Searching for Lepton Flavour Violation with the

Mu3e Experiment

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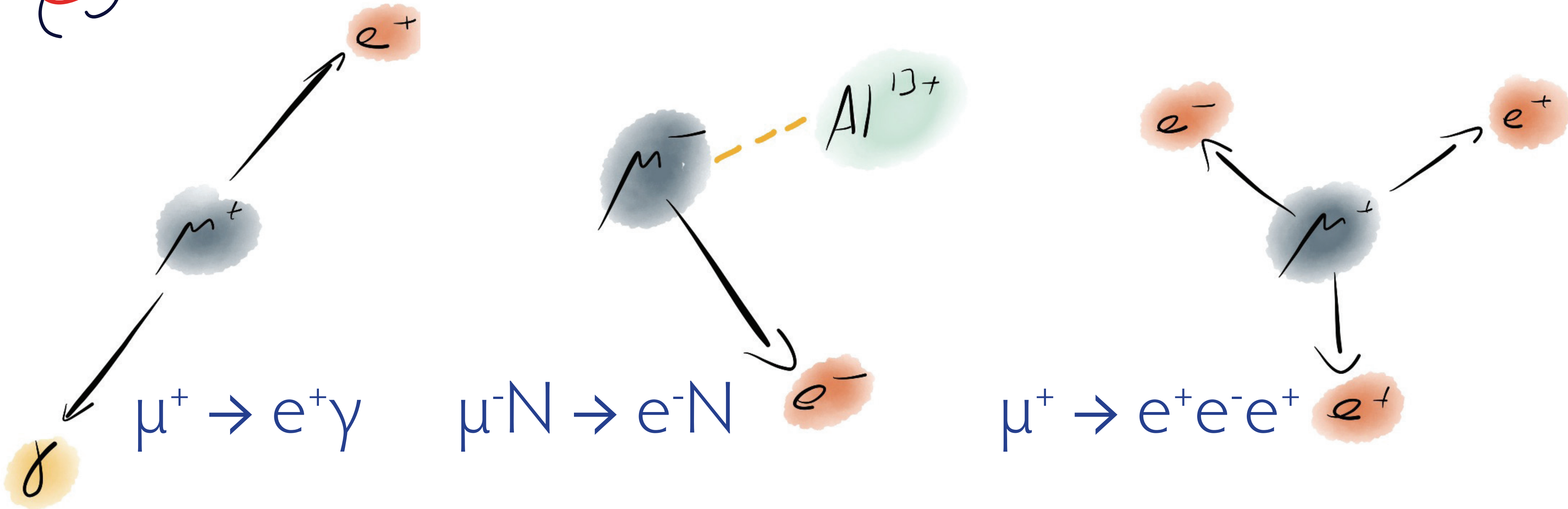
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

LFV Muon Decays: Experimental Situation



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

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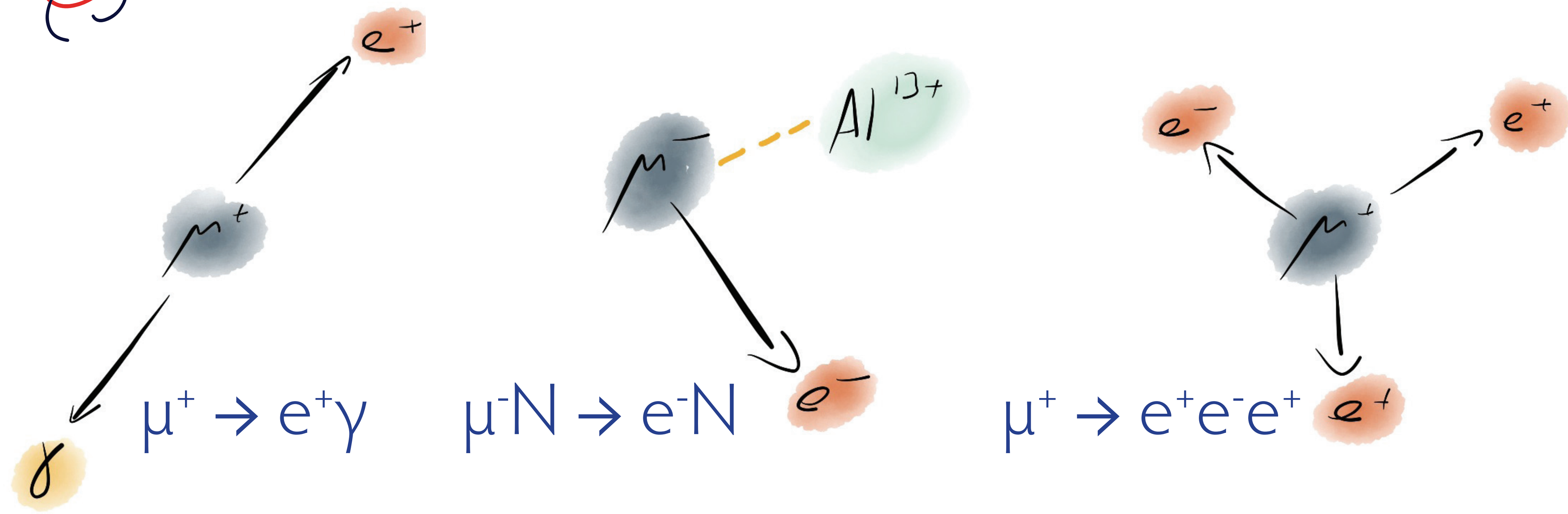


MEG (PSI)

$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$
(2016)

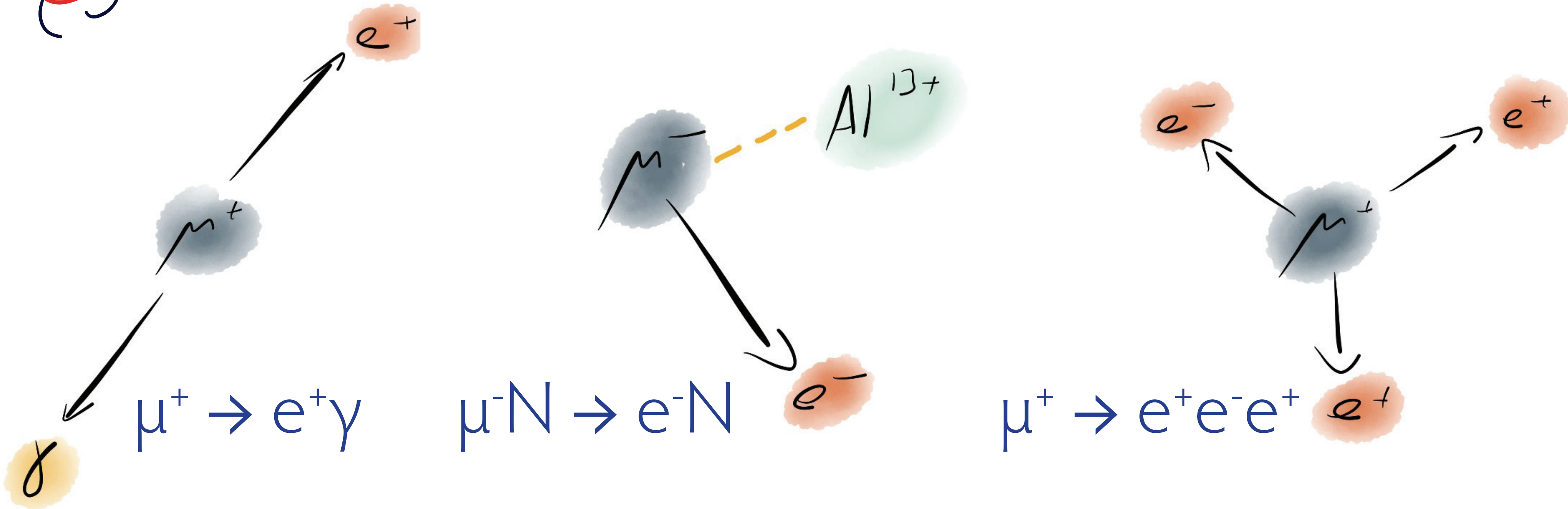
SINDRUM II (PSI)

$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$
(2006)

SINDRUM (PSI)

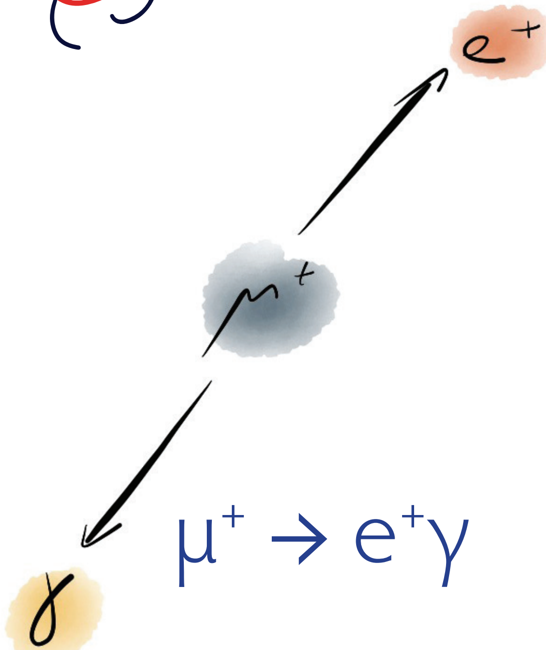
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(1988)

LFV Muon Decays: Experimental Situation

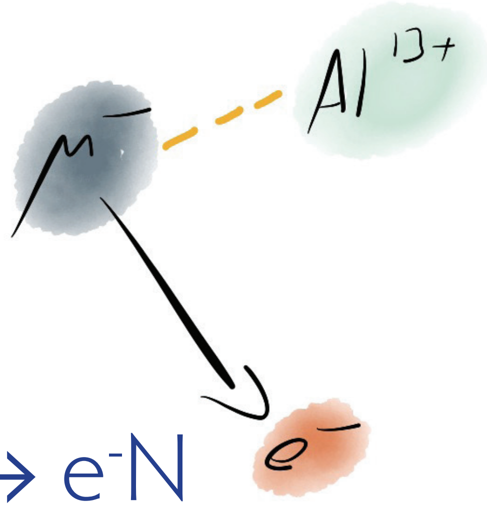


MEG (PSI)	SINDRUM II (PSI)	SINDRUM (PSI)
$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$	$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$	$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(2016)	(2006)	(1988)
upgrading	Mu2e/Comet	Mu3e

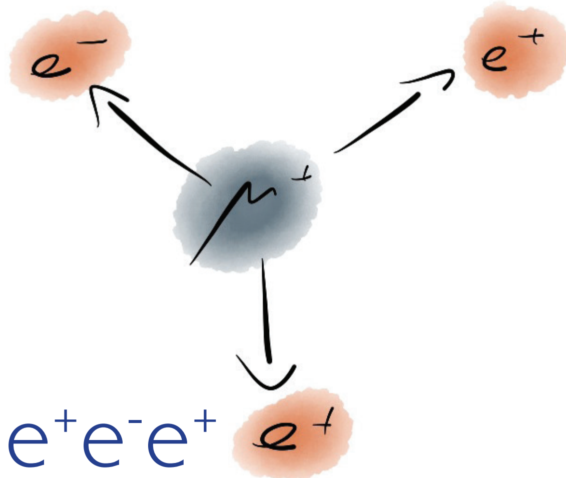
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

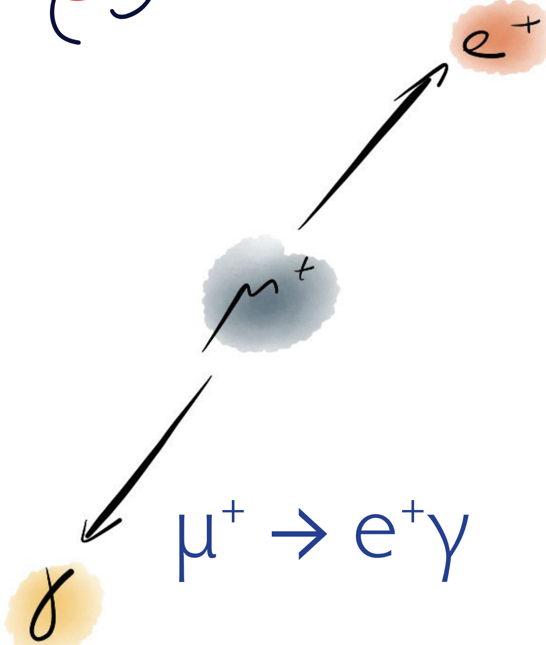
Kinematics

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

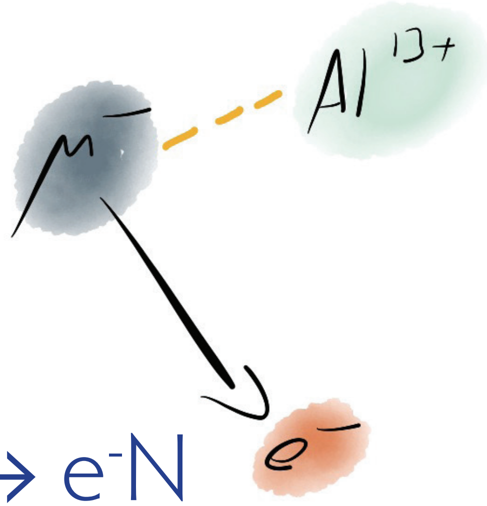
Kinematics

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

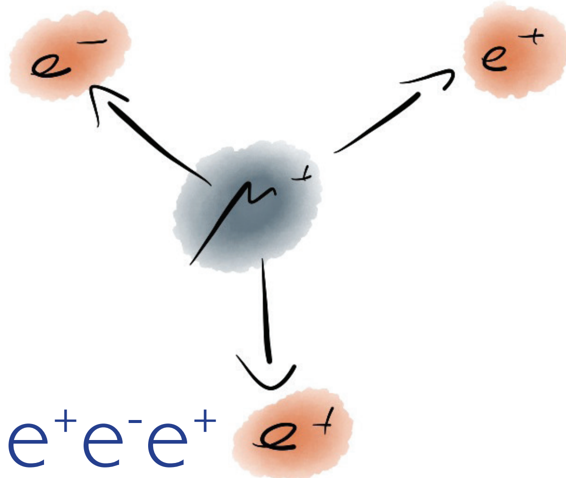
LFV Muon Decays: Experimental signatures



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



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



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

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

Background
- Accidental background

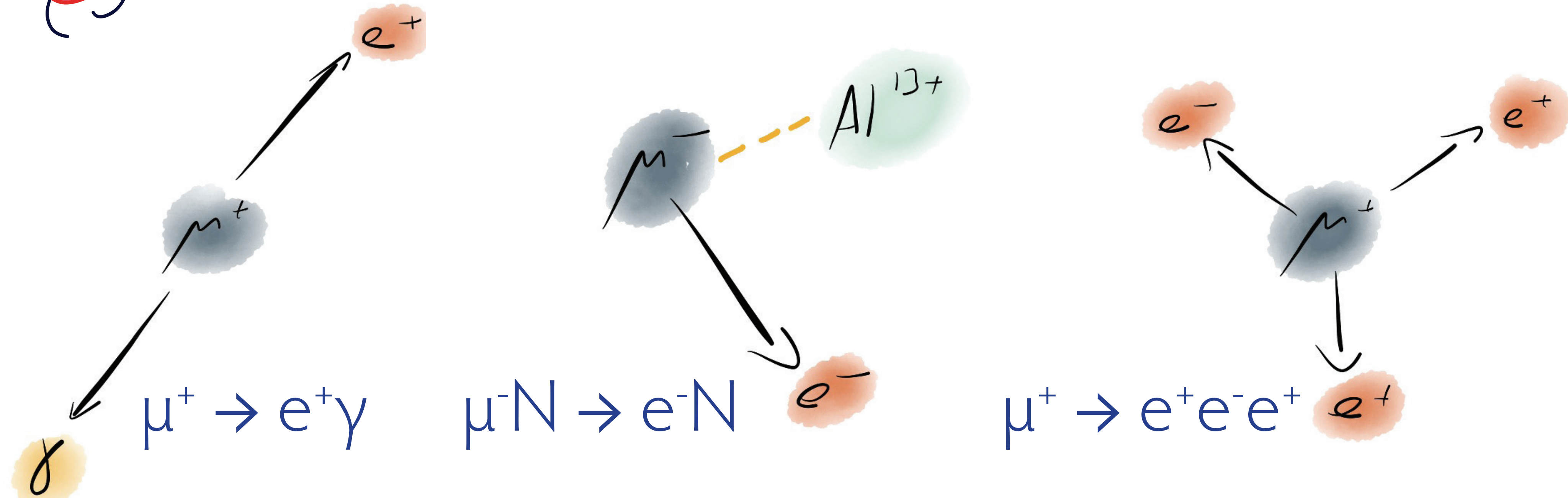
Kinematics
- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

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



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

Kinematics
- 2-body decay
- Monoenerge
- Back-to-b

Backgro
- A ...al background

Continuous Beam

Kinematics
- Quasi 2-body d
- Monoenerge
- Single p ...etected

Backgro
- D ... orbit
- A ... protons, pions

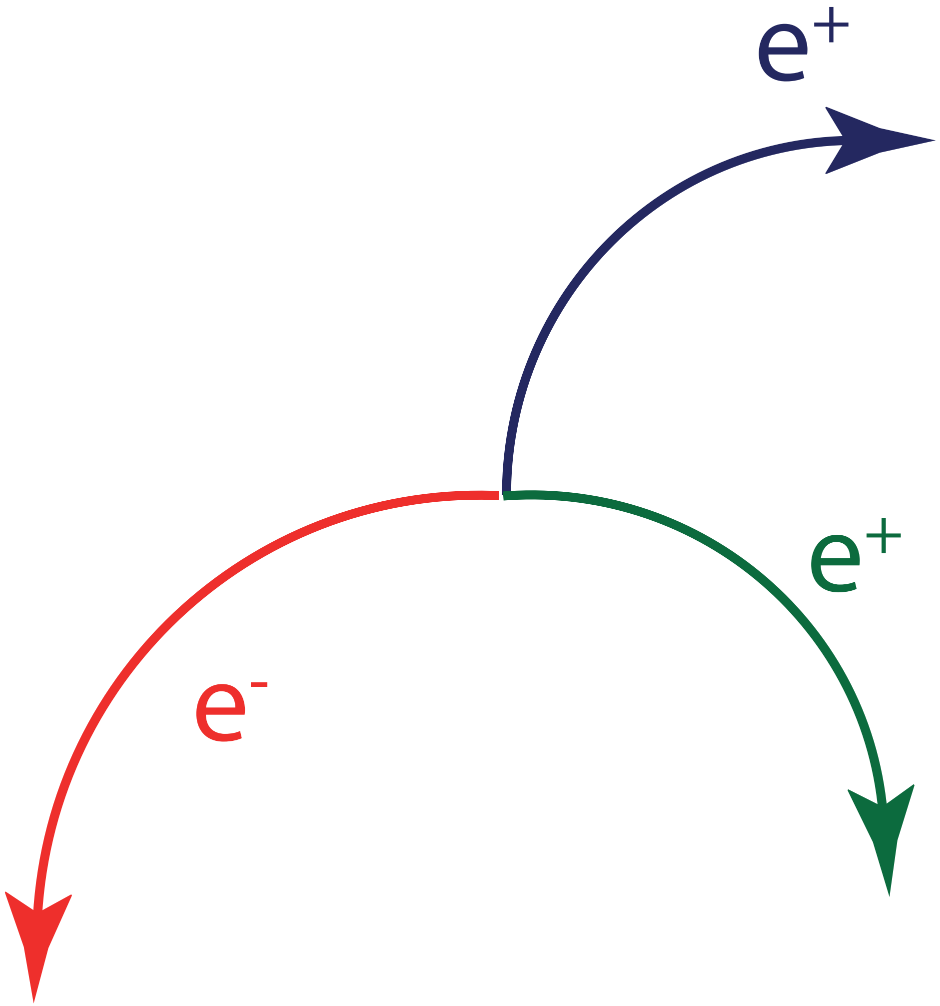
Pulsed Beam

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

Backgro
- R ... decay
- Ac ...dental background

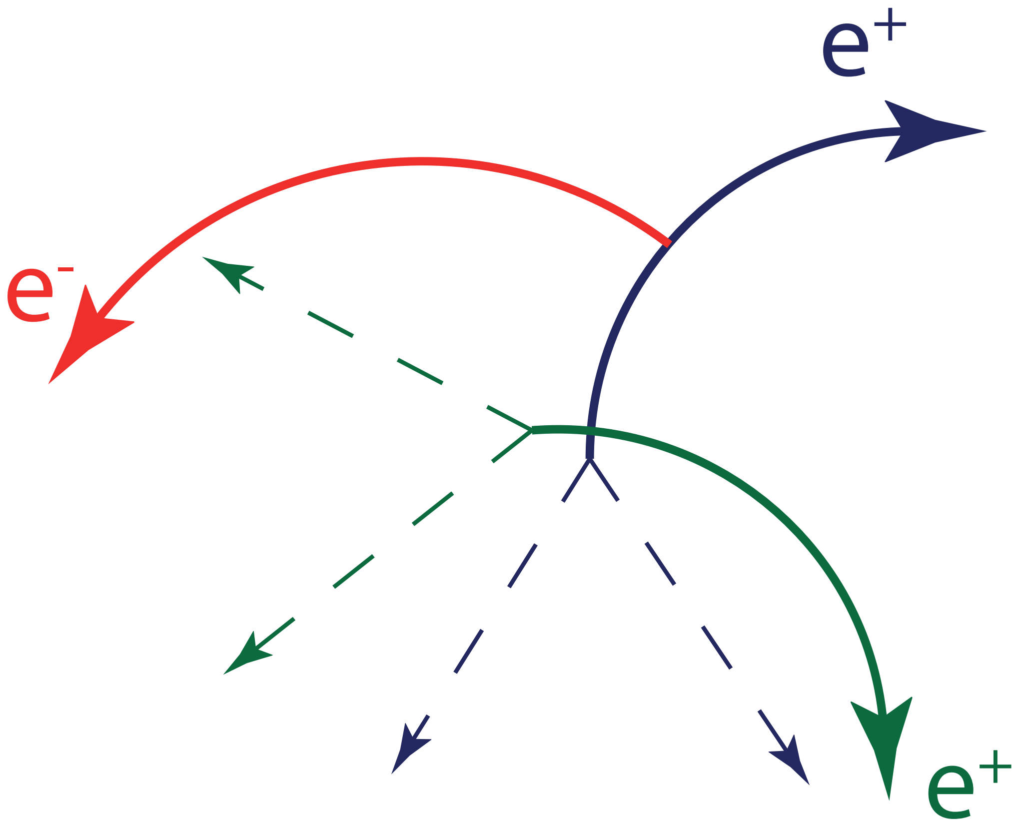
Continuous Beam

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

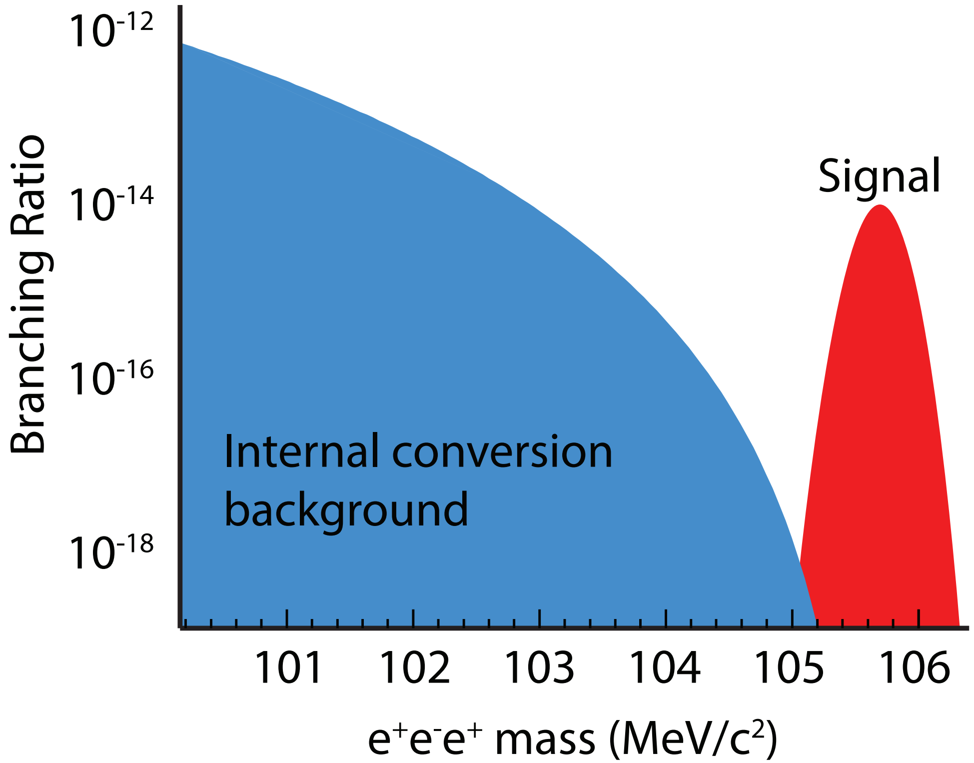
- Need very good timing, vertex and momentum resolution

