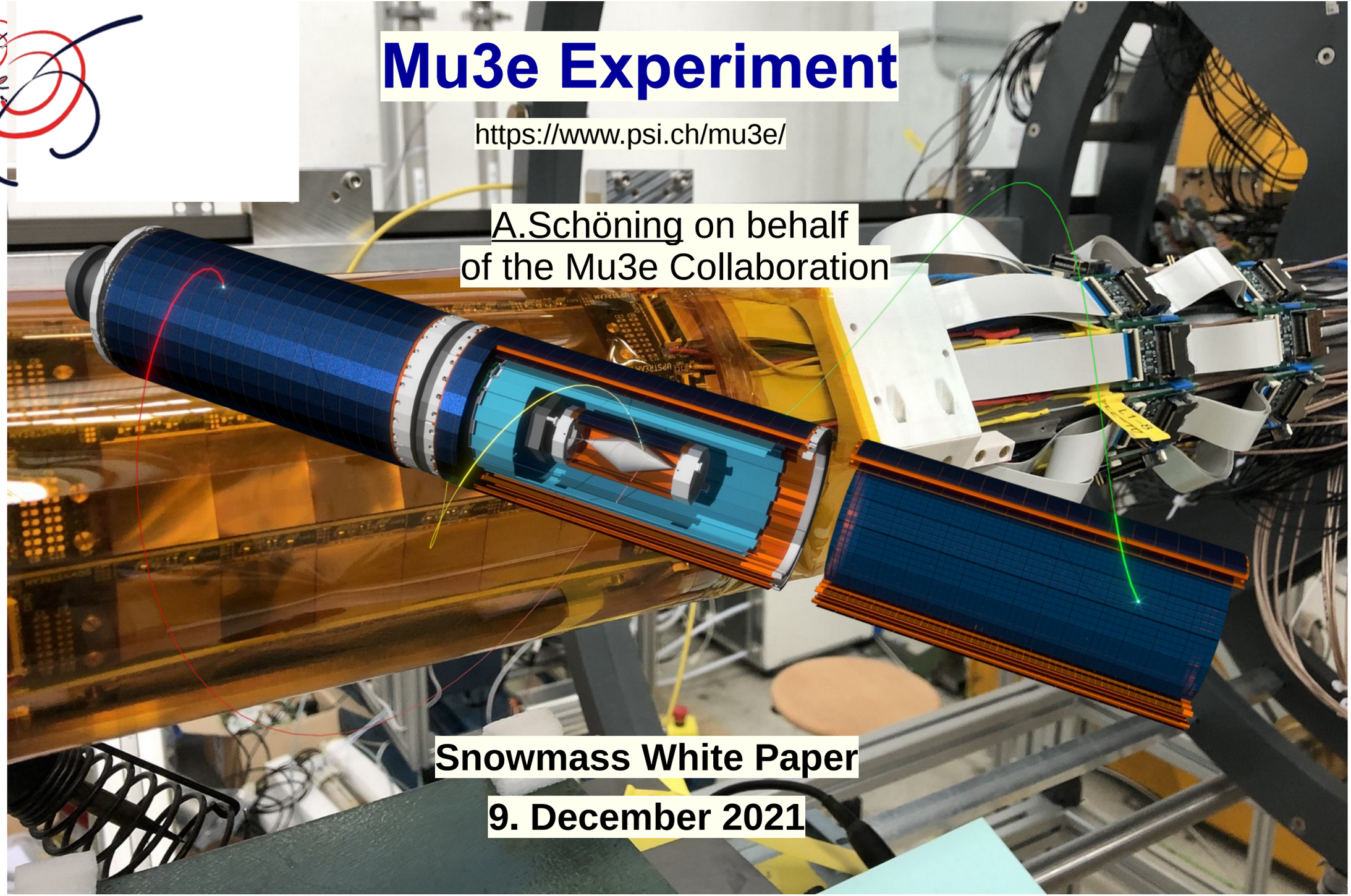
Mu3e Experiment

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

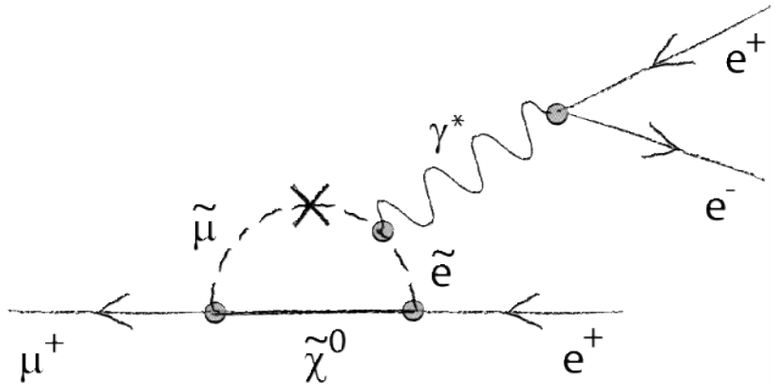
A.Schöning on behalf
of the Mu3e Collaboration



