The Mu3e Experiment
A new search for μ → eee

https://www.psi.ch/mu3e/

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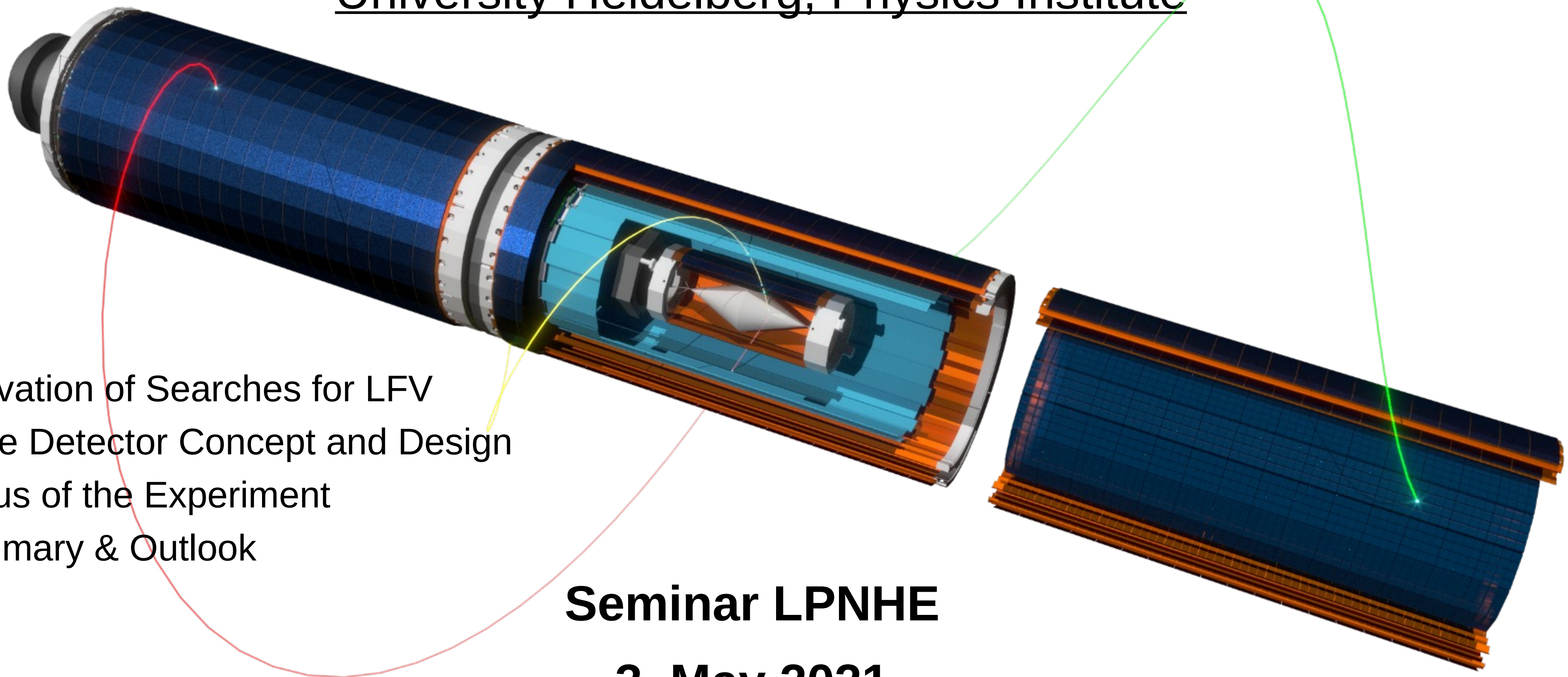
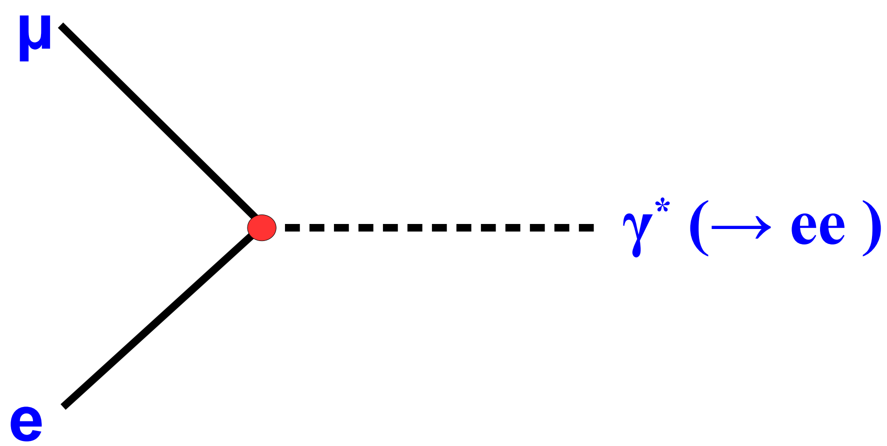


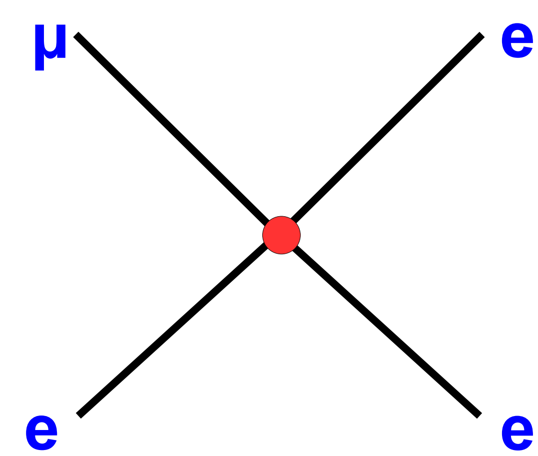
- Motivation of Searches for LFV
- Mu3e Detector Concept and Design
- Status of the Experiment
- Summary & Outlook

Seminar LPNHE

3. May 2021

Why Mu3e? (in short)





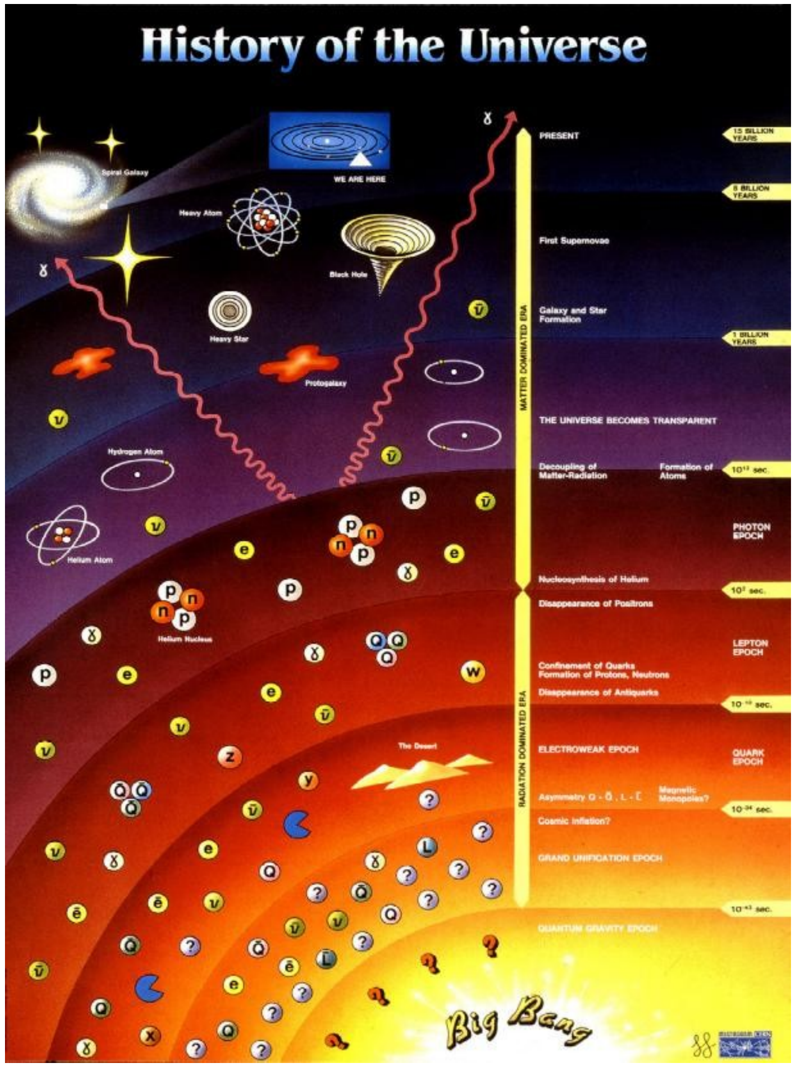
$\mu \rightarrow e\,\gamma^{*}\,(\rightarrow ee)$

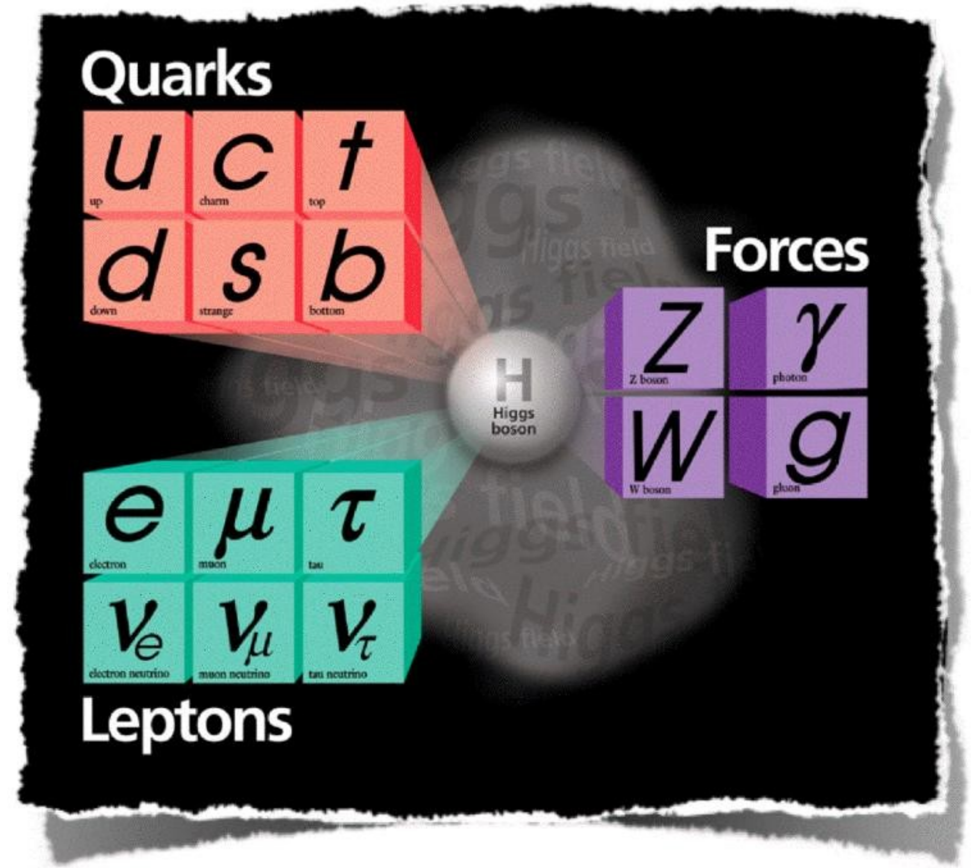
$\mu \rightarrow eee$

Lepton Flavor violating (LFV), and FCNC in more general, are forbidden in the SM

→ **Very promising process to look for New Physics**

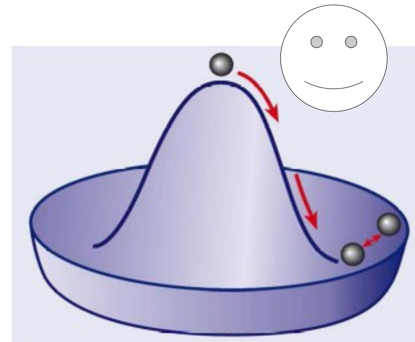
SM of Particle Physics



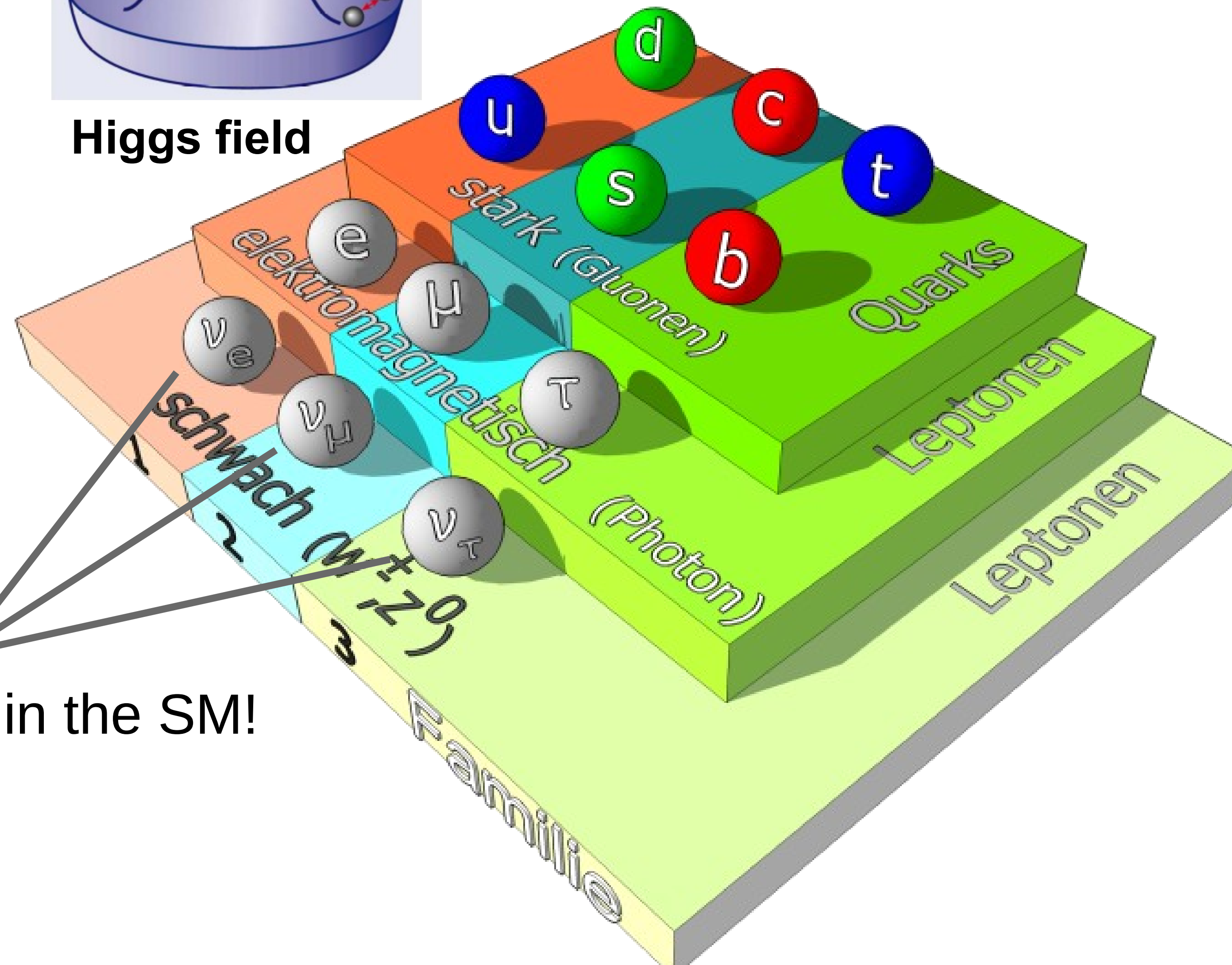


Physics after the electroweak epoch is described by the SM

Fermions in the Standard Model (SM)

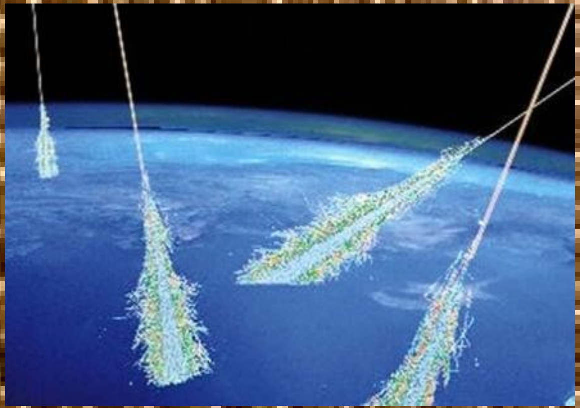


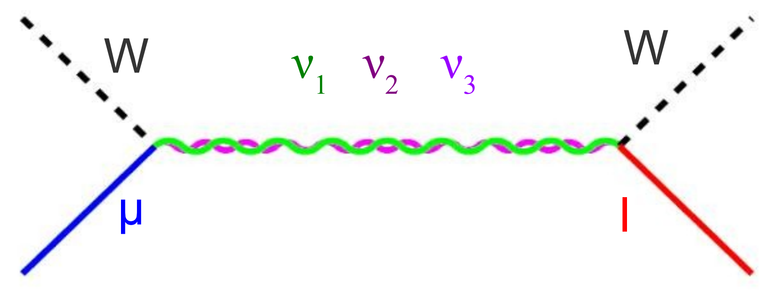
Higgs field



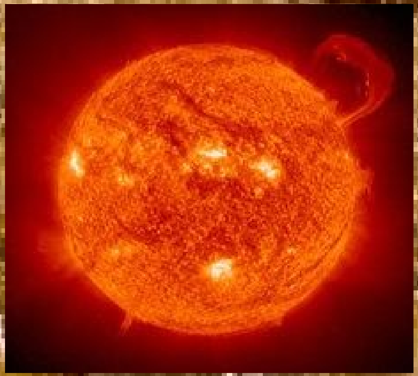
neutrinos have no mass in the SM!

Discovery of Neutrino Oscillations

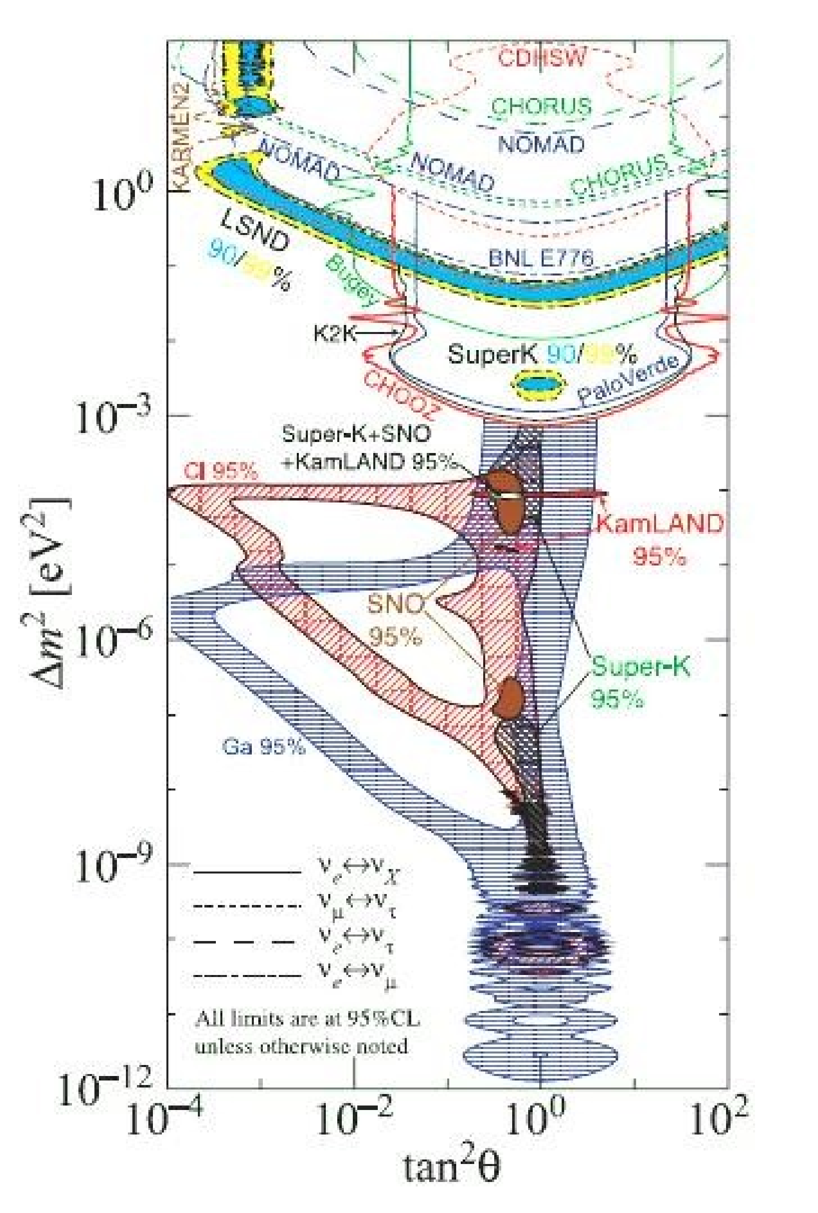




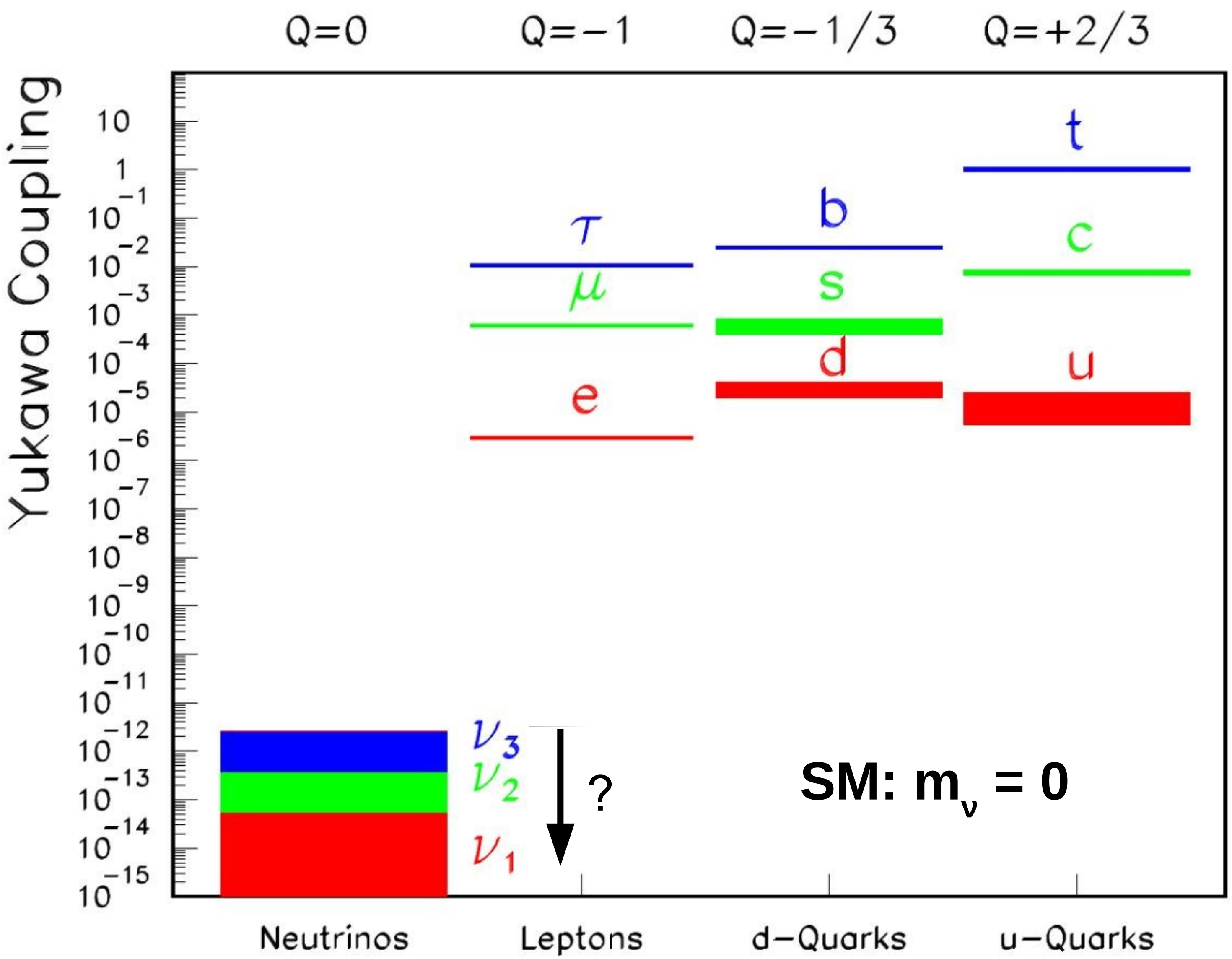
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\Theta)\,\sin^2\left(\Delta m^2_{\alpha\beta}\frac{L}{E_\nu}\right)$$



- Neutrino Oscillations:
  - solar neutrinos
  - reactor neutrinos
  - atmospheric neutrinos
  - neutrino beams



The Fermion Masses in the SM

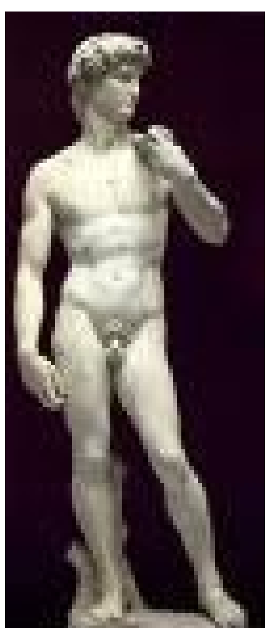


y_t~1 (within 1%)

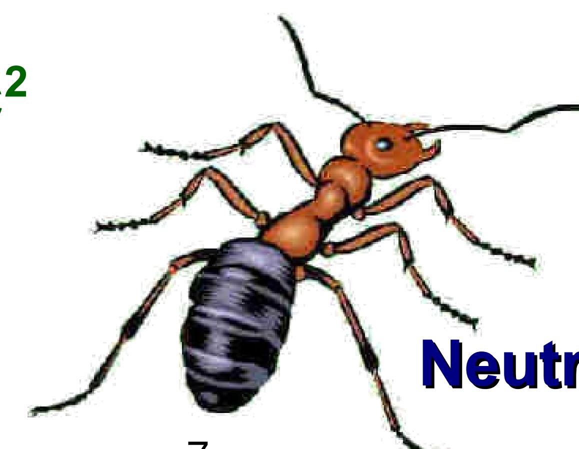
The Fermion Masses in the SM

Top Quark m = 171 GeV/c^2

Proton/Neutron: m ≈ 1 GeV/c^2



Elektron:
m ≈ 0.5 MeV/c^2



Why Higgs couplings so different?

Neutrinos: m ≈ 0.01 - 0.1 eV/c^2

Physics Beyond the SM (BSM)

Experimental Observations

- Matter-antimatter asymmetry in universe → **CP-Violation**
- Observation **Dark matter**

→ require new particles or interactions beyond the SM

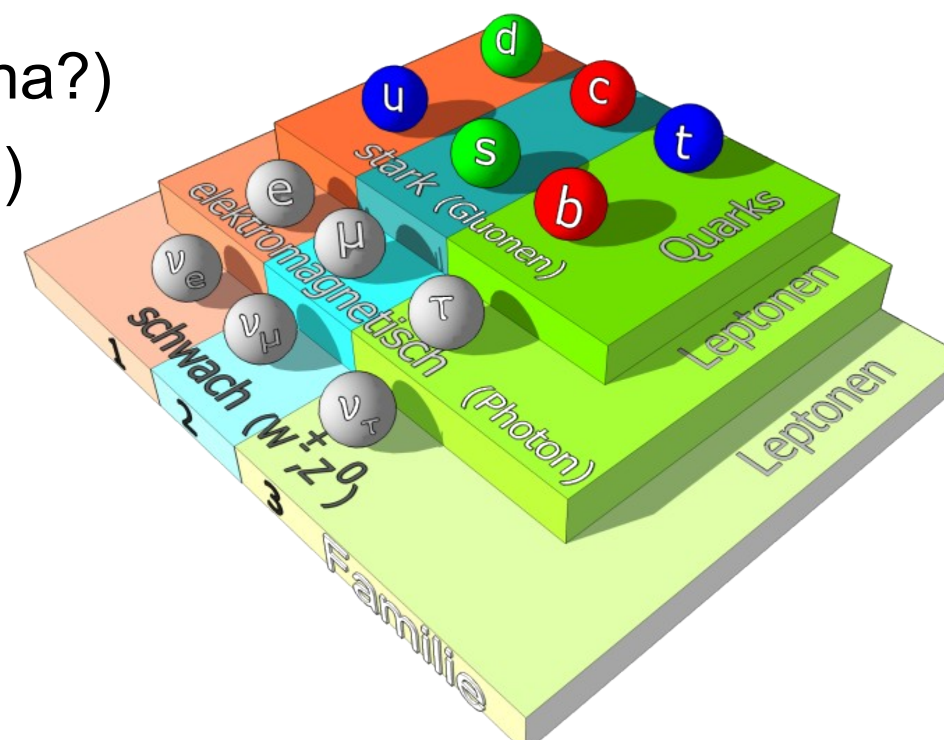
Unknowns

- Fermion **generations**
- Nature of **neutrinos** (Dirac or Majorana?)
- Fermion masses (**Yukawa couplings**)

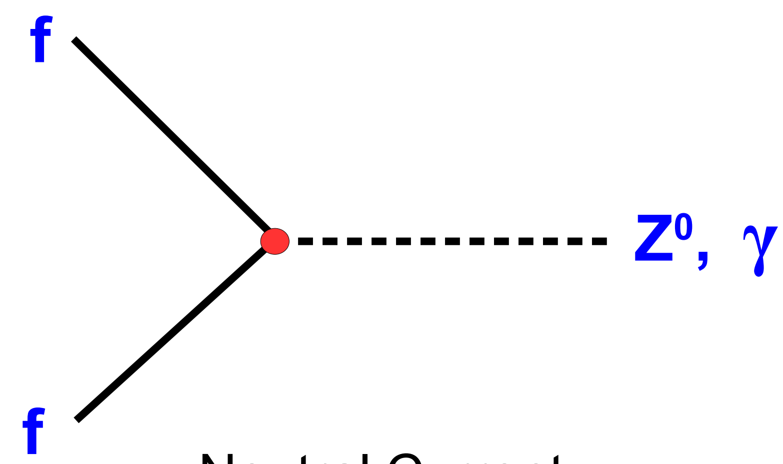
→ no explanation yet

Problems

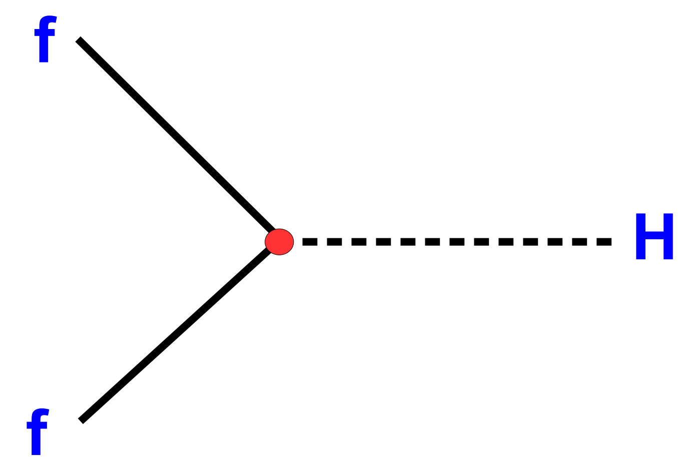
- Hierarchy “problem” (fine tuning)
- Stability of Higgs field, ...



