The Mu3e experiment:
Status and short-term plans

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UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

Aims of the talk:

Design

From theoretical motivation to experimental design.

Construction

Update on the construction of each subdetector.

Short-term plans

Cosmic run.
First physics run.

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Physics of Mu3e: Lepton Flavour Violation

Charged Lepton Flavour Violation (cLFV):

- Neutrinos (ν) oscillate…
  - Consequently, lepton flavour violated…
  - Need to adapt the Standard Model (SM) to account for this → νSM.
- Implications:
  - cLFV possible through higher order processes but **highly supressed**
  - Still, cLFV impossible at tree level in ν SM.

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Opens "box of Pandora" for physicists…

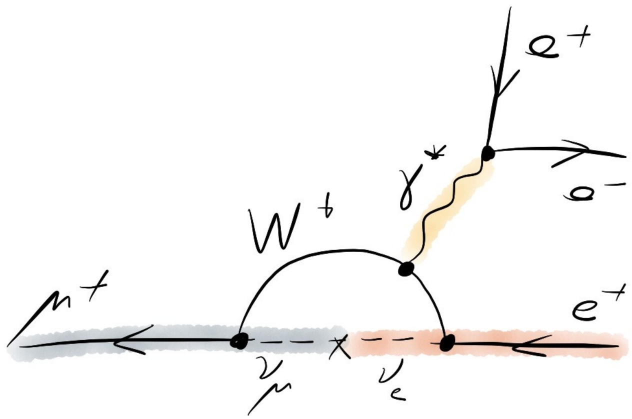
$\mu^+ \to e^+e^+e^-$	(Mu3e @ PSI)
$\mu^+ \to e^+\gamma$.	(MEG @ PSI)
$\mu^- + N \to e^- + N$	(Mu2e @ Fermilab, COMET @ JParc)
$\tau^+ \to e^+/\mu^+\ \gamma$	(Belle 2 @ KEK)
$\tau^+ \to \mu^+\ \mu^+\ \mu^-$	(LHC @ CERN)

Further infos: A. El-Khadra Talk

Physics of Mu3e: $\mu^+ \rightarrow e^+e^+e^-$

Mu3e aims to look for the Charged Lepton Flavour Violation decay: $\mu^+ \rightarrow e^+e^+e^-$

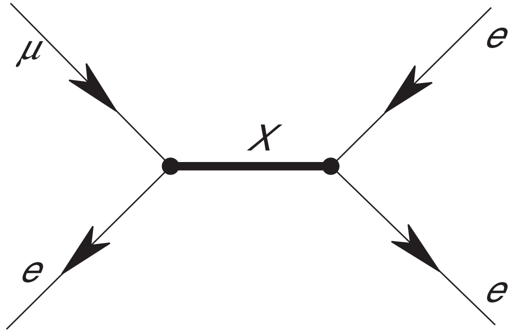
- $\mu^+ \rightarrow e^+e^+e^-$ … Technically allowed in the νSM but highly supressed (O^{50})
- Any sign of $\mu^+ \rightarrow e^+e^+e^-$ would imply physics Beyond the Standard Model (BSM) as decay is strongly supressed in SM.
- Possible mechanism: Supersymmetric particles etc…



Further infos: S. Middleton Talk

Further infos: A. El-Khadra Talk

Further infos: T. Menzo Talk



Previous attempts to measure $\mu^+ \rightarrow e^+e^+e^-$

See latest results from MEG 2 [here]

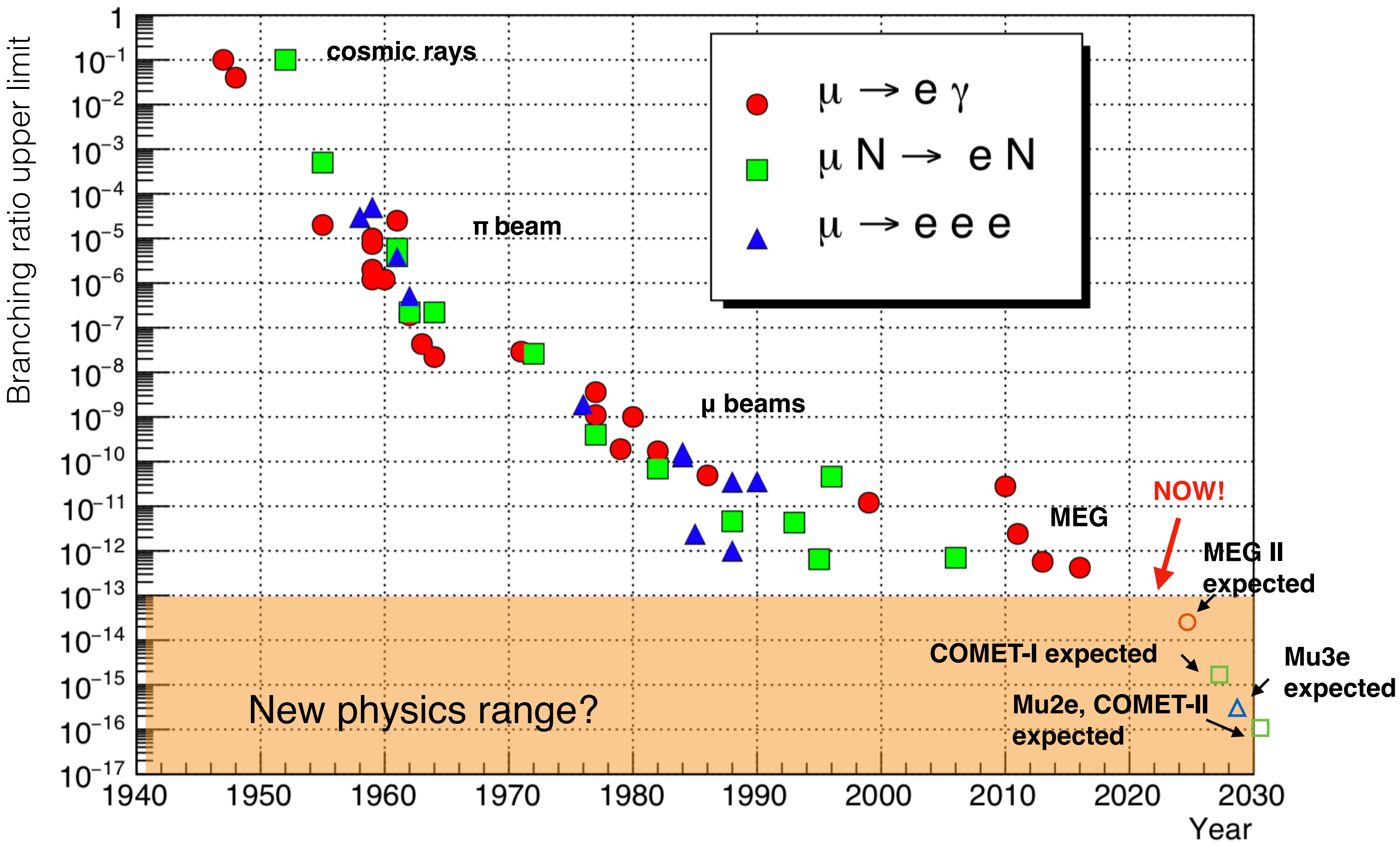
- Processes like :
  - $\mu^+ \rightarrow e^+ \gamma$,
  - $\mu^- N \rightarrow e^- N$,
  - $\mu^+ \rightarrow e^+ e^- e^+$

    → **not observed!**
- Best limits on LFV come from PSI muon experiments
  - $\mu^+ \rightarrow e^+ e^- e^+$

    BR < 1 x 10^{-12} (SINDRUM, 1988)
  - $\mu^- Au \rightarrow e^- Au$

    BR < 7 x 10^{-13} (SINDRUM II, 2006)
  - $\mu^+ \rightarrow e^+ \gamma$

    BR < 3.1 x 10^{-13} (MEG II, 2024)



Callibbi and Signorelli, Riv. Nuovo Cimento, Vol. 41 (2018) 71 (updated by MDG)

Current and future CLFV searches

Process	Current Sensitivity	Future
$\mu \rightarrow e\,\gamma$	$< 4.2\ 10^{-13}$ (MEG)	$\sim 10^{-14}$
$\mu \rightarrow e\,e\,e$	$<1.0\ 10^{-12}$ (SINDRUM)	$\sim 10^{-16}$ (Mu3e)
$\mu\,A \rightarrow e\,A$	$< 7\ 10^{-13}$ (SINDRUM II)	$\sim 10^{-16}$ (COMET, Mu2e)
$\tau \rightarrow l\,\gamma$	$3.3\ 10^{-8}$ (Babar)	10^{-9} (Belle 2)

Limits reached by beam rate capabilities and high rates of irreducible background!

Complementarity between “golden” channels

Challenge lies in plenty of operators (90 + with EFT).

- ***Eur.Phys.J.C82(2022)9,836*** describes the three muon processes through 6 terms only…
- Each term contributes to the three channels through certain physics.

$$
\begin{aligned}
\delta\mathcal{L} \;=\; \frac{1}{\Lambda^2_{LFV}}\Big[& C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re) + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re) \\
& + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]
\end{aligned}
$$

Λ_2^{LFV} = heavy mass scale term, S = Scalar, V = Vector, D = Dipole

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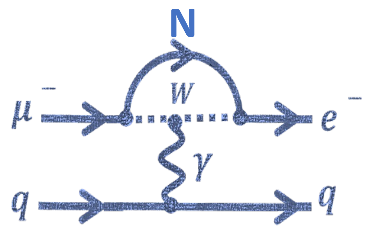
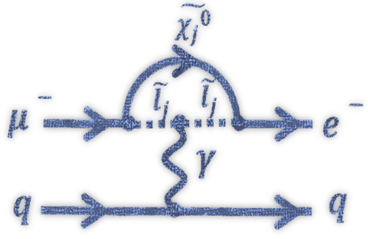
Dipole term:

- Mediates μ → e γ
- Contributes to μ → eee and μ A→ e A



Heavy Neutrinos

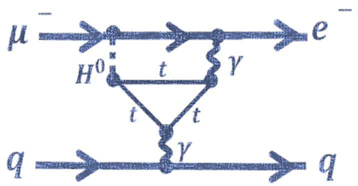
$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



SO(10) SUSY

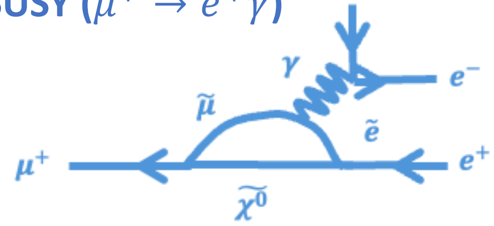
Rate ~ 10^{-15}

2 Higgs Doublets



$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$

SUSY ($\mu^+ \to e^+\gamma$)



***See Eur.Phys.J.*C82(2022)9,836 for further details on theory. Feynman diagram credits [S. Middleton Talk, NuFact 2024]**

Complementarity between "golden" channels

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Contact scalar term.
Leading order contribution to μ → eee.
Heavily suppressed for the others.

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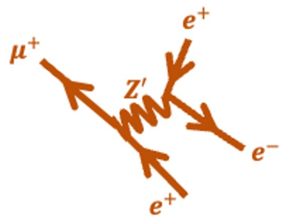

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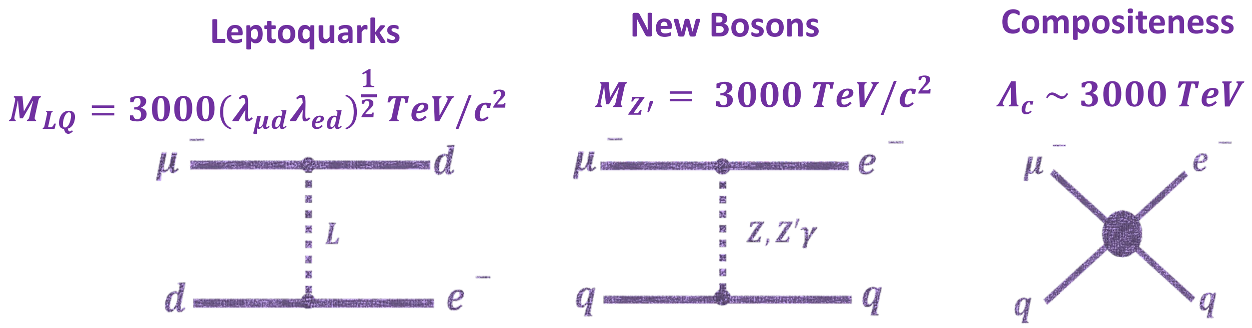
Quark contact term
Leading order contribution to μ A→ e A
Heavily suppressed for μ → eee.



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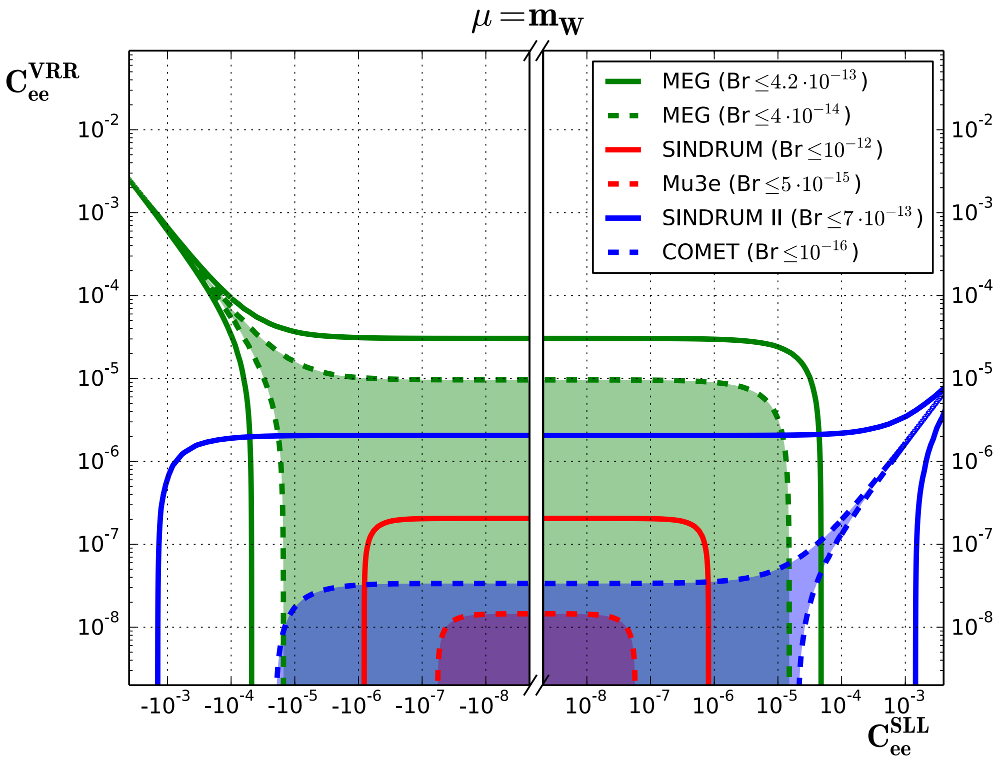
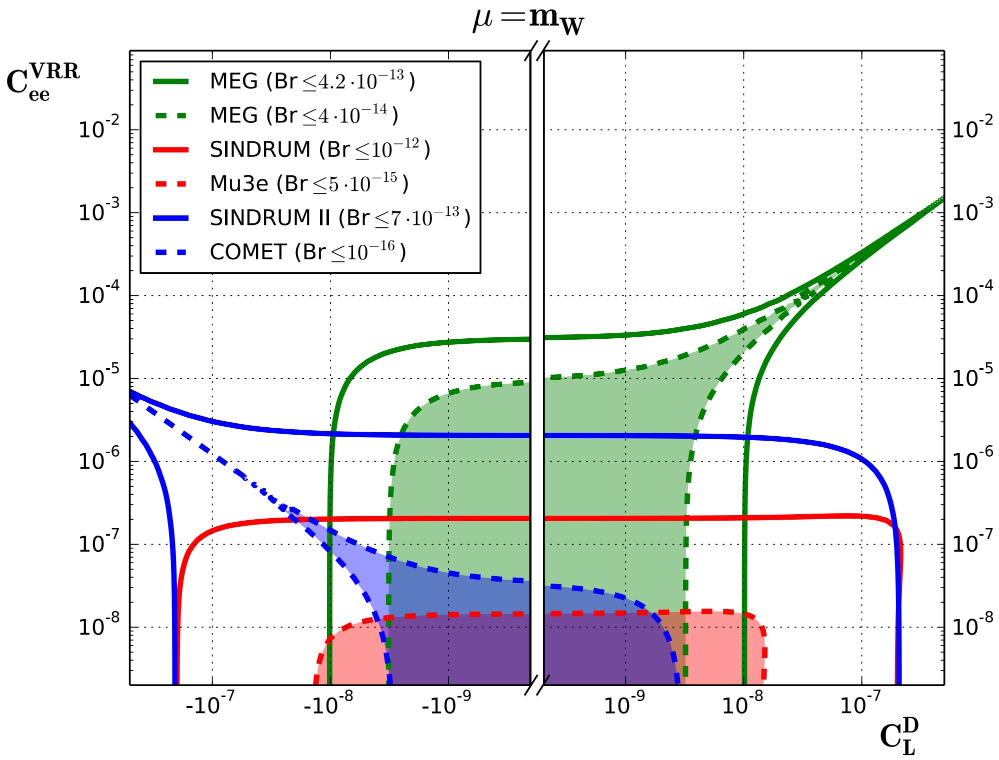




https://arxiv.org/abs/2204.00001

Wilson coefficients: $C_{ee}^{V\,RR}, C_{ee}^{S\,LL}, C_L^D$

V vector type, S scalar type interaction

C_L^D dypole interaction contributes to all

Complementarity between "golden" channels

All channels are sensitive to several new physics models.
Rates are going to be model dependent, therefore experiments can rule out certain physics models.

