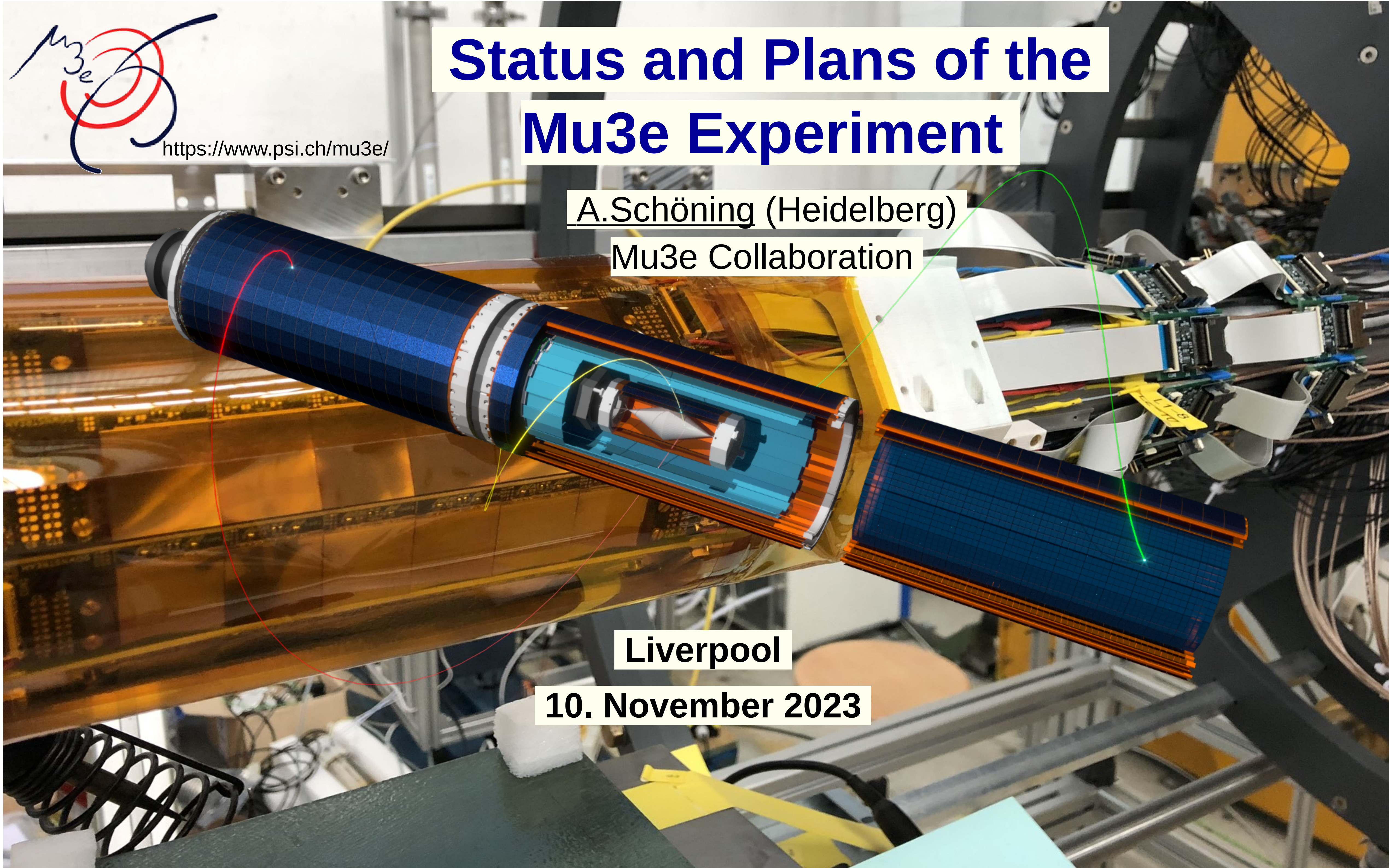
Status and Plans of the Mu3e Experiment

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

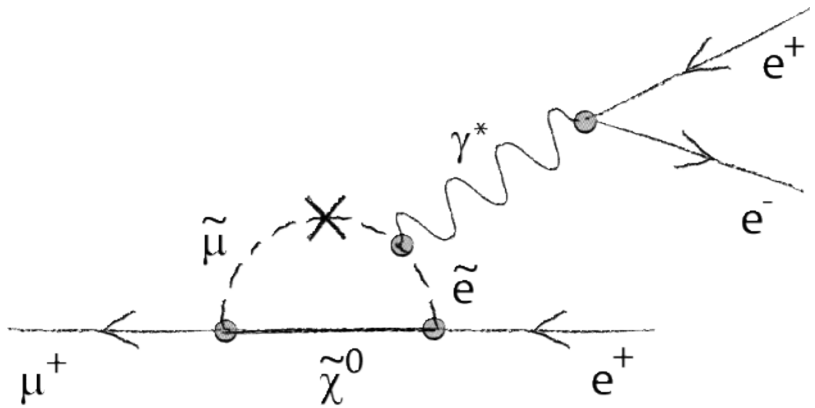
A.Schöning (Heidelberg)
Mu3e Collaboration

Liverpool

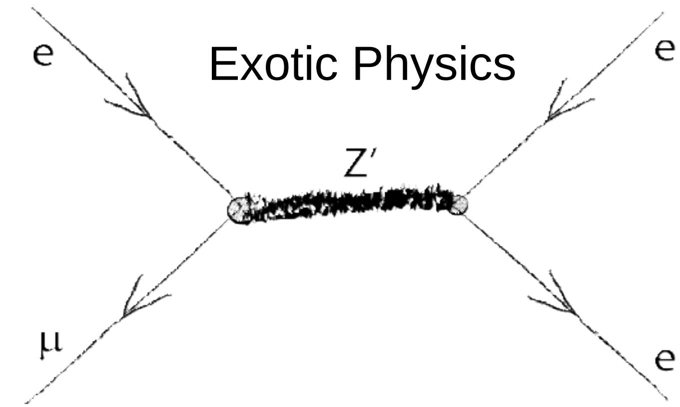
10. November 2023



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



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



tree diagram (Mu3e specific)

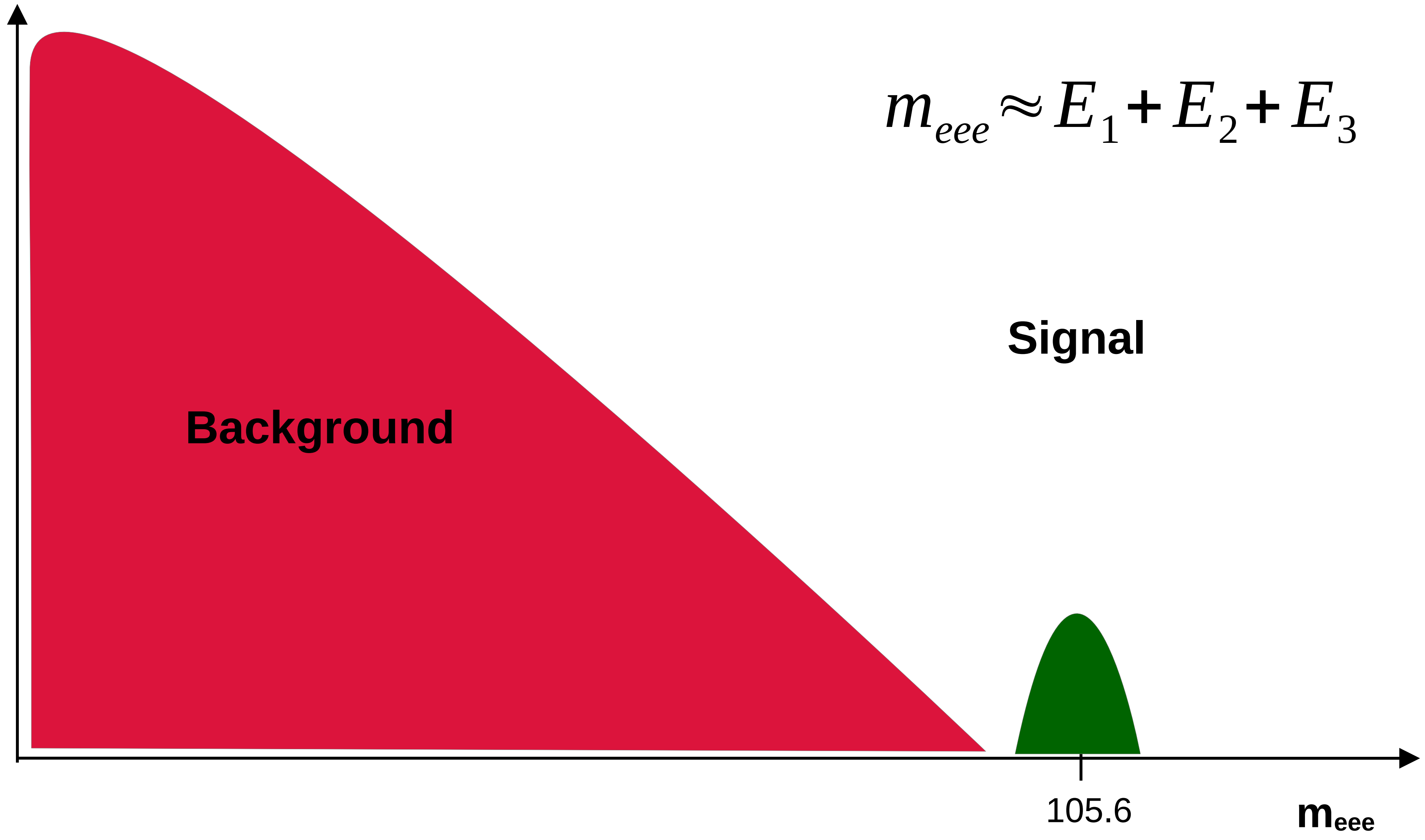
- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**

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

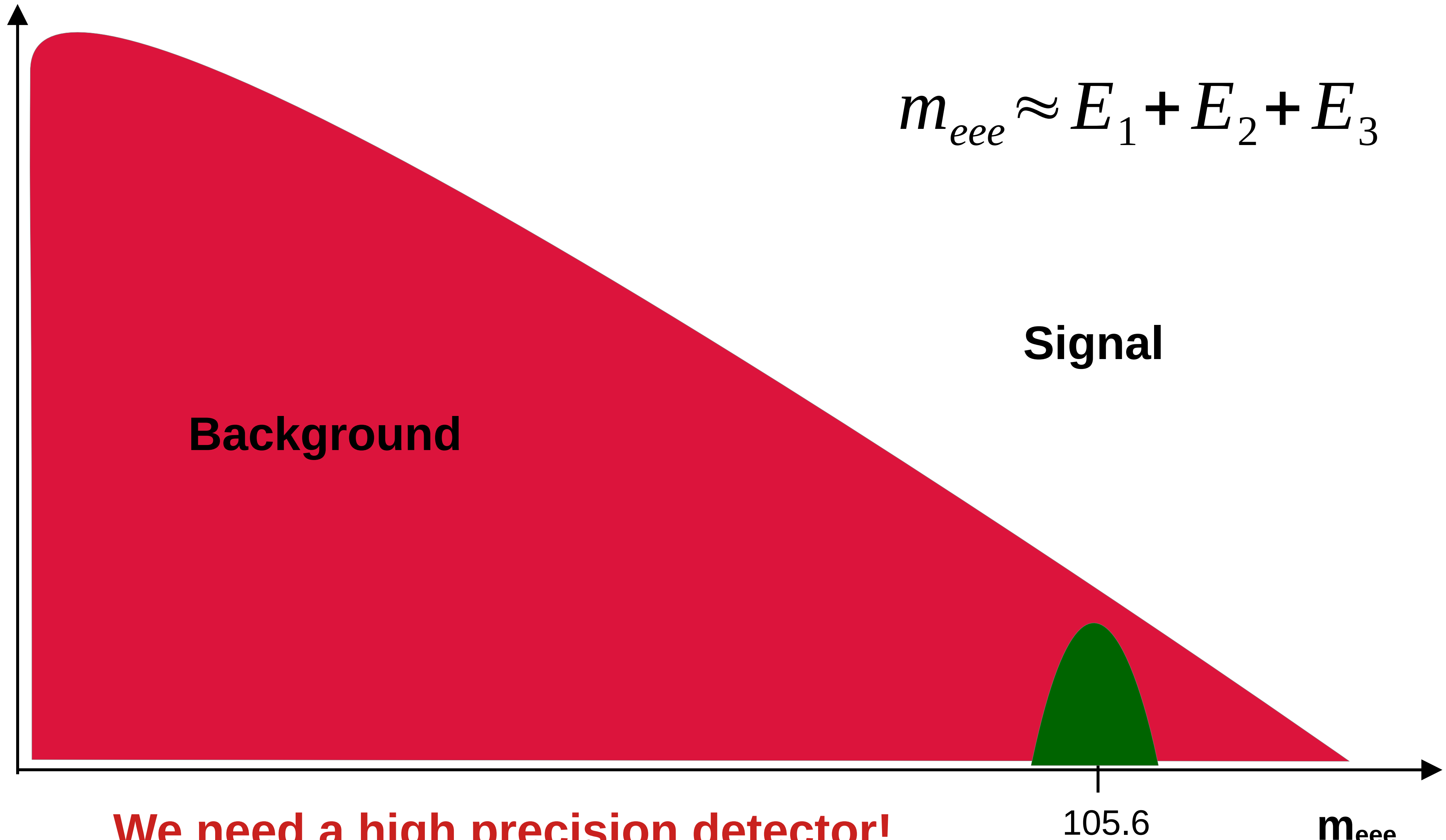
Most models "naturally" induce lepton flavor violation!

Mu3e: Searching for $\mu^+ \rightarrow e^+ e^+ e^-$

$$m_{eee} \approx E_1 + E_2 + E_3$$



Mu3e: Searching for $\mu^+ \rightarrow e^+ e^+ e^-$



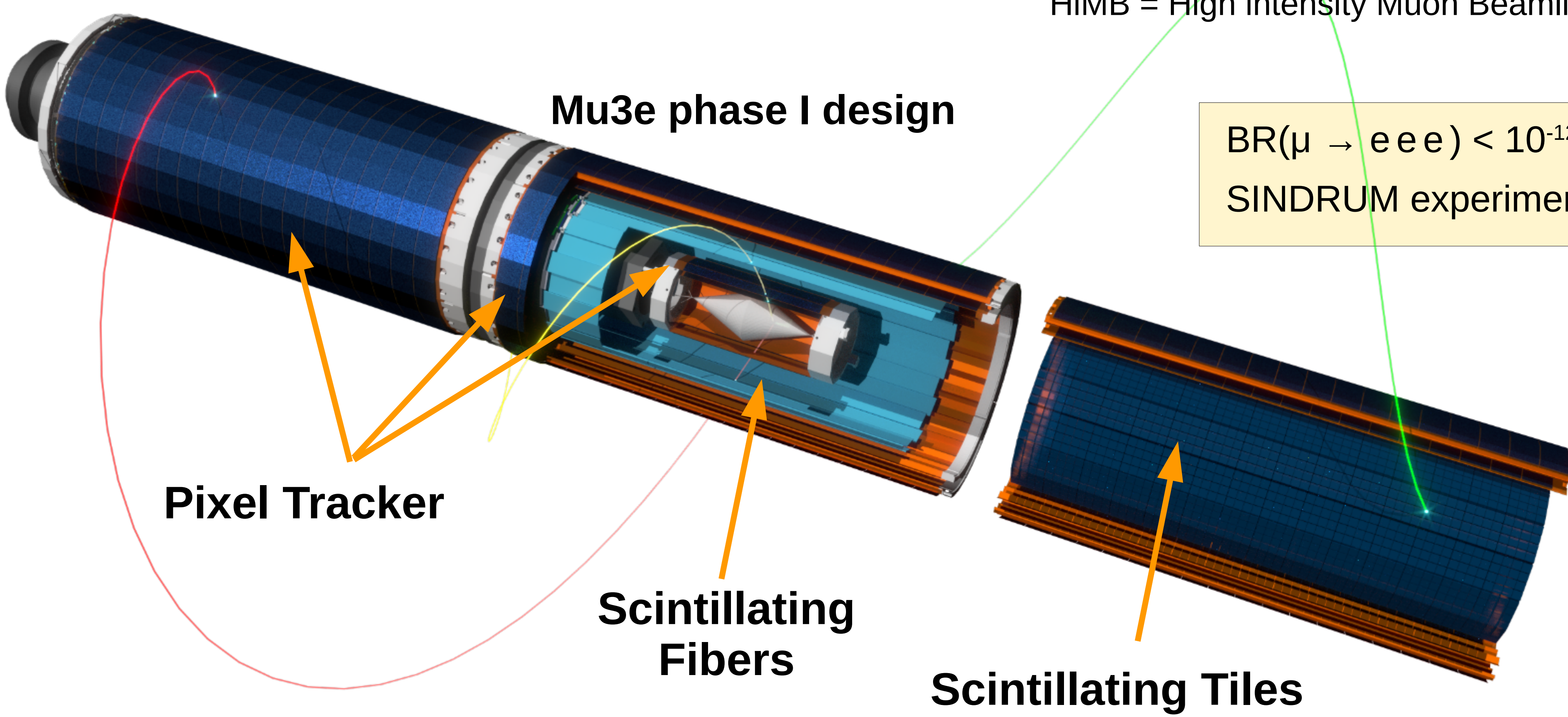
We need a high precision detector!

Mu3e Experiment

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

BR($\mu \rightarrow eee$) < $2 \cdot 10^{-15}$	(phase I)	→	**10^{8} muons/s**	(PiE5 beamline)
BR($\mu \rightarrow eee$) < 10^{-16}	(phase II)	→	**>10^{9} muons/s**	(HIMB=High Intensity Beamline)

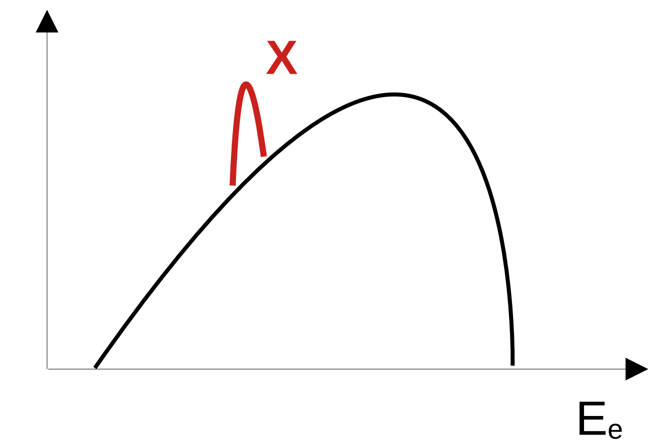
HiMB = High intensity Muon Beamline (under study)



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

Exotic Physics and other Ideas for Mu3e

- **Search for light cLFV particles:** $\mu \to e X$
  - *X* invisible → peak in Michel spectrum
  - ***X*** → ***ee*** at displaced vertex or $\mu \to eee$ signature
    - → special search strategy and upgrade of online filter farm



- **Search for dark photons:** $\mu \to e \nu \nu A'$
  - ***A'* invisible** → no chance for detection
  - ***A'*** → ***ee*** *at* displaced vertex or peak in the ee inv. mass spectrum of $\mu \to ee e\nu\nu$ events

- **Search for cLFV in:** $\mu \to e \gamma$
  - Mu3e is a tracking detector and is able to detect converted photons $\gamma \to ee$ *using* dedicated converter layers
  - "Beyond Phase II"

Paul-Scherrer Institut (Schweiz)

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

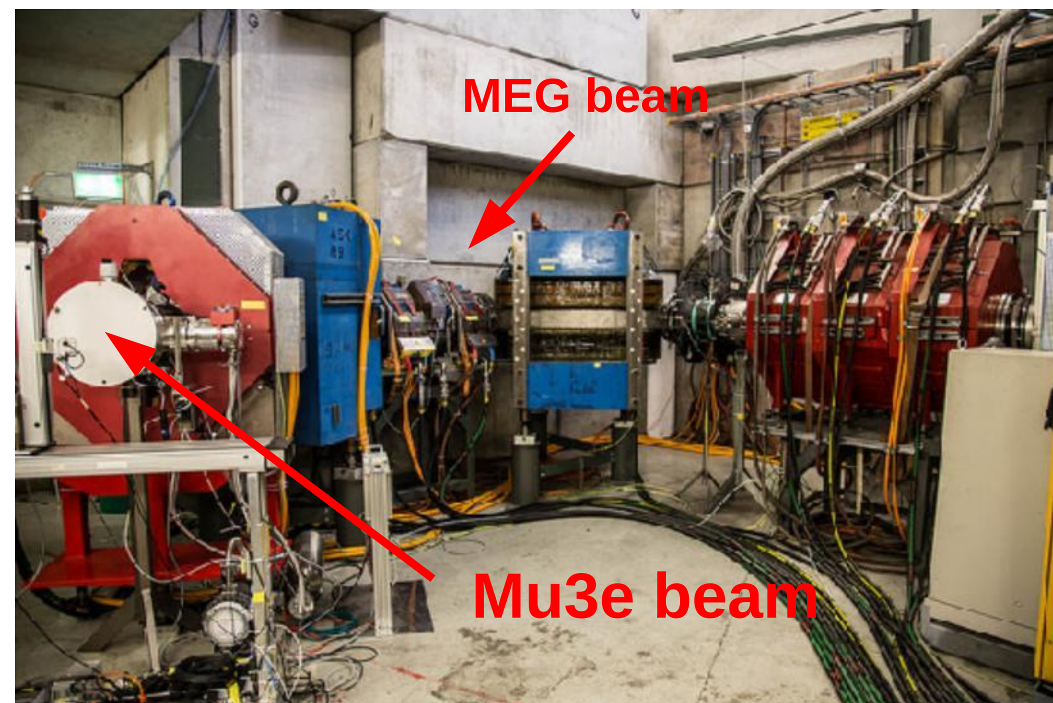
PiE5 Muon Beamline:

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

Phase I:

- **expect 1.4·10^8 μ^+/s at 2.4 mA**
- **about half is stopped on μ-stopping target**

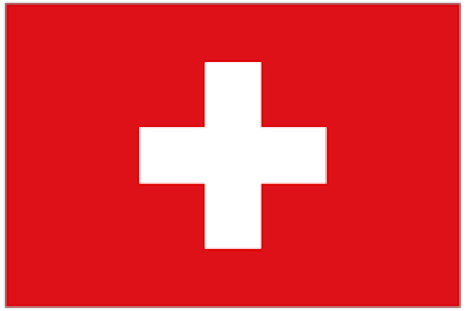
PiE5: Compact Muon Beamline for Mu3e



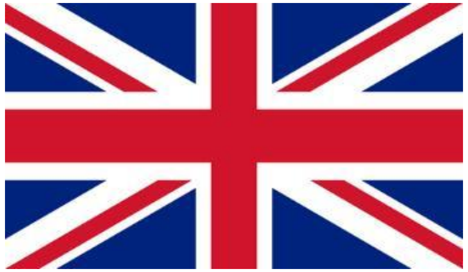
Mu3e Collaboration

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

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



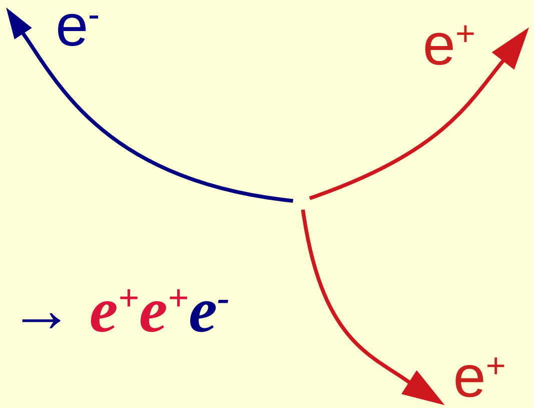
United Kingdom
- Bristol
- Liverpool
- Oxford
- UC London



~ 85 members (~15 PhD students)

