The Mu3e experiment

Frederik Wauters on behalf of the Mu3e collaboration
Johannes Gutenberg University Mainz

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

Why searching for CLFV? ➜ Morning Session

Not a fundamental Standard Model symmetry

We have Neutral LFV, ν oscillations

For $p_{exp} \ll m_{BSM}$: EFT approach

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

Why searching for CLFV? ➜ Morning Session

How to search for CLFV, i.e. looking for small BSM couplings?
➜ Intensity Frontier Measurement
➜ Processes with a low Standard Model Background

<u>Muons are great!</u>

- ➢ They are leptons with 100% leptonic decay modes very well described in the SM
- ➢ SM background free
- ➢ BSM contributions can be described by EFT arXiv:1702.03020 as $m_{mu} \ll \Lambda_{NP}$
- ➢ We can make a lot of them at p-accelerator facilities
- ➢ They live long enough to production → experiment

Sweet spot between sensitivity and availability

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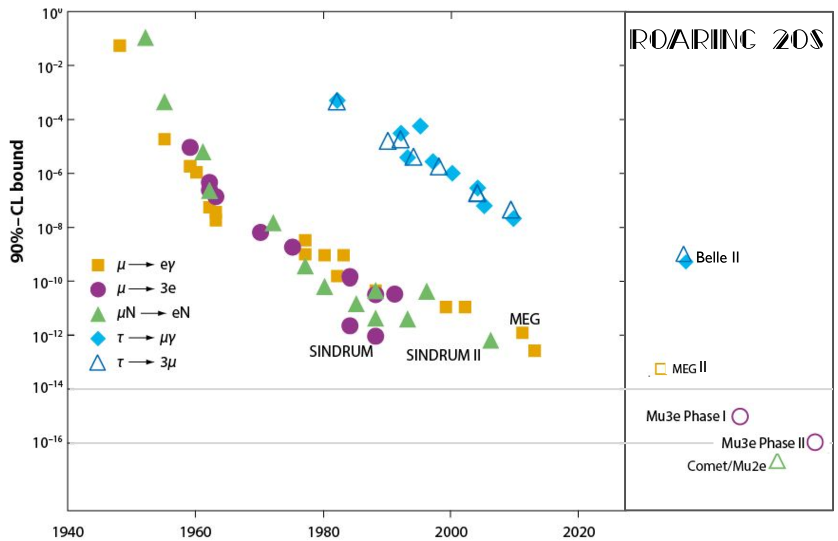
Sweet spot between sensitivity and availability

Three golden channels

And no neutrinos

❑	$\mu^+ \to e^+\gamma$	MEG $< 4\cdot10^{-13}$	⇨	MEGII $< 5\cdot10^{-14}$
❑	$\mu^- N \to e^- N$	SUNDRUMII $< 7\cdot10^{-13}$	⇨	DeeMee, Mu2e, COMET $< 10^{-16}$
❑	$\mu^+ \to e^+e^+e^-$	SINDRUM $< 1\cdot10^{-12}$	⇨	Mu3e $< 2\cdot10^{-15}$ ($1\cdot10^{-16}$ in a second phase)

CLFV & $\mu^+ \to e^+e^+e^-$



4 orders-of-magnitude for new physics searches!

Sweet spot between sensitivity and availability

<u>Three golden channels</u>

- ❑ $\mu^+ \to e^+\gamma$ MEG < $4\cdot10^{-13}$ ➪ MEGII < $5\cdot10^{-14}$
- ❑ $\mu^-N \to e^-N$ SUNDRUMII < $7\cdot10^{-13}$ ➪ DeeMee, Mu2e, COMET < 10^{-16}
- ❑ **$\mu^+ \to e^+e^+e^-$** SINDRUM < $1\cdot10^{-12}$ ➪ **Mu3e < $2\cdot10^{-15}$** ($1\cdot10^{-16}$ in a second phase)

Figure adapted from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)

Why (look at all) three golden channels?

- $\mu^+ \to e^+\gamma$
- $\mu^- N \to e^- N$
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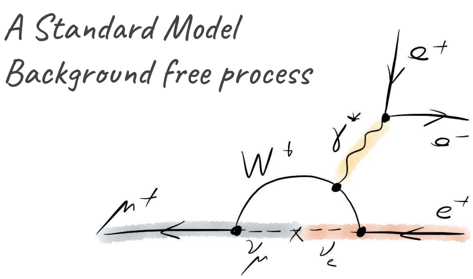
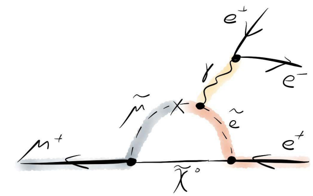
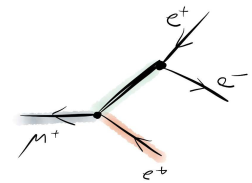


BR(SM) < 10^{-54}

Sensitive to loop and tree/contact level *new* interactions





…

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- ❑ $\mu^+ \to e^+\gamma$
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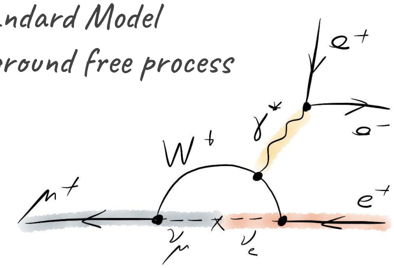
- ❑ **$\mu^+ \to e^+e^+e^-$**

For dipole interactions,
MEG ~100 times more sensitive

A Standard Model
Background free process



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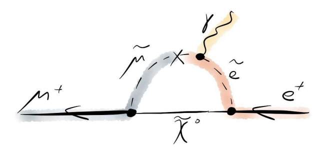
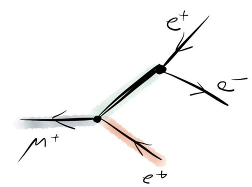
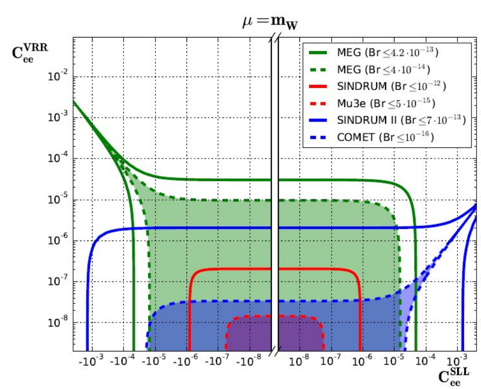




	$\mathrm{Br}(\mu^+ \to e^+\gamma)$		$\mathrm{Br}(\mu^+ \to e^+e^-e^+)$		$\mathrm{Br}_{\mu\to e}^{\mathrm{Au/Al}}$	
	$4.2 \cdot 10^{-13}$	$4.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-15}$	$7.0 \cdot 10^{-13}$	$1.0 \cdot 10^{-16}$
C_L^D	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$	$2.0 \cdot 10^{-7}$	$2.9 \cdot 10^{-9}$
$C_{ee}^{S\,LL}$	$4.8 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$8.1 \cdot 10^{-7}$	$5.8 \cdot 10^{-8}$	$1.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-5}$
$C_{\mu\mu}^{S\,LL}$	$2.3 \cdot 10^{-7}$	$7.2 \cdot 10^{-8}$	$4.6 \cdot 10^{-6}$	$3.3 \cdot 10^{-7}$	$7.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
$C_{\tau\tau}^{S\,LL}$	$1.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$2.4 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$2.4 \cdot 10^{-5}$	$3.5 \cdot 10^{-7}$
$C_{\tau\tau}^{T\,LL}$	$2.9 \cdot 10^{-9}$	$9.0 \cdot 10^{-10}$	$5.7 \cdot 10^{-8}$	$4.1 \cdot 10^{-9}$	$5.9 \cdot 10^{-8}$	$8.5 \cdot 10^{-10}$
$C_{\tau\tau}^{S\,LR}$	$9.4 \cdot 10^{-6}$	$2.9 \cdot 10^{-6}$	$1.8 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$2.7 \cdot 10^{-6}$
$C_{bb}^{S\,LL}$	$2.8 \cdot 10^{-6}$	$8.6 \cdot 10^{-7}$	$5.4 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$9.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$
$C_{bb}^{T\,LL}$	$2.1 \cdot 10^{-9}$	$6.4 \cdot 10^{-10}$	$4.1 \cdot 10^{-8}$	$2.9 \cdot 10^{-9}$	$4.2 \cdot 10^{-8}$	$6.0 \cdot 10^{-10}$
$C_{bb}^{S\,LR}$	$1.7 \cdot 10^{-5}$	$5.1 \cdot 10^{-6}$	$3.2 \cdot 10^{-4}$	$2.3 \cdot 10^{-5}$	$9.1 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$
$C_{cc}^{S\,LL}$	$1.4 \cdot 10^{-6}$	$4.4 \cdot 10^{-7}$	$2.8 \cdot 10^{-5}$	$2.0 \cdot 10^{-6}$	$1.8 \cdot 10^{-7}$	$2.4 \cdot 10^{-9}$

...



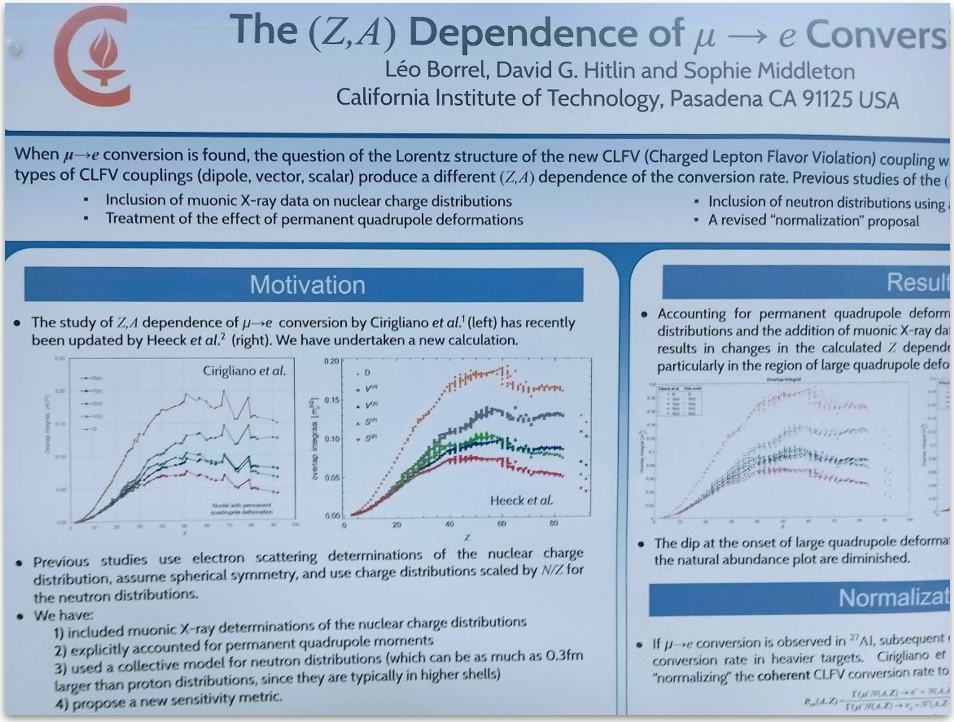
"Any of the 3 projects can have a plot where they come out on top "
A. S.

Renormalisation-group improved analysis of $\mu \to e$ processes in a systematic effective-field-theory approach. arXiv:1702.03020v3

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

<u>Why (look at all) three golden channels?</u>

- ❏ $\mu^+ \rightarrow e^+\gamma$ → Only one single signal, but there is $\mathbf{P}_\mu$
- ❏ $\mu^-N \rightarrow e^-N$ → Some differentiation via *N*
- ❏ $\boldsymbol{\mu^+ \rightarrow e^+e^+e^-}$



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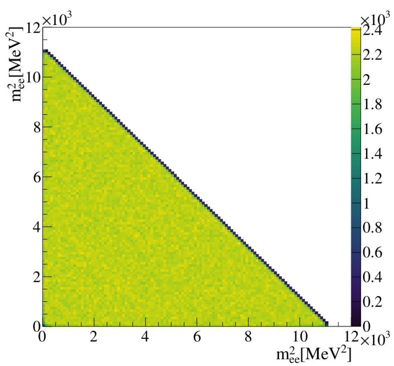
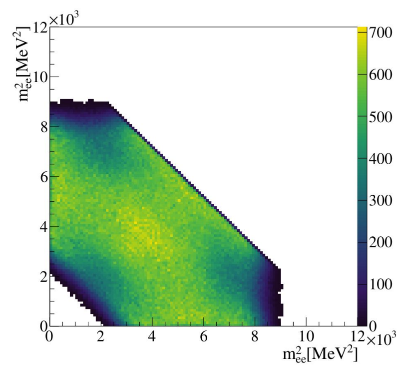
Phase space decay (Dalitz plot)



acceptance of
some detector
→



Figures from PhD Thesis A.-K. Perrevoort, operators from Rev.Mod.Phys.73:151-202,2001

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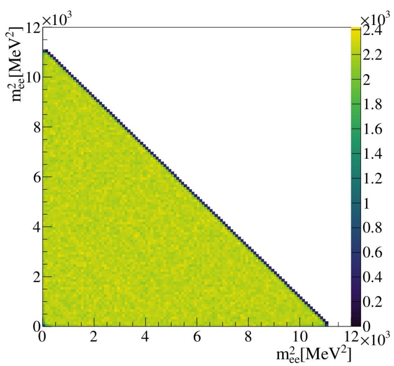
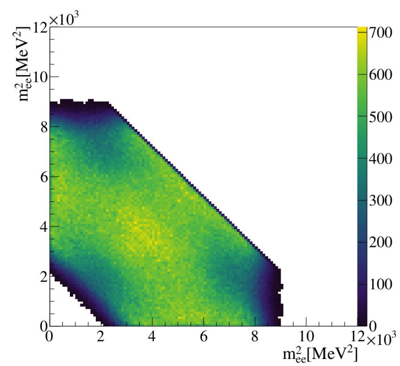
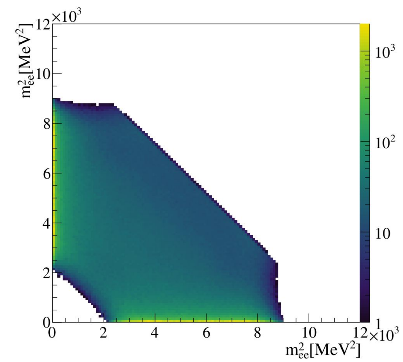


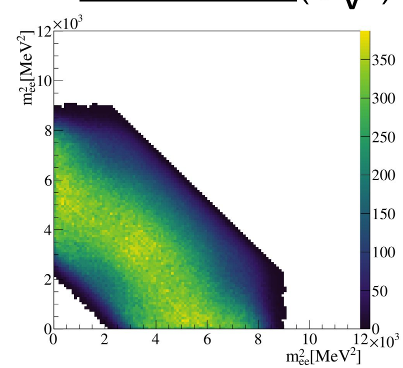
acceptance of *some* detector →



Dipole operator ($\mathcal{O}_D^{L*}$)



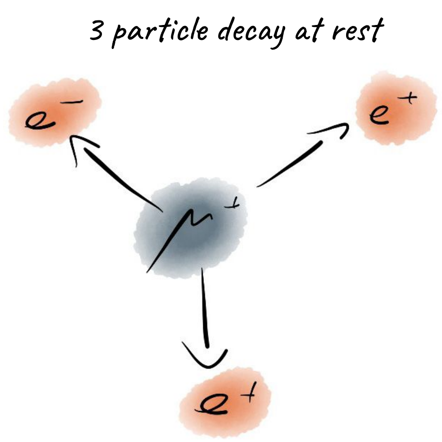
Four Fermion ($\mathcal{O}_V^{LL*}$)



Figures from PhD Thesis A.-K. Perrevoort, operators from Rev.Mod.Phys.73:151-202,2001

Experimental concept

How to look for $\mu^+ \rightarrow e^+e^+e^-$?



- ➔ Common vertex
- ➔ Time coincident
- ➔ $\sum E = m_\mu$
- ➔ $\sum \mathbf{p} = 0$

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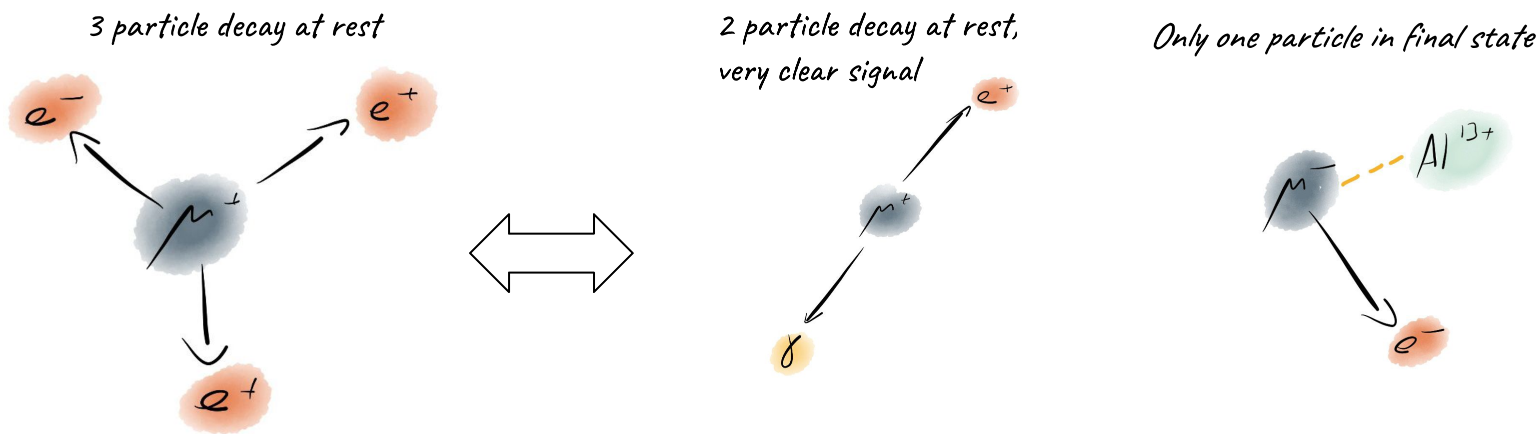

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- ➔ Mono-energetic e^+ and γ
- ➔ back-back coincidence

- ➔ Mono-energetic e^-
- ➔ No coincidence

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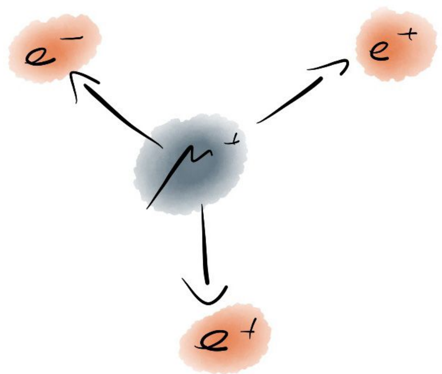
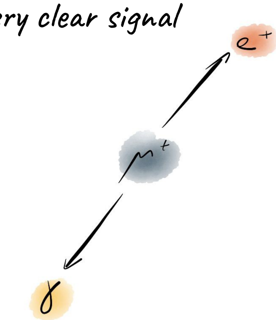
How to look for $\mu^+ \rightarrow e^+e^+e^-$?

DC muons
3 particle decay at rest



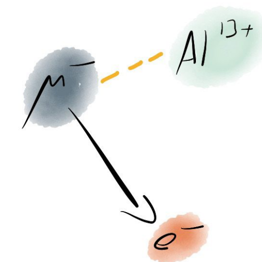
- ➔ Common vertex
- ➔ Time coincident
- ➔ $\sum E = m_\mu$
- ➔ $\sum \mathbf{p}=0$

DC muons
2 particle decay at rest,
very clear signal



- ➔ Mono-energetic e^+ and γ
- ➔ back-back coincidence

Pulsed muon beam
Only one particle in final state



- ➔ Mono-energetic e^-
- ➔ No coincidence

Mu3e & MEG @ PAUL SCHERRER INSTITUT PSI

Mu2e @ Fermilab

COMET @ J-PARC

Experimental concept

How to look for $\mu^+ \rightarrow e^+e^+e^-$?

