Charged Lepton Flavour Violation: COMET, Mu3e & Mu2e

PPAP meeting, Birmingham 26/07/2016

J Vossebeld

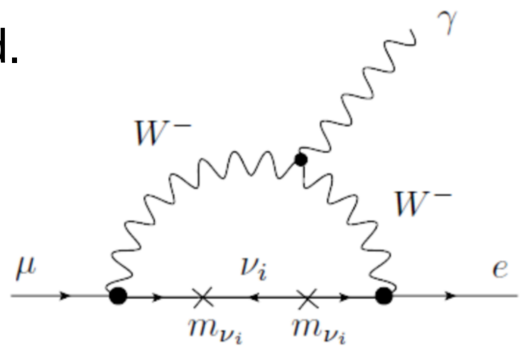
(with thanks to Yoshi Uchida and Mark Lancaster for their inputs on COMET and Mu2e)

Charged Lepton Flavour Violation (cLFV)

Flavour violation established for quarks and neutrinos.

SM (with m_ν) allows for cLFV but this is heavily suppressed.

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$



Any observation of cLFV is evidence of NP.

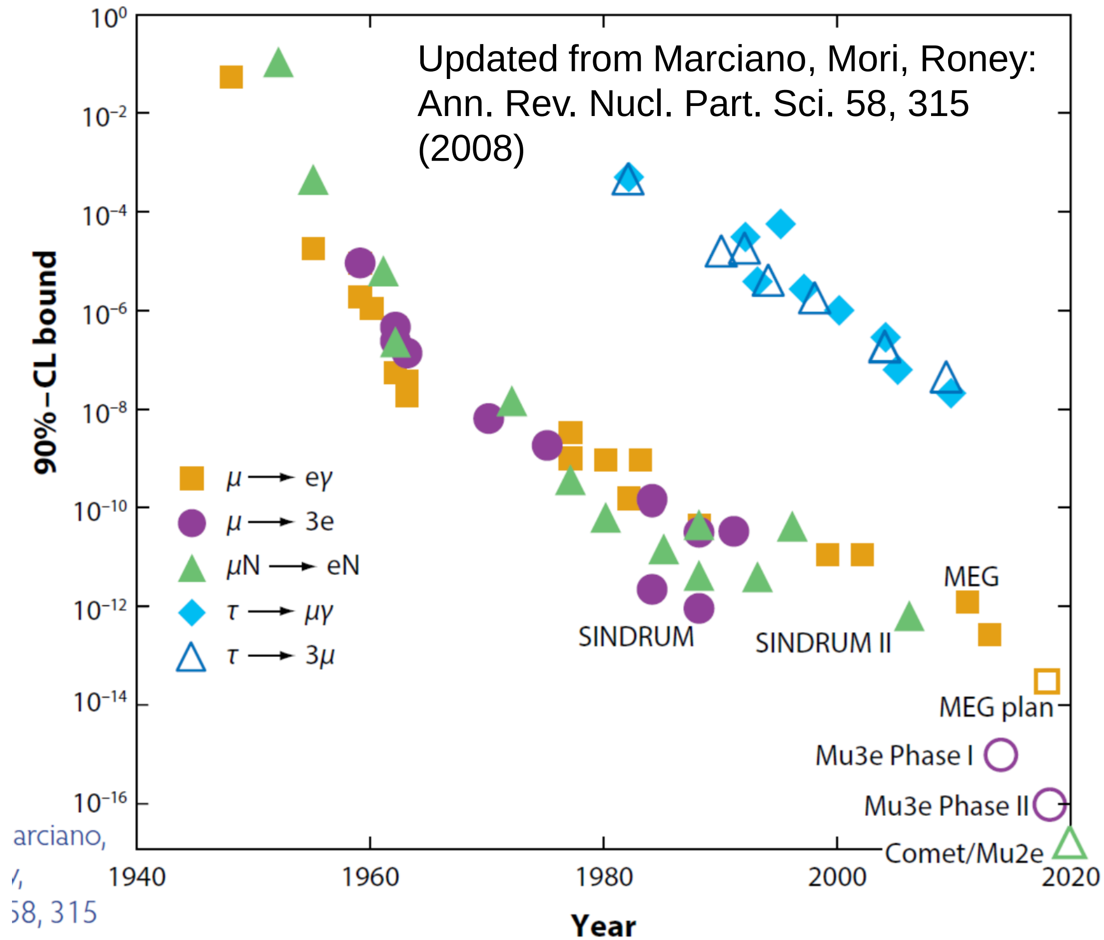
Many models for NP naturally include cLFV:
Leptogenesis models, Higgs Doublets, Little Higgs, SUSY, Extra Dimensions,

New experiments coming online will probe NP at multi-PeV scales.

cLFV experiments

Best sensitivity for NP from muon decay experiments

MEG II, Mu3e, COMET and Mu2e will push sensitivity by a up to **four orders of magnitude** in the different channels.



All sensitivities 90% C.L. bound
= Single Event Sensitivity * 2.3

	Best limits	Projected sensitivities (90%CL)
$\mu \rightarrow e\gamma$	< 4.3×10^{-13} MEG (PSI)	4×10^{-14} MEG II (PSI)
$\mu \rightarrow eee$	< 1.0×10^{-12} SINDRUM (PSI)	1×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)
$\mu N \rightarrow eN$	< 7.0×10^{-13} SINDRUM II (PSI)	6×10^{-17} Mu2e (FNAL) 7×10^{-15} COMET I (J-PARC) 6×10^{-17} COMET II (J-PARC)

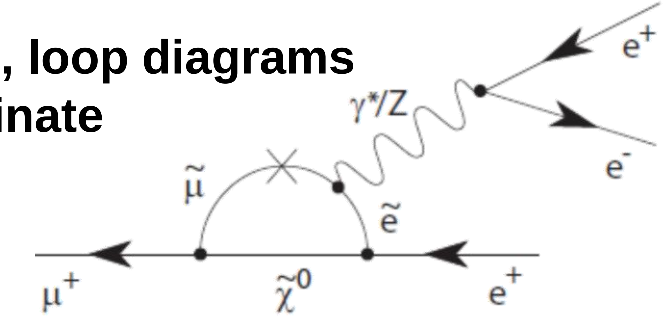
Physics reach

Generic Lagrangian model
De Gouvea & Vogel :

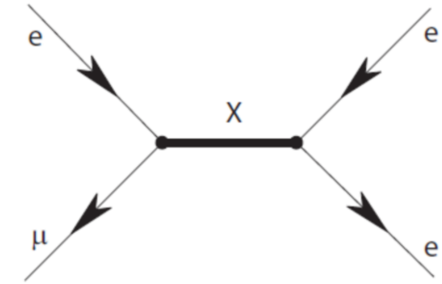
$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$