The Tree Diagrams in the SM

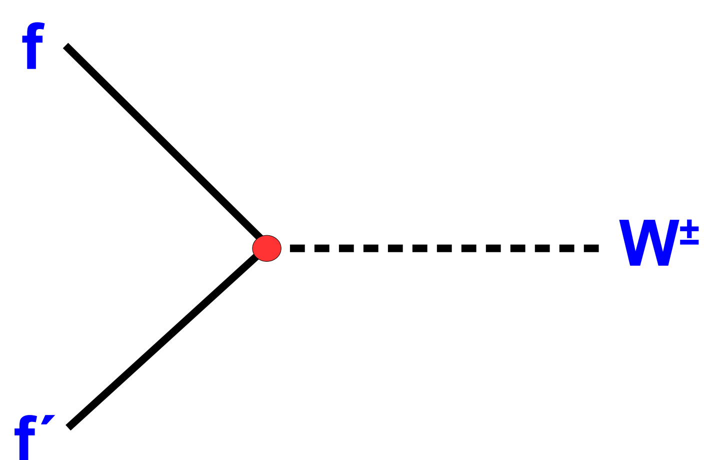


Neutral Current



Higgs-Yukawa coupling

→ flavor is **conserved** in neutral currents



Charged Current

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

→ but flavor **mixing** in charged currents

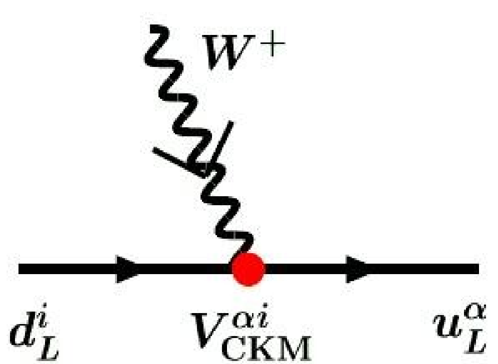
Flavor Mixing

<u>Quarks</u>

Cabibbo Kobayashi Maskawa (CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} v_{ud} & v_{us} & v_{ub} \\ v_{cd} & v_{cs} & v_{cb} \\ v_{td} & v_{ts} & v_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak mass



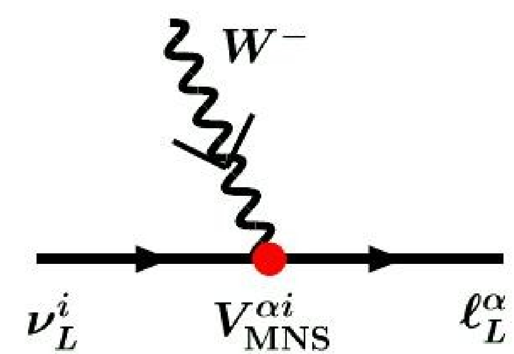
Q=-1/3 **Q=+2/3**

<u>Leptons</u>

Pontecorvo Maki Nakagawa Sakata (PMNS)

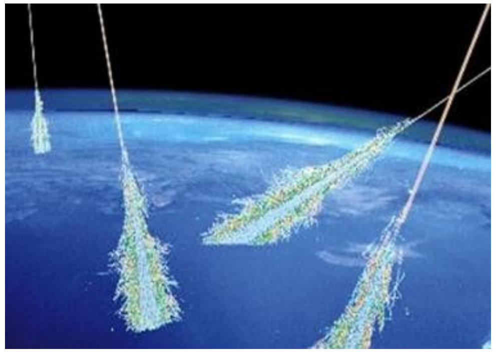
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} v_{e1} & v_{e2} & v_{e3} \\ v_{\mu 1} & v_{\mu 2} & v_{\mu 3} \\ v_{\tau 1} & v_{\tau 2} & v_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

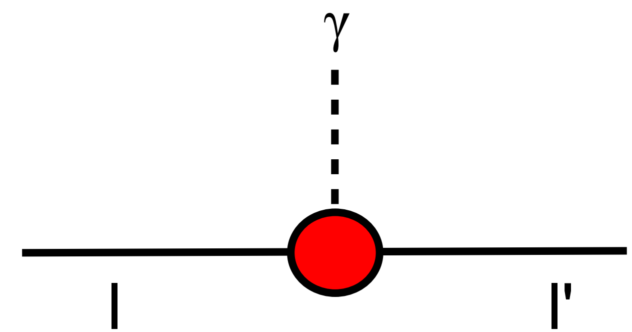
weak mass



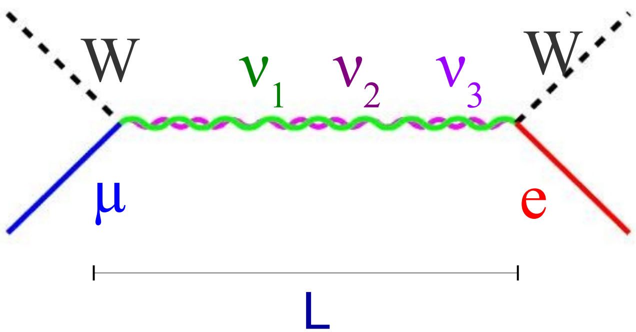
Q=0 **Q=-1**

Lepton Mixing & Lepton Flavor Violation





$\mu \to e$ via ν-oscillation

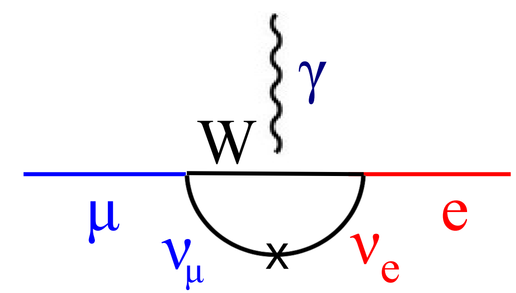


$L \to 1/m_W$

$E_\nu \to m_W$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\Theta)\,\sin^2\left(\Delta m^2_{\alpha\beta}\,\frac{L}{E_\nu}\right)$$

$\mu \to e\,\gamma$ via quantum loop

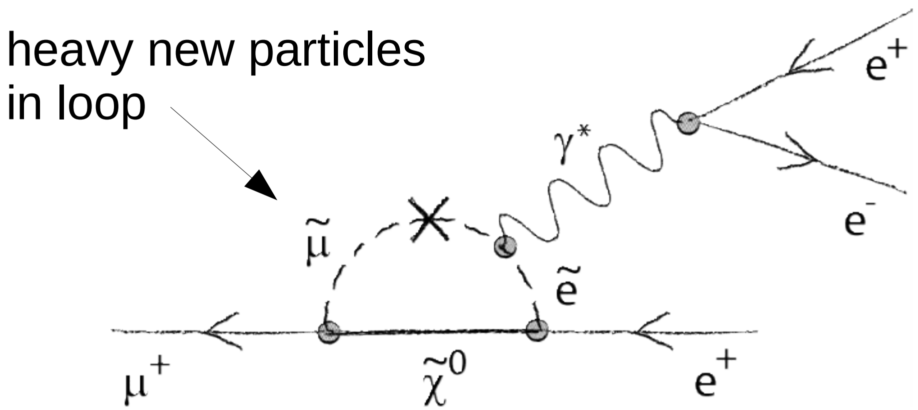


$$B(\mu \to e\gamma) \propto \sin^2(2\Theta)\,\left(\Delta m^2_{\alpha\beta}/m^2_W\right)^2$$

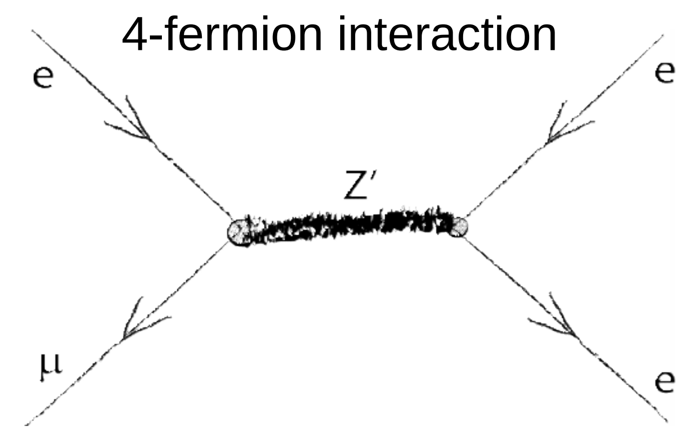
$$\propto \frac{(\Delta m^2_\nu)^2}{m^4_t} \approx y^4_\nu \approx 10^{-50}$$

Conservation of Lepton Flavor is an Accidental Symmetry!

Beyond the SM: $\mu^+ \rightarrow e^+e^+e^-$



loop diagrams (similar to $\mu \rightarrow e\,\gamma$)



tree diagram (Mu3e specific)

- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**

- **Higgs Triplet Model**
- **New Heavy Vector bosons (Z')**
- **Extra Dimensions (KK towers)**

Many models "naturally" generate lepton flavor violation!

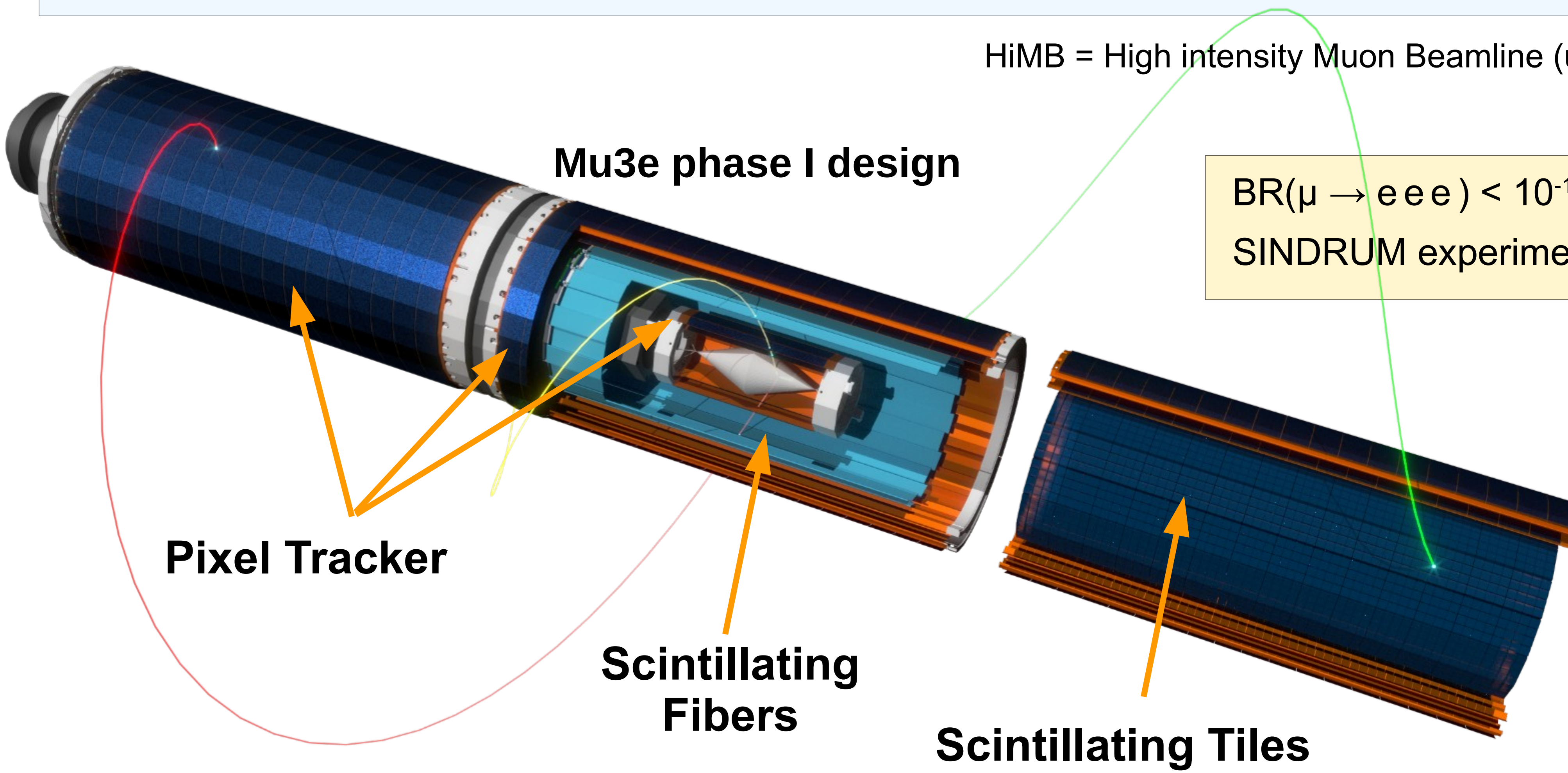
Mu3e Experiment

Aiming for a sensitivity (SES) requires:

$BR(\mu \rightarrow eee) < 2 \cdot 10^{-15}$	(phase I)	$\rightarrow$	10^8 muons/s (PiE5)	**~next 5 years**
$BR(\mu \rightarrow eee) < 10^{-16}$	(phase II)	$\rightarrow$	$>10^9$ muons/s (HiMB)	**R&D**

HiMB = High intensity Muon Beamline (under study)

$BR(\mu \rightarrow eee) < 10^{-12}$ (90% CL)
SINDRUM experiment (1986)



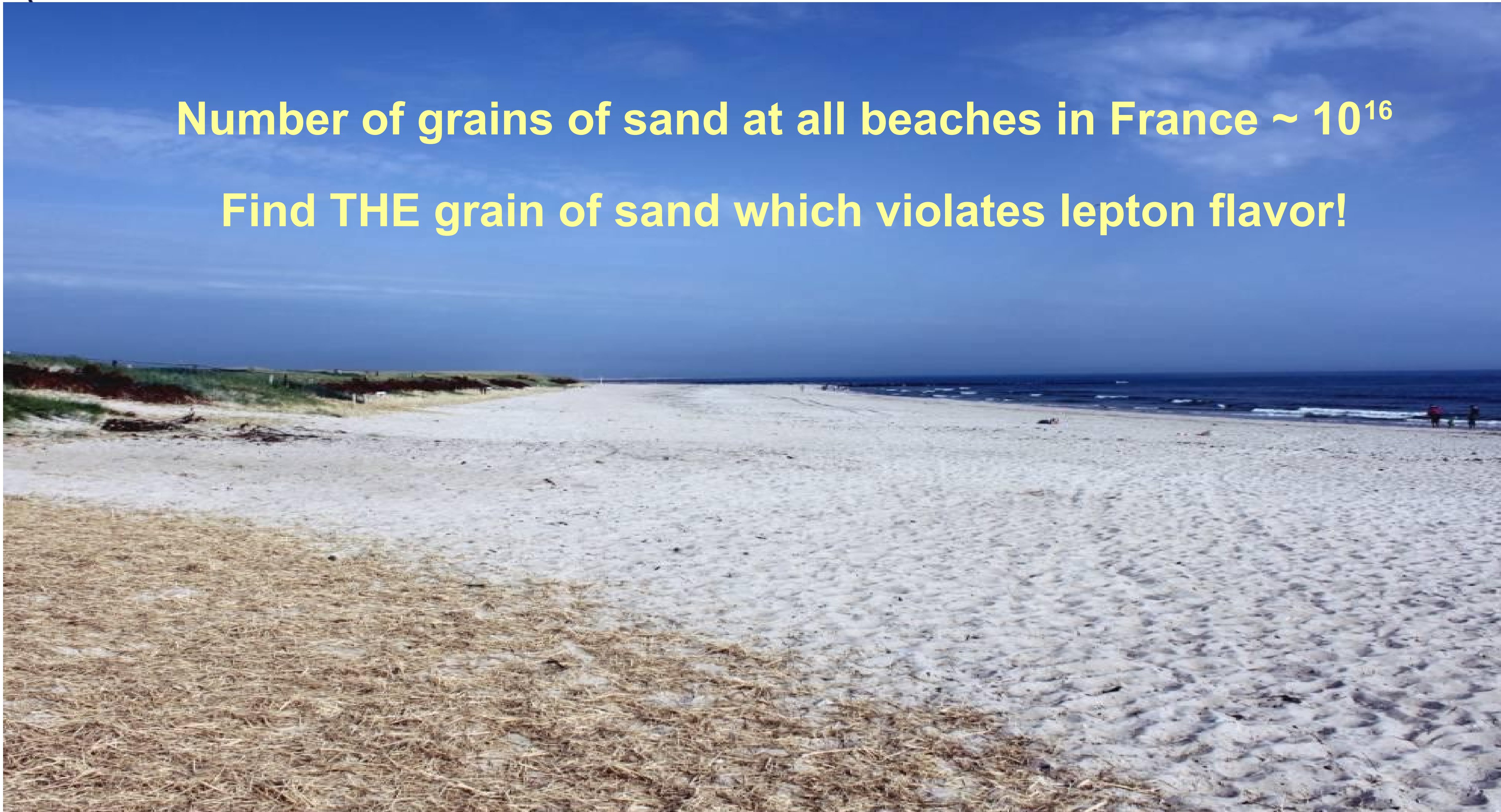
Challenge Number 1: Rate

Goal → **10^{16} muon decays**

- running time: ~3 years → $3 \cdot 10^7$s (experimental year ~ 10^7s)
- detector acceptance: 30%
- required muon rate: **10^9 μ/s** → defines technological challenge

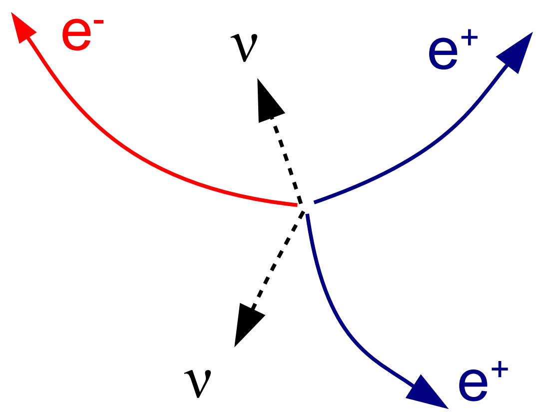
Detector has to stand high rates! → e.g. silicon detectors for tracking

Challenge Number 2: Background

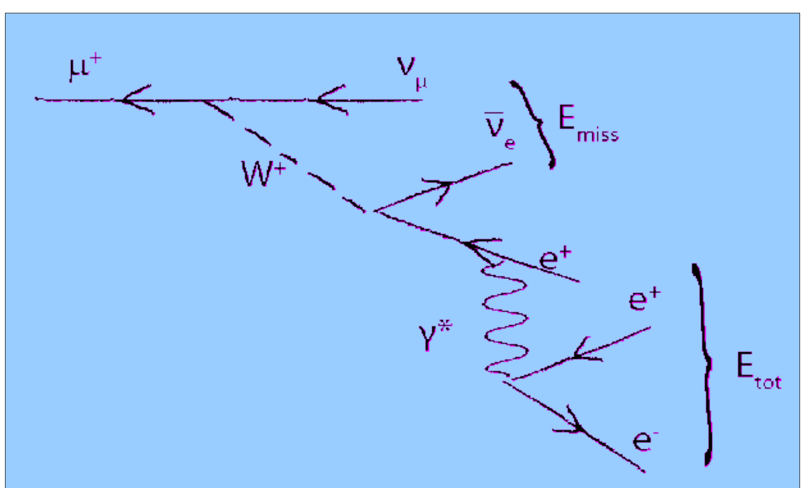


Irreducible Background

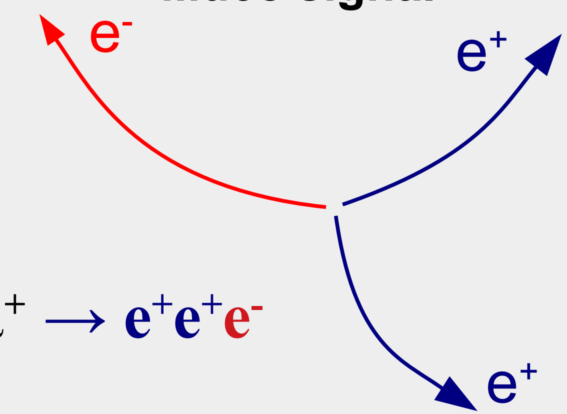
Radiative decay with internal conversion



$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$



Mu3e signal

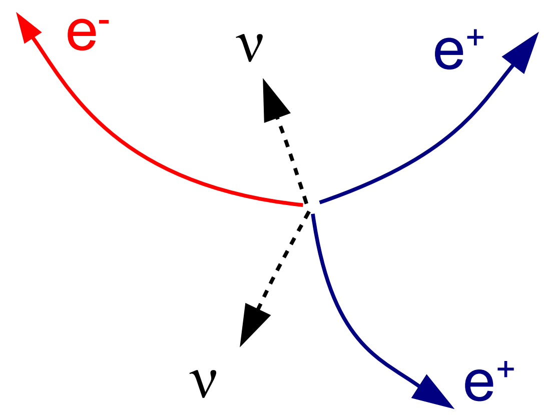


$\mu^+ \rightarrow e^+e^+e^-$

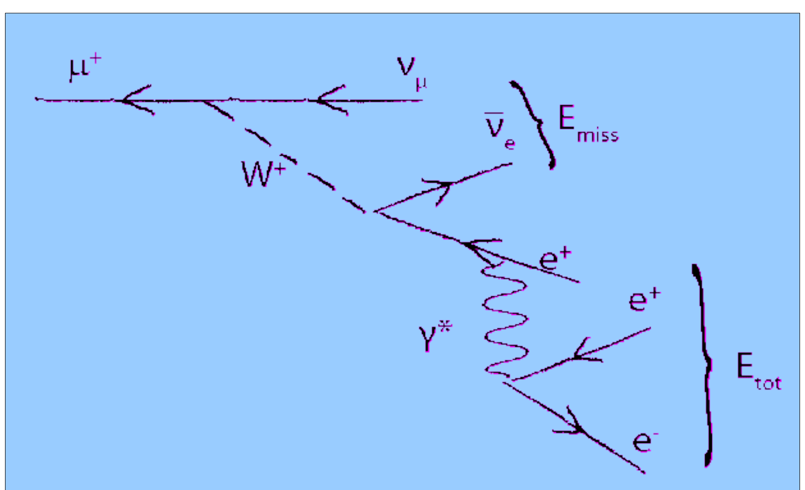
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

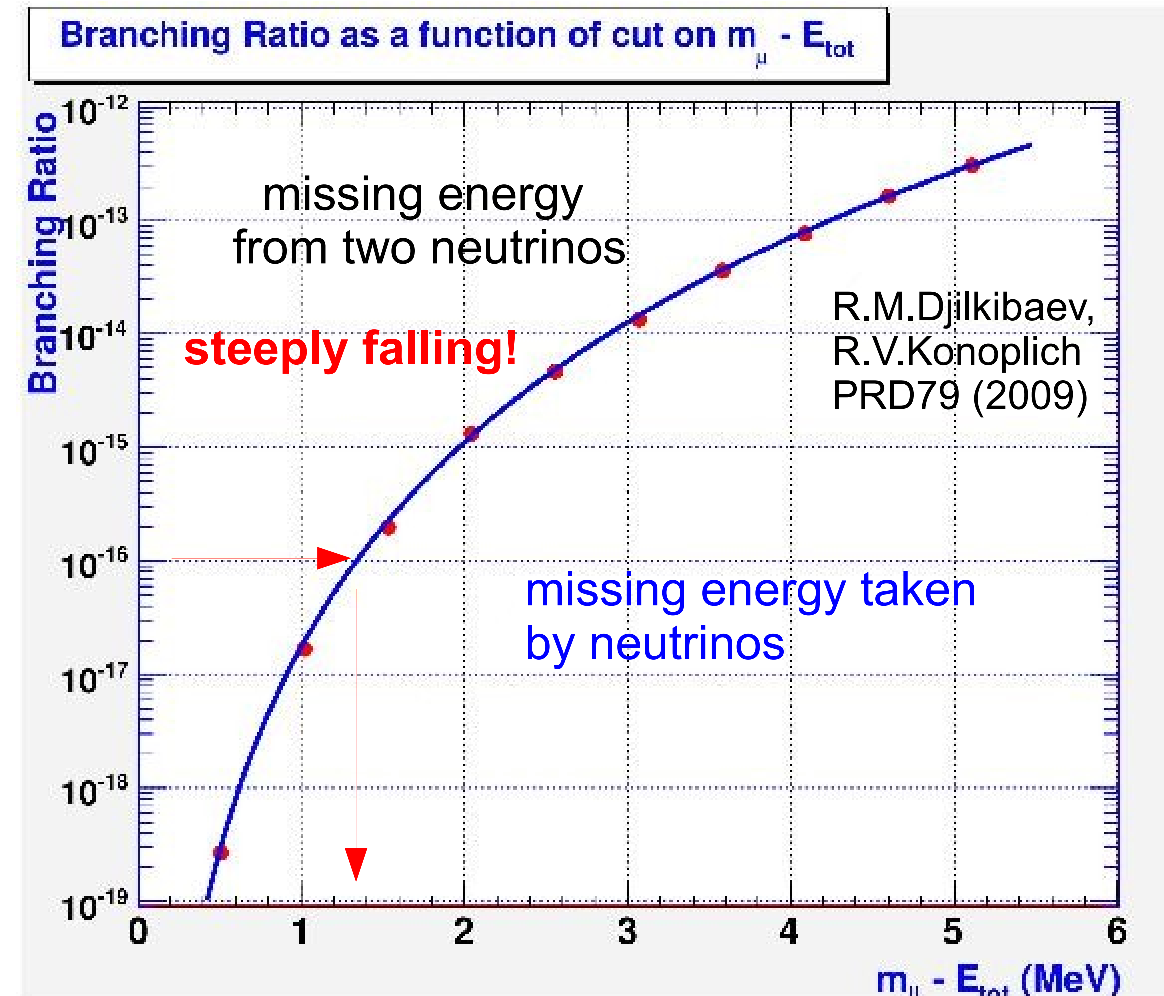
Irreducible Background

Radiative decay with internal conversion



$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$

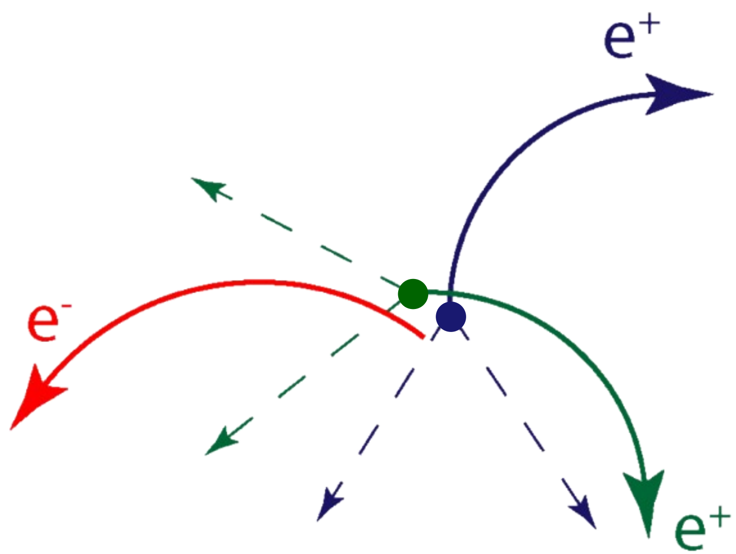


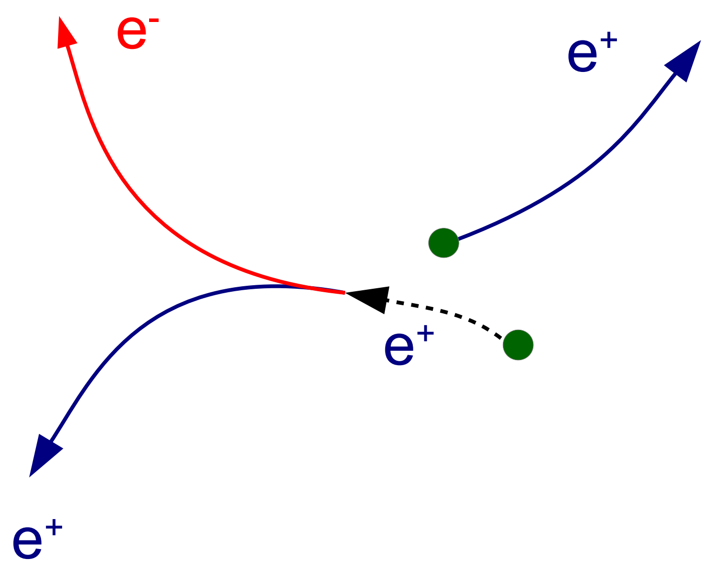


very good momentum + total energy resolution required!

