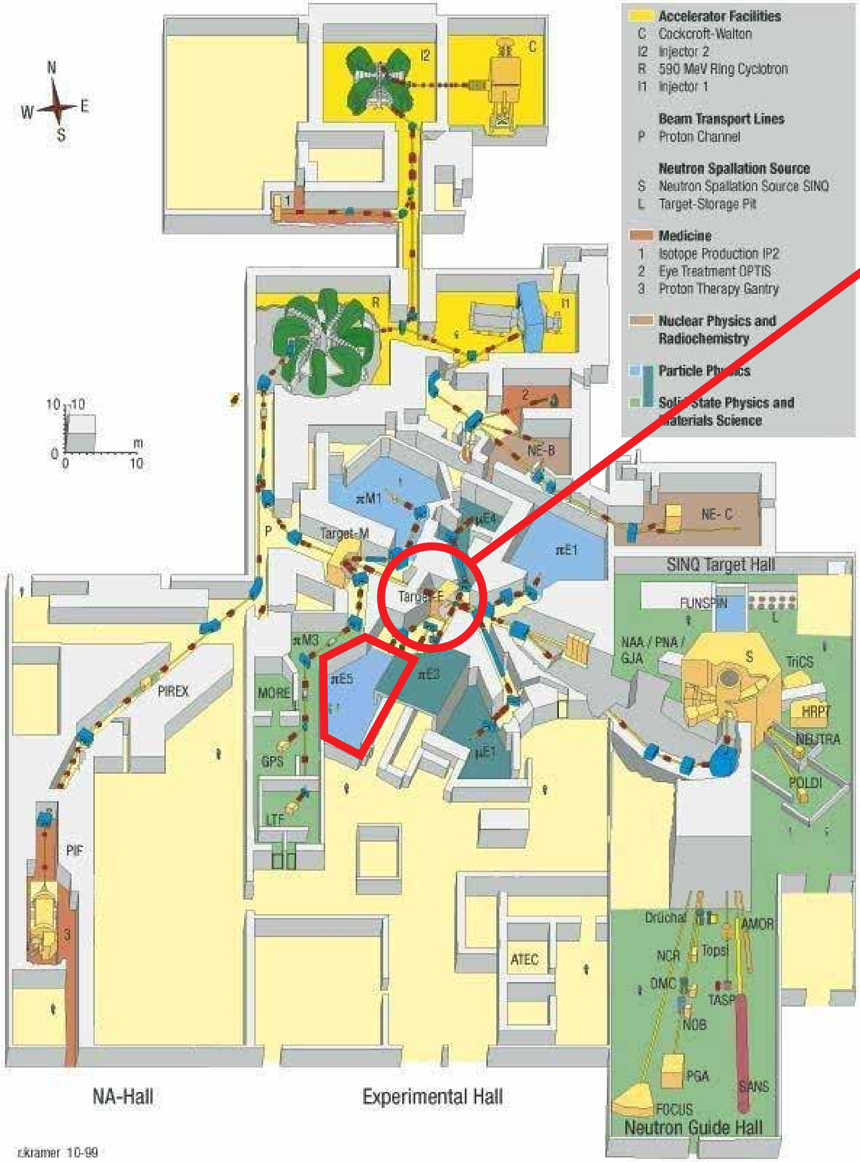

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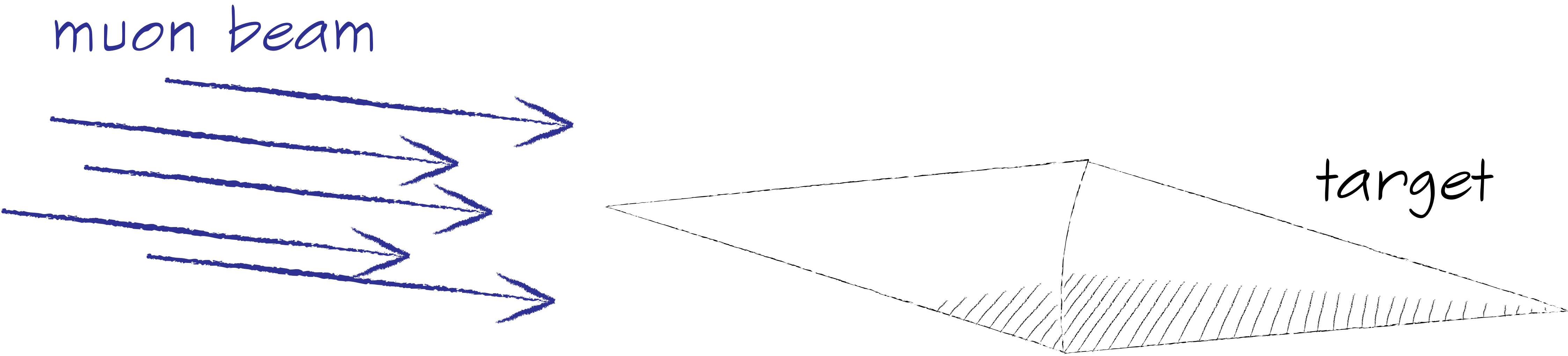
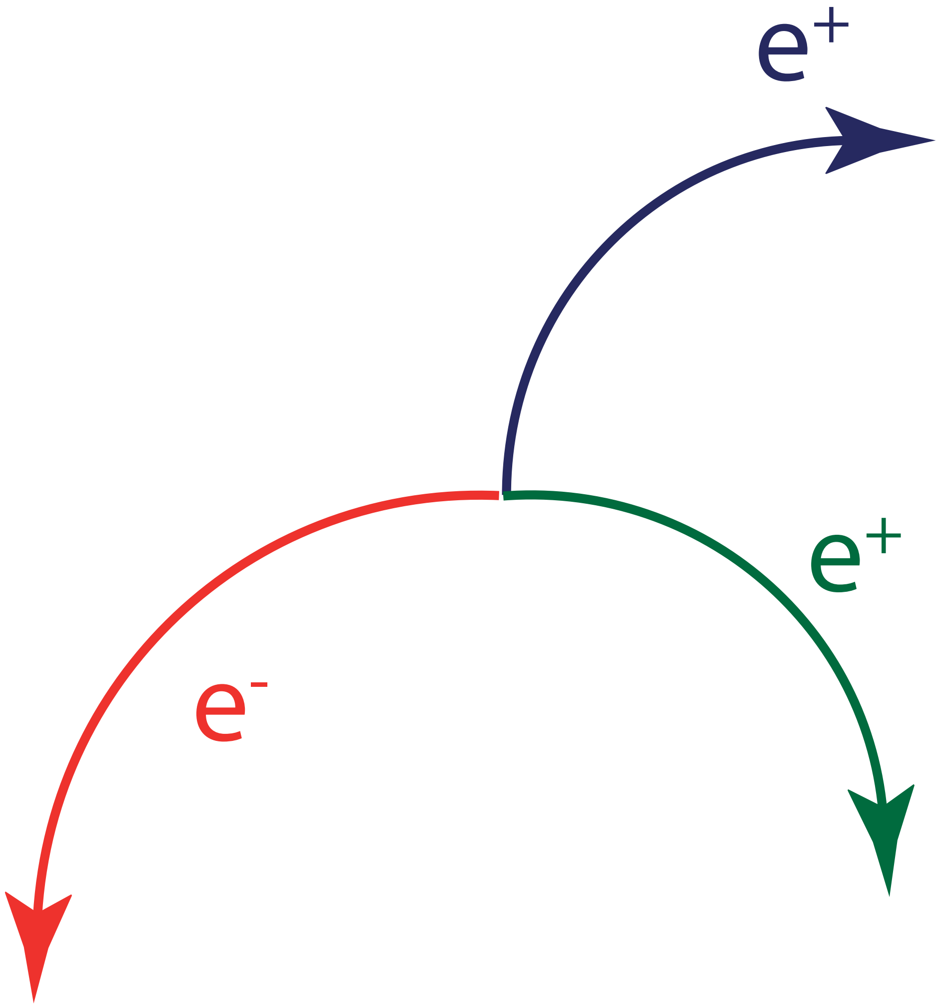
  Stopped in < 1 mm of plastic
- The $\mu \to eee$ experiment (final stage) requires 2×10^9 muons/s focused and collimated on a ~2 cm spot
- More than ~ 10^{11} muons/s are produced; bring magnetic elements closer to capture them:
  High intensity muon beamline (HiMB) study currently ongoing

Building the Mu3e Experiment

Stop muons, let them decay

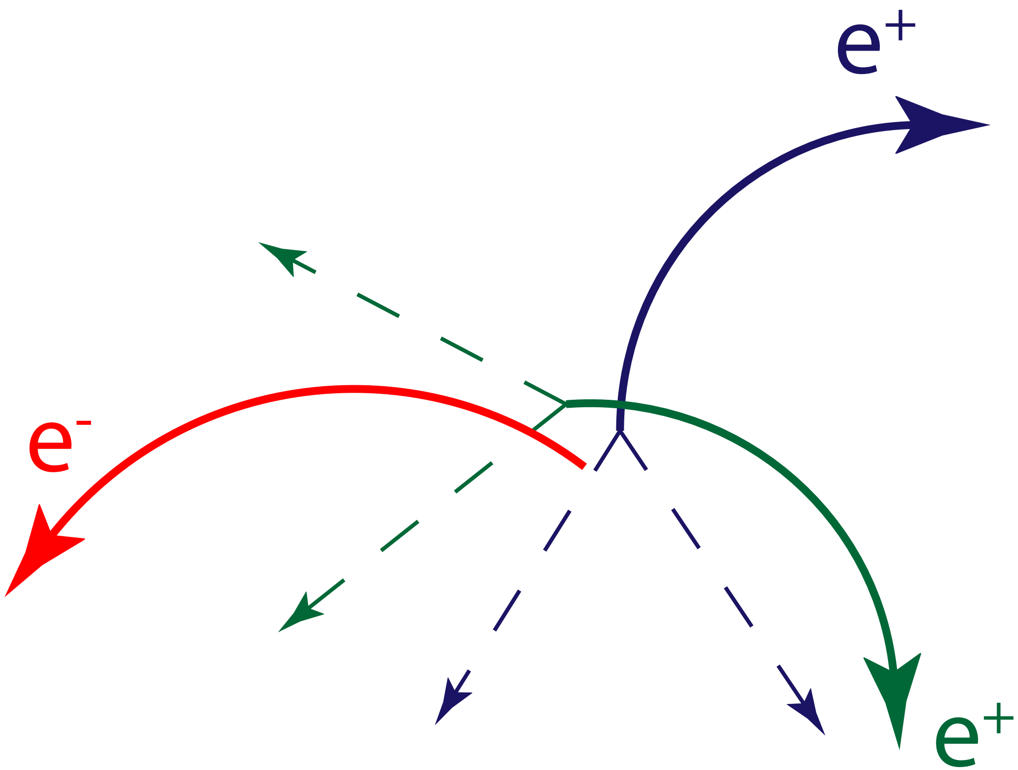


The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: $\frac{1}{2}\, m_\mu$ = 53 MeV/c

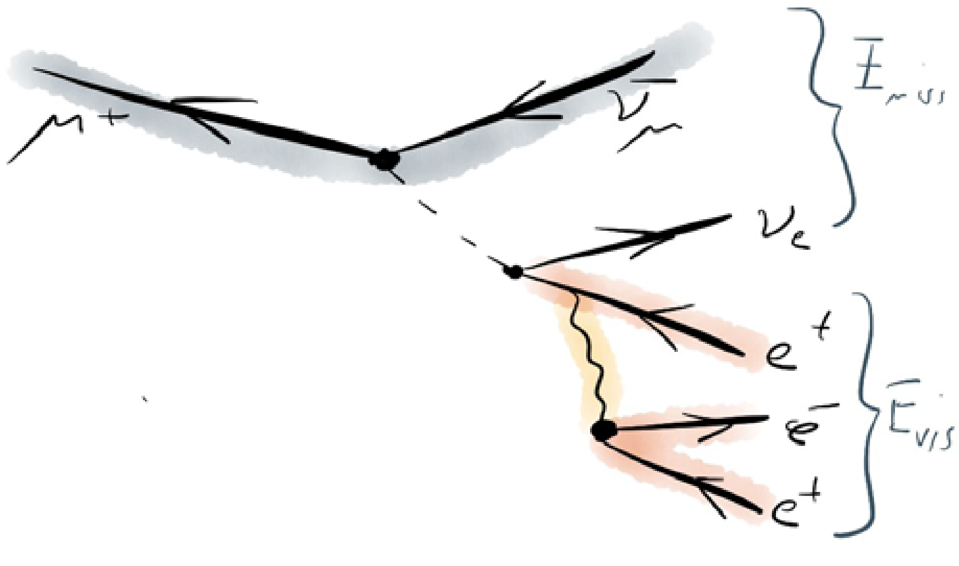
Accidental Background



- 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

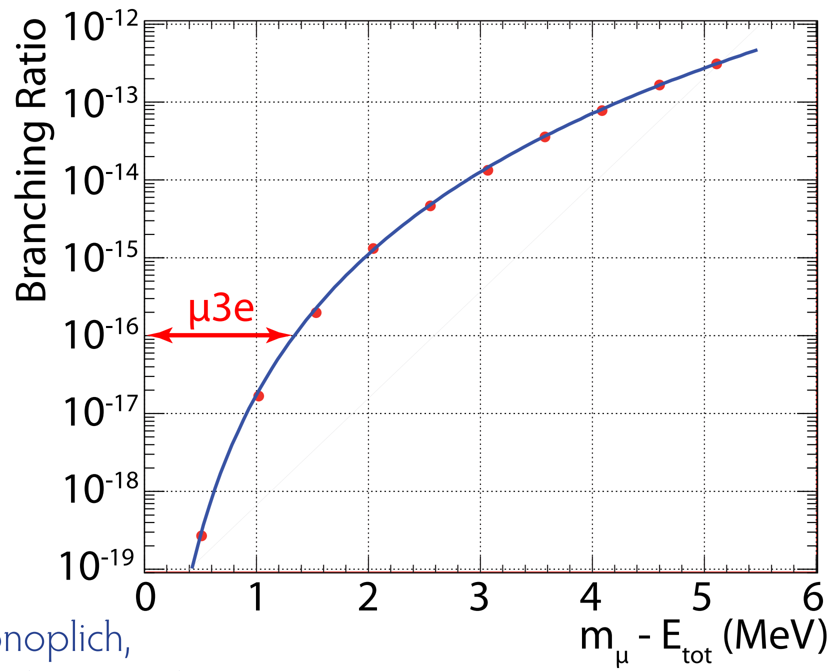


- Allowed radiative decay with internal conversion:

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

- Only distinguishing feature: Missing momentum carried by neutrinos

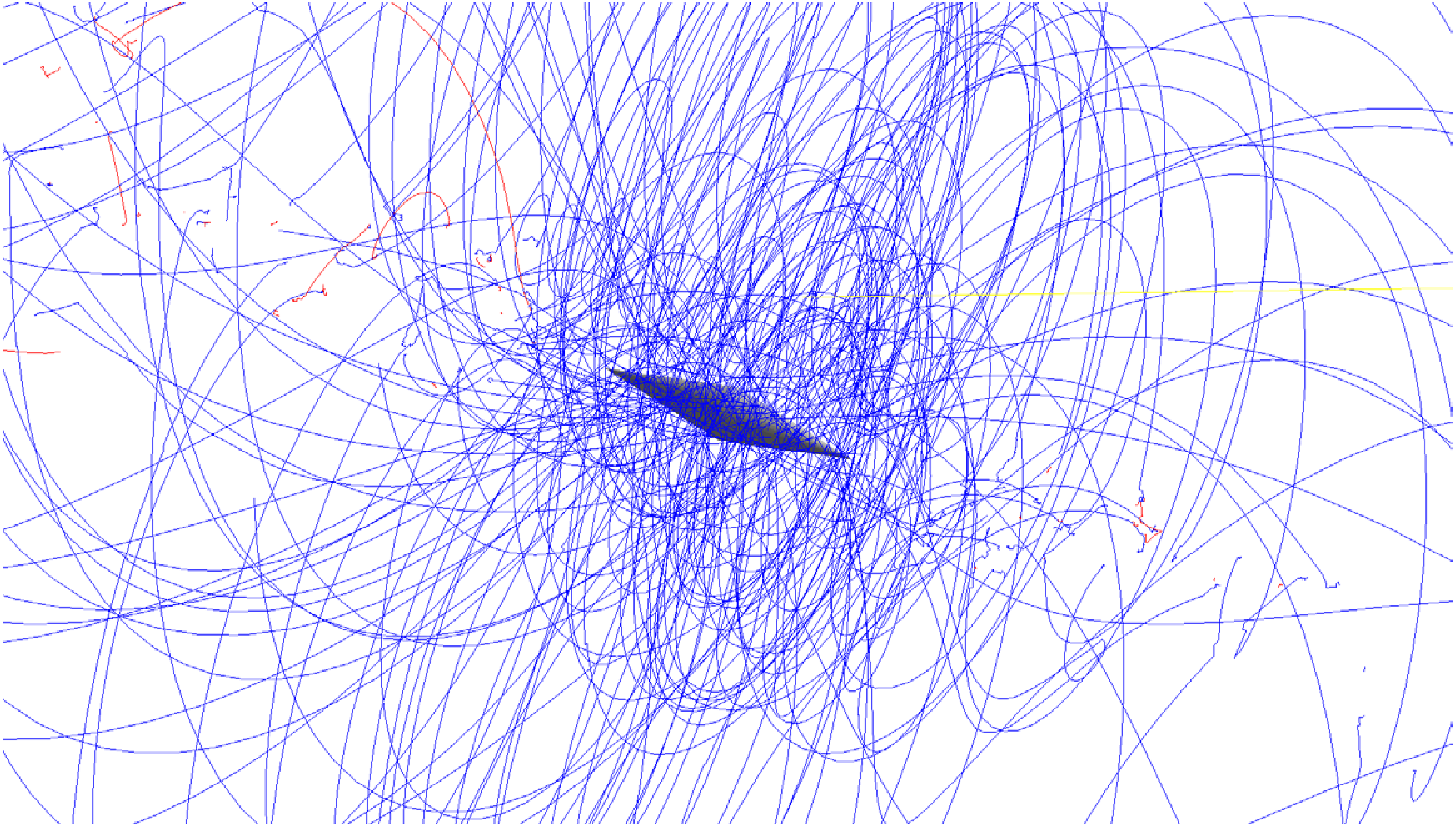
- Need excellent momentum resolution



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

2 Billion Muon Decays/s

50 ns, 1 Tesla field

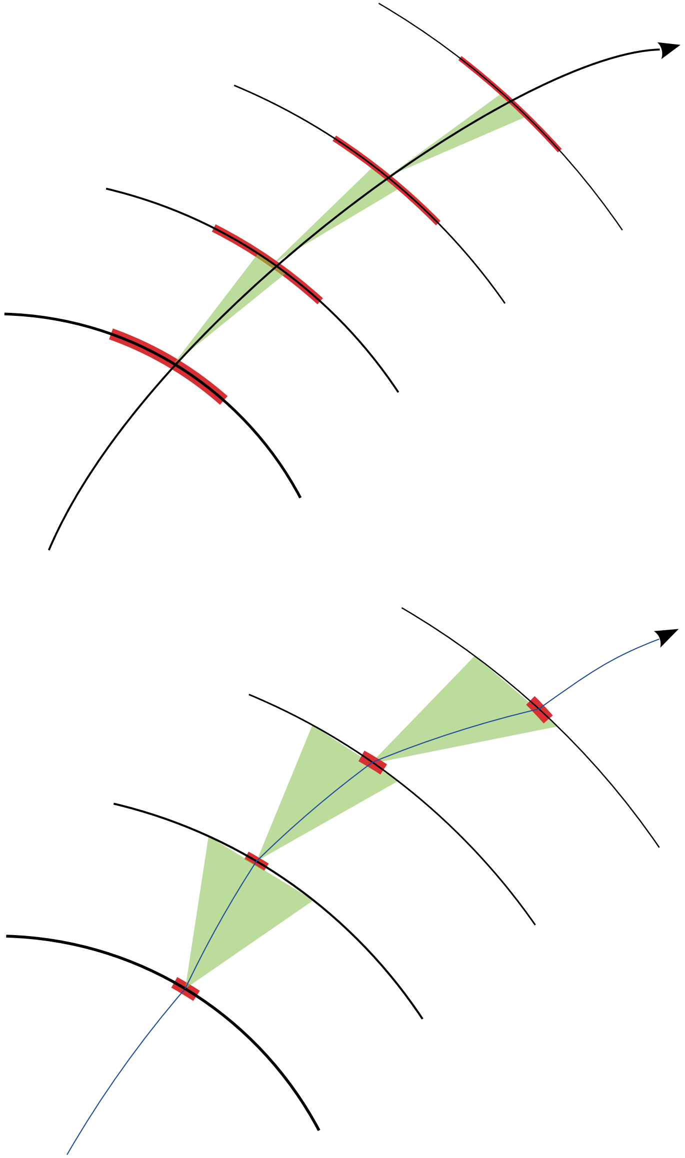


Detector Technology

- 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)

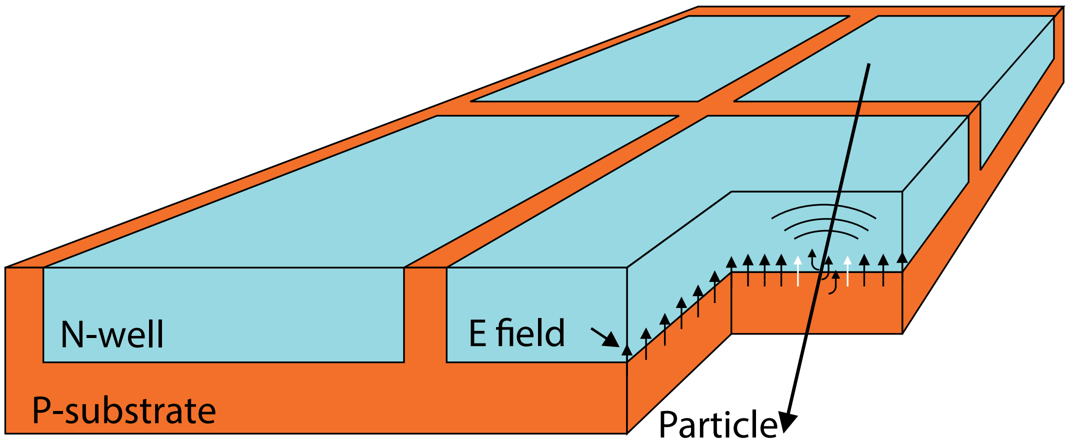
Scattering dominated tracking



- Maximum electron/positron momentum: 53 MeV/c $(m_\mu/2)$
- Momentum resolution dominated by multiple Coulomb scattering
- As little material as possible

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

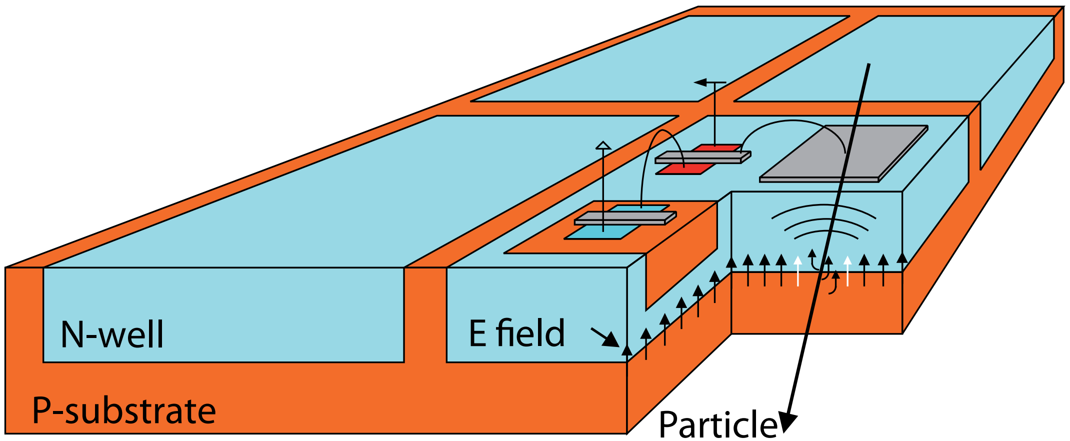
Fast and thin sensors: HV-MAPS



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

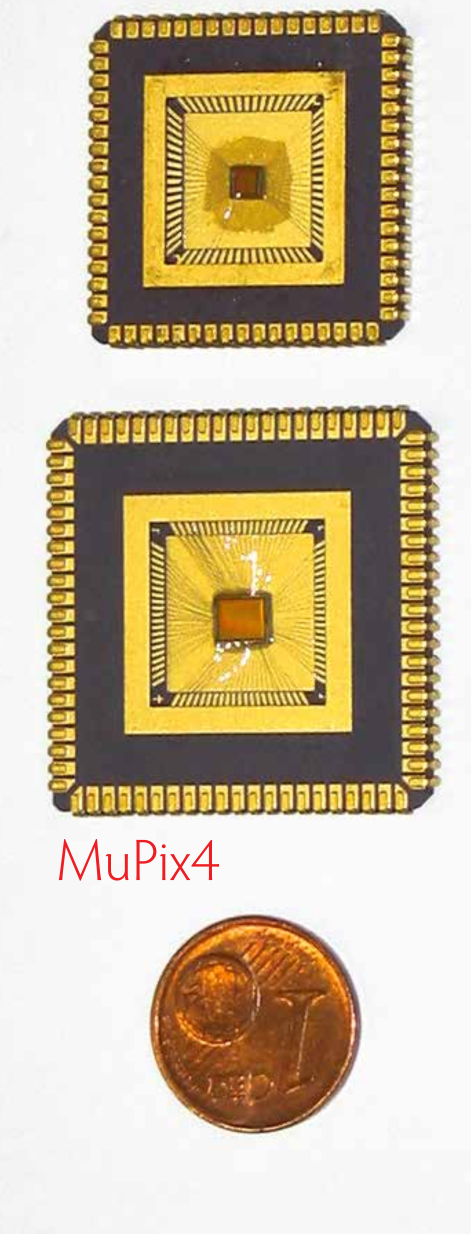


High voltage monolithic active pixel sensors - Ivan Perić

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

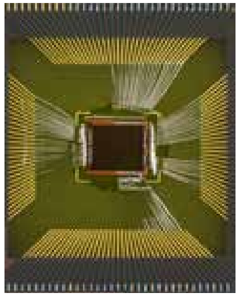
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)