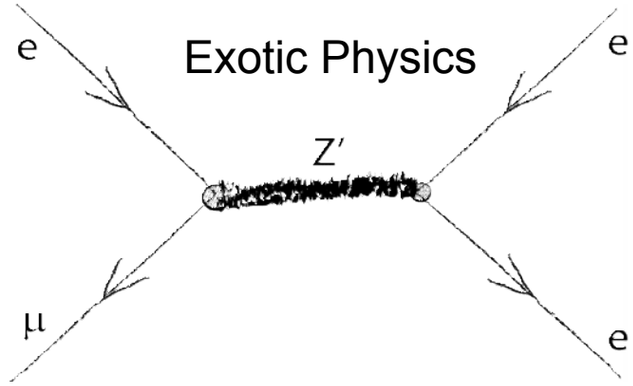
Snowmass White Paper

9. December 2021

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)**

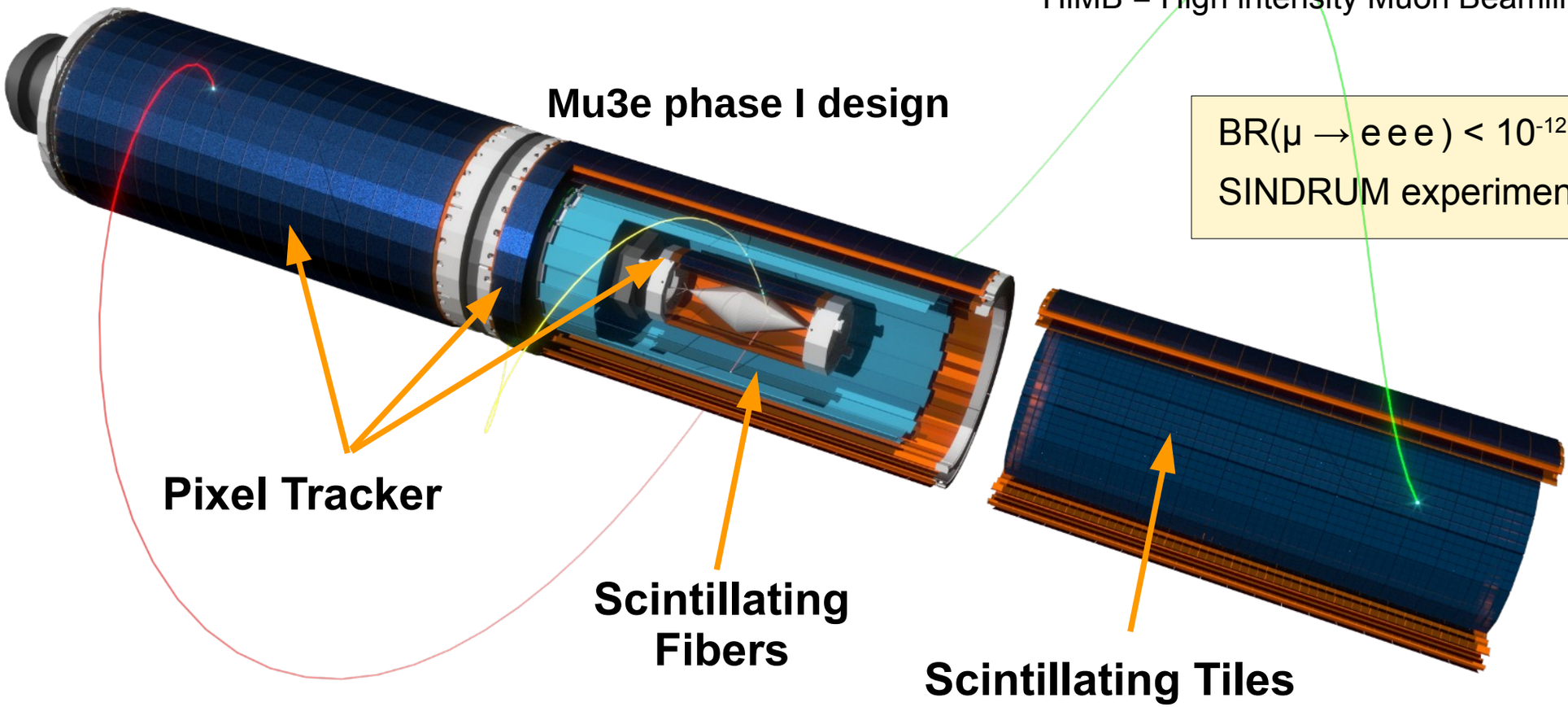
Most models "naturally" induce lepton flavor violation!

Mu3e Experiment

Aiming for a sensitivity (SES) requires:

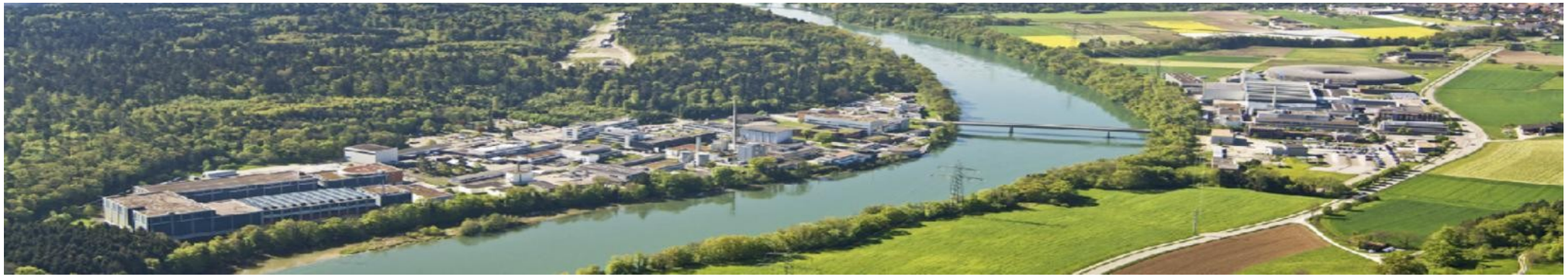
$BR(\mu \rightarrow eee) < 2 \cdot 10^{-15}$	(phase I)	→ 10^8 muons/s (PiE5)	~next 5 years
$BR(\mu \rightarrow eee) < 10^{-16}$	(phase II)	→ >10^9 muons/s (HiMB)	R&D

HiMB = High intensity Muon Beamline (under study)



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

Paul-Scherrer Institut (Schweiz)



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

Muon Beam:

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

- **expect 1.4·10^{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

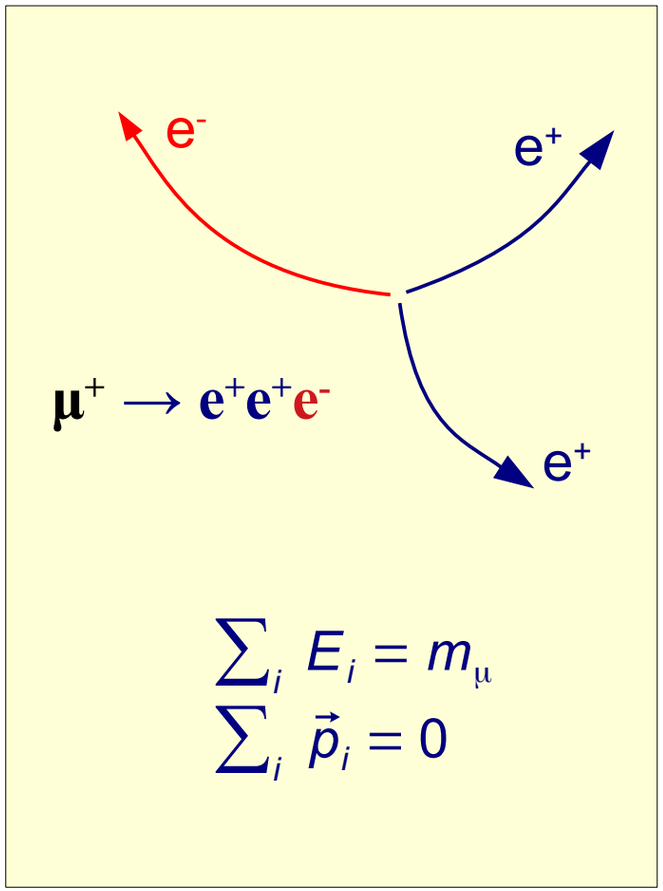
Switzerland
- University of Geneva
- Paul Scherrer Institute
- ETH Zurich
- University Zurich
- [University of Applied Sciences Northwestern Switzerland] associated partner

