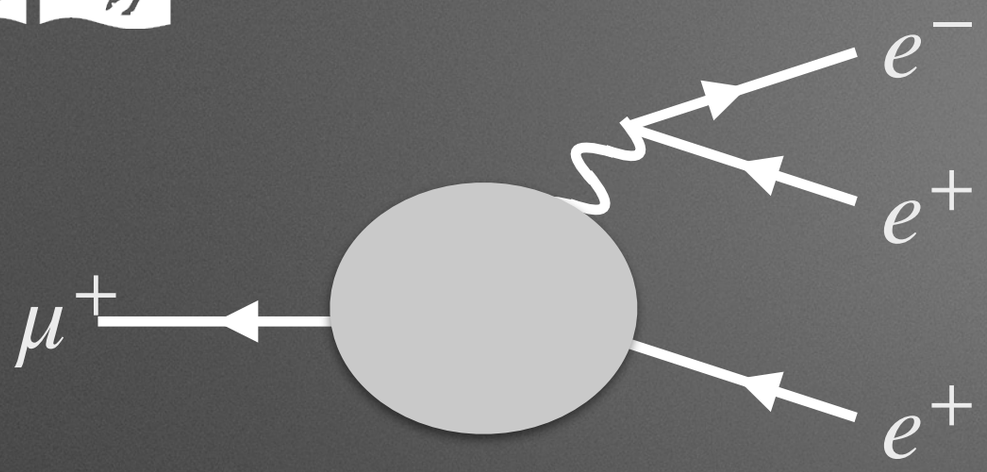
Lepton Flavour Violation
PPAP July 2018

Joel Goldstein
University of Bristol

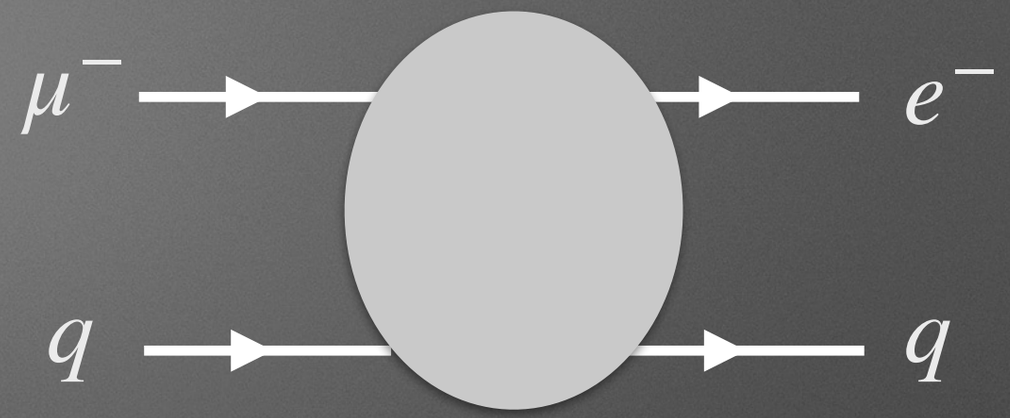
Introduction

- **Dedicated charged LFV experiments**
  1. Mu2e
  2. Mu3e
  3. COMET
     - *(MEG has no UK involvement)*
  4. Future
- **Thanks for input from Yoshi, Joost and Mark**

Background



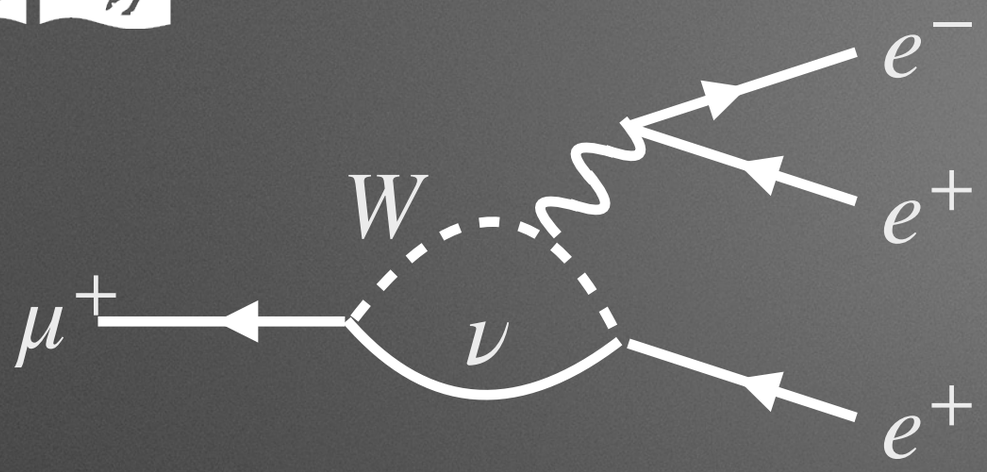
Mu3e/MEG



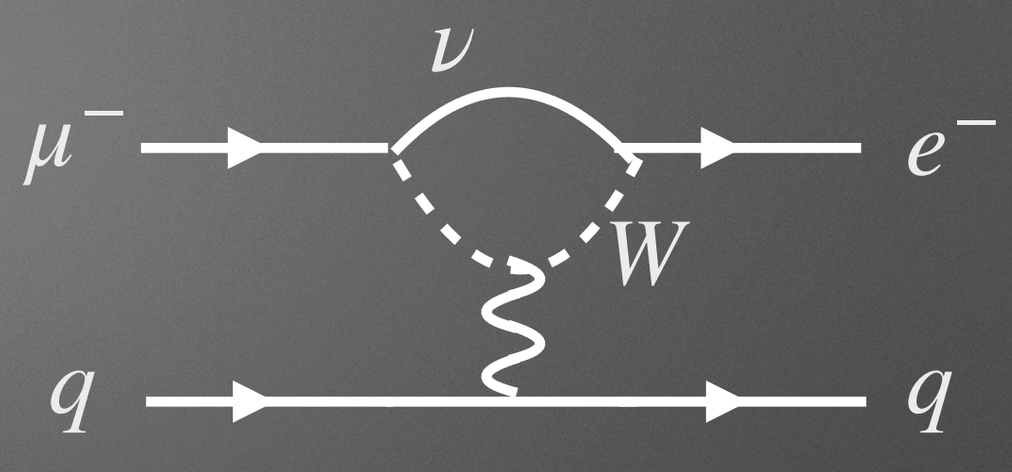
Mu2e/COMET

- LFV already established in the neutrino sector
- Resulting effects in charged lepton decays *Br* << 10^{-50}
- Existing limits ~ 10^{-12}
- Sensitive to multi-TeV scale new physics
  - SUSY, leptoquarks, dark matter…

Background



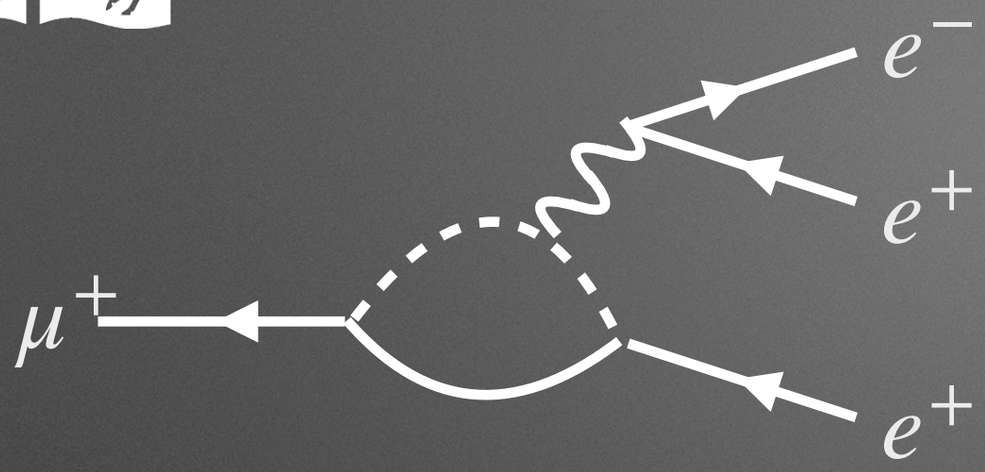
Mu3e/MEG



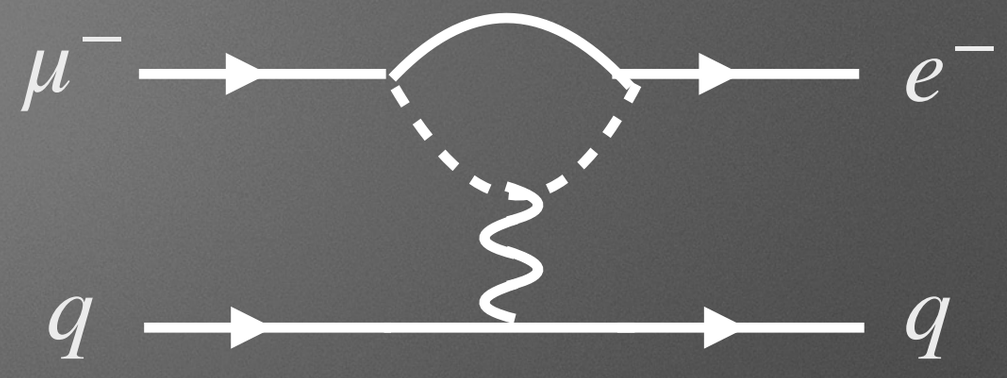
Mu2e/COMET

- LFV already established in the neutrino sector
- Resulting effects in charged lepton decays $Br << 10^{-50}$
- Existing limits ~ 10^{-12}
- Sensitive to multi-TeV scale new physics
  - SUSY, leptoquarks, dark matter…