The MuPix chip prototypes

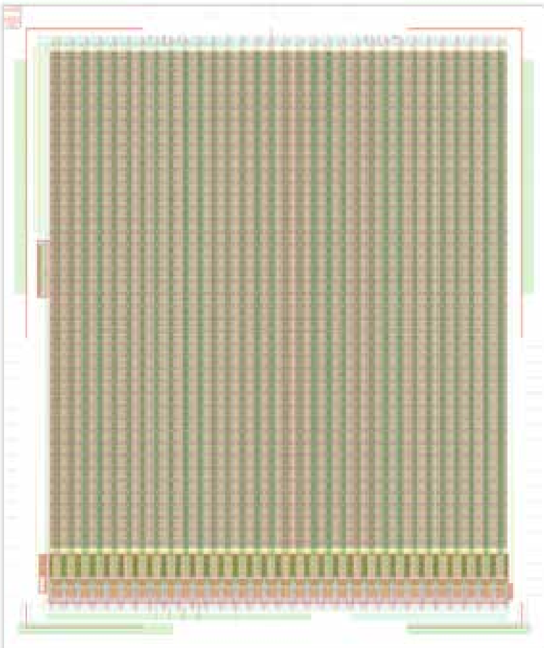


MuPix2

MuPix4



MuPix6



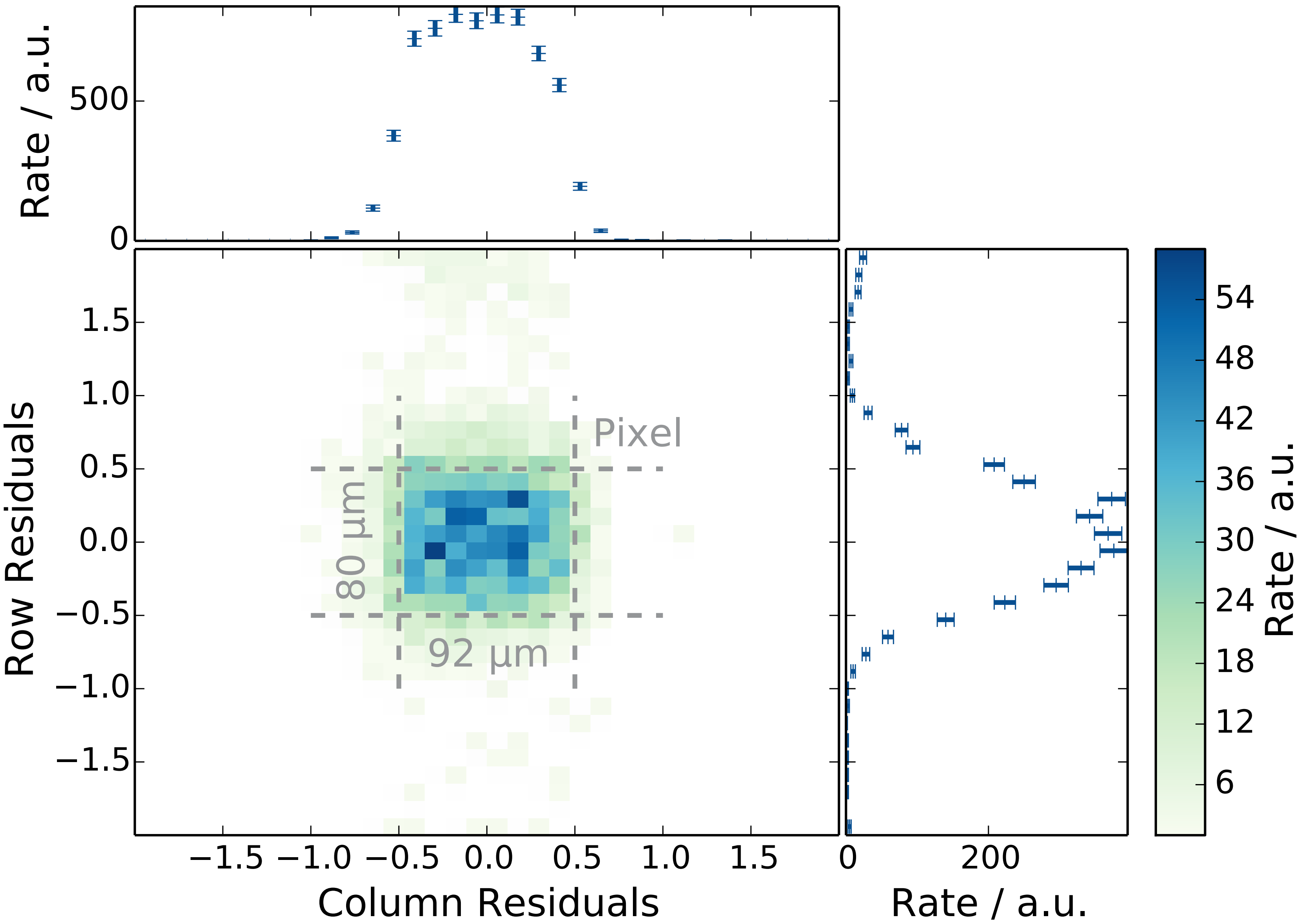
HV-MAPS chips: AMS 180 nm HV-CMOS

- 5 generations of prototypes
- Current generation:
  MuPix7
  40 x 32 pixels
  80 x 103 µm pixel size
  9.4 mm^2 active area
- Test beam results with MuPix4/6
- MuPix7 has all features of final sensor, currently under test
- Left to do: Scale to 2 x 2 cm^2

Test beam at DESY

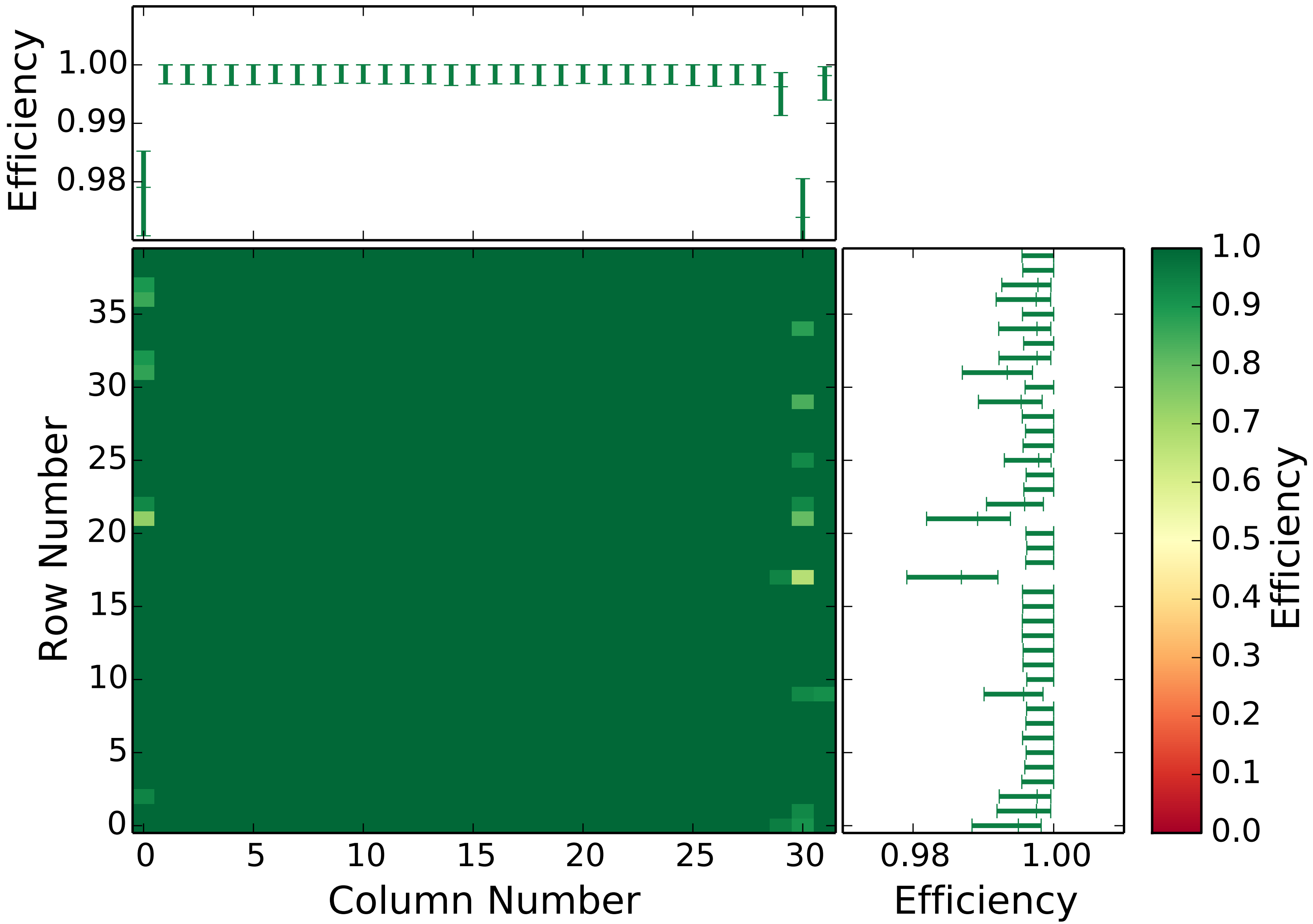
Position Resolution

Position resolution given by pixel size

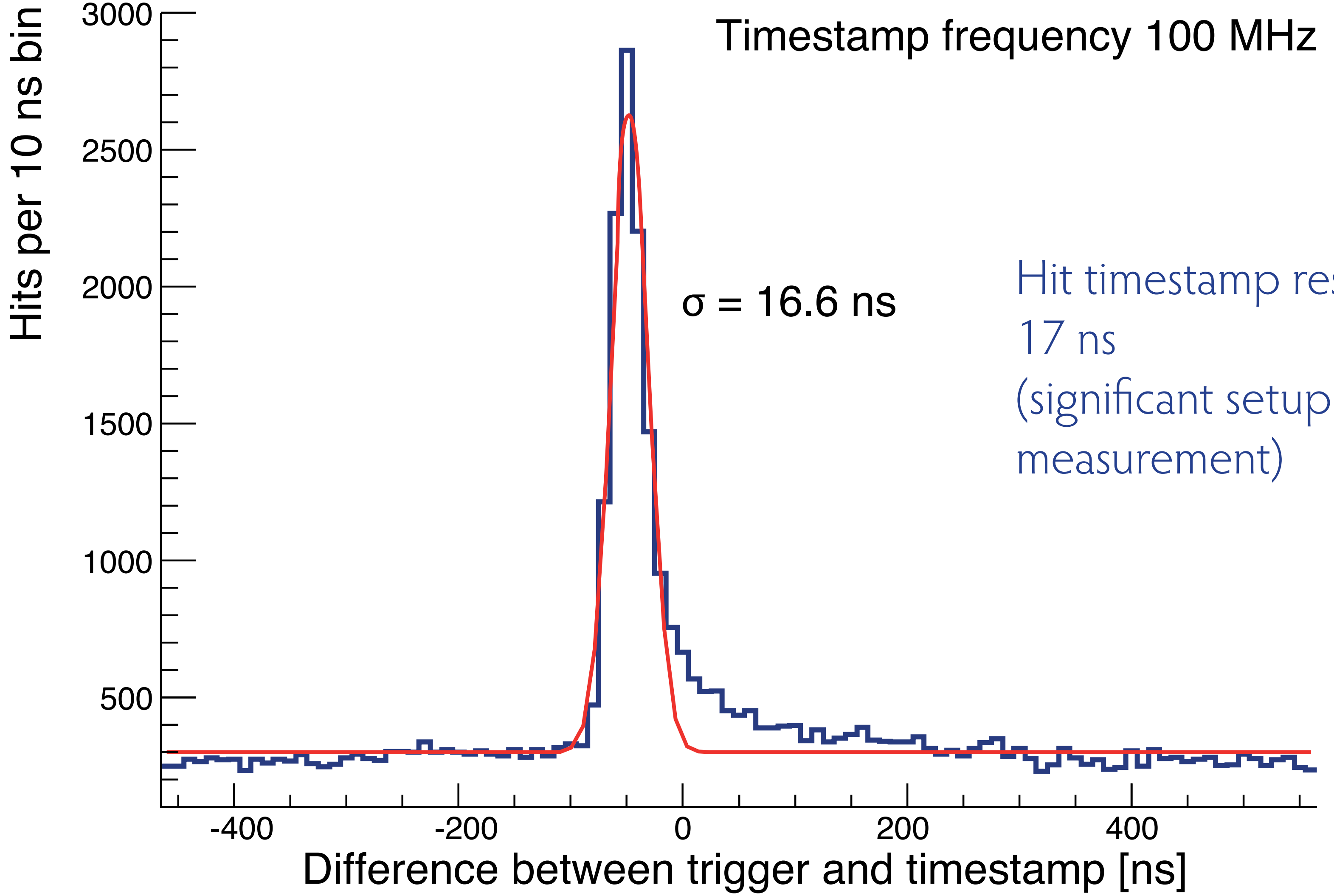


Efficiency

Hit efficiency above 99% without tuning



Time resolution

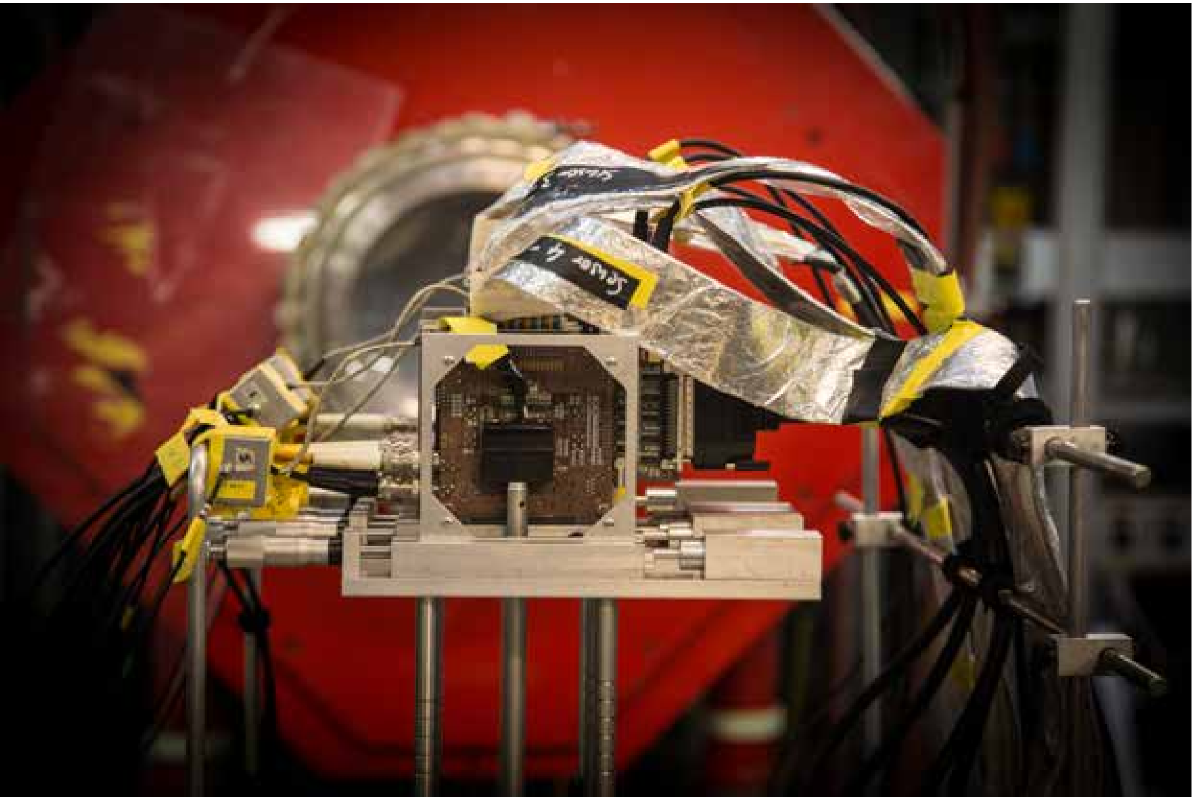


Hit timestamp resolution better than 17 ns
(significant setup contribution in the measurement)

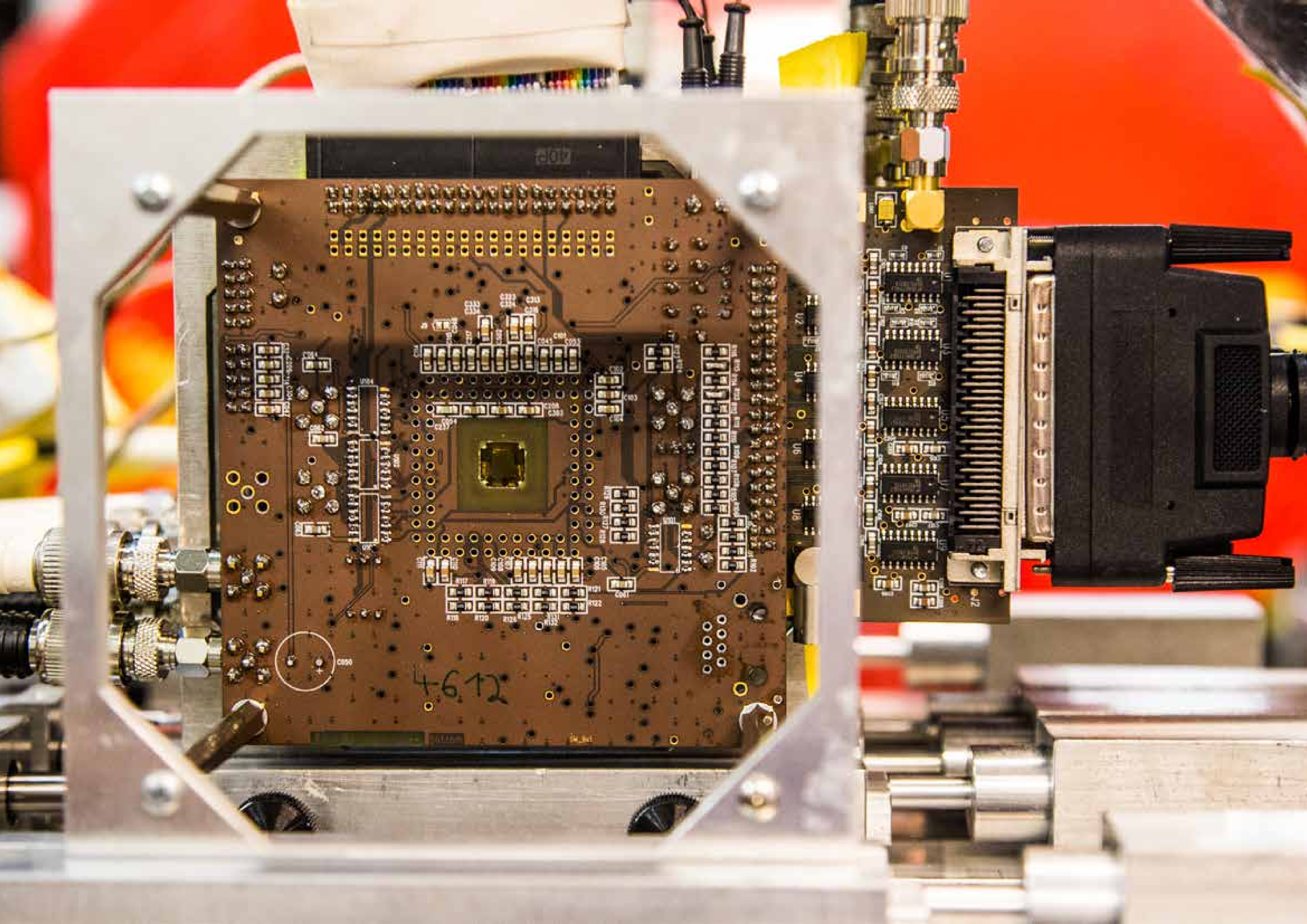
MuPix Telescope

Built our own pixel telescope

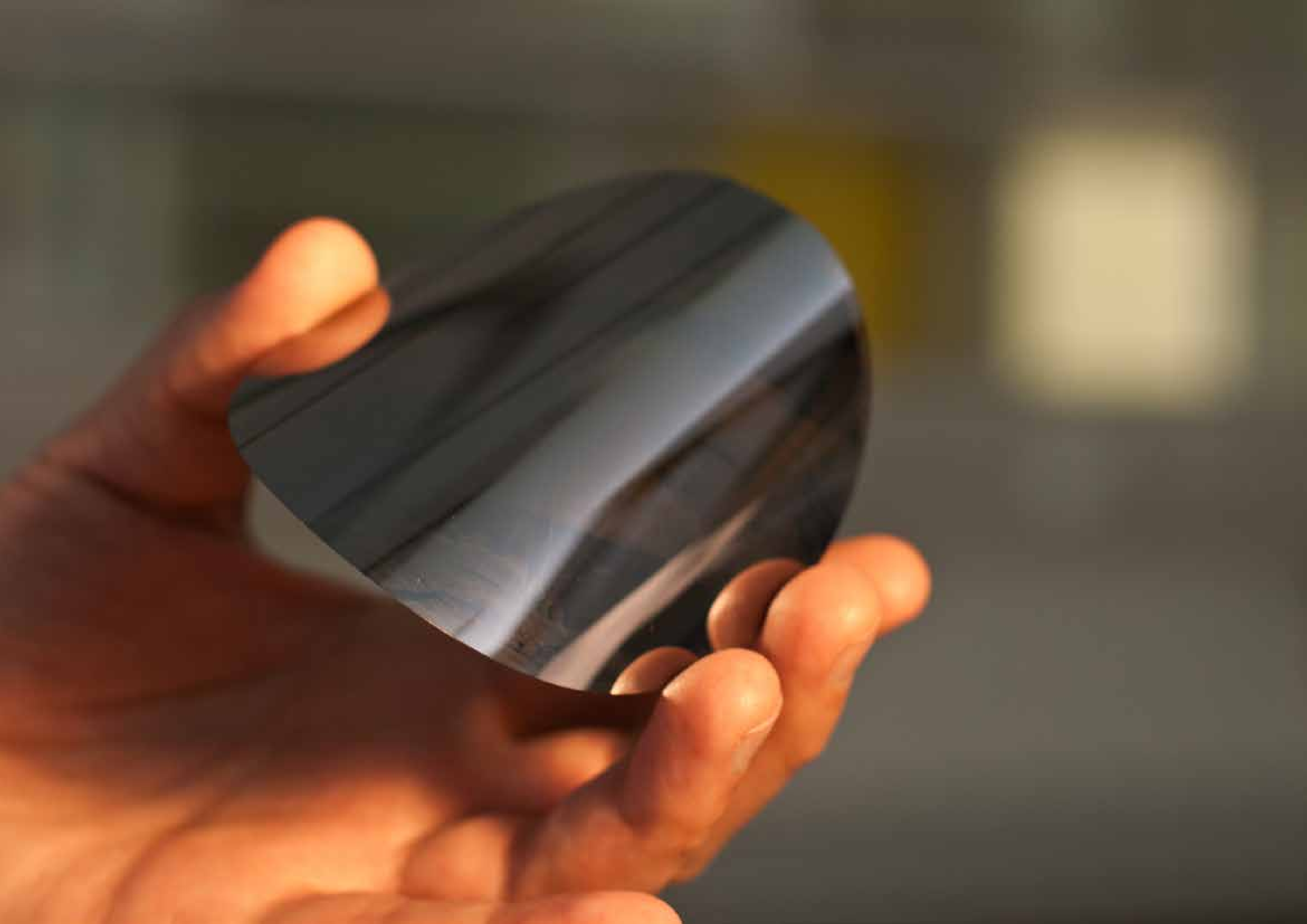
- Four planes of thin MuPix sensors
- Fast readout into PCIe FPGA cards
- Currently about 1 MHz hits/plane possible
- Tested at DESY and PSI



