The Mu3e experiment

Searching for the Charged Lepton Flavour Violating decay $\mu^+ \rightarrow e^+e^+e^-$

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

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

Why searching for Charged Lepton Flavour Violation?

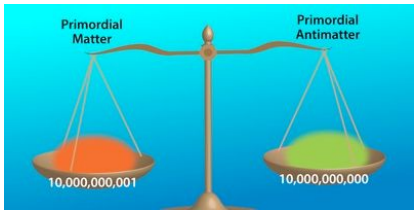
Not a fundamental Standard Model symmetry

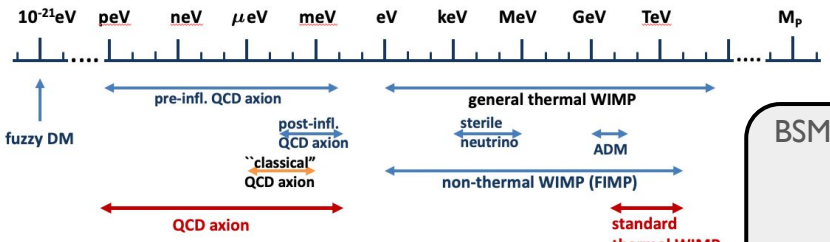
Lepton flavour
Baryon number
Lepton Number

⟷

Electric charge
Color charge
Lorentz invariance

→ *Outstanding (B)SM puzzles can be linked to CLFV*

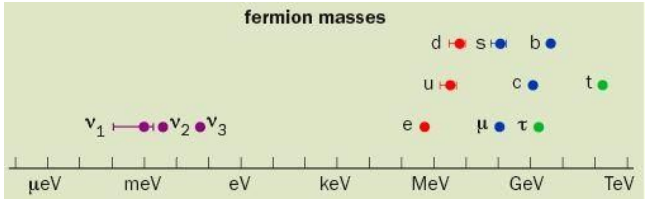




https://arxiv.org/abs/2104.07634

BSM models

CLFV models



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

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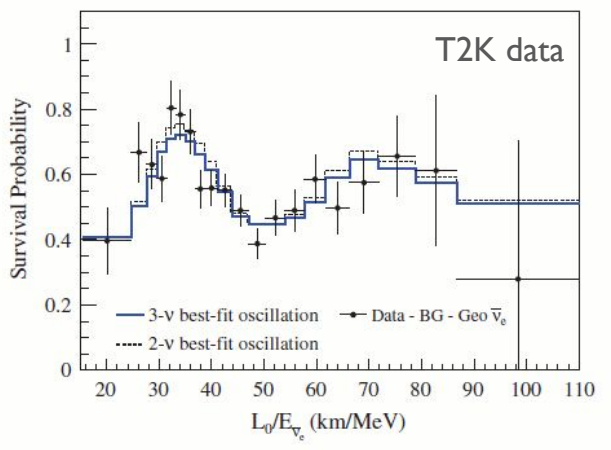
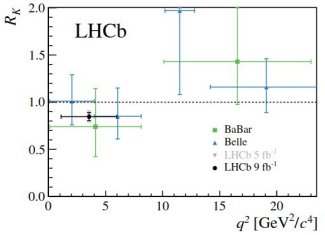
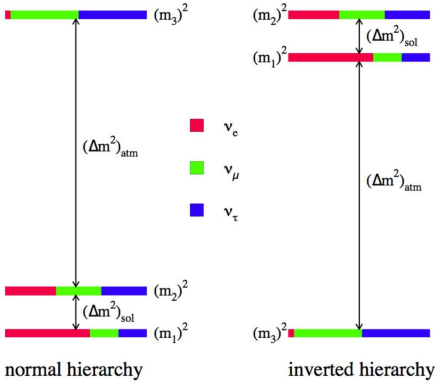
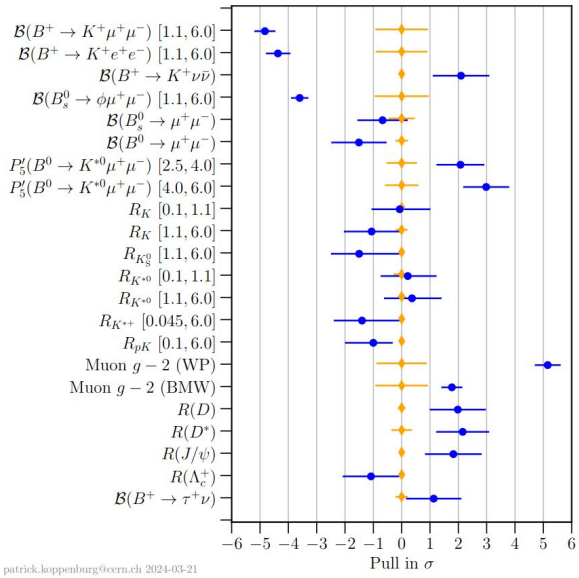
Not a fundamental Standard Model symmetry

We have Neutral LFV: ν oscillations + flavour anomalies









https://www.nikhef.nl/~pkoppenb/anomalies.html

Next update at Moriond and Beyond Flavour Anomalies (Siegen)

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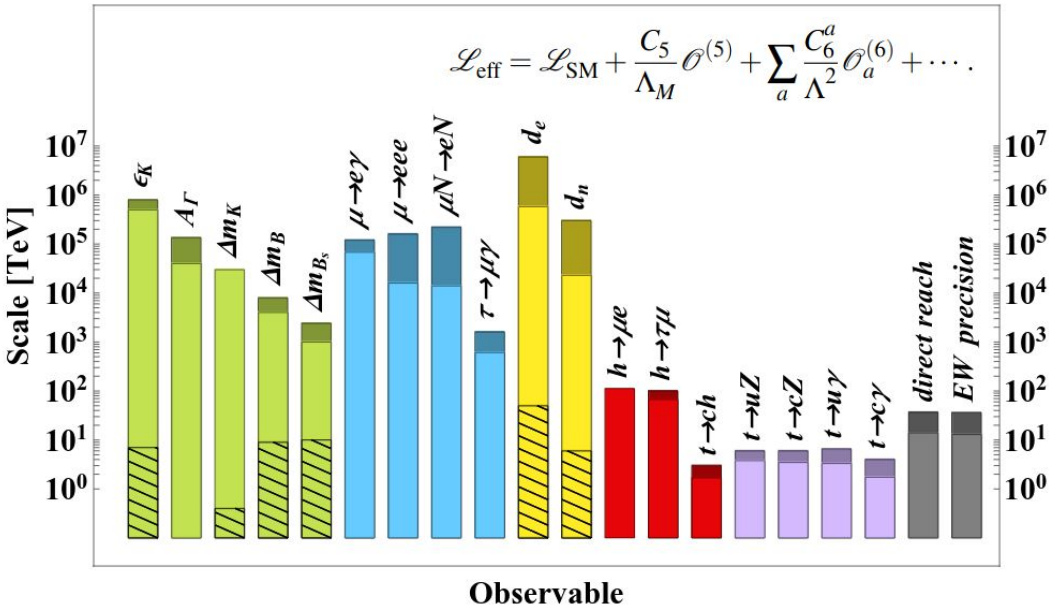
For $p_{exp} \ll m_{BSM}$: EFT approach



From Input for the European Strategy for Particle Physics Update 2020

The EFT formulation we tend to use in rare muon decays: https://arxiv.org/abs/1702.03020

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QCD}} + \frac{1}{\Lambda^2}\Big[C_L^D e\, m_\mu (\overline{e_R}\sigma^{\mu\nu}\mu_L)F_{\mu\nu} + \sum_{f=q,\ell}\Big[C_{ff}^{S\,LL}(\overline{e_R}\mu_L)(\overline{f_R}f_L) + C_{ff}^{V\,LL}(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_L}\gamma_\mu f_L) + C_{ff}^{V\,LR}(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_R}\gamma_\mu f_R)\Big] + \sum_{h=q,\tau}\Big[C_{hh}^{T\,LL}(\overline{e_R}\sigma_{\mu\nu}\mu_L)(\overline{h_R}\sigma^{\mu\nu}h_L) + C_{hh}^{S\,LR}(\overline{e_R}\mu_L)(\overline{h_L}h_R)\Big] + \alpha_s\, m_\mu G_F (\overline{e_R}\mu_L)G_{\mu\nu}^a G_a^{\mu\nu} + L \leftrightarrow R + \text{h.c.}\Big]$$

$$\text{Br}(\mu \to 3e) = \frac{\alpha_e^2 m_\mu^5}{12\pi\Lambda^4\Gamma_\mu}\left(\left|C_L^D\right|^2 + \left|C_R^D\right|^2\right)\left(8\log\left[\frac{m_\mu}{m_e}\right] - 11\right) + X_\gamma + \frac{m_\mu^5}{3(16\pi)^3\Lambda^4\Gamma_\mu}\Big(\left|C_{ee}^{S\,LL}\right|^2 + 16\left|C_{ee}^{V\,LL}\right|^2 + 8\left|C_{ee}^{V\,LR}\right|^2 + \left|C_{ee}^{S\,RR}\right|^2 + 16\left|C_{ee}^{V\,RR}\right|^2 + 8\left|C_{ee}^{V\,RL}\right|^2\Big)$$

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

Why searching for Charged Lepton Flavour Violation?

How to search for CLFV, i.e. looking for small BSM couplings?

➜ Intensity Frontier Measurement

➜ Processes with a low Standard Model Background

Muons are great!

- They are leptons with 100% leptonic decay modes very well described in the SM
- BSM contributions can be described by EFT arXiv:1702.03020 as $m_{mu} \ll \Lambda_{NP}$
- SM background free

The is <1 SM event in the CLFV decay phase space of interest.

Sensitivity ~ N (and not $\sqrt{N}$)

μ MASS (atomic mass units u)			$0.1134289259 \pm 0.0000000025$ u		
μ MASS			$105.6583755 \pm 0.0000023$ MeV		
μ MEAN LIFE τ			$(2.1969811 \pm 0.0000022) \times 10^{-6}$ s		
$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO			1.00002 ± 0.00008		
$(\tau_{\mu^+}-\tau_{\mu^-})/\tau_{\text{average}}$			$(2 \pm 8) \times 10^{-5}$		
μ/p MAGNETIC MOMENT RATIO			$3.18334514 \pm 0.00000007$		
Mode			Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$e^-\bar{\nu}_e\nu_\mu$		$\approx 100\%$		53
Γ_2	$e^-\bar{\nu}_e\nu_\mu\gamma$		[1] $(6.0 \pm 0.5) \times 10^{-8}$		53
Γ_3	$e^-\bar{\nu}_e\nu_\mu e^+e^-$		[2] $(3.4 \pm 0.4) \times 10^{-5}$		53
▾ Lepton Family number (LF) violating modes					
Γ_4	$e^-\nu_e\bar{\nu}_\mu$	LF	[3] $< 1.2\%$	CL=90%	53
Γ_5	$e^-\gamma$	LF	$< 4.2 \times 10^{-13}$	CL=90%	53
Γ_6	$e^-e^+e^-$	LF	$< 1.0 \times 10^{-12}$	CL=90%	53
Γ_7	$e^-2\gamma$	LF	$< 7.2 \times 10^{-11}$	CL=90%	53

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- SM background free
- We can make a lot of them at p-accelerator facilities
- They live long enough to production → experiment

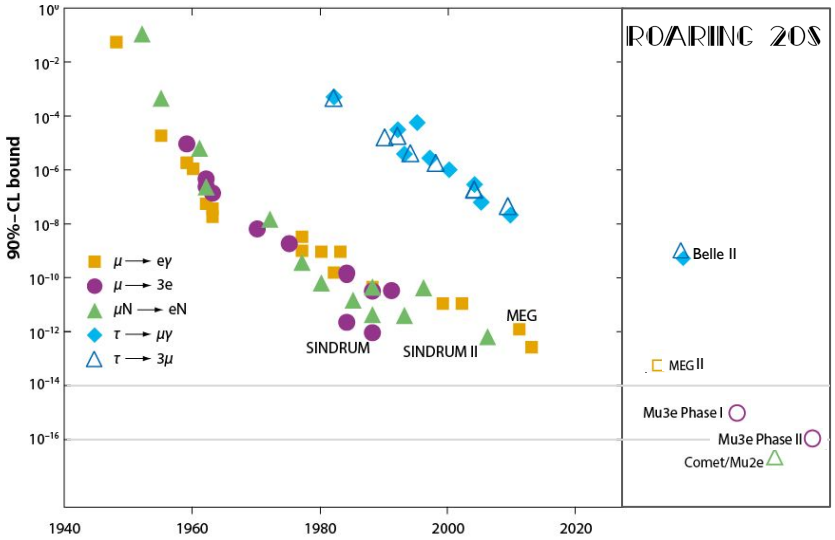
Sweet spot between sensitivity and availability

Three golden channels

And no neutrinos

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

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



4 orders-of-magnitude for new physics searches!

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- ❑ **$\mu^+ \to e^+e^+e^-$** SINDRUM < $1 \cdot 10^{-12}$ ⇨ **Mu3e < $2 \cdot 10^{-15}$** ($1 \cdot 10^{-16}$ in a second phase)

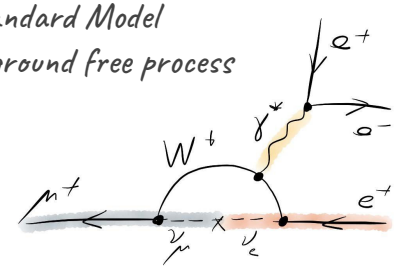
Figure adapted from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)

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

Why (look at all) three golden channels?

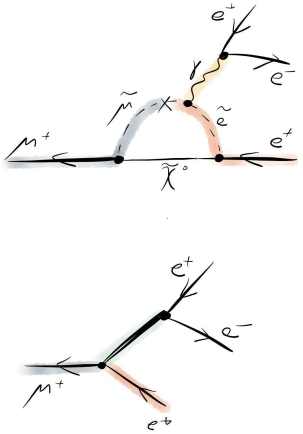
- $\mu^+ \to e^+\gamma$
- $\mu^-N \to e^-N$
- **$\mu^+ \to e^+e^+e^-$**

A Standard Model Background free process



$BR(SM) < 10^{-54}$

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



…

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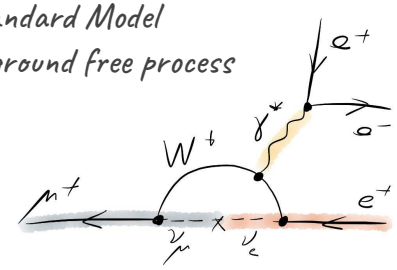
- **$\mu^+ \to e^+e^+e^-$**

For dipole interactions, MEG ~100 times more sensitive

A Standard Model Background free process



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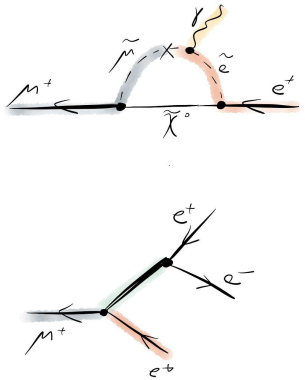
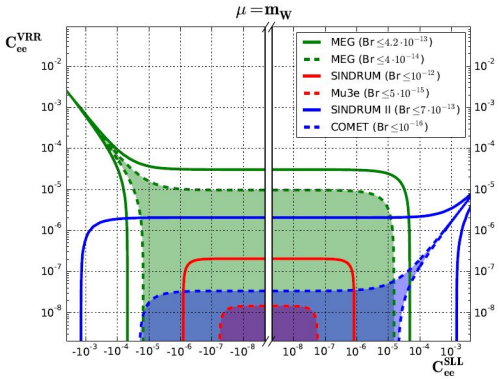


	$\mathrm{Br}(\mu^+ \to e^+\gamma)$		$\mathrm{Br}(\mu^+ \to e^+e^-e^+)$		$\mathrm{Br}^{\mathrm{Au/Al}}_{\mu\to e}$	
	$4.2 \cdot 10^{-13}$	$4.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-15}$	$7.0 \cdot 10^{-13}$	$1.0 \cdot 10^{-16}$
C_L^D	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$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

...



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

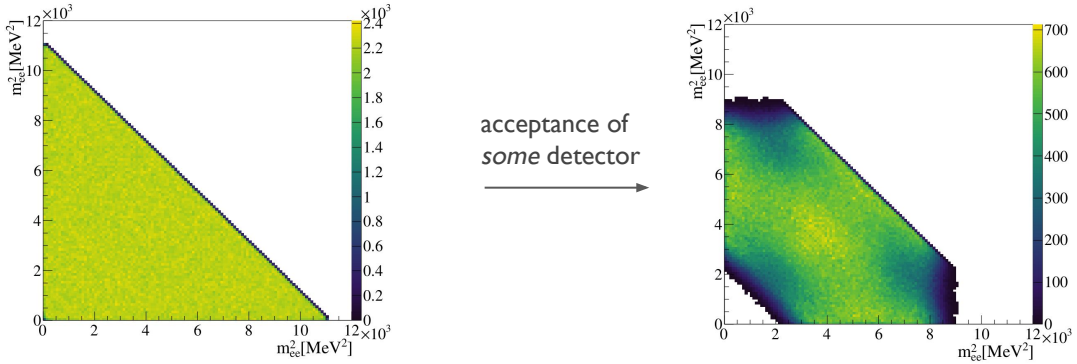
Renormalisation-group improved analysis of $\mu \to e$ processes in a systematic effective-field-theory approach. arXiv:1702.03020v3

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

Why (look at all) three golden channels?

- ❑ $\mu^+ \to e^+\gamma$ → Only one single signal
- ❑ $\mu^-N \to e^-N$ → Some differentiation via *N*
- ❑ **$\mu^+ \to e^+e^+e^-$** → Full 3-body decay kinematics

Phase space decay (Dalitz plot)



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

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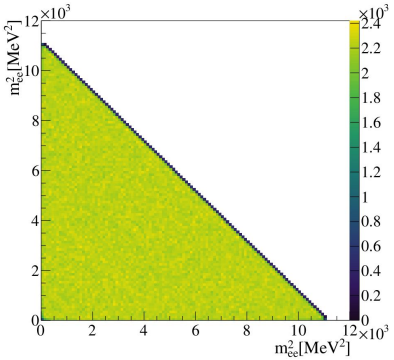
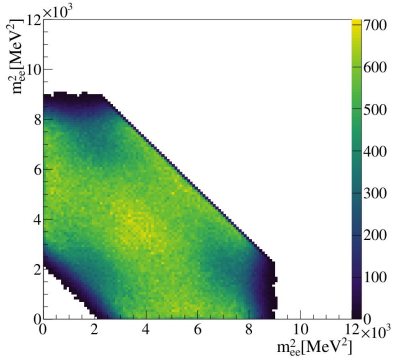
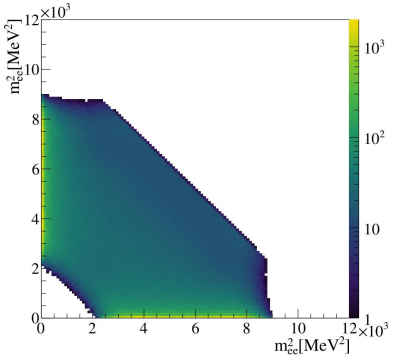


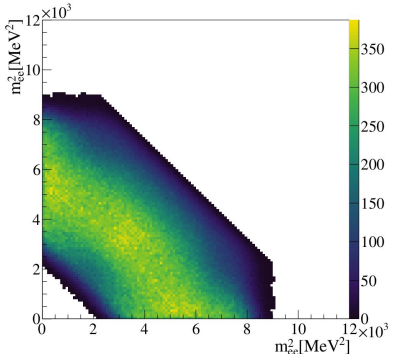
acceptance of *some* detector



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



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



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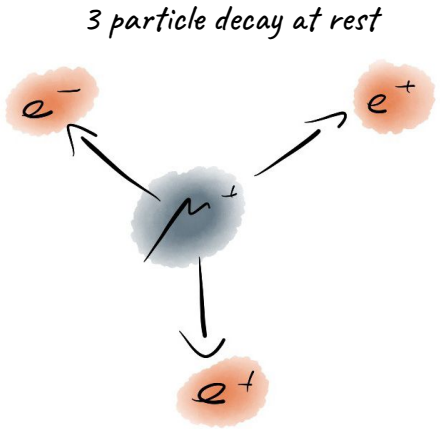
Experimental concept

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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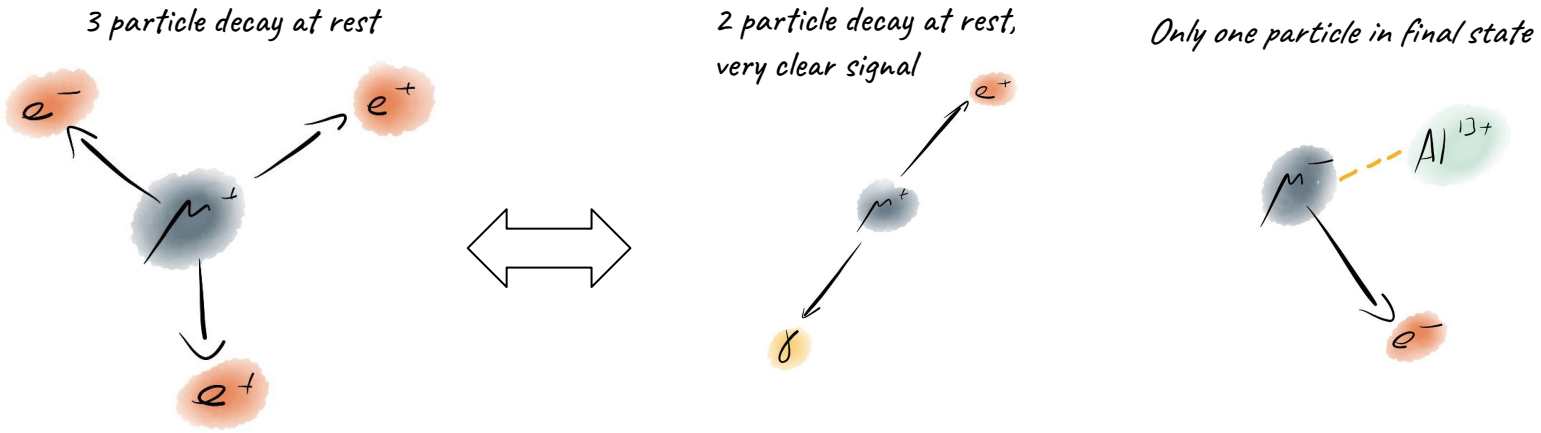

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- ➔ Mono-energetic e^+ and γ
- ➔ back-back coincidence

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

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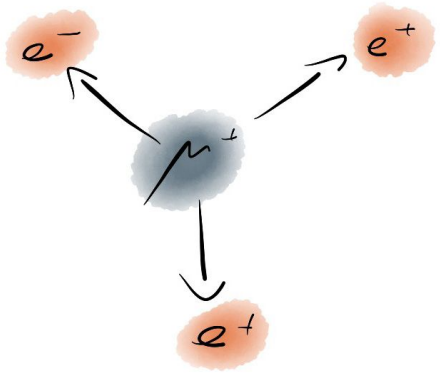
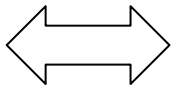
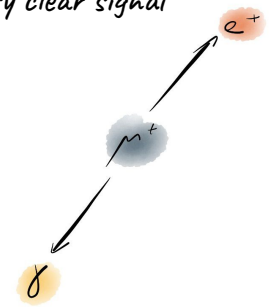
How to look for $\mu^+ \rightarrow e^+e^+e^-$?