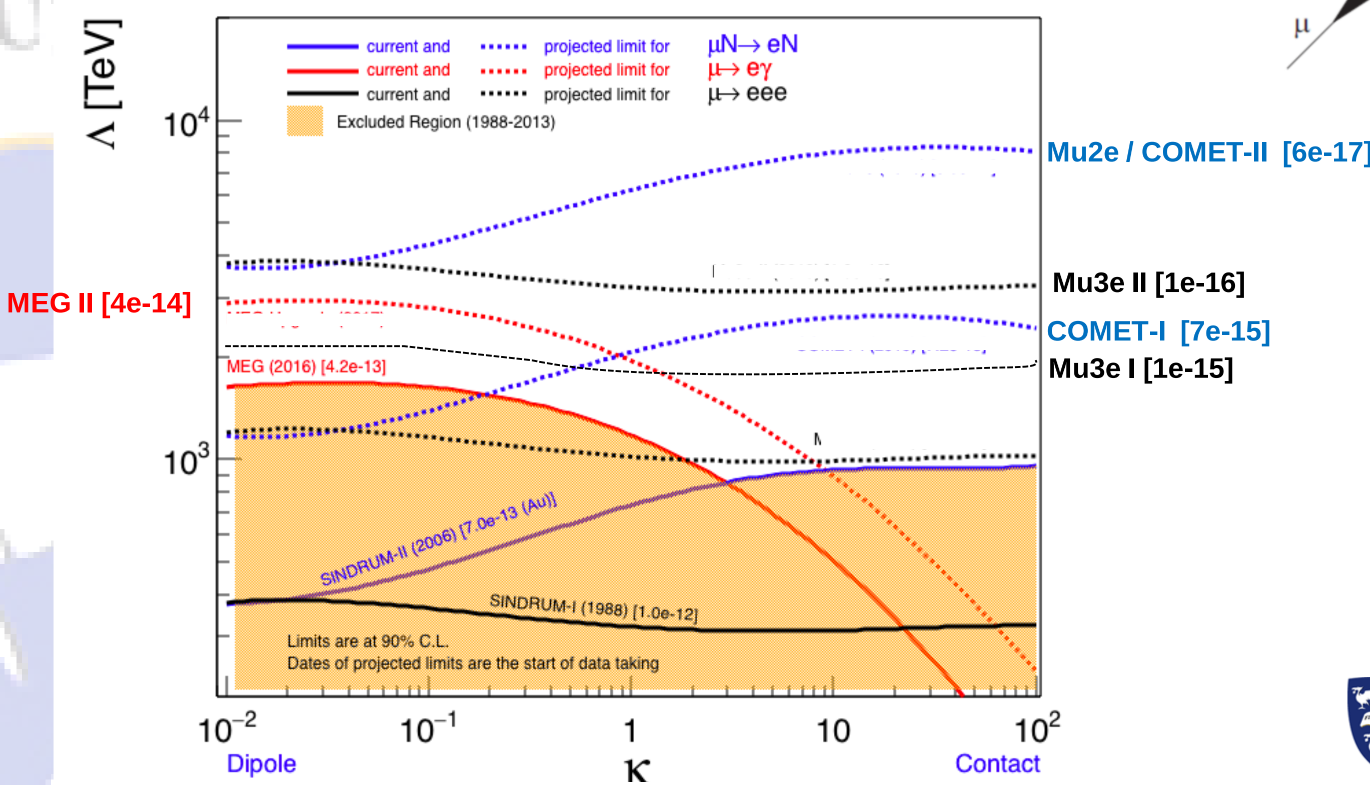
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c.\,.$$

κ = 0, loop diagrams dominate



κ = 1, tree level diagrams dominate





Update from de Gouvea & Vogel, Prog. in Part. and Nucl. Phys. 71 (2013).

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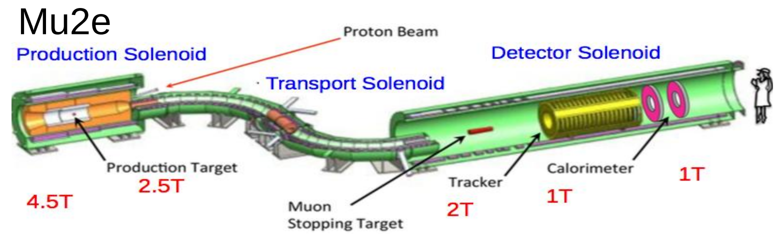
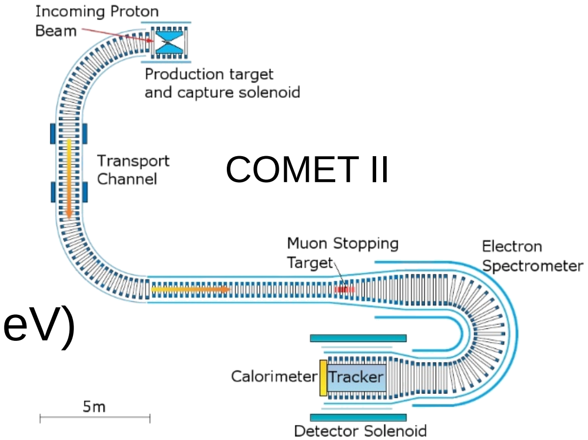
$\mu N \rightarrow eN$ conversion (COMET/Mu2e)



Beam delivery system optimised to achieve high intensity, very pure, muon beam on target.
Stopped muons are trapped in orbit around the nucleus.



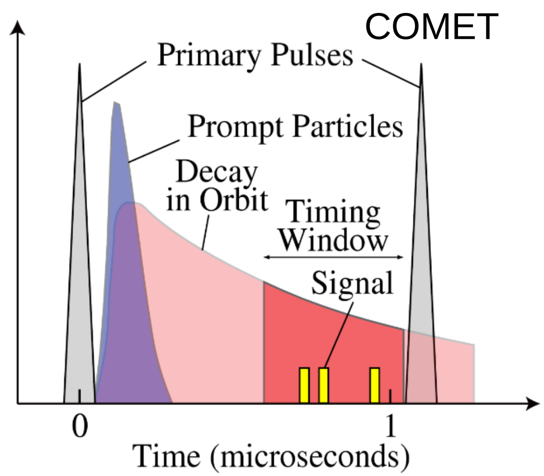
Search for coherent decay $\mu N \rightarrow eN$

$\rightarrow$ mono-energetic electron (for aluminium: E_e=104.96 MeV)

$\rightarrow$ delayed w.r.t. prompt particles (τ_μ = 864 ns)

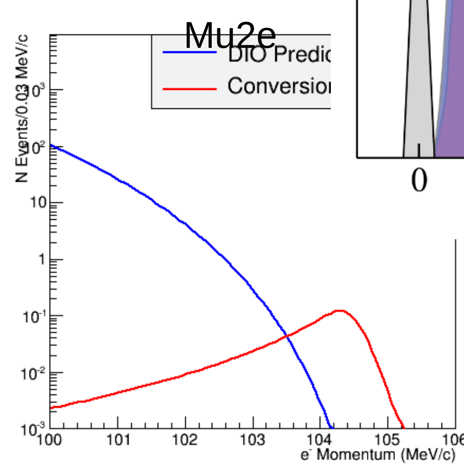
Prompt backgrounds (radiative nuclear capture, muon decay in flight, pions, protons).

- Curved solenoid transport channel
- Pulsed beam with delayed time-window
- Strong extinction factor (less than 10^{-9})

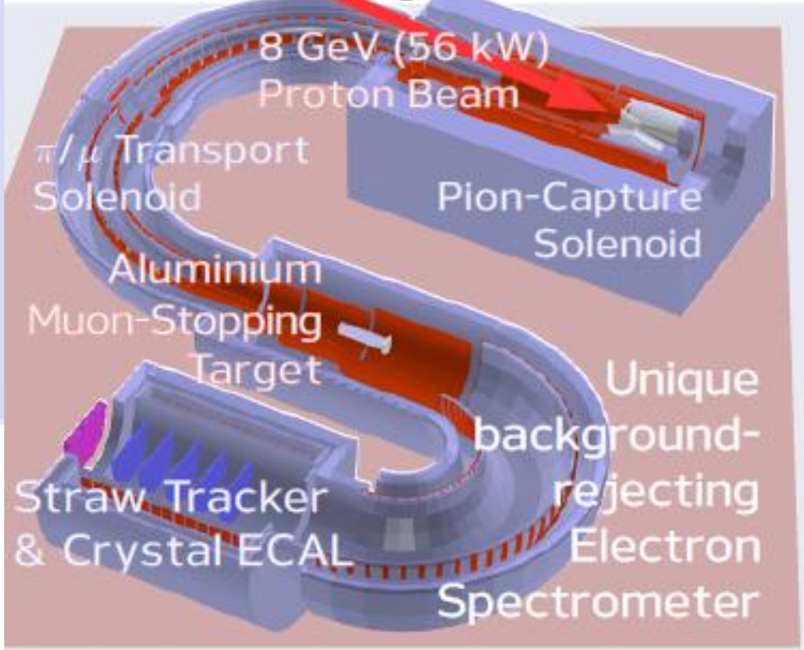


Muon decay in orbit ($\mu N \rightarrow e\nu\nu N$)