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



- Need excellent momentum resolution

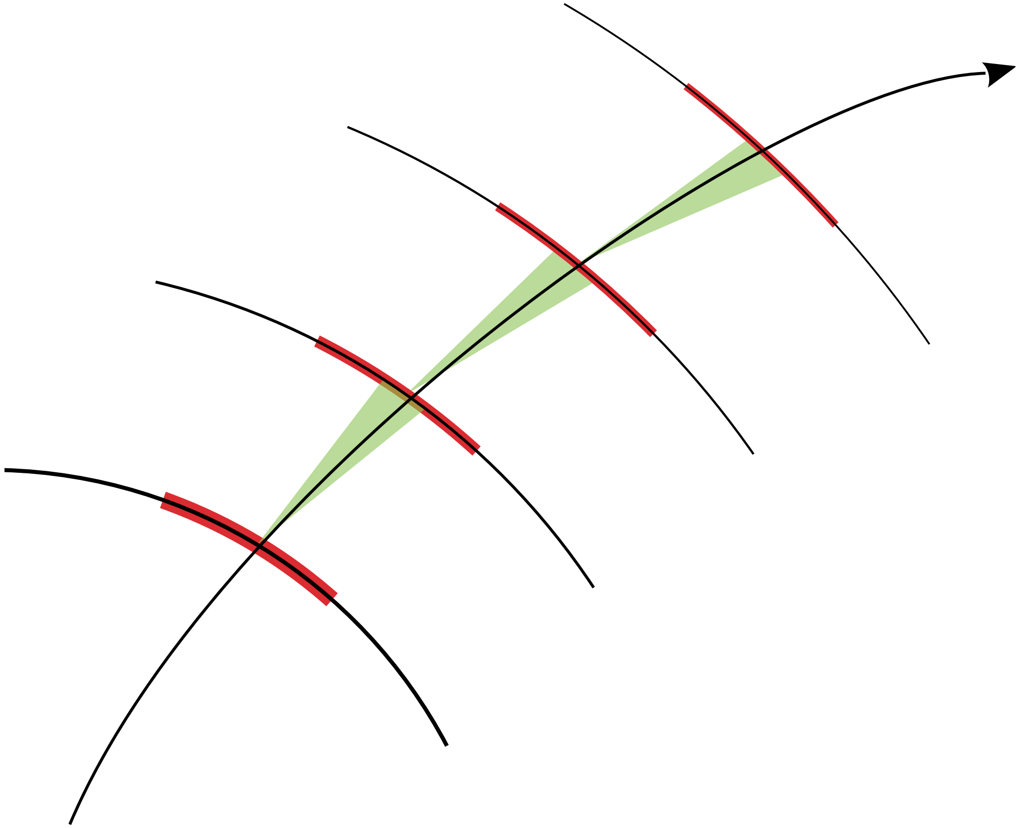
- New: NLO available from Matteo Fael and Signer et al. - now 10-20% easier

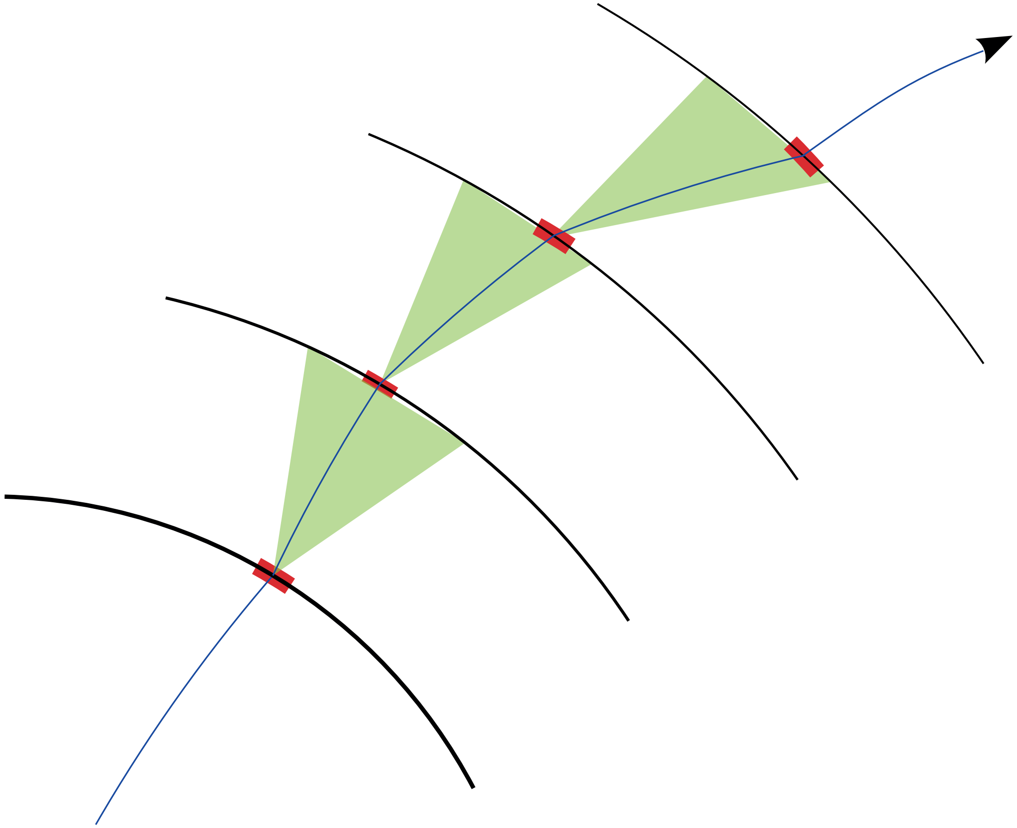
Building the
Mu3e Experiment

aiming for a branching ratio sensitivity of 10^{-16}

Momentum measurement

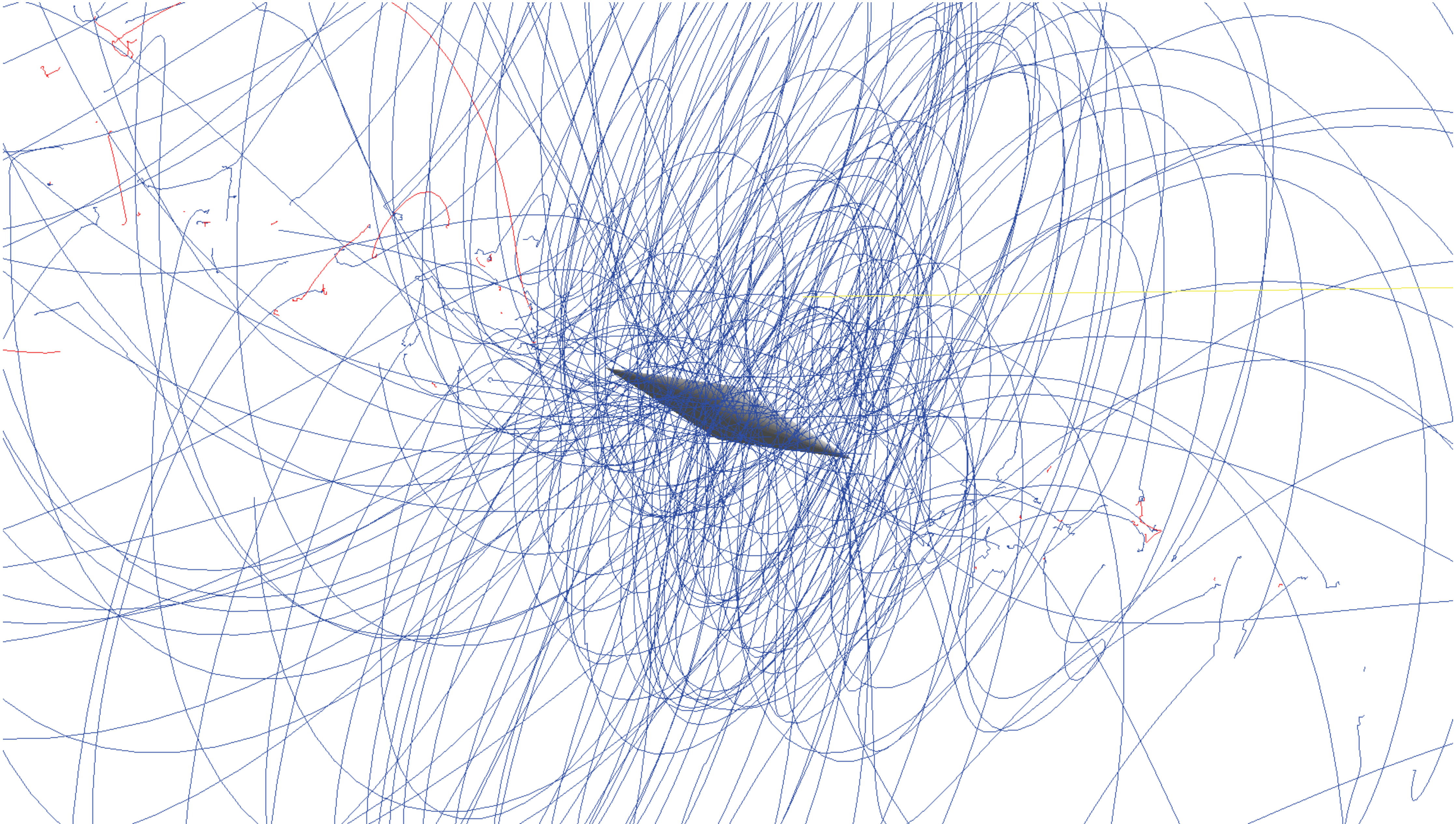
- Apply magnetic field (e.g. 1 Tesla)
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector





2 Billion Muon Decays/s

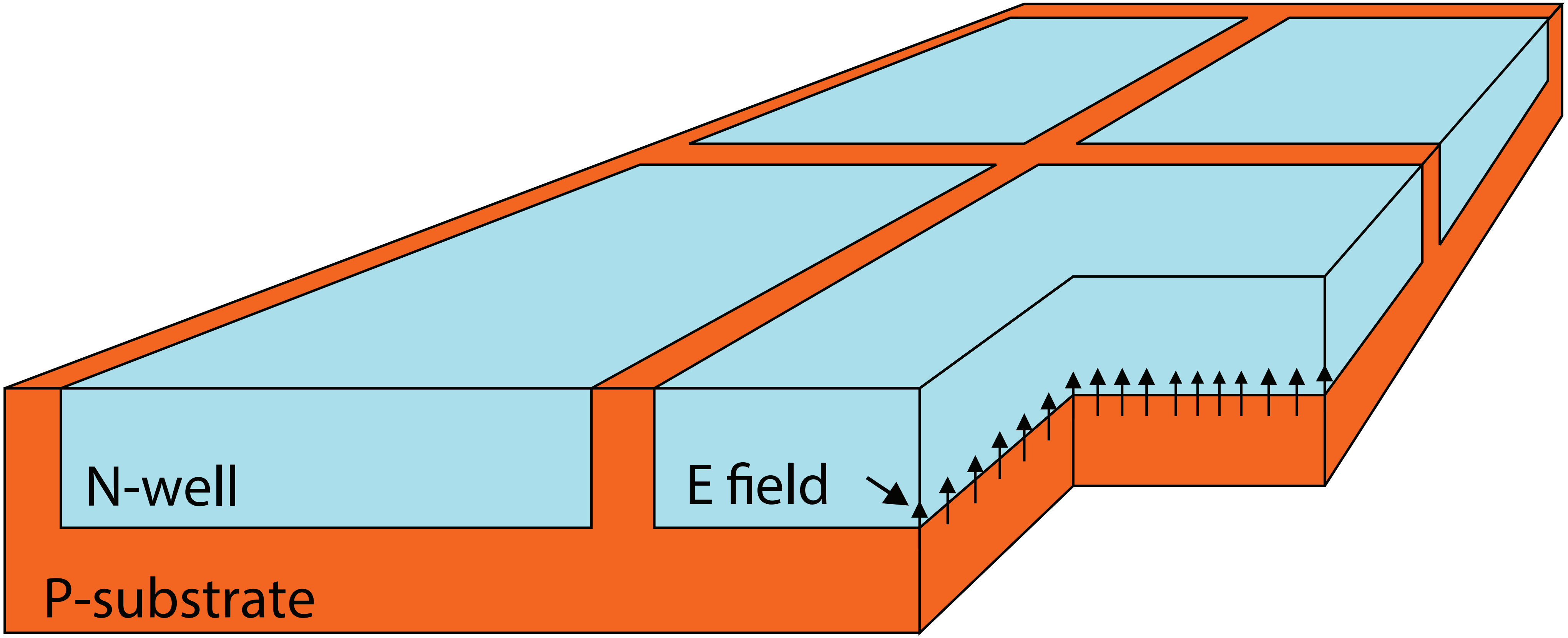
50 ns, 1 Tesla field



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

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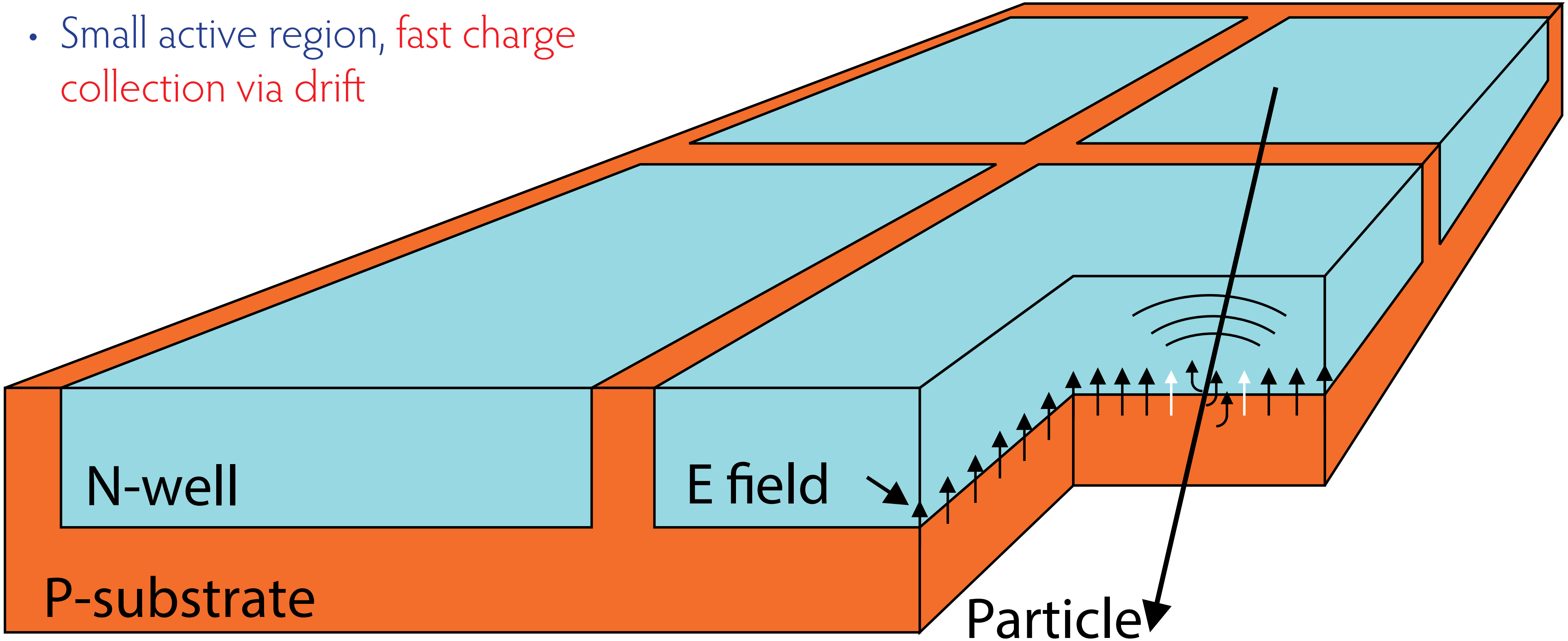


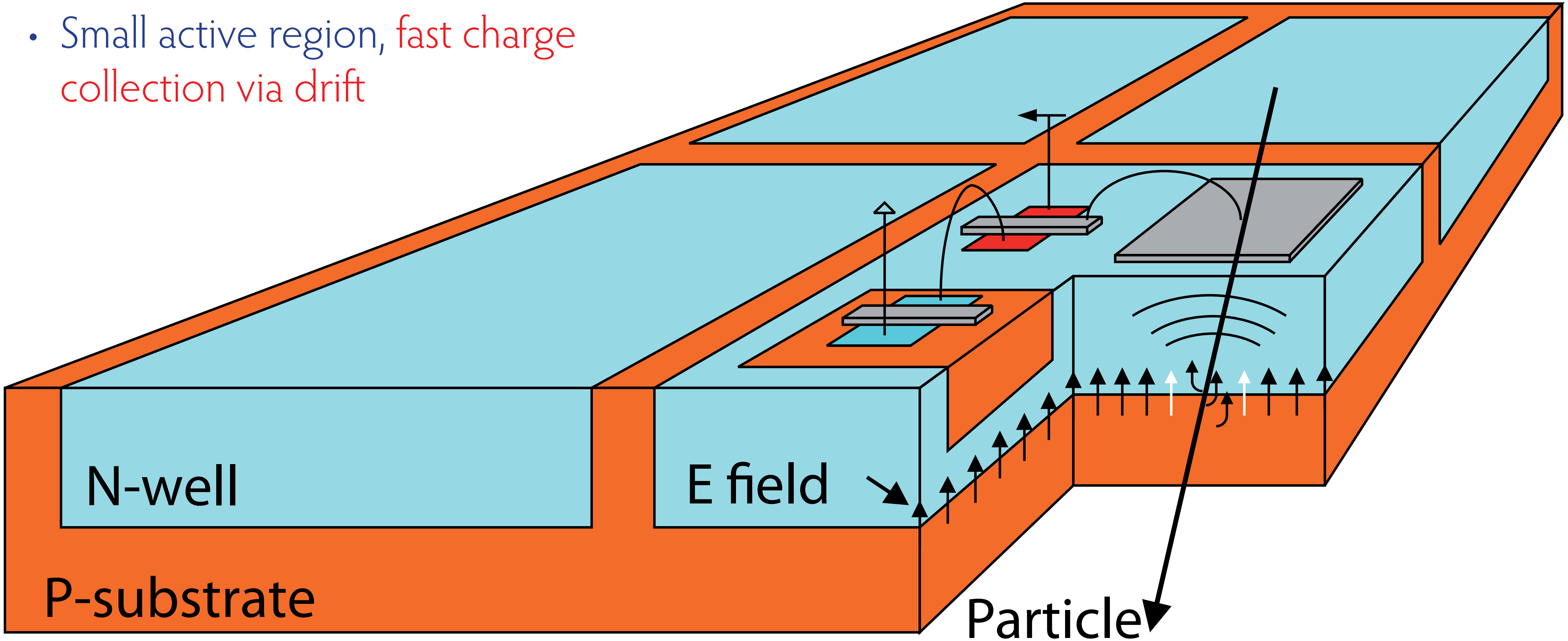
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

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

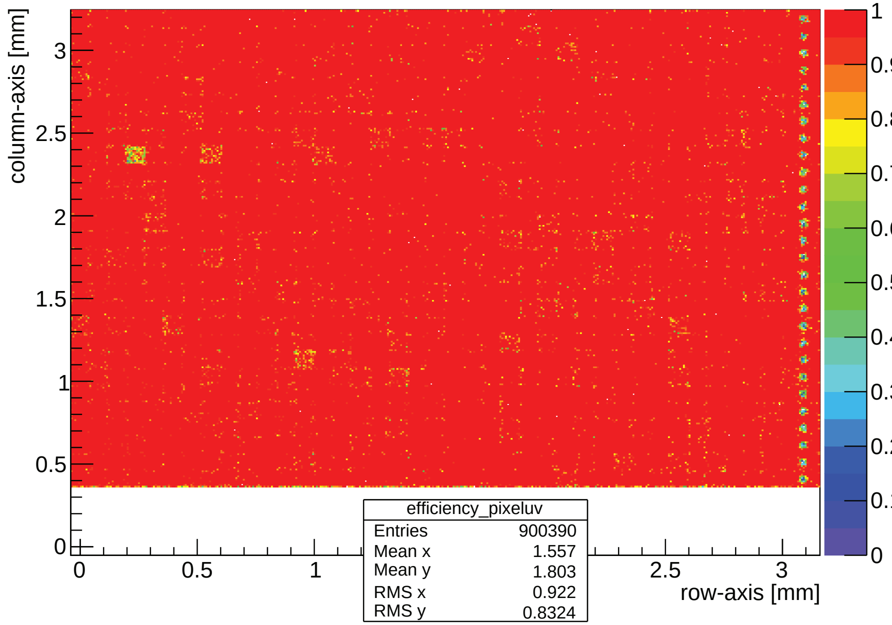
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 μm

