Update from the Mu3e Experiment

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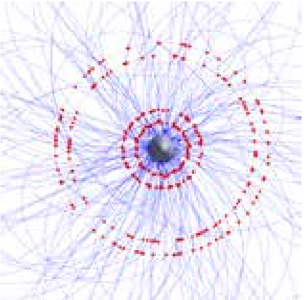
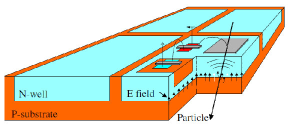
Charged Lepton Working Group,
February 2013

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Overview



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

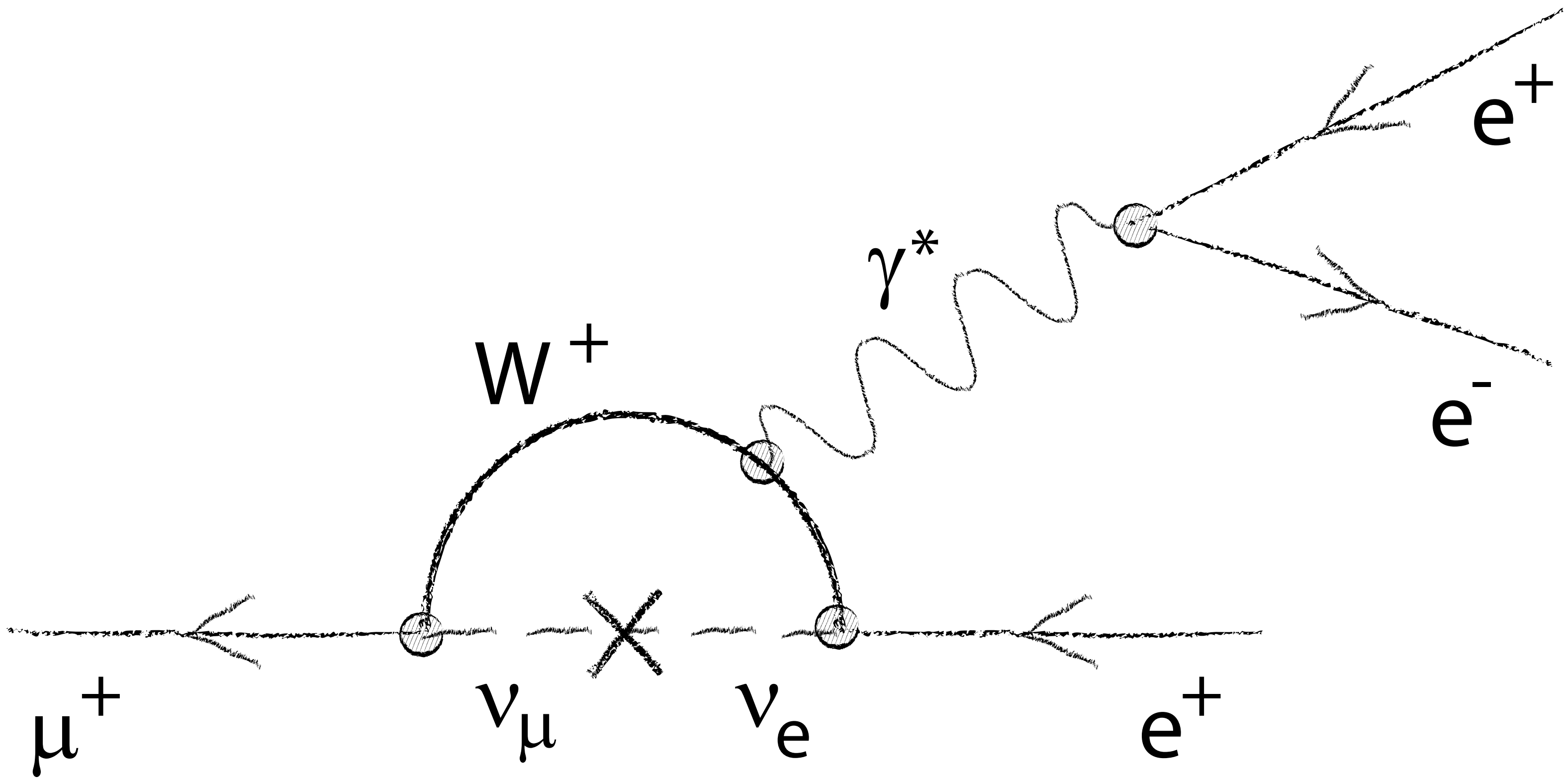


- The Technology:
  High Voltage Monolithic Active Pixel Sensors

- The Mu3e Detector:
  Minimum Material, Maximum Precision

The Physics: Charged Lepton Flavour Violation

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



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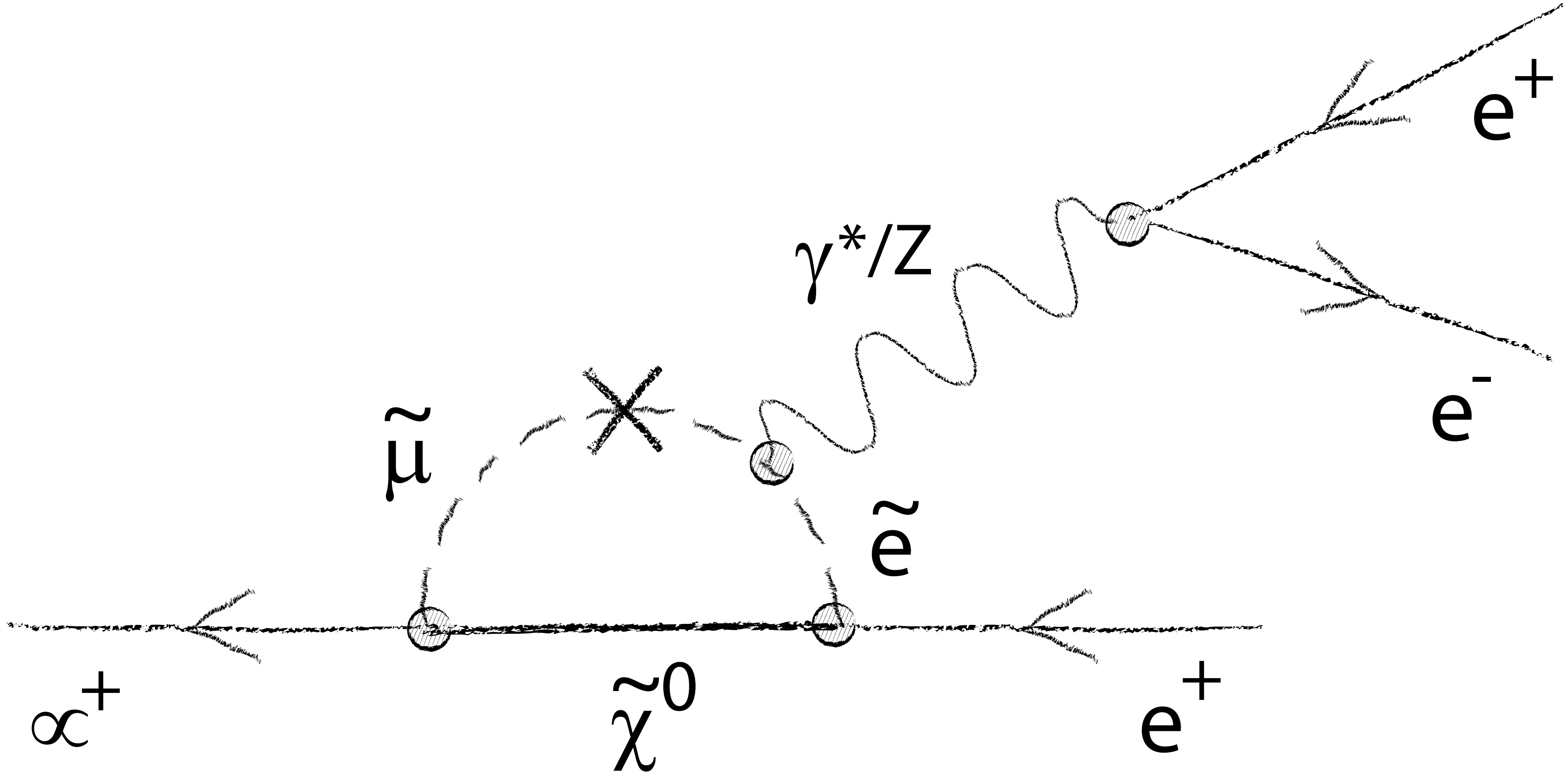
- Can be much bigger with new physics



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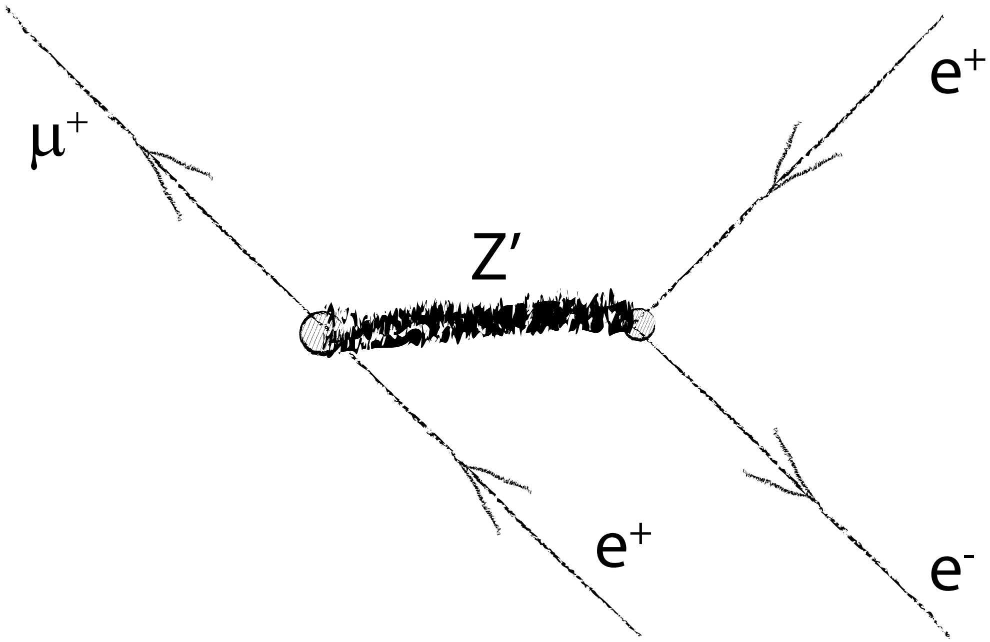

