Detector concept for $\mu \longrightarrow eee$ decay at Project X

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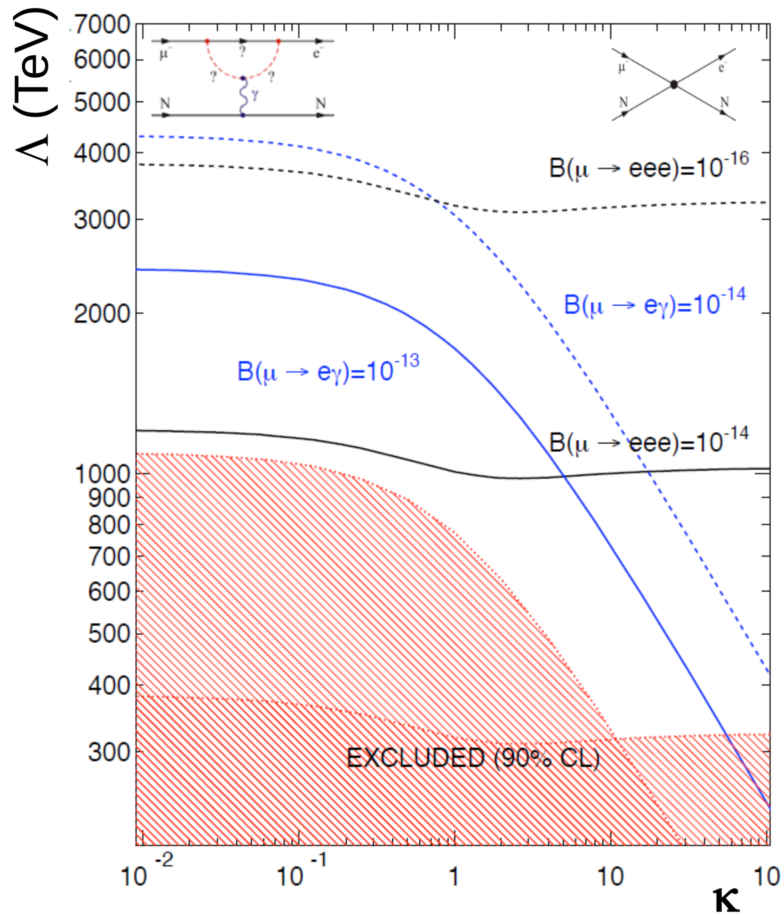
- The $\mu \to eee$ decays is a charged lepton flavor violating process (CLFV)
- These reactions are strongly suppressed in the Standard Model
- New Physics could enhance CLFV rates to observable values
- Can probe mass scales way beyond direct reach of LHC

Observation is a clear sign of New Physics

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$



A. De Gouvea and P. Vogel, arxiv:1303.4097

Y. Okada *et al.*, PRD 61 (200) 094001

Dalitz plot of $\mu \to eee$ defined with help of the muon polarization carry information on chirality and Lorentz structure of CLFV couplings (same for $\tau \to \mu\mu\mu$)

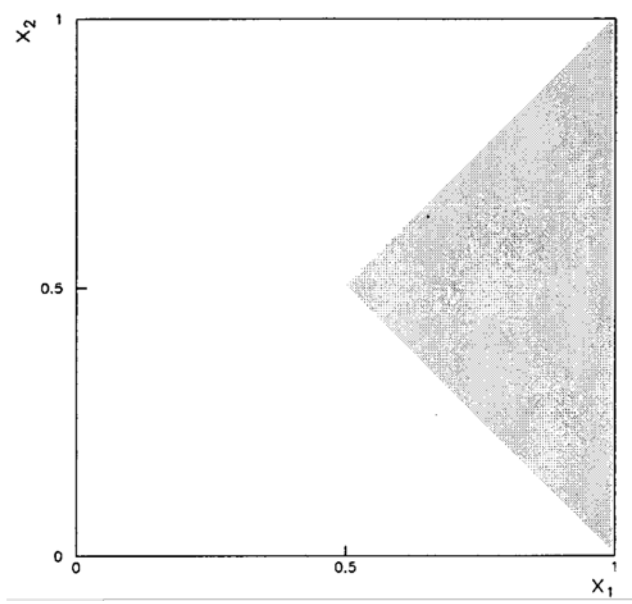
Generic Lagrangian

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\{m_\mu A_R \overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu} + m_\mu A_L \overline{\mu_L}\sigma^{\mu\nu}e_R F_{\mu\nu}$$
$$+ g_1(\overline{\mu_R}e_L)(\overline{e_R}e_L) + g_2(\overline{\mu_L}e_R)(\overline{e_L}e_R)$$
$$+ g_3(\overline{\mu_R}\gamma^\mu e_R)(\overline{e_R}\gamma_\mu e_R) + g_4(\overline{\mu_L}\gamma^\mu e_L)(\overline{e_L}\gamma_\mu e_L)$$
$$+ g_5(\overline{\mu_R}\gamma^\mu e_R)(\overline{e_L}\gamma_\mu e_L) + g_6(\overline{\mu_L}\gamma^\mu e_L)(\overline{e_R}\gamma_\mu e_R)$$
$$+ \mathrm{H.c.}\},$$

