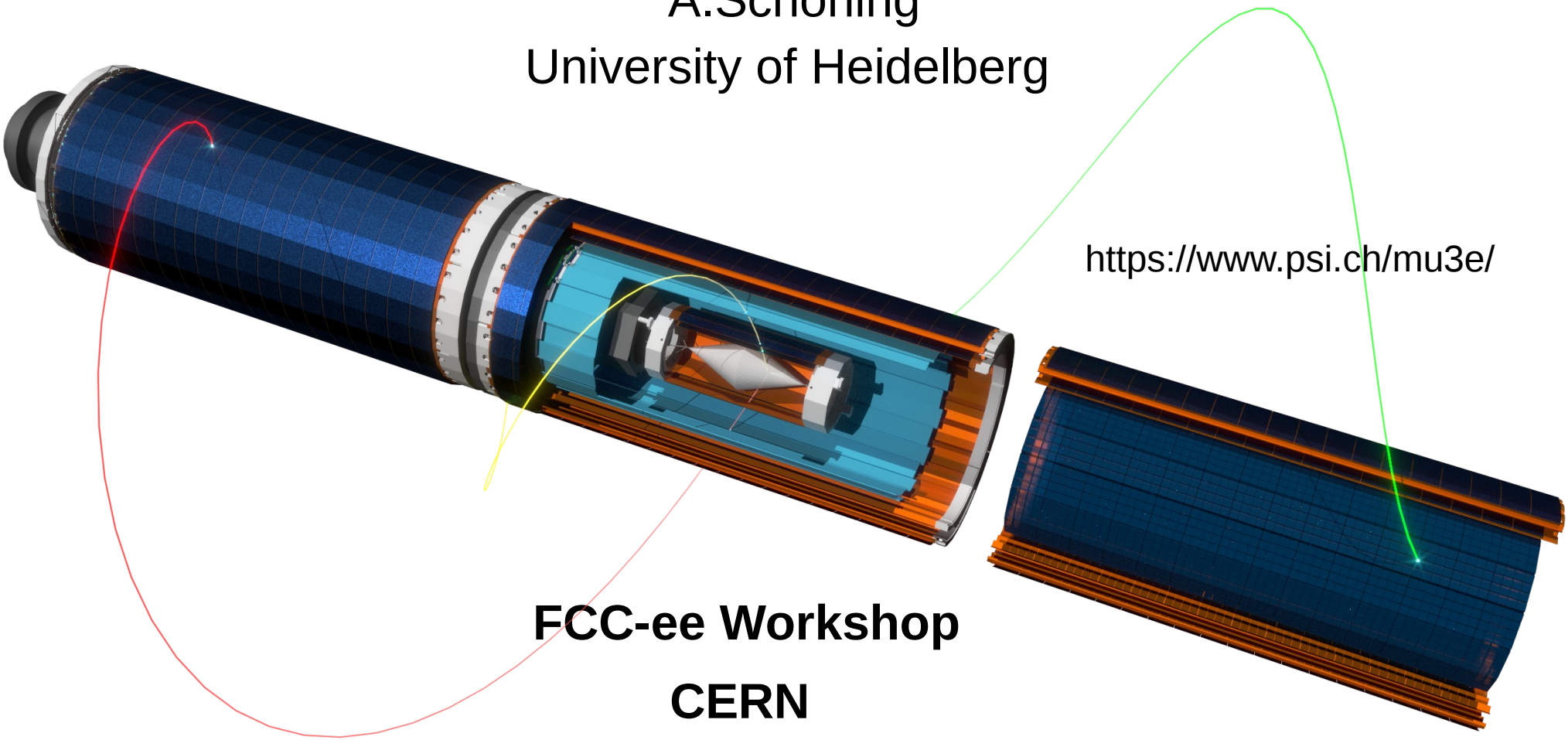
The ultra-light Mu3e Tracker
& possibilities for future trackers

A.Schöning
University of Heidelberg



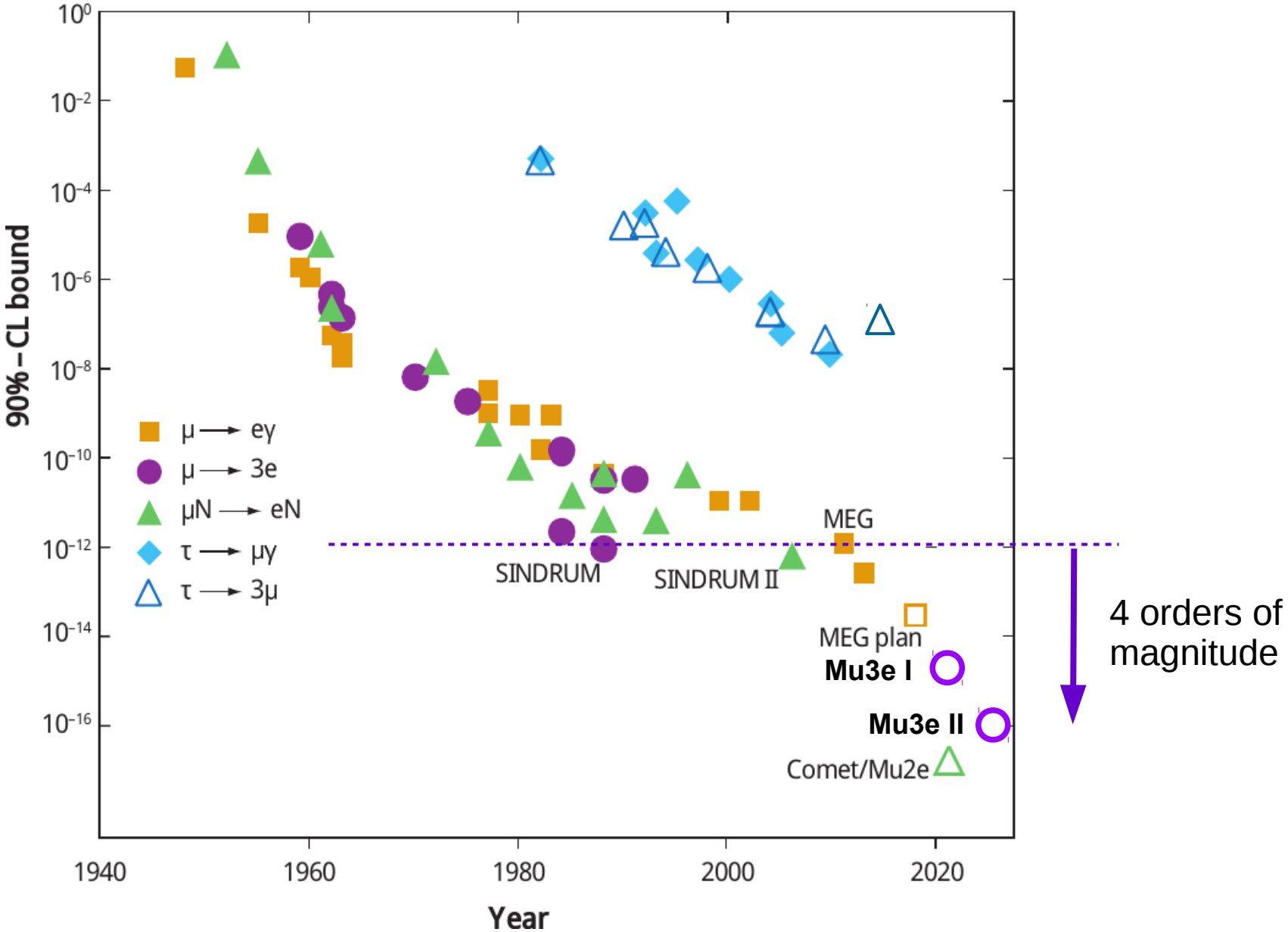
https://www.psi.ch/mu3e/

FCC-ee Workshop

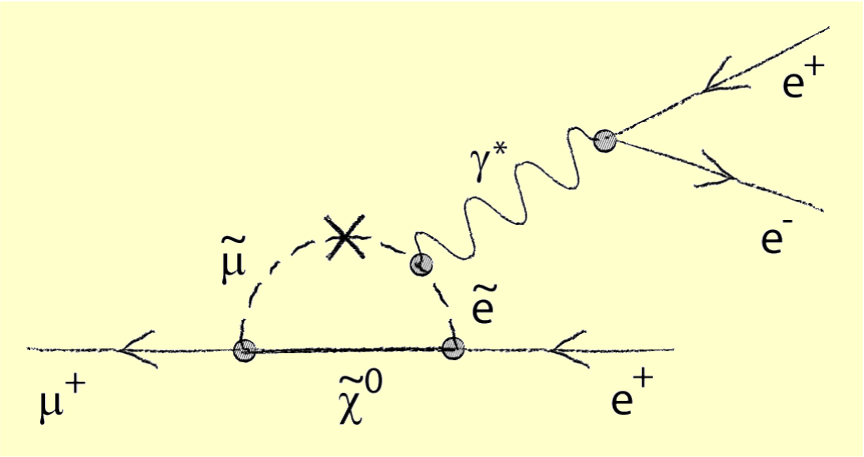
CERN

8.-11. January 2019

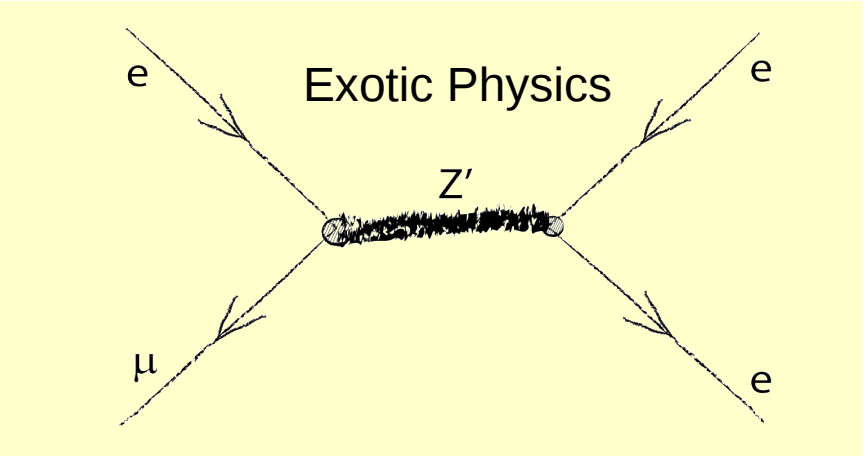
History of LFV Decay experiments



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



loop diagrams



tree diagram

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

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

Most models "naturally" induce lepton flavor violation!

Mu3e Experiment @ PSI

- World's most intense continuous muon beam ($f_{cycl.}$ = 50MHz)
- **2.4 mA** protons at **590 MeV** = **1.5 MW** → **O(10^{10-11}) muons**

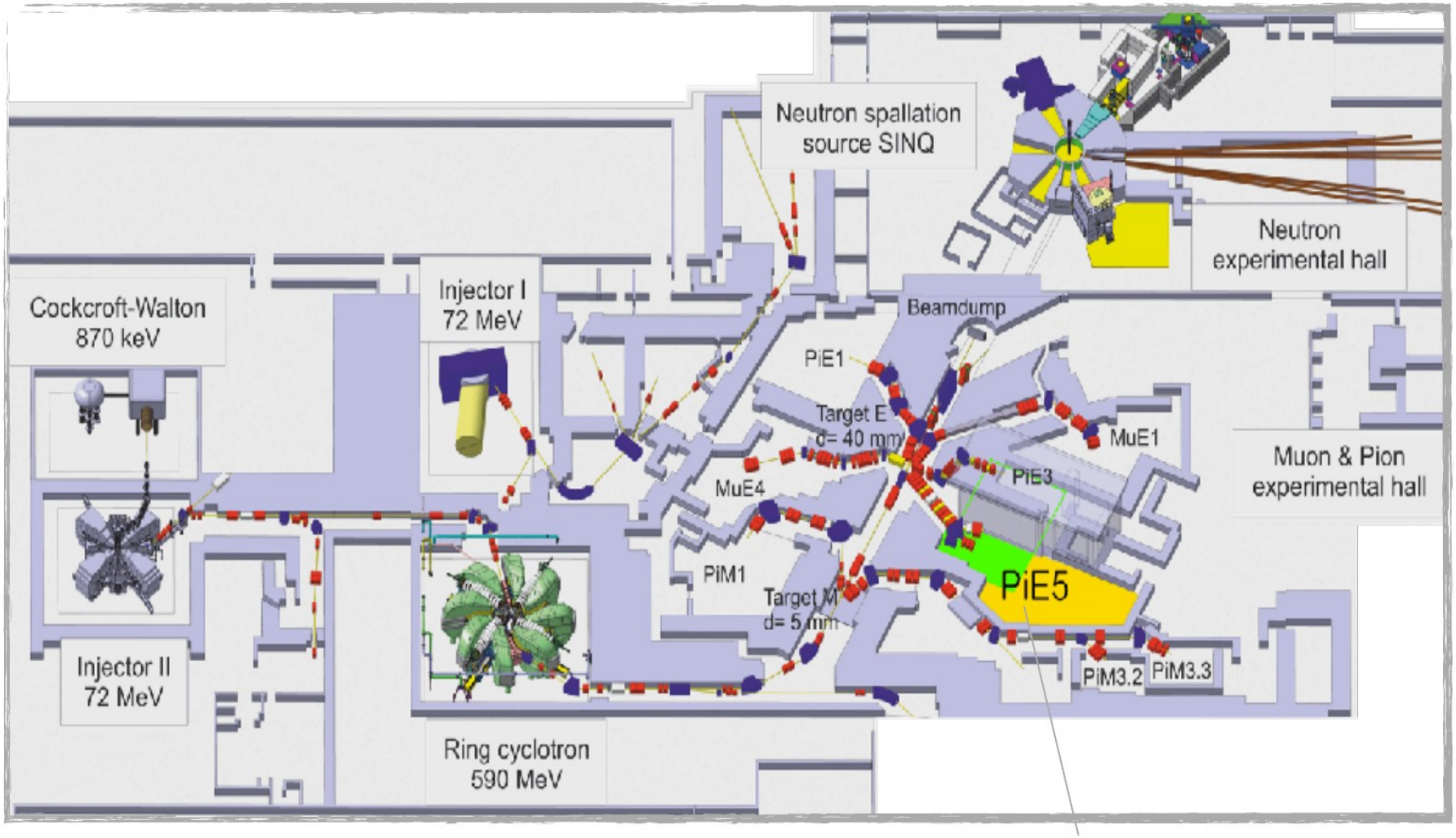
<u>Aiming for sensitivity (SES)</u> <u>requires:</u>

$BR(\mu \rightarrow eee) < 2 \cdot 10^{-15}$ (phase I) → **10^8 muons/s (PiE5)**

$BR(\mu \rightarrow eee) < 10^{-16}$ (phase II) → **>10^9 muons/s (→new HiMB)**

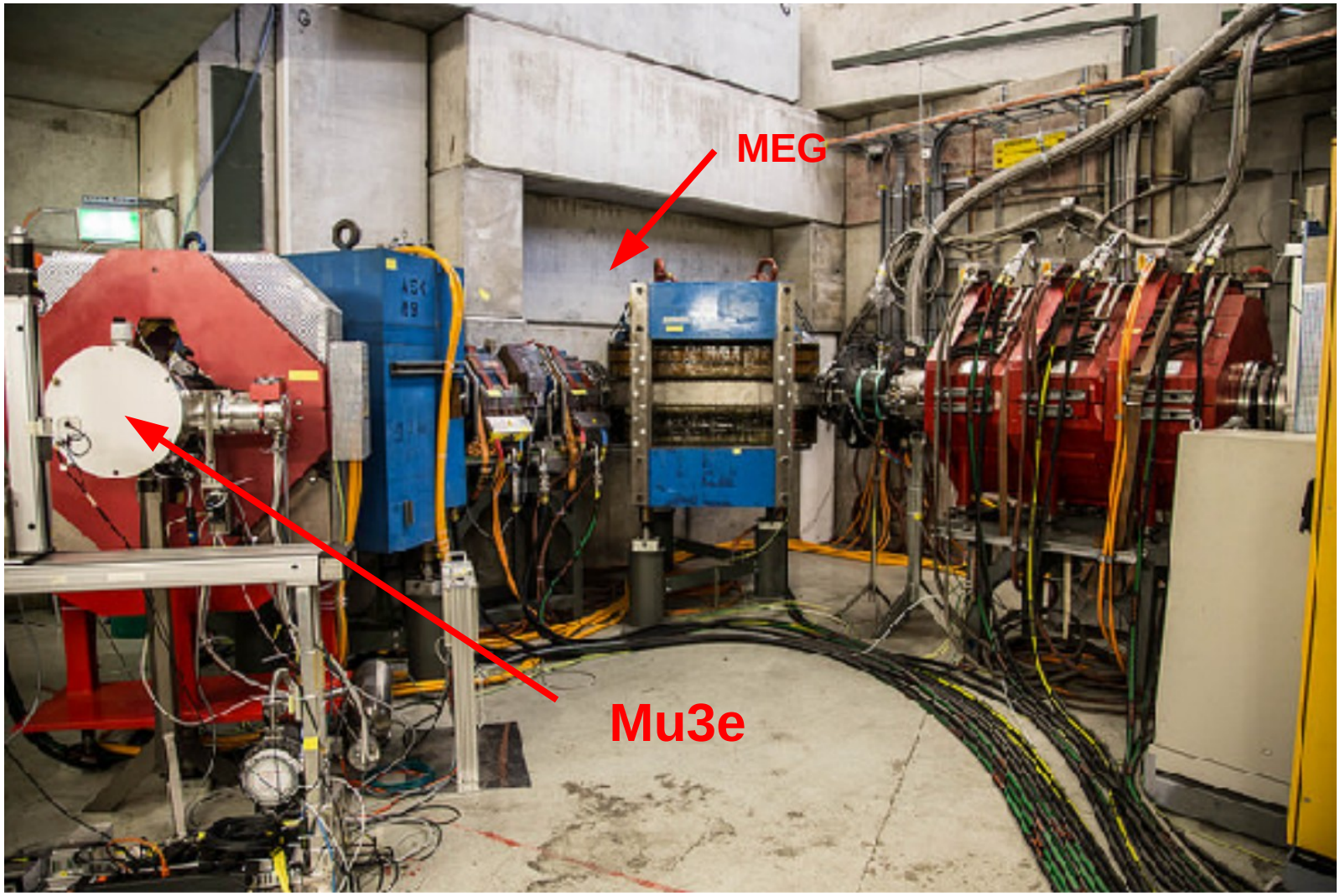
PiE5 Muon Beamline @ PSI

- O(10^8) muons per second
- Low momentum muons 28 MeV/c
- PiE5 beamline shared between MEG2 and Mu3e



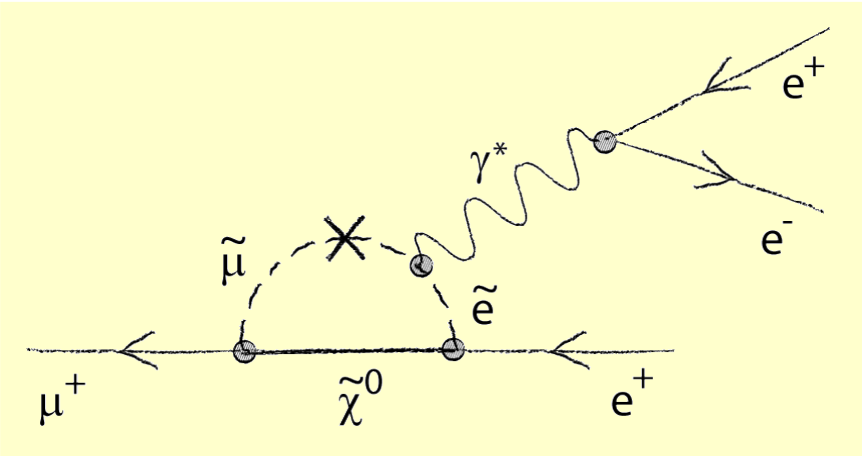
PiE5 Area

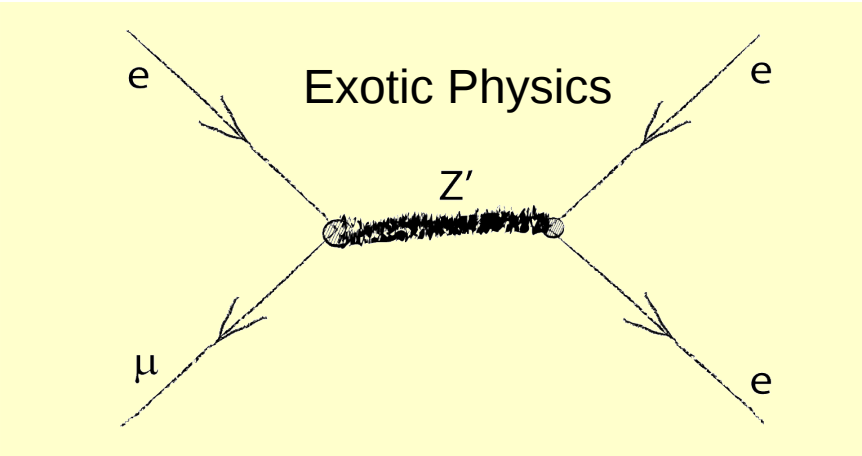
Compact Muon Beamline (CMBL) for Mu3e

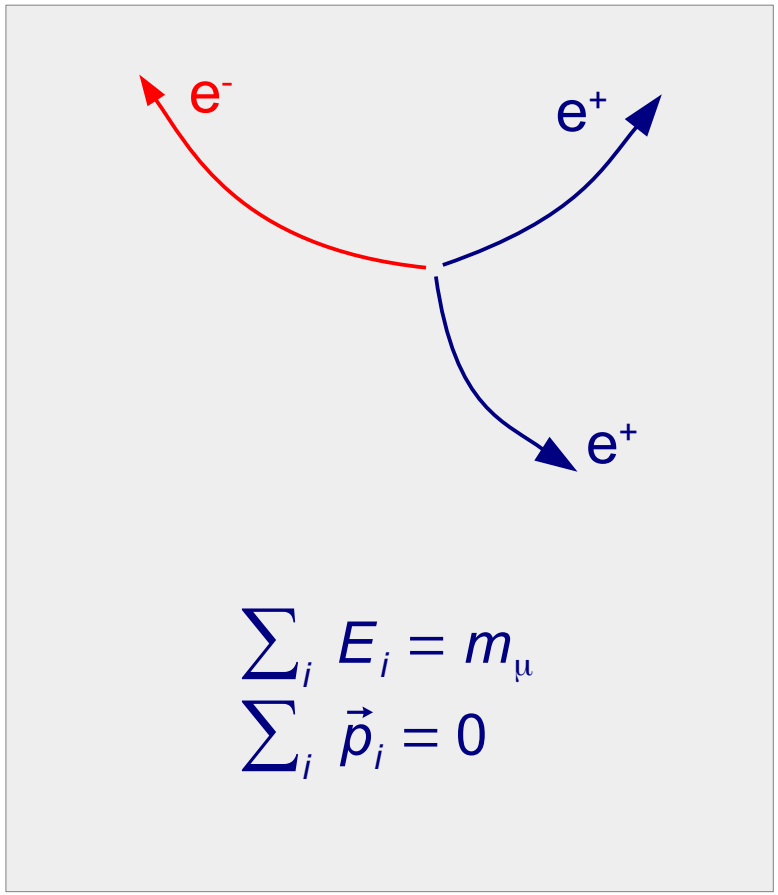


Signal $\mu^+ \rightarrow e^+e^+e^-$

- 3-prong signature
- muons decay at rest:
  - ➔ two positrons and electron in common plane