- precise momentum resolution



COMET (Muon-to-Electron Conversion)



Basic principles shared with Mu2e, but some fundamental design differences

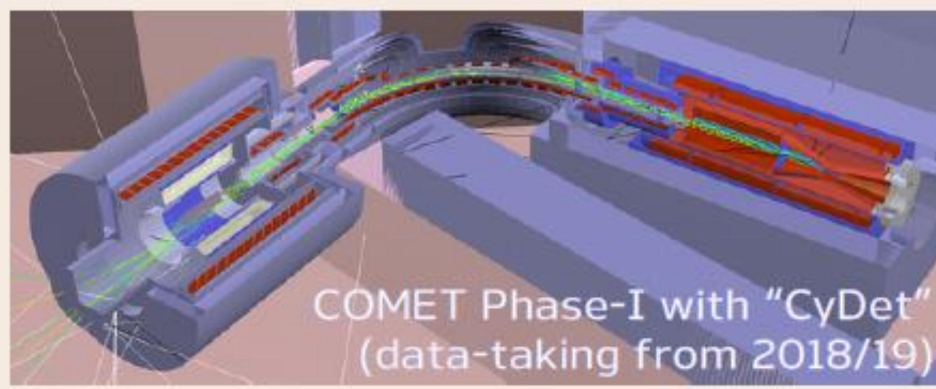
- Unique to COMET: vertical B-fields to "steer" desired-momentum particles along curved solenoids:

Signal electron density along curved beam line

Muon-stopping target   to detectors ⇒

Very high-rate/rare signal experiment

- detector background hit rates and data-rate management, subsystem integration and detailed signal and background studies are critical
- **Phase-I** experiment allows novel muon beam line to be studied in detail, while also making world-leading CLFV physics measurements

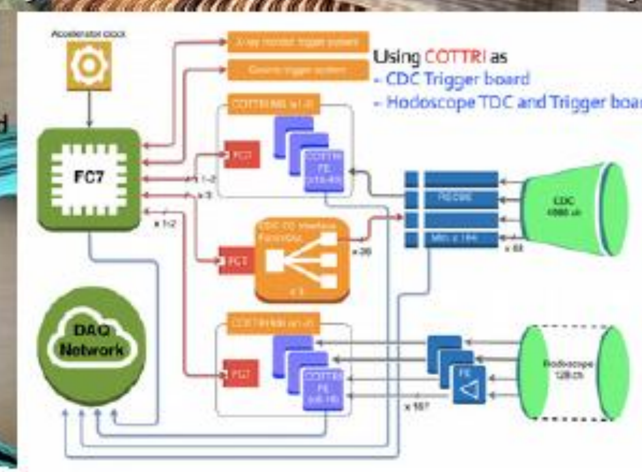


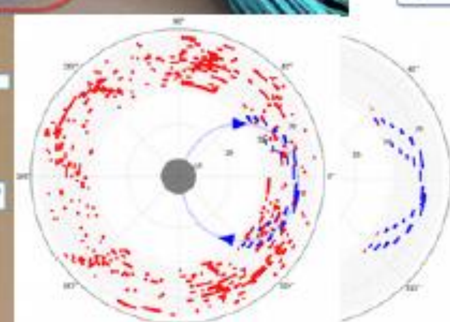
Two Phase-I detector systems: "CyDet" for CLFV physics and "StrECAL" for beam measurements and Phase-II prototyping

COMET Status (I)

COMET Status (II)

Front-end boards communicate with central FC7s using UK-designed DAQ / Trigger hardware system; currently undergoing and testing and integration





UK leadership in Online and Offline Software and Computing across the collaboration (UK/FR/DE/GE/RU/CN) and Physics Analysis

Mu2e (Liverpool, Manchester, UCL)

Same $\mu N \rightarrow eN$ conversion measurement as COMET.

Will come online in 2020. Now approved and funded to the full projected sensitivity of 2.6×10^{-17} (SES).
DOE CD-3c approved in June 2016 : this released the remaining DOE budget for construction : $274M total including contingency.

In P5 report: Mu2e along with LBNF and HL-LHC was one of the 3 priorities of the US medium/long-term programme

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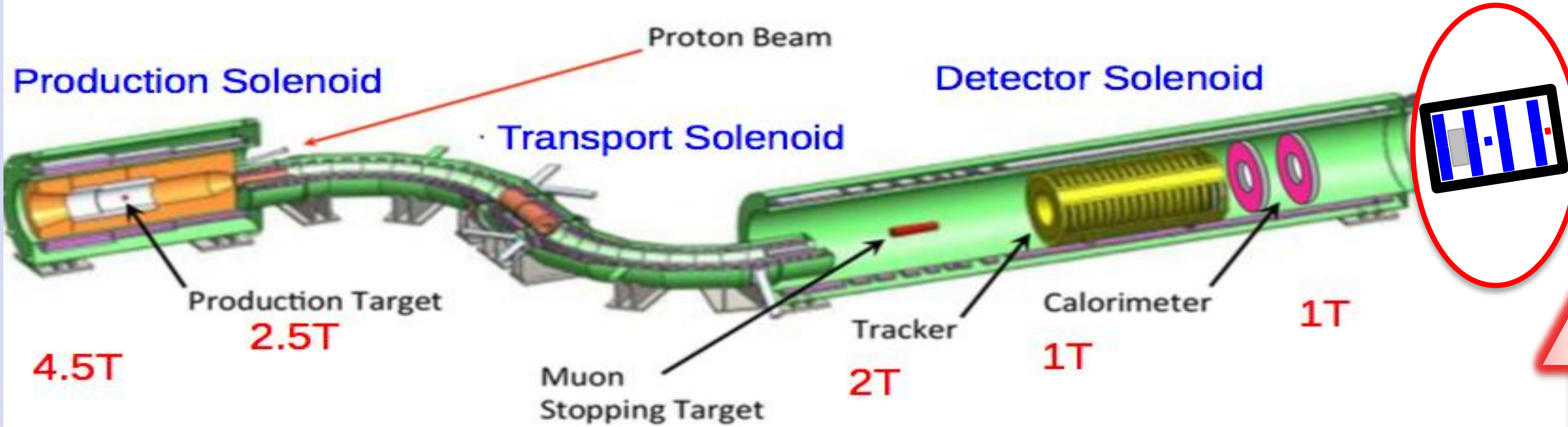

Five detector systems:

- solenoids (USA)
- straw tracker (USA)
- cosmic ray veto (USA)
- calorimeter (Italy)
- Stopping Target Monitor (STM) X ray detector (UK proposal)

n-type coaxial HPGe detector

RAL TD has already received $1M of DOE funding to design/provide the production target.

Monitoring 10^{10} stopped muons/sec !