Background



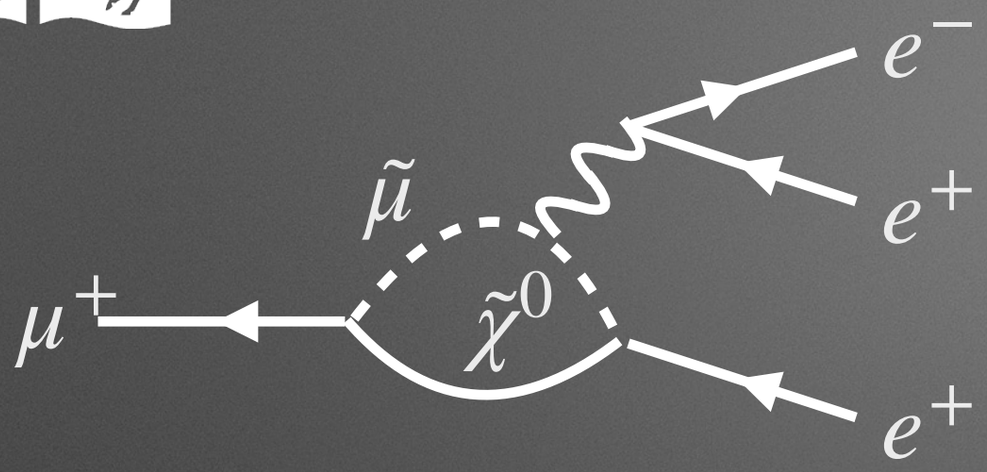
Mu3e/MEG



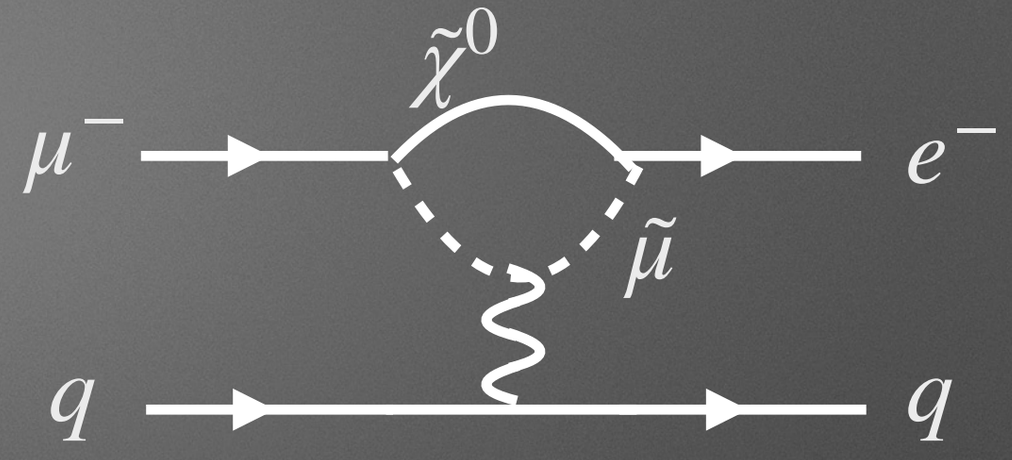
Mu2e/COMET

- LFV already established in the neutrino sector
- Resulting effects in charged lepton decays *Br* << 10^{-50}
- Existing limits ~ 10^{-12}
- Sensitive to multi-TeV scale new physics
  - SUSY, leptoquarks, dark matter…

Background



Mu3e/MEG

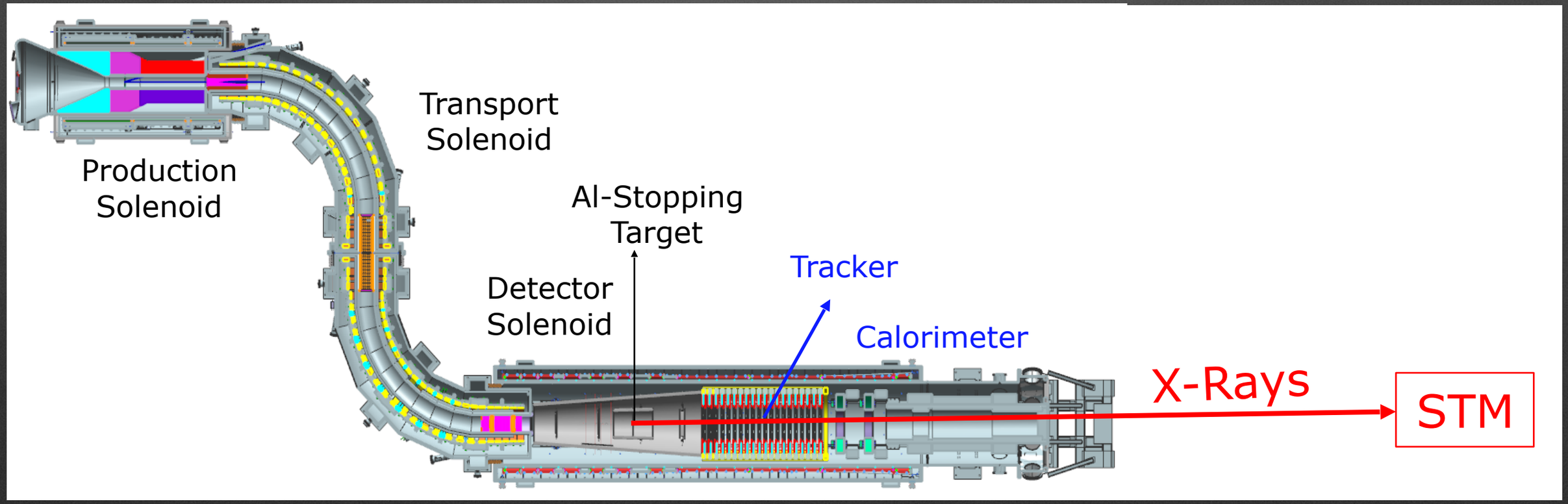


Mu2e/COMET

- LFV already established in the neutrino sector
- Resulting effects in charged lepton decays $Br << 10^{-50}$
- Existing limits ~ 10^{-12}
- Sensitive to multi-TeV scale new physics
  - SUSY, leptoquarks, dark matter…

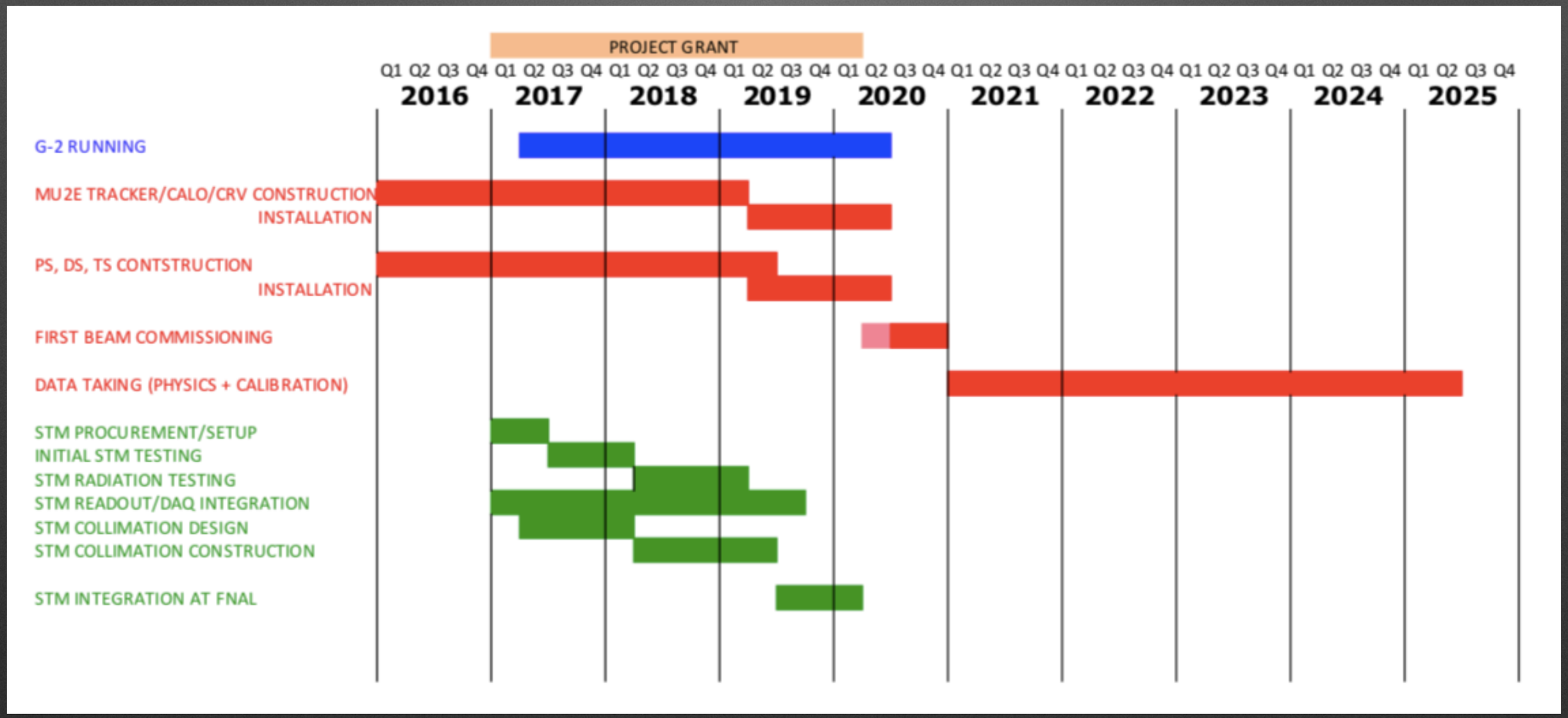
Mu2e - Status

- DOE approved in July 2016
- UK providing the Stopping Target Monitor (STM)
- STFC-TD to provide the proton target *(DOE Funded)*

