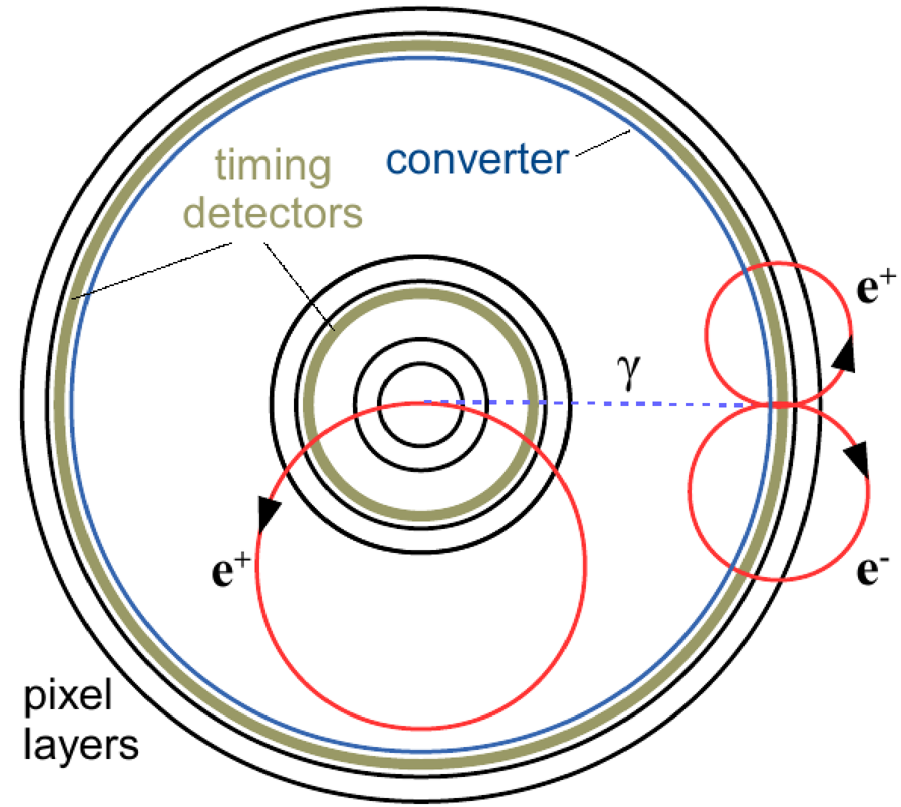
Status of Detector R&D for an All Silicon $\mu^+ \rightarrow e^+ \gamma$ Pixel Detector

Meeting on Future $\mu^+ \rightarrow e^+ \gamma$

A.Schöning

University Heidelberg, Physics Institute

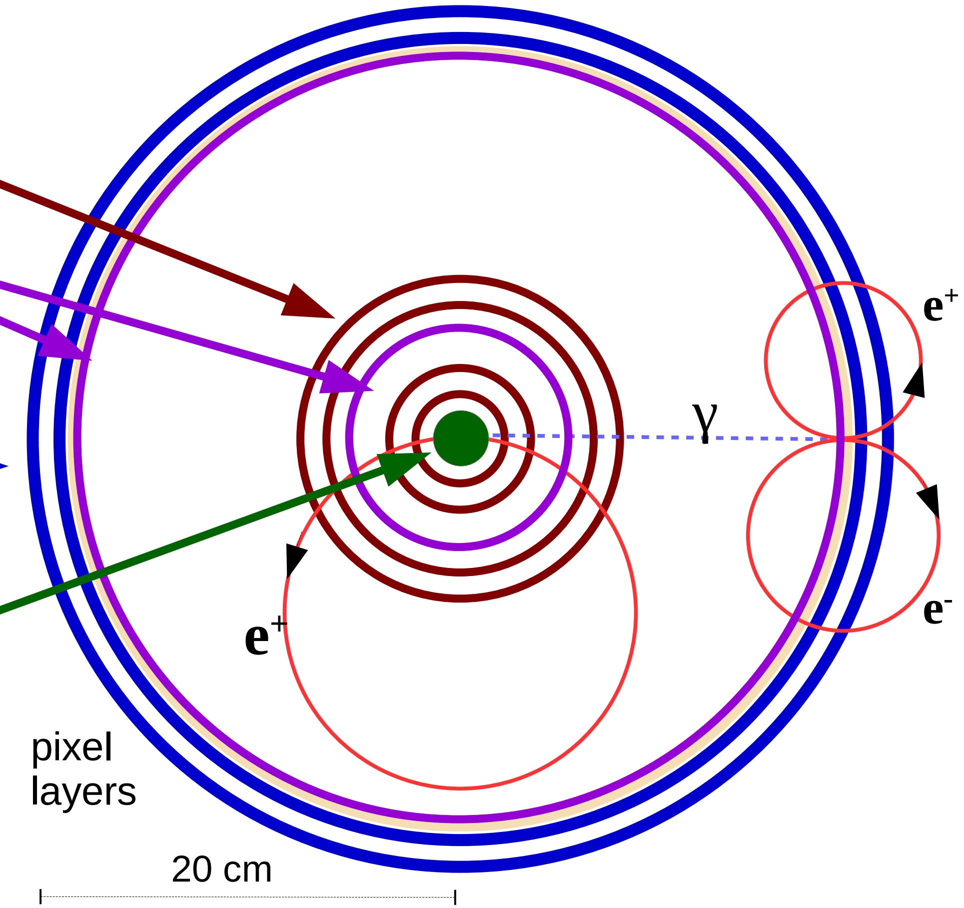


Taken from HIMB case study

All Silicon Pixel Tracker for $\mu^+ \rightarrow e^+ \gamma$

$$\frac{N_{acc}}{N_{sig}} \stackrel{\text{def}}{=} B_{acc} \propto R_\mu \, \sigma(p_e) \, \sigma(E_\gamma)^2 \, \sigma(\Theta_{e\gamma})^2 \, \sigma_{t_{e\gamma}}$$

- **Positron Tracker (incl. Vertex Detector)**
  - high rate tolerance (+++)
  - good vertex resolution (+++)
- **Ultra-Fast Silicon Pixel Detector (UFSPD)**
  - thin HVMAPS possible (+++)
  - time resolution <100 ps very challenging (---)
- **Converted Photon Tracker**
  - high spatial resolution (+++)
  - good directional resolution (+++)
  - low efficiency (---)
- **Active Muon Stopping Target**
  - precise decay vertex (+++)
  - technologically challenging (---)



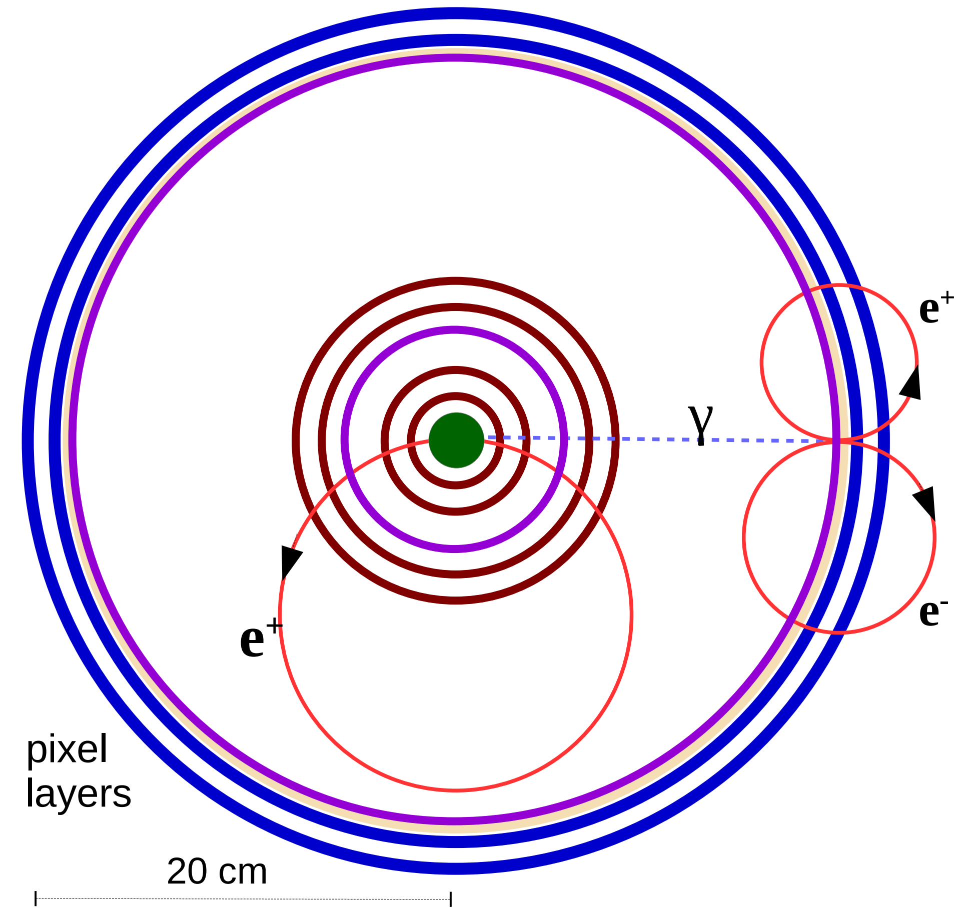
→ **Concept allows for high muon-stopping rates (R_μ)** → **high single event sensitivity (SES)**

All Silicon Pixel Tracker for $\mu^+ \rightarrow e^+ \gamma$

$$\frac{N_{acc}}{N_{sig}} \stackrel{\text{def}}{=} B_{acc} \propto R_\mu \, \sigma(p_e) \, \sigma(E_\gamma)^2 \, \sigma(\Theta_{e\gamma})^2 \, \sigma_{t_{e\gamma}}$$

Ongoing Detector R&D in Heidelberg:

- Positron measurement
  - **thin** HVMAPS vertex layer
- **Ultra-Fast** Silicon Pixel Detector (→ timing)
- Photon measurement
  - Development of **thick HVMAPS converter**
  - Measurement of **in-situ** ionisation loss in silicon
- Overall Design
  - Mu3e-Gamma Concept
  - Positron momentum resolution

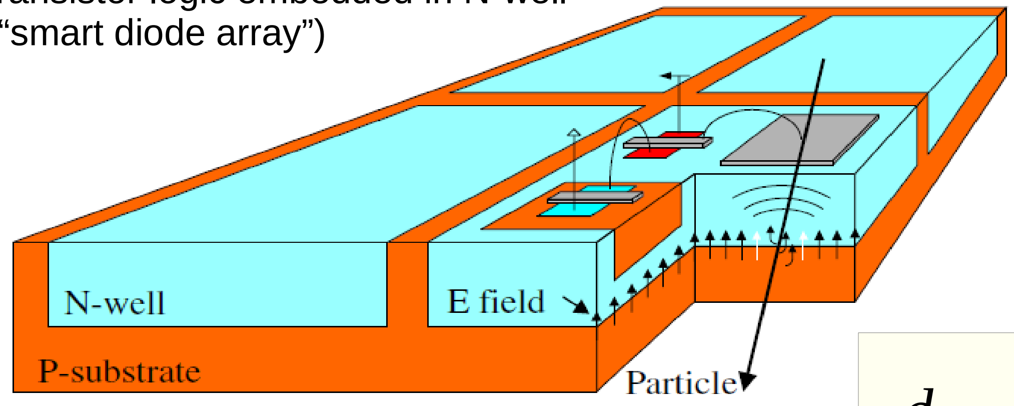


Very Challenging Detector Design!

High Voltage Active Monolithic Pixel Sensors

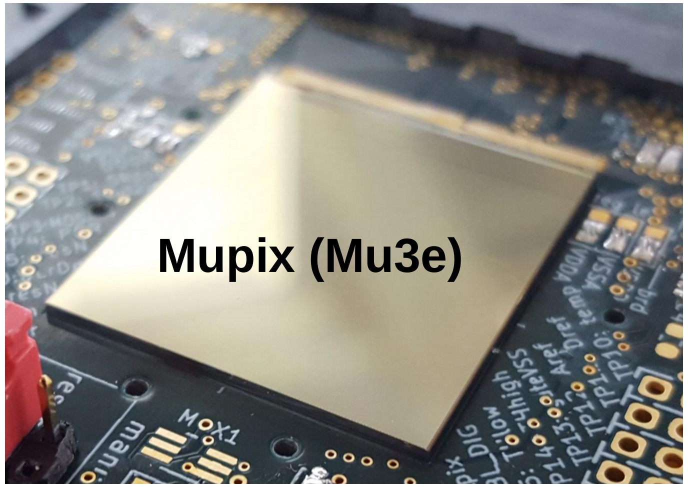
High Voltage-Monolithic Active Pixel Sensor (HV-MAPS)