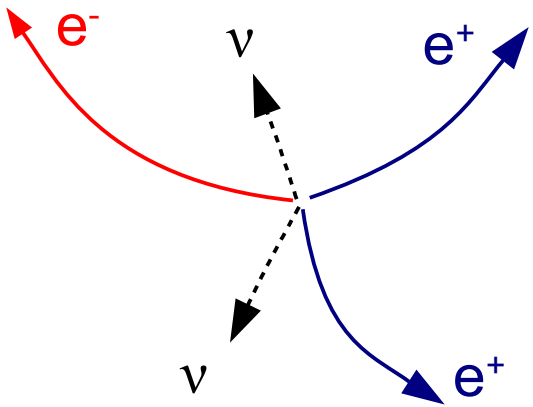




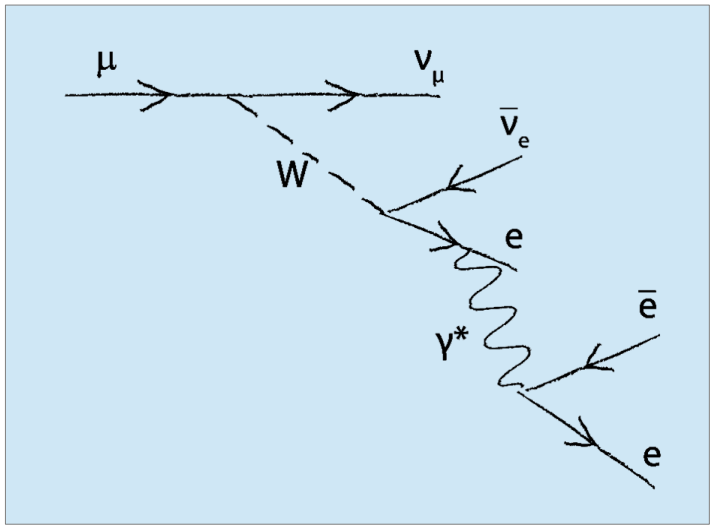


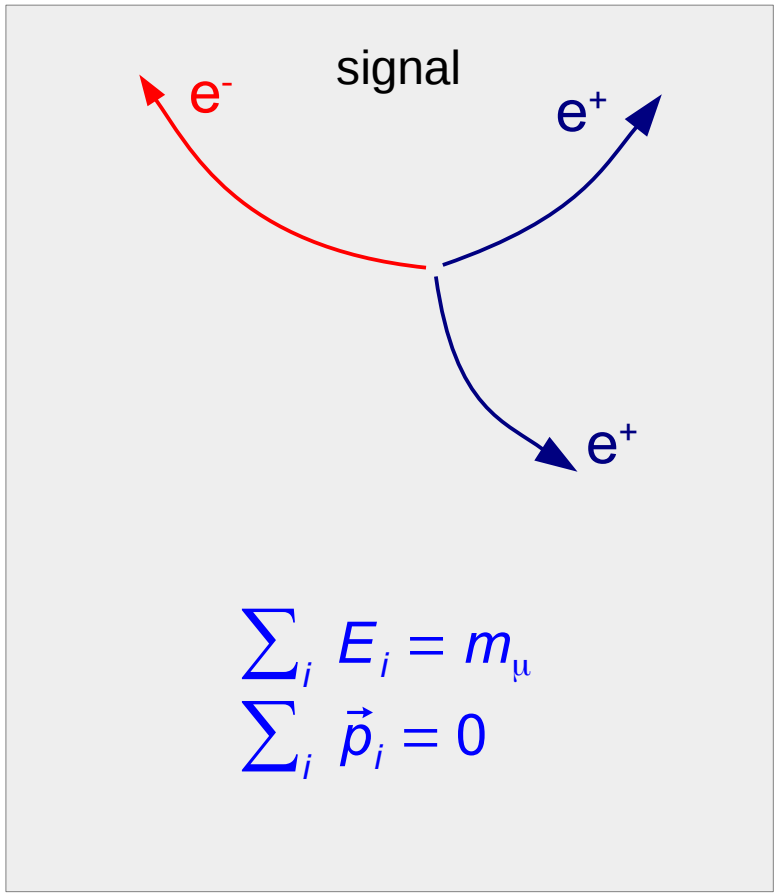
Irreducible Background

Radiative decay with internal conversion



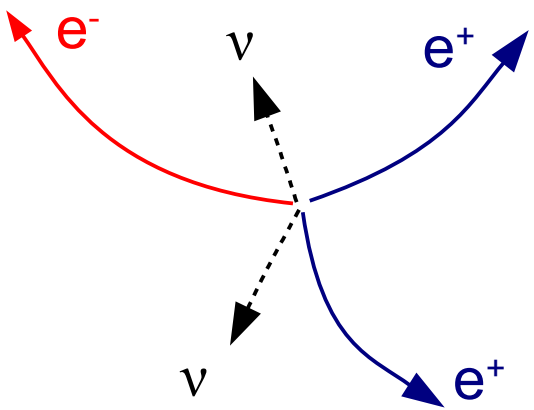
$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$



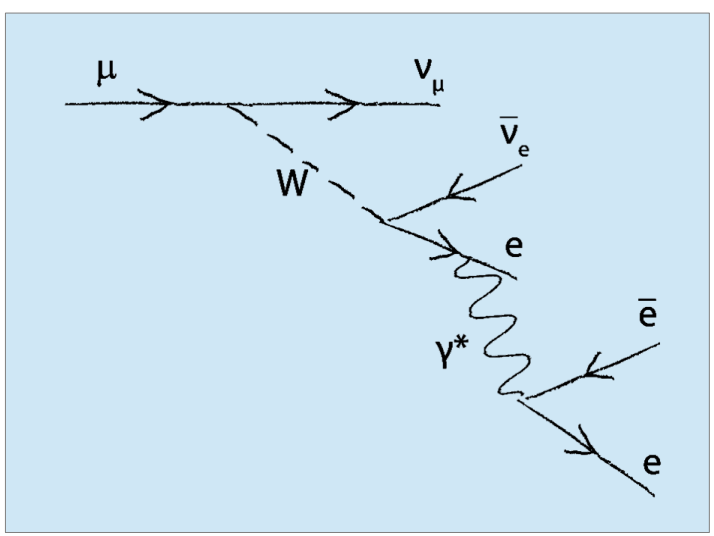


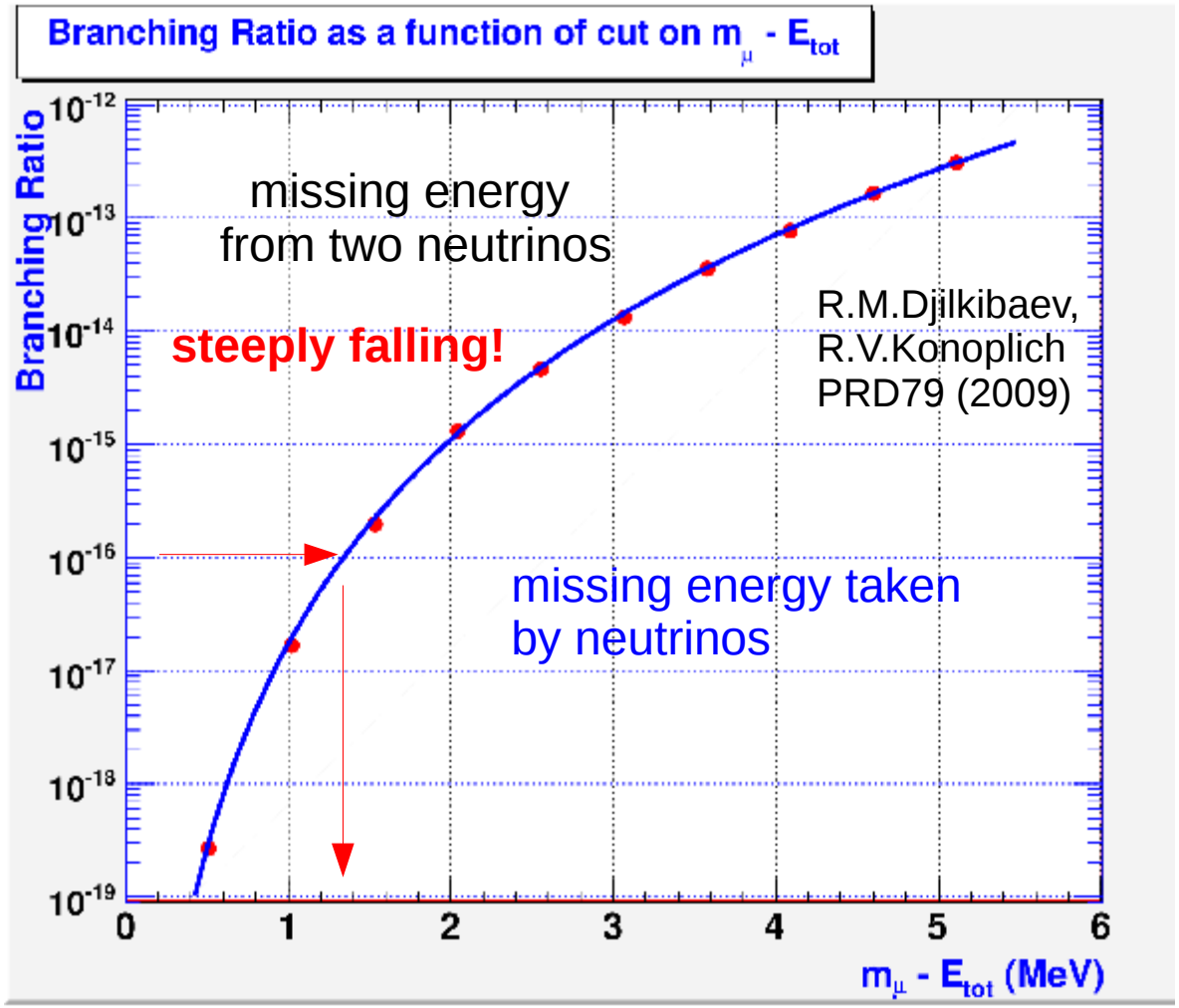
Irreducible Background

Radiative decay with internal conversion



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

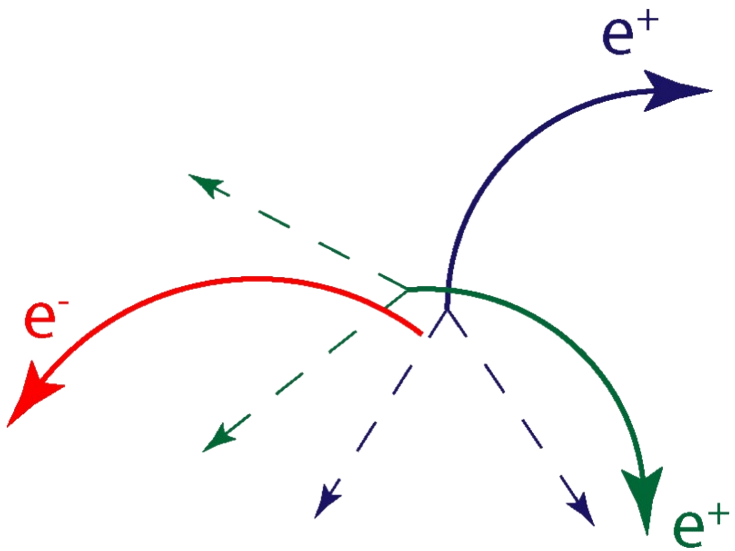


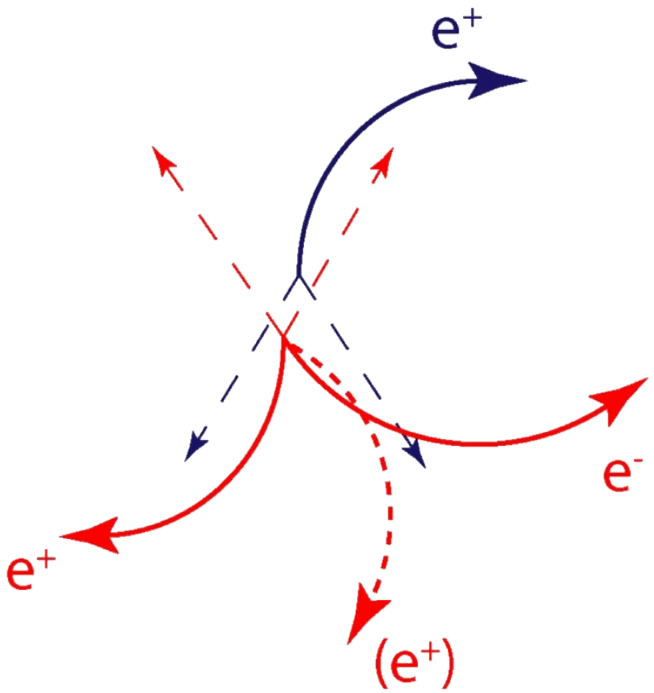


very good momentum +
total energy resolution required!

Accidental Backgrounds

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



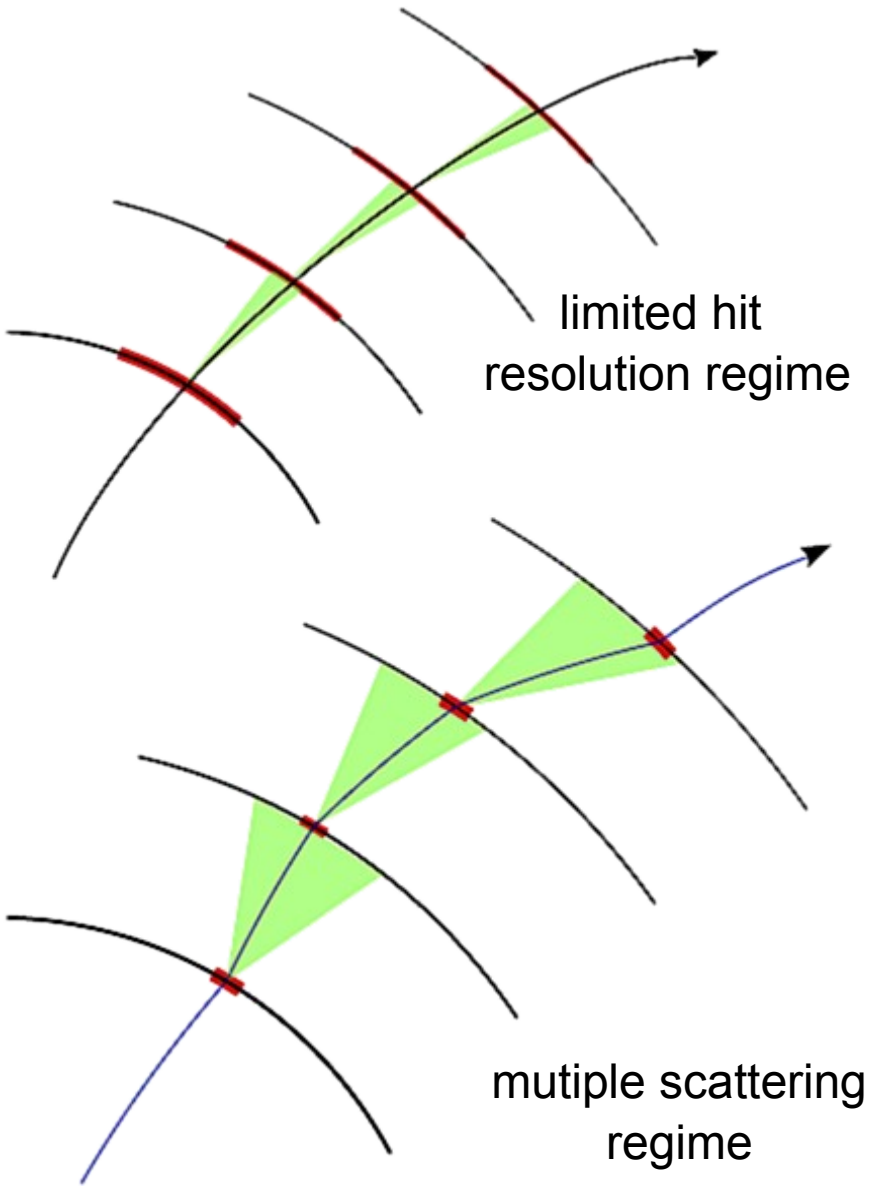


Need excellent:

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

+ little material (avoid high Z)

Tracking Resolution & Multiple Scattering



- **Muon decay (m = 105.6 MeV):**

  → electrons at low momentum:

  p < 53 MeV/c

- **Multiple scattering is dominant!**

→ **Need thin, fast and high resolution tracking detectors operated at high rate (>10^9 particles/s @ phase II)**

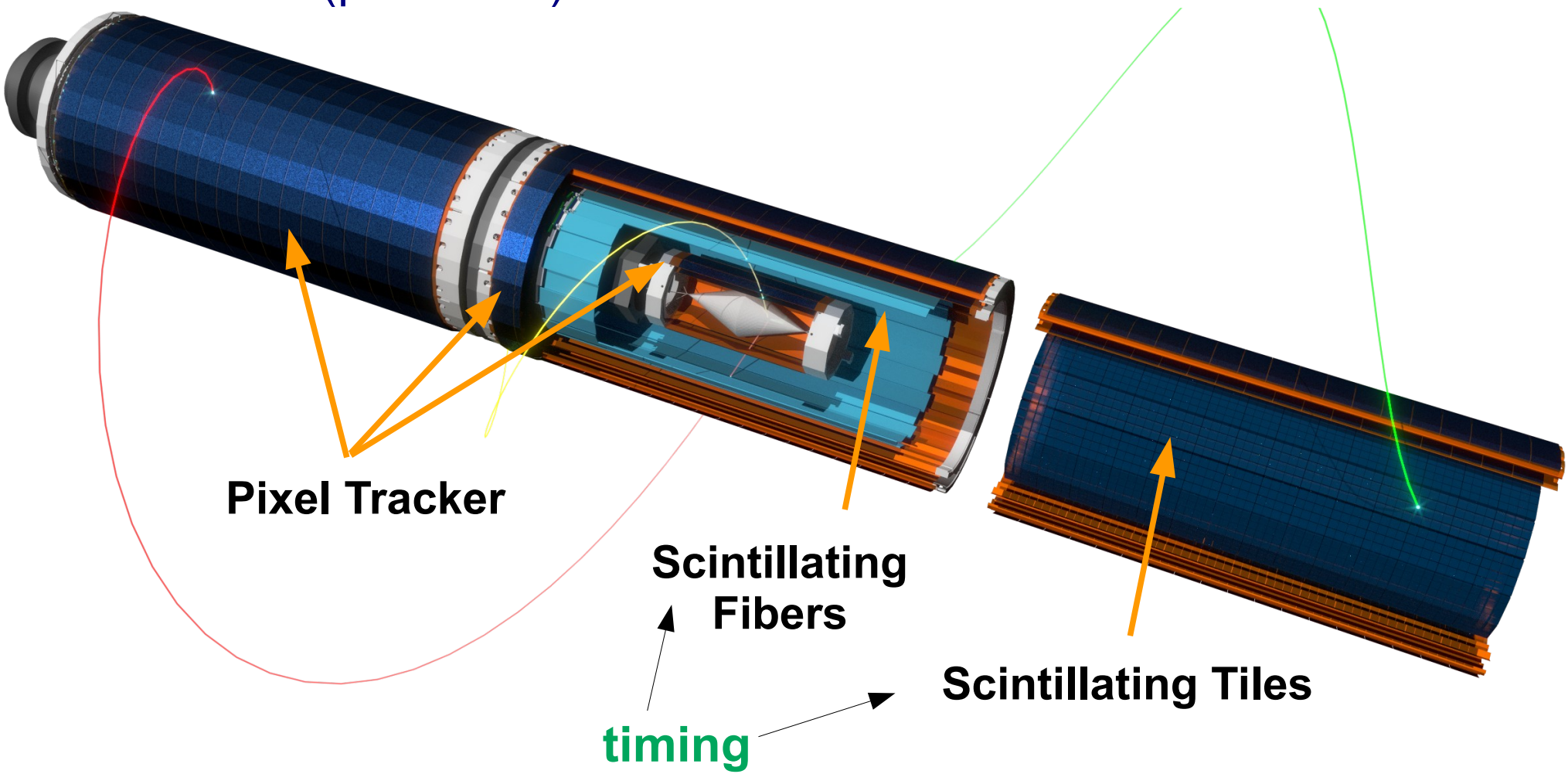
$$\Theta_{MS} \sim \frac{1}{P}\sqrt{X/X_0}$$

Mu3e Experiment

Aiming for a sensitivity (SES) requires:

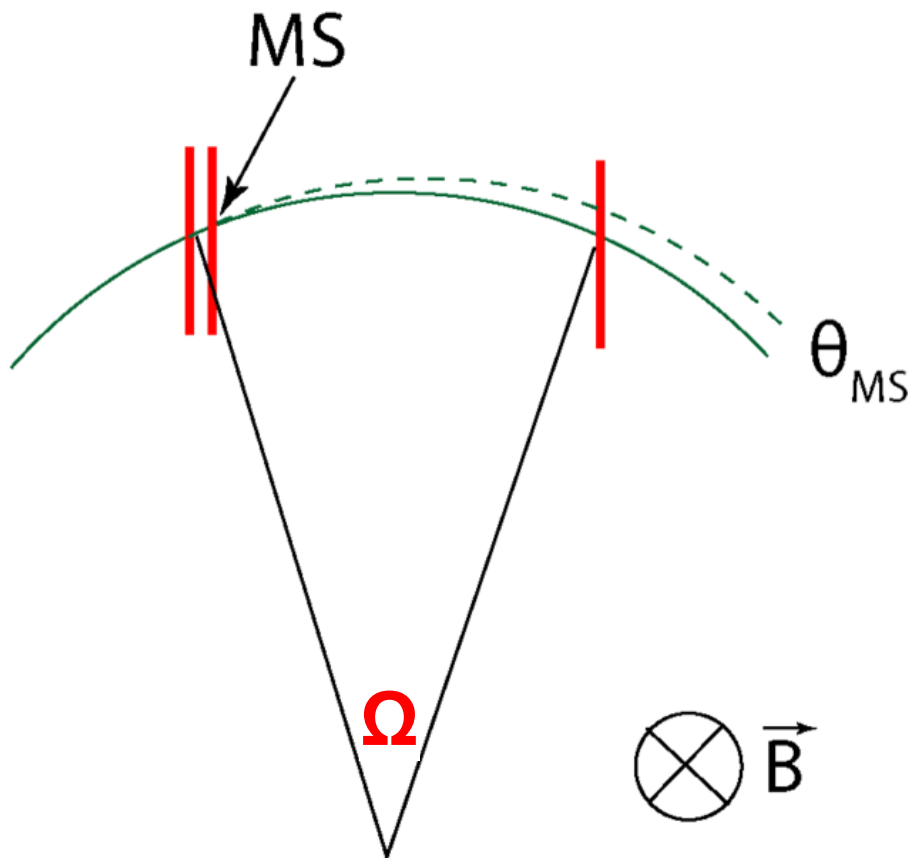
$BR(\mu \rightarrow e\,e\,e) < 2 \cdot 10^{-15}$ (phase I) → **10^8 muons/s (PiE5)**

$BR(\mu \rightarrow e\,e\,e) < 10^{-16}$ (phase II) → **$>10^9$ muons/s (→ HiMB)**



Momentum Resolution in MS Regime

- Standard spectrometer:



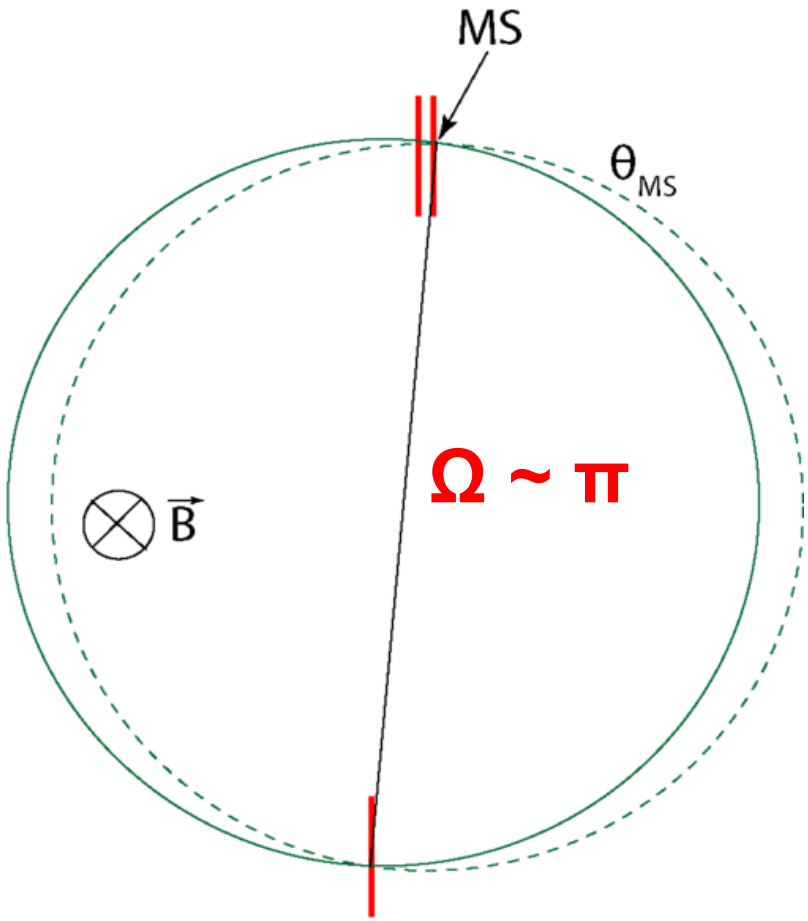
$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega} \sim \frac{\sqrt{X}}{\Omega}$$ (linearised)

precision requires large lever arm

→ large bending angle Ω

Momentum Resolution in MS Regime

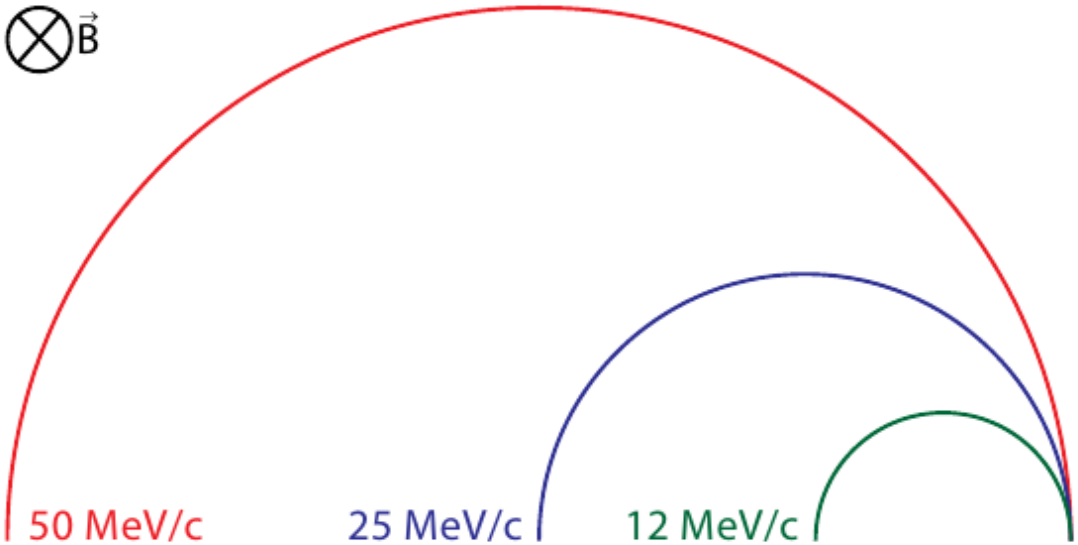
- “Half turn” spectrometer:



$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right) \sim \frac{X}{X_0}$$

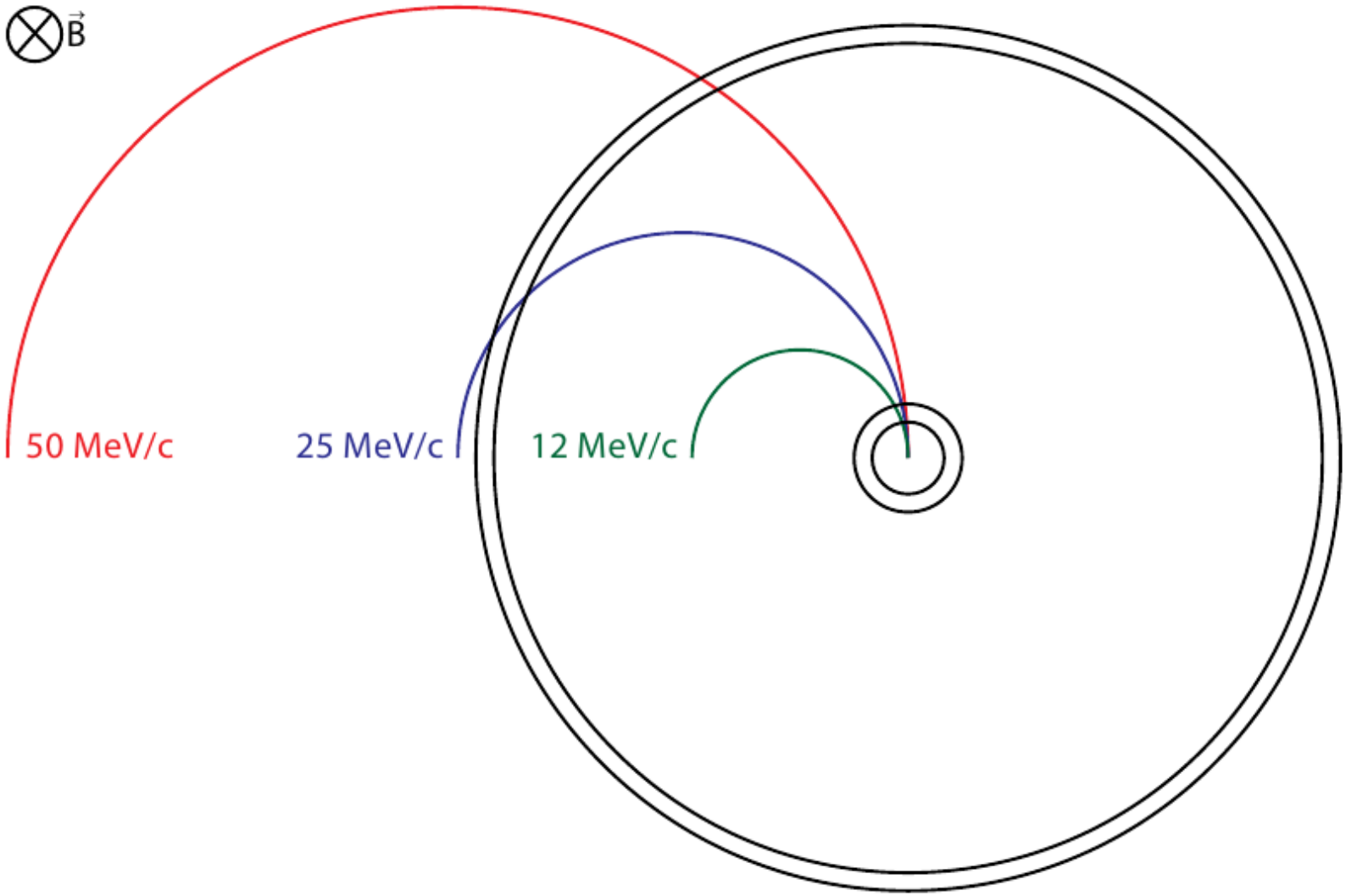
- **best precision for half turn tracks**
- **measure recurlers**

Tracking Design Considerations

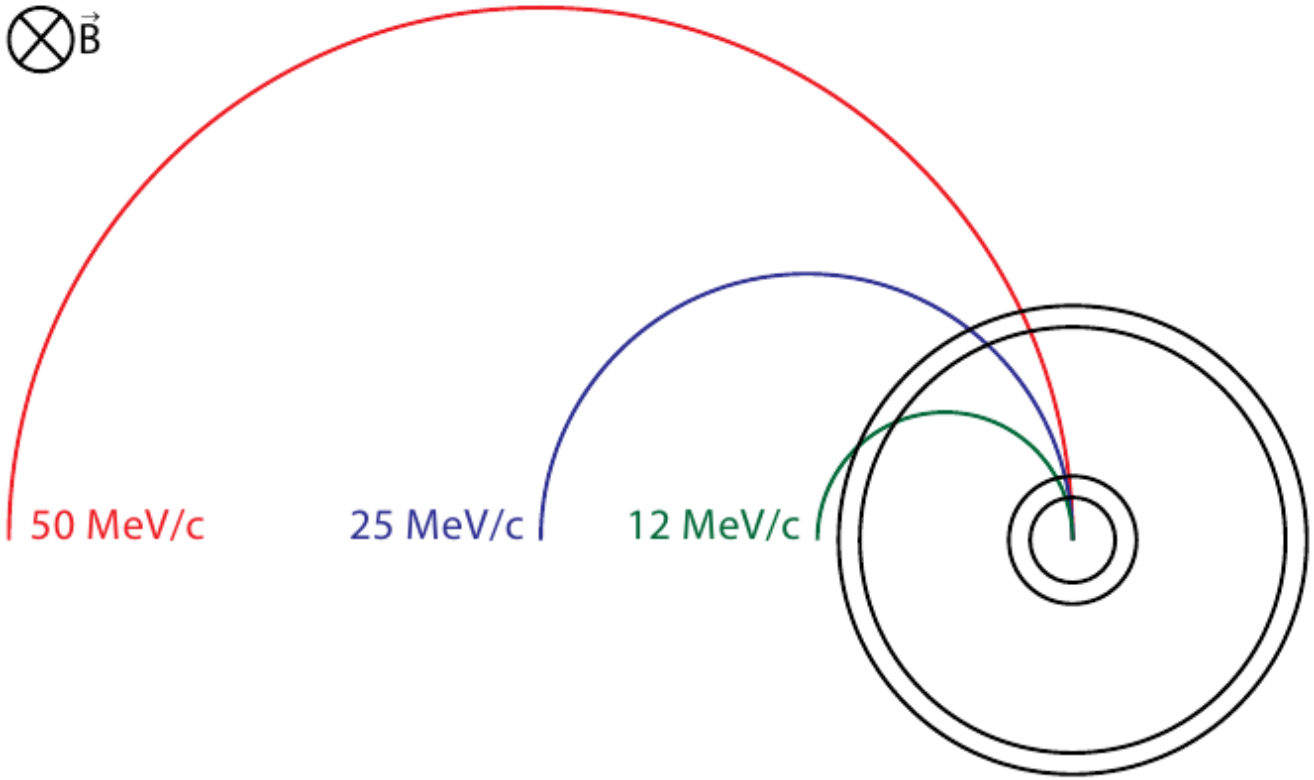


muon mass ~ 105 MeV/c^2

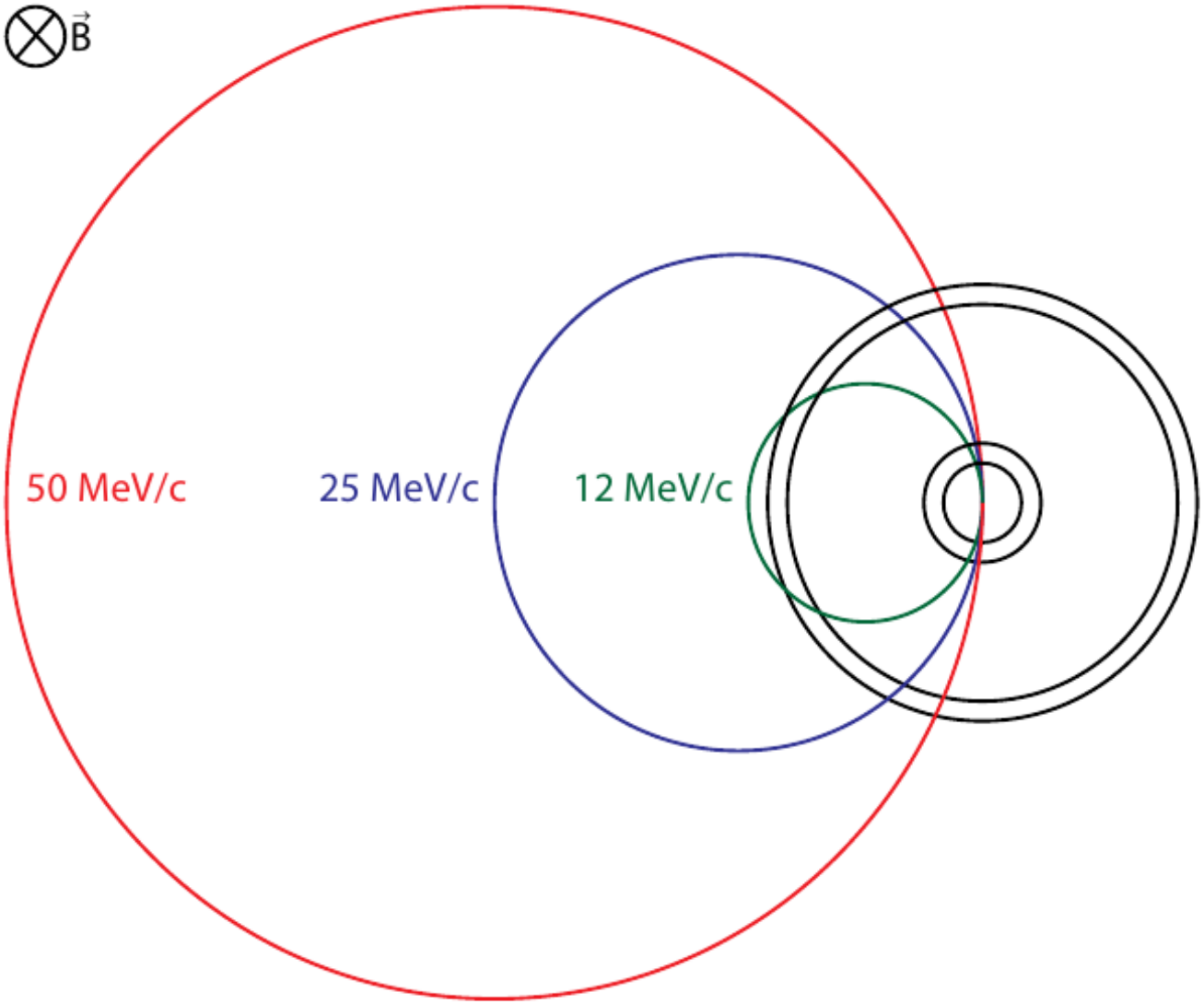
Tracking Design Considerations



Tracking Design Considerations



Tracking Design Considerations

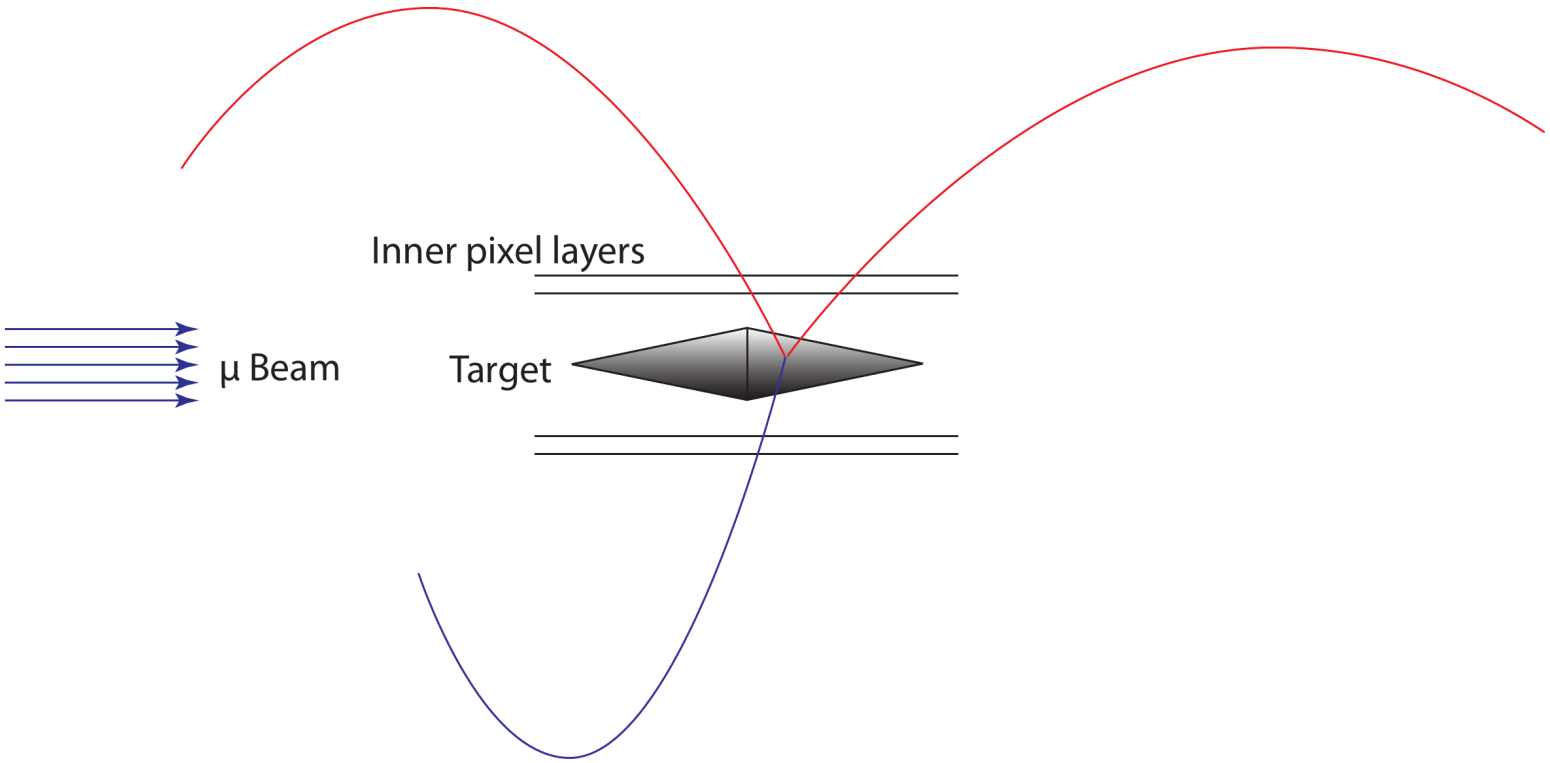


Mu3e Baseline Design

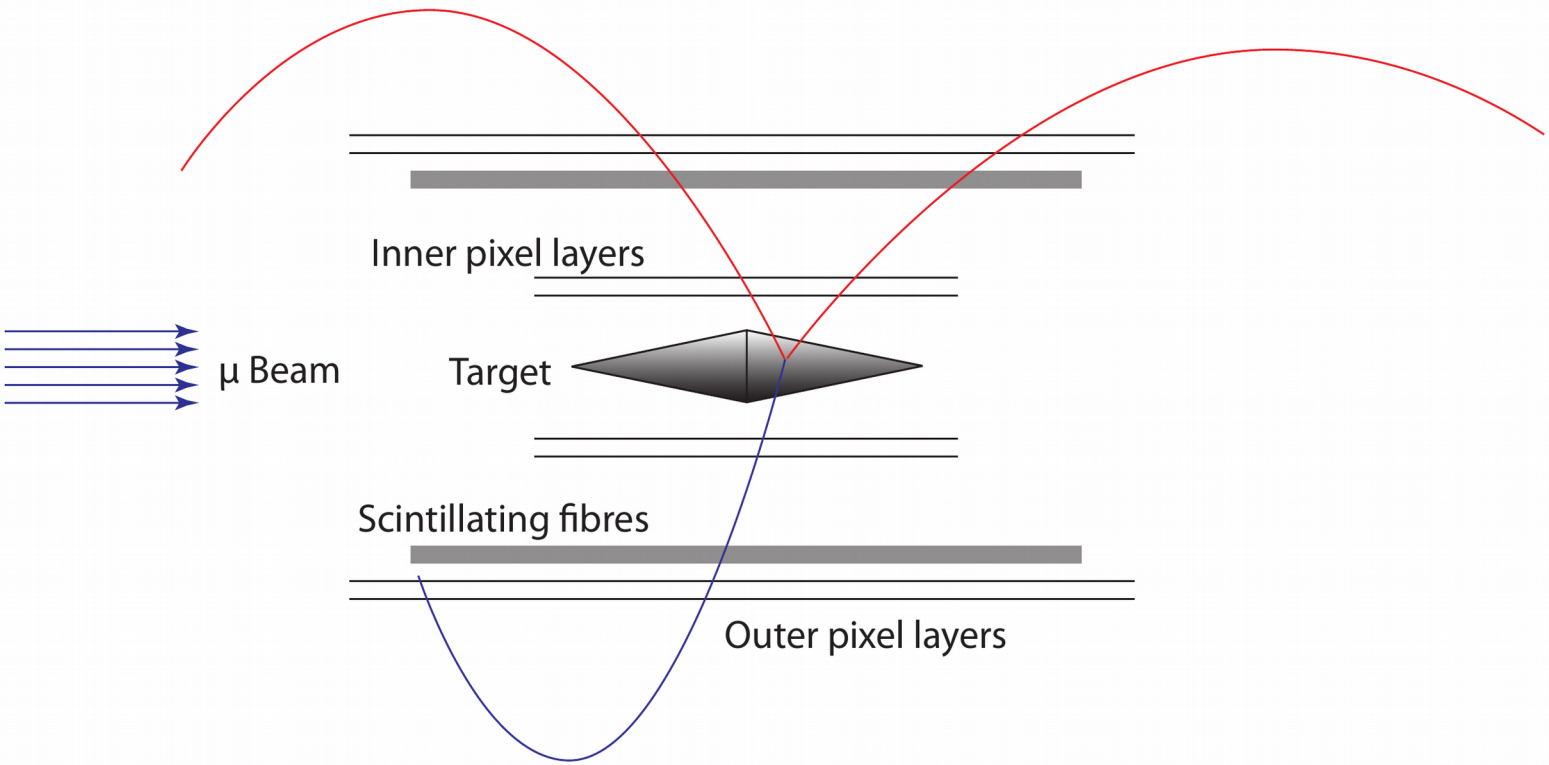
10^8 muons per second (phase I)

p=28 MeV/c

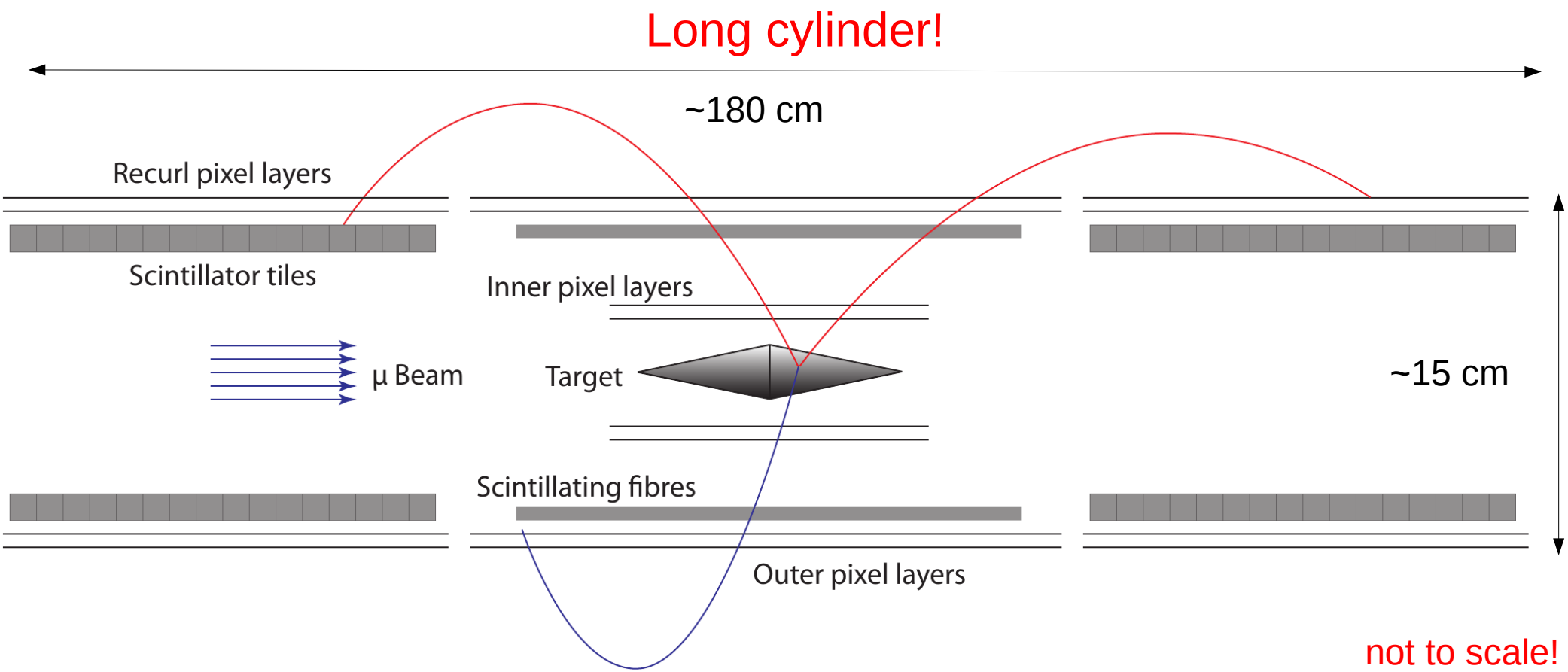
Mu3e Baseline Design



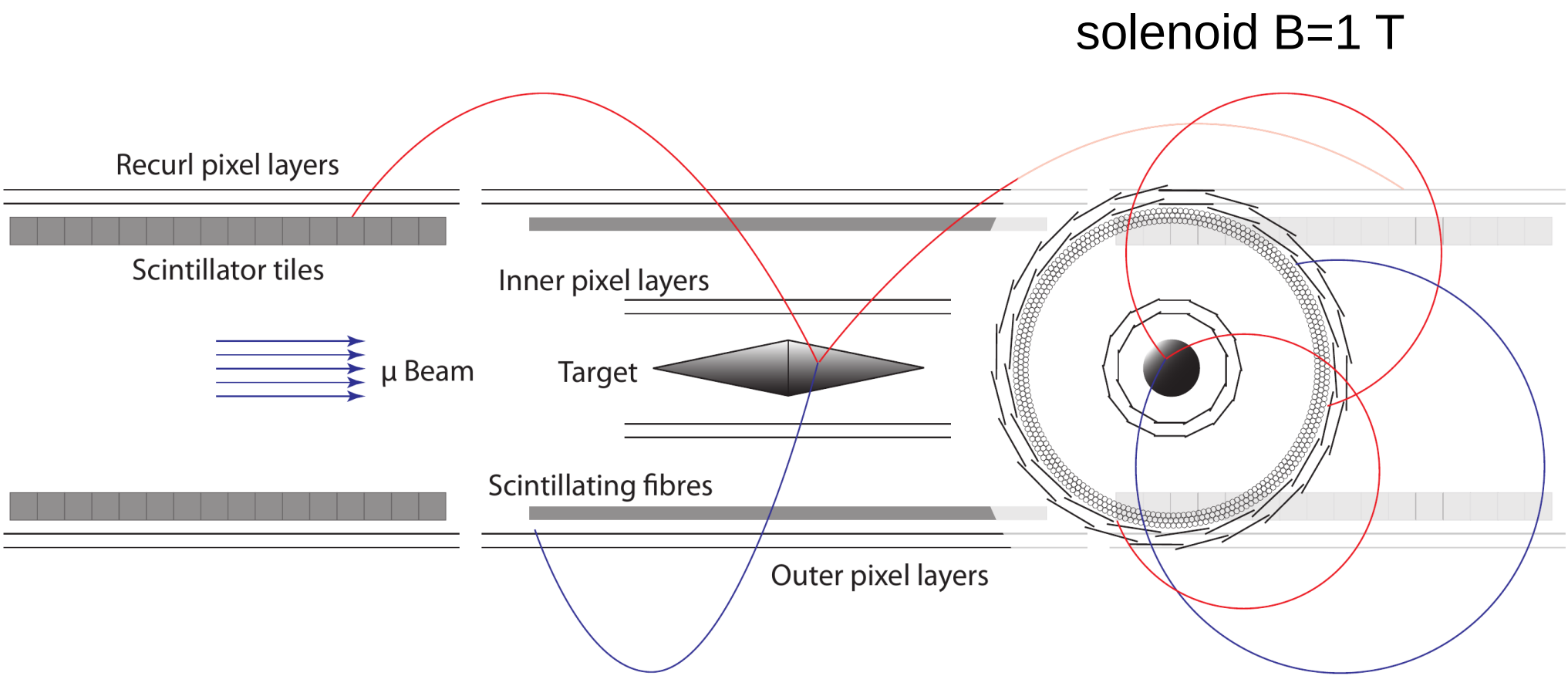
Mu3e Baseline Design



Mu3e Baseline Design



Mu3e Baseline Design

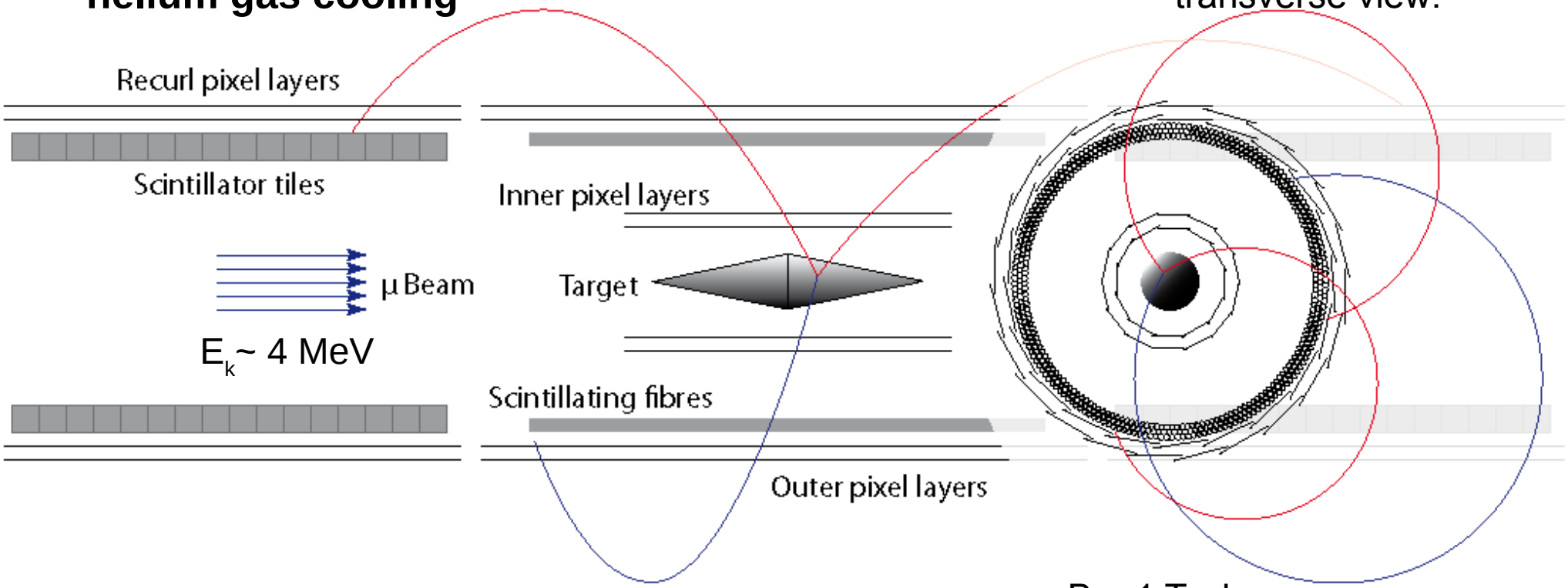


Mu3e Design

Features:

- surface muons (p=29 MeV/c, DC) stopped on target at high rate: **10^8 - 10^9 /s**
- ultra thin **silicon pixel detector** (HV-MAPS) with **1 per mill radiation length** / layer
- high precision tracking using **recurling tracks** in strong magnetic field
- **fast timing** detectors (scintillating fibers & tiles)
- **helium gas cooling**

transverse view:



B = 1 Tesla

helium atmosphere

A light-weight pixel tracker

Mu3e: SES scales with the third power of the tracker material!

$$SES \sim \left(\frac{X_{layer}}{X_0} \right)^3$$

Experiment	Material per layer
ATLAS IBL	1.9% X_0
ALICE ITS mid/outer	0.8% X_0
ALICE ITS inner	0.3% X_0
STAR	0.4% X_0
BELLE II vertex	0.2% X_0
Mu3e (all layers)	**0.1% X_0**

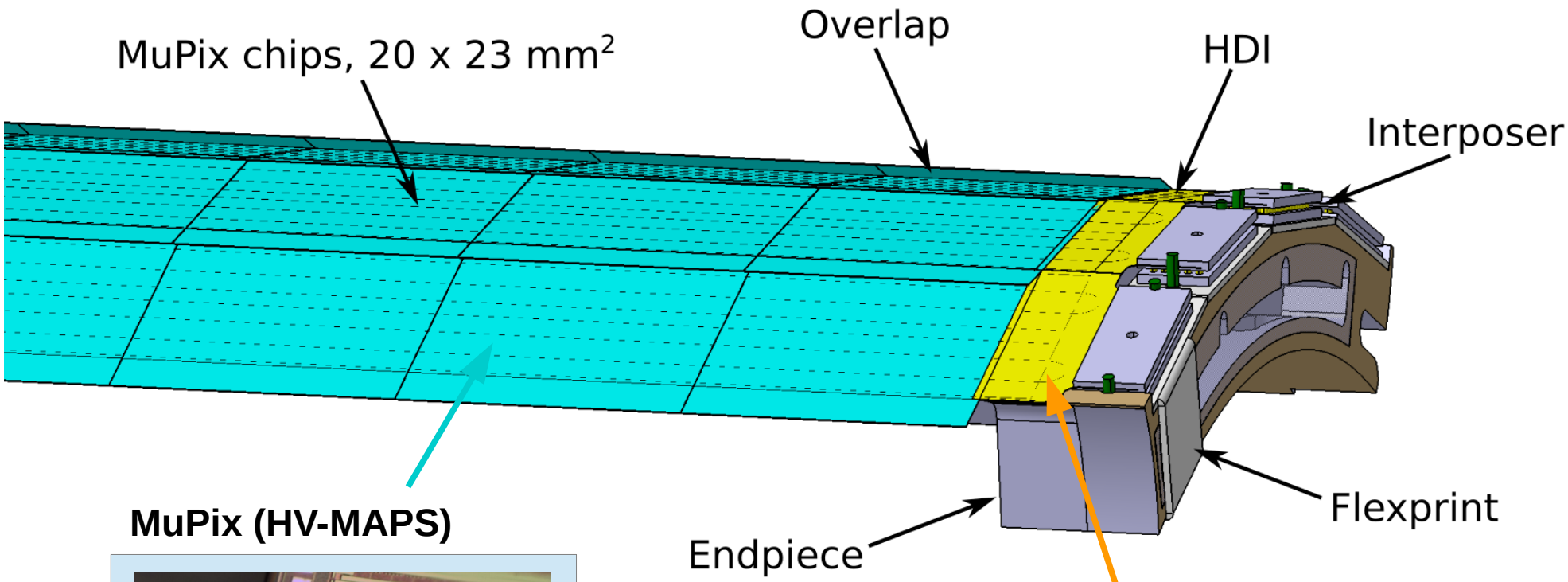
➔ goal Mu3e: **X/X_0 = 0.001**

- 50 µm HV-MAPS
- ~150 mu flexprint
  + mechanical support

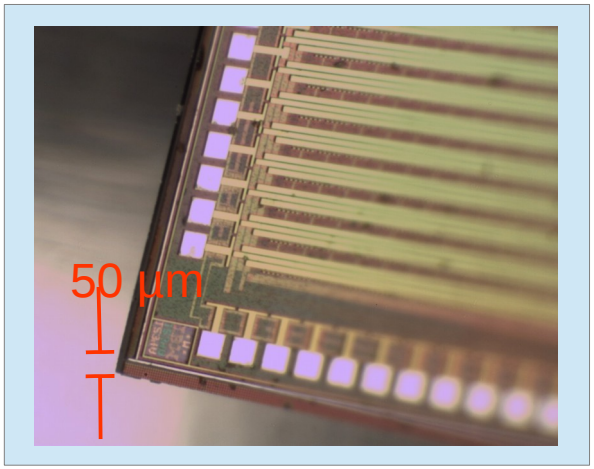
In addition:

- helium atmosphere → reduces multiple scattering
- cooling of pixel tracker with helium gas

(Outer) Pixel Tracker Module

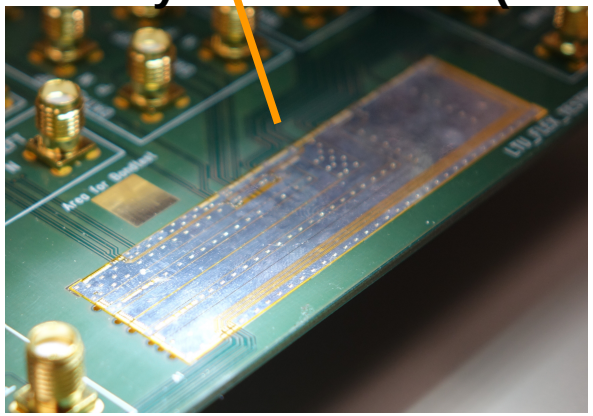


MuPix (HV-MAPS)



180 nm HV-CMOS (AMS)

High Density Interconnect (LTU, Ukraine)

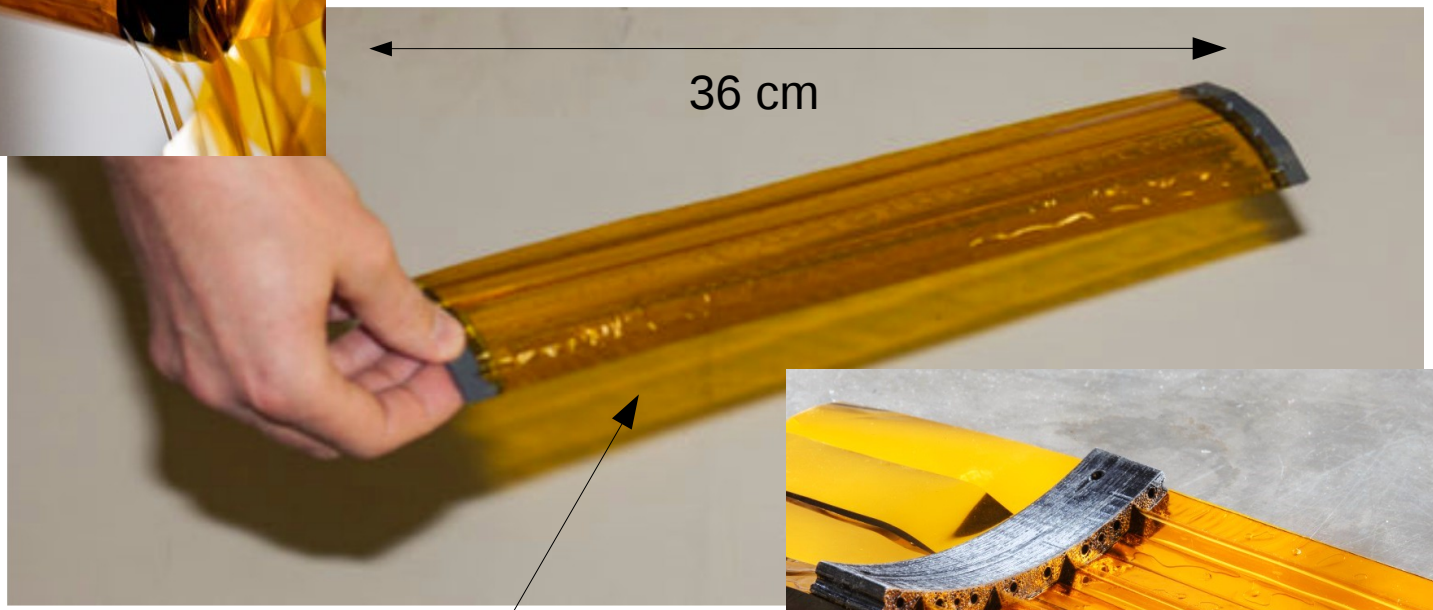


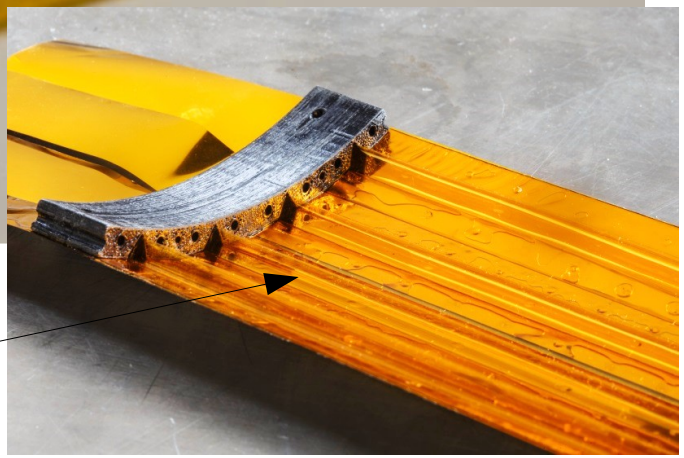
Mechanical Mockups

Ultra-thin mechanical mockup:

- sandwich of 25 µm Kapton®
- 50 µm glass (instead of Si)

Even larger stable structures possible



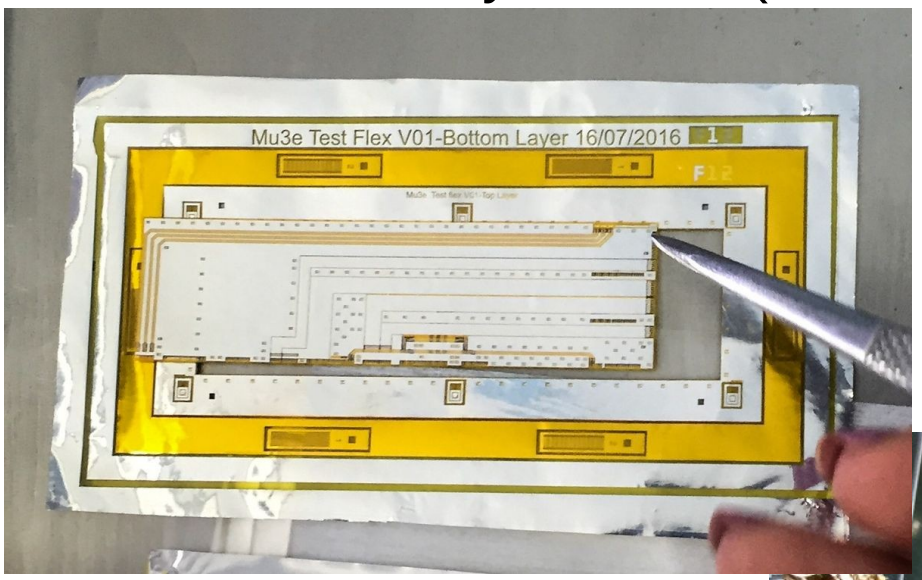


by using Kapton V-folds

Flexprint Production and Bonding

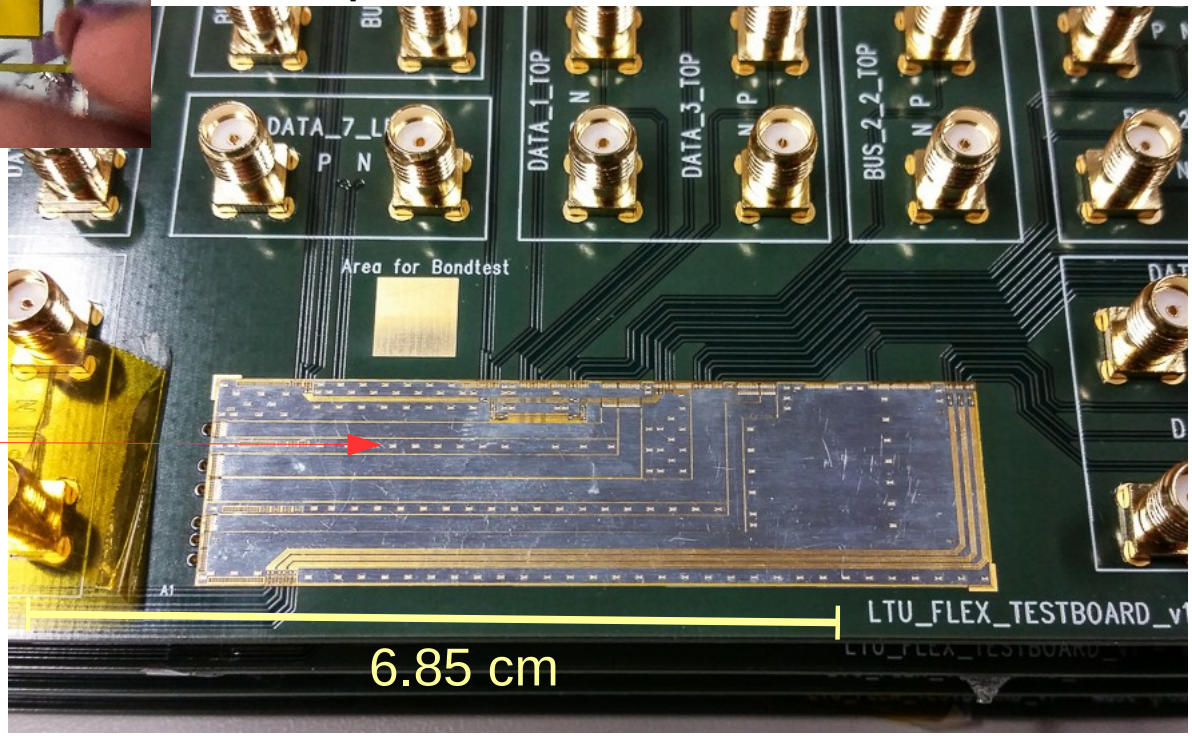
spTAB = single point tape automated bonding
FPC = flexible printed circuit

FPC Production by LTU Ltd (Ukraine)

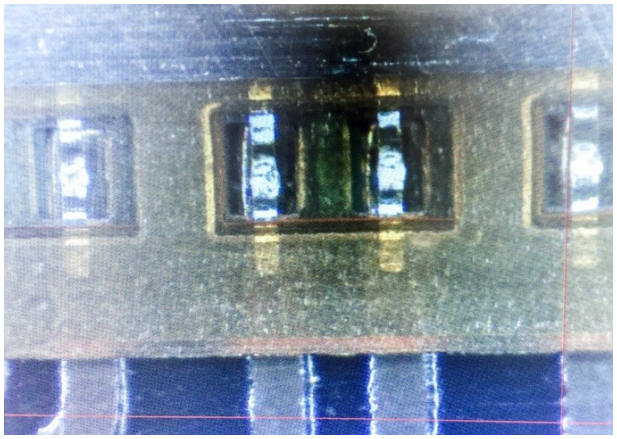


→ bonding yield 100%

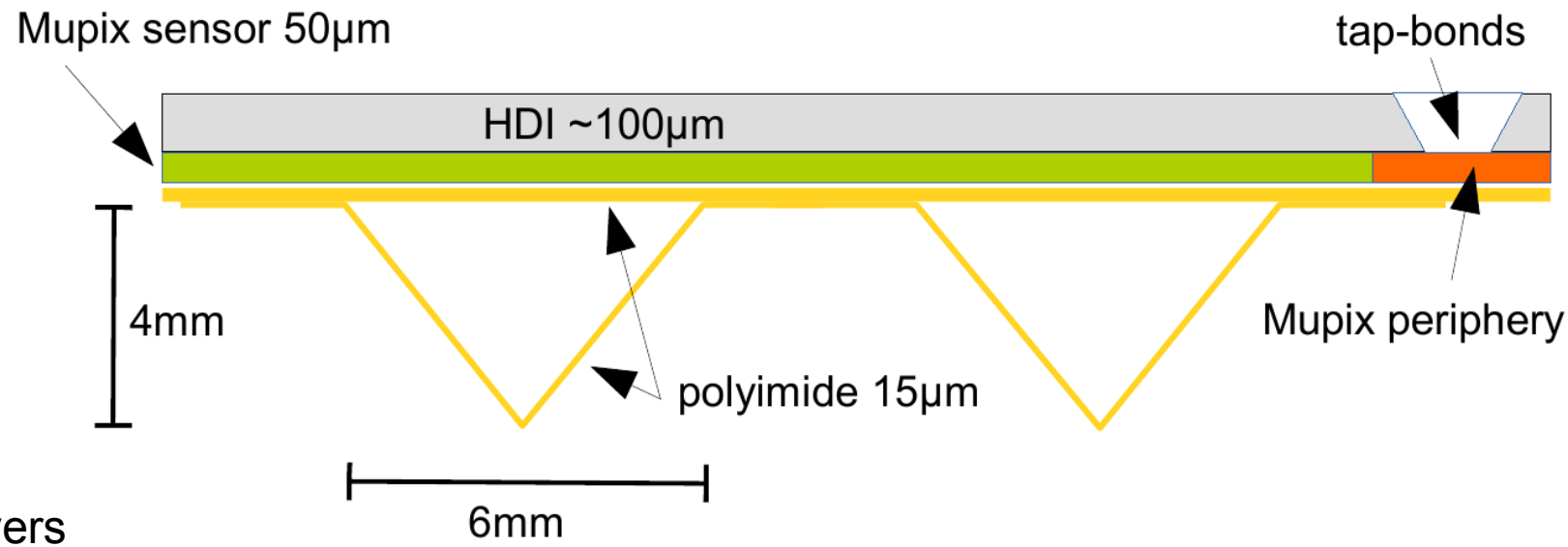
FPC spTAB-bonded on test board and qualified



spTAB bond zoomed in



Ultralight Pixel Ladder



2 Al layers

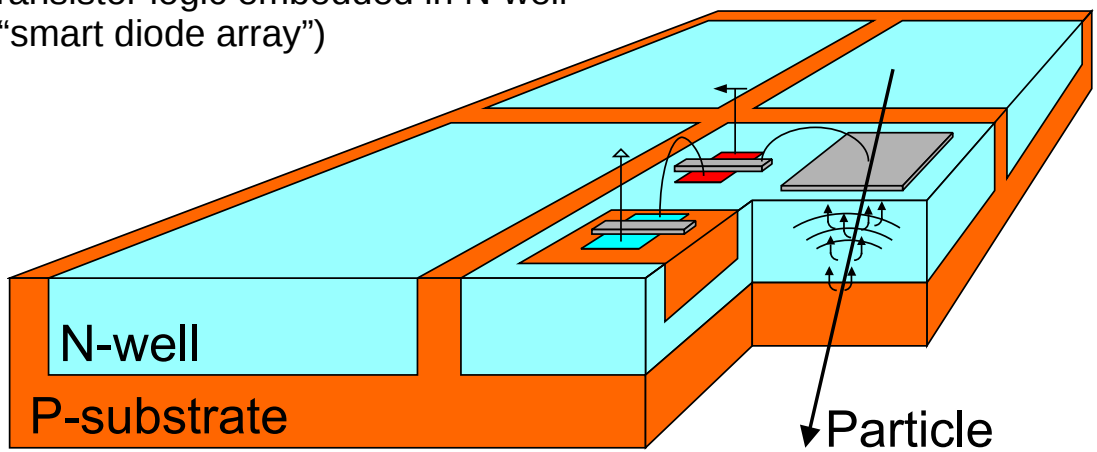
	Layer 1-2		Layer 3-4	
	thickness [µm]	X/X_0	thickness [µm]	X/X_0
MuPix Si	45	$0.48 \cdot 10^{-3}$	45	$0.48 \cdot 10^{-3}$
MuPix Al	5	$0.06 \cdot 10^{-3}$	5	$0.06 \cdot 10^{-3}$
HDI polyimide & glue	45	$0.18 \cdot 10^{-3}$	45	$0.18 \cdot 10^{-3}$
HDI Al	28	$0.31 \cdot 10^{-3}$	28	$0.31 \cdot 10^{-3}$
polyimide support	25	$0.09 \cdot 10^{-3}$	≈ 30	$0.10 \cdot 10^{-3}$
adhesives	10	$0.03 \cdot 10^{-3}$	10	$0.03 \cdot 10^{-3}$
total	158	$1.15 \cdot 10^{-3}$	163	$1.16 \cdot 10^{-3}$

pixel layer: ~ 1.15 per mille radiation length

Pixel Detector Technology

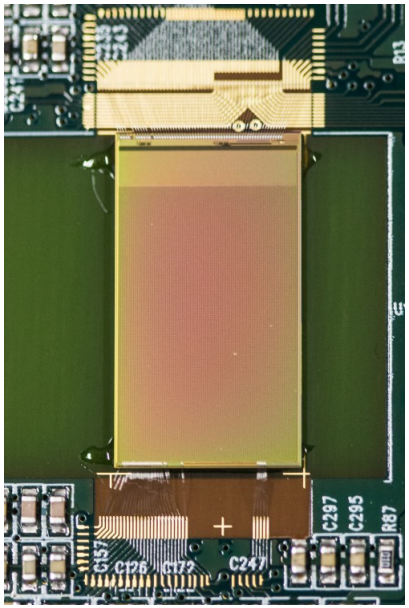
High Voltage-Monolithic Active Pixel Sensor (HV-MAPS)