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

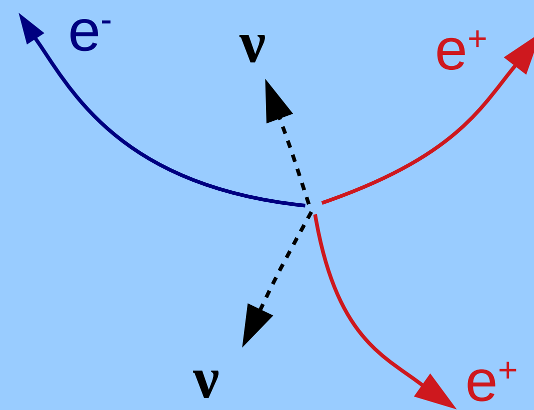
Signal



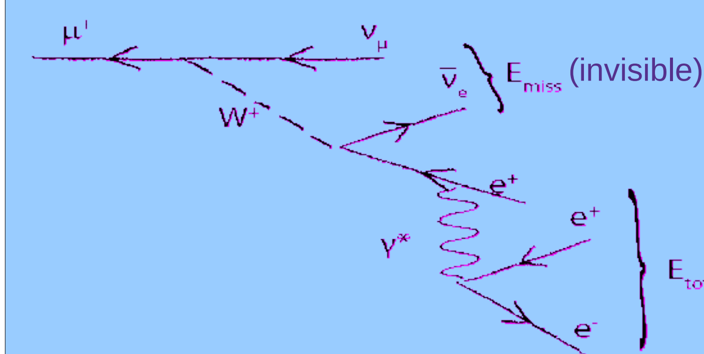
$\mu^+ \rightarrow e^+e^+e^-$

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

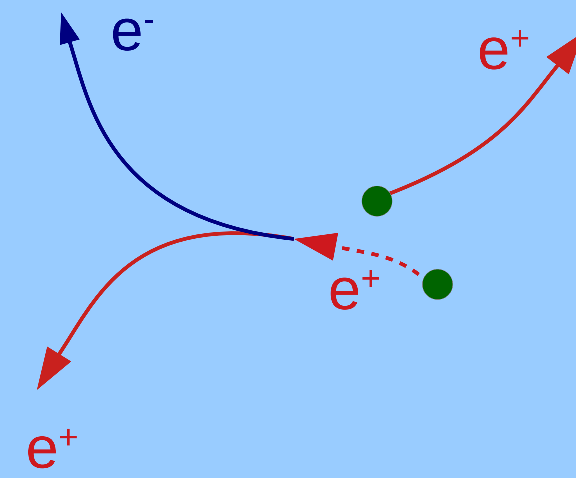
Radiative muon decay with internal conversion



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



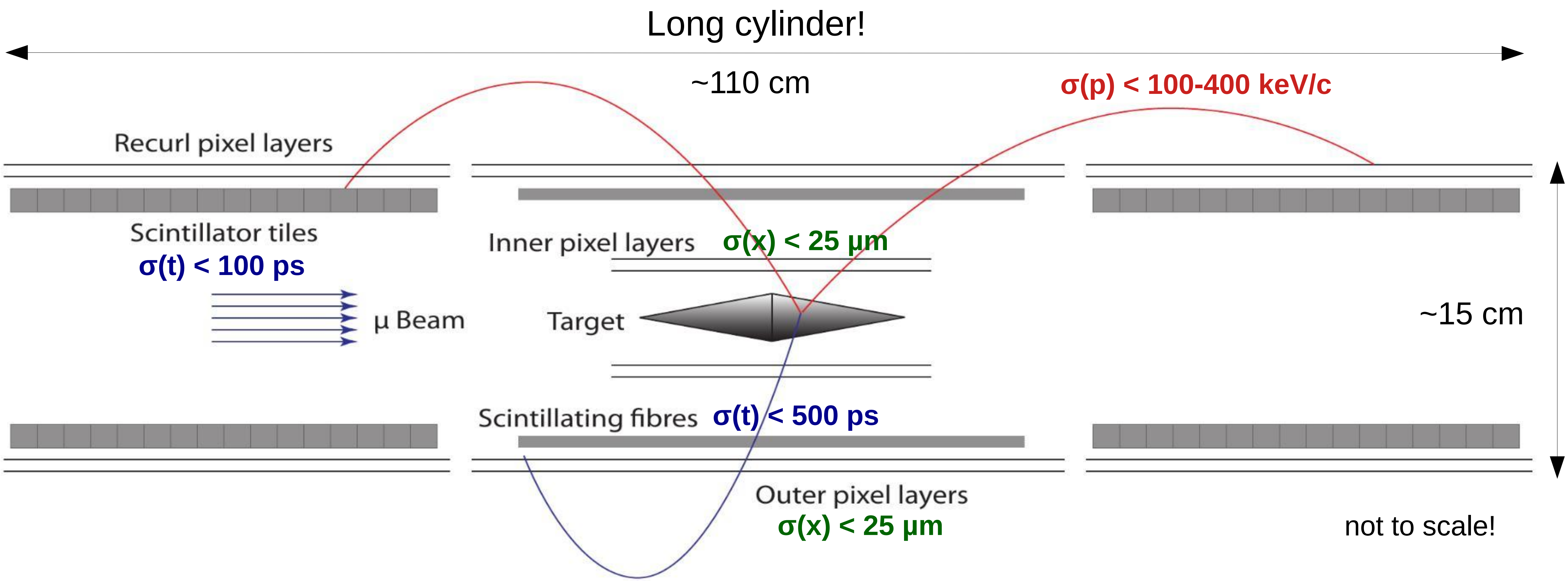
Accidental Background



pileup of **Michel decays** and electrons from **Bhabha scattering**

need excellent: **Kinematic reconstruction + Vertex & Timing resolution**

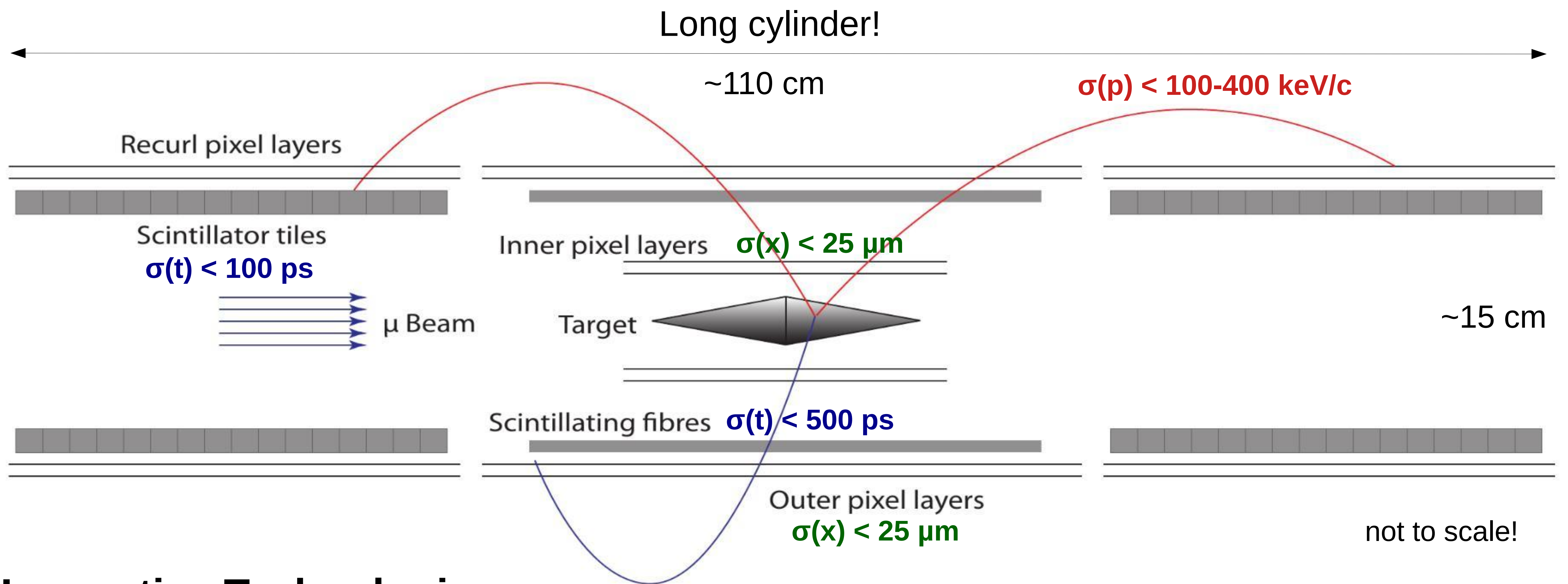
Mu3e Phase I Design



Challenges:

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

Mu3e Phase I Design



Innovative Technologies:

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

Charge Collection in (HV-)MAPS

Drift-Diffusion Equation: $\vec{j} = q D \nabla n + q n \mu \vec{E}$

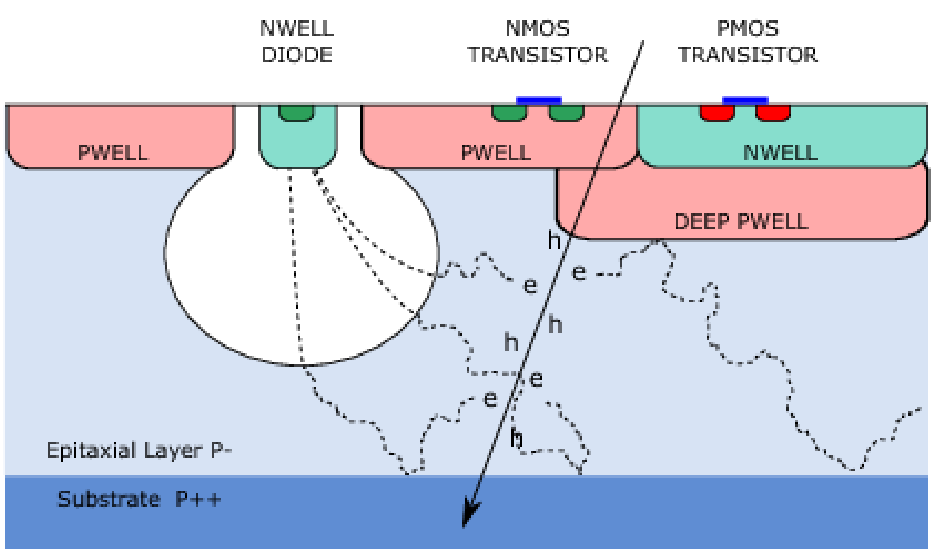
D=diffusion constant, μ=mobility, n=charge density

$$\tau_{collection}^{-1} = \tau_{diffusion}^{-1} + \tau_{drift}^{-1}$$

(depends on substrate, temperature, pixel geometry, electric field, ...)

Standard MAPS

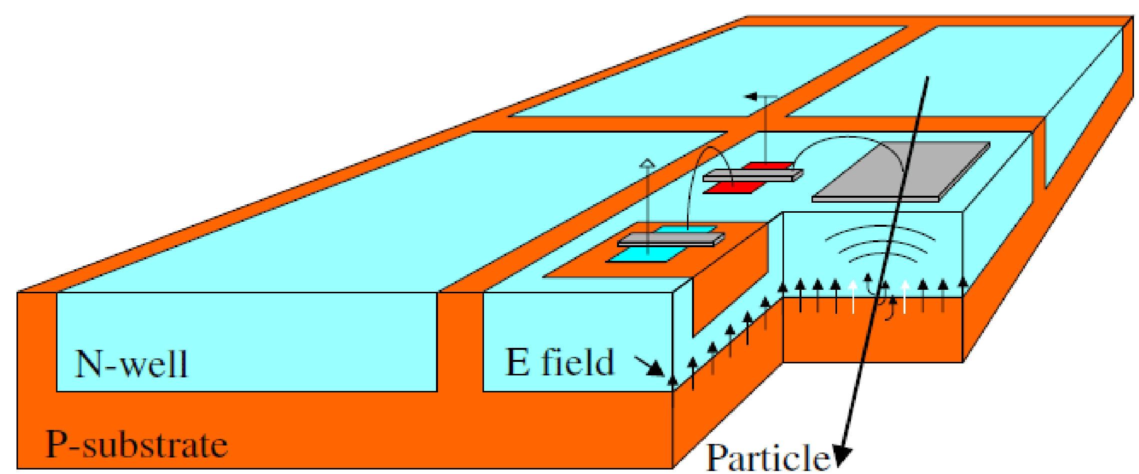
$\tau_{diffusion}^{-1} \approx 10-1000\,\text{ns}$



(from Besson et al. 2016)

High Voltage-MAPS (depleted MAPS)

$\tau_{drift}^{-1} \approx 10-100\,\text{ps}$



e.g. High Voltage – Monolithic Active Pixel Sensor

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

Charge Collection in MAPS

Drift-Diffusion Equation: $\vec{j} = q D \nabla n + q n \mu \vec{E}$

D=diffusion constant, μ=mobility, n=charge density

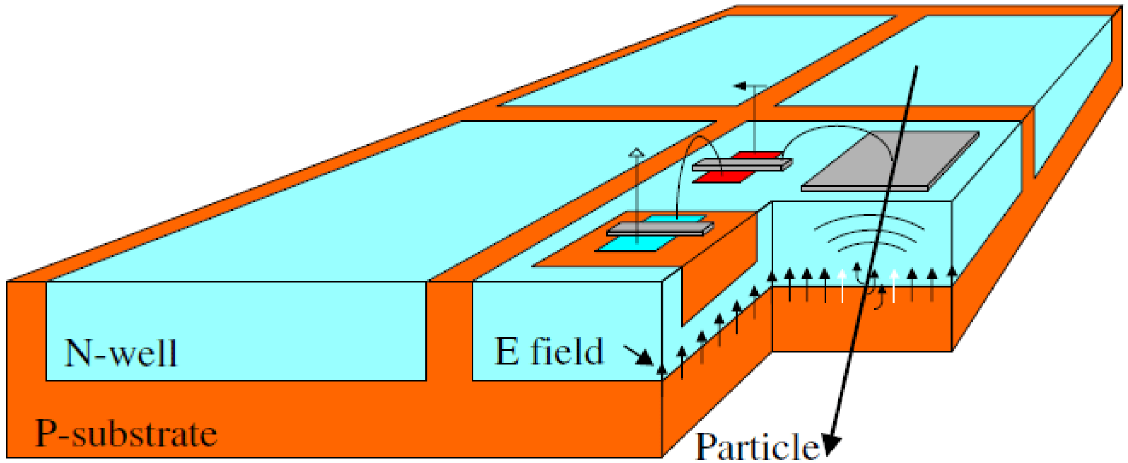
$$\tau^{-1}_{collection} = \tau^{-1}_{diffusion} + \tau^{-1}_{drift}$$

(depends on substrate, temperature, pixel geometry, electric field, ...)

High Voltage-MAPS (depleted MAPS)

$\tau^{-1}_{drift} \approx 10-100\,\mathrm{ps}$

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



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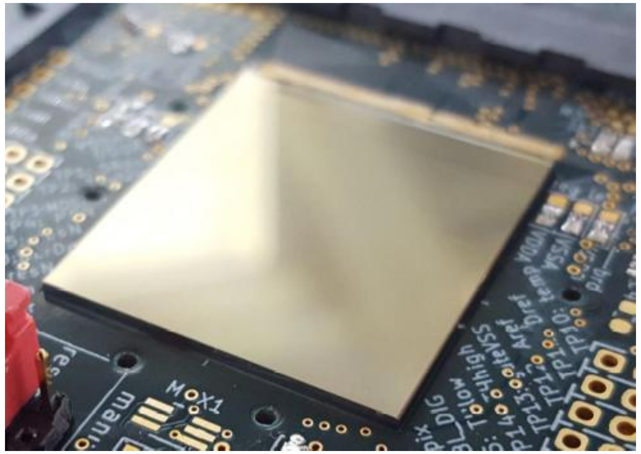
Mupix Sensor



(KIT, Heidelberg)

MuPix is the fastest monolithic sensors in the world!

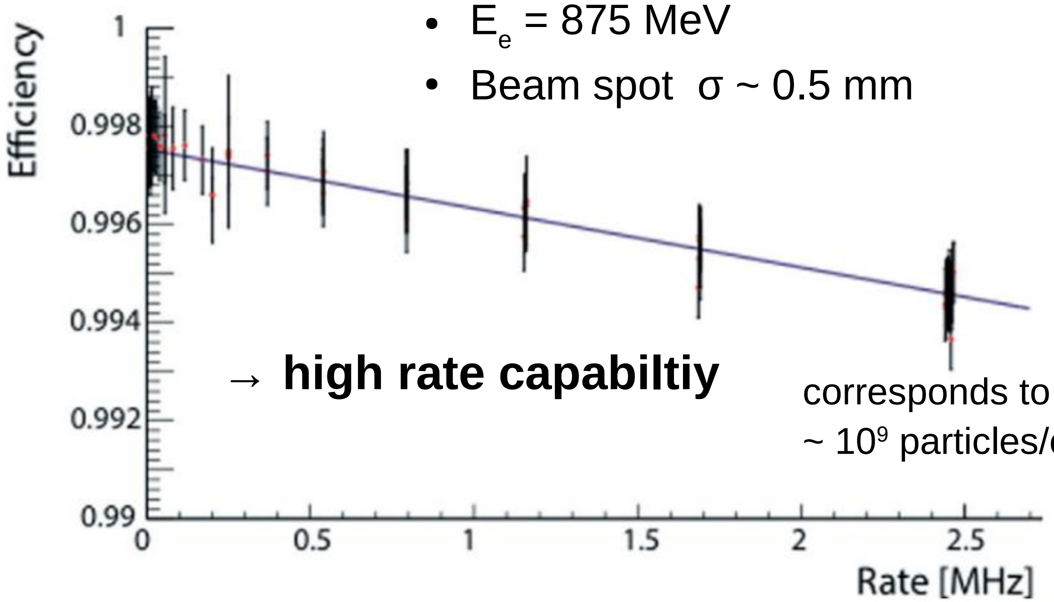
Specifications [https://arxiv.org/abs/2009.11690]

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

all specifications fulfilled by Mupix11

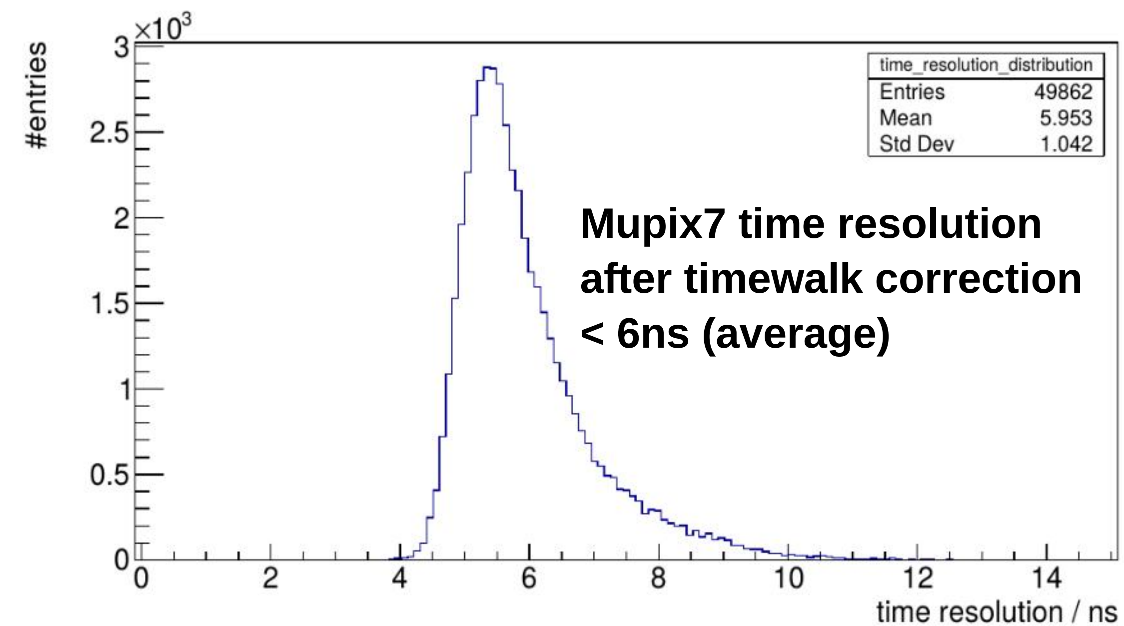
Single hit efficiency at MAMI (Mainz)

- E_e = 875 MeV
- Beam spot σ ~ 0.5 mm



→ **high rate capabiltiy**

corresponds to ~ 10^9 particles/cm^2

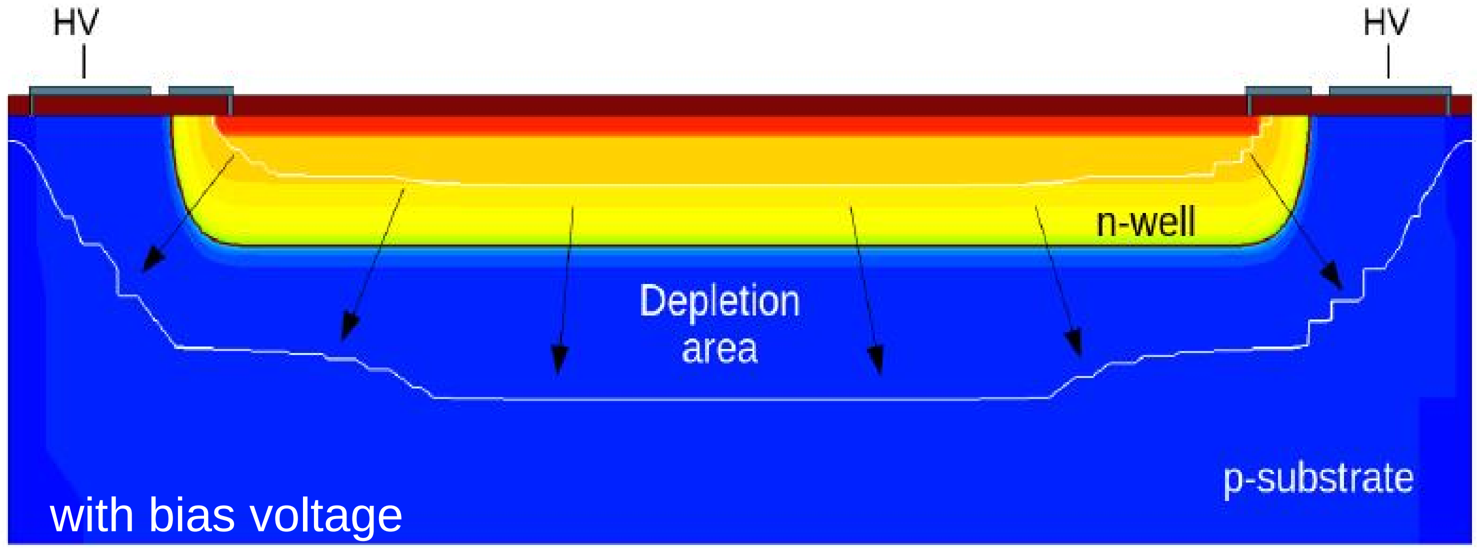


Mupix7 time resolution after timewalk correction < 6ns (average)

HV-MAPS Charge Collection

HV-MAPS Charge Collection

electrical field
up 10^5 V/cm



"depleted MAPS"

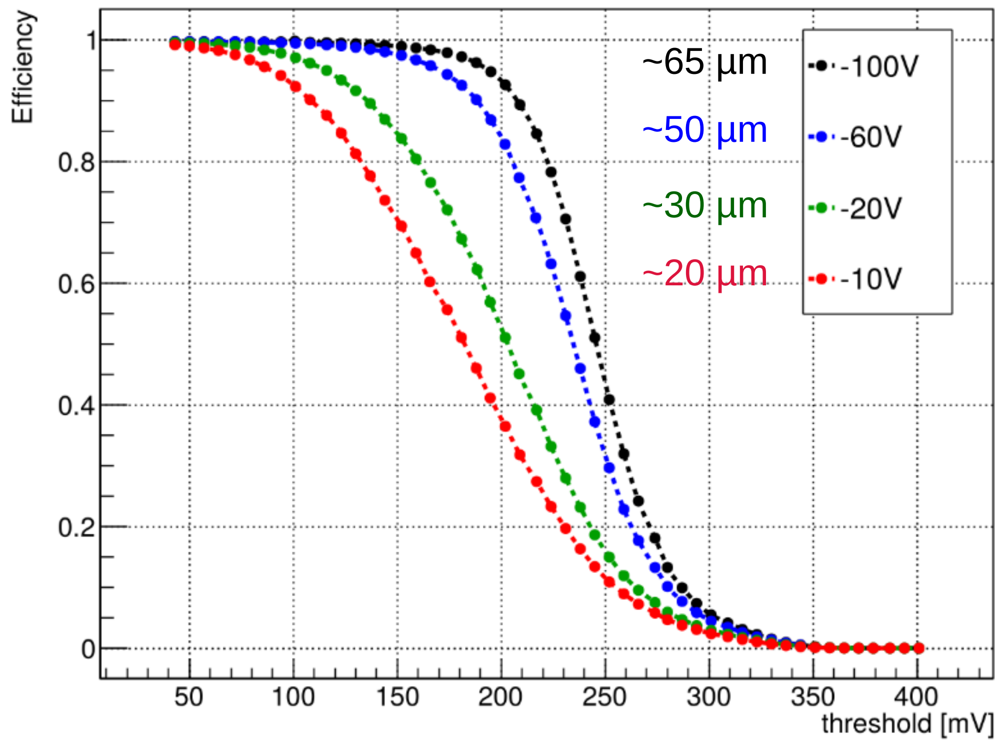
depletion depth: $d \propto \sqrt{\rho \cdot U}$ electric field: $E \propto \sqrt{U / \rho}$

