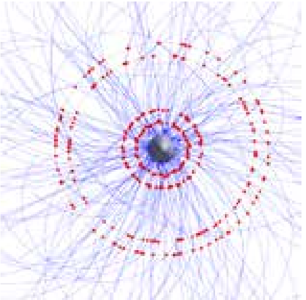
The
Mu3e Experiment

Niklaus Berger

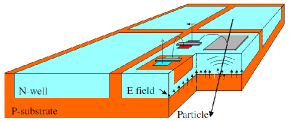
PI Palaver,
April 2013

Emmy
Noether-
Programm
Deutsche
Forschungsgemeinschaft
DFG

Overview



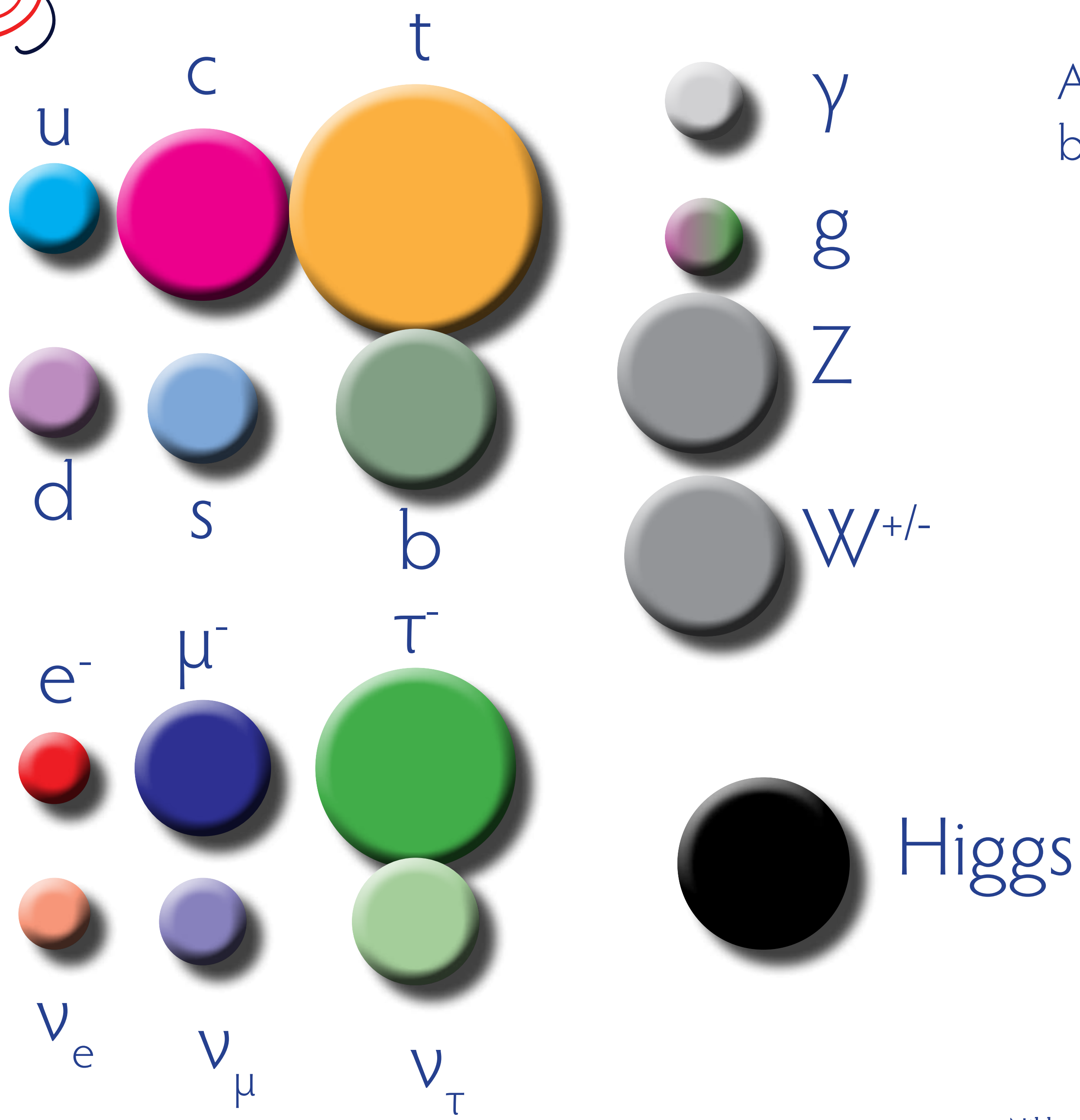
- The Challenge:
  Finding one in 10^{16} muon decays



- The Technology:
  High Voltage Monolithic Active Pixel Sensors

- The Mu3e Detector:
  Minimum Material, Maximum Precision

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...)

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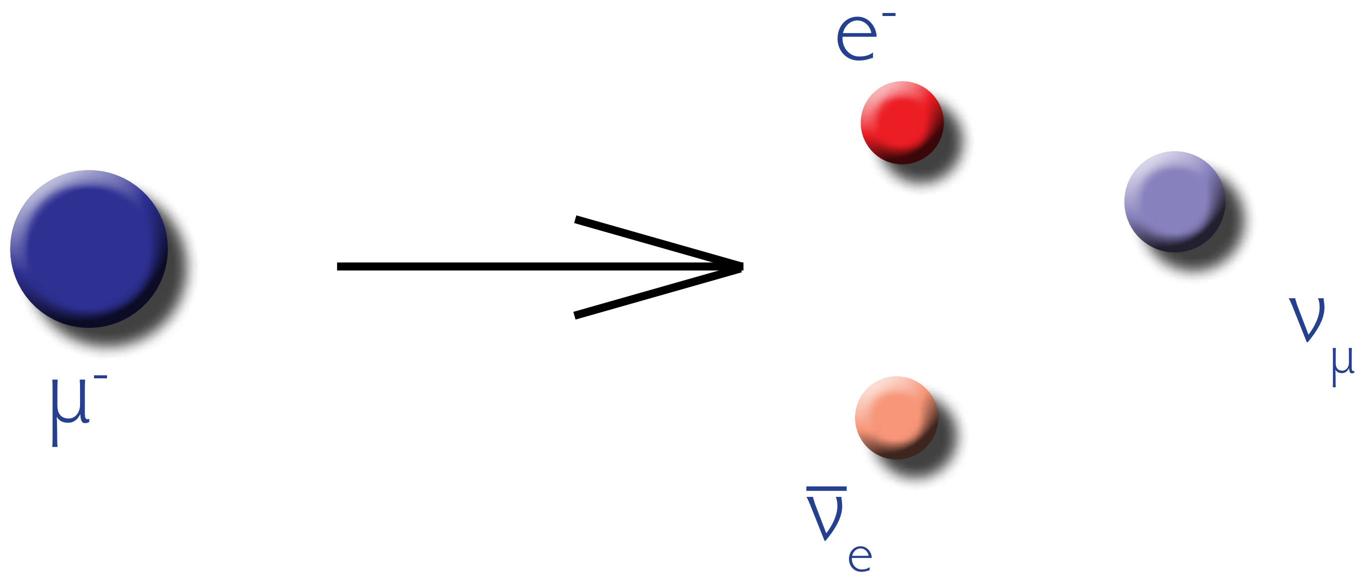
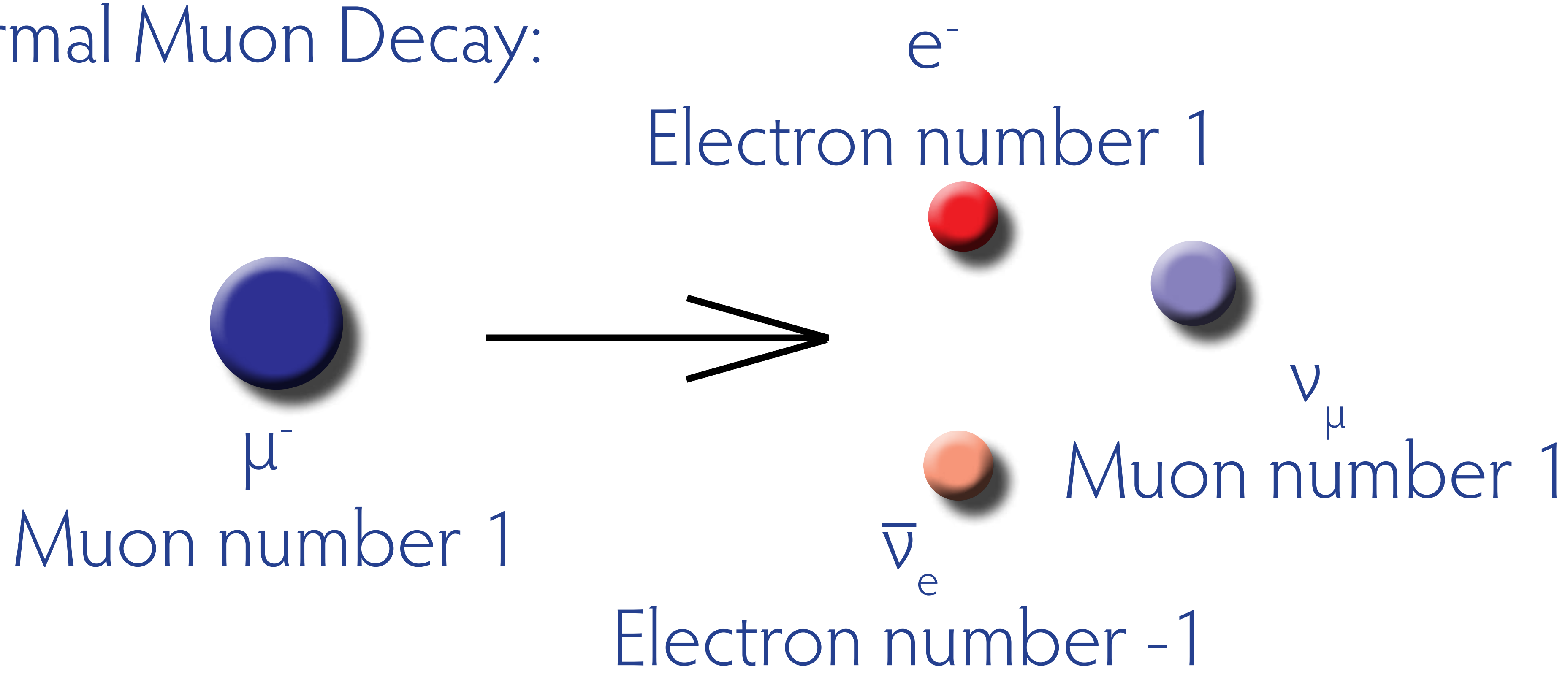
Lepton Bookkeeping

Normal Muon Decay:



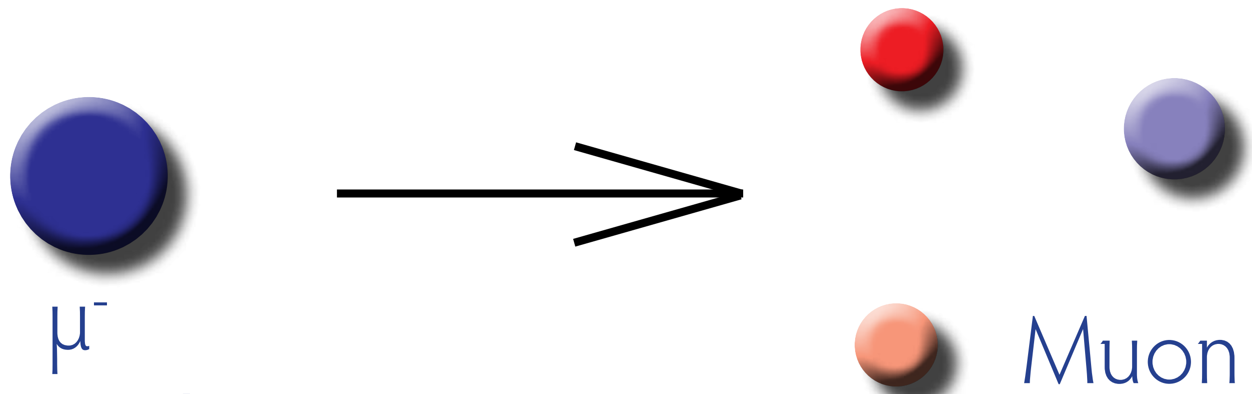
Lepton Bookkeeping

Normal Muon Decay:



Lepton Bookkeeping

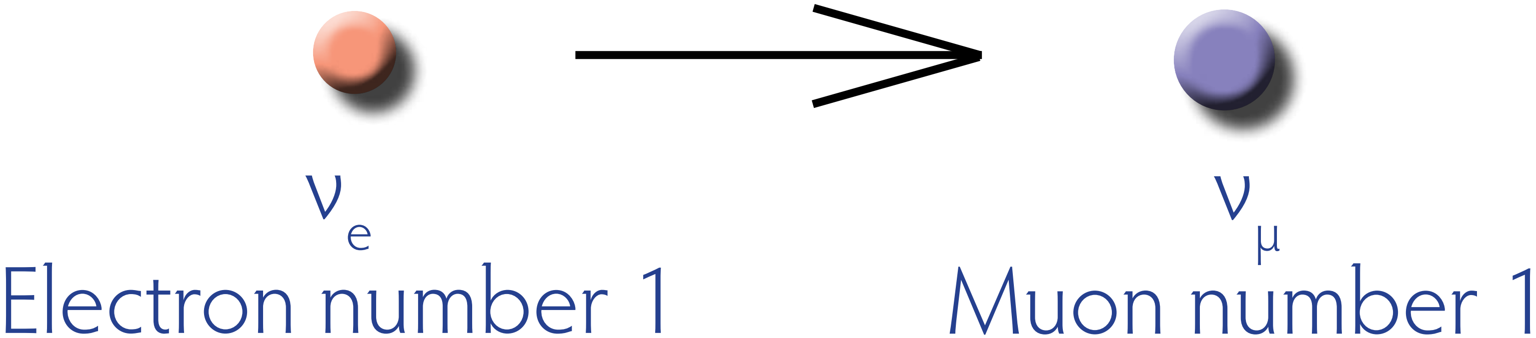
Normal Muon Decay:



Before:
Muons 1
Elektrons 0

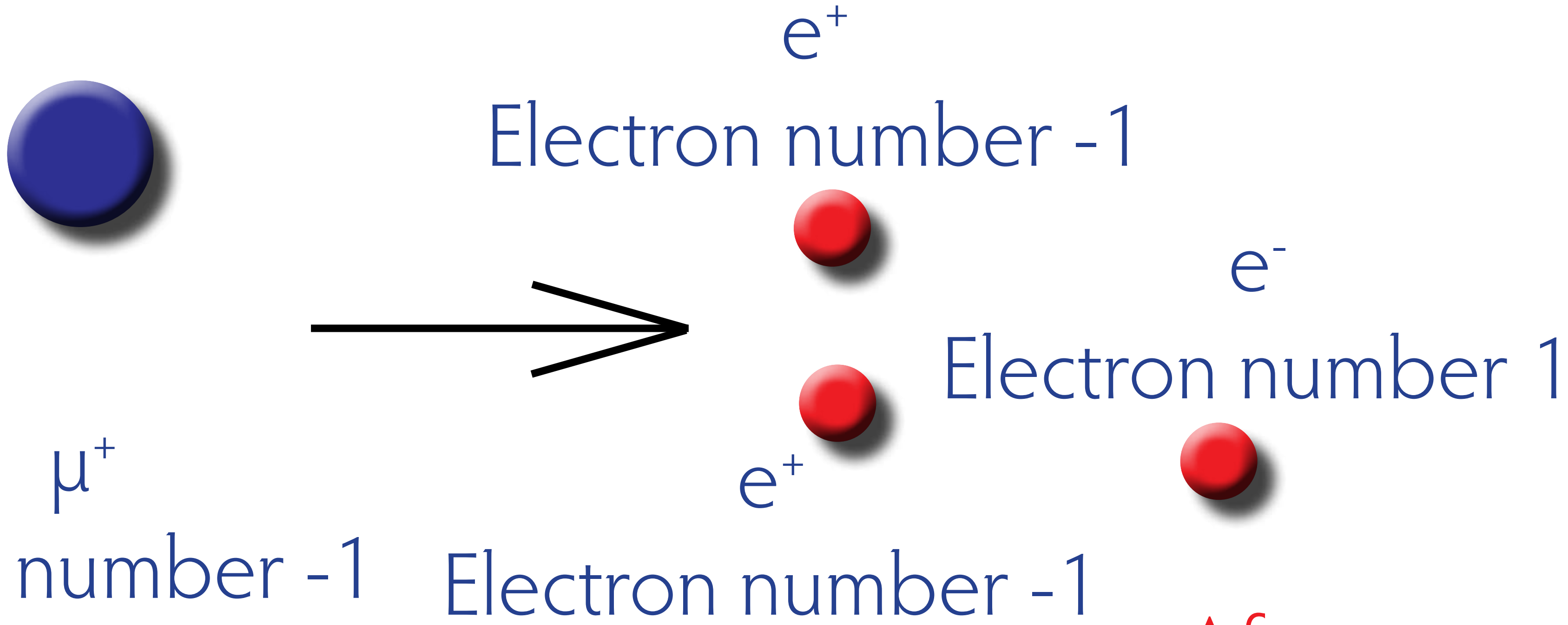
After:
Muons 1
Electrons 0

Cooked books?



Cooked books?

How about charged leptons (Muons)?