Mode	$\mu^+ \to e^+ e^+ e^-$	$\mu^- N \to e^- N$	$\frac{BR(\mu^+ \to e^+ e^+ e^-)}{BR(\mu^+ \to e^+ \gamma)}$	$\frac{BR(\mu^- N \to e^- N)}{BR(\mu^+ \to e^+ \gamma)}$
MSSM	Loop	Loop	~ 6×10^{-3}	$10^{-3} - 10^{-2}$
Type I Seesaw	Loop	Loop	$3 \times 10^{-3} - 0.3$	0.1-10
Type II Seesaw	Tree	Loop	$(0.1 - 3) \times 10^{3}$	10^{-2}
Type III Seesaw	Tree	Tree	~10^{3}	10^{3}
LFV Higgs	Loop	Loop	10^{-2}	0.1
Composite Higgs	Loop	Loop	0.05-0.5	2-20

Slide adapted from S. Middleton's talk at NuFact 2024

Design

From theoretical motivation to experimental design.

Construction

Update on the construction of each subdetector.

Mu3e physics

Potential physics directions with Mu3e.

Prerequisites for a $\mu^+ \rightarrow e^+e^+e^-$ experiment

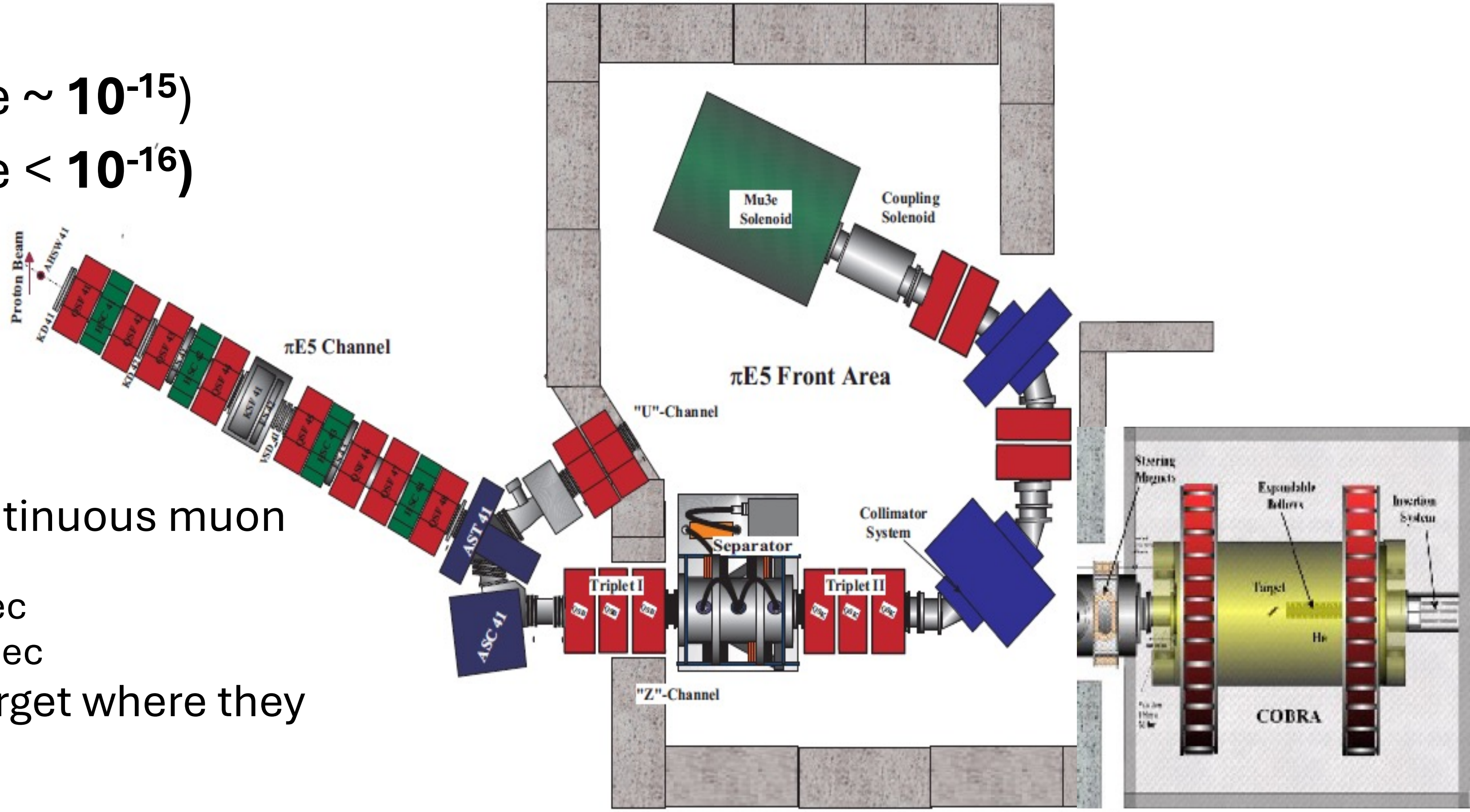
Physics goals of Mu3e:

- Phase 1 goal: $B(\mu \rightarrow eee \sim \mathbf{10^{-15}})$
- Phase 2 goal: $B(\mu \rightarrow eee < \mathbf{10^{-16}})$

Need ~ 10^{16} muon decays for phase 1.

Only one option:

- World's highest intensity continuous muon beam (πE5 @ PSI)
  - Phase 1: ~10^8 muon stops/sec
  - Phase 2: >10^9 muon stops /sec
- Muons stopped on hollow target where they decay.



muon rates of 1.4×10^8 μ / s achieved in the past

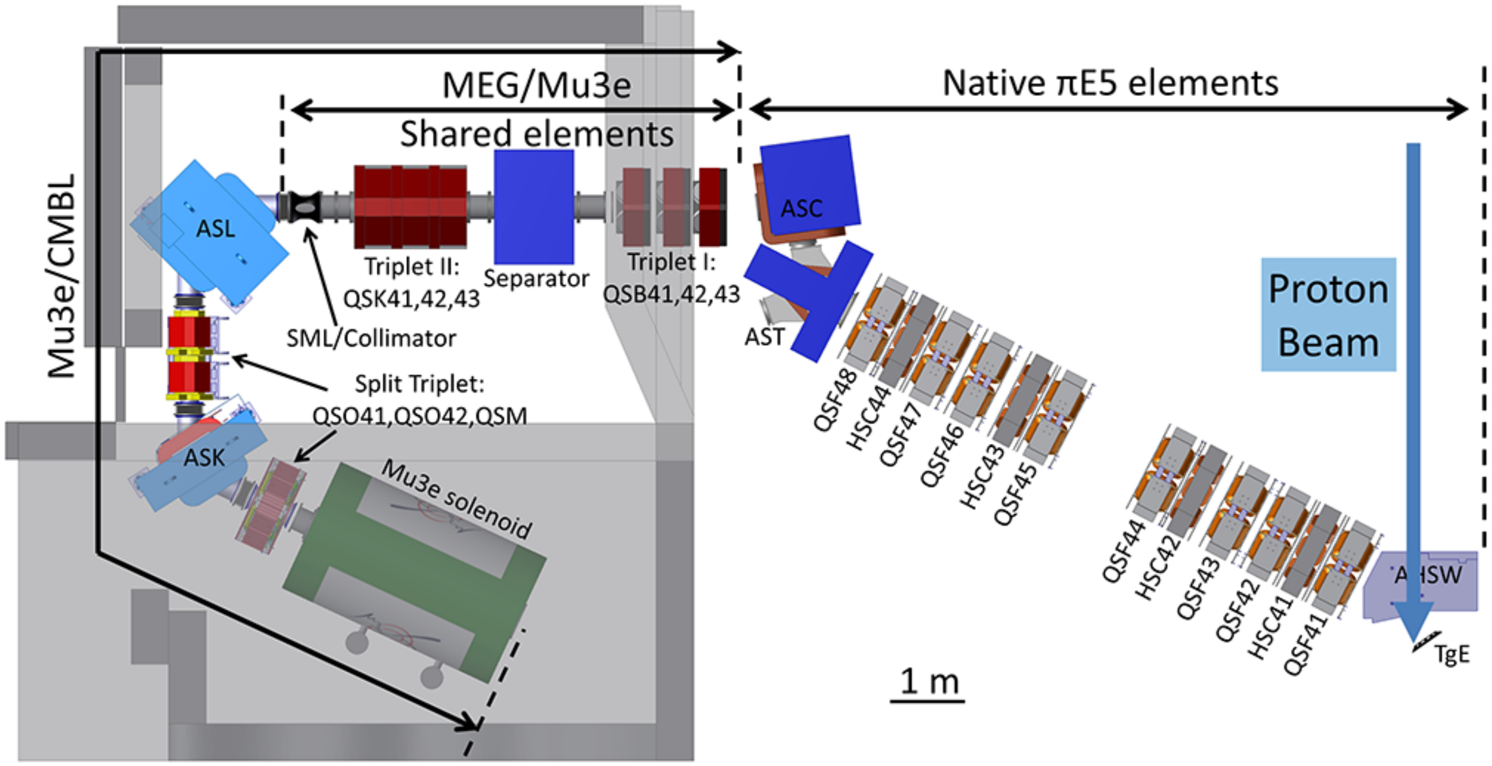
The πE5 beam at PSI

The High Intensity Proton Accelerator Complex (HIPA):

- 1.4 MW power
- Continuous beam (i.e. lower instantaneous rate)

πE5 muon beam:

- Compact design
- Average muon momentum: 28 MeV/c
- Placed right in front of the Mu3e magnet.



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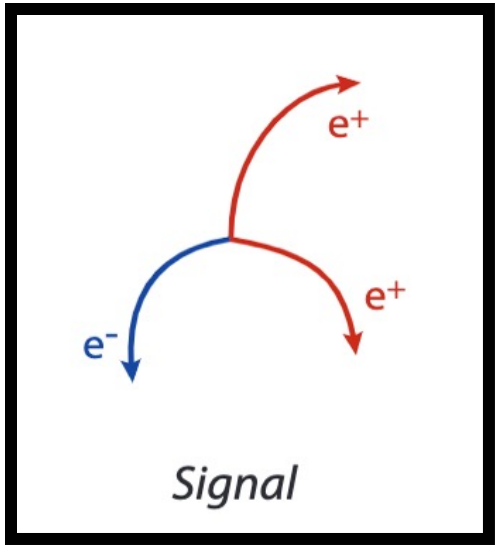
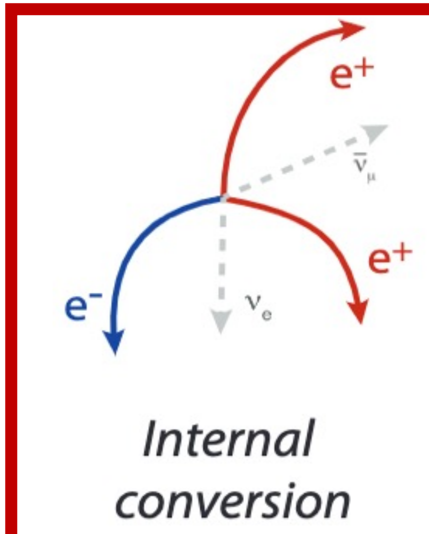
Signal and Backgrounds



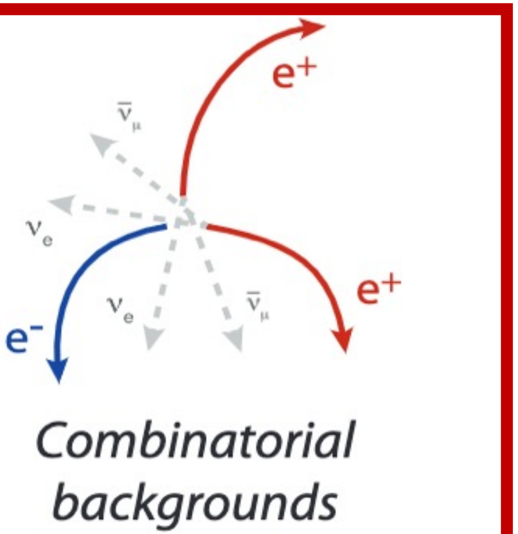
- Common vertex
- $\sum \mathbf{p}_i = 0$
- $\sum E_i = m_\mu$
- $\sum t_{eee} = 0$ (in time)

The signal of interest



- Common vertex
- $\boldsymbol{\sum \mathbf{p}_i \neq 0}$
- $\boldsymbol{\sum E_i < m_\mu}$
- $\sum t_{eee} = 0$ (in time)

Need good momentum resolution

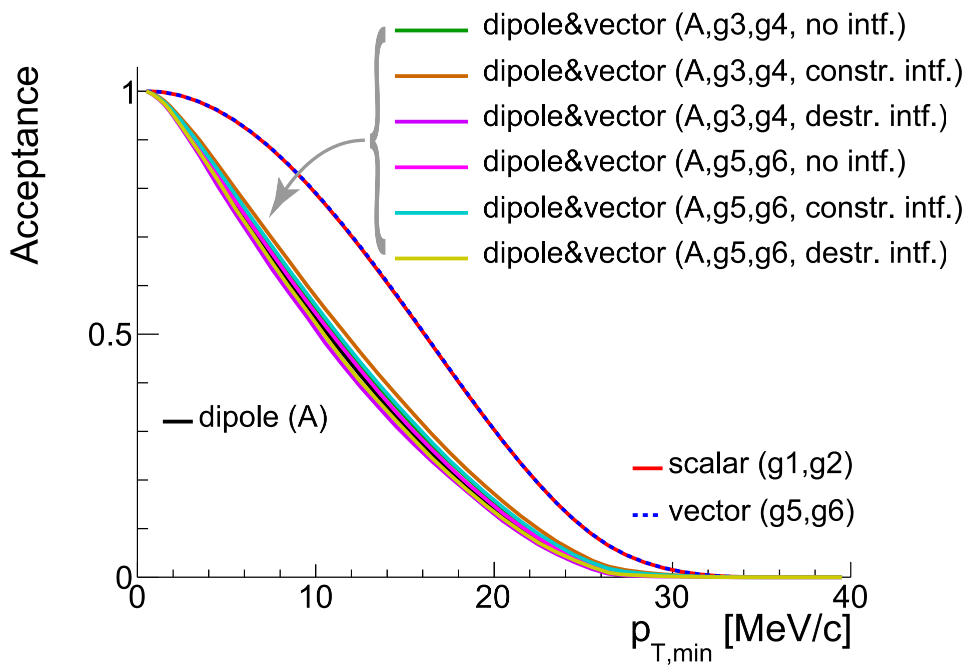


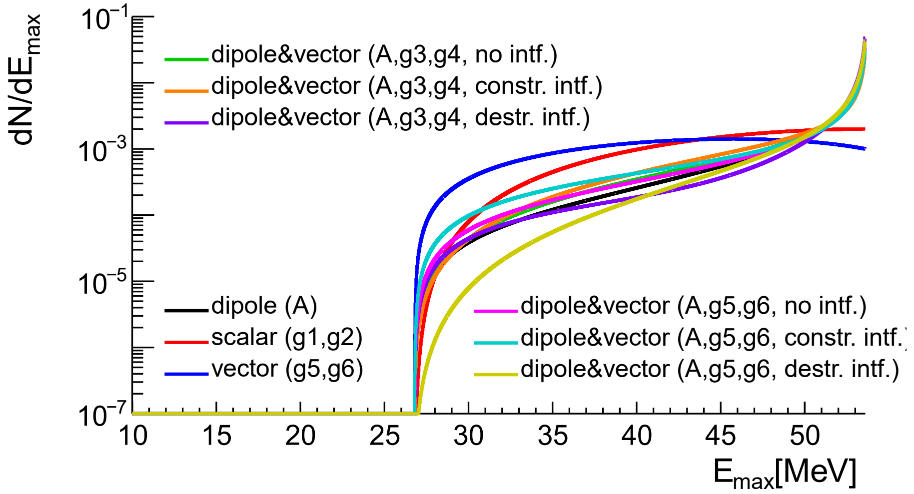
- **No common vertex**
- $\boldsymbol{\sum \mathbf{p}_i \neq 0}$
- $\boldsymbol{\sum E_i \neq m_\mu}$
- $\boldsymbol{\sum t_{eee} \neq 0}$ **(out of time)**

Need very good timing, vertex and momentum resolution

Detection thresholds for Mu3e

- Acceptance defined as the fraction of μ → eee decays where all decay product have momentum higher than p_t
- Highest energy decay product for different models.