Accidental Backgrounds

- **Overlays** of two ordinary **μ^+ decays** with a (fake) **electron (e^-)**
- Electrons from: **Bhabha** scattering, photon conversion, mis-reconstruction





Need excellent:
- **Vertex resolution**
- **Timing resolution**
- **Kinematic reconstruction**

example for Bhabha pileup

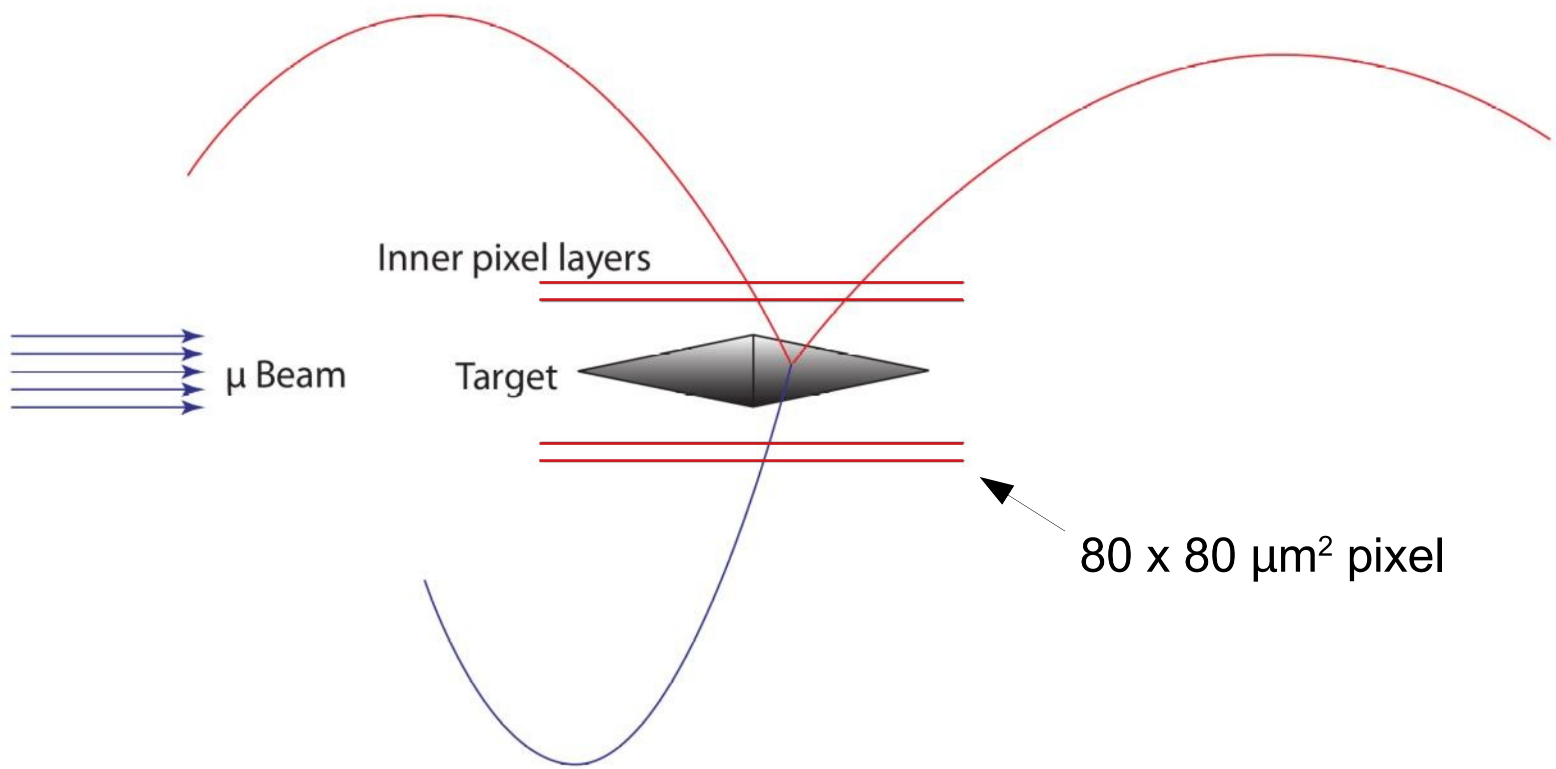
Mu3e Design (Phase I)

10^8 muons per second (phase I)

p=28 MeV/c

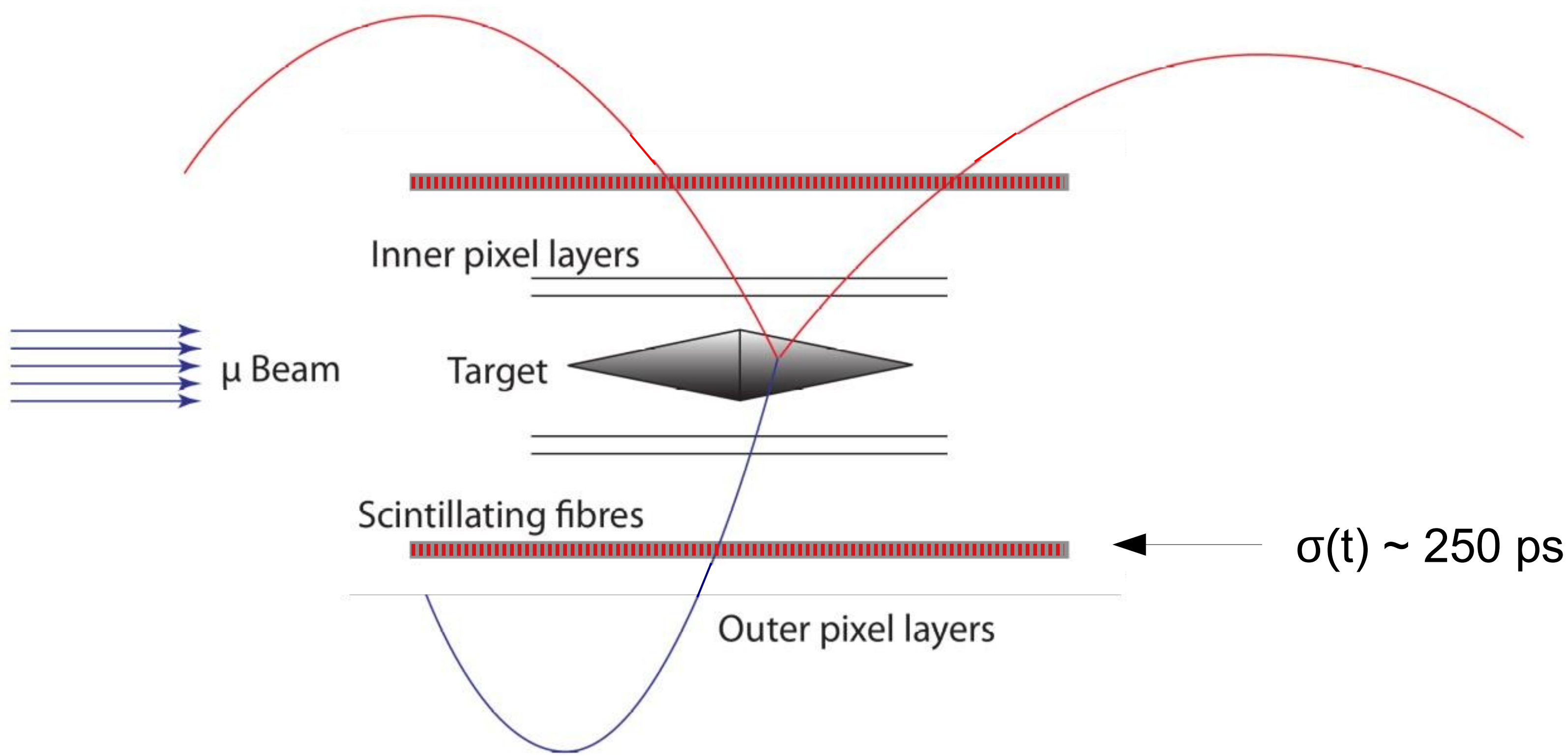
muon stopping target (hollow)

Mu3e Design (Phase I)



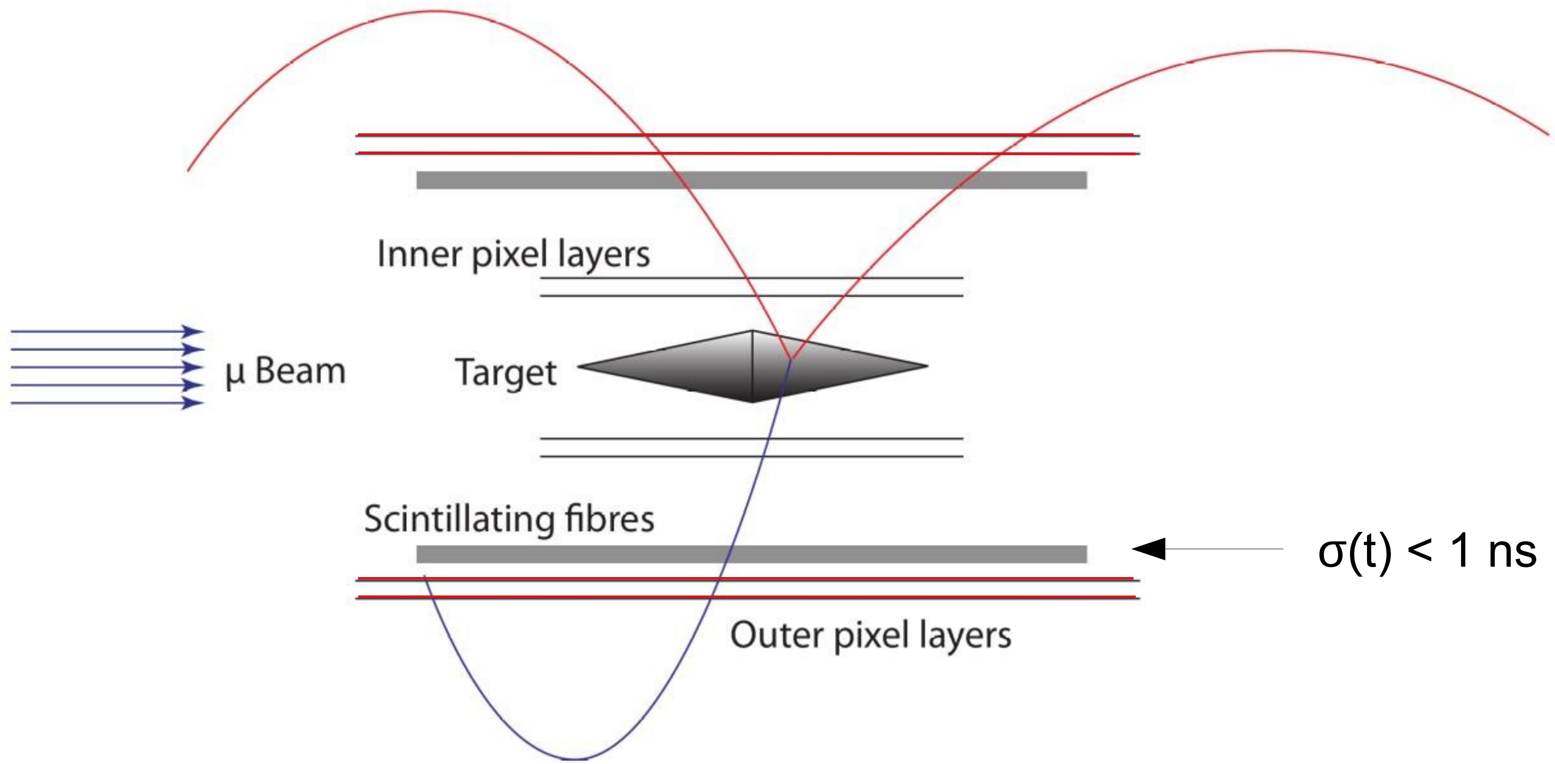
- ultra thin **silicon pixel detector** (HV-MAPS) with **1 per mill radiation length** / layer for vertexing

Mu3e Design (Phase I)



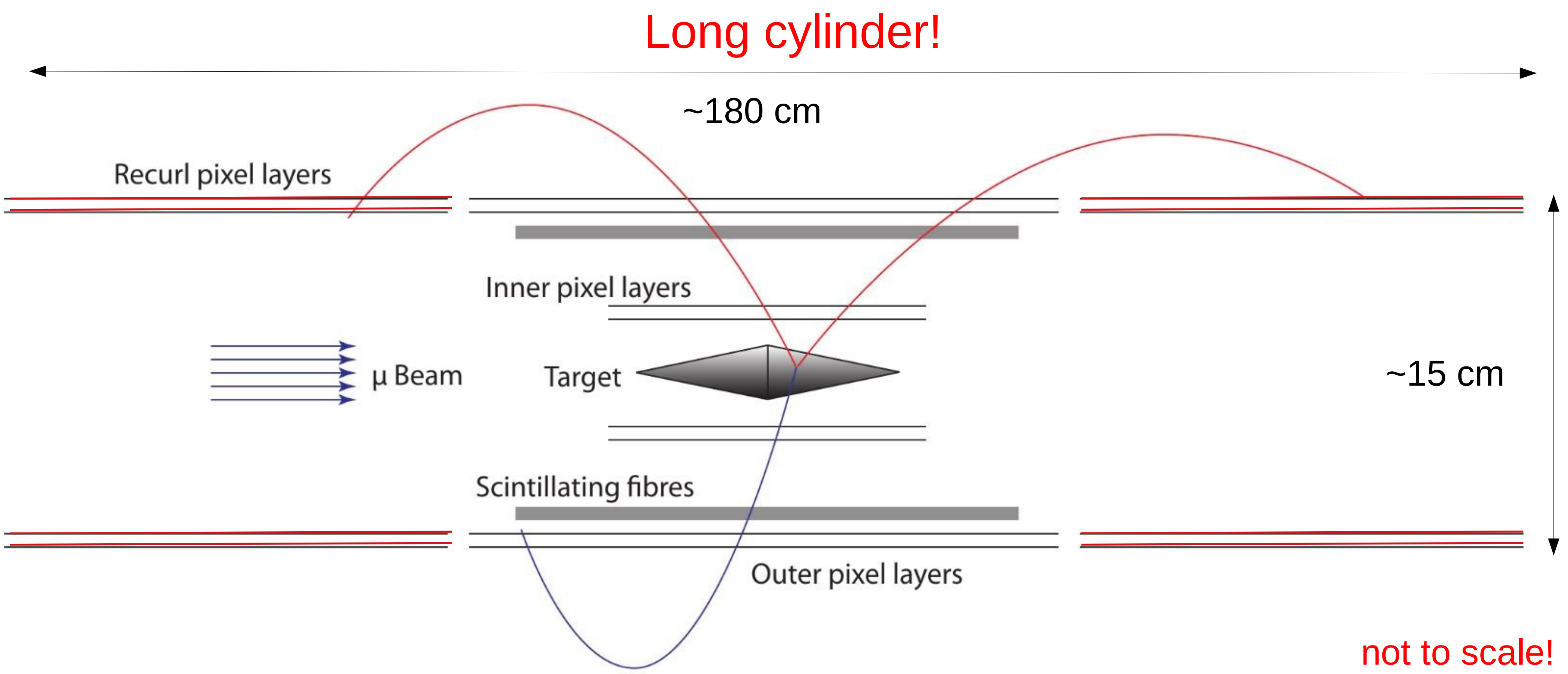
- **fast timing** detectors (**scintillating fibers**) → time coincidence

Mu3e Design (Phase I)



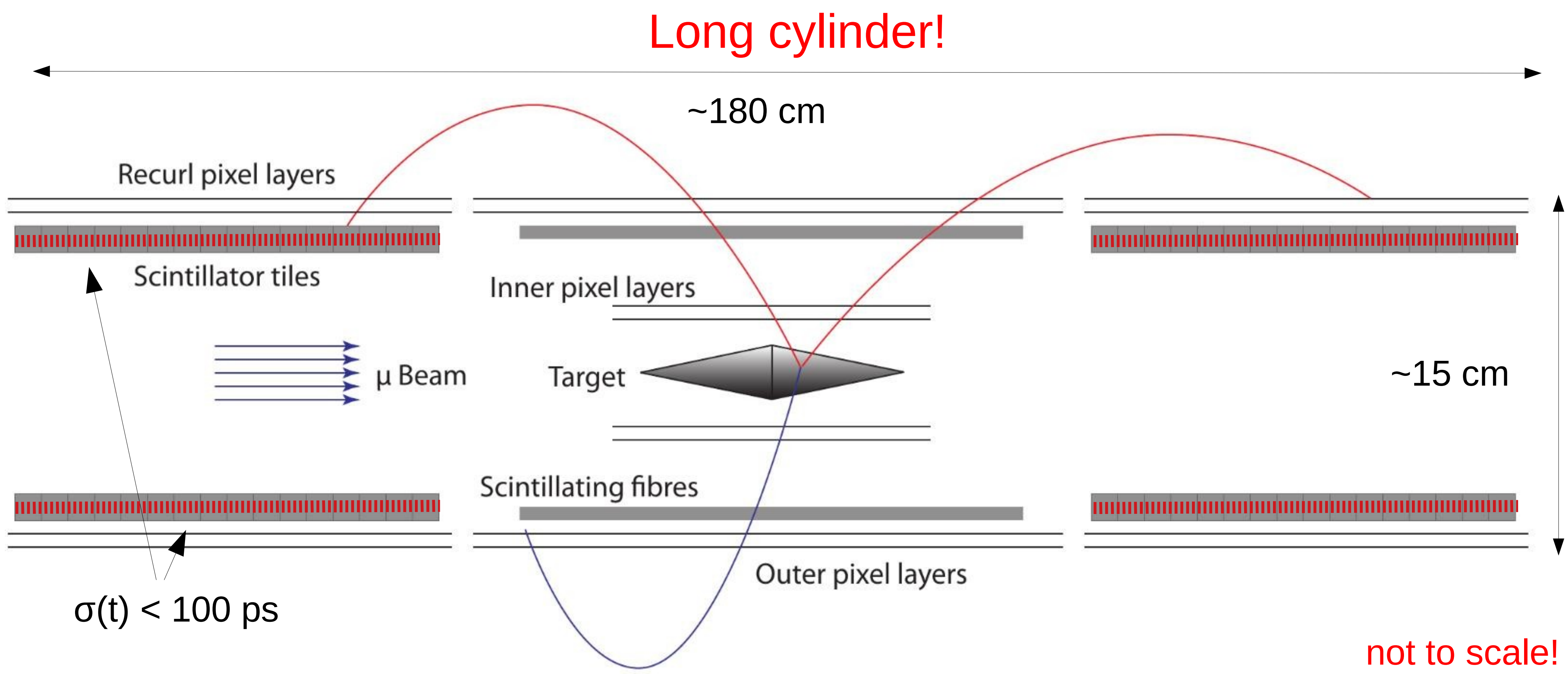
- ultra thin **silicon pixel detector** (HV-MAPS) with **1 per mill radiation length** / layer for outer tracking layers → momentum information

Mu3e Design (Phase I)



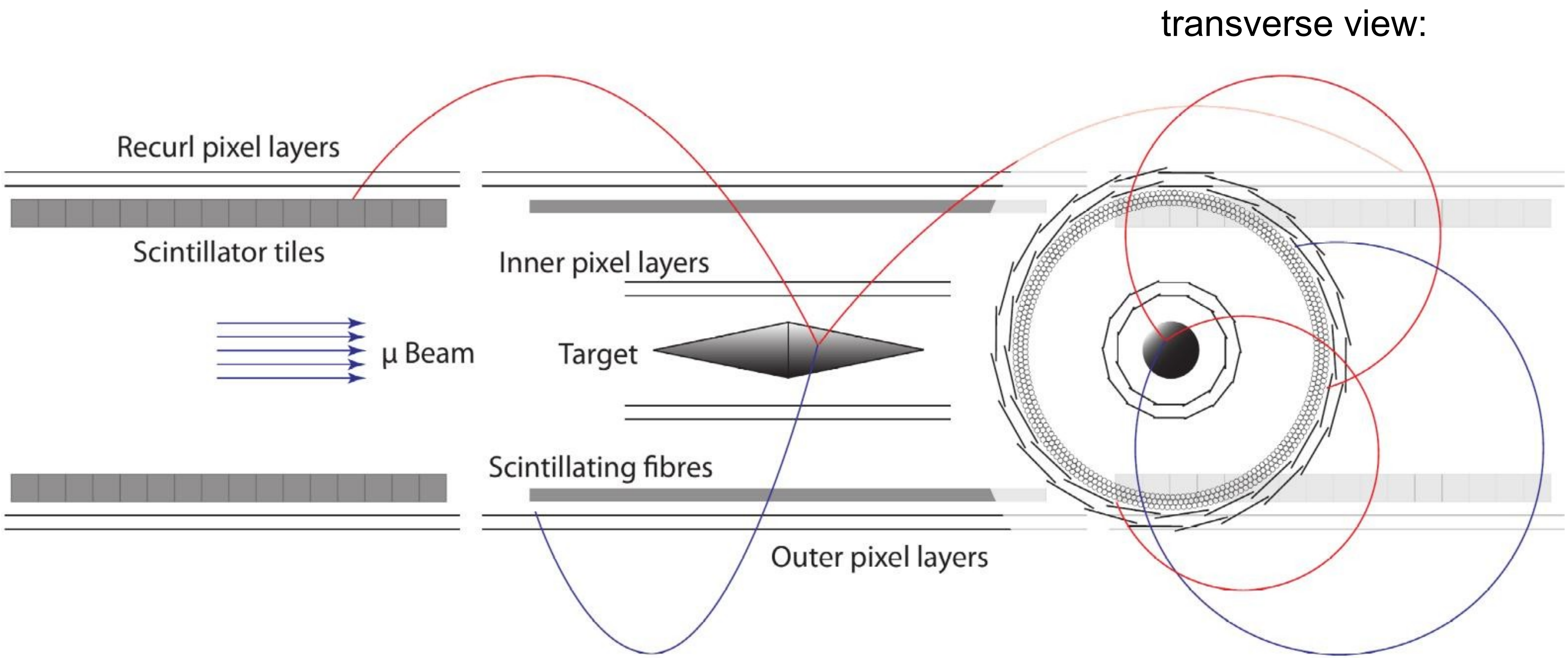
- **recurl** stations with **silicon pixel detector** (HV-MAPS) → increased acceptance

Mu3e Design (Phase I)



recurl stations with extra **scintillating tiles** → very precise timing

Mu3e Design (Phase I)

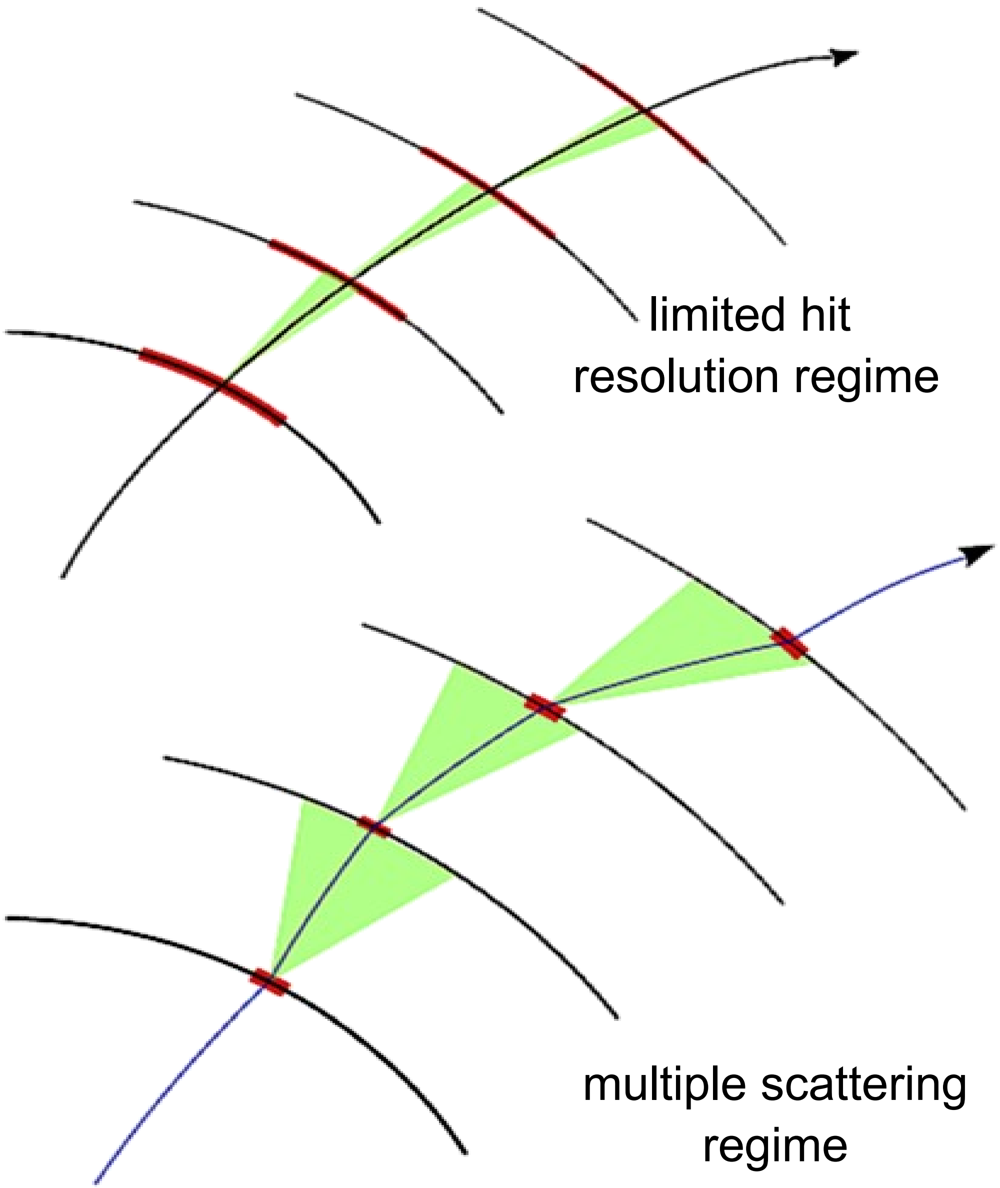


+ strong magnetic field (B=1T)

+ helium gas cooling

in helium atmosphere

Tracking Resolution + Multiple Scattering



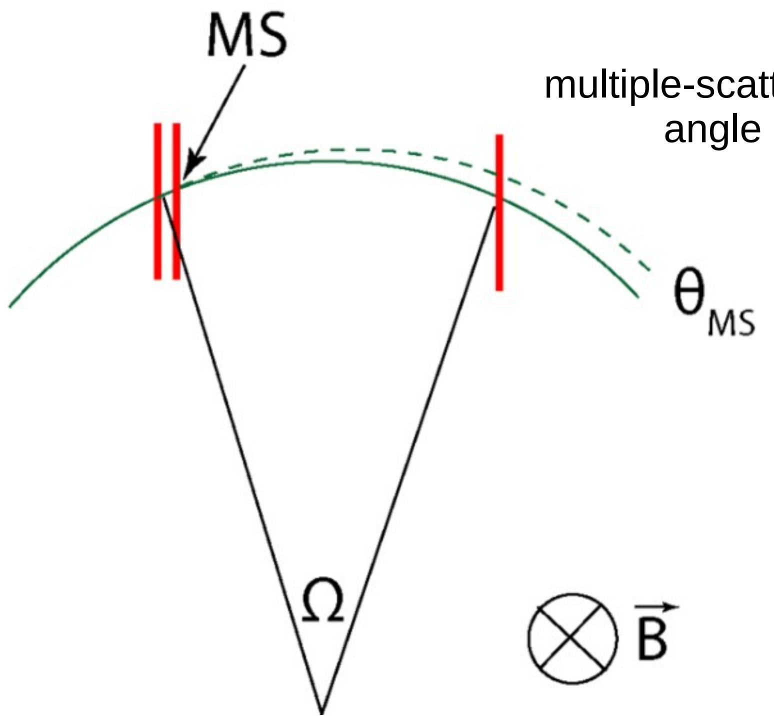
- Muon decay (m=105.6 MeV):
  → electrons in low momentum range
  p < 53 MeV/c
- Multiple scattering is dominant!

➜ **Need thin, fast and high resolution tracking detectors operated at high rate (>10⁹ particles/s @ phase II)**

$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X / X_0}$$

Momentum Resolution

Standard spectrometer:

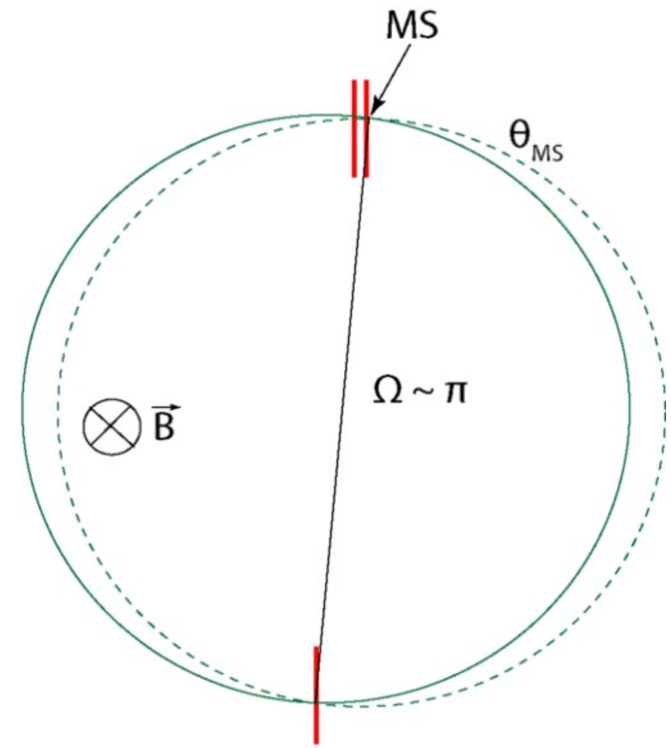


$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$

(linearised)

- **requires large lever arm**
- **large bending angle Ω**

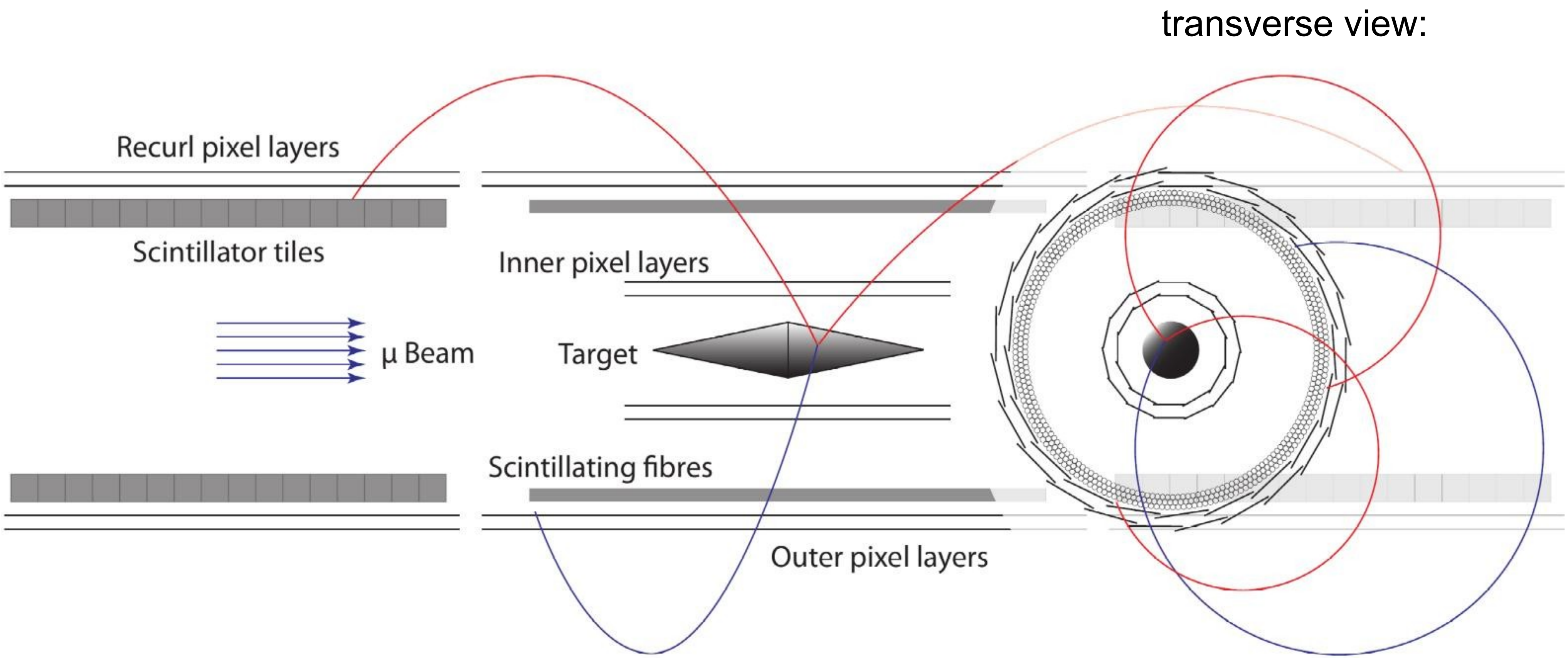
"Half turn" spectrometer:



$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

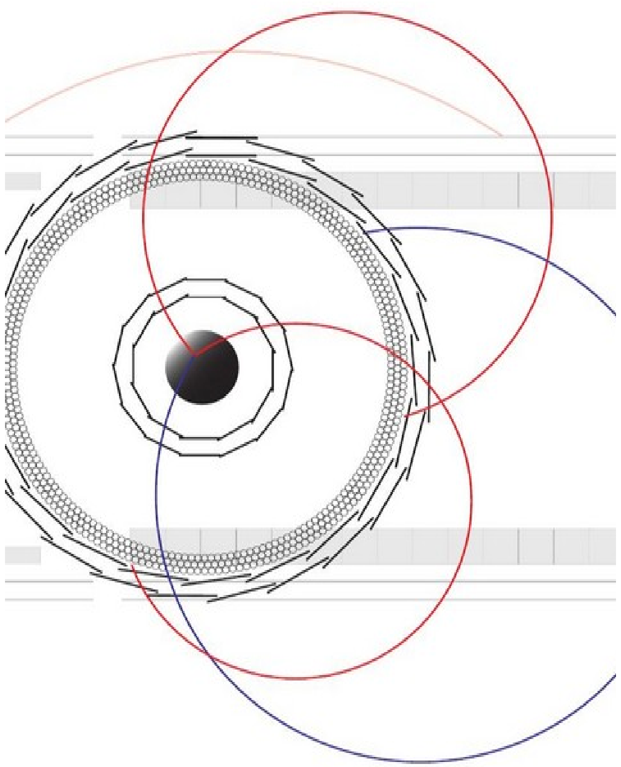
- **best precision for half turn tracks**
- **measure recurlers**

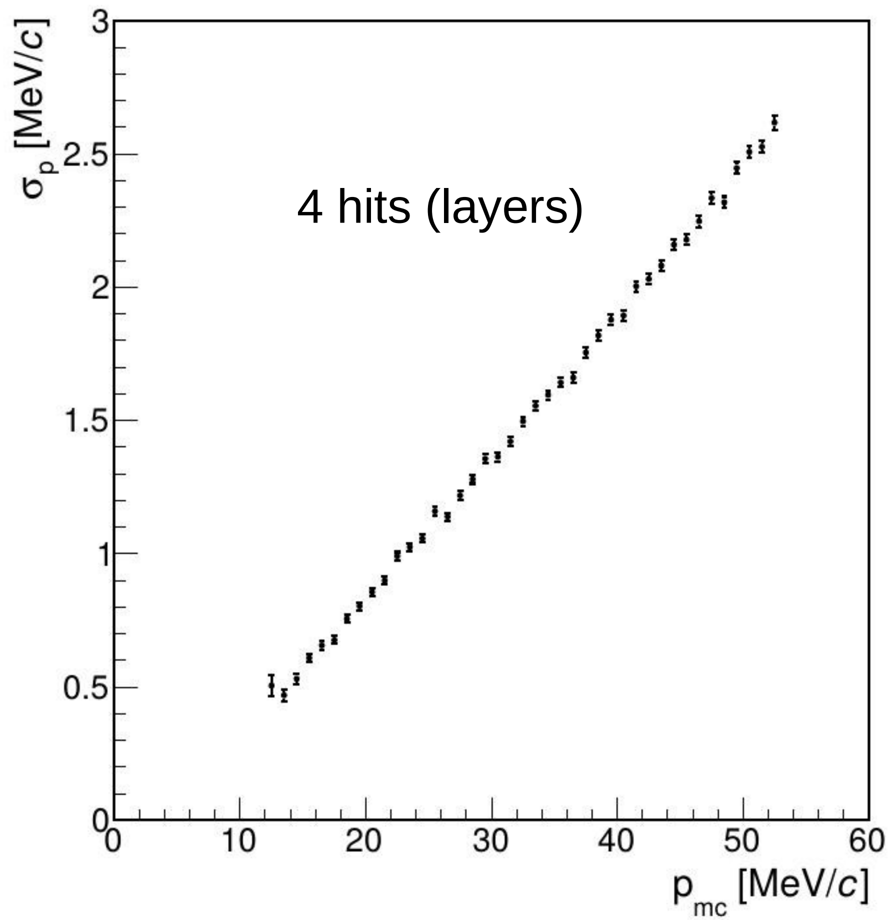
Mu3e Design (Phase I)

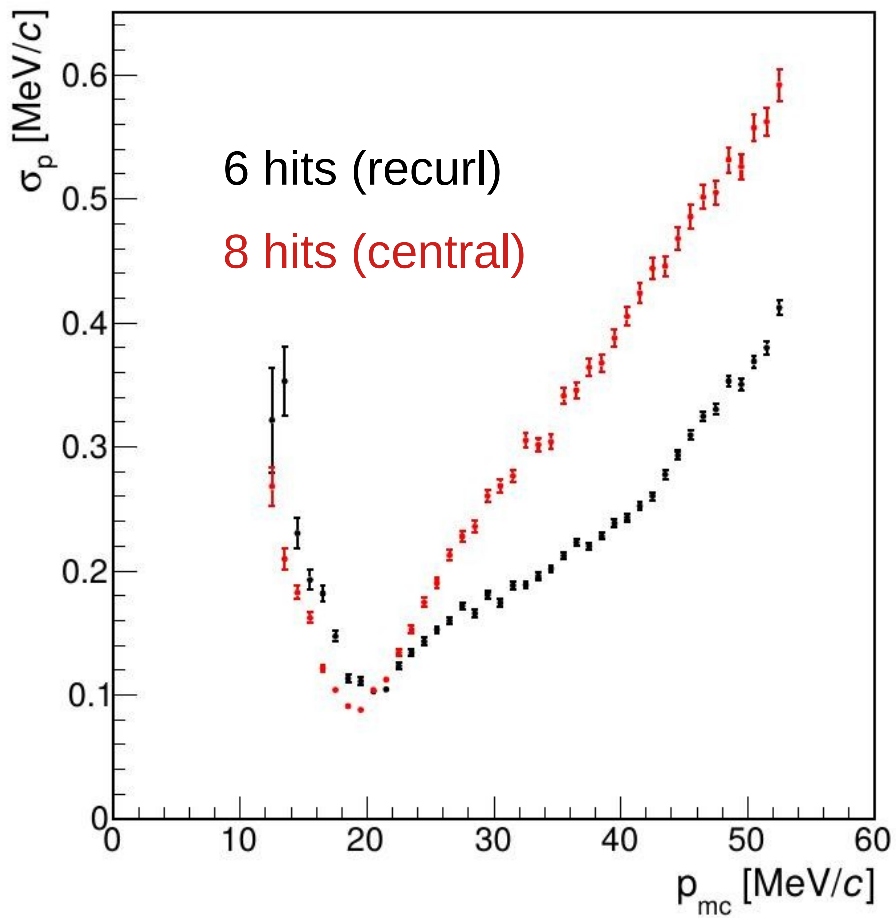


electrons with p~33 MeV/c make roughly semi-circles!

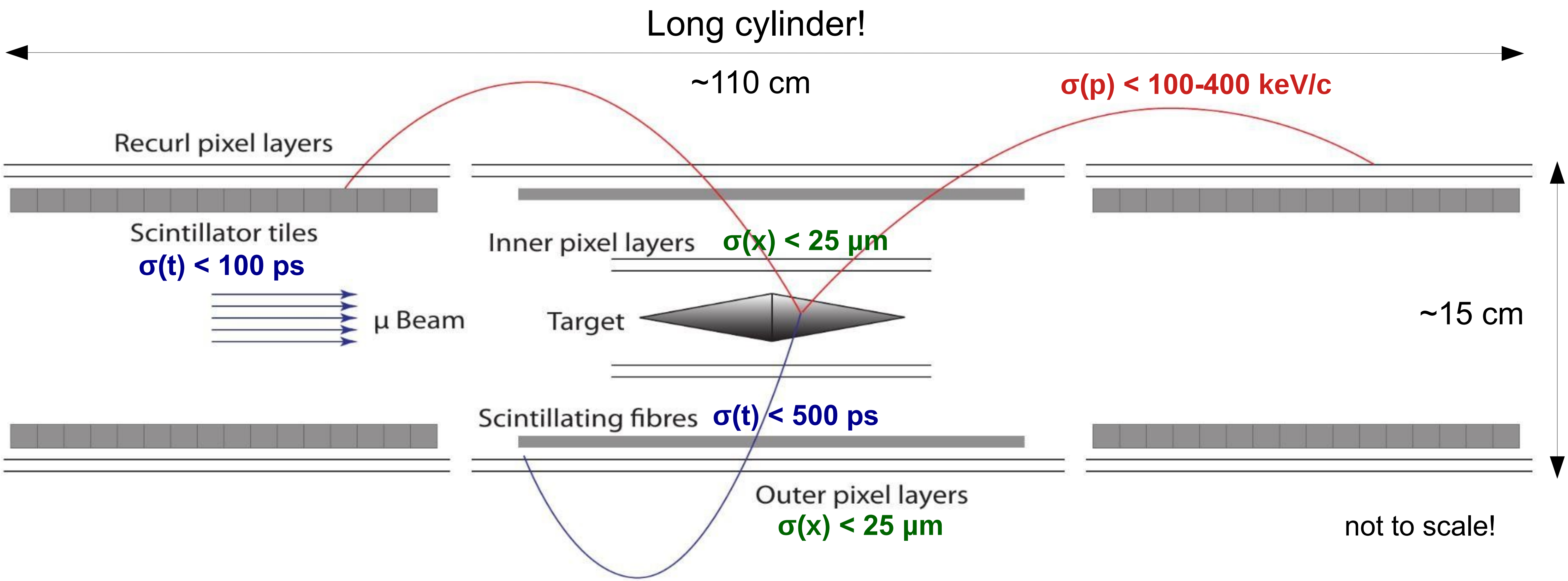
Momentum Resolution (Simulation)







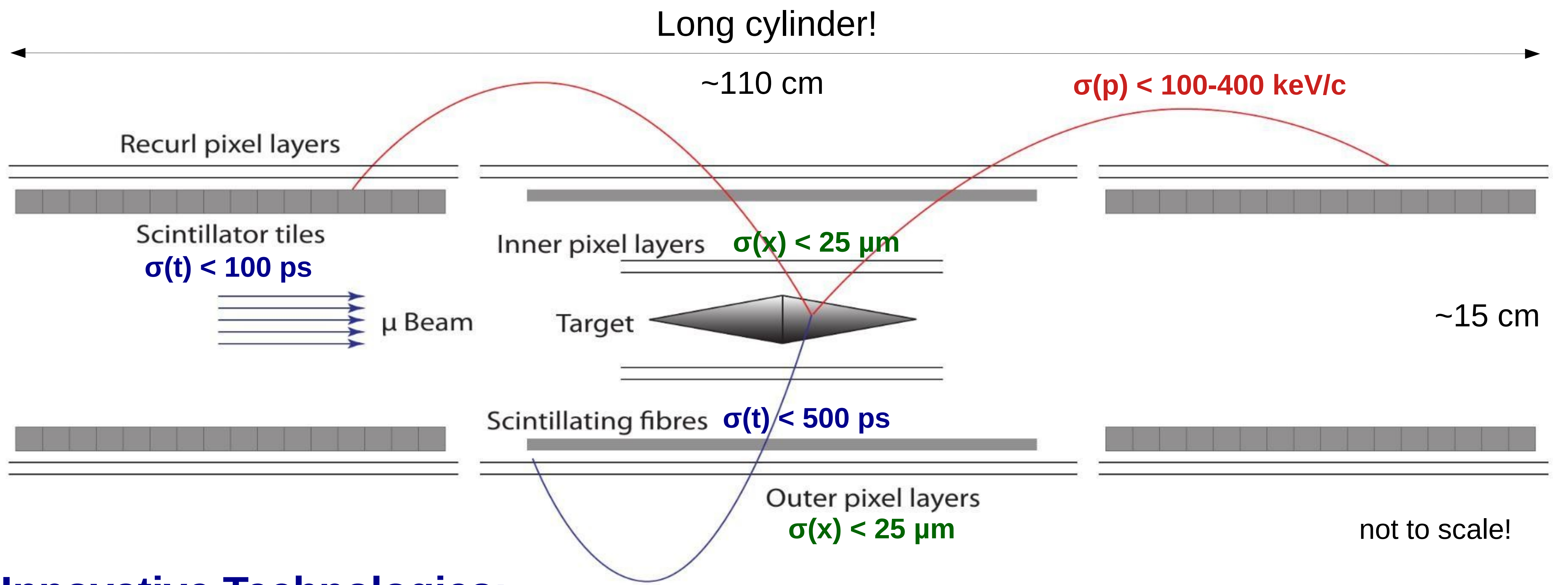
Mu3e Phase I Design



Technical Challenges:

- multiple Coulomb **scattering** → **ultra-thin** tracking layers
- high particles **rates** → **highly granular** detectors and **fast online reconstruction**
- **compact** design → high **integration** level (sensors, readout ASICs)

Mu3e Phase I Design



Innovative Technologies:

- High Voltage Monolithic Active Pixel Sensors (**HV-MAPS**) for tracking
- **gaseous helium cooling** system (<400mW/cm²) and ultra-thin pixel modules (0.1 % X_0)
- **MuTrig** readout ASIC for timing detectors with ~30 ps time resolution
- Online filter farm based on **Graphical Processing Units**

Paul-Scherrer Institute (CH)

High intensity Proton Accelerator (HiPA) → 2.4 mA protons at 590 MeV (1.5 MW)

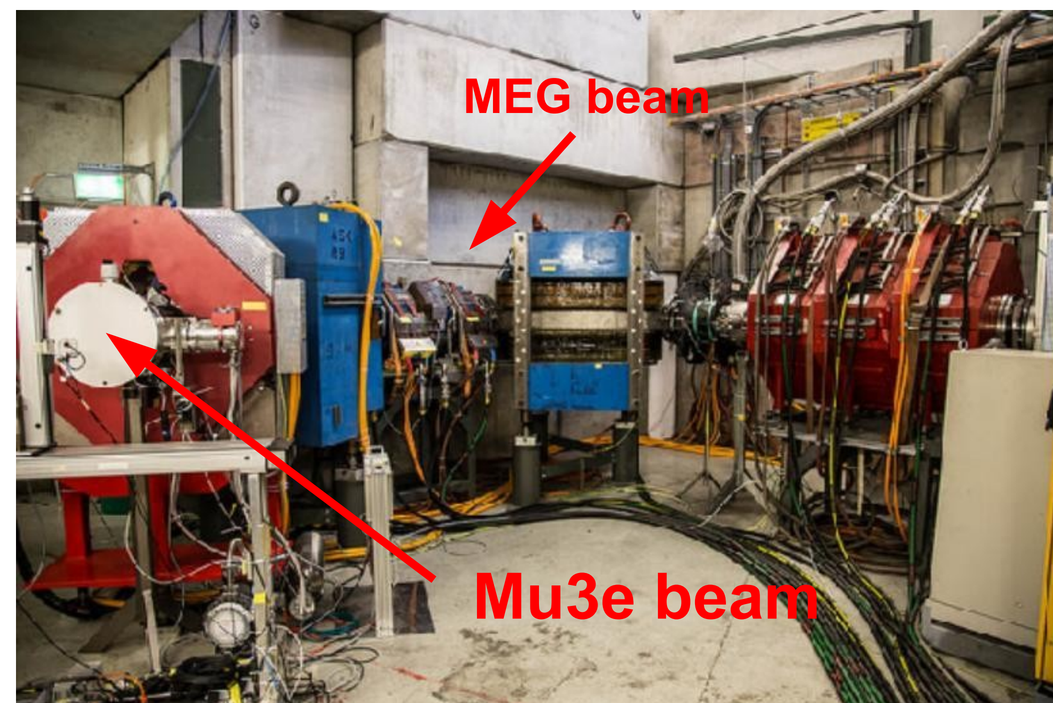
Muon Beam:
- World's most intense continuous muon beam
- Low momentum muons ~**28 MeV/c**
- PiE5 beamline shared between **MEGII** and **Mu3e**

➢ **expect 1.4·10⁸ μ^+/s at I_p= 2.4 mA**

➢ **about half is stopped on μ-stopping target**

→ **Mu3e Phase I**

PiE5: Compact Muon Beamline for Mu3e



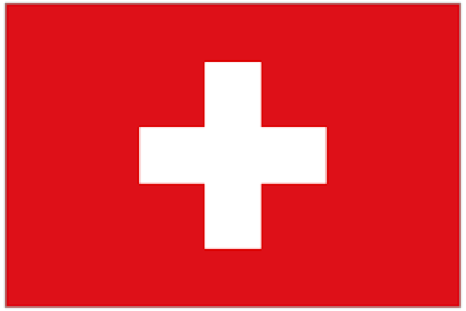
Mu3e Collaboration

Germany

- **University Heidelberg (KIP)**
- **University Heidelberg (PI)**
- **Karlsruhe Institute of Technology**
- **University Mainz**

Switzerland

- **University of Geneva**
- **Paul Scherrer Institute**
- **ETH Zurich**
- **University Zurich**
- **[University of Applied Sciences Northwestern Switzerland]**
  associated partner



United Kingdom

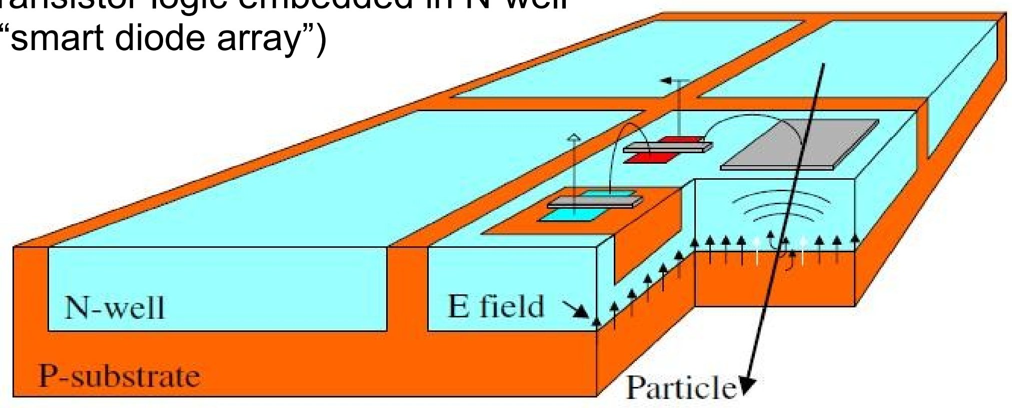
- **Bristol**
- **Liverpool**
- **Oxford**
- **UC London**

about 70 members; ~15 PhD students

HV-MAPS Detector Technology

High Voltage-Monolithic Active Pixel Sensor (HV-MAPS)

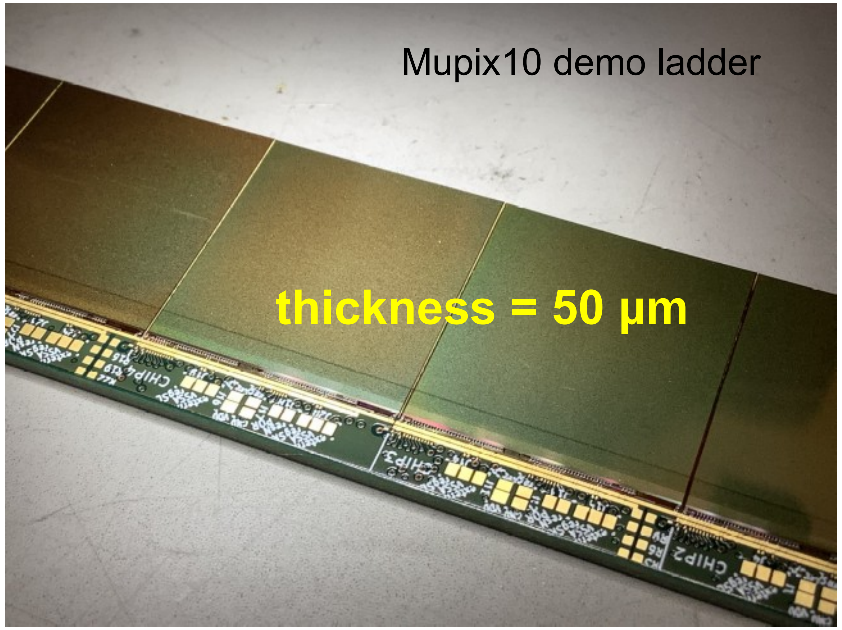
transistor logic embedded in N-well
("smart diode array")



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

- **active sensor:**
  → hit finding + digitisation + readout
- HV-CMOS 180nm: **60-120 V**
- low cost process (AMS, **TSI**)
- thinned to ~**50 µm** (~ 0.0005 X_0)

MuPix10 prototype ladder



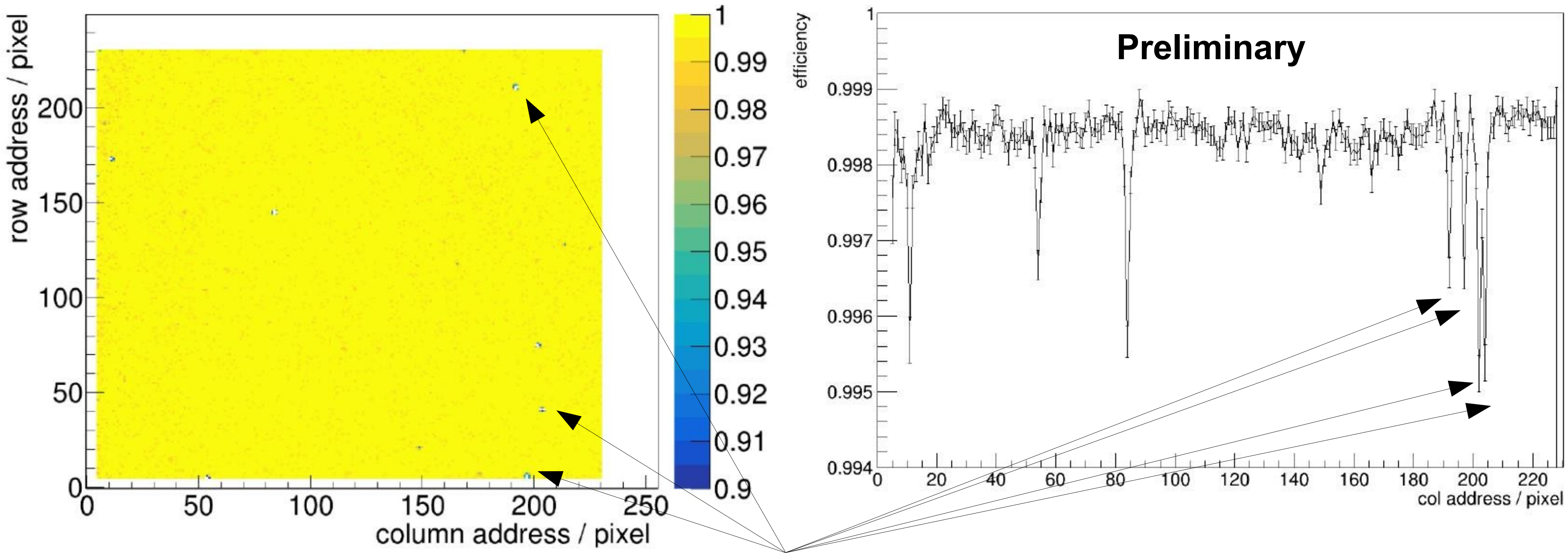
sensor: 20 x 20 mm^2 pixel: 80 x 80 µm^2

MuPix prototypes characterized in lab and in several test beams

- efficiency (>99%) & noise
- time resolution (<20 ns)
- high rates (radiation hardness)
- temperature-dependence
  - → specifications fulfilled

Preliminary Mupix10 Efficiency (PSI)

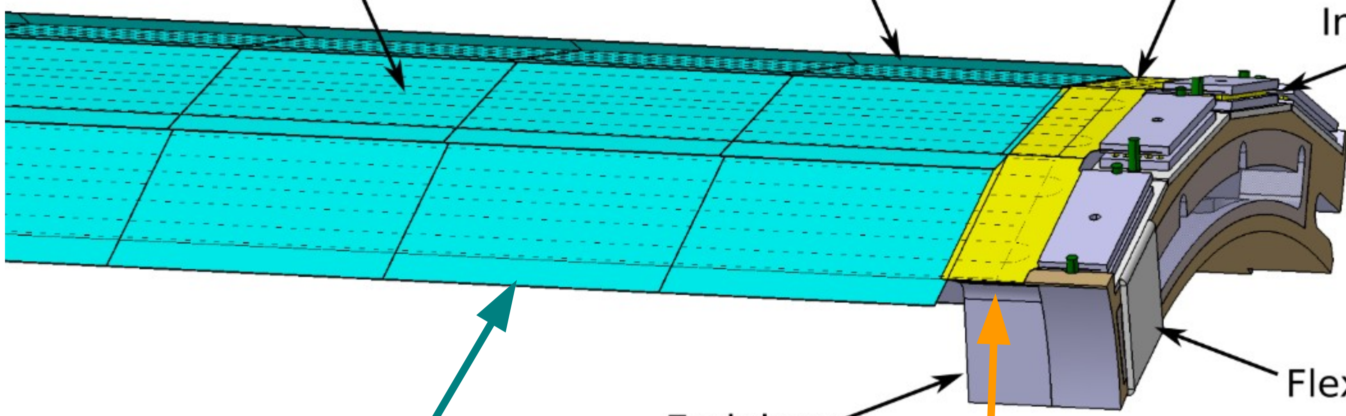
- threshold 42mV (~670 e^-)
- average efficiency ~ 99.85% (noise & rate dependent → dead time)
- no pixels masked!
- no TDAC tuning of individual pixels
- O(10) noisy pixel out of 64000 → lead to some deadtime losses



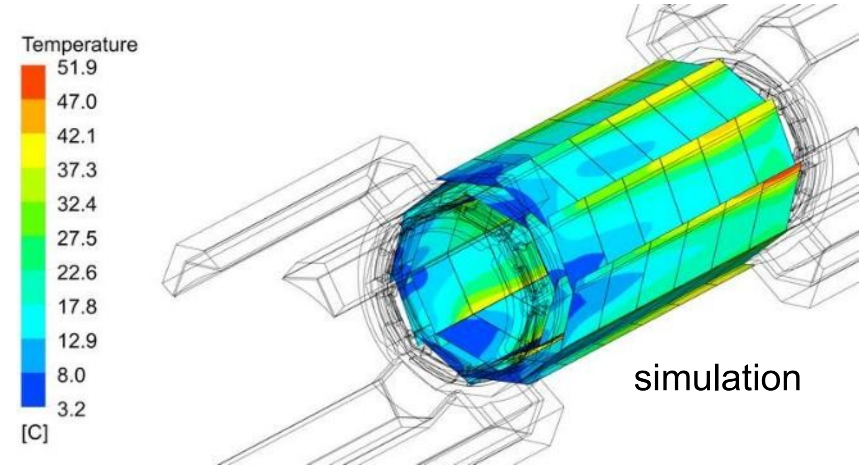
noisy pixel (not masked)

Pixel Tracking Detector

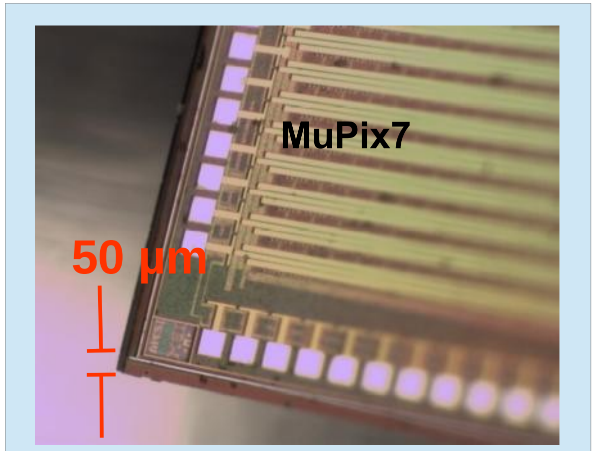
Ultra-thin pixel sensor modules (X/X_0 = 1.15 per mille)



Gaseous He-Cooling System

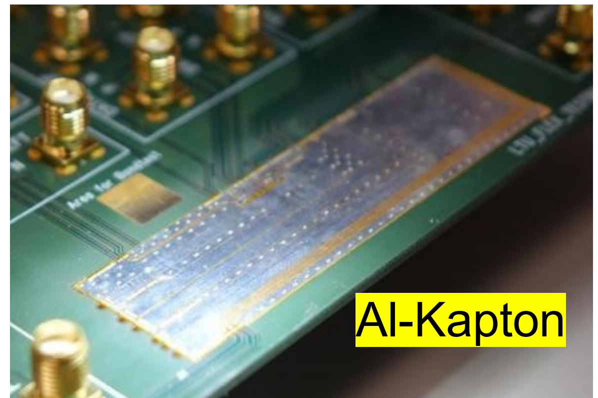


MuPix (HV-MAPS)

