

The Mu3e Experiment at PSI



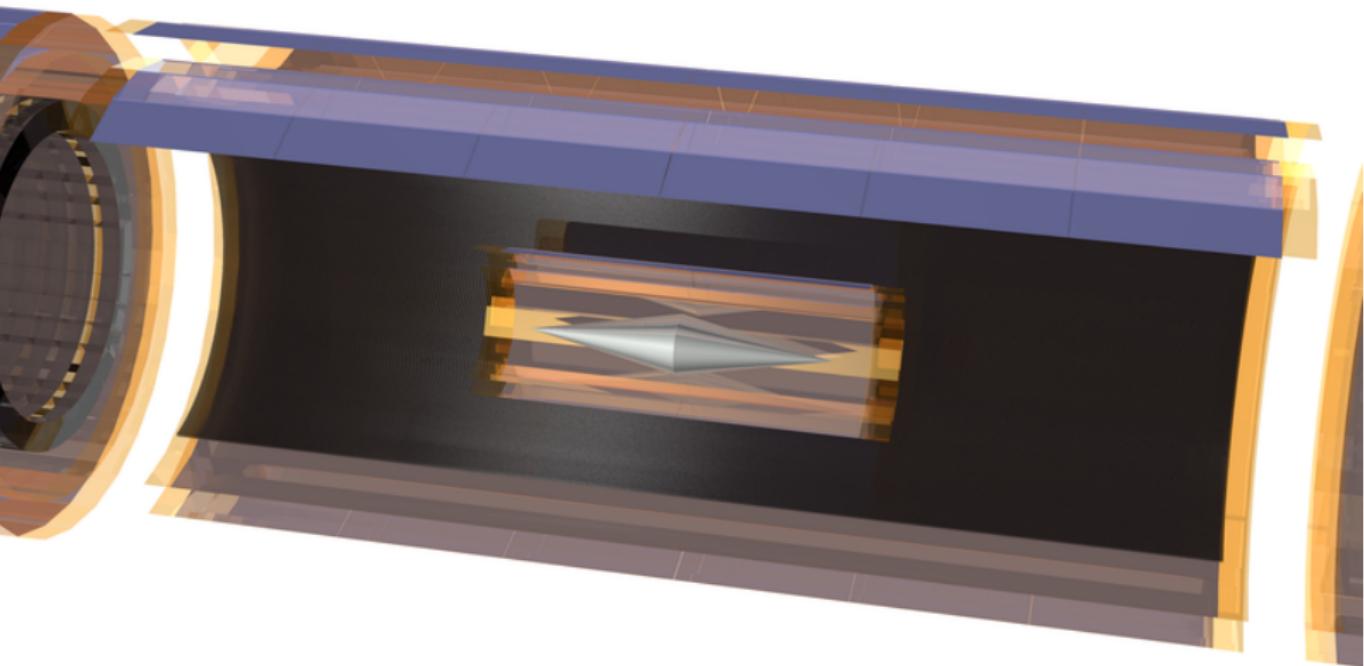
Antoaneta Damyanova

On behalf of the Mu3e Collaboration

5th International Conference on New Frontiers in Physics
OAC, July 2016

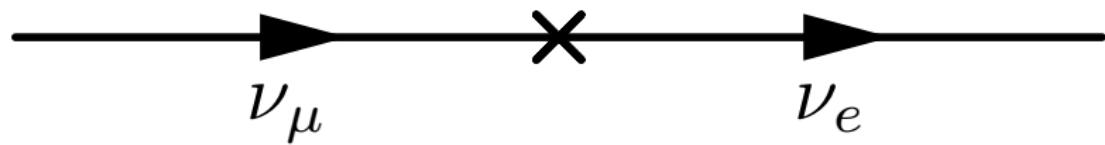
Mu3e

An experiment searching for
charged Lepton Flavour Violation (cLFV)
in the muon decay $\mu^+ \rightarrow e^+ e^- e^+$