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

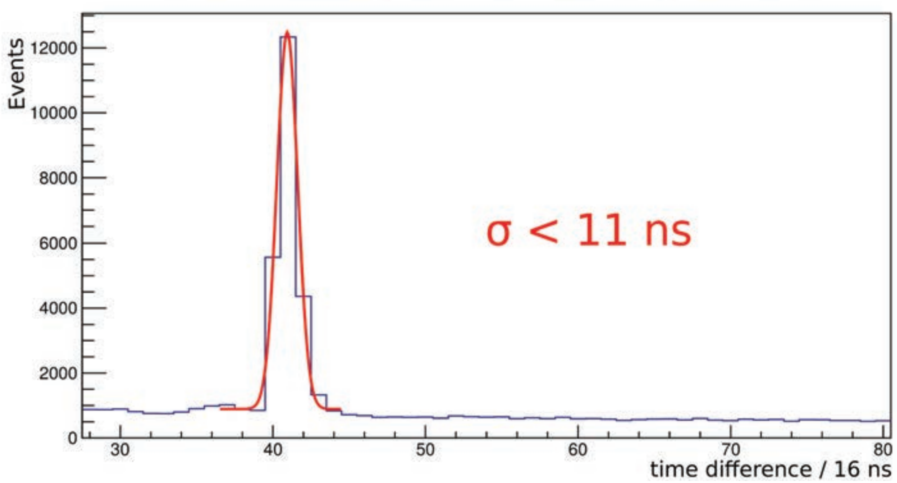


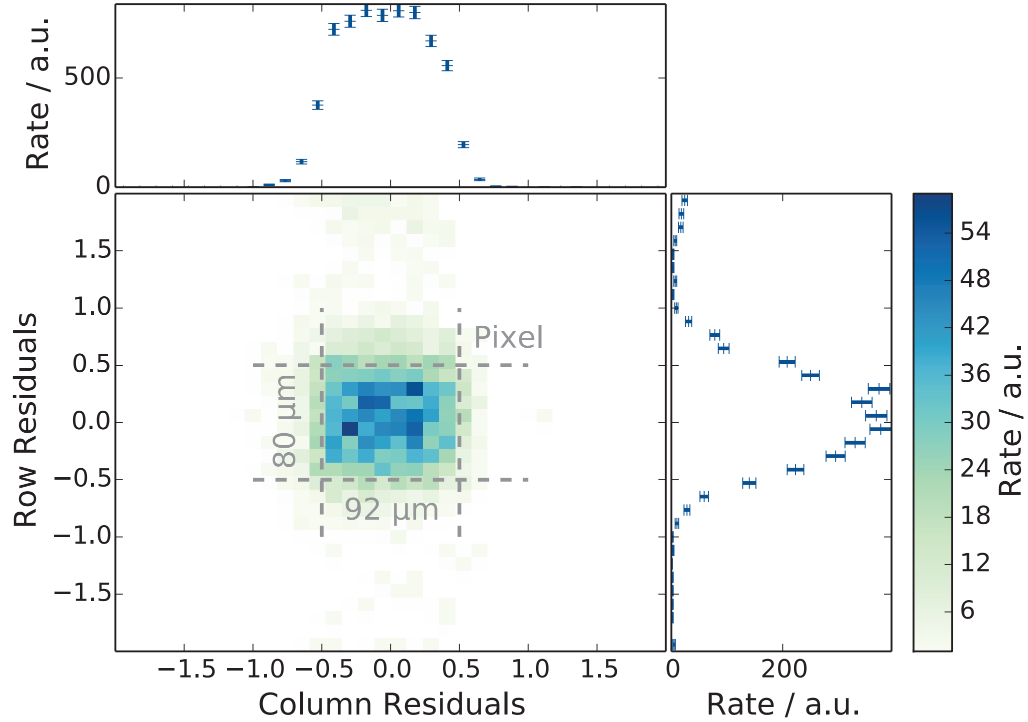
Performance

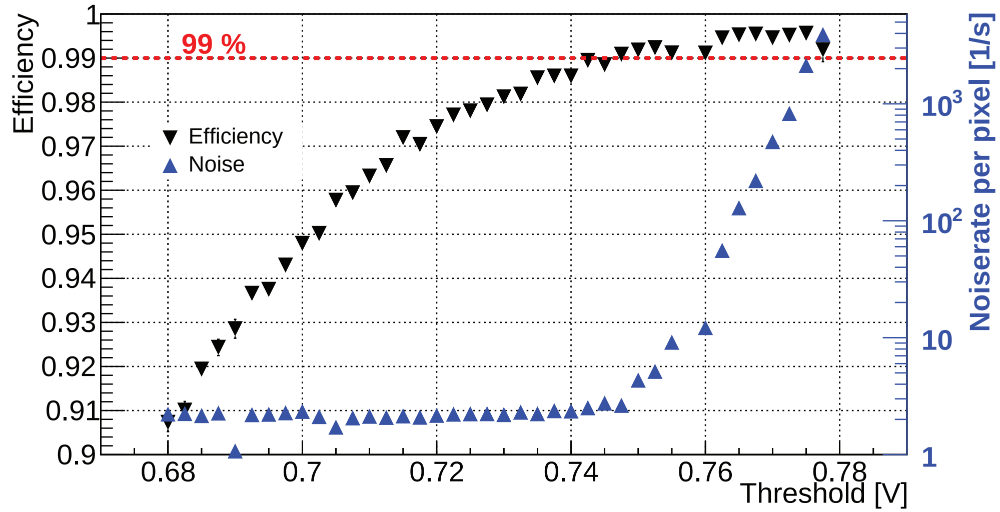
Mupix7, 735 mV threshold, HV = -85 V



Trigger TimeStamp Difference Distribution for Single Events

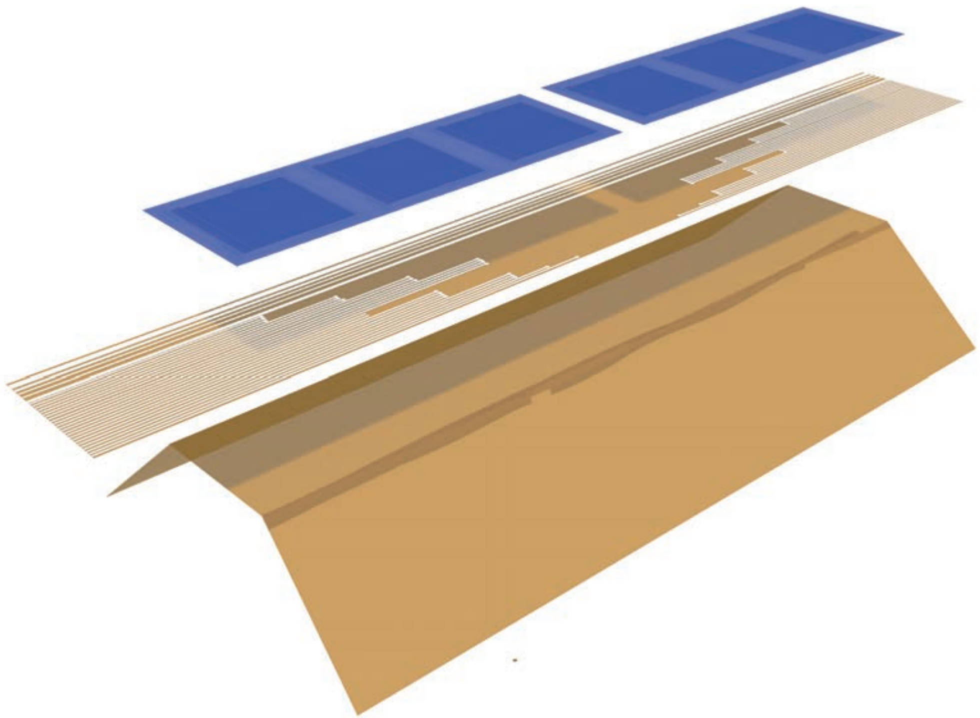






Submitting large (2×1 cm^2) prototype in next weeks

Mechanics

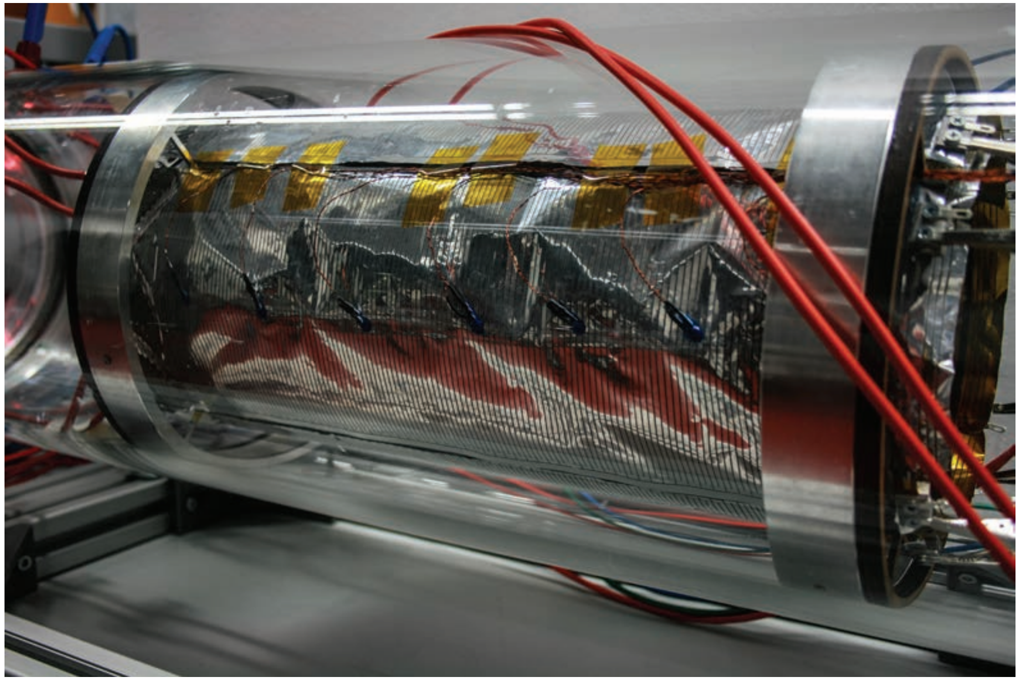


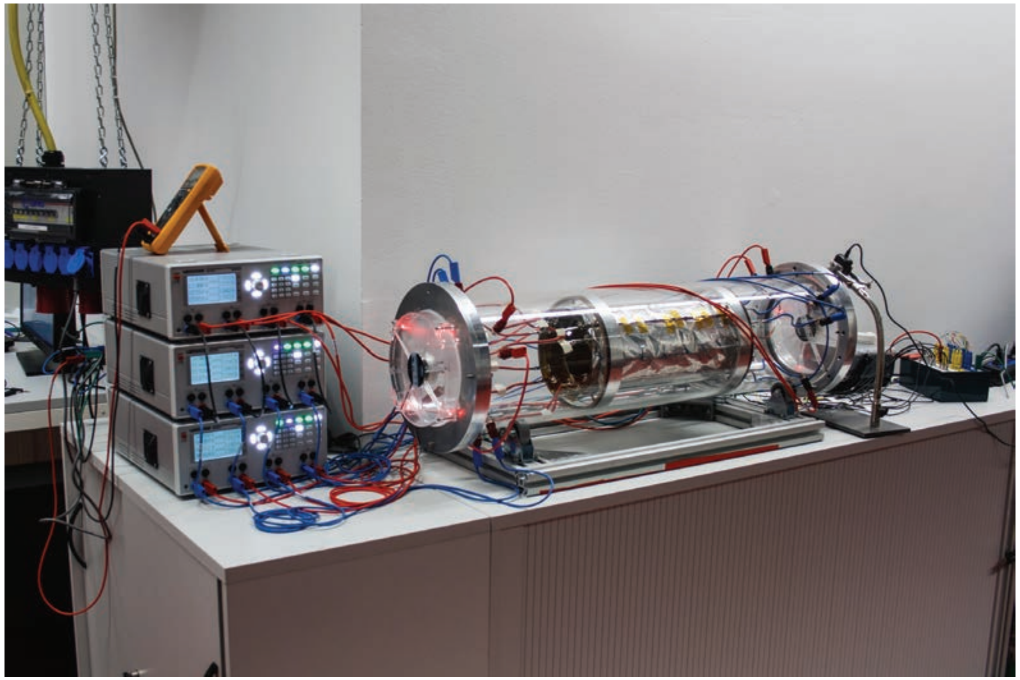
- 50 μm silicon
- 25 μm Kapton™ flexprint with aluminium traces
- 25 μm Kapton™ frame as support
- About 1‰ of a radiation length per layer

Cooling

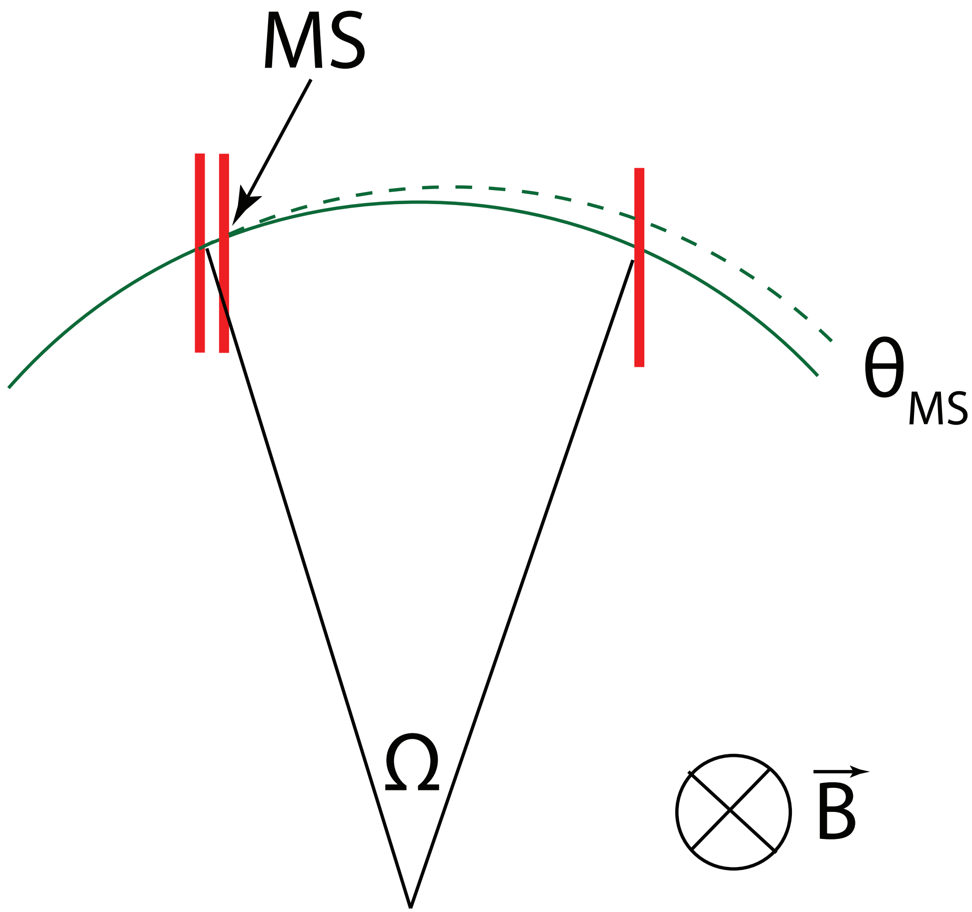
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 250 mW/cm^2 - total ~3 kW
- Simulations: Need ~ several m/s flow

- Full scale heatable prototype built
- 36 cm active length
- Vibrations studied using Michelson-Interferometer
- Can keep temperature below 70°C





Momentum measurement

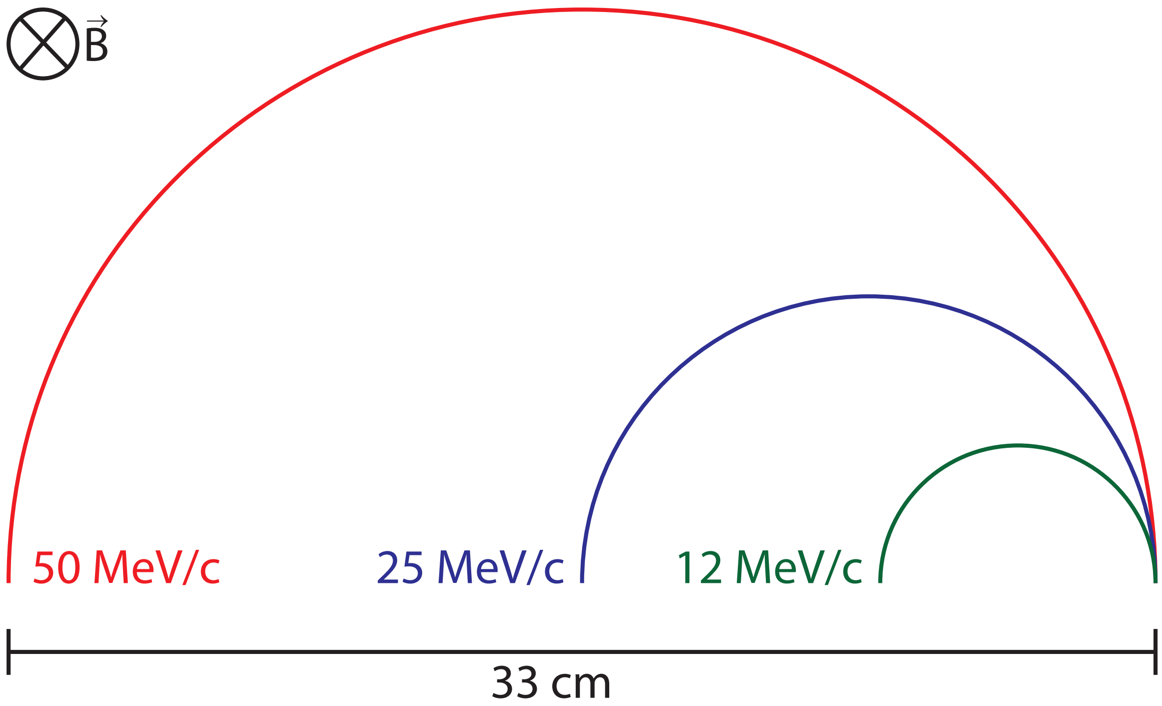


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

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

Precision vs. Acceptance



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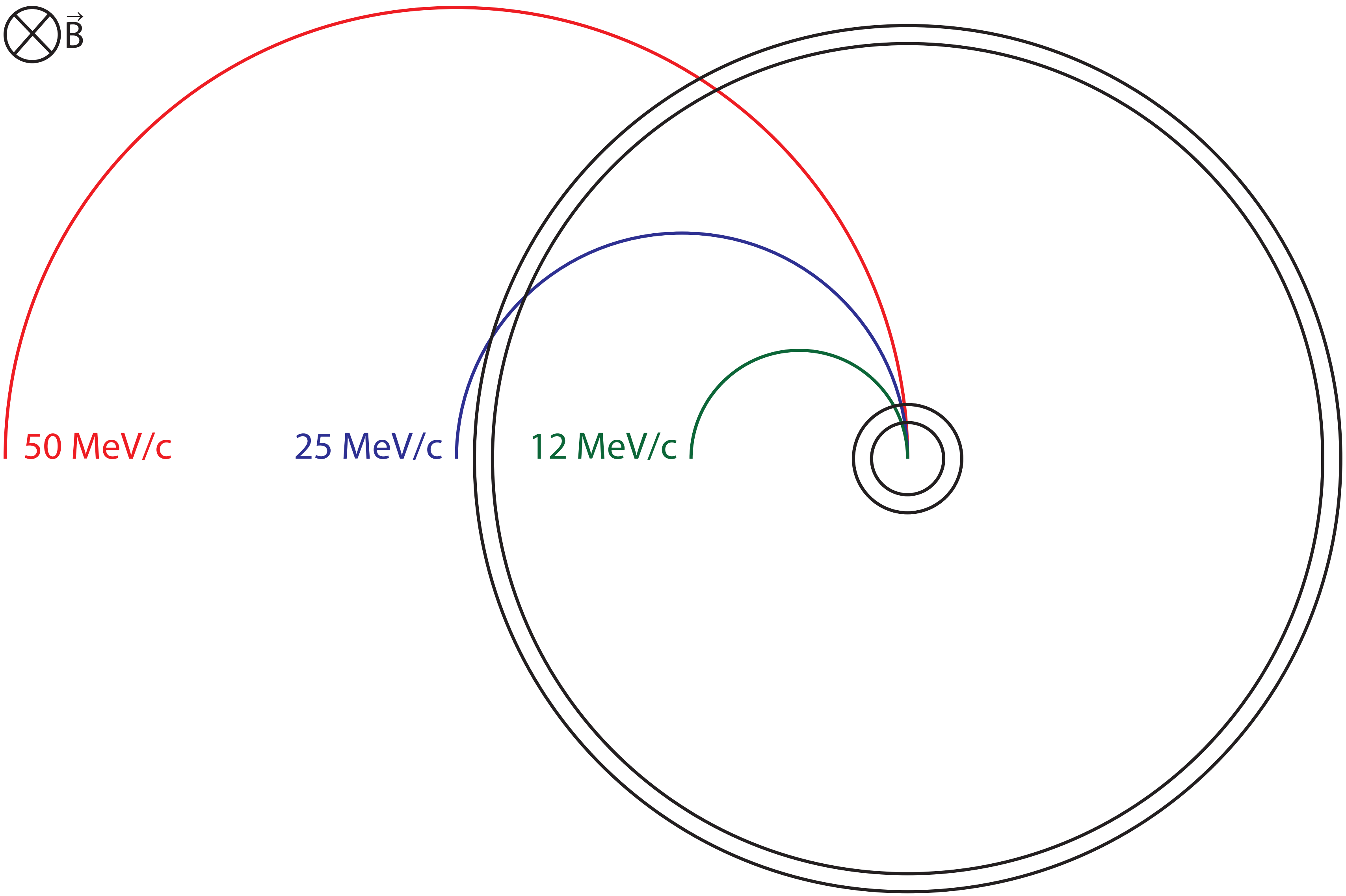

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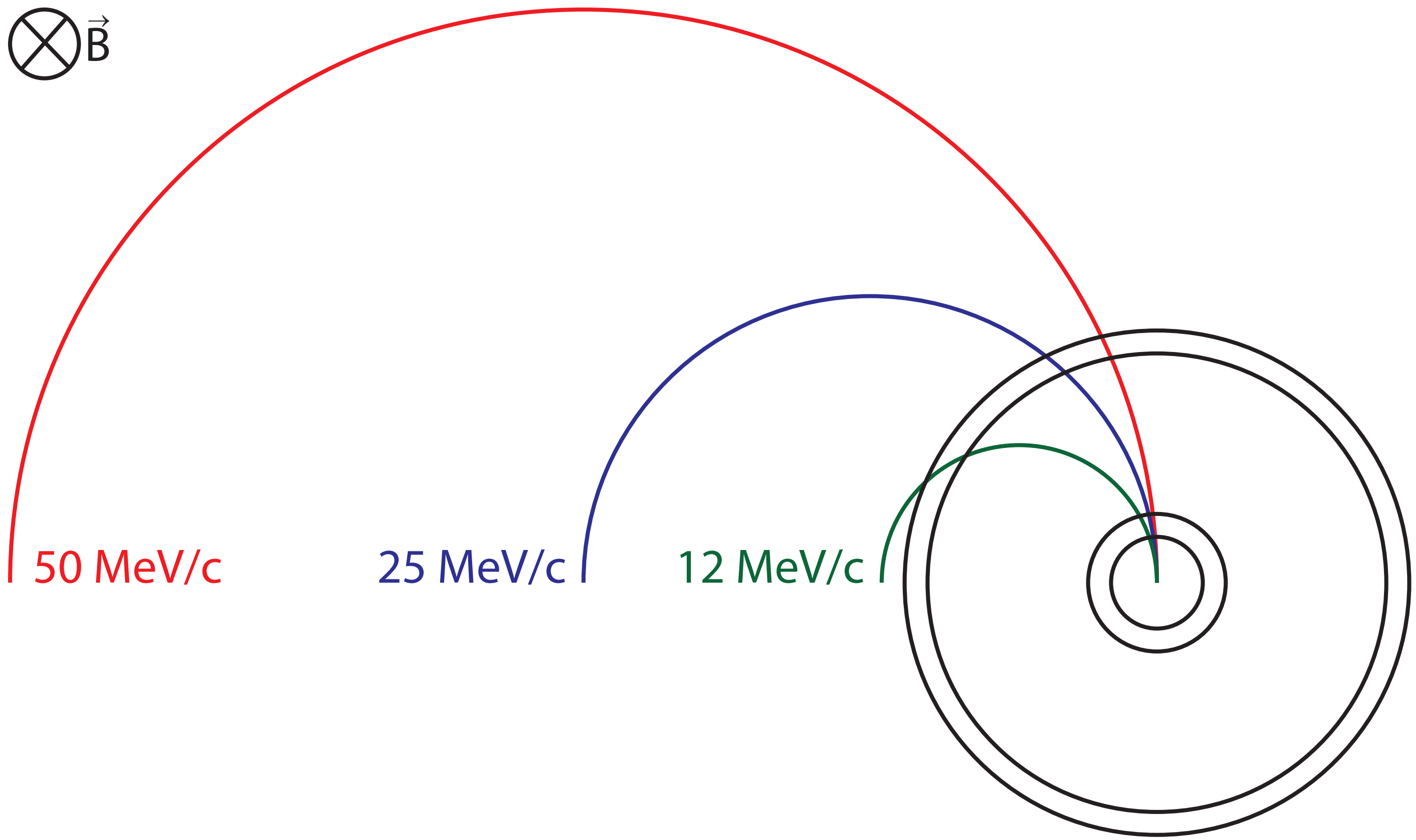

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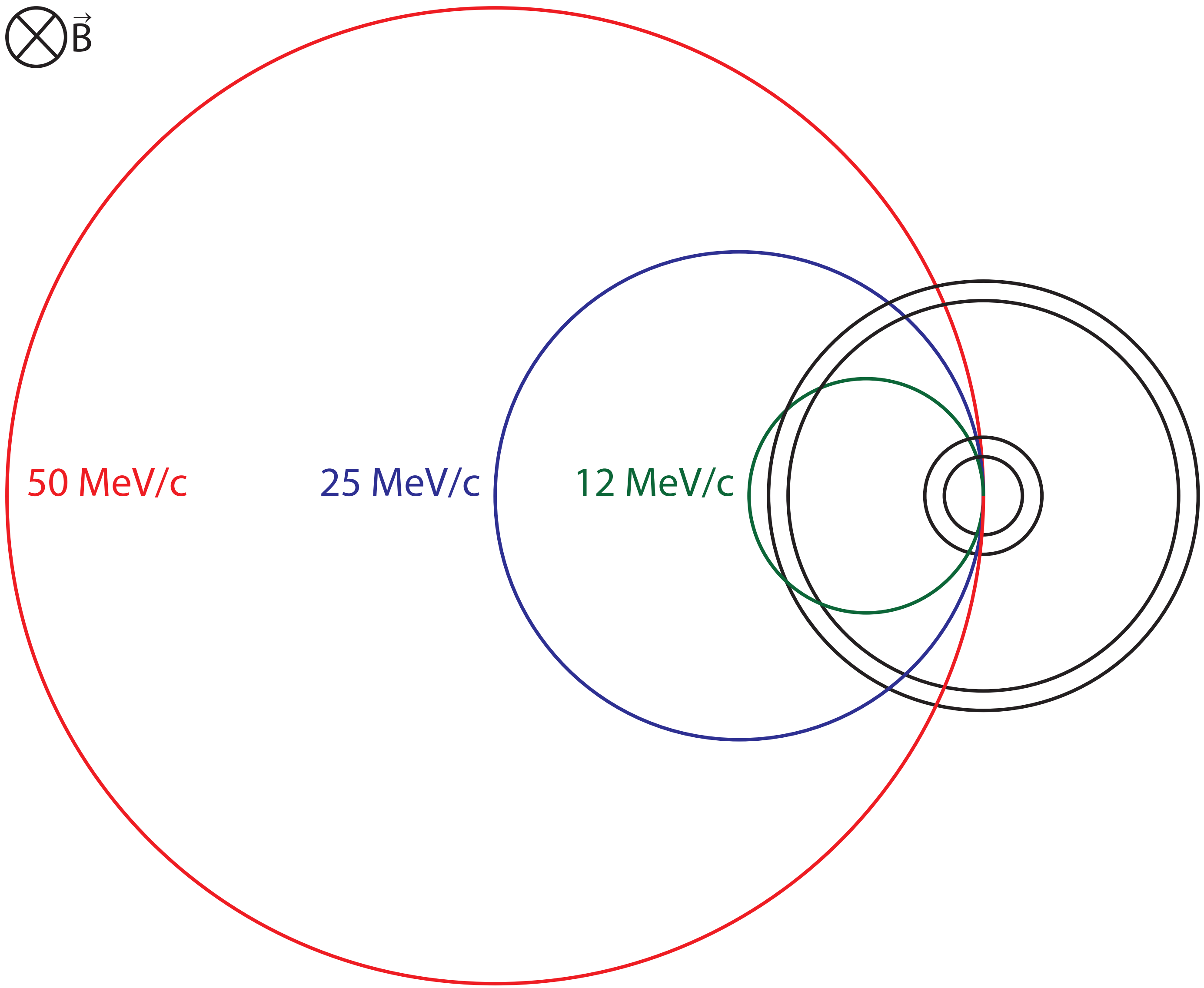

