The Mu3e Experiment

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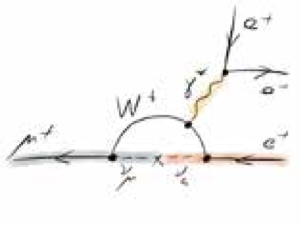
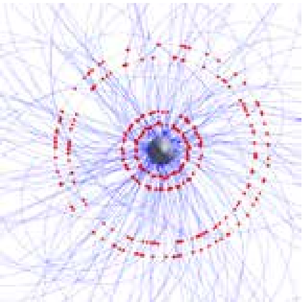
DESY Joint Instrumentation Seminar

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Overview



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

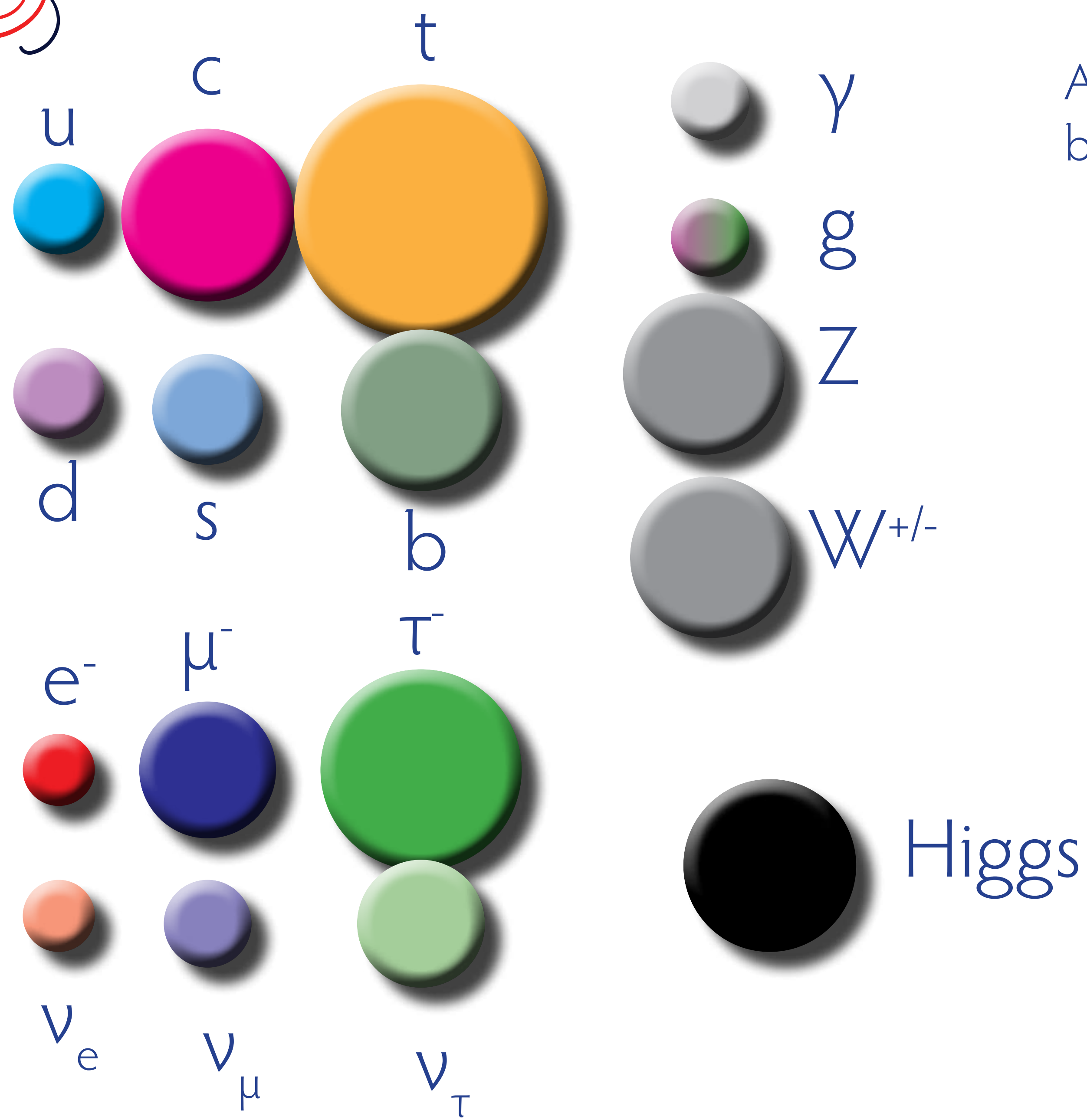


- The Challenge:
  Finding one in 10^{16} muon decays

- The Mu3e Detector:
  Minimum Material, Maximum Precision

The hunt for
charged lepton flavour violation

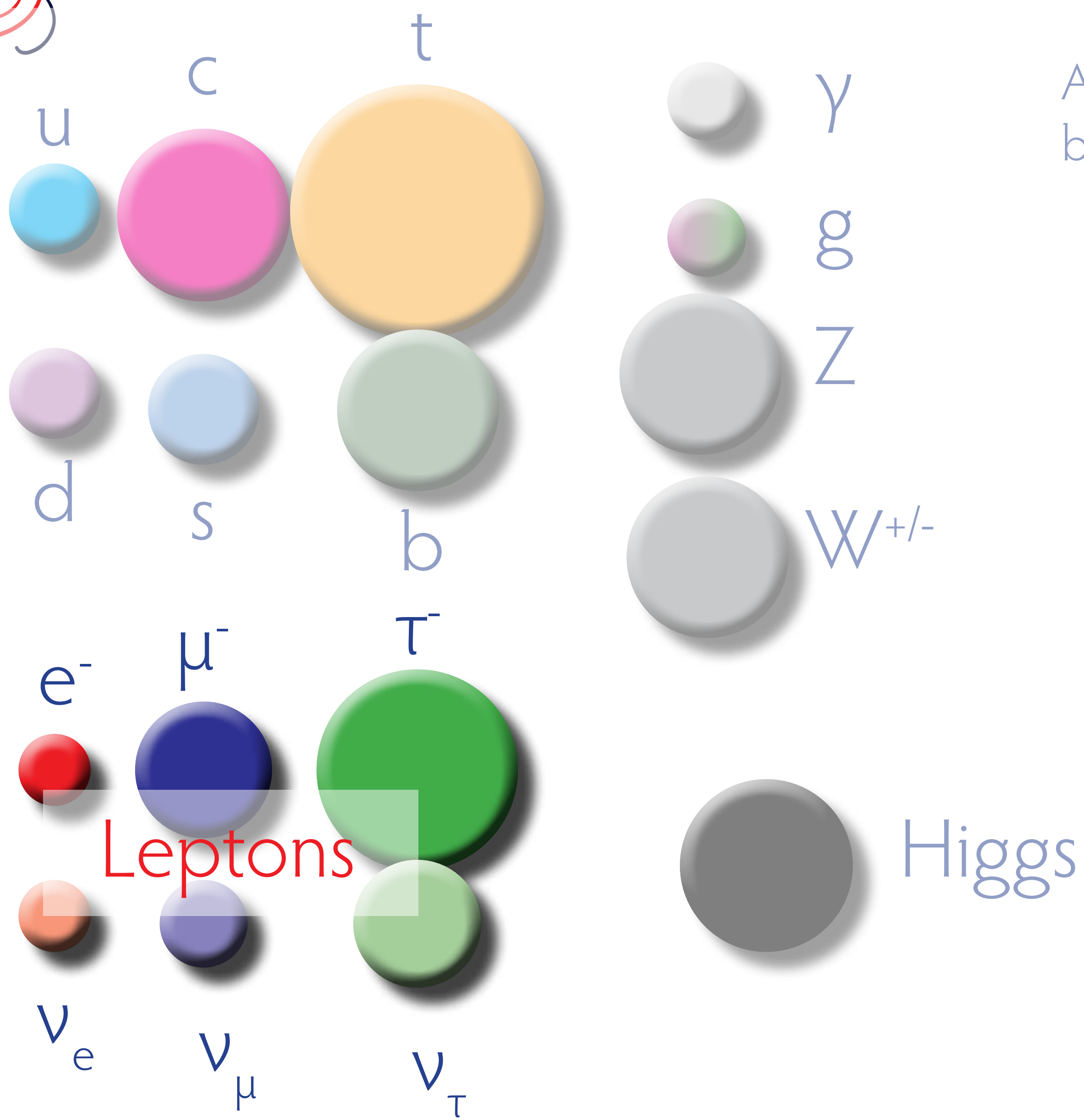
The Standard Model of Elementary Particles



All there, works beautifully, but…

- Why three generations?
- Why the mixing patterns between generations?
- Is there more to it? (the dark universe…)

The Standard Model of Elementary Particles



All there, works beautifully, but...

- Why three generations?
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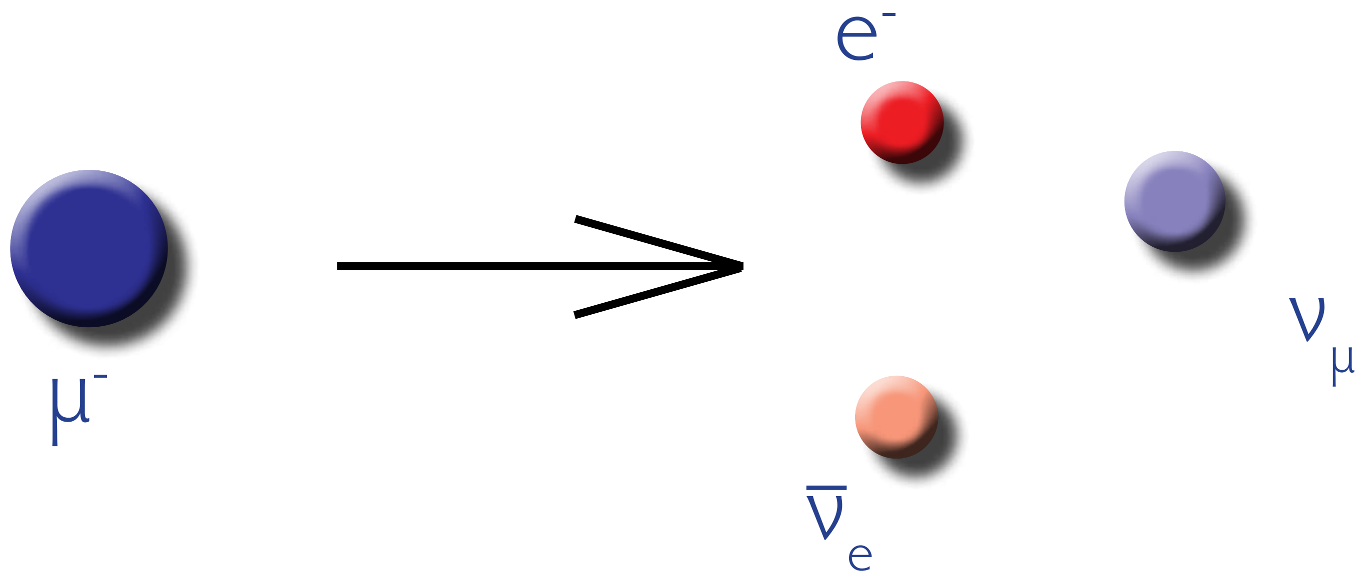
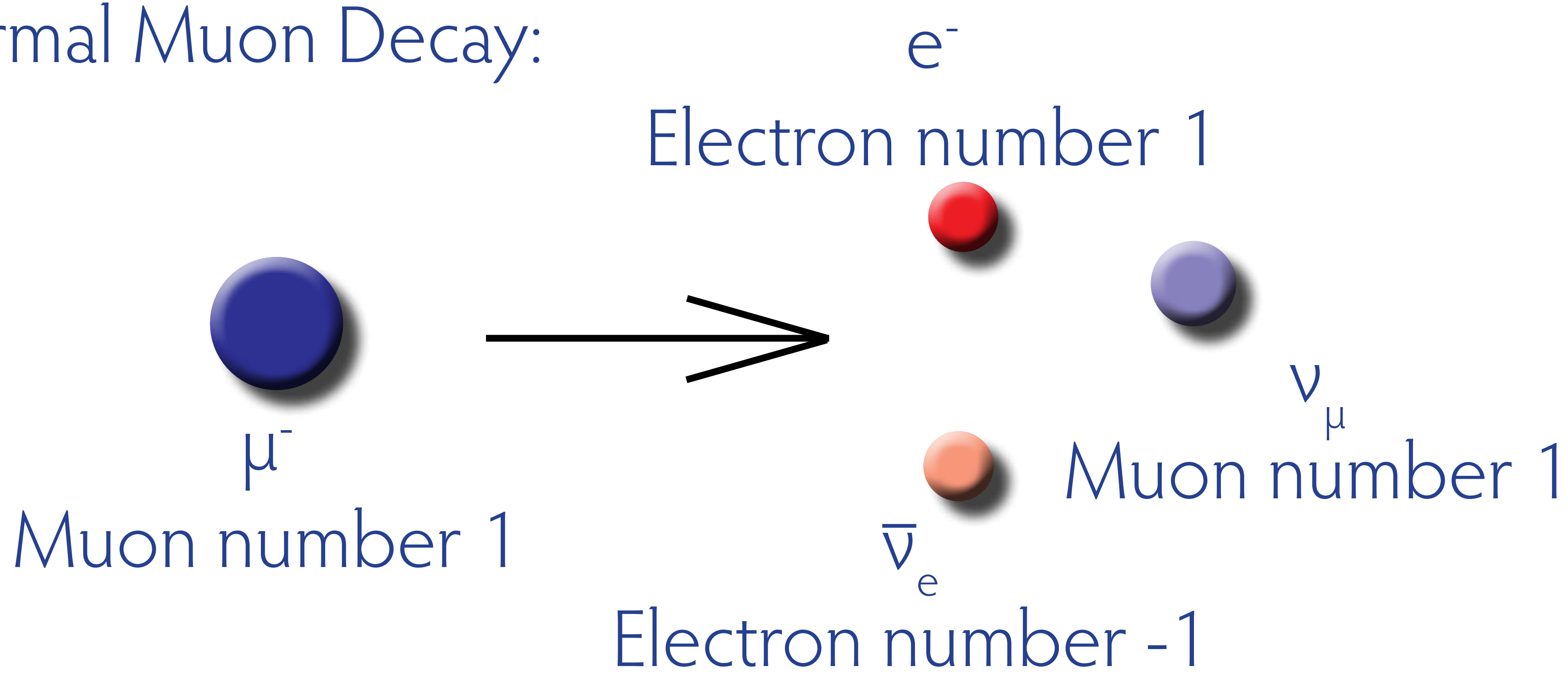
Lepton Bookkeeping

Normal Muon Decay:



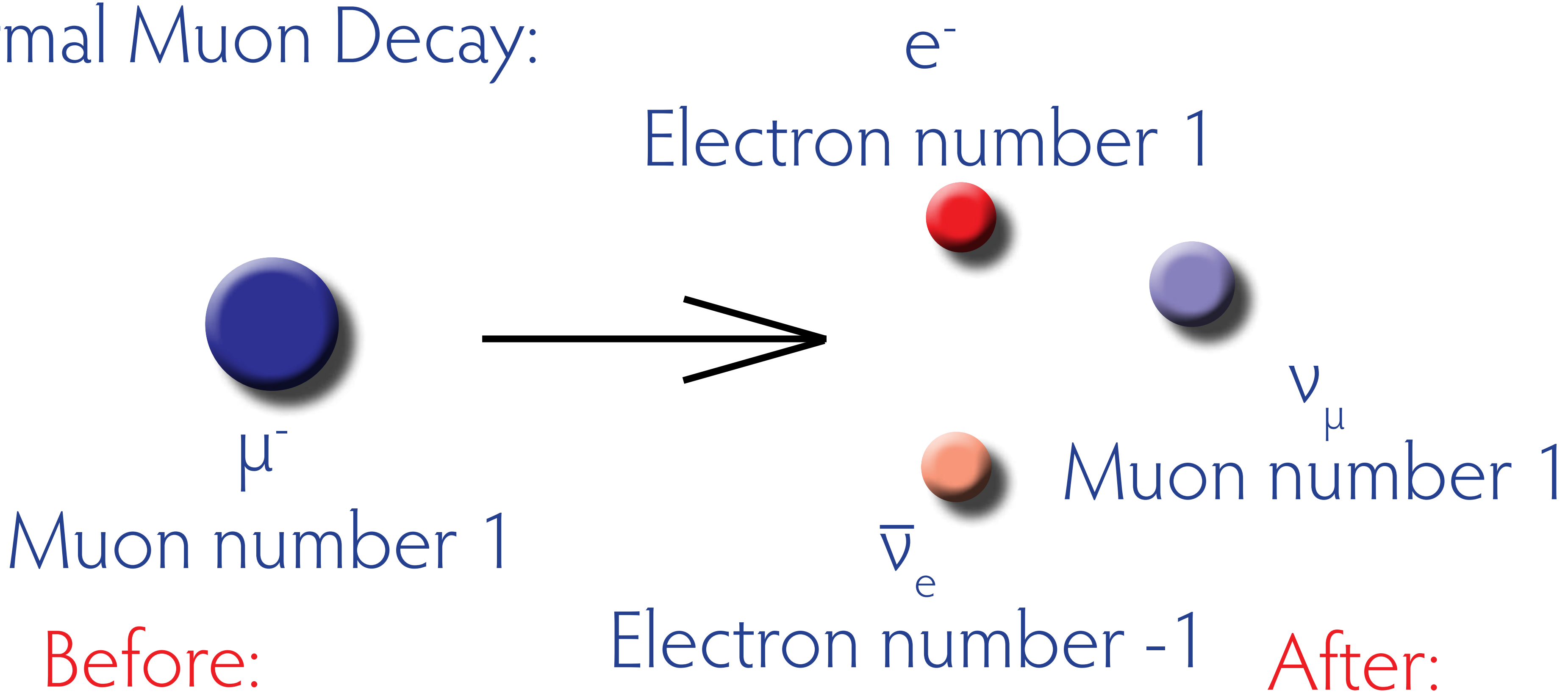
Lepton Bookkeeping

Normal Muon Decay:



Lepton Bookkeeping

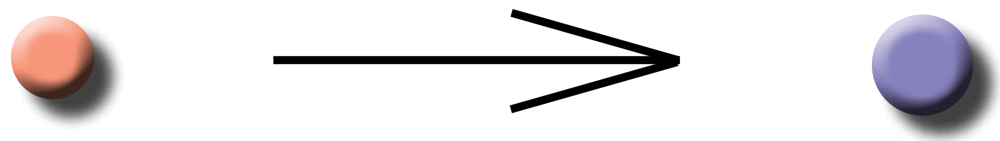
Normal Muon Decay:



Before:
Muons 1
Elektrons 0

After:
Muons 1
Electrons 0

Cooked books?

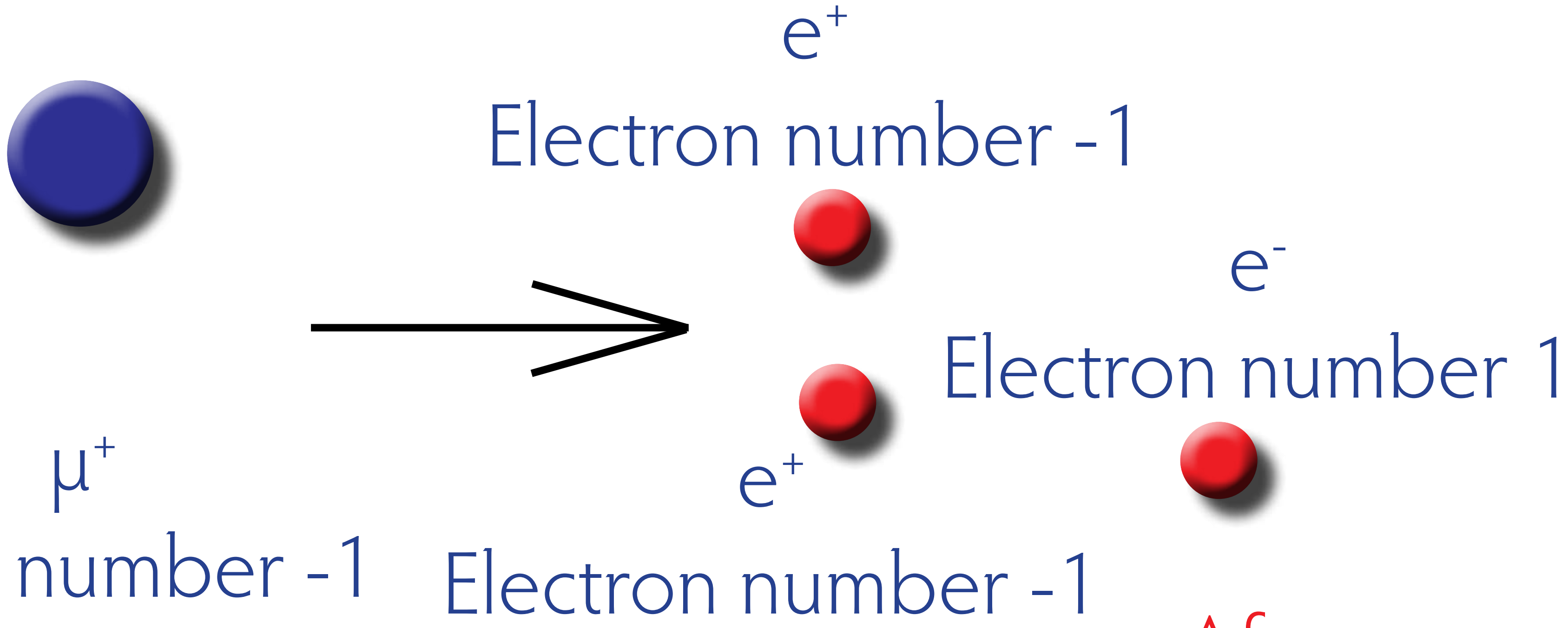


ν_e Electron number 1

ν_μ Muon number 1

Cooked books?

How about charged leptons (Muons)?



Before:

Muons -1

Electrons 0

After:

Muons 0

Electrons -1

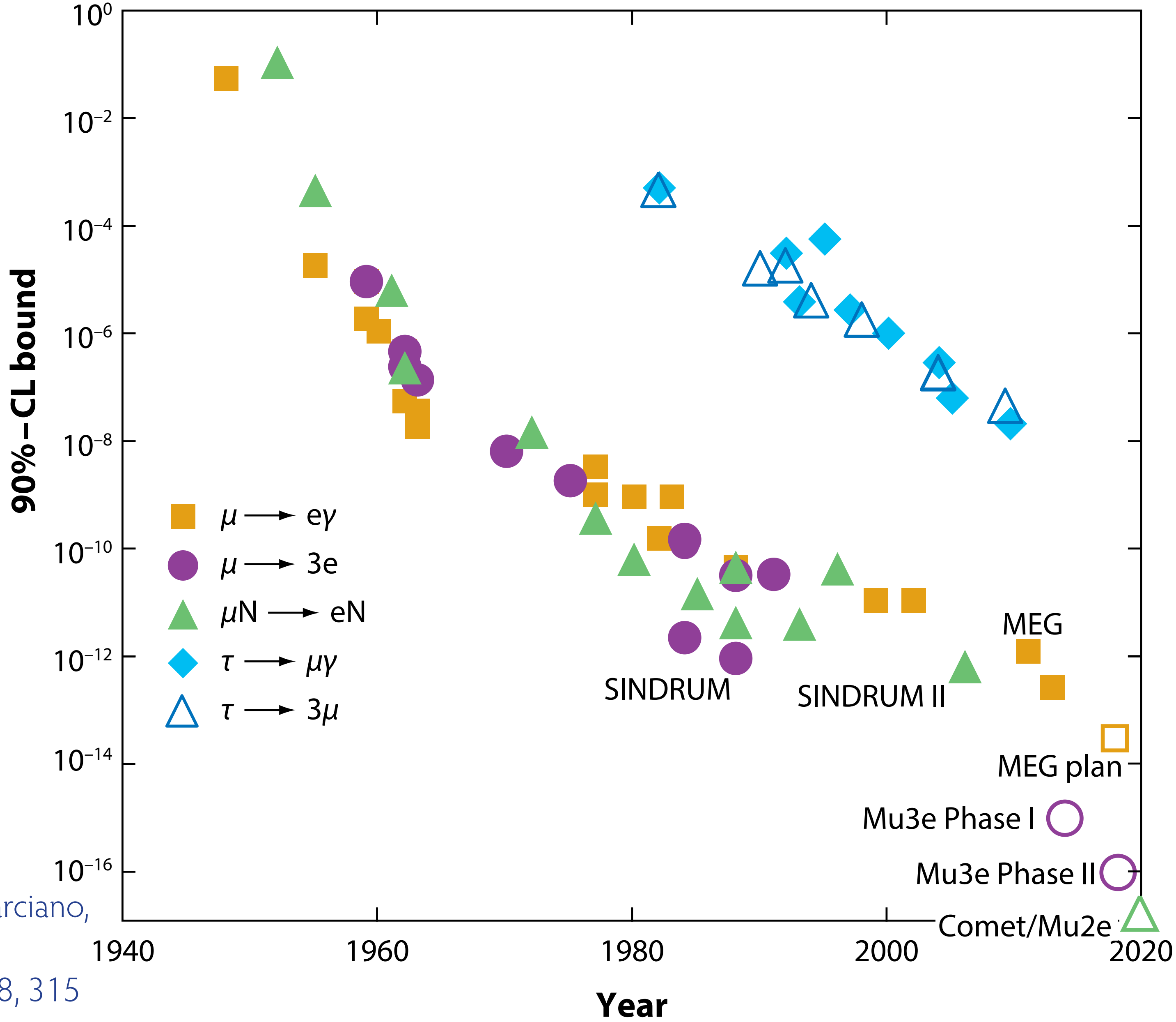
This

(charged lepton flavour violation)

has never been seen

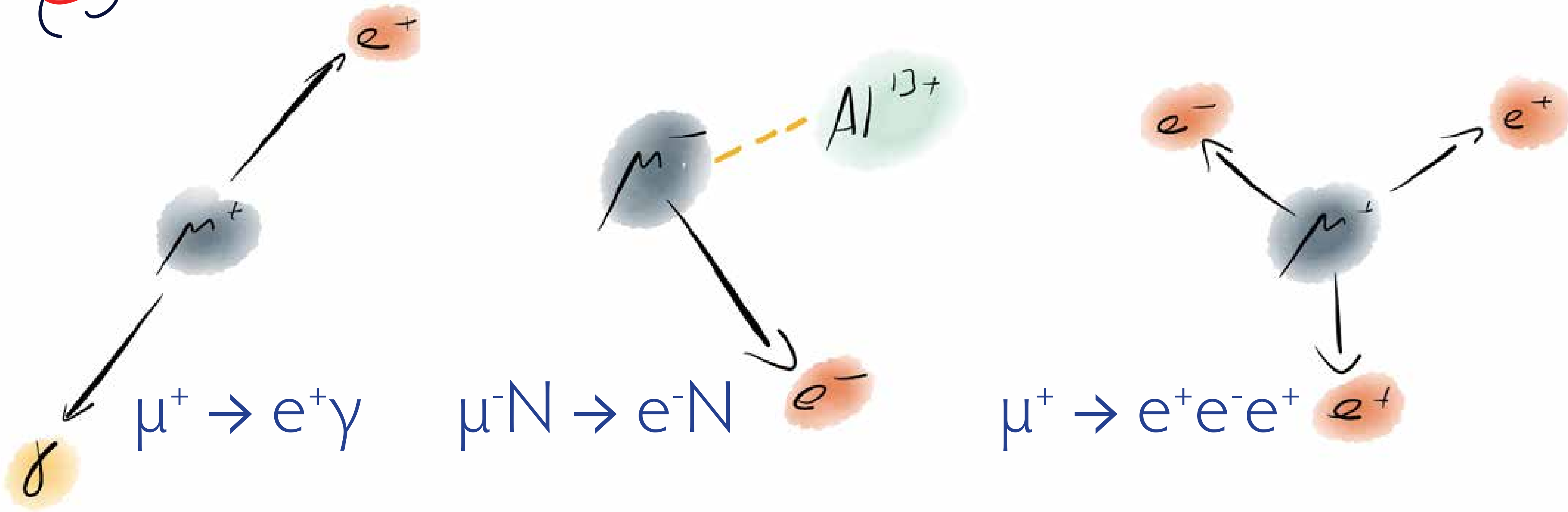
and not because we have not looked

History of LFV experiments



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

LFV Muon Decays: Experimental Situation



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

MEG (PSI)

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

(2013)

running

SINDRUM II (PSI)

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

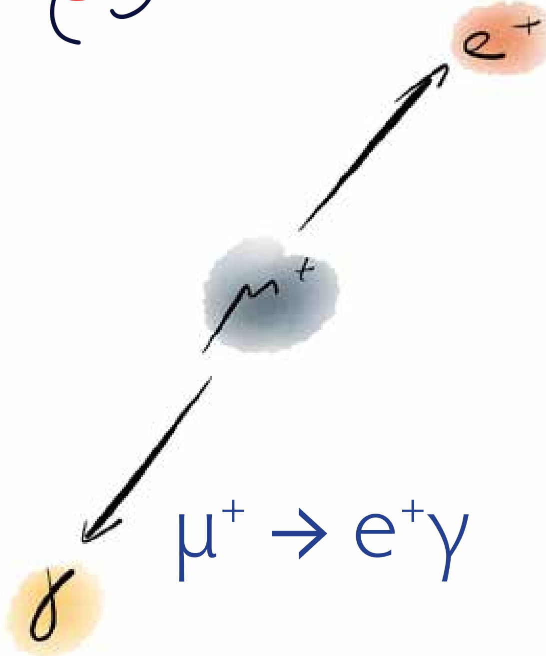
(2006)

SINDRUM (PSI)

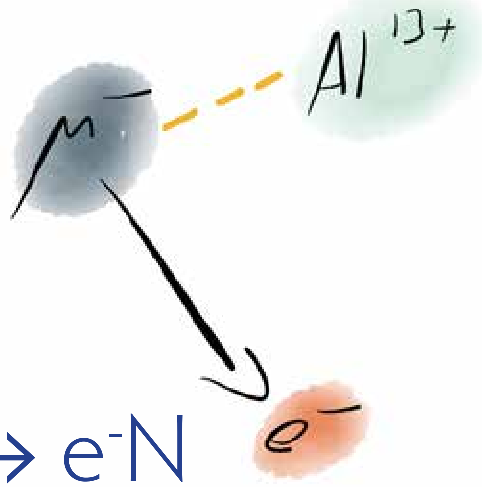
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$

(1988)

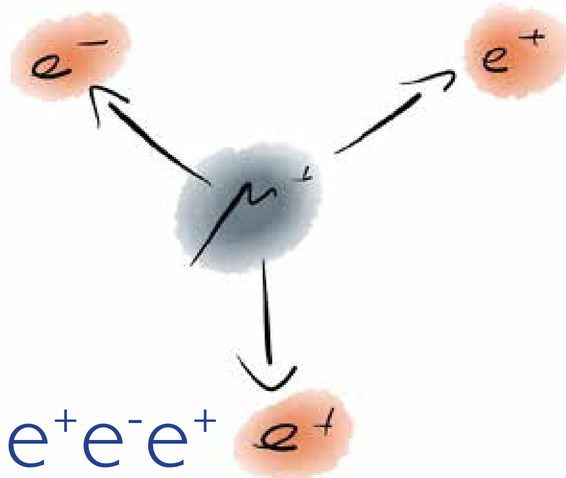
LFV Muon Decays: Standard Model



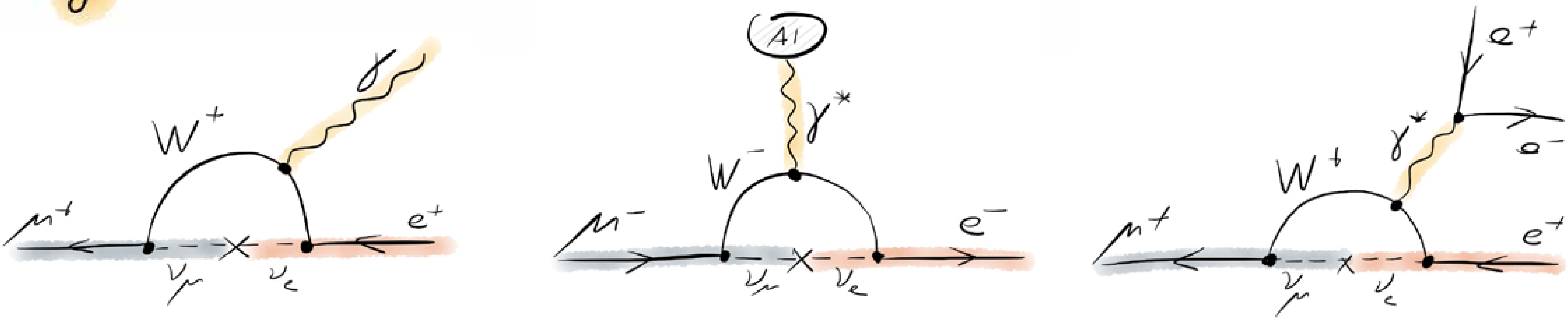
$\mu^+ \rightarrow e^+\gamma$



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

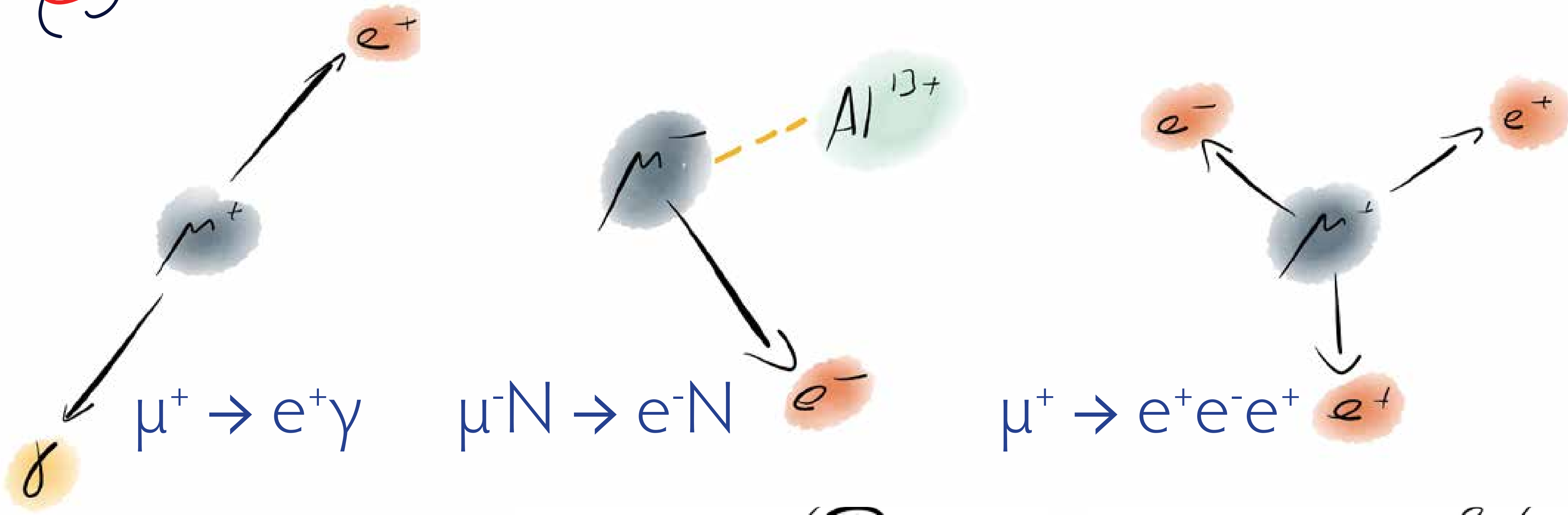


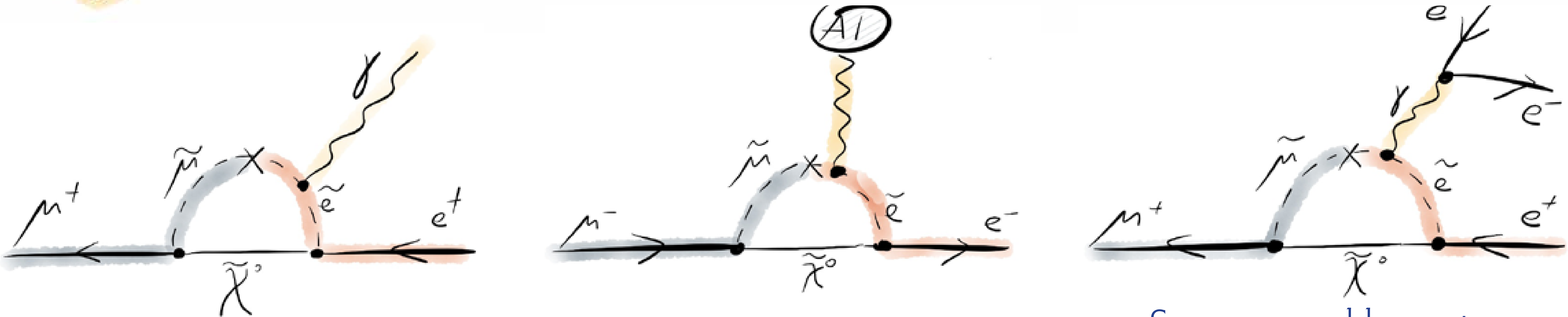
$\mu^+ \rightarrow e^+e^-e^+$



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

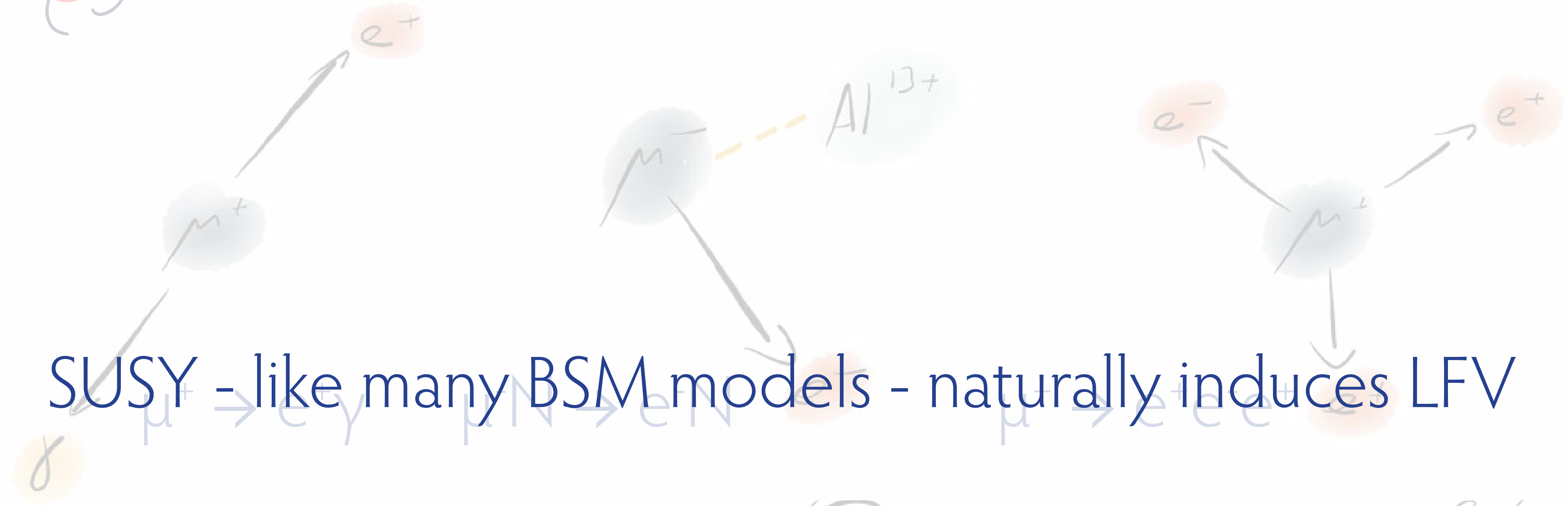
LFV Muon Decays: Susy Loops





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

LFV Muon Decays: Susy Loops



SUSY - like many BSM models - naturally induces LFV

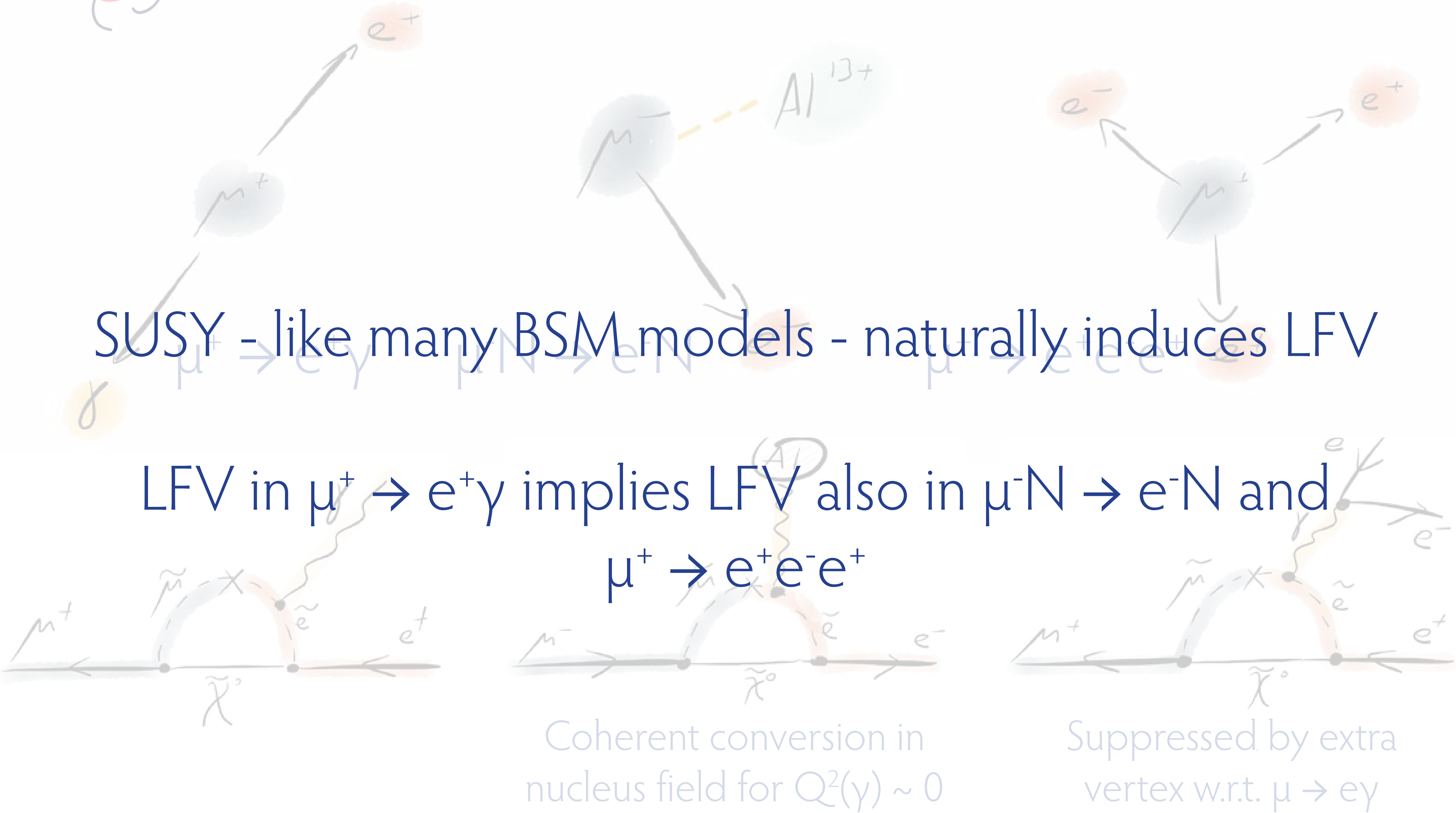
Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$