United Kingdom
- Bristol
- Liverpool
- Oxford
- UC London

about 70 members; ~15 PhD students

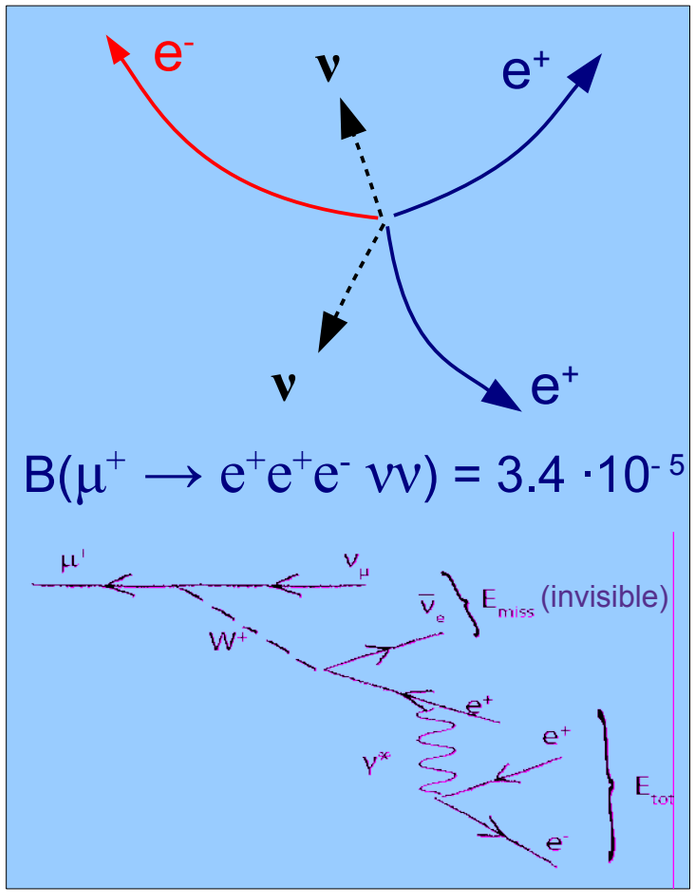
Signal + Backgrounds

Signal

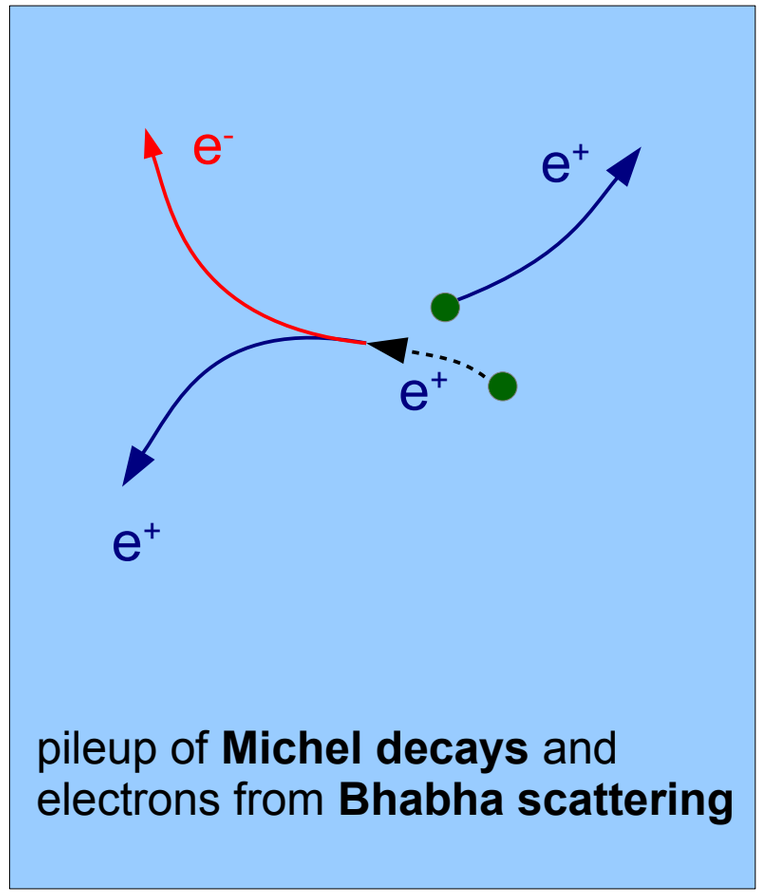


$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

Radiative muon decay with internal conversion

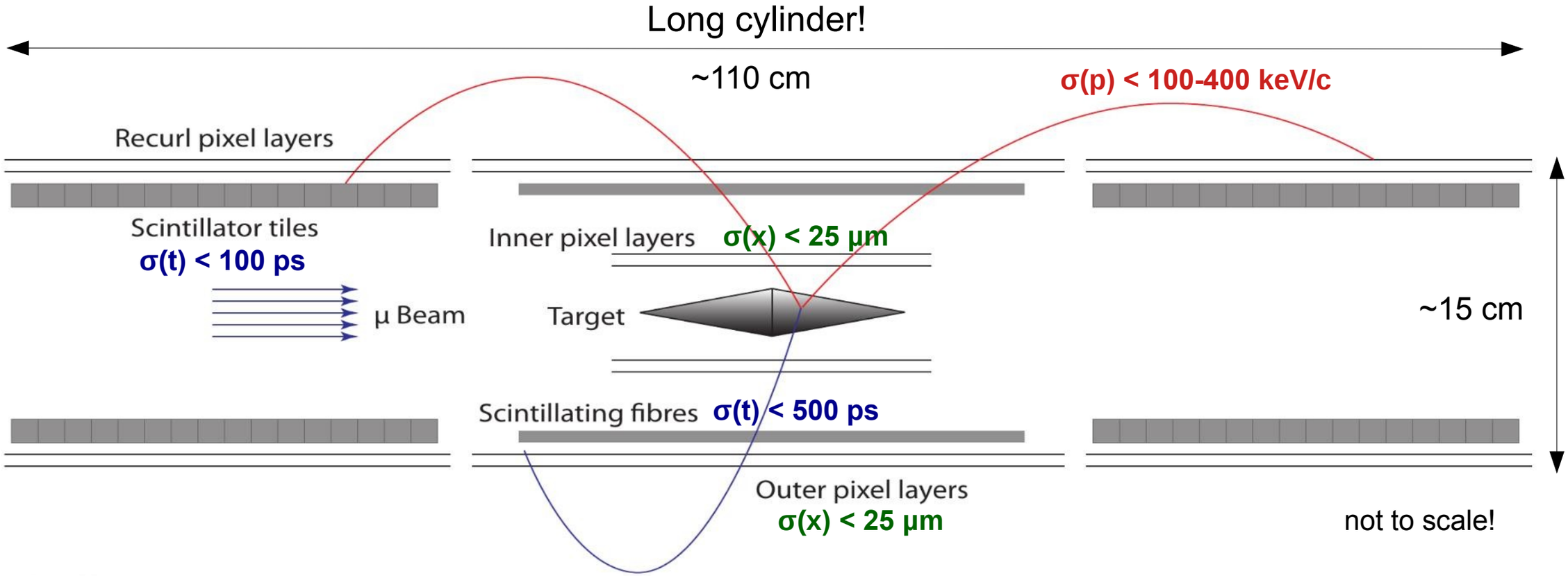


Accidental Background



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

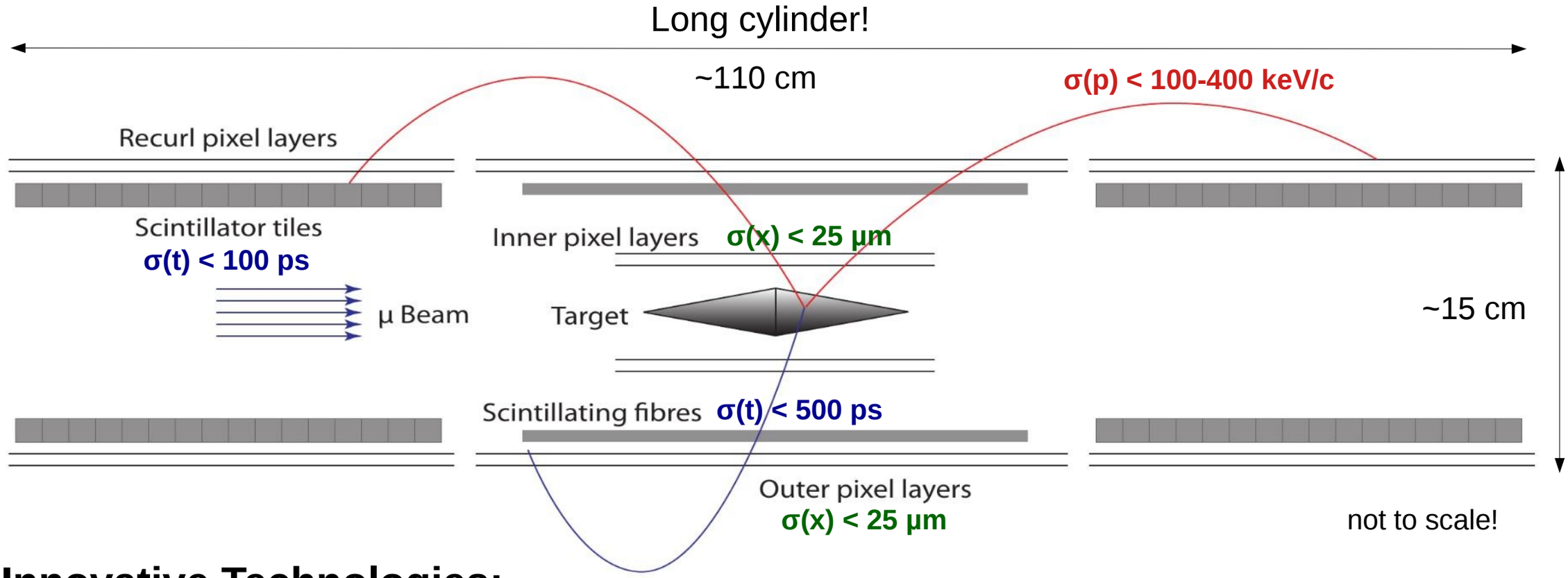
Mu3e Phase I Design



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/cm^2) 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**

Mu3e Timeline

Schedule