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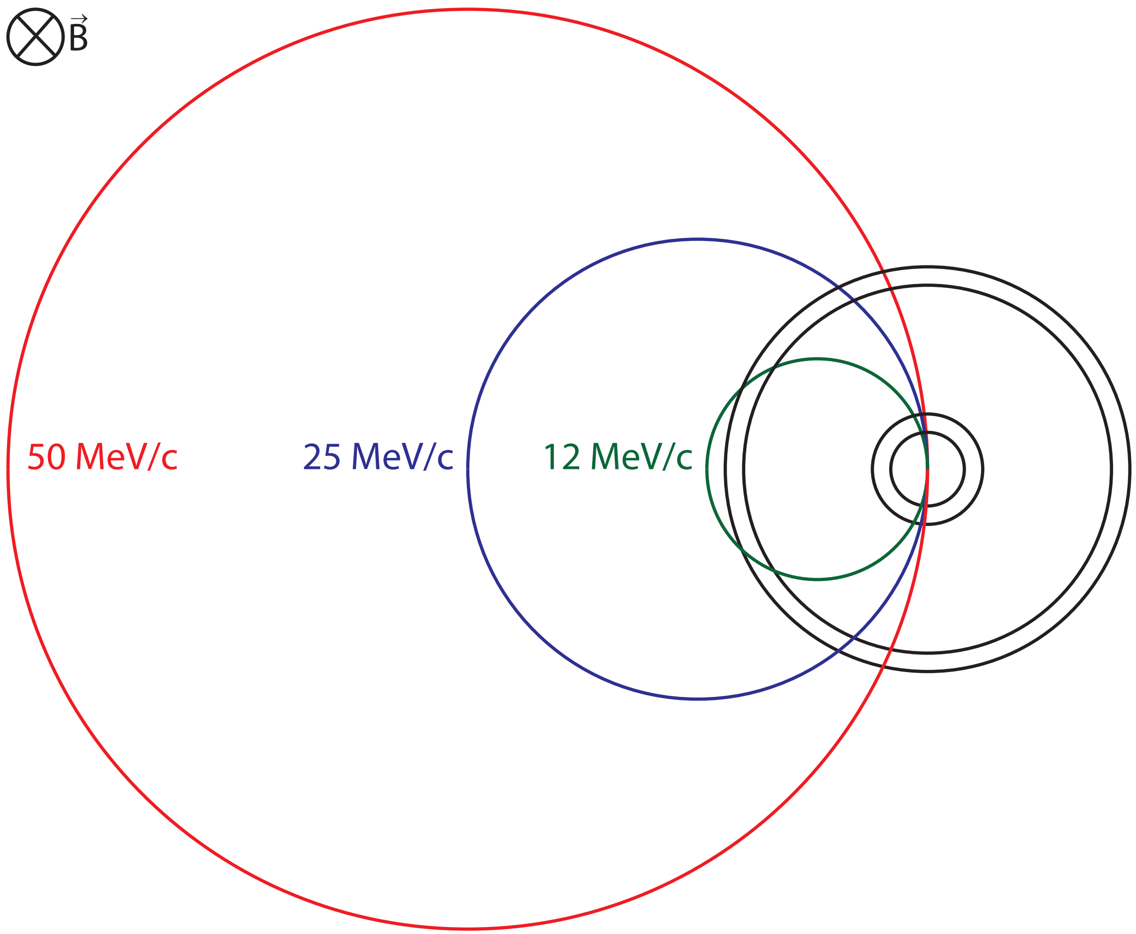
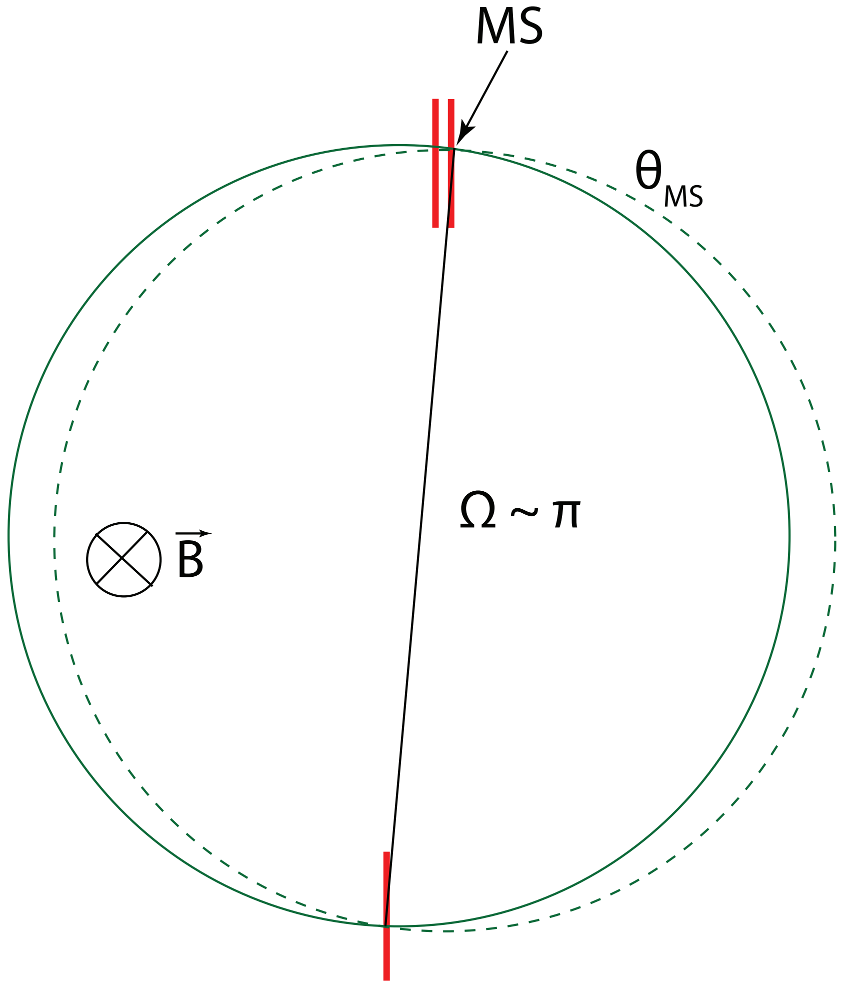
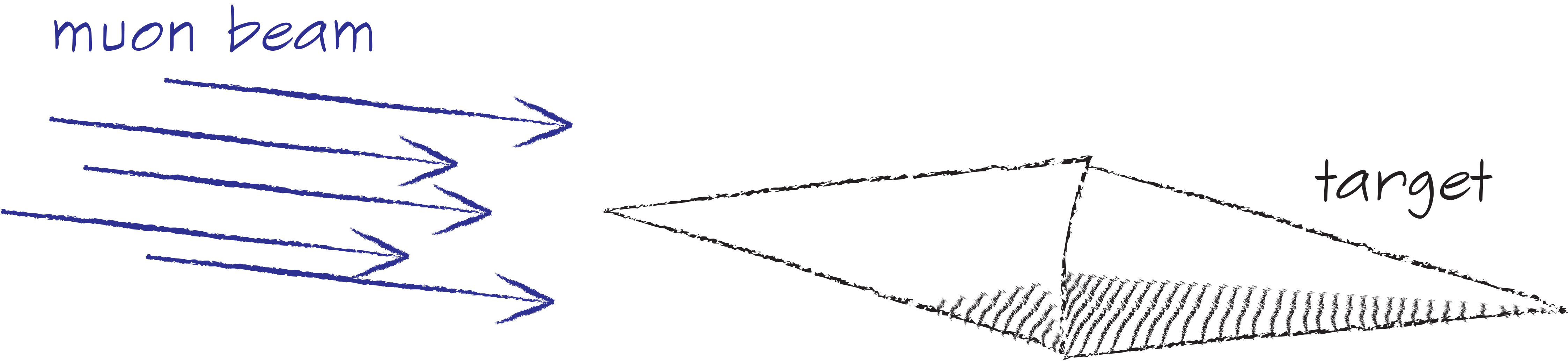




Detector Design



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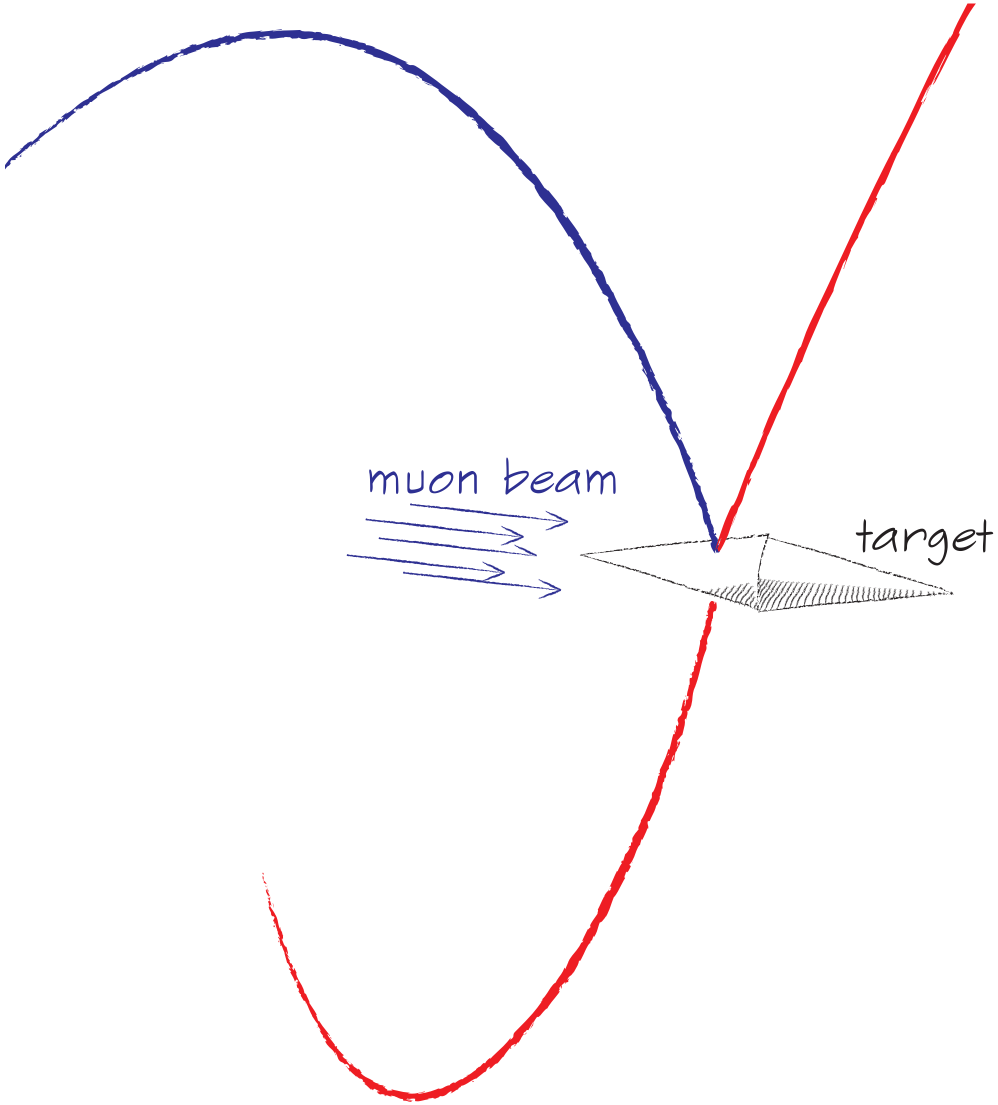

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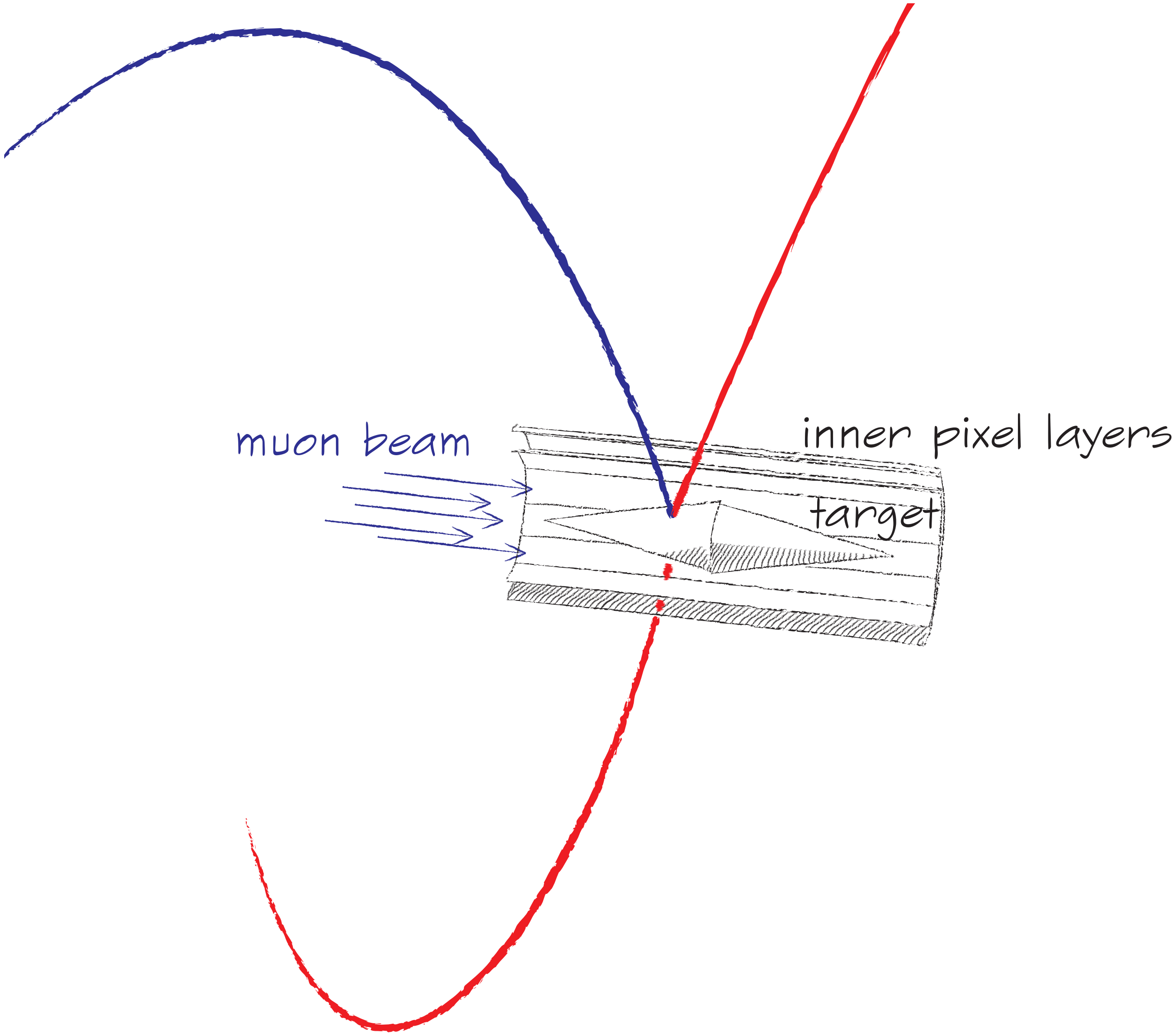

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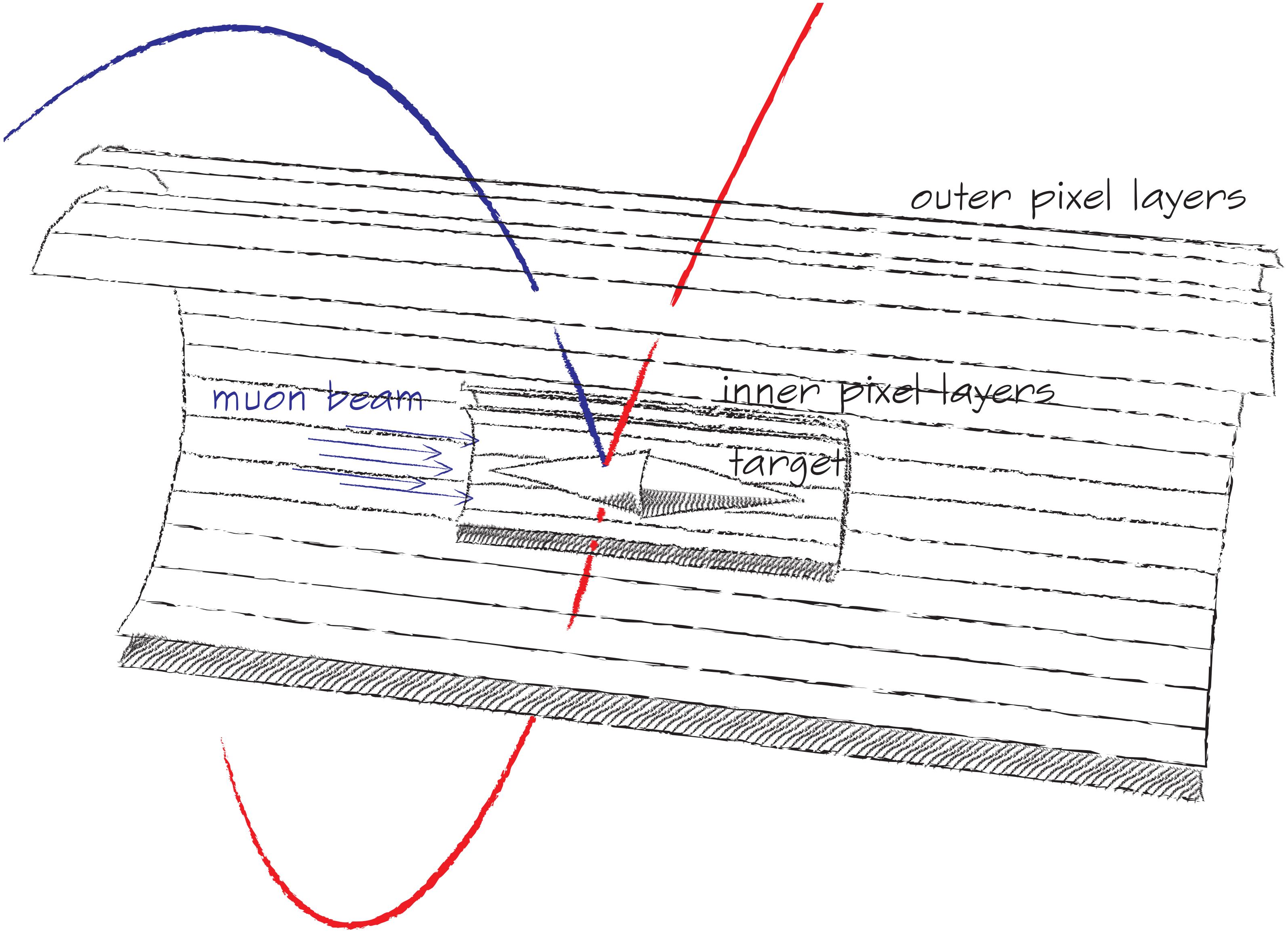
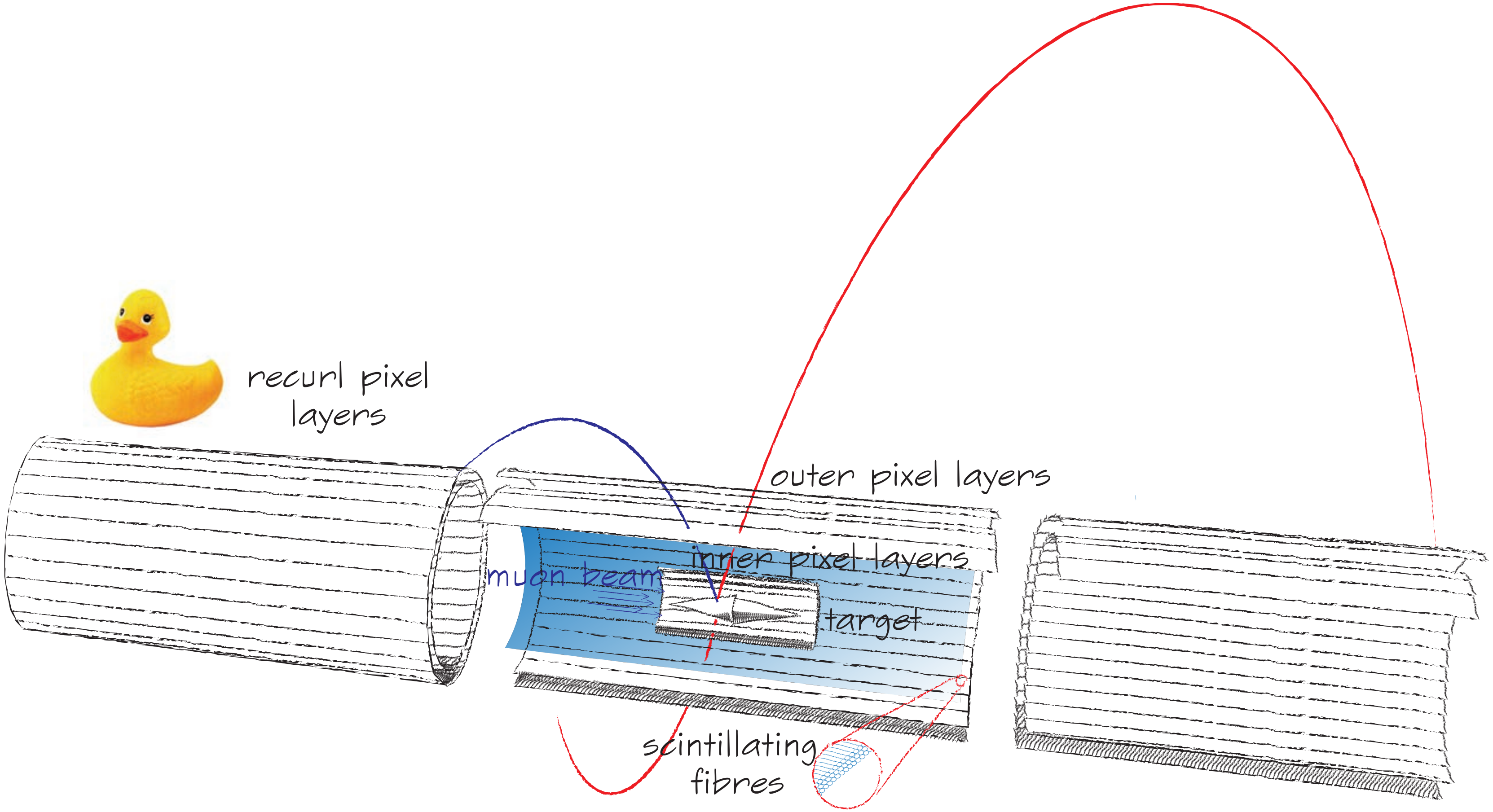
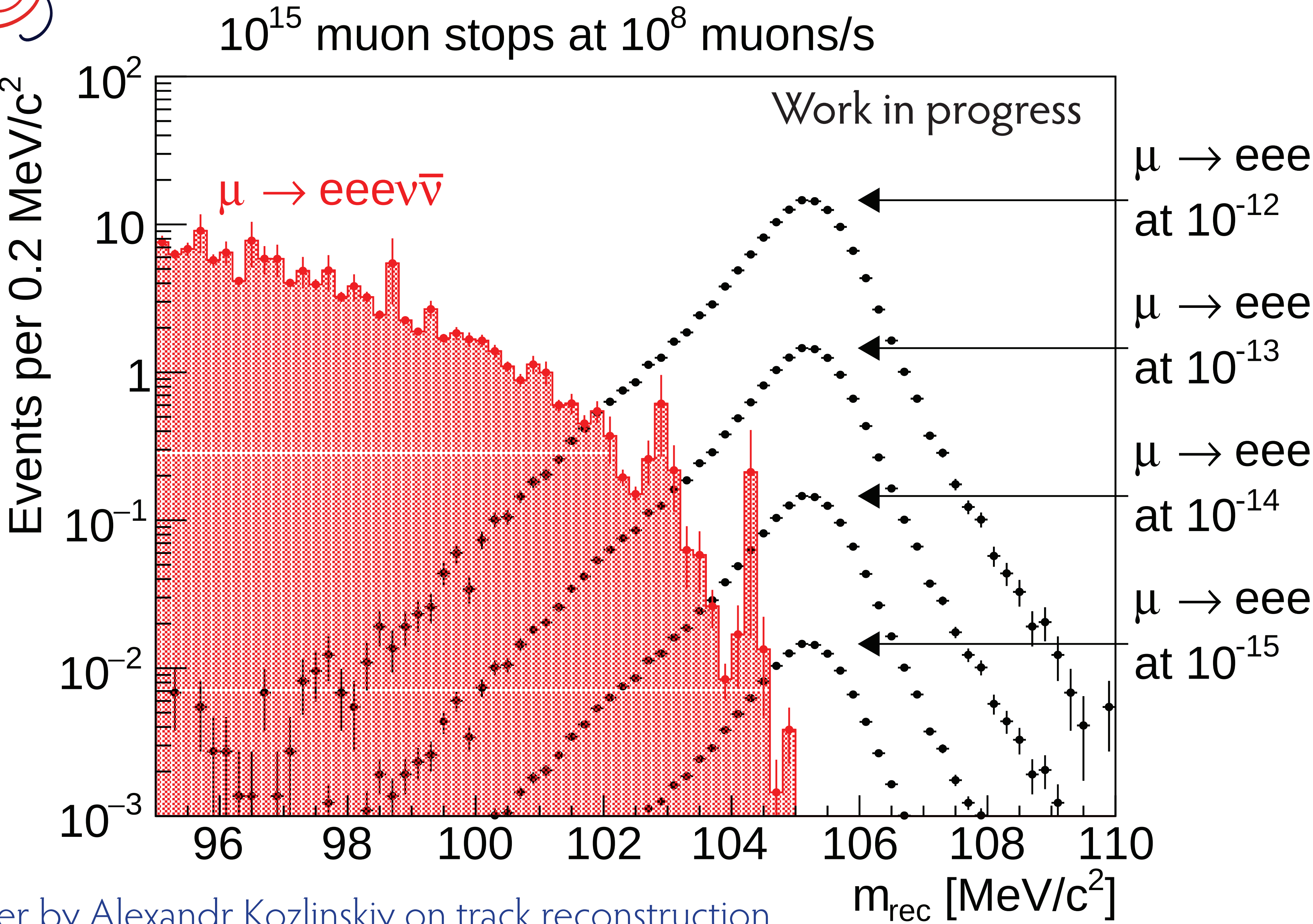