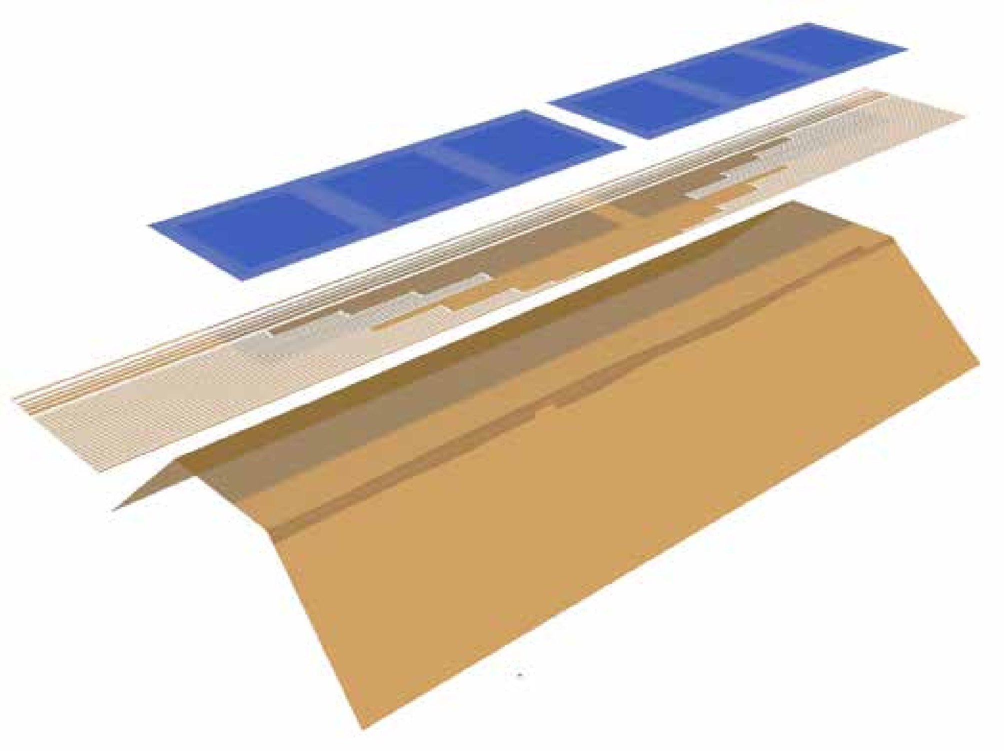

+HV
Tile 3


4612

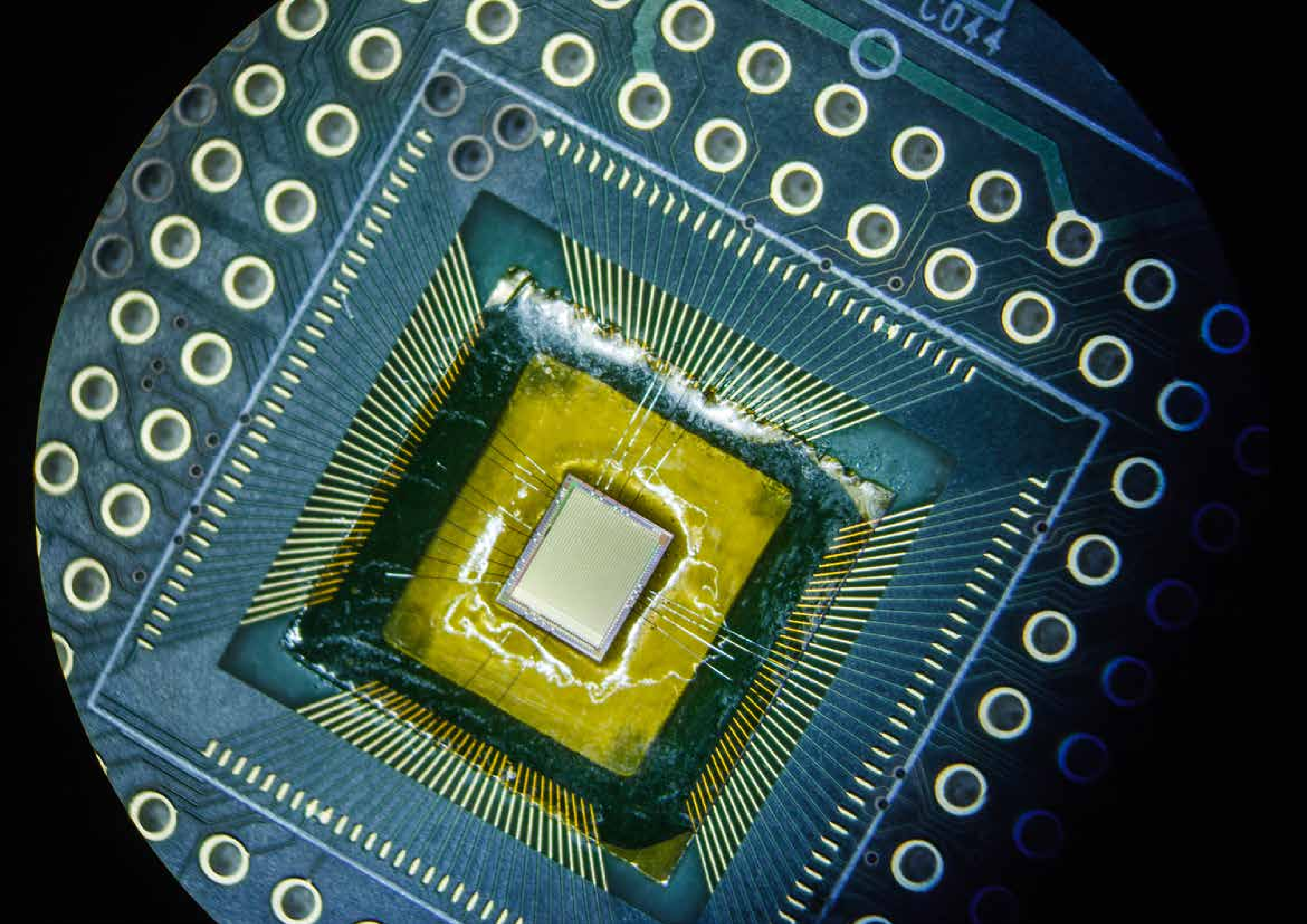
Building a detector thinner than a hair



Mechanics



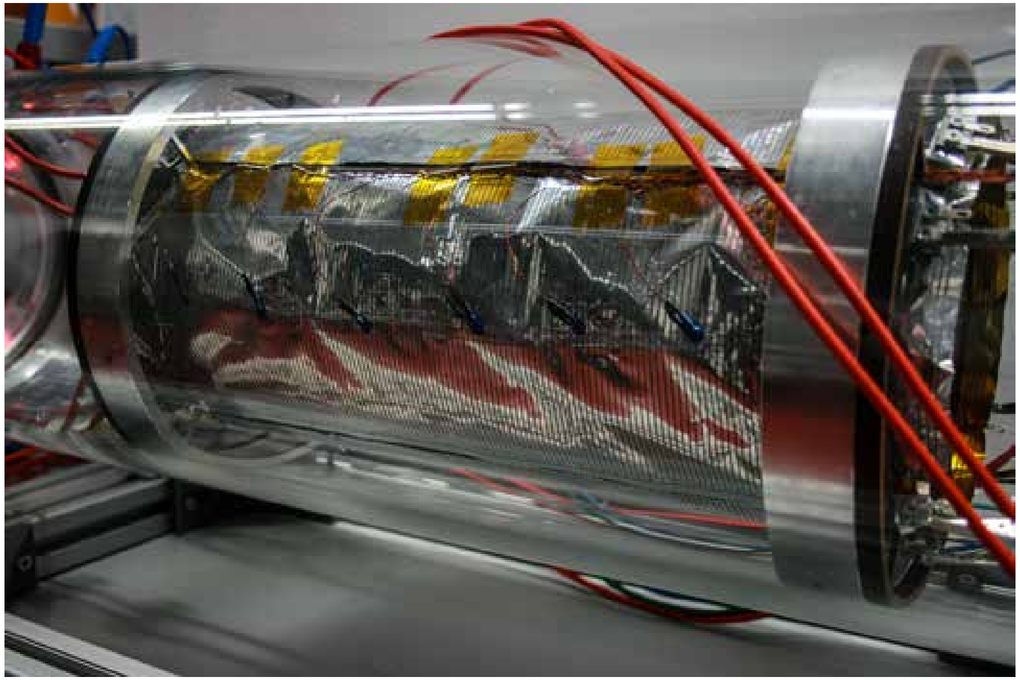
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

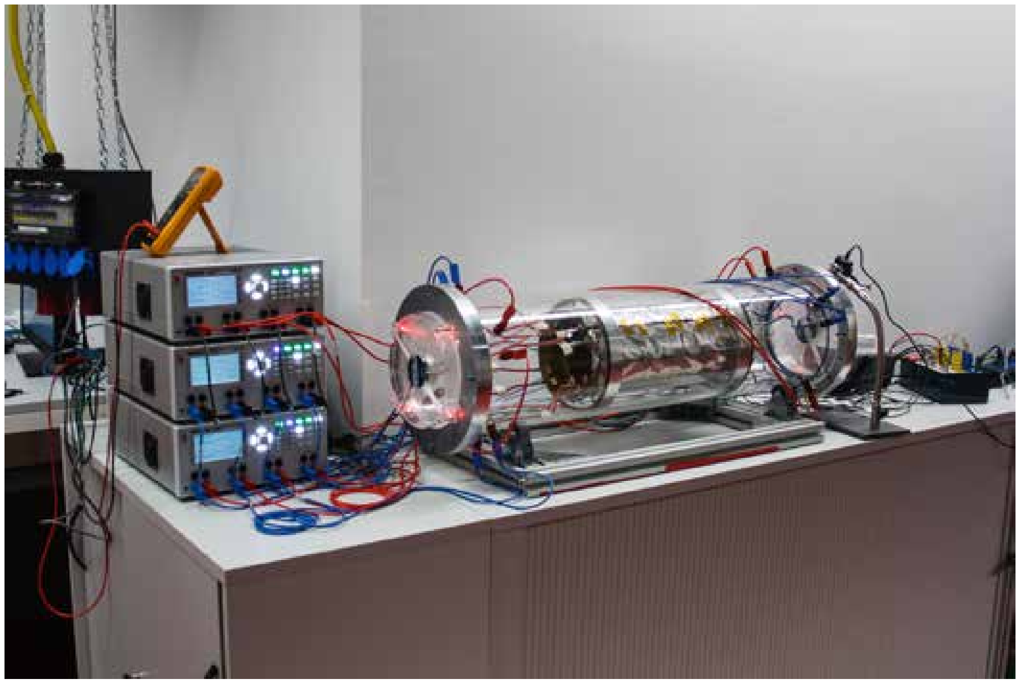

C044

Cooling

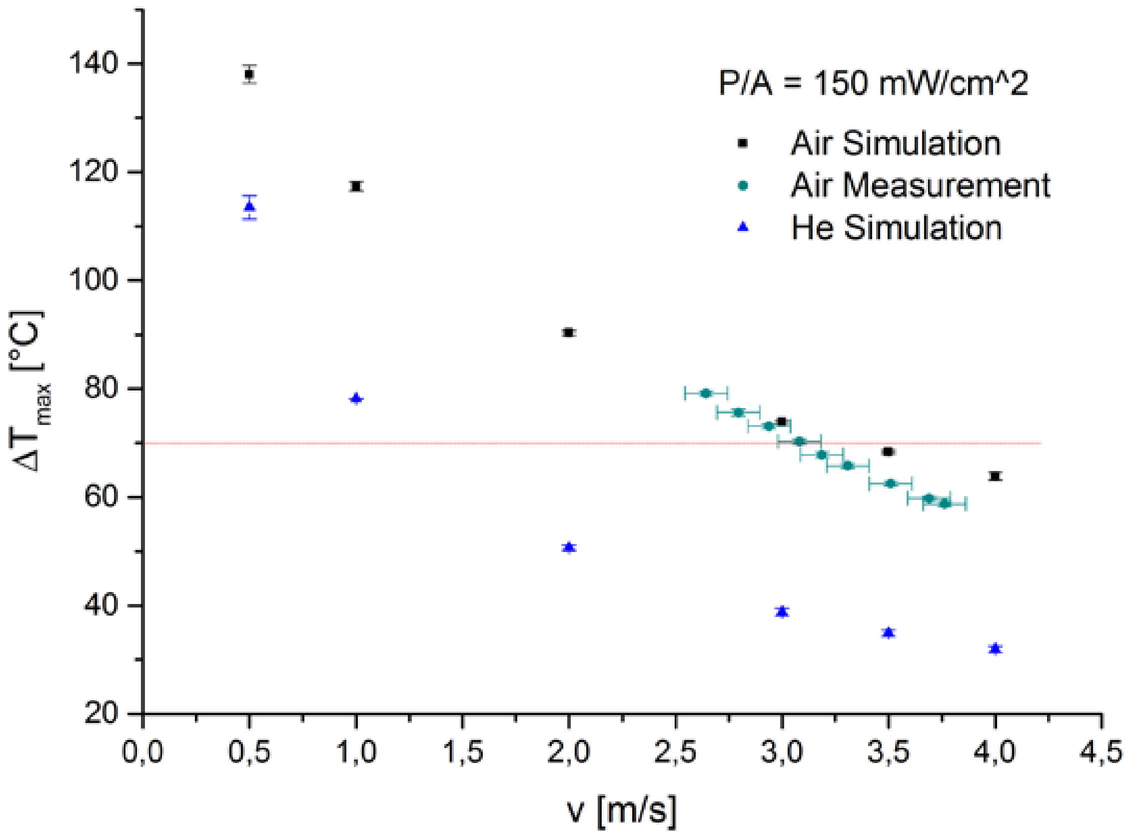
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 150 mW/cm^2 - total 2 kW
- Simulations: Need ~ several m/s flow

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



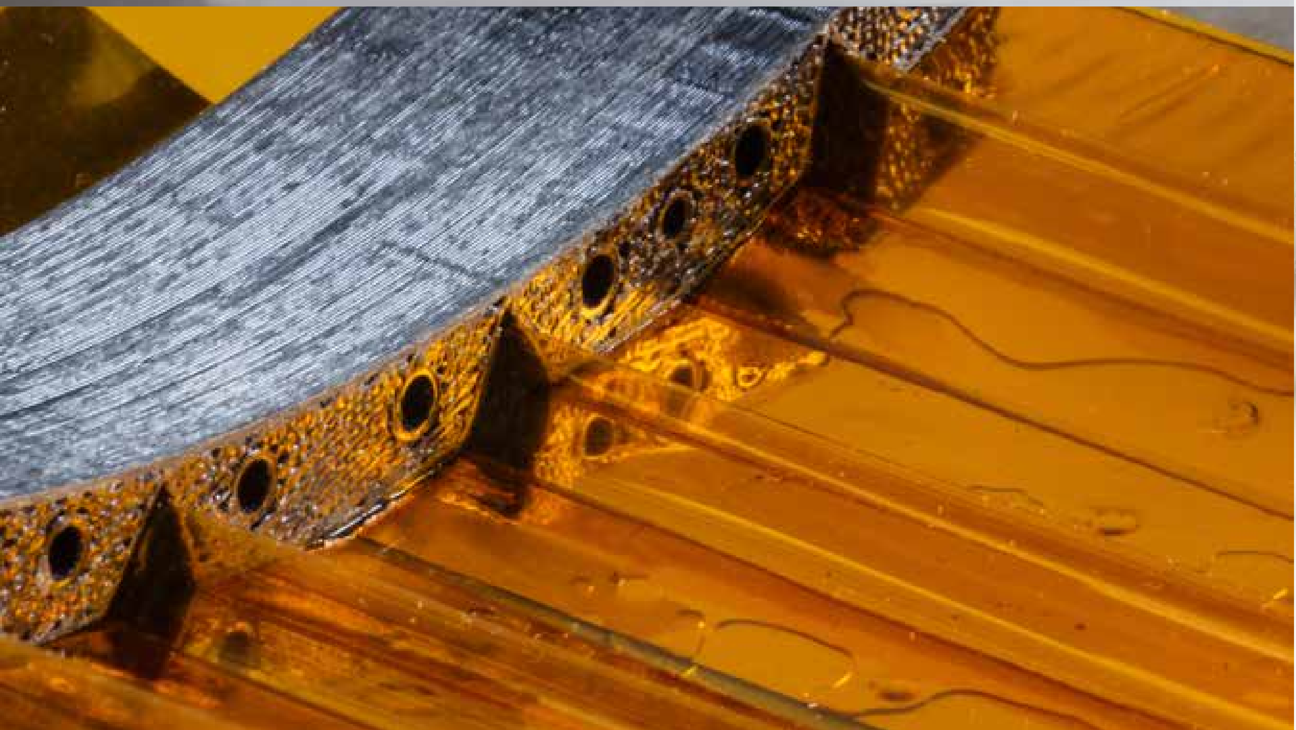


Cooling tests

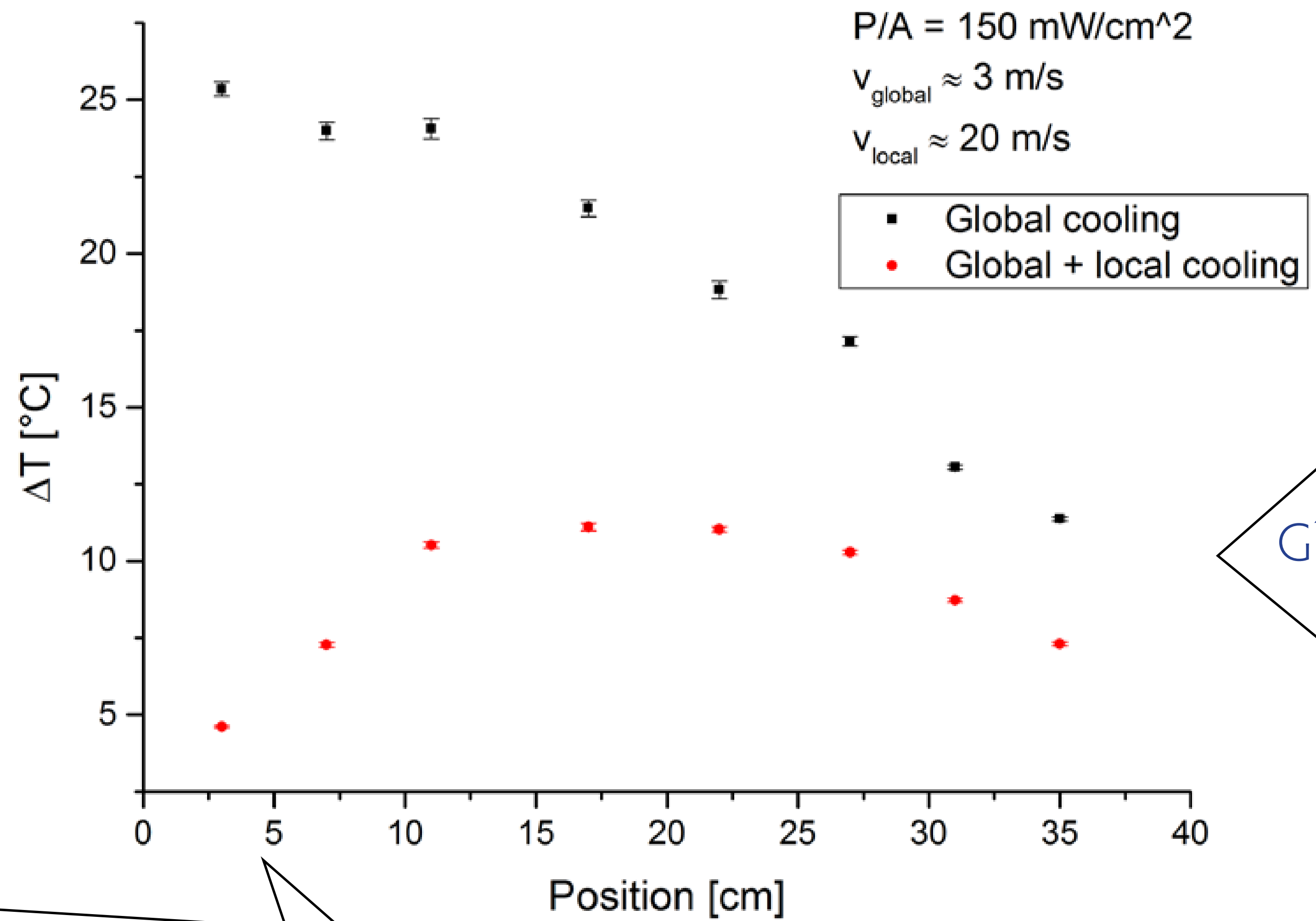


- Can keep gradients under 30°C over 36 cm with helium cooling
- Can add local cooling


