The Mu3e Experiment

Dorothea vom Bruch
for the Mu3e Collaboration

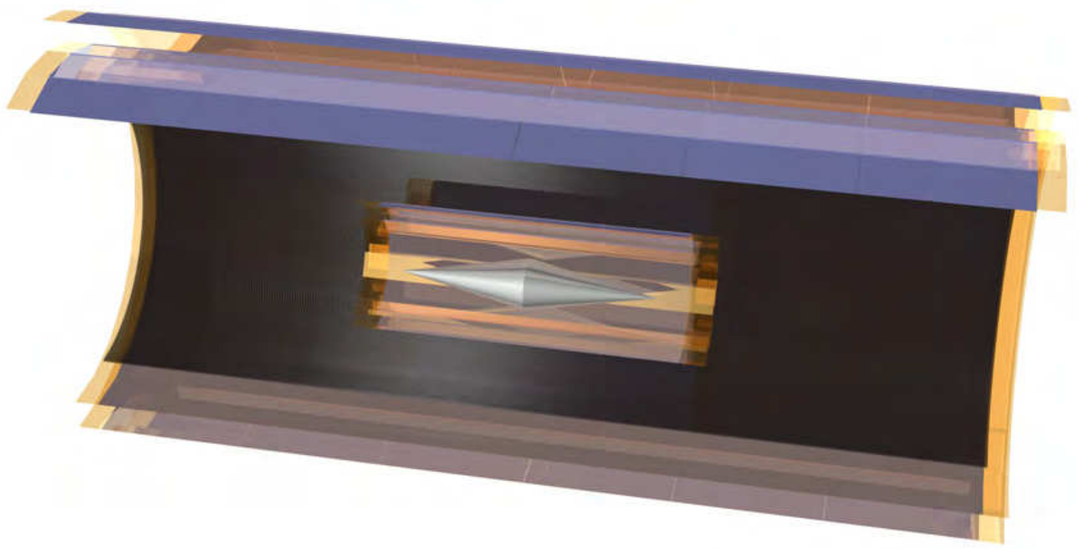
2nd International Conference on Charged Lepton Flavor Violation
Charlottesville, VA

The Mu3e Experiment

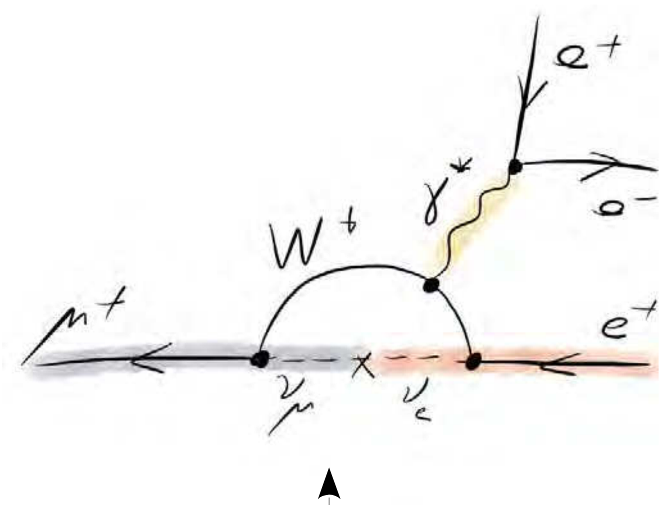
Search for charged lepton flavor violating decay $\mu^+ \rightarrow e^+e^-e^+$

This talk:

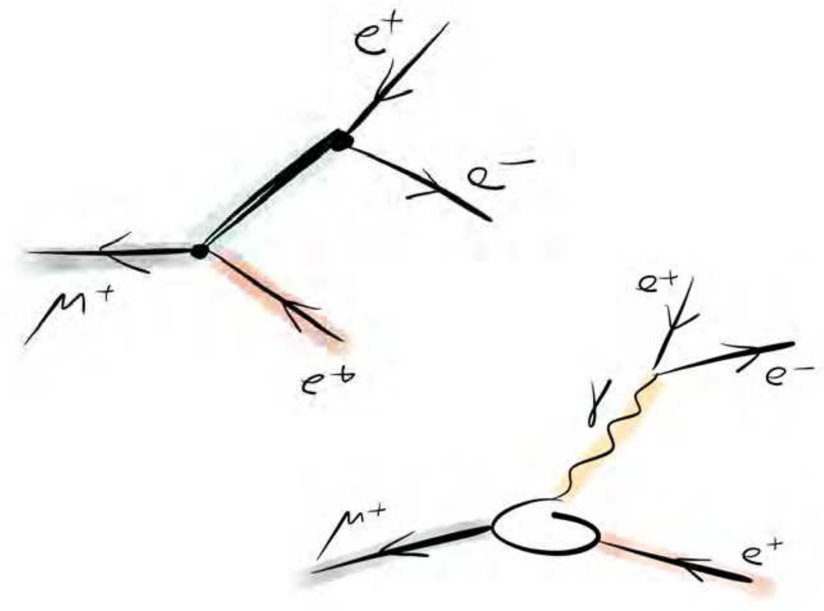
- Experimental concept
- R&D
  - Pixel detector
  - Fiber detector
  - Tile detector
  - Readout



Lepton Flavor Violation



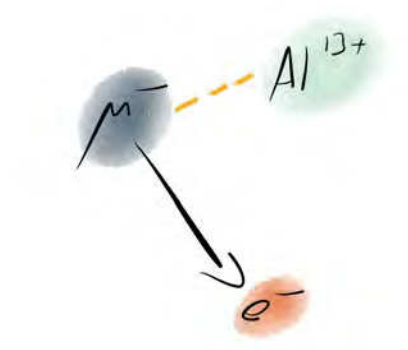
Branching ratio suppressed in Standard Model to below 10^{-54}



Any hint of signal → new physics

- Supersymmetry
- Grand unified models
- Extended Higgs sector
- ...

Experimental Signature



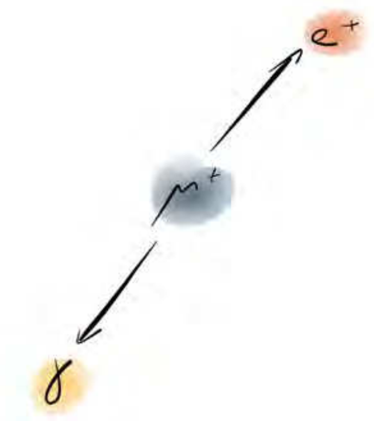
$\mu^- N \rightarrow e^- N$

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

Background

- Decay in orbit
- Beam-related particles

→ Pulsed beam



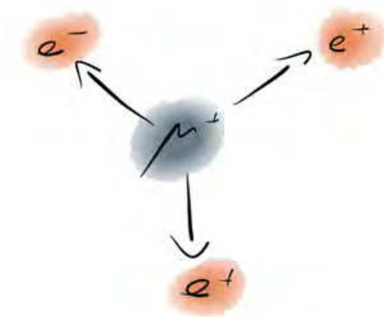
$\mu^+ \rightarrow e^+ \gamma$

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

Background

- Accidentals

→ Continuous beam



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

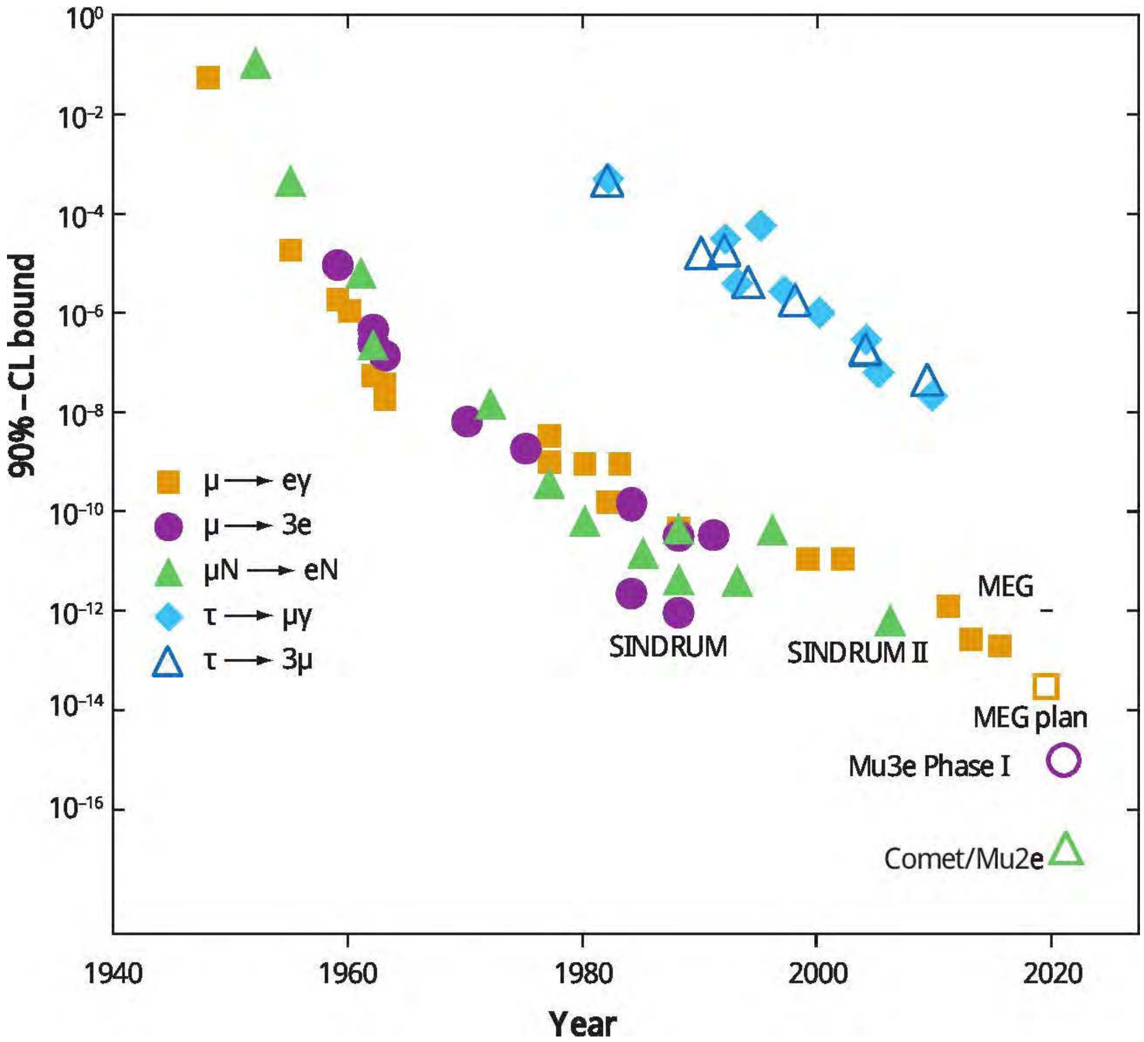
- 3-body decay
- $E = m_\mu$
- $\Sigma p_i = 0$

Background

- Accidentals
- Radiative decay

→ Continuous beam

Experimental Status



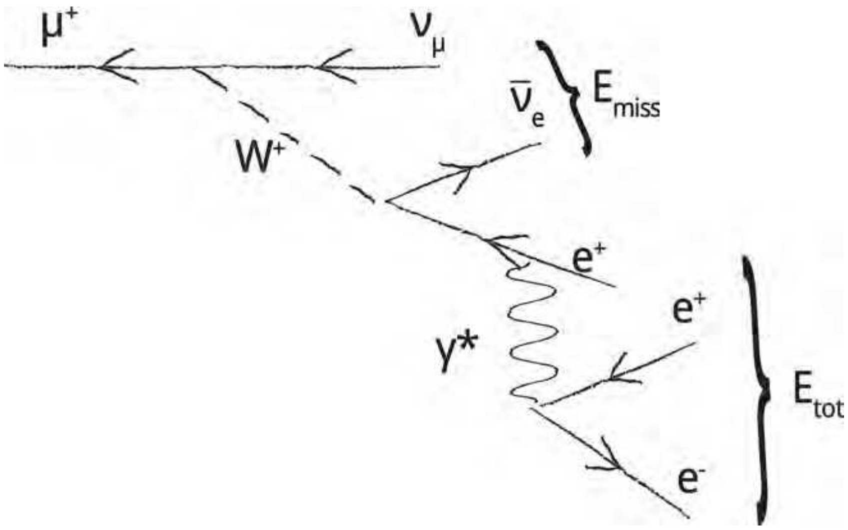
Adapted from W.J. Marciano, T. Mori, J.M. Roney, Ann.Rev.Nucl.Part.Sci 58, 315 (2008)

Mu3e

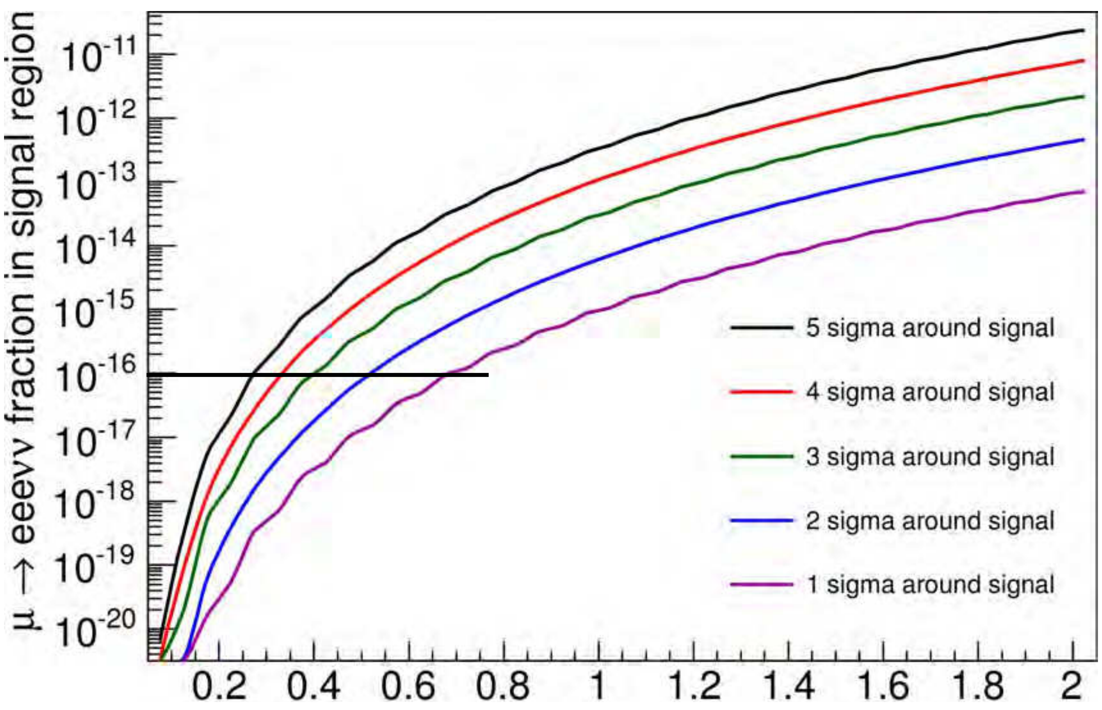
- SINDRUM (1988): BR($\mu \to eee$) $< 1.0 \cdot 10^{-12}$
- Mu3e Phase I: Reach 10^{-15} BR sensitivity
- Phase II: Increased rate, upgraded detector: reach 10^{-16}

→ Improve current limit by 4 orders of magnitude

Internal Conversion Background



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



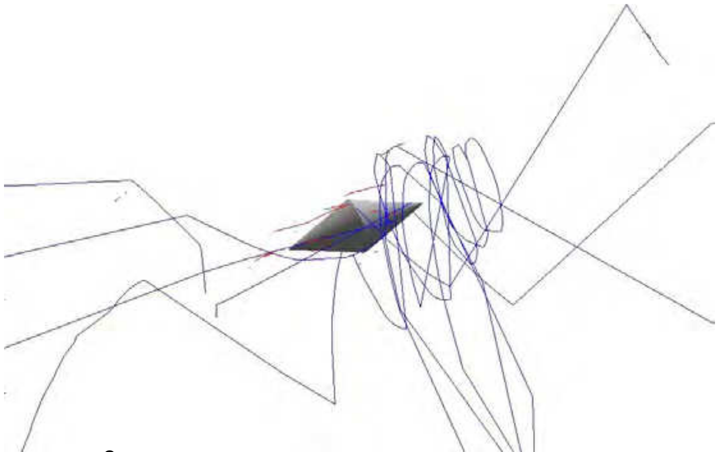
Reconstructed E_{tot} resolution [MeV/c^2]

- Coincident in time
- Single vertex
- $\Sigma\, p_i \neq 0$
- $E \neq m_\mu$

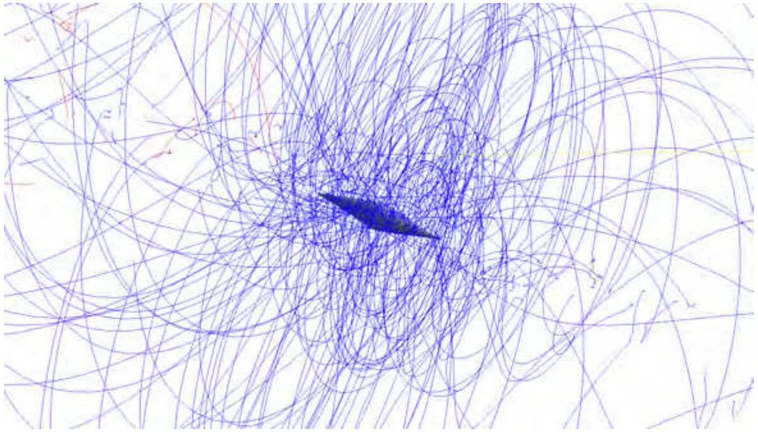
→ Need extremely good momentum resolution

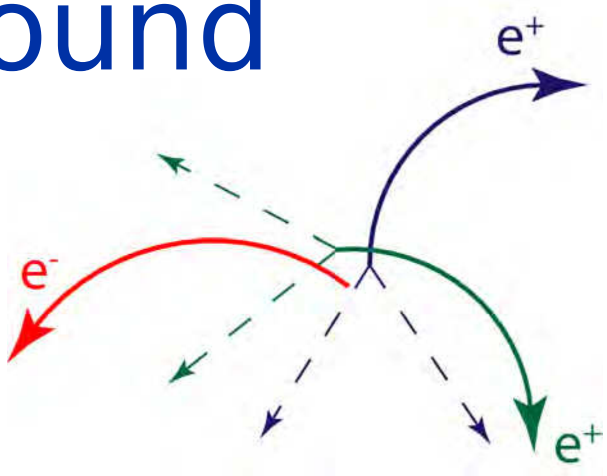
Accidental Background

@ 10^8 muons/s stopping rate (phase I):
~ 5 muons on target / 50 ns



@ 10^9 muons/s stopping rate (phase II):

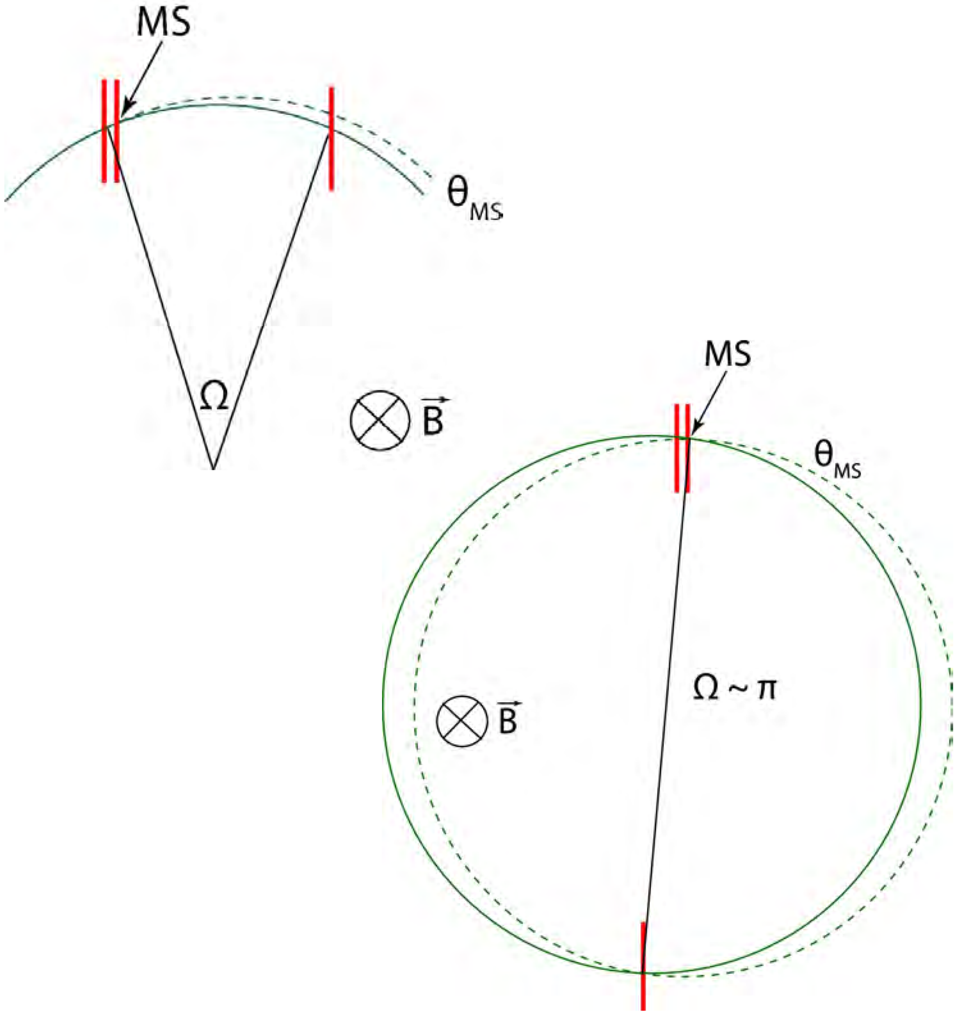




- Positrons from ordinary muon decay
- Electrons from
  - Bhabha scattering
  - Photon conversion
  - Misreconstruction
- Not coincident in time
- No single vertex
- $\Sigma p_i \neq 0$
- $E \neq m_\mu$

→ Need good time and vertex resolution

Multiple Scattering



- Muons decay at rest

  → momentum < 53 MeV/c
- Momentum resolution to first order:

$$\frac{\sigma_p}{p} \sim \frac{\theta_{MS}}{\Omega}$$

- RMS of θ_{MS}:

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

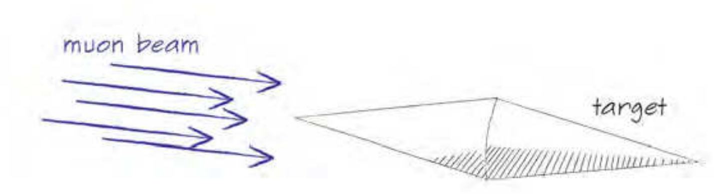
→ Use recurling tracks for momentum measurement
→ Minimize material budget

Detector Concept

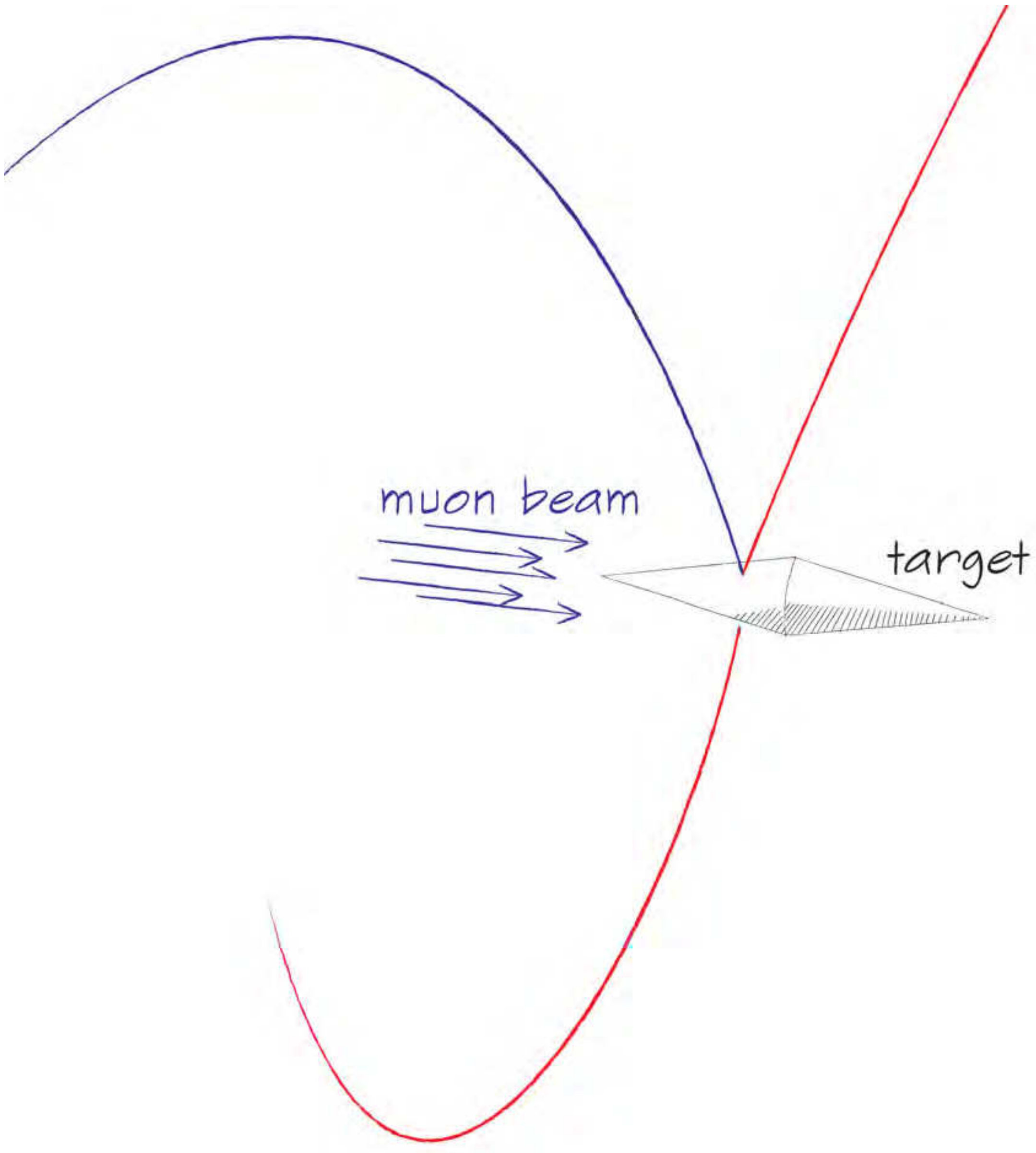
Requirements

- Excellent momentum resolution: < 0.5 MeV/c
- High rates: 10^8 -10^9 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: 300 μm
- Minimum material budget