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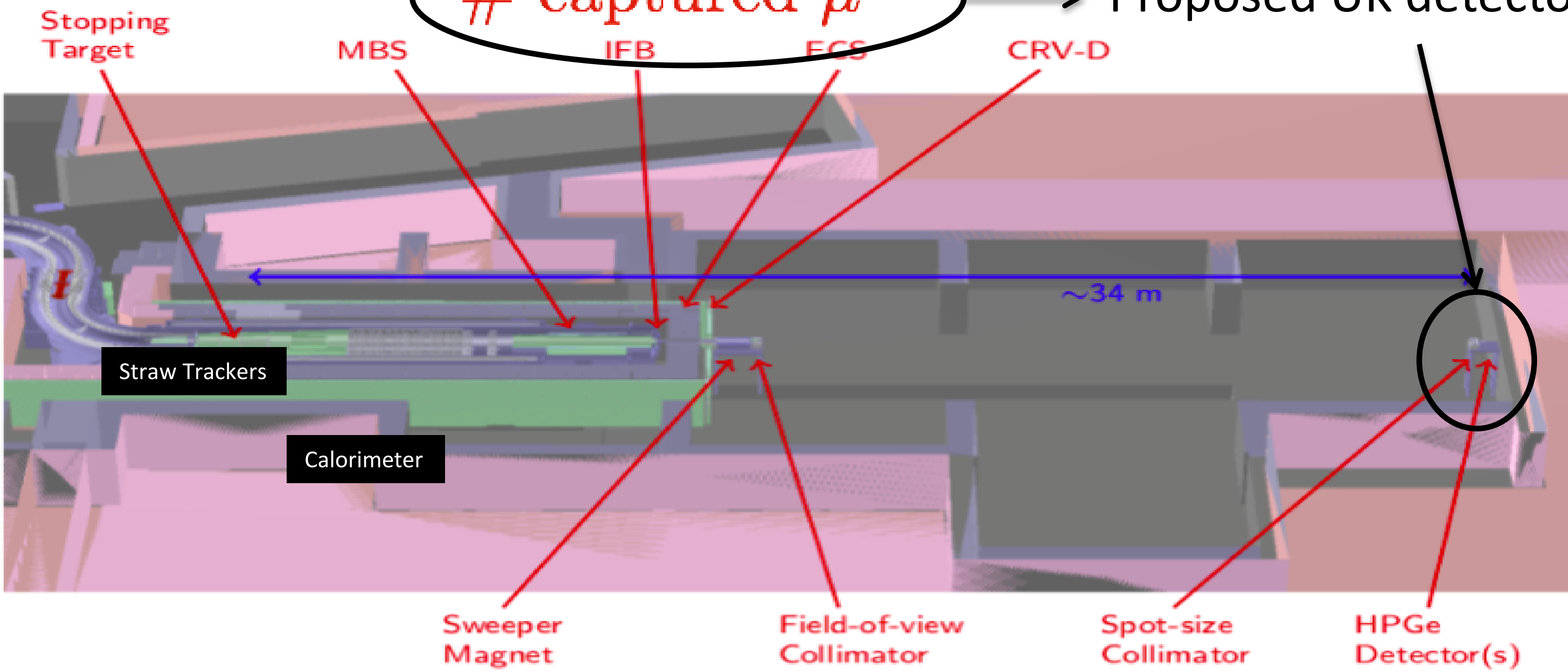
$$\text{Conversion BR} = \frac{\#\mu \to e}{\#\ \text{captured}\ \mu}$$

Like luminosity measurement at a collider

Proposed UK detector



Needs to measure X-rays at **BOTH** high rate in high radiation environment with strict tolerance on alignment and access for detector annealing.

Will measure:

- Prompt 2p-1s muon transitions in muonic-Aluminium
- Delayed (864 ns) [1.8 MeV] gamma from muon nuclear capture
- Slow (9-min) gamma from Mg*

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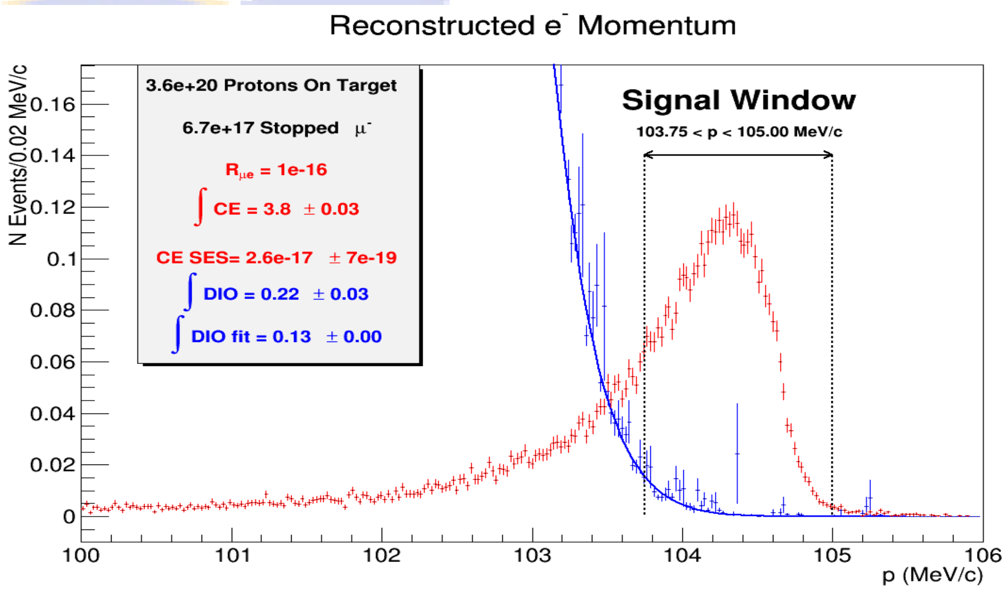
Real-time information from STM on muon yield will also provide vital diagnostics for proton beam, proton target, stopping target, detectors and efficacy of the transport and production solenoids.

UK will be on a par with the Italians with the leading non-US involvement.
PPRP bid: £150k capital + £440k resource over 3 years to April 2020.

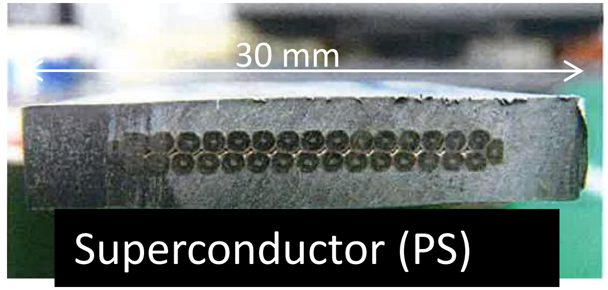
Data taking will begin Q3 FY-2020 after the g-2 running for 4 years



Single event sensitivity of 2.6×10^{-17}
1/100 that of COMET-I

0.15 MeV resolution at 105 MeV from straws

Detector and solenoid prototypes now under test at FNAL

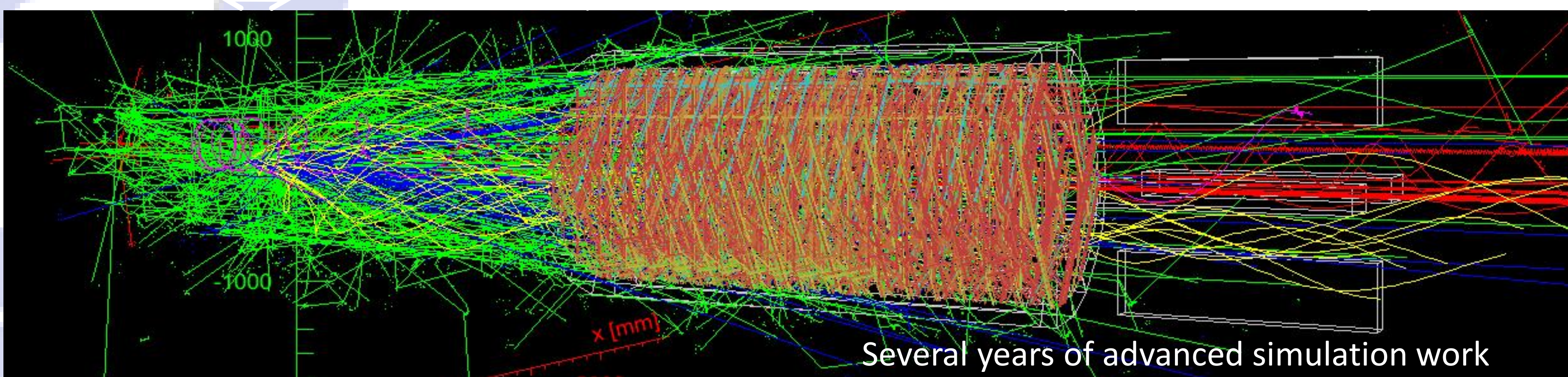


Superconductor (PS)

Over 50% (400 km!) of s/conducting cable for solenoids is fabricated and required performance demonstrated.

