The search for $\mu^+ \to e^+e^-e^+$ and what it may need beyond Mu3e phase II

Snowmass'21 Workshop on High Power Cyclotrons

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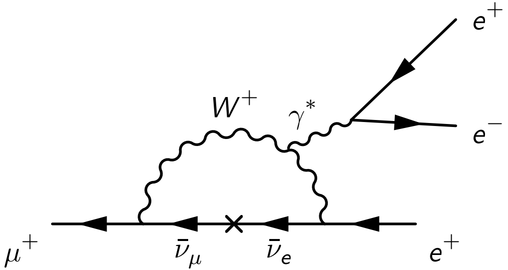
Paul Scherrer Institute

September 8, 2021

Introduction to Mu3e

$\mu^+ \rightarrow e^+ e^- e^+$ is a lepton flavour changing process (cLFV). In the standard model this is only possible through something like this:



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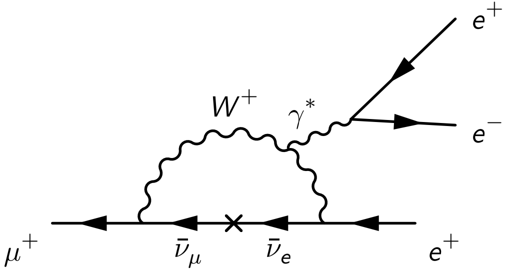
SM: $< 1 \times 10^{-54}$
Suppression from $m(\nu)$.

Current best limit: $< 1 \times 10^{-12}$ (SINDRUM 1988)

Alternative models predict BR within reach of Mu3e ($< 1 \times 10^{-16}$).



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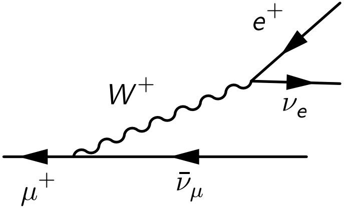
Introduction to Mu3e – backgrounds for Mu3e

The standard Michel decay

SM: $\approx 99.997\%$



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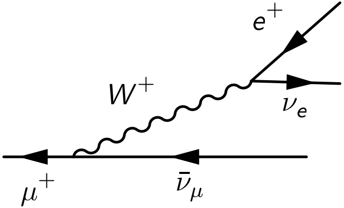
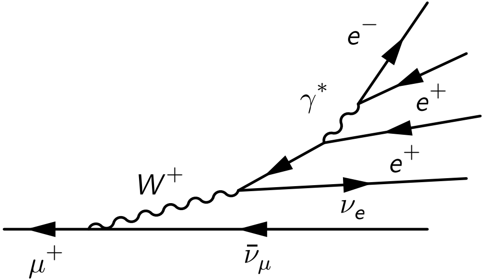
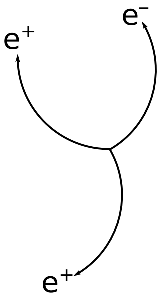


The radiative SM decay

SM: $(3.4 \pm 0.4) \times 10^{-5}$



Introduction to Mu3e — Signal in a B-field, $r\phi$-view



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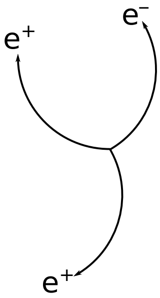

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$\sum p_i = 0$

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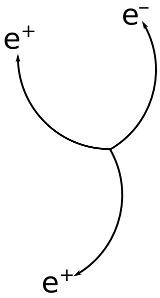

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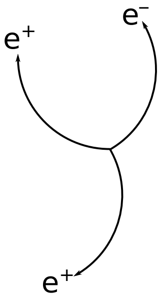

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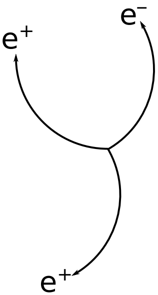

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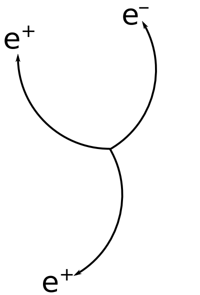

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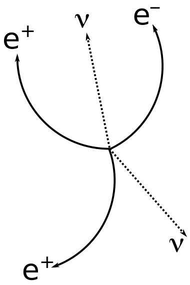