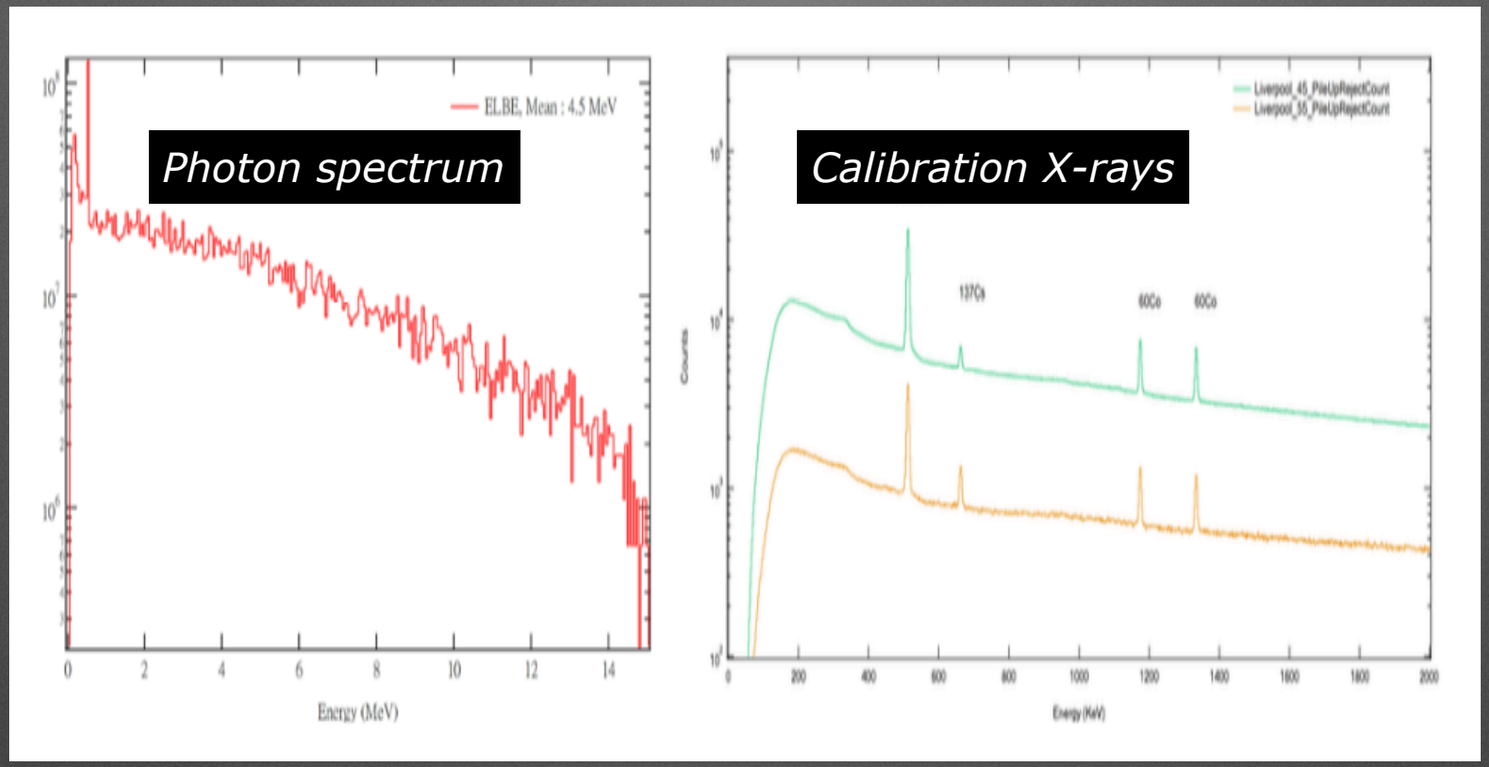


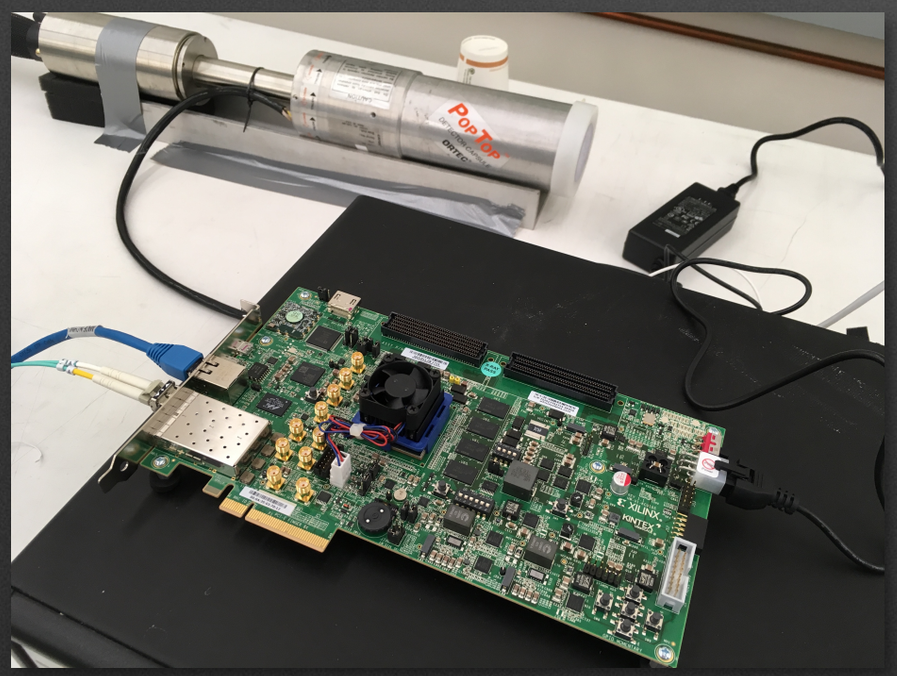
Mu2e - Plans

- First beam in 2020/21; concluding 2025.