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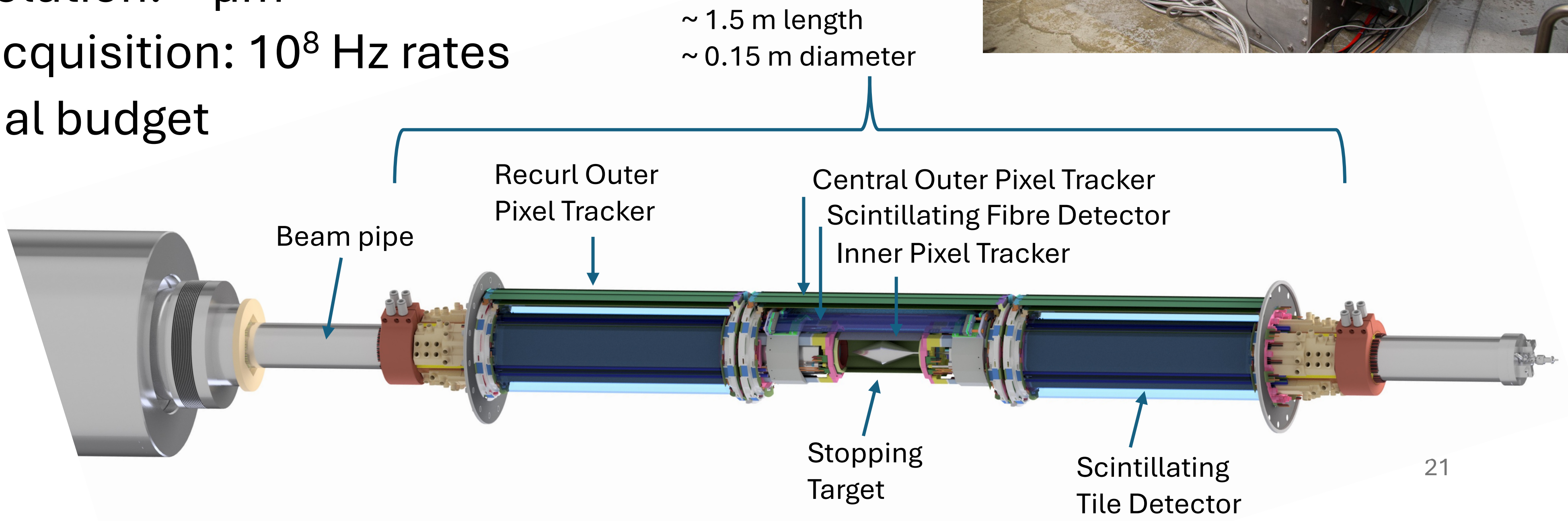
Mu3e – General Detector Requirements

General technical requirements:

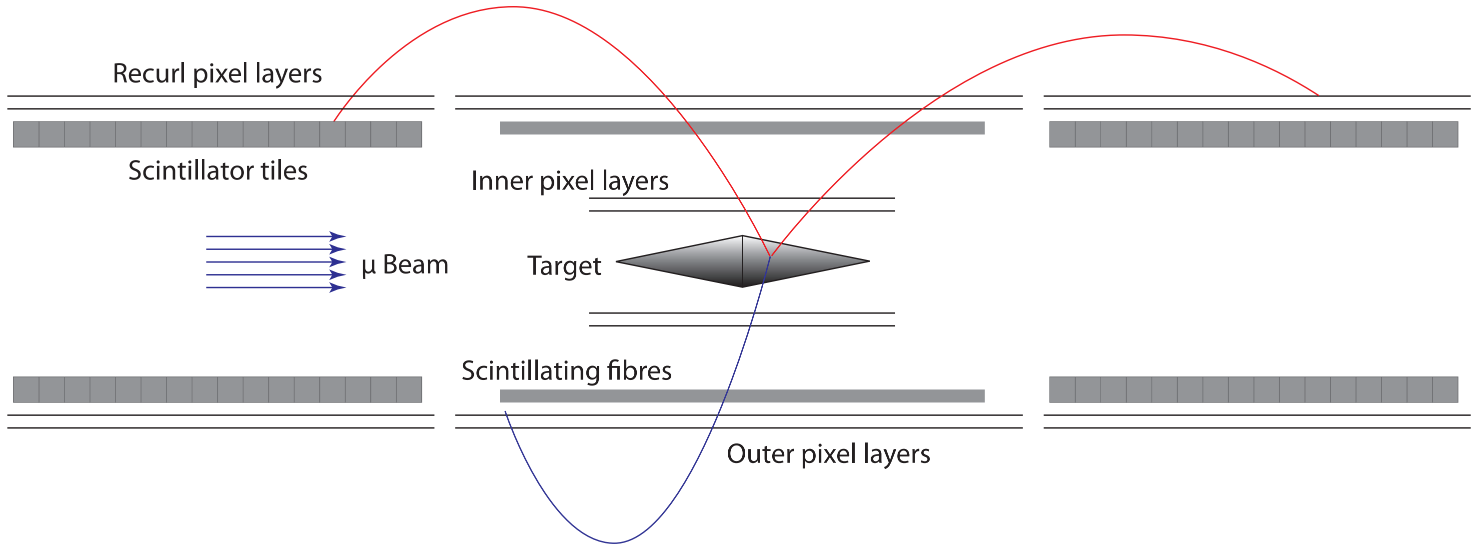
- Many muon decays needed (Phase 1+2): 10^{17}
- Timing resolution: Better than 500 ps
- Momentum resolution: < 0.5 MeV/c
- Spatial resolution: ~ µm
- Fast data acquisition: 10^8 Hz rates
- Low material budget



Mu3e – Particle Detection Principle

Particle's direction through detector:

- Muons decay at rest in target
- Electrons and positrons start propagating in magnetic field
- Place fine grained detector (pixel) for tracking and scintillation detectors for timing.

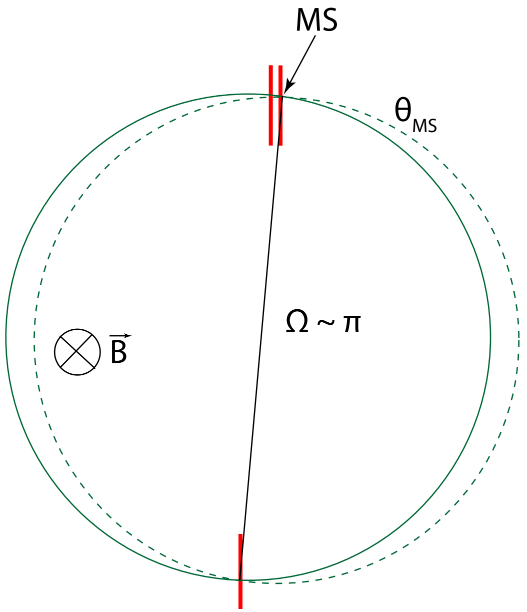


How to make a low momentum resolution detector?

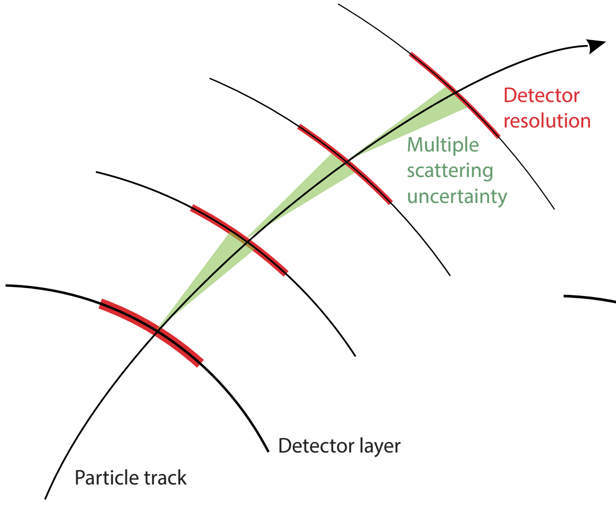
With a fine grained detector Mu3e is in the multiple scattering (MS) dominated regime.

- Two factors to improve resolution:
  - Large radius
  - Low scattering angle

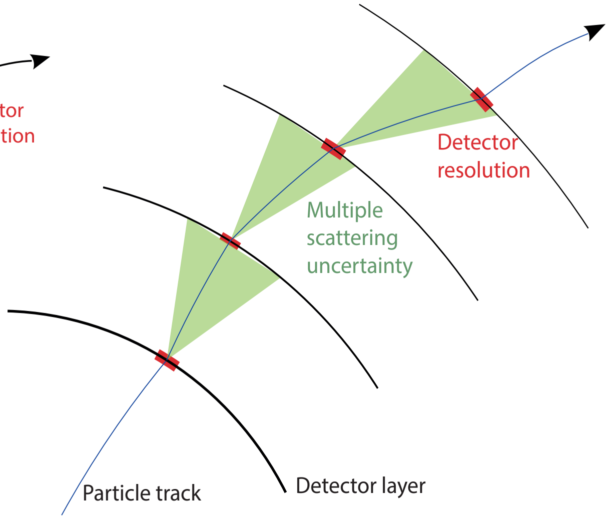
$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$



MS effects cancel to first order after a half a turn.



Spatial dominated



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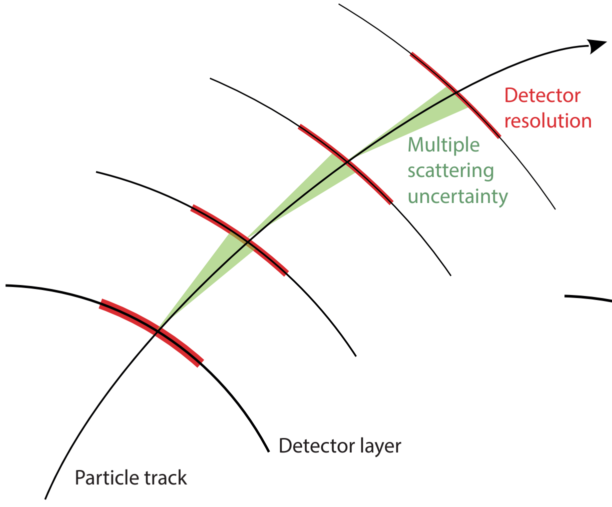

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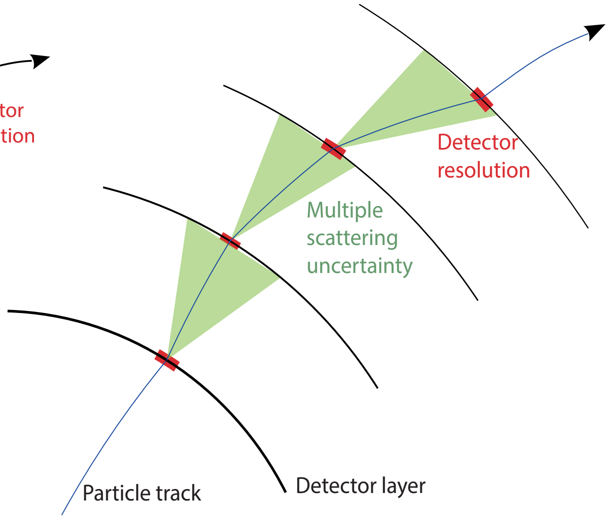

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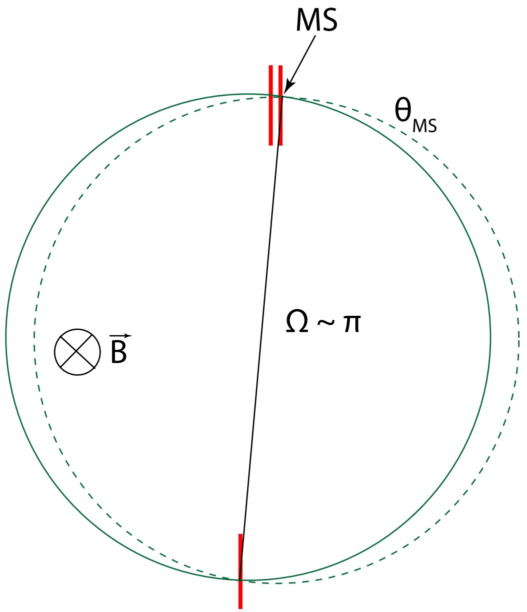
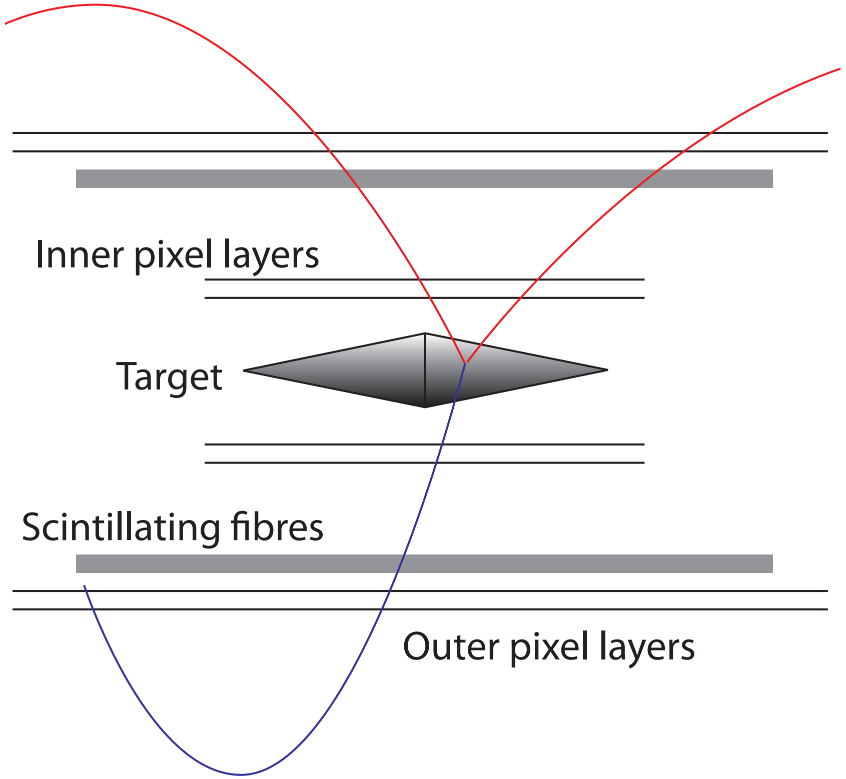


MS effects cancel to first order after a half a turn.

Catch the particle after half a turn!

Make a compact detector, long enough to cath the particles after half a turn.