Radiative decay
SM: 3.4×10^{-5}

$\sum p_i \neq 0$
$m_{\text{inv}} < m_\mu$
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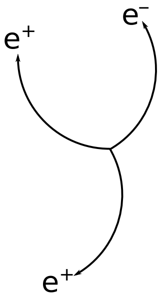

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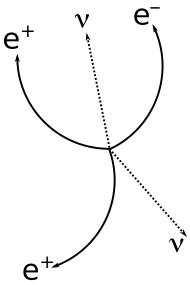

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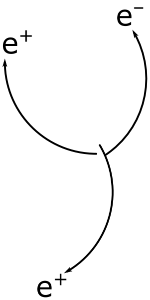

Accidental
background

$\sum p_i \approx 0$
$m_{\text{inv}} \approx m_\mu$
$t_i \approx t_j$
"bad vertex"

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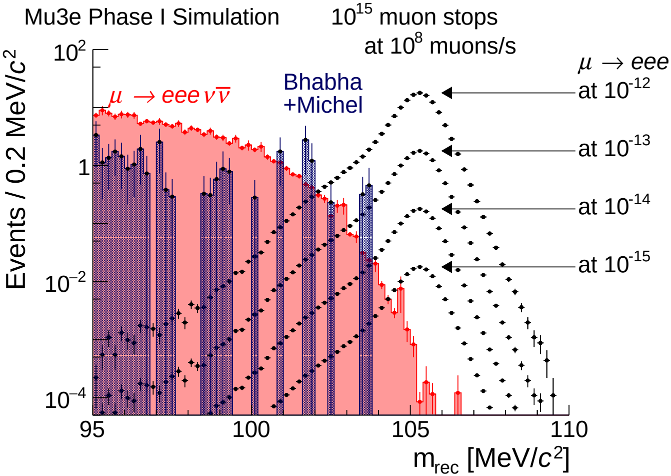
Introduction to Mu3e



Note: simulated data

m_{rec} is the invariant mass for a reconstructed event

Mu3e ingredients

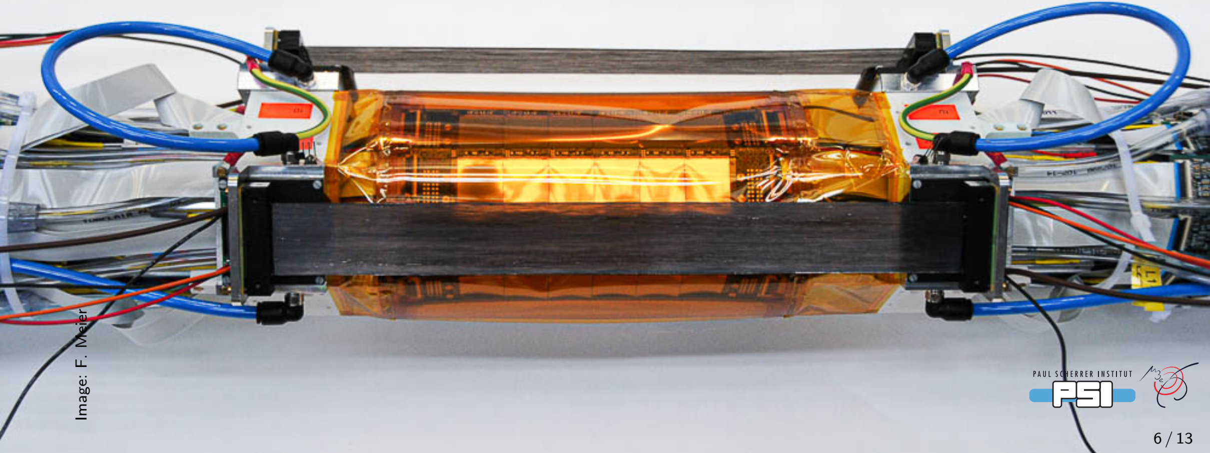


Image: F. Meier

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Mu3e ingredients – what we need

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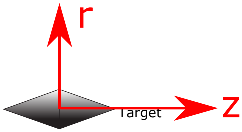

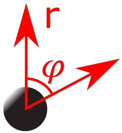

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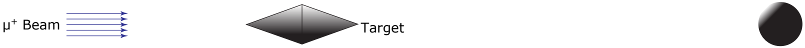

$1 \times 10^8\ \mu^+/\mathrm{s}$ $\rightarrow$ Accelerator, target, beamline

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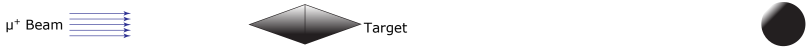

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B field	$\rightarrow$	Mu3e solenoid, 1 T, 1 m I.D.

