# The Mu3e Experiment

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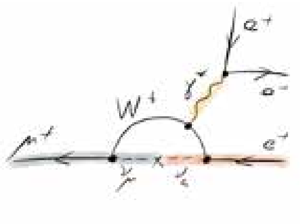
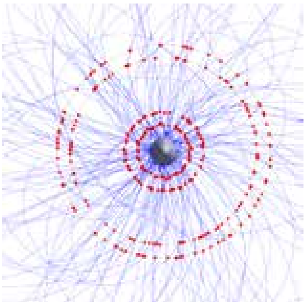
Charged Lepton Flavour Violation Workshop,
Lecce, May 2013

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

# Overview



- The Question:
  Can we observe charged lepton flavour violation?

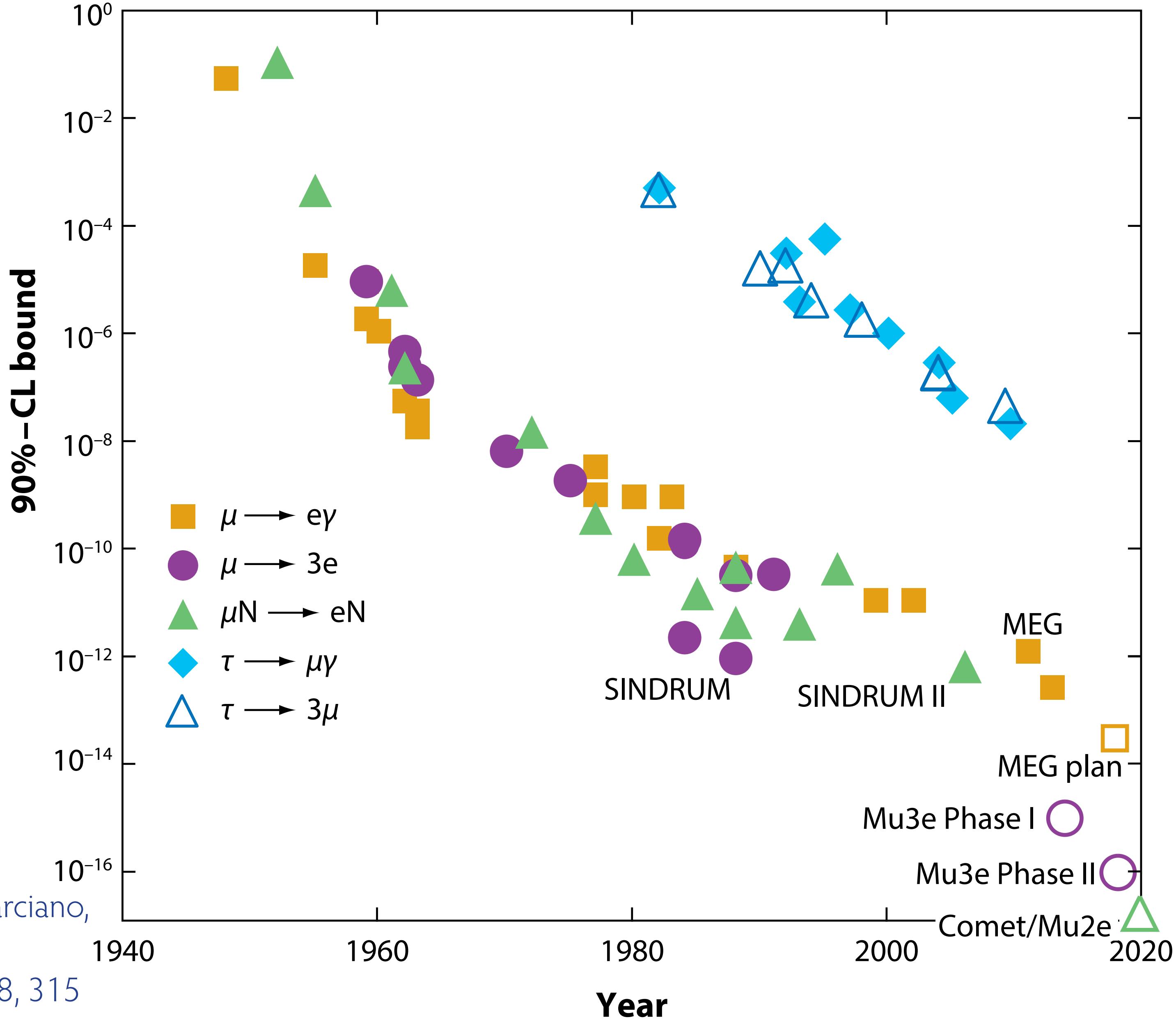


- The Challenge:
  Finding one in $10^{16}$ muon decays

- The Mu3e Detector:
  Minimum Material, Maximum Precision

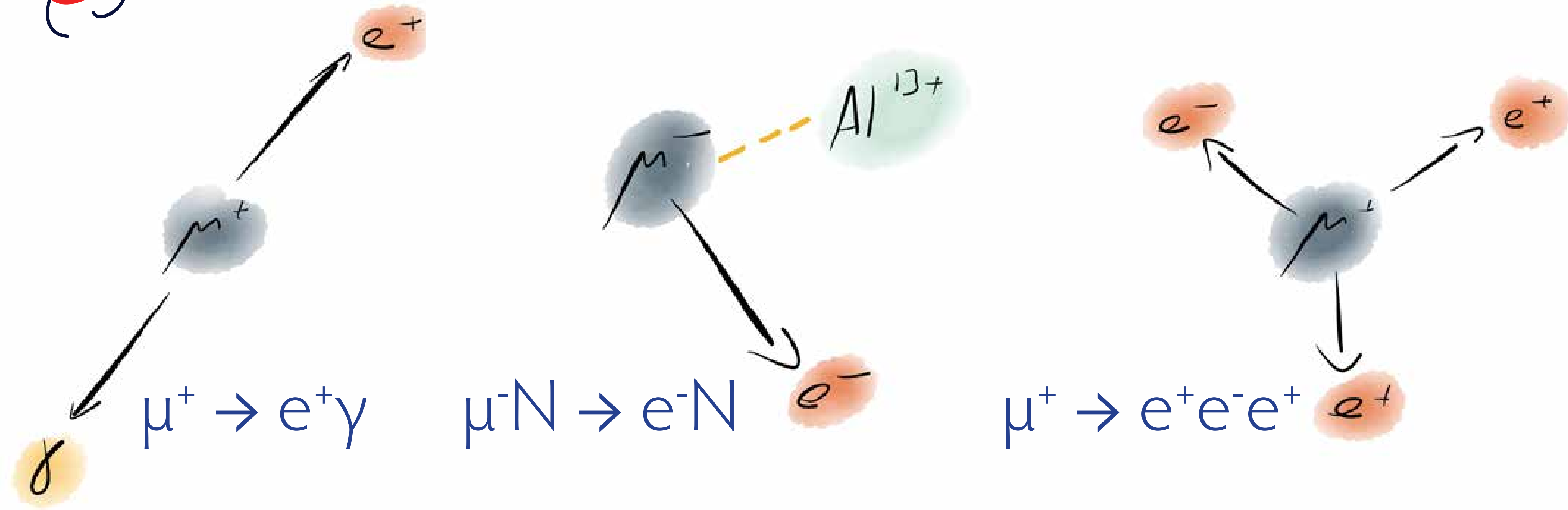
# The hunt for
# charged lepton flavour violation

# History of LFV experiments



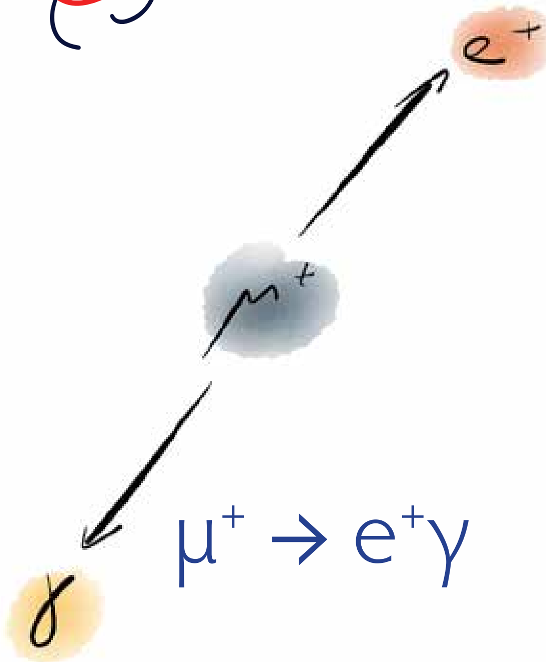

(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

# LFV Muon Decays: Experimental Situation

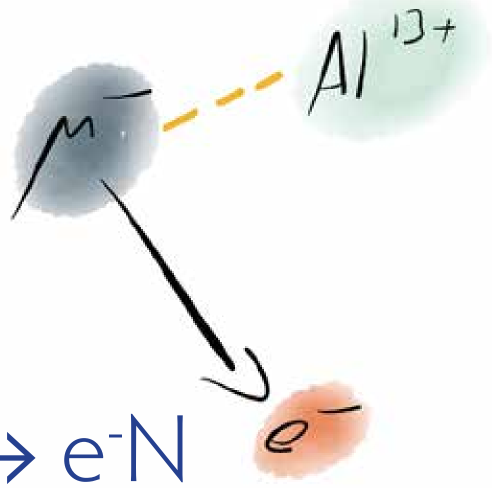



| MEG (PSI) | SINDRUM II (PSI) | SINDRUM (PSI) |
|---|---|---|
| $B(\mu^+ \to e^+\gamma) < 5.7 \cdot 10^{-13}$ | $B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$ | $B(\mu^+ \to e^+e^-e^+) < 5.7 \cdot 10^{-13}$ |
| (2013) | (2006) | (1988) |
| running | | |