Before:
Muons -1
Electrons 0

After:
Muons 0
Electrons -1

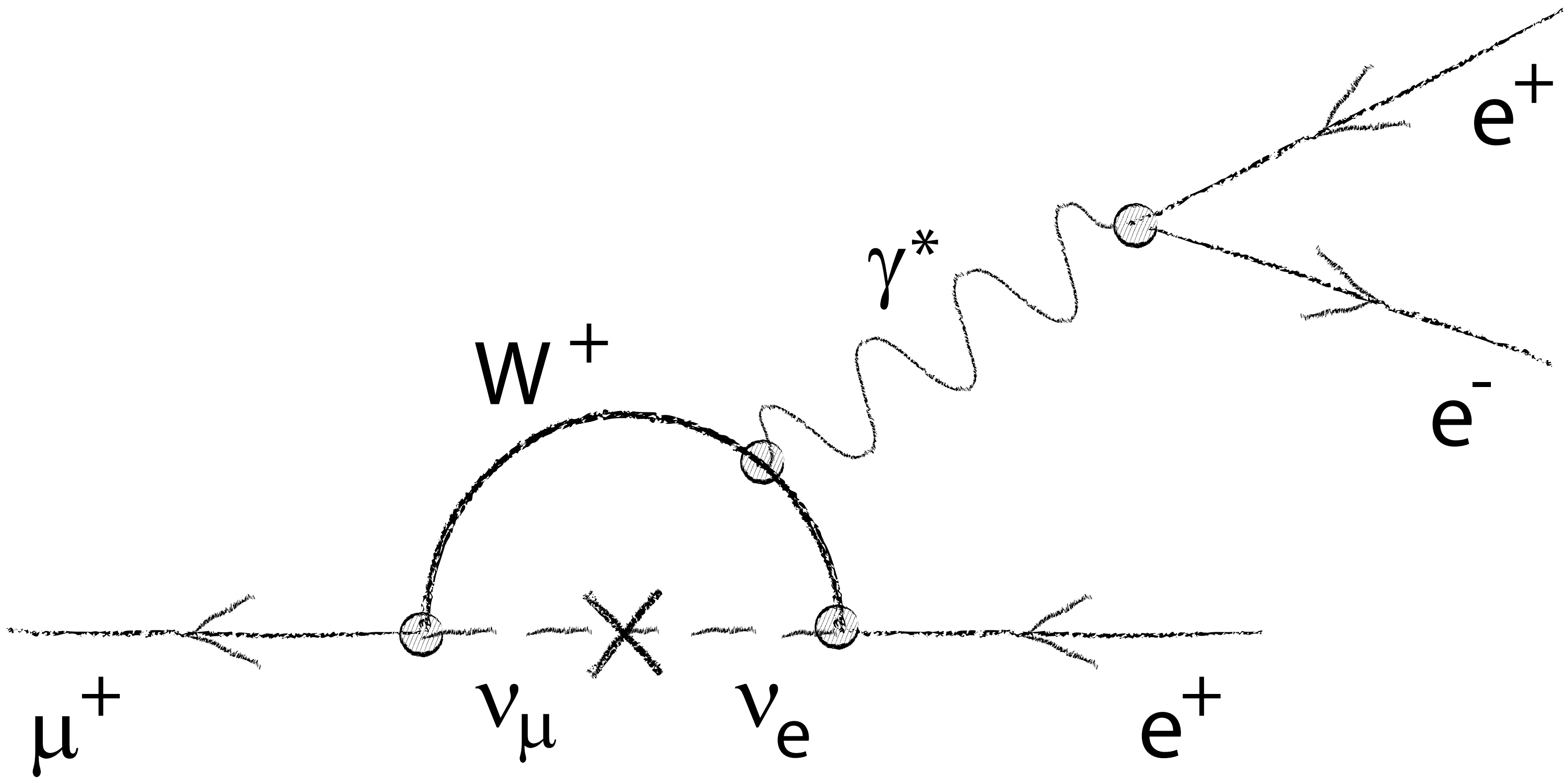
This

(charged lepton flavour violation)

has never been seen

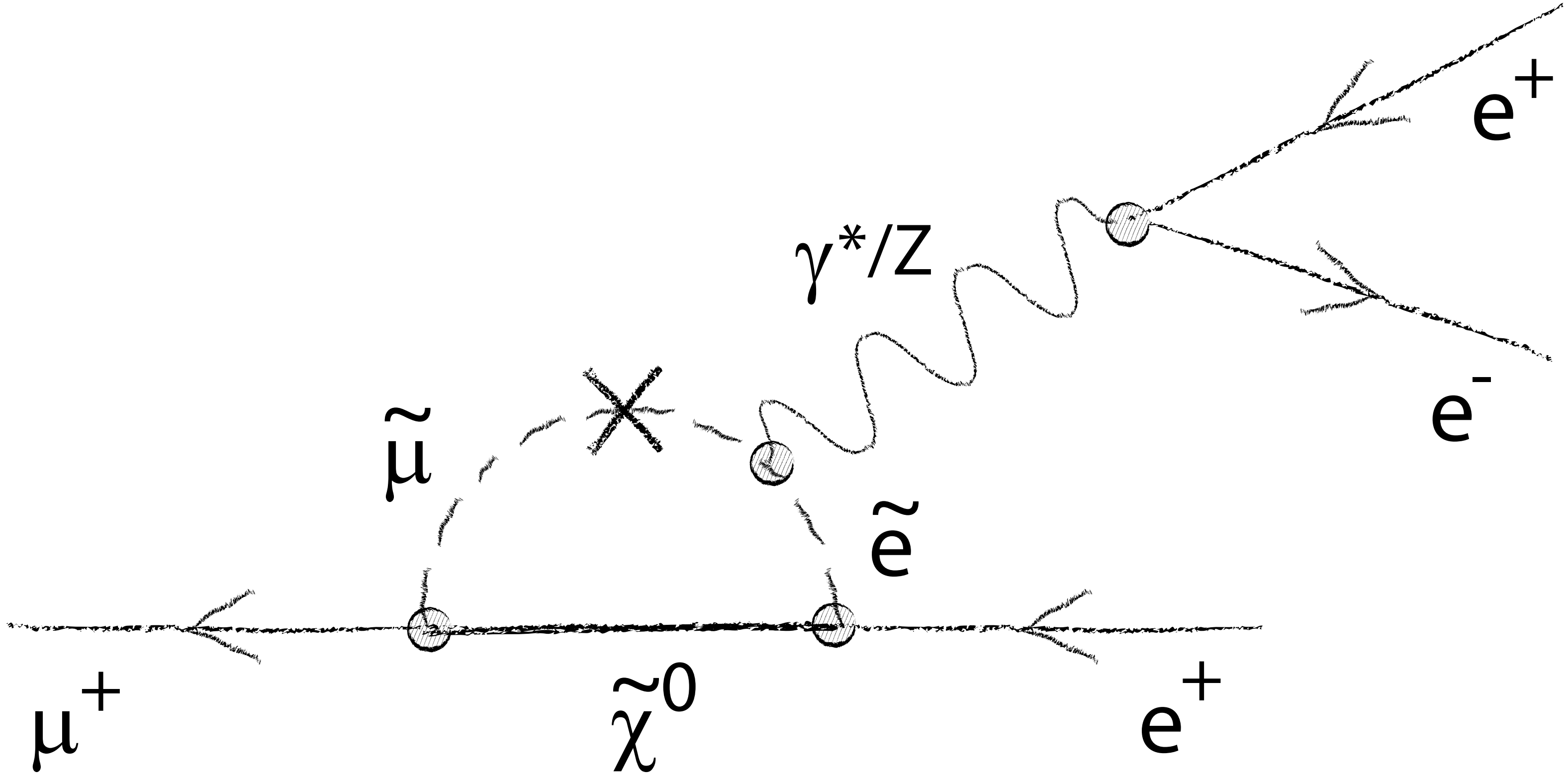
Charged Lepton Flavour Violation

- Neutrinos have mass
- Leptons do change flavour
- However: Standard Model branching ratio for $\mu \rightarrow eee < 10^{-50}$



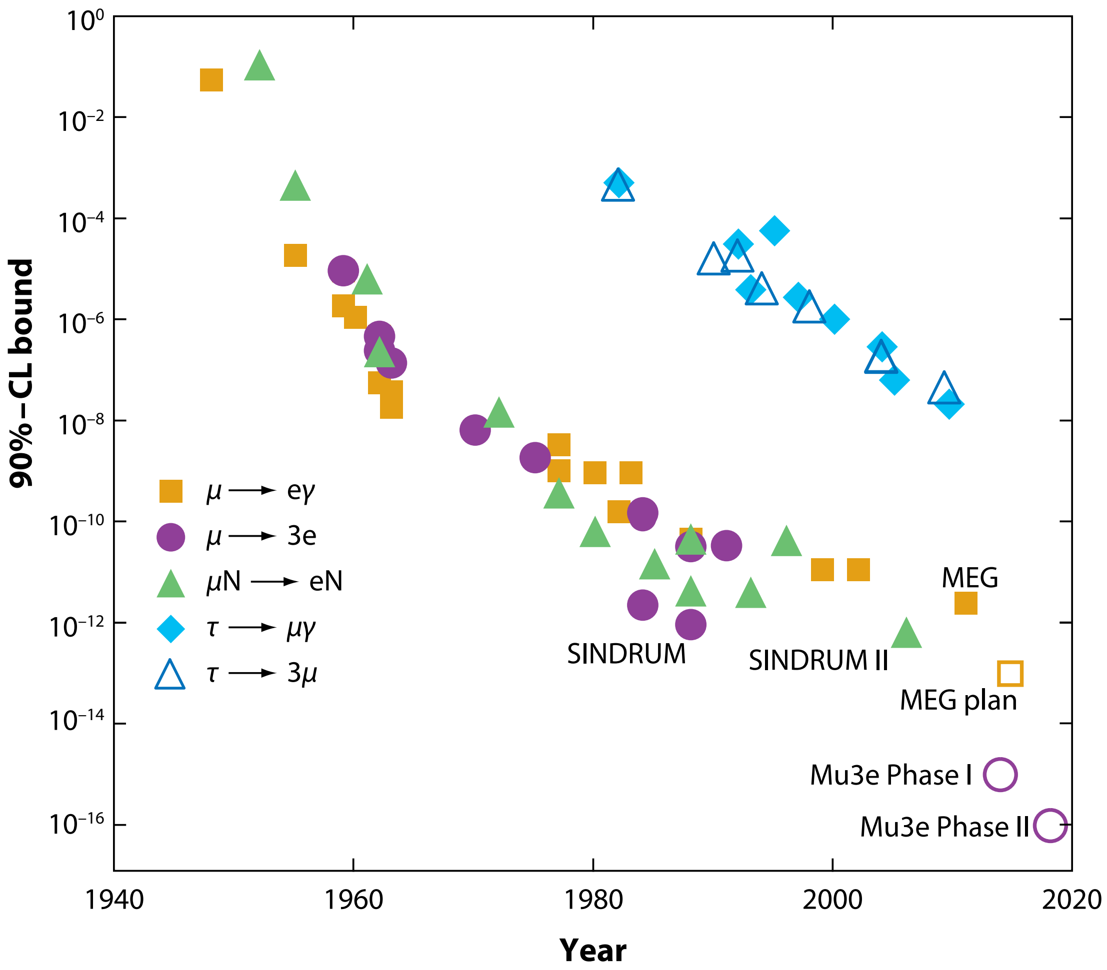
Charged Lepton Flavour Violation

- Neutrinos have mass
- Leptons do change flavour
- However: Standard Model branching ratio for $\mu \rightarrow eee < 10^{-50}$
- Can be much bigger with new physics



The Goal: 10^{-16}

- We want to find or exclude $\mu \rightarrow eee$ at the 10^{-16} level
- 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))

Search with SINDRUM (1988)

Less than one in 10^{12} muon decays is to three electrons

Corresponding to one gray hair in the population of Baden-Württemberg

Our goal

Check whether more than one in 10^{16} muon decays is to three electrons

Corresponding to one gray hair in all humans that ever lived

The Challenges

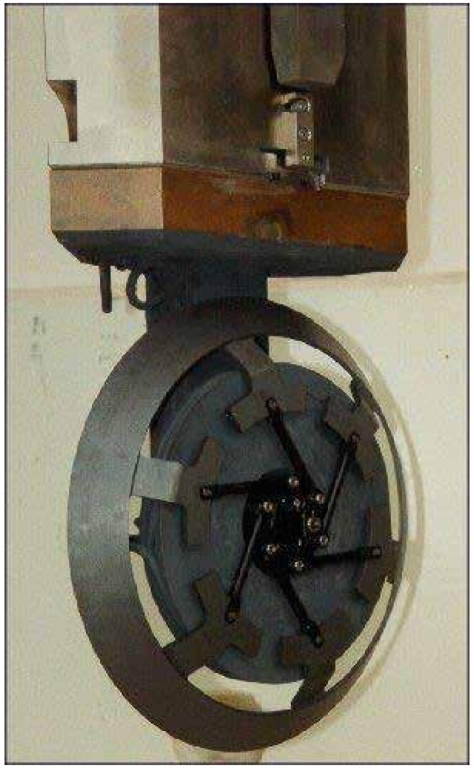
- Observe more than 10^{16} muon decays:
  2 Billion muons per second

- Suppress backgrounds by more than 16 orders of magnitude

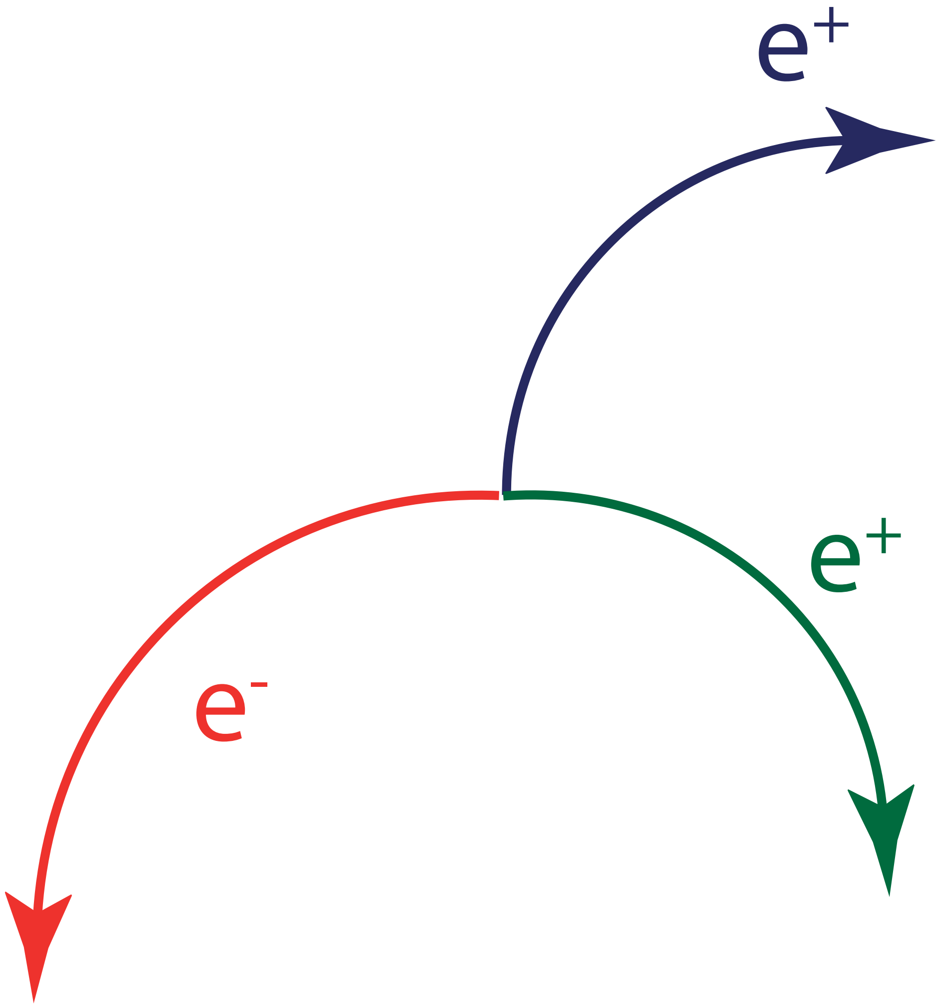
- Be sensitive for the signal

Muons from PSI

- The Paul Scherrer Institut (PSI) in Villigen, Switzerland has the world's most powerful DC proton beam (2.2 mA at 590 MeV)
- Pions and then muons are produced in rotating carbon targets

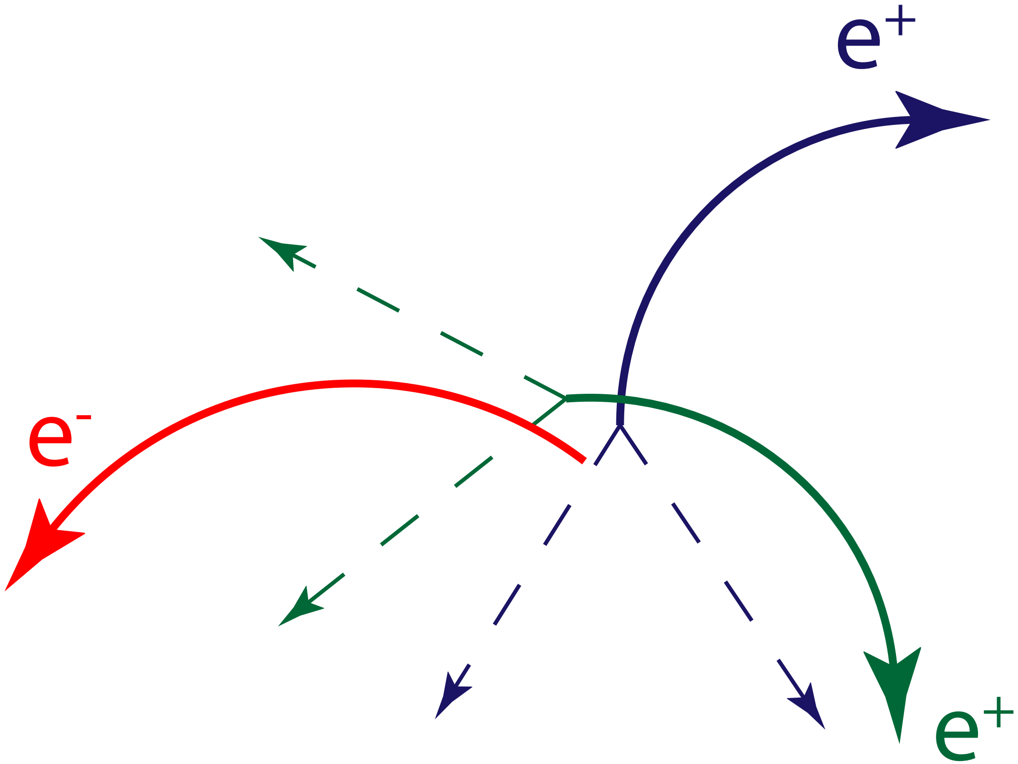


The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: ½ m_μ = 53 MeV/c

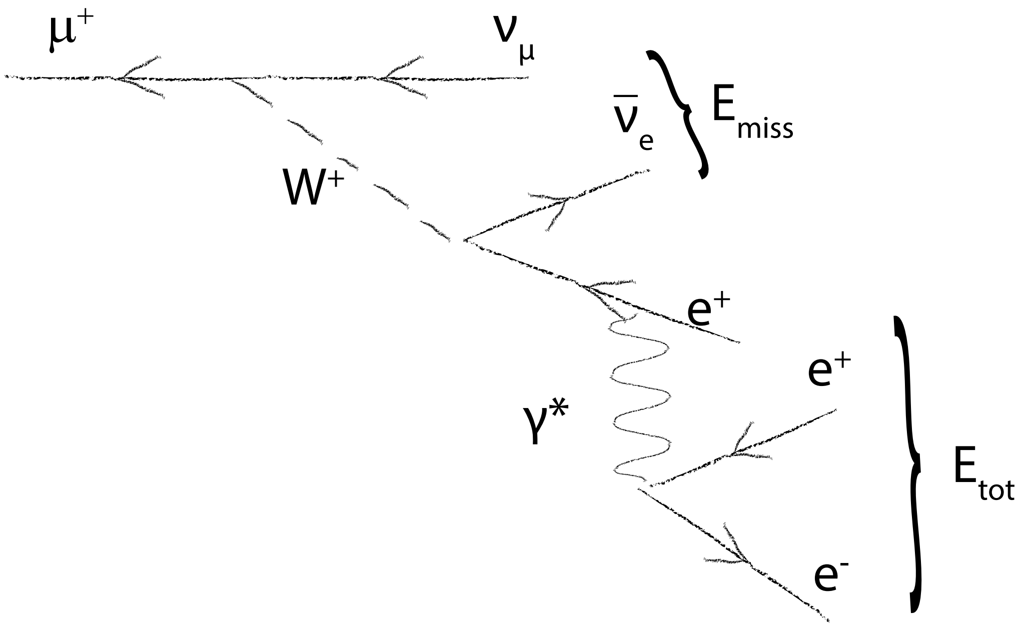
Accidental Background



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

- Need very good timing, vertex and momentum resolution

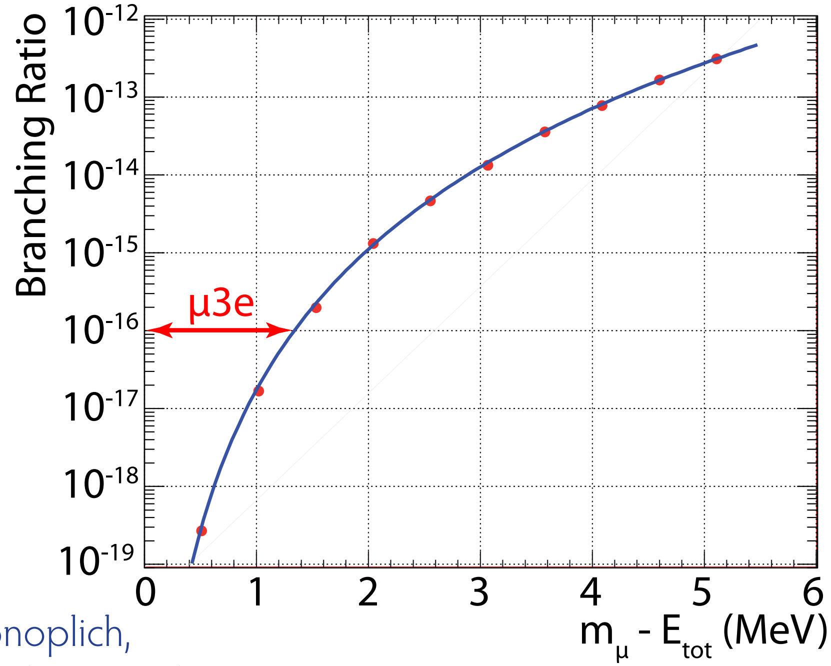
Internal conversion background



- Allowed radiative decay with internal conversion:

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

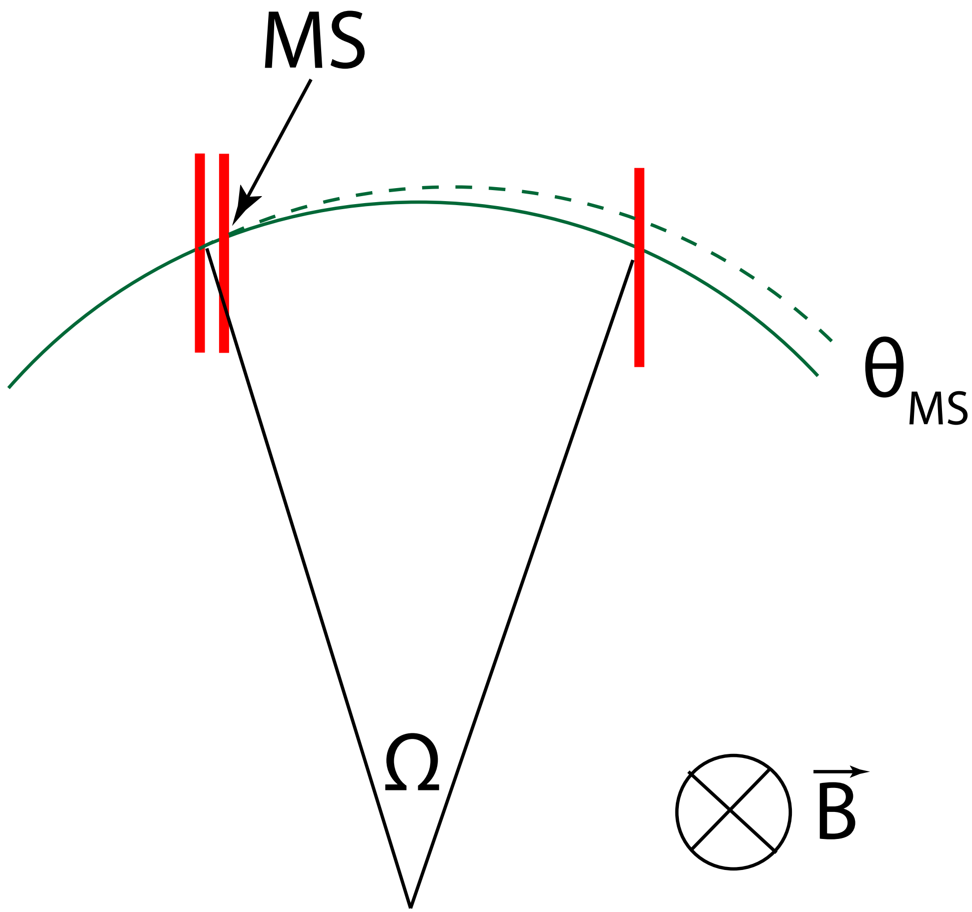
- Only distinguishing feature: Missing momentum carried by neutrinos



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

- Need excellent momentum resolution

Momentum measurement

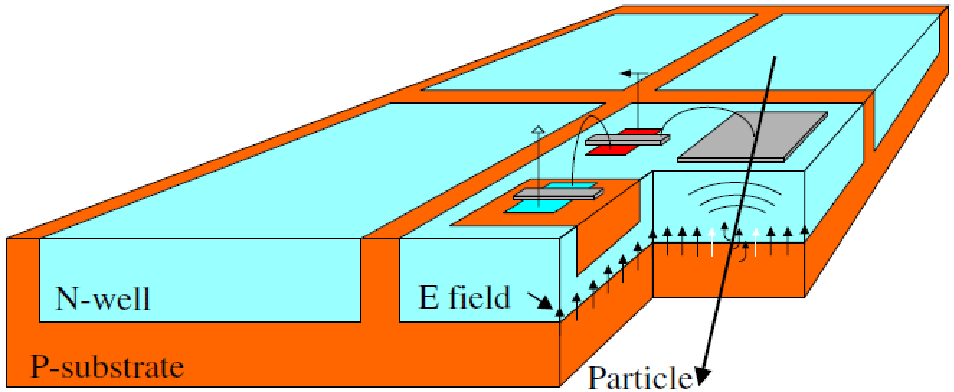


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

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

Fast and thin sensors: HV-MAPS



High voltage monolithic active pixel sensors

- Implement logic directly in N-well in the pixel - smart diode array
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Can be thinned down to < 50 µm
- Invented by Ivan Peric at ZITI Mannheim

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

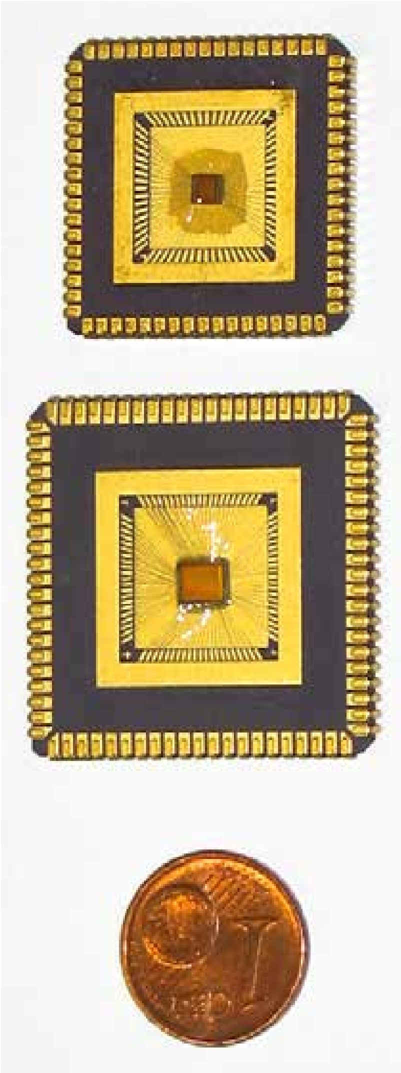
The MUPIX chips

HV-MAPS chips: AMS 180 nm HV-CMOS

MUPIX2
36 x 42 pixels
30 x 39 µm pixel size
1.8 mm^2 active area

MUPIX3
40 x 32 pixels
80 x 92 µm pixel size
9.4 mm^2 active area

For Mu3e:
256 x 256 pixels
80 x 80 µm pixel size
4 cm^2 area, 95% active

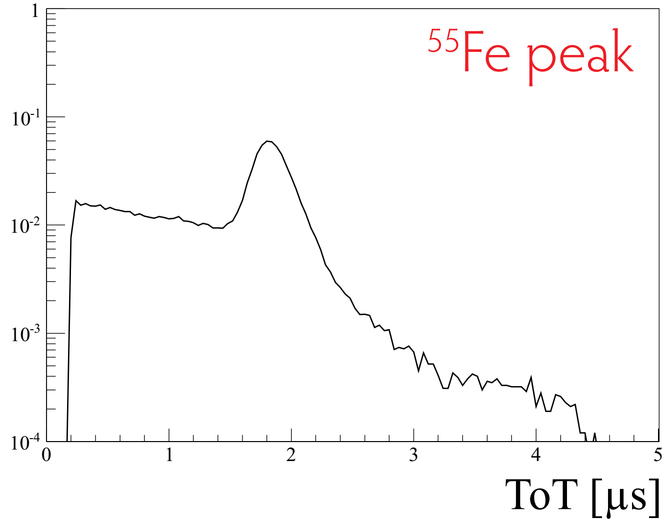


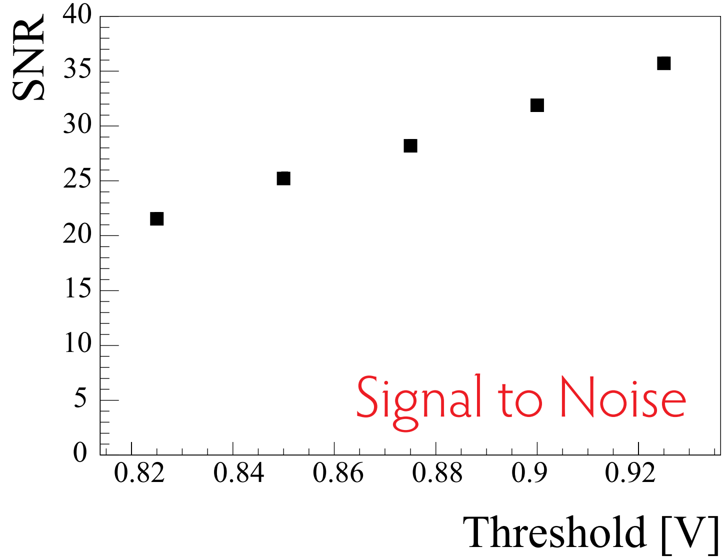
- MUPIX2:
  Characterization during 2012
  Single pixel Time-Over-Threshold
  Binary pixel matrix

- MUPIX3:
  Column logic with address generation

Extensive test beam campaign 2013

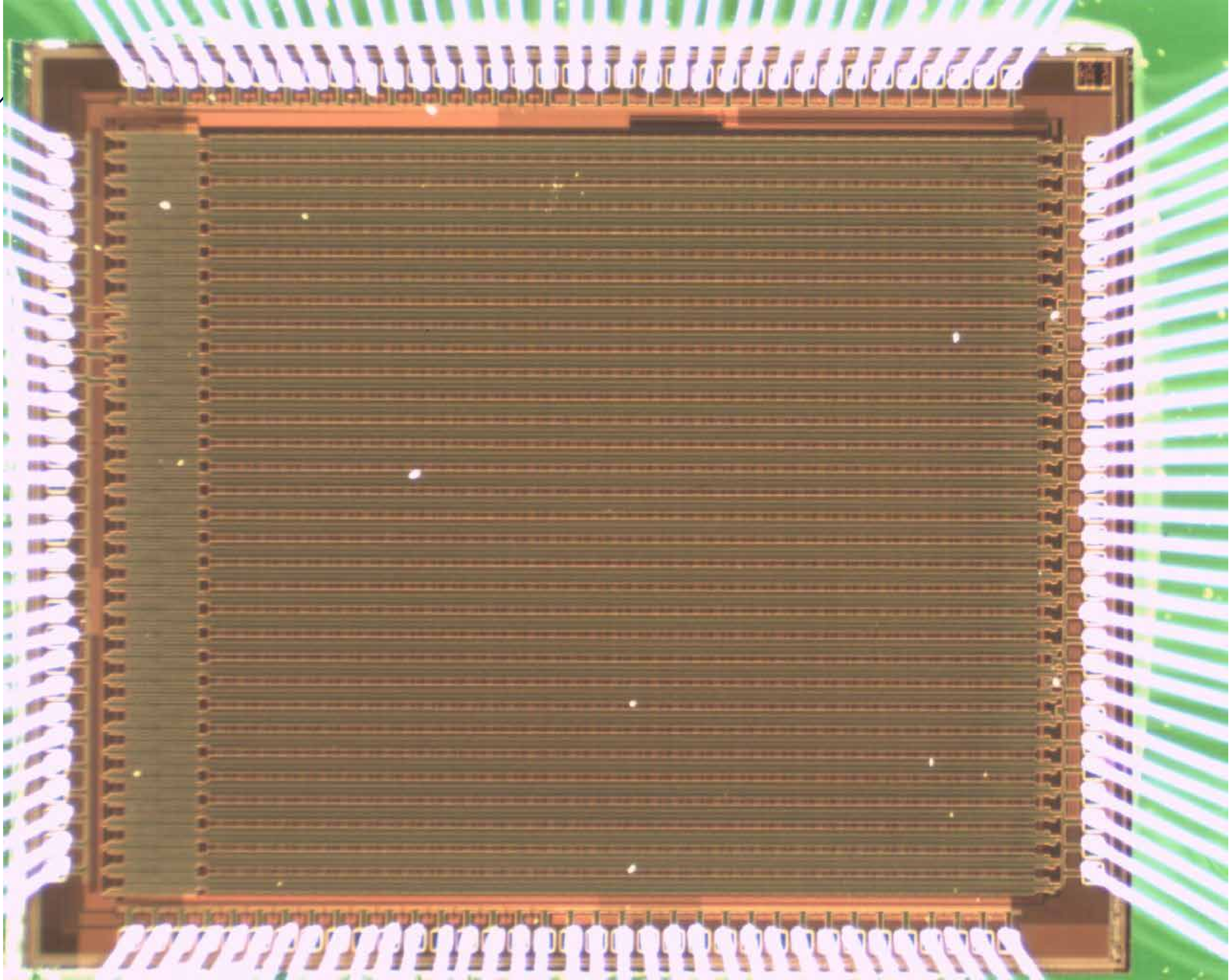
MUPIX 2 Results



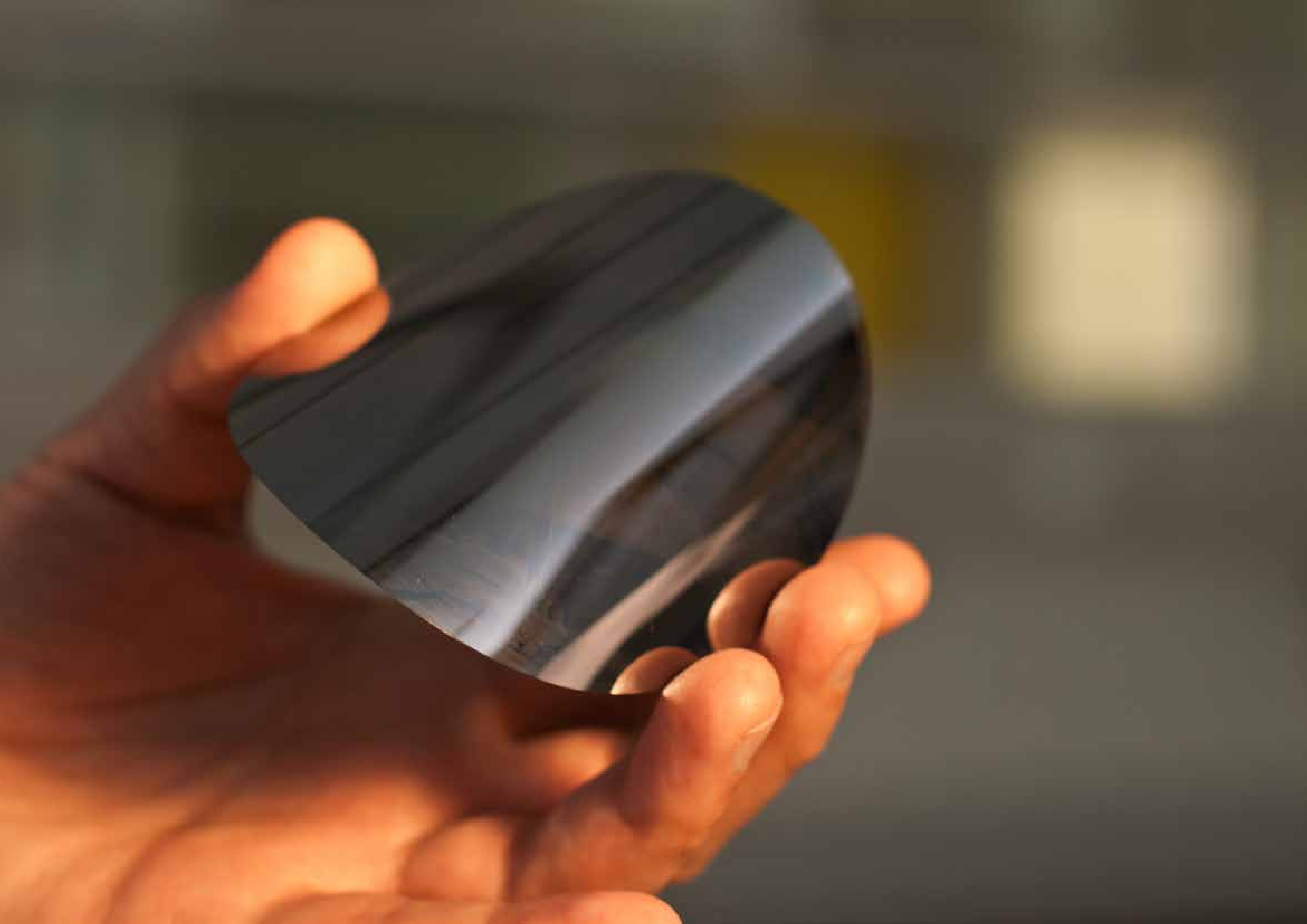


- Measurements with ^{55}Fe source
- Good energy measurement
- Very good signal to noise