Winding into cables has begun in Italy

Prototype solenoid



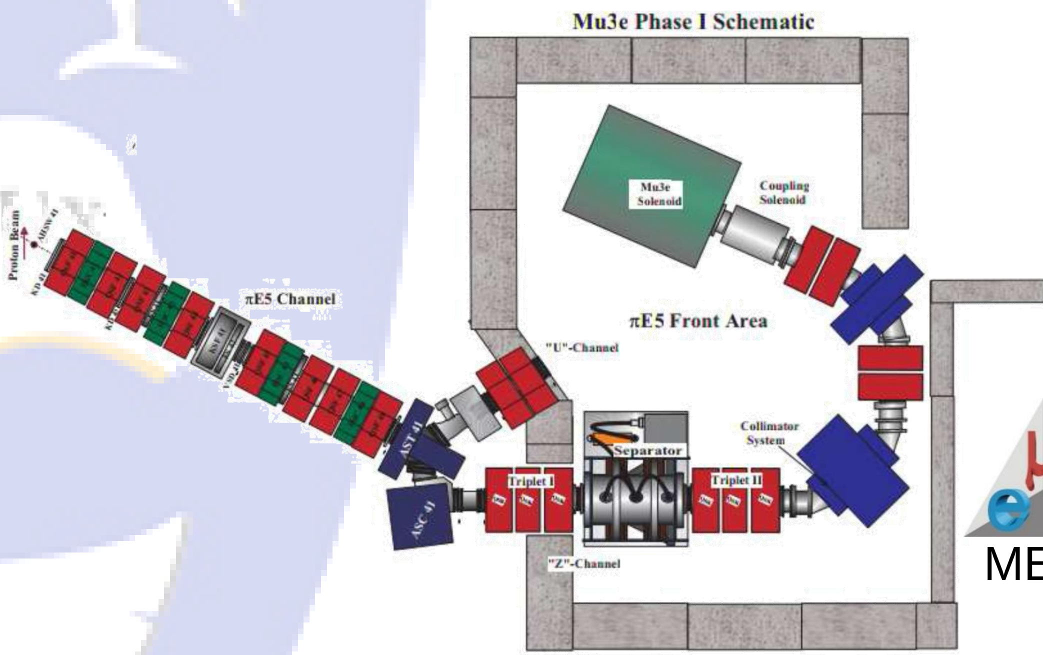
Several years of advanced simulation work

Mu3e Bristol, Liverpool, Oxford, UCL

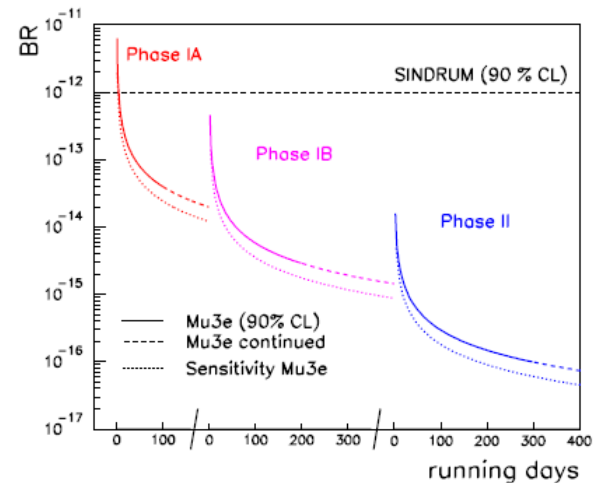
<u>Phase 1A & 1B (**2018-2020**):</u> BR($\mu \rightarrow eee$) < 10^{-15} approved (2013) and funded

PSI πE5 DC beam, shared with MEG, 10^{8} μ/s on target for Mu3e demonstrated

Large bore 1T solenoid to be delivered spring 2017.



MEG

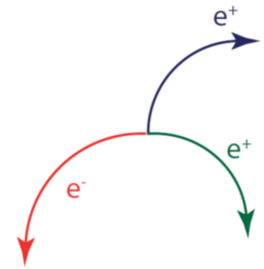


<u>Phase 2: (2020):</u> BR($\mu \rightarrow eee$)<10^{-16} (**10^{4} improvement w.r.t. SINDRUM)**

HiMB beam (PSI target 10^{10} muons of which 10^{9} μ/s on target in Mu3e)

Development work focussing on improving muon yield from "E-target" (see back-up) using solenoids to capture muons

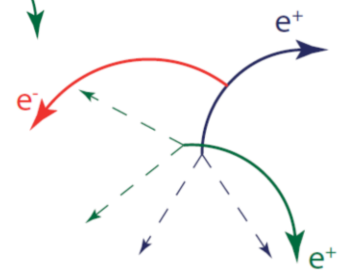
Mu3e the challenge



Accidental backgrounds:

Michel decay + photon conversion:

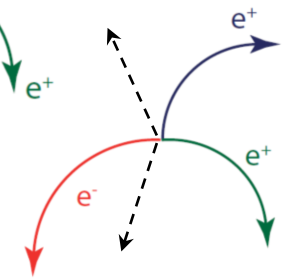
Need excellent vertex discrimination (time & position)



Michel decays with internal conversion:

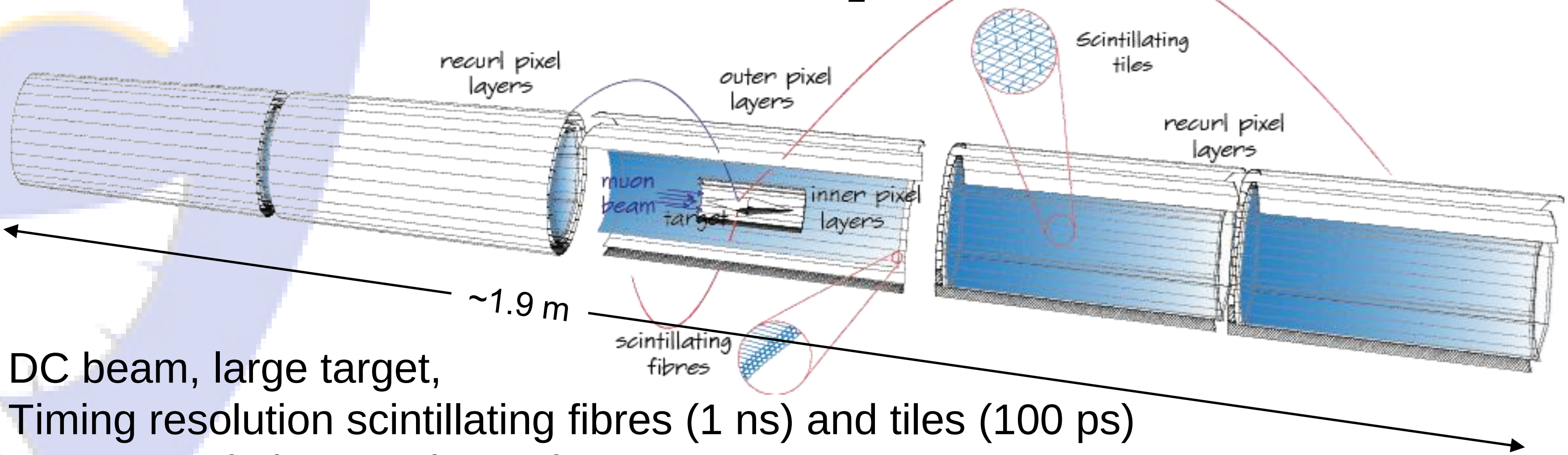
$\mu^+ \rightarrow e^+ e^+ e^- \nu\nu$ (missing E_T)