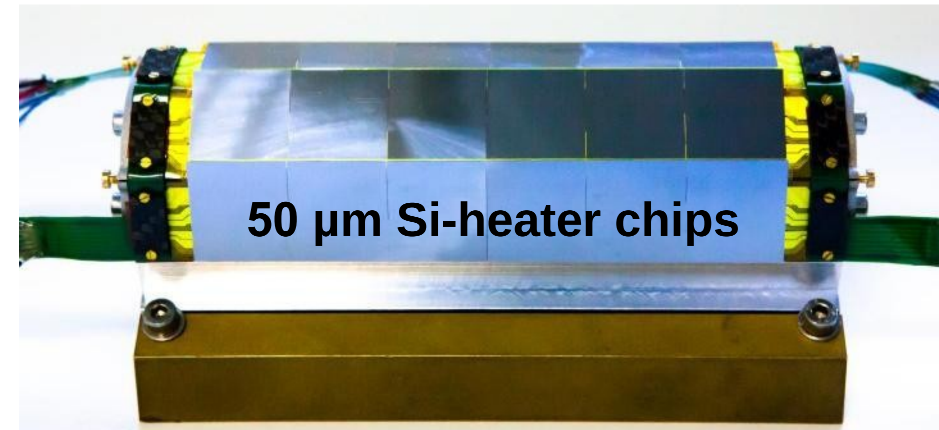


Monolithic pixel sensor in
180 nm HV-CMOS

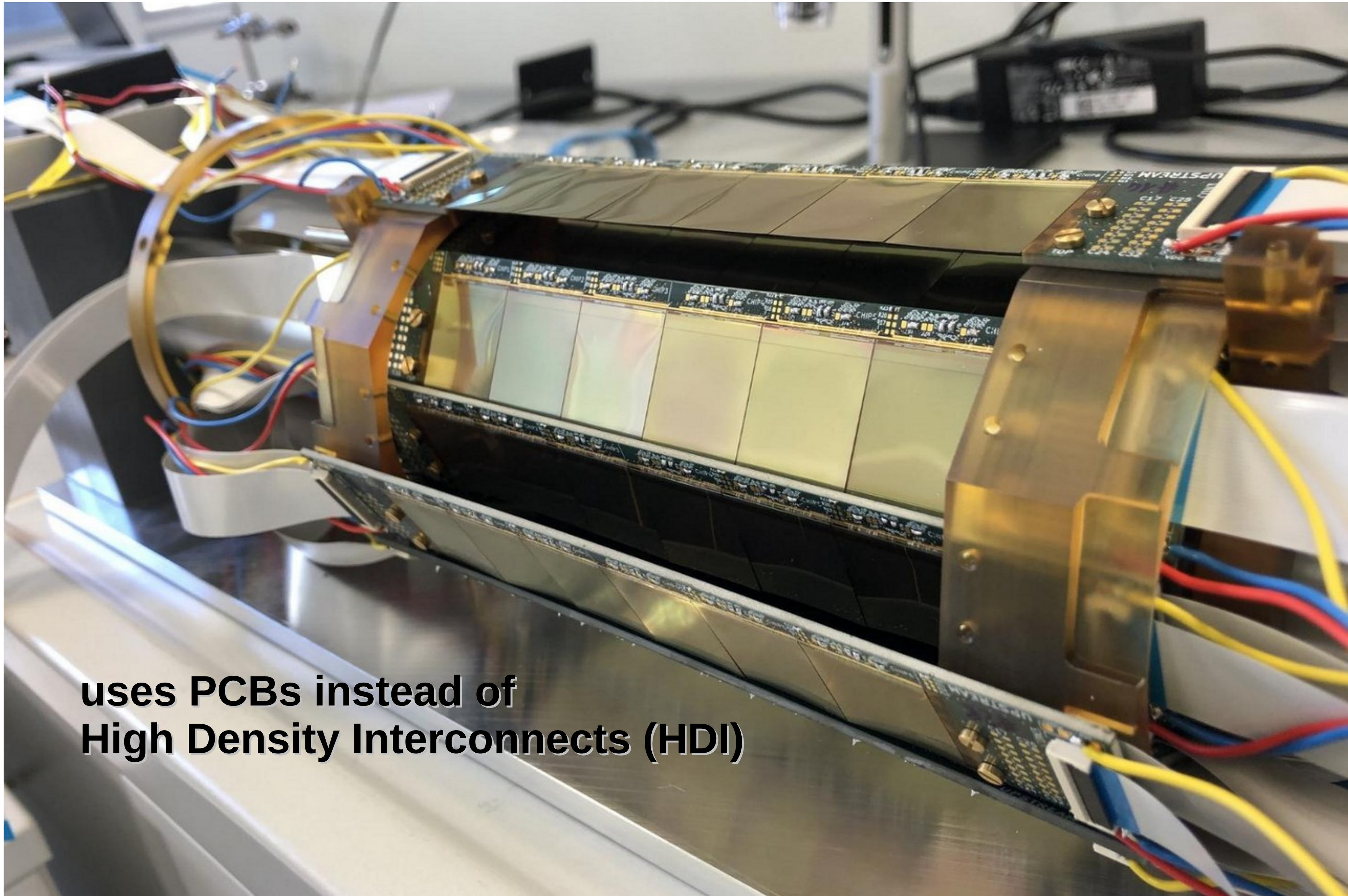
High Density Interconnect
d < 100 µm (LTU, Ukraine)



Thermo-Mechanical Mockup (vertex)



Pixel Tracking Detector Prototype

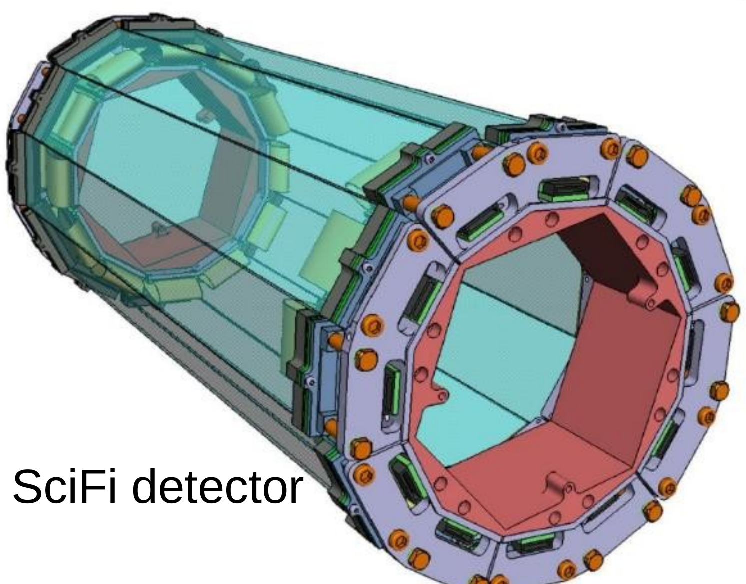


Scintillating Fibres

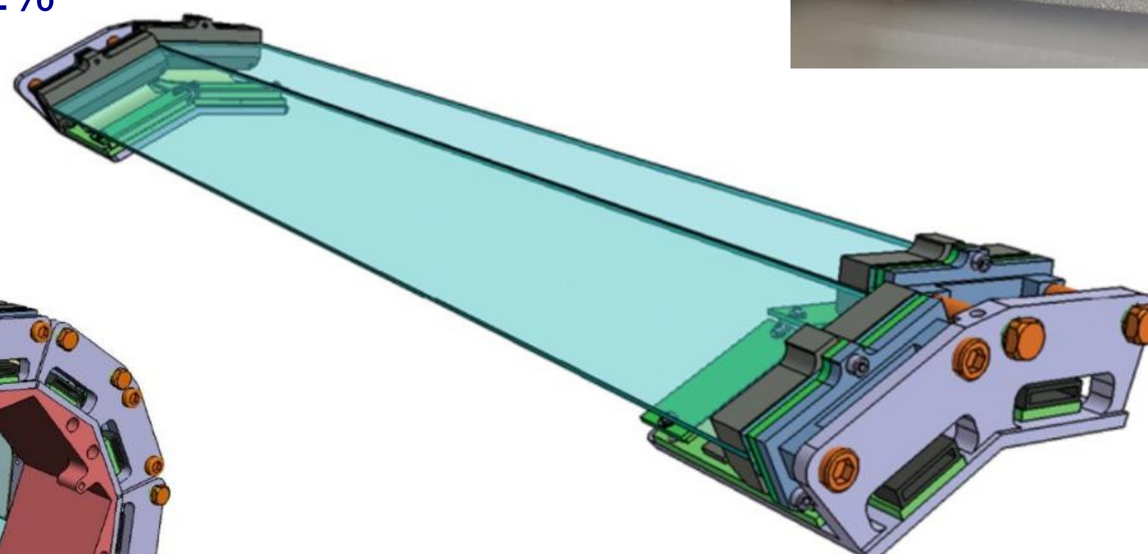
Scintillating Fibre Detector

- Scintillating fibres: Kuraray SCSF-78MJ (multi-clad)
- SiPM Hamamatsu S13552-HRQ
- MuTrig TDC ASIC (Heidelberg-KIP) for readout
  - → very challenging space constraints
  - → time resolution ~250 ps
  - → thickness X/X_0 0.2%

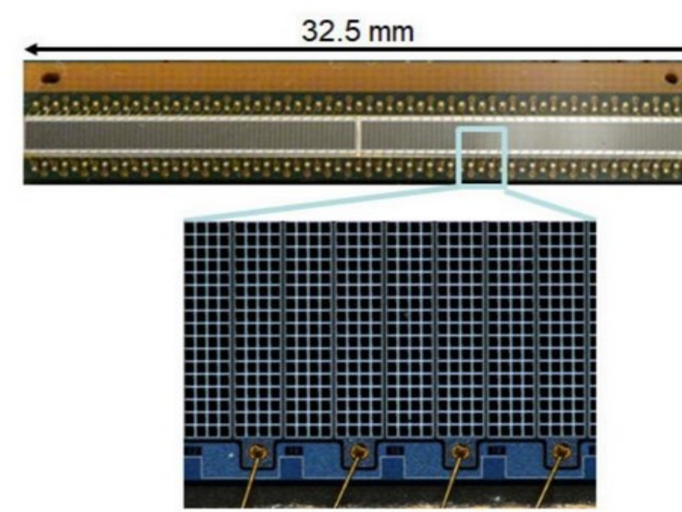
prototype ladder



SciFi detector

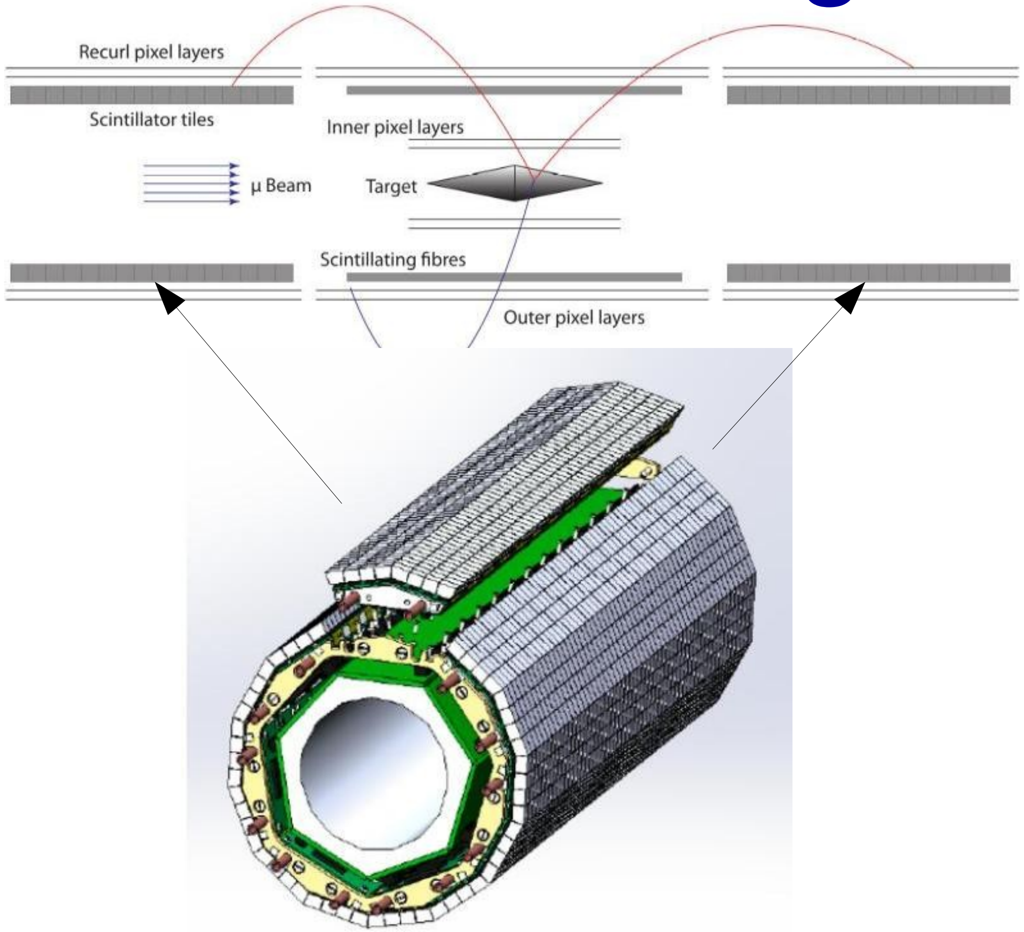


double SciFi ladder



Hamamatsu S13552-HRQ

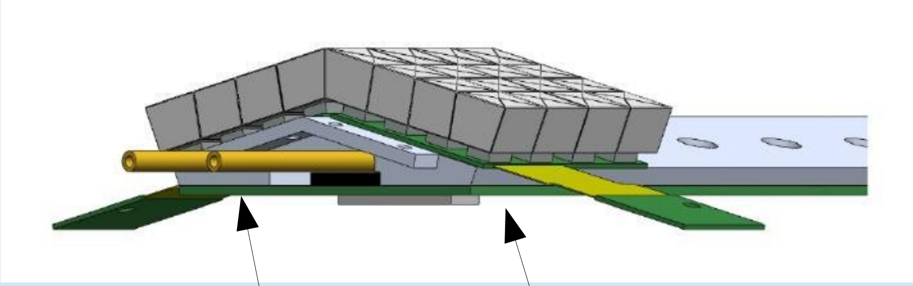
Scintillating Tiles Timing Detectors

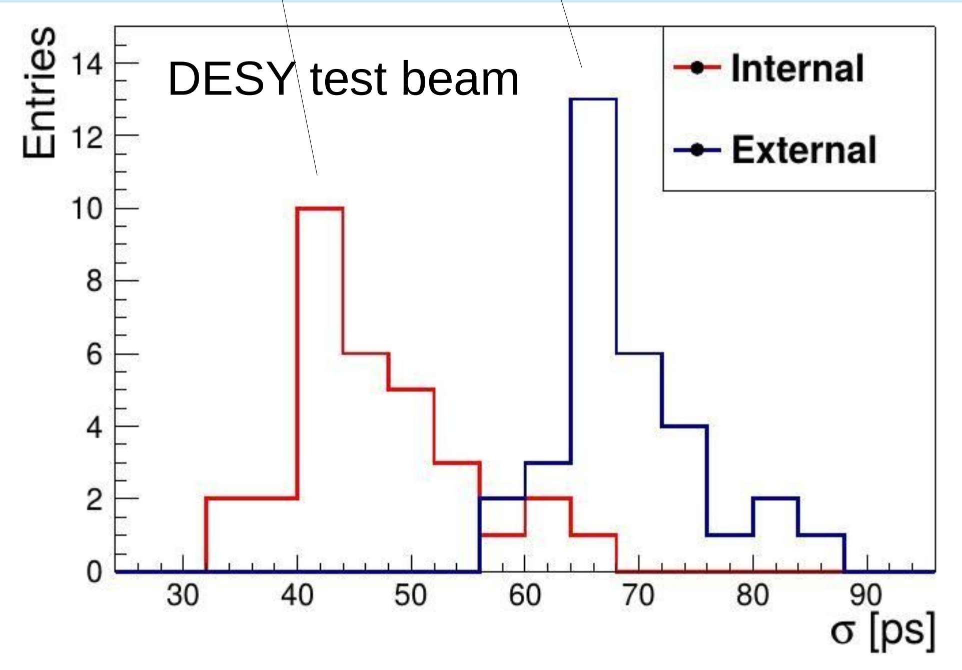


Scintillating Tiles

- tiles ~ 6.5 × 6.5 × 5mm³
- SiPM 3 x 3 mm²
- Readout with MuTrig ASIC (Heidelberg-KIP)
- time resolution < 100ps

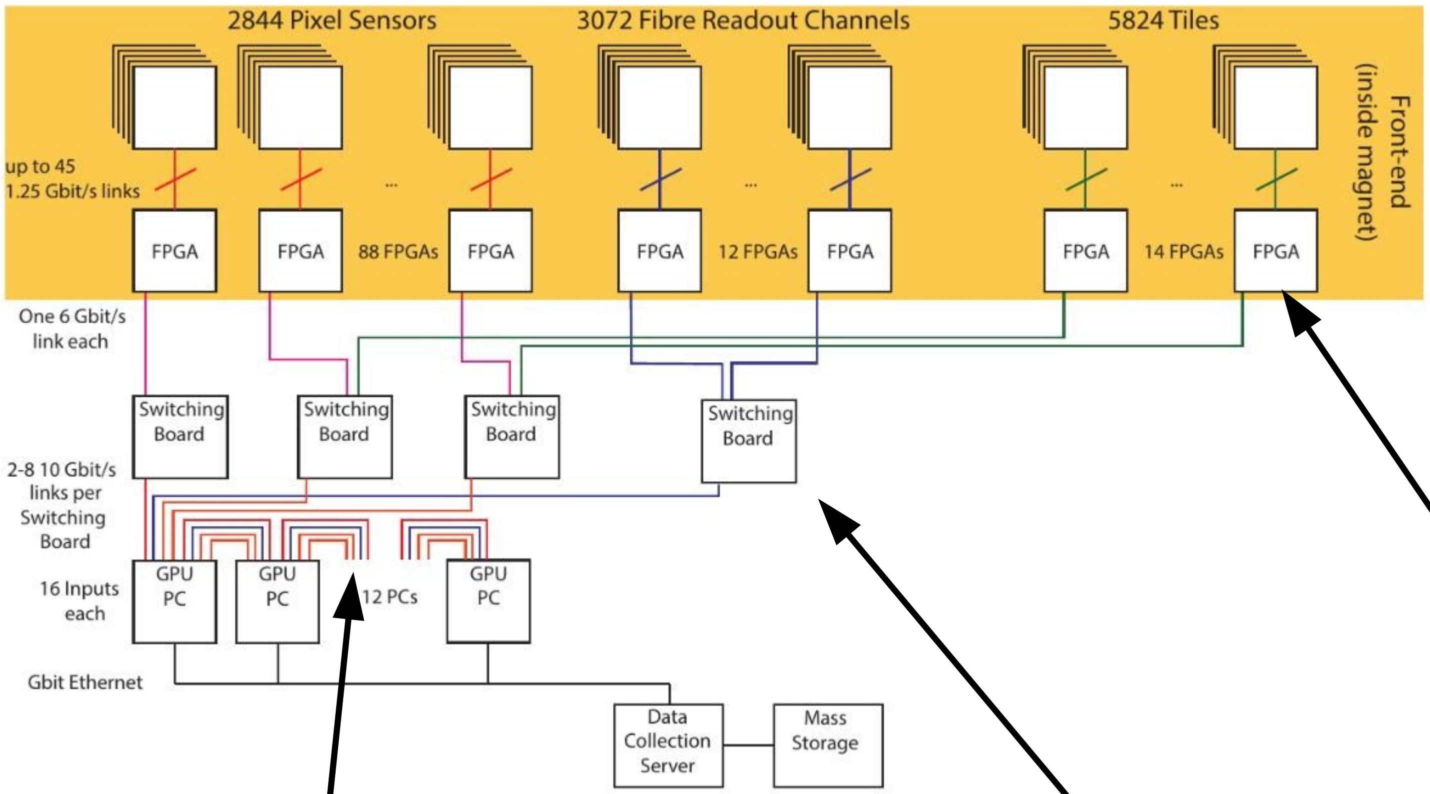
Scintillating Tile Sub-Module





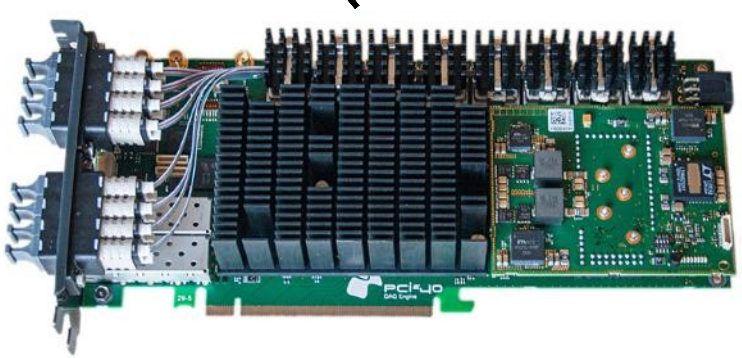
Time resolution < 100ps

Data Acquisition and Filter Farm

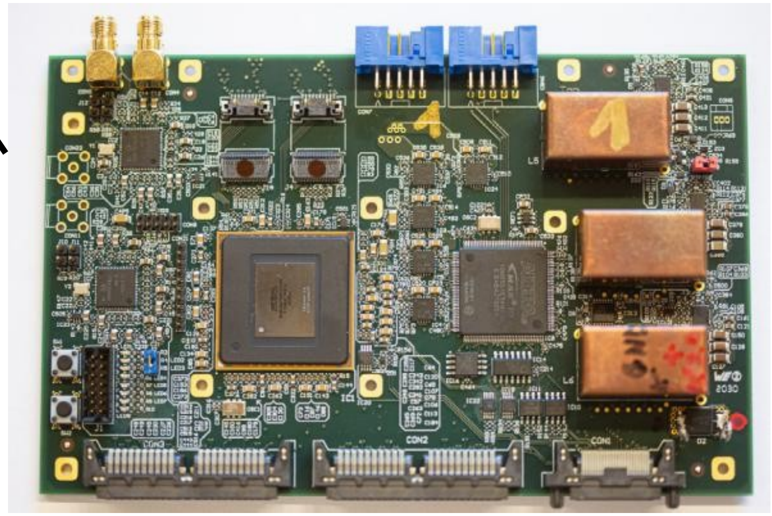


- Continuous readout with frontend zero-suppression
- Online track reconstruction based on new multiple scattering fit *(https://arxiv.org/abs/1606.04990)*
- Filter farm based on NVIDIA GPUs
- DAQ hardware is ready!
- hard working on firmware and SW

DE5aNet Receiving Board (Arria 10)

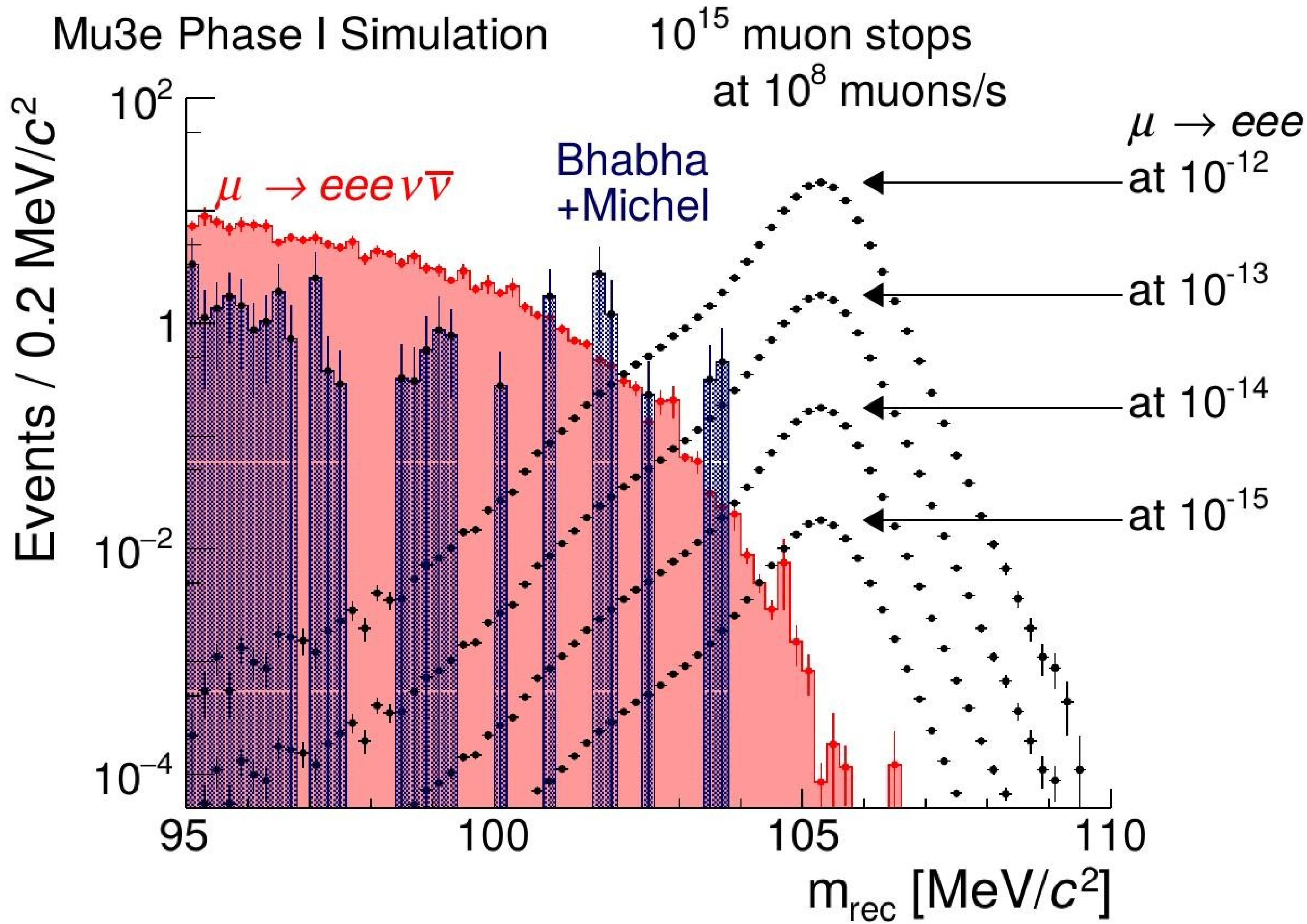


“Switching Board” PCIe40 (from CPPM)

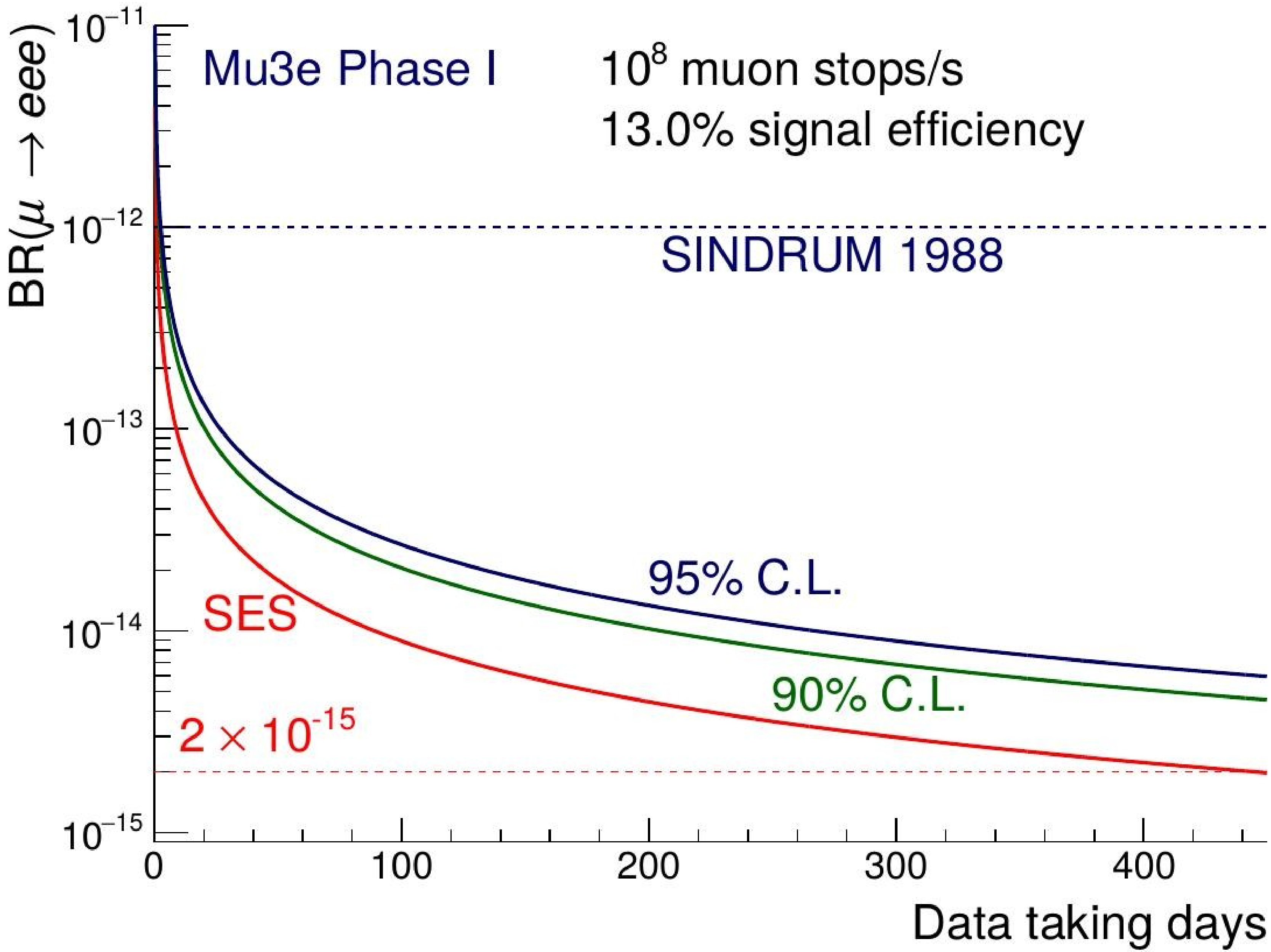


Mu3e Frontend Board with Arria V FPGA (inside the magnet)

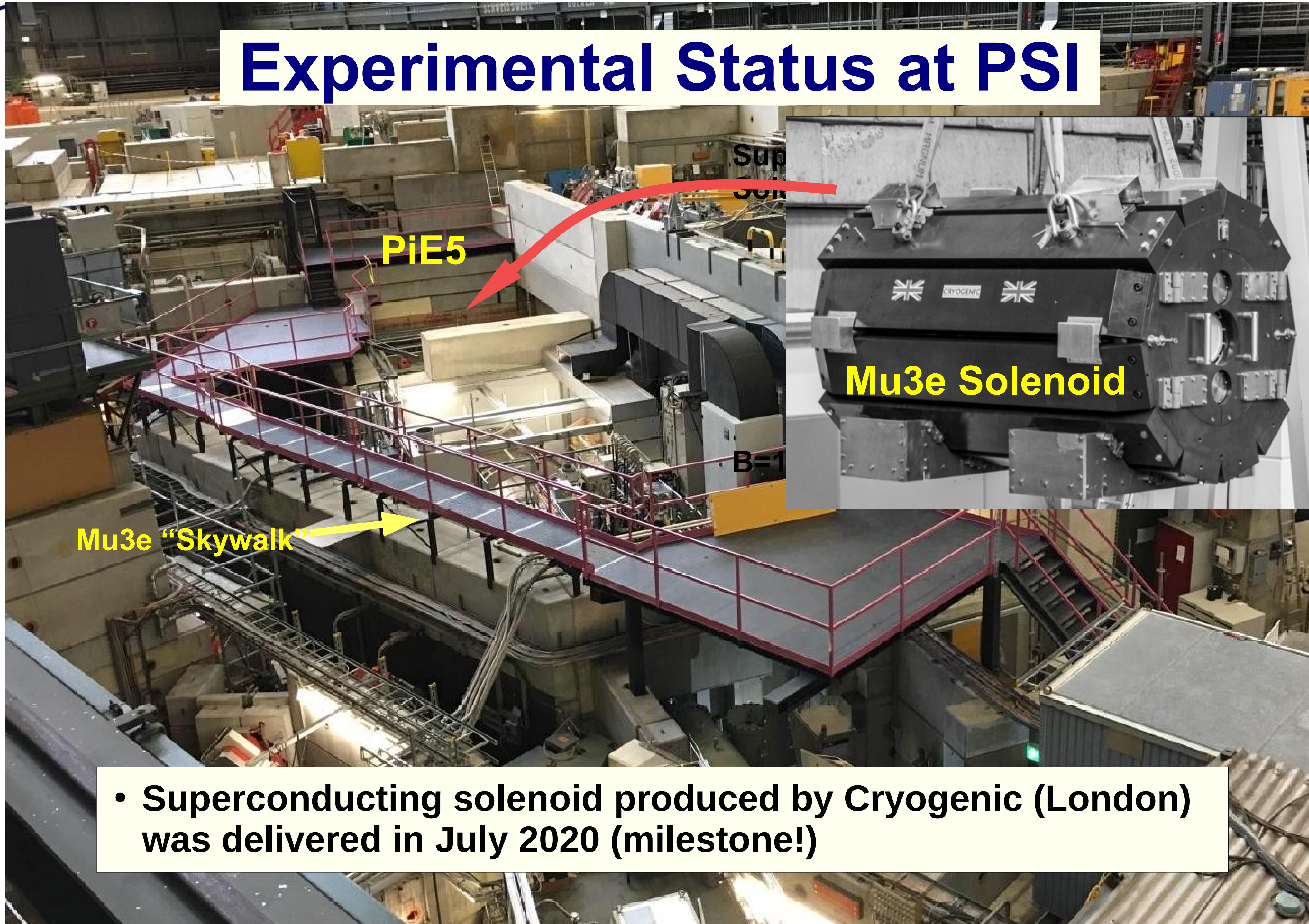
Mu3e Mass Plot (Simulation)