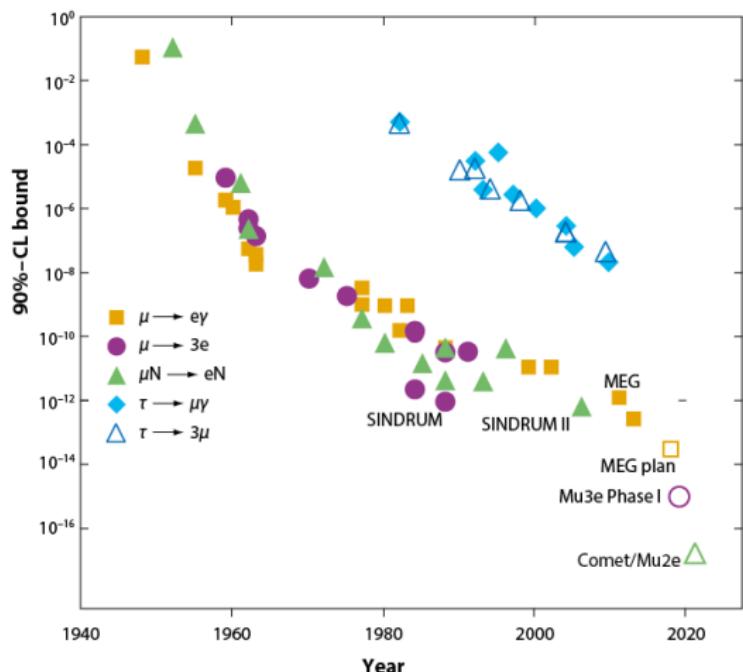
Lepton Flavour Violation

It has been observed in the neutrino sector



...but **not** in the charged lepton sector

History of LFV Experiments



- SINDRUM (1988)
 $BR(\mu \rightarrow eee) < 1 \times 10^{-12}$
- SINDRUM II (2006)
 $BR(\mu Au \rightarrow eAu) < 7 \times 10^{-13}$
- MEG (2016)
 $BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$

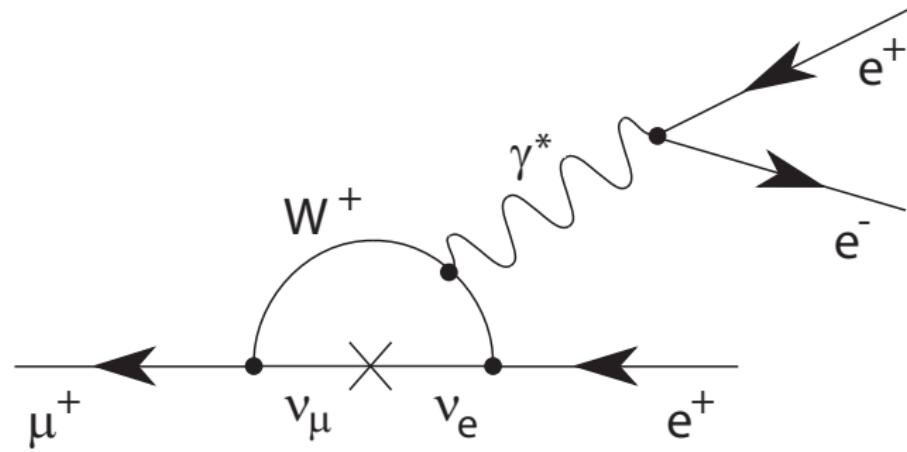
Updated from W.J. Marciano, T. Mori and J.M. Roney,

Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)

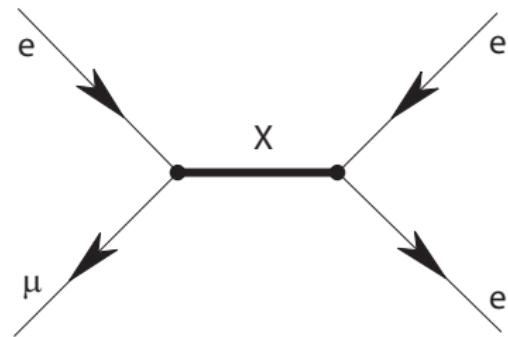
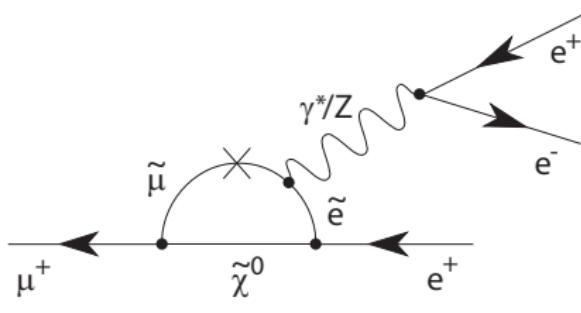
LFV within the Standard Model

Heavily suppressed: $\sim (\Delta m_\nu^2 / m_W^2)^2$

$$BR(\mu \rightarrow eee) \sim \mathcal{O}(10^{-54})$$



Observing cLFV = New Physics

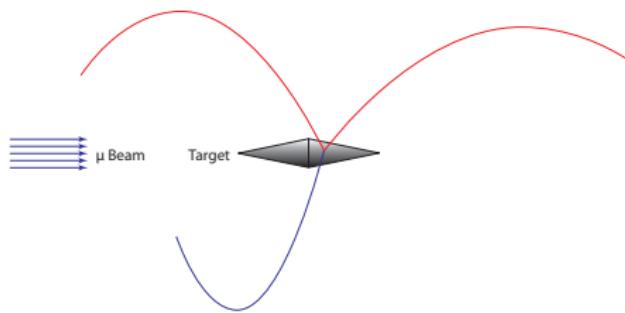


$\mu^+ \rightarrow e^+ e^- e^+$ is sensitive to new physics!

e.g. SUSY, Seesaw models, GUT, new heavy bosons, etc.