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

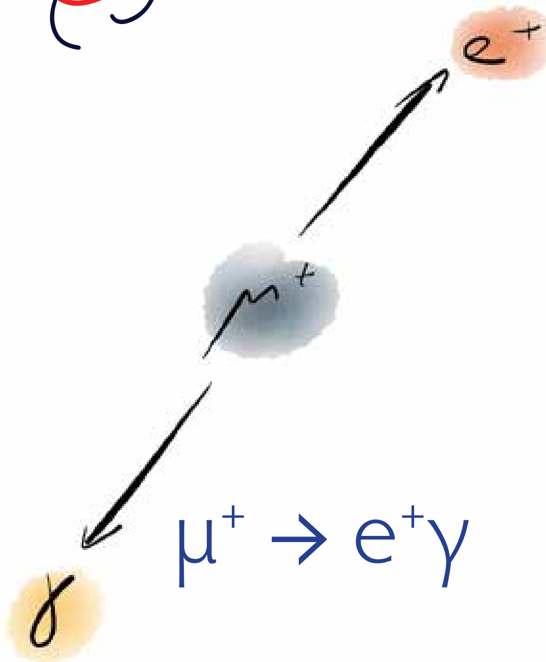
LFV Muon Decays: Susy Loops

SUSY - like many BSM models - naturally induces LFV

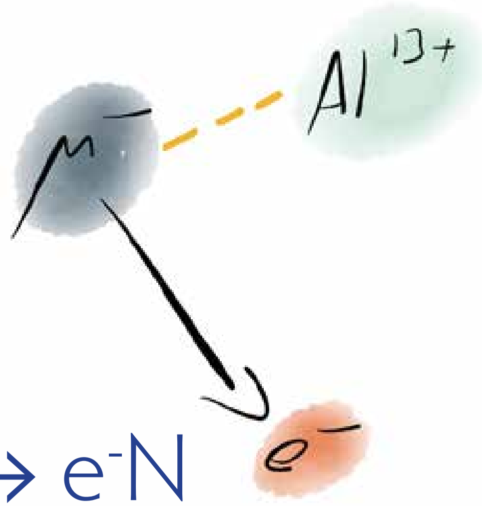
LFV in $\mu^+ \rightarrow e^+\gamma$ implies LFV also in $\mu^-N \rightarrow e^-N$ and $\mu^+ \rightarrow e^+e^-e^+$



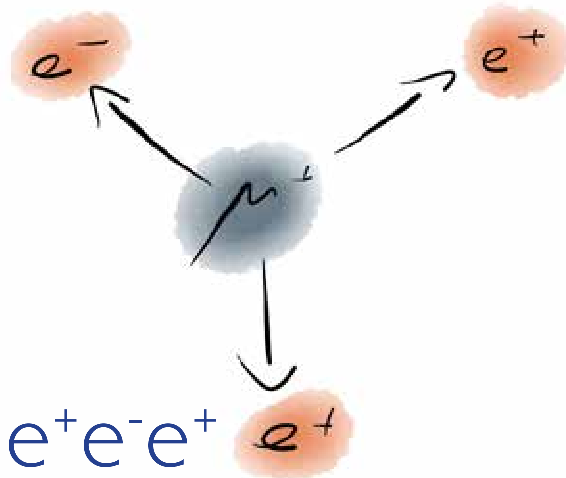
LFV Muon Decays: Tree diagrams



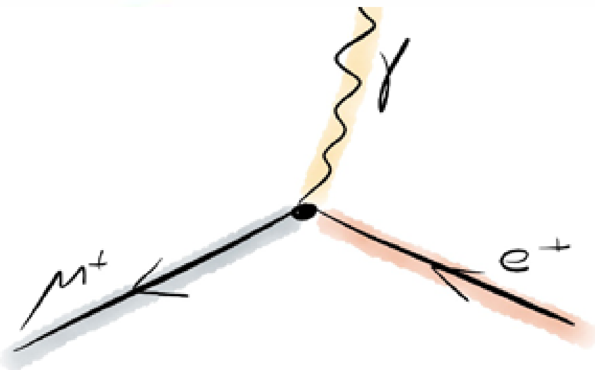
$\mu^+ \to e^+\gamma$



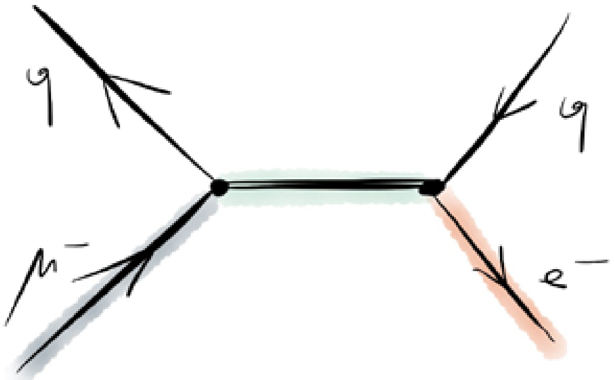
$\mu^-N \to e^-N$



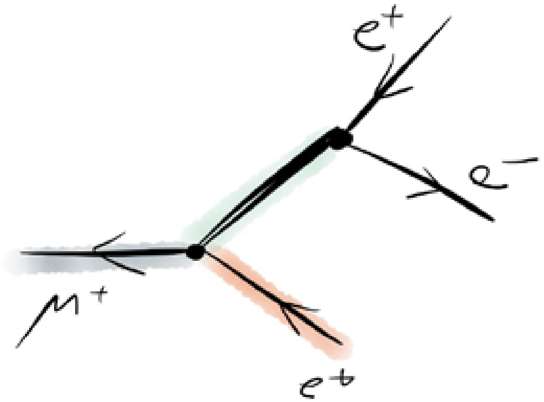
$\mu^+ \to e^+e^-e^+$



Not allowed

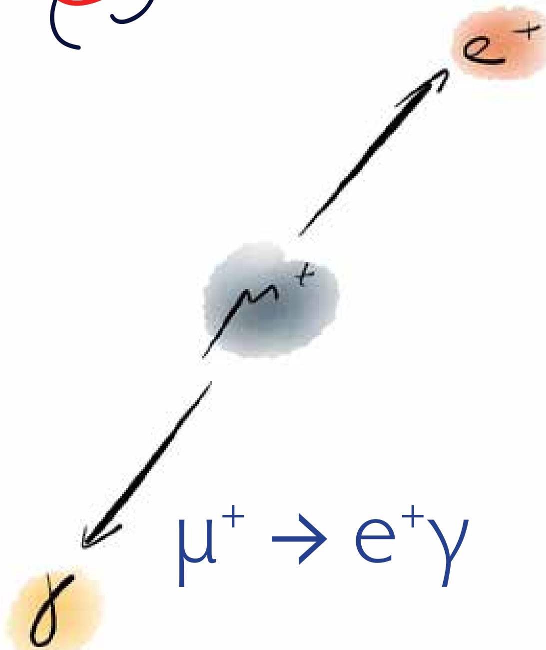


e.g. Leptoquarks

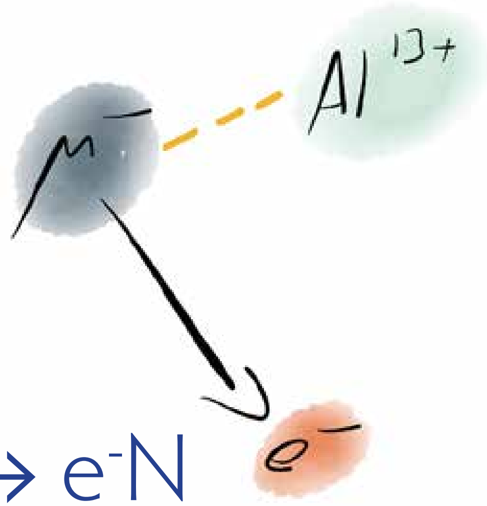


e.g. extra Z', LFV Higgs etc.

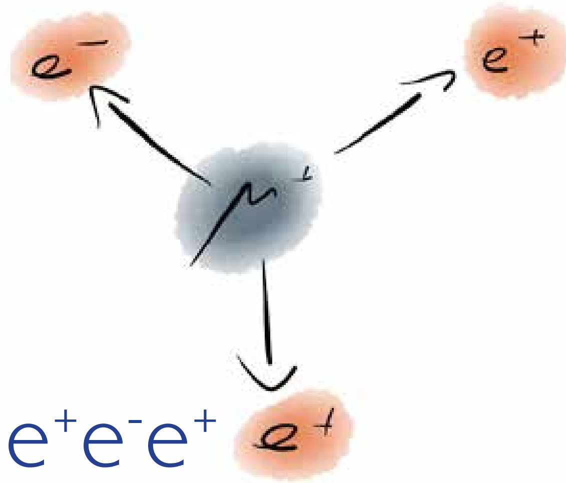
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

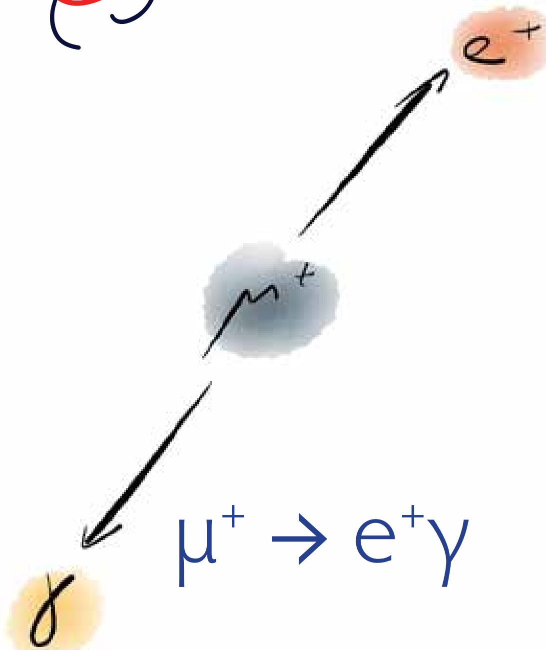
Kinematics

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

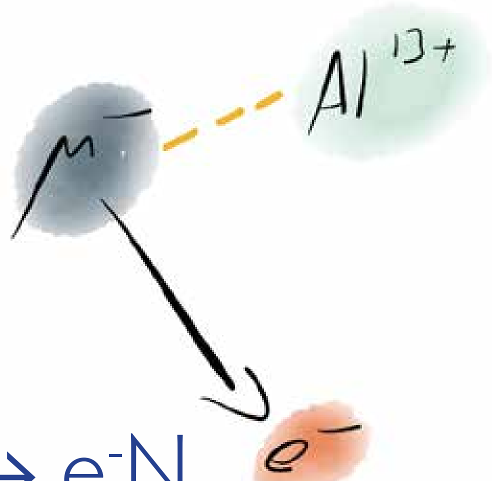
Kinematics

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

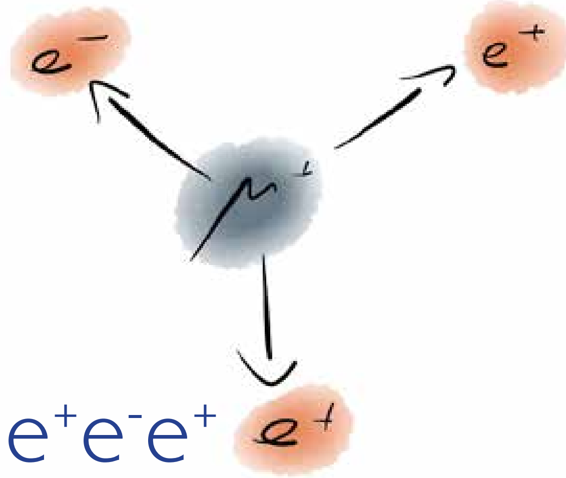
LFV Muon Decays: Experimental signatures



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



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



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

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

Background
- Accidental background

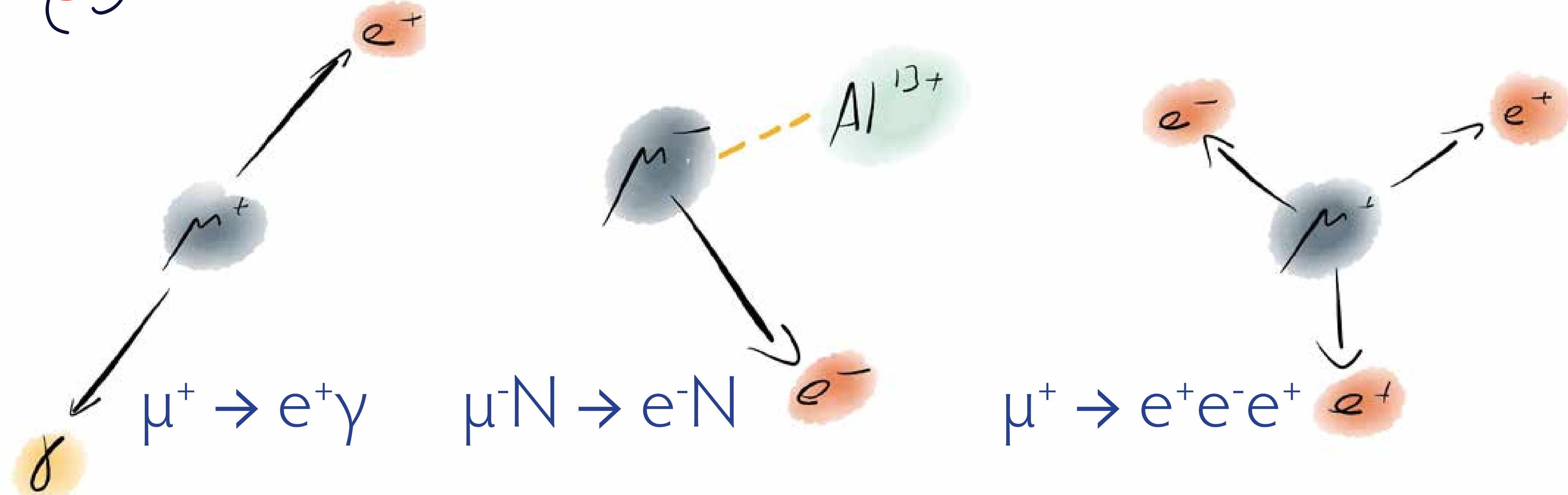
Kinematics
- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

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



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

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

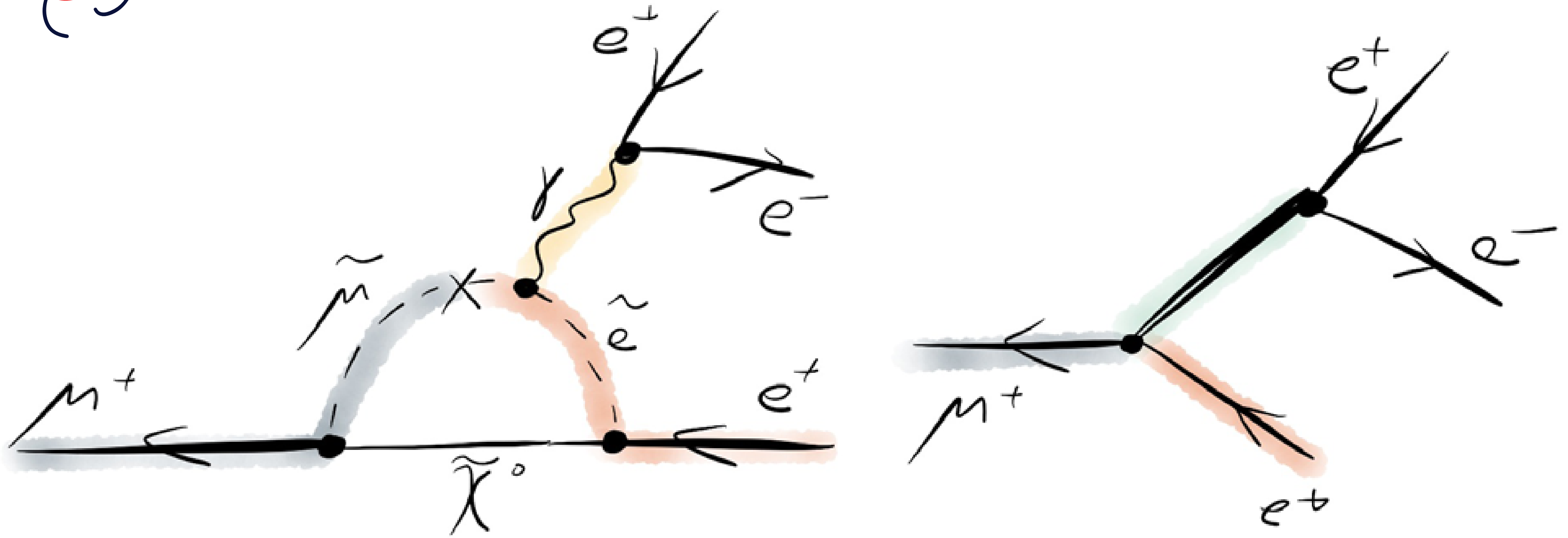
- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro

- R decay
- Ac dental background

Continuous Beam

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



Loop diagrams

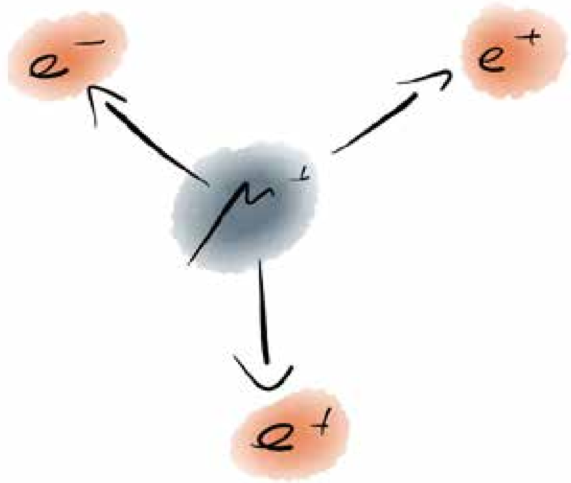
- Supersymmetry
- Little Higgs models
- Seesaw models
- GUT models (leptoquarks)
- and much more...

Tree diagrams

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

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

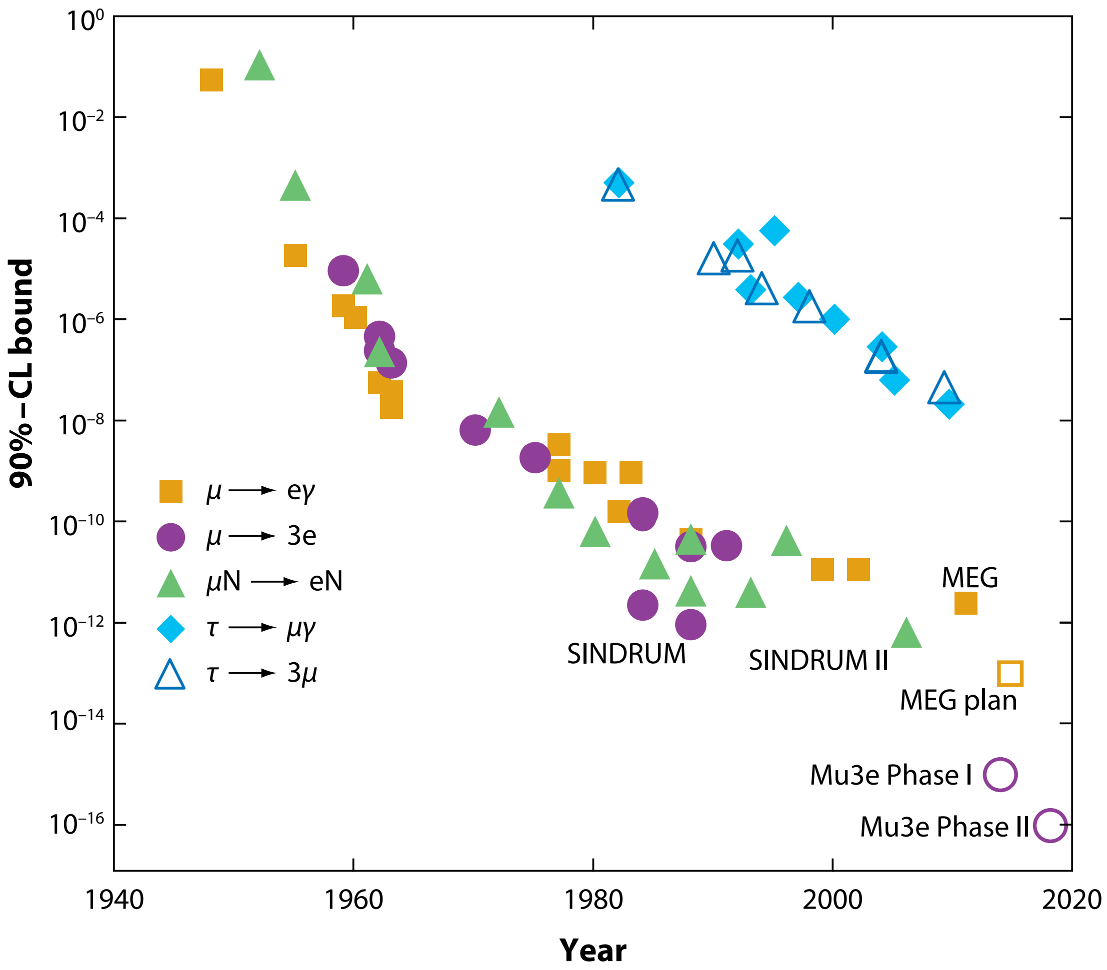
Project approved in January 2013
just passed first review

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}

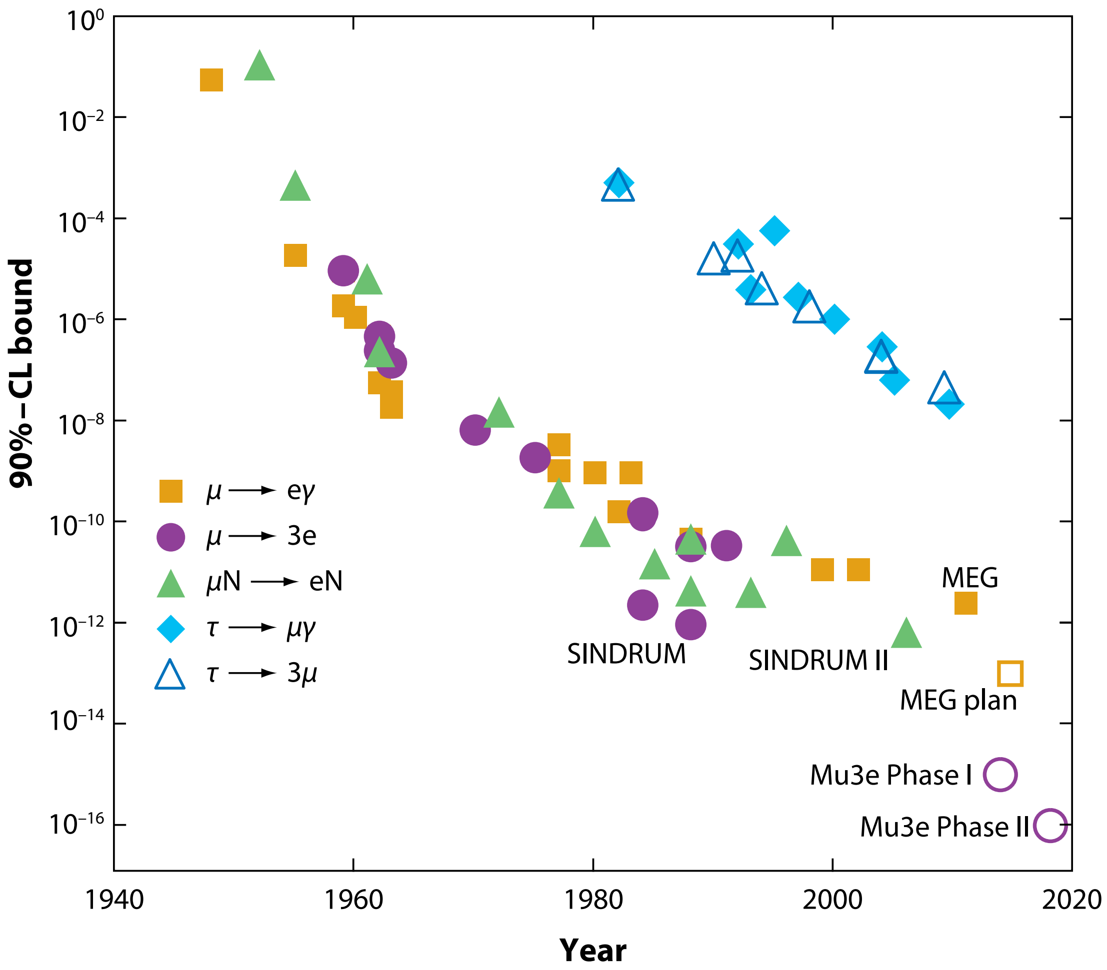
- We want to find or exclude $\mu \rightarrow eee$ at the 10^{-16} level
- 4 orders of magnitude over previous experiment (SINDRUM 1988)



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

The Challenges

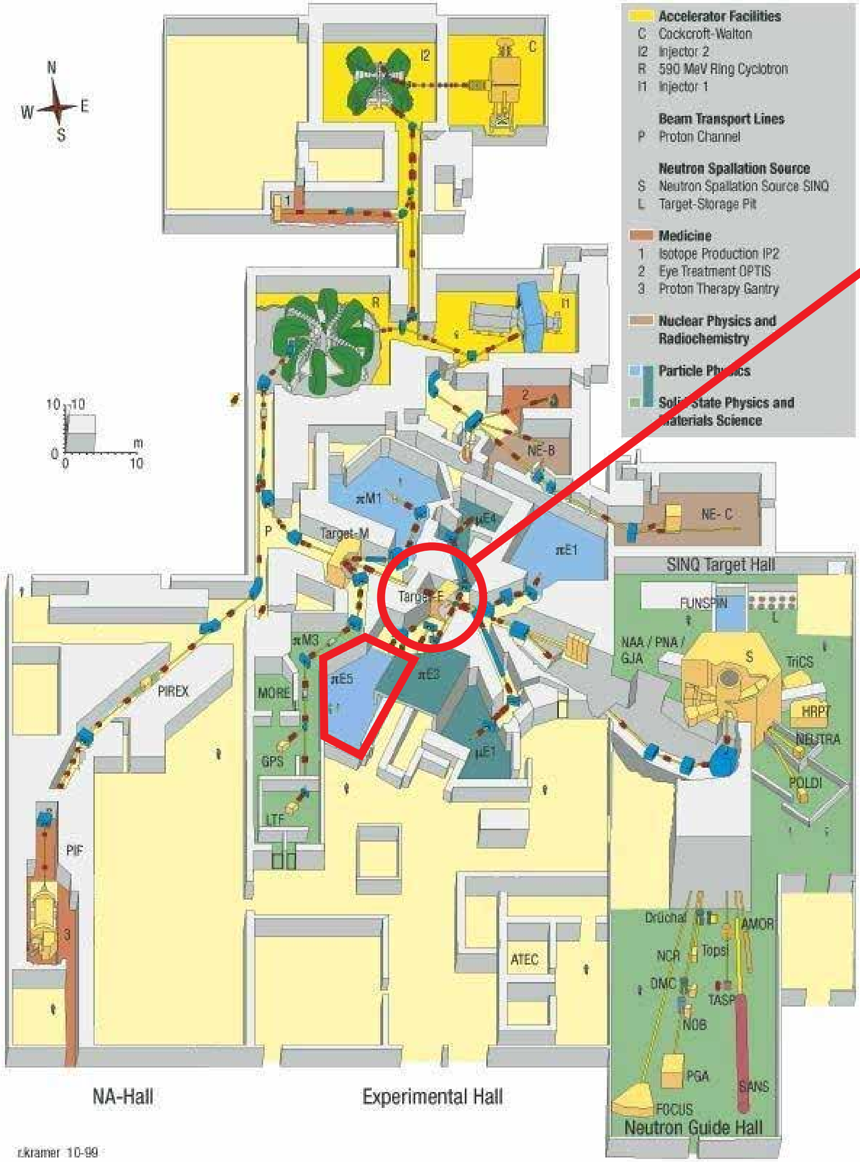
- Observe more than 10^{16} muon decays:
  2 Billion muons per second
- Suppress backgrounds by more than 16 orders of magnitude
- Be sensitive for the signal



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


SINQ

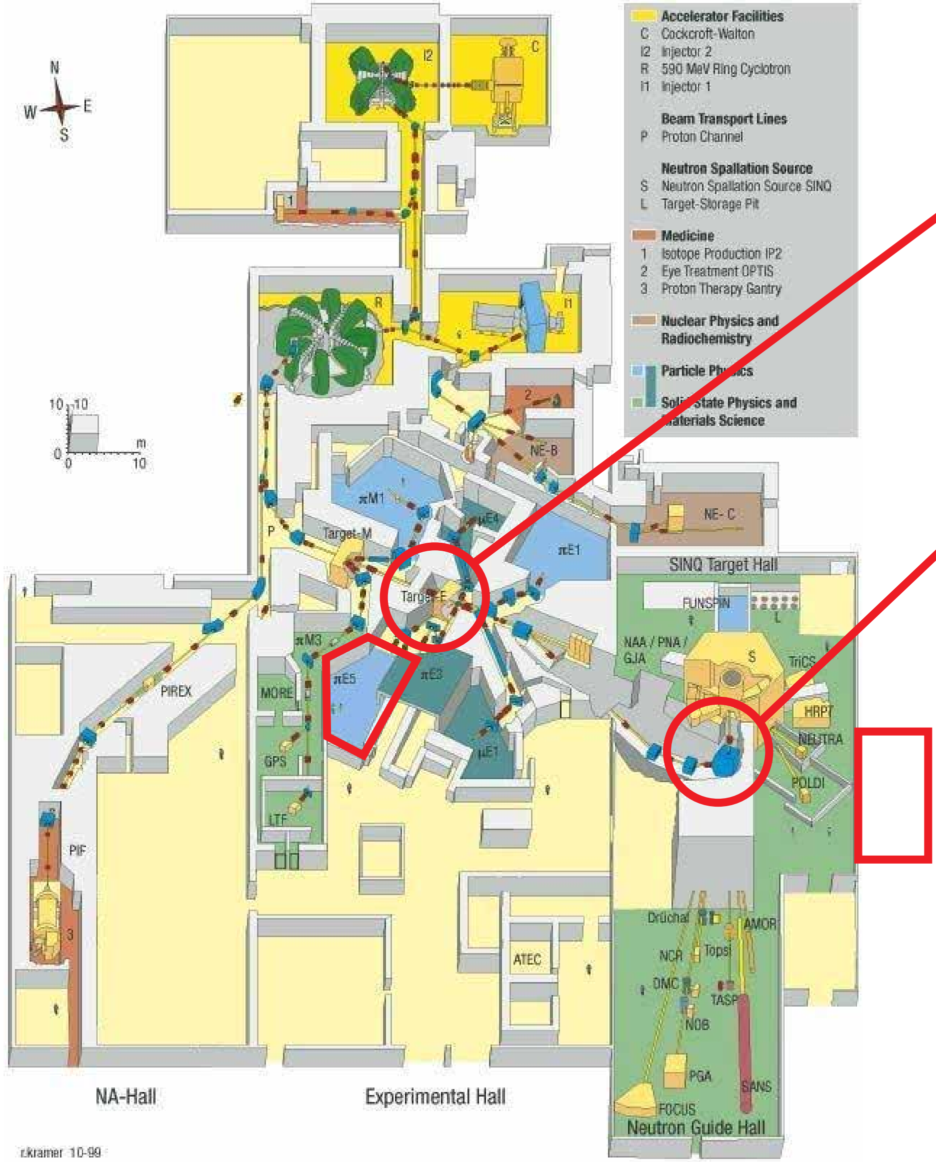
Muons from PSI



DC muon beams at PSI:

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

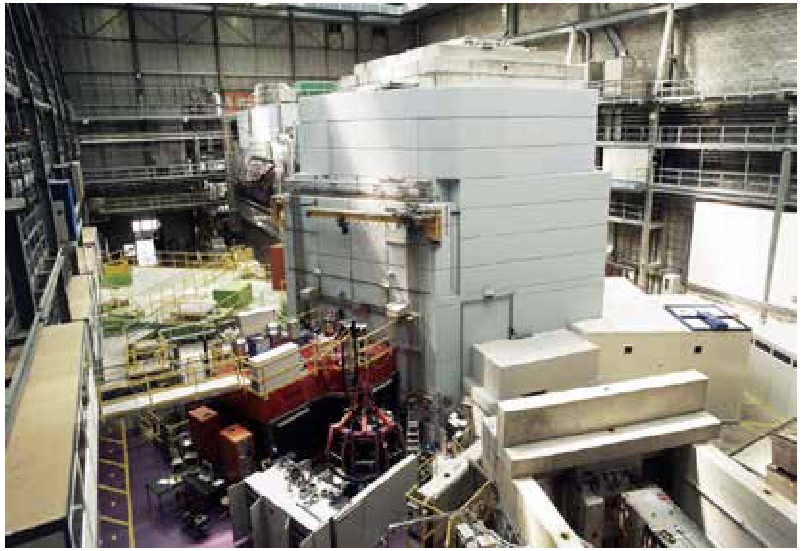
Muons from PSI



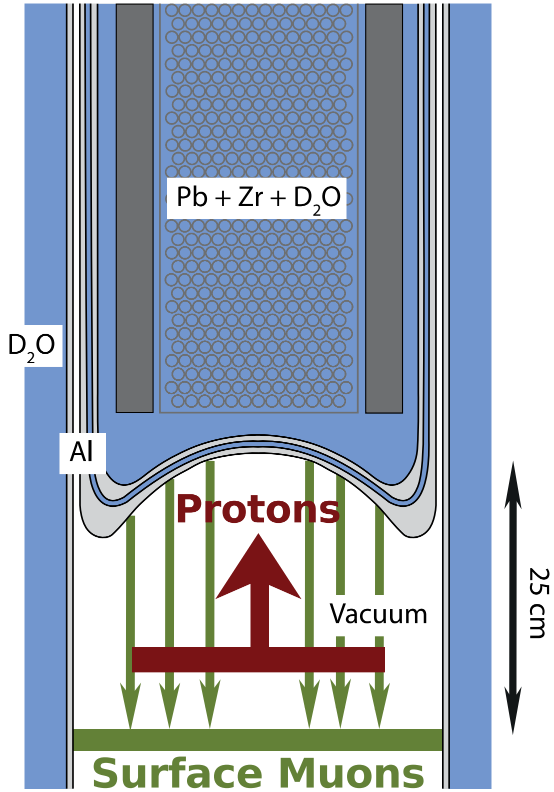
DC muon beams at PSI:

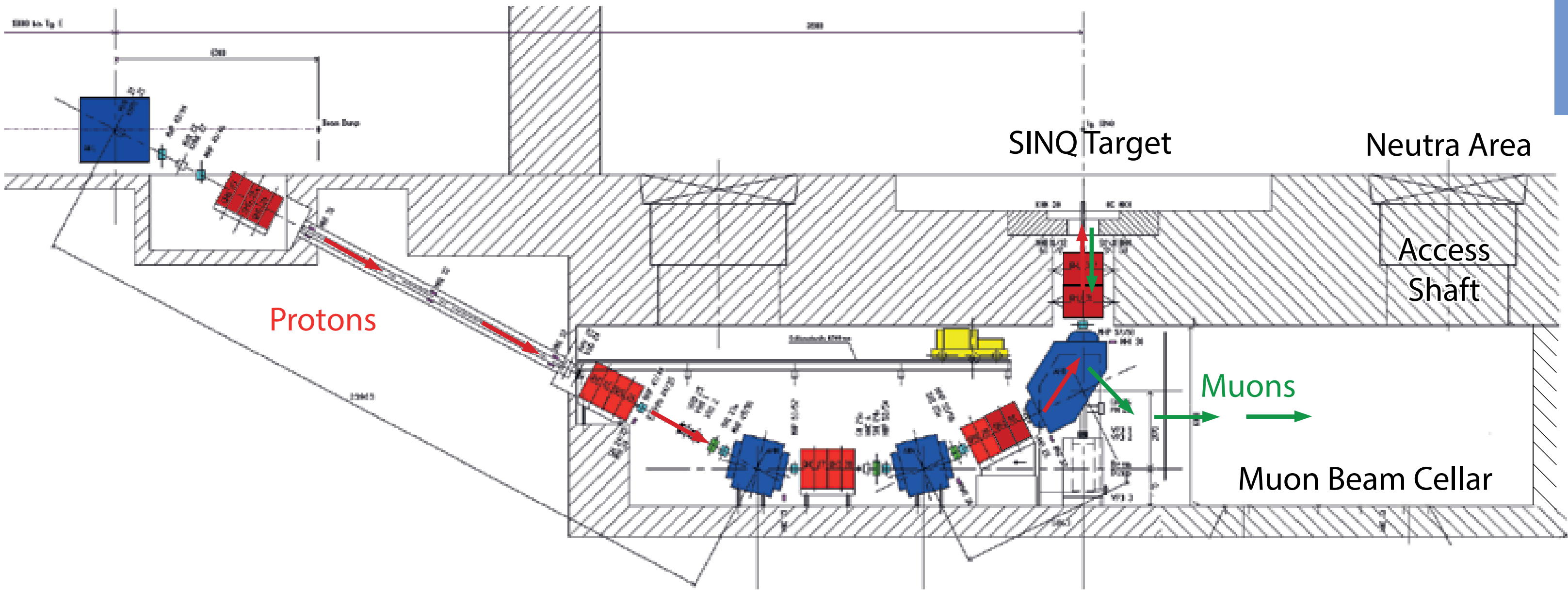
- πE5 beamline: $\sim 10^{8}$ muons/s
  (MEG experiment, Mu3e phase I)
- SINQ (spallation neutron source) target could even provide
  $\sim 5 \times 10^{10}$ muons/s
  High intensity muon beamline (HIMB) proposal
- The $\mu \to eee$ experiment (final stage) requires 2×10^{9} muons/s focused and collimated on a ~2 cm spot
- These are slow muons (29 MeV/c)
  Stop and wait for decay

The High-Intensity Muon Beamline (HIMB)

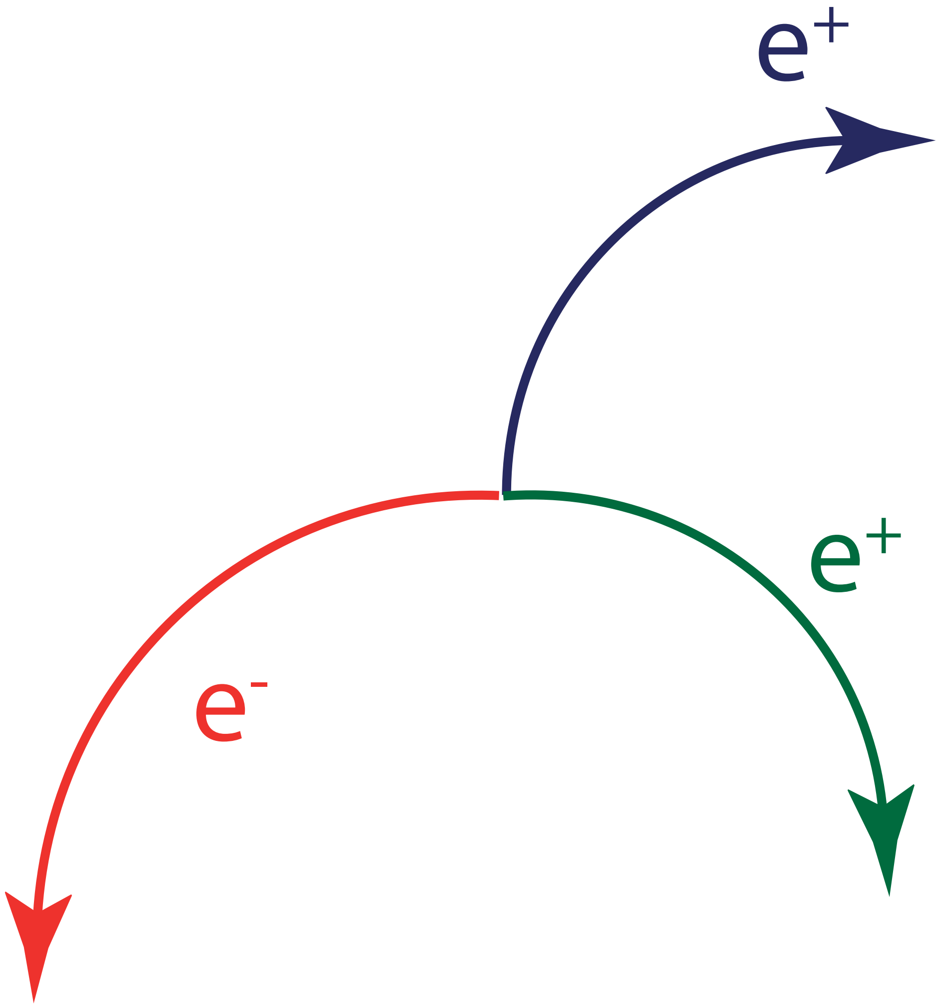


- Muon rates in excess of 10^{10}/s in acceptance
- $2 \cdot 10^9$/s needed for $\mu \rightarrow eee$ at 10^{-16}
- Not before 2017



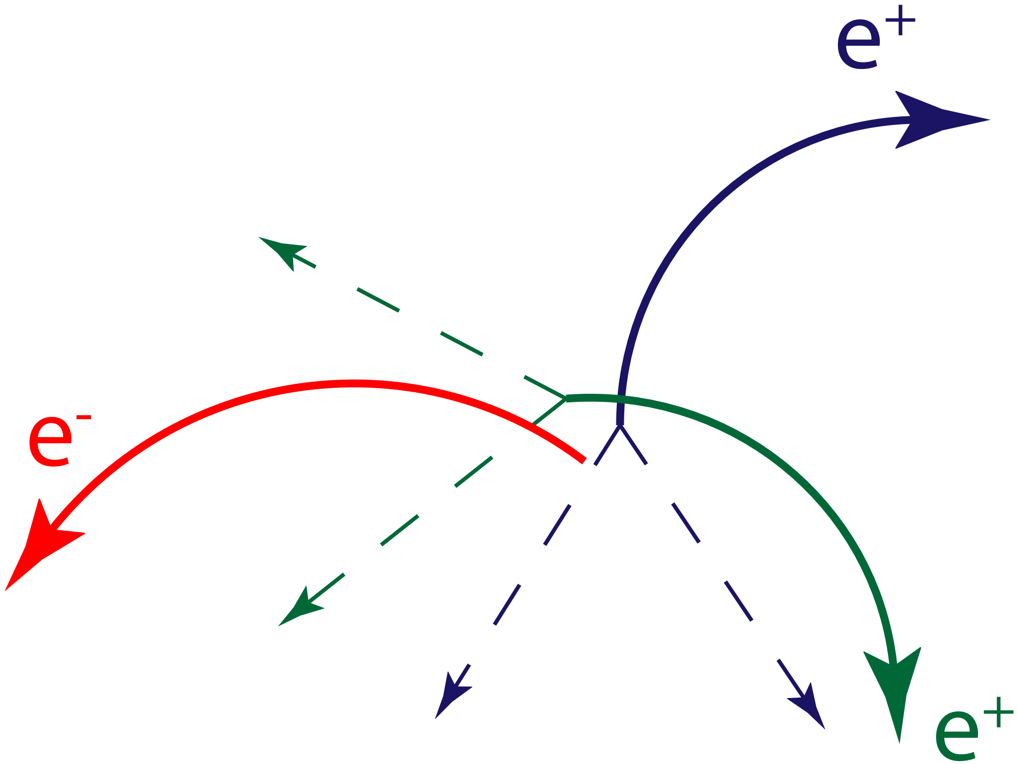


The signal



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

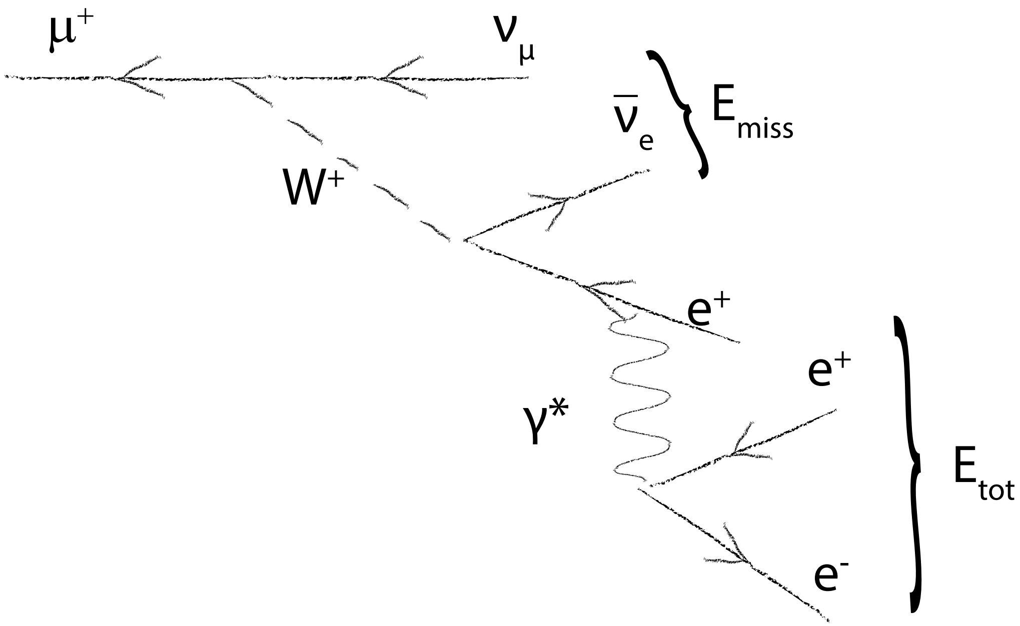
Accidental Background



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

- Need very good timing, vertex and momentum resolution

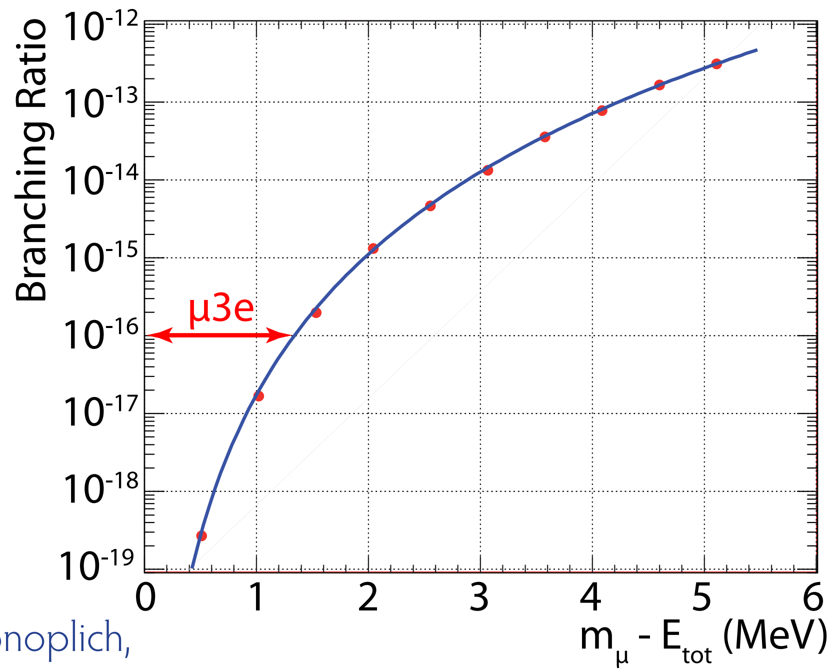
Internal conversion background



- Allowed radiative decay with internal conversion:

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

- Only distinguishing feature: Missing momentum carried by neutrinos

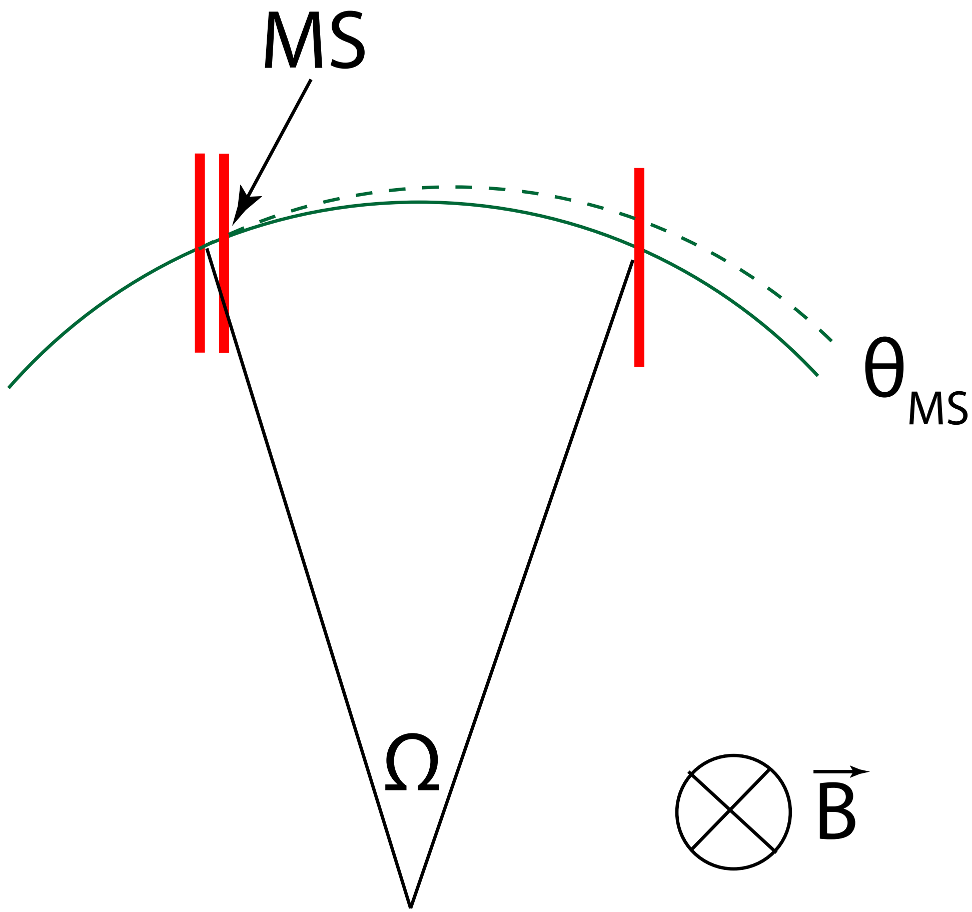


(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

- Need excellent momentum resolution

Building the Mu3e Experiment

Momentum measurement

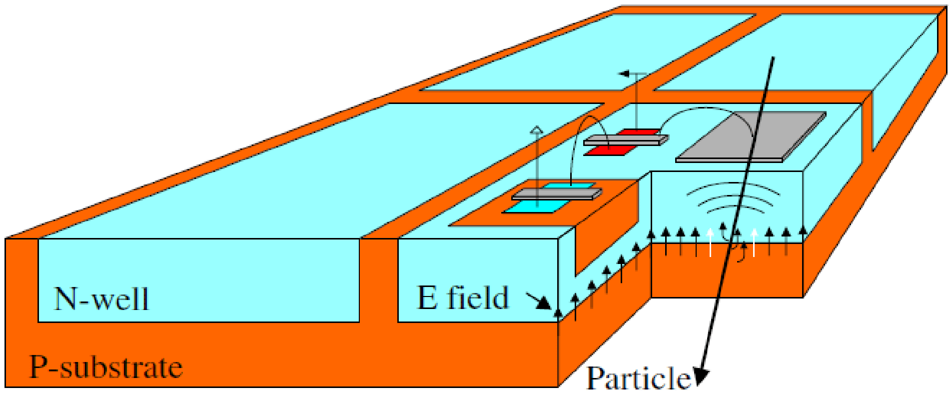


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

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

- Precision requires large lever arm (large bending angle 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)

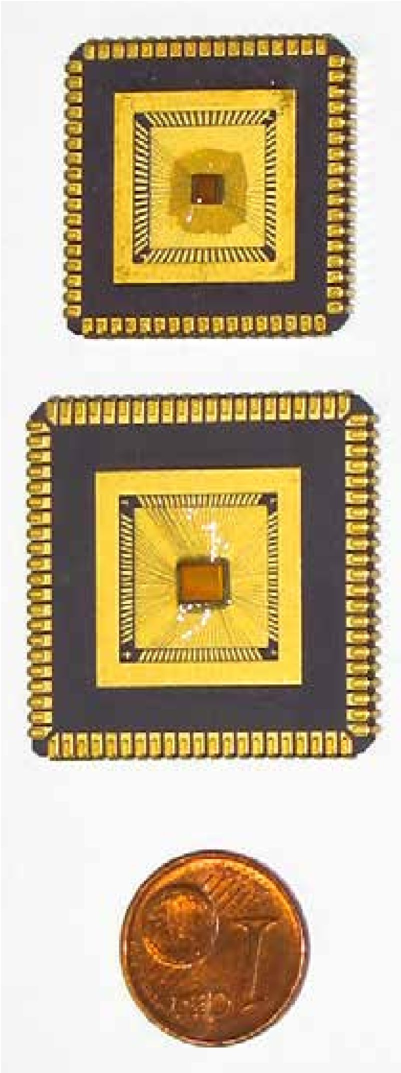
The MUPIX chips

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

MUPIX3 and 4
40 x 32 pixels
80 x 92 μm pixel size
9.4 mm^2 active area

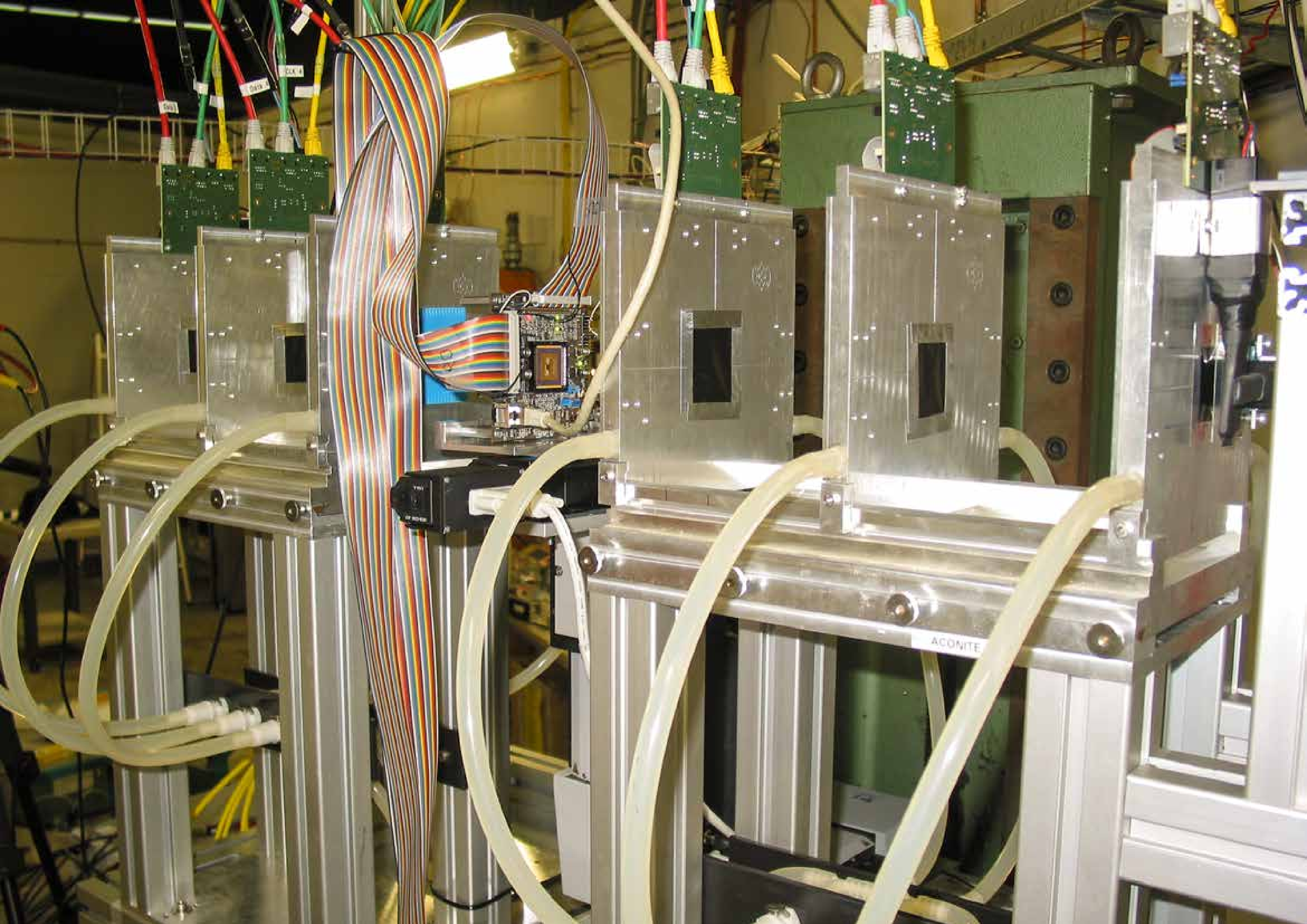
MUPIX6
submitted

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



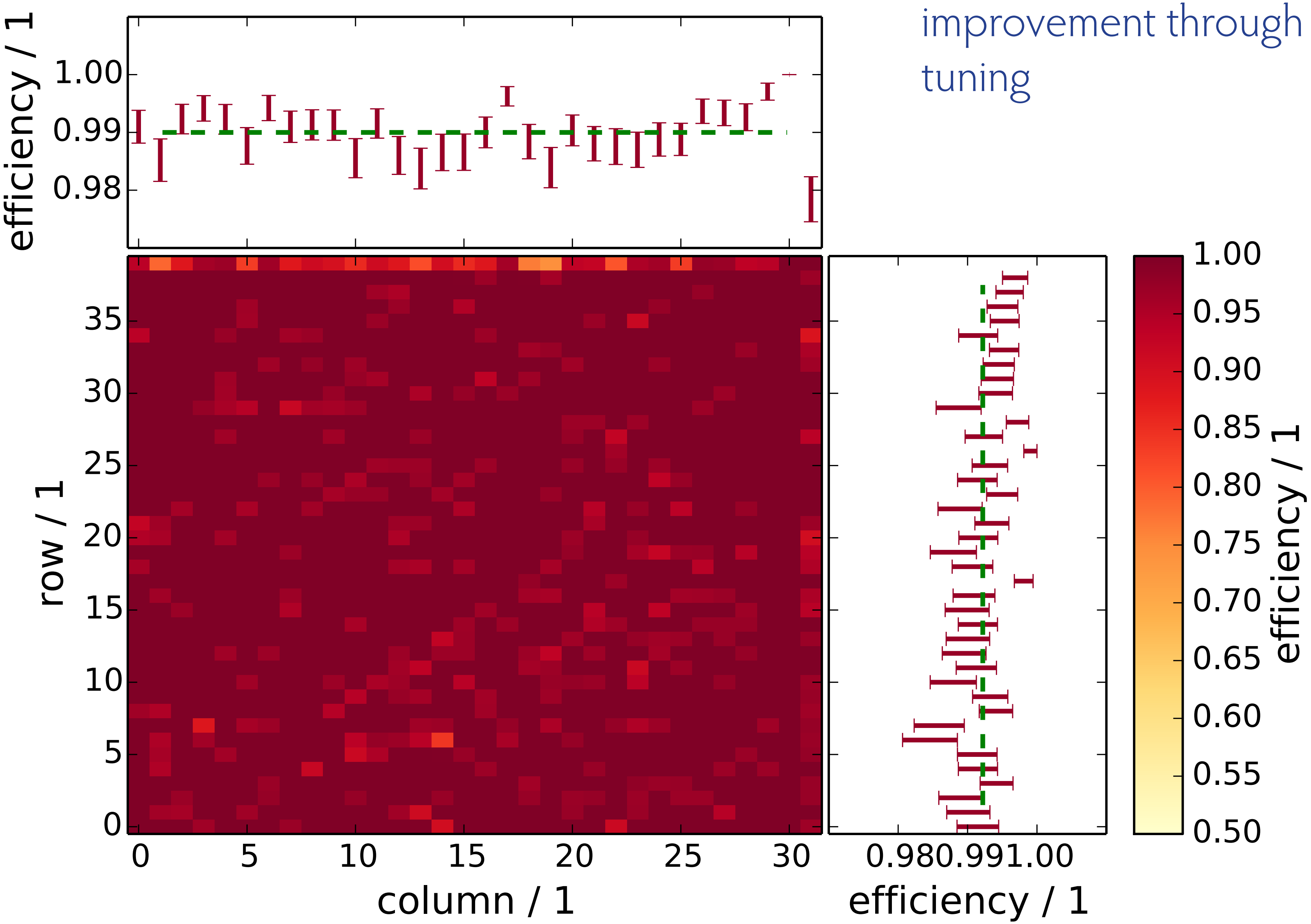
HV-MAPS chips: AMS 180 nm HV-CMOS

- MUPIX2:
  Characterization during 2012
  Single pixel Time-Over-Threshold
  Binary pixel matrix
- MUPIX3 and 4:
  Tested extensively during 2013 and right now here at Testbeam 22
  Column logic with address generation
  (#3 had configuration problems,
  #4 works nicely, address problems in half the columns)

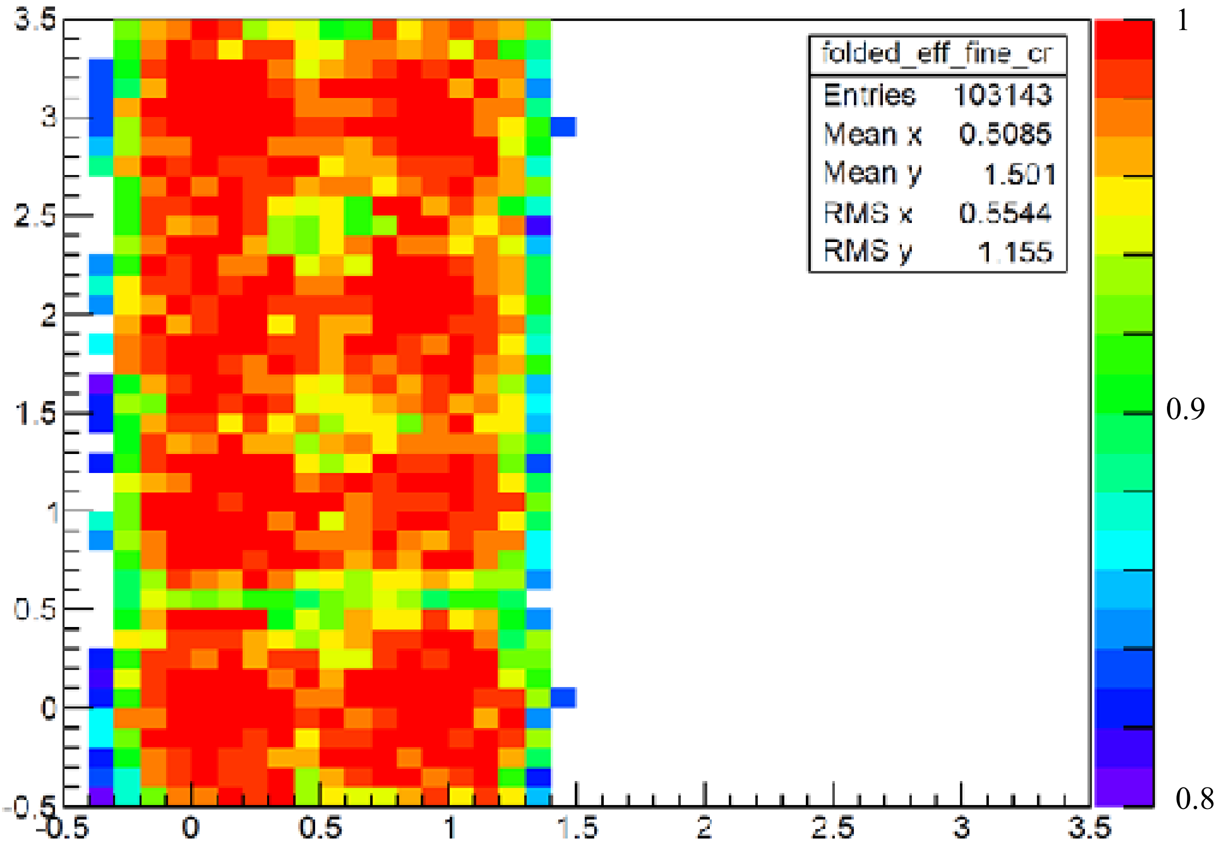

ACONITE

MUPIX4 Results

99% efficient - some room for improvement through individual pixel tuning



Pixel structure

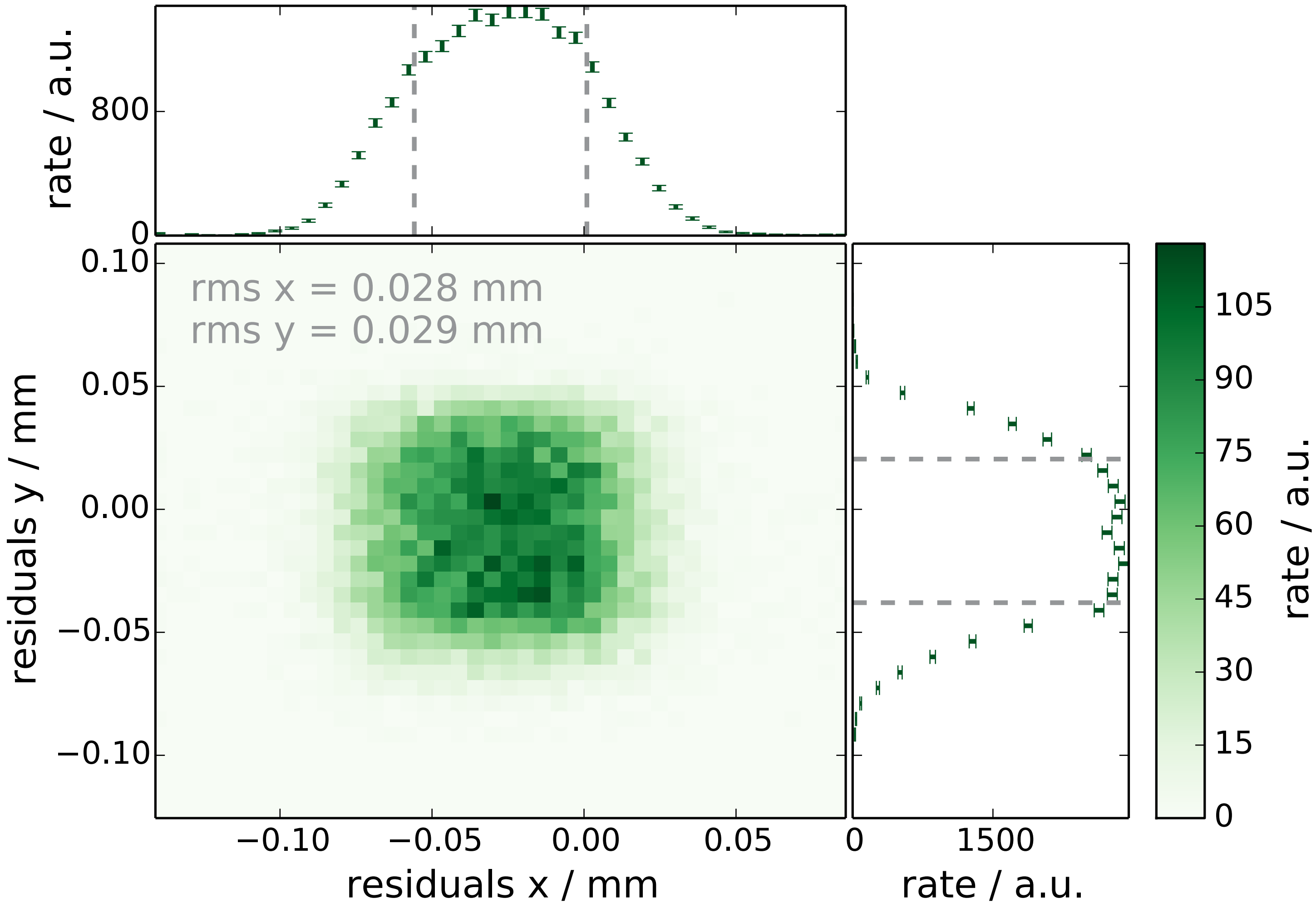


Data folded to four by four pixels

- Some loss at edges through charge sharing
- Guard ring at wrong potential (fixed in MUPIX 6)
- Half the pixels without row address (fixed in MUPIX6)

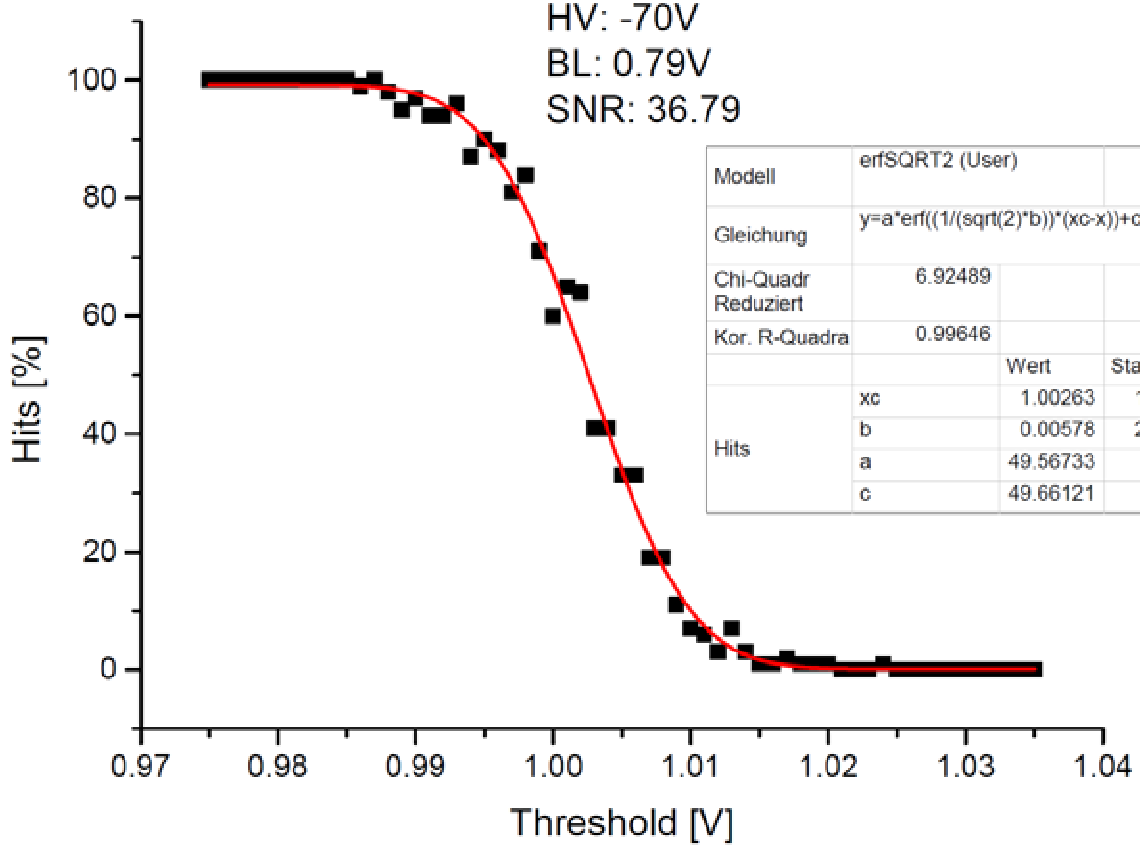
Spatial resolution

- Binary readout:
  Given by pixel size plus telescope contribution



Signal-to-Noise

- Signal calibrated with Strontium source
- Noise from fit to S-curve (width of threshold) with a fixed injection signal
- Signal/Noise above 30

