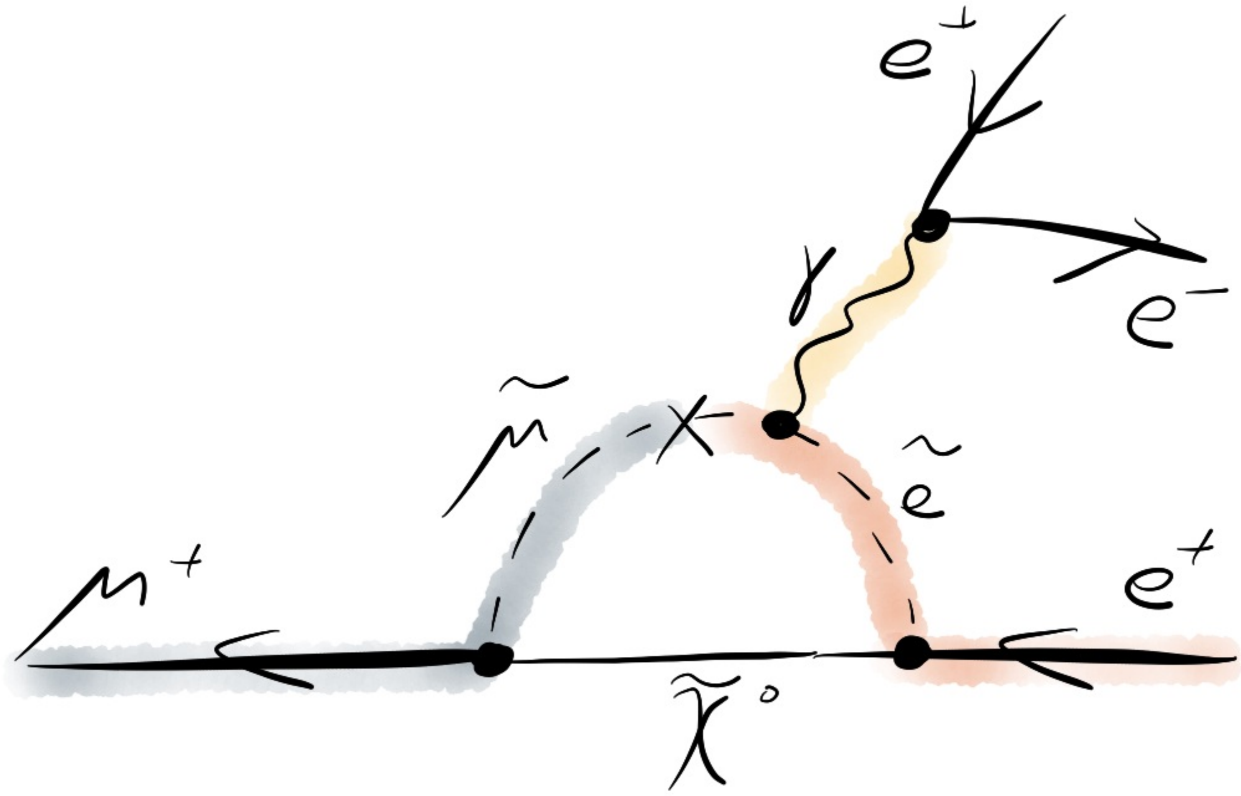
Charged Lepton Flavour Violation:

mu2e, mu3e and Comet

Gavin Hesketh, UCL



Thanks to Mark Lancaster, Yoshi Uchida, Joost Vossebeld

Imperial College London · University of Bristol · UCL · University of Liverpool · Manchester 1824 The University of Manchester · University of Oxford

Charged Lepton Flavour Violation (cLFV) complimentary way to search for new physics

→ no new particles discovered at LHC

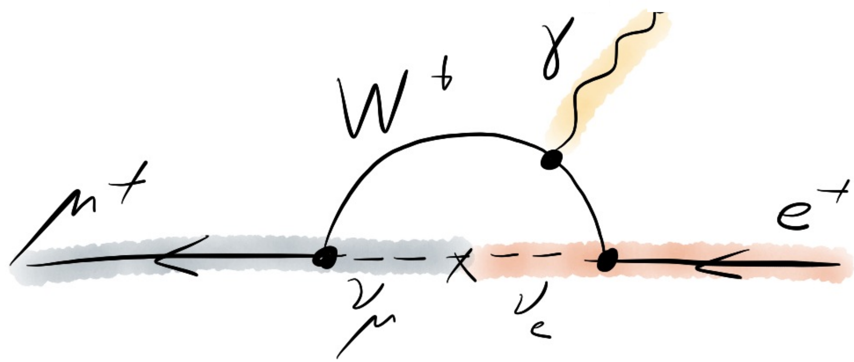
→ neutrino masses already reveal neutral LFV

- how about the charged leptons?

→ Several BSM models allow cLFV

→ possible antimatter asymmetry through leptogenesis

→ *part of UK's charged lepton programme*



Rate in the Standard Model ~$(m_\nu/m_W)^4$ → ~10^{-54} *(zero without neutrino masses)*

→ Any observation is new physics!

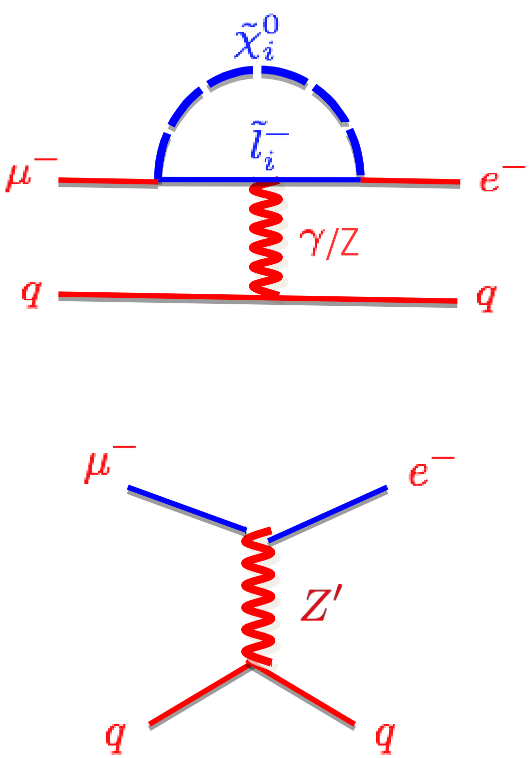
Theoretical uncertainties ~zero

→ sensitivity purely limited by experiment

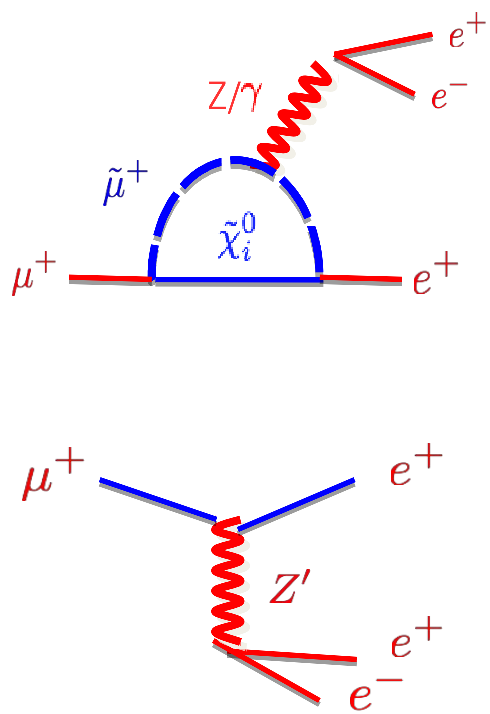
High rate of muons (up to 10^{10} muons/second), very rare signal