DC muons

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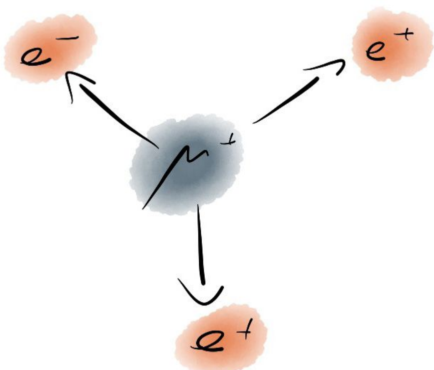
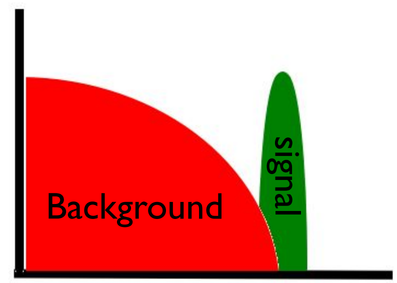


Internal conversion

Accidental background

➔ Common vertex
➔ Time coincident
➔ $\sum E = m_\mu$
➔ $\sum \mathbf{p}=0$



Michel decay positrons + electron from:

- ❑ Bhabha scattering
- ❑ Photon conversion
- ❑ Misreconstruction

Our detector needs:

- ➢ Excellent momentum resolution
- ➢ Good time and vertex resolution
- ➢ High rate capability
- ➢ Large acceptance

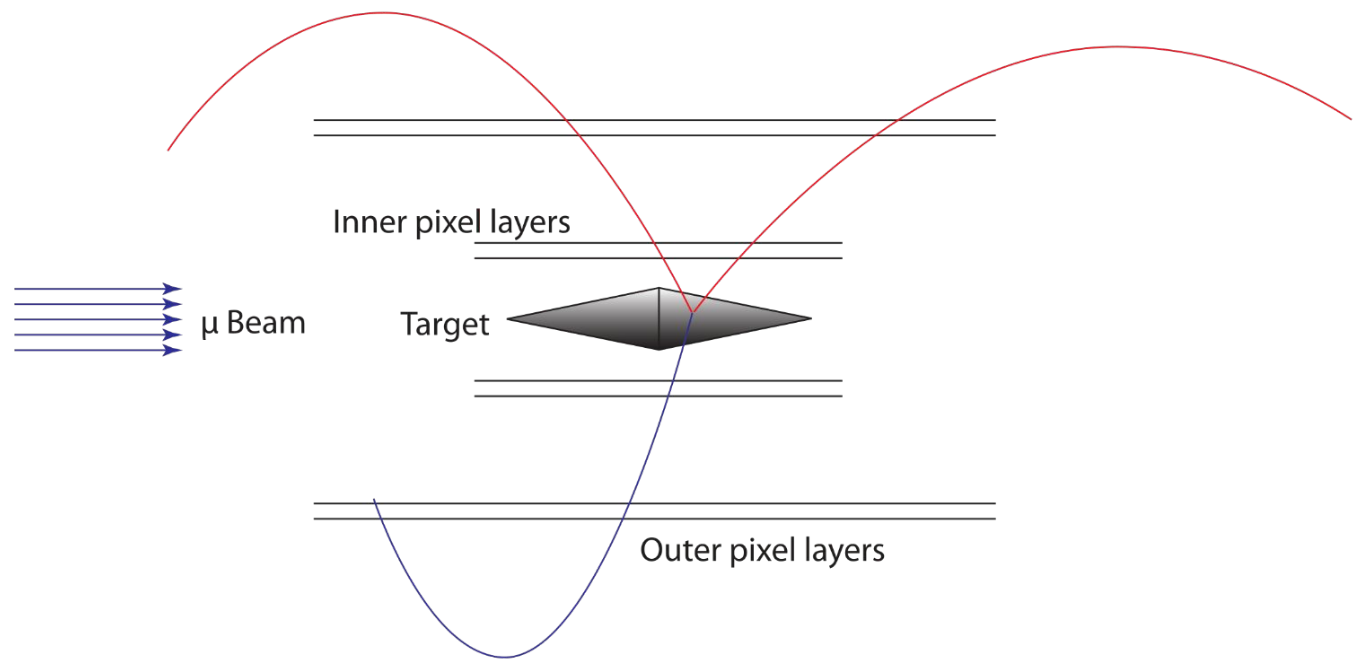
Fully differential NLO predictions for the rare muon decay arXiv:1611.03617

Experimental concept

- Step 1: Stop muons

Experimental concept

- Step 1: Stop muons
- Step 2: Two layer vertex detector
- Step 3: A 1T magnetic field and add 2 more Si pixel layers and start tracking (see our dedicated fast track fitter: https://arxiv.org/abs/1606.04990)



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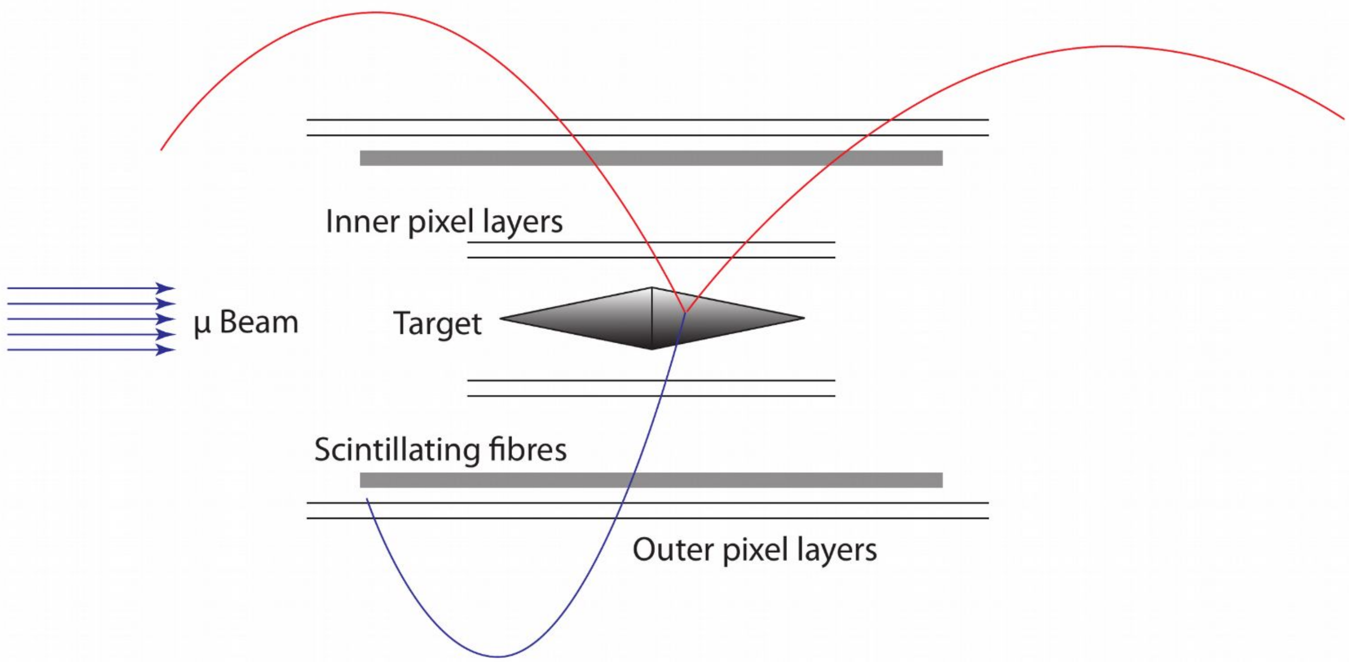

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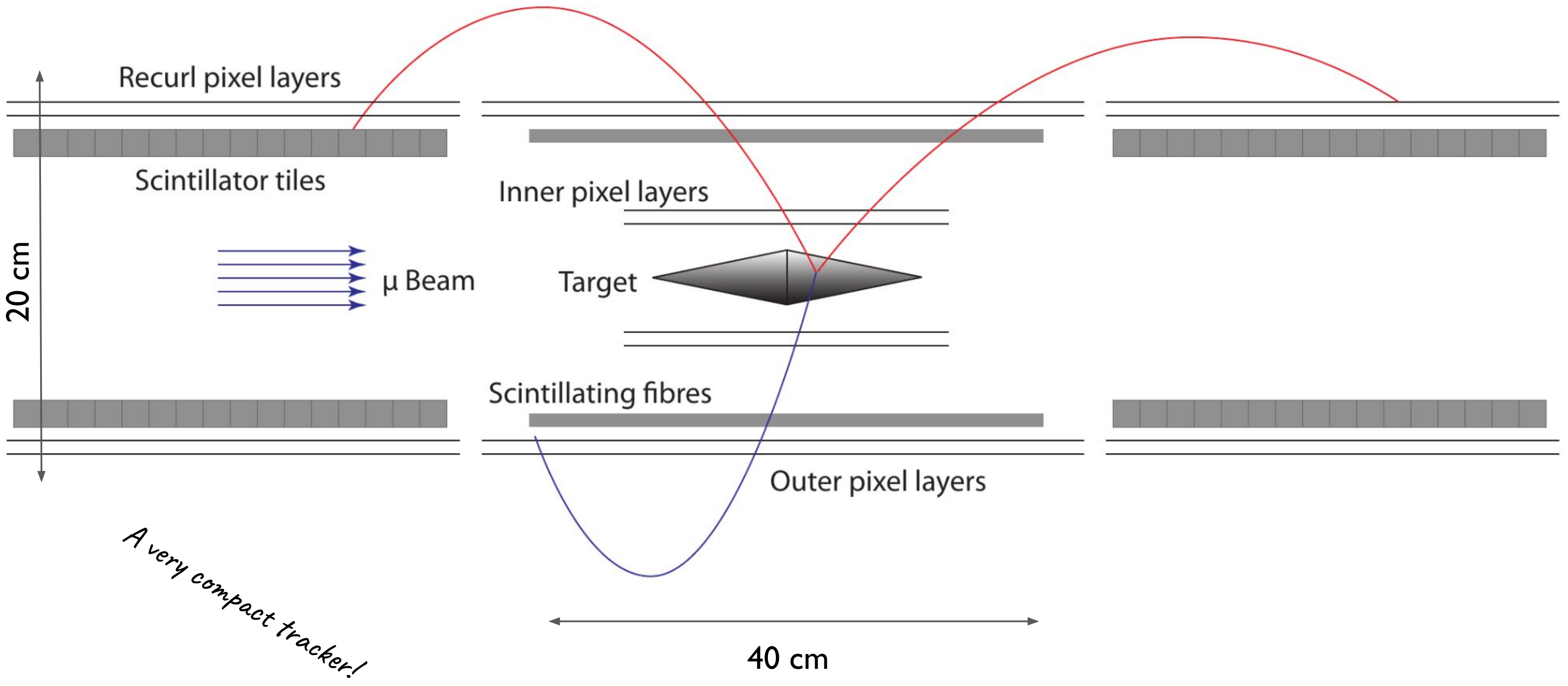
- Step 6: Add Scintillating Tiles to get the optimal timing resolution



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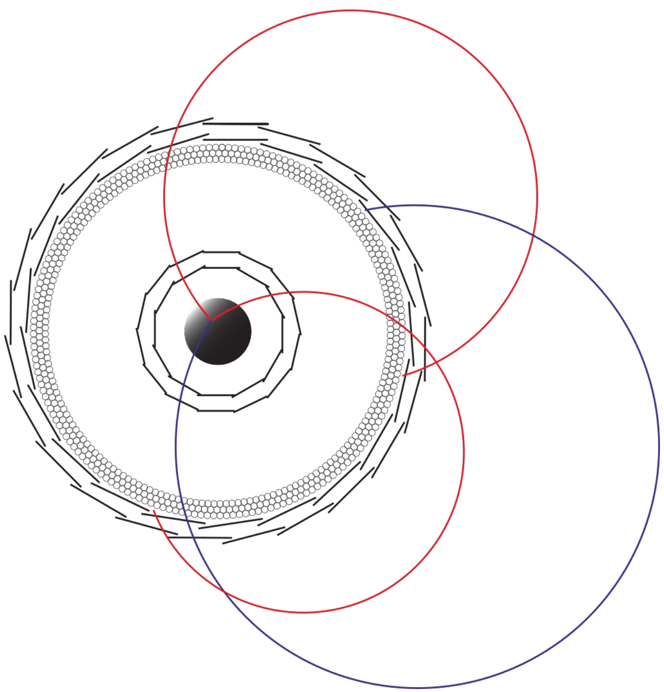
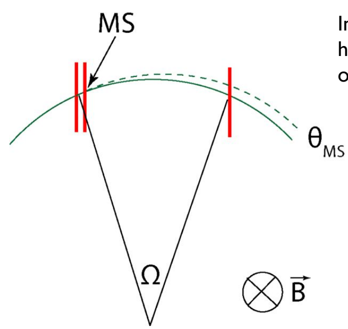
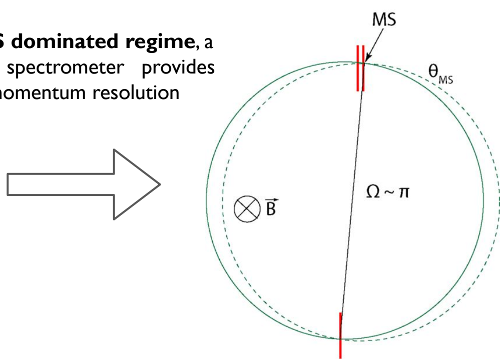
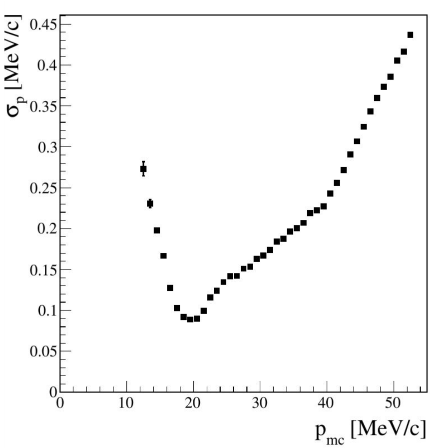




In the **MS dominated regime**, a half-turn spectrometer provides optimal momentum resolution





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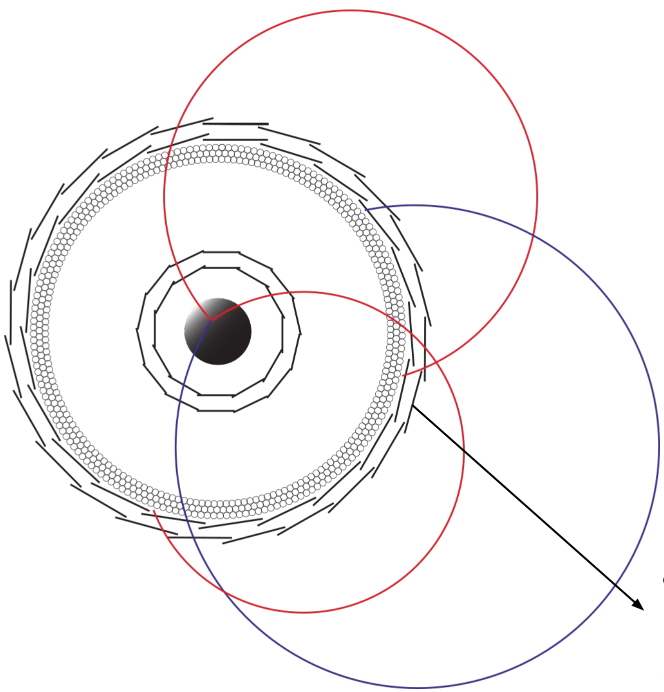

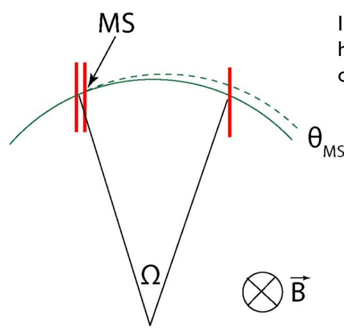

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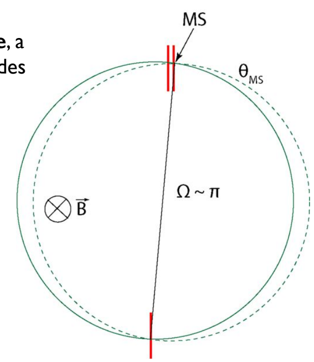
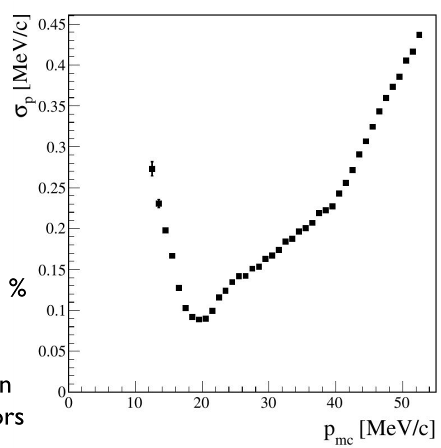


If each tracking layers is ~0.1 % of a radiation length

□ need fast (~20 ns) and thin (~50um) silicon pixel detectors



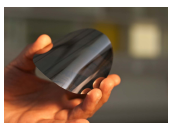
HV-MAPS

Lightweight pixel tracker build from
High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) called MuPix

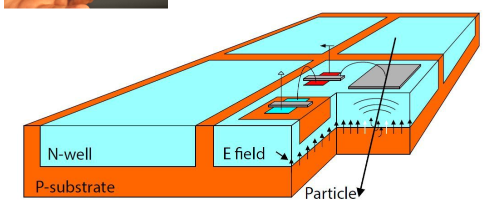
- ❏ Commercial HV-CMOS process
- ❏ Fast Charge collection
- ❏ Integrated analogue and digital RO
- ❏ Can be thinned to 50 µm
- ❏ 256x250 pixels / 2 x 2 cm

A decade of detector development and test beams

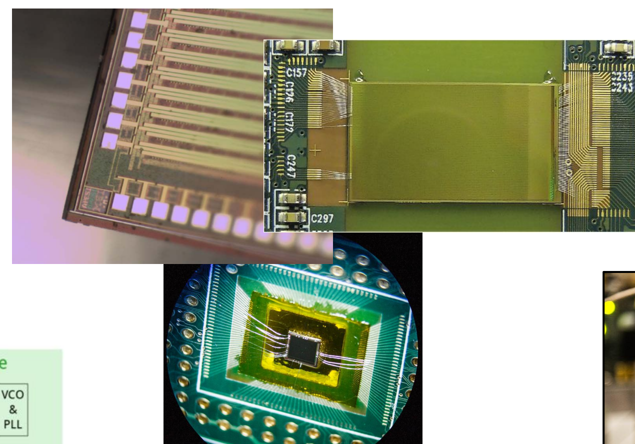
10-15 Master and PhD theses

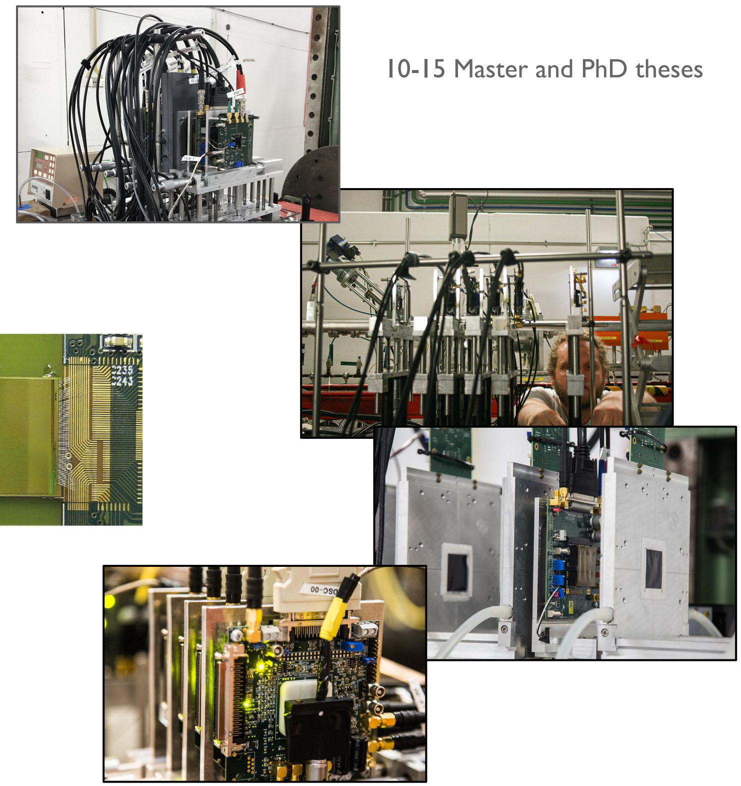


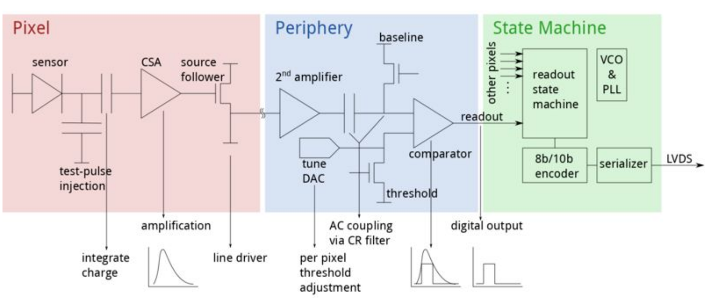
Concept



Prototyping MuPiX ... → 9







https://arxiv.org/abs/1603.08751, https://arxiv.org/abs/2002.07253, 10.1016/j.nima.2007.07.115

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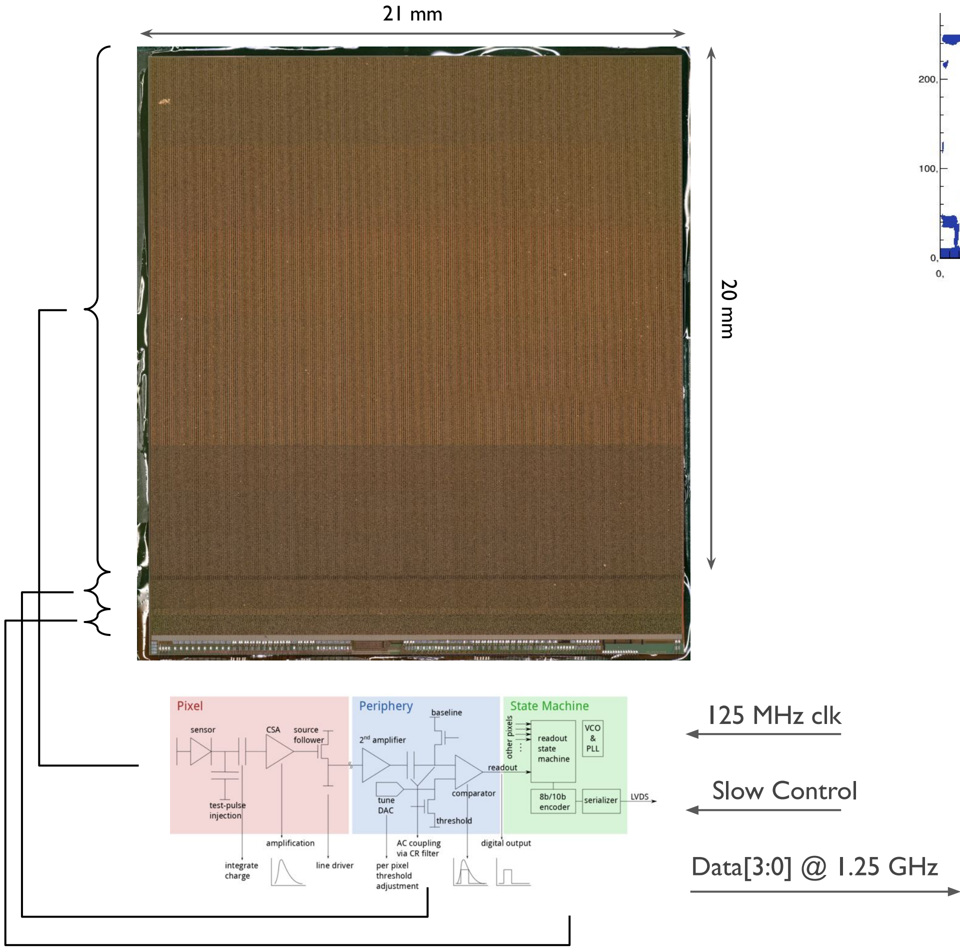
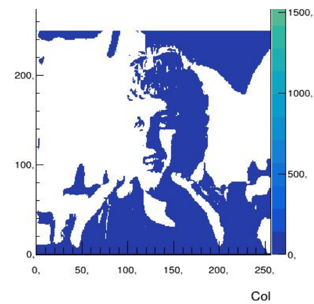
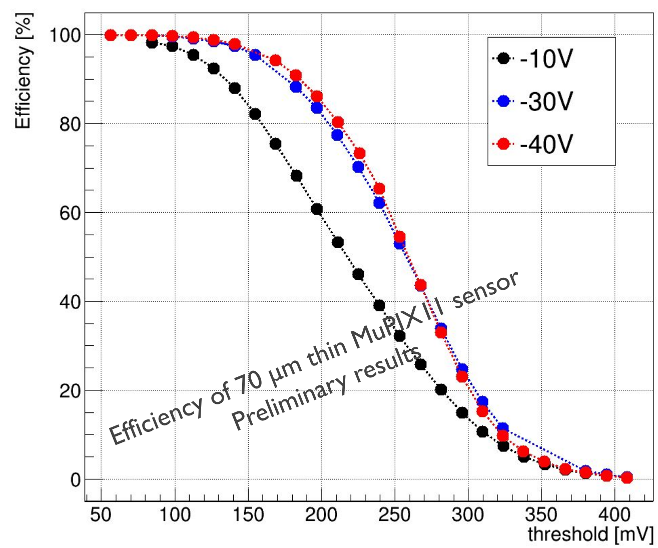
Poster David Immig