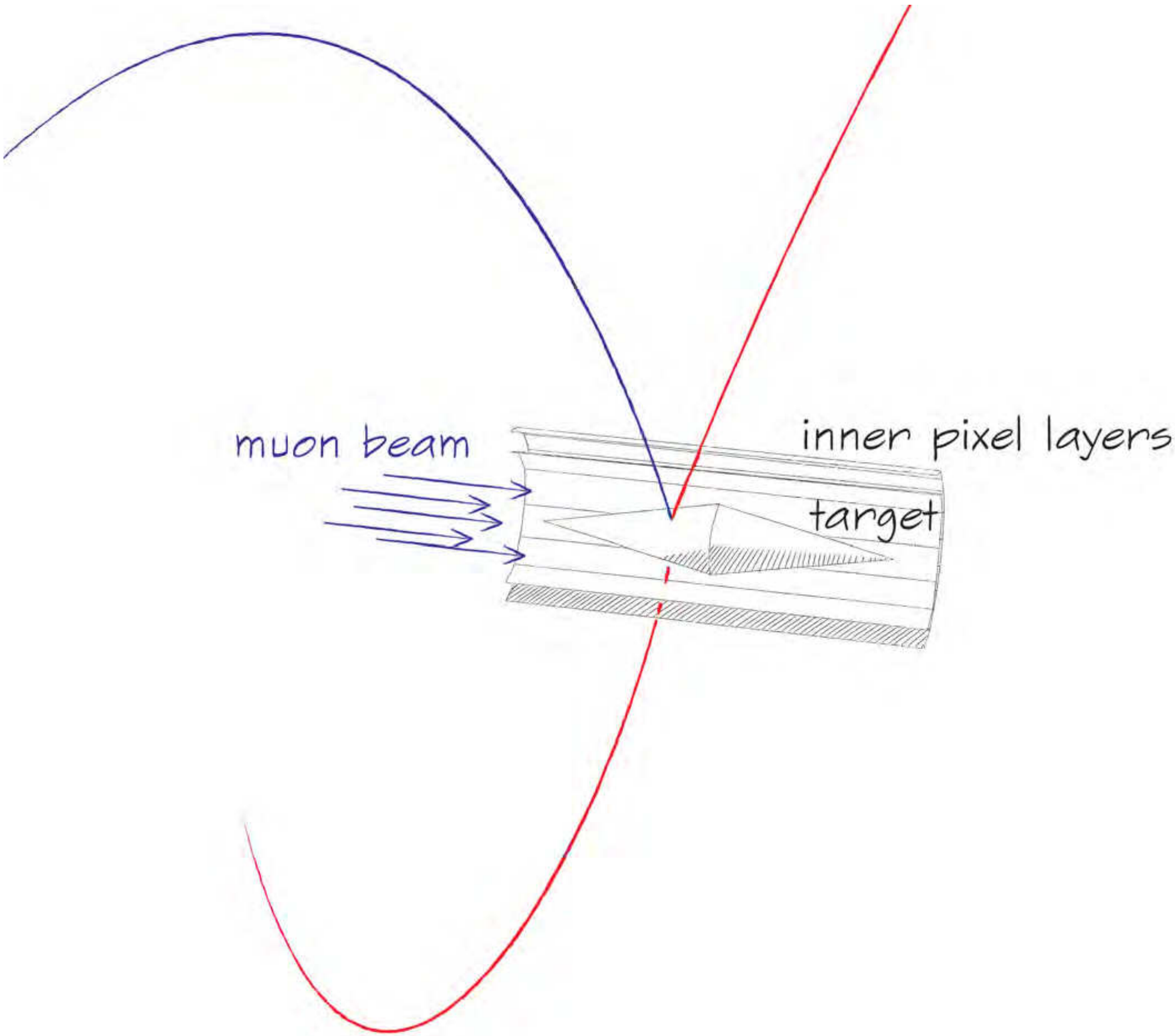
Detector Concept



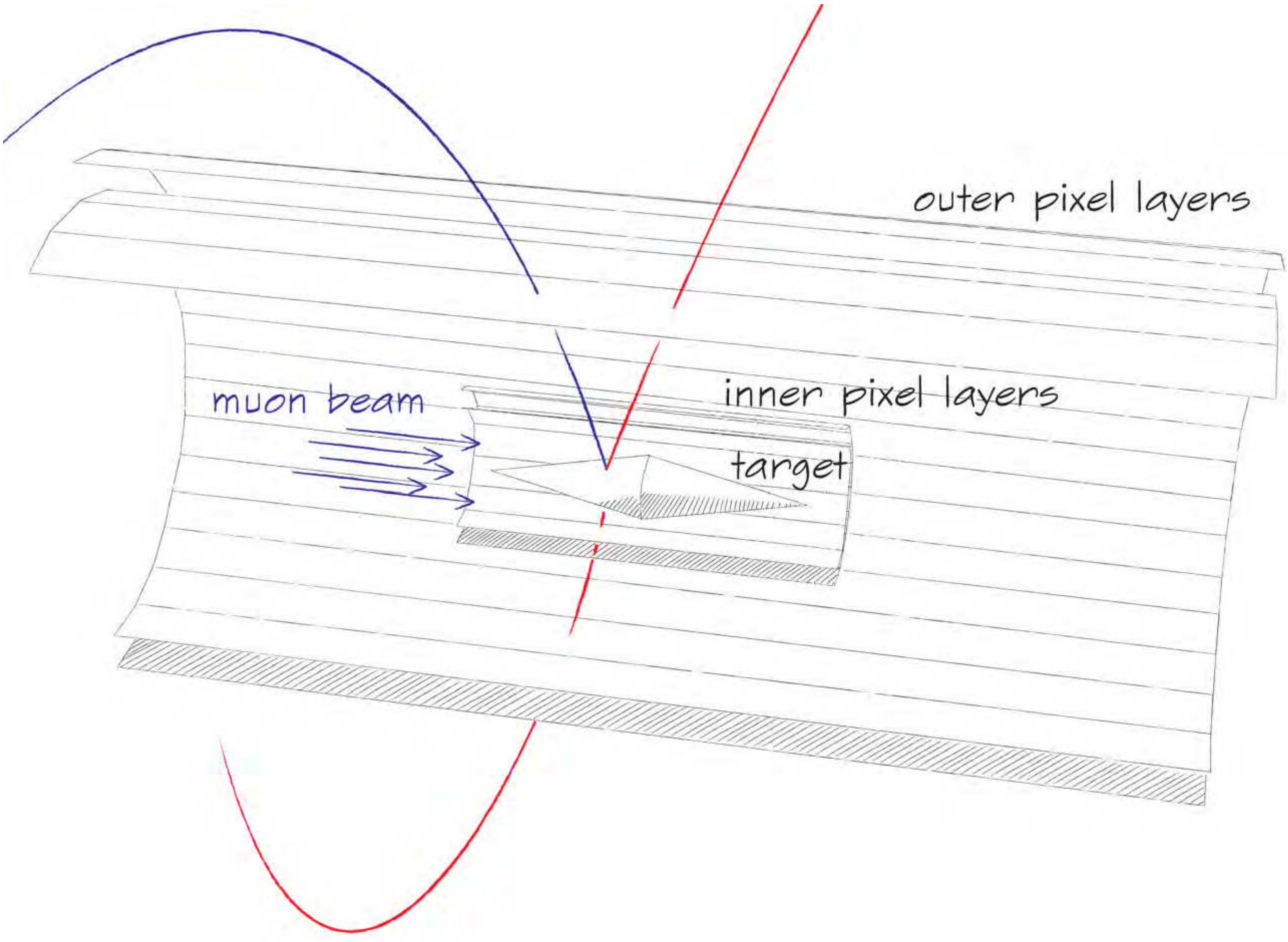
Detector Concept



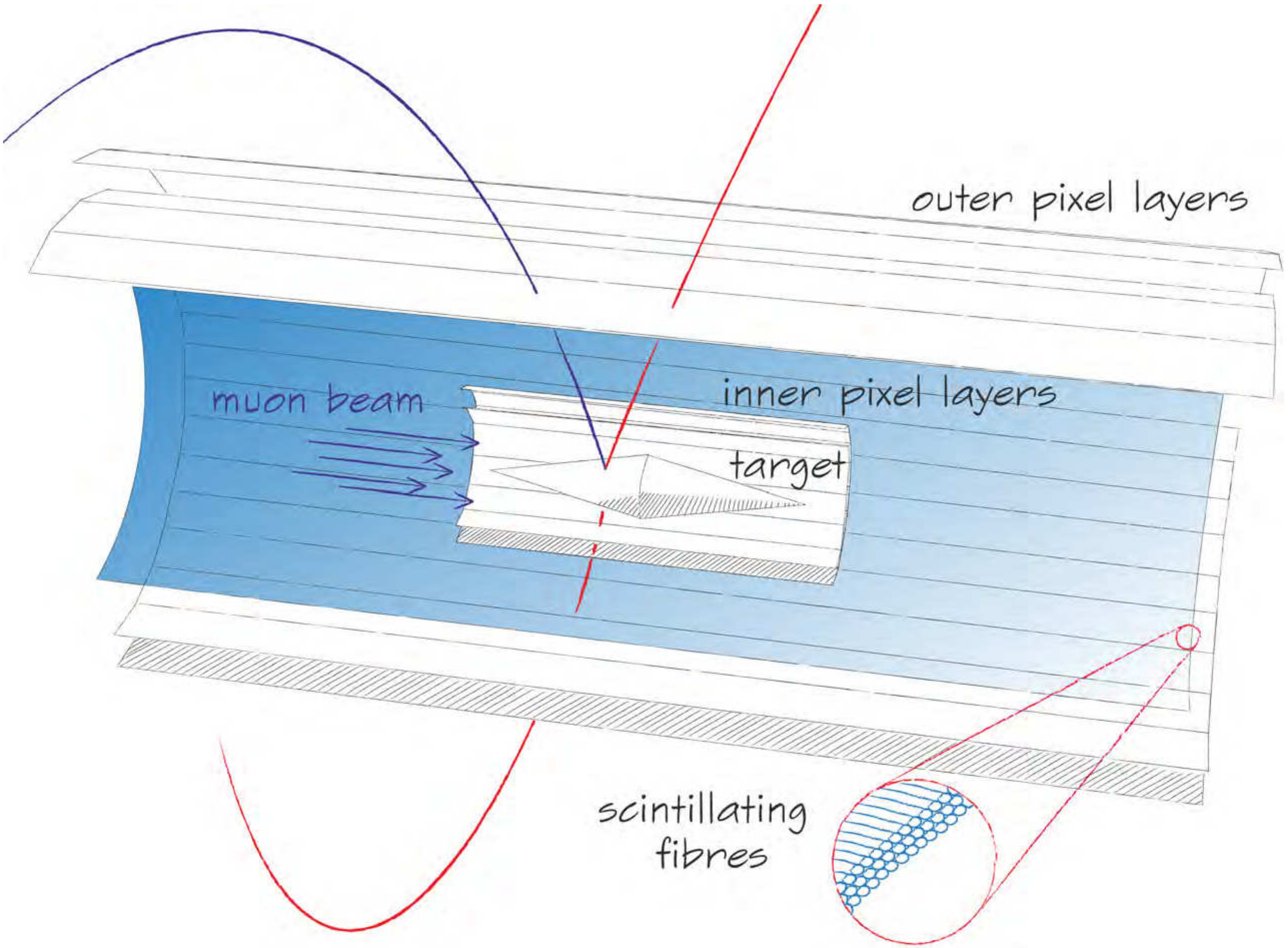
Detector Concept



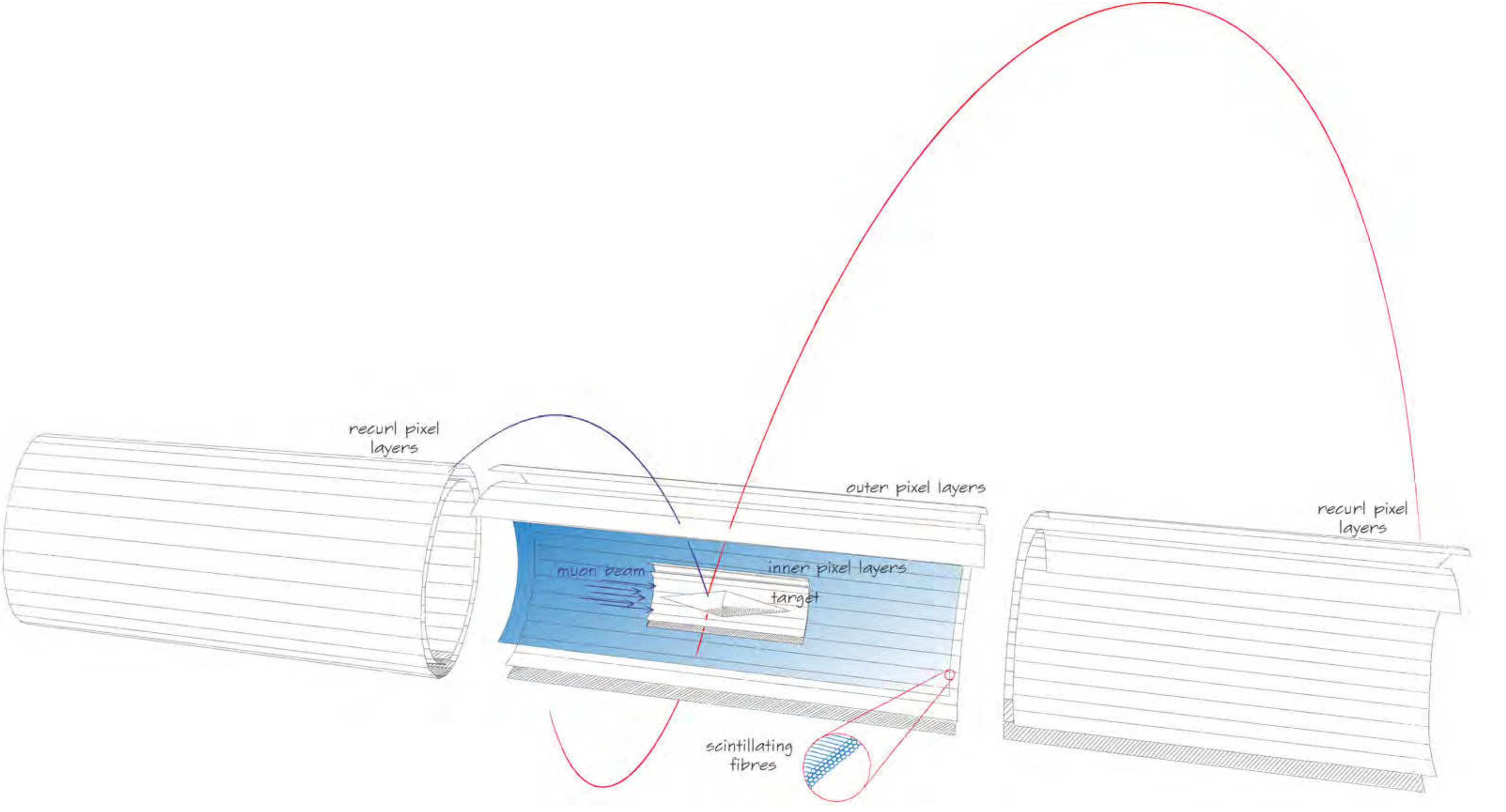
Detector Concept



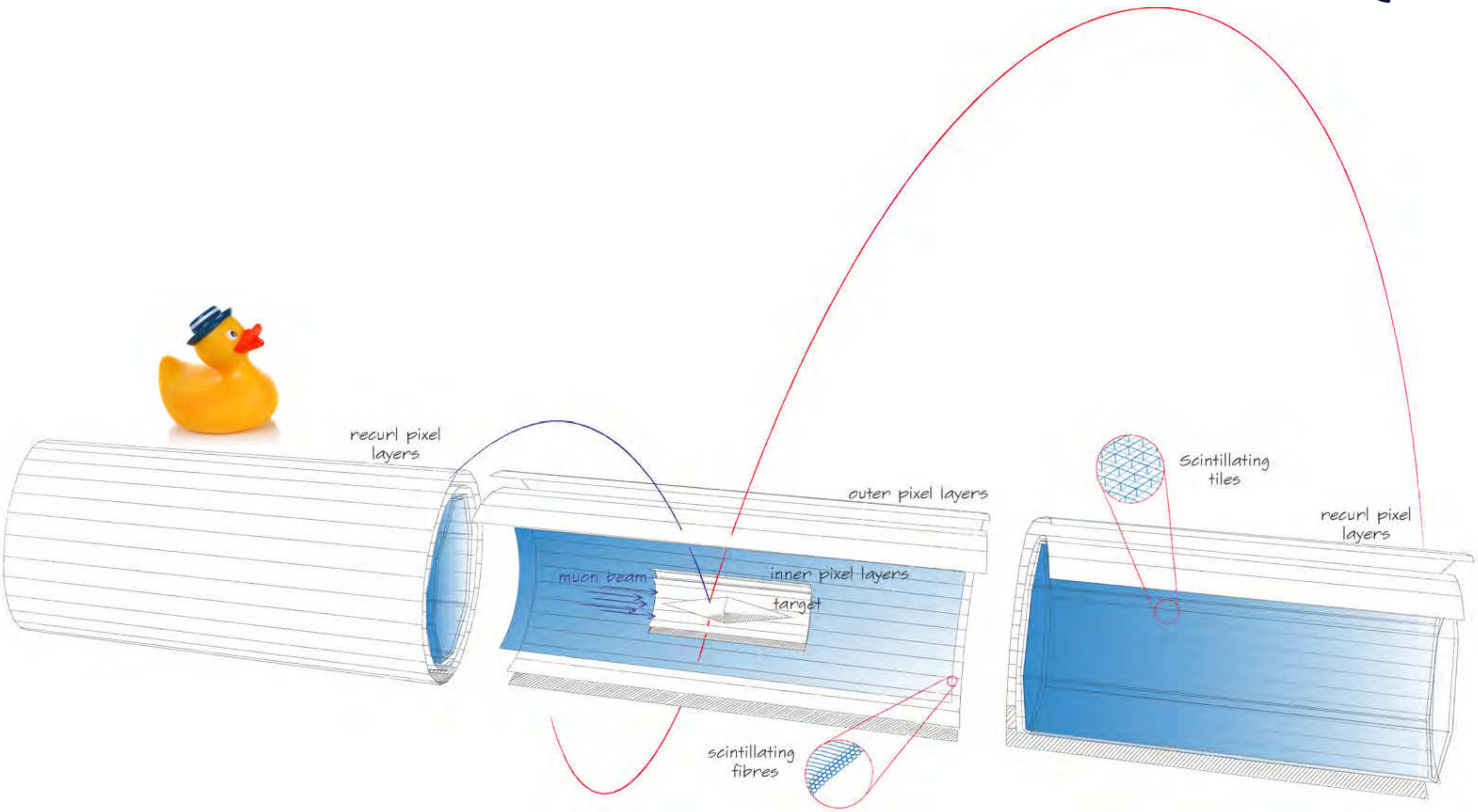
Detector Concept



Detector Concept



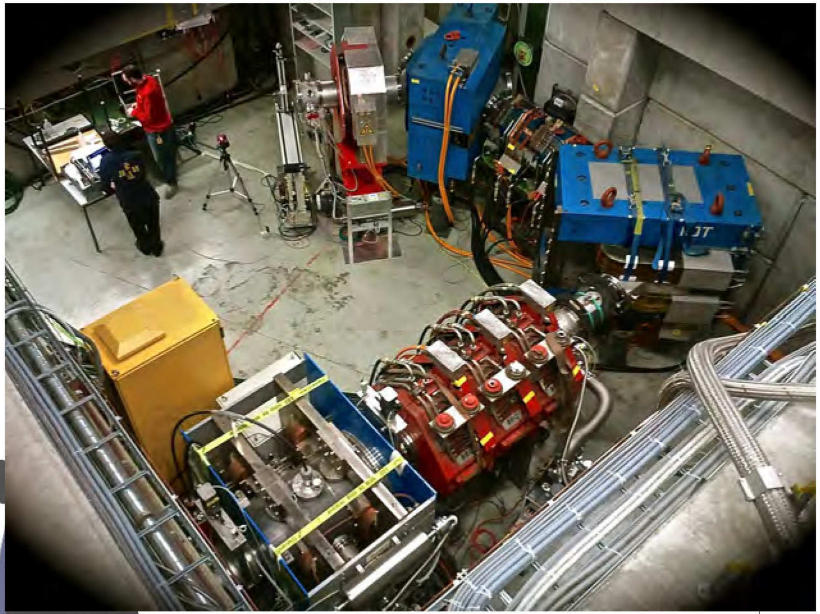
Detector Concept

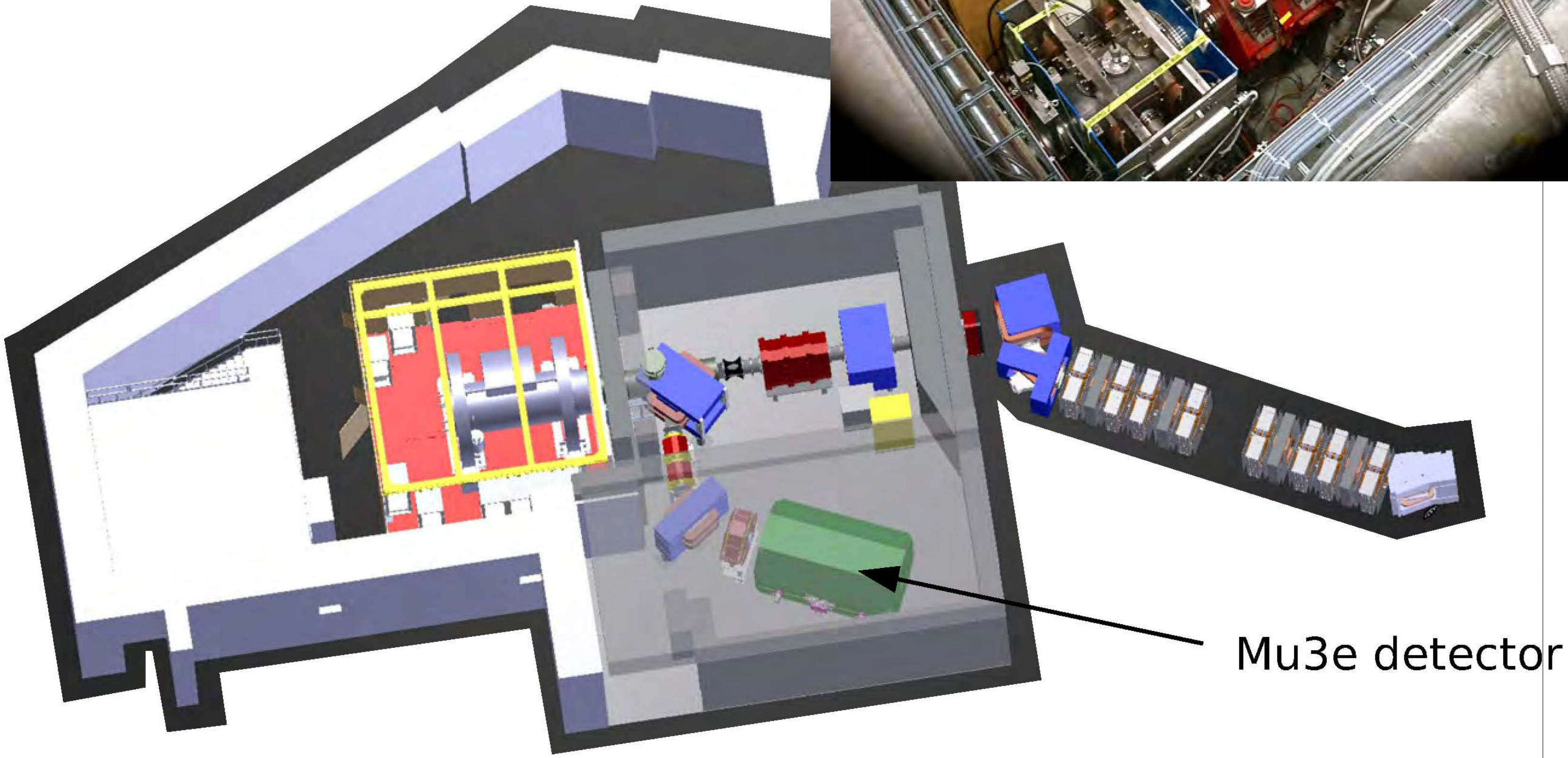


Muon Beam @ PSI

- 590 MeV cyclotron
- 2.2 mA proton beam
- Most powerful proton beam worldwide
- Target E: 28 MeV/c surface muons to πE5 beamline

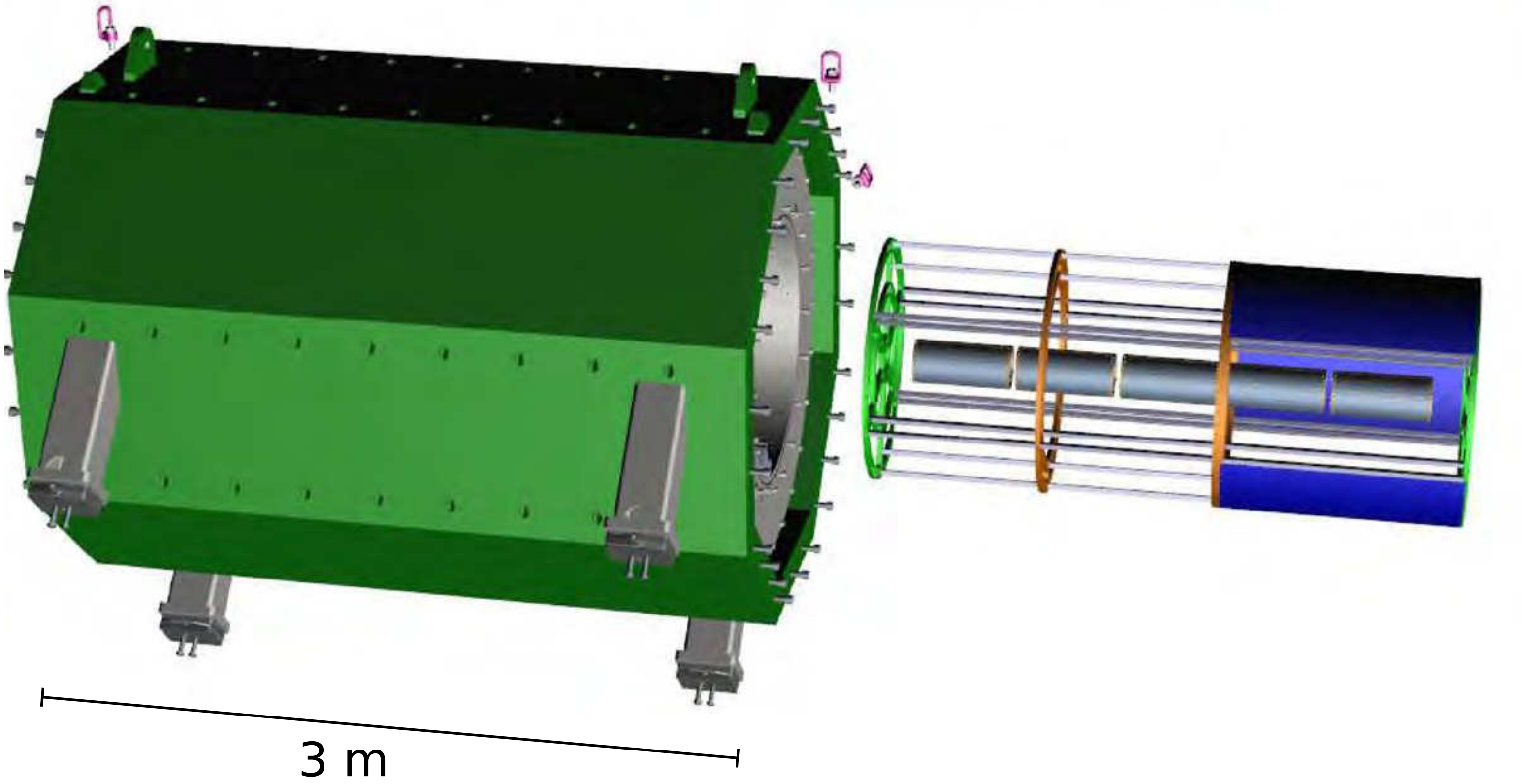
πE5 Area



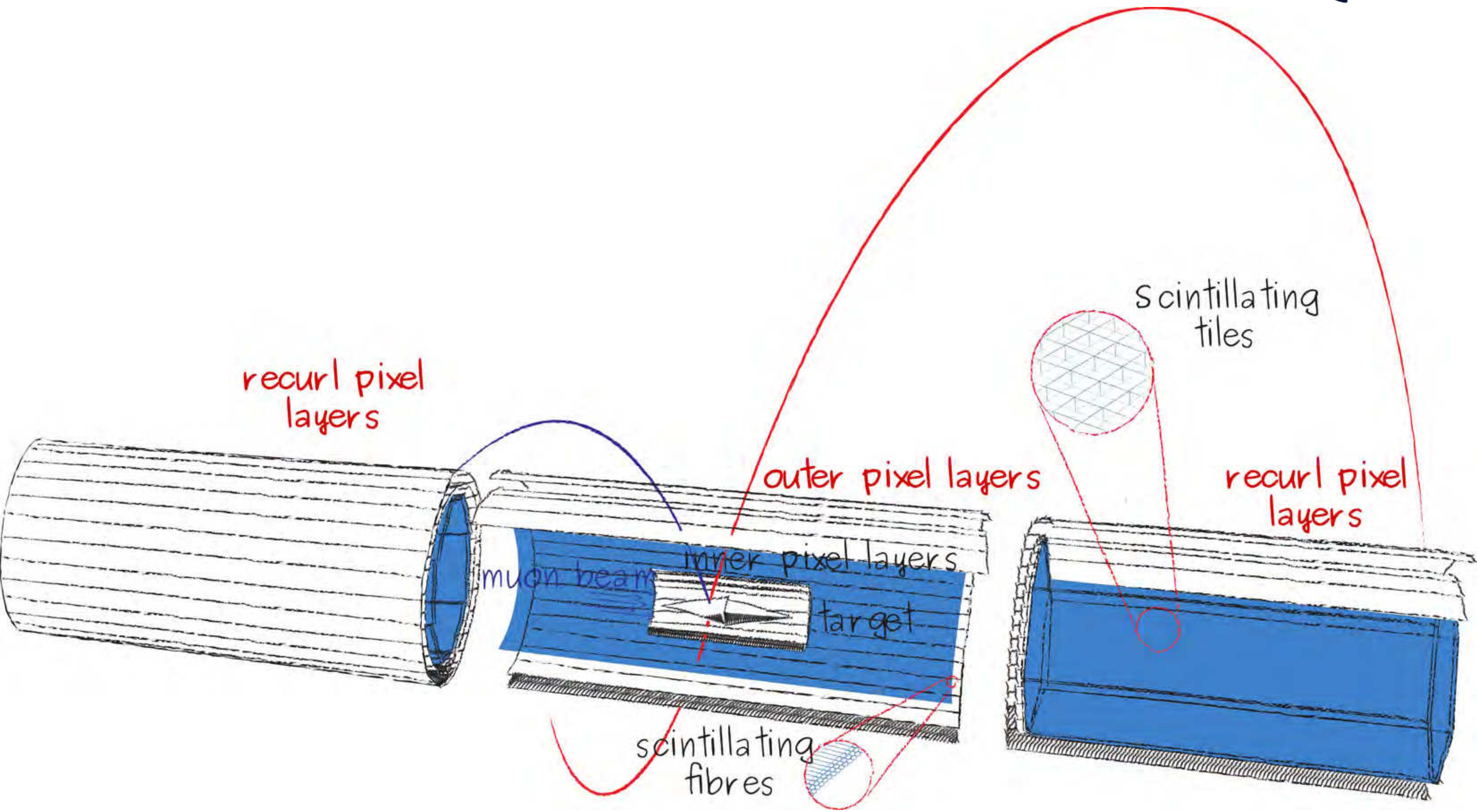


Magnet

- Superconducting magnet produced by Danfysik
- Delivery 2017
- Up to 2 T magnetic field
- Nominal field strength: 1 T in central part

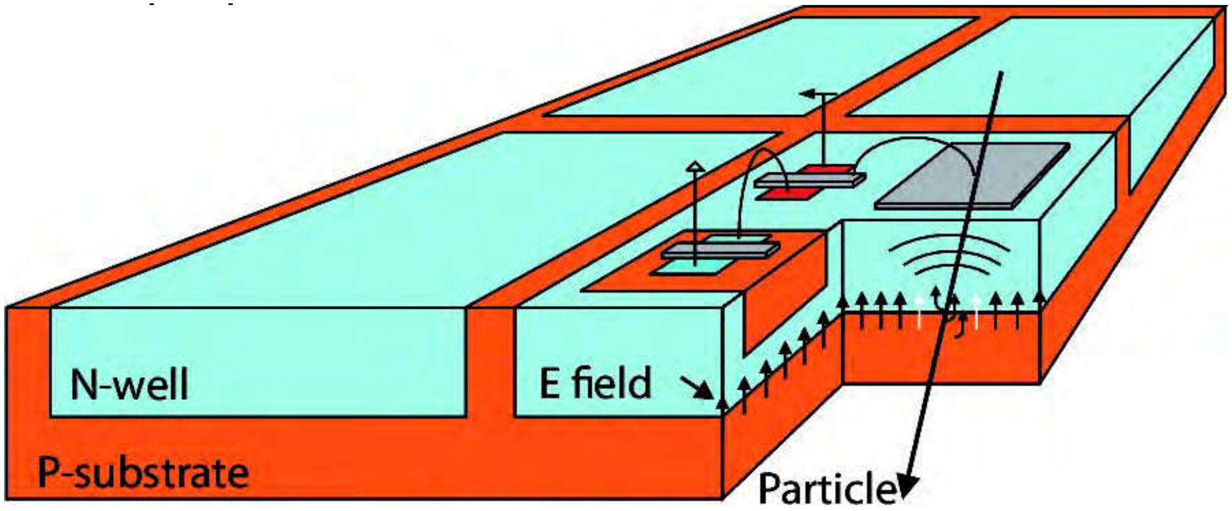


Pixel Detector



Pixel Detector

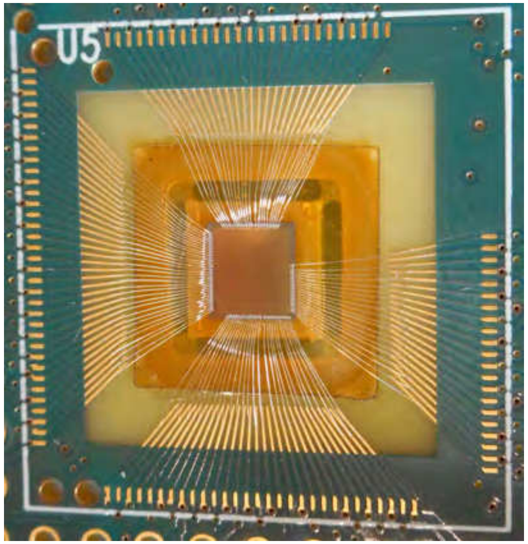
- High Voltage Monolithic Active Pixel Sensors (HV-MAPS)
- Operated at HV = 85 V
- Fast charge collection via drift
- Readout logic on chip: zero-suppressed hit addresses and timestamps
- Made of silicon
- Thinned down to 50 µm
- Pixel size: 80 µm x 80 µm
- Chip size: 2 cm x 2 cm

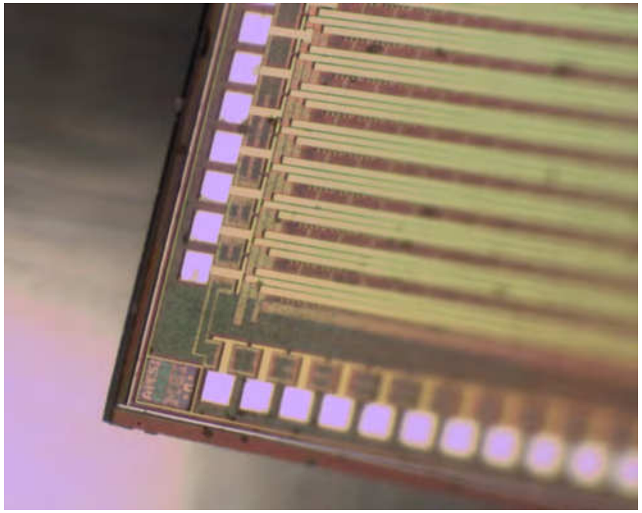


I. Peric, P. Fischer et al, NIM A 582 (2007) 876

Mupix Protoype

- Mupix7: latest prototype
- Thinned to 50 µm
- 32 x 40 pixel matrix
- Pixel size: 103 µm x 80 µm
- 3.2 x 3.2 mm^2