Ring 4
vorne



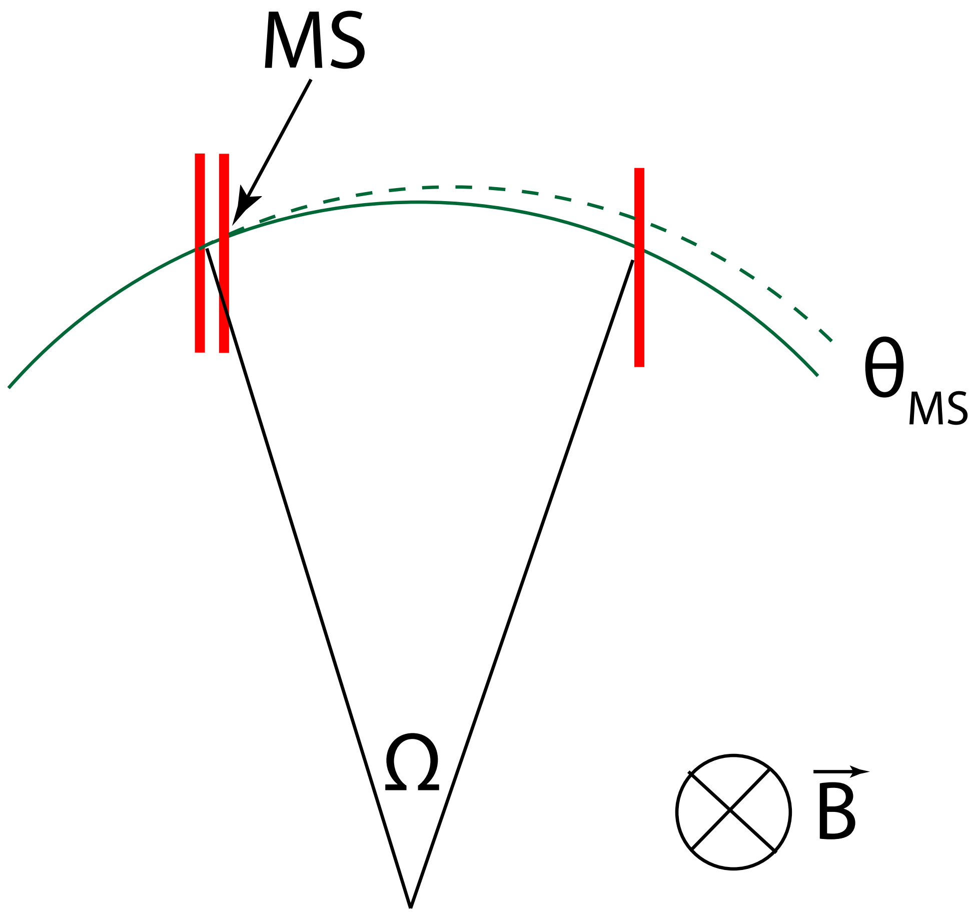
Cooling tests



Global helium stream

Local helium stream

Momentum measurement

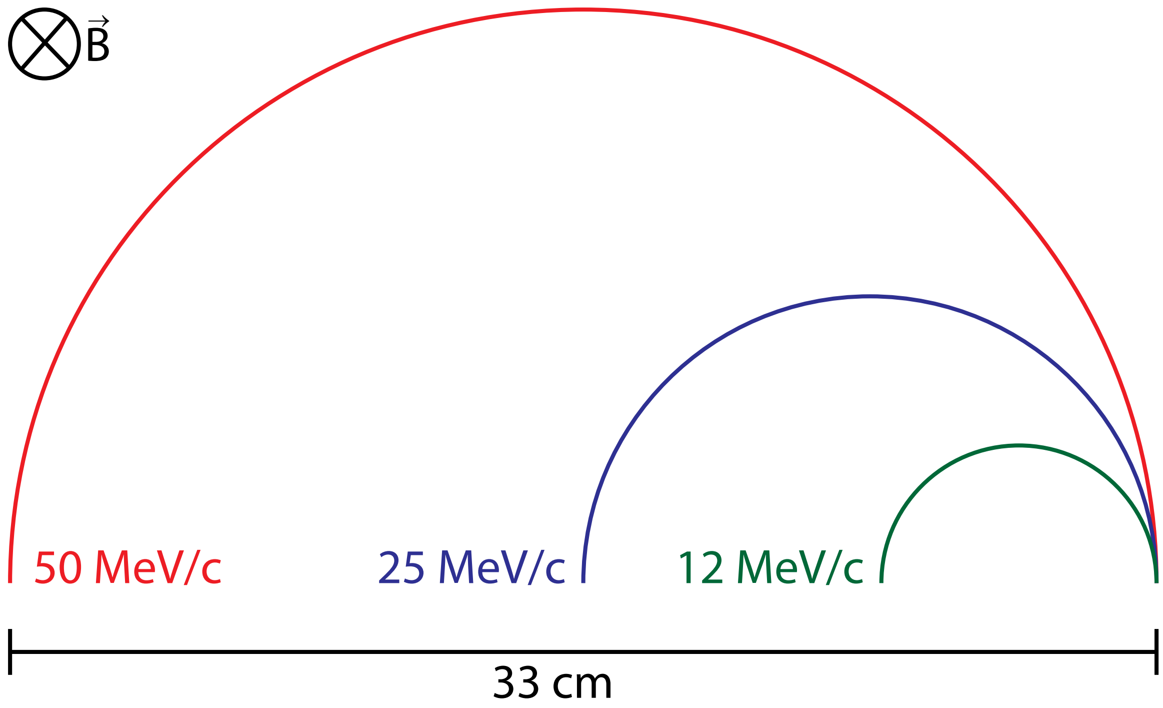


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

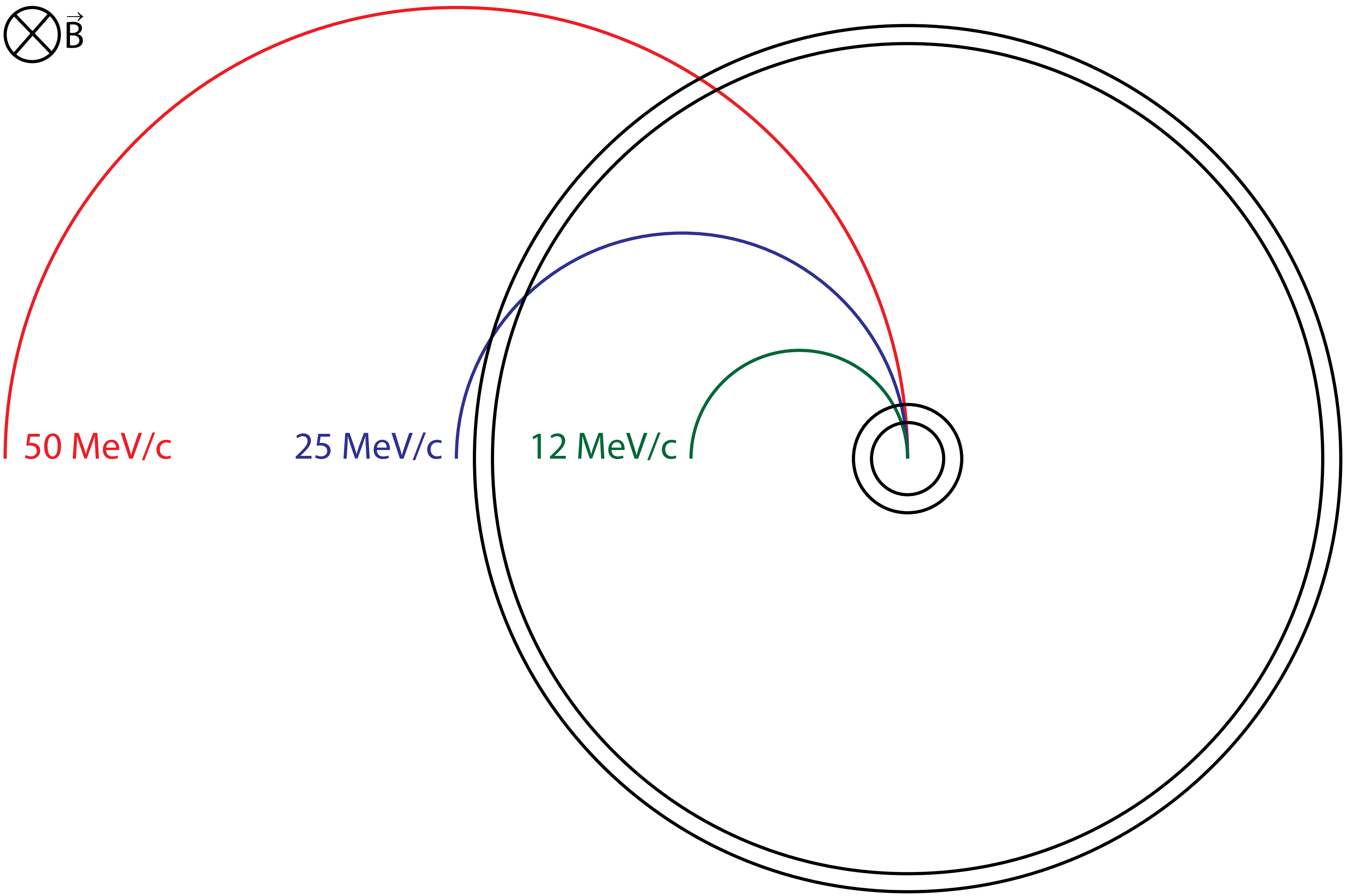
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