$A_{R,L}$ photon-penguin coupling, contributes to $\mu \to e\gamma$, $\mu \to eee$

g_i 4-point contact interaction, contributes to $\mu \to eee$

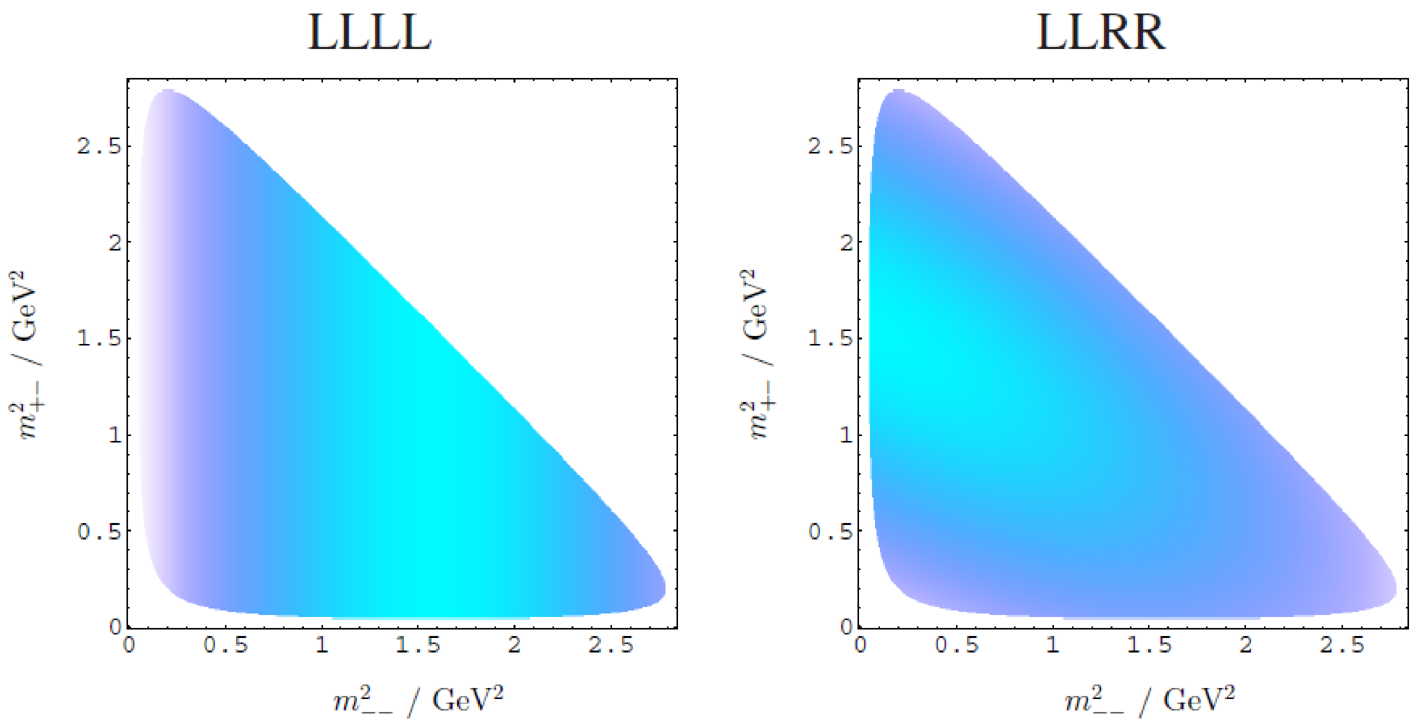
Positron 1 *vs* Positron 2 ($E_1 > E_2$)
$x_i = 2E_i / m_m$



Need at least dozens of events and polarized muons

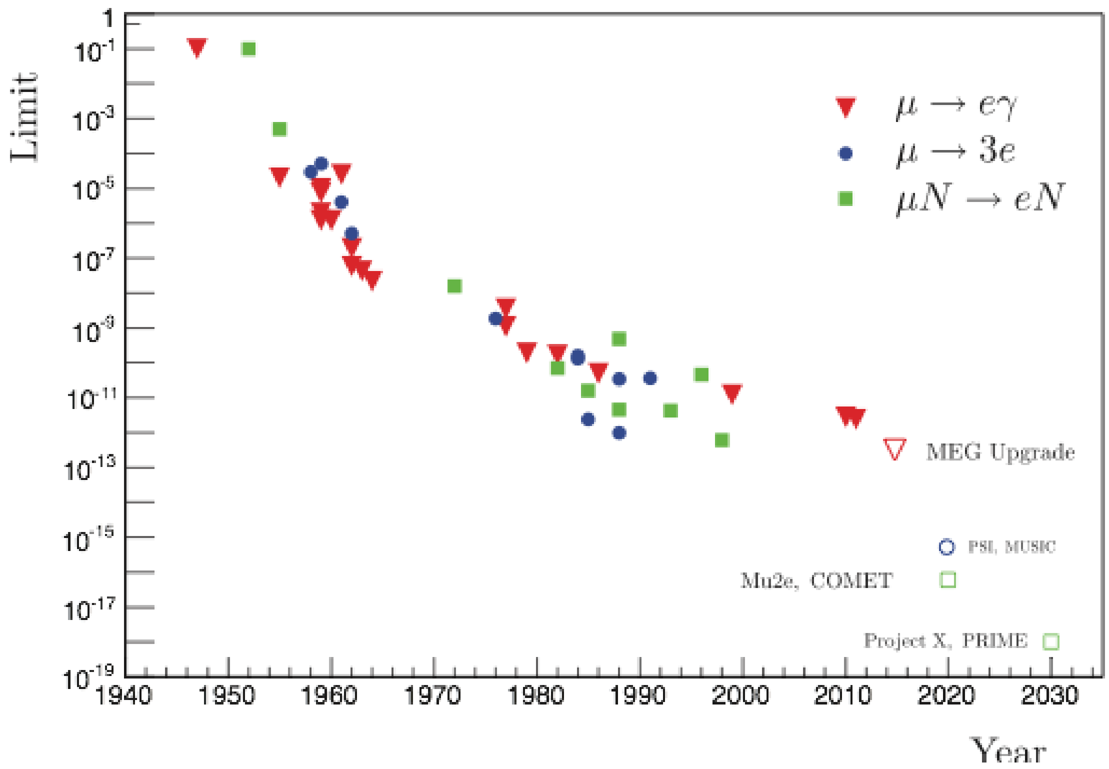
B.M. Dassinger *et al.*, JHEP 0710 (2007) 039