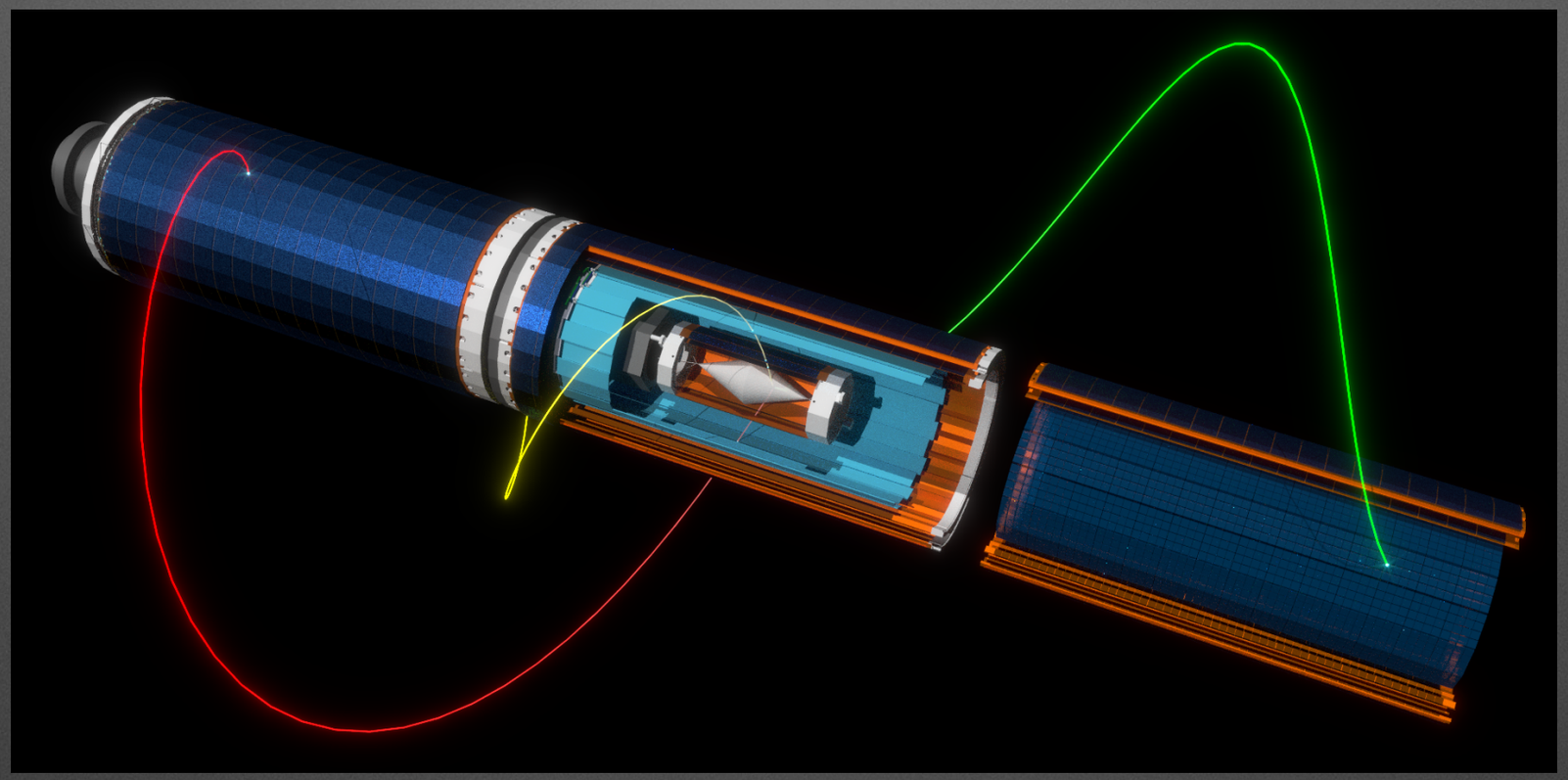
Mu2e UK





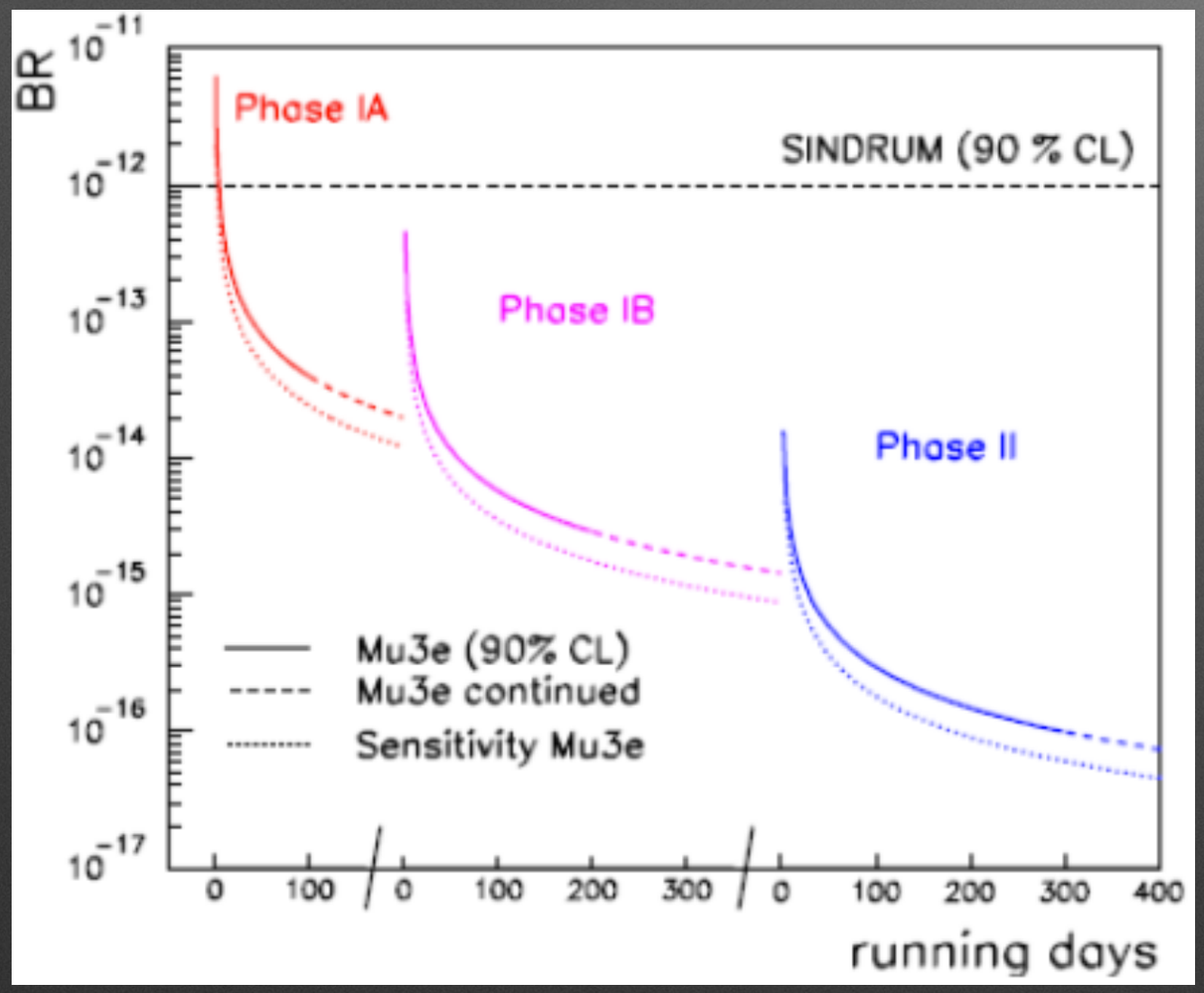
- **Prototype STM irradiated at HZDR.**
  - No degradation in resolution
  - 100 Hz signal (60 kHz photon bkgnd)
- **DAQ/readout tests at FNAL**

Mu3e - Status



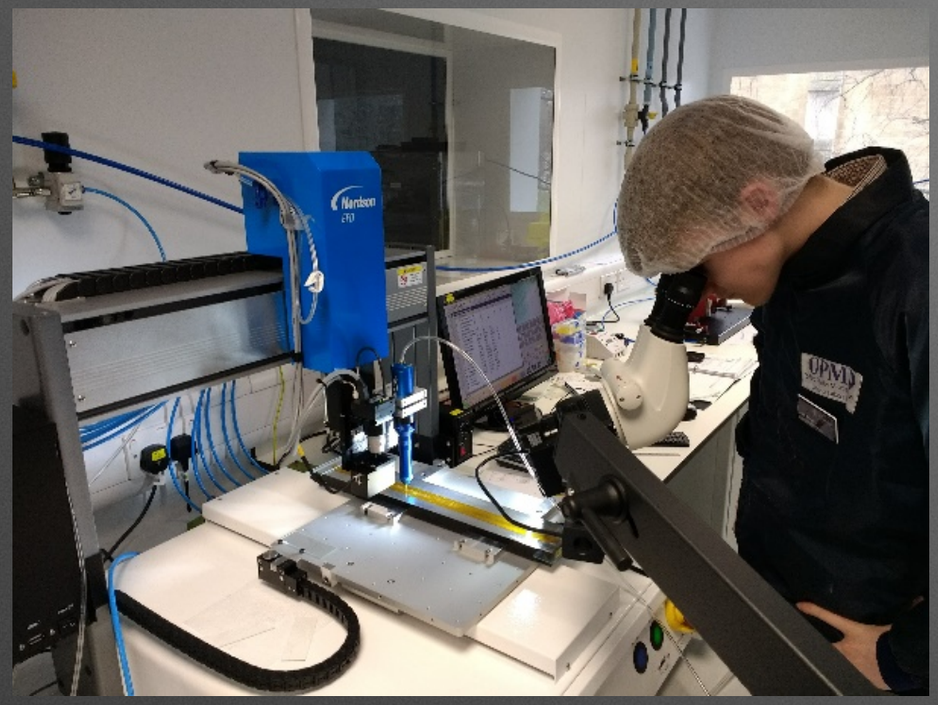
- Approved by PSI in 2013
- UK responsible for outer pixel layers
  - HV CMOS Mupix sensor
- Also clock and timing

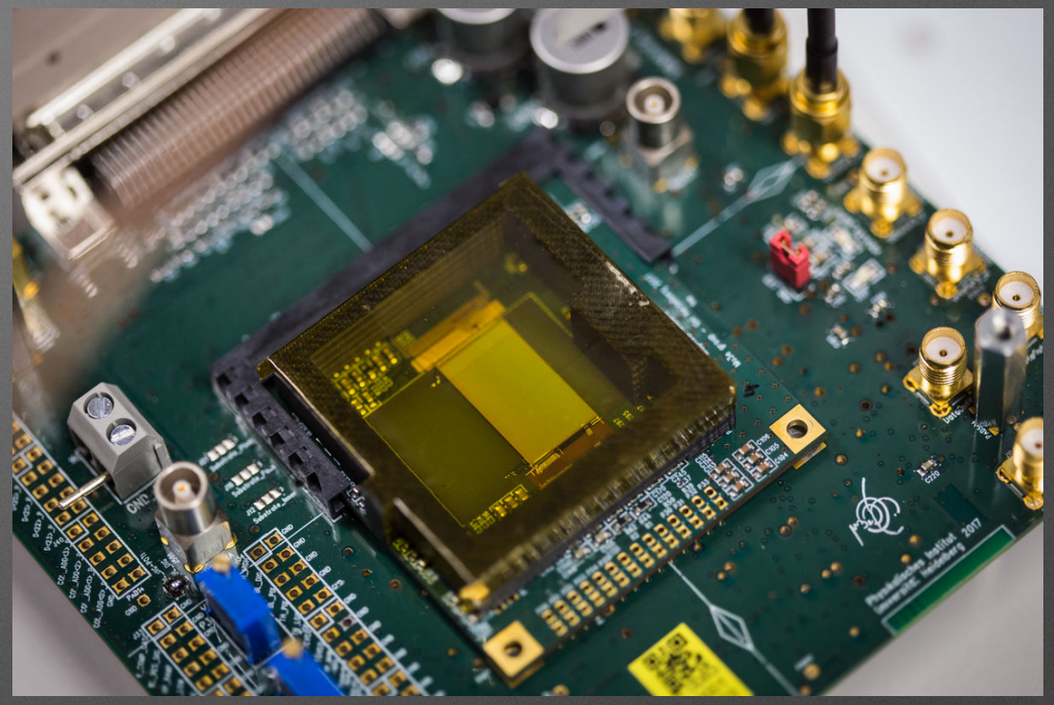
Mu3e - Plans



- Commissioning late 2019
- Physics operation in 2020
- Recurl stations added 2021
- **Phase-II ~2024:**
  - Upgraded beam line
  - Increased acceptance
  - Possible e-gamma option