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

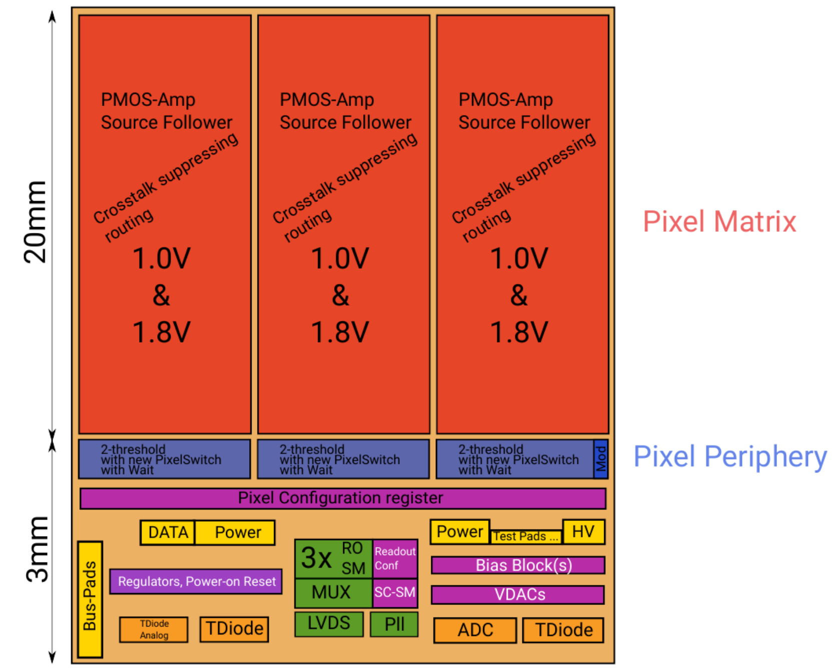


$$d_{depletion} \propto \sqrt{U_{bias}\,\rho}$$

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



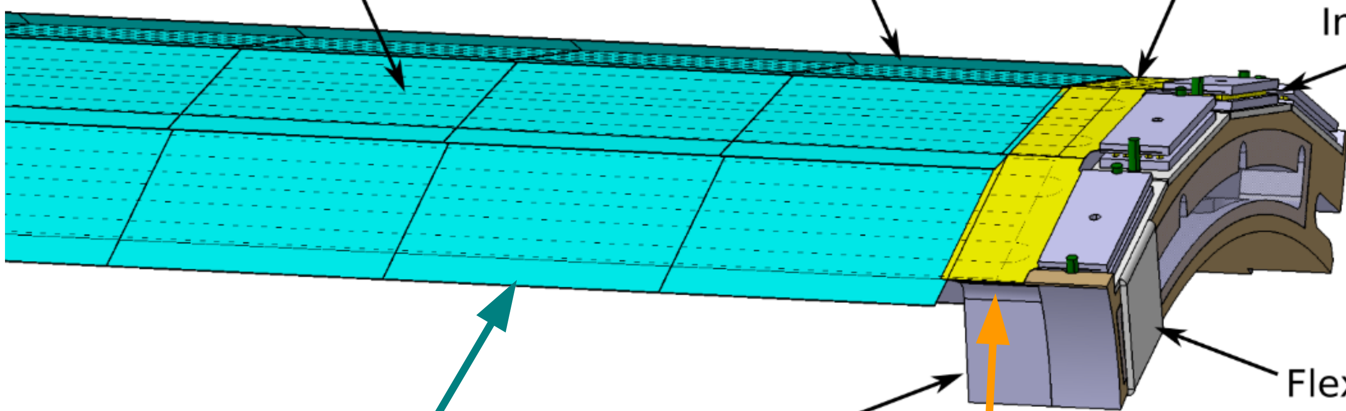
sensor: 20 x 20 mm^2 pixel: 80 x 80 µm^2



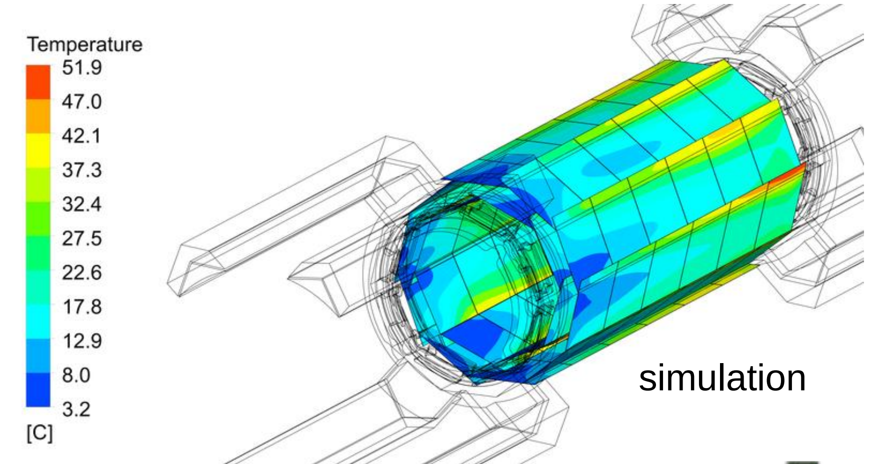
- **fully monolithic: hit detection + digitisation + readout**
- 180nm HV-CMOS process
- "low" cost
- capable of high hit rates and fast readout
- can be thinned to ~**50 µm** (~ 0.0005 X_0)

HVMAPS Tracking Detector (Mu3e)

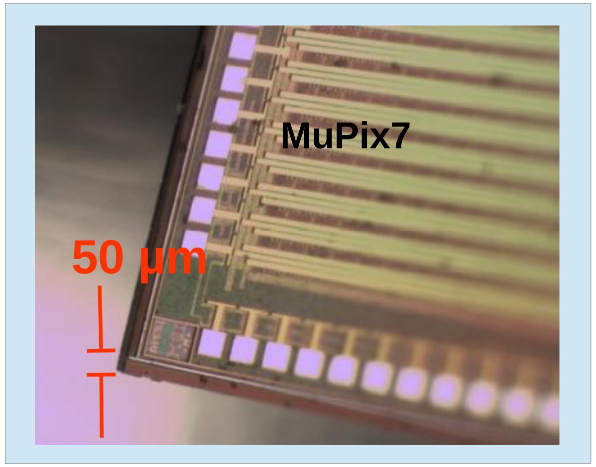
Ultra-thin pixel sensor modules (X/X_0 = 1.15 per mille)



Gaseous He-Cooling System

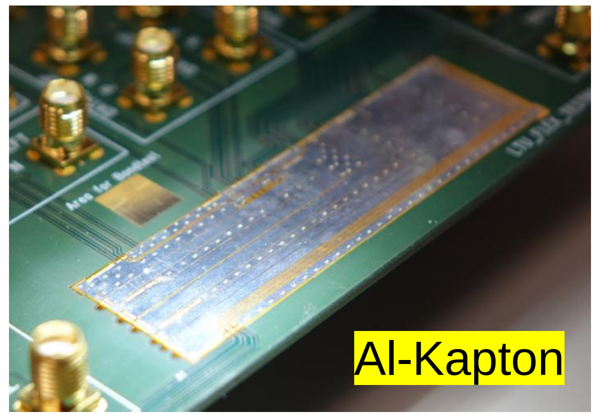


MuPix (HV-MAPS)



Monolithic pixel sensor in
180 nm HV-CMOS

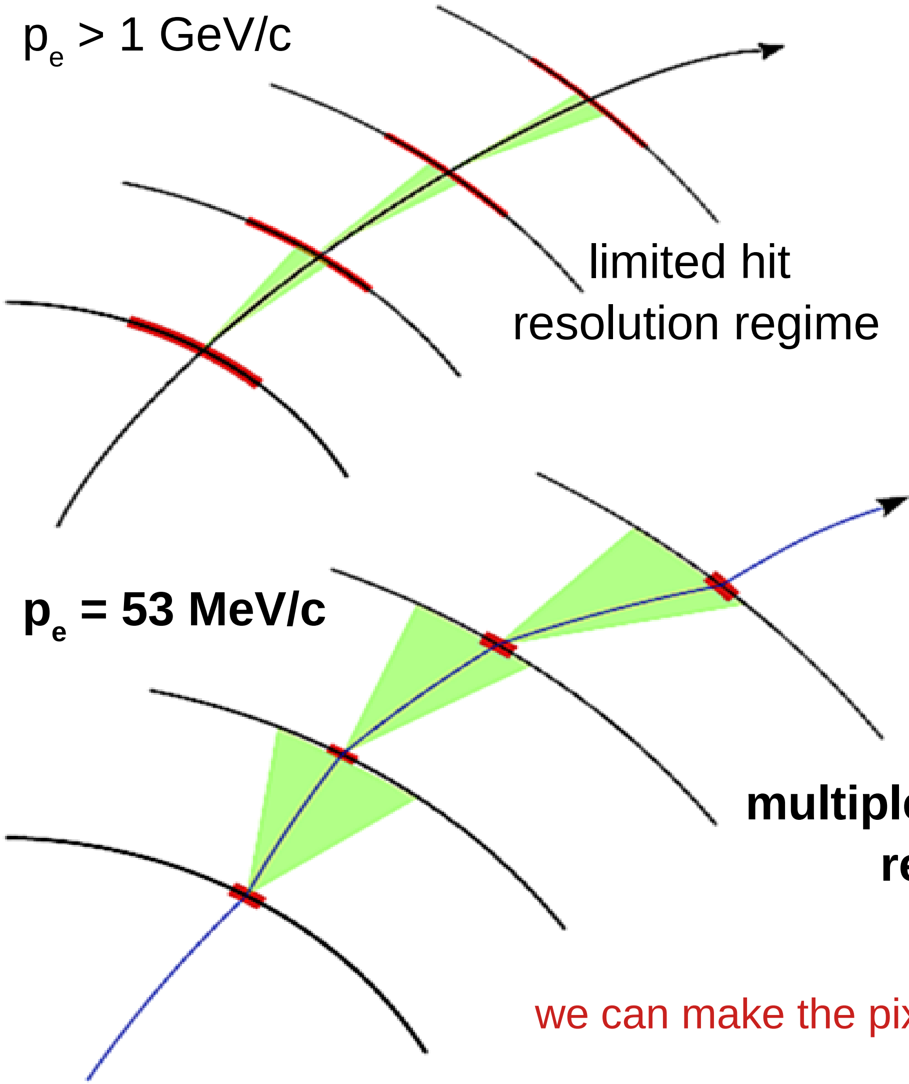
High Density Interconnect
d < 100 µm (LTU, Ukraine)



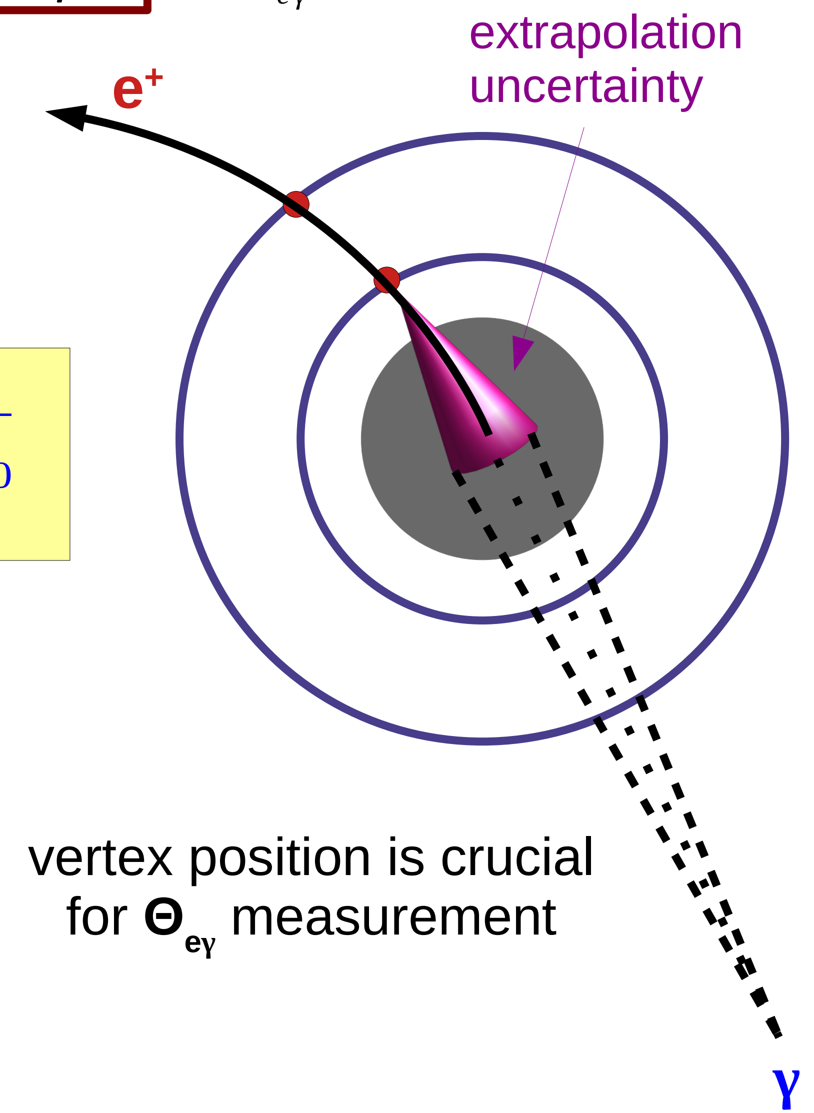
connectivity: spTAB method

Silicon Pixel Vertex Detector

$$B_{acc} \propto R_\mu \; \sigma(p_e) \; \sigma(E_\gamma)^2 \; \boxed{\sigma(\Theta_{e\gamma})^2} \; \sigma_{t_{e\gamma}}$$



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

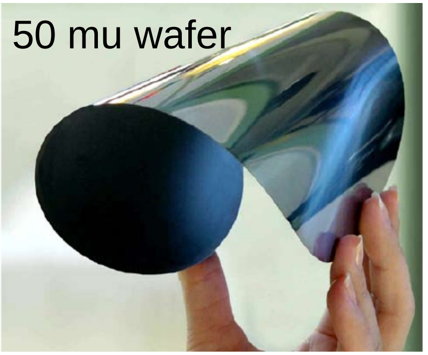


we can make the pixels sufficiently small

Thin HVMAPS Vertex Layers

Pixel sensors	MIMOSA	DEPFET	ALPIDE	HV-MAPS
TRACKING DETECTOR	STAR PXL	BELLE II PXD	ALICE ITS	**Mu3e PTD**
radiation length per layer in X_0	0.5%	0.2-0.5%	0.3-0.8%	**0.11%**

Accidental Background scales as: $$B_{acc} \propto \sigma\left(\Theta_{e\gamma}\right)^2 \propto x/X_0$$



p_e=53 MeV/c:

- 50 µm Si → $\sigma(\Theta_e) = 6.0\ \mathrm{mrad}$
- 30 µm Si → $\sigma(\Theta_e) = 4.6\ \mathrm{mrad}$

(neglecting multiple scattering in the stopping target)

Remark:
ALICE is also investigating sensors with thickness <50 µm for ITS III upgrade

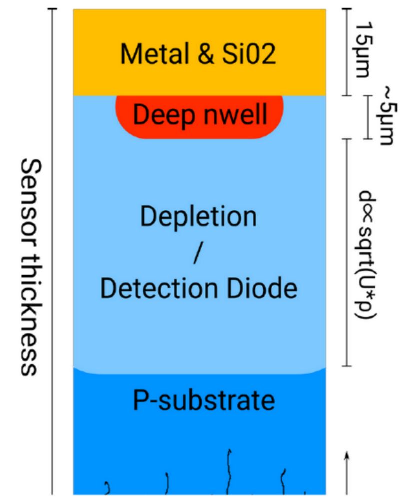
	Drift Chambers	
MEG II TDR	MEG	MEG II
$\sigma^{core}_{p_{e^+}}$ (keV)	306	130
$\sigma^{core}_{\theta_{e^+}}$ (mrad)	9.4	5.3
$\sigma^{core}_{\phi_{e^+}}$ (mrad)	8.7	3.7