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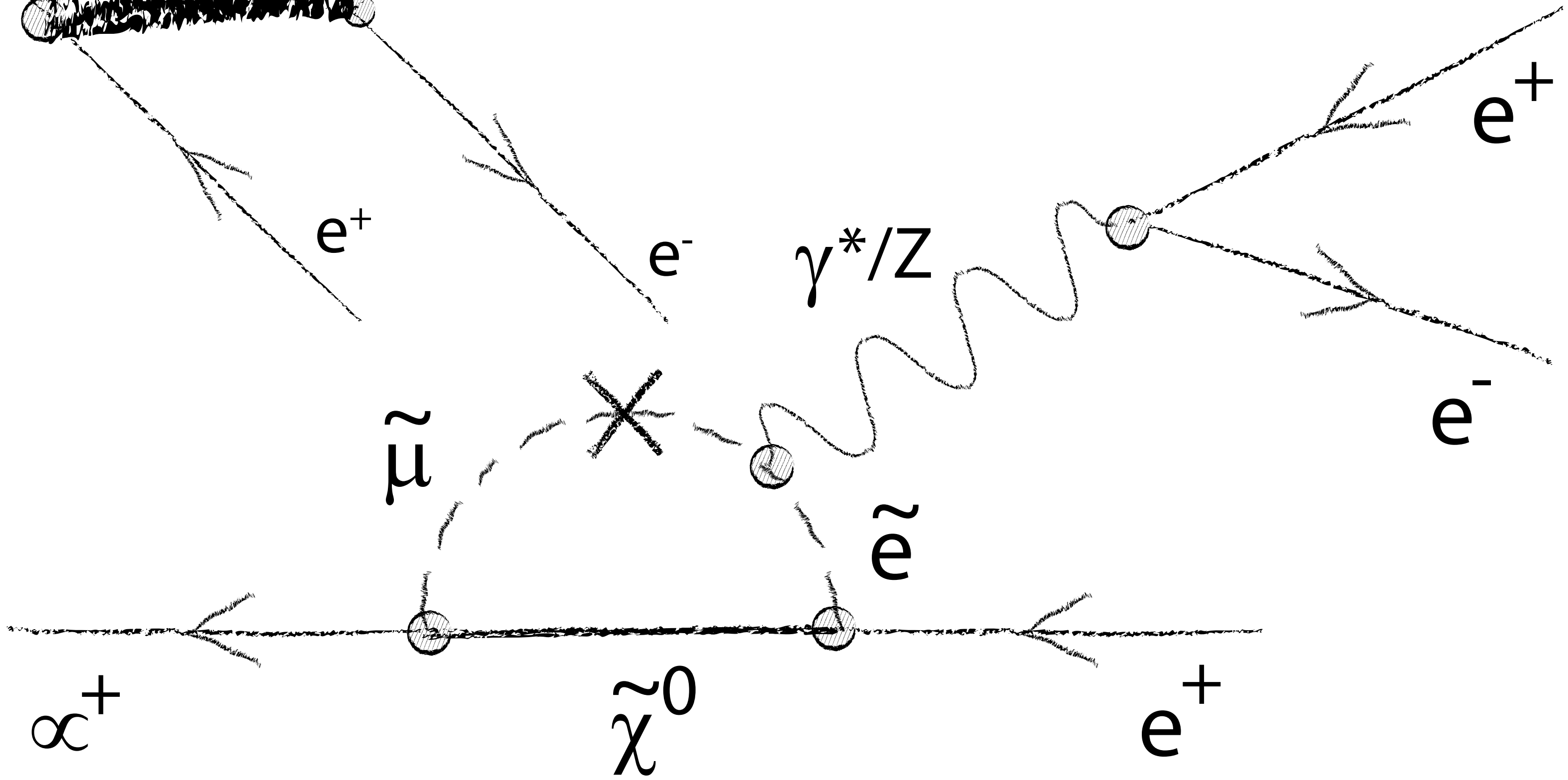
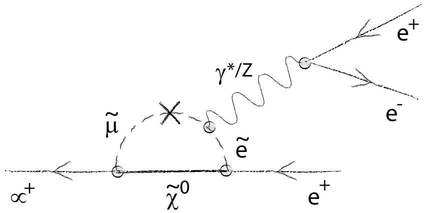
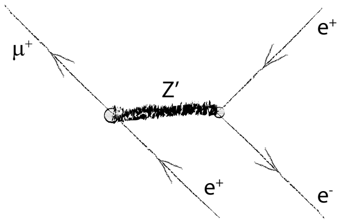
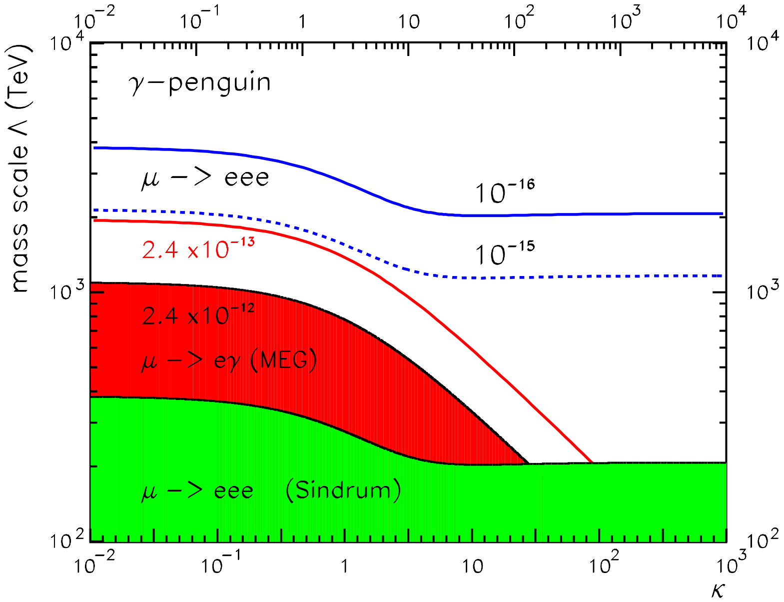


Comparison with μ → eγ

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



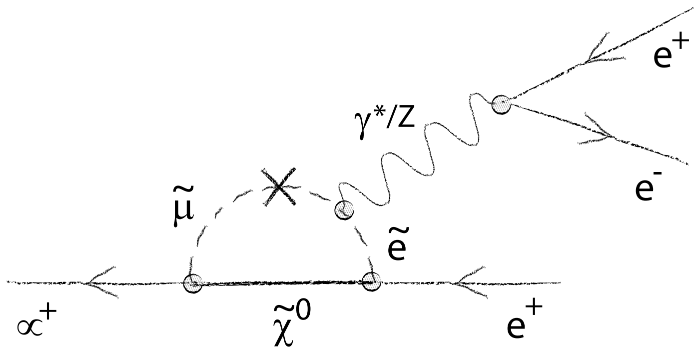


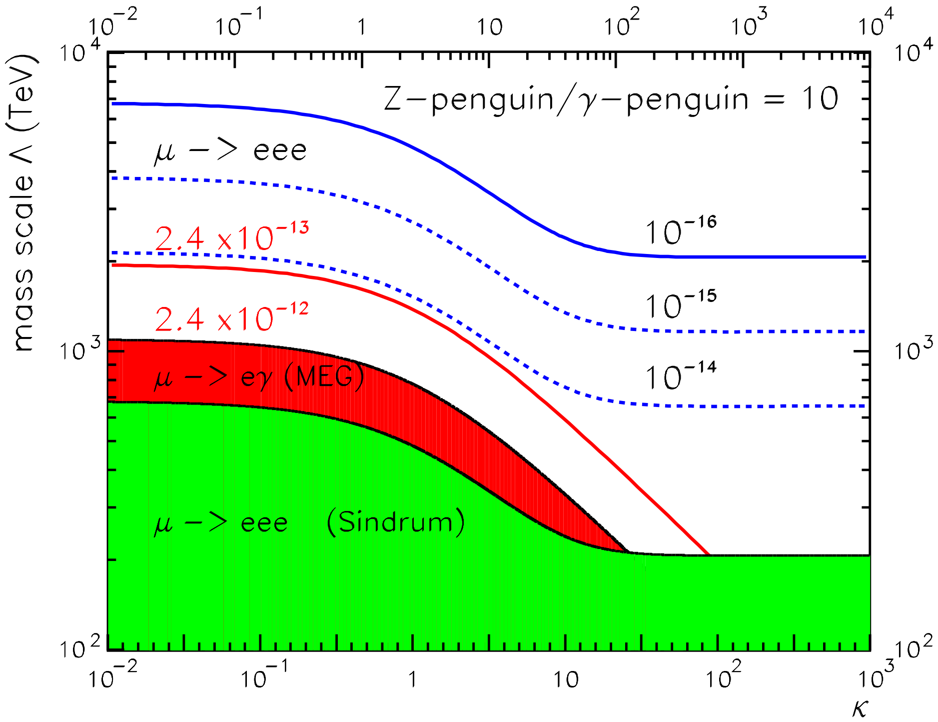


- Ratio κ between dipole and contact
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \to eee$ and $\mu \to e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

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

Comparison with μ → eγ

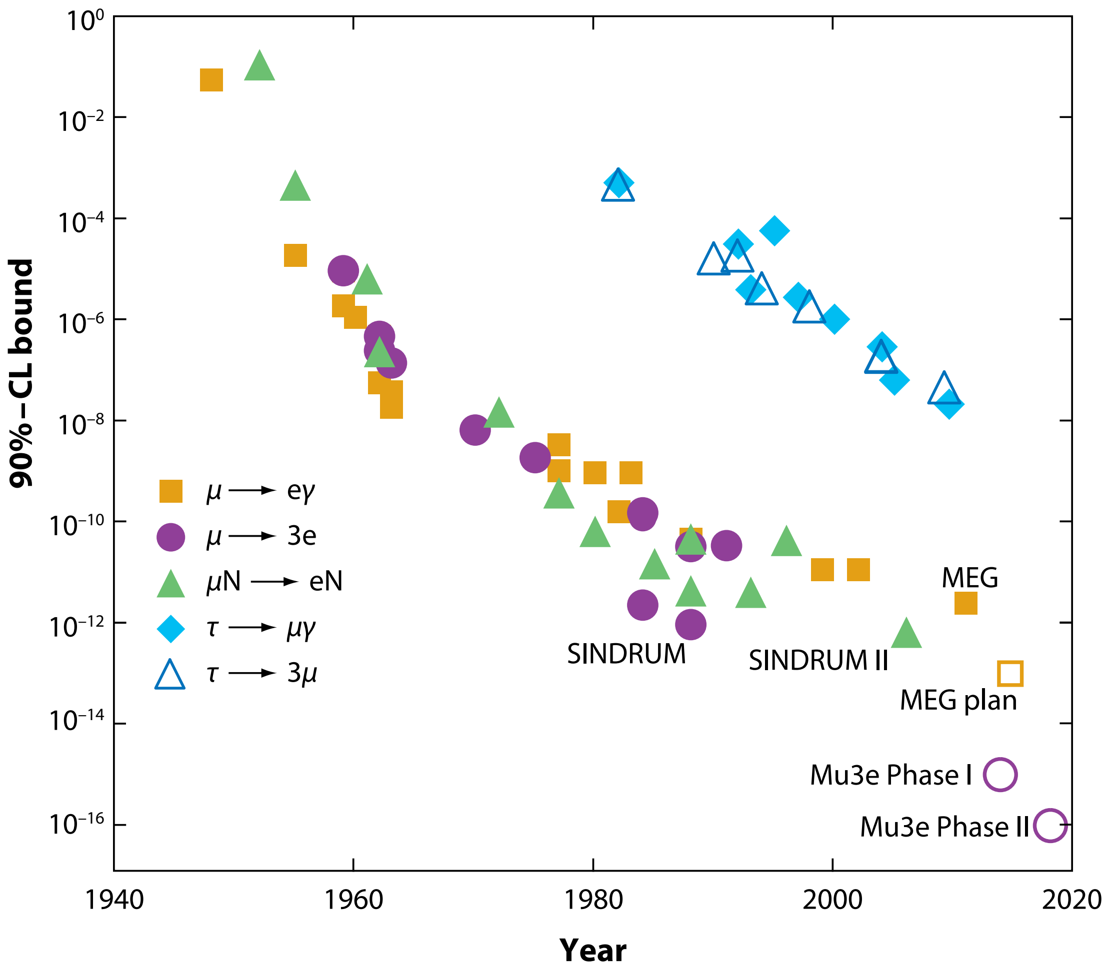




- Z-penguins could be important
- Lots of theory activity

The Goal: 10^{-16}

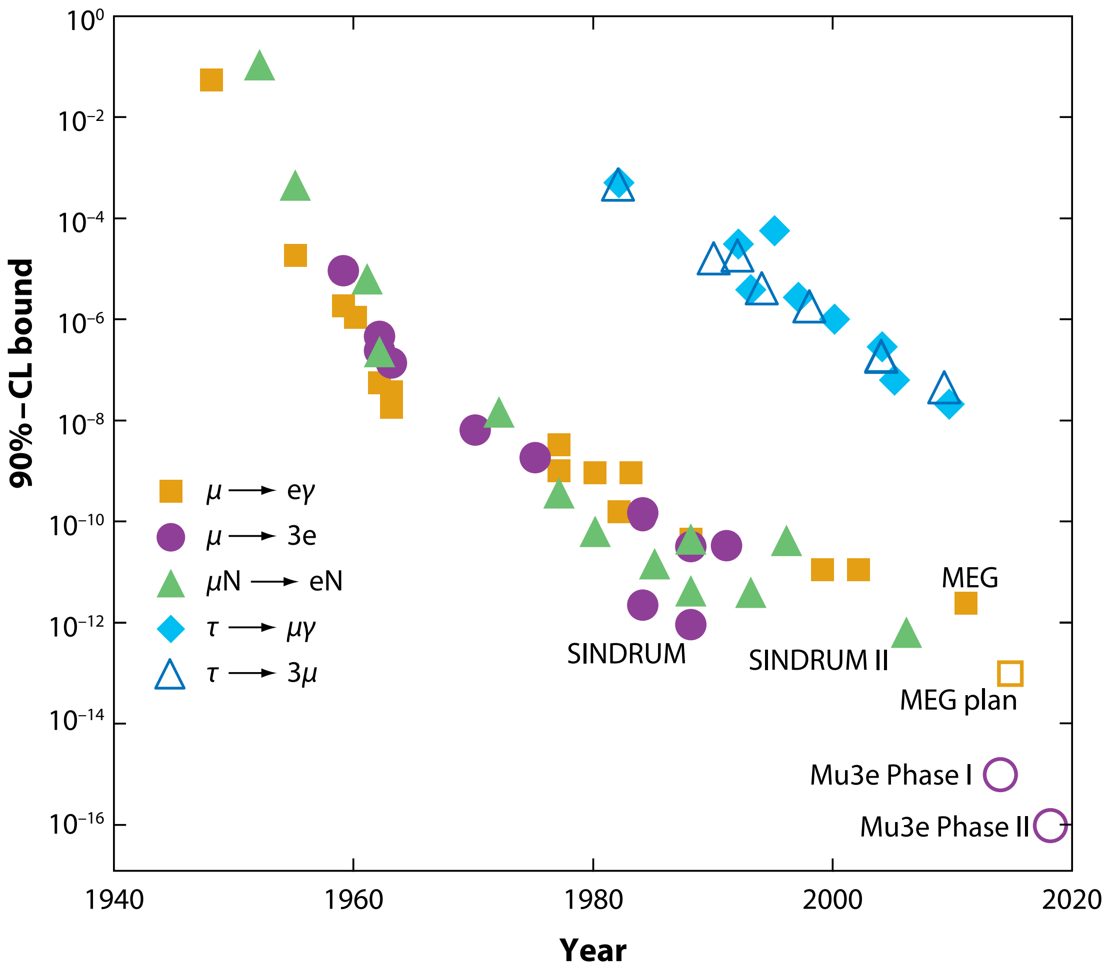
- We want to find or exclude $\mu \rightarrow eee$ at the 10^{-16} level
- 4 orders of magnitude over previous experiment (SINDRUM 1988)