The Idea of Mu3e

Probe the muon decay $\mu^+ \rightarrow e^+ e^- e^+$ with a branching ratio sensitivity $BR(\mu \rightarrow eee) < 10^{-16}$



- ▶ Stop $> 10^{16} \mu^+$ in a thin target
- ▶ Wait until they decay
- ▶ Look for $e^+ e^- e^+$
- ▶ Suppress backgrounds by more than 16 orders of magnitude

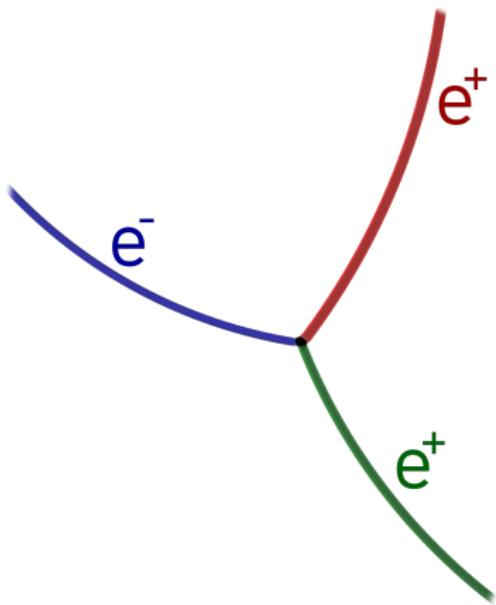
Seems easy, doesn't it?

Mu3e Requirements: Beam Line

- ▶ $2 \times 10^9 \mu/s$ stopped on target
- ▶ continuous beam
- ▶ focussed on a spot of ~ 2 cm
- ▶ surface muons with momentum $28 \text{ MeV}/c$

Mu3e Requirements: Identify the Signal

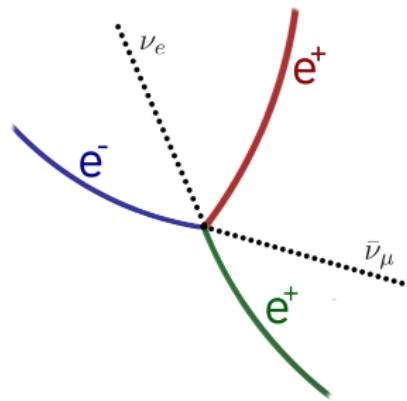
Identify the signal: $\mu^+ \rightarrow e^+ e^- e^+$



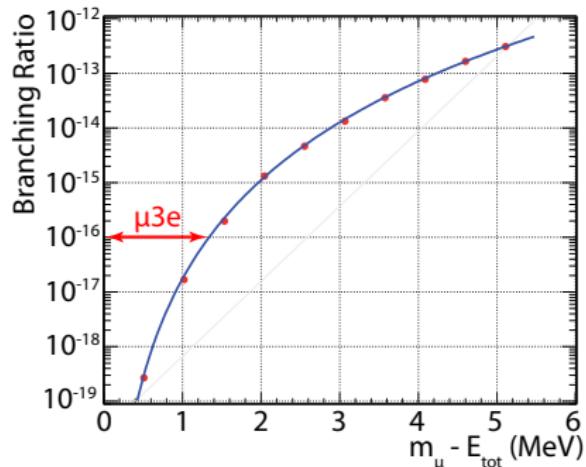
- ▶ two e^+ , one e^-
- ▶ from the same vertex
- ▶ at the same time
- ▶ $\sum \vec{p}_i = 0$
- ▶ $\sum E_i = m_\mu c^2$
- ▶ $p^{max} = 53 \text{ MeV}/c$

Mu3e Requirements: Discriminate Internal Conversion

Irreducible background: $\mu^+ \rightarrow e^+ e^- e^+ \nu_e \bar{\nu}_\mu$



- $\sum \vec{p}_i \neq 0$
- $\sum E_i \neq m_\mu c^2$



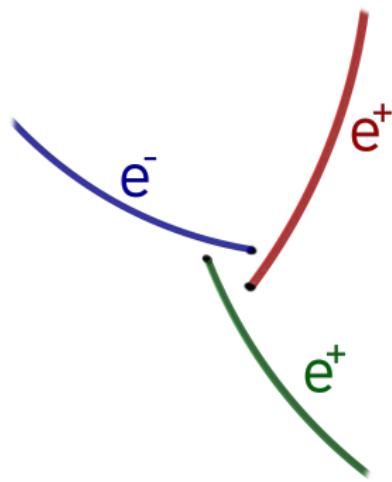
R. M. Djilkibaev, R. V. Konoplich,

Phys. Rev. D79 (2009) 073004

Only momentum resolution better than 0.5 MeV/c can discriminate the signal!