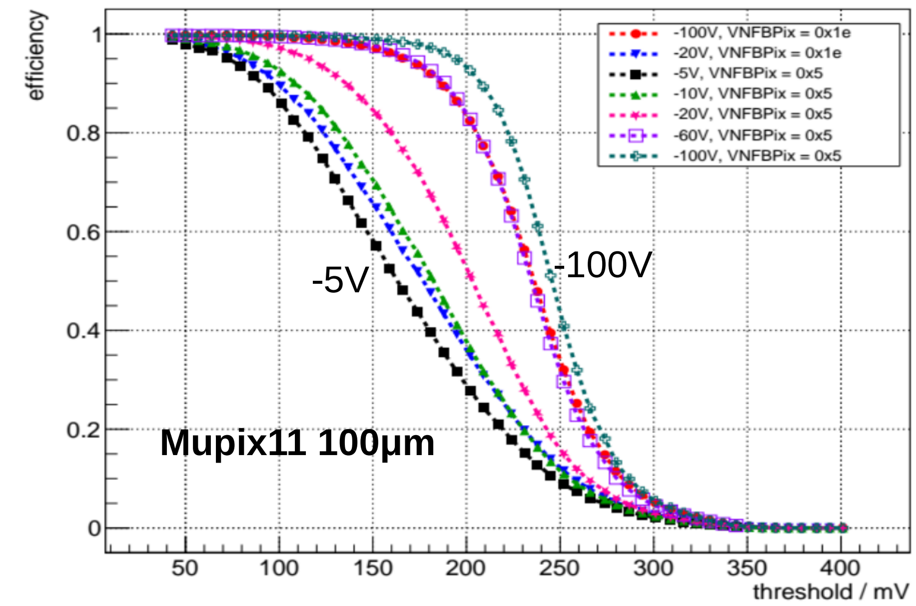
Single Hit Efficiency of thin HVMAPS

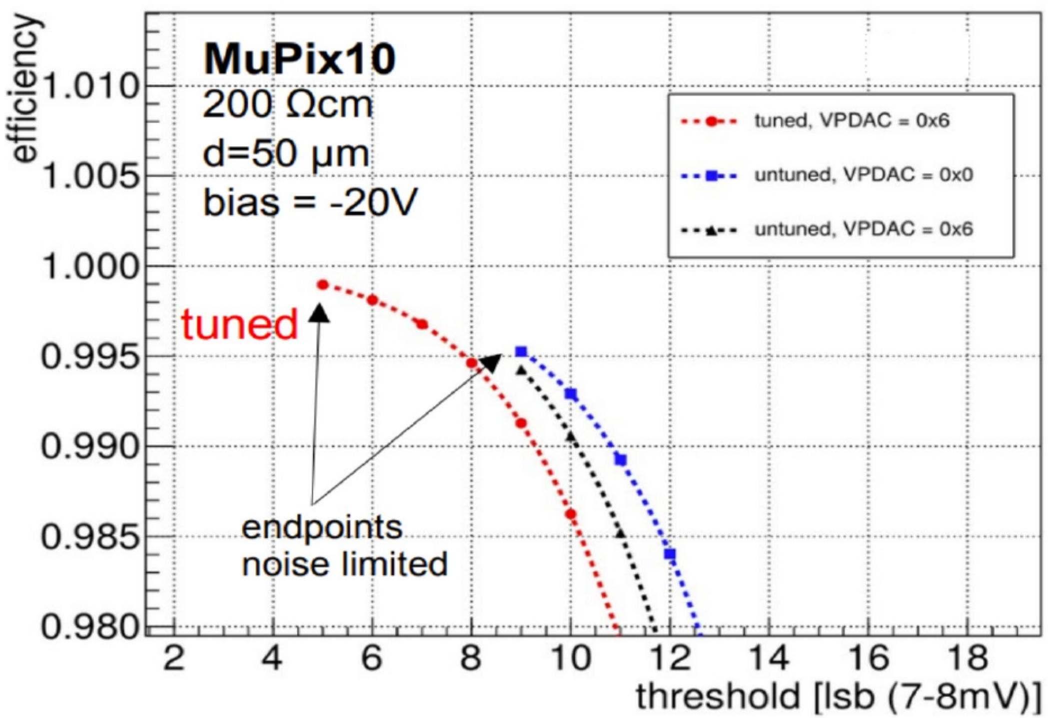
Depleted region scales with bias voltage

$$\Delta x_{bias} \propto \sqrt{U \rho}$$

- **Thinner** sensor provides smaller **signal!**
- Goal is to achieve a single **hit eff. > 99.5%**







- **50 µm sensor → x_{bias} ~ 30 µm → eff. ~ 99.9%**
- 30 µm sensor → x_{bias} ~ 10 µm → eff. ~ 97-98%

lower threshold possible?

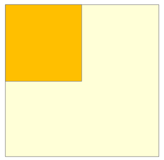
R&D for thin HVMAPS

Detection efficiency depends on signal over noise ratio:

$$\frac{S}{N} \approx \frac{x_{bias}}{C_{pixel}} \approx \frac{x_{bias}}{A_{pixel}}$$

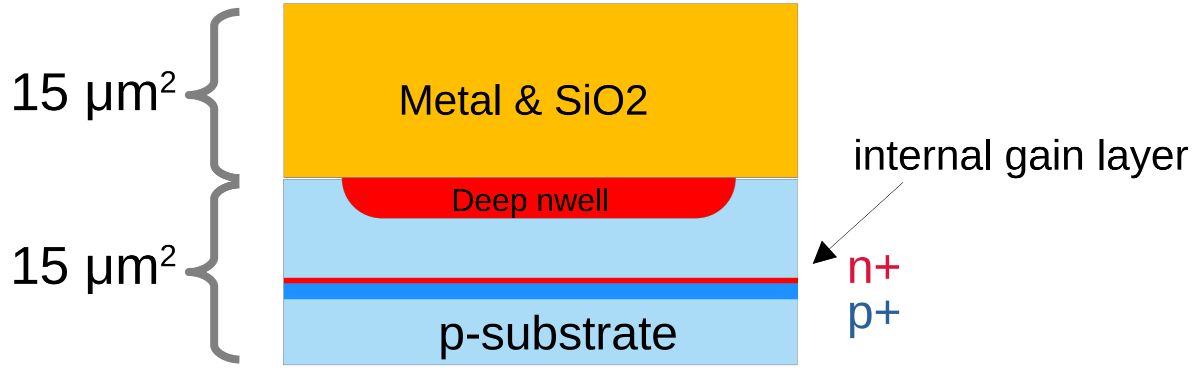
Idea 1:

- make pixel size smaller: 80 x 80 µm^2 → 40 x 40 µm^2
- efficiency can be fully restored! → higher power density



Idea 2:

- use design with internal gain layer
- factor 25 internal gain w/o additional power

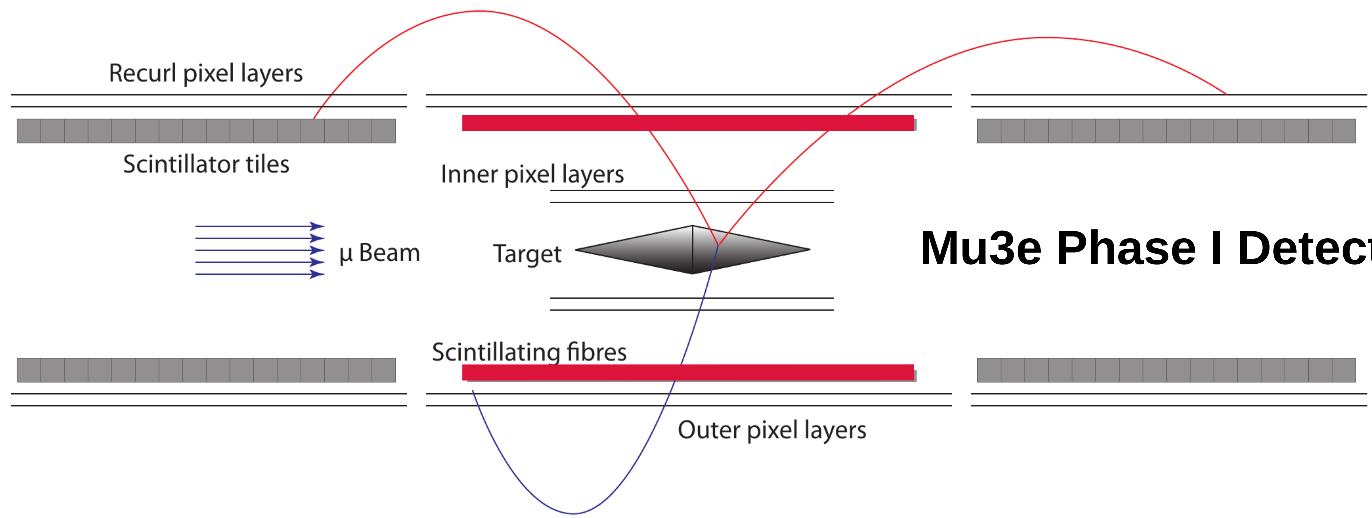


Plan:

We will test both ideas using the 180nm HVCMOS process from XFAB. First submission planned for 2024

Ultra Fast Silicon Pixel Detector (UFSPD) Motivation

Mu3e Phase I Detector:



Mu3e Phase I Sinctillating Fibres:

- time resolution ~ 250 ps
- rate limit 10^8 μ-stops/s (occupancy & irradiation)
- cannot be used at HIMB rates

Mu3e Phase II

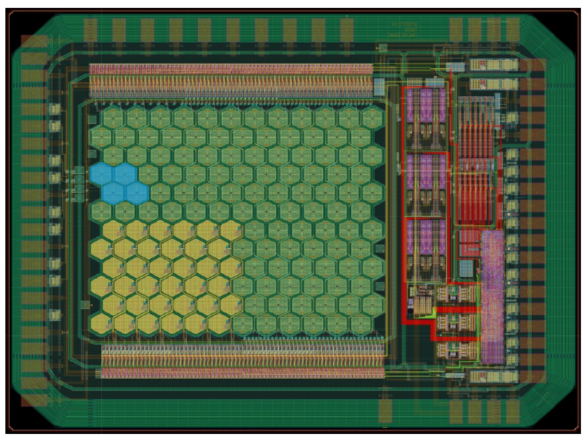
- high beam rate of several 10^9 μ-stops/s
- better time resolution required to suppress acc. BG
- ➢ need ultra fast HVMAPS (UFSPD) with time resolution of 100 ps or better

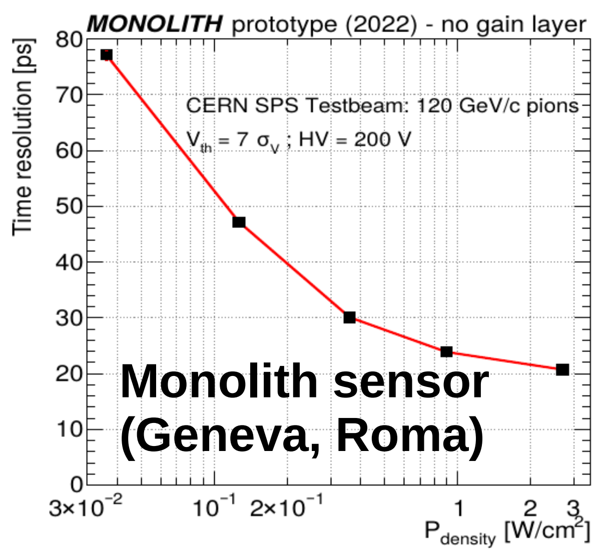
UFSPD Concepts

Sensor without Internal Gain Layer

- IHP 130nm SiGe BiCMOS process
- high cut off frequency (350 GHz)
- use (fast) bipolar transistors for amplifiers and serial drivers

Zambito et al. arXiv:2301.12244



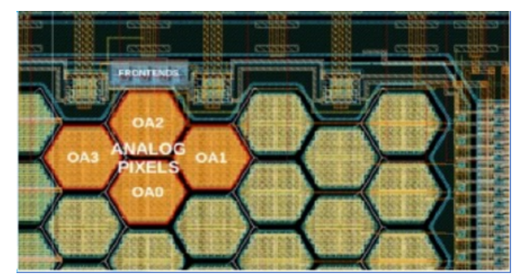


- Best times resolution ~ 20ps
- $P_{density}$ = 200 W/cm2 → 40ps

Sensor with Internal Gain Layer

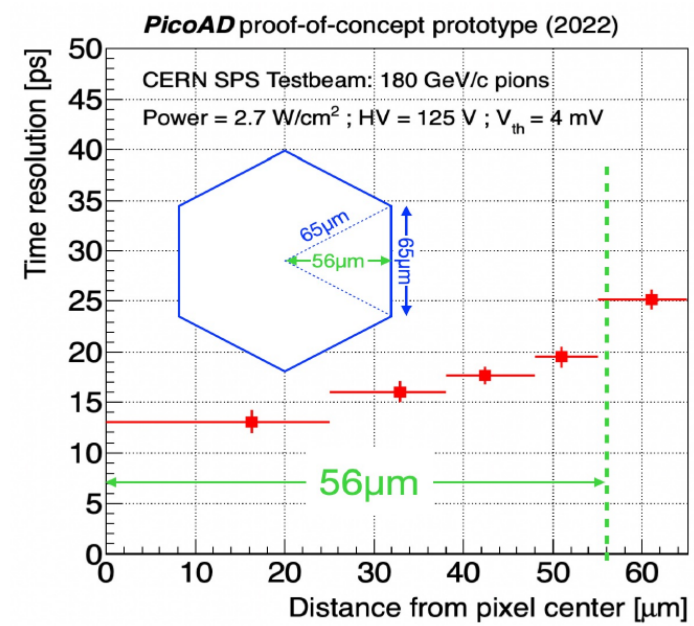
- IHP 130nm SiGe BiCMOS process (option)
- use internal gain layer for fast timing and power saving (ampl. factor ~25)