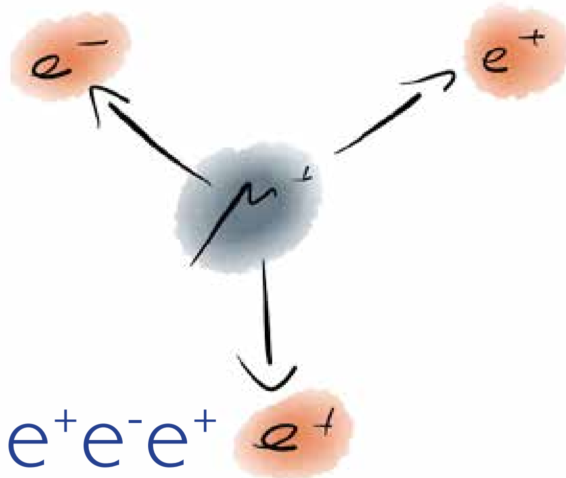
# LFV Muon Decays: Standard Model



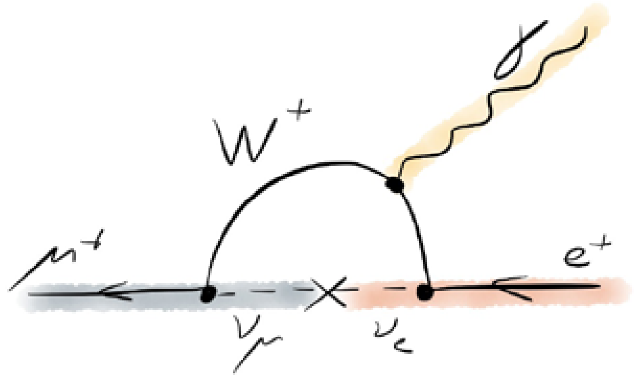

$\mu^+ \rightarrow e^+\gamma$

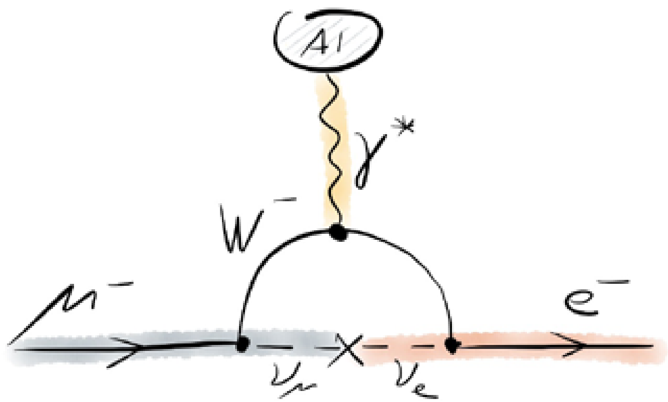


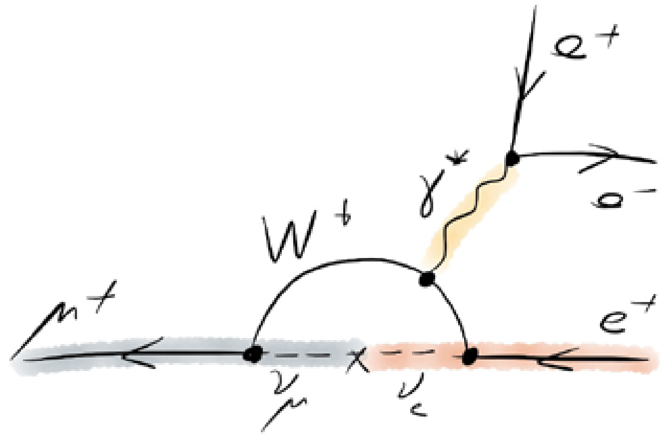

$\mu^- N \rightarrow e^- N$




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

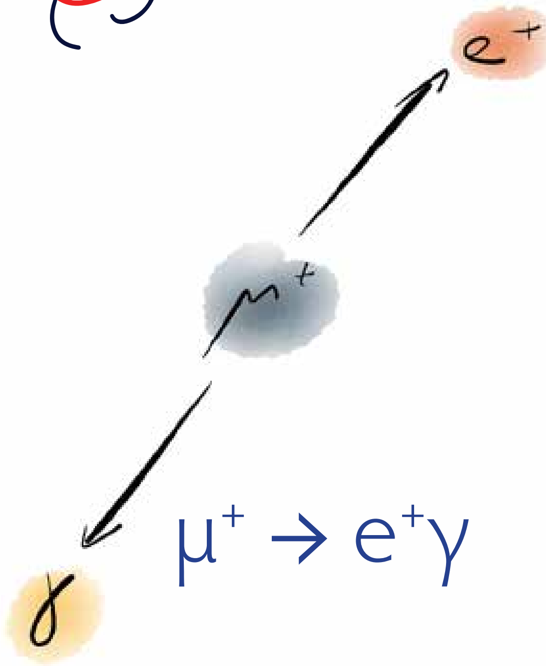


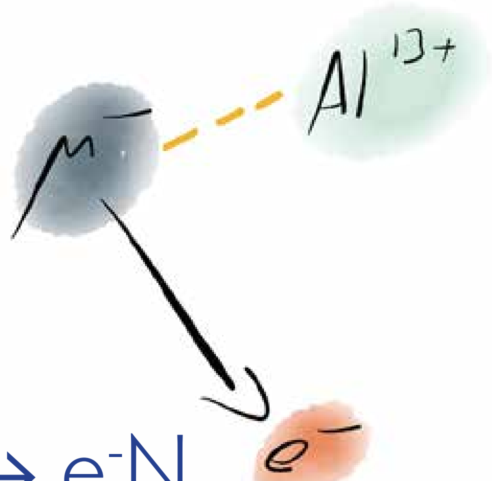




Branching ratios suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

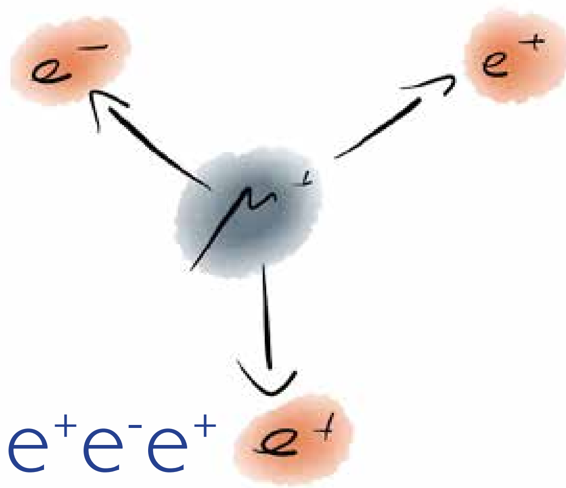
# LFV Muon Decays: Susy Loops



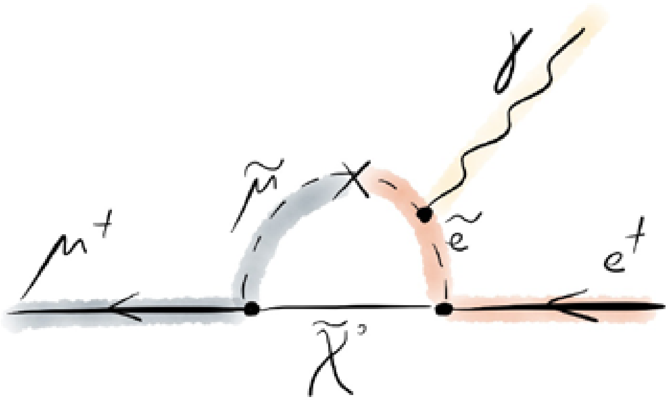

$\mu^+ \rightarrow e^+\gamma$

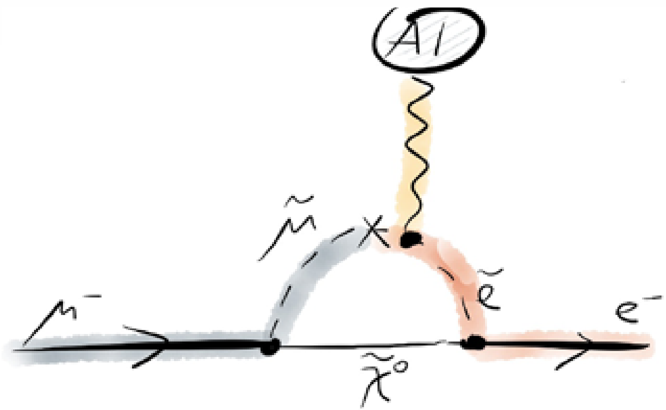



$\mu^-N \rightarrow e^-N$

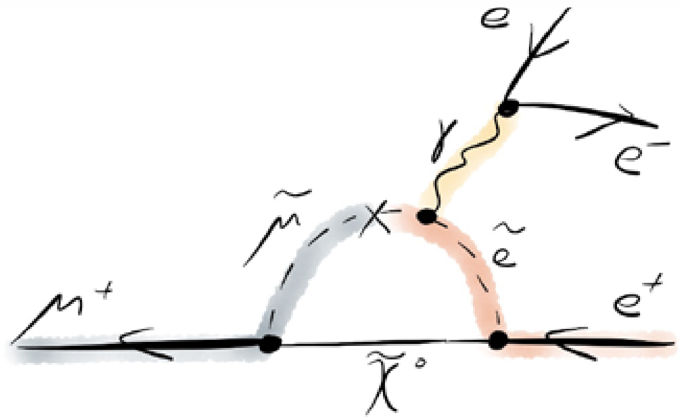



$\mu^+ \rightarrow e^+e^-e^+$



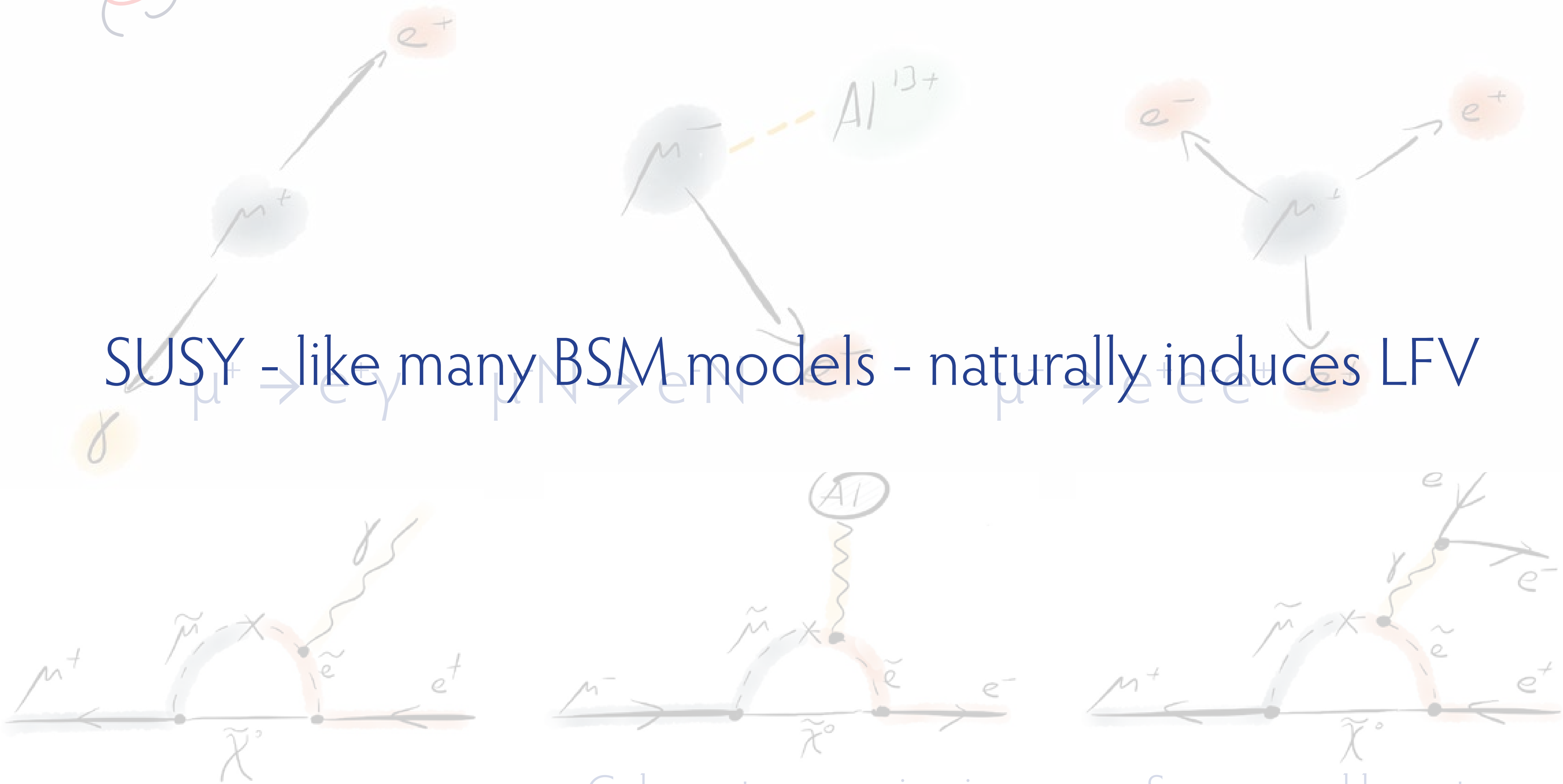

Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$




Suppressed by extra vertex w.r.t. $\mu \rightarrow e\gamma$

# LFV Muon Decays: Susy Loops

SUSY - like many BSM models - naturally induces LFV




Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$

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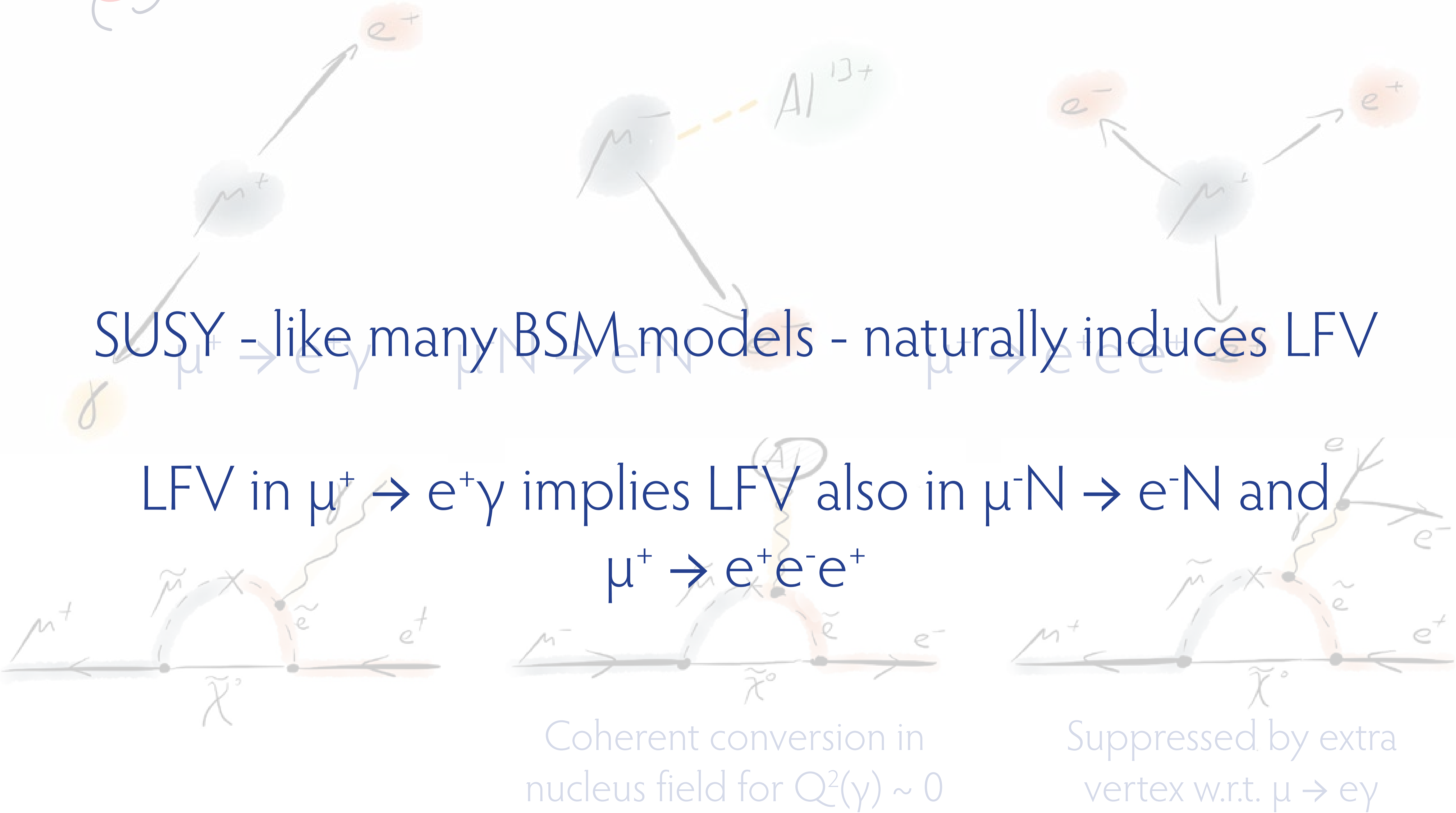
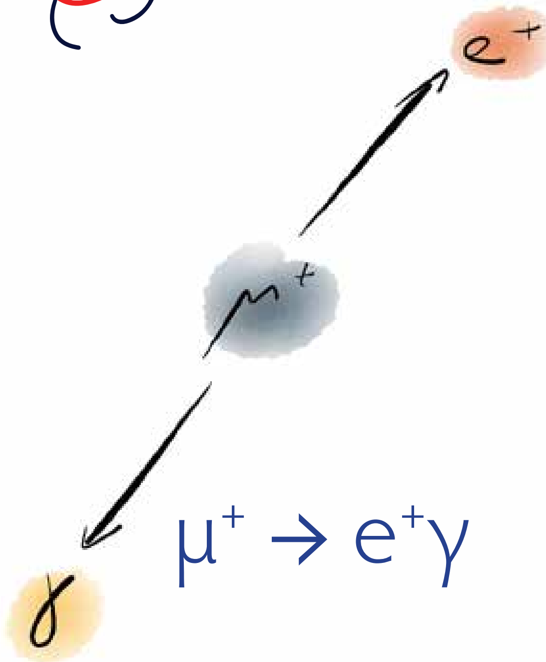
# LFV Muon Decays: Susy Loops



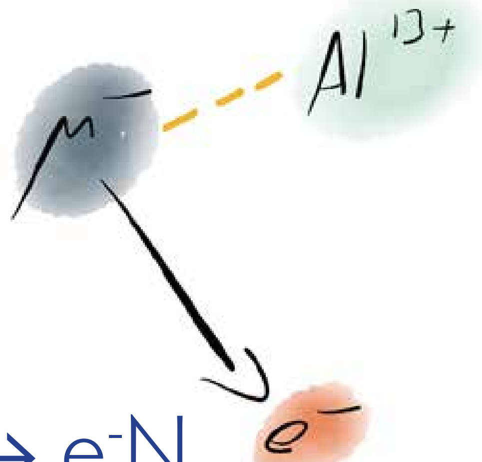

SUSY - like many BSM models - naturally induces LFV

LFV in $\mu^+ \to e^+\gamma$ implies LFV also in $\mu^- N \to e^- N$ and $\mu^+ \to e^+e^-e^+$

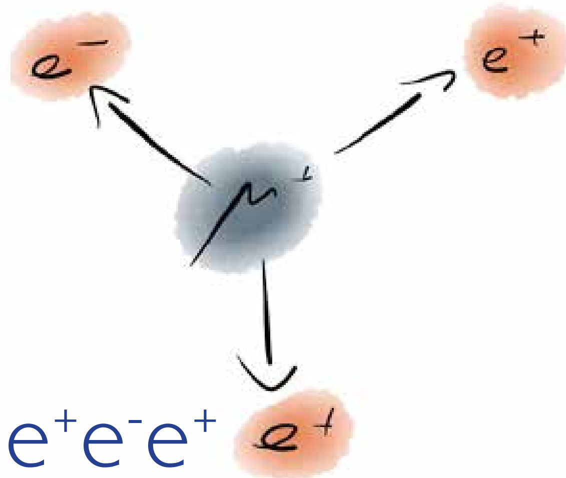
# LFV Muon Decays: Tree diagrams



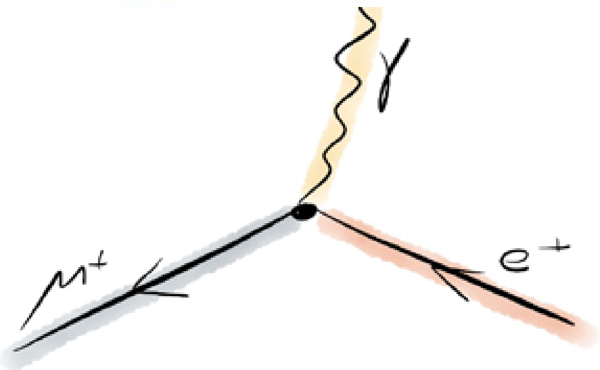

$\mu^+ \rightarrow e^+\gamma$



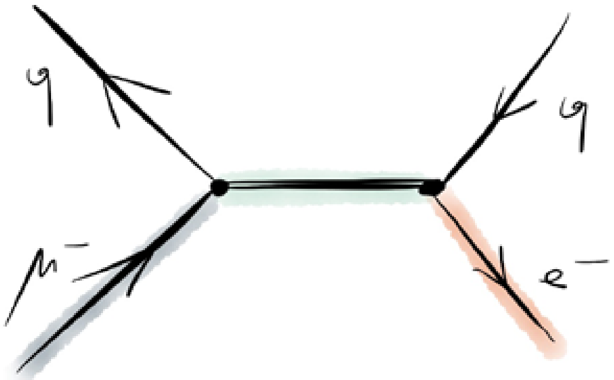

$\mu^- N \rightarrow e^- N$



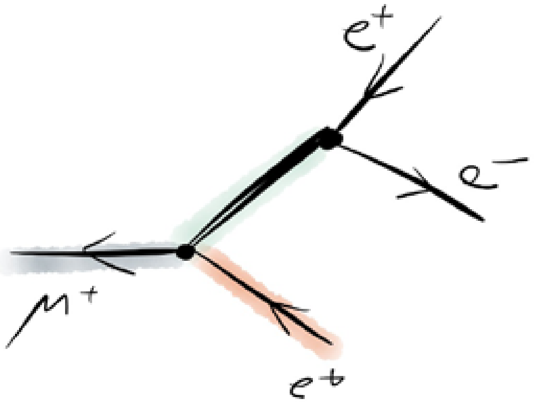

$\mu^+ \rightarrow e^+e^-e^+$




Not allowed

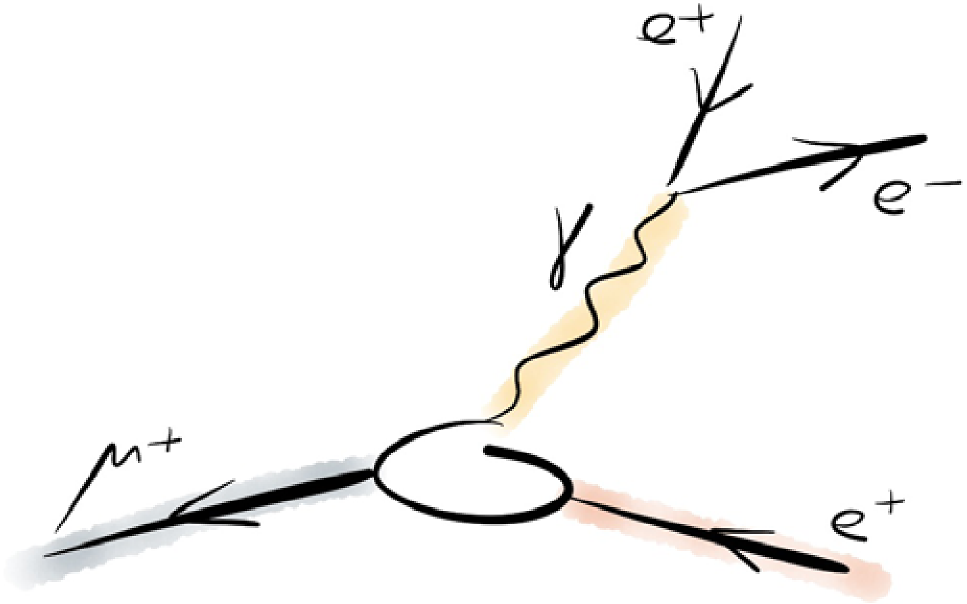


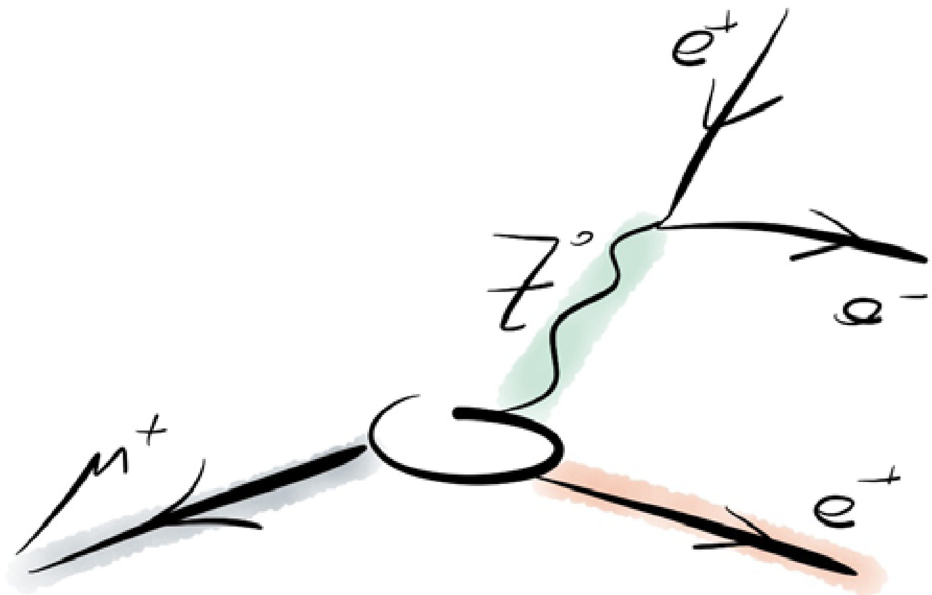

e.g. Leptoquarks




e.g. extra Z', LFV Higgs etc.

# Z-Penguin diagrams in $\mu^+ \to e^+e^-e^+$



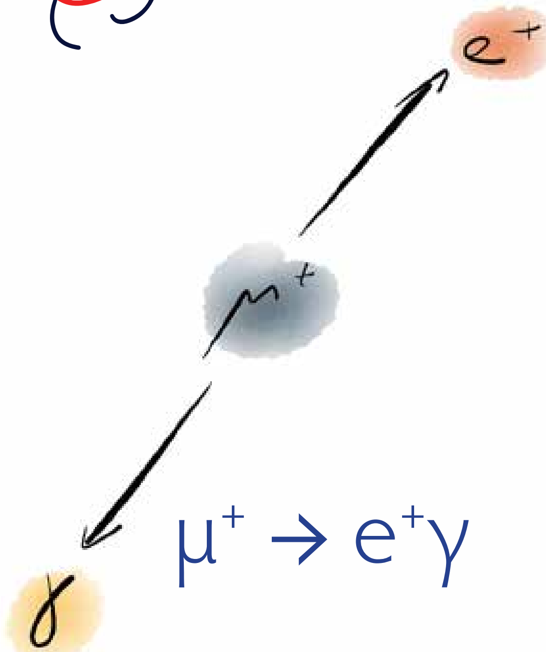

from dimensional analysis:

$$BR \propto \frac{m_\mu^4}{\Lambda^4}$$

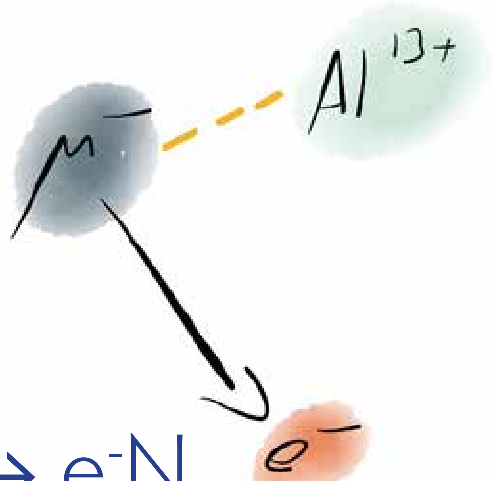
$$BR \propto \frac{m_\mu^4}{m_Z^4}$$

No decoupling in some models

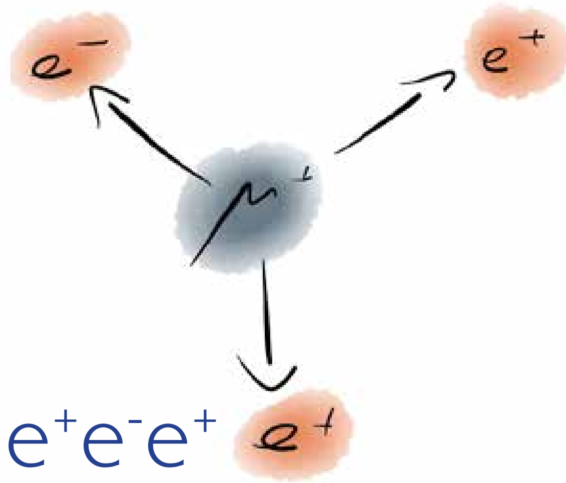
# LFV Muon Decays: Experimental signatures



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




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



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

Kinematics

- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

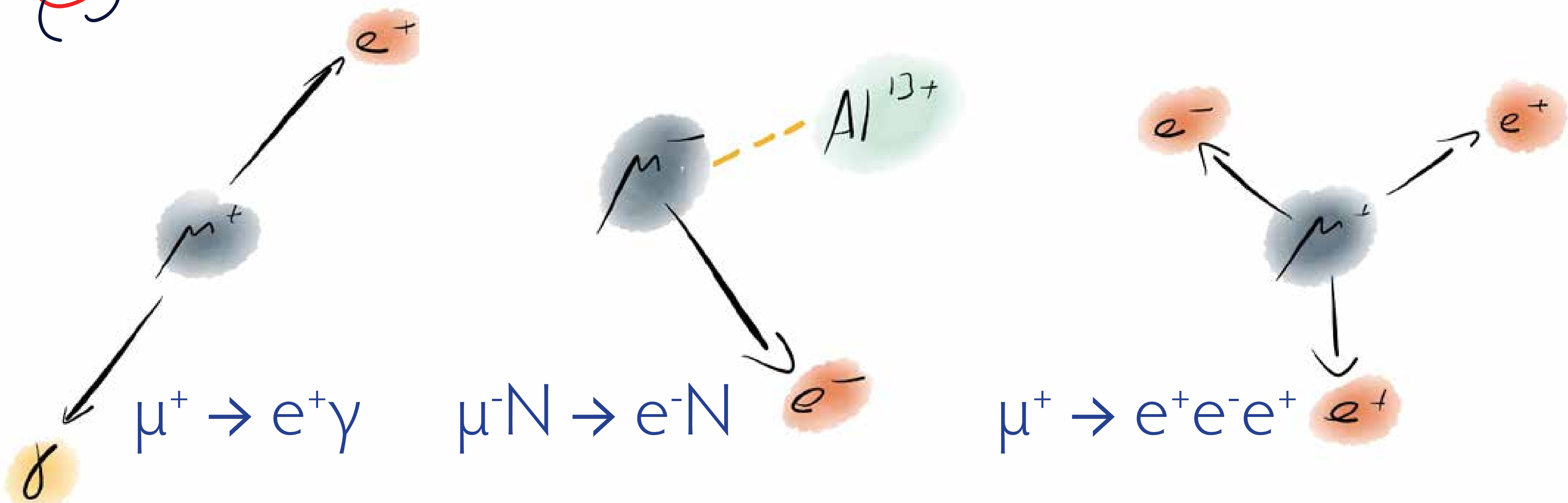
Kinematics

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

Kinematics

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

# LFV Muon Decays: Experimental signatures




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

Kinematics

- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

Background

- Accidental background

Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions

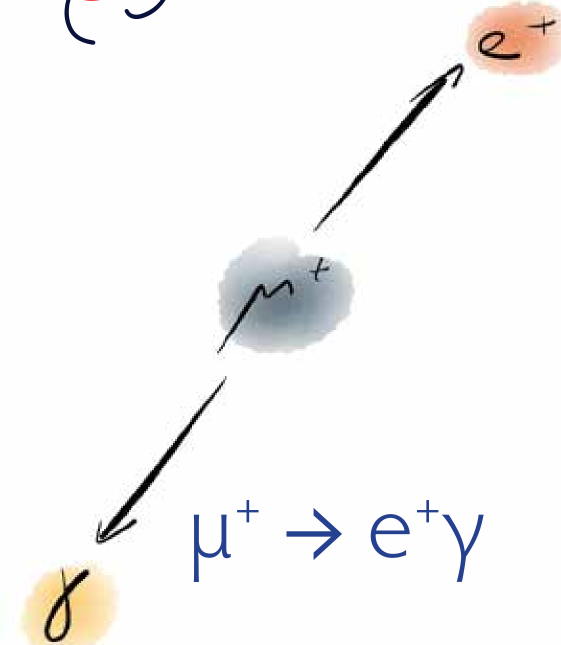
Kinematics

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

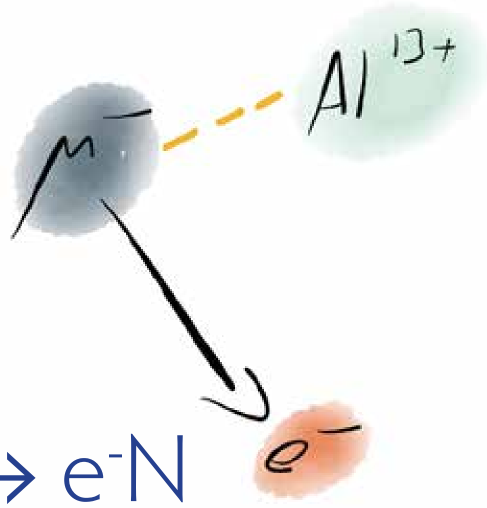
Background

- Radiative decay
- Accidental background

# LFV Muon Decays: Experimental signatures




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

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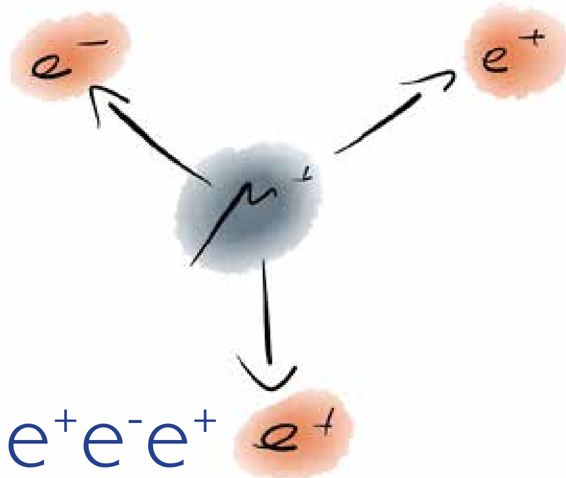



$\mu^+ \rightarrow e^+e^-e^+$

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
- Ar protons, pions

Pulsed Beam

Kinematics

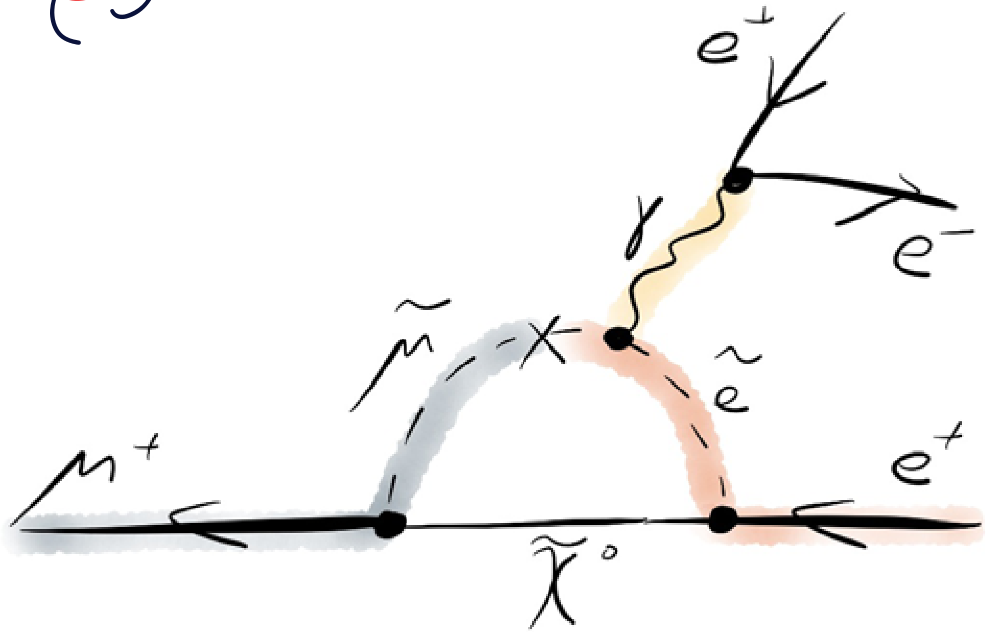
- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