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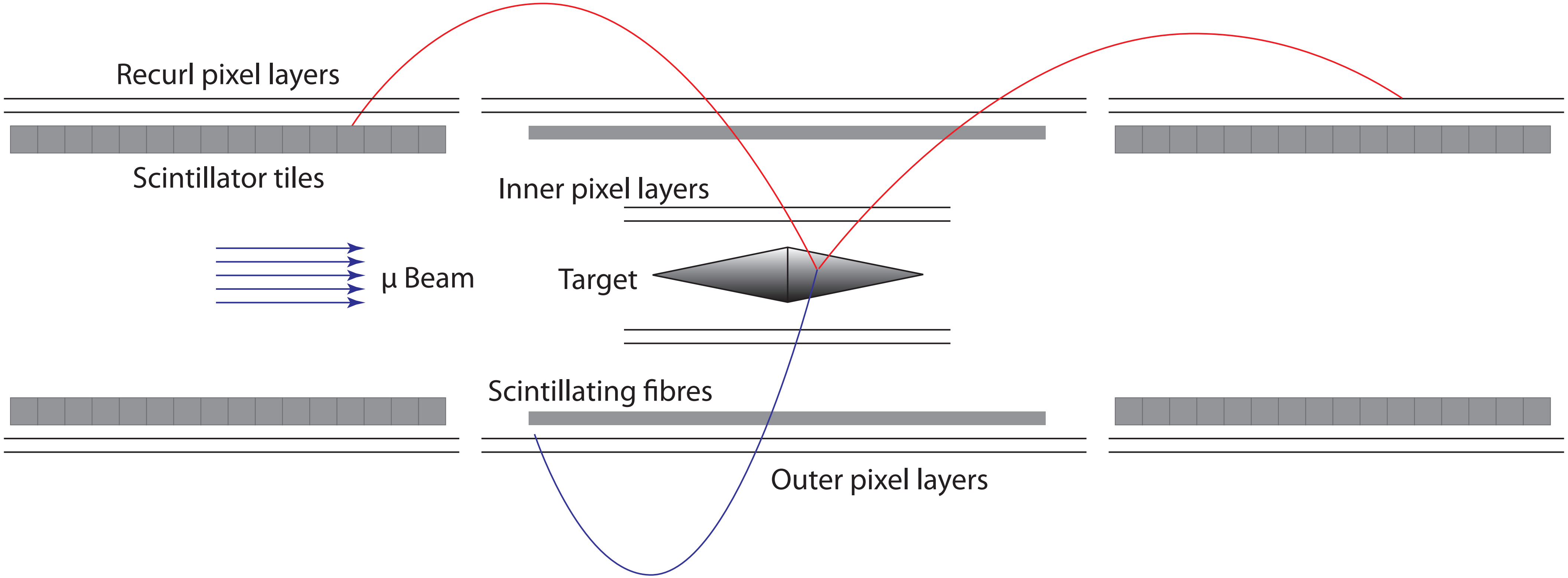
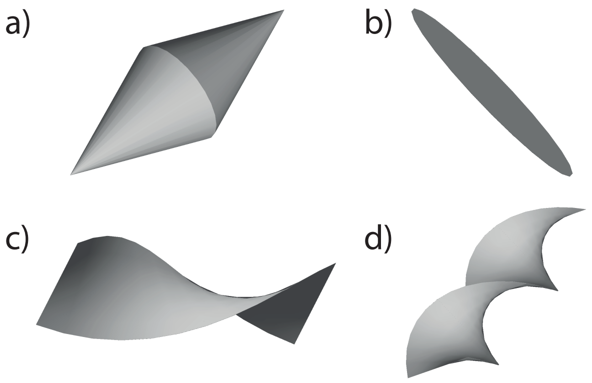
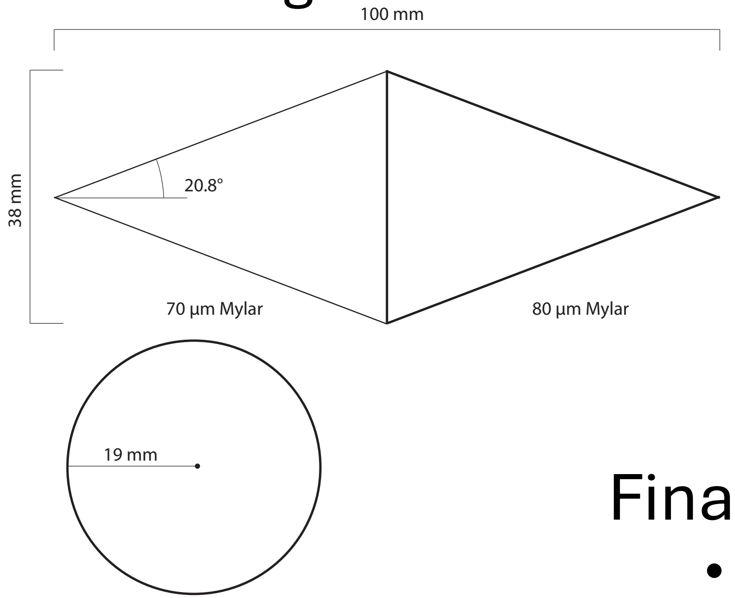


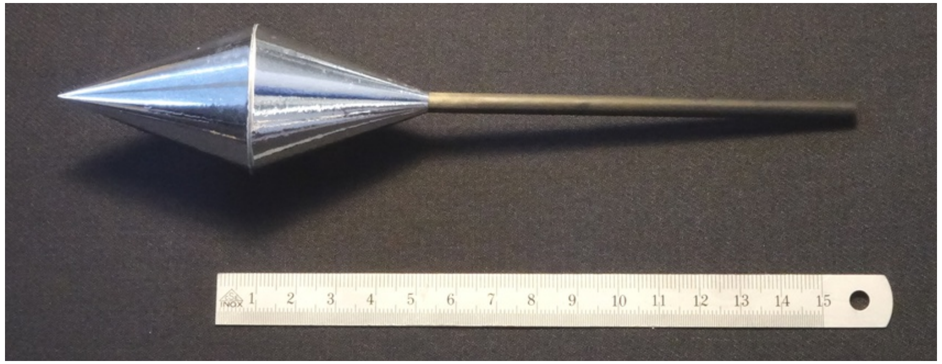
The target of the Mu3e detector



Challenge: optimise stopping power while minimising material...

- Several shapes studied
- Target à la Sindrum (see more here)





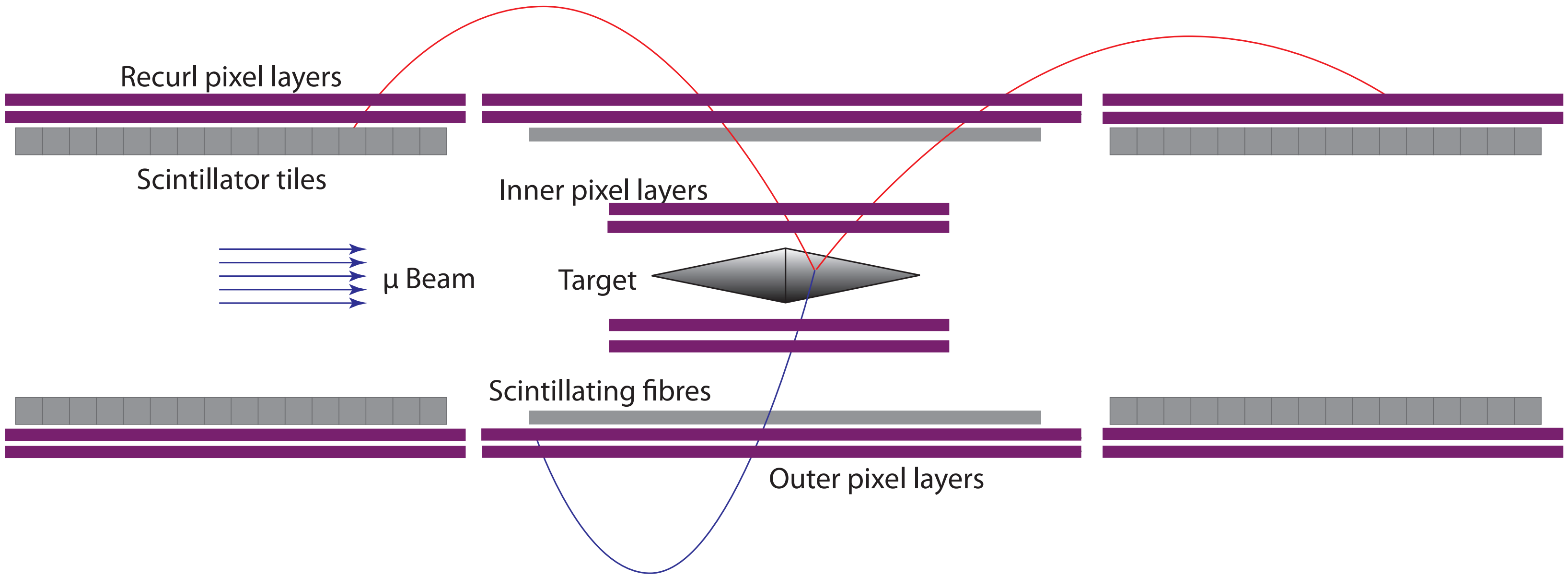
Final design:

- Double cone made of Mylar
- 95.5 % of muons reaching target are stopped

Mu3e – Subdetector roles - Pixel

Detectors:

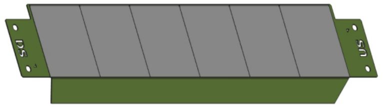
- **Pixel** detectors for tracking: vertex, outer-central, and recurl
- Thin Scintillating Fibers for timing: central
- Scintillating Tiles for timing: recurl



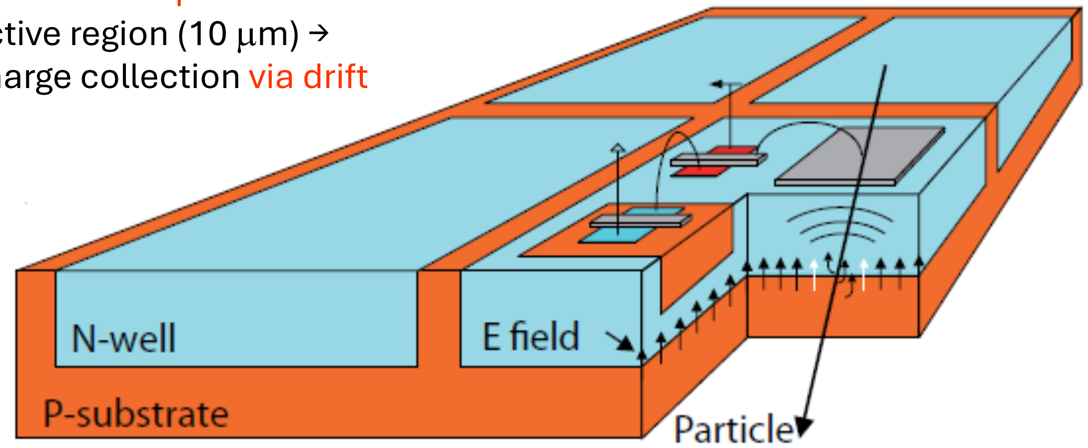
Silicon pixel detector HV-MAPS

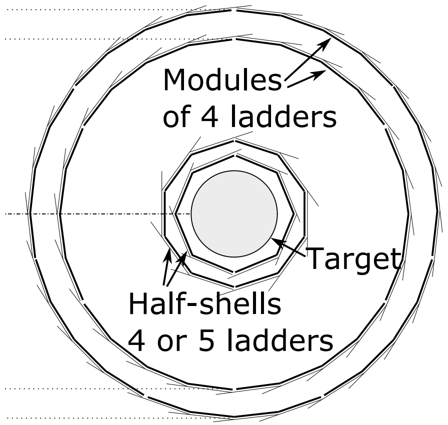
Pixel tracker – High Voltage Monolitic Active Pixel Sensors (HV-MAPS) - MuPix

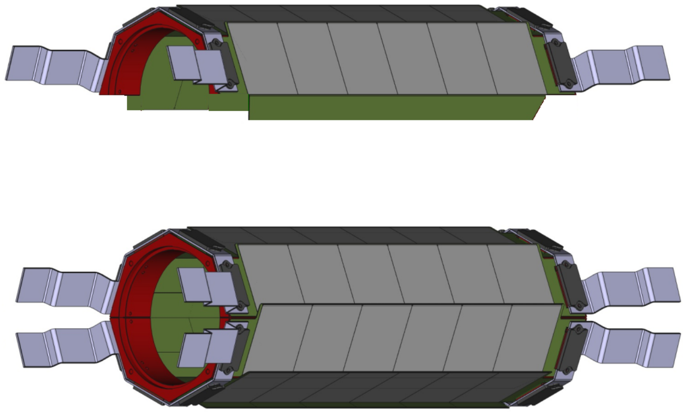
- Hits matched between two inner layers and two outer layers
- Cooled with helium gas
- Acceptance increased with recurl stations
- 50 µm thickness (vertex), 70 µm (recurl)
- Active area 20 x 20 mm^2 (23 mm including readout area)
- Operated with up to 70 V



- readout logic and amplifiers embedded in the pixel n-well
- thin active region (10 µm) → fast charge collection via drift



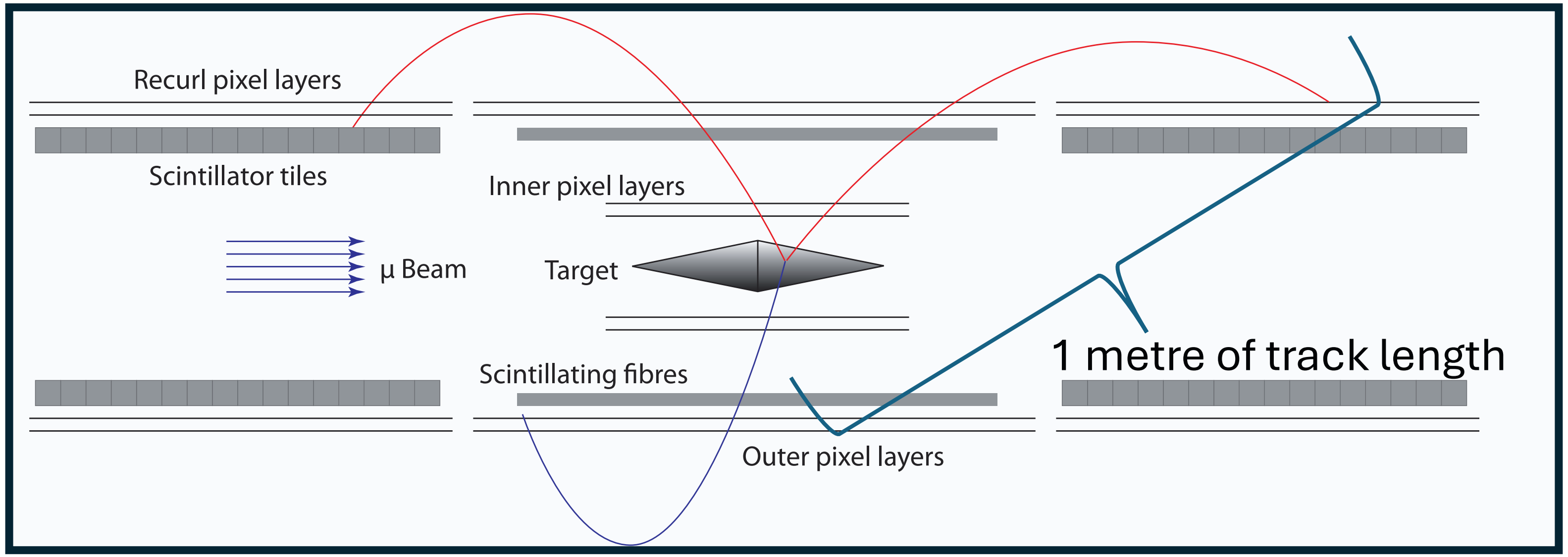




Helium cooling

MuPix dissipates 215 mW/cm² → Needs cooling

- Liquid cooling → High material budget
- Gas cooling
  - Air → High material budget: 1 m of air ~ 0.33 % X_0.
  - Helium 1 m ~ 0.018 % X_0



Turbo compressor providing 16 g/s helium (from Fischer)

Pixel tracker - Status

11 year R&D period over…

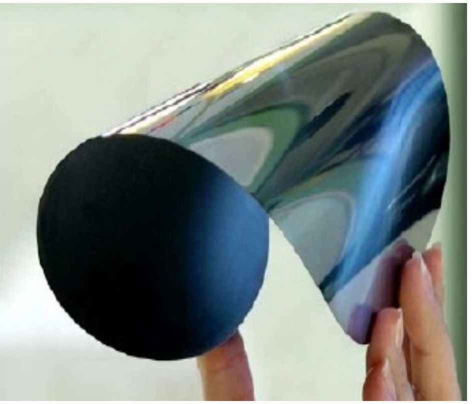
Inner pixels installation in progress

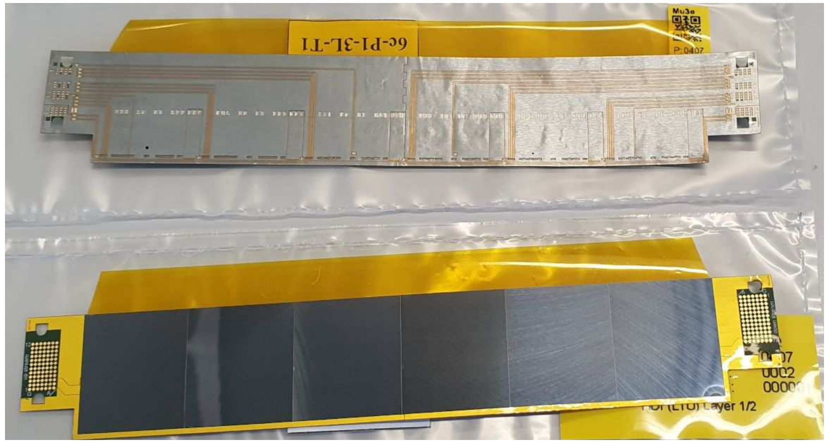
Helium gas cooling installed

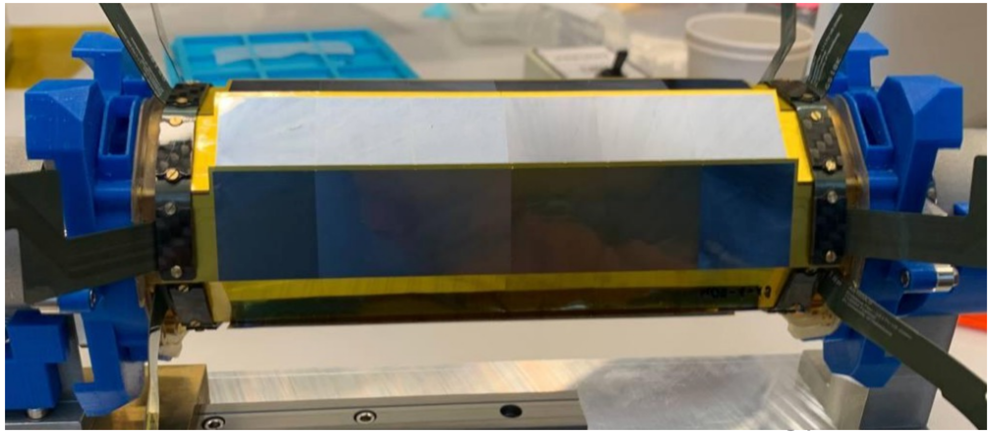
~23 μm spatial resolution, efficiency 99%*, < 20 ns time resolution