Milanesio et al.
NIMA 1046 (2023) 167807



PicoAD sensor (Geneva, Roma)

- Best time resolution ~ 17ps (unpublished)



Preliminary UFSPD Specification Requirements Mu3e Phase II

Dimensions

Lengths:	40 cm
Radius:	6 cm
Area:	1500 cm^2

Rate Assumptions (input)

Myon stopping rate:	$2 \cdot 10^9$ /s	
Total hit rate in UFSPD:	$6 \cdot 10^9$ /s	(estimated)

Requirements

Mean hit rate:	$4 \cdot 10^6$ /cm^2/s	
Maximum hit rate:	$8 \cdot 10^6$ /cm^2/s	(estimated)
Max fraction of dead time:	10^{-3}	
dead time of pixel	~300 ns	
Pixel size:	200 µm x 200 µm	

Time resolution:	100 ps
Max. heat dissipation:	400 mW / cm^2

(my personal best guess)

→ **Common Mu3e Phase II R&D Project between Geneva, Heidelberg and KIT**

→ **Also interesting development for an All-Silicon $\mu^+ \rightarrow e^+ \gamma$ detector**

All Silicon Pixel Tracker for $\mu^+ \rightarrow e^+ \gamma$

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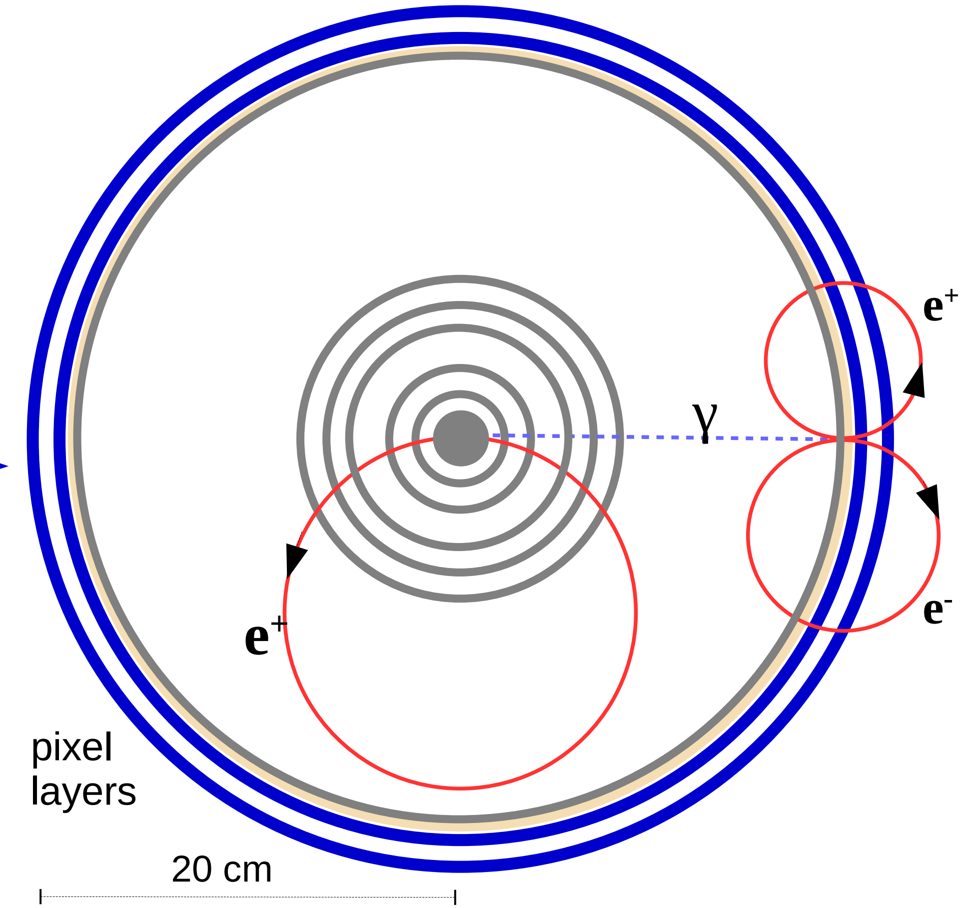
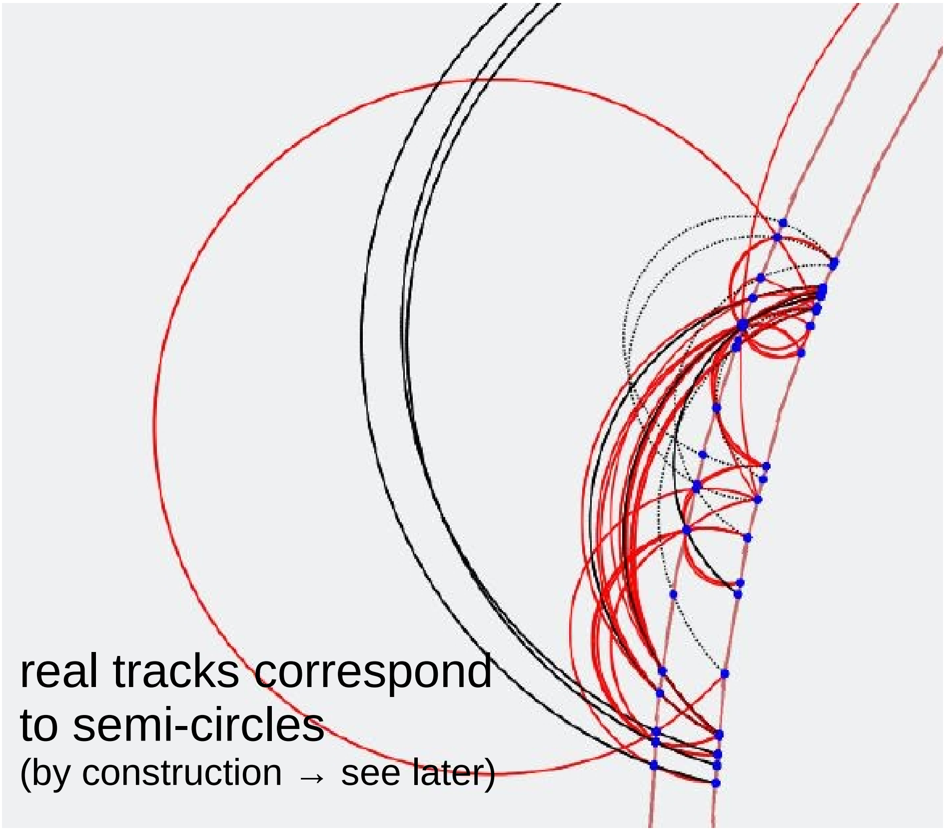


e^+ e- Track Reconstruction with 2 Pixel Layers

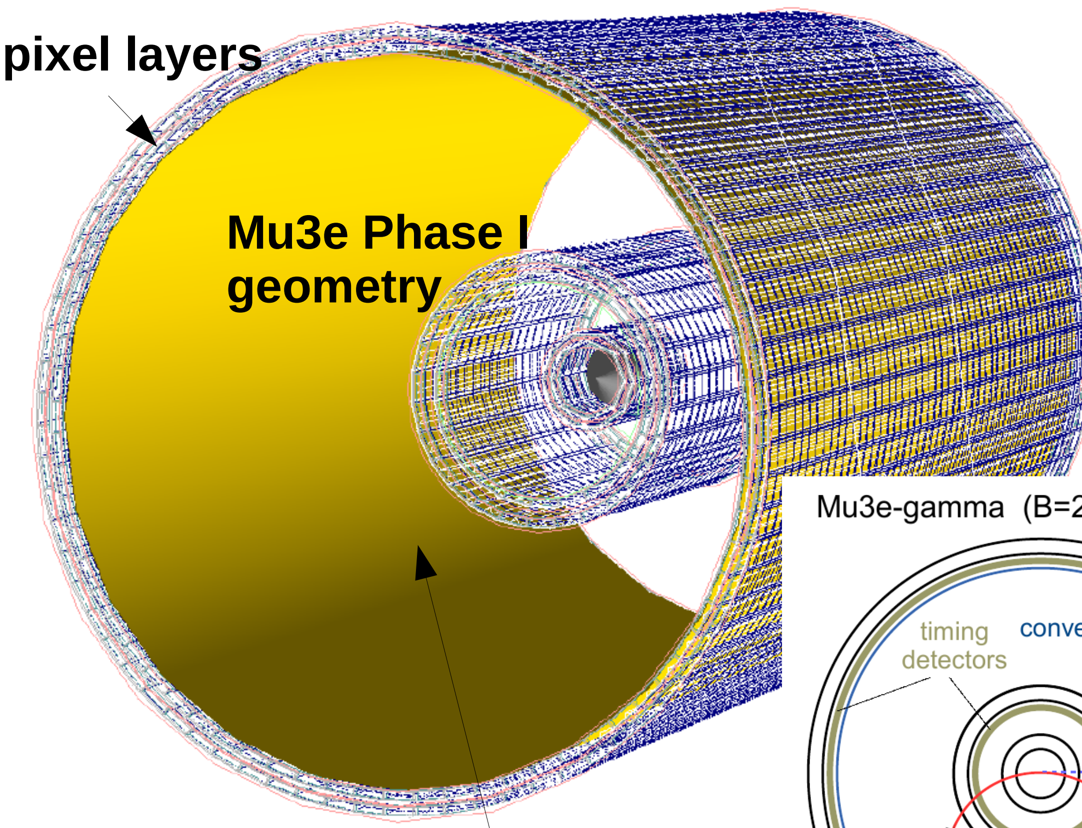
Master Thesis H.Leuschner, Heidelberg, 2019

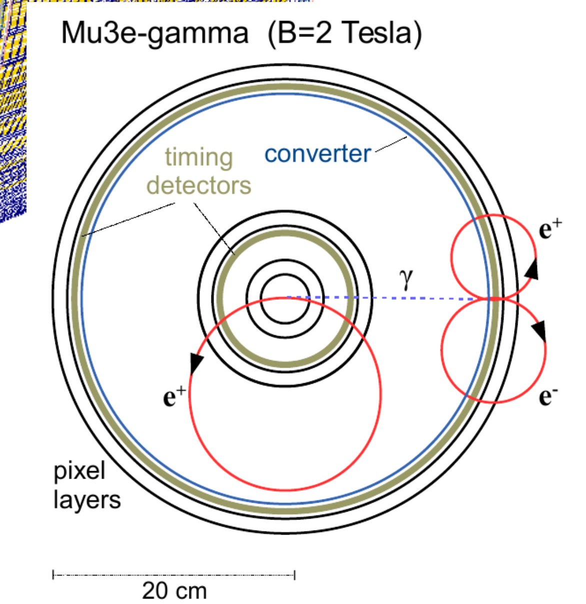
GEANT4 simulation



+2 pixel layers

Mu3e Phase I
geometry





Converter

- **0.1mm gold**
- **~ 3% X_0**

Main results of the study:

- high momentum resolution due to small pixels
- two layer tracking of curling tracks works
- proof of concept

Photon Energy Resolution

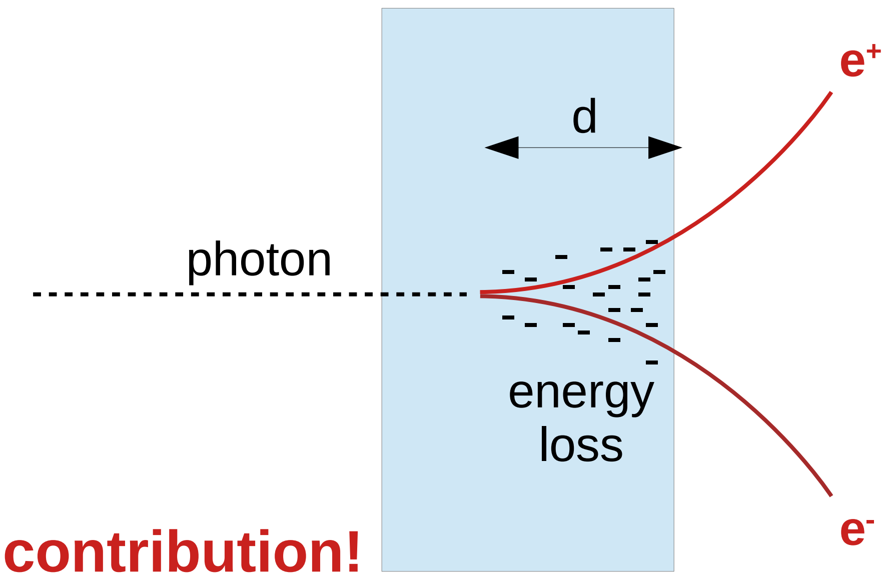
Reconstruction Photon Energy:

$$E_\gamma = p_{ele} + p_{pos} + E_{loss,ele} + E_{loss,pos}$$

Photon Energy Resolution:

$$\sigma(E_\gamma) = \sigma(p_{ele}) + \sigma(p_{pos}) + \sigma(E_{loss,ele}) + \sigma(E_{loss,pos})$$

dominant

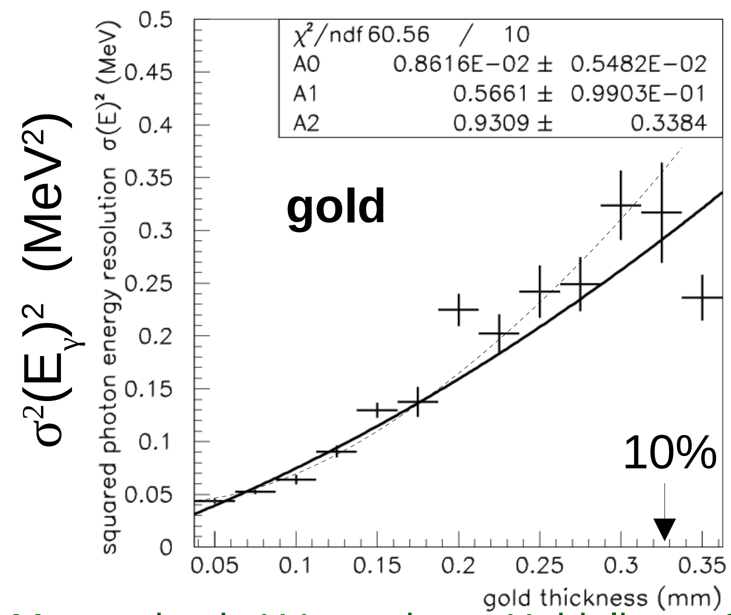


Energy loss (ionisation+Brems) in converter is largest contribution!