U = voltage

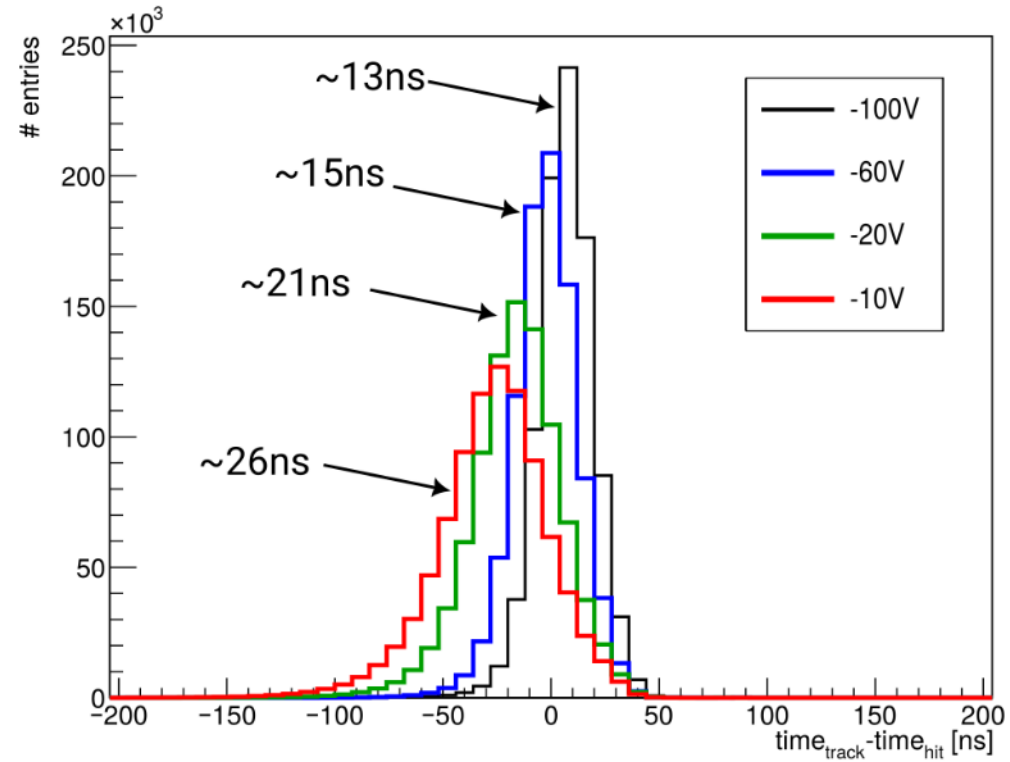
ρ = substrate resistivity

Depletion, Efficiency and Time Resolution

Efficiency - 100µm thick sensor



Time resolution (Gaussian estimate)



Efficiency as function of the threshold and **HV (depletion depth)**

$$d \propto \sqrt{\rho \cdot U}$$

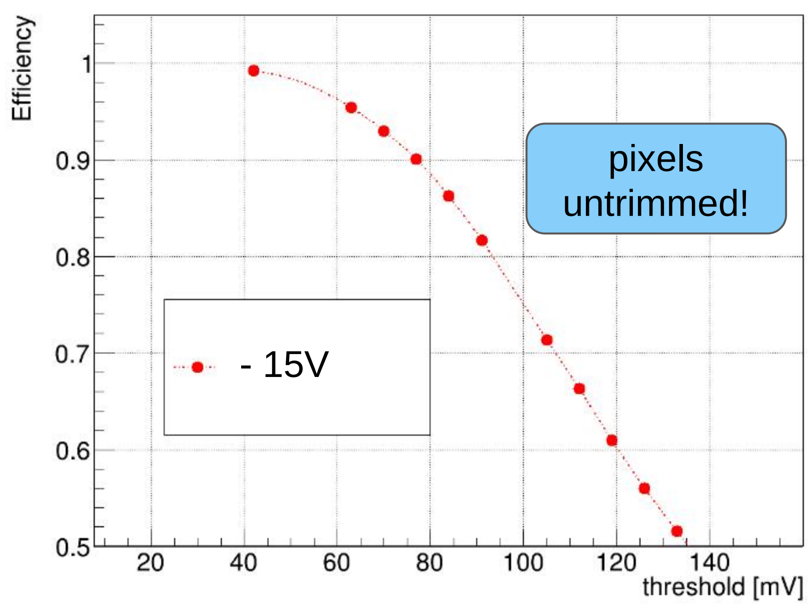
Raw time resolution (no corrections applied)

$$\sigma_t \propto \frac{1}{amplitude} \sim \frac{1}{\sqrt{U}}$$

Thinner sensor → lower maximum depletion → lower efficiency and worse time resolution

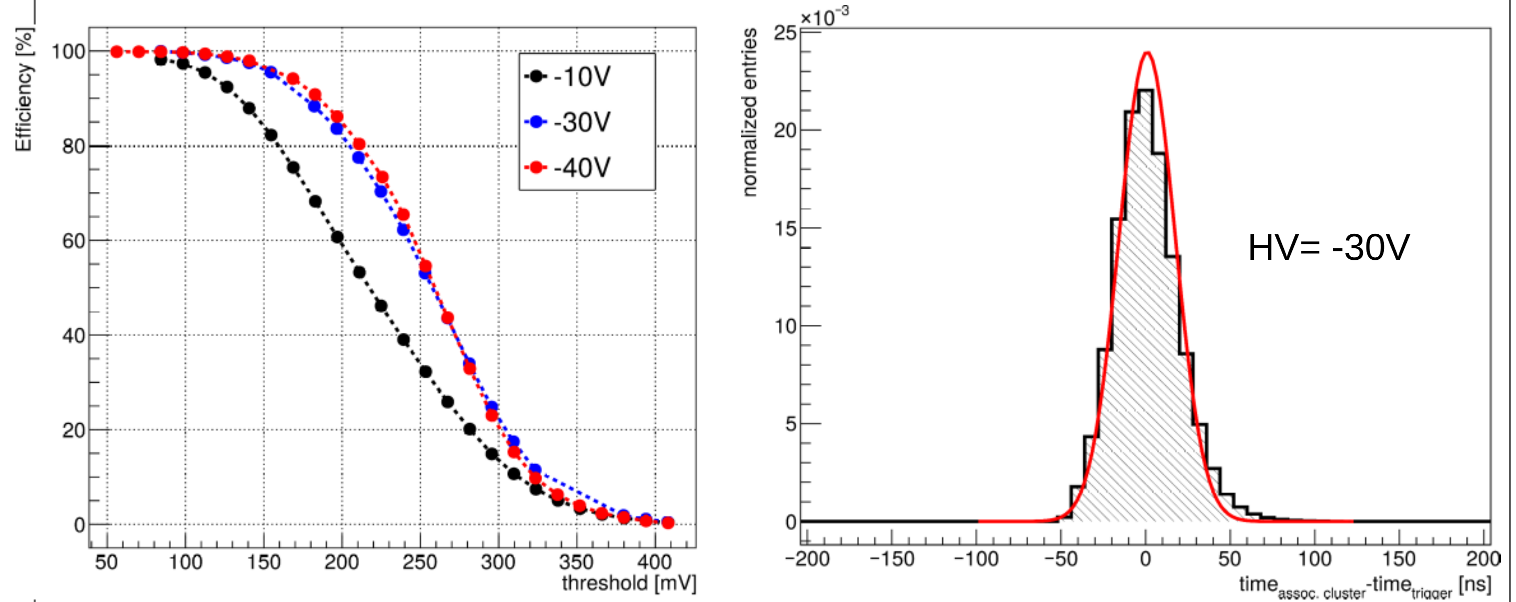
"Best" Mupix Thickness for Mu3e

50µm thickness



- Needs calibration/trimming of all pixels!

70µm thickness



$\sigma_{\text{uncorrected}} \sim 16.6\,\text{ns}$

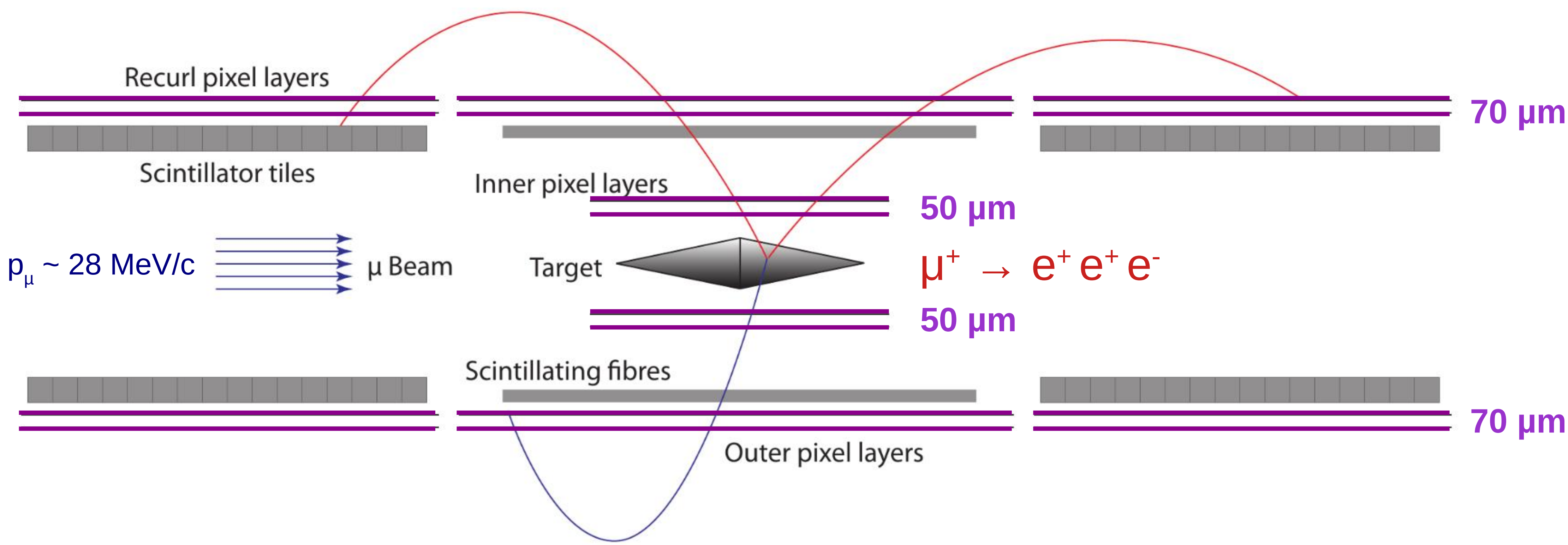
- Works out of the box!

Mu3e Phase I: 50µm sensors for the vertex detector (~100 Sensors) [baseline]

70µm sensors for the outer layers (~3000 Sensors)

Mu3e Silicon Pixel Tracker Design (Phase I)

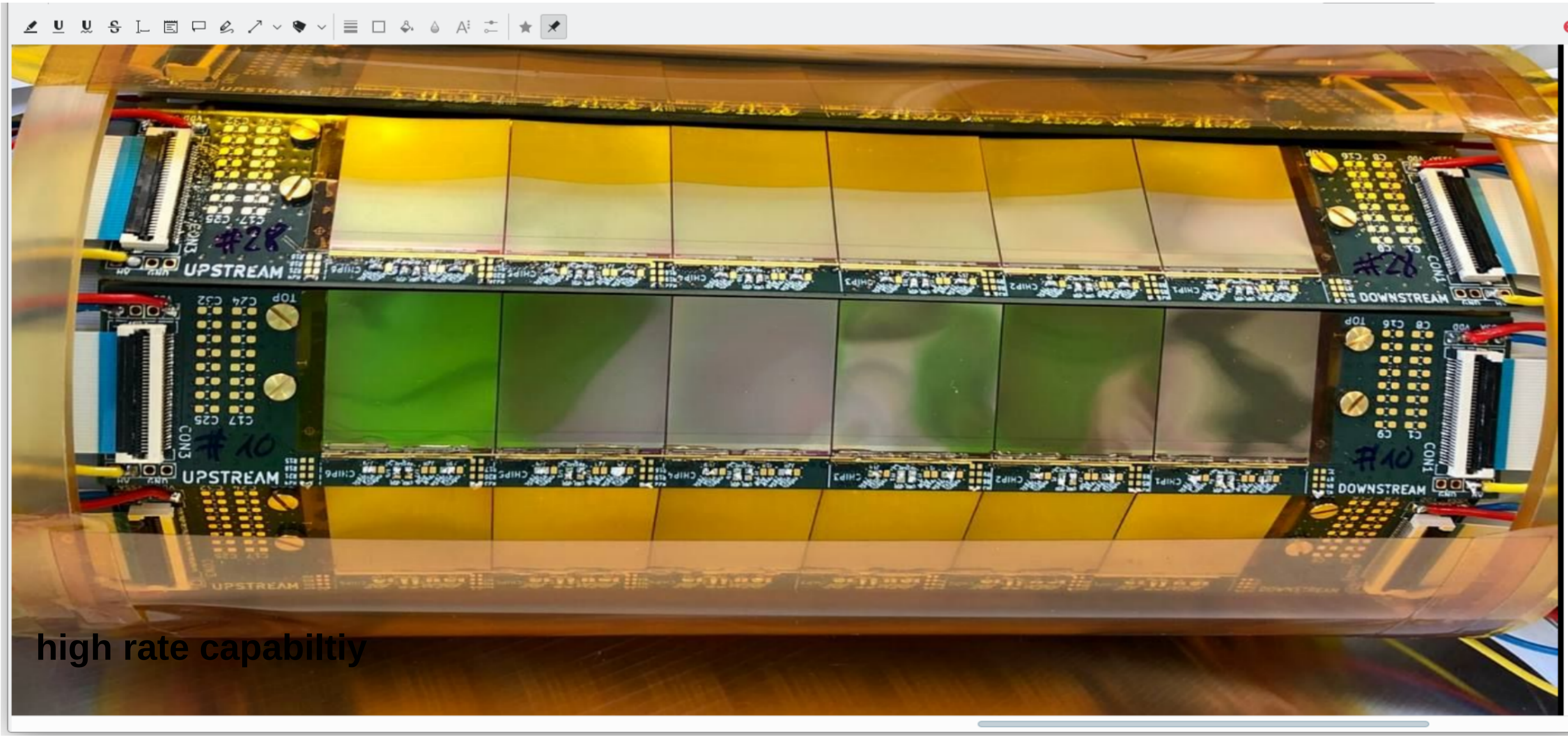
tracking of electrons (positrons) in low momentum range: **$p_e \leq 53$ MeV/c**



- **4 layers** of HVMAPS (MuPix) in **central** region
- **2 layers** of HV-MAPS (MuPix) **upstream** and **downstream** (recurl stations)
- pixel size **80 µm x 80 µm** → resolution **$\sigma_{spatial}$ ~ 23 µm**

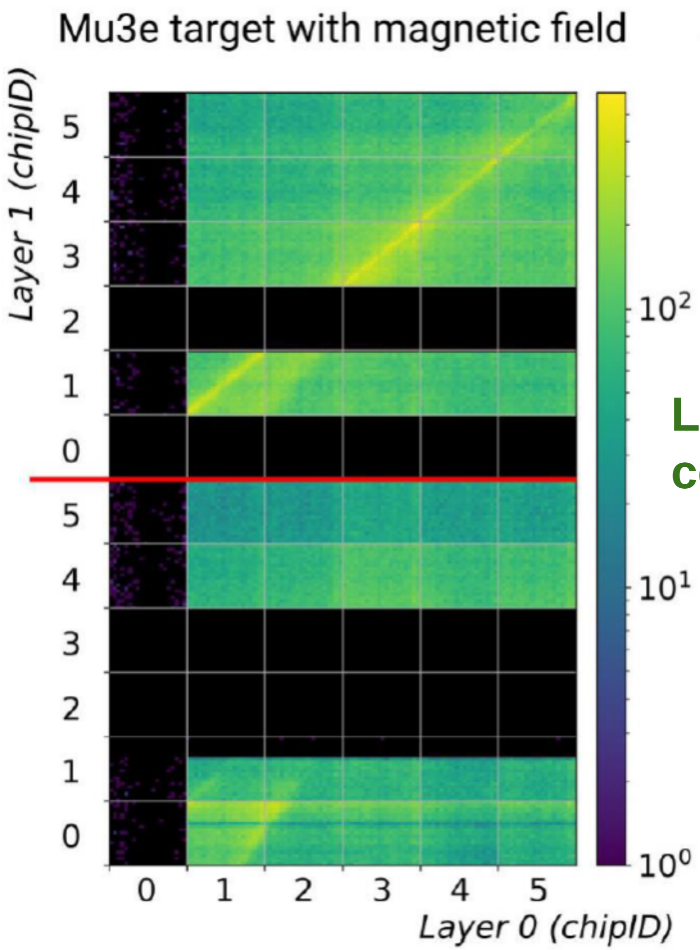
Multiple Scattering is dominant!

Mu3e Vertex Detector Prototype
2021 Integration Run



Vertex Prototype Results from 2021/2022 Integration Runs

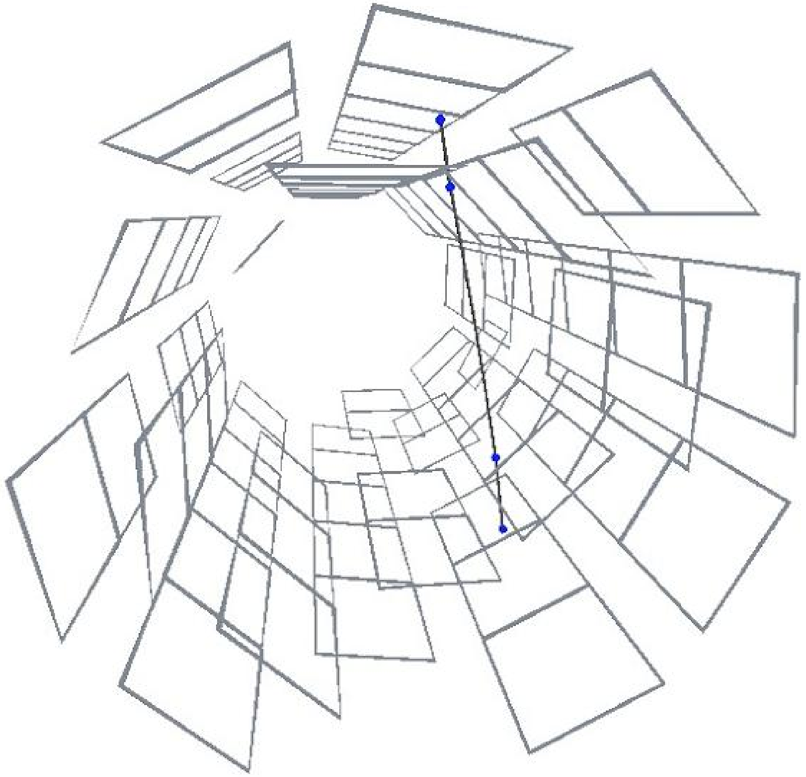
With beam (2021)



Layer 0-1 correlation!

first operation under experimental conditions

With cosmics (2022)



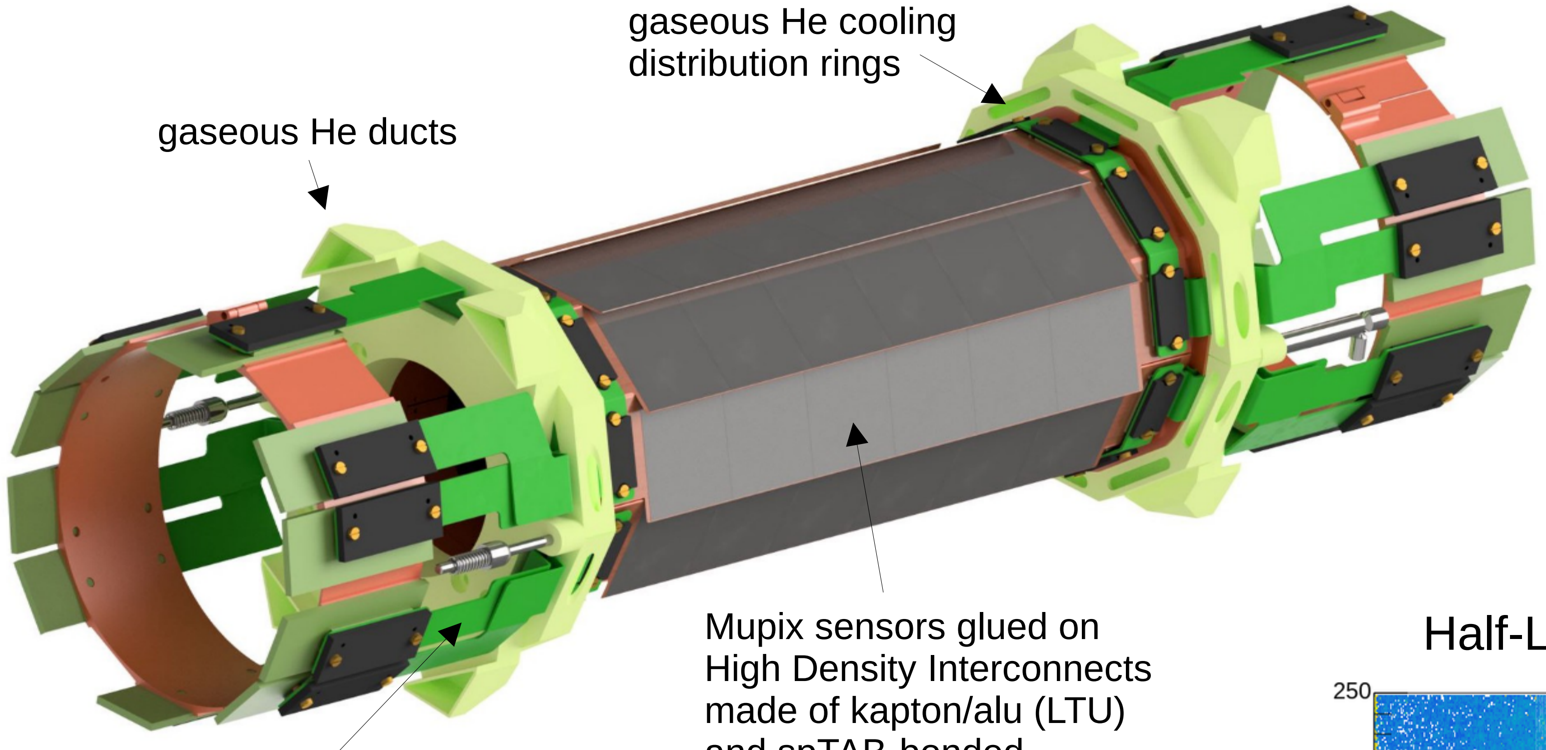
challenge:
→ reduce pixel noise to see low rate cosmics