Two layer vertex detector to be installed by November

50 μm thick silicon wafer





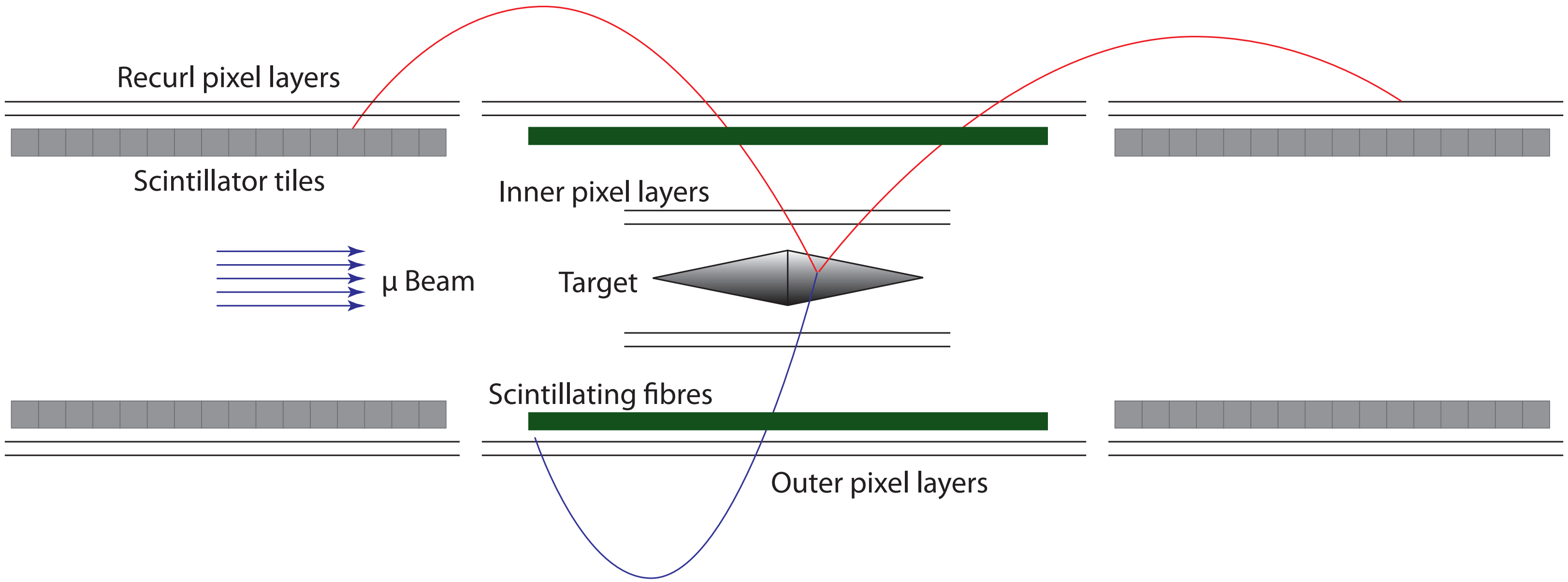


easily achievable with 70 μs, a bit more challenging with 50 μs

Mu3e – Subdetector roles - SciFi

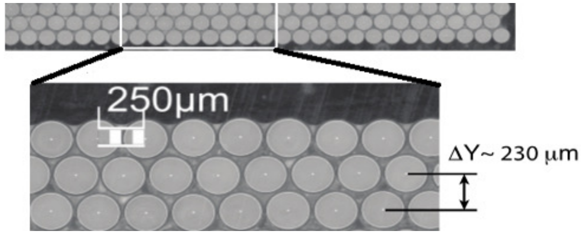
Detectors:

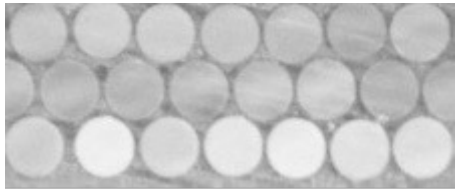
- Pixel detectors for tracking: vertex, outer, and recurl
- Thin **Scintillating Fibers (SciFi)** for timing: central
- Scintillating Tiles for timing: recurl

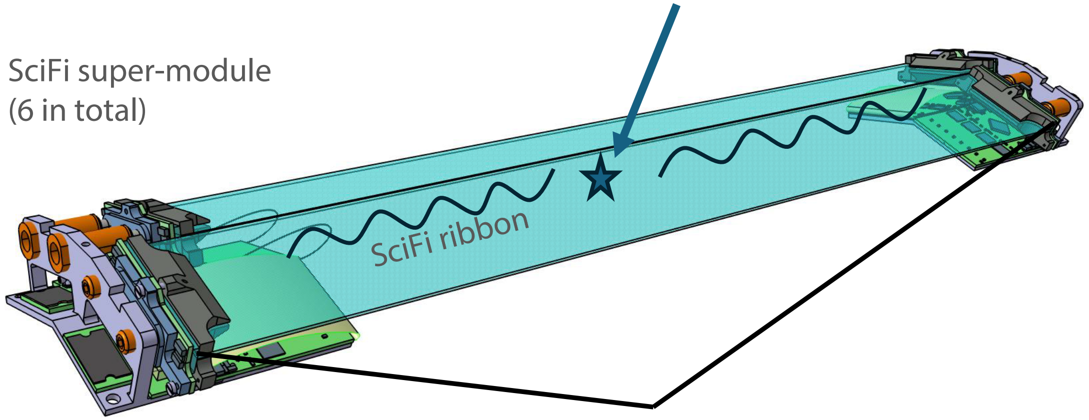


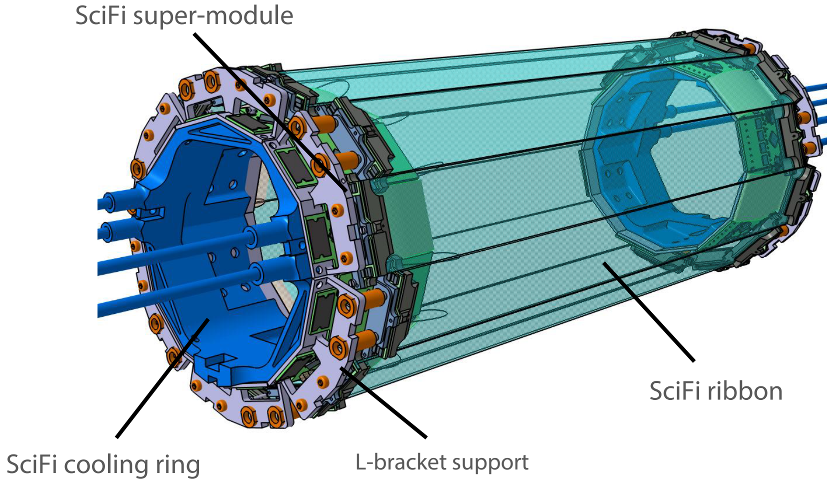
Timing at centre: Scintillating Fibre (SciFi) detector

- SciFi basics:
  - 3 layers of 250 µm staggered fibres
  - 12 long fibre ribbons covering 4 π
  - 1 ribbon = 720 µm thick, 0.2 % radiation length
  - 300 ps time resolution
  - Liquid cooling (SilOil, -20°) through the Cooling Ring (CR).







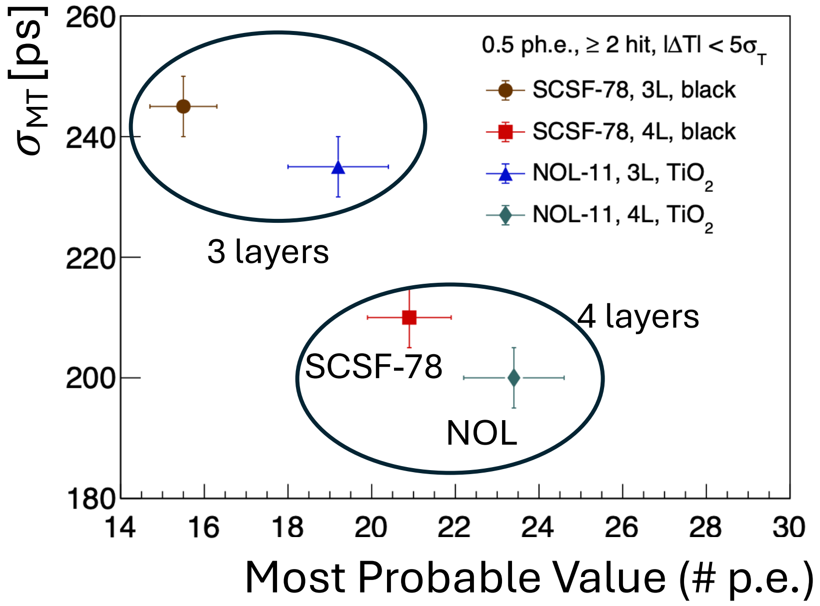


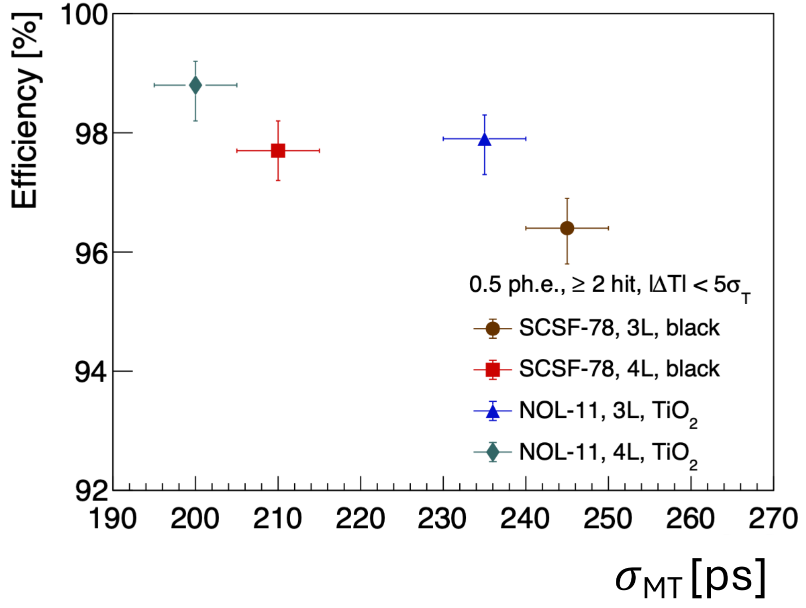
Particles produce photons which propagate towards the ends

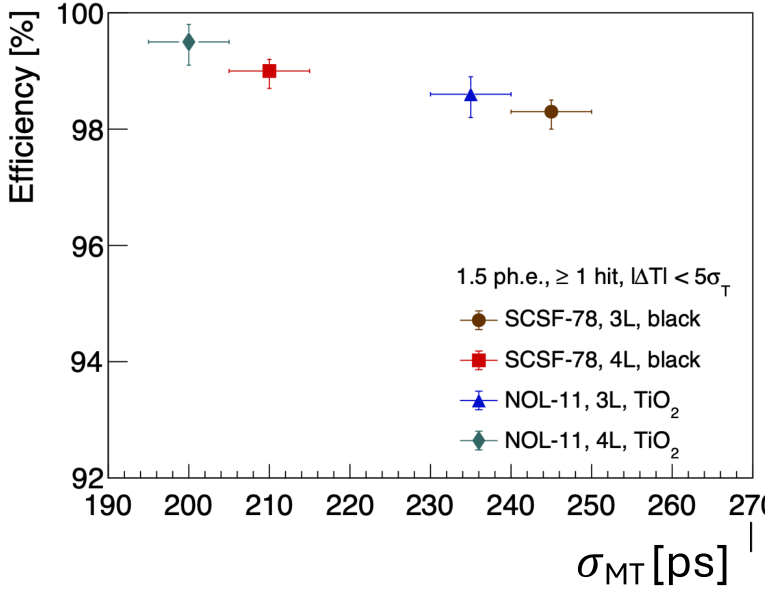
- Each ribbon has SiPM arrays at its ends
- 256 channels per ribbon, 3072 for SciFi.

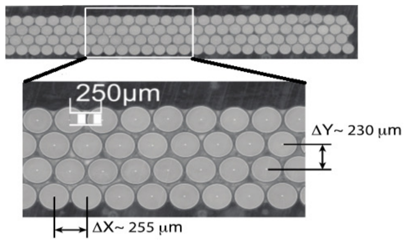
Timing at centre: Scintillating Fibre (SciFi) detector

Performance of the SciFi detector







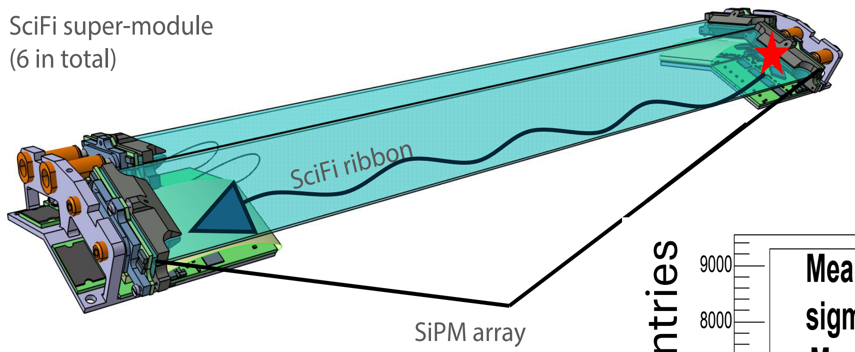


NOL (1.1 ns) – shorter decay time than **SCSF-78** (2.8 ns)
Not a great impact on the time resolution
→ **Photon number is the dominant contribution.**

3 layer SCSF-78 scintillator
radiation length X/X_0 ~ 0.2%
→ Final design

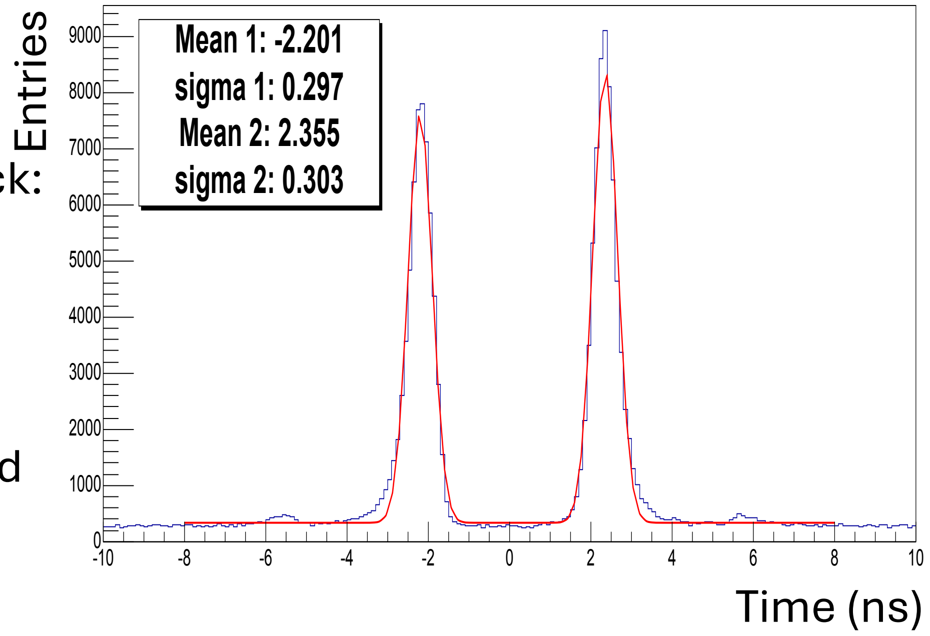
Defining quality control methods for mass production

A dark-count photon can produce cluster both on the left or the right of the ribbon.



Double peak plot used to check:

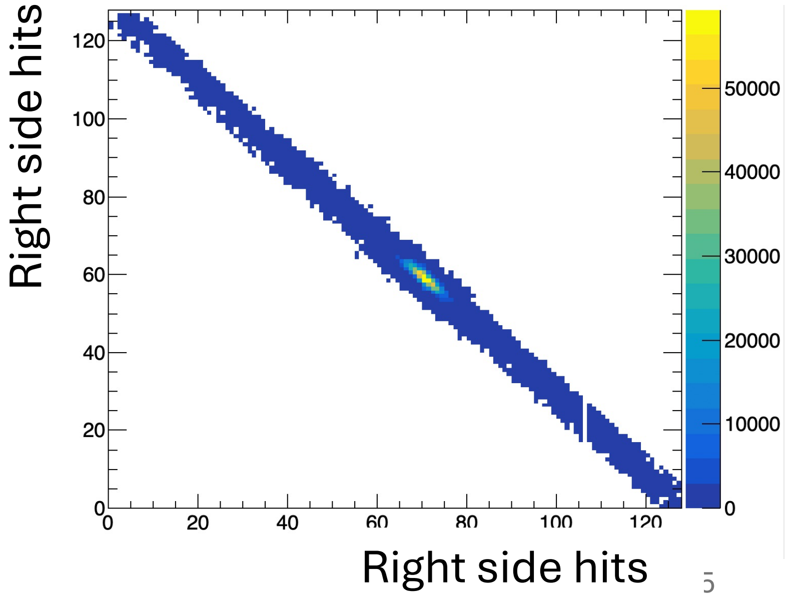
- Good overal optical properties
- Width → expected resolution ~300 ps
- Allignment at 0 → Good time sync between left and right.