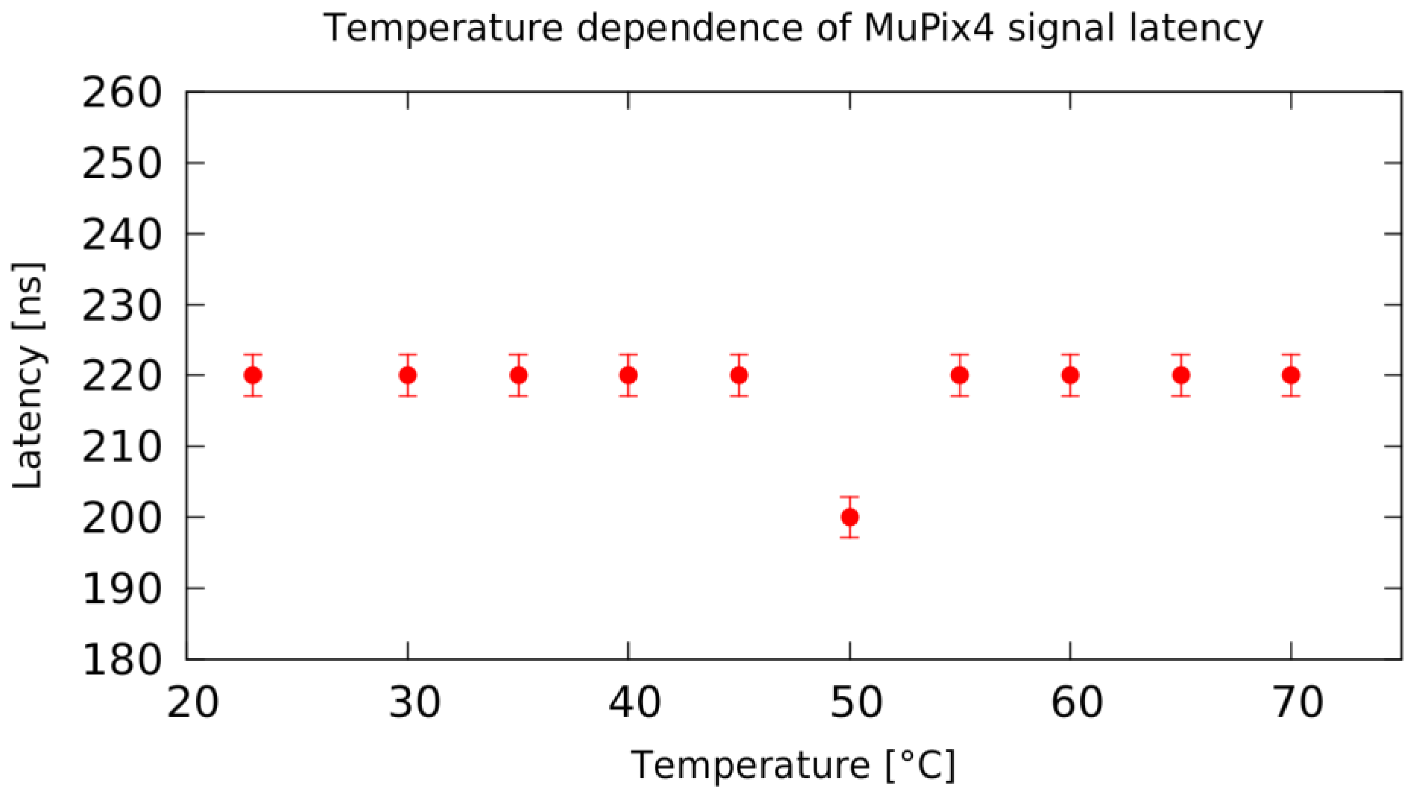


Modell	erfSQRT2 (User)		
Gleichung	y=a*erf((1/(sqrt(2)*b))*(xc-x))+c		
Chi-Quadr Reduziert		6.92489	
Kor. R-Quadra		0.99646	
		Wert	Standardfehler
Hits	xc	1.00263	1.61603E-4
	b	0.00578	2.12187E-4
	a	49.56733	0.44927
	c	49.66121	0.43005

Temperature stability

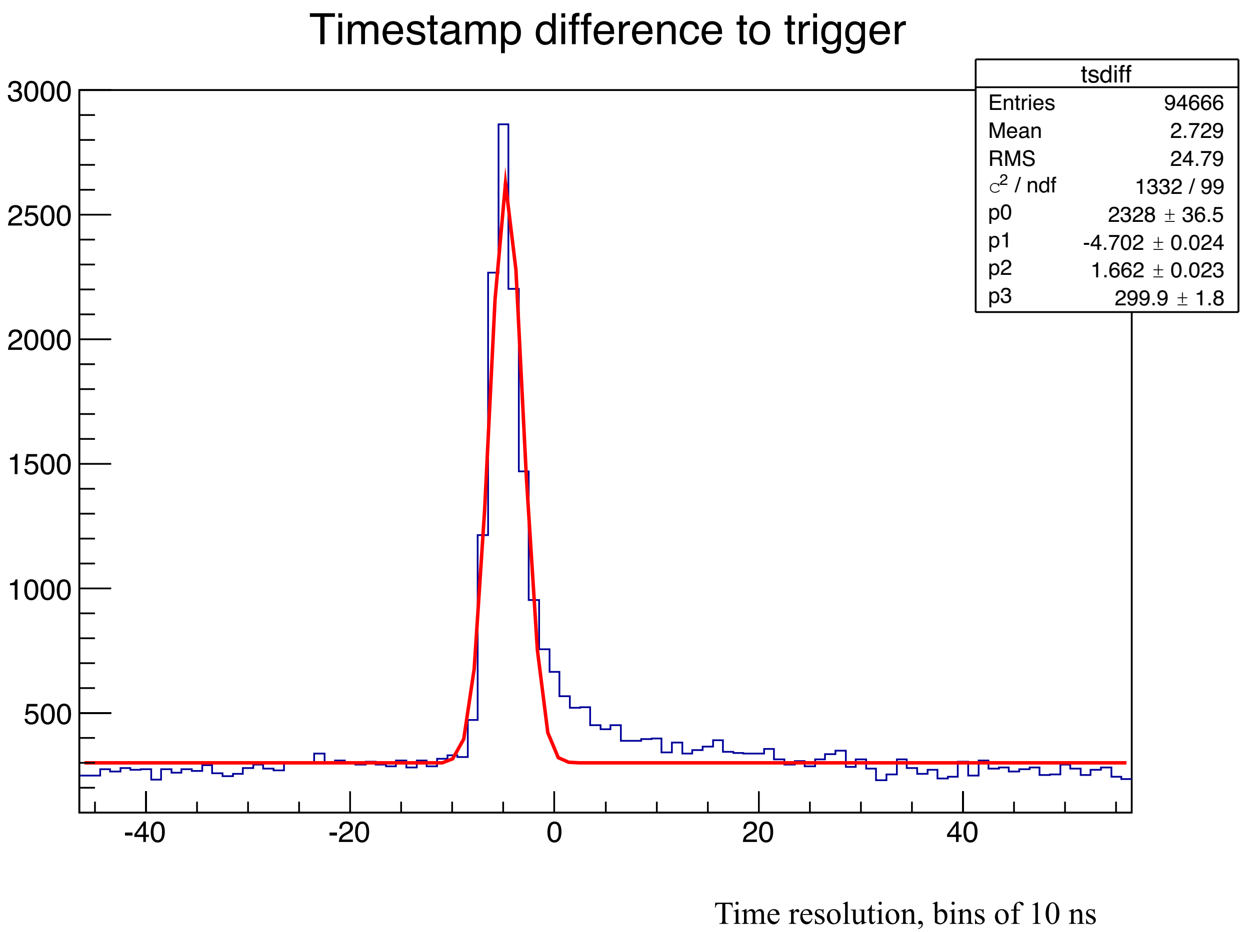
Latency measurement

- LED pulse to pixel discriminator output
- Setup in oven, 20-70°C
- Temperature dependence within resolution of setup

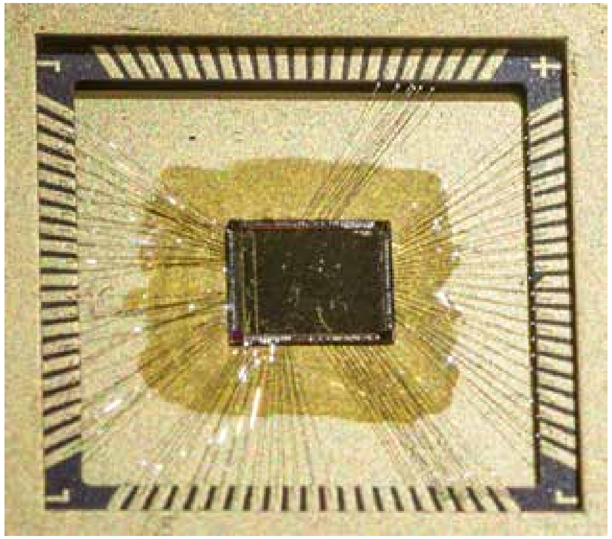


Time measurement

- External Gray-counter (100 MHz) registered on hit
- 17 ns time resolution, with significant contribution from setup

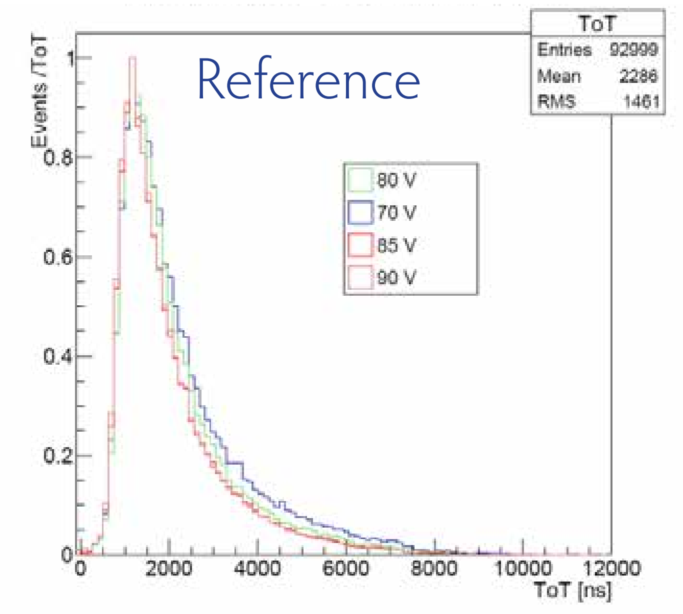


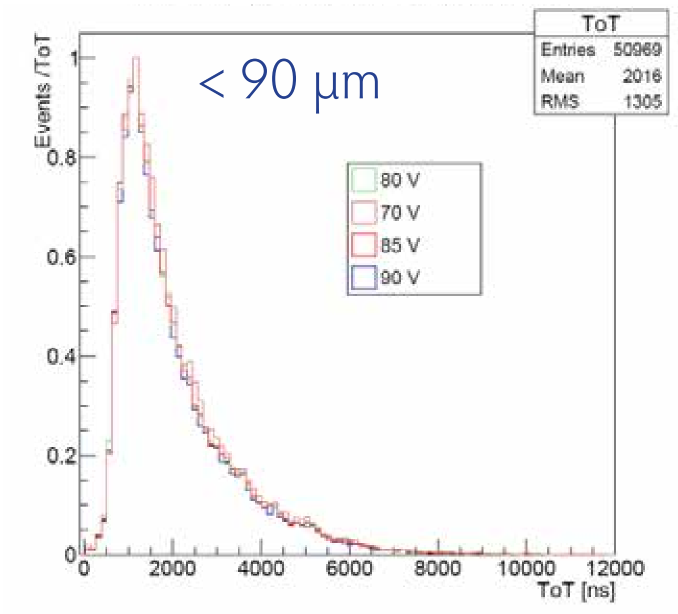
Thinned sensors

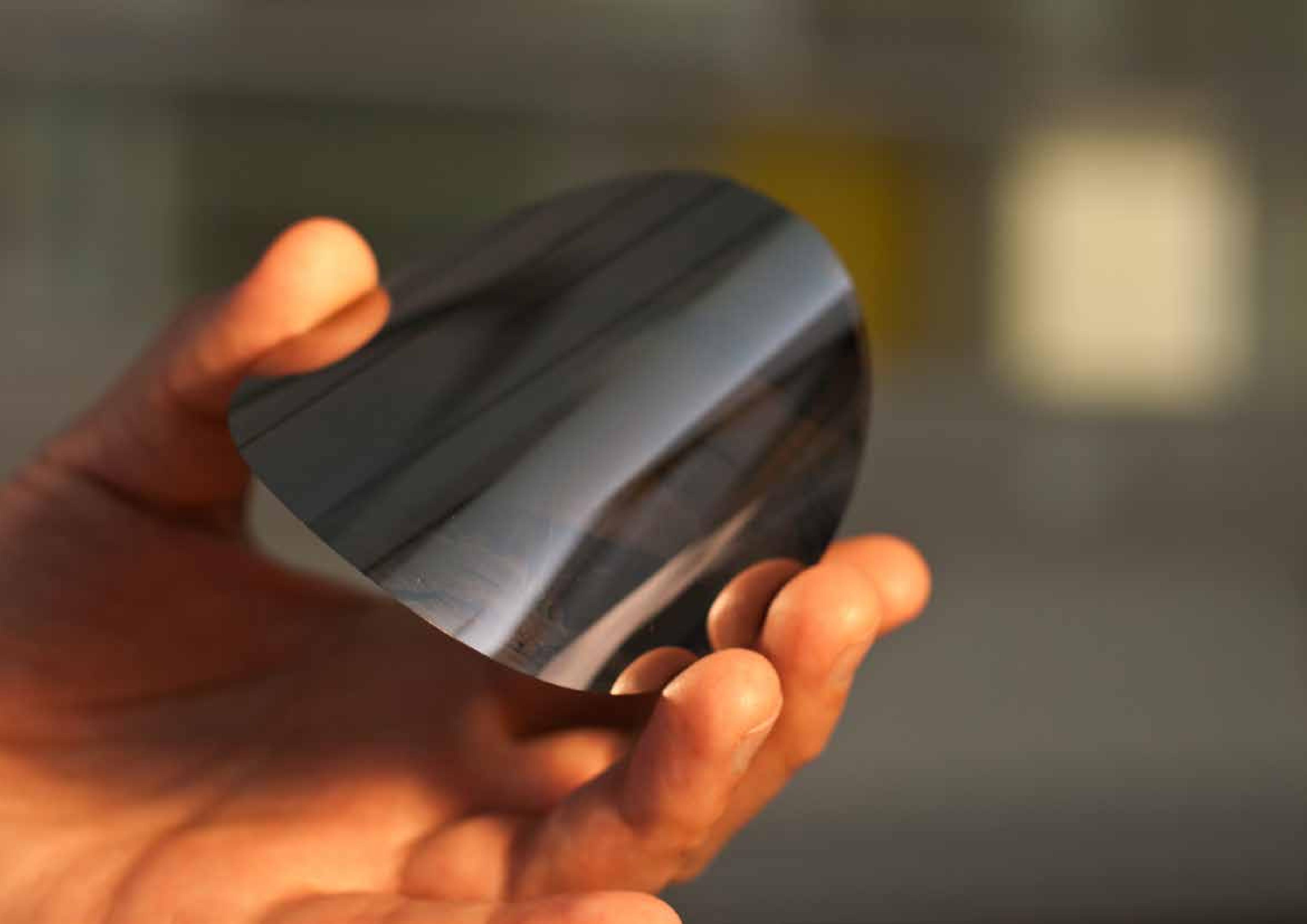


Single dies thinned to < 90 µm

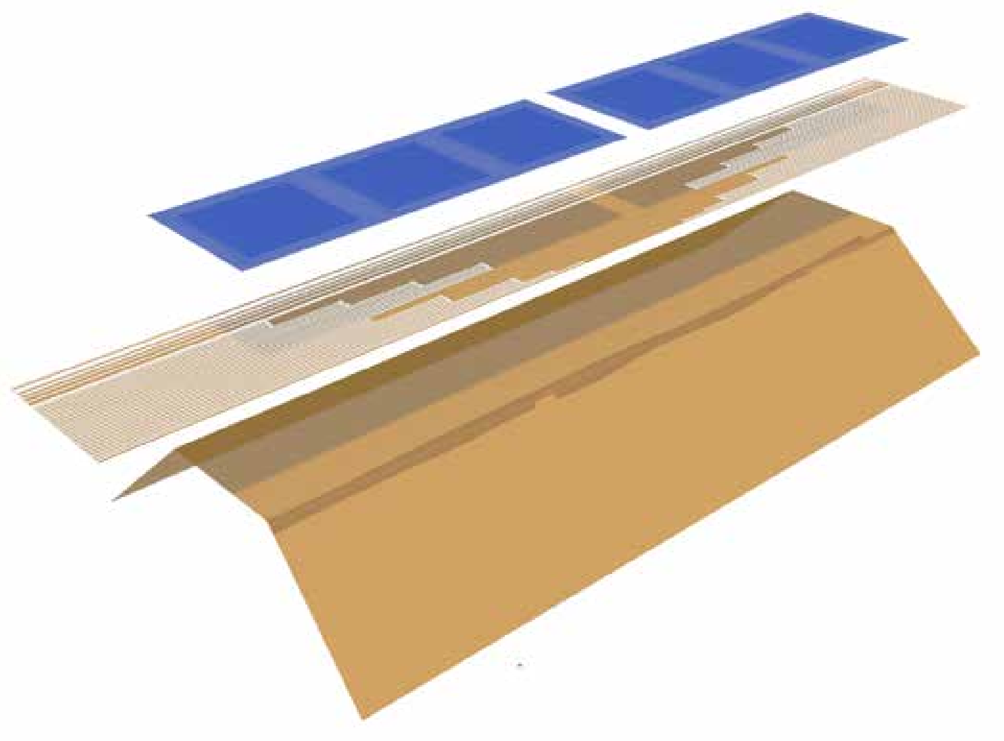
- Tested in lab and PSI test beam (193 MeV π^+)
- No significant difference in pulse shape







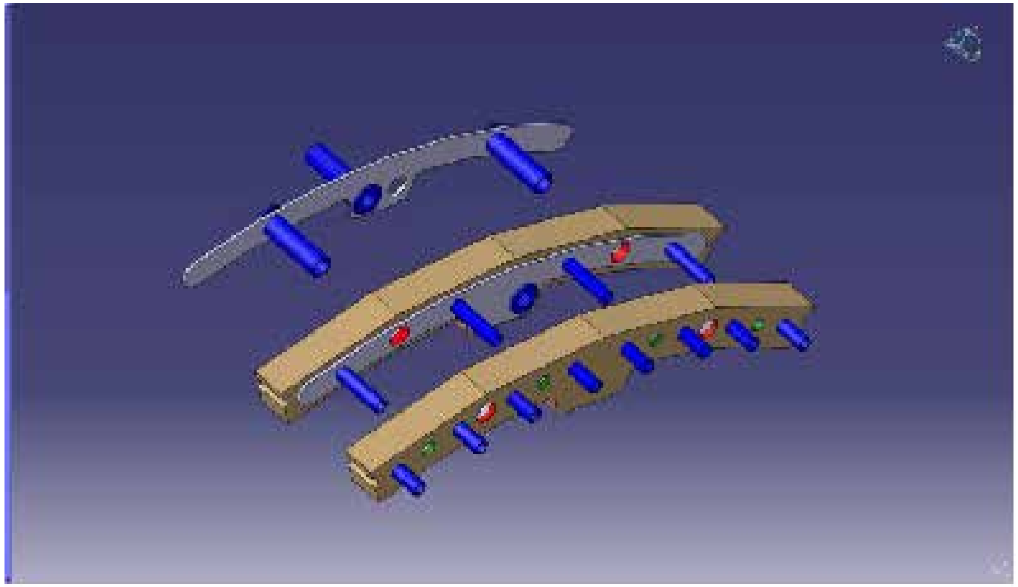
Mechanics



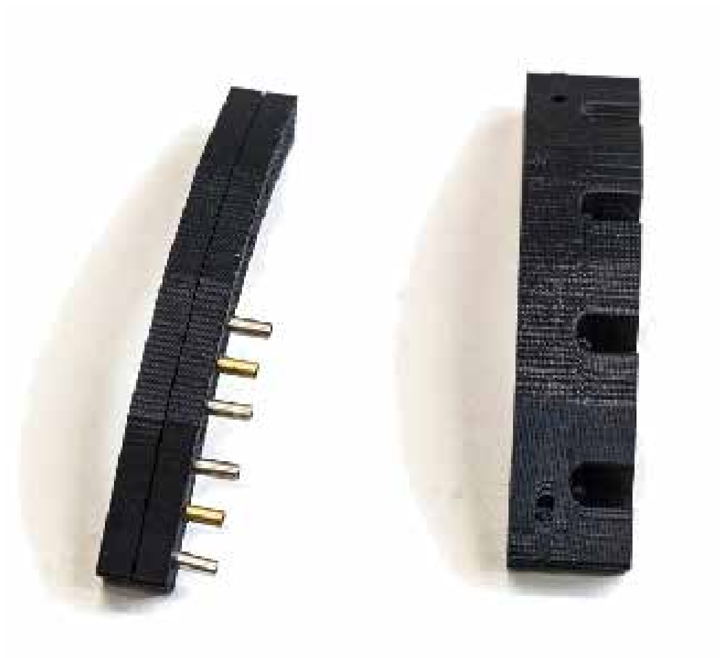
- 50 μm silicon
- 25 μm Kapton™ flexprint with aluminium traces
- 25 μm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer



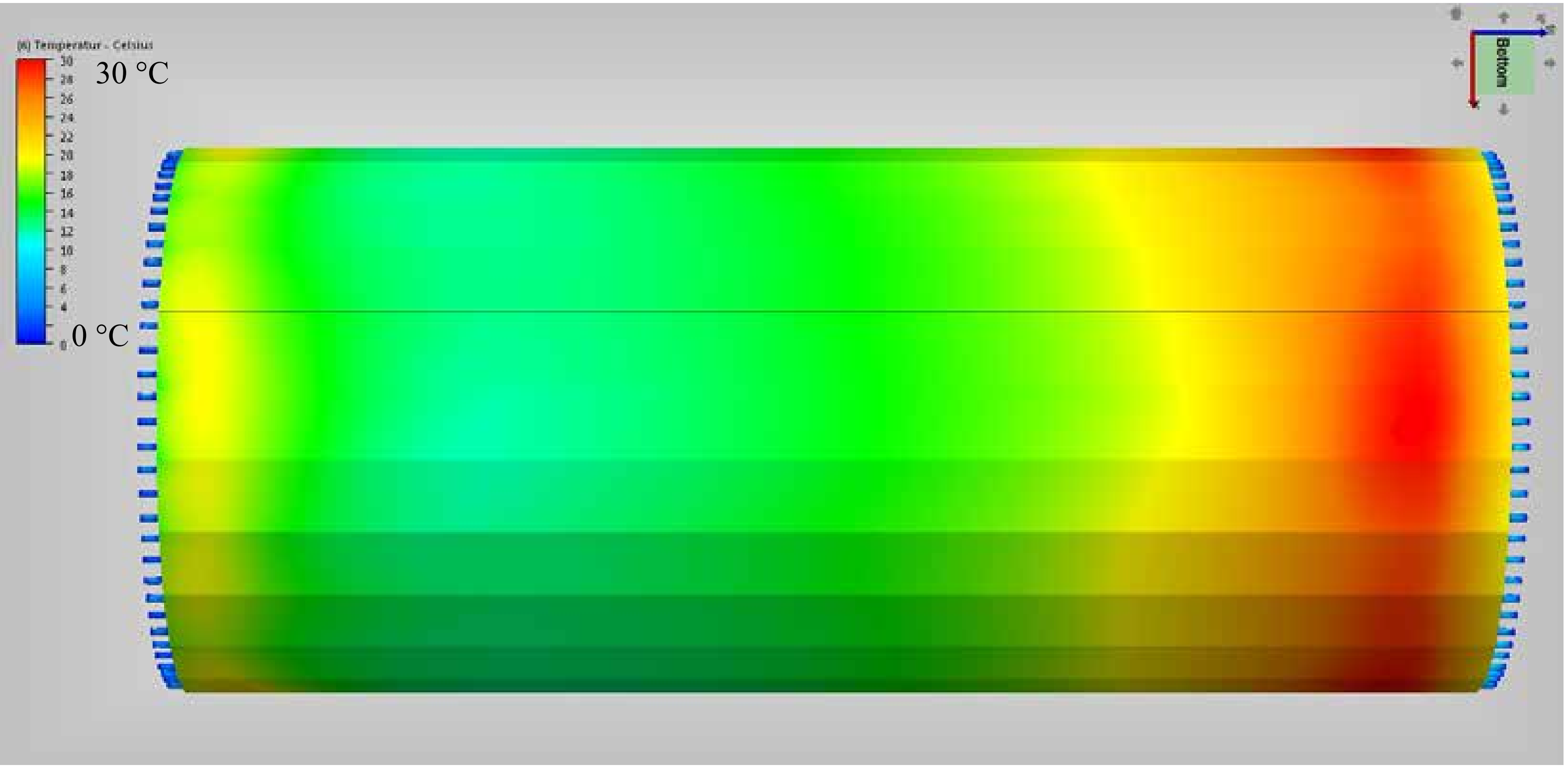
Cooling



- Add no material:
  Cool with gaseous Helium
- ~ 150 mW/cm^2 - total 2 kW
- Helium has 16 times mobility of air
- Simulations: Need ~ 1 m/s flow



Cooling simulation



Configuration:

Main helium flux: v = 0.5m/s

Flux in Nozzle: v = 5 m/s

31.42 mL/s per nozzle

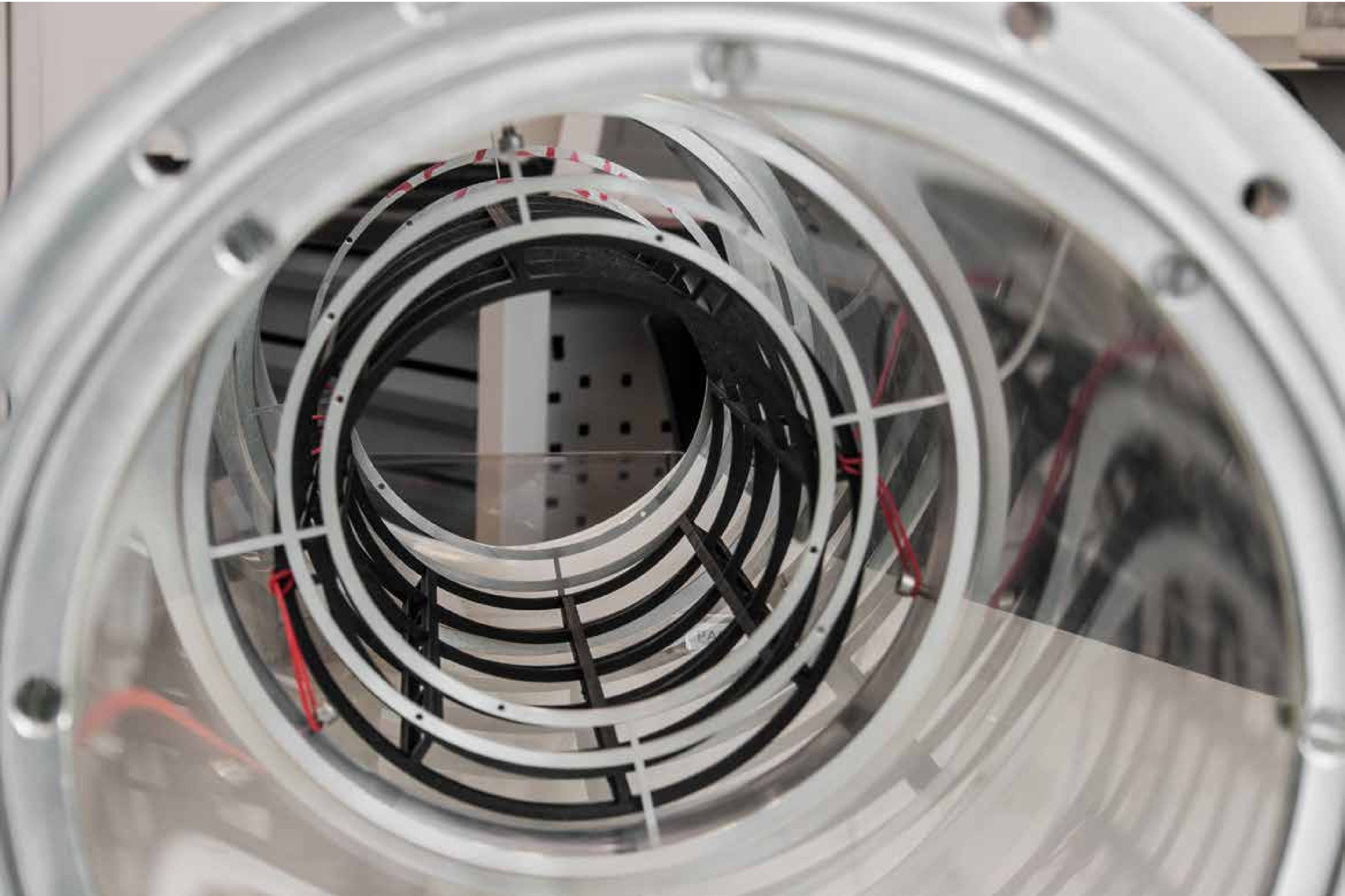
6.786 L/s for 3. Layer

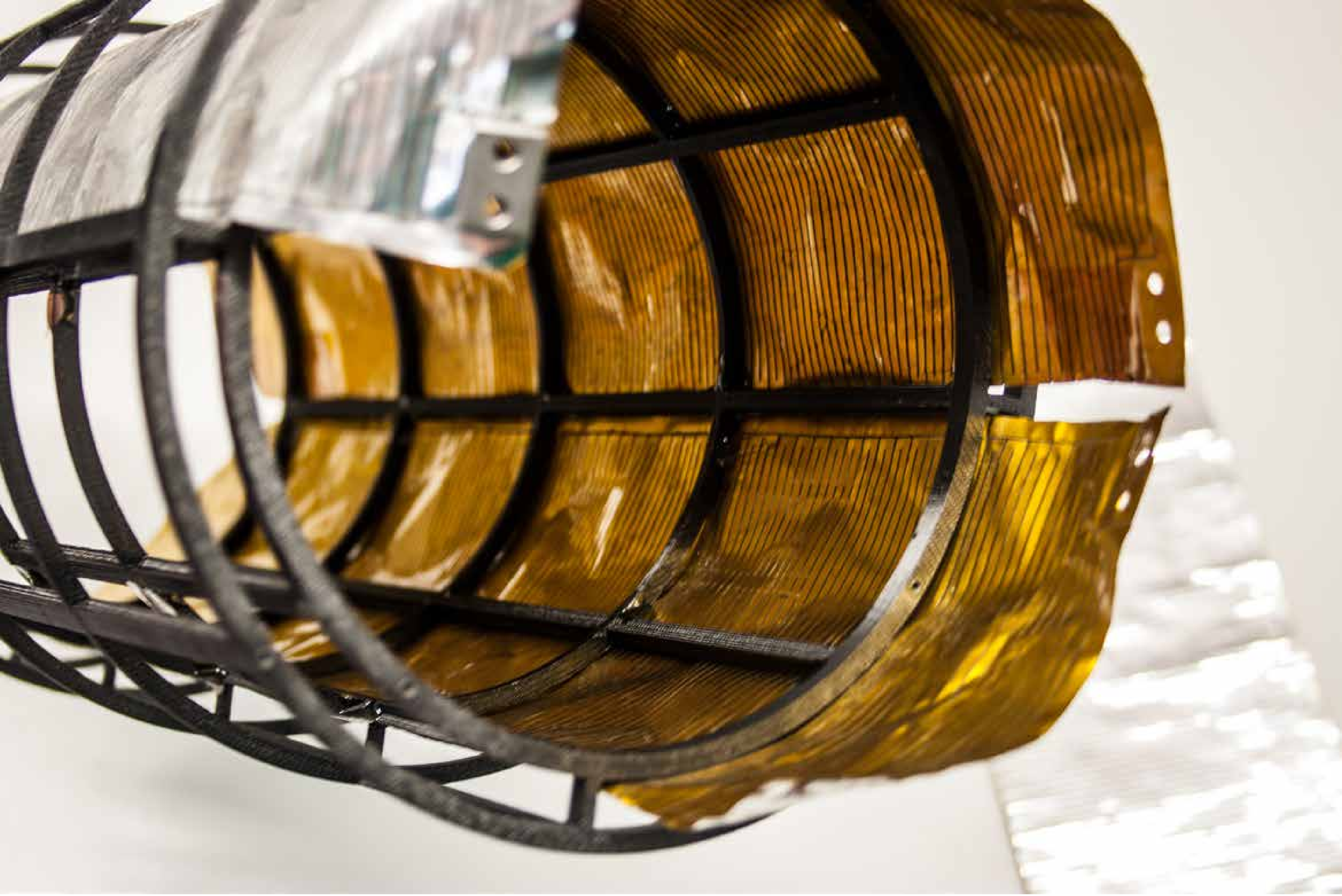
Results:

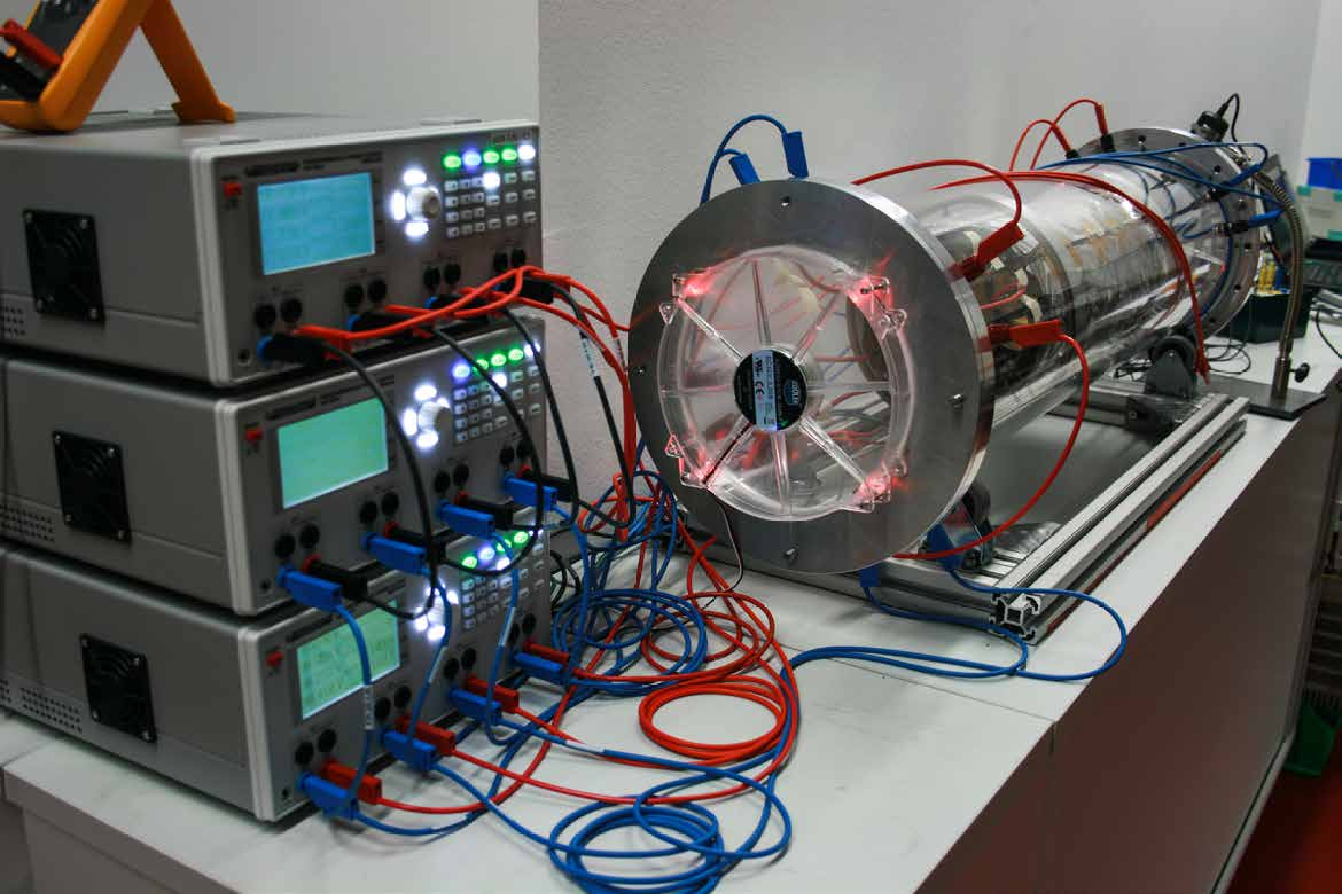
Tmax ≈ 42°C

Tmax close to end of tube

T raises at last third of tube



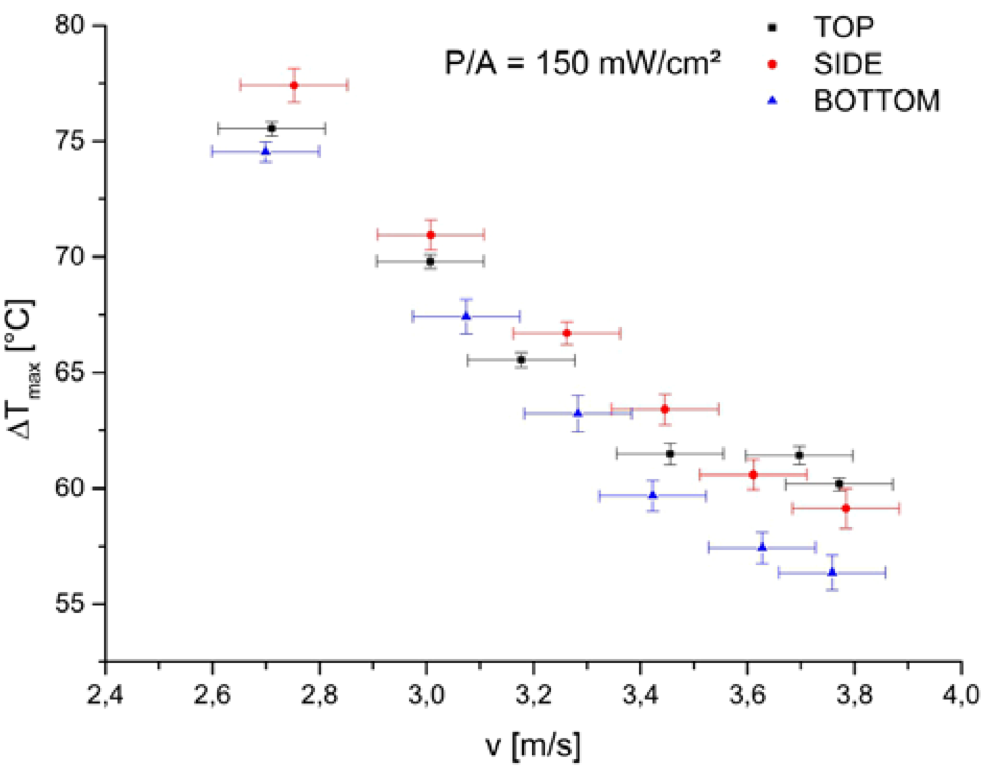




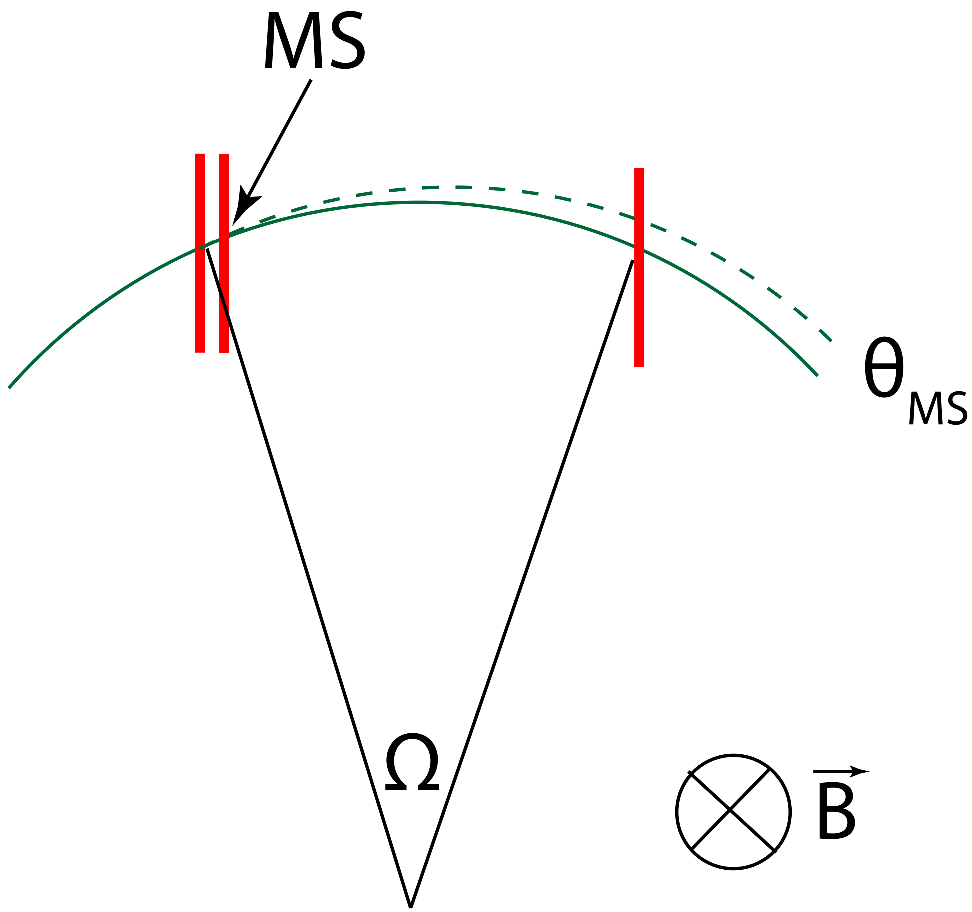
Cooling test results

- Ohmic heating, 150 mW/cm^2
  560 W for two layers
- ΔT < 60° C for sufficient air flow
- No problems with foil vibrations

Next: Tests with Helium



Momentum measurement

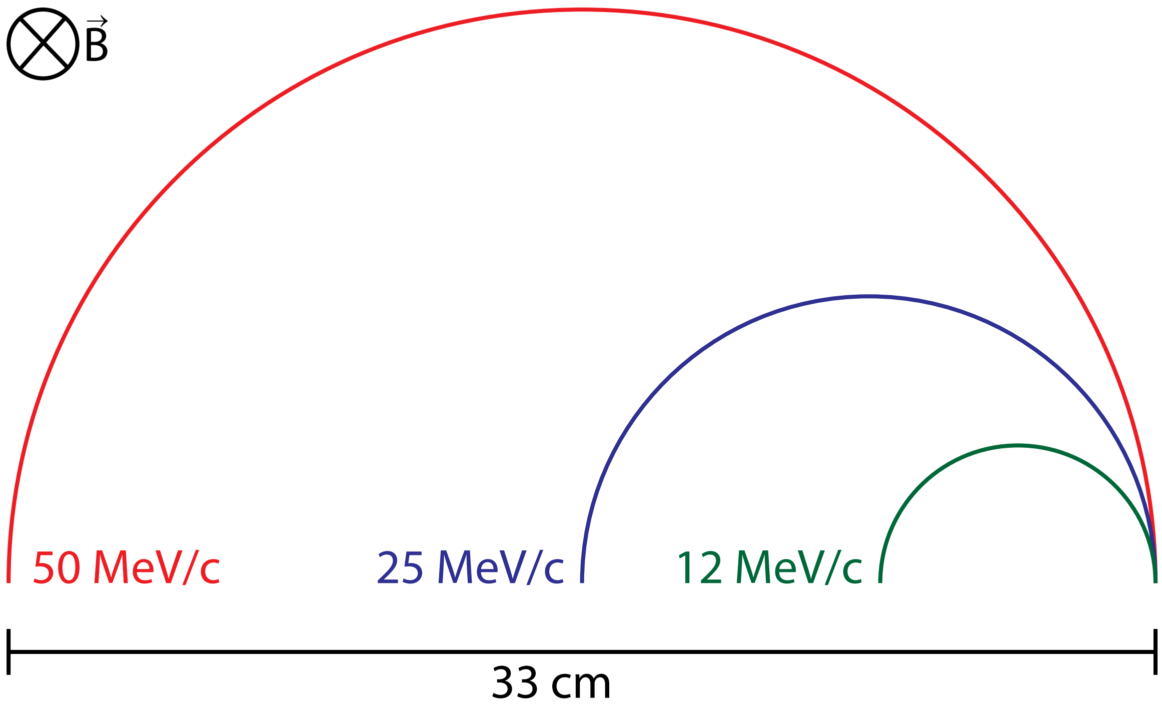


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

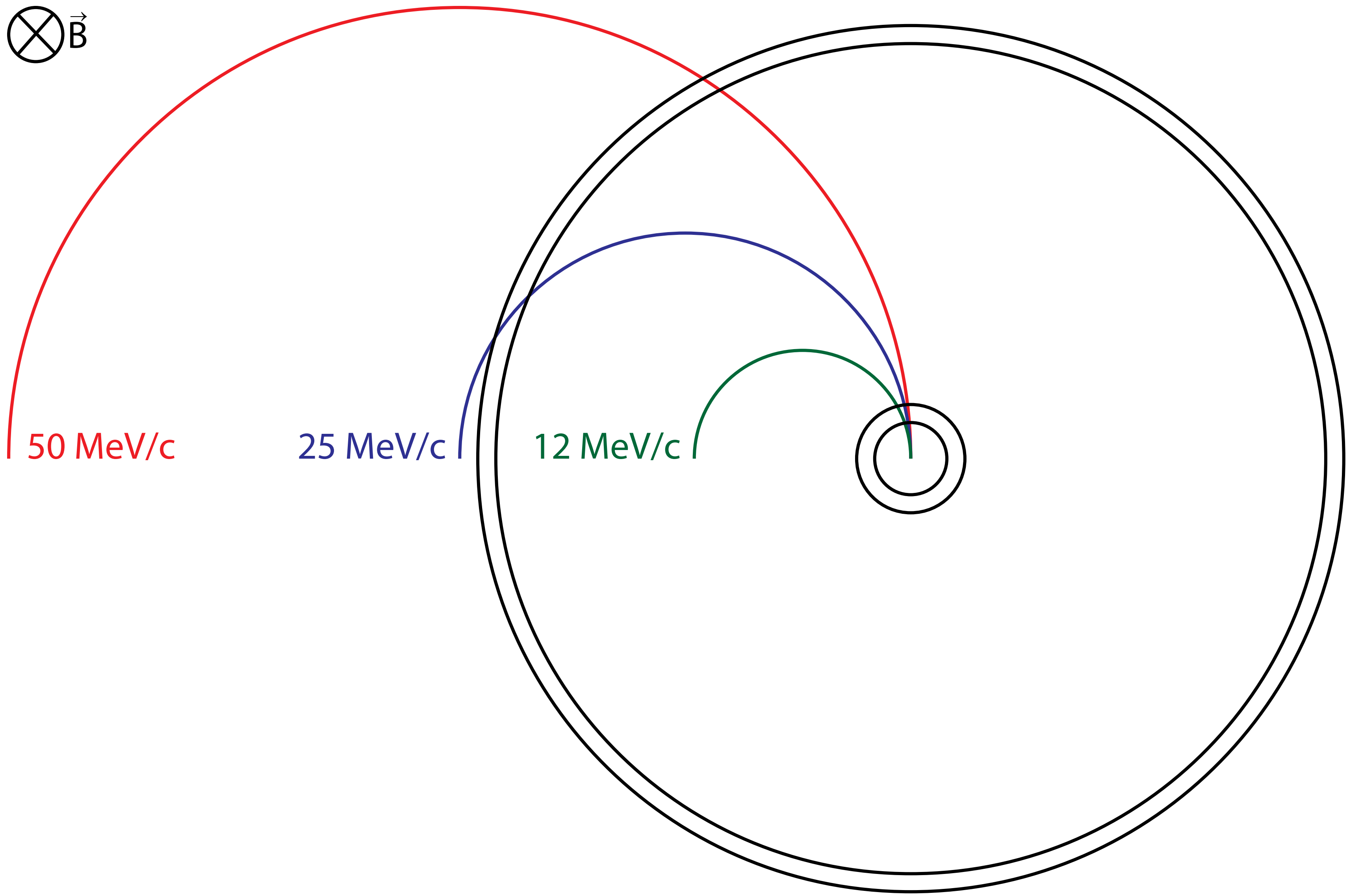
$$\sigma_P/_P \sim \theta_{MS}/_\Omega$$