➜ MuPix11 as a fast, efficient, thin, and large HV-MAPS sensor





> 99.5 % efficient
< 15ns time resolution
Threshold/mask pixel by pixel

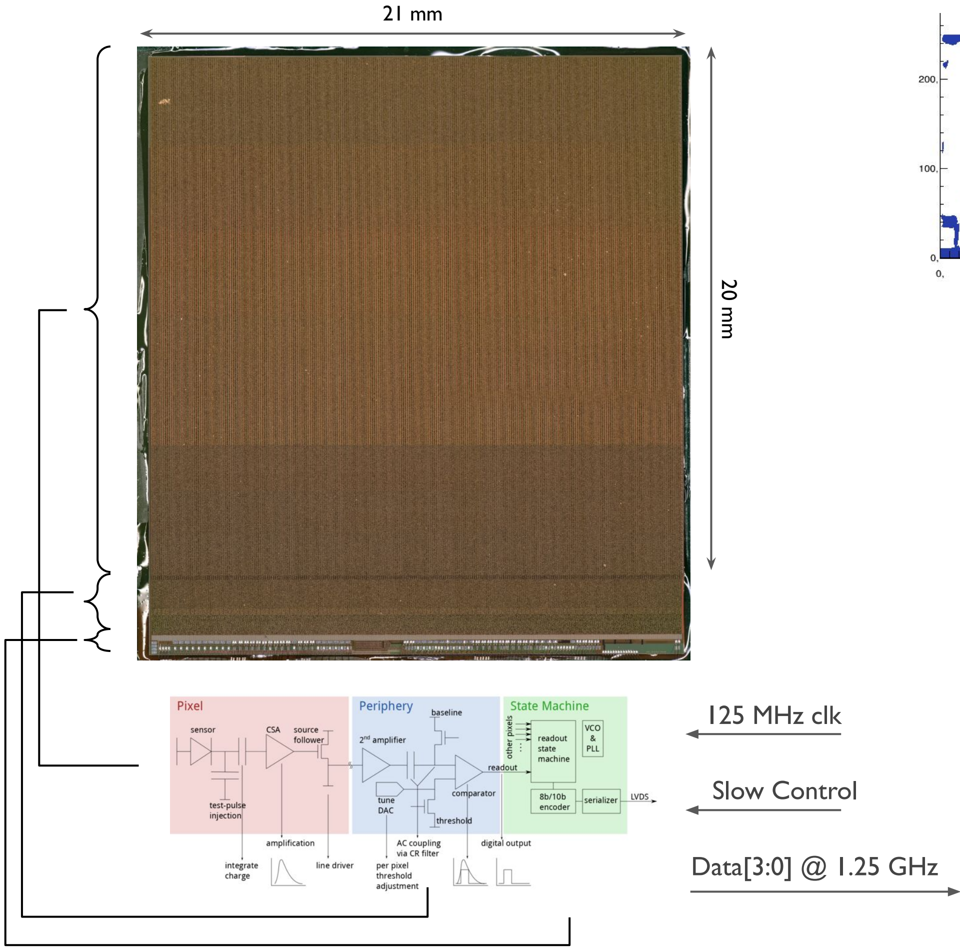


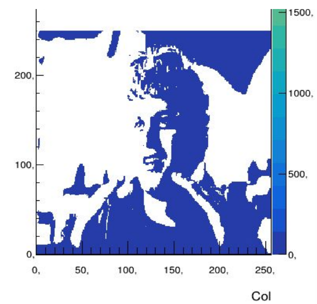
HV-MAPS

Lightweight pixel tracker build from
High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) called MuPix

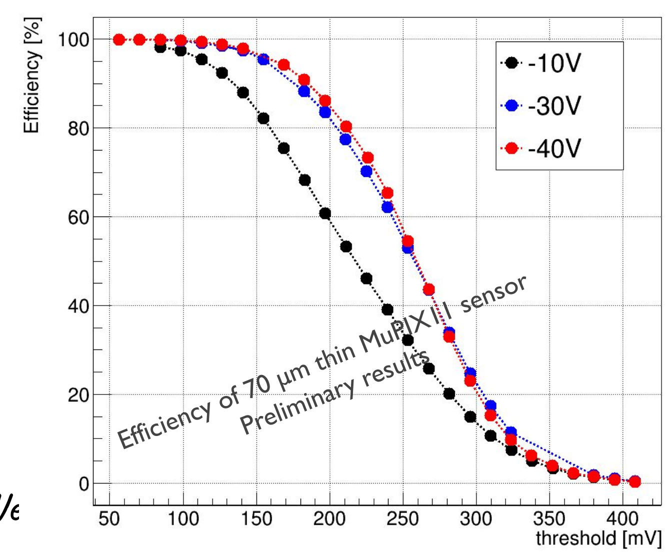
Poster David Immig

➜ MuPix11 as a fast, efficient, thin, and large HV-MAPS sensor

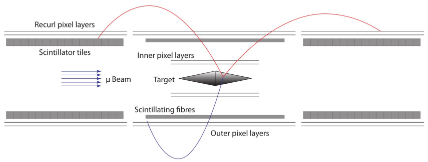


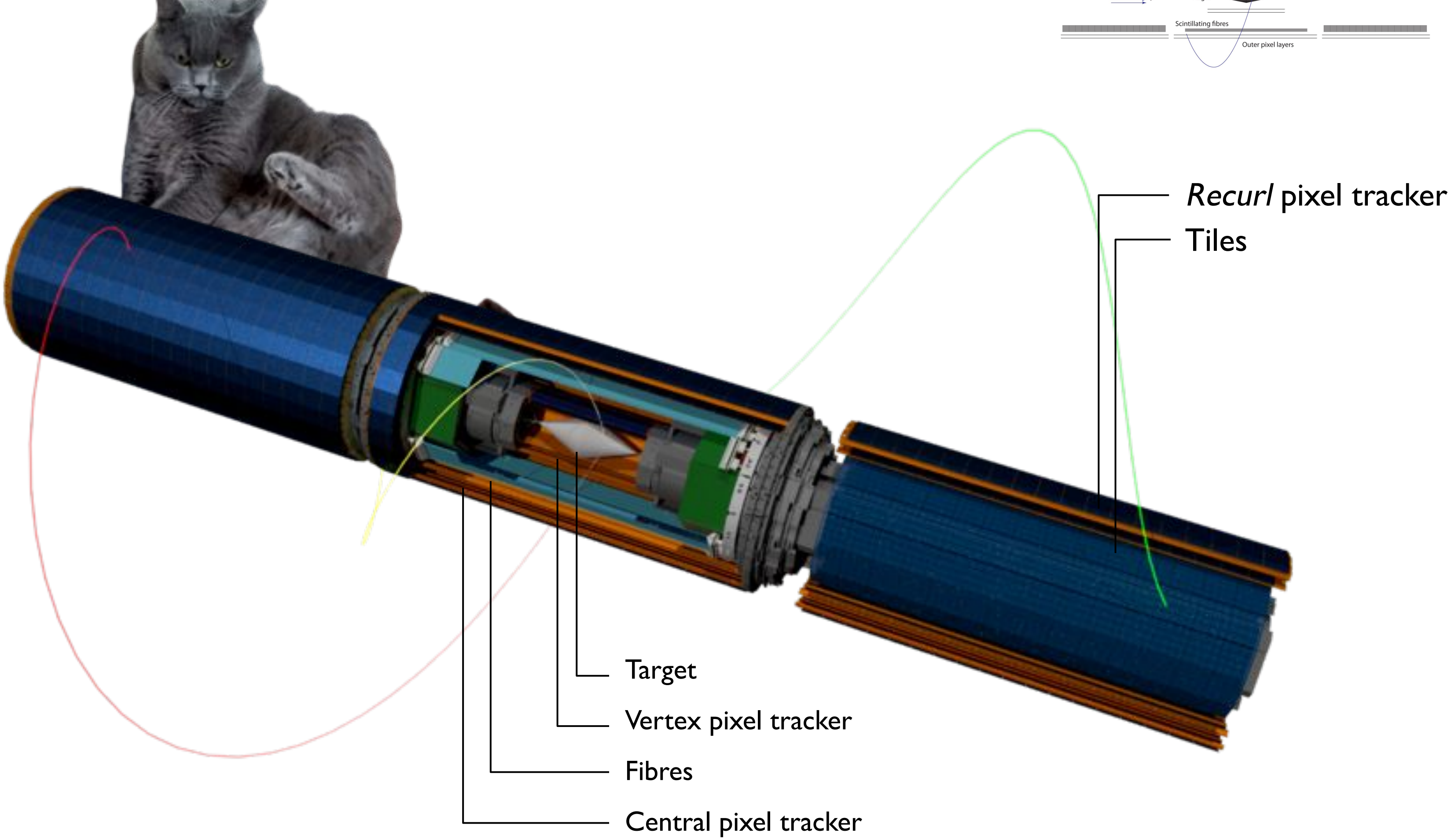


> 99.5 % efficient
< 15ns time resolution
Threshold/mask pixel by pixel



Mu3e detector



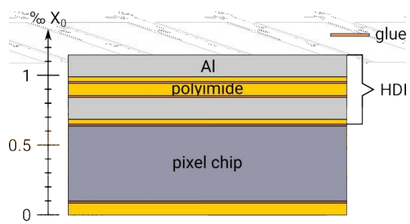


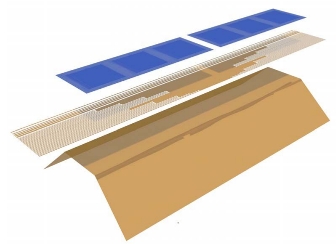
Mu3e detector

Lightweight pixel tracker build from MuPIX sensors

Thesis + Poster Thomas Rudzki

Ladders from 50-70 µm of Si,
25 µm of Alu/Kapton flex, and
25 µm of kapton support.
→ ca. 0.1% of a radiation length!

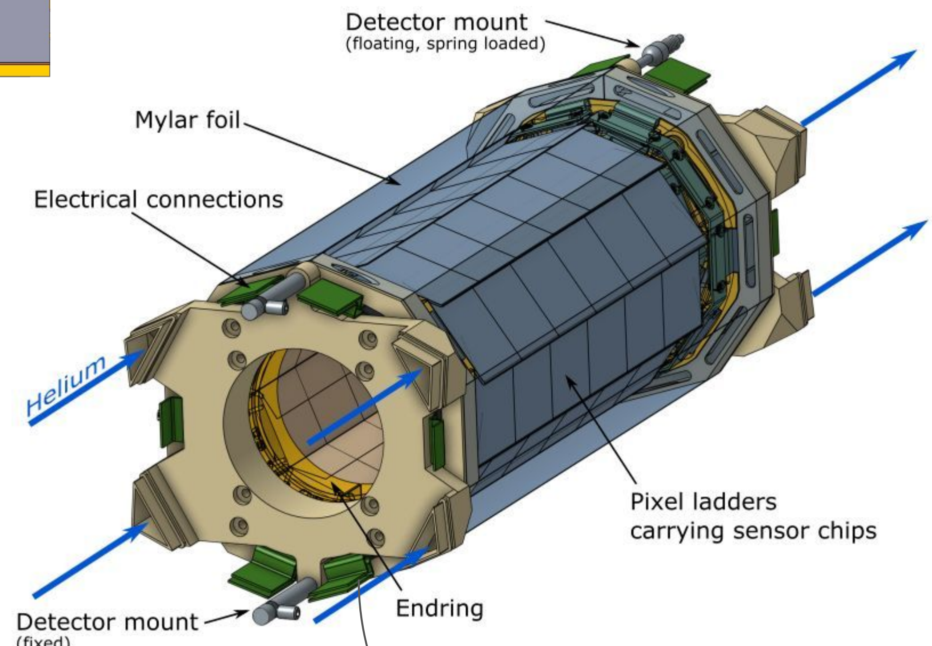


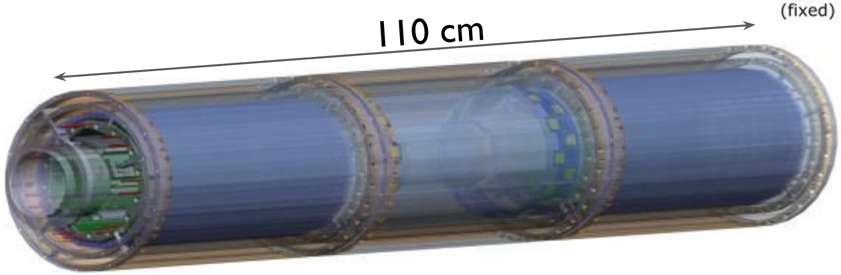


- 2 vertex layers
- 3 x 2 outer layers
- 174 ladders
- 2844 2x2 cm^2 MuPiX chips
- 182 016 000 pixels
- 3060 1.25 Gb/s data links
- 50 g/s, 10m/s 5kW gaseous helium cooling

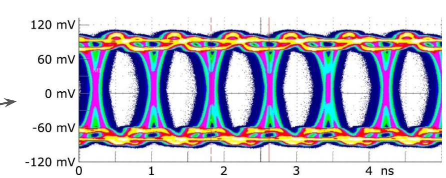
The is a compact but large pixel tracker!

Vertex tracker





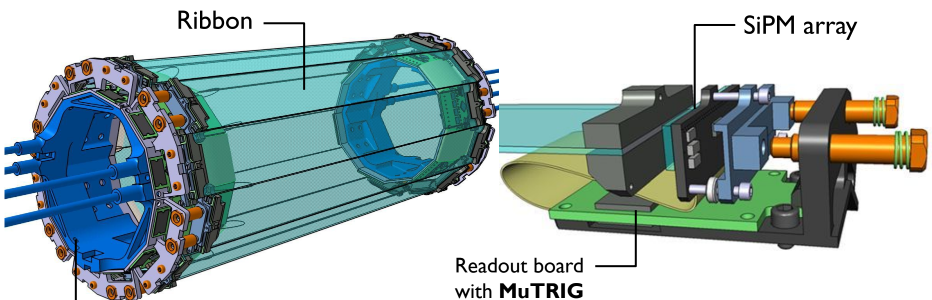
+ HV & power



Mu3e detector

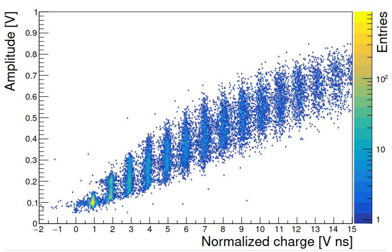
Timing detectors

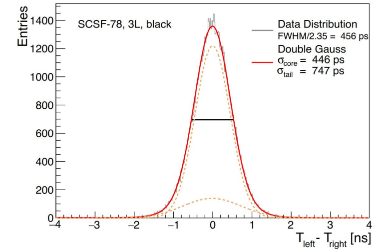
- 12 ribbon - 3 layer scintillating fibre detector surrounding the vertex detector
- Highly granular tile detector under the recurl stations



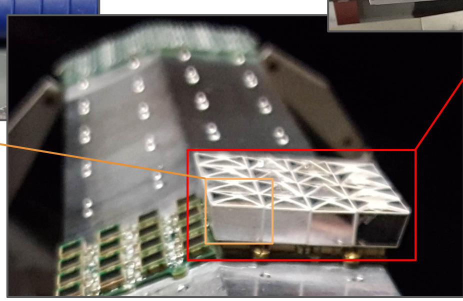
All fibre and pixel modules are spring loaded to compensate for thermal expansions.

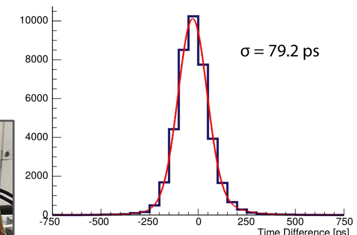
Operate fibre detector < p.e.

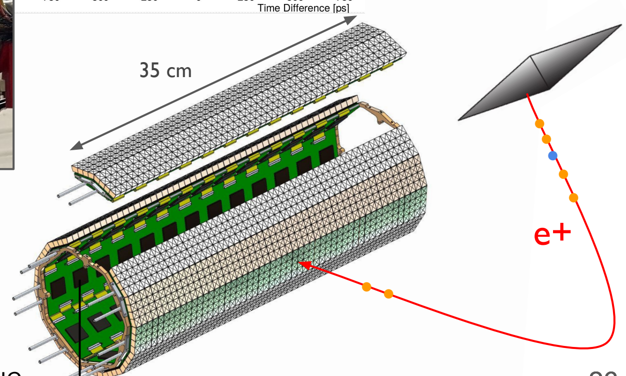




*Both detectors use a custom readout chip called MuTrig**





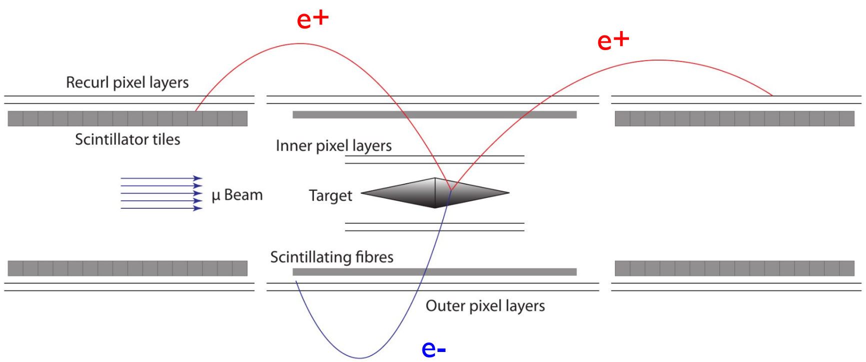


6272 tiles with plenty of light give us ca. 70 ps time resolution

*H. Chen *et al* 2017 *JINST* **12** C01043

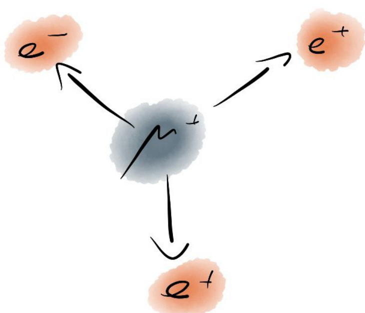
Development of the Scintillating Fiber Timing Detector for the Mu3e Experiment arXiv:2208.09906

Mu3e DAQ



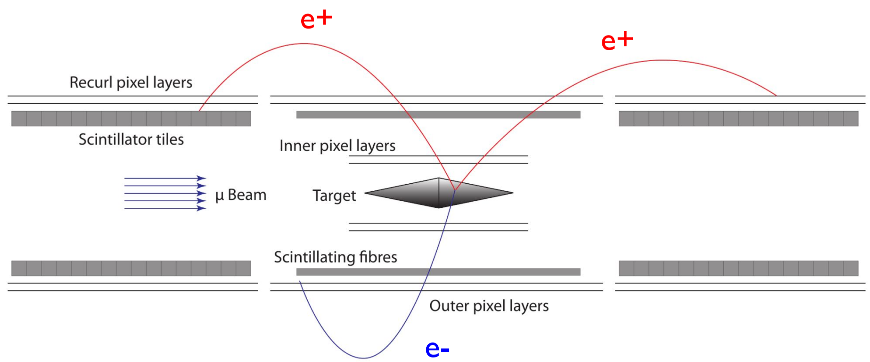
Reminder: the Mu3e event topology does not allow for a RO trigger, every $e^{+/-}$ track could potentially be part of a $\mu^+ \to e^+e^+e^-$ event. Only the kinematics of the combined final state positrons/electron gives us an event selection criteria.