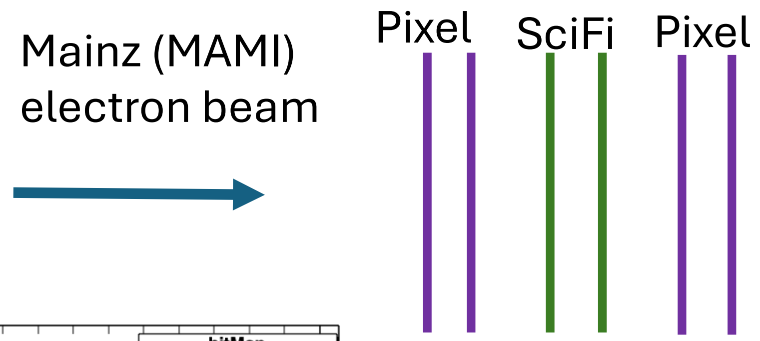
Ribbon scan with source

Used to check:

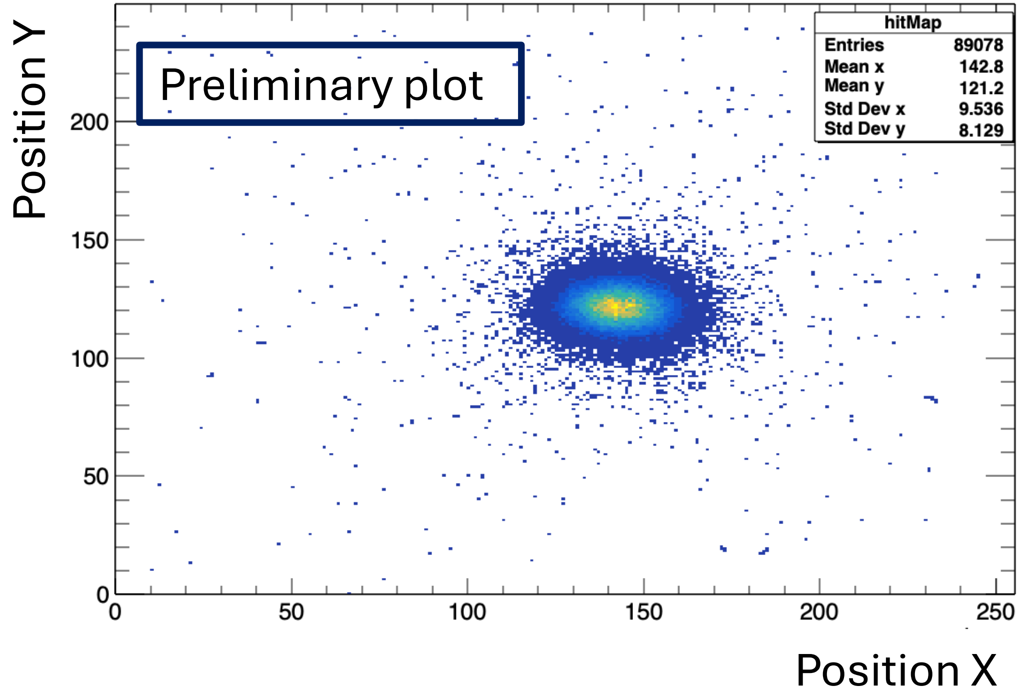
- Dead/noisy channels
- General data quality from one ribbon.



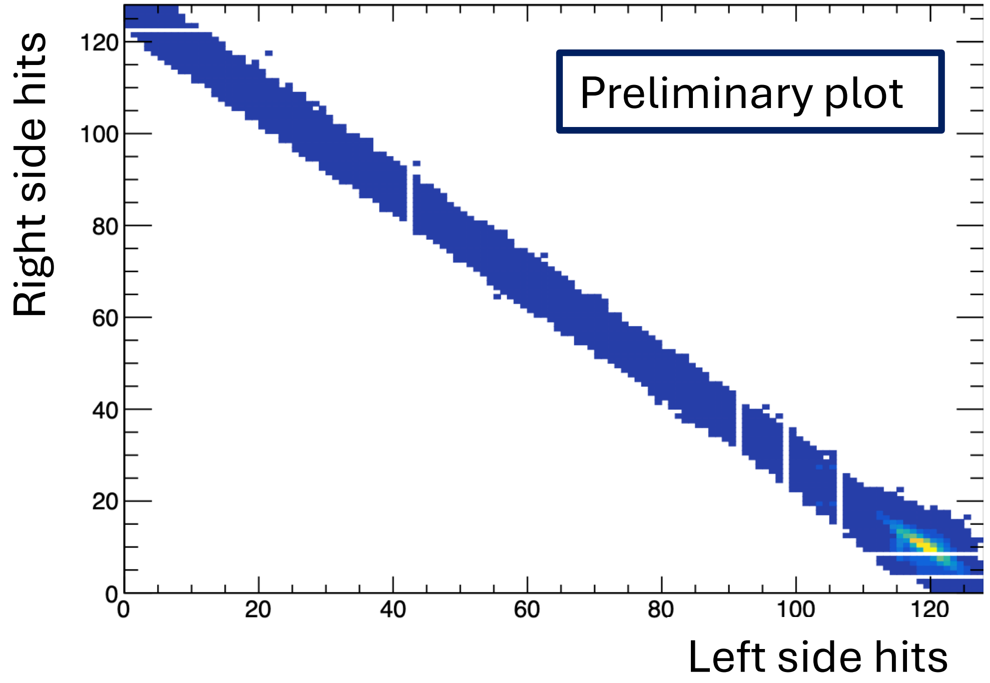
Beam test results – SciFi qualification with MuTRiG ASICs



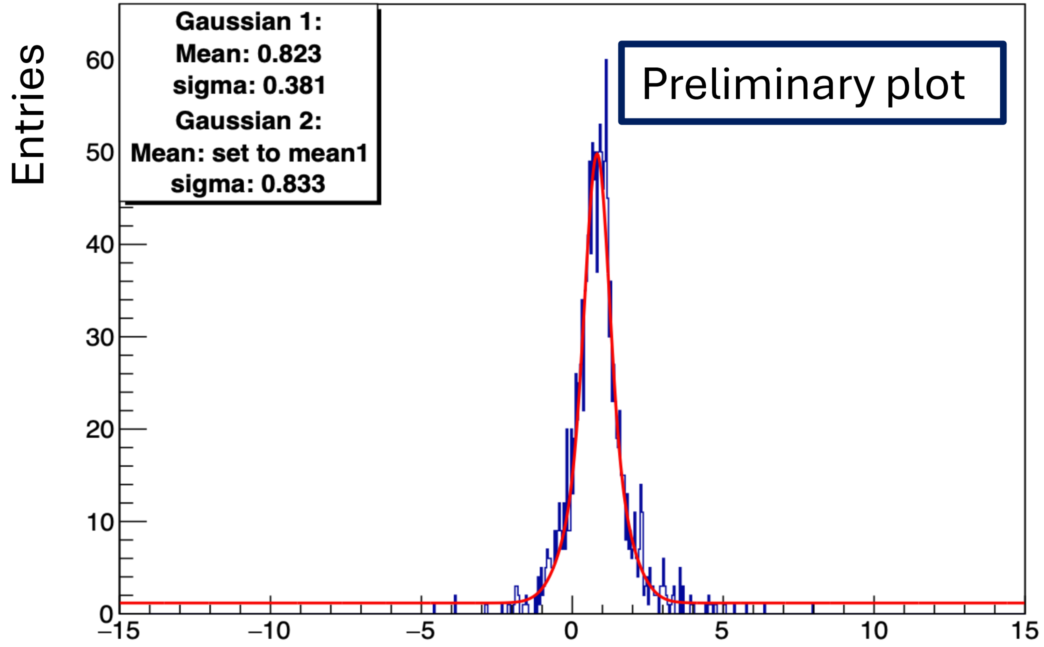
Pixel module



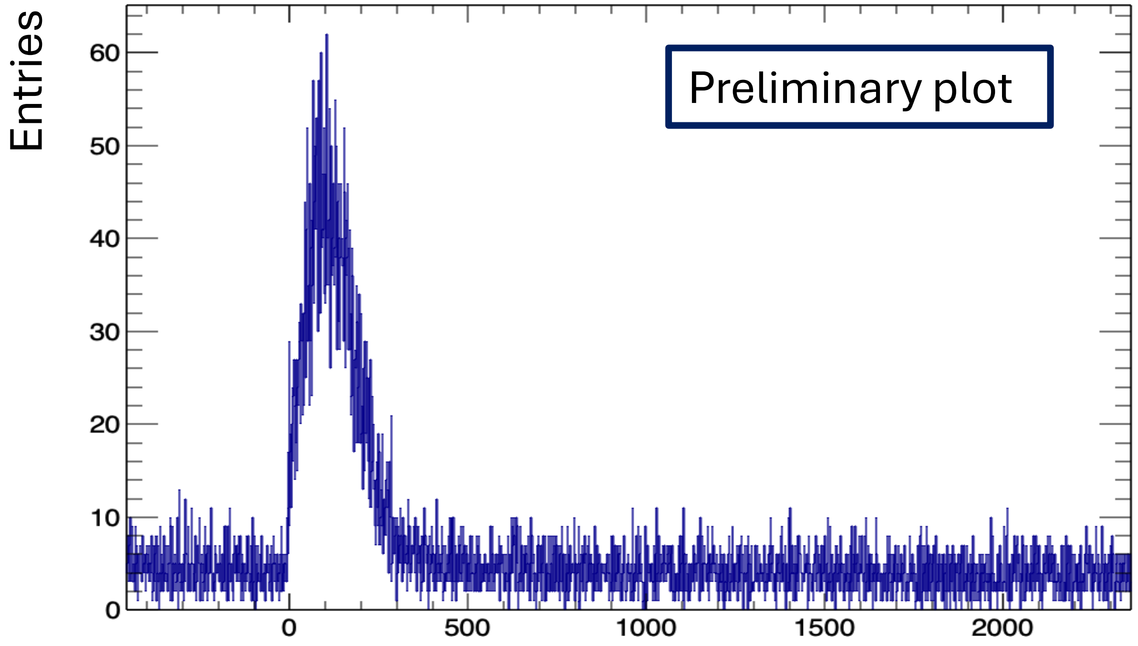
SciFi module



Beam test results – SciFi qualification with MuTRiG ASICs



Time difference between coincidences at two ribbons (ns)



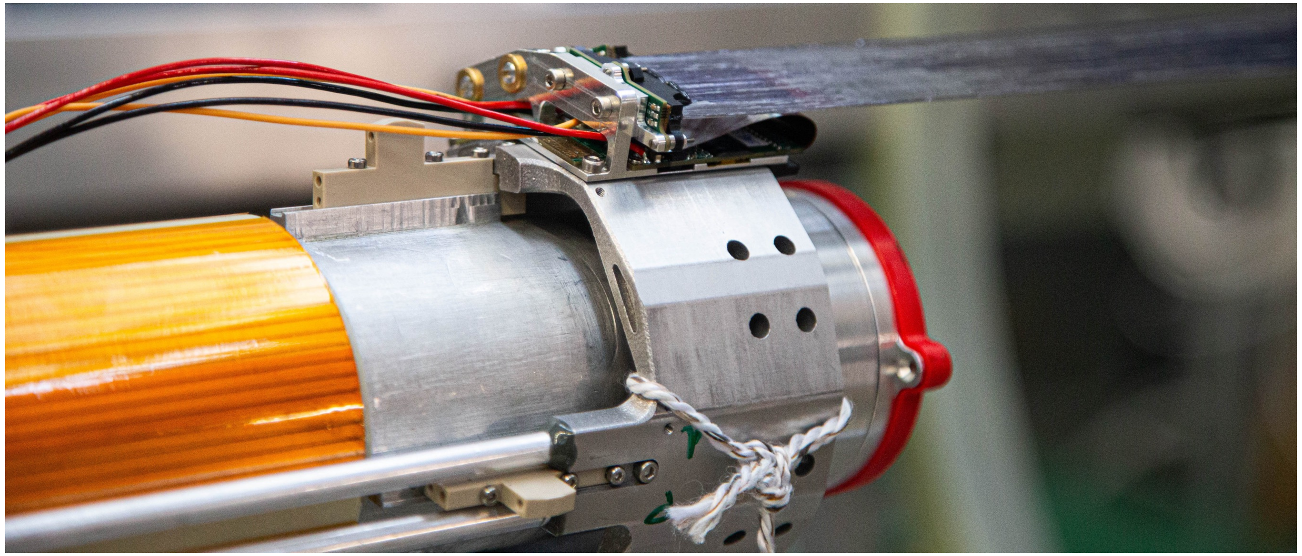
Time correlation between Pixel and SciFi (ns)

Excellent Mean Time resolution maintained for two ribbon coincidences: ~ 381 ps.

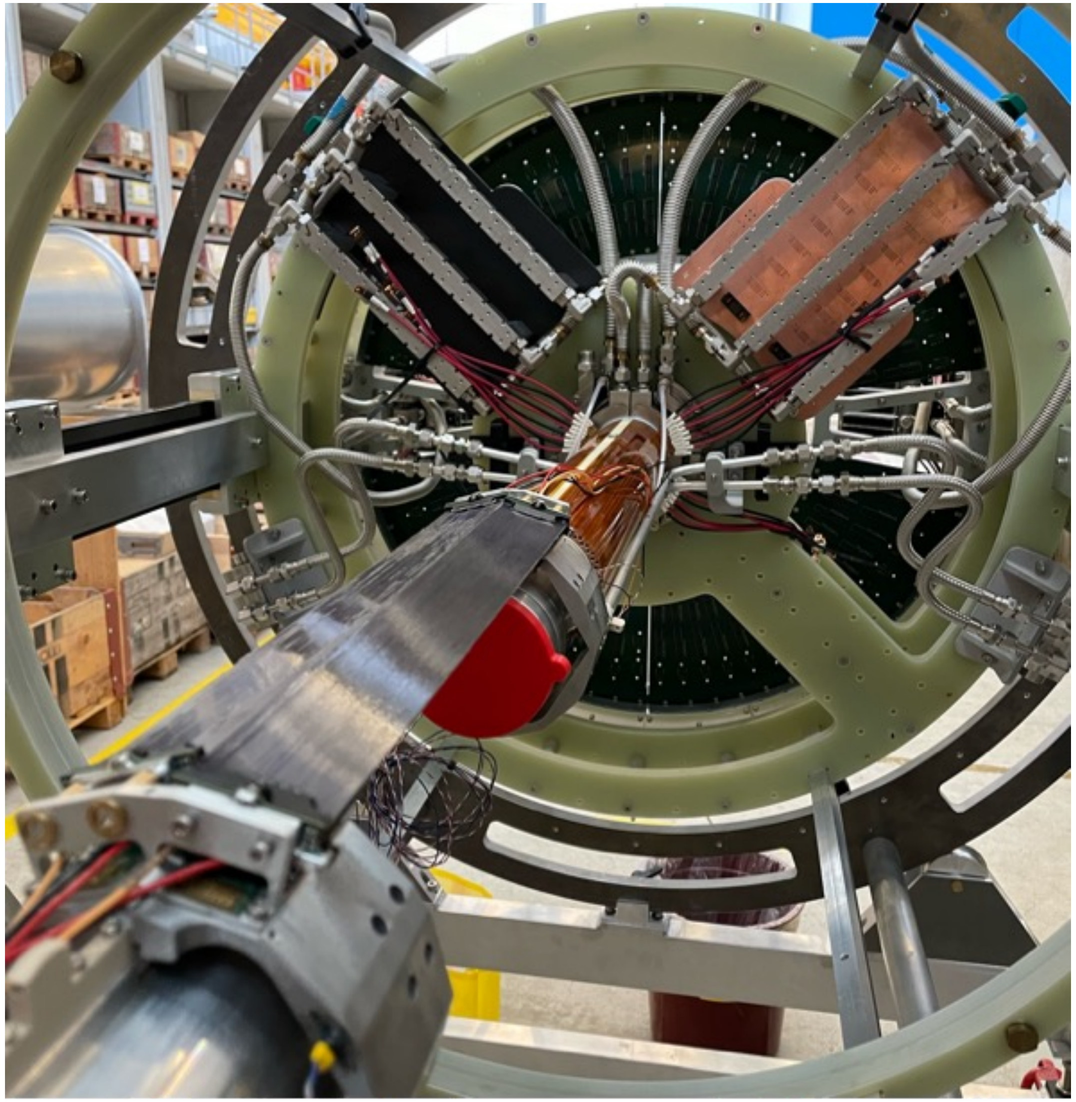
Preliminary plot: Correlation between final version of both pixel detectors and SciFi.