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

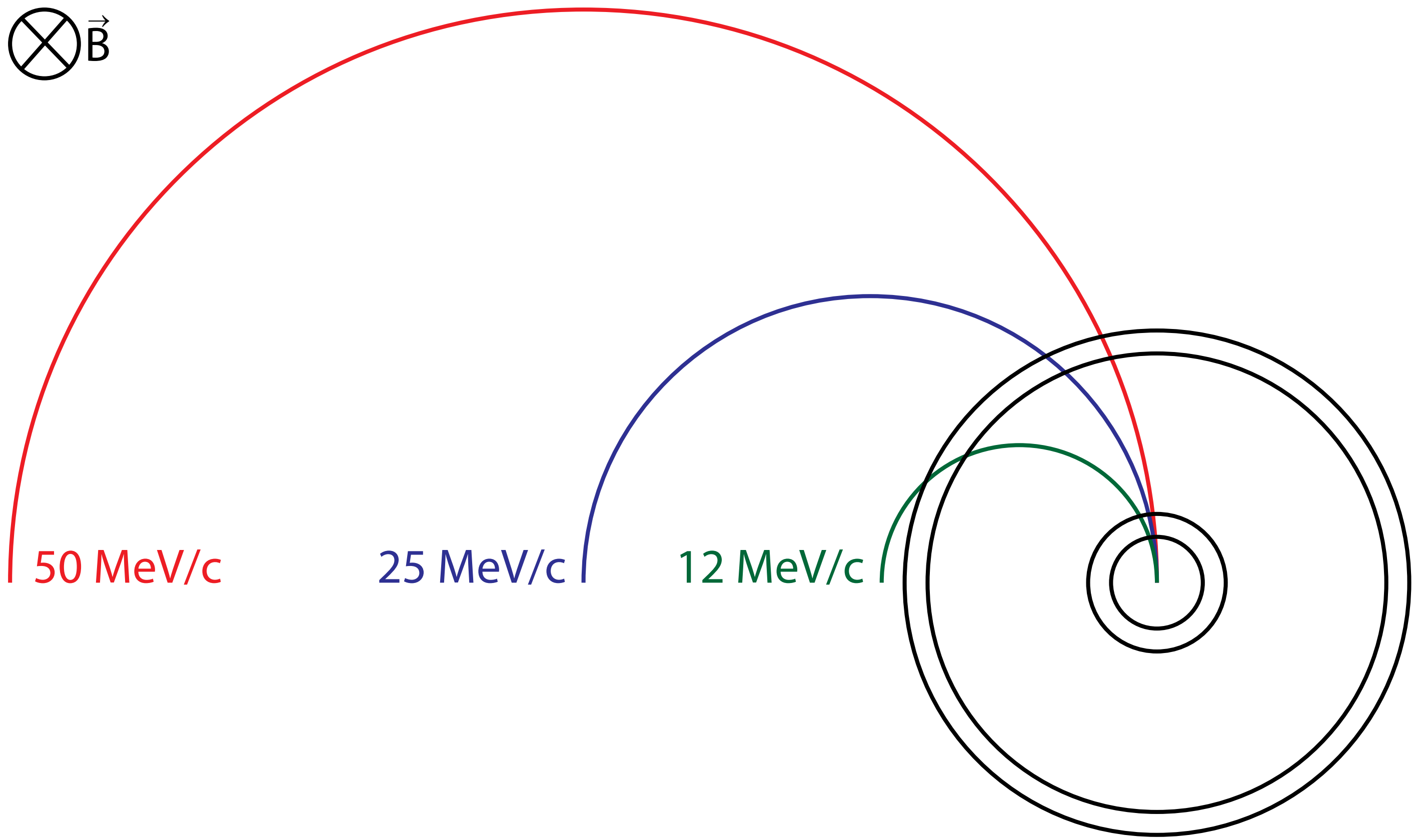
Precision vs. Acceptance



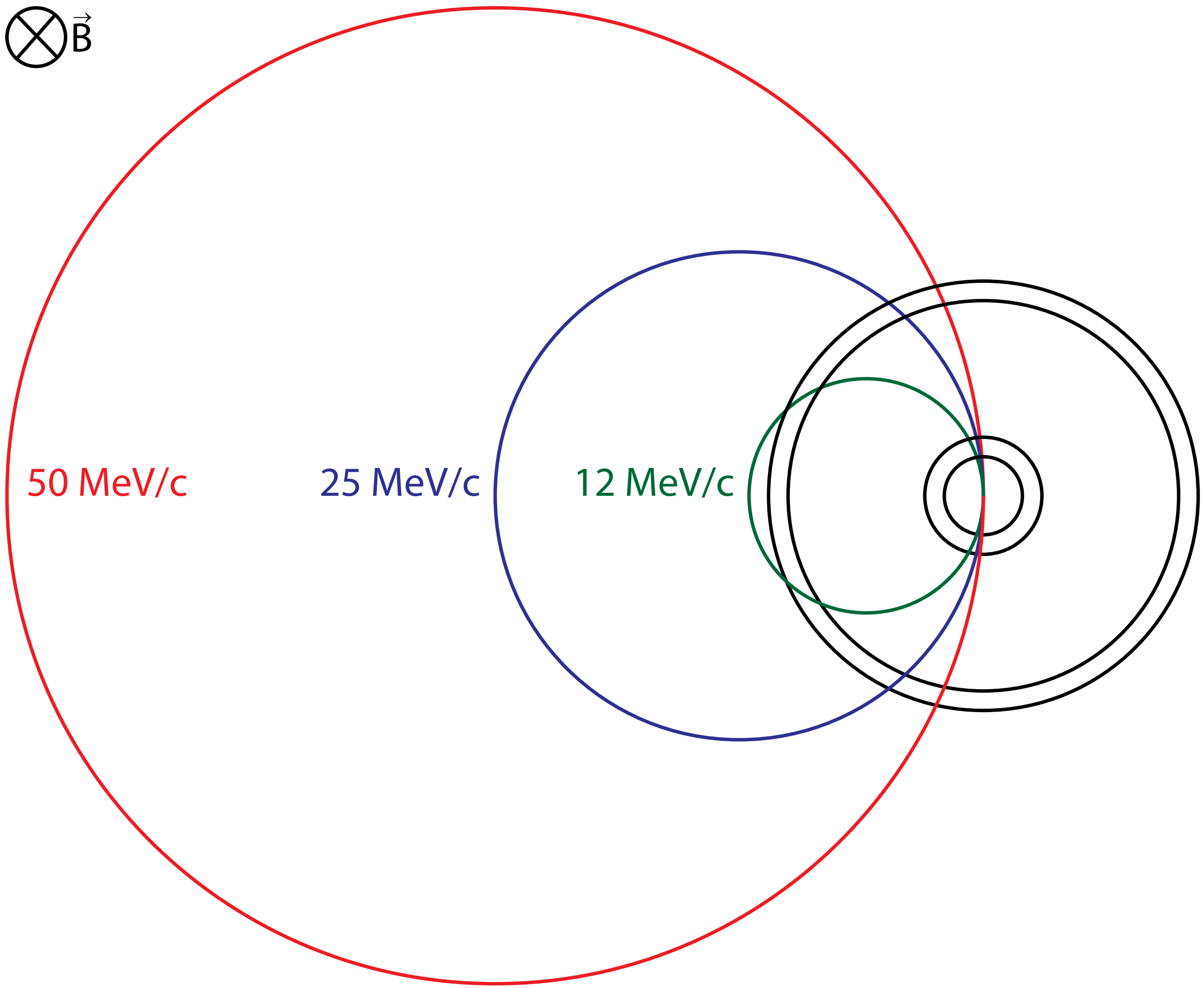
Precision vs. Acceptance



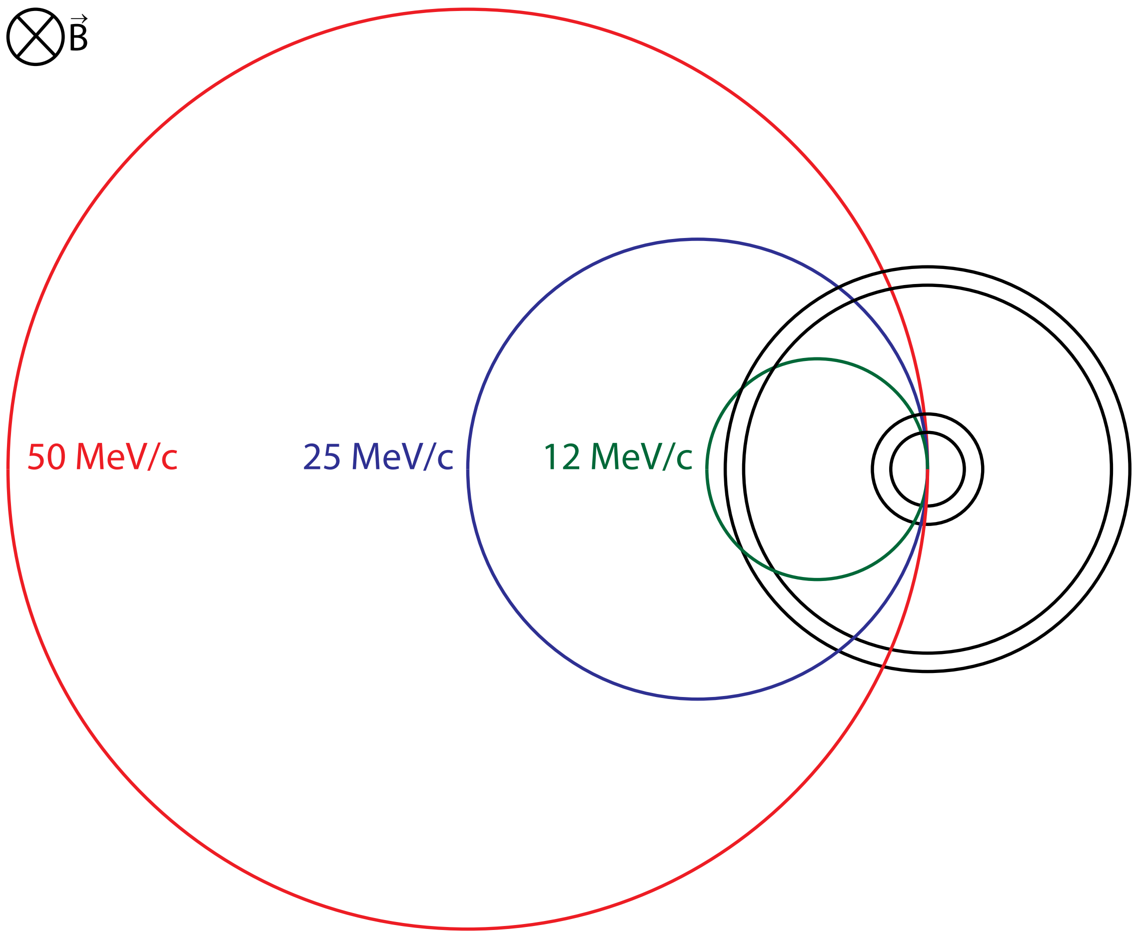
Precision vs. Acceptance

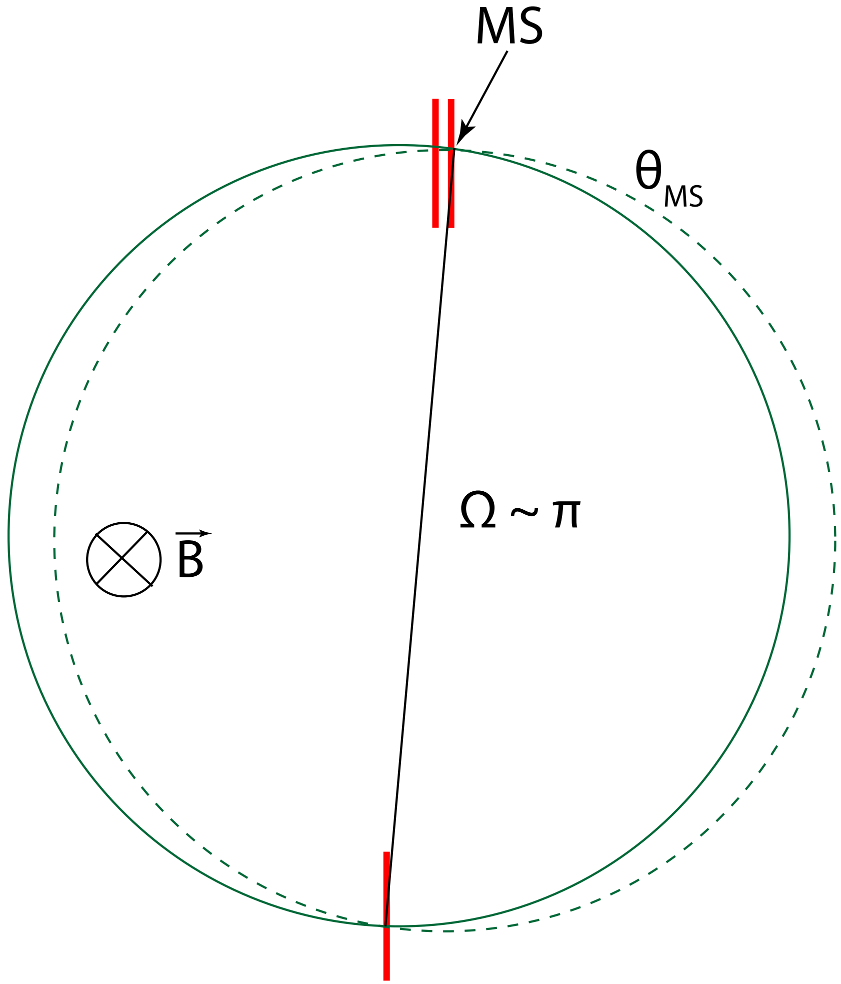


Precision vs. Acceptance

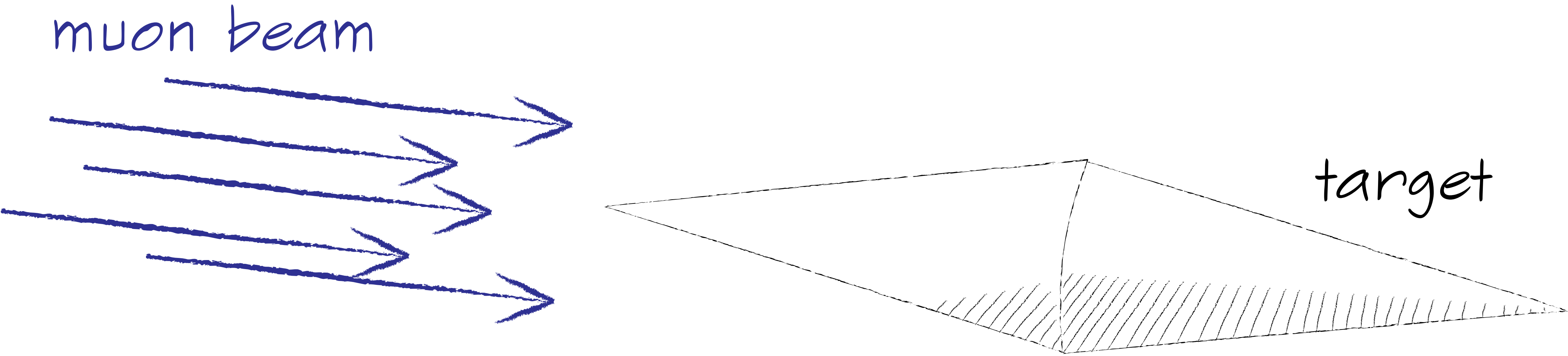


Precision vs. Acceptance

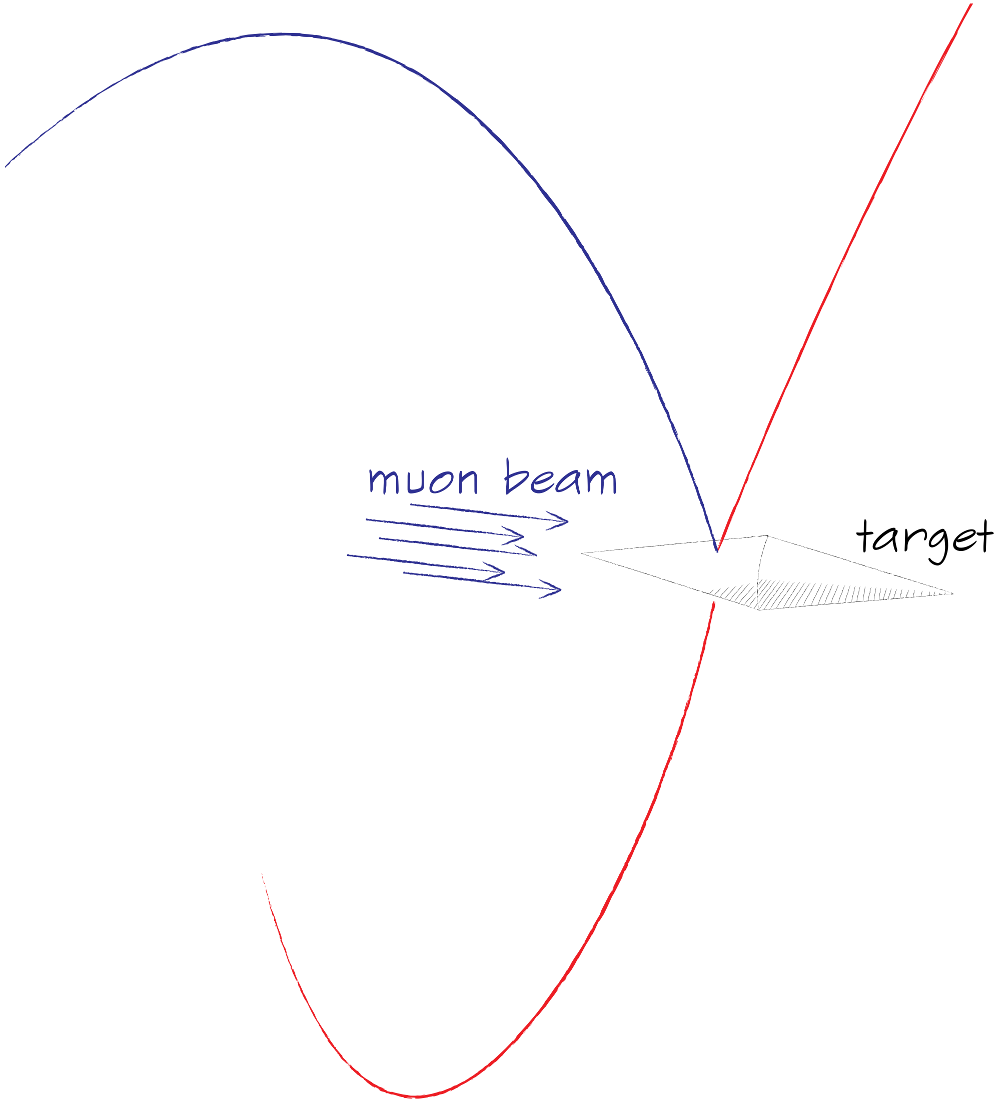




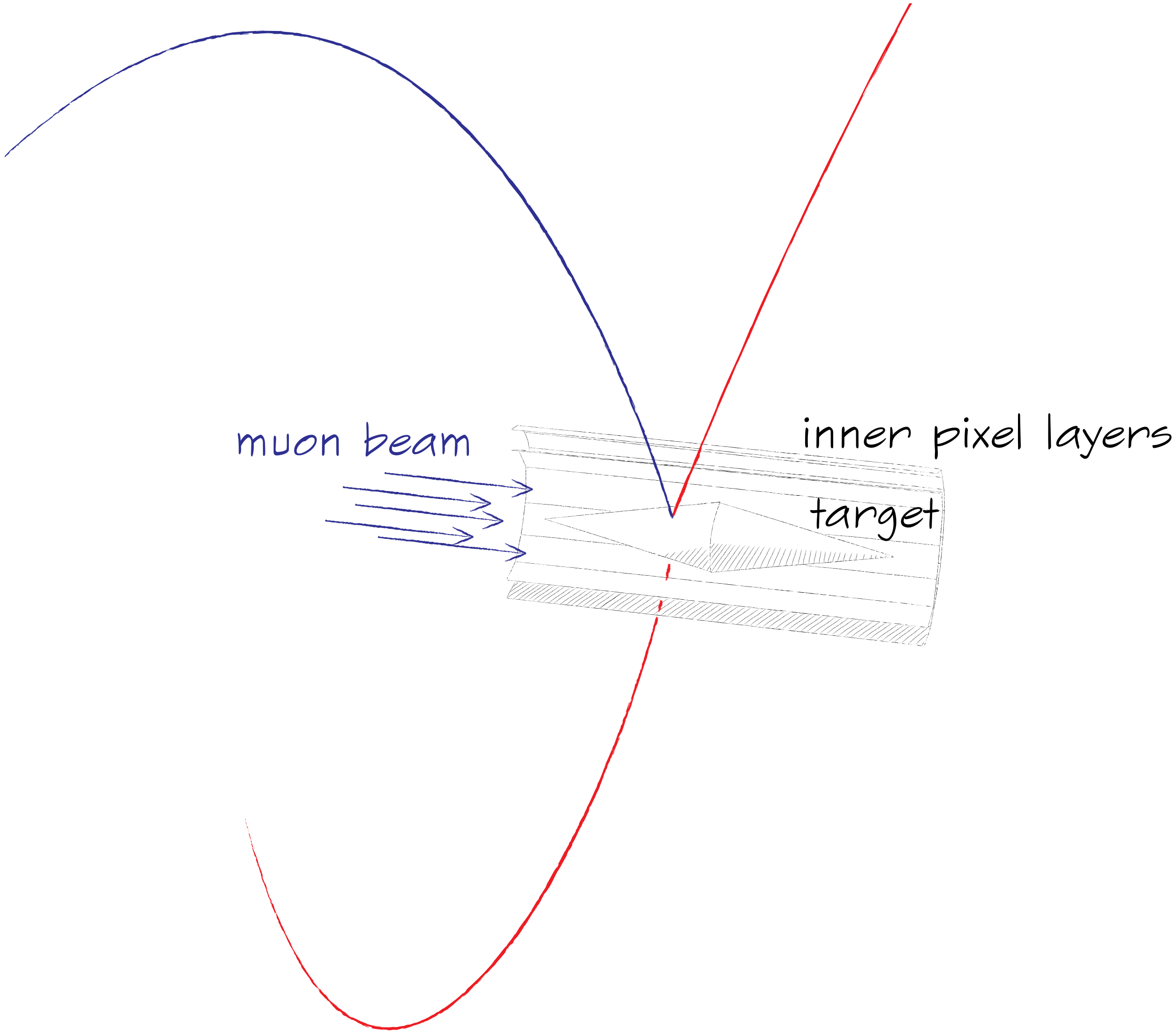
Detector Design



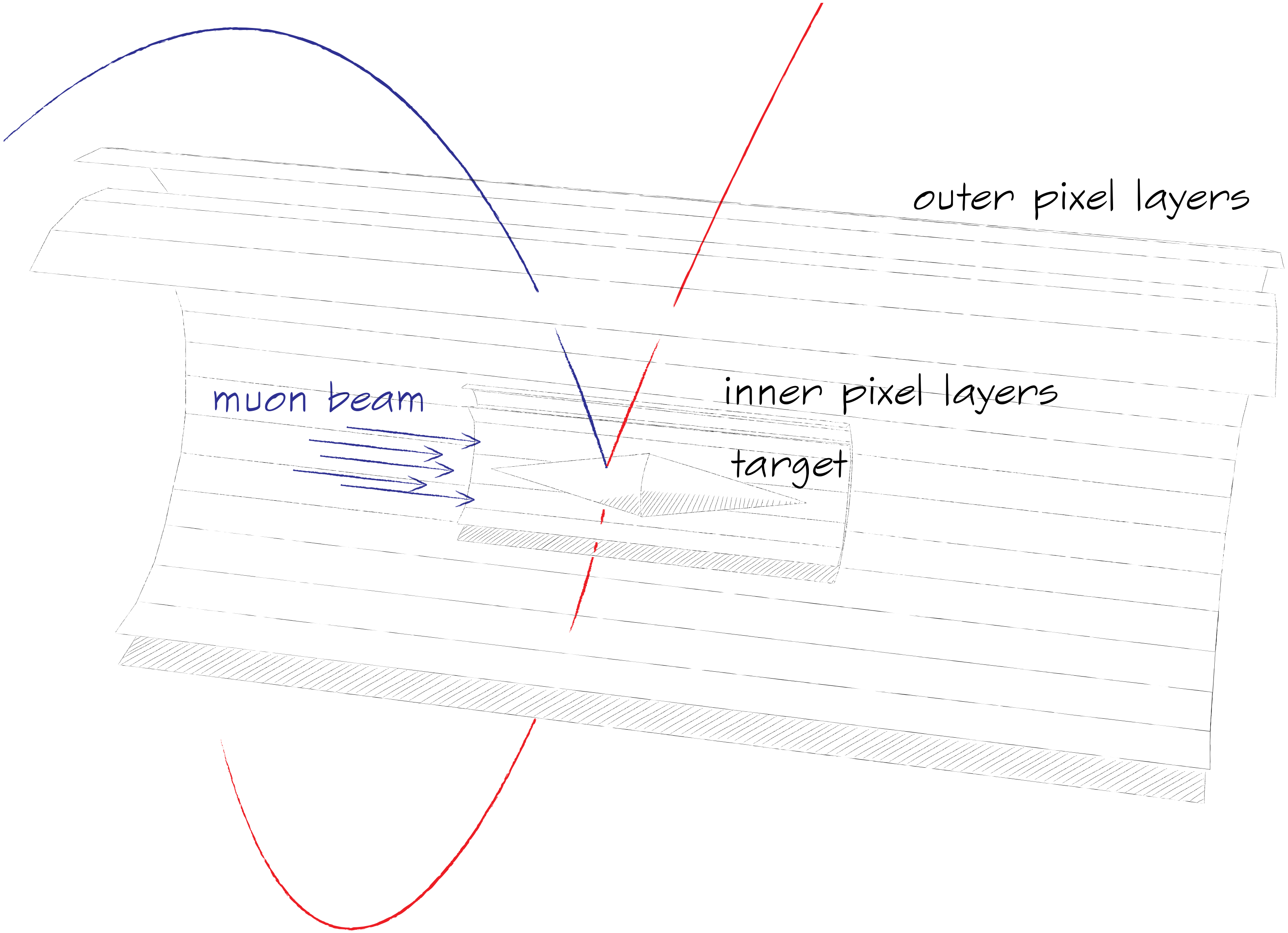
Detector Design



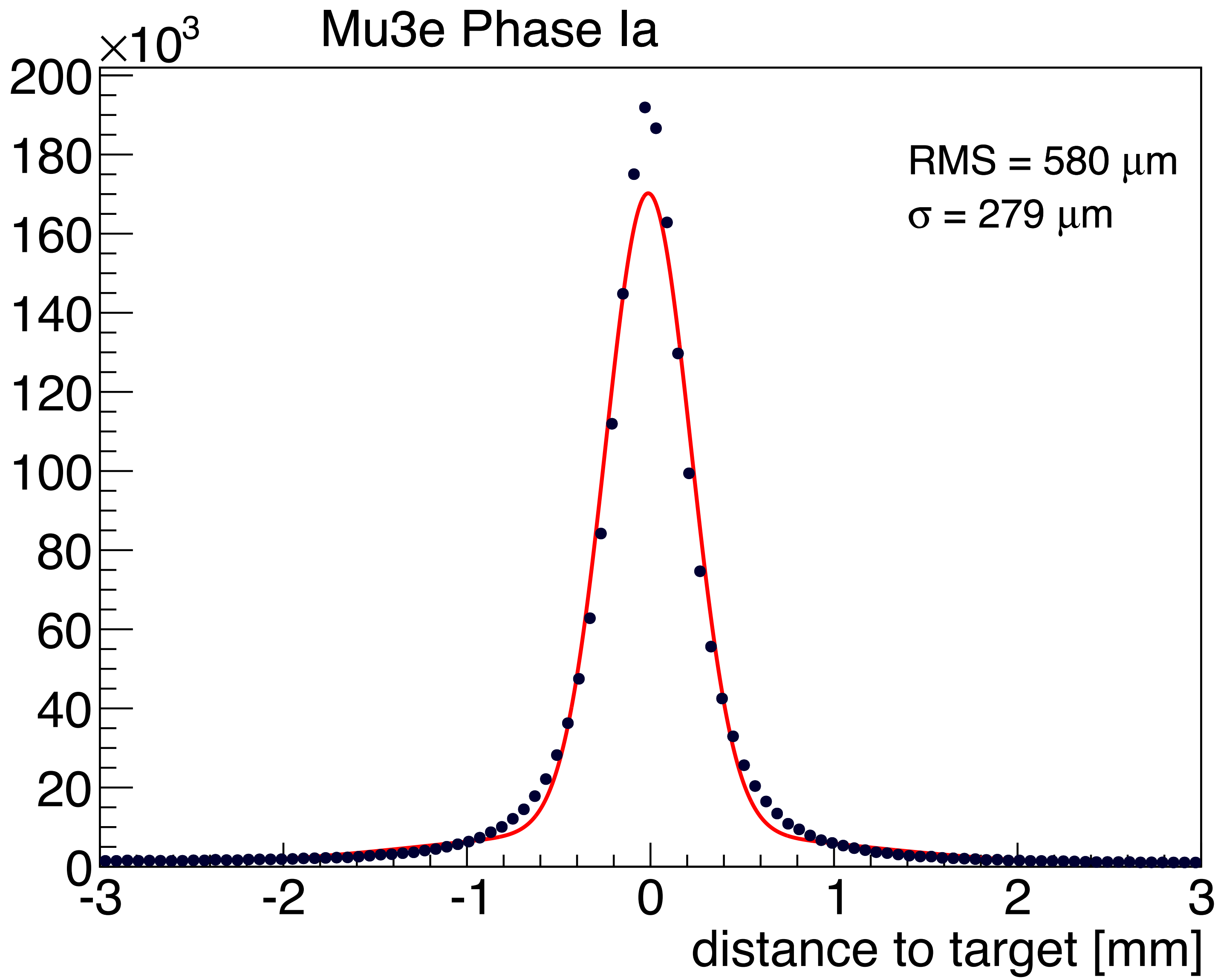
Detector Design



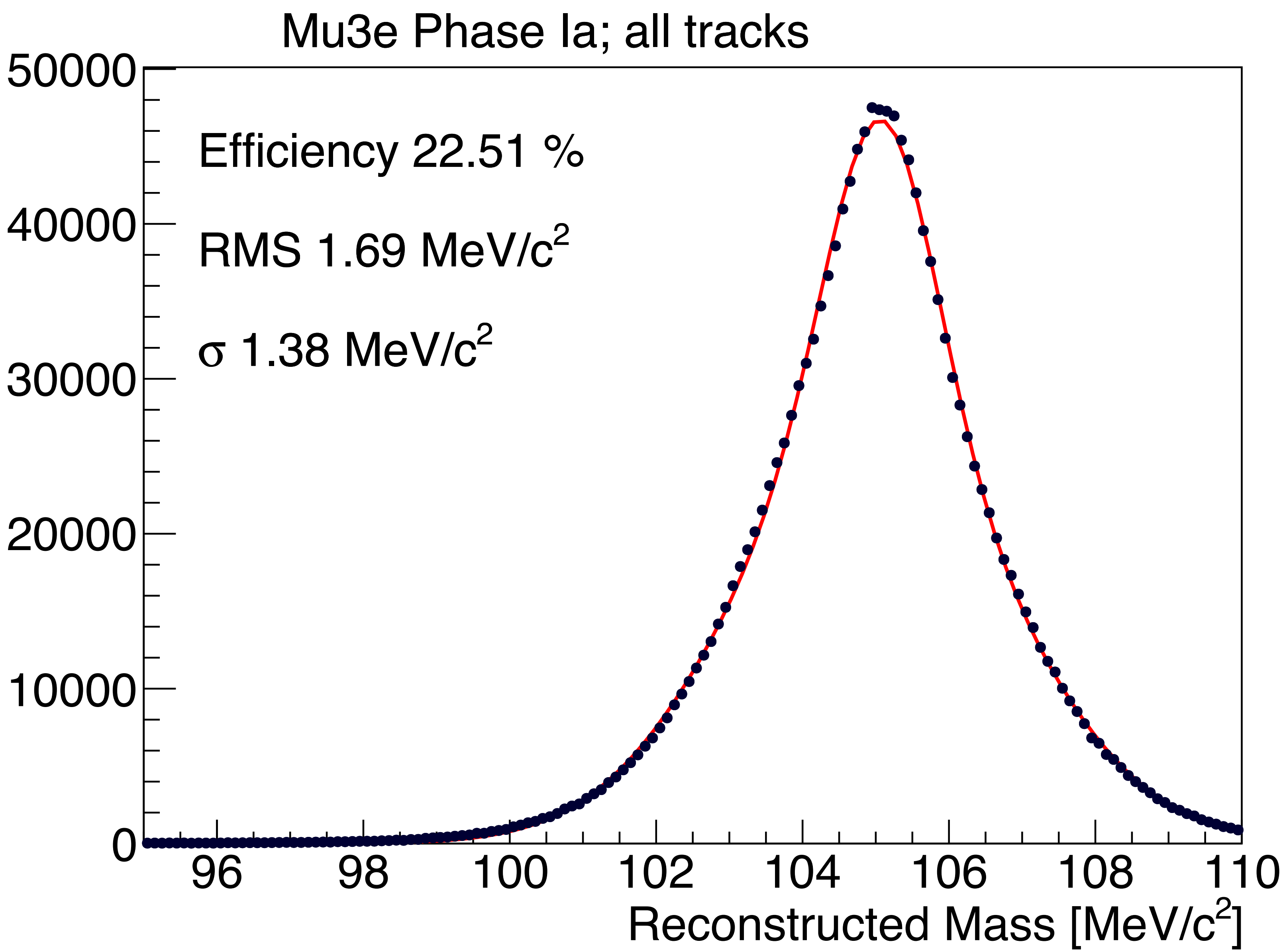
Detector Design



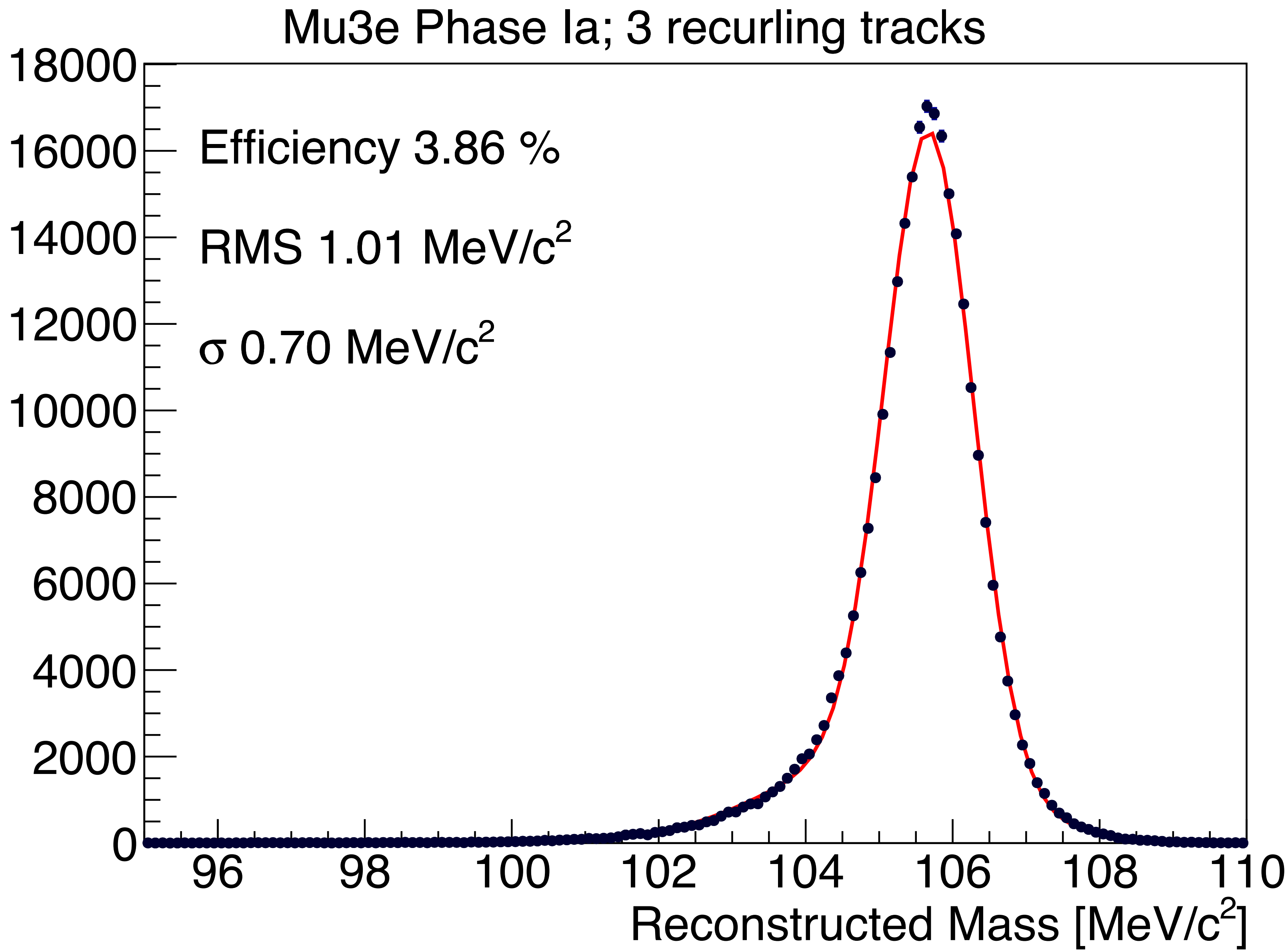
Performance Simulations: Vertexing



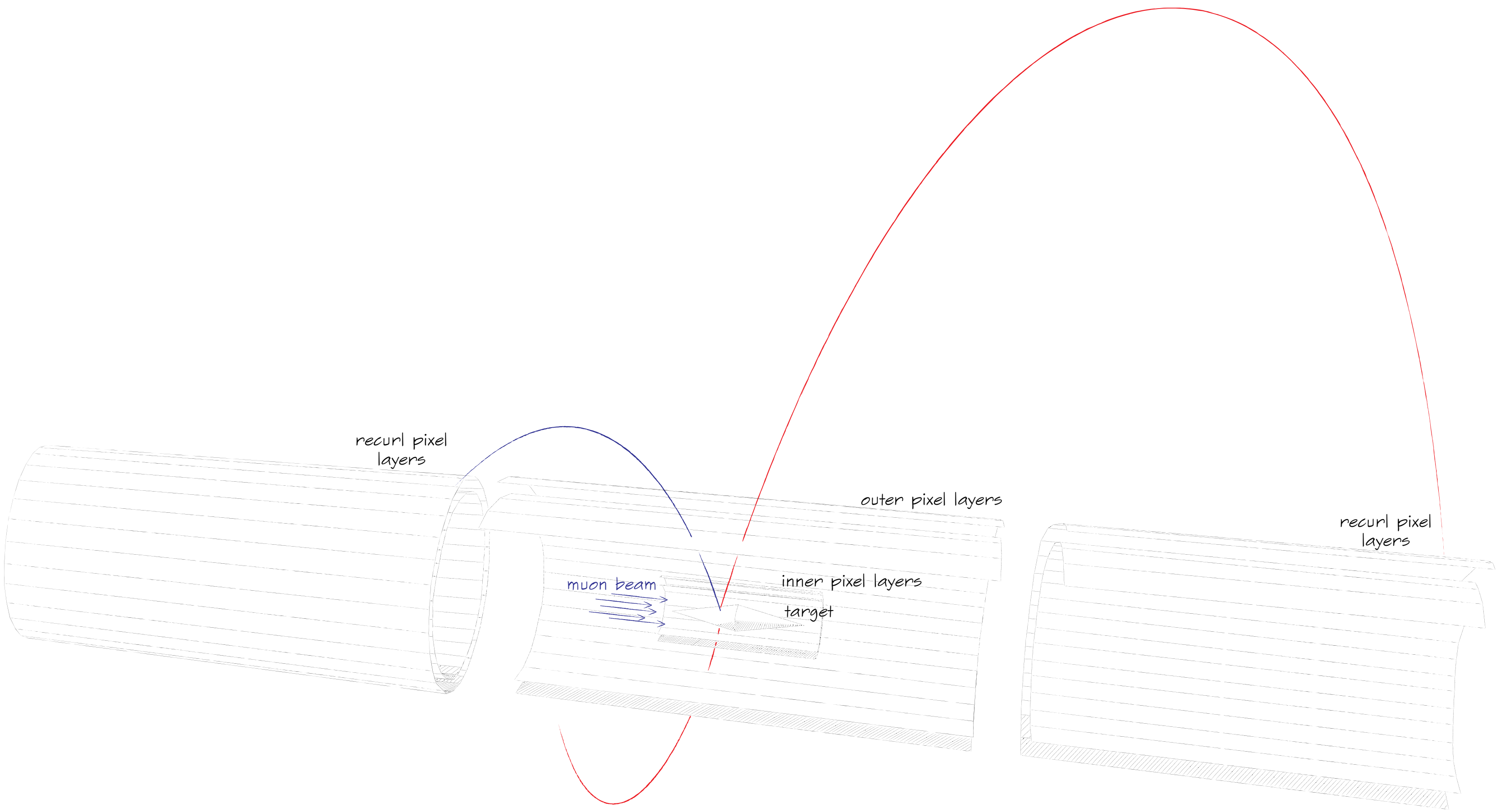
Performance Simulations: Mass reconstruction