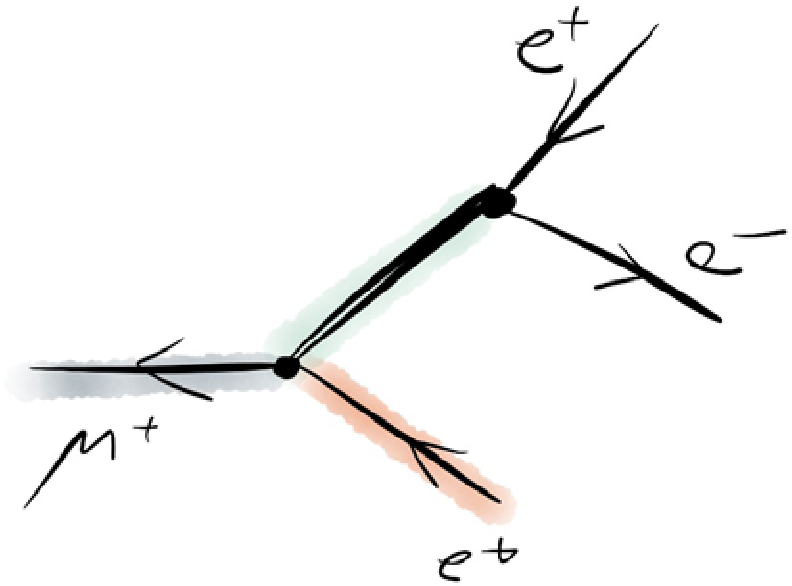
Backgro

- R decay
- Ac ental background

Continuous Beam

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



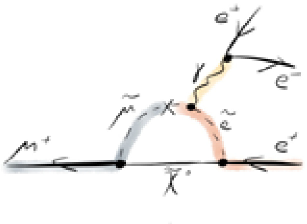

Loop diagrams

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

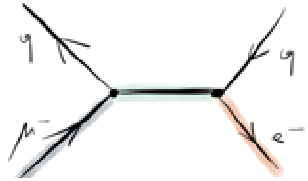
Tree diagrams

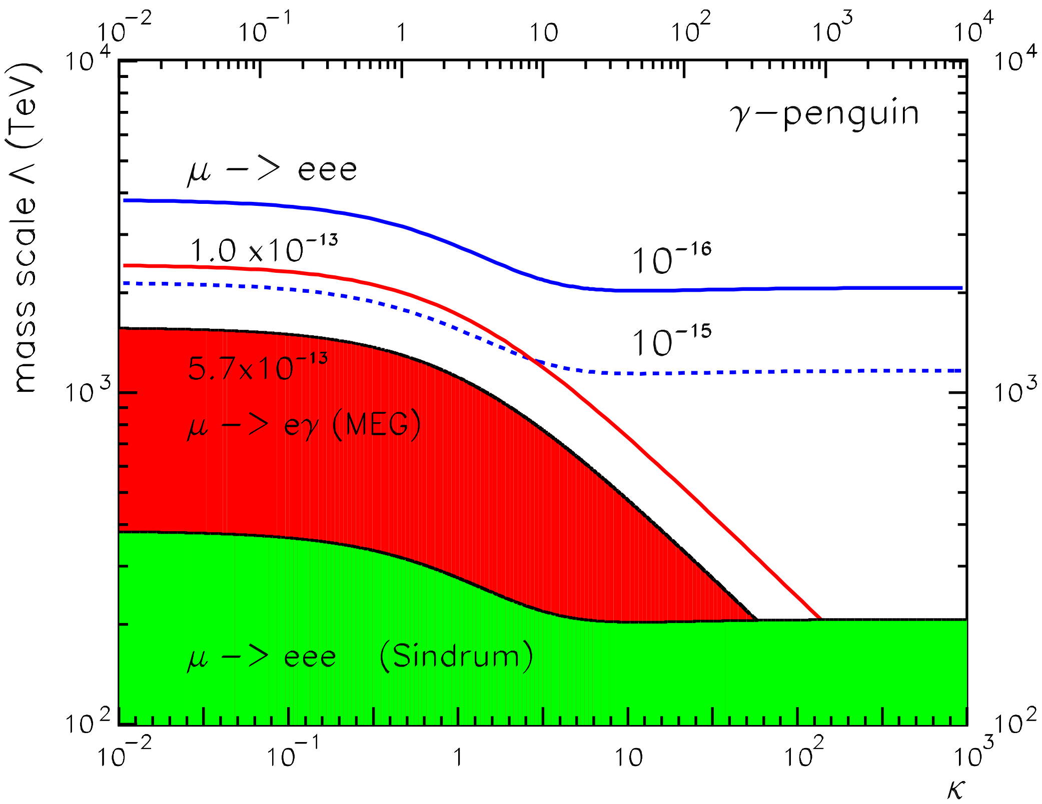
- Higgs triplet model
- Extra heavy vector bosons (Z')
- Extra dimensions (Kaluza-Klein tower)

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



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





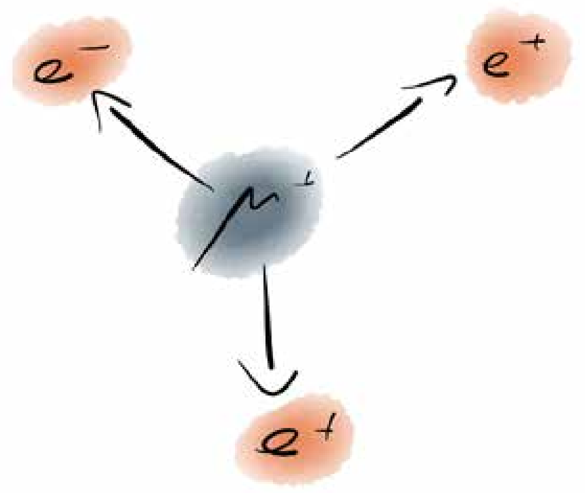

- One loop term and one contact term
- Ratio $\kappa$ between them
- Common mass scale $\Lambda$
- Allows for sensitivity comparisons between $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

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

# Searching for

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

# The Mu3e experiment at PSI




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

Aim for sensitivity

- $10^{-15}$ in phase I
- $10^{-16}$ in phase II

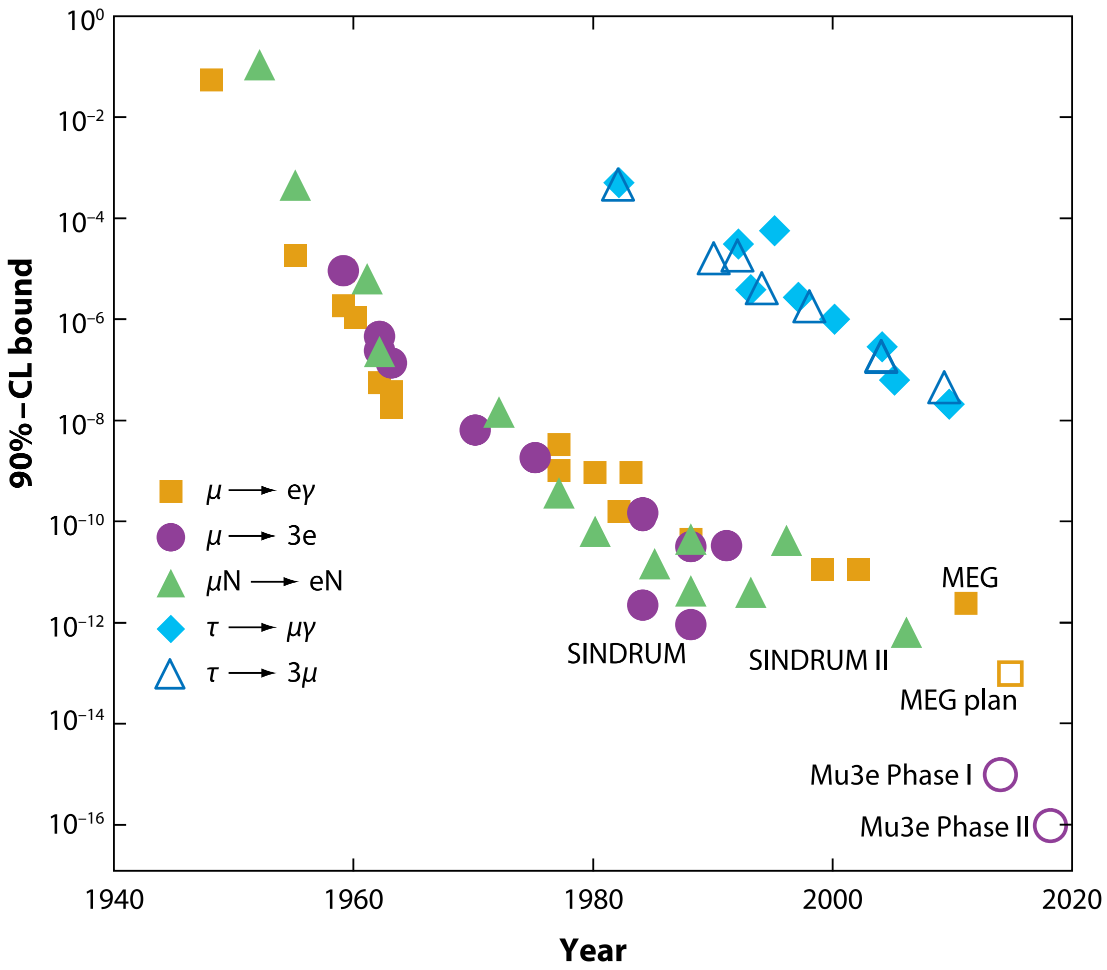
Project approved in January 2013

# The Mu3e Collaboration

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

# The 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)



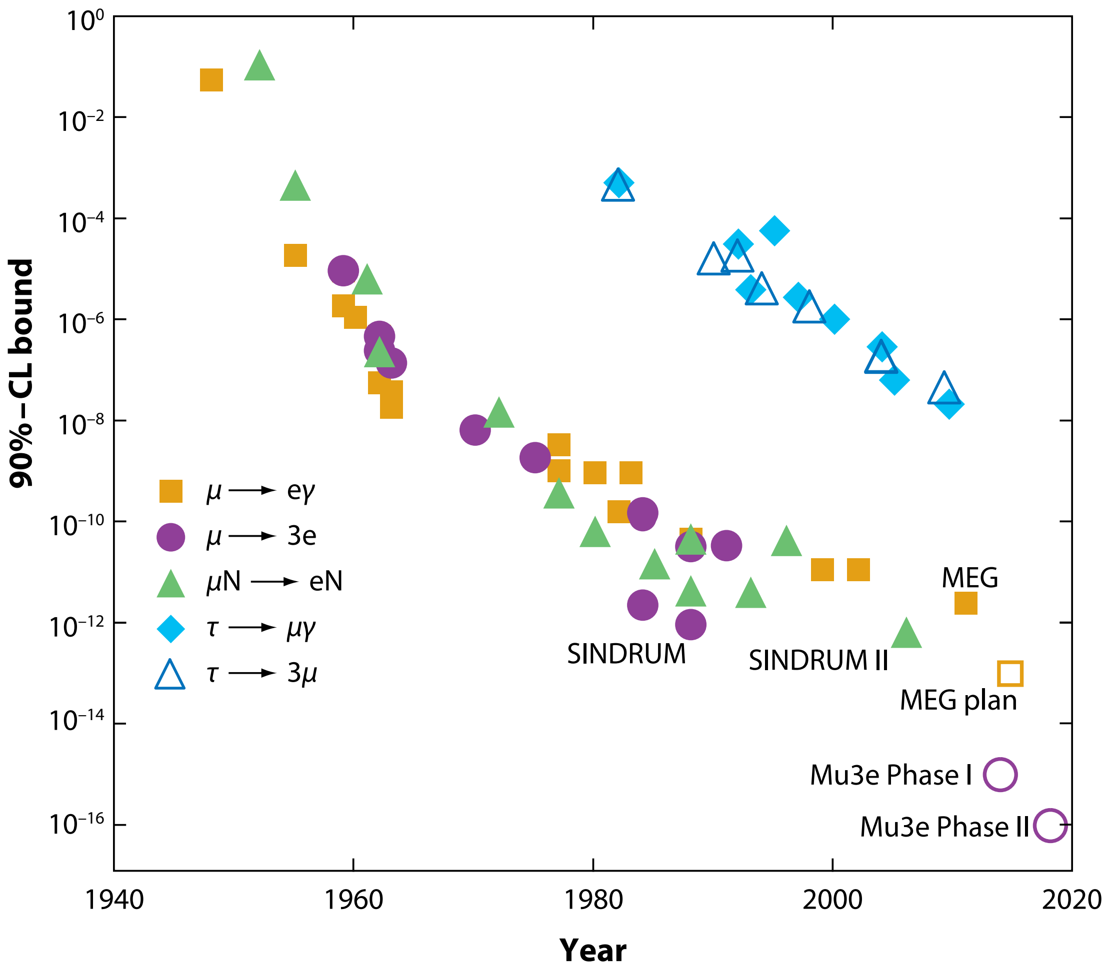

(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

# The Challenges

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

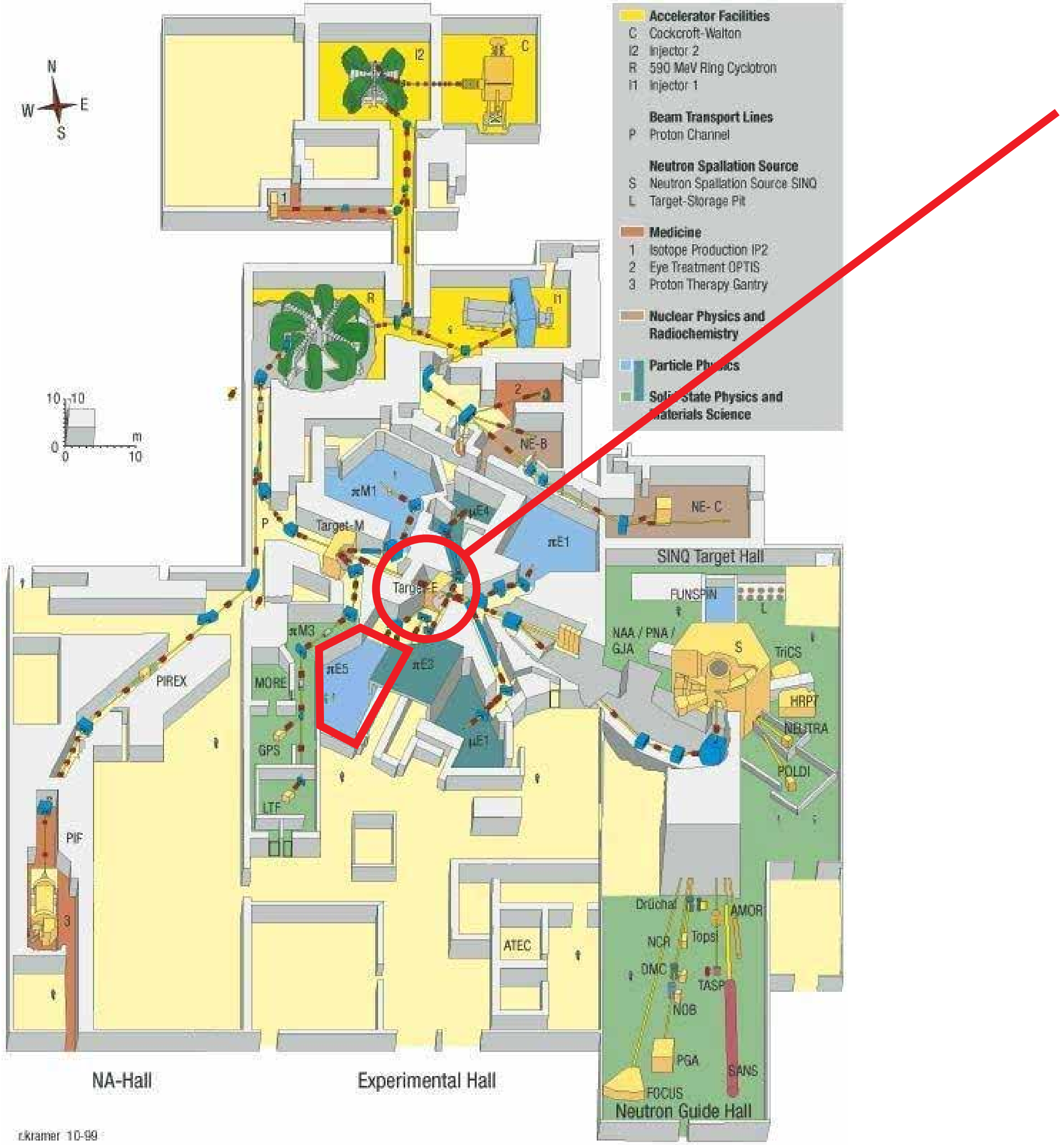
- Suppress backgrounds by more than 16 orders of magnitude

- Be sensitive for the signal




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

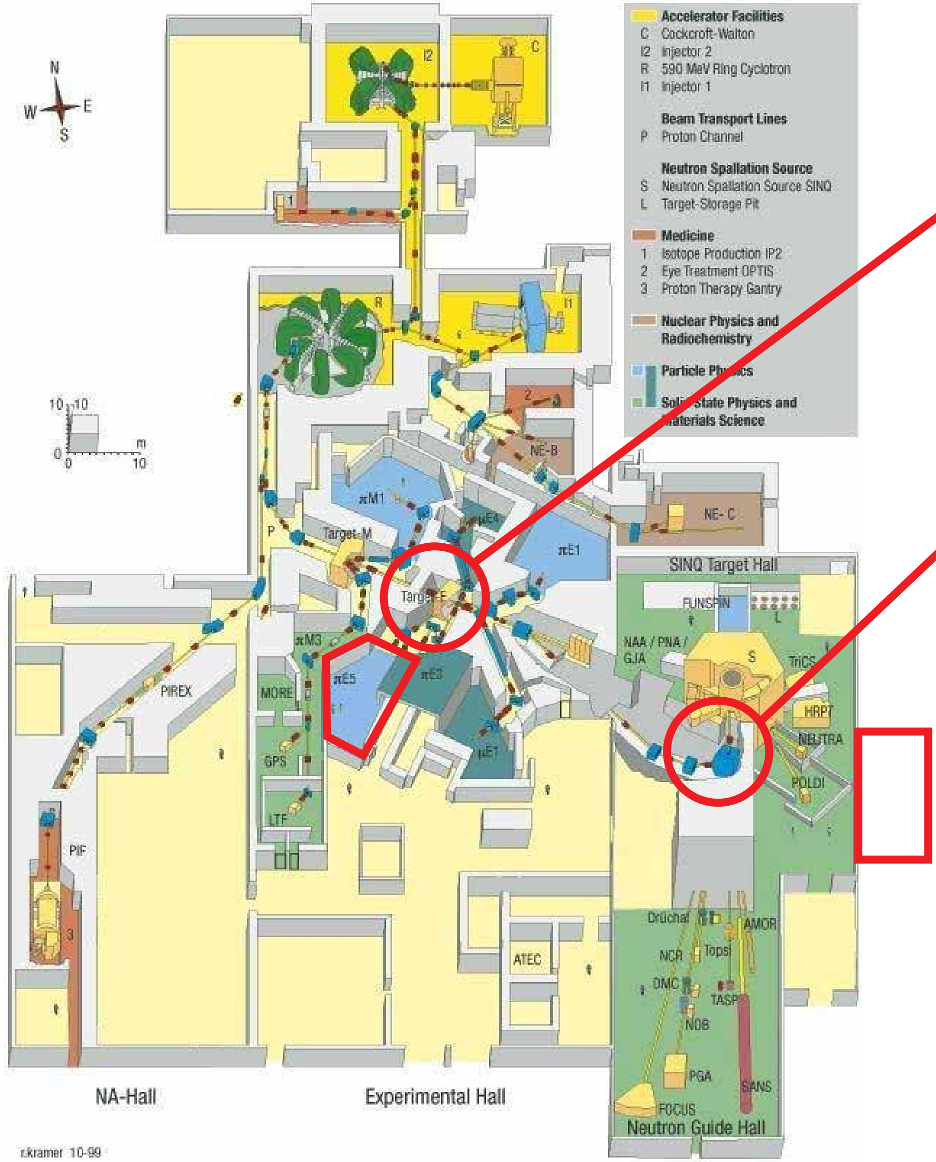
# Muons from PSI




DC muon beams at PSI:

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

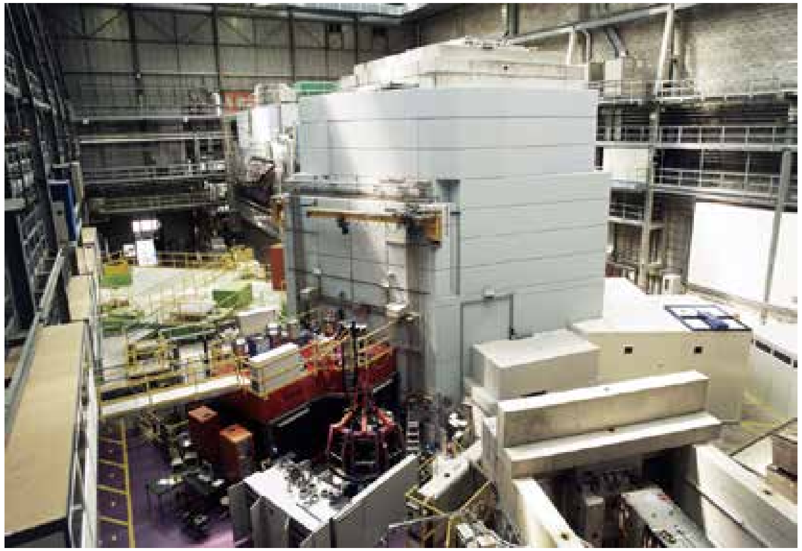
# Muons from PSI



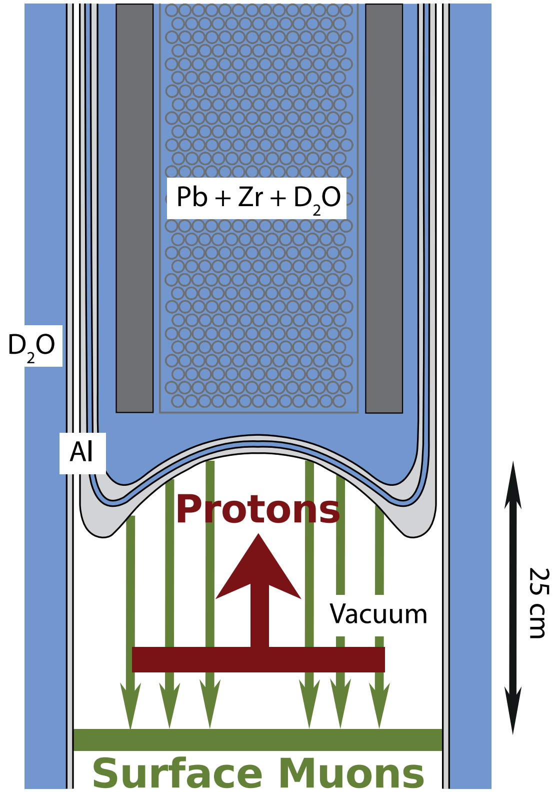

DC muon beams at PSI:

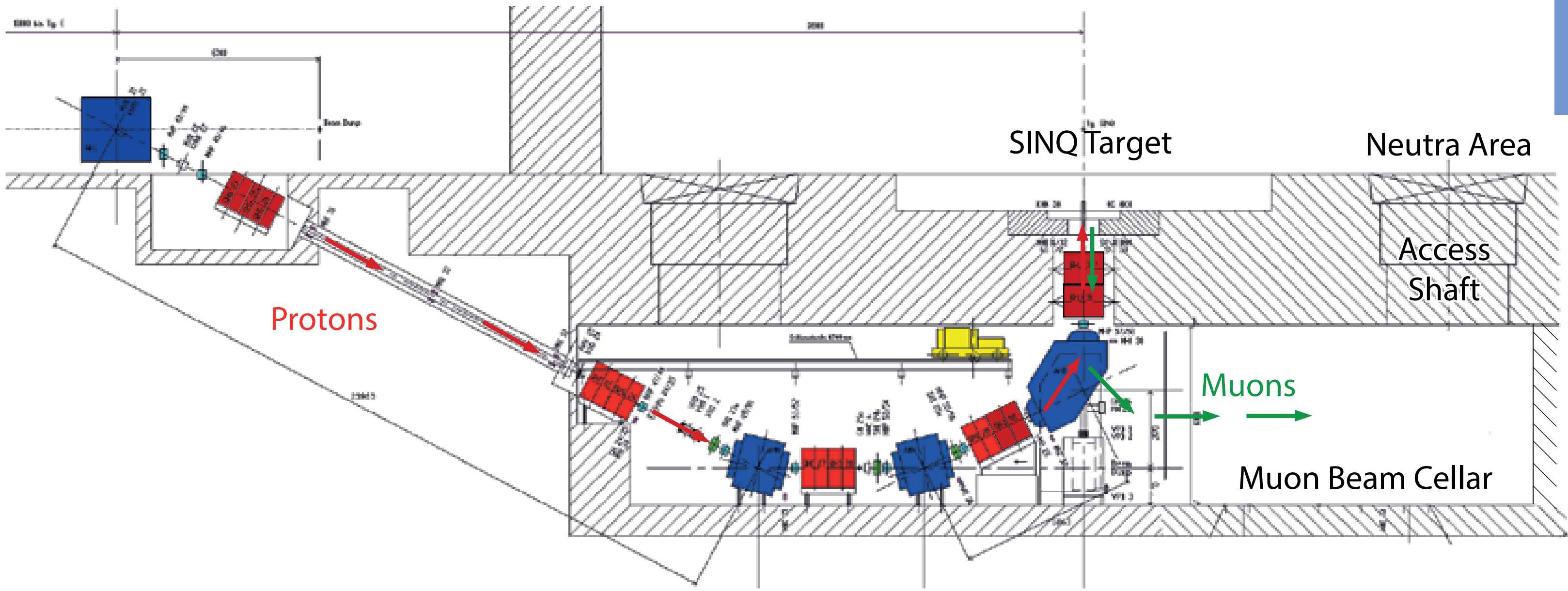
- πE5 beamline: ~ $10^8$ muons/s
  (MEG experiment, Mu3e phase I)
- SINQ (spallation neutron source) target could even provide
  ~ $5 \times 10^{10}$ muons/s
  High intensity muon beamline (HIMB) proposal
- The μ → eee experiment (final stage) requires $2 \times 10^9$ muons/s focused and collimated on a ~2 cm spot

# The High-Intensity Muon Beamline (HIMB)

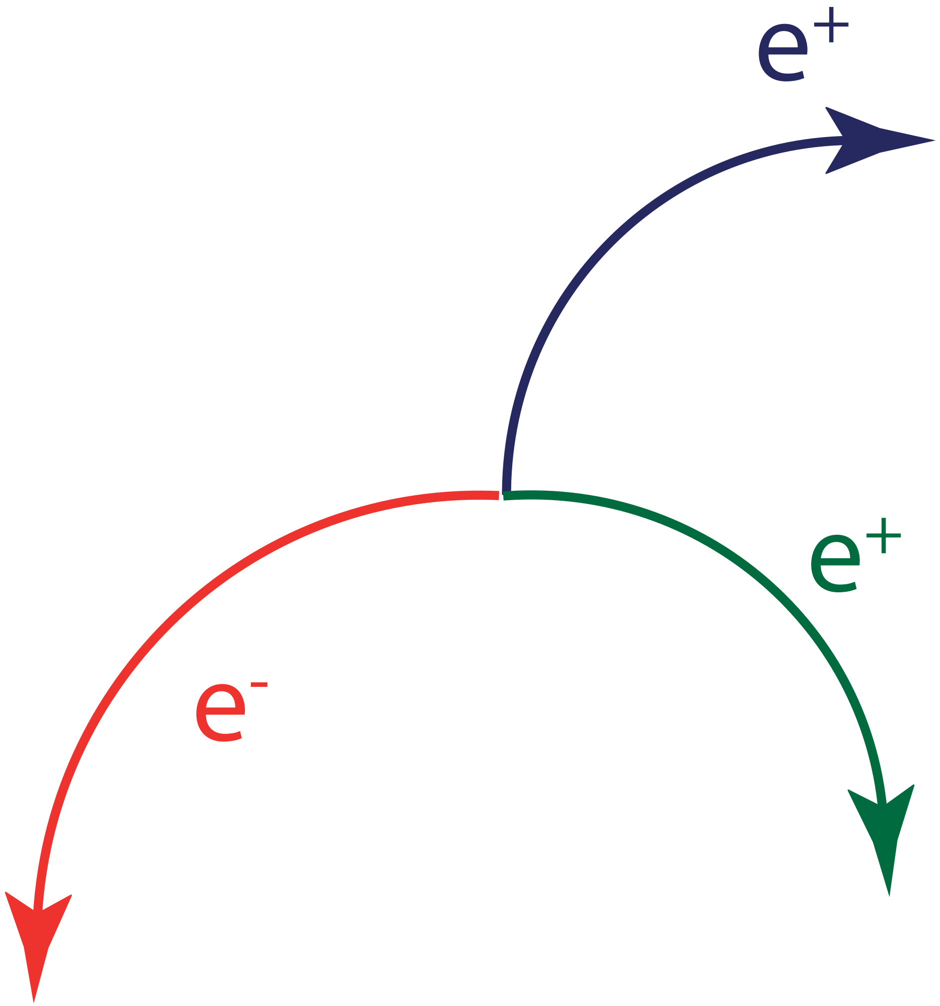


- Muon rates in excess of $10^{10}$/s in acceptance
- $2 \cdot 10^{9}$/s needed for $\mu \rightarrow eee$ at $10^{-16}$
- Not before 2017



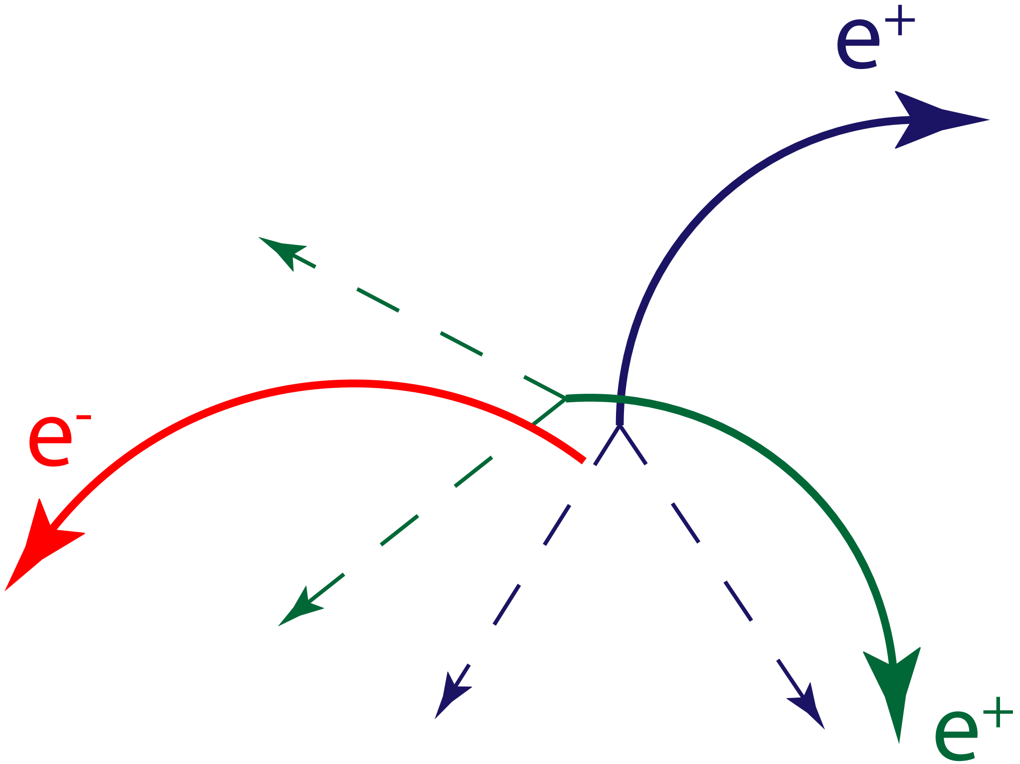



# The signal




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

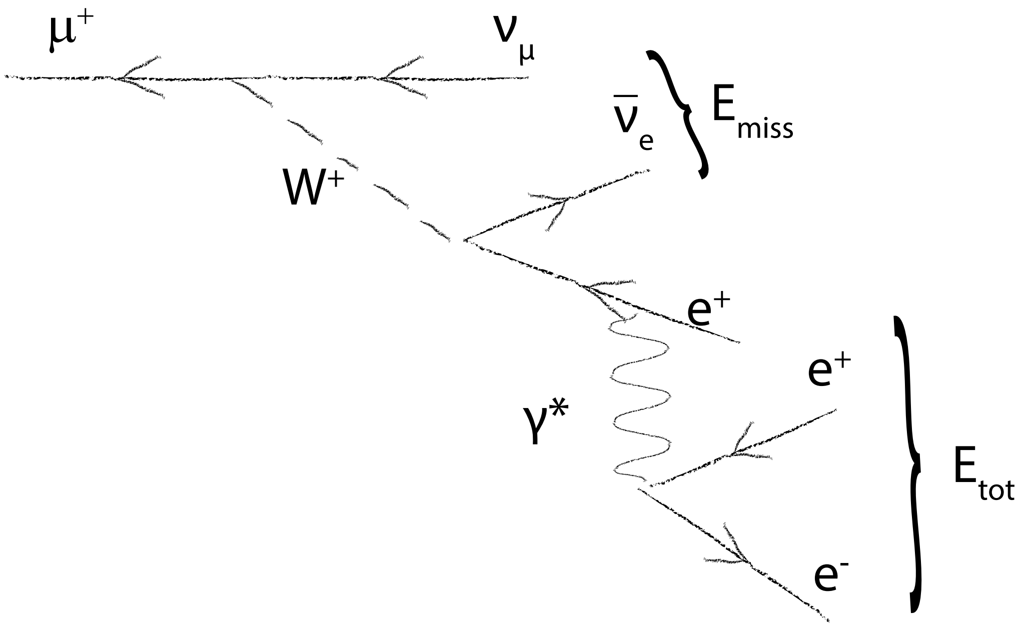
# Accidental Background




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

- Need very good timing, vertex and momentum resolution

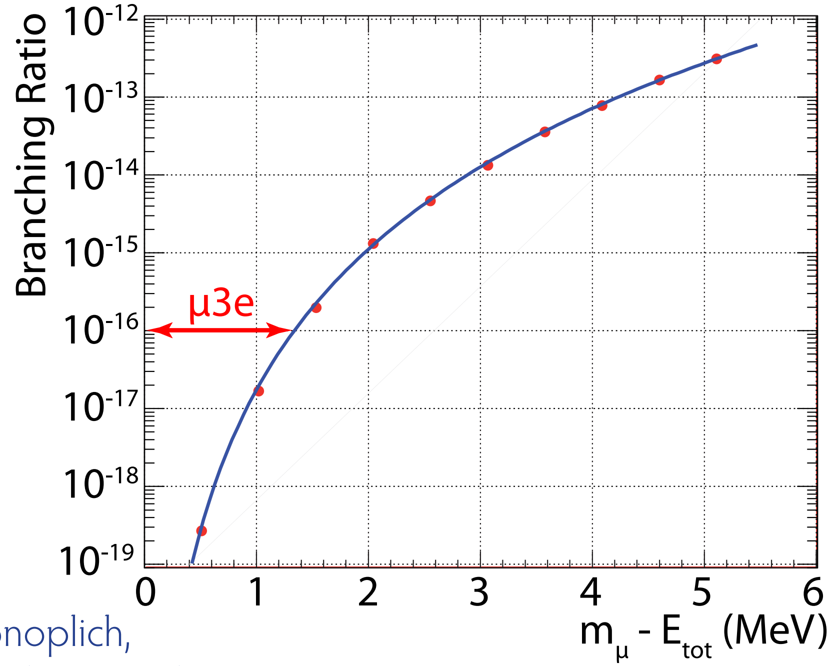
# Internal conversion background




- Allowed radiative decay with internal conversion:

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

- Only distinguishing feature: Missing momentum carried by neutrinos

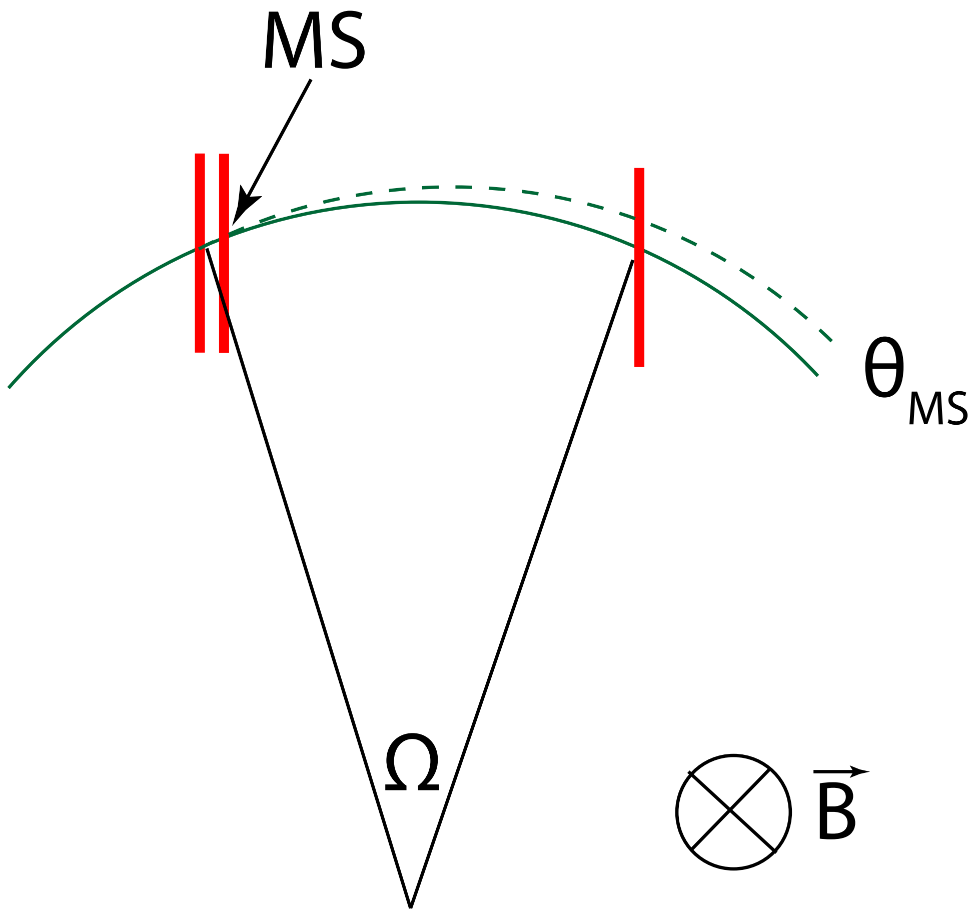



(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

- Need excellent momentum resolution

# Building the
# Mu3e Experiment

# Momentum measurement

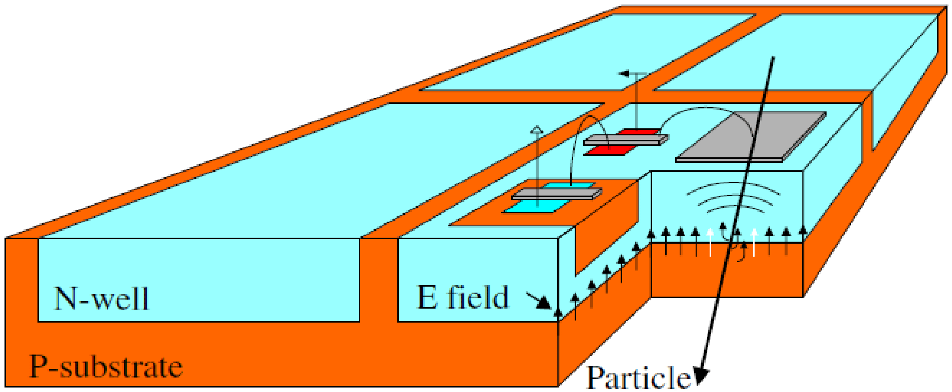



- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

- Precision requires large lever arm (large bending angle $\Omega$) and low multiple scattering $\theta_{MS}$

# 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 )

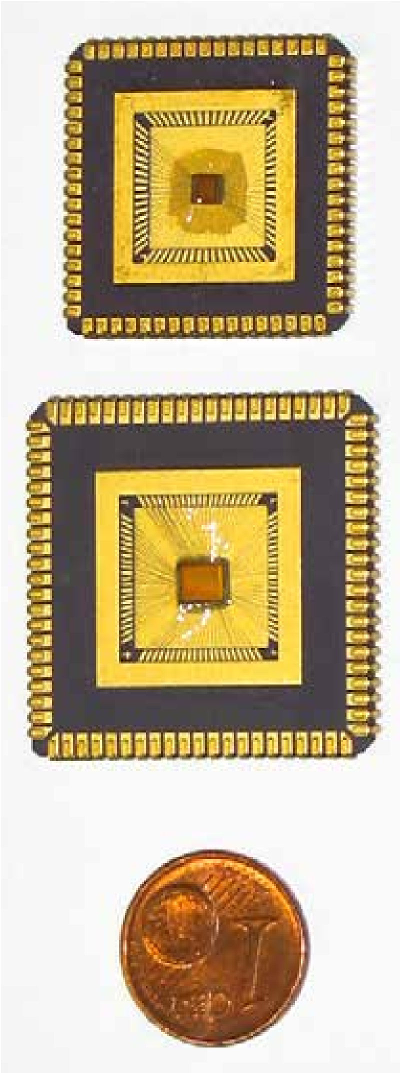
# The MUPIX chips

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

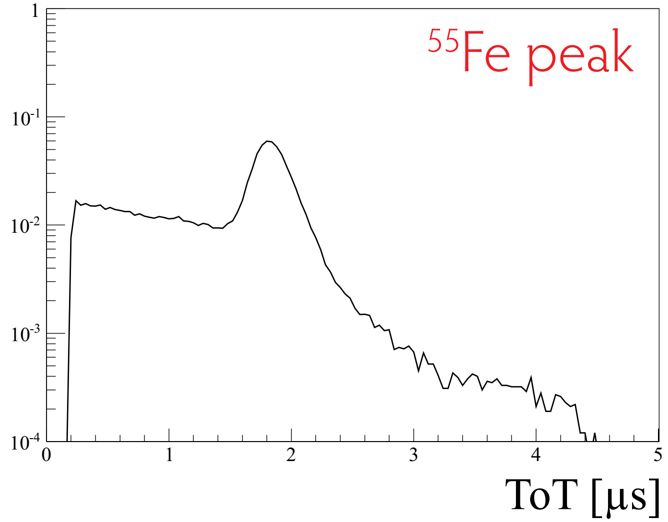


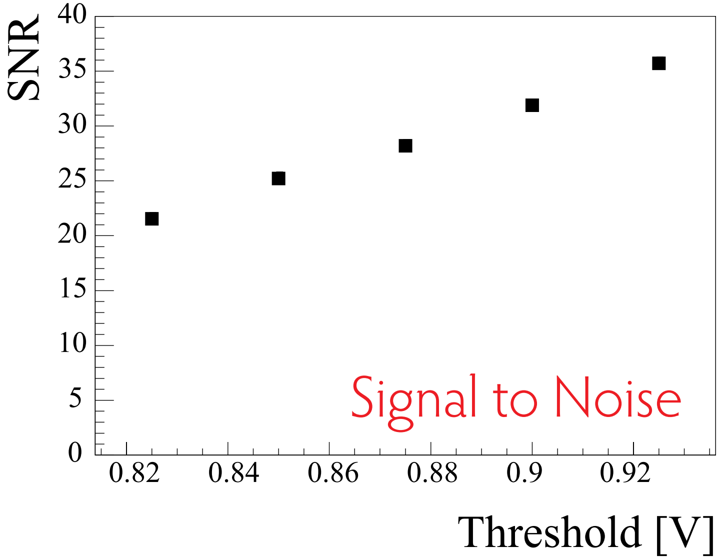
- MUPIX2:
  Characterization during 2012
  Single pixel Time-Over-Threshold
  Binary pixel matrix

- MUPIX3:
  Just bonded
  Column logic with address generation

  Extensive test beam campaign 2013

# MUPIX 2 Results

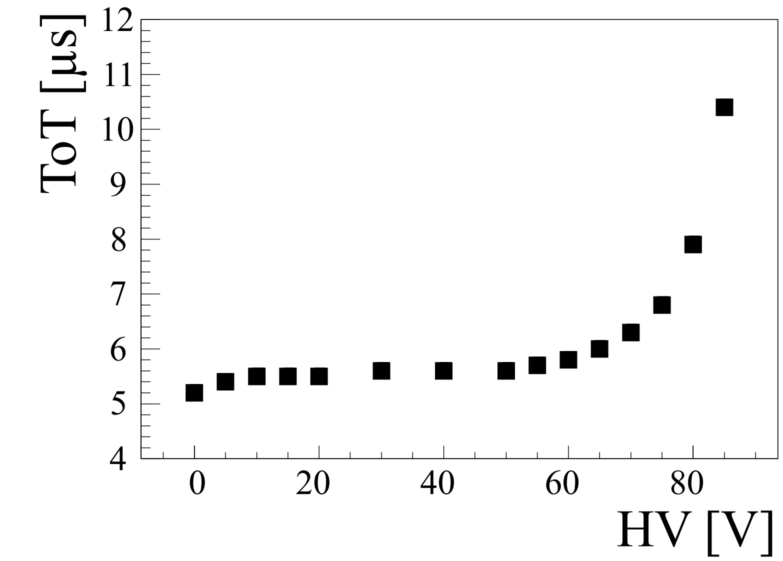


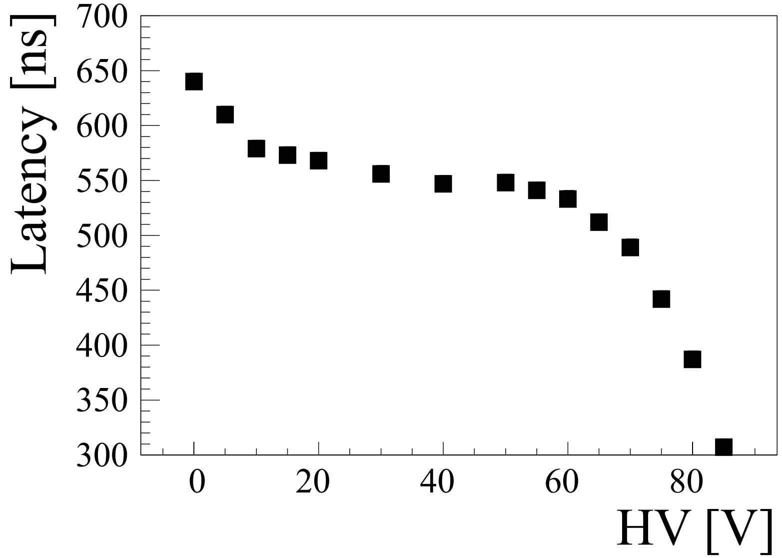




- Measurements with $^{55}$Fe source
- Good energy measurement
- Very good signal to noise