Similar situation in $\tau \to \mu\mu\mu$



Need at least dozens of events and polarized taus

Experimental situation

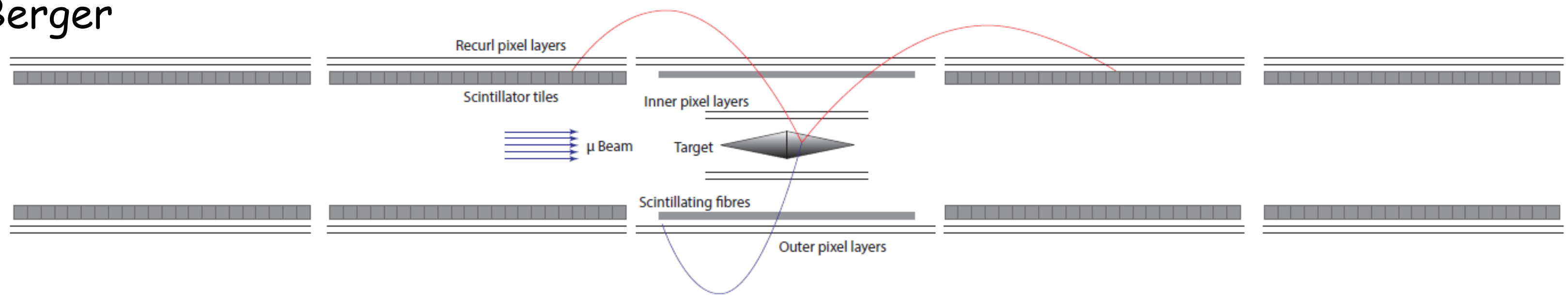


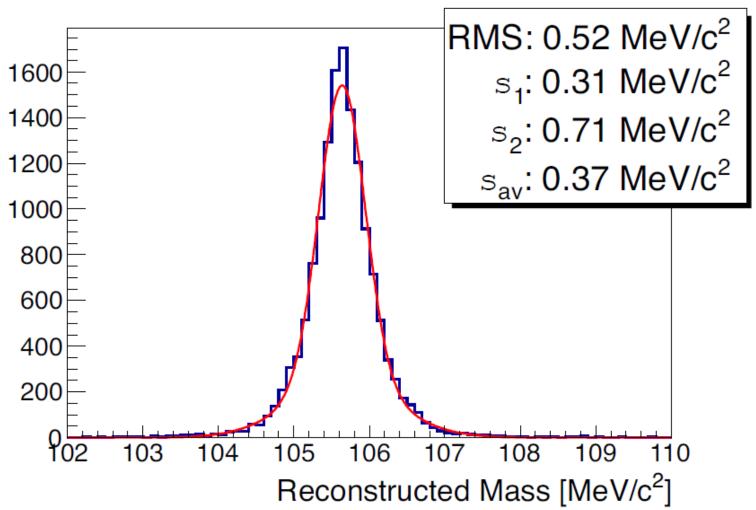
The Mu3e experiment at PSI will search for $\mu \rightarrow eee$ with a single event sensitivity at the level of $4\mathrm{x}10^{-16}$ (phase 1, 2015+) - $7\mathrm{x}10^{-17}$ (phase II, 2017+)

arXiv:1301:6113

The Mu3e experiment

N. Berger





Niklaus Berger – Charged Leptons, February 2013 – Slide 31

Mass resolution (RMS) ~ 520 keV

Time resolution
~50 ps (tile) / ~500 ps (fiber)

Passive target

How well can an active target help to improve the resolution / bkg rejection?

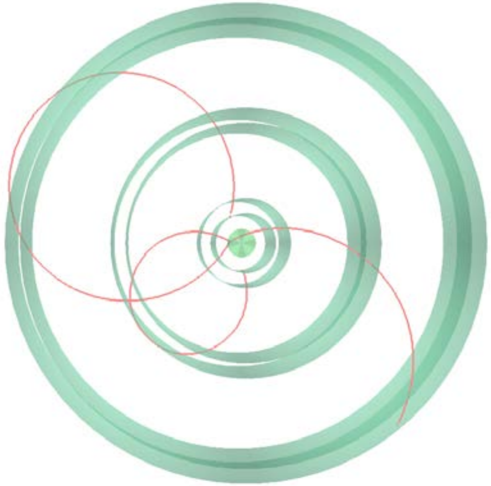
Introduction to FastSim

Studies based on SuperB Fastsim:

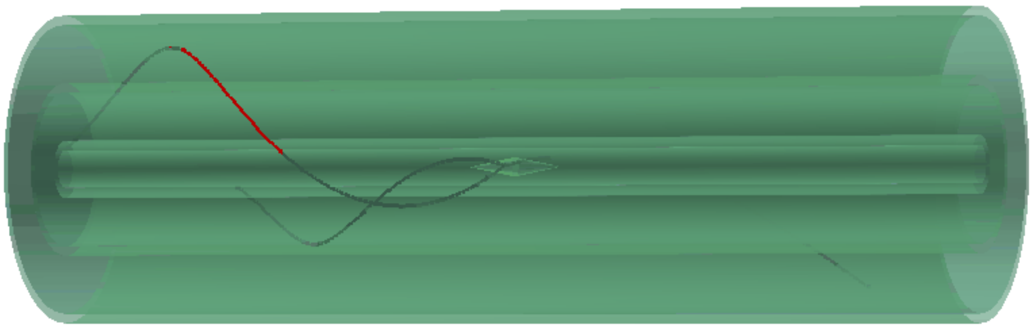
- Spin-off of the BABAR software framework, developed mainly for SuperB. Extensively tested and used.
- Detectors are described with 2D cylinders, planes, and cones, configured by xml files. Authors state that it is very easy and quick to modify.
- Can interface any generator (EvtGen by default), or your own code.
- Simulates particle scattering, energy loss, secondary particles,…, at the interaction of each detector piece. Includes Compton, Bremsstrahlung, conversion, EM/hadron showers and more.
- Tracks are reconstructed with a Kalman filter into piece-wise trajectories (software adapted to low-momentum tracks).
- BABAR framework used to build and analyze higher level objects (tracks, composite candidates, …).

Detector concept largely inspired from the Mu3e detector

Front view



Side view

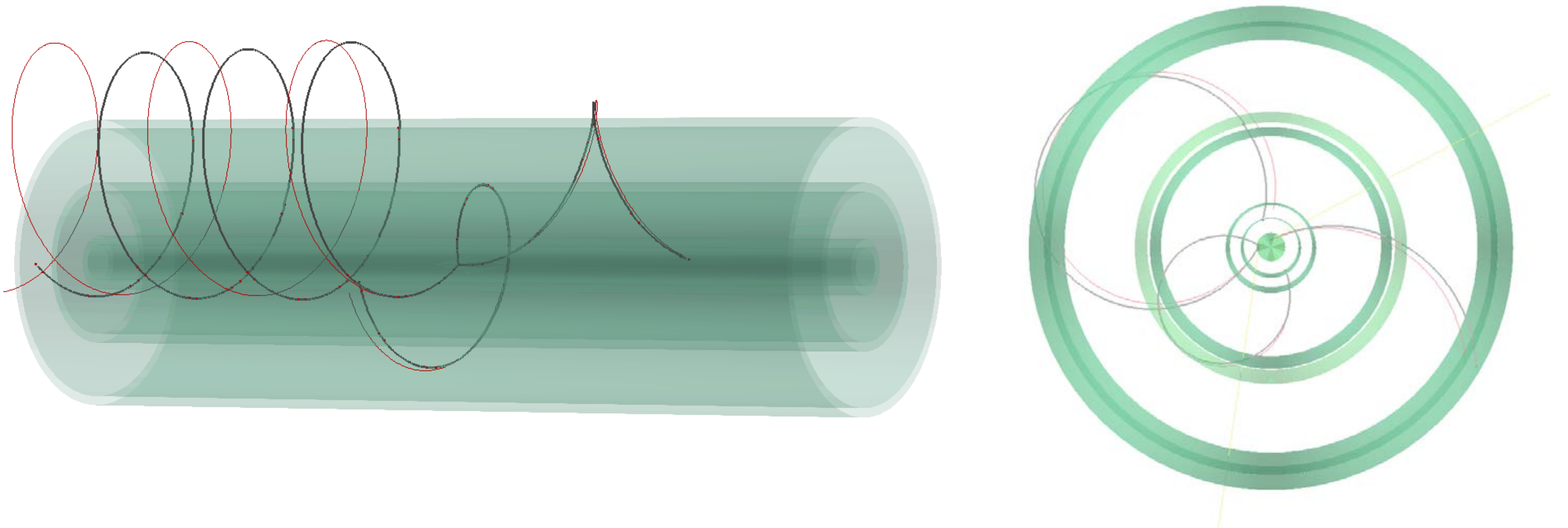


Active target: - two hollow cones of 1cm radius and 10cm long made of silicon pixel detector
- pixel size 50 μm x 50 μm.

