Low energy muon experiments

(as seen by non specialist).

Krzysztof Doroba, Faculty of Physics,
University of Warsaw

Based on CERN seminar

The Mu3e Experiment:
A new search for μ→ eee with unprecedented sensitivity

CERN Detector Seminar, March 31st 2017

André Schöning

+Mu3e proposal

and review paper **Prog.Part.Nucl.Phys. 84 (2015) 73-123, arXiv:1506.01465**

Precision Muon Physics

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Outlook of the talk:

- Motivation
- Experimental resources
- Lifetime measurements (G_F)
- Charged Lepton Flavor Violation

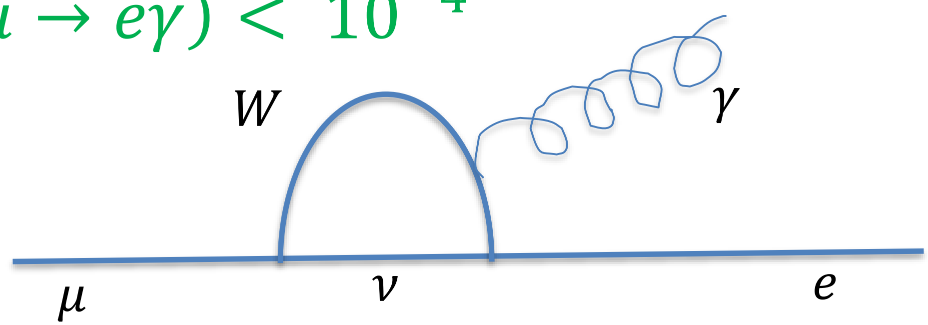
$\mu \to e\gamma, \quad \mu \to eee, \; \mu^- N \to e^- N \quad ???$

- ~~Muon decay (V-A structure)~~

Muon – discovered by Anderson and Nedermeyer at CELTECH in 1936 .

From “ Who ordered that…” (Isidor Isaac Rabi (?))
to „excellent object for precise test of the Standard Model”

- 1941 lifetime measurement (with cosmics)
- 1947 hint of flavor conservation (B.Pontecorvo)
  $BR(\mu \rightarrow e\gamma) < 10^{-4}$



- 1947 muonium (μe), muonic atoms, nuclear capture, Fermi theory, lepton universality
- 1956 Parity violation, V-A structure, muon and electron polarization in decays: $\pi \rightarrow \mu\nu, \mu \rightarrow e\nu\nu$
- 1959 g-2 experiment at CERN
- . . .

From experimental point of view muon is

- Heavy enough (bremsstrahlung)
- Subject of electroweak interactions only (+corr)
- Relatively long living particle ($c\tau \approx 660\ m$)

→ beautiful object for electroweak tests at energies from a fraction of a MeV (MEG, Mu3e, MuLan, …)to multi TeV energy range (CMS ☺)

Disagreement between exp and theory in precise tests ?

→ New physics ? (or more precise theory calc.?)

2016 PDG data on muon

$$m = 105.6583745 \pm 0.00000026\ MeV$$

$$\tau = (2.1969811 \pm 0.0000022) * 10^{-6} s$$

$$\tau^{+}/\tau^{-} = 1.00002 \pm 0.000008$$

$$(g-2)/2 = (11659209 \pm 6) * 10^{-10}$$

$$\mu^{-} \rightarrow \bar{\nu}_e \nu_\mu e^{-} \approx 100\%$$

Charged Lepton Flavor Violating BR:

$$\mu^{-} \rightarrow e^{-}\gamma < 5.7 * 10^{-13}$$

$$\mu^{-} \rightarrow e^{-}e^{+}e^{-} < 1.0 * 10^{-12}$$

How to improve/achieve such limits?

Where to take the muons from ???

COSMICS ?

At student lab. $\tau_\mu = 2.2 \pm 0.2\ \mu s$ with ~300 good events (out of ~10000) and 2 weeks of data taking

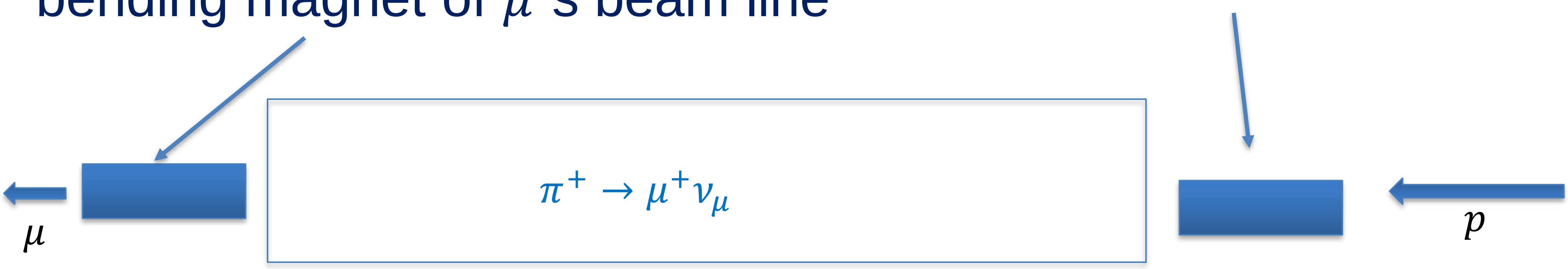
MuLand plans for 10^{12} events ☹

BEAMS: (Paul Scherrer Institut, Villingen (PSI), TRIUMP)

from $\pi^+ \to \mu^+ \nu_\mu$ decay, $\pi`s\ from$ 1.3 MW PSI proton cyclotron

- Cloud beam

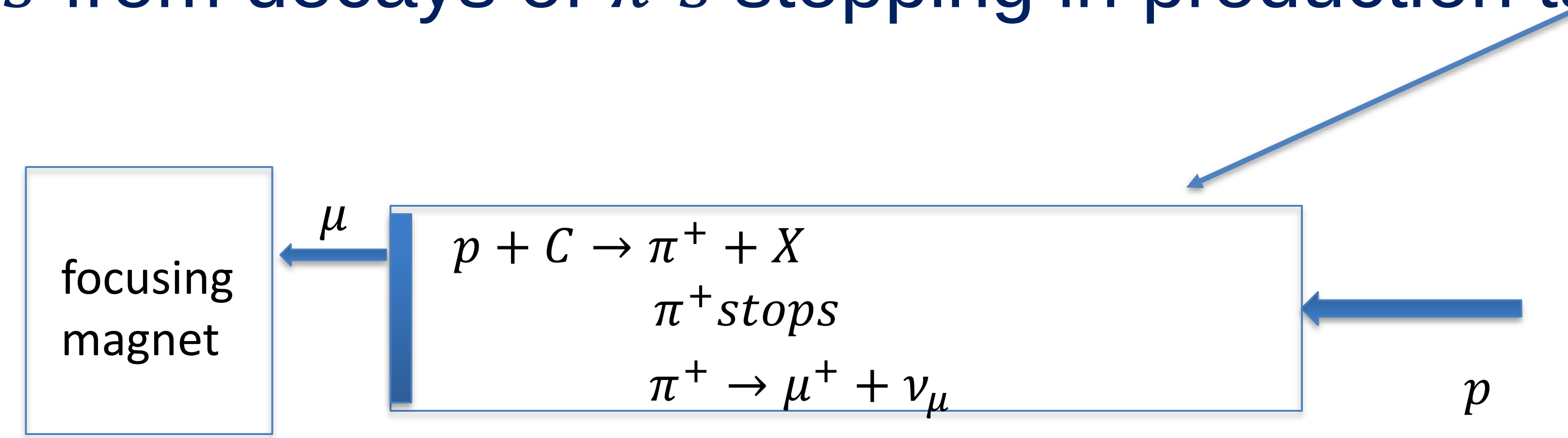
$\mu`s$ from $\pi`s$ decays between production target and first bending magnet of μ`s beam line



Mostly fwd, bkwd decays → low μpolarization

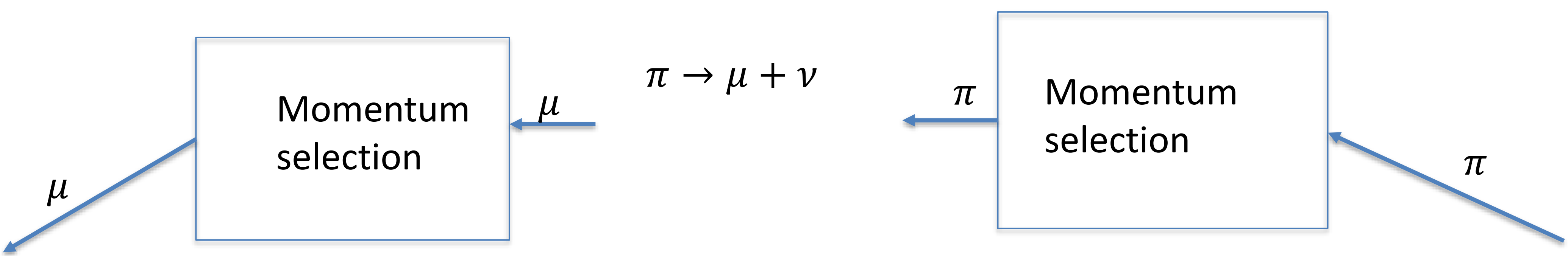
- Surface beam

$\mu`s$ from decays of $\pi`s$ stopping in production target



μ from the target surface has 29.8 MeV/c and 100% longitudinal polarization, as coming from localized area muons can be nicely focused

- Decay beam



μ are typically highly polarized, no e contamination

Where to send the muon beam? (MuLan detector)

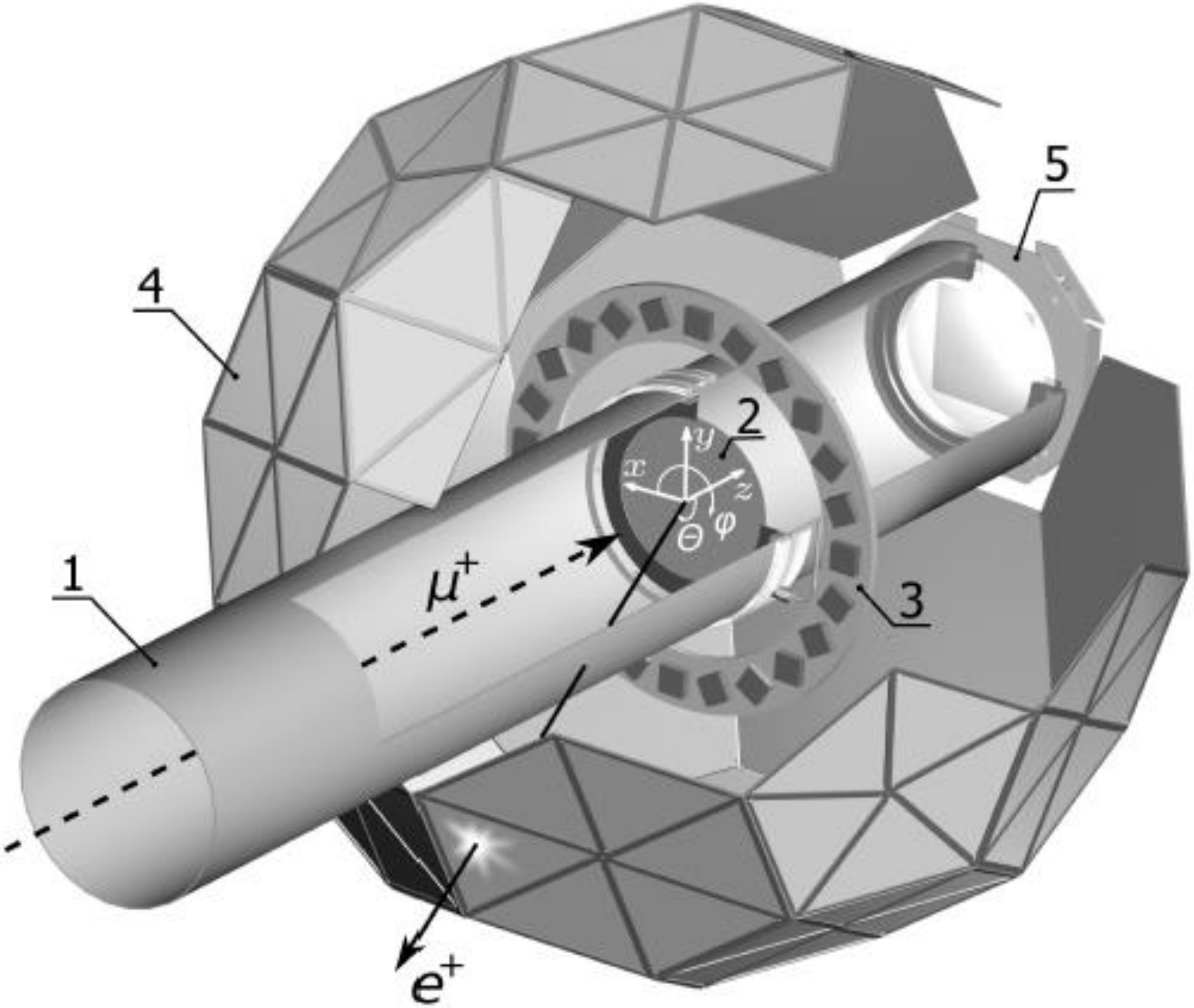


Figure 2: Cutaway diagram of the MuLan experiment indicating an incoming muon and outgoing positron and showing the beam pipe (1), stopping target (2), optional magnet array (3), scintillator detector (4) and beam monitor (5). Figure courtesy MuLan collaboration.

Main issues in data collection and processing:

- Large total number of events

  example: $(\mu\ lifetime)$ FAST $\approx 10^{10}$ events

  - only histograms written to disc

  MuLan $\approx 10^{12}$ events

- Very high event rate

  FAST $\approx 30\ kHz$ trigger rate

  - FPGA based trigger

  MuLan eff. $10^{5-6}\ events/sec$

  Mu3e $10^{9}\ events/sec$

CMS : $\sim 10^{17}$events in 2016 $(\int Ldt \cong 40\ fb^{-1})$

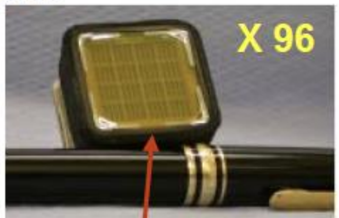
$L = 10^{34} cm^{-2} sec^{-1}$ → rate pp $\sim 10^{9} Hz$

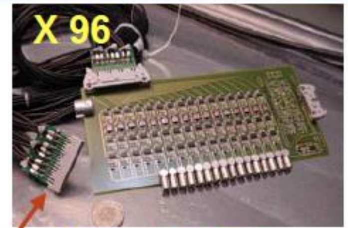
Experiment FAST

Lifetime measurement with active target

FAST READOUT & DAQ CHAIN

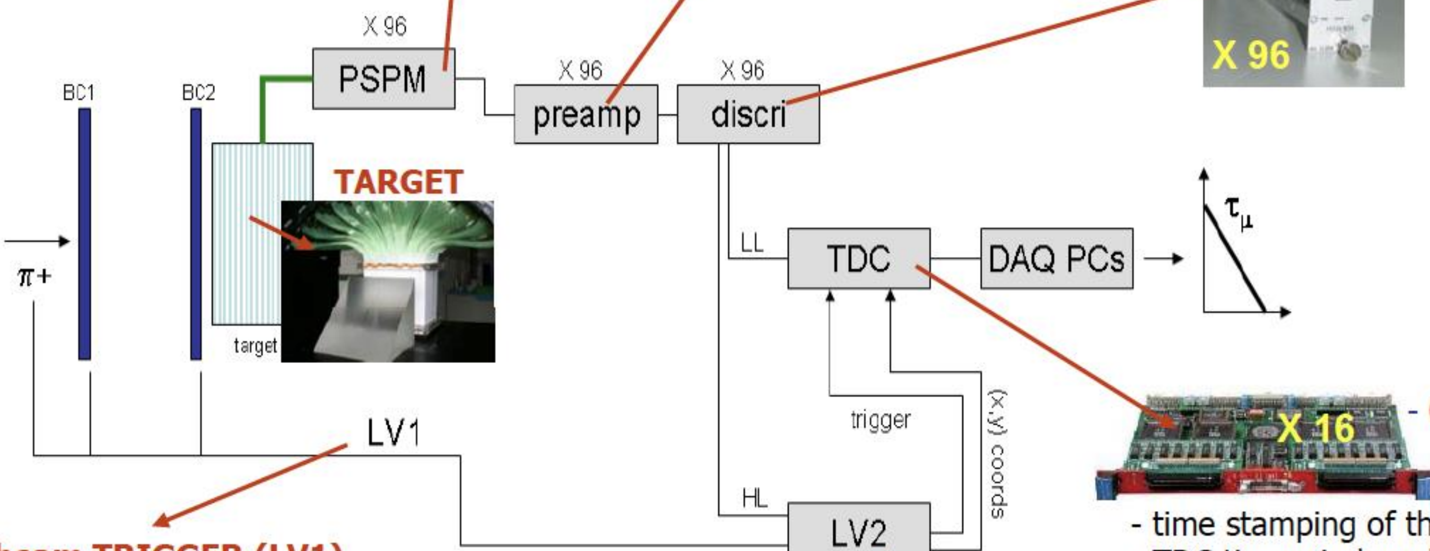
- Position Sensitive **PhotoMultipliers (PSPM's)**
- Hamamatsu H6568-10
- multianode (4x4)





- **Preamplifiers**
- shaper & preamp (x5)
- custom made units (PSI)

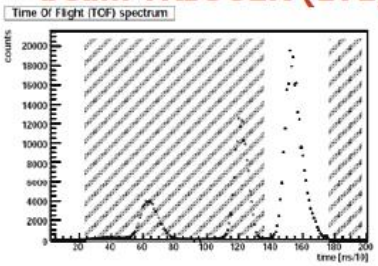
- **Double THR discriminators**
  LOW (LL) & HIGH (HL)
  LL → mip's (e^+ tracks)
  HL → π^+/μ^+ (stop points)
- remotely adjustable thr (50 mV – 2 V)
- custom made units (PSI)



- CAEN v767 128-channs **TDCs**

- time stamping of the raw pulses from discri
- TDC time window: [-10,+20]μs w.r.t. Trigger
- trigger : π in the target (entry/π stop time)
- output of the TDCs: into the DAQ PC's

beam TRIGGER (LV1)



Second Level TRIGGER (LV2)
- Hardware trigger for the TDCs
- Selective trigger (definition of ROI, around the pion stopping point)
- Event quality selection
- DATA REDUCTION SYSTEM
- Custom made FPGA based electronics (CIEMAT)

MuLan approach to rate handling

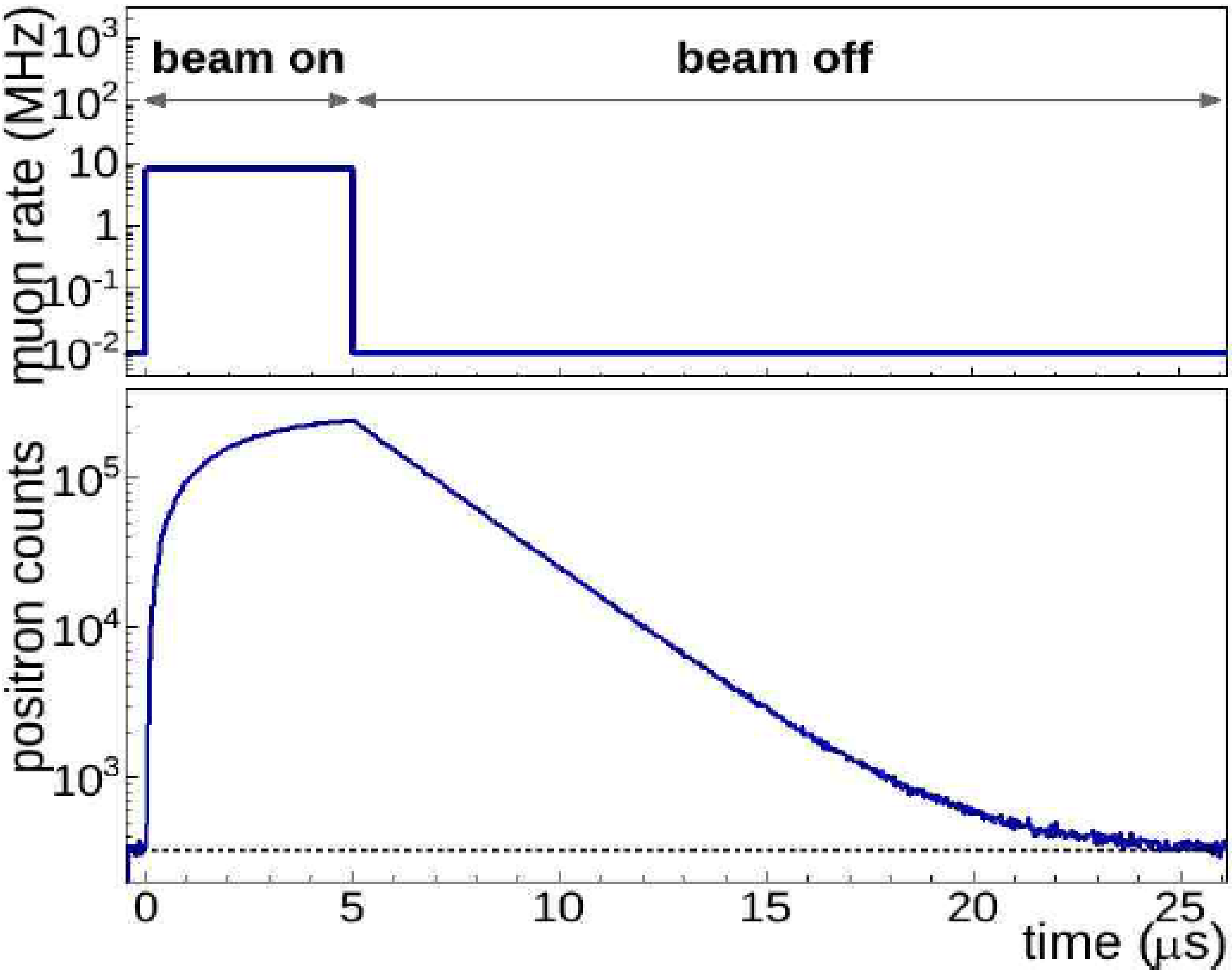
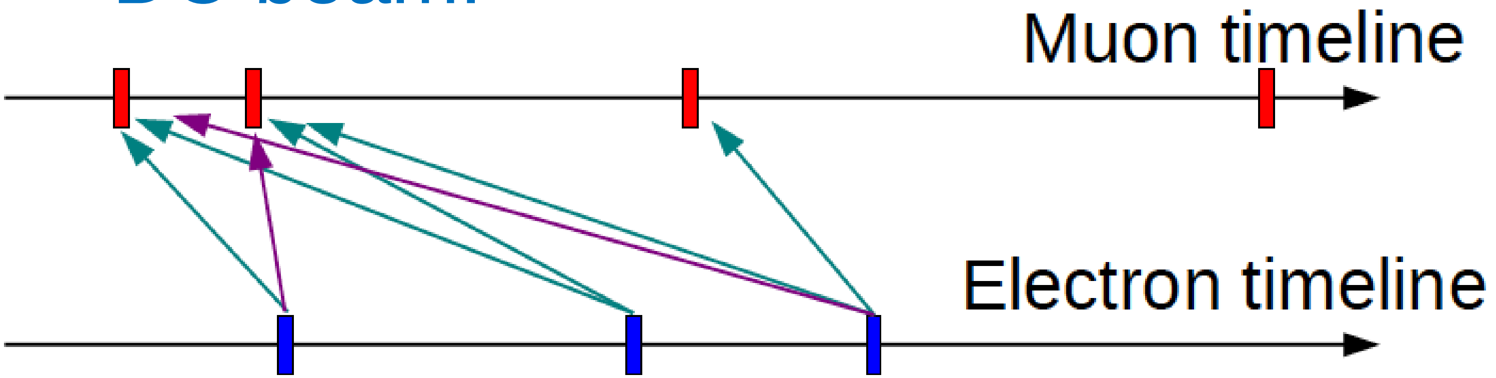


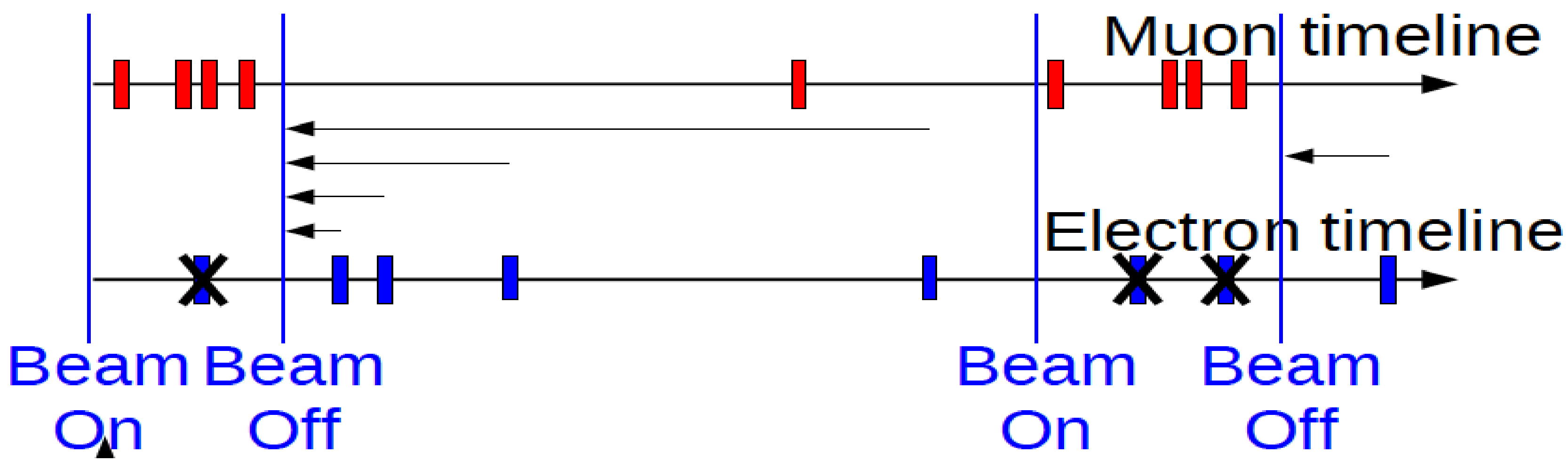
Figure 3: The 5-μs beam-on, 22-μs beam-off, time structure of the MuLan experiment. The upper panel shows the muon arrival time distribution and the lower panel shows the decay electron time distribution.

Background level

DC beam:



AC beam:



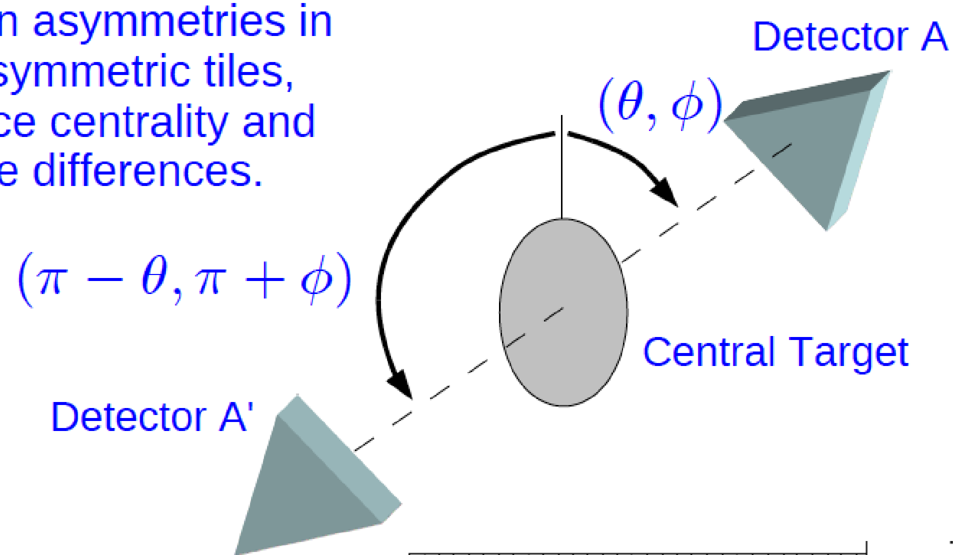
Much less background with AC beam

Principal issues of MuLan analysis

- muon polarization

Solution 1:
Add symmetric tiles

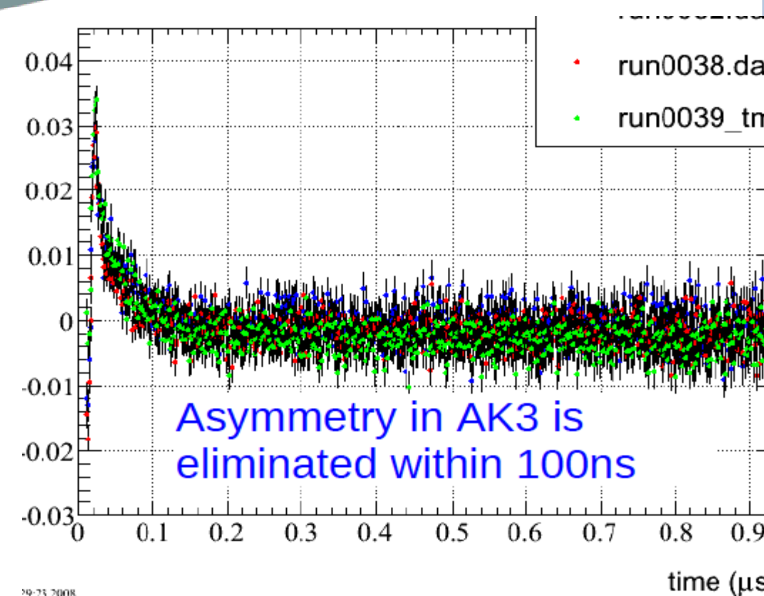
Point symmetry of the detector cancels polarization asymmetries in sum over symmetric tiles, up to source centrality and acceptance differences.



Solution 2:

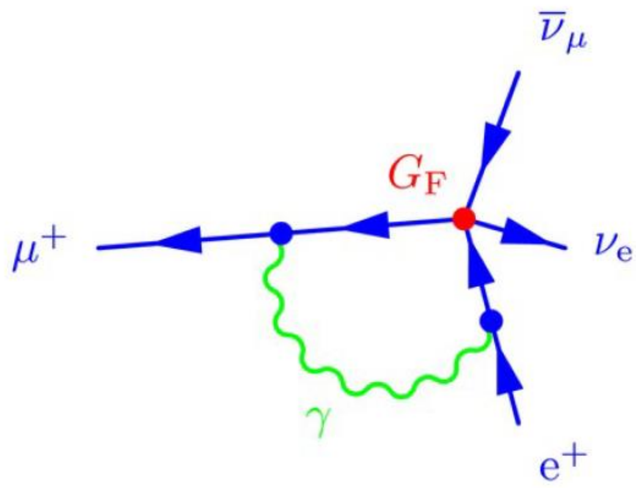
Depolarize with B in ~ 100 ns (μSR)

Assymetry →



- Pile up

What for ?



$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}(1+q)$$

q – *non_weak corrections*

G_F, m_{Z^0}, α —base of all predictions for electroweak precision tests

also muon capture rate (τ_+, τ_-), ...

Charged Leptons Flavor Violating Decays

1. $\mu^+ \to e^+\gamma$ $(BR :< 5.7 \times 10^{-13})$
2. $\mu^+ \to e^+e^-e^+$ $(BR :< 1.0 \times 10^{-12})$
3. $\mu^- + N \to e^-N$ $(BR :< 7 \times 10^{-13})$

MEG Experiment $(\mu^+ \to e^+\gamma)$

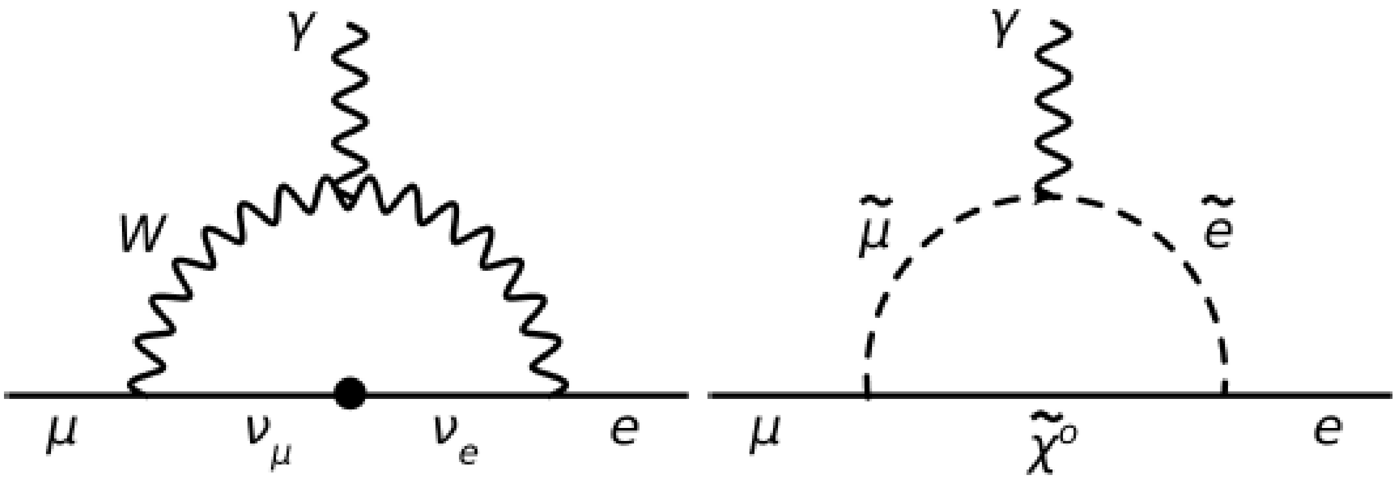


Figure 10: a) The standard model allowed decay $\mu \to e\gamma$, which proceeds through a loop process involving neutrino mixing at the unmeasureably low branching ratio below 10^{-54}. b) A SUSY based diagram depicting smuon-selectron mixing inducing the same process.