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**

# 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)
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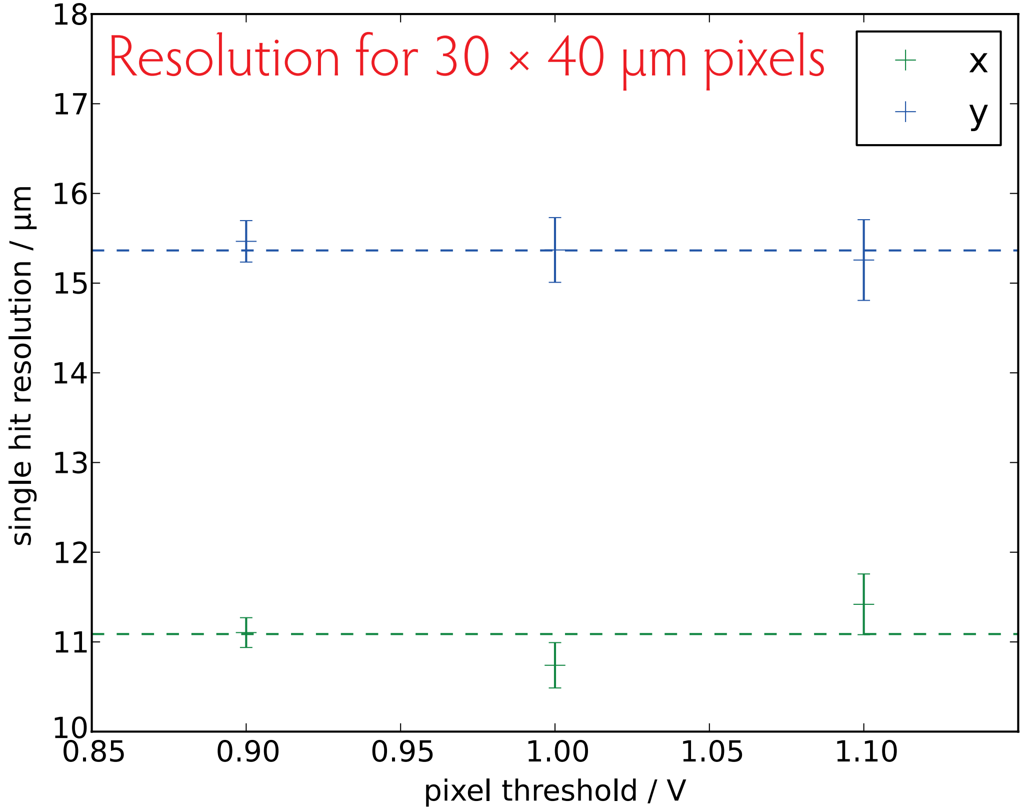
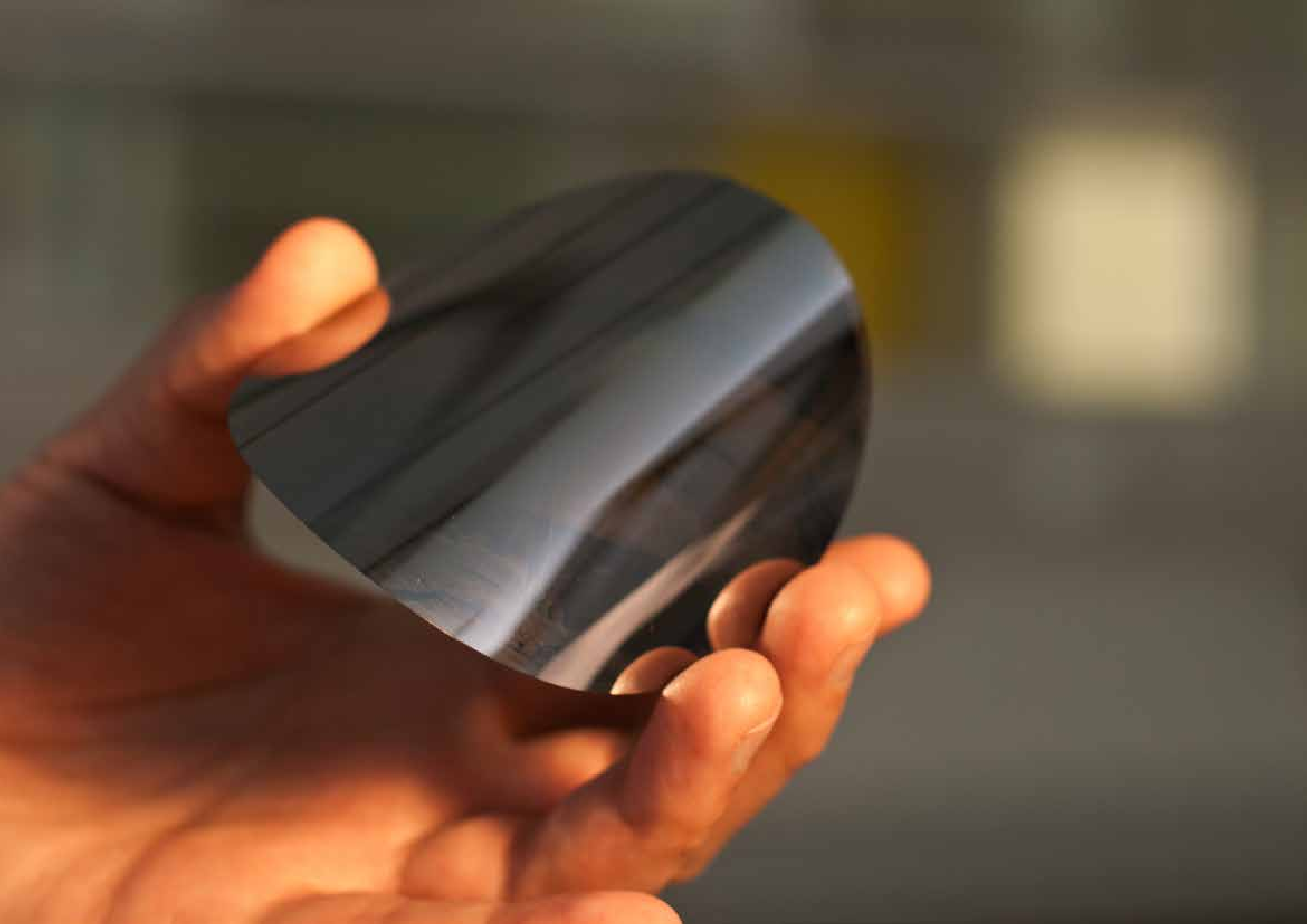
# MUPIX 2 results

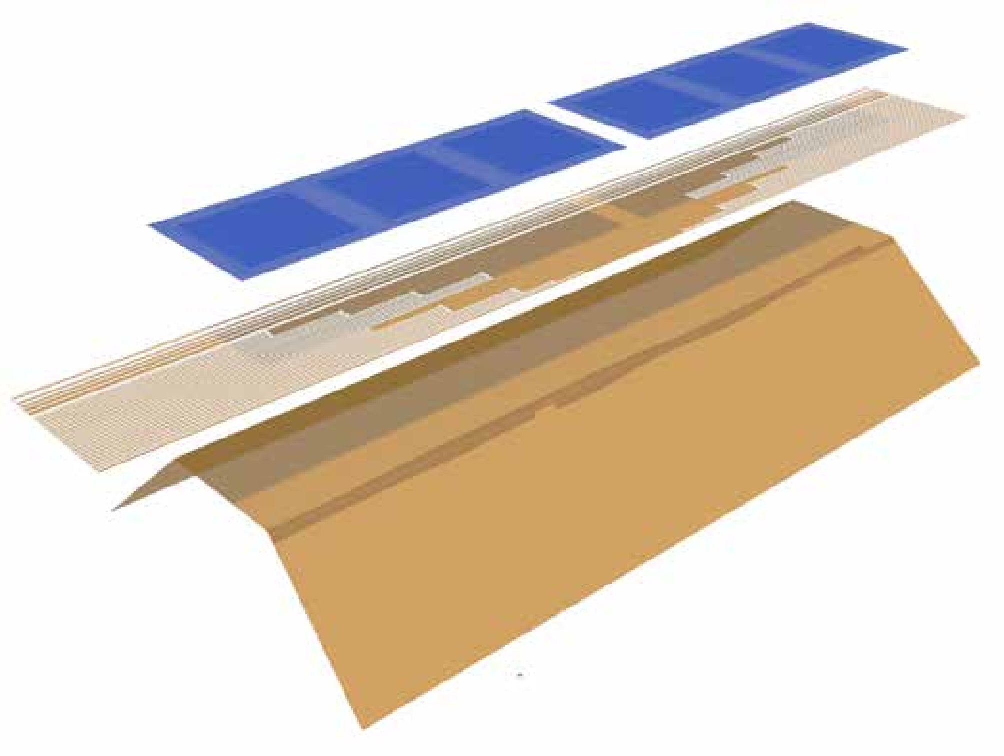



- Test beam at CERN SPS (170 GeV/c pions)
- Timepix telescope
- 2 hours data taking
- Mostly single pixel clusters
- Resolution as expected (pixel size/$\sqrt{12}$)

- More test beam data under study



# Mechanics



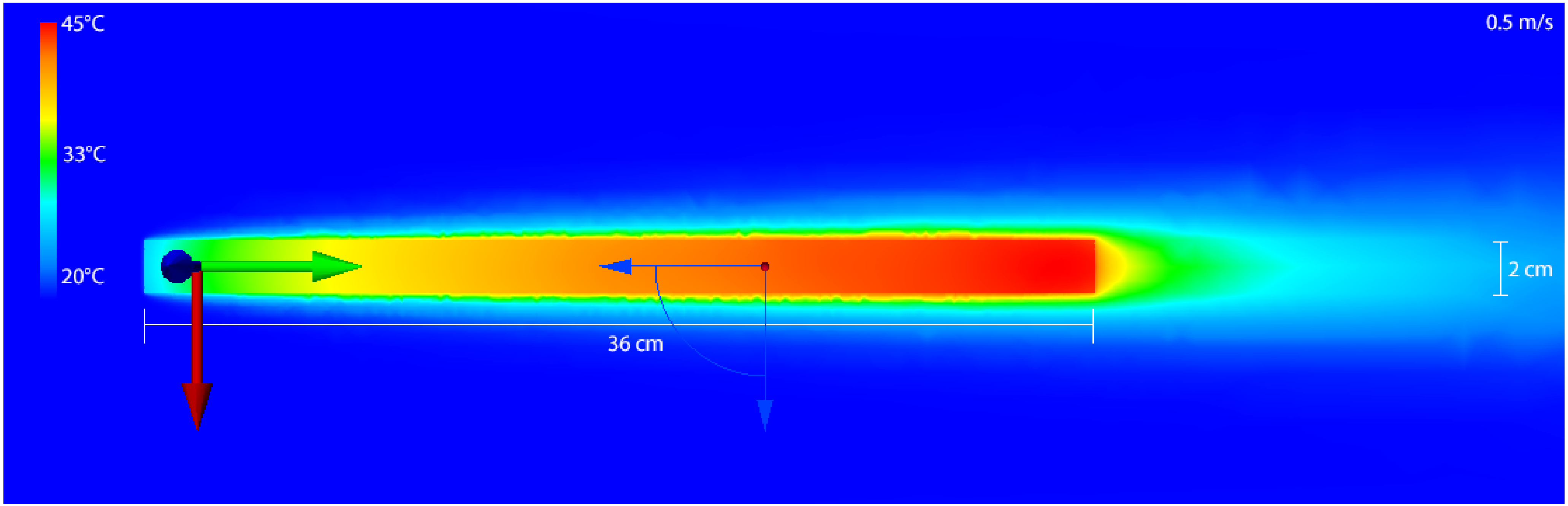
- 50 μm silicon
- 25 μm Kapton™ flexprint with aluminium traces
- 25 μm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

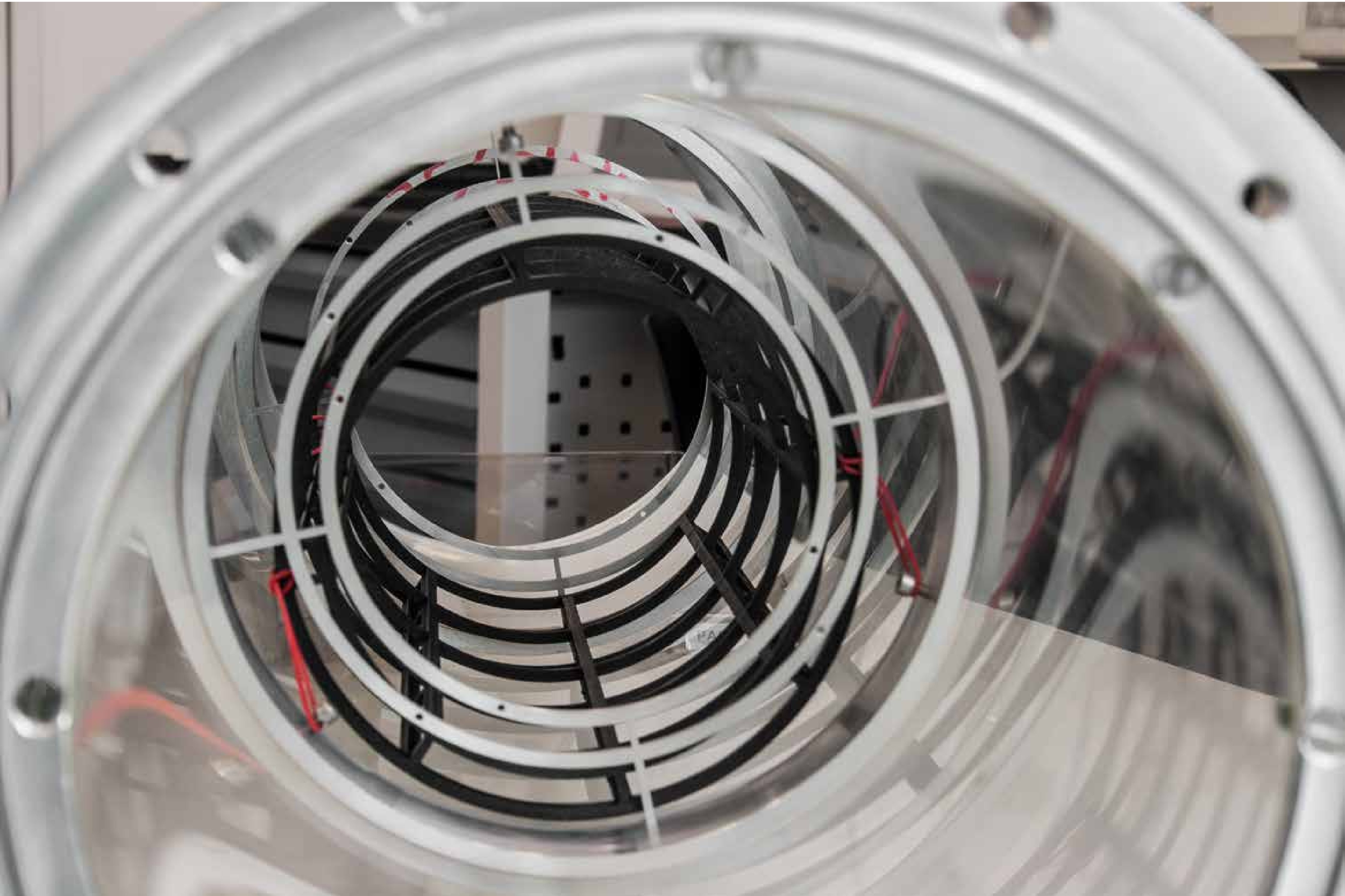


# Cooling

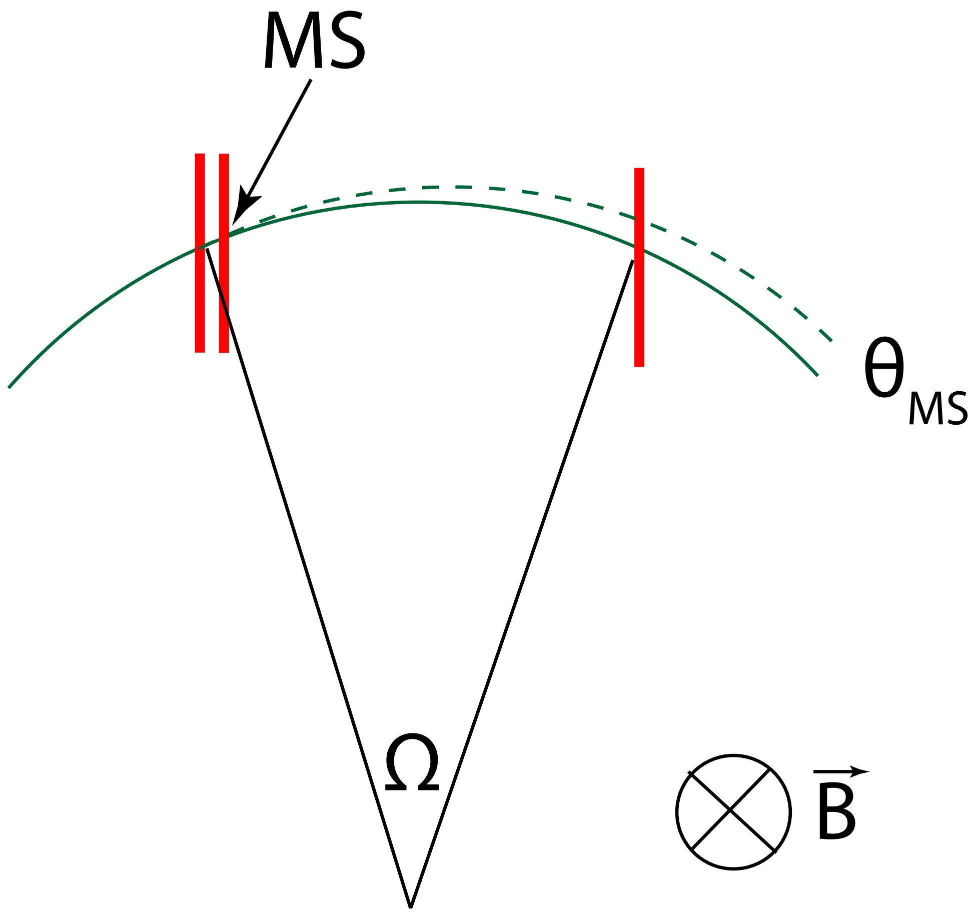
- Add no material:
  Cool with gaseous Helium
- ~ 150 mW/cm$^2$ - total 2 kW
- Simulations: Need ~ 1 m/s flow
- First measurements: Need several m/s
- Full scale prototype on the way

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





# Momentum measurement

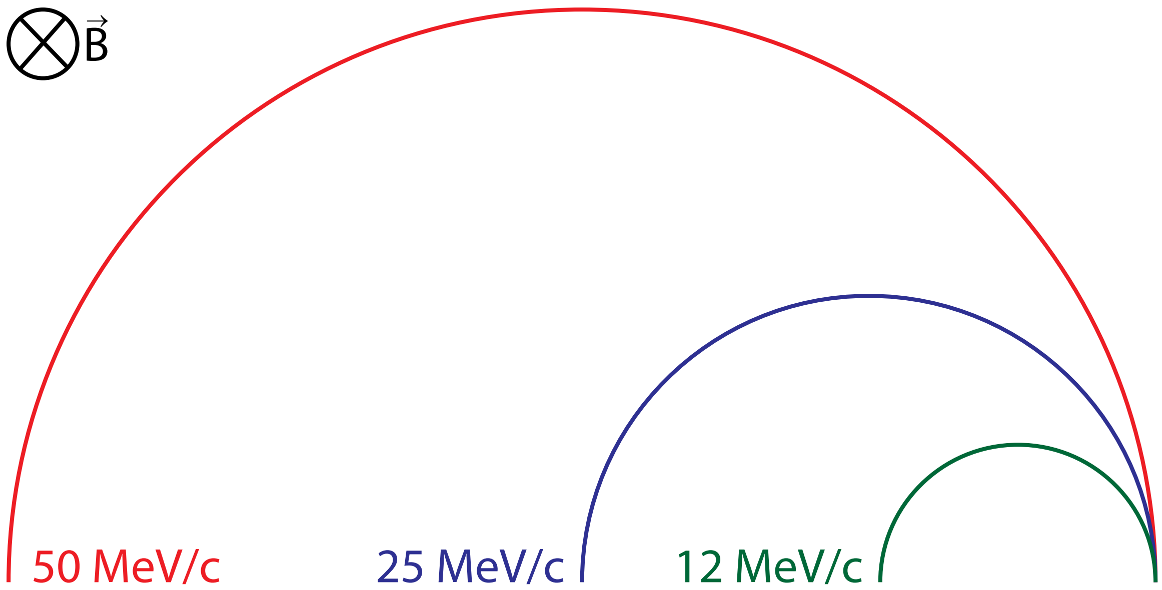



- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

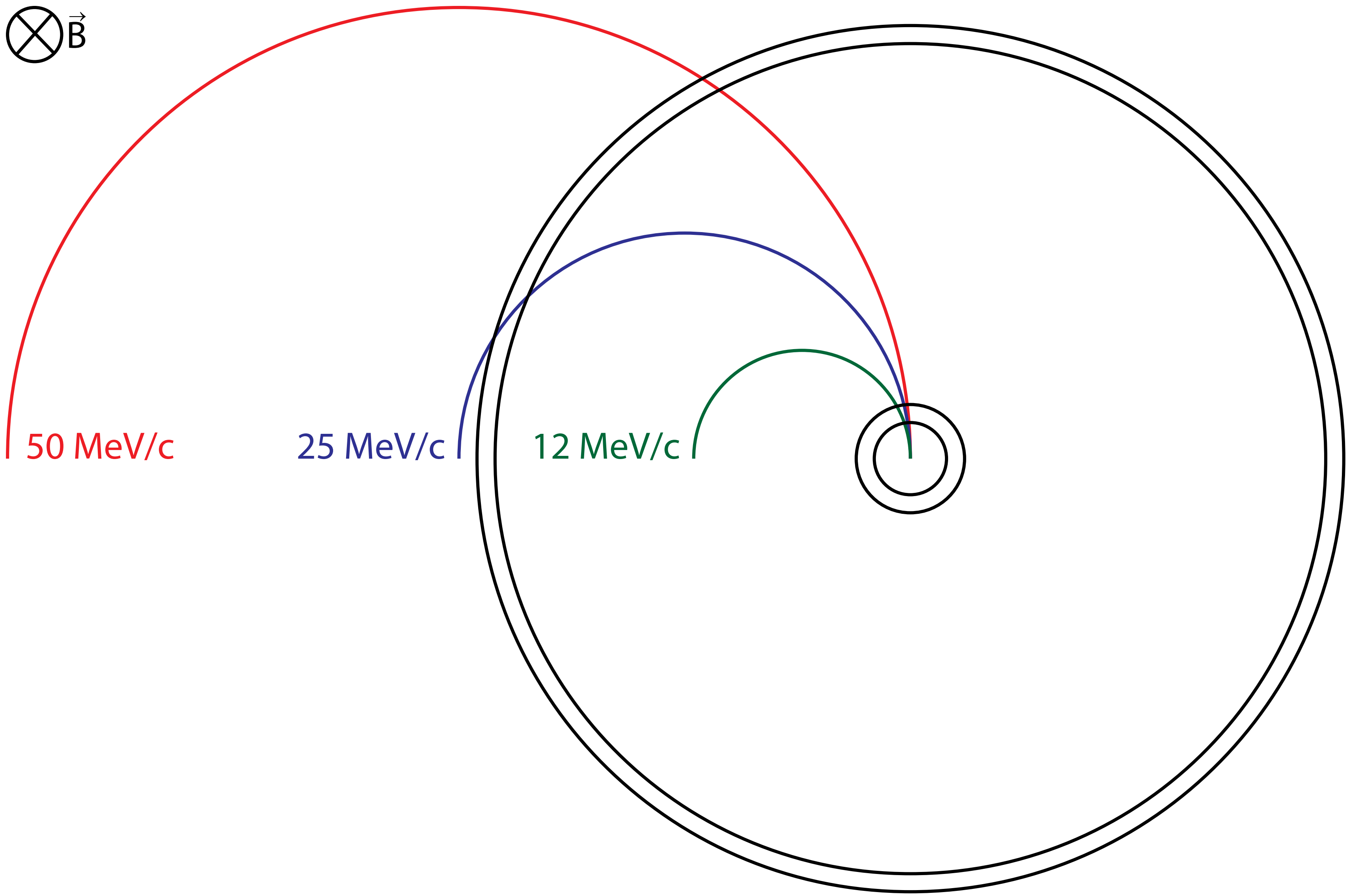
$$\sigma_P/_P \sim \theta_{MS}/_\Omega$$