Silicon tracker: - 6 cylindrical layers at radius = 2,3,8,9,15,16 cm with a length of 100 cm
- silicon sensor 50 μm thick on 50 μm of kapton, modeled after SuperB double-sided striplets, with resolution of 8 μm plus 20 μm tail, 90% hit efficiency

Time-of-flight: -not included yet, but assume a 50-500 ns resolution (similar to Mu3e) for bkg estimates

Event display

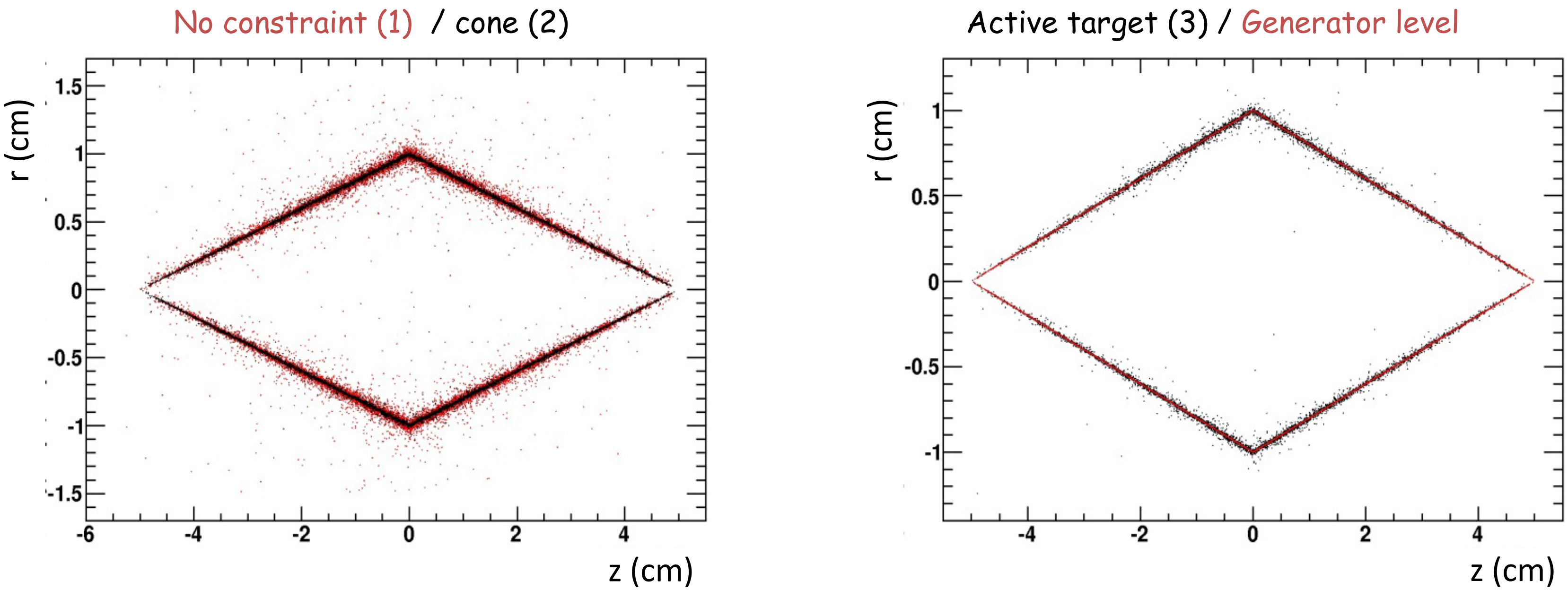


Generated track (thin red)
Reconstructed track (thick dark red)
Photon (yellow lines)

Vertex reconstruction

Reconstruct $\mu \to eee$ events after all detector effects imposing a common vertex for all tracks using three settings:

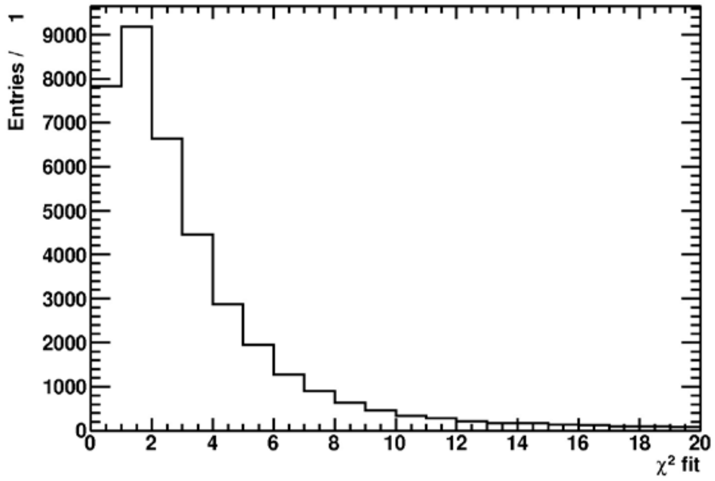
- 1- no constrain on the decay vertex
- 2- the decay vertex is on the cone. The vertex is chosen by trying all intersections between the tracks and the target, and taking the point that provides the best fit **(default)**
- 3- use the generated muon decay point as decay vertex to simulate the effect of the active target



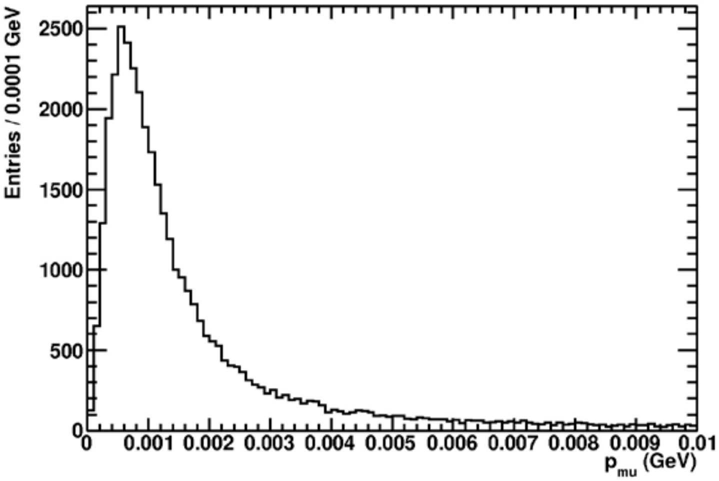
Vertex constraint still not fully working, problem under study