SciFi detector - Status

- 6 modules produced
- To be installed by November
- Liquid cooling system installed



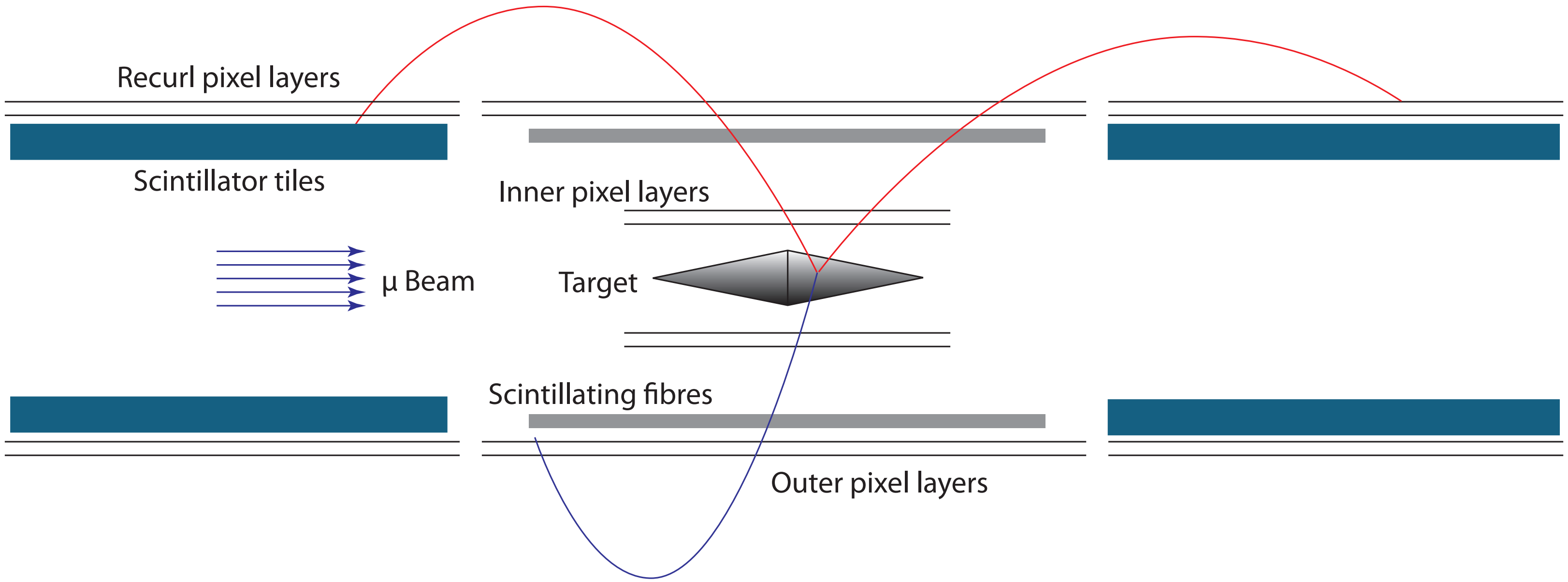
cc Niklaus Berger – Flickr Mu3e



Mu3e – Subdetector roles - SciTile

Detectors:

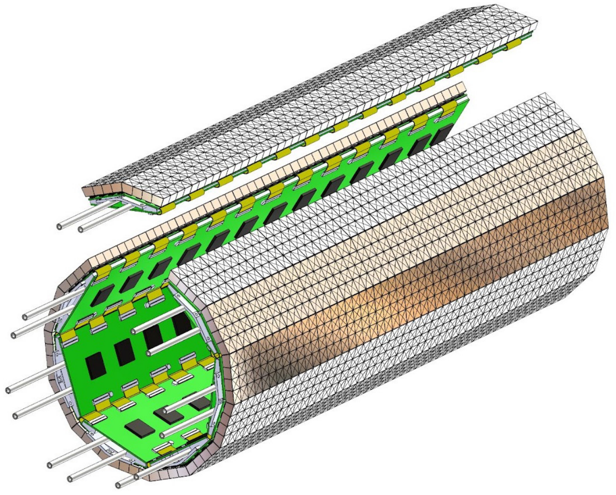
- Pixel detectors for tracking: vertex, outer, and recurl
- Thin Scintillating Fibers for timing: central
- **Scintillating Tiles** (SciTi) for timing: recurl

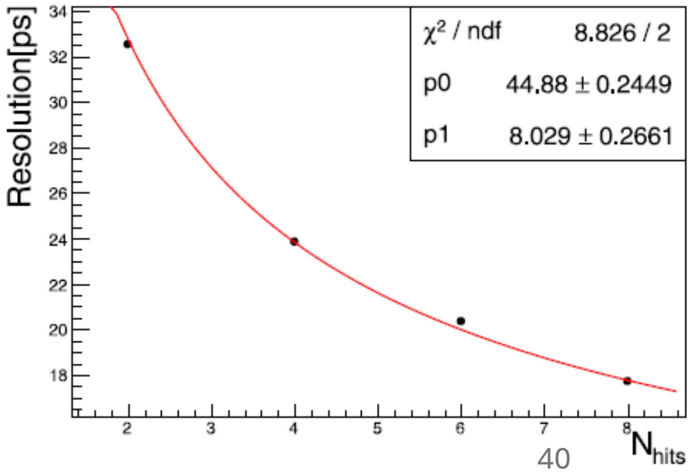


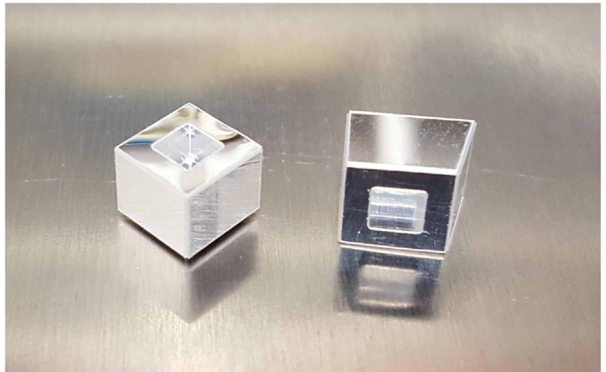
Mu3e – Subdetector roles - SciTile

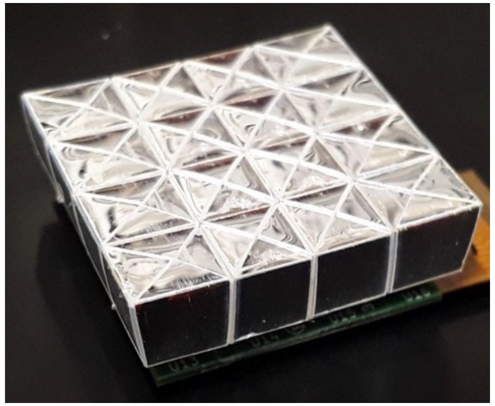
No tight material limitation on Detector volume → "Thick" detector
Highly segmented in ~6k tiles
Very compact design

- Tiles from fast Ej-228 plastic scintillator (6 x 6 x 5 mm^3)
- Individually wrapped in ESR foil - Minimize crosstalk
- Coupled to Hamamatsu SiPMs read out by Mutrig ASIC (S13360-3050VE @ -10°C, Silicon oil cooling)
- Efficiency > 99%, single-channel time resolution ~ **40 ps**
- Performance validated in Demonstrator Modules
- First final modules produced



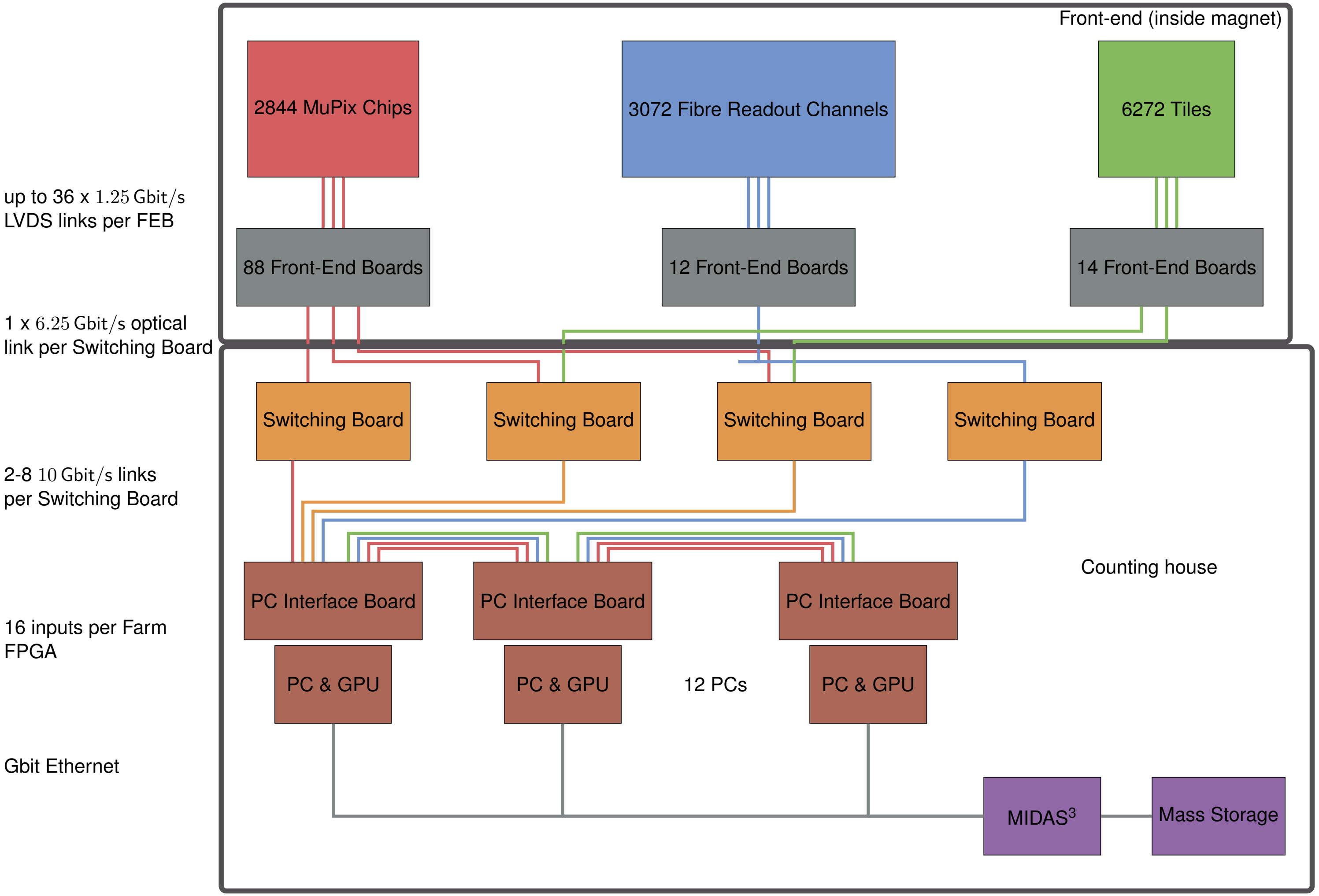






Mu3e – Data Acquisition

- Trigger-less conitnuous readout: 100 GB/s data rate
- Hits collected by FPGAs (inside the magnet)
- Optical transmission to switching boards
- Decays reconstructed and interesting events are stored.



More info in M. Koeppel's talk

Mu3e – Plans for 2024 and further

Achievements so far:

- DAQ operational with different detector types
- Cooling for detectors
- Pixel, SciFi, SciTile → First modules installed

Aims for rest of the year:

- Cosmic run
- Complete experimental chain
  - Detector installation
  - Data taking

Cosmic run with inner pixel and SciFi

Nov/Dec 2024

Full detector commissioning

2025

Physics data taking

2026

Design

From theoretical motivation to experimental design.

Construction

Update on the construction of each subdetector.

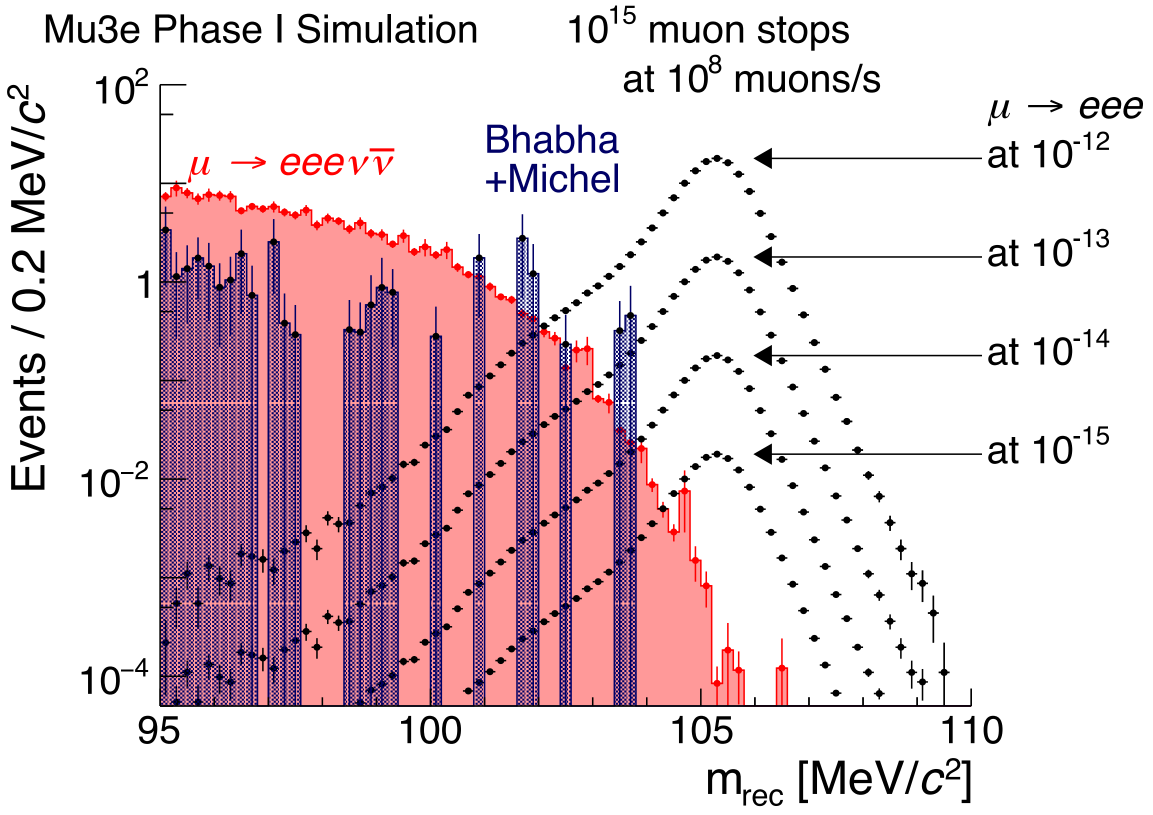
Mu3e physics

Potential physics directions with Mu3e.

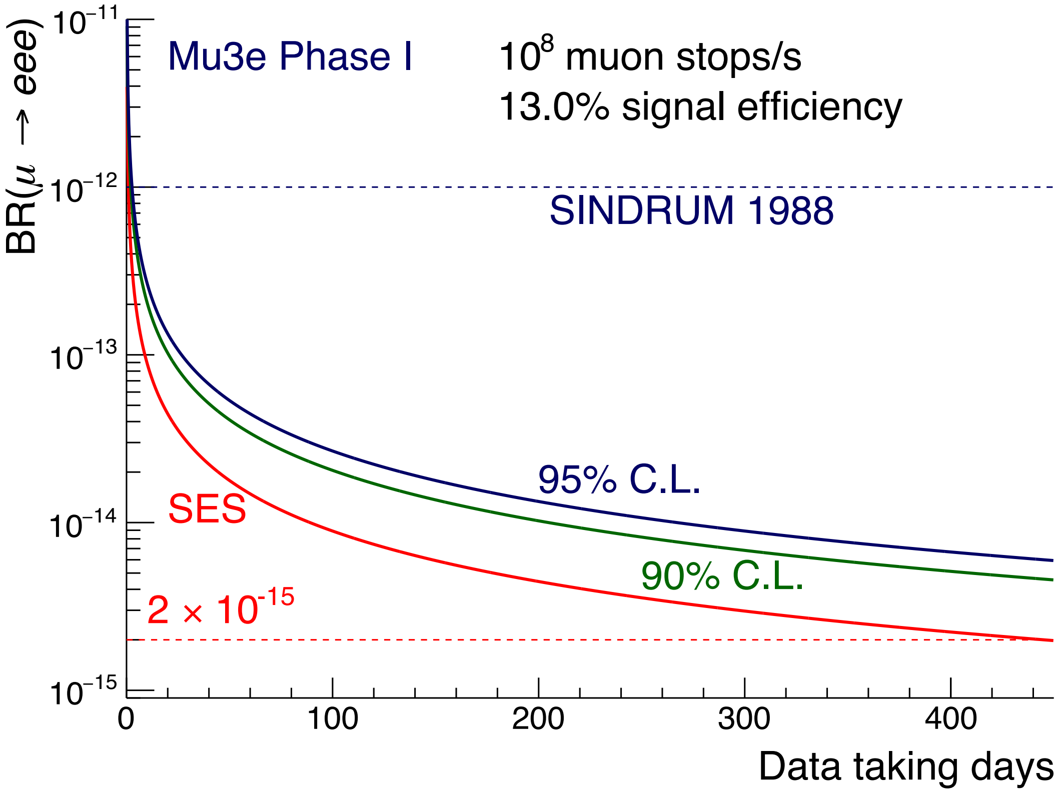
Physics reach with current design

- $\mu^+ \rightarrow e^+e^+e^-$
- $\mu^+ \rightarrow e^+ X$
- $\mu^+ \rightarrow e^+$ + Long lived particles
- The search for e+e- resonances in $\mu^+ \rightarrow e^+e^+e^-$ ν_e \bar{ν_μ }
- Precision muon decay measurement and improvements on the weak interactions.