Goal: $BR < 10^{-13}$

requires well above 10^{14}muon decays

Method:

Look for $e^{+} and\ \gamma$ from stopped μ^{+} $(at\ 30\ MHz)$

- In coincidence $\left(T_{e\gamma} = 0\right)$
- Back to back
- 52.8 MeV each

Maximum likelihood analysis to extract signal

Detector:

- Liquid Argone $\frac{\sigma E}{E} = 1.9\%$
- Drift chamber $(\sigma E_{e^{+}} \sim 330\ keV)$
- Timing counters $\left(\sigma T_{e\gamma} \sim 122 ps\right)$
- COBRA magnet

Superconducting COBRA magnet:

- Provides bending radius nearly independent from emission angle
- Sweeps away positron tracks out of stopping target

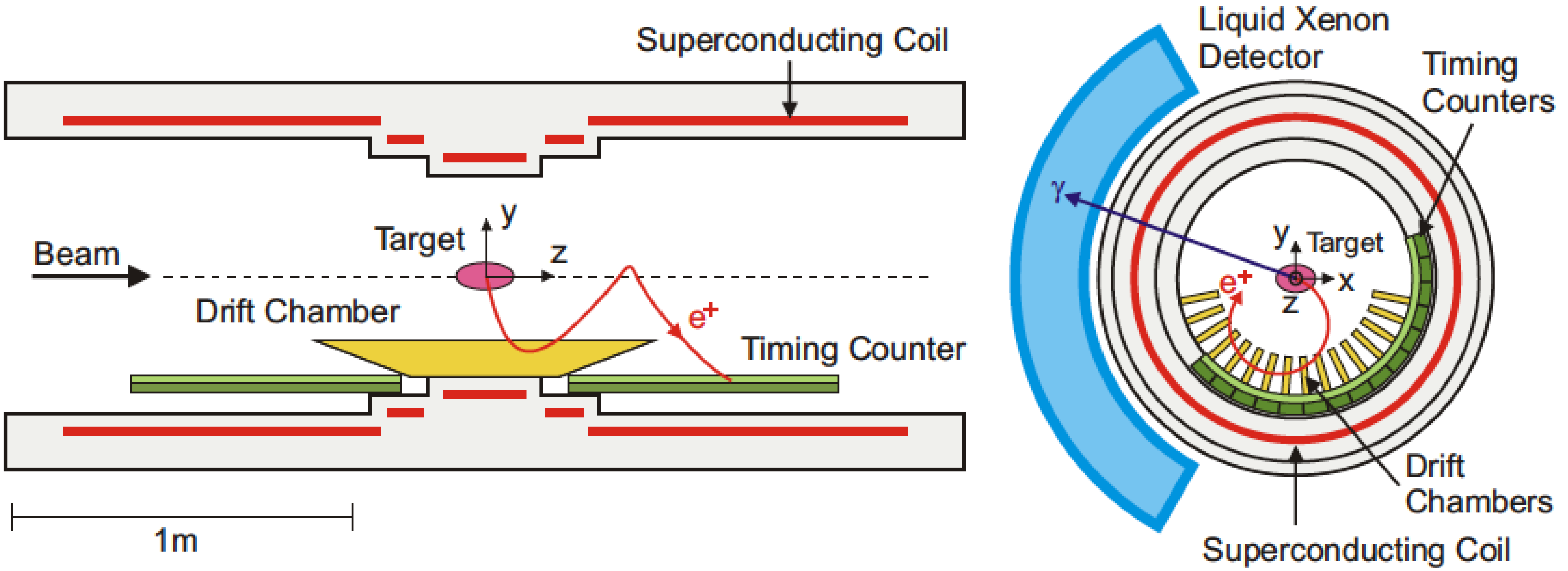


Figure 2.1: Schema of the MEG detector with the superconducting magnet COBRA, the drift chamber system, the timing counters, and the liquid xenon detector.

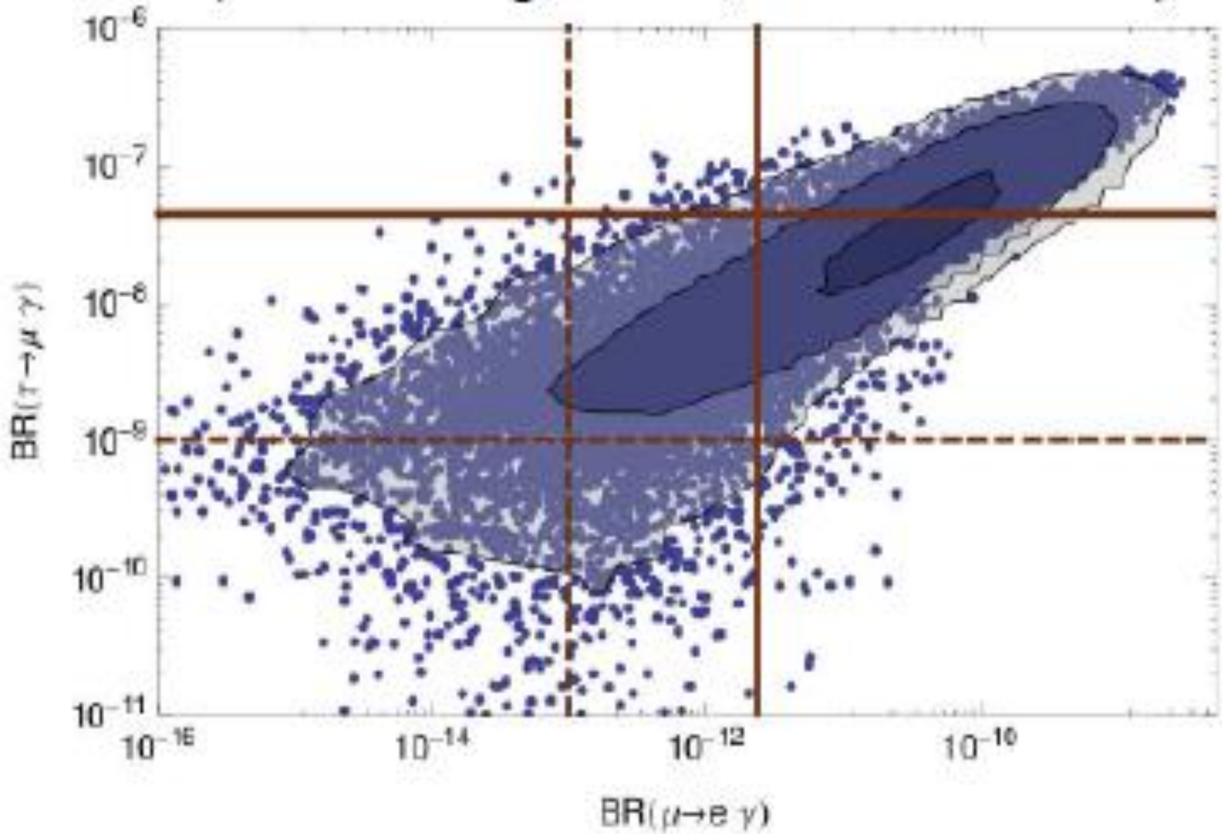
Results:

EXP: $BR(\mu \to e\gamma) < 5.7 * 10^{-13}$

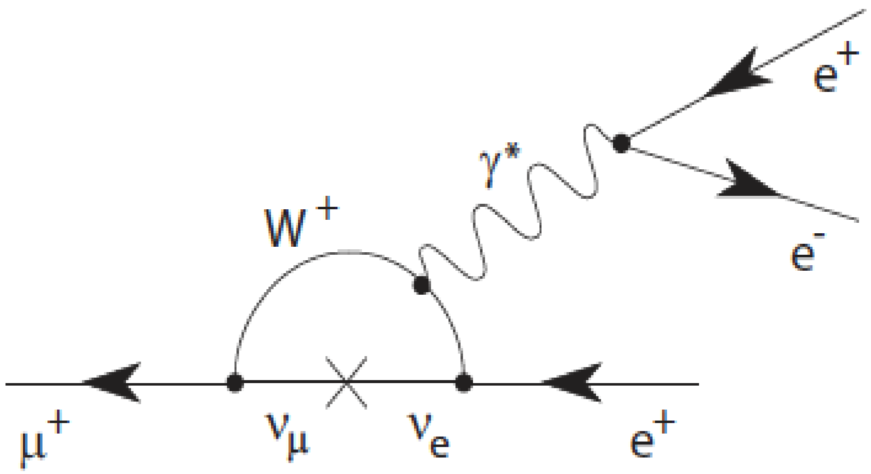
SM: $BR(\mu \to e\gamma) < 1.* 10^{-54}(\upsilon_e \leftrightarrow \upsilon_\mu)$

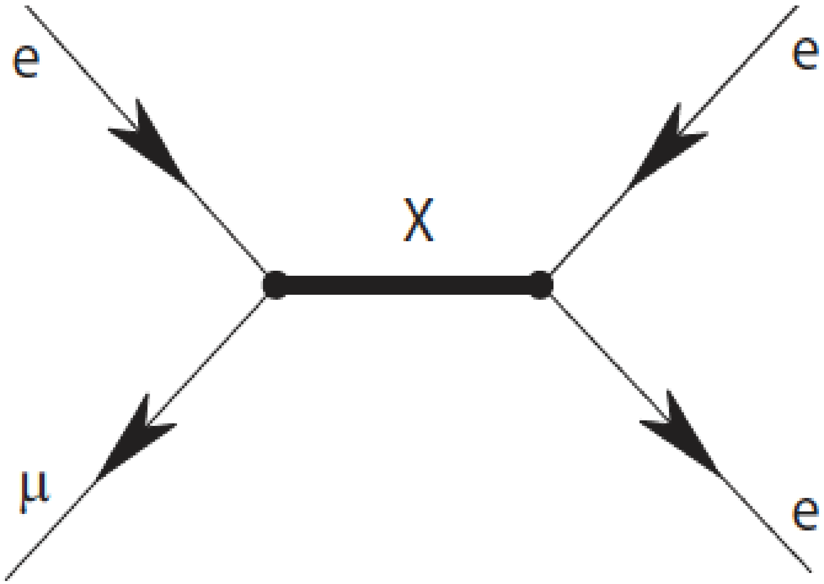
SUSY: $BR(\mu \to e\gamma)\ -\ measurable$

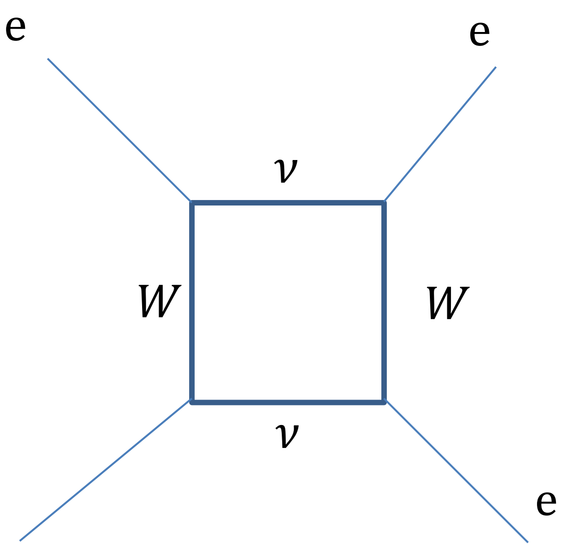
(Blankenburg, Isidori, Jones-Pérez '12)



Mu3e experiment: $\mu^+ \to e^+ e^- e^+$





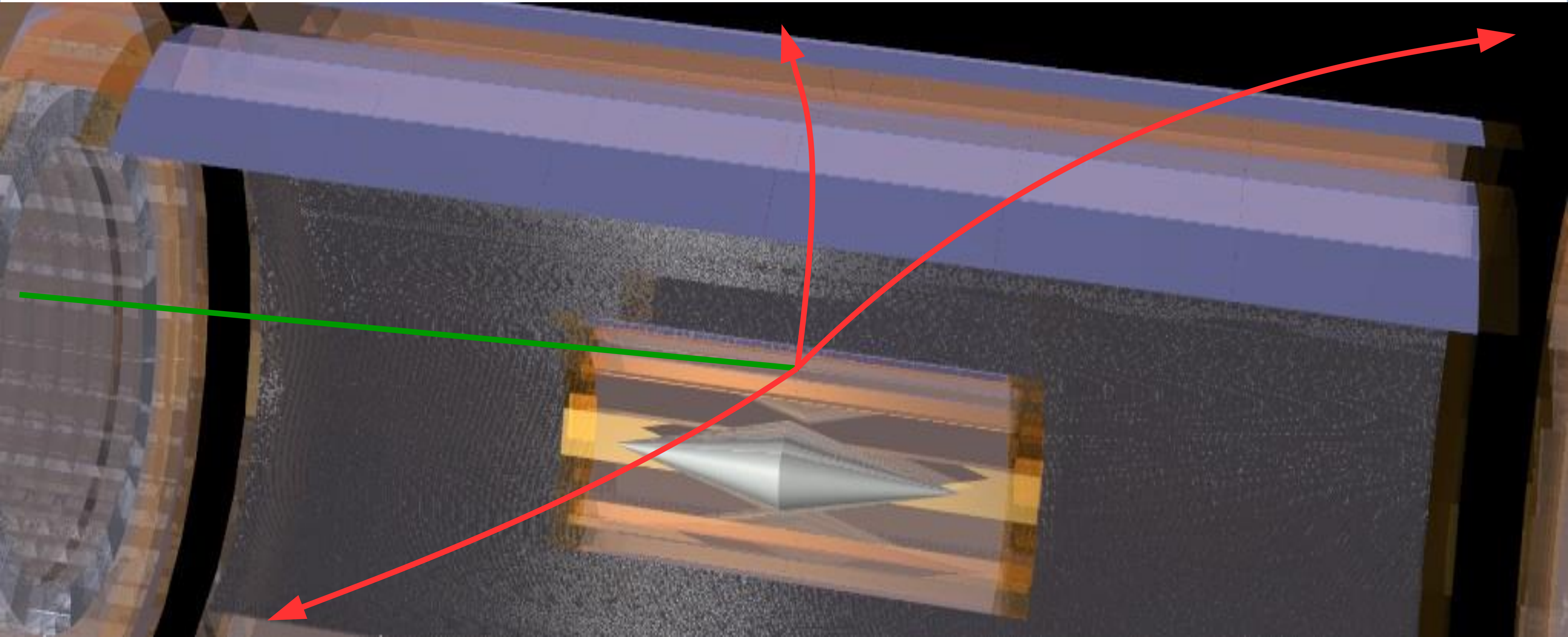


The Mu3e Experiment:
A new search for μ→ eee with unprecedented sensitivity

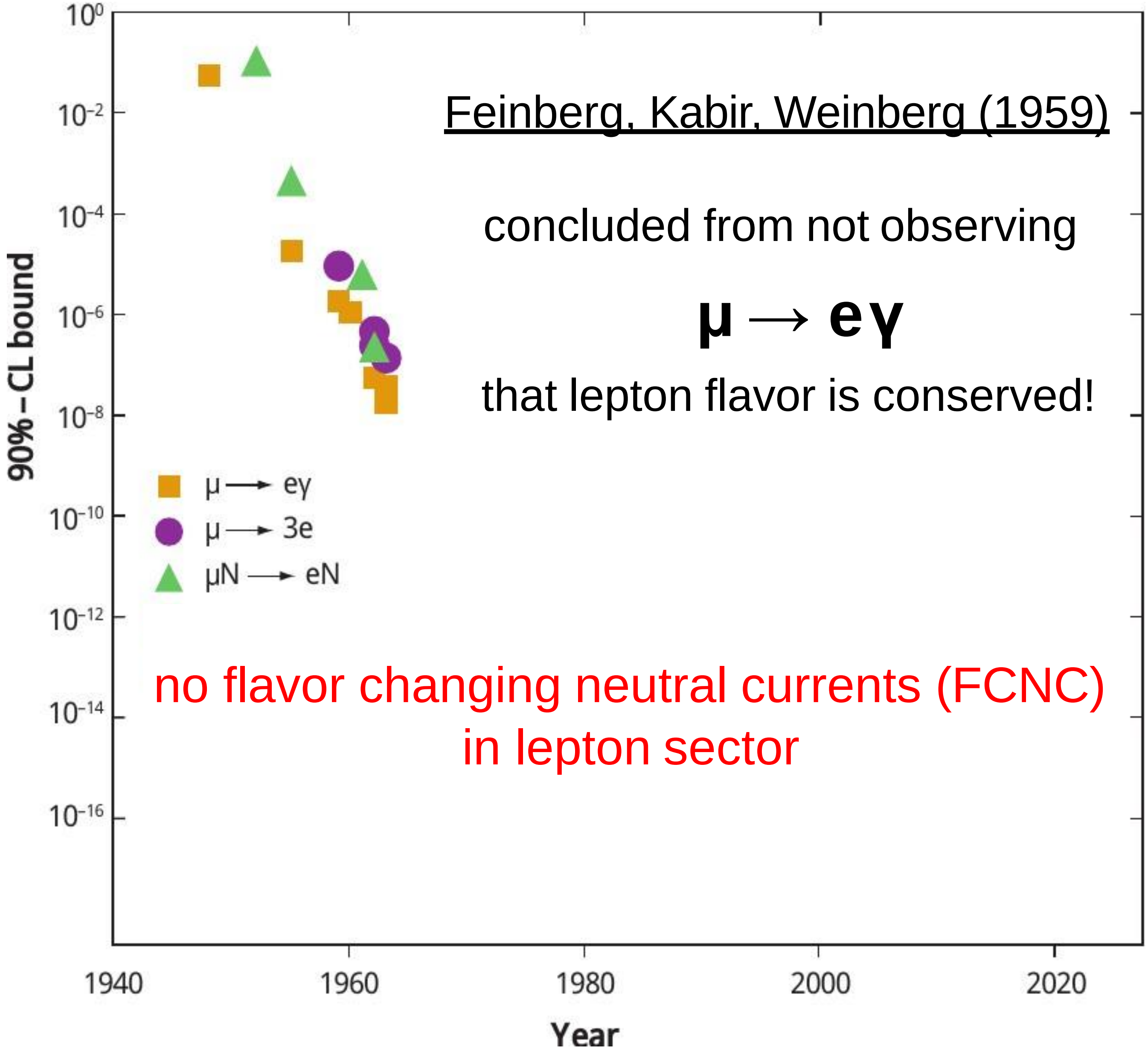
CERN Detector Seminar, March 31st 2017

André Schöning

Physikalisches Institut, Universität Heidelberg



History of LFV Decay experiments



<u>Feinberg, Kabir, Weinberg (1959)</u>

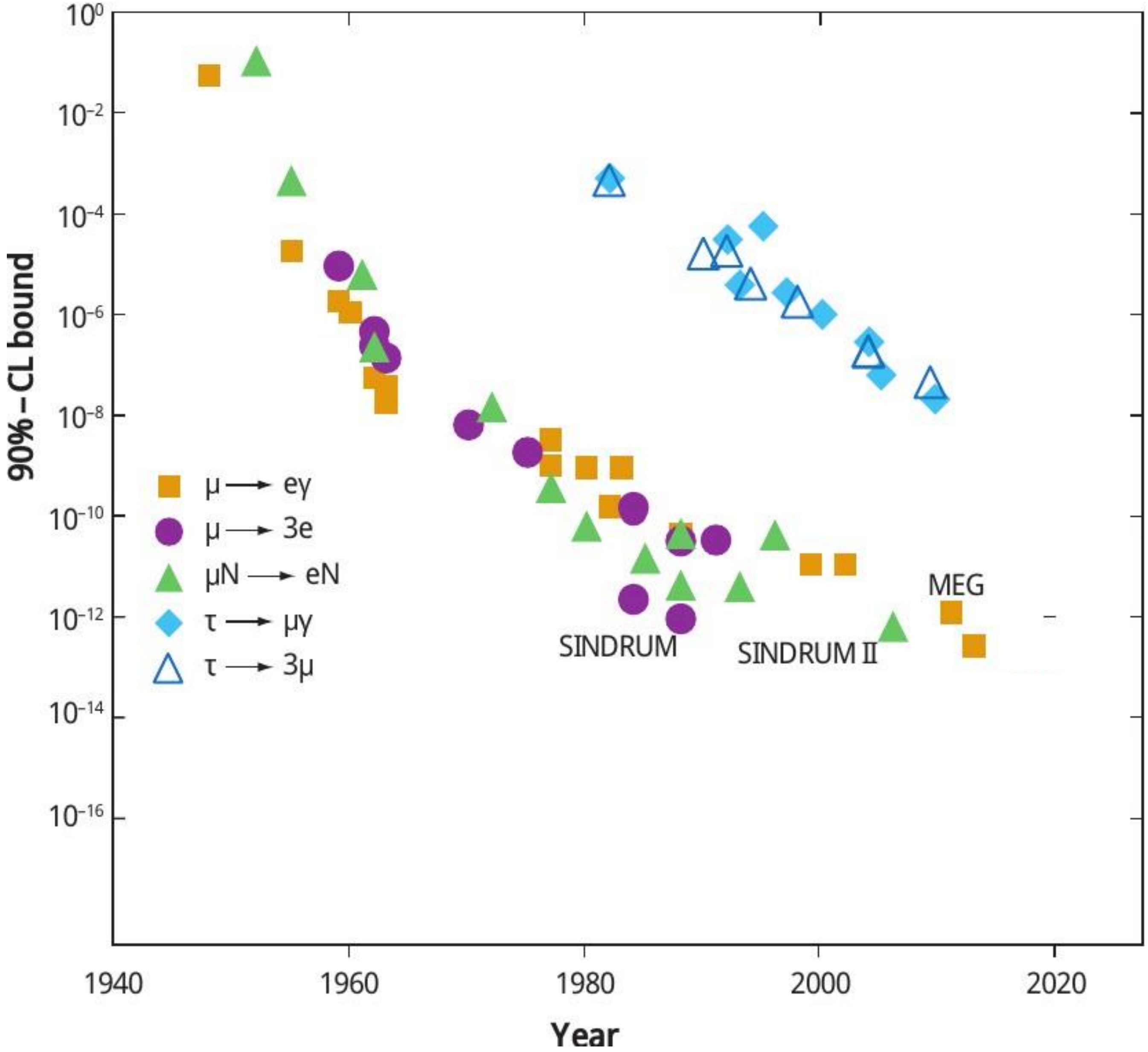
concluded from not observing

$$\mu \to e\gamma$$

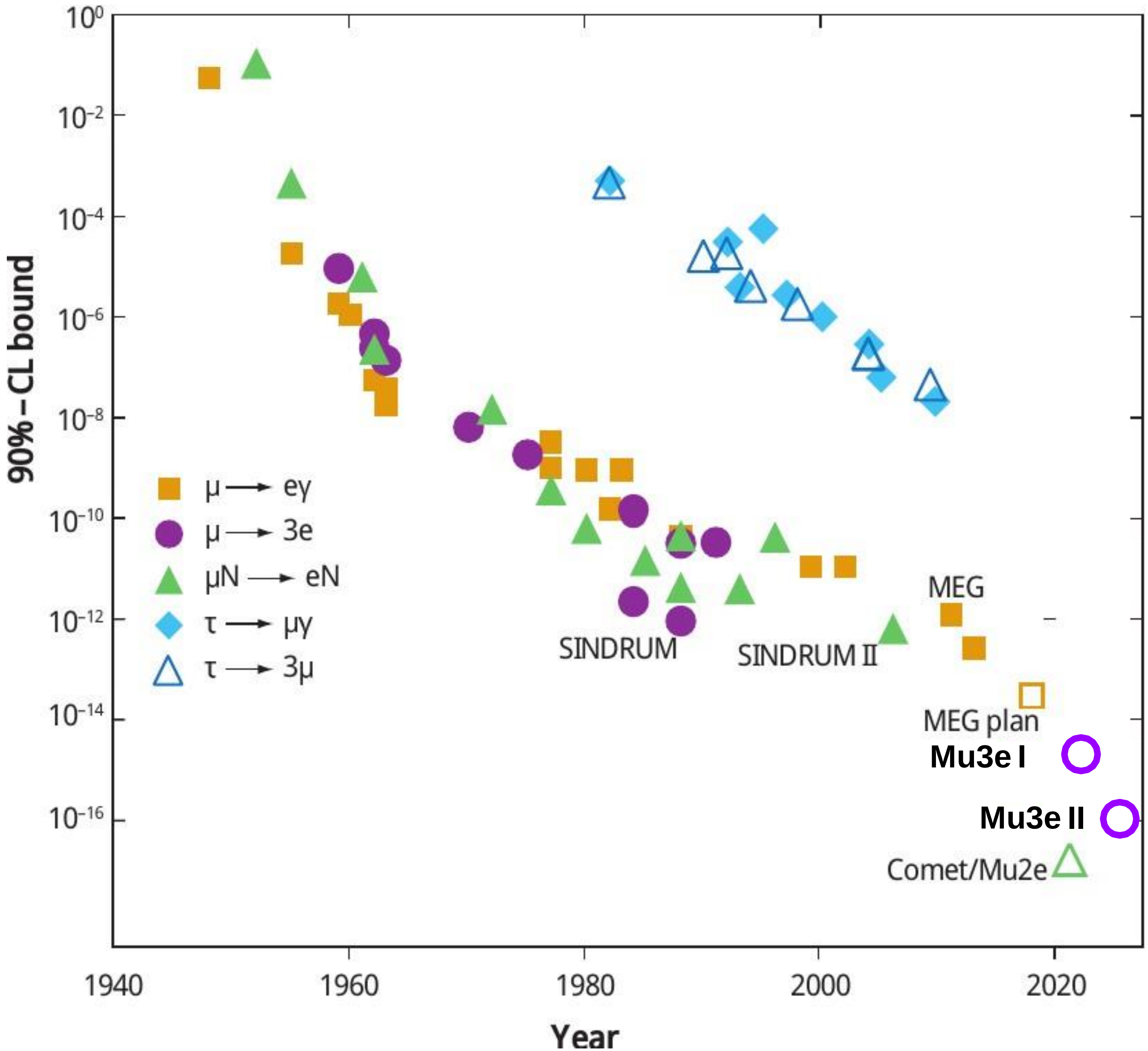
that lepton flavor is conserved!

no flavor changing neutral currents (FCNC)
in lepton sector

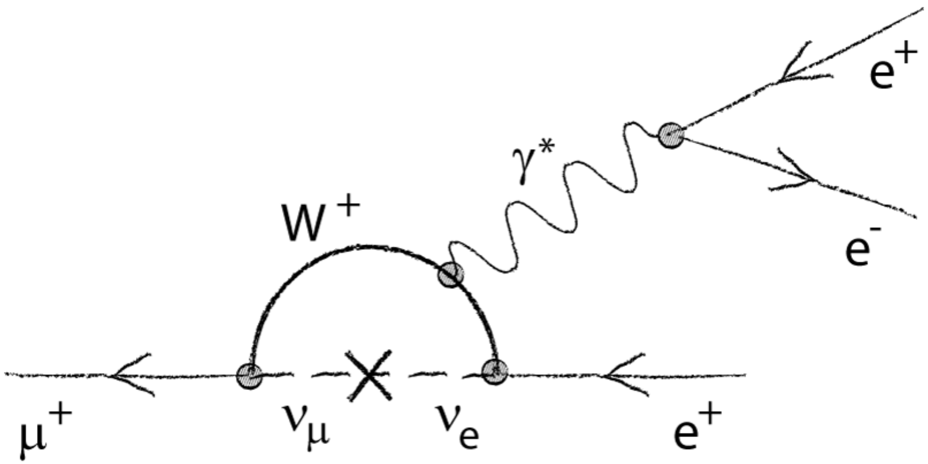
History of LFV Decay experiments



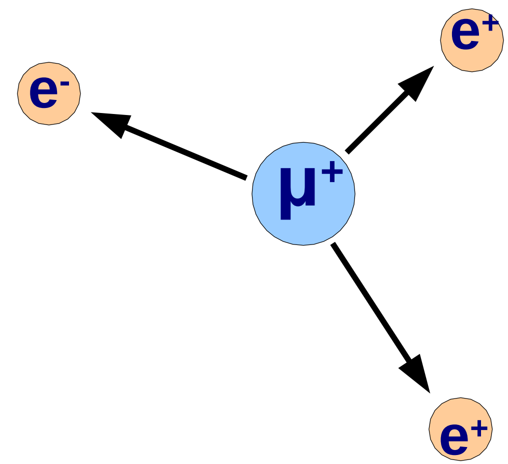
History of LFV Decay experiments



SM Loop Diagrams

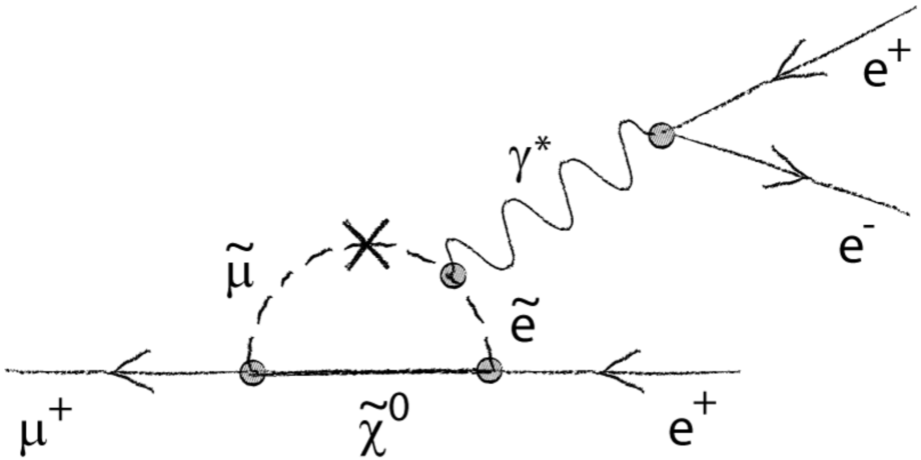


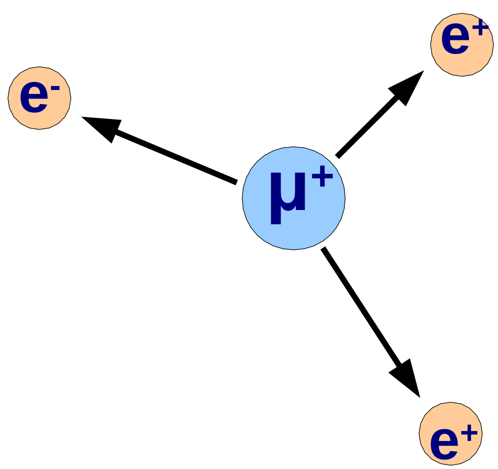
$\mu^+ \rightarrow e^+e^+e^-$



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

SM Loop Diagrams



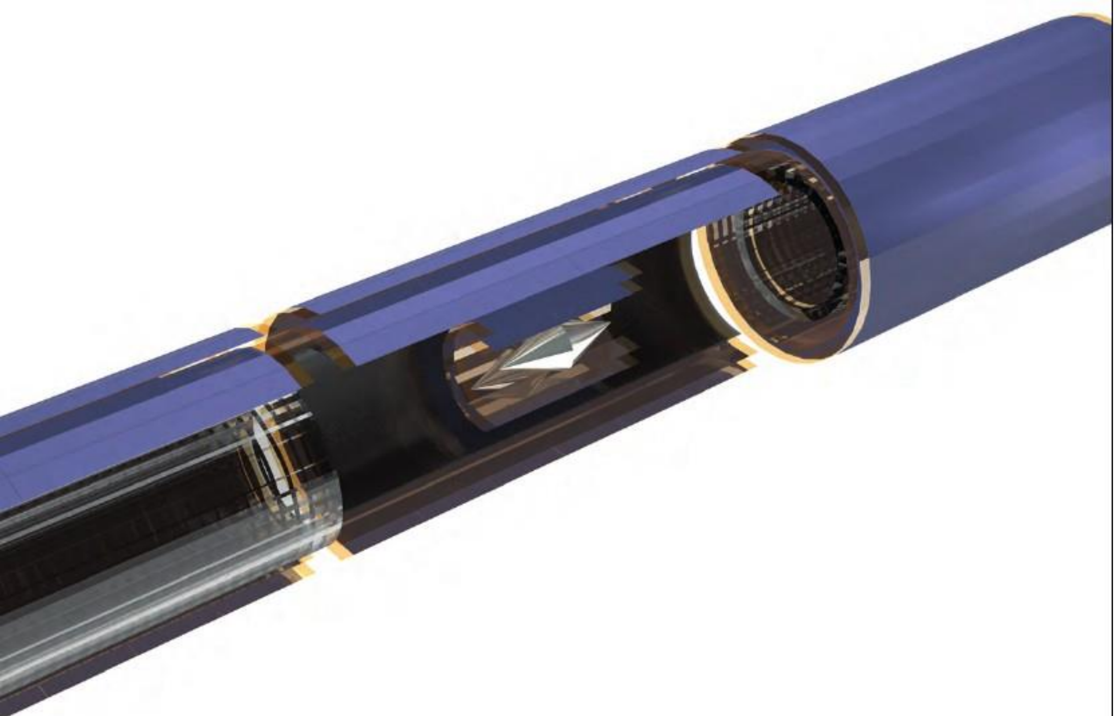


BR can be as large as $\approx 10^{-12}$

Most BSM models (e.g. SUSY) induce naturally LFV

Technical design of the Phase I

Mu3e Experiment



first version (not published yet)

Technical Design of the Phase I

Mu3e Experiment

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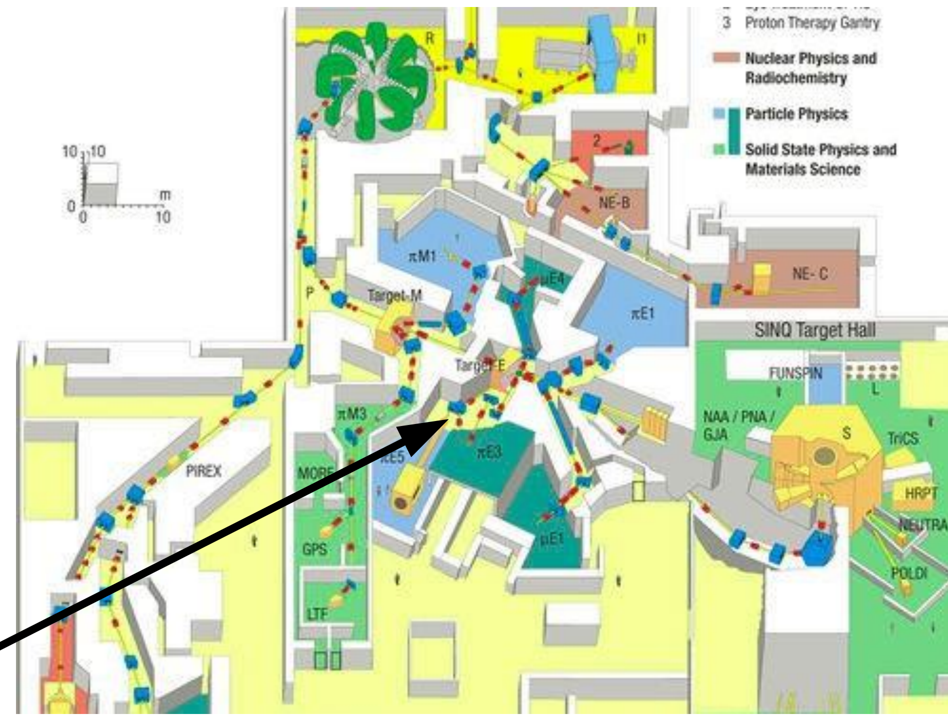
December 2016

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

project approved in Jan 2013



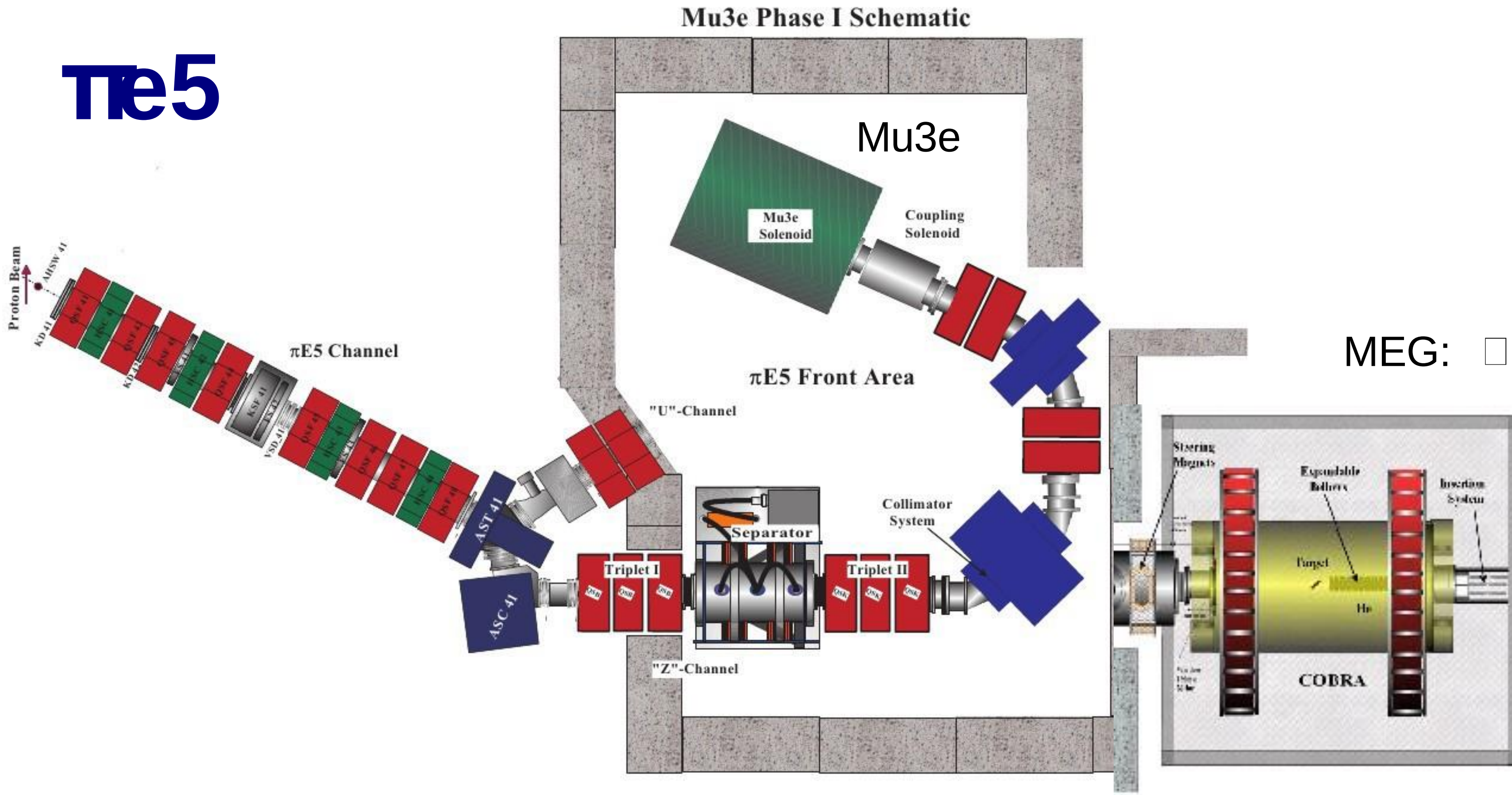
<u>Aiming for a sensitivity of</u>

$BR(\mu \rightarrow e\,e\,e) < 10^{-15}$ (phase I)

$BR(\mu \rightarrow e\,e\,e) < 10^{-16}$ (phase II at new High Intensity Beamline)

Compact Muon Beamline (Phase I)

πe5



MEG: □→ e

- muon rates of up to **8.4·10^{7}/s** at **solenoid entrance** achieved in 2016
- further optimizations might be possible
- aiming for: → **10^{8} muons/s on target**

Compact Muon Beamline (CMB)

First CMB beam commissioning in December 2014

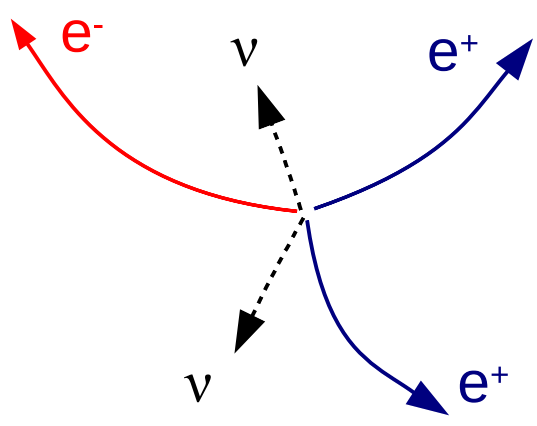
How Big is 10^{-16} ?