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

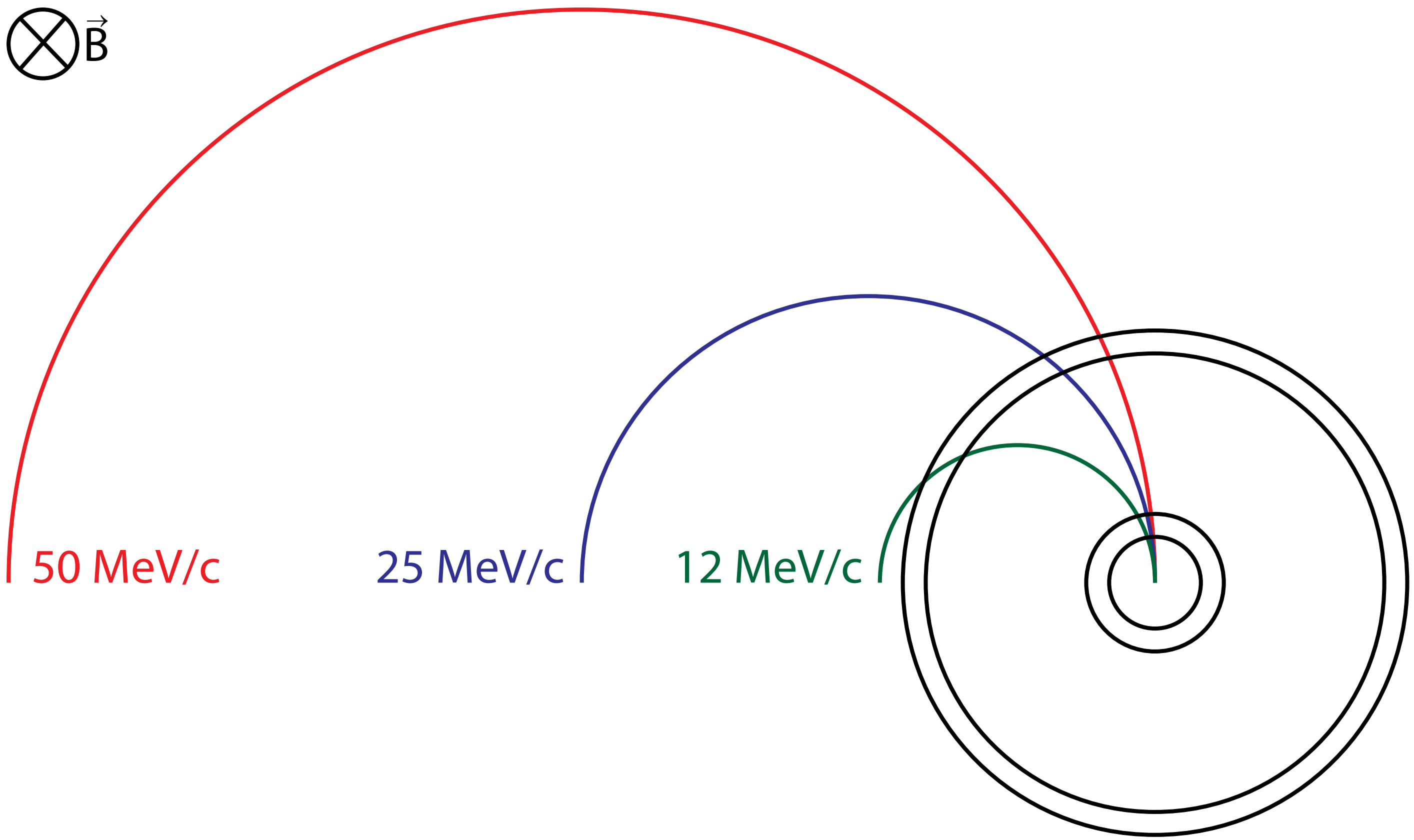
Precision vs. Acceptance



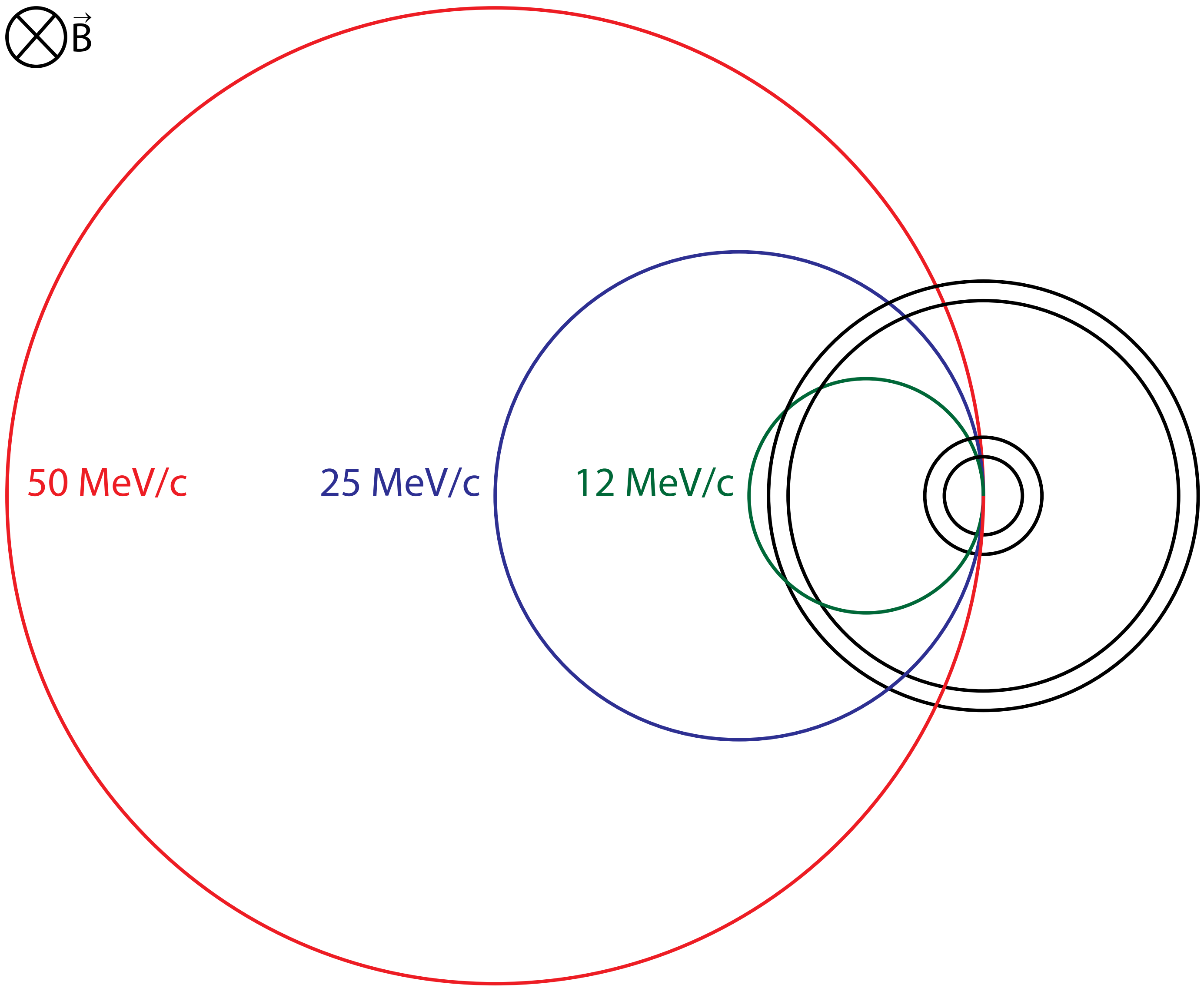
Precision vs. Acceptance



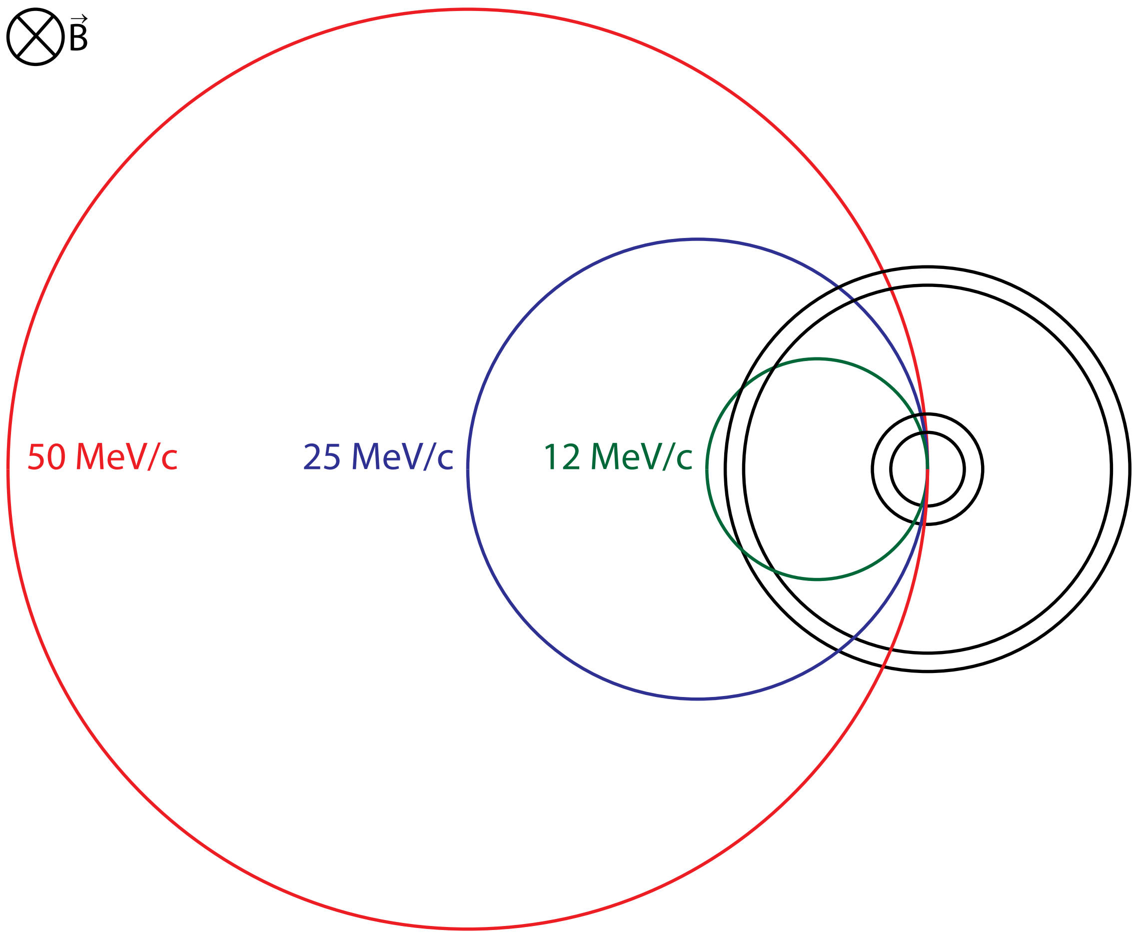
Precision vs. Acceptance

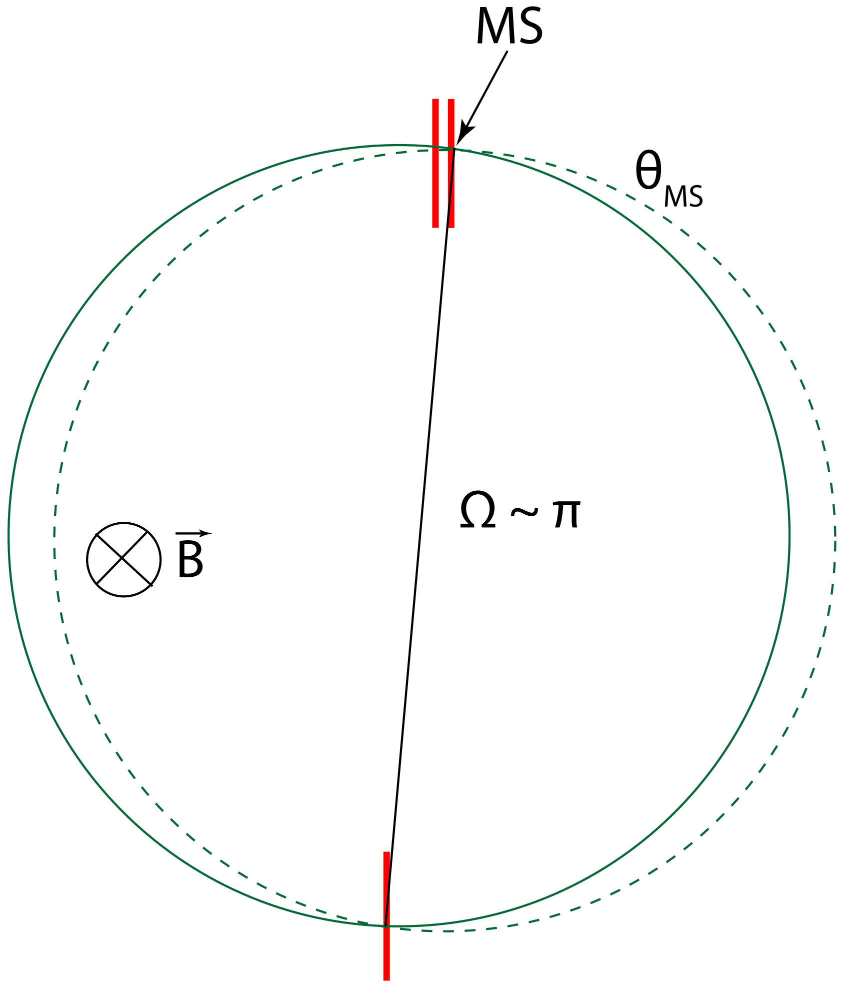


Precision vs. Acceptance

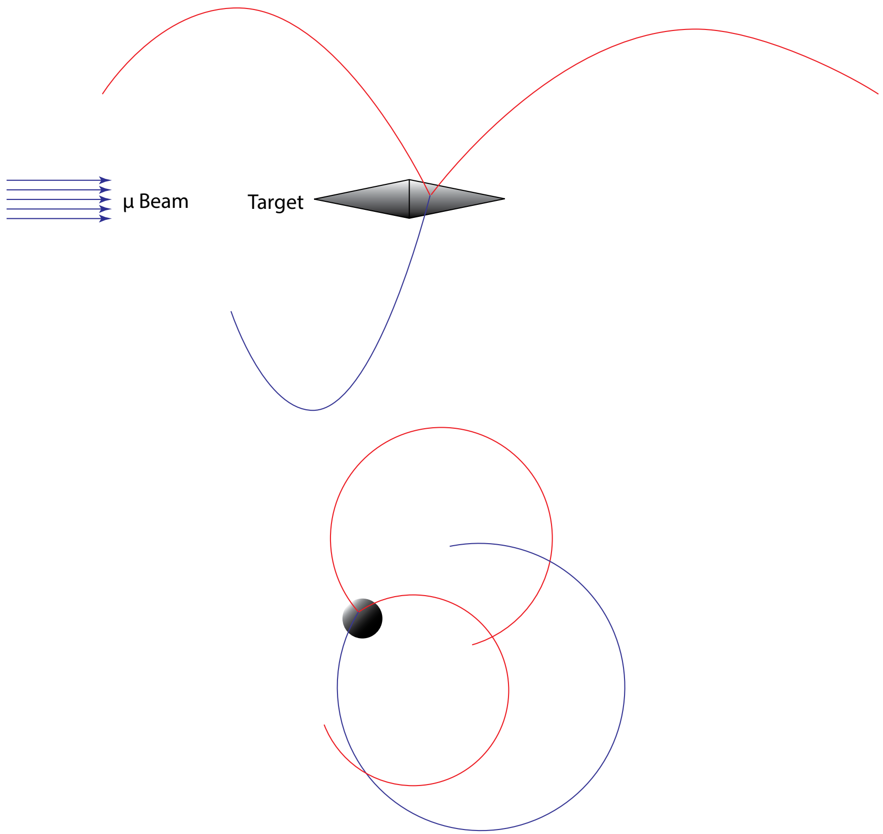


Precision vs. Acceptance

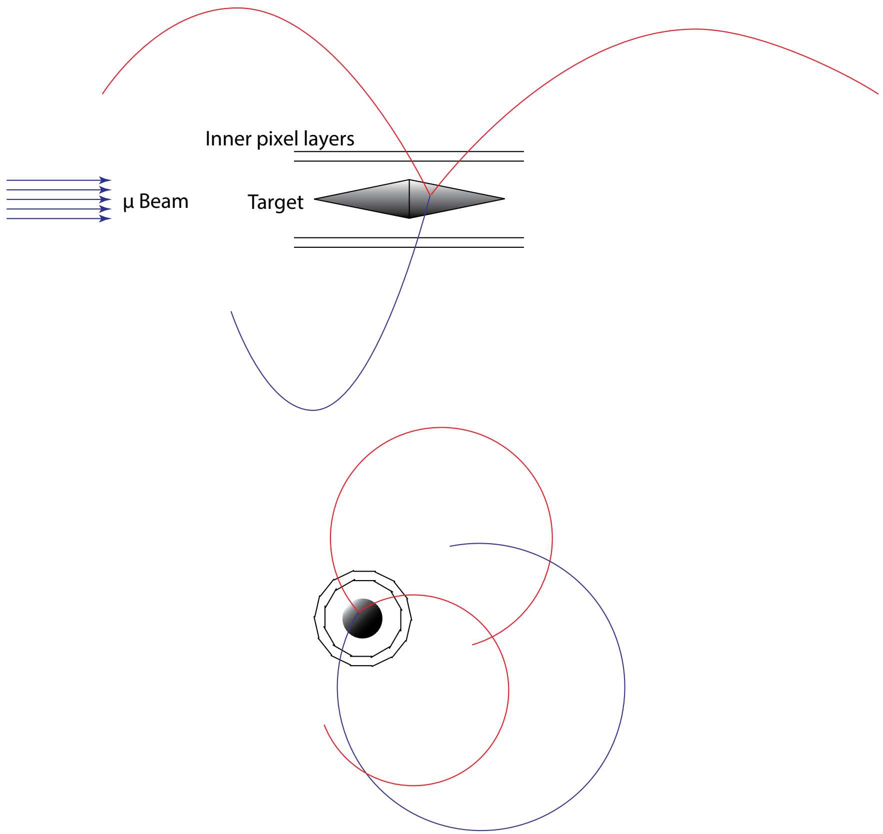




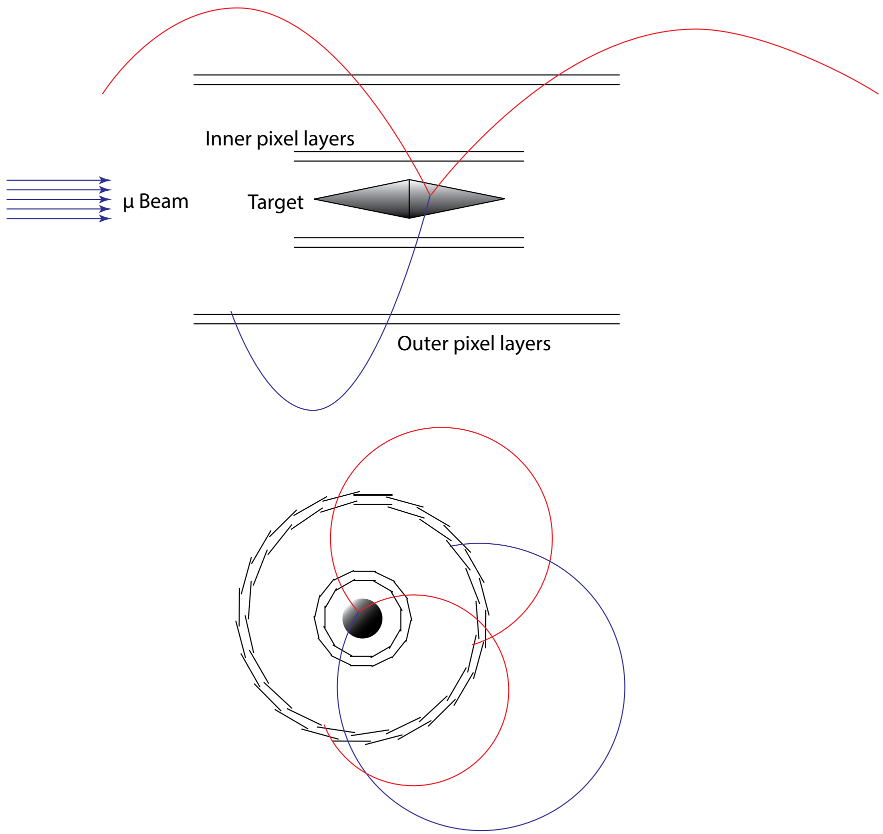
Detector Design



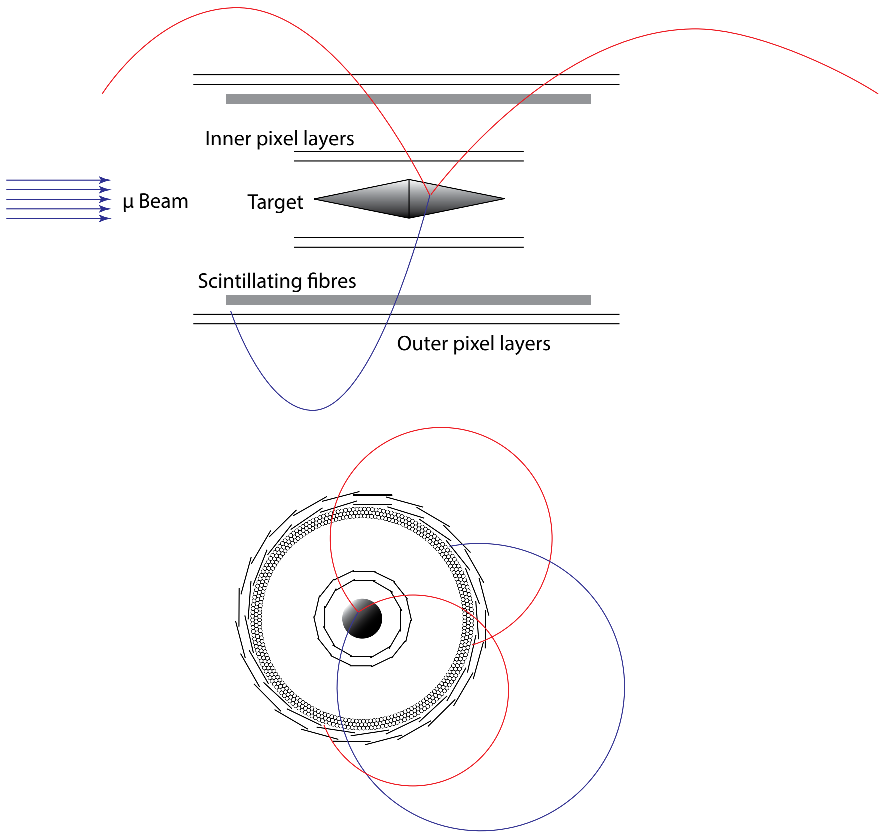
Detector Design



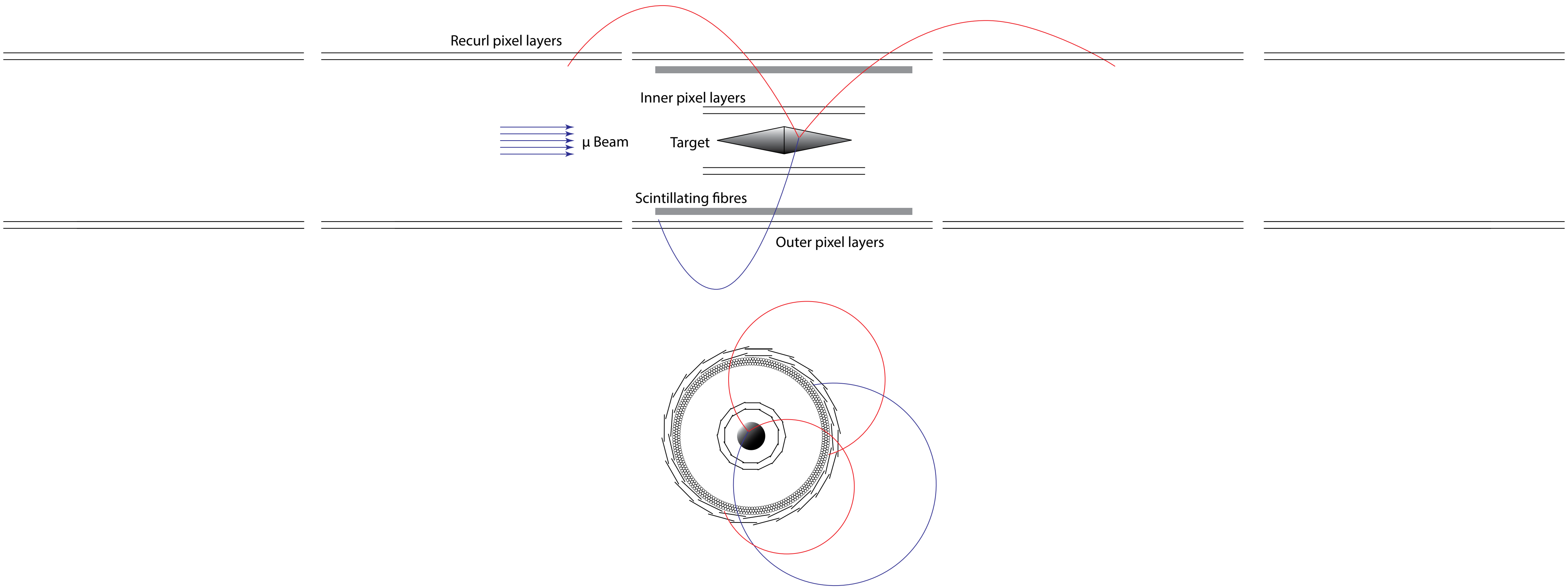
Detector Design



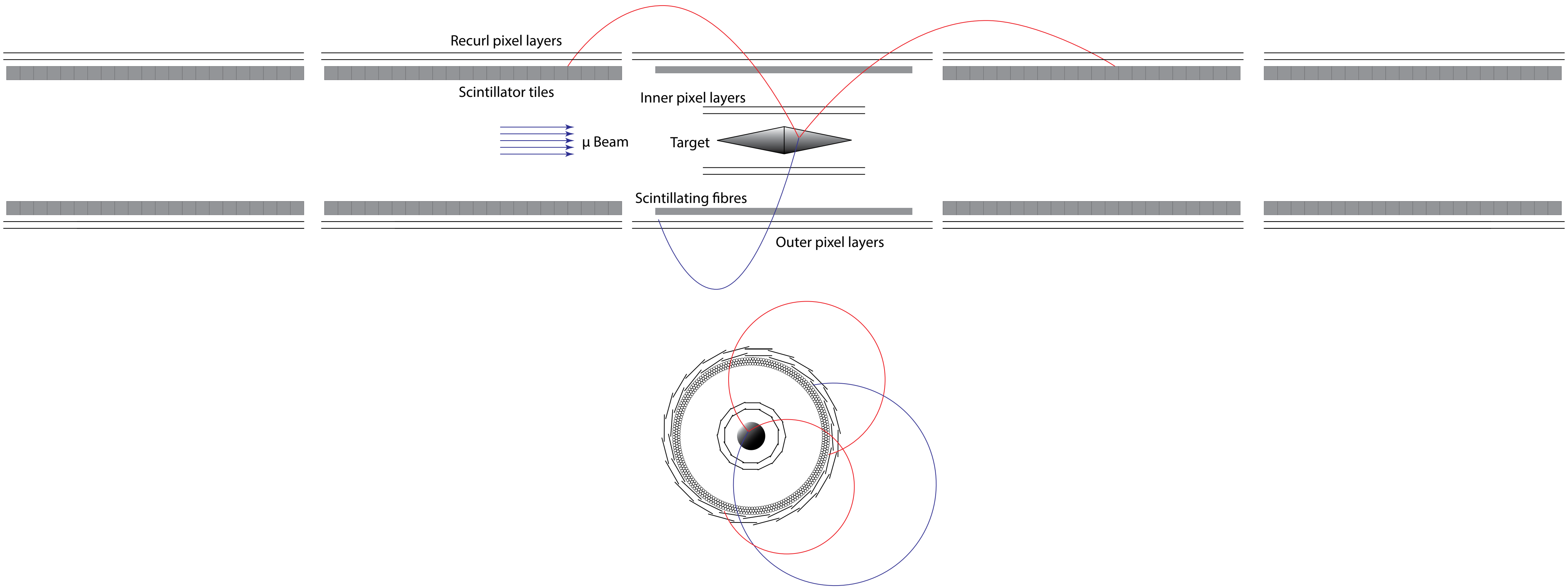
Detector Design



Detector Design

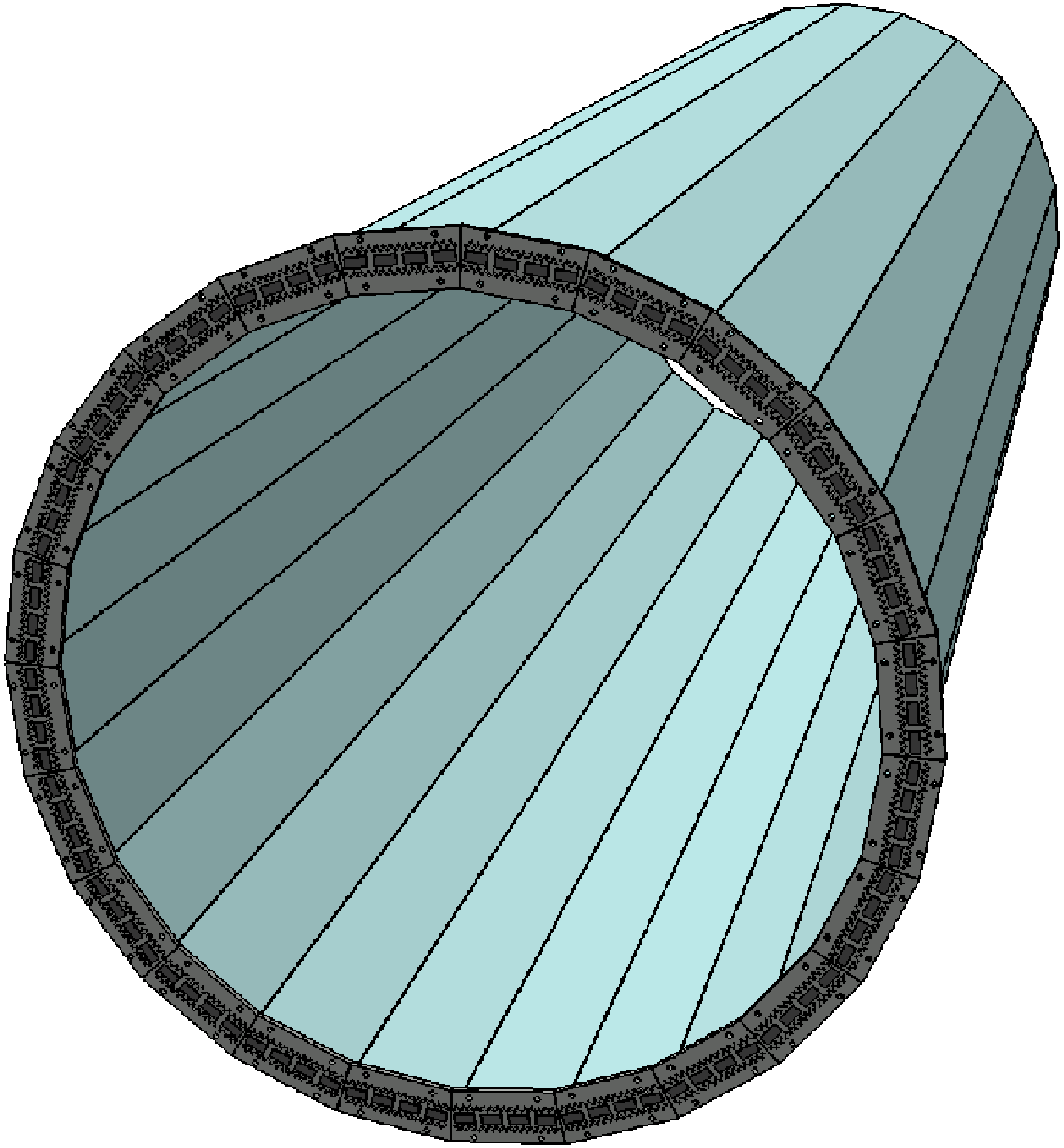


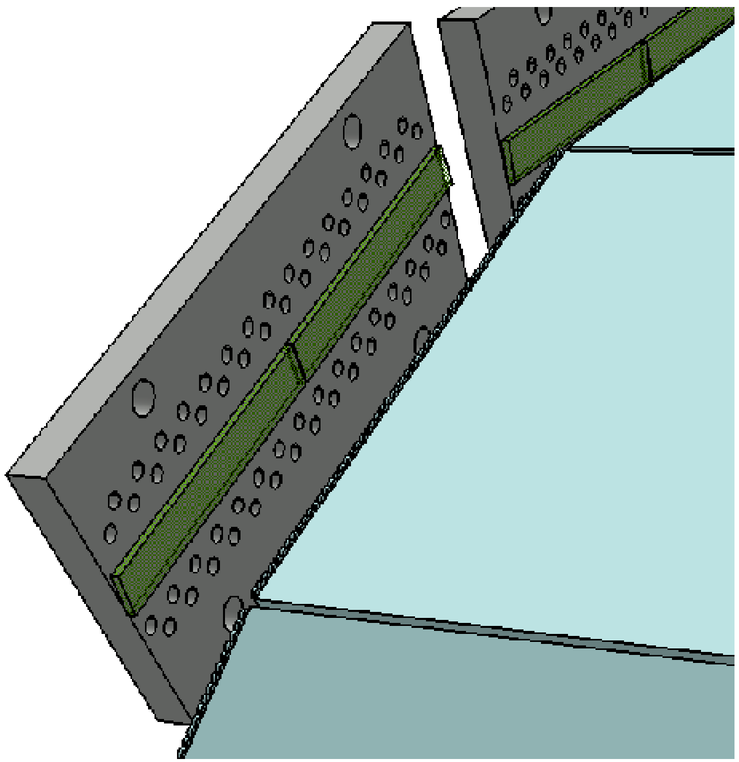
Detector Design



Timing Detector: Scintillating Fibres

- 3 layers of round 250 µm scintillating fibres or 2 layers of square 250 µm fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC from KIP Heidelberg)
- Timing resolution < 1 ns



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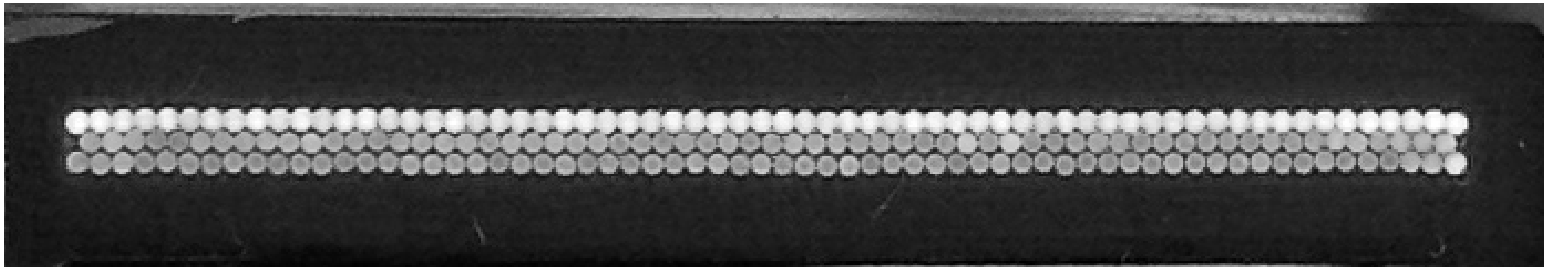
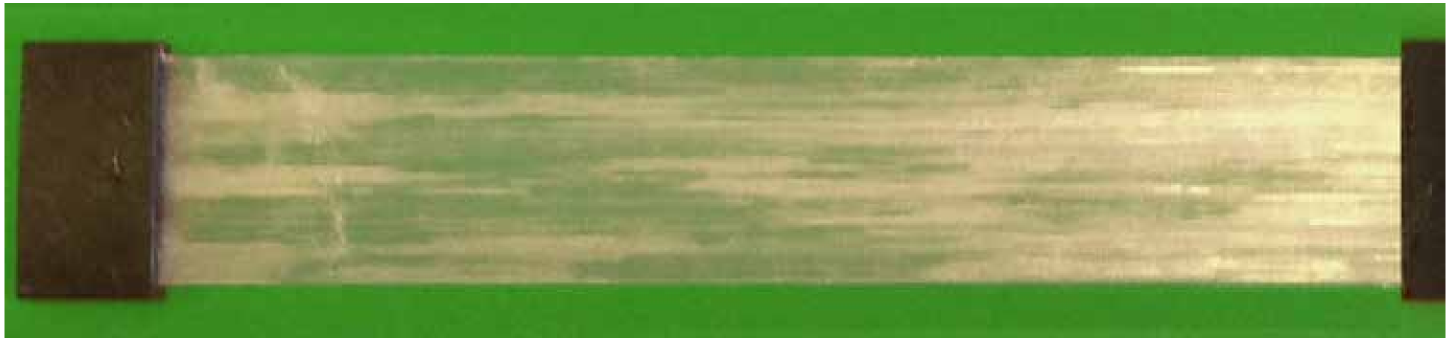
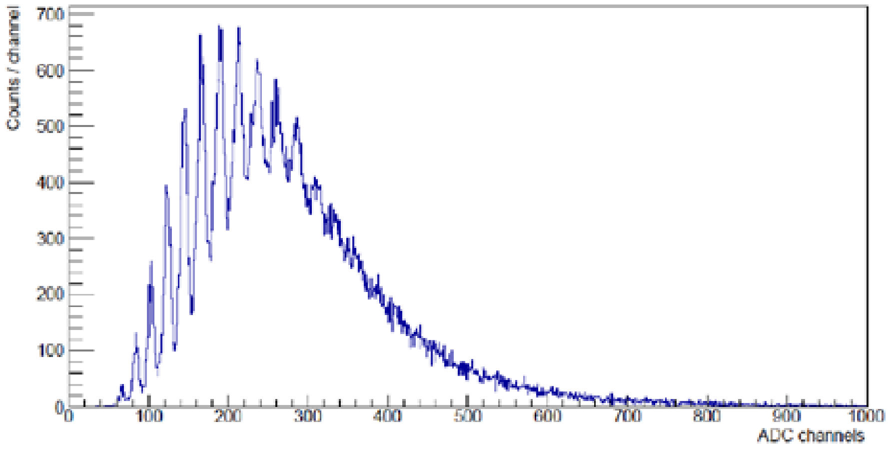
Timing Detector: Scintillating Fibres

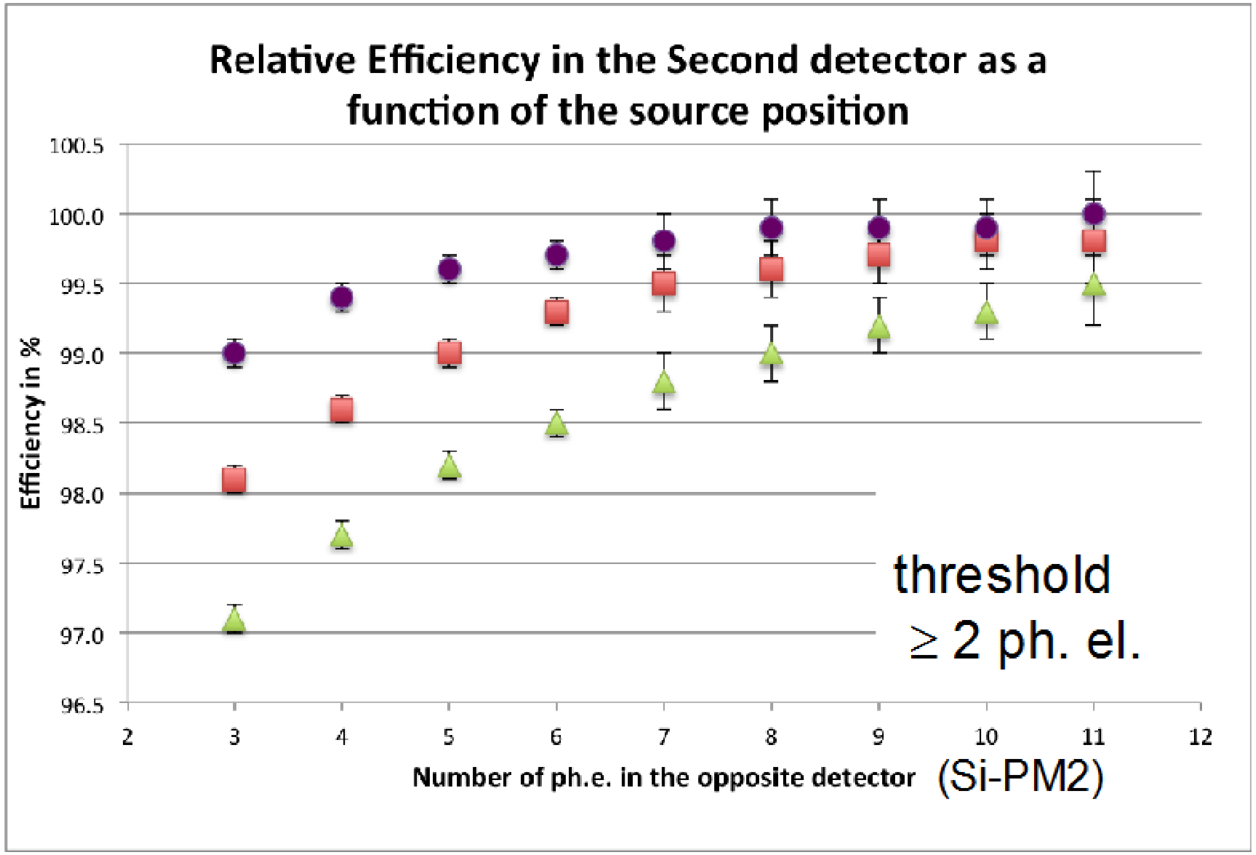
- Single fibre readout (Geneva, Zürich, ETHZ)



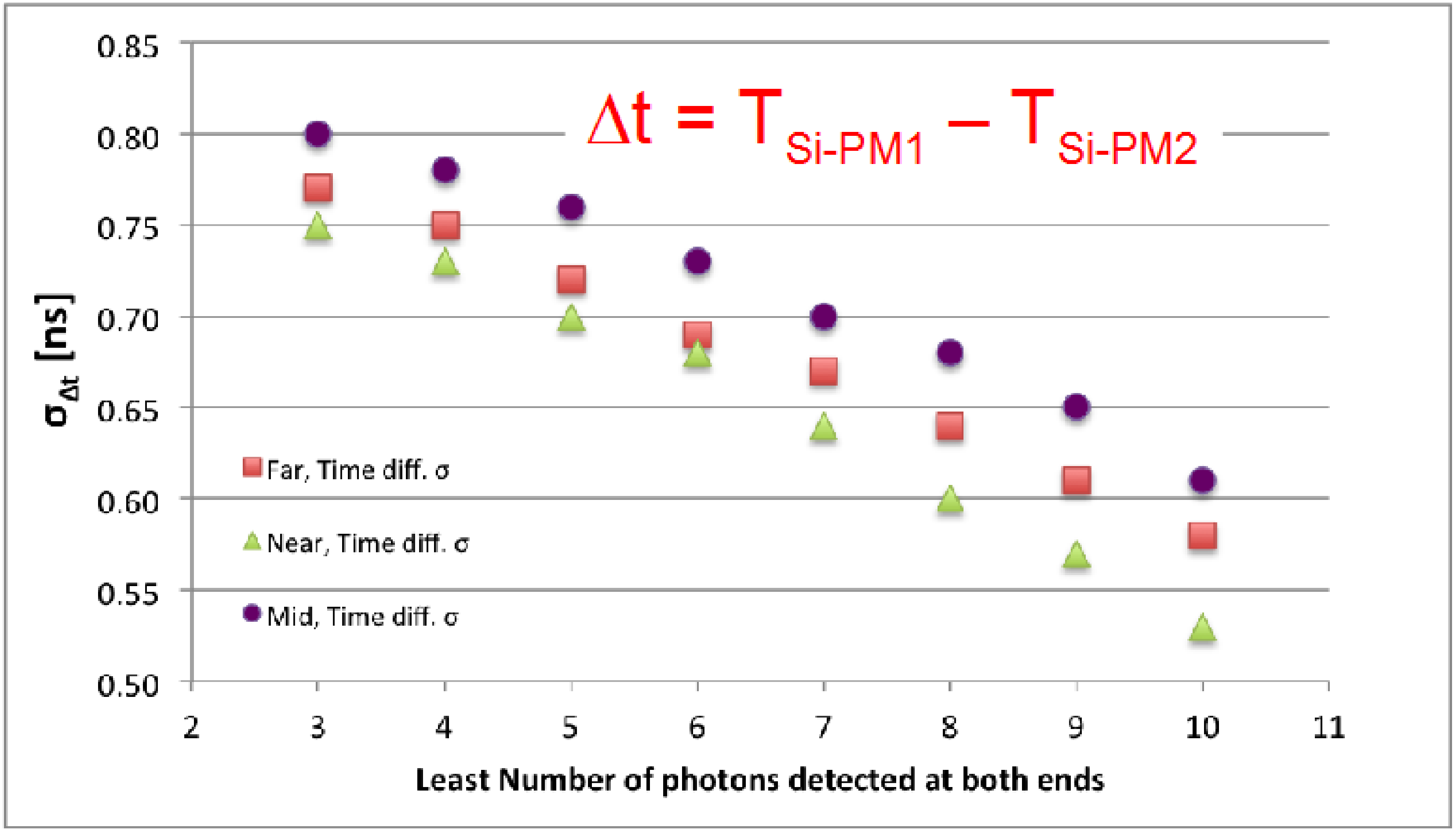


Timing Detector: Scintillating Fibres

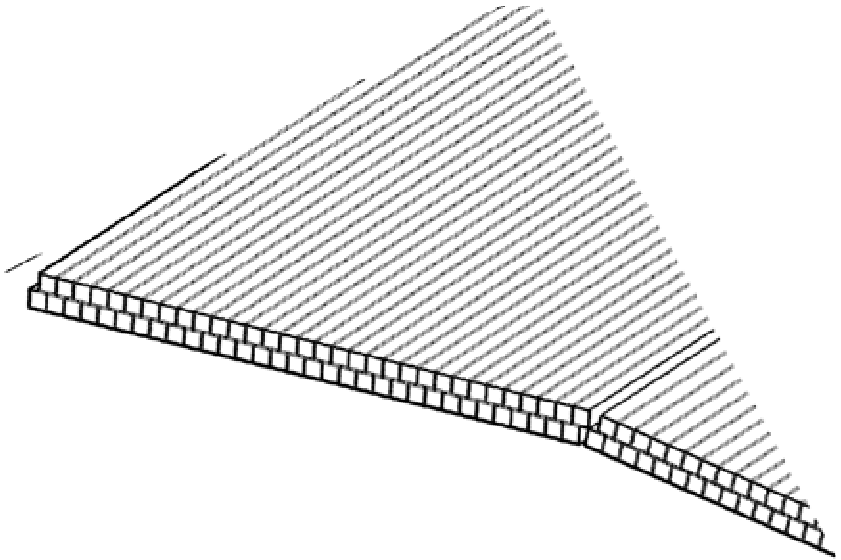




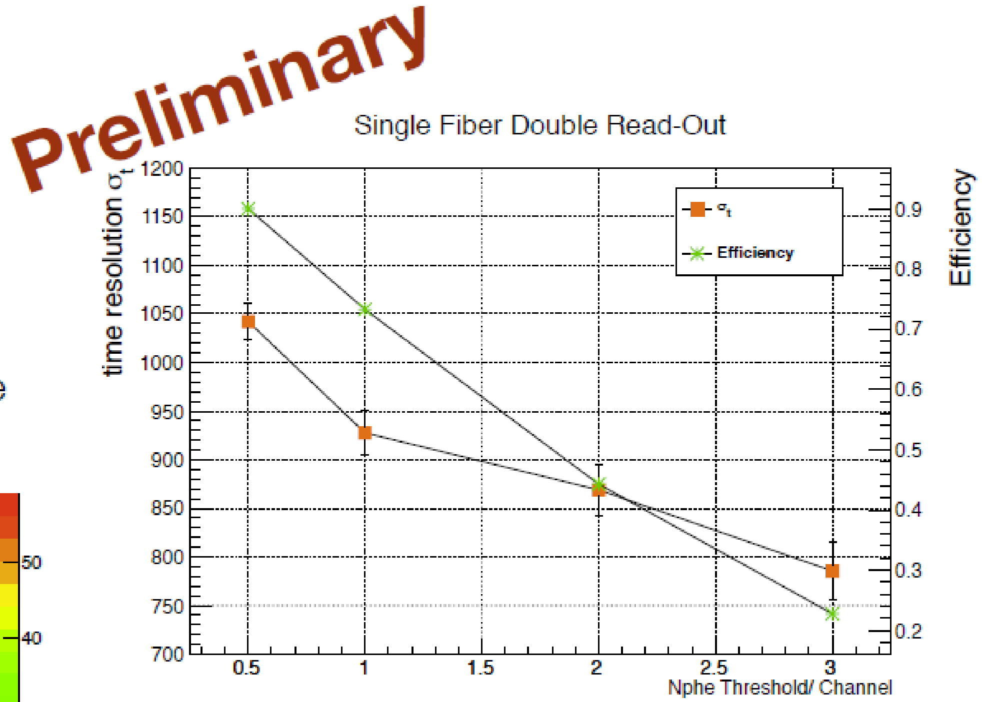
Timing Detector: Scintillating Fibres



Timing Detector: Scintillating Fibres

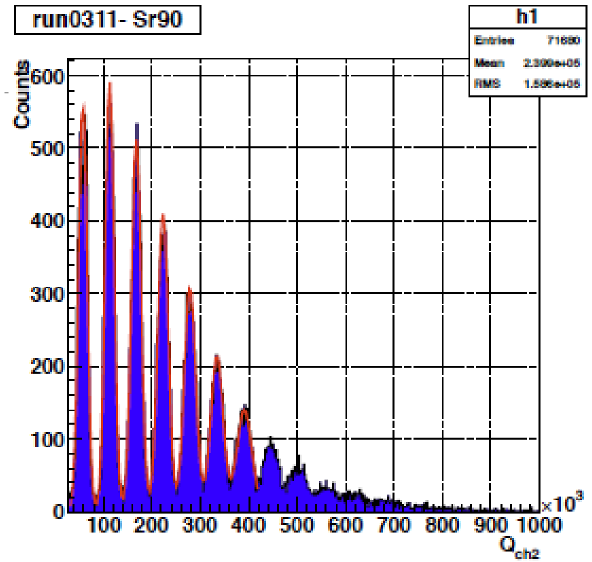


Alternative: Square fibres
(Paul Scherrer Institut)

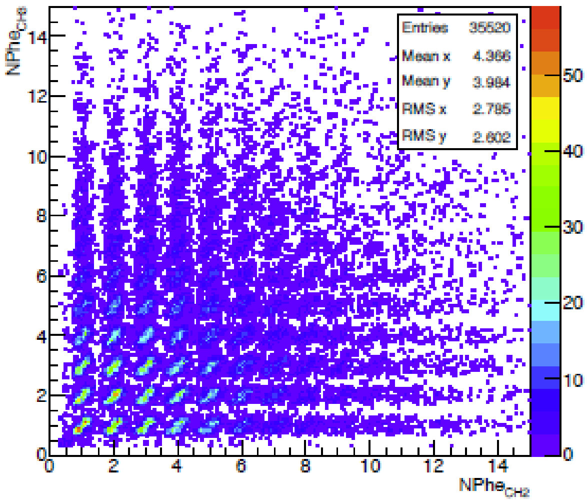


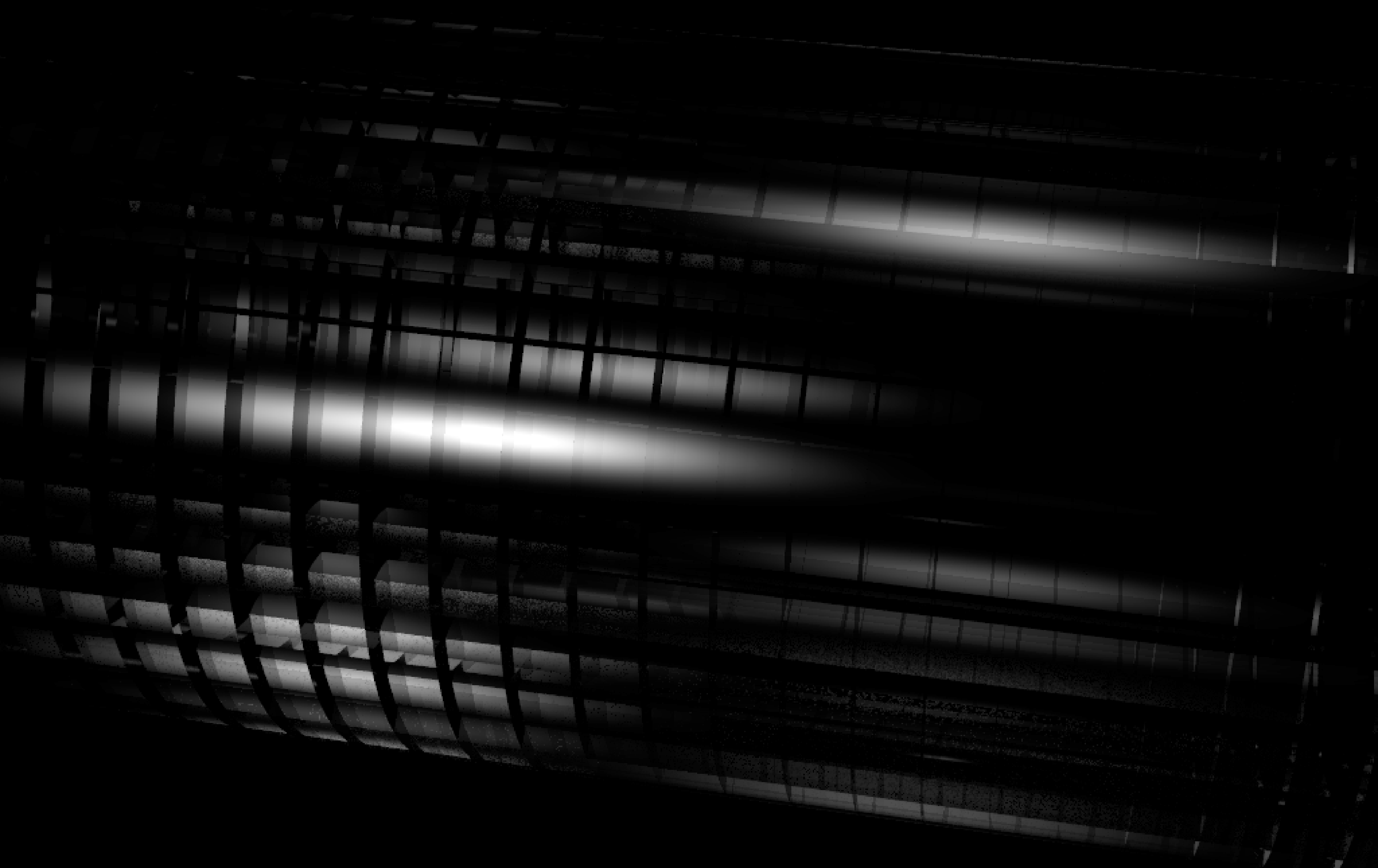
note: Nphe threshold: Channel1&Channel2 > Nphe thr

Example of charge spectrum on one of the two SiPMs

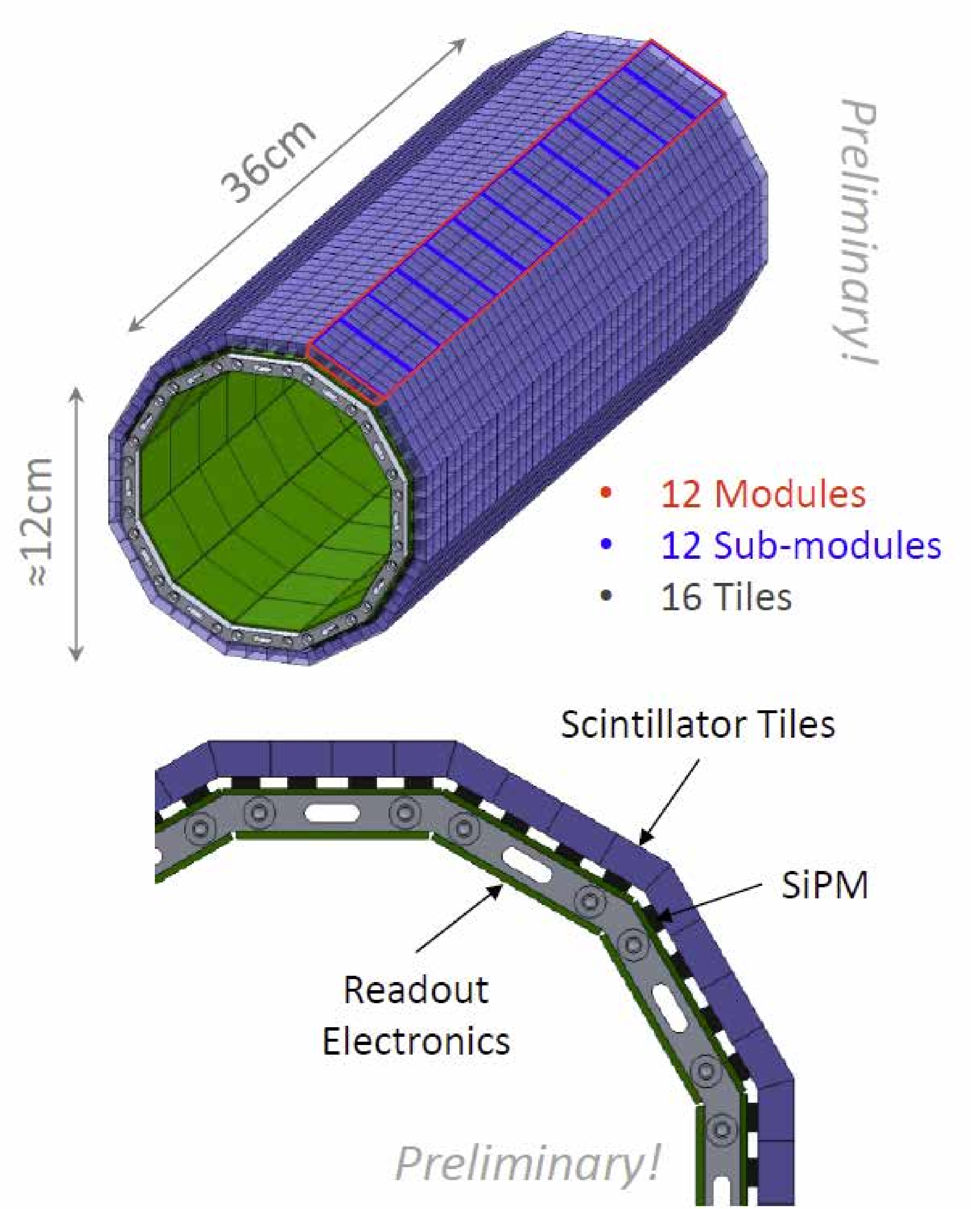


Example of charge spectrum on one SiPM vs the other one



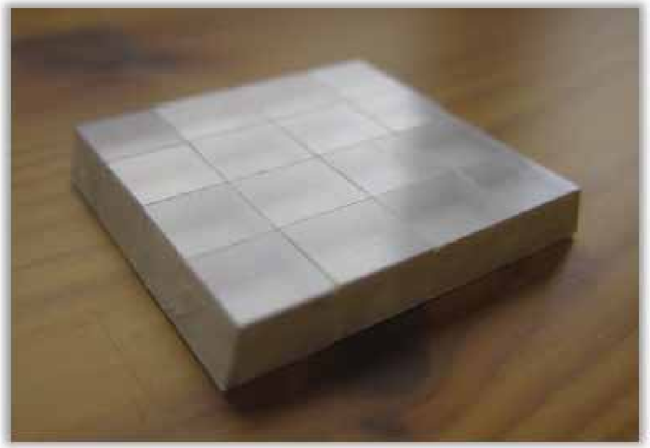


Timing Detector: Scintillating tiles



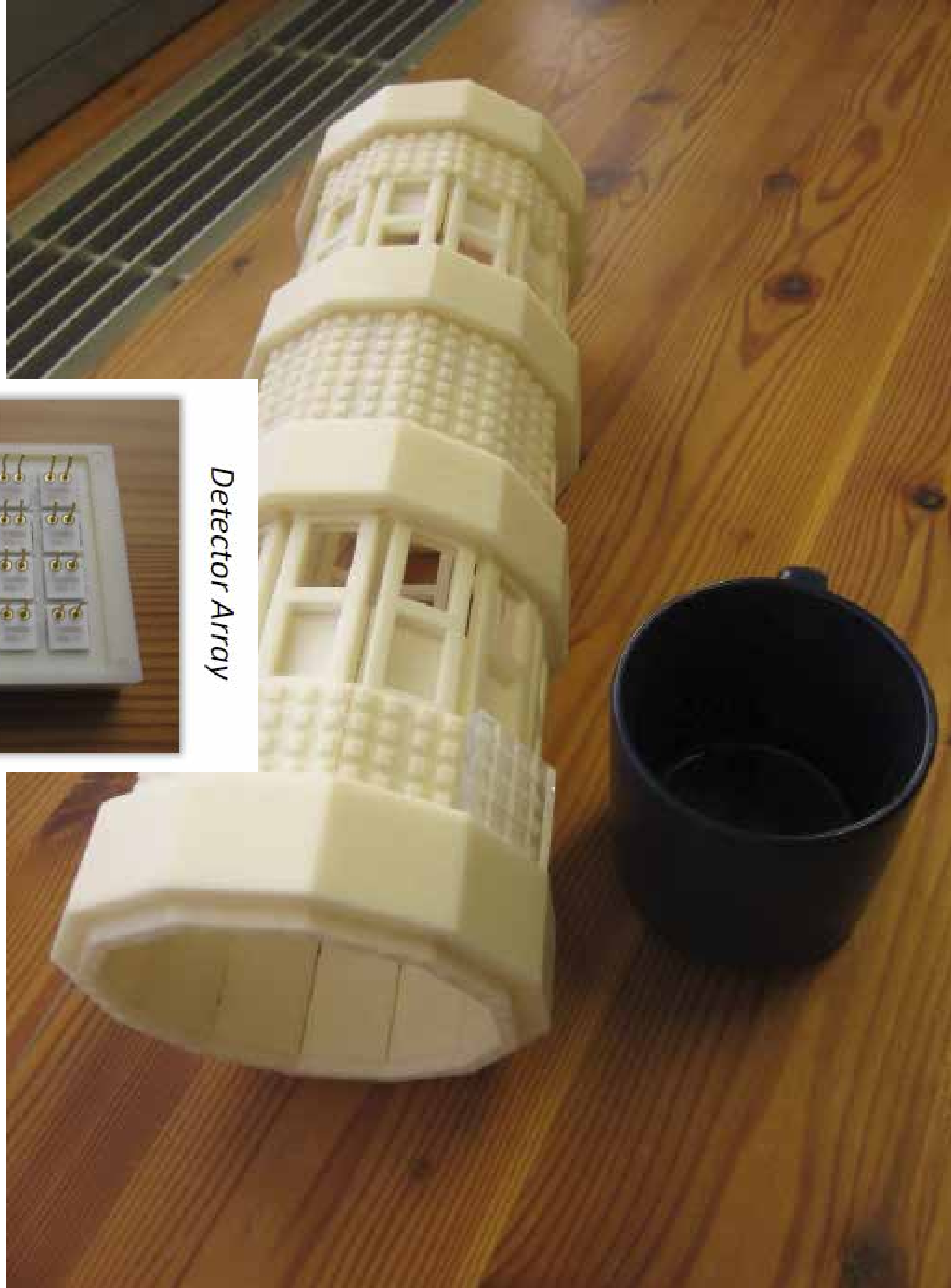
- 7.5 x 8.5 x 5.0 mm^3 scintillating tiles
- 2304 tiles per station
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC, KIP Heidleberg)
- Timing resolution $\mathcal{O}$(100 ps)