DC muons
3 particle decay at rest

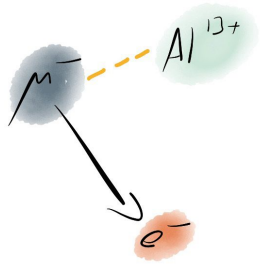




DC muons
2 particle decay at rest,
very clear signal



Pulsed muon beam
Only one particle in final state



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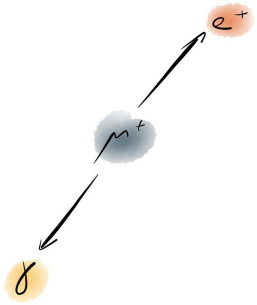
- ➔ Mono-energetic e^-
- ➔ No coincidence

Mu3e & MEG @ PAUL SCHERRER INSTITUT PSI

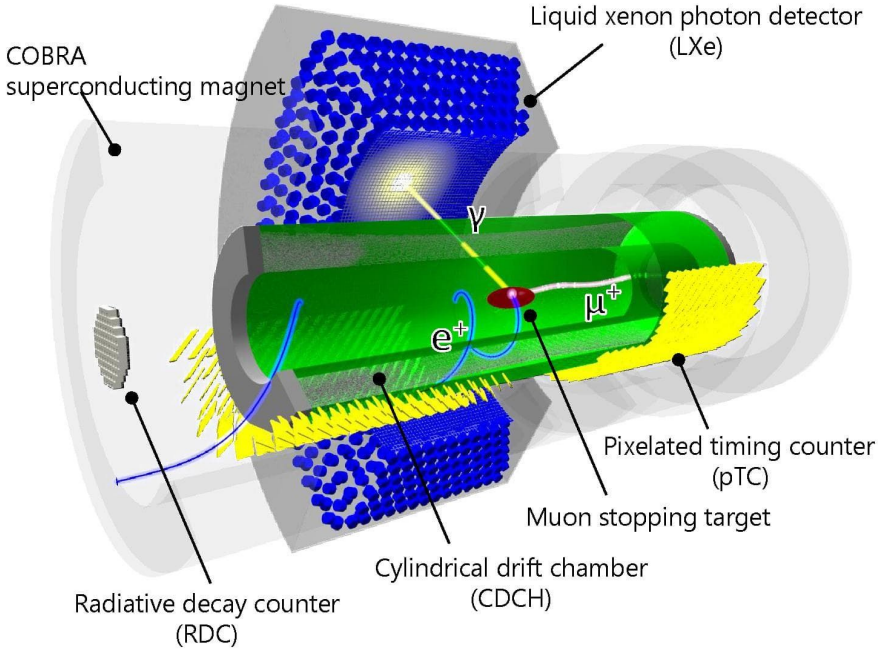
Mu2e @ Fermilab

COMET @ J-PARC

MEGII

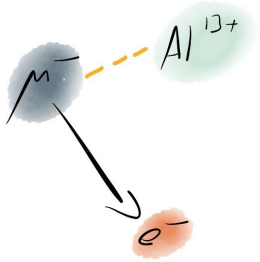


MEGII is running and has put a limit of $3.1 < 10^{-14}$ on $\mu^+ \rightarrow e^+\gamma$

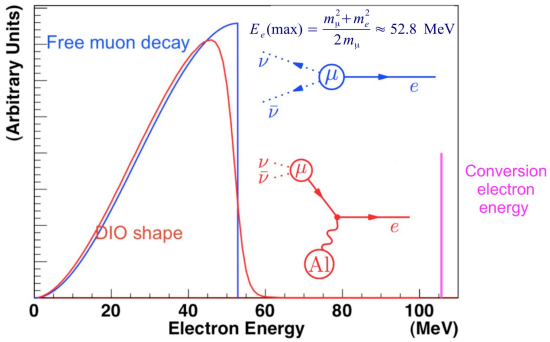


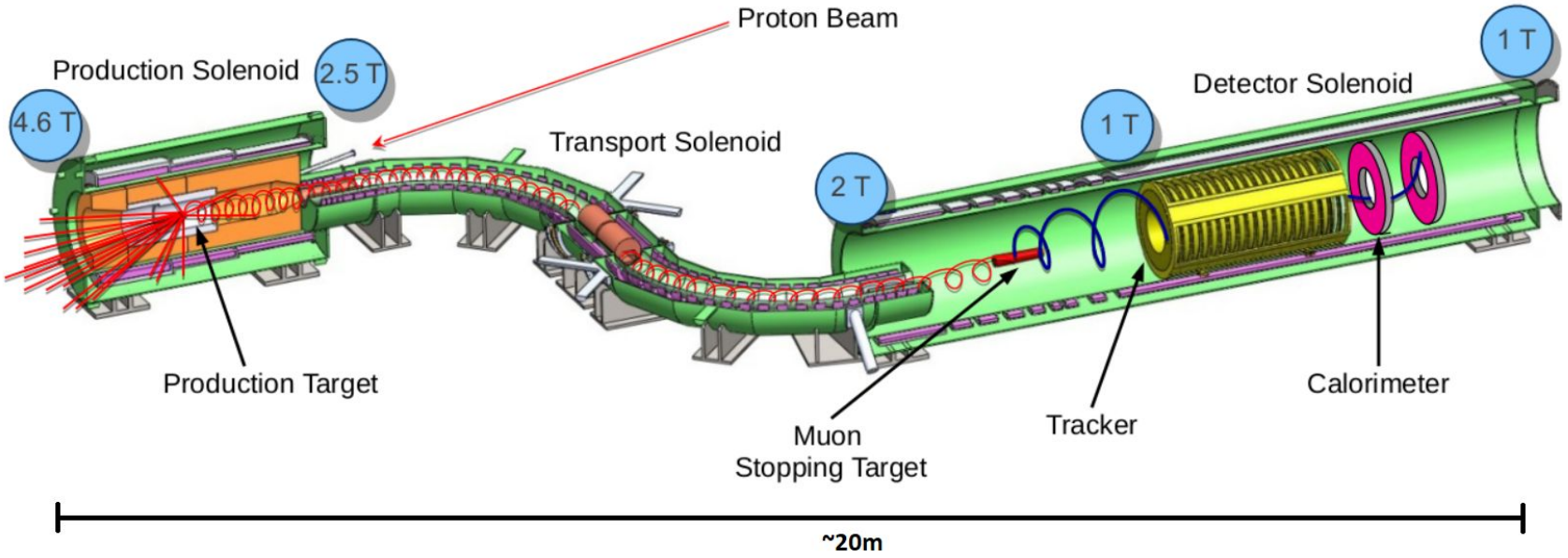
MEGII design: https://arxiv.org/abs/1801.04688

Mu2e and COMET



Mu2e and COMET are under construction at FermiLab and J-PARC.





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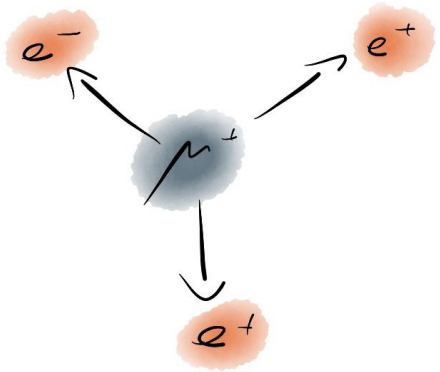
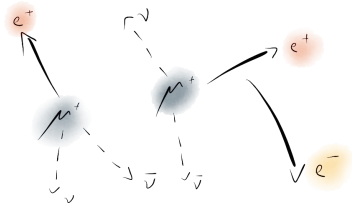
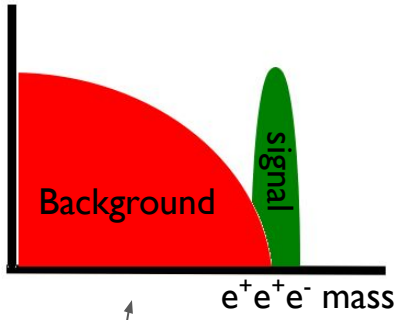


Internal conversion

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

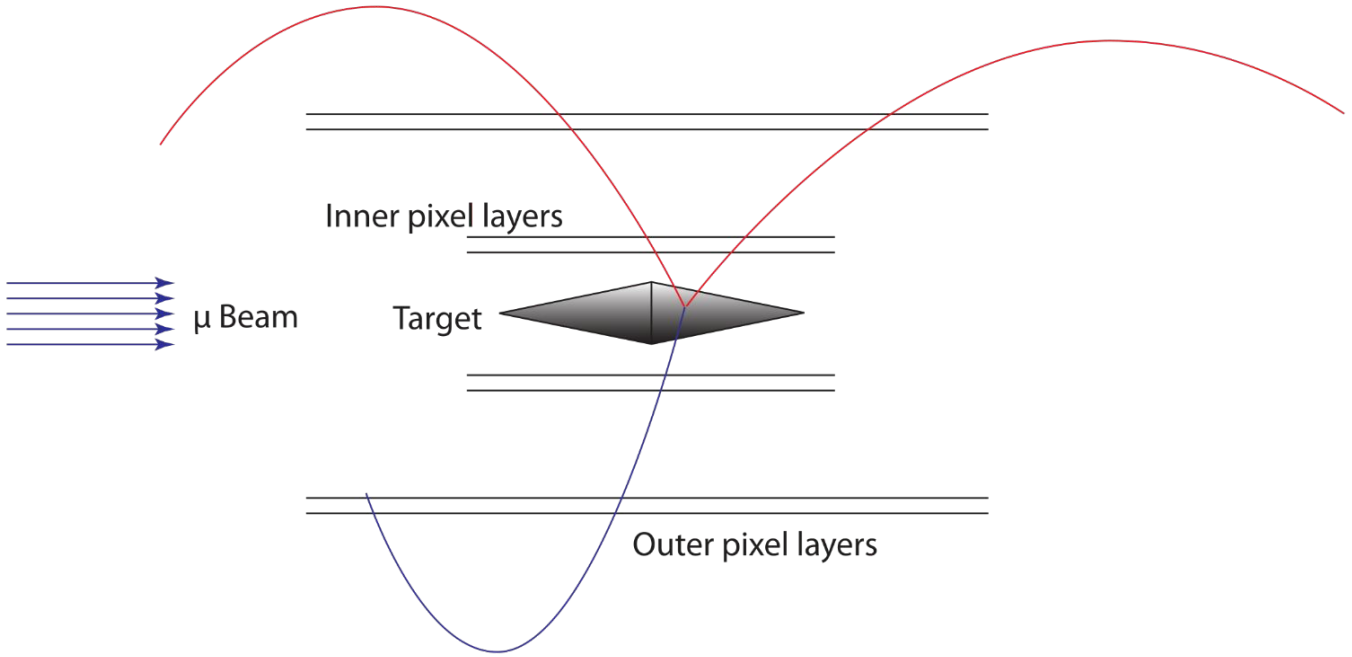
Fully differential NLO predictions for the rare muon decay arXiv:1611.03617

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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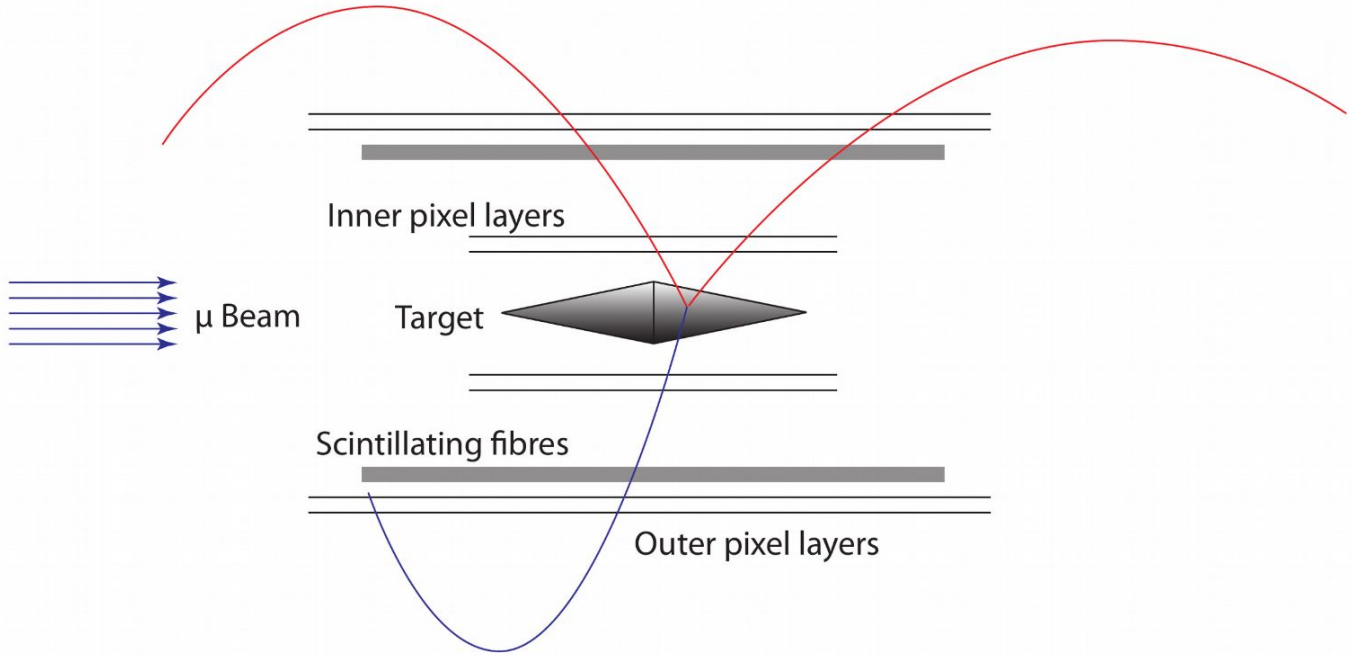

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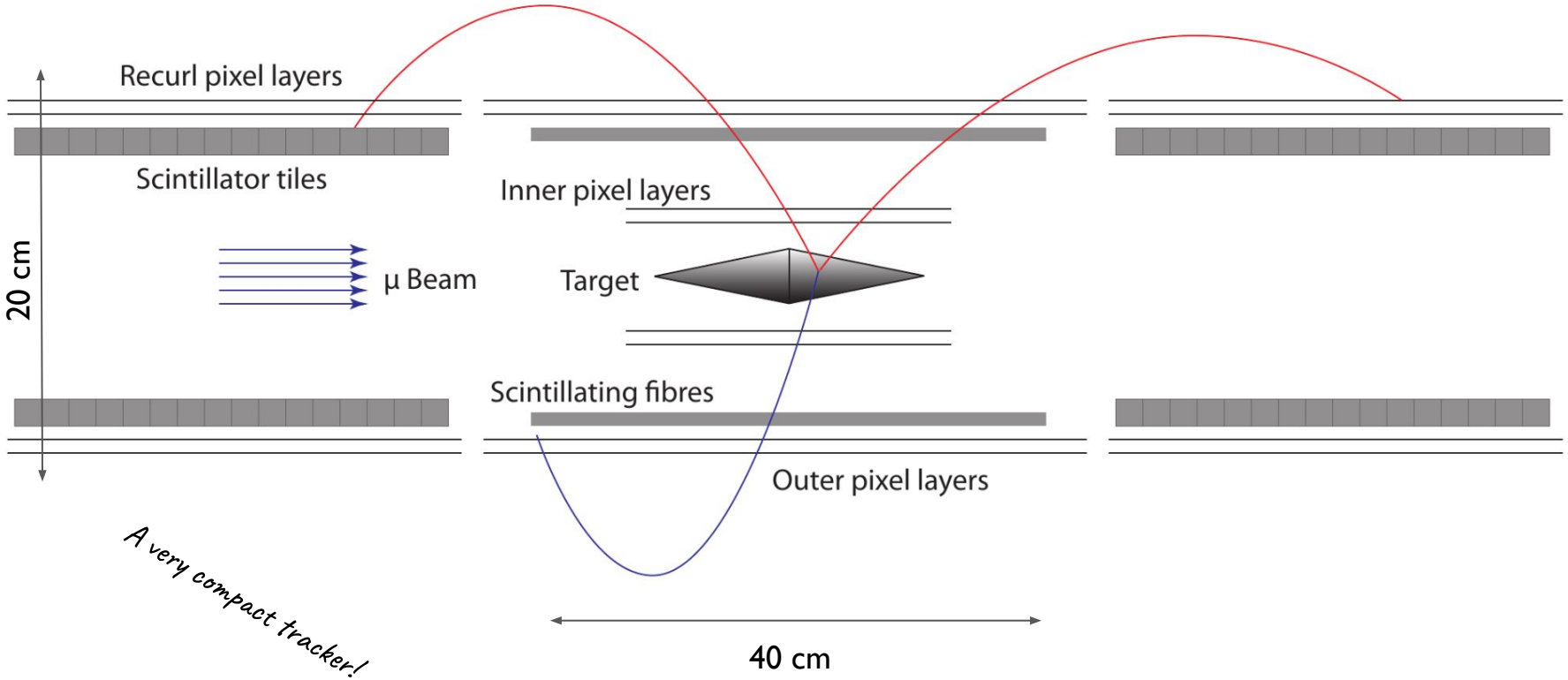
- Step 6: Add Scintillating Tiles to get the optimal timing resolution



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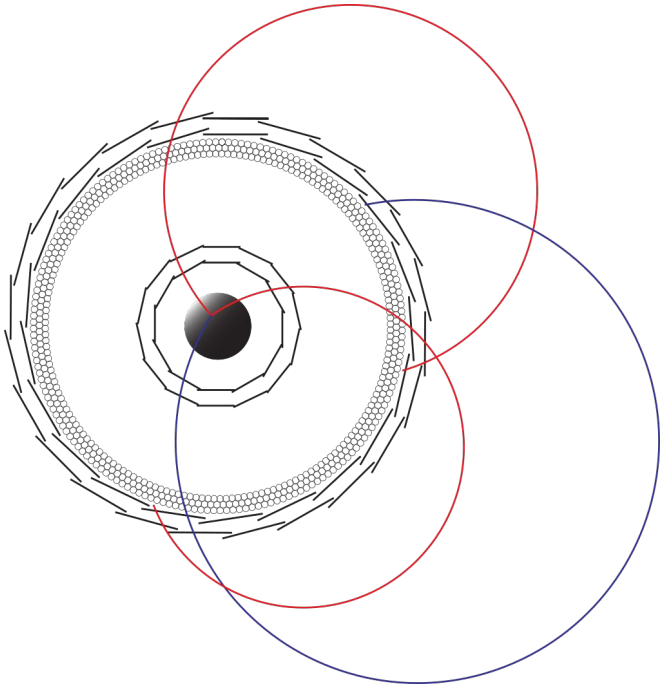
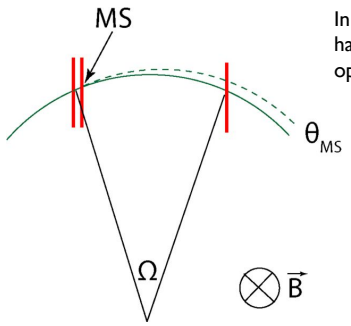
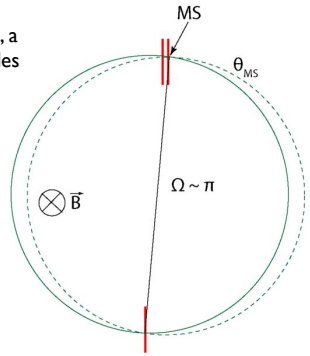
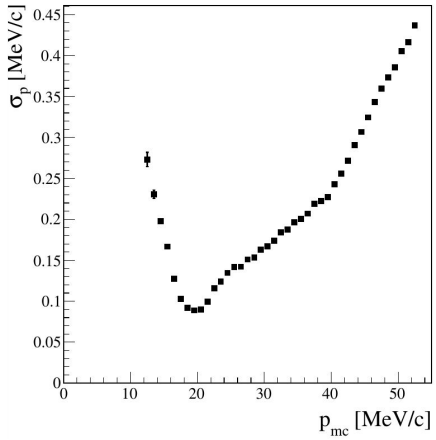




In the **MS dominated regime**, a half-turn spectrometer provides optimal momentum resolution





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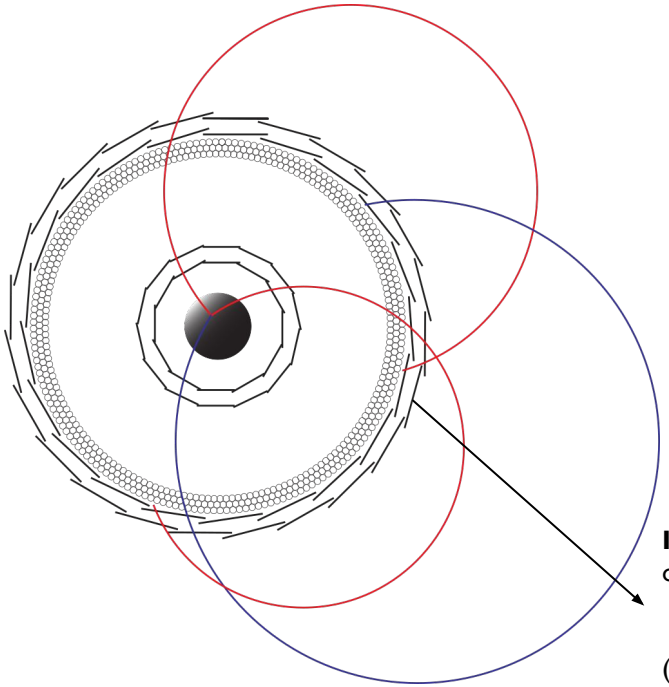