Mu3e Vertex Detector (Final Design)

https://www.physi.uni-heidelberg.de/~schoning/First_Vertex_Ladders_IMG_7211.mp4

gaseous He cooling distribution rings

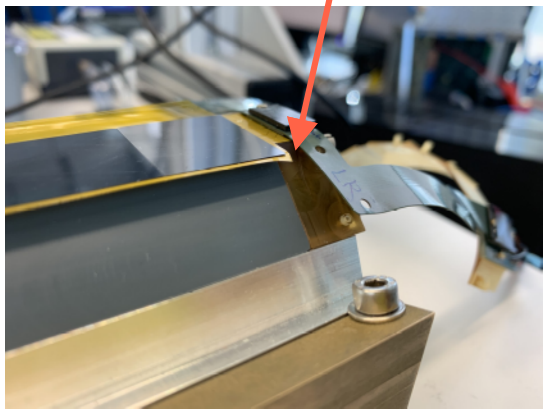
gaseous He ducts



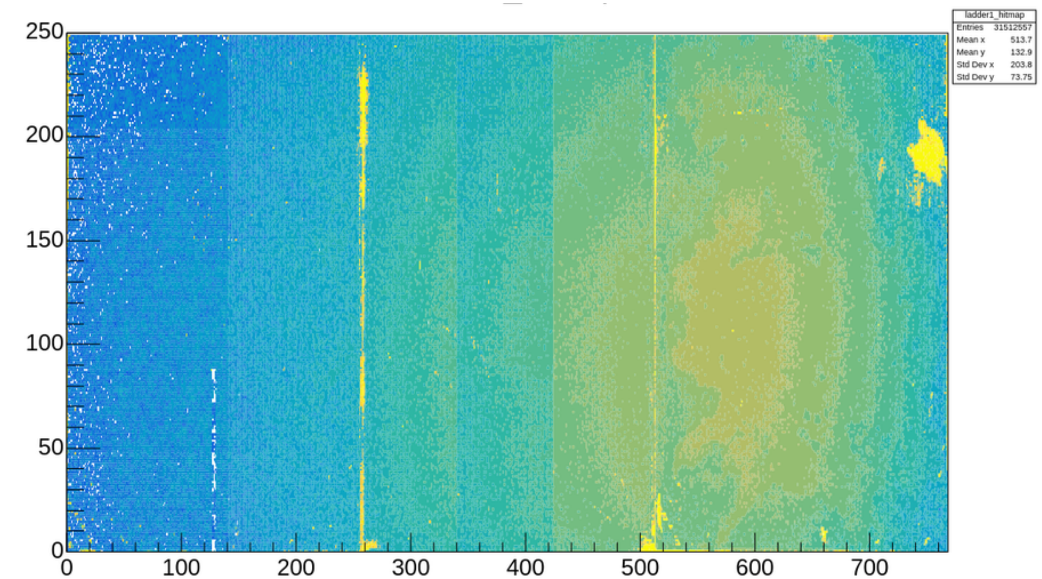
Mupix sensors glued on High Density Interconnects made of kapton/alu (LTU) and spTAB-bonded

flex prints for readout, control and powering

broken ladder



Half-Ladder in PSI testbeam (Oct. '23)



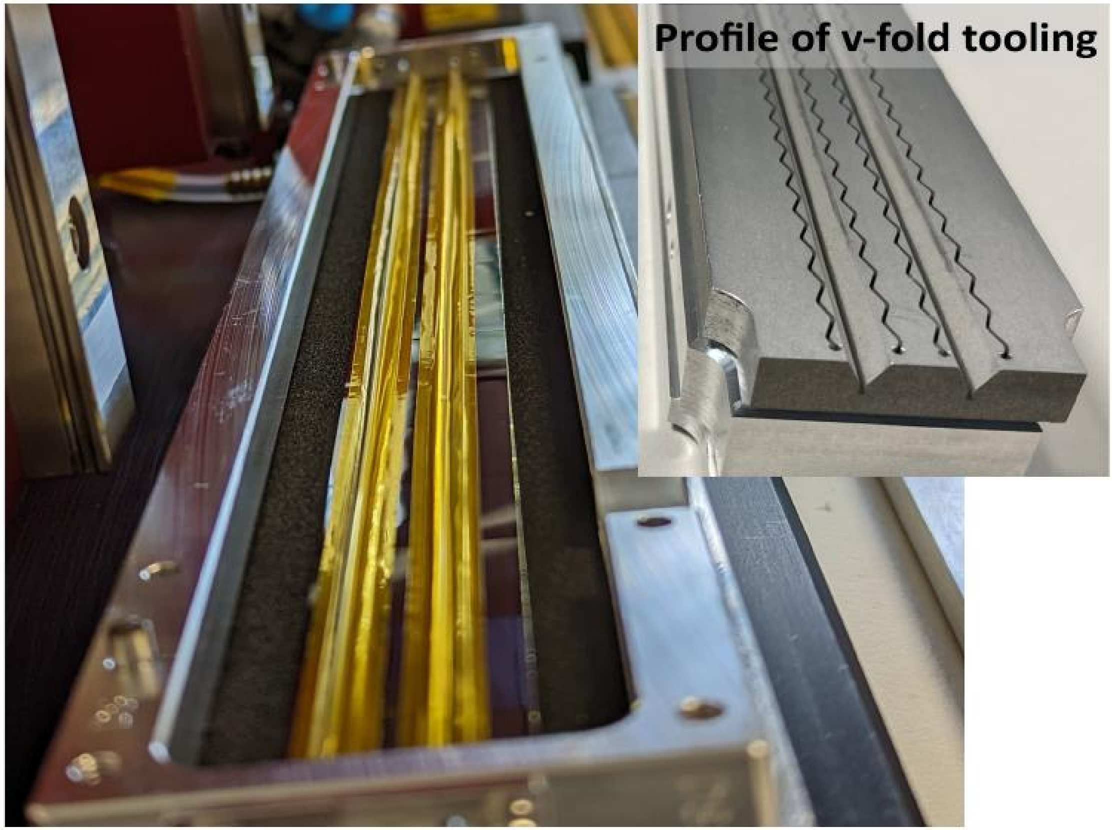
Ultra-light design: the mass of one vertex ladder is < 1g

radiation lengths: $$\frac{x}{X_0} \approx 1.1 \cdot 10^{-3}$$

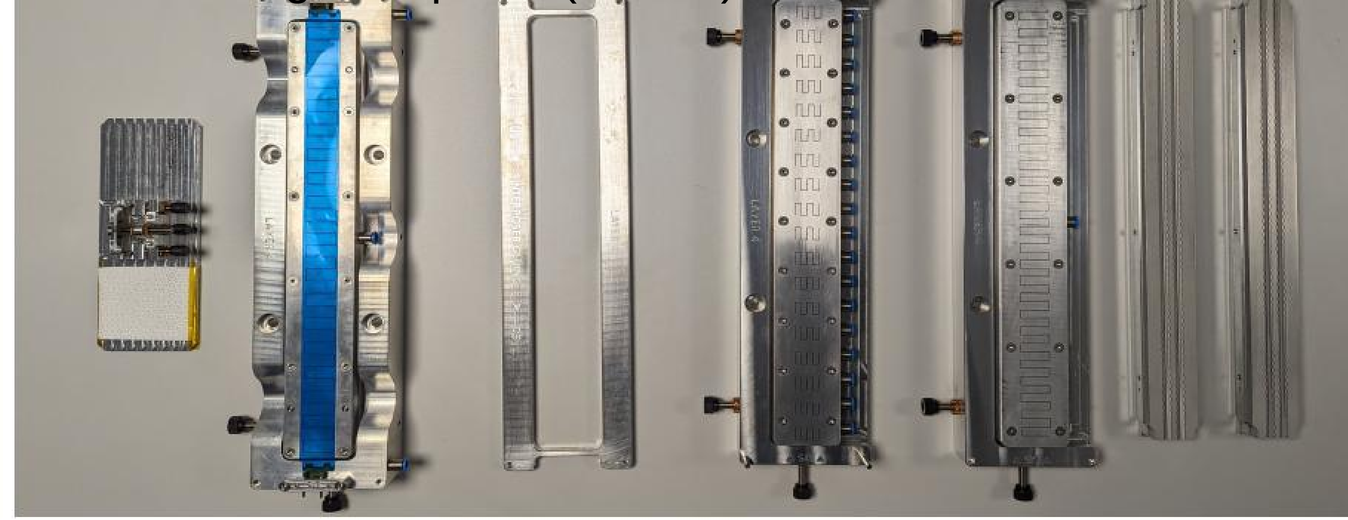
Mu3e Outer Pixel Detector

(Bristol, Oxford and Liverpool)

Prototype outer pixel layers have been fabricated.



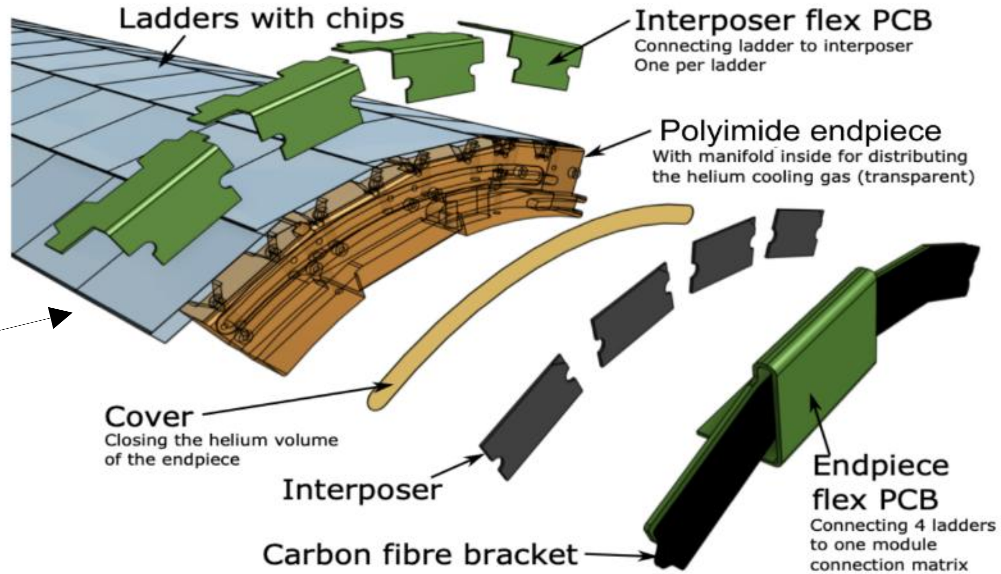
Lot of tooling is required (Oxford)



Big challenge:

- ladder size of 36cm!
- Ladders are supported by kapton v-folds only

SpTA-Bond

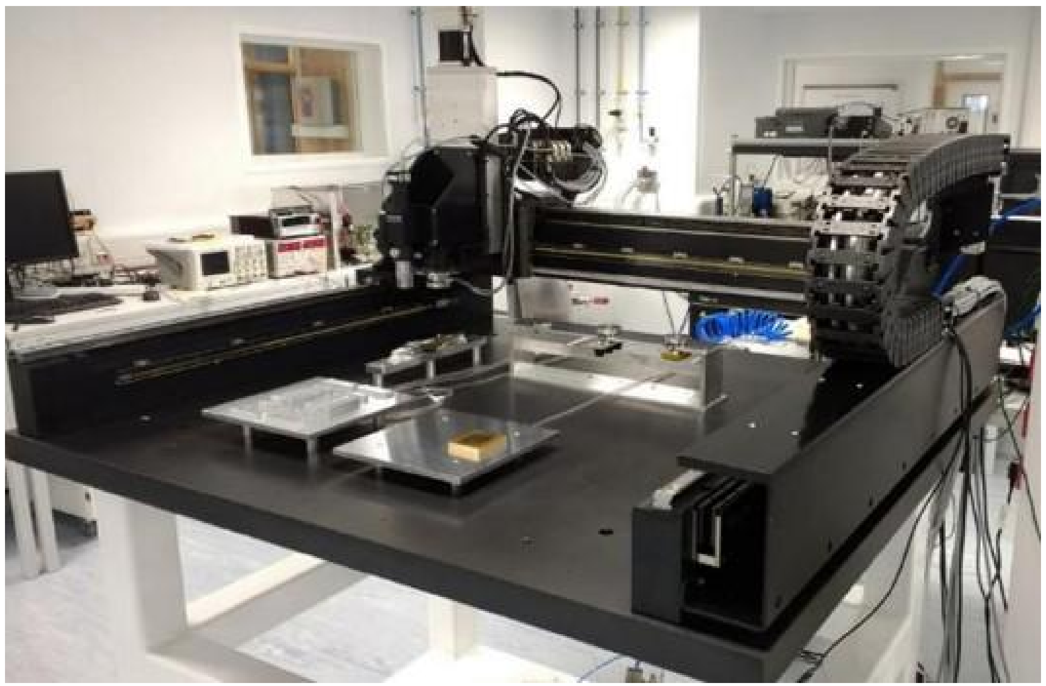


Outer Module production → **Liverpool**

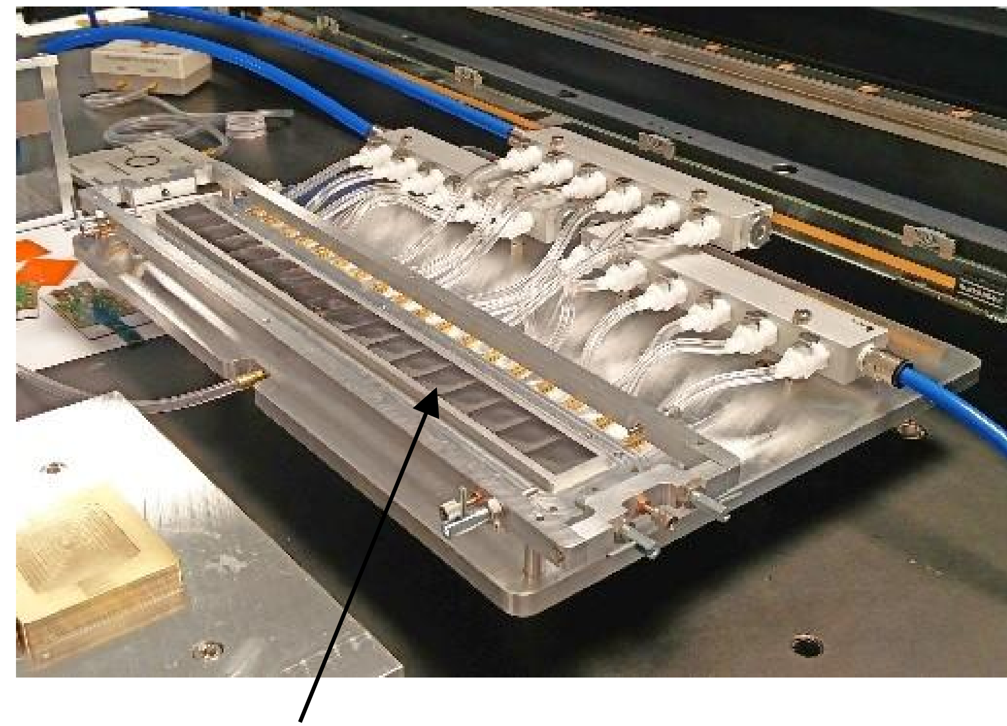
Mu3e Outer Pixel Detector

(Bristol, Oxford and Liverpool)

Production of Outer Pixel Modules is automated to a large extend



Gantry in Oxford



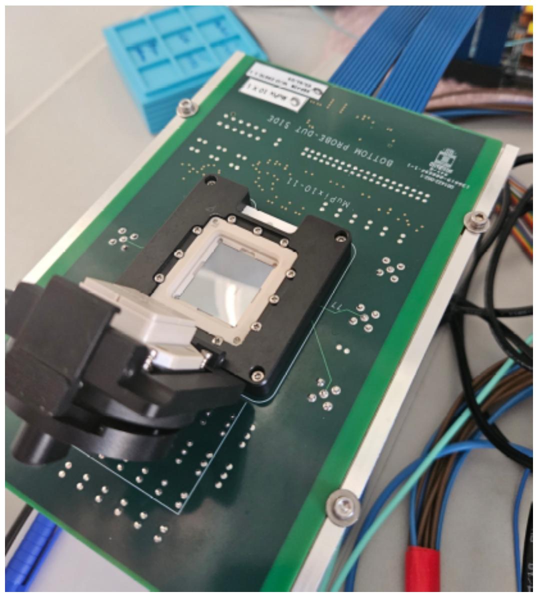
18 Mupix sensors per ladder

→ active area in total 1.2 m^2 (~3000 sensors)

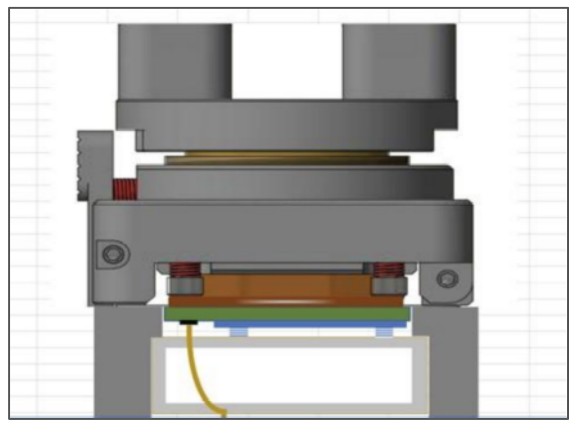
Quality Assurance and Control

All detector components need to be tested at different stages, from single parts to modules

Single chip probe station



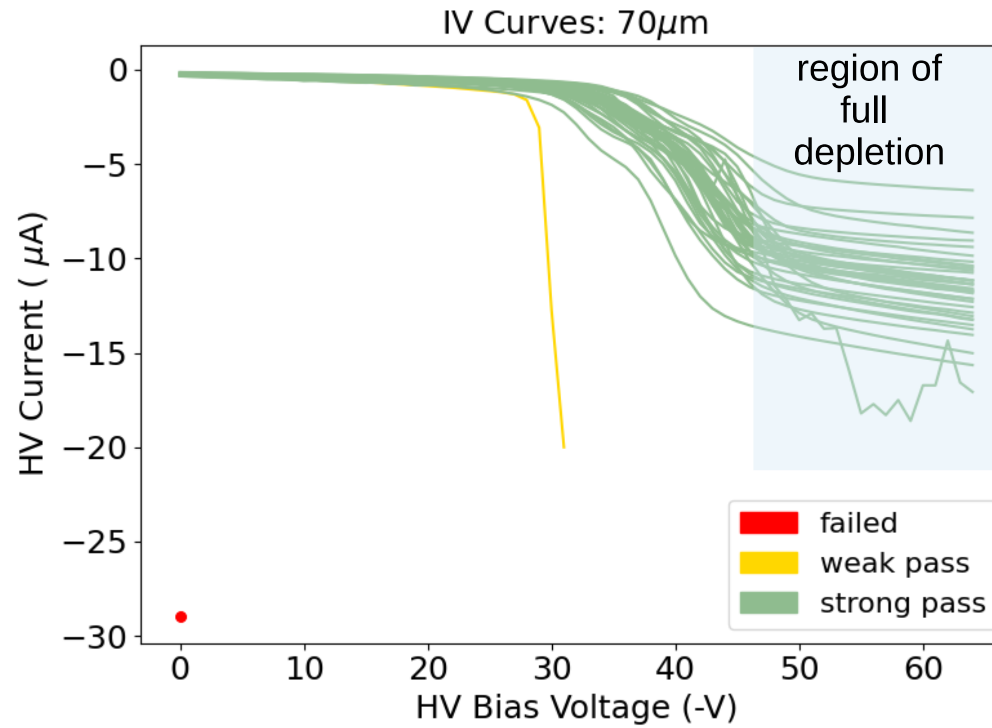
press down mechanism



All individual Mupix sensors need to be qualified before ladder construction (gluing)

about 10000 sensors to be tested!

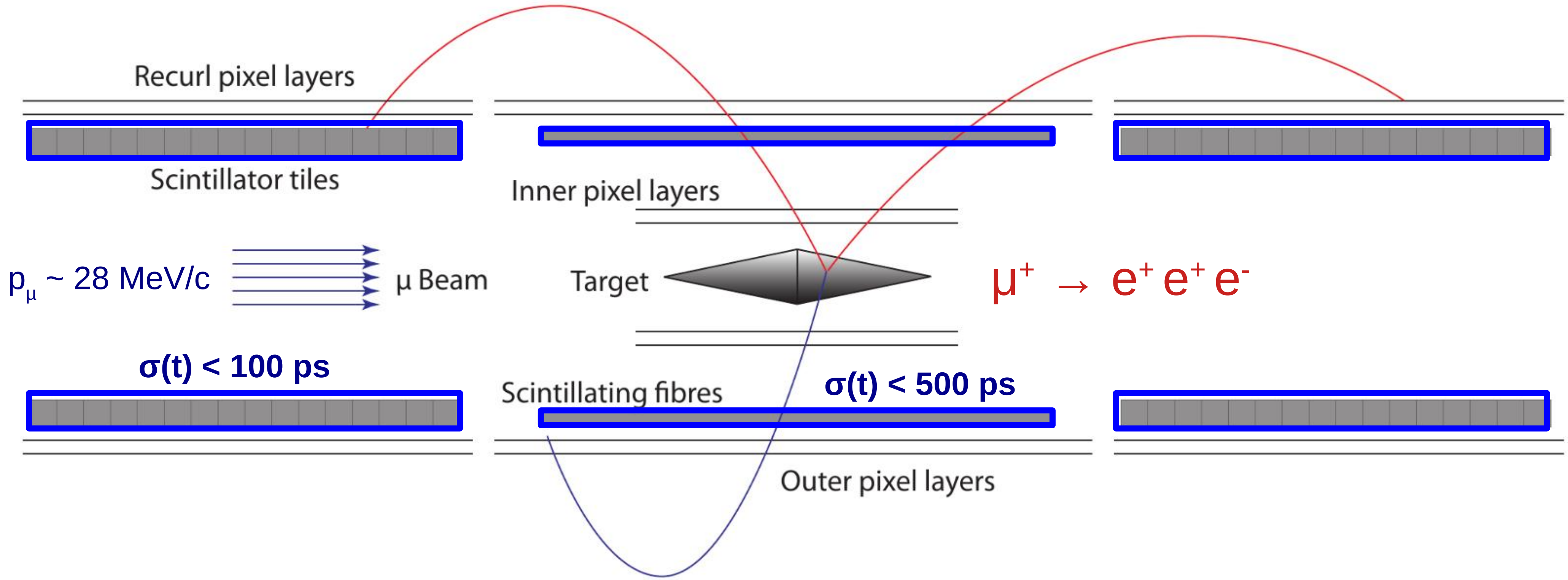
Measured Current Voltage diagrams



plus other parameters:

- power consumption
- voltage levels
- data links

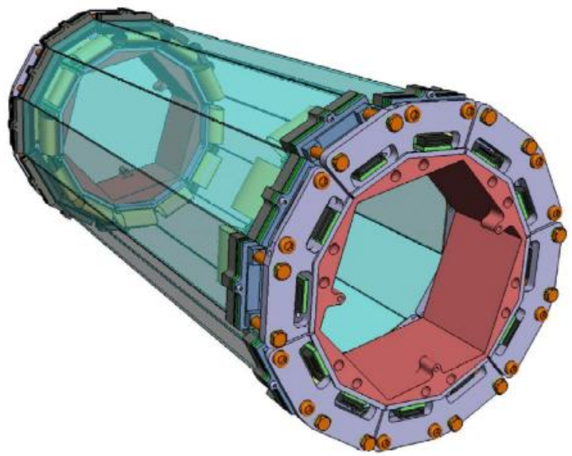
Mu3e Timing Detectors



- in central region: Scintillating Fibers → **σ(t) < 500 ps**
- up-/downstream: Scintillating Tiles → **σ(t) < 100 ps**

Timing is crucial to fight accidental background at high rate ~ 10^8 muon stops/s