Tiles



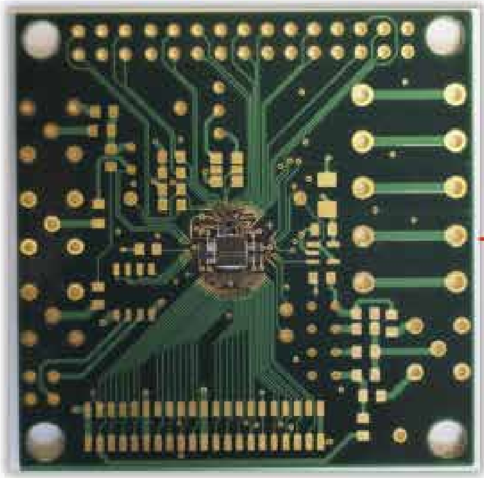
Tile Array

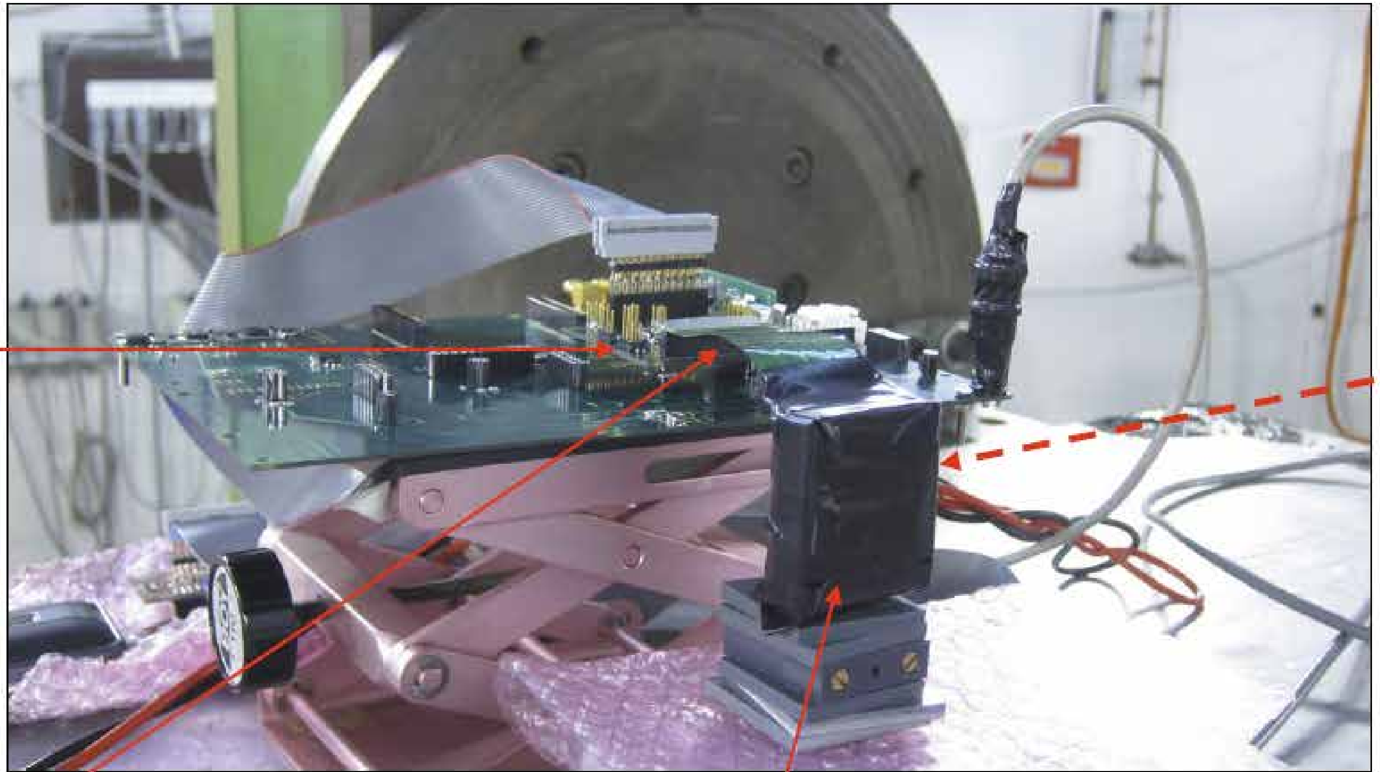
Detector Array



Tiles in the testbeam

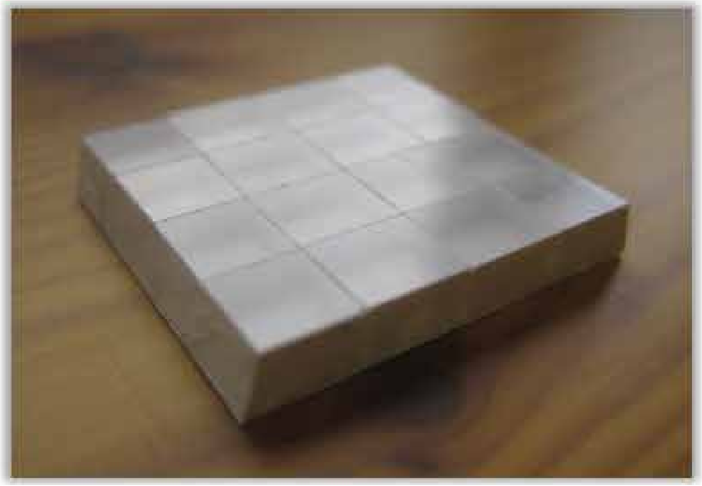
STiC Board

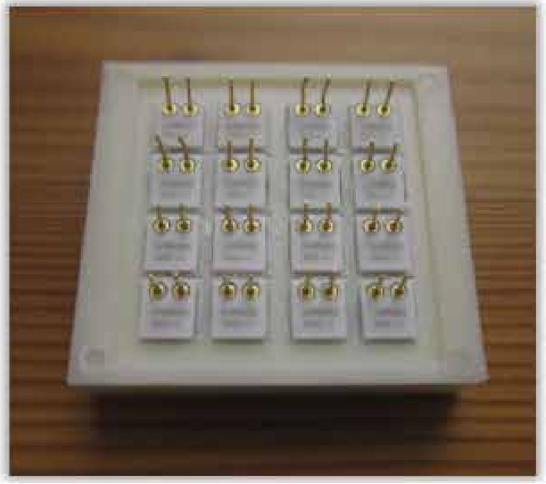




Flex Cable

Tile Array

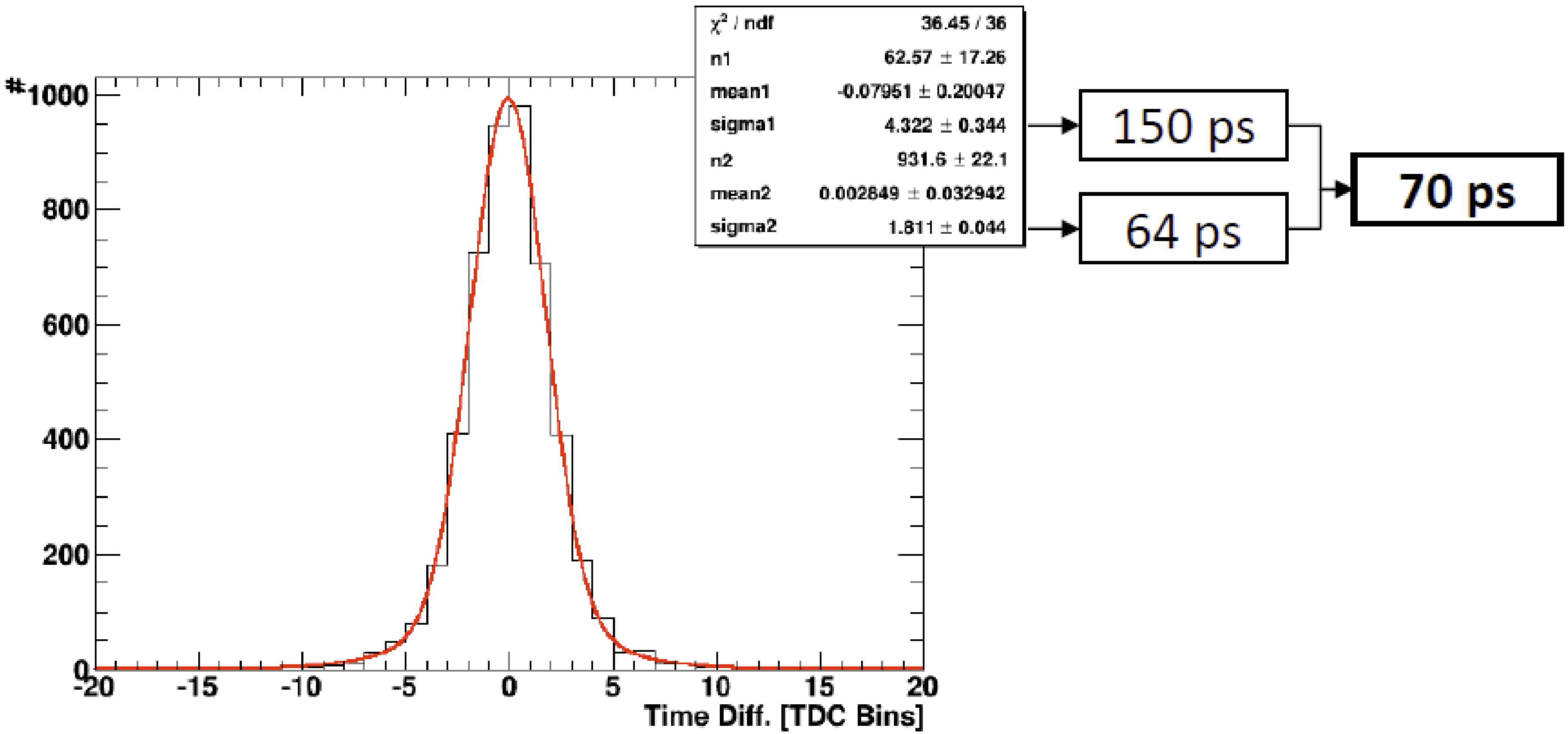


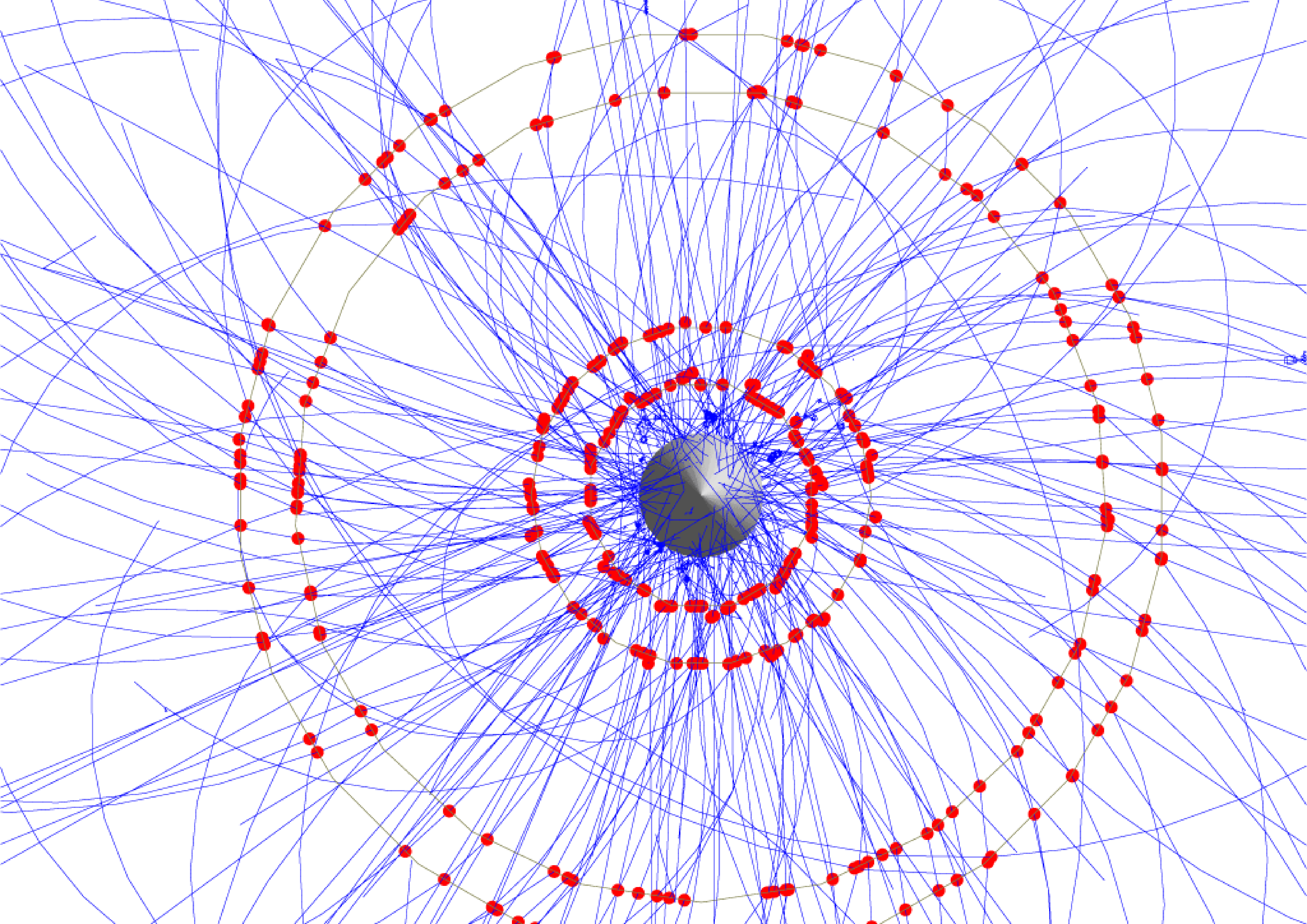


Detector Array

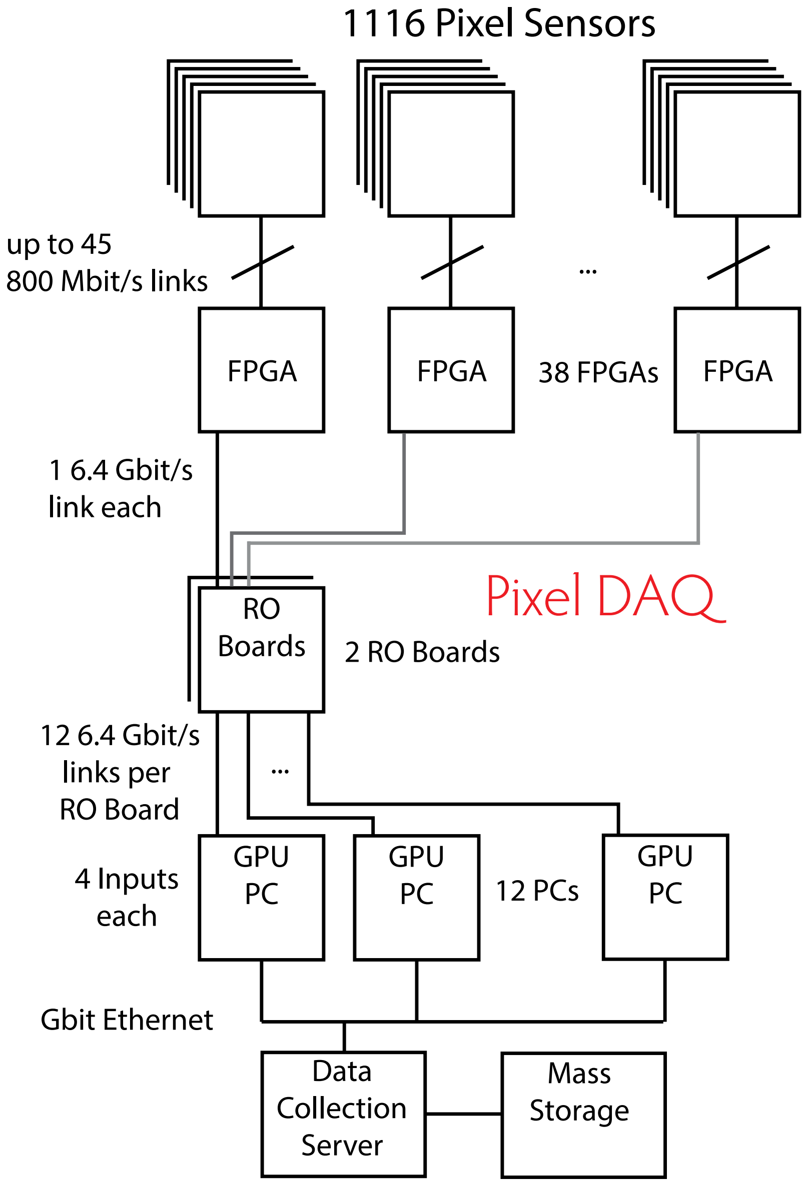
Tile results

- 70 ps time resolution
- Dominated by tile geometry: 40 ps possible with smaller tiles matched to SiPMs
- Efficiency > 99.5%



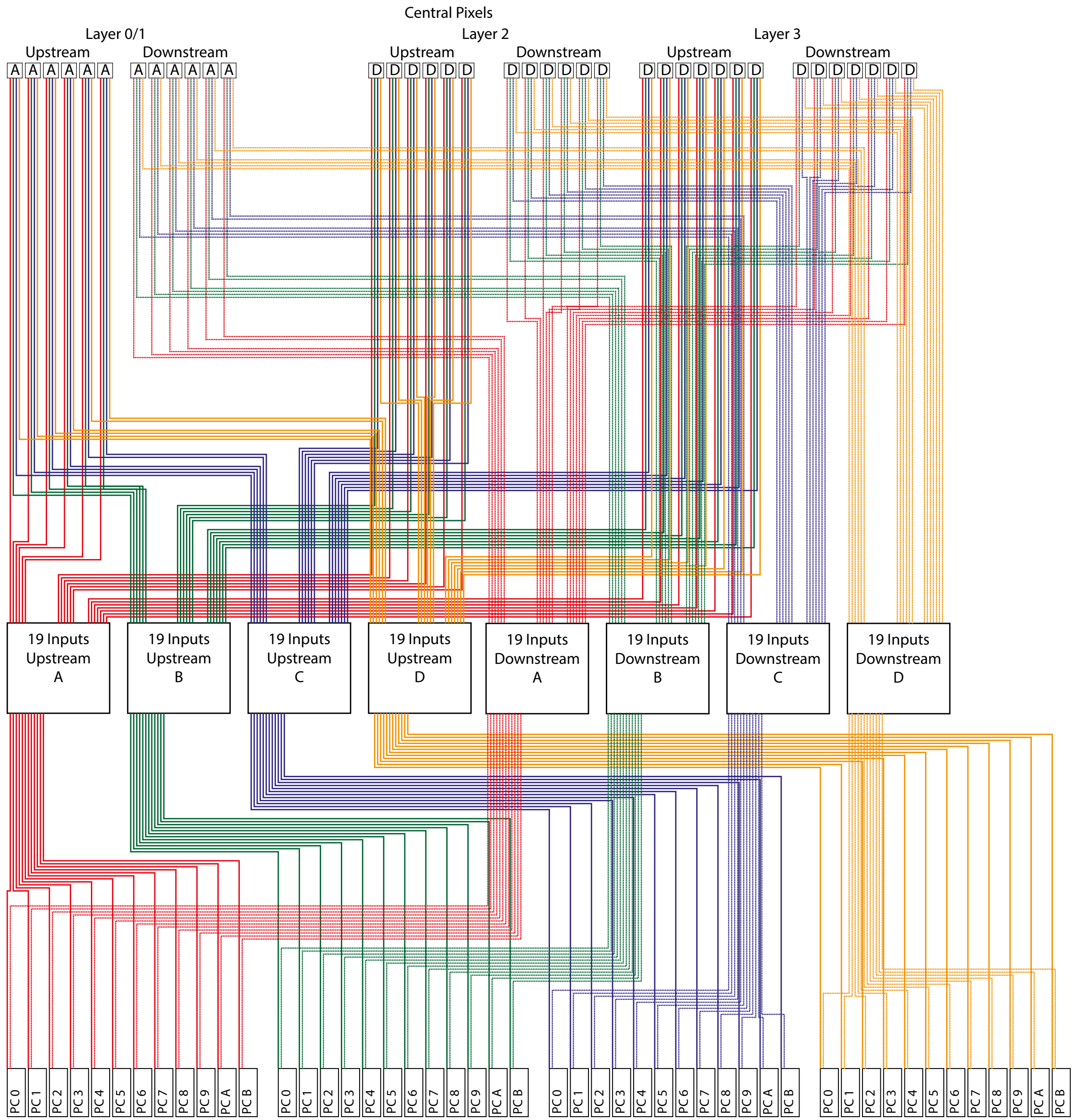


Data Acquisition



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

Data Acquisition

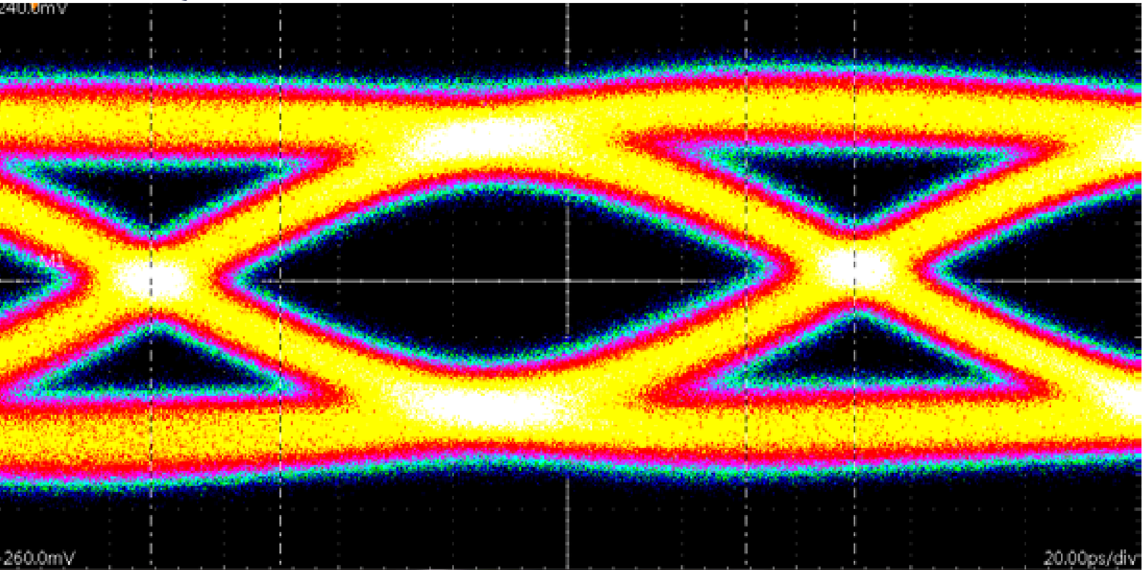


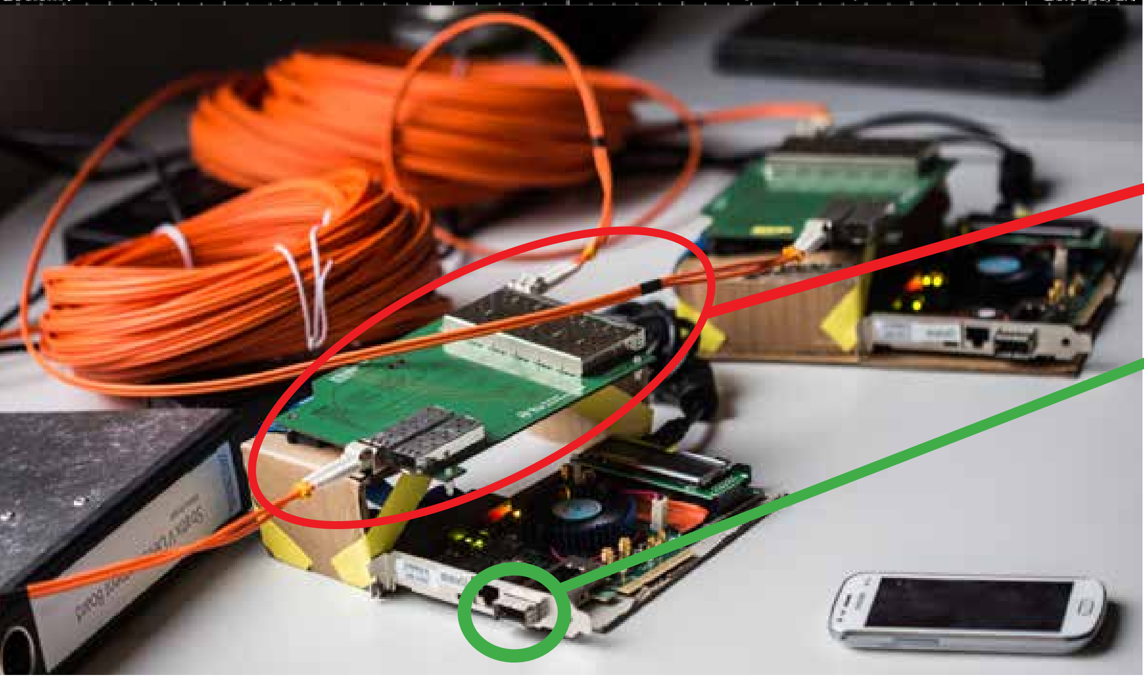
Online filter farm

Online software filter farm

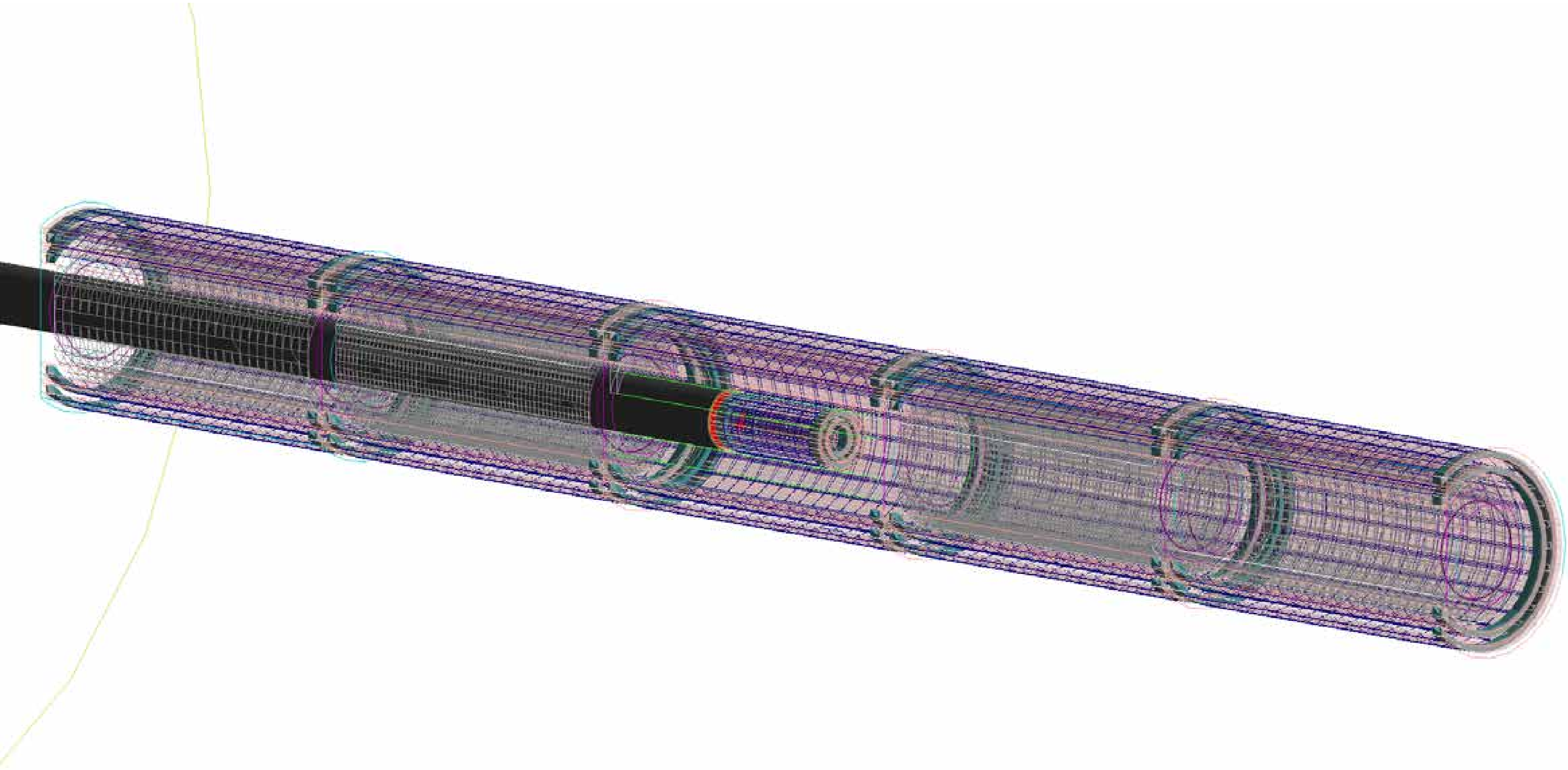
- Continuous front-end readout (no trigger)
- ~ 1 Tbit/s
- PCs with FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

Optical links



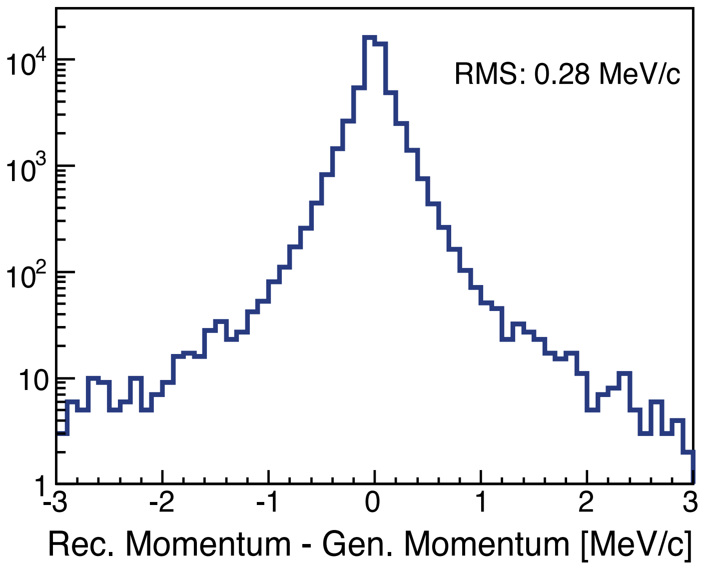


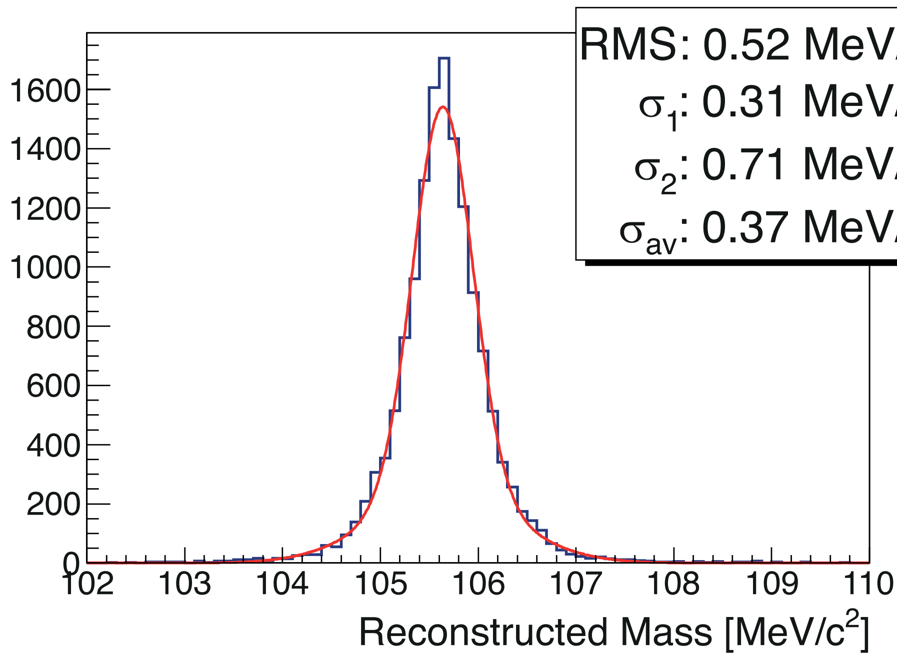
- Bit error rate < 10^{-16} at 6.4 Gbit/s (Mezzanine card)
- Tests at 8 Gbit/s ongoing (Mezzanine card)
- Bit error rate < 10^{-16} at 4 x 11.3 Gbit/s (On-board QSFP transceiver)
- More than sufficient for phase Ia and Ib (Mezzanine cards)
- More than sufficient for phase 2 (QSFP)
- Also: 3.2 Gbyte/s DMA from FPGA to PC