New physics with cLFV

Mu2e/COMET

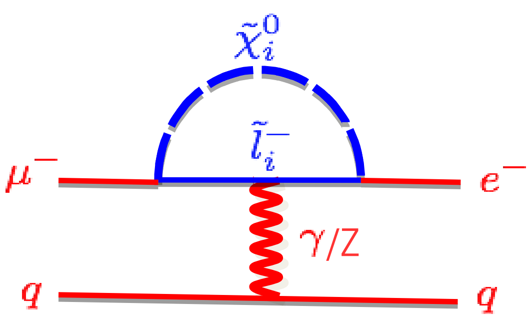


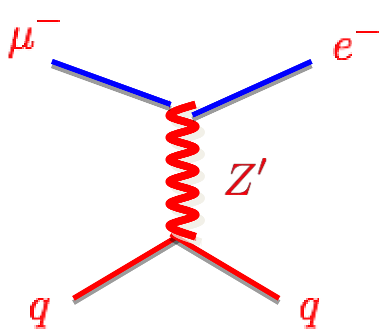
Mu3e



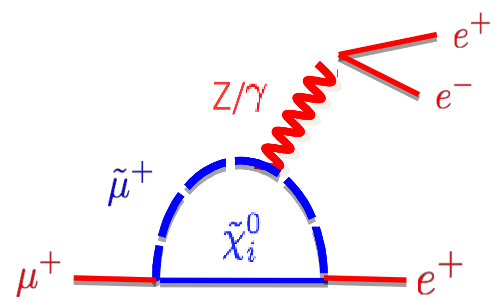
New physics with cLFV

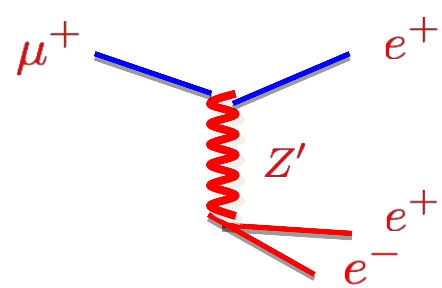
Mu2e/COMET

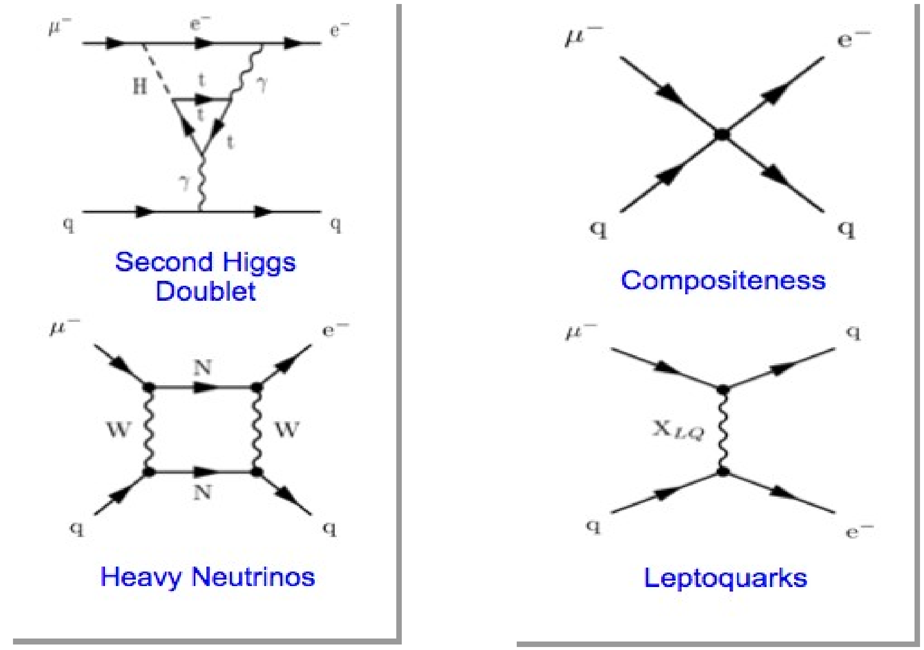




Mu3e

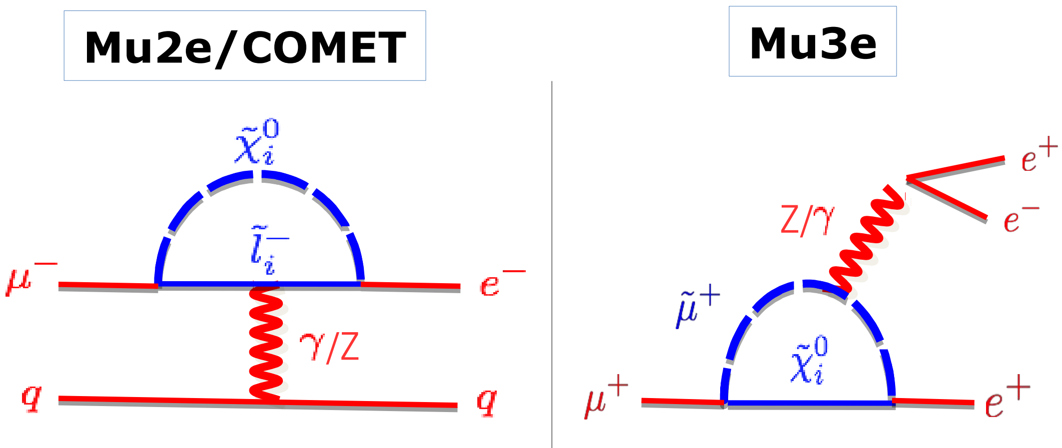


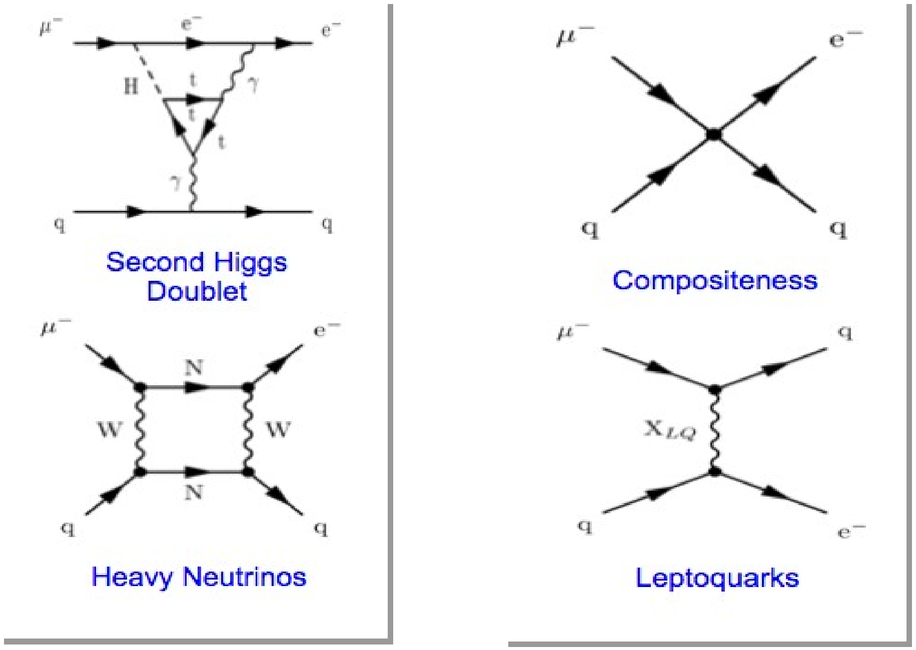




Probe LQ masses up to 300 TeV
cf 1 (120) TeV at HL-LHC (LHCb)

New physics with cLFV





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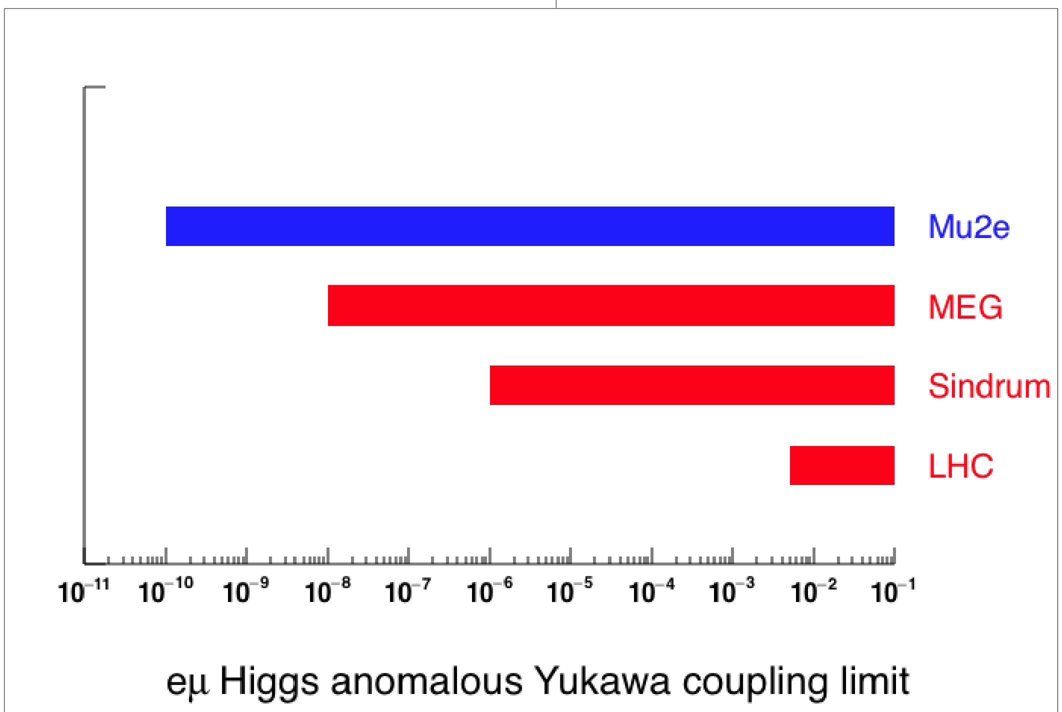
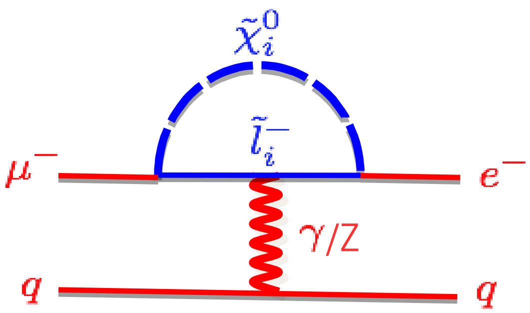
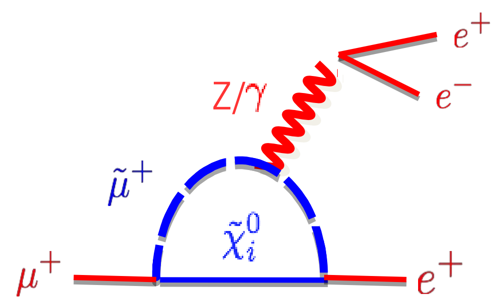


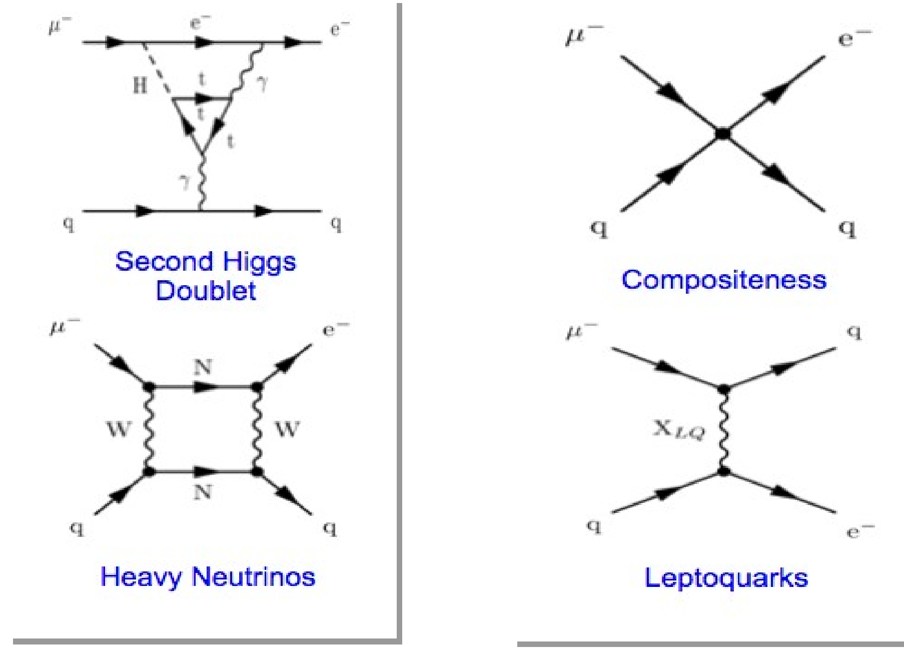
New physics with cLFV

Mu2e/COMET

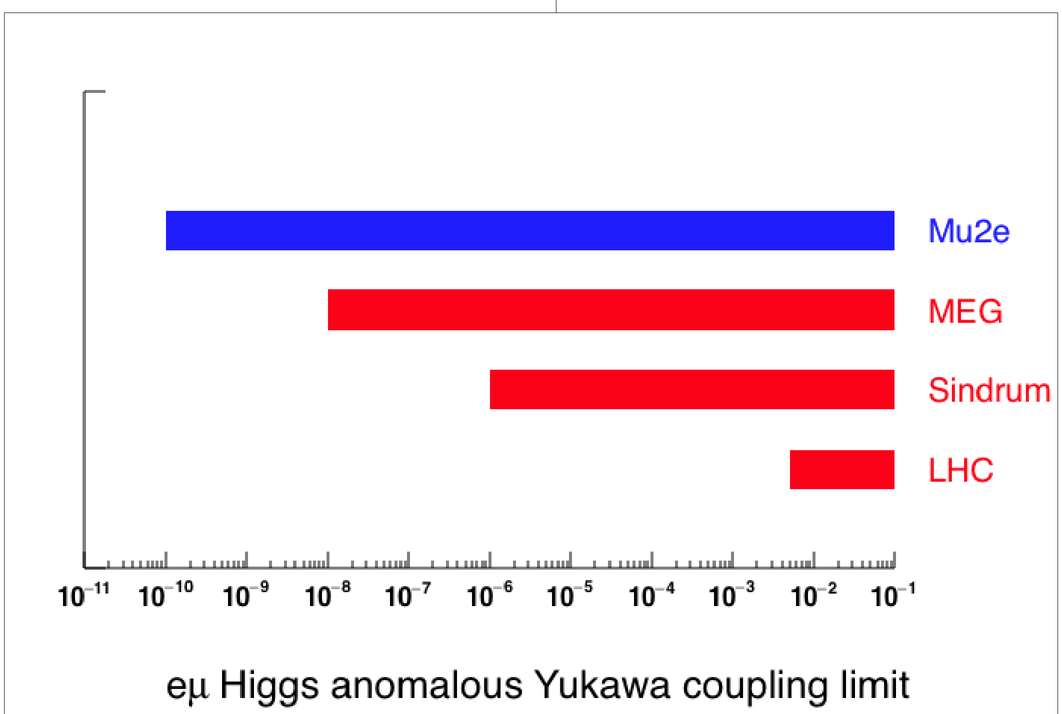


Mu3e





Probe LQ masses up to 300 TeV
cf 1 (120) TeV at HL-LHC (LHCb)