Number of grains of sand at all beaches in Germany ~ 10^{16}

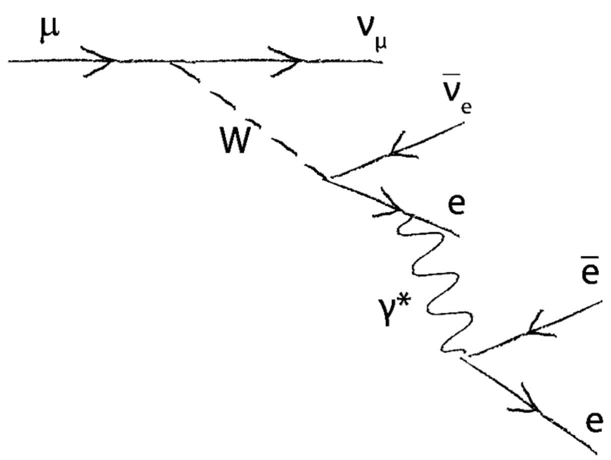
Find THE grain of sand which violates lepton flavor!

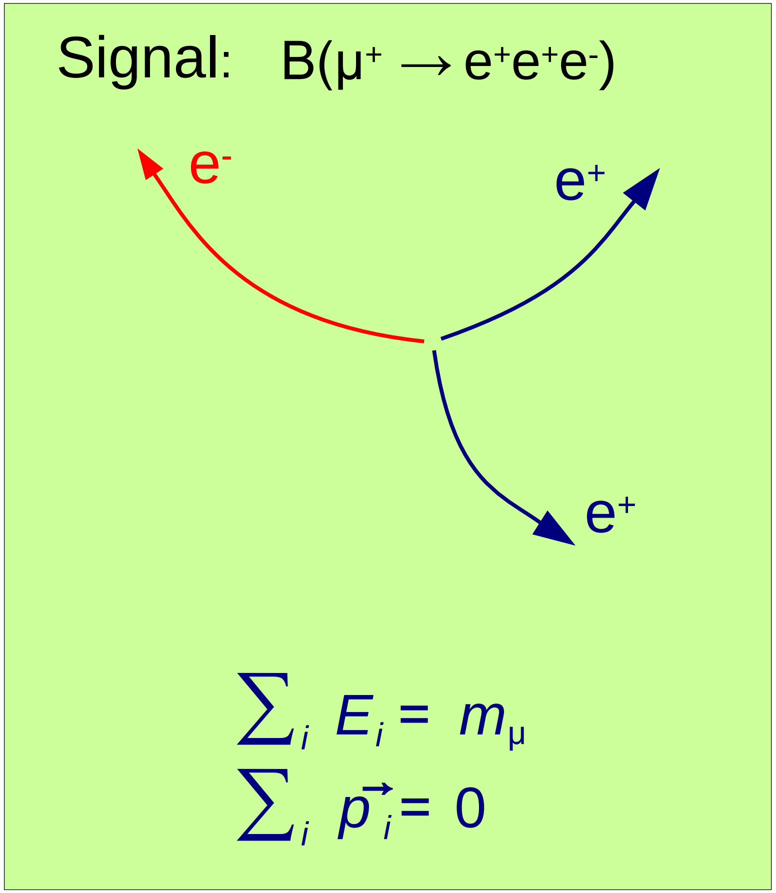
Backgrounds for Mu3e

Irreducible BG: radiative decay with internal conversion (IC)



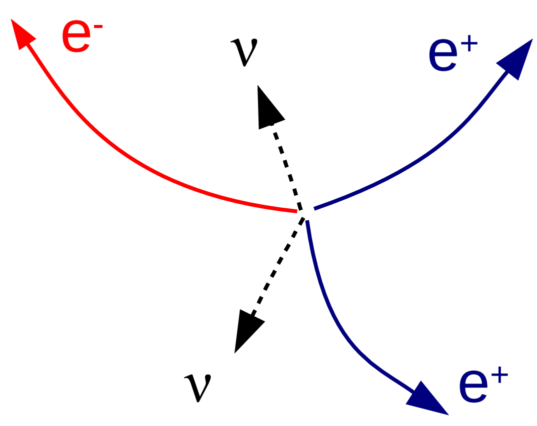
$B(\mu^+ \rightarrow e^+e^+e^-\nu\nu) = 3.4 \cdot 10^{-5}$



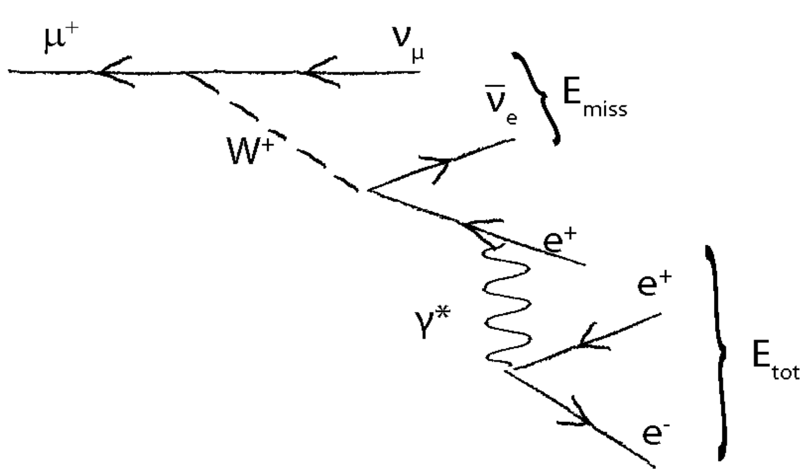


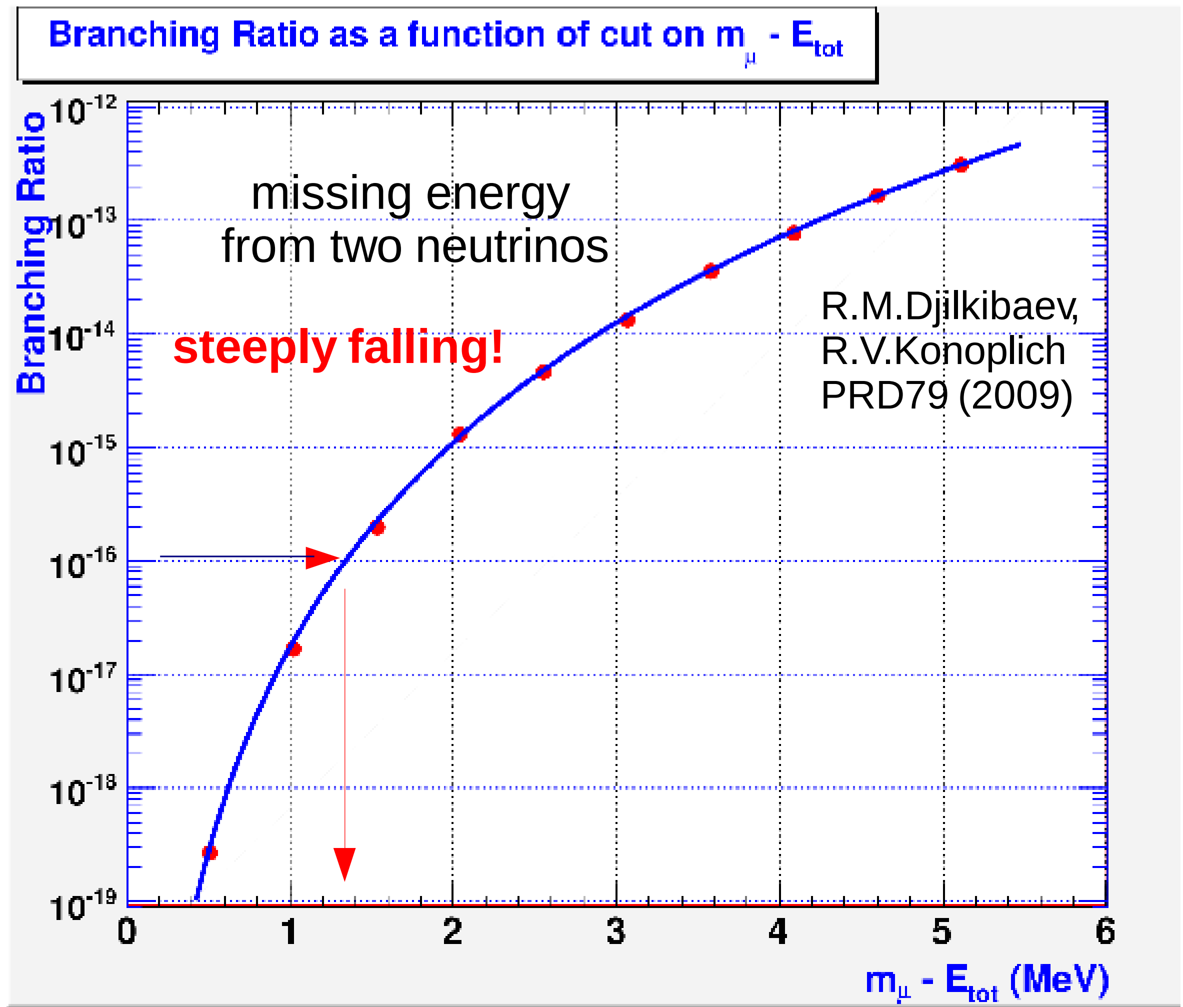
Backgrounds

Irreducible BG: radiative decay with internal conversion (IC)



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

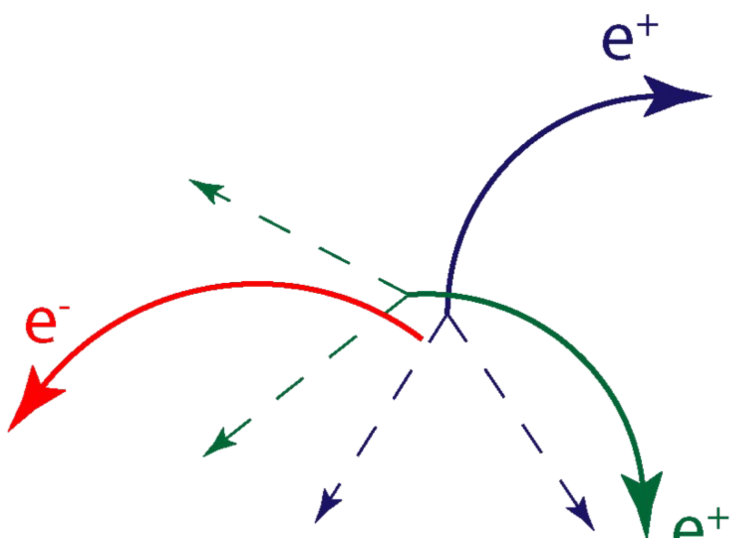


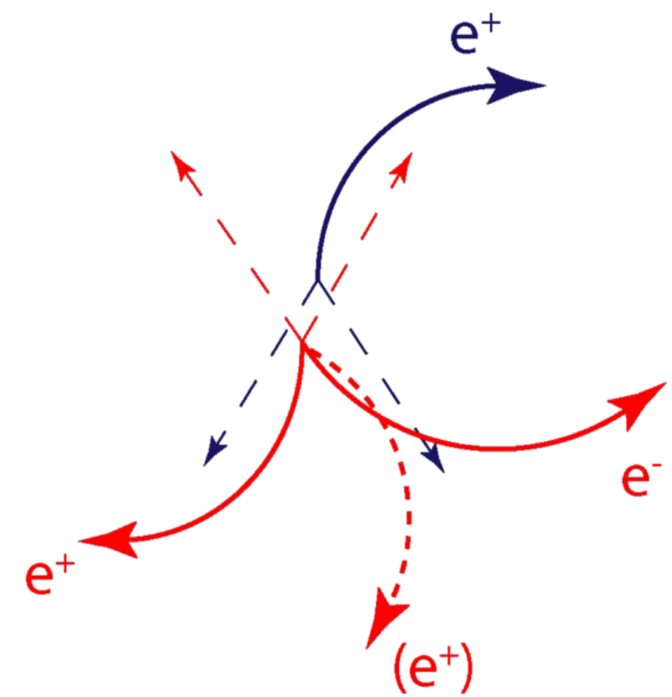


very good momentum / total energy resolution required!

Accidental Backgrounds

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

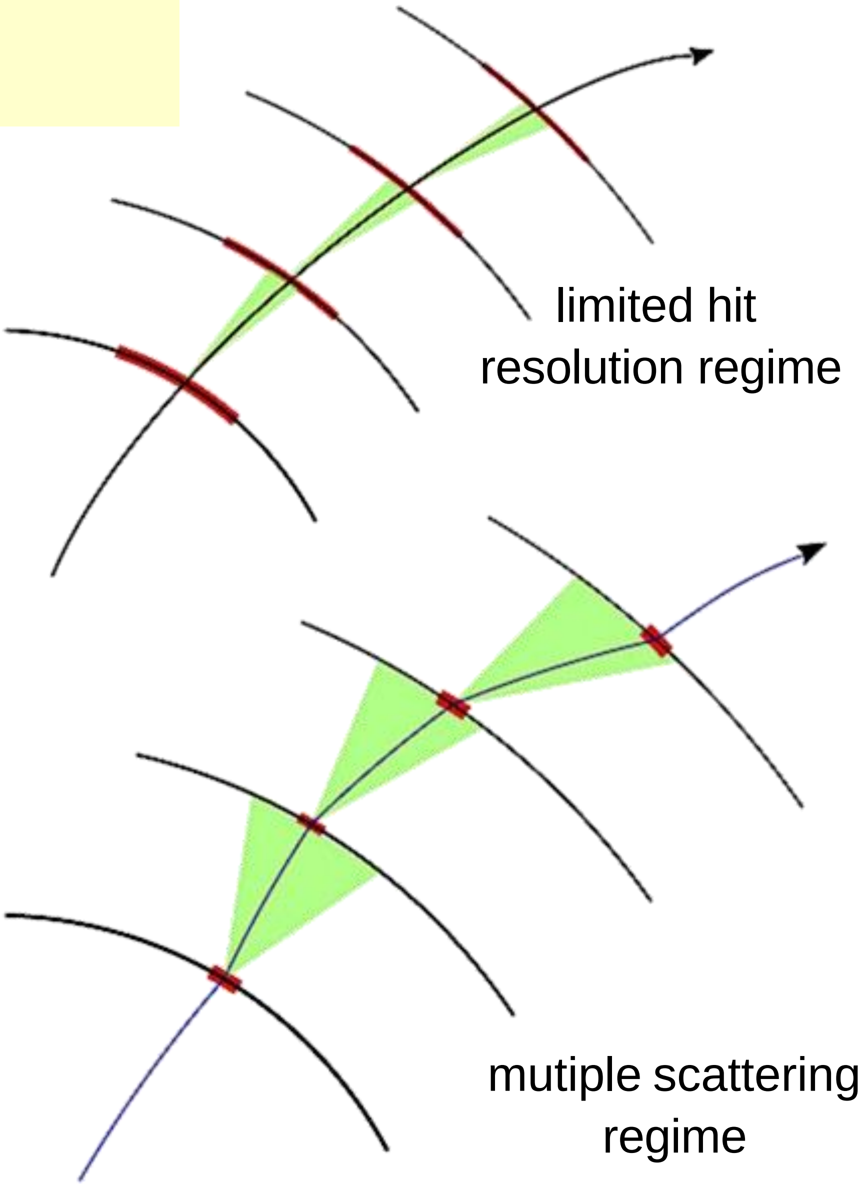




Detector requirements:

- **Vertex resolution**
- **Timing resolution**
- **Kinematic reconstruction**

Tracking Resolution + Multiple Scattering



- <u>Muon decay (m=105.6 MeV):</u>

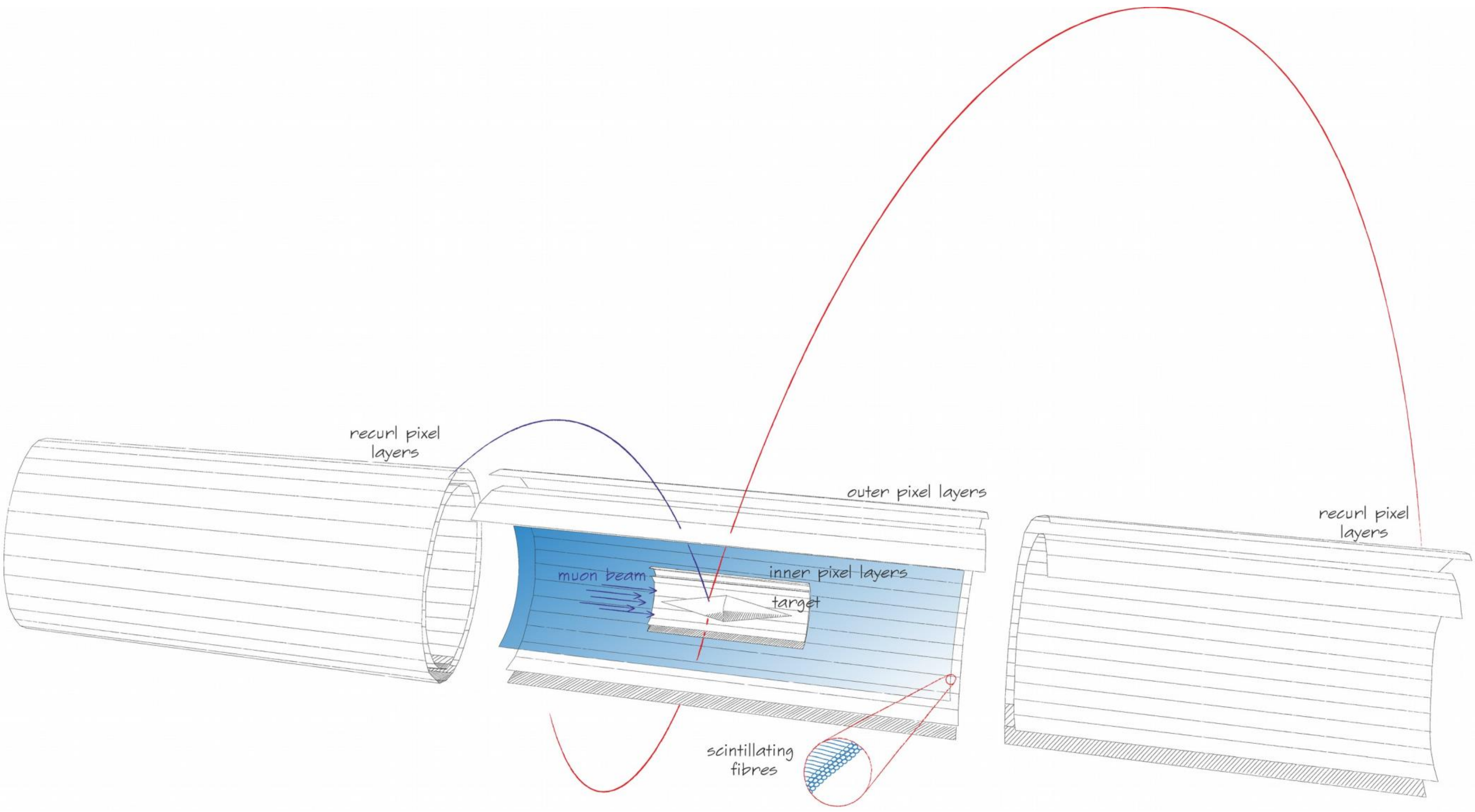
  → electrons in low momentum range
  p < 53 MeV/c

- Multiple scattering is dominant!

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

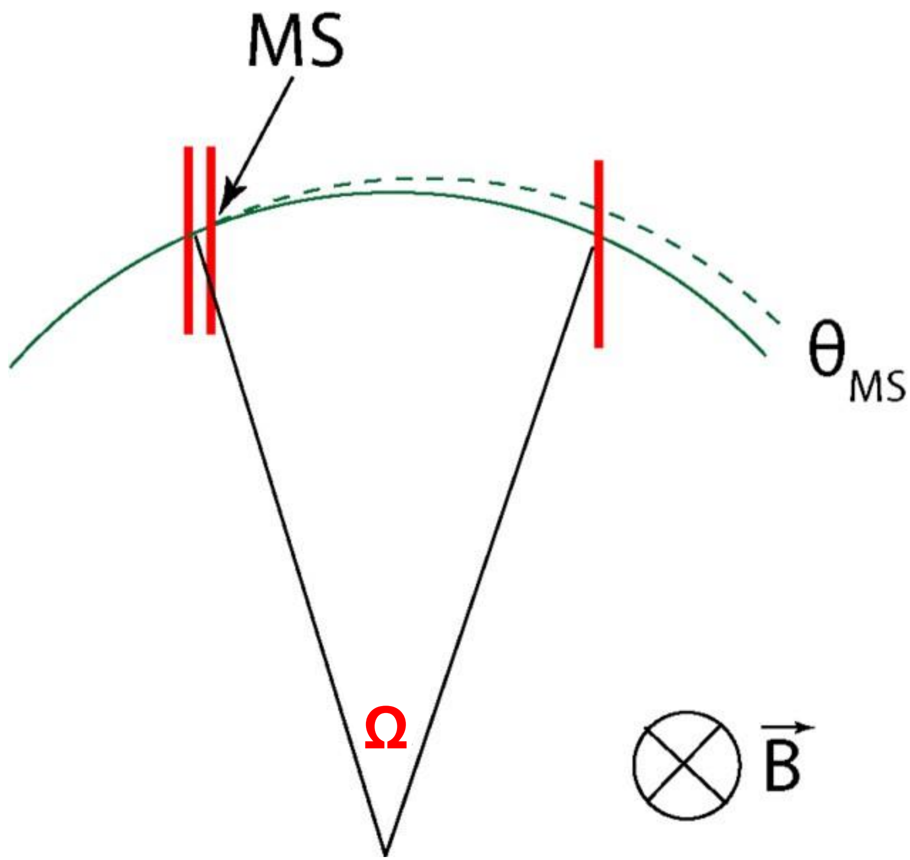
$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X / X_0}$$

Mu3e Detector Layout Concept



Momentum Resolution in MS Regime

- Muon decay: **p(electron) < 53 MeV/c → multiple scattering**
- Standard spectrometer:



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

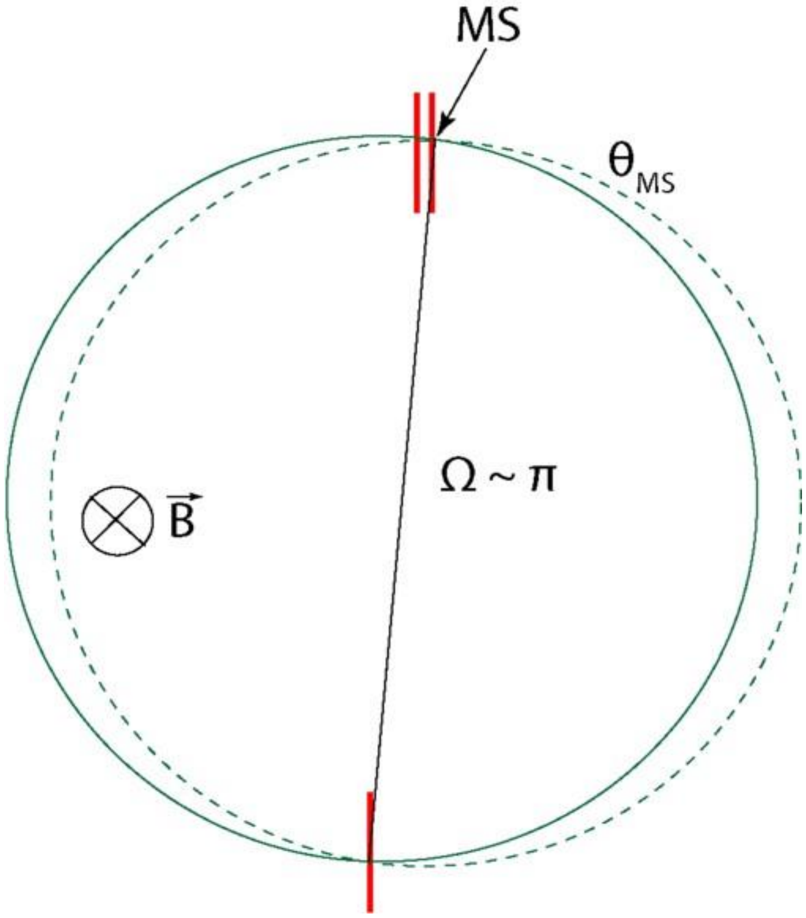
precision requires
→ little material X

$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$ (linearised)

precision requires lever arm
→ large bending angle Ω

Momentum Resolution in MS Regime

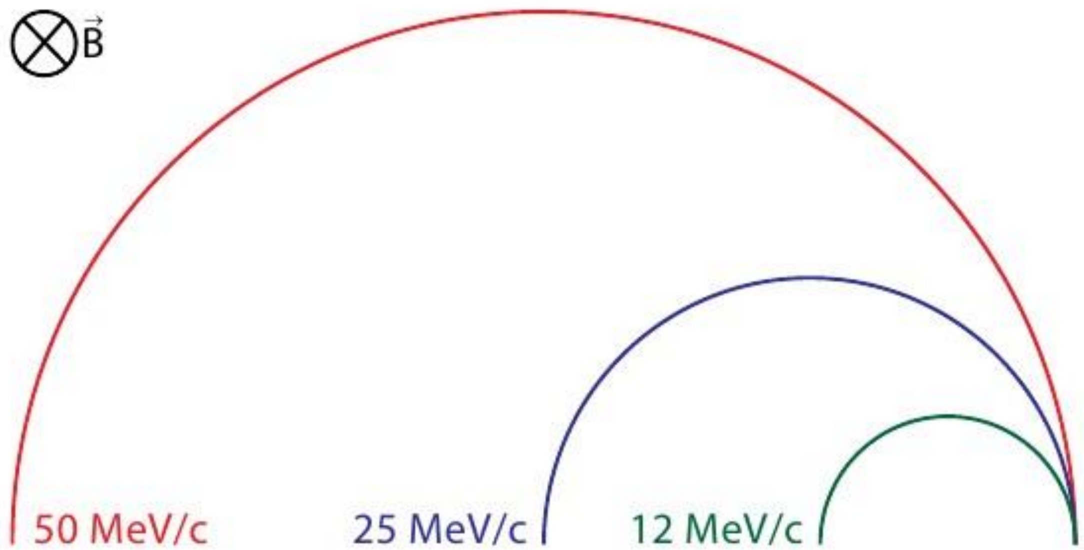
- "Half turn" spectrometer:



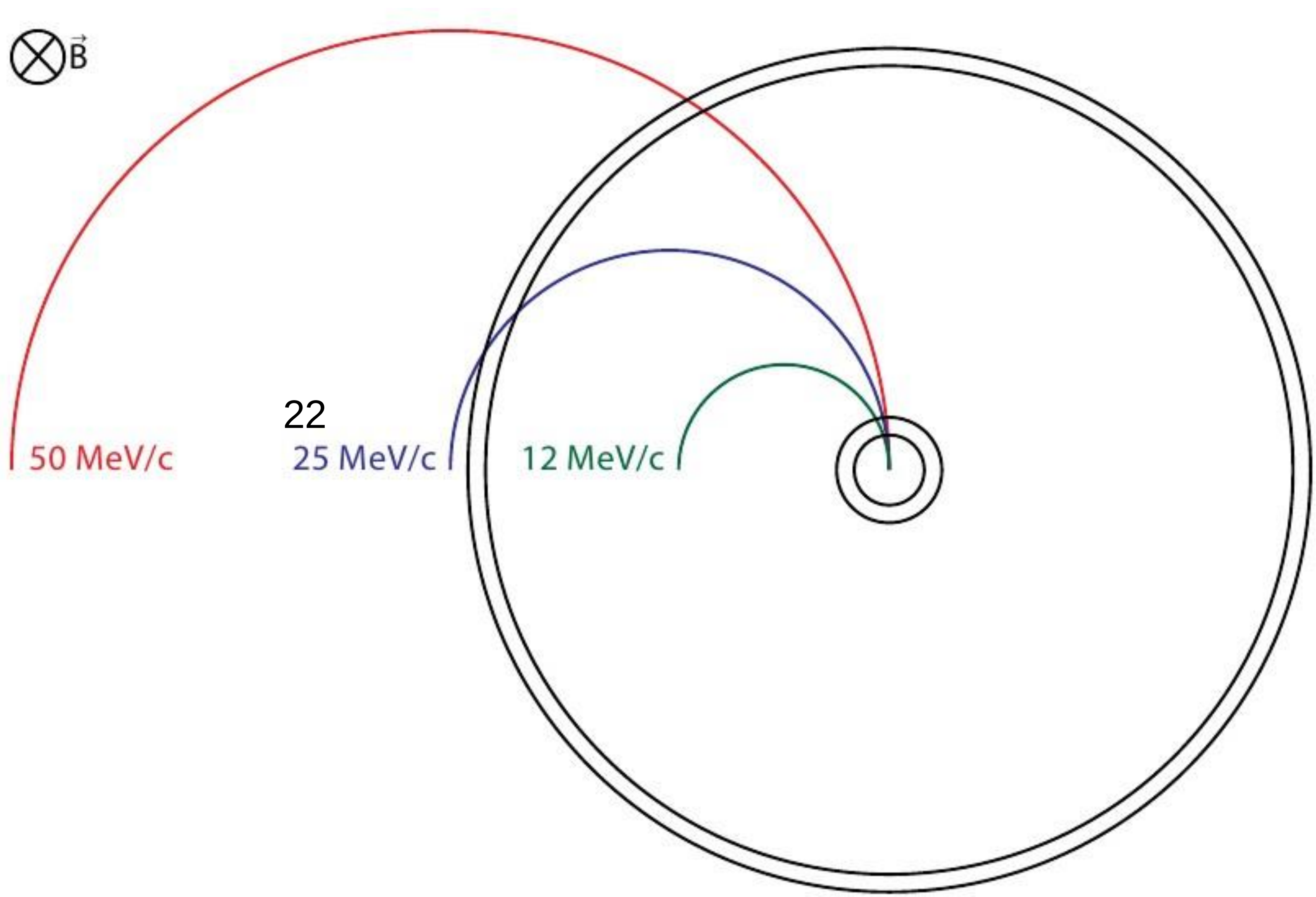
$$\frac{\sigma_p}{P} \sim O(\Theta_{MS}^2)$$