Ansatz: $\sigma^2(E) \approx 2\,\sigma(\text{track}) + \alpha\, d + \beta\, d^2$

tracking (negligible) | **stat.** | **conversion position uncertainty**

energy loss is dominant

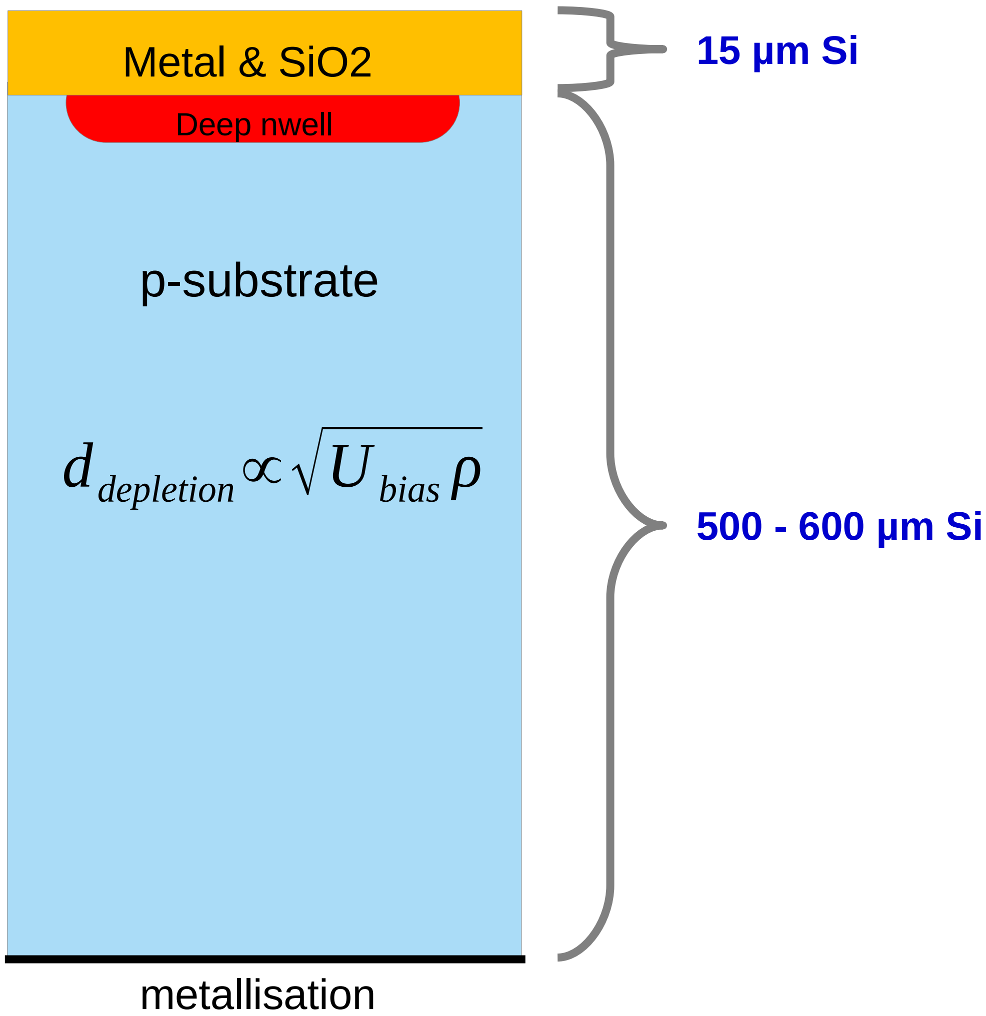


Master thesis H.Leuschner, Heidelberg, 2019

Idea:

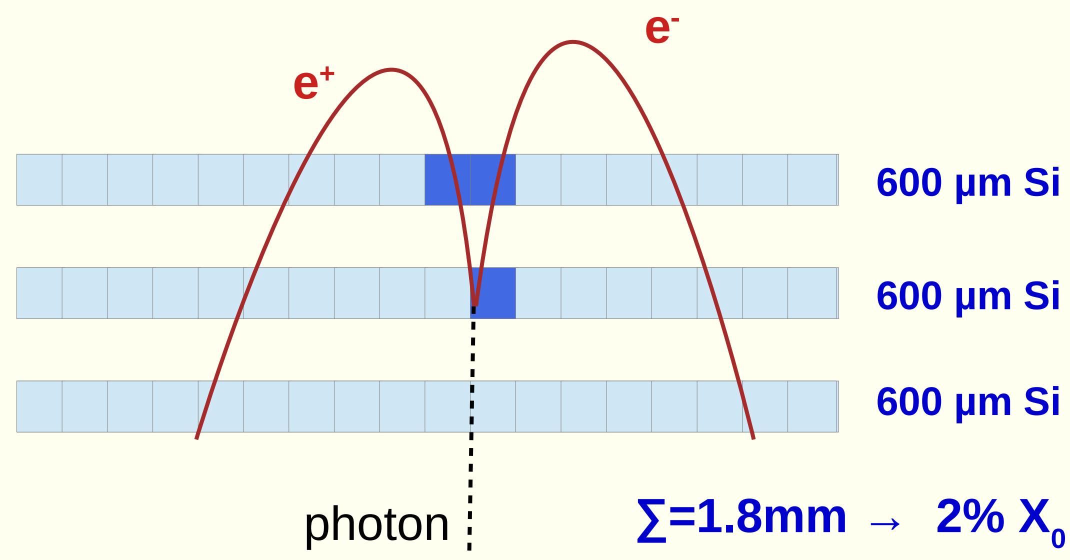
➔ **use an Active Silicon Converter (note E_{crit} ~ 40 MeV)**

Thick Active HVMAPS Converter Concept



Example:

$$550\,mu \approx \sqrt{1000\,V \cdot 3000\,\Omega\,cm}$$



- Measure actual energy loss and conversion point in thick HVMAPS
- Caveat: only small radiation length possible is possible

Challenges:

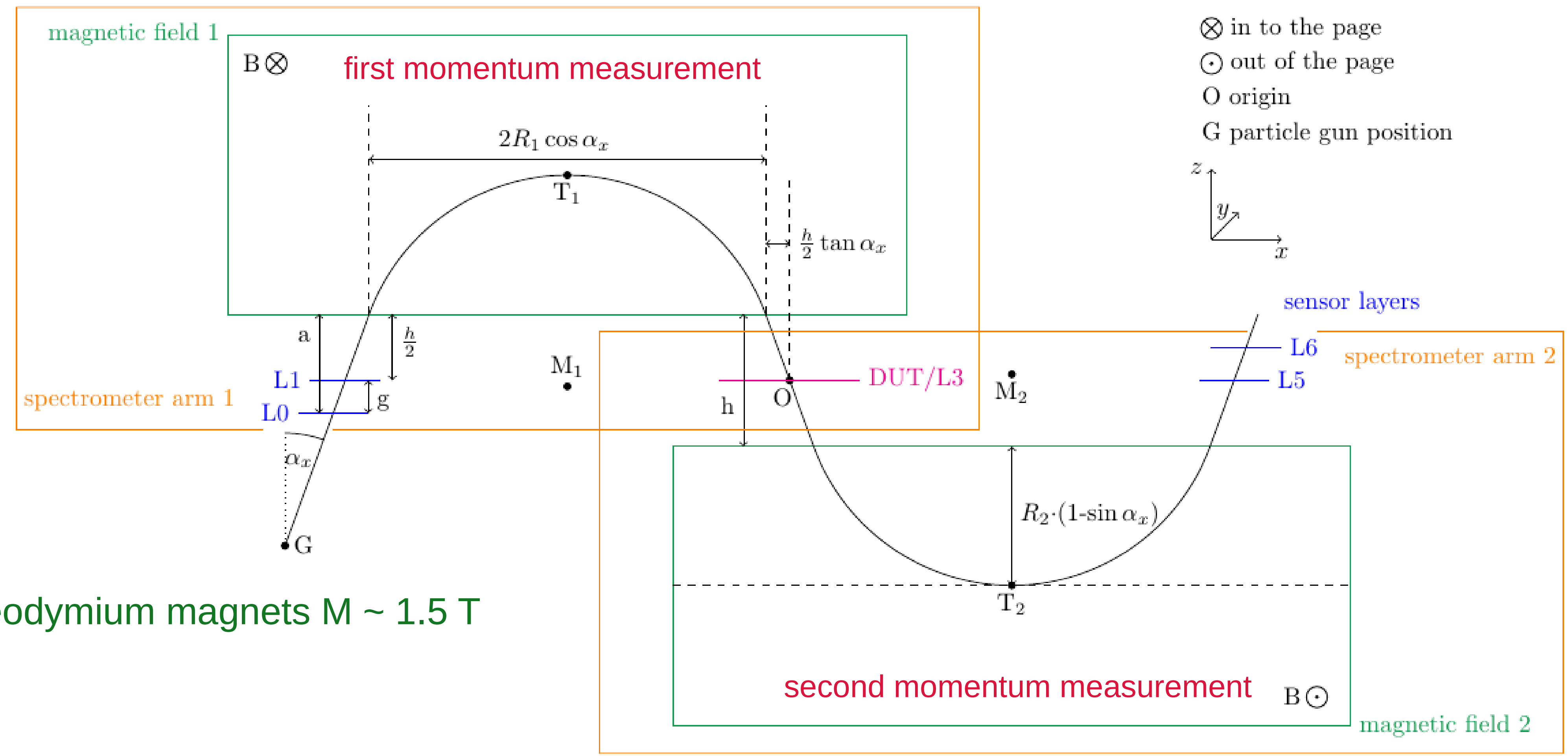
- have to deal with high voltages
- metallisation
- special guard ring structures needed
- first design in 2025 planned

Double Arm Spectrometer Project

(bachelor thesis L.Bees 2024)

Motivation:

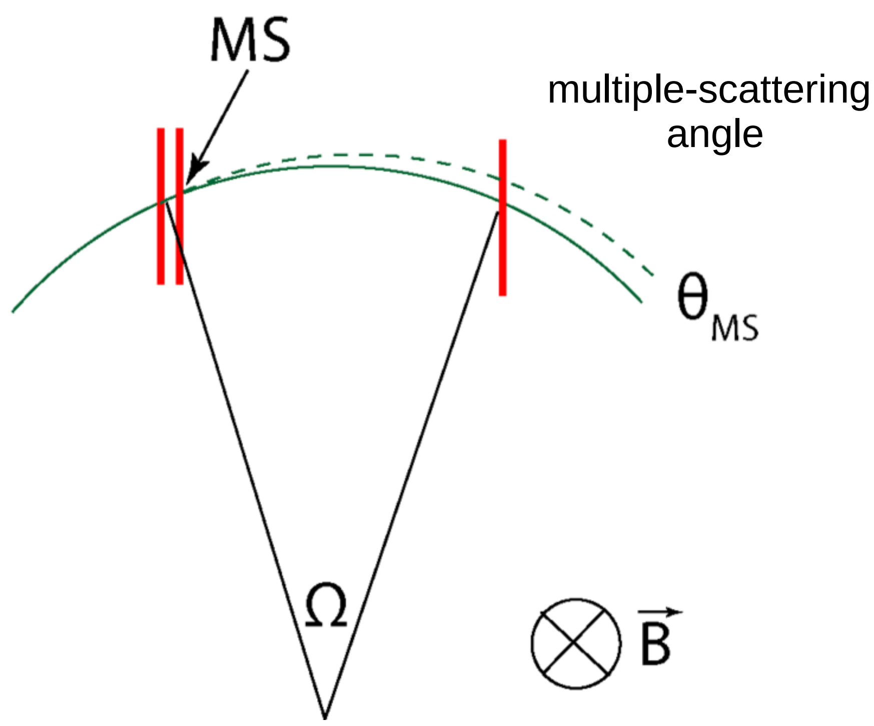
- Energy loss of e^+ / e^- particles in silicon sensors is small ~ 390 keV/mm
- For **sensor characterisation studies** precise reference measurement of **actual energy loss** in DUT is required → ~ 10-20 keV



neodymium magnets M ~ 1.5 T

Momentum Resolution

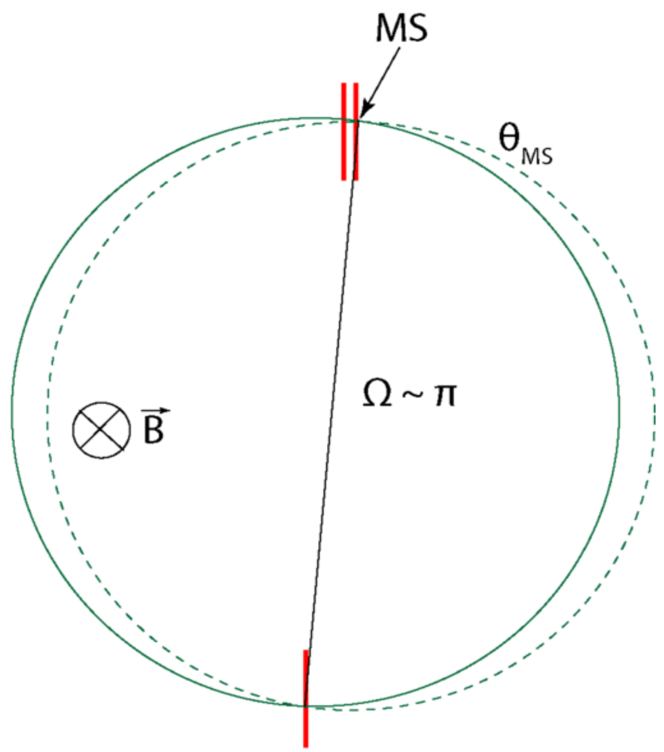
Standard spectrometer:



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

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

"Half turn" spectrometer:



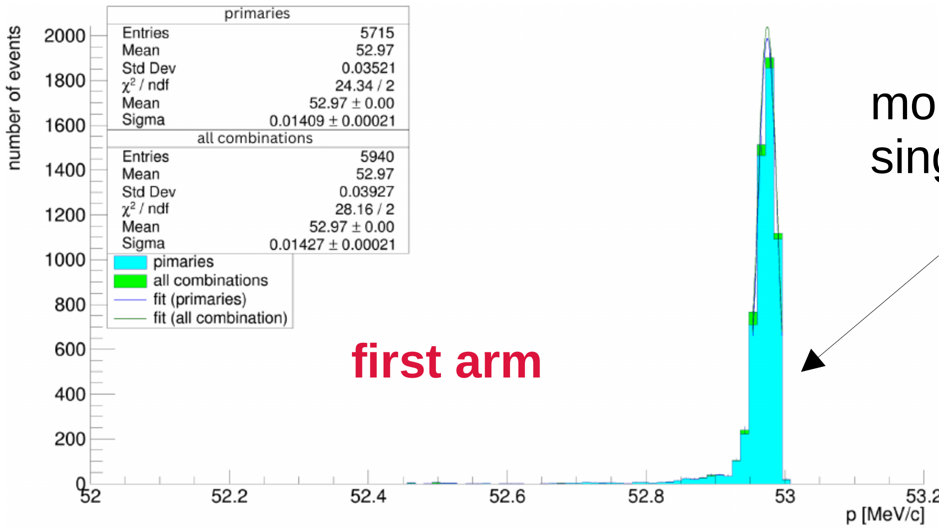
$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

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

GEANT4 Simulation Results

(bachelor thesis L.Bees 2024)

Electron beam with p=53 MeV/c

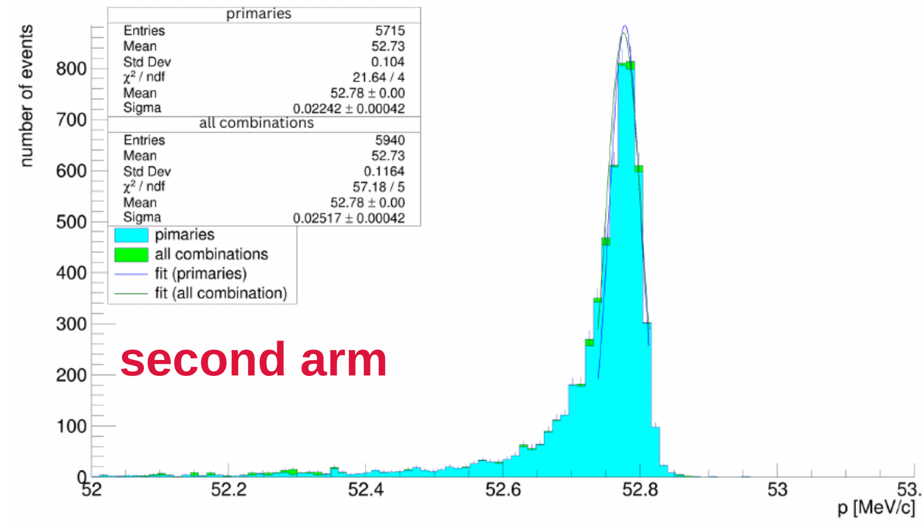


first arm

momentum resolution in single arm is about

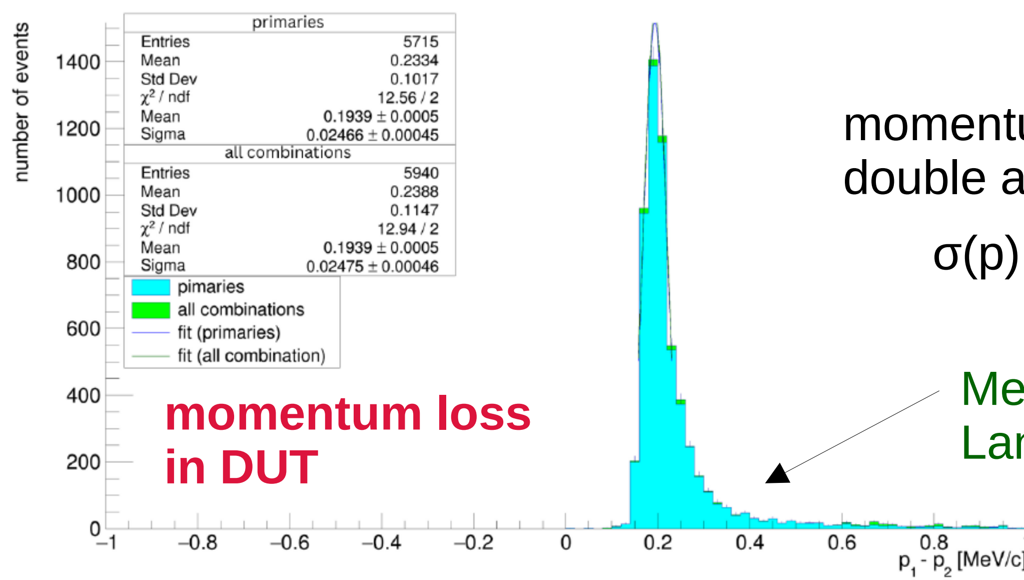
σ(p) ≈ 14 keV/c

DUT: 600 mu Si



second arm

Construction of setup is planned for 2025



momentum loss in DUT

momentum loss resolution of double arm setup is about

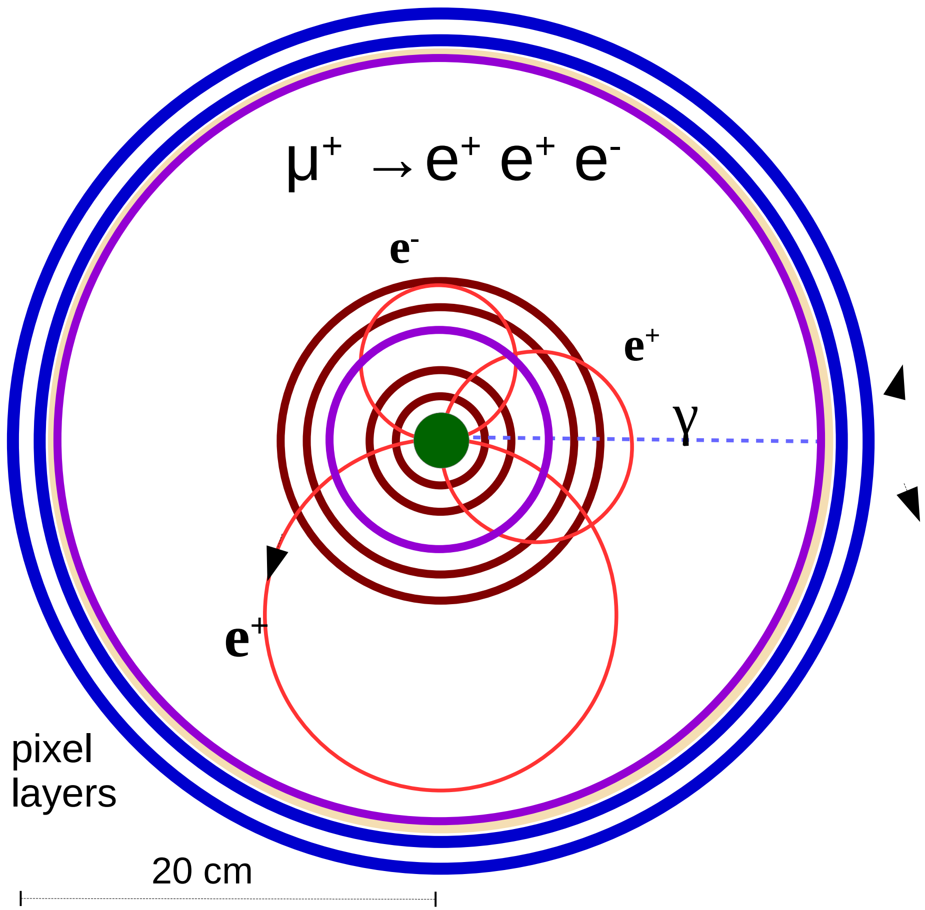
σ(p) ≈ 20 keV/c

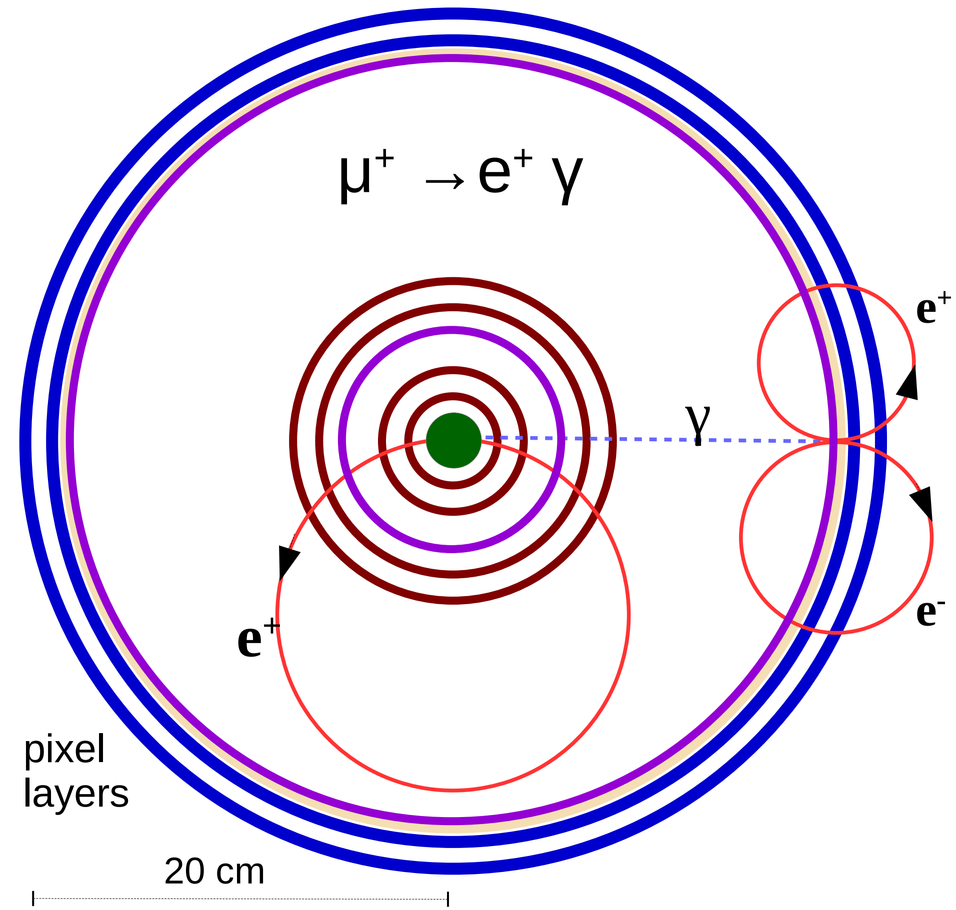
Measurement of Landau tail is possible

Mu3e-Gamma

Question:

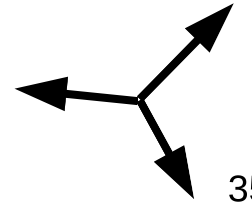
can one combine two experiments Mu3e (Phase II) and search for $\mu^+ \rightarrow e^+ \gamma$?





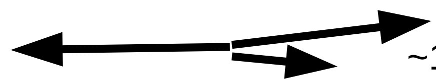
Design Optimisations for Mu3e Phase II

four fermion coupling:



35 MeV/c

tensor coupling:

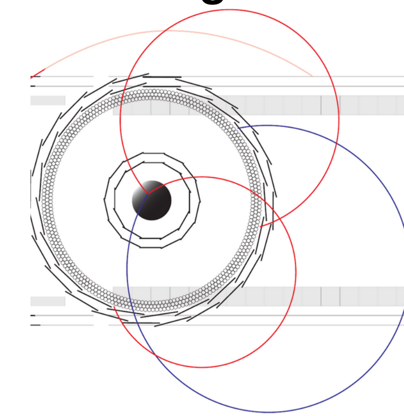


~10-35 MeV/c

53 MeV/c

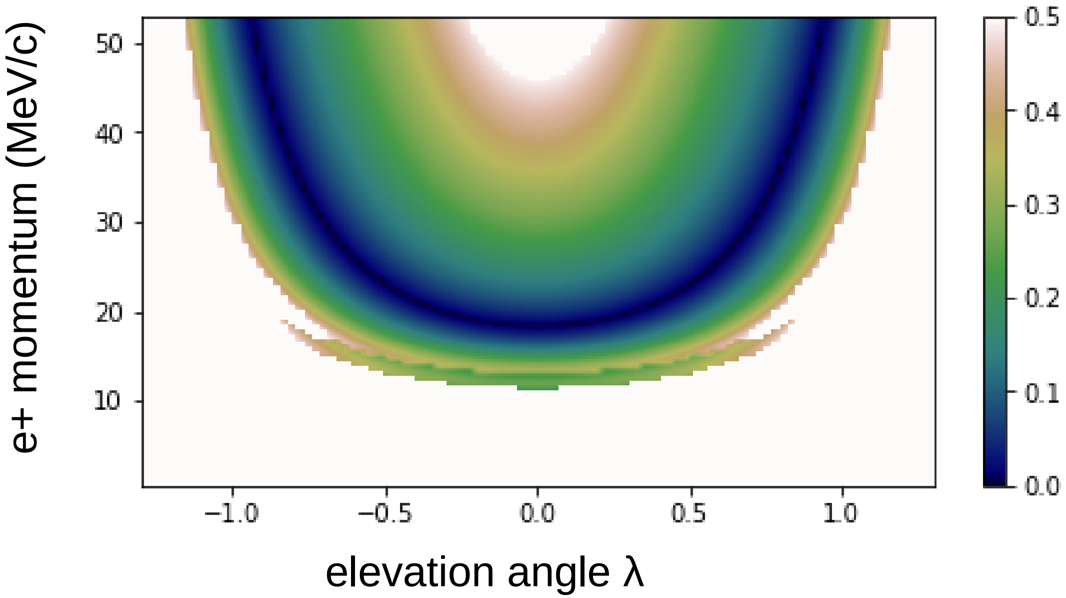
Phase I Design

radii:
- 23 mm
- 30 mm
- 74 mm
- 86 mm

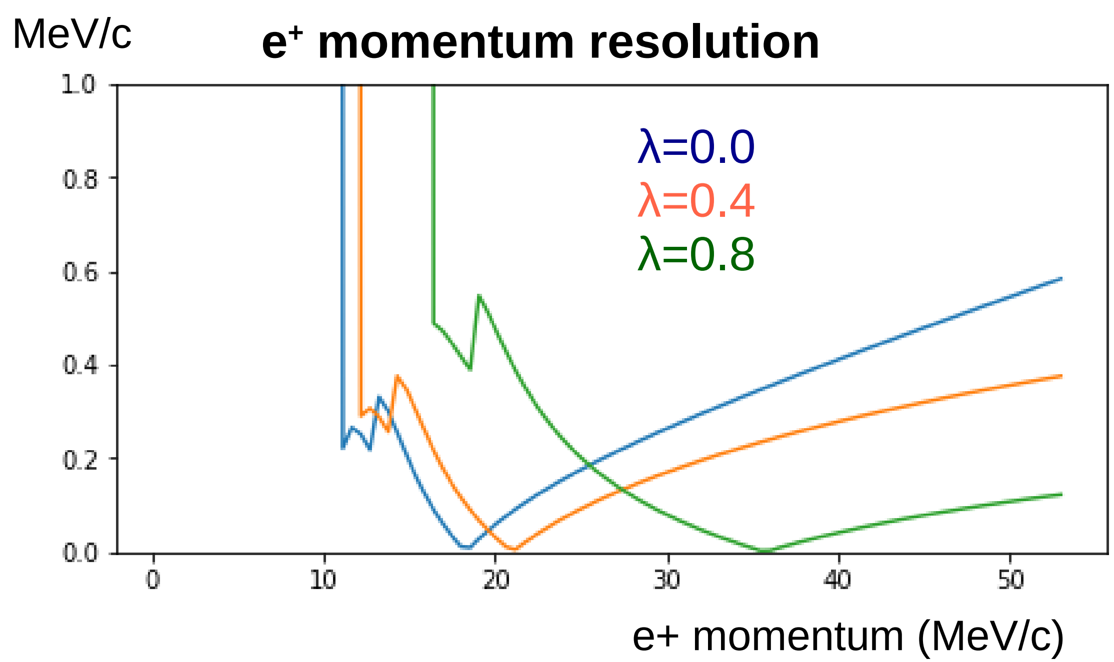


B=1T

e⁺ momentum resolution

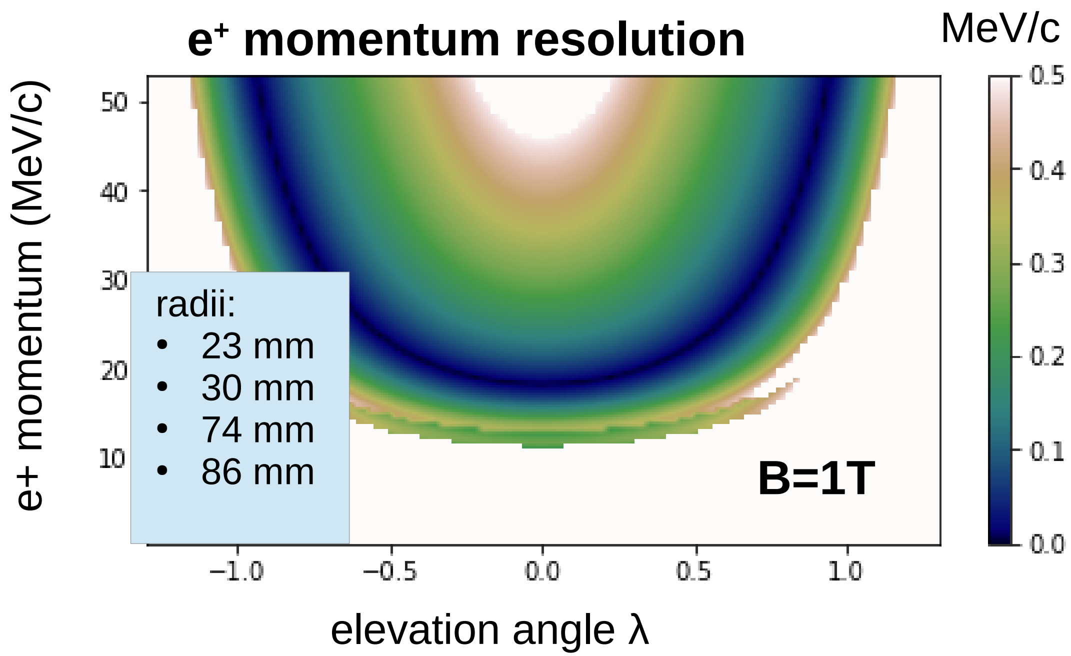


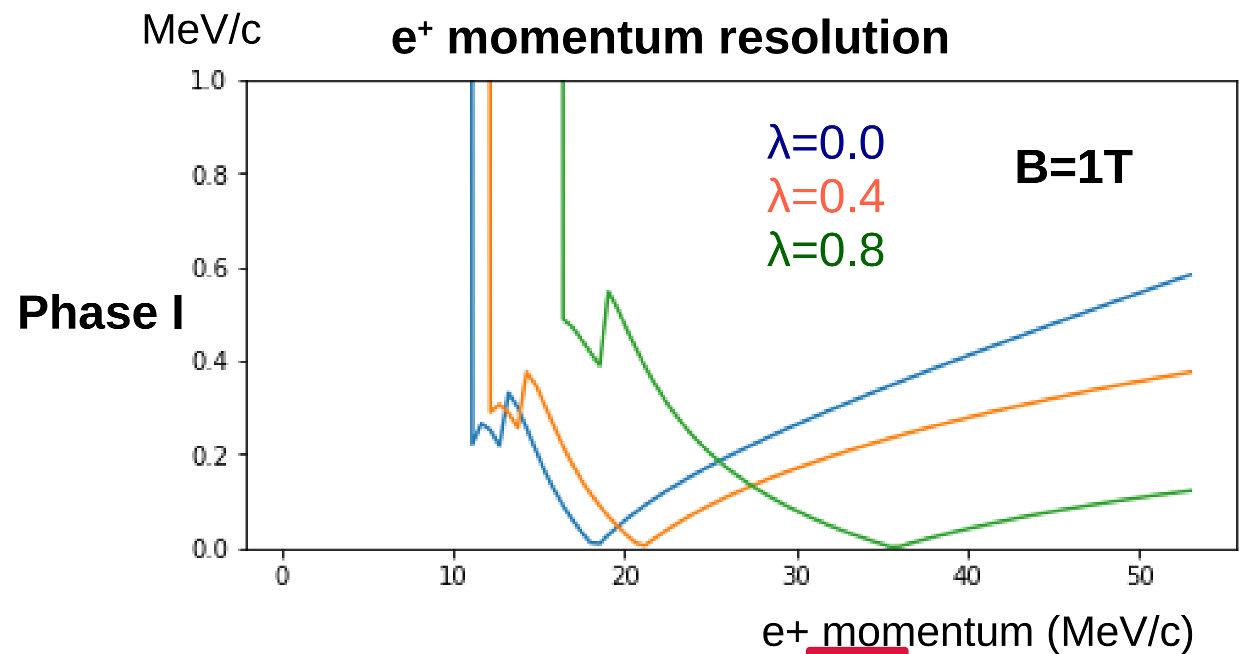
e⁺ momentum resolution

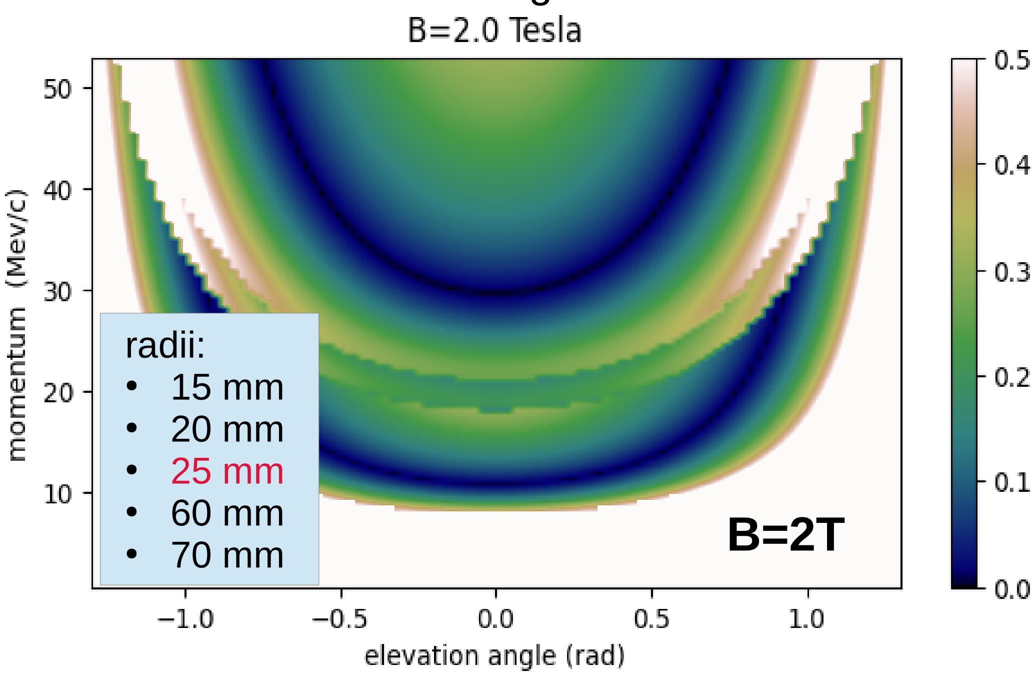


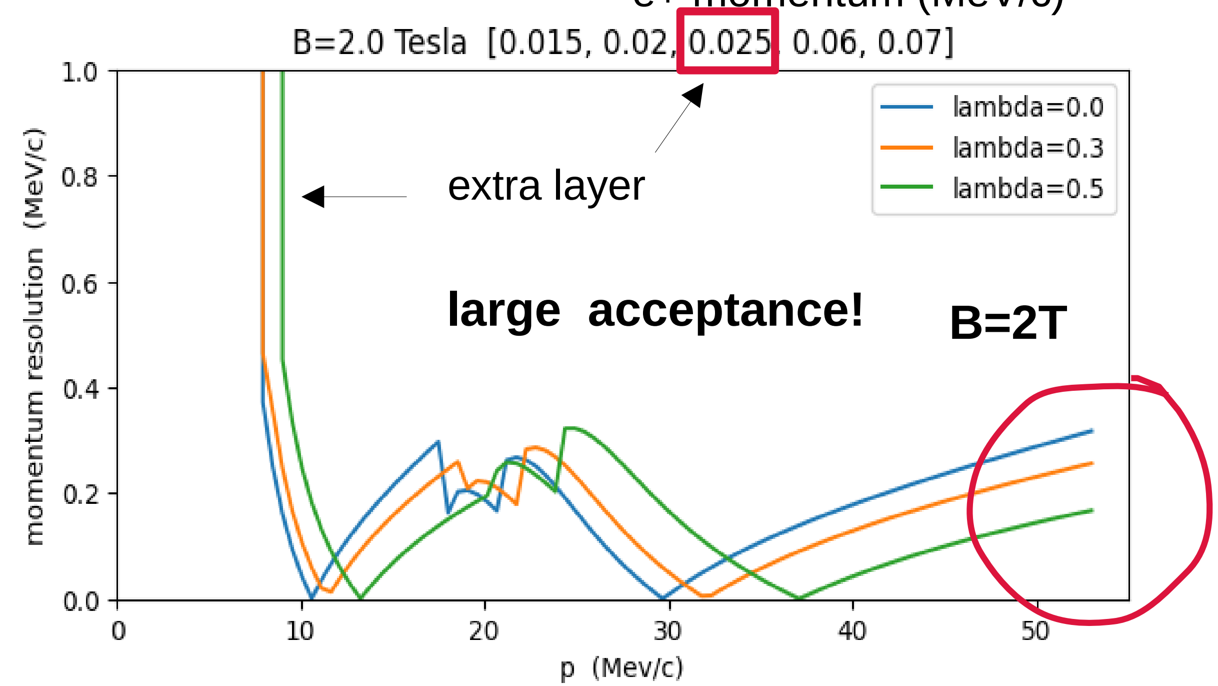
Note: momentum resolution is calculated with multiple scattering model

Design Optimisations for Mu3e Phase II



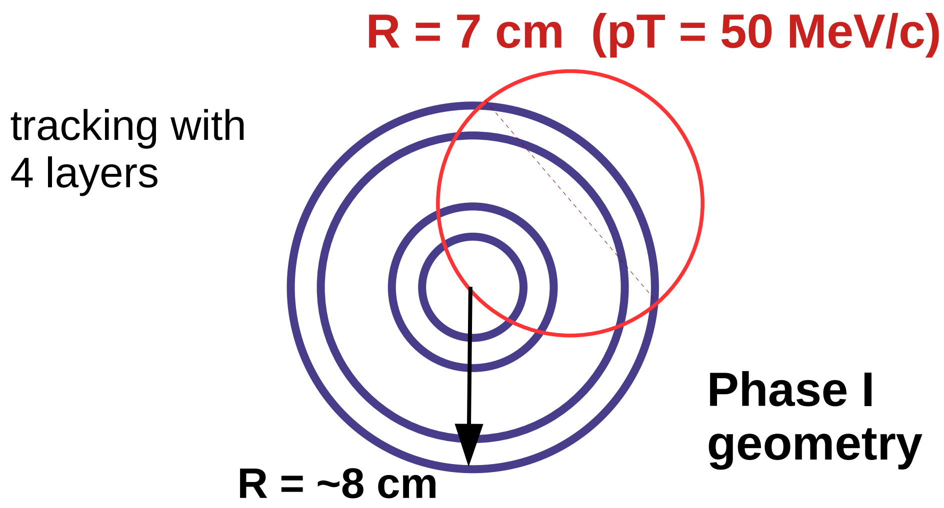






Optimised Solution for $\mu^+ \to e^+ \gamma$

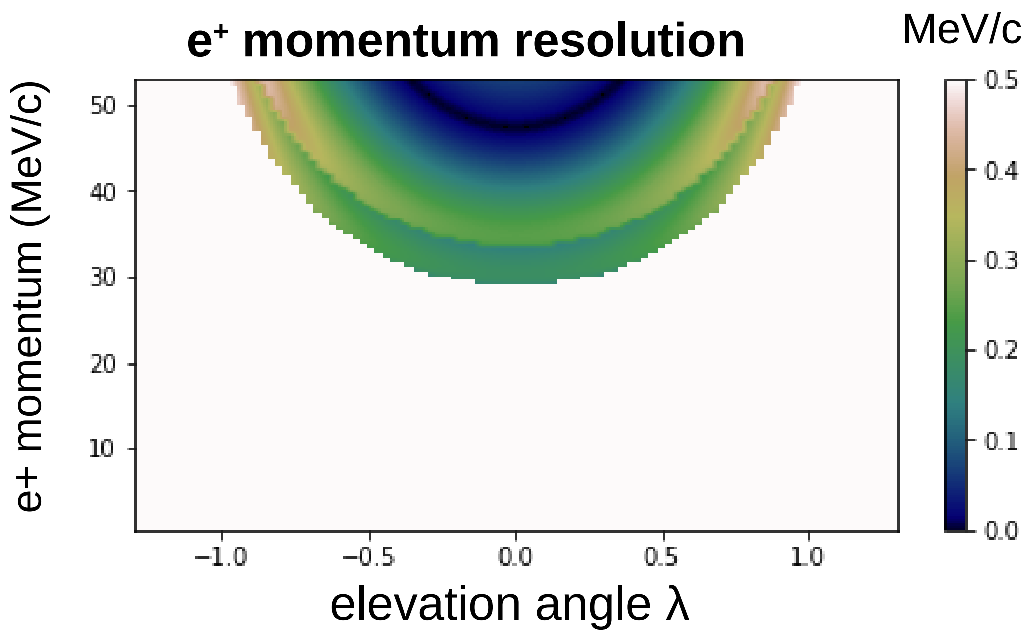
B = 2.6 Tesla (→ helps also for the μ-stop rate)