Need good momentum resolution



Compact experiment in high rate environment (~10^9 μ/s)

Scattering dominated tracking regime (E_e < 53 MeV)



DC beam, large target,

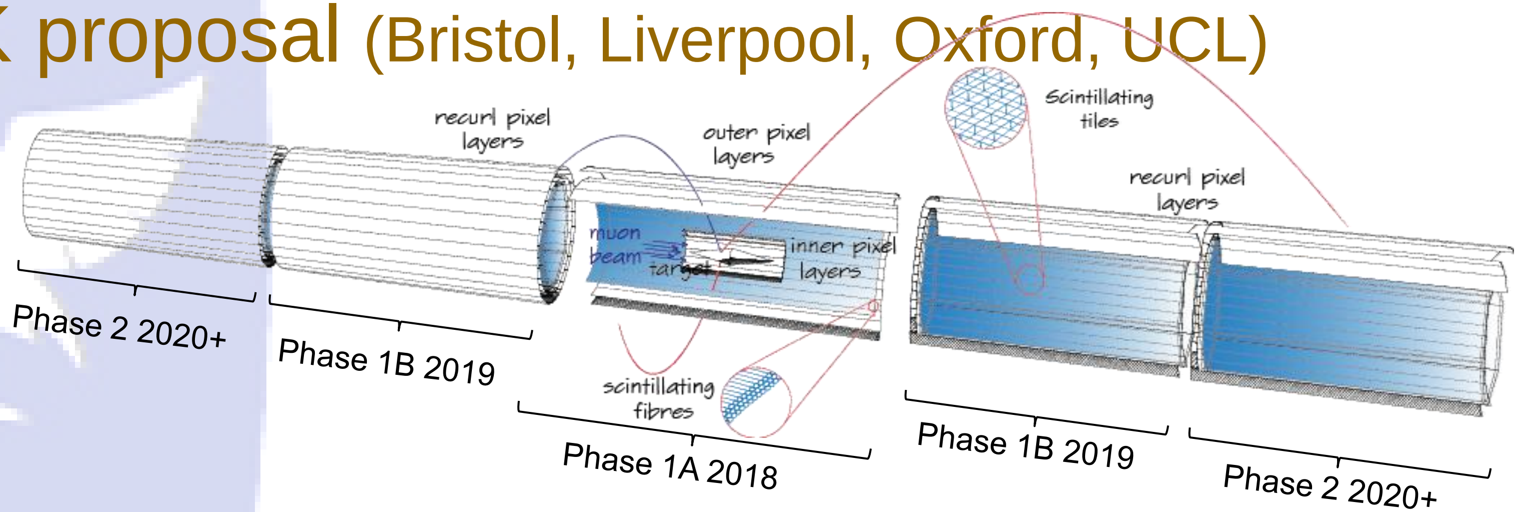
Timing resolution scintillating fibres (1 ns) and tiles (100 ps)

Vertex resolution MuPiX tracker 200 μm

Re-curling tracks in 1T field

Momentum resolution MuPiX tracker (0.5 MeV)

UK proposal (Bristol, Liverpool, Oxford, UCL)



Proposal to PPRP: £150k capital + £410k resources

UK deliverables:

- to build **50% of pixel layers** for the MuPix outer barrel and phase 1B re-curl stations.
- to deliver the Mu3e **clock-and-control system** for the time-slice based DAQ

Both are critical components for Mu3e that will ensure a strong role for the 4 UK institutes joining the existing 8 Swiss and German institutes:
PSI, ETH, Geneva, Zűrich, Heidelberg, KIP, KIT, Mainz.

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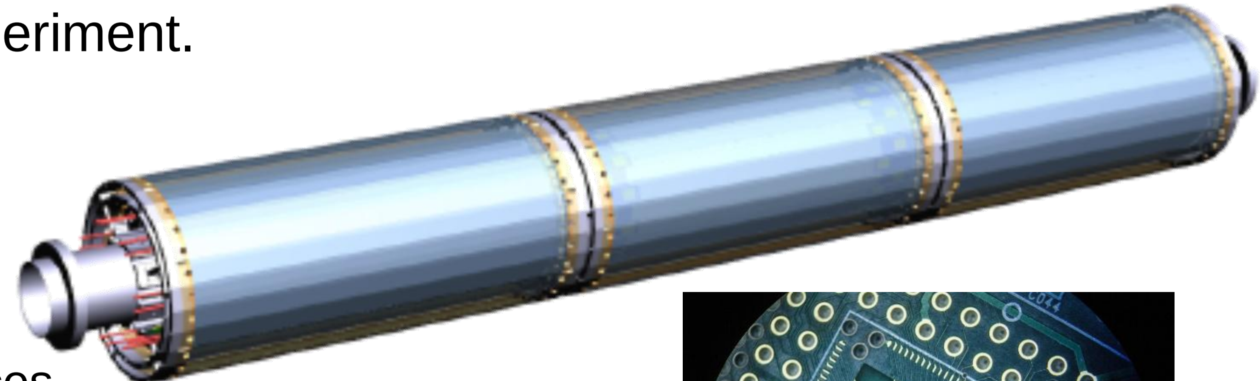
MuPix outer pixel layers for Phase 1

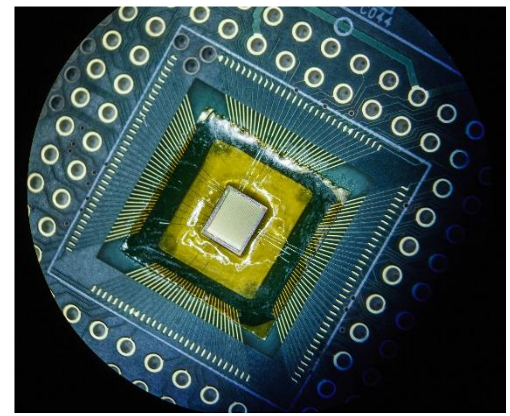
1.1 m^2 **HV-MAPS pixel tracker**. First tracker to employ HV-CMOS technology in a PP experiment.



Material budget is critical

- 50 μm HV-MAPS,
- 25 μm support,
- 25 μm flex-print,
- 12 μm aluminium traces,
- 10 μm adhesive,
- Gaseous helium cooling,

Resulting in **~0.1% X_0 per tracking layer**



In total for Phase 1 2808 HV-MAPS chips will be mounted to 156 high density interconnect flex circuits

4 flex-print assemblies glued to folded kapton support structures to end up with 39 modules.

The UK will construct ~50% of these modules

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Case for a participation in both $N\mu \rightarrow Ne$ and $\mu \rightarrow eee$

The physics is highly complementary: Generic mass scale sensitivity is comparable, but in specific models substantial differences appear. E.g.

- Rate variations between $N\mu \rightarrow Ne$ and $\mu \rightarrow eee$ in leptogenesis models depending on the neutrino mass hierarchy
- Reliance on NP coupling to leptons only ($\mu \rightarrow eee$) or to leptons and quarks ($N\mu \rightarrow Ne$)

Determination of NP parameters: E.g.

- $N\mu \rightarrow Ne$ rate dependent mass heavy neutrino and target isotope in type I see-saw
- $\mu \rightarrow eee$ final state can be used to measure CP phases

Not obviously who will get to a signal or best limits first/ultimately

Will depend on the physics, when data taking starts and how fast data collection and analysis progresses. *As all experiments pursue $\mathcal{O}(10^4)$ improvements in sensitivity, some unforeseen challenges to be expected.*

Long term prospects: if higher muon on target rates can be achieved both channels can be pushed beyond current projected sensitivities.