Detector Design



Performance Simulations: Mass reconstruction

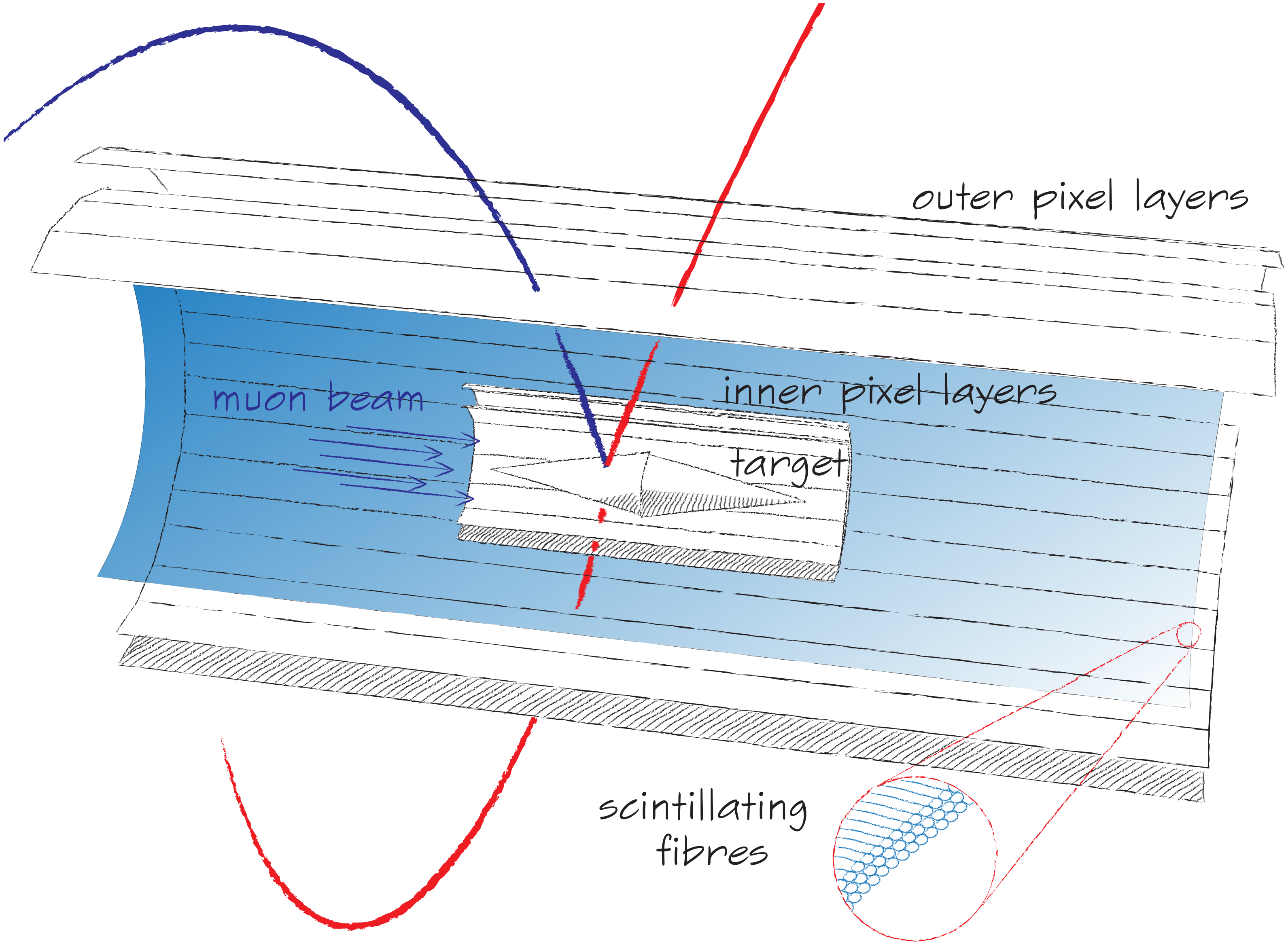


Poster by Alexandr Kozlinskiy on track reconstruction

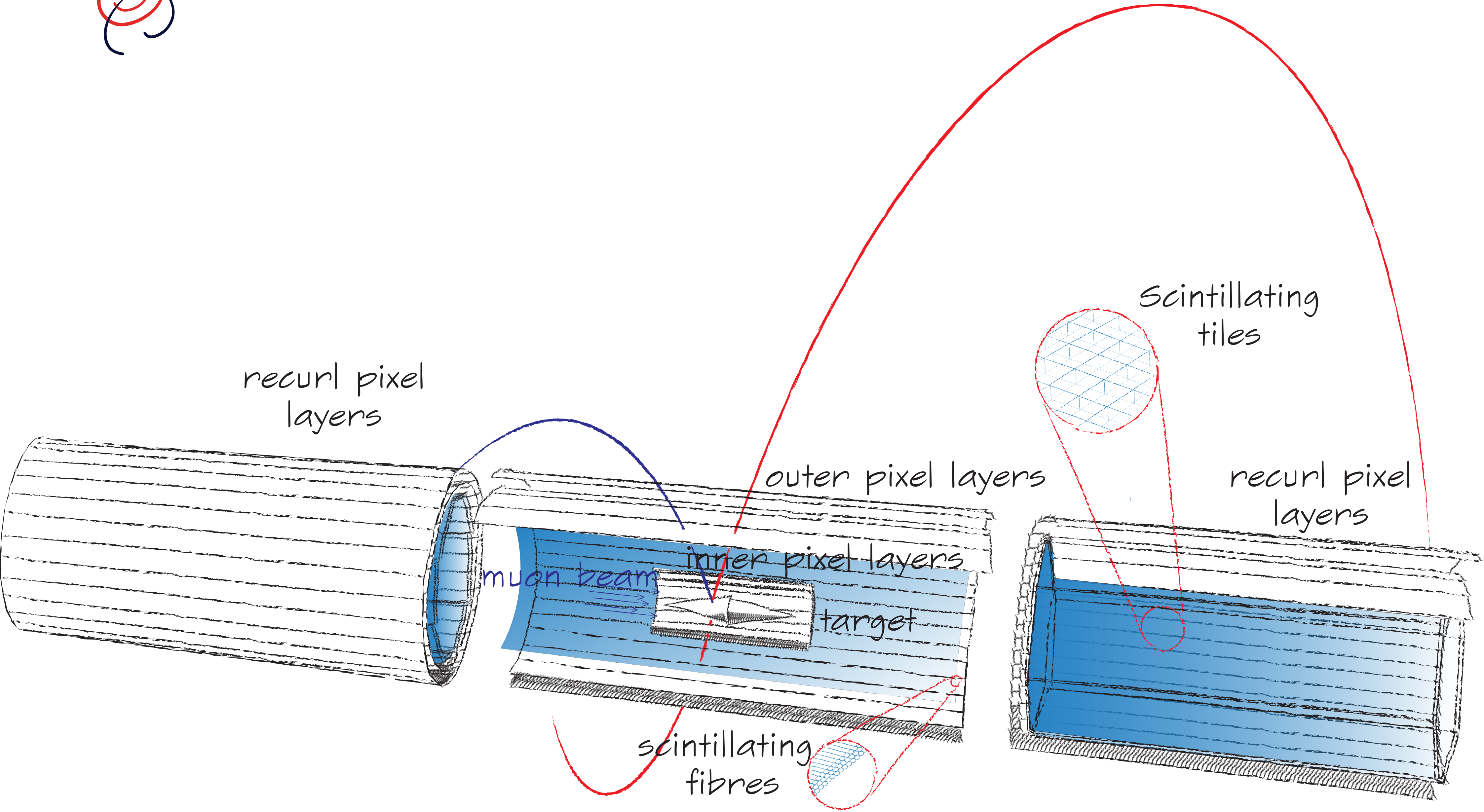
Need suppression of accidental background:

Timing

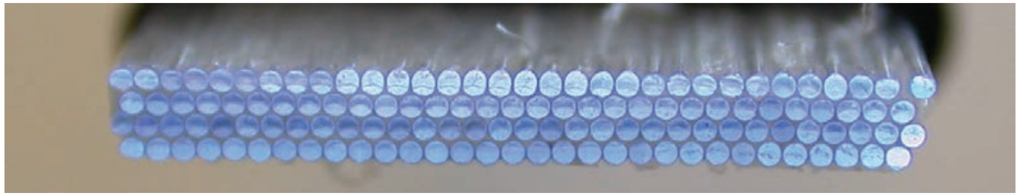
Detector Design



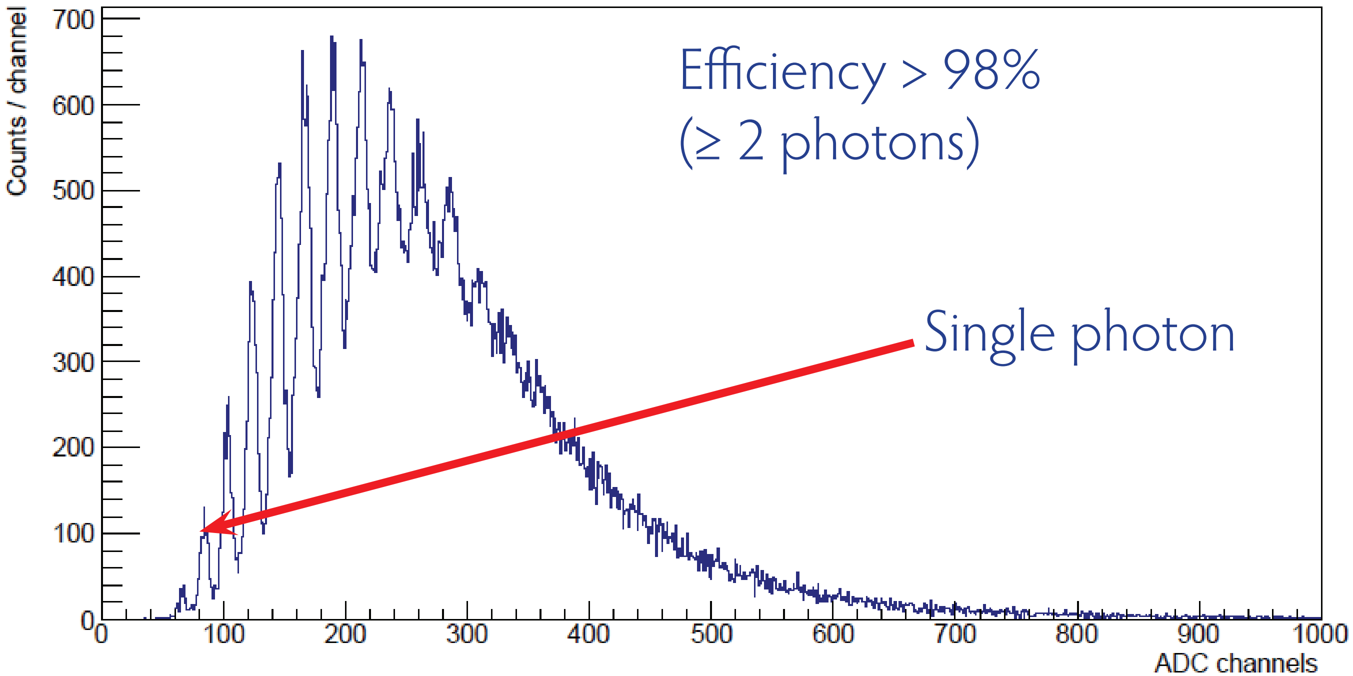
Detector Design



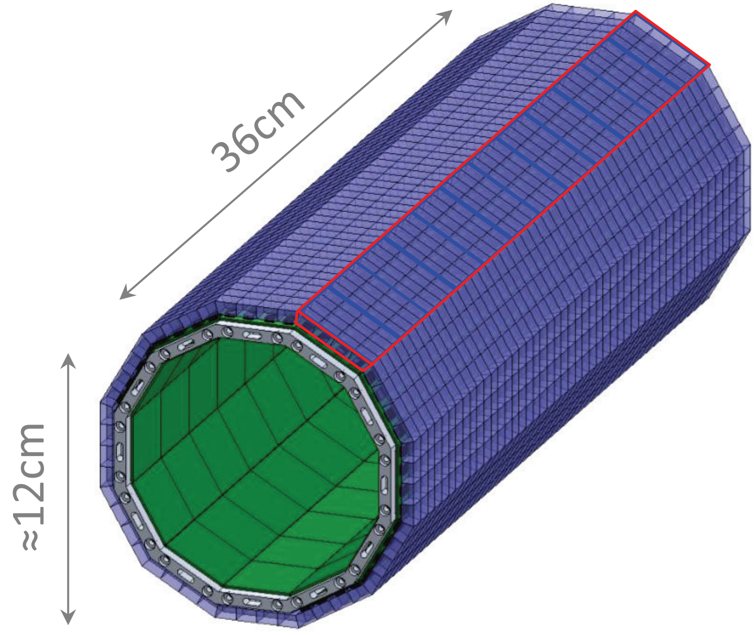
Timing Detector: Scintillating Fibres

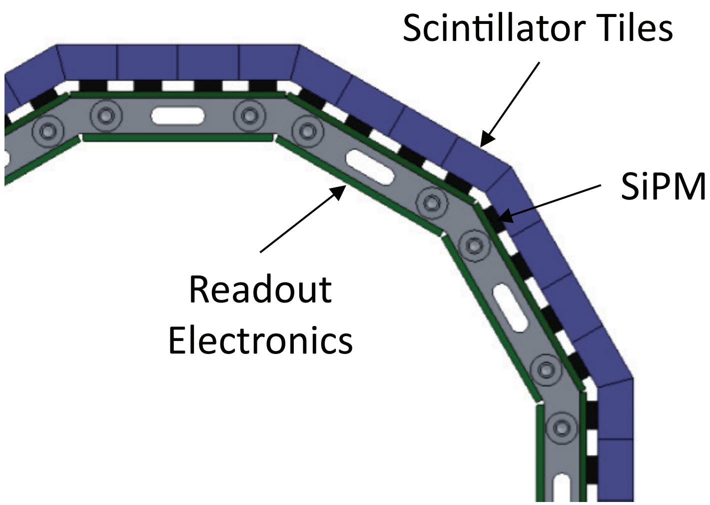


- 3 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)
- Timing resolution $\mathcal{O}$(0.5 - 1 ns) (See posters by Giada Rutar, Angela Papa)

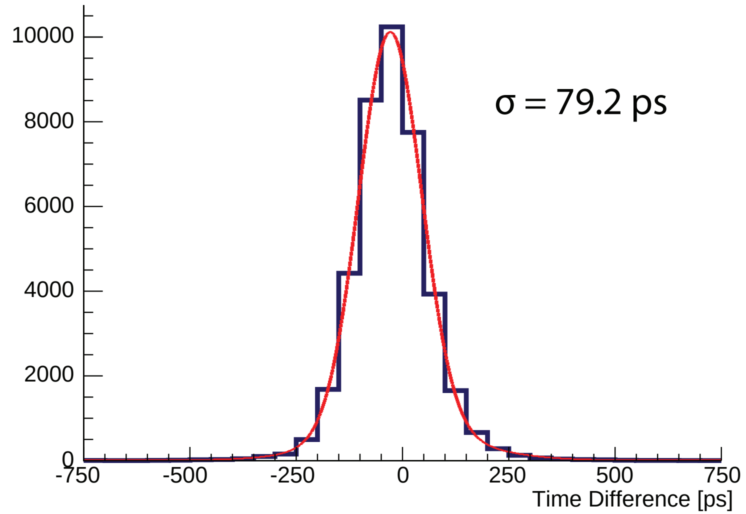


Timing Detector: Scintillating tiles



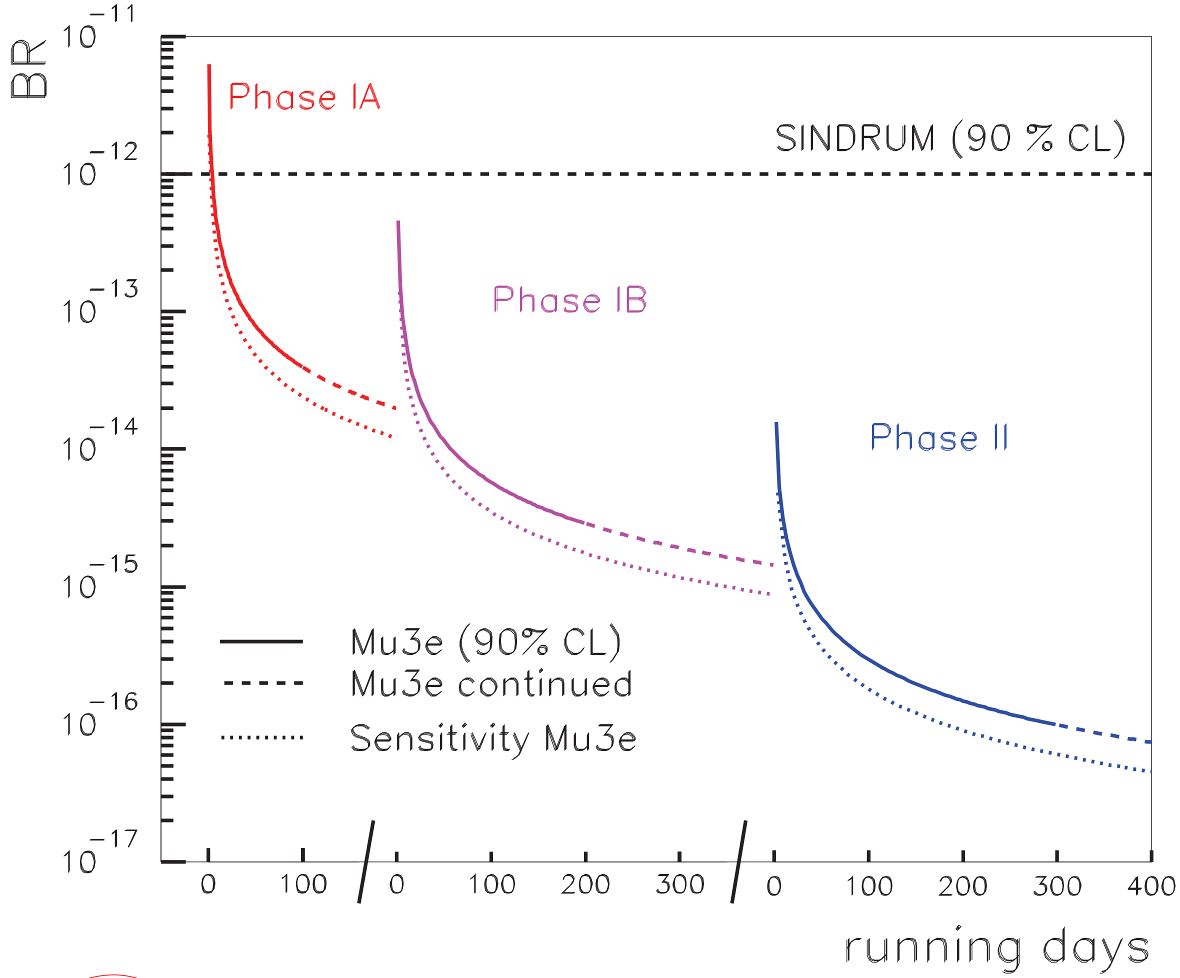


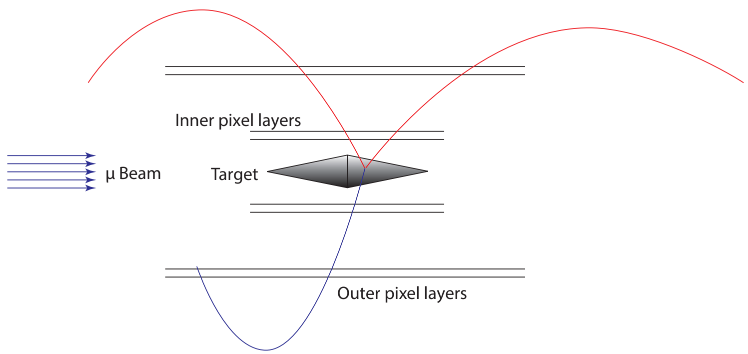
- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)