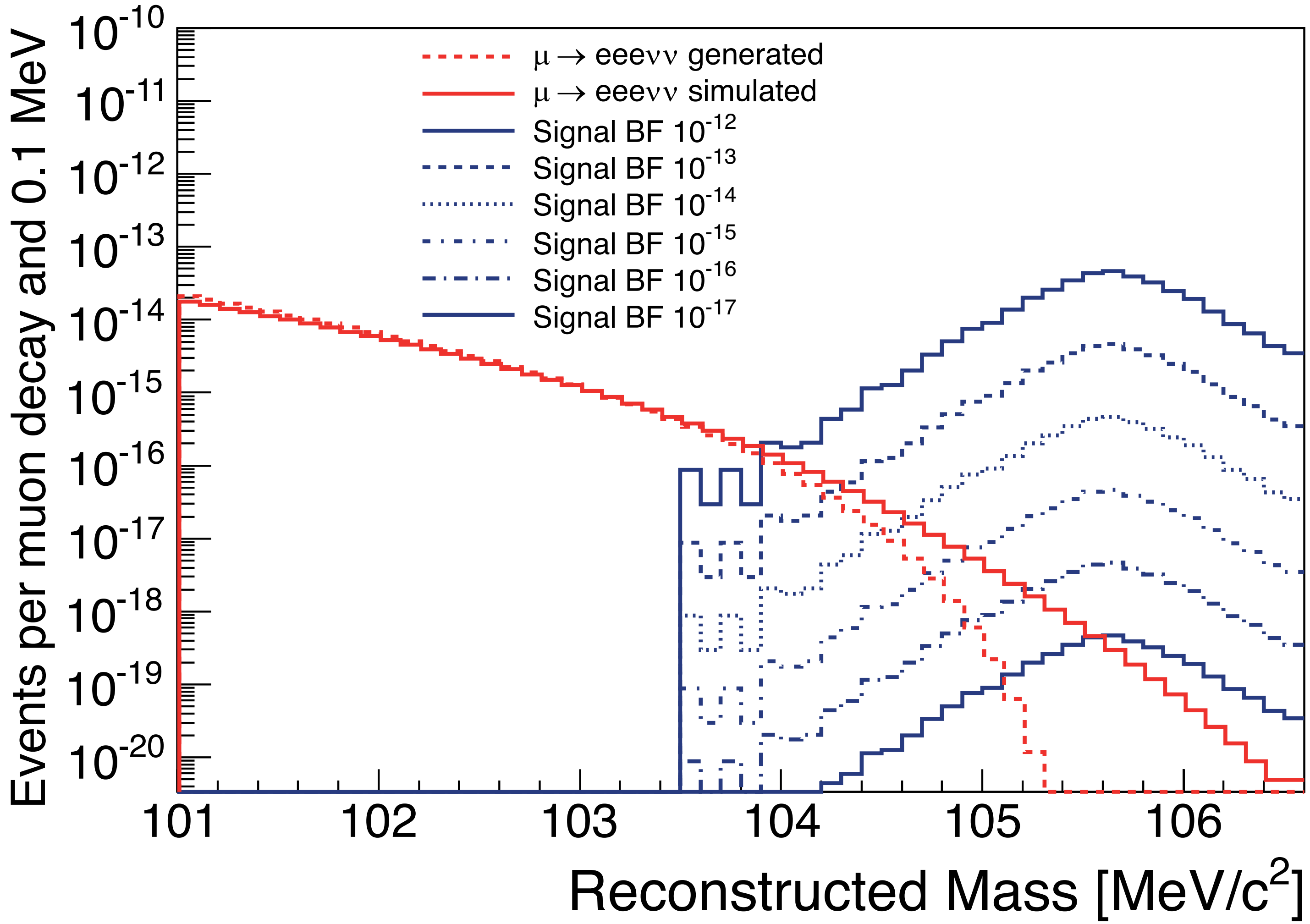
Simulated Performance

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

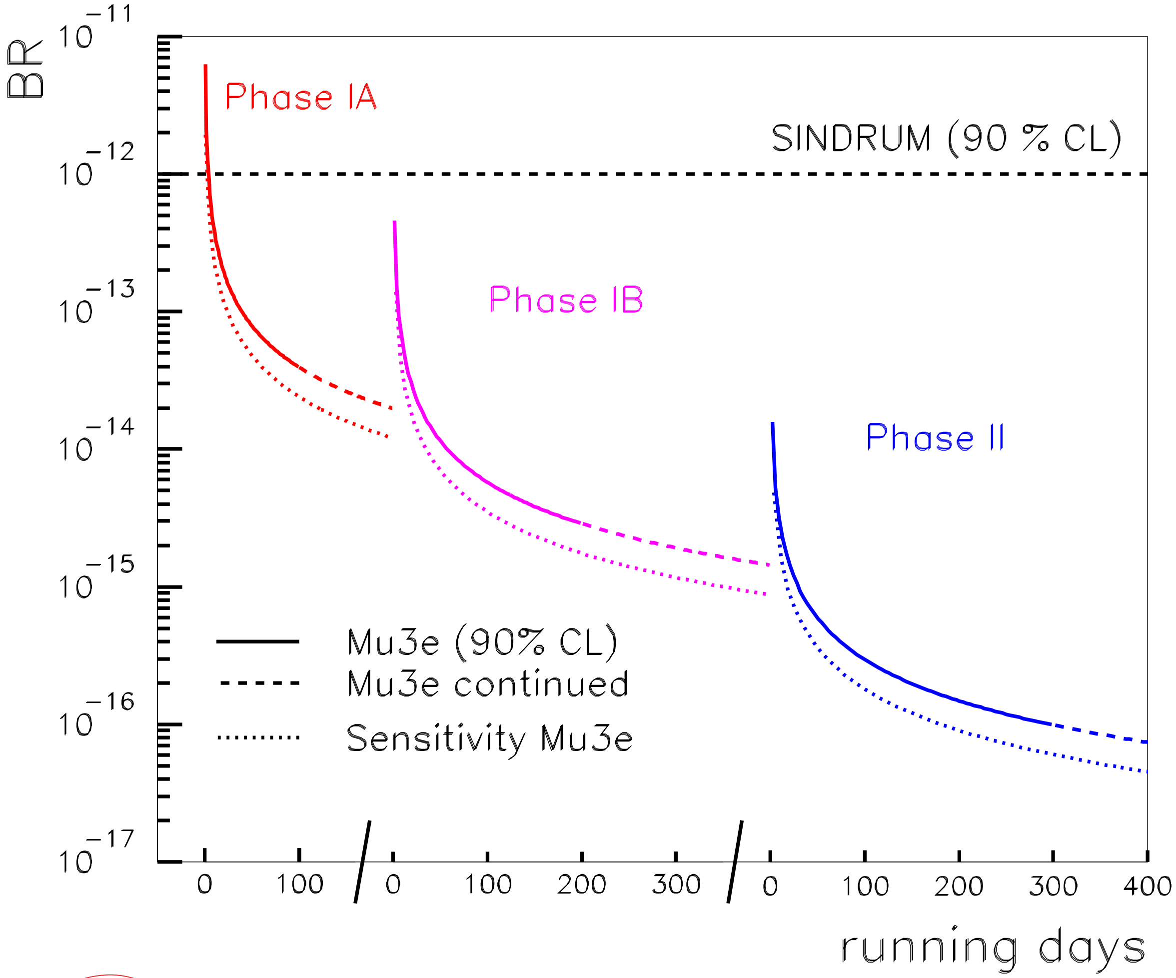


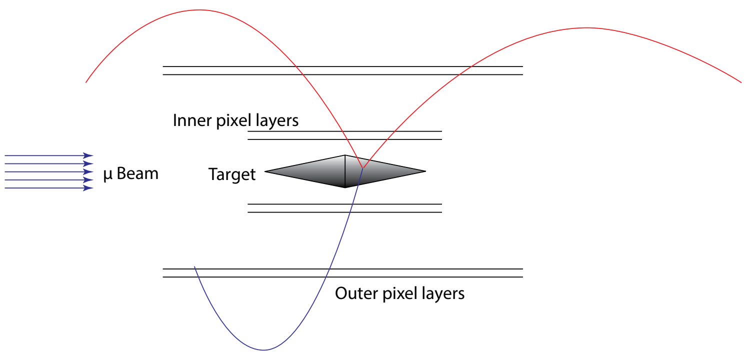


Simulated Performance



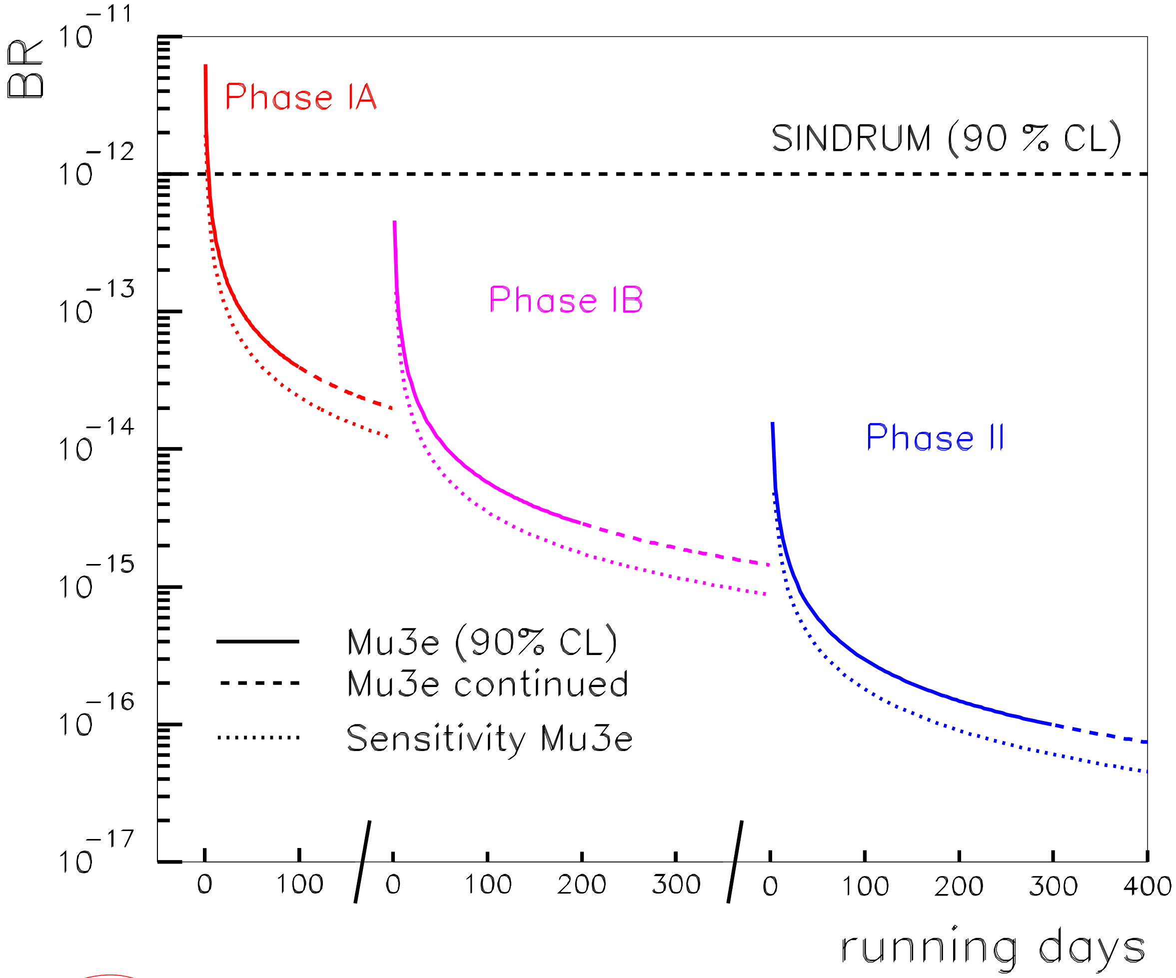
Sensitivity

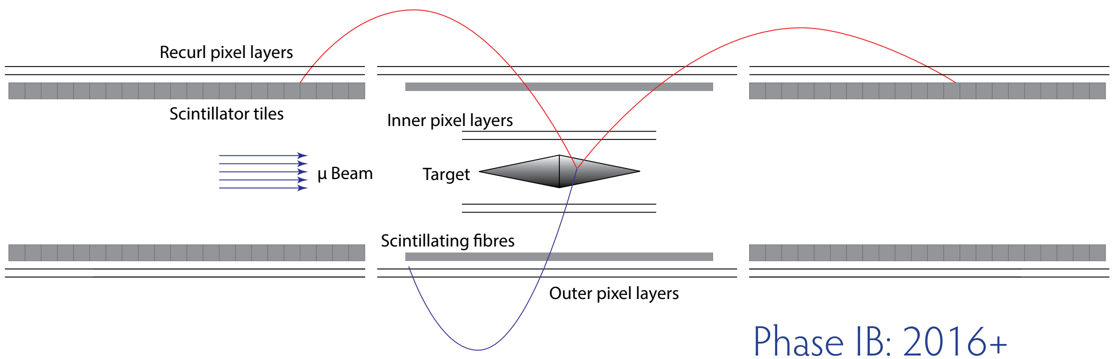




Phase IA: Starting 2015

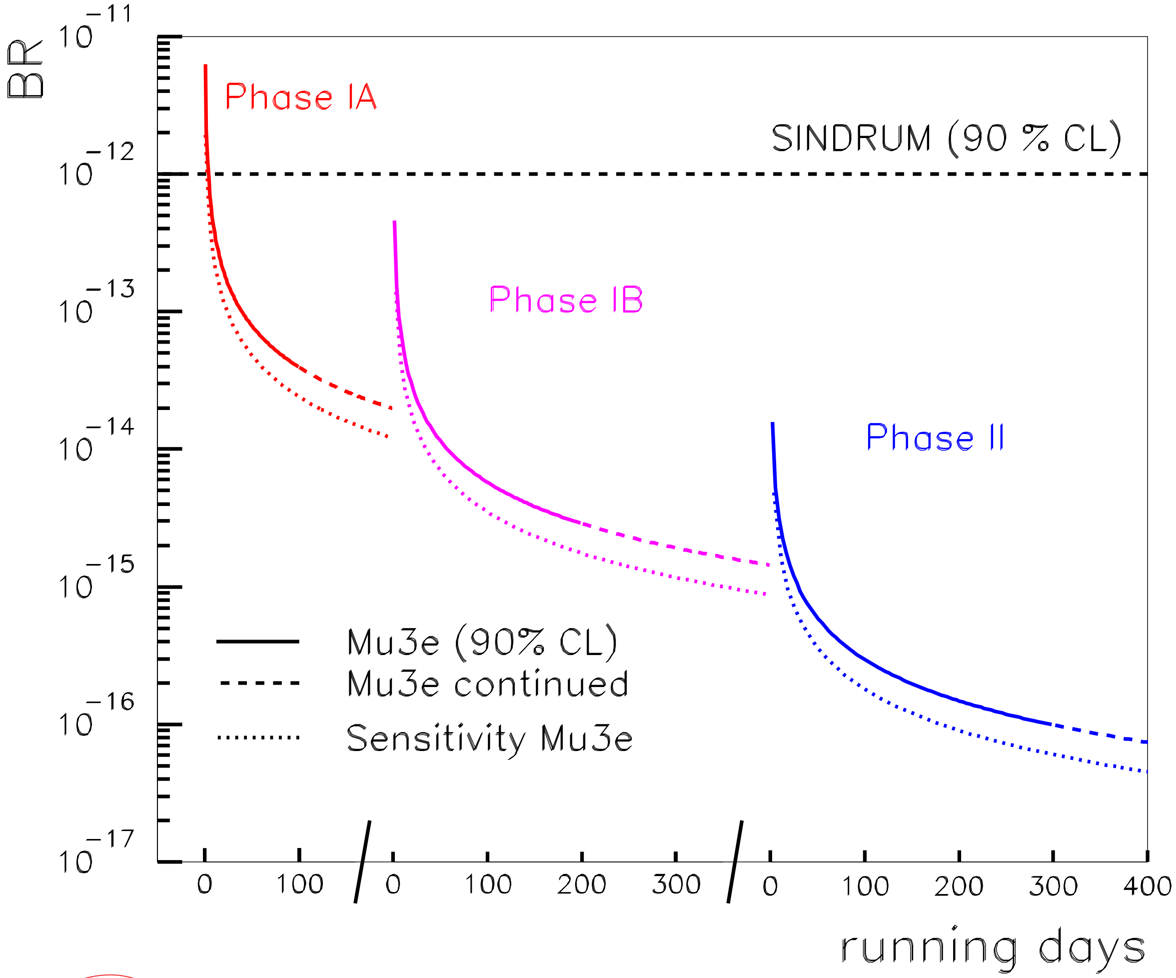
Sensitivity

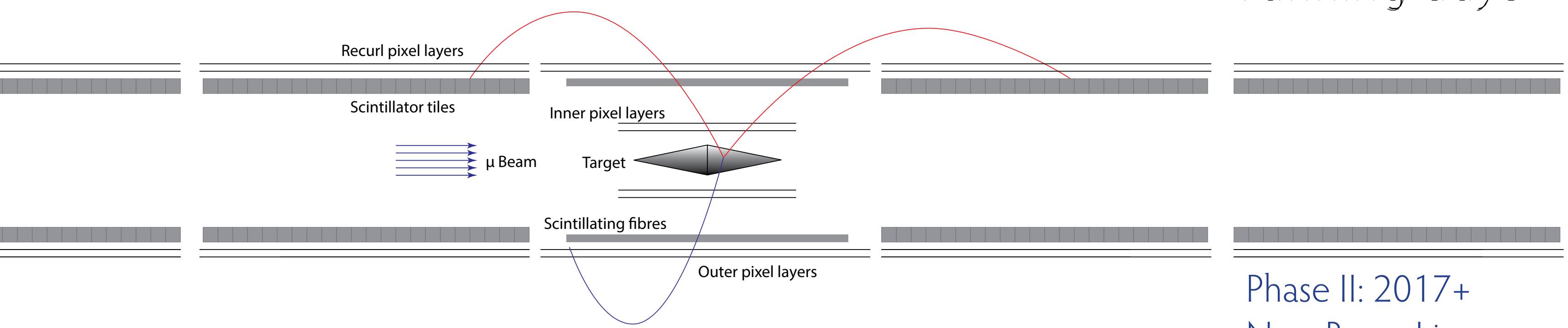




Phase IB: 2016+

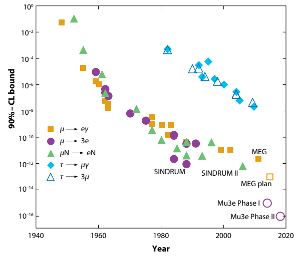
Sensitivity



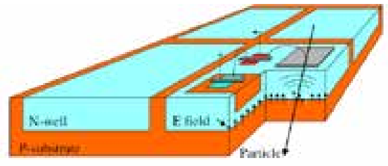


Phase II: 2017+
New Beam Line

Conclusion



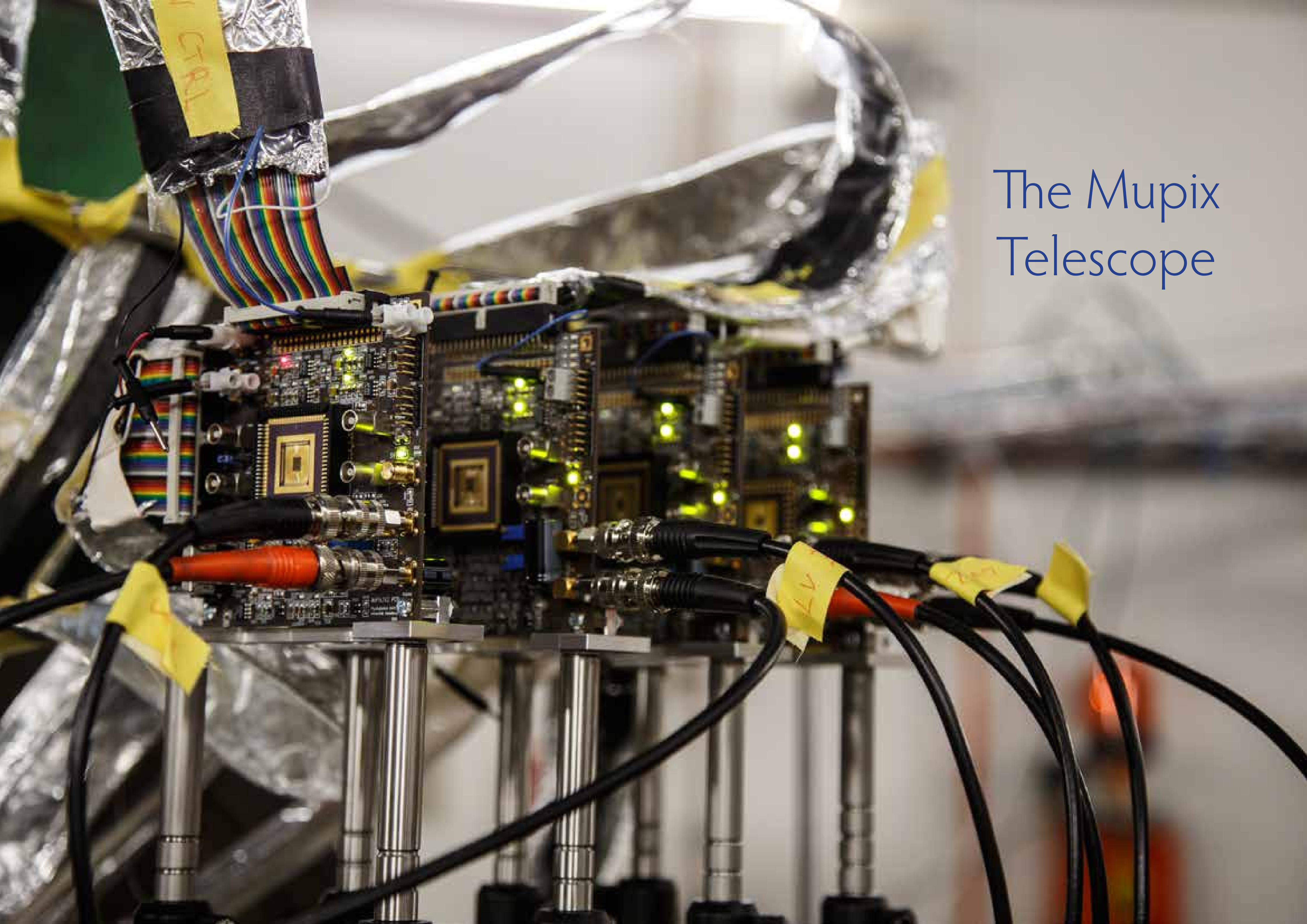
- Mu3e aims for $\mu \rightarrow eee$ at the 10^{-16} level
- First large scale use of HV-MAPS



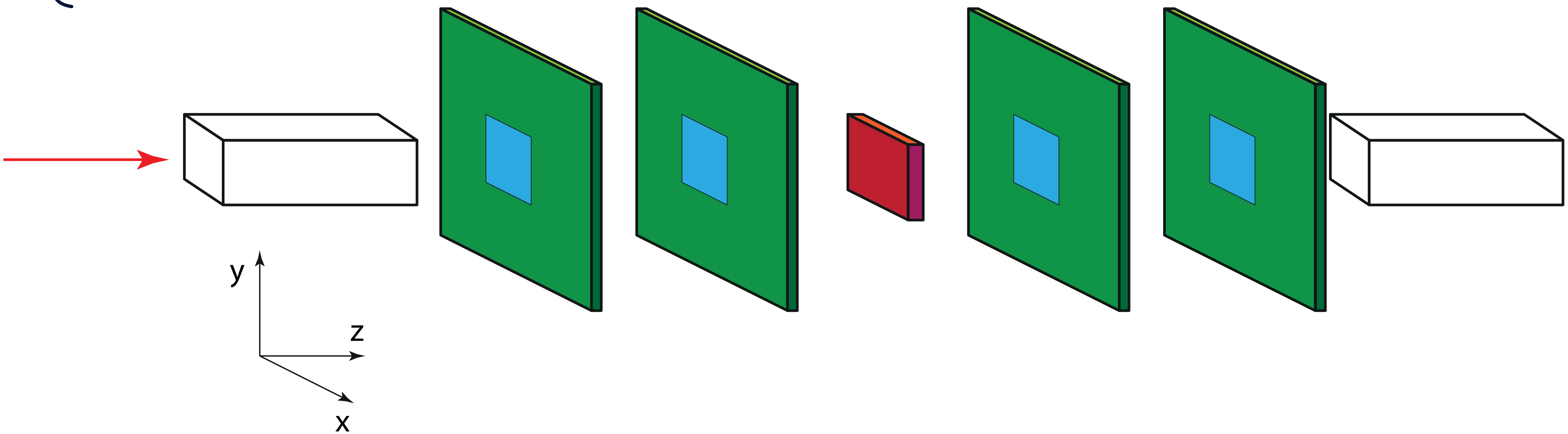
- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs

- Start data taking in 2016
- 2 billion muons/s from HIMB after 2017

The Mupix Telescope



The MuPix Telescope



Idea: Use Mu3e components to build a beam telescope

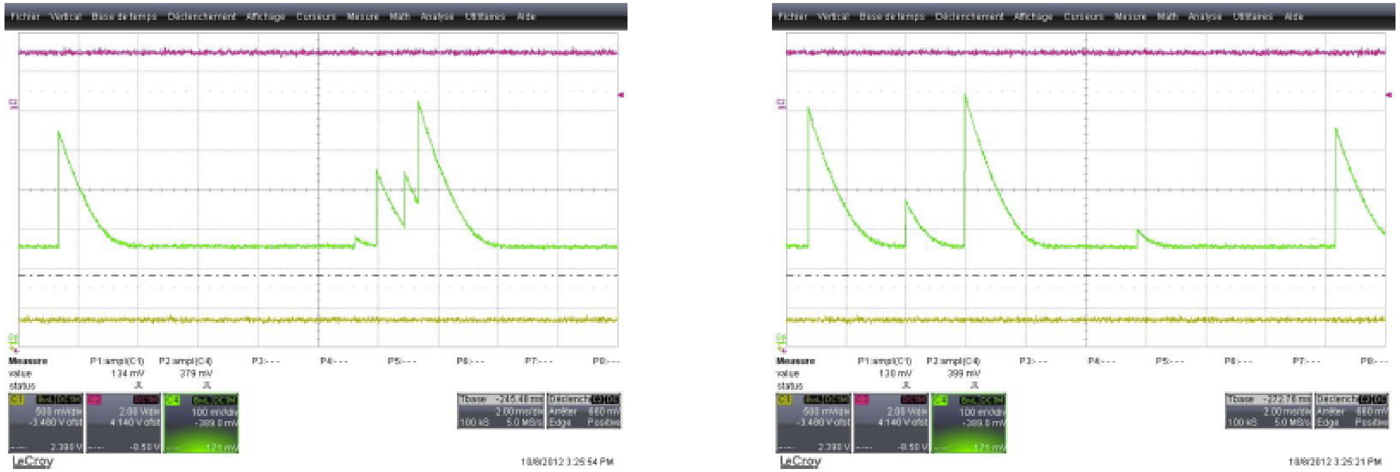
- Scintillating tiles for trigger and timing reference
- Thinned MuPix 4 (or 6) chips on thinned PCBs
- Fast readout, online tracking

- $\mathcal{O}$(200 µm) pointing resolution for 50 MeV/c electrons
- Few MHz track rates
- Ideal for PSI beam tests
- First tests this week very promising

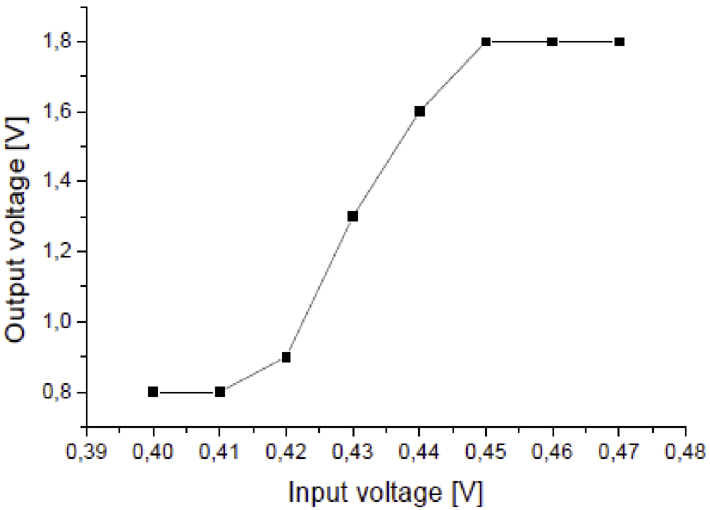
Backup Material

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

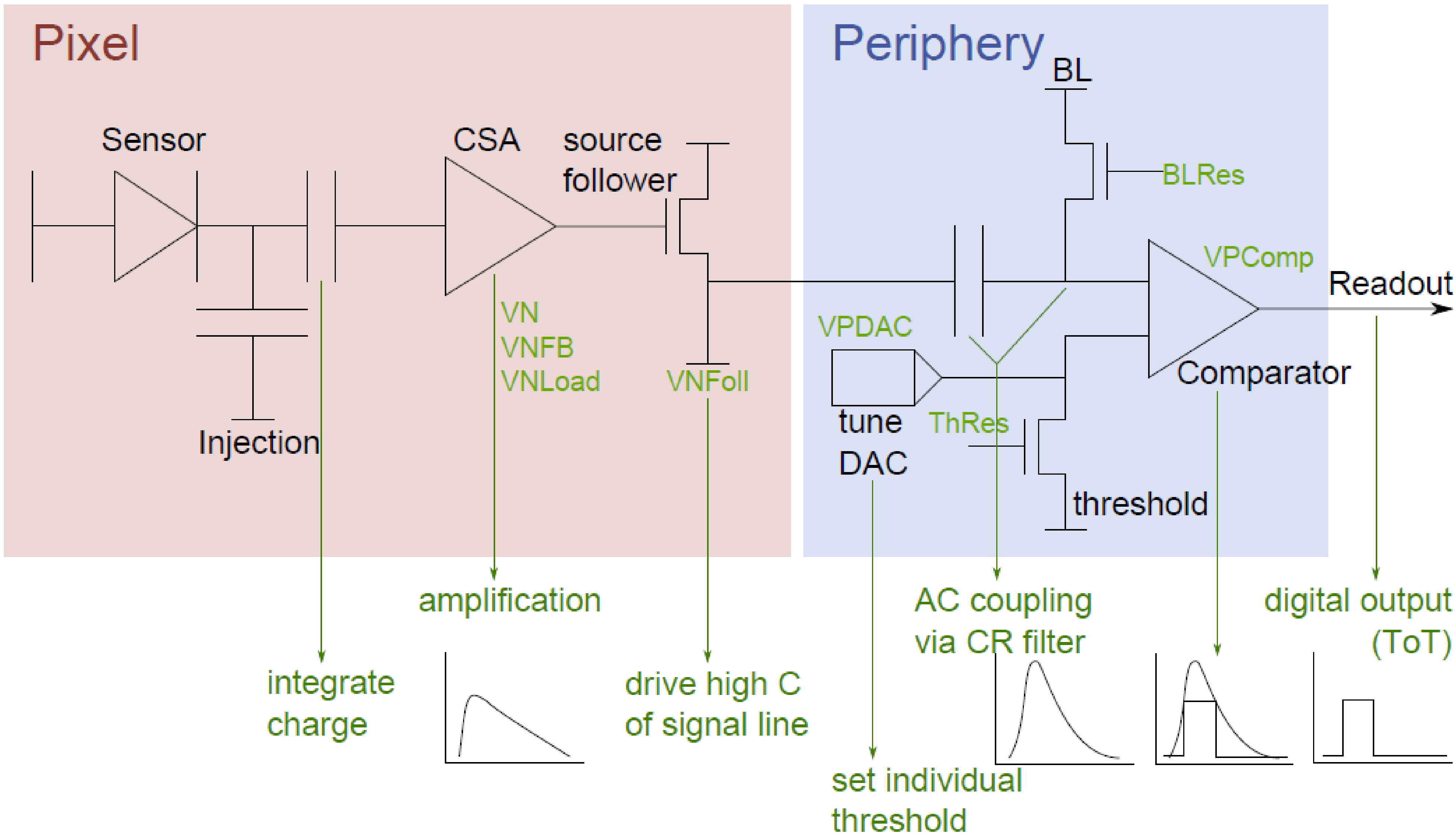


Comparator characteristics.

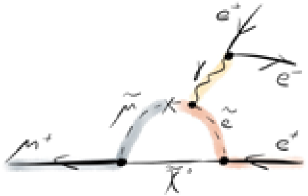
- Irradiation at PS
- After 380 MRad (8×10^{15} n_{eq}/cm^2)
- Chip still working

(Courtesy Ivan Perić, RESMDD 2012)

MUPIX electronics



A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

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

Four-fermion terms e.g. Z'

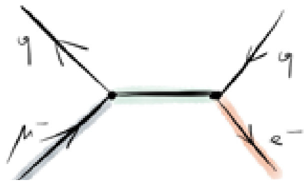
$$+ g_1 (\bar{\mu}_R e_L)(\bar{e}_R e_L) \qquad + g_2 (\bar{\mu}_L e_R)(\bar{e}_L e_R)$$

scalar

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

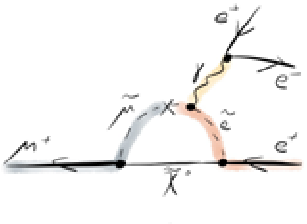
$$+ g_5 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_L \gamma^\mu e_L) \qquad + g_6 (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_R \gamma^\mu e_R) \;\; + \mathrm{H.\,C.}\,)$$

vector

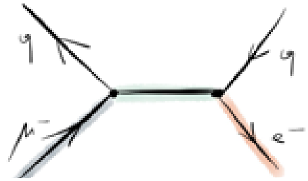


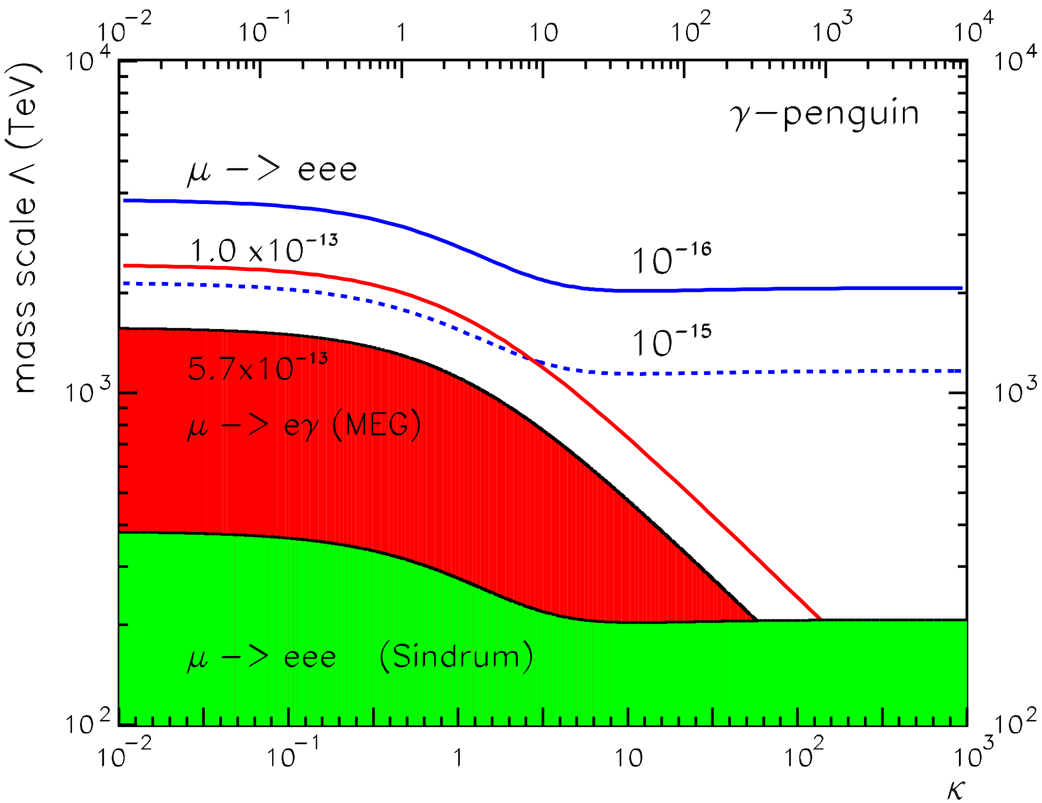
(Y. Kuno, Y. Okada,
Rev.Mod.Phys. 73 (2001) 151)

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



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

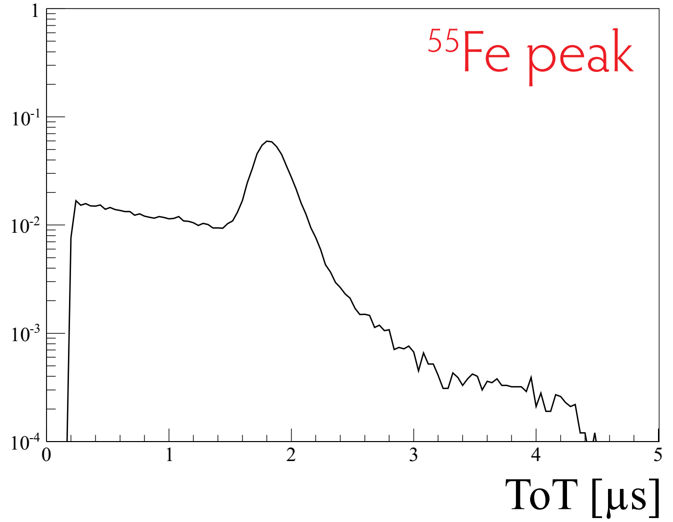


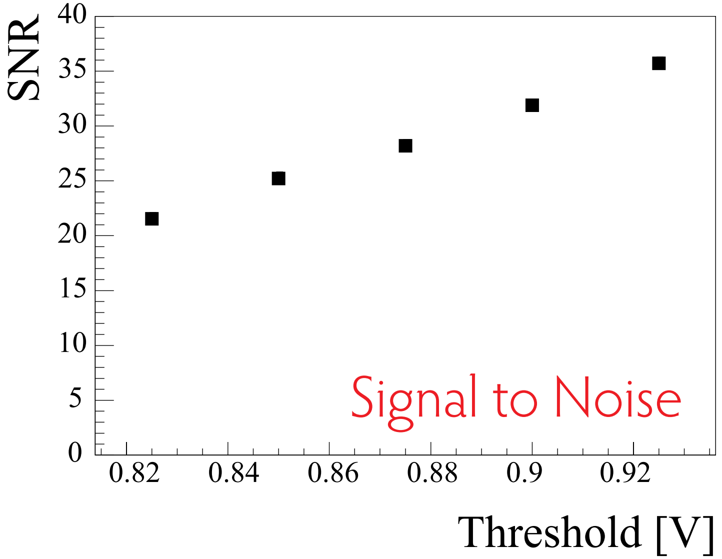


- One loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

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

MUPIX 2 Results

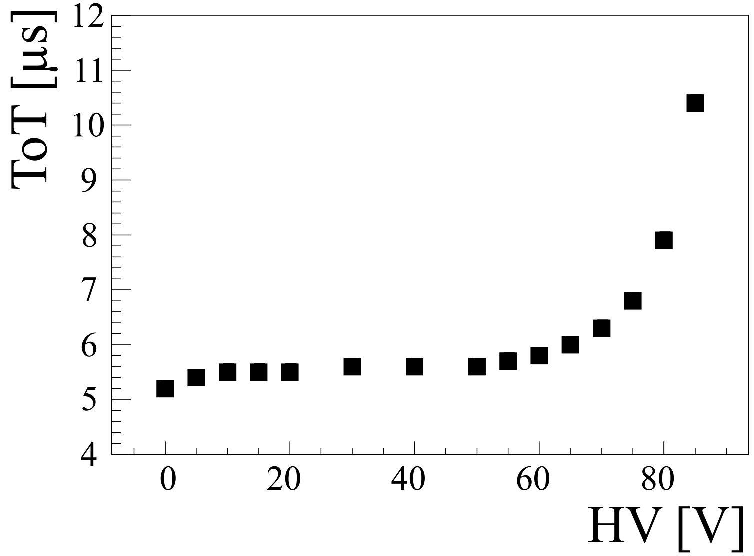


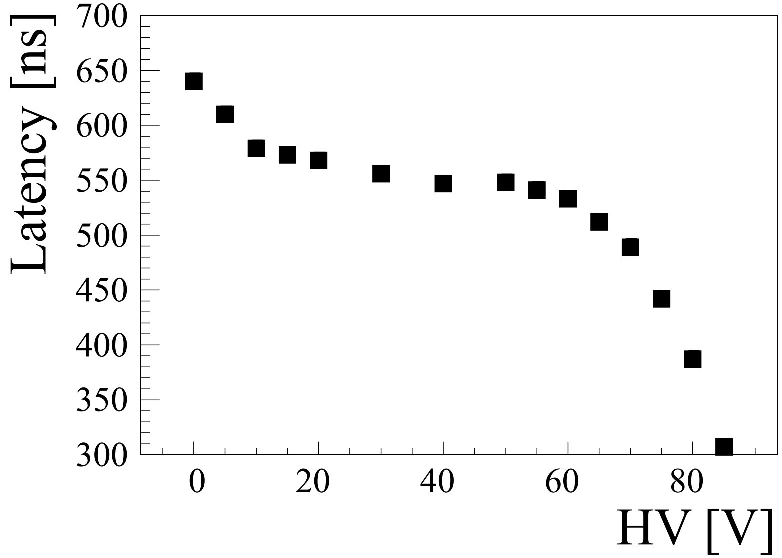


- Measurements with ^{55}Fe source
- Good energy measurement
- Very good signal to noise

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

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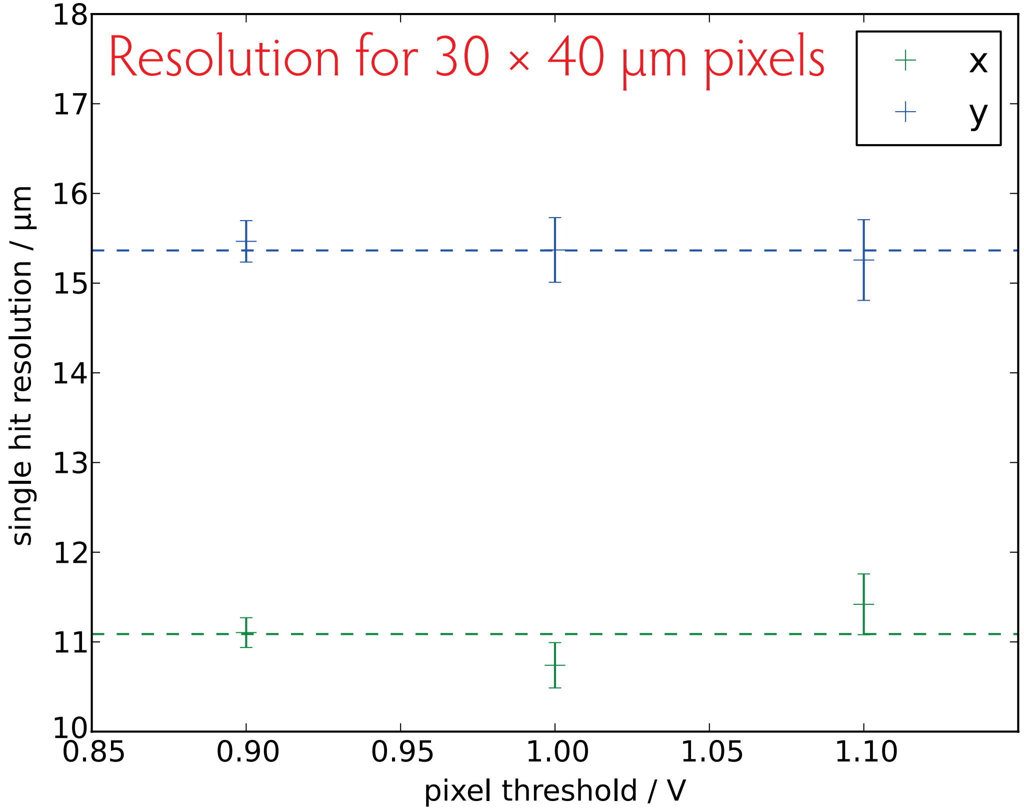
MUPIX 2 results



- 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