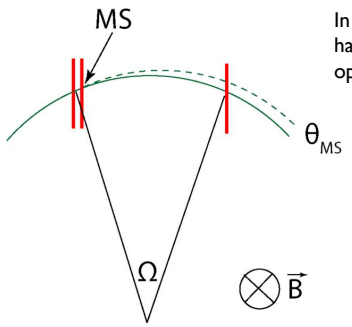

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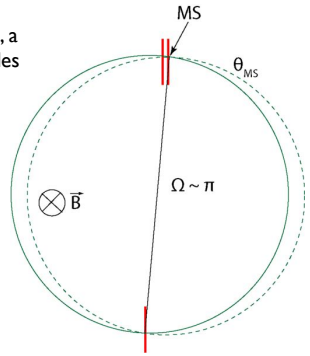
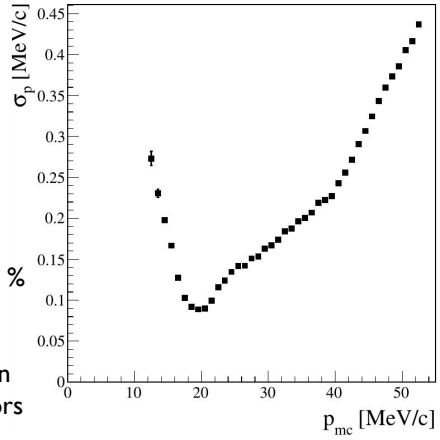


If each tracking layers is ~0.1 % of a radiation length

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

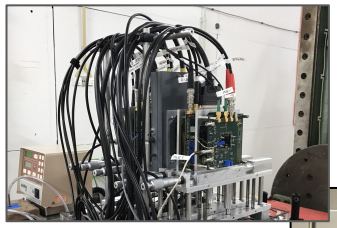


HV-MAPS

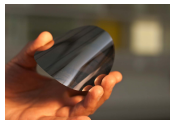
Lightweight pixel tracker build from
High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) called MuPix

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

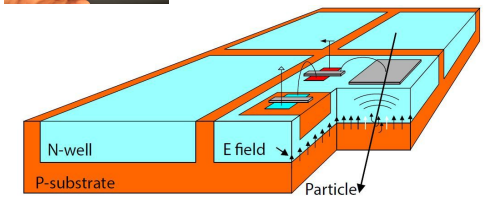
A decade of detector development and test beams



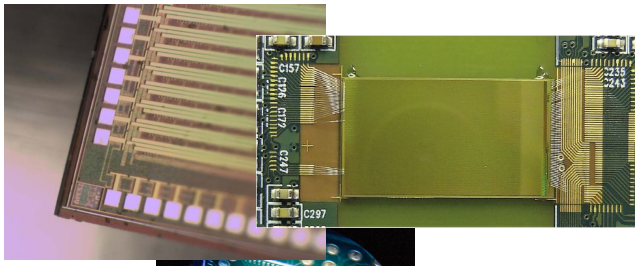
10-15 Master and PhD theses

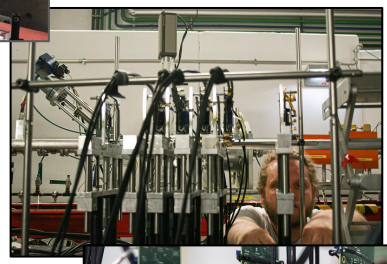


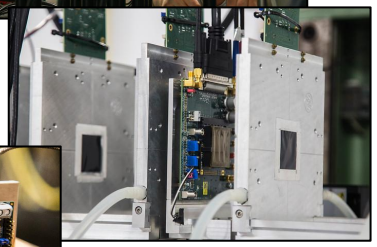
Concept

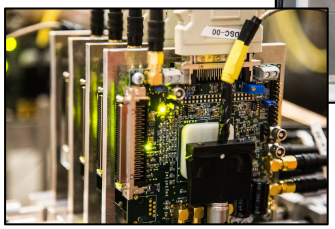


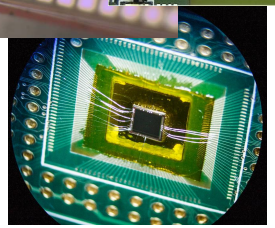
Prototyping MuPiX ... → 9

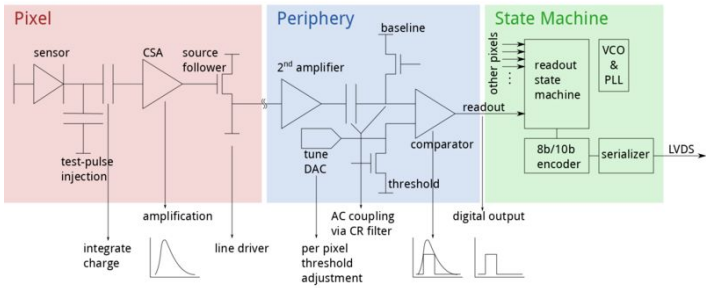










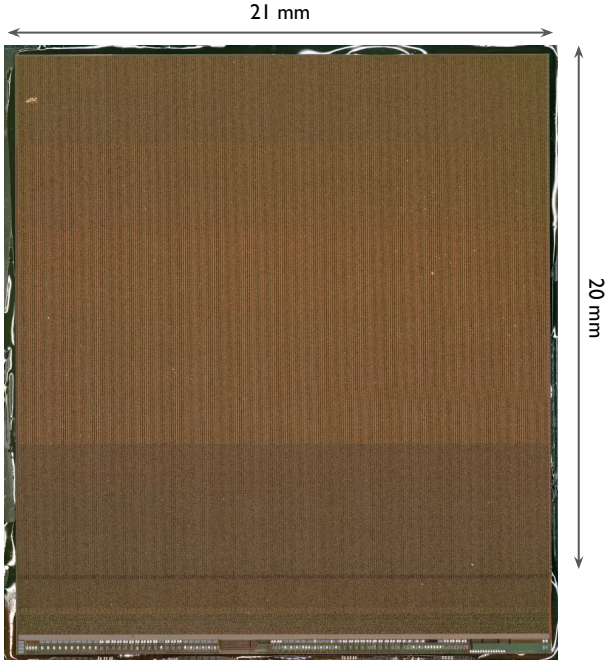


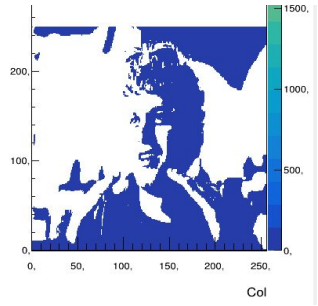
https://arxiv.org/abs/1603.08751, https://arxiv.org/abs/2002.07253, 10.1016/j.nima.2007.07.115

HV-MAPS

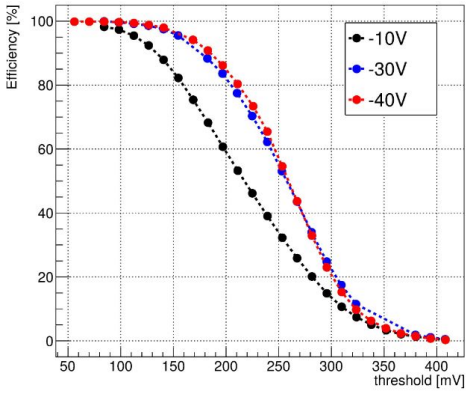
Lightweight pixel tracker build from
High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) called MuPix

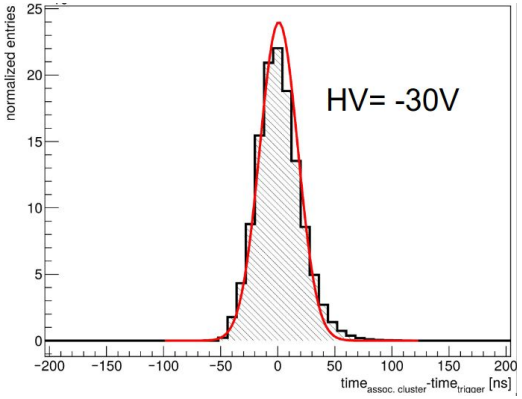
➜ MuPix11 as a fast, efficient, thin, and large HV-MAPS sensor

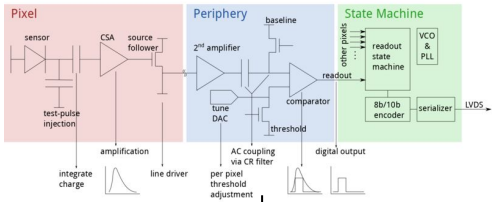




> 99.5 % efficient
< 15ns time resolution
Threshold/mask pixel by pixel



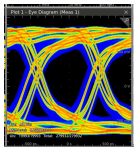




125 MHz clk

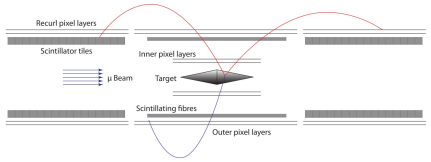
Slow Control

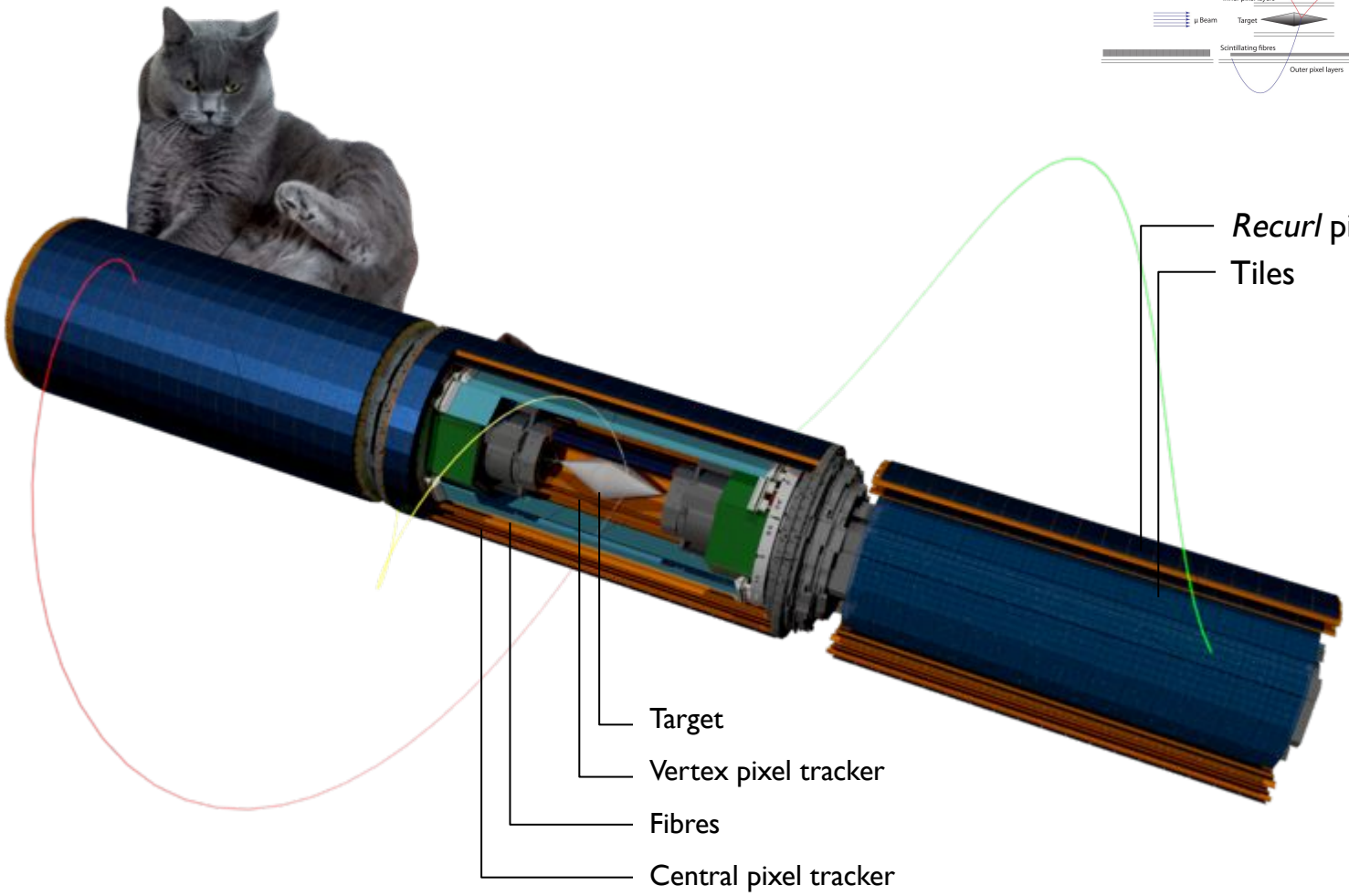
Data[3:0] @ 1.25 GHz



We have a sensor, now we have to build a detector

Mu3e detector

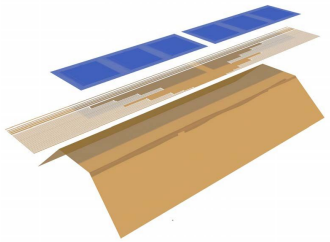


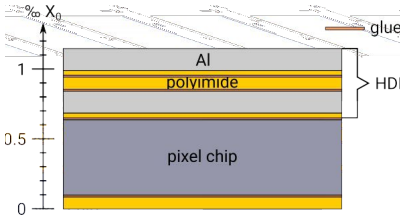


Mu3e detector

Lightweight pixel tracker build from MuPIX sensors

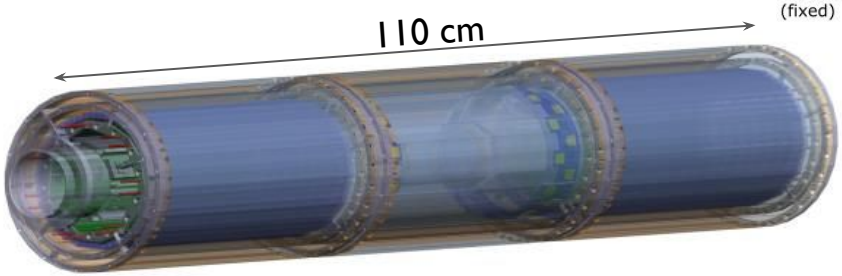
Ladders from 50-70 µm of Si,
25 µm of Alu/Kapton flex, and
25 µm of kapton support.
→ ca. 0.1% of a radiation length!



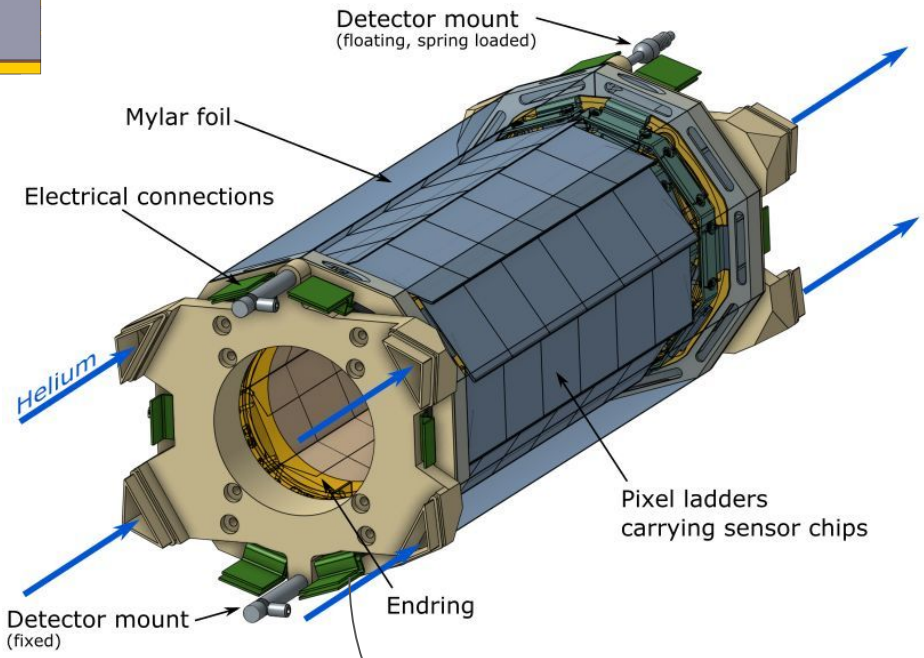


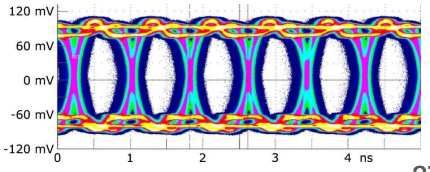
- 2 vertex layers
- 3 x 2 outer layers
- 174 ladders
- 2844 2x2 cm^2 MuPiX chips
- 182 016 000 pixels
- 3060 1.25 Gb/s data links
- 50 g/s, 10m/s 5kW gaseous helium cooling

The is a compact but large pixel tracker!



Vertex tracker

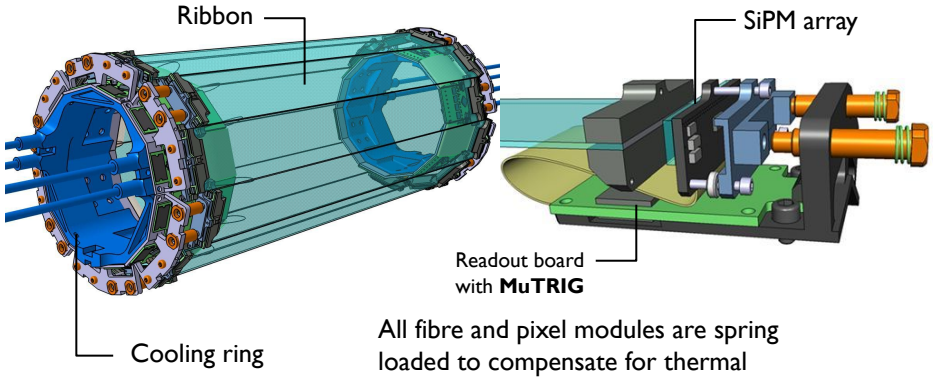




Mu3e detector

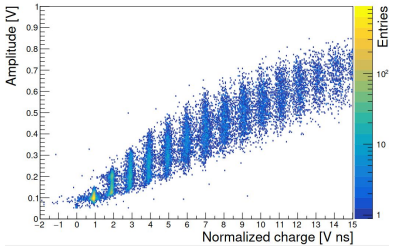
Timing detectors

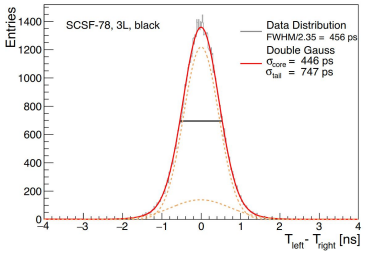
- 12 ribbon - 3 layer scintillating fibre detector surrounding the vertex detector
- Highly granular tile detector under the recurl stations



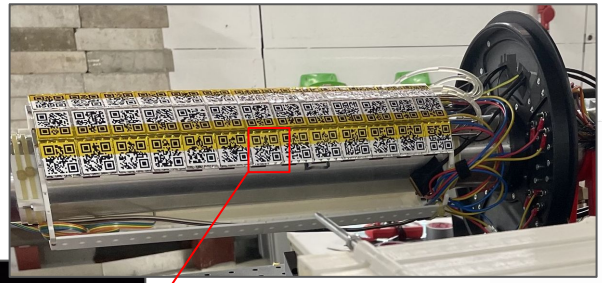
All fibre and pixel modules are spring loaded to compensate for thermal expansions.

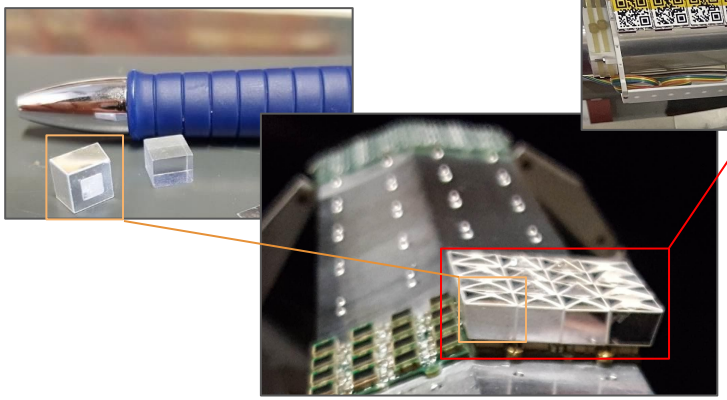
Operate fibre detector < p.e.