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

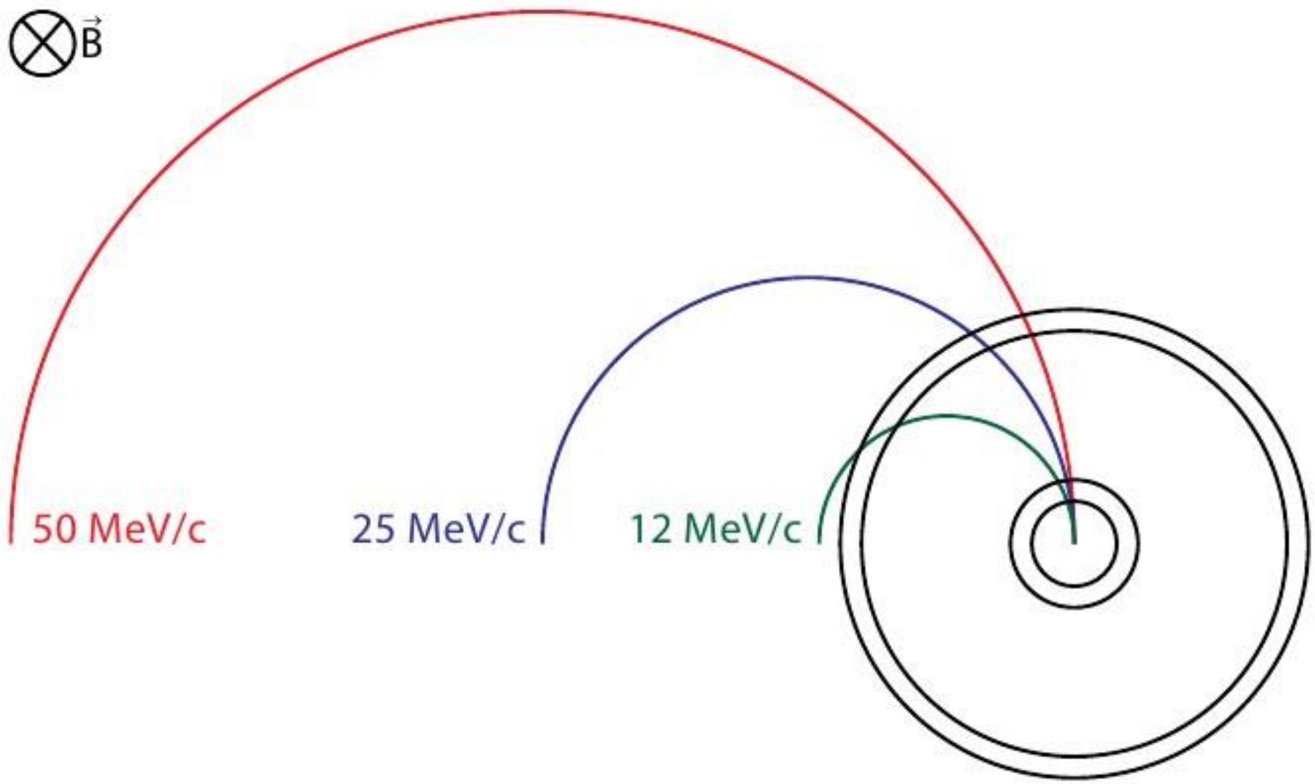
Tracking Design Considerations



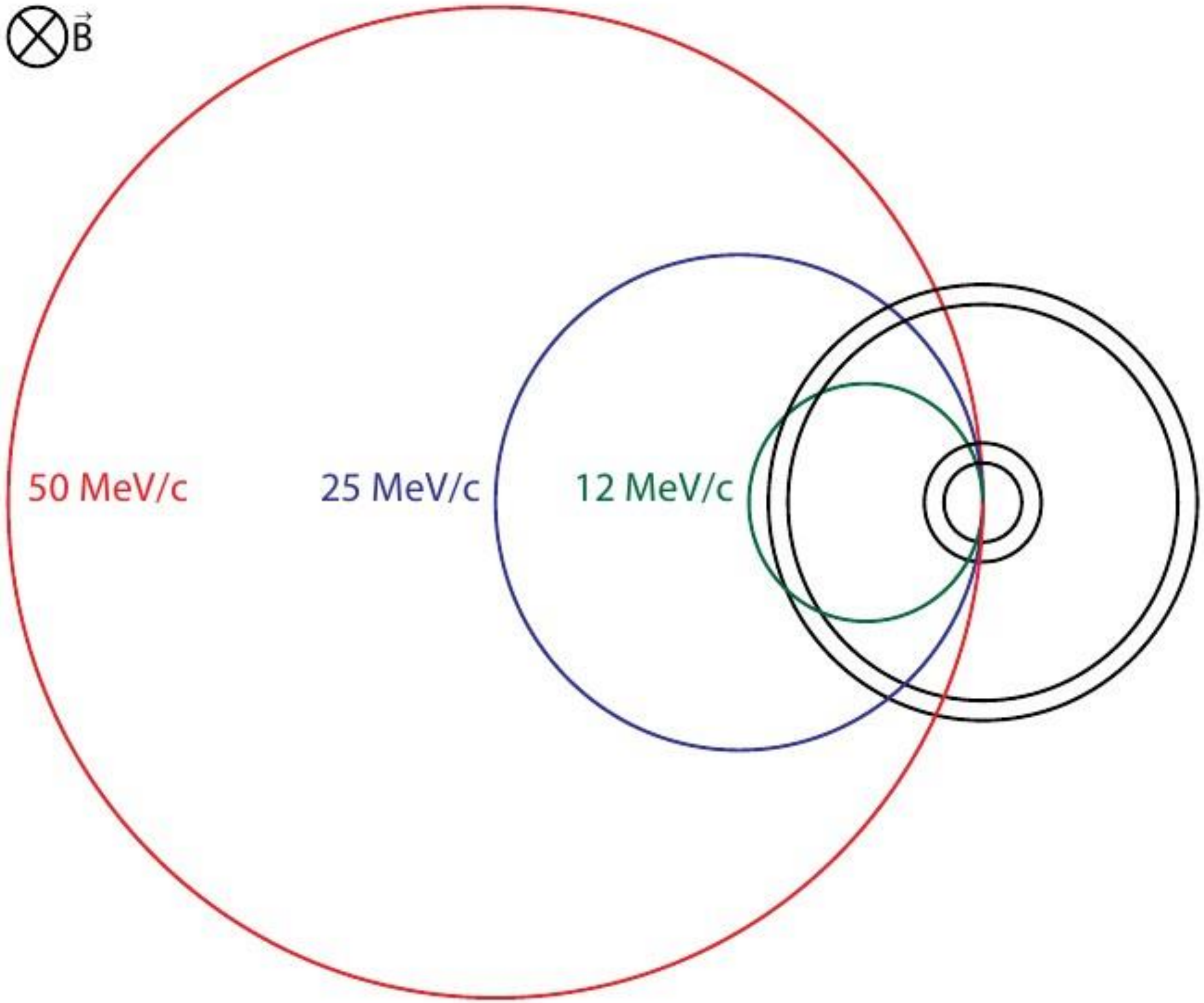
Tracking Design Considerations



Tracking Design Considerations



Tracking Design Considerations

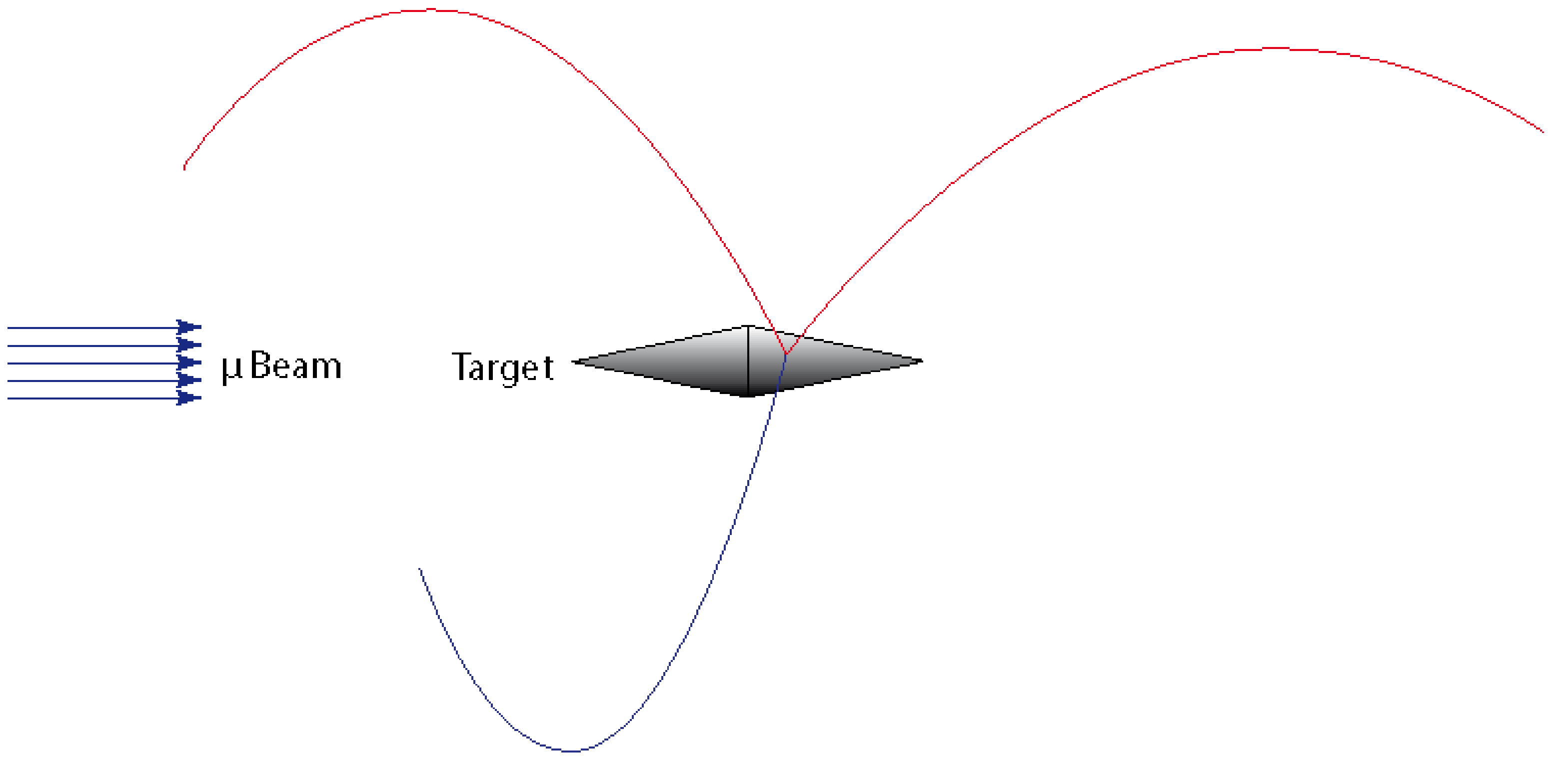


Mu3e Design

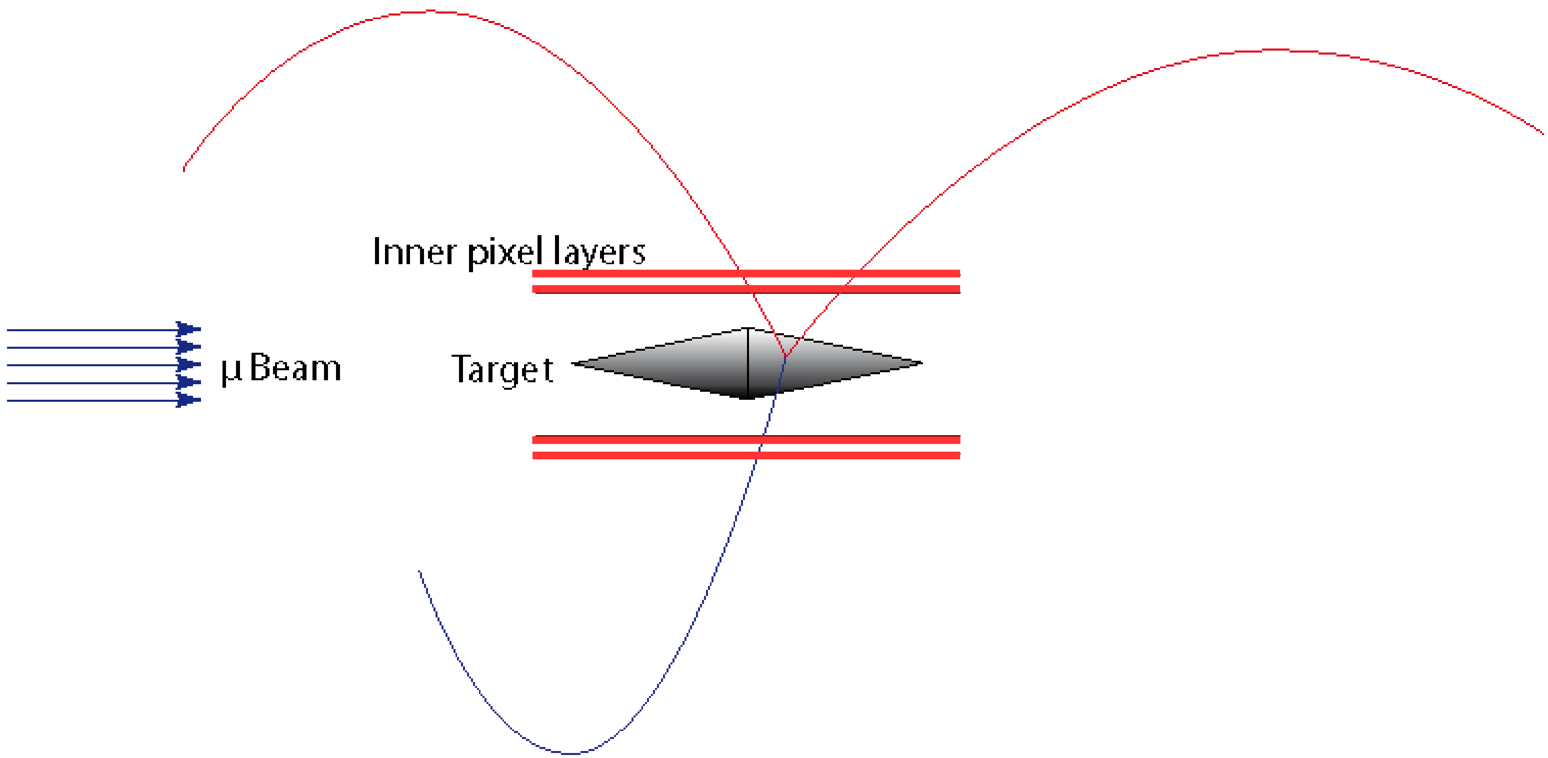
10^8 muons per second (phase I)

p = 28 MeV/c (E$_{kin}$=4.1 MeV)

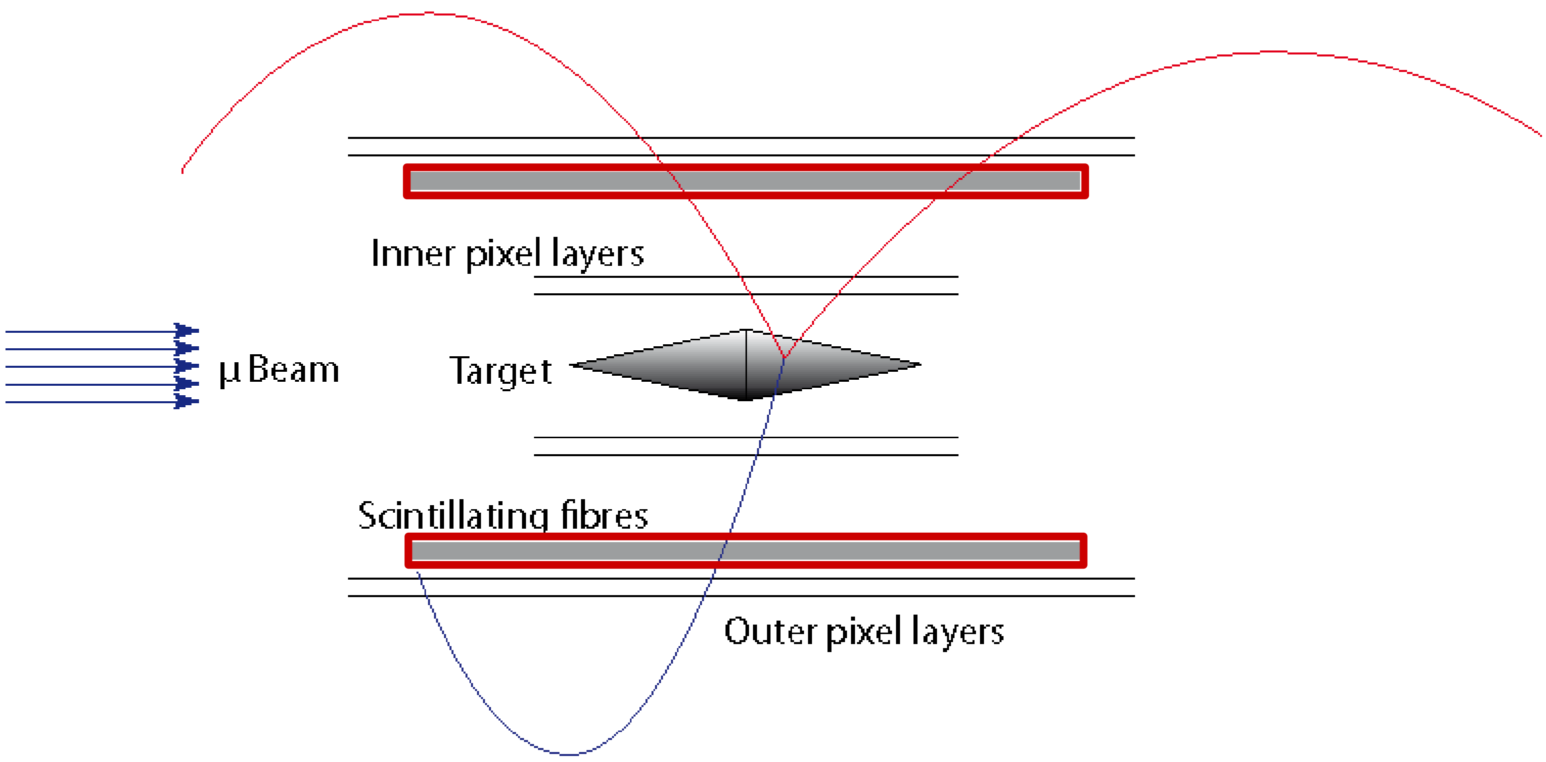
Mu3e Design



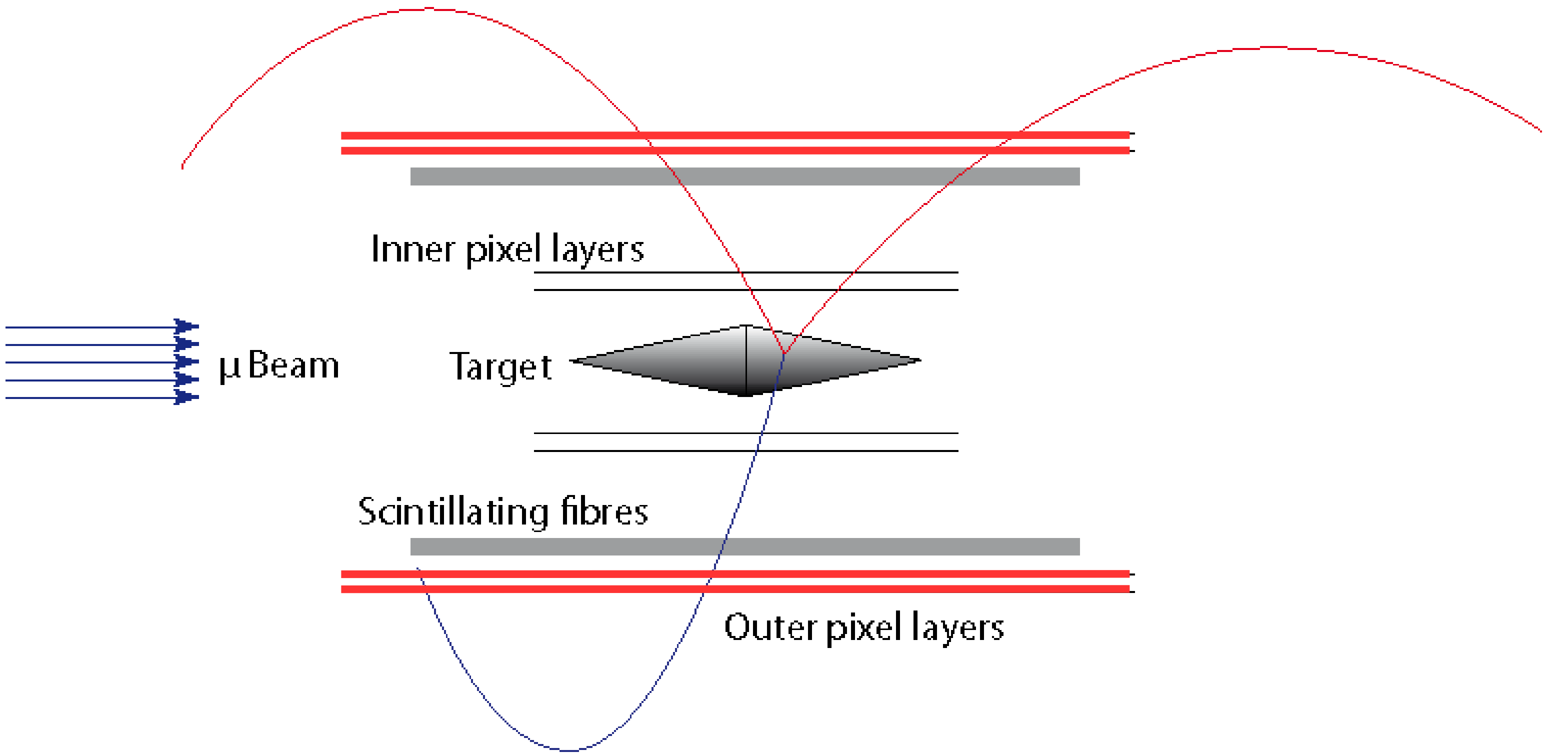
Mu3e Design



Mu3e Design


Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

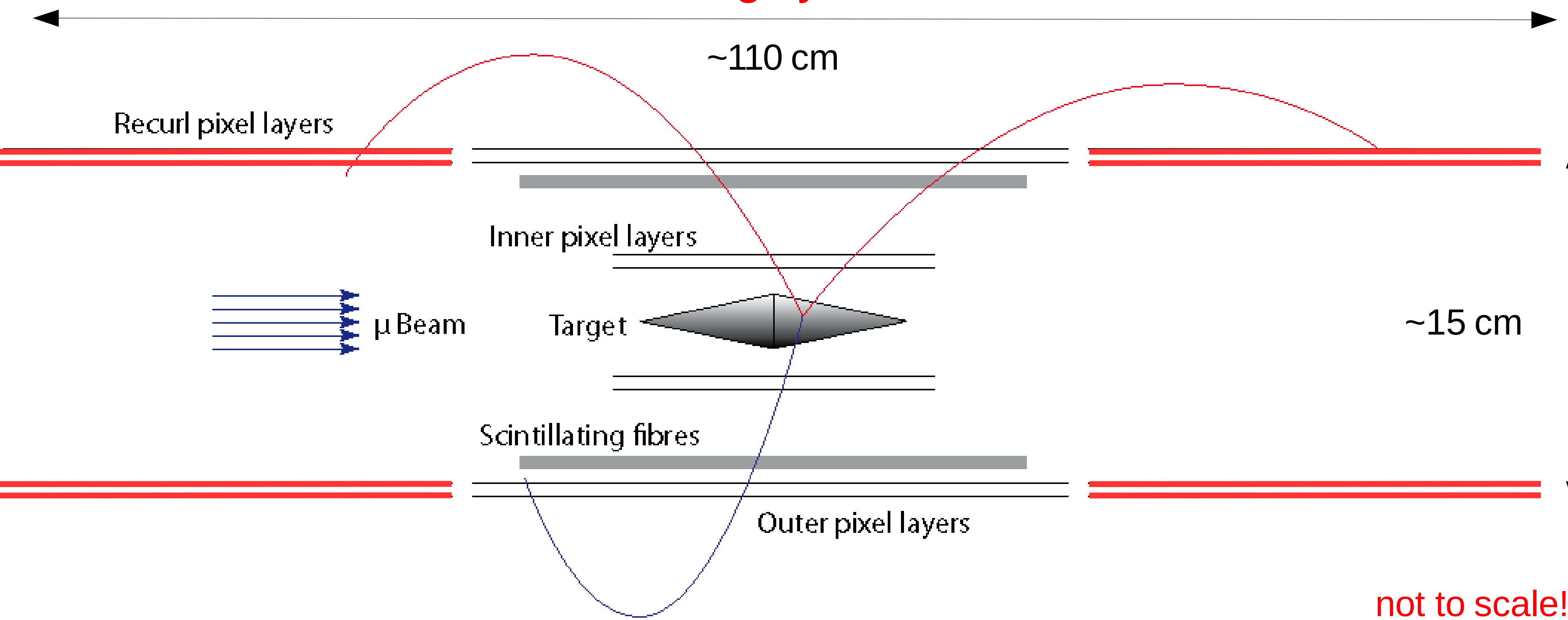
Mu3e Design



Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

Mu3e Design

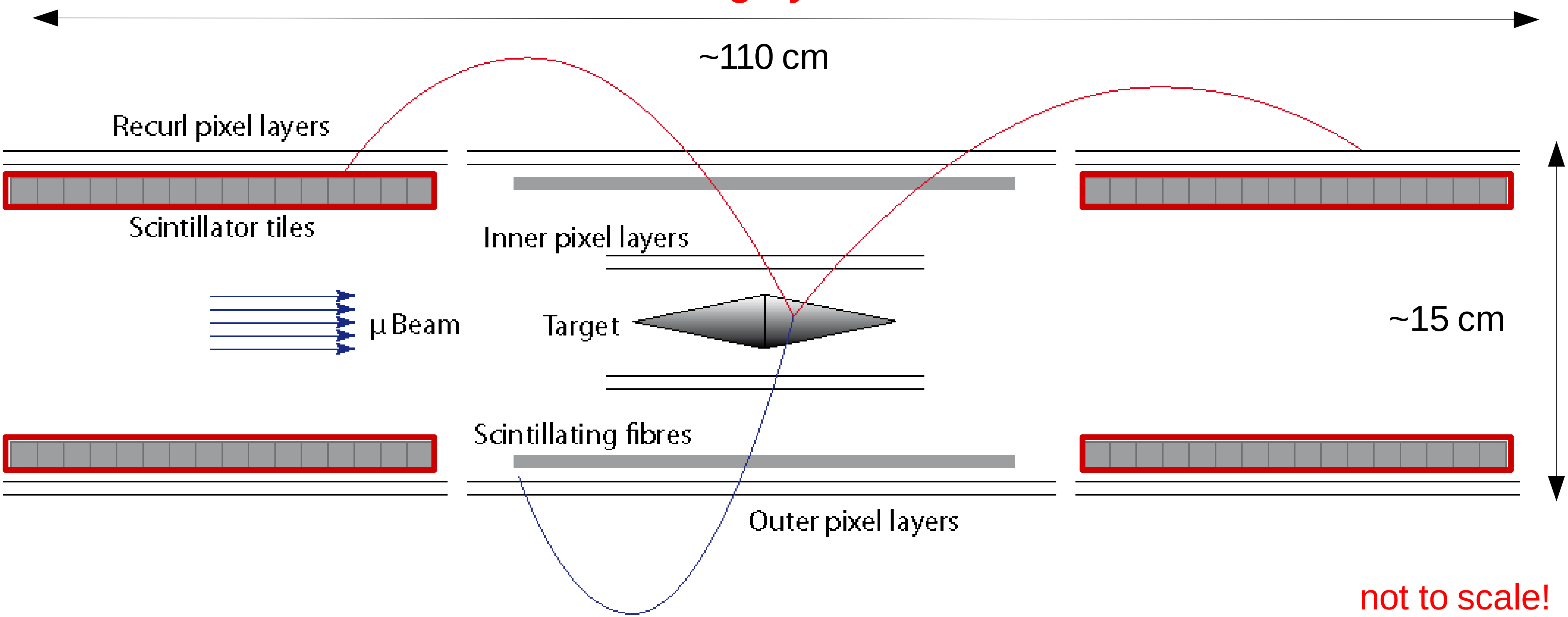
Long cylinder!



not to scale!

Mu3e Design

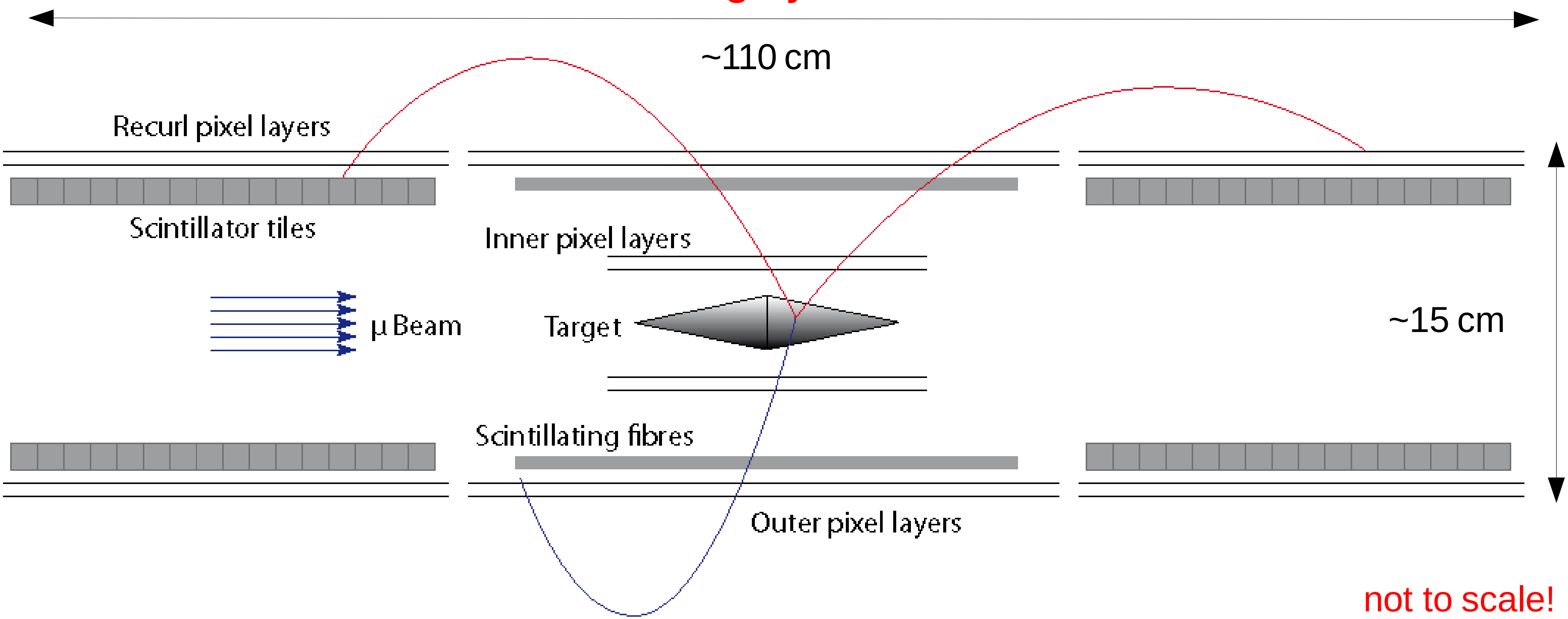
Long cylinder!



not to scale!

Mu3e Design

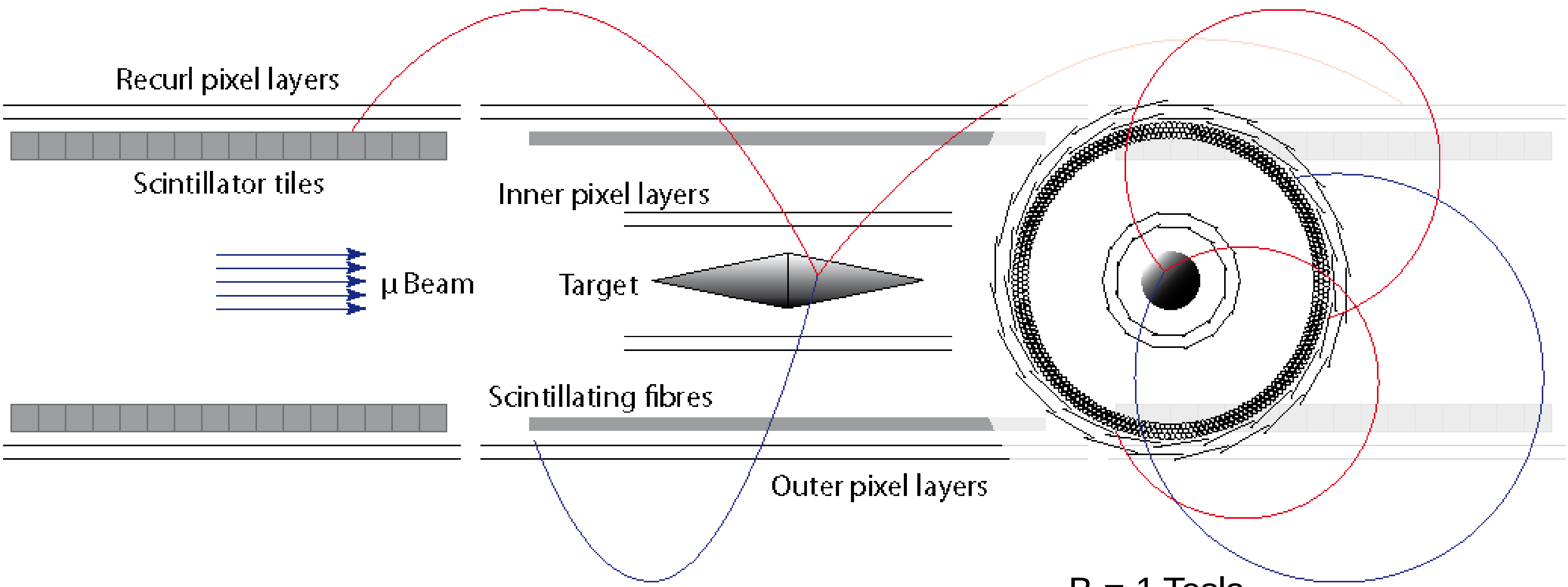
Long cylinder!



not to scale!