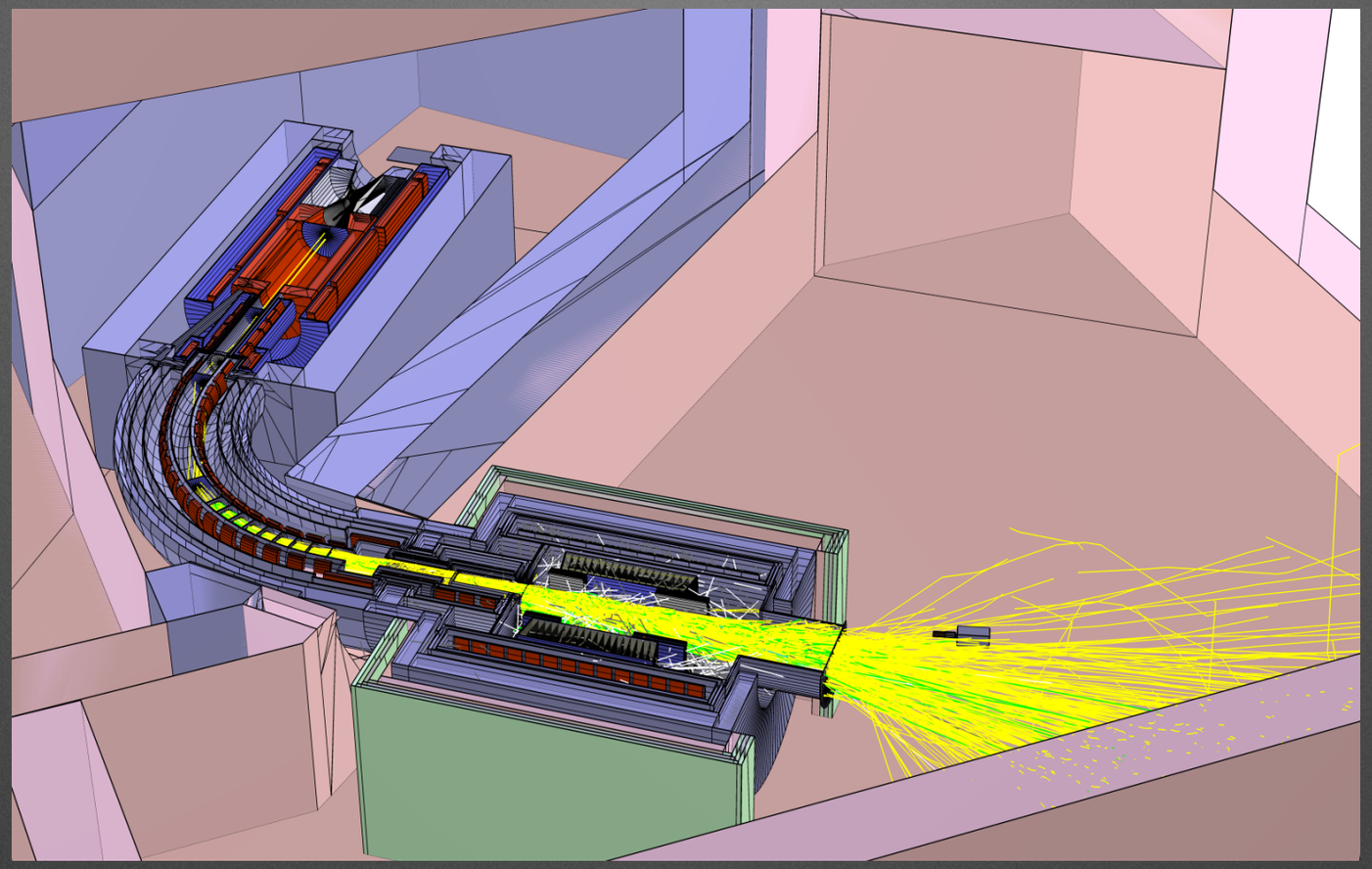
Mu3e UK





- Deliver complete pixel outer tracker by 2020
- Participate in installation and commissioning 2019-21
- Operations and exploitation 2020-2024
- *Natural for UK to build Mu3e-II pixel extension*

COMET - Status



- Phase-I detector systems approaching completion
- UK designed DAQ/fast control
- UK leading software and analysis

COMET - Plans

- Protons to COMET by end 2019
- Phase-II construction in parallel to operations
  - 100x increase in sensitivity
- Growing international collaboration
  - 16+ countries, 40+institutions

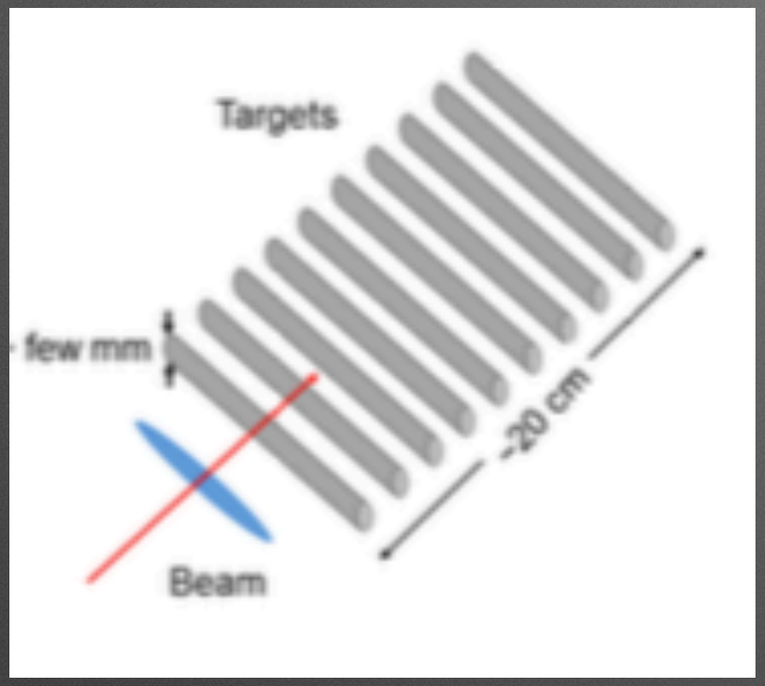
Funding

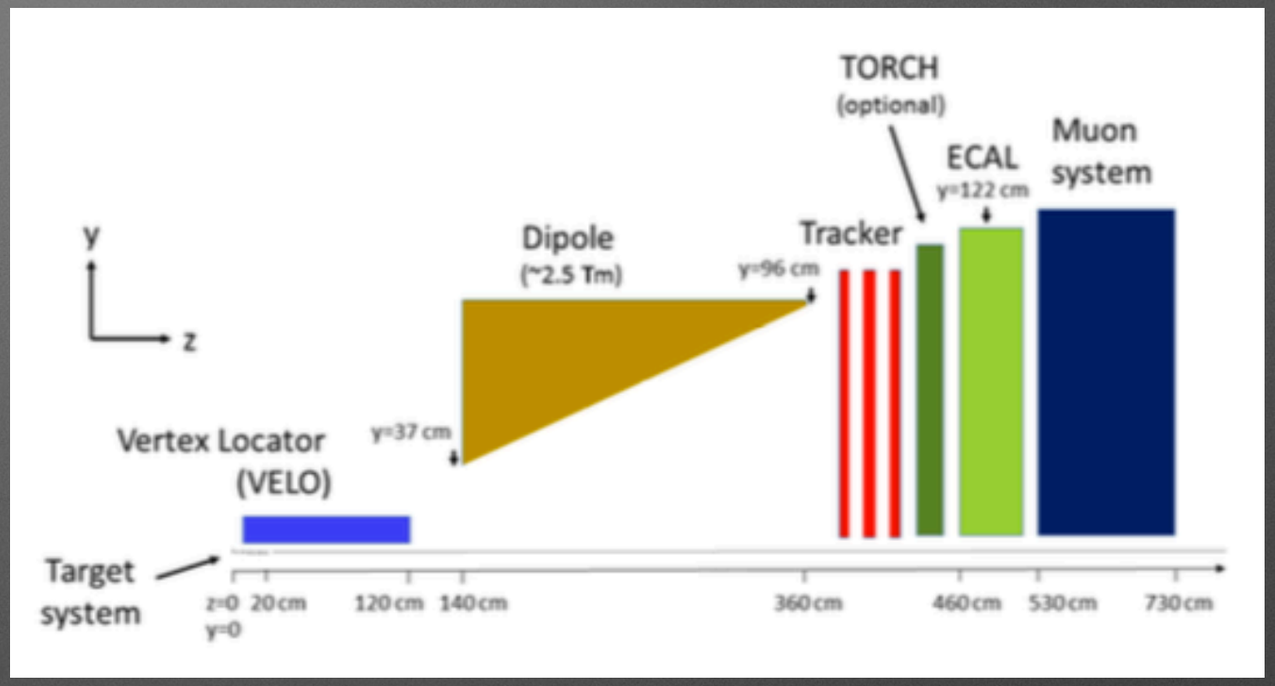
- **Phase I construction:**
  - Support from CG
  - Mu2e and Mu3e supported by STFC project funding
  - *Construction of all three experiments fully funded*
- **Operations**
  - Bid for common fund/engineer, travel and RA support in CG
- **Phase-II less certain (UK, international)**
  - Mu3e-II pixel extension PPRP bid, …??