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



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

MuPix8 prototype



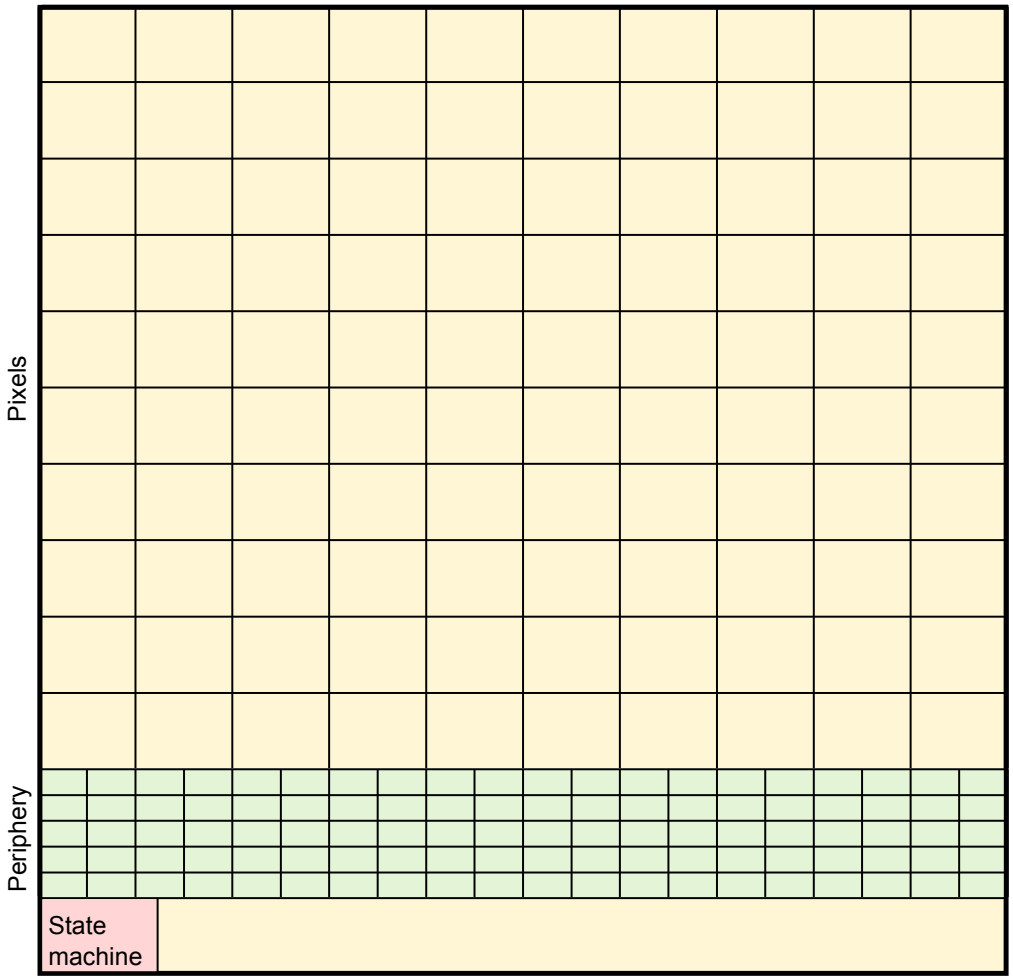
2 cm

- **active sensors**
  → hit finding + digitisation + readout
- HV-CMOS: 60-120 V, commercial process (AMS, GlobalFaundry, TSI)
- different substrates possible 20-1000 Ω cm
- thickness ~**50 µm** (~ 0.0005 X_0)

MuPix has been characterized in the lab and at test beams

- efficiency
- noise
- rate
- temperature-dependence
- (radiation hardness)

MuPix Chip Design



“active” cells

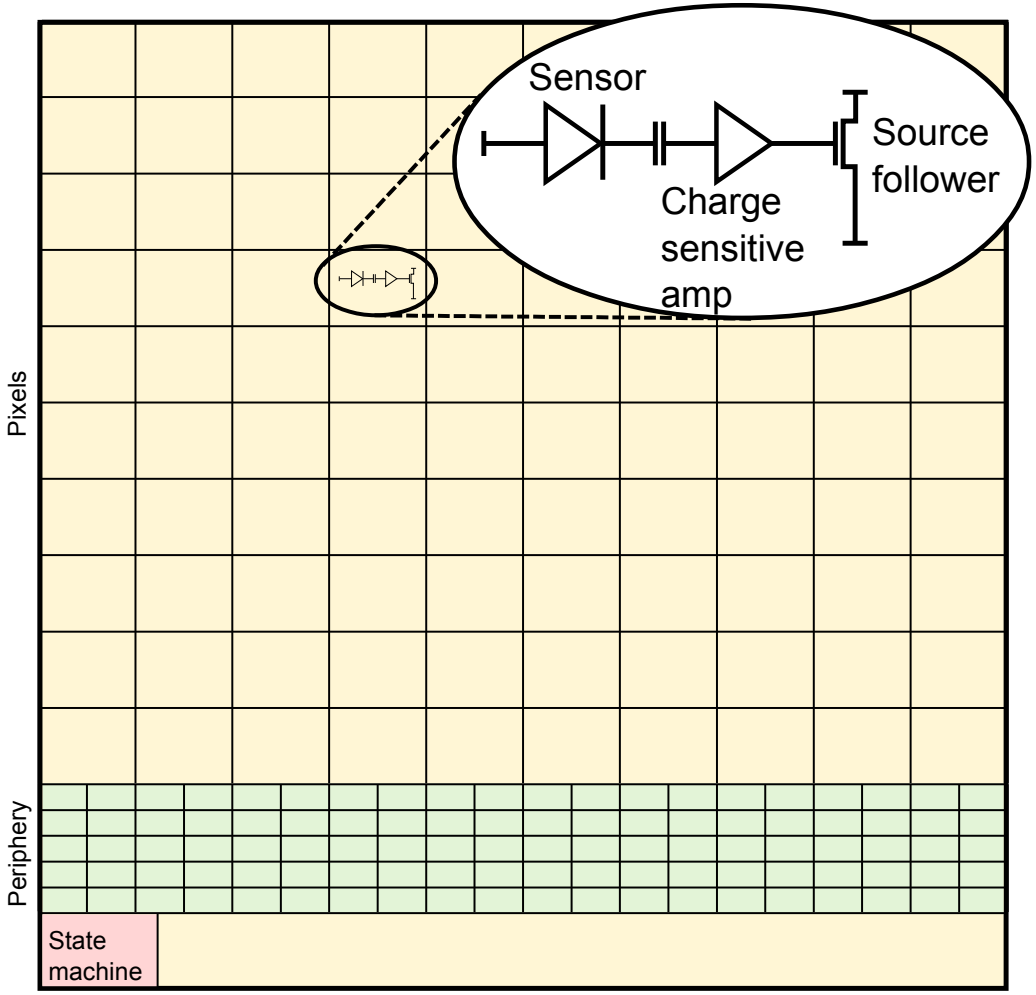
pixel matrix

“mirror” cells

state machine
VCO, PLL, ...

periphery
(5-10% total area):

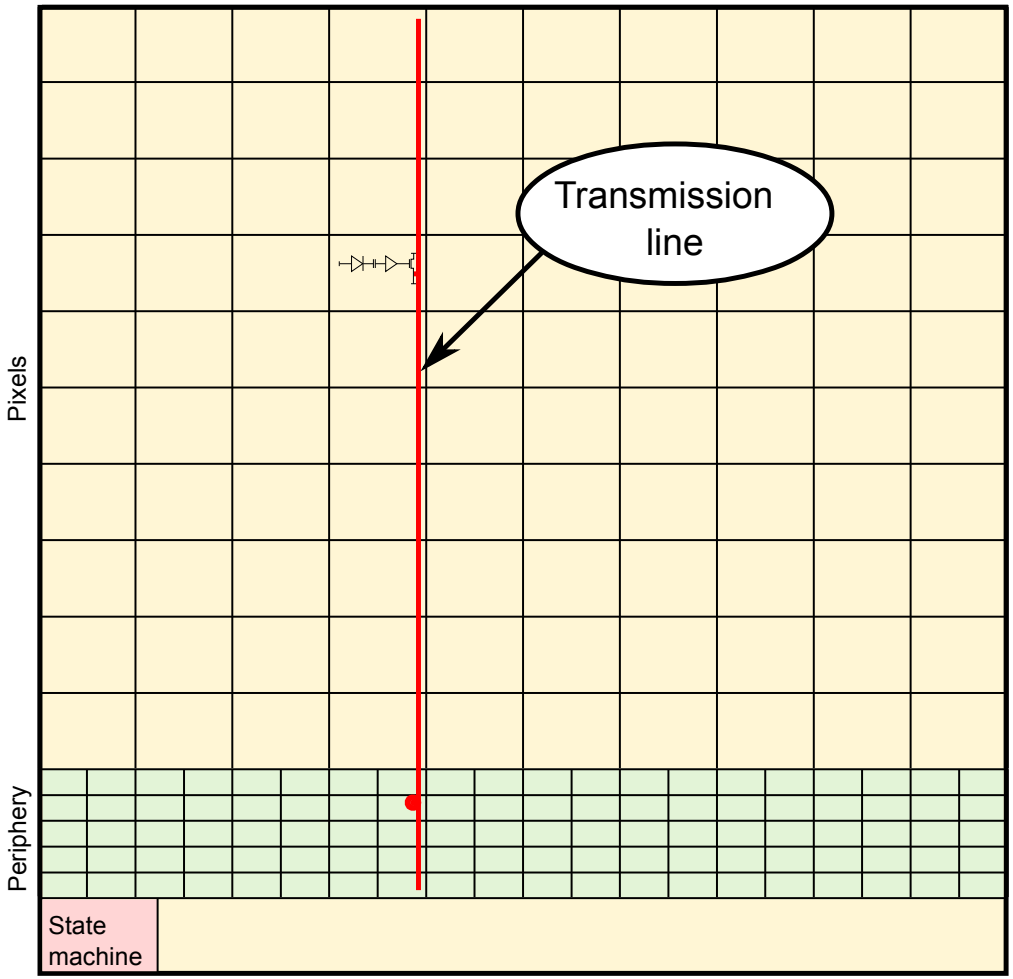
MuPix Chip Design



analog cell:

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

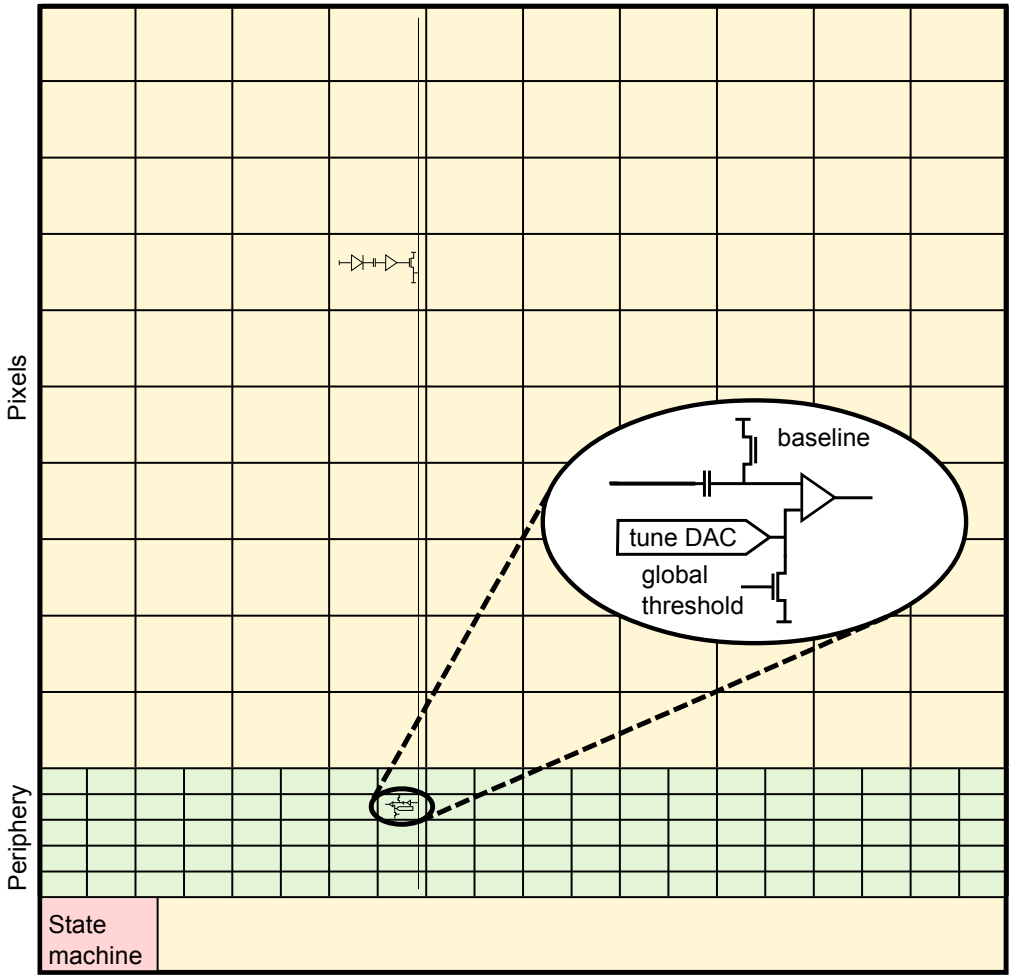
MuPix Chip Design



transmission line:

- send signal to corresponding mirror cell

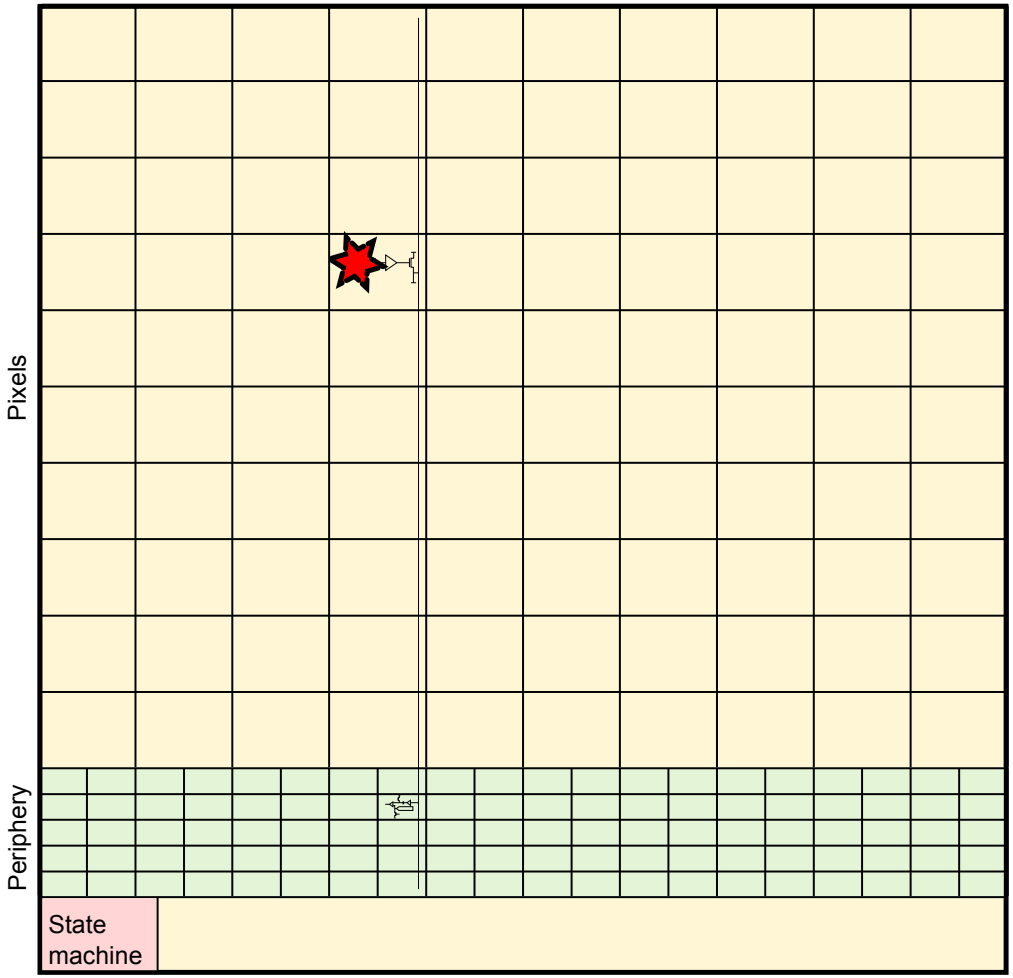
MuPix Chip Design



mirror cell:

- comparator for discrimination
- threshold and baseline by tune DACs

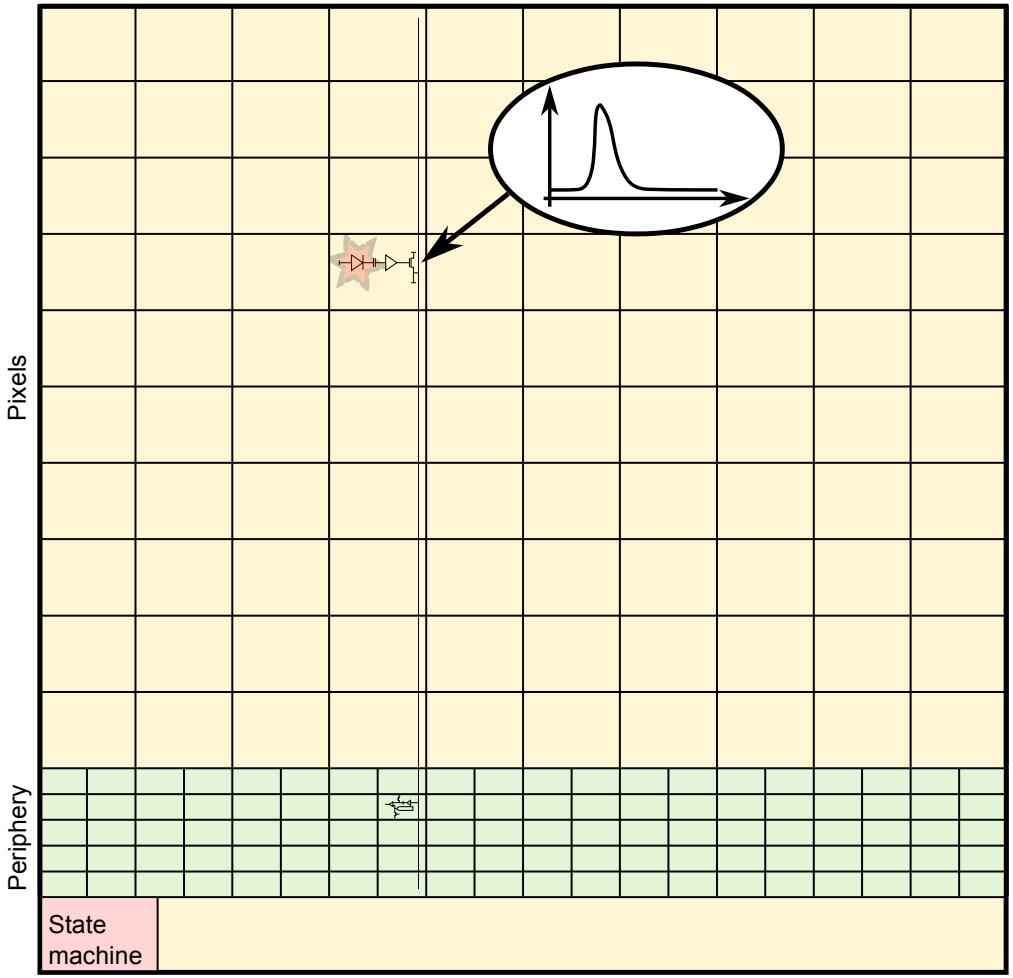
MuPix Hit Detection



hit sequence:

- signal generation

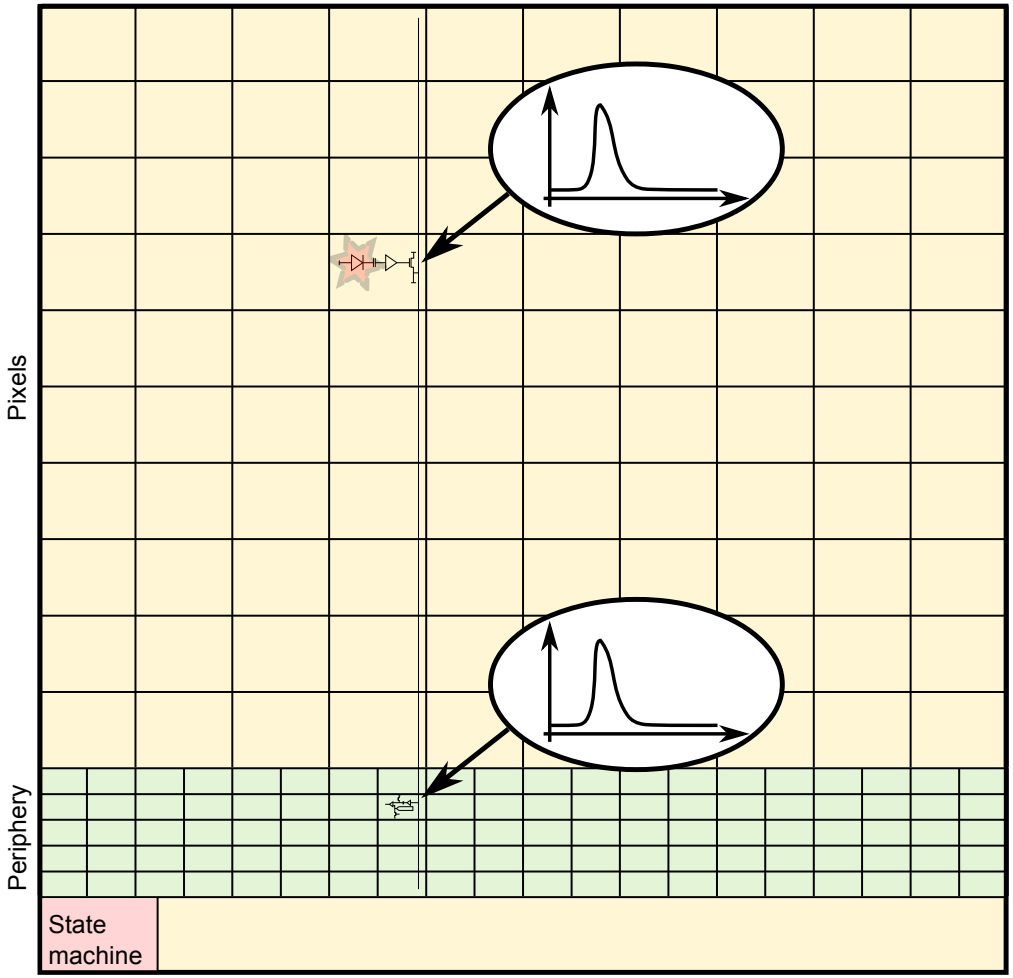
MuPix Hit Detection



hit sequence:

- signal generation
- amplification

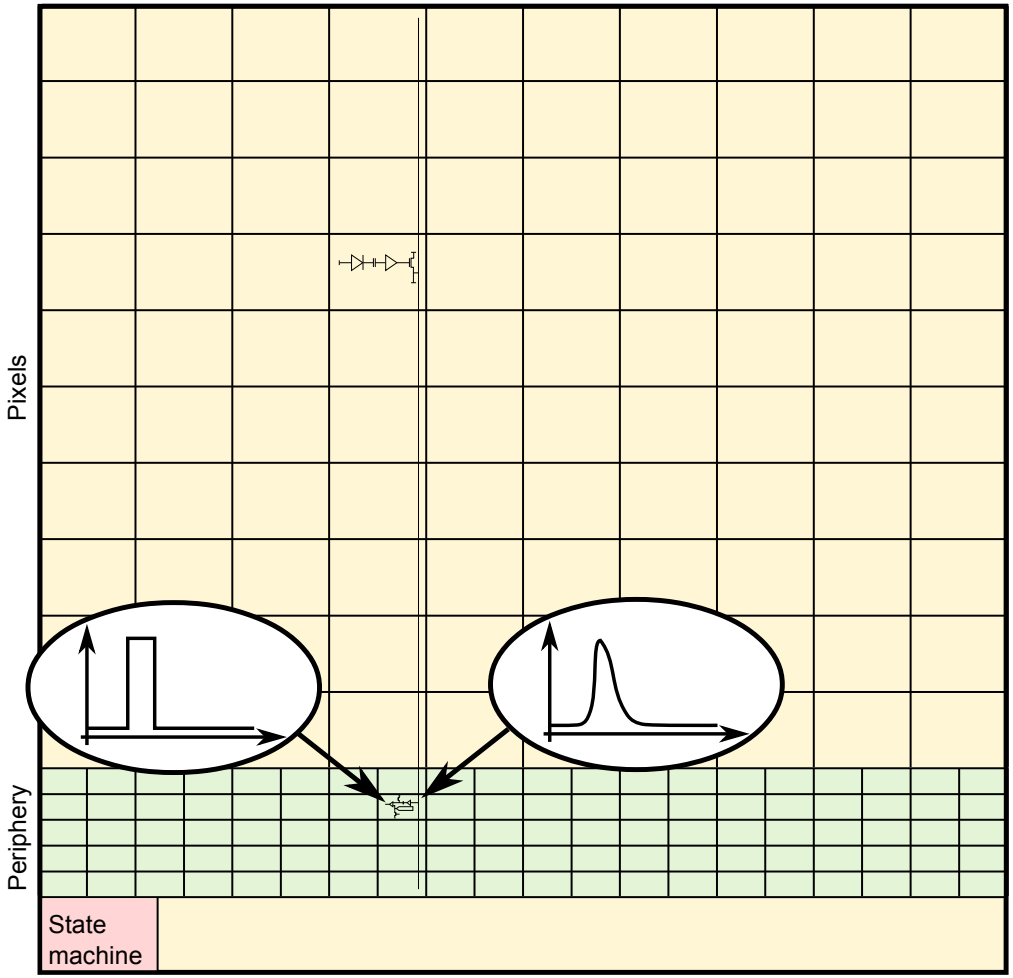
MuPix Hit Detection



hit sequence:

- signal generation
- charge amplified
- received in mirror pixel

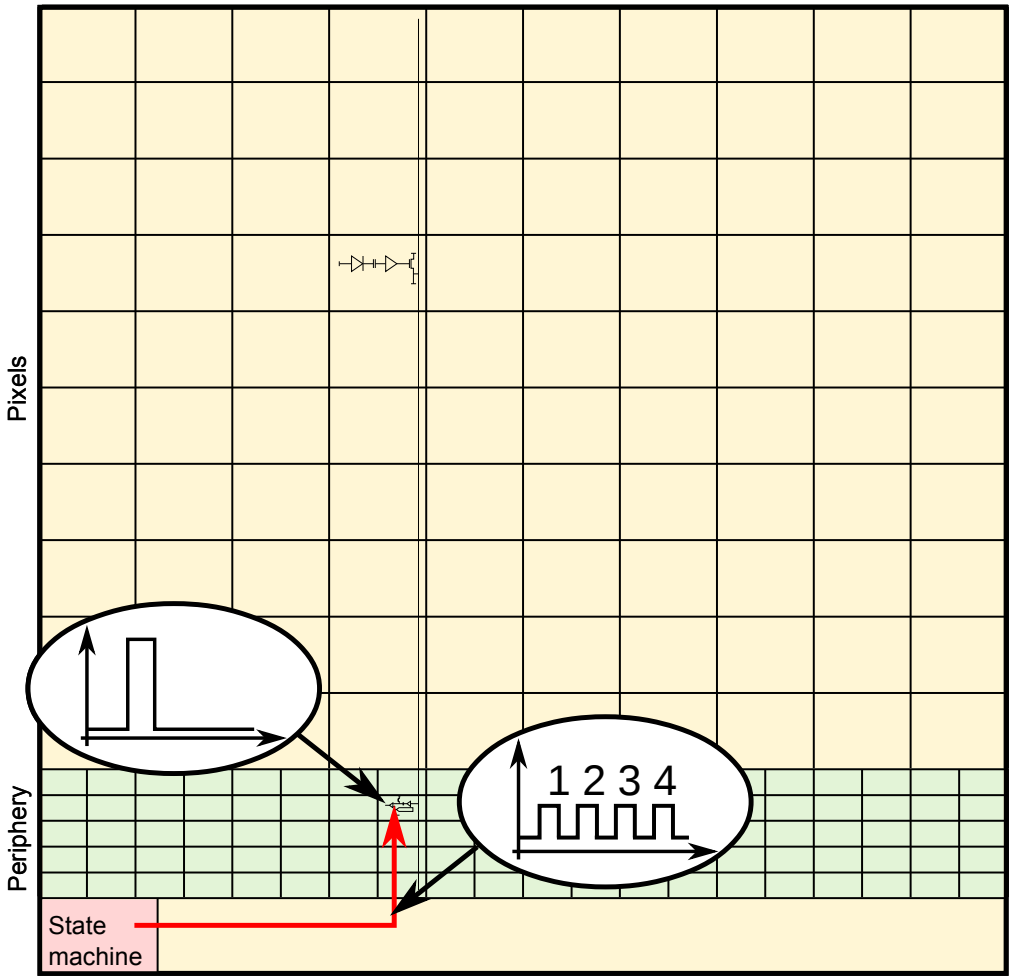
MuPix Hit Detection



hit sequence:

- signal generation
- charge amplified
- received in mirror pixel
- discriminated

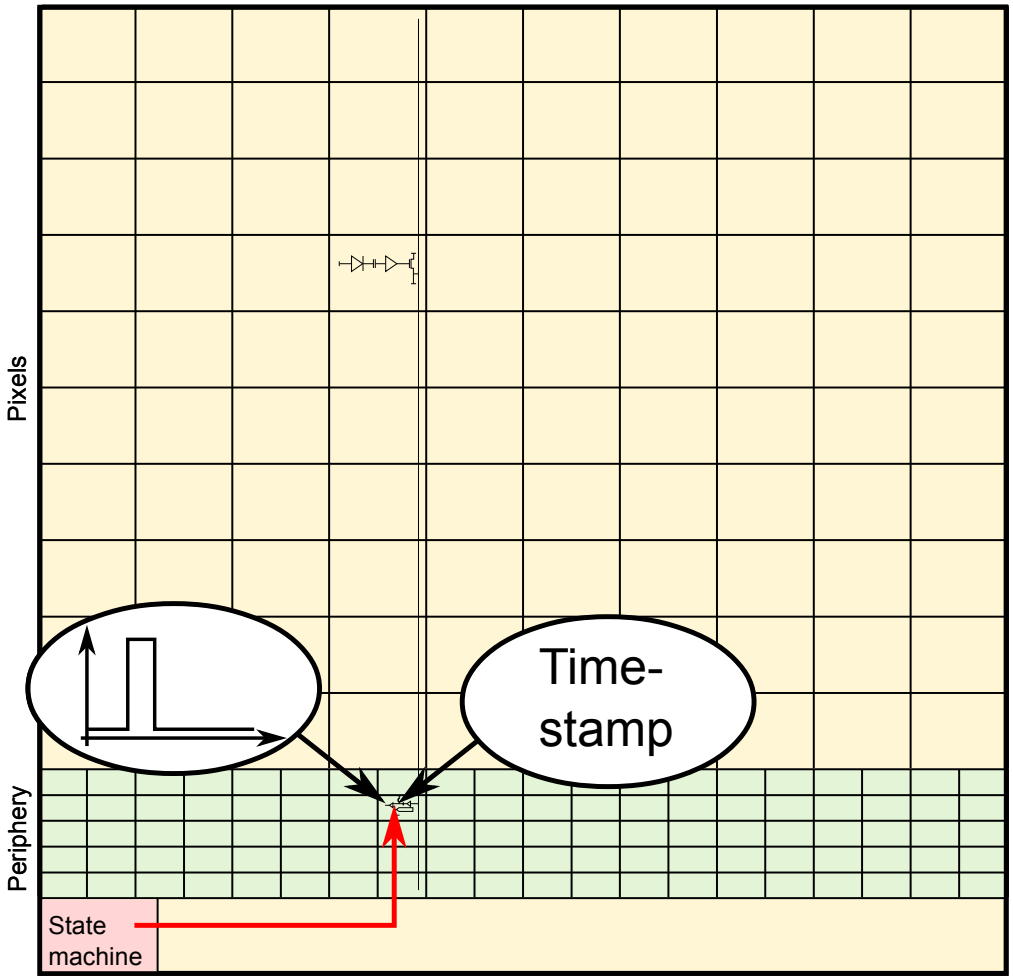
MuPix Hit Detection



hit sequence:

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

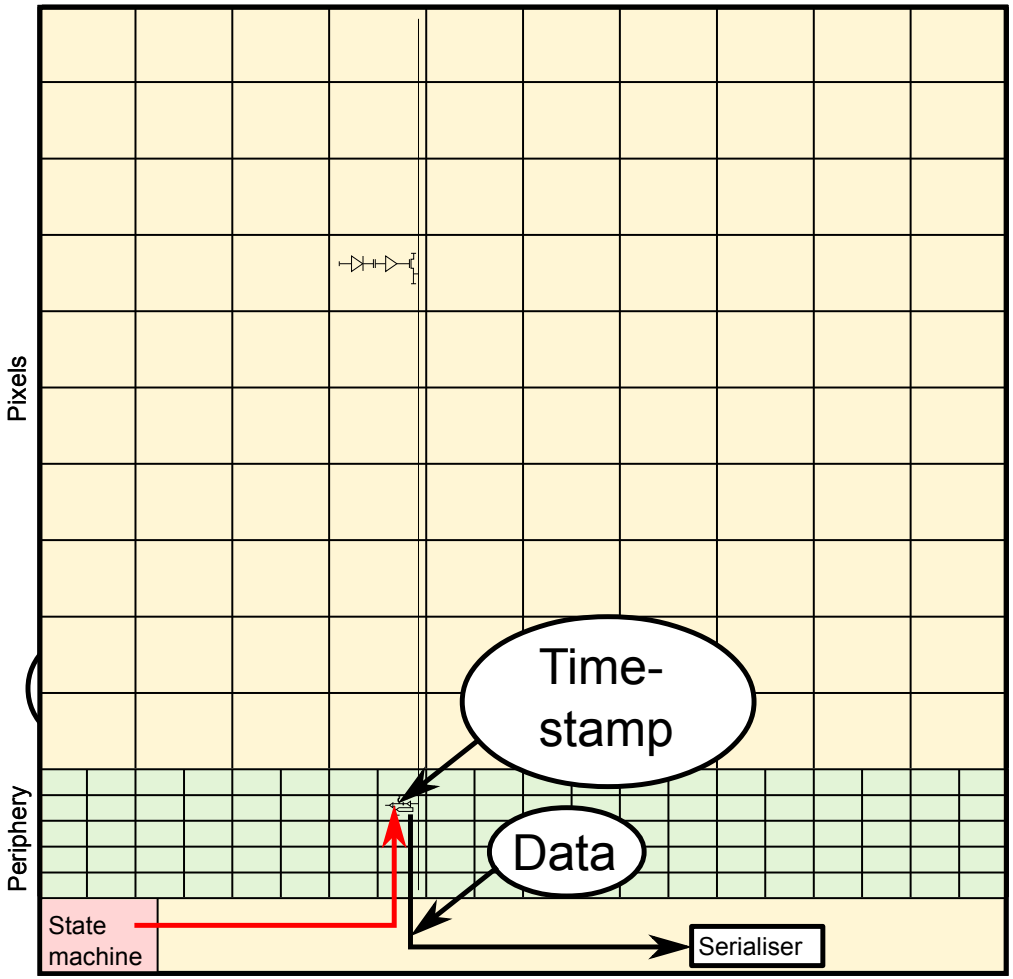
MuPix Hit Detection



hit sequence:

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

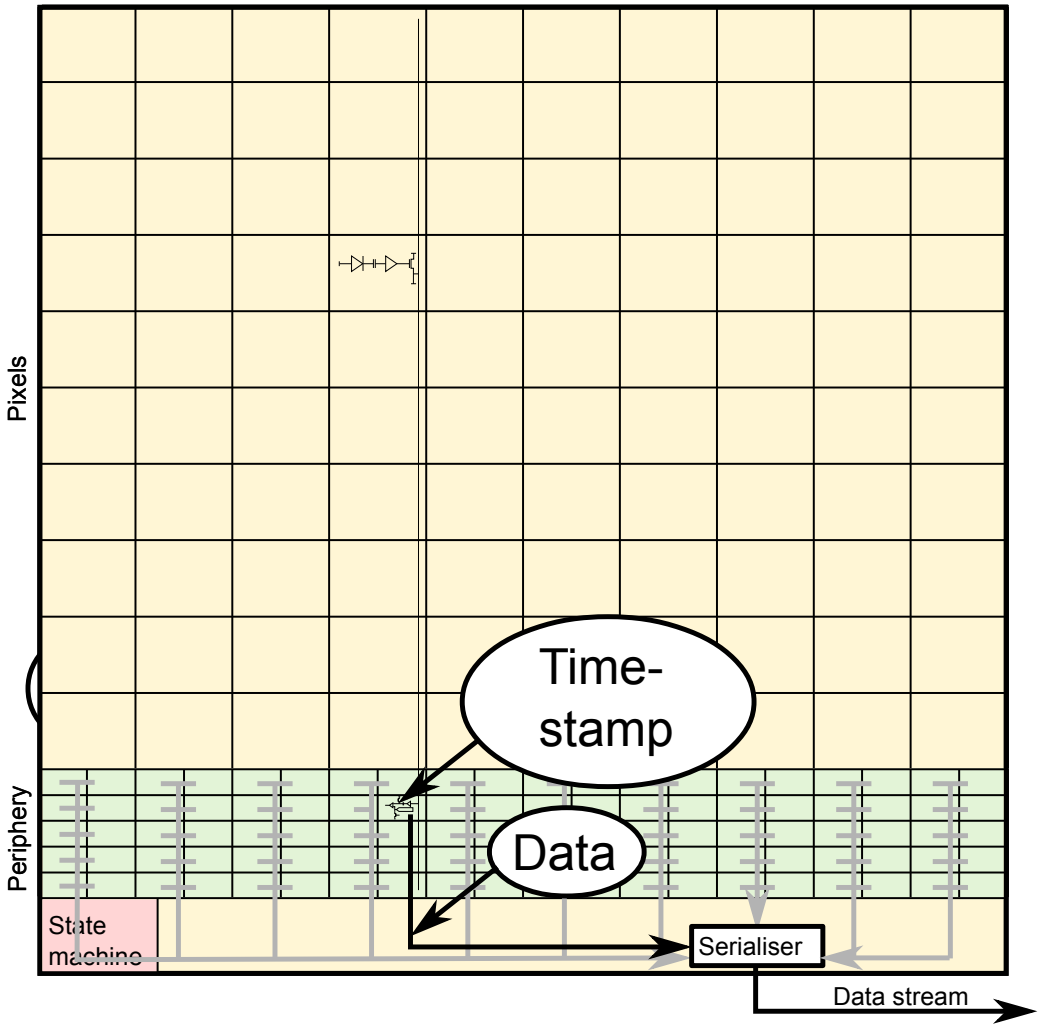
MuPix Hit Detection



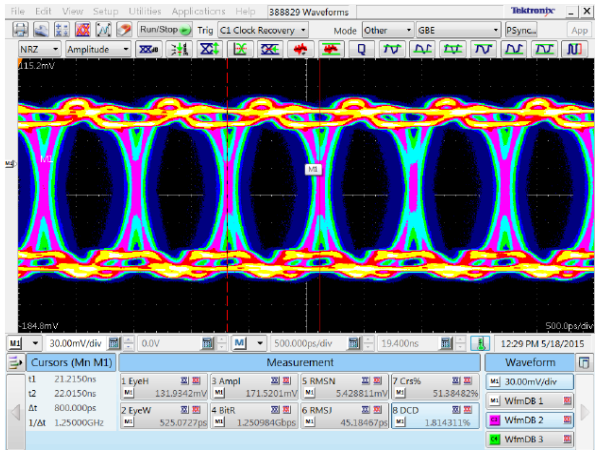
hit sequence:

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

MuPix Hit Detection



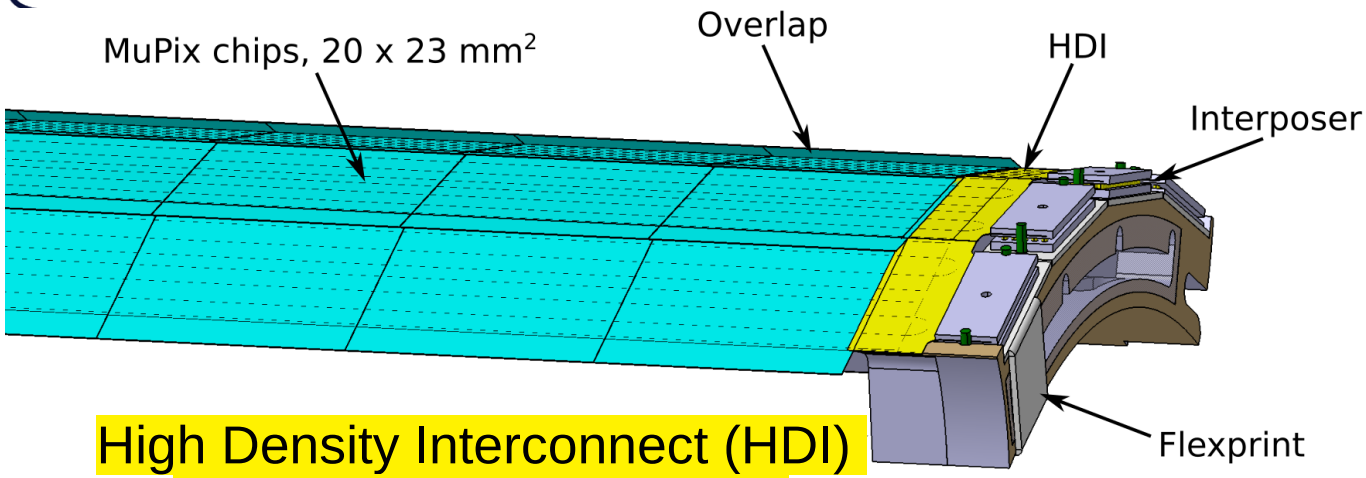
Finally, **all detected hits** are sent out via a **1.25 (1.6) Gbit/s** serial link



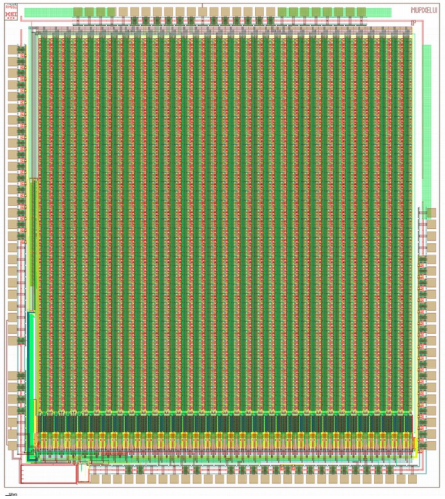
Eye diagram measured with Mupix7 prototype

Maximum readout rate is 33 Mhits/s per link

Integration & Connectivity

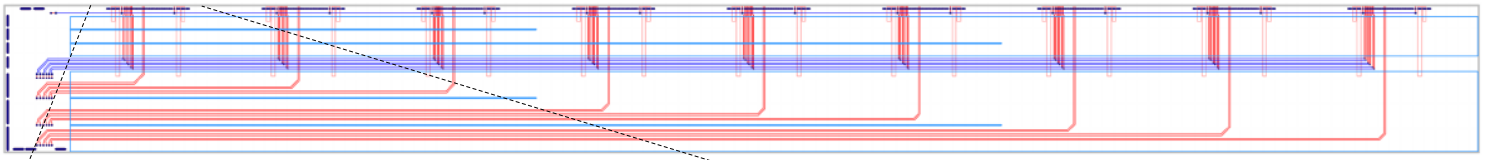


High Density Interconnect (HDI) has only two metal layers!

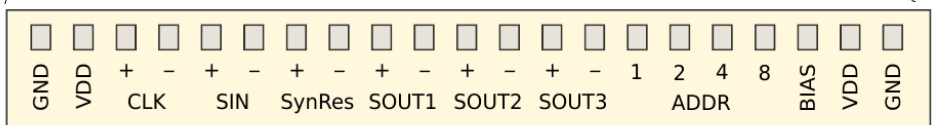


Mupix7 prototype
~100 pins (incl. test)

→ **Routing of power, control and signal lines is critical!**



HDI design (prel.)



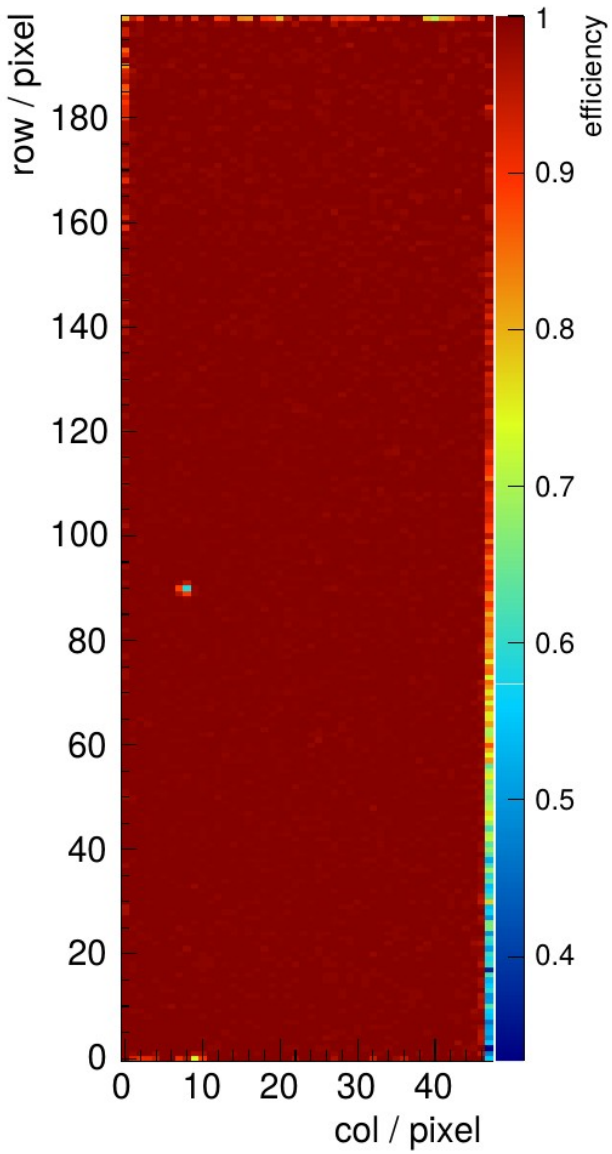
Mupix pinout with ~ 21 pins including 3 serial links

Requires high level of chip integration:

- power regulators
- state machine
- clock management
- etc.