If new physics is observed at the LHC, cLFV may be critical to resolve degenerate models

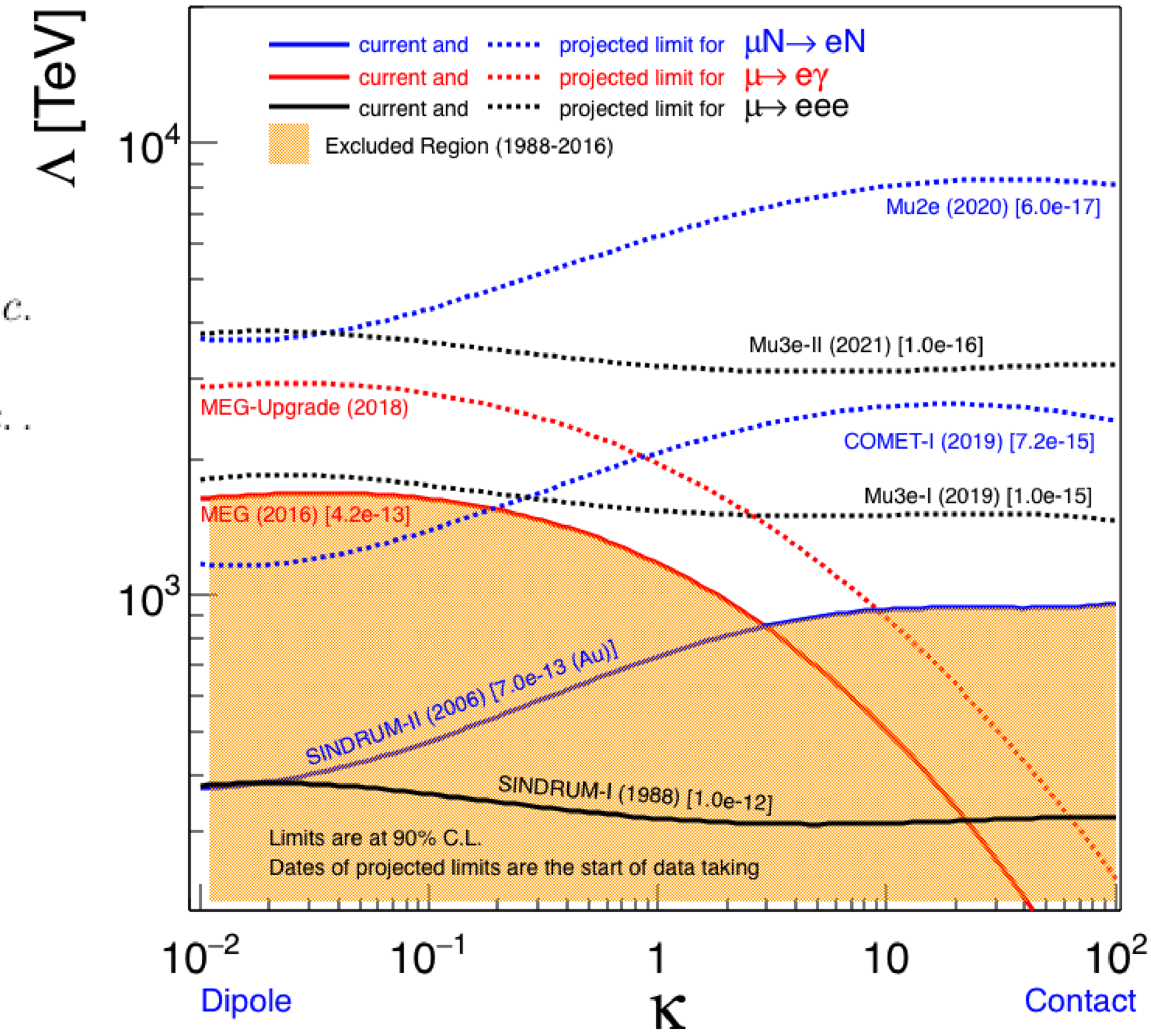
If the new physics is at a higher scale then cLFV can probe it

Effective Lagrangian for cLFV
(de Gouvea & Vogel)

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c. \,.$$

Extend scale by ~factor 5-10
cf jump from Tevatron to LHC

Extend sensitivity by 10^4



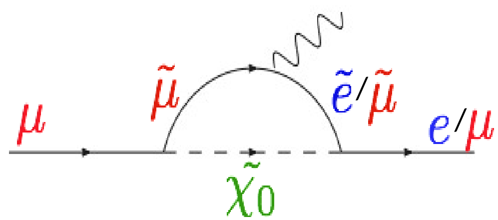
Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

	Best limits	Projected sensitivities (90%CL)
μ→eγ	< 4.3x10^{-13} MEG (PSI)	4x10^{-14} MEG II (PSI)
μ→eee	< 1.0x10^{-12} SINDRUM (PSI)	1x10^{-15} Mu3e I (PSI) 1x10^{-16} Mu3e II (PSI)
μN→eN	< 7.0x10^{-13} SINDRUM II (PSI)	6x10^{-17} Mu2e (FNAL) 7x10^{-15} COMET I (J-PARC) 6x10^{-17} COMET II (J-PARC)

Synergy with g-2

$$\text{Rate (CLFV)} \sim g^2 \times \theta_{e\mu}^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$

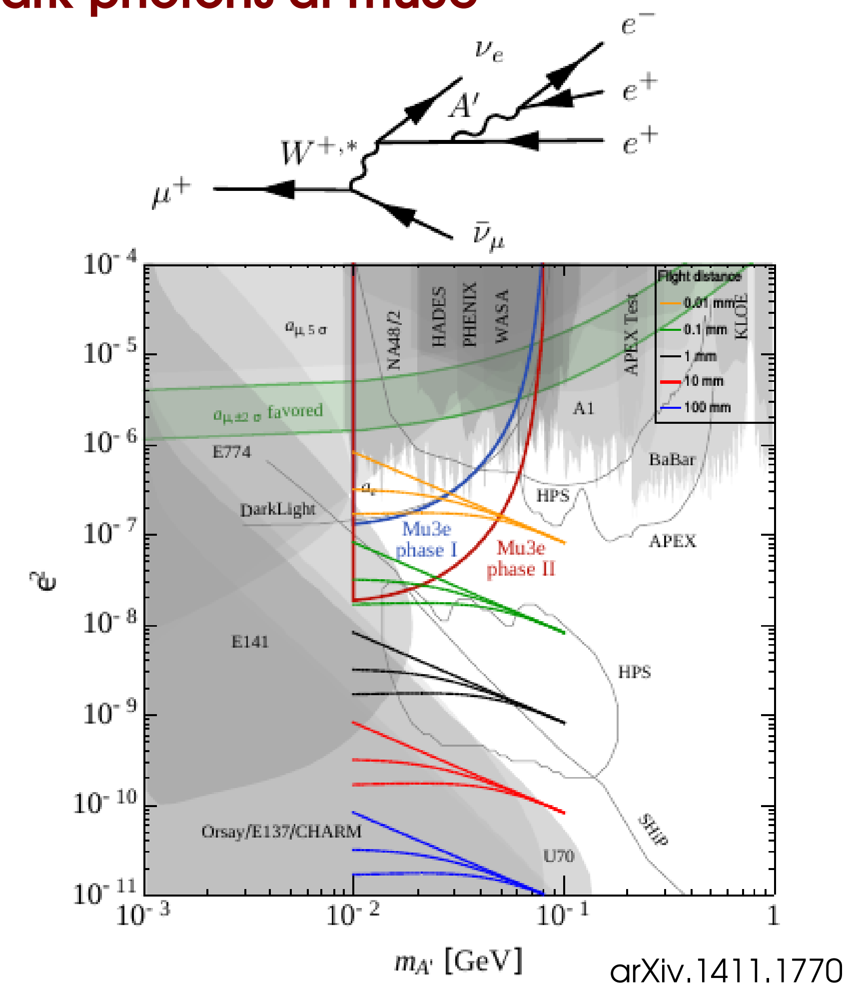
$$a_\mu \sim g^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$



If g-2 anomaly is confirmed,
we have evidence for BSM muon interactions

→ need g-2 and cLFV measurements
to resolve model dependency

Dark photons at mu3e

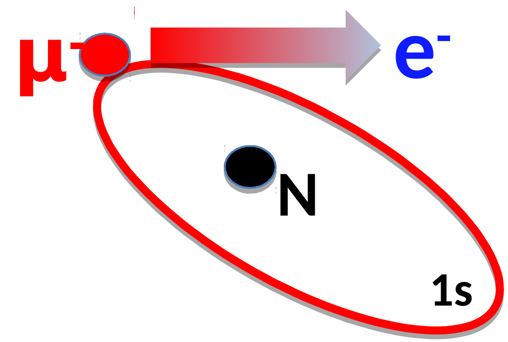


arXiv.1411.1770

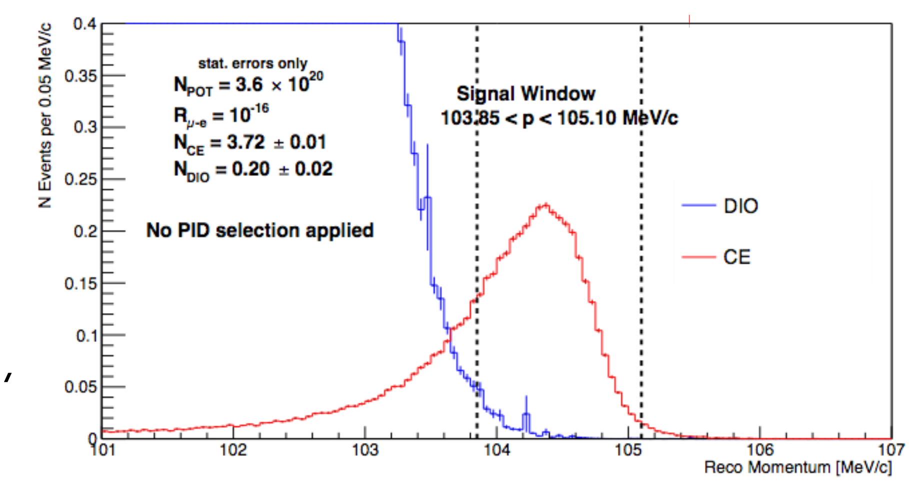
cLFV ties in to four main areas on the STFC science roadmap:

C:1. What are the fundamental particles?
C:3. Is there a unified framework?
C:4. What is the nature of dark matter?
C:7. What is the origin of the matter - antimatter asymmetry?