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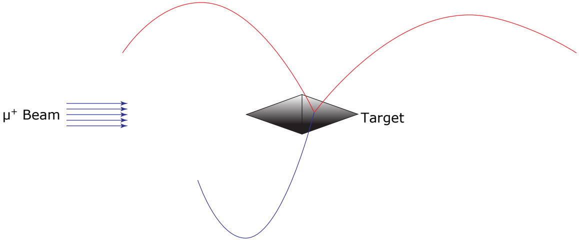

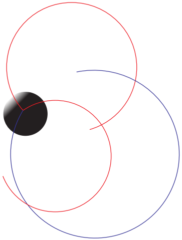

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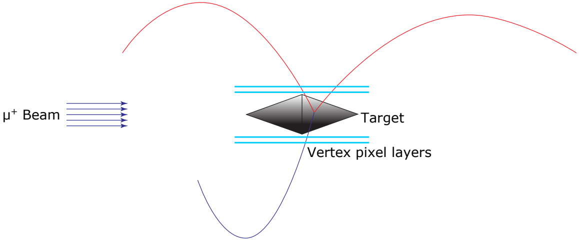

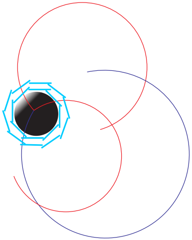

$1 \times 10^8\ \mu^+/s$ → Accelerator, target, beamline

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Determine the common vertex → Vertex tracker

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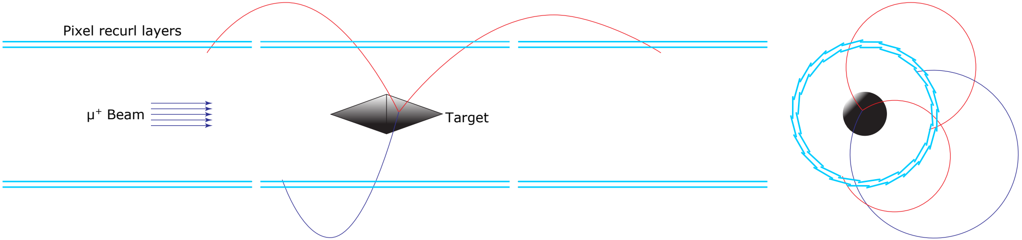

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$\sum p_i = 0$	$\rightarrow$	B-field, momentum tracker

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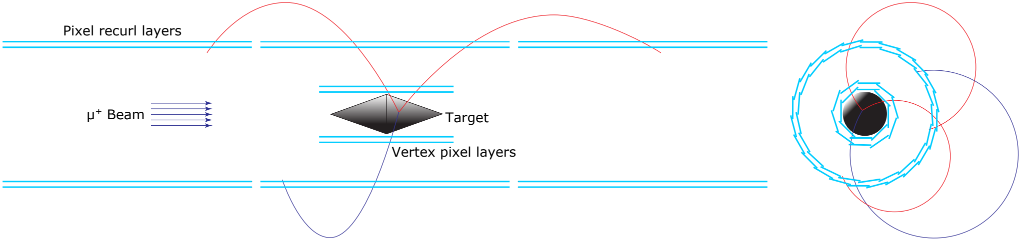

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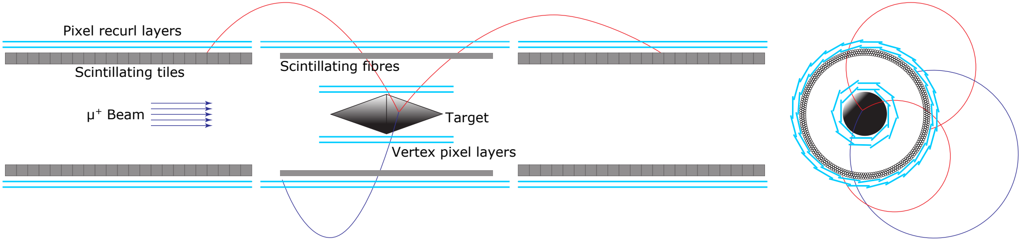

