

The Mu3e Experiment



Niklaus Berger

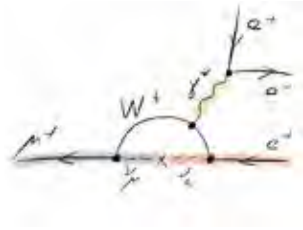
Institut für Kernphysik, Johannes-Gutenberg Universität Mainz



Seminar SFB 1044
Mainz, June 2015

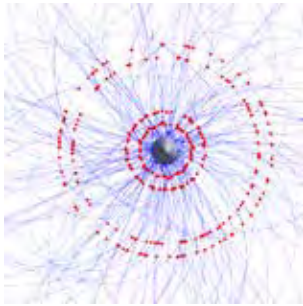


Overview



- The Motivation:

New physics in lepton flavour violating μ -decays?



- The Challenge:

Finding one in 10^{16} muon decays



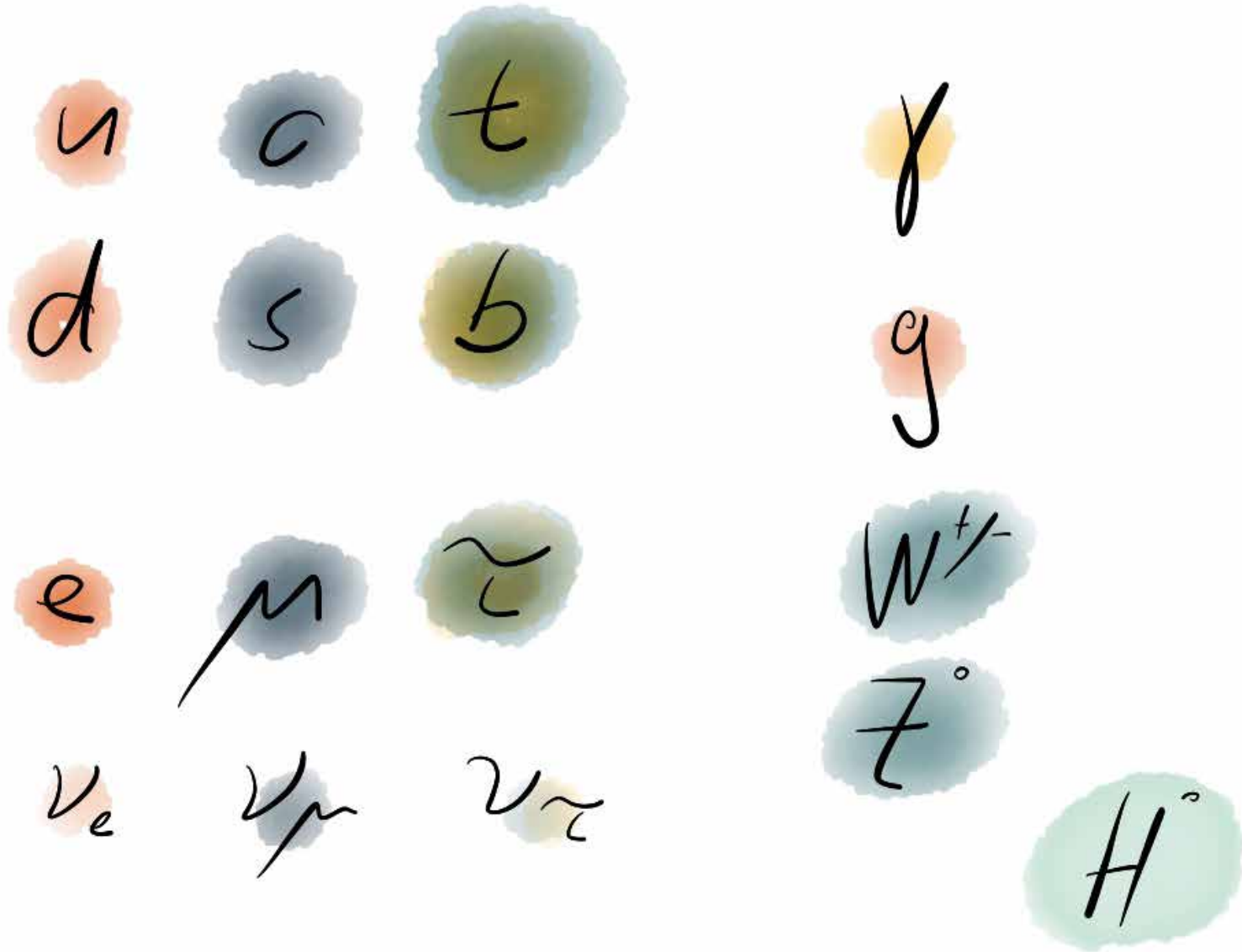
- The Mu3e Detector:

Minimum Material, Maximum Precision

The hunt for
charged lepton flavour violation

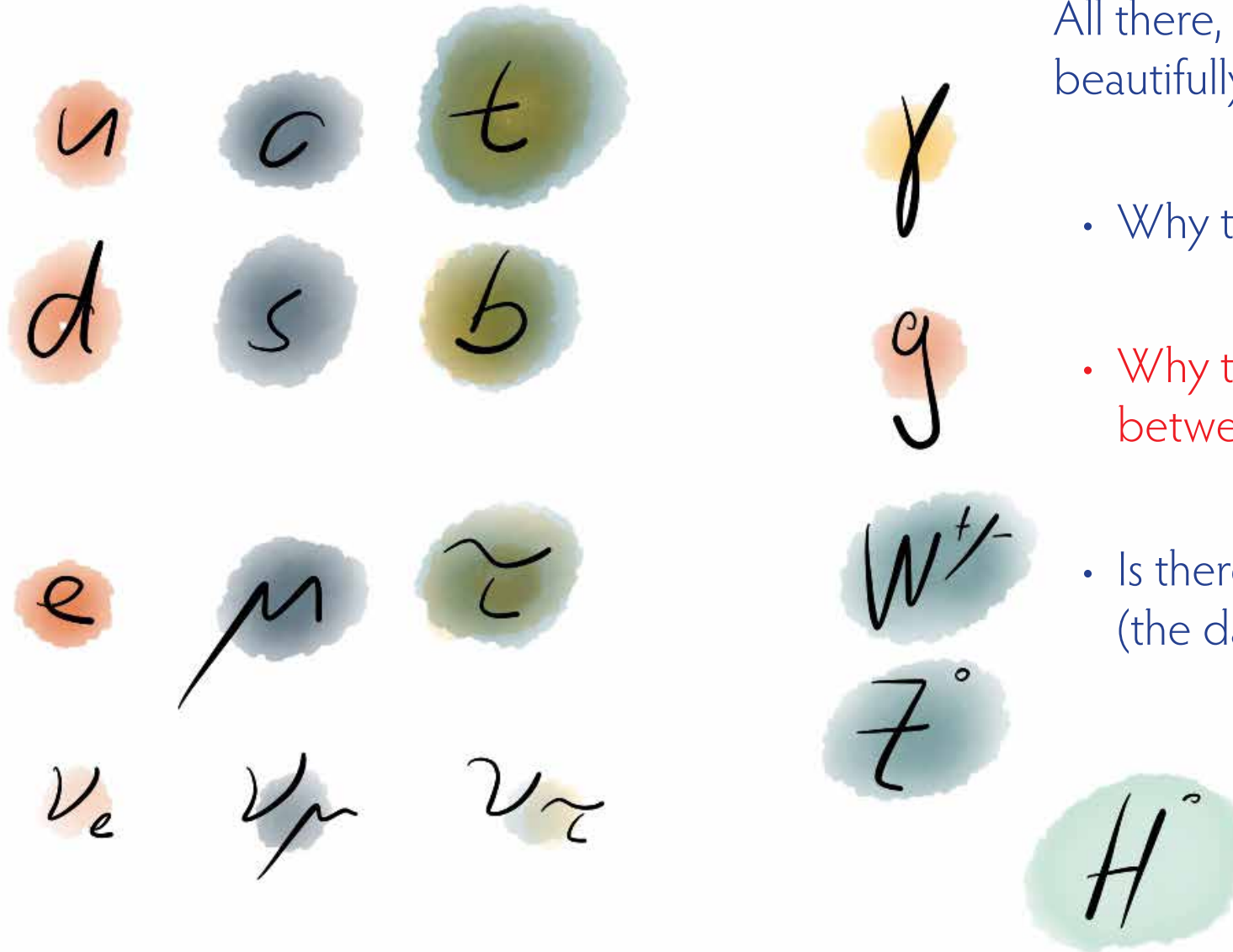


The Standard Model of Elementary Particles





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

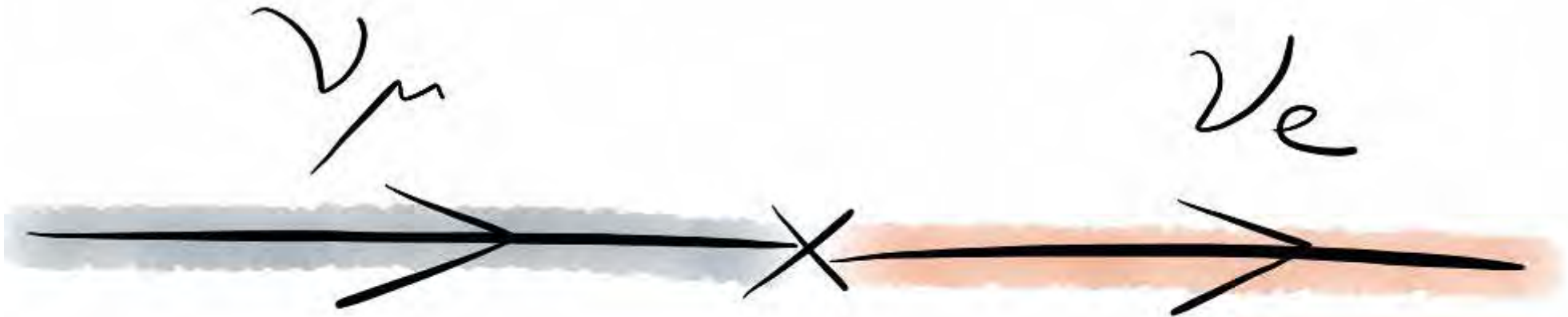


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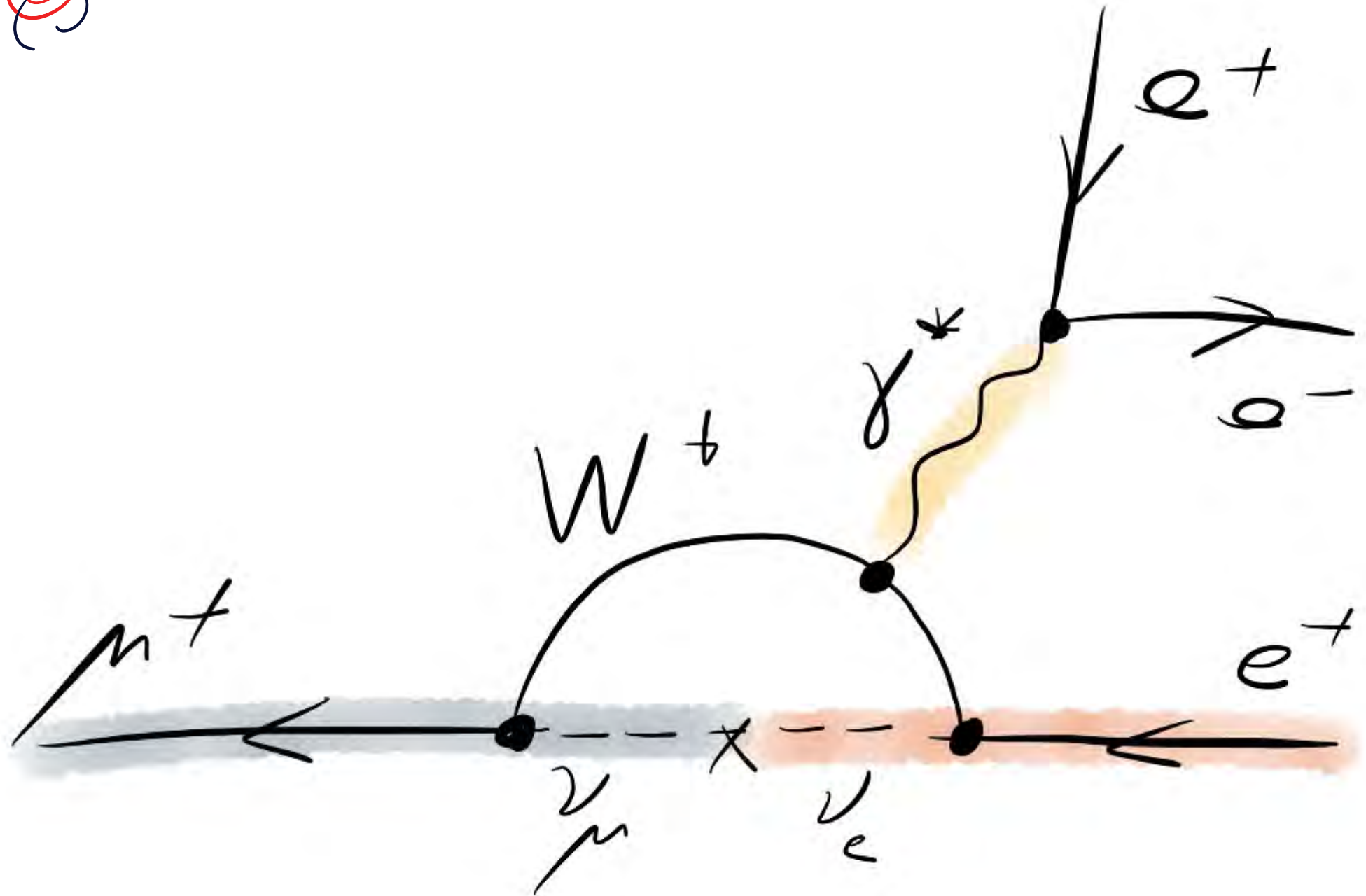


Lepton Flavour Violation!





Charged Lepton Flavour Violation?



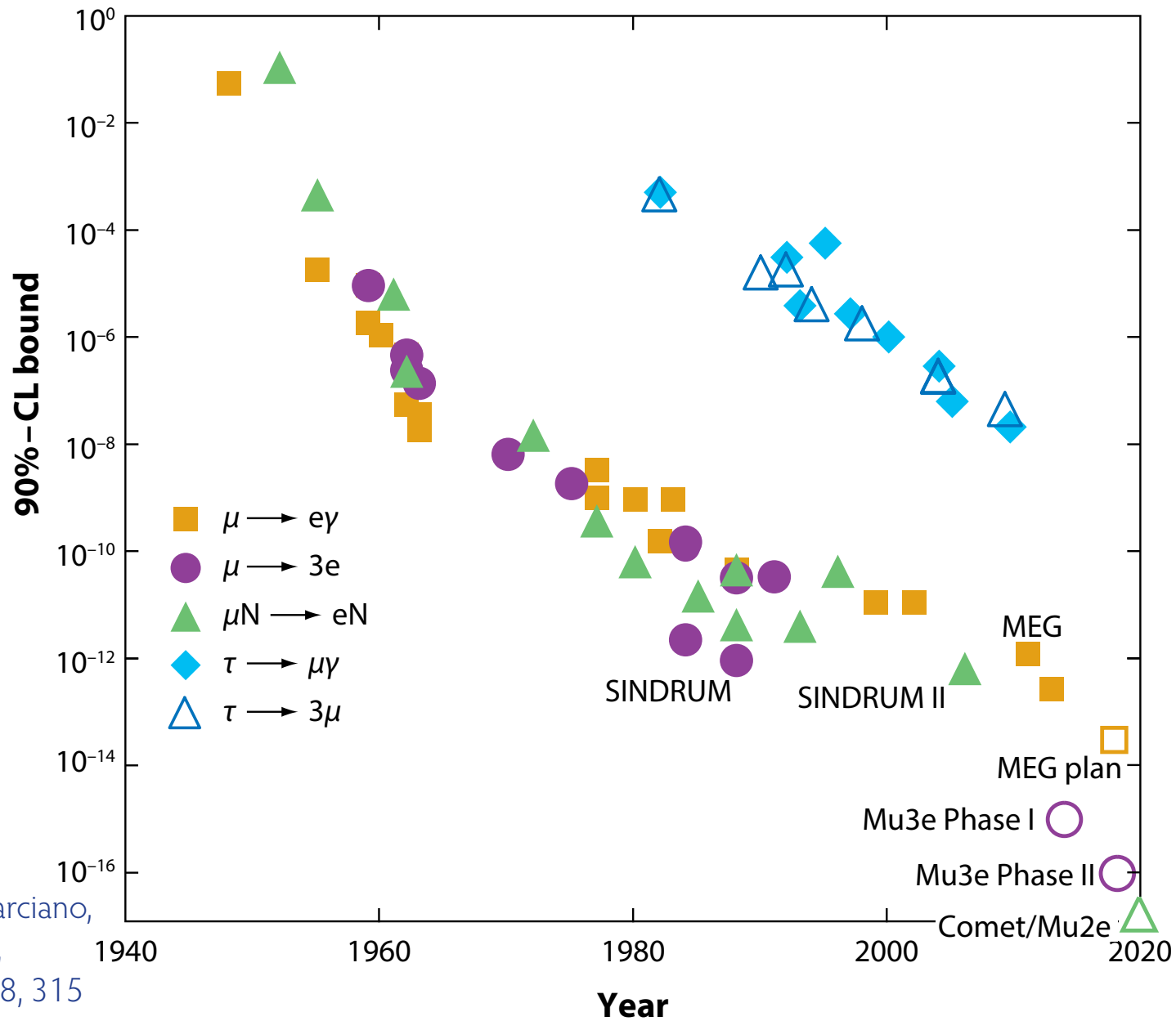


This
(charged lepton flavour violation)
has never been seen

and not because we have not looked



History of LFV experiments

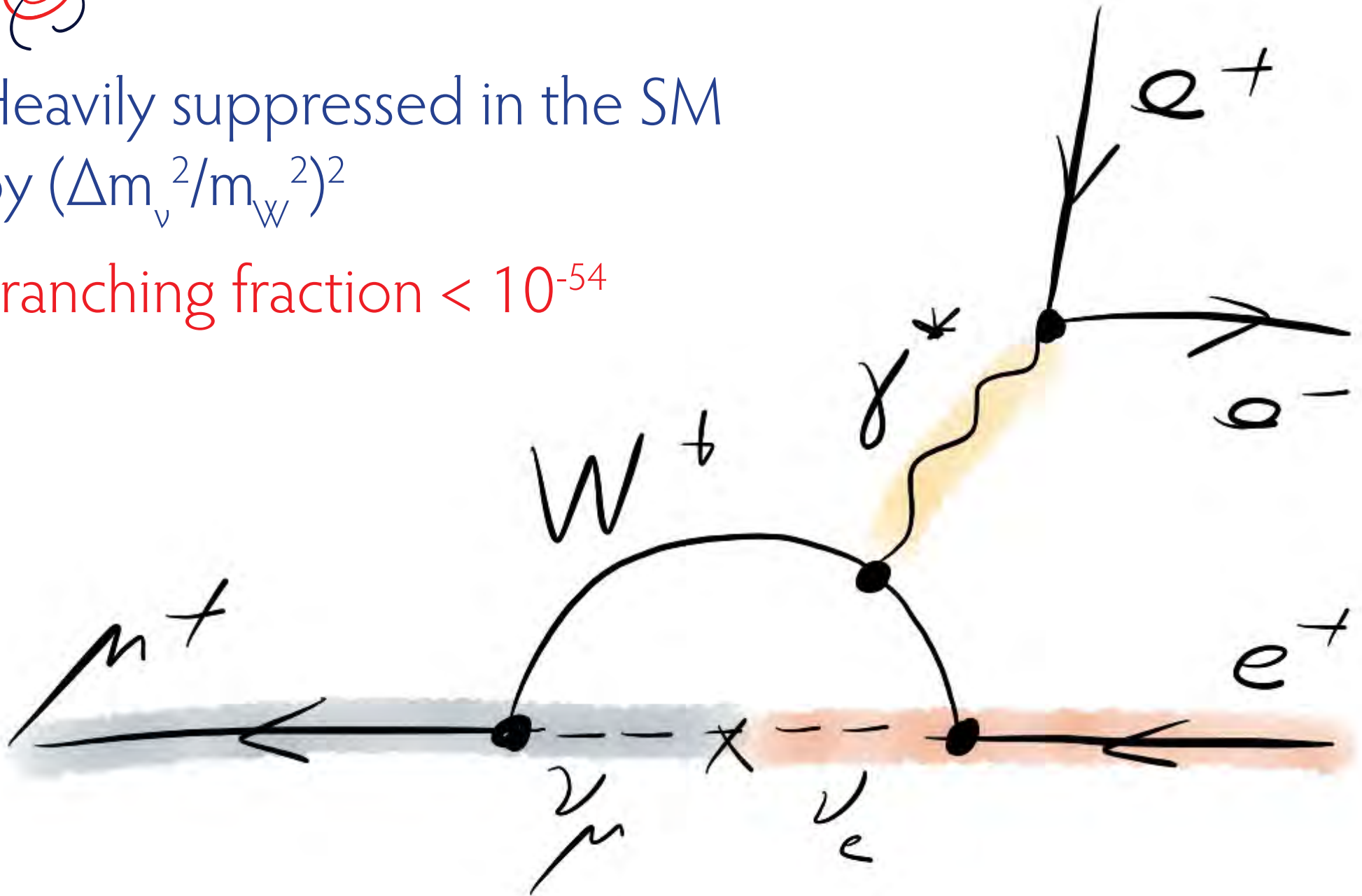


(Updated from W.J. Marciano,
T. Mori and J.M. Roney,
Ann.Rev.Nucl.Part.Sci. 58, 315
(2008))

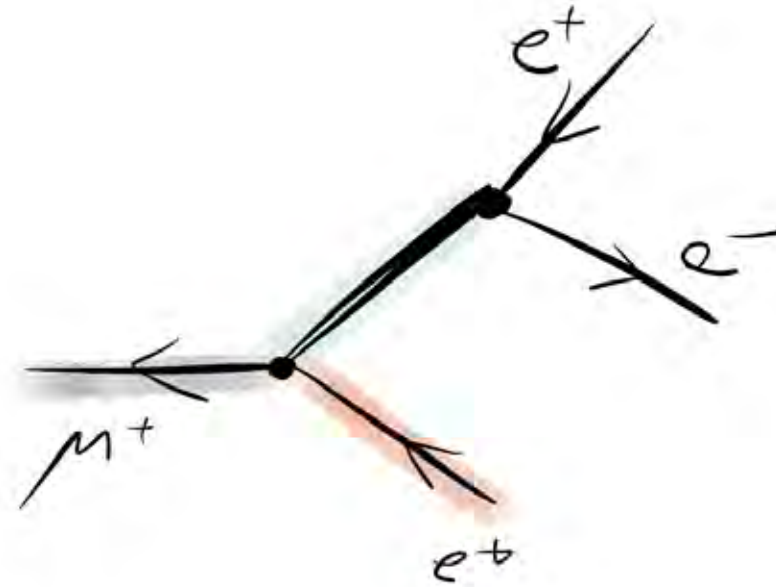
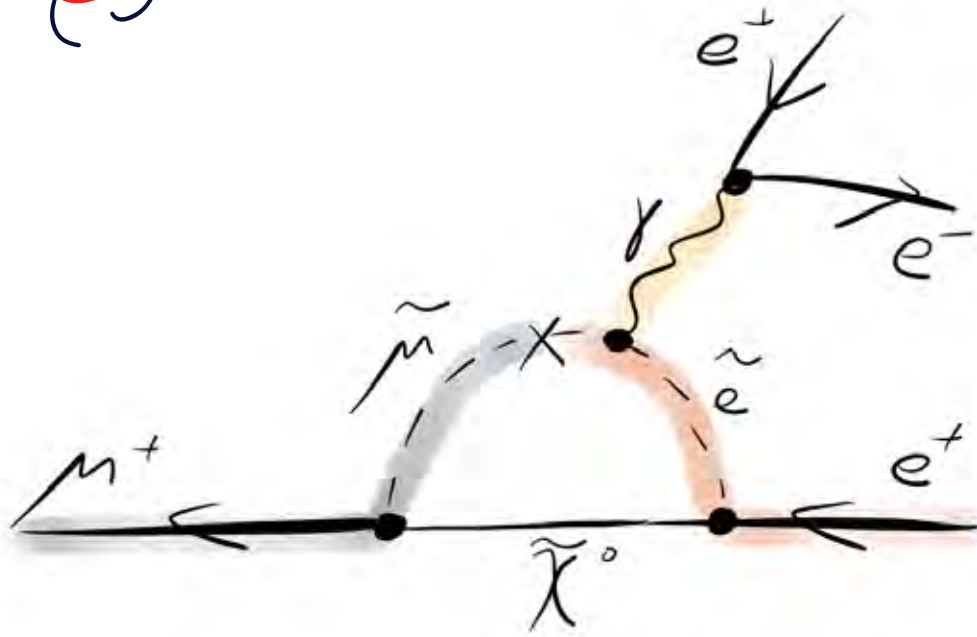


Heavily suppressed in the SM
by $(\Delta m_\nu^2/m_W^2)^2$

Branching fraction $< 10^{-54}$



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



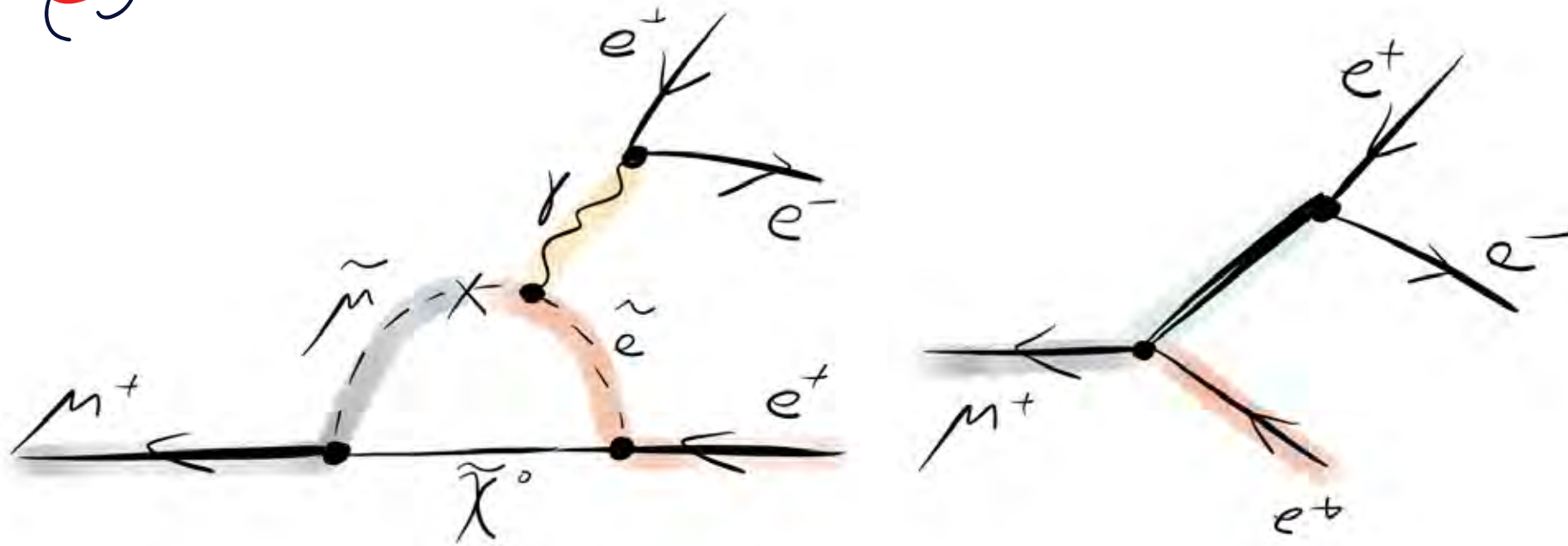
Loop diagrams

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

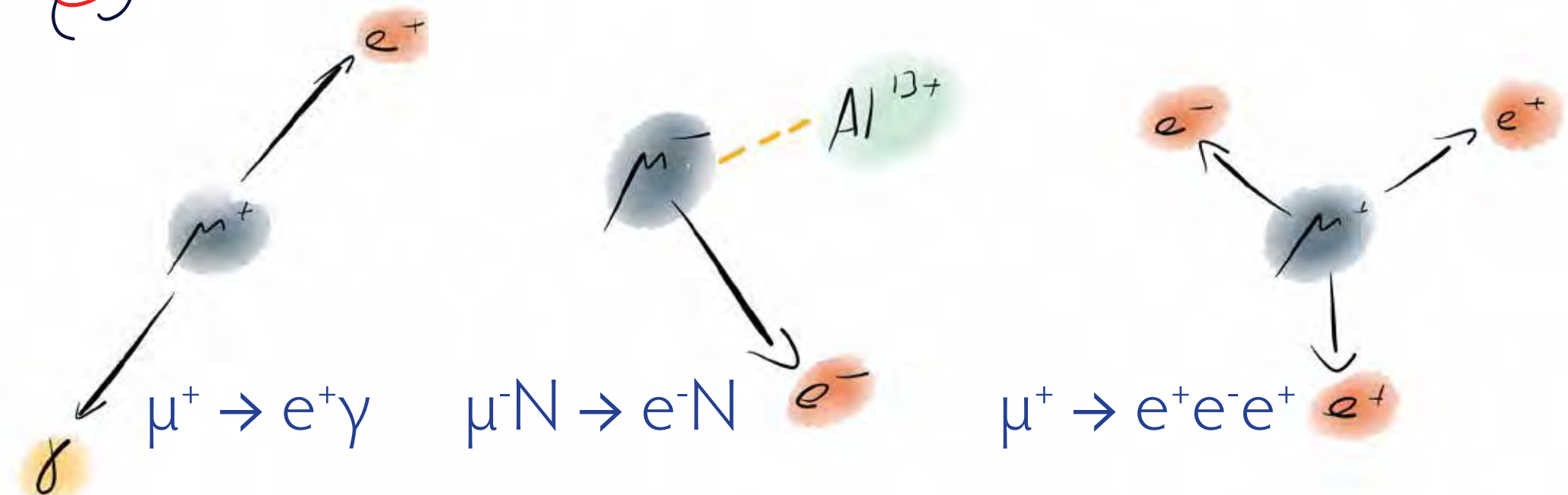


Muon decays sensitive to new physics at $O(1000 \text{ TeV})$
scale for $O(1)$ couplings!