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

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



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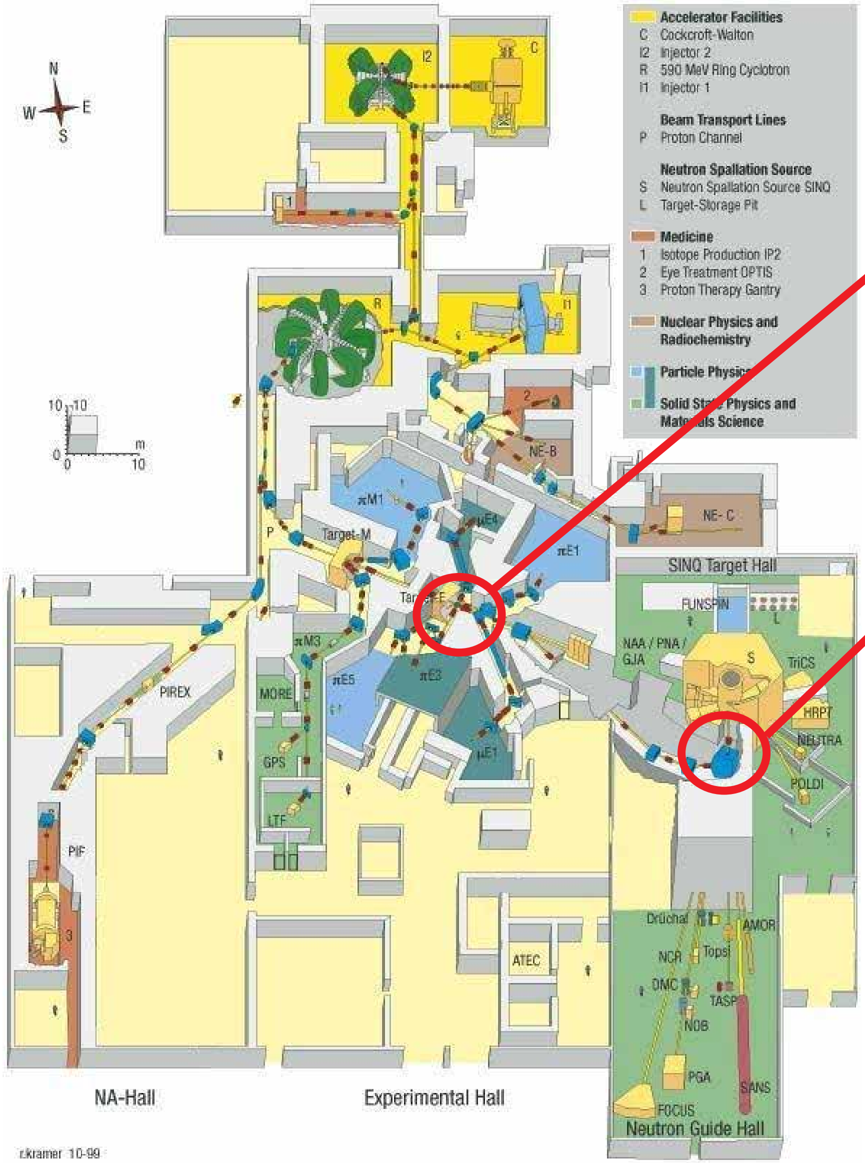
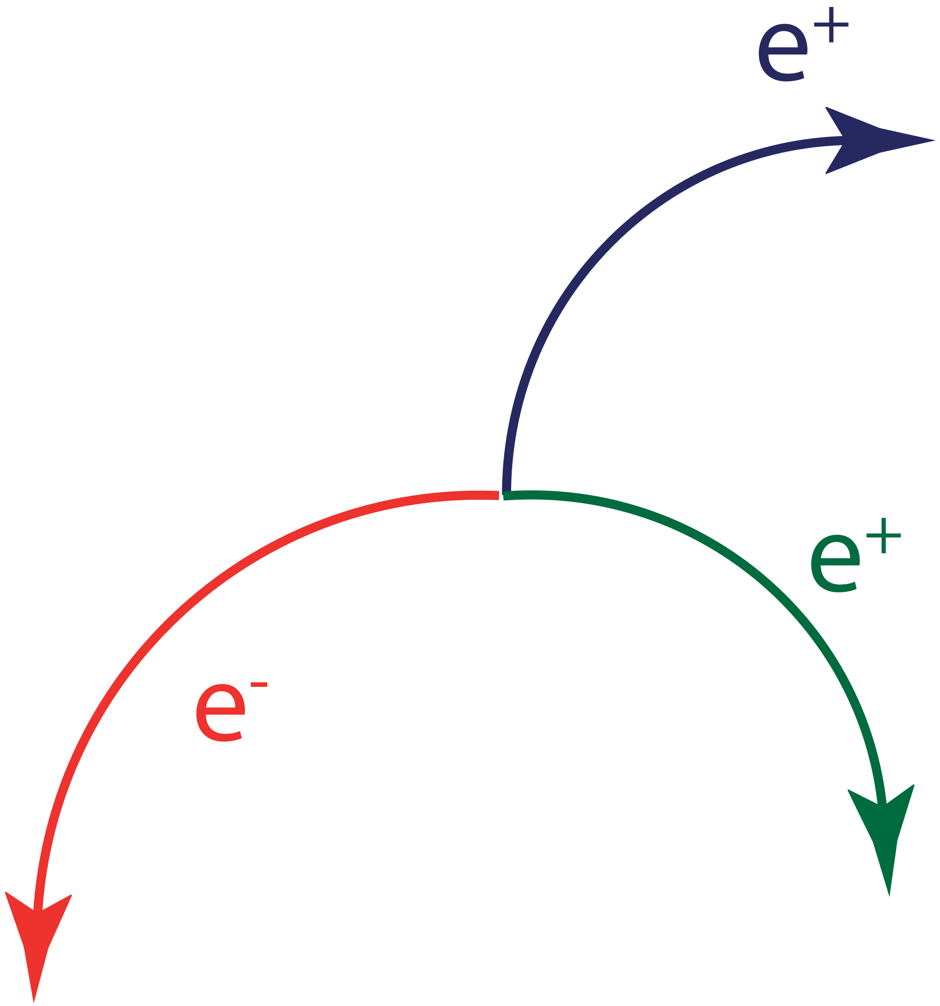
Muons from PSI



DC muon beams for particle physics at PSI:

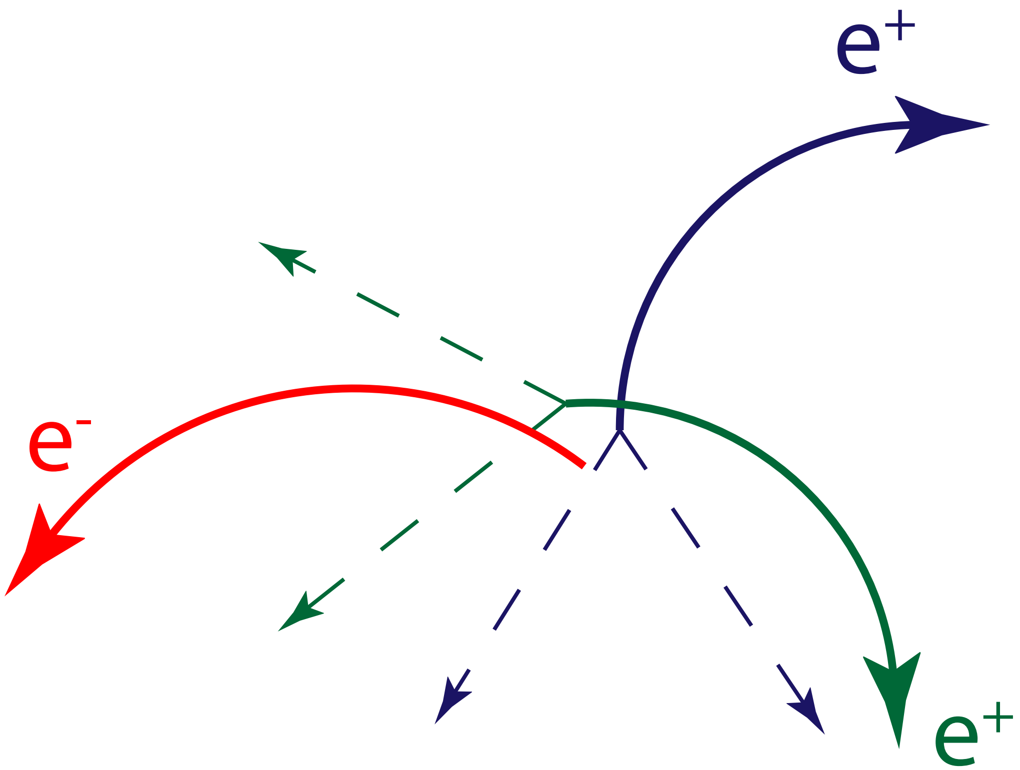
- πE5 beamline: ~ 10^8 muons/s (MEG experiment)
- SINQ (spallation neutron source) target could even provide ~ 5×10^{10} muons/s
- The $\mu \rightarrow eee$ experiment (final stage) requires 2×10^9 muons/s focused and collimated on a ~2 cm spot

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

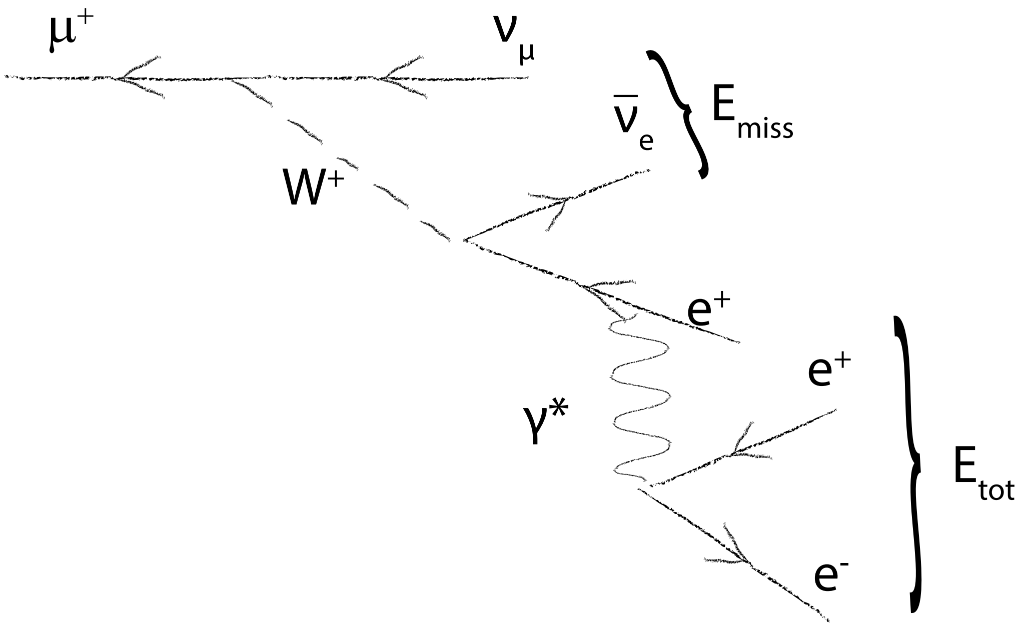
Accidental Background



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

- Need very good timing, vertex and momentum resolution

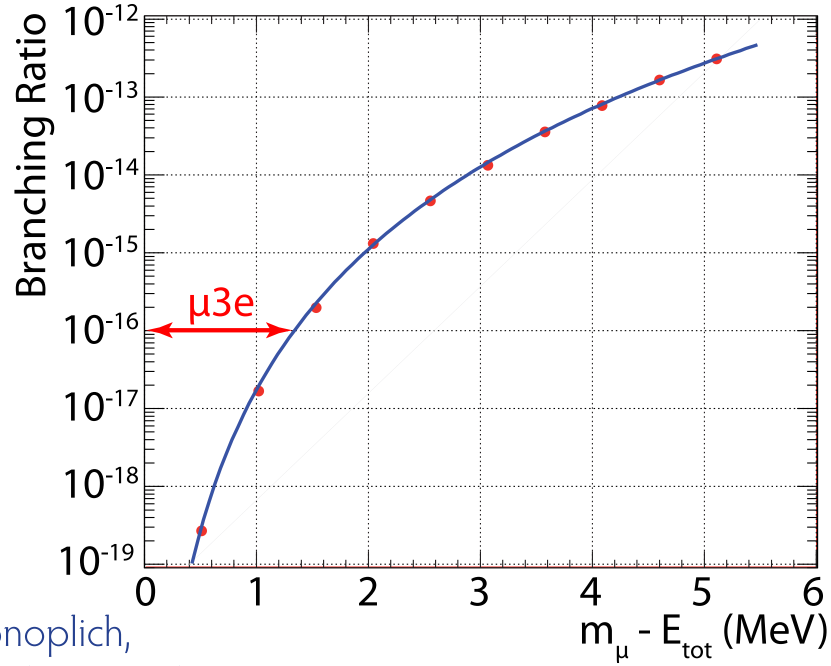
Internal conversion background



- Allowed radiative decay with internal conversion:

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

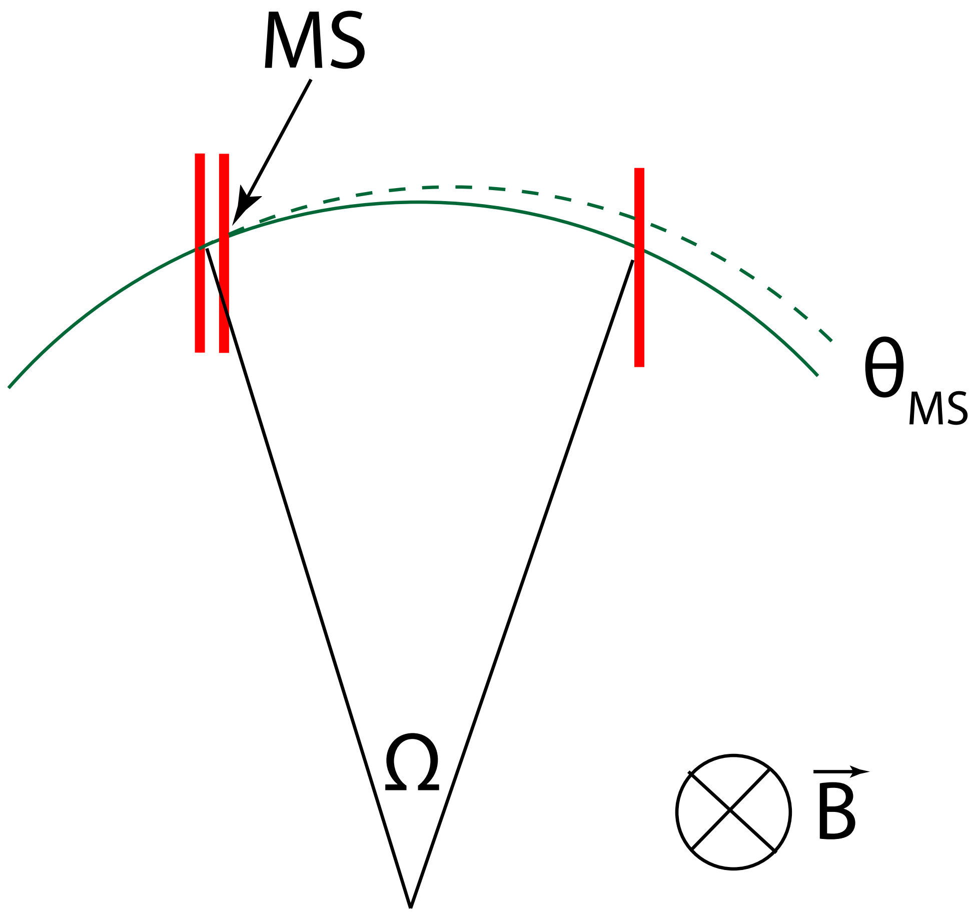
- Only distinguishing feature: Missing momentum carried by neutrinos



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

- Need excellent momentum resolution

Momentum measurement

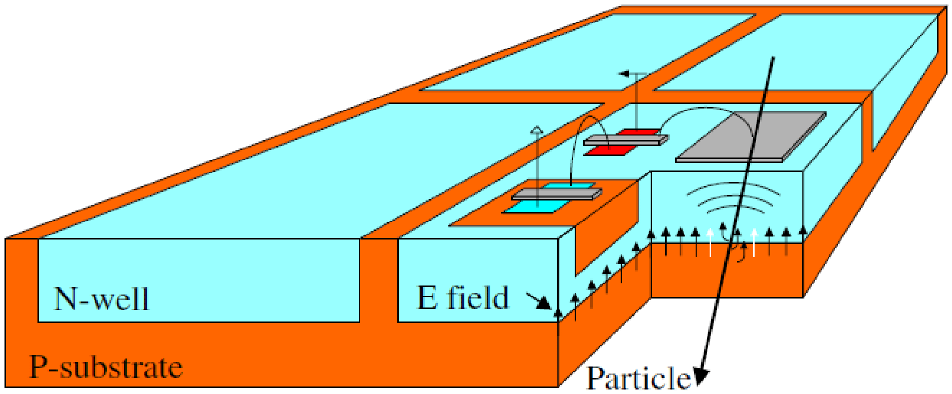


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

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

Fast and thin sensors: HV-MAPS



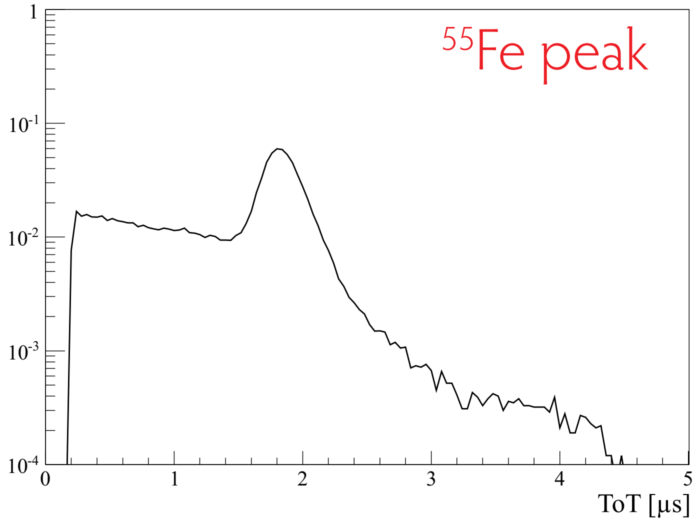
High voltage monolithic active pixel sensors

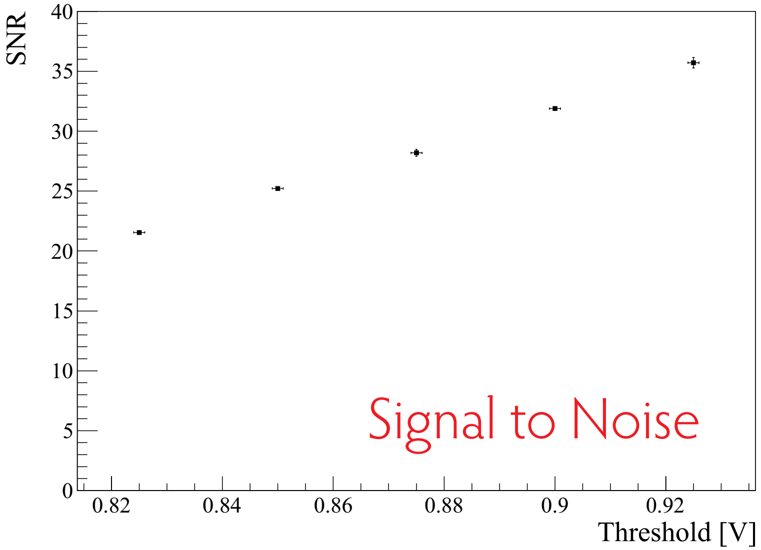
- Implement logic directly in N-well in the pixel - smart diode array
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Can be thinned down to < 50 µm

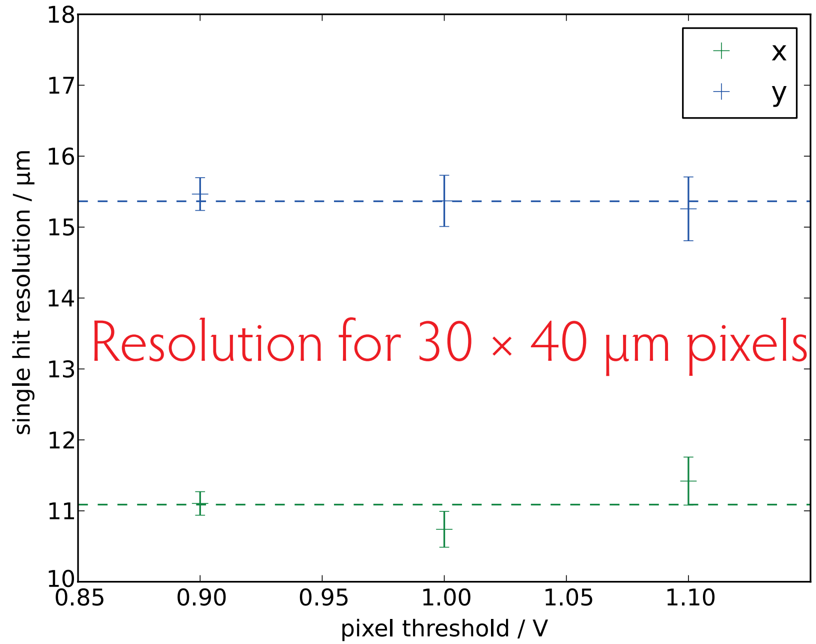
(I.Peric, P. Fischer et al., NIM A 582 (2007) 876)

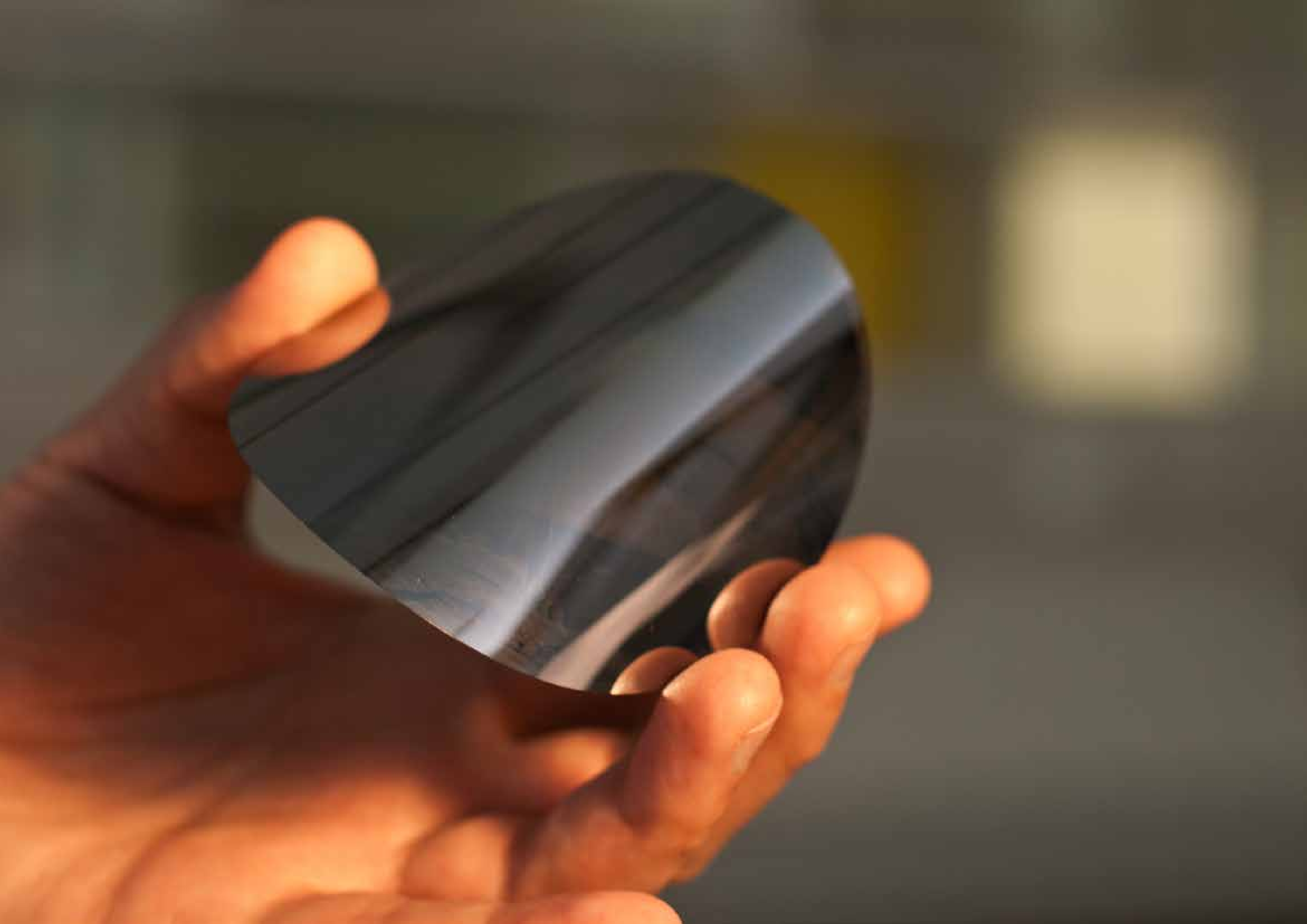
The MUPIX chips

- Module size 6 × 1 cm (inner layers)
  6 × 2 cm (outer layers)
- Pixel size 80 × 80 µm
- Goal for thickness: 50 µm
- 1 bit per pixel, zero suppression on chip
- Power: 150 mW/cm²
- Data output up to 3.2 Gbit/s
- Time stamps every 50 ns