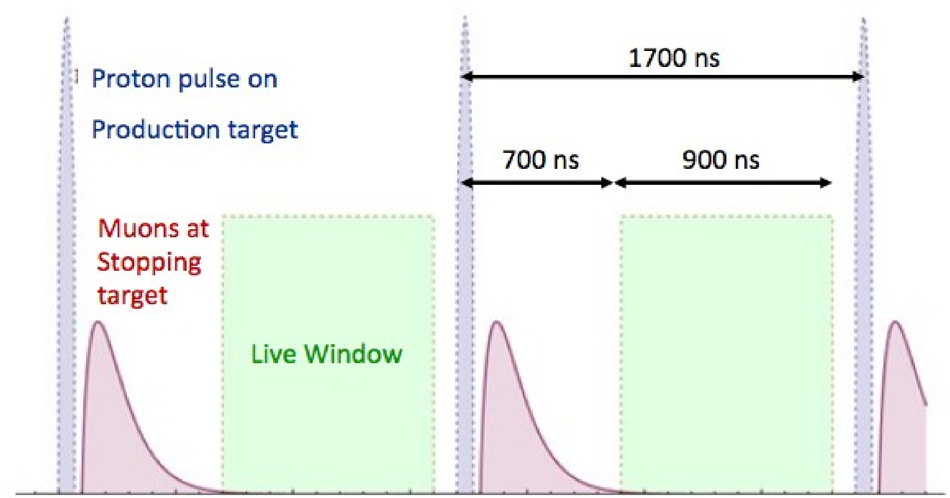
μN → eN: mu2e and COMET



Stopped muons in orbit around nucleus.
- neutrinoless conversion of muon to electron
- mono-energetic electron
    - for aluminium: E_e=104.96 MeV
- delayed w.r.t. prompt particles
    - for aluminium: 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})



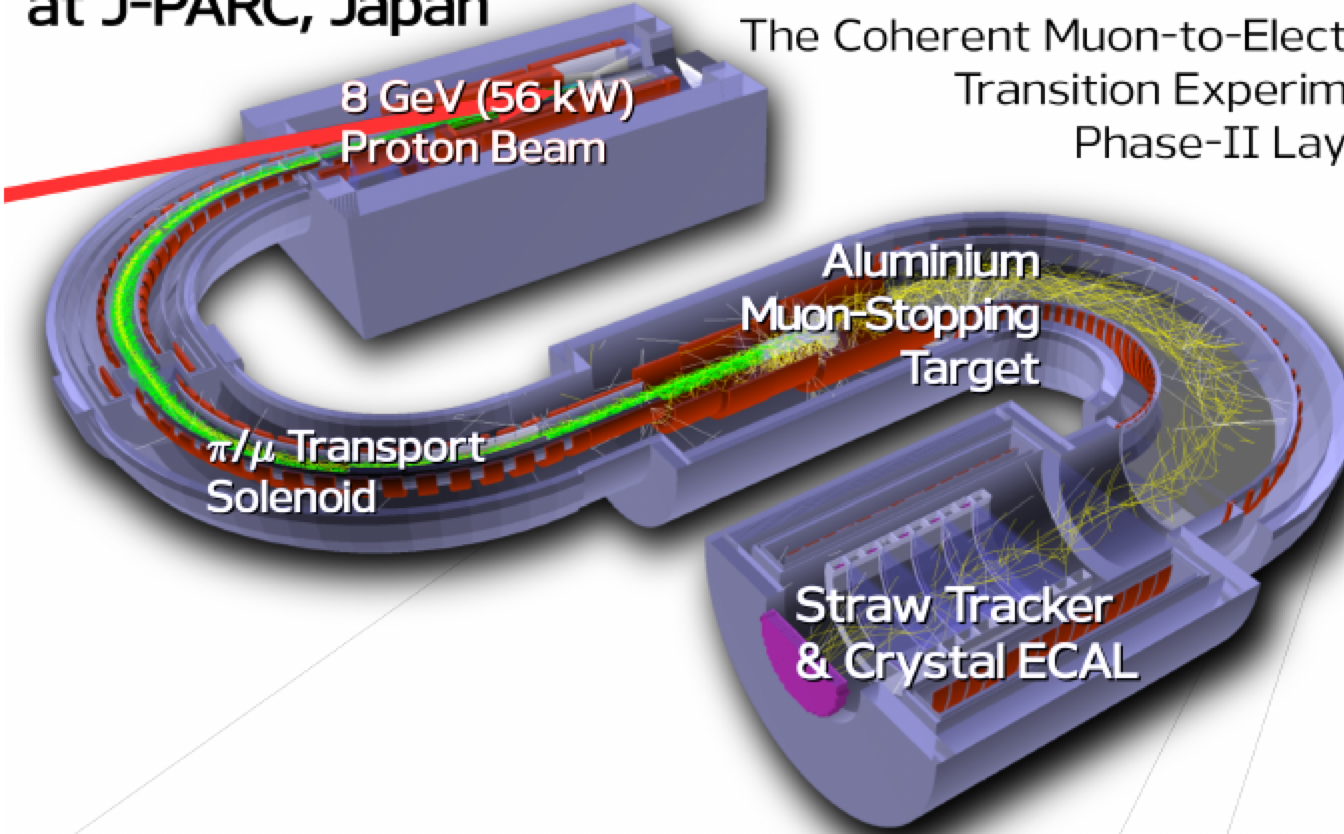
Muon decay in orbit (μN→eννN)
- precise momentum resolution

Cosmics
- cosmic veto detector

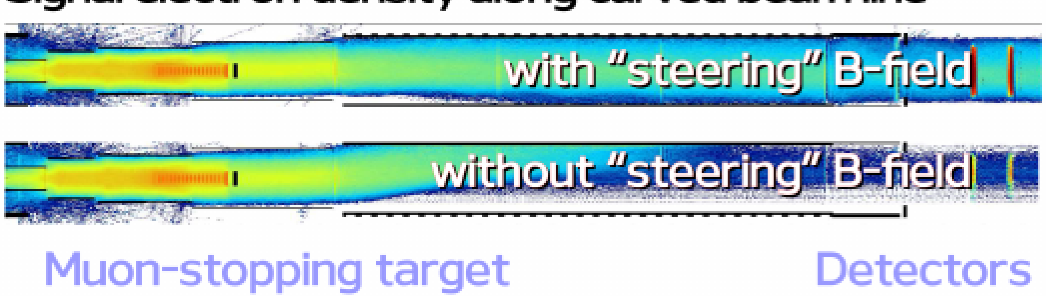
The COMET Experiment

Muon-to-electron conversion experiment at J-PARC, Japan

The Coherent Muon-to-Electron Transition Experiment Phase-II Layout



Signal electron density along curved beam line

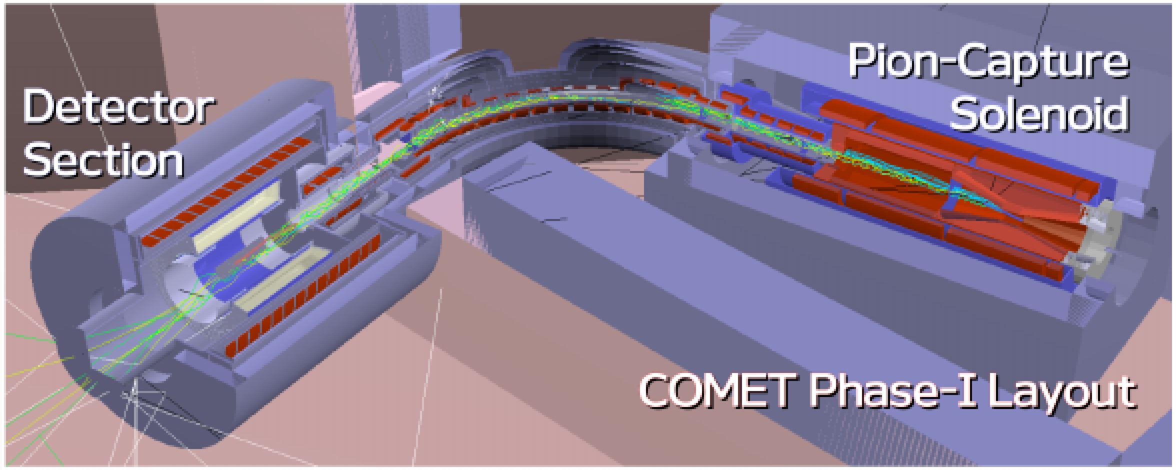


Curved solenoids with vertical B-fields: ***steerable*** **momentum-and-charge selection** for muons and signal electrons

56 kW proton beam: Seven times the muon production rate of Mu2e

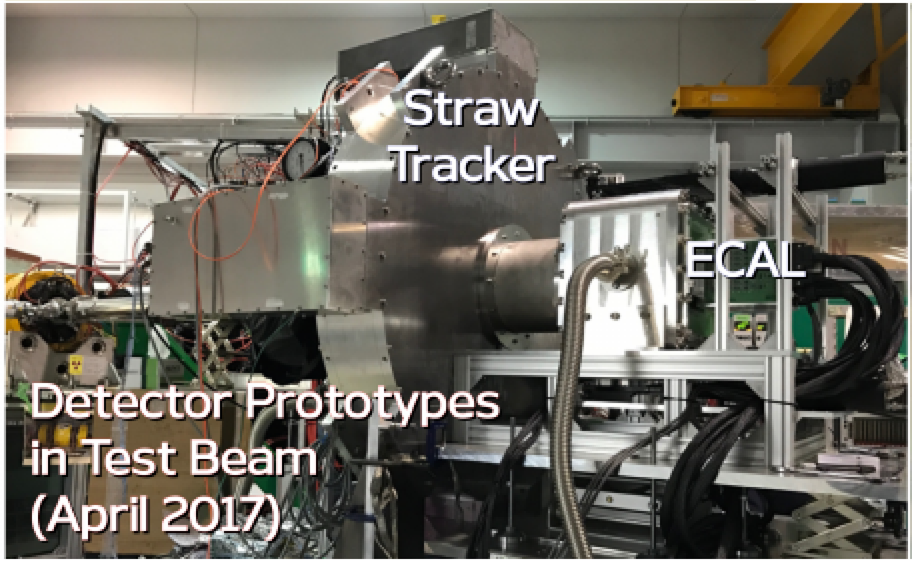
Fully physics study by Ben Krikler (PhD Thesis, 2016)

COMET Phase-I

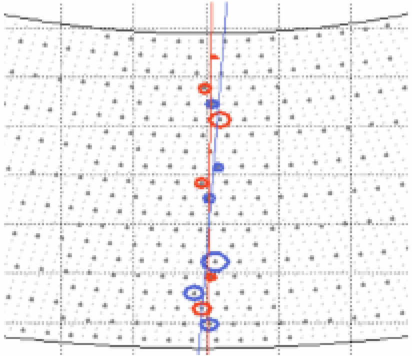


Very high-rate/rare signal experiment

- 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



Drift Chamber Cosmic Ray Tests (Ongoing)



COMET Status

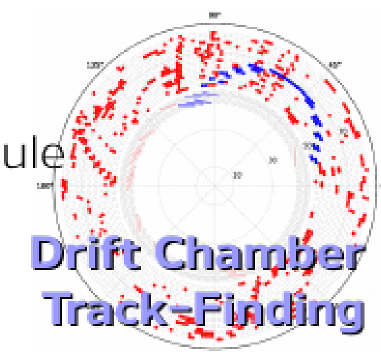
More than 150 collaborators from 32 institutions in 15 countries

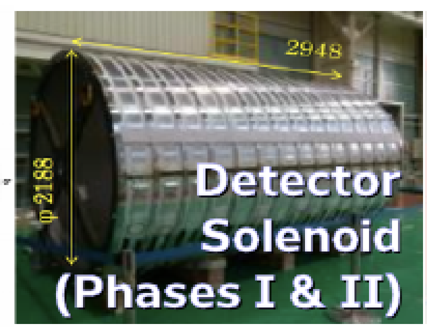
UK leadership includes:

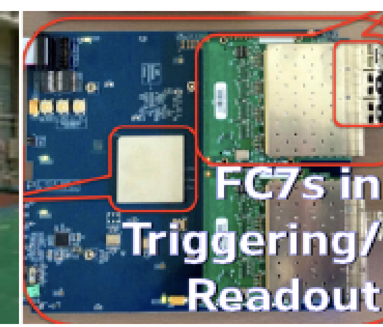
- Founding member, participation since 2006
- Collaboration Board Chair
- Physics and Software Coordinator
- Lead Editor of TDR
- Online/Offline Software, Data Processing
- Triggering/DAQ Electronics and Firmware
- Detector Raw Data Interface
- Triggering, Tracking and Reconstruction

COMET Phase-I

- fully-approved at J-PARC/KEK
- no technical constraints to schedule
- beam arriving in two years
- S.E.S to $B(\mu \rightarrow e) = 3 \times 10^{-15}$

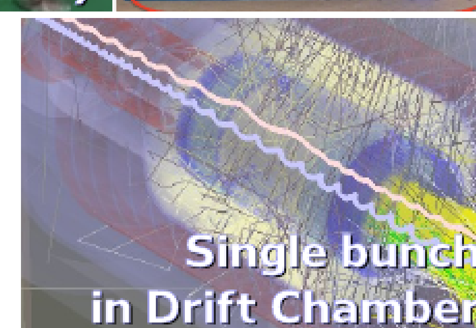




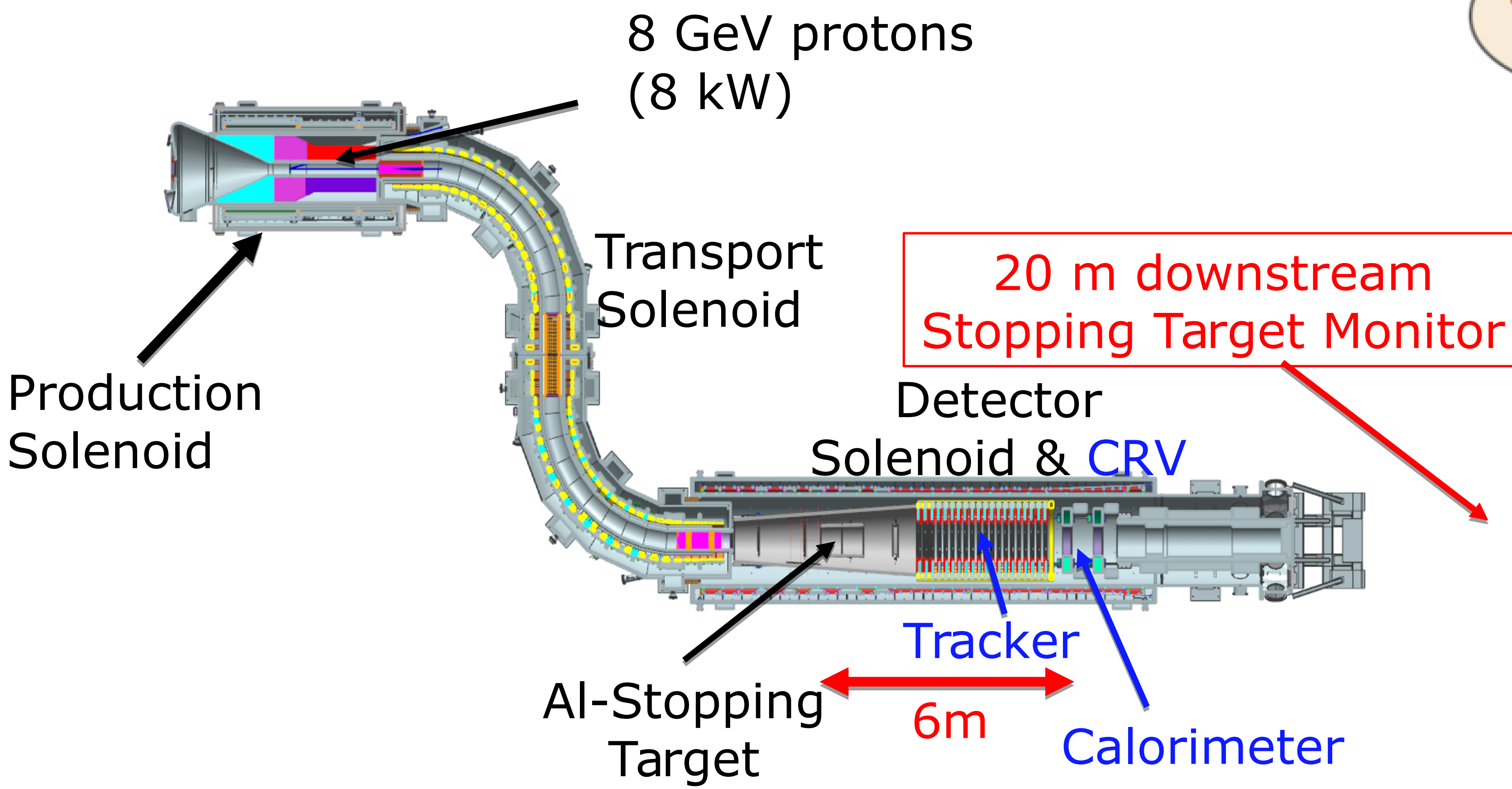


COMET Phase-II

- Phase-I components to be redeployed for Phase-II
- Within approximately two years of successful Phase-I start
- Seven times higher muon production rate compared to Mu2e
- Designed for $B(\mu \rightarrow e) = 3 \times 10^{-17}$, but aim to improve using knowledge from Phase-I



mu2e Experiment

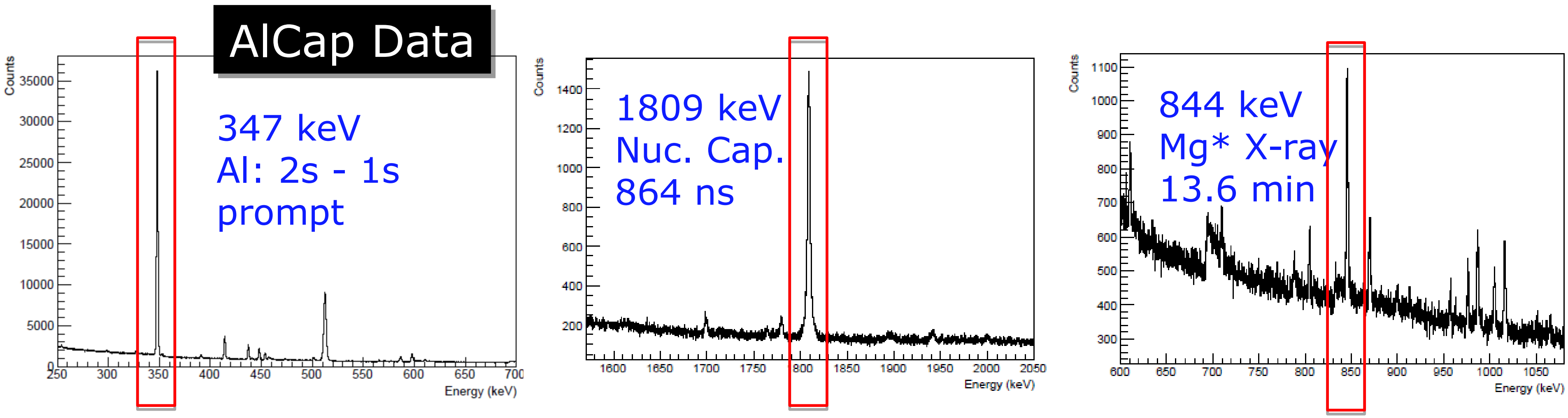


UK contribution (Liverpool, Manchester, UCL): STM

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

cf luminosity at collider

- determine "background" impurities in target and beamline
- verify integrity of DIO modelling



Need excellent resolution at high rate (γ: 90 kHz/cm^2) in broad range: 300 – 1800 keV → n-type coaxial HPGe detector.

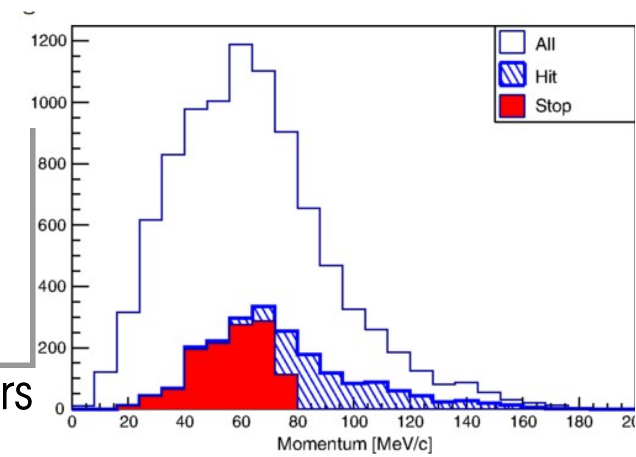
Delivering the world's most intense muon beam

S. Cook, R. D'Arcy, A. Edmonds, M. Fukuda, K. Hatanaka, Y. Hino, Y. Kuno, M. Lancaster, Y. Mori, T. Ogitsu, H. Sakamoto, A. Sato, N. H. Tran, N. M. Truong, M. Wing, A. Yamamoto, and M. Yoshida

Phys. Rev. Accel. Beams **20**, 030101 – Published 15 March 2017

—— UK

+ COMET members



HEPAP P5: 2014

mu2e (& g-2) to be completed in all budget scenarios
- only also recommended for HL-LHC, LBNF

Approval of full-budget : July 2016 : $274M

Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context

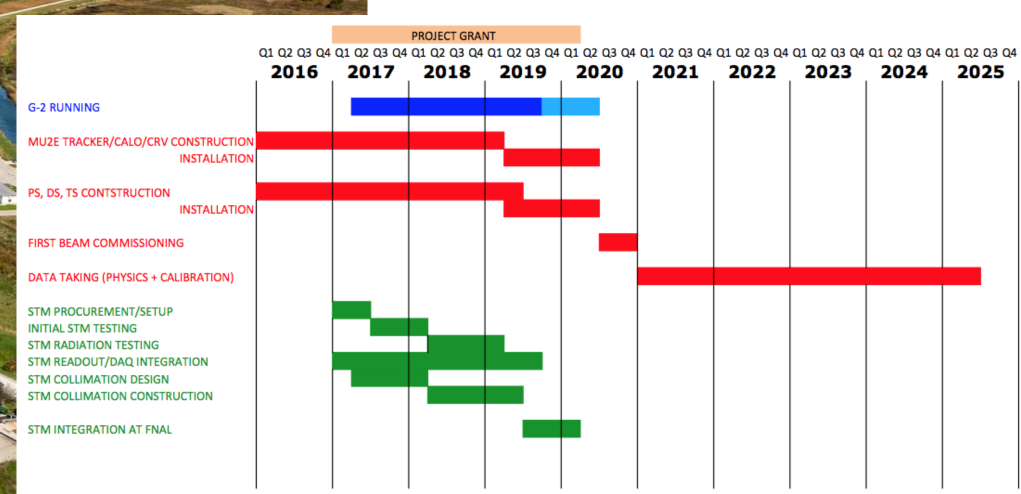
220 members: 35 institutes.

Beamline into mu2e building already completed.