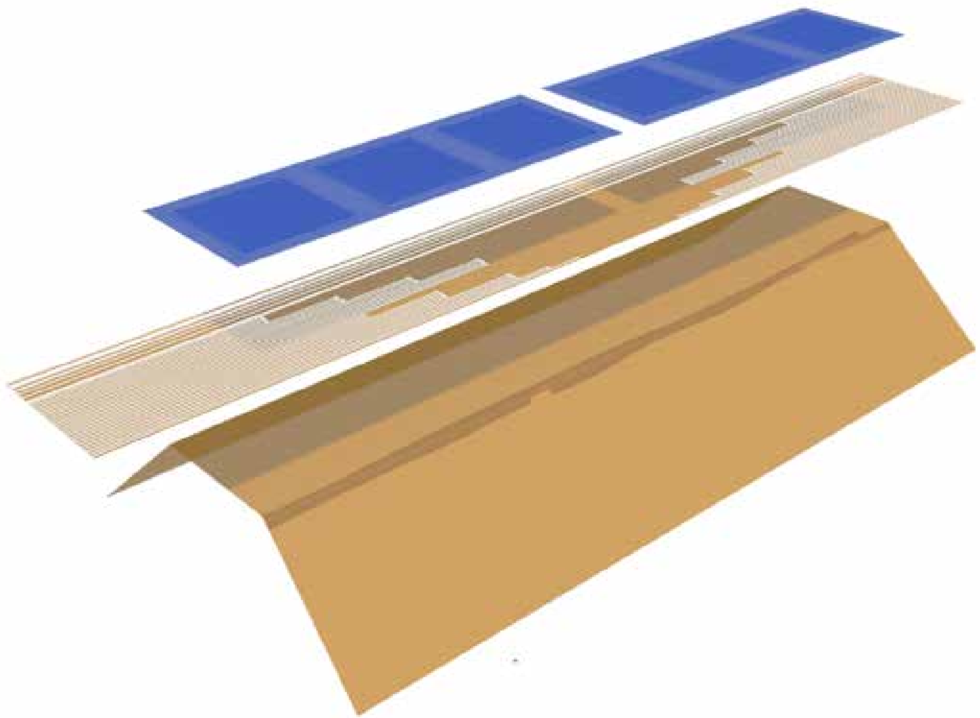
Details in theses:
A.K. Perrevoort: *Characterization of HV-MAPS for Mu3e* (Master thesis, 2012)
H. Augustin: *Charakterisierung von HV-MAPS* (Bachelor thesis, 2012)
available from **`www.psi.ch/mu3e`**



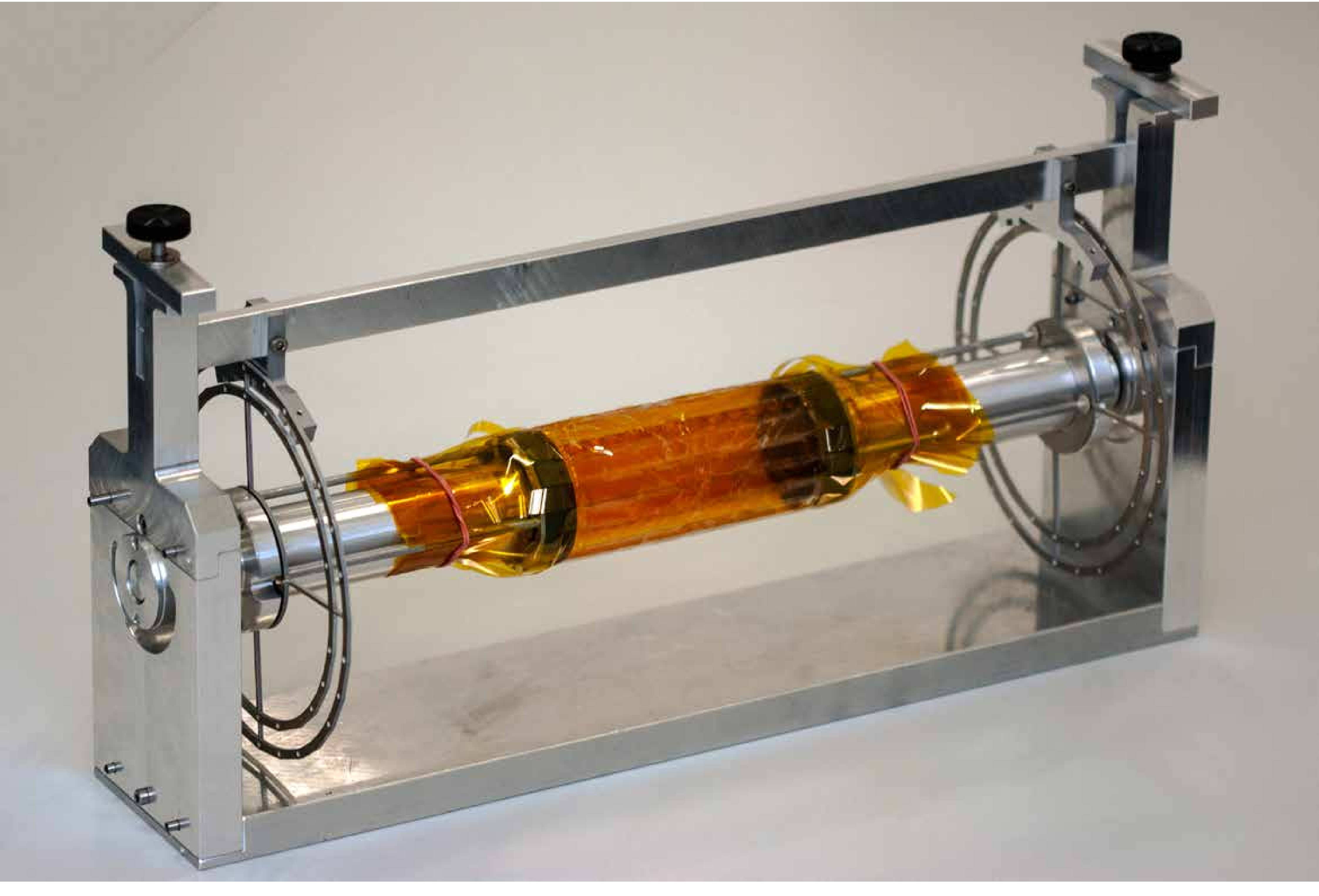
MUPIX3 Set-up



Mechanics



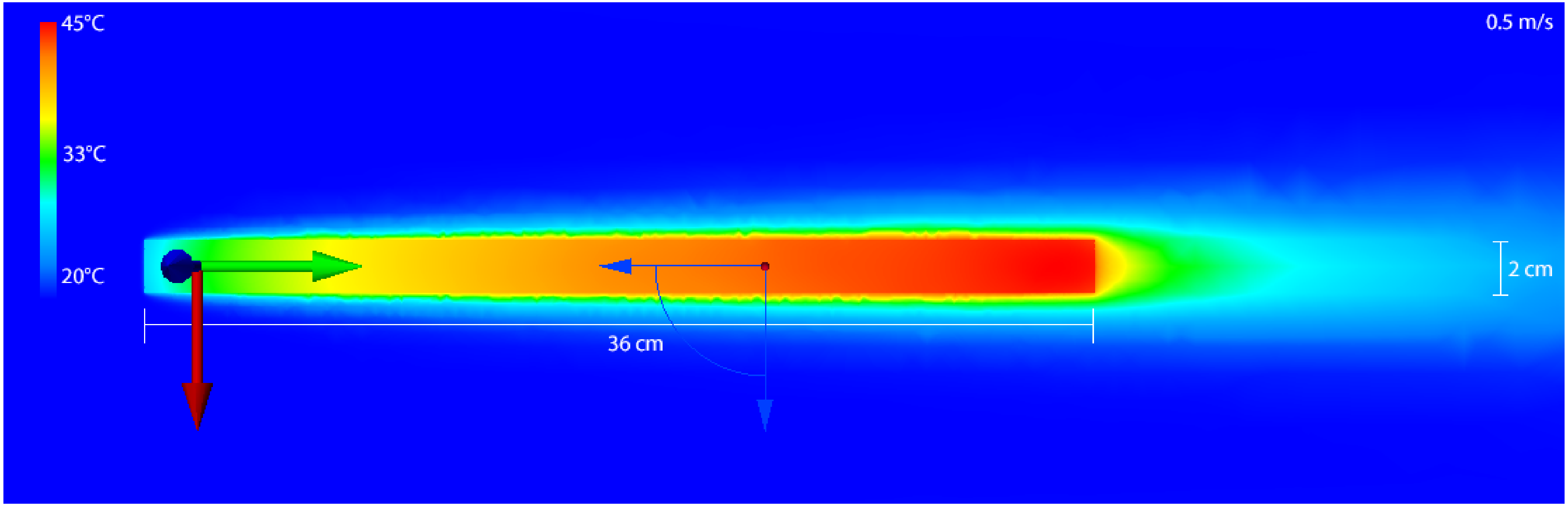
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

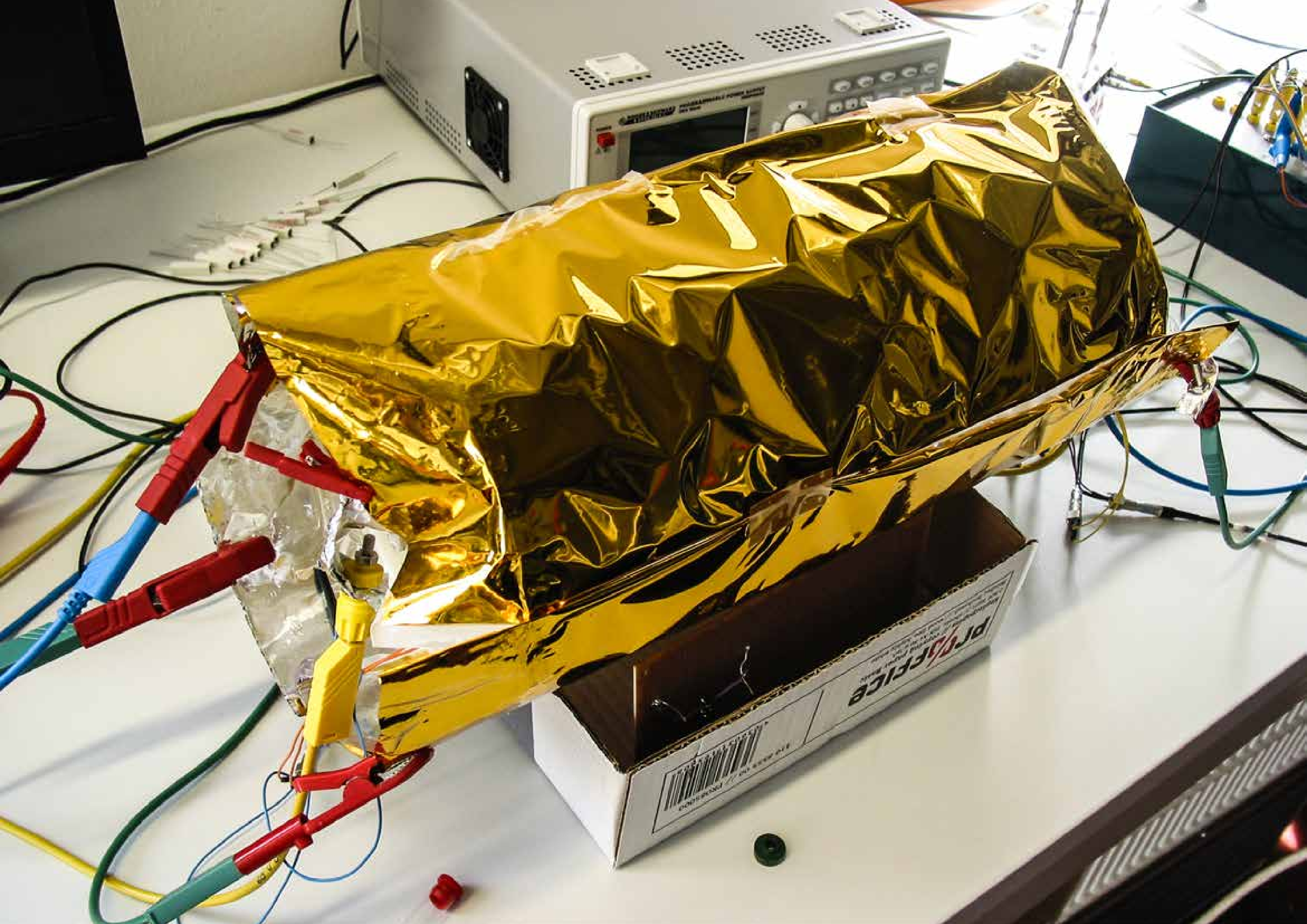


Cooling

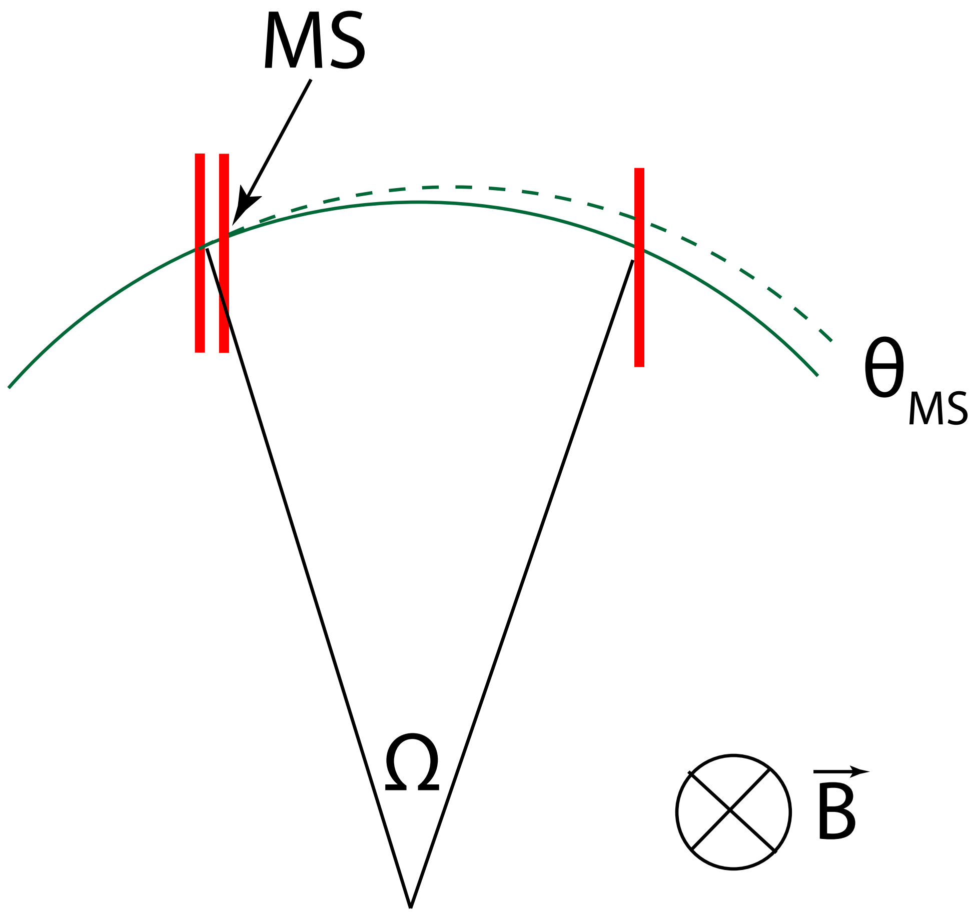
- Add no material:
  Cool with gaseous Helium
- ~ 150 mW/cm^2 - total 2 kW
- Simulations: Need ~ 1 m/s flow
- First measurements: Need several m/s
- Full scale prototype on the way

Details in thesis:
M. Zimmermann: *Cooling with Gaseous Helium for the Mu3e Experiment*
(Bachelor thesis, 2012)
available from **`www.psi.ch/mu3e`**





Momentum measurement



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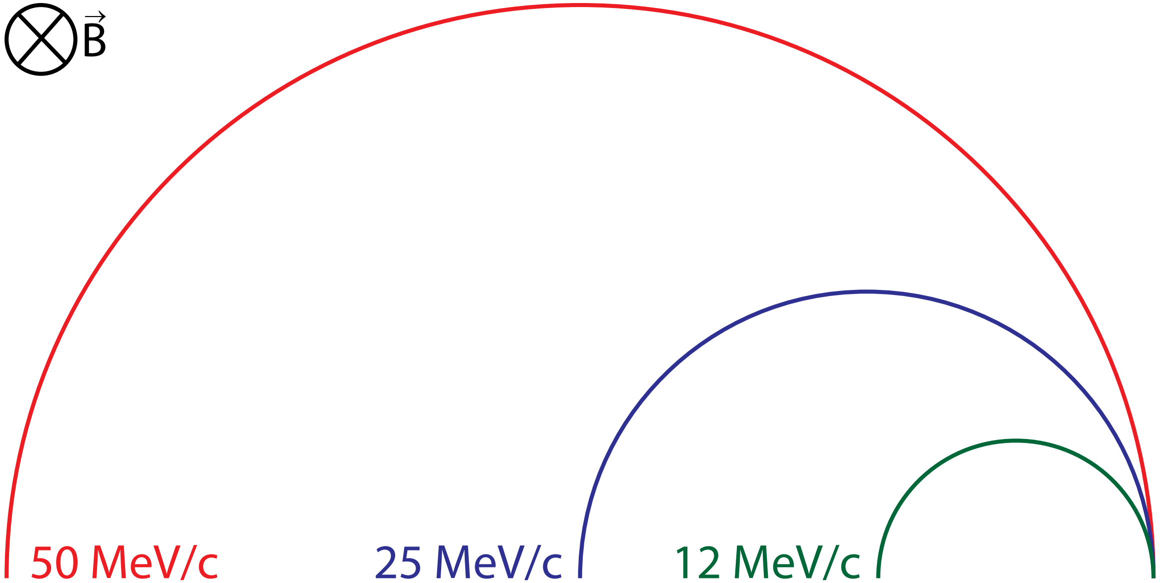
Precision vs. Acceptance