Mu3e Requirements: Reduce Accidental Coincidences

Higher beam intensity \iff higher accidental coincidence probability



Combination of e^+ from one or more Michel decays and e^- from

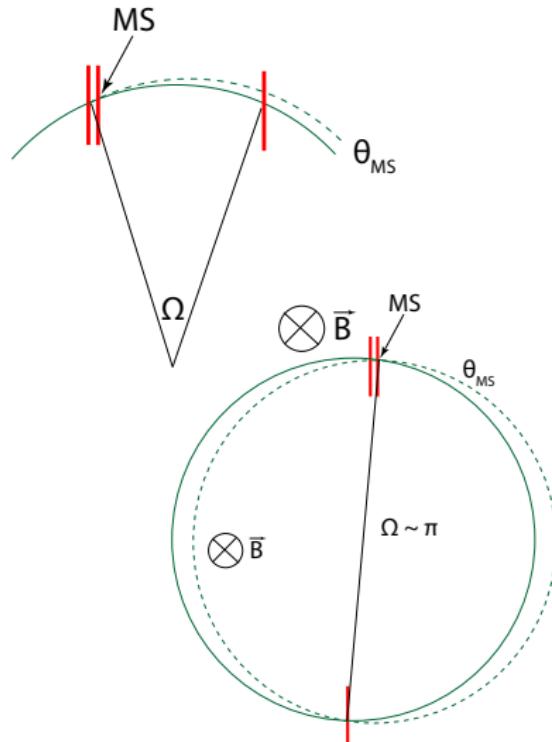
- ▶ Bhabha scattering
- ▶ photon conversion
- ▶ misreconstruction

Signature:

- ▶ not coincident in time
- ▶ not from the same vertex
- ▶ $\sum \vec{p}_i \neq 0$, $\sum E_i \neq m_\mu c^2$

Requires very good time, momentum and vertex resolutions.

Mu3e Requirements: Minimize Multiple Scattering



Momentum measurement:
use 1T magnetic field

Momentum resolution:
 $p_e^{max} = 53 \text{ MeV}/c \Rightarrow$
 dominated by **multiple scattering**, not pixel size
 and time resolutions.

$$\frac{\sigma_p}{p} \sim \frac{\theta_{MS}}{\Omega}$$

$$\text{RMS } \theta_{MS} \sim \frac{x}{X_0}$$

Good momentum resolution requires low material budget.

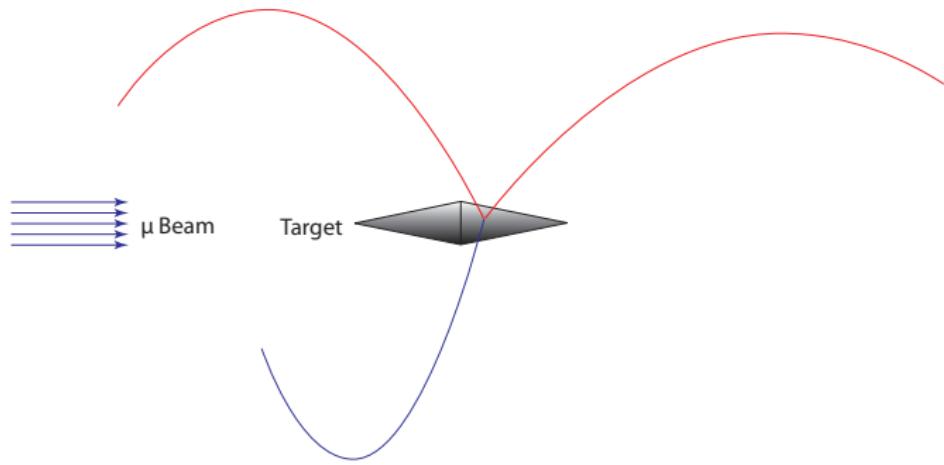
Mu3e Requirements: Detector Summary

To probe the $\mu^+ \rightarrow e^+ e^- e^+$ at a level of 10^{-16} , the Mu3e detector needs:

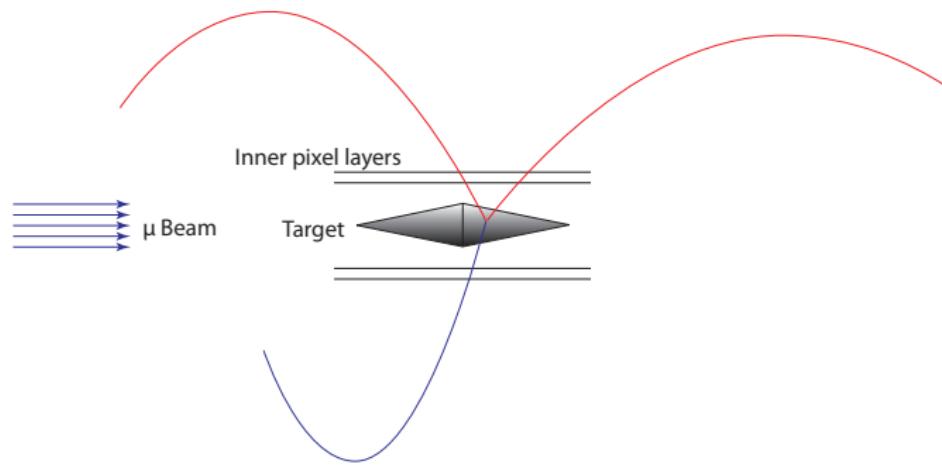
- ▶ to handle very high rates $10^8 - 10^9 \mu/s$
- ▶ high momentum resolution $\lesssim 0.5 \text{ MeV}$
- ▶ very good timing resolution $\sim \mathcal{O}(100ps)$
- ▶ excellent vertex resolution $\sim 300 \mu m$
- ▶ very low material budget $\sim 1\% X_0 / \text{layer}$

Still looking easy?