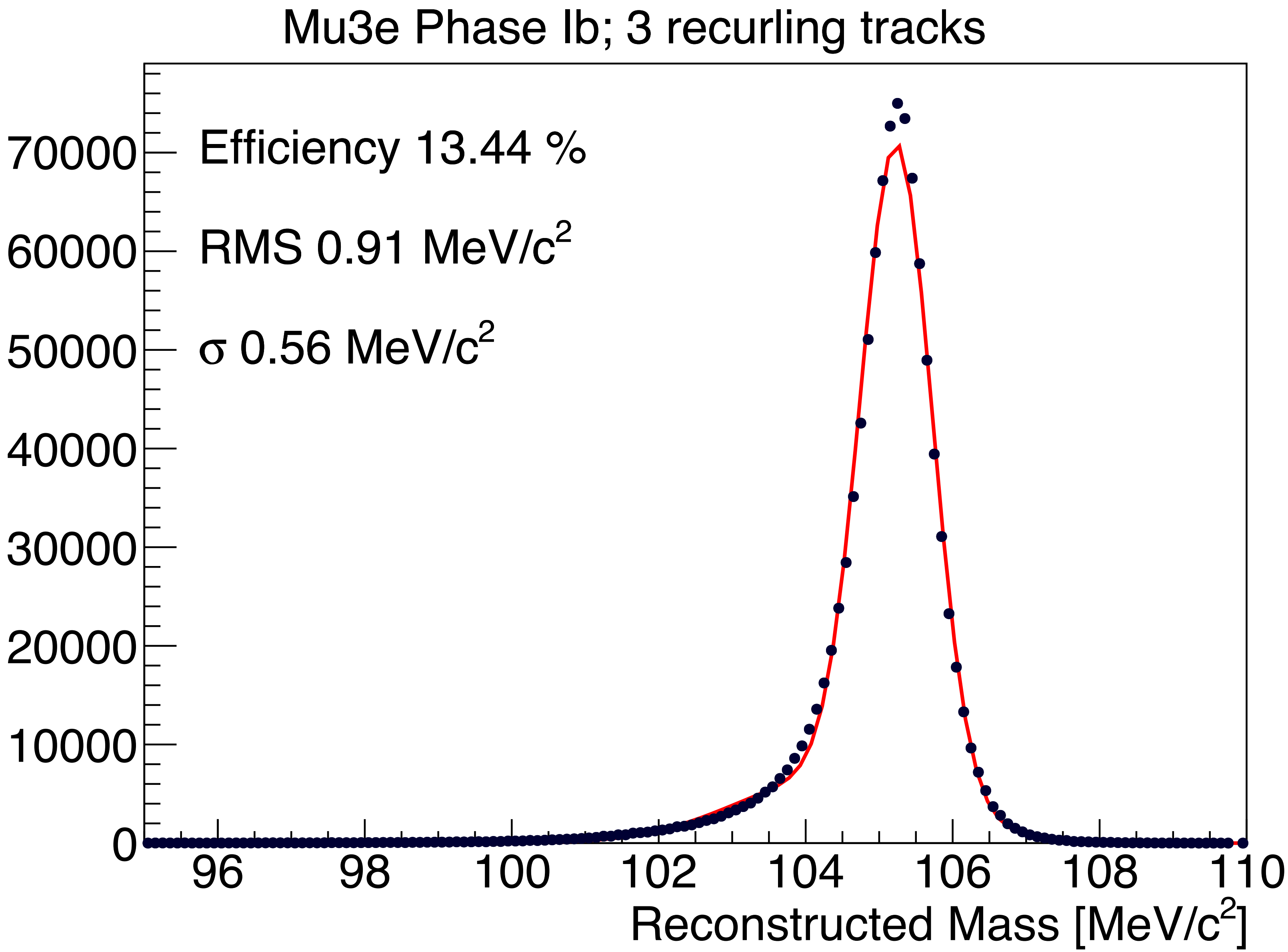
Performance Simulations: Mass reconstruction



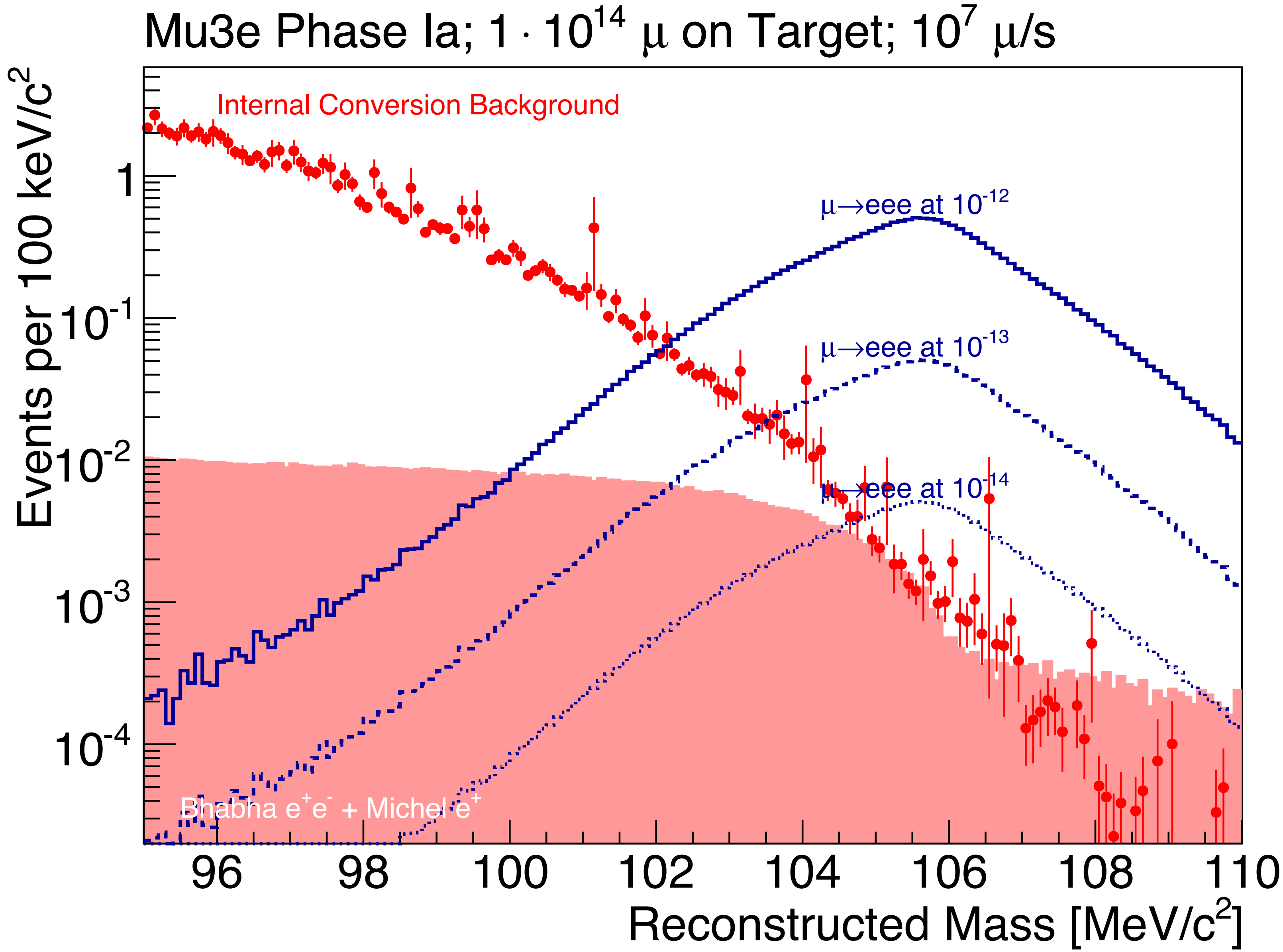
Detector Design



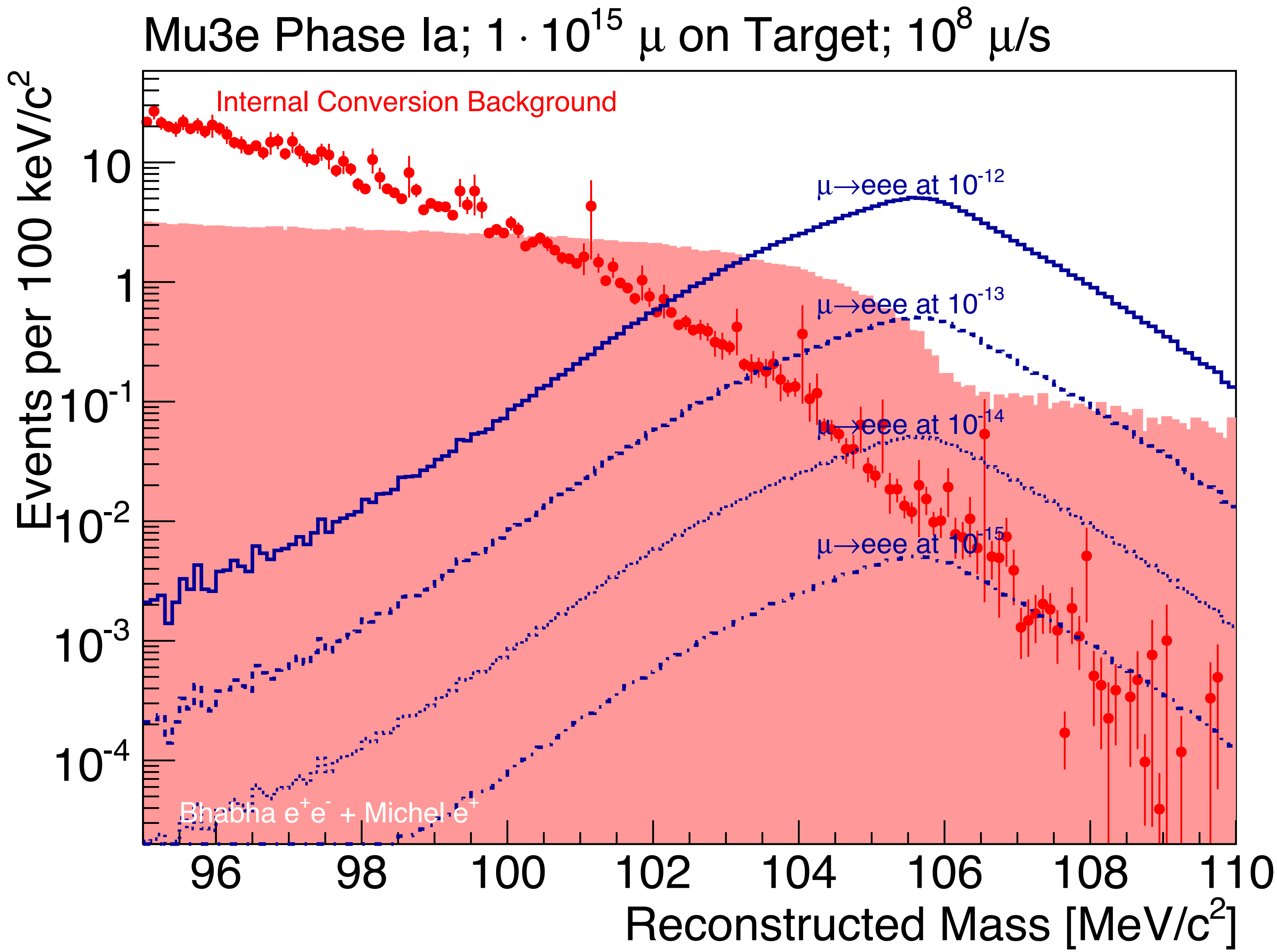
Performance Simulations: Mass reconstruction



Performance Simulations: Background



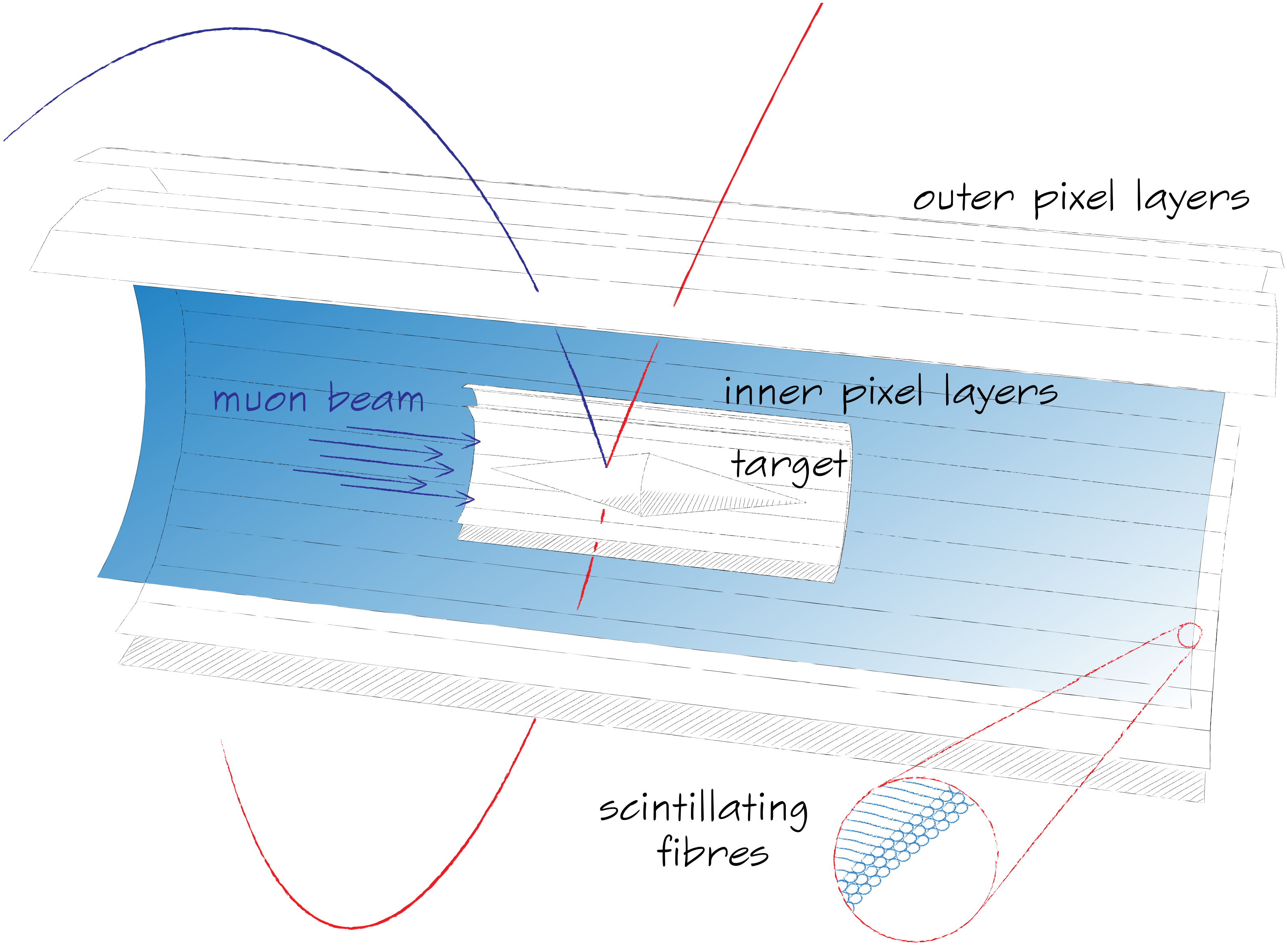
Performance Simulations: Background



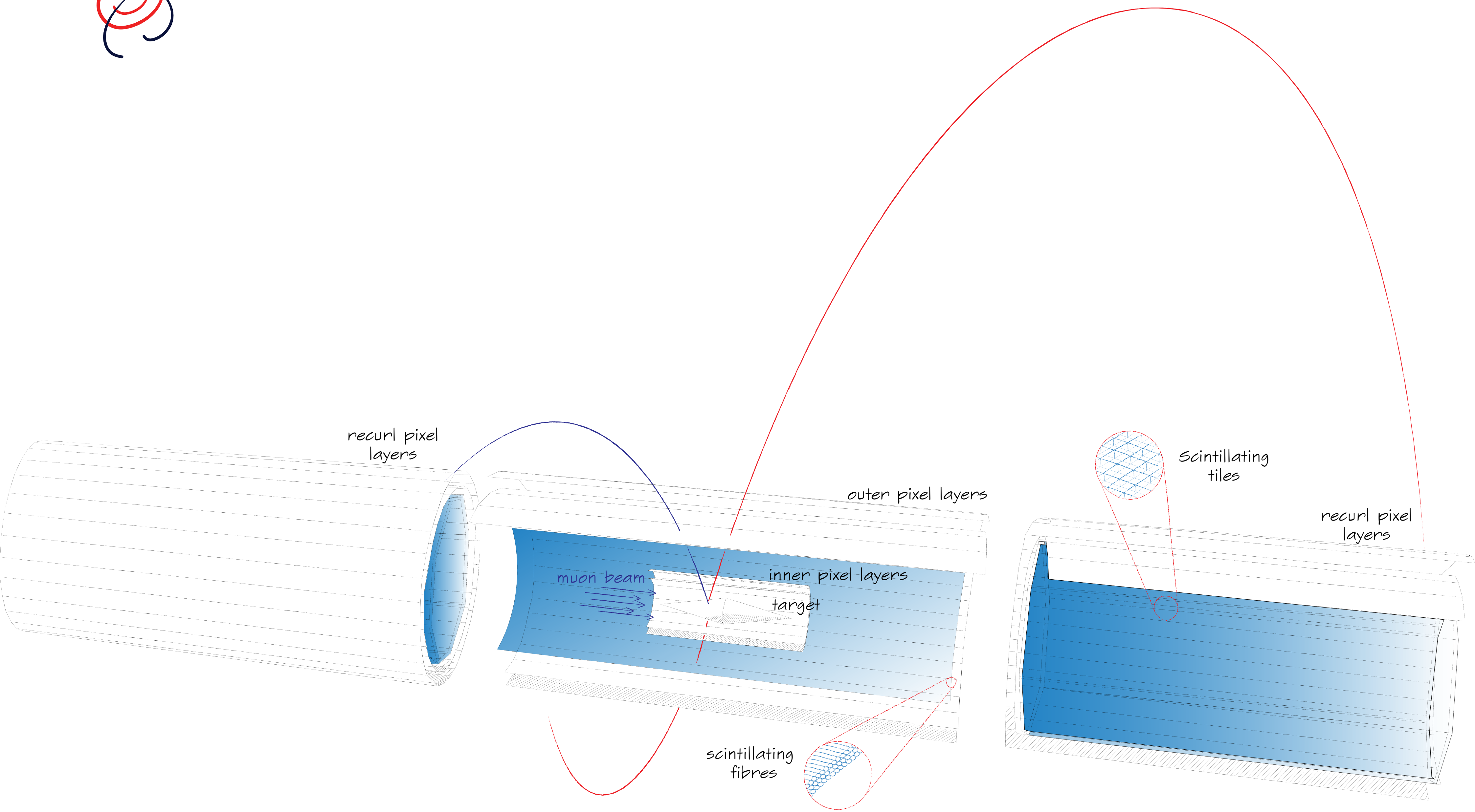
Need better suppression of accidental background:

Timing

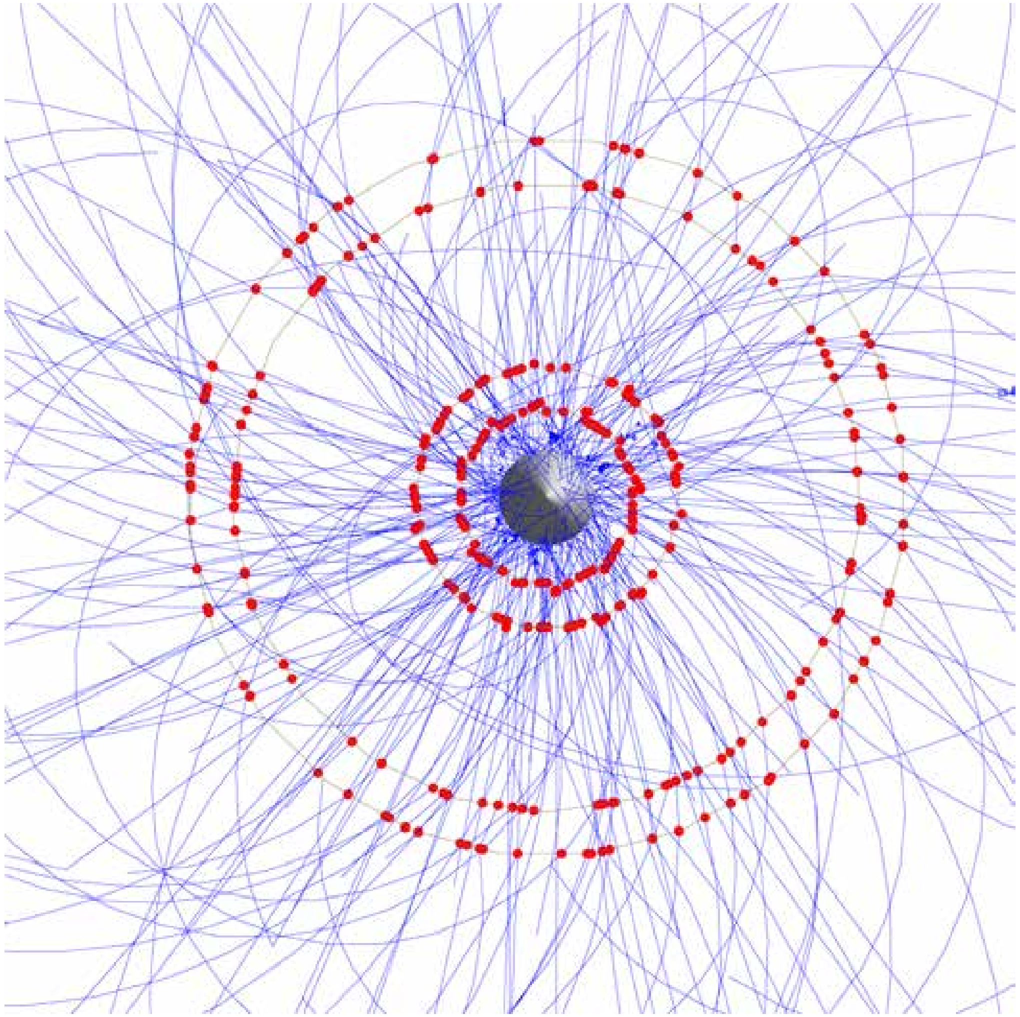
Detector Design



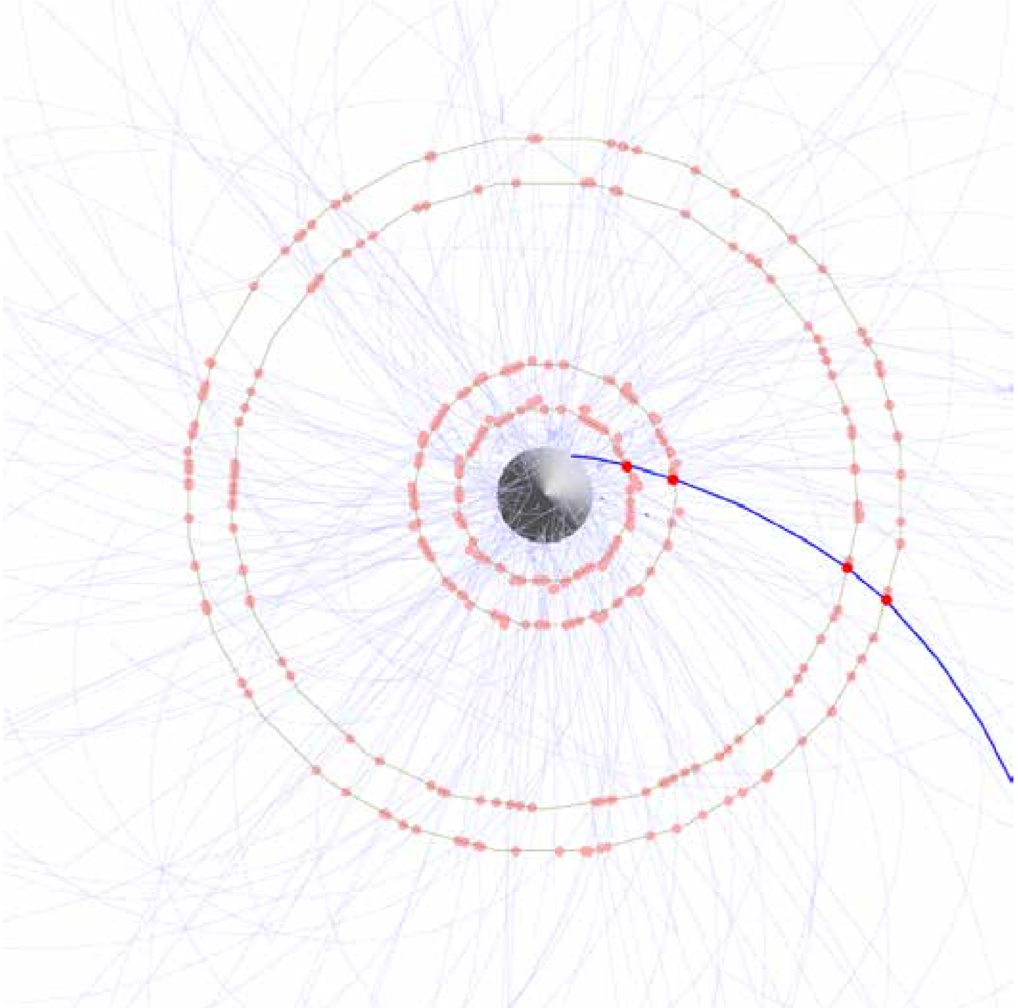
Detector Design



Timing measurements

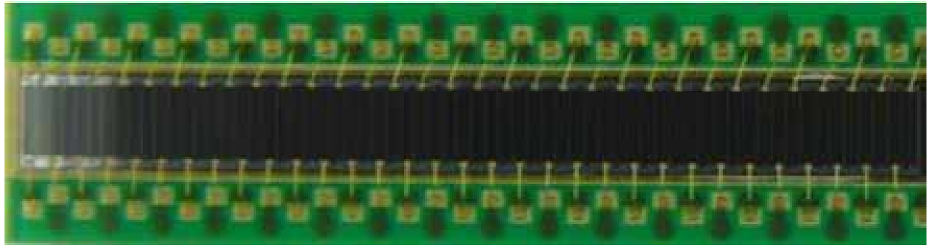


Pixels: O(50 ns)