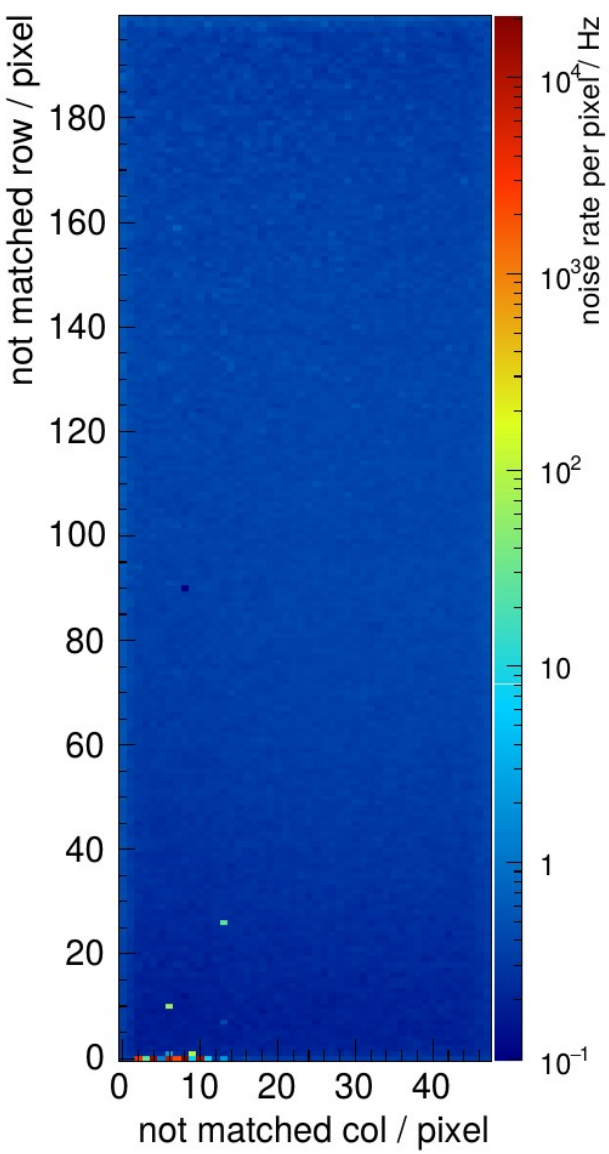
MuPix8 Performance Maps

Efficiency

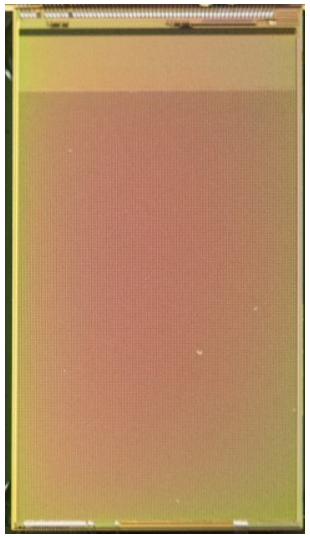


16 mm

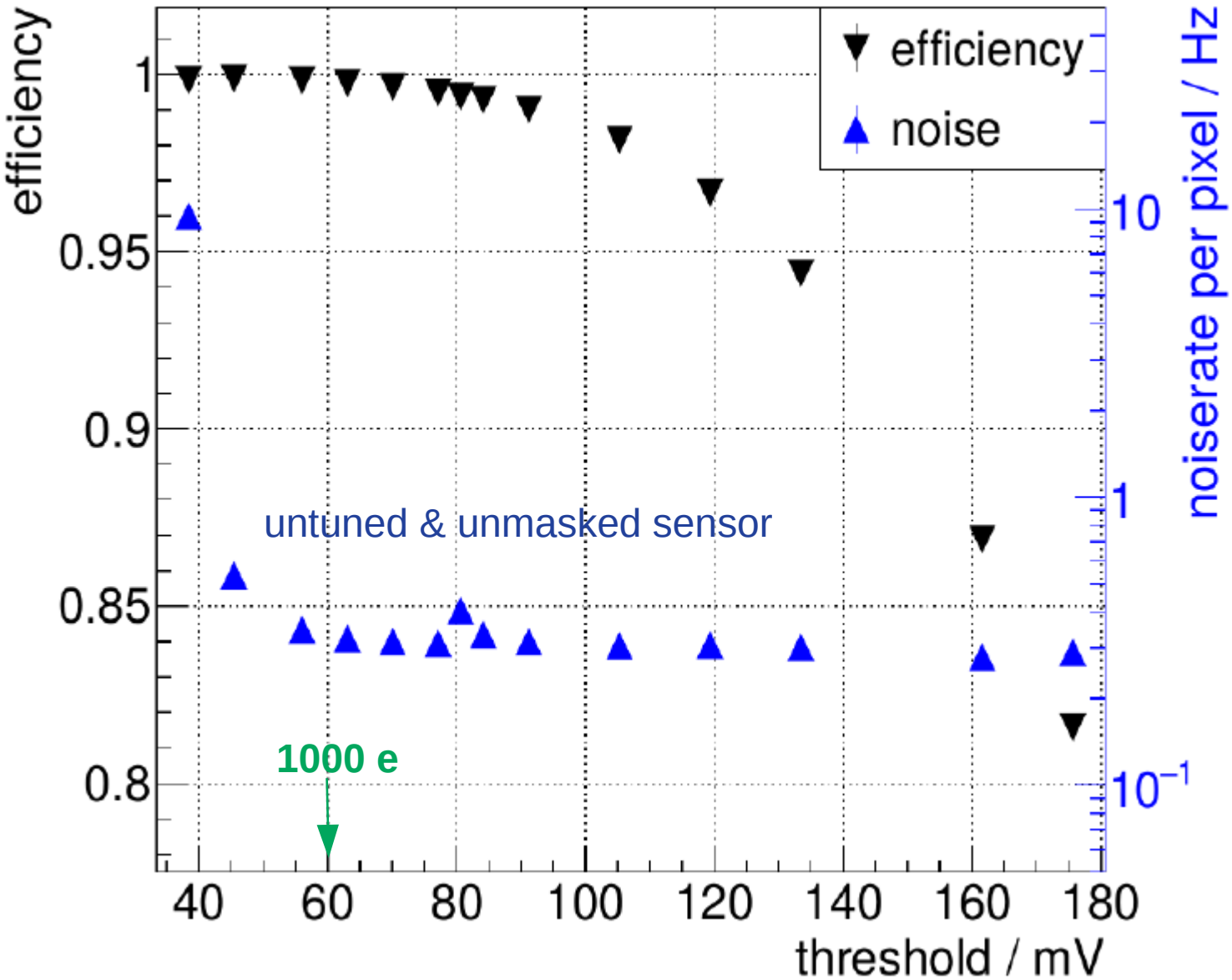
Noise



Mupix8 is the first large scale prototype

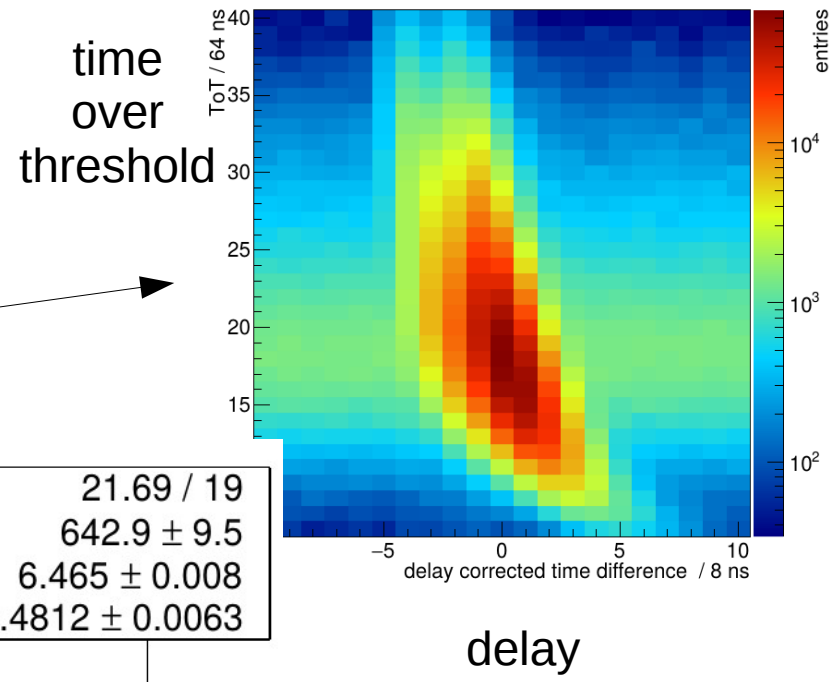


MuPix8 Efficiency and Noise

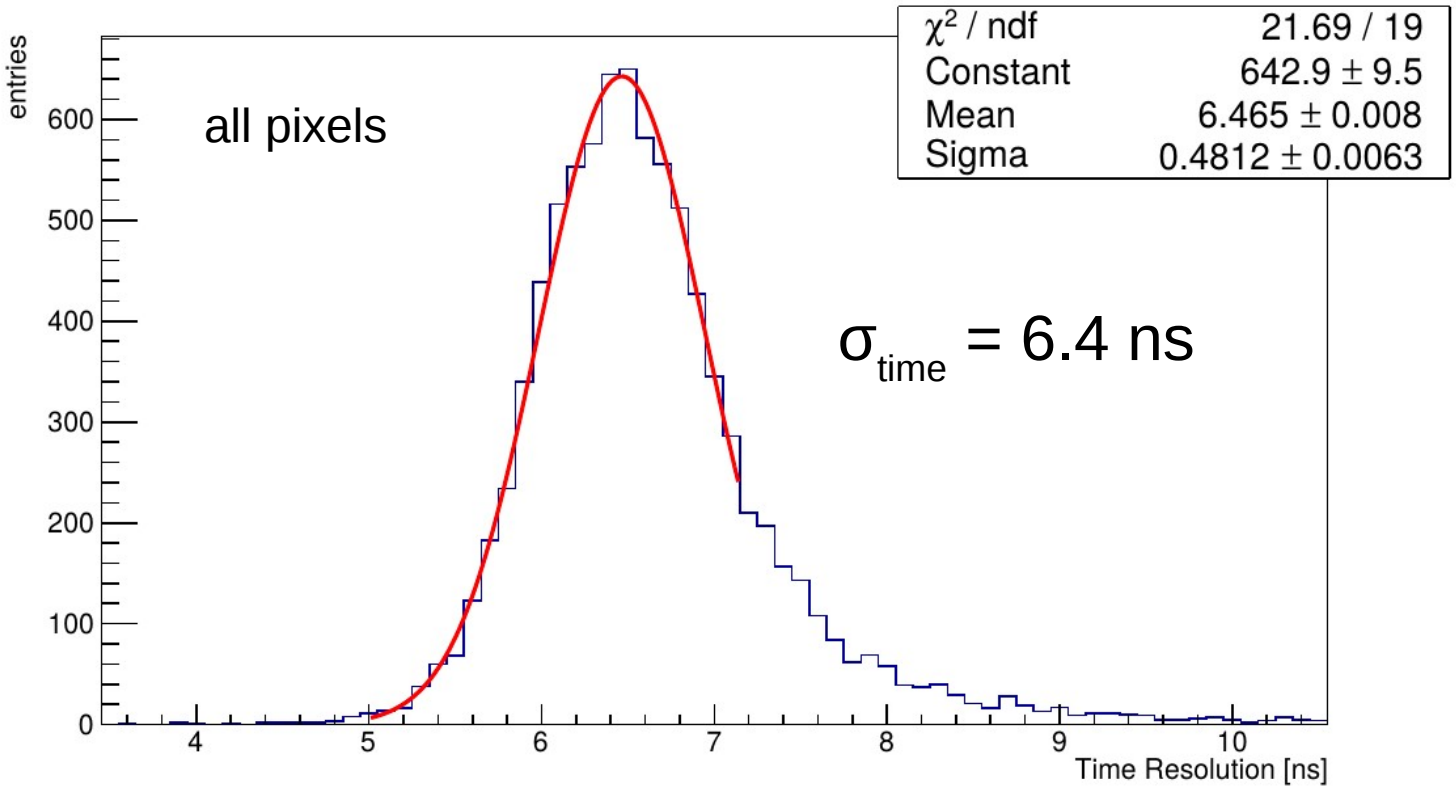


→ almost 100% efficient

MuPix8 Timing Resolution



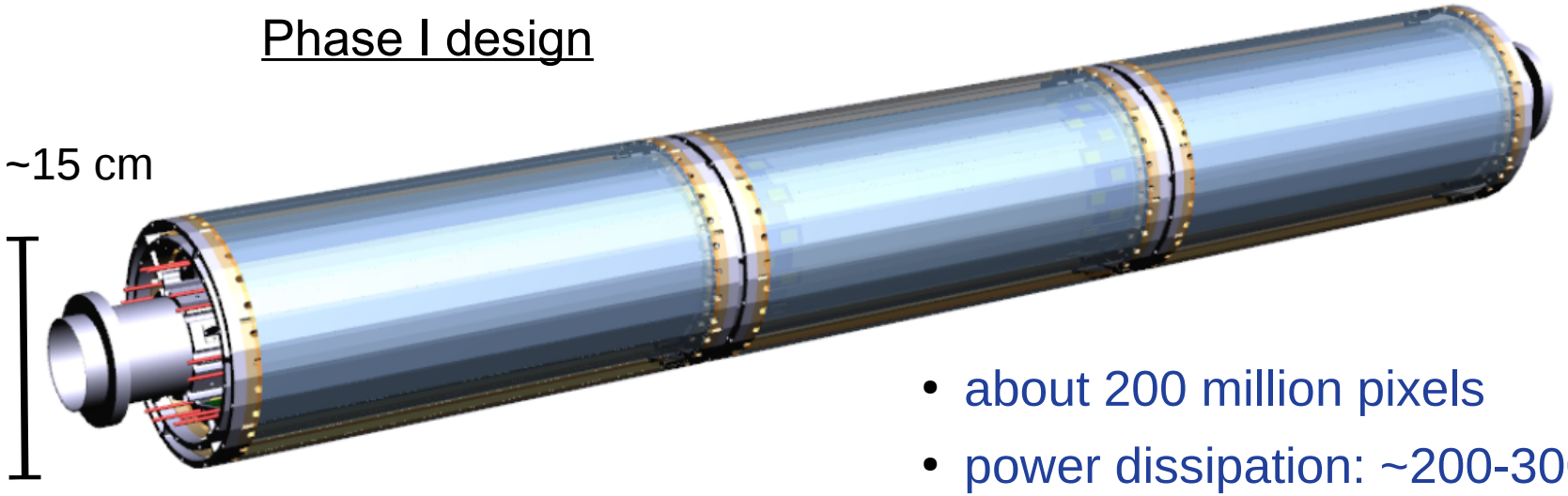
After offline timewalk correction:



Pixel Detector + Helium Gas Cooling

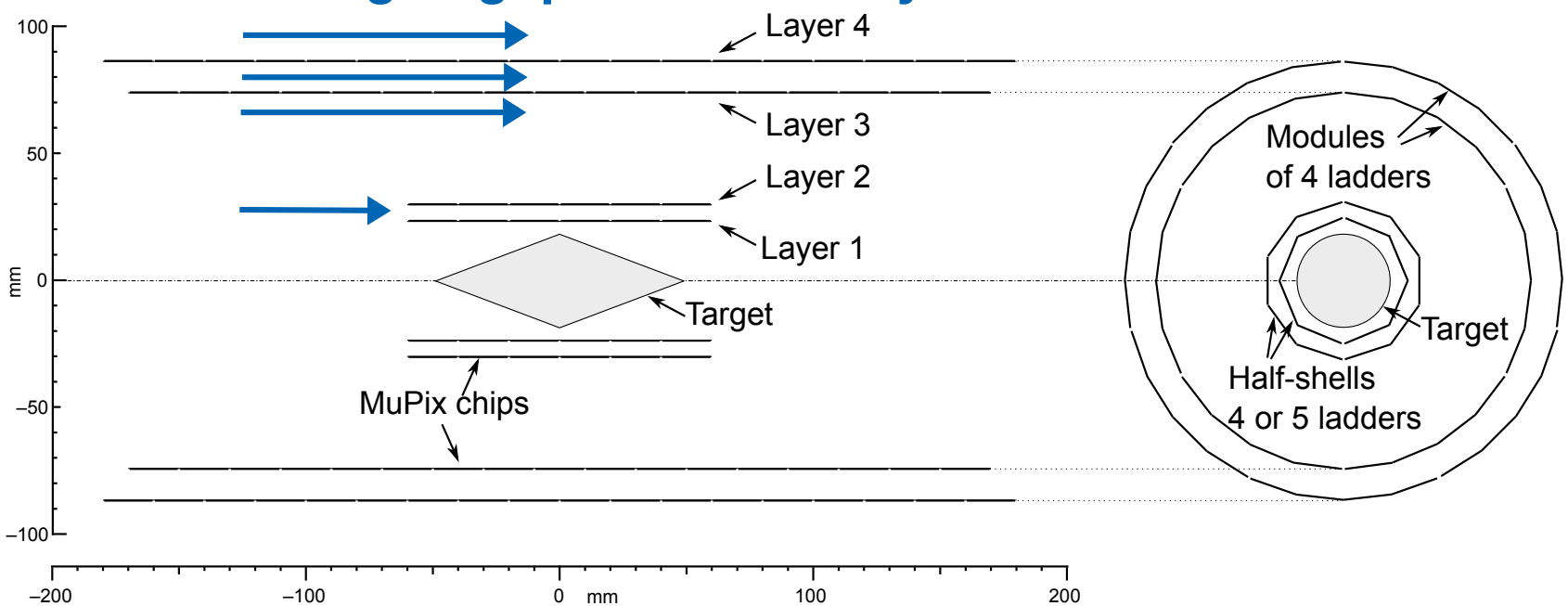
Phase I design

~15 cm

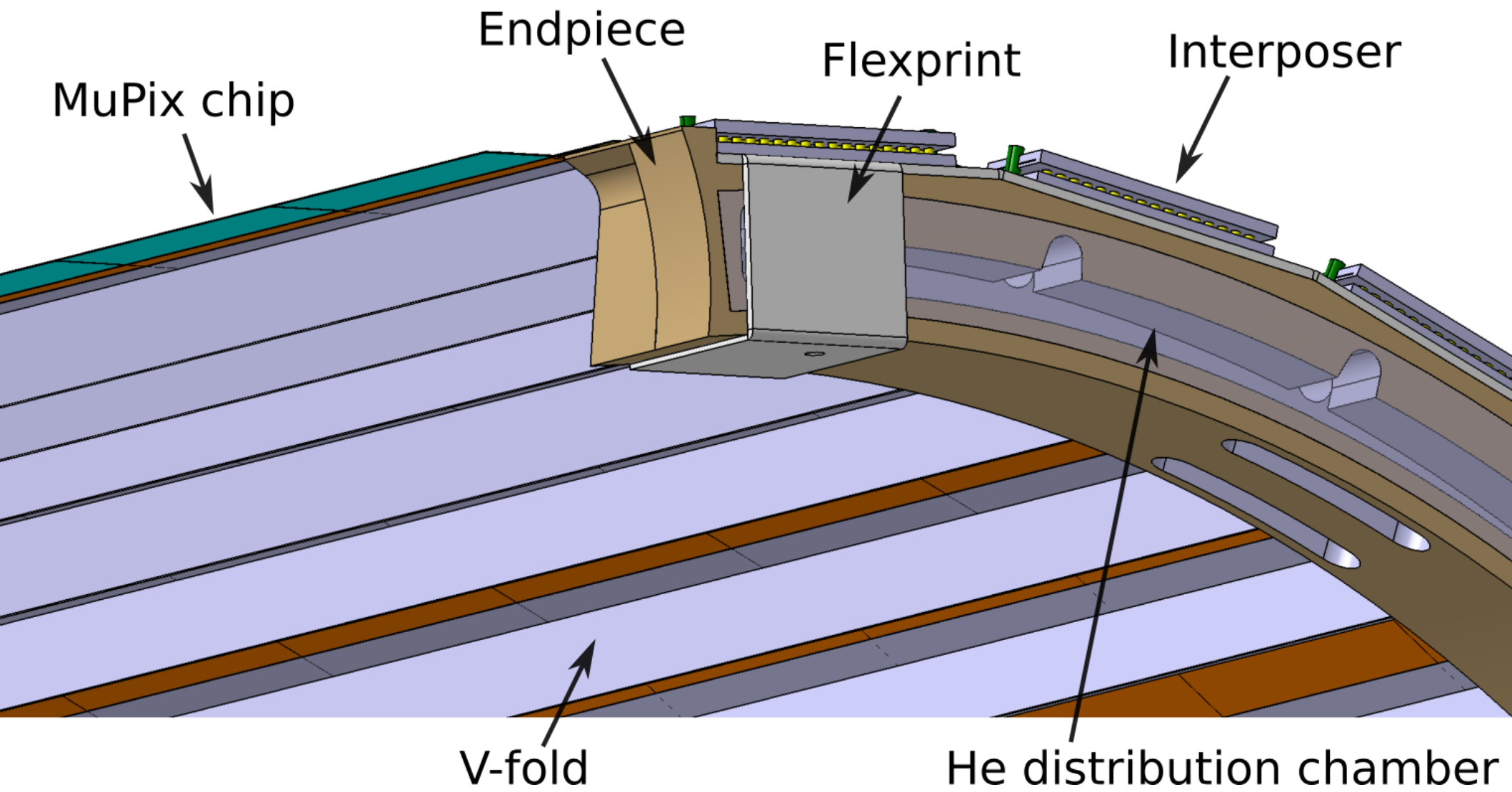


- about 200 million pixels
- power dissipation: ~200-300 mW/cm^2

He cooling in gaps between layers and detectors

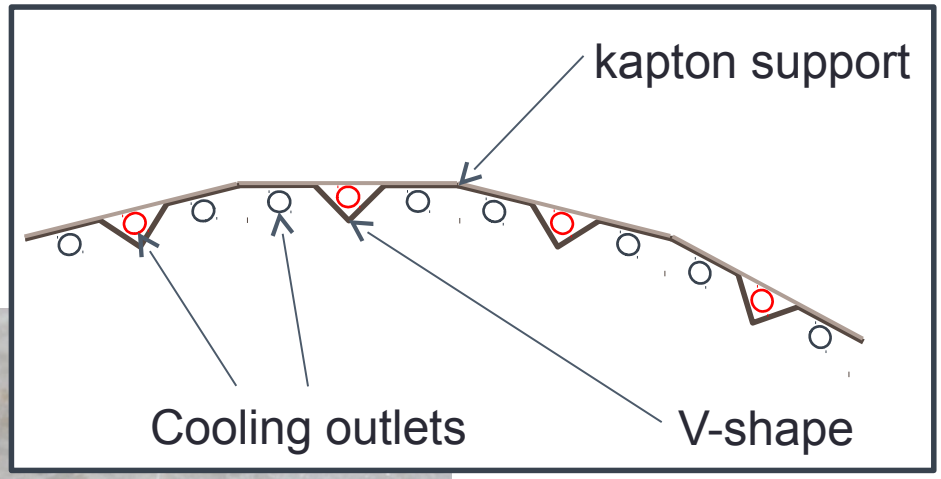


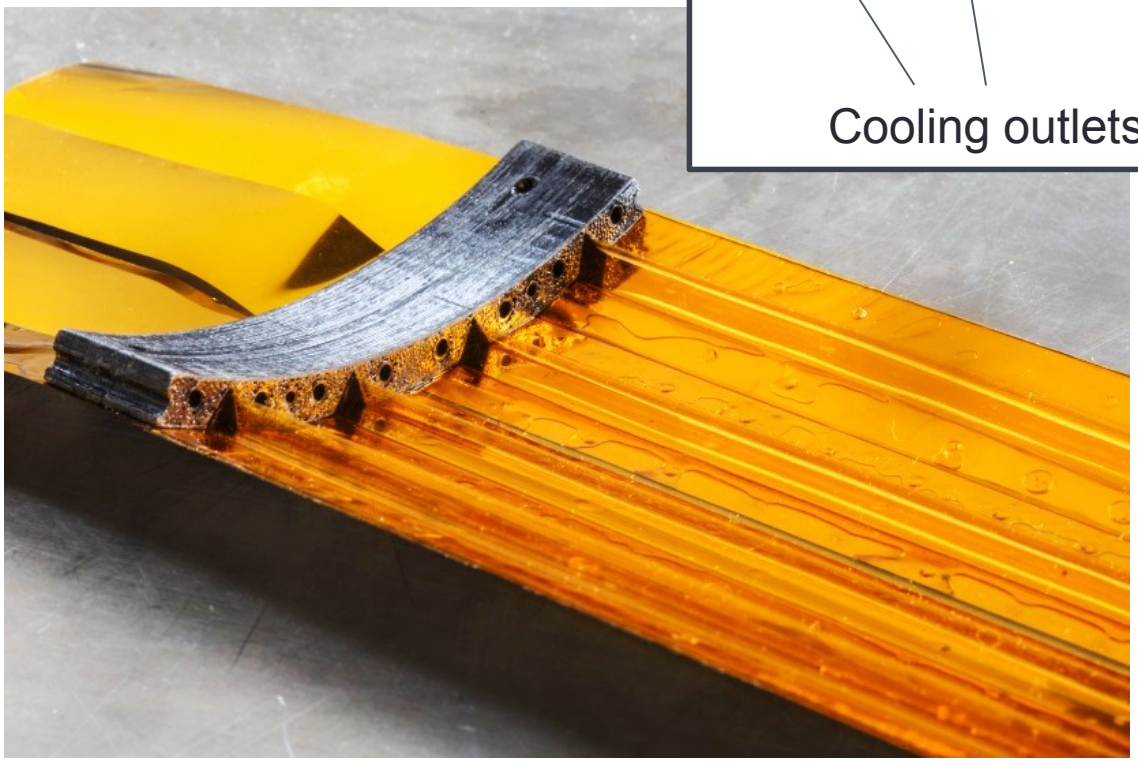
V-Fold Cooling Channels



Mechanics Prototype with V-folds

V-shapes for local cooling channels





early pixel module prototype

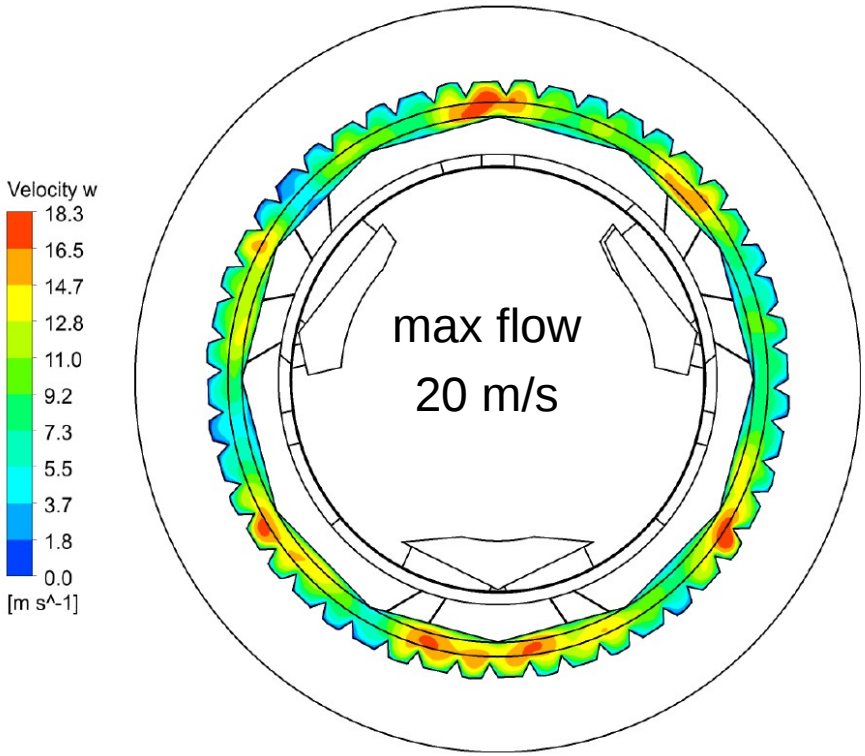
Helium cooling:

- global flow
- flow between layers
- flow in V-shapes

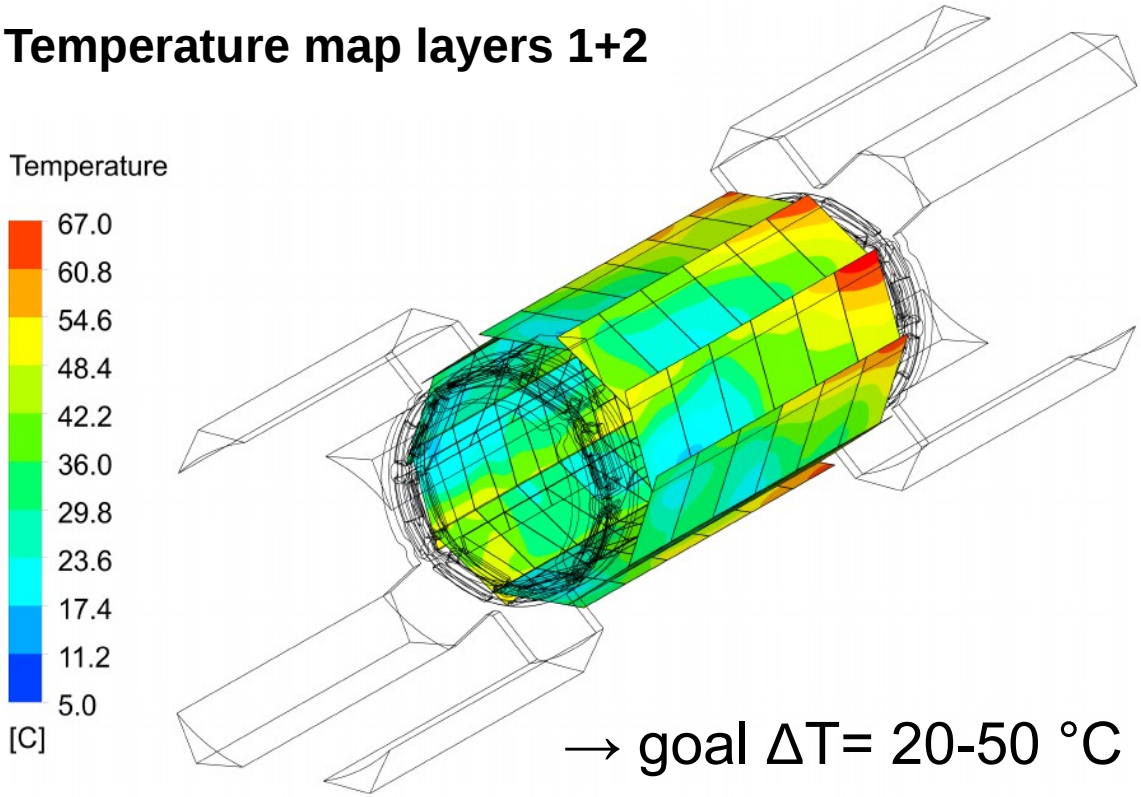
Preliminary Simulation Results

M. Deflorin (FHNW)

Velocity map layer 4



Temperature map layers 1+2



→ goal ΔT= 20-50 °C

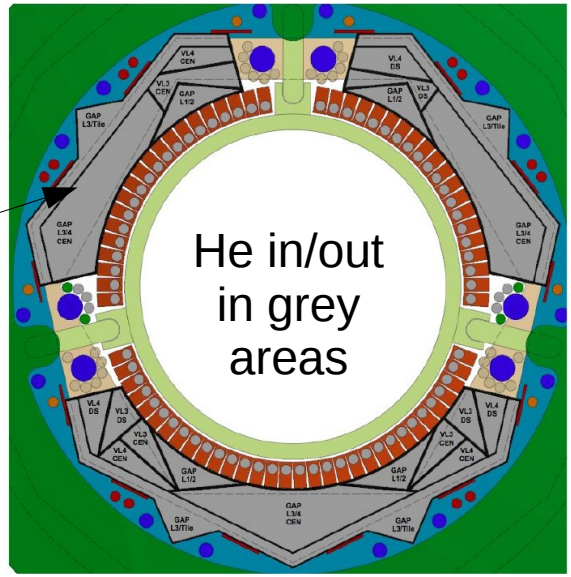
CFD Simulationsare validated by lab-measurements

- Targeted power consumption (P=250 mW/cm²)
- Maximum allowed power consumption (P=400 mW/cm²)

Light-Weight Gas Cooling System

Considerations

- Gas supply lines (pipes) require significant space
- Significant pressure drop of 50-100 mbar in detector
- He-gas needs to be pumped in and out



Mu3e cross section

150 mm

Example:

- Mupix power dissipation is max. 4 kW in Mu3e 1
- For 1m^2 active area and <ΔT>=15K → **50 g/s He**

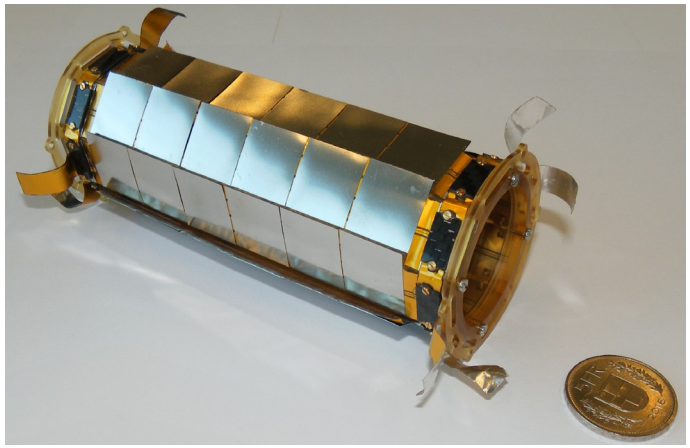
(corresponds to about 20 m^3 per minute at atmospheric pressure)

I believe up to 100 m^3 per minute (or maybe more) could be realized in future experiments → 20 kW cooling power!

Lessons and Final Remarks

Mu3e ultralight pixel tracker is based on

- monolithic pixel sensors → HV-MAPS
- ultra-light polyimide/aluminium HDIs
- polyimide mechanical support
- He-gas cooling system



mockup: Mu3e inner pixel layers

Critical points:

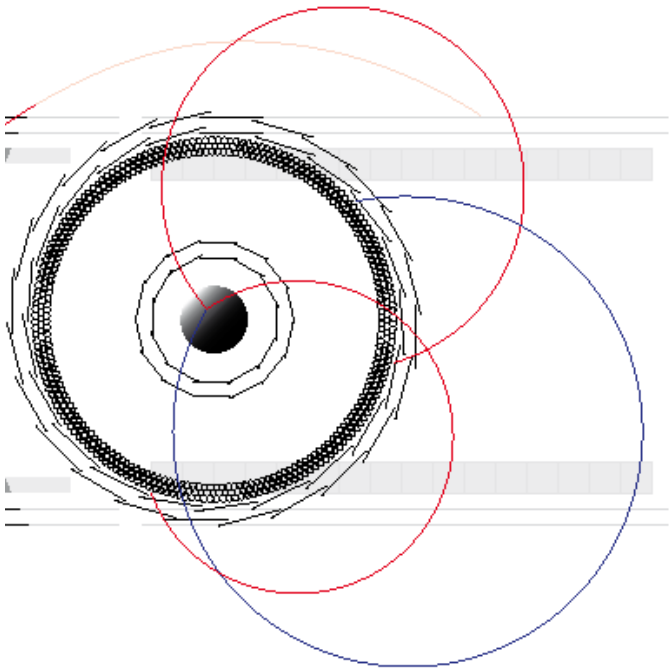
- precision of pixel modules + vibration due to gas cooling
  - ➔ vibrations measured in lab to be < 5µm
  - ➔ Mu3e will constantly monitor alignment online (studied in PhD thesis)

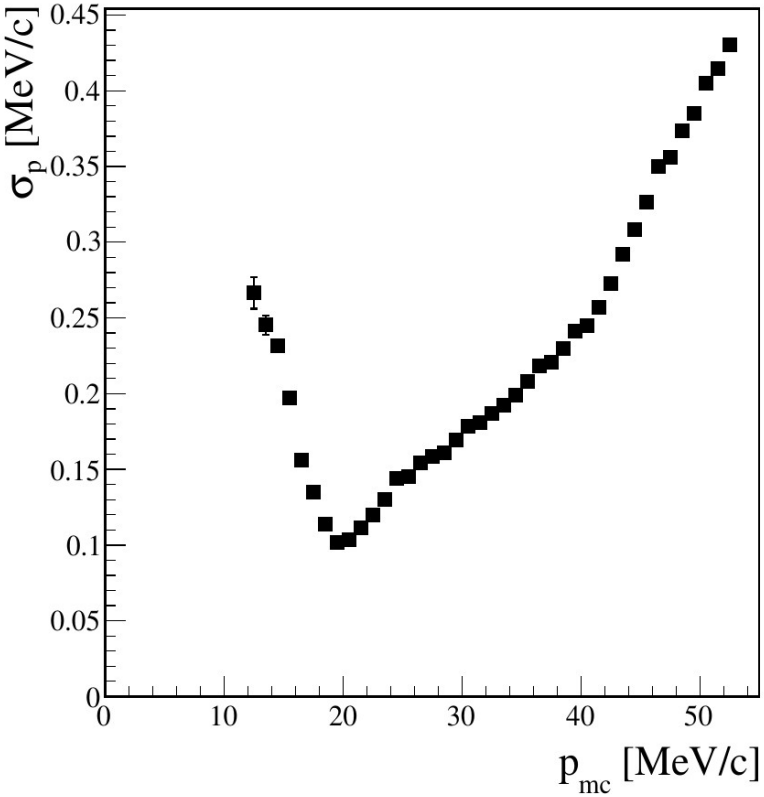
- Aging of polyimide in helium atmosphere in presence of radiation
  - ➔ currently under study

- Would like to have longer modules (>36 cm) for Mu3e phase II
  - ➔ we believe that is possible if modules are strained (tbc)

Last Comment I

Momentum resolution in Mu3e is **100 keV/c** for **20 MeV/c** positrons due to the recurler design

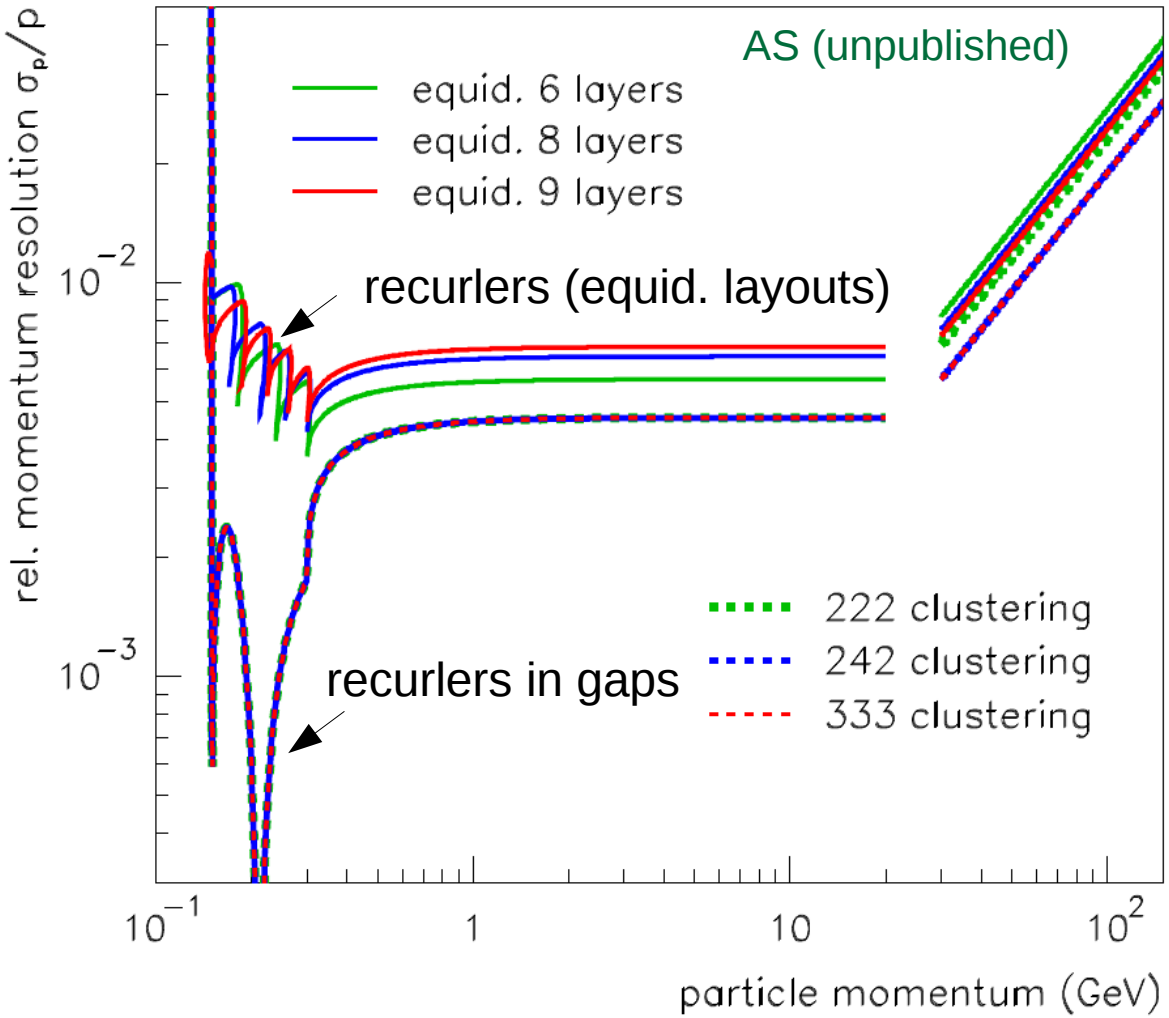




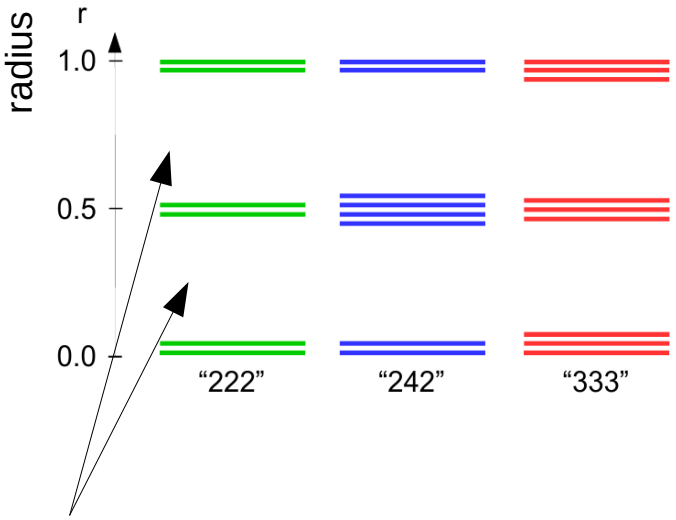
Similar “trick” works also for HEP experiments → next page

Last Comment II

Momentum resolution of an “ATLAS-like” detector with B=2T
for different designs of barrel layers



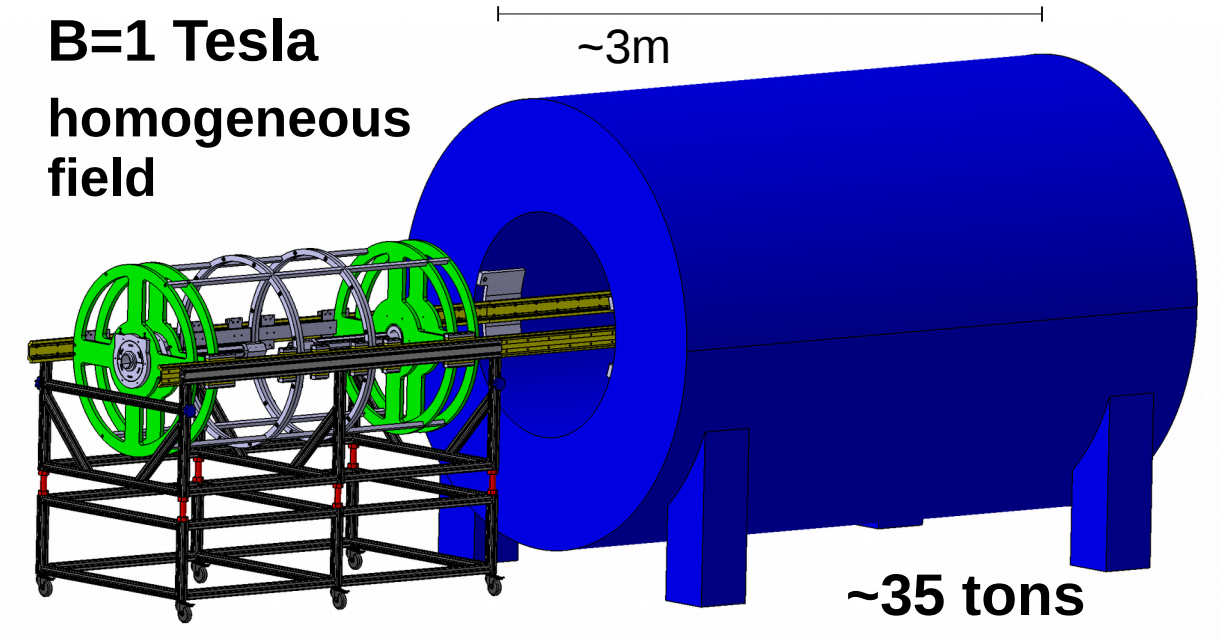
considered “clusters” of barrel layers



large gaps allow for recurling tracks

… might be interesting for physics at the “soft scale” ...

Mu3e Status and Plans



Phase I

- Comprehensive R&D (HV-MAPS, SciFi) program completed
- Detector construction starting this year
- Magnet will be delivered by Cryogenic Ltd. mid 2019
- First data taking in 2020

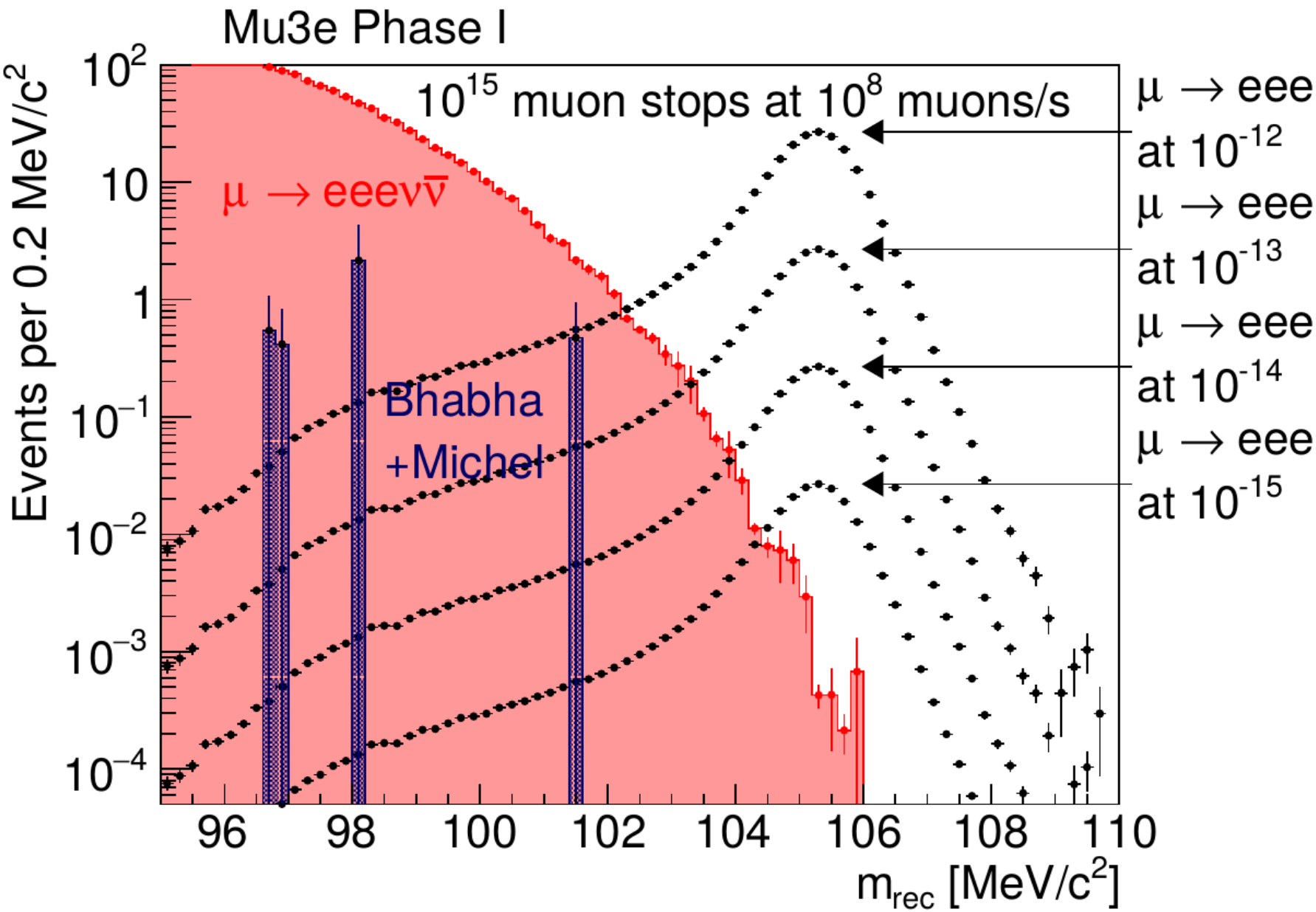
Phase II

- requires design and approval of **Hi**gh Intensity **M**uon **B**eam Line (**HiMB**)

➔ not before 2025, physics program up to ~2030

Backup

Mu3e Mass Plot (Phase I)



Mu3e Collaboration

Germany (Deutsche Forschungsgemeinschaft, Germany)

- **University Heidelberg**
- **Karlsruhe Institute of Technology**
- **University Mainz**

Switzerland (Swiss National Font, Switzerland)

- **University of Geneva**
- **Paul Scherrer Institute**
- **ETH Zurich**
- **University Zurich**

United Kingdom (STFC Council, UK)

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

about 60 members including 14 PhD students

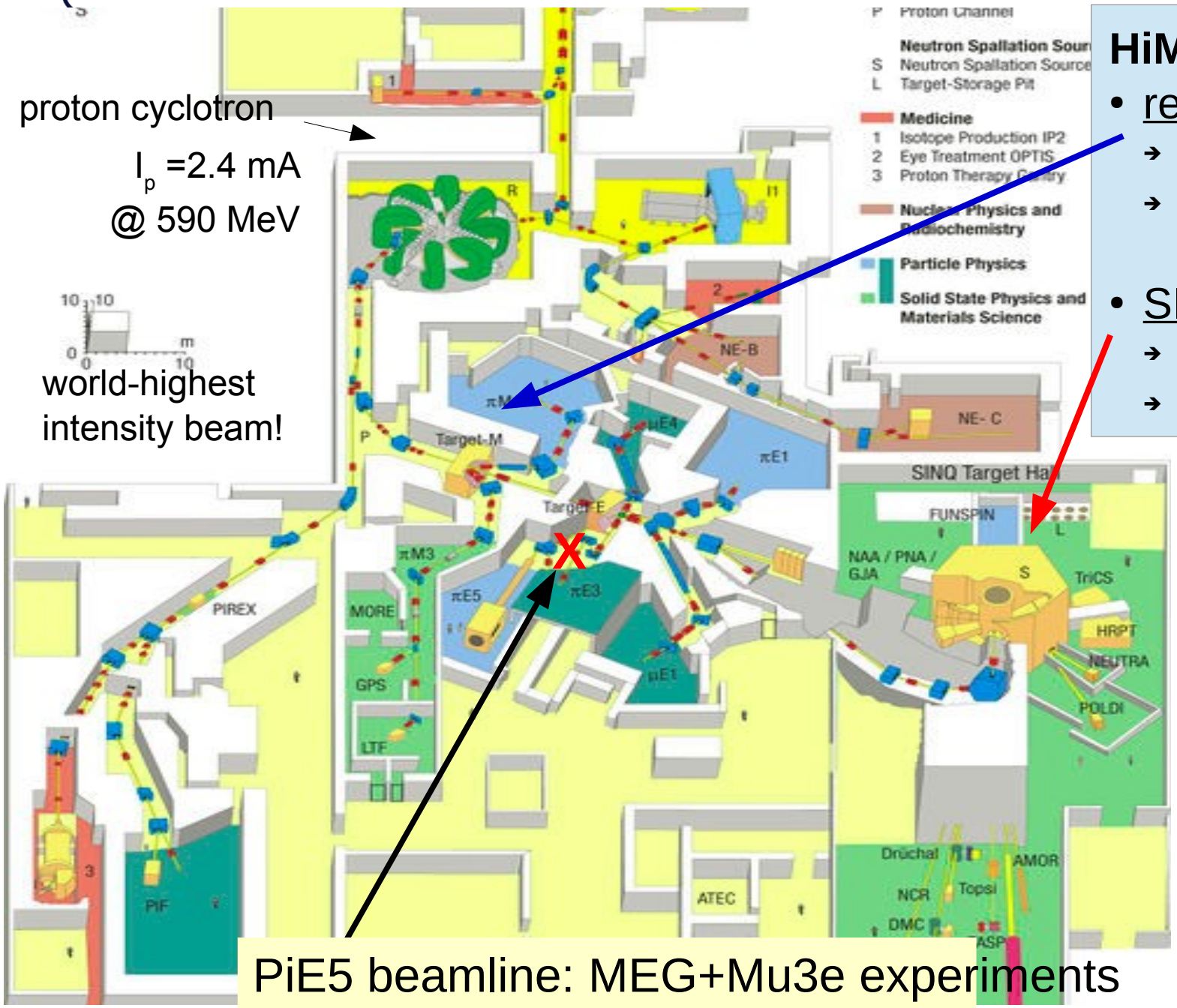
High Intensity Muon Beamline (HiMB)

proton cyclotron

I_p =2.4 mA

@ 590 MeV

world-highest intensity beam!



HiMB Studies:

- refurbish target M
  - → μ rates >> 10^9/s
  - → **promising!**
- SINQ target:
  - → rates >10^{10}/s possible
  - → but extremely difficult

PiE5 beamline: MEG+Mu3e experiments