The hunt for charged lepton flavour violation in μ -decays

LFV Muon Decays: Experimental Situation



MEG (PSI)

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

(2013)

SINDRUM II (PSI)

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

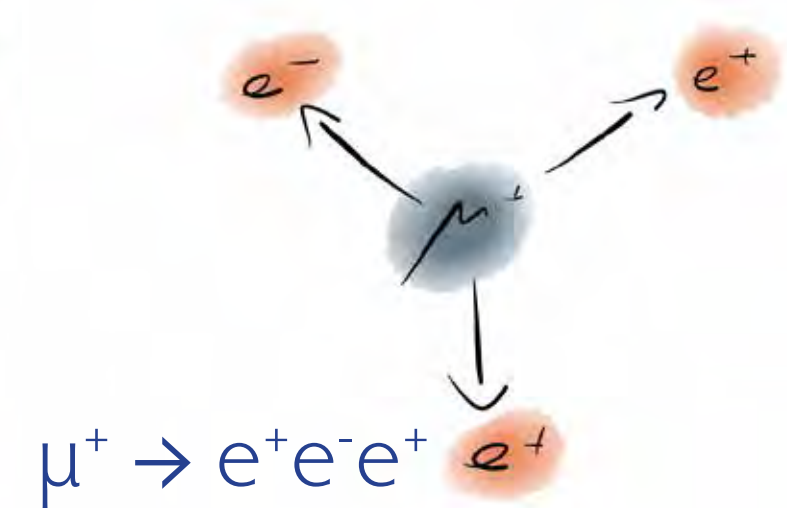
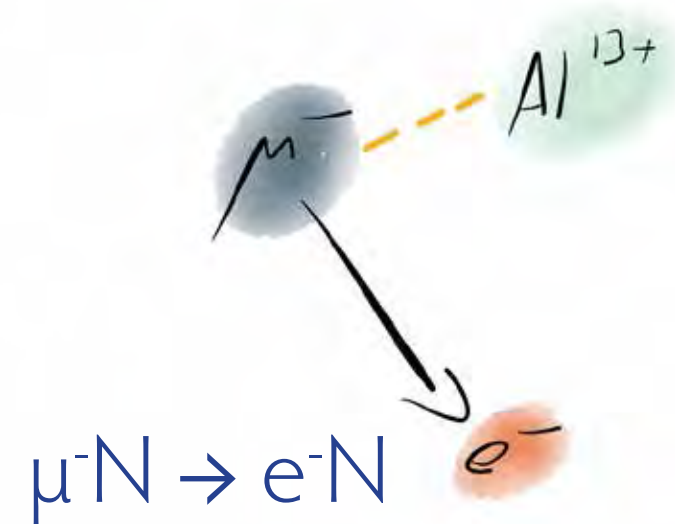
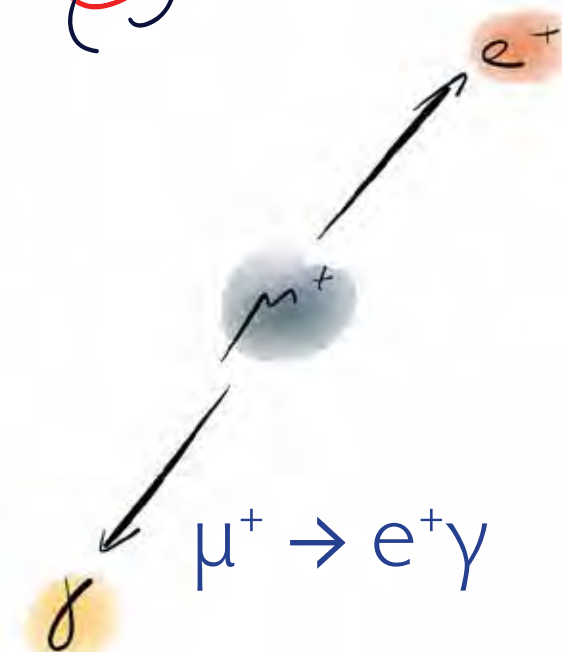
(2006)

SINDRUM (PSI)

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

(1988)

LFV Muon Decays: Experimental Situation



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)

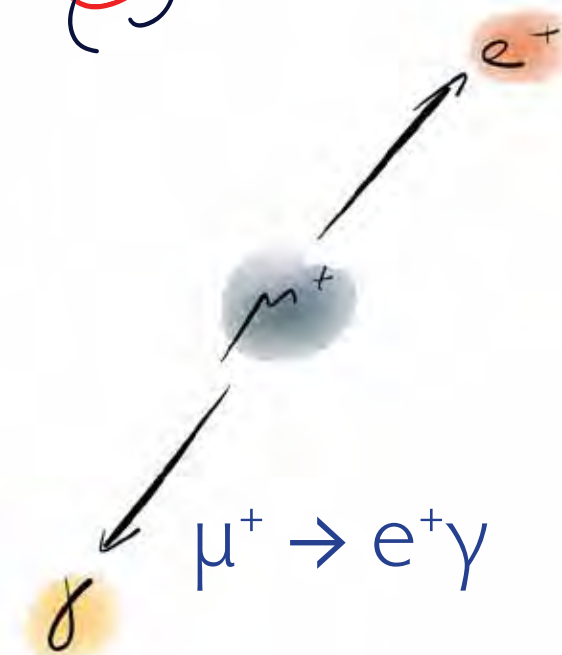
Mu2e/Comet

SINDRUM (PSI)

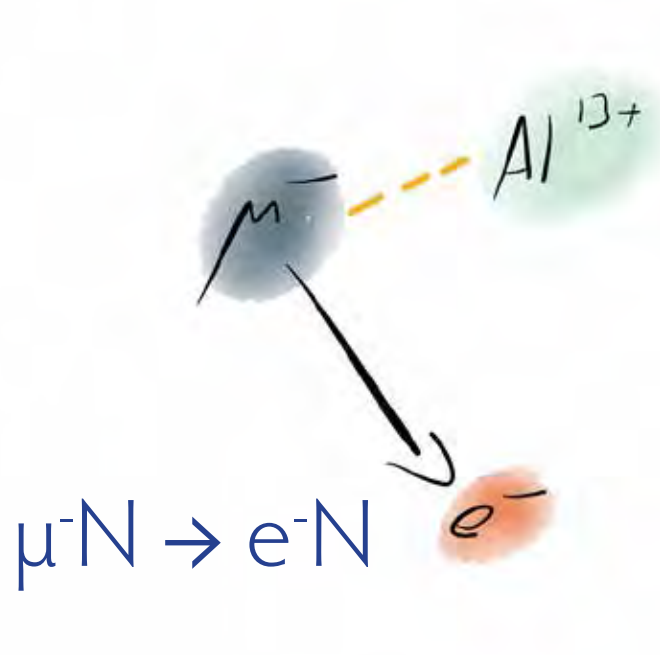
$B(\mu^+ \rightarrow e^+ e^- e^+) < 1.0 \cdot 10^{-12}$
(1988)

Mu3e

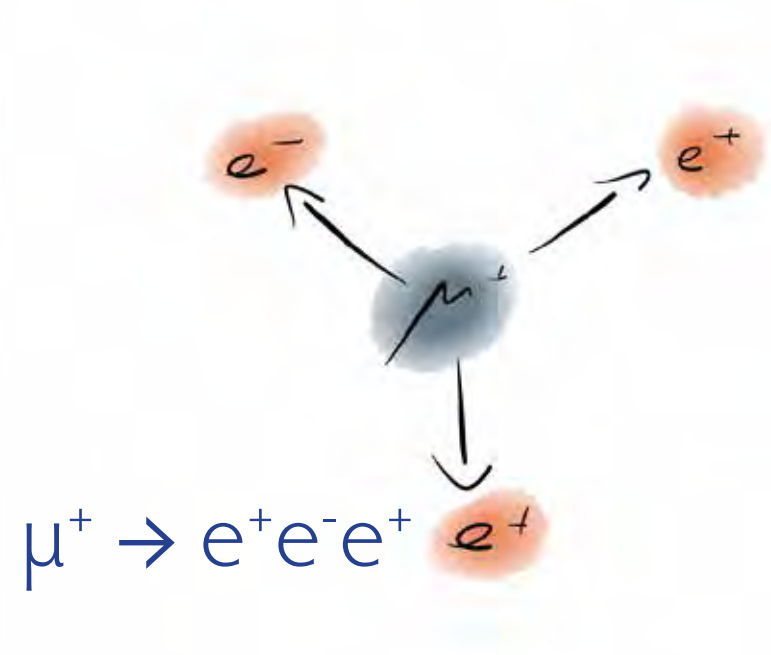
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

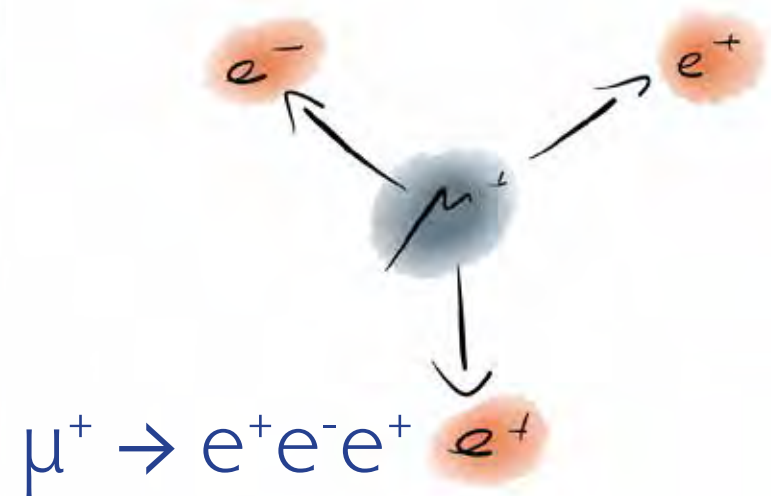
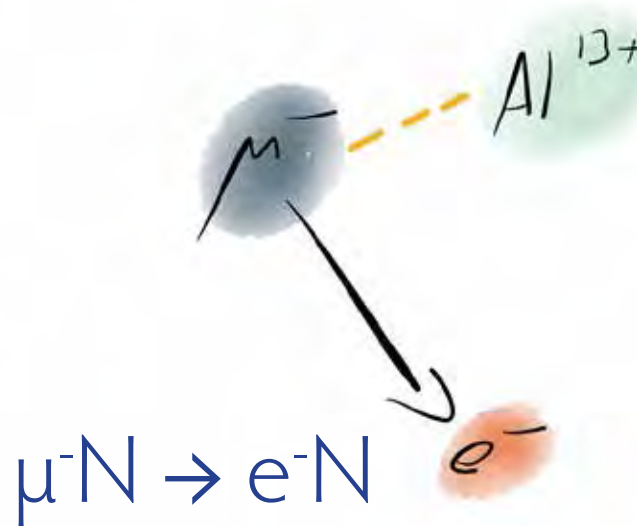
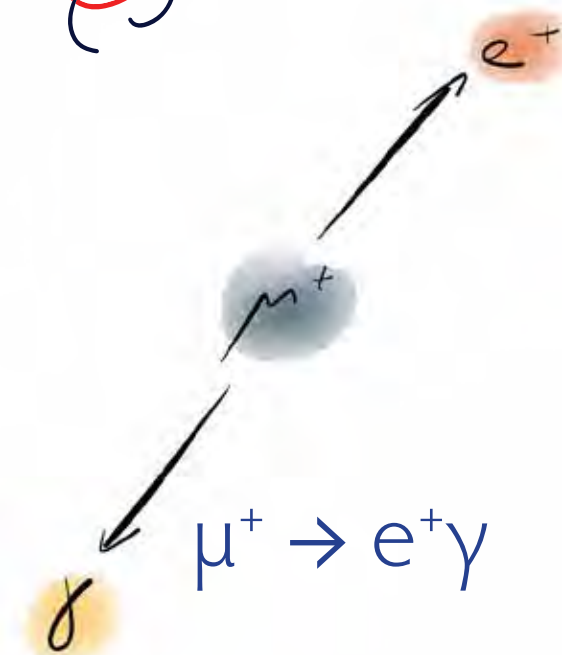
Kinematics

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

Kinematics

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

LFV Muon Decays: Experimental signatures



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

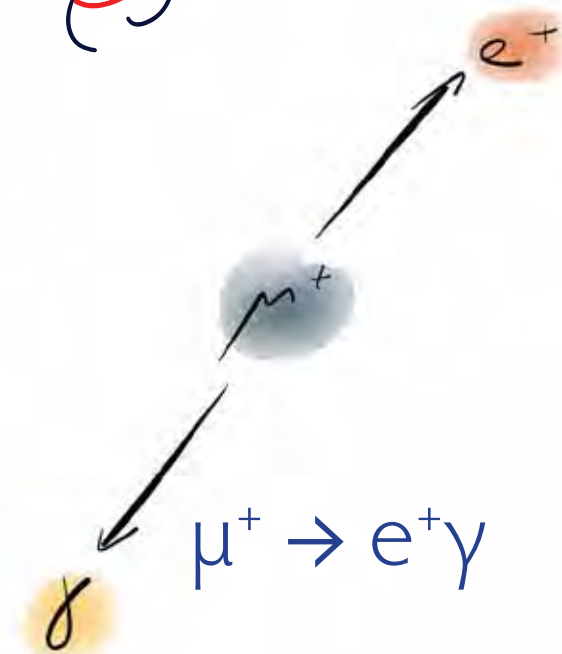
Kinematics

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

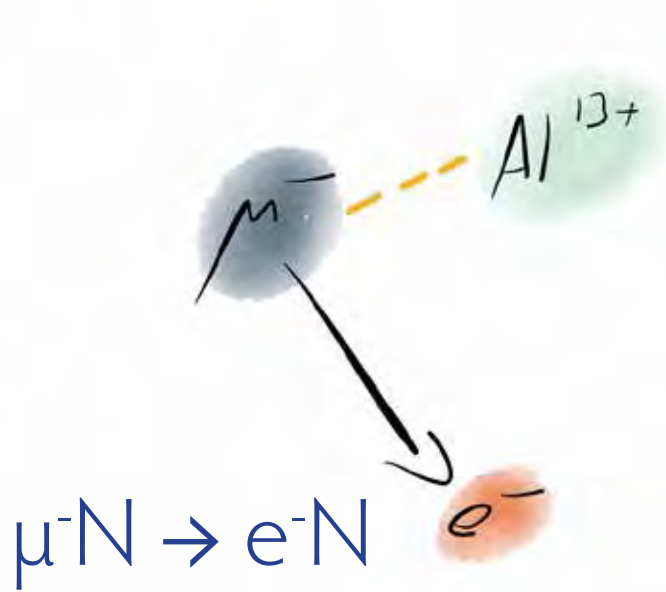
Background

- Radiative decay
- Accidental background

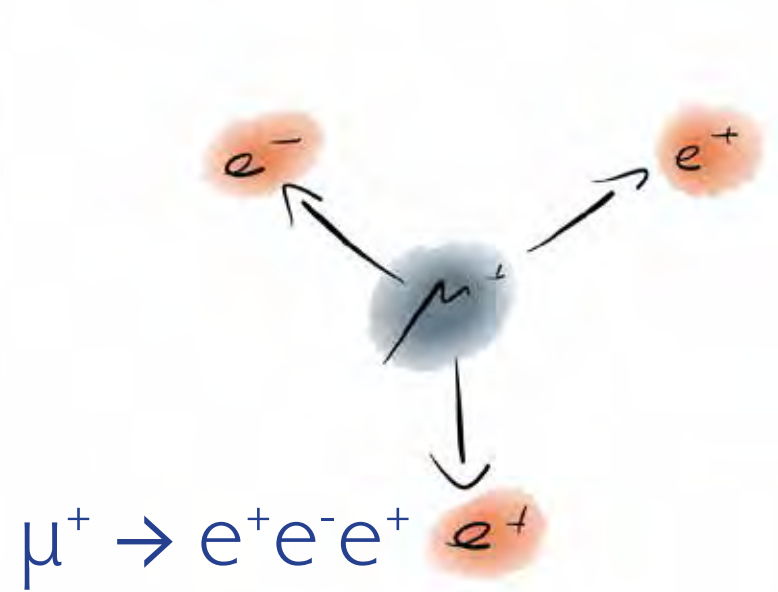
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

- 2-body decay
- Monoenergetic
- Back-to-back

Background

- Atomic background

Continuous Beam

Kinematics

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

Background

- Γ orbit
- Atomic protons, pions

Pulsed Beam

Kinematics

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

Background

- Radiative decay
- Atomic background

Continuous Beam

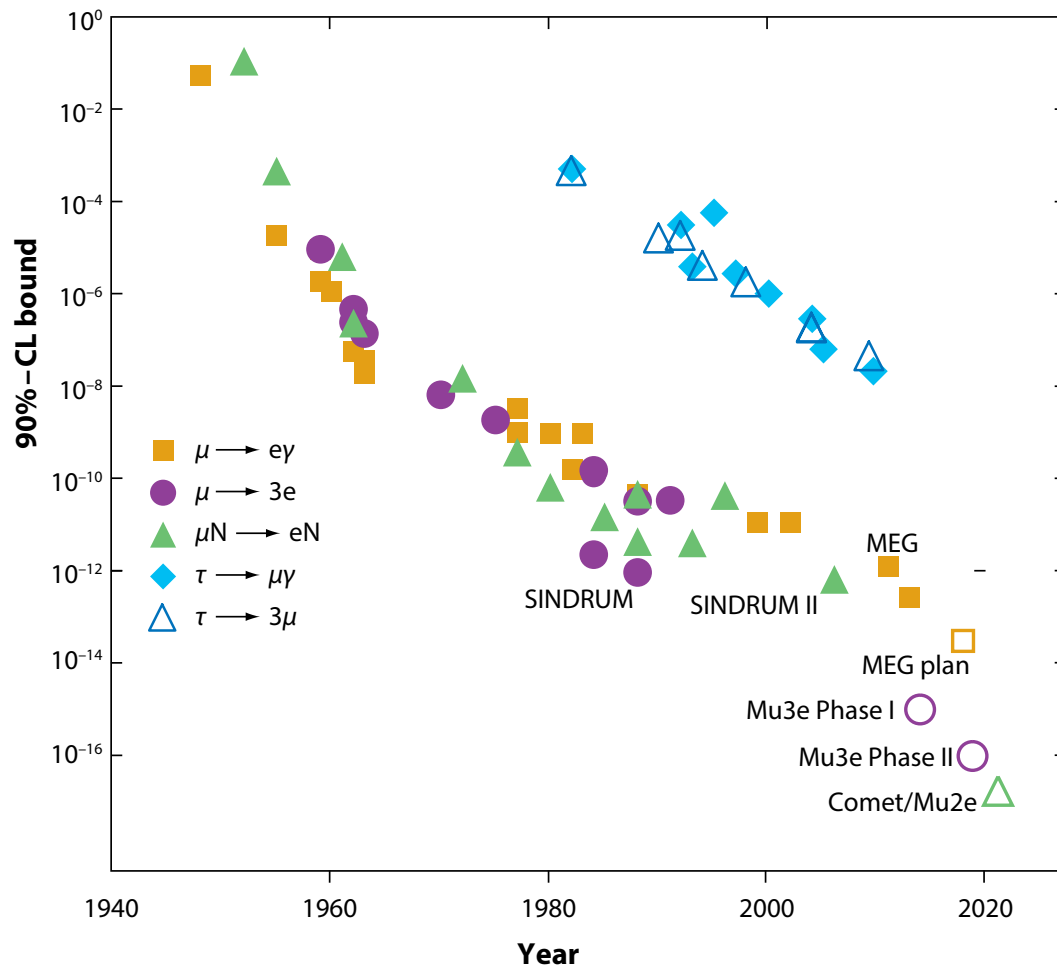


Searching for
 $\mu^+ \rightarrow e^+e^-e^+$ at the 10^{-16} level



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



**UNIVERSITÉ
DE GENÈVE**

- DPNC, Geneva University



- Physics Institute, Heidelberg University



- KIP, Heidelberg University



- IPE, Karlsruhe Institute of Technology



- Paul Scherrer Institute



- Physics Institute, Zürich University

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

- Institute for Particle Physics, ETH Zürich

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

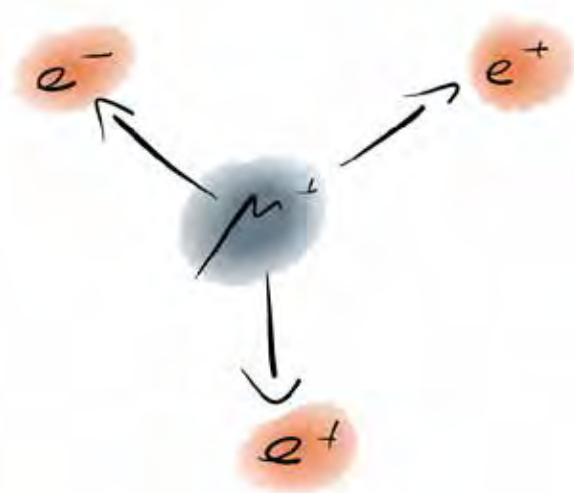


- Institute for Nuclear Physics, JGU Mainz



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:

- $\pi E5$ beamline: $\sim 10^8$ muons/s
(MEG experiment, Mu3e phase I)
- Surface muons, $p = 29.7$ MeV/c
Stopped in < 1 mm of plastic



©Kramer 10-99

Muons from PSI

DC muon beams at PSI:



- $\pi E5$ beamline: $\sim 10^8$ muons/s
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Muons from PSI




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- Surface muons, $p = 29.7$ MeV/c
Stopped in < 1 mm of plastic
- The $\mu \rightarrow eee$ experiment (final stage) requires 2×10^9 muons/s focused and collimated on a ~ 2 cm spot
- More than $\sim 10^{11}$ muons/s are produced; bring magnetic elements closer to capture them:
High intensity muon beamline (HiMB) study currently ongoing

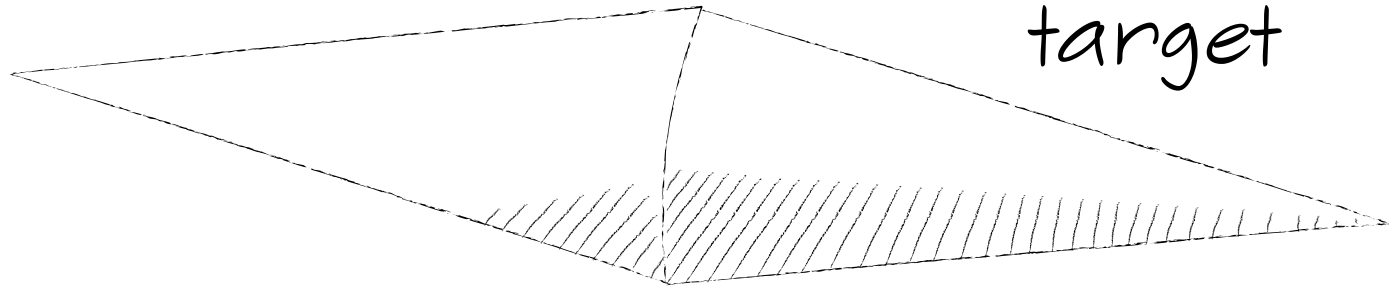
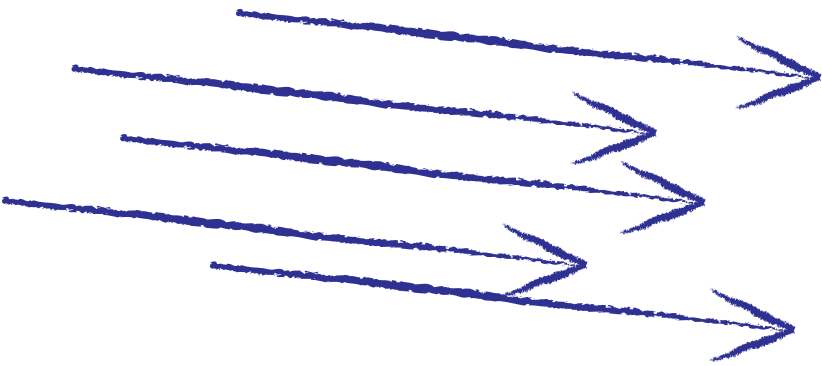


Building the Mu3e Experiment



Stop muons, let them decay

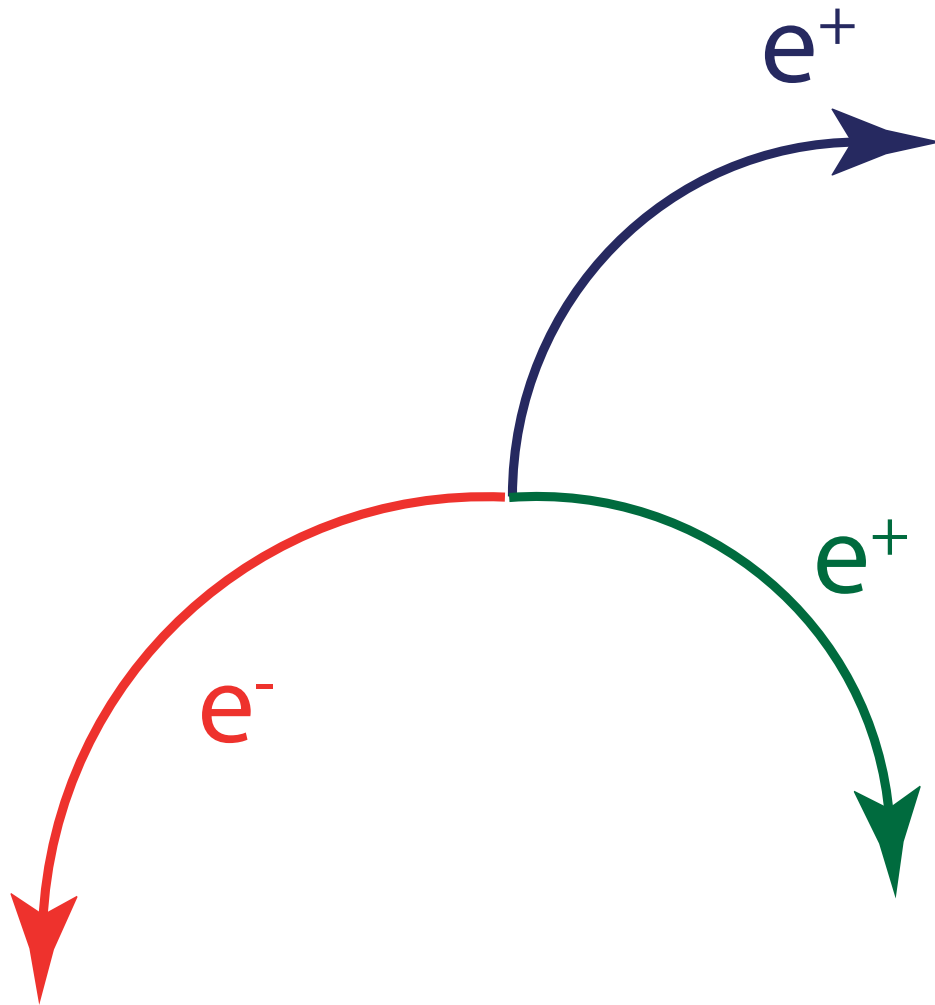
muon beam



target

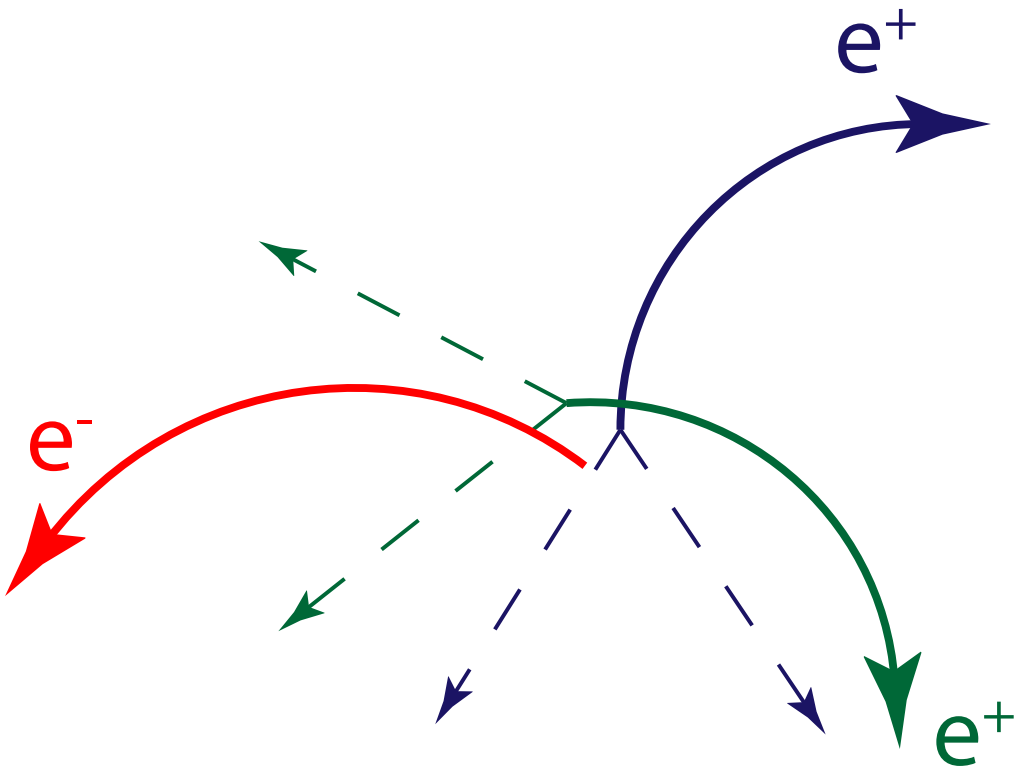


The signal



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

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

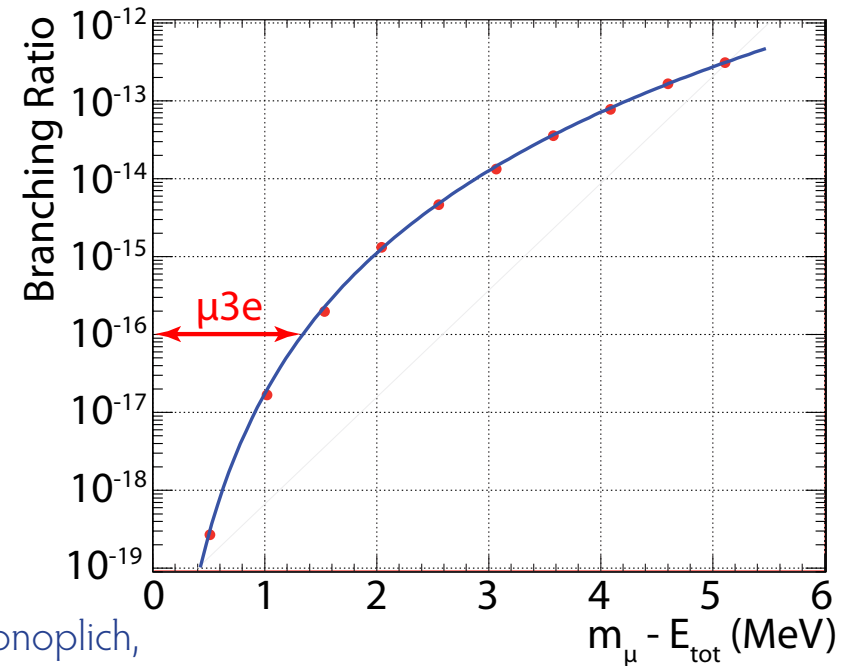


- Allowed radiative decay with internal conversion:



- 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





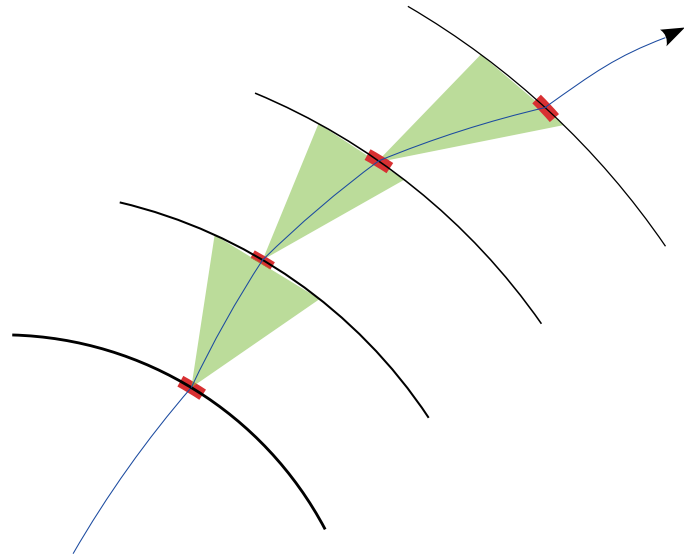
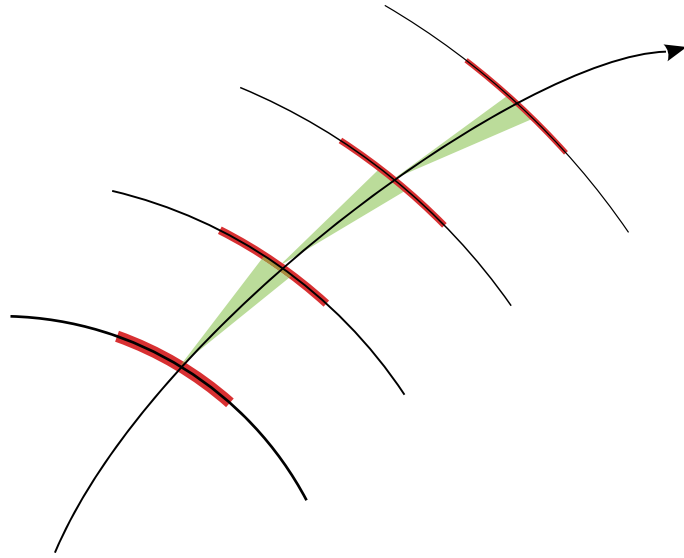
Detector Technology



- 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:
 $53 \text{ MeV}/c$ ($m_\mu/2$)
- Momentum resolution dominated by multiple Coulomb scattering
- As little material as possible

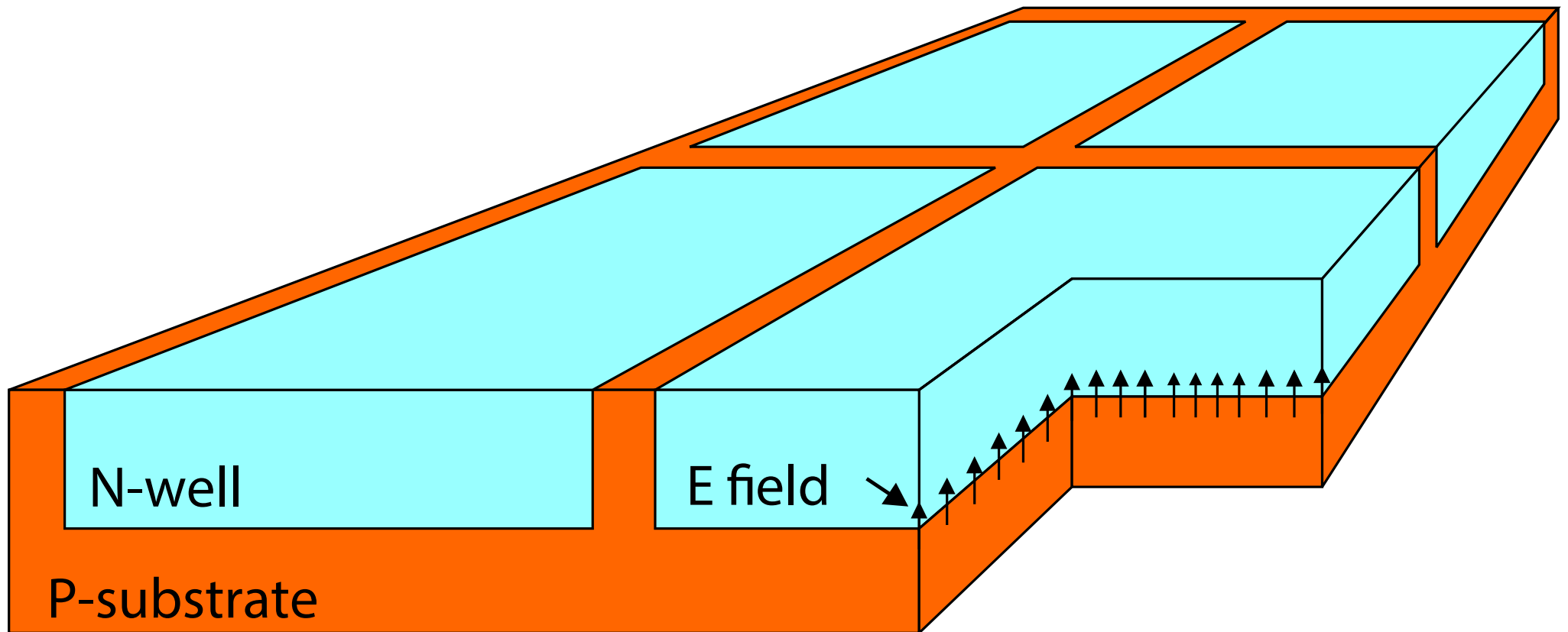
$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta cp} z \sqrt{x/X_0} \left[1 + 0.038 \ln(x/X_0) \right]$$



Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)

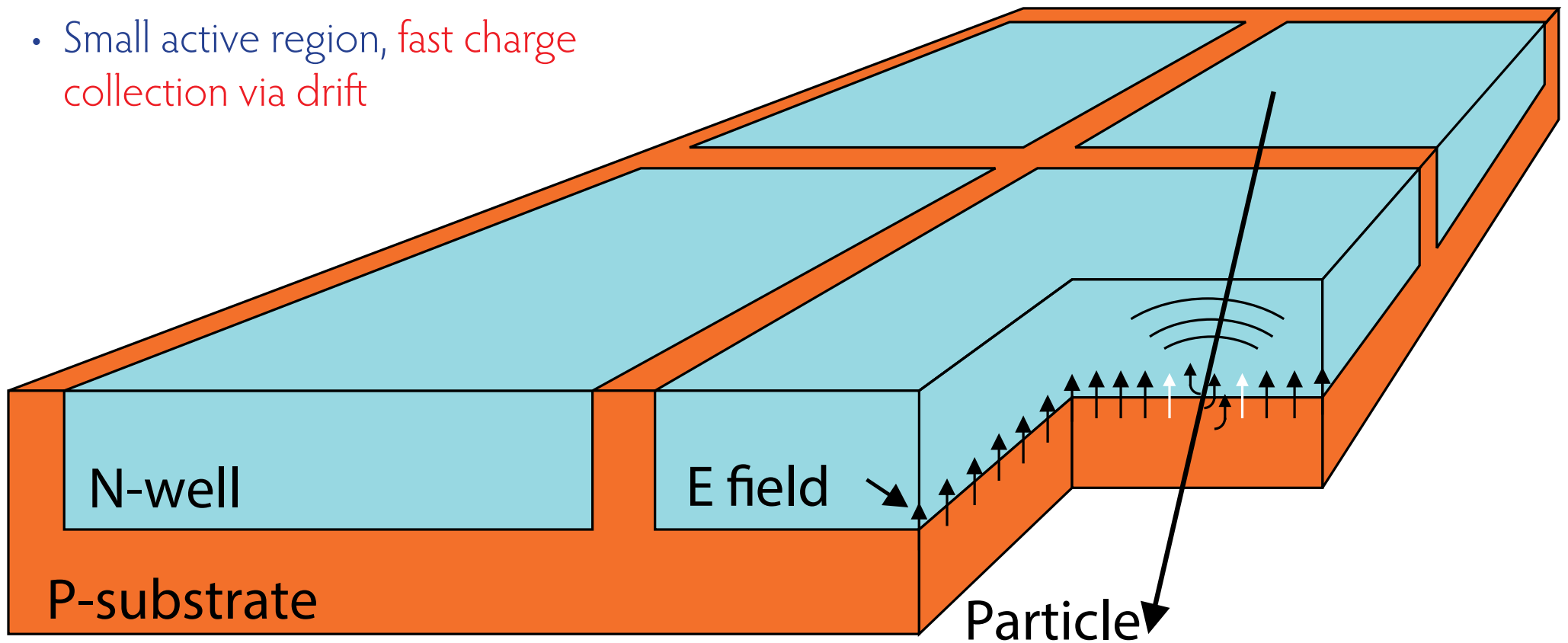




Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

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





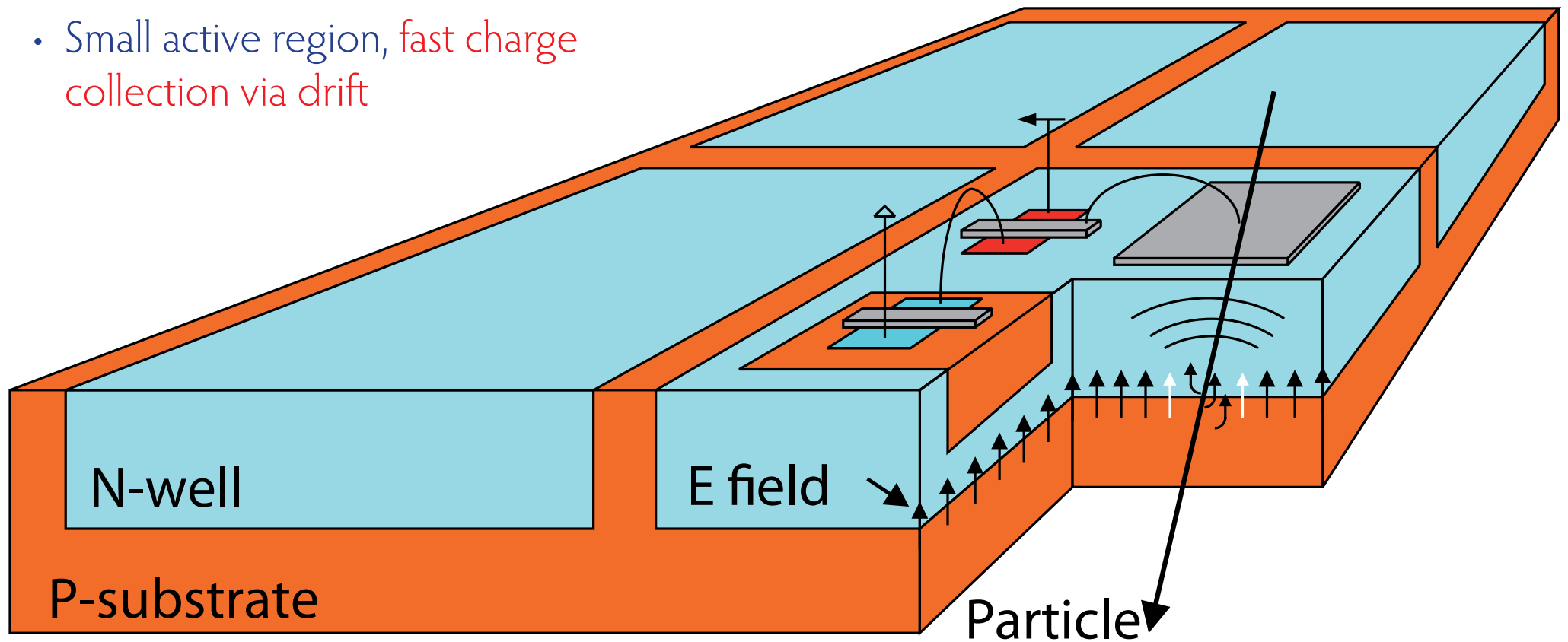
Fast and thin sensors: HV-MAPS

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 $< 50 \mu\text{m}$

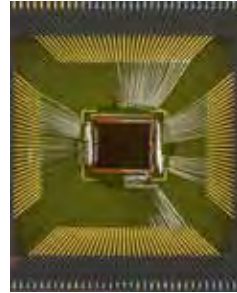
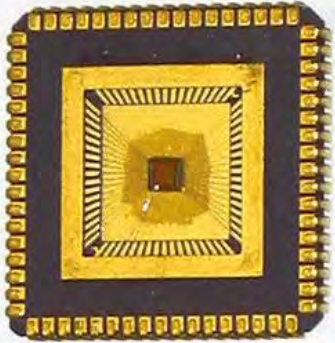
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)