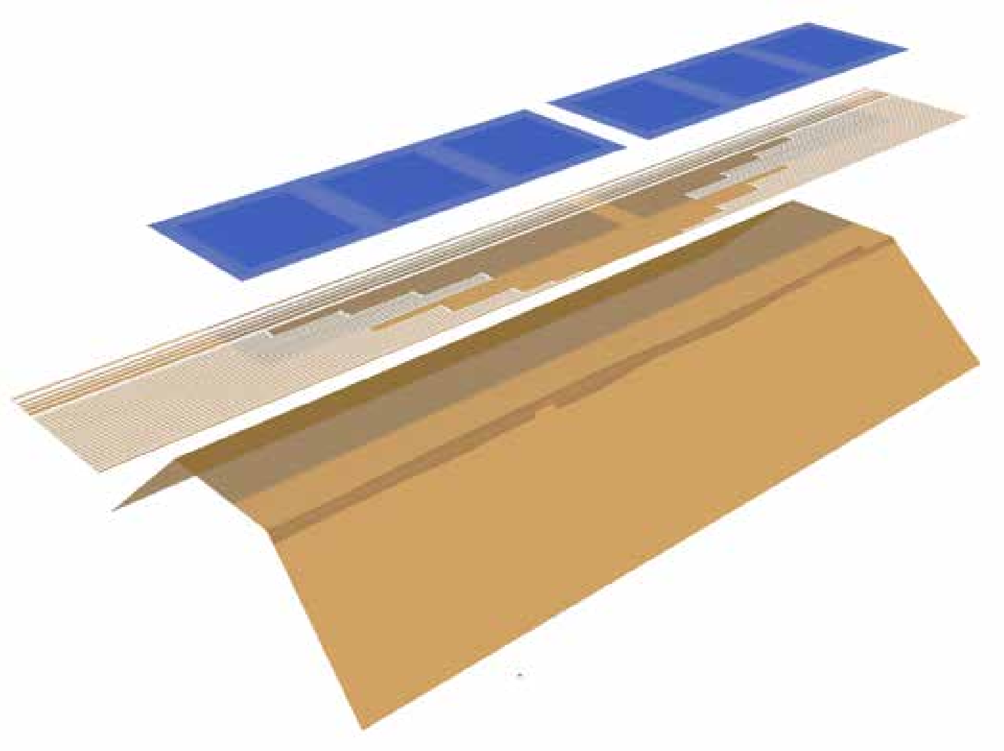








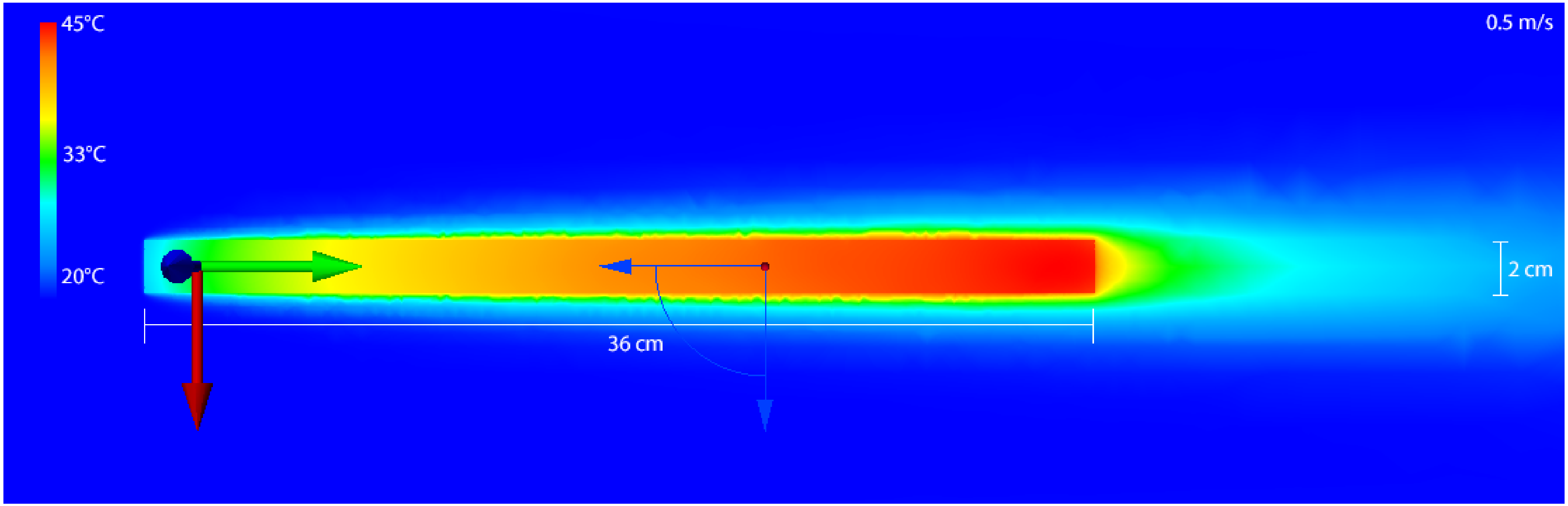
Mechanics



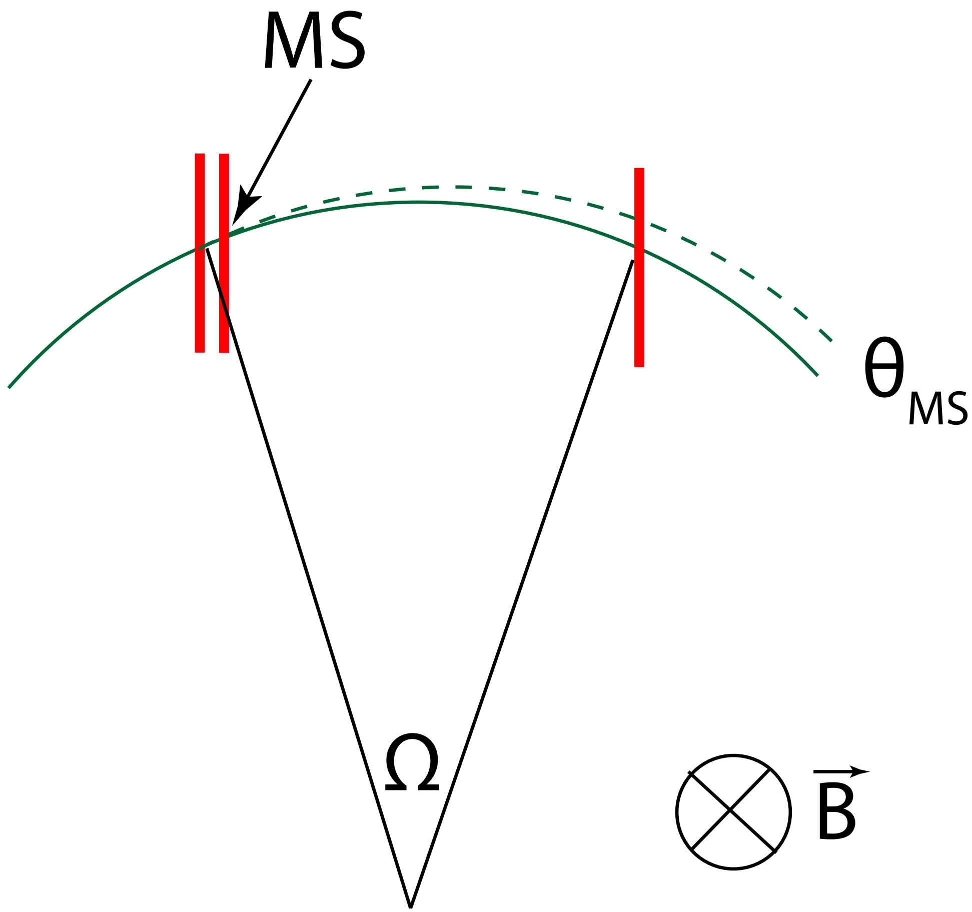
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