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

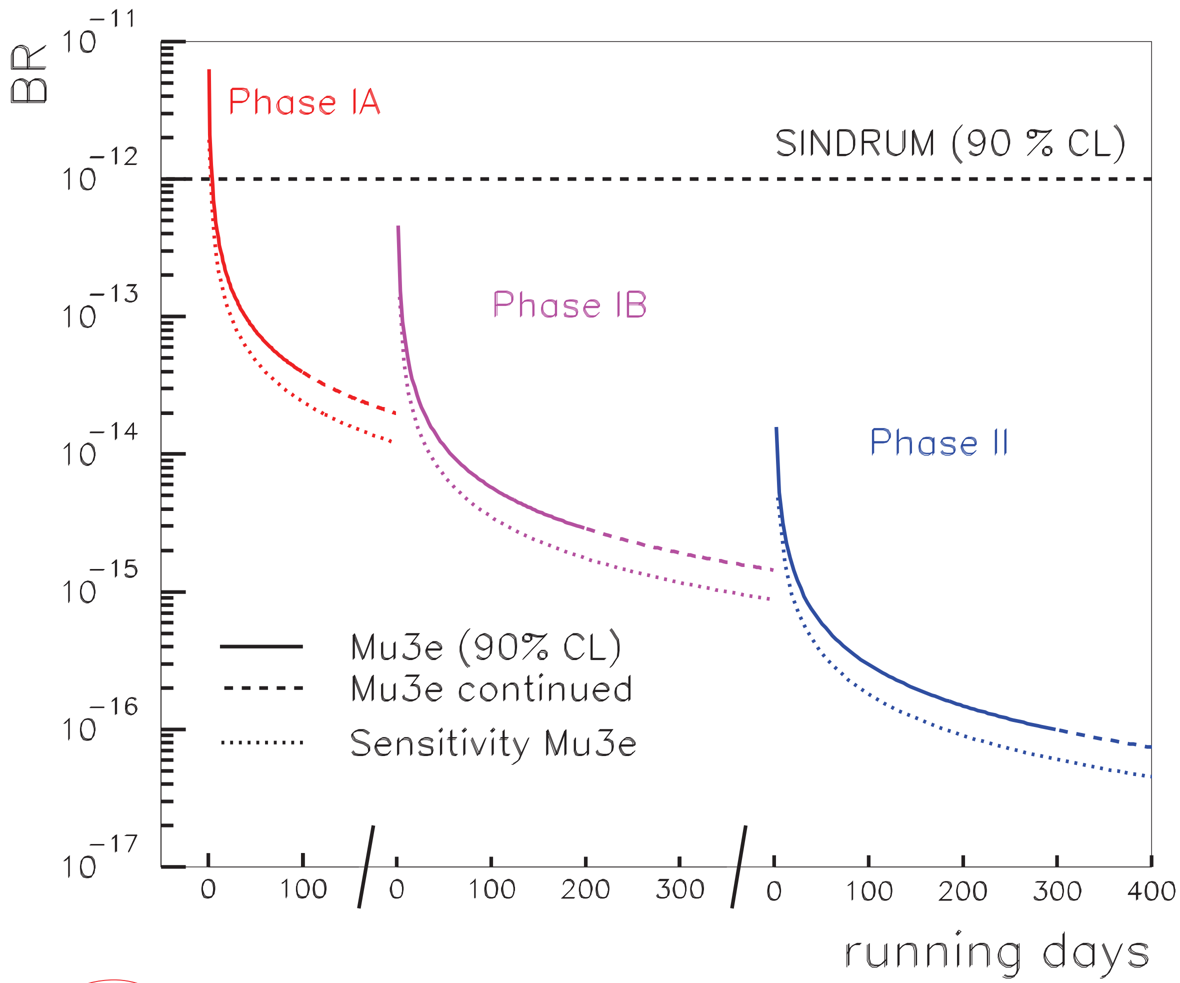
Sensitivity

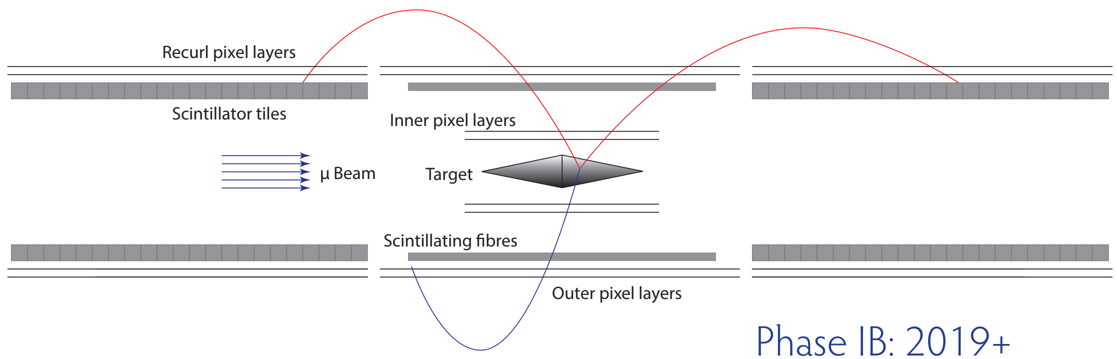




Phase IA: Starting 2018
$2 \cdot 10^7$ μ/s

Sensitivity

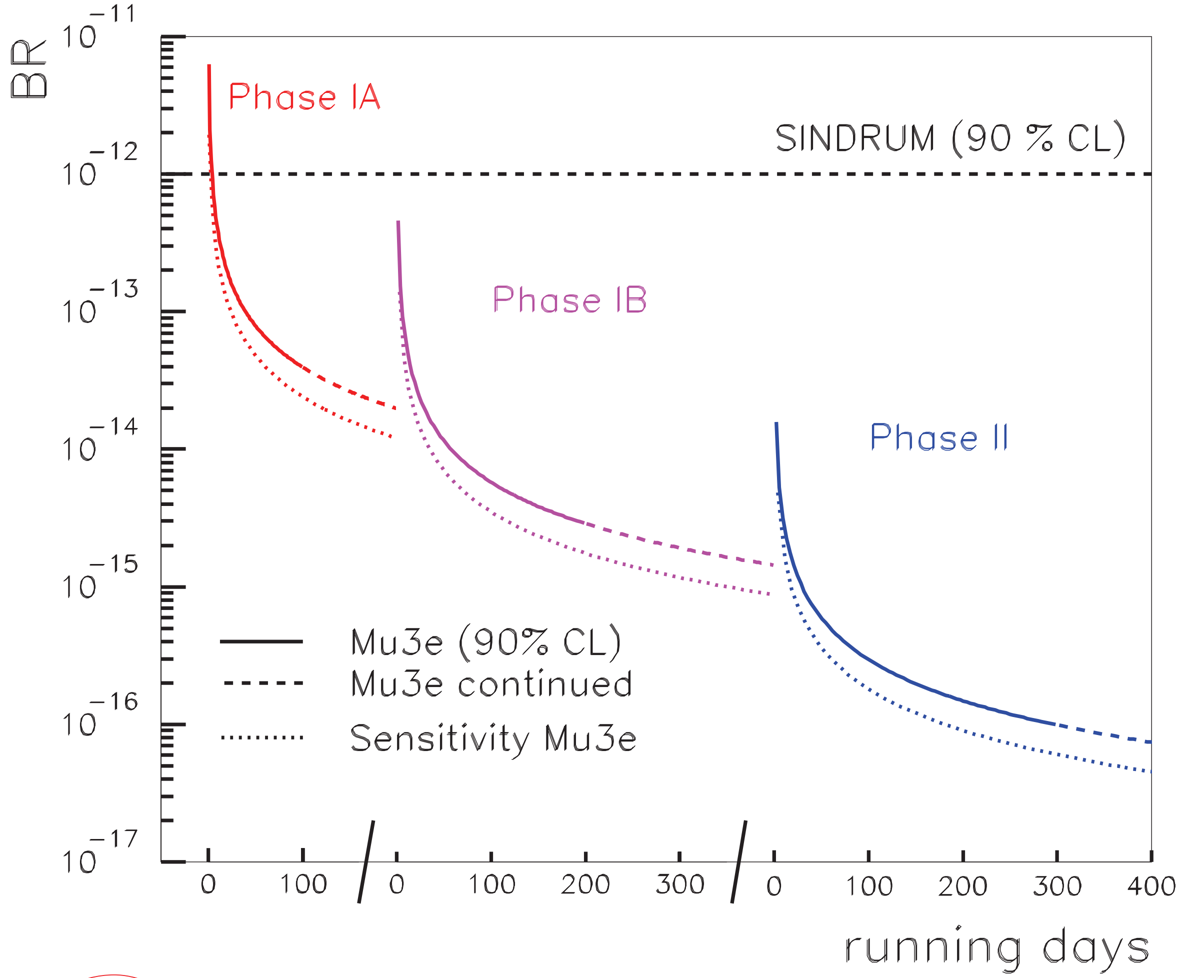


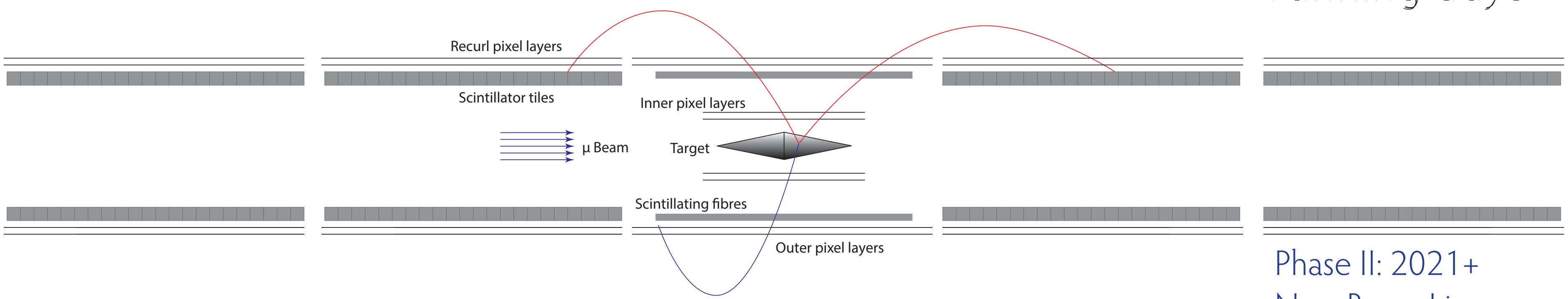


Phase IB: 2019+

$1 \cdot 10^8$ μ/s

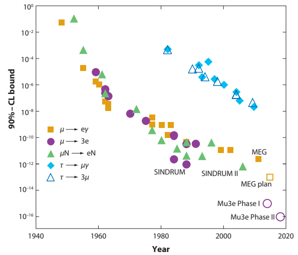
Sensitivity



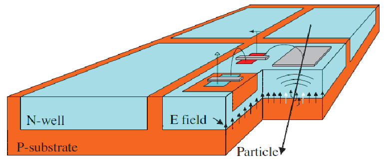


Phase II: 2021+
New Beam Line
$2 \cdot 10^{9}$ μ/s

Conclusion



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

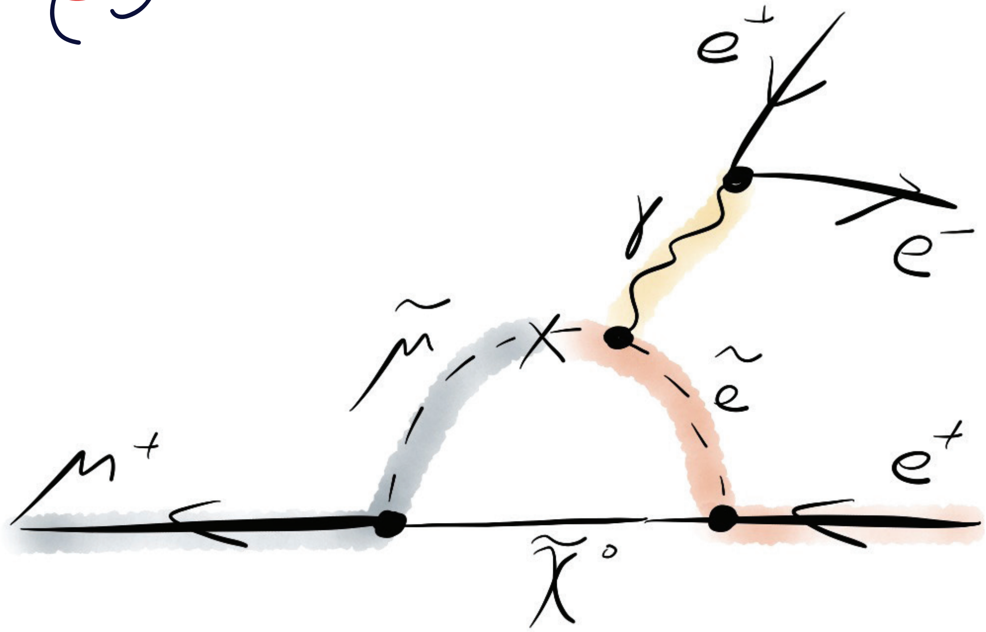


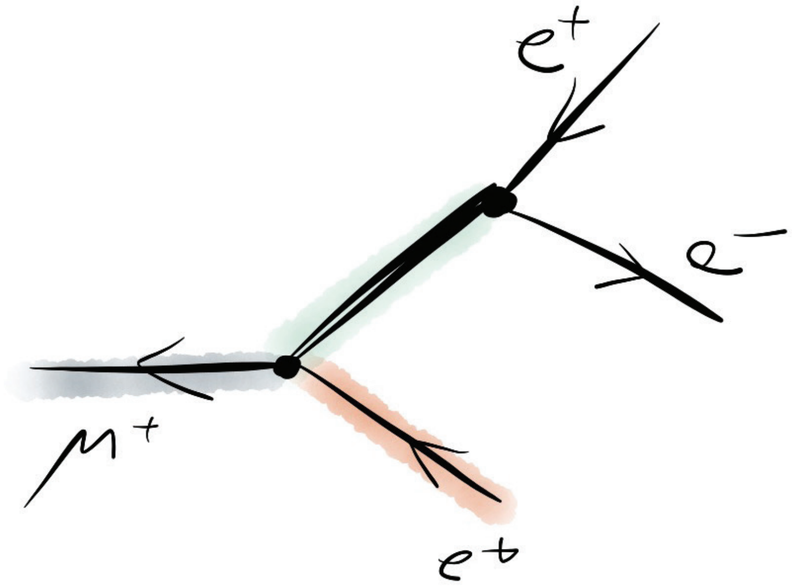
- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs

- Start data taking in 2018
- 2 billion muons/s not before 2021

Backup Material

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





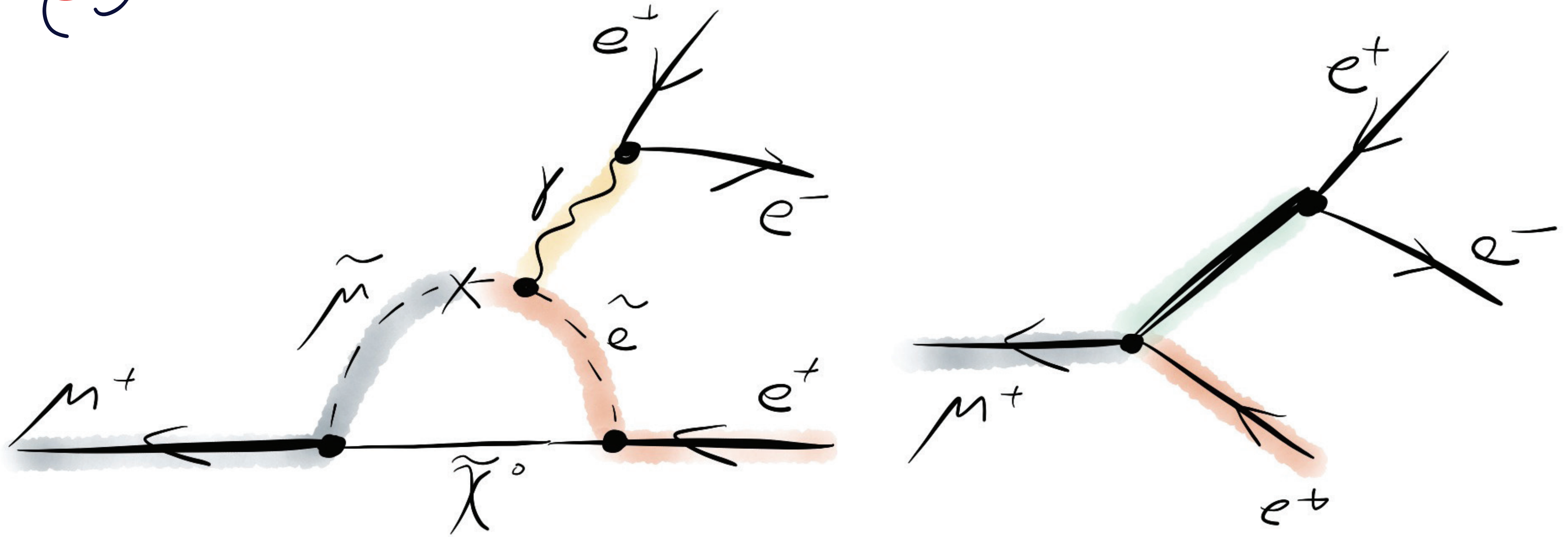
Loop diagrams

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

Tree diagrams

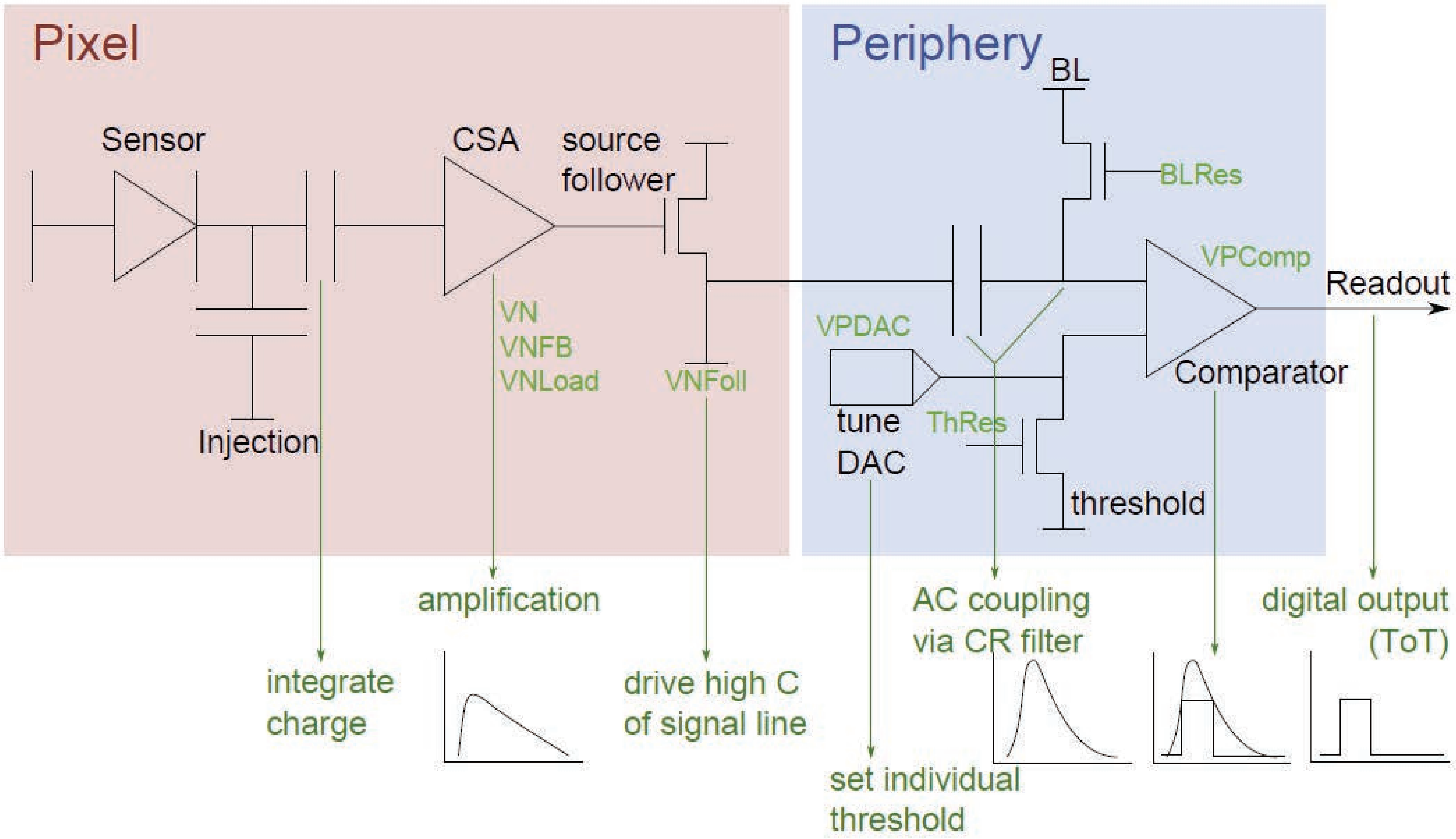
- Higgs triplet model
- Extra heavy vector bosons (Z')
- Extra dimensions (Kaluza-Klein tower)

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

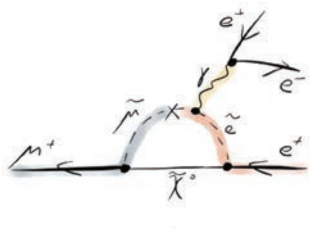


Muon decays at the 10^{-16} level sensitive to new physics at $\mathcal{O}(1000\ \text{TeV})$ scale for $\mathcal{O}(1)$ couplings!

MUPIX electronics



A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

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

Four-fermion terms e.g. Z'

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

scalar

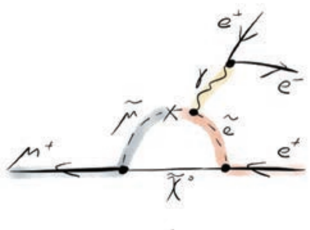
$$+ g_3 (\overline{\mu}_R \gamma^\mu e_R)(\overline{e}_R \gamma^\mu e_R) \qquad + g_4 (\overline{\mu}_L \gamma^\mu e_L)(\overline{e}_L \gamma^\mu e_L)$$

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

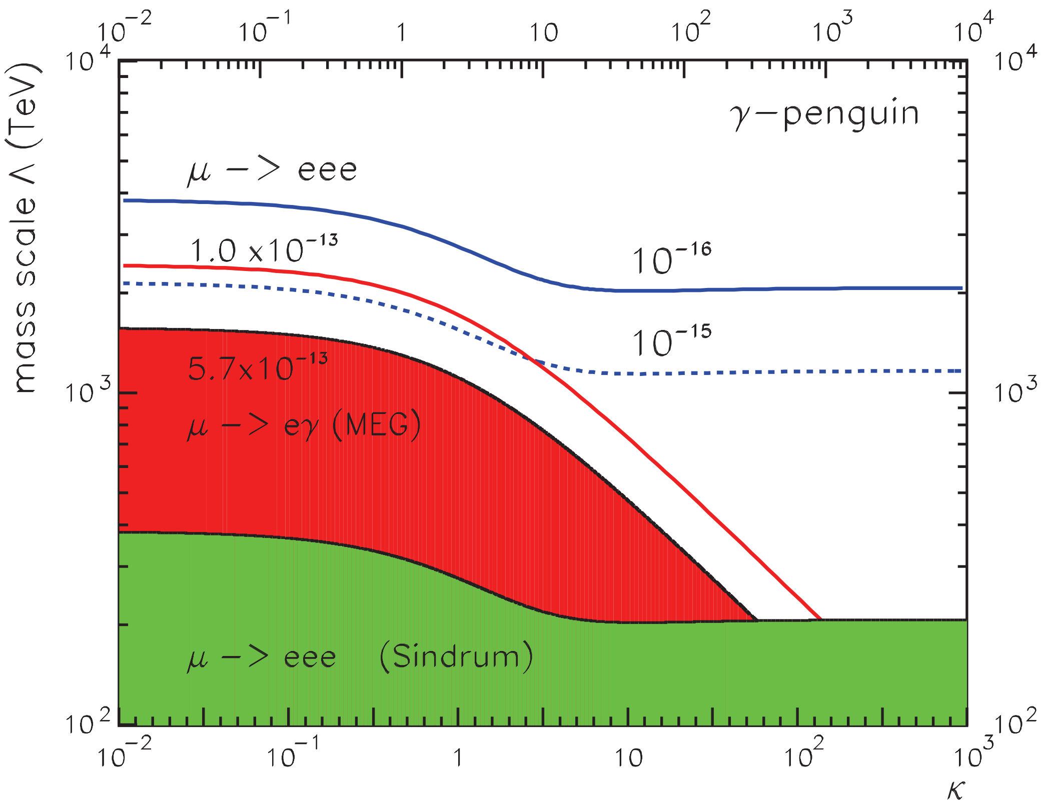
vector

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

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



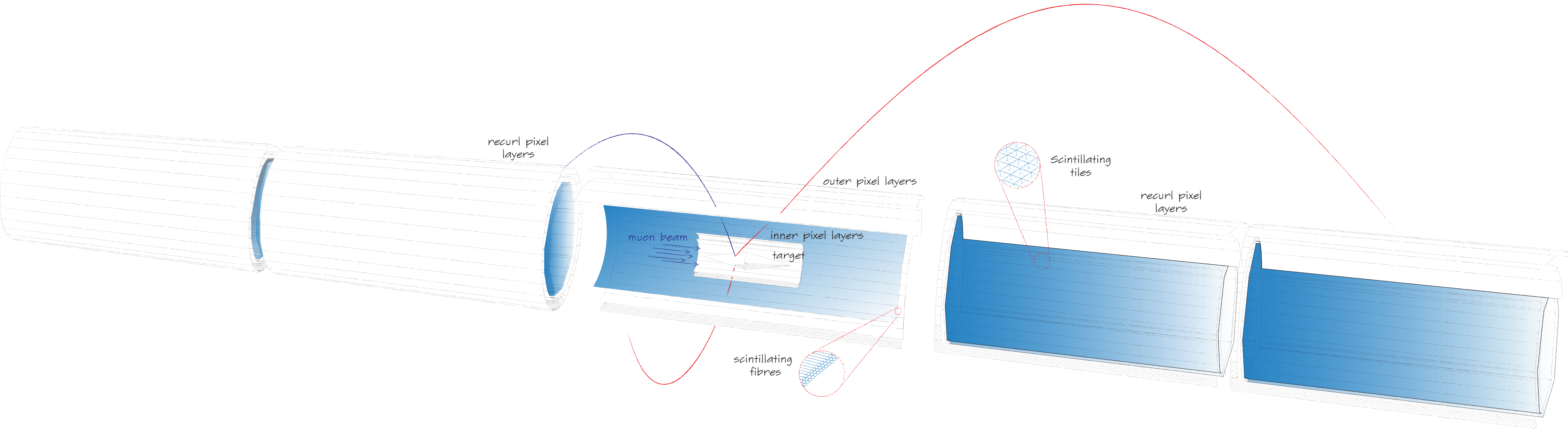
$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$



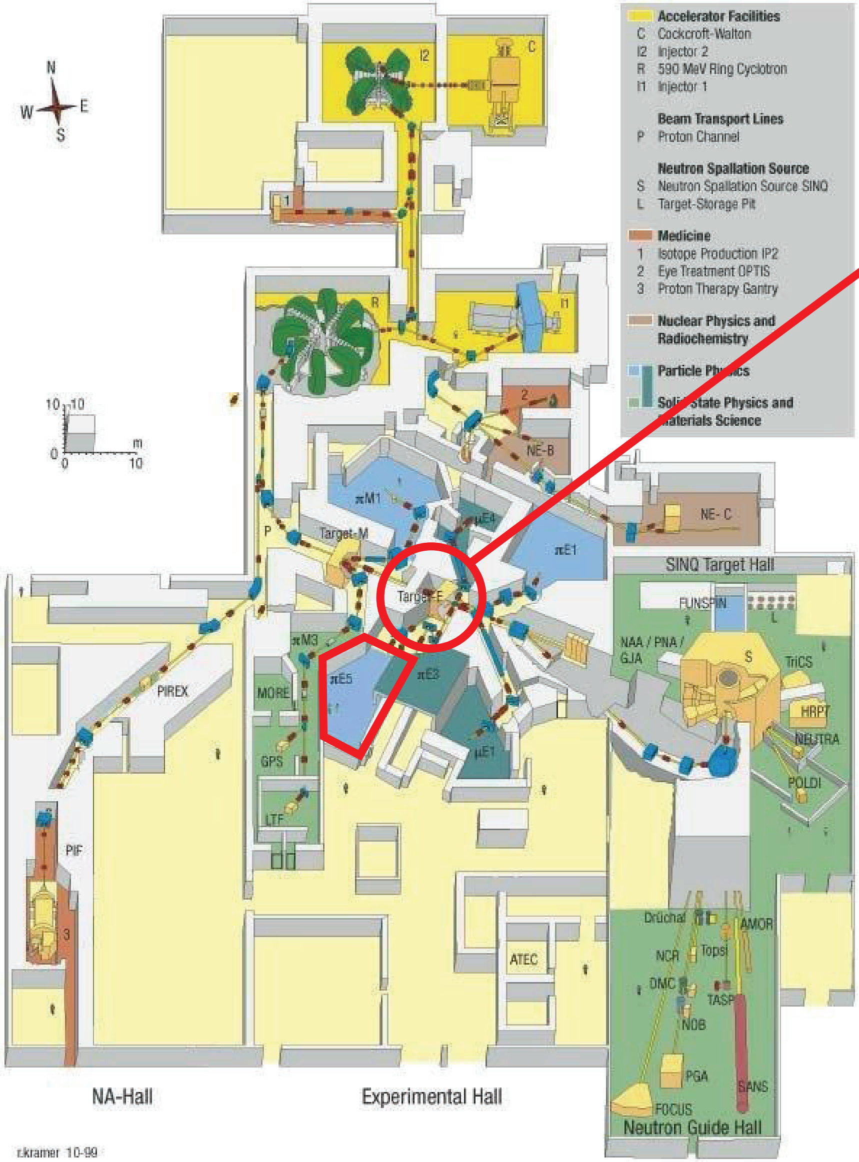
- One loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

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

Detector Design



Muons from PSI

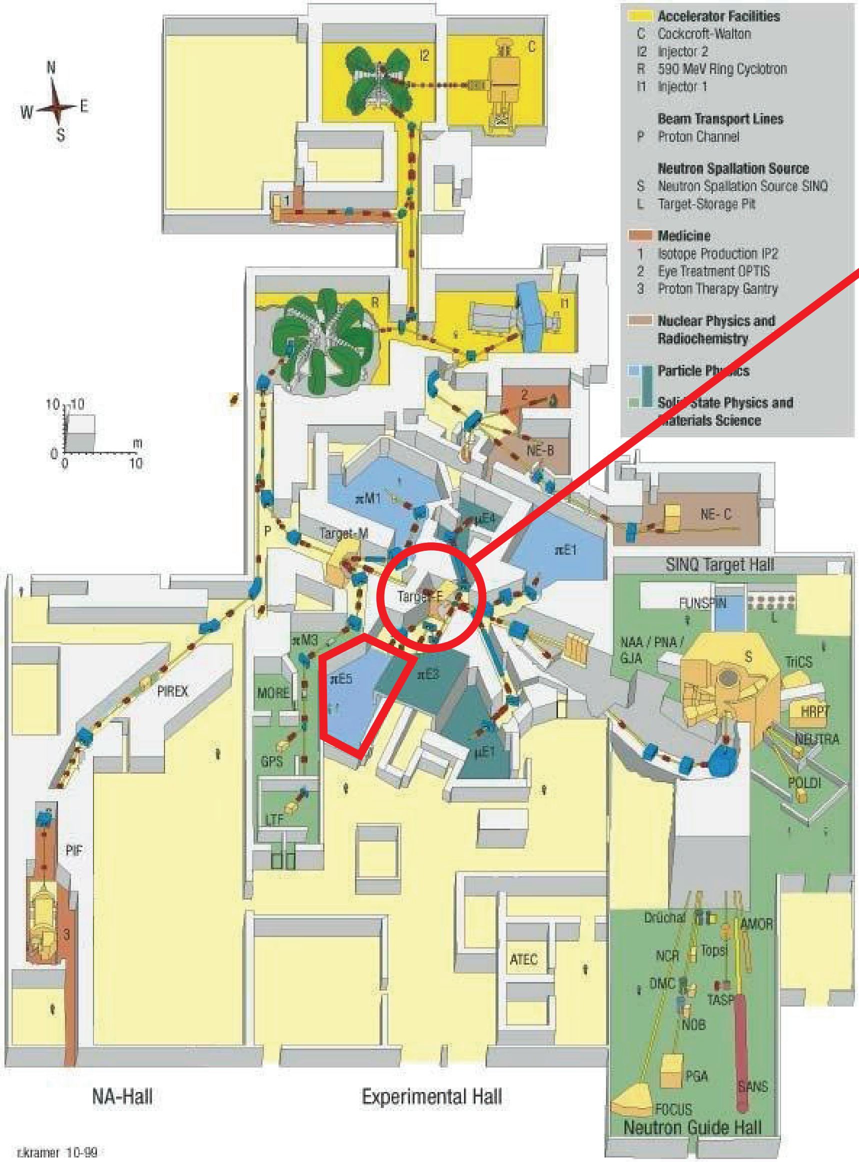


DC muon beams at PSI:

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

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

Muons from PSI



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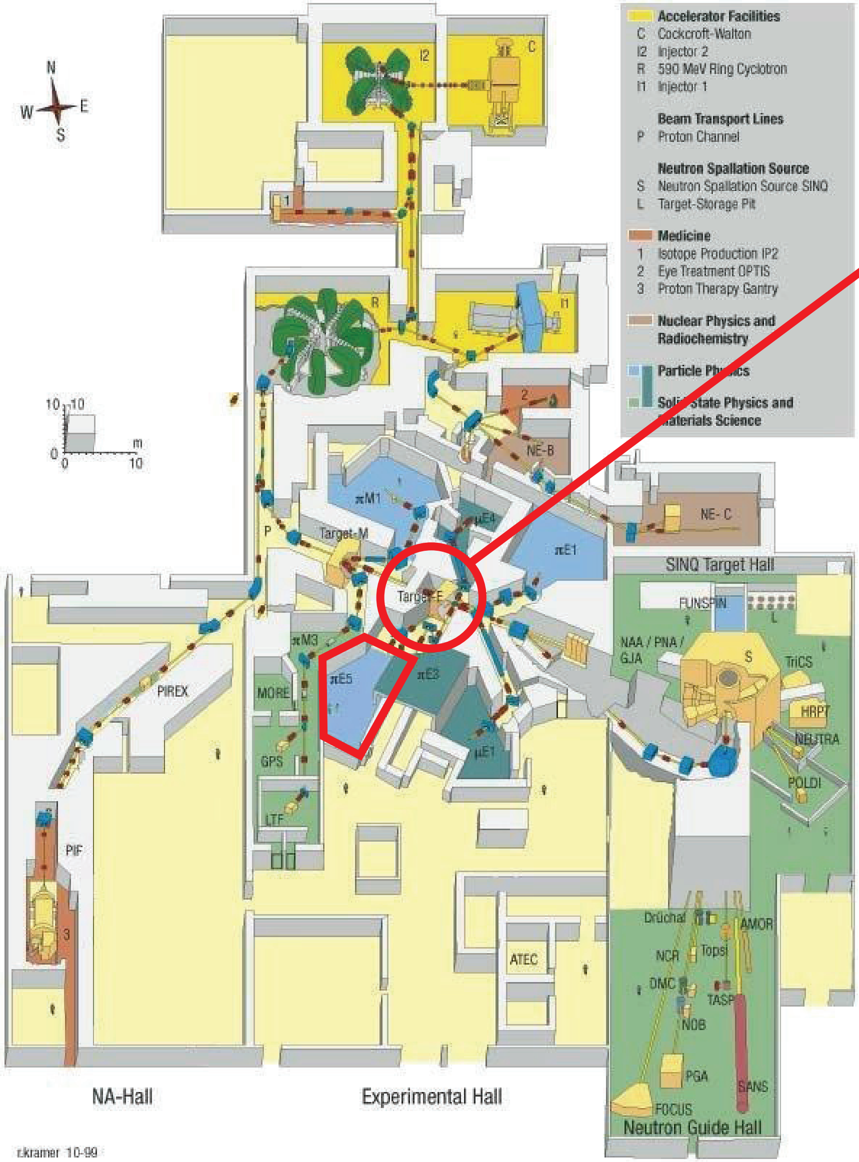

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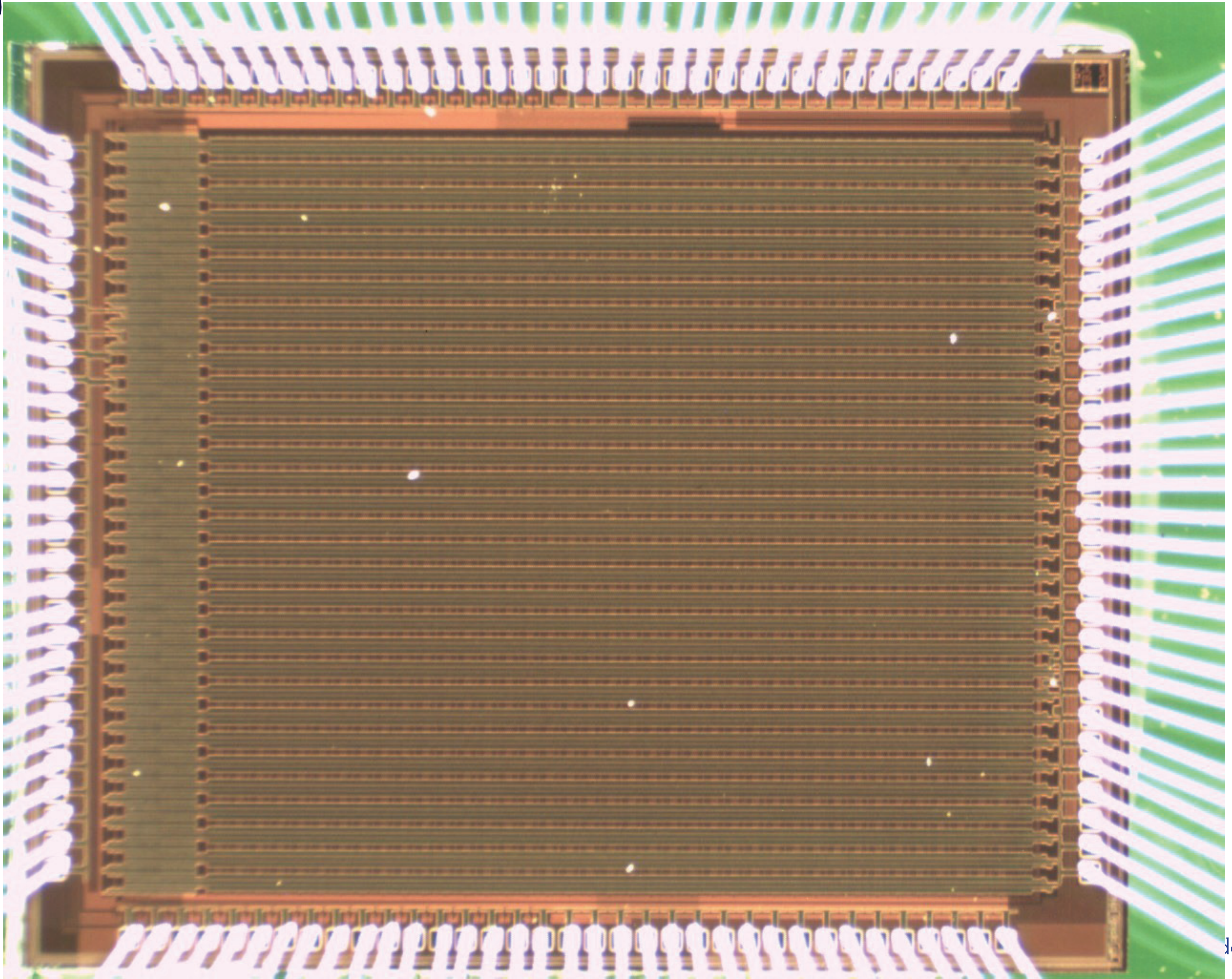
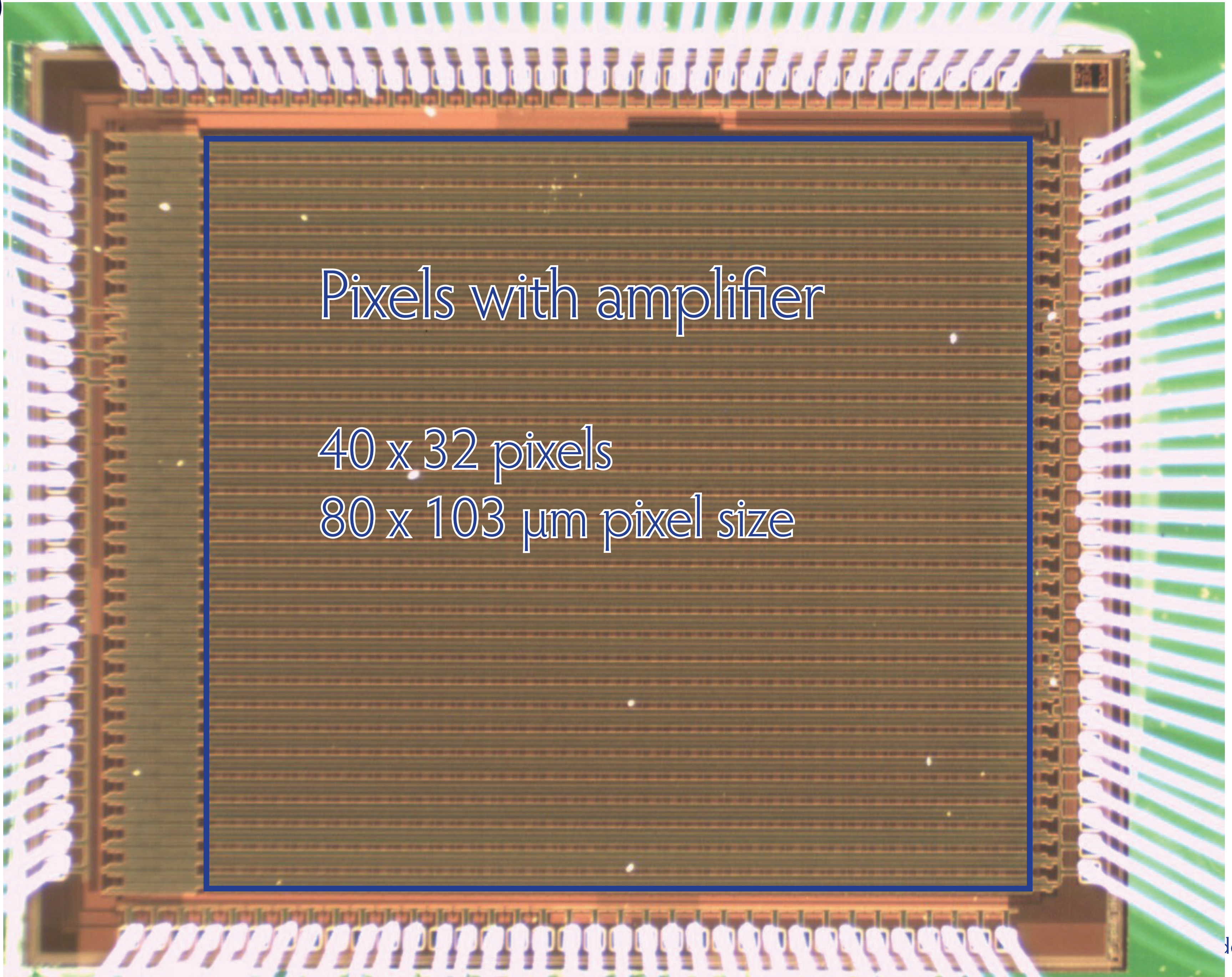
  (MEG experiment, Mu3e phase I)
- Surface muons, p = 29.7 MeV/c
  Stopped in < 1 mm of plastic
- The $\mu \rightarrow eee$ experiment (final stage) requires 2×10^9 muons/s focused and collimated on a ~2 cm spot
- More than ~ 10^{11} muons/s are produced; bring magnetic elements closer to capture them:
  High intensity muon beamline (HiMB) study currently ongoing

HV-MAPS



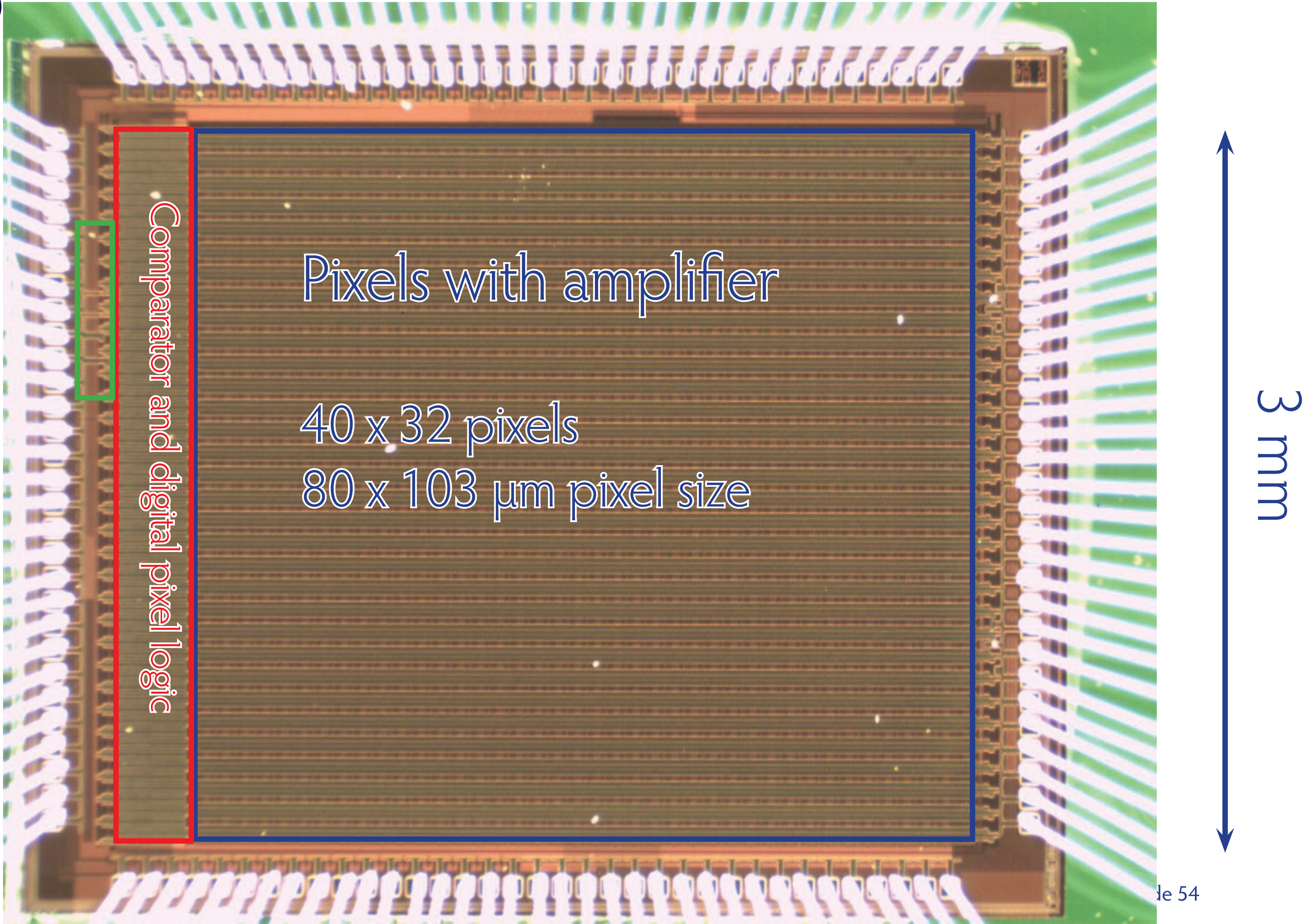
3 mm

HV-MAPS

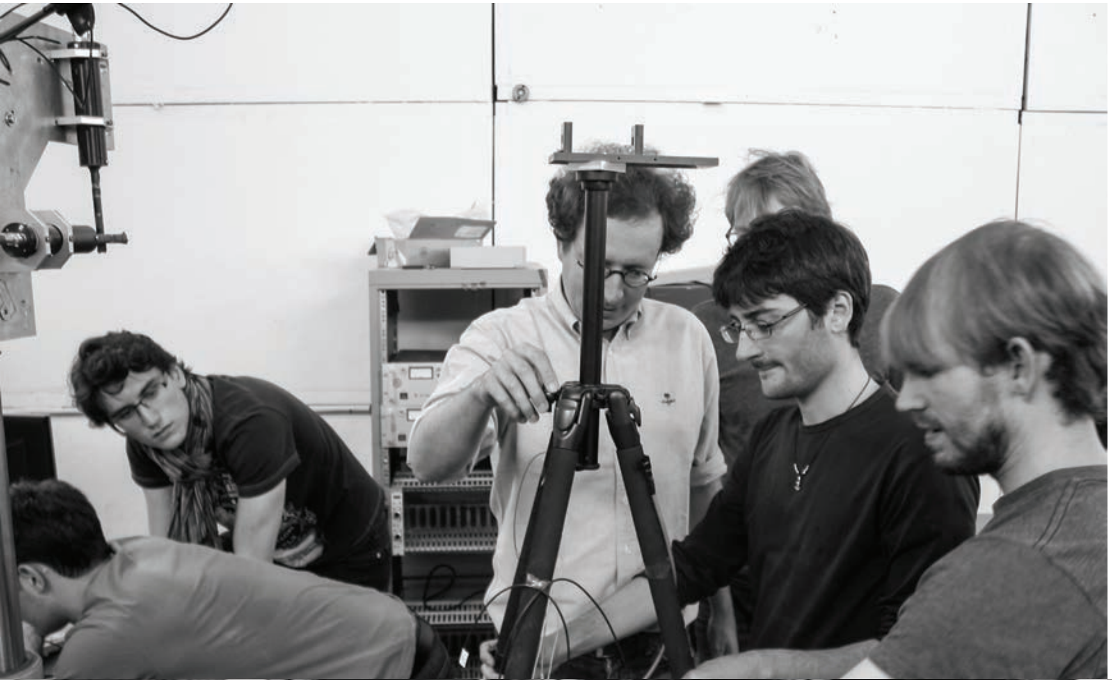


3 mm

HV-MAPS


Comparator and digital pixel logic
Pixels with amplifier
40 x 32 pixels
80 x 103 µm pixel size
3 mm