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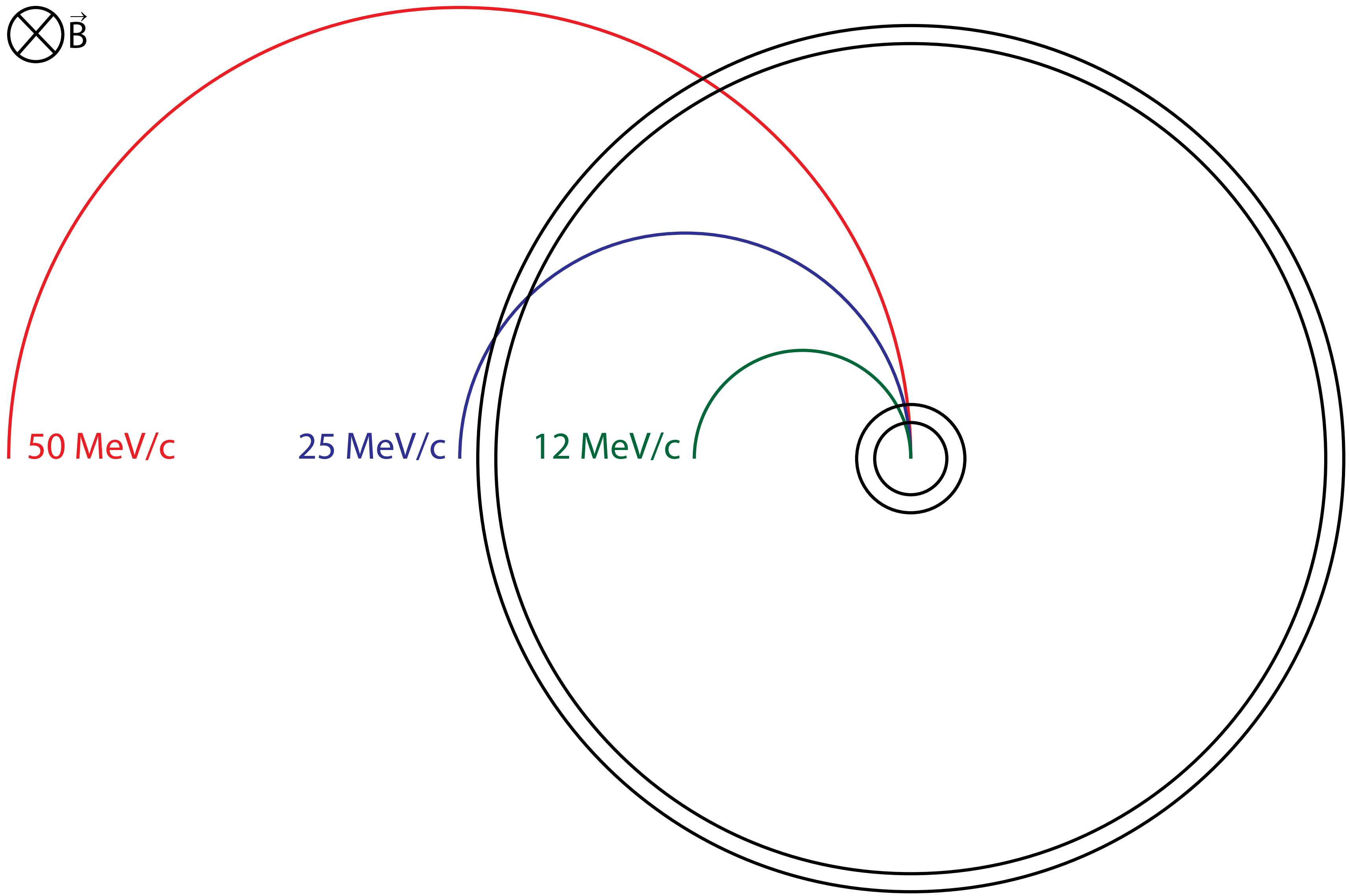

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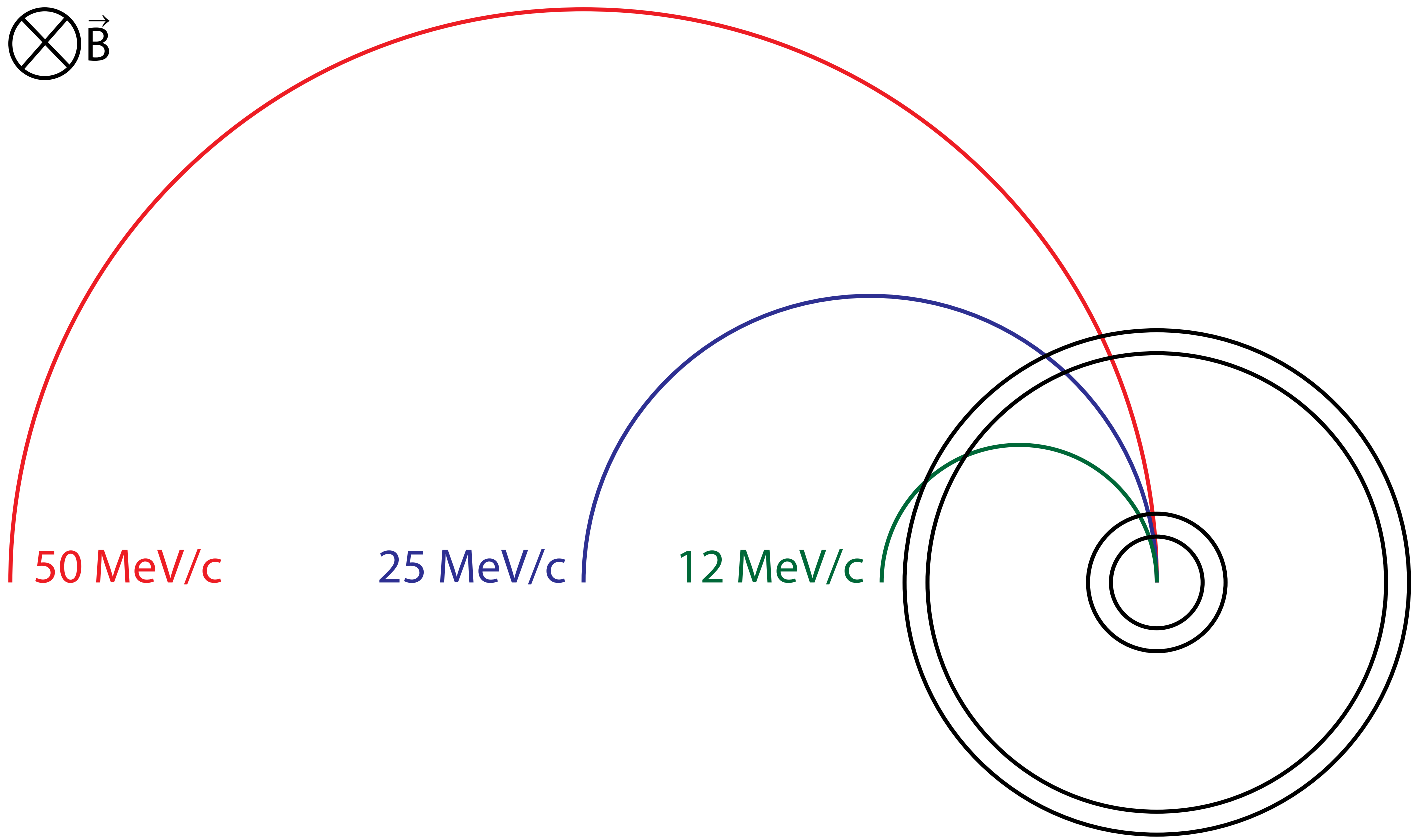

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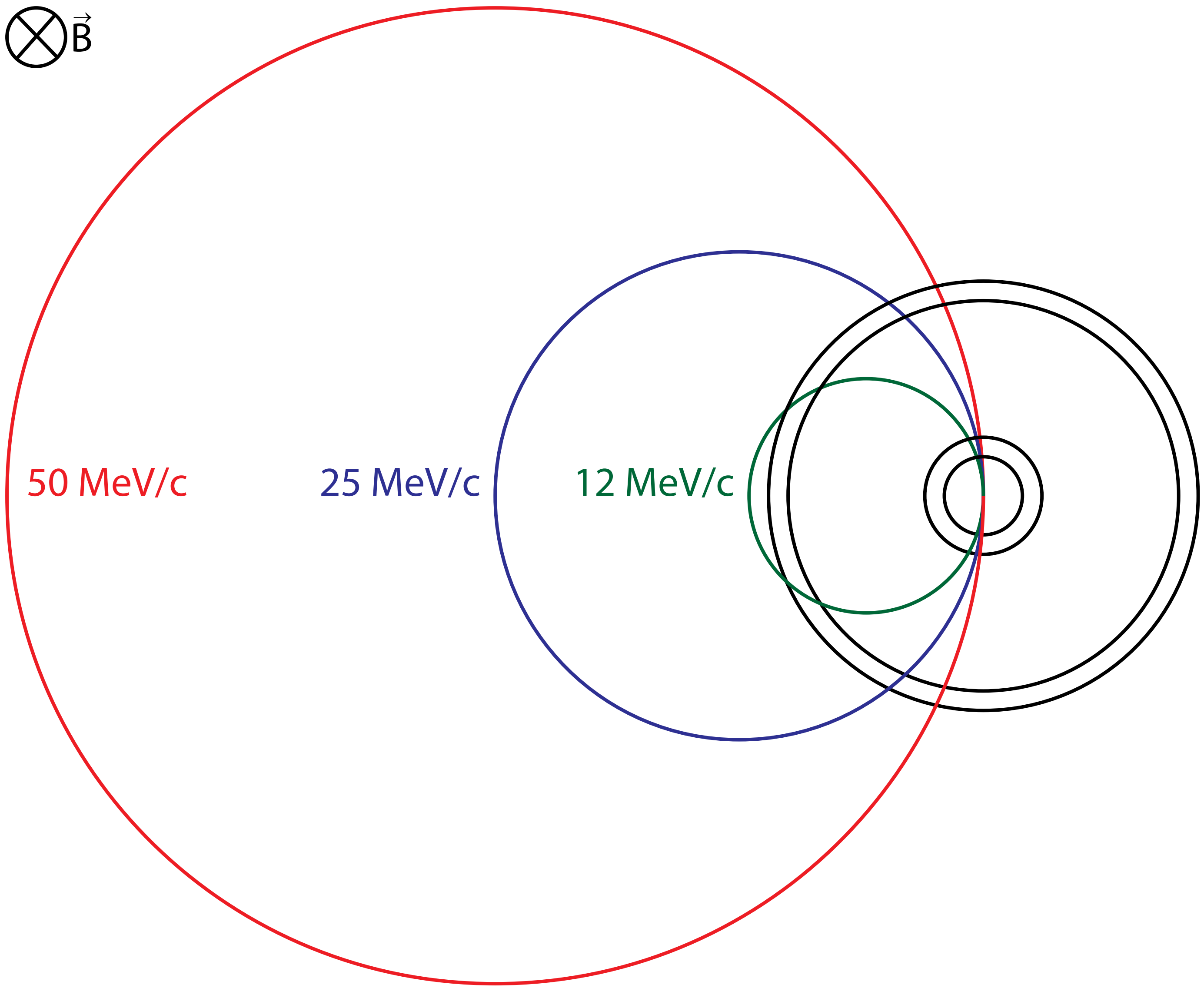

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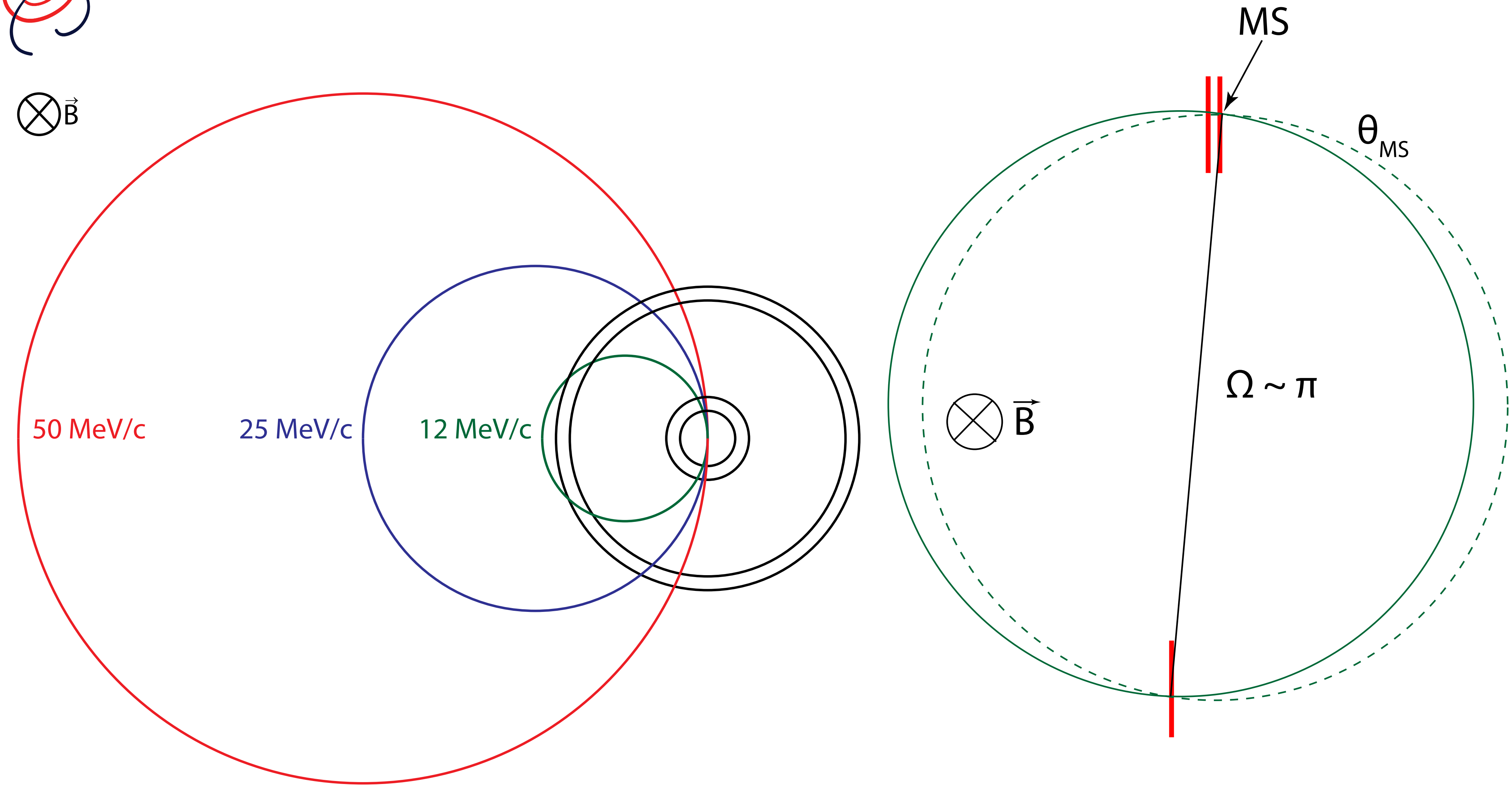
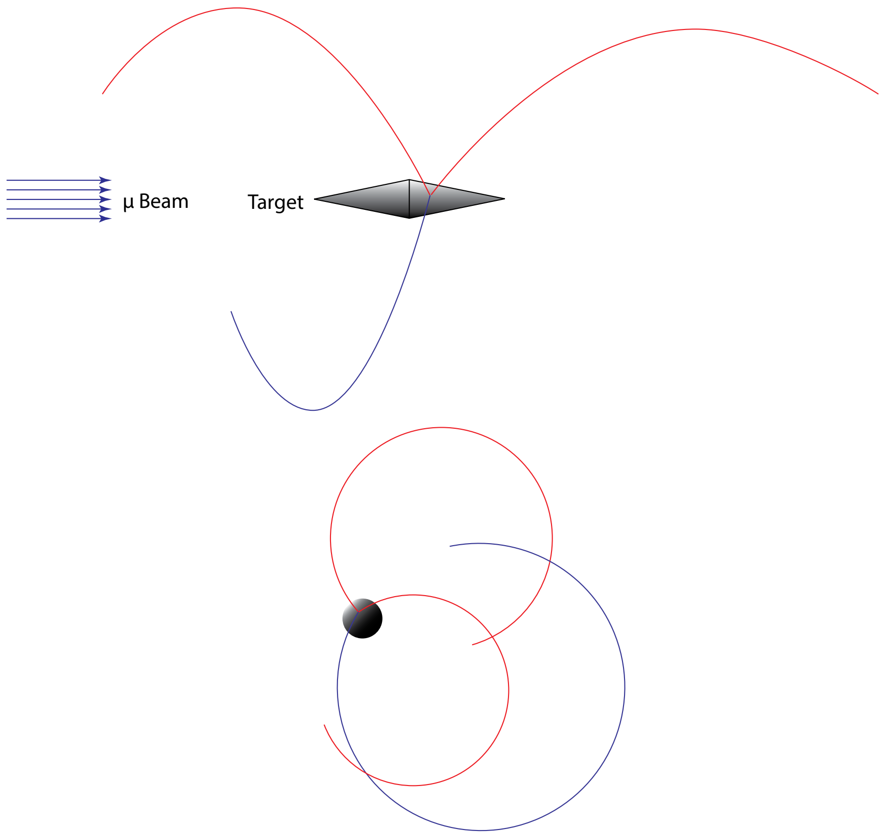


Detector Design



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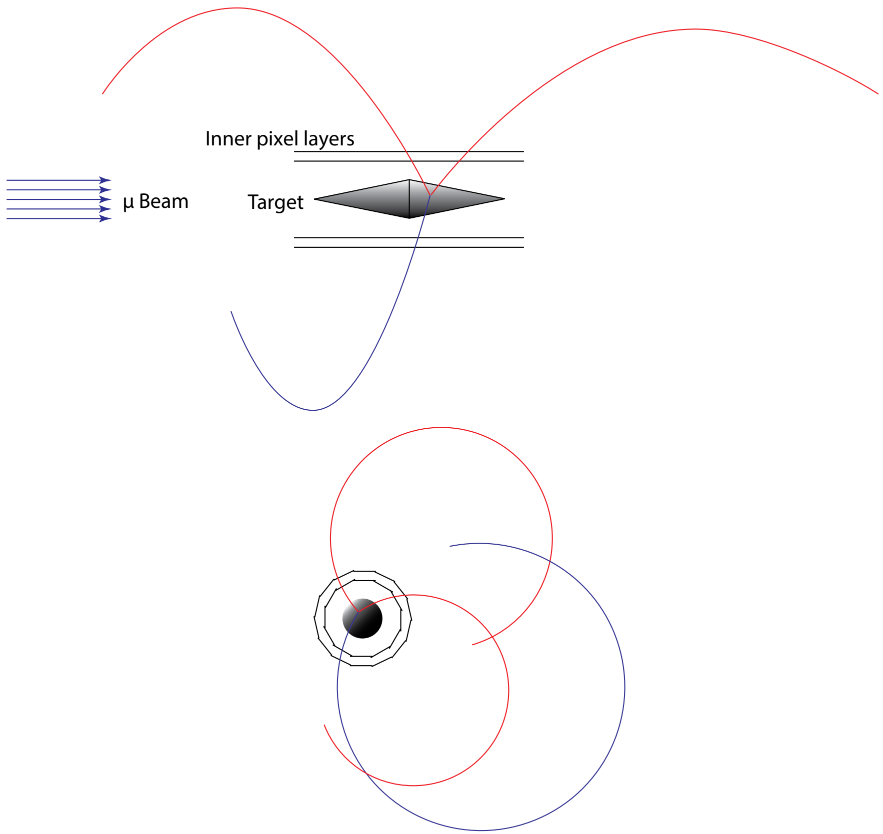