	2021	2022	2023	2024	2025	2026	2027	2028	2029 and after
Mu3e Phase I 1st 4 years	construction & commissioning first data								
Mu3e Phase I 2nd 4 years					operation & high sensitivity preparation HiMB				
Mu3e Phase II	**R&D**				**R&D**				upgraded and extended experiment at HiMB

Planned improvements for Mu3e Phase II

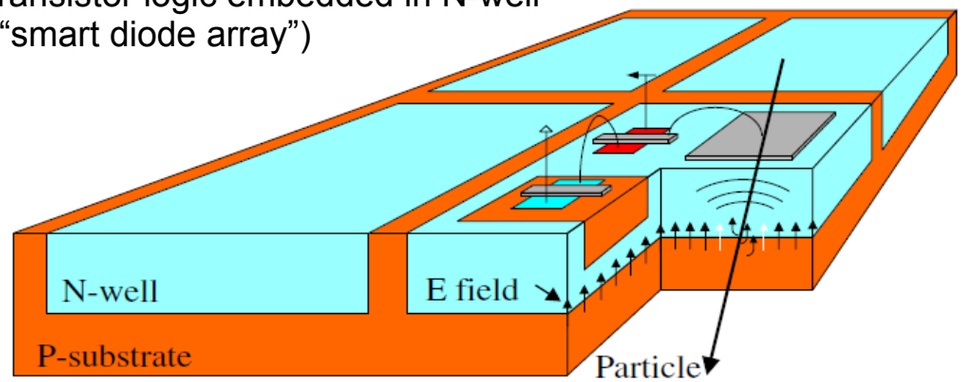
- Improve time resolution of pixel HV-MAPS detector: 5ns → 1ns
- Increase size of vertex layers (new geometry)
- Replacement of Sci-Fi Detector by SiGe Pixel detector with time resolution < 200 ps
- Improve radiation tolerance of scintillating tile detector
  - **requires many test beam campaigns at CERN, DESY, MAMI, PSI**