Mu3e = lightweight and fast Michel electron tracker + high throughput online reconstruction & selection DAQ system



- ➔ Common vertex
- ➔ Time coincident
- ➔ $\sum E = m_\mu$
- ➔ $\sum \mathbf{p}=0$

Mu3e DAQ



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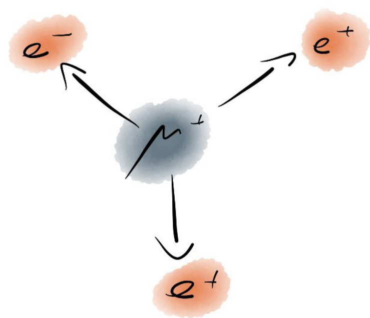
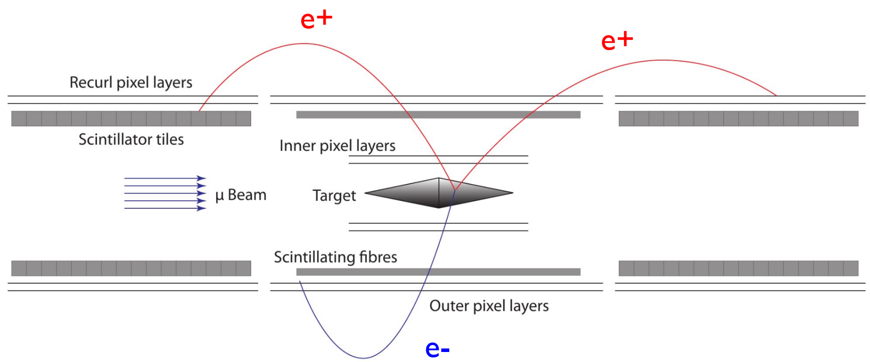


- ➔ Common vertex
- ➔ Time coincident
- ➔ $\sum E = m_\mu$
- ➔ $\sum \mathbf{p} = 0$

Readout system at scale: 3122 ASIC spitting out data at 1.25 Gb/s

Mu3e DAQ



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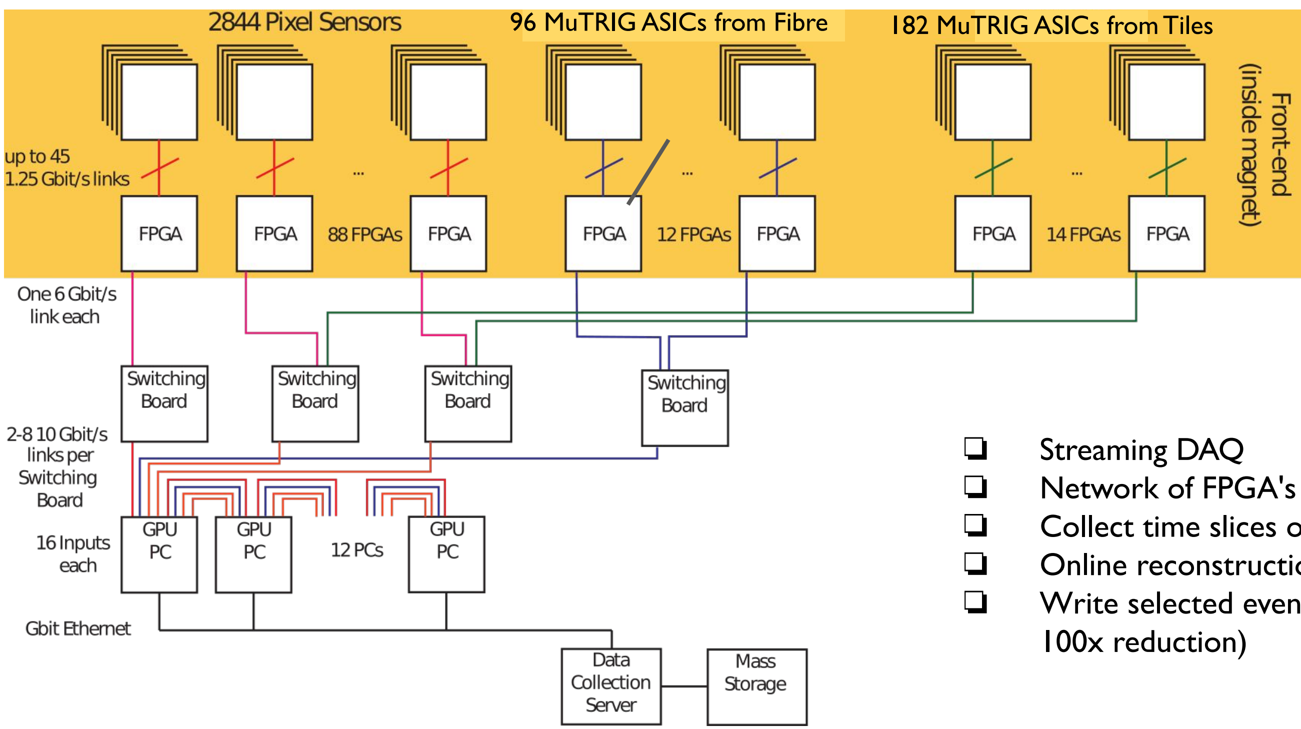
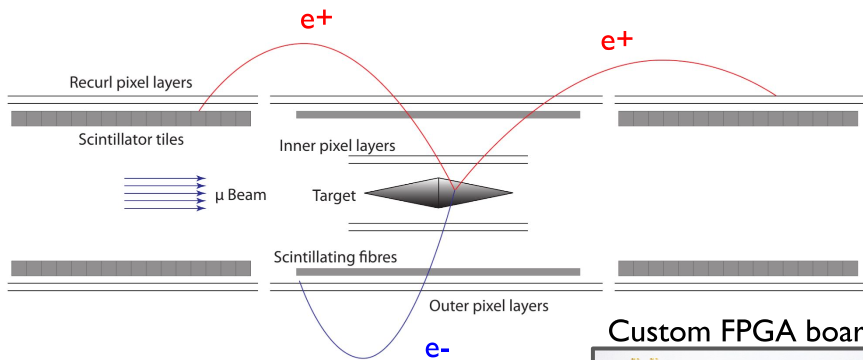


- ❑ Streaming DAQ
- ❑ Network of FPGA's and optical connections
- ❑ Collect time slices of the full detector on a single PC
- ❑ Online reconstruction and event selection on a GPUs
- ❑ Write selected events to disk at max 100 MB/s (up to 100x reduction)

Mu3e DAQ



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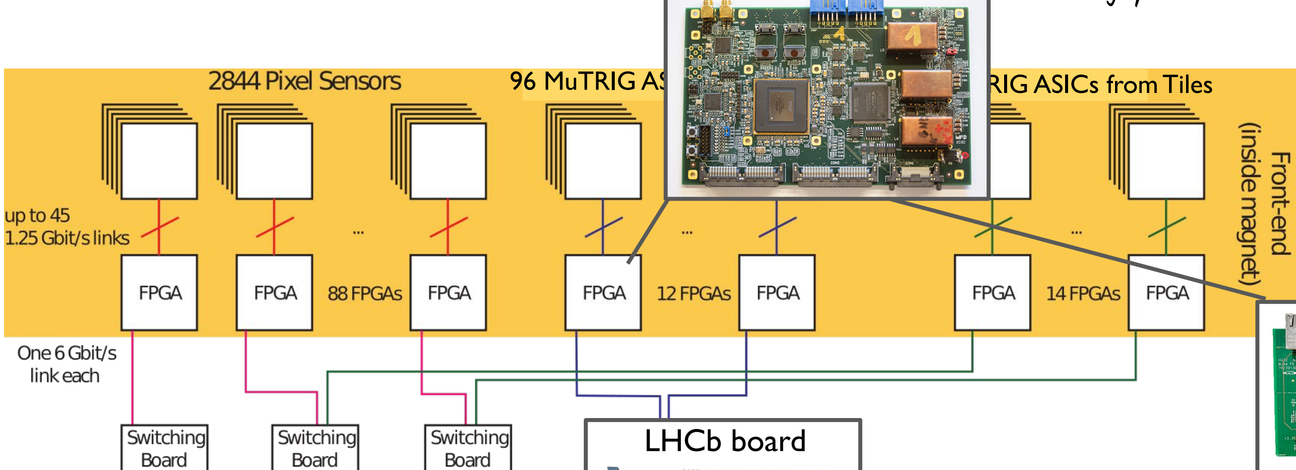
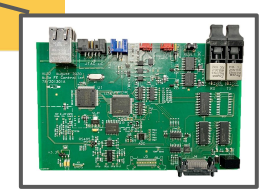
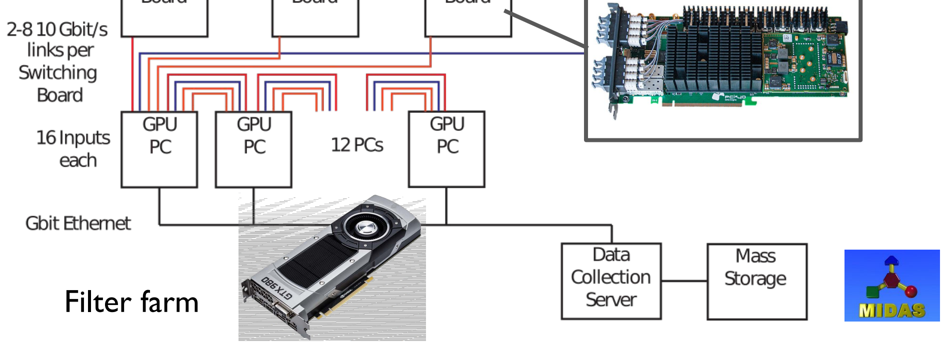


The Mu3e Data Acquisition:
[arXiv:2010.15648v2](https://arxiv.org/abs/2010.15648v2)

Online event selection:
[arXiv:2206.11535](https://arxiv.org/abs/2206.11535)



Crate controllers integrated in the MIDAS (Slow Control) System



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- ❑ Collect time slices of the full detector on a single PC
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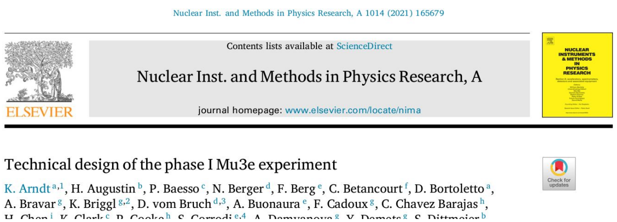
For data collection, configuration, monitoring, slow control, …

Mu3e sensitivity

Based on full Monte Carlo simulation of the experiment, an analytical track fitter, and a lot of detector R&D, we claim that:

The Mu3e Phase I detector can achieve a $2 \cdot 10^{-15}$ SES on $\mu^+ \rightarrow e^+e^+e^-$


Nuclear Inst. and Methods in Physics Research, A 1014 (2021) 165679

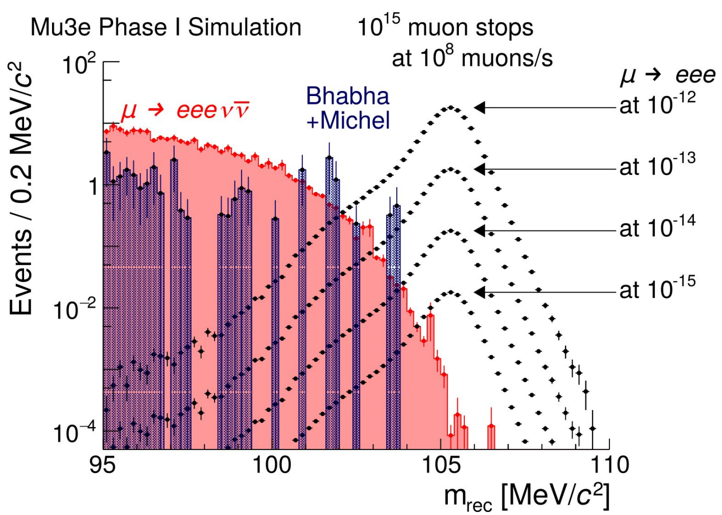
Contents lists available at ScienceDirect

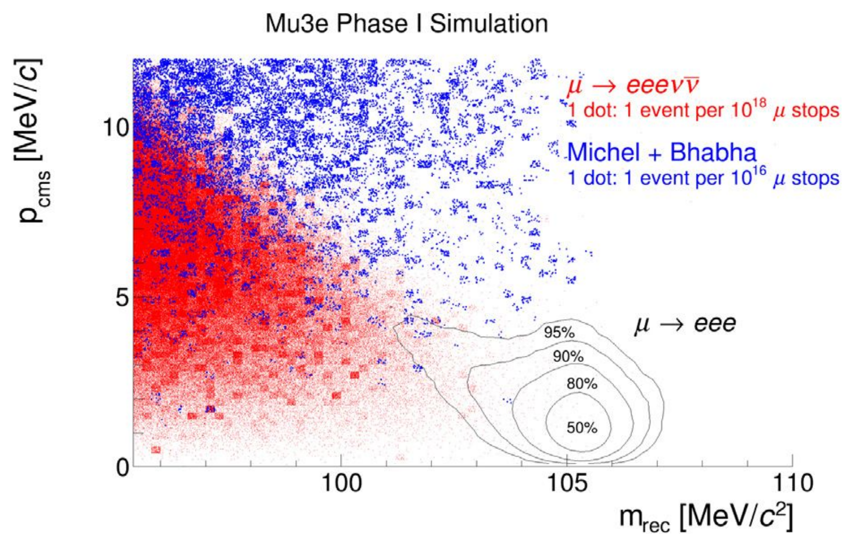
Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Technical design of the phase I Mu3e experiment

K. Arndt[a,1], H. Augustin[b], P. Baesso[c], N. Berger[d], F. Berg[e], C. Betancourt[f], D. Bortoletto[a], A. Bravar[g], K. Briggl[g,2], D. vom Bruch[d,3], A. Buonaura[e], F. Cadoux[g], C. Chavez Barajas[h],

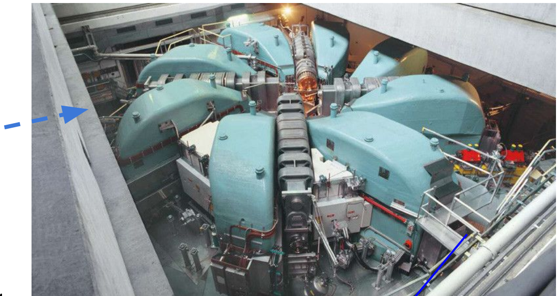




Building Mu3e

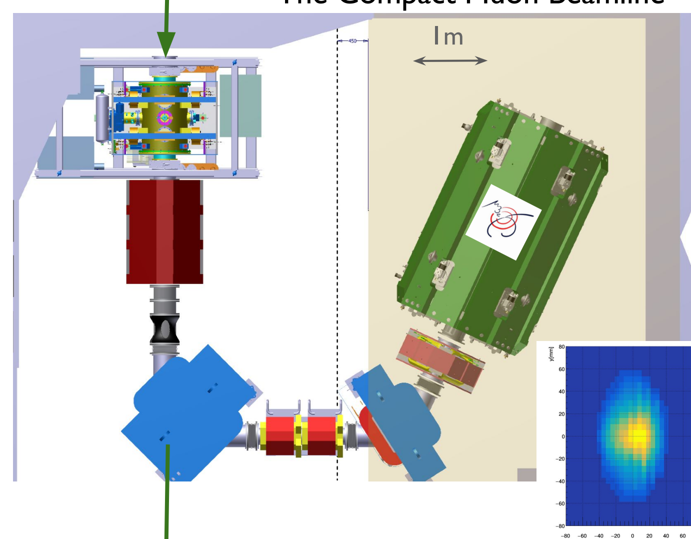
First we need muons, a beamline and a magnet ✓

590 MeV c.w. proton beam with currents of up to 2.4 mA, i.e. 1.4 MW beam power.



Target E

The Compact Muon Beamline



Towards MEGII @ PIE5

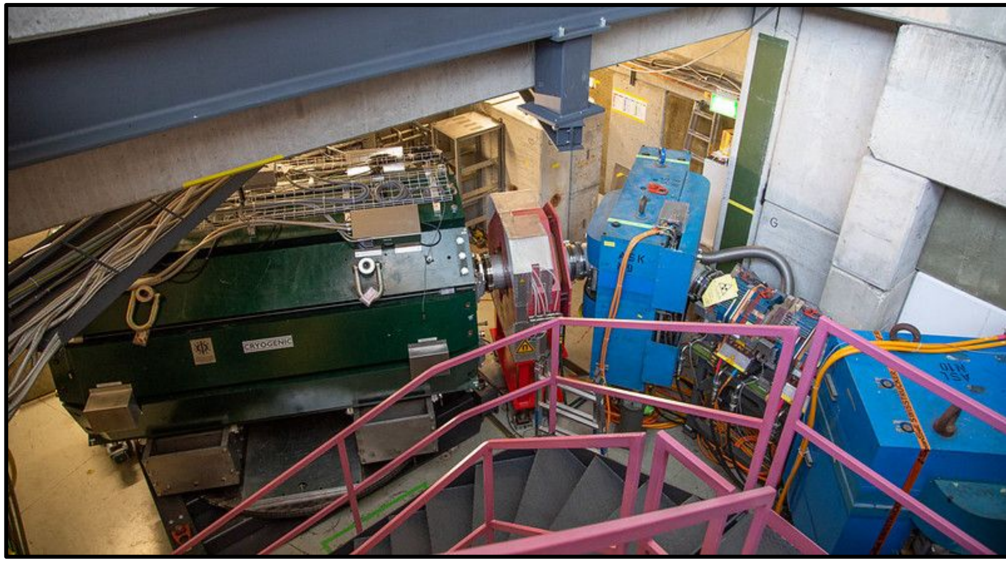
Beam Commissioning Comparison			
Rates	Collimator	QSM41	Mu3e
2021	$2.11\ 10^8\ \mu^+/s$	$1.2\ 10^8\ \mu^+/s$	$4.76\ 10^7\ \mu^+/s$
2022	$2.47\ 10^8\ \mu^+/s$	$1.8\ 10^8\ \mu^+/s$	$7.46\ 10^7\ \mu^+/s$

Table: All rates are normalised to 2.4 mA.

- ❑ 2.3 mA 600 MeV proton beam from HIPA at PSI
- ❑ 10^8 μ^+/s (DC) at the πE5 area
- ❑ Stopped on a thin Mylar target

Building Mu3e

First we need muons, a beamline and a magnet ✓



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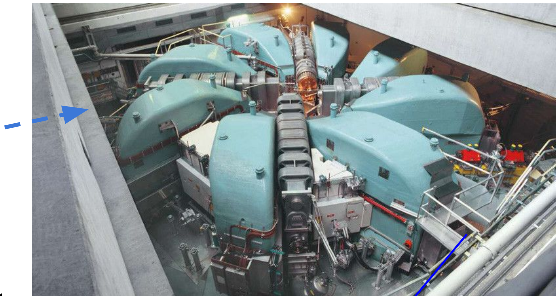
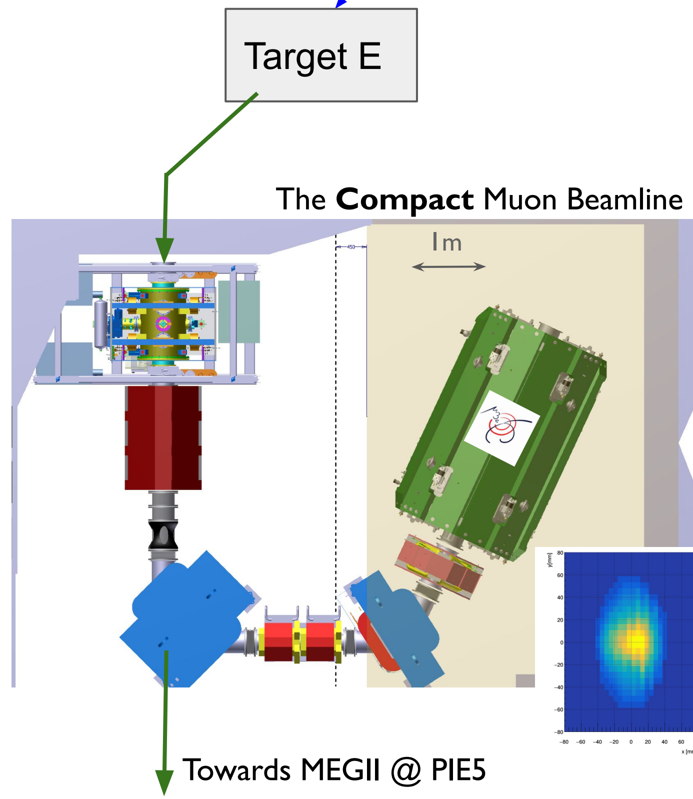


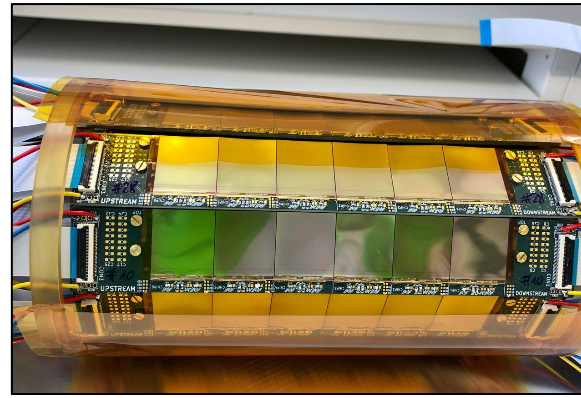


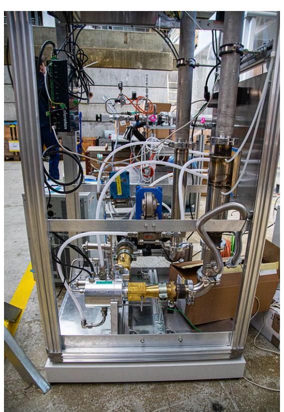
Building Mu3e

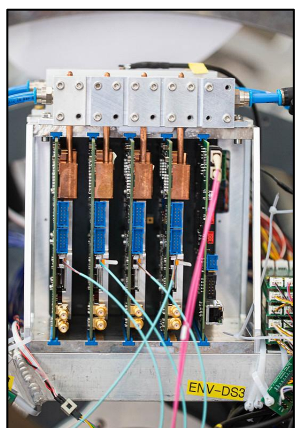
<u>Vertex, Scintillating Fibre & Tile detector under construction</u> …

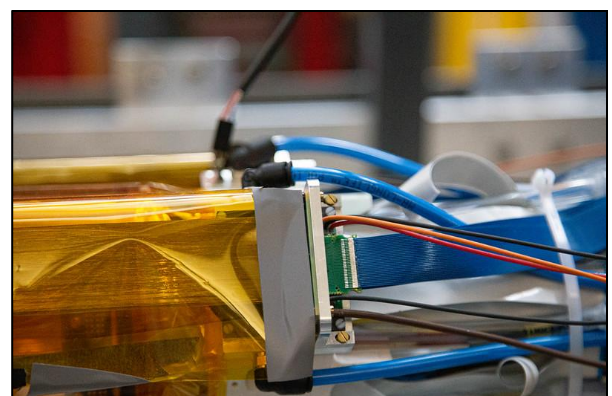
… but first a demonstrator/prototype

- ❏ Vertex detector module with MuPIX10 chips
- ❏ SciFi Module
- ❏ Crate with Front-End Boards
- ❏ Detector Cage
- ❏ 2g/s Helium cooling
- ❏ …









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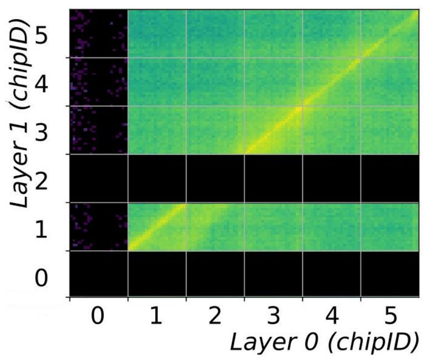
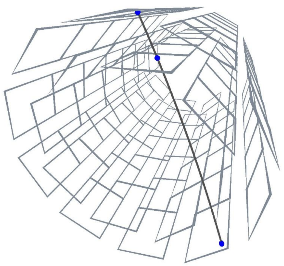
- ❏ …