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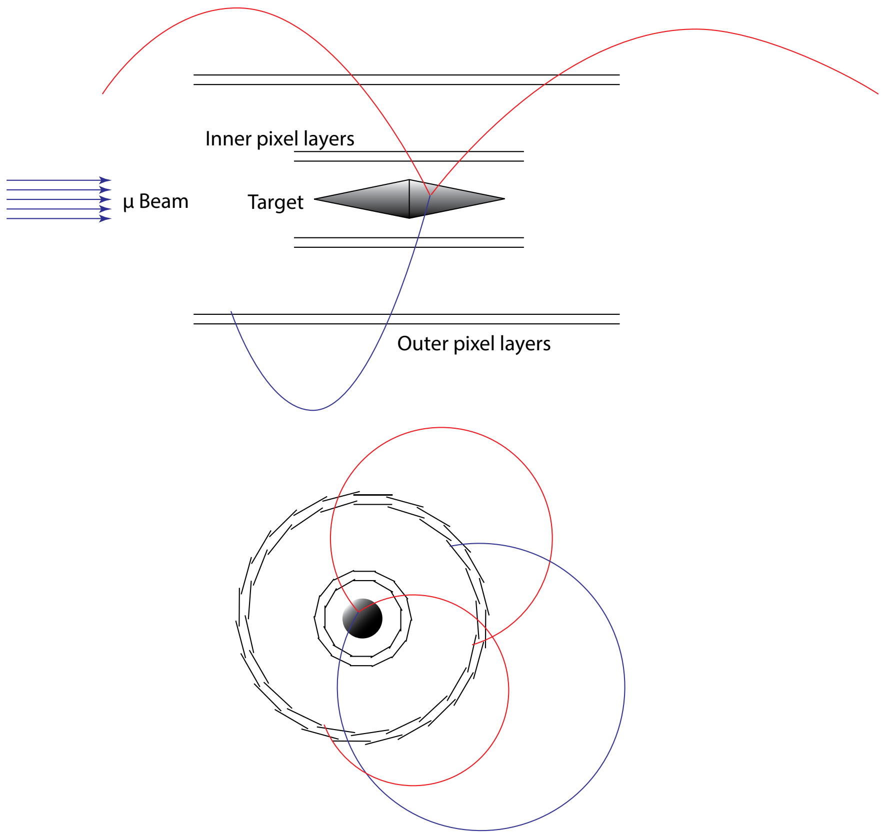

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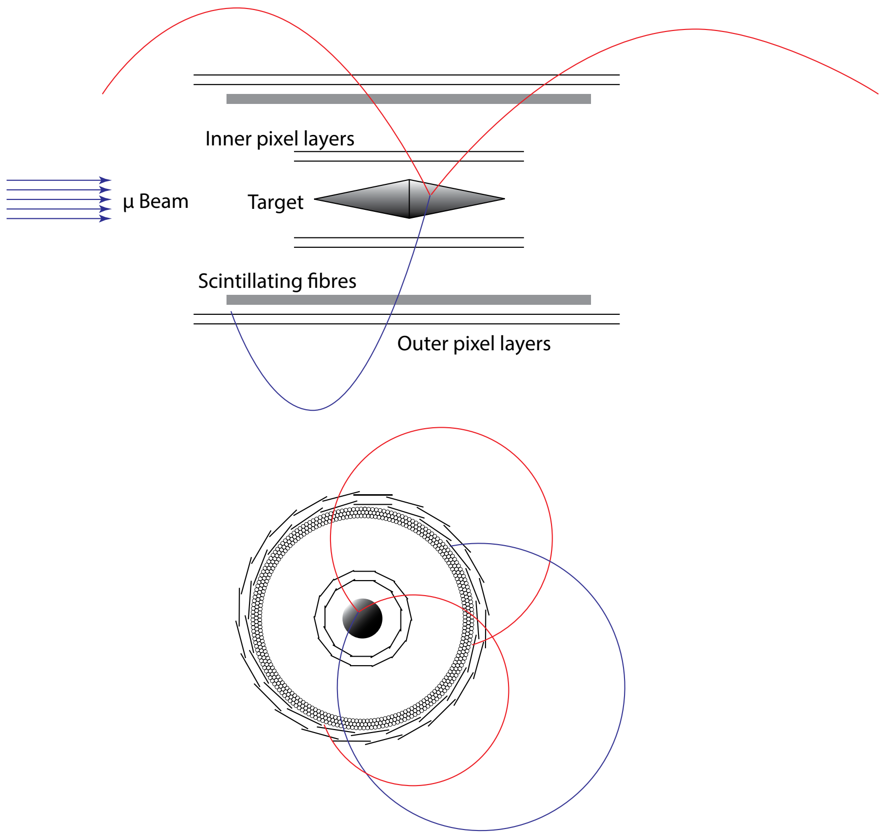

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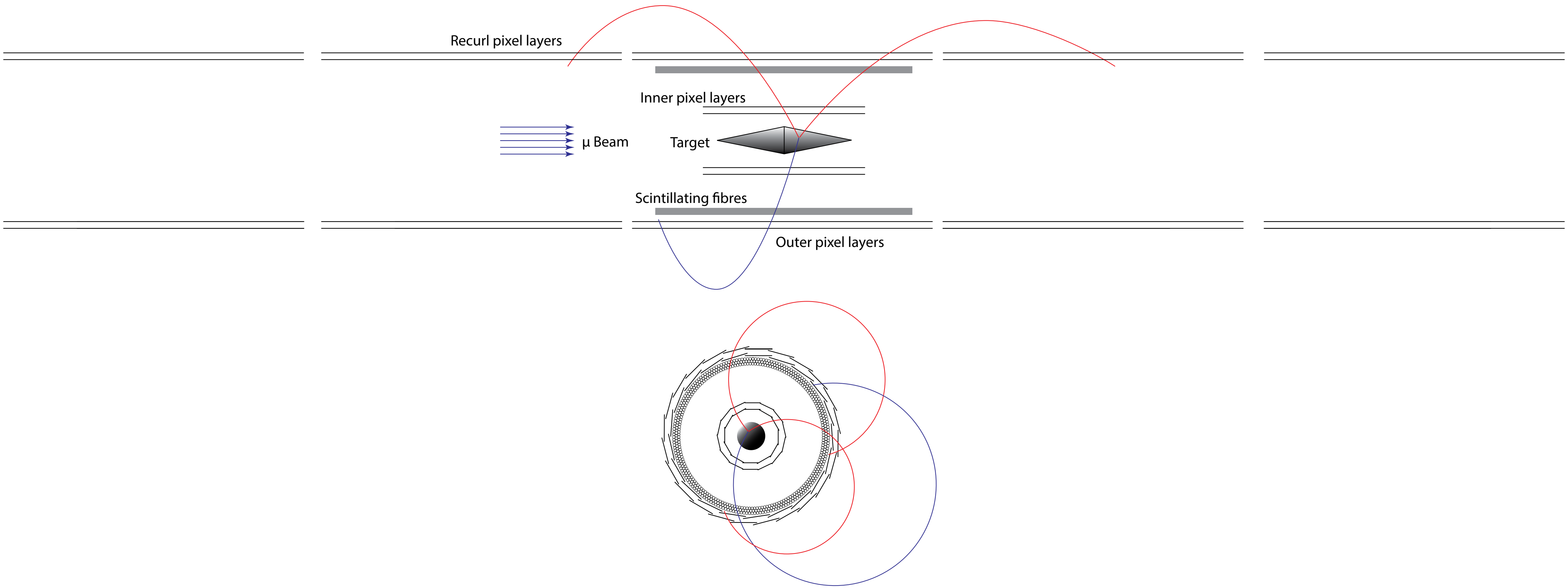

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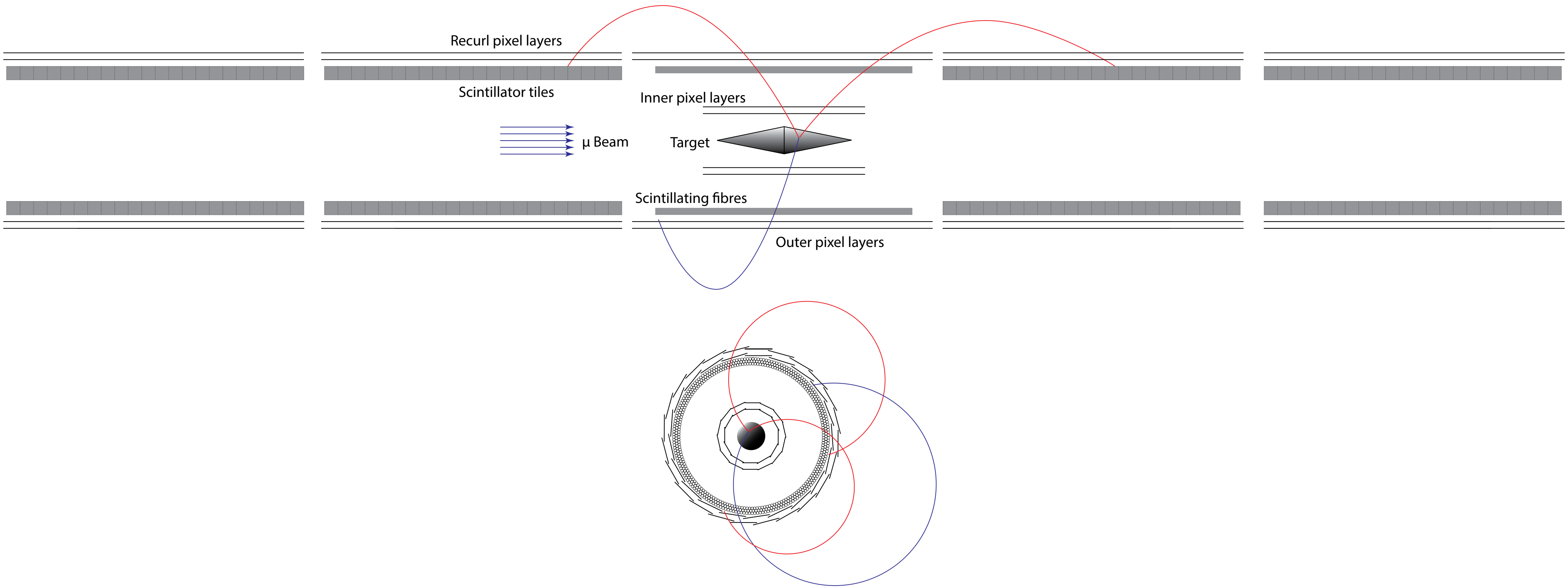
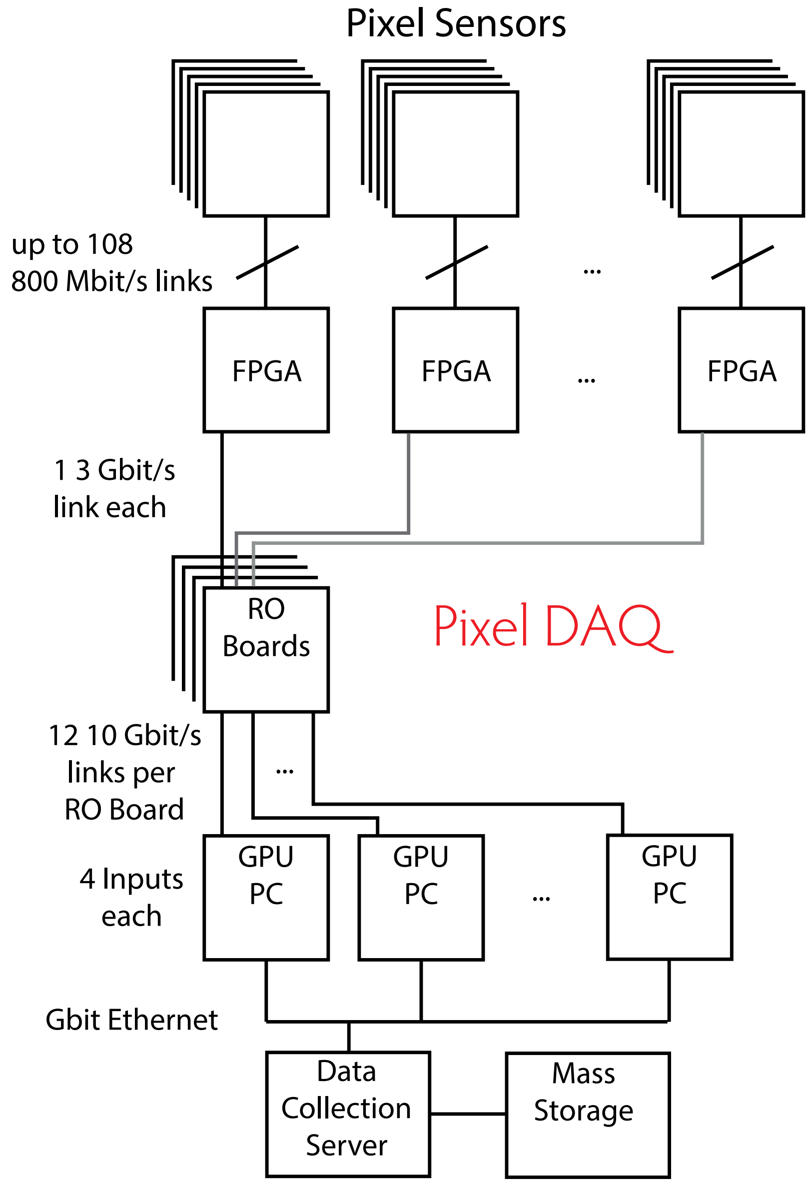


Data Acquisition



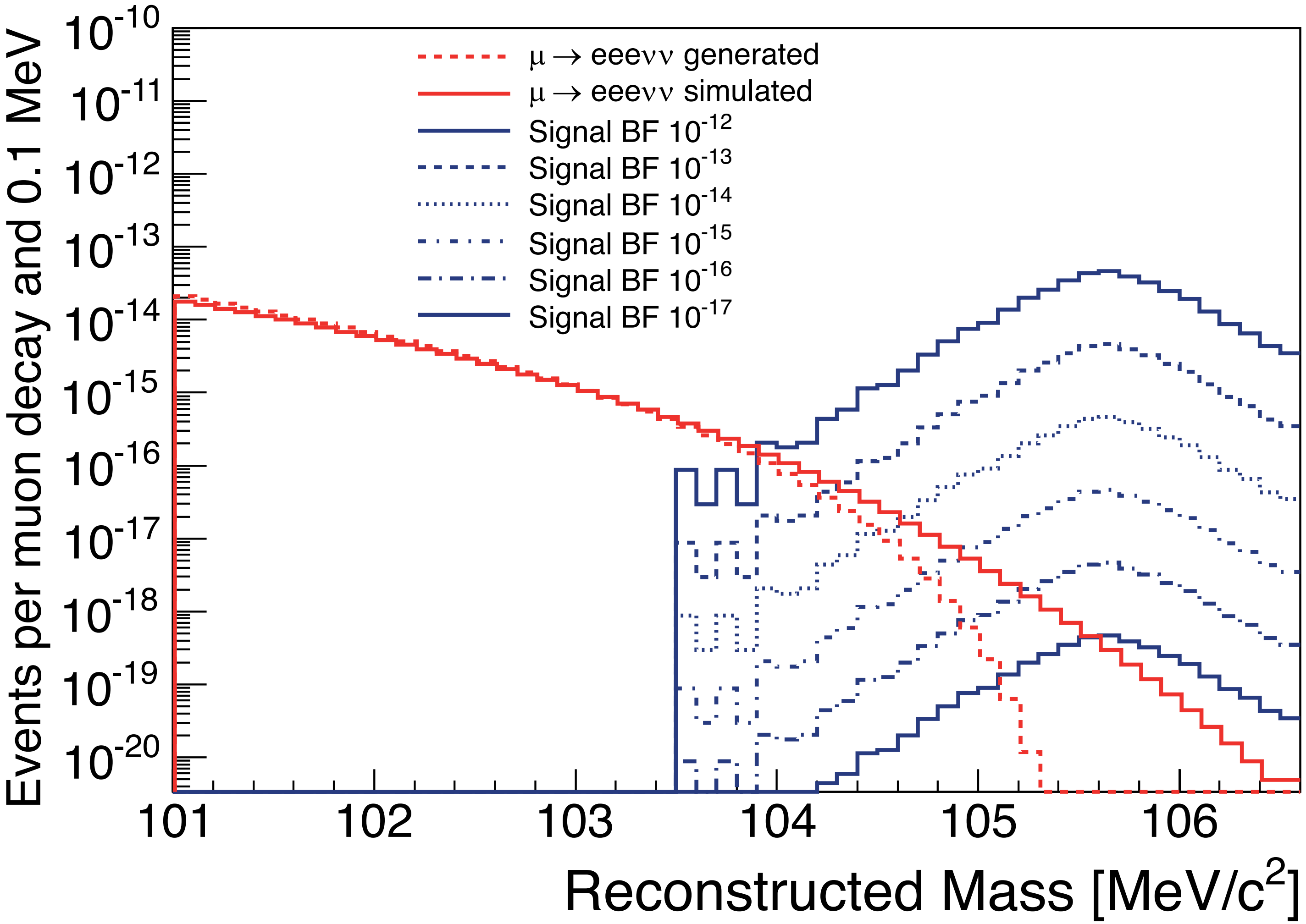
- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(50) PCs with GPUs