Most of the accelerator mods done since also needed by g-2
First beam in 2020 with data-taking to conclude in 2025

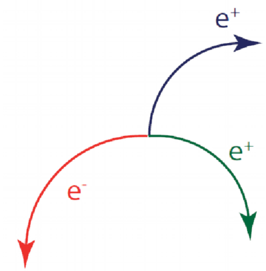
Possibility for Mu2e-II (extra factor of 10 in sensitivity)

- to be finalised in 2020 HEPAP P5.

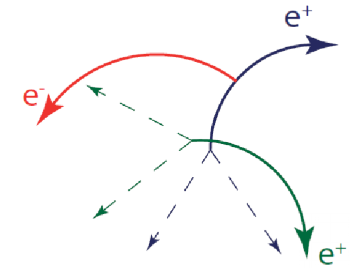


The mu3e experiment at Paul Scherrer Institut

- search for mu→eee



DC beam of up to 10^{10} μ/s on target, triggerless DAQ.

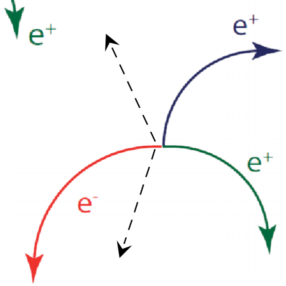


Backgrounds:

Combinatorics, Michel decay + photon conversion

→ time and position resolution

- Scintillating fibres (1ns) and tiles (100ps)
- vertex resolution 200 μm

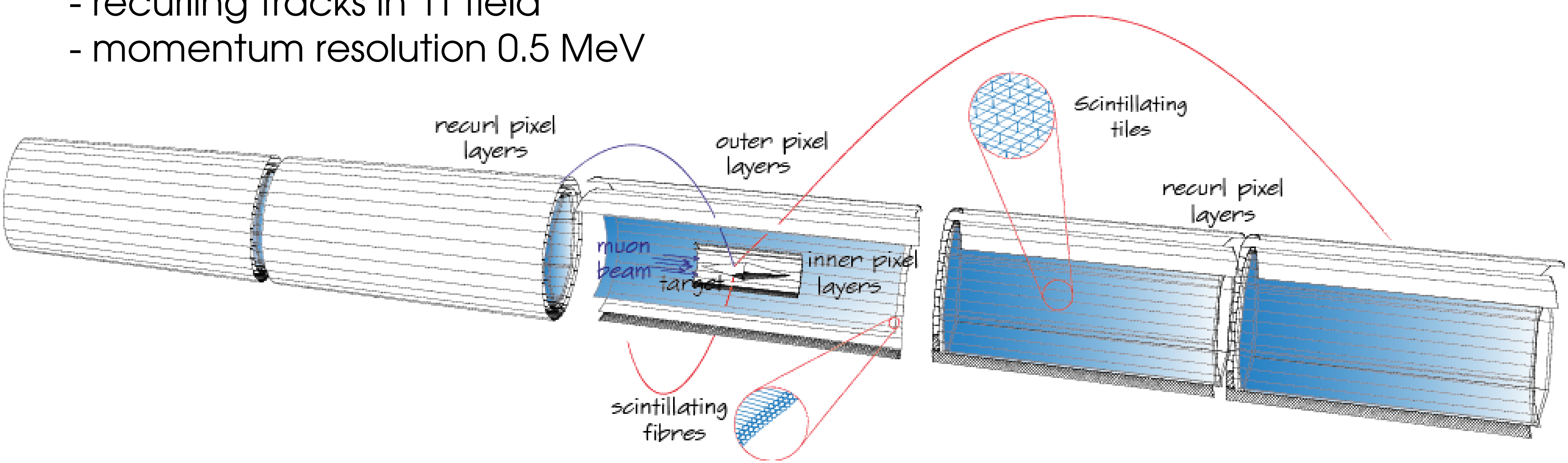


Michel decay + internal conversion

→ momentum resolution

Operating in scattering dominated regime (E<53 MeV)

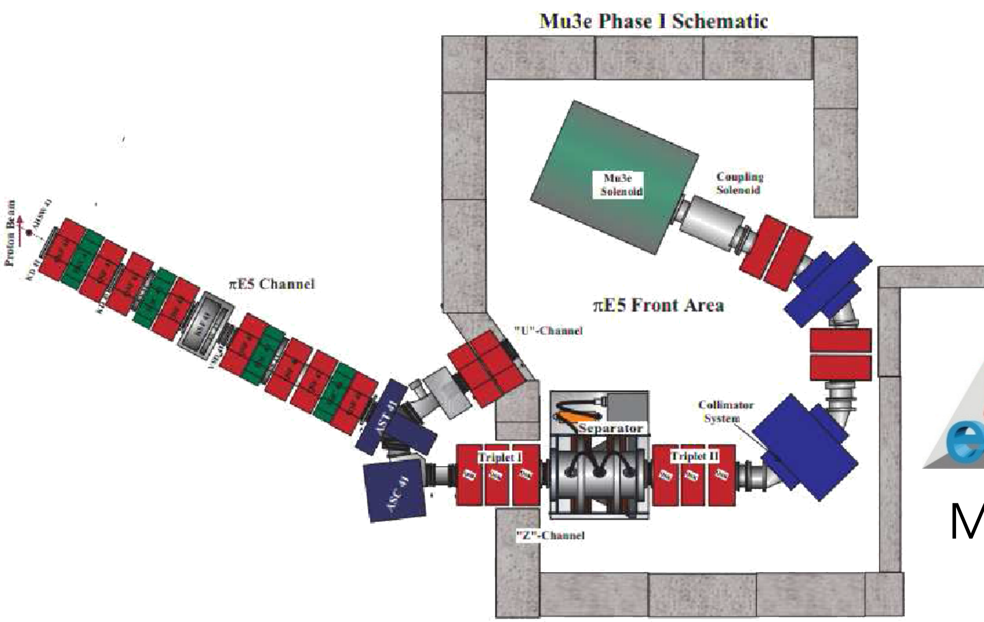
- recurling tracks in 1T field
- momentum resolution 0.5 MeV



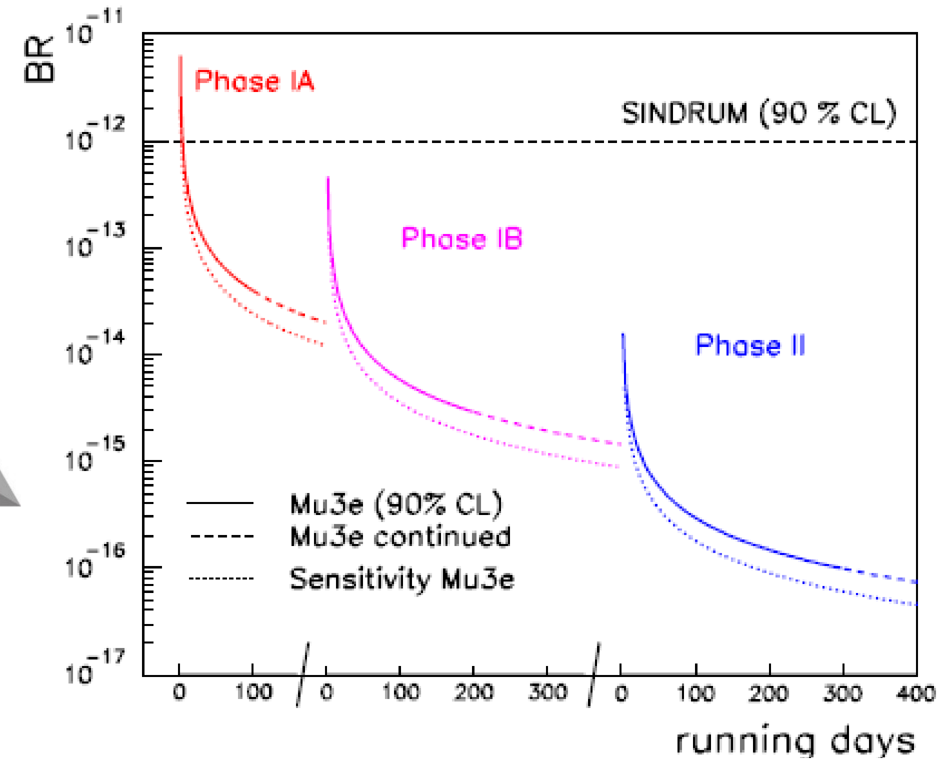
mu3e Schedule

Phase 1A and 1B (2019-2021): Br($\mu \rightarrow eee$) < 10^{-15}

- Approved (2013) and funded. PSI πE5 beam, shared with MEG.
- 10^8 μ/s on target for mu3e demonstrated.



MEG



Phase 2 (2021): Br($\mu \rightarrow eee$) <10^{-16} (10^4 improvement wrt SINDRUM)

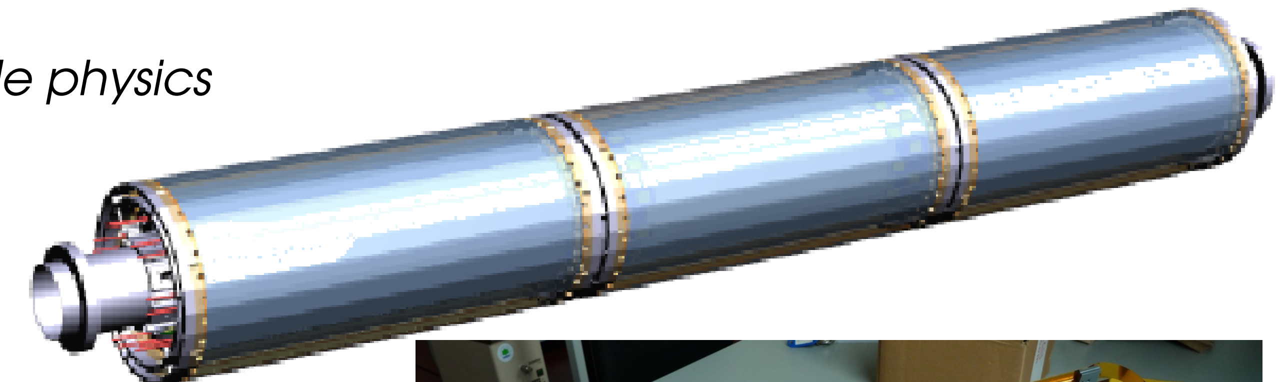
HiMB beam at PSI → 10^9 μ/s on target for mu3e

Development work focussed on improving muon yield from "E-target" using solenoids to capture muons

MuPix outer pixel layers for Phase 1

1.1 m^2 HV-MAPS pixel tracker

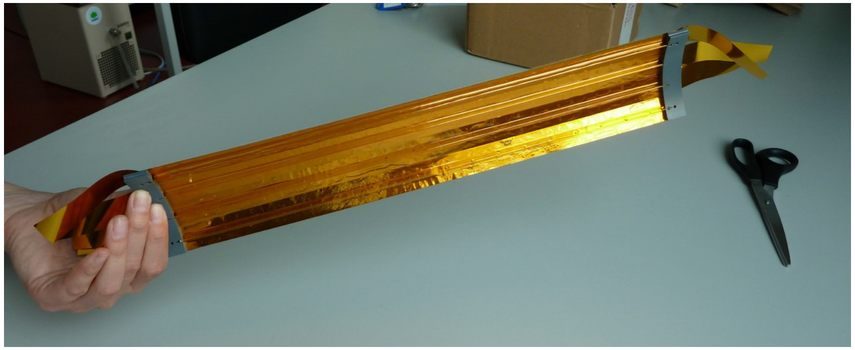
- first HV-CMOS tracker in particle physics



Material budget critical:

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

    → 0.1% X_0 per tracking layer



UK Deliverables (Bristol, Liverpool, Oxford, UCL)

- Commission assembly tooling & procedures (Aug 2017)
- Participate in final pre-production towards MuPix chip (start production Summer 2018)
- Tooling for chip-to-ladder assembly, ladder prototype production.
- Assembly of all Phase 1A outer tracker (Spring 2019).