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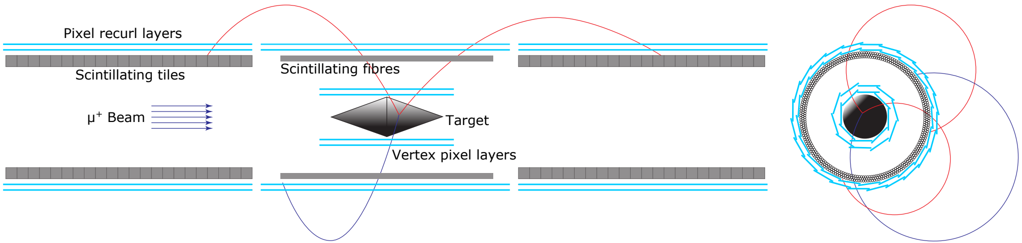

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Determine the charge sign	$\rightarrow$	Timing detectors again

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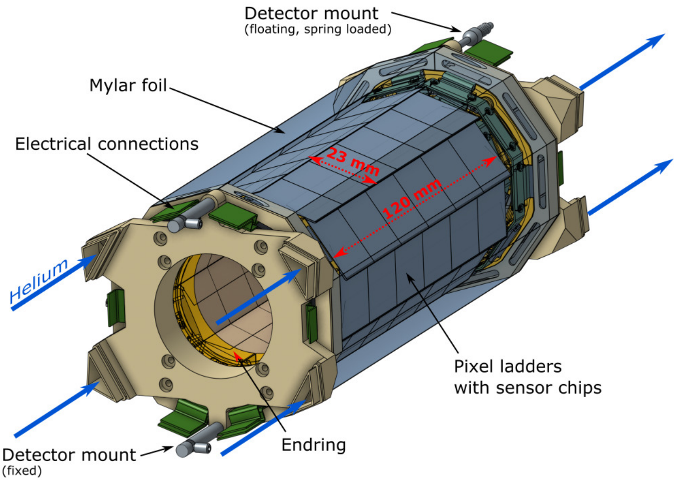
Mu3e ingredients



Why can we do this?

Latest depleted CMOS pixel sensors, specifically developed for Mu3e.

Single chip dimensions: $23 \times 20\,\mathrm{mm}^2$ and thinned down to $50\,\mu\mathrm{m}$.

Chip is self-triggered, always on. $250\,\mathrm{mW/cm}^2$ heat dissipation, cooled by gaseous helium.

(Image shows the vertex detector)