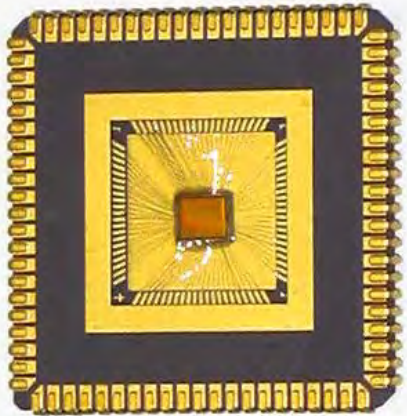


The MuPix chip prototypes

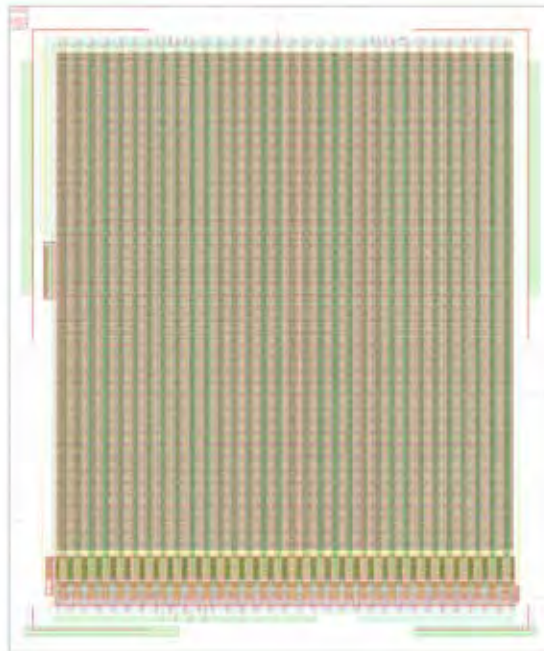
MuPix2



MuPix6



MuPix4

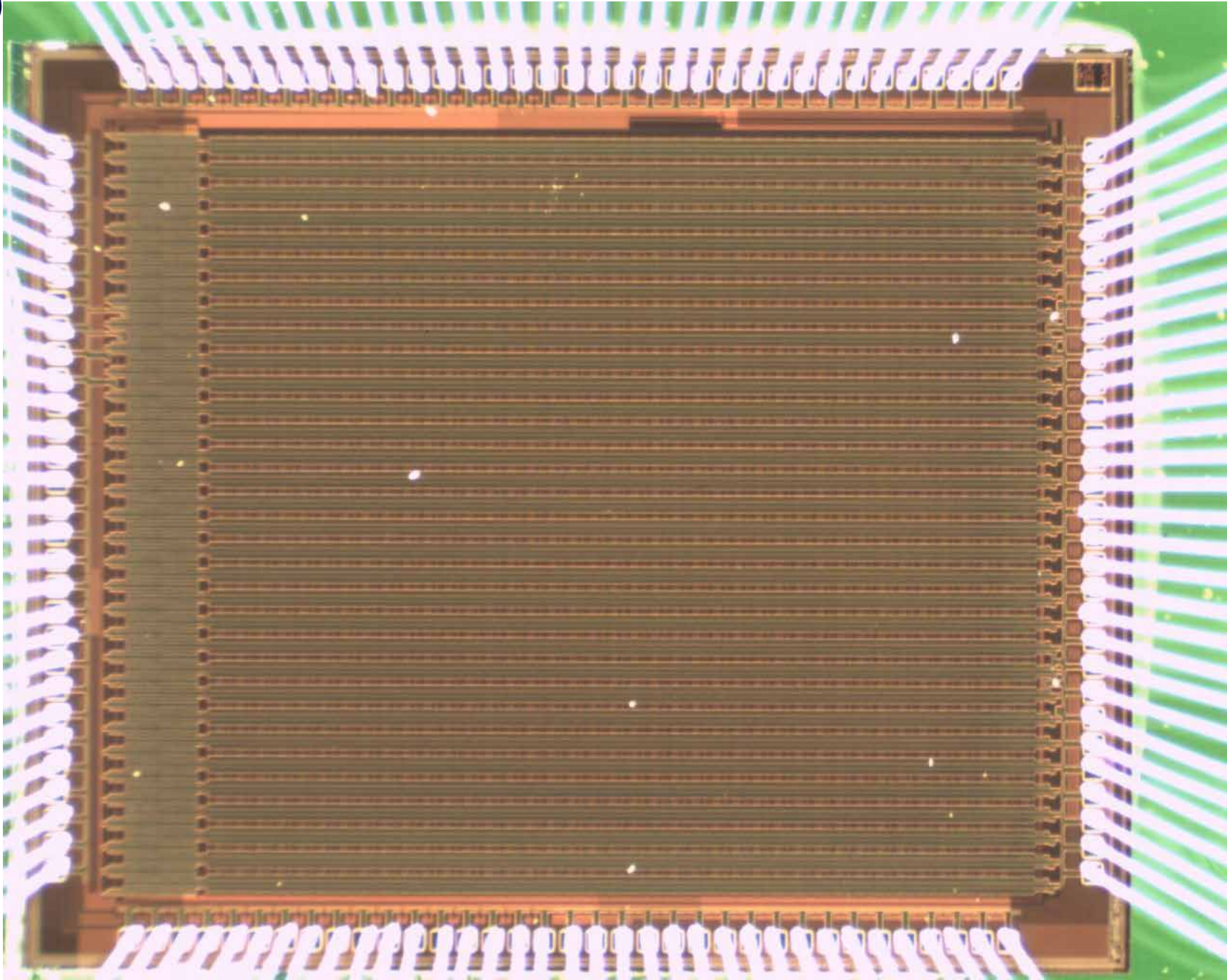


HV-MAPS chips: AMS 180 nm HV-CMOS

- 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



HV-MAPS



3 mm



HV-MAPS



Pixels with amplifier

40 x 32 pixels

80 x 103 μm pixel size

3 mm



INTRO ADPSON



Comparator and digital pixel logic

Pixels with amplifier

40 x 32 pixels

80 x 103 μm pixel size

3 mm



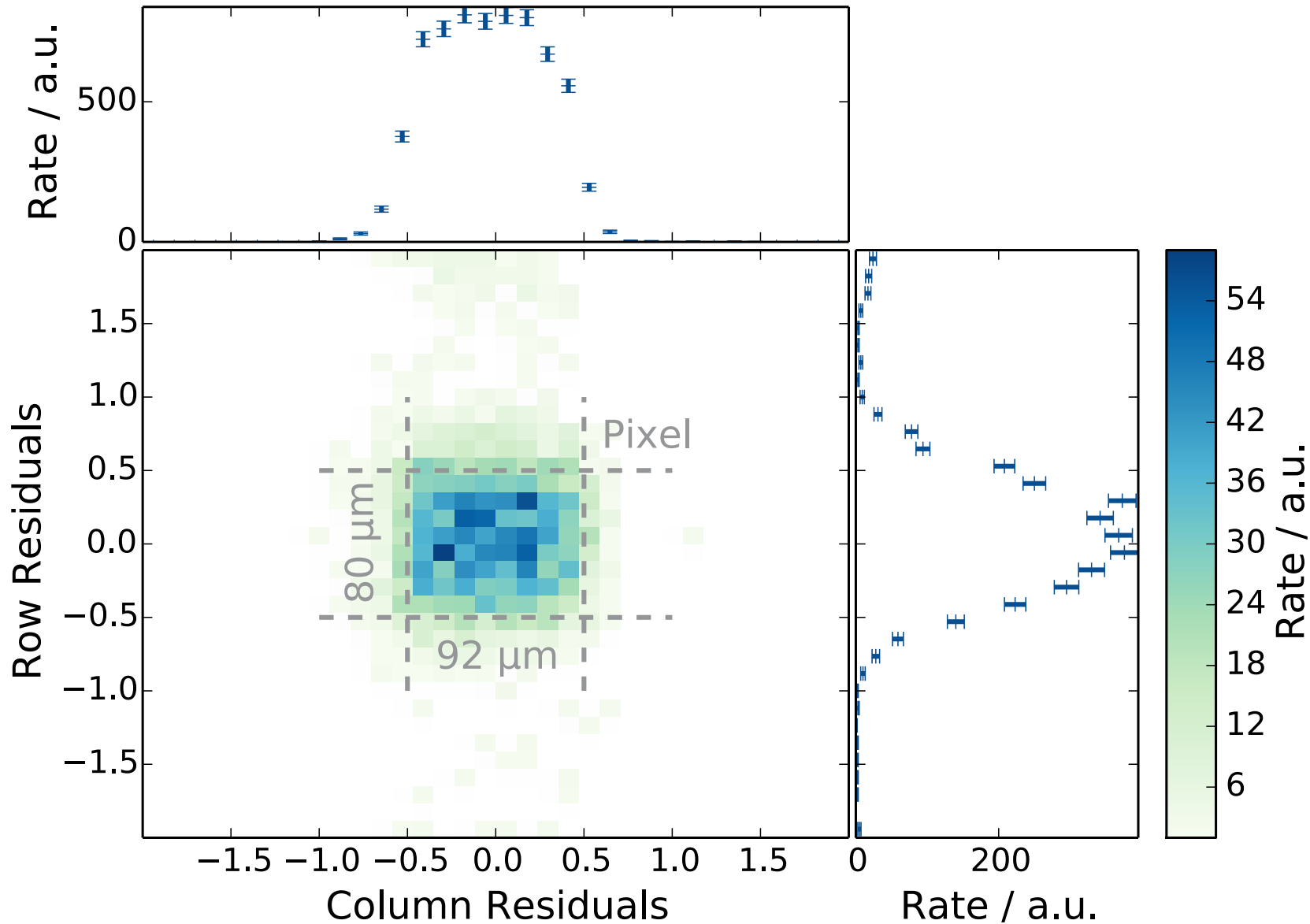
Test beam at DESY





Position Resolution

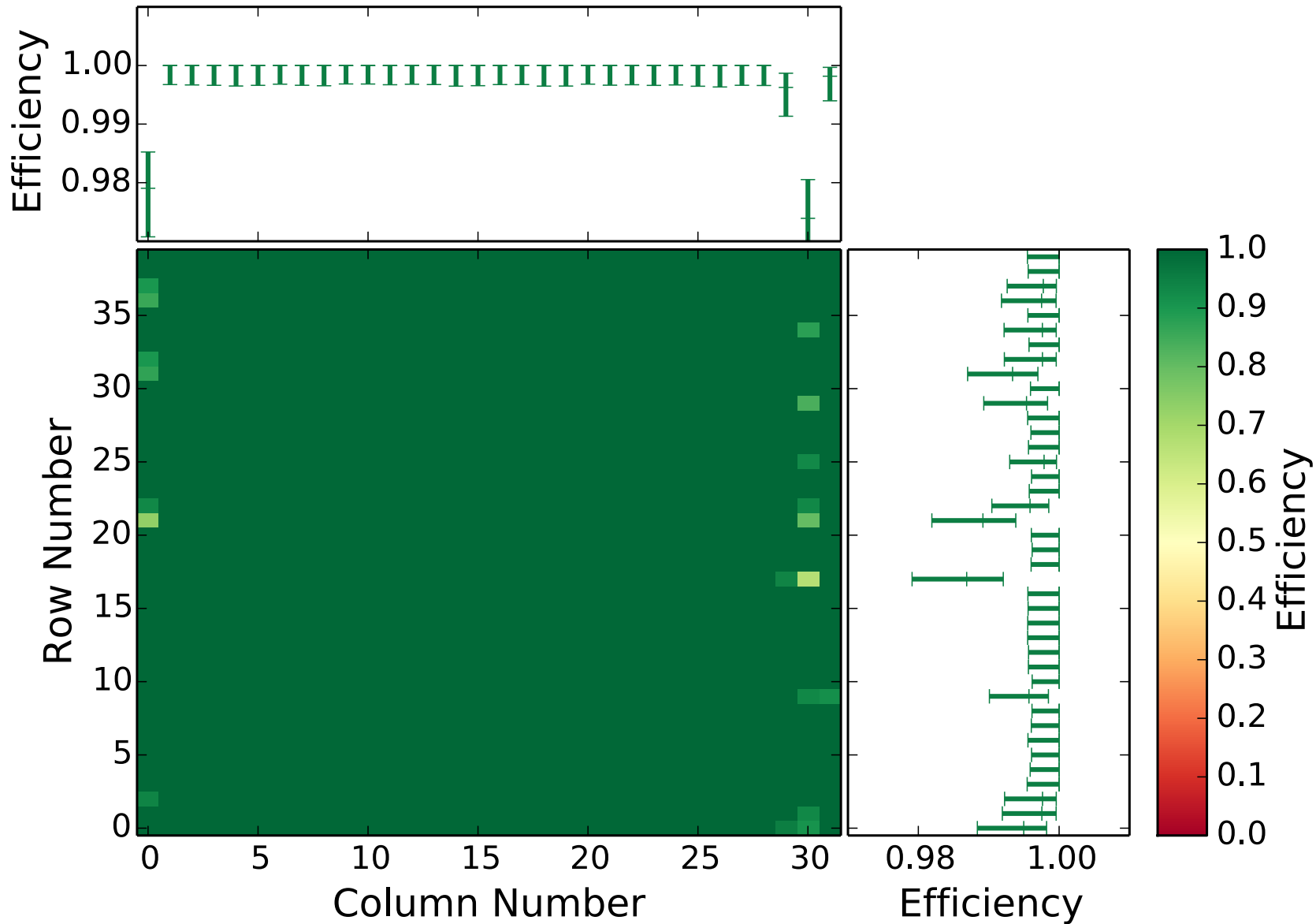
Position resolution given by pixel size





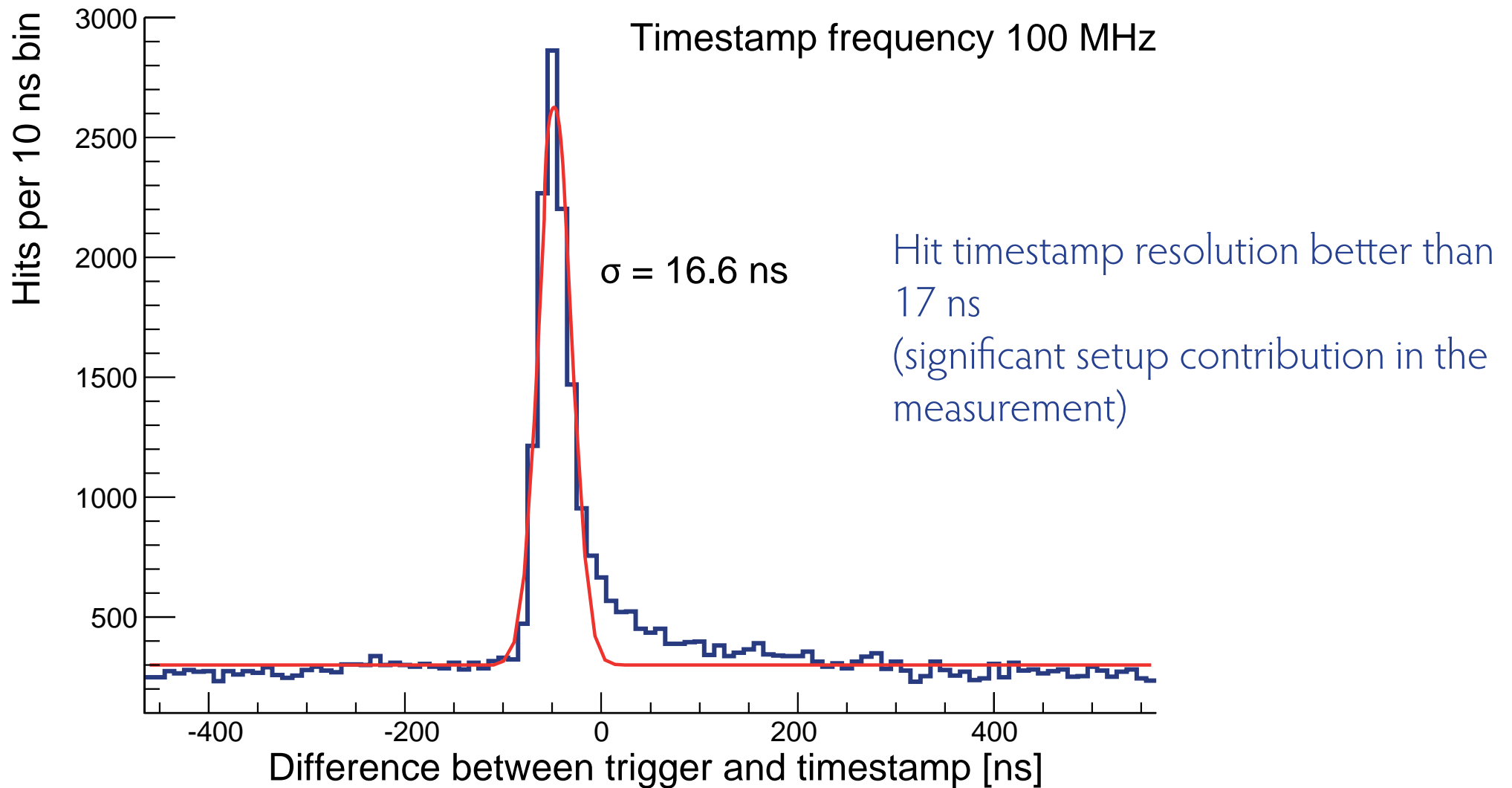
Efficiency

Hit efficiency above 99% without tuning





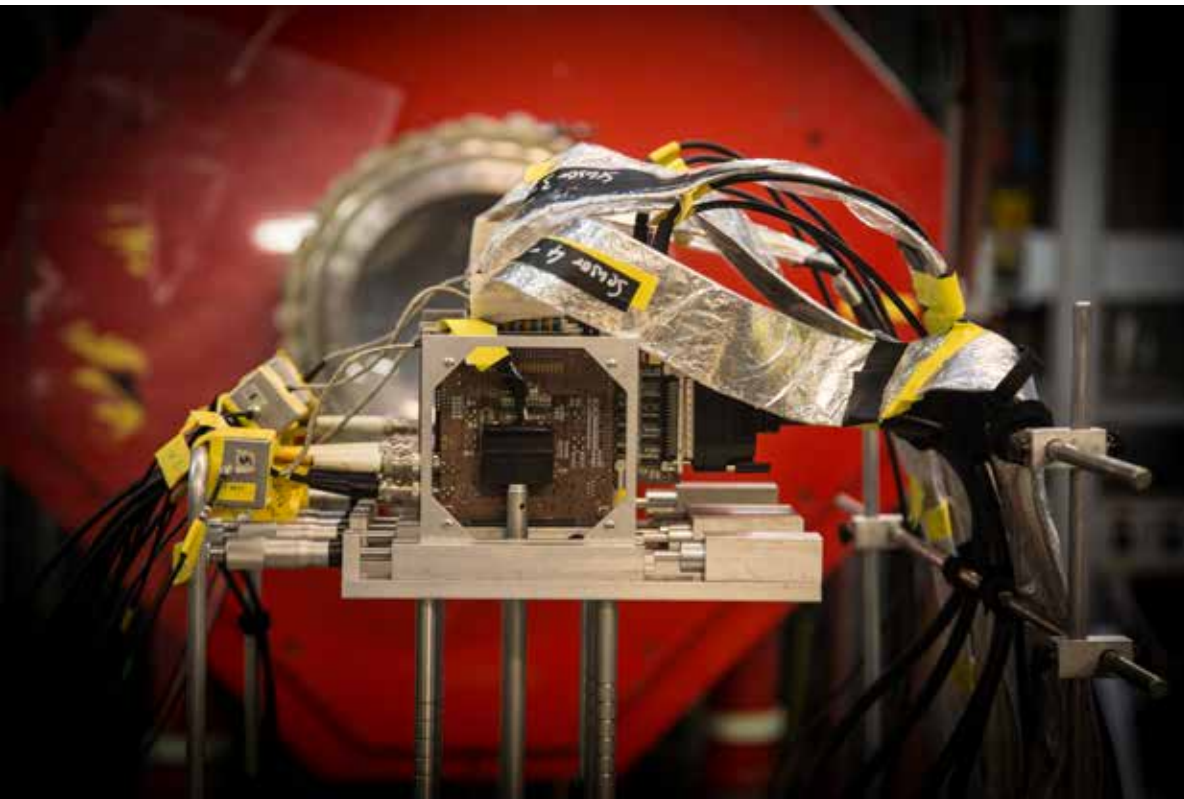
Time resolution



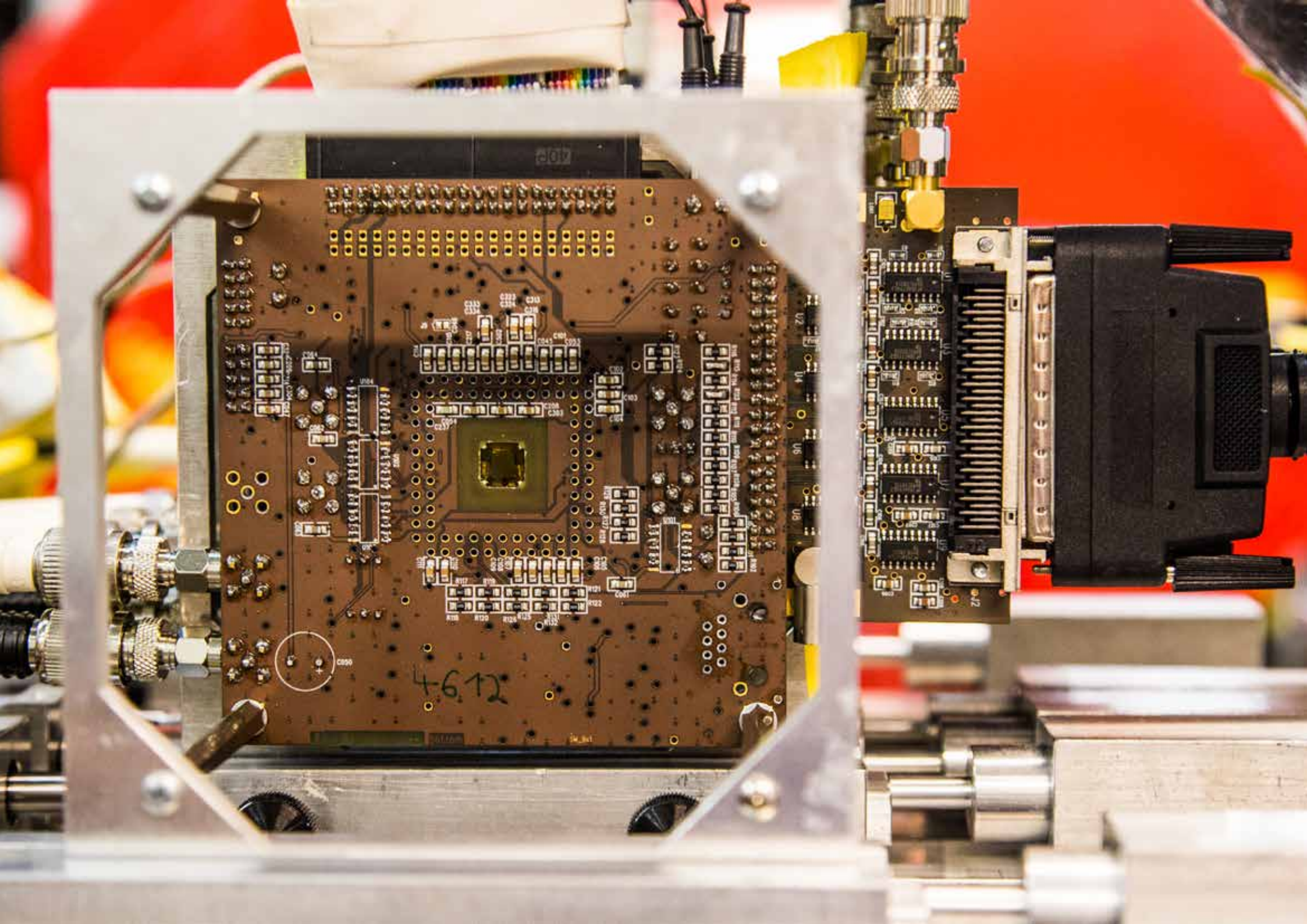
MuPix Telescope

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, PSI and MAMI







46.12

C90

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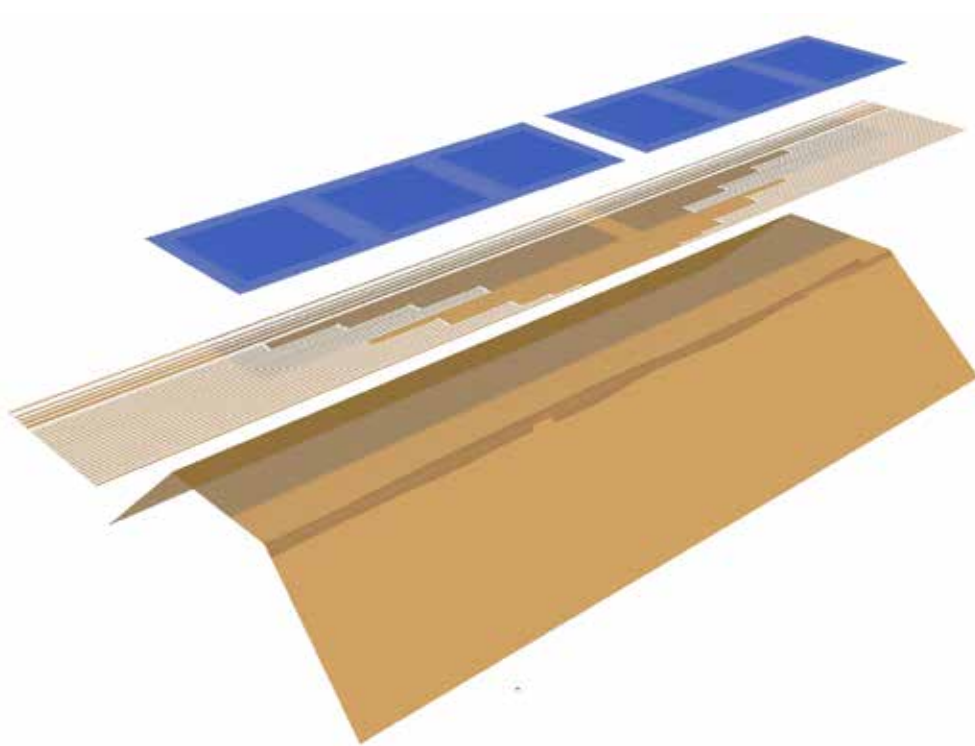
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Building a detector thinner than a hair

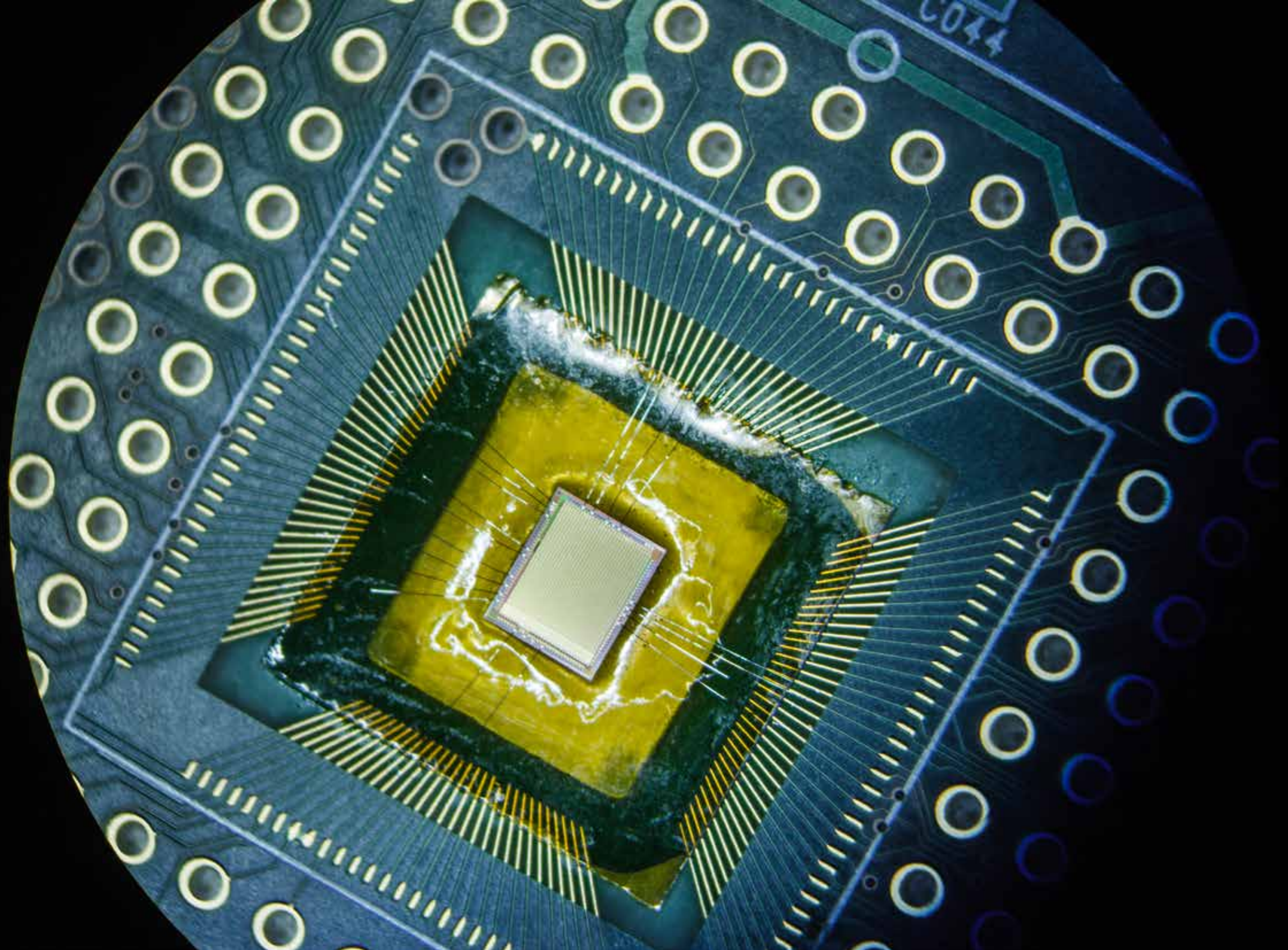




- 50 μm silicon
- 25 μm Kapton™ flexprint with aluminium traces
- 25 μm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer



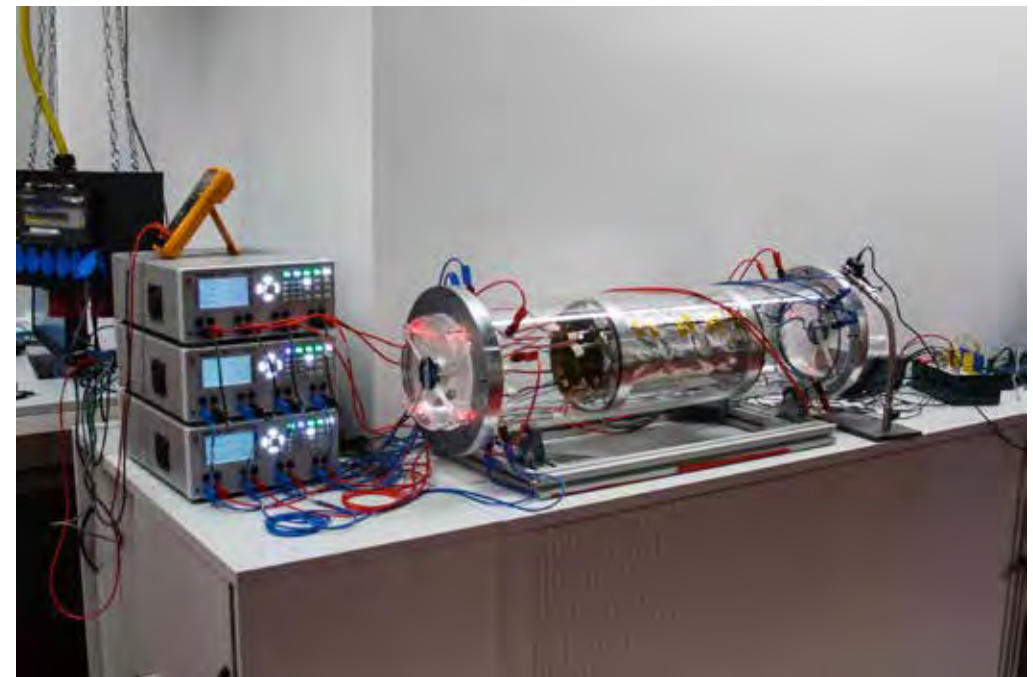
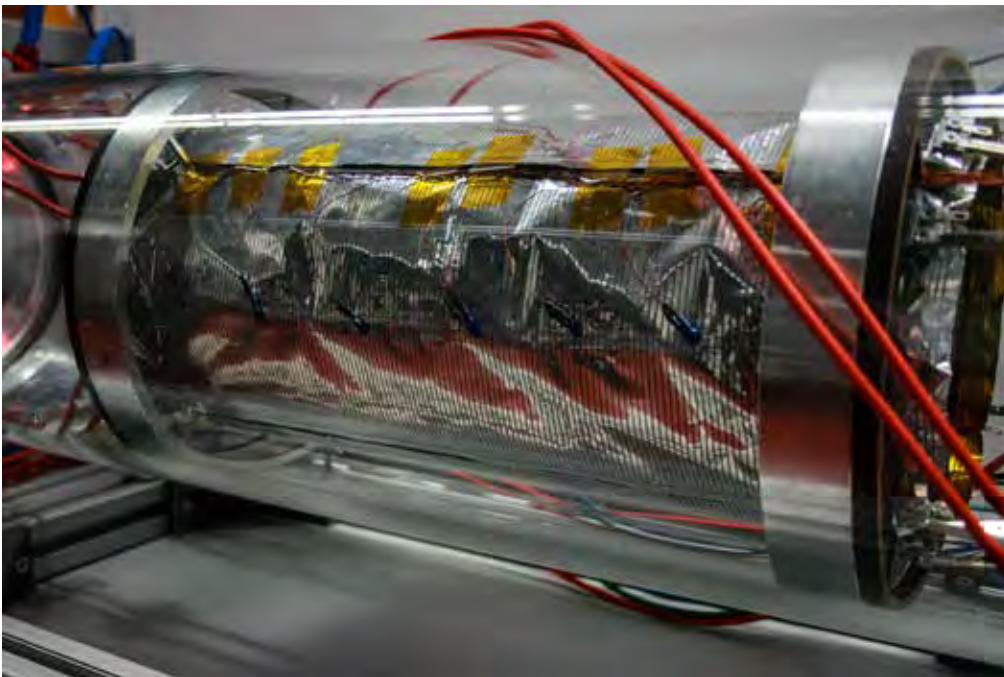


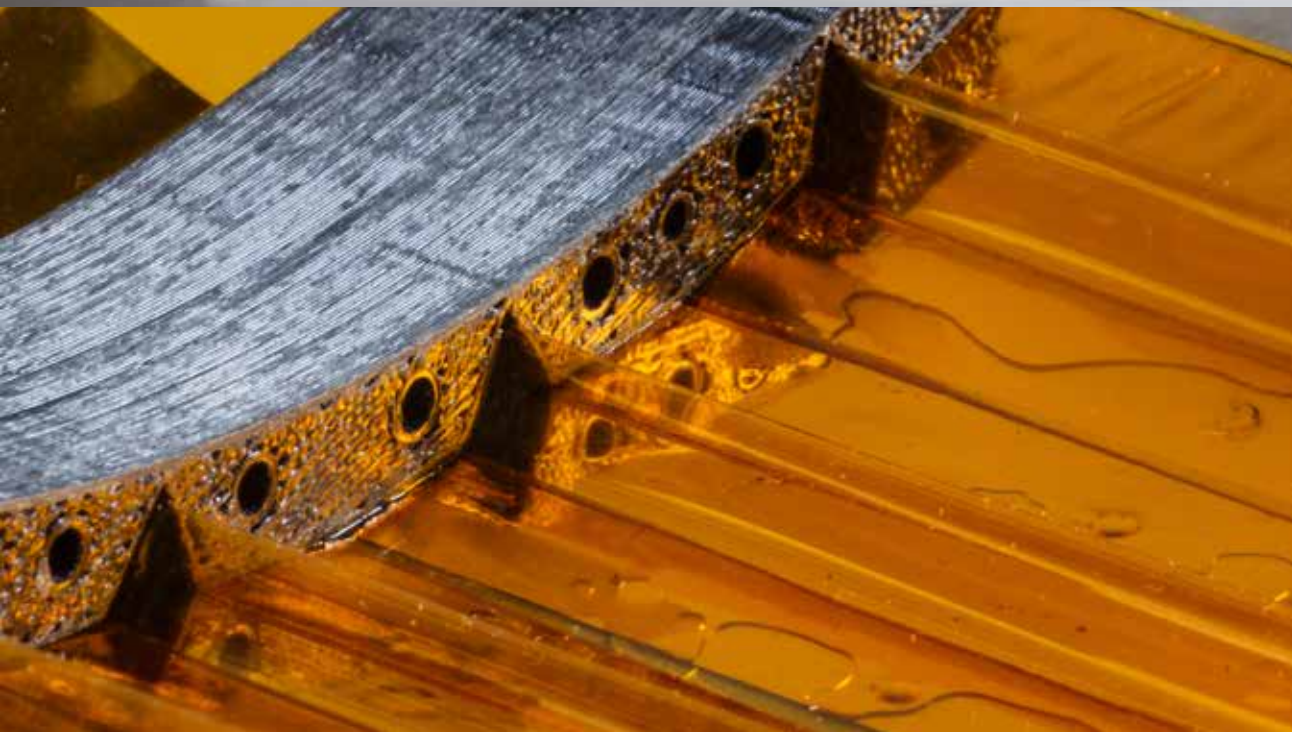


Cooling

- Add no material:
Cool with **gaseous Helium**
(low scattering, high mobility)
- $\sim 150 \text{ mW/cm}^2$ - total 2 kW
- Simulations: Need \sim **several m/s flow**

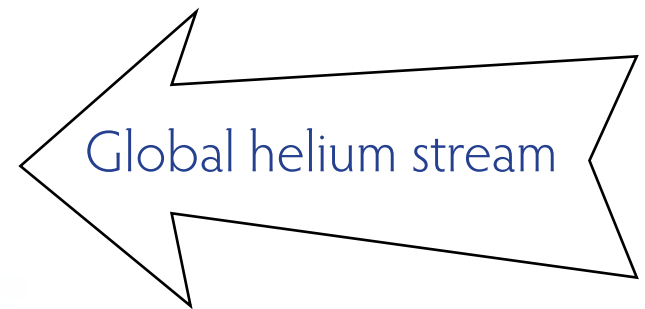
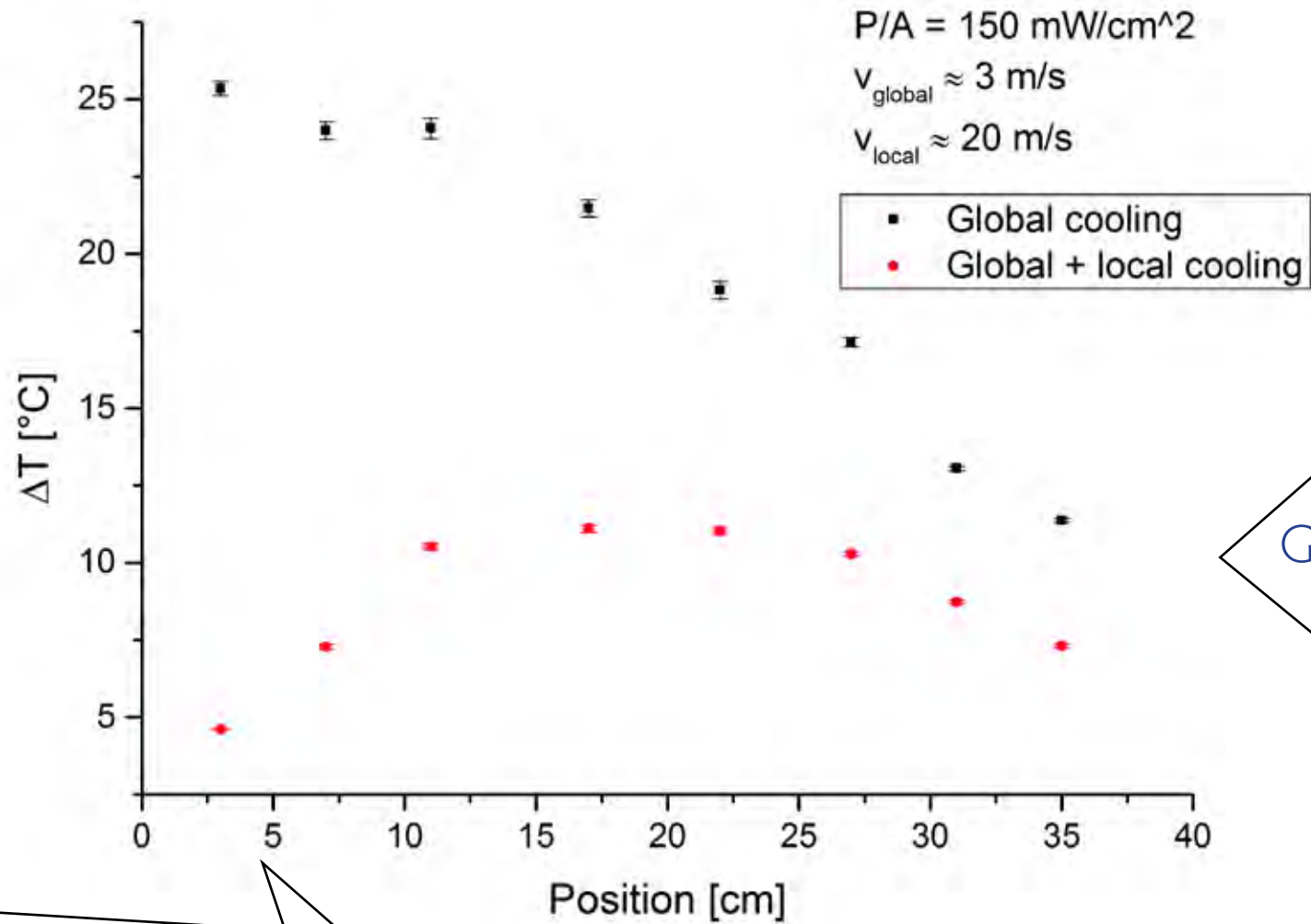
- Full scale heatable prototype built
- 36 cm active length
- No visible vibrations



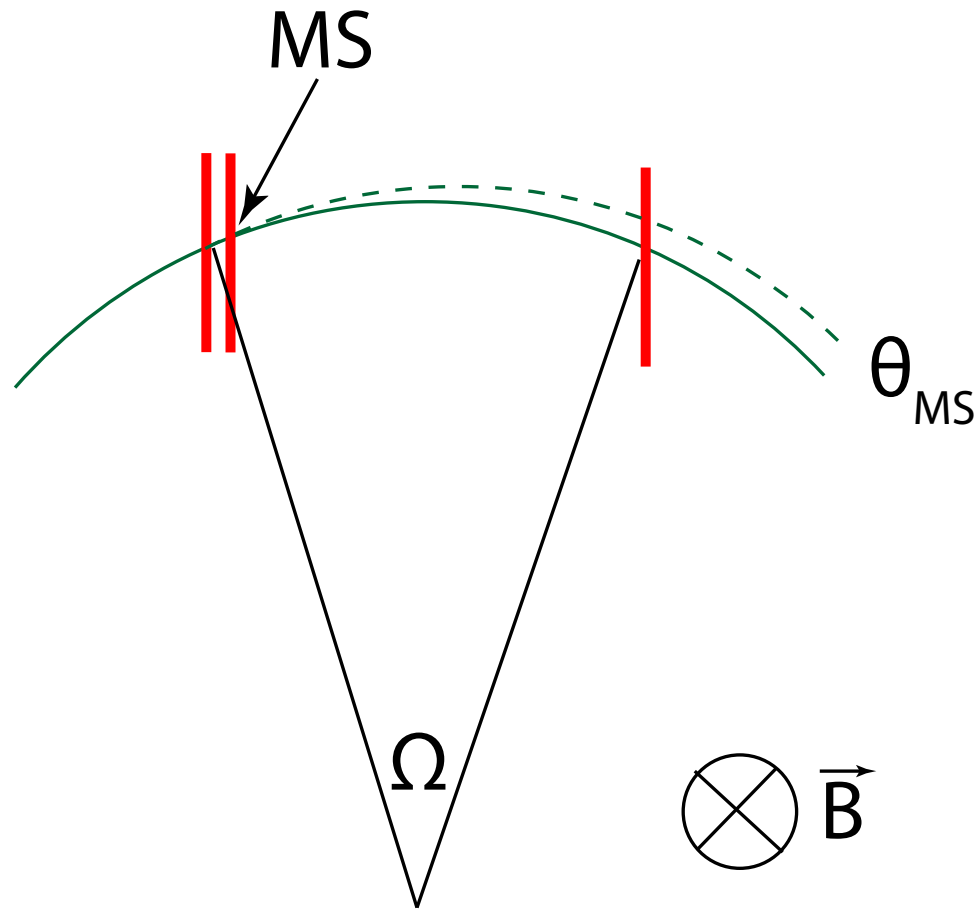




Cooling tests



Momentum measurement

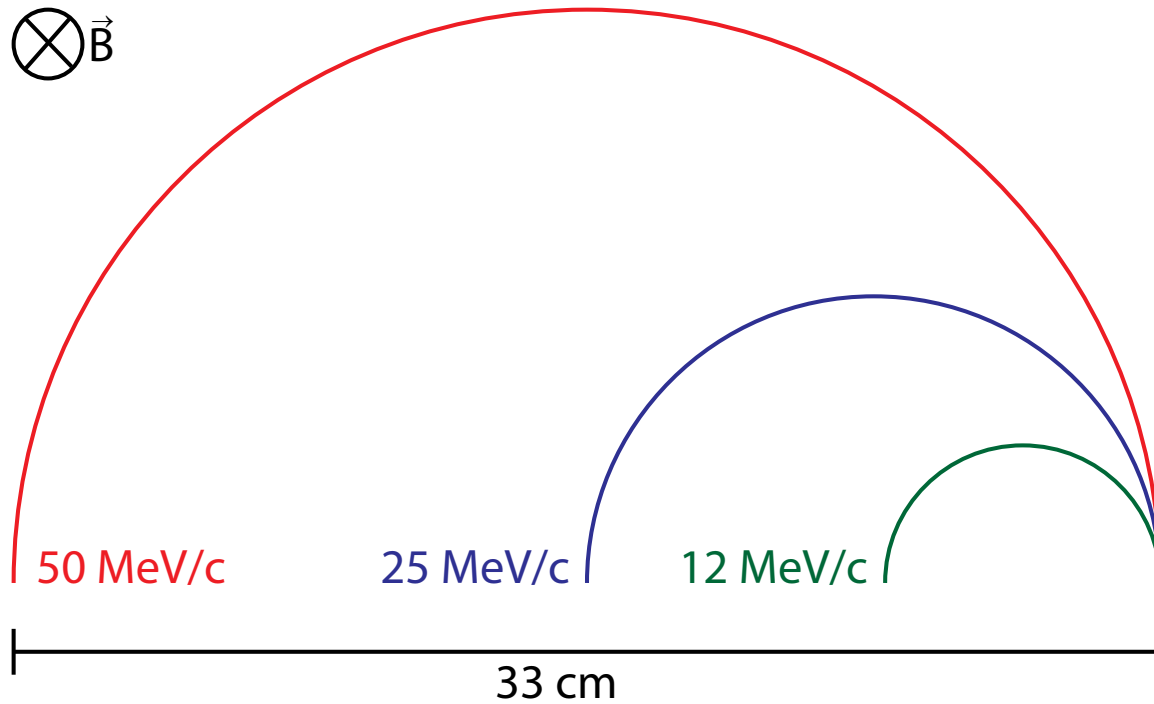


- 1 T magnetic field
- Resolution dominated by **multiple scattering**
- Momentum resolution to first order:

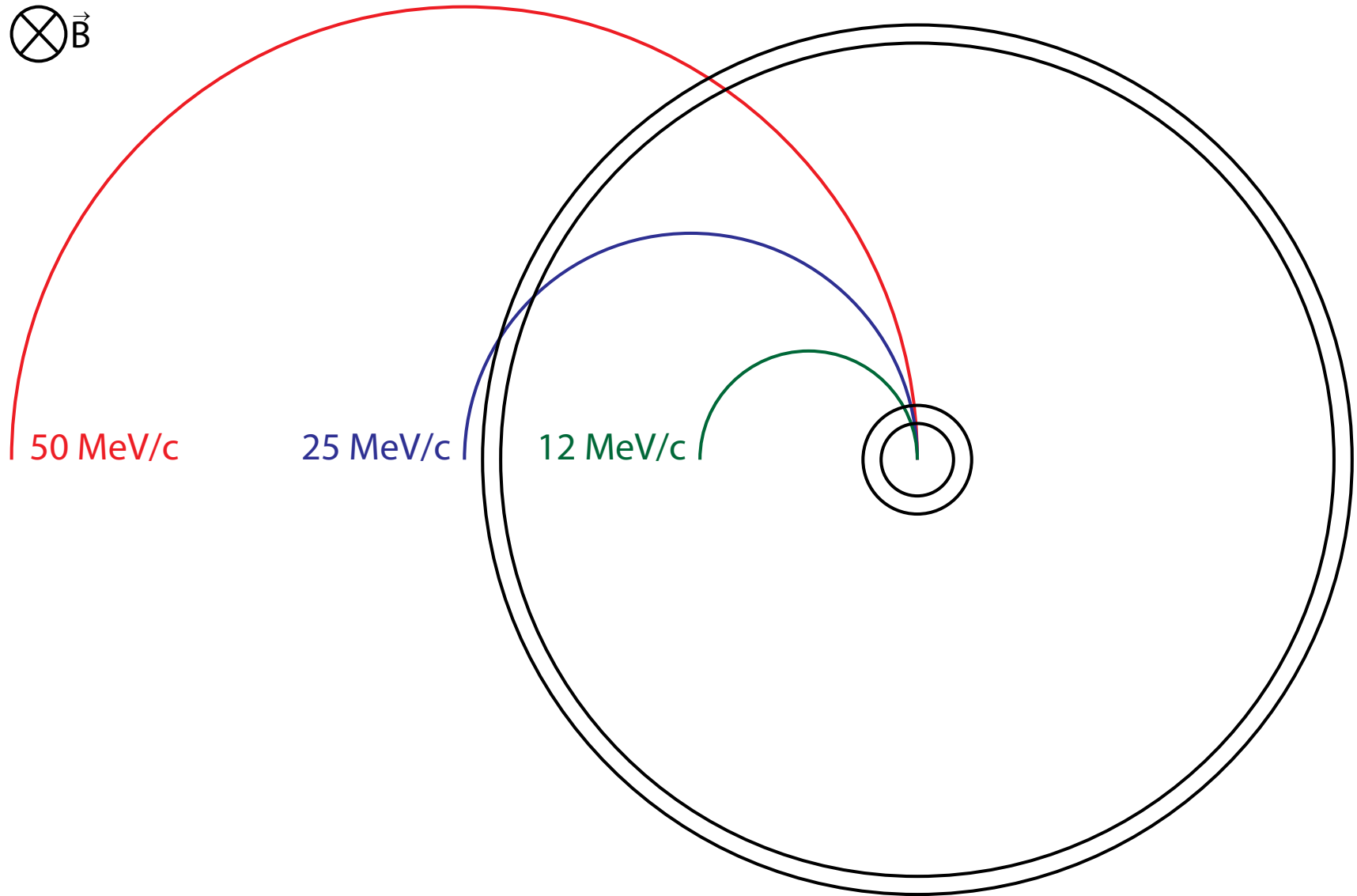
$$\sigma_{P/P} \sim \theta_{MS}/\Omega$$

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

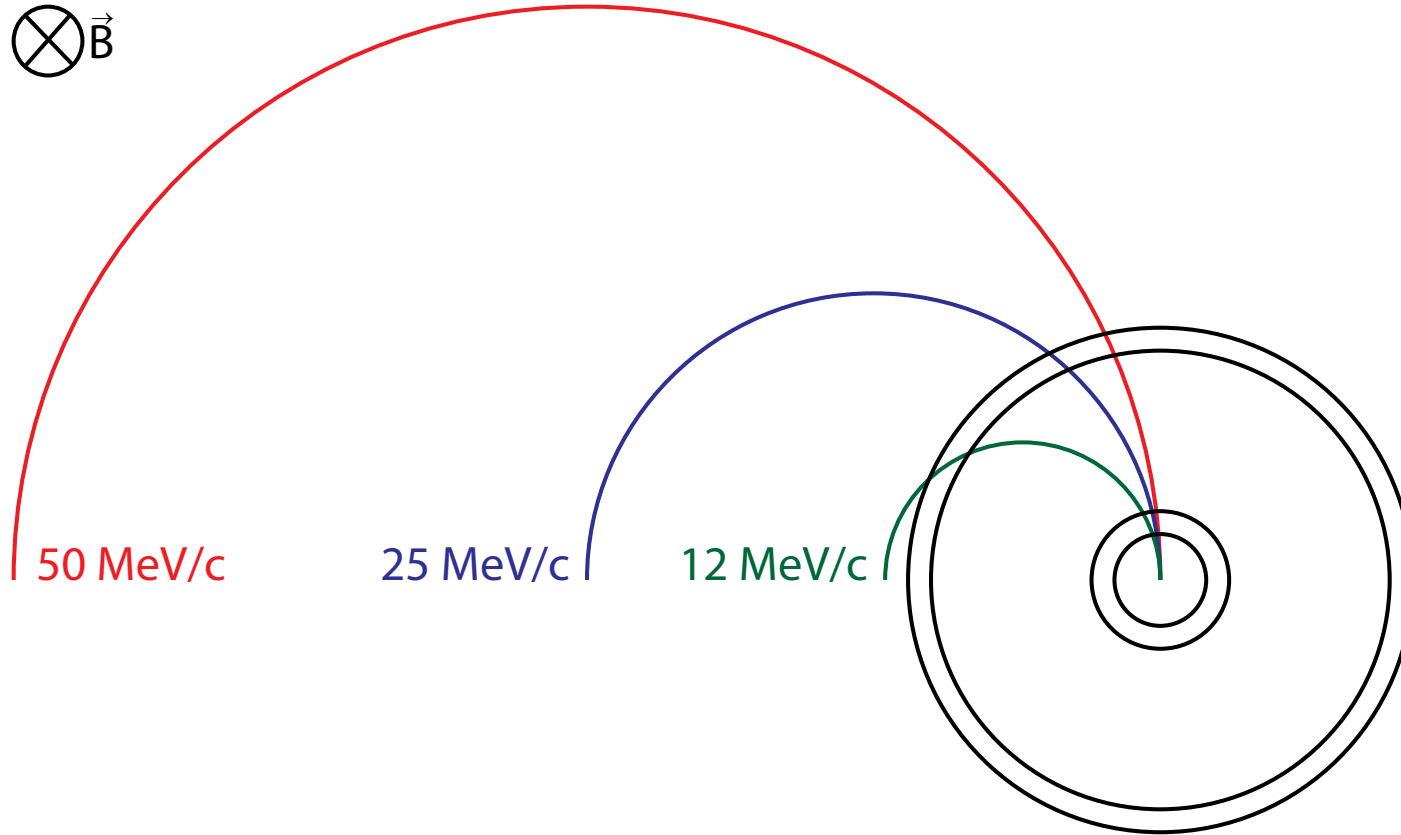
Precision vs. Acceptance



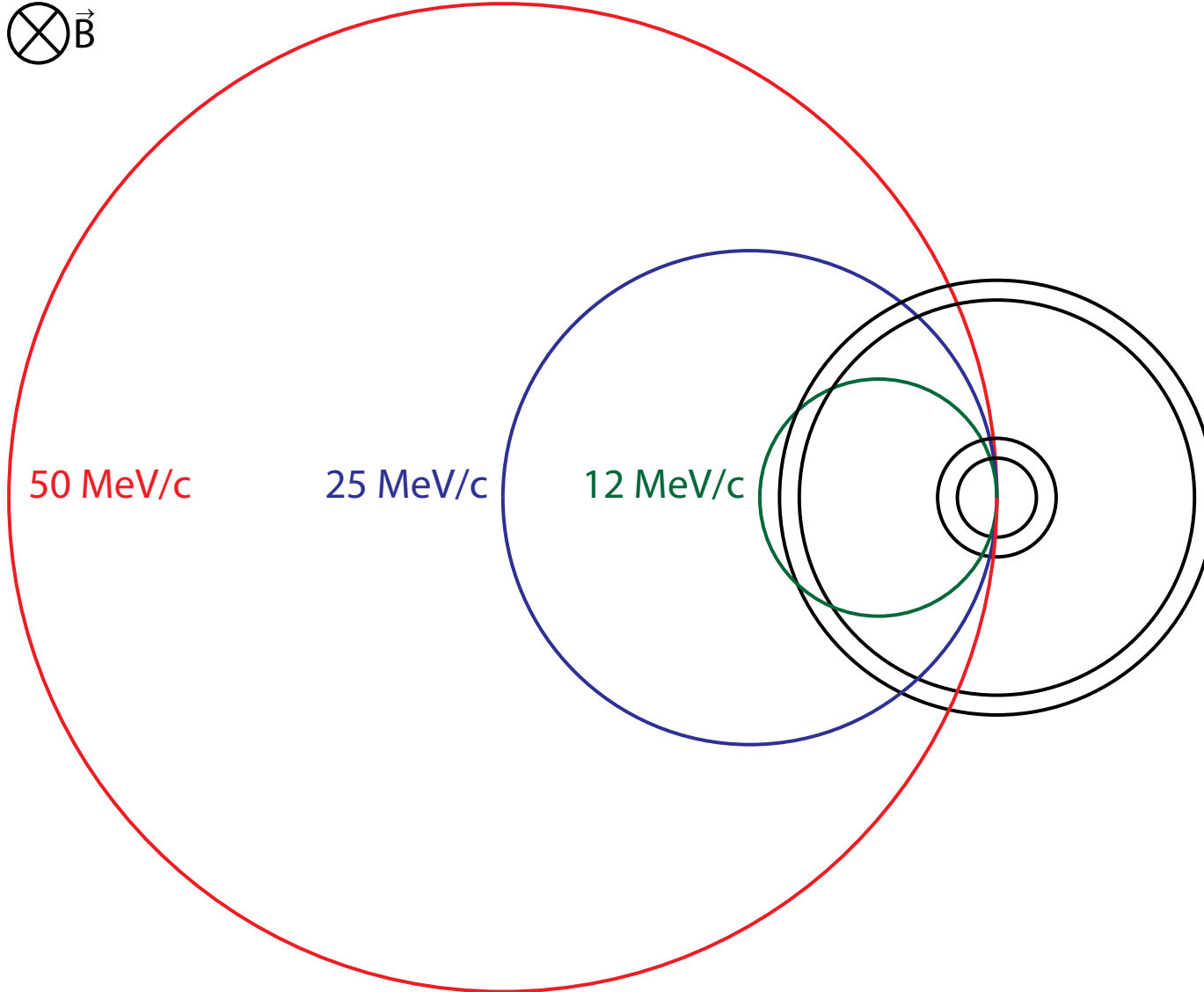
Precision vs. Acceptance



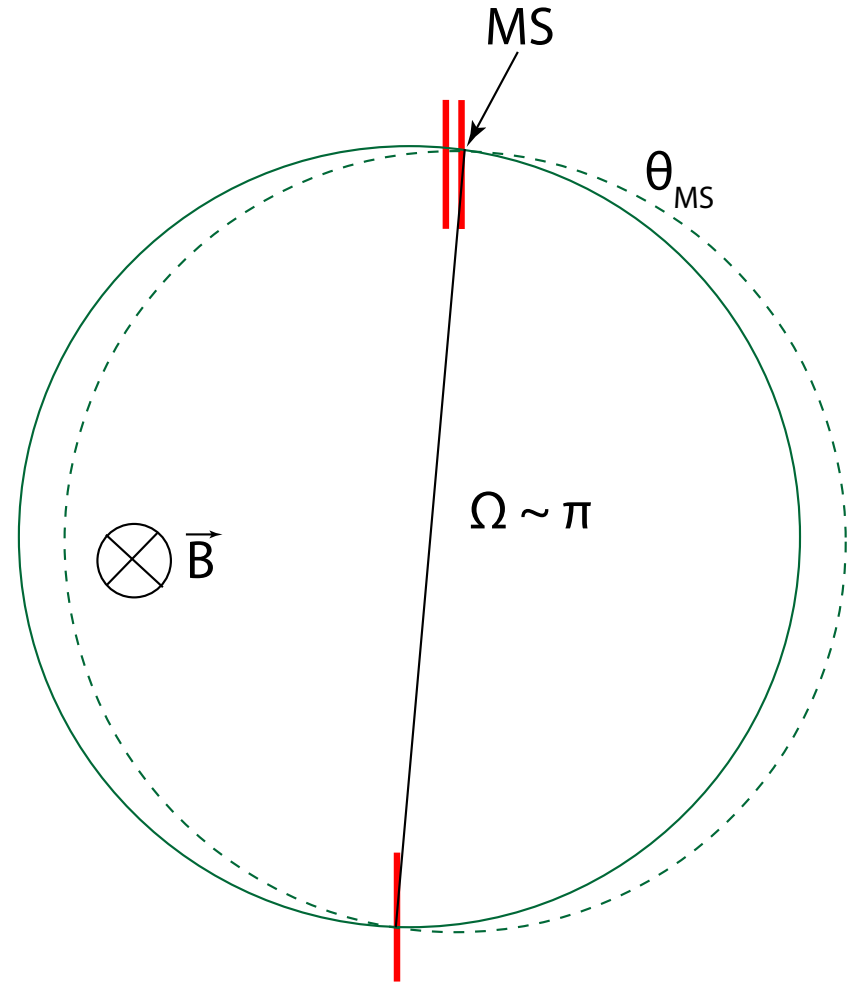
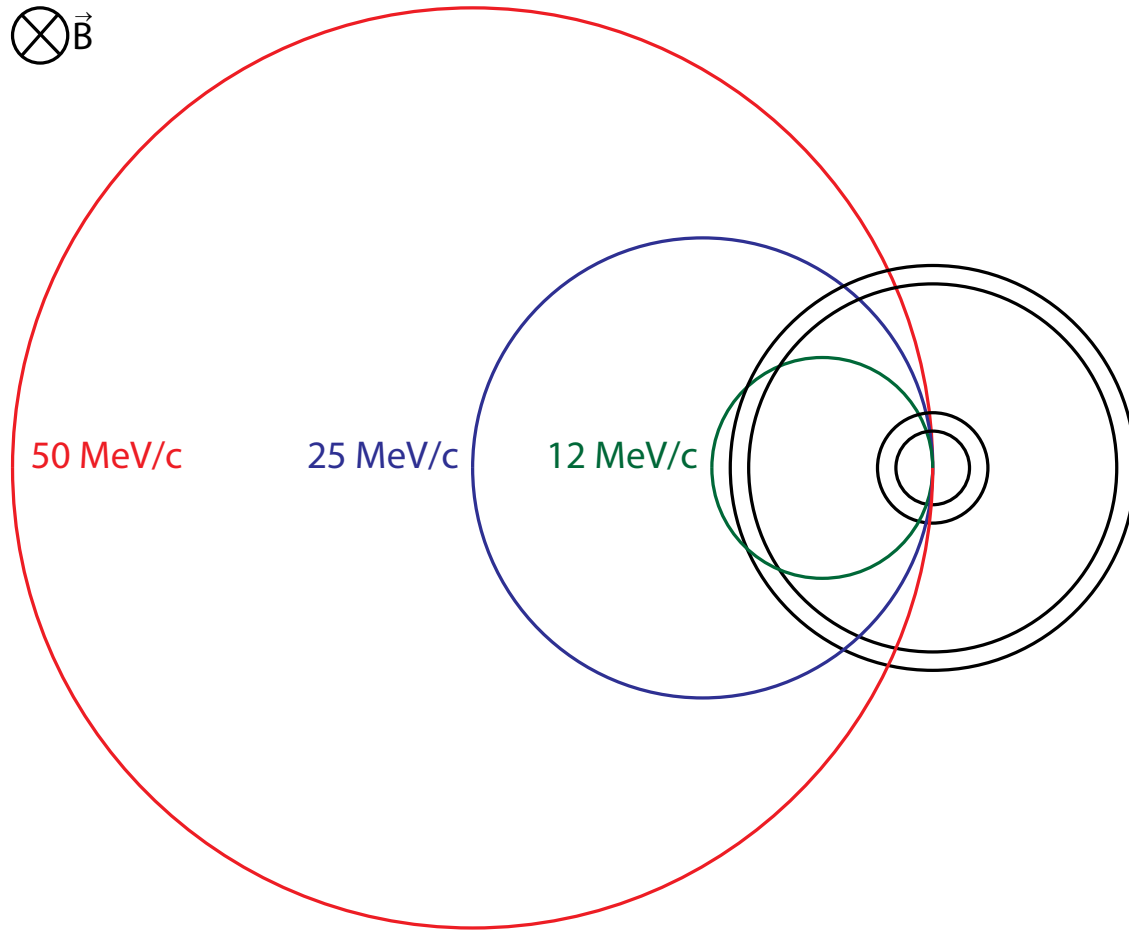
Precision vs. Acceptance