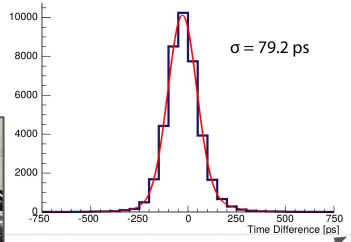


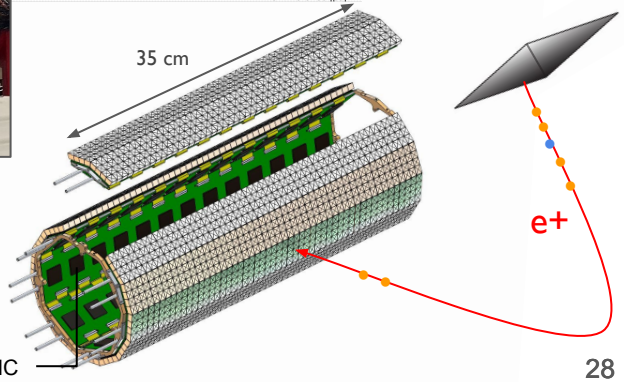


*Both detectors use a custom readout chip called MuTrig**







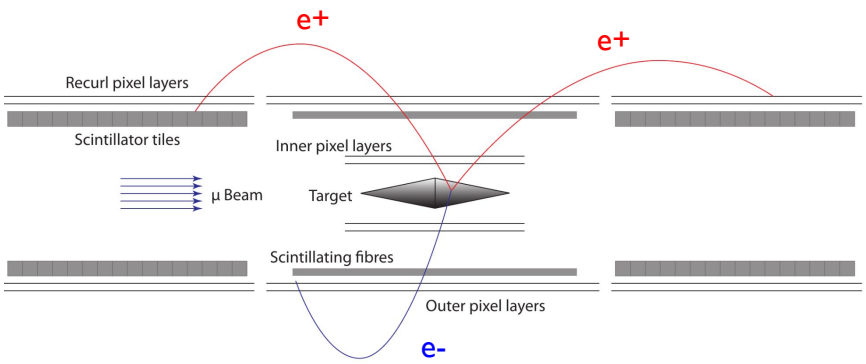


6272 tiles with plenty of light give us ca. 70 ps time resolution

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

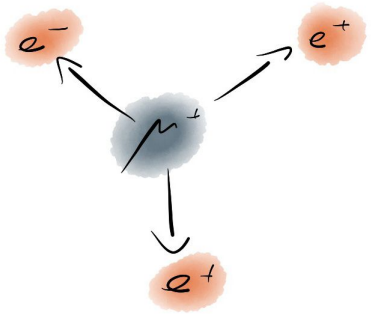
Development of the Scintillating Fiber Timing Detector for the Mu3e Experiment arXiv:2208.09906

Mu3e DAQ



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

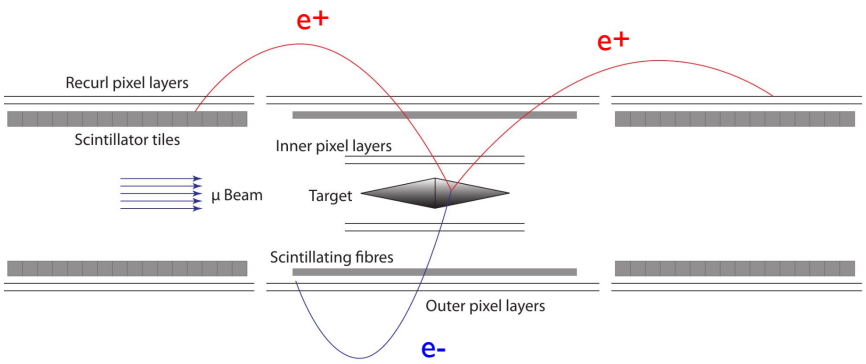
Mu3e = lightweight and fast Michel electron tracker + high throughput online reconstruction & selection DAQ system



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

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

Mu3e DAQ



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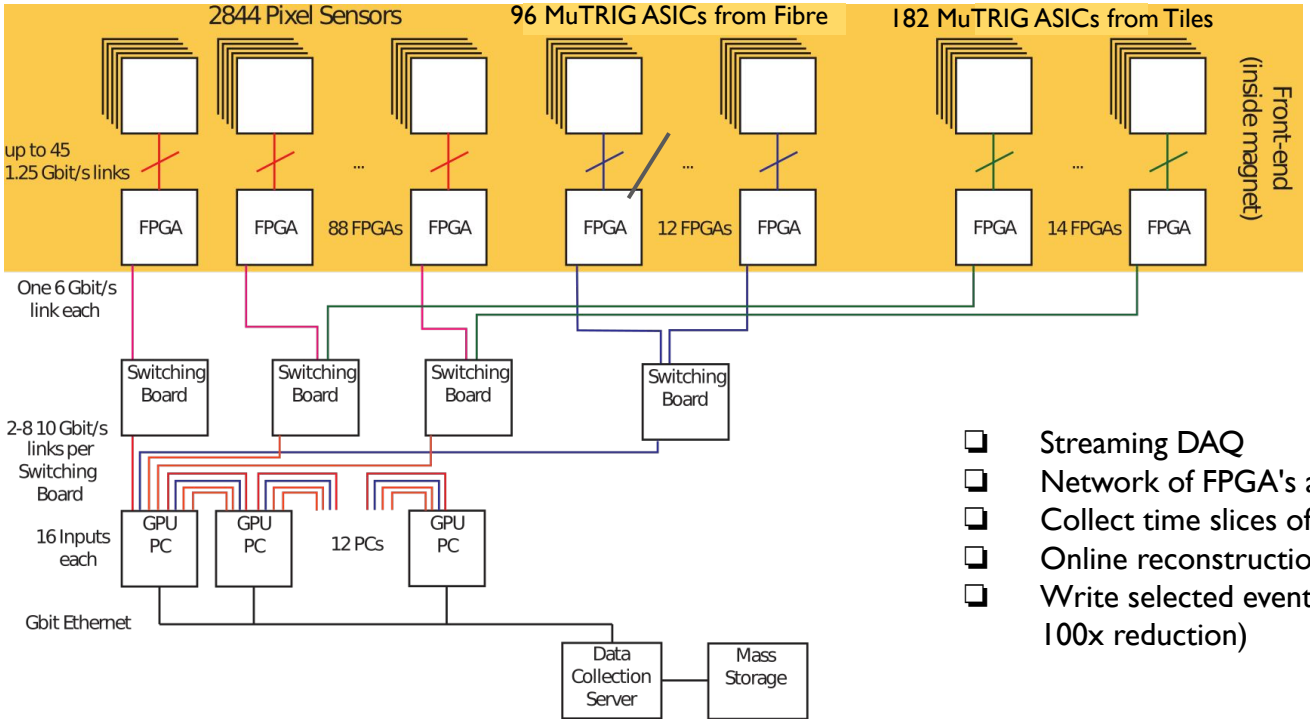
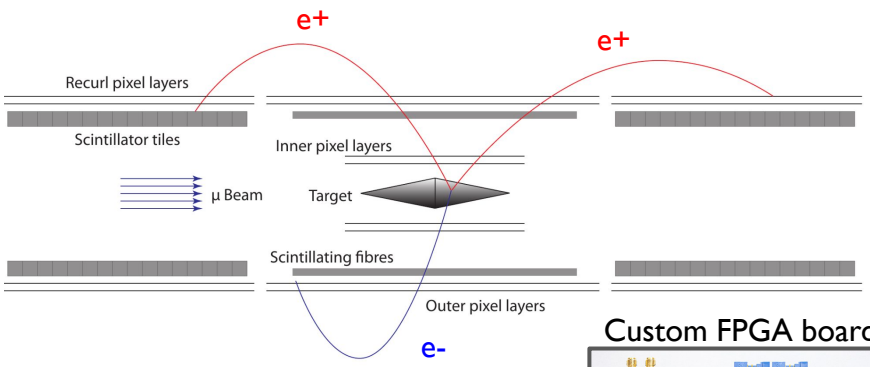


- Streaming DAQ
- Network of FPGA's and optical connections
- Collect time slices of the full detector on a single PC
- Online reconstruction and event selection on a GPUs
- Write selected events to disk at max 100 MB/s (up to 100x reduction)

Mu3e DAQ



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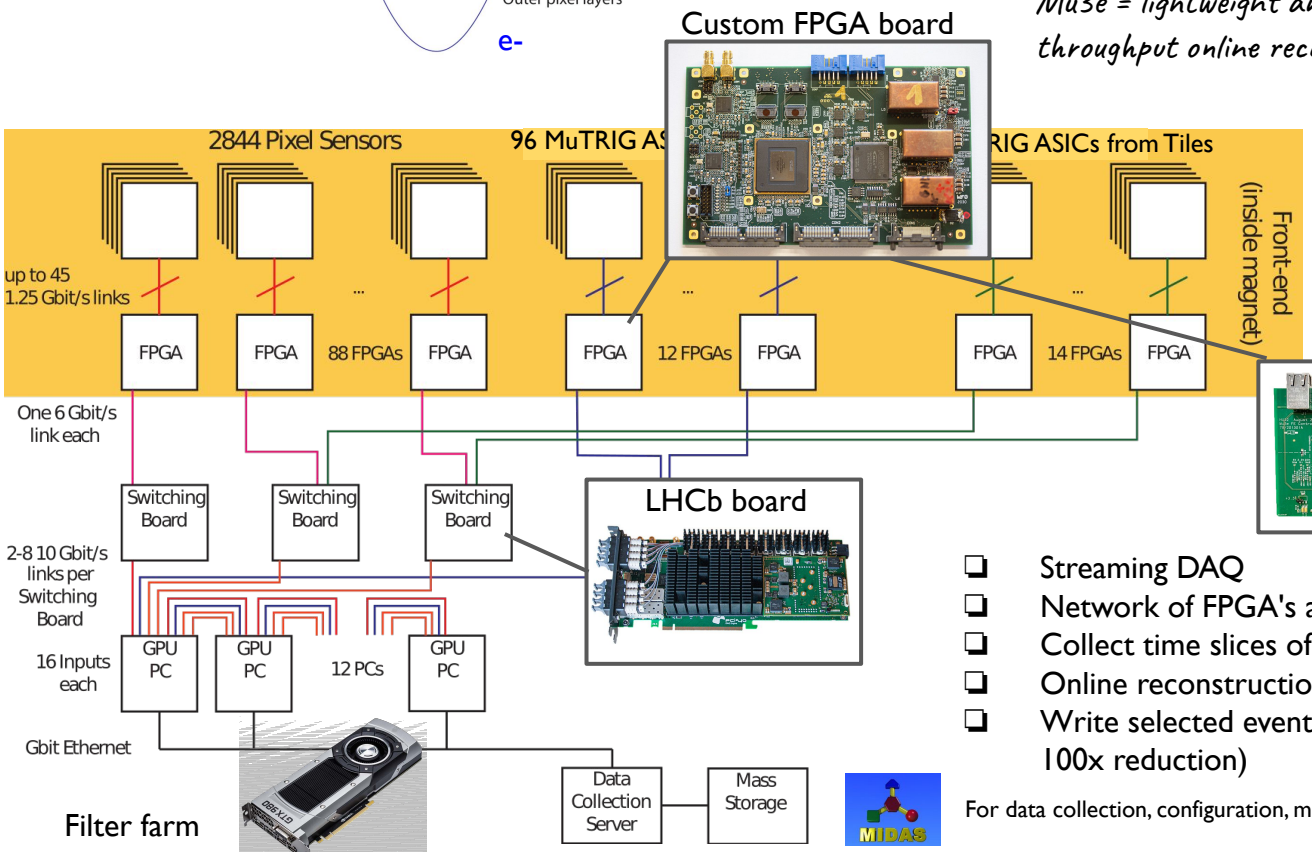
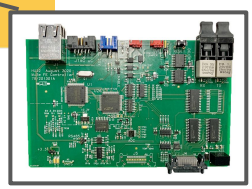
Mu3e = lightweight and fast Michel electron tracker + high throughput online reconstruction & selection DAQ system



The Mu3e Data Acquisition:
arXiv:2010.15648v2

Online event selection:
arXiv:2206.11535



Crate controllers integrated in the MIDAS (Slow Control) System

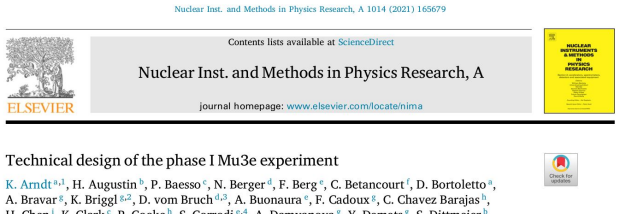
- ❏ Streaming DAQ
- ❏ Network of FPGA's and optical connections
- ❏ Collect time slices of the full detector on a single PC
- ❏ Online reconstruction and event selection on a GPUs
- ❏ Write selected events to disk at max 100 MB/s (up to 100x reduction)

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


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

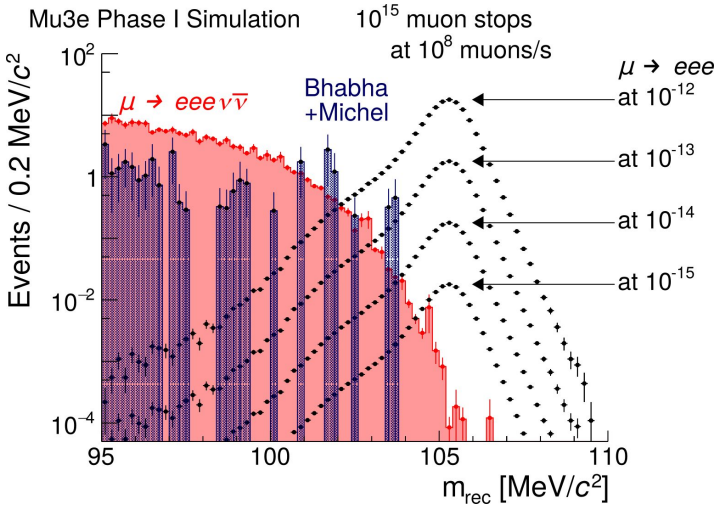
Contents lists available at ScienceDirect

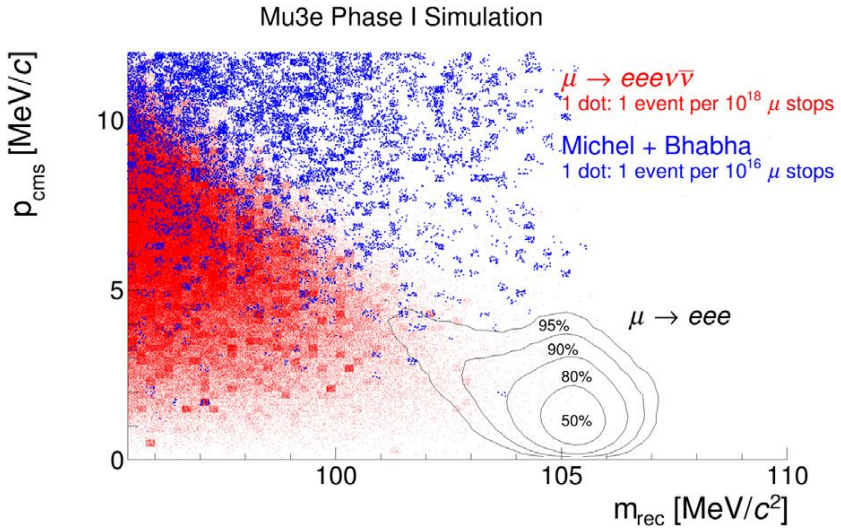
Nuclear Inst. and Methods in Physics Research, A

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 [g], F. Cadoux [g], C. Chavez Barajas [h],





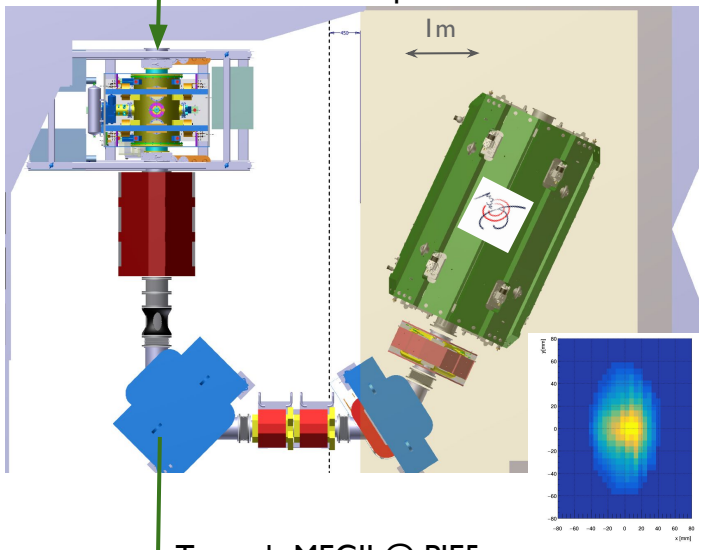
Building Mu3e

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



- 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

CMBL commissioning rates comparison			
	Rate [μ^+/s] @ 2.2 mA		
Year	Collimator	QSM41	Mu3e
2021	1.94 10^8	1.10 10^8	4.40 10^7
2022	2.26 10^8	1.66 10^8	6.89 10^7
2023	2.38 10^8	1.88 10^8	7.50 10^7*

Building Mu3e

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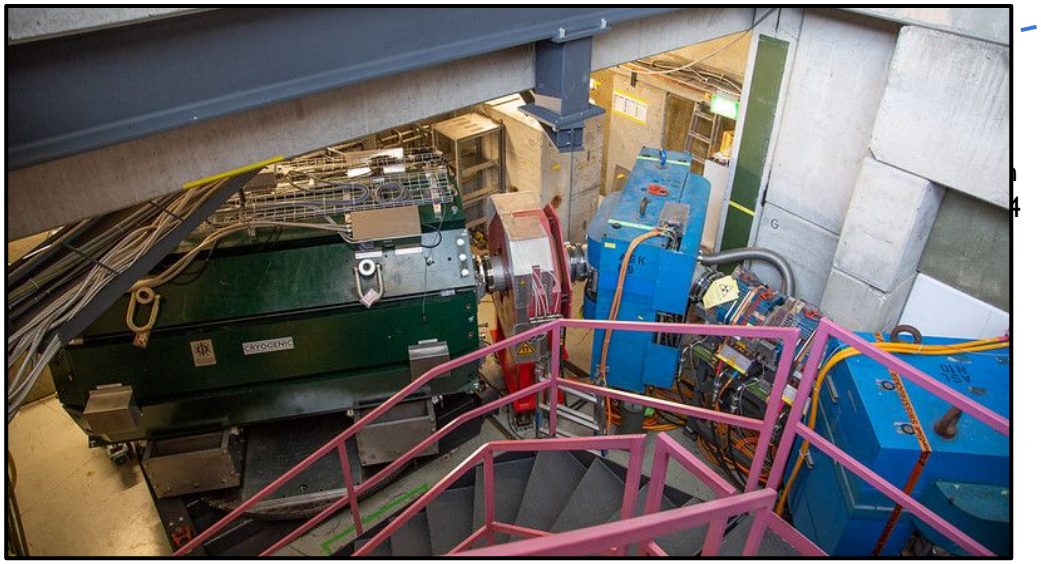

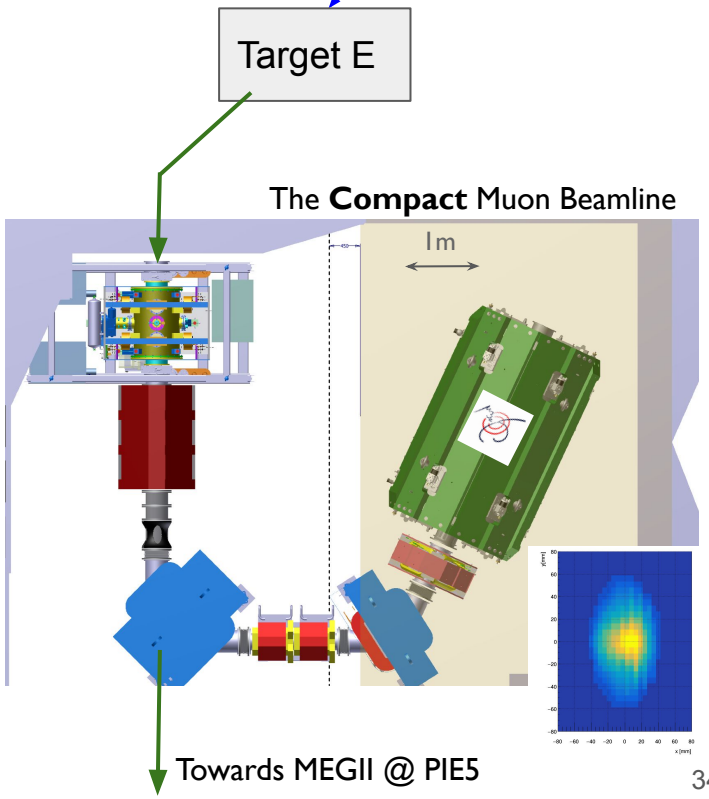

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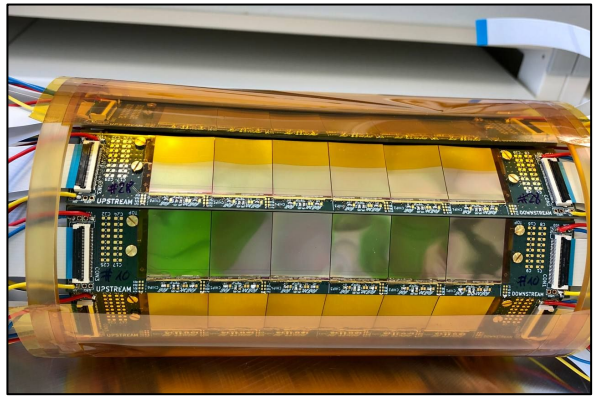
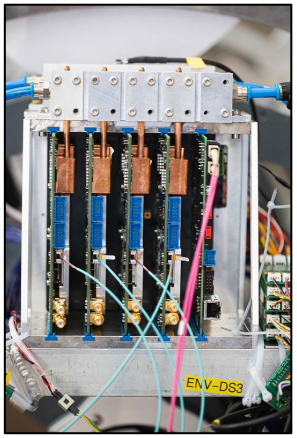
Building Mu3e

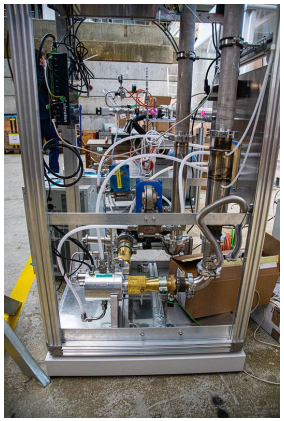
Vertex, Scintillating Fibre & Tile detector under construction …

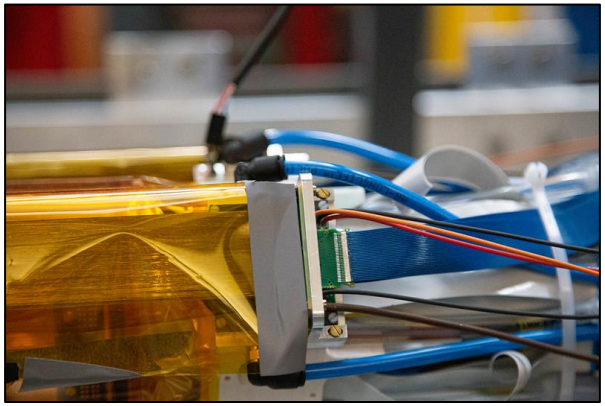
… but first a demonstrator/prototype

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









Building Mu3e

Vertex, Scintillating Fibre & Tile detector under construction …

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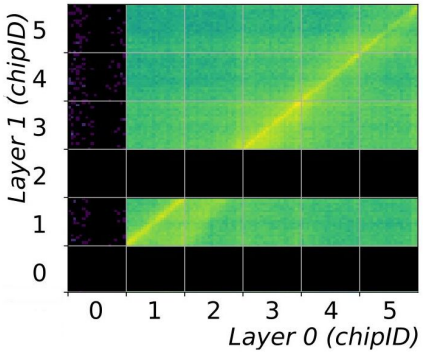
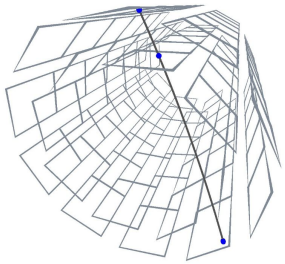
- ❏ …