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



Expected vertex mass based on full offline selection



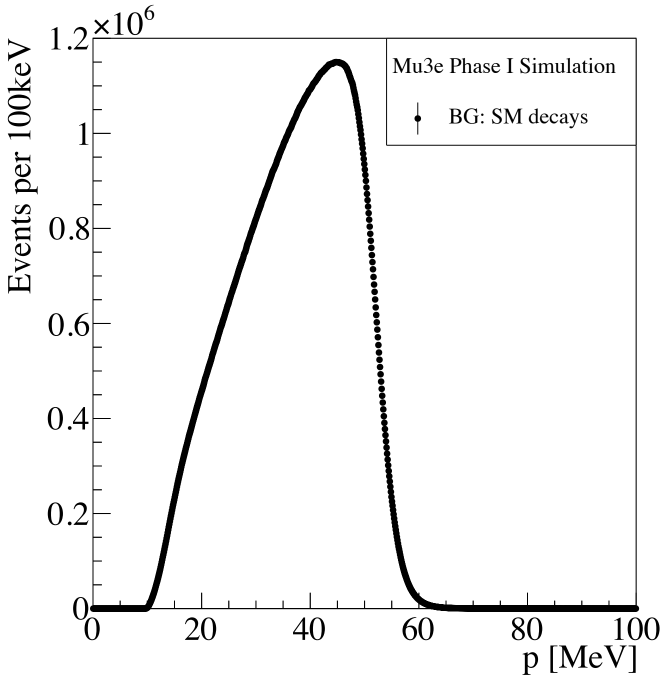
Expected sensitivity with running time. Current limits will be exceeded within days.

https://arxiv.org/abs/2204.00001

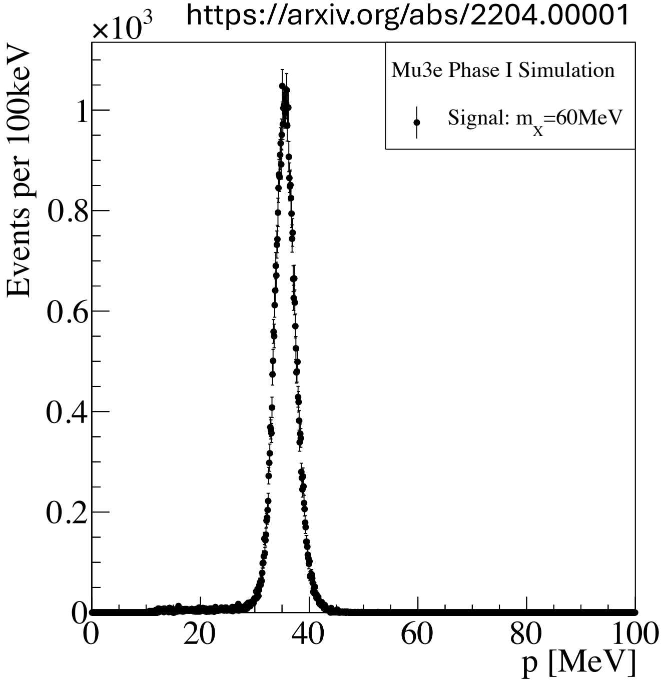
$\mu^+ \rightarrow e^+ X$

Mu3e can also look for decays of the type $\mu^+ \rightarrow e^+ X$, where X is a neutral light particle.

- Limits set by TRIUMF in *1986* (Highly polarized muon beam – details here and here)
- Mass of X is imposed by detectors acceptance.
- For minimum 10 MeV for positron energy, max Mx ~ 95 MeV
- One track does not pass selection conditions → need way around it.

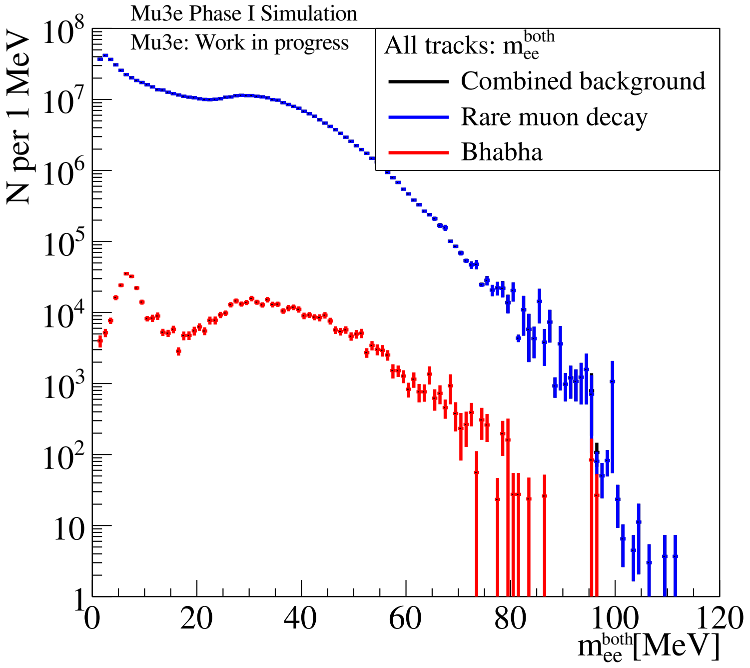


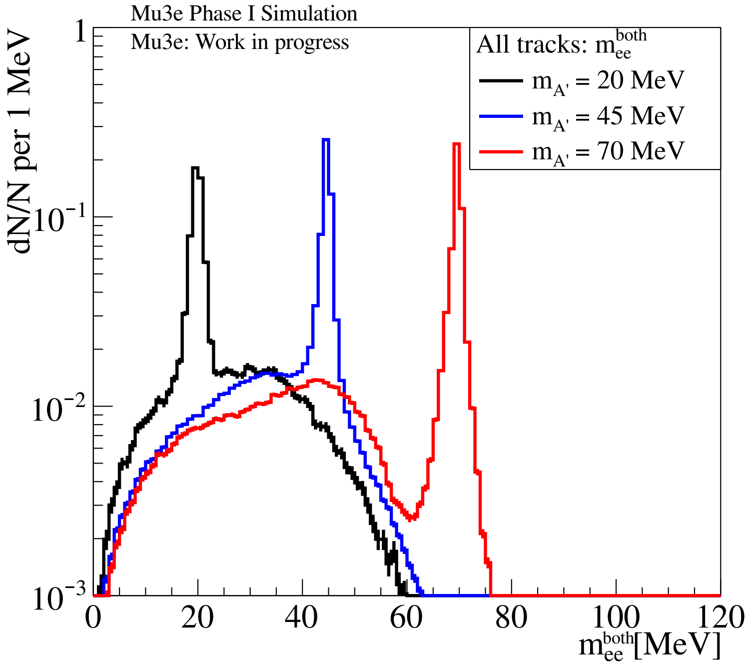
https://arxiv.org/abs/2204.00001



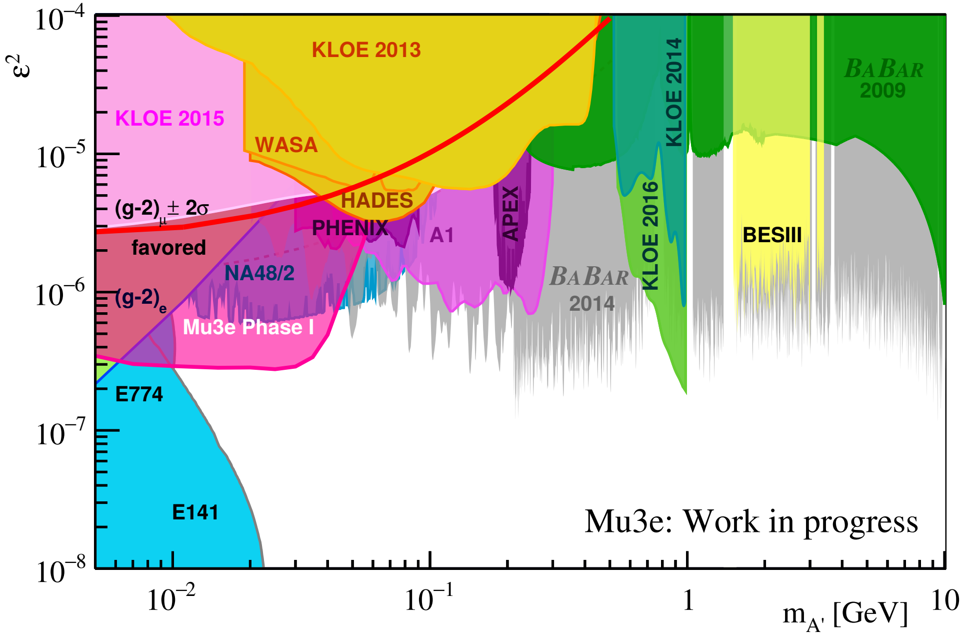
Dark photon e^+e^- resonances in $\mu^+ \rightarrow e^+e^+e^- \nu_e \bar{\nu}_\mu$

Mu3e can look for dark photons using the standard three track data set.
Dark photons can decay into e^+e^- pairs.
Masses probed up to 80 MeV.





https://arxiv.org/abs/2204.00001



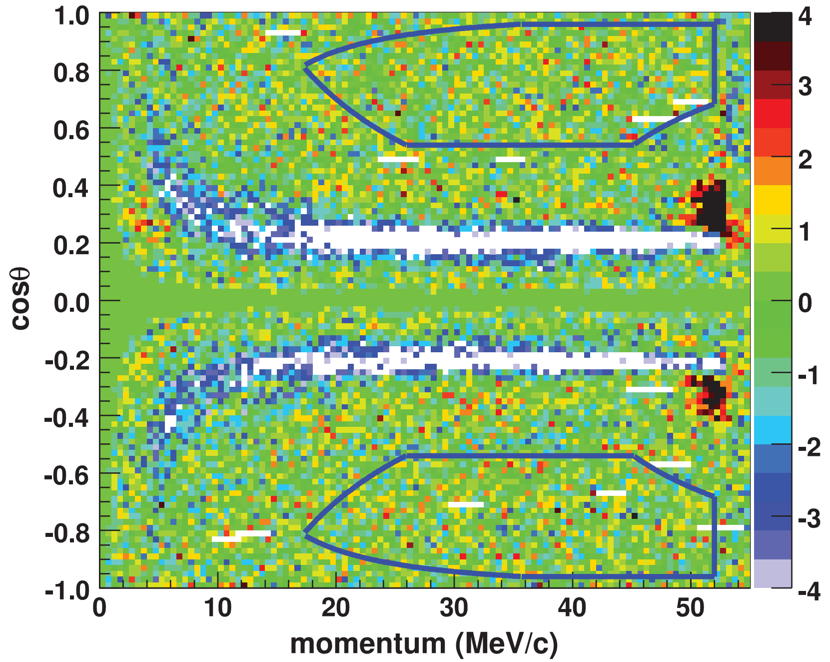
Invariant e+e- mass from background and for signal. Both high and low energy positrons are considered.

Back to Earth: Precise measurement of SM

Michel decay of muon: $\mu^+ \rightarrow e^+ \; \nu_e \, \bar{\nu}_\mu$

Standard model decay process described by four parameters (link to PDG)

- ρ and η measured with limited statistics by Twist (link to publication)
- Twist constraints: pz > 14 MeV/c, pt > 10 MeV/c



$$F_{\text{IS}}(x) = x\,(1-x) + \frac{2}{9}\,\rho\,(4x^2 - 3x - x_0^2) + \eta \cdot x_0\,(1-x)$$

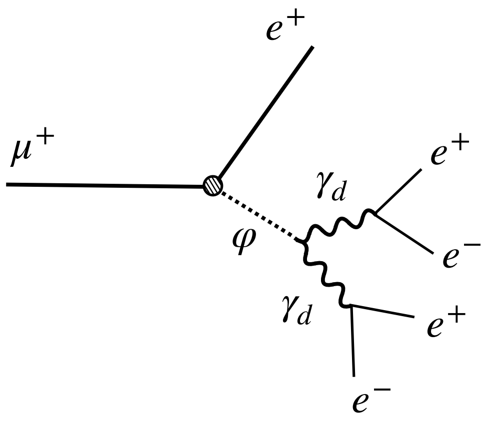
The contribution to η becomes imporatnt at lower energies (*x*).

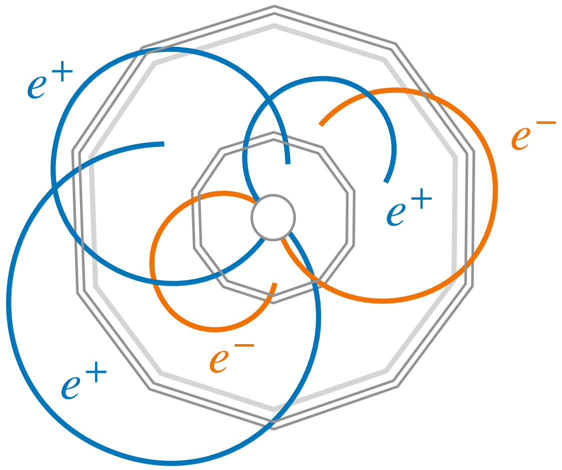
Mu3e will be able to access lower momentum ranges and also will have much better statistics.

One limitation: DAQ optimized for three track processes.

Is this the end?

Three track topology of muon decay is very appealing for theorists…
See for example this study on “New Physics in multi electron muon decays”.



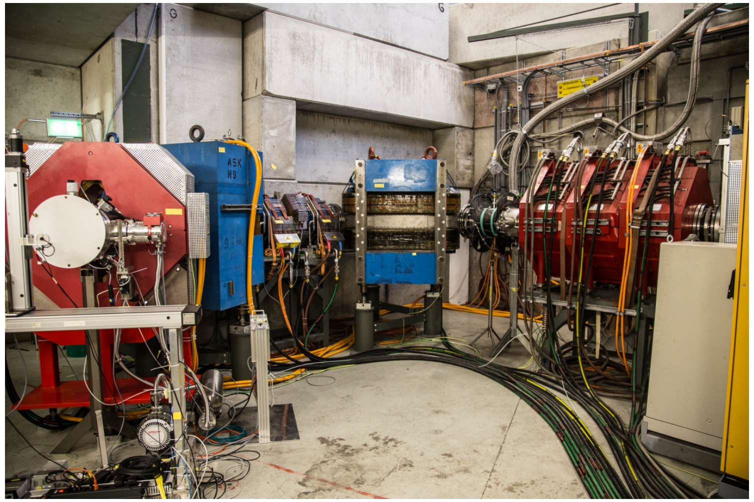


Mu5e, Mu7e, Mu(Nx2-1)e???
Let’s not get greedy!

https://arxiv.org/pdf/2306.15631

Thank you!

Mu3e gallery (Nik Berger)



Bibliography:

[1] Mu3e Letter of Intent (2012), https://www.psi.ch/sites/default/files/import/mu3e/DocumentsEN/LOI_Mu3e_PSI.pd
[2] Mu3e Technical Design Report (2020), https://arxiv.org/abs/2009.11690

Backups

Lagrangian proposed by Kuno and Okada

$$
\begin{aligned}
\mathcal{L}_{\mu\to eee} = -\frac{4G_F}{\sqrt{2}} \big[& m_\mu A_R\, \overline{\mu_R}\sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L\, \overline{\mu_L}\sigma^{\mu\nu} e_R F_{\mu\nu} \\
& + g_1\, (\overline{\mu_R} e_L)\, (\overline{e_R} e_L) + g_2\, (\overline{\mu_L} e_R)\, (\overline{e_L} e_R) \\
& + g_3\, (\overline{\mu_R}\gamma^\mu e_R)\, (\overline{e_R}\gamma_\mu e_R) + g_4\, (\overline{\mu_L}\gamma^\mu e_L)\, (\overline{e_L}\gamma_\mu e_L) \\
& + g_5\, (\overline{\mu_R}\gamma^\mu e_R)\, (\overline{e_L}\gamma_\mu e_L) + g_6\, (\overline{\mu_L}\gamma^\mu e_L)\, (\overline{e_R}\gamma_\mu e_R) \;+\; H.c. \big]
\end{aligned}
$$

g1,2 describing scalar-type and g3–6 vector-type interactions.

Wilson coefficients C_{ee}^{VRR} (equivalent to g_3 in eq. 2.1), C_{ee}^{SLL} (equivalent to g_1 in eq. 2.1), and C_L^D (equivalent to A_R in eq. 2.1).