    & Phase 1B recurl layers (Spring 2020).
- Design and deliver clock and control system for time-slice based daq (Spring 2019)

Conclusion

cLFV complements and extends two major research themes in the UK:
- BSM searches and Higgs physics at the LHC
- Neutrino mass hierarchy and CPV in the neutrino sector

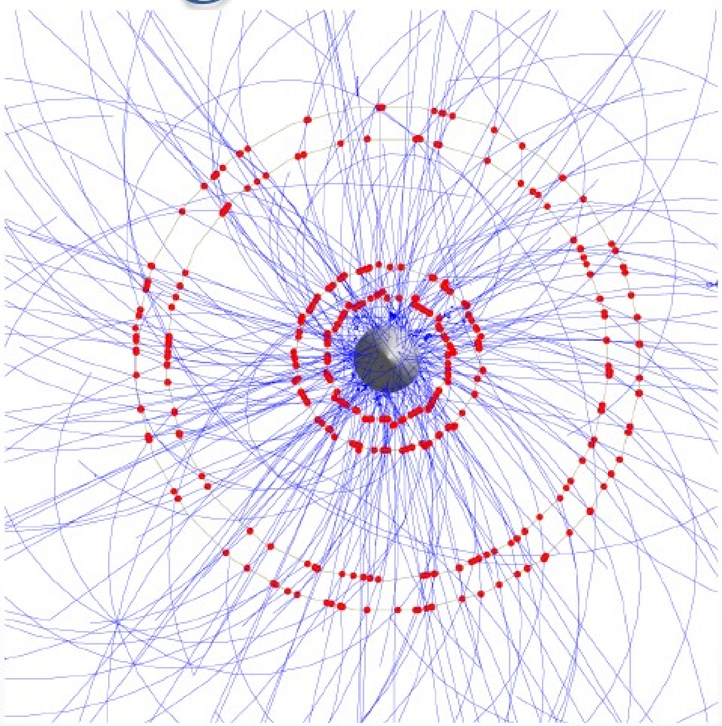
mu3e, mu2e and Comet will increase sensitivity by 10^4
- possibility to discover new physics orders of magnitude beyond LHC reach

Exciting physics programme for ~decade

Involvement in both $\mu \to eee$ and $\mu N \to eN$ important:
- complementary to each other (and to g-2)
- not clear which will provide the first/best limits or discovery!

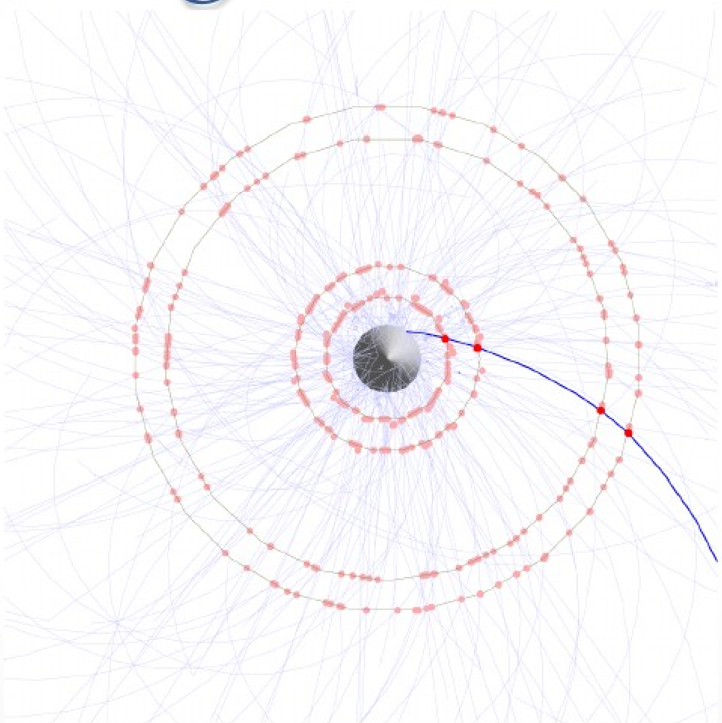
Imperial College London | University of BRISTOL | UCL | UNIVERSITY OF LIVERPOOL | MANCHESTER 1824 The University of Manchester | UNIVERSITY OF OXFORD backup