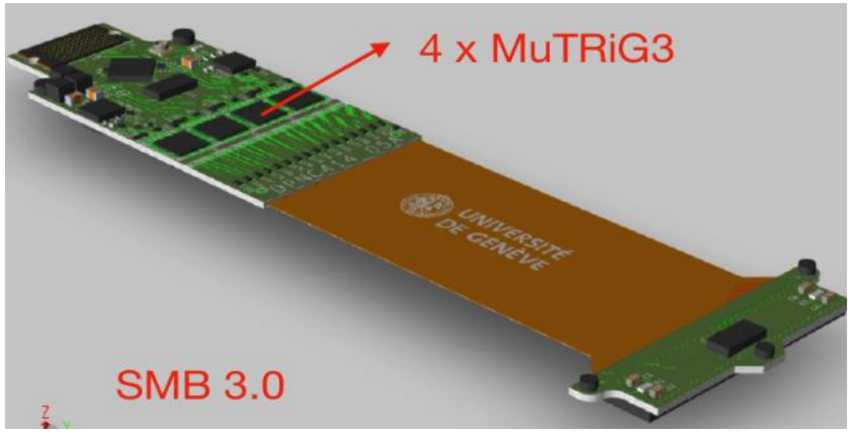
Scintillating Fibres



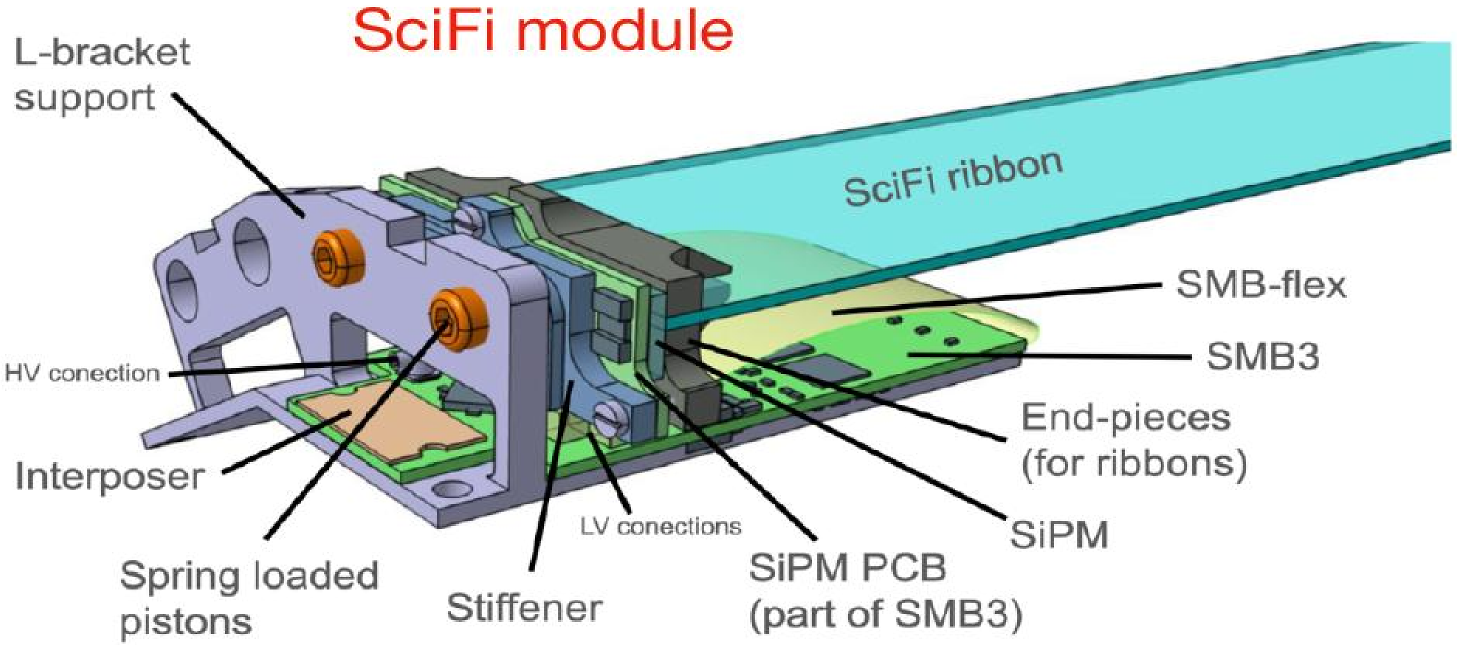
SciFi detector

Scintillating Fibre Detector

- Scintillating fibres: Kuraray SCSF-78MJ
- SiPM Hamamatsu S13552-HRQ
- MuTrig TDC ASICs for readout
- → very challenging space constraints

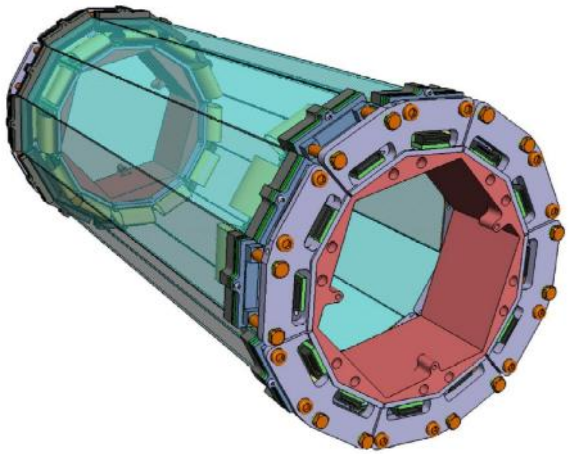


Final hardware prototypes exists and successfully tested in testbeam!



Hamamatsu S13552-HRQ

Scintillating Fibres



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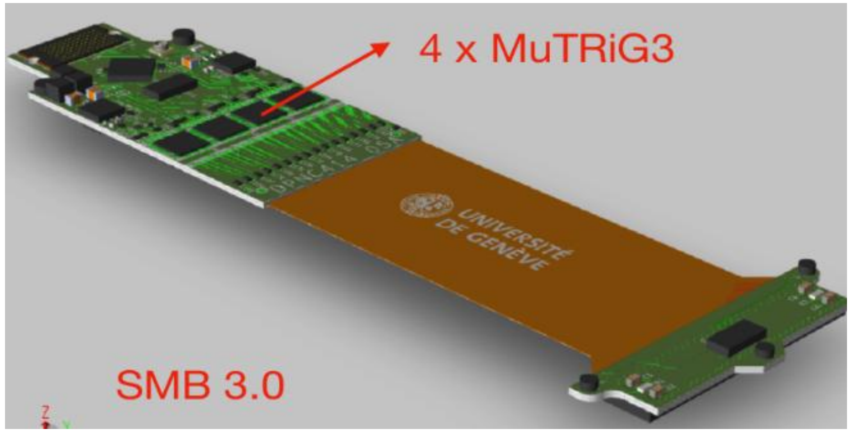
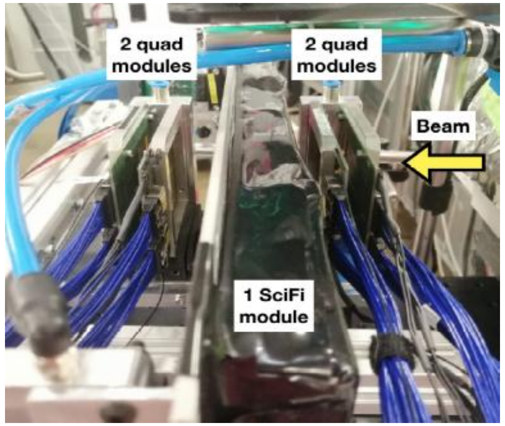
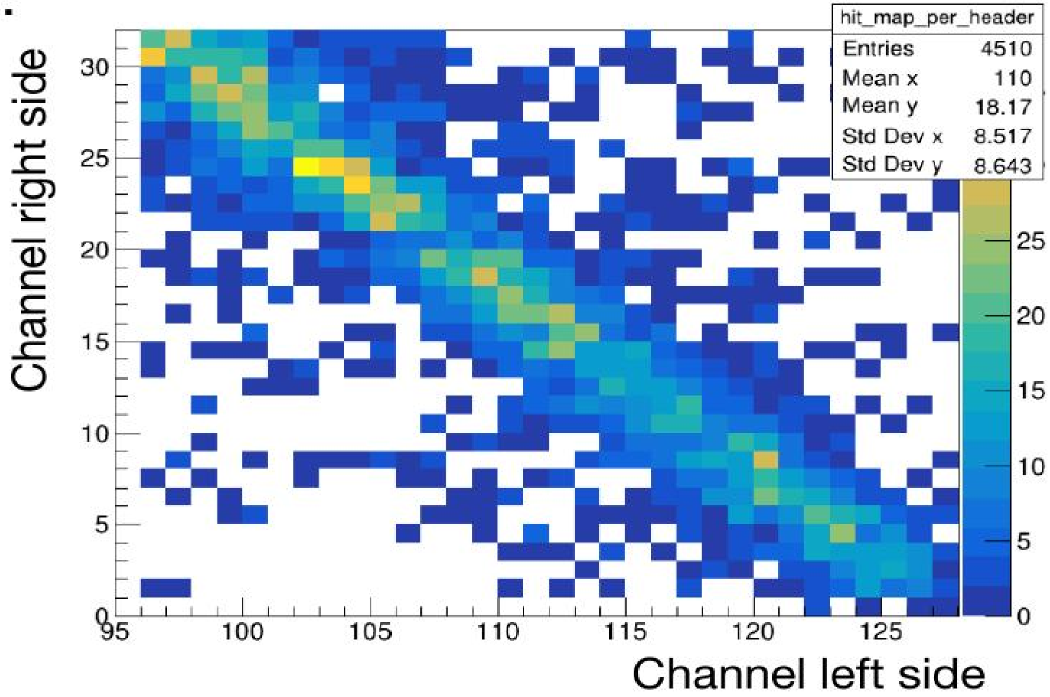


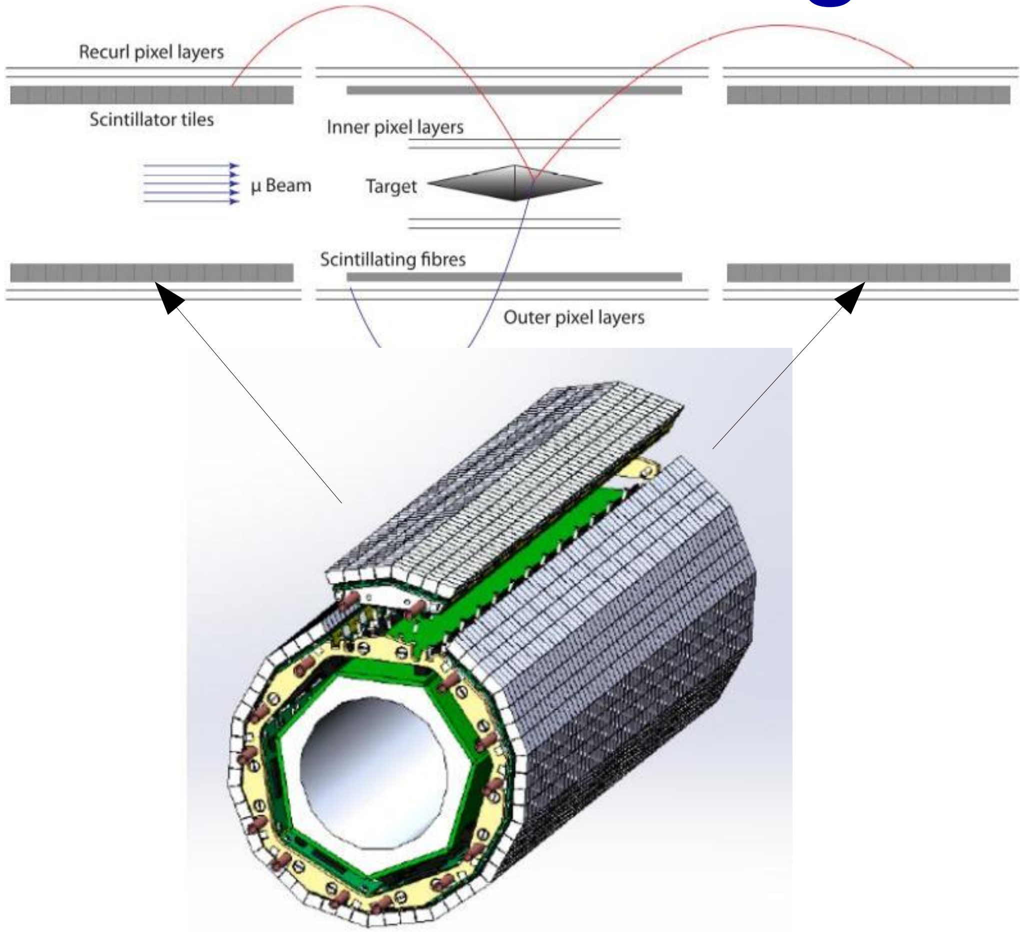
Final hardware prototypes exists and successfully tested in testbeam!

"First Light" from recent October testbeam

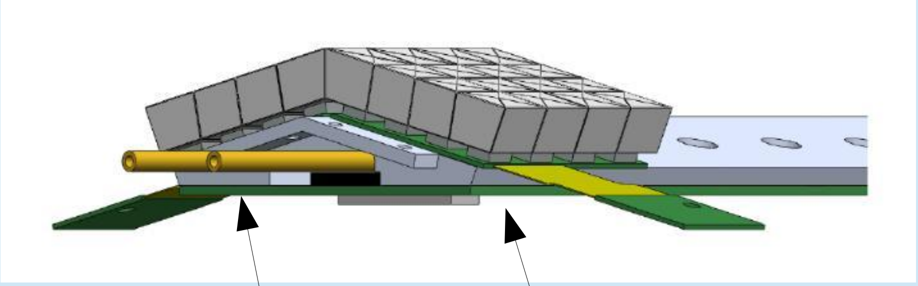


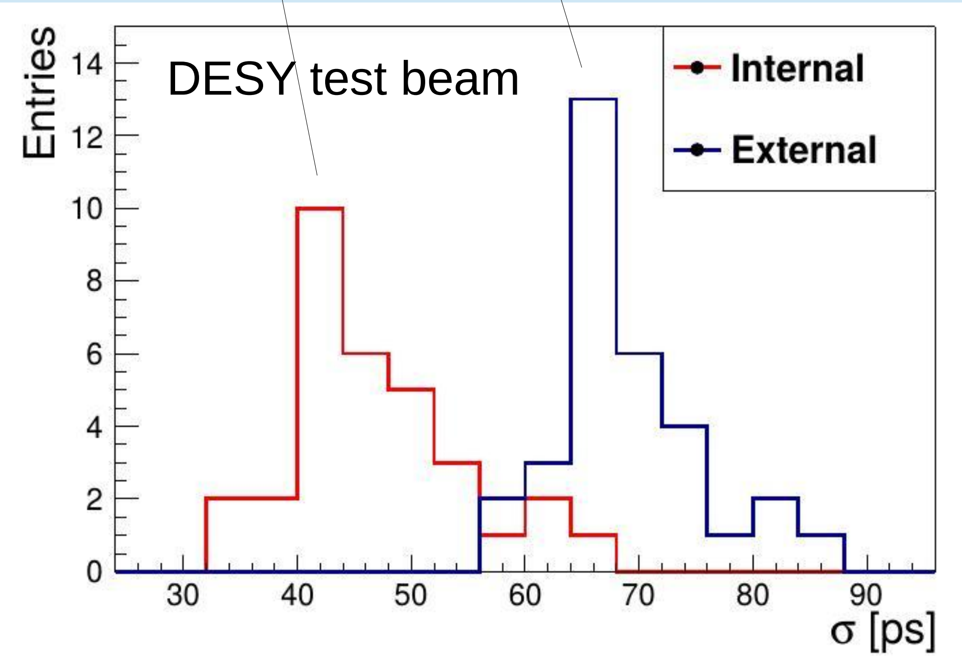


Scintillating Tiles Timing Detectors



Scintillating Tile Sub-Module





Time resolution < 100ps

Scintillating Tiles

- tiles ~ 6.5 × 6.5 × 5mm^3
- SiPM 3 x 3 mm^2
- Readout with MuTrig ASIC (developed at HD-KIP)
- time resolution < 100ps

Mu3e “Crisis” and Delays

2017: Termination of Mu3e magnet contract after 2 years → changed producer

2018: 180nm HV-CMOS process abandoned by *austriamicrosystems* → fab change

2019: Main Engineer in Oxford (Kirk Arndt) passed away

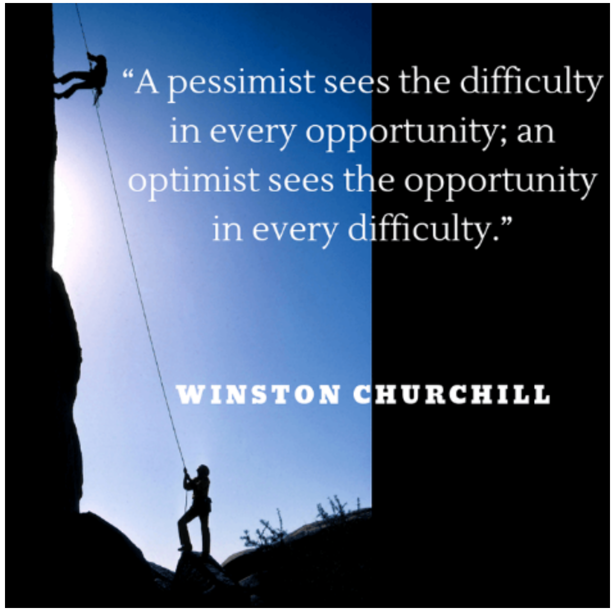
2020: Covid19 pandemic ...

2021: Production stop of Frontend Boards (main Mu3e electronics) due to delivery problems (e.g. FPGAs) for more than two years

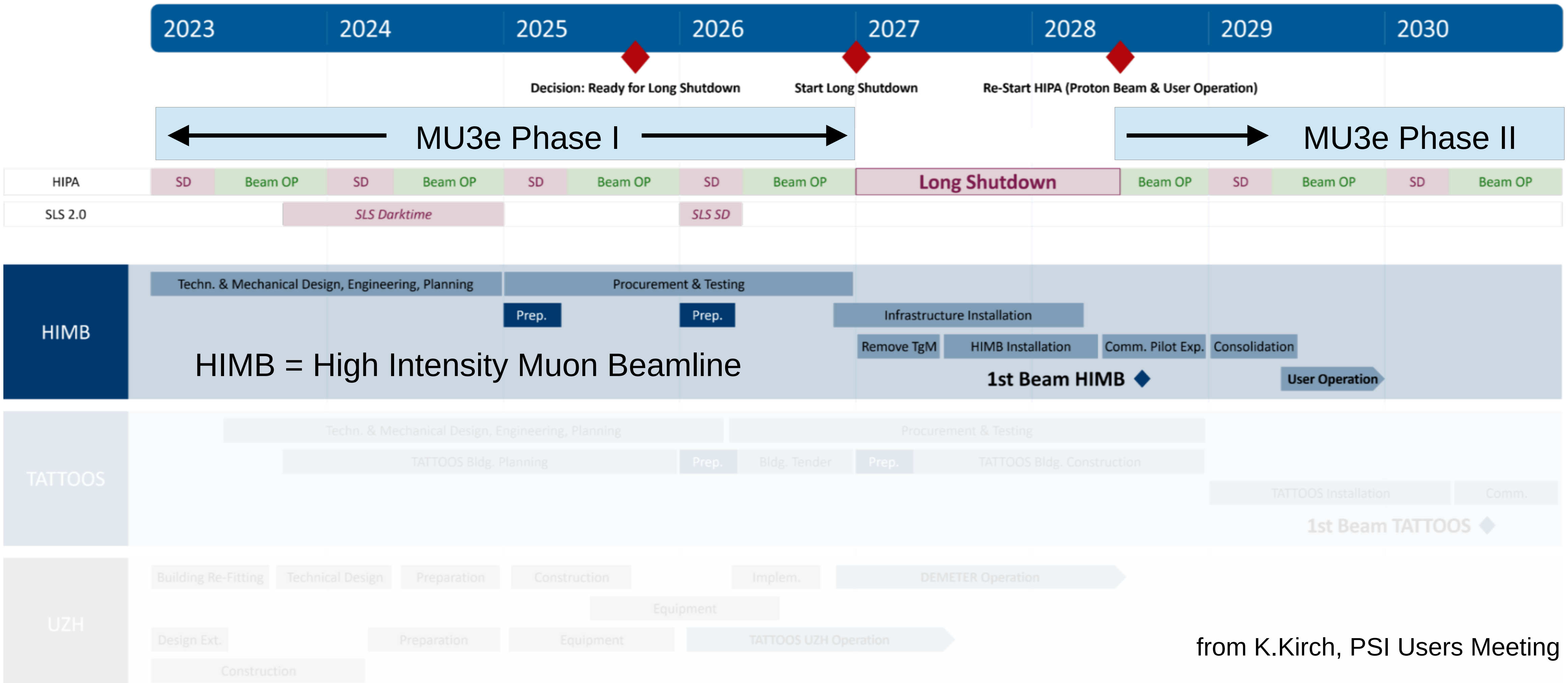
2022: Pixel Tracker flexprint production in Kharkiv stopped for ~1 year because of Ukraine war

+ many smaller problems which delayed and still delay production

In general, the Mu3e collaboration was (and still is) very optimistic



Mu3e and PSI Schedule ("IMPACT")

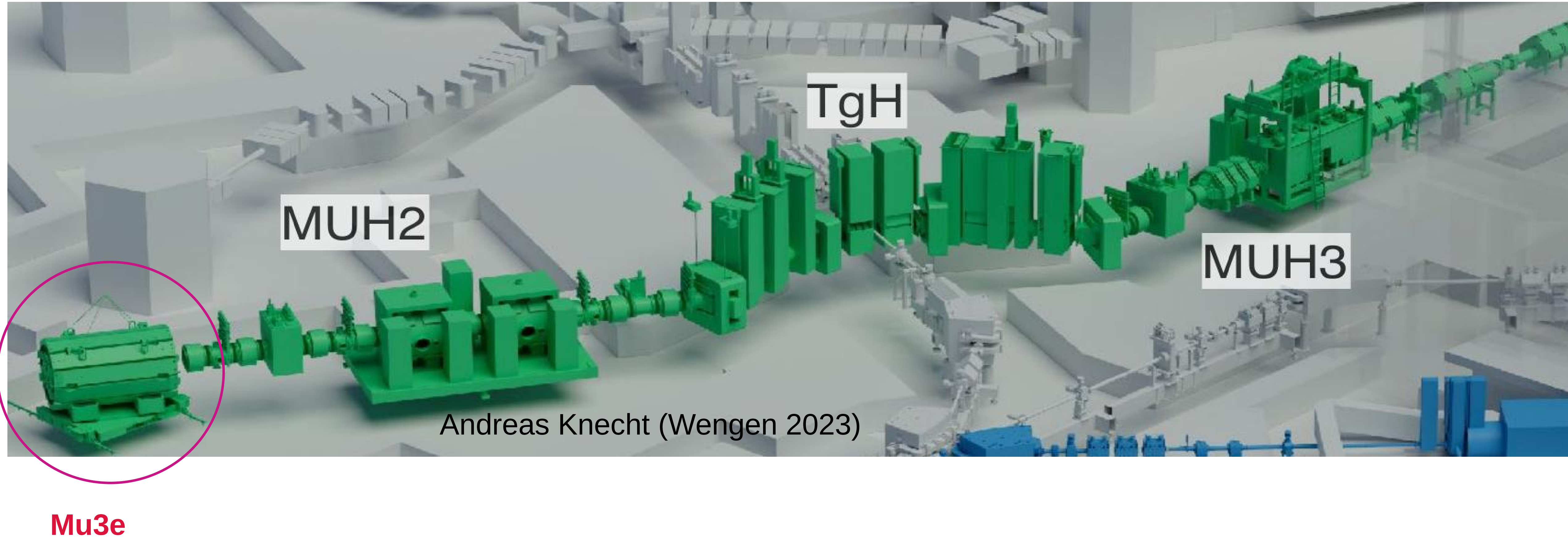


from K.Kirch, PSI Users Meeting 2023

Optimistically, at most **two years** of Mu3e phase I data taking before Long Shutdown in 2027

High Intensity Muon Beamline (HIMB)

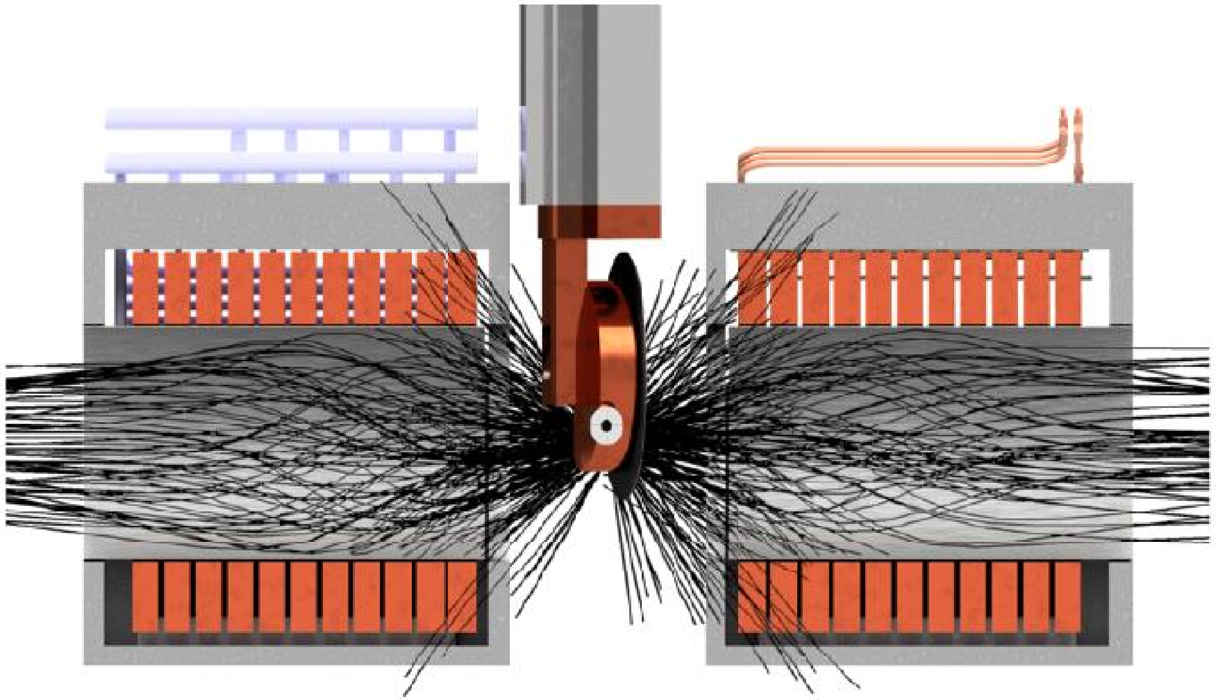
Main user (particle Physics) will be Mu3e!