Backup

HV-MAPS Detector Technology

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

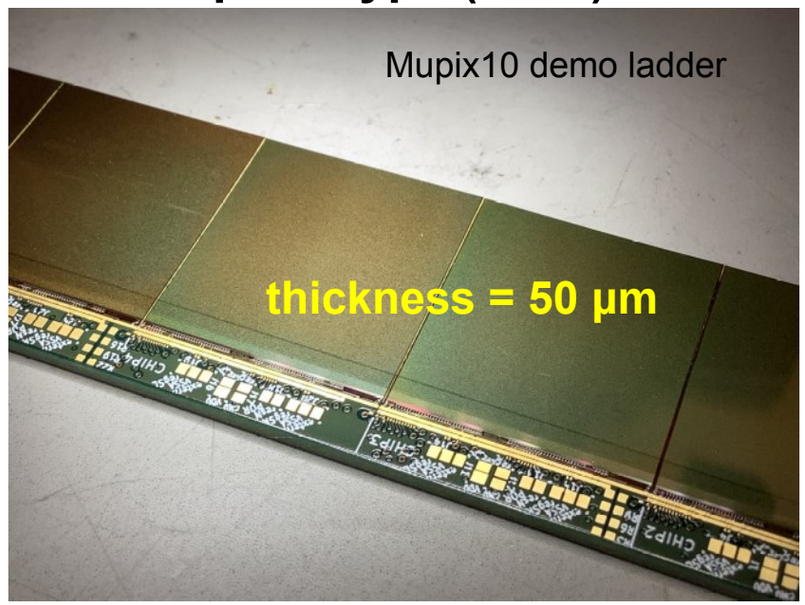
transistor logic embedded in N-well
("smart diode array")



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

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

MuPix10 prototype (2020)



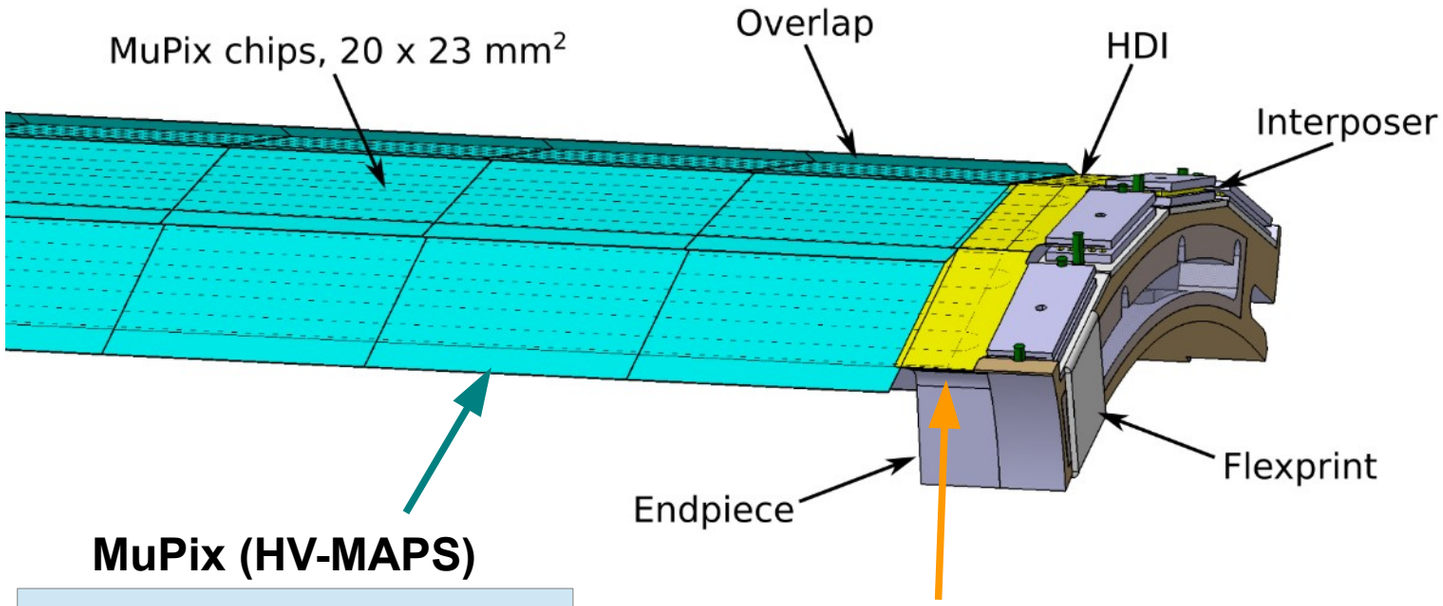
sensor: 20 x 20 mm² pixel: 80 x 80 µm²

MuPix prototypes characterized in lab and in several test beams

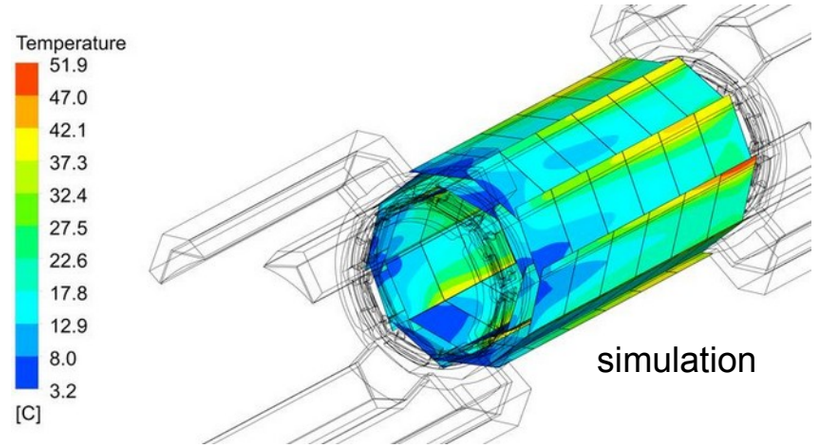
- efficiency & noise
- high rates (radiation hardness)
- temperature-dependence
  - ➔ specifications fulfilled

Pixel Tracking Detector

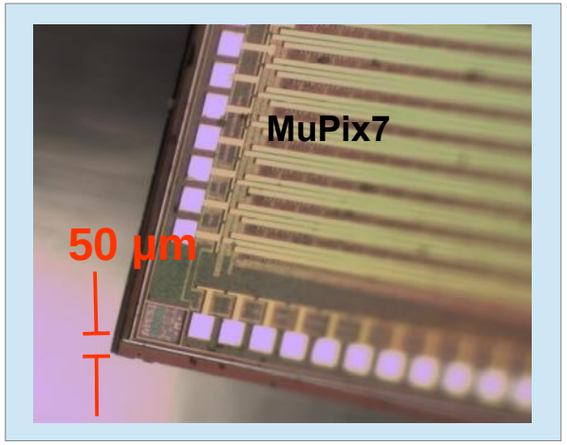
Ultra-thin pixel sensor modules (X/X_0 = 1.15 per mille)