A lot of operational experience

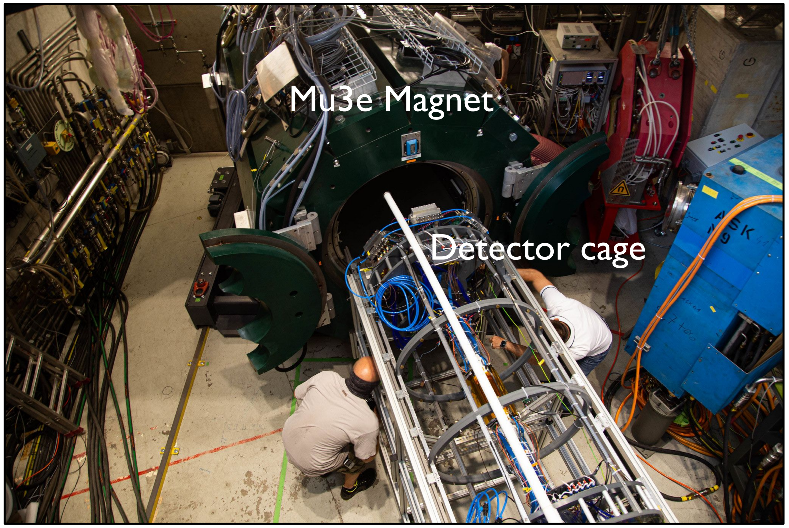
Spatial correlations of recurling e+



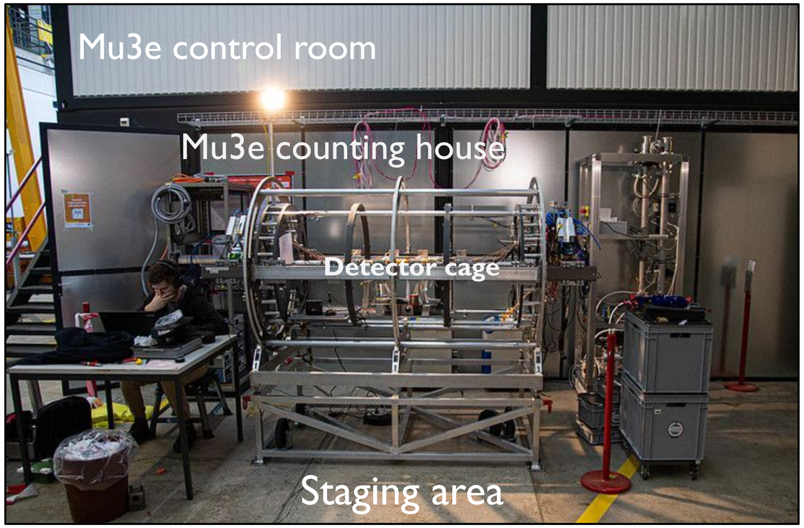
Cosmic tracks



Beam in 2021



Cosmics in 2022



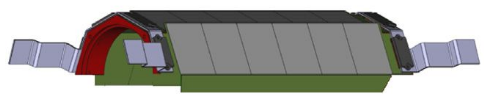
Mu3e Integration Run 2021 arXiv:2203.07855

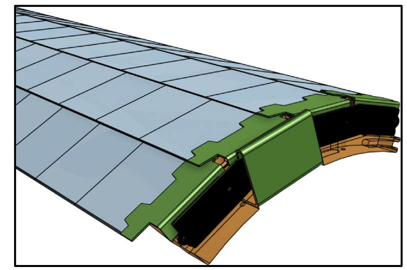
Building Mu3e

Vertex, Scintillating Fibre & Tile detector under construction …

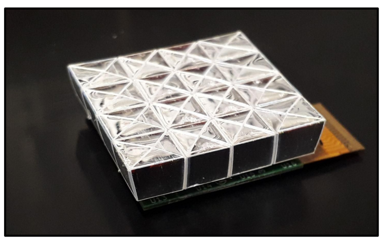
Now producing
- ❏ Vertex pixel ladders
- ❏ SiPM arrays and readout board
- ❏ Tile Matrix and readout board

MuPix chip →(+ Flex) Ladder →(+ support & connections) Module →(Integrate) Detector

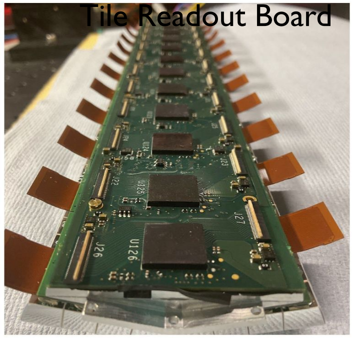




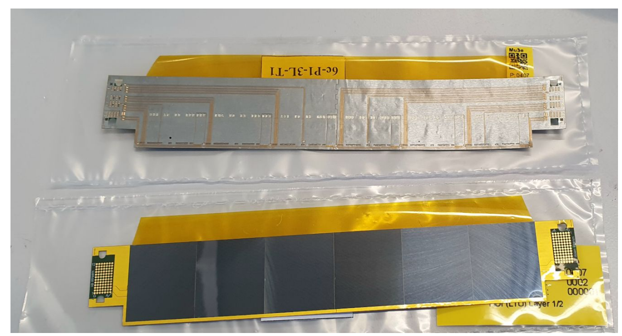
Tile Matrix

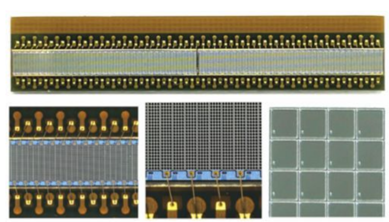


Tile Readout Board

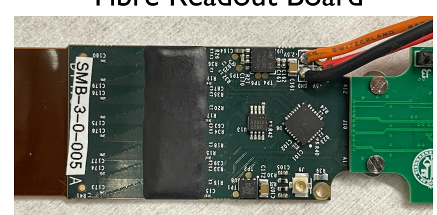


Vertex detector ladder (last week)





Fibre Readout Board



Building Mu3e

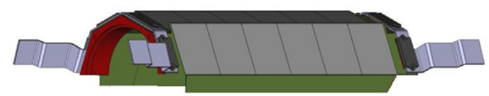
Vertex, Scintillating Fibre & Tile detector under construction …

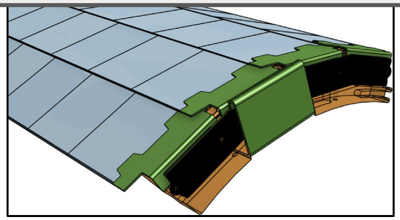
+ Flex

+ support

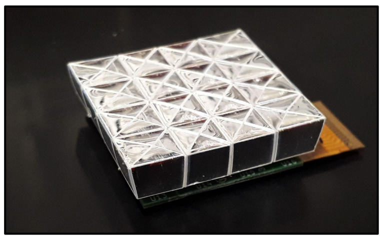
Detector installation at PSI later this year

- ❑ Tile Matrix and readout board





Tile Matrix



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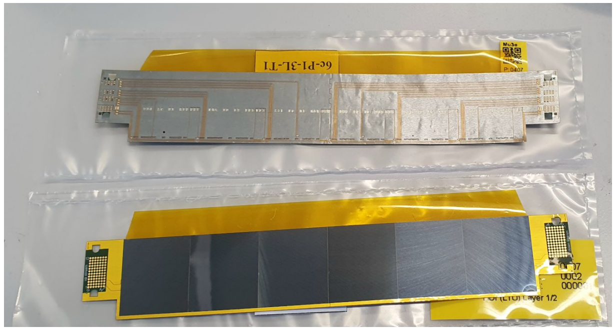
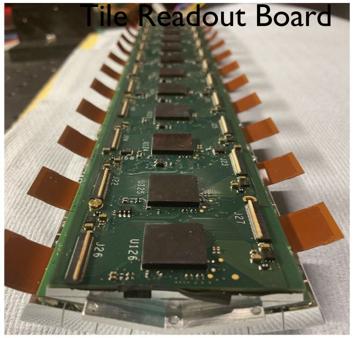
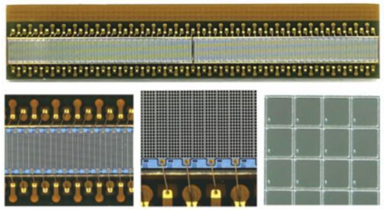
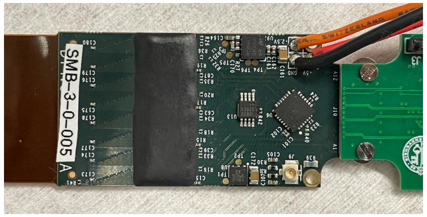


Tile Readout Board





Fibre Readout Board



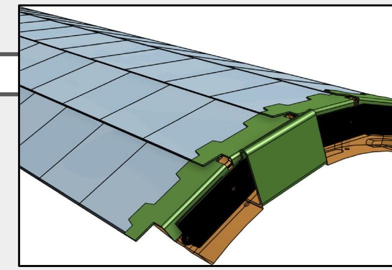
Building Mu3e

Vertex, Scintillating Fibre & Tile detector under construction …

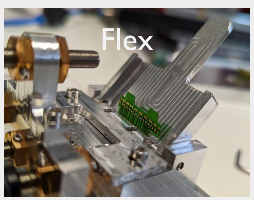
+ support

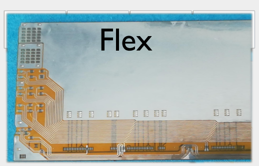
Detector installation at PSI later this year

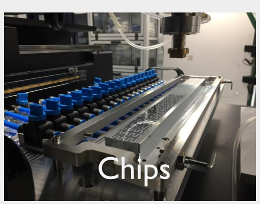
❑ Tile Matrix and readout board

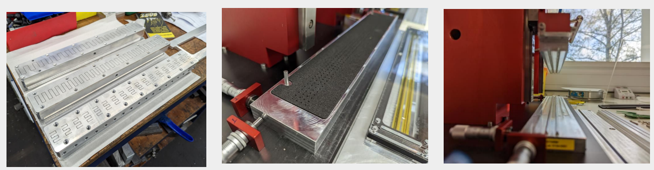


Outer pixel detector will follow soon

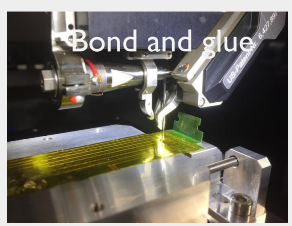


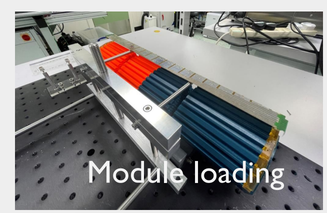


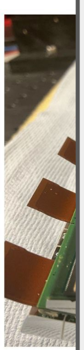




Unique set of tooling to construct 18 MuPix chip long *ladders* , Oxford University



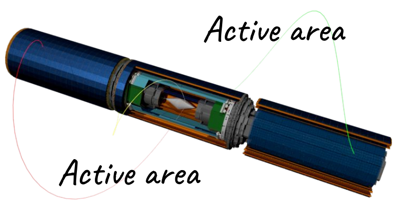


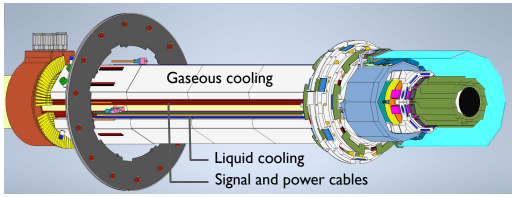


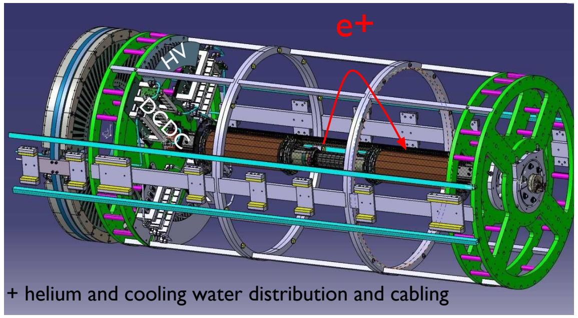
Install Central pixel tracker in 2024

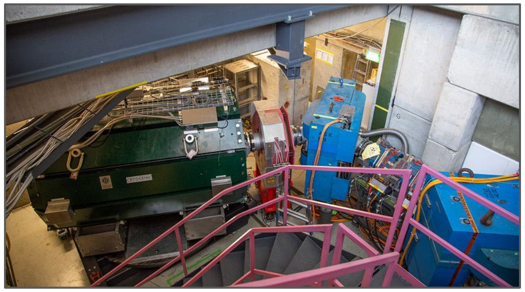
Building Mu3e

Zone outside of the tracker is active detector area
→ All services run along the beam pipe



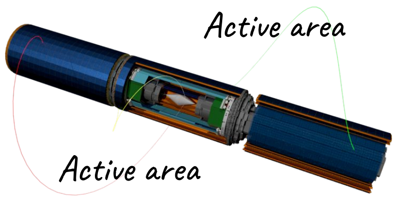


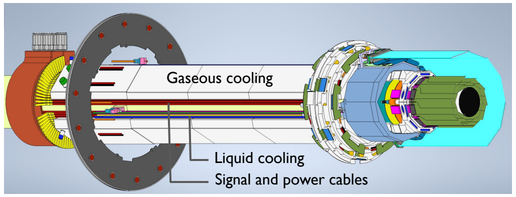


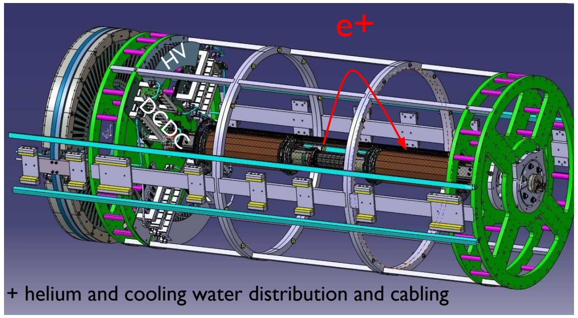


Building Mu3e

Zone outside of the tracker is active detector area
→ All services run along the beam pipe

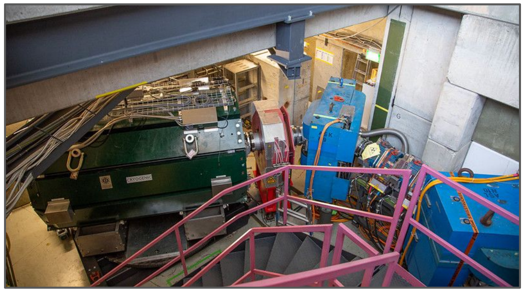




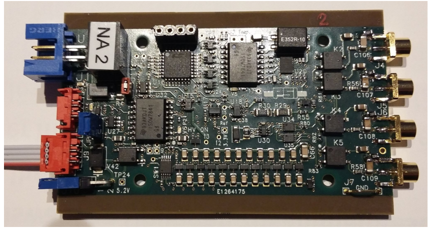


Mu3e detector services

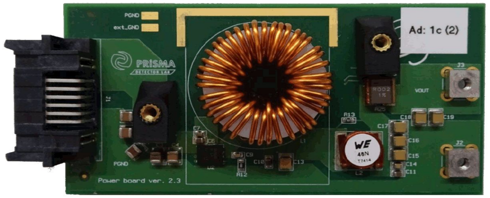
- Micro-twisted pair cable for each ASIC (LVDS)
- HV & LV channel for each detector module
- -15 °C liquid cooling for the MuTRIG ASIC and SiPMs
- Up to 5kW power to and from Frontend Boards and DC-DC
- Up to 5kW from and to the pixel detector



Custom HV

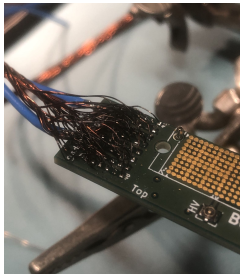


Custom DC-DC



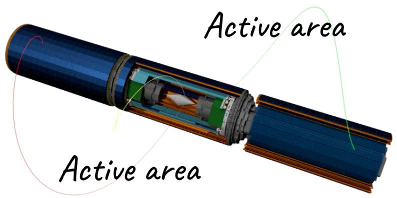
Chillers

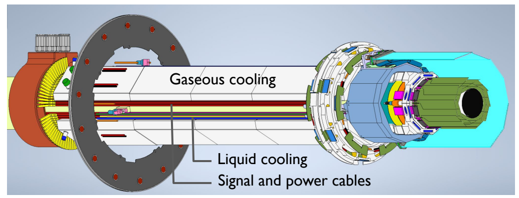
And a lot of cables

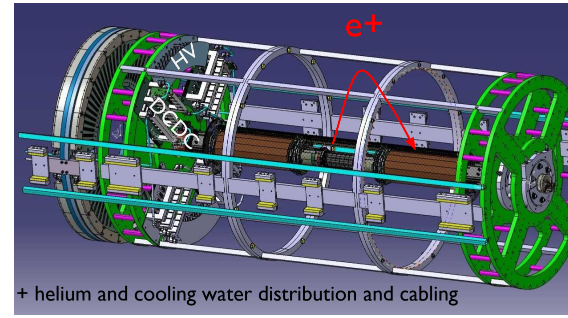


Building Mu3e

Zone outside of the tracker is active detector area
⟶ All services run along the beam pipe

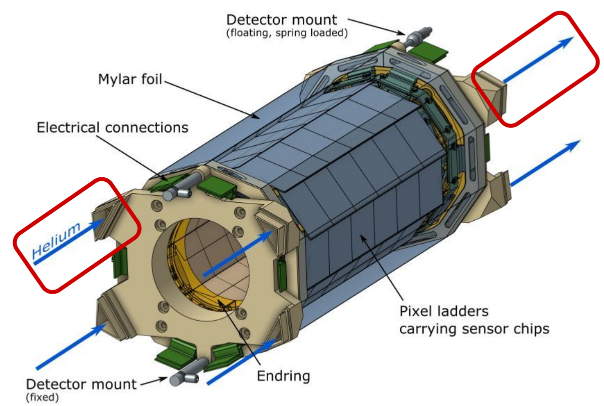


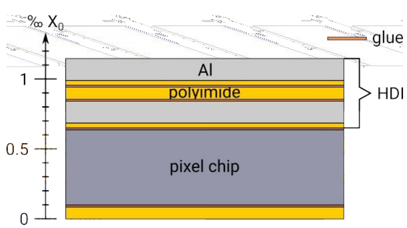




<u>Mu3e detector services</u>

- ❑ Micro-twisted pair cable for each ASIC (LVDS)
- ❑ HV & LV channel for each detector module
- ❑ -15 °C liquid cooling for the MuTRIG ASIC and SiPMs
- ❑ Up to 5kW power to and from Frontend Boards and DC-DC
- ❑ **Up to 5kW from and to the pixel detector**
  - ❑ 200-400 mW/cm^2
  - ❑ No pipes, no liquids, …
  - ❑ Helium has almost the same volumetric heat capacity as air!
    - 50 g/s gaseous helium cooling system for the Mu3e pixel detector



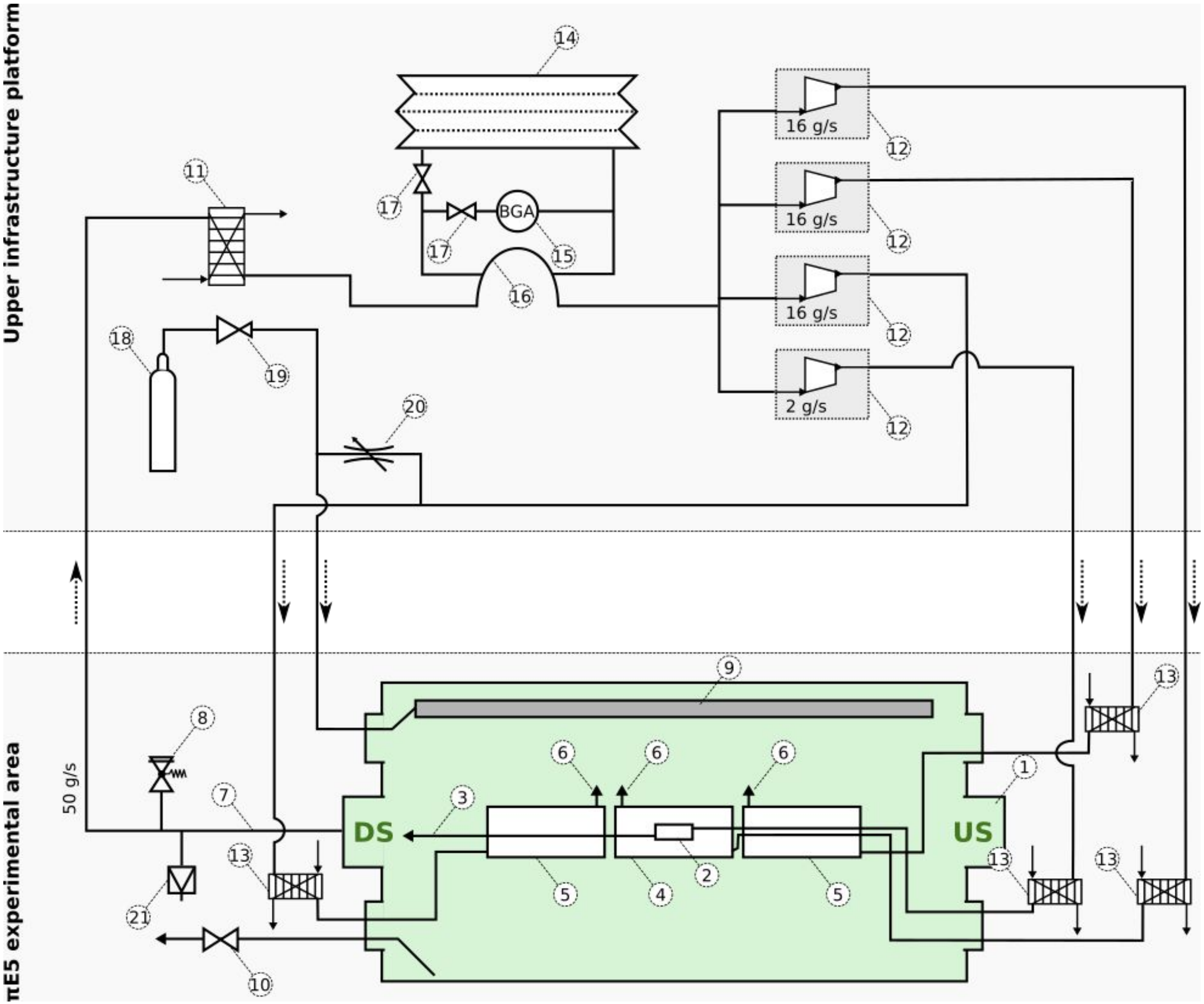


Compact turbo compressors with gas bearing for the circulation and compression of Helium.