A lot of operational experience

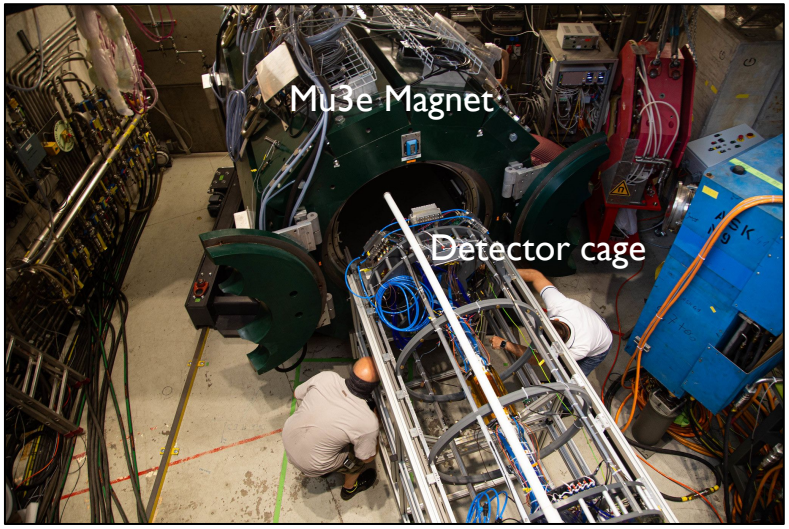
Spatial correlations of recurling e+



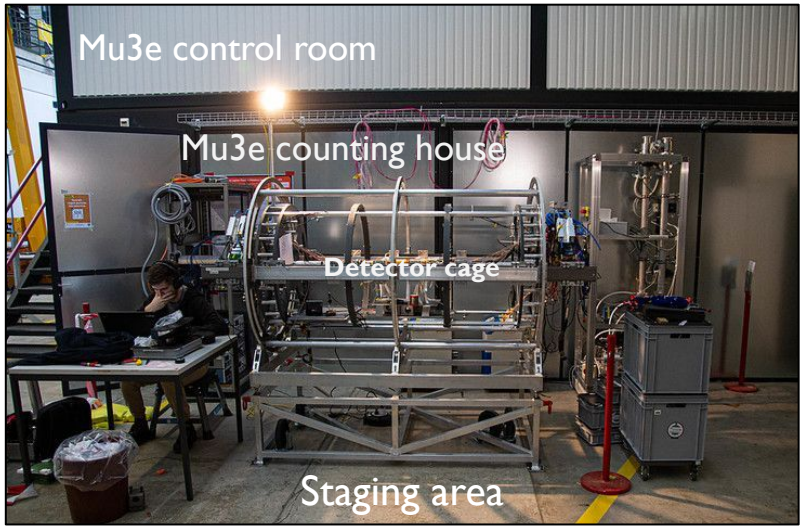
Cosmic tracks



Beam in 2021



Cosmics in 2022



Mu3e Integration Run 2021 arXiv:2203.07855

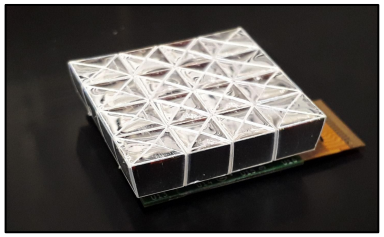
Building Mu3e

Vertex, Scintillating Fibre & Tile detector under construction …

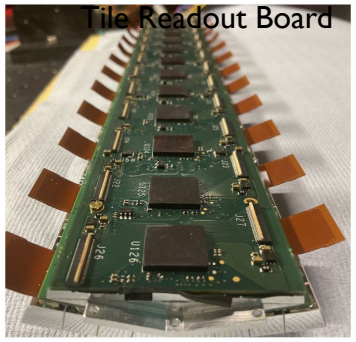
MuPix chip → (+ Flex) Ladder → (+ support & connections) Module → (Integrate) Detector

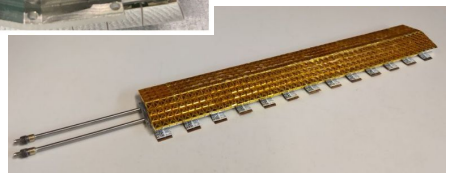
Now producing
- ❑ Vertex pixel ladders
- ❑ SiPM arrays and readout board
- ❑ Tile Matrix and readout board

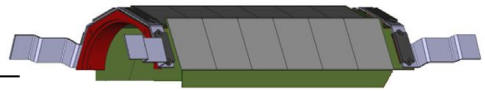
Tile Matrix



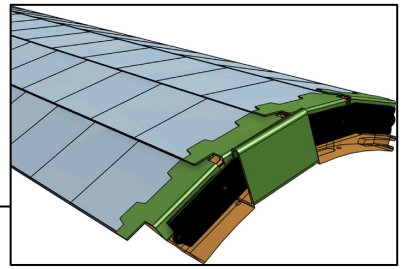
Tile Readout Board

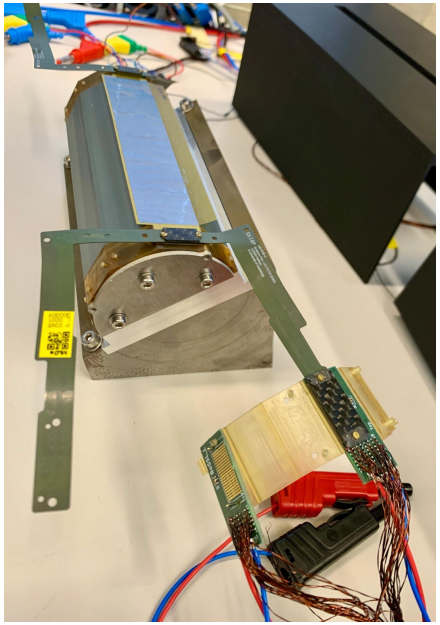


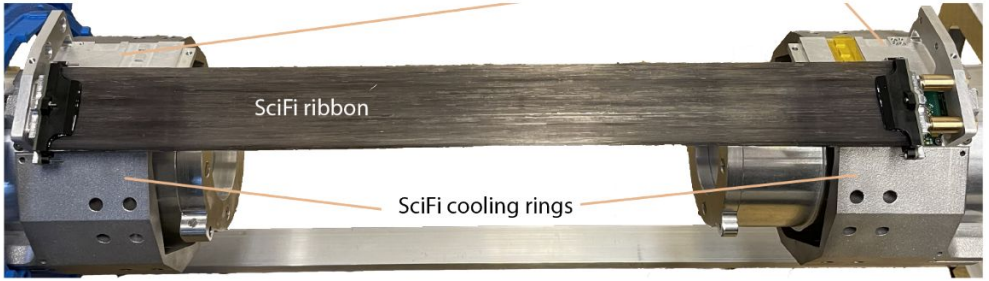




Vertex detector ladder (last month):





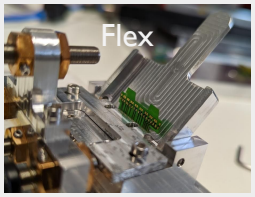


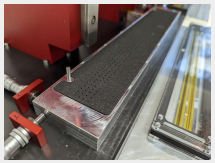
Building Mu3e

Vertex, Scintillating Fibre & Tile detector under construction …

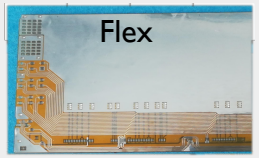
First detector installation at PSI later this summer

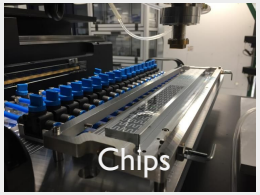
Outer pixel detector will follow soon

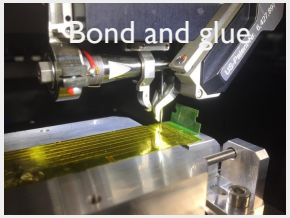


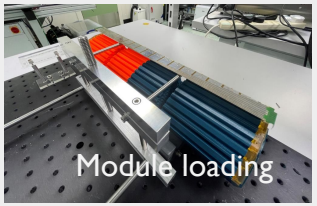


Unique set of tooling to construct 18 MuPix chip long *ladders* , Oxford University





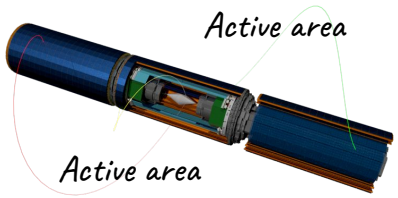


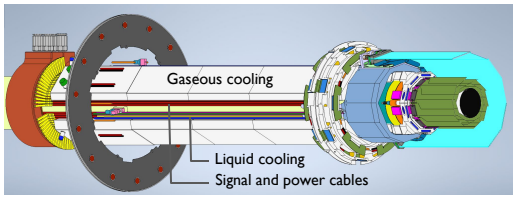


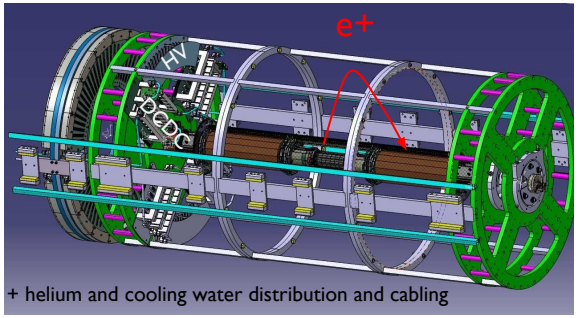
Install Central pixel tracker in 2024

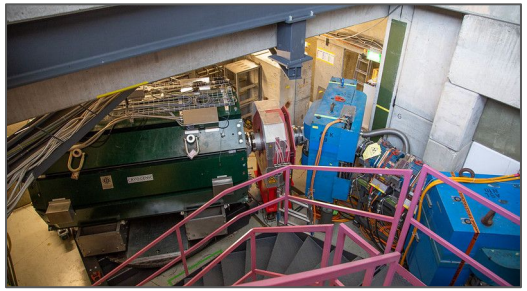
Building Mu3e

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









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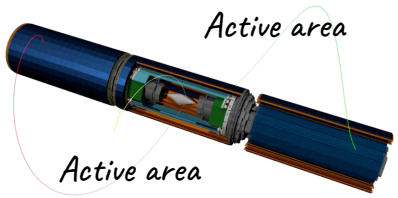
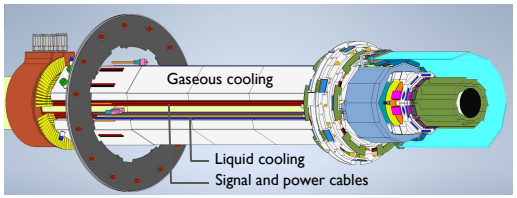
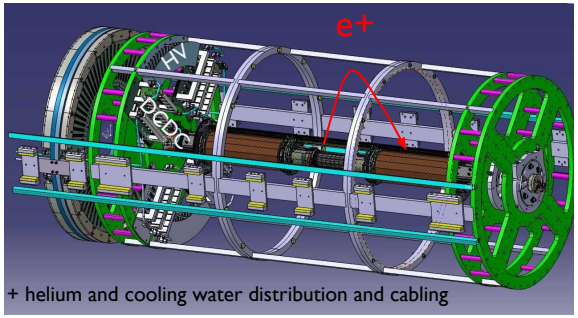
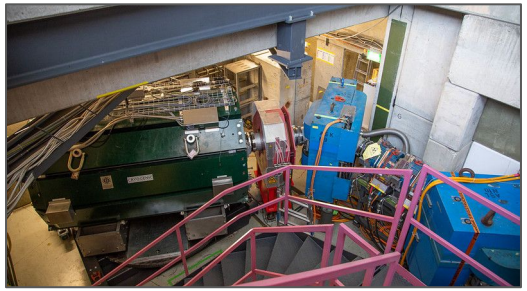




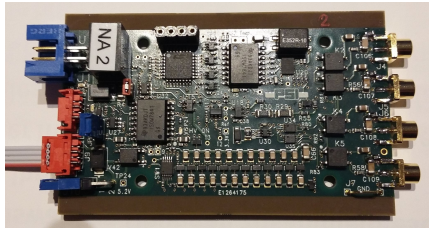


Mu3e detector services

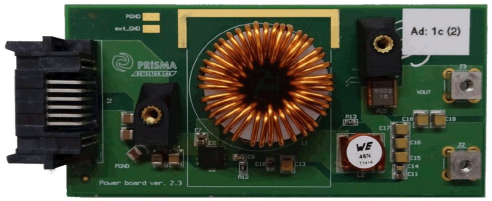
- ❑ Micro-twisted pair cable for each ASIC (LVDS)
- ❑ HV & LV channel for each detector module
- ❑ -15 °C liquid cooling for the MuTRIG ASIC and SiPMs
- ❑ Up to 5kW power to and from Frontend Boards and DC-DC
- ❑ Up to 5kW from and to the pixel detector



Custom HV

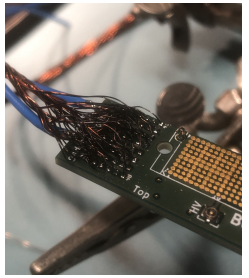


Custom DC-DC



Chillers

And a lot of cables



Building Mu3e

Zone outside of the tracker is active detector area
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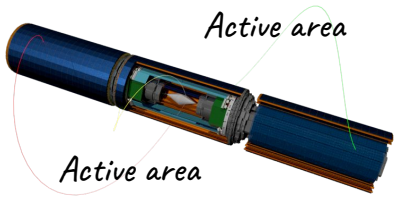

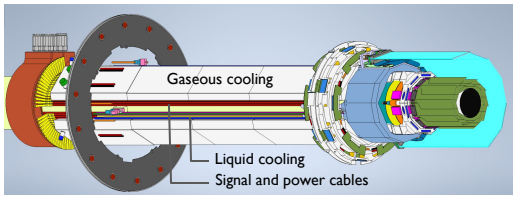

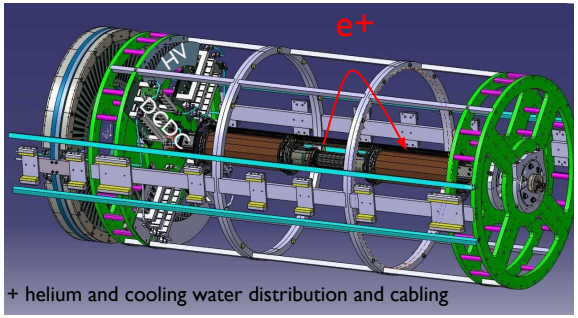

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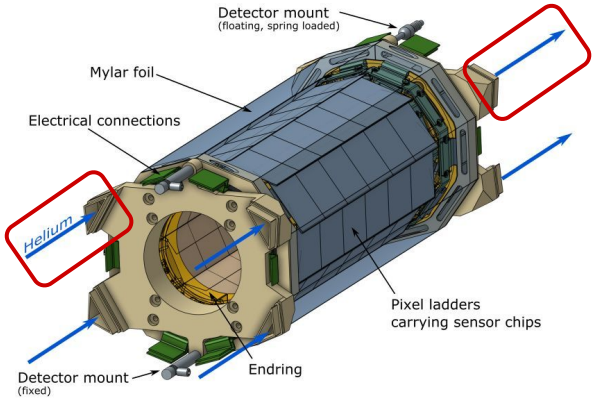
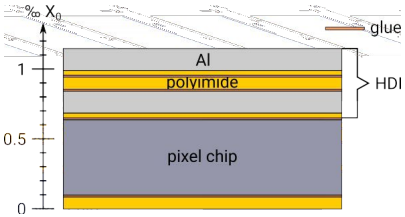
- Up to 5kW power to and from Frontend Boards and DC-DC
- **Up to 5kW from and to the pixel detector**
  - 200-400 mW/cm^2
  - No pipes, no liquids, …
  - Helium has almost the same volumetric heat capacity as air!
    - 50 g/s gaseous helium cooling system for the Mu3e pixel detector



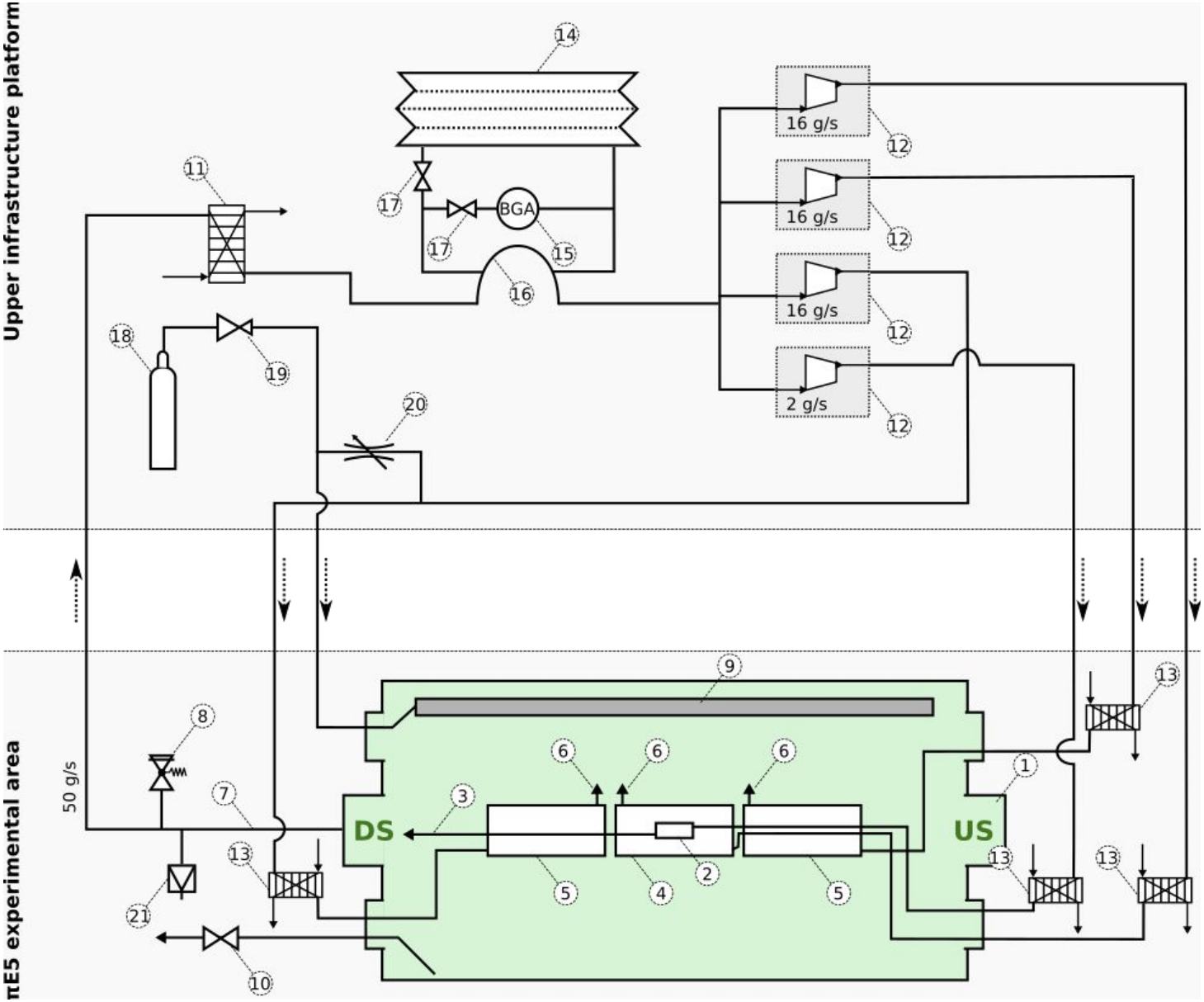


Compact turbo compressors with gas bearing for the circulation and compression of Helium.

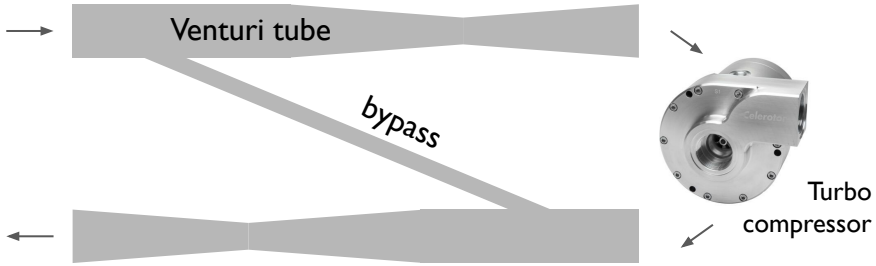
- High throughput
- Low compression ratio

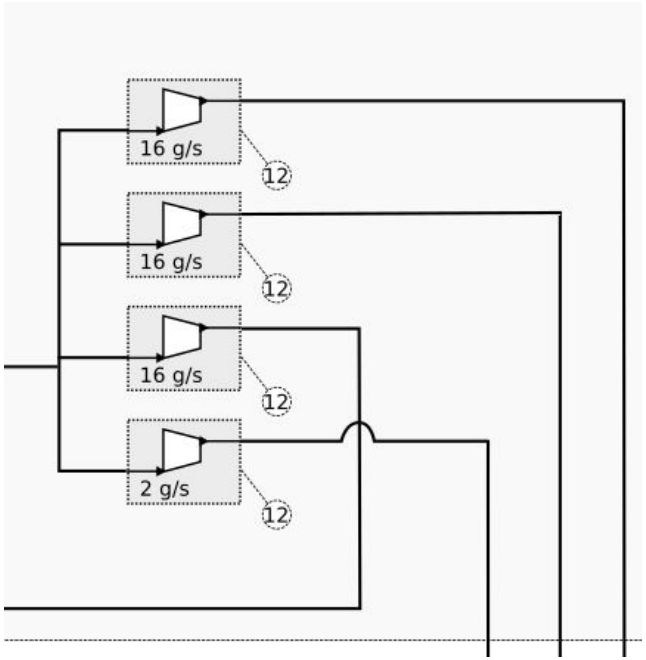
Entire System optimized for low pressure drops