Expecte Sensitivity versus Time

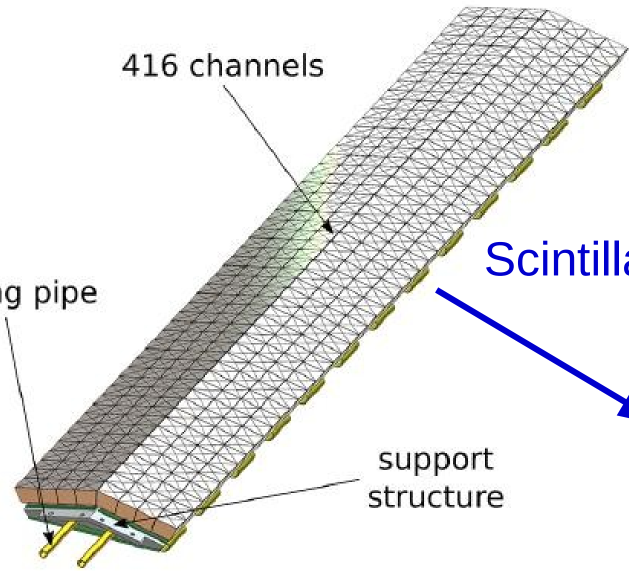


Experimental Status at PSI

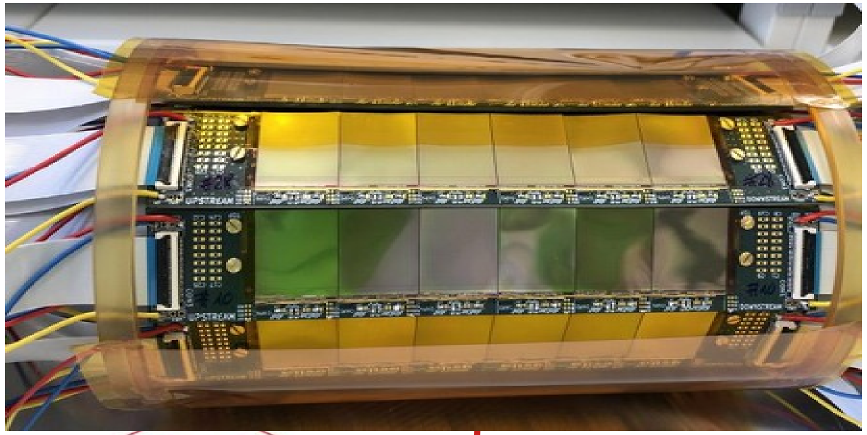


- **Superconducting solenoid produced by Cryogenic (London) was delivered in July 2020 (milestone!)**

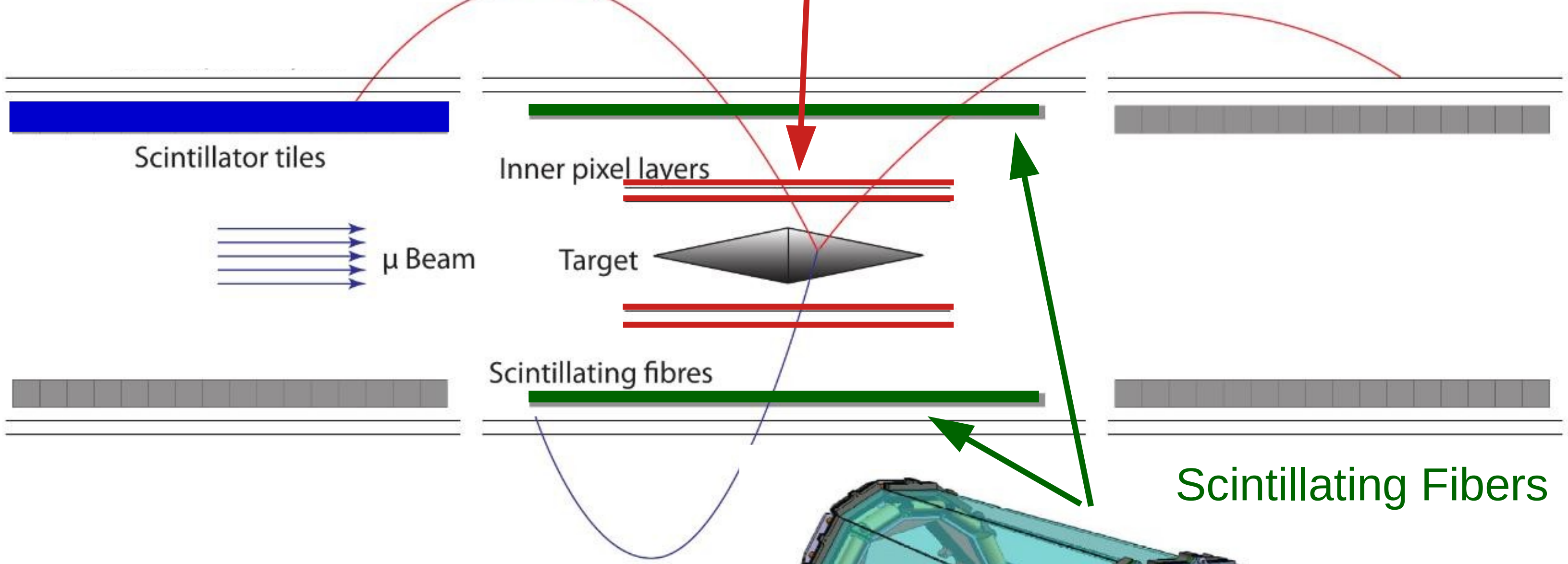
June 2021 Integration Run

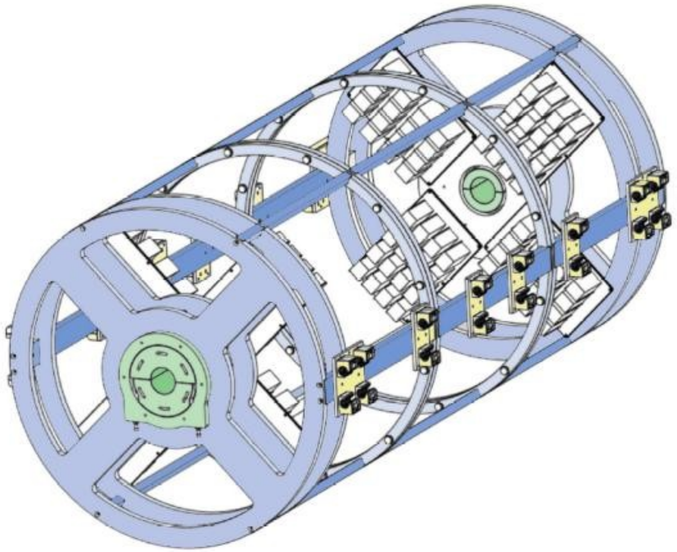


Scintillator Tiles (2x)

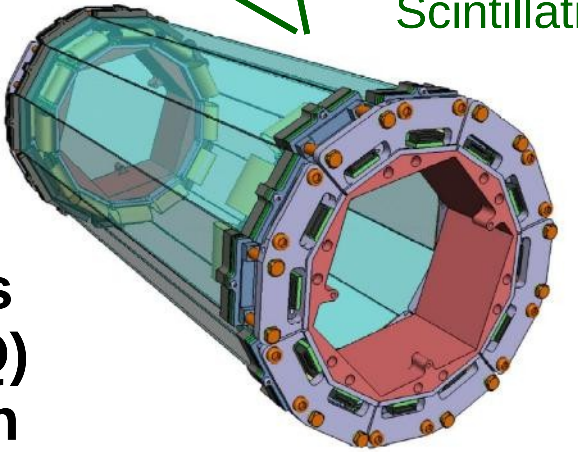


Pixel Detector Prototype





experimental cage



Scintillating Fibers

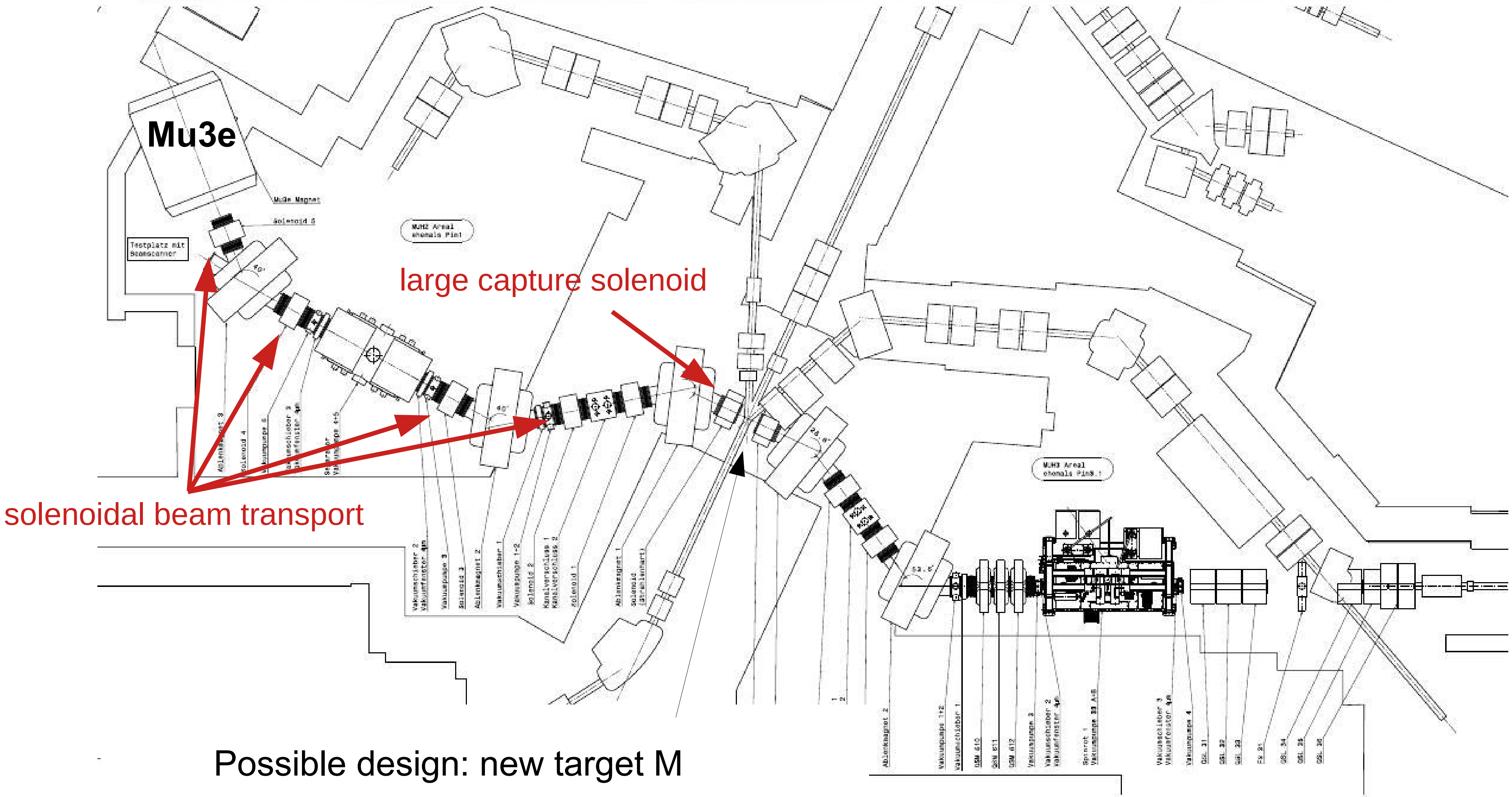
Goal:
final test of all detector systems including data acquisition (DAQ) before starting mass production

Summary

- **Mu3e has an unique discovery potential for New Physics**
- **Technical Design Report published in 2020 *(https://arxiv.org/abs/2009.11690)***
- **First Integration Run with all detector systems planned for May/June 2021**
  - **production readiness**
  - **construction phase of about two years**
- **Start of data taking in 2023 → goal for Phase I $B(\mu^+ \to e^+e^+e^-) \leq 5 \cdot 10^{-15}$ (90% CL)**

Mu3e Phase II and High Intensity Muon Beamline (HiMB)

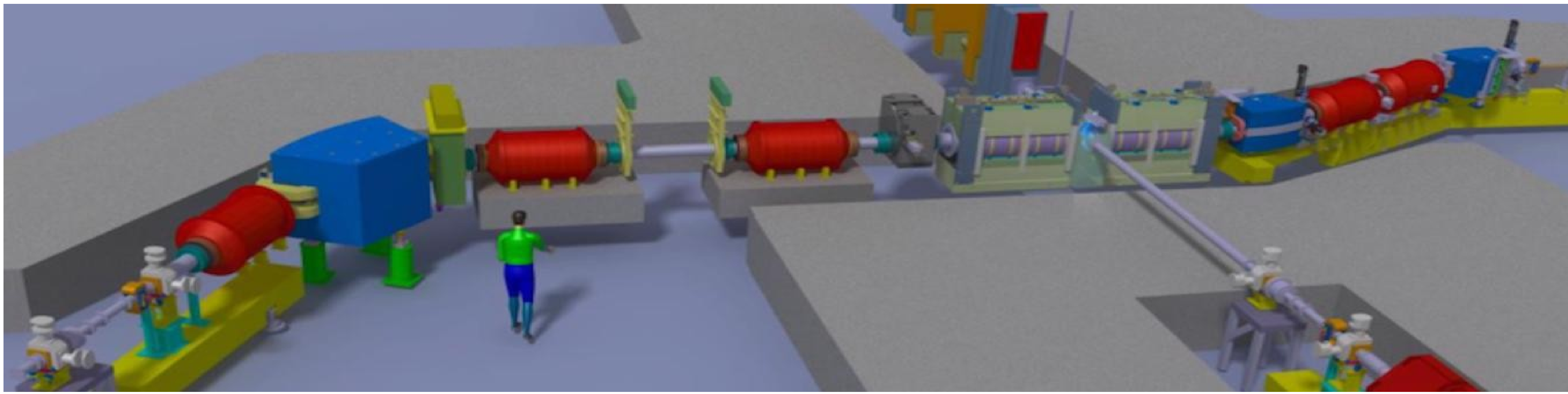
Goal: deliver ~10^{10} muons/s to two experiments (Mu3e, muSR)



Possible design: new target M

Mu3e Phase II and High Intensity Muon Beamline (HiMB)

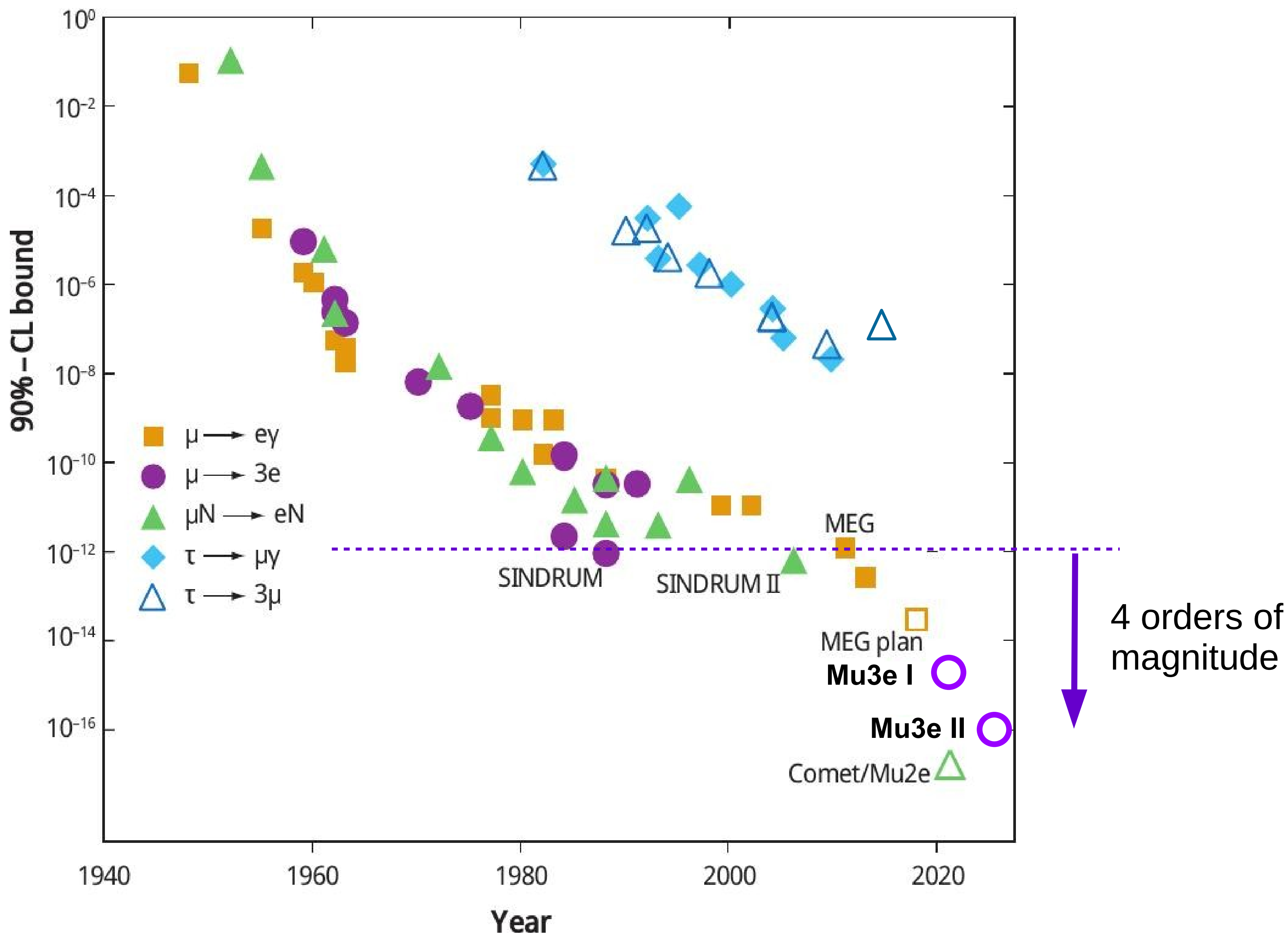
Goal: deliver 10^{10} muons/s to two experiments (Mu3e, muSR)



- **Mu3e Phase II: B($\mu^+ \to e^+e^+e^-$) ≤ 10^{-16} (90% CL)**
- **HiMB Physics Case Workshop 6.-9. April 2021 *(https://indico.psi.ch/event/10547/)***

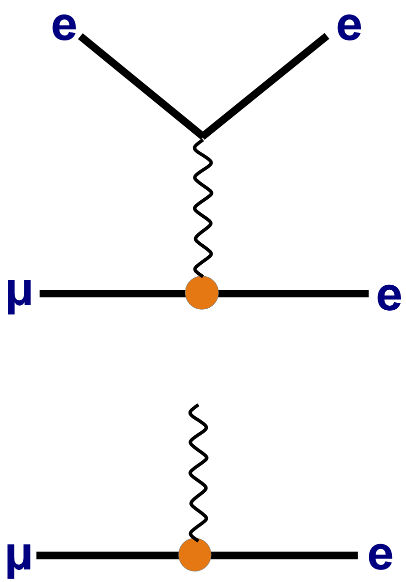
Backup

History of LFV Decay experiments



Model Independent Comparison

dipole



$\kappa \rightarrow 0$

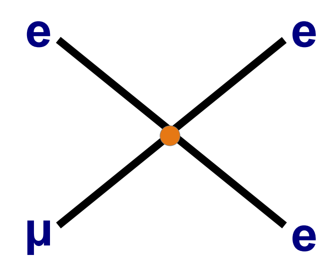
Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J^{e\mu}_{\nu} J^{\nu,ee}$$

κ = parameter

Λ = common effective mass scale

μeee contact IA



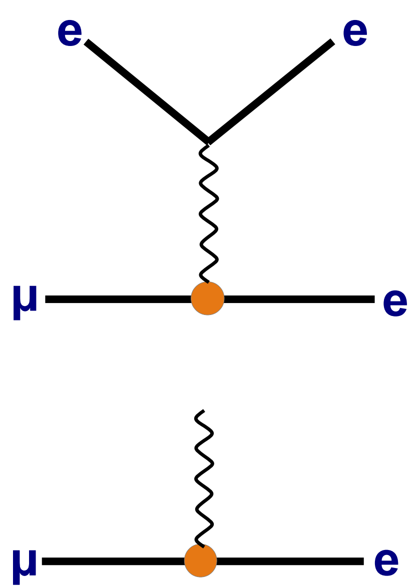
$\kappa \rightarrow \infty$

$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} \sim 0.006$$

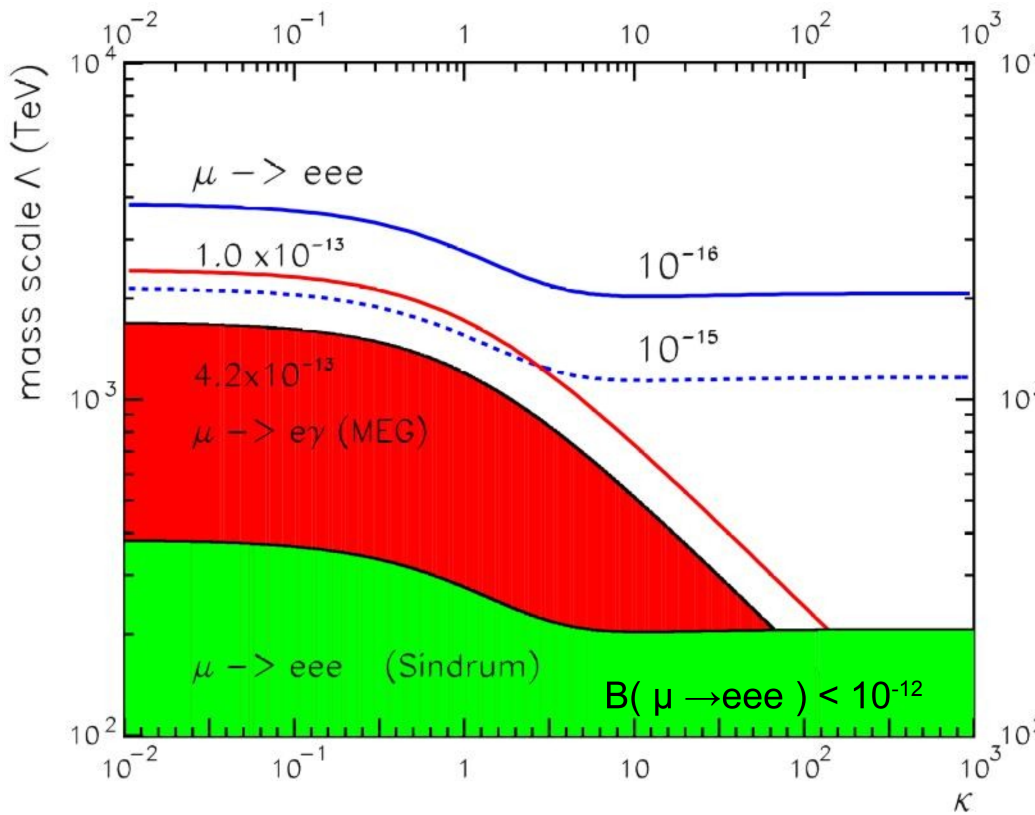
$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{\text{~~B(μ⁺ → e⁺γ)~~}} \rightarrow \infty$$

Model Independent Comparison

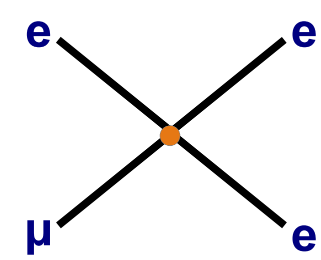
dipole



κ → 0



μeee contact IA



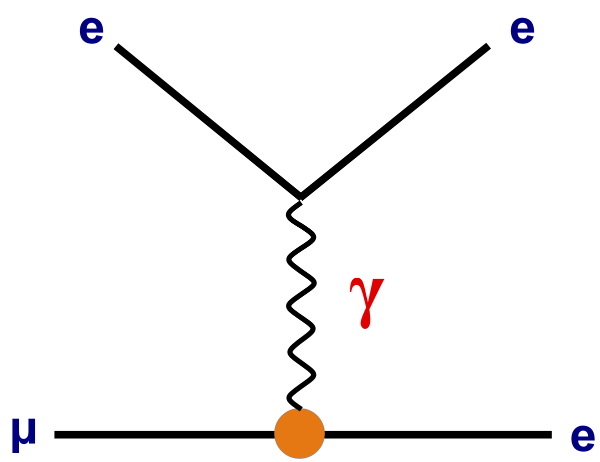
κ → ∞

$$\frac{B(\mu^+ \to e^+e^+e^-)}{B(\mu^+ \to e^+\gamma)} \sim 0.006$$

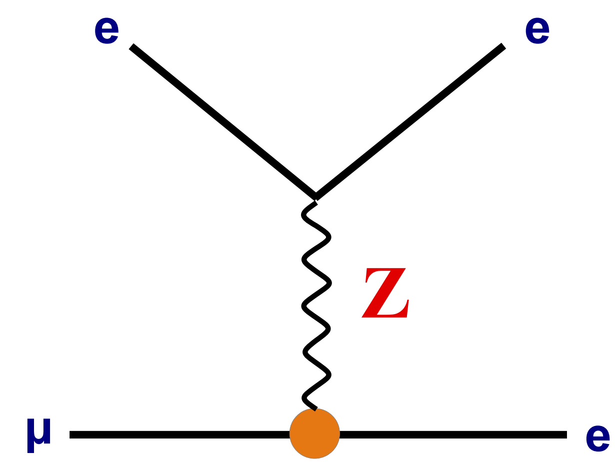
$$\frac{B(\mu^+ \to e^+e^+e^-)}{\cancel{B(\mu^+ \to e^+\gamma)}} \to \infty$$

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

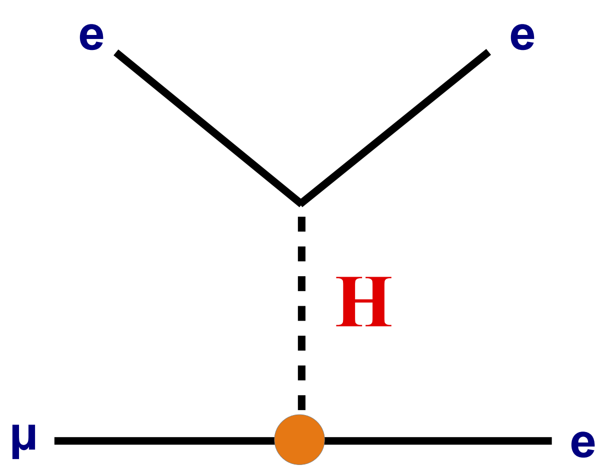
$\mu^+ \rightarrow e^+e^+e^-$



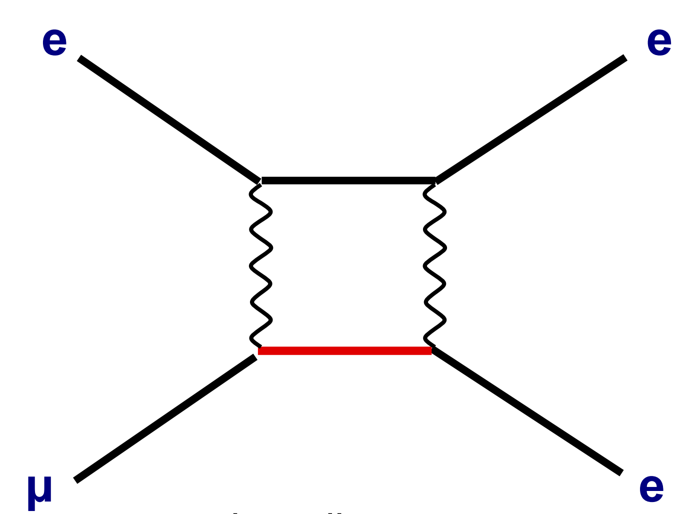
photon penguin



Z - penguin



Higgs-penguin



box diagram

LFV-Effective Field Theory

A.Crivellin et al., PSI-PR-16-15

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED+QCD}} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Representation by Wilson coefficients and higher-dimensional operators:

$$O_L^D = e\, m_\mu \,(\bar{e}\sigma^{\mu\nu}P_L\mu)\, F_{\mu\nu},$$

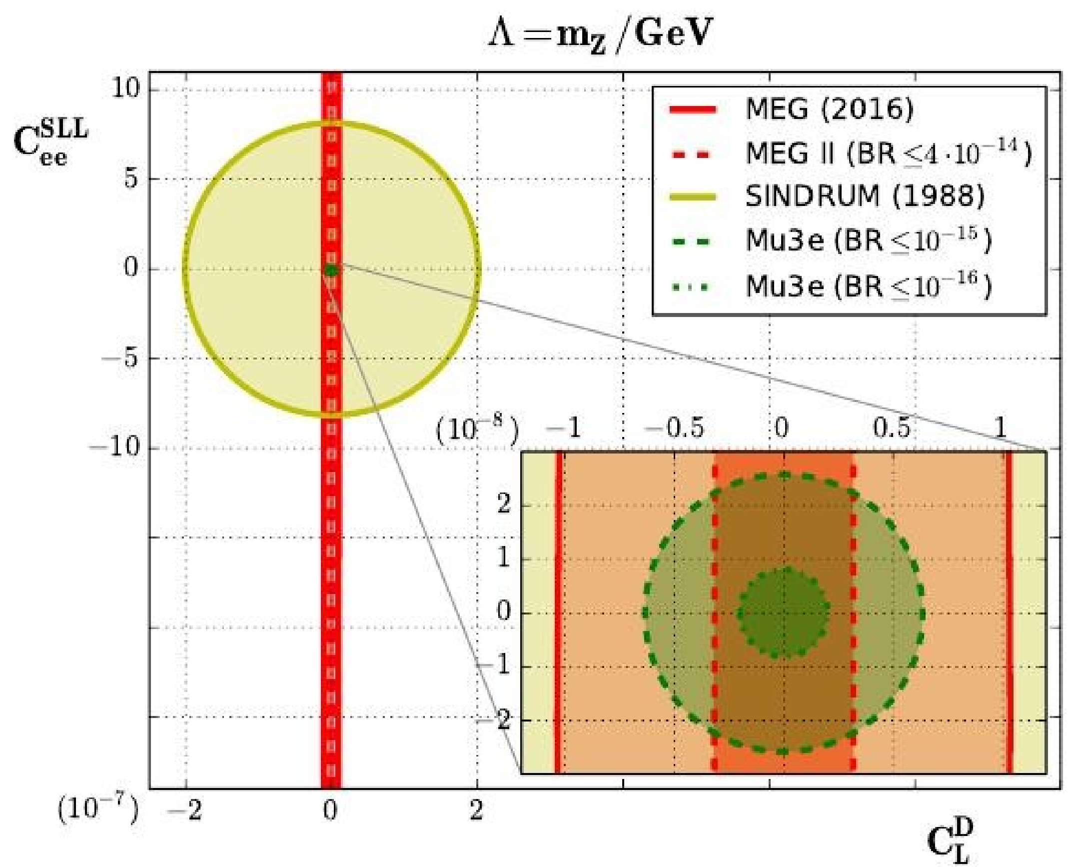
$$O_{ff}^{V\,LL} = (\bar{e}\gamma^\mu P_L\mu)\left(\bar{f}\gamma_\mu P_L f\right),$$

$$O_{ff}^{V\,LR} = (\bar{e}\gamma^\mu P_L\mu)\left(\bar{f}\gamma_\mu P_R f\right),$$

$$O_{ff}^{S\,LL} = (\bar{e}P_L\mu)\left(\bar{f}P_L f\right),$$

$$O_{ff}^{S\,LR} = (\bar{e}P_L\mu)\left(\bar{f}P_R f\right),$$

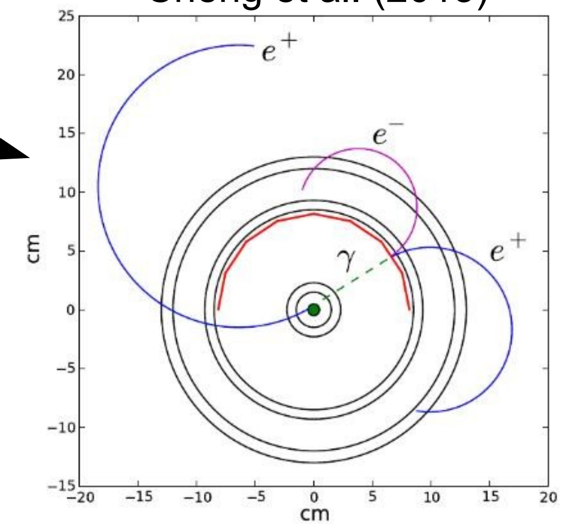
$$O_{ff}^{T\,LL} = (\bar{e}\sigma_{\mu\nu}P_L\mu)\left(\bar{f}\sigma^{\mu\nu}P_L f\right),$$