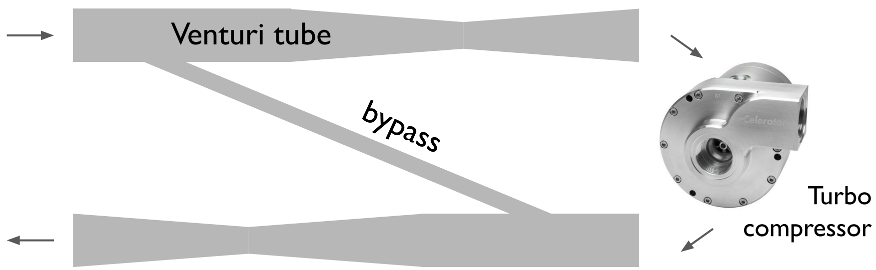
- ❑ High throughput
- ❑ Low compression ratio

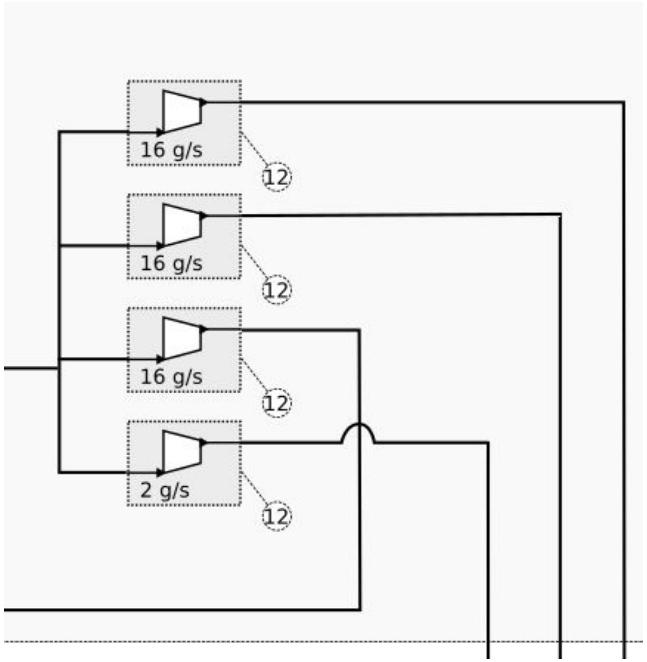
Entire System optimized for low pressure drops

Mu3e Cooling system

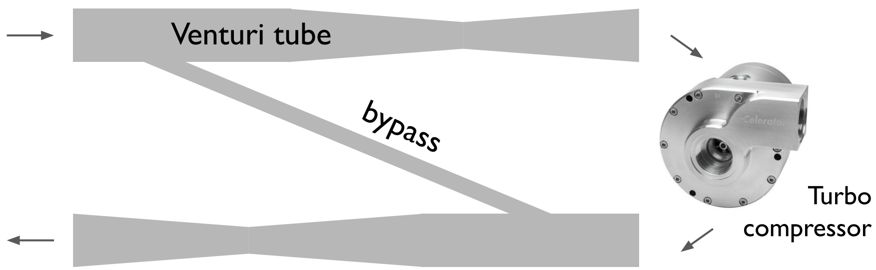


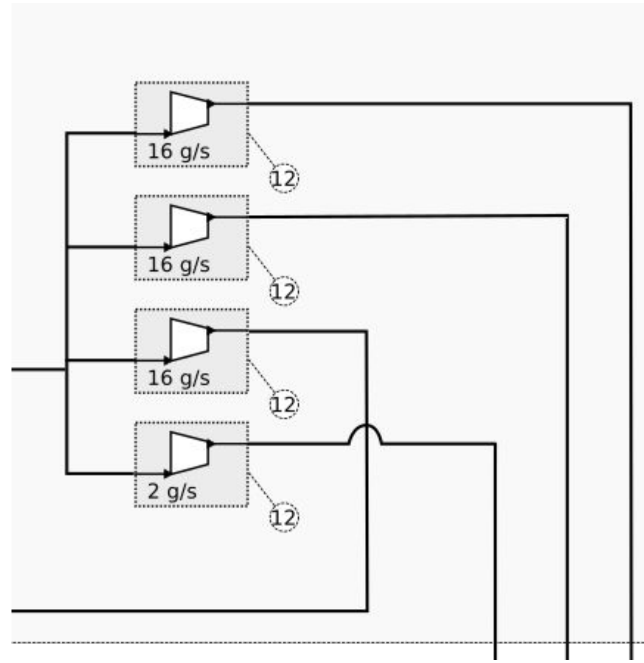
Mu3e Cooling system



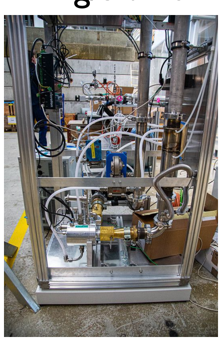


Mu3e Cooling system



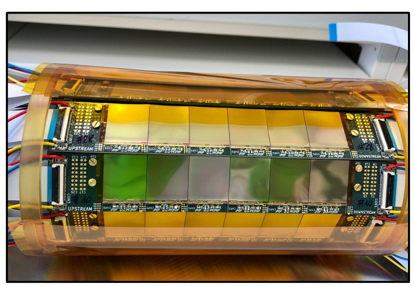


2g/s unit



+

Vertex detector



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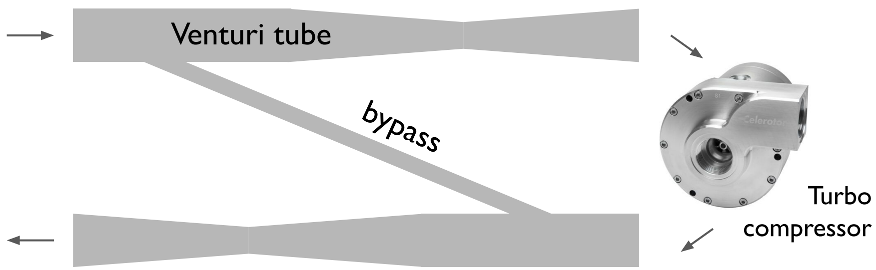
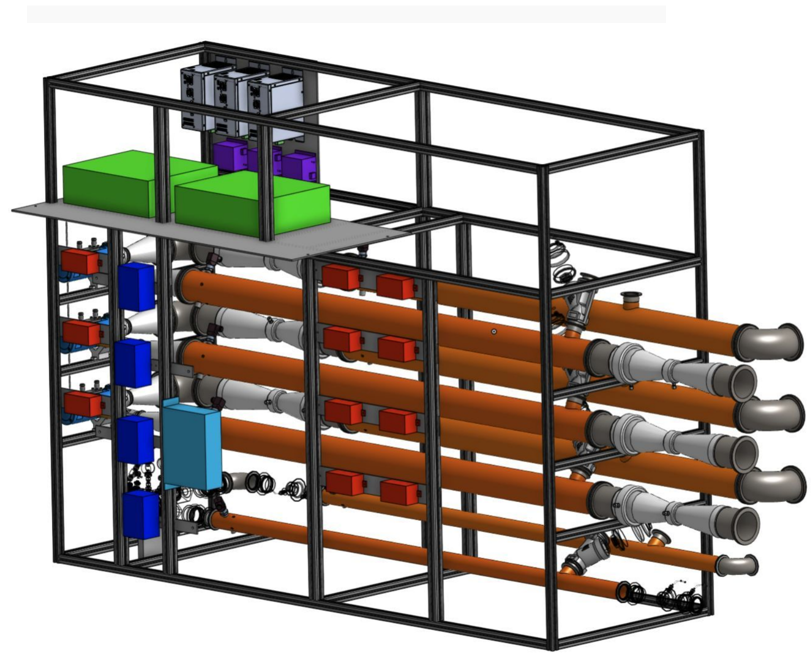
Successful cooling of a pixel tracker using gaseous helium
arXiv:2301.13813

Mu3e Cooling system





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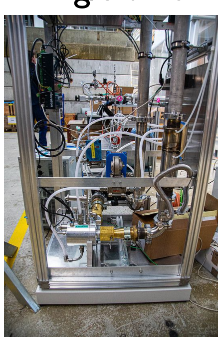
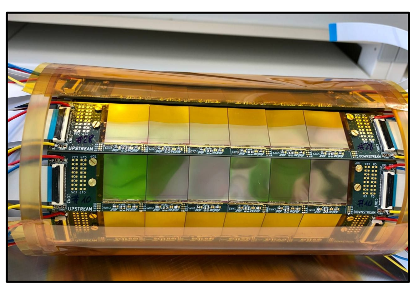


+

Vertex detector



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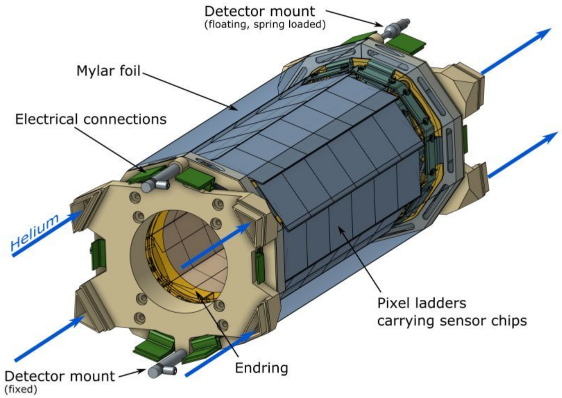
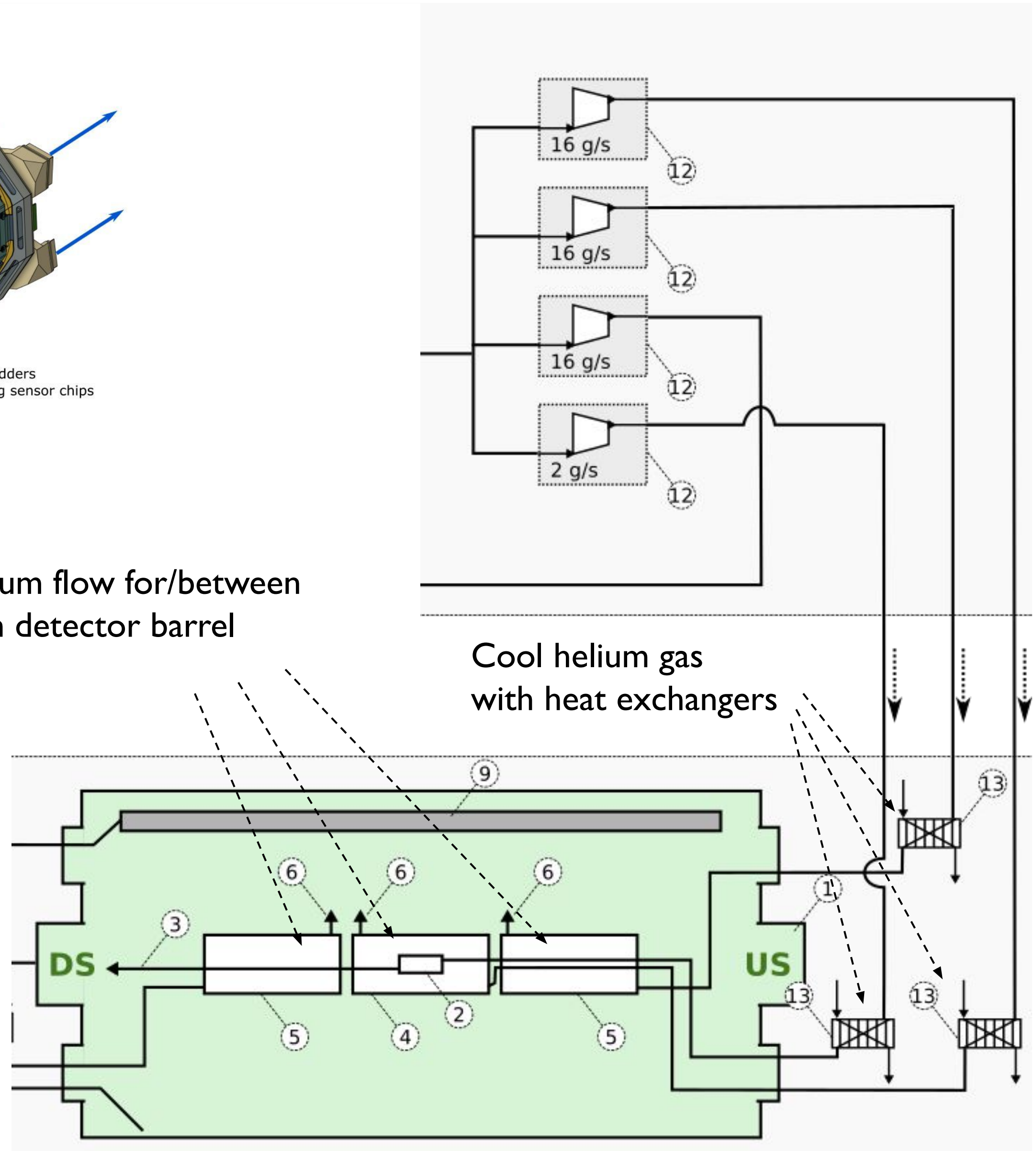
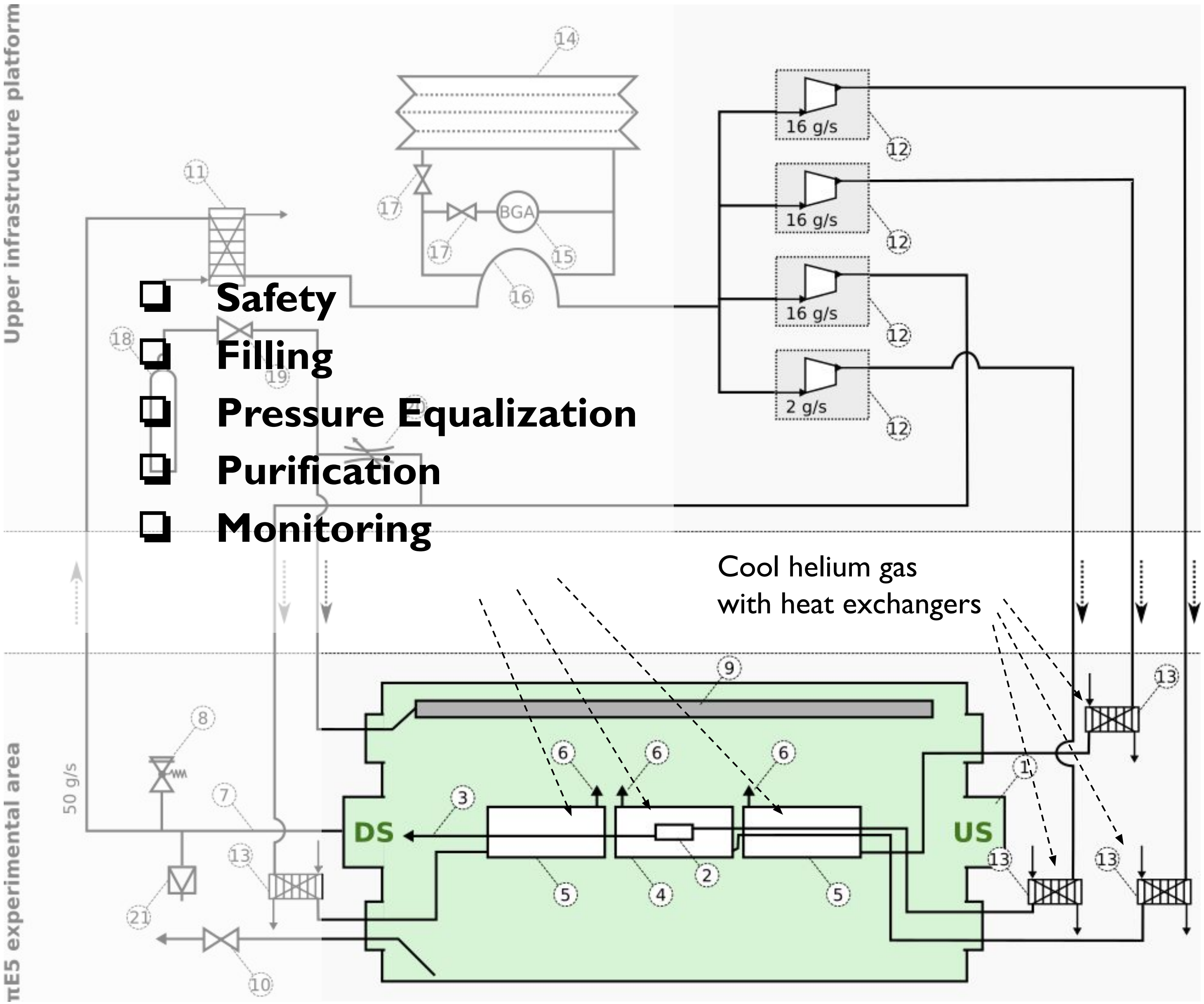


Helium flow for/between each detector barrel

Cool helium gas with heat exchangers



Mu3e Cooling system

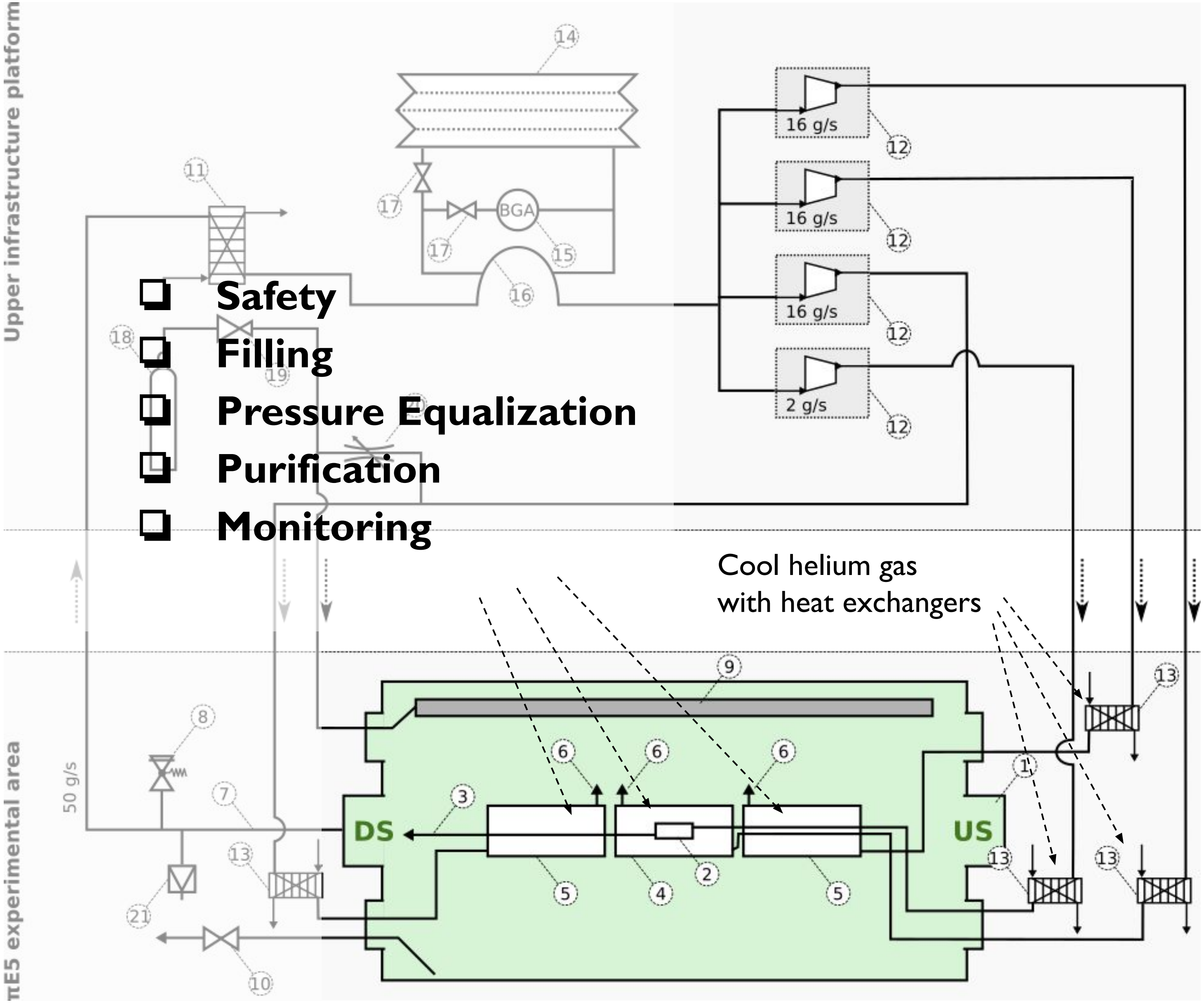


- Safety
- Filling
- Pressure Equalization
- Purification
- Monitoring

Cool helium gas
with heat exchangers

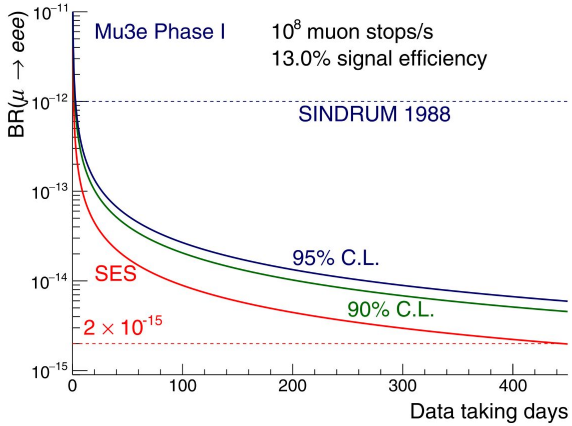
Mu3e Cooling system

- Safety
- Filling
- Pressure Equalization
- Purification
- Monitoring

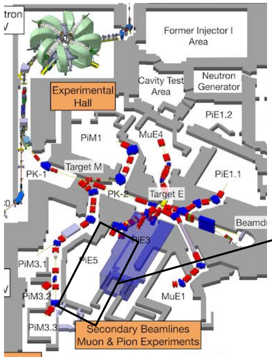


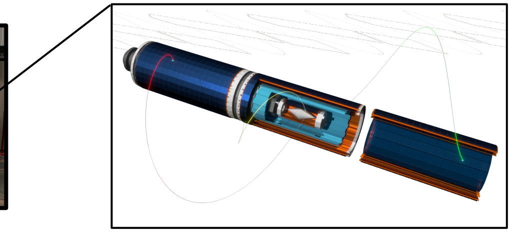
Mu3e phase I

- Run at the πE5 CMBL
- Reach 2 x 10^{-15} S.E.S in 400 days
- First detector installation in 2023
- Infrastructure installation in next 1.5 years
- Commissioning in 2024-2025
- First physics data taking in 2025-2026



When you are at PSI, pay us a visit!





Technical design of the phase I Mu3e experiment: arXiv:2009.11690

Mu3e phase I

- Run at the πE5 CMBL
- Reach 2 x 10^{-15} S.E.S in 400 days
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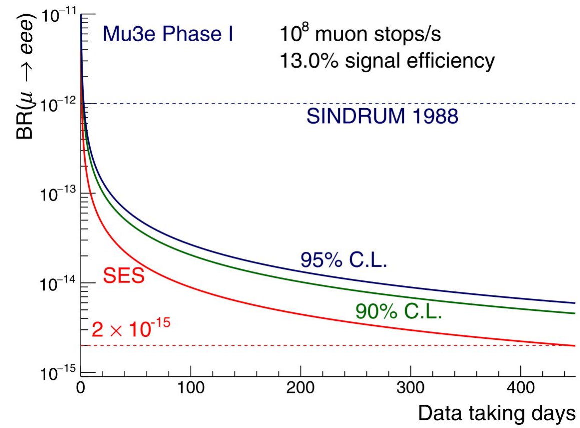


MuPix11 - The Mu3e Pixel Track Chip

Not scheduled
20m
Conference 1-3 (Heidelberg University, Physics Institute)

Speaker

David Maximilian Immig (Physikalisches Insti...

The Mu3e pixel detector

Not scheduled
20m
Conference 1-3 (Heidelberg University, Physics Institute)

Speaker

Thomas Theodor Rudzki (Physikalisches Insti...