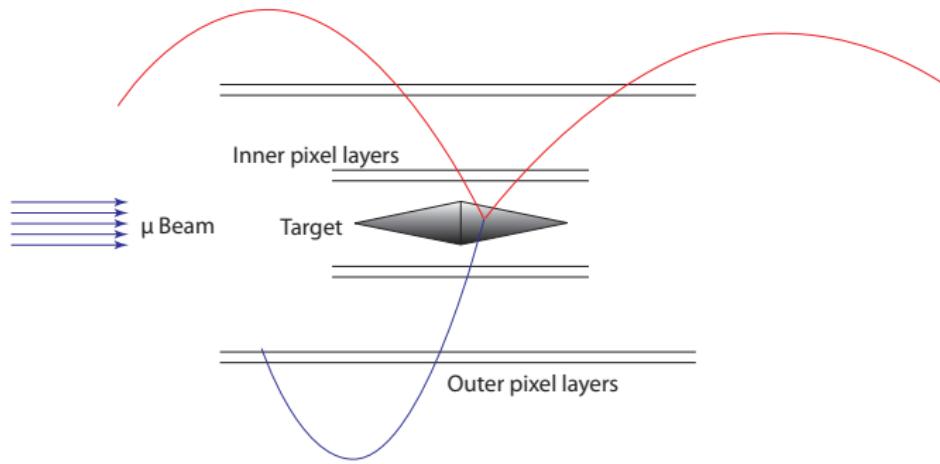
Mu3e Detector Design: Target



Mu3e Detector Design: Inner Pixel Layers



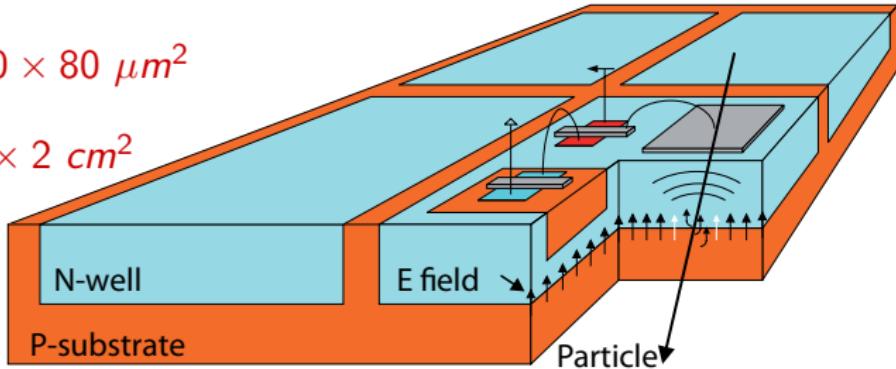
Mu3e Detector Design: Outer Pixel Layers



Mu3e Detector Design: Pixels

High Voltage Monolithic Active Pixel Sensors: **HV-MAPS**

- ▶ Fast charge collection **via drift**
- ▶ Readout logic and amplifier **embedded in the pixel N-well**
- ▶ Can be thinned **down to $< 50 \mu m$**
- ▶ Final pixel size **$80 \times 80 \mu m^2$**
- ▶ Final chip size **$2 \times 2 cm^2$**
- ▶ **> 270 million pixels**



I.Perić, P. Fischer et al., NIM A 582 (2007) 876

Mu3e R&D Status: Pixels

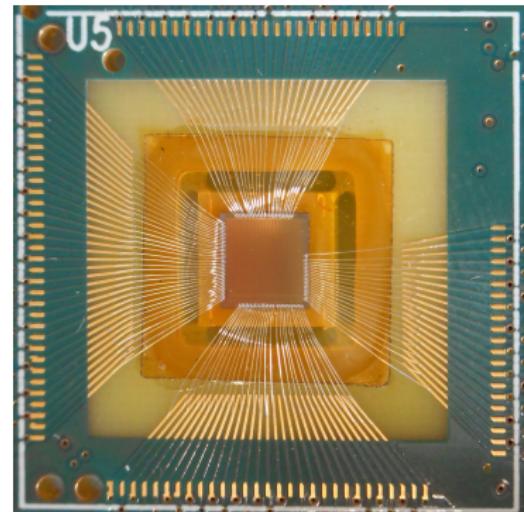
Current prototype version: **MUPIX 7**

Characteristics:

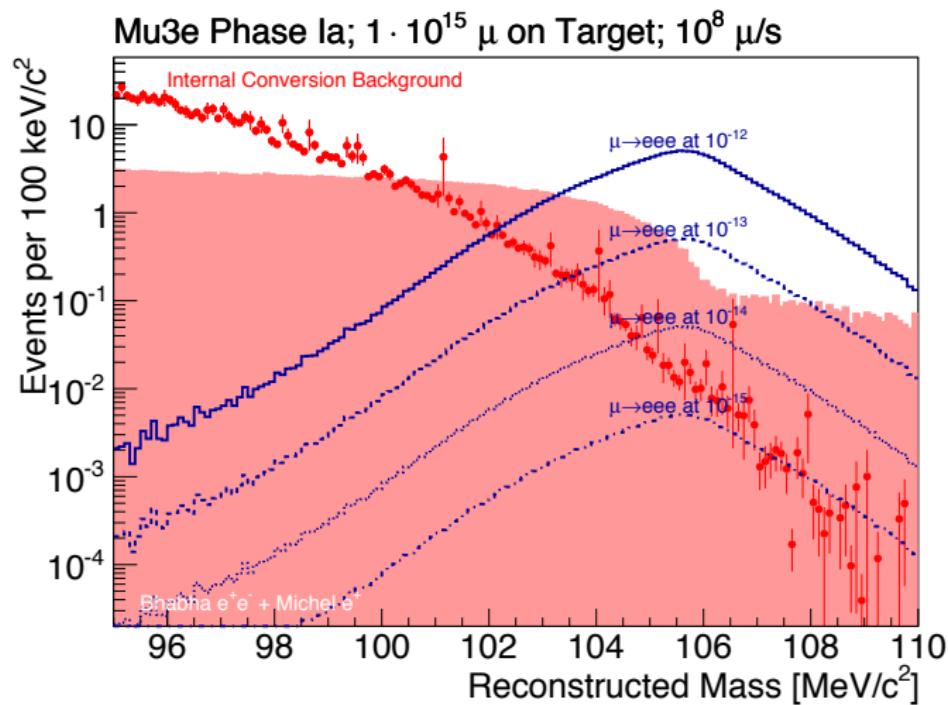
- ▶ Thickness: $50 \mu m$
- ▶ Pixel size: $103 \mu m \times 80 \mu m$
- ▶ Chip size: $3.2 \times 3.2 mm^2$
- ▶ Pixel matrix: 30×40
- ▶ LVDS link: 1.25 Gbit/s

Performance:

- ▶ Efficiency: $> 98\%$
- ▶ Time resolution: $< 14 ns$

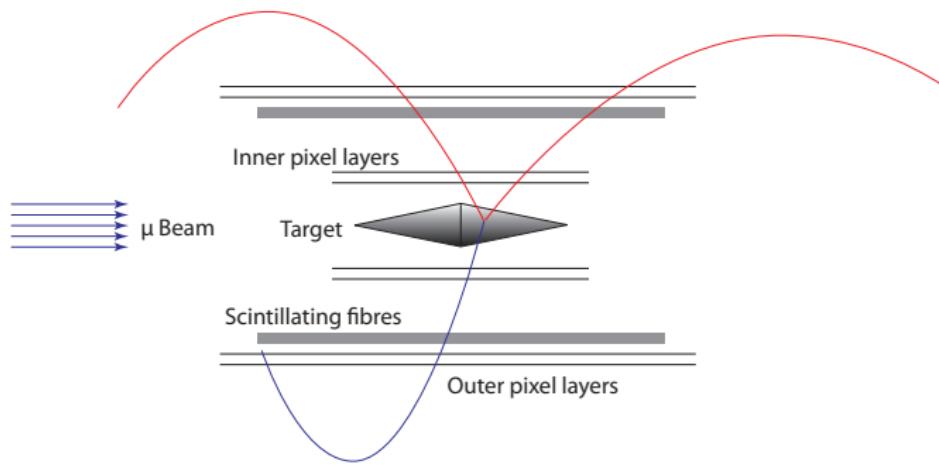


Mu3e Simulated Performance: Pixels Only



Needs better accidental suppression \Leftrightarrow better timing

Mu3e Detector Design : Scintillating Fibers

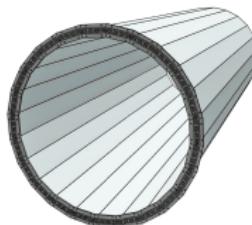


Mu3e R&D Status: Fibers

Thin plastic scintillating fibers readout by silicon photomultipliers.
Low material budget & good timing resolution

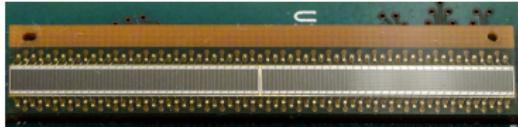
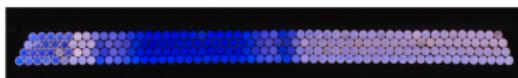
Characteristics:

- ▶ Fibers thickness: $250 \mu\text{m}$
- ▶ Fiber ribbons: $2\text{-}4$ staggered fiber layers
- ▶ Ribbon dimensions: $280 \text{ mm} \times 16 \text{ mm}$
- ▶ SiPM readout: in array configuration
- ▶ Custom SiPM digitizer: MuStic