Online filter farm

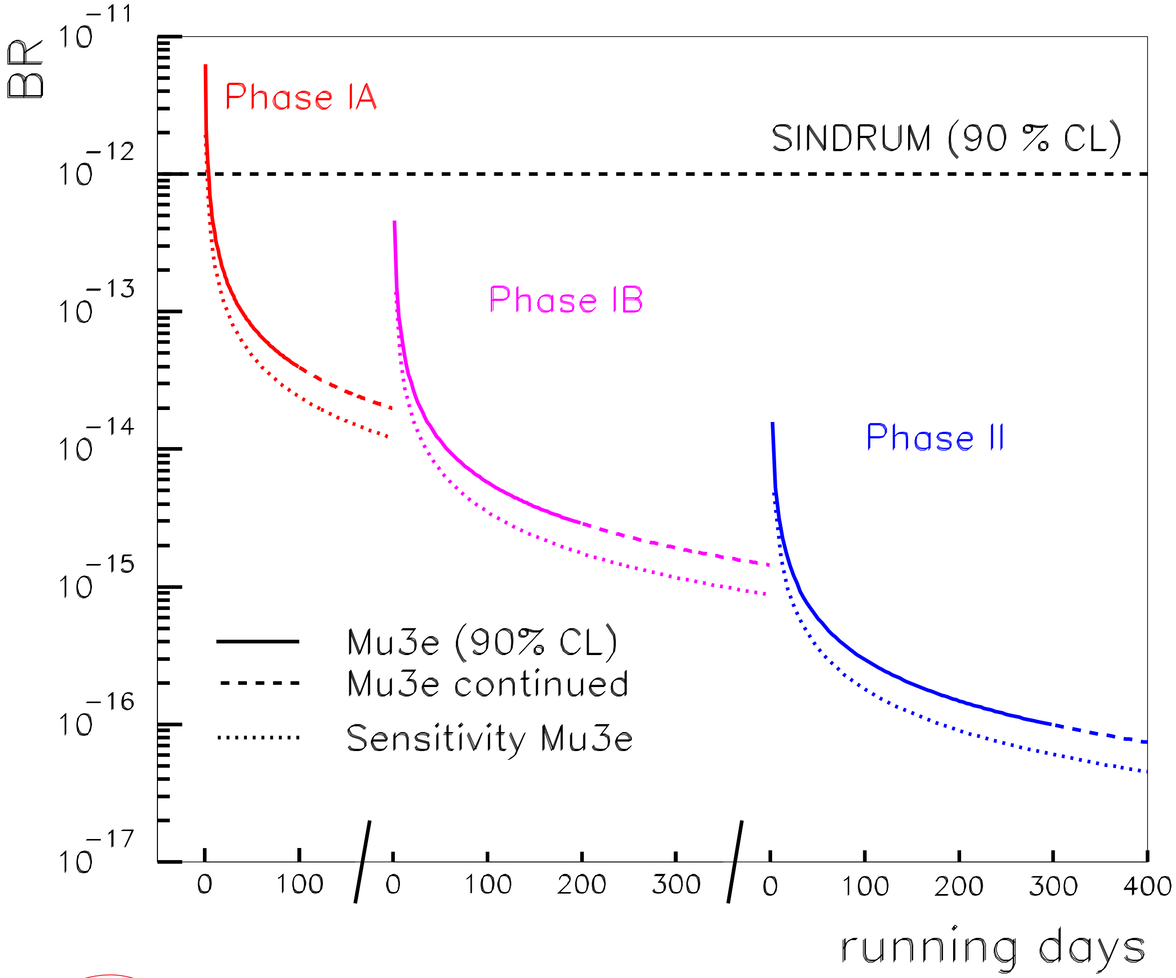
Online software filter farm

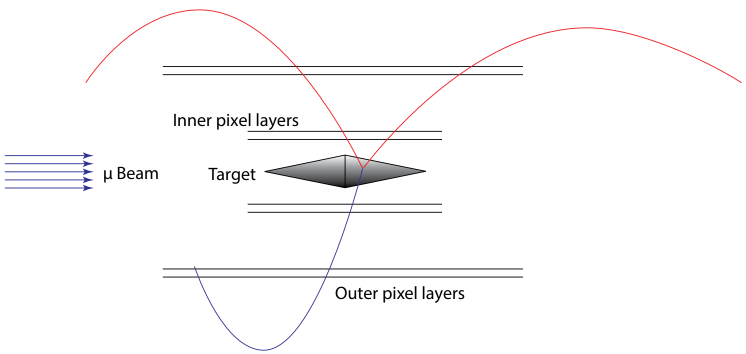
- Continuous front-end readout (no trigger)
- ~ 1 Tbit/s
- PCs with FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

Simulated Performance



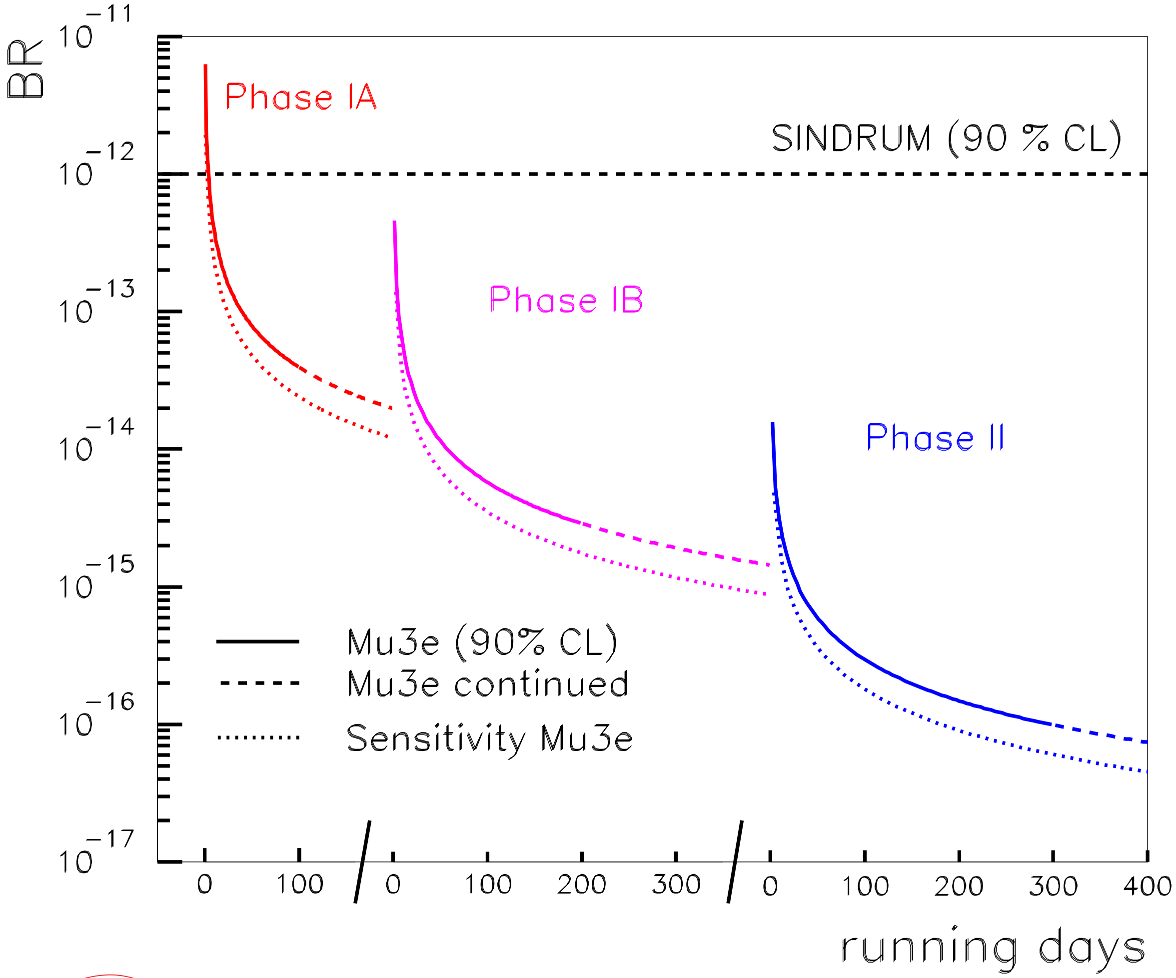
Sensitivity

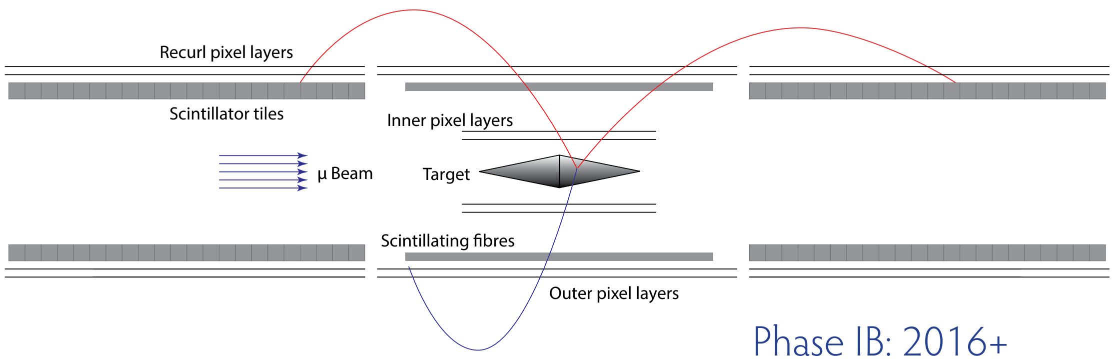




Phase IA: Starting 2015

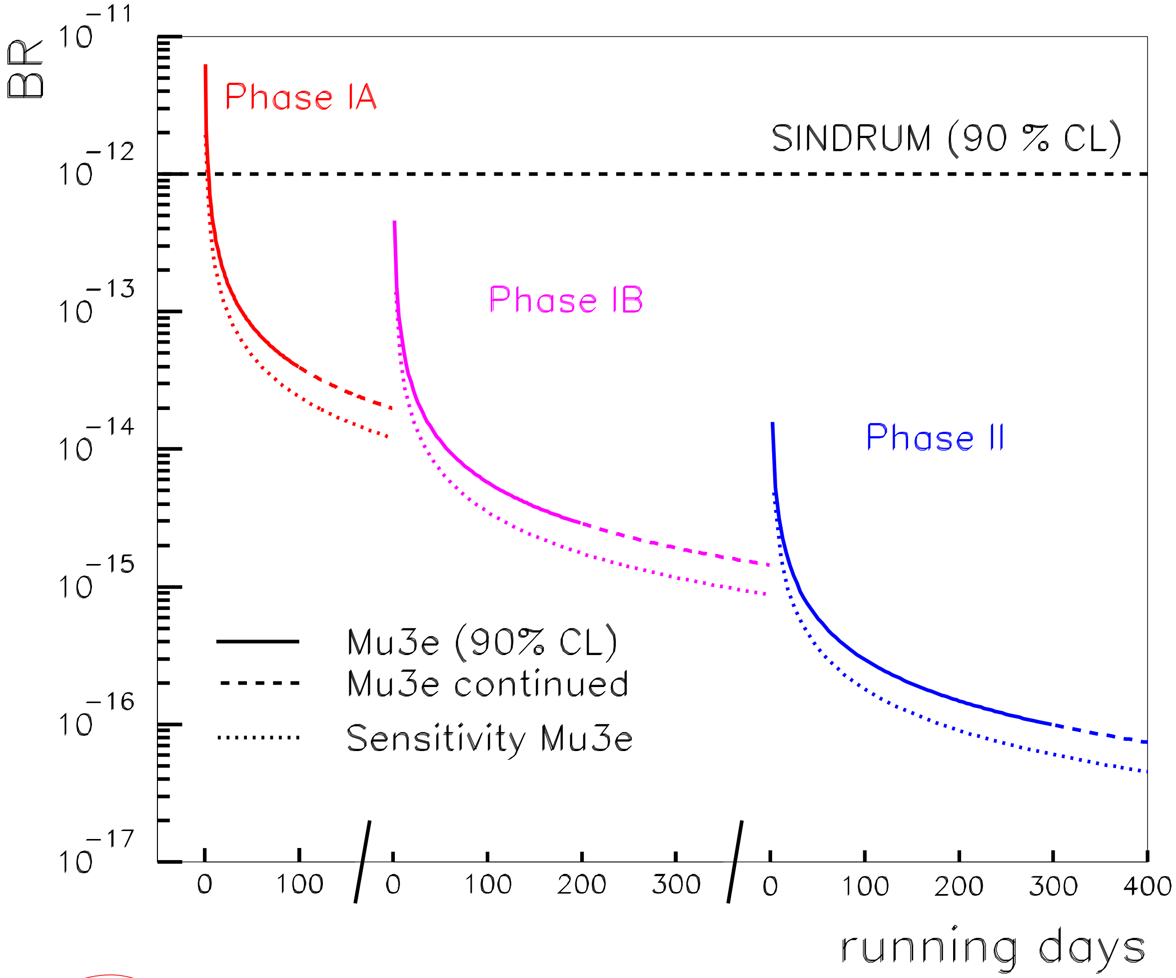
Sensitivity

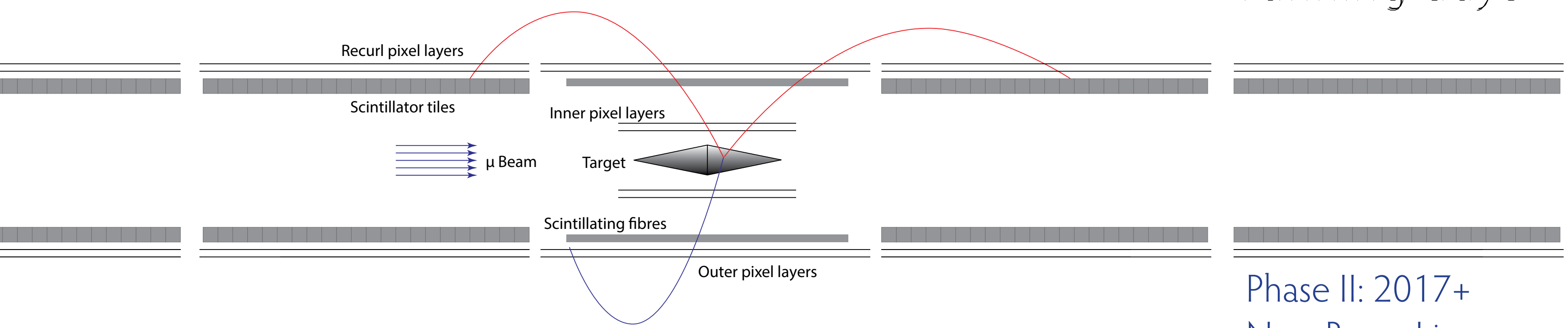




Phase IB: 2016+

Sensitivity





Phase II: 2017+
New Beam Line

Collaboration

UNIVERSITÉ DE GENÈVE

PAUL SCHERRER INSTITUT
PSI

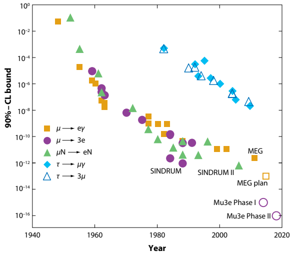
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

A collaboration has formed and submitted a research proposal to PSI

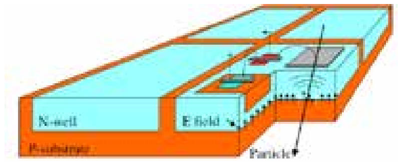
- University of Geneva
- University of Heidelberg: PI and KIP
- Paul Scherrer Institut (PSI)
- University of Zurich
- ETH Zurich

Also in contact with other interested groups

Conclusion



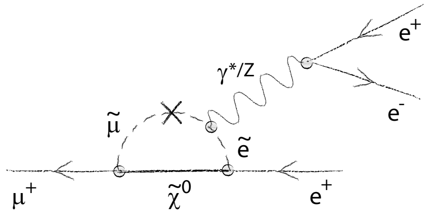
- Mu3e aims for μ → eee at the 10^{-16} level
- First large scale use of HV-MAPS
- Build detector layers thinner than a hair
- Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs
- Start taking first data in 2015

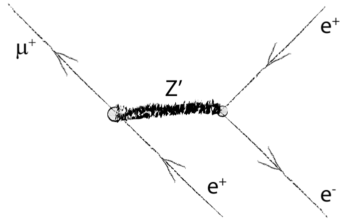


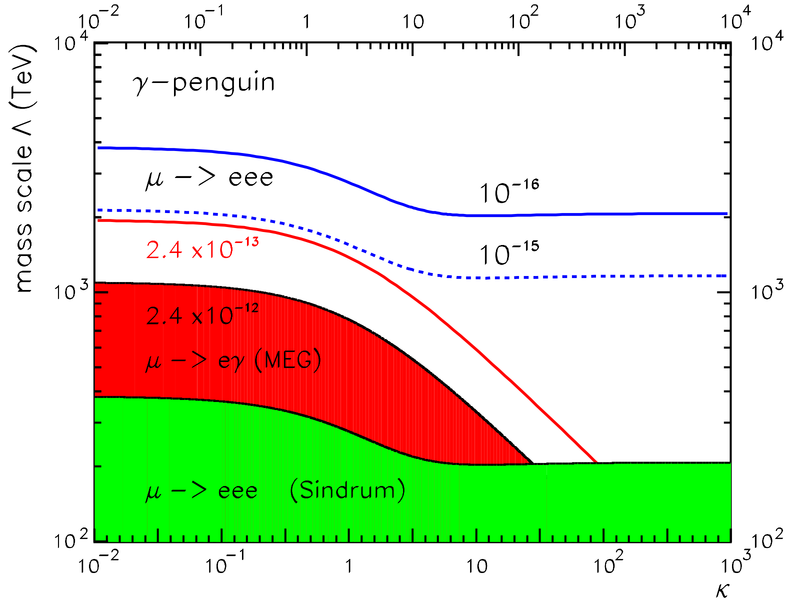
Backup Material

Comparison with $\mu \to e\gamma$

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





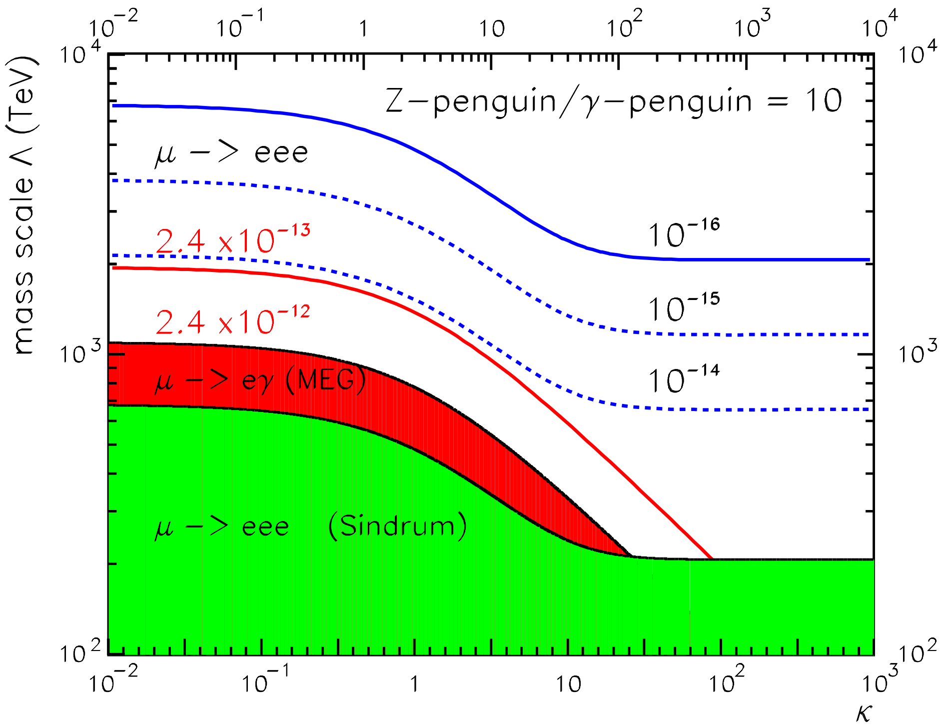


- One loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \to eee$ and $\mu \to e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

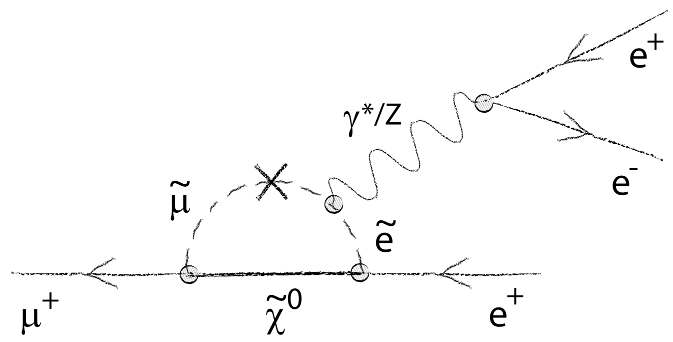
$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