Mu3e Cooling system

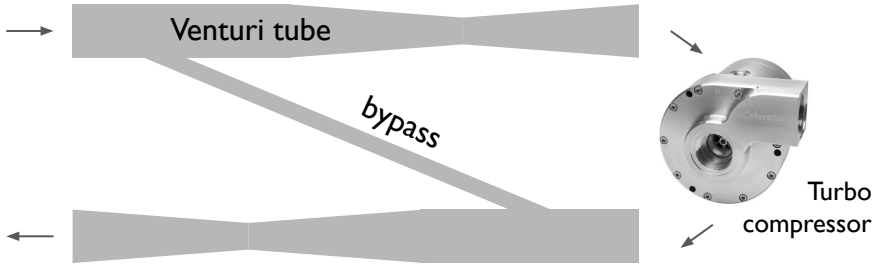


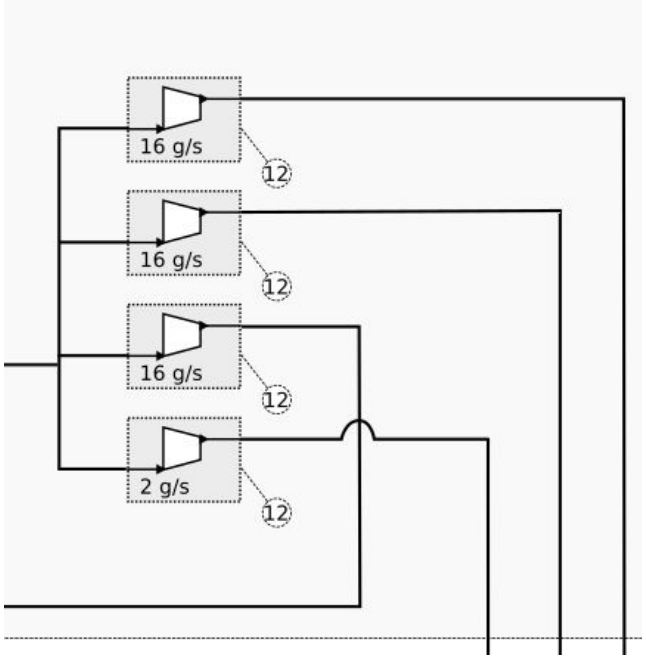
Mu3e Cooling system



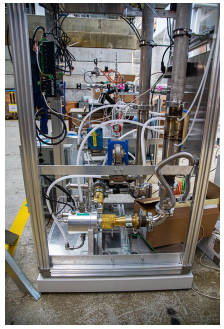


Mu3e Cooling system



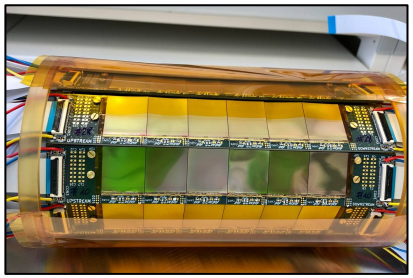


2g/s unit



+

Vertex detector



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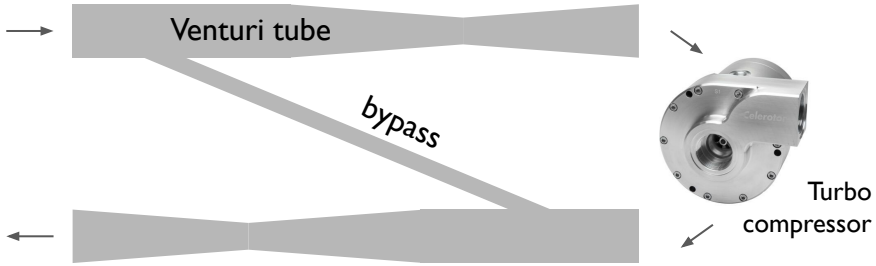
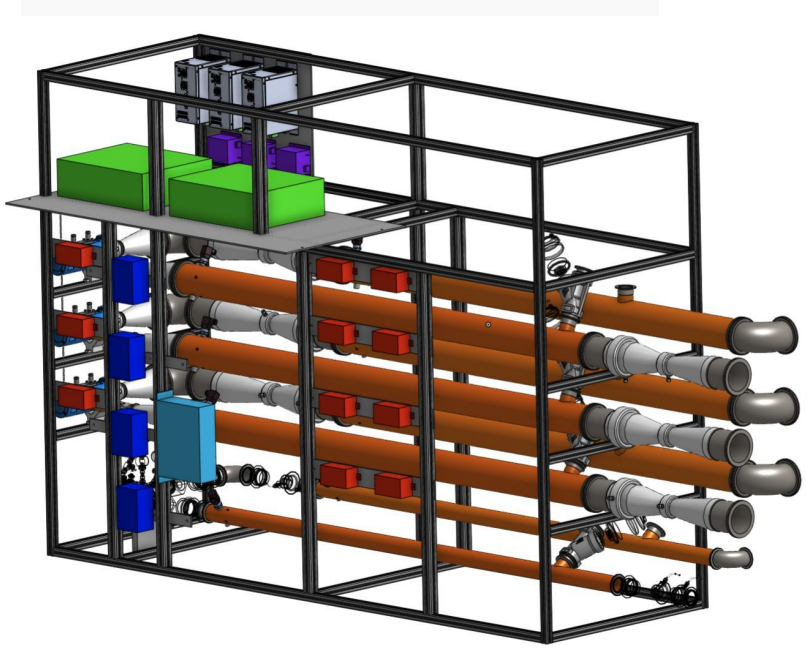
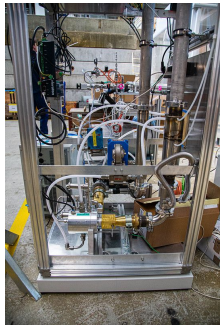
Successful cooling of a pixel tracker using gaseous helium
arXiv:2301.13813

Mu3e Cooling system



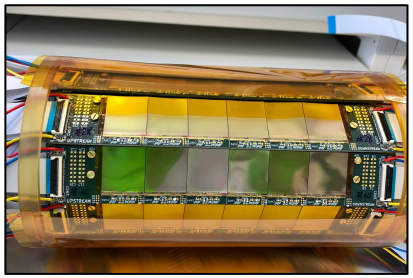


2g/s unit



+

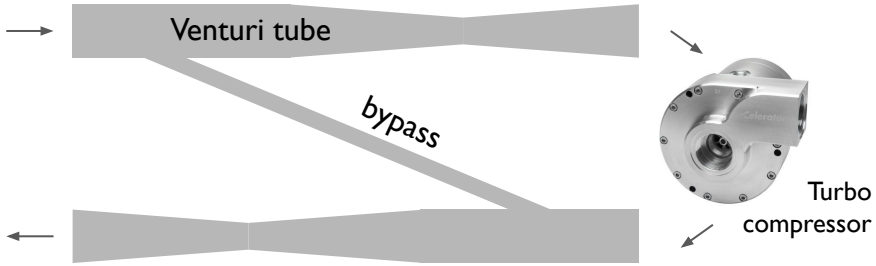
Vertex detector

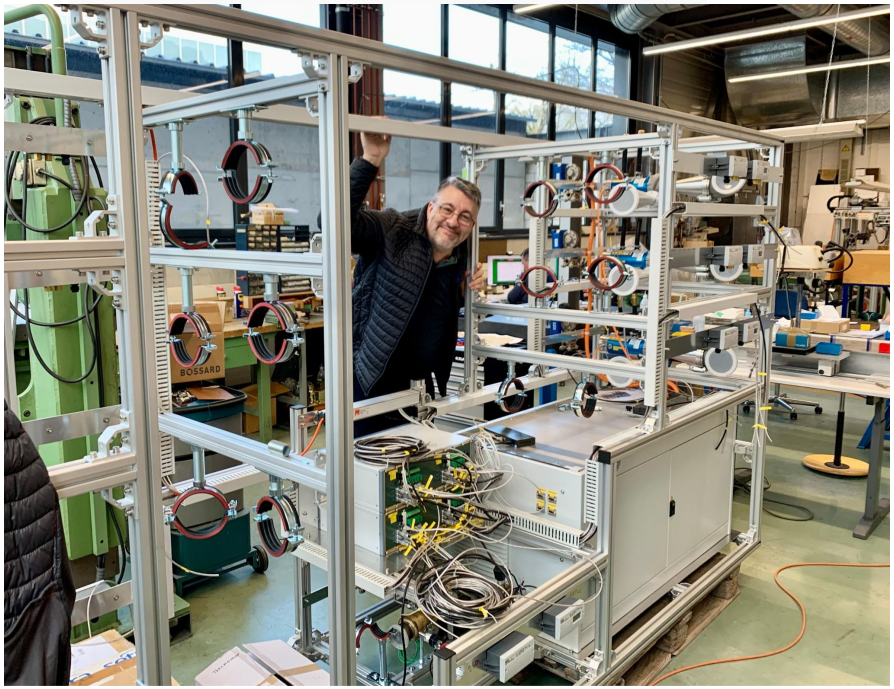


=

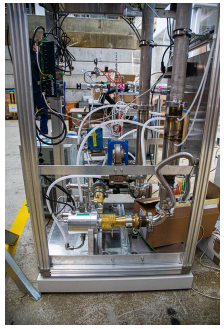
Successful cooling of a pixel tracker using gaseous helium
arXiv:2301.13813

Mu3e Cooling system



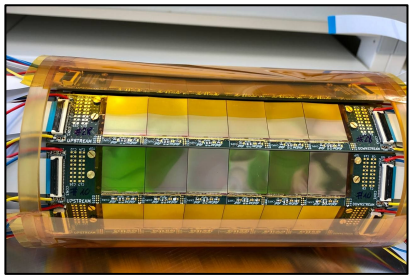


2g/s unit



+

Vertex detector



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Successful cooling of a pixel tracker using gaseous helium
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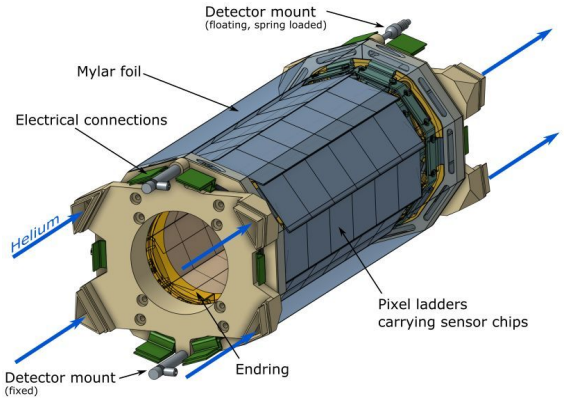
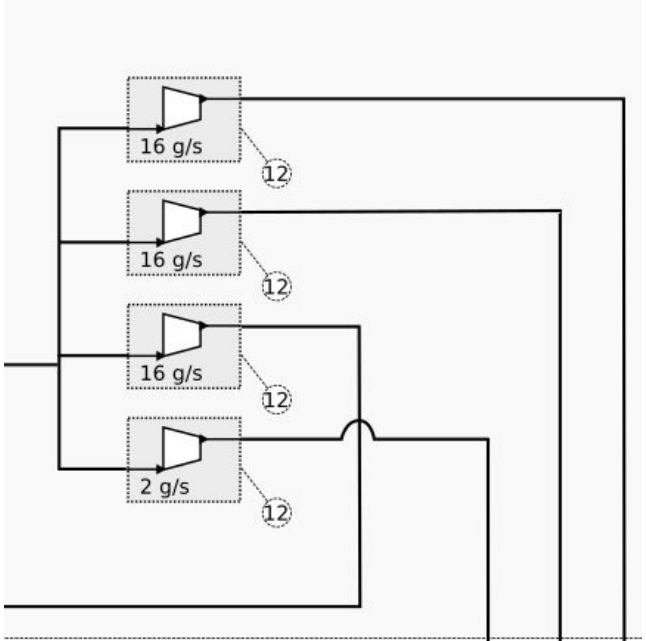
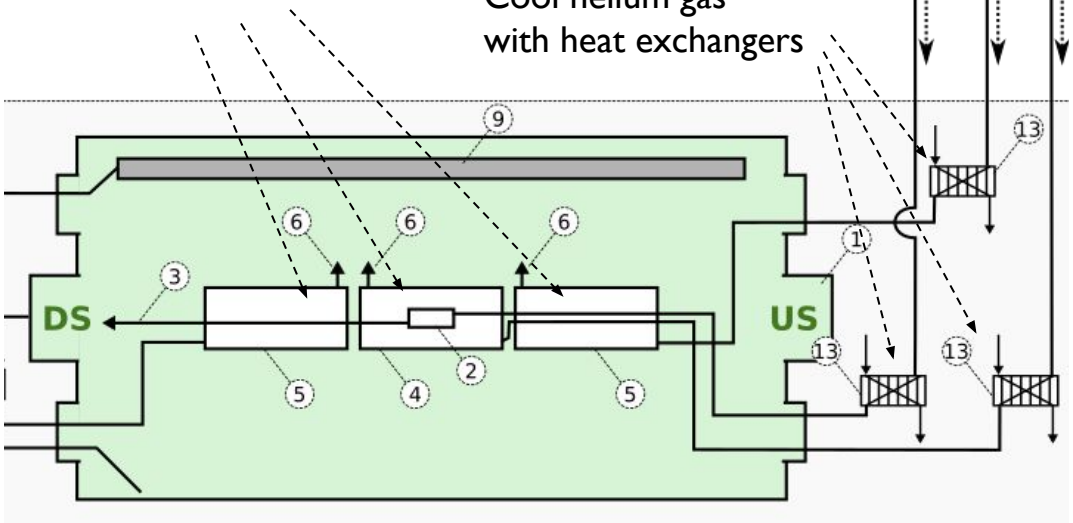
Mu3e Cooling system



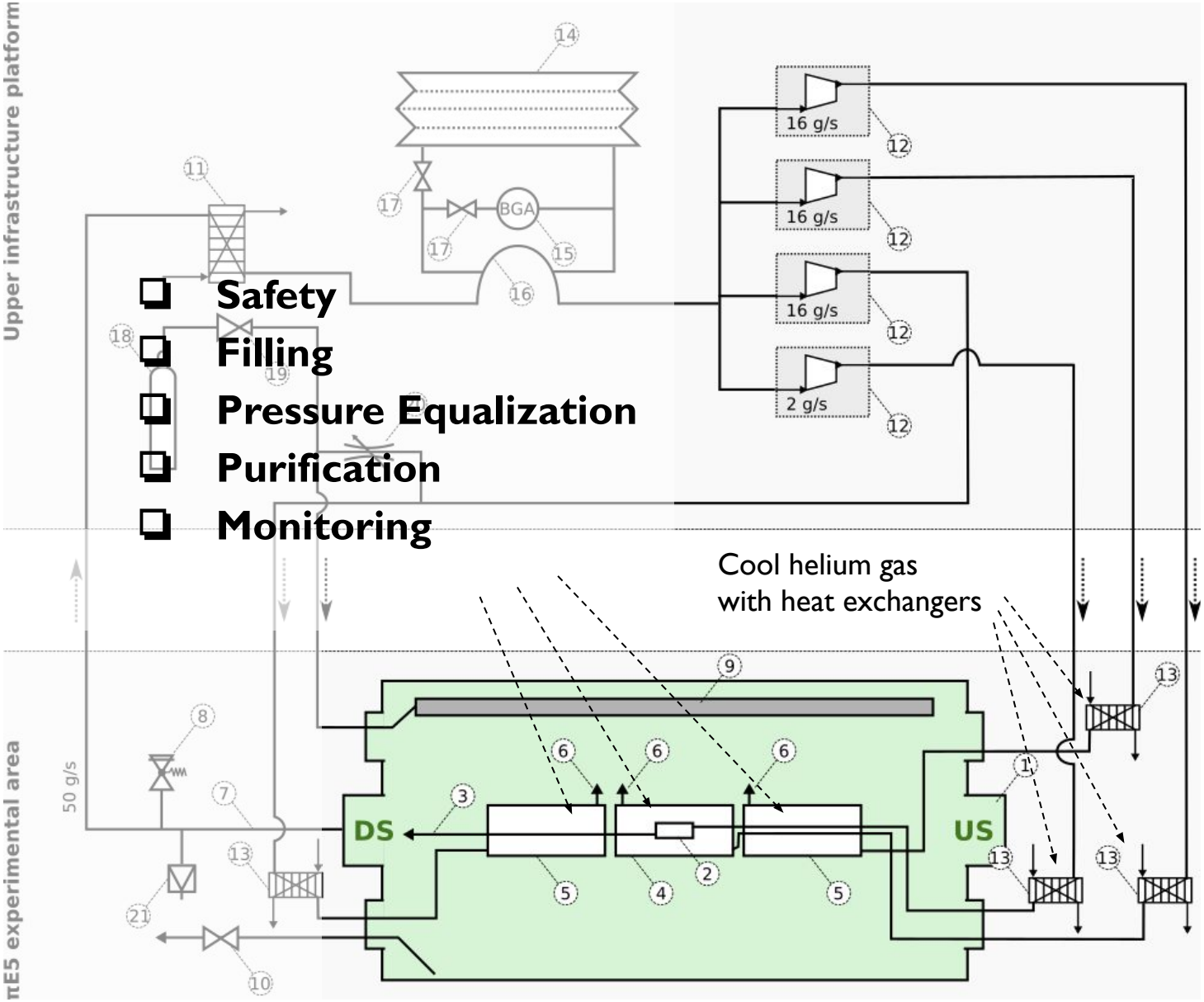
Helium flow for/between each detector barrel



Cool helium gas with heat exchangers

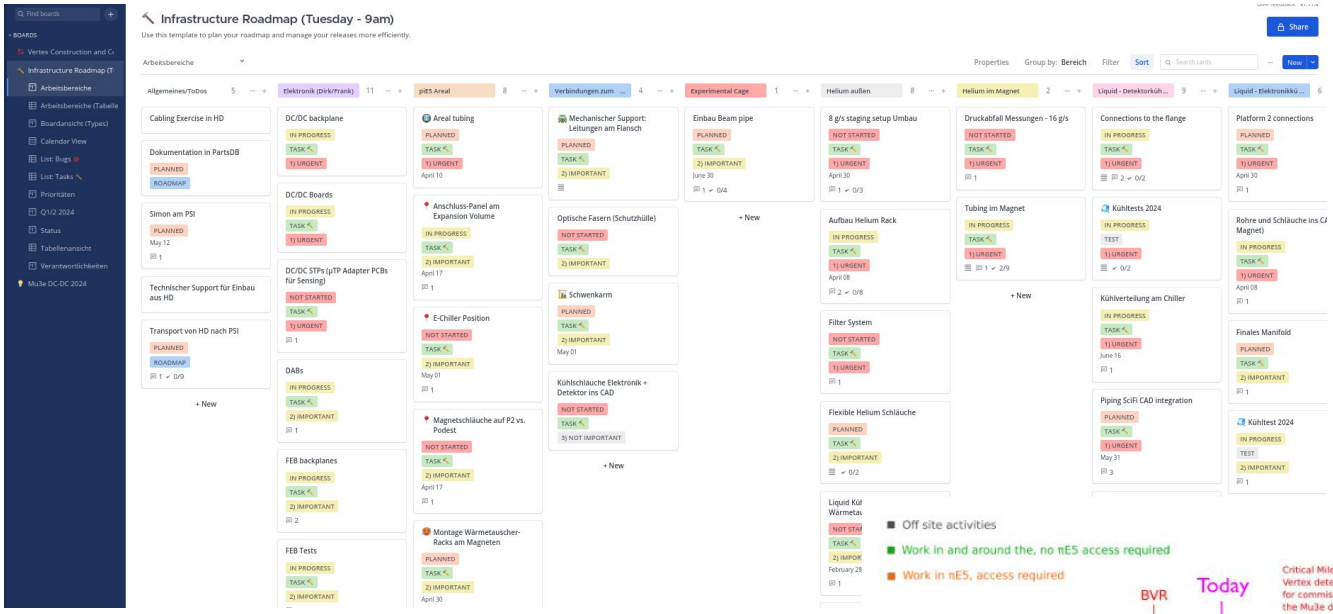


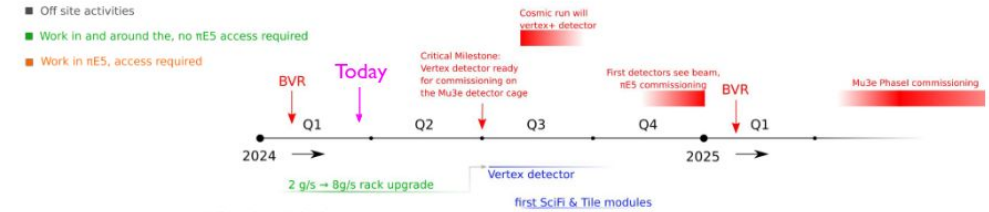
Mu3e Cooling system

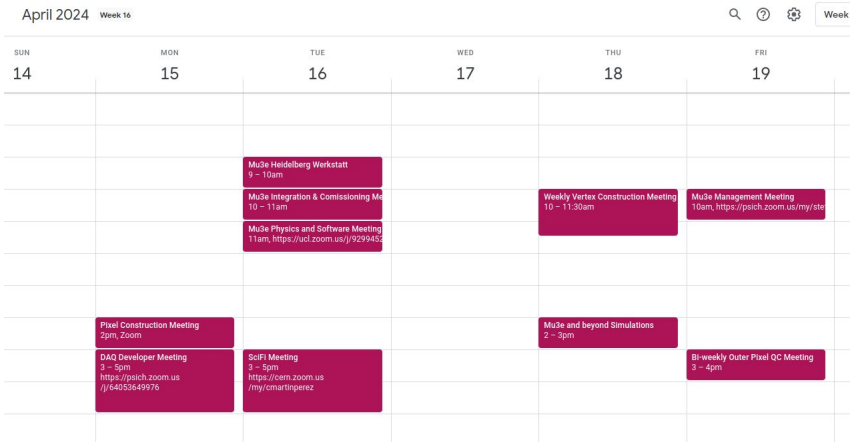


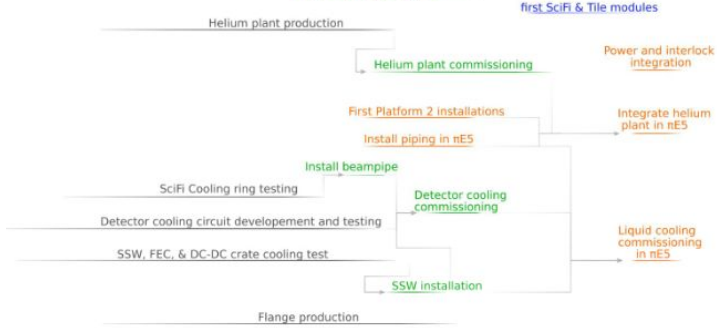
- Safety
- Filling
- Pressure Equalization
- Purification
- Monitoring