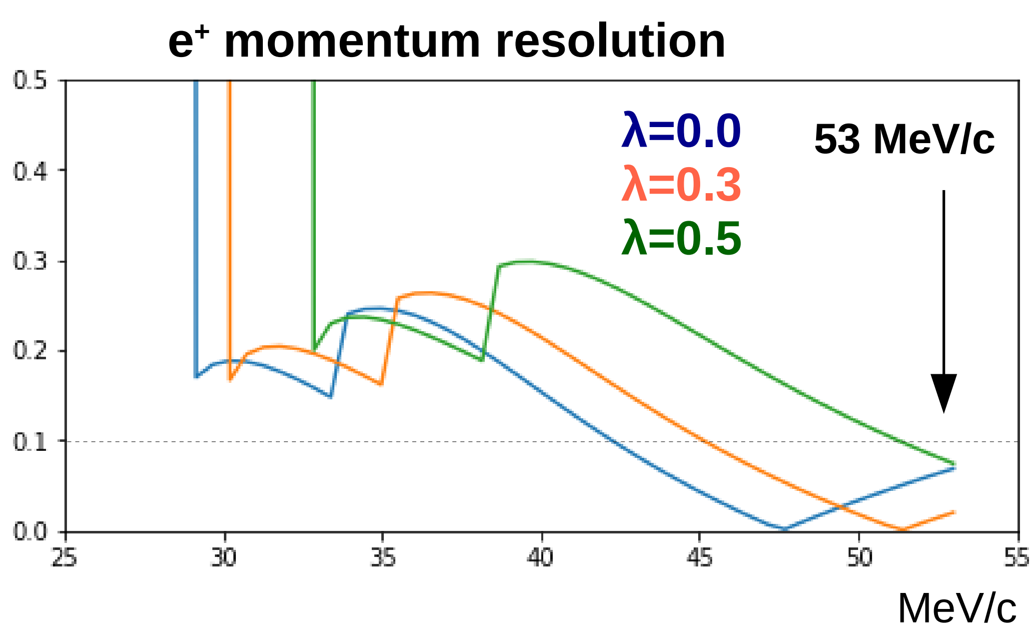


Momentum resolution for half-circles:

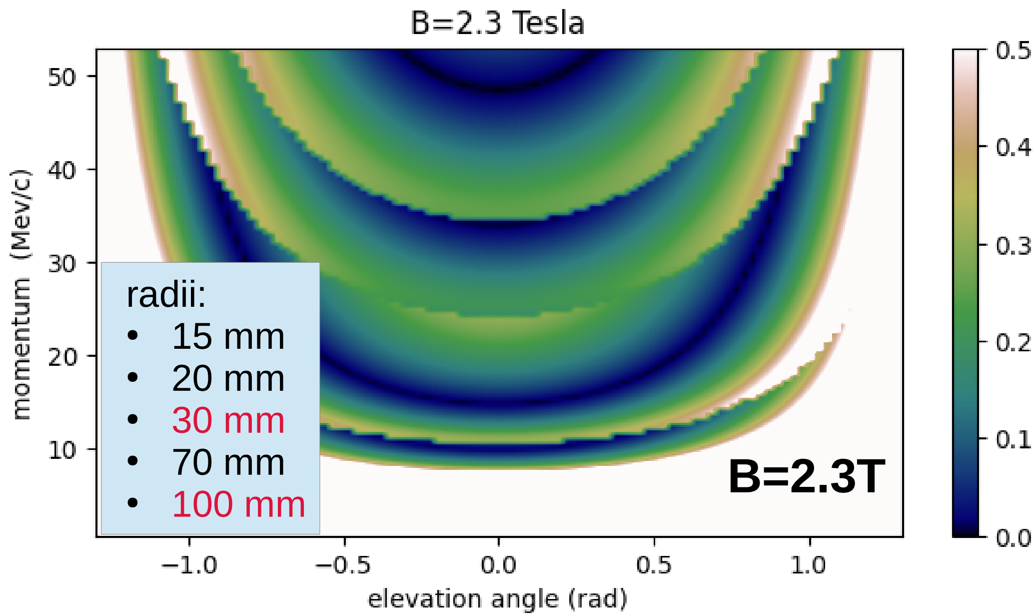
- **~12 keV/c** from finite pixel size (80 μm MuPix)
- about **60 keV/c** from scattering in **helium** gas (assuming B=2.6T)
- multiple scattering in detector (0.1% X_0) → plot

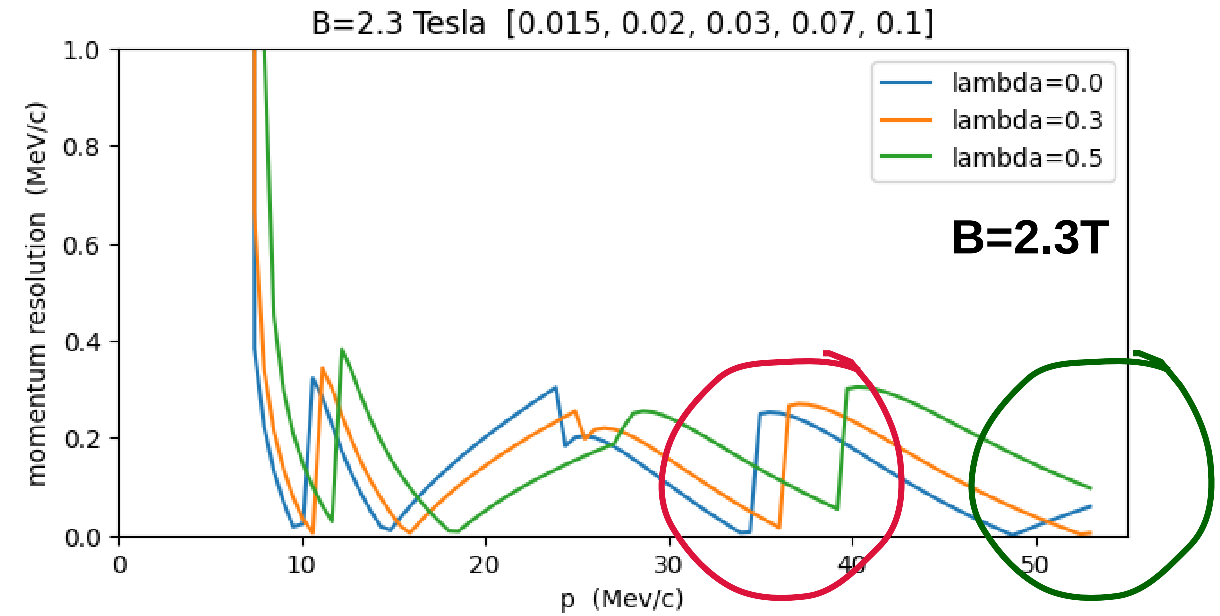
A momentum resolution of about **<80 keV/c** is expected for p=53 MeV/c positrons in the central region **-0.5 < λ < 0.5** by measuring one curl

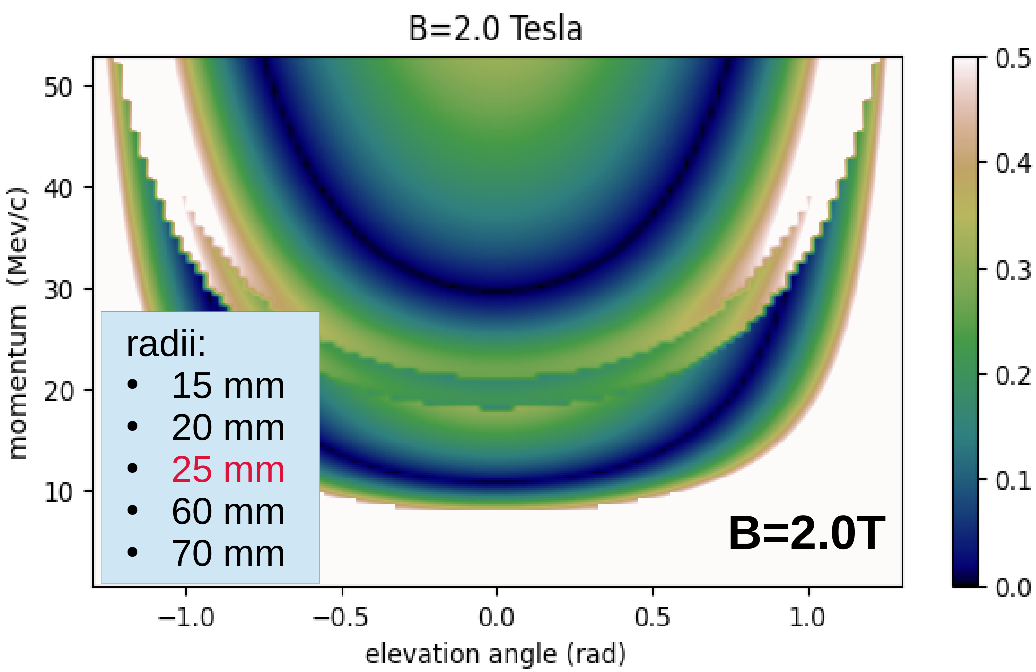


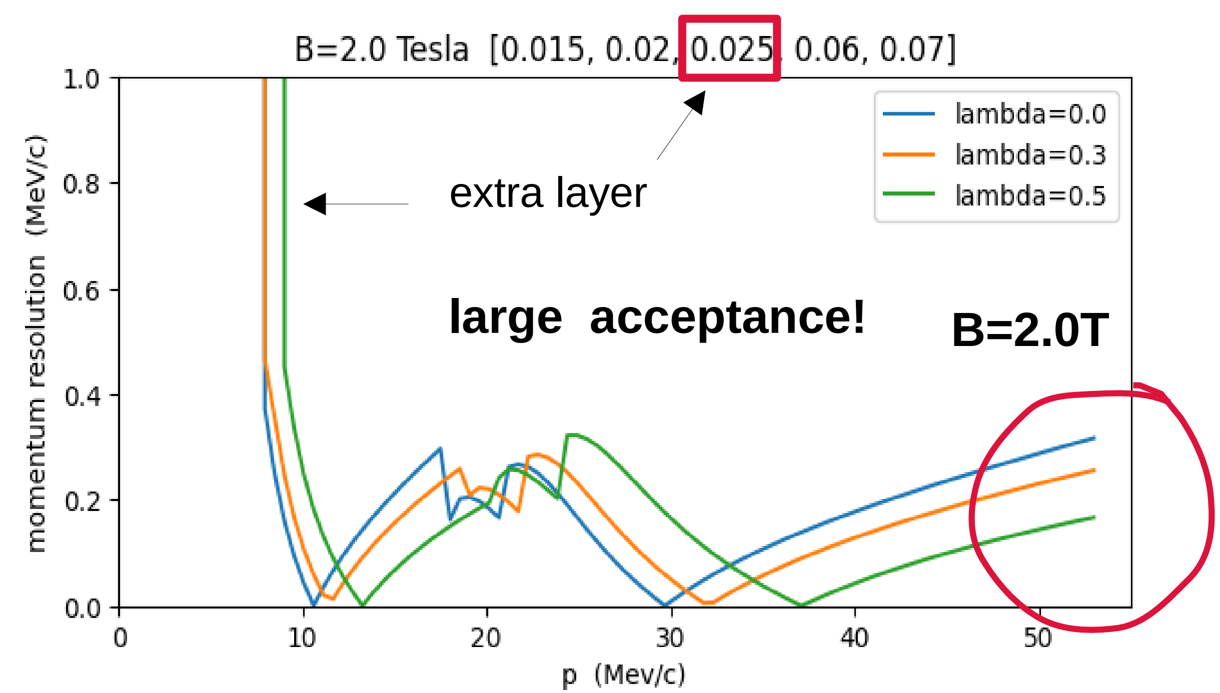


Study Optimal Mu3e-Gamma Geometry









Summary

Several R&D studies for Mu3e-Gamma performed in Heidelberg

- **Vertexing (also relevant for Mu3e Phase II) :**
  - development of thin HVMAPS (30 mu)
  - mechanical stability and handling
- **Ultra Fast Silicon Pixel Detector (crucial for Mu3e Phase II)**
  - focus on concept with internal gain layer ($\rightarrow$ save power)
- **Active HVMAPS Converter**
  - requires very thick sensors and high voltage
  - Construction of Double Arm Spectrometer for characterisation studies
- **Design Studies for Mu3e-Gamma:**
  - aiming for optimum momentum resolution in large momentum range
  - and in particularly for p=53 MeV/c.