- Precision requires large lever arm (large bending angle $\Omega$) and low multiple scattering $\theta_{MS}$

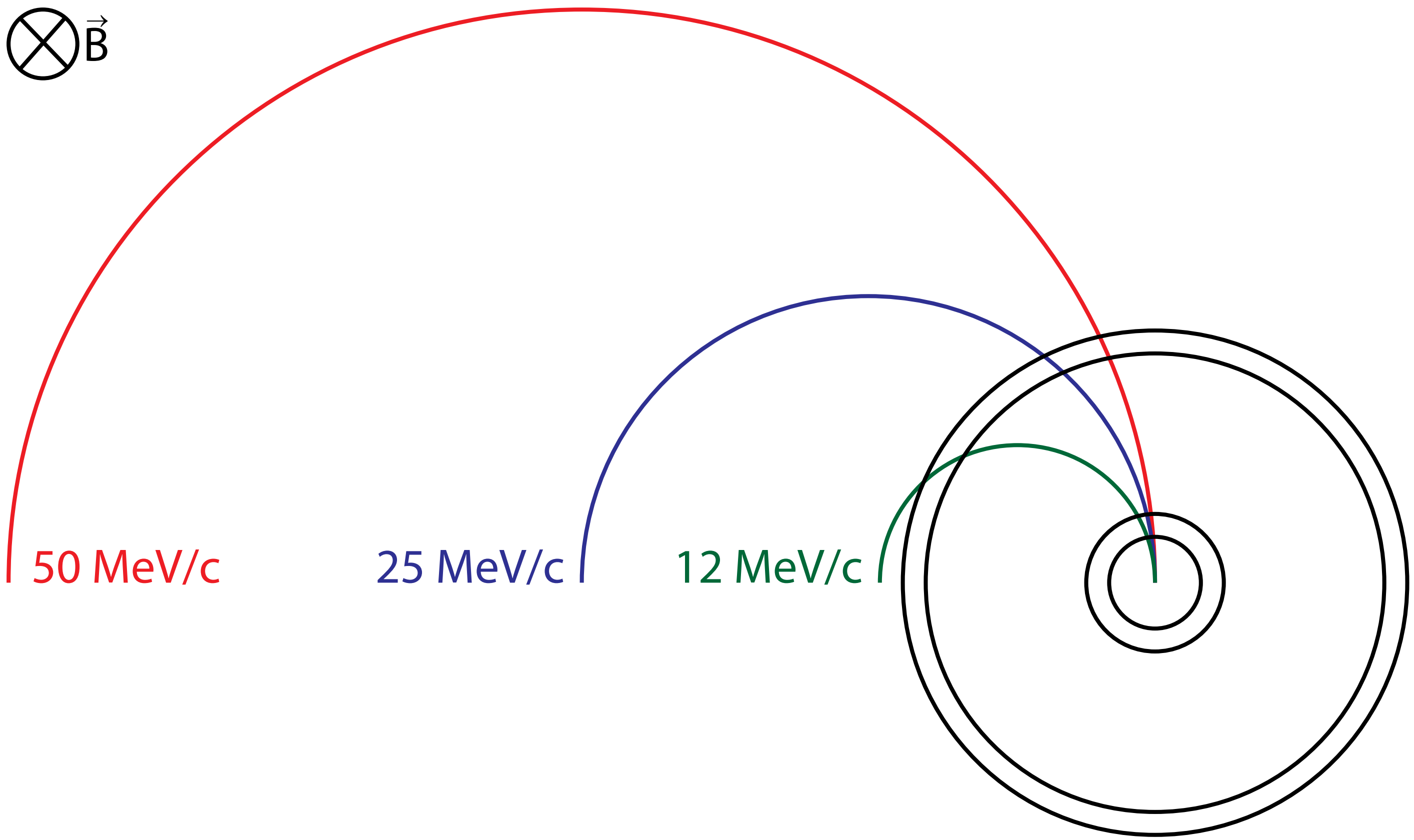
# Precision vs. Acceptance



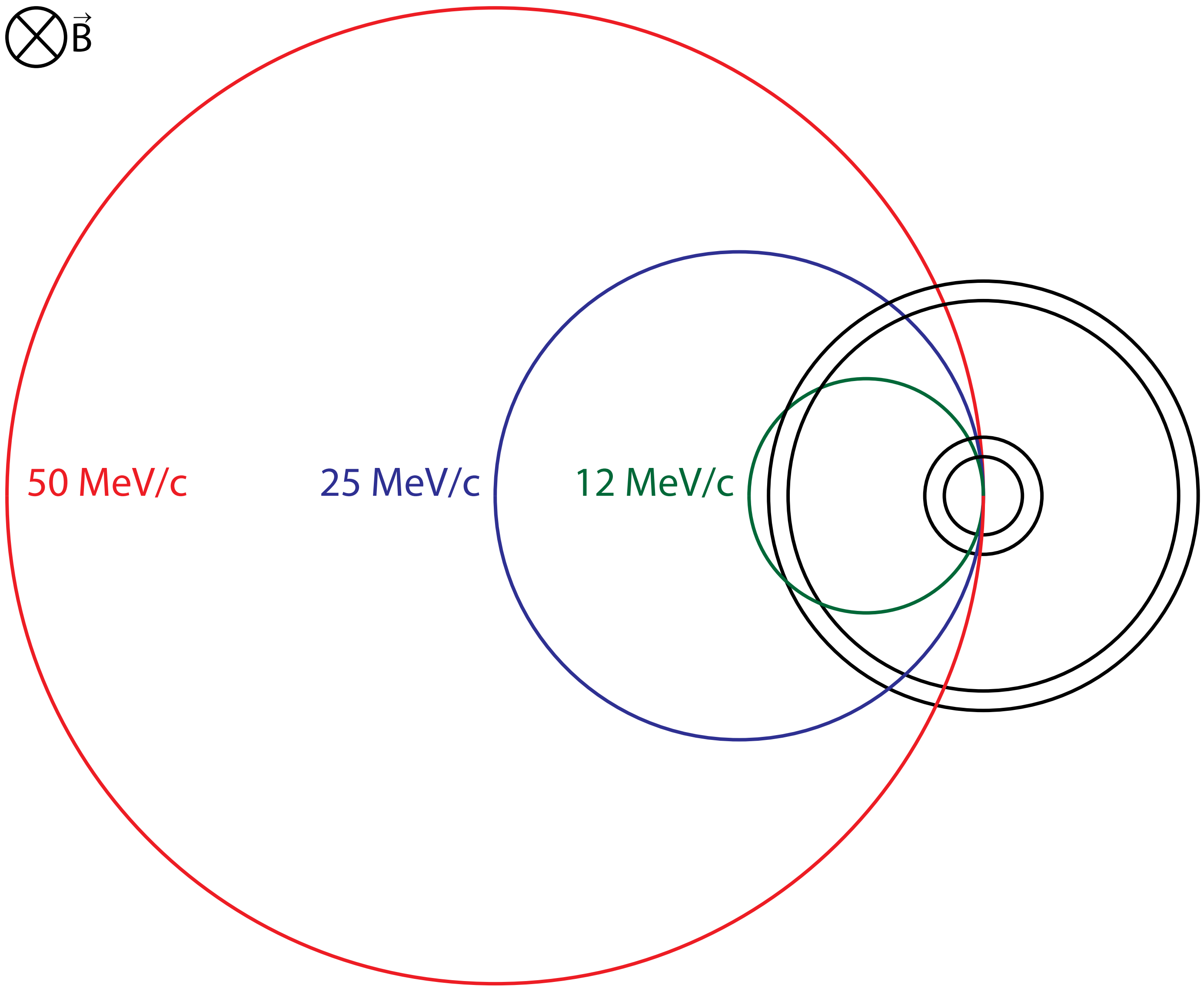
# Precision vs. Acceptance



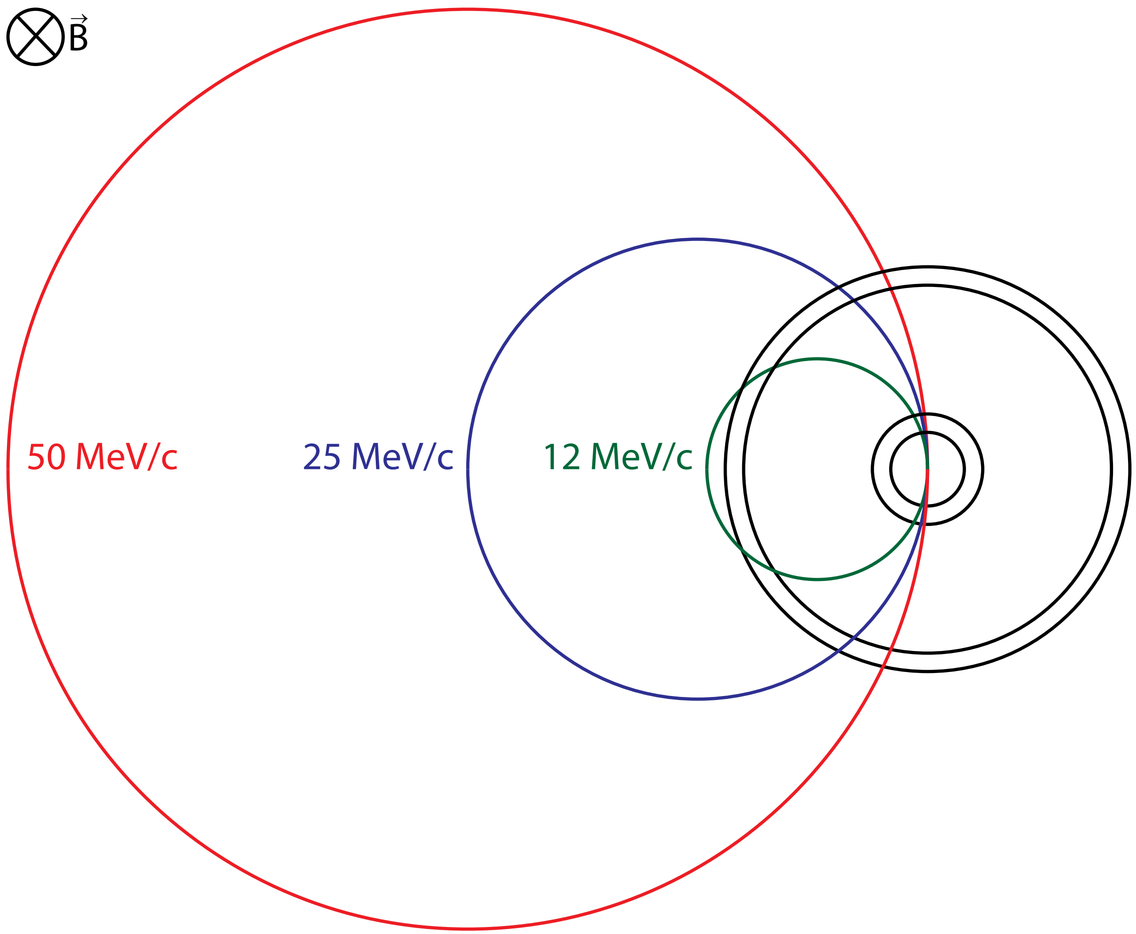
# Precision vs. Acceptance

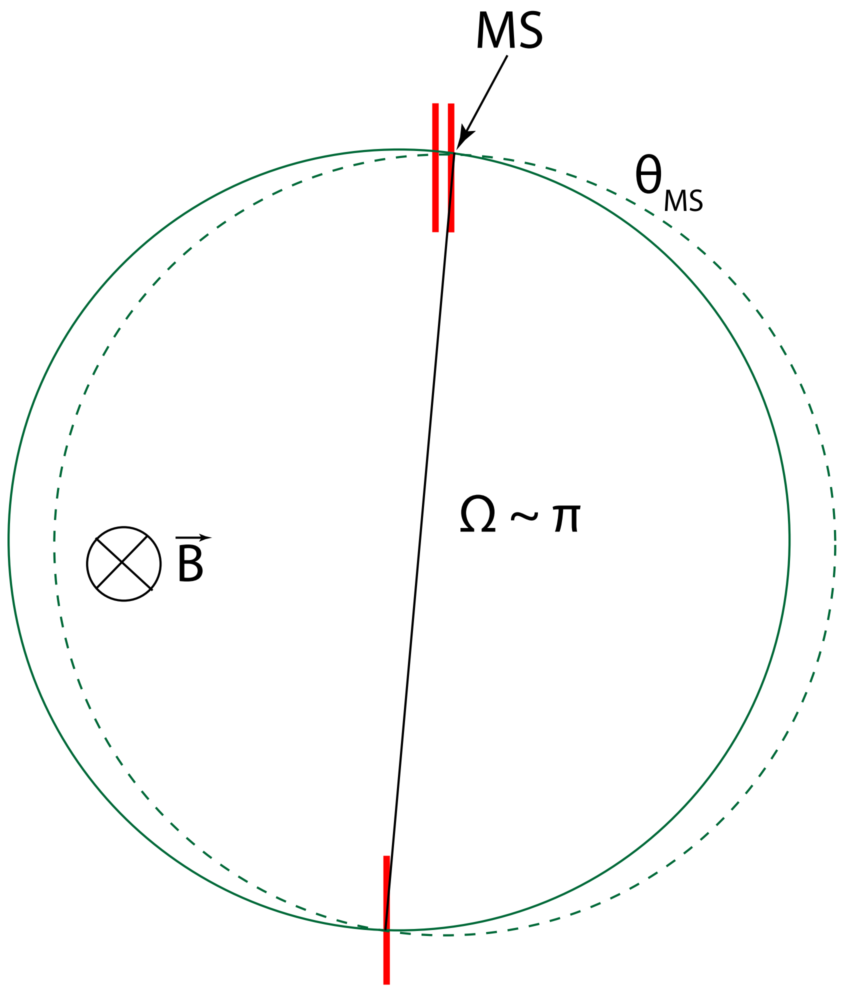


# Precision vs. Acceptance

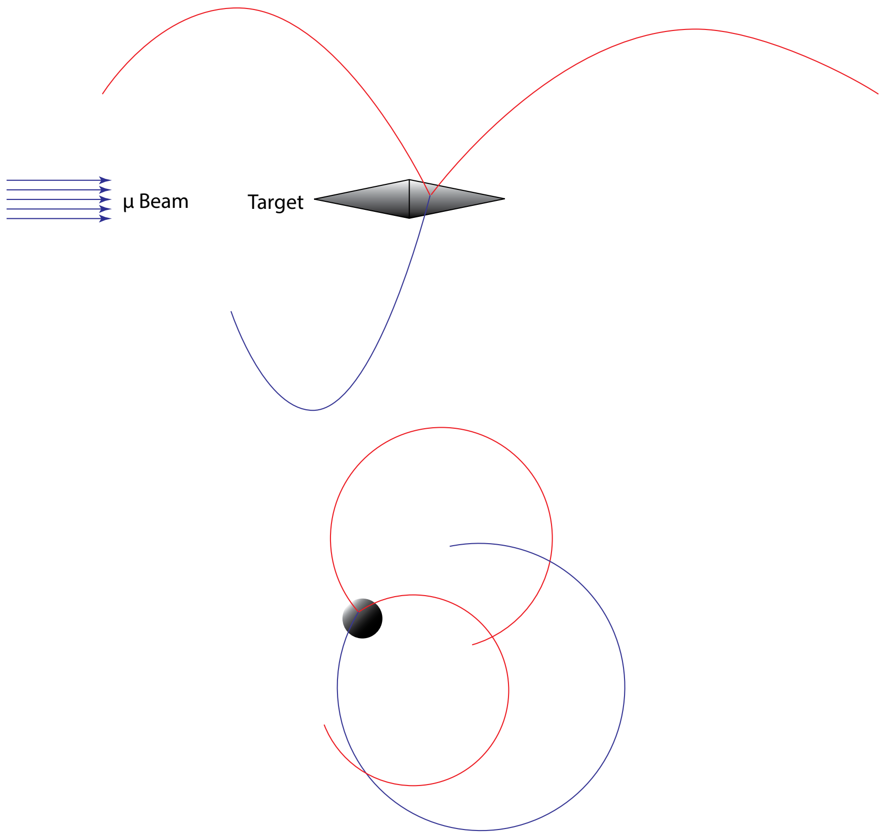


# Precision vs. Acceptance

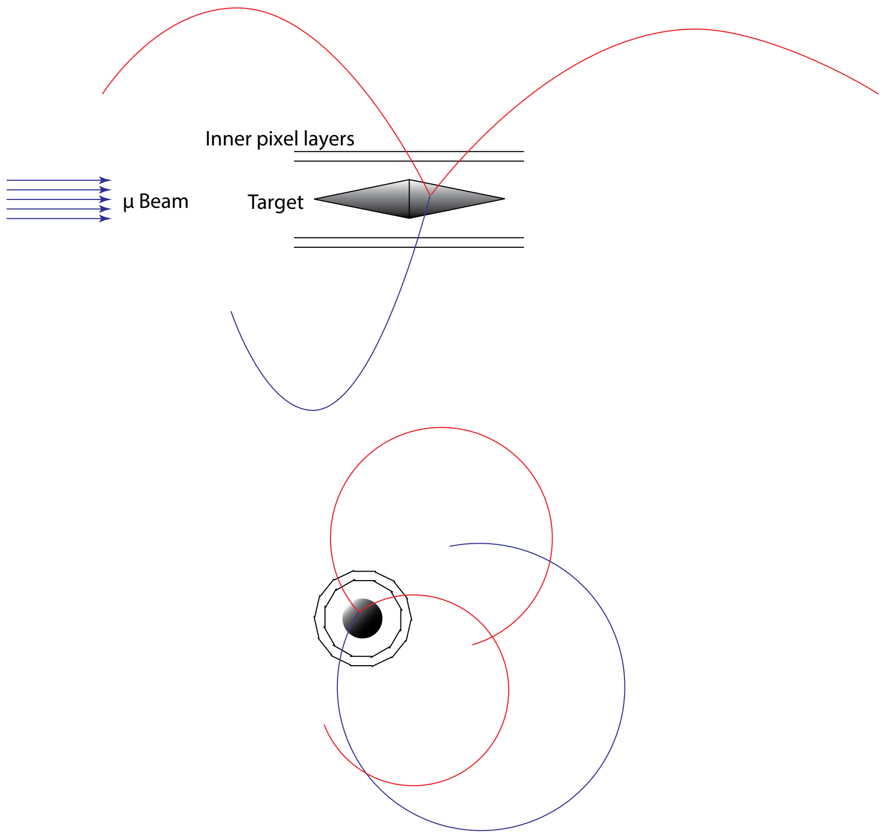


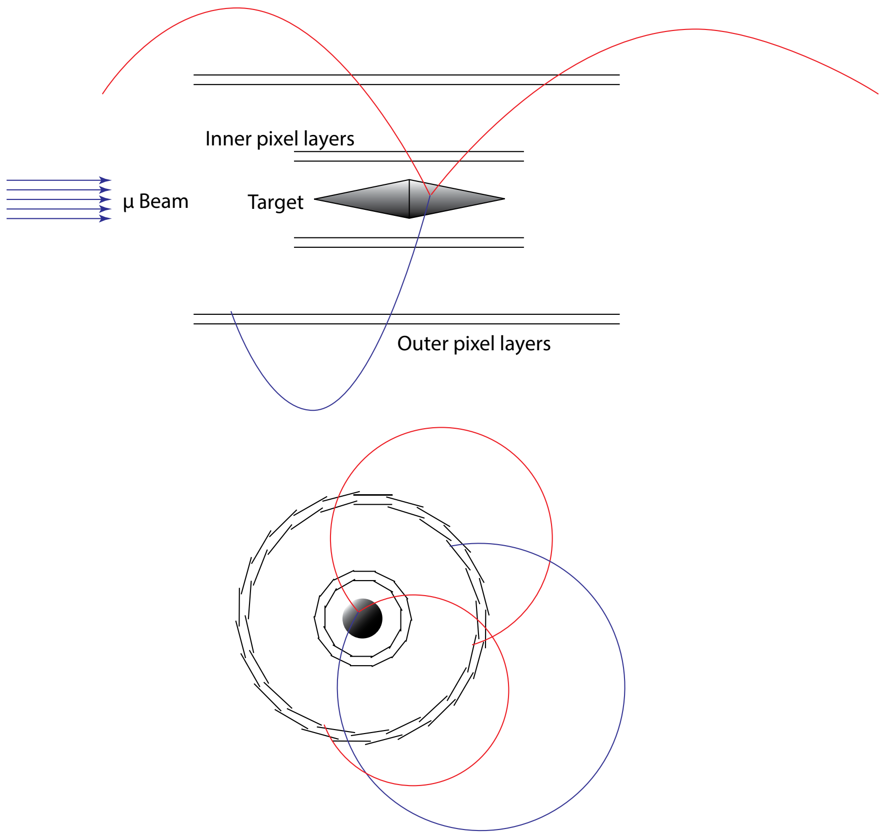
# Detector Design



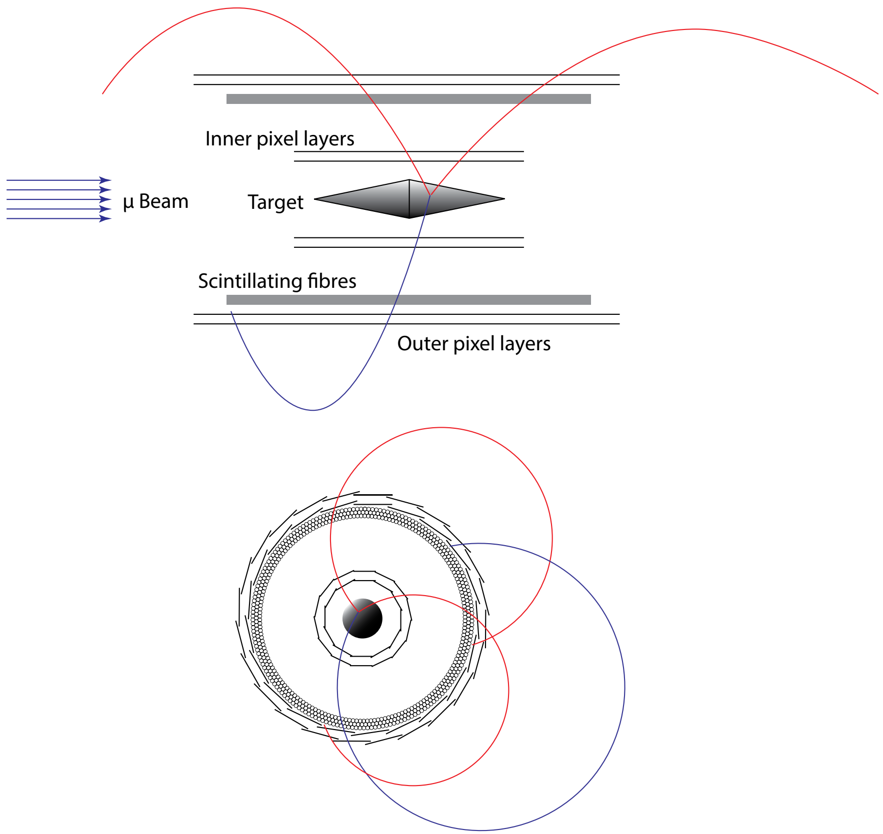
# Detector Design



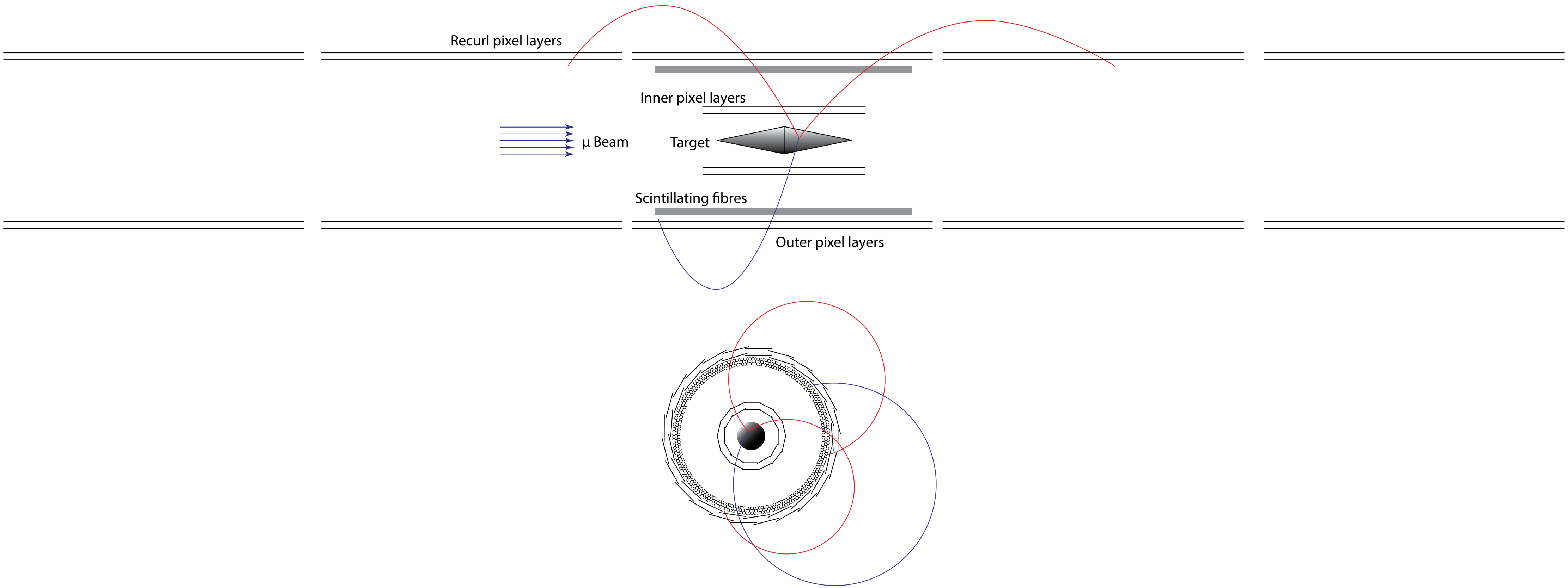