Precision vs. Acceptance



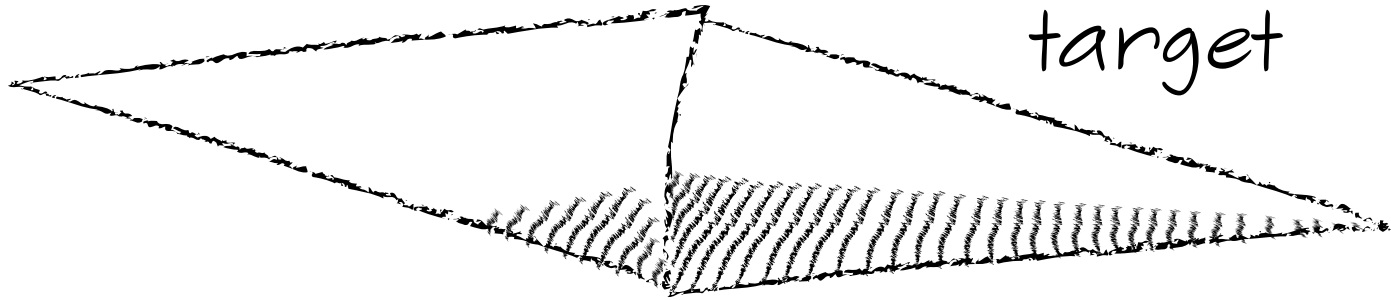
Precision vs. Acceptance





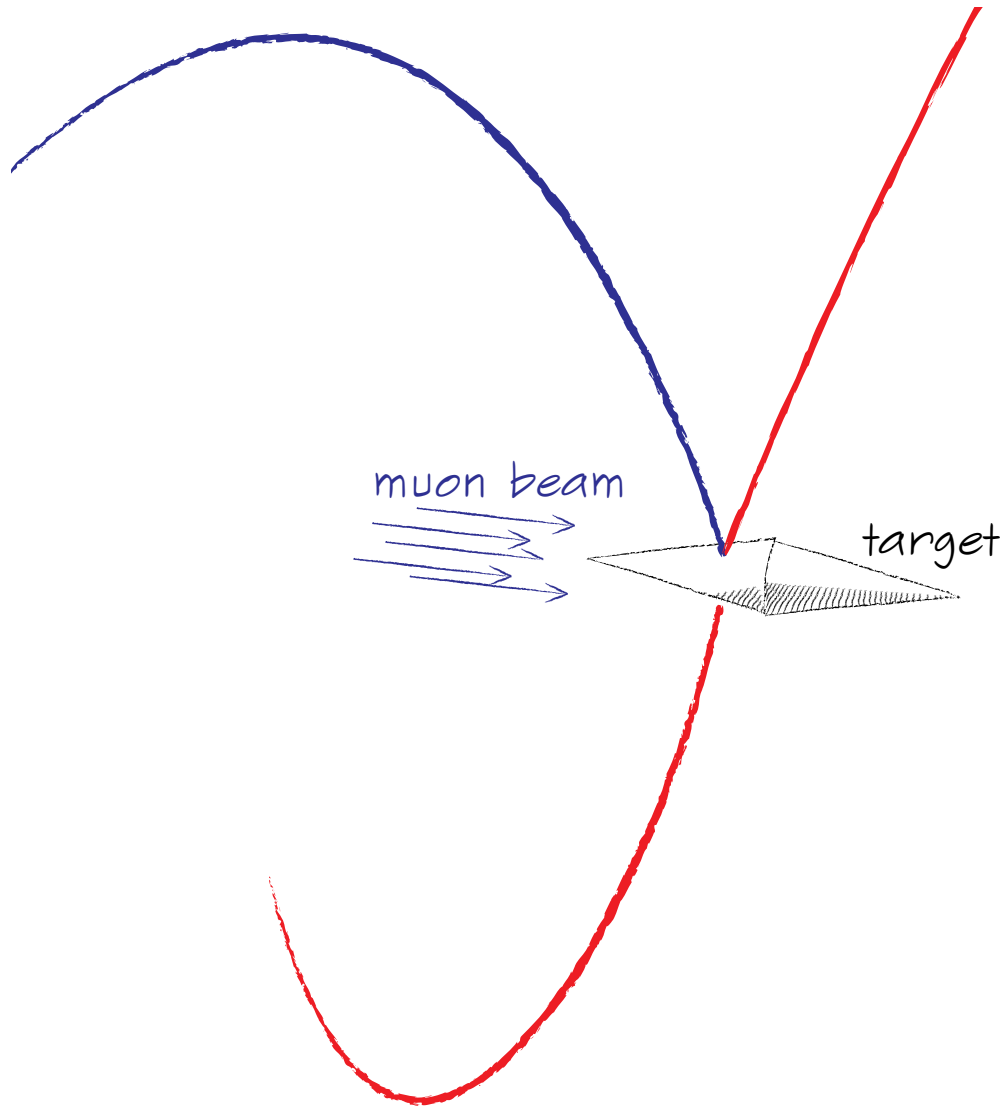
Detector Design

muon beam



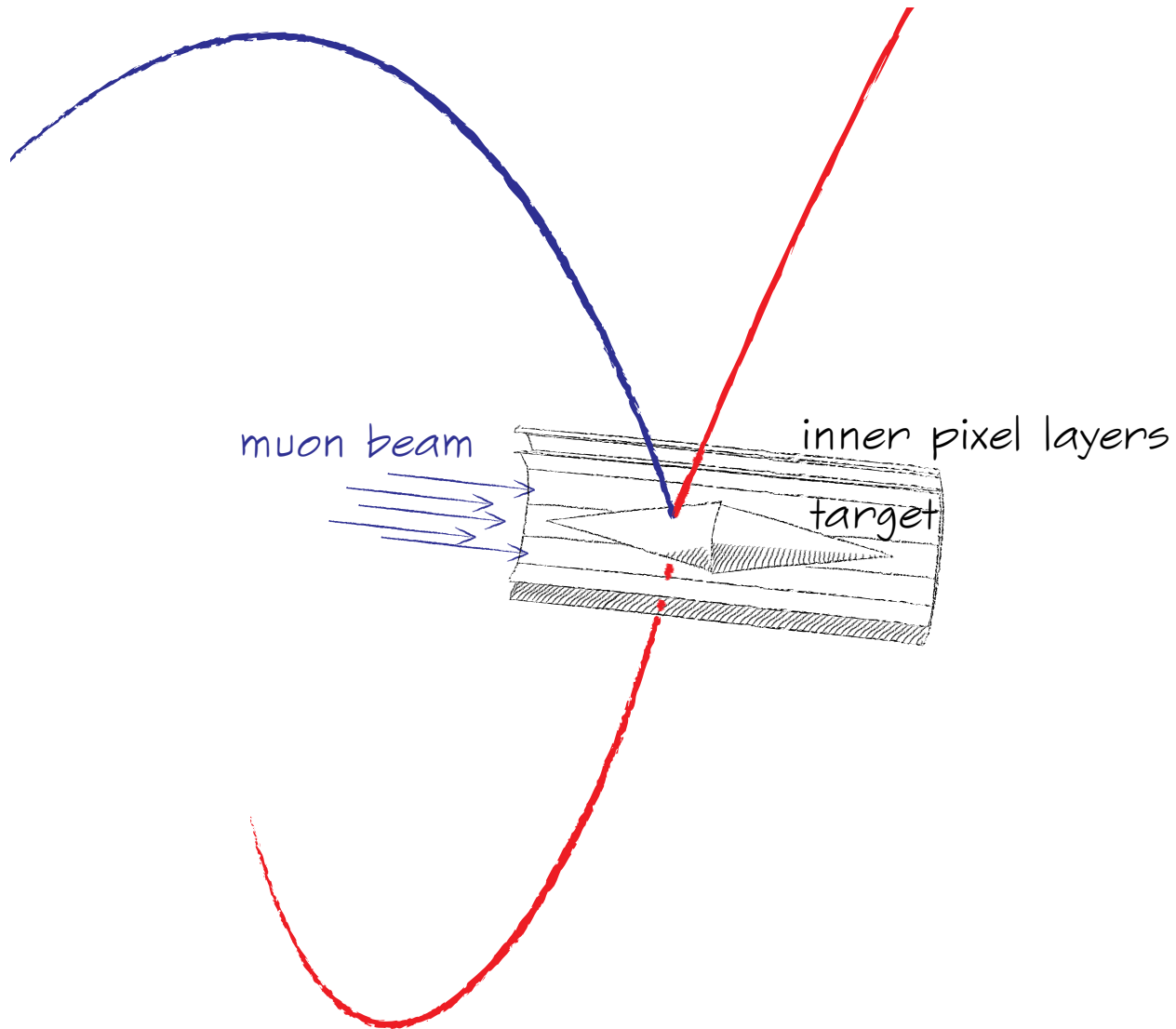


Detector Design



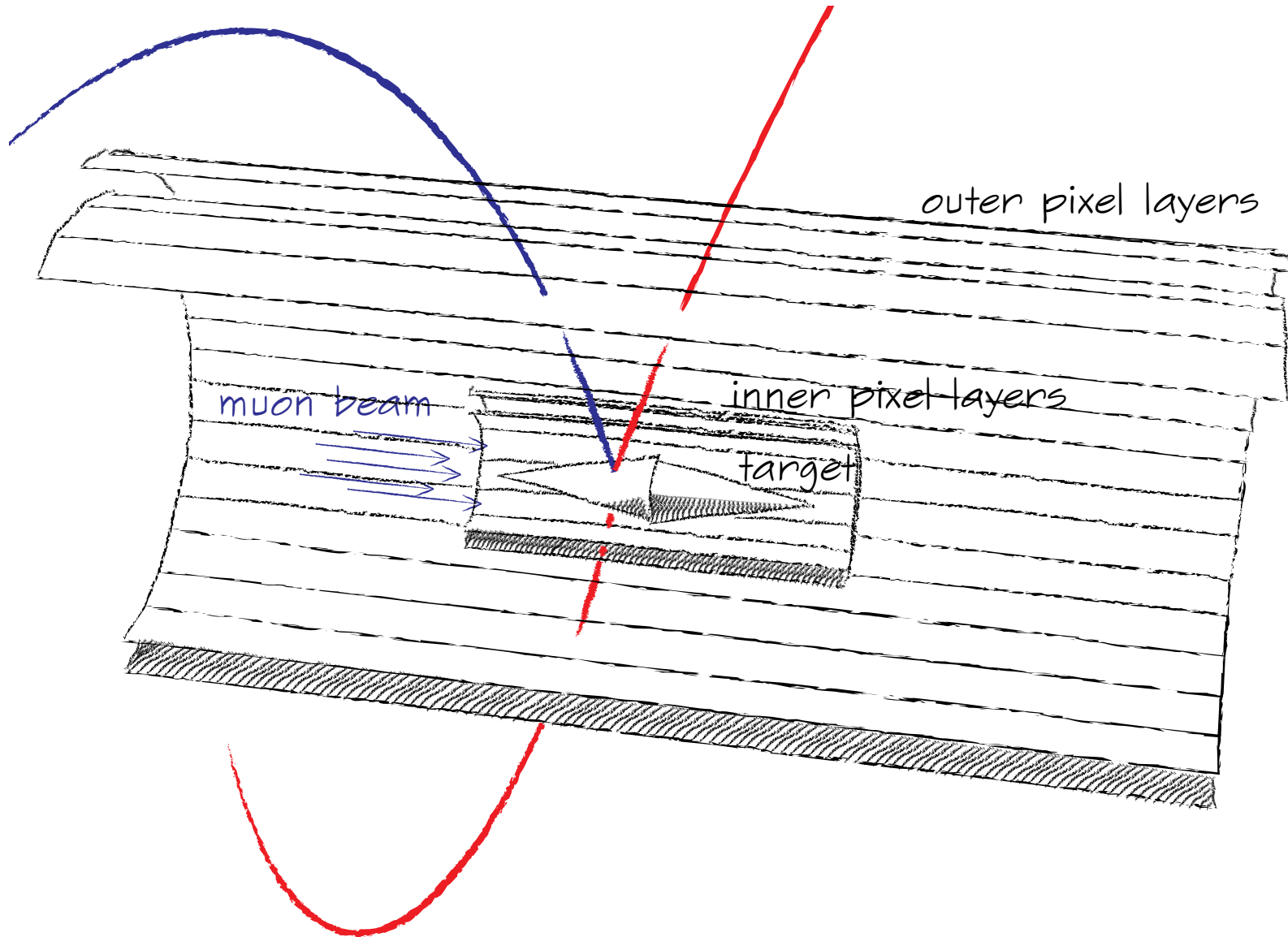


Detector Design



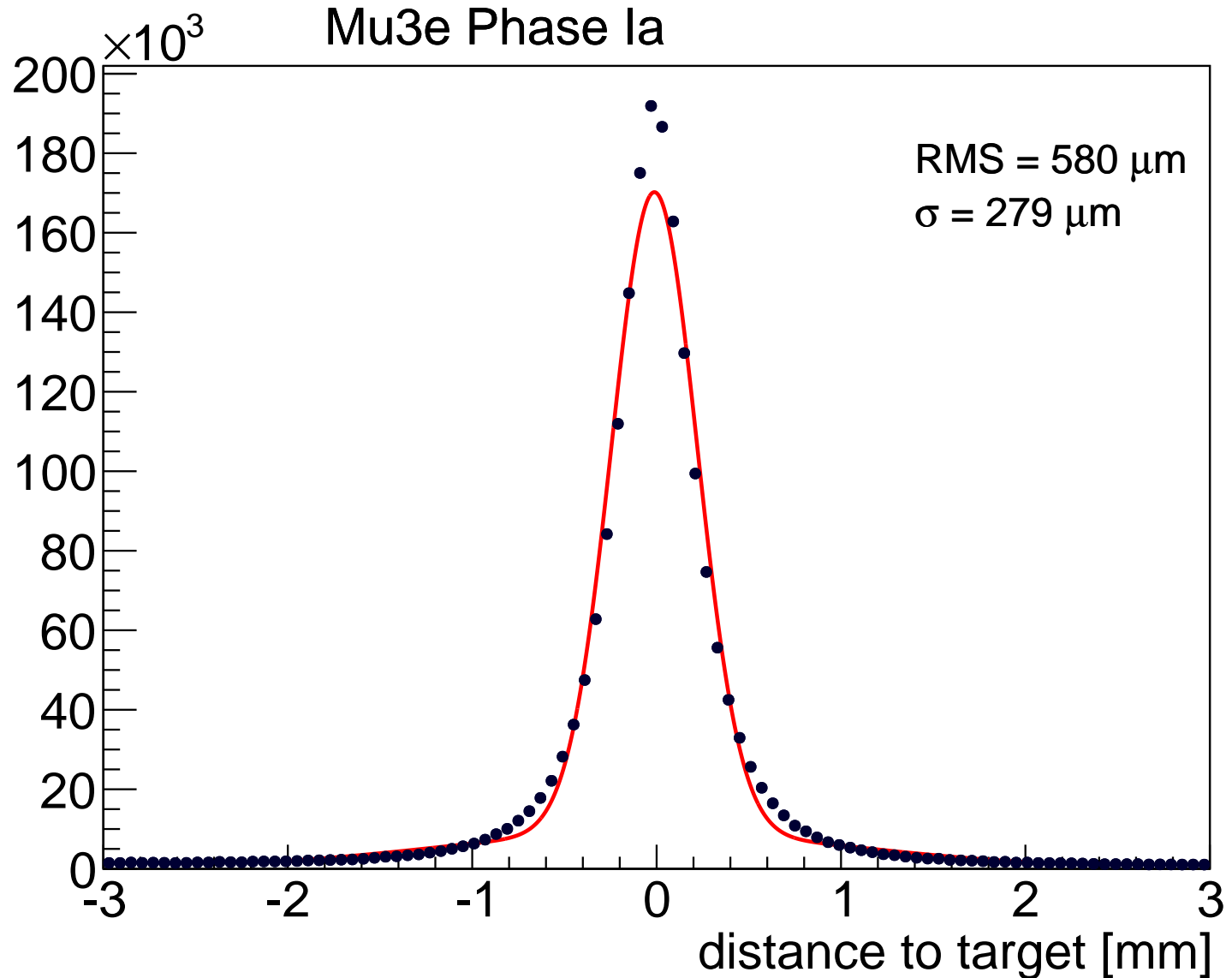


Detector Design



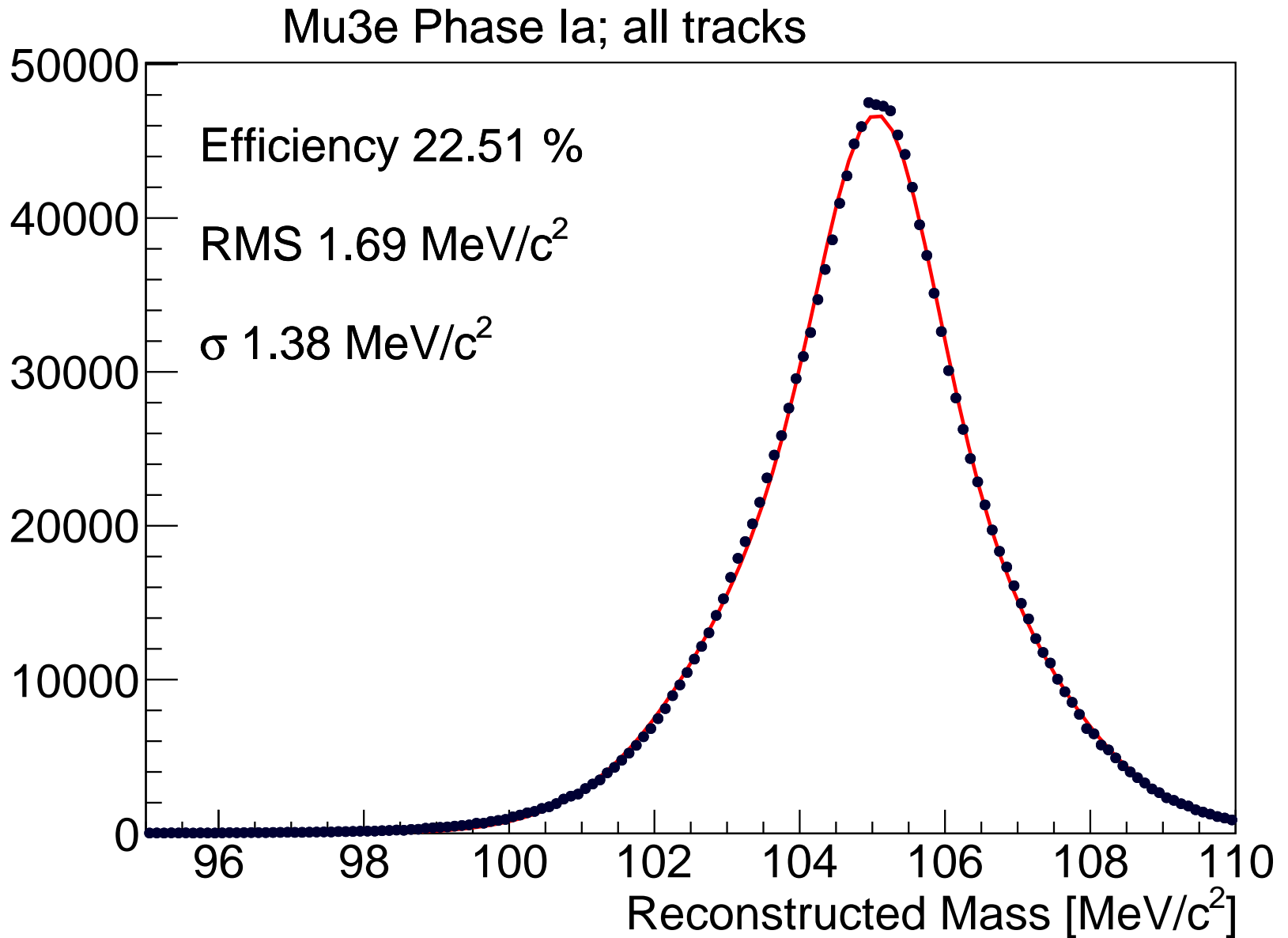


Performance Simulations: Vertexing



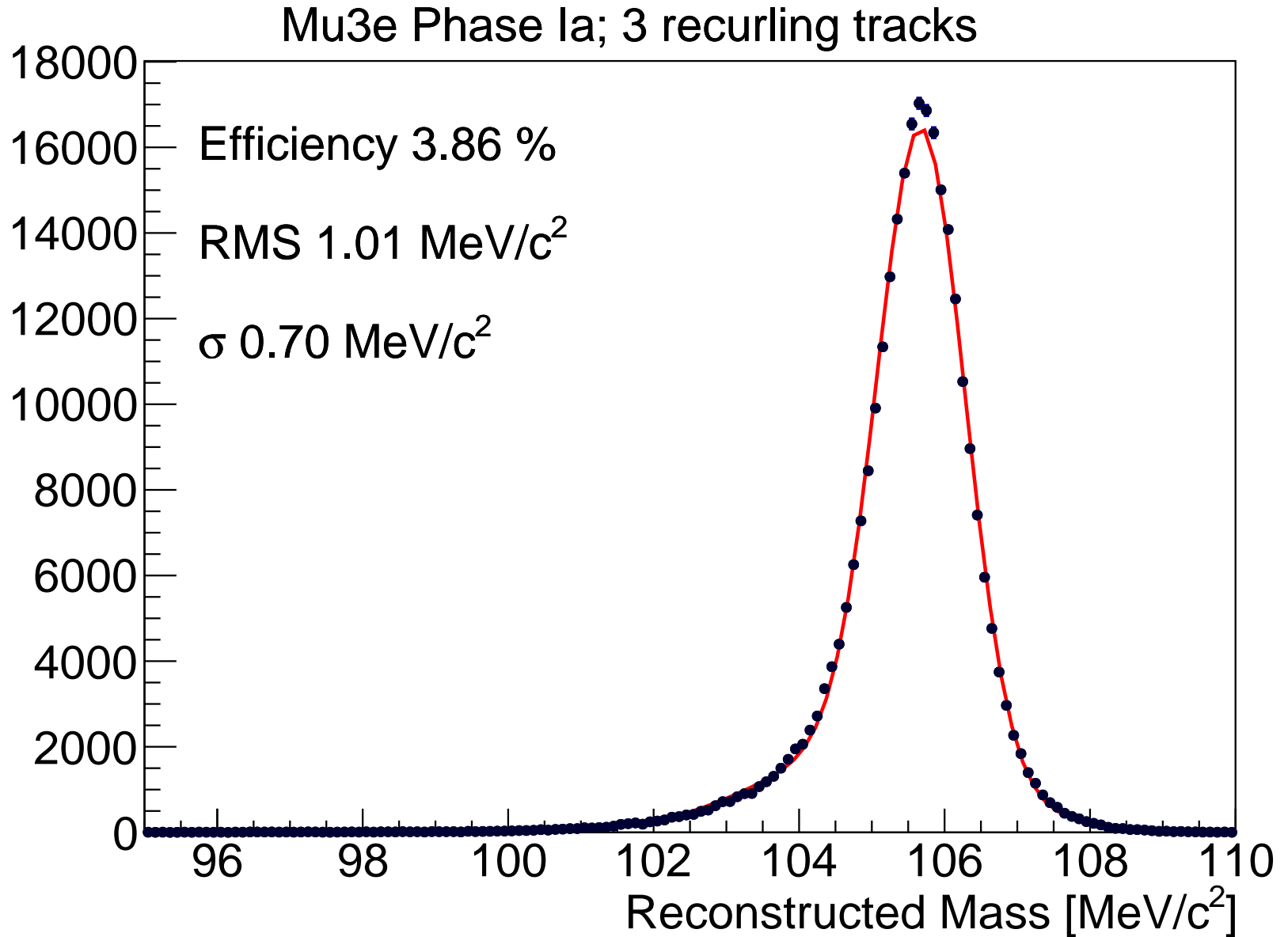


Performance Simulations: Mass reconstruction



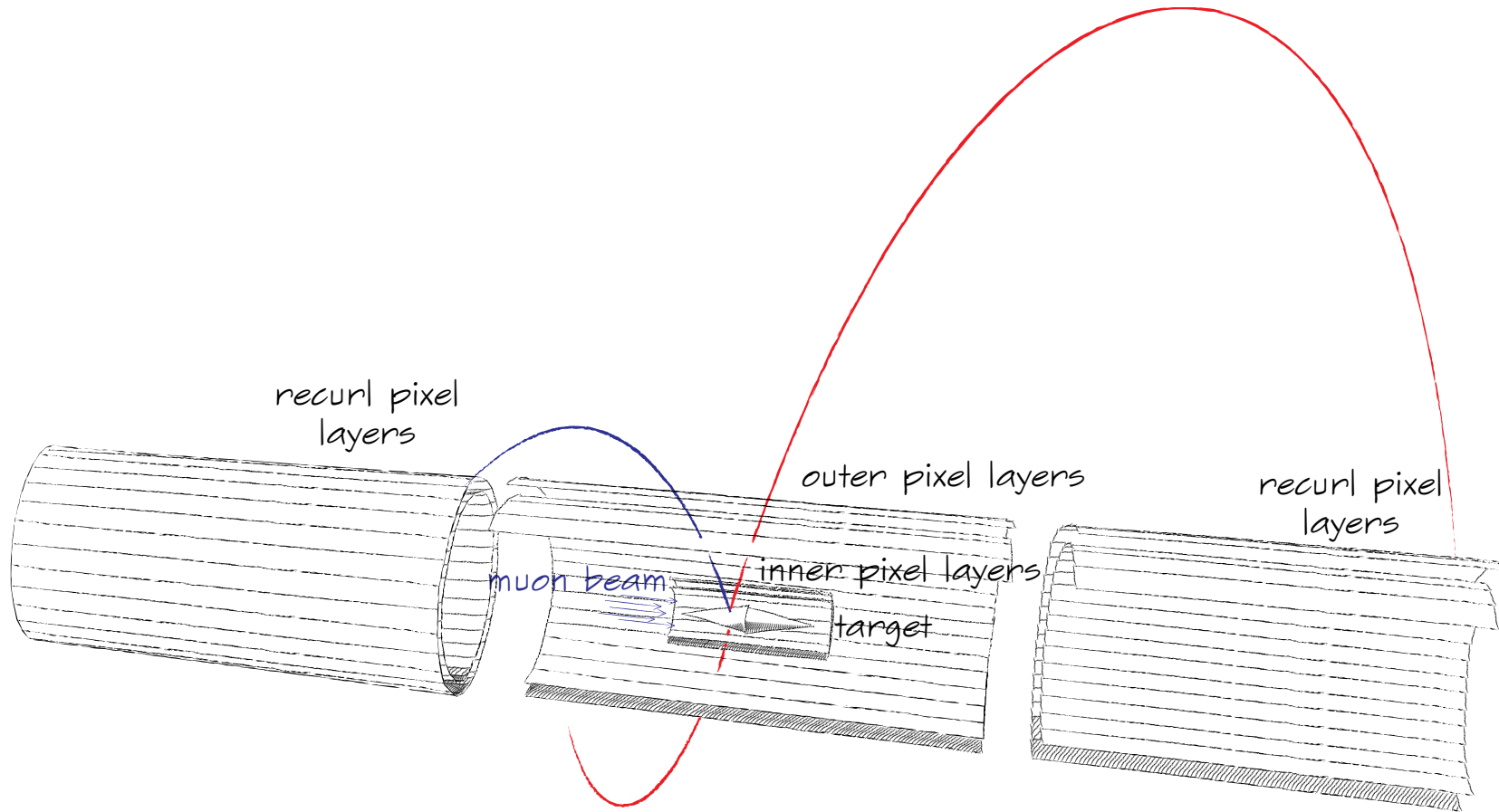


Performance Simulations: Mass reconstruction





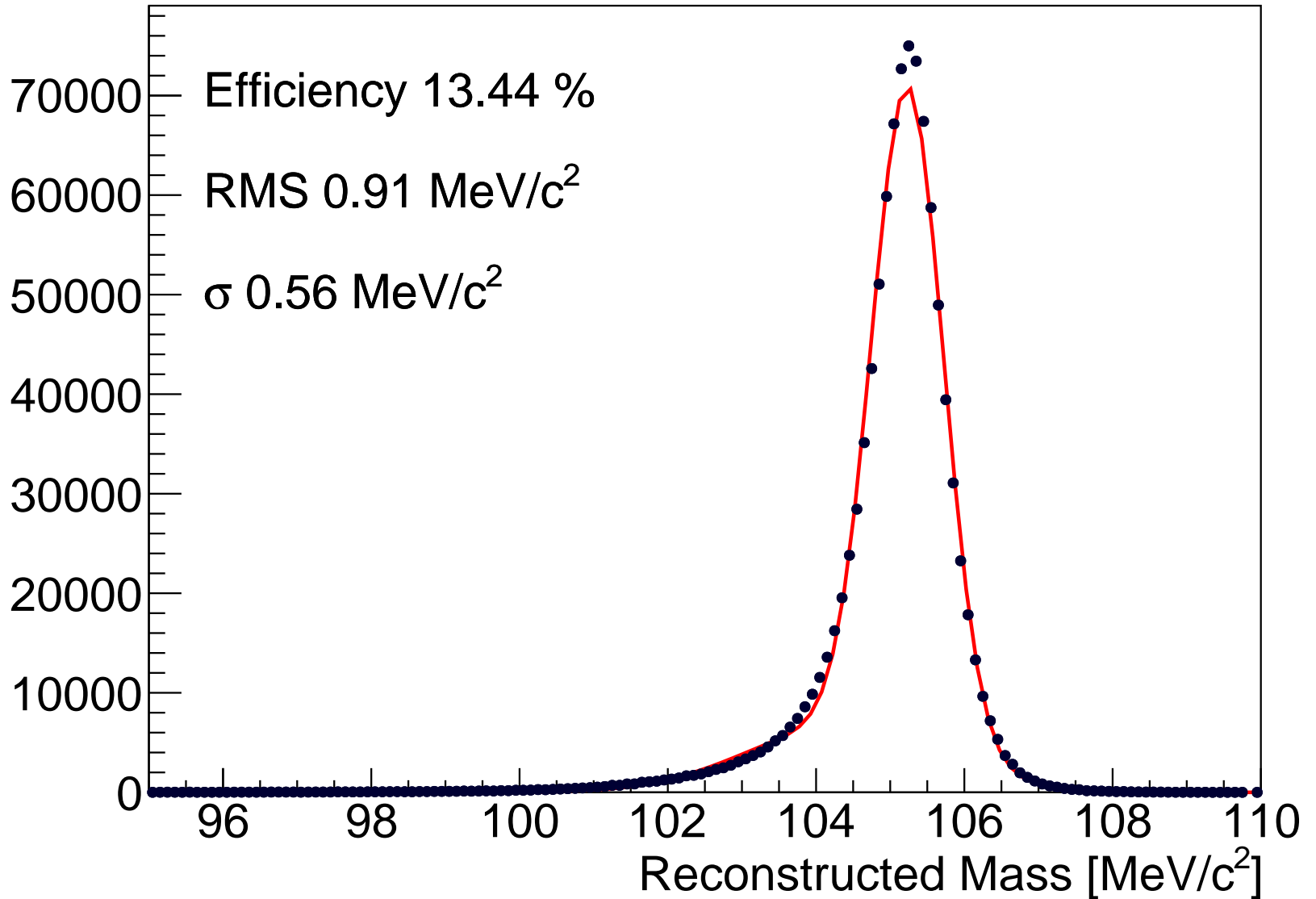
Detector Design





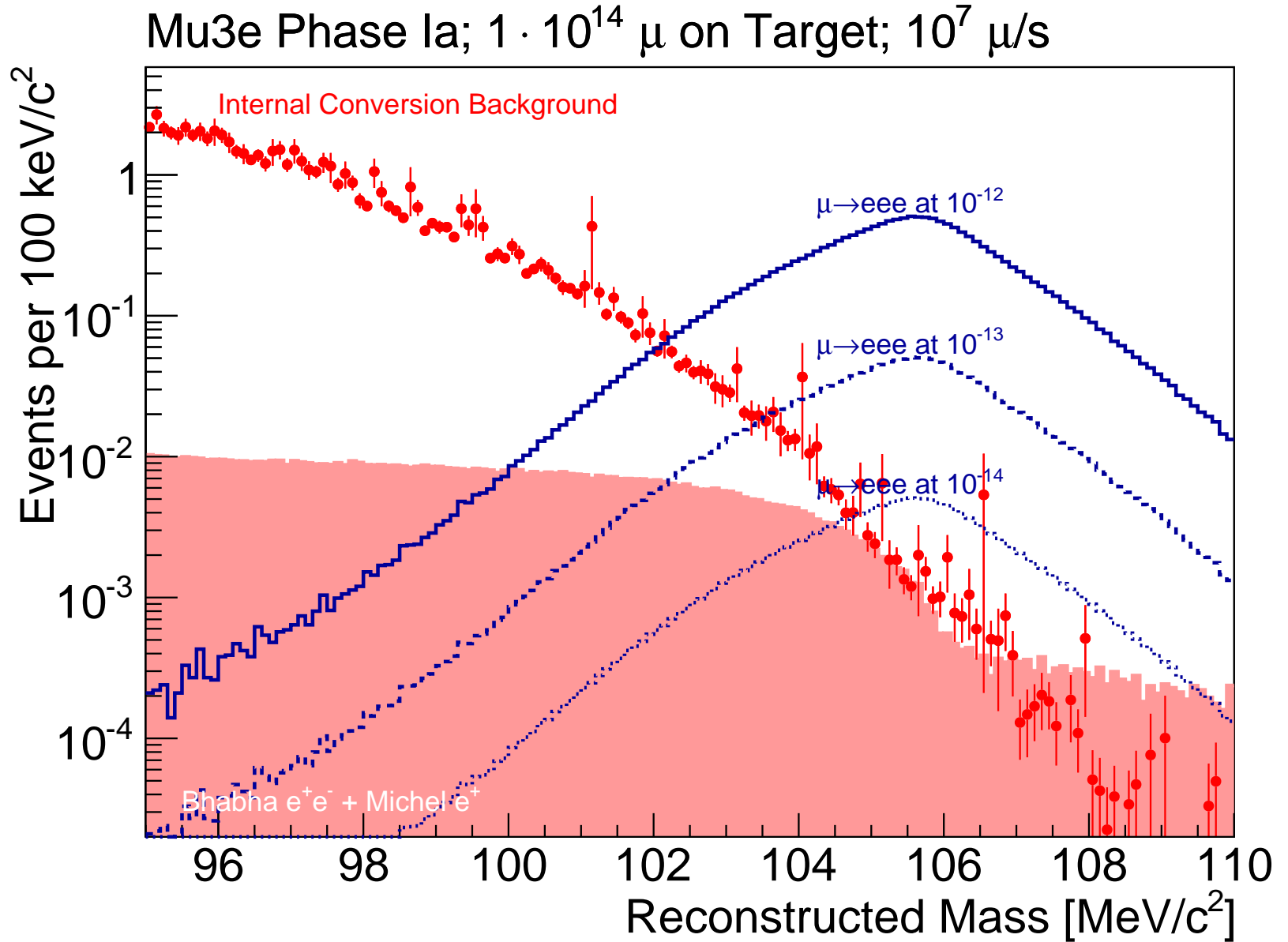
Performance Simulations: Mass reconstruction

Mu3e Phase Ib; 3 recurling tracks



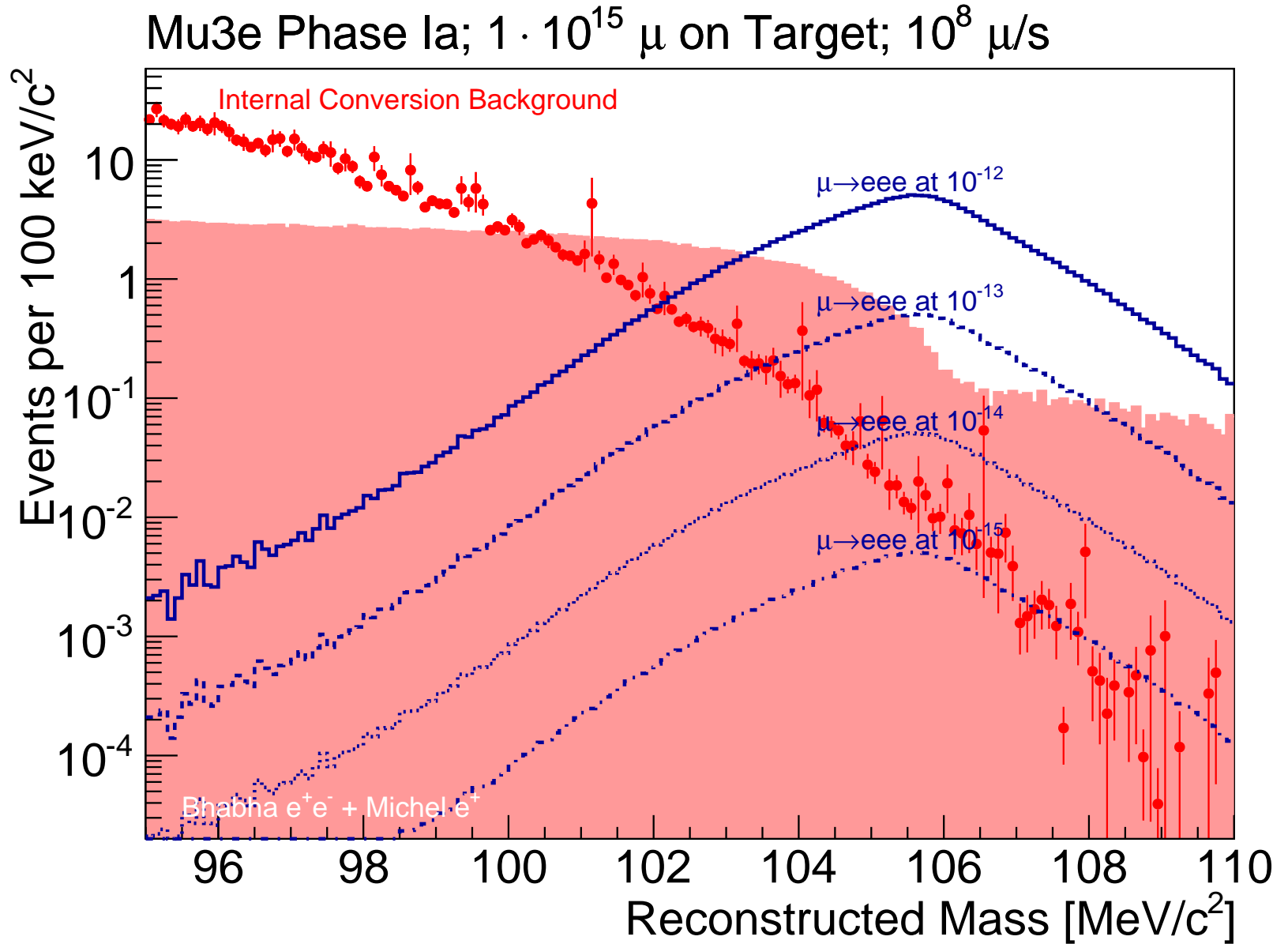


Performance Simulations: Background





Performance Simulations: Background



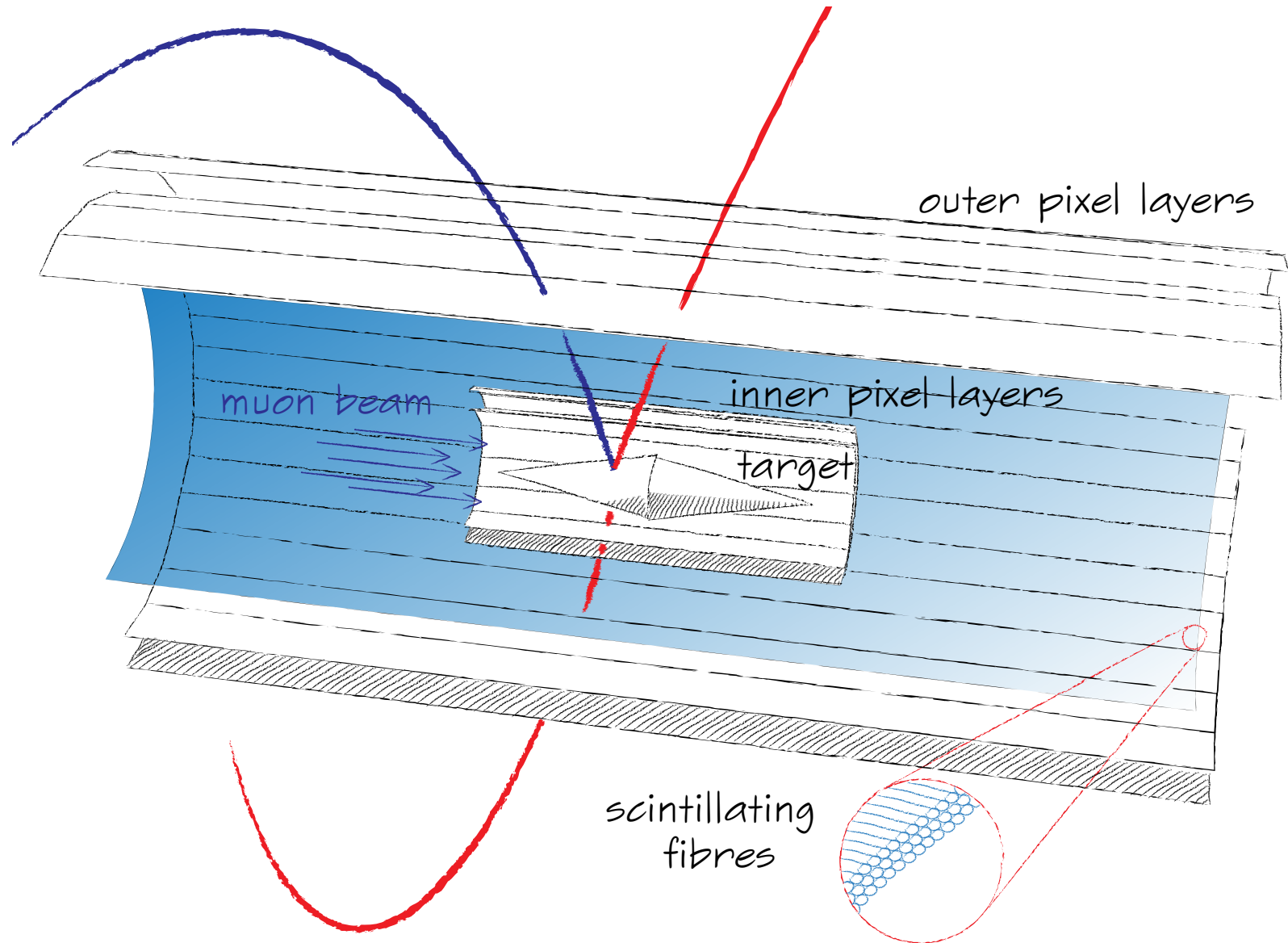


Need better suppression of accidental background:

Timing

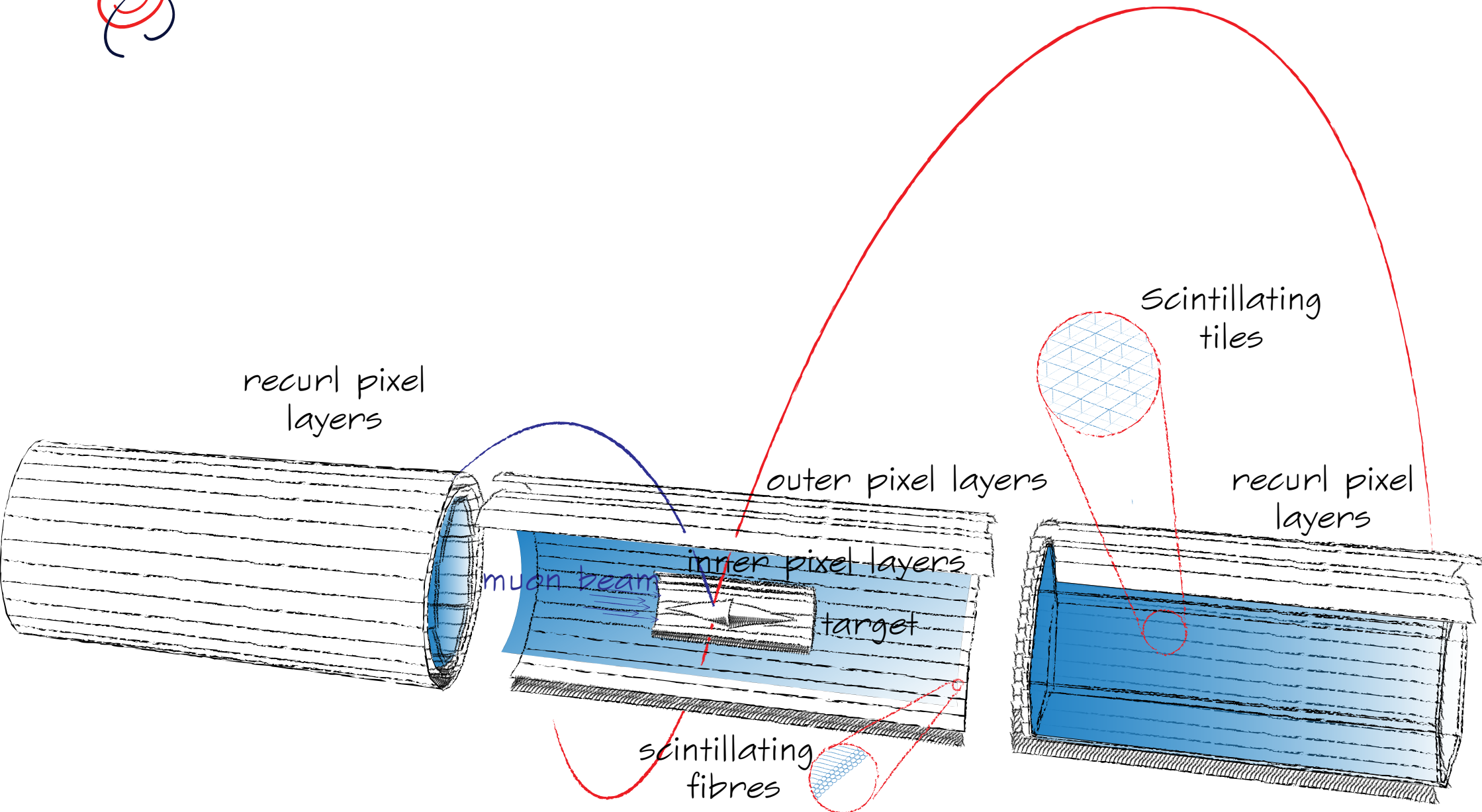


Detector Design



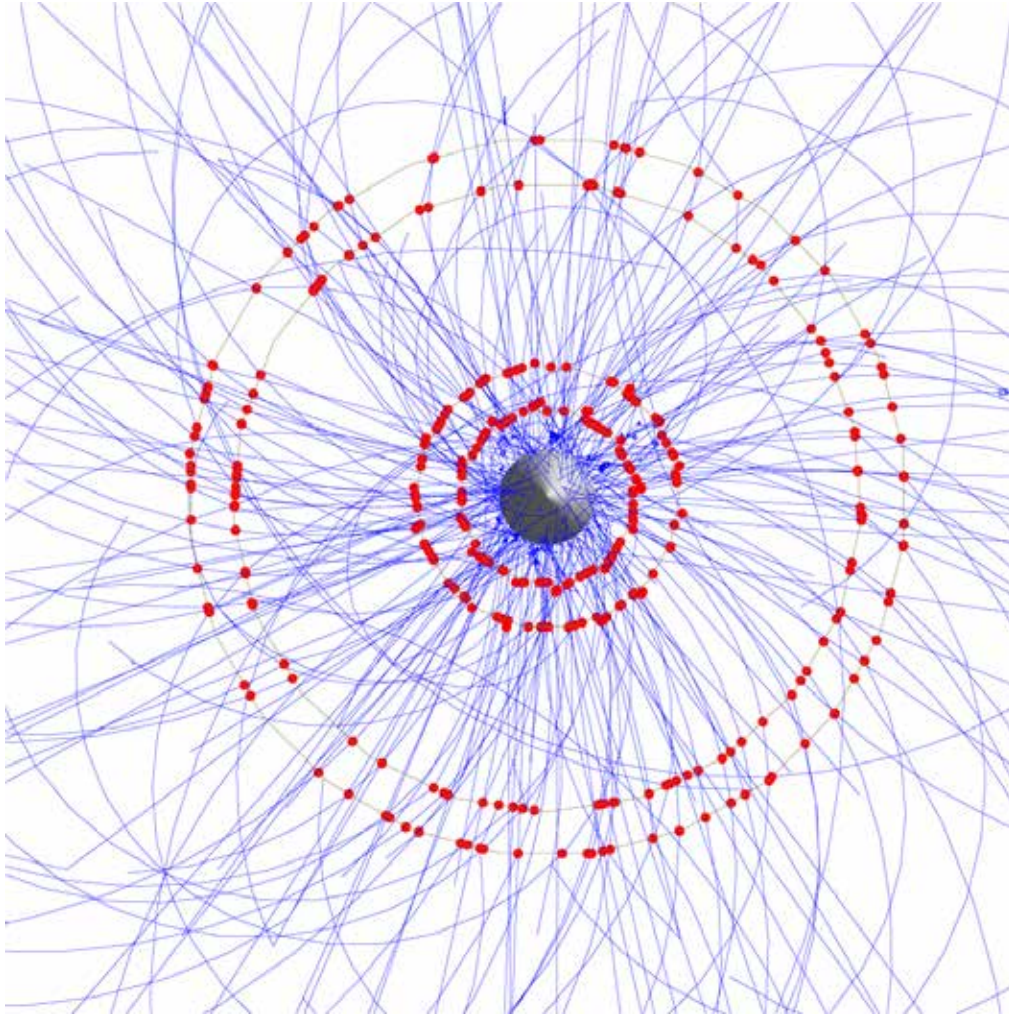


Detector Design

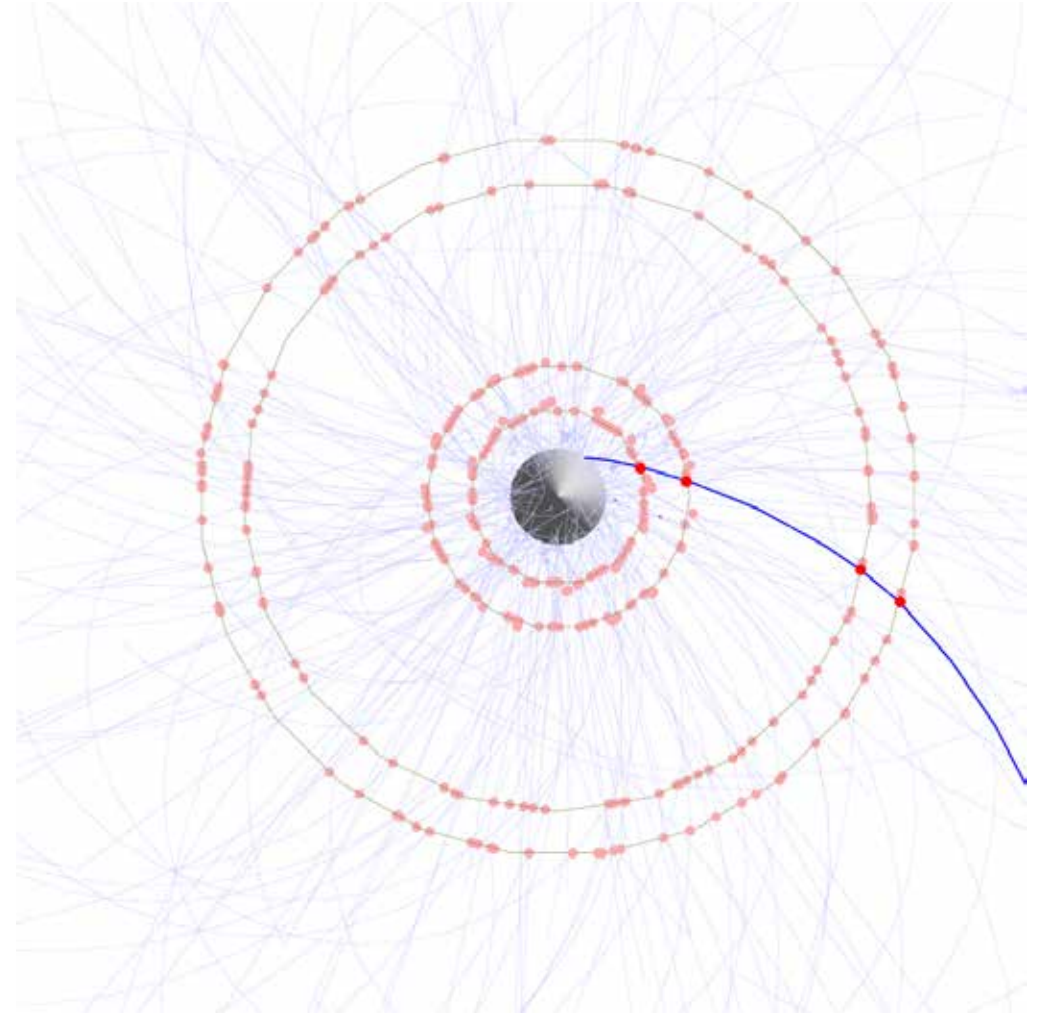




Timing measurements



Pixels: $O(50 \text{ ns})$

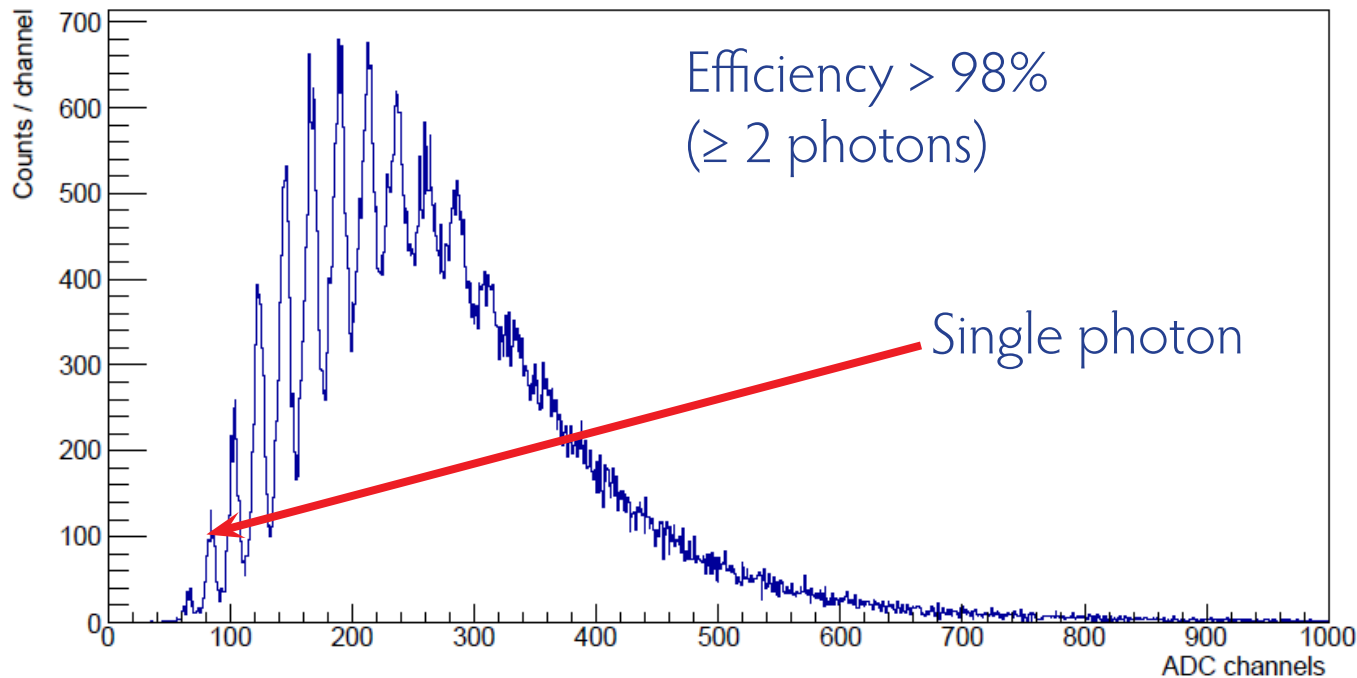
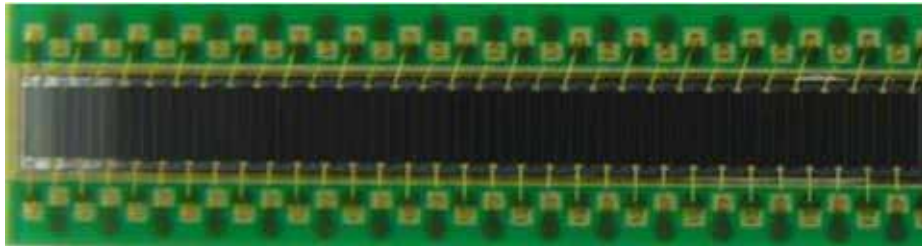
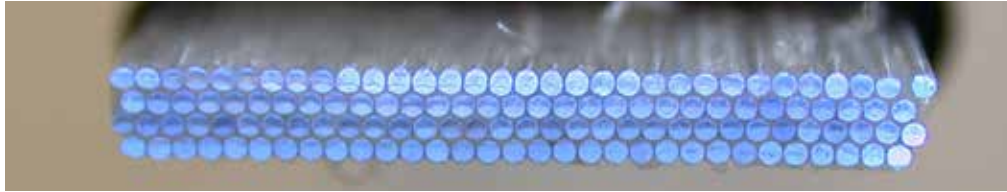


Scintillating fibres $O(1 \text{ ns})$;
Scintillating tiles $O(100 \text{ ps})$



Timing Detector: Scintillating Fibres

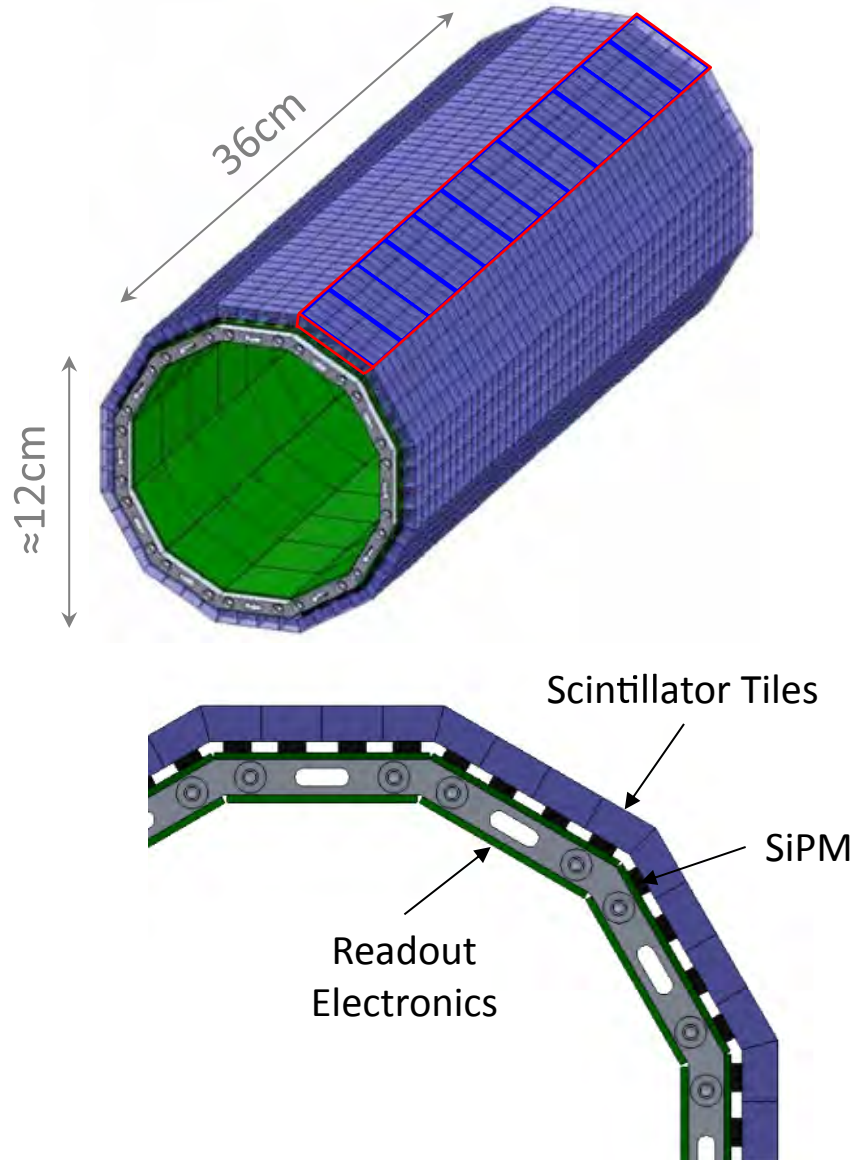
- 3-5 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution $\mathcal{O}(1 \text{ ns})$ (measured with sodium source)





Timing Detector: Scintillating tiles

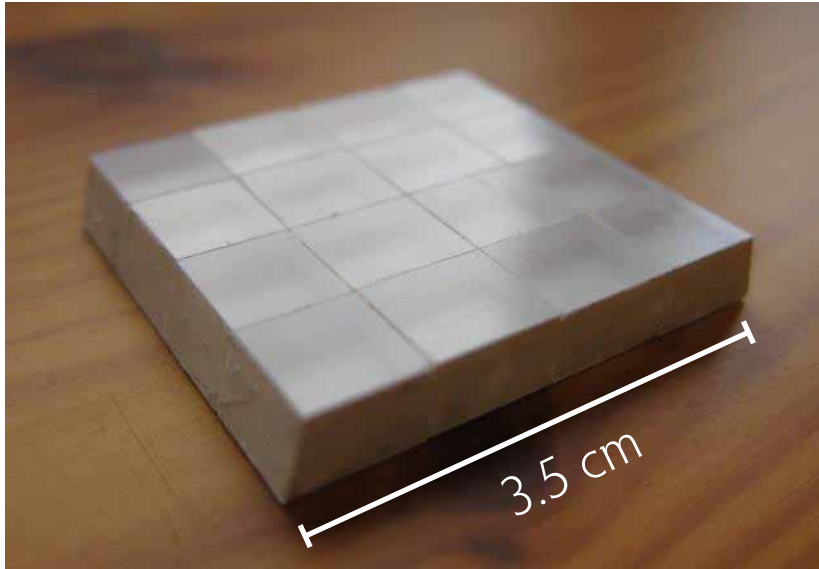
- $\sim 0.5 \text{ cm}^3$ scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)