Gaseous He-Cooling System

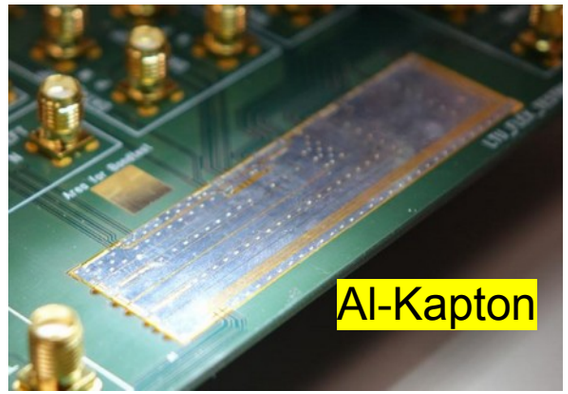


MuPix (HV-MAPS)

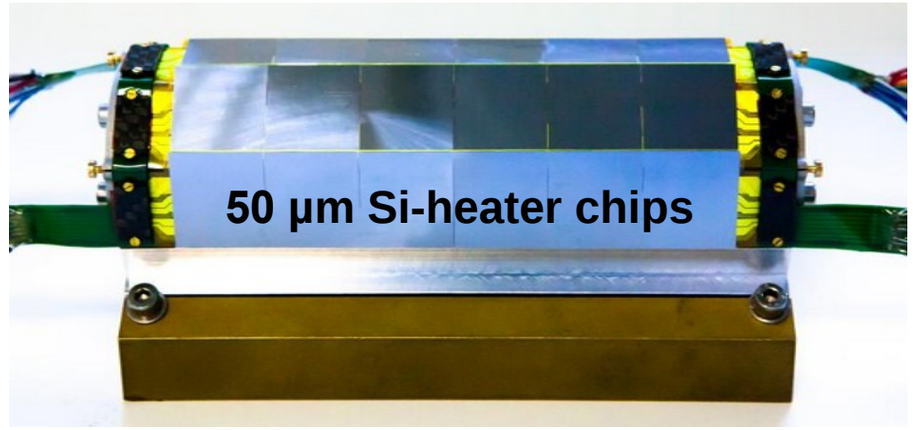


Monolithic pixel sensor in
180 nm HV-CMOS

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



Thermo-Mechanical Mockup (vertex)



Scintillating Fibres

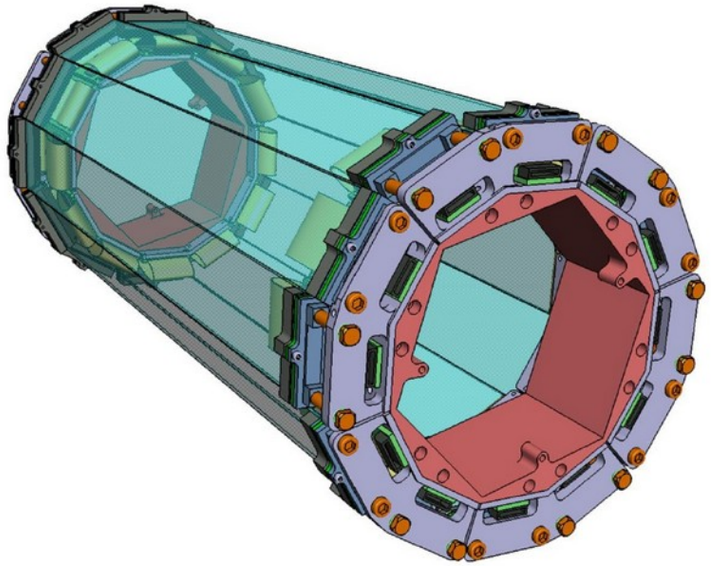
Scintillating Fibre Detector

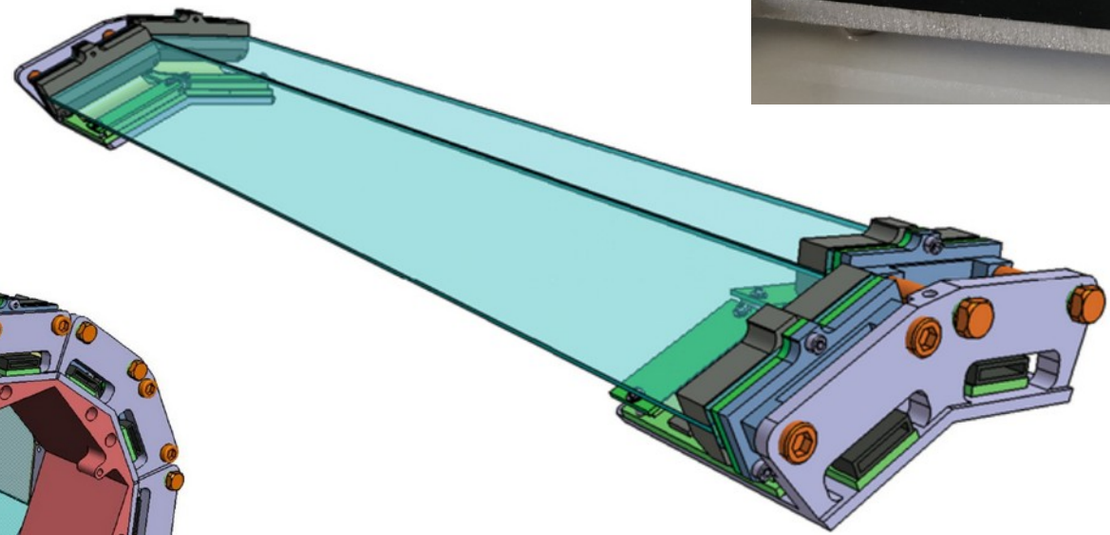
- Scintillating fibres: Kuraray SCSF-78MJ (multi-clad)
- SiPM Hamamatsu S13552-HRQ
- MuTrig TDC ASICs for readout