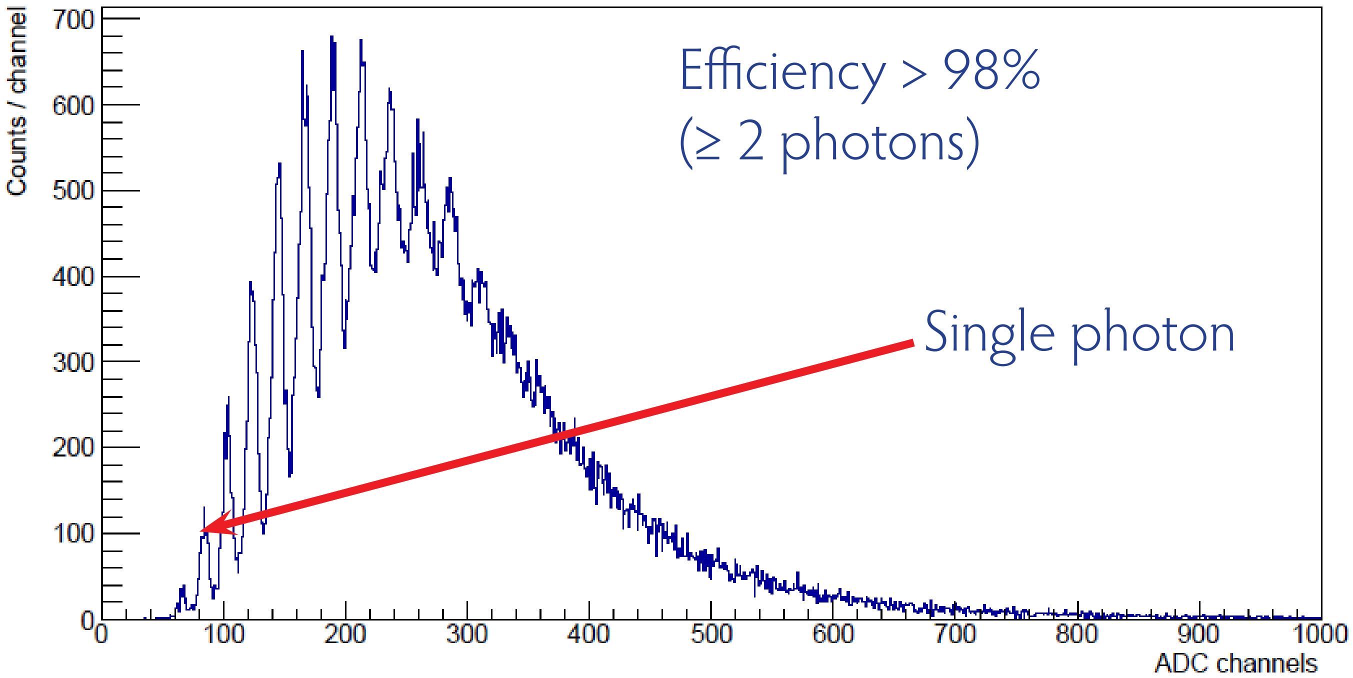


Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

Timing Detector: Scintillating Fibres

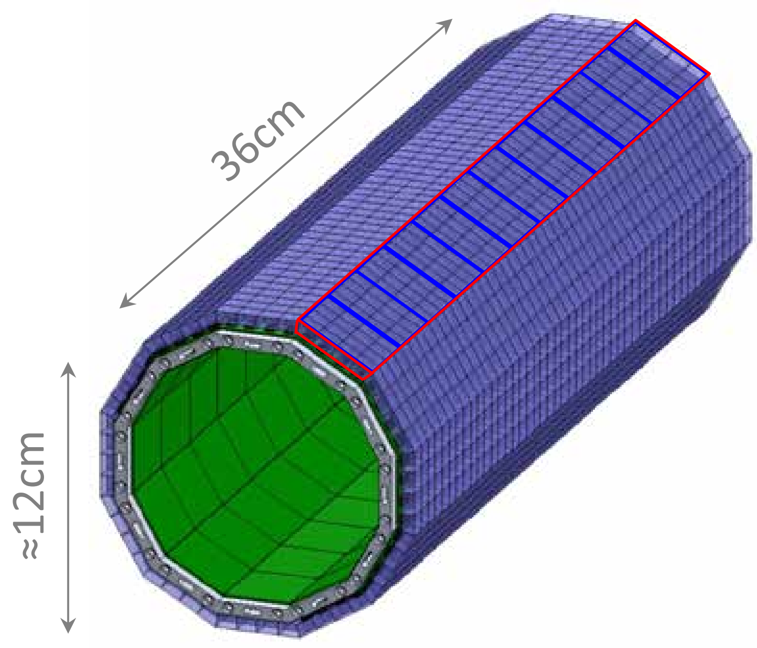


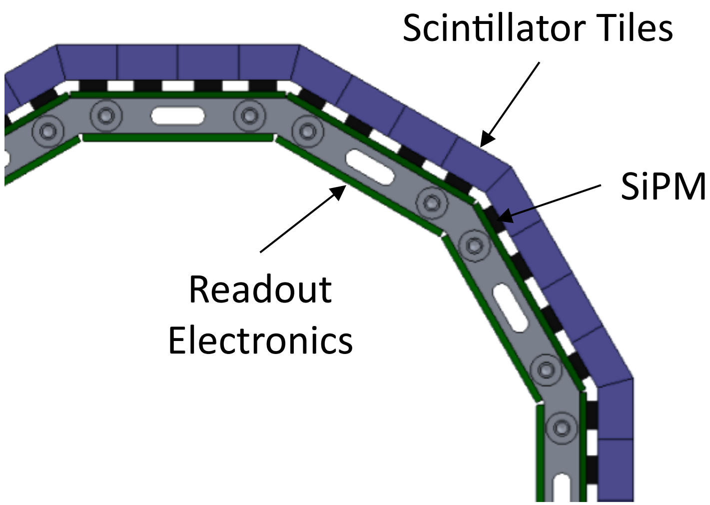
- 3-5 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution $\mathcal{O}$(1 ns) (measured with sodium source)



Timing Detector: Scintillating tiles

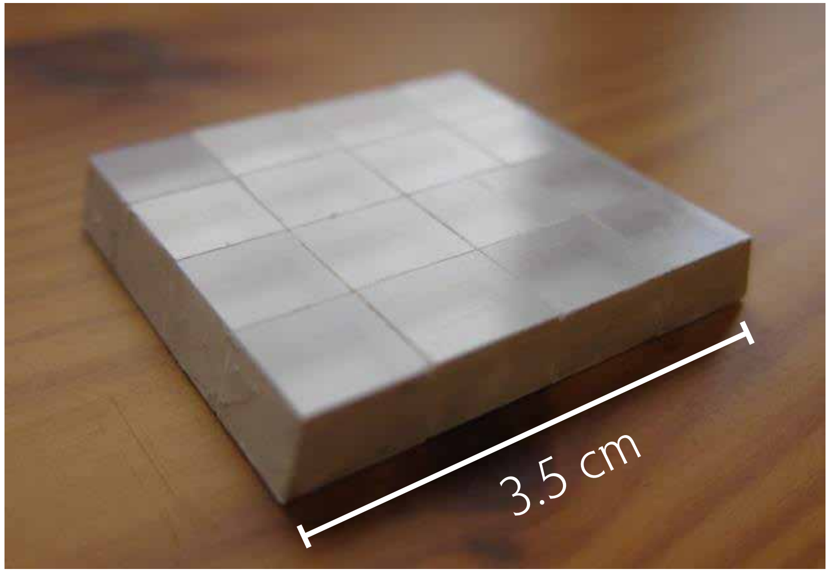
- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)



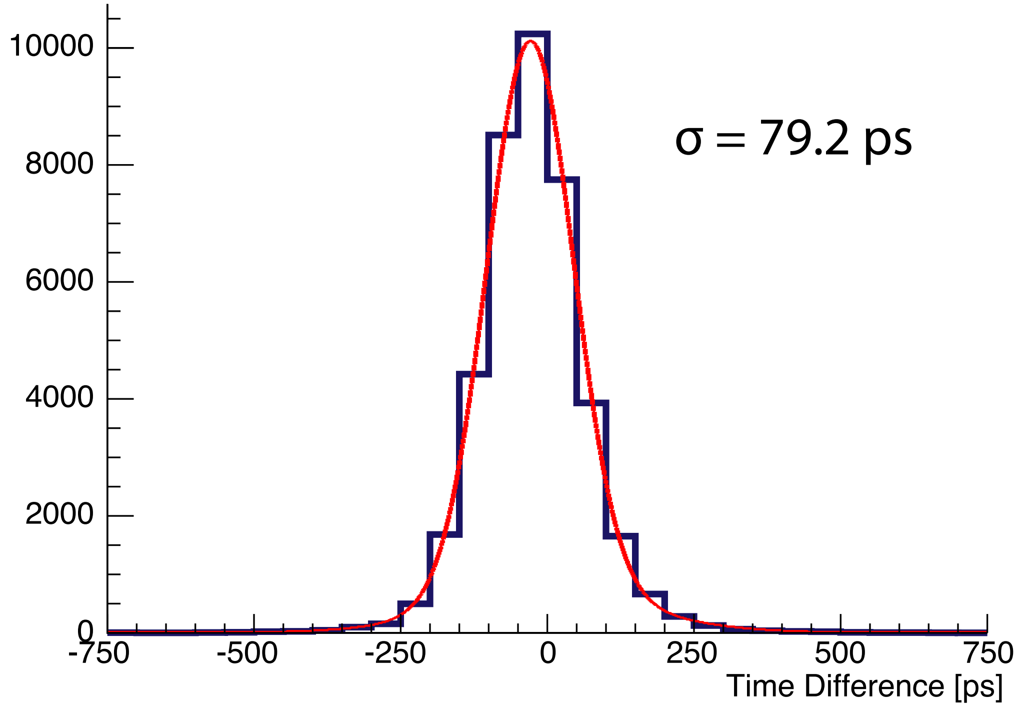


Timing Detector: Scintillating tiles

Front

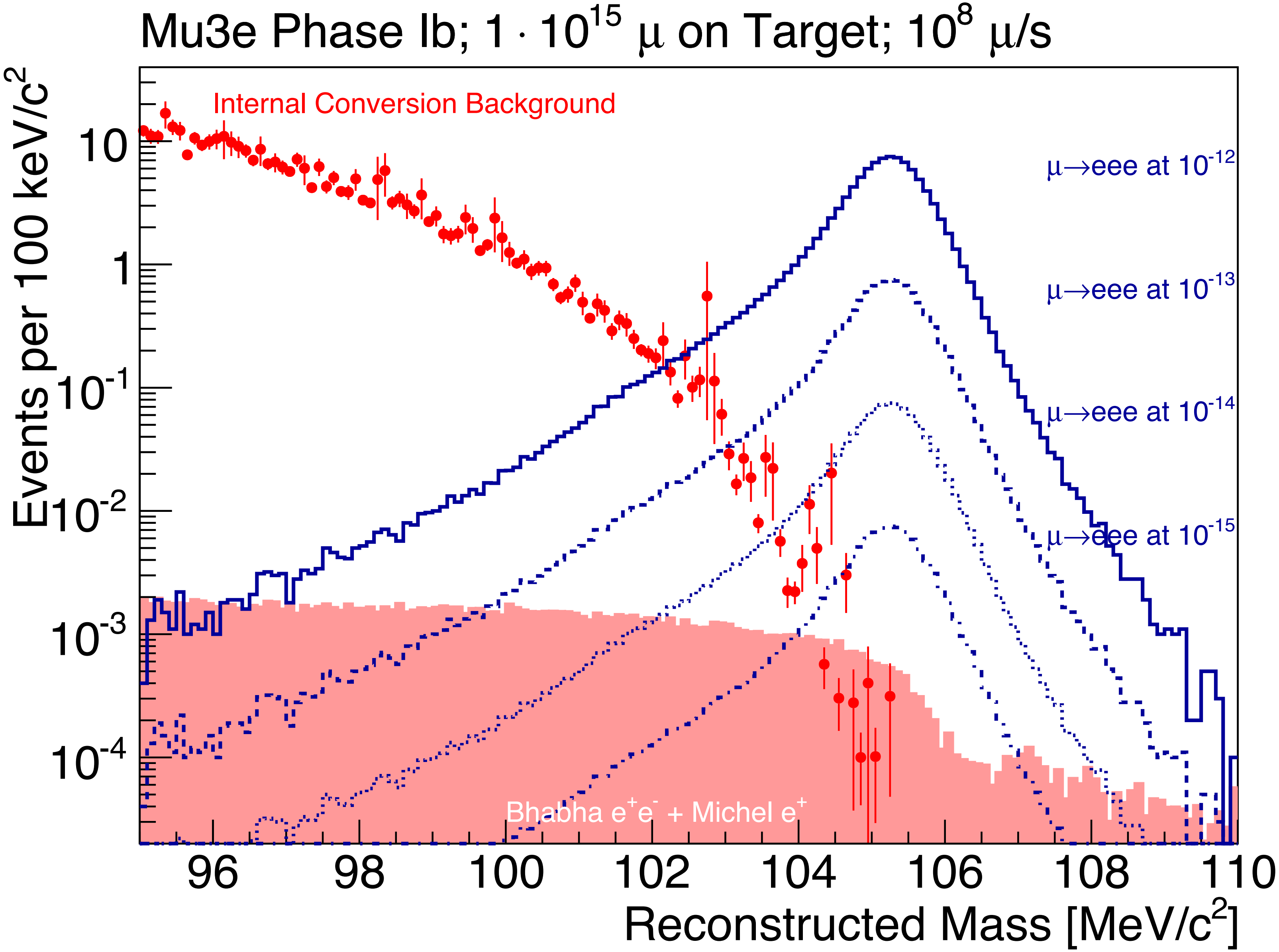


Back

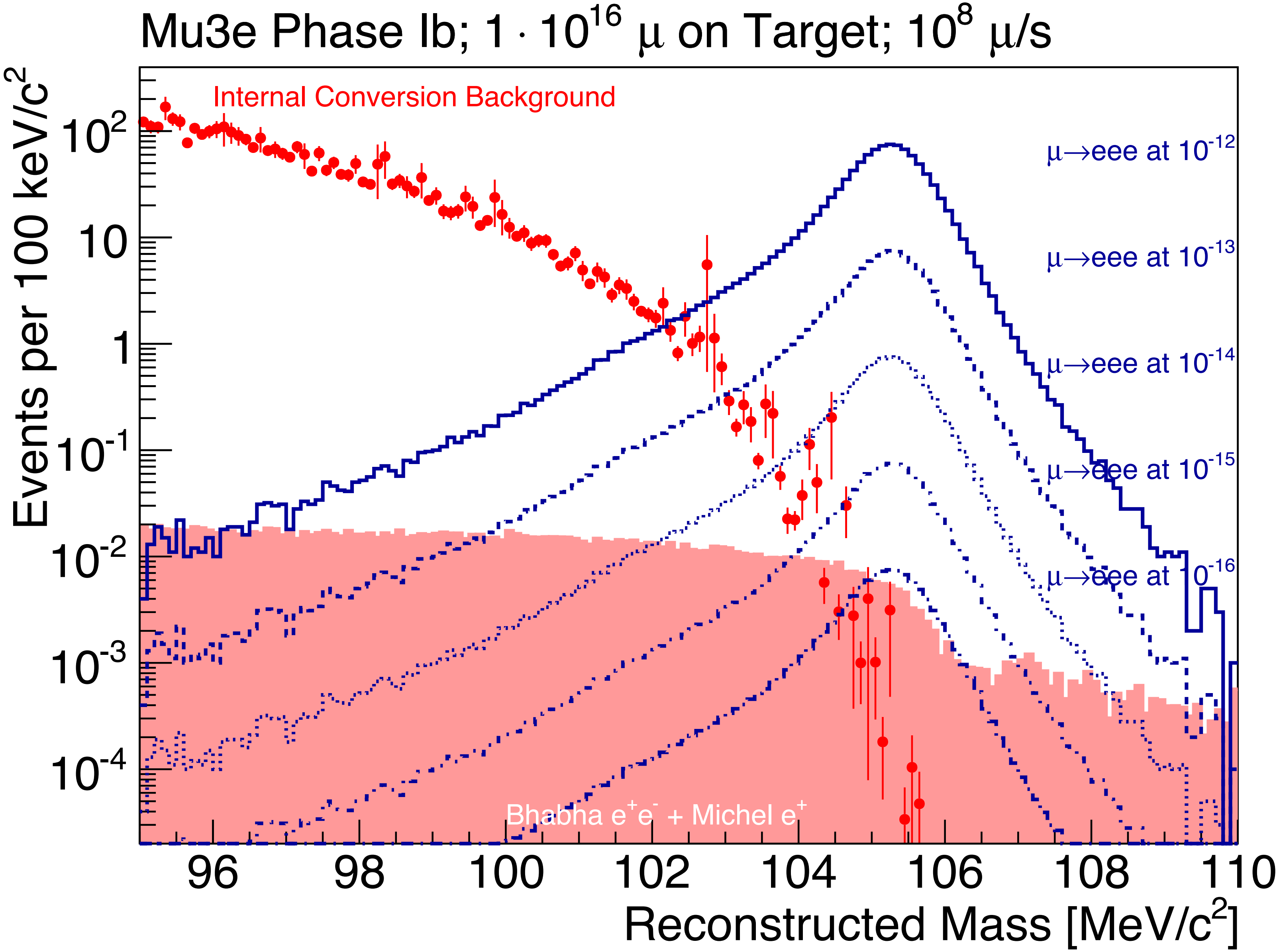


- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps

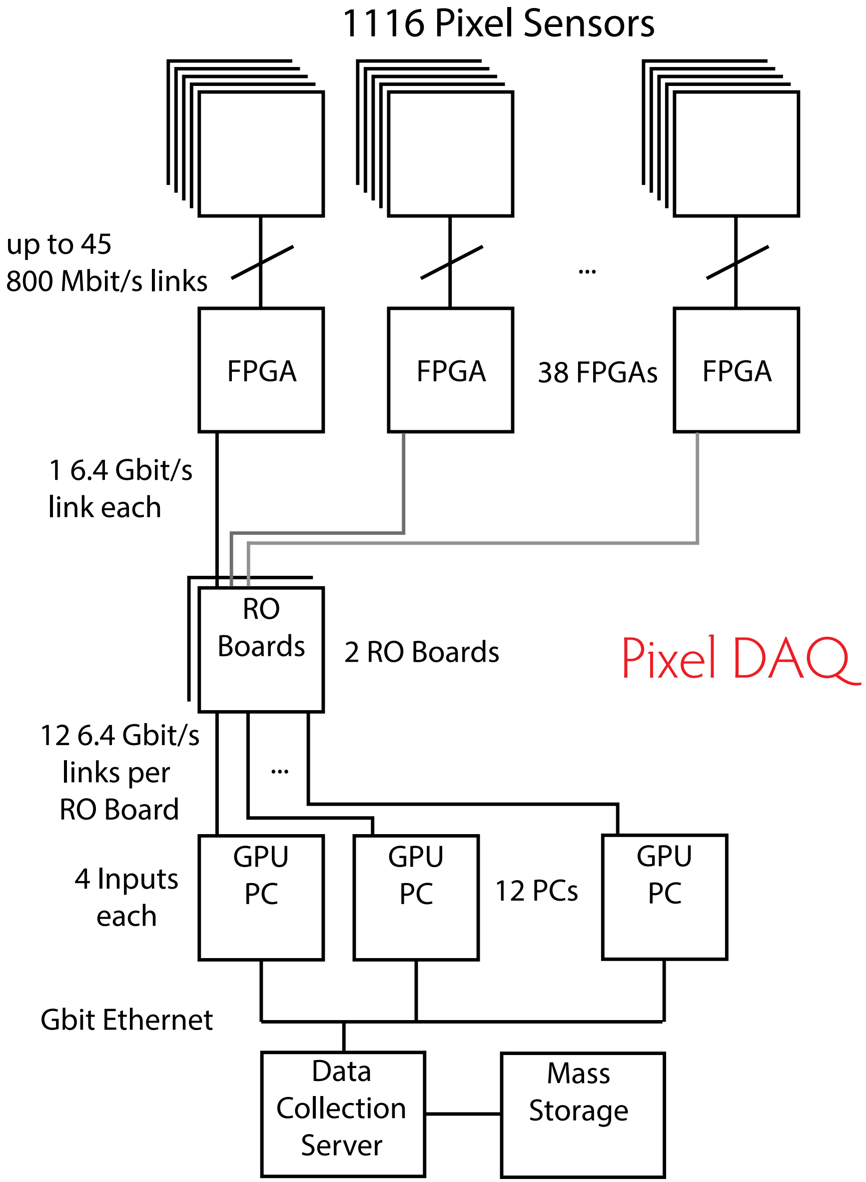
Performance Simulations: Background



Performance Simulations: Background



Data Acquisition



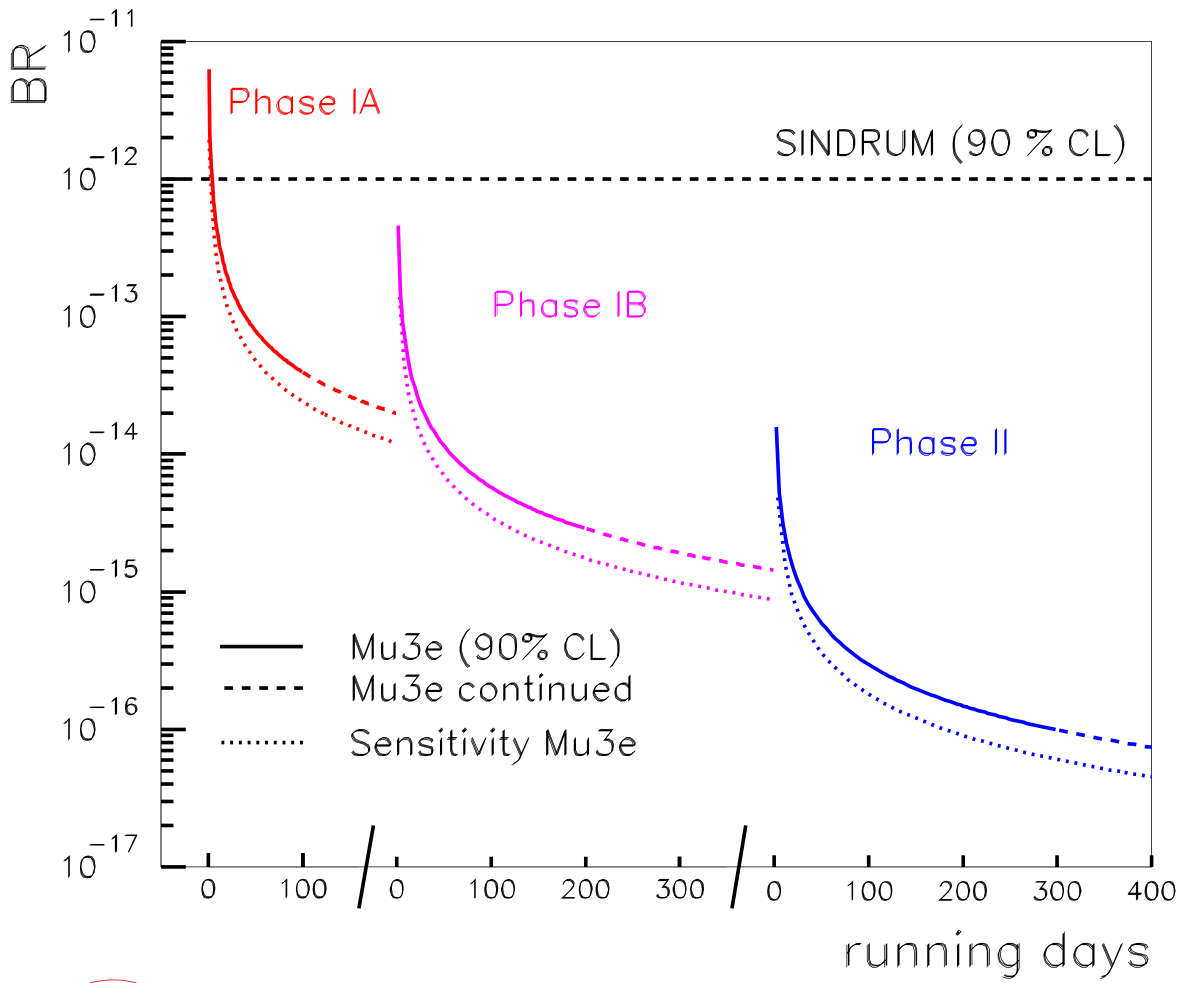
- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(50) PCs with GPUs