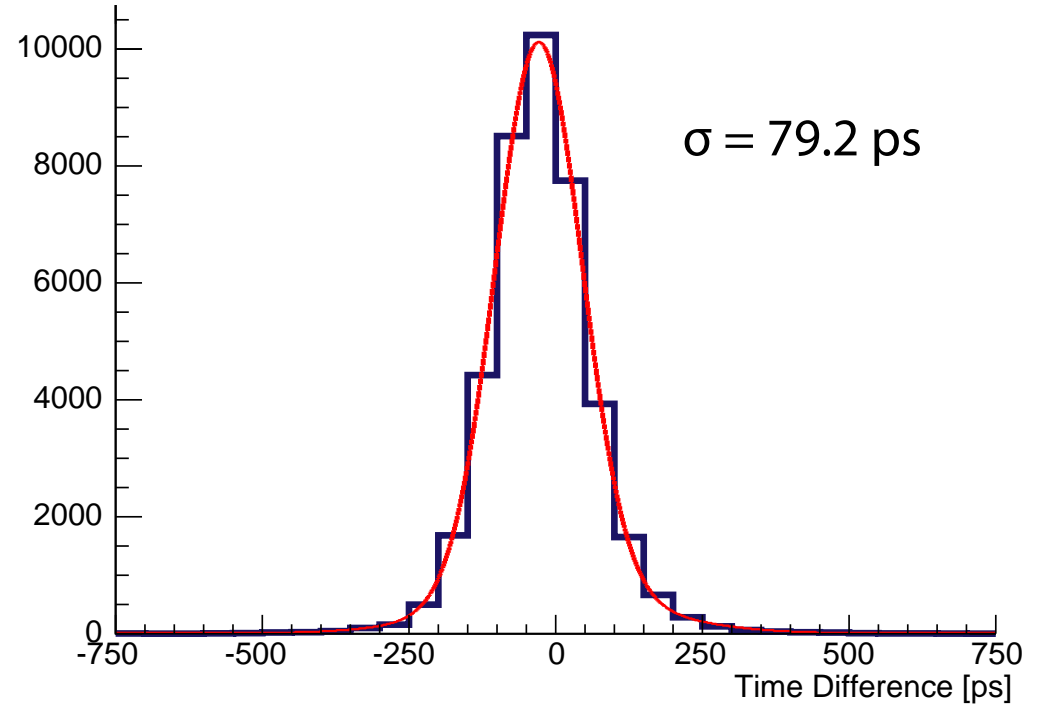


Timing Detector: Scintillating tiles

Front



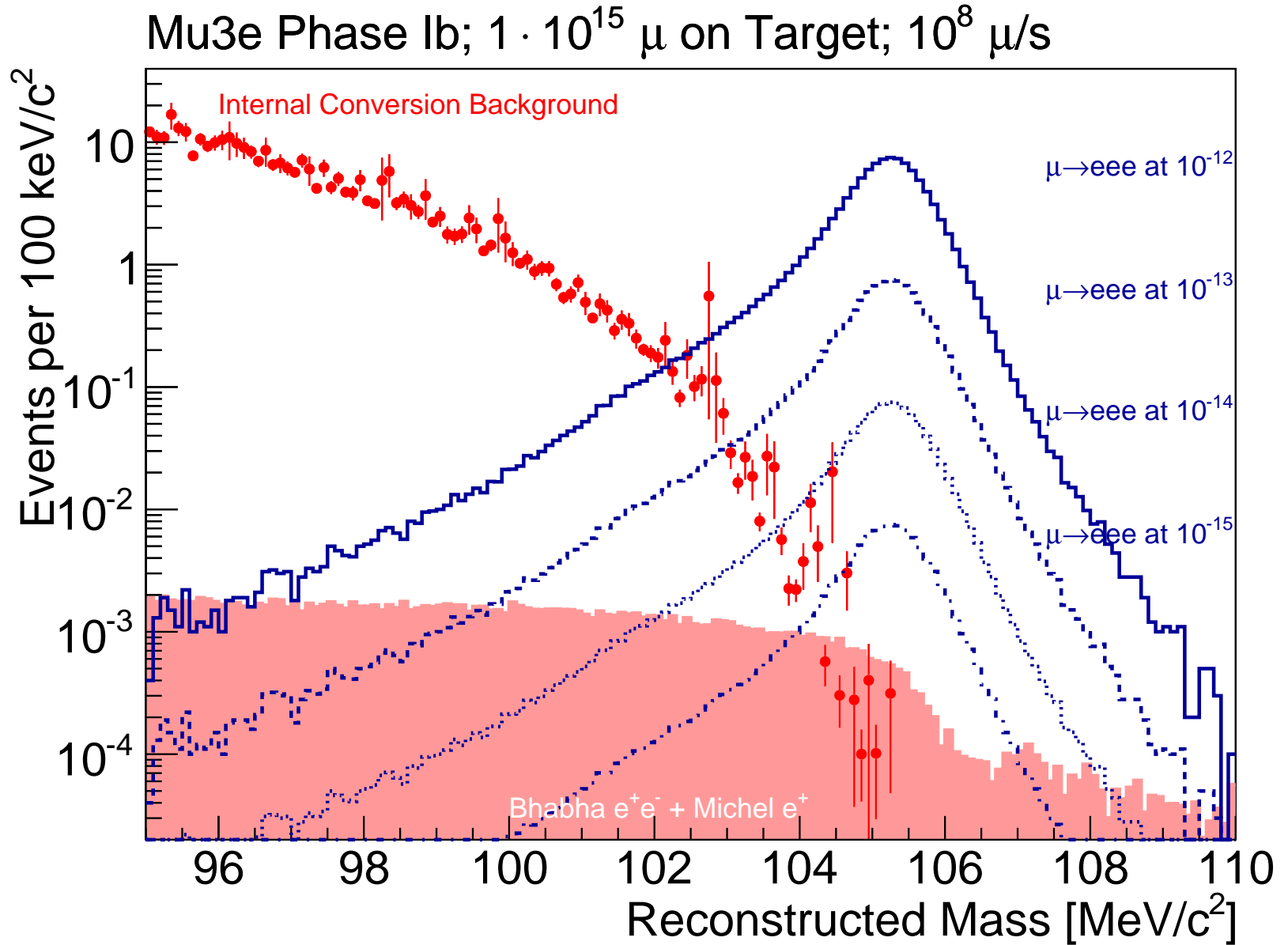
Back



- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution $\sim 80 \text{ ps}$

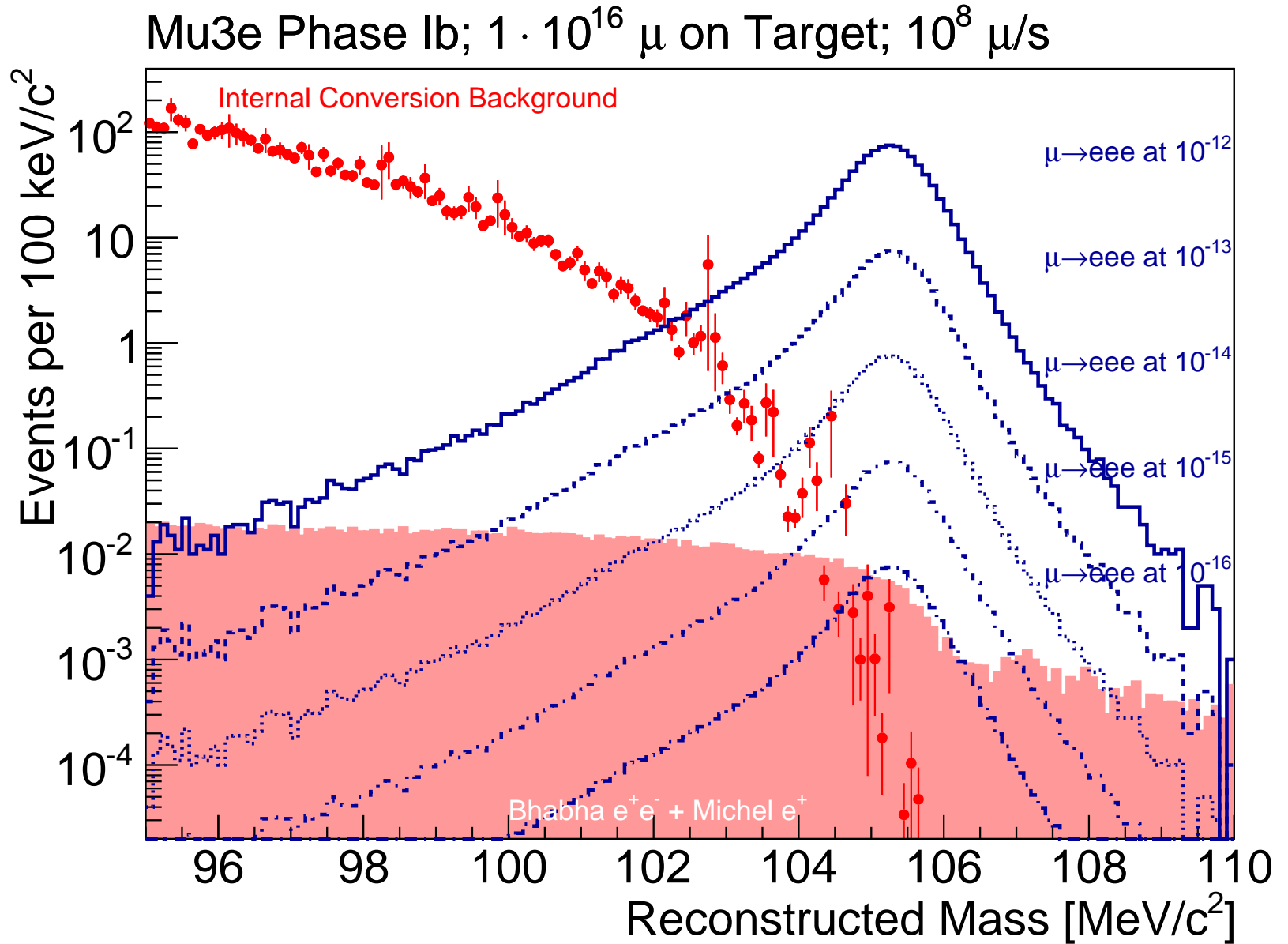


Performance Simulations: Background



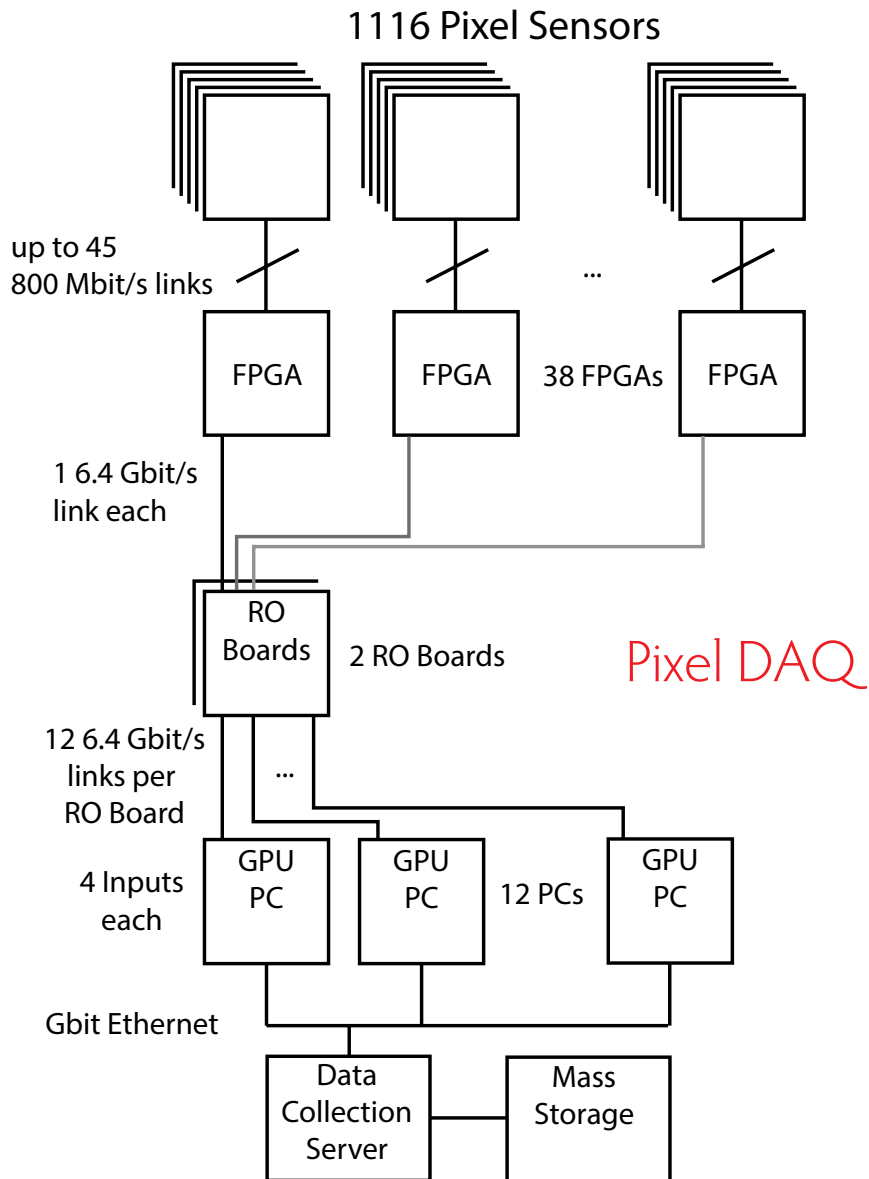


Performance Simulations: Background





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

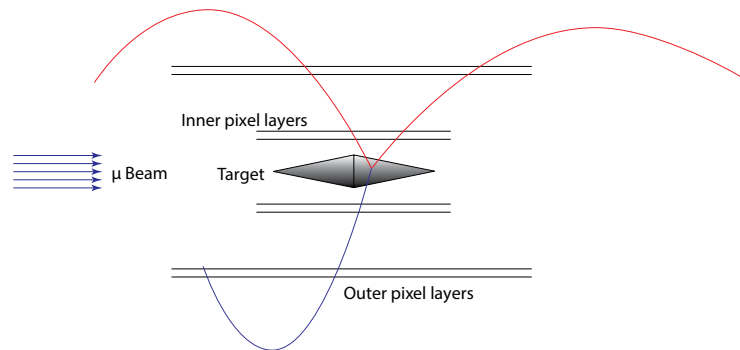
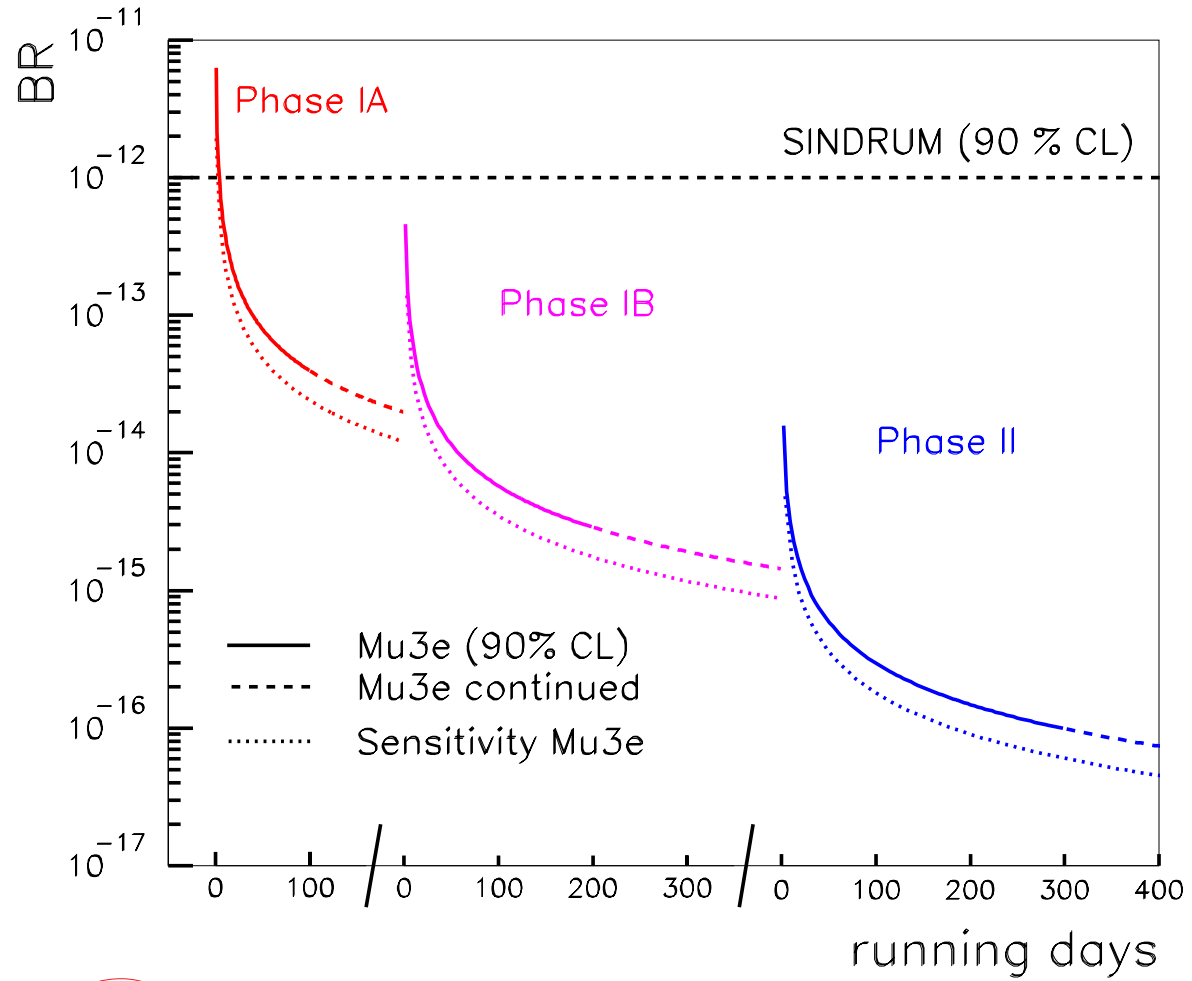


Online software filter farm

- 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



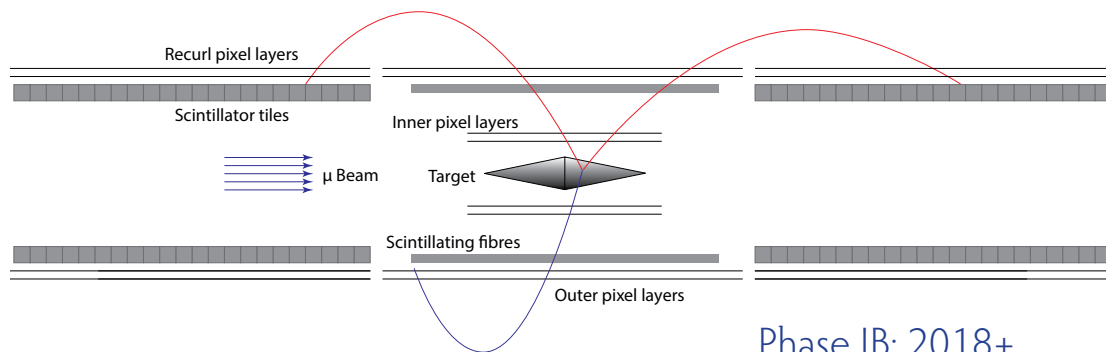
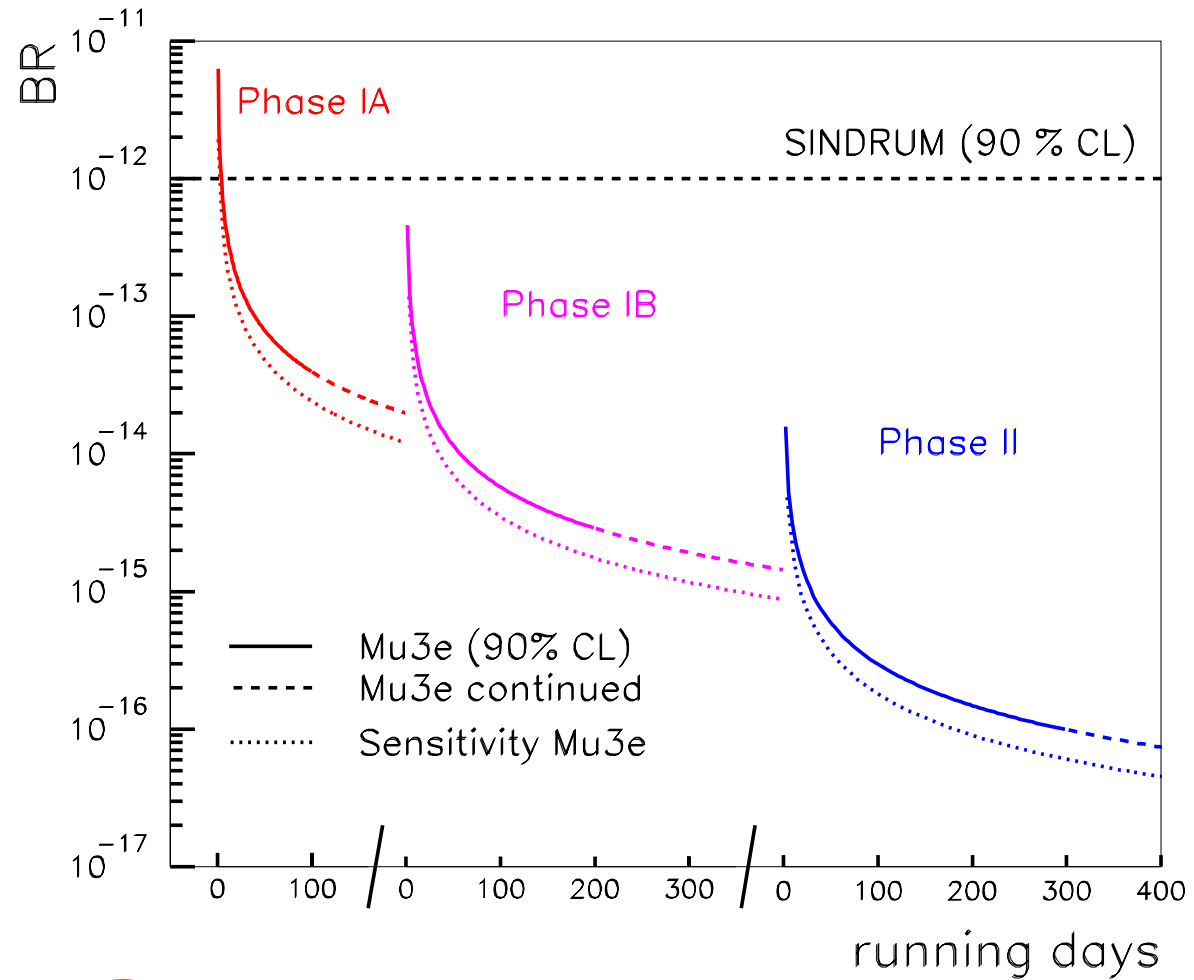
Sensitivity



Phase IA: Starting 2017
 $2 \cdot 10^7 \mu/s$



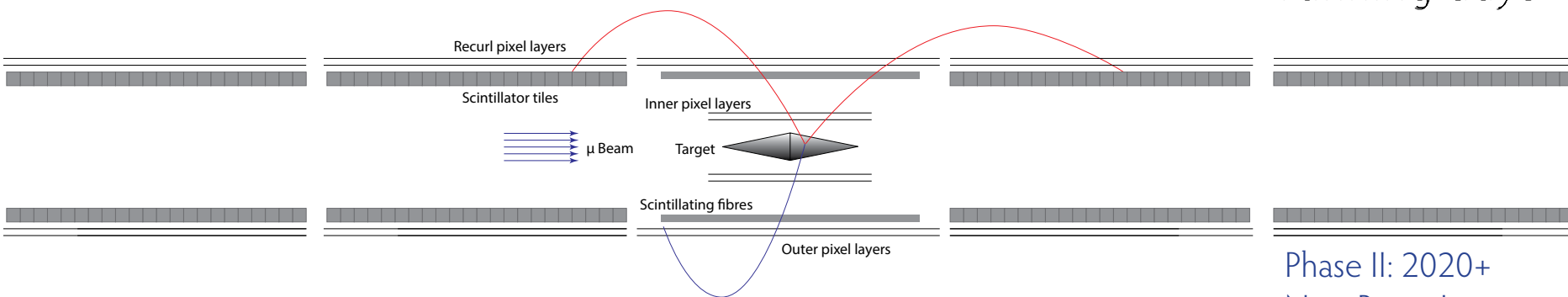
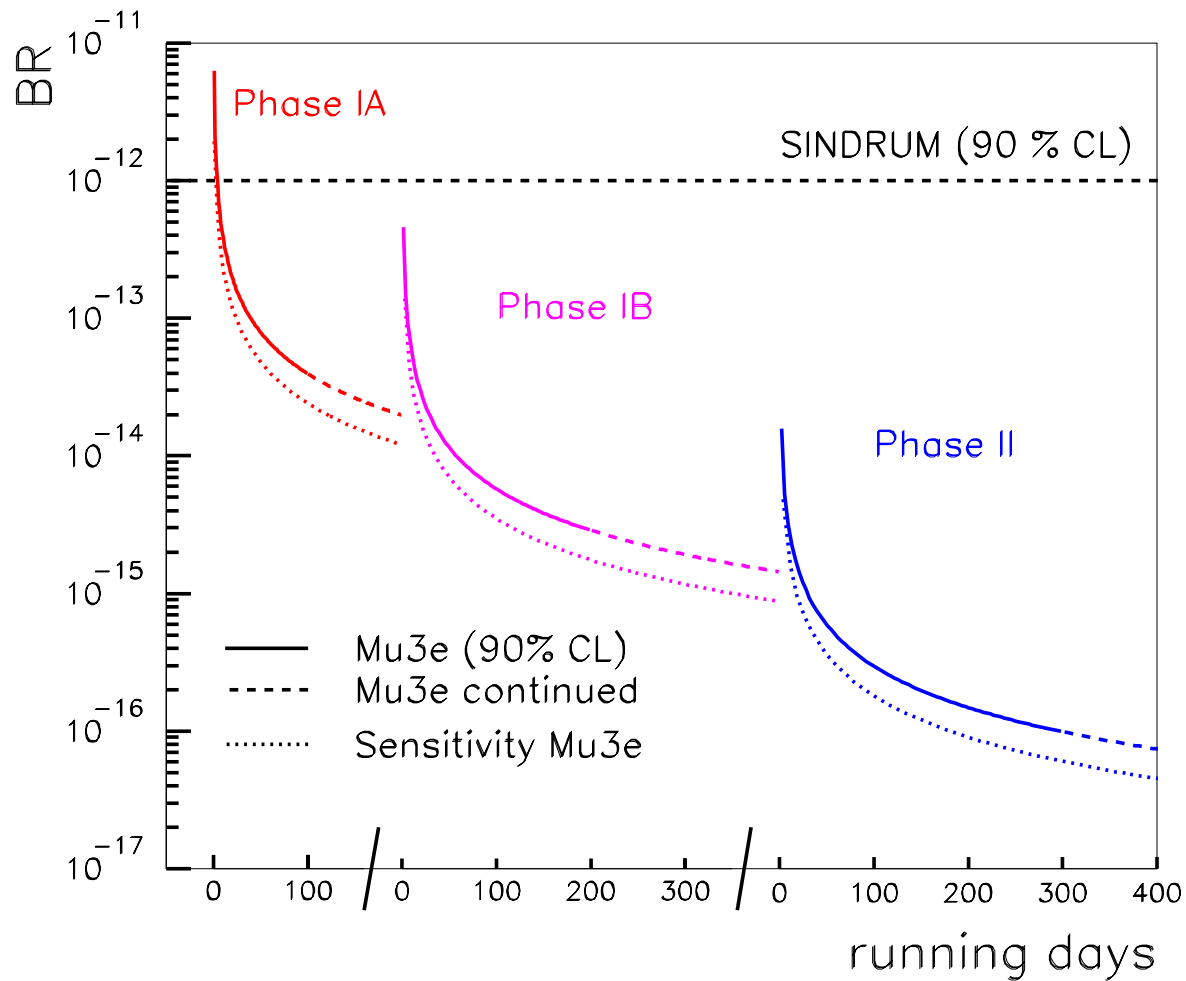
Sensitivity



Phase IB: 2018+
 $1 \cdot 10^8 \mu/s$

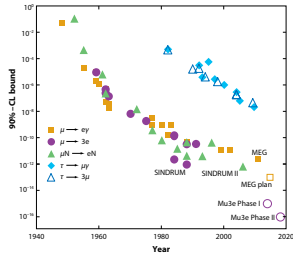


Sensitivity



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

Conclusion



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

- First large scale use of HV-MAPS

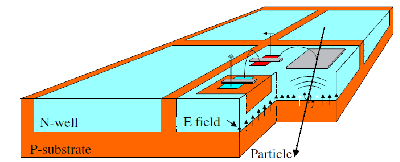
- Build detector layers thinner than a hair

- 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





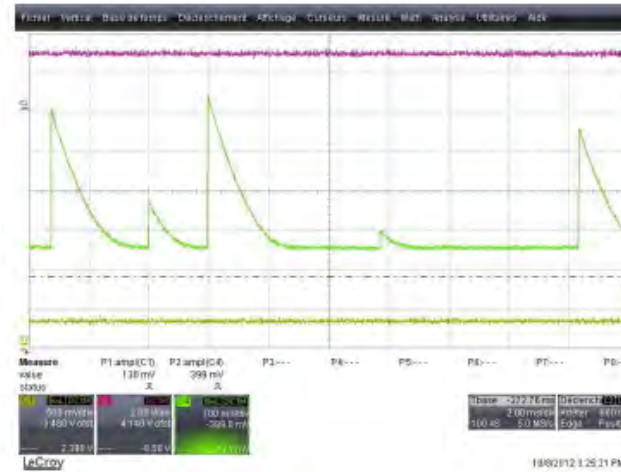
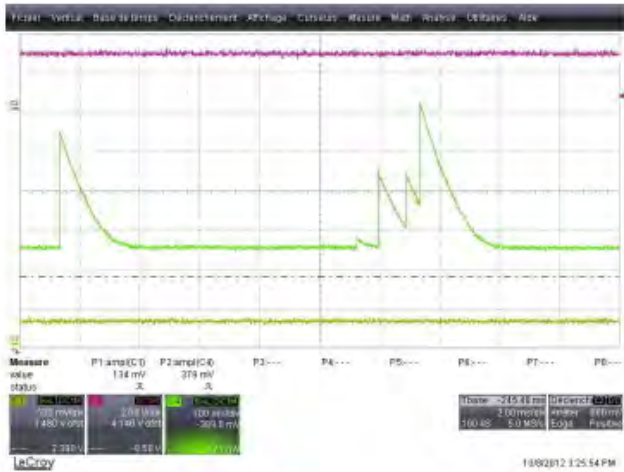
Backup Material



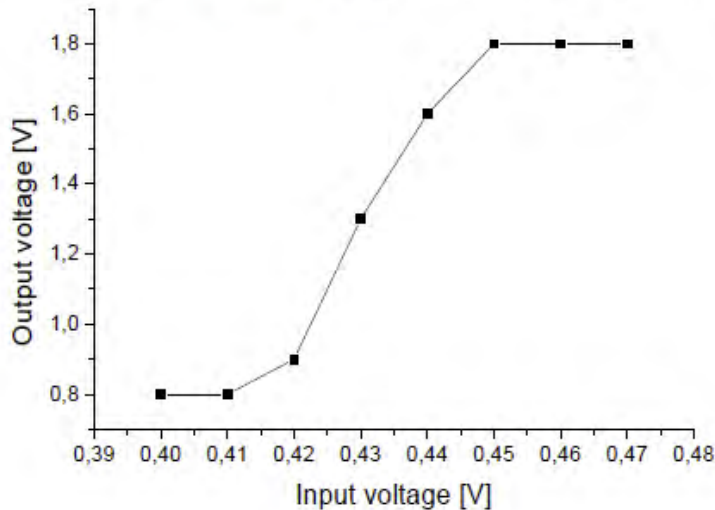


Radiation Hardness

- Requirements not as strict as at LHC



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



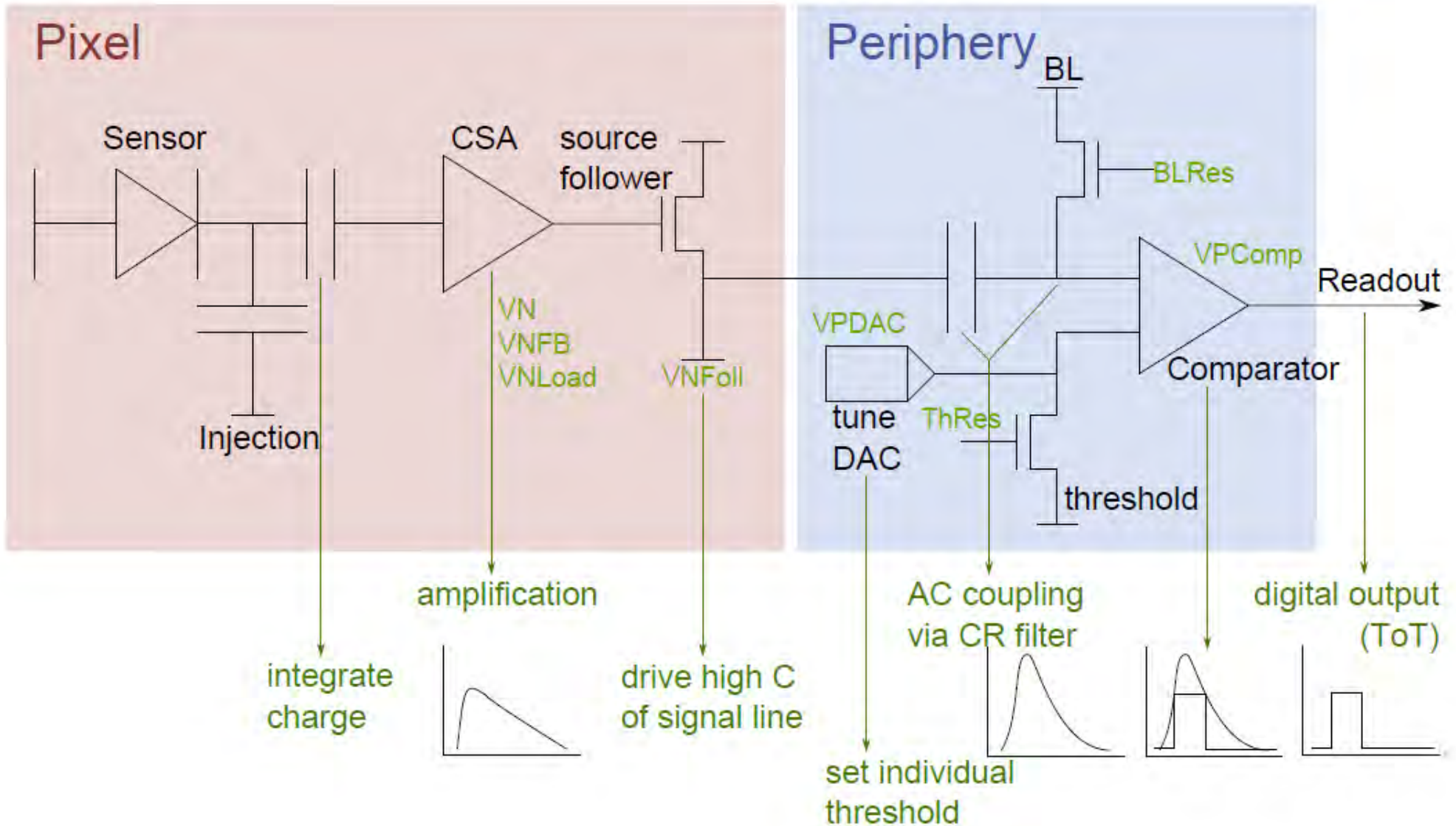
Comparator characteristics.

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

(Courtesy Ivan Perić, RESMDD 2012)

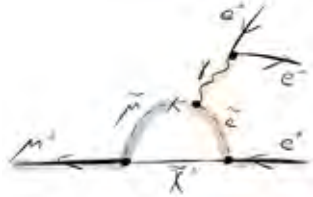


MUPIX electronics





A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

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

Four-fermion terms e.g. Z'

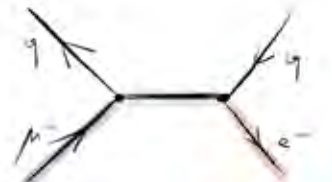
$$+ g_1 (\bar{\mu}_R e_L) (\bar{e}_R e_L) + g_2 (\bar{\mu}_L e_R) (\bar{e}_L e_R)$$

scalar

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

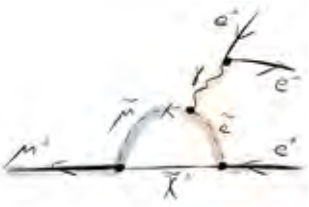
$$+ g_5 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_L \gamma^\mu e_L) + g_6 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_R \gamma^\mu e_R) + \text{H. C.}$$

vector

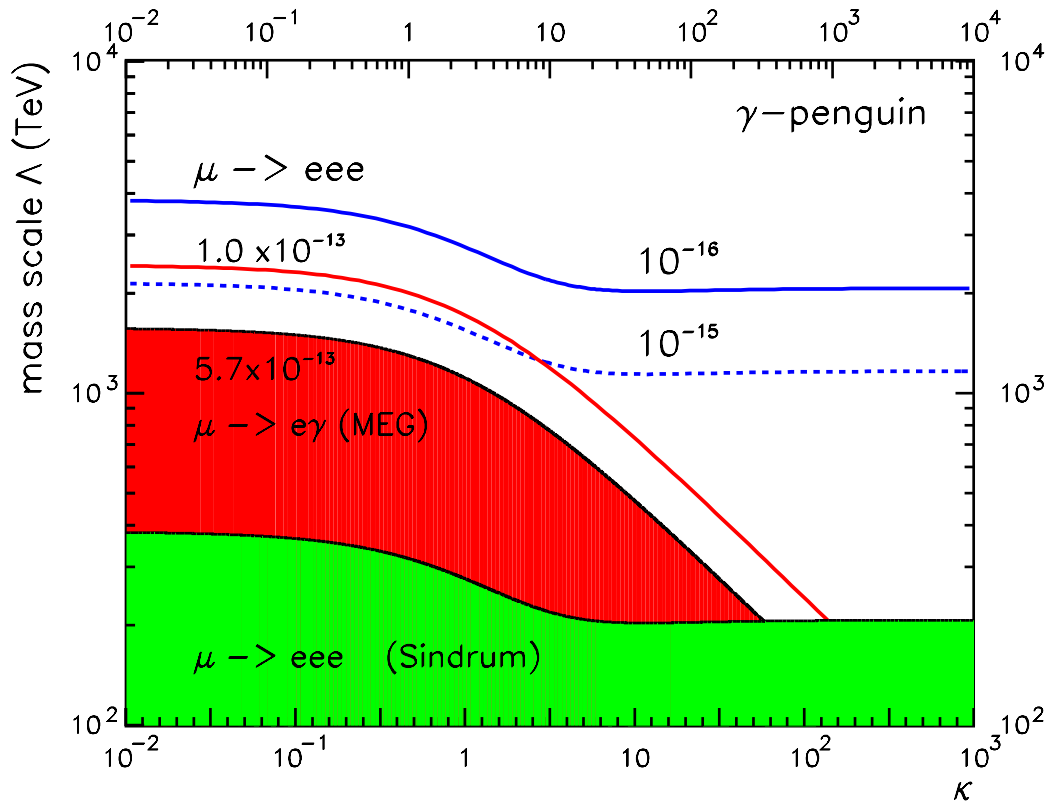
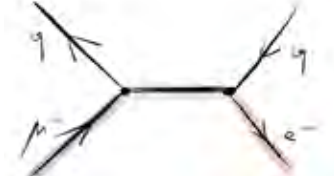


(Y. Kuno, Y. Okada,
Rev.Mod.Phys. 73 (2001) 151)

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



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



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

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



Detector Design