➔ very challenging space constraints

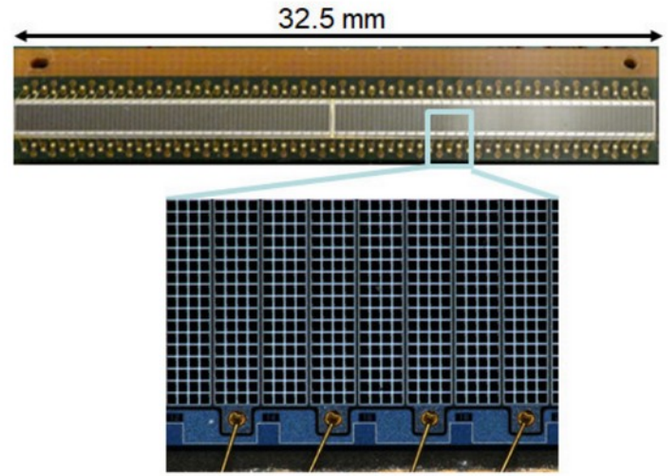
prototype ladder

SciFi detector



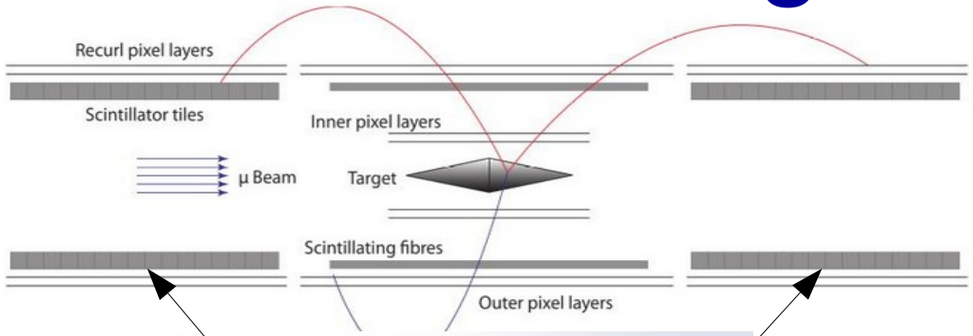


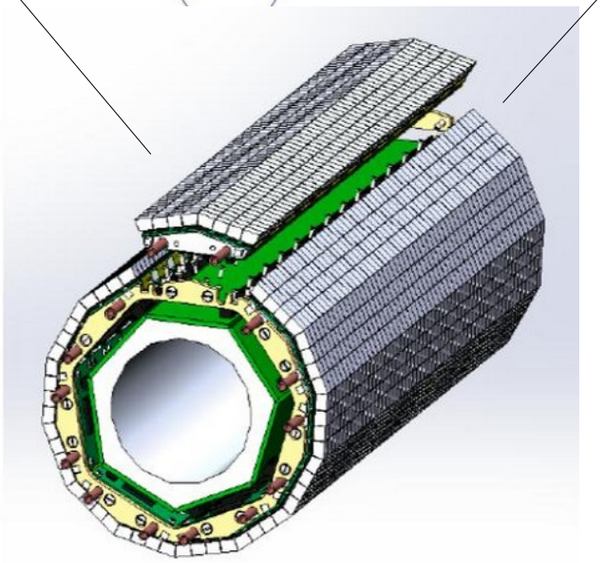
double SciFi ladder



Hamamatsu S13552-HRQ

Scintillating Tiles Timing Detectors

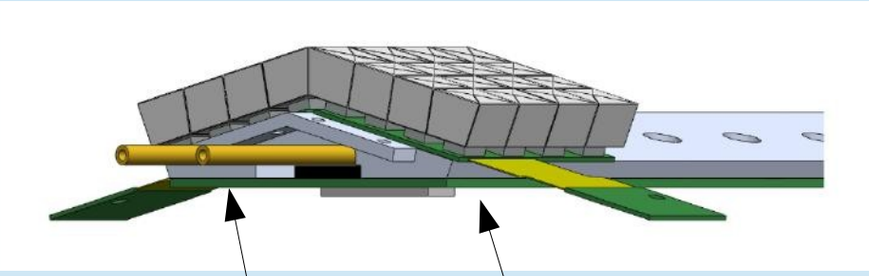


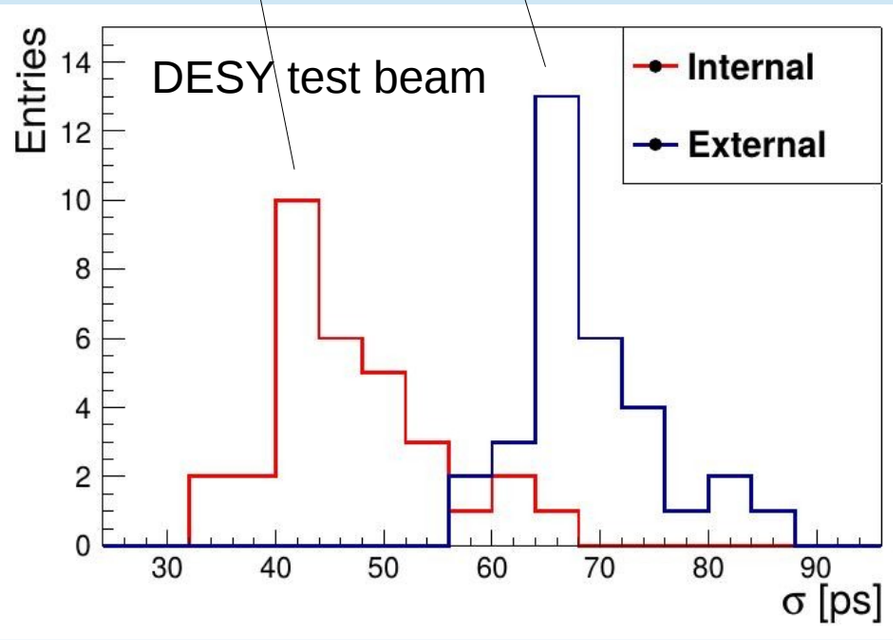


Scintillating Tiles