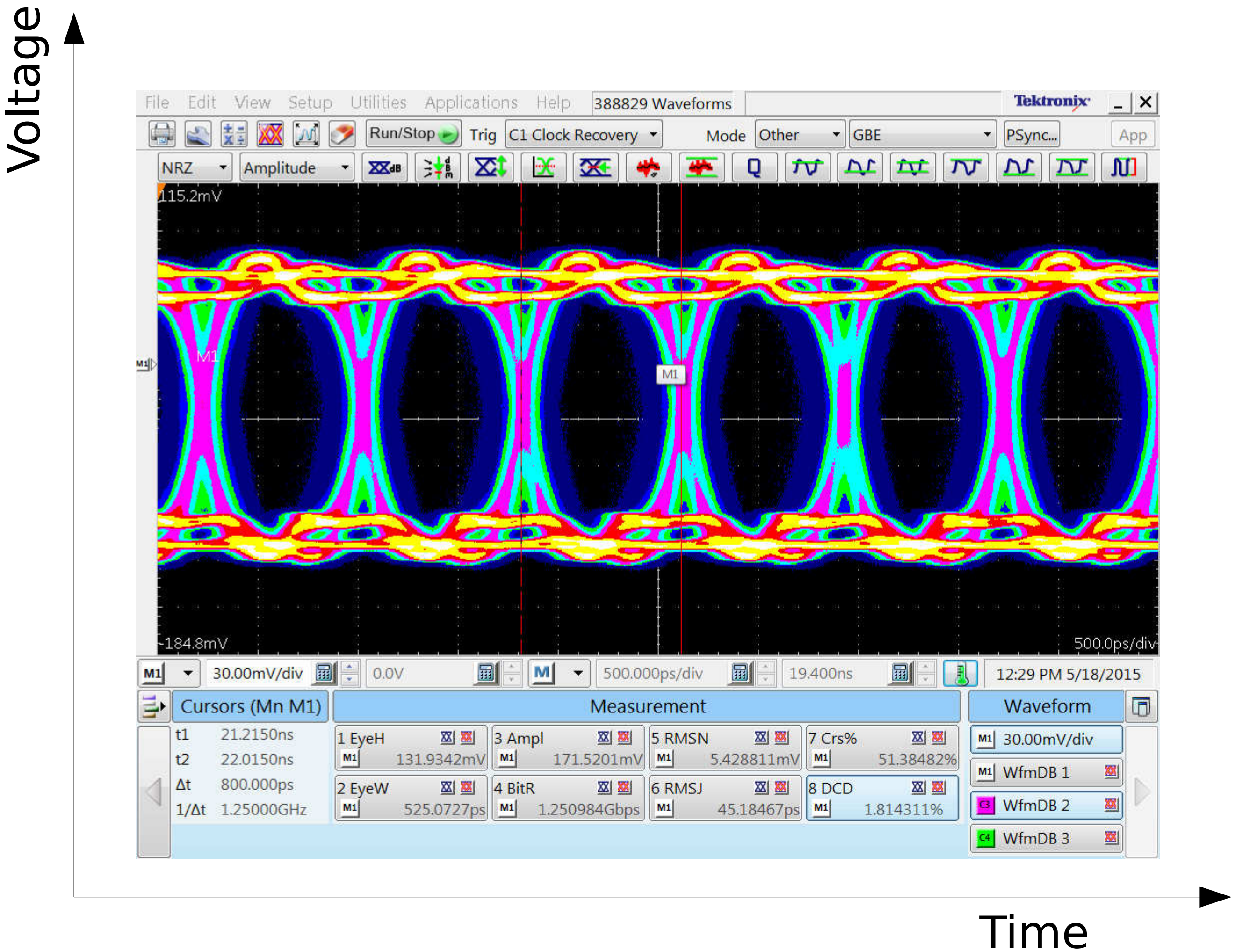




- Readout electronics on chip
- Fast LVDS link: 1.25 Gbit/s,

  ~ 30 million hits/s

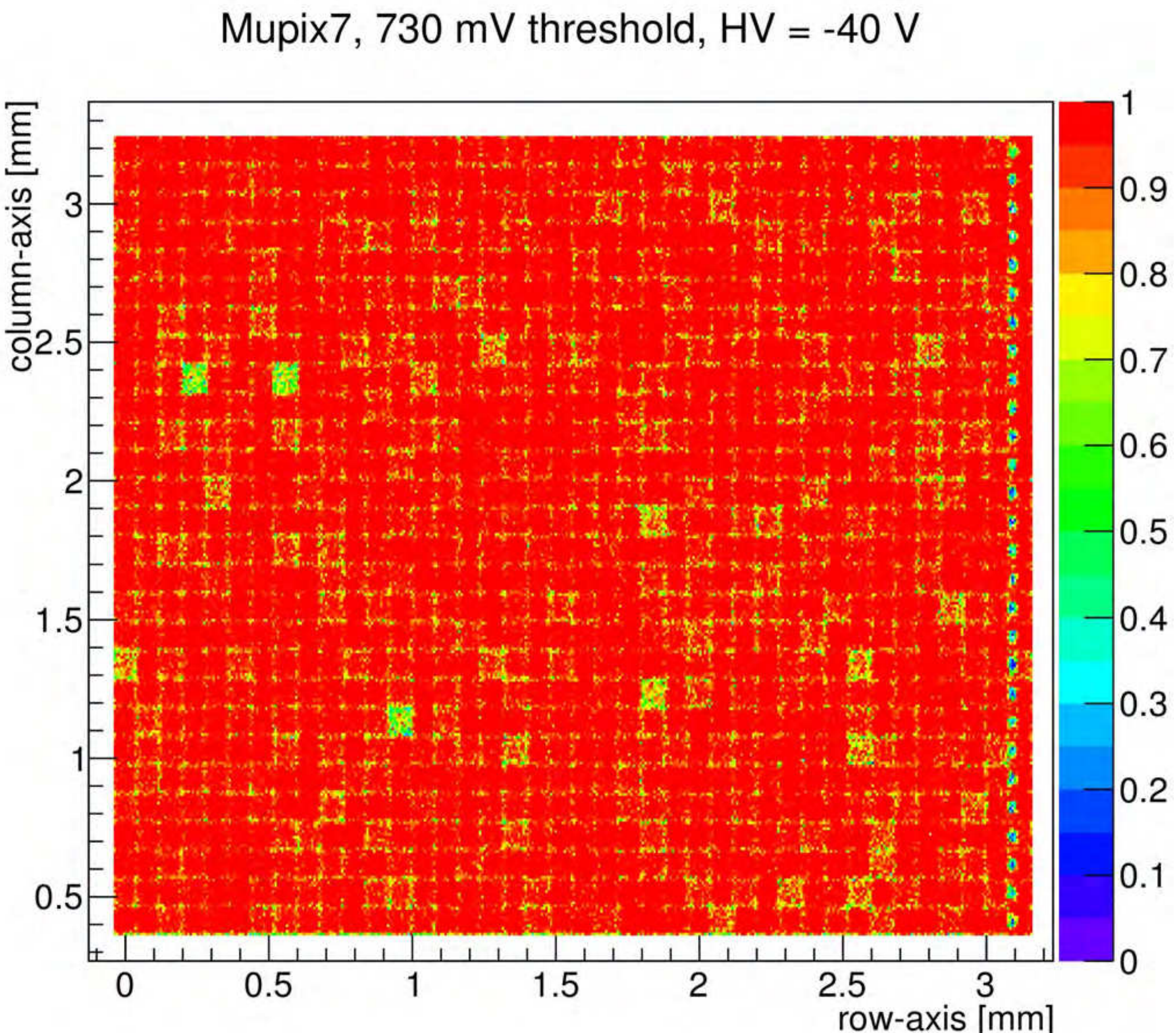
Mupix7: Readout



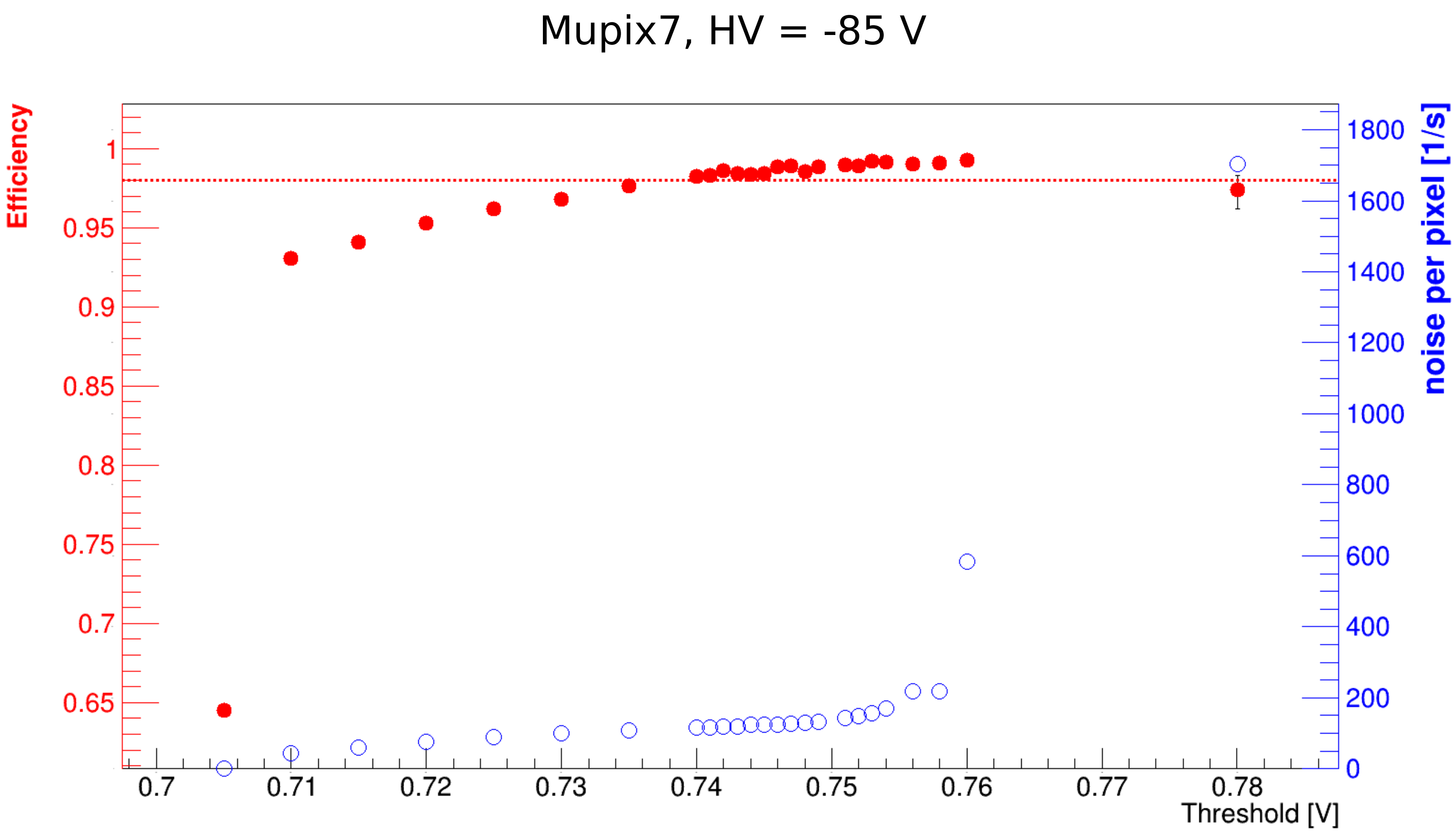
- 1.25 Gbit/s link
- 8bit / 10bit encoded
- Bit error rate ≤ $5 \cdot 10^{-14}$

Mupix7: Efficiency

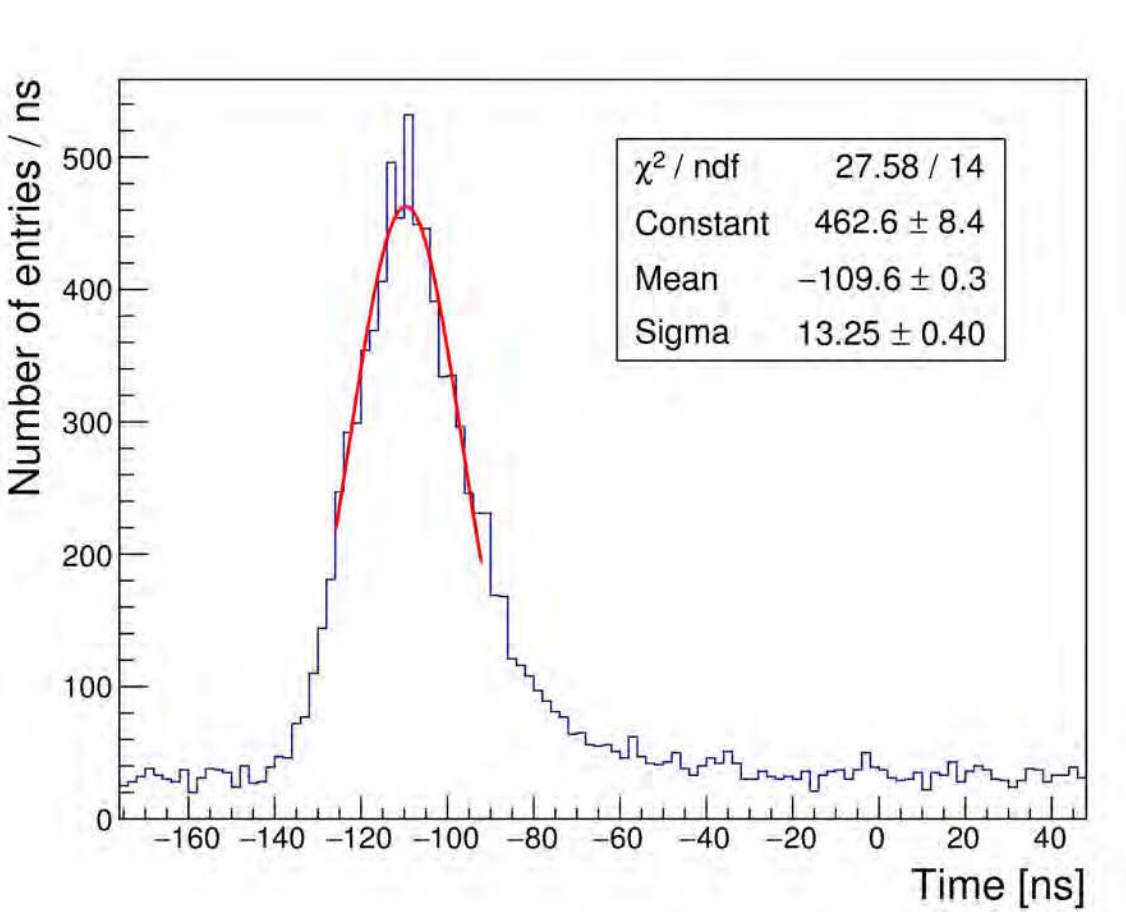
Reduced High Voltage



Mupix7: Efficiency
Nominal High Voltage



Mupix7: Time Resolution



Time resolution < 14 ns

Mupix8

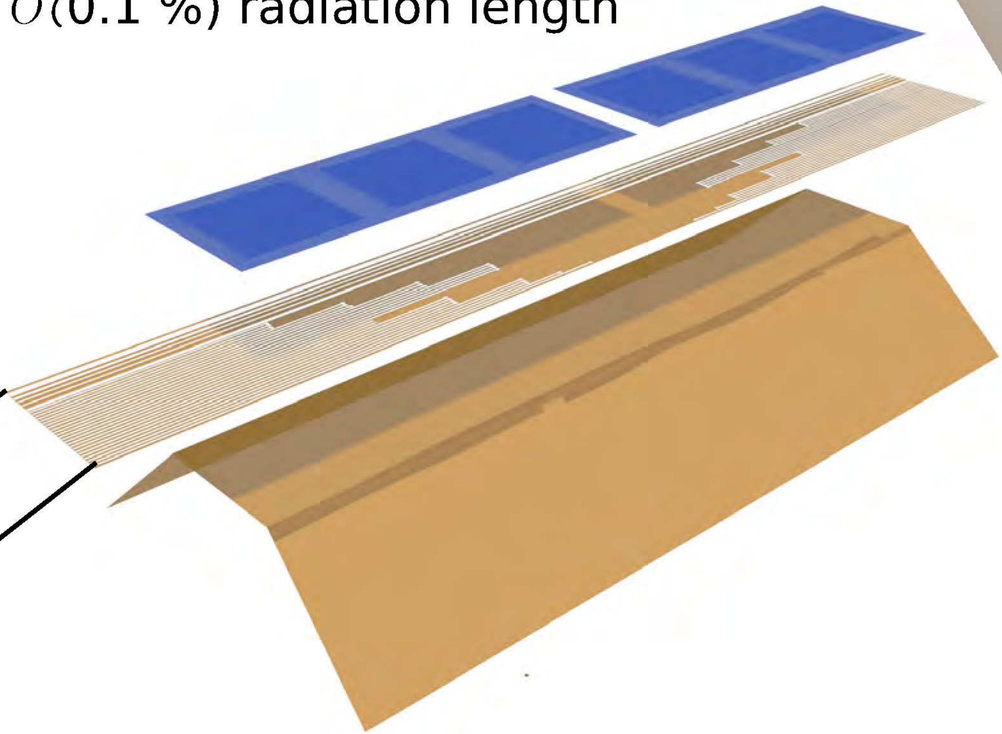
- First large chip

  → Study long rows and columns
- Digital and analog part as in Mupix7
- All pads on one side → integration into modules
- To be submitted this summer

Mupix: Mechanics

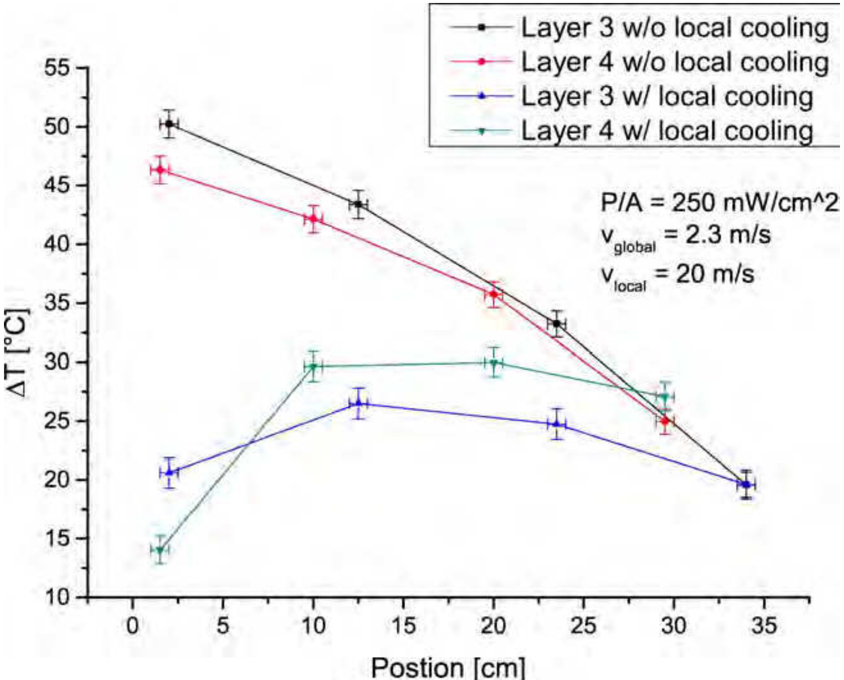
- 50 µm silicon
- ~ 50 µm flexprint: Kapton, aluminum, copper
- 25 µm Kapton foil

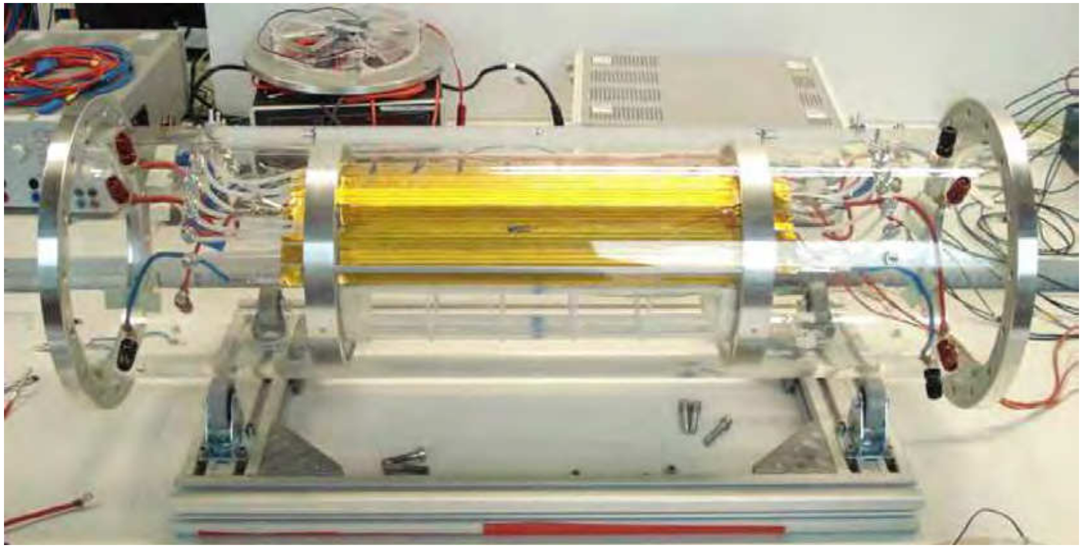
→ $\mathcal{O}(0.1\ \%)$ radiation length



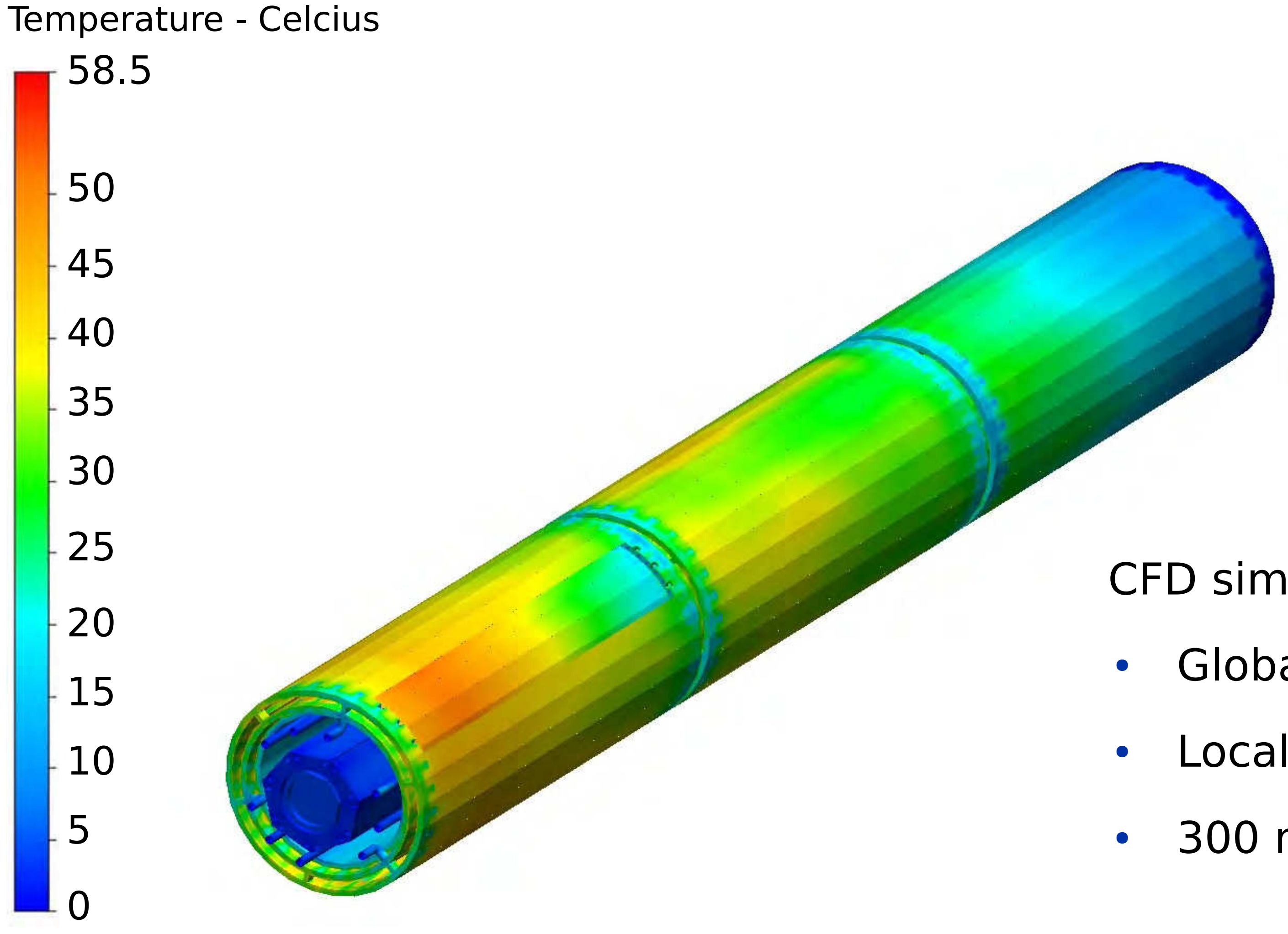
Cooling with Gaseous Helium

- Heatable module prototypes
- Temperature sensors
- Flow container
- Local and global helium flow