Mu3e Design

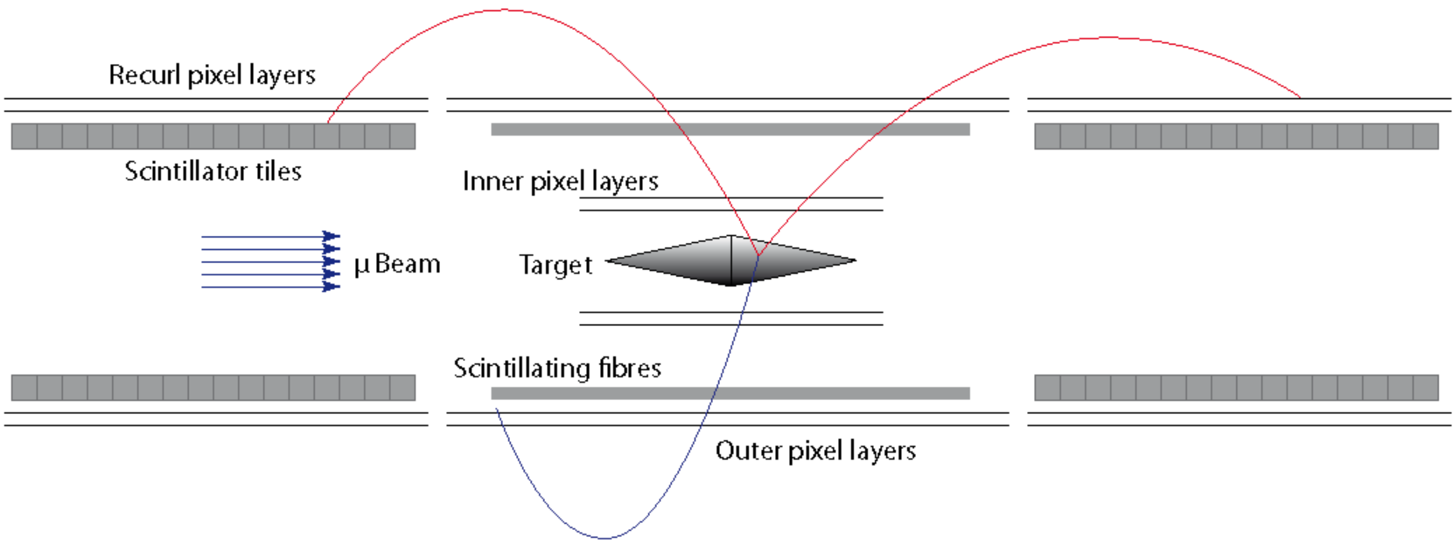
transverse view:



B = 1 Tesla

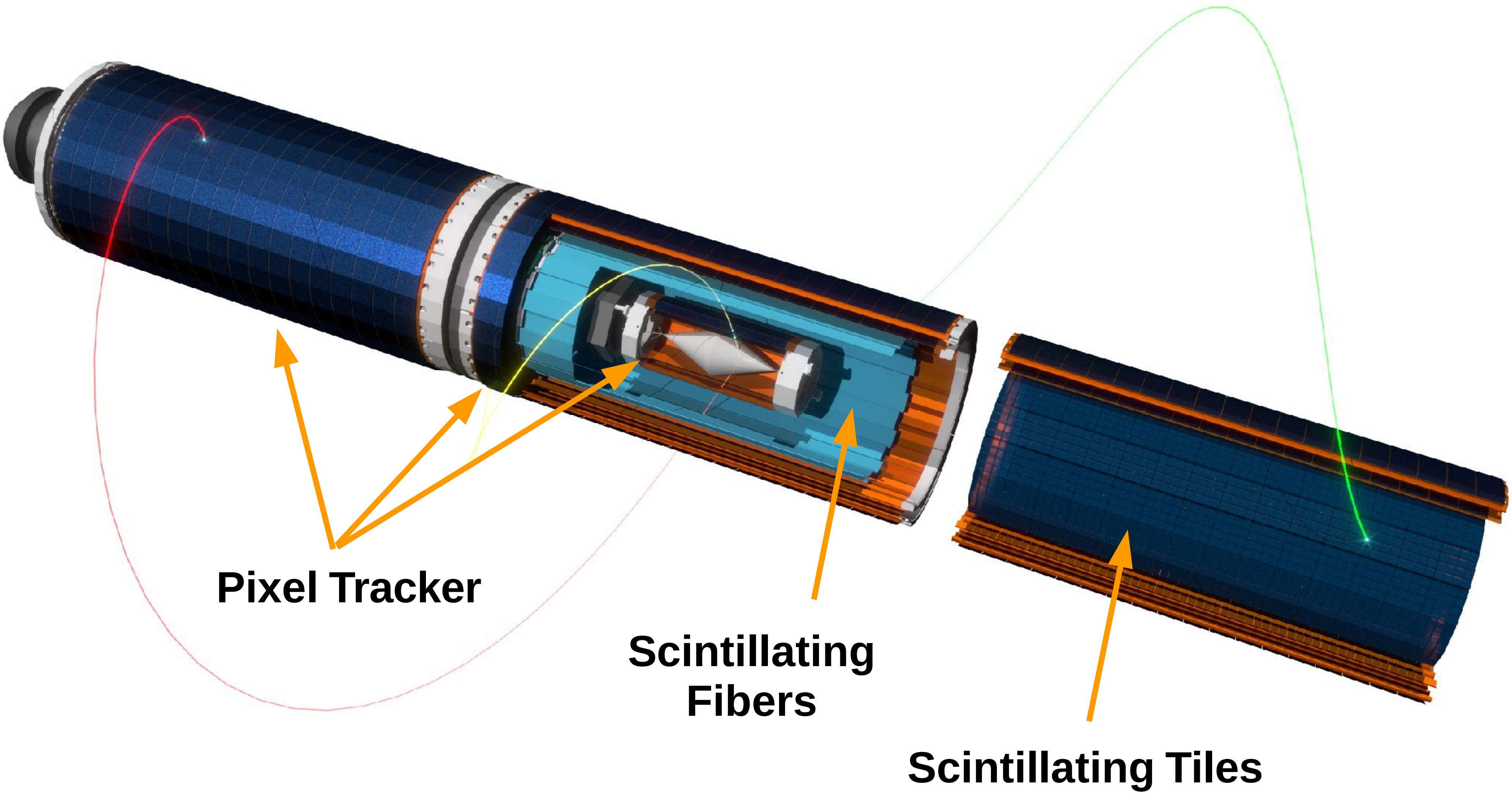
helium atmosphere

Main Technological Challenges



- Large area O(1m^2) fats monolithic pixel detectors with $X/X_0 = 0.1\%$ per tracking layer
- Novel helium gas cooling concept
- Thin scintillating fiber detector with ≤ 1mm thickness
- Timing resolution 100-500 ps
- Filter farm reconstructing and processing 10^8-10^9 tracks per second

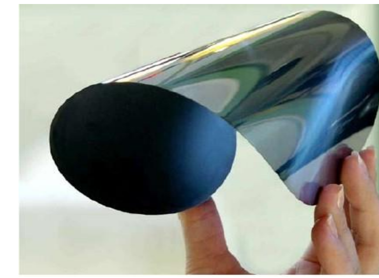
Mu3e Detector



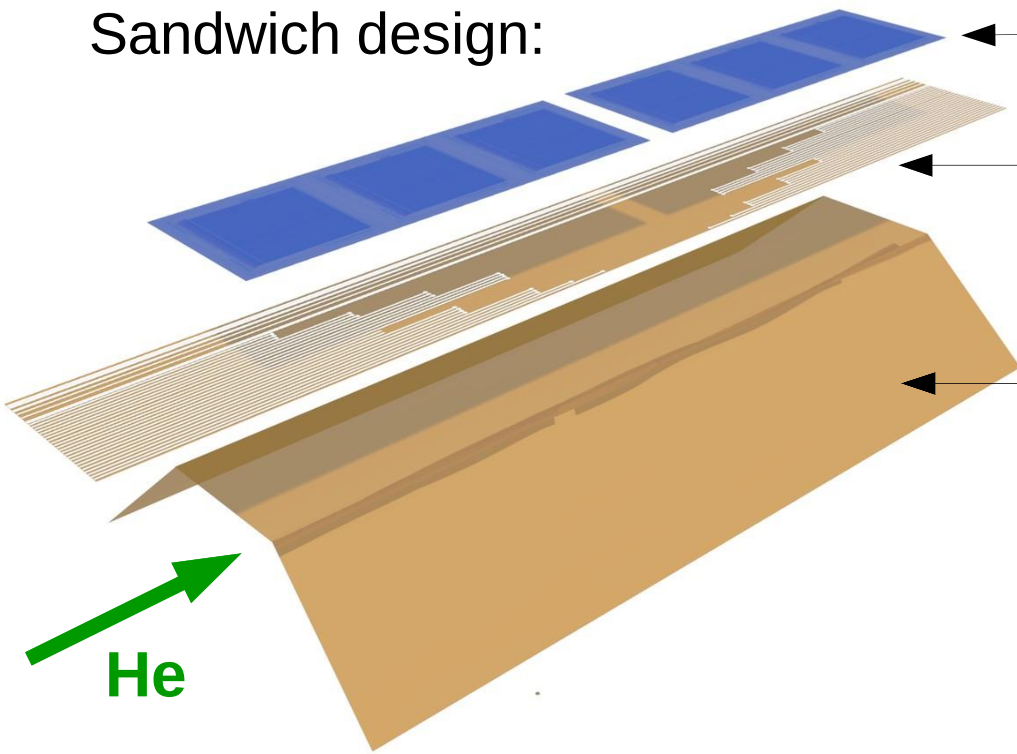
Mu3e Pixel Mechanics

Mu3e physics sensitivity: $\sim (X/X_0)_3$

Most challenging requirement: $X/X_0 \leq 0.1\%$



Sandwich design:



monolithic HV-CMOS sensor (50 µm)

thin aluminium / kapton flexprint

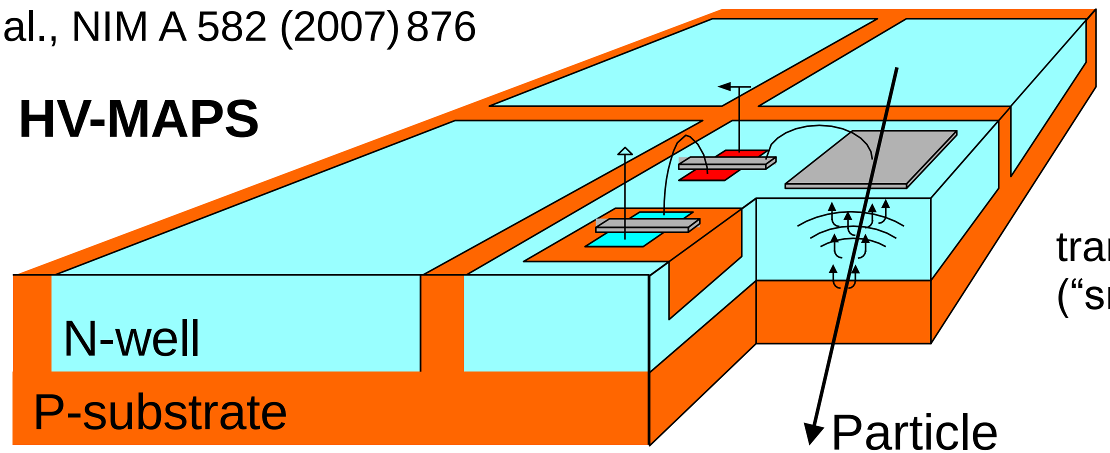
kapton support foil (25 µm)

+ gaseous helium cooling

$X \sim 0.1\%\ X_0$ per layer possible

The MuPix Sensor for Mu3e

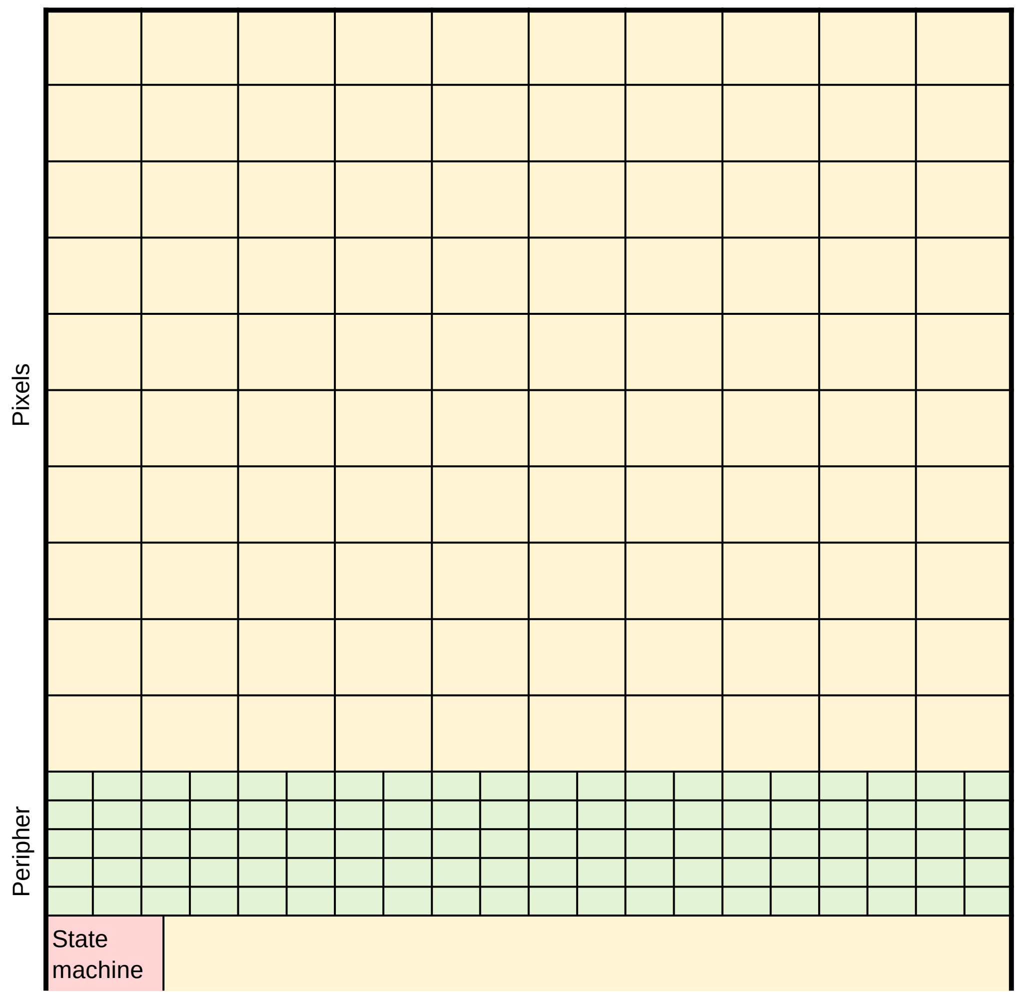
I.Peric, et al., NIM A 582 (2007) 876



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

- **active sensor → hit finding + digitisation + zero suppression + readout**
- high precision → pixels 80 x 80 μm^2
- low noise ~ 40 - 50e → low threshold
- small depletion region of ~ 10 μm → thin sensor ~50 μm (~ 0.0005 X_0)
- standard HV-CMOS process (60 - 90 V) → low production costs
- continuous and fast readout (serial link) → online reconstruction

MuPix Chip Design



cells

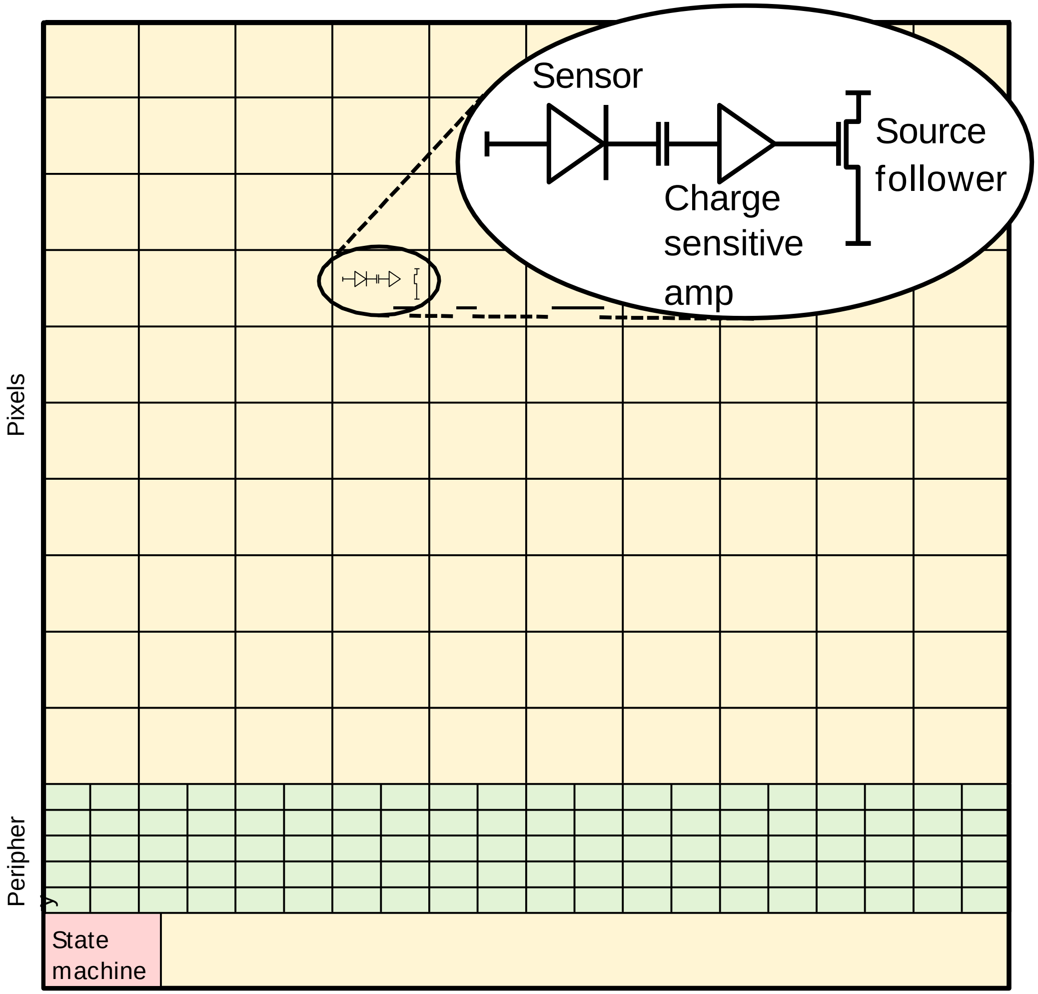
active pixel matrix

“mirror” cells

state machine
VCO, PLL, ...

periphery
(5-10% total area):

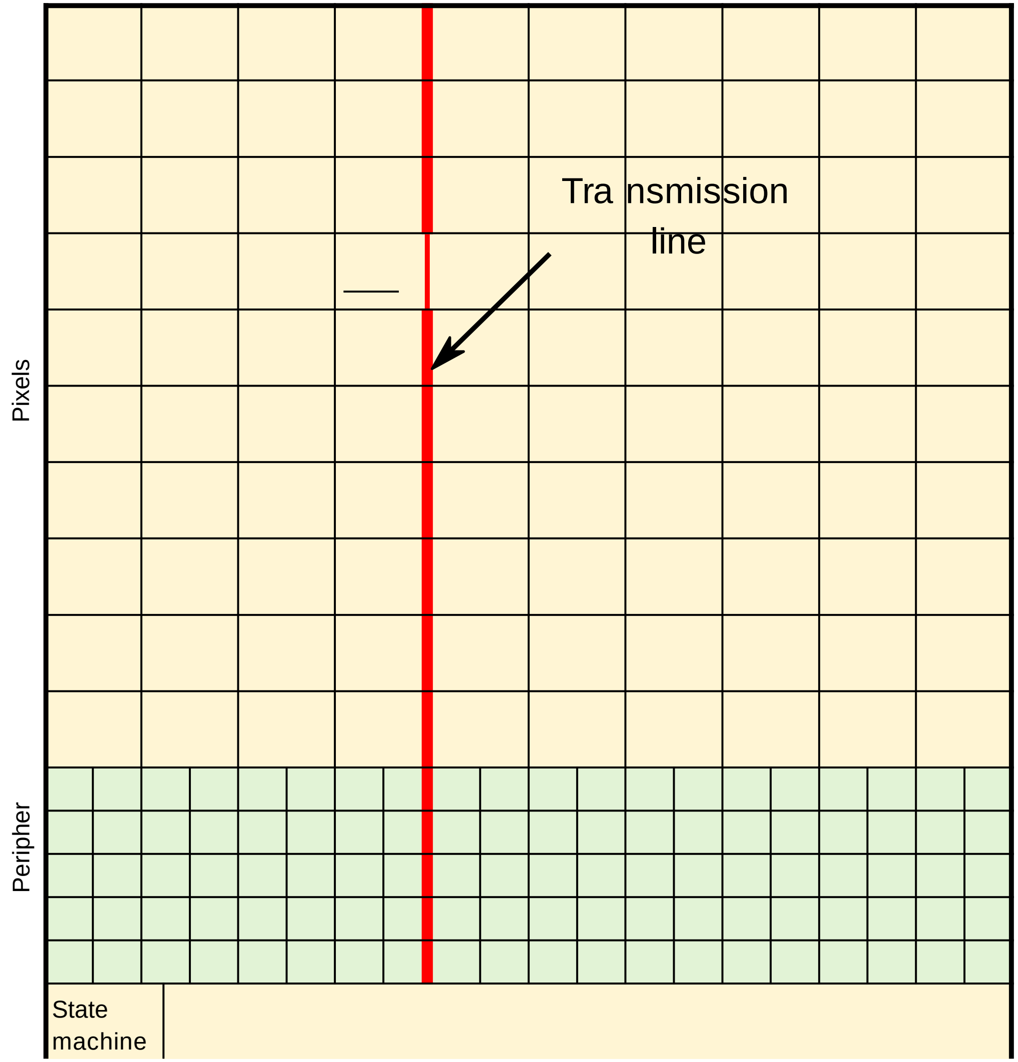
MuPix Chip Design



analog cell:

- reverse biased -85V
- charge sensitive amplifier
- source follower

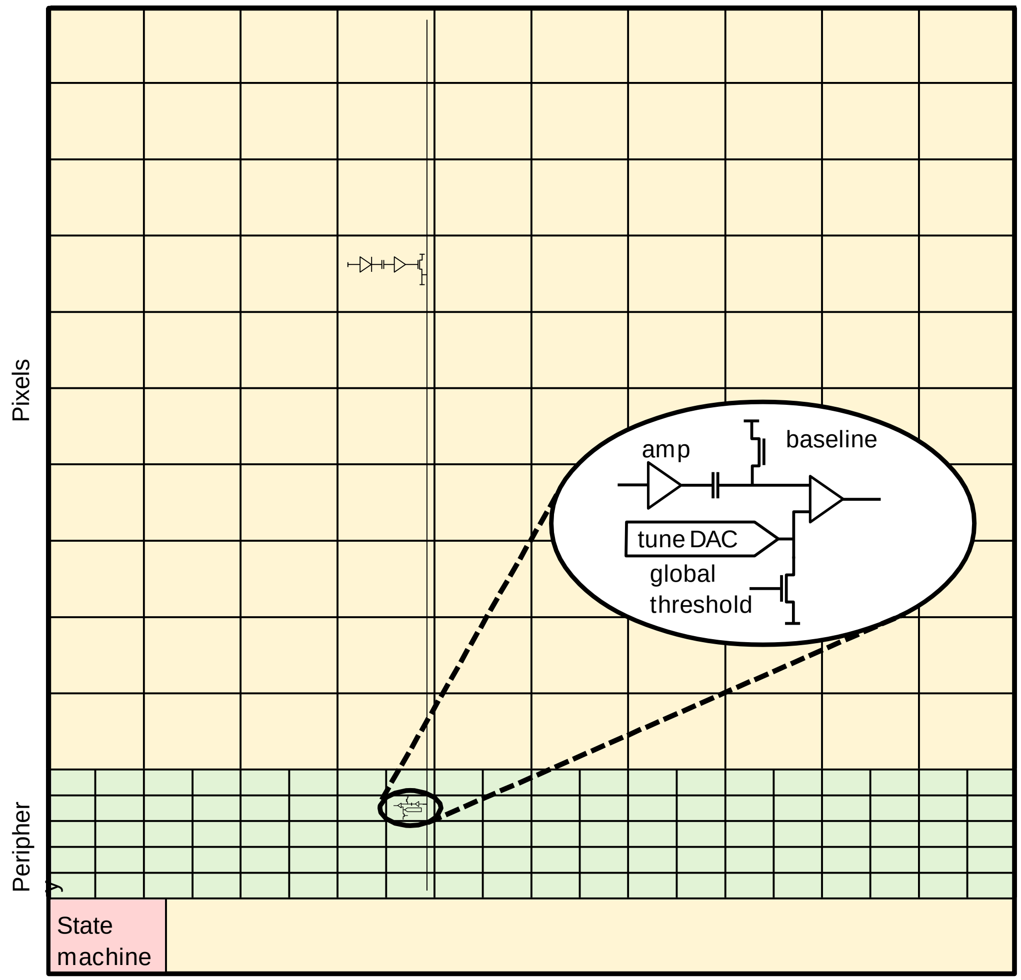
MuPix Chip Design



transmission line:

- send signal to corresponding mirror cell

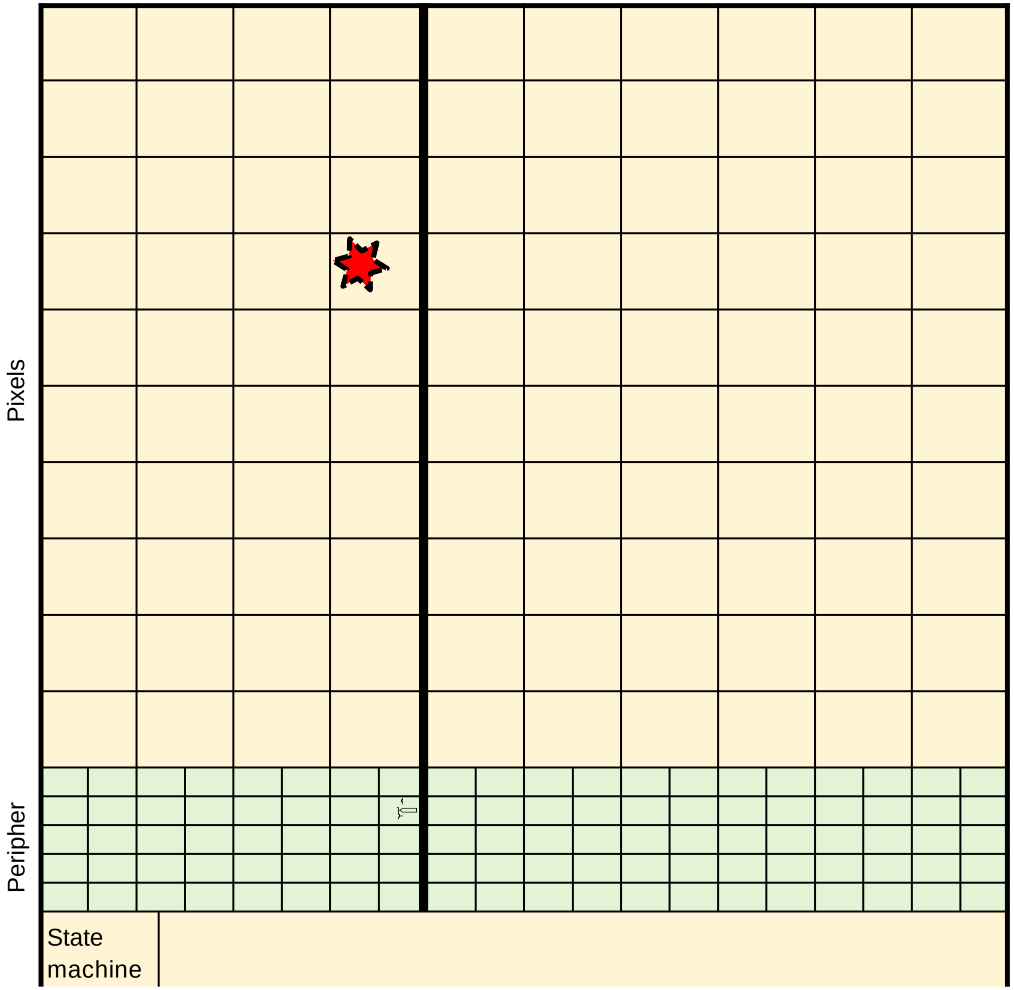
MuPix Chip Design



mirror cell:

- 2nd amplifier (Mupix7)
- comparator for discrimination
- threshold and baseline by tuning DACs

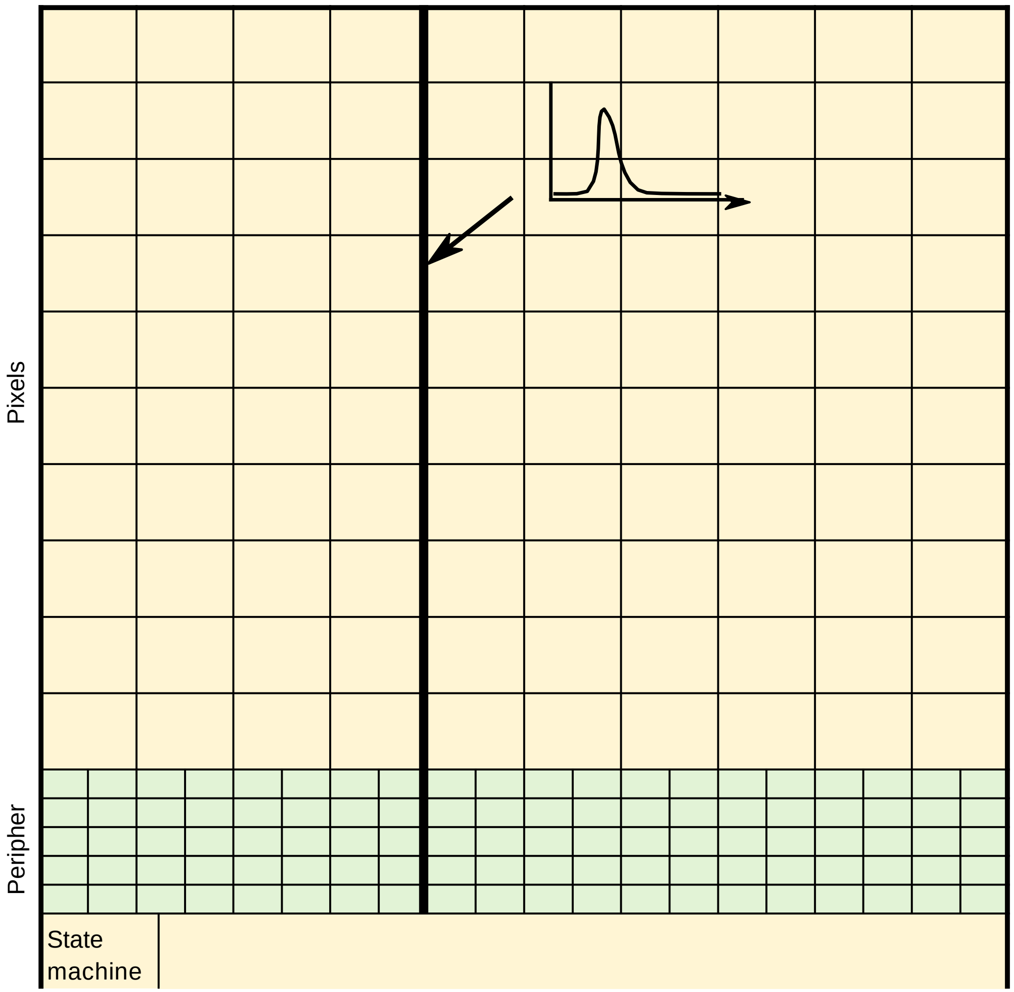
MuPix Hit Detection



hit sequence:

- signal generation

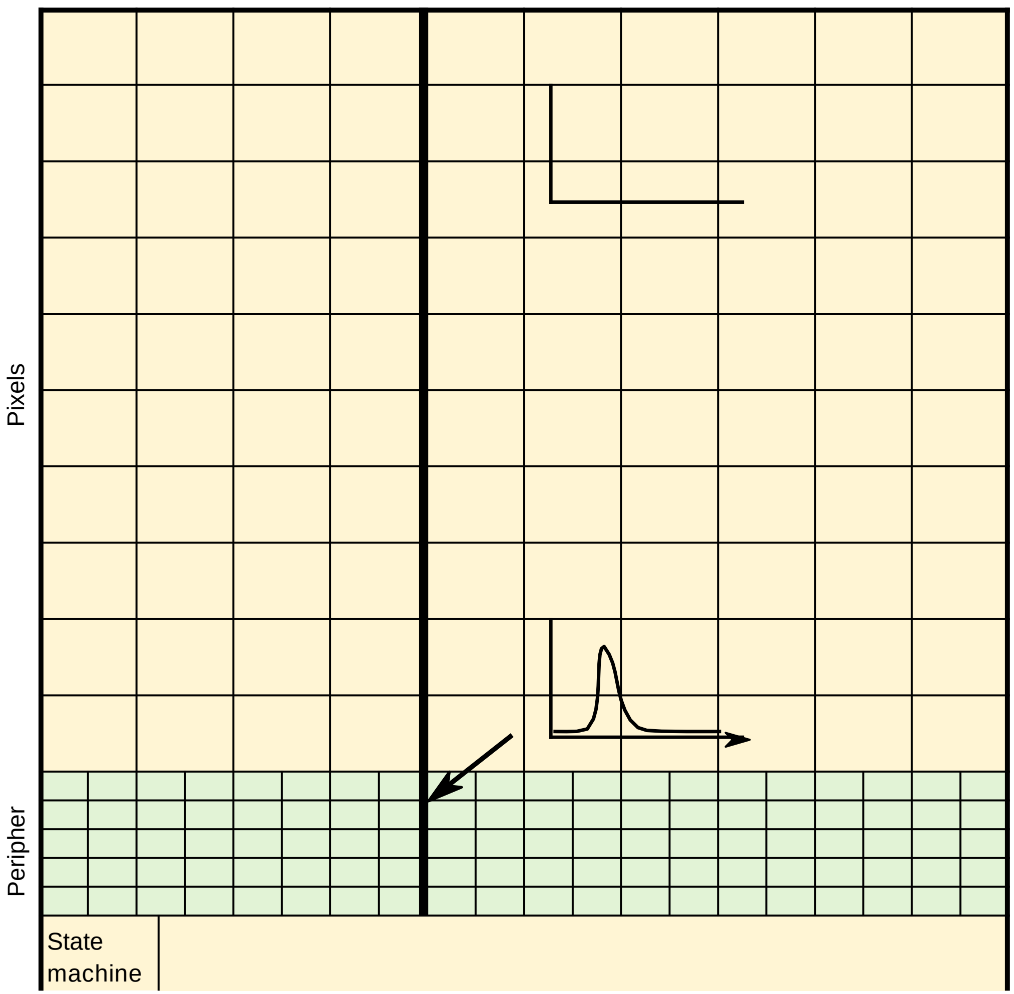
MuPix Hit Detection



hit sequence:

- signal generation
- amplification

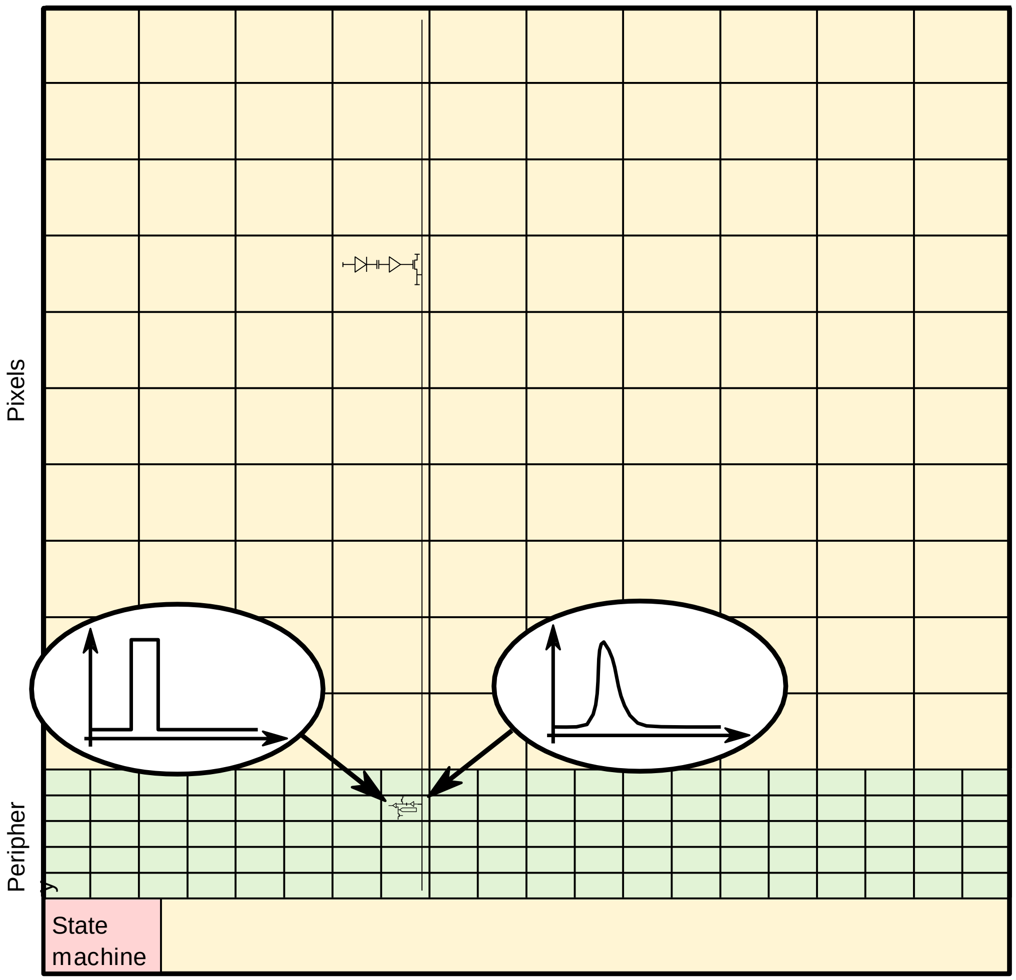
MuPix Hit Detection



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel

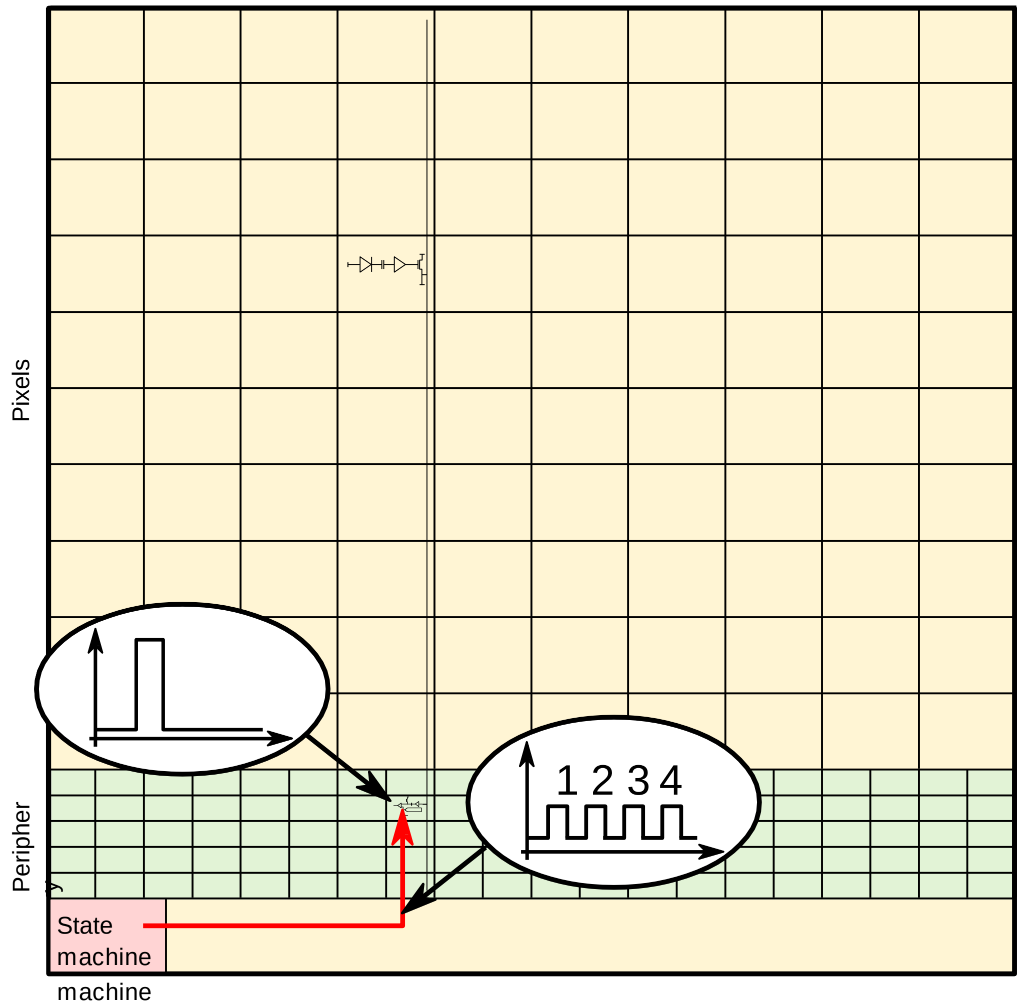
MuPix Hit Detection



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated

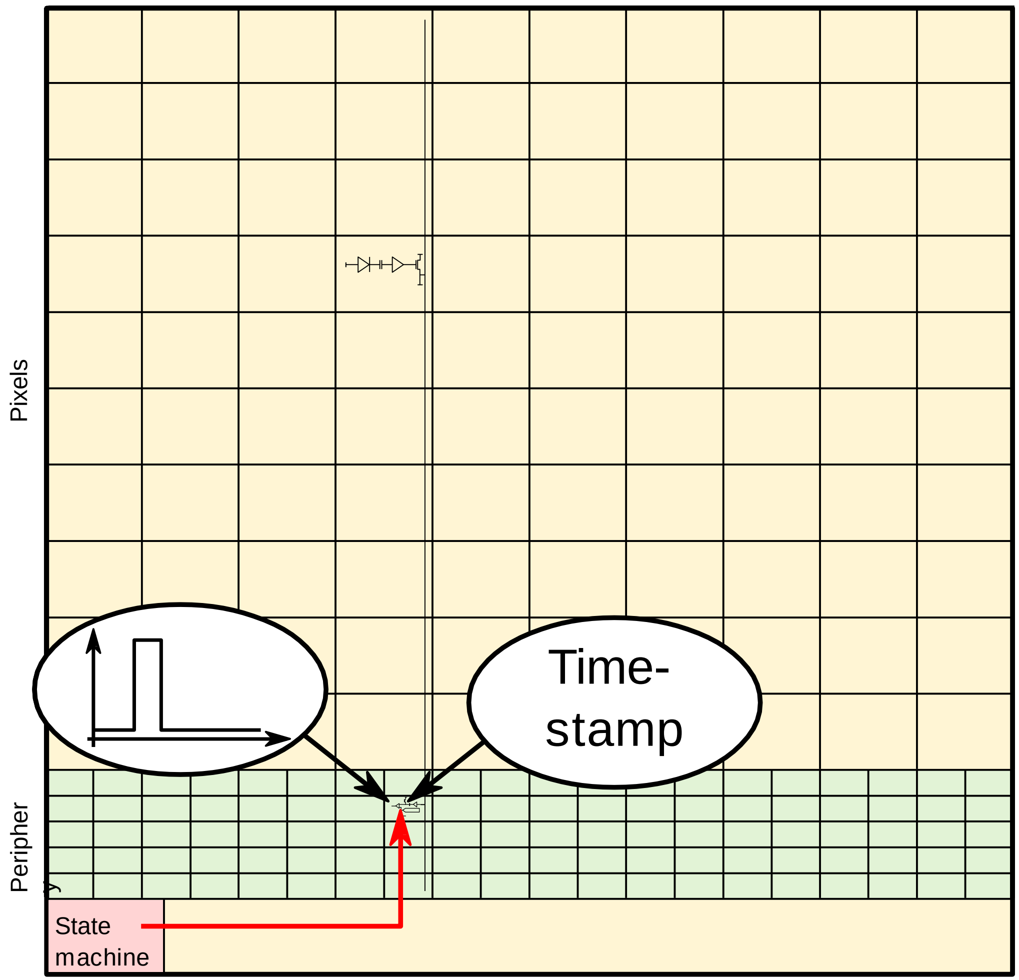
MuPix Hit Detection



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk

MuPix Hit Detection

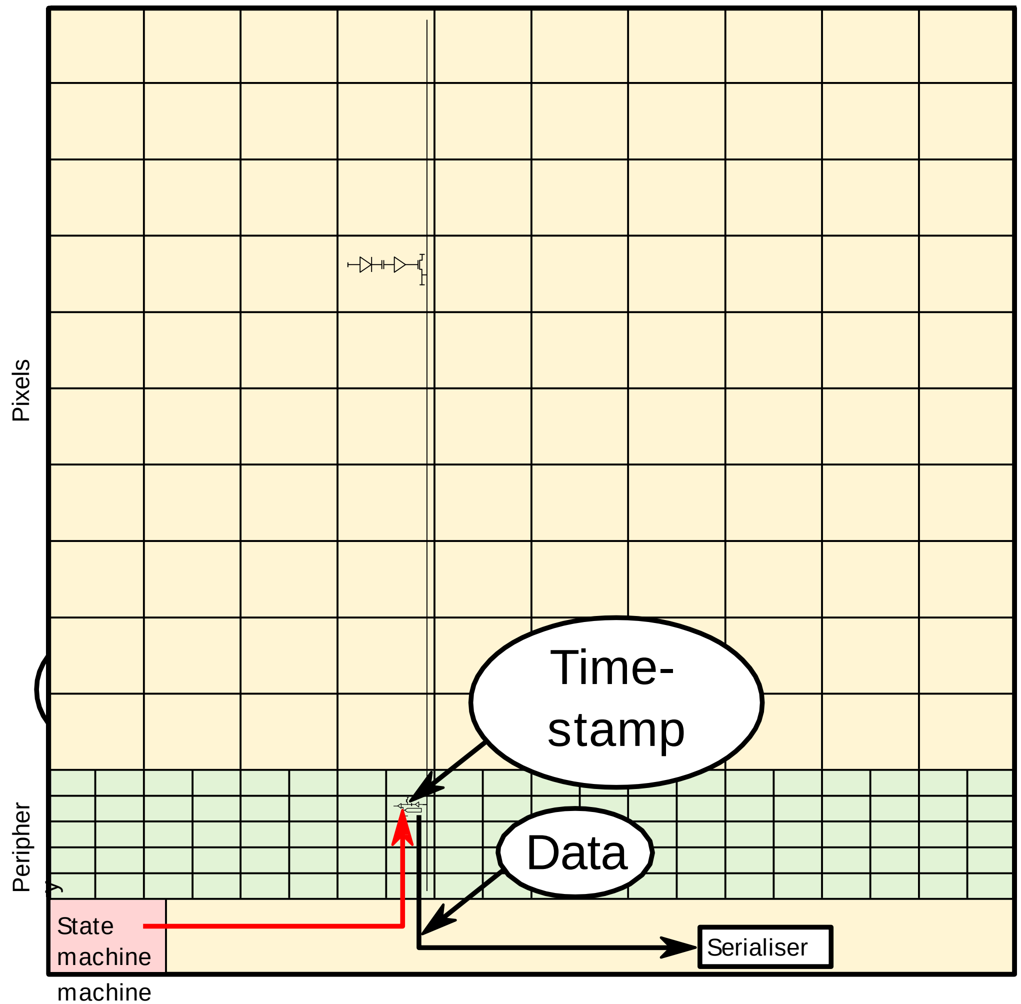


machine

hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation

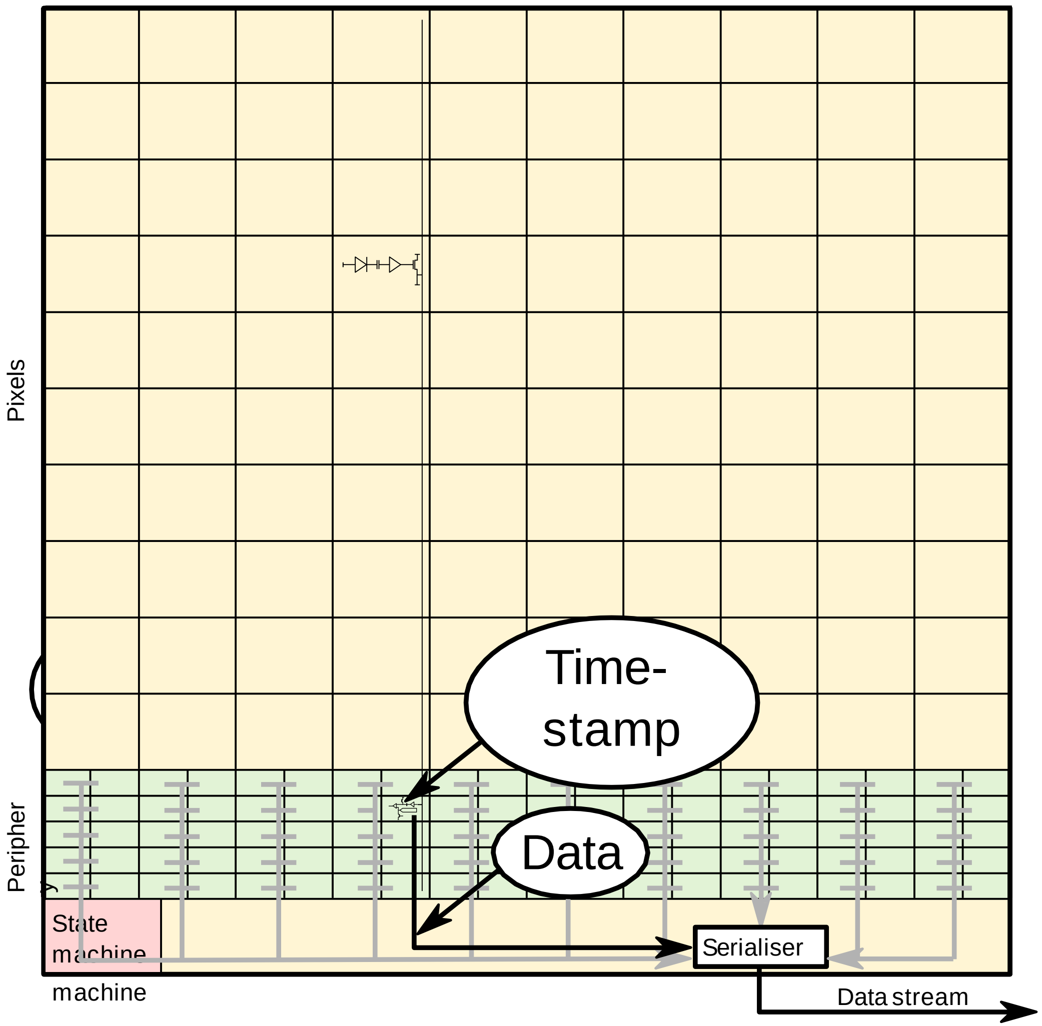
MuPix Hit Detection



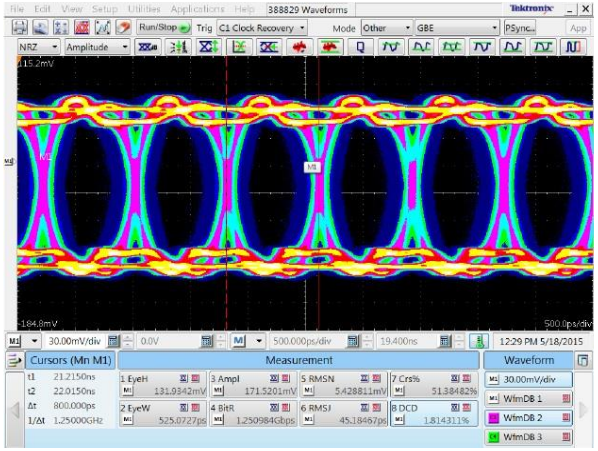
hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation
- hit address and timestamp send to serializer

MuPix Hit Detection



Finally, **all detected hits** are sent out via a **1.25 (1.6) Gbit/s** serial link

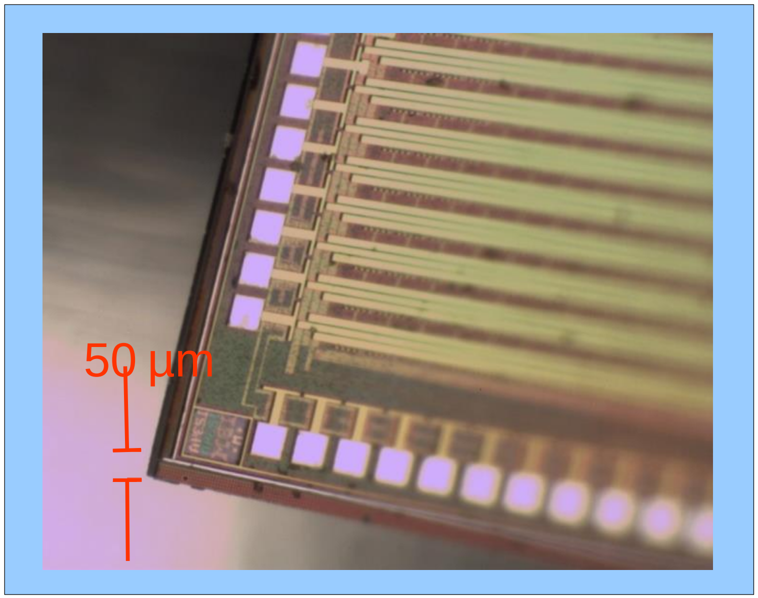


Eye diagram measured with Mupix7 prototype

Maximum readout rate is 33 Mhits/s per link

MuPix7 Prototype

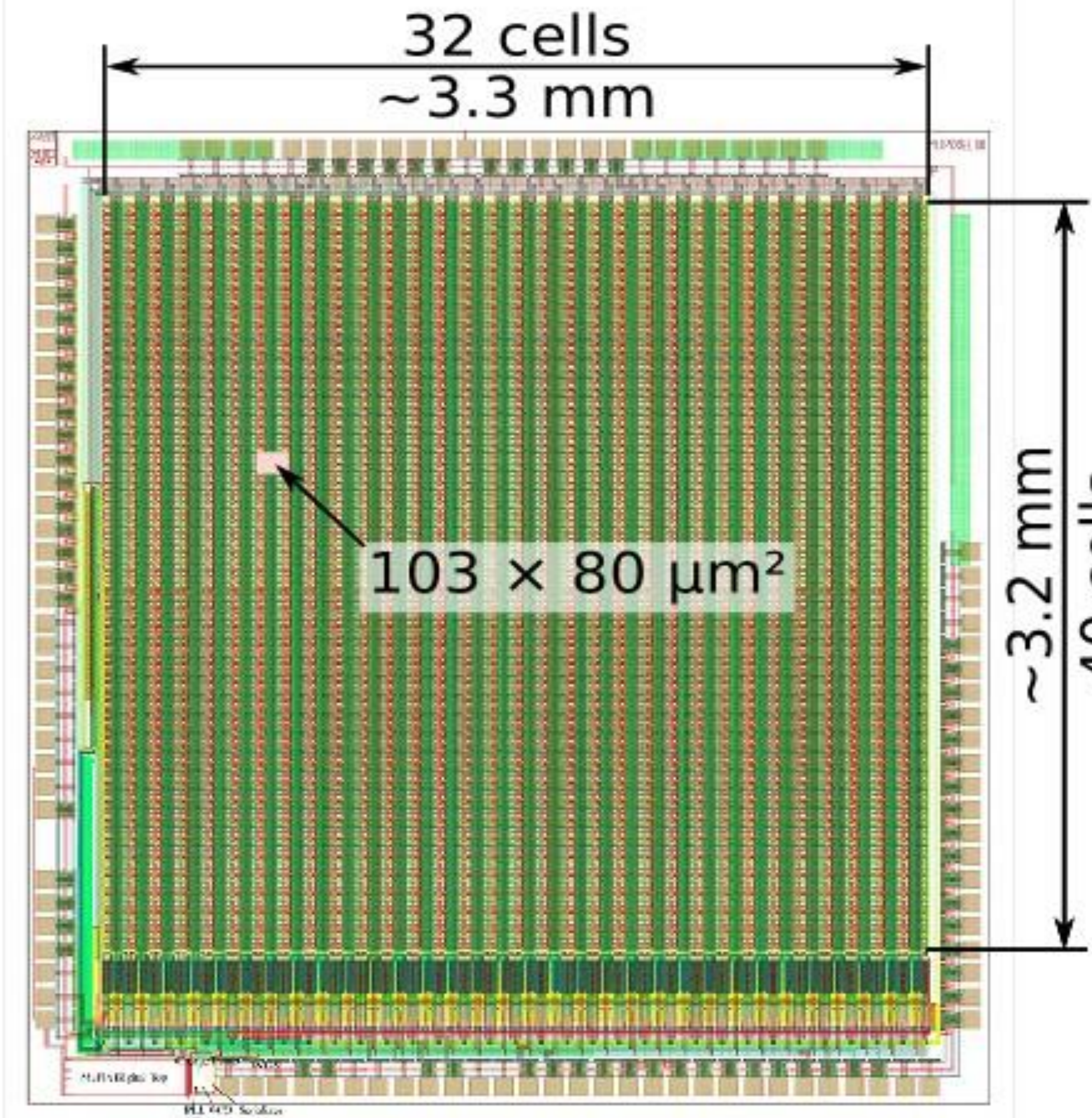
Institutes: Heidelberg, Karlsruhe, Mainz



Austria Microsystems (AMS)

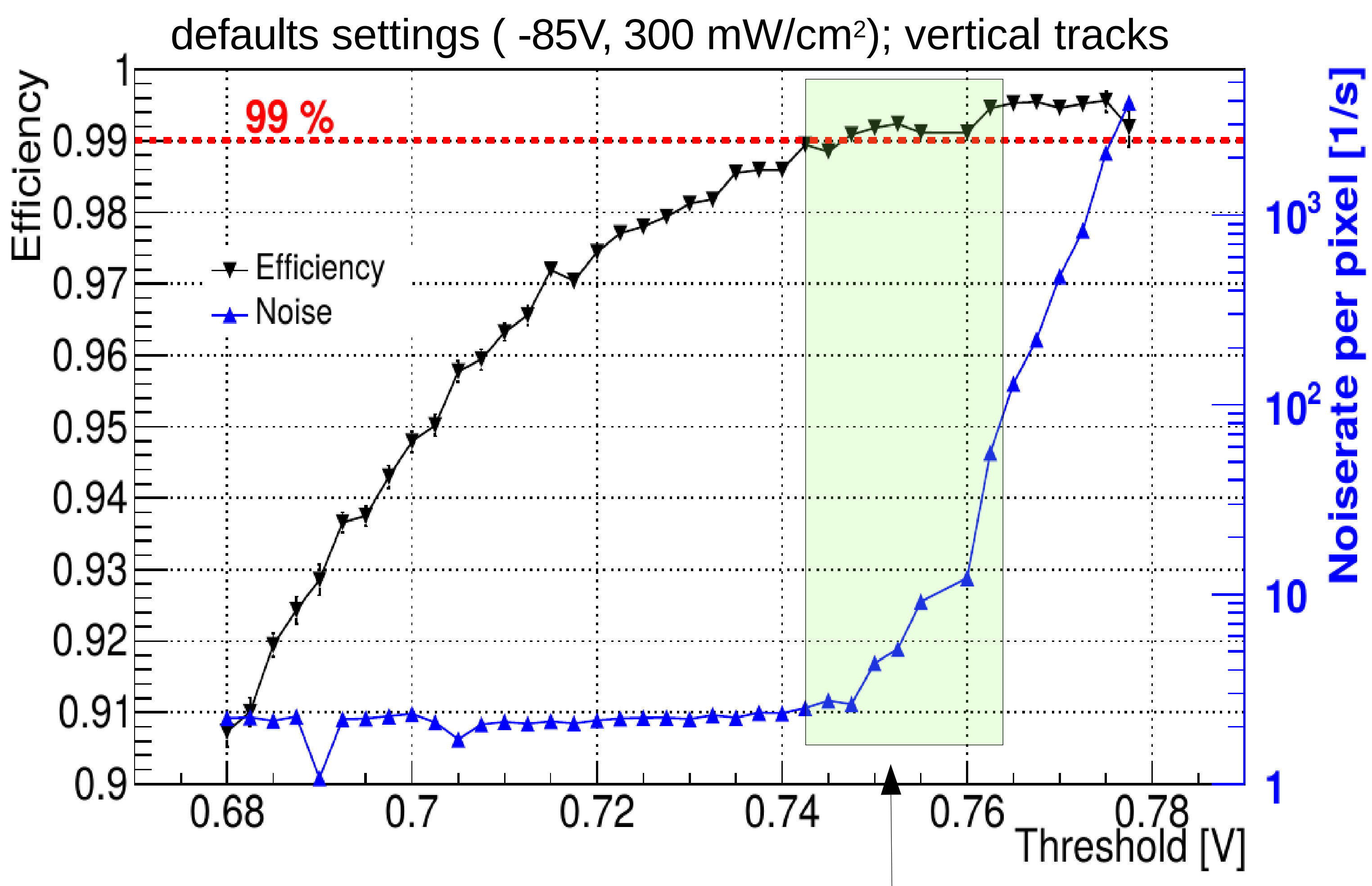
HV-CMOS 180 nm

20 Ωcm p-substrate



MuPix7 Efficiency and Noise

Data obtained from PSI beamtest (PiM1) using MuPix telescope



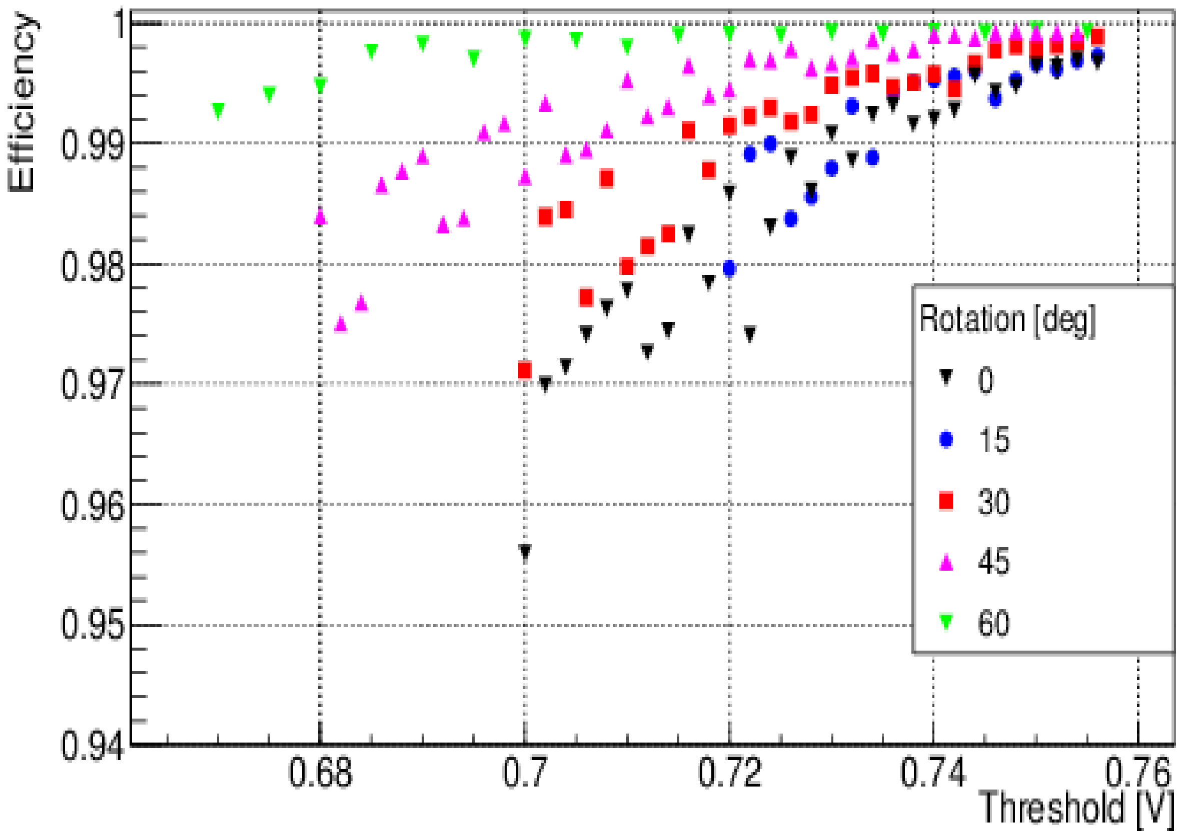
Mu3e noise limit $<10^{-6}$

operation region

Efficiency with Rotated Sensors

Increase deposited ionisation charge by using tilted sensor

default settings; -85V; ±48ns search window

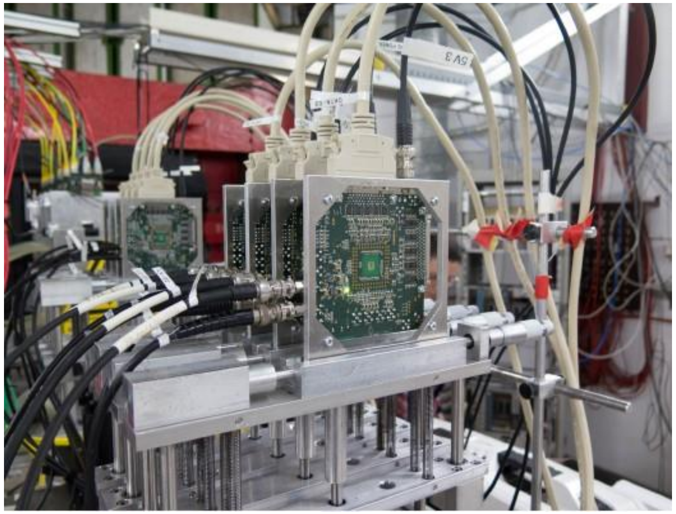


with factor 2 more charge (rot=60°) → ~100% efficiency

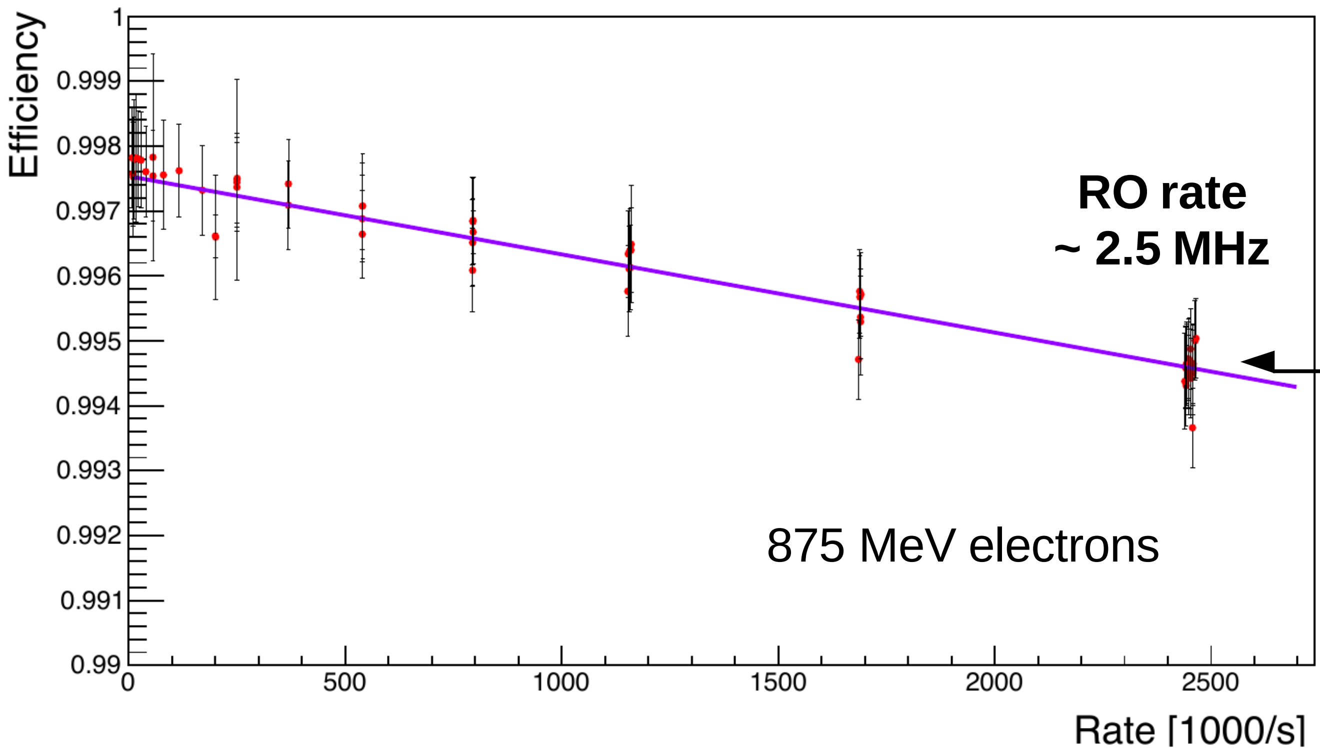
MuPix Telescopes + Rate Tests

Mu3e readout architecture (DMA transfer) implemented in beam telescopes

- one telescope with 8 stations
- two telescopes with 4 stations
- successfully used at CERN, DESY, MAMI, PSI



Rate test at MAMI:



MAMI rate test

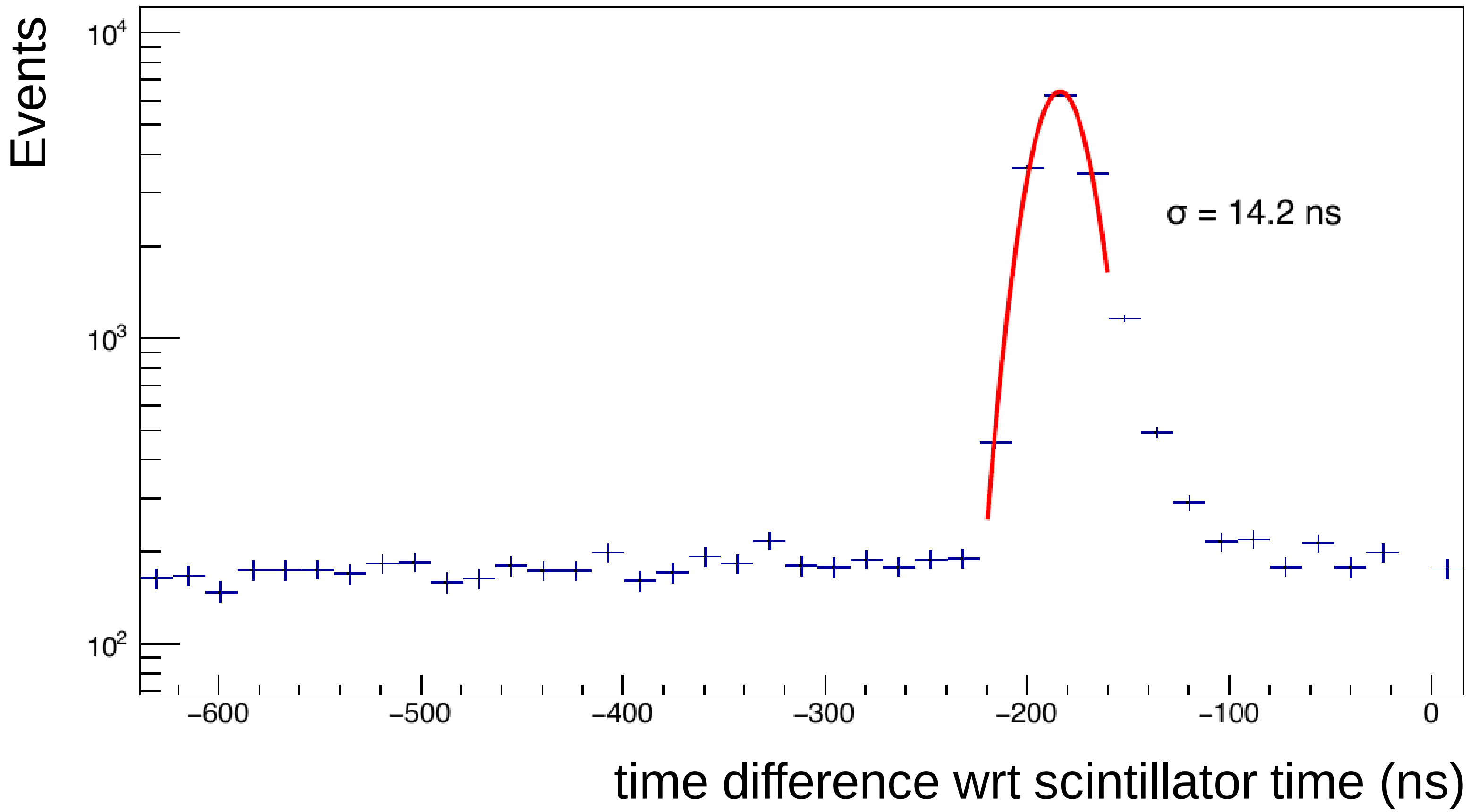
- **875 MeV e⁻**
- maximum rate rate of **2.5 MHz / 5x5 pixels**
- corresponds to **780 Mhits/cm²/s**

→ very small rate dependence of efficiency!