Non cLFV physics Mu3e can study rare $\mu \rightarrow eee\nu\nu$ processes, e.g. to look for dark photons in low mass (10 - 90 MeV) low coupling regime.

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Summary

All sensitivities 90% C.L. bound (= SES * 2.3)

Muon cLFV experiments will make a big step in sensitivity in the next 5-8 years, probing new physics at multi-PeV scales. Strong UK interest in this area.

COMET I (approved), scheduled start 2018/2019, BR(N$\mu\rightarrow$Ne) ~ 7x10^{-15}

Detector and beamline construction progressing well.

Strong UK (IC) involvement since 2006: beamline, trigger/DAQ, software and leadership roles (Collaboration Board Chair, Analysis Coordinator)

COMET II, after phase I (2020 earliest), BR(N$\mu\rightarrow$Ne) ~ 6x10^{-17}

R&D during phase I. high (56 kW) power proton beam. Challenging, but offers very fast data accumulation, (*Yoshi*: *forthcoming UK work suggests 2.3x10^{-17} is feasible*.)

Mu2e (approved), scheduled start 2020, BR(N$\mu\rightarrow$Ne) ~ 6x10^{-17}

Construction underway. Lower power (8kW) beam. PPRP bid for strong UK (LIV,MAN,UCL) involvement: HPGe STM

Mu3e Phase 1A/1B (approved), scheduled start 2018, BR($\mu\rightarrow$eee) ~ 1x10^{-15}

Beamline in place, detector development on target. PPRP bid for strong UK (BRIS,LIV,OXF,UCL) involvement: HV-MAPS MUPIX tracker, clock-and-control.

Mu3e Phase 2, after phase 1B (2020 earliest), BR($\mu\rightarrow$eee) ~ 1x10^{-16}

Extended acceptance detector, HiMB R&D ongoing at PSI.

If new PPRP bids are successful, look forward to an exciting cLFV programme with the existing IC involvement in COMET and a new involvement by several UK groups in Mu2e and Mu3e.

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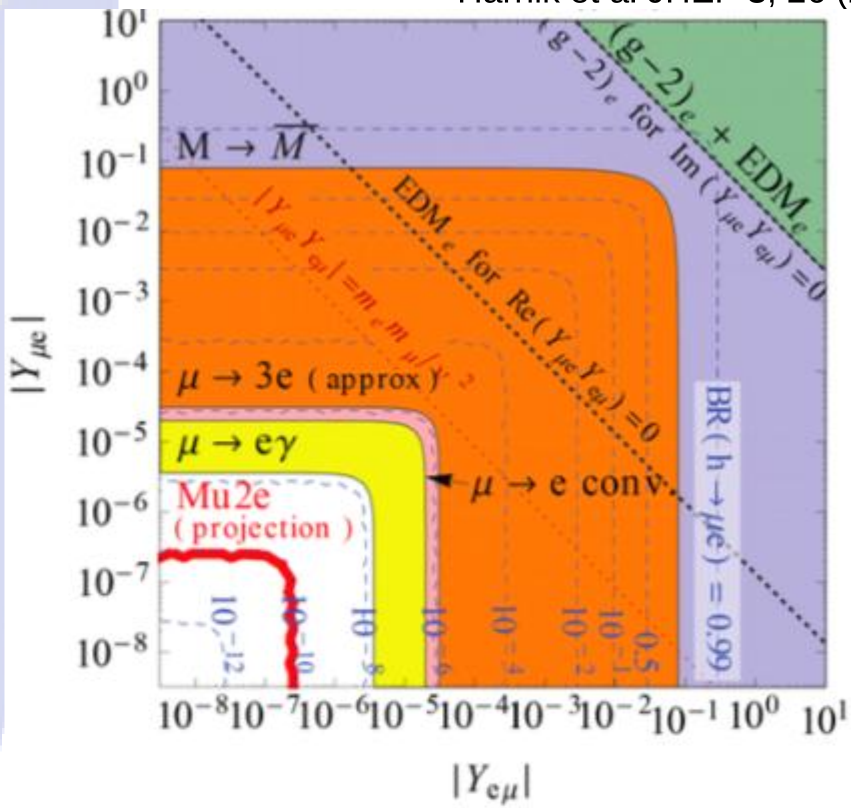
Better sensitivity to LFV Higgs couplings than LHC

Harnik et al JHEP **3**, 26 (2013)



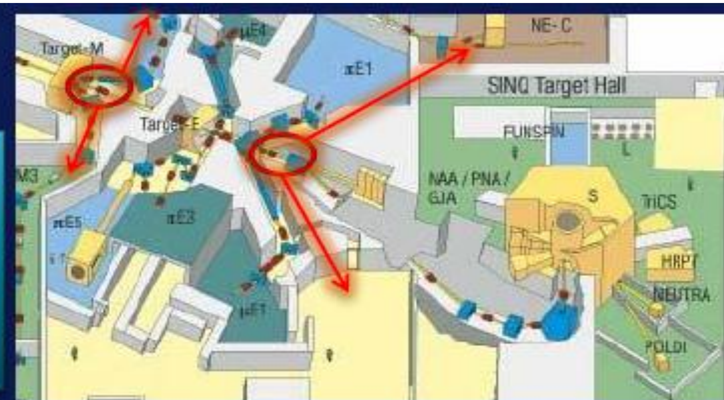
Sensitive down to BR $(H \to \mu e)$ of 10^{-10} (cf current LHC limit of 3×10^{-4})

HIMB: using PSI E-target

Alternative Possibilities

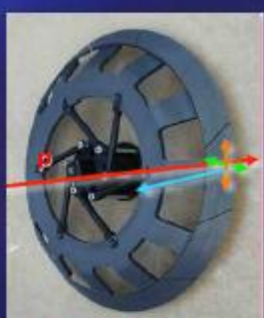
Constraints - any intervention to the proton beam line must:

- **Not significantly increase the beam losses**
- **Preserve the proton footprint and energy on SINQ**
- **Preserve the total material budget seen by the beam**



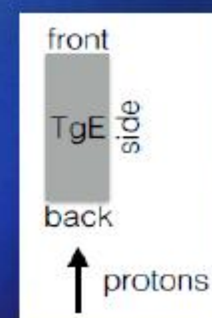
Just started to look at "conventional targets" in combination with solenoids
Possibilities under assessment

As a "conventional target", Target E is surprisingly efficient at producing surface muons: for I_p=2.3 mA



Polycrystalline Graphite, 1700K

TgE length	Front	Back	Side
10 mm	9.6×10^{9}/s	1.5×10^{10}/s	1.9×10^{10}/s
20 mm	1.3×10^{10}/s	1.9×10^{10}/s	5.8×10^{10}/s
30 mm	1.6×10^{10}/s	1.7×10^{10}/s	9.5×10^{10}/s
40 mm	1.6×10^{10}/s	2.0×10^{10}/s	1.3×10^{11}/s
60 mm	1.6×10^{10}/s	2.1×10^{10}/s	2.2×10^{11}/s