Cooling with Gaseous Helium

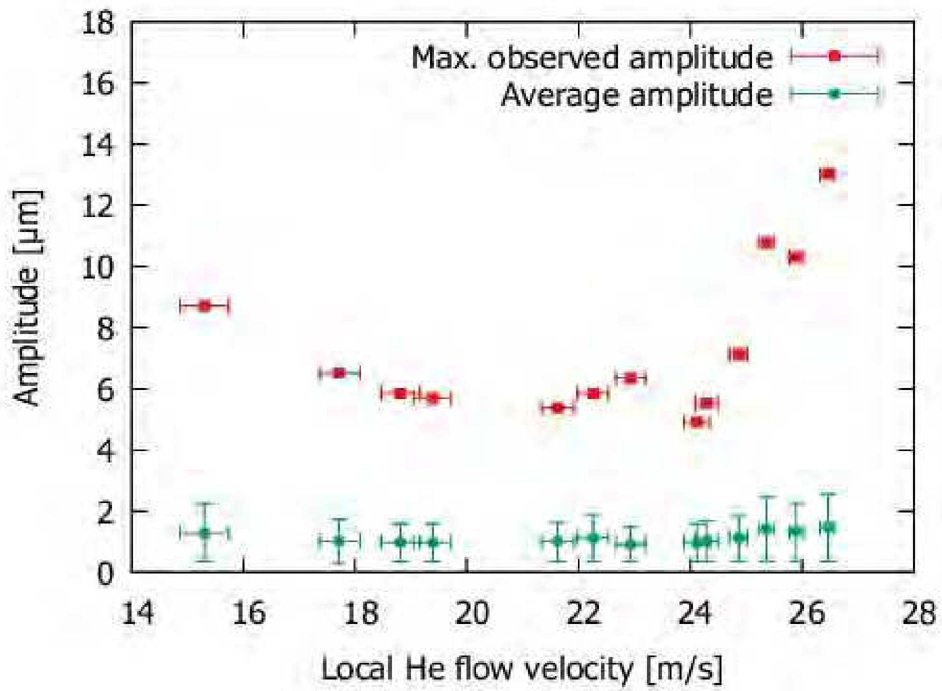


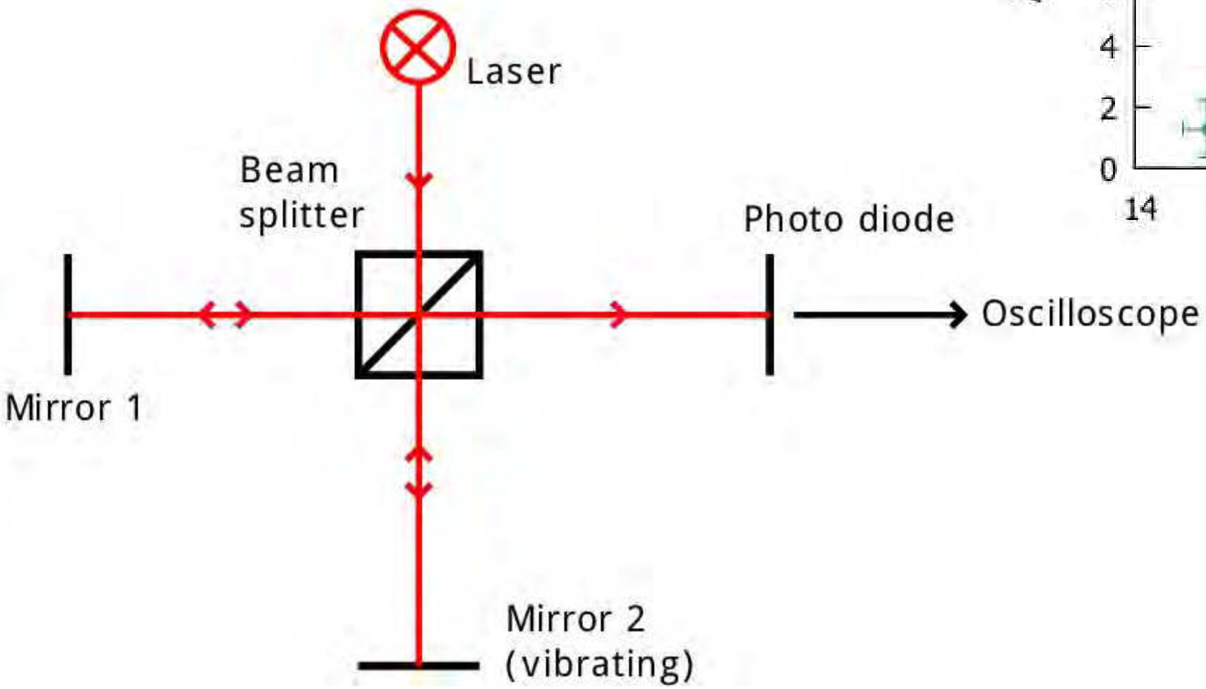
CFD simulation with

- Global flow velocity: 4 m/s
- Local flow velocity: 16 m/s
- 300 mW/cm^2

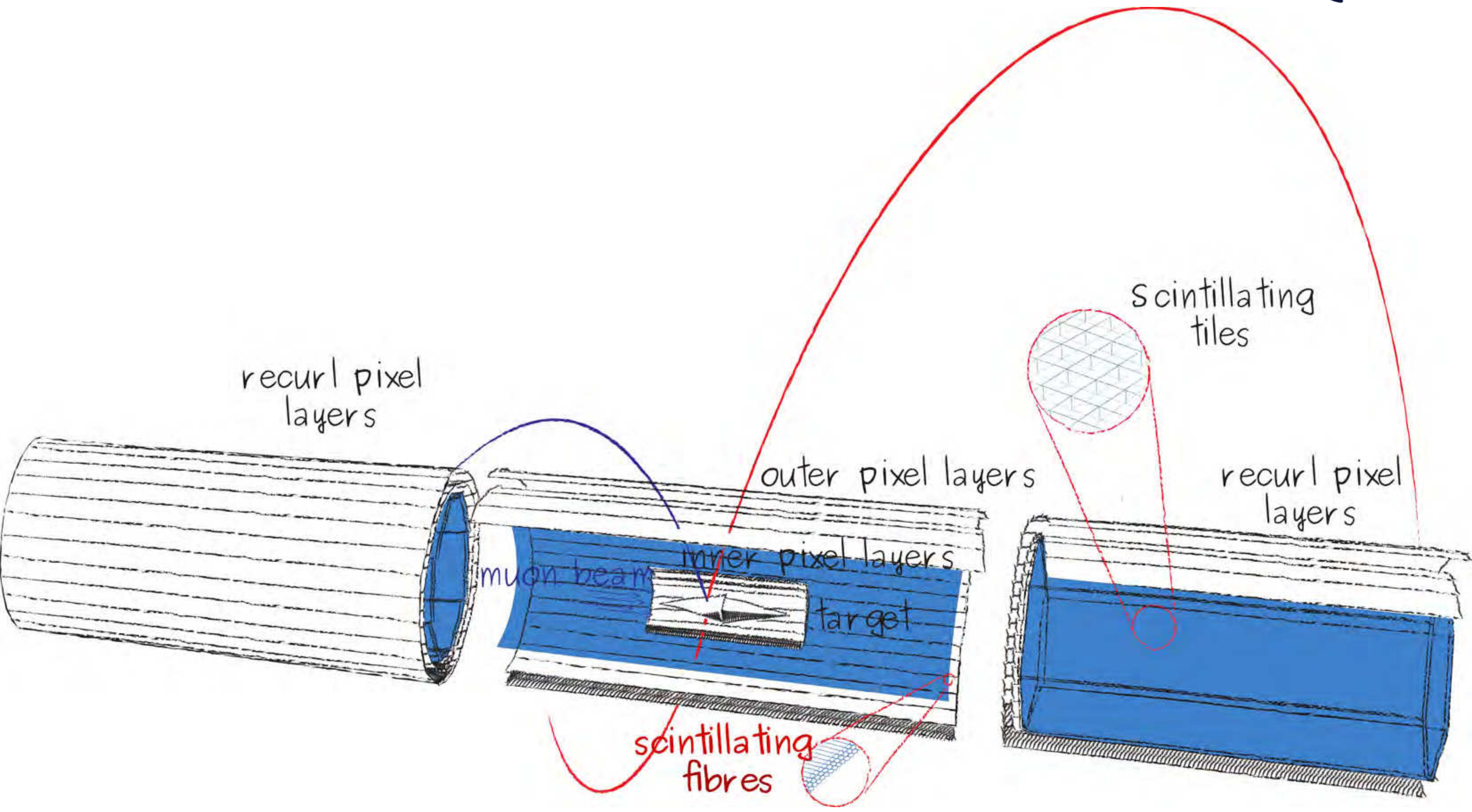
Vibration Measurement

Measurement of flow-induced vibrations with Michelson interferometer





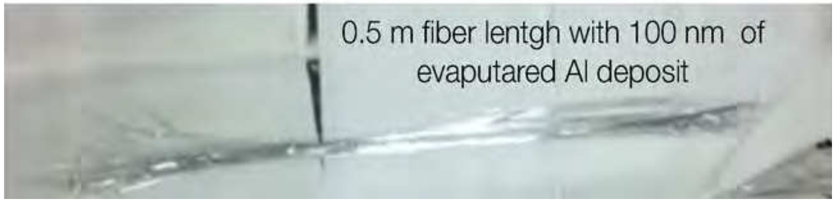
Scintillating Fibers



Scintillating Fibers

- 2 or 3 layers of scintillating fibers
- Two types of prototypes, 250 µm diameter:
  - Round
  - Square
- Read out by Silicon Photomultipliers (SiPMs) at both ends
- Thickness < 0.1 % radiation length per layer

Scintillating Fibers: Coating

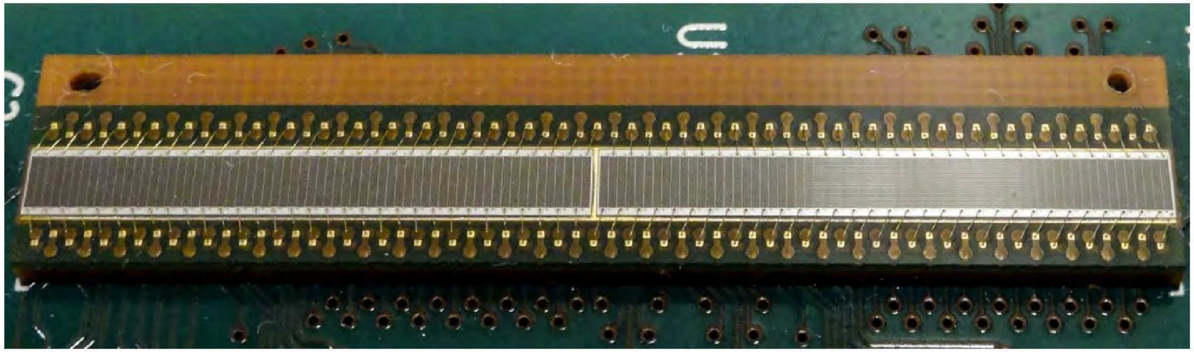


- Standard coating: TiO
- Titanium increases material budget
- Use aluminum instead
- 100 nm Al coating via evaporation
- Optical cross talk < 1%

Scintillating Fibers: Readout

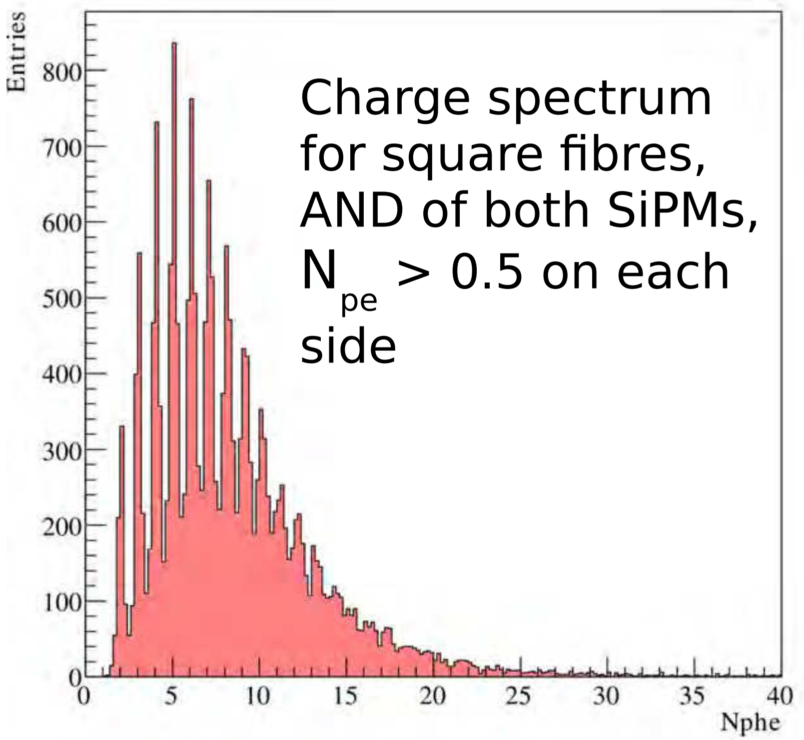
- Fibers read out column-wise
- Hamamatsu SiPMs
- Use LHCb like SiPM array