Timing Detectors



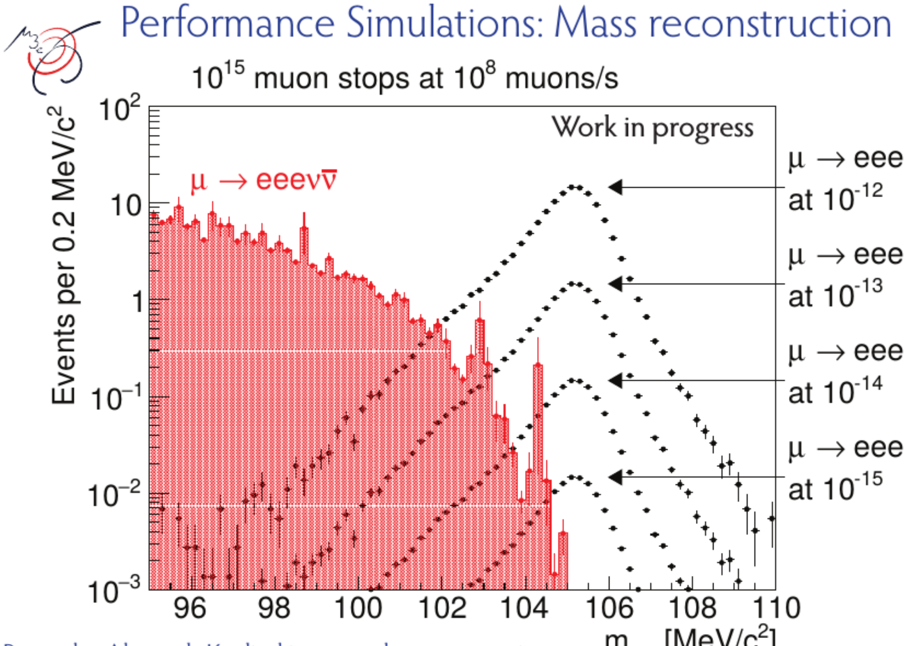
50 ns

Timing Detectors

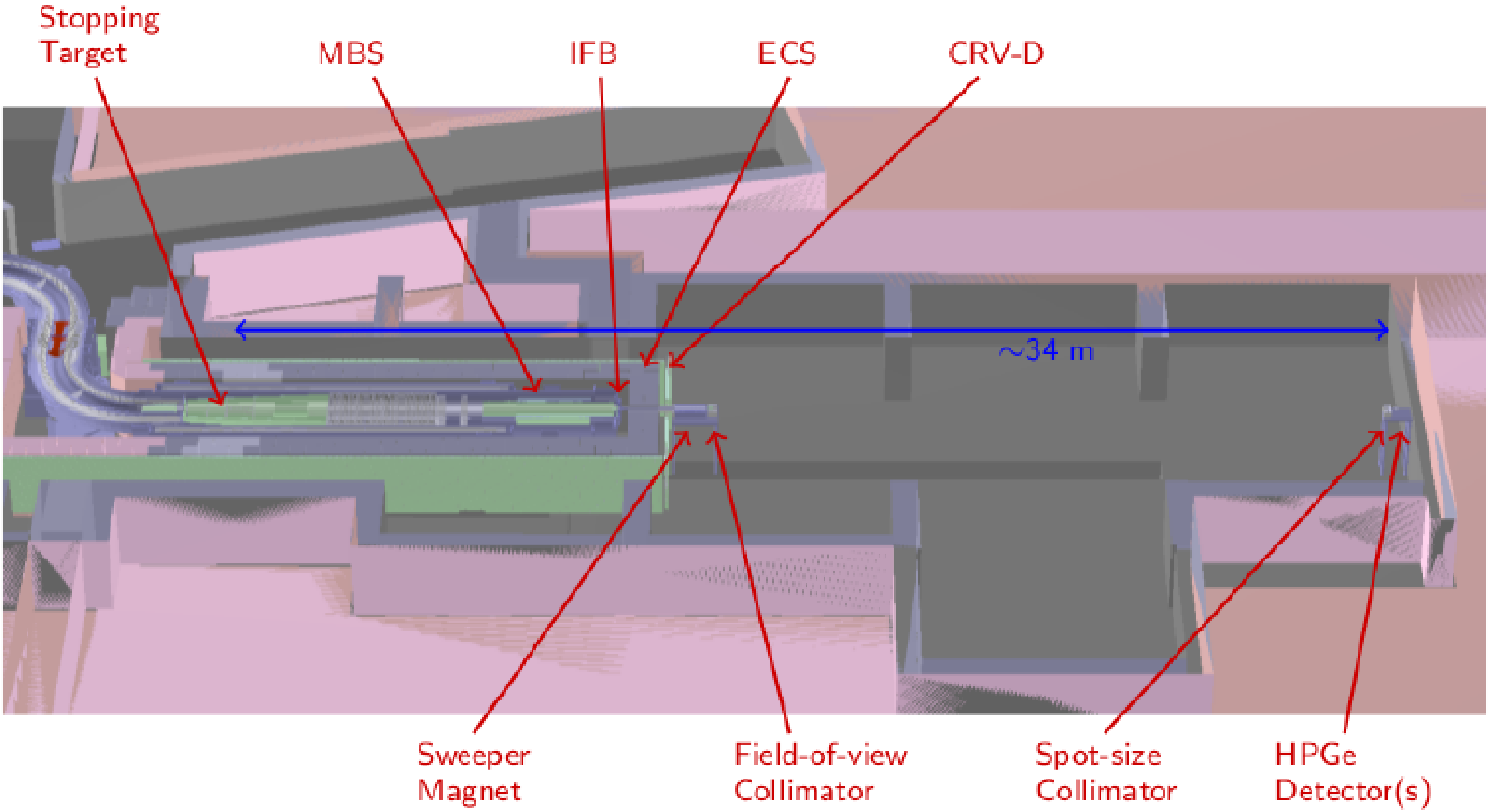


0.1 ns

Performance Simulations: Mass reconstruction

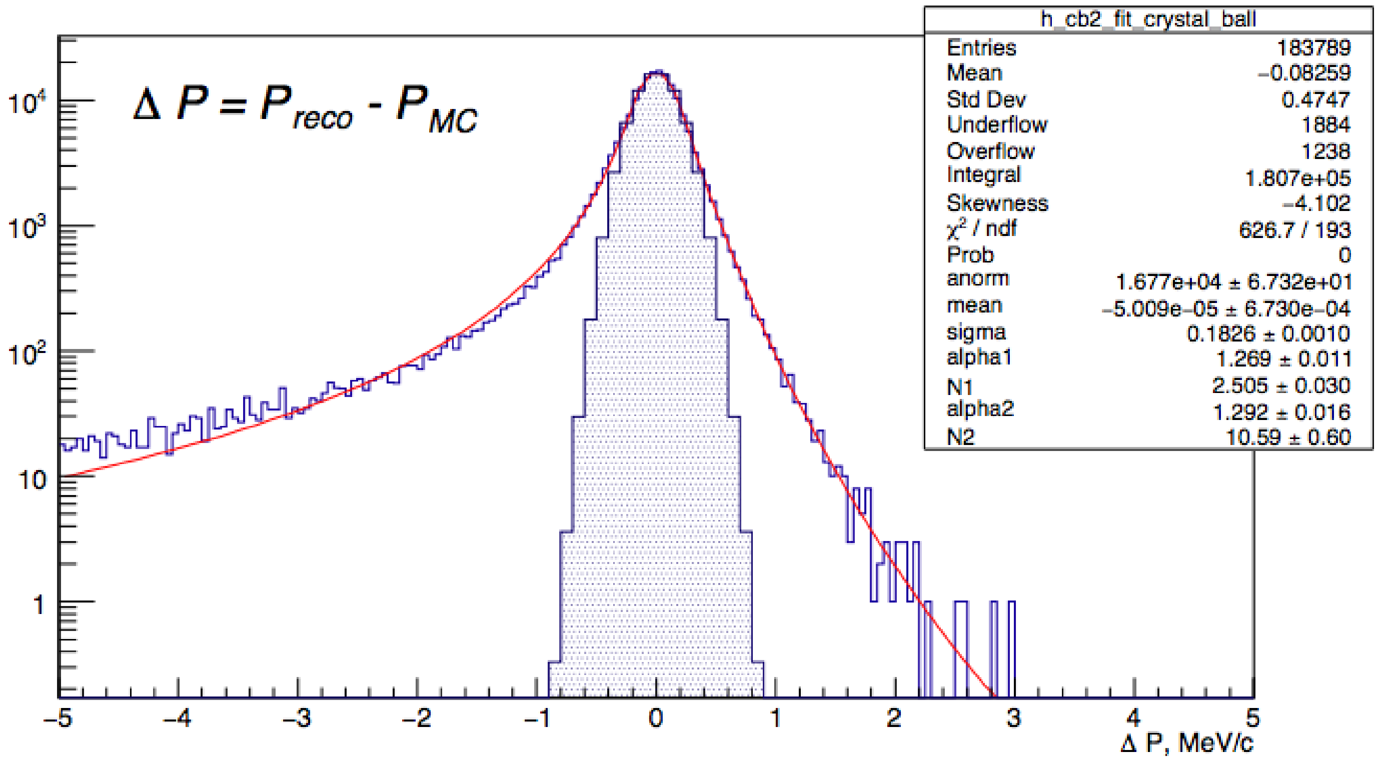


Poster by Alexandr Kozlinskiy on track reconstruction



Stopping
Target
MBS
IFB
ECS
CRV-D
~34 m
Sweeper
Magnet
Field-of-view
Collimator
Spot-size
Collimator
HPGe
Detector(s)

mu2e Straw Tracker

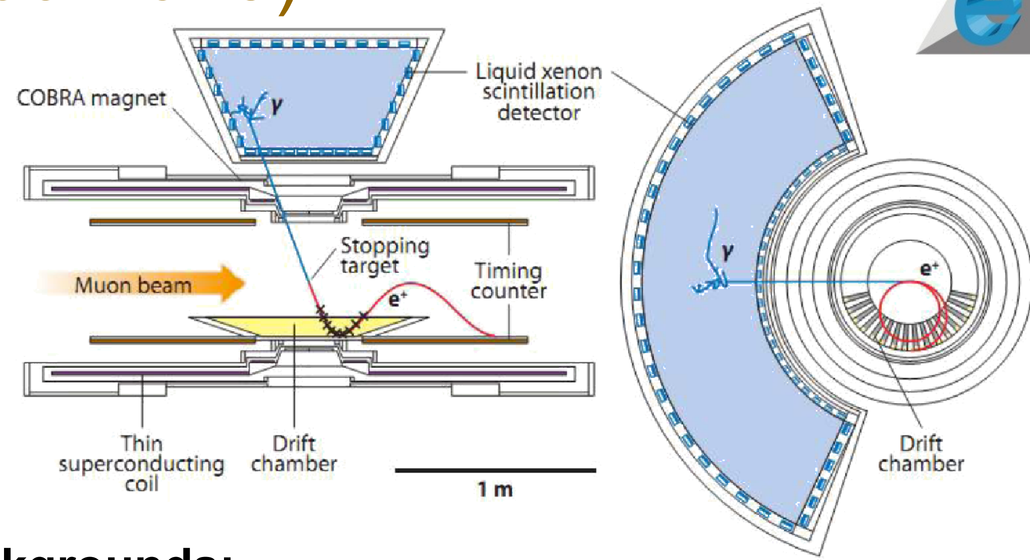


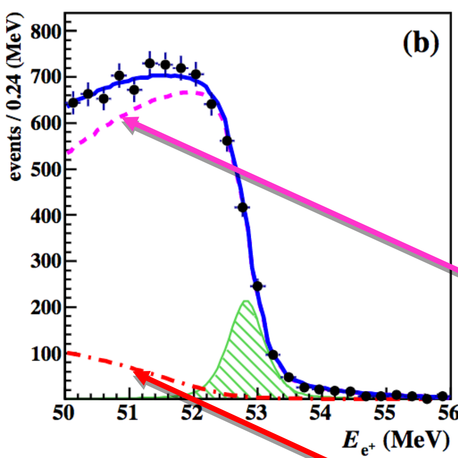
Resolution (core) : 183 keV ie $\frac{\sigma(p)}{p}$ ~ 0.2% at 100 MeV

Non Gaussian tail ~ 4%

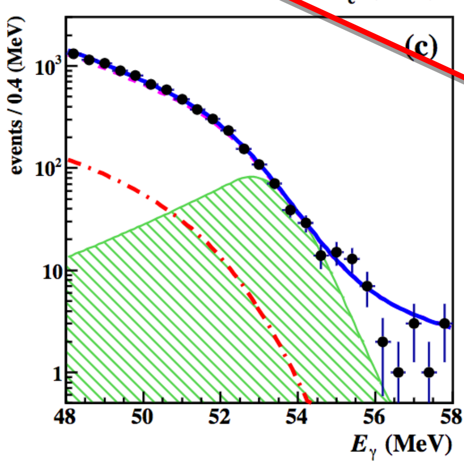
MEG: μ→eγ (2009-2013)

Search for μ→eγ
PSI πE5 beam
(3x10^{7} muons/s)





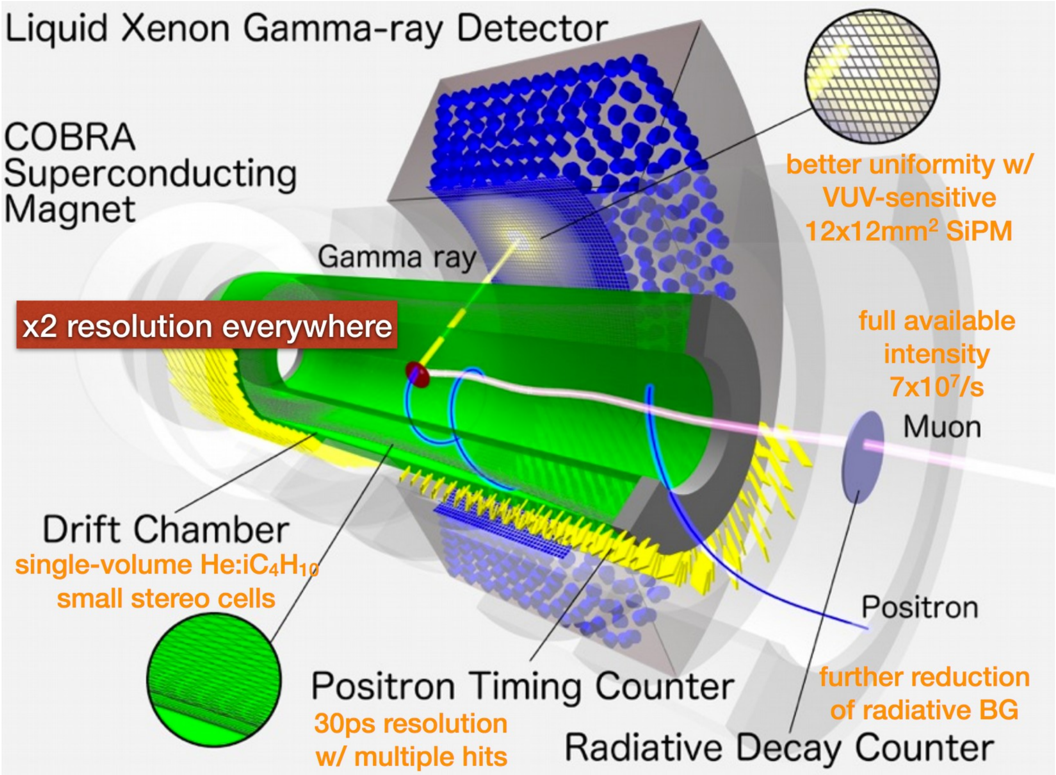
Main backgrounds:
Accidental: e$^+$ from Michel decay + γ photon from e$^+$ annihilation or Bremsstrahlung or from radiative Michel decay .



Radiative Michel decays

Final result (2016)
BR(μ →eγ) < 4.3x10^{-13} (90% C.L.)

MEG II: μ→eγ (2017-2019)



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

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

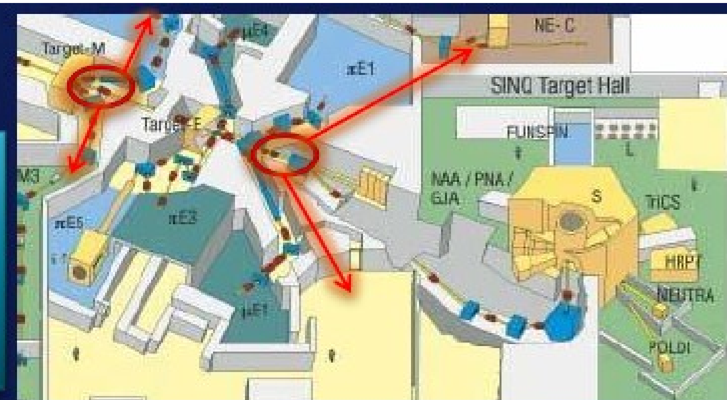
Need better timing and momentum resolution.

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($\mu \rightarrow e\gamma$) < 4×10^{-14} (90% C.L.)

HIMB: using PSI E-target

Alternative Possibilities



Constraints - any intervention to the proton beam line must:

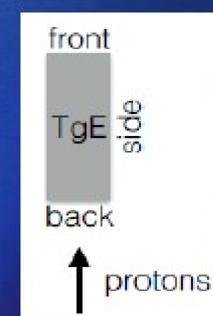
- Not significantly increase the beam losses
- Preserve the proton footprint and energy on SINQ
- Preserve the total material budget seen by the beam

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, 2015

The Mu3e collaboration

Paul Scherrer Institute

Université de Genève

ETH Zürich

University Zürich

Heidelberg University

Karlsruhe Institute of Technology

Mainz University

COMET I (approved), start earliest 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, ~2 years after phase I, 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 2019, 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 (2021 earliest), BR($\mu \rightarrow eee$) ~ $1x10^{-16}$

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