Apply cuts on the χ^2 of the fit and the muon momentum to improve the mass resolution

χ^2 of the constrained fit



Reconstructed muon momentum

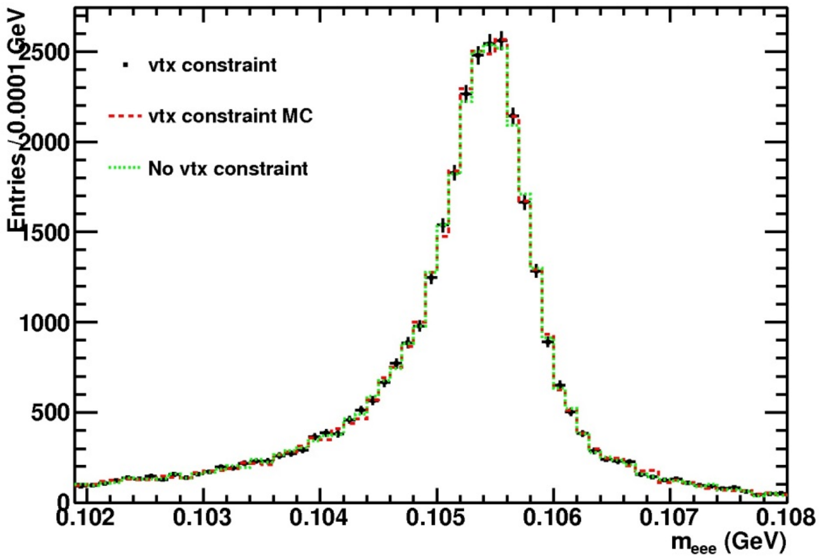


Cuts: $\chi^2 < 10$ and $P_\mu < 0.001$

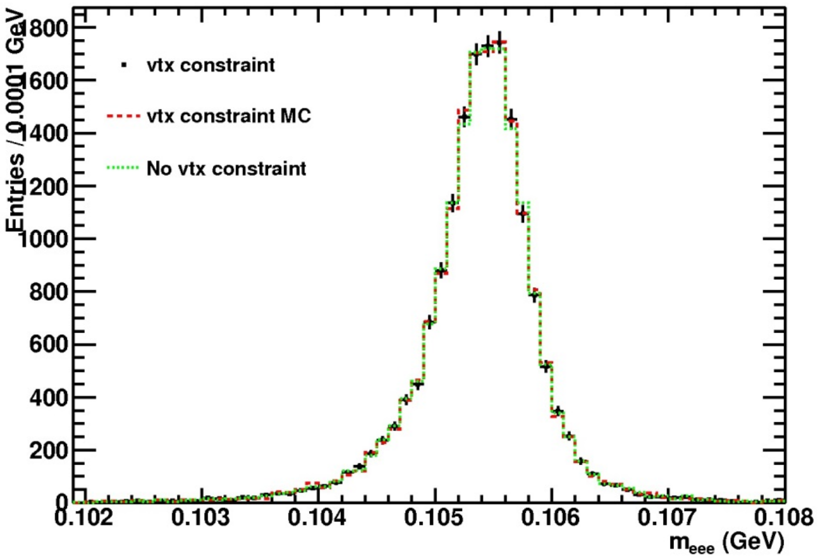
Might be possible to add a constraint on the muon momentum when fitting, or improve the fit somehow.