Future

- **Mu2e Phase II**
  - Presented to FNAL PAC yesterday
  - Timescale ~2030, 10x sensitivity
  - Change targets to allow model discrimination
- **COMET - PRISM**
  - FFAG baseline lattice established, larger acceptance (UK)
  - 100x improvement in sensitivity
- **TauFV**
- **Future “combined facility”…?!?**
- **UK charged lepton “medium” Big Idea proposal**

TauFV





- Dedicated search for $(D_s \rightarrow)\,\tau \rightarrow 3\mu$
- Sensitivity $\sim 10^{-10}$
- Installed at SPS BDF
  - Parasitic to SHiP

Fit in ES

- Smaller, cheaper and faster experiments
- Clear discovery potential
  - No SM backgrounds
- Complimentary to energy frontier
- Maintain breadth and diversity
- Train next generations

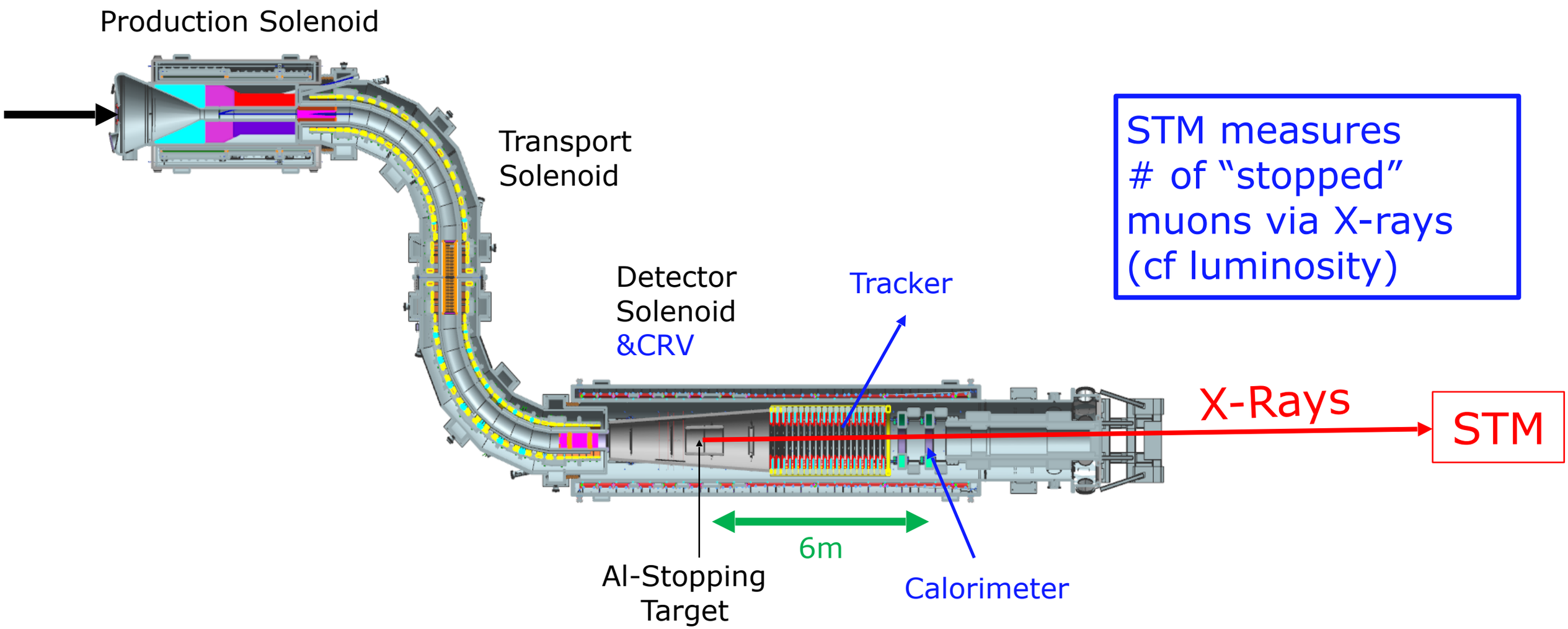
Backup

MU2E (Mark Lancaster)

Mu2e Status

Full-budget ($274M) DOE approved in July 2016.

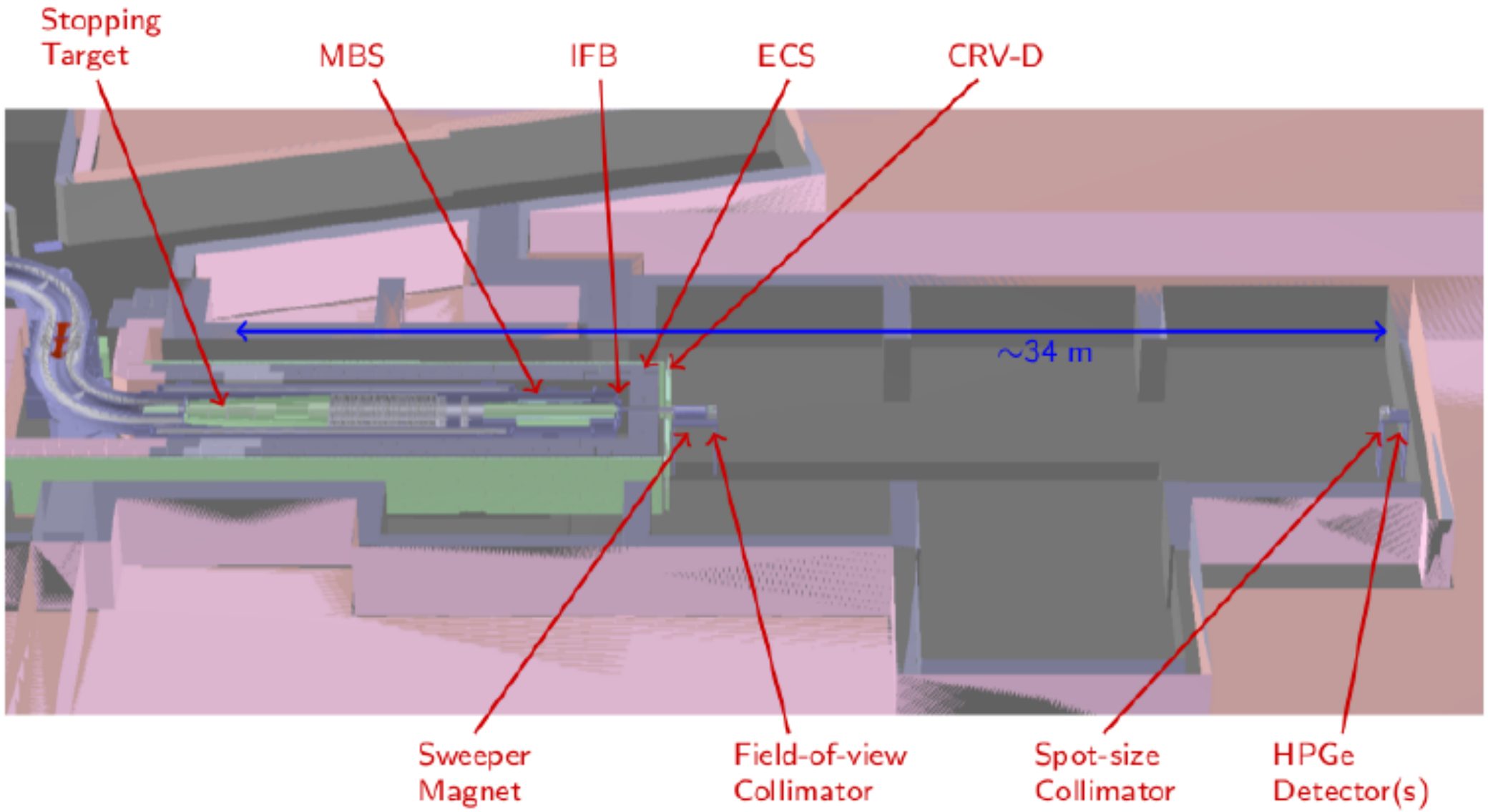
UK PPRP funding from April 2017 – April 2020 to provide the **S**topping **T**arget **M**onitor (STM) & DOE has funded STFC-TD to provide the proton target ($1M).



STM measures # of "stopped" muons via X-rays (cf luminosity)

HPGe STM detector

Located 34m from aluminium target where muons are captured



UK providing detector(s), readout and collimation system.

Mass Production of solenoids/tracker

Mu2e Hall

Transport Solenoid Production

Tracker Production

Production Target

Mu2e-II

arXiv:1802.02599

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

Presented to FNAL-PAC yesterday.