Cooling

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



Momentum measurement



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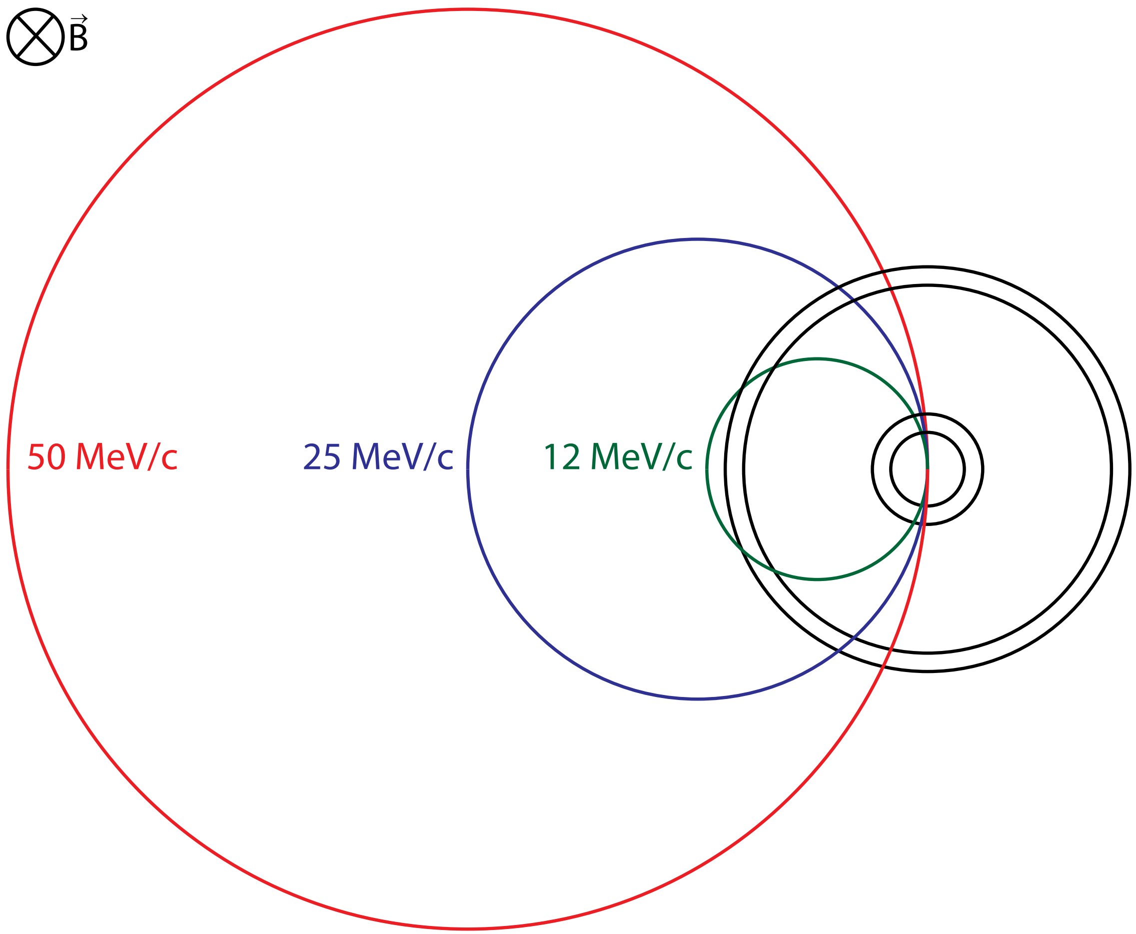
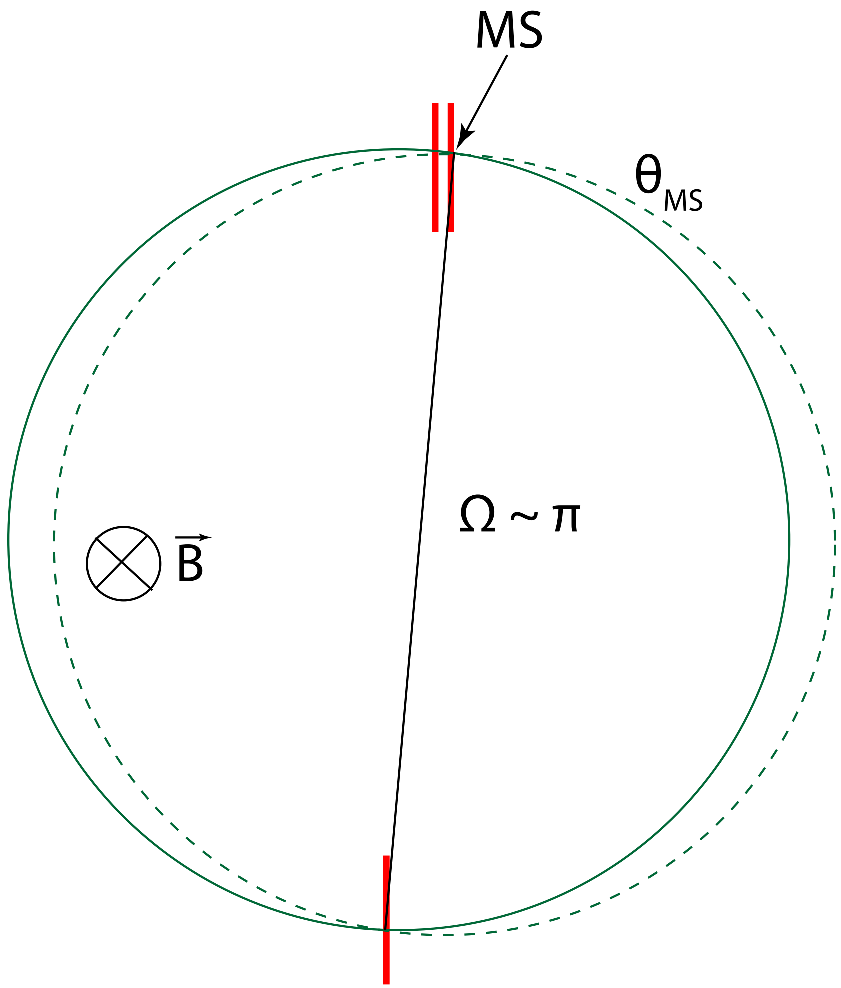
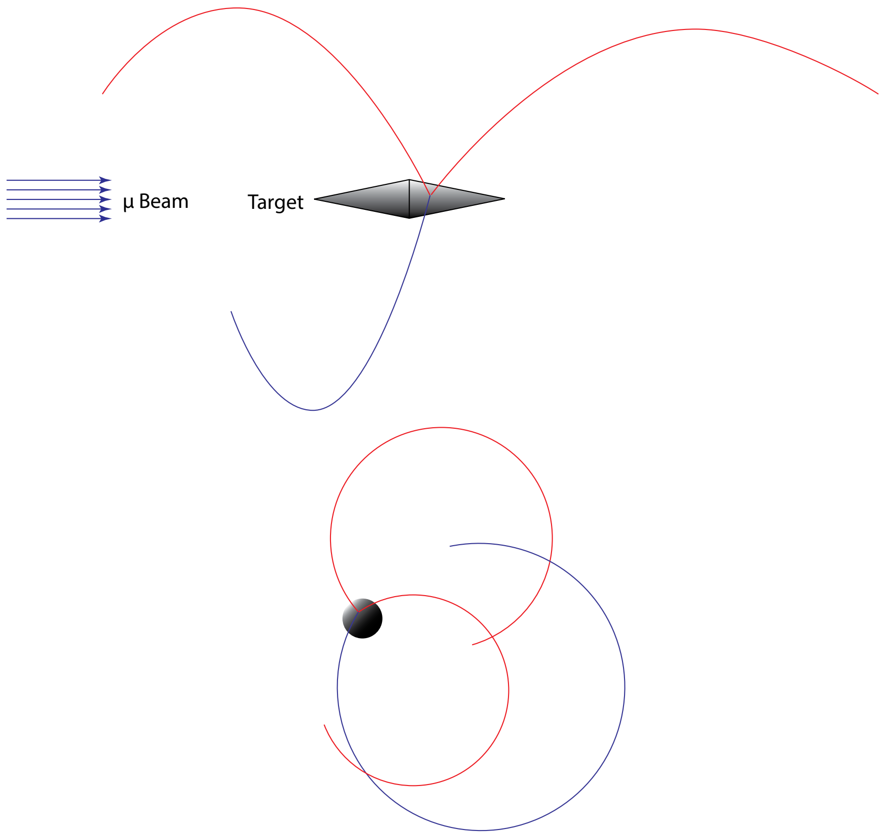
Precision vs. Acceptance





Detector Design



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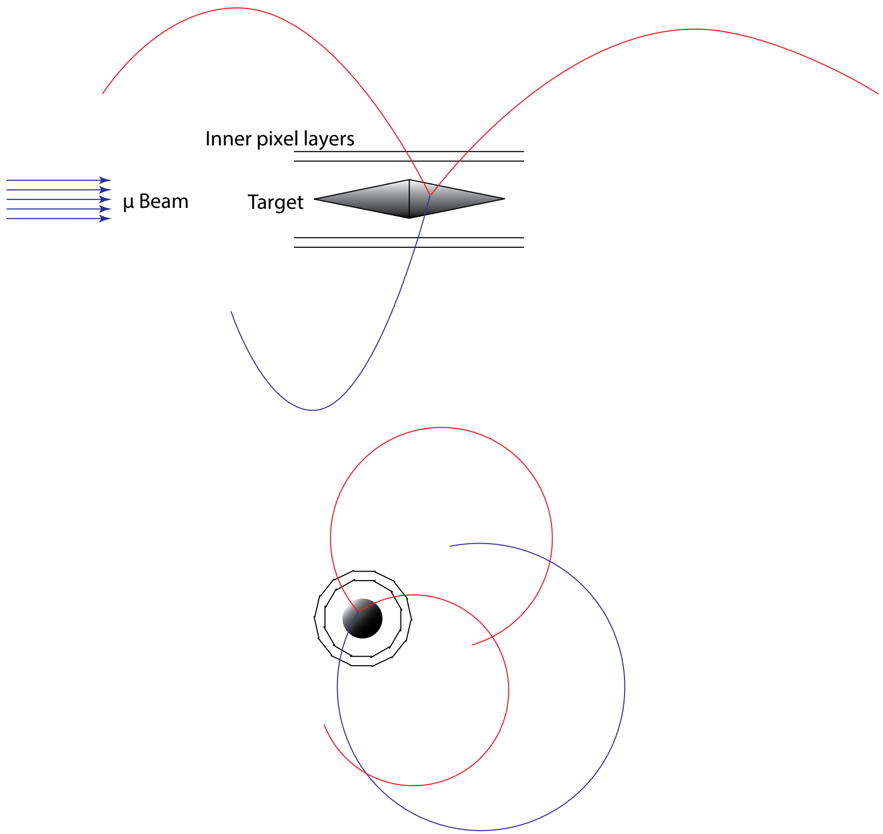

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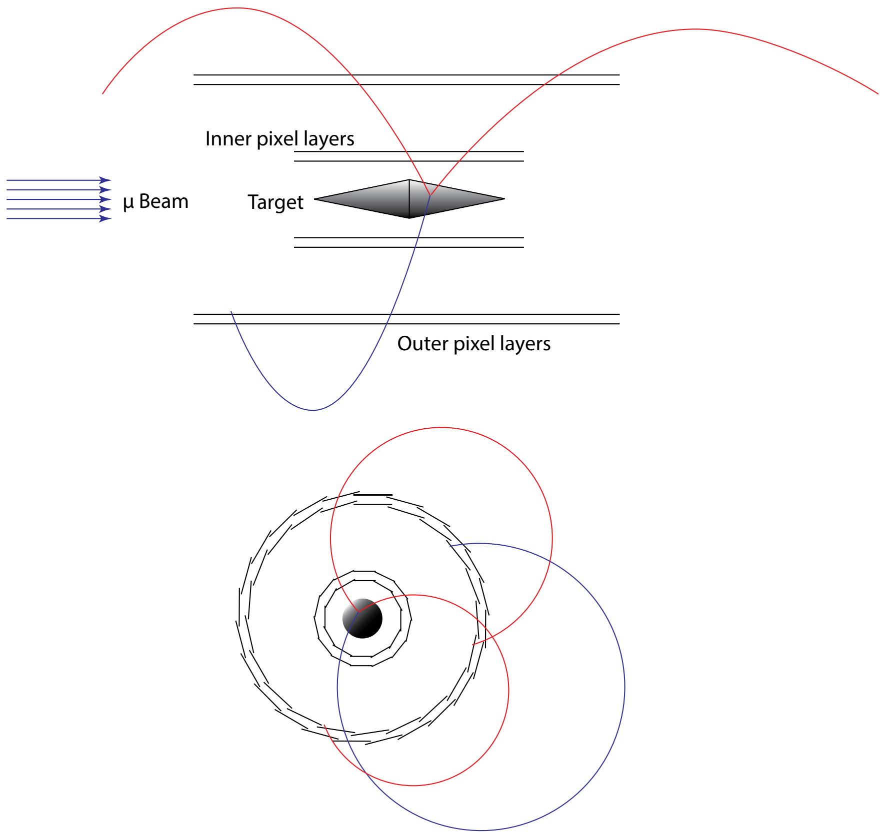

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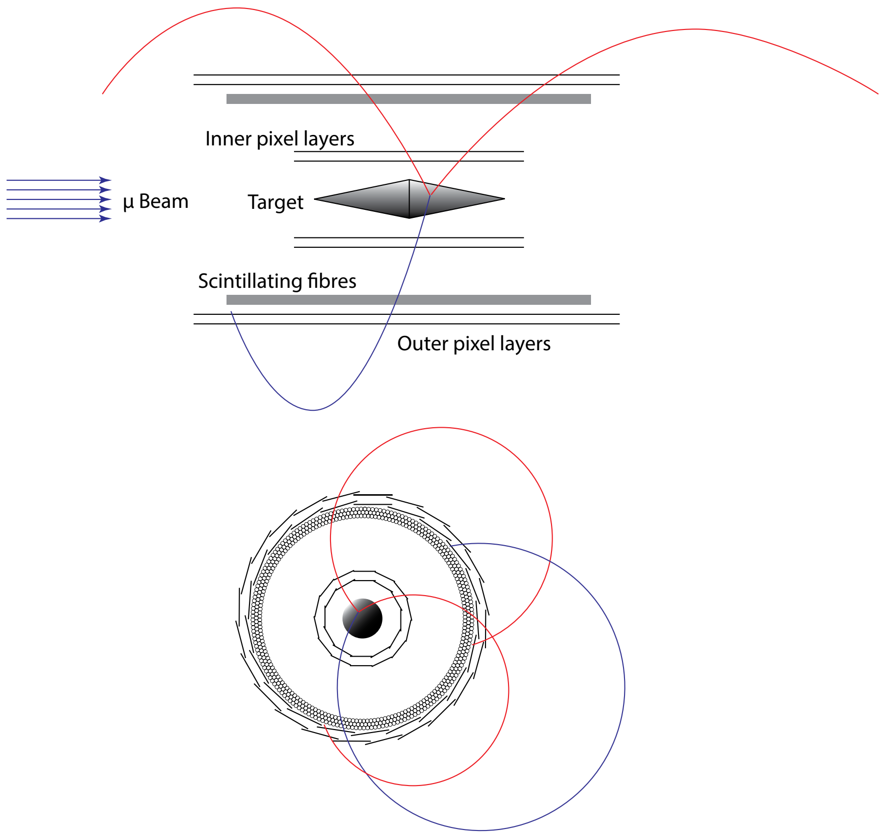