MuPix7 Time Resolution

MuPix telescope with scintillator as time reference:

default settings; -85V; 300 mW/cm²

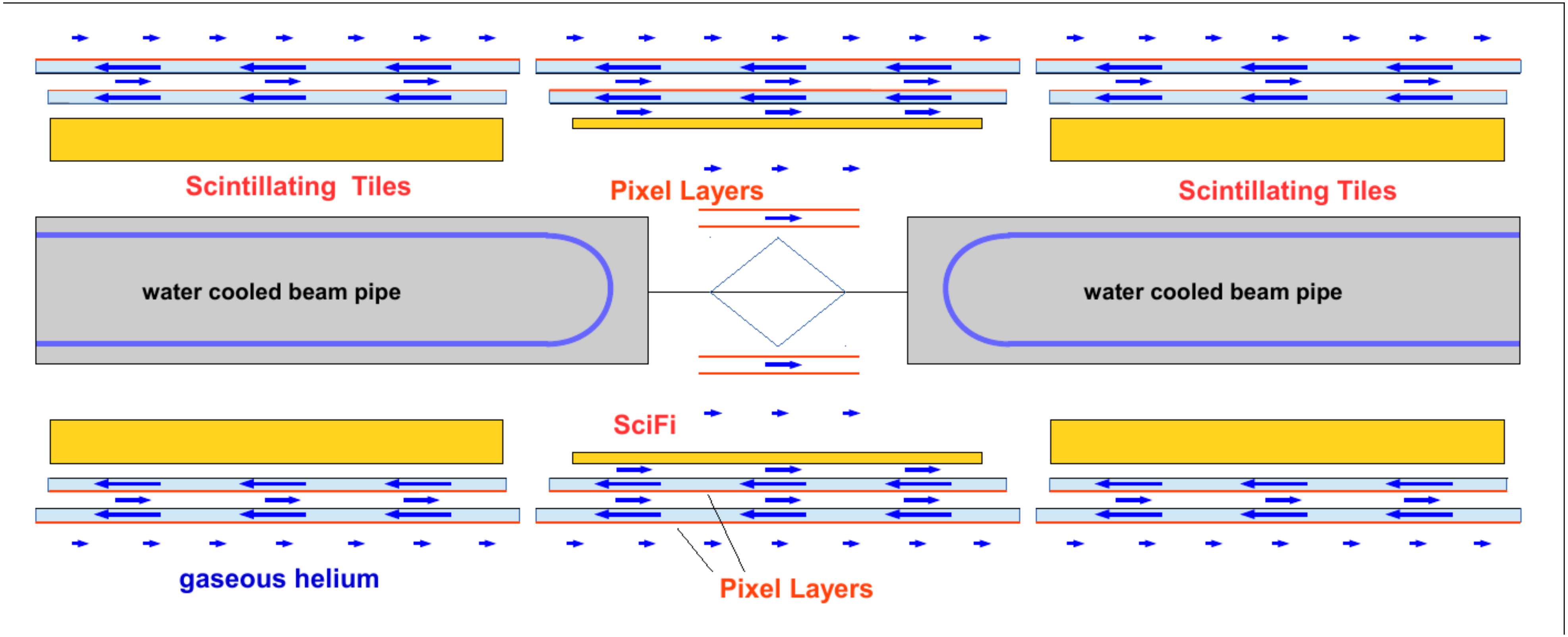


Mu3e requirement sigma (t) < 20 ns fulfilled

Mu3e Cooling System

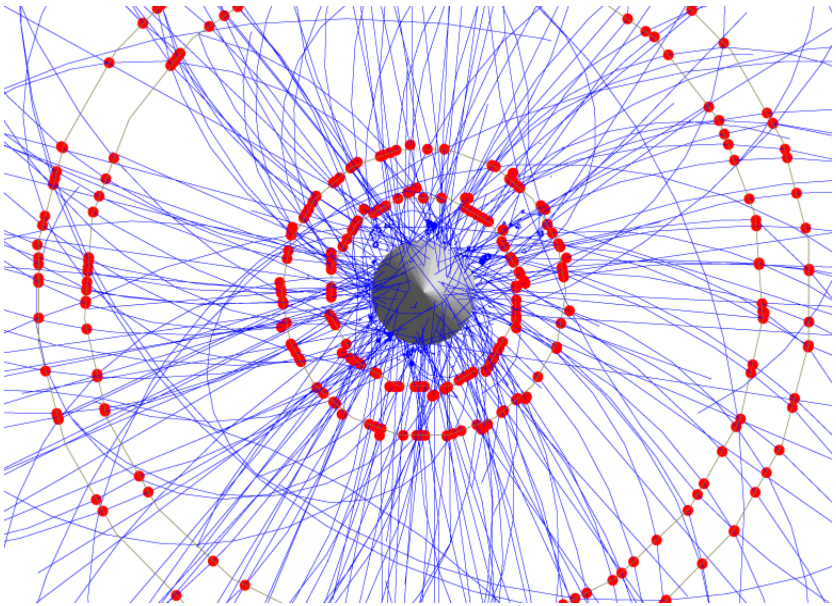
Total Power Consumption: ~10 KW

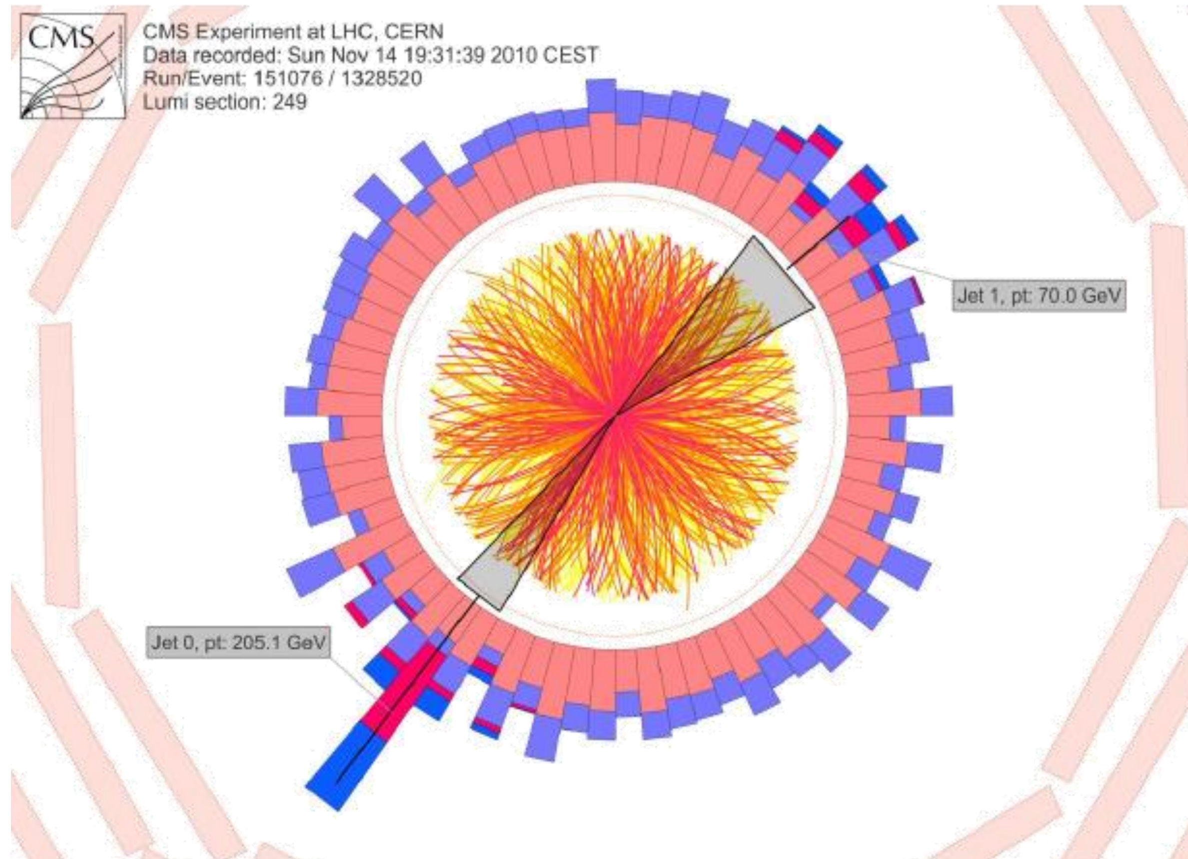
- **Water cooling** system around beam pipe: DC-DC converters, electronics (~5KW)
- Novel **Helium gas cooling** system: pixel tracker modules (~5KW)
  - He flow in V-folds (channels) up to 20 m/s
  - He flow in gaps between layers up to 5 m/s
  - global He-flow



Pileup

Mu3e reconstructed tracks



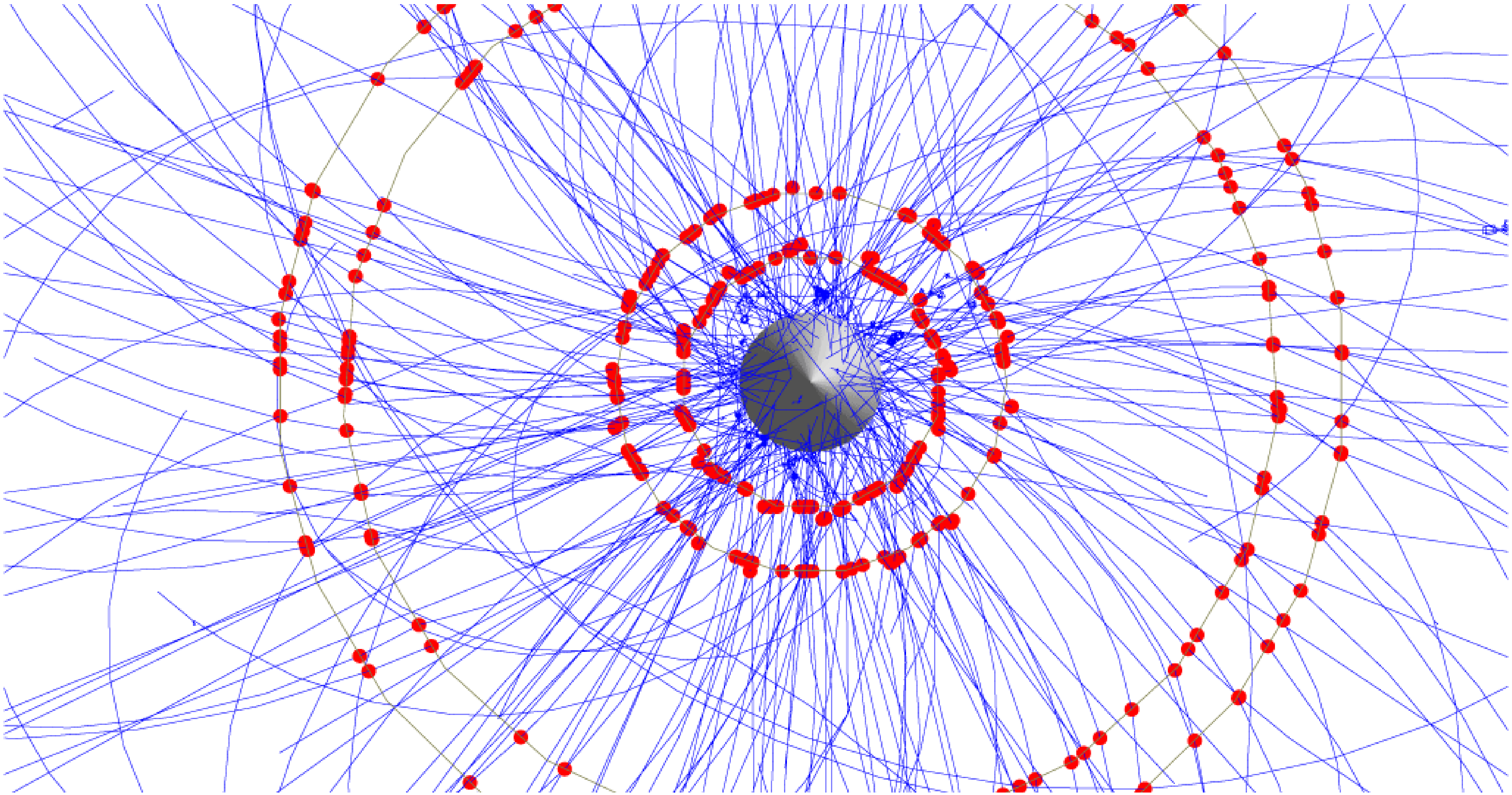


≈16 cm
Readout in frames of 50 ns
E ~ 10-50 MeV

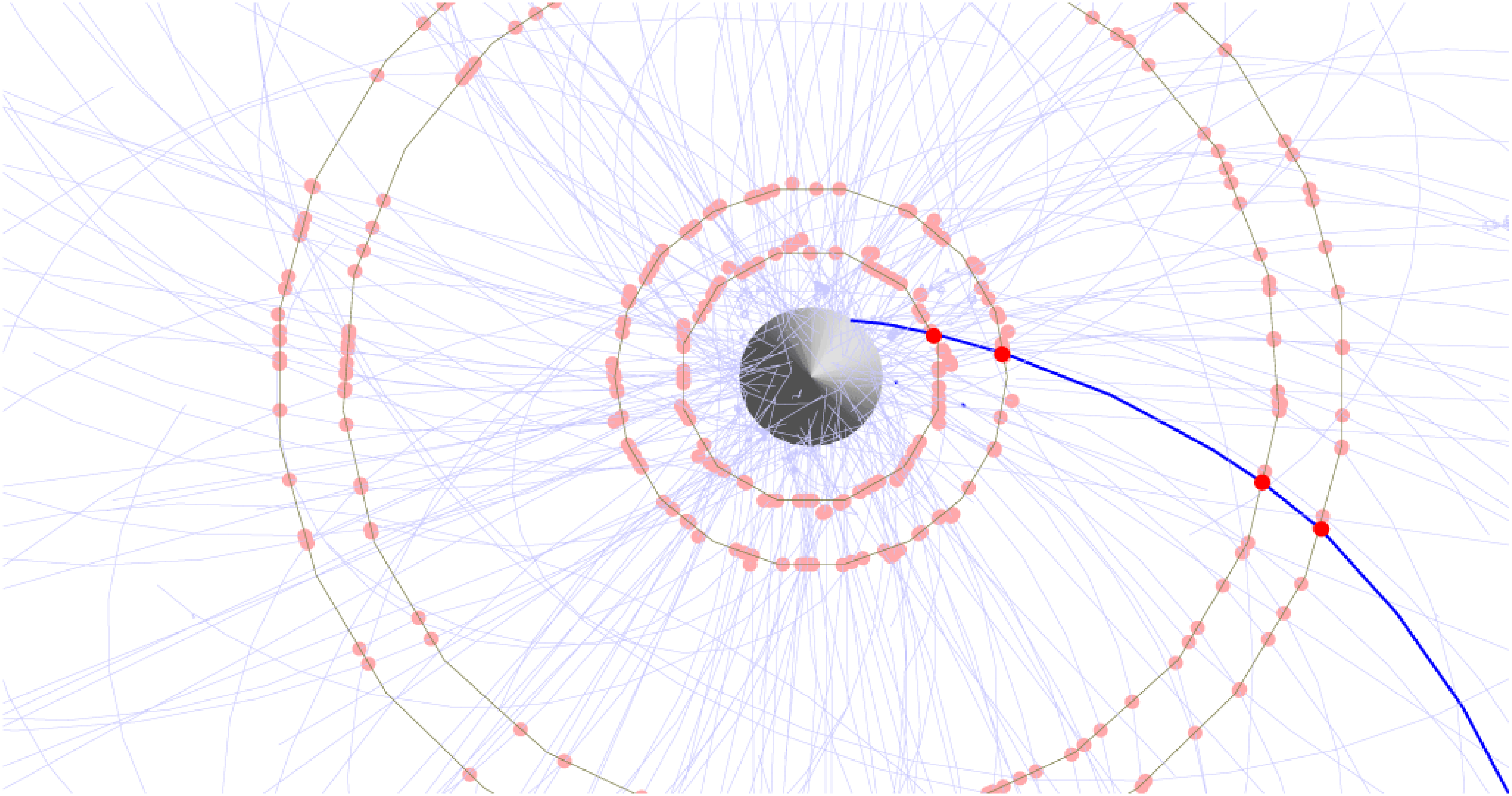
≈2.5 m
Collision every 25 ns
E ~ 200 GeV

Tracks in Pixel Detector

10^9 muon stops per second, 50ns readout frame

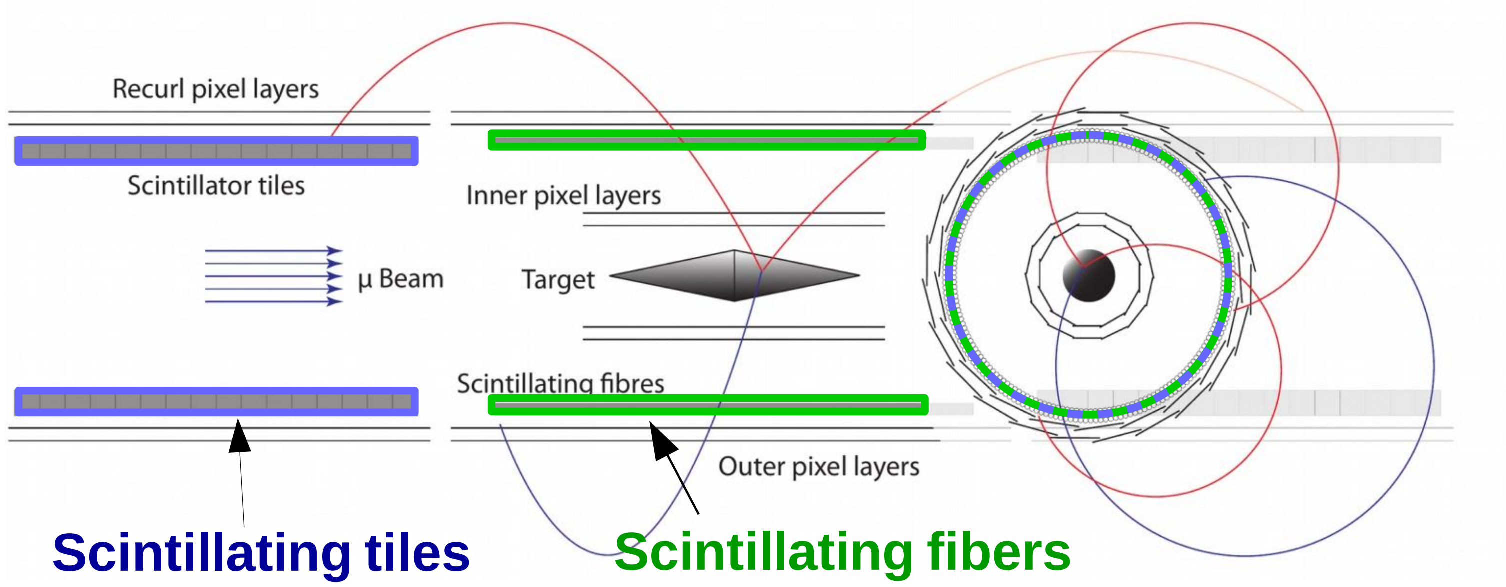


Tracks in Pixel Detector

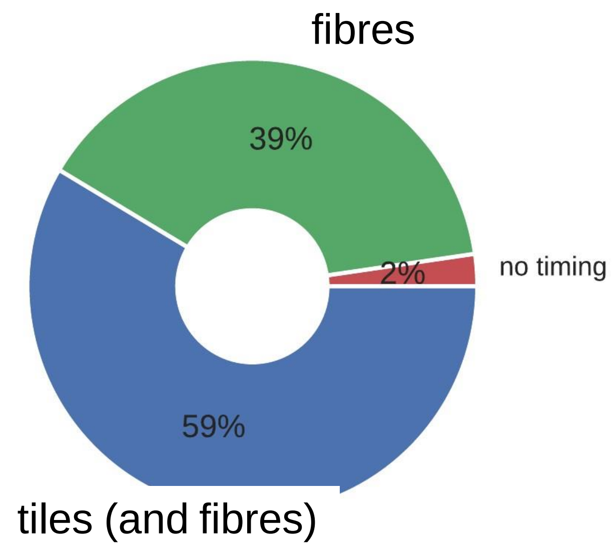


➜ **additional timing detectors needed < 1ns**

Mu3e Time Timing Detector

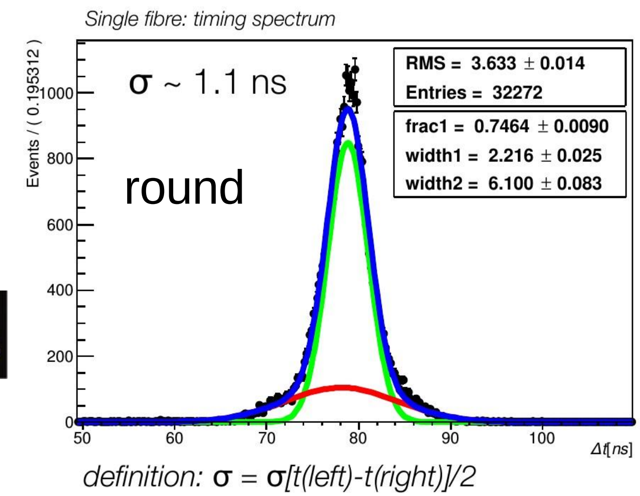


→ **background suppression factor of 100!**

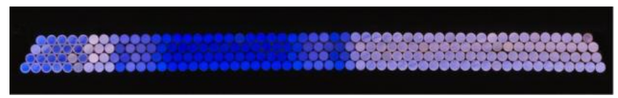


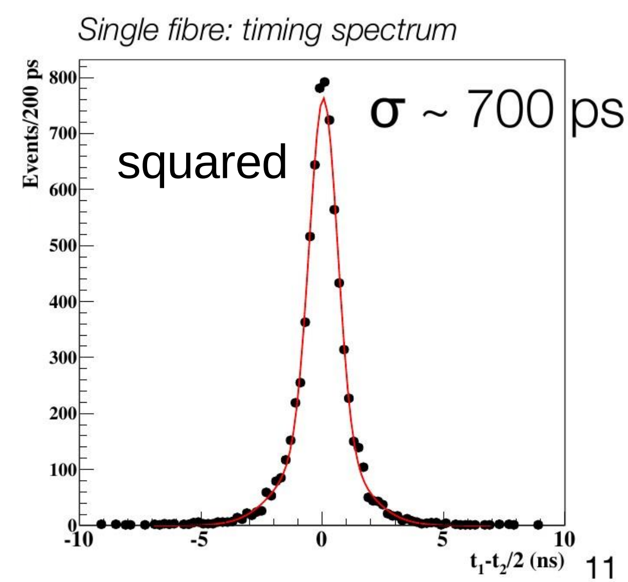
Scintillating Fibres

Single fibre time resolutions

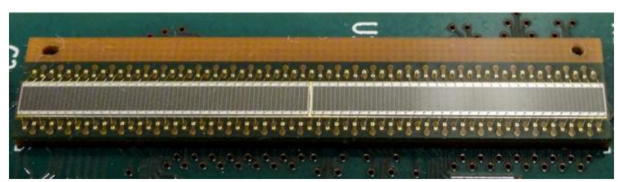


- Two types of scintillating 250µm fibres studied:
  - round (Kuraray SCSF-81M)
  - squared (Saint Gobain BC 418) (coated with Al)

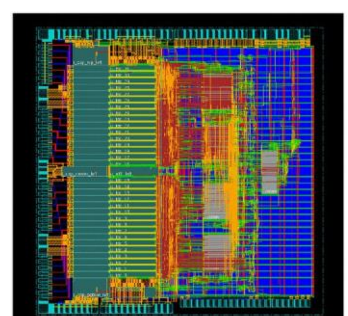




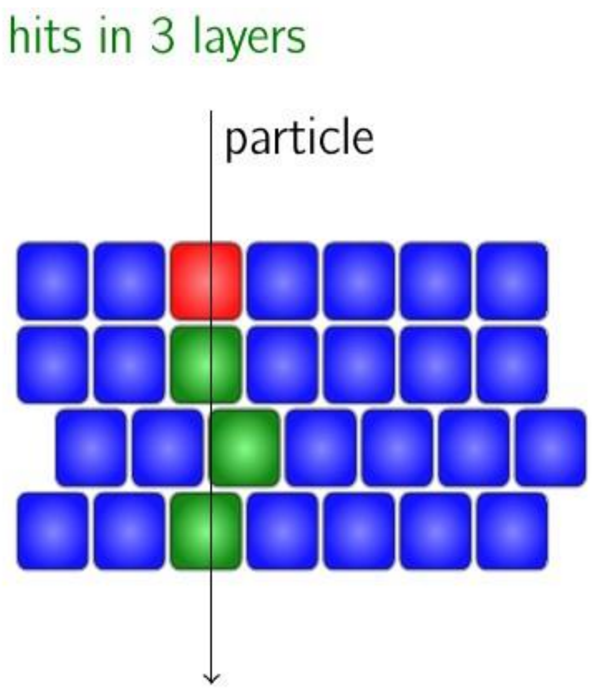
- SiPM: Hamatsu S12571-050P (LHCb)
  - SiPM array
  - 1 x 1 mm^2, 50 µm pitch

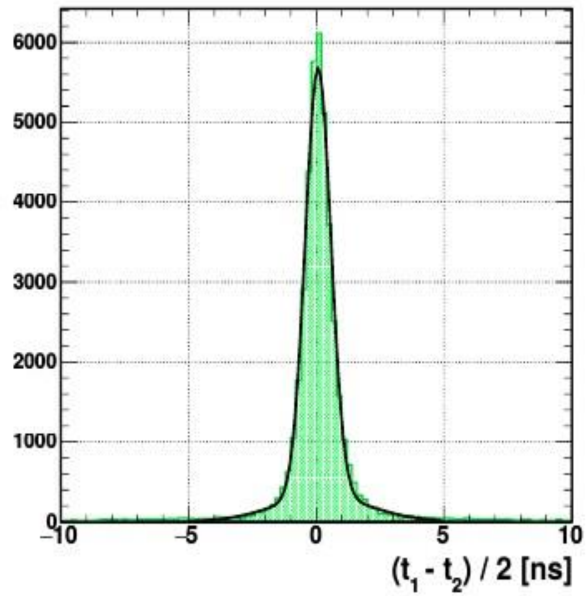


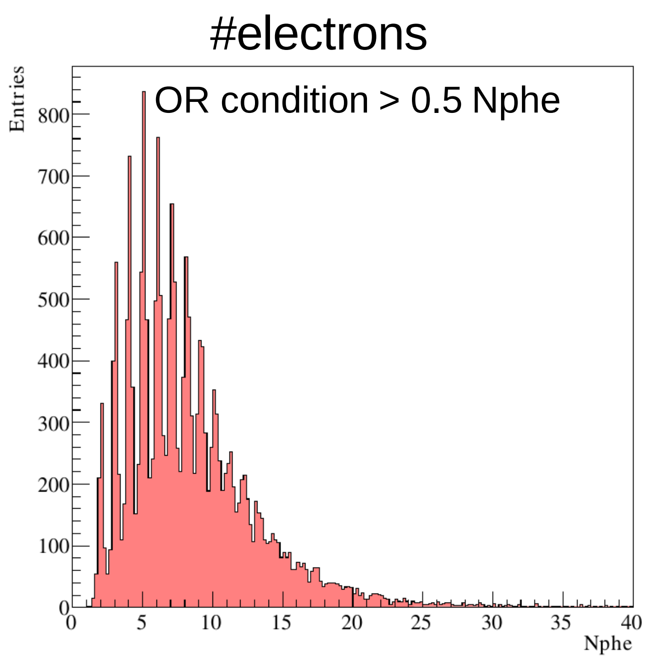
- MuTRig readout chip (KIP Heidelberg)
  - time resolution 50 ps
  - 32 channels
  - bandwidth 1.25 Gbit/s
  - chip received in January 2017

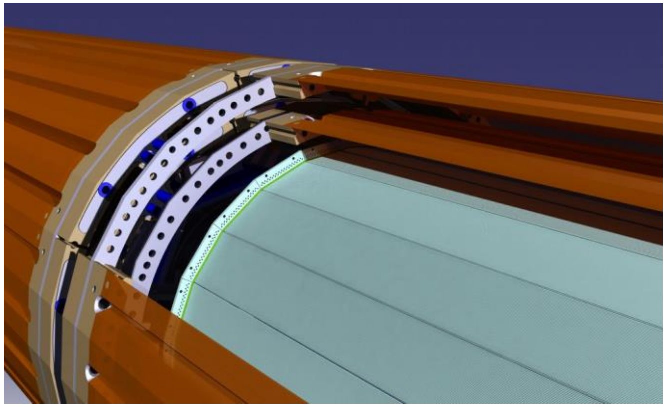


Scintillating Fibre Test Beams



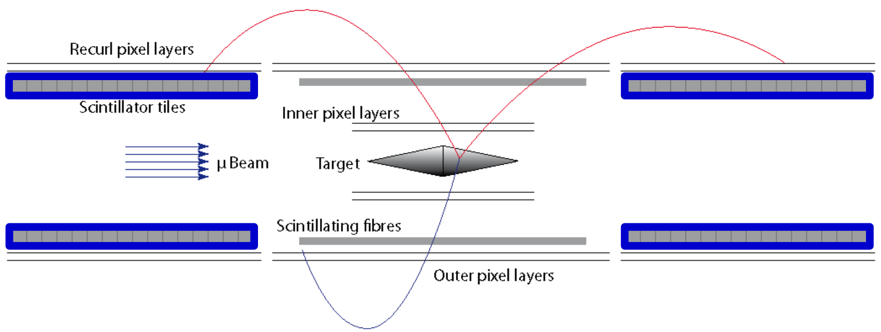


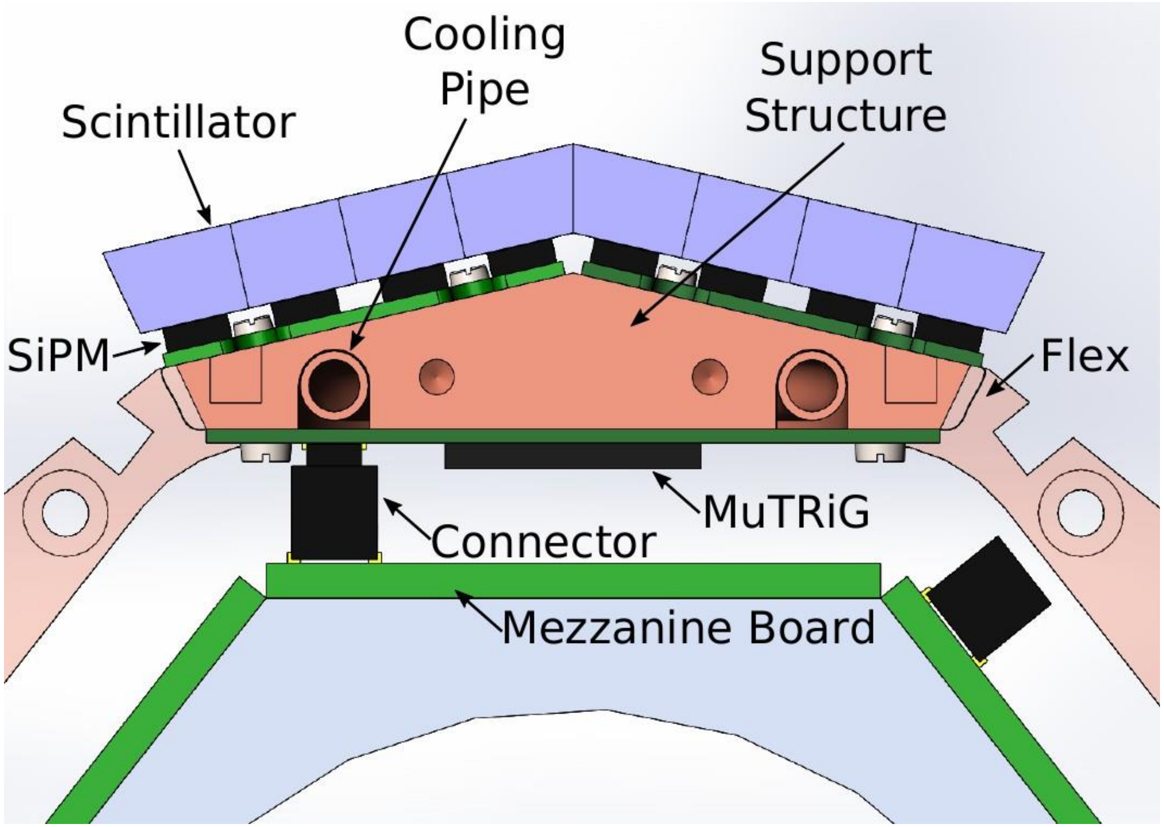


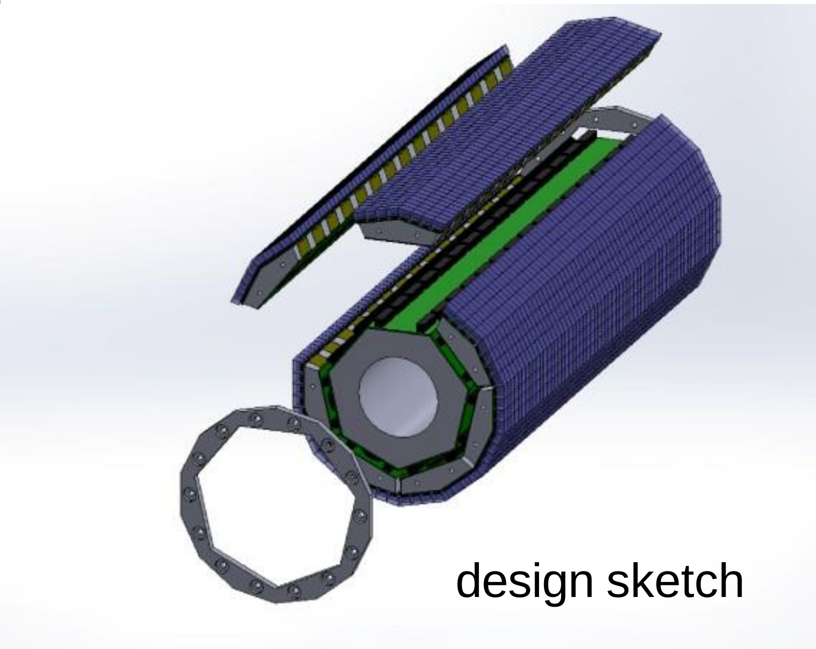


Requirements and expectations fulfilled in test beams!