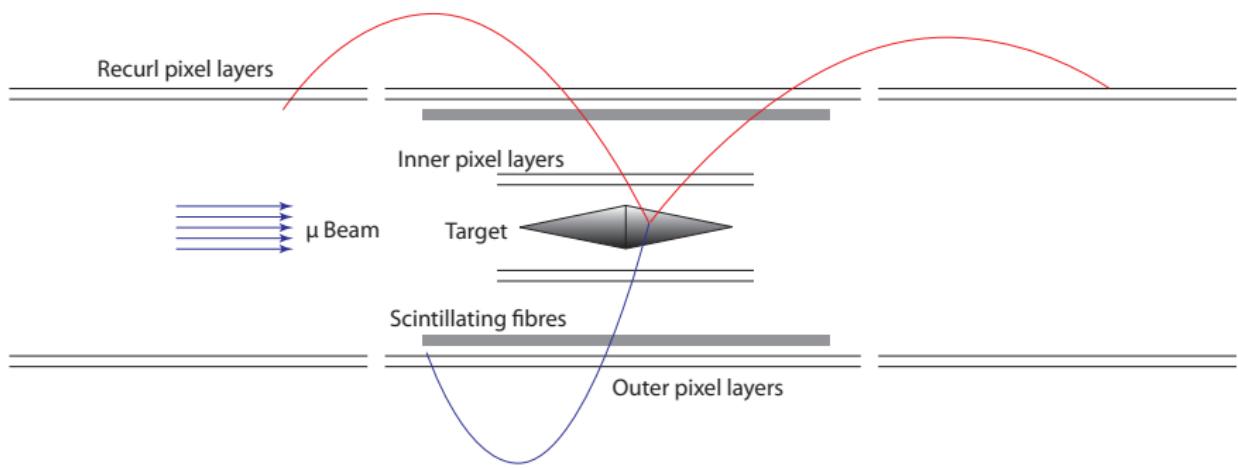


Performance:

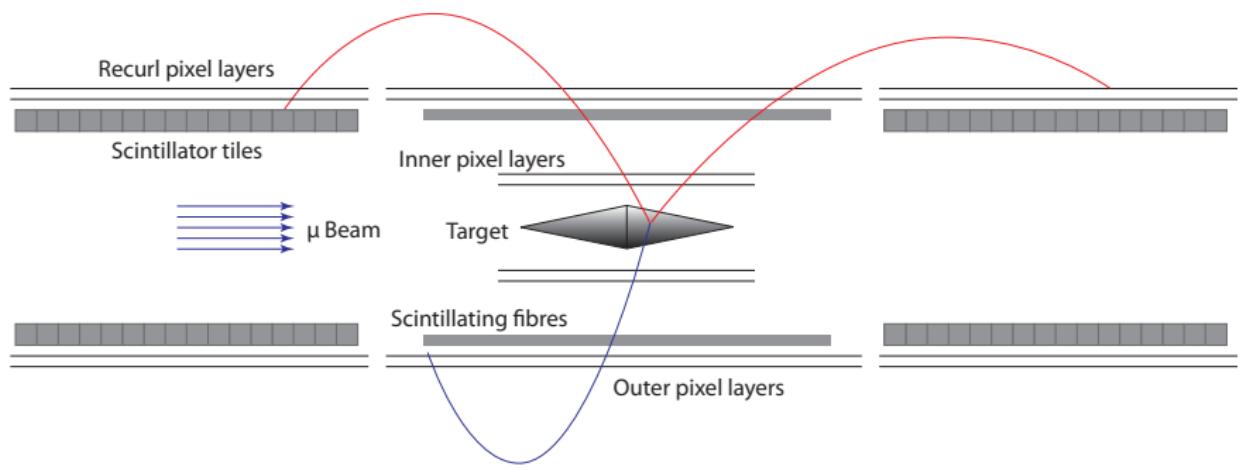
- ▶ $\sigma_t \sim 1 \text{ ns}$ round fibers, clear coating, single fiber resolution;
- ▶ $\sigma_t \sim 550 \text{ ps}$ square fibers, Al coating, triple fiber readout ;



Mu3e Detector Design: Recurl Pixel Stations



Mu3e Detector Design: Scintillating Tiles



Mu3e R&D Status: Scintillating Tiles

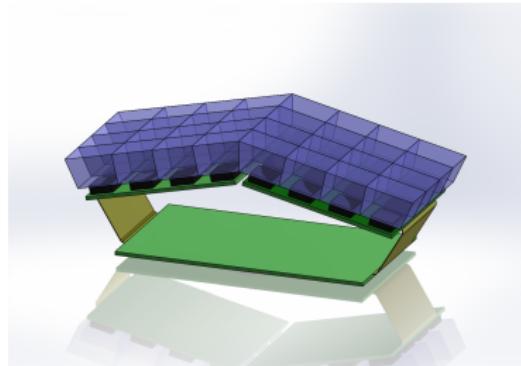
Large scintillating tiles provide accurate time information for tracks recurling out of the central region.