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

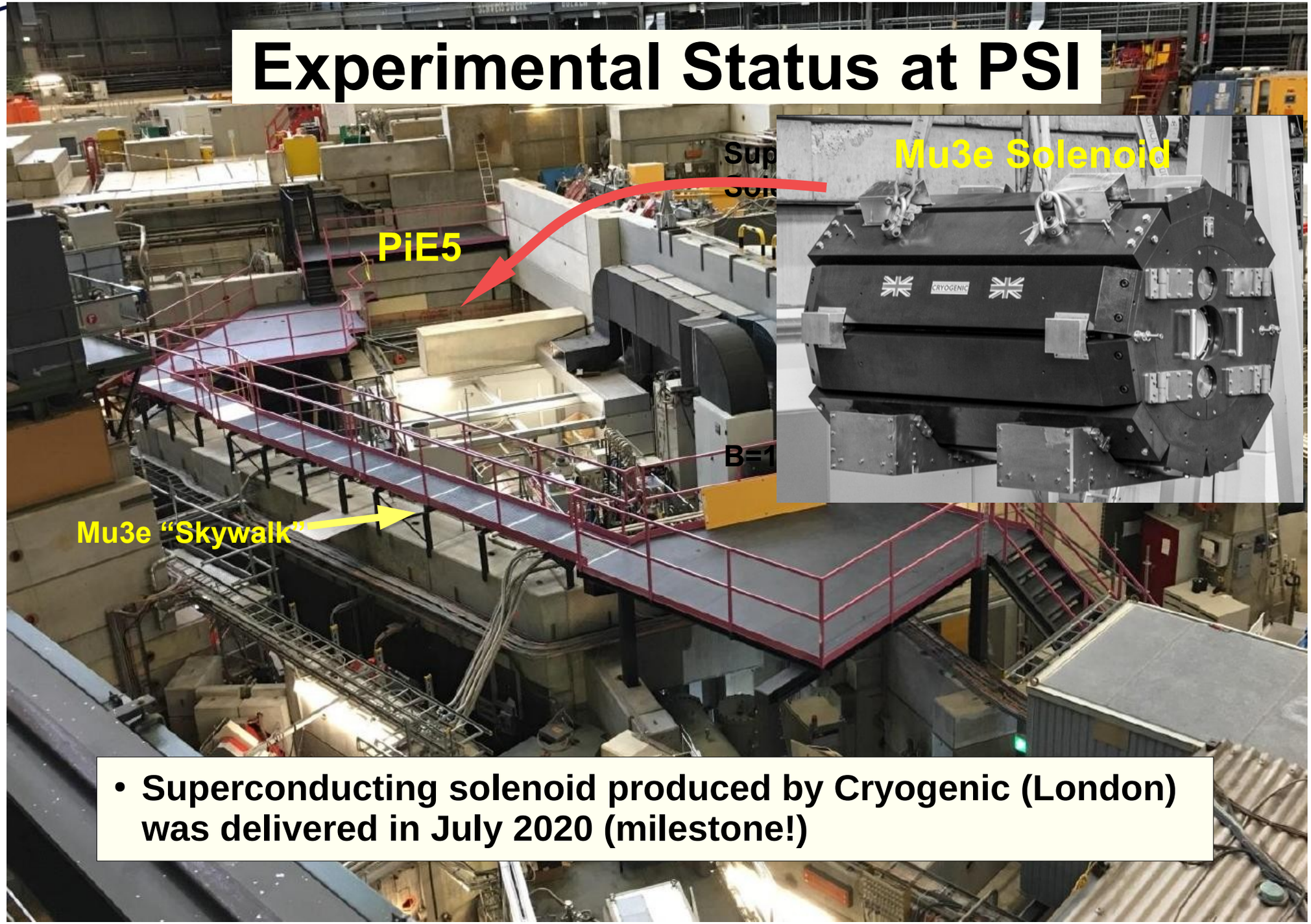
Scintillating Tile Sub-Module





Time resolution < 100ps

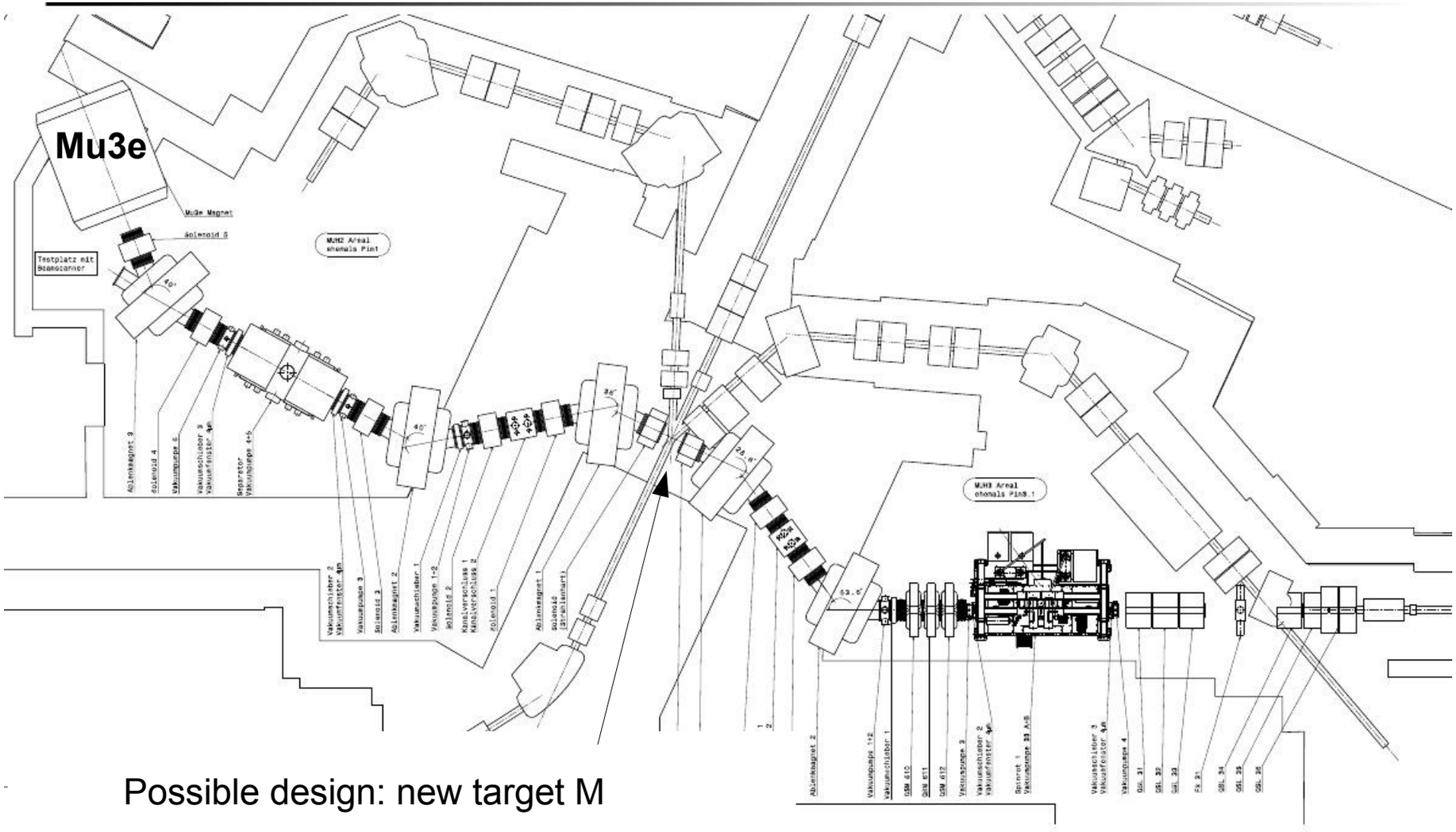
Experimental Status at PSI



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

Mu3e Phase II and High Intensity Muon Beamline (HiMB)

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



Possible design: new target M