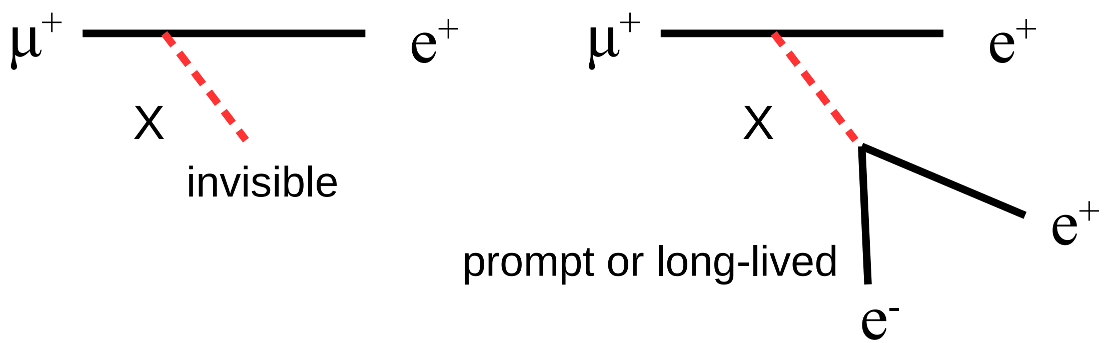
Other Possible Searches with Mu3e

- Search for $\mu \rightarrow e\gamma$ (LFV) with converted photons
  - better reduction of accidental BG than MEG

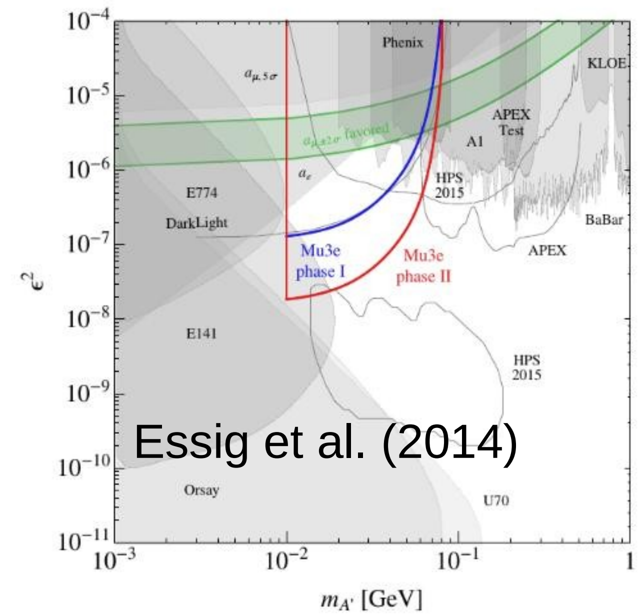
Cheng et al. (2013)



- Search for **familons**
  - pseudo Goldstone bosons of spontaneously broken flavor symmetry
  - dark matter candidate



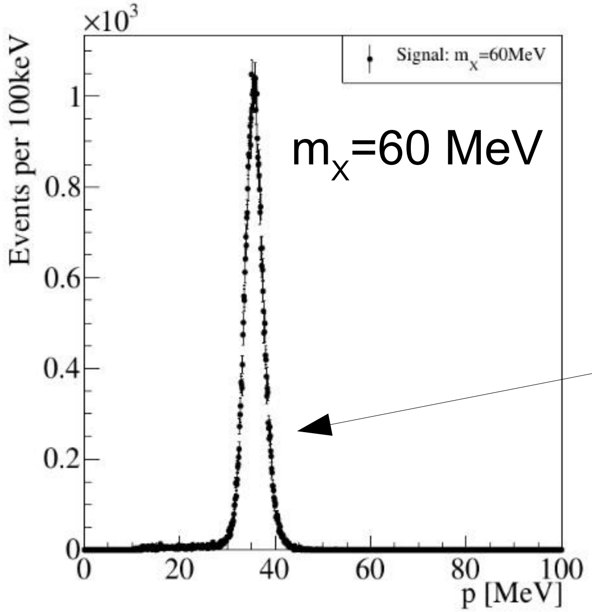
- Search for **dark photons A'**:
  - process $\mu \rightarrow e\, \nu\nu\, A'$

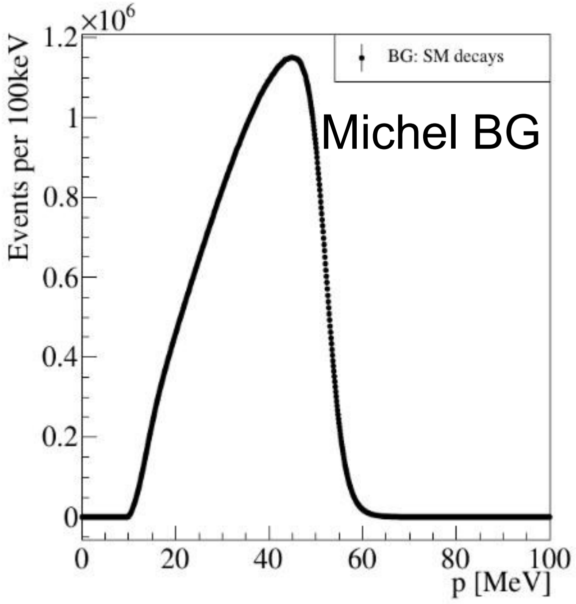


Essig et al. (2014)

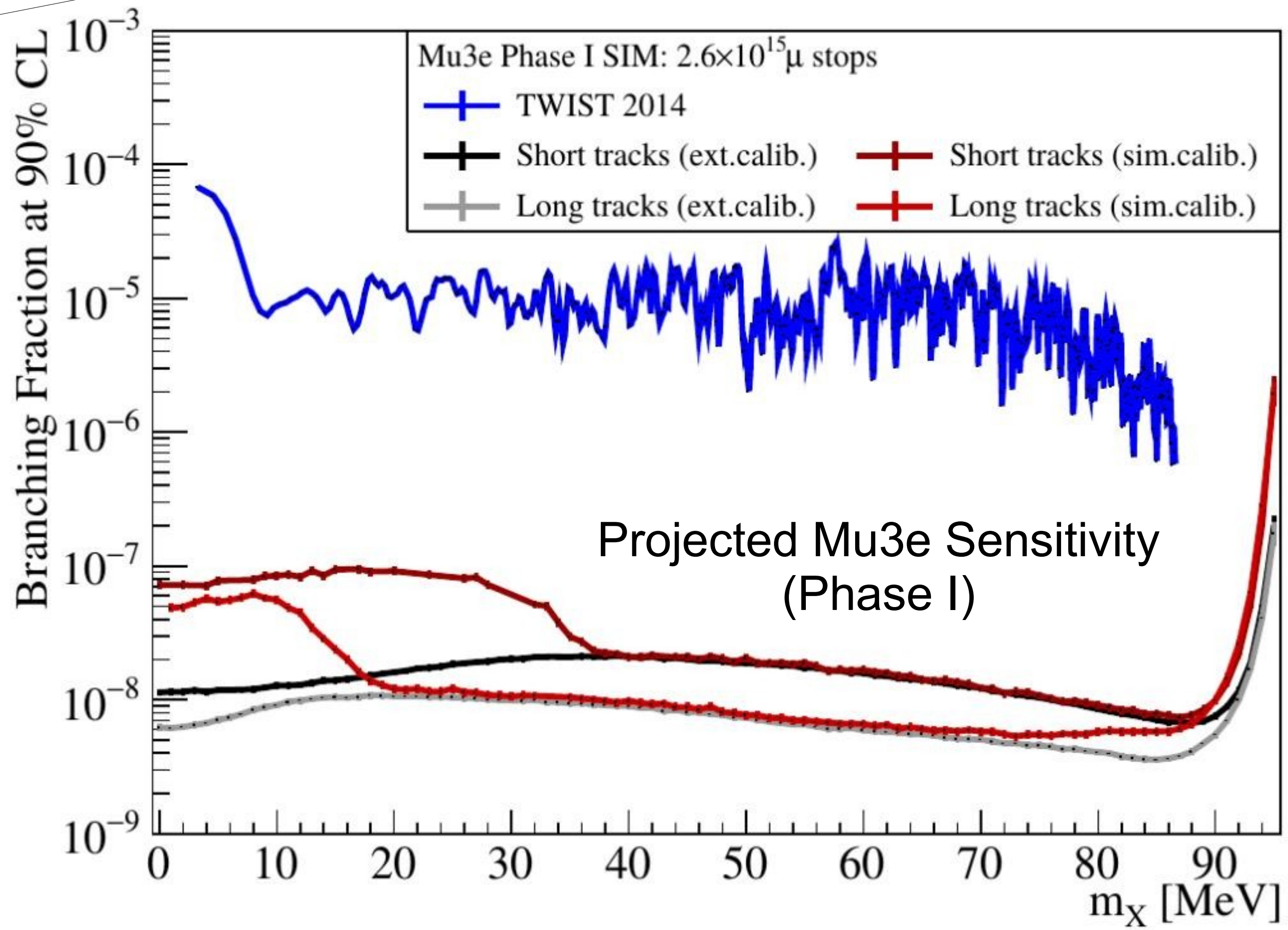
Search for Familons $\mu^+ \to e^+ X$

- Familons are the Goldstone Bosons of a spontaneously broken flavor symmetry
- $\mu^+ \to e^+ X$ is 2-body decay
- Search for a **peak** on the e^+ momentum distr.





thesis A.-K.Perrevoort

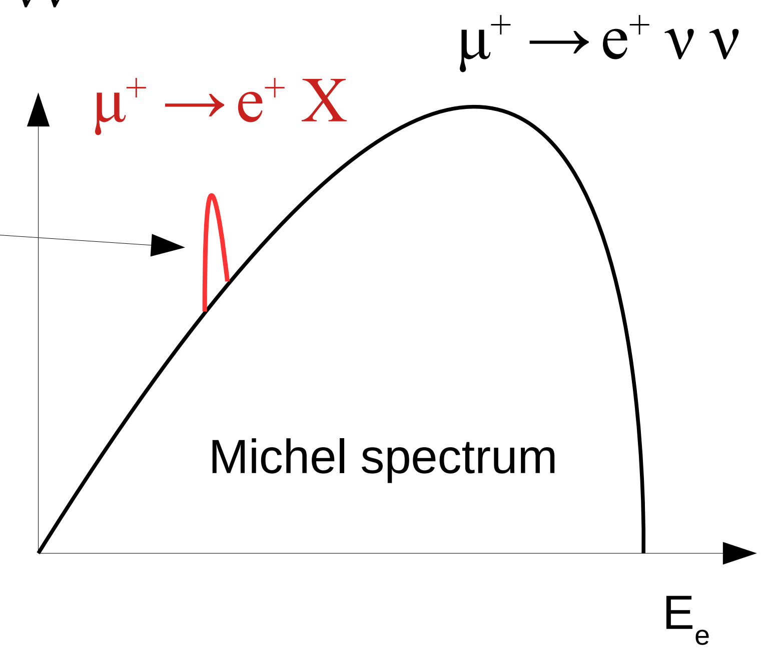


Side Remark: Exotic LFV Decays

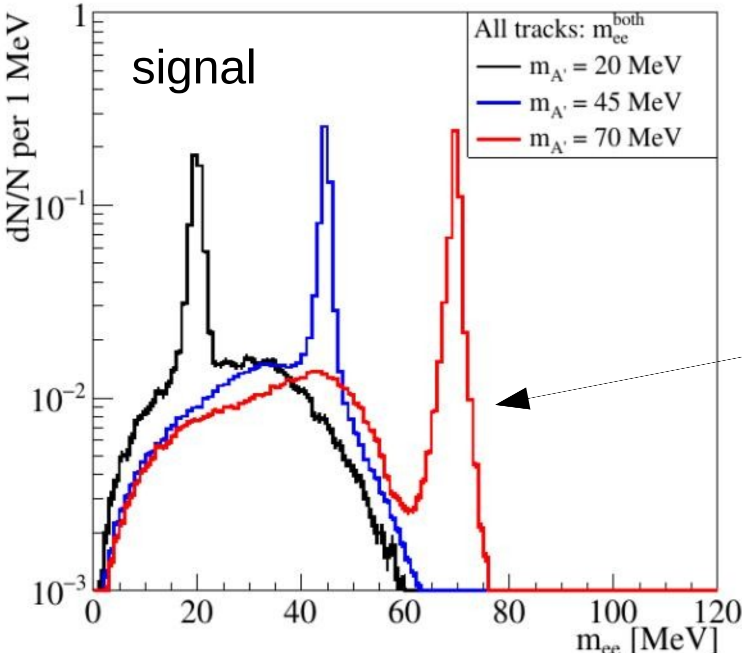
Weakly Interaction Slim Particles (WISP)

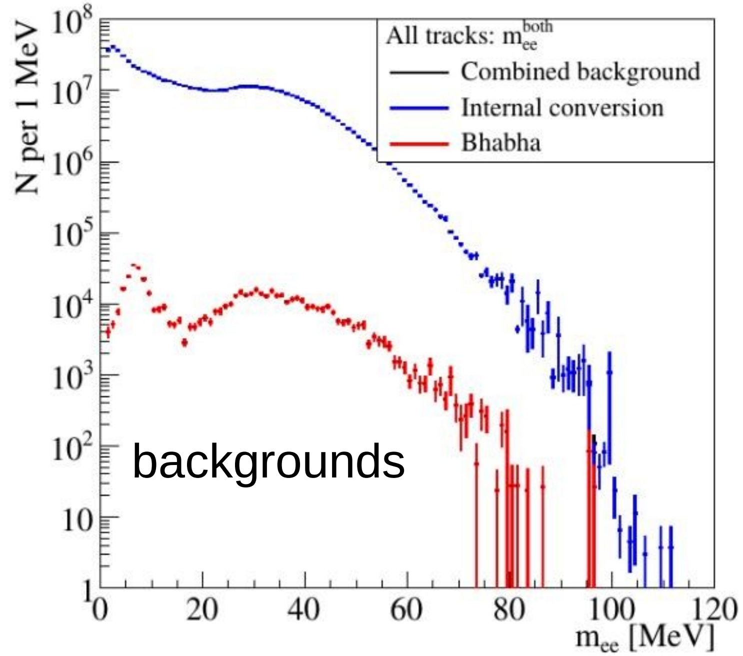
- light axions are theoretically well motivated
- axions X could be LFV familons
  - pseudo-Nambu-Goldstein boson of spontaneously broken family asymmetry
  - addressing dark matter
- X could weakly couple to SM particles: $\mu^+ \to e^+ X \quad (\mu^+ \to e^- \gamma X)$
- X would be long-living or decay in detector: $X \to e^+e^-, \nu\nu$

- Search topologies:
  - peak in Michel spectrum
  - displaced e^+e^- vertex
  - $\mu^+ \to e^+e^+e^-$ signature with M(ee) peak



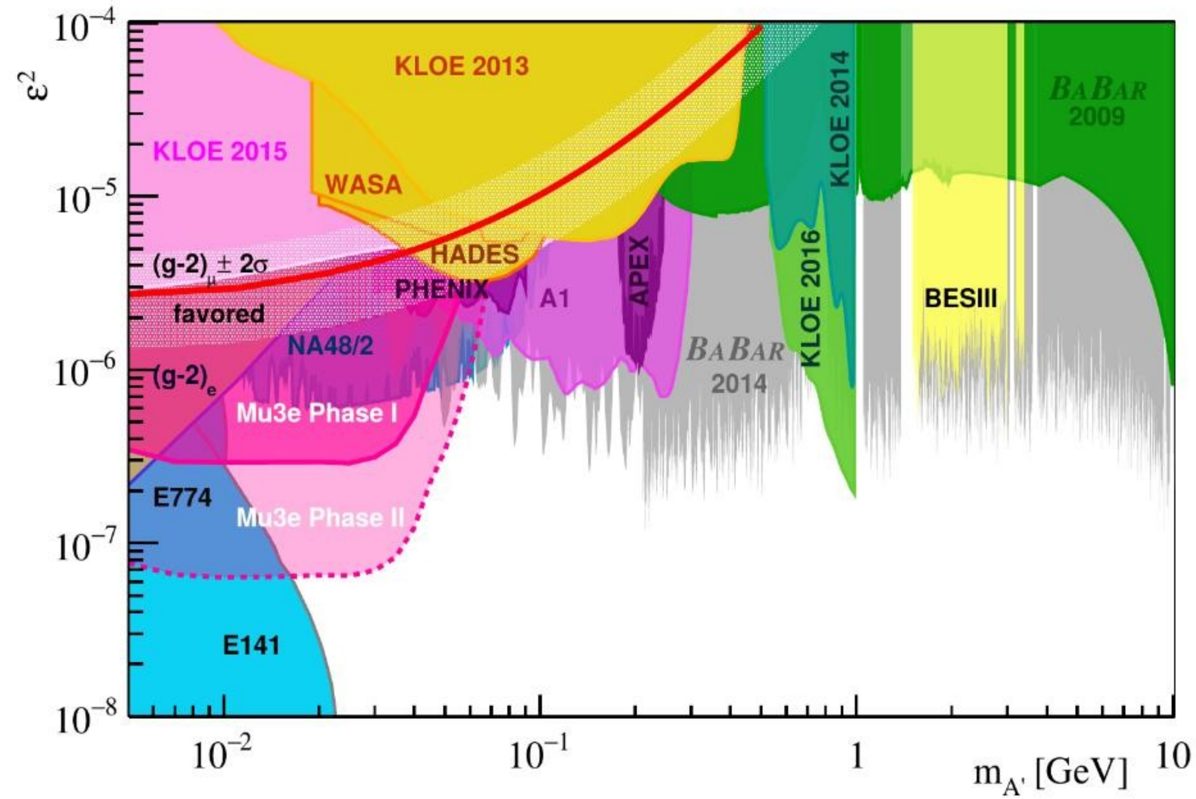
Search for Dark Photons in $A' \rightarrow e^+e^-$



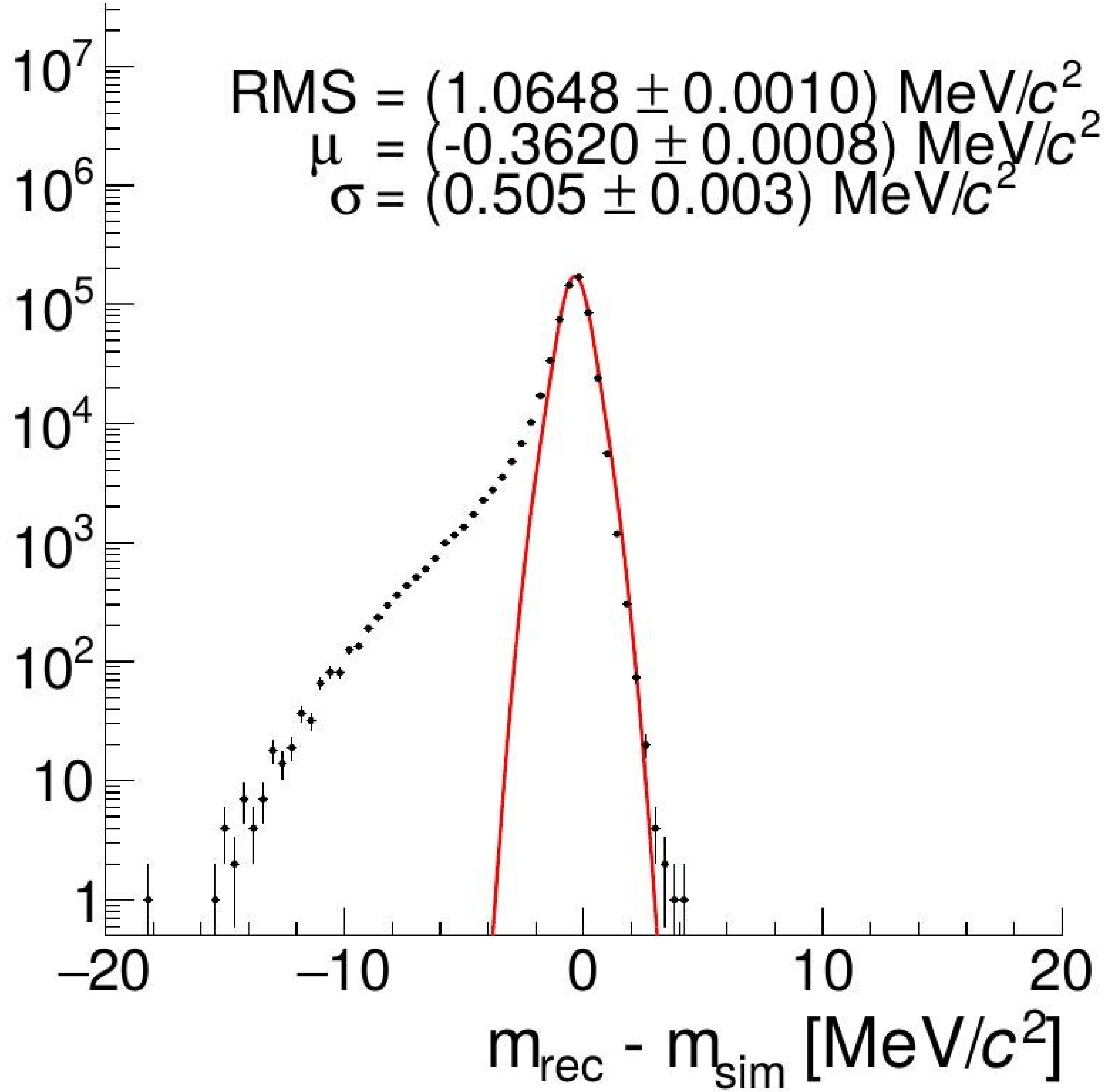


- Search for Dark Photons with zero or short lifetime:
  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu A'$ with $A' \rightarrow ee$
- **peak** in $m(e^+e^-)$ invariant mass