Mass spectrum

Before cuts



After cuts

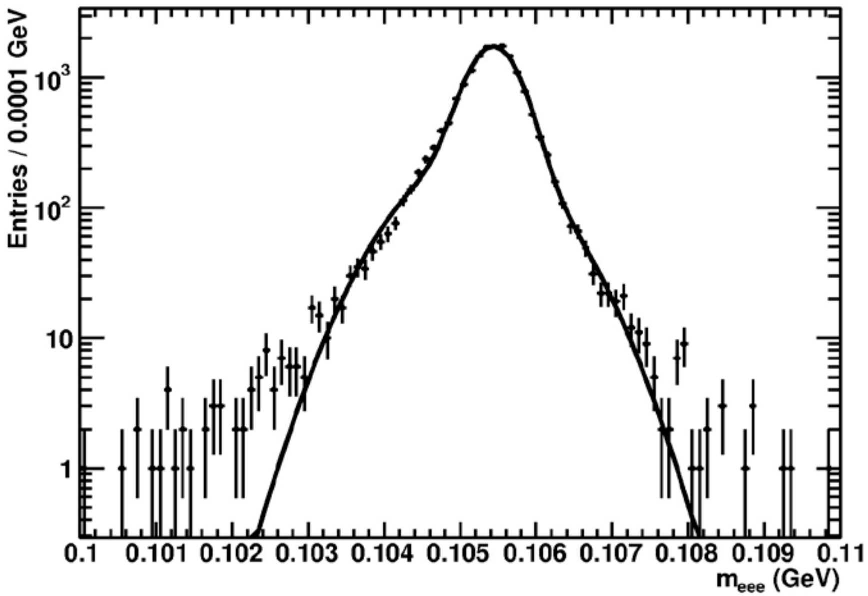


Cuts are clearly needed to improve the mass resolution

Marginal effect of the vertex constraint

Fit the mass spectrum with a sum of two Gaussians

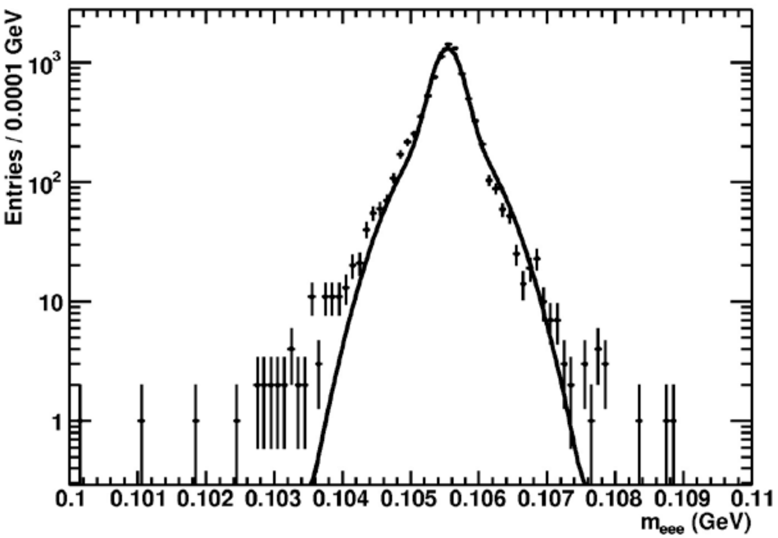
50 μm thick silicon detectors / kapton



Mass = 105.44 MeV
σ_1 = 0.31 ± 0.01 MeV
σ_2 = 0.79 ± 0.2 MeV
Fraction of σ_2 = 30 ± 2 %

Efficiency = 35%

25 μm thick silicon detectors / kapton



Mass = 105.53 MeV
σ_1 = 0.21 ± 0.01 MeV
σ_2 = 0.60 ± 0.1 MeV
Fraction of σ_2 = 37 ± 2 %

Efficiency = 40%

Estimate of rate of stopped muons needed

Mu3e expect a final single event sensitivity (SES) at the level of 7×10^{-17}. We want to reach a SES of 5×10^{-18}.

Stopped muons/second rates R needed to reach a SES of 5×10^{-18} with

1 year of running **100% duty cycle** **35% efficiency** **$R=2\times10^{10}$**	**4 years of running** **100% duty cycle** **50% efficiency** **$R=3.5\times10^{9}$**

For comparison, the muon rate on the target for Mu3e Phase-II using the HiMB at PSI is 2×10^{9}.

Is such a beam feasible at Project X?

arXiv:1301:6113

Expected performance of Mu3e

	Phase IA	Phase IB	Phase II
Backgrounds:			
Michel	0	$< 2.5 \cdot 10^{-18}$	$5 \cdot 10^{-18}$
$\mu \to ee e\nu\nu$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$1 \cdot 10^{-17}$
$\mu \to eee\nu\nu$ and accidental Michel	0	$< 2.5 \cdot 10^{-21}$	$7.5 \cdot 10^{-18}$
Total Background	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$2.3 \cdot 10^{-17}$
Signal:			
Track reconstruction and selection efficiency	26 %	39 %	38 %
Kinematic cut (2σ)	95 %	95 %	95 %
Vertex efficiency $(2.5\sigma)^2$	98 %	98 %	98 %
Timing efficiency $(2\sigma)^2$	-	90 %	90 %
Total efficiency	24 %	33 %	32 %
Sensitivity:			
Single event sensitivity	$4 \cdot 10^{-16}$	$3 \cdot 10^{-17}$	$7 \cdot 10^{-17}$
muons on target rate (Hz)	$2 \cdot 10^{7}$	$1 \cdot 10^{8}$	$2 \cdot 10^{9}$
running days to reach $1 \cdot 10^{-15}$	2600	350	18
running days to reach $1 \cdot 10^{-16}$	-	3500	180
running days to reach single event sensitivity	6500	11 700	260

Phase II : expect roughly one background event

Background studies

Two sources of background are considered:

- irreducible, arising from $\mu \rightarrow eee\nu\nu$ decays
- accidental

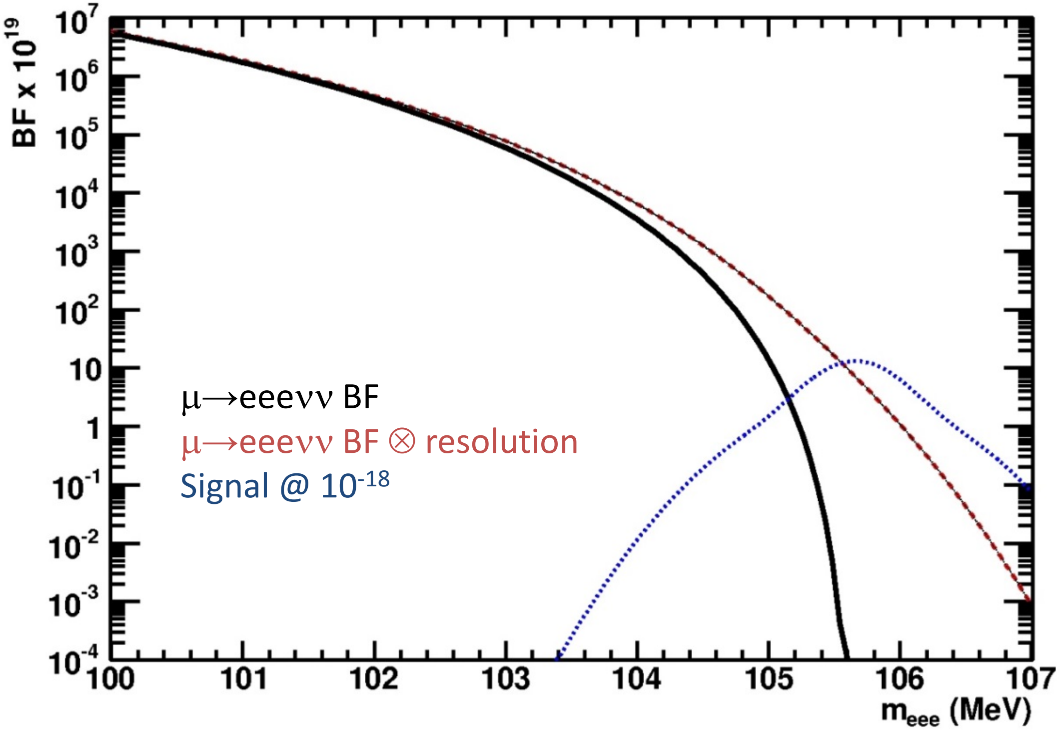
We consider two sources of accidental background:

- pile-up of 3 Michel decays, where one positron is mis-reconstructed as an electron, or "produces" an electron through Bhabha scattering (3e)

- combination of a Michel decay + radiative Michel decay where the photon converts into a e^+e^- pair (2eγ). Consider only conversion inside the target. Expected to be comparable to Michel decay + $\mu \rightarrow eee\nu\nu$ within our setup.

Irreducible background

The level of $\mu \to ee e\nu\nu$ background can be estimated by convolving the $\mu \to eee\nu\nu$ branching fraction with the resolution function and integrating in the signal region. Signal region = 104.8 – 106.6 MeV (contains ~90% of the signal).



Expect bkg rate ~2×10^{-17} with current resolution → few events for a SES of 5×10^{-18}

Irreducible background

Background rate very sensitive to the tail resolution

σ_1	σ_2	Fraction of σ_2	Bkg rate	Bkg evt*
0.2	0.5	0.3	6.9e-19	0.1
0.2	0.5	0.5	1.7e-18	0.4
0.2	0.7	0.3	5.1e-18	1.1
0.2	0.7	0.5	1.6e-17	3.4
0.3	0.5	0.3	1.3e-18	0.3
0.3	0.5	0.5	2.6e-18	0.5
0.3	0.7	0.3	7.8e-18	1.6
0.3	0.7	0.5	1.9e-17	4.0
0.3	0.8	0.3	1.7e-17	3.6
0.3	0.8	0.5	4.5e-17	9.5
0.4	0.6	0.3	6.2e-18	1.3
0.4	0.6	0.5	1.1e-17	2.3
0.4	0.7	0.3	1.3e-17	2.7
0.4	0.7	0.5	2.6e-17	5.4
0.4	0.8	0.3	2.6e-17	5.4
0.4	0.8	0.5	5.6e-17	11.8

* For SES of 5×10^{-18}

Accidental background

To calculate the rate of accidental background, we assume the two (three) decays occur in the same pixel in the target during the same time window of 250 ps.

Spatial rejection factor (pixel area / target area) dS = $7.8\text{x}10^{-7}$
Timing rejection factor dt = $2.5\text{x}10^{-10}$

$$N(2e\gamma) = 3\text{x}10^{7}\ R^{2}\ dS\ dt\ BF(\mu \rightarrow e\nu\nu\gamma)\ P(\gamma \rightarrow ee)\ P_{\mu} \quad \sim 2\text{x}10^{7}\ P_{\mu}$$
$$N(3e) = 3\text{x}10^{7}\ R^{3}\ dS^{2}\ dt^{2}\ P_{\mu} \quad \sim 8\text{x}10^{6}\ P_{\mu}$$

- $P(\gamma \rightarrow ee) \sim 0.001$, probability of converting in the target ($\sim 0.001\ X_0$)
- P_{μ}: probability to reconstruct a muon for 2/3 simultaneous decays in the same pixel

- Simulation shows $P_{\mu} \sim$ few 10^{-8} - 10^{-7} for 3e events $\rightarrow$ O(0.1-1) background events
- On-going work to get estimate of P_{μ} for $2e\gamma$ events (note that Mu3e has a level comparable for both). If background too large, can cut on the e^+e^- invariant mass, though you lose some sensitivity as well.

A full simulation is needed to fully understand the performance of the detector, but this looks promising, or at least not completely hopeless…

Summary

- We investigate a thin, cylindrical silicon detector to investigate the $\mu \rightarrow eee$ decay.

- The setup is similar to the Mu3e experiment, but includes an active target

- Toy studies show that a single event sensitivity an order of magnitude smaller than Mu3e as long as the muon stopping rate can be achieved.

- In particular, the active target can help to maintain the background at an acceptable level.

- Further improvement:

    - improve fitting to impose vertex constraint, try to recover some resolution as well
    - improve estimation of accidental background
    - detector layout optimization