To form part of 2020/P5 & CLFV European Strategy document

Will allow running with different targets

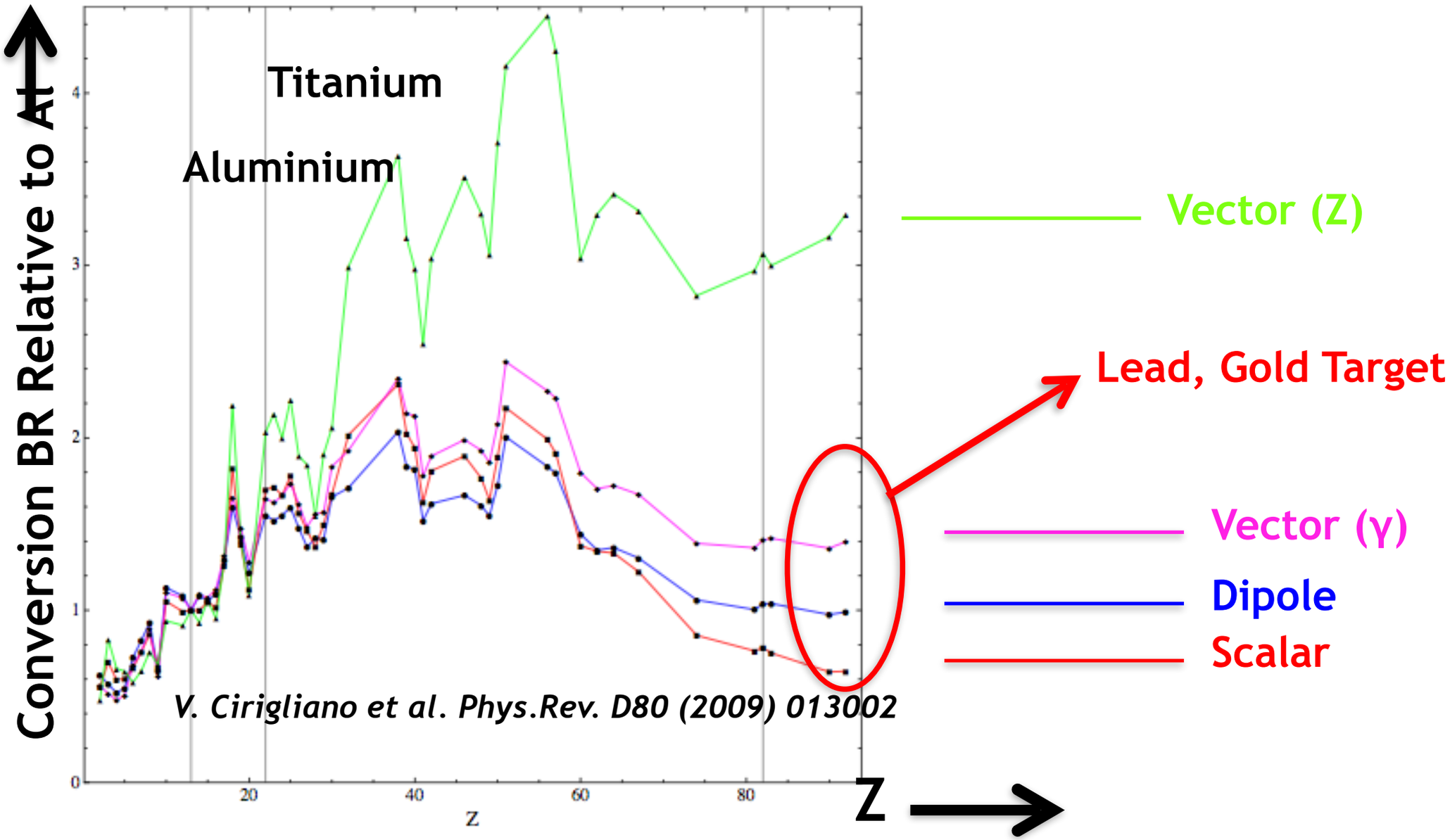
Achieve a sensitivity x10 that of Mu2e.

Timescale: 2030.

Mu2e-II

In event of a signal, Mu2e-II would give x10 stats and running with Al, titanium and gold targets would give sensitivity to BSM interaction type.

In absence of signal improve sensitivity by x10.



Mu2e-II challenges

Challenges:

- high resolution tracking in a v. high-rate environment e.g.
  8μm vs 15μm straws required.
- UK interested in developing ASIC/FPGA tracking.

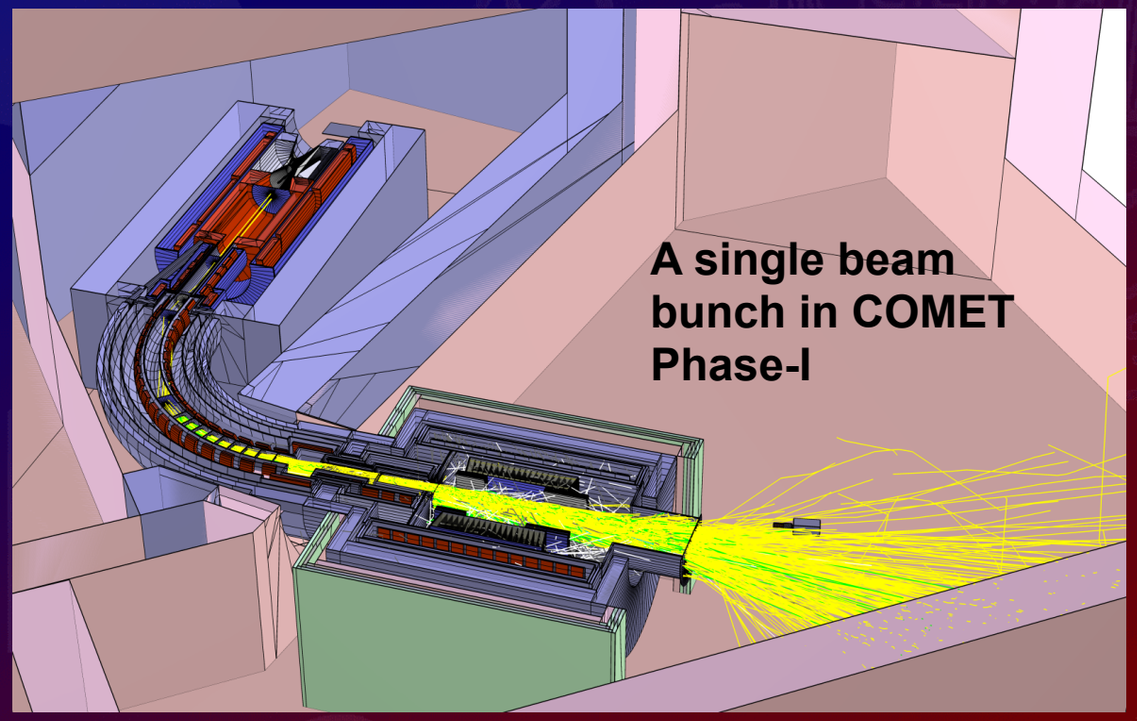
- handling the radiation/power issues from a 100kW (0.8 GeV) PIP-II beam.
  cf. Mu2e (COMET-I) is 8 (3kW).
  Expertise for this is in STFC-TD (C. Densham)

COMET Status

- Phase-I Detector systems approaching completion: physics detector & Phase-II prototypes
- Clarification of schedule by J-PARC/KEK:
  - to ensure Phase-I and II are “competitive internationally”
  - by end of JFY 2019, proton beam line to COMET branch to be completed and detector systems to be ready and tested; beam studies to follow
- PRISM progress
  - New Fixed Field Accelerator ring baseline lattice established with significantly larger horizontal dynamical acceptance

Main drift chamber, in cosmics testing

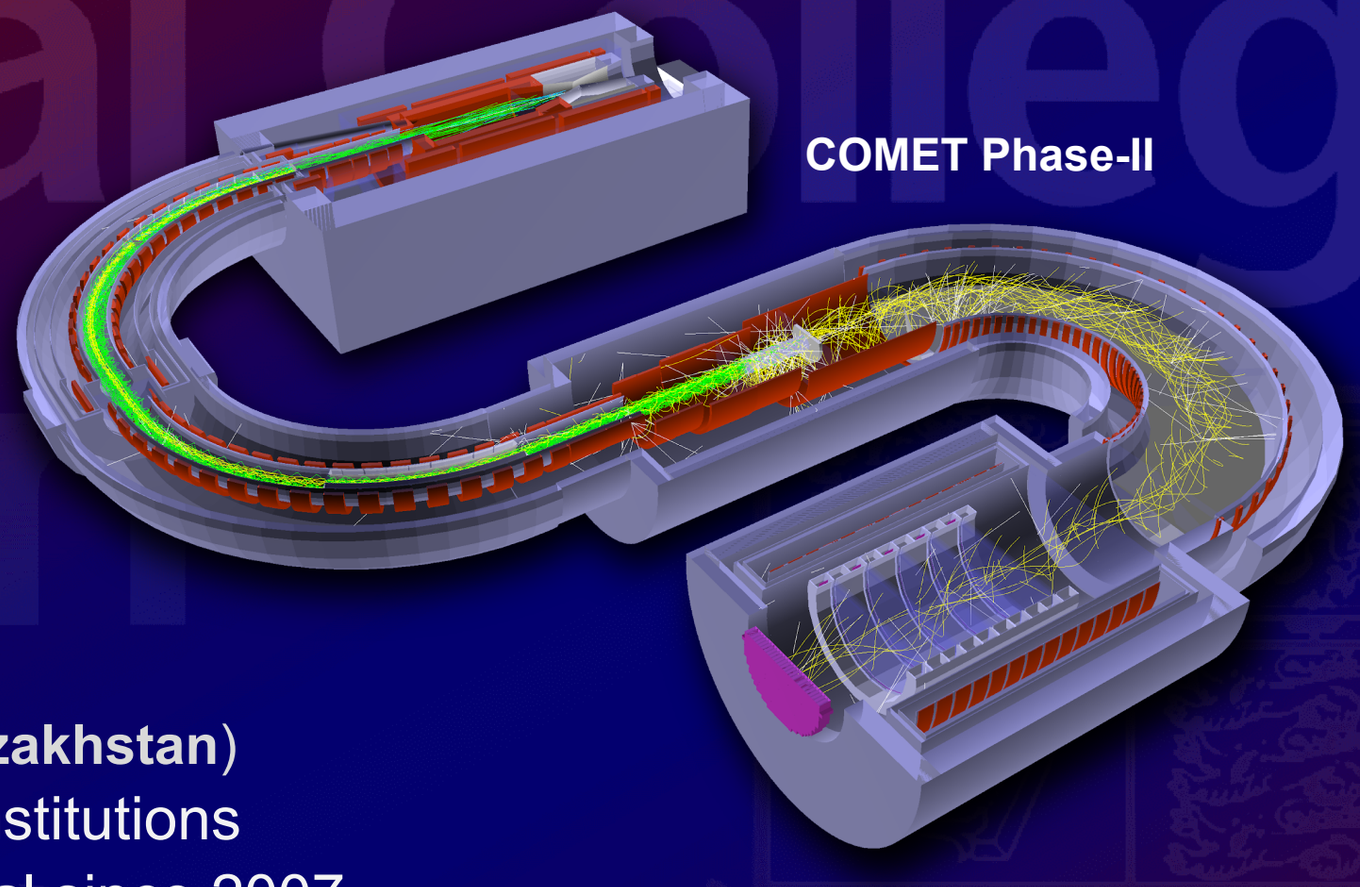
Left: COMET beam line under construction
Far right: existing Kaon beam line