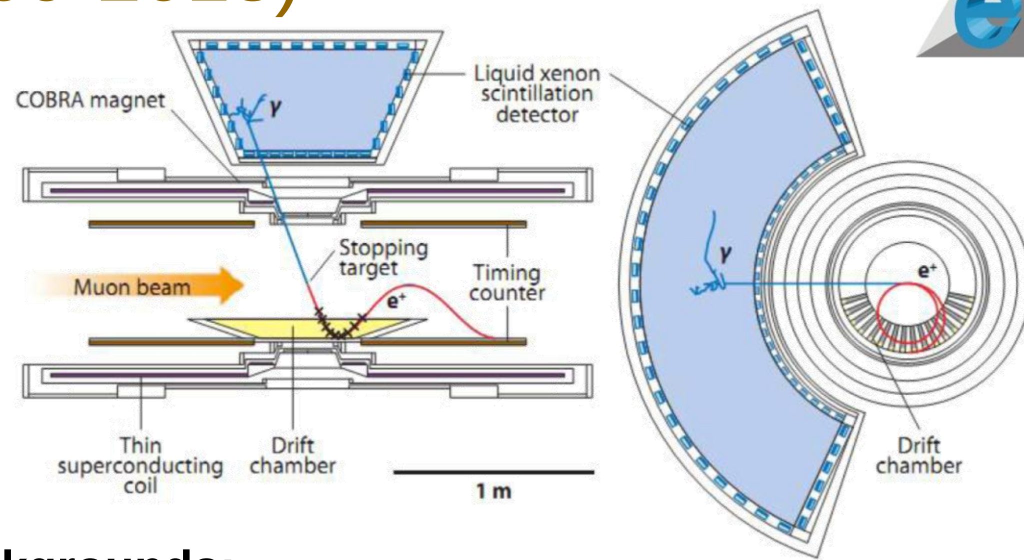
- **Front/back surfaces saturate with L**
- **side surface viewing very efficient**

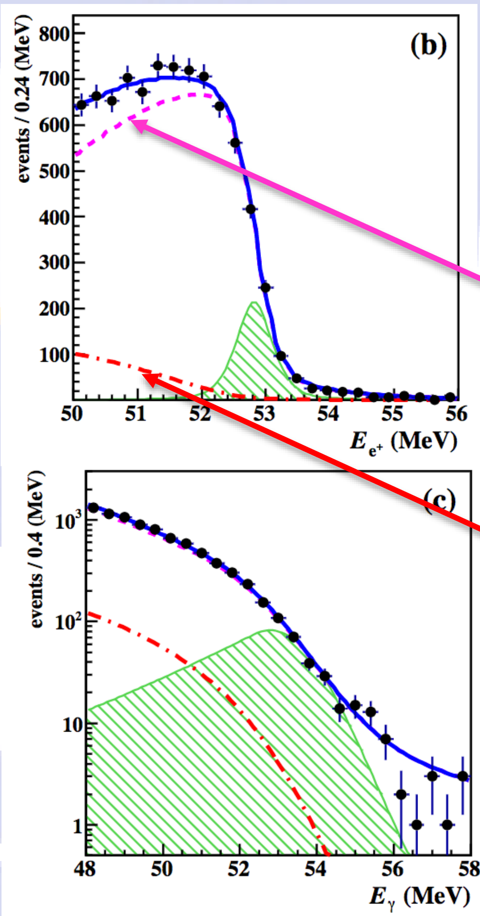
Peter-Raymond Kettle *Future Muon Sources Workshop – Univ. of Huddersfield 2015* *16*

Peter-Raymond Kettle, 2015

MEG: $\mu \to e\gamma$ (2009-2013)

Search for $\mu \to e\gamma$
PSI πE5 beam
(3×10^{7} muons/s)





Main backgrounds:
Accidental: **e^+ from Michel decay + γ photon from e^+ annihilation or Bremsstrahlung or from radiative Michel decay .**

Radiative Michel decays

Final result (2016)
BR($\mu \to e\gamma$) < 4.3×10^{-13} (90% C.L.)

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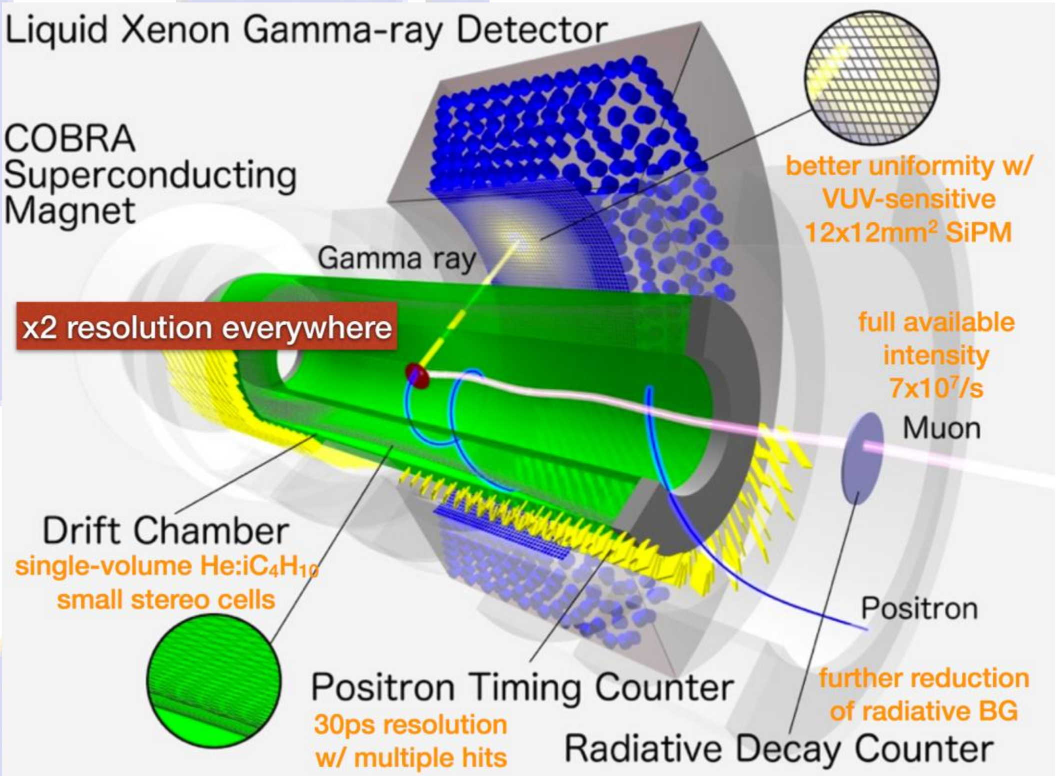
MEG II: $\mu \to e\gamma$ (2017-2019)



Push muons-on-target to 7×10^7 muons/s

Higher accidental BG ($\propto$ intensity^2)

Need better timing and momentum resolution.

New detector, to run from 2017 to 2019

Performance targets:
$\Delta E(e^+)$ ~ 130 keV
$\Delta t\ (e^+)$ ~ 35 ps
$\Delta E(\gamma)$ ~ 1%
$\Delta t\ (\gamma)$ ~ 60 ps
Projected MEG-II Sensitivity:
$BR(\mu \to e\gamma) < 4 \times 10^{-14}$ (90% C.L.)

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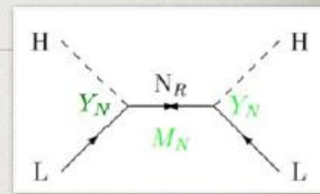
slides Jure Zupan, CLFV Charlottesville 2016

Chu, Dhen, Hambye, 1107.1589;
Alonso, Dhen, Gavela, Hambye, 1209.2679;

TYPE I SEE-SAW



- for instance in type I see saw (with quasi-degenerate N_i)

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

$$\Gamma(\mu \to e\gamma) \propto \frac{1}{m_N^4} \sum_{N_i} \left| Y_{N_{ie}} Y^\dagger_{N_{i\mu}} \right|^2$$

  - using (approximate) symmetries possible to have large cLFV and small neutrino masses

- for quasi-degenerate N_i to a good extend the product of Yukawas cancel in ratios of cLFV processes

$$\frac{R^N_{\mu\to e}}{\Gamma(\mu \to e\gamma)} = \left(\frac{b^N + b'^N \log[m_N^2/m_W^2]}{c \ + c' \ \log[m_N^2/m_W^2]}\right)^2$$

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to eee)} = \left(\frac{c + c' \log[m_N^2/m_W^2]}{d + d' \log[m_N^2/m_W^2]}\right)^2$$

- can probe scale of m_N from $\mu\to e$ conversion