Scintillating Tile Detector



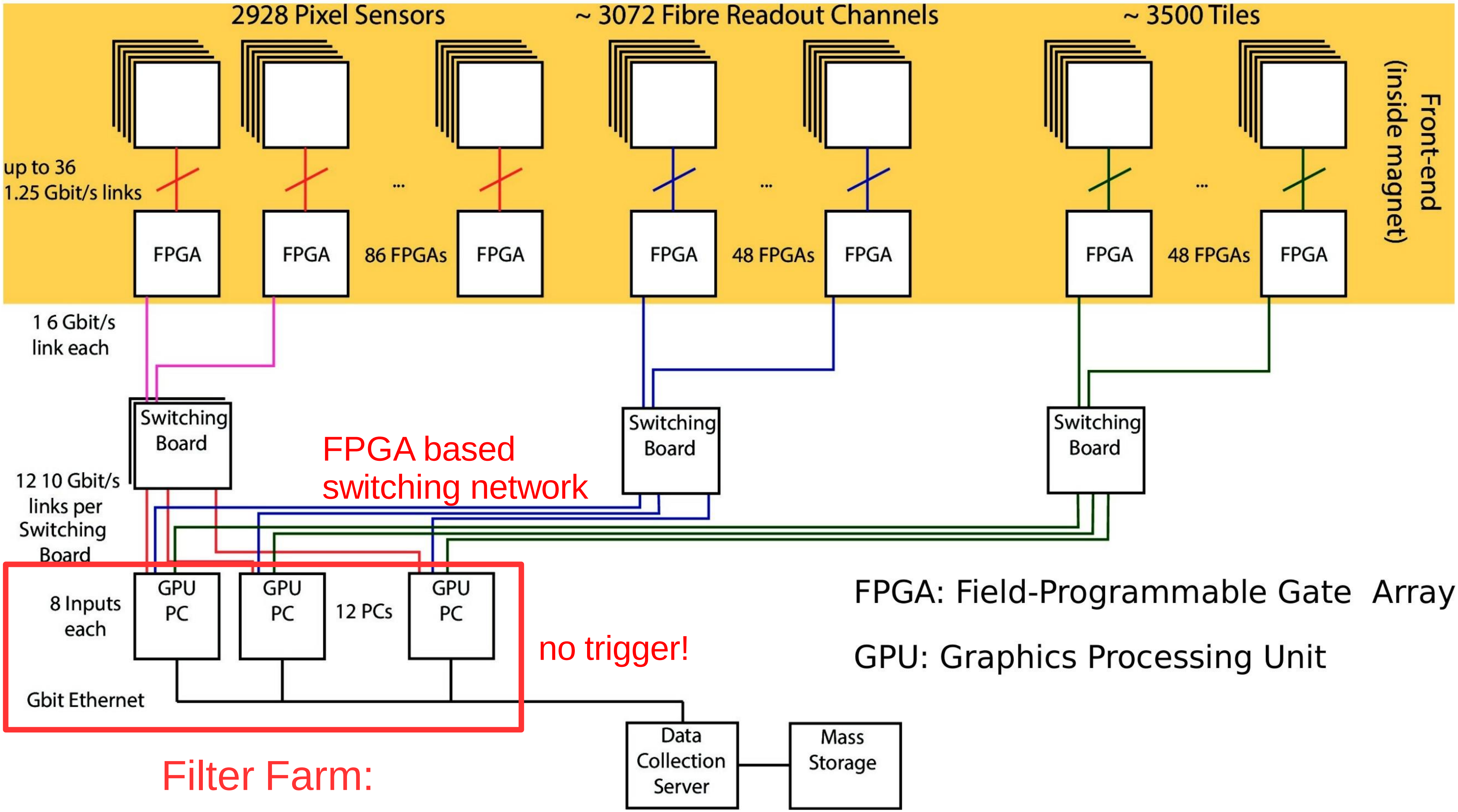




design sketch

- 56 x 56 tiles (6.5 x 6.5 x 5.0 mm^3)
- 3 x 3 mm^2 single SiPM
- timing resolution of ≤ 100 ps
- mixed mode ASIC (MuTRig)

Mu3e Readout Concept



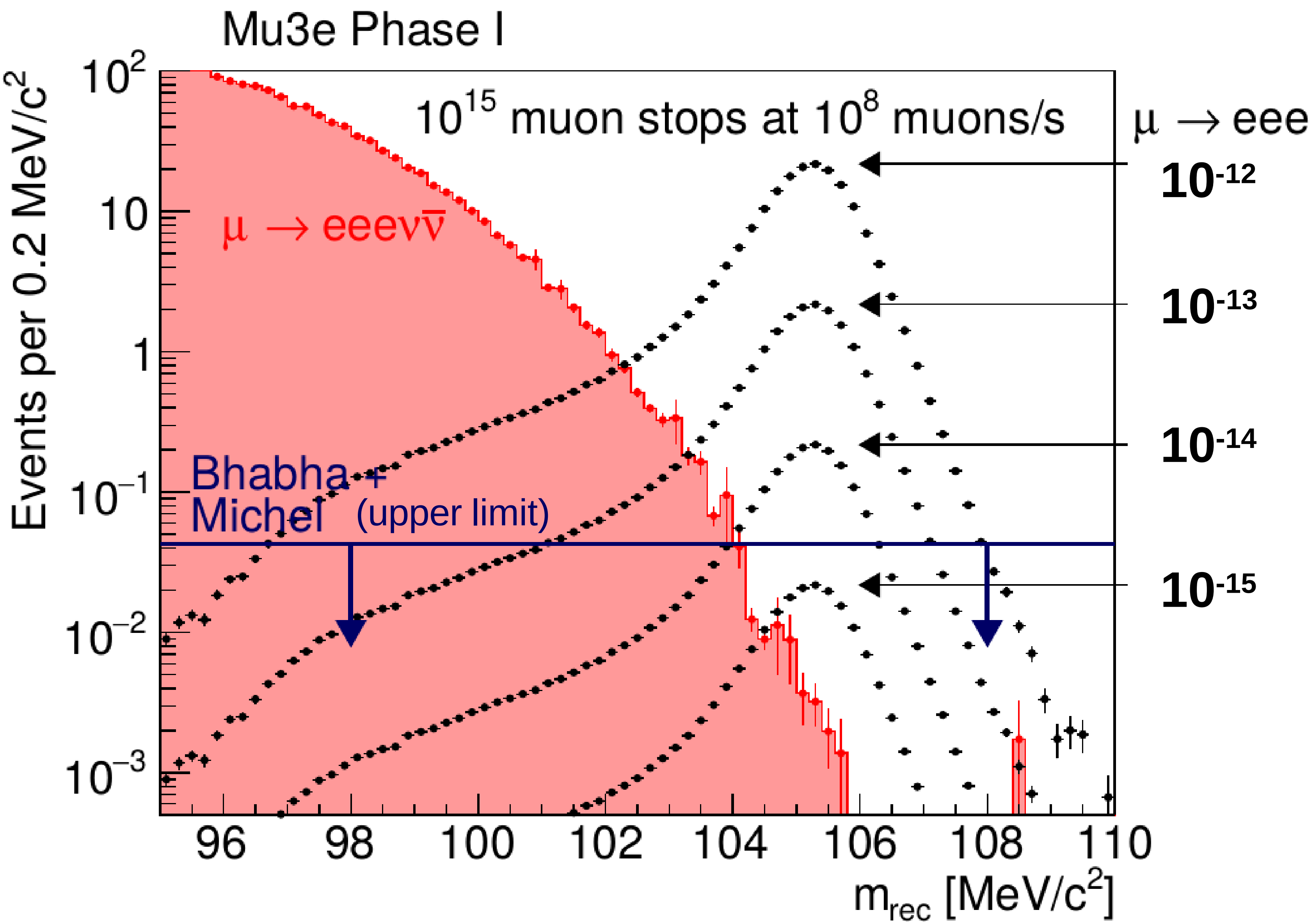
FPGA: Field-Programmable Gate Array

GPU: Graphics Processing Unit

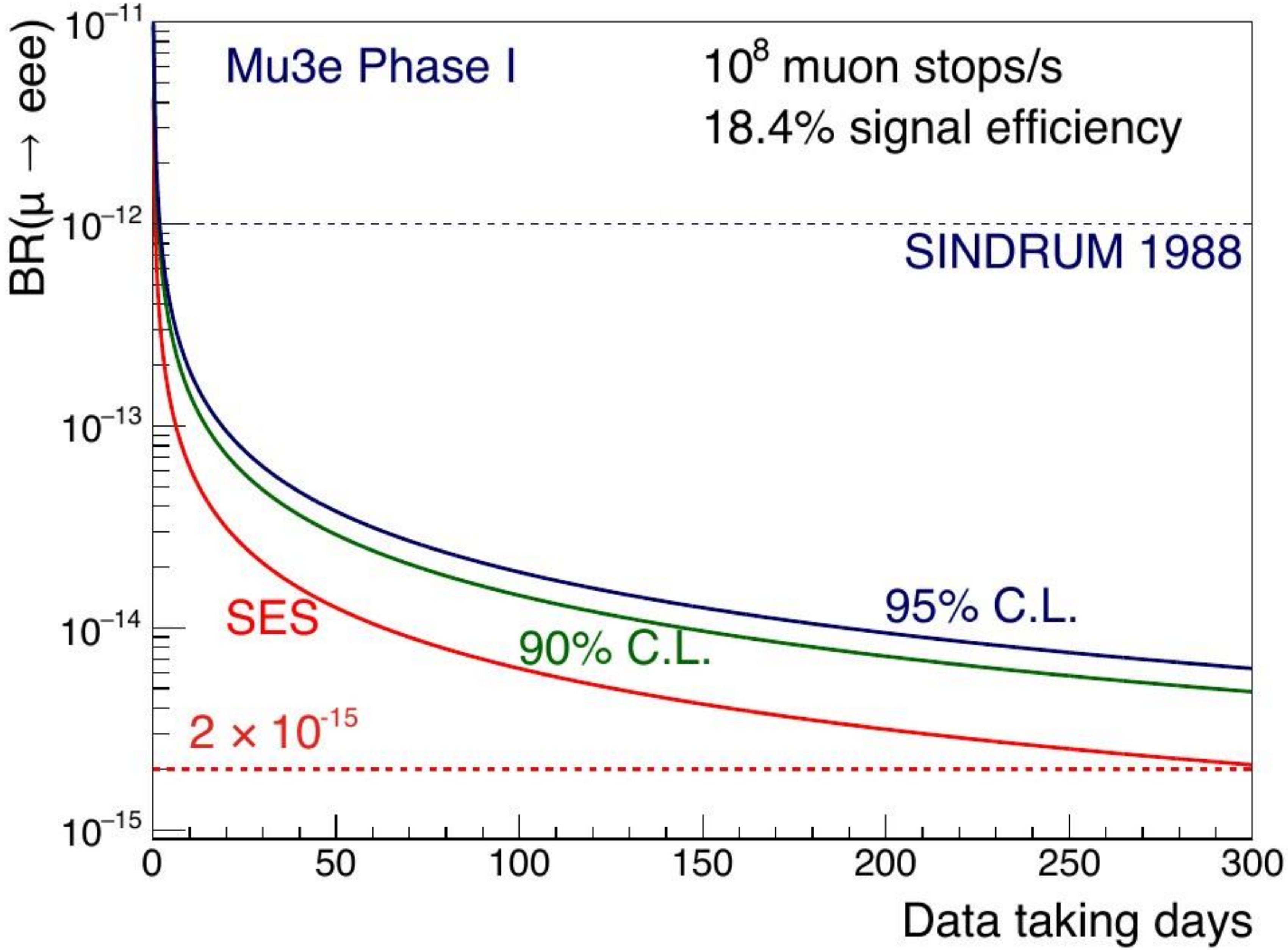
Filter Farm:

Online track reconstruction using fast algorithm → arXiv:1606.04990

Mu3e Mass Plot



Sensitivity versus Time



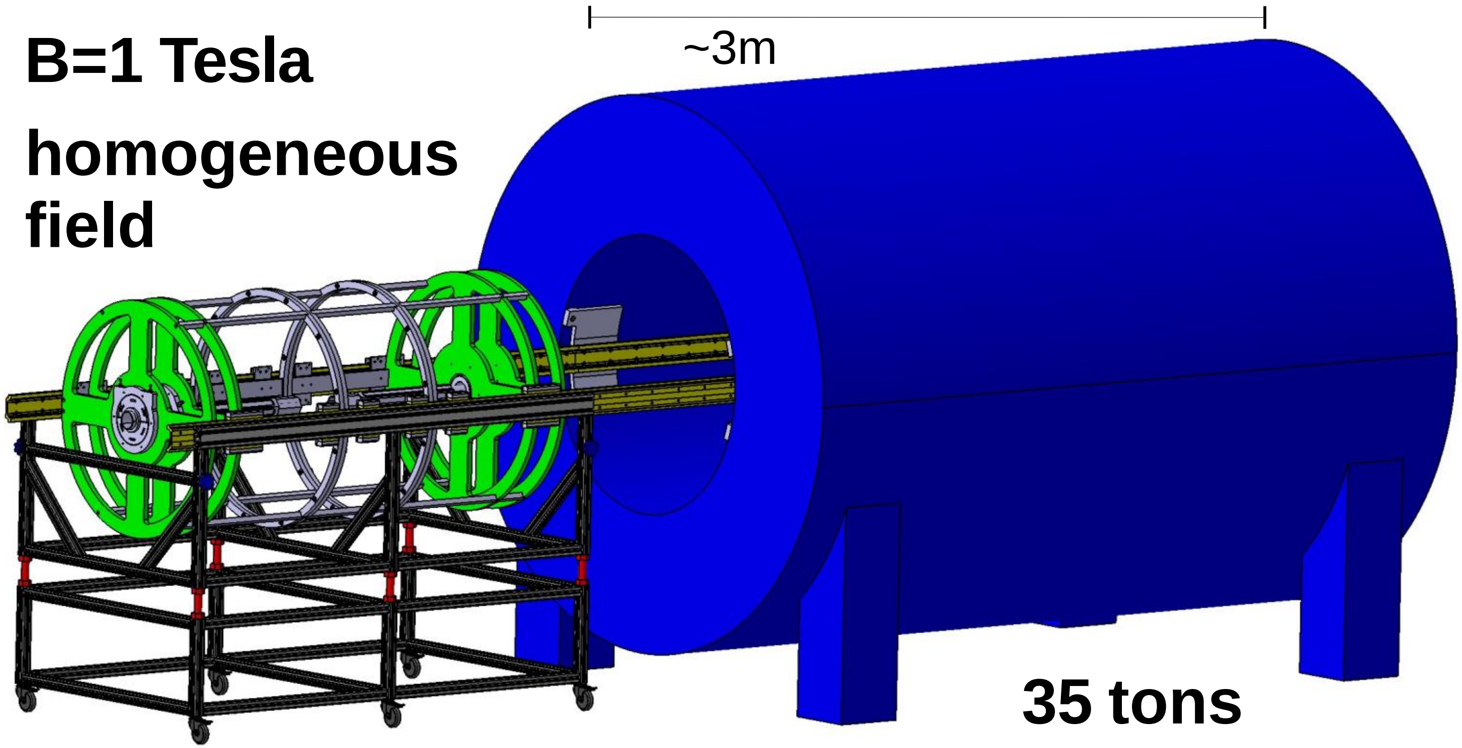
Mu3e Collaboration

- University of Geneva (CH)
- University Heidelberg (D)
- Karlsruhe Institute of Technology (D)
- University Mainz (D)
- Paul Scherrer Institute (CH)
- ETH Zurich (CH)
- University Zurich (CH)

Several UK institutes interested to join

- Bristol
- Liverpool
- Oxford
- UC London

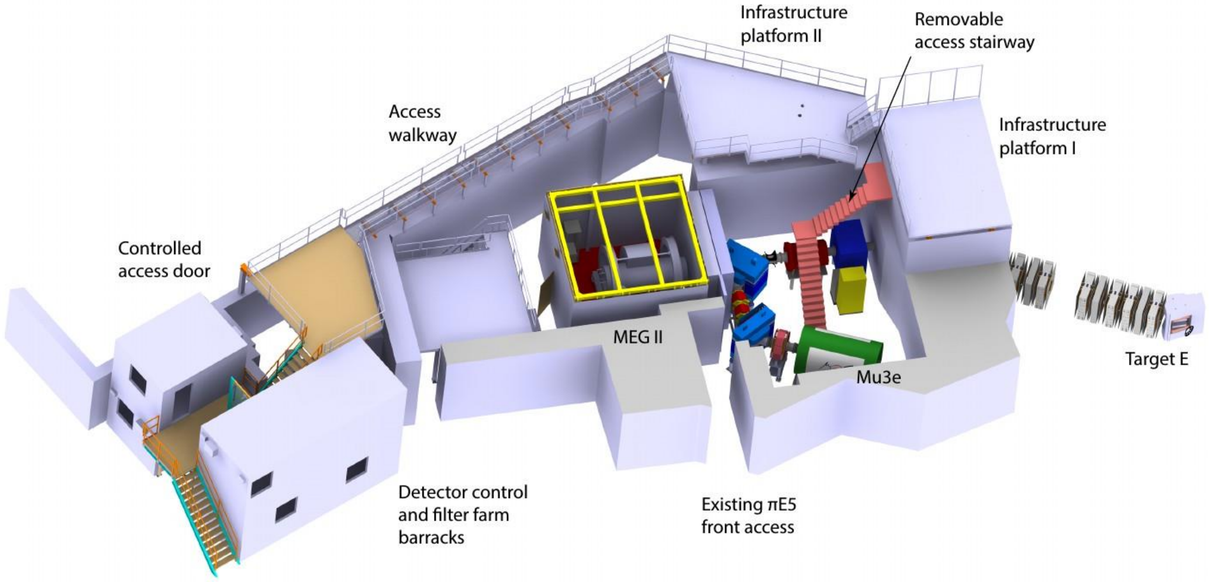
Mu3e Magnet



- First tendering process in 2015 → Danfysik (Denmark)
- Contract canceled in January 2017
- New tendering process is about to start
- Earliest possible delivery of magnet end of 2019

Mu3e Experimental Status

- **Detector construction will start end of 2017**
- **Commissioning of the two inner HV-MAPS pixel layers in 2018**
- **Construction of outer pixel layers in 2019**
- **Timing detectors ready in 2019**
- **First physics results in 2020/21**



THANK YOU

for patience !!!

BACKUP TRANSPARECIES

Laboratory/ Beam line	Energy/ Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
$\pi E5$	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10}(\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8(\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11}(\mu^-)$ (2019/20)
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12}(\mu^-)$ ($>$ 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10}(\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12}(\mu^-)$ ($>$ 2022)
TRIUMF (CA)	(500 MeV, 75 kW, 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, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8(\mu^+)$ (2012) means $> 10^{11}$ per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

BR($\mu Au \rightarrow eAu$) $< 7 * 10^{-13}$at present (SINDRUM II)
future
J-PARK exp. DeeMe $BR \sim 10^{-14}$
J-PARK exp. COMET, PRISM; FERMILB exp. Mu2e $BR \sim 10^{-16}$

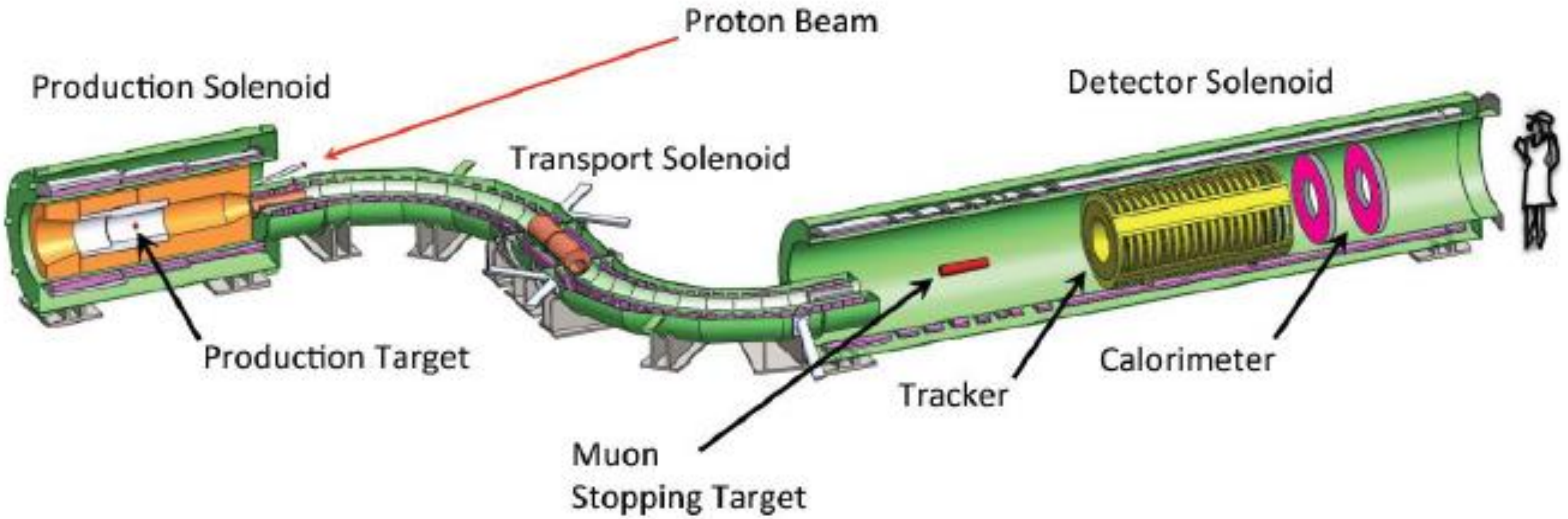
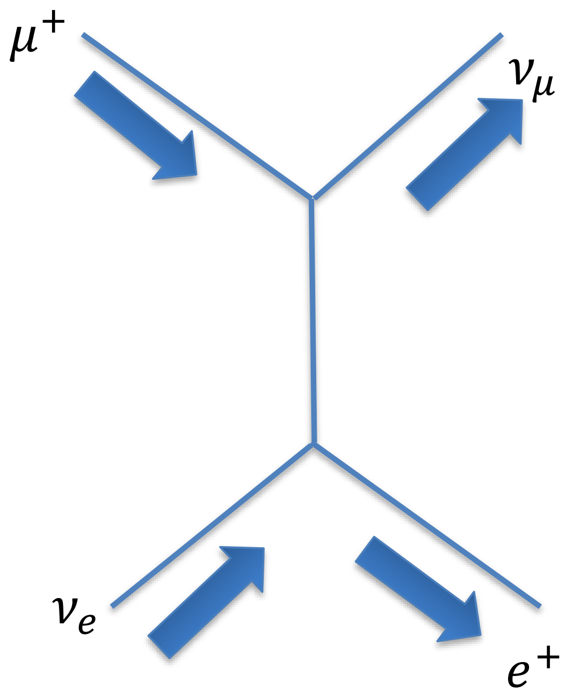
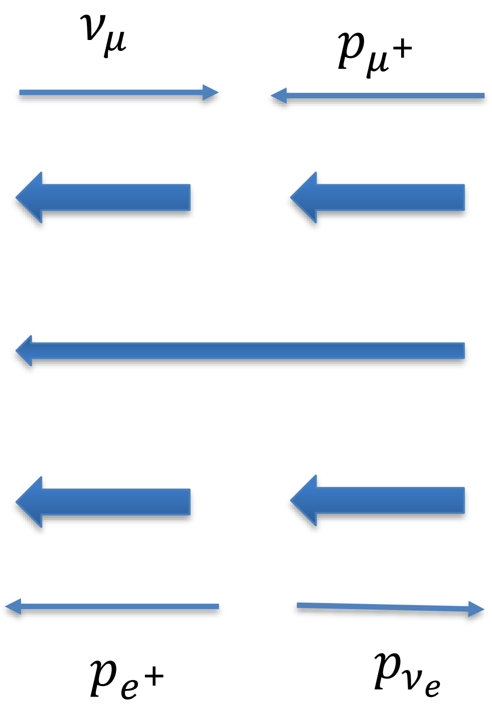


Figure 16: The Mu2e Experimental concept. The pulsed proton beam enters the production solenoid and passes through a tungsten rod. Pions produced there, decay to muons which are directed via magnetic gradients into the S–shaped transport solenoid, arriving in the detector solenoid region. The momentum-selected negative muons stop in an Al target. The signature decay 105 MeV electron is measured with a tracking chamber followed by an electromagnetic calorimeter. Figure courtesy Mu2e collaboration.


μ^+
ν_μ
ν_e
e^+


ν_μ
p_{μ^+}
p_{e^+}
p_{ν_e}

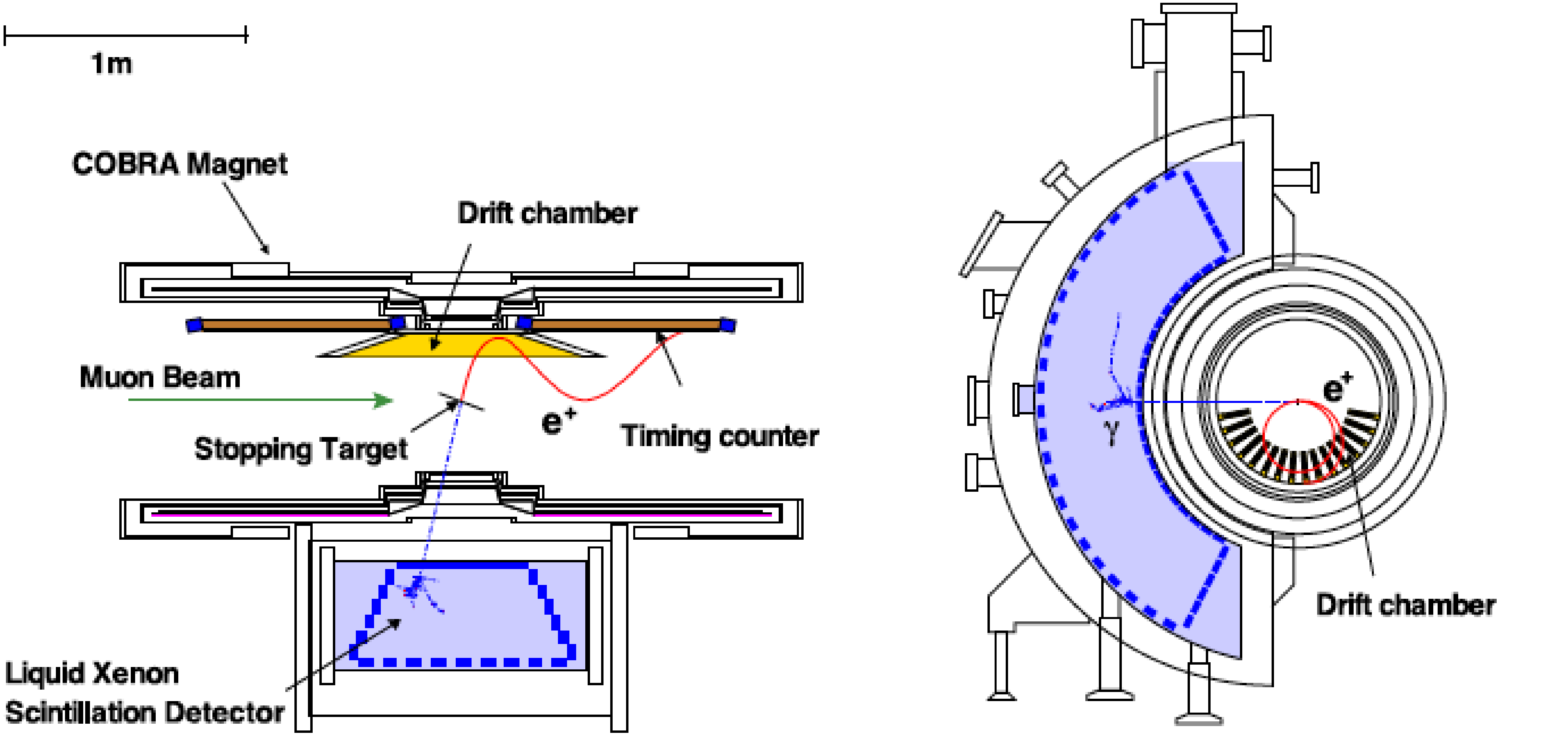
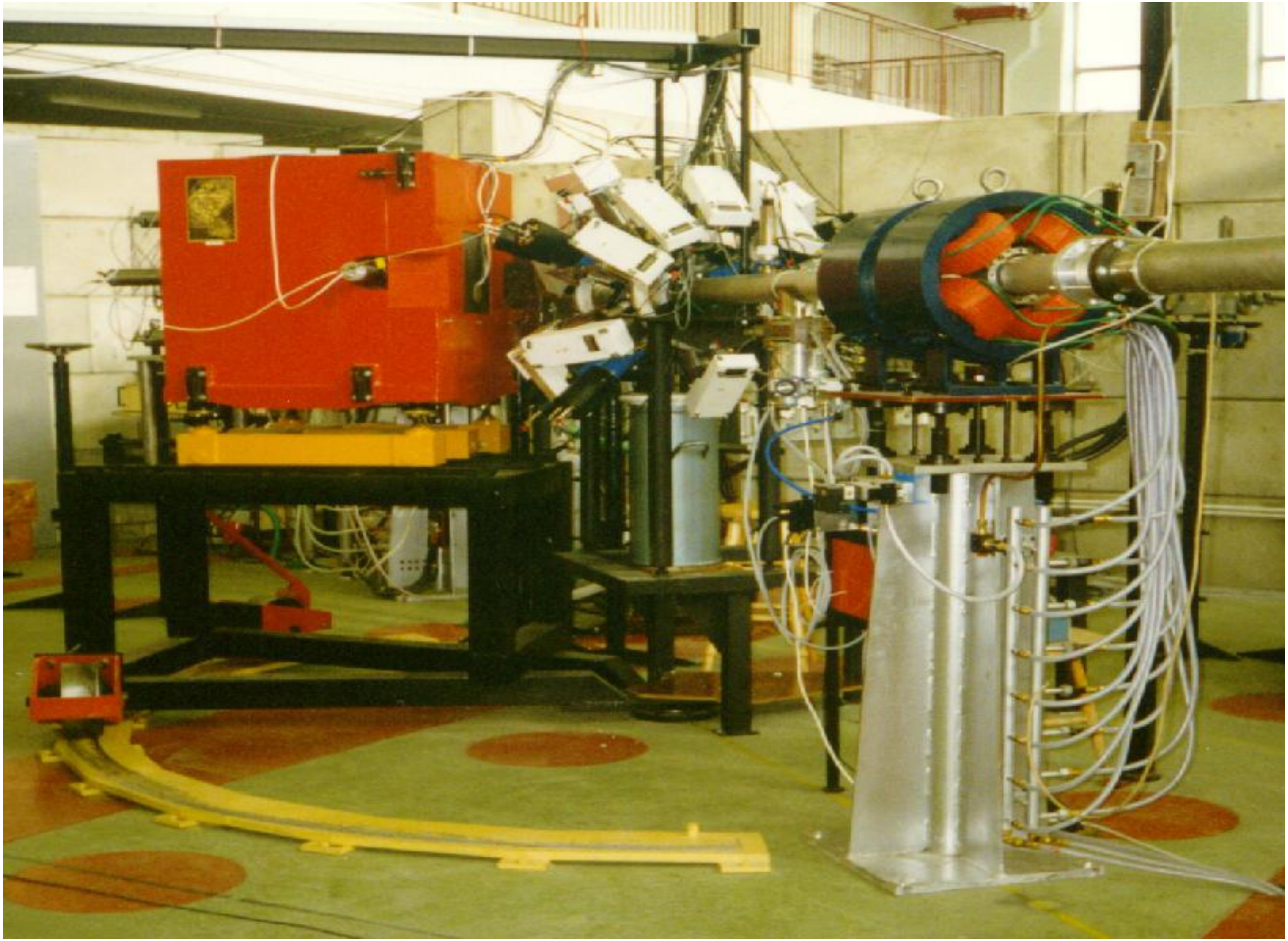


Figure 13: The side and front schematic of the MEG detector with a hypothetical $\mu \to e\gamma$ event superimposed. Figure courtesy MEG collaboration.

Układ JANOSIK w cyklotronie warszawskim (SLCJ)



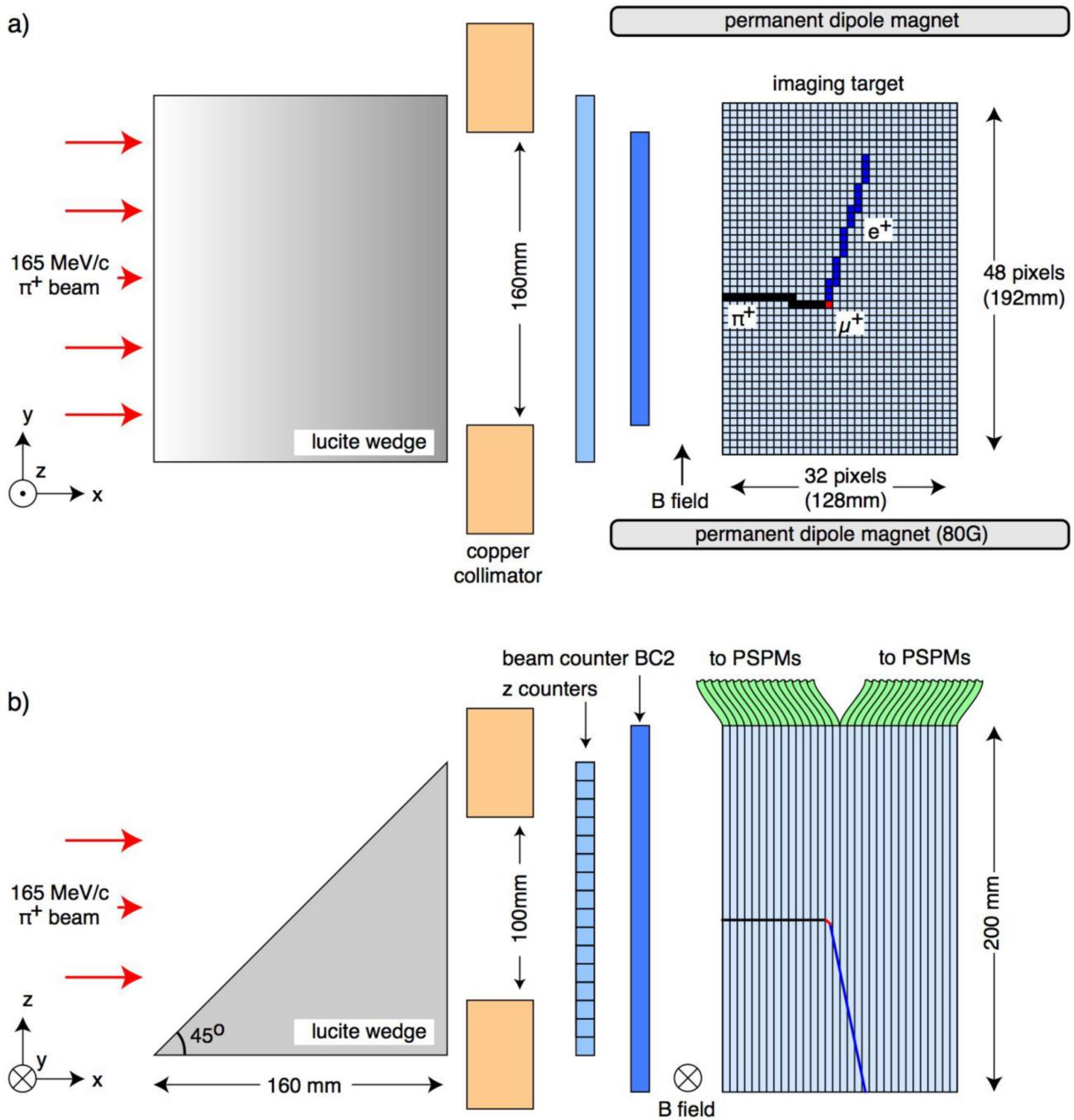


Figure 1: Schematic drawing of the FAST detector: a) top view, and b) side view. A representative event shows the π^+ beam particle stopping in the target followed by a $\pi \rightarrow \mu$ decay and finally a $\mu \rightarrow$ e decay. This sequence is imaged by the target in the xy projection and the decay times recorded.

Fiber Active Scintillating Target - FAST

decays in parallel. The imaging target (Fig. 1) essentially comprises a large number of replicated mini-detectors placed side-by-side, each one capable of making an independent and simultaneous measurement of a μ^+ decay. With regards systematic uncertainties, the detector is designed to suppress several effects that limited previous experiments. Firstly, pile-up effects are reduced by a fast, imaging detector. Secondly, possible gain shifts and additional event losses at the start of the muon decay period due to the higher counting rate are avoided by operating in a DC beam (uniform counting rate). Thirdly, muon spin polarisation systematics are highly suppressed by a) using a π^+ beam (spin 0) and tagging the $\pi \to \mu$ transition, b) applying range cuts that further suppress residual beam muons, c) designing a uniform detector with large angular acceptance, and d) providing an 80 G magnetic field across the target, which causes rapid precession of the muons so that any residual spin effects can be observed and measured.

MuLan

2.1 Systematics effects

If a hit occurs in the artificial deadtime of an earlier hit it is lost. Because these losses are more frequent during the high rates at early measurement times than the low rates at late measurement times, such pile-up distorts the time spectrum.

Our procedure for correcting for pileup took advantage of the time structure of the incident beam. The pileup losses were statistically recovered by replacing the lost hits in each measurement period with measured hits at equivalent times in neighboring measurement periods. For example, to correct for leading-order pileup, if a hit is observed at time t_i in fill j (the "trigger" hit), a hit is searched for within the interval $t_i \rightarrow t_i + \mathrm{ADT}$ in fill $j+1$ (the "shadow" hit). Adding the resulting histogram of shadow hit times to the original histogram of trigger hit times thereby statistically recovers the lost hits. Similar methods were used to correct for higher-order pileup and accidental coincidences.