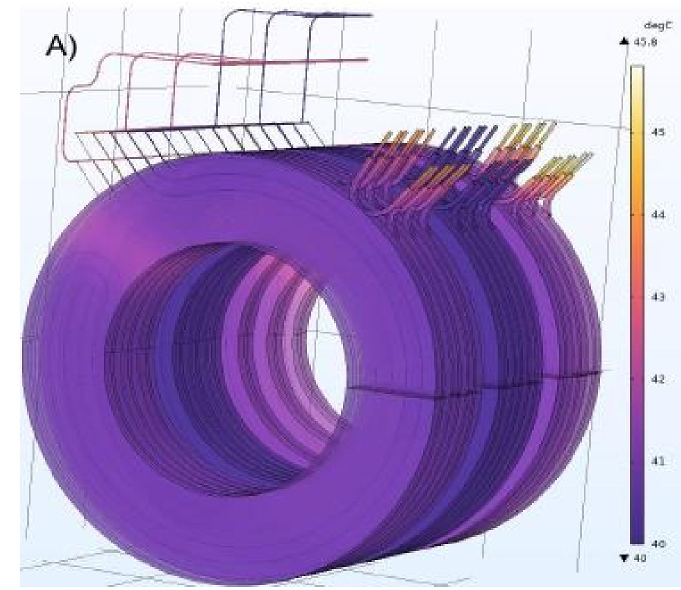


~20 times higher muon stopping rate → Mu3e phase II

accidental background will increase by factor 400 = 20^2

The Future @ PSI → HIMB!

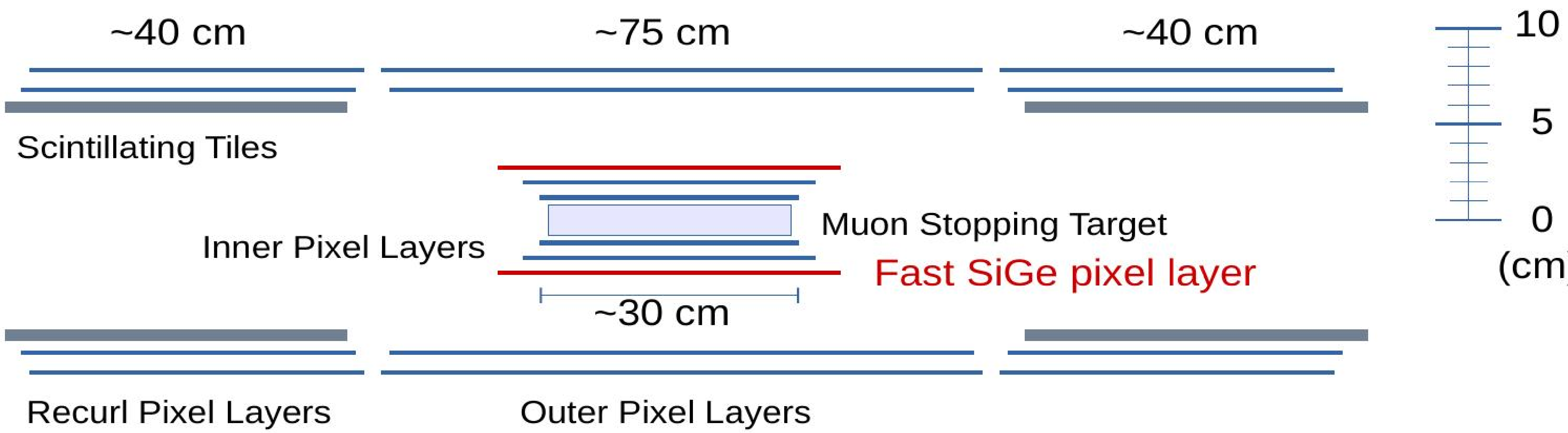




- Two normal-conducting, radiation-hard solenoids 250 mm away from target to capture surface muons
- Central field of solenoids up to 0.45 T
- Graded-field capture solenoid for improved muon collection: stronger field at capture side, weaker at exit

Andreas Knecht (Wengen 2023)

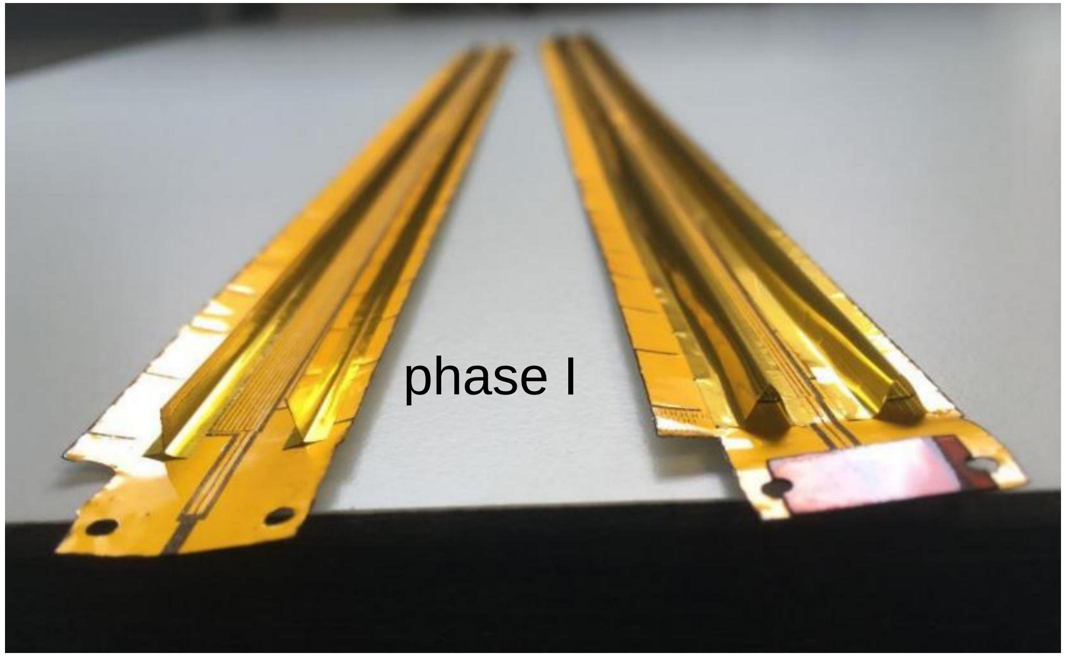
Sketch of Mu3e Phase II
(HIMB Science Case Publication)



Main Changes with respect to phase I

- much **longer muon stopping target** required to reduce accidental BG: 10 cm → 30 cm
- **thinner** and **smaller vertex detector** to improve pointing resolution
- much **longer pixel detector modules** to match longer muon stopping target
- replace SciFi timing detector with **Ultra Fast Silicon Pixel Detector** (UFSPD)
- increase **readout bandwidth** at front end
- option to **increase magnetic field** from B=1T to B=2T to increase resolution and acceptance

Long Ultra-Light Pixel Tracker modules



Mu3e Phase I:

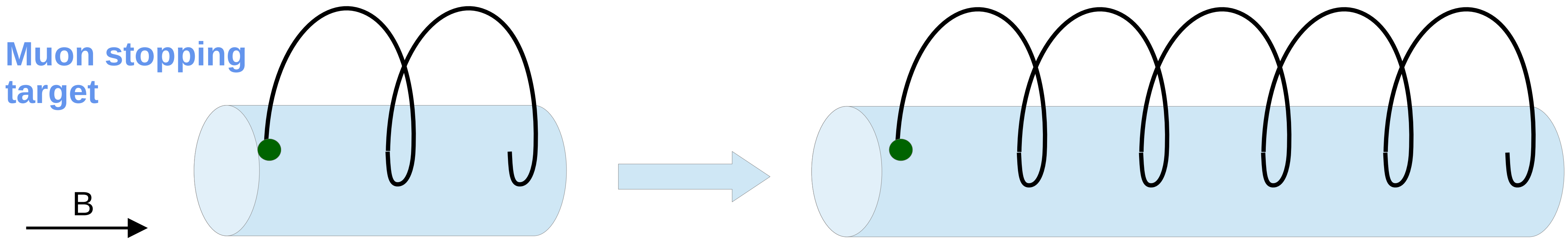
- world record for building the lightest pixel tracking detect ever
- 36cm long pixel modules hanging "freely"

Is this the physical limit or can we build even longer modules at even more reduced weight?

60 mu carbon fiber ladder

The Bandwidth Challenge

- **Hit occupancy** is highest for **inner pixel layers**
- Phase I hit rate of 1.5 MHz/cm^2 increases to **30 MHz/cm^2** for **Phase II** w/o design changes (x20)
- **Elongated muon stopping** target reduces hit occupancy but at the same time the number of **recurling tracks** increases:



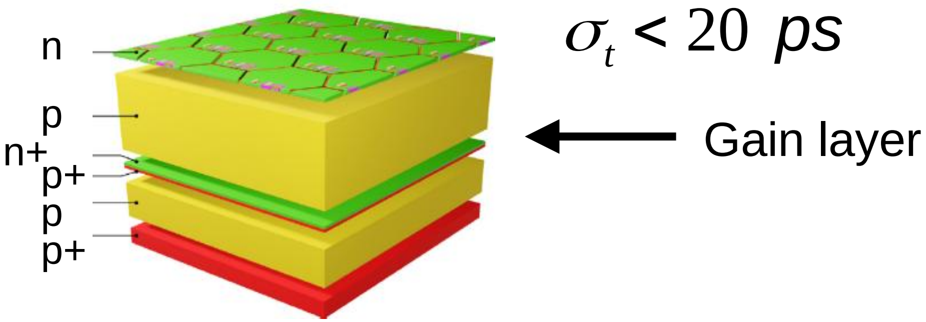
Consequences:

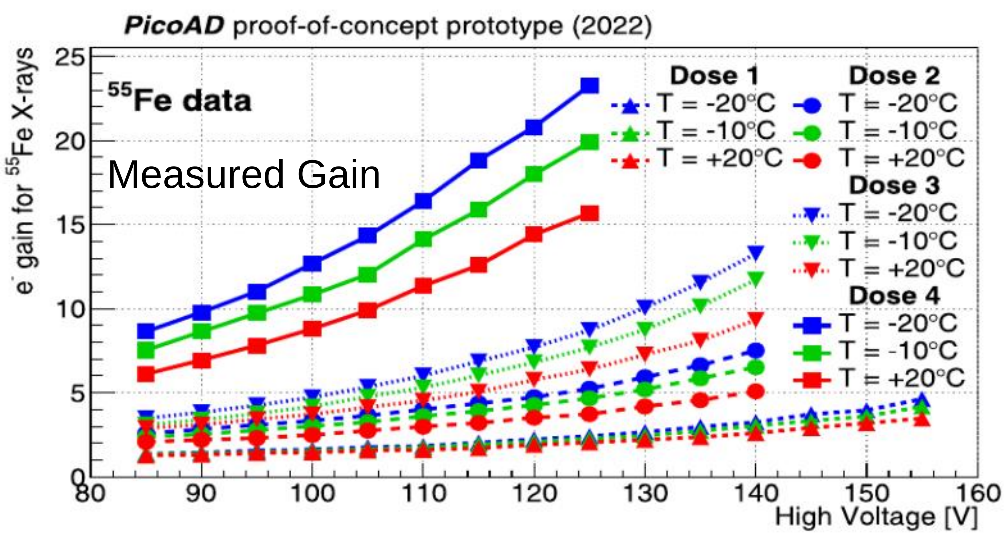
1) Phase II Mupix sensors will require a much higher readout bandwidth!

2) Total hit rate will increase by almost 2 orders of magnitude!

Ultra Fast Monolithic Silicon Pixel Prototypes

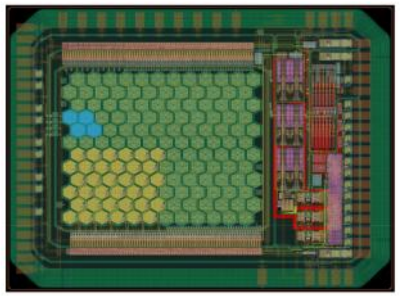
Gain Layer for HV-MAPS

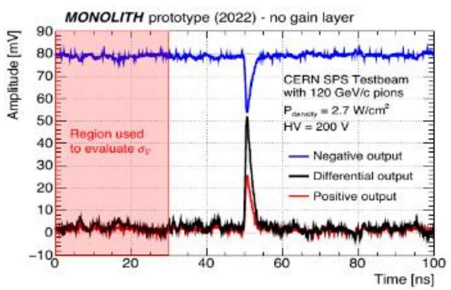


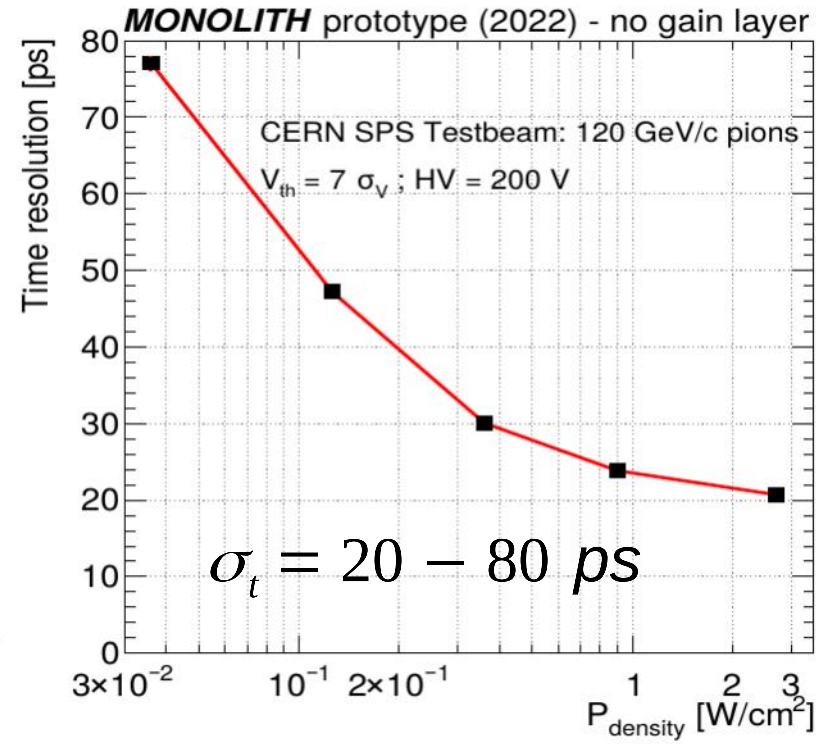


M.Milanesio et al., *Gain measurements of the first proof-of-concept PicoAD prototype with a 55 Fe X-ray radioactive source,* NIMA 1046 (2023) 167807

High Power Amplifier with SiGe Bipolar Transistors







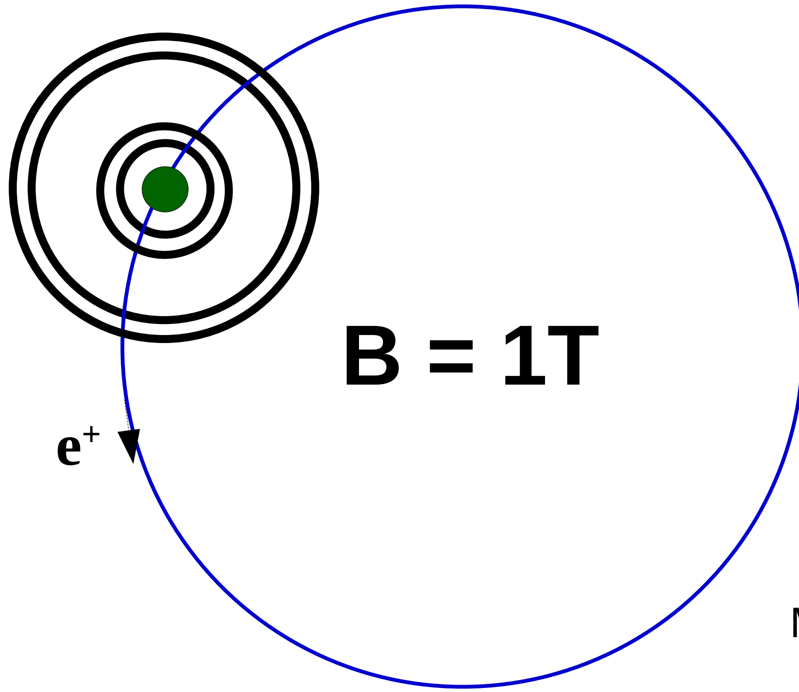
S. Zambito et al., 20 ps time resolution with a fully-efficient monolithic *silicon pixel detector without internal gain layer,* 2023 JINST 18 P03047

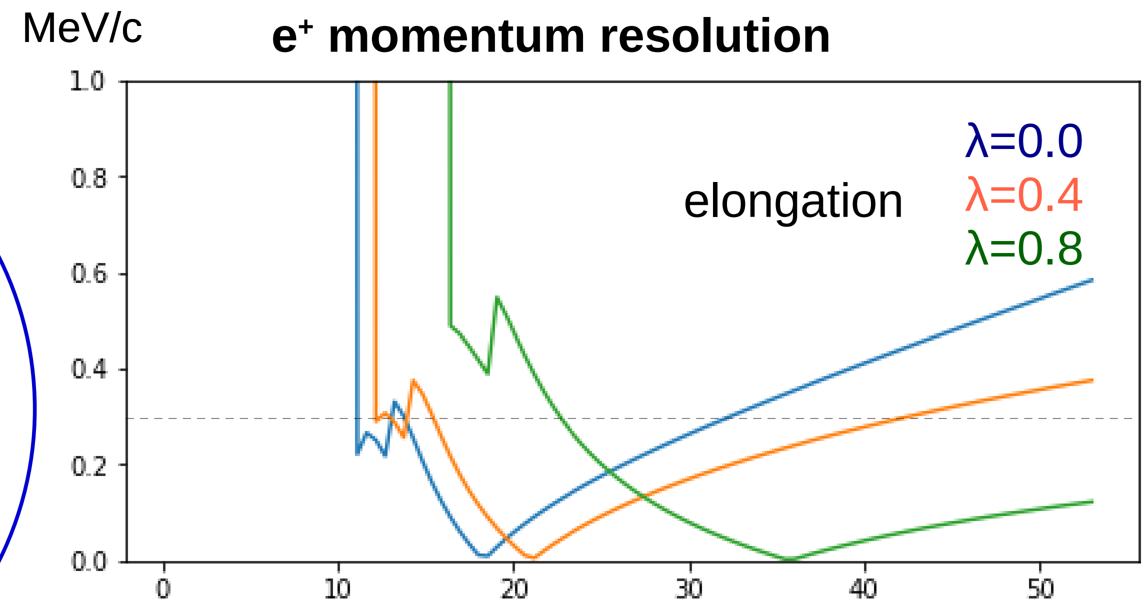
Warning! A fast prototype sensor does not make a full detector!
≥ ~5 years R&D needed for fully monolithic sensor (from my experience)