# Detector Design



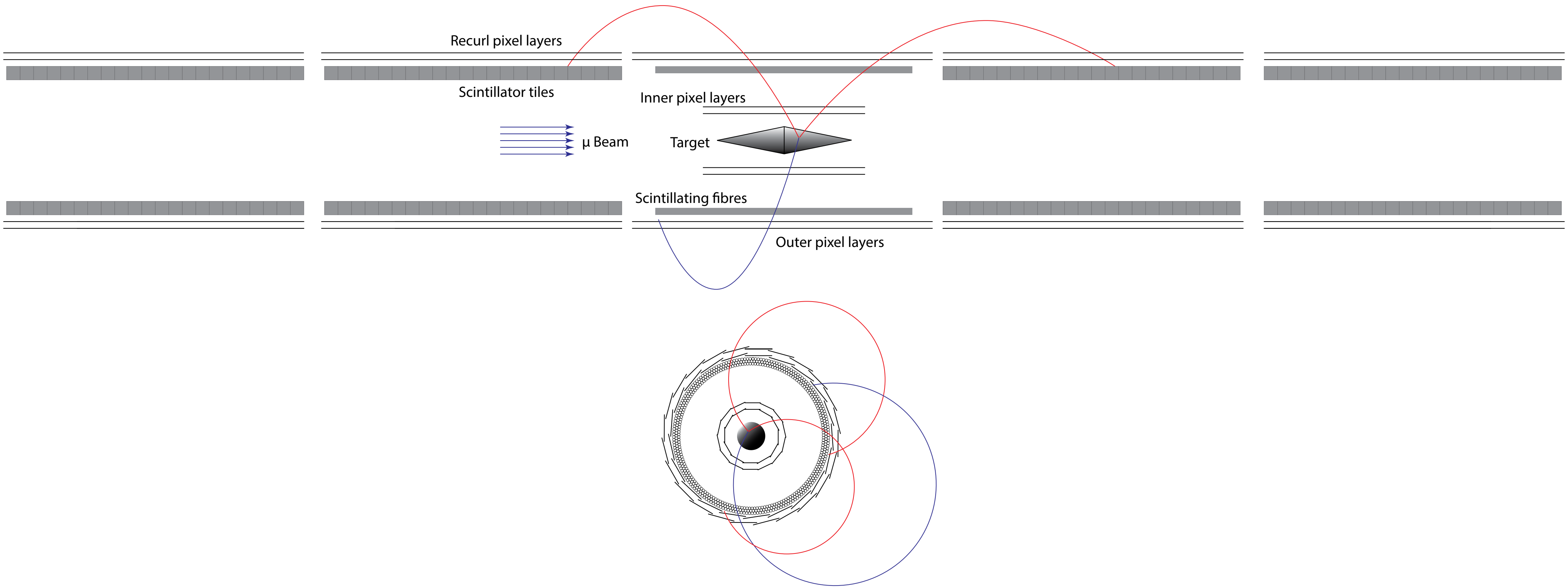
# Detector Design



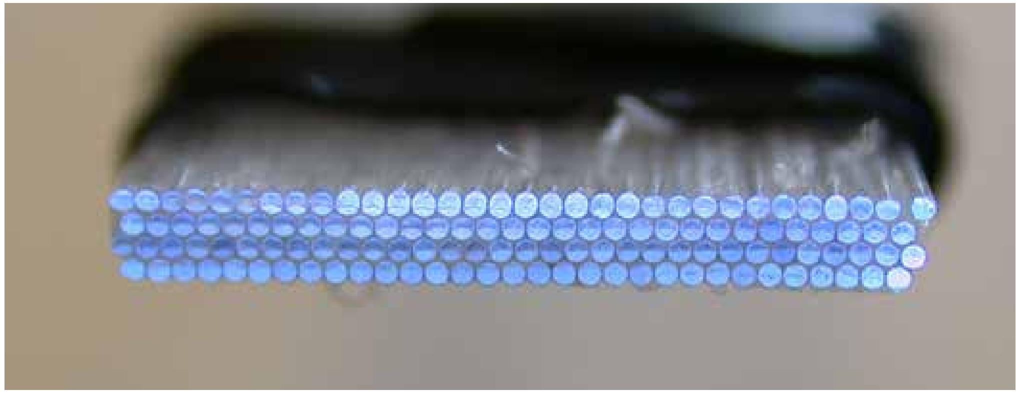
# Detector Design

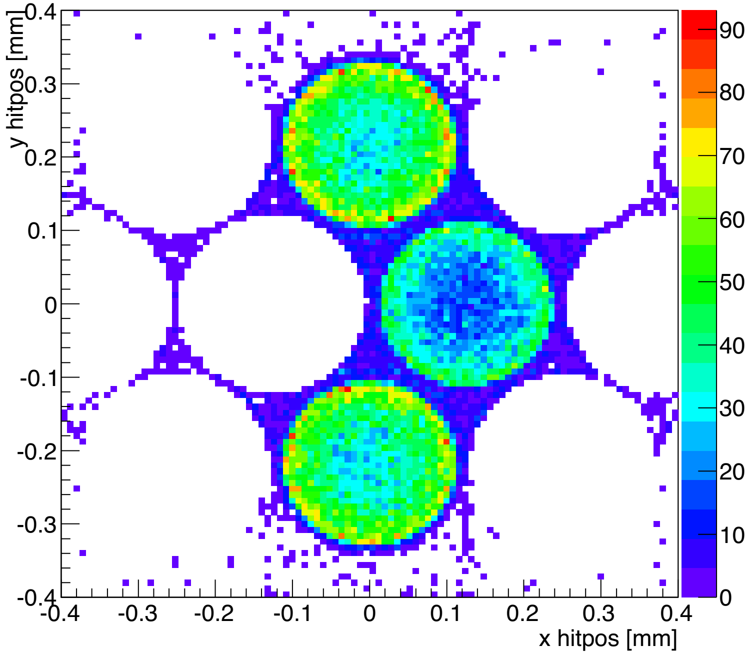


# Detector Design



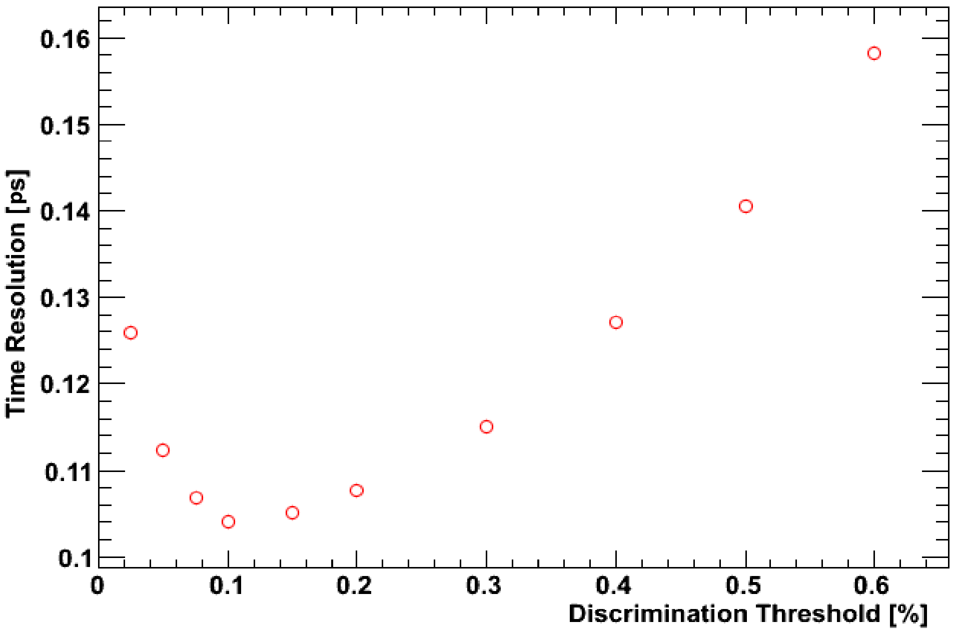
# Timing Detector: Scintillating Fibres



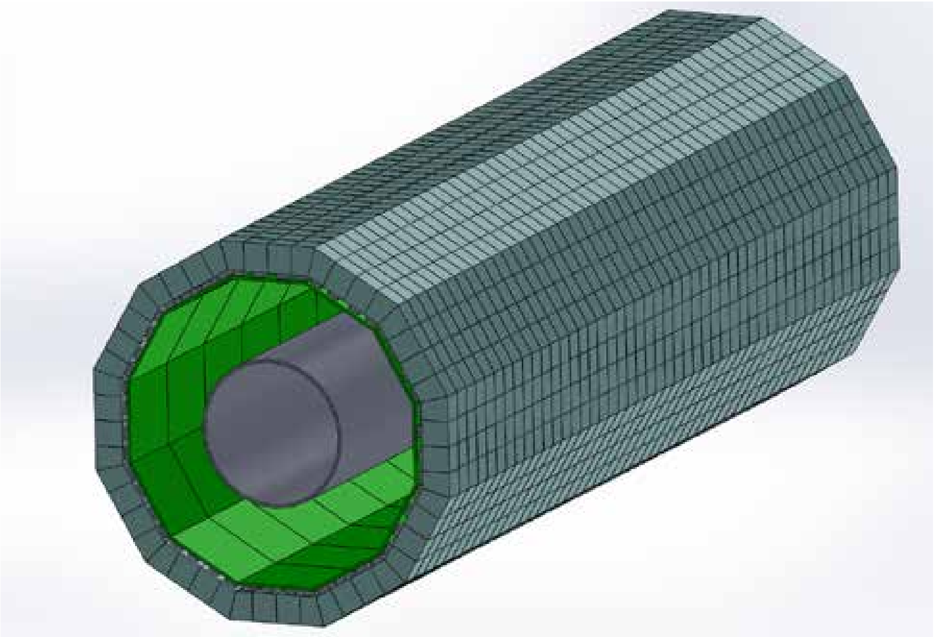



- 3-5 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC
- Timing resolution $\mathcal{O}$(1 ns)

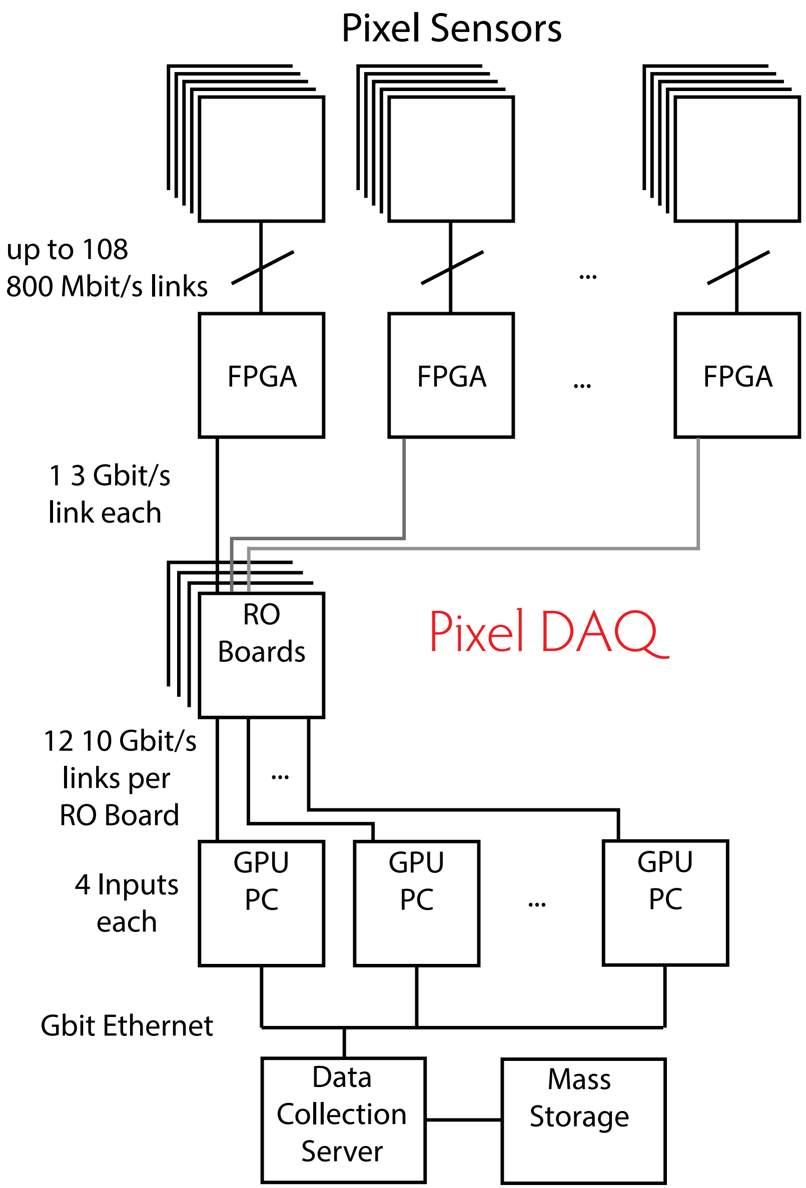
# Timing Detector: Scintillating tiles




- ~ 1 cm$^3$ scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC
- Timing resolution $\mathcal{O}$(100 ps)