Building Mu3e

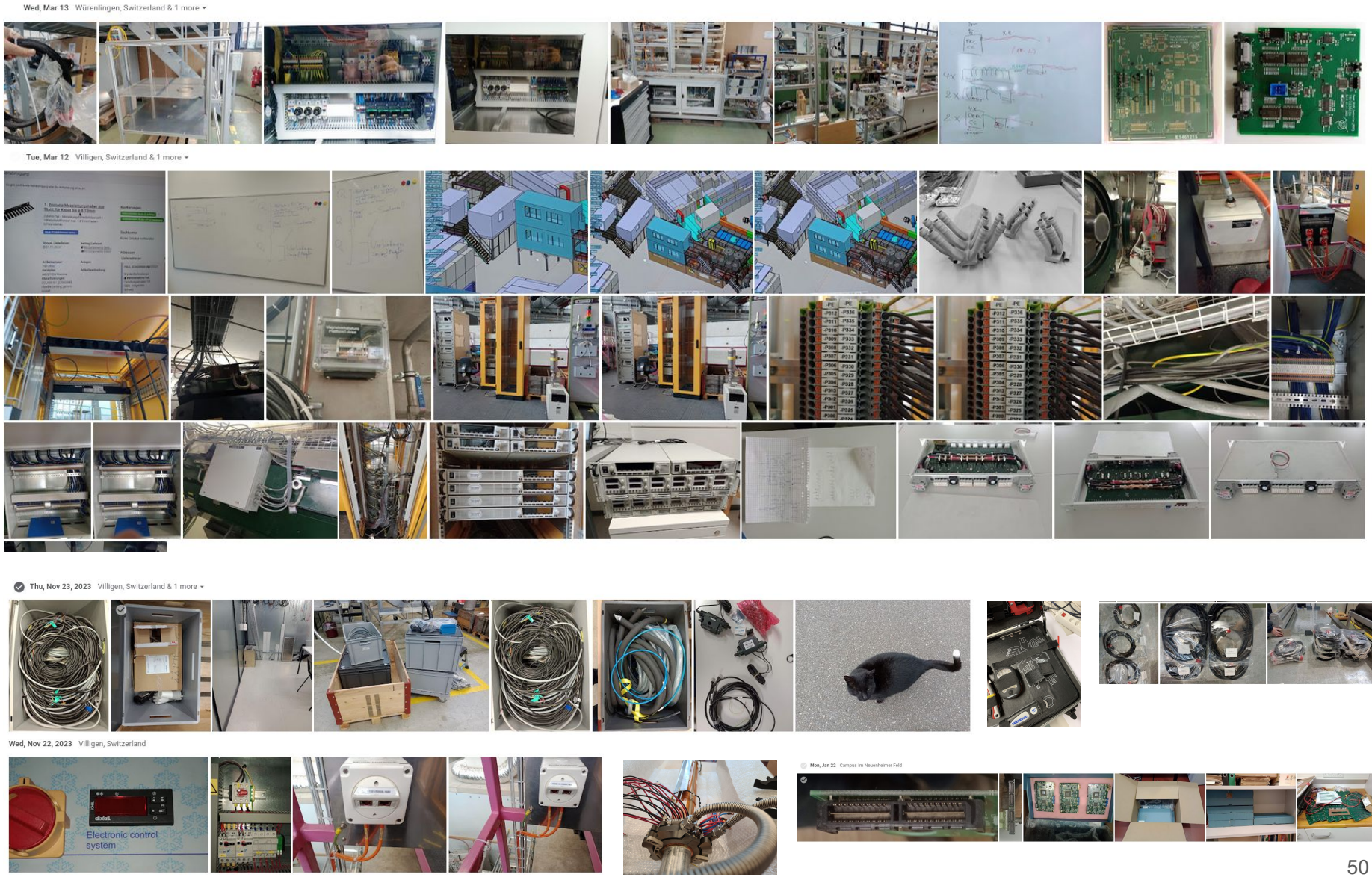






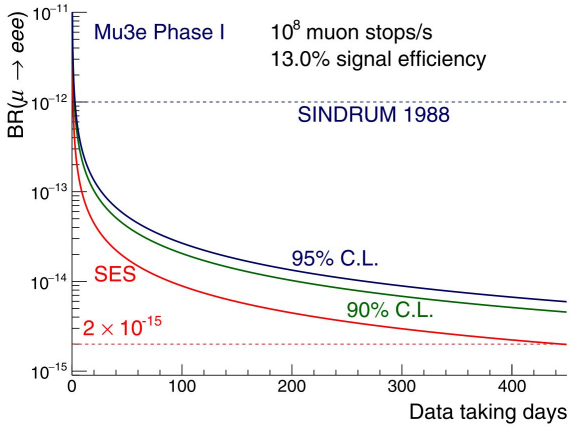


Building Mu3e



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



Mu3e phase I

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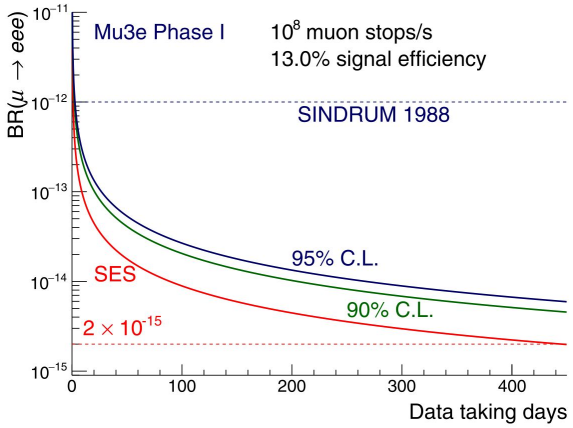
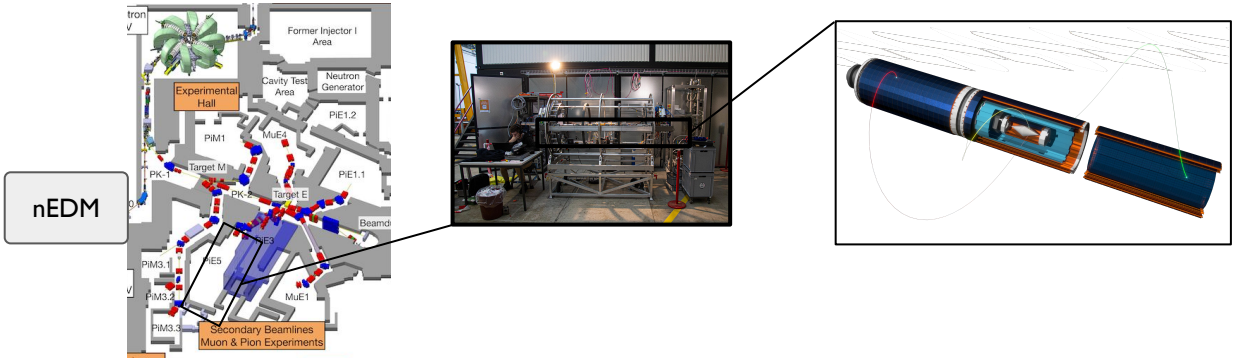


When you are at PSI, pay us a visit!



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

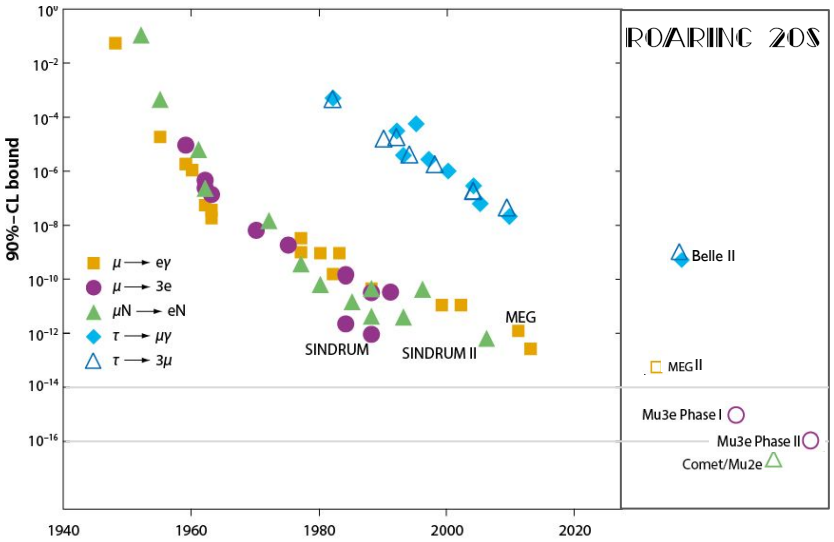
Mu3e phase II

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

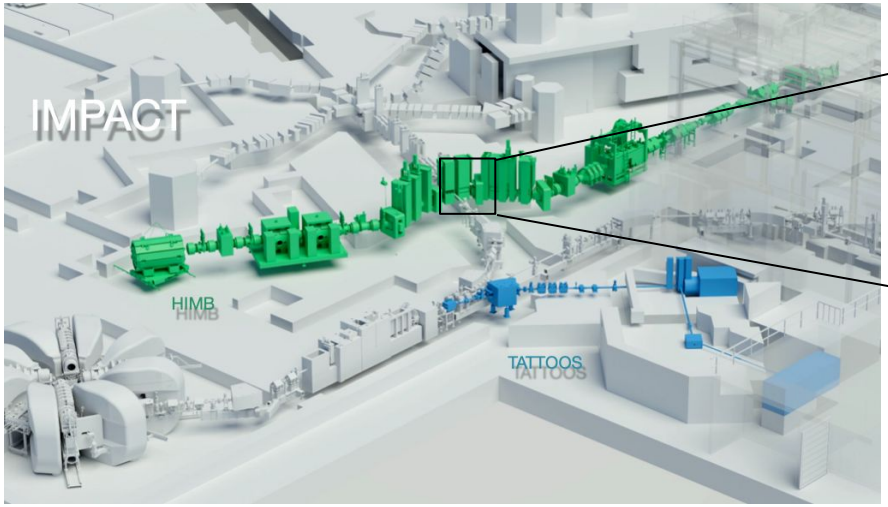


Mu3e one of the main physics cases for this next generation facility.

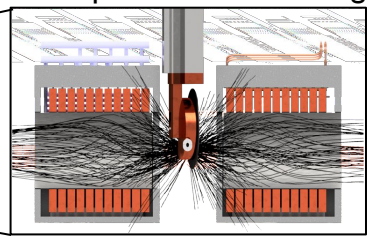
Science Case for the new High-Intensity Muon Beams HIMB at PSI
Edited by A. Knecht, F. Meier Aeschbacher, T. Prokscha, S. Ritt, A. Signer

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:

- ❑ Run at the πE5 CMBL
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Phase I, so there is a phase II?

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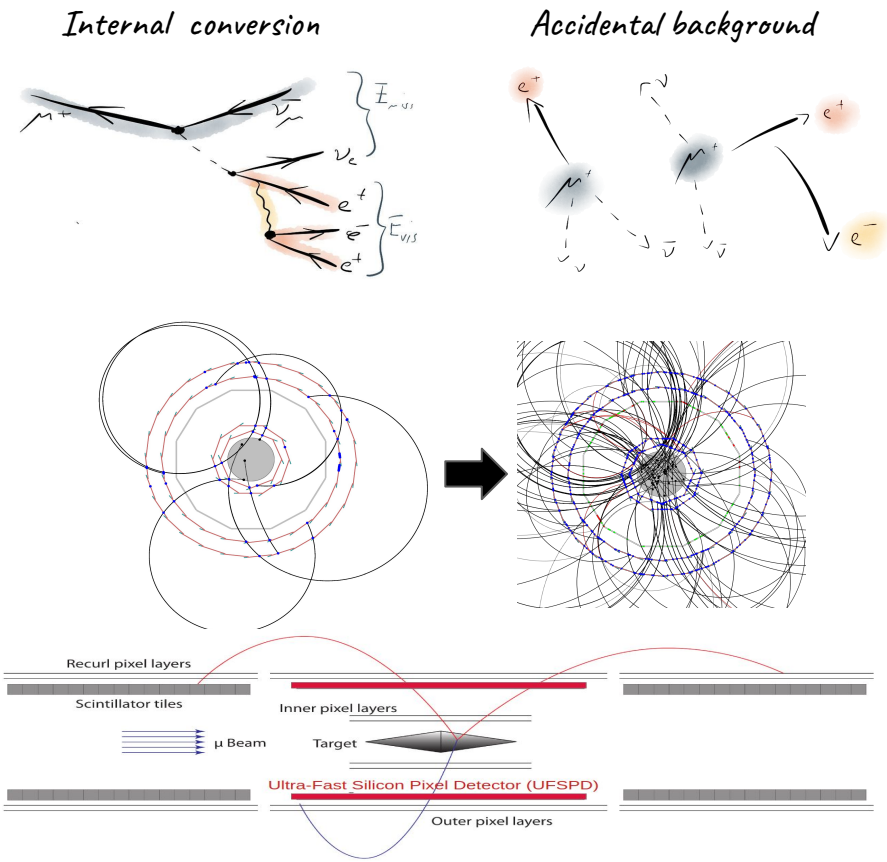
  ➜ HIMB

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 x 10^{-15} S.E.S in 400 days

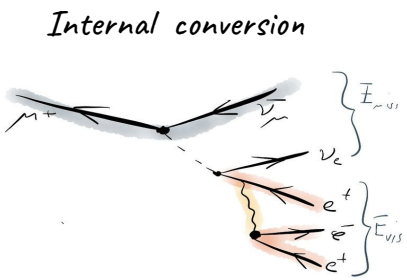
Phase I, so there is a phase II?

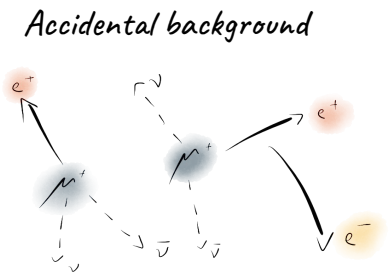
- ❑ Reach 10^{-16} S.E.S. on $\mu^+ \to e^+e^+e^-$
- ❑ Can not run at the existing beamline, Need 10^9 μ^+/s on target
  ➜ HIMB

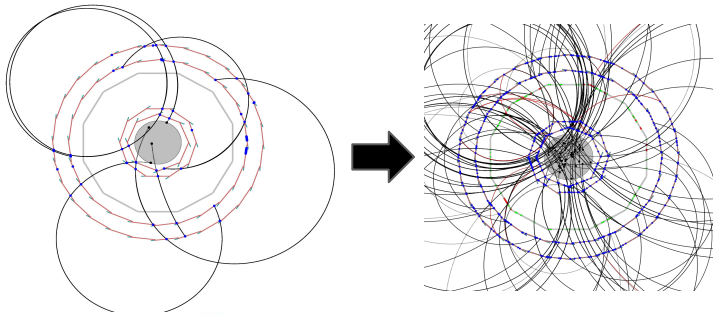
Mu3e Phase II Challenges:

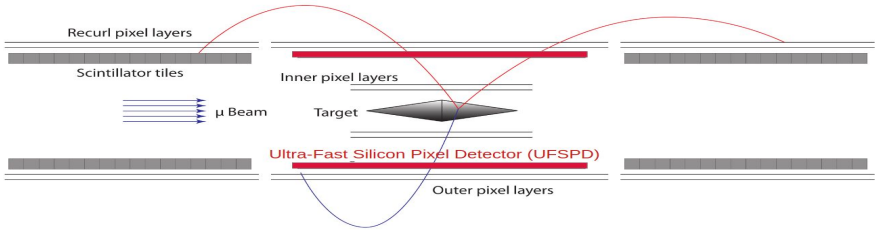
- ❑ Internal conversion goes with #muons
  → Thinner (total material budget) ~~Fibre Detector~~
- ❑ Accidental goes with #muons^2
  → Faster (silicon sensors)
  → Smal
  → Larg
- ❑ As does
  → Smal
- ❑ Large p

With Phase I&II detector







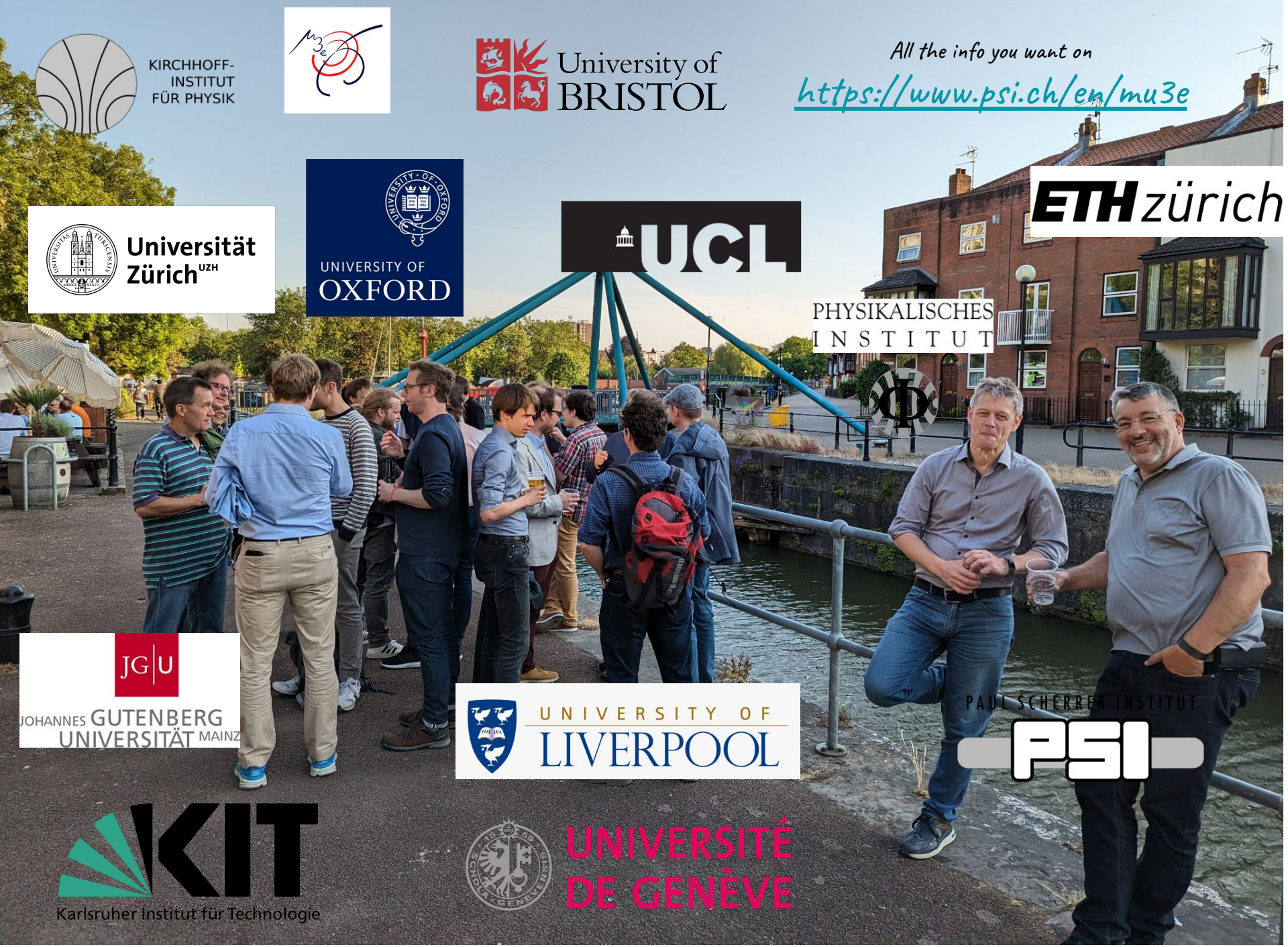


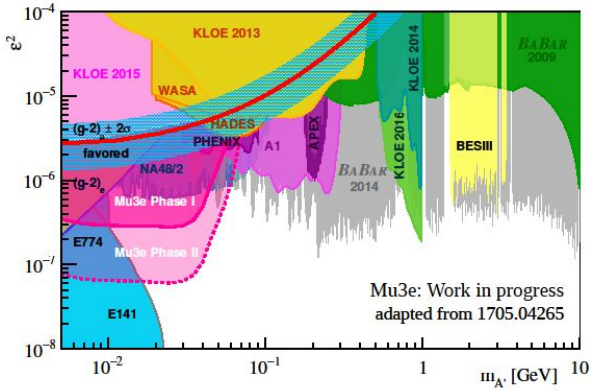
➡ Most of the Phase I detector needs a redesign
➡ We need new, fast the active pixel detector

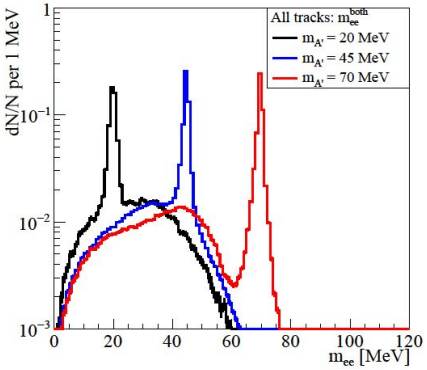
Mu3e beyond $\mu^+ \to e^+e^+e^-$

- $\mu^+ \to e^+\gamma \to e^+e^+e^-$ with γ-conversion layer
- $\mu^+ \to e^+$ + exotic particle

Snowmass paper


KIRCHHOFF-
INSTITUT
FÜR PHYSIK
University of
BRISTOL
All the info you want on
https://www.psi.ch/en/mu3e
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





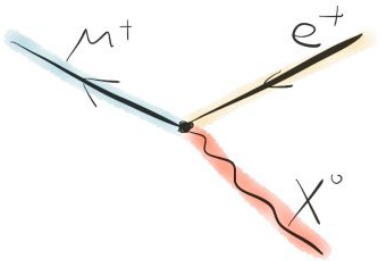
Other Exotic Physics with Mu3e

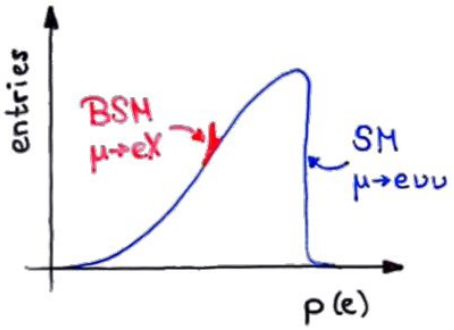
Familons

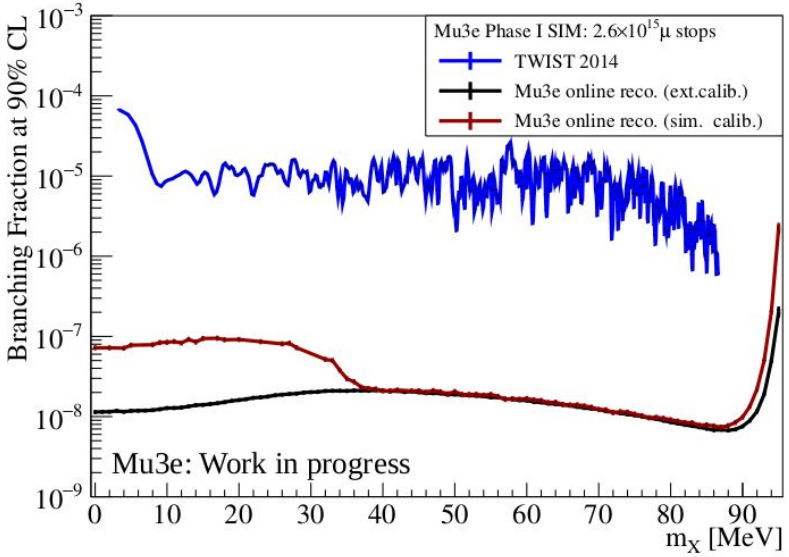
Karlsruhe Institute of Technology

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)