Phase II Detector Design Studies

Phase I with 4 layers

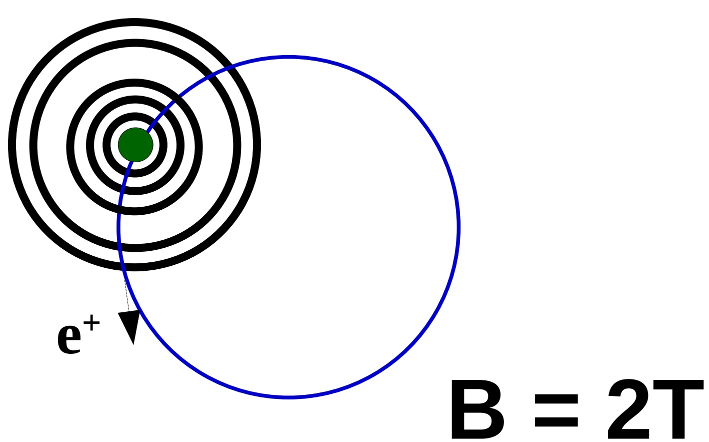
radii:
- 23 mm
- 30 mm
- 74 mm
- 86 mm

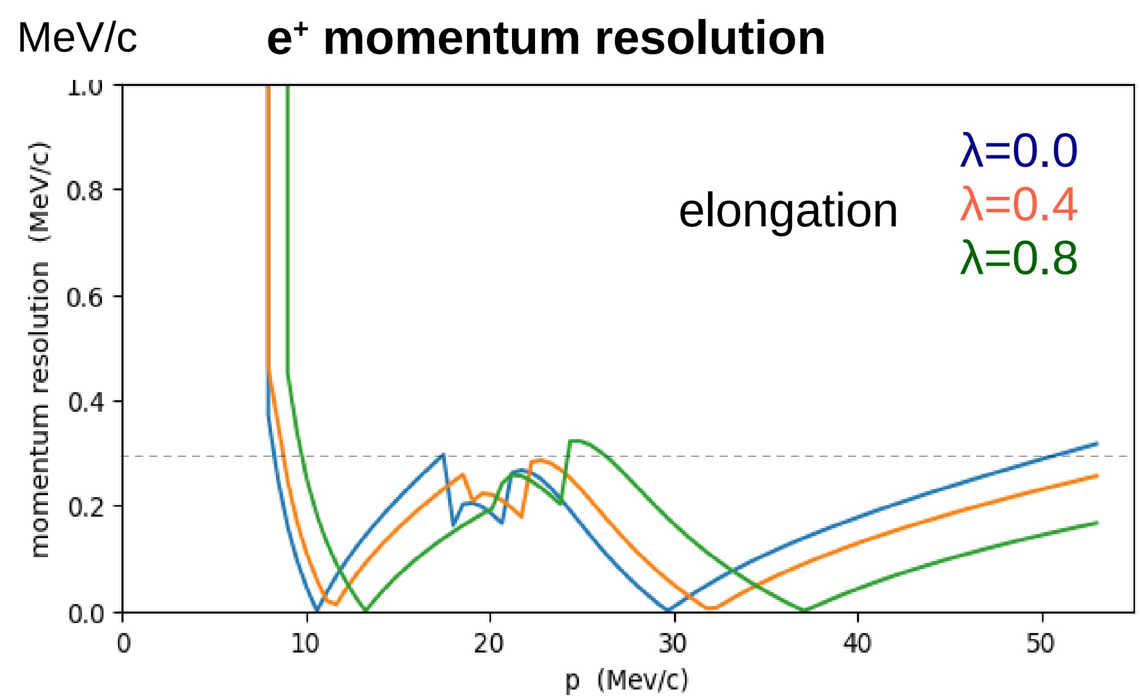




Phase II with 5 layers

radii:
- 15 mm
- 20 mm
- 25 mm
- 60 mm
- 70 mm



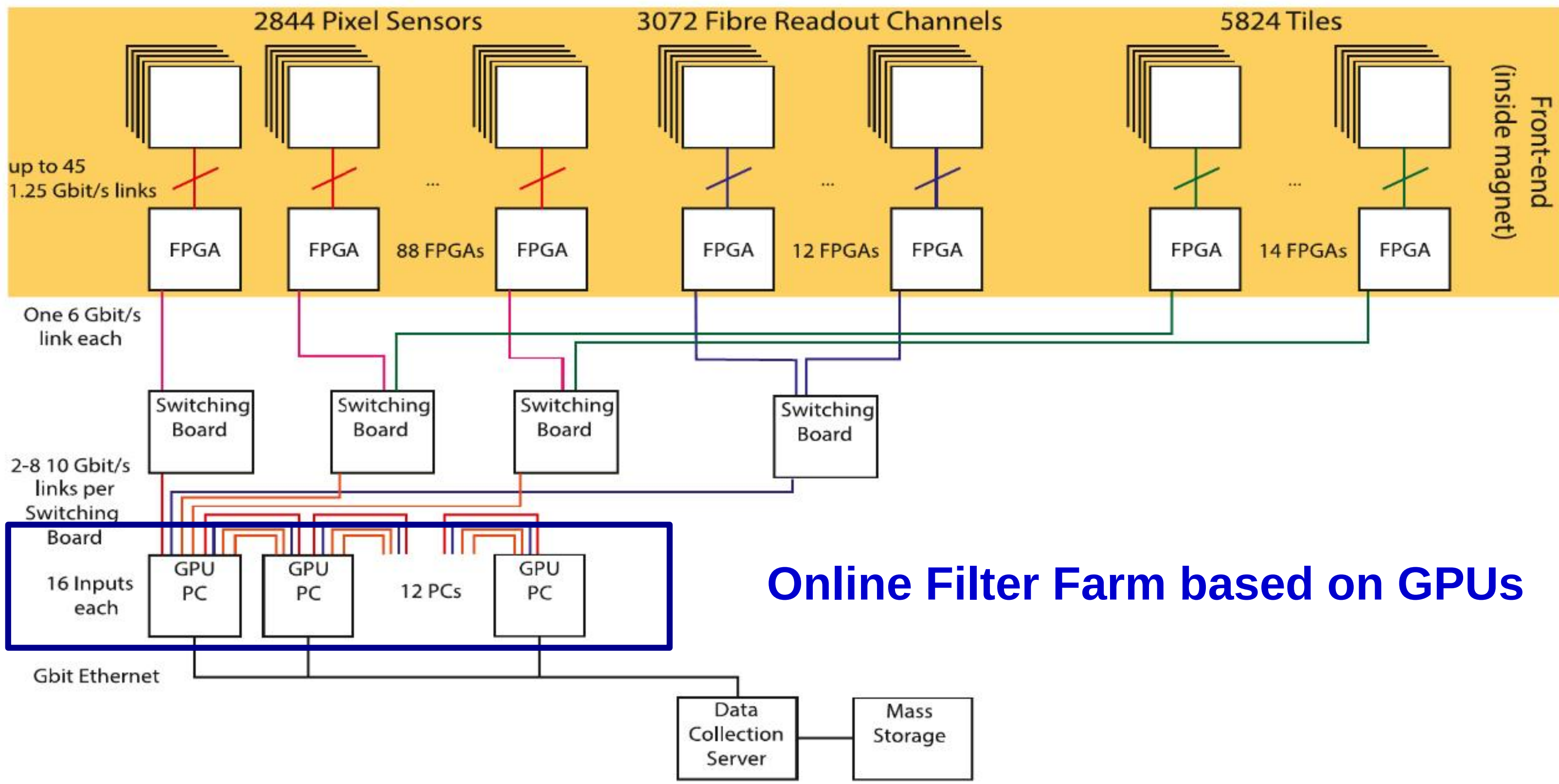


studies are ongoing

Further Improvements for Phase II

- **Serial powering** of detector modules to reduce cables and to free some space
- **Upgrade Filter Farm** (+GPUs, + FPGAs) to tackle the drastically increased combinatorial problem in the online track reconstruction

Mu3e Detector



Online Filter Farm based on GPUs

Most important we want to learn from the phase I experience (design, production and operation)

Beyond Phase II

Idea: use a modified detector to also search for $\mu^+ \rightarrow e^+ \gamma \quad (\gamma \rightarrow e^+ e^-)$

- Master formula for accidental background (main BG):

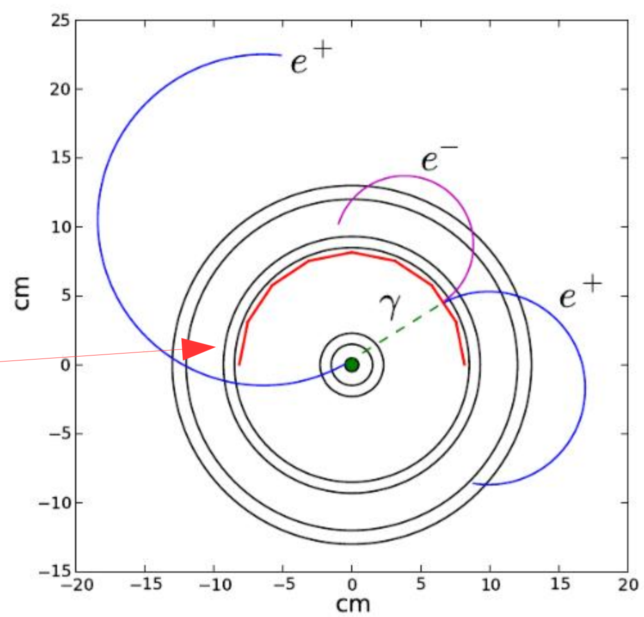
$$B_{acc} \sim R_\mu \, \sigma(t_{e\gamma}) \, \sigma(\theta_{e\gamma})^2 \, \sigma(p) \, \sigma(E_\gamma)^2$$

MEG2 LXe calorimeter: $\sigma \approx 1\ MeV$

- It is known that significantly better photon energy resolutions can be achieved by measuring **converted photons**.
- Penalty: significant loss of rate
- Photon converter design is well motivated if there are plenty of muons (→ HIMB project)

Proposal by C.-h. Cheng, B. Echenard and D.G. Hitlin [arXiv:1309.7679]

0.56mm lead ($0.1\ X_0$)



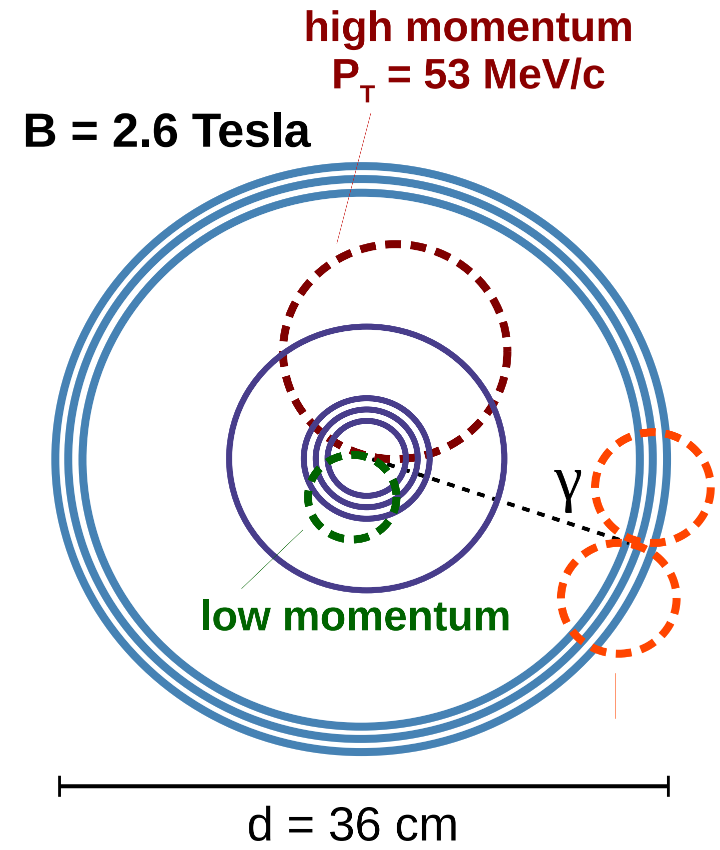
Disadvantages of the simulated design:

- only half the phase space covered by converter
- converter compromises "normal" track reconstruction
- photons to be reconstructed in a sea of Michel electrons

Beyond Phase II

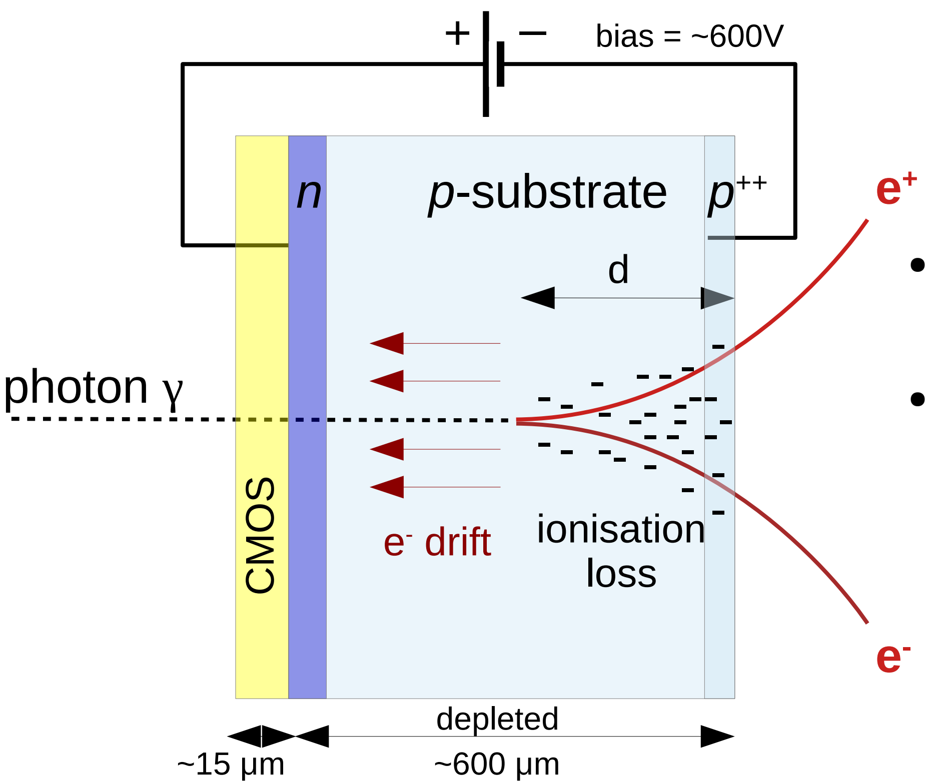
Mu3e-gamma proposal

→ studied for HIMB Science Case arXiv:2111.05788



Features:

- Michel electrons do not reach converter layers (**no BG**)
- Michel electrons have an excellent momentum resolution of ~ 100 keV due to high magnetic field (**B=2.6T**)
- Photons are detected in **Active Silicon Sensor Converters**



- Energy resolution of converted photons is usually given by **energy loss** of e+ and e- pair in converter.
- An active converter measures this energy loss!

→ expected energy resolution: $\sigma(E_\gamma) = 100-200\ keV$

The same setup can also be used to search for displaced decays of X → ee or A' → ee

Summary & Schedule

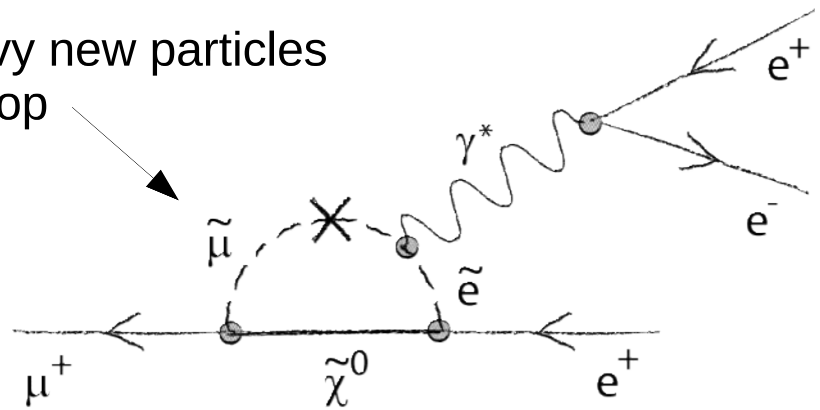
- Pre-production of Mu3e sub-detectors has started for most systems
- In 2024, we expected the inner vertex detector and the timing system to be completed or almost completed
- For end of 2024, we are studying the possibility of a first physics run at low rate without outer pixel layers at high magnetic field
- Optimistically, the Mu3e phase I detector will be completed in 2025 and ready for data taking

- Design for Mu3e phase II at HIMB is starting now

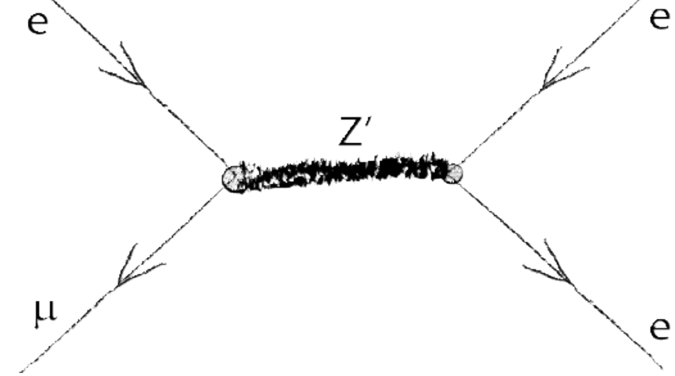
Backup

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

heavy new particles
in loop

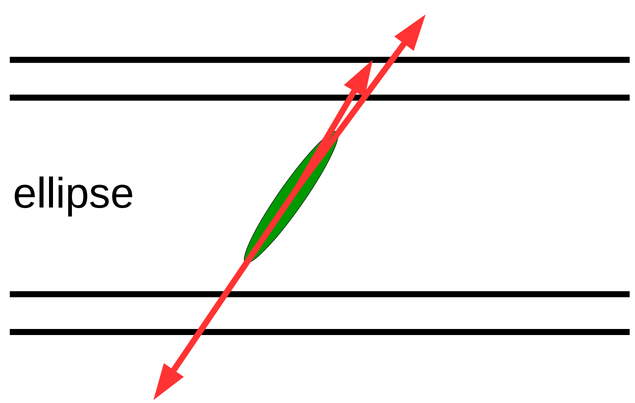


4-fermion interaction

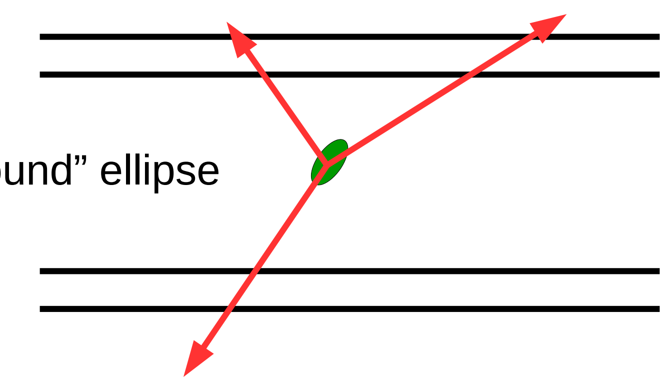


Typical decay topologies:

long ellipse

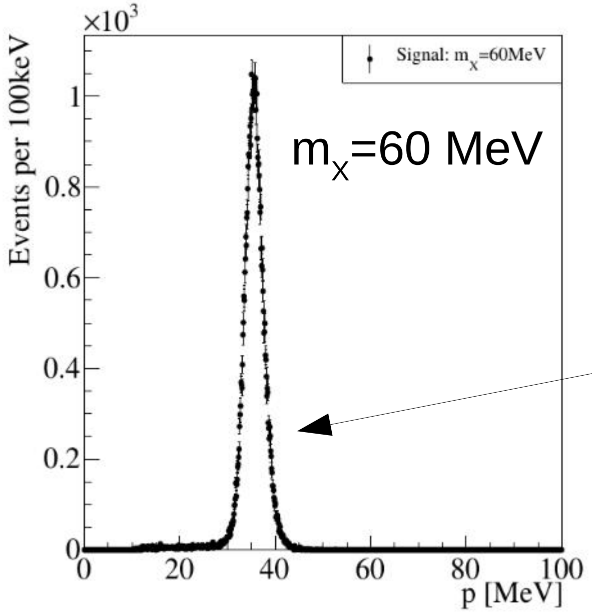


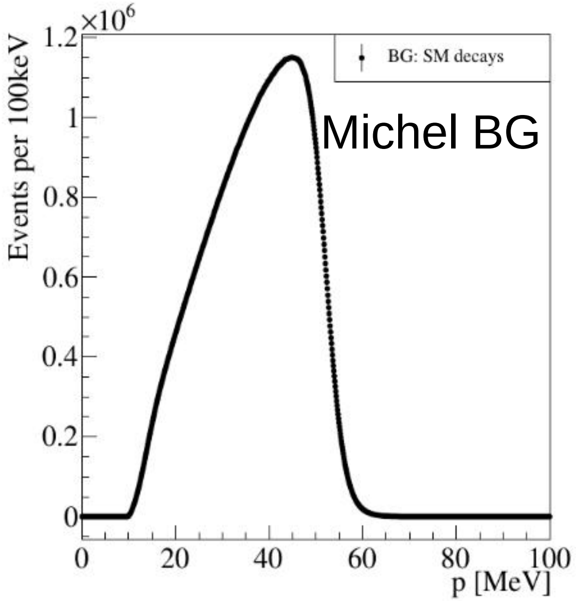
“round” ellipse



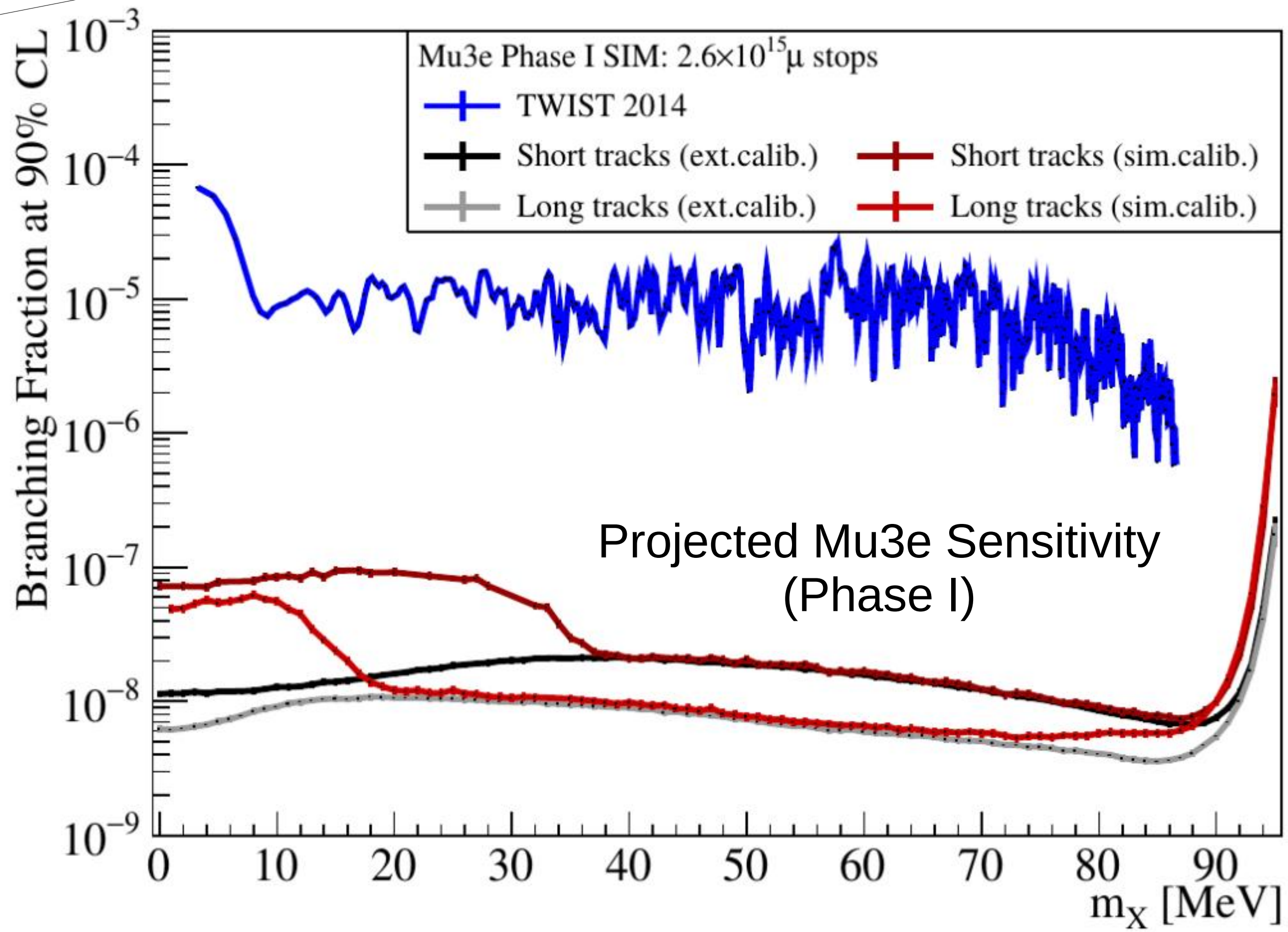
Search for Familons $\mu^+ \rightarrow e^+X$