thesis A.-K.Perrevoort



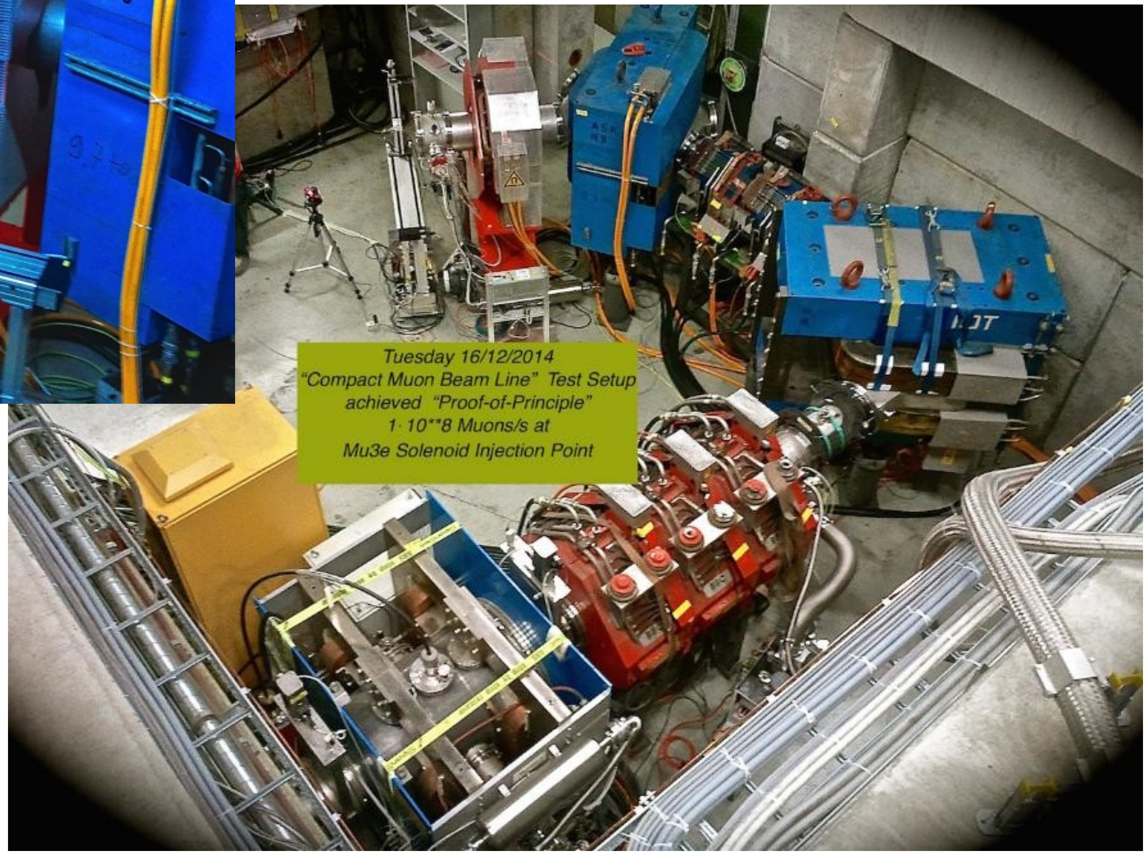
Mu3e Phase I Simulation, 3 recurlers



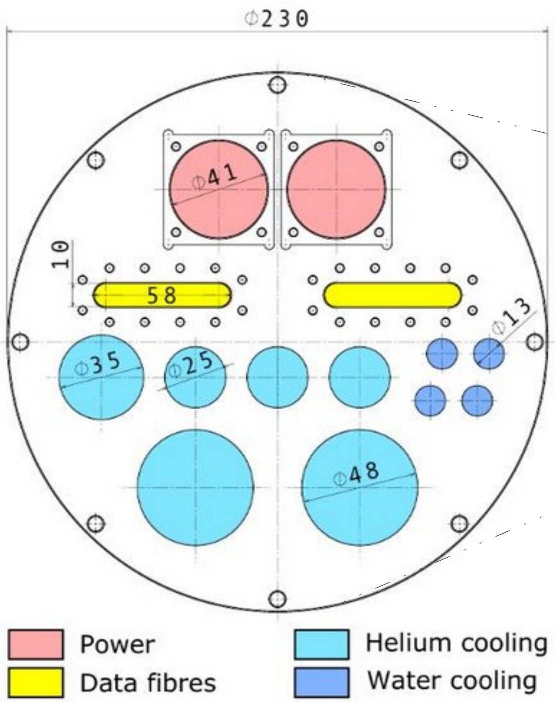
PiE5 Beamline + Experimental Region

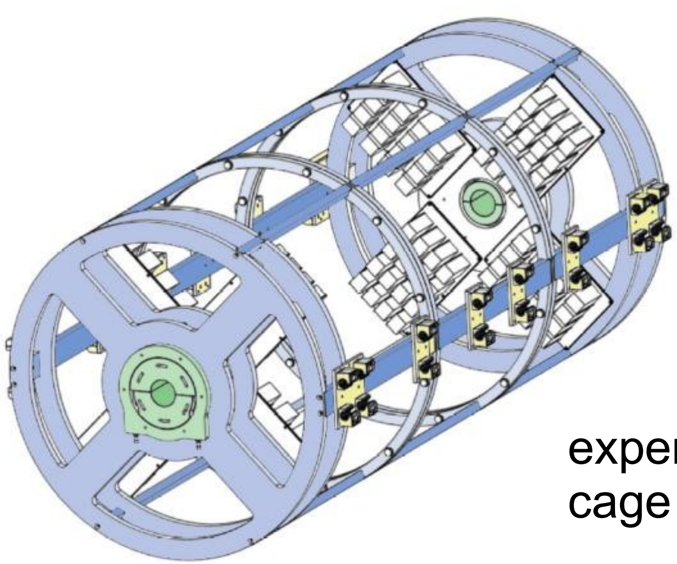
mockup for Mu3e solenoid

Compact Muon Beamline was successfully commissioned providing up to 10^8 muons/s

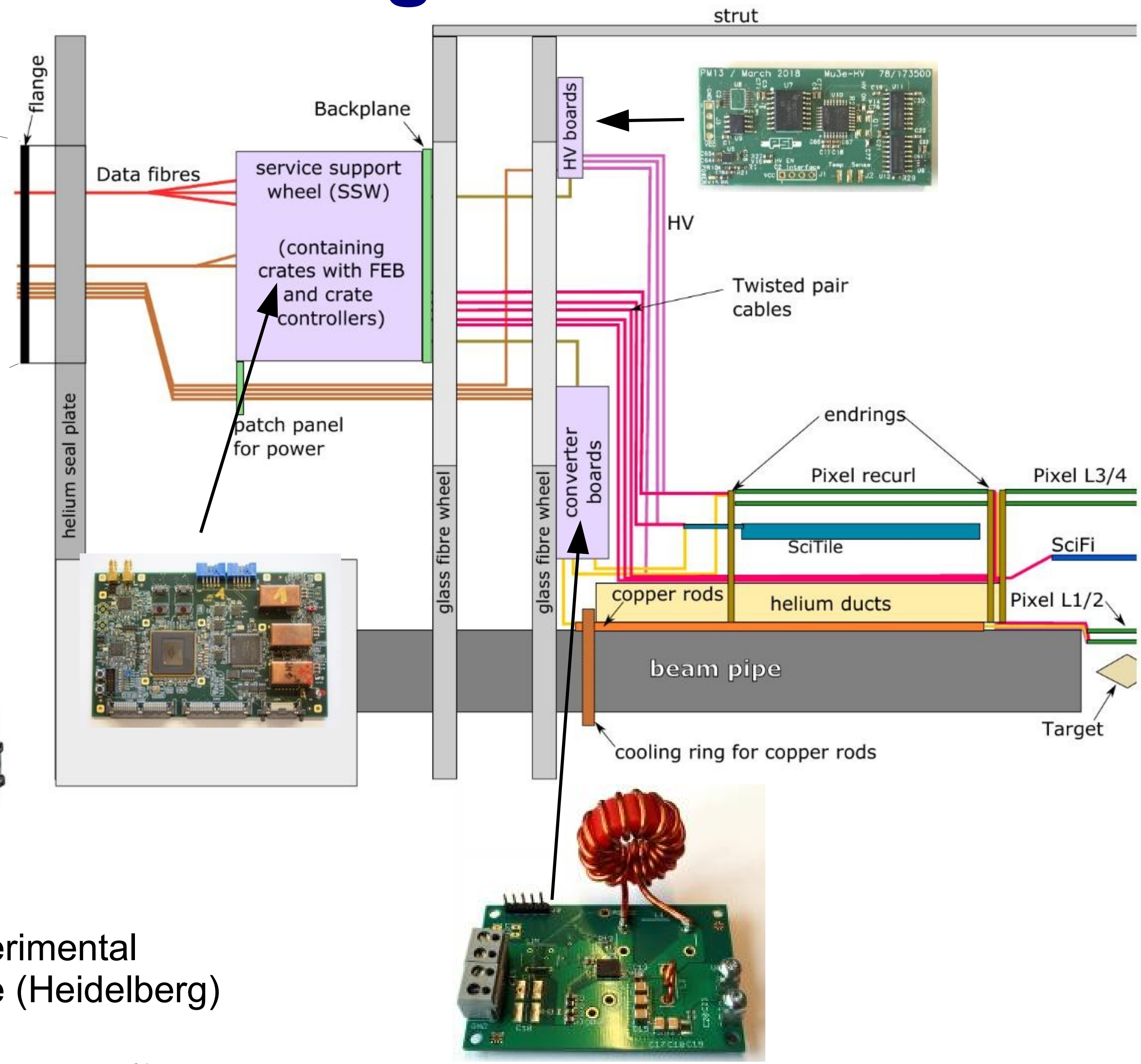


Experimental Cage & Services

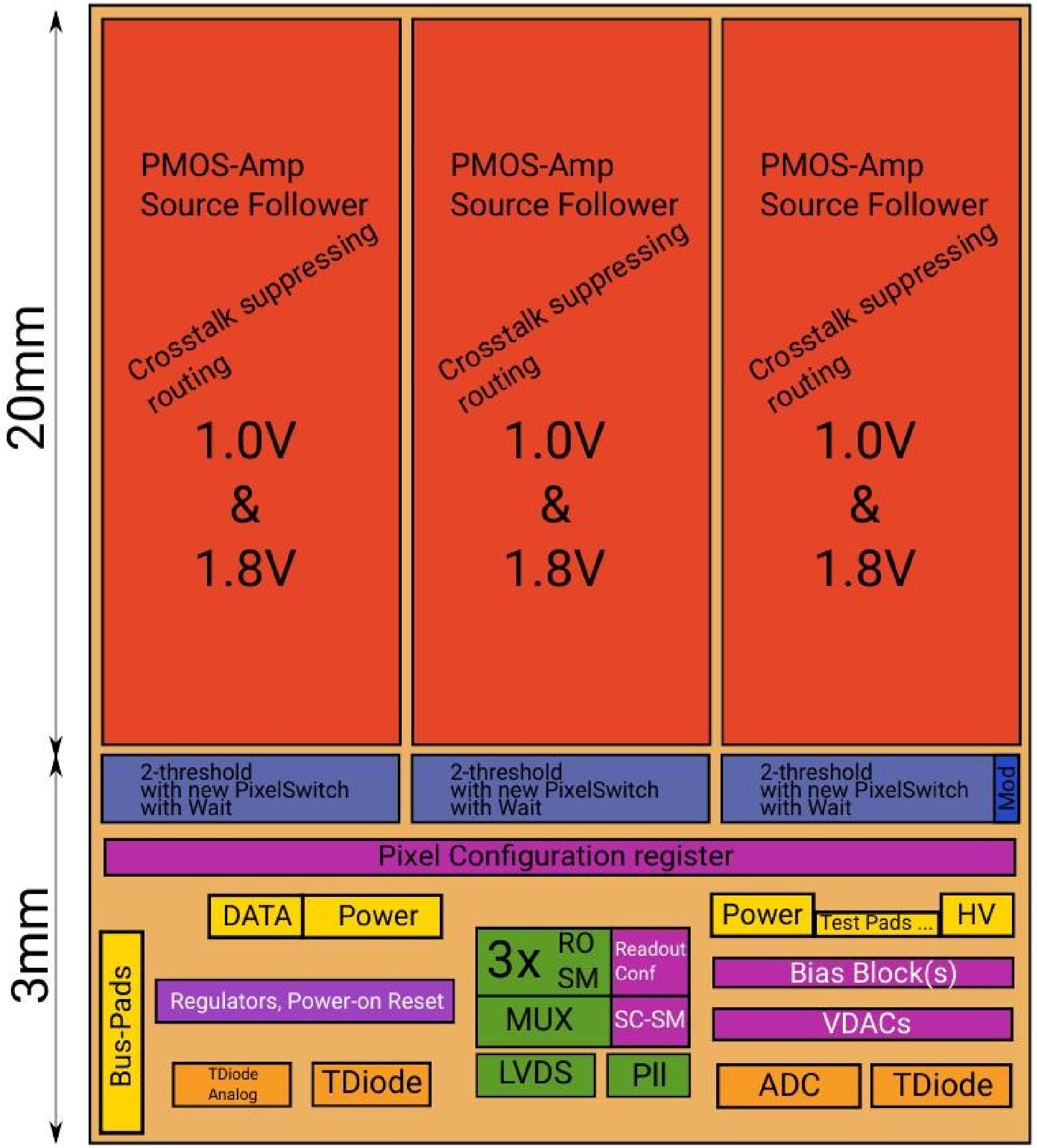




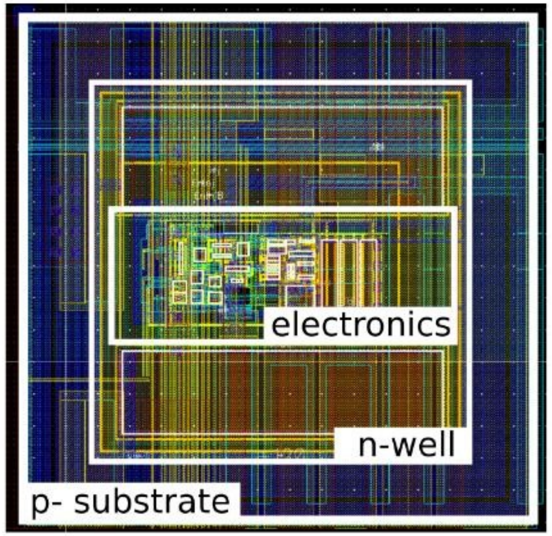
experimental
cage (Heidelberg)



Mupix10 Design & Specifications



Pixel Matrix



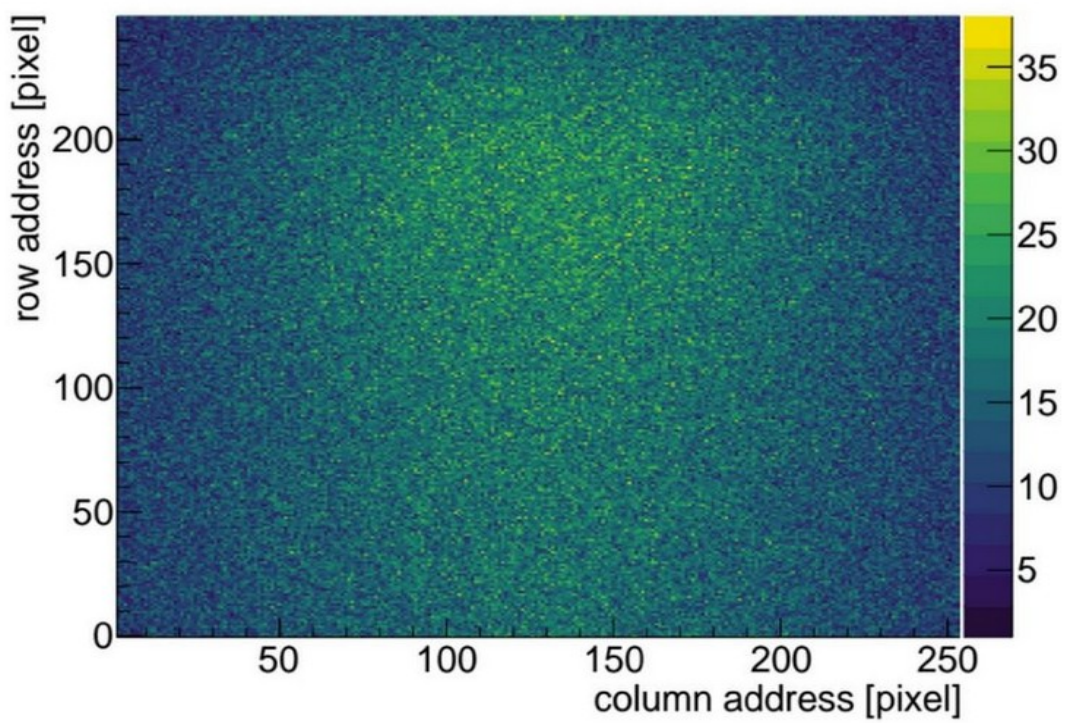
Specification from TDR

sensor dimensions [mm^2]	$\leq 21 \times 23$
sensor size (active) [mm^2]	$\approx 20 \times 20$
thickness [µm]	≤ 50
spatial resolution µm	≤ 30
time resolution [ns]	≤ 20
hit efficiency [%]	≥ 99
#LVDS links (inner layers)	1 (3)
bandwidth per link [Gbit/s]	≥ 1.25
power density of sensors [mW/cm^2]	≤ 350
operation temperature range [°C]	0 to 70

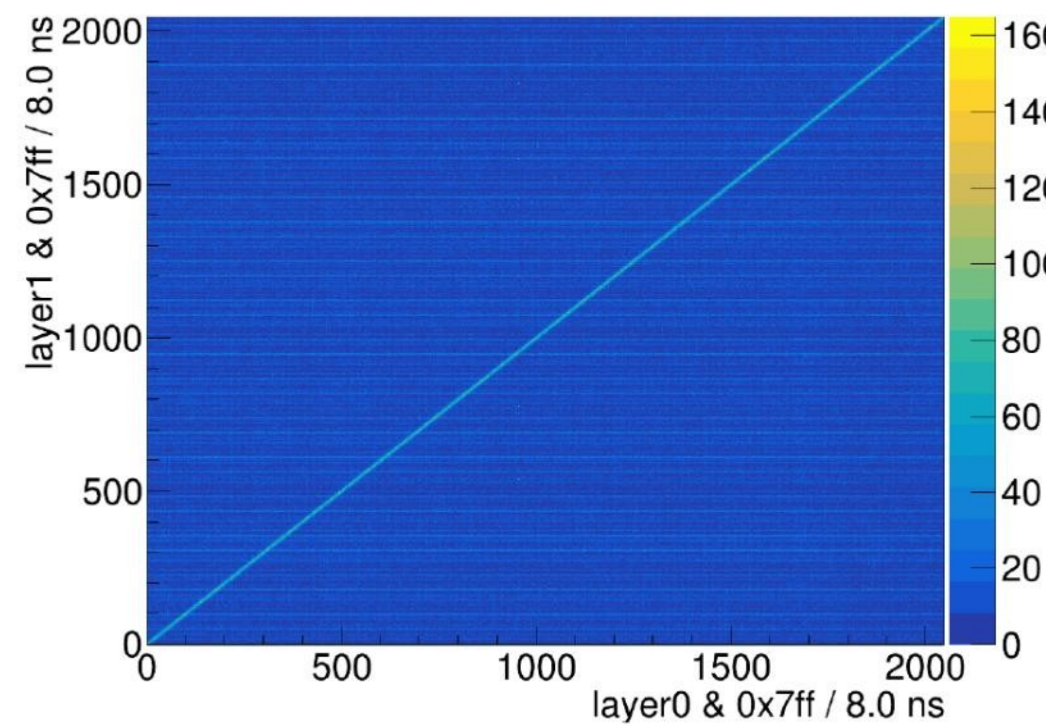
Beam Test Results and Mupix10 Telescope

- Telescope: 3+1 (DUT) layers
- DESY & PSI testbeams (despite Corona)
- MuPix works fine in general!

Note, all following results are very first results and preliminary!



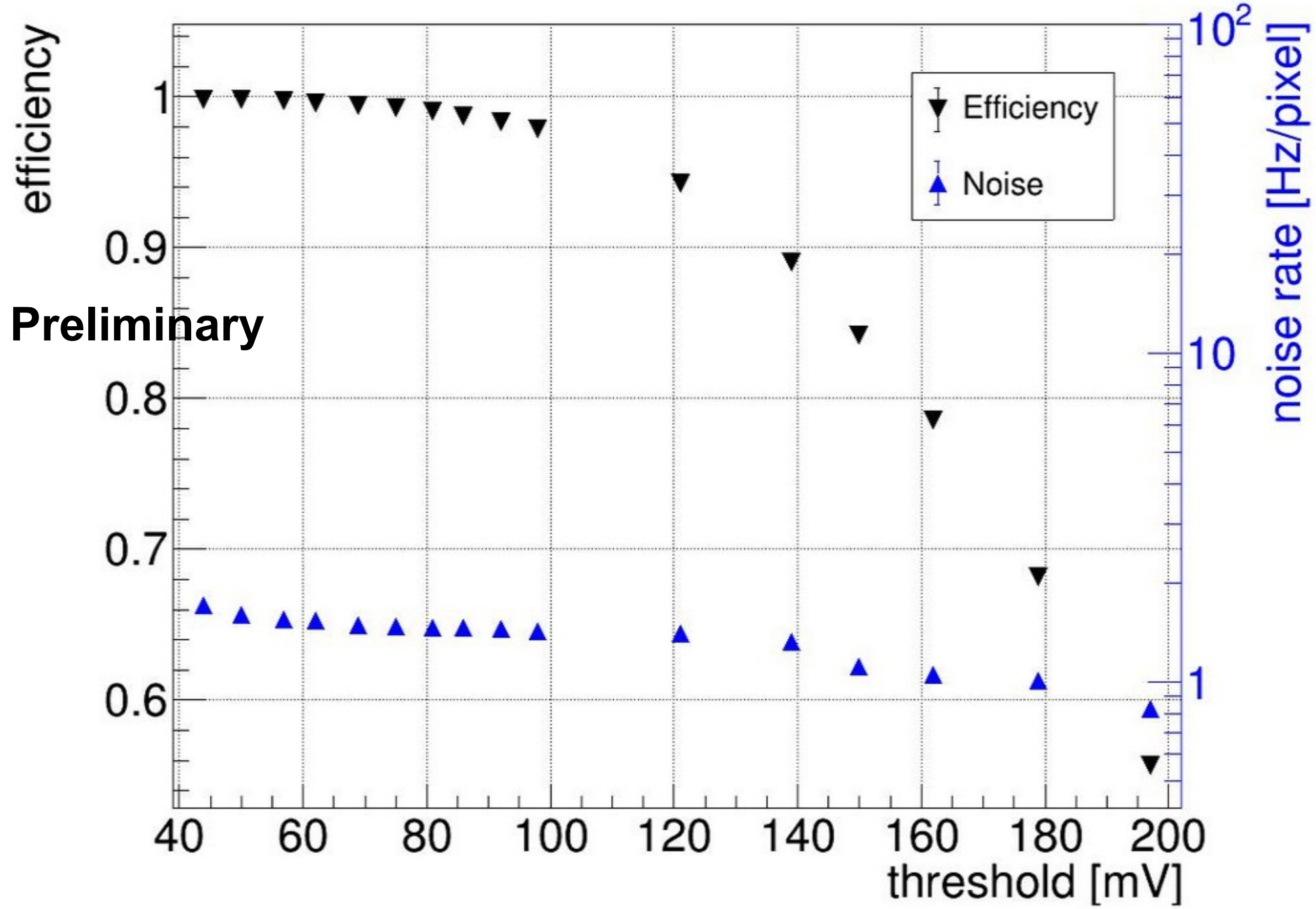
Hit map (electrons @DESY)



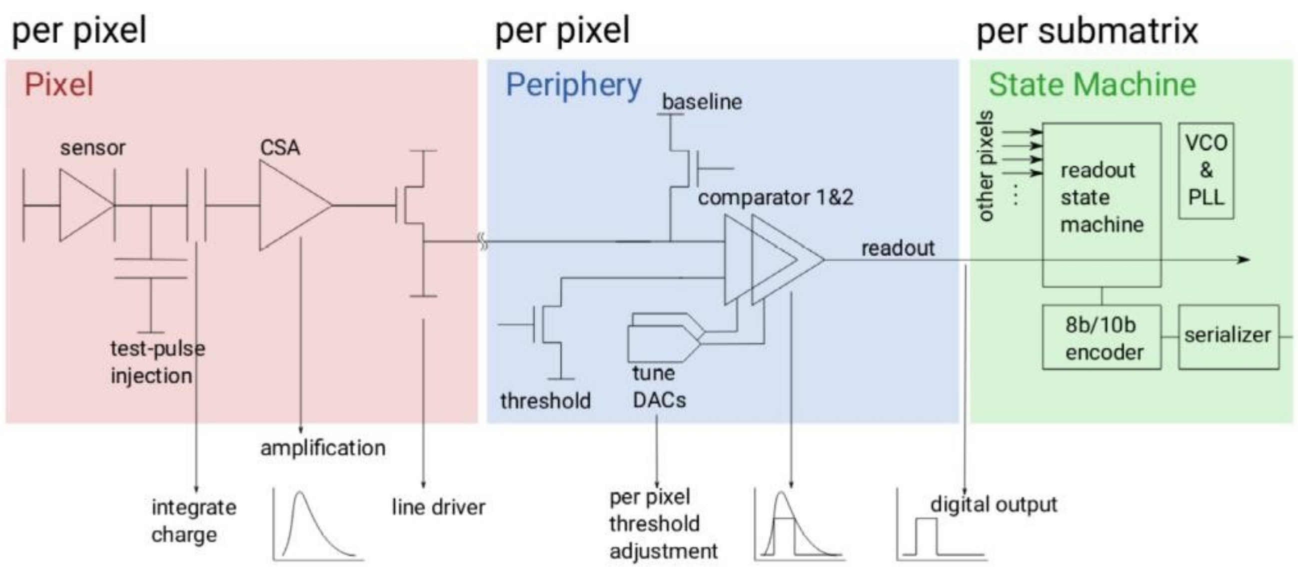
Time correlation between layers (PSI)

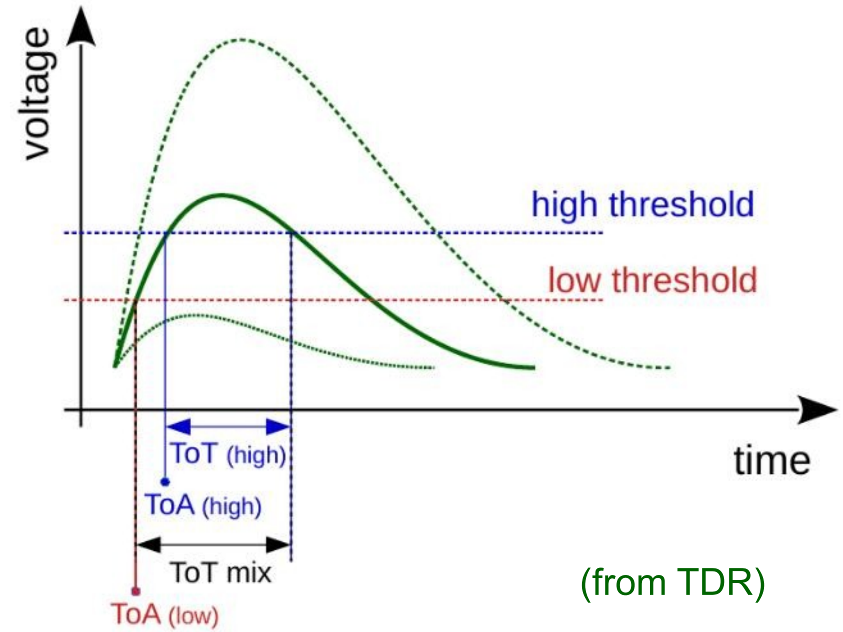
Mupix10: Noise and Efficiency Scan

- wide efficiency plateau!
- efficiency > 99% for thresholds< 80 mV
- noise is rather flat and it includes here many scattered beam particles (~90%)
- noise < 0.1 Hz/pixel after beam particle and hot pixel removal (~10 out of 64000) (→ not shown)



2-Comparators





(from TDR)

Motivation of 2-comparator design

- use lower threshold for reducing time walk (ToA)
- use higher threshold for hit validation
- use higher threshold for measuring falling edge more precisely → better ToT

Two methods to measure ToT:

- rising and falling edge from single or high threshold (“high”)
- rising lower edge and falling higher threshold (“mix”) → not yet tested

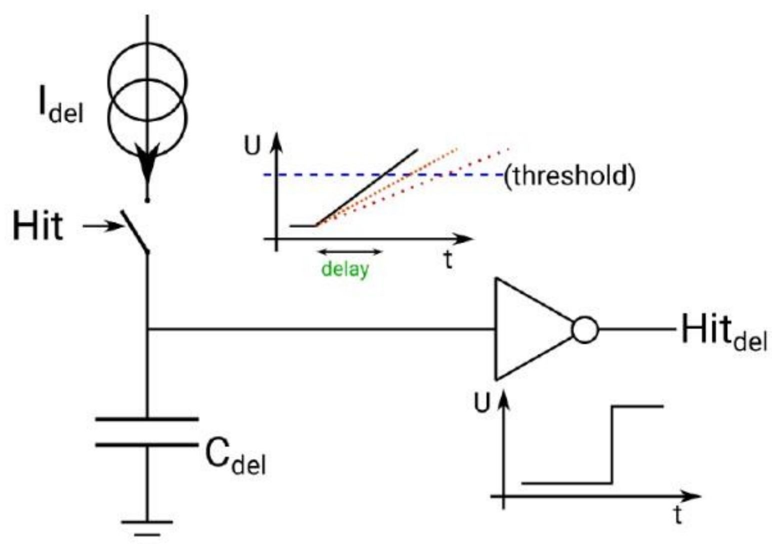
MuPix10 Delay Circuit

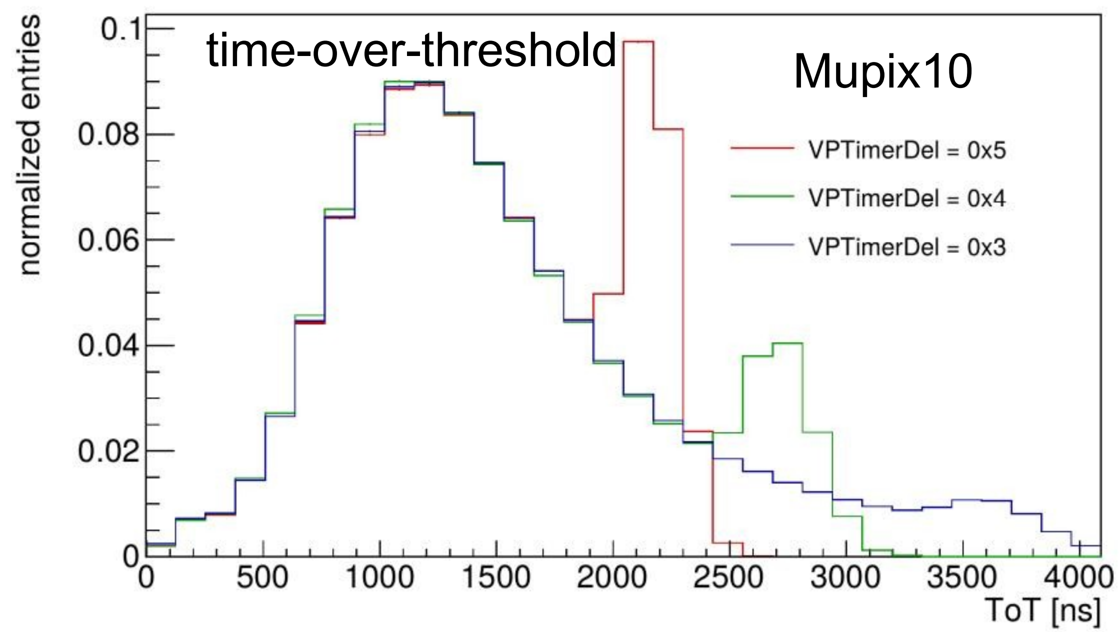
Issue:

- Hits should be read out after completion of ToT measurement
- ToT measurement depends on pulse height → disturbs chronological order of hits
- Solution: read hits after adjustable fixed delay

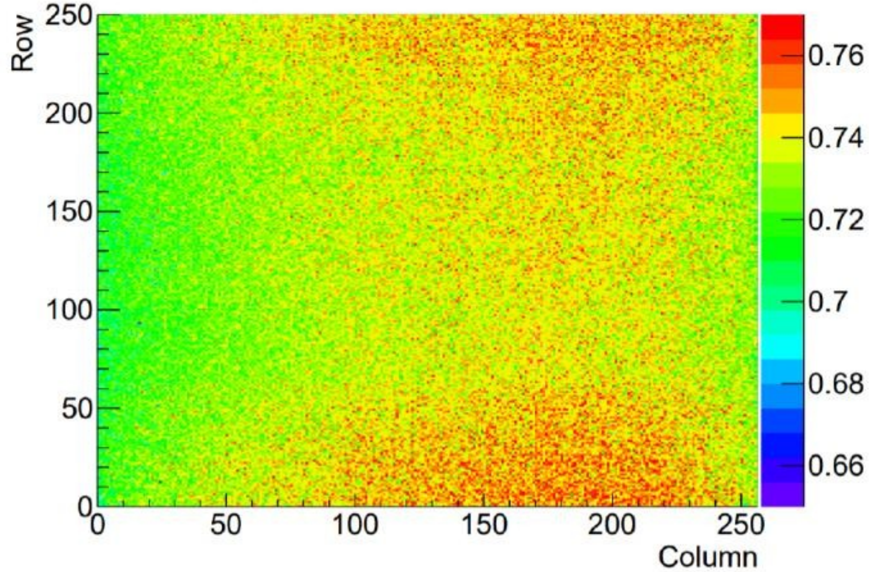
Challenges:

- Handling of overflows (~huge pulses) is required → counter stops
- Delay dispersion of pixels should be small

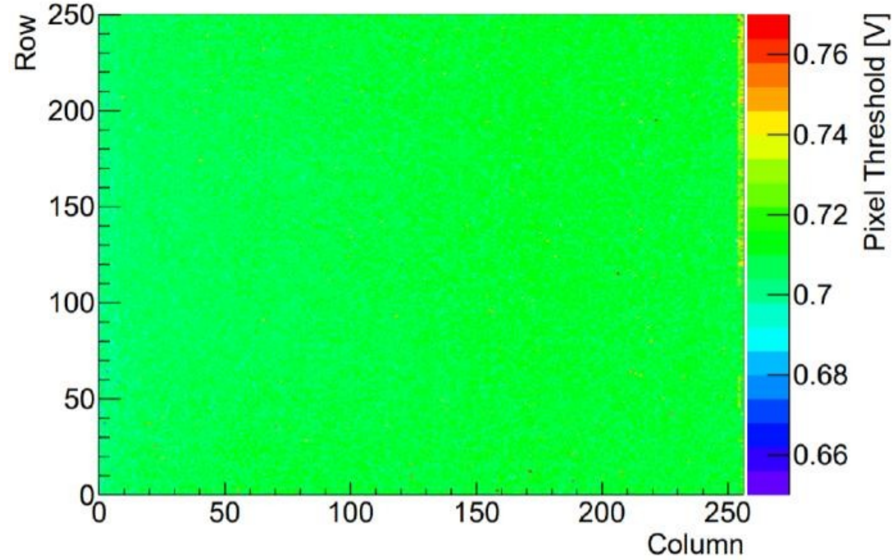




Mupix10: Pixel Tuning

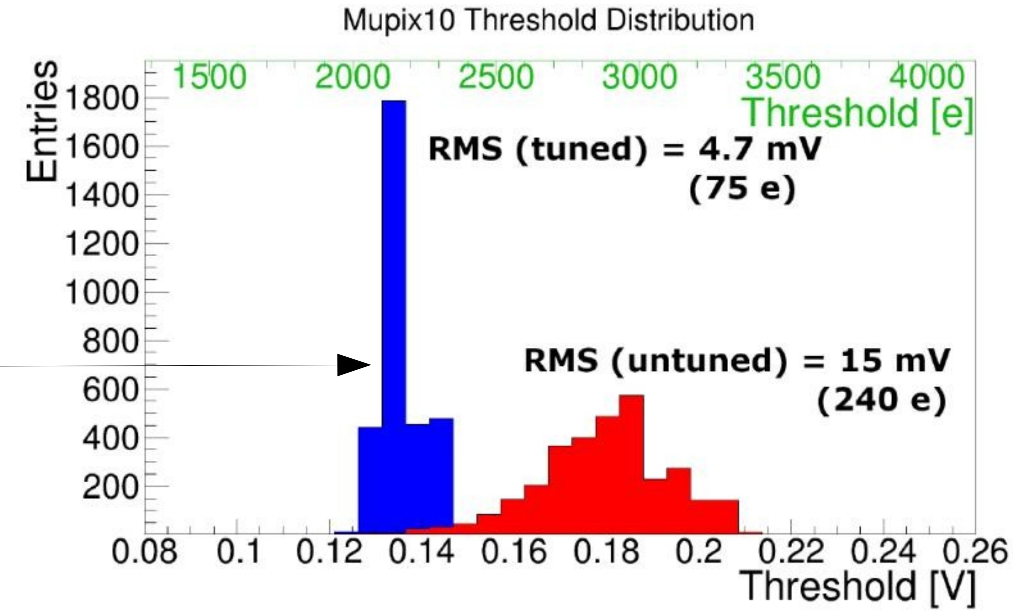


(a) Untuned pixel threshold distribution.



(b) Tuned pixel threshold distribution.

- 3 bit tune dac (TDAC) per pixel
- tune with charge injection
- significant dispersion reduction measured



Mu3e Timeline

Schedule

	2021	2022	2023	2024	2025	2026	2027	2028	2029 and after
Mu3e Phase I	construction & commissioning first data								
					operation & high sensitivity preparation HiMB				
Mu3e Phase II	**R&D**				**R&D**				upgraded and extended experiment at HiMB

HiMB = High Intensity Muon Beamline

→ delivers more than 10^9 muons per second