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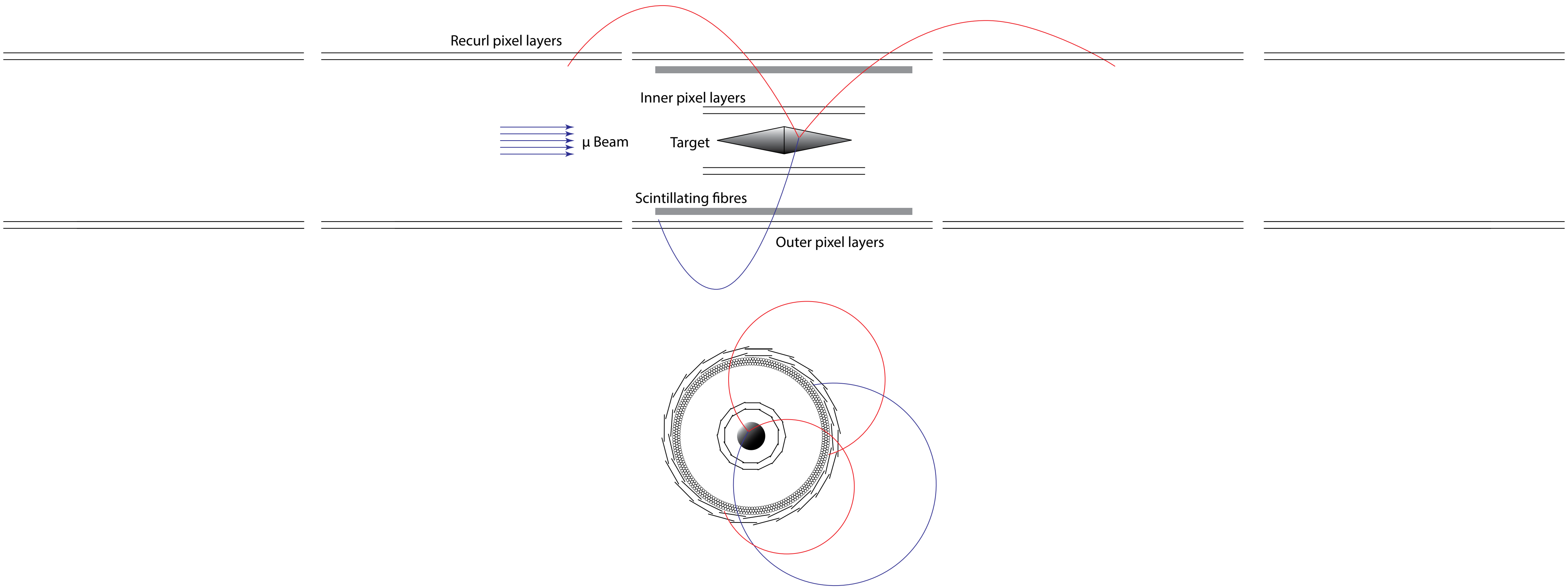

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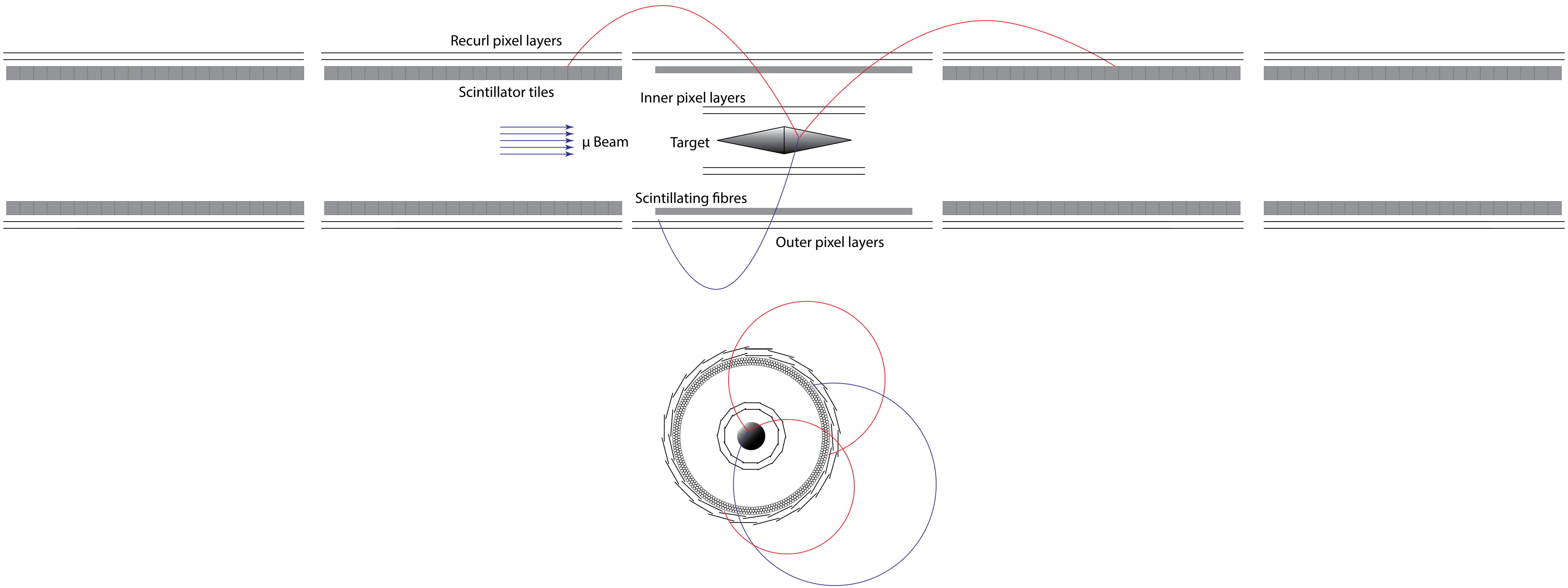
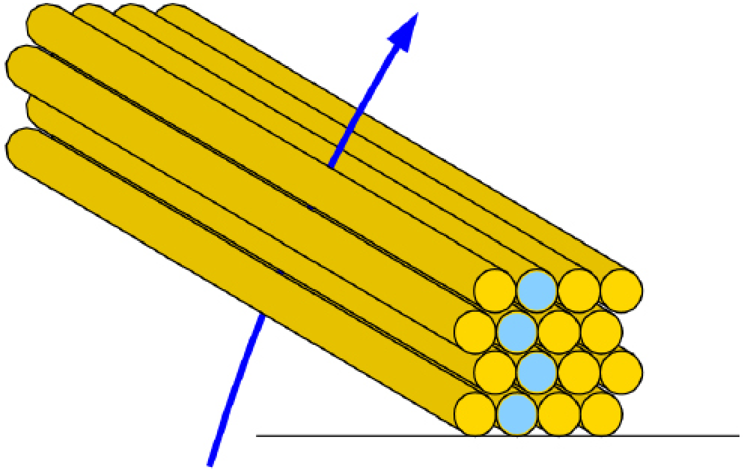
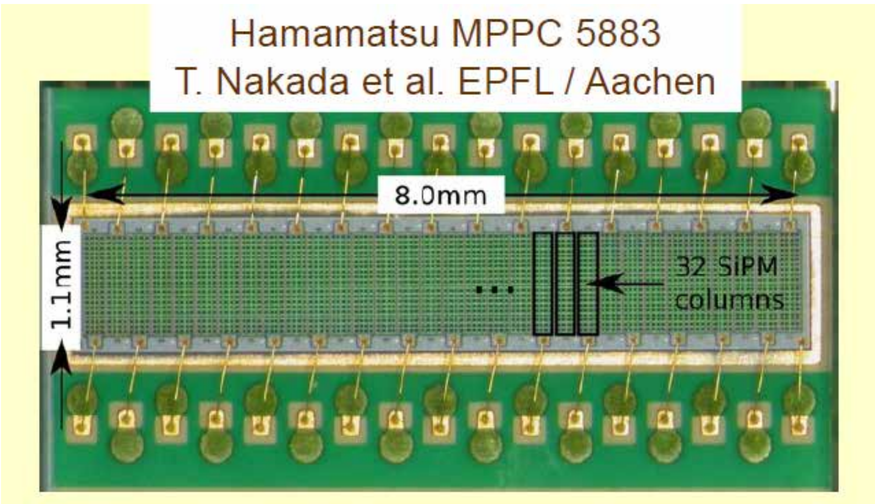
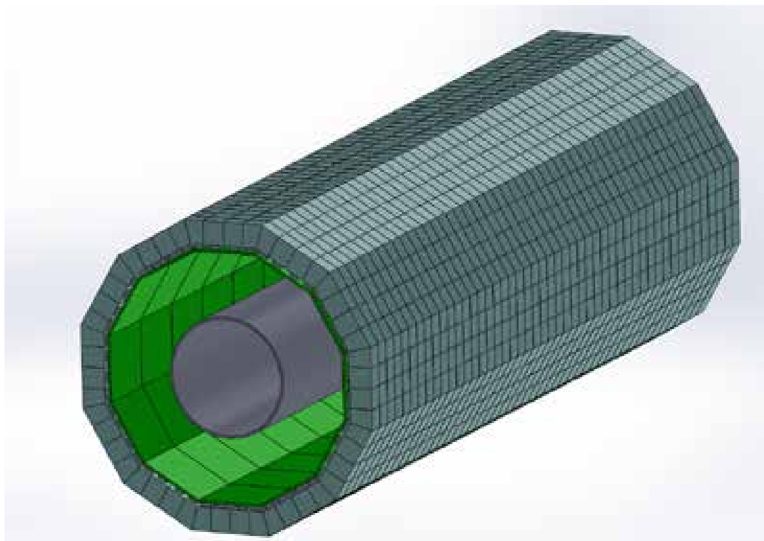


Timing measurements



- 250 µm fibres - O(0.5 ns)
- 0.5 cm^3 tiles - O(60 ps)
- Photosensor: SiPM;
  high gain, high frequency
- Readout via switched capacitor array
  (PSI developed DRS5 chip) or
  STiC ASIC developed in Heidelberg





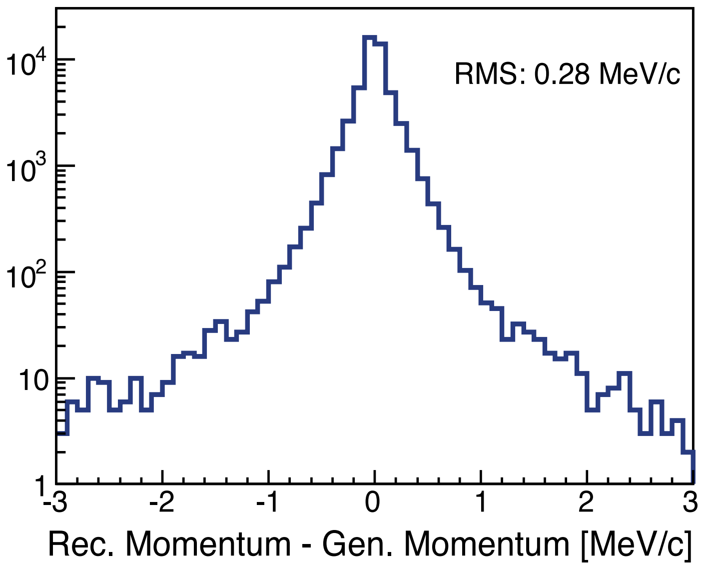
Online filter farm

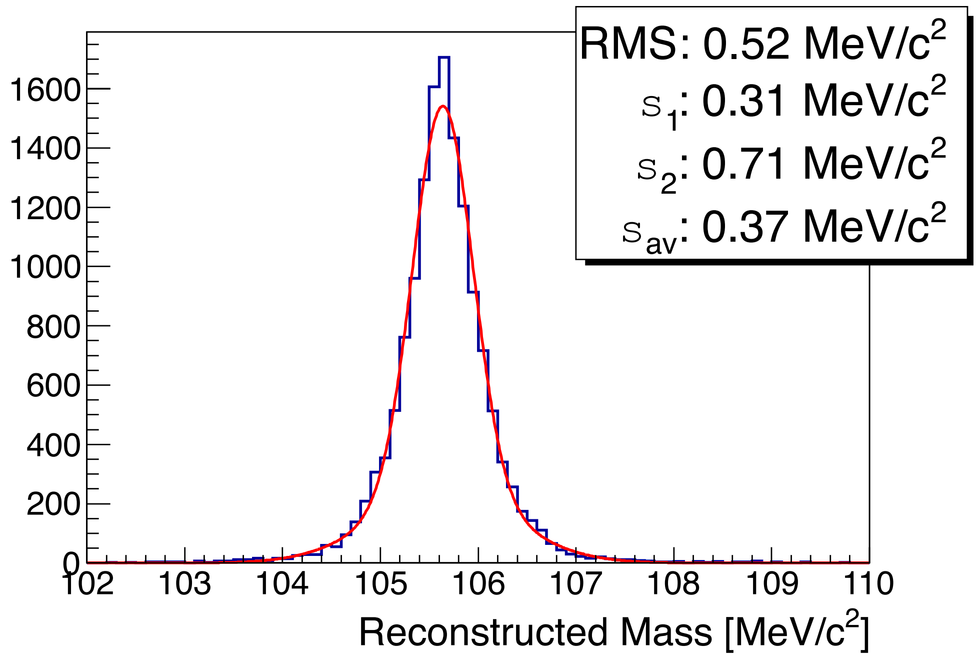
Online software filter farm

- Continuous front-end readout (no trigger)
- ~ 1 Tbit/s
- 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