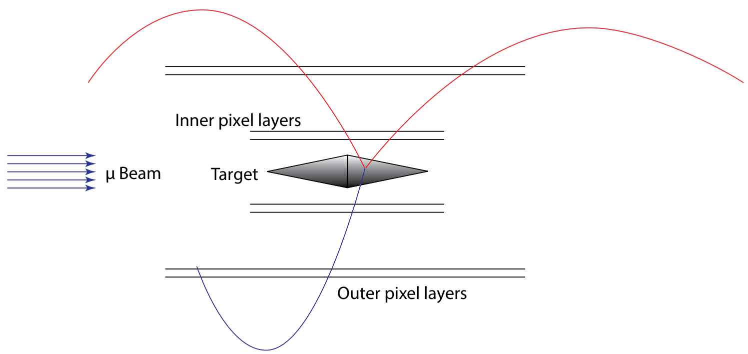
Online filter farm

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

Sensitivity

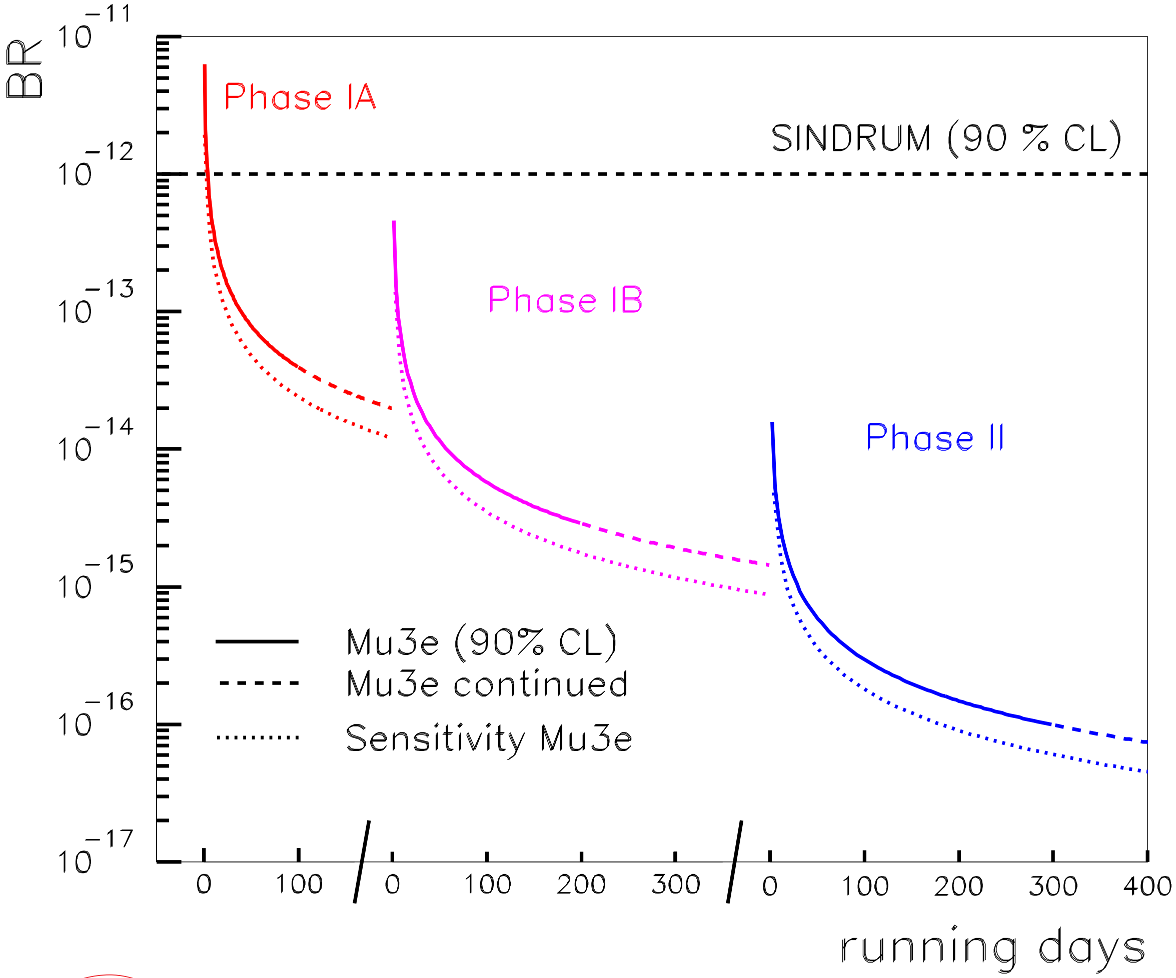


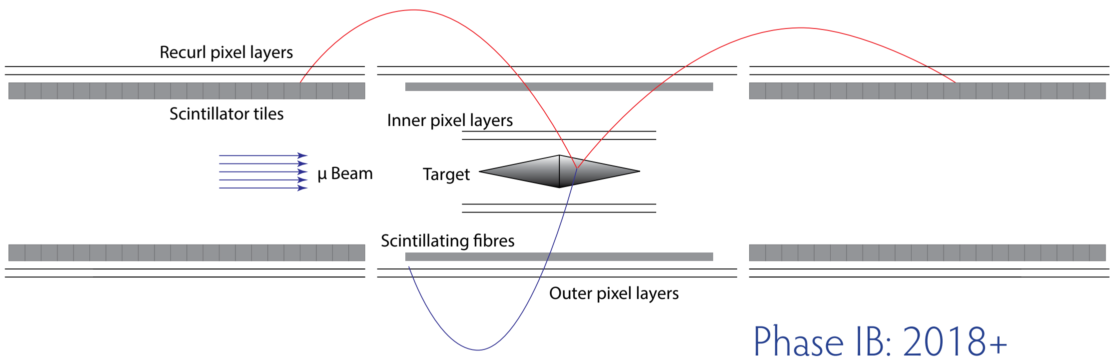


Phase IA: Starting 2017

$2 \cdot 10^{7}$ μ/s

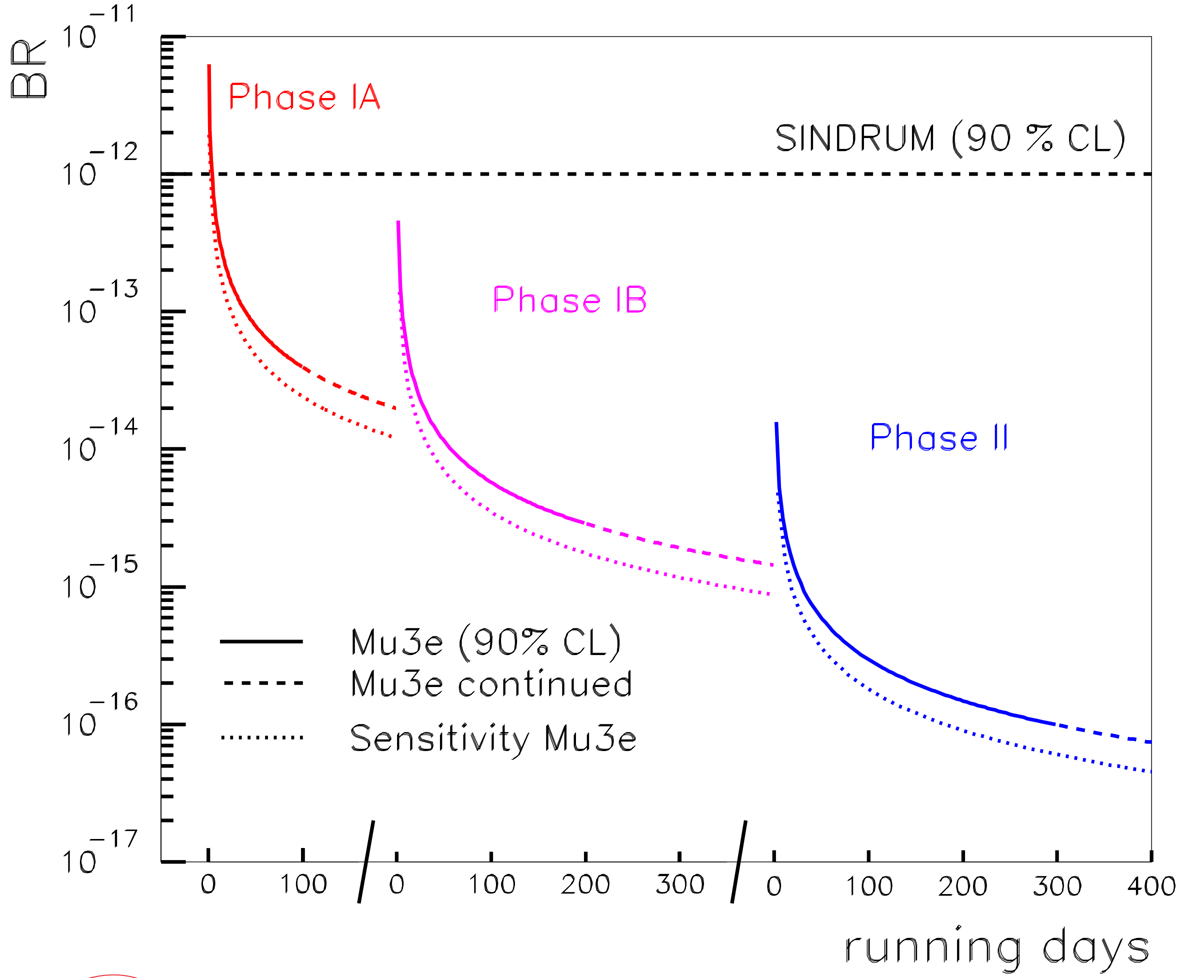
Sensitivity

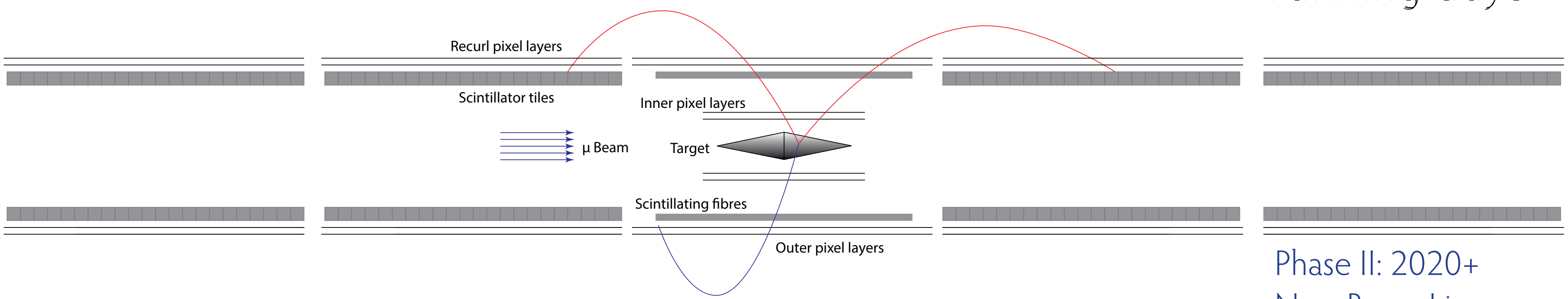




Phase IB: 2018+
$1 \cdot 10^8$ μ/s

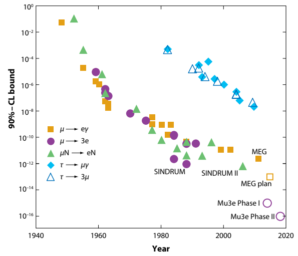
Sensitivity



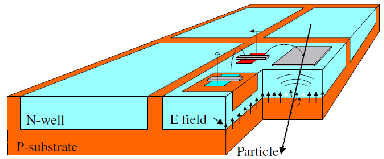


Phase II: 2020+
New Beam Line
$2 \cdot 10^9$ μ/s

Conclusion



- Mu3e aims for $\mu \to eee$ at the 10^{-16} level
- First large scale use of HV-MAPS



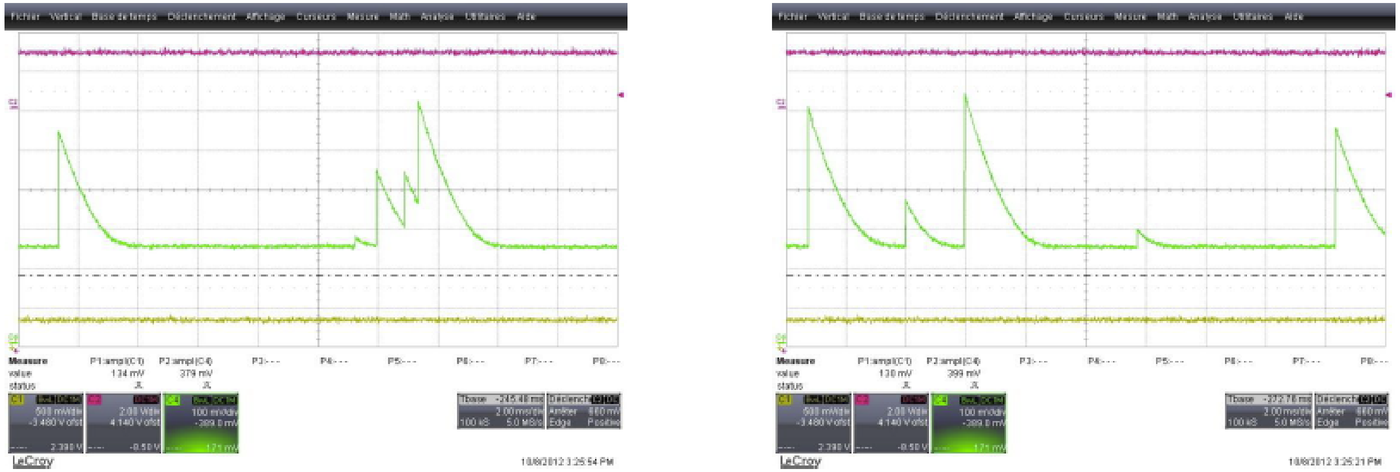
- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs

- Start data taking in 2017
- 2 billion muons/s not before 2020

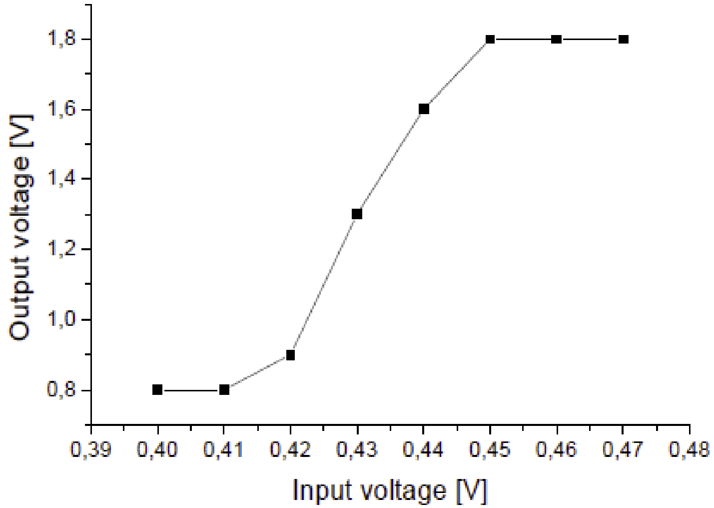
Backup Material

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

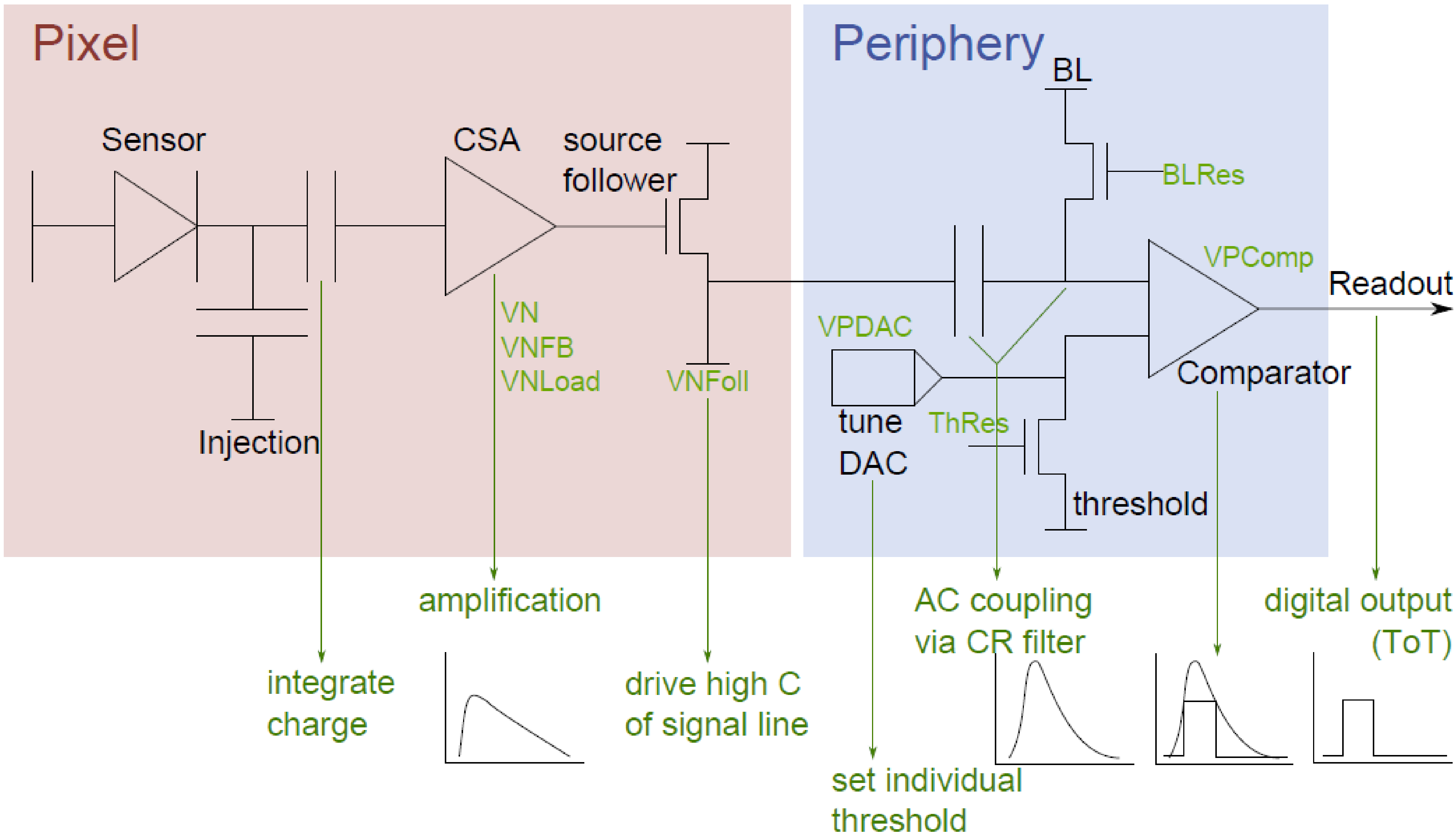


Comparator characteristics.

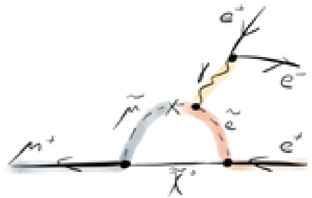
- Irradiation at PS
- After 380 MRad (8×10^{15} n_{eq}/cm^2)
- Chip still working

(Courtesy Ivan Perić, RESMDD 2012)

MUPIX electronics



A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

$$L_{\mu \to eee} = 2\,G_F\,(\,m_\mu A_R\,\bar{\mu}_R\,\sigma^{\mu\nu}\,e_L\,F_{\mu\nu} \qquad + m_\mu A_L\,\bar{\mu}_L\,\sigma^{\mu\nu}\,e_R\,F_{\mu\nu}$$

Four-fermion terms e.g. Z'

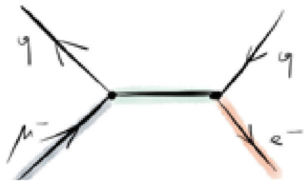
$$+\,g_1\,(\bar{\mu}_R\,e_L)\,(\bar{e}_R\,e_L) \qquad + g_2\,(\bar{\mu}_L\,e_R)\,(\bar{e}_L\,e_R)$$

scalar

$$+\,g_3\,(\bar{\mu}_R\,\gamma^\mu\,e_R)\,(\bar{e}_R\,\gamma^\mu\,e_R) \qquad + g_4\,(\bar{\mu}_L\,\gamma^\mu\,e_L)\,(\bar{e}_L\,\gamma^\mu\,e_L)$$

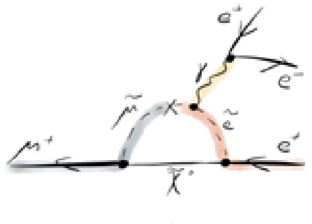
$$+\,g_5\,(\bar{\mu}_R\,\gamma^\mu\,e_R)\,(\bar{e}_L\,\gamma^\mu\,e_L) \qquad + g_6\,(\bar{\mu}_L\,\gamma^\mu\,e_L)\,(\bar{e}_R\,\gamma^\mu\,e_R)\ \ + \mathrm{H.\,C.}\,)$$

vector

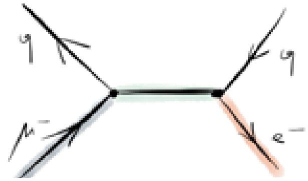


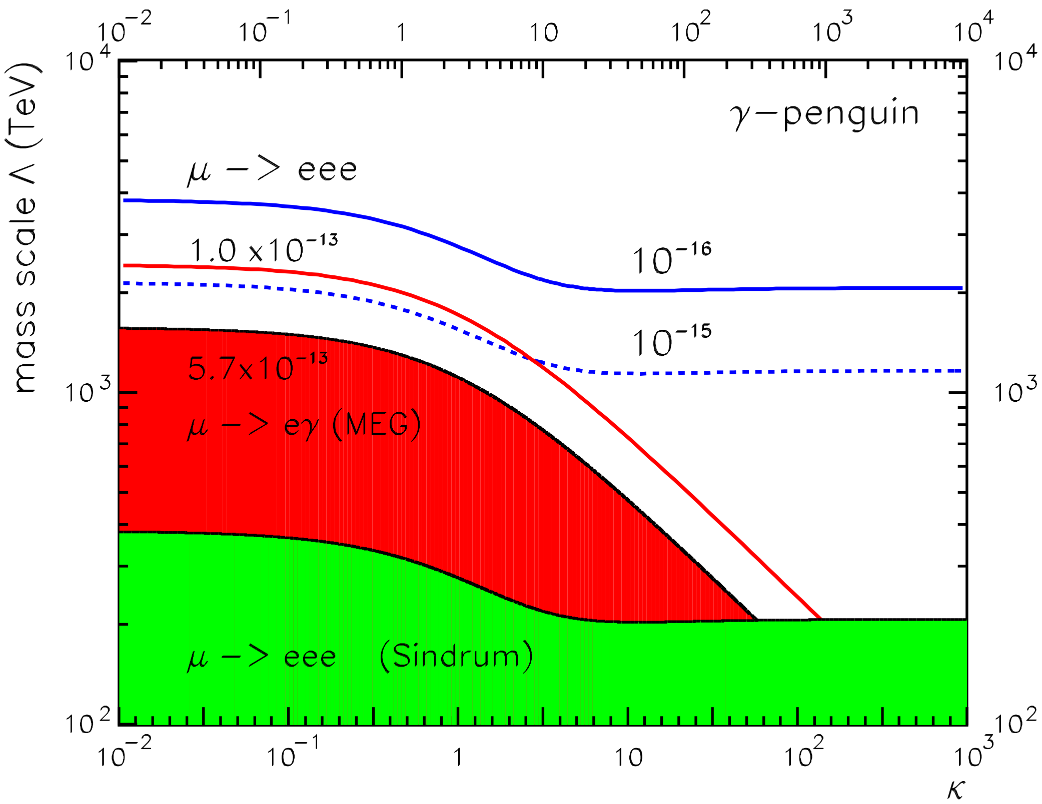
(Y. Kuno, Y. Okada,
Rev.Mod.Phys. 73 (2001) 151)

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



$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$





- One loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \to eee$ and $\mu \to e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

Detector Design