Mu3e status and plans for the future

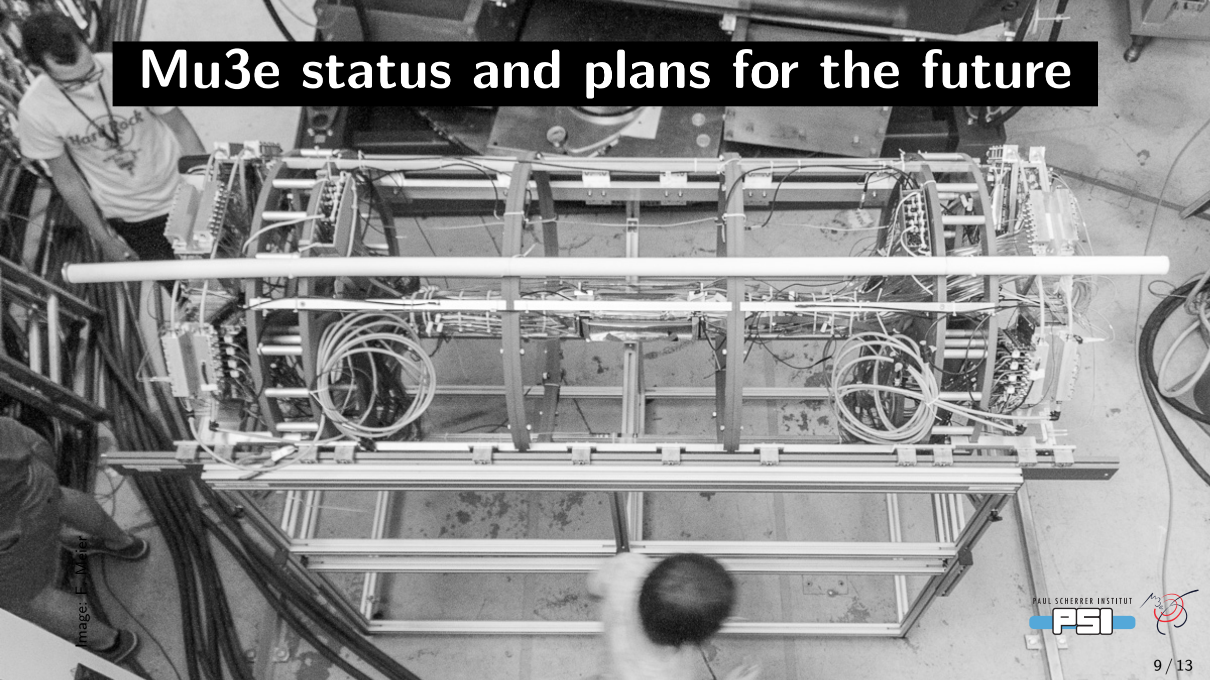


Image: F. Meier

Mu3e status and plans for the future

- Mu3e phase I
  - $10^8\ \mu/s$ stops on target (s.o.t.) at PSI's πE5 beamline
  - Concepts are now **proven** (integration run 2021)
  - Fabrication of remaining detectors starts this year
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  - 10^9 μ/s s.o.t. at the upcoming *high intensity muon beamline* (HIMB) at PSI
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- And beyond...
  - Main issue with HIMB: Transporting the muons into the detector
    HIMB will deliver 10^{10} but only $1/10^{\text{th}}$ reaches the target
  - Pixels are developing rapidly. Higher rates will be possible.

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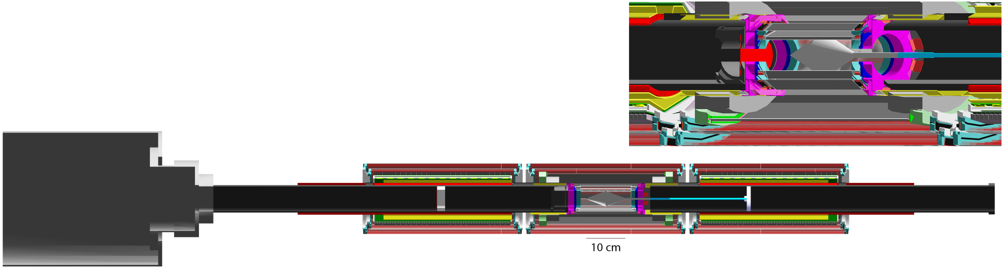

We go from a ISO-320-K vacuum flange down to a beampipe with I.D. 40 mm.

The experiment is inside a I.D. 1 m warm bore superconducting solenoid at 1 T field.

The solenoidal field focusses the beam and $10^9\,\mu/s$ on target are possible.
But you see the challenge.

Mu3e status and plans for the future

- The challenges are known
- We've started our efforts for Phase II
  - Optimising the target shape for 10^9 μ/s s.o.t.
  - Algorithmic improvements on track reconstruction
  - Improvements for scintillating fibre detector **OR** replacing it with fast silicon pixels
- Still left for beyond: Transport of the high rate to the target

  The Mu3e concept requires a relatively small target size.

Conclusions

- Mu3e is a challenging search for cLFV
- A path to reach a sensitivity down to 10^{-16} exists: Mu3e phases I and II
- Increasing the stopping rate and dealing with the background events will be the challenge
- And to you: yes, we would like to have higher rates

Mu3e TDR: `https://doi.org/10.1016/j.nima.2021.165679`

Mu3e collaboration members:
UK: U Bristol, U Liverpool, University College London, U Oxford
Germany: U Heidelberg, Kalrsruhe Institute of Technology, U Mainz
Switzerland: U Geneva, U Zürich, Eidg. Technische Hochschule Zürich, **Paul Scherrer Institut**

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