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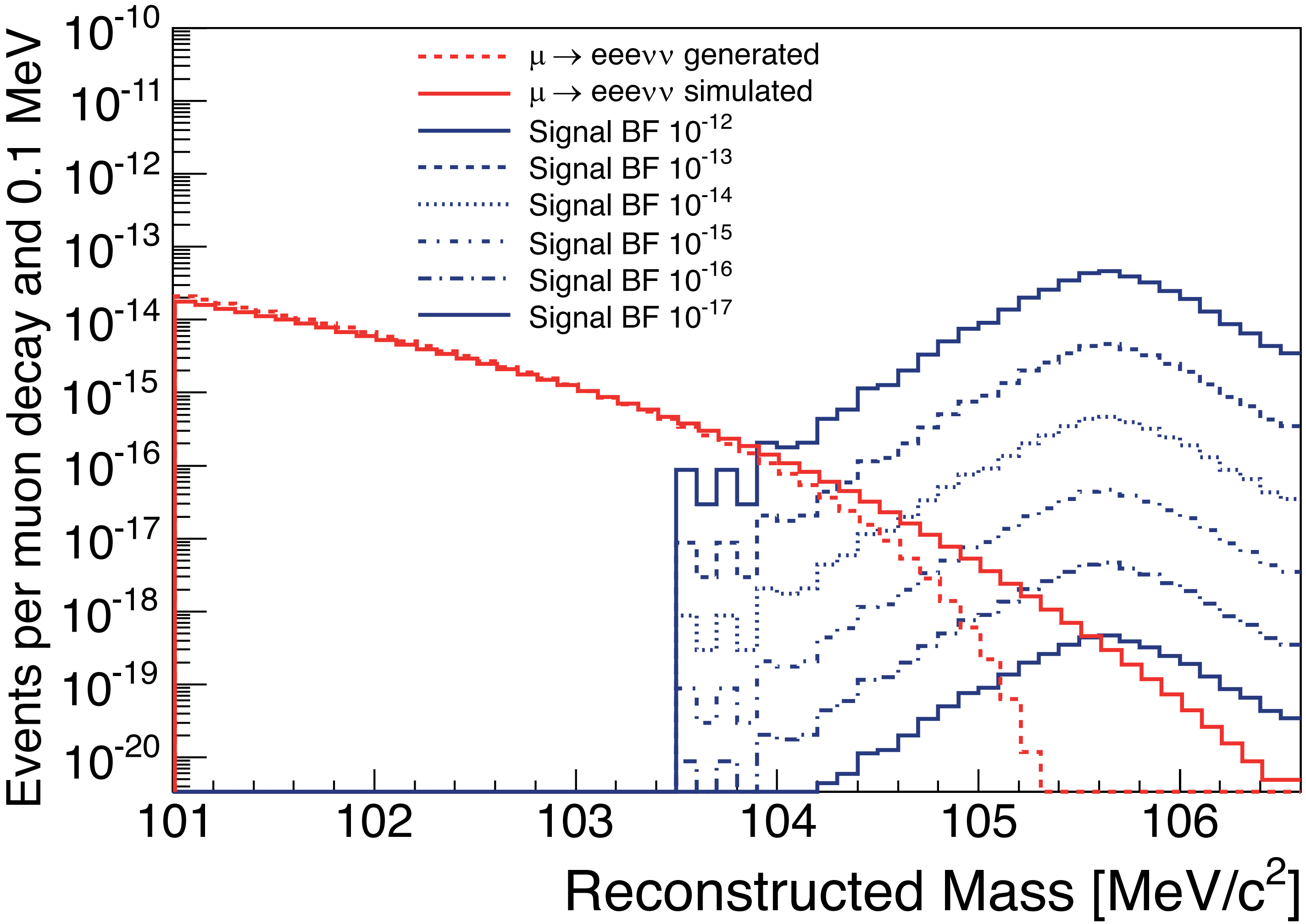
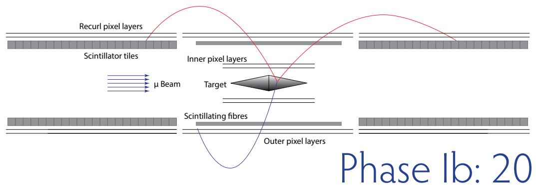
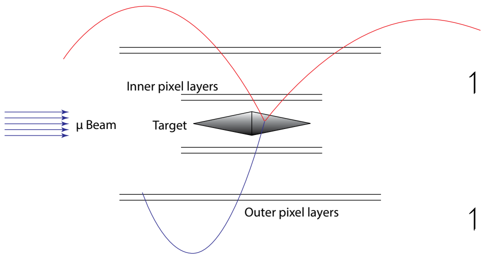


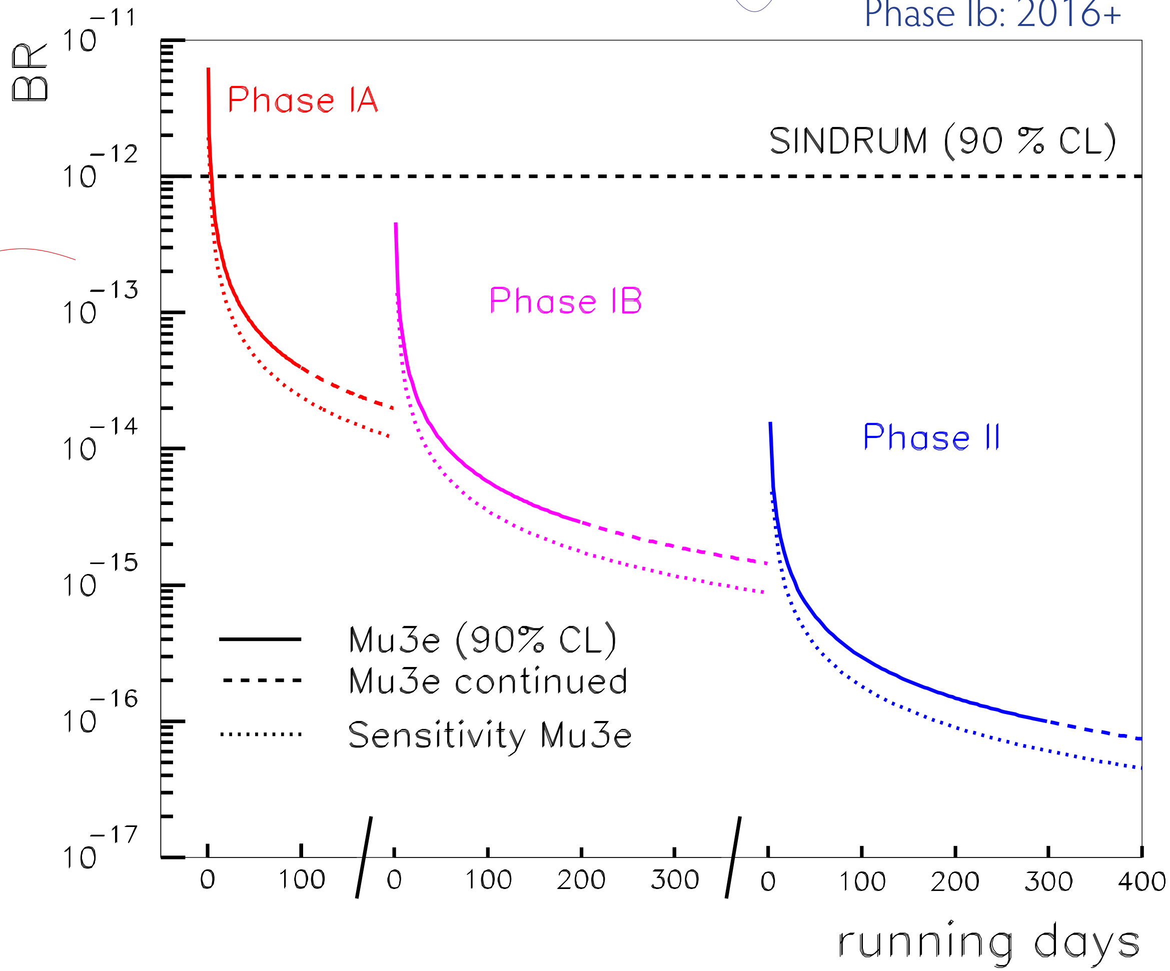
Sensitivity



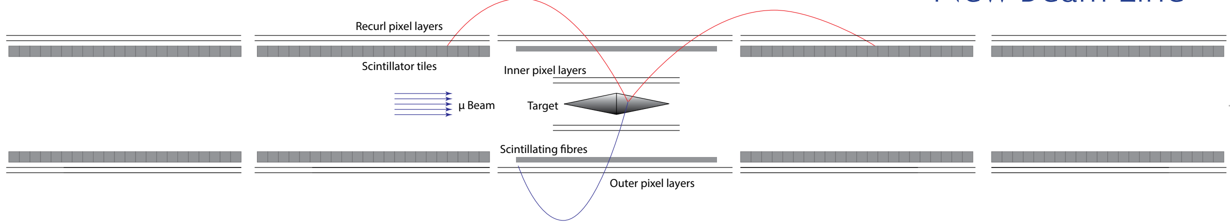
Phase Ib: 2016+



Phase Ia: Starting 2015



Phase II: 2017+
New Beam Line



Current Status

- The Mu3e Research Proposal was approved by the PSI research committee in January

  Proposal available on arXiv:1301:6113

- Phase I experiment mostly funded

- Aim for first measurements in 2015

- High-intensity beam line under study (earliest availability 2017+)

Collaboration

Participating Institutes:

- University of Geneva
- University of Heidelberg (3 Institutes)
- Paul Scherrer Institut (PSI)
- University of Zurich
- ETH Zurich

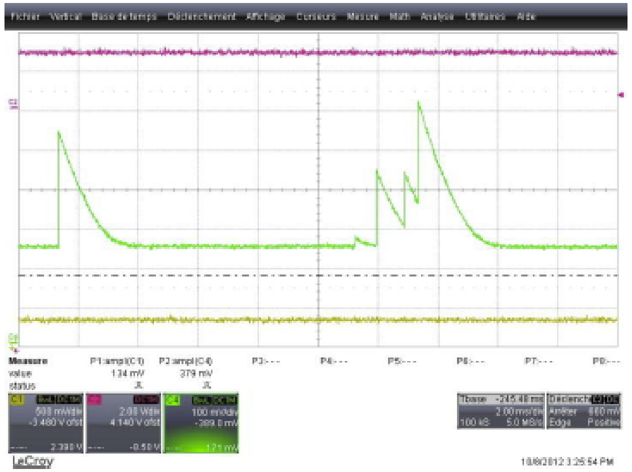
Also in contact with other interested groups

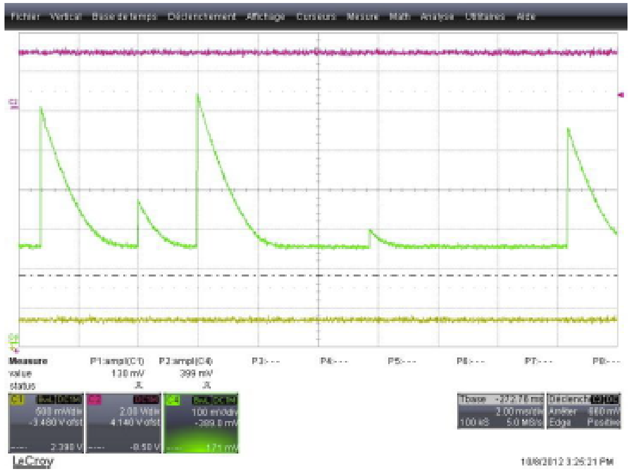
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Backup Material

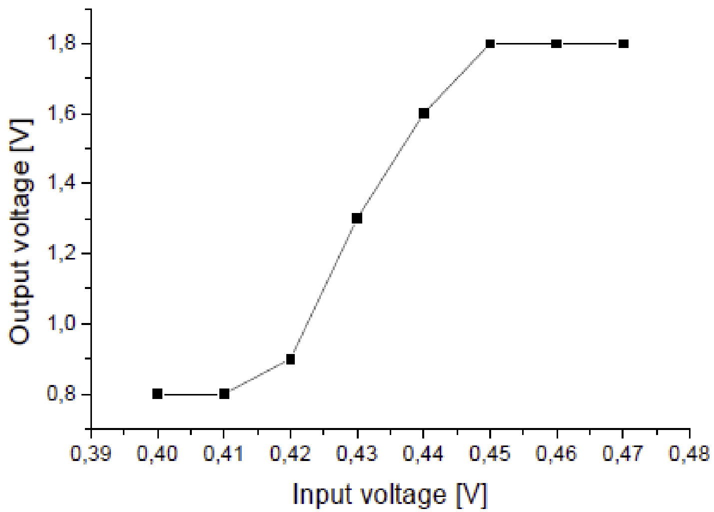
Radiation Hardness

- 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 ($8\times10^{15}\ n_{eq}/cm^2$)
- Chip still working

(Courtesy Ivan Perić)