  → Fits spatial constraints

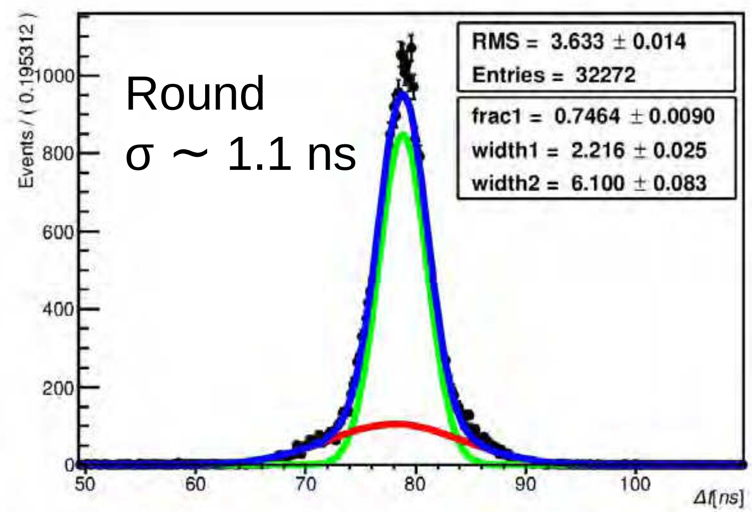


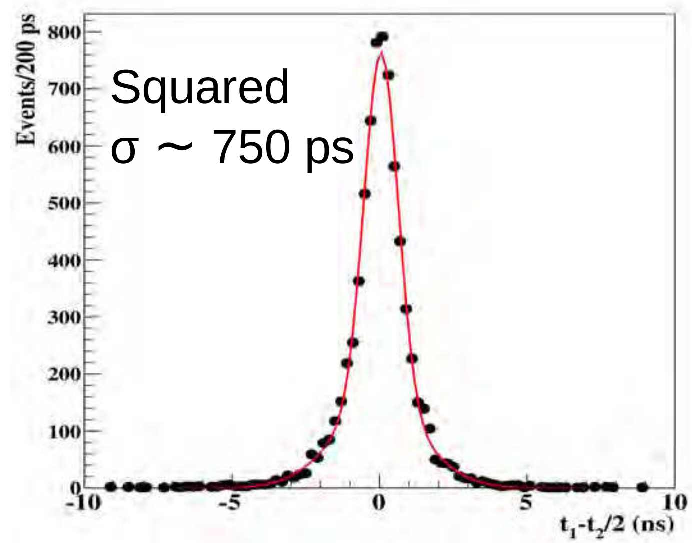
128 channel LHCb SiPM array

Scintillating Fibers



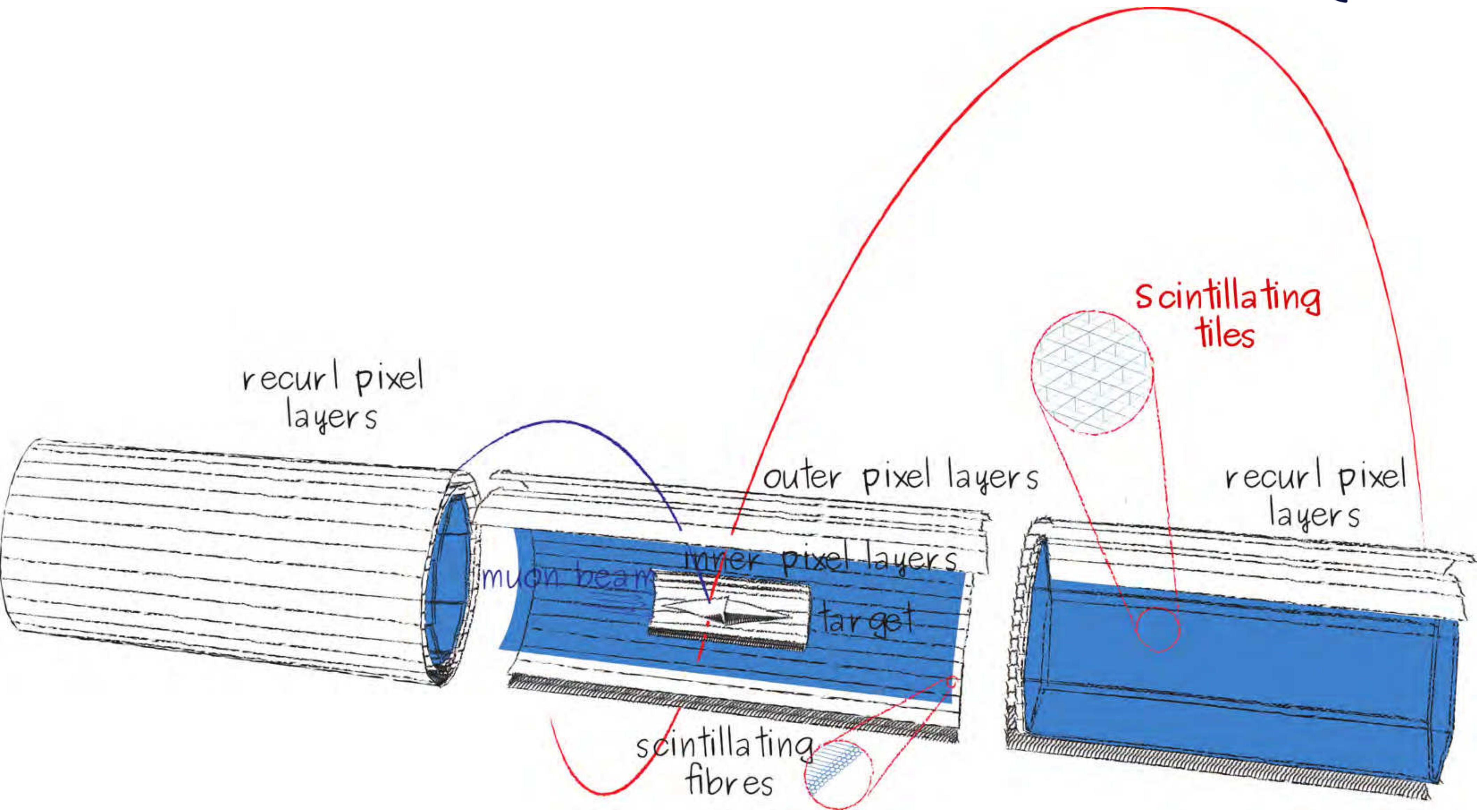
Single fiber time resolutions



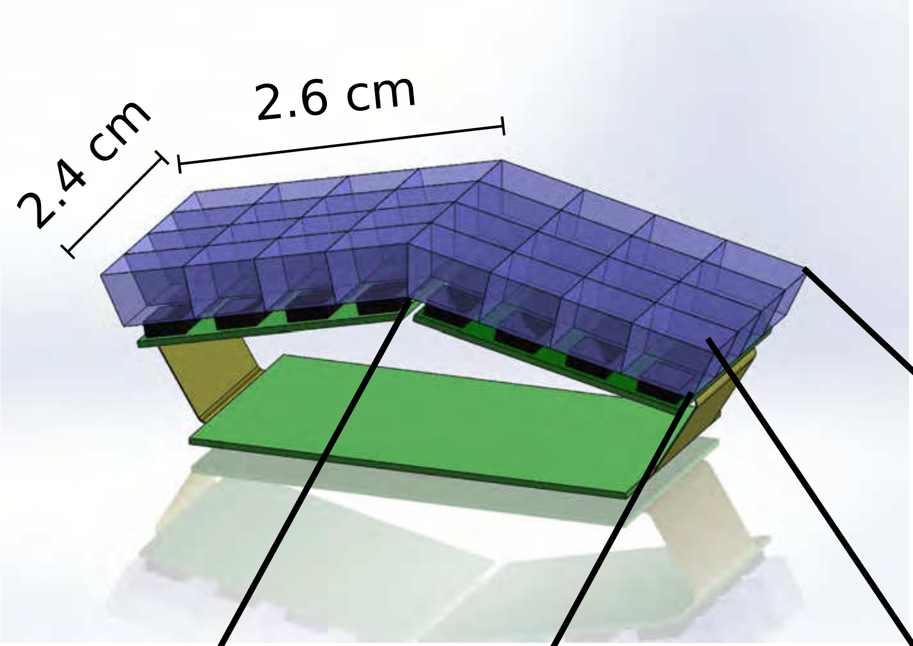


Double layer square fibres, AND configuration, N_{pe} > 0.5: 93 % efficiency

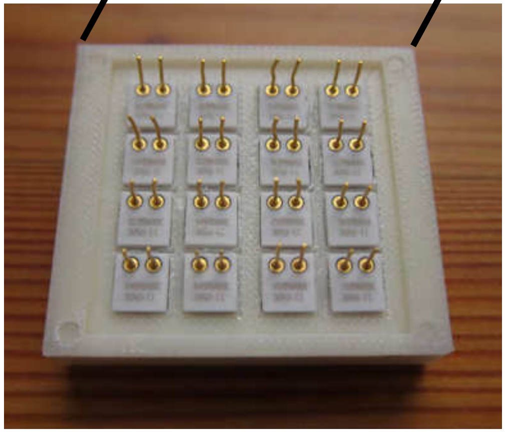
Scintillating Tiles

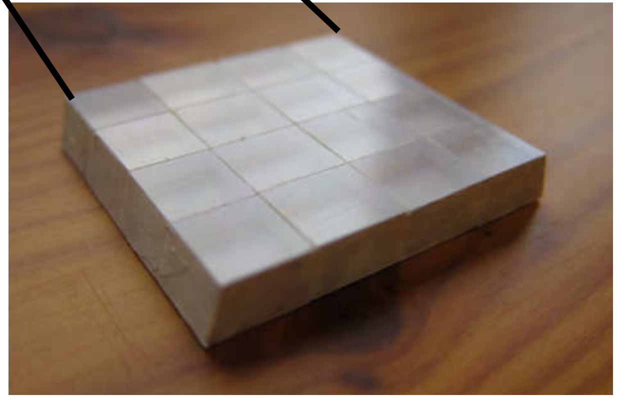


Scintillating Tiles



- Plastic scintillator
- 6.5 x 6.0 x 6.5 mm³

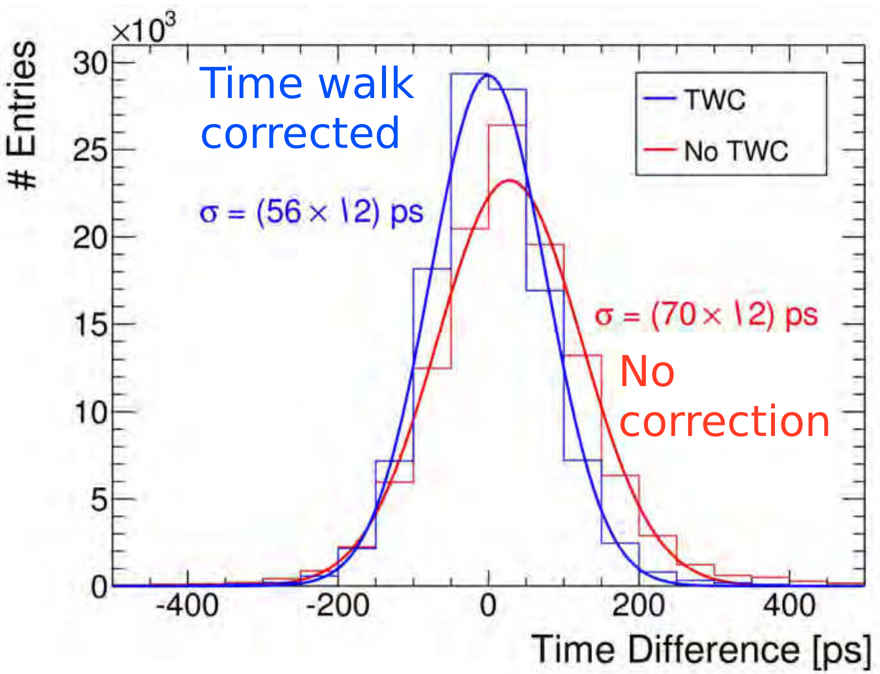


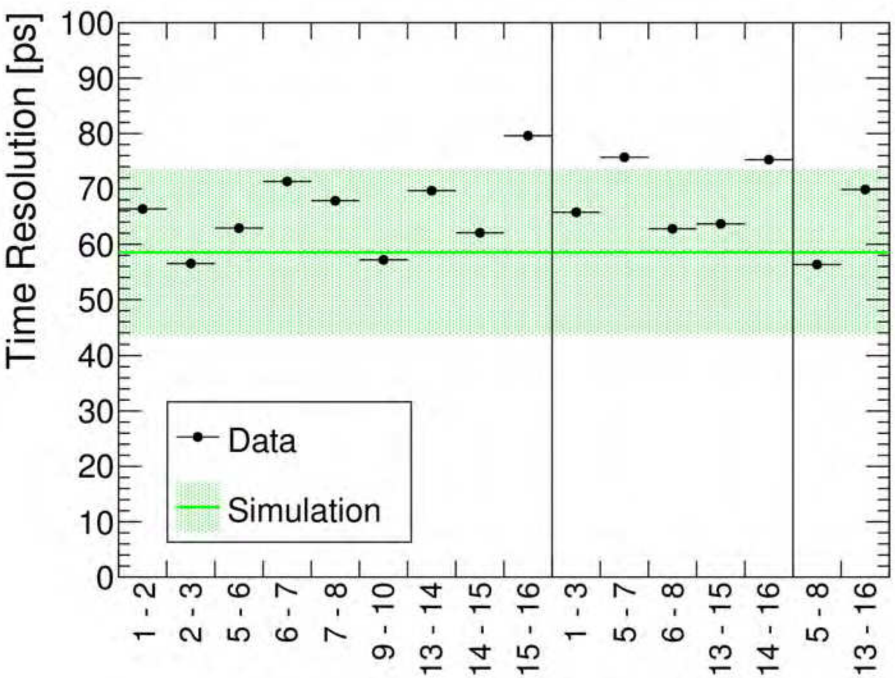


- Each read out by SiPM

Scintillating Tiles

- Efficiency > 99.7 %
- Time resolution ~ 66 ps

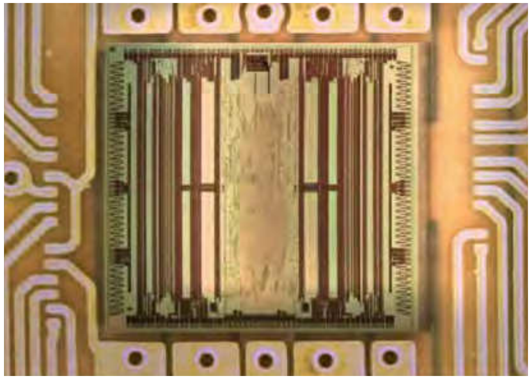




STiC Readout Chip

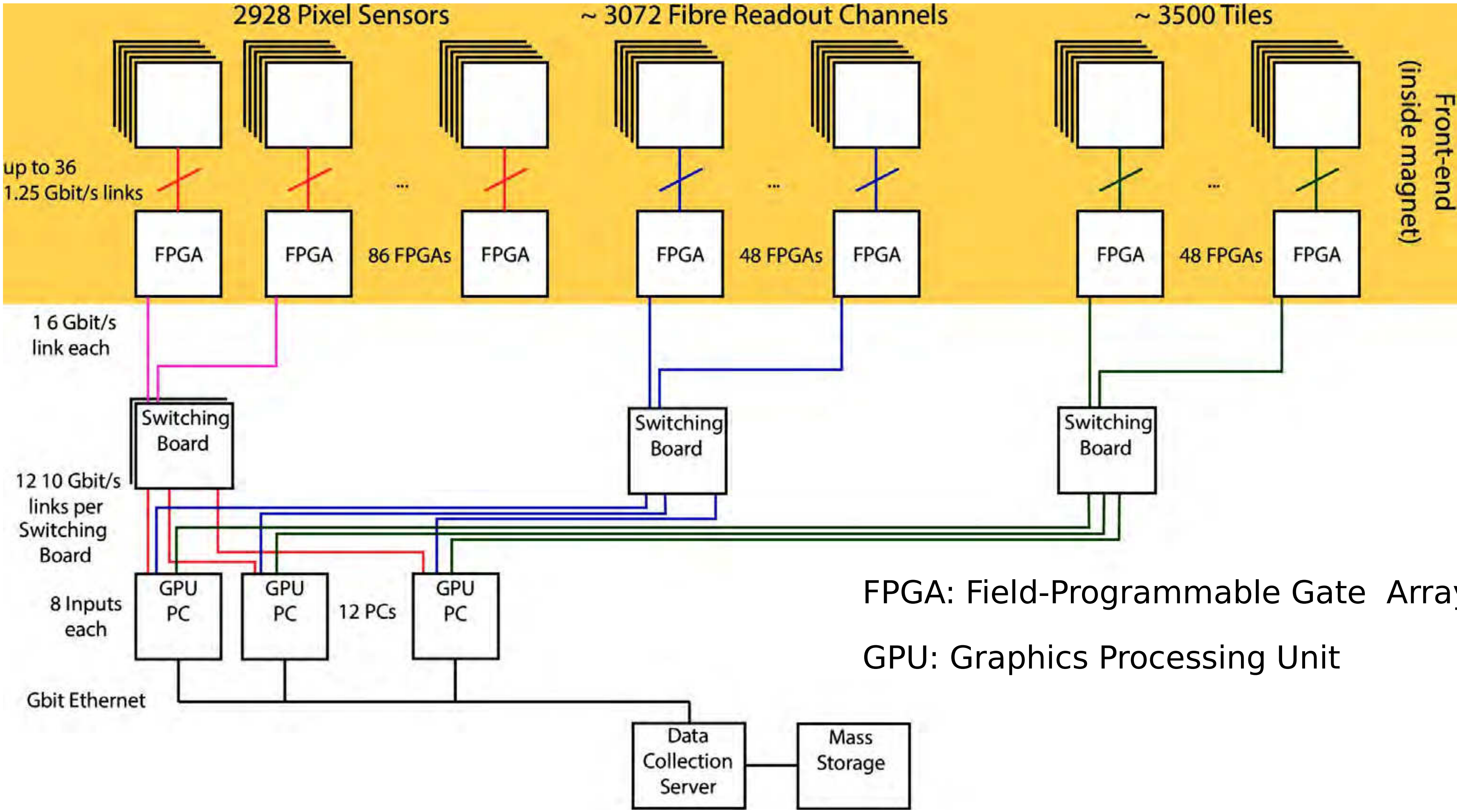
For tiles and fibers

- Mixed signal Application-Specific Integrated Circuit (ASIC)
- Developed for readout of SiPMs
- Time to digital converter
- Intrinsic time resolution: ≤30 ps
- Adjust individual SiPM bias voltages
- LVDS output link: 160 Mbit/s
- Ongoing development for MuSTiC: LVDS output link: 1.25 Gbit/s



STiC version 3.1

Readout Scheme



FPGA: Field-Programmable Gate Array

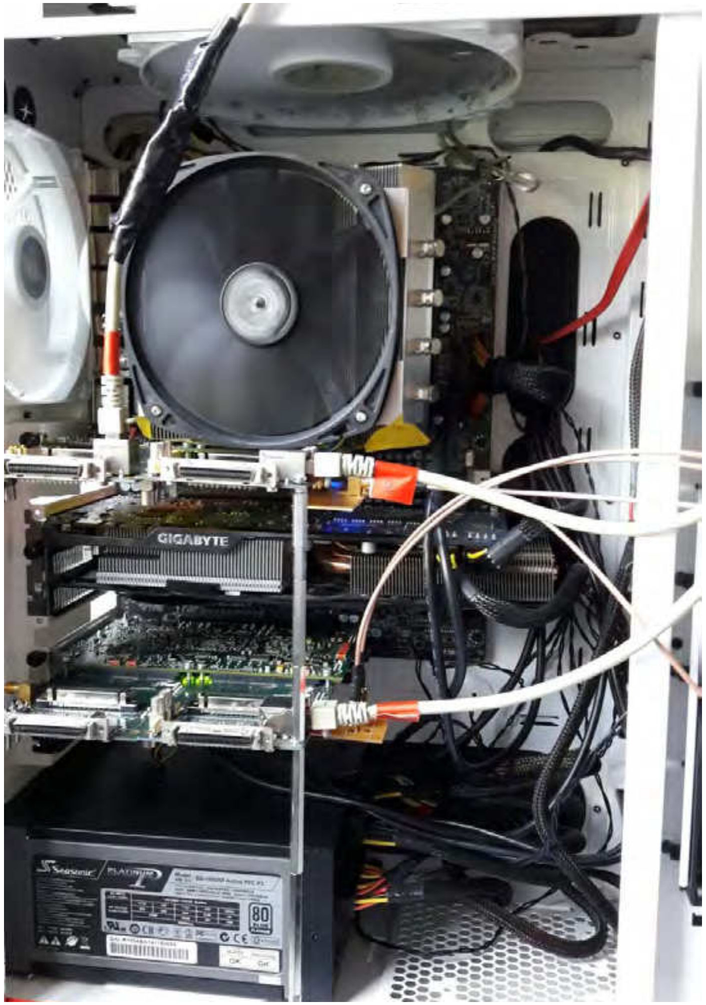
GPU: Graphics Processing Unit

Online Filter Farm

- Triggerless readout →

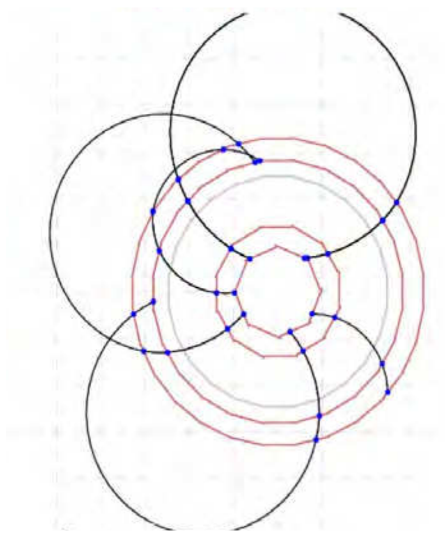
  50 Gbit/s data rate @ 10^9 muons/s
- Online data reduction
- DAQ PCs with GPUs and FPGAs
- Online track and vertex reconstruction
- 10^{10} track fits/s achieved
- Data reduction by factor ~1000

  → Store < 100 MB/s

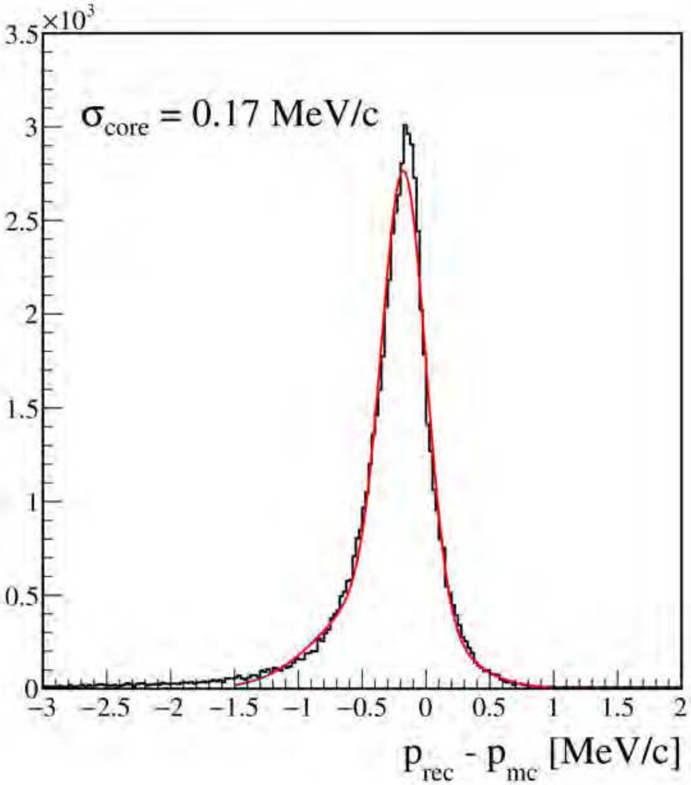


Offline Track Reconstruction

- 3D multiple scattering fit specifically developed for Mu3e
- Consider hits in 3 layers as triplet
- Minimize multiple scattering angles during fit
- Ignore spatial uncertainty of hit positions

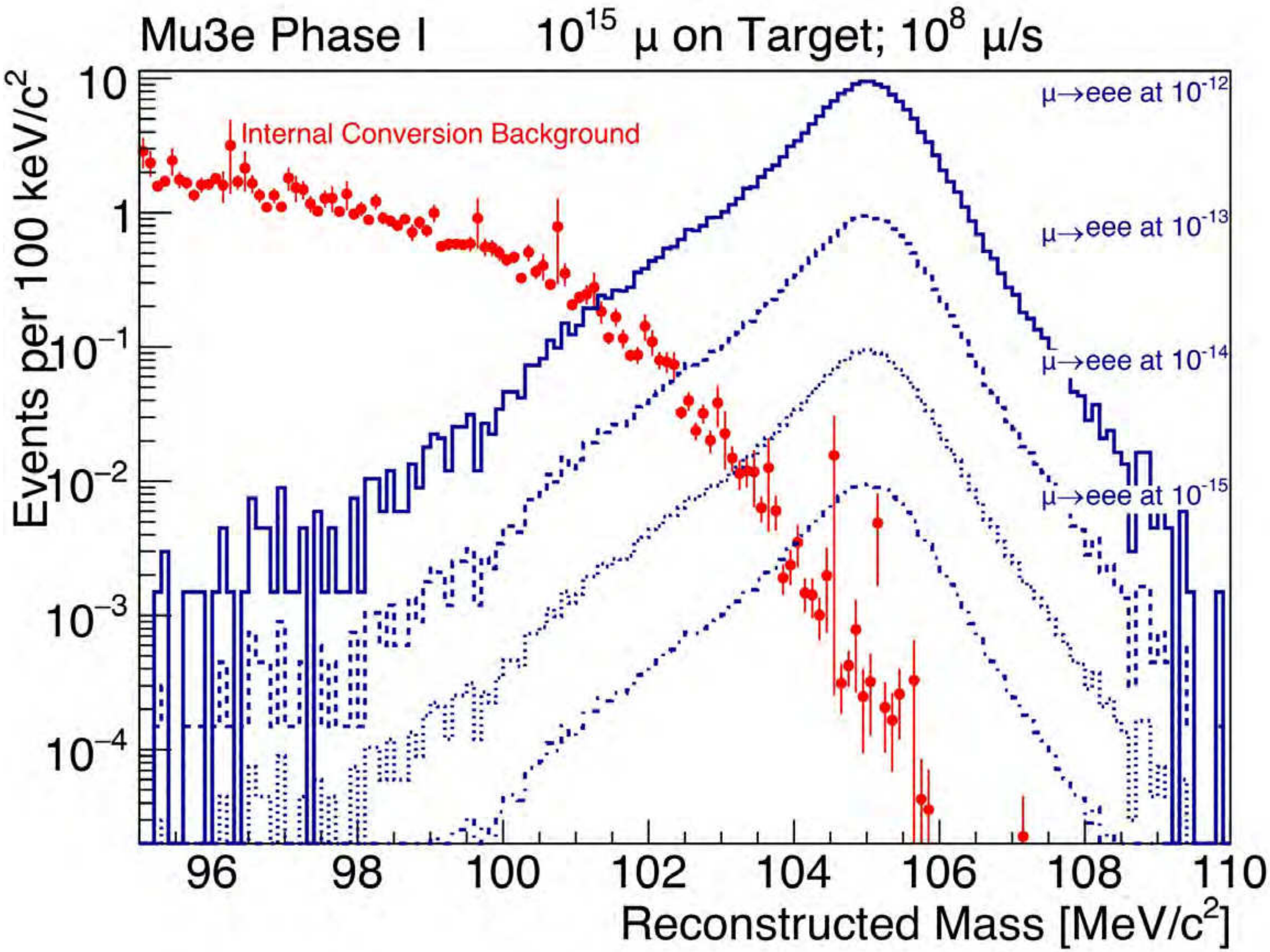


Recurling tracks from GEANT simulation, 25 MeV/c < p < 35 MeV/c



→ Specification fulfilled

Sensitivity Study



Institutions

- University of Geneva
- Heidelberg University
- Karlsruhe Institute of Technology
- Mainz University
- Paul Scherrer Institut
- ETH Zurich
- University of Zurich

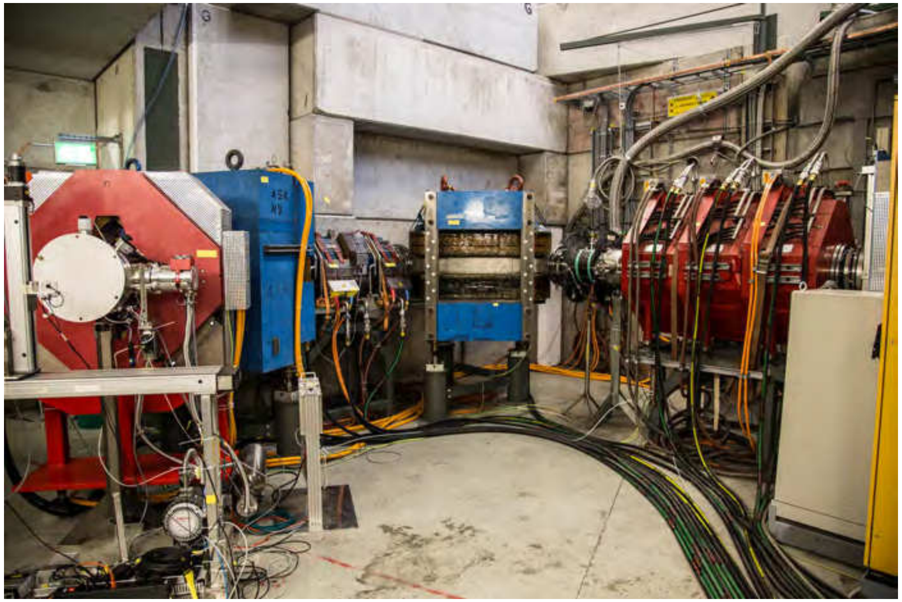
Summary

Phase I

- Search for $\mu^+ \rightarrow e^+e^-e^+$ with a sensitivity in branching ratio of 10^{-15}
- Up to 10^8 muons/s
- Minimum material budget
- Pixel, fiber and tile prototypes meet the requirements
- Magnet will be delivered in 2017
- Construction in 2017
- Commissioning earliest in 2018

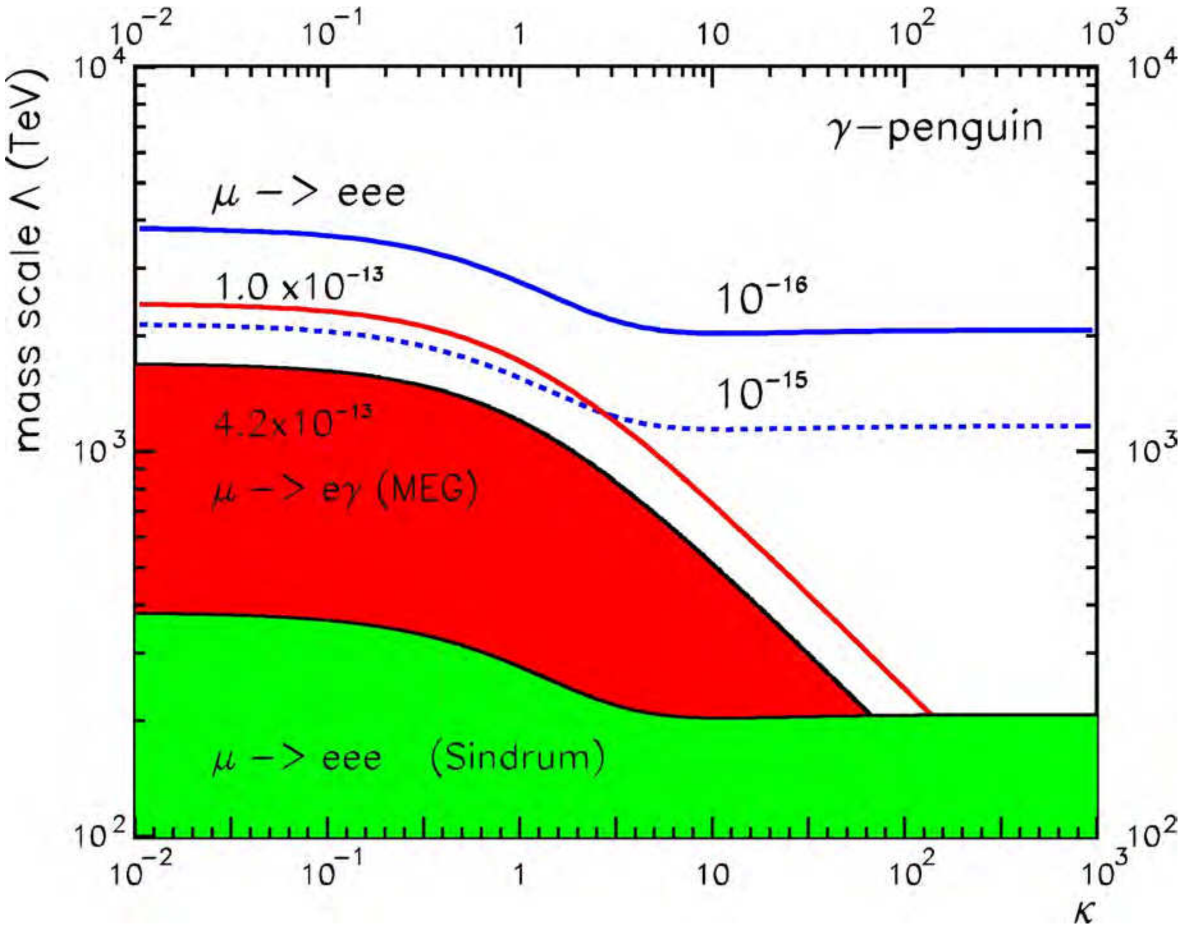
Phase II: Upgrade

- Rates up to 10^9 muons/s with high intensity muon beamline
- Reach sensitivity of 10^{-16}