The Camera Alignment System for the Mu3e Experiment

Not scheduled
20m
Conference 1-3 (Heidelberg University, Physics Institute)

Speaker

Sophie Gagneur (Johannes Gutenber...

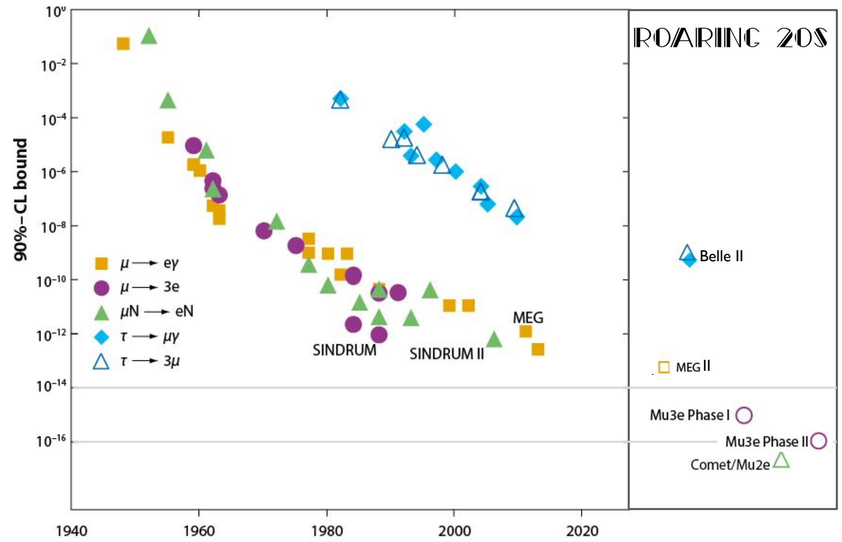
Mu3e phase II

Mu3e Phase I experiment:

- ❑ Run at the πE5 CMBL
- ❑ Reach 2 x 10^{-15} S.E.S in 400 days

Phase I, so there is a phase II?

- ❑ Reach 10^{-16} S.E.S. on $\mu^+ \rightarrow e^+e^+e^-$
- ❑ Can not run at the existing beamline,
  Need 10^9 μ^+/s on target
  ➜ HIMB



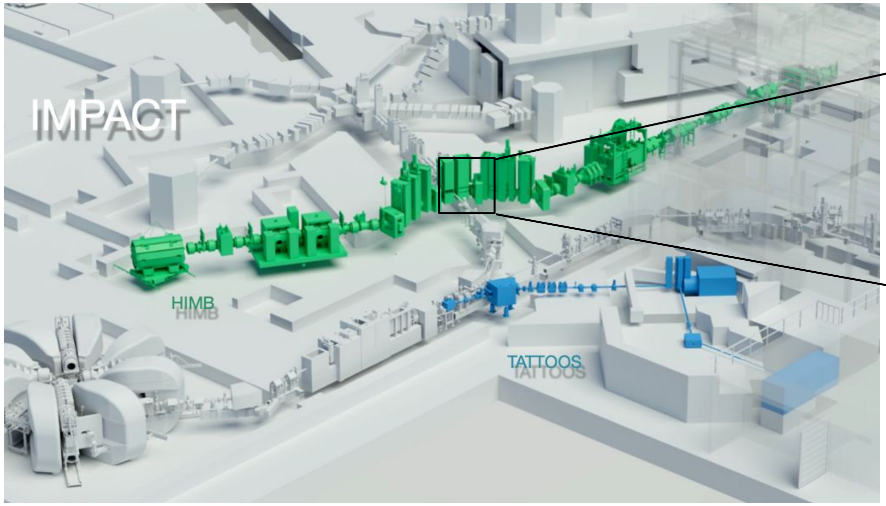
Mu3e one of the main physics cases for this next generation facility.

Science Case for the new High-Intensity Muon Beams HIMB at PSI

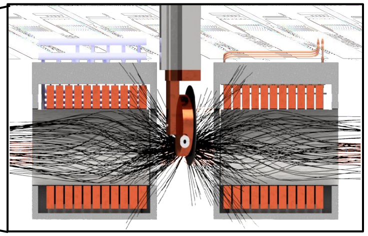
Edited by A. Knecht, F. Meier Aeschbacher, T. Prokscha, S. Ritt, A. Signer

arXiv:2111.05788

+ https://www.psi.ch/en/impact
+ Thursday afternoon at this conference



Repace target M with
a capture solenoid configuration



Mu3e phase II

Mu3e Phase I experiment:

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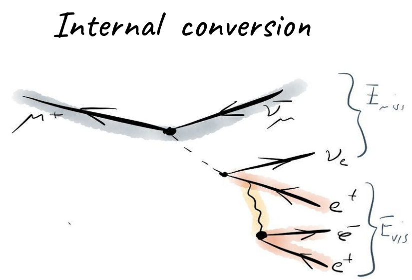
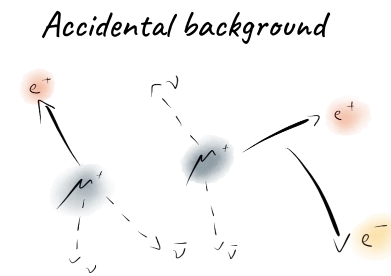
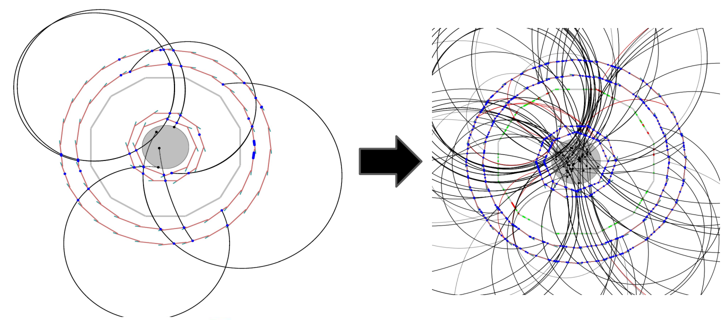
  Need 10^9 μ^+/s on target
  ➜ HIMB

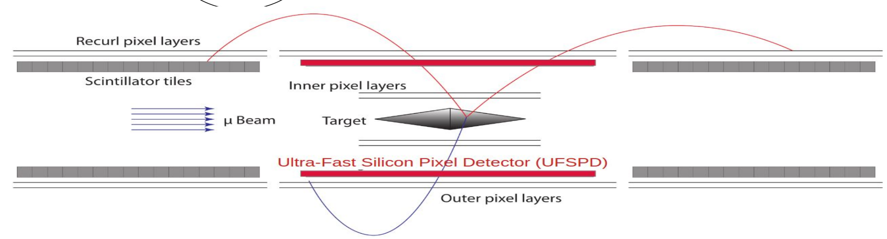
Mu3e Phase II Challenges:

- ❑ Internal conversion goes with #muons
  ⟶ Thinner (total material budget) ~~Fibre Detector~~
- ❑ Accidental goes with #muons^2
  ⟶ Faster (silicon sensors)
  ⟶ Smaller (silicon pixels)
  ⟶ Larger (target)
- ❑ As does the combinatorics of track finding
  ⟶ Smarter (online filtering)
- ❑ Large phase space of the beam









➡ Most of the Phase I detector needs a redesign
➡ We need new, fast the active pixel detector
- SiGe CMOS?

Mu3e phase II

Mu3e Phase I experiment:
- ❑ Run at the πE5 CMBL
- ❑ Reach 2×10^{-15} S.E.S in 400 days

Phase I, so there is a phase II?
- ❑ Reach 10^{-16} S.E.S. on $\mu^+ \rightarrow e^+e^+e^-$
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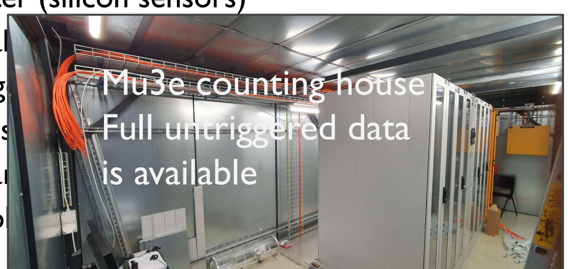
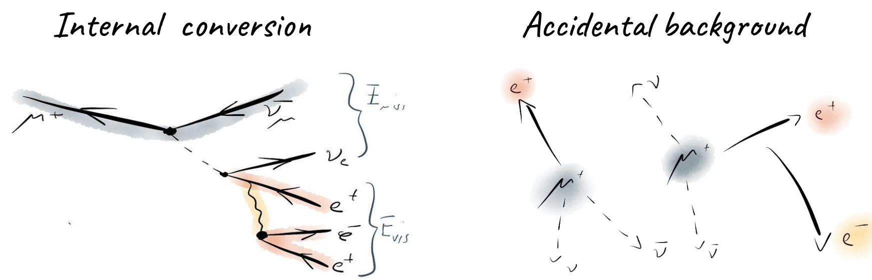
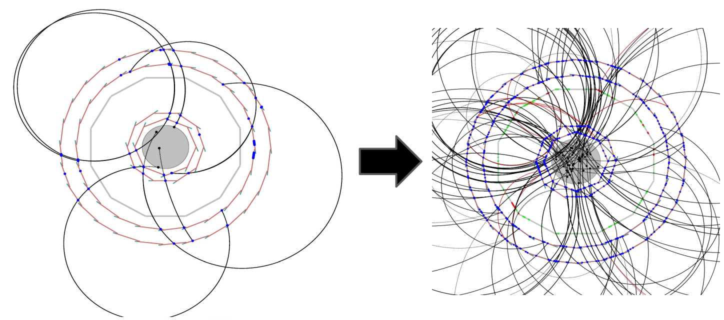
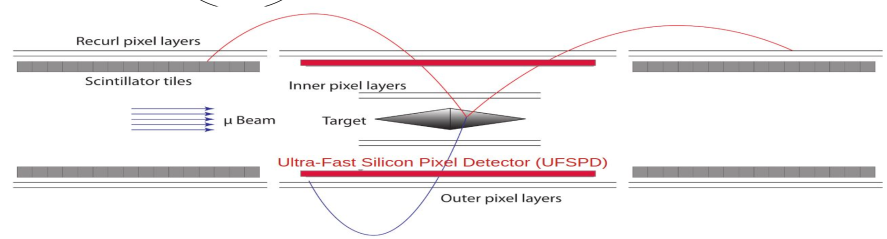
  Need 10^9 μ^+/s on target
  ➜ HIMB

Mu3e Phase II Challenges:
- ❑ Internal conversion goes with #muons
  → Thinner (total material budget) ~~Fibre Detector~~
- ❑ Accidental goes with #muons^2
  → Faster (silicon sensors)
  → Smal
  → Larg
- ❑ As does
  → Smal
- ❑ Large p









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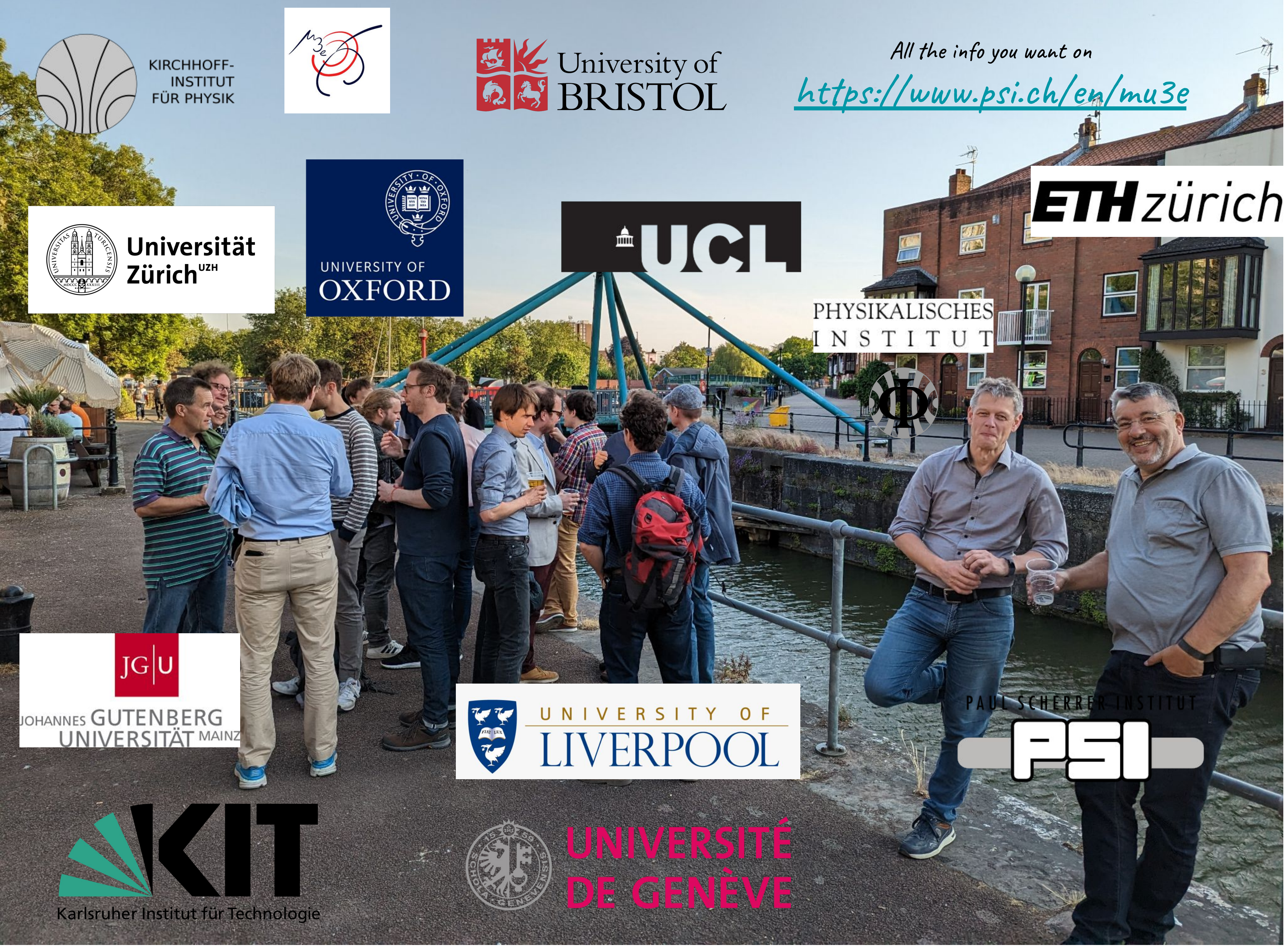
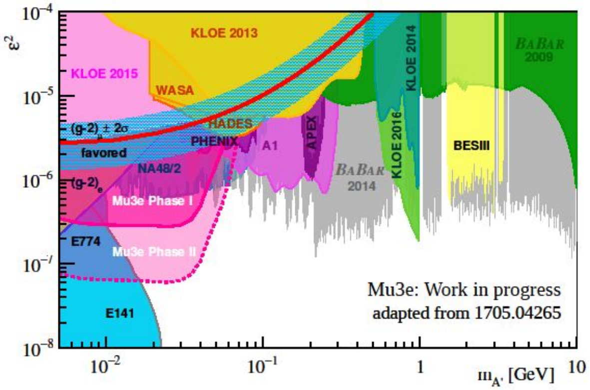
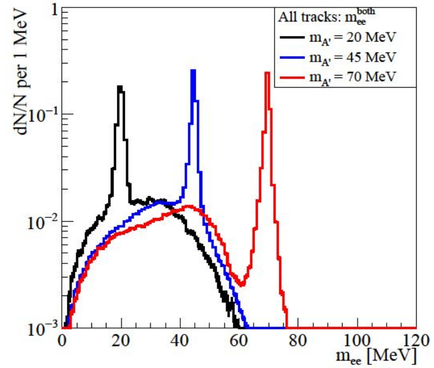
➡ We need new, fast the active pixel detector

Mu3e beyond $\mu^+ \rightarrow e^+e^+e^-$
- ↗ $\mu^+ \rightarrow e^+\gamma \rightarrow e^+e^+e^-$ with γ-conversion layer
- ↘ $\mu^+ \rightarrow e^+$ + exotic particle
  Snowmass paper

With Phase I&II detector


All the info you want on
https://www.psi.ch/en/mu3e
KIRCHHOFF-INSTITUT FÜR PHYSIK
University of BRISTOL
Universität Zürich UZH
UNIVERSITY OF OXFORD
UCL
ETH zürich
PHYSIKALISCHES INSTITUT
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
UNIVERSITY OF LIVERPOOL
PAUL SCHERRER INSTITUT
PSI
KIT
Karlsruher Institut für Technologie
UNIVERSITÉ DE GENÈVE



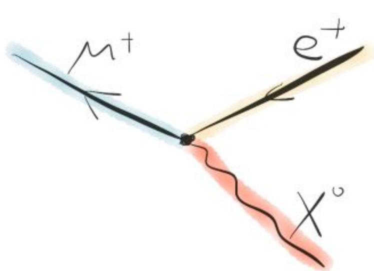


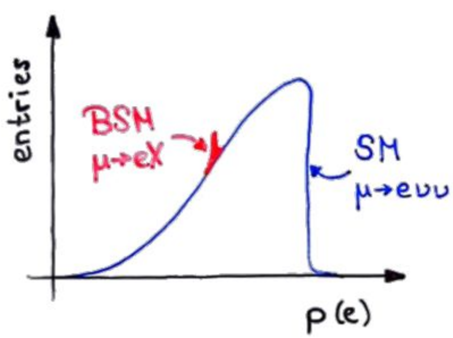
Other Exotic Physics with Mu3e

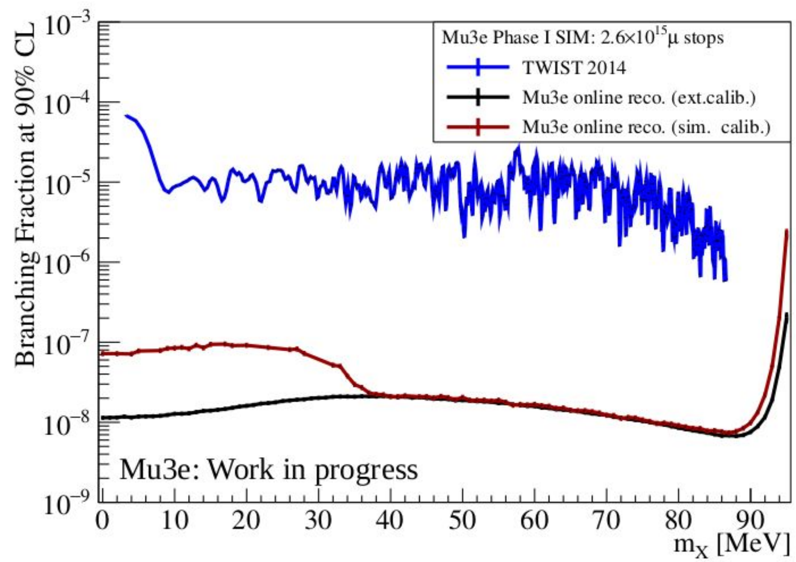
Familons

Slide A. PerreVoort

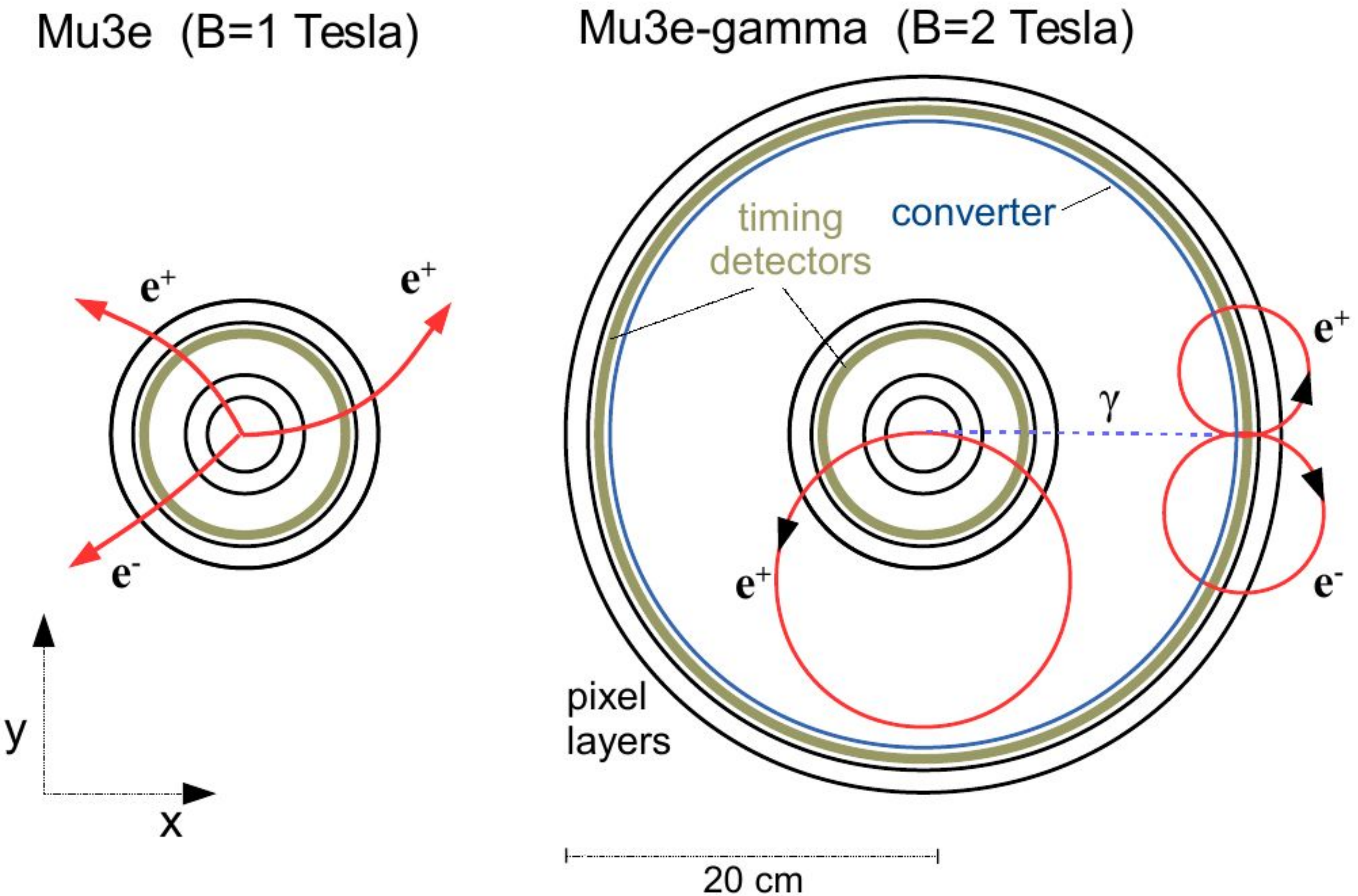
- Search for $\mu^+ \to e^+ X^0$ decays
- Ex: Familon
  (Goldstone boson from spontaneously broken flavour symmetry, Wilczek, PRL 49 (1982) 1549)