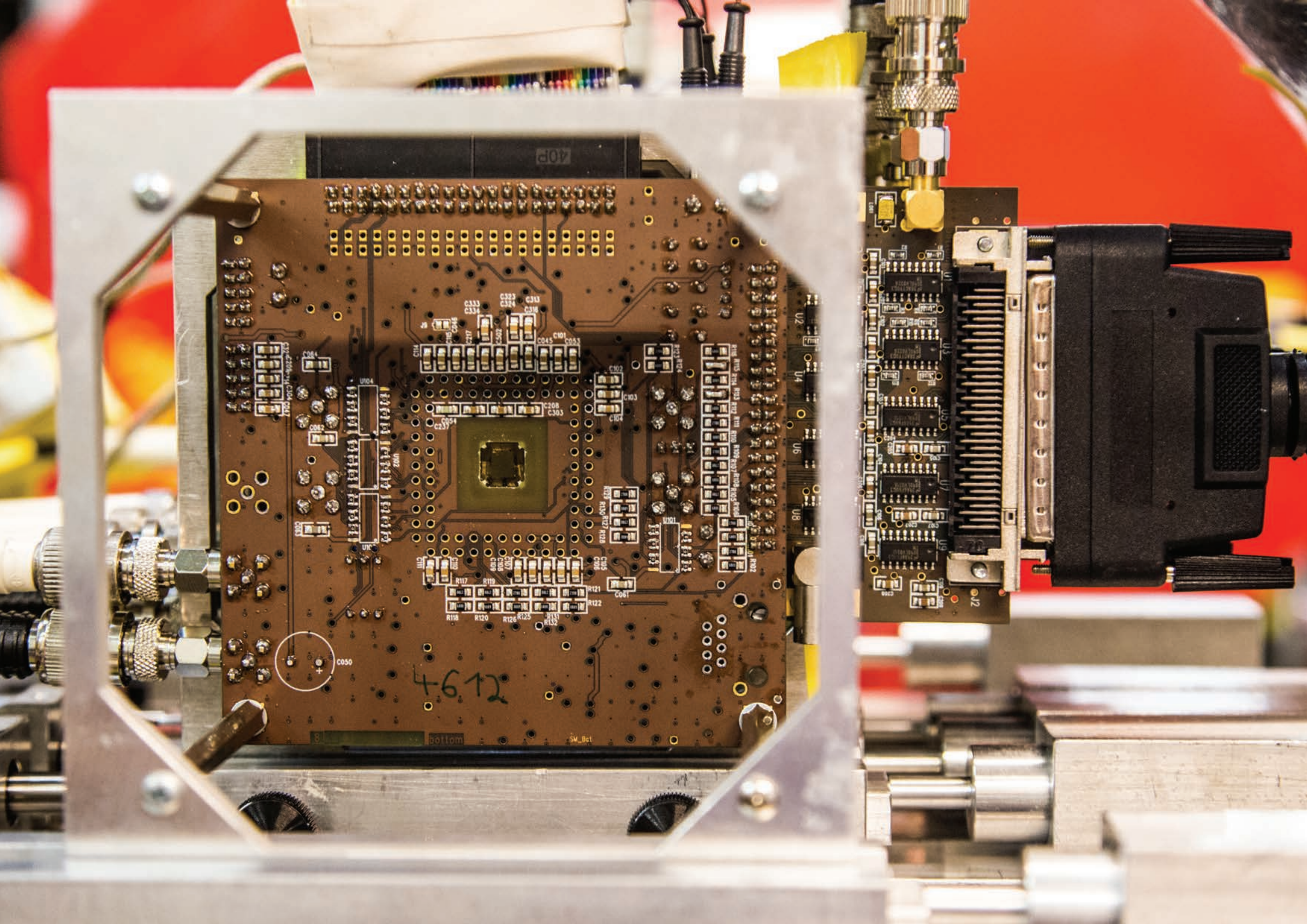
Beam tests

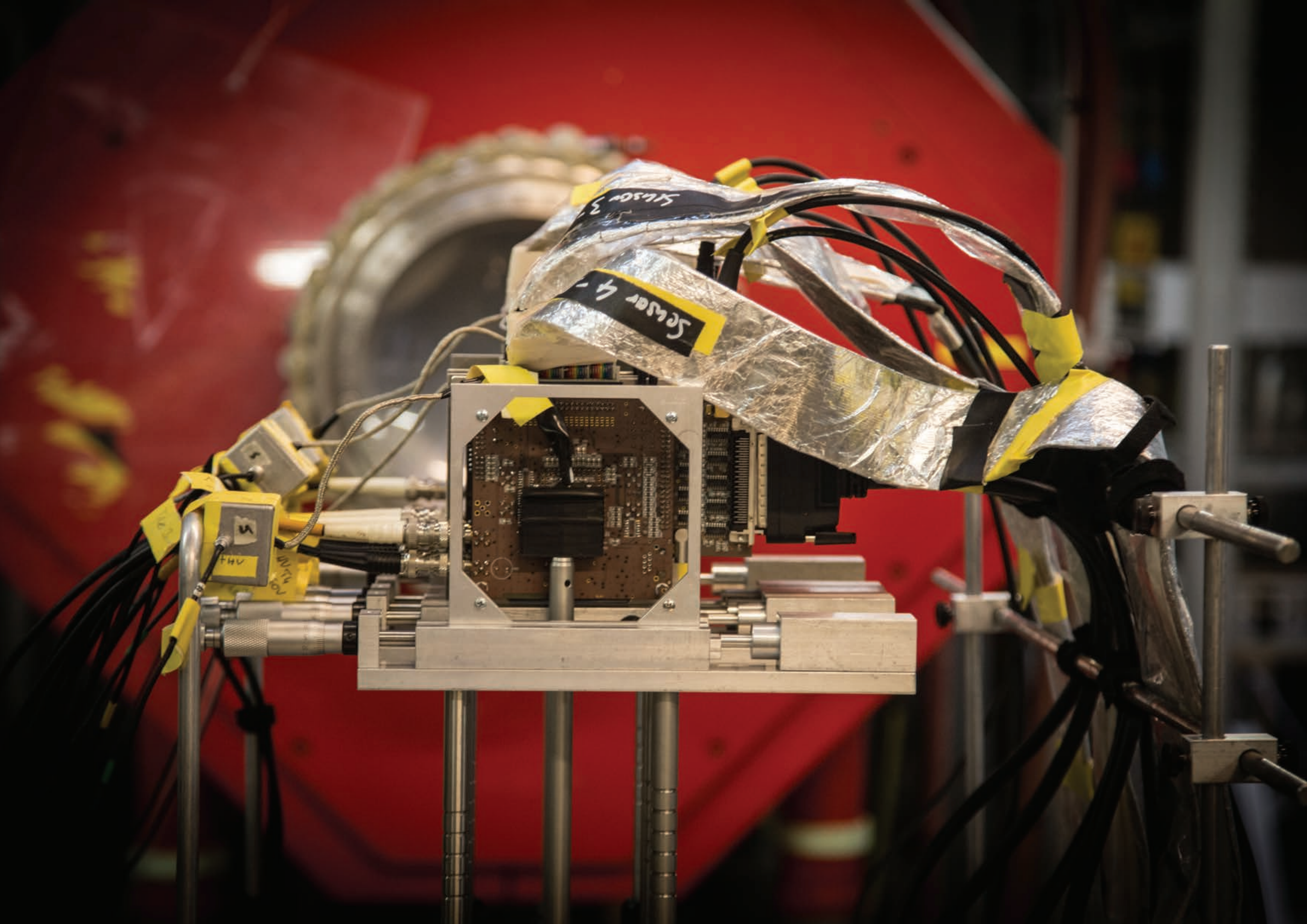


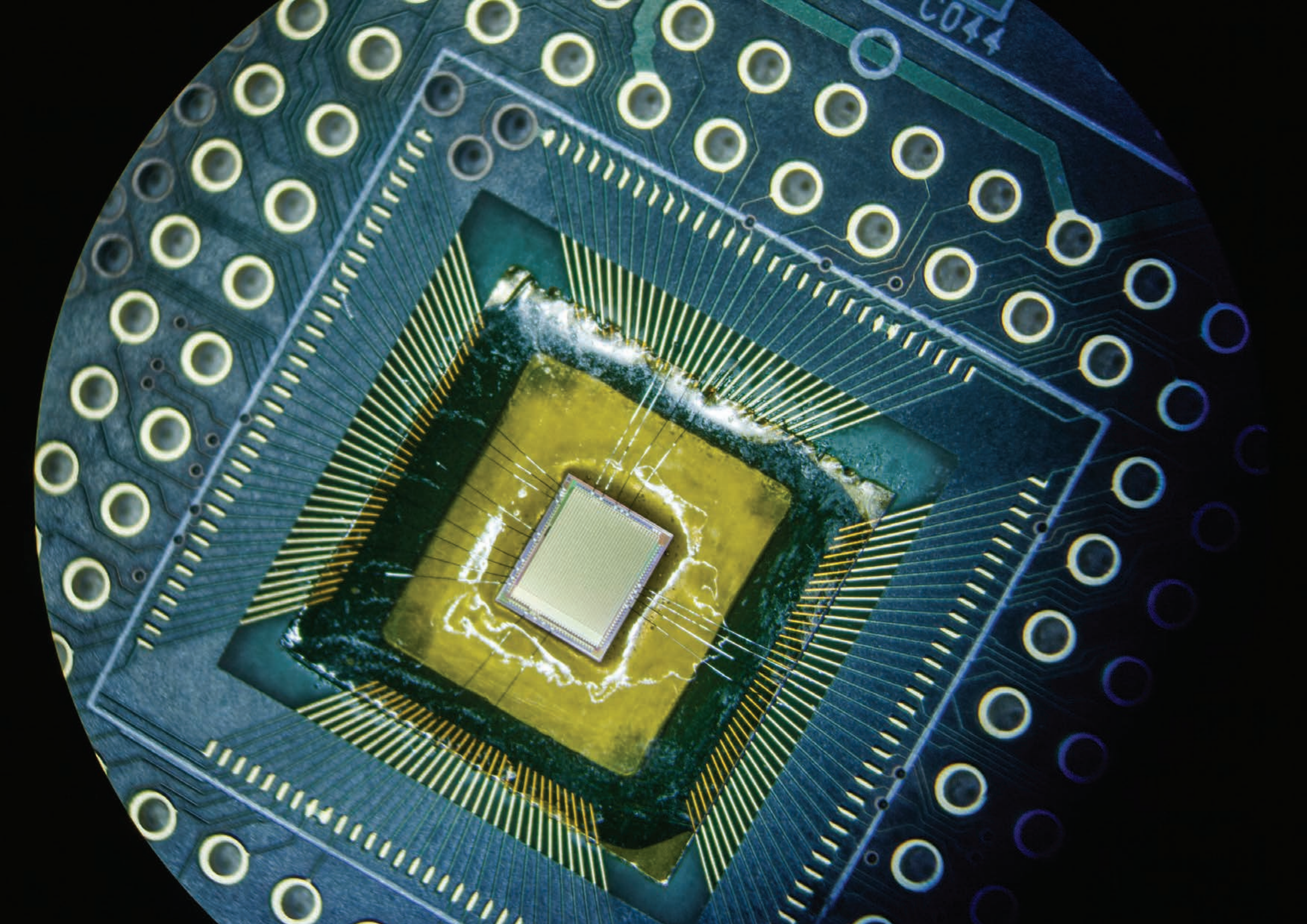
Tests done at

- CERN 250 GeV pions
- DESY 5 GeV electrons
- PSI 250 MeV pions
- Mainz 1.5 GeV electrons

- Thanks for all the beam time and support!

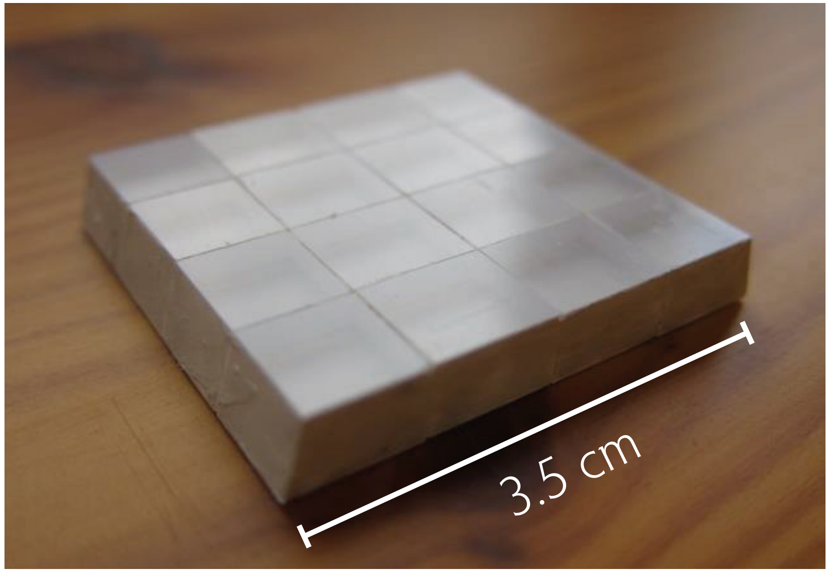

40P
4612
bottom
SM_Bct


Sensor 4

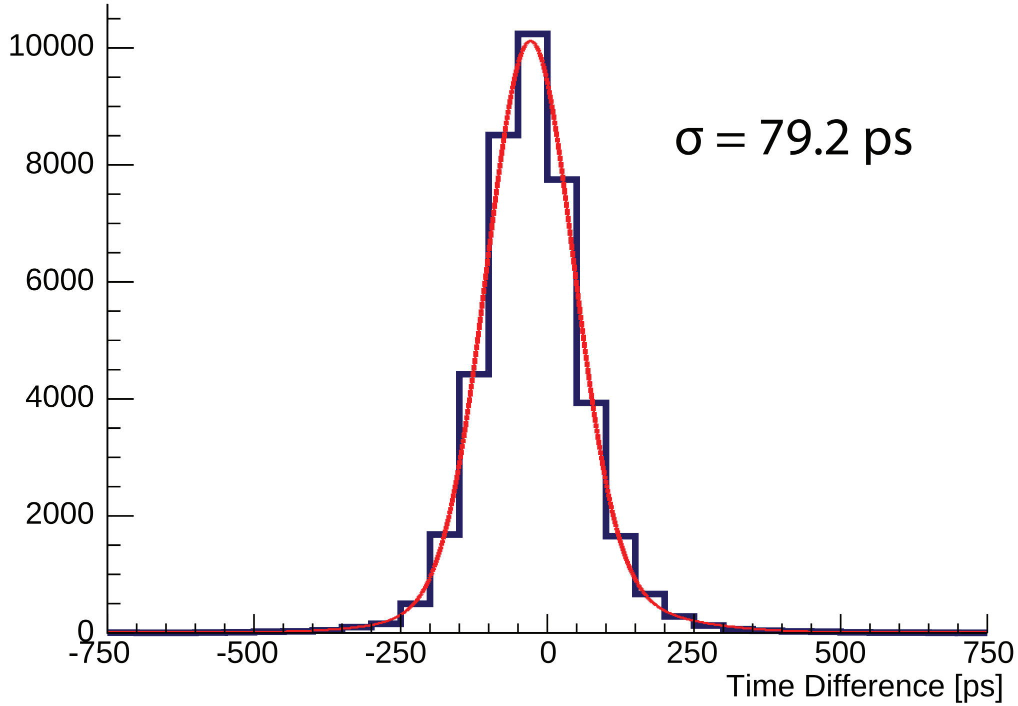

C044

Timing Detector: Scintillating tiles

Front



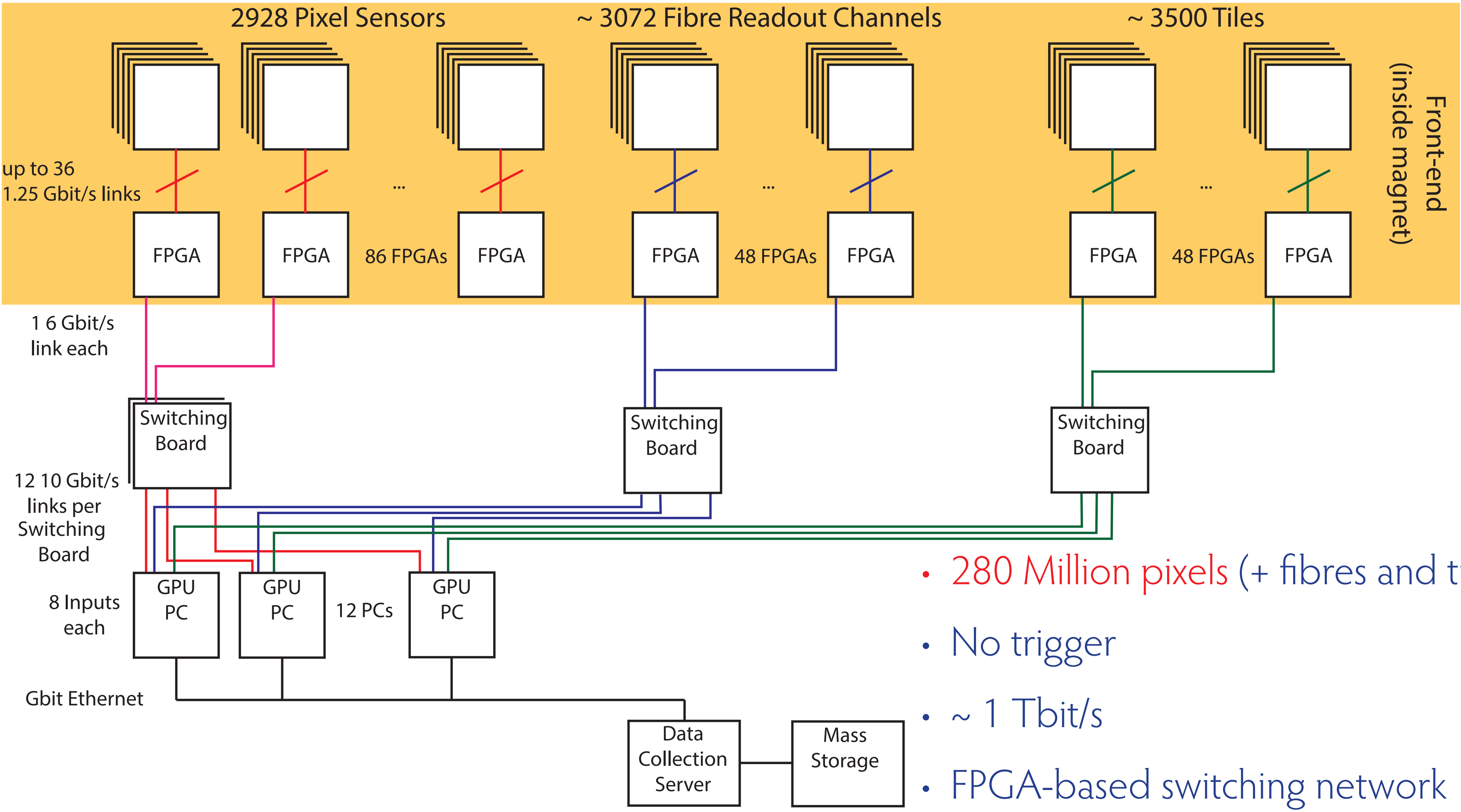
Back



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

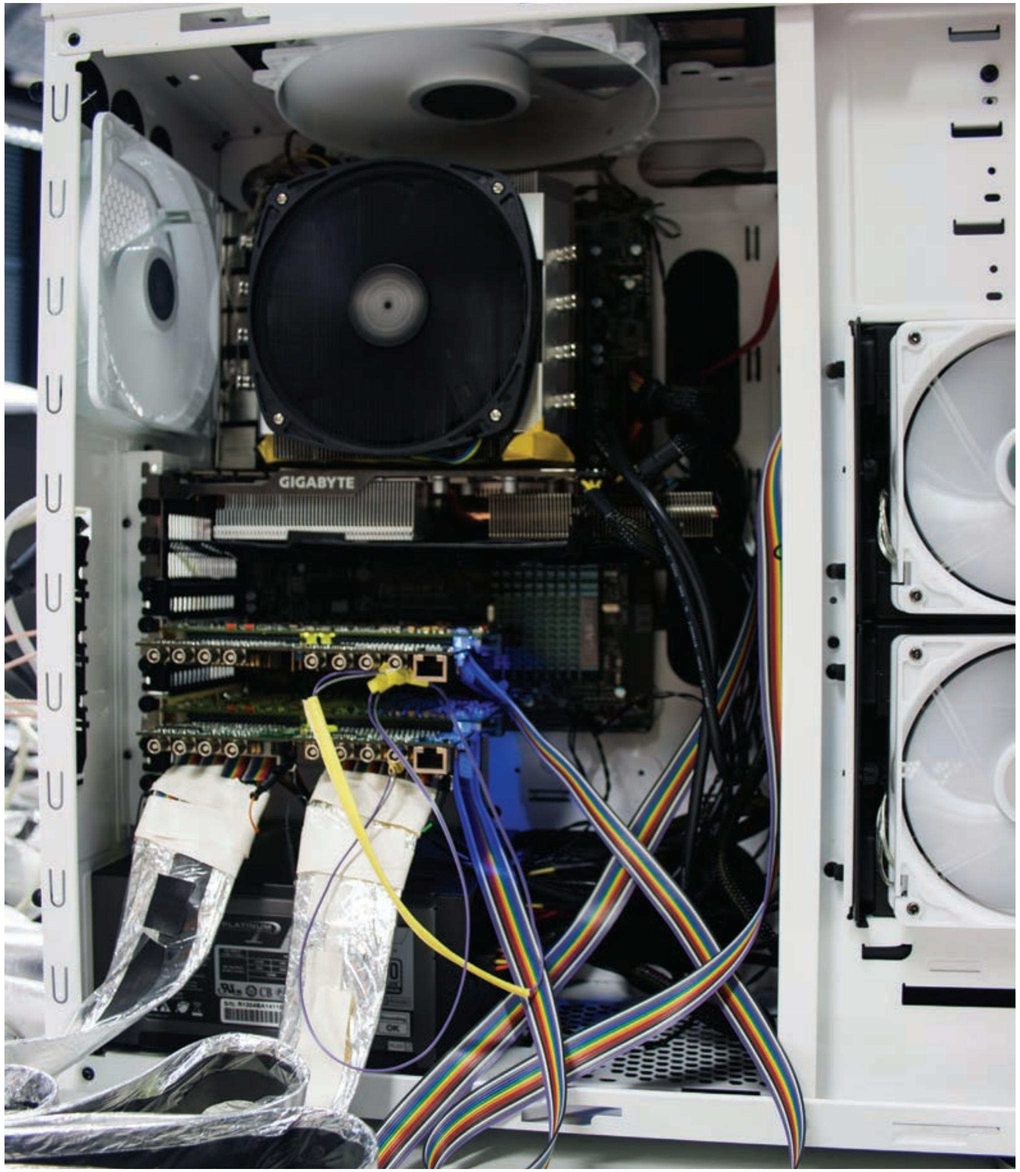
Data Acquisition

Data Acquisition



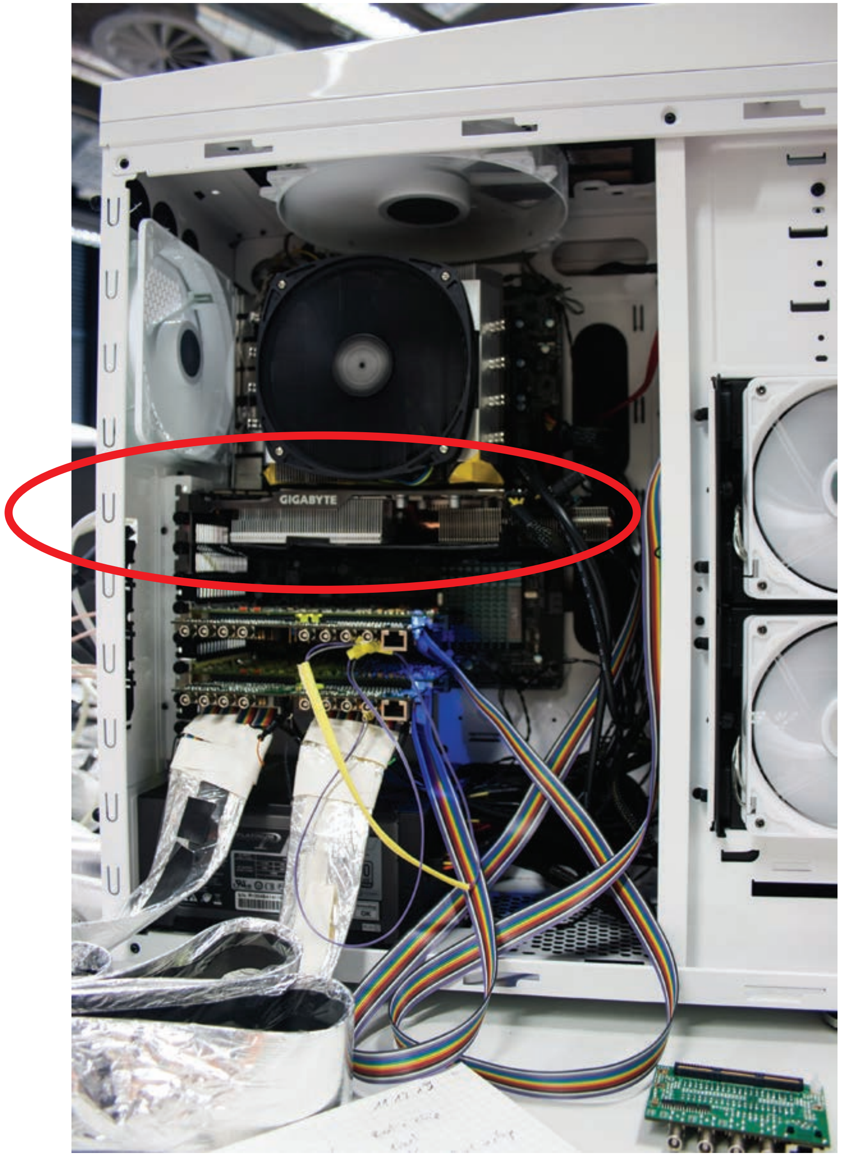
- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(50) PCs with GPUs

Online reconstruction



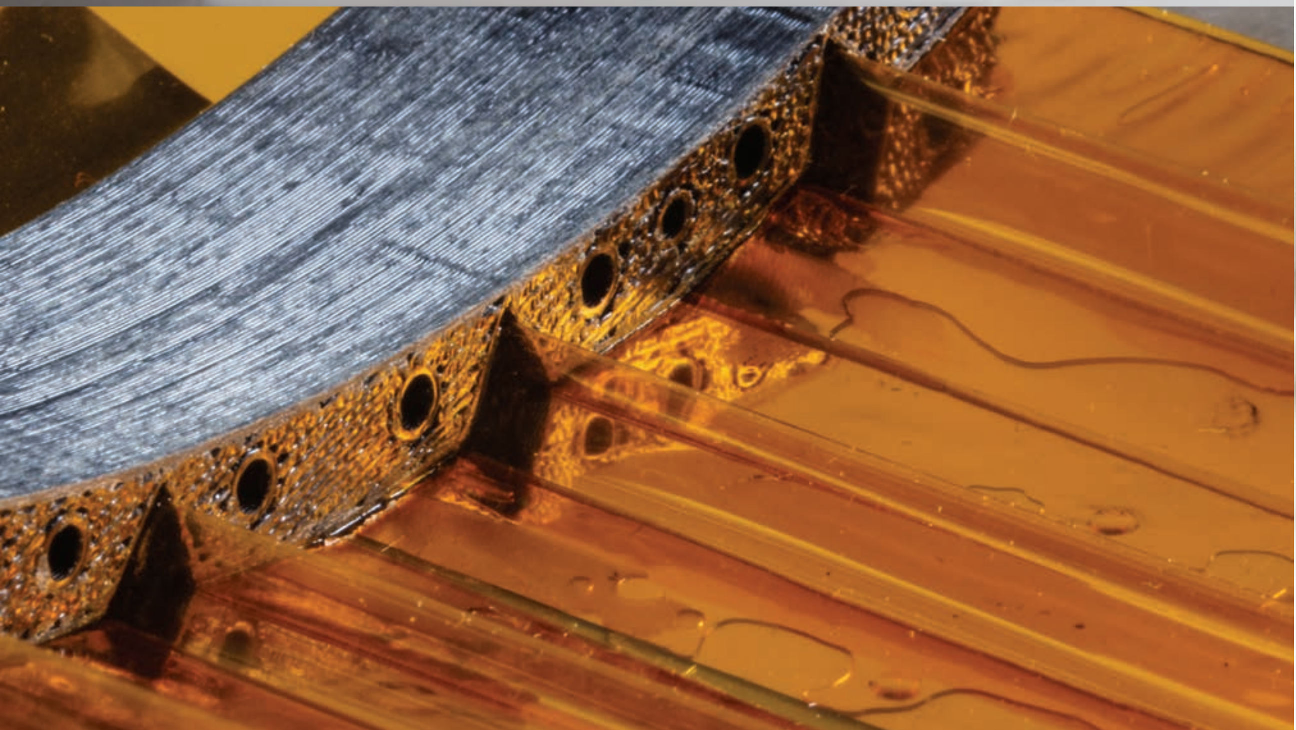
- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- Need to find and fit billions of tracks/s

Online filter farm

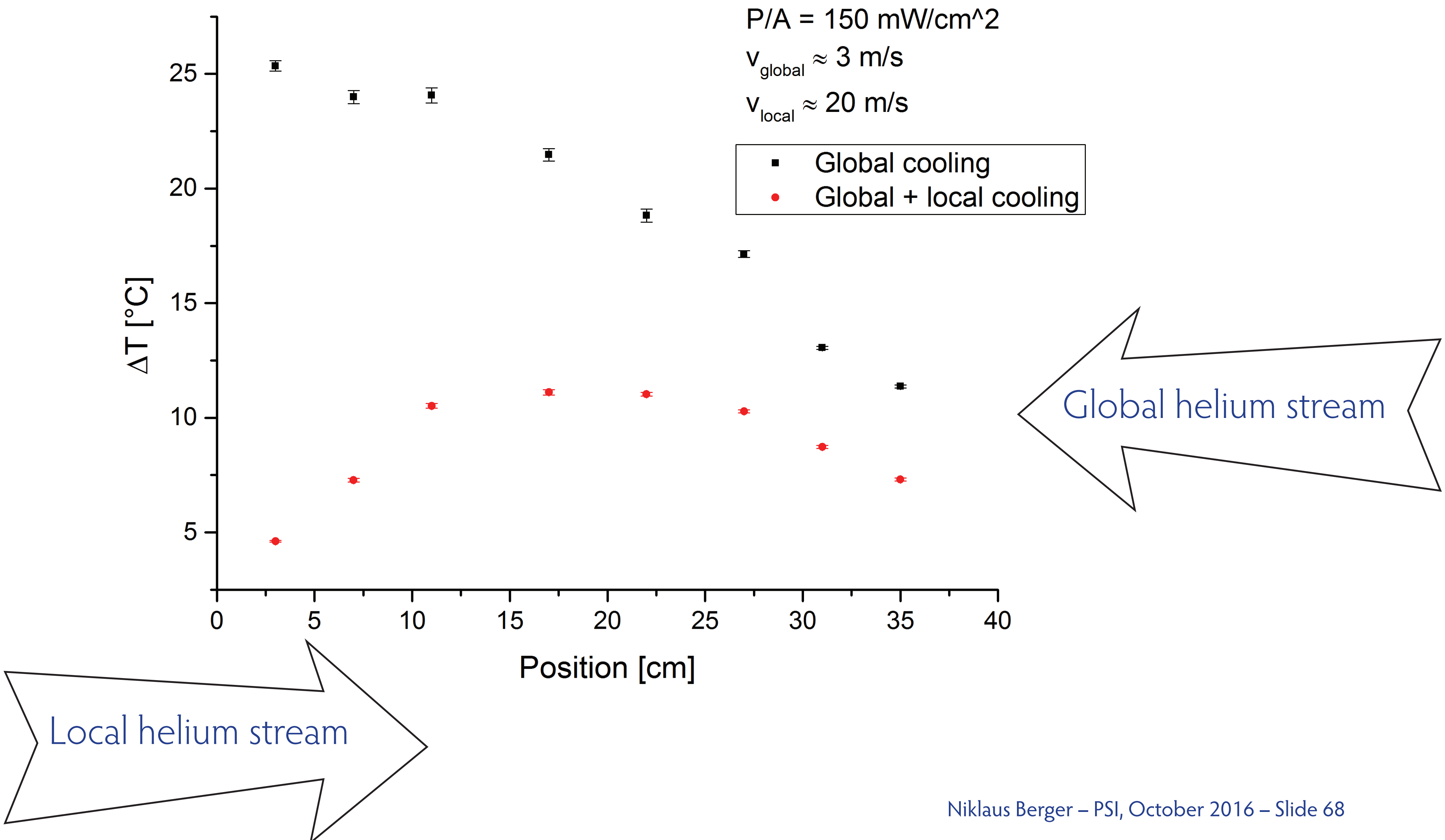


- PCs with Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s


Ring 4
vorne



Cooling tests



Momentum measurement

- Limited by detector resolution and scattering in detector

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