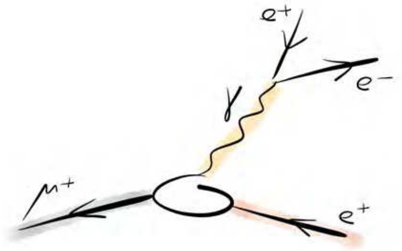


Backup

Lepton Flavor Violation

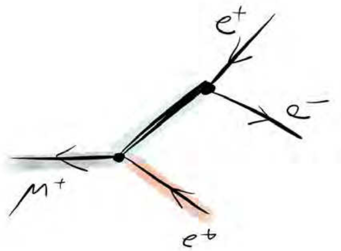


Based on A. de Gouvêa, P. Vogel, Prog.Part.Nucl.Phys 71, 75-92 (2013)



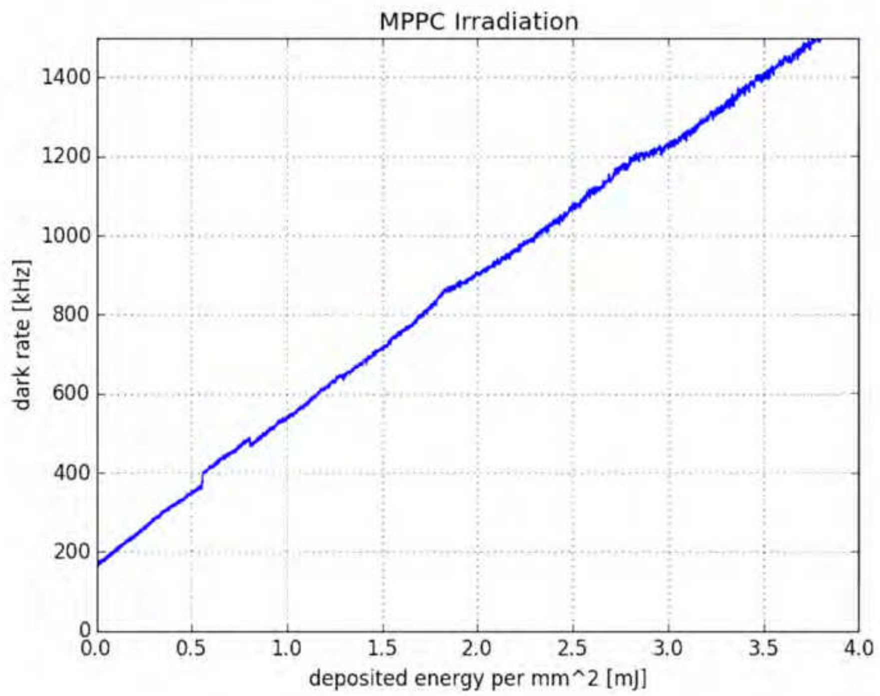
$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + h.c.$$

$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L (\bar{e}\gamma^\mu e) + h.c.$$



SiPM Radiation Hardness

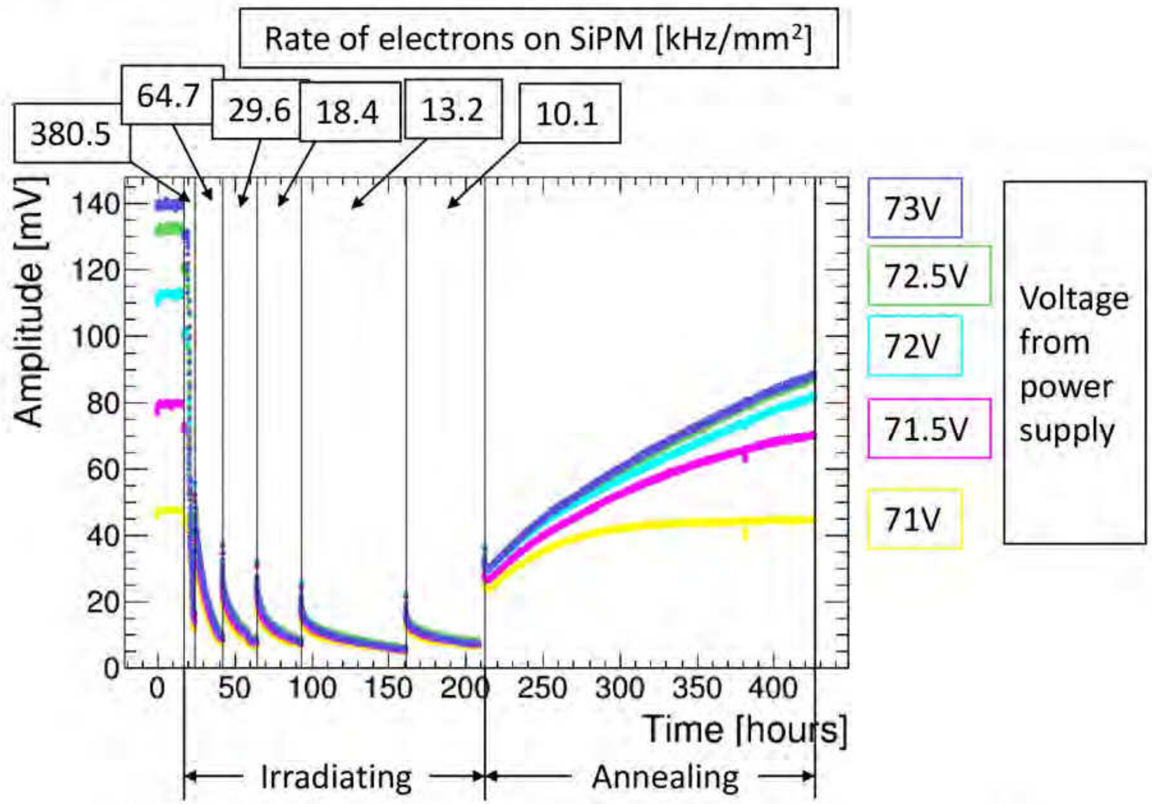
- Phase I: electron / positron flux per mm^2 active sensor in SiPM: 0.9 kHz (1.7 kHz)
- Average deposit: 42 keV
- 0.8 (1.4)$\cdot 10^{10}$ e^+/mm^2/year
- 24 (42) Gy/year
- Measurement: 1x1 mm^2 active area Hamamatsu S12571-050P, 50x50 µm^2 pixels, 20 MBq ^{90}Sr



SiPM: Radiation Hardness

Old Style SiPM - Amplitude

- Amplitude falls dramatically after 3 hours of radiation at highest rate
- Rate of decay depends on rate of incoming electrons
- Cause of breakdown unclear
- At 25˚C annealing significantly slower than radiation damage



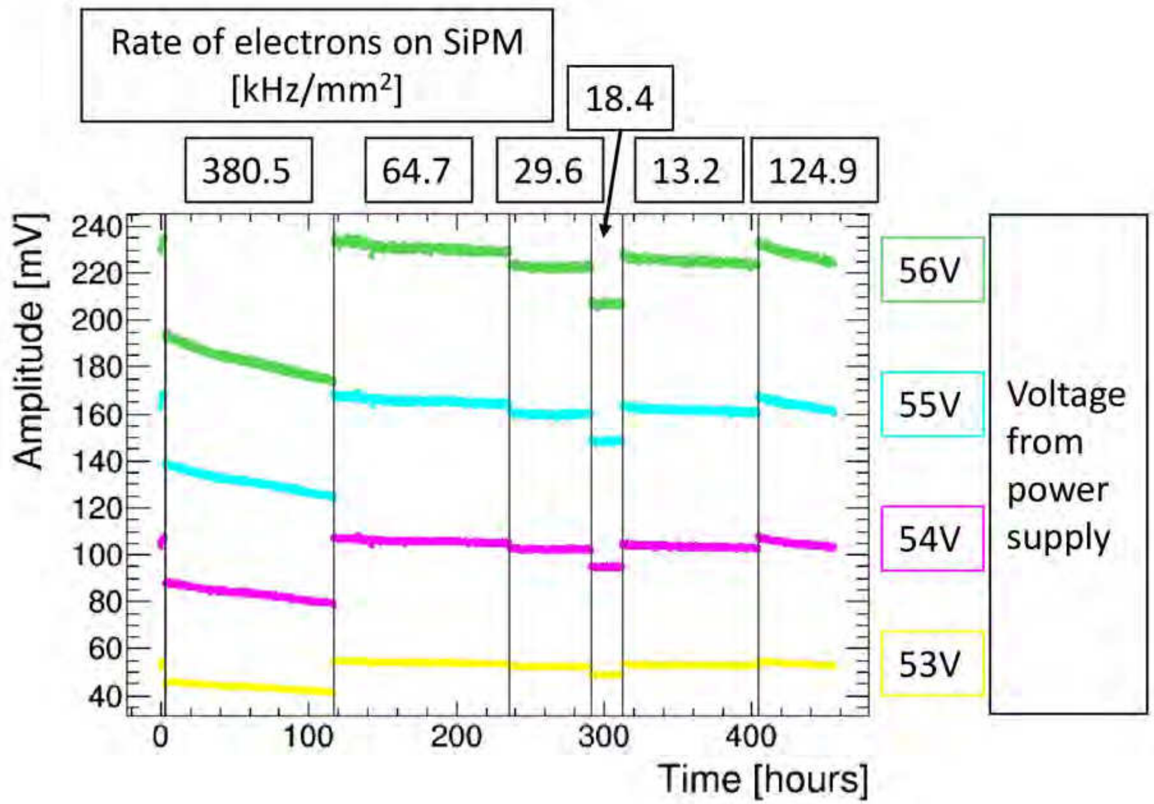
28/4/16 Mu3e Meeting 4

Slide by Stephanie Mellor

SiPM: Radiation Hardness

Current Style SiPM - Amplitude

- Amplitude decreases linearly with time
- At highest rate SiPM dies after 10^{13} electrons, 2 orders of magnitude higher than in phase 1b of Mu3e
- Positron rate at Mu3e ≈ 1 kHz/mm^2
  - ➢ Almost no decrease in amplitude seen for electron rates 10 times greater than this



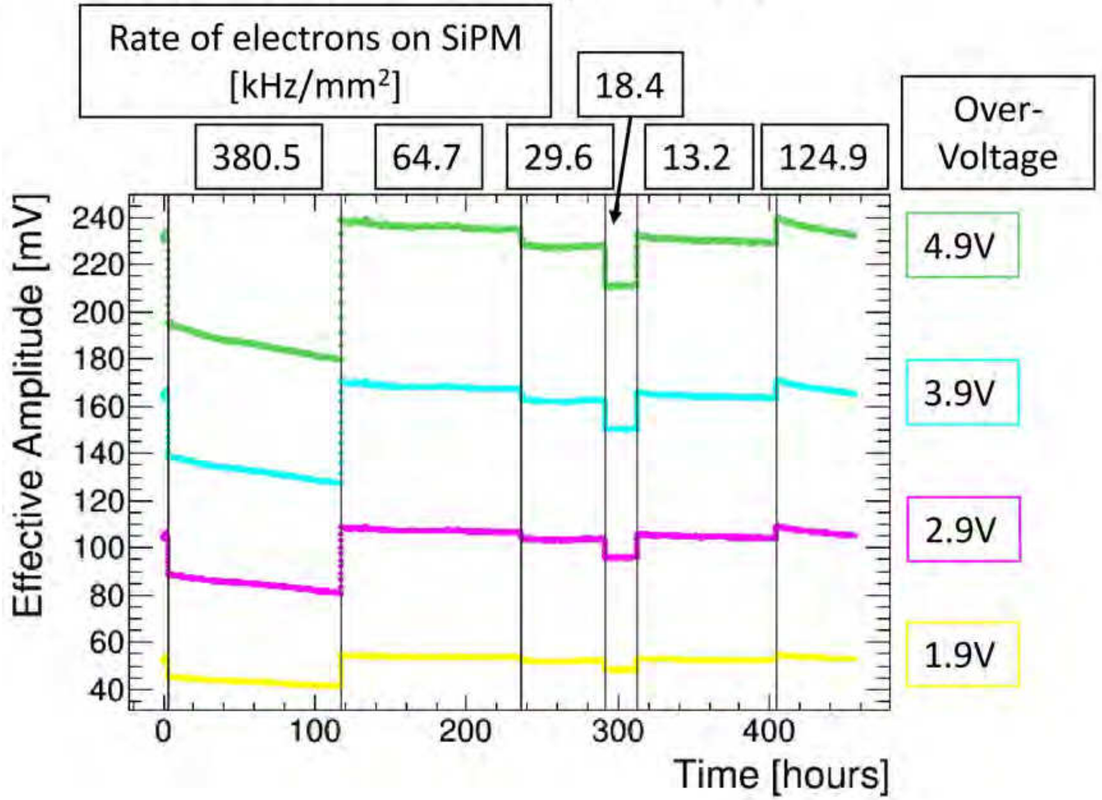
28/4/16 Mu3e Meeting 5

Slide by Stephanie Mellor

SiPM: Radiation Hardness

Current Style SiPM – Corrected Amplitude

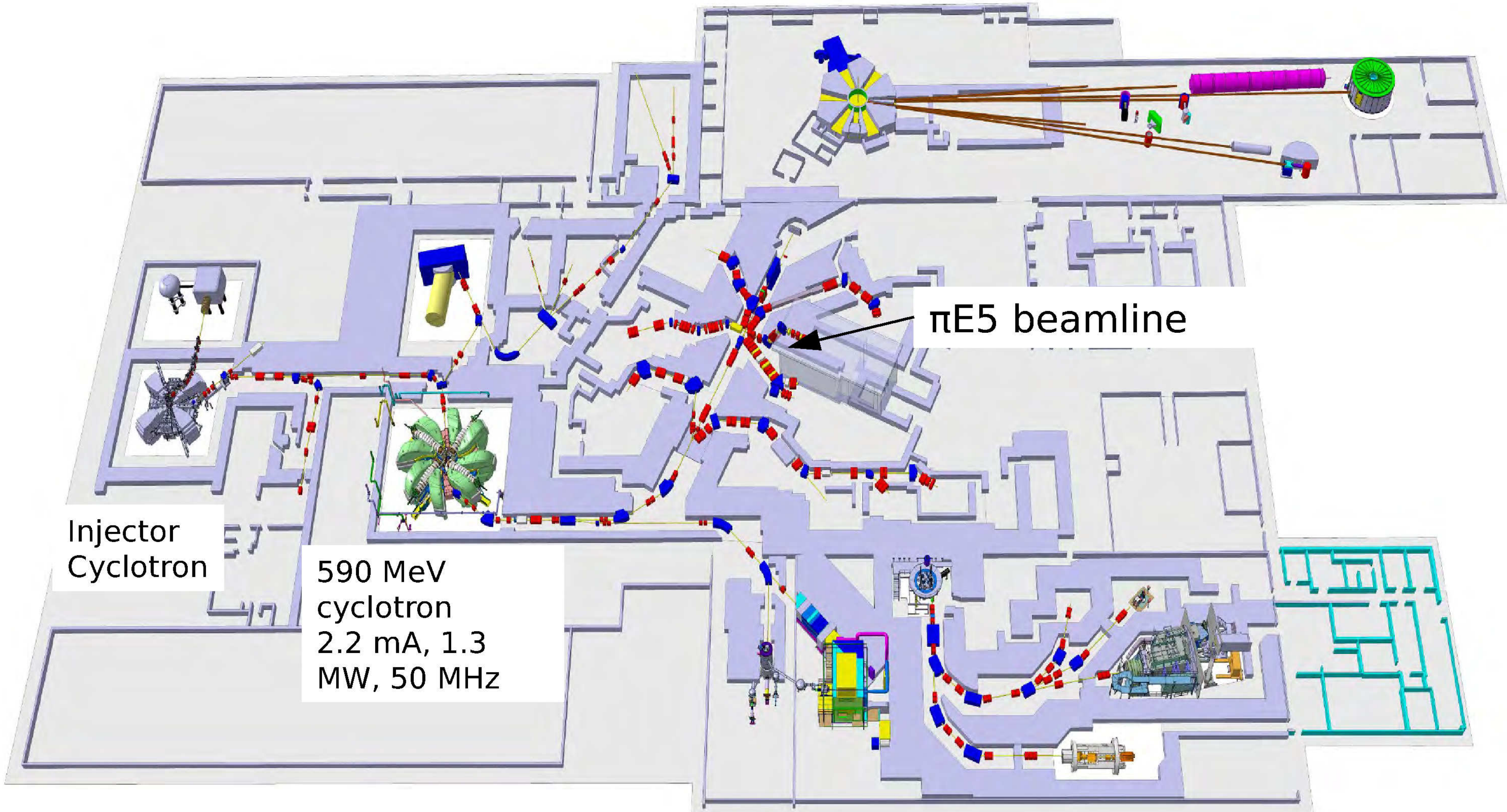
- Right shows amplitude calculated for constant over-voltage
- Amplitude still decreases linearly with time
  - ➢ Voltage drop is not what caused the amplitude decrease
  - ➢ Cause of decrease not known



28/4/16 Mu3e Meeting 7

Slide by Stephanie Mellor

High Intensity Proton Accelerator @ PSI



Muon Beam Facilities

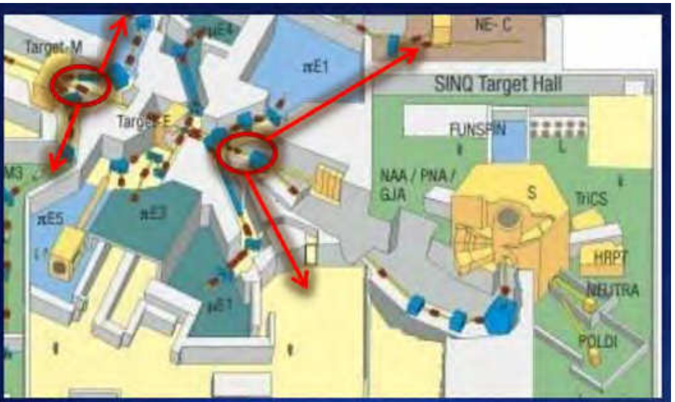
Laboratory/ Beam Line	Energy/ Power	Present Surface μ^+ Rate Hz	Future estimated μ^+/μ^- Rate Hz
PSI (CH)	(590 MeV, 1.3MW, DC)		
- LEMS	"	$4 \cdot 10^8$	
- πE5	"	$1.6 \cdot 10^8$	
- HiMB	(590 MeV, 1 MW DC)		$4 \cdot 10^{10}$ (μ+) (for cf. only)
J-PARC (JP)	(3 GeV, 1MW Pulsed) currently 300kW		
- MUSE D-line	"	$4.5 \cdot 10^6$	$1.5 \cdot 10^7$ (μ+) 2013
- MUSE U-Line	"	$1.5 \cdot 10^8$	$2 - 5 \cdot 10^8$ (μ+) 2013
- COMET	(8 GeV, 56kW Pulsed)		10^{11} (μ-) 2019/2020
- PRIME/PRISM	(8 GeV, 300 kW Pulsed)		10^{11-12} (μ-) >2020
FNAL (FermiLab) (USA)			
- Mu2e	(8GeV, 25kW Pulsed)		$5 \cdot 10^{10}$ (μ-) 2019/2020
- Project X Mu2e	(3GeV, 750kW Pulsed)		$2 \cdot 10^{12}$ (μ-) >2022
TRIUMF (CA)	(500 MeV, 75kW, DC)		
-M20		$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW Pulsed)		
- Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160kW, Pulsed)		
- RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400W DC)		
- MUSIC	currently max 4W		10^8 (μ+) * 2012 * (≡ > 10^{11} per MW!!!)
DUBNA (RU)	(660 MeV, 1.65kW Pulsed)		
- Phasotron Ch:I-III		$3 \cdot 10^4$	

High Intensity Muon Beamline

Alternative Possibilities

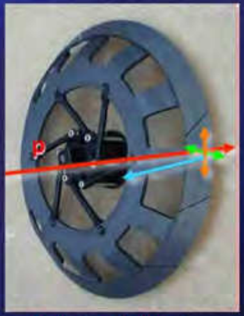
Constraints - any intervention to the proton beam line must:

- Not significantly increase the beam losses
- Preserve the proton footprint and energy on SINQ
- Preserve the total material budget seen by the beam



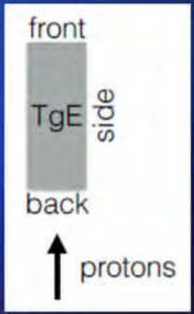
Just started to look at "conventional targets" in combination with solenoids
Possibilities under assessment

As a "conventional target", Target E is surprisingly efficient at producing surface muons: for I_p=2.3 mA



Polycrystalline Graphite, 1700K

TgE length	Front	Back	Side
10 mm	9.6×10^{9}/s	1.5×10^{10}/s	1.9×10^{10}/s
20 mm	1.3×10^{10}/s	1.9×10^{10}/s	5.8×10^{10}/s
30 mm	1.6×10^{10}/s	1.7×10^{10}/s	9.5×10^{10}/s
40 mm	1.6×10^{10}/s	2.0×10^{10}/s	1.3×10^{11}/s
60 mm	1.6×10^{10}/s	2.1×10^{10}/s	2.2×10^{11}/s

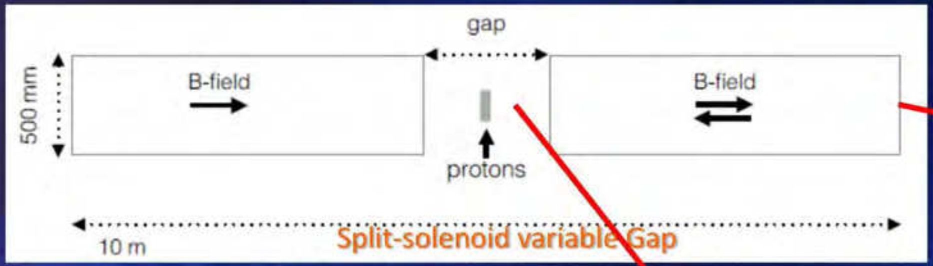


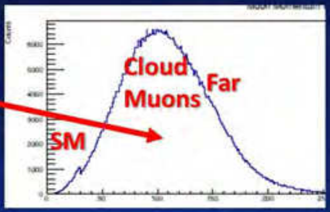
- Front/back surfaces saturate with L
- side surface viewing very efficient