Comparison with $\mu \to e\gamma$

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

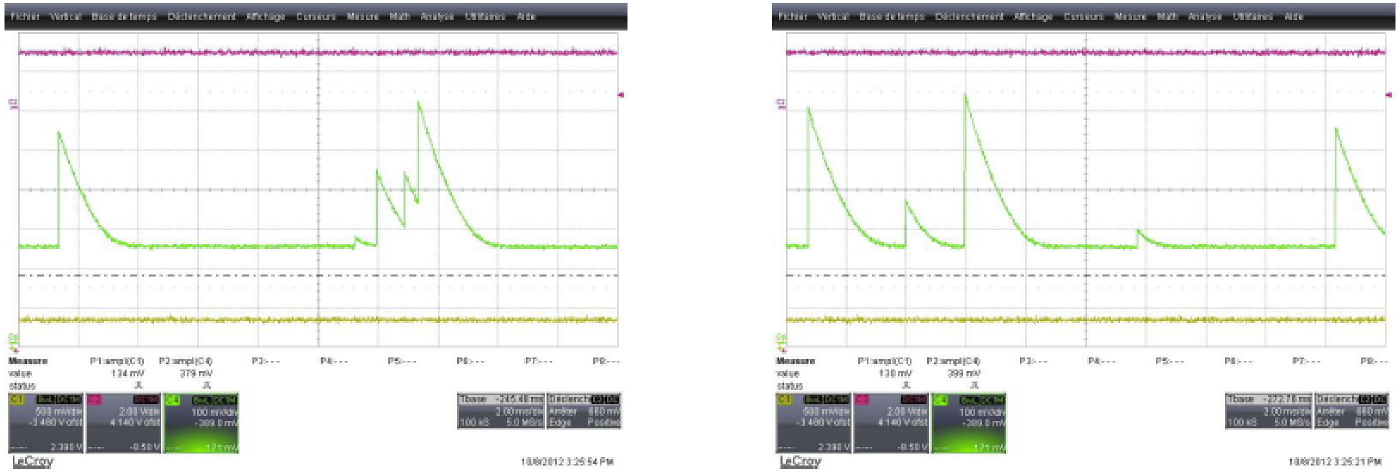


- Z-Penguins can be important
- Lots of ongoing theory activity

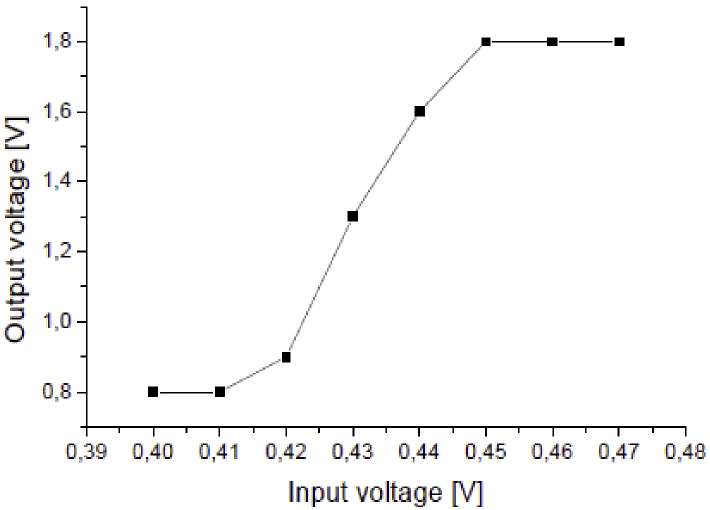


Radiation Hardness

- Requirements not as strict as at LHC



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

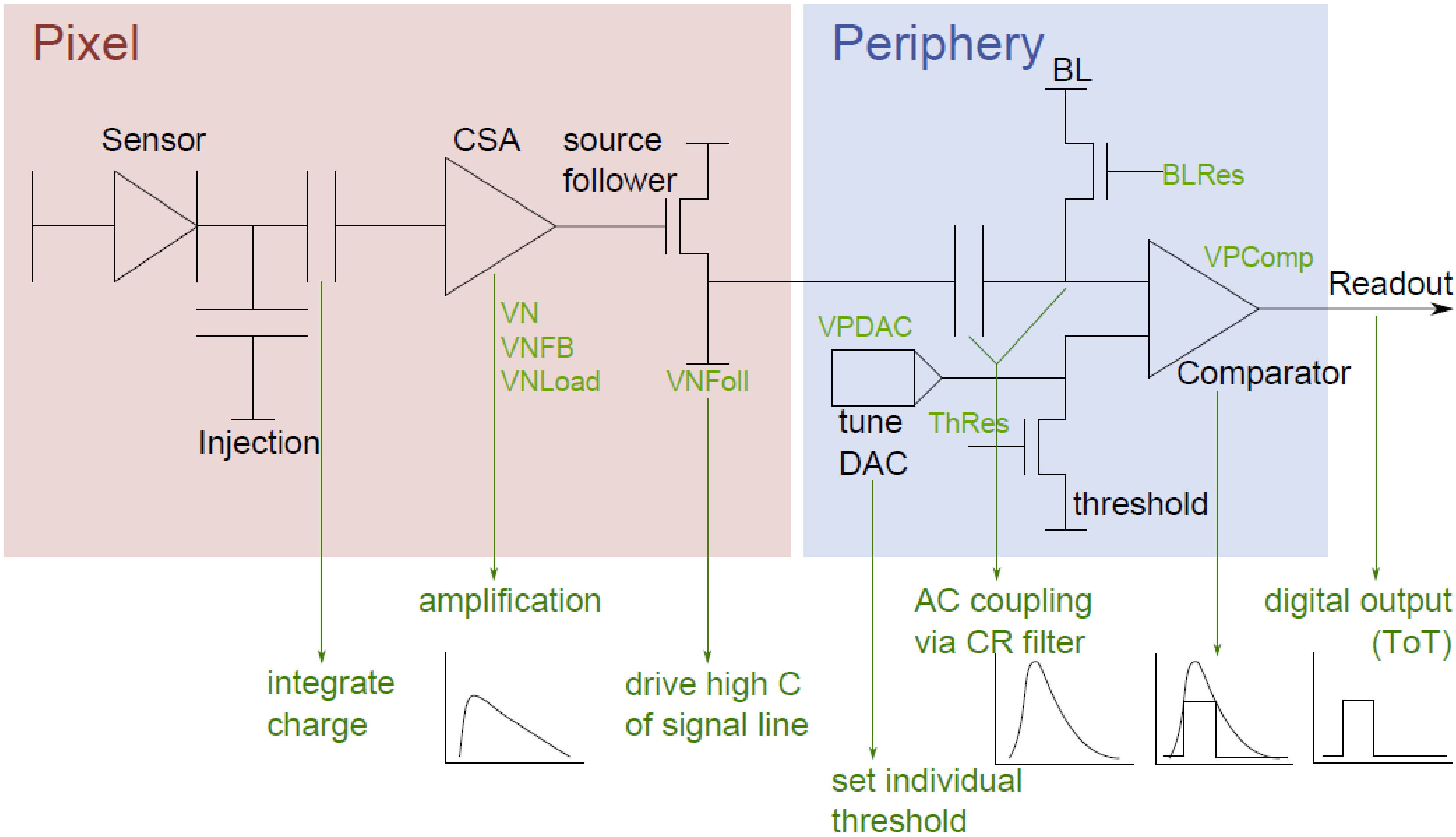


Comparator characteristics.

- Irradiation at PS
- After 380 MRad ($8\times10^{15}\ n_{eq}/cm^2$)
- Chip still working

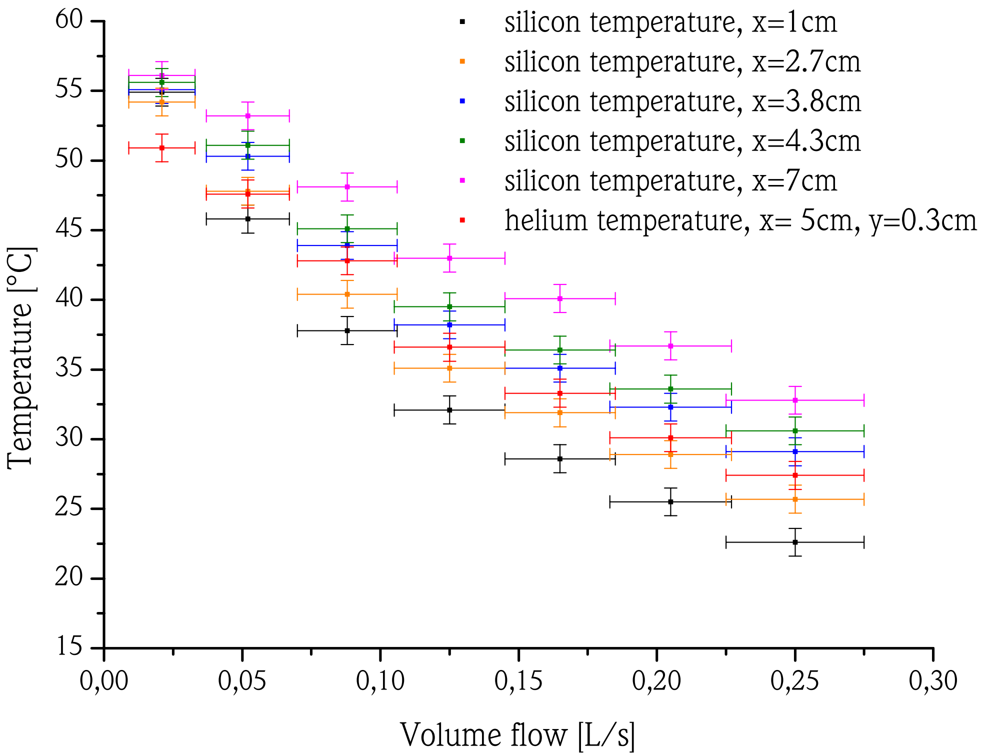
(Courtesy Ivan Perić, RESMDD 2012)

MUPIX electronics

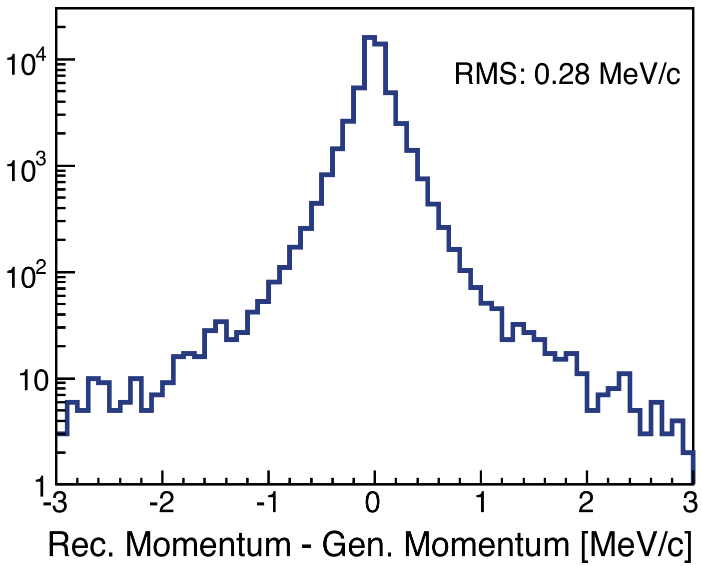


More on Cooling

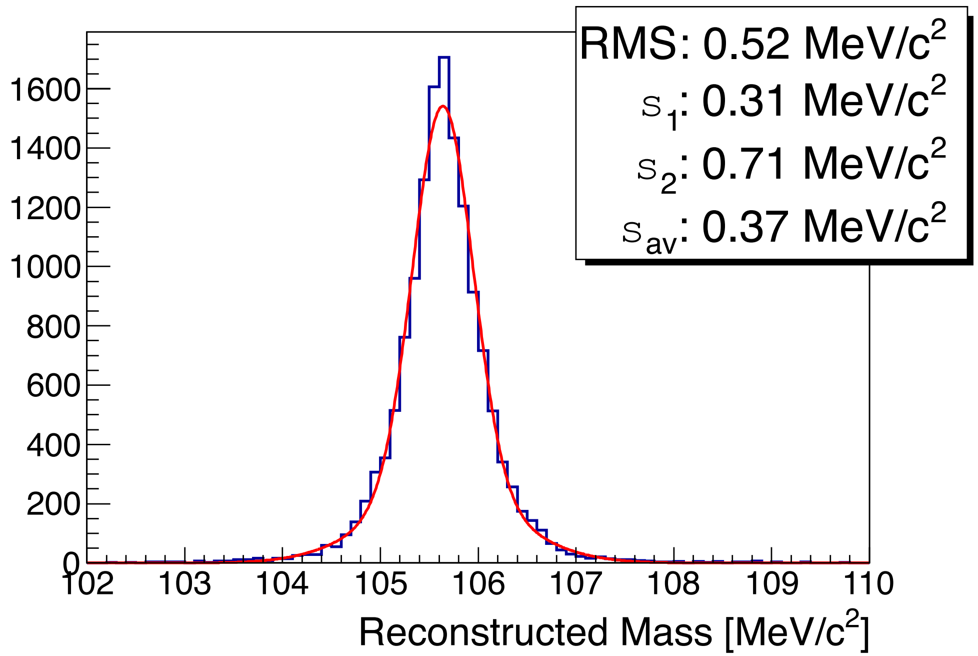
- Inductively heated sample
- Helium flow cooling



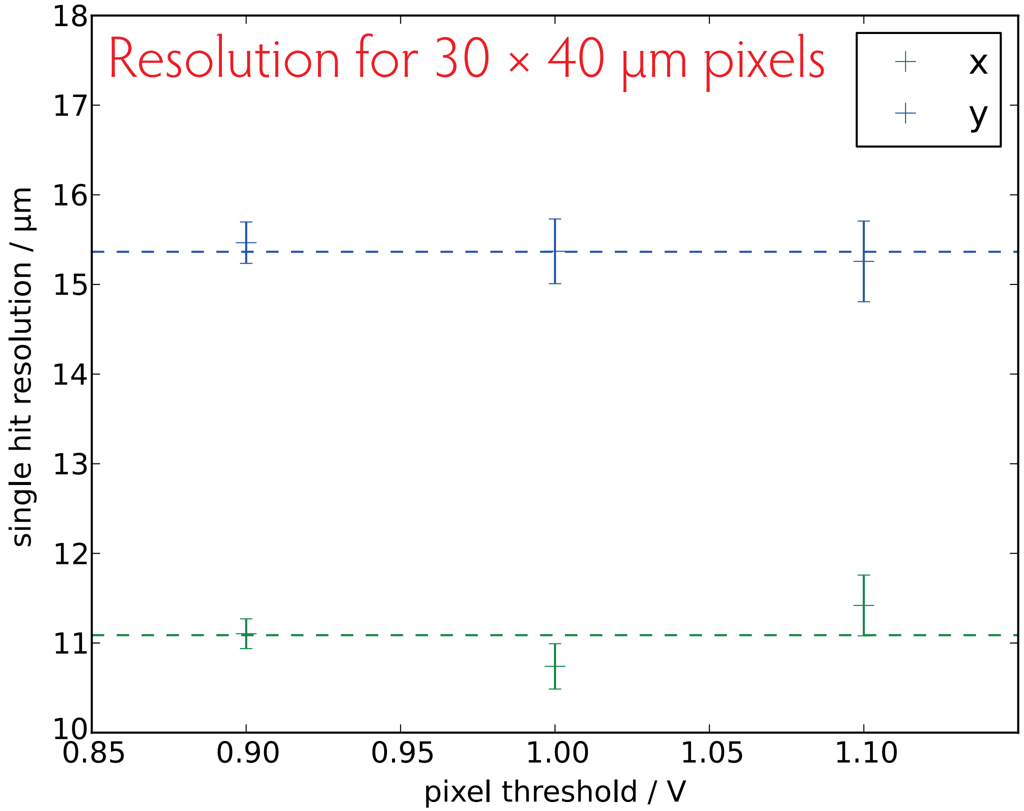
Simulated Performance



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

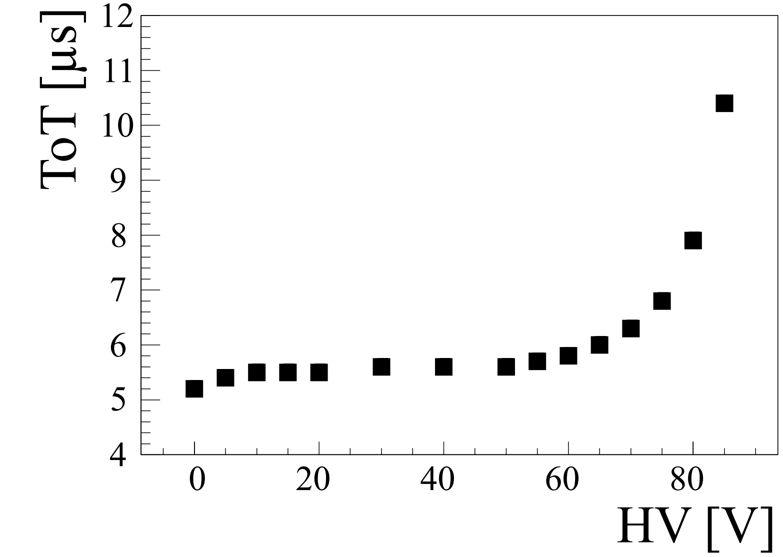


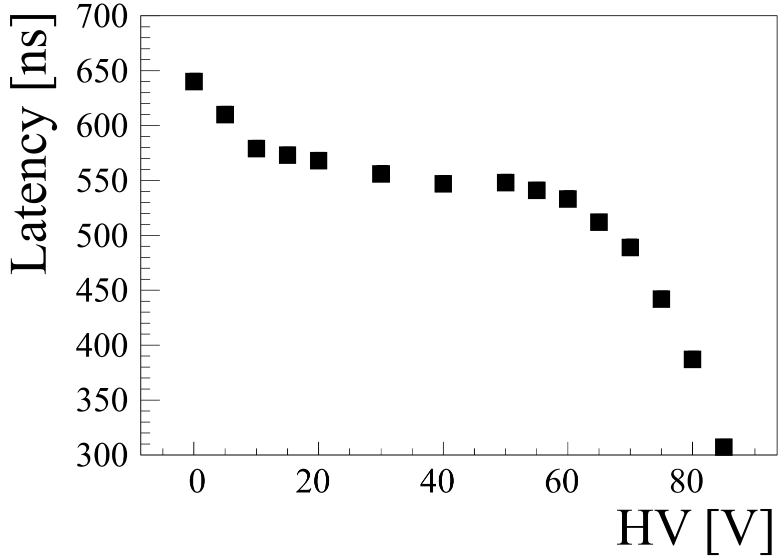
MUPIX 2 results



- Test beam at CERN SPS (170 GeV/c pions)
- Timepix telescope
- 2 hours data taking
- Mostly single pixel clusters
- Resolution as expected (pixel size/√12)
- March test beam data (DESY, electrons) currently being analysed
- Next beam week in June

MUPIX 2 Results





- Measurements with LED pulses
- High-Voltage important for fast signal
- Amplification above ~70 V

Details in theses:
A.K. Perrevoort: *Characterization of HV-MAPS for Mu3e* (Master thesis, 2012)
H. Augustin: *Charakterisierung von HV-MAPS* (Bachelor thesis, 2012)
available from **www.psi.ch/mu3e**