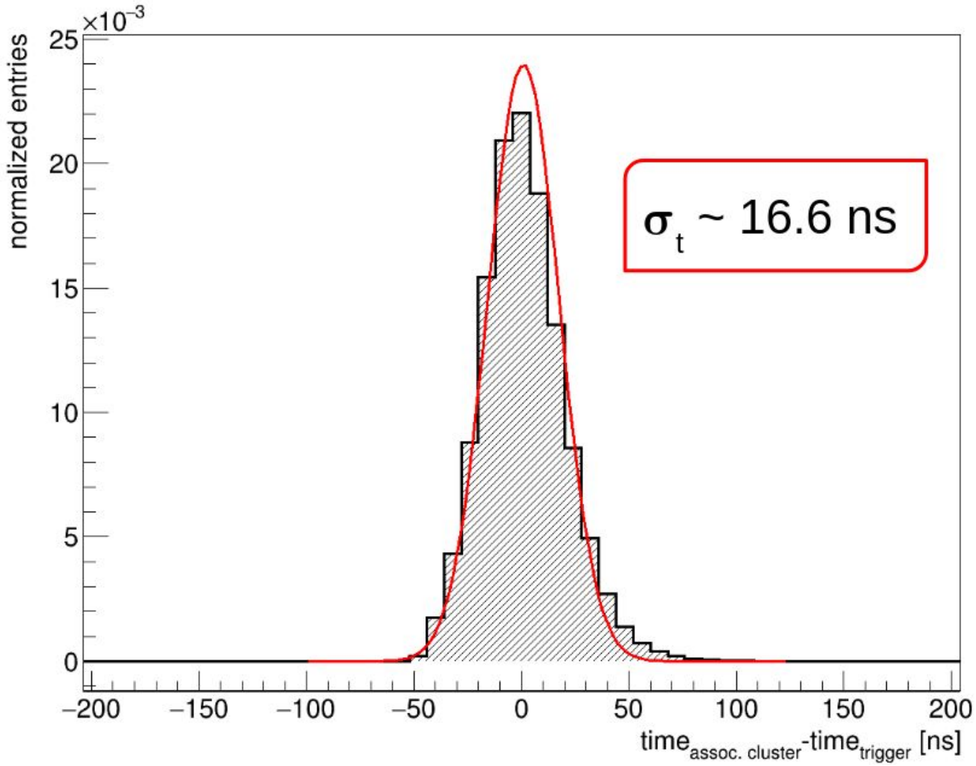




- Challenge: single-*e* events are not saved
- Histogramming on filter farm



Mu3e (B=1 Tesla)
Mu3e-gamma (B=2 Tesla)
timing
detectors
converter
e^+
e^+
e^-
e^+
e^+
e^-
γ
pixel
layers
y
x
20 cm



$\times 10^{-3}$
normalized entries
25
20
15
10
5
0
−200
−150
−100
−50
0
50
100
150
200
σ_t ~ 16.6 ns
$time_{assoc.\ cluster}$-$time_{trigger}$ [ns]

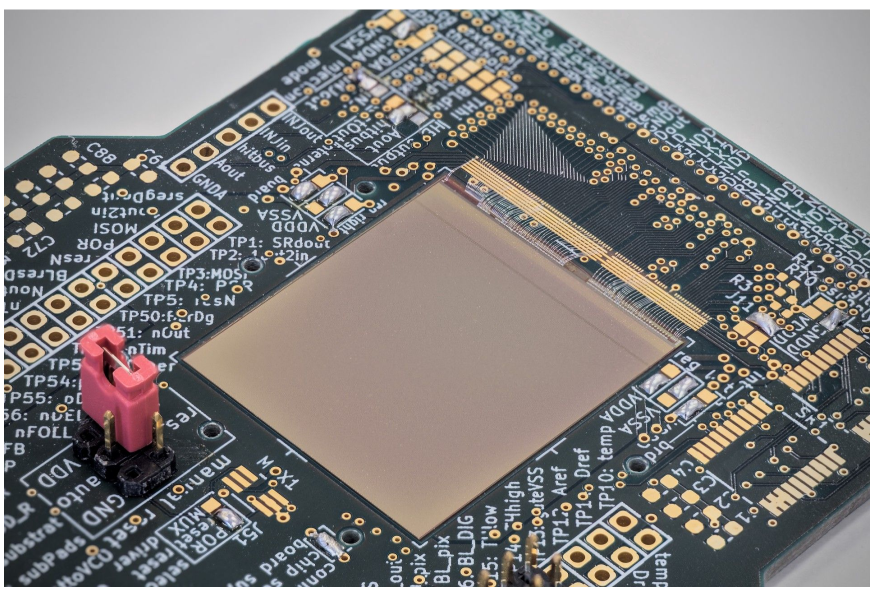


Table 22.1
Efficiency of the various reconstruction and analysis steps.

Step	Step efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	38.1%	38.1%
Geometrical acceptance, long tracks	68.0%	25.9%
Short track reconstruction	89.5%	34.1%
Long track reconstruction[a]	67.2%	17.4%
[illegible]	[illegible]	[illegible]

Parameter	Symbol	Air	Helium	Unit	Condition	Ref
Density	ρ	1.205	0.1663	kg/m^3	20 °C, 1013 mbar	**[pdg]**
Specific heat capacity	c_p	1.006	5.193	kJ/(kg K)	25 °C, 1 bar	**[CRCHandbookChemPhys]**
Volumetric heat capacity		1.212	0.864	kJ/(m^3 K)	25 °C, 1 bar	calc
Dynamic viscosity	η	18.2	18.6	µPa s		**[wikipediaVisko]**
Mean free path	λ	60	174	nm		**[wikipediaVisko]**
Speed of sound	c	331	981	m/s	0 °C, 1 bar	**[CRCHandbookChemPhys]**
Radiation length	X_0	36.6	94.3	g/cm^2		**[pdg]**
		304	5670	m	20 °C, 1013 mbar	calc

line).

Layer	1	2	3	4
number of modules	2	2	6	7
number of ladders	8	10	24	28
number of MuPix sensors per ladder	6	6	17	18
instrumented length [mm]	124.7	124.7	351.9	372.6
minimum radius [mm]	23.3	29.8	73.9	86.3

Parameter	Symbol	Air	Helium	Unit	Condition	Ref
Density	ρ	1.205	0.1663	kg/m^3	20 °C, 1013 mbar	[**pdg**]
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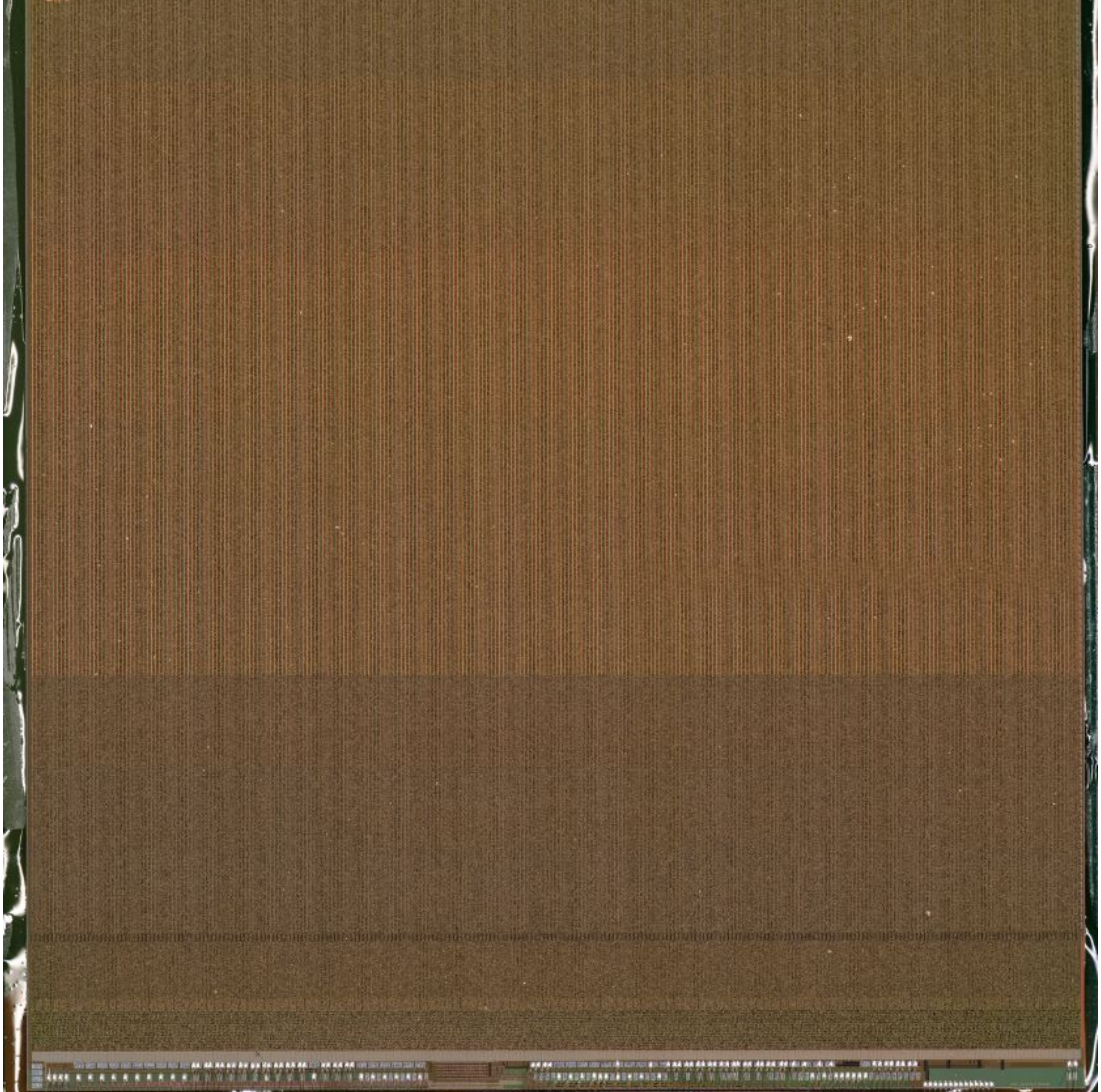
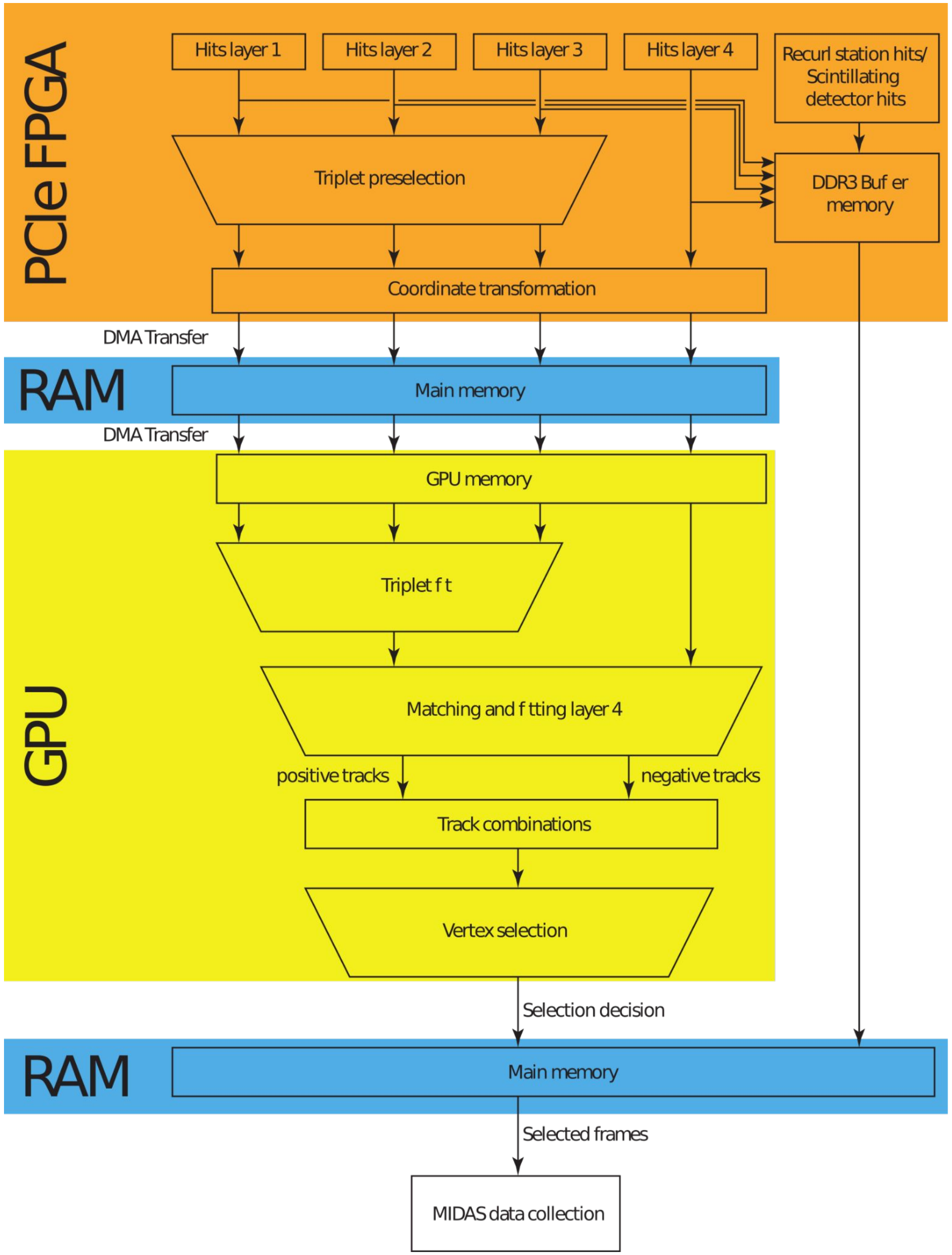
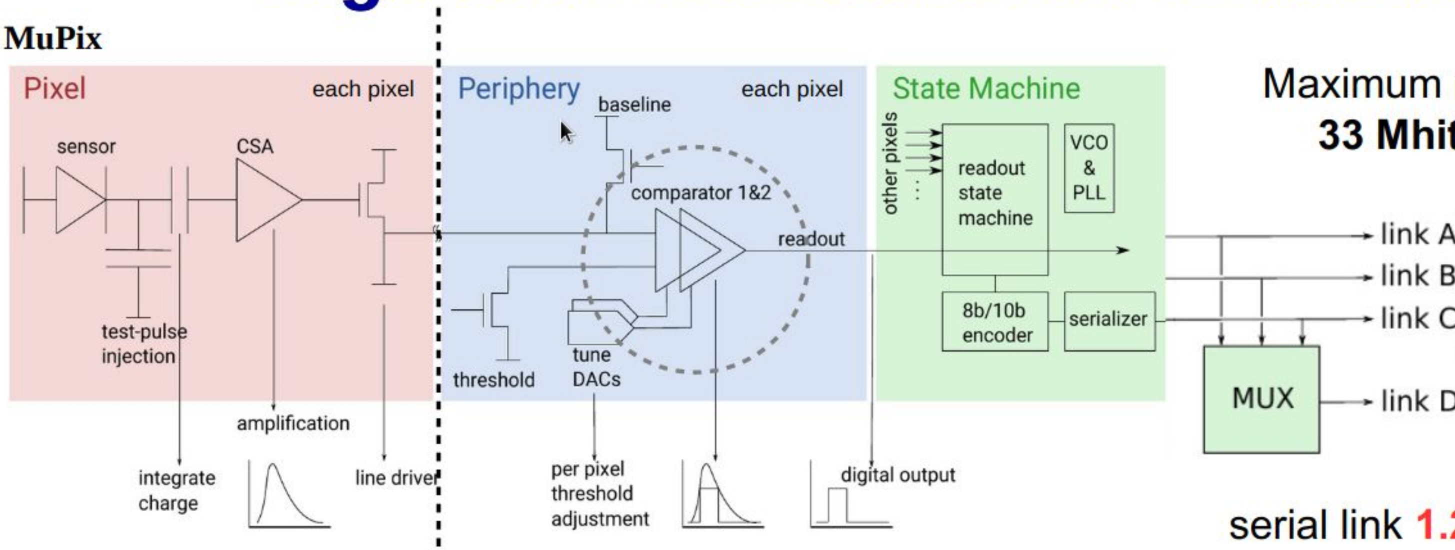



PCIe FPGA
Hits layer 1
Hits layer 2
Hits layer 3
Hits layer 4
Recurl station hits/ Scintillating detector hits
Triplet preselection
DDR3 Buf er memory
Coordinate transformation
DMA Transfer
RAM
Main memory
DMA Transfer
GPU
GPU memory
Triplet f t
Matching and f tting layer 4
positive tracks
negative tracks
Track combinations
Vertex selection
Selection decision
RAM
Main memory
Selected frames
MIDAS data collection


GTX 980

High Rate & Continuous Readout

MuPix



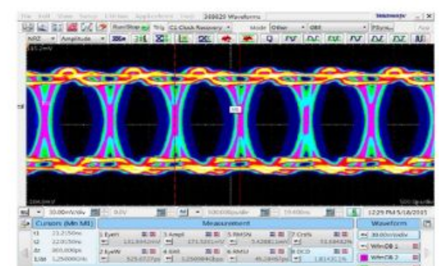
Maximum readout rate is **33 Mhits/s** per link

serial link **1.25 -1.6 Gbit/s**

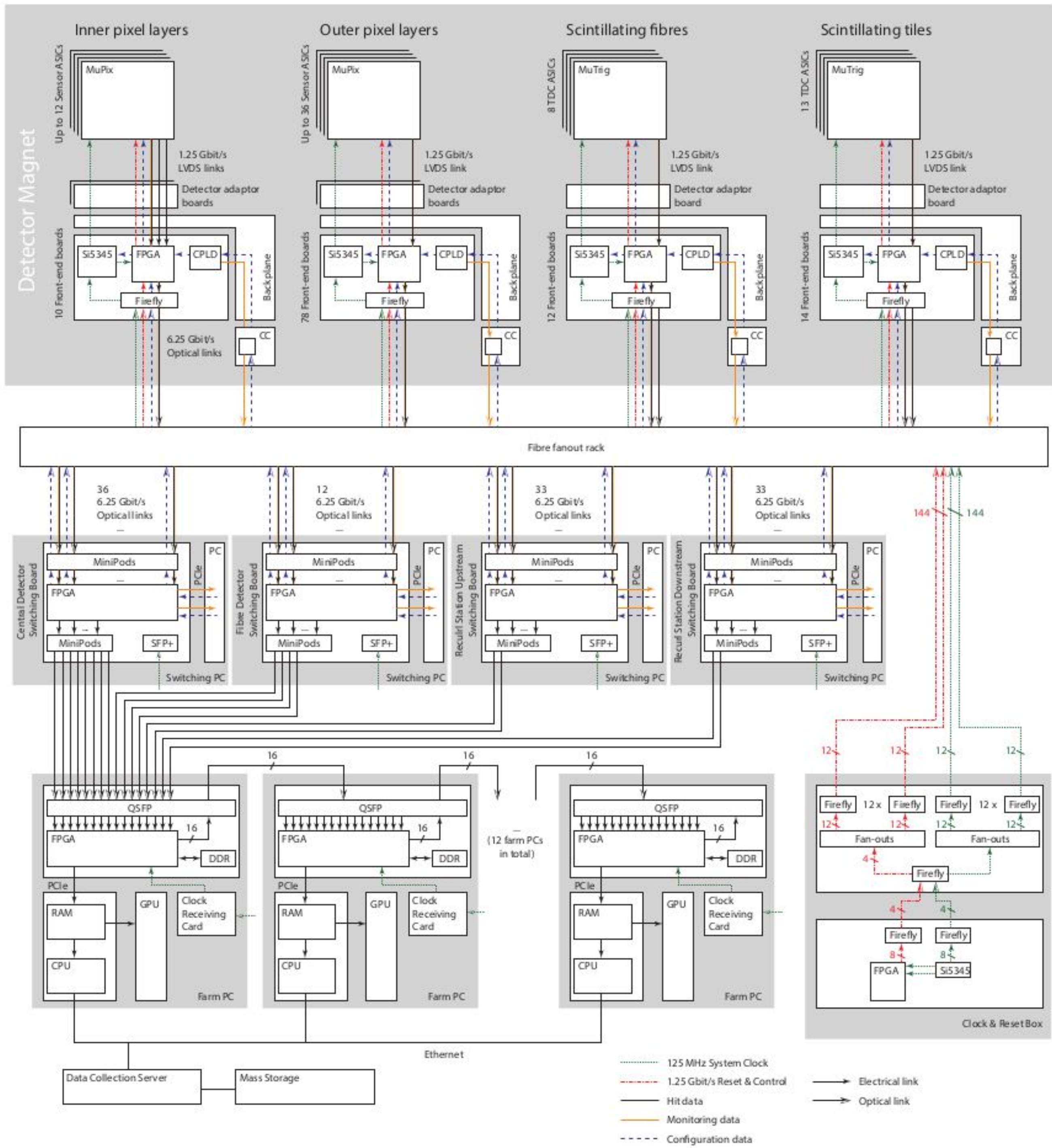
MuPix8 sensor

periphery & SM

eye diagram



MuPix series is the first monolithic pixel sensor with continuous sampling and readout!



Detector Magnet
Inner pixel layers
Outer pixel layers
Scintillating fibres
Scintillating tiles
Up to 12 Sensor ASICs
Up to 36 Sensor ASICs
8 TDC ASICs
13 TDC ASICs
MuPix
MuTrig
1.25 Gbit/s LVDS links
1.25 Gbit/s LVDS link
Detector adaptor boards
Detector adaptor board
10 Front-end boards
78 Front-end boards
12 Front-end boards
14 Front-end boards
Si5345
FPGA
CPLD
Firefly
Backplane
CC
6.25 Gbit/s Optical links
Fibre fanout rack
36 6.25 Gbit/s Optical links
12 6.25 Gbit/s Optical links
33 6.25 Gbit/s Optical links
144
MiniPods
PC
PCIe
SFP+
Central Detector Switching Board
Fibre Detector Switching Board
Recurl Station Upstream Switching Board
Recurl Station Downstream Switching Board
Switching PC
16
QSFP
DDR
RAM
GPU
CPU
Clock Receiving Card
Farm PC
(12 farm PCs in total)
12 x
Fan-outs
Clock & Reset Box
Ethernet
Data Collection Server
Mass Storage
125 MHz System Clock
1.25 Gbit/s Reset & Control
Hit data
Monitoring data
Configuration data
Electrical link
Optical link