# Data Acquisition




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

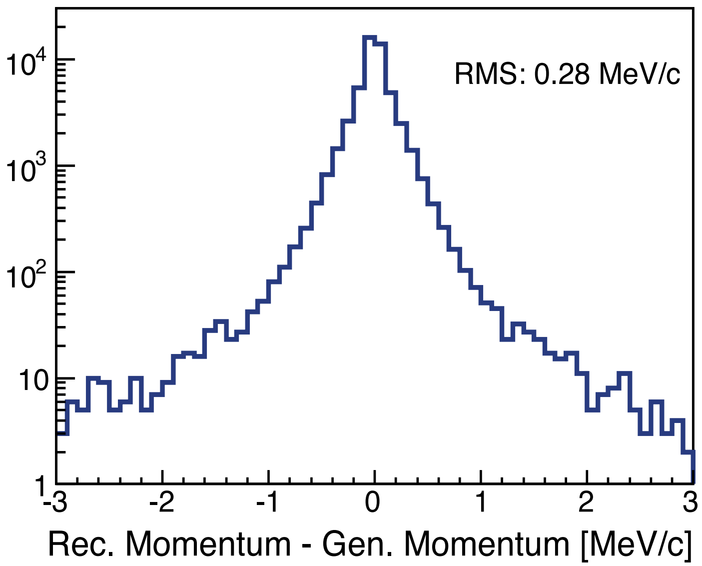
# Online filter farm

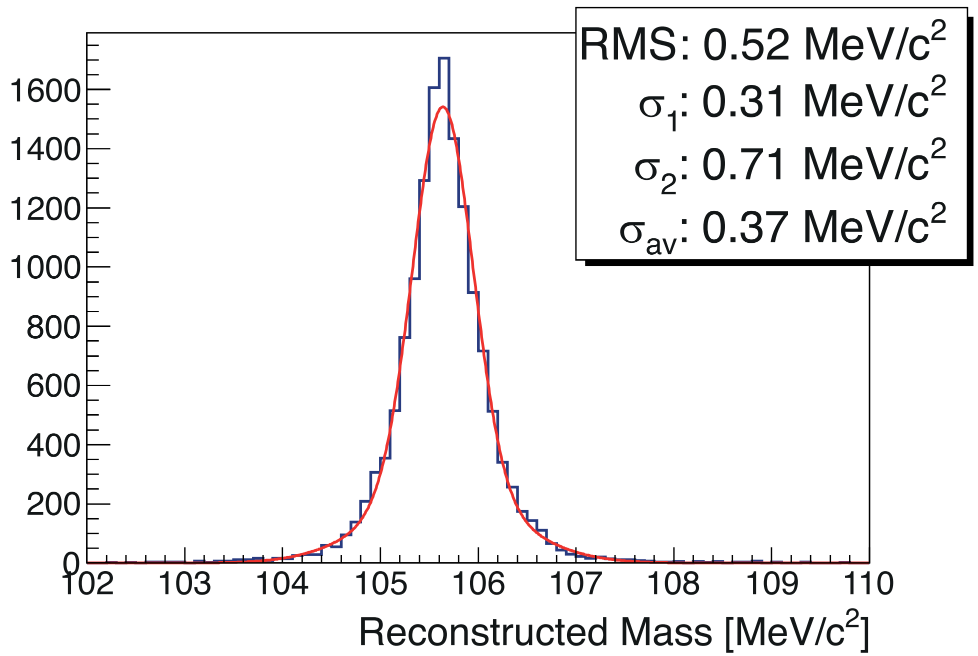

Online software filter farm

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

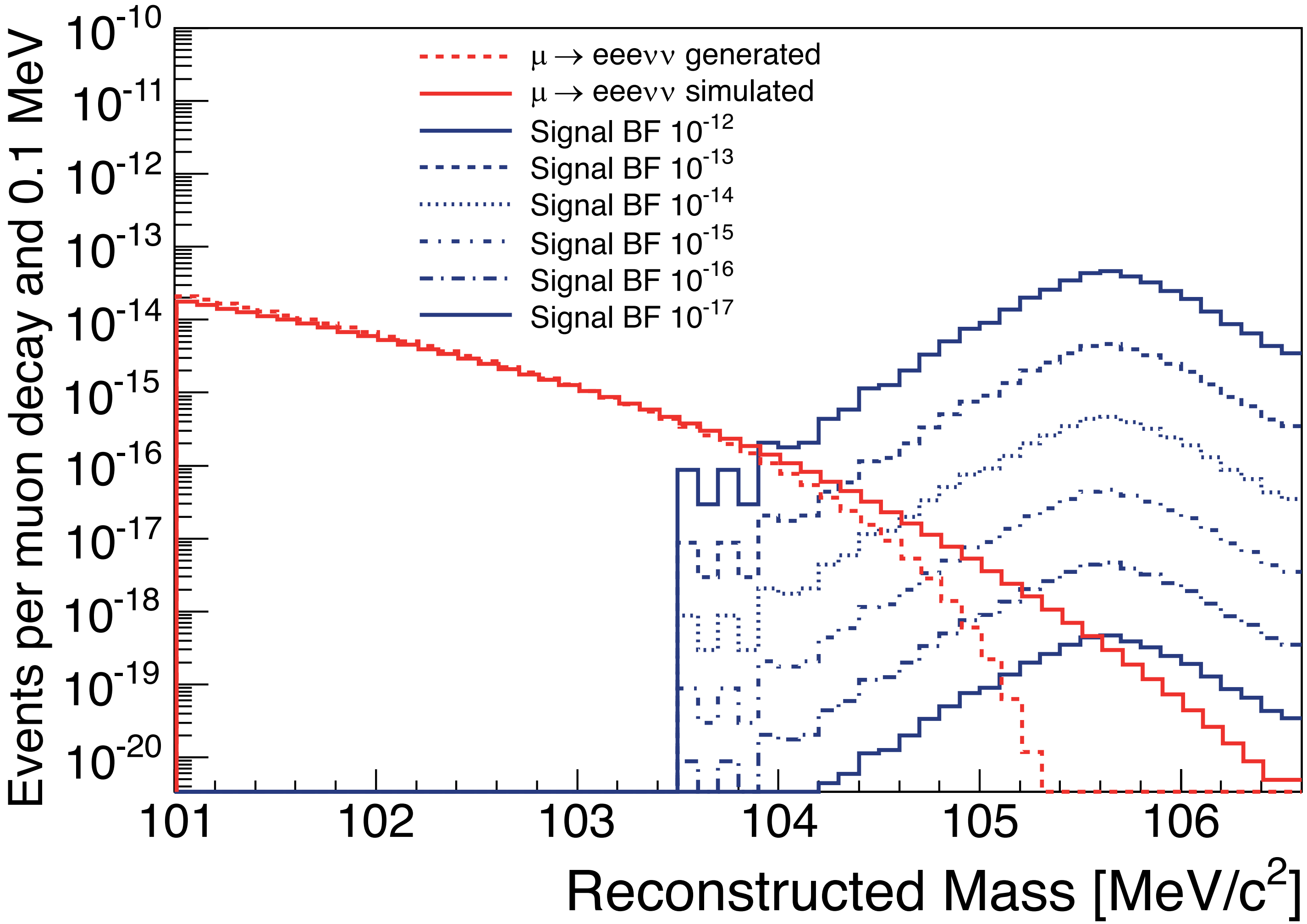
# Simulated Performance

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

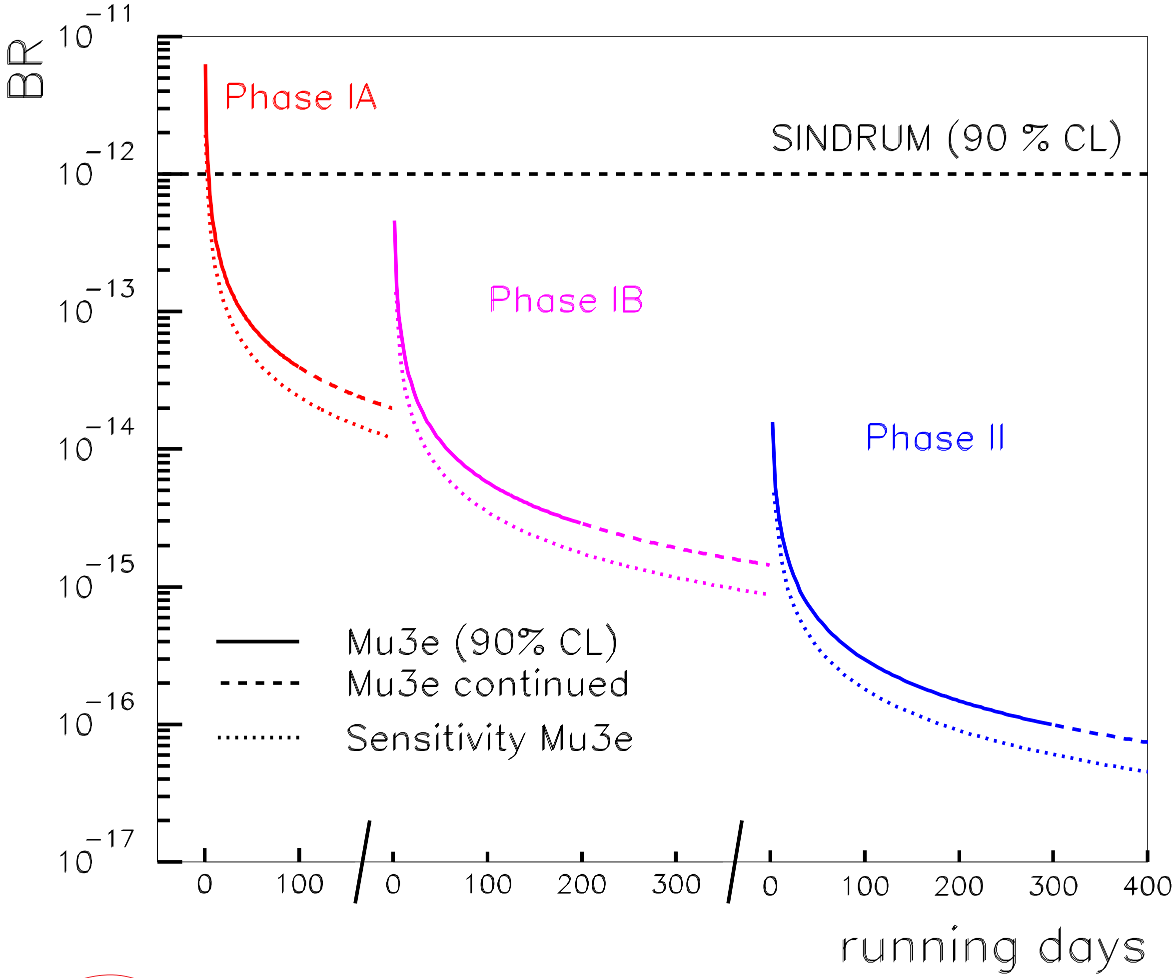


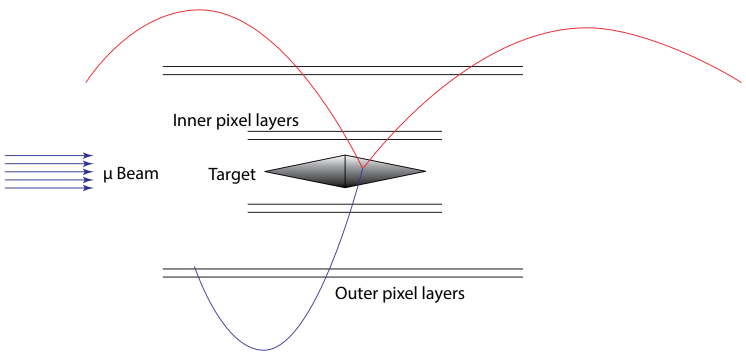



# Simulated Performance



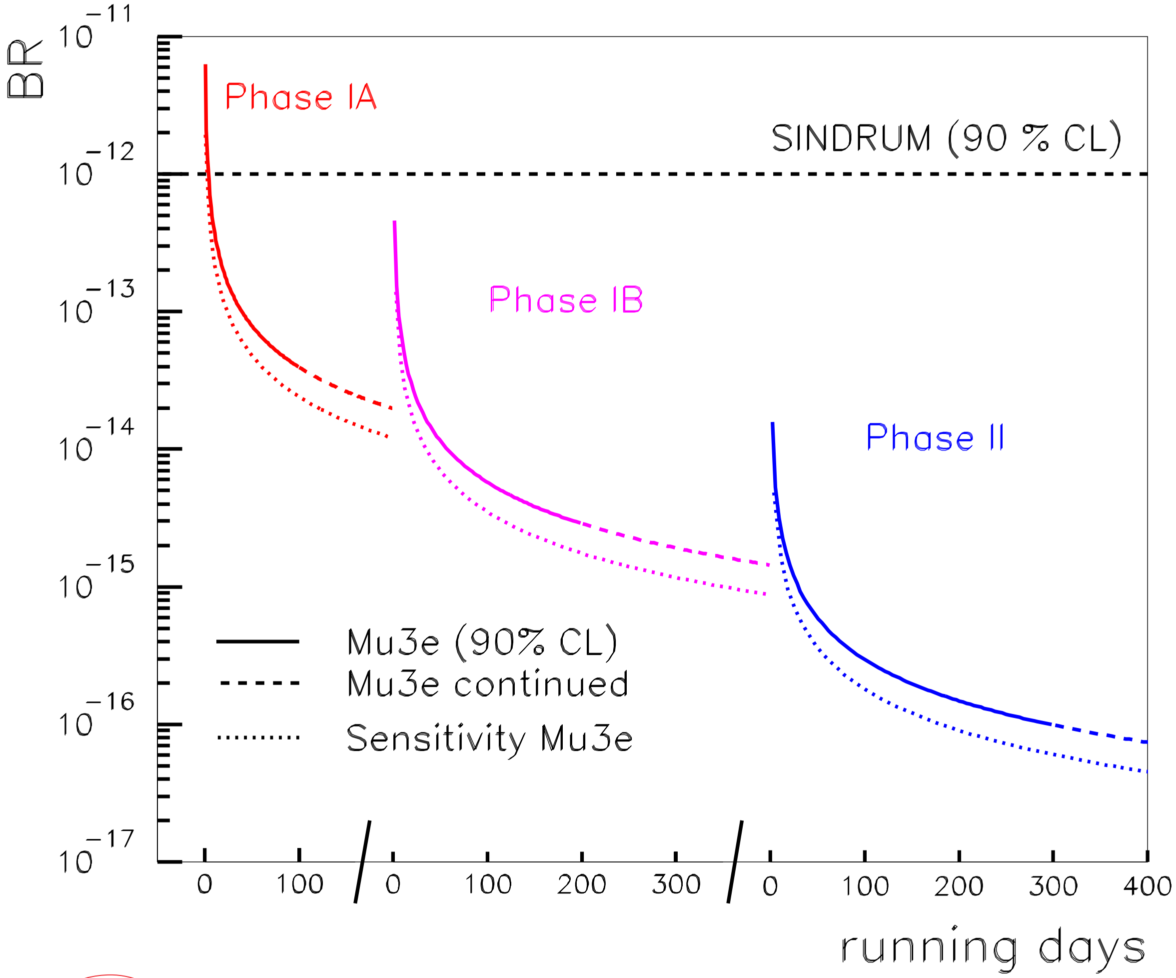
# Sensitivity

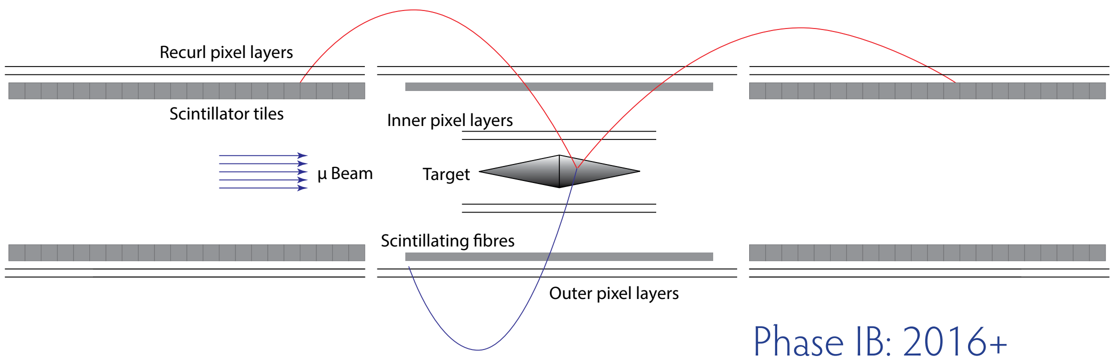



Phase IA: Starting 2015

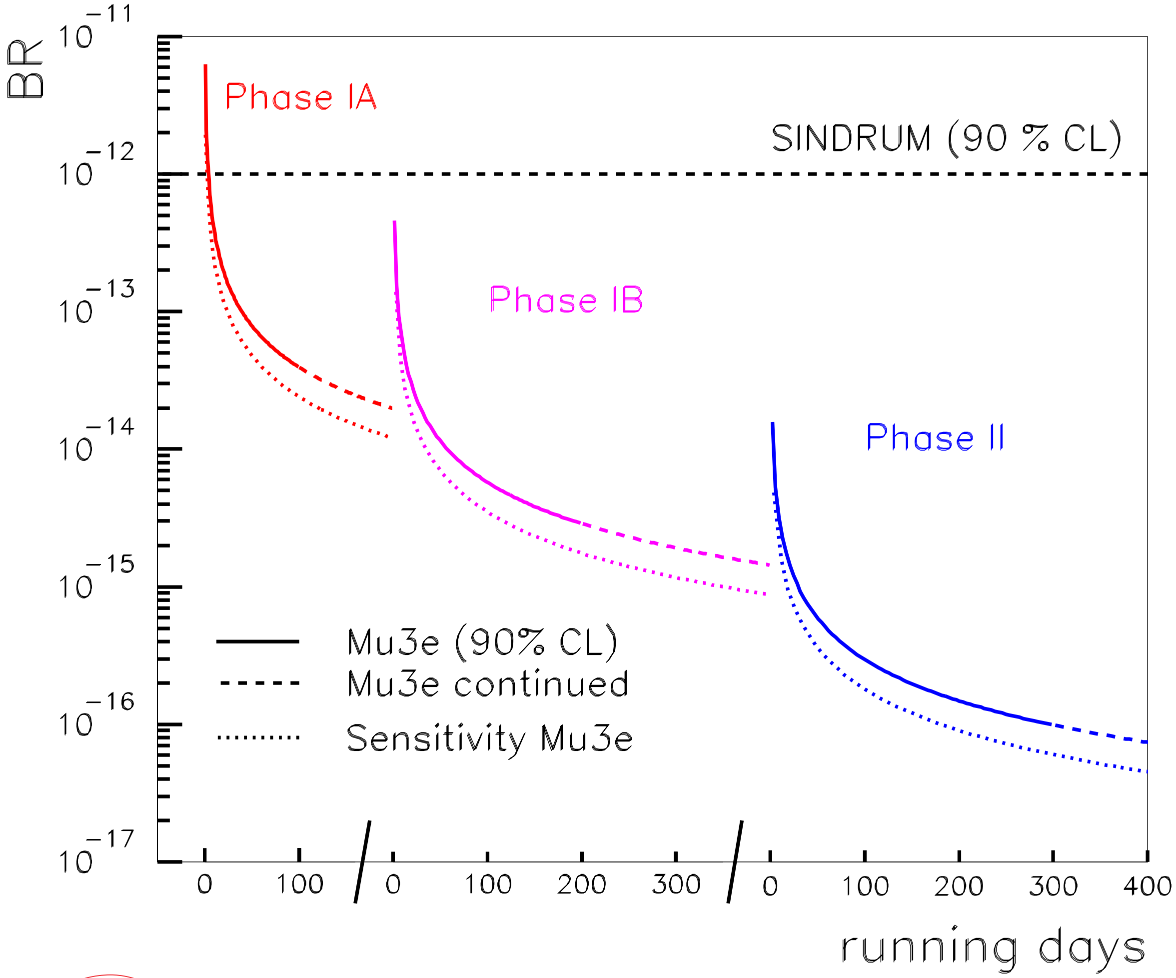
# Sensitivity

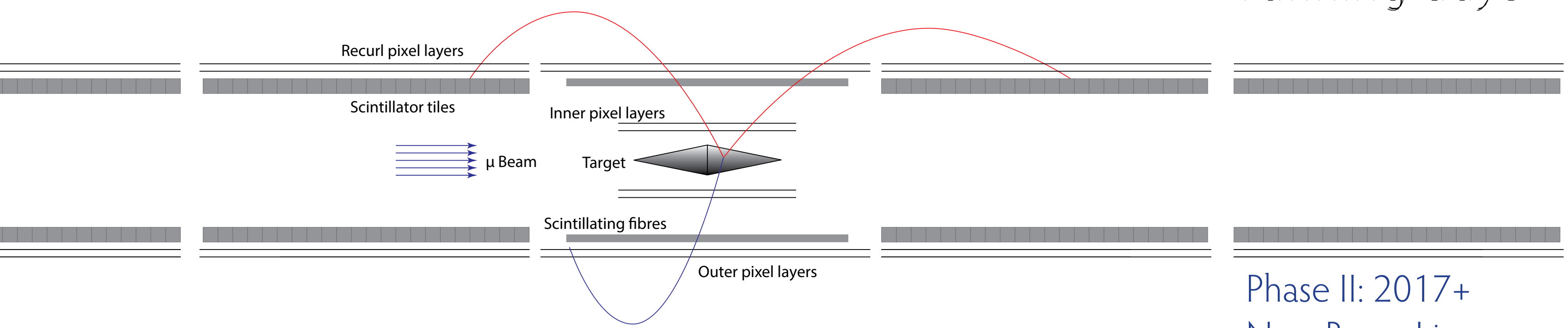



Phase IB: 2016+

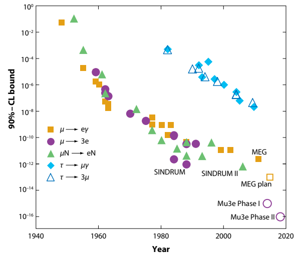
# Sensitivity



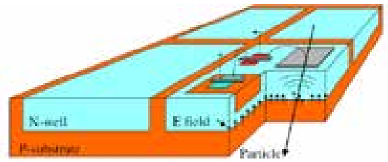




Phase II: 2017+
New Beam Line

# Conclusion




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



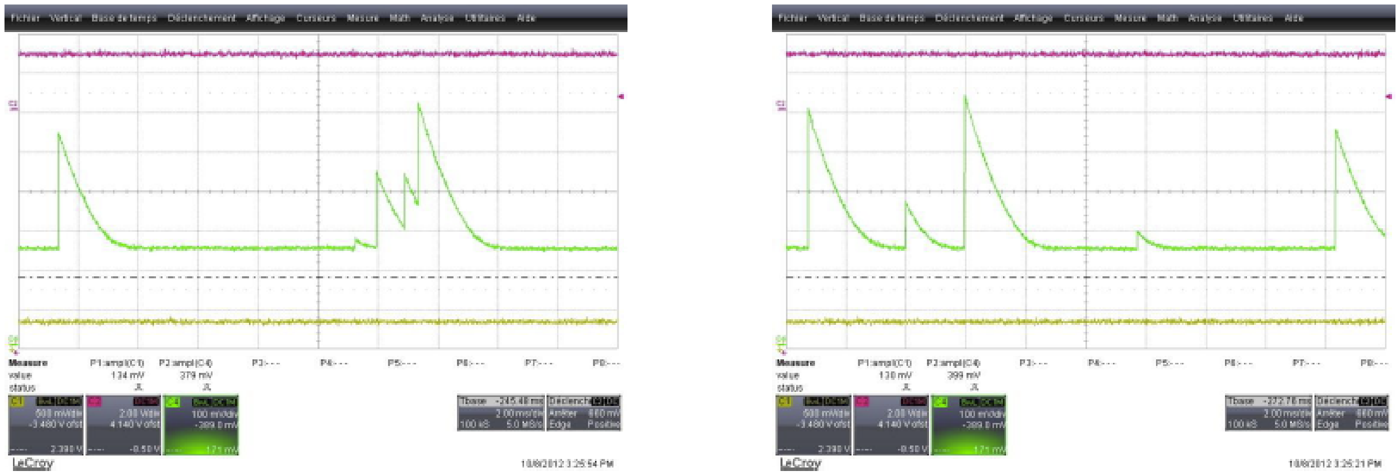

- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs

- Start data taking in 2015
- 2 billion muons/s from HIMB after 2017

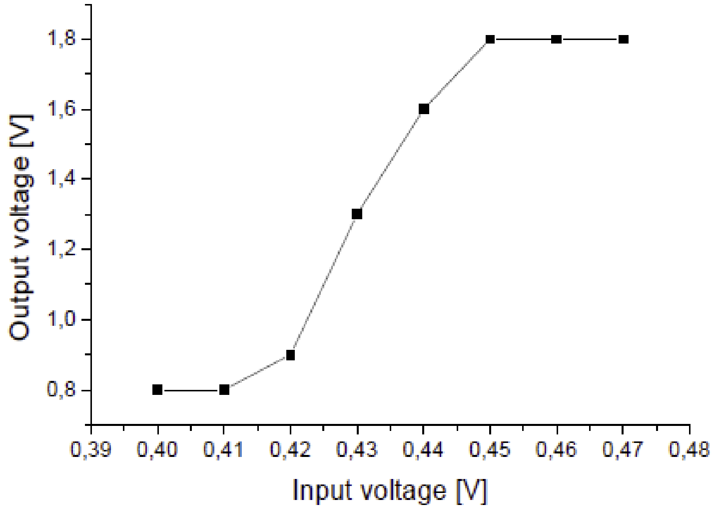
# Backup Material

# 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

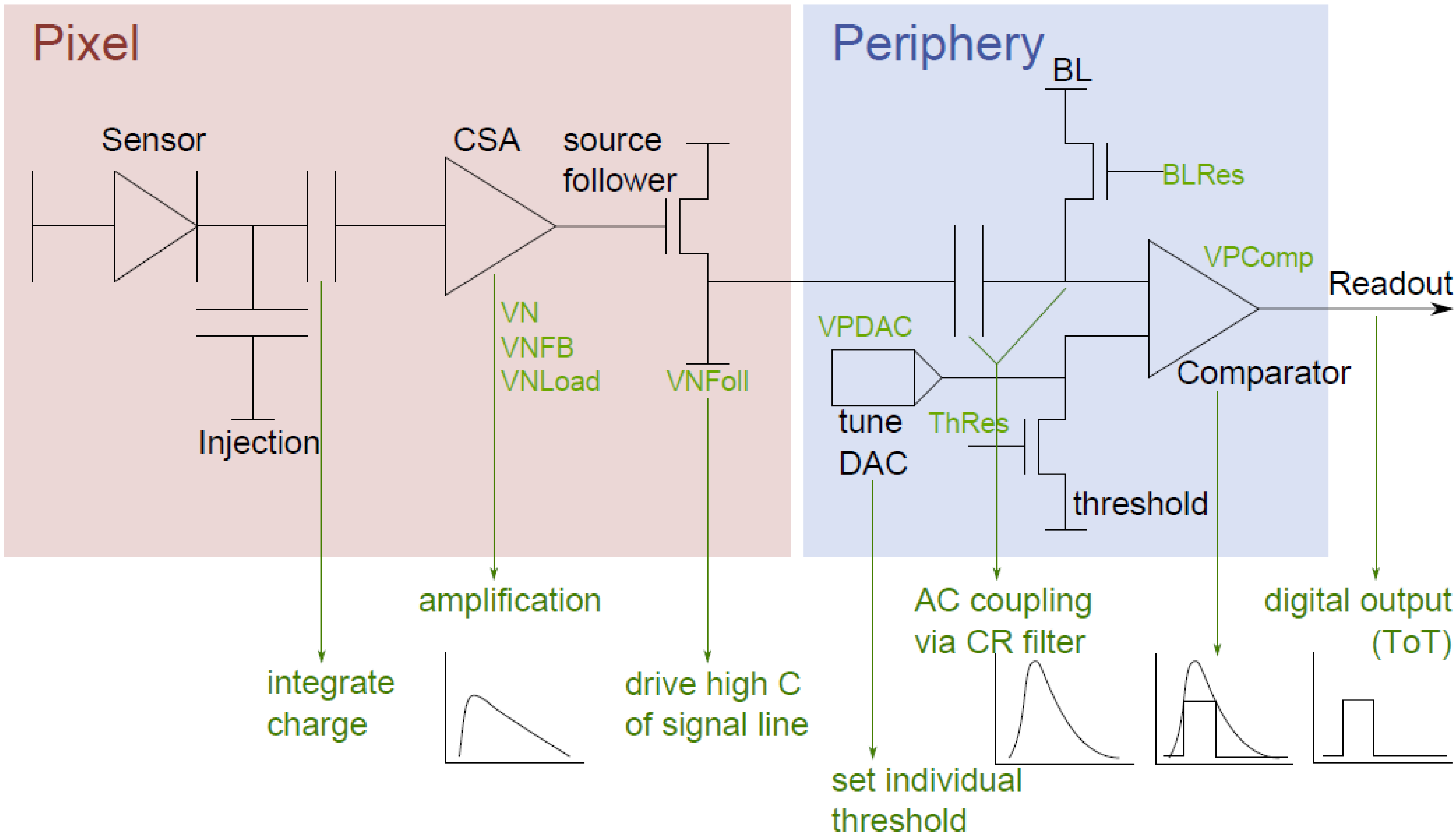



Comparator characteristics.

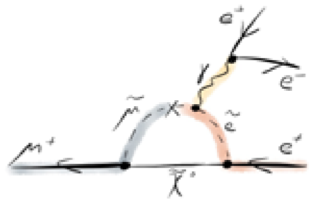
- Irradiation at PS
- After 380 MRad ($8\times10^{15}$ $n_{eq}/cm^2$)
- Chip still working

(Courtesy Ivan Perić, RESMDD 2012)

# MUPIX electronics



# A general effective Lagrangian



**Tensor terms (dipole)** e.g. supersymmetry

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

**Four-fermion terms** e.g. Z'

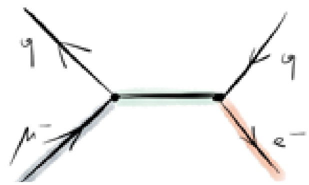
$$+ g_1\, (\bar{\mu}_R\, e_L)\, (\bar{e}_R\, e_L) \quad + g_2\, (\bar{\mu}_L\, e_R)\, (\bar{e}_L\, e_R)$$

scalar

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

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

vector



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