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

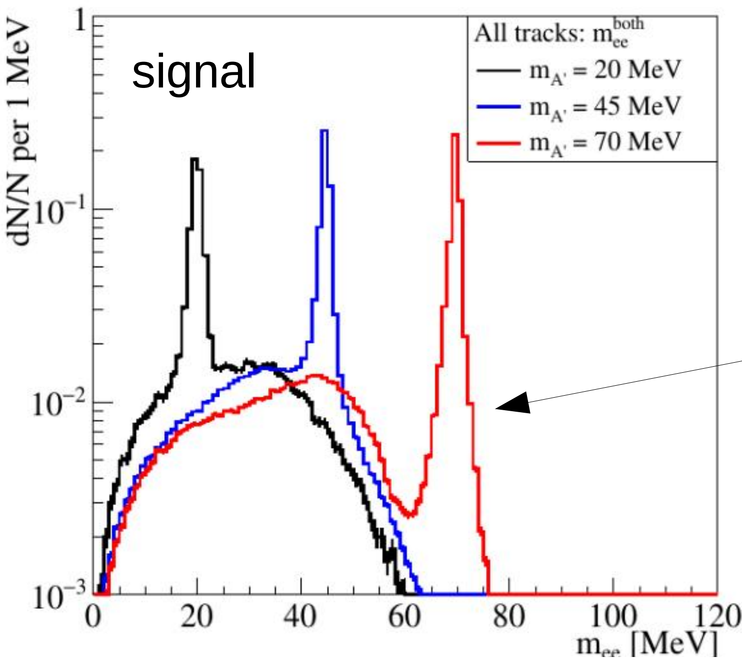


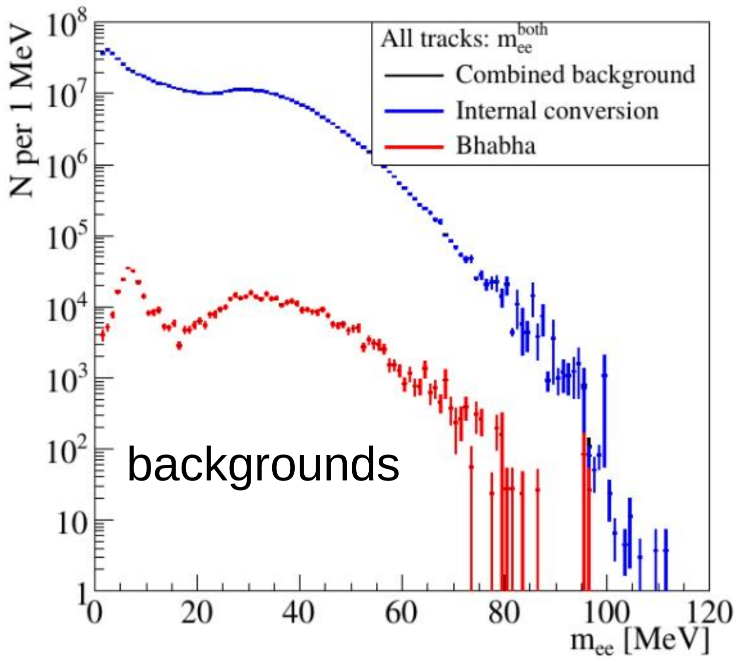


thesis A.-K.Perrevoort



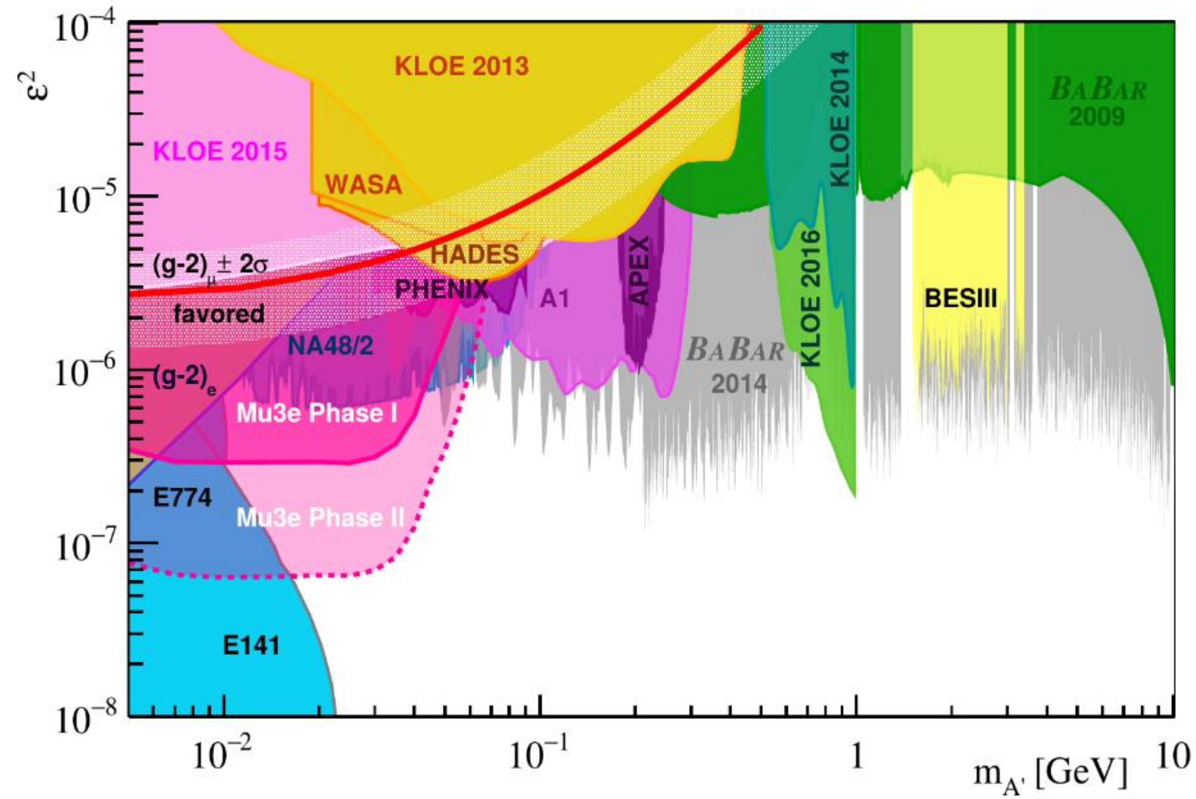
Search for Dark Photons in $A' \rightarrow e^+e^-$





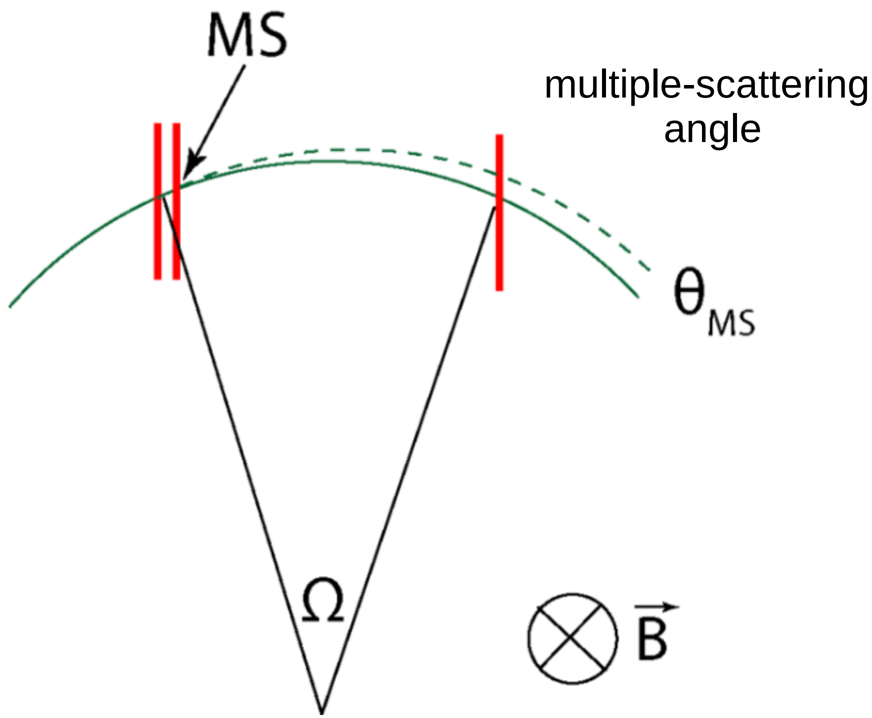
- Search for Dark Photons with zero or short lifetime:
  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu A'$ with $A' \rightarrow ee$
- **peak** in $m(e^+e^-)$ invariant mass

thesis A.-K.Perrevoort



Momentum Resolution

Standard spectrometer:

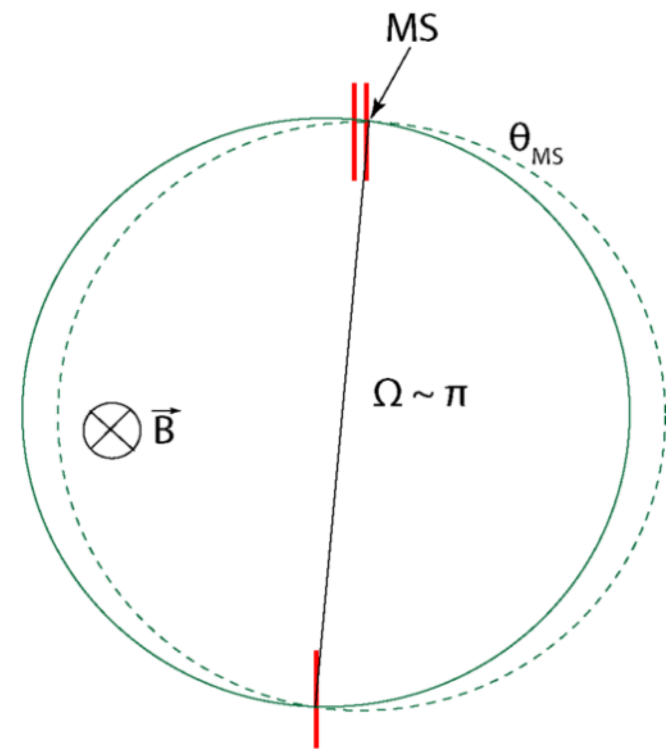


$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$

(linearised)

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

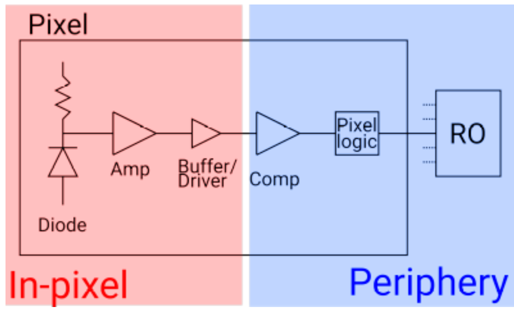
“Half turn” spectrometer:

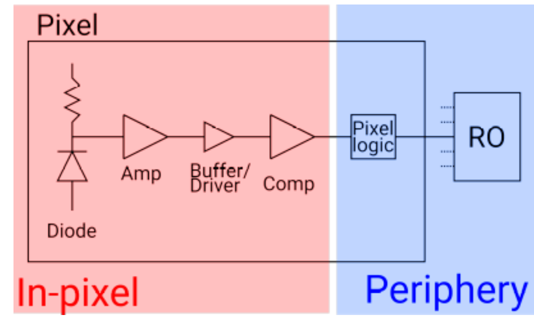


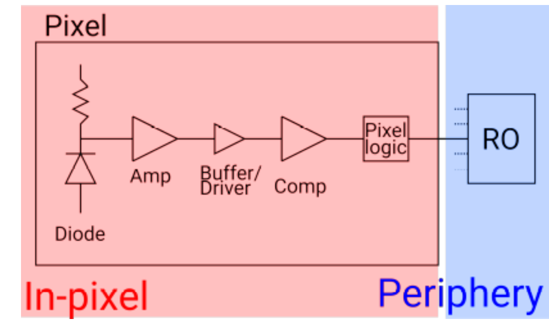
$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

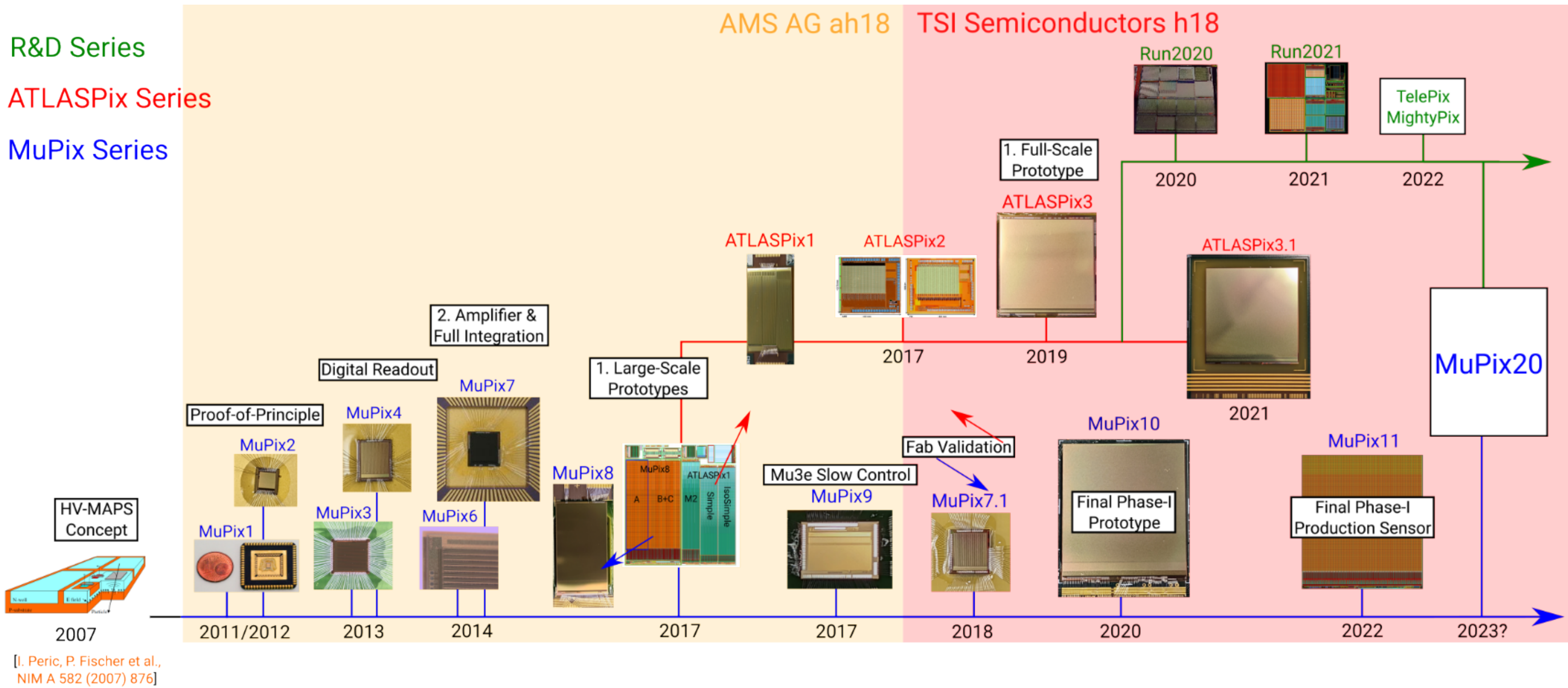
- **best precision for half turn tracks**
- **measure recurlers**

HVMAPS Roadmap and Architectures



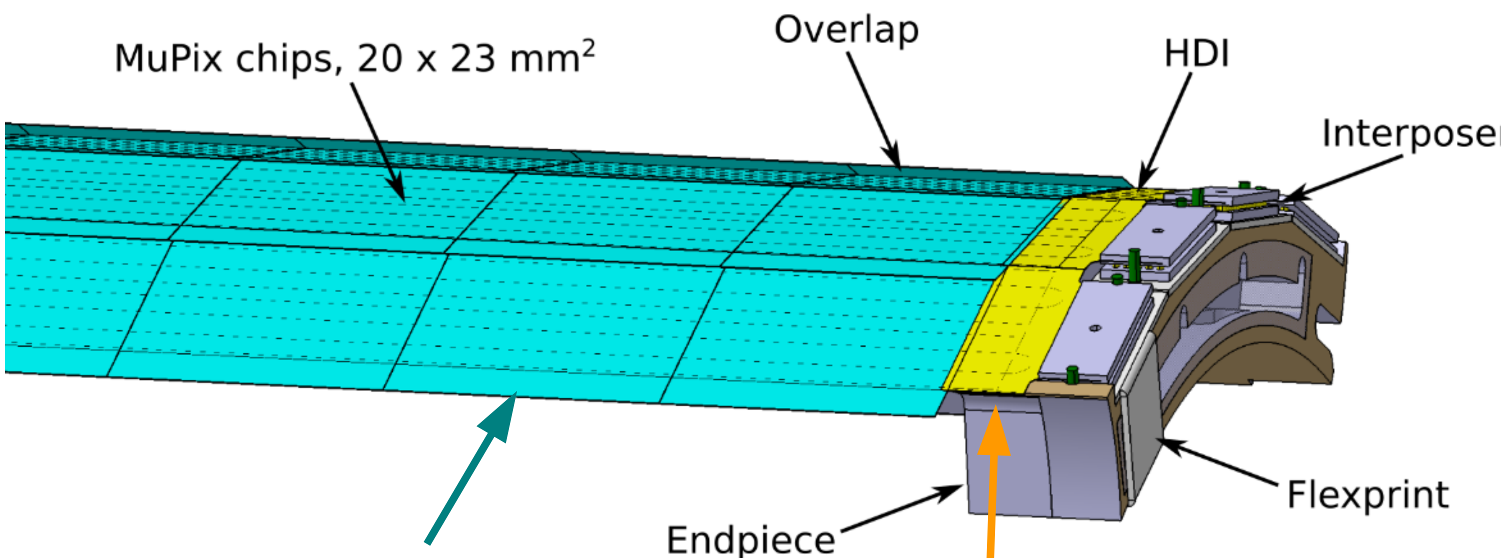




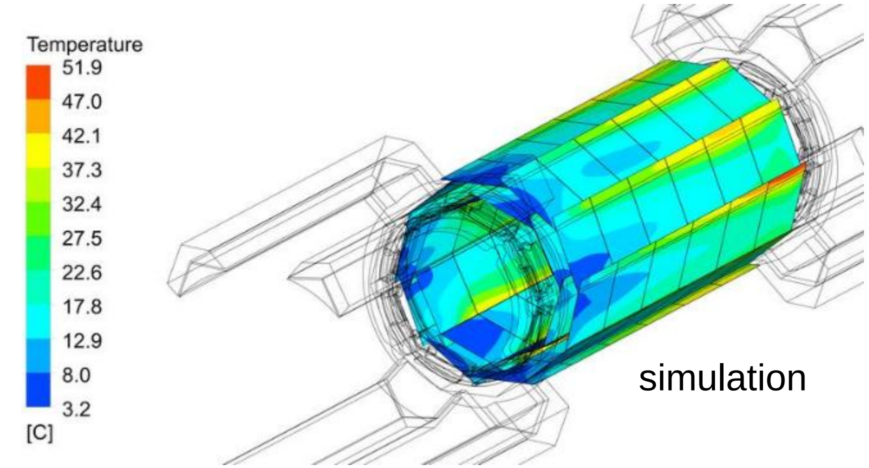


Pixel Tracking Detector

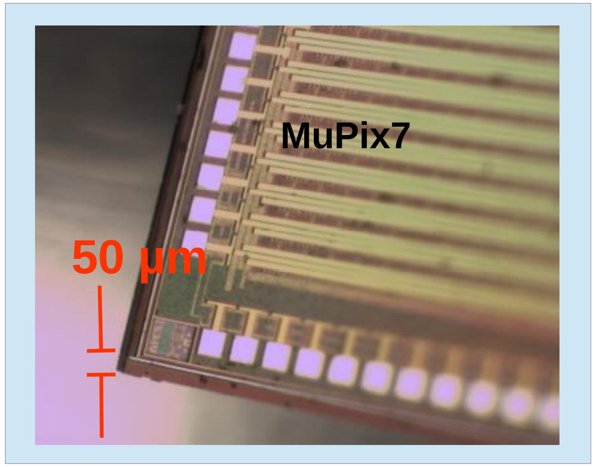
Ultra-thin pixel sensor modules (X/X_0 = 1.15 per mille)



Gaseous He-Cooling System

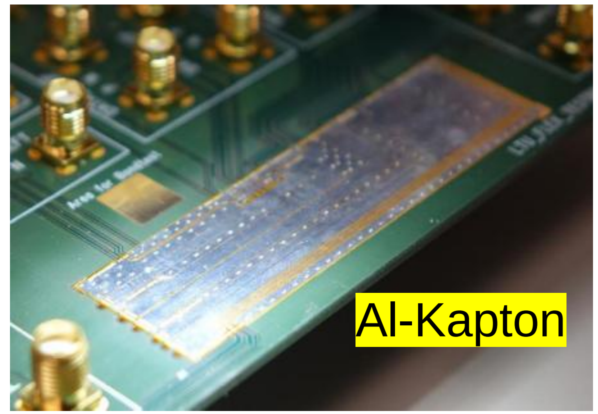


MuPix (HV-MAPS)

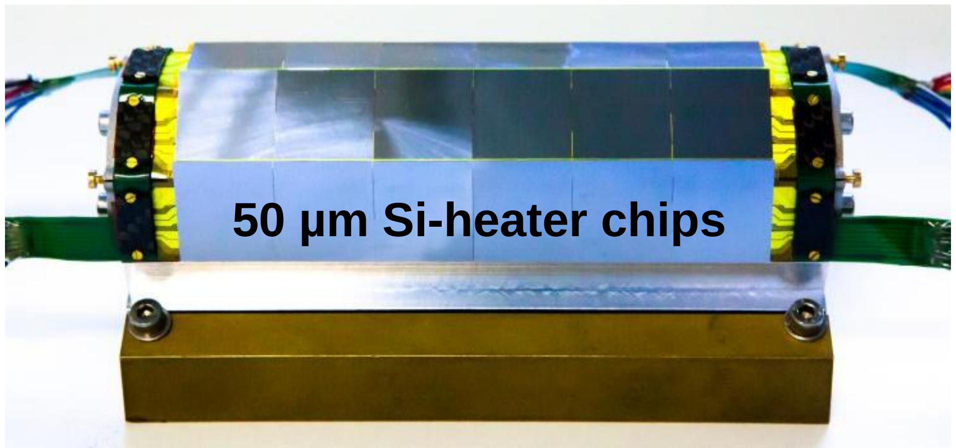


Monolithic pixel sensor in
180 nm HV-CMOS

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

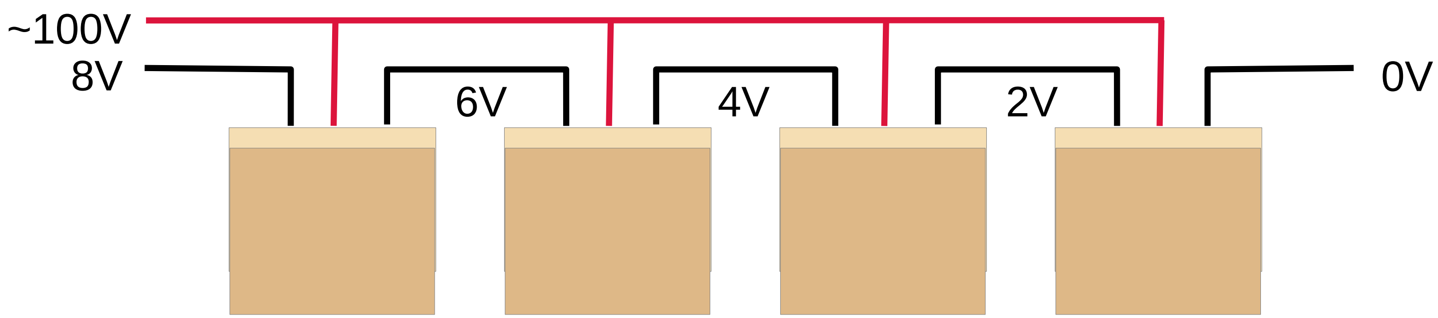


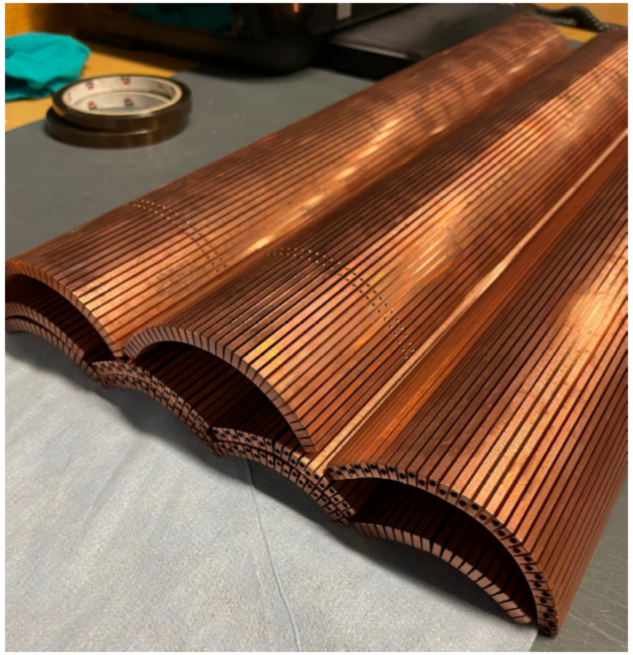
Thermo-Mechanical Mockup (vertex)



Serial Powering of Mupix Sensors

- Phase I Mupix11 Sensors will be powered with about 1500 Amps (big copper bars)
- MuPix11 has differential in-/outputs except for power and bias voltage and is prepared for serial powering → but not used for Mu3e Phase I
- For Mu3e Phase II serial powering will be mandatory
- Concept:





<u>Issues and Open Questions</u>

- how to prevent over-voltages?
- if connected to same bias voltage → sensors see different HV (different performance)
- sensors are operated in different modes
  - low power mode
  - regular operation
  - large noise situation