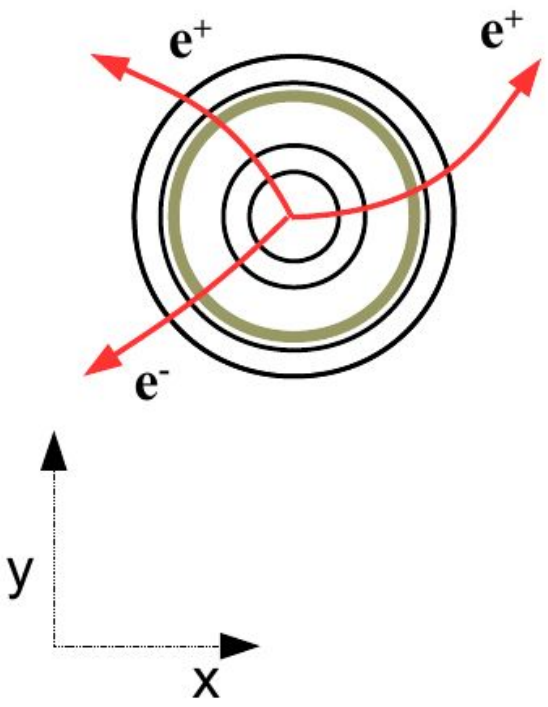




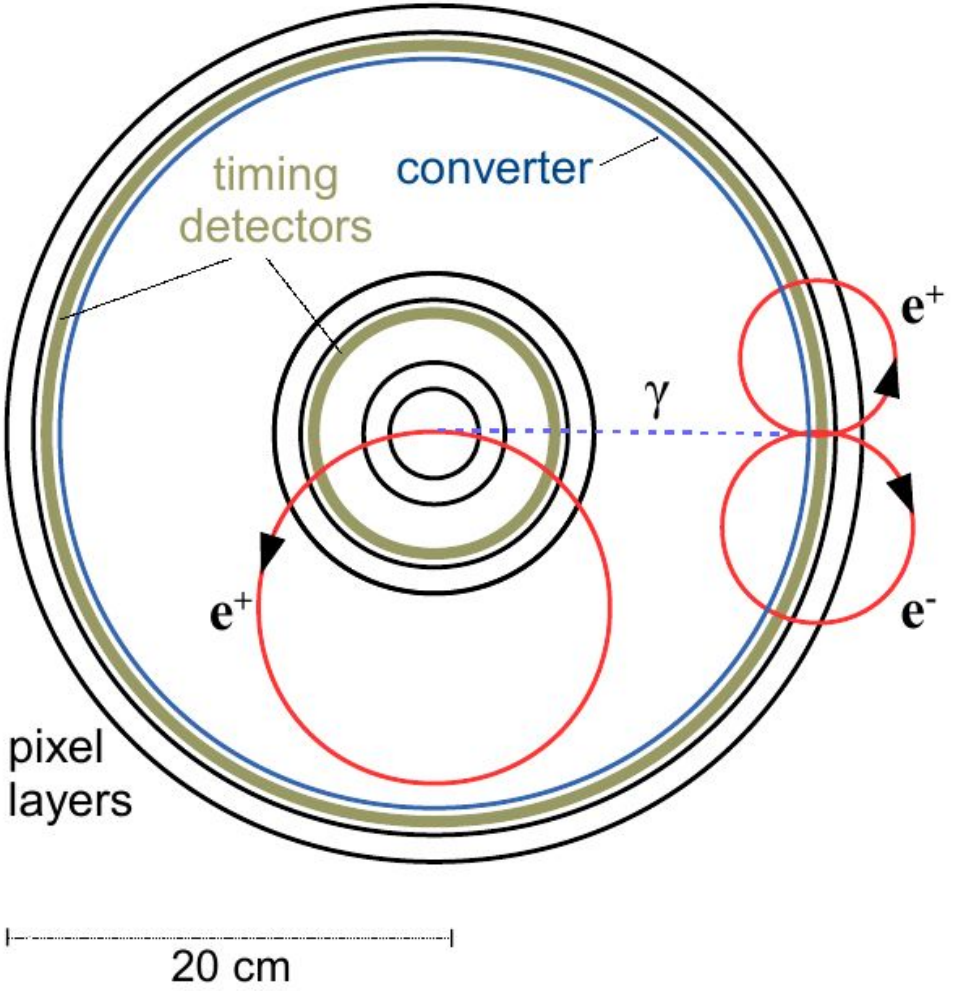


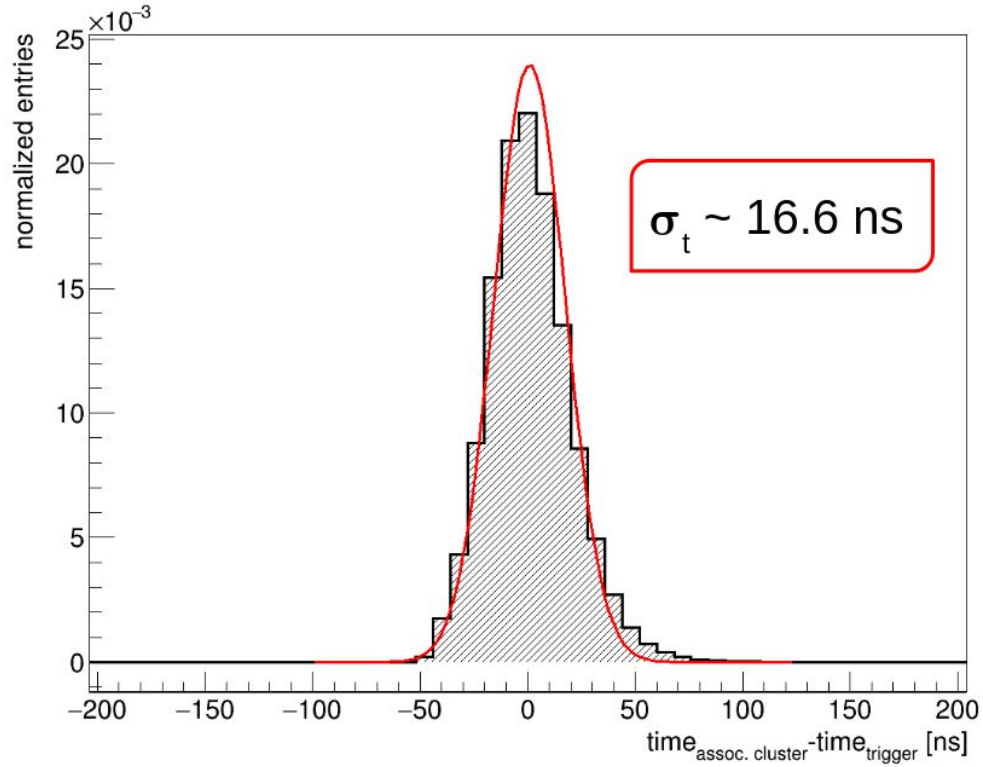
- Challenge: single-e events are not saved
- Histogramming on filter farm

Mu3e (B=1 Tesla)



Mu3e-gamma (B=2 Tesla)




normalized entries
×10⁻³
25
20
15
10
5
0
−200
−150
−100
−50
0
50
100
150
200
σt ~ 16.6 ns
time assoc. cluster -time trigger [ns]

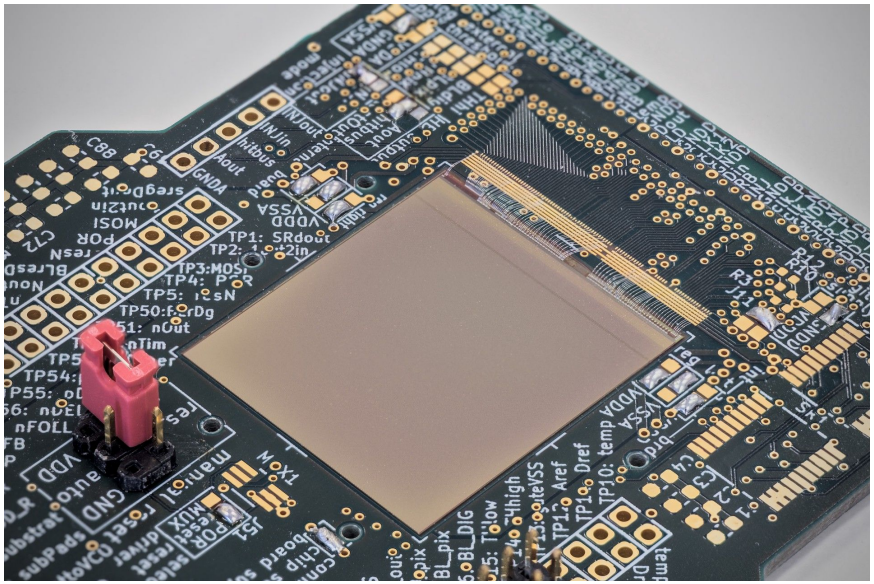


Table 22.1
Efficiency of the various reconstruction and analysis steps.

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%

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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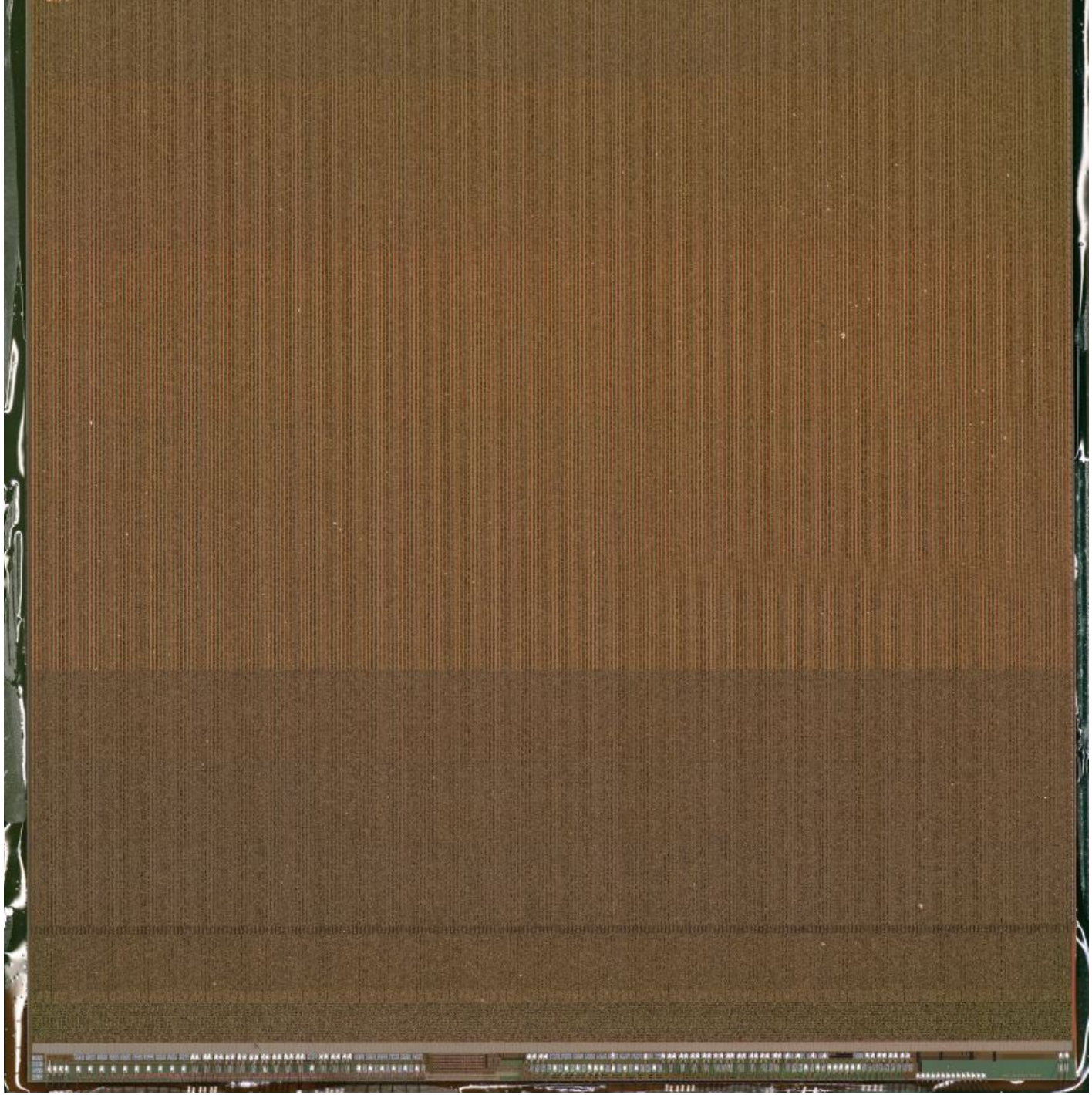
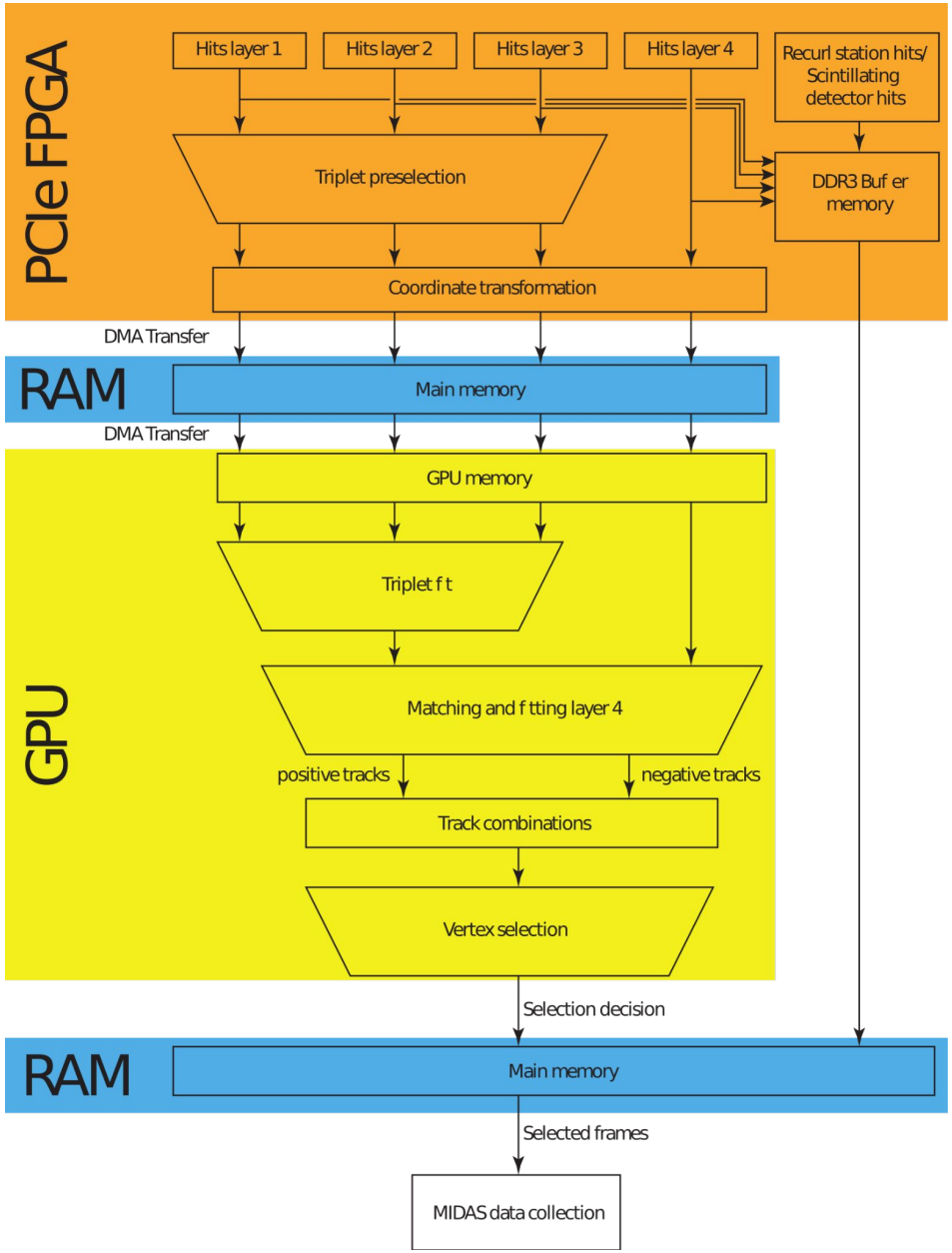
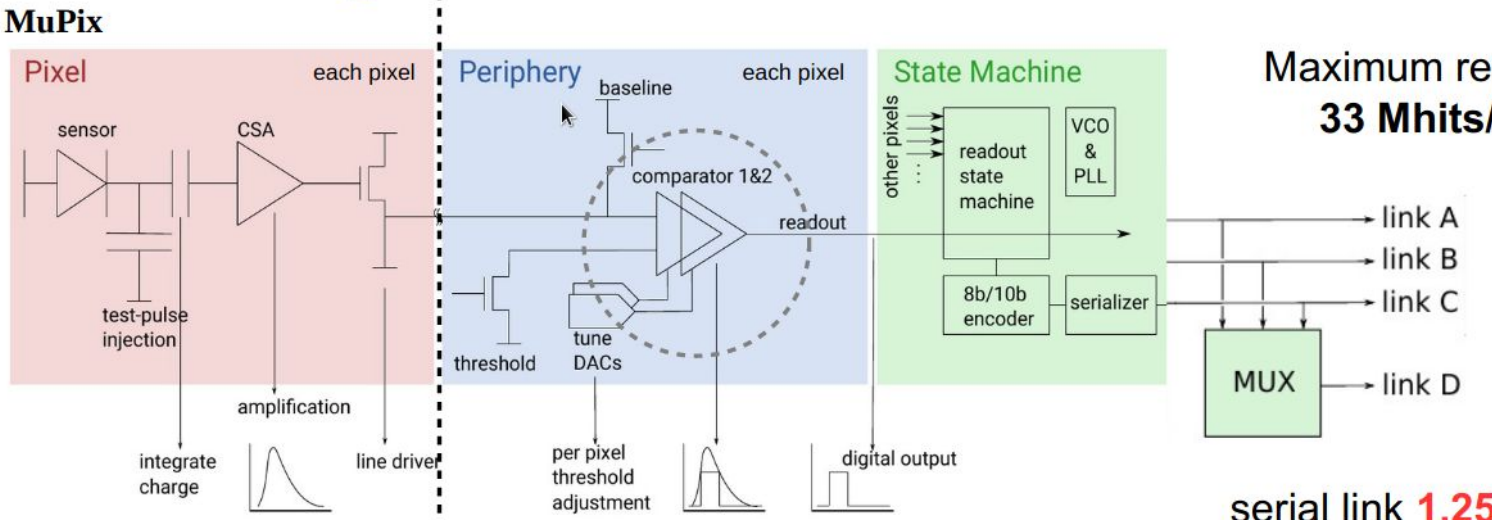
Radiation length	X_0	36.6	94.3	g/cm^2		[**pdg**]
		304	5670	m	20 °C, 1013 mbar	calc




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


GTX980

High Rate & Continuous Readout



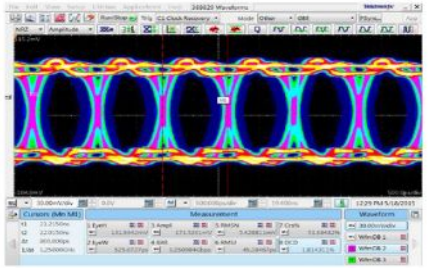
Maximum readout rate is **33 Mhits/s** per link

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

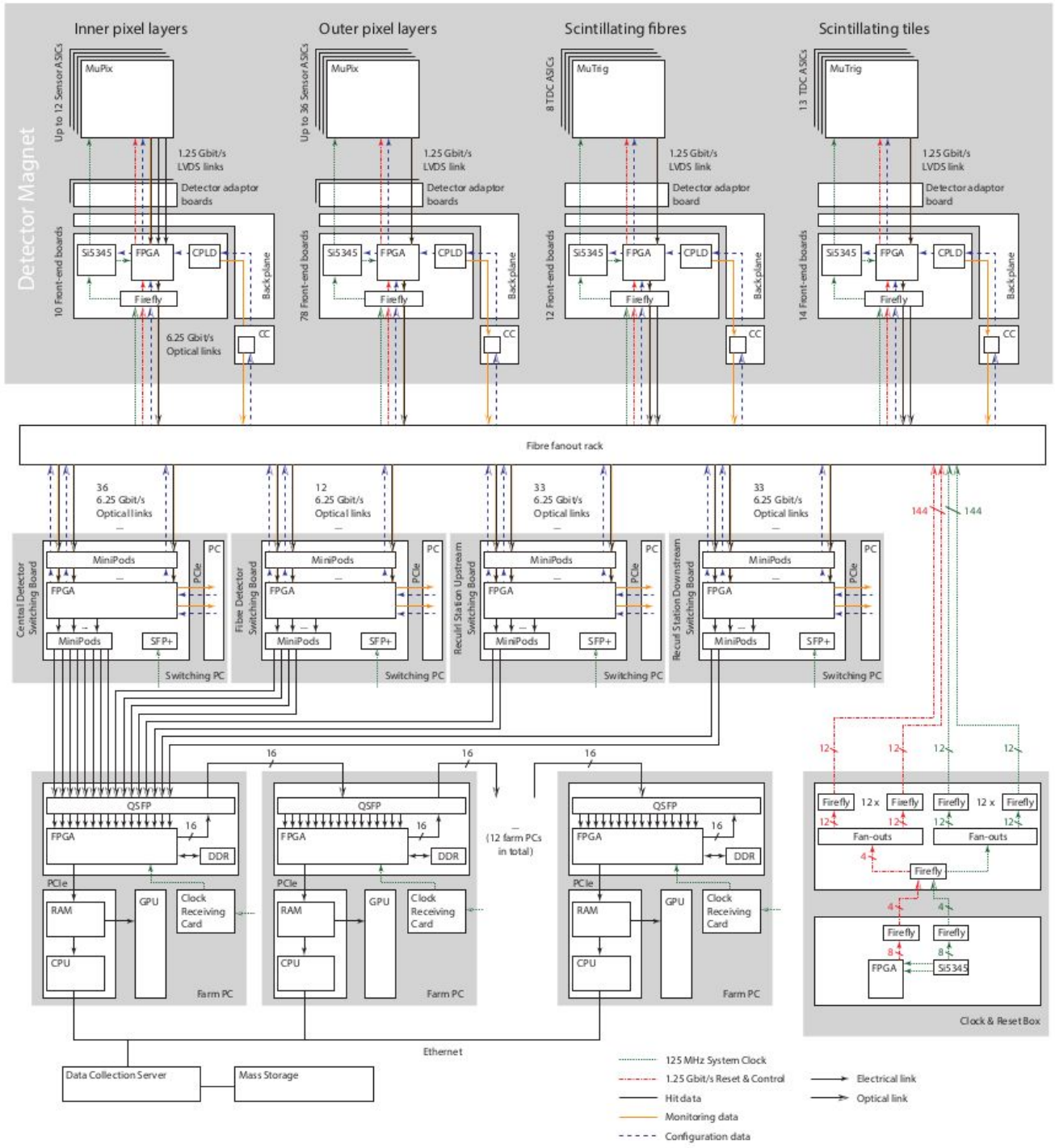
MuPix8 sensor

periphery & SM

eye diagram



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


Inner pixel layers
Outer pixel layers
Scintillating fibres
Scintillating tiles
Detector Magnet
Up to 12 Sensor ASICs
Up to 36 Sensor ASICs
8 TDC ASICs
13 TDC ASICs
MuPix
MuTrig
1.25 Gbit/s LVDS links
Detector adaptor boards
Detector adaptor board
10 Front-end boards
28 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
33 6.25 Gbit/s Optical links
144
MiniPods
PCIe
PC
SFP+
Central Detector Switching Board
Fibre Detector Switching Board
Recuil Station Upstream Switching Board
Recuil Station Downstream Switching Board
Switching PC
QSFP
DDR
RAM
GPU
CPU
Clock Receiving Card
Farm PC
(12 farm PCs in total)
Firefly
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