Peter-Raymond Kettle *Future Muon Sources Workshop – Univ. of Huddersfield 2015* *16*

High Intensity Muon Beamline

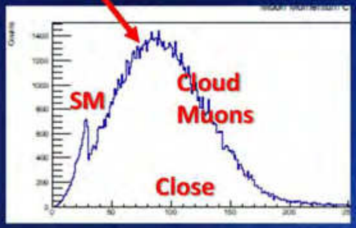
The Solenoid Approach

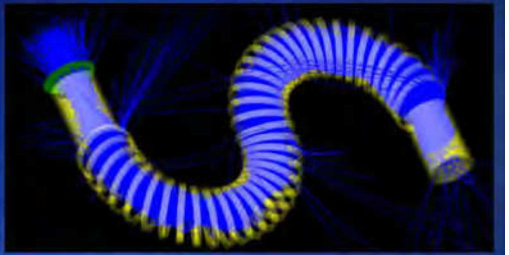




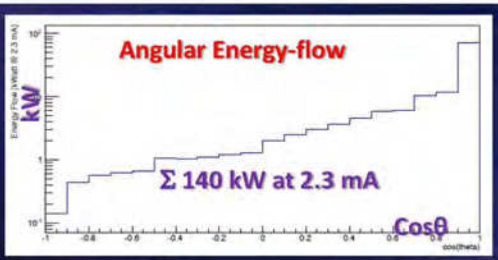
60mm long target

B-field	Gap	Close	(All) Far (Origin Tg)
0	0	2.4×10^{11}	6.3×10^{8} (2.8×10^{8})
0.5 T (++)	0	2.7×10^{11}	1.7×10^{11} (1.3×10^{11})
1.5 T (++)	0	5.2×10^{11}	6.1×10^{11} (2.3×10^{11})
5.0 T (++)	0	5.3×10^{11}	7.3×10^{11} (2.3×10^{11})
3.0 T (++)	500 mm	6.7×10^{12}	2.8×10^{11} (8.1×10^{10})
5.0 T (++)	500 mm	2.4×10^{13}	3.0×10^{11} (7.5×10^{10})
3.0 T (++)	1000 mm	2.5×10^{12}	8.6×10^{10} (3.7×10^{10})
5.0 T (++)	1000 mm	1.0×10^{13}	1.5×10^{11} (3.9×10^{10})
3.0 T (+-)	500 mm	6.5×10^{11}	1.1×10^{11} (4.5×10^{10})
5.0 T (+-)	500 mm	9.2×10^{11}	1.0×10^{11} (4.5×10^{10})
3.0 T (+-)	1000 mm	4.0×10^{11}	4.4×10^{10} (2.0×10^{10})
5.0 T (+-)	1000 mm	5.8×10^{11}	4.6×10^{10} (2.0×10^{10})





- For 500 mm Bore can already efficiently transport all muons with B = 1.5 T
- Like-polarities give axial field continuity in gap
- The smaller the gap the better the transmission
- High cloud muon content – also a decay-channel!

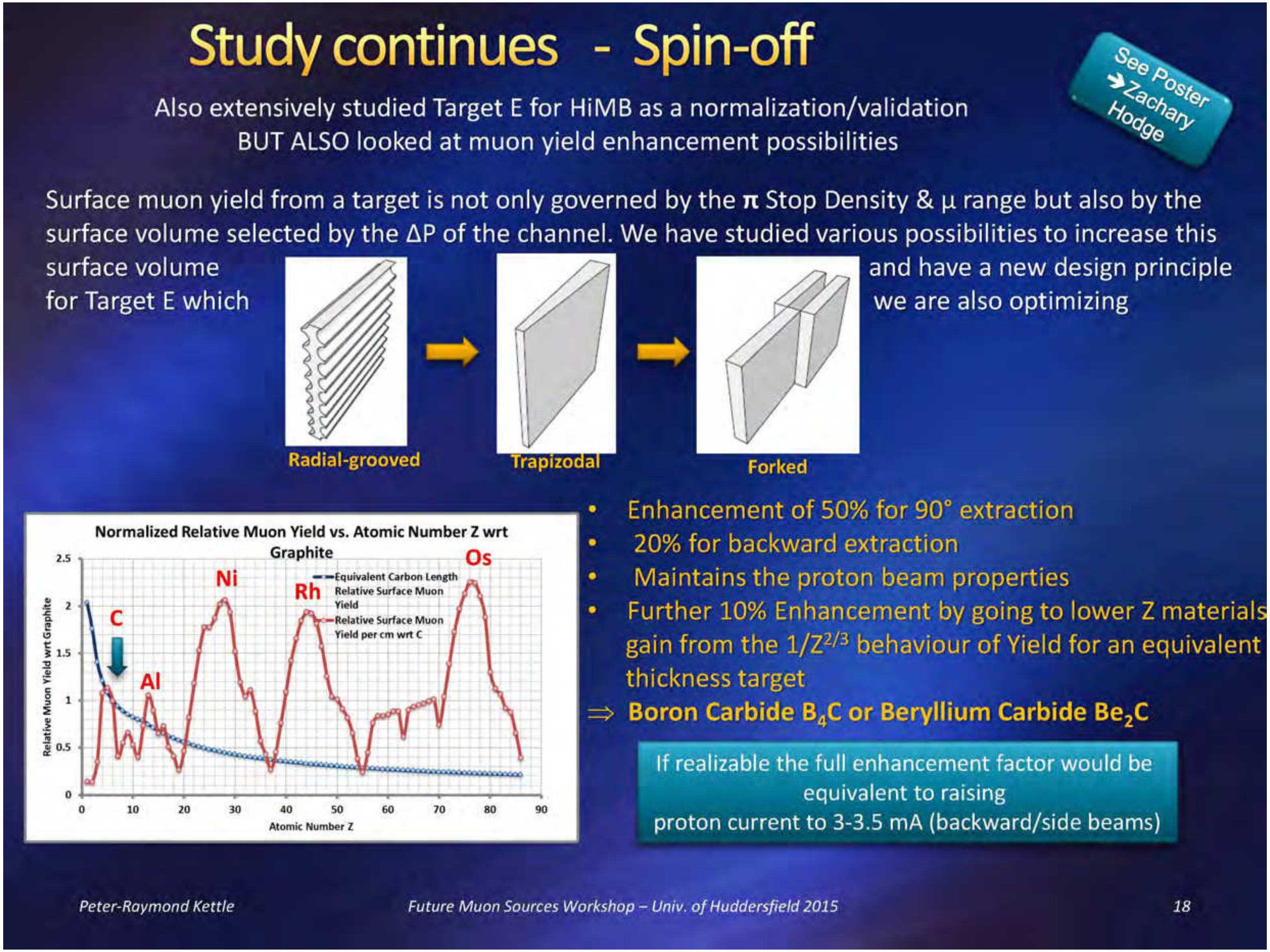


Further considerations – thermal induction from particle interactions - 140 kW propagated mainly in the forward direction (72% p, 21% n, 5% γ, 2% π)

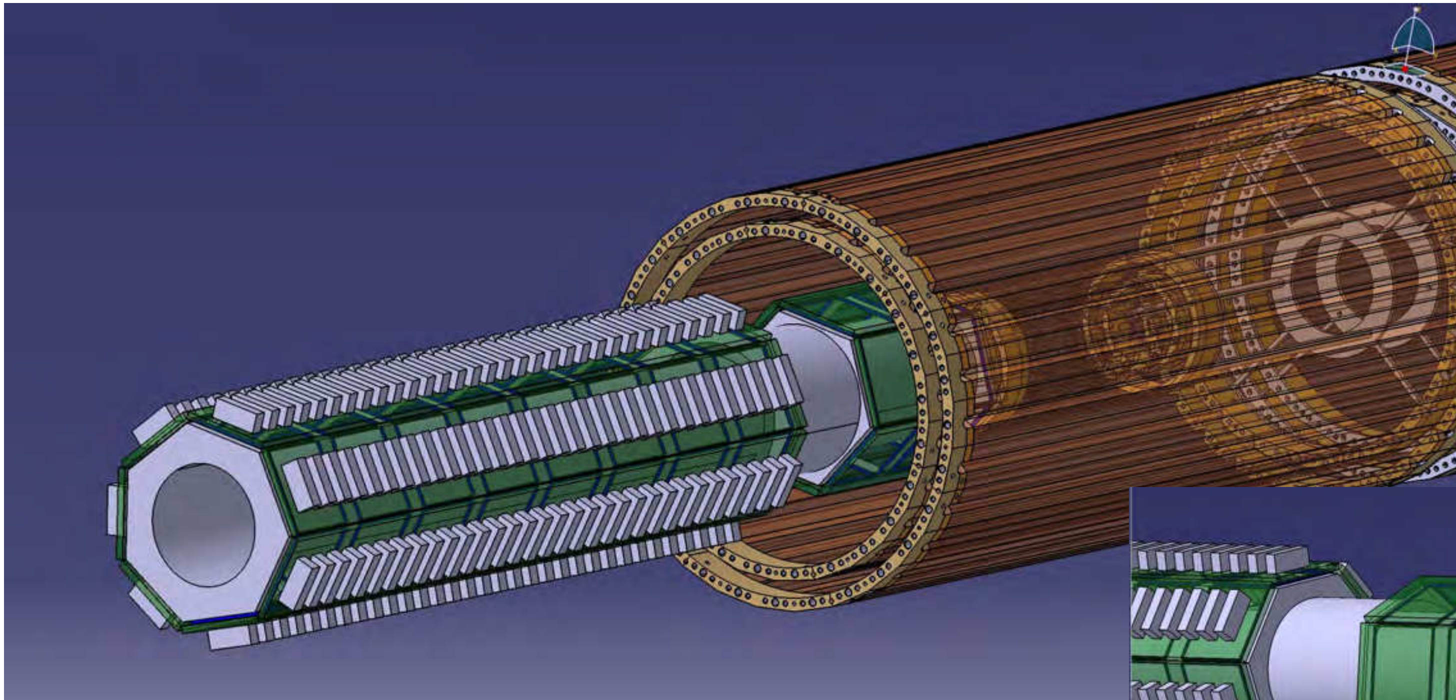
Requires heavy shielding inside solenoid

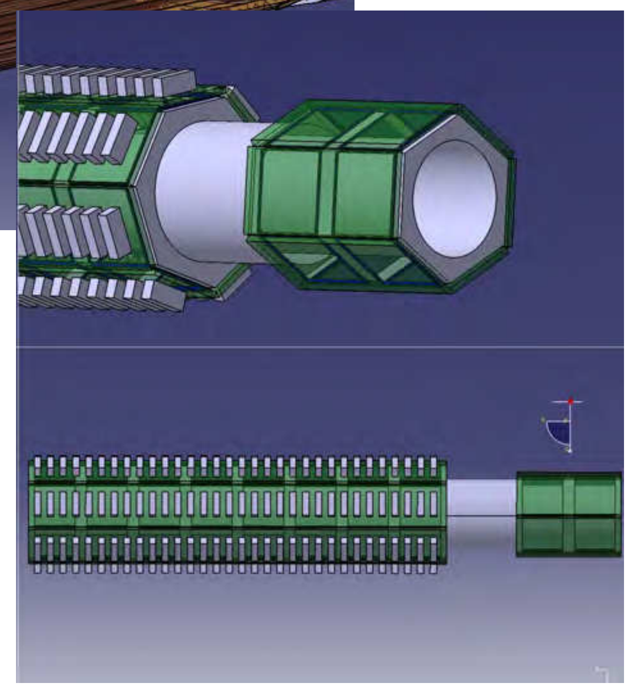
Peter-Raymond Kettle *Future Muon Sources Workshop – Univ. of Huddersfield 2015* *17*

High Intensity Muon Beamline



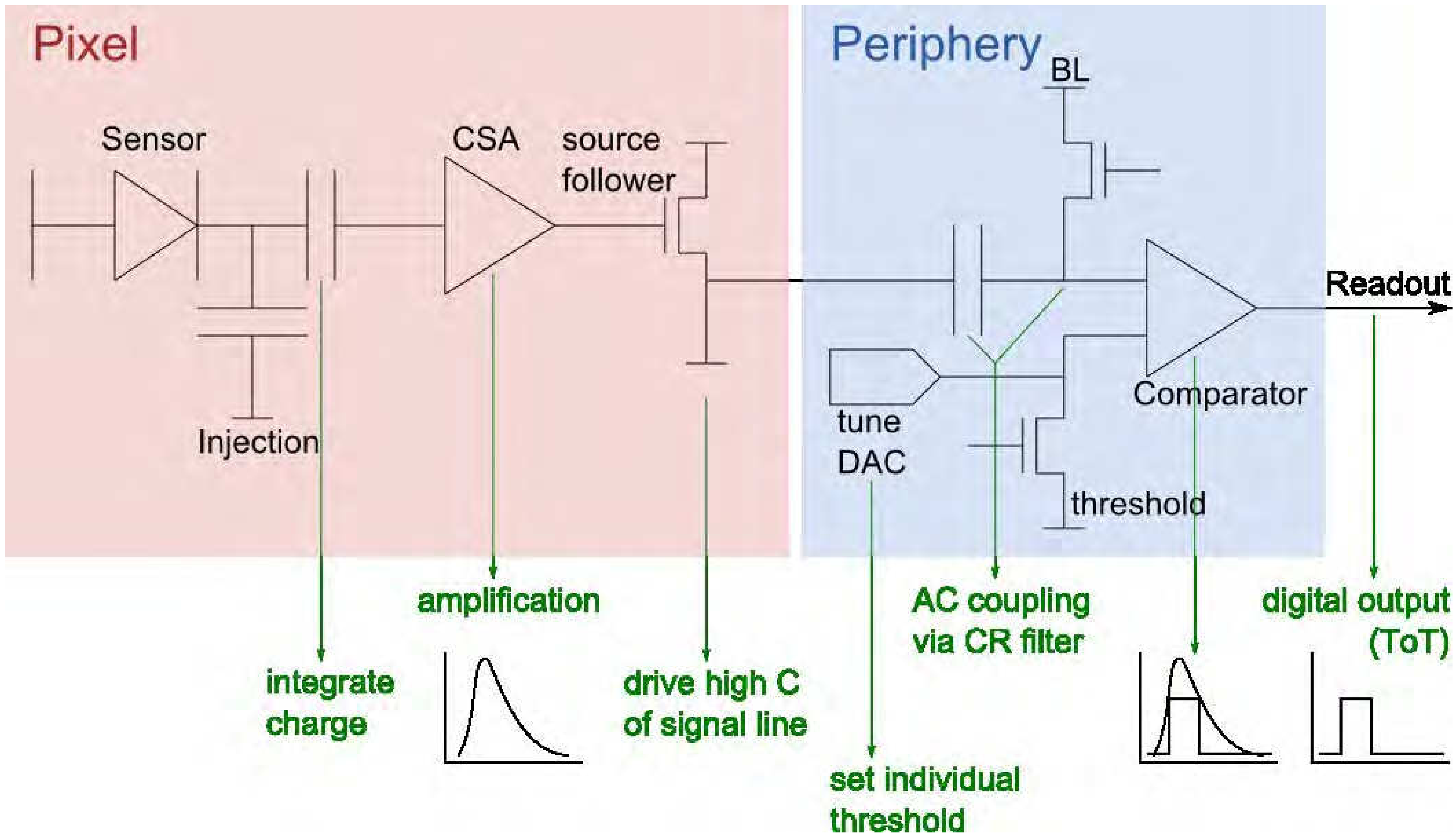
Peripherals



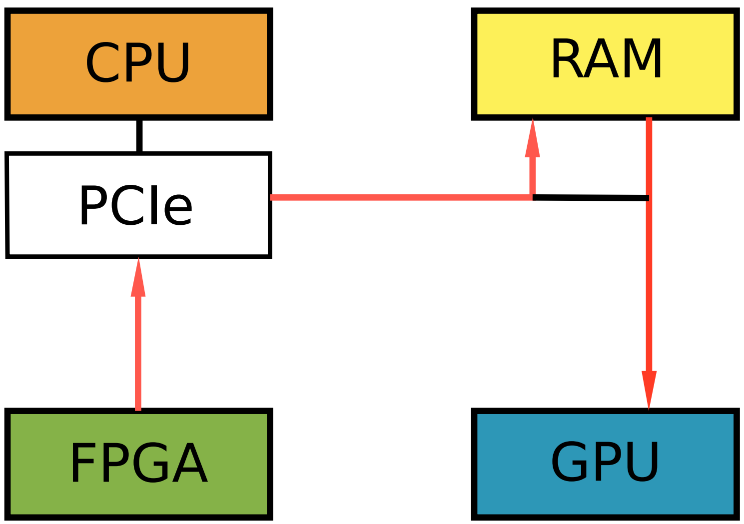


- Readout boards along beam pipe
- Cabling, flex prints along beam pipe
- No material outside of detector

Mupix Electronics

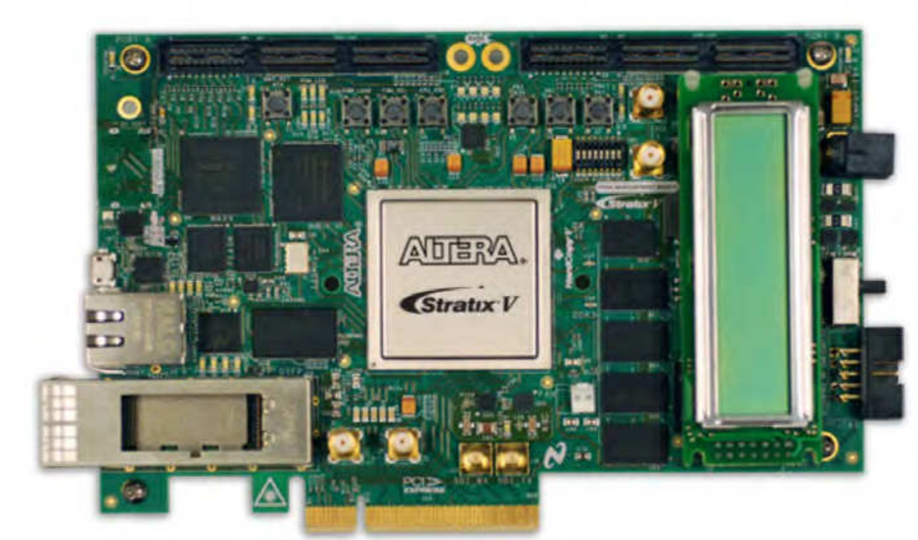


Fast Data Transfer

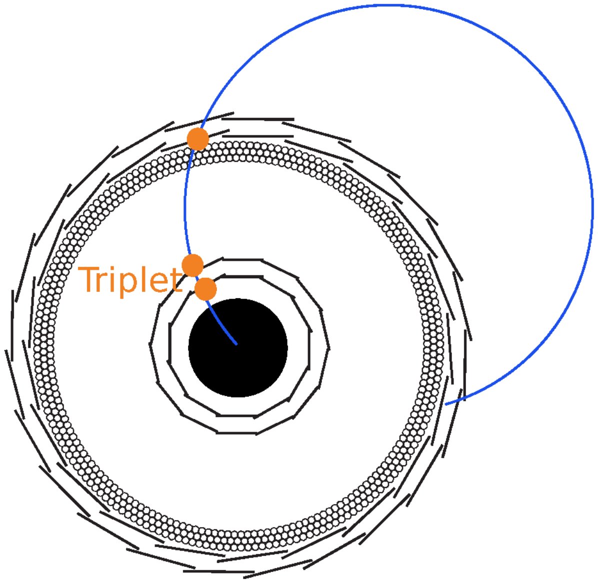


- Direct Memory Access to main memory
- Copy to GPU memory
- At 1.5 GB/s: measured bit error rate

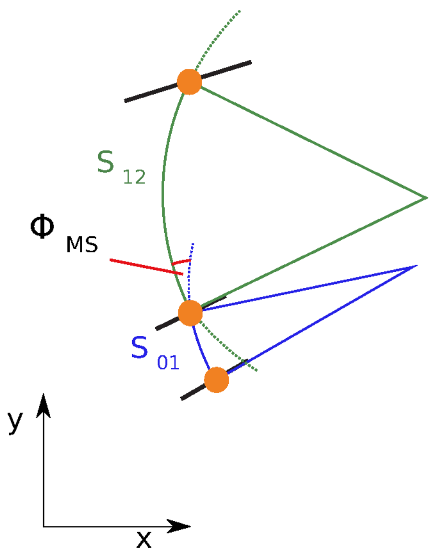
  $< 4 \times 10^{-16}$

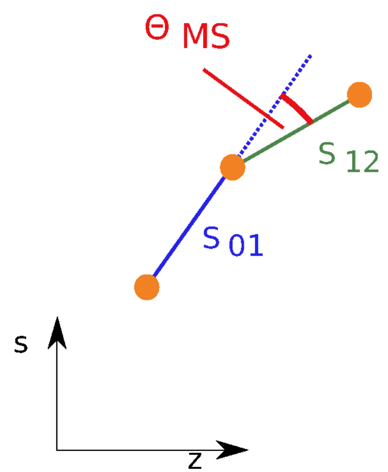


Multiple Scattering Fit



$$\chi^2 = \frac{\varphi_{MS}^2}{\sigma_{MS}^2} + \frac{\theta_{MS}^2}{\sigma_{MS}^2}$$





- Ignore hit uncertainty
- Describe track as sequence of hit triplets
- Multiple scattering at middle hit of triplet
- Minimize χ^2
- R_{3D} from fit
- Sign of $R_{3D} \rightarrow$ track curvature
- Cut on fit success and

Performance

10^8 muons / s	GTX680	GTX980
Fits / s	$2\text{x}10^7$	$3\text{x}10^7$
10^9 muons / s		
Fits / s	$9.7\text{x}10^9$	$1.6\text{x}10^{10}$

10^8 muons / s	Reduction factor	Triplets / s
Total		$2\text{x}10^{10}$
After geometrial selection	50	$4\text{x}10^8$
After multiple scattering fit	2	$2\text{x}10^8$
After propagation to 4^{th} layer	2.5	$8\text{x}10^7$

Pictures: pcmag.com, nvidia.com

@ 10^8 μ/s: $\mathcal{O}(10)$ DAQ computers are sufficient