Characteristics:

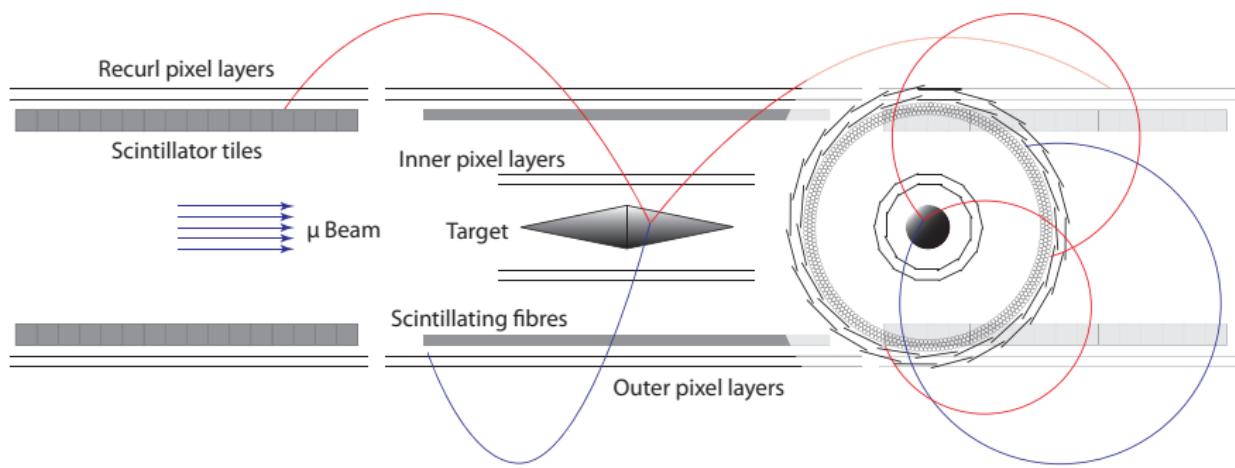
- ▶ Tiles dimensions: $6.5 \times 6.0 \times 6.5 \text{ mm}^3$
- ▶ SiPM readout: $3 \times 3 \text{ mm}^2$ area
- ▶ Custom SiPM digitizer: MuStic

Performance:

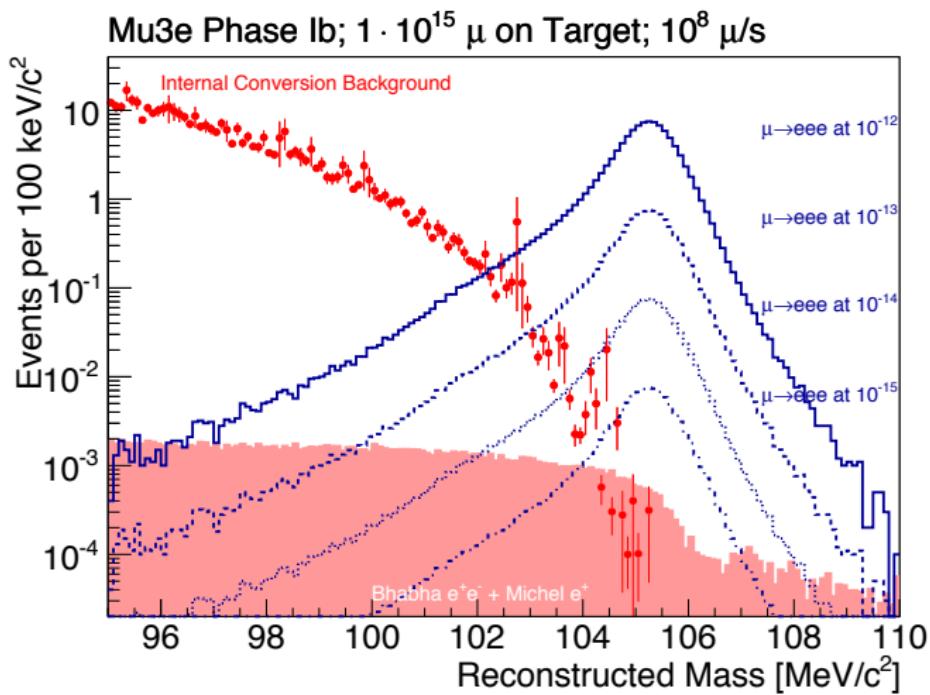
- ▶ Time resolution: $\sim 70 \text{ ps}$
- ▶ Efficiency: $> 99.7\%$



Mu3e Detector Design: Full Phase I



Mu3e Simulated Performance: Phase I



Summary and Outlook

The Phase I Mu3e Experiment aims to

- ▶ Probe $\mu^+ \rightarrow e^+ e^- e^+$ with a sensitivity of 1 in 10^{15}
- ▶ Handle up to $10^8 \mu/s$
- ▶ Pixel, fiber and tile prototypes meet the requirements
- ▶ Superconducting magnet delivery expected in 2017
- ▶ Assembly at PSI will start in 2017

The Mu3e Collaboration



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