COMET: Medium and Long-Term Plans

- Phase-I (×100 improvement to current measurement)
  - No technical or funding issues to achieve completion
  - UK to continue to lead Software and Analysis efforts
  - UK-designed DAQ and Trigger/Fast Control systems being deployed across subdetector systems
    - approximately 13 FC7 boards being used by collaboration
    - will continue to support subdetector and DAQ systems
  - Further intra-European collaboration with Czech Republic, France, Georgia, Germany
- Phase-II (better than ×10000 improvement)
  - 56kW beam power
  - 6×10^{-17} (90%CL) sensitivity for 2×10^{7} seconds of running
  - Continuing R&D to improve sensitivity beyond current design
  - Start construction soon after Phase-I running
- PRISM (a further ×100 improvement)
  - Long-term plan for muon-to-electron conversion, using PRISM FFAG storage ring
  - R&D by UK-led PRISM Task Force

COMET Funding



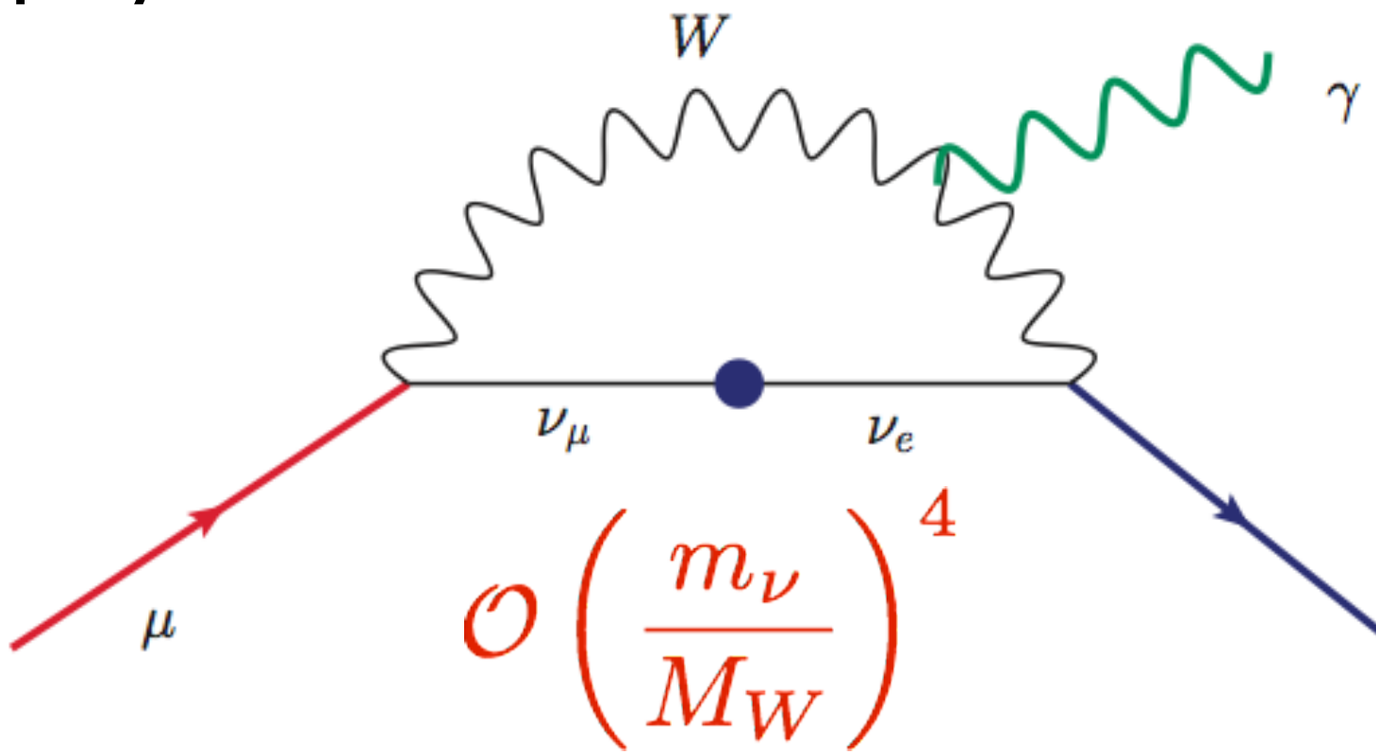
- Collaboration growing
  - New institutions in past year:
    - Monash (**Australia**)
    - Caen (**France**)
    - Clermont Ferrand (**France**)
    - Sun Yat Sen University (**China**)
    - Institute of Nuclear Physics (**Kazakhstan**)
  - Now at 16 nations + JINR, 40+ institutions
  - UK with participation from Imperial since 2007
- Phase-I: All funding secured to Phase-I completion
  - Recent funding news:
    - German funding granted through to Phase-II (one institution)
    - France to become official IN2P3-funded experiment (four institutions)
- UK Leadership
  - European coordination (funding, European Strategy)
  - TDR executive editor (for publication)
  - Collaboration Board Chair (also Executive Board member)
  - Analysis and Software working group leadership

GENERAL STUFF (Mark L)

Why cLFV ?

Rate in SM is O(10^{-50}) per muon capture

Observation **IS** new physics



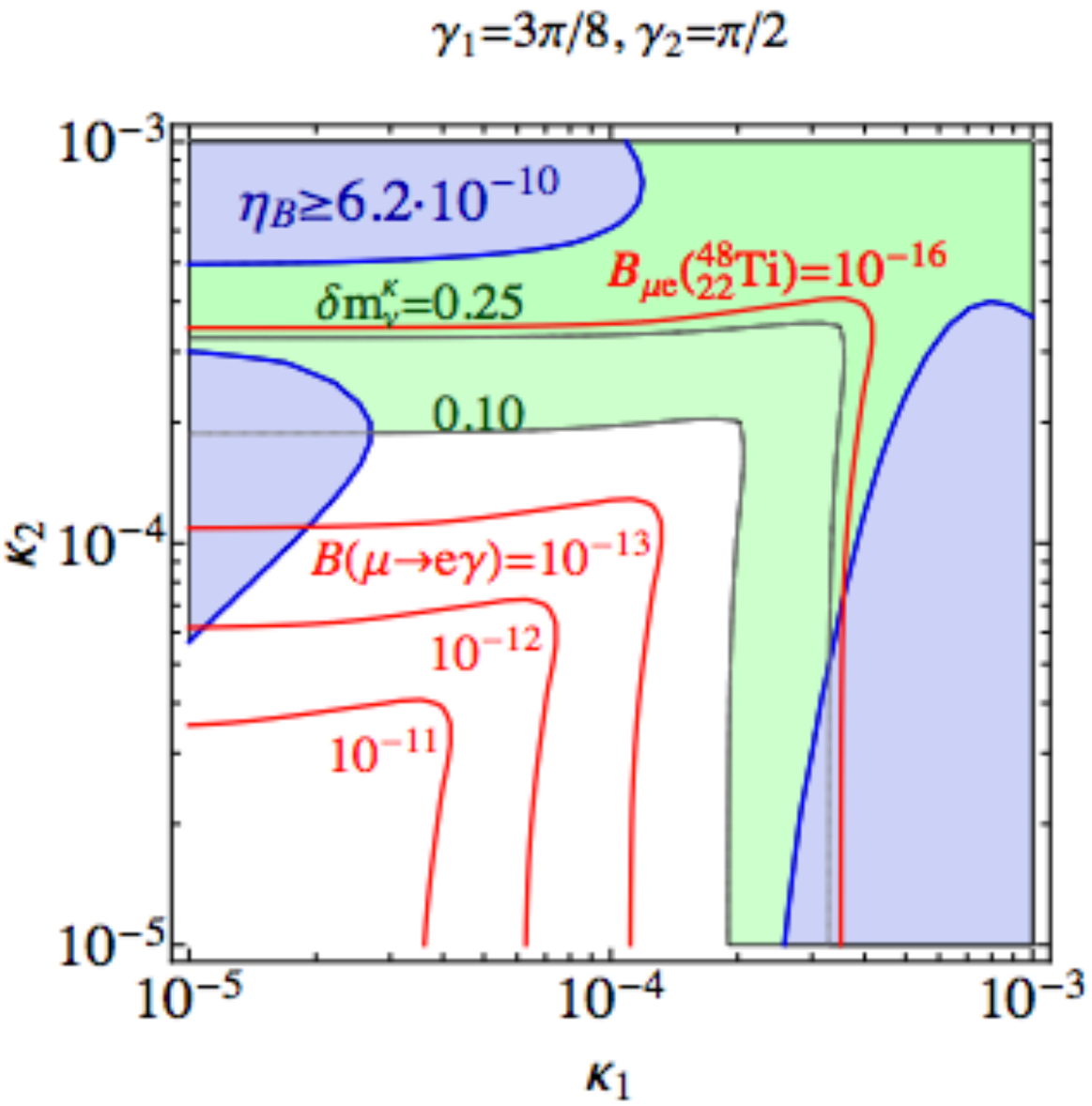
No SM theory systematic

How far we can probe is limited by experiment

Why cLFV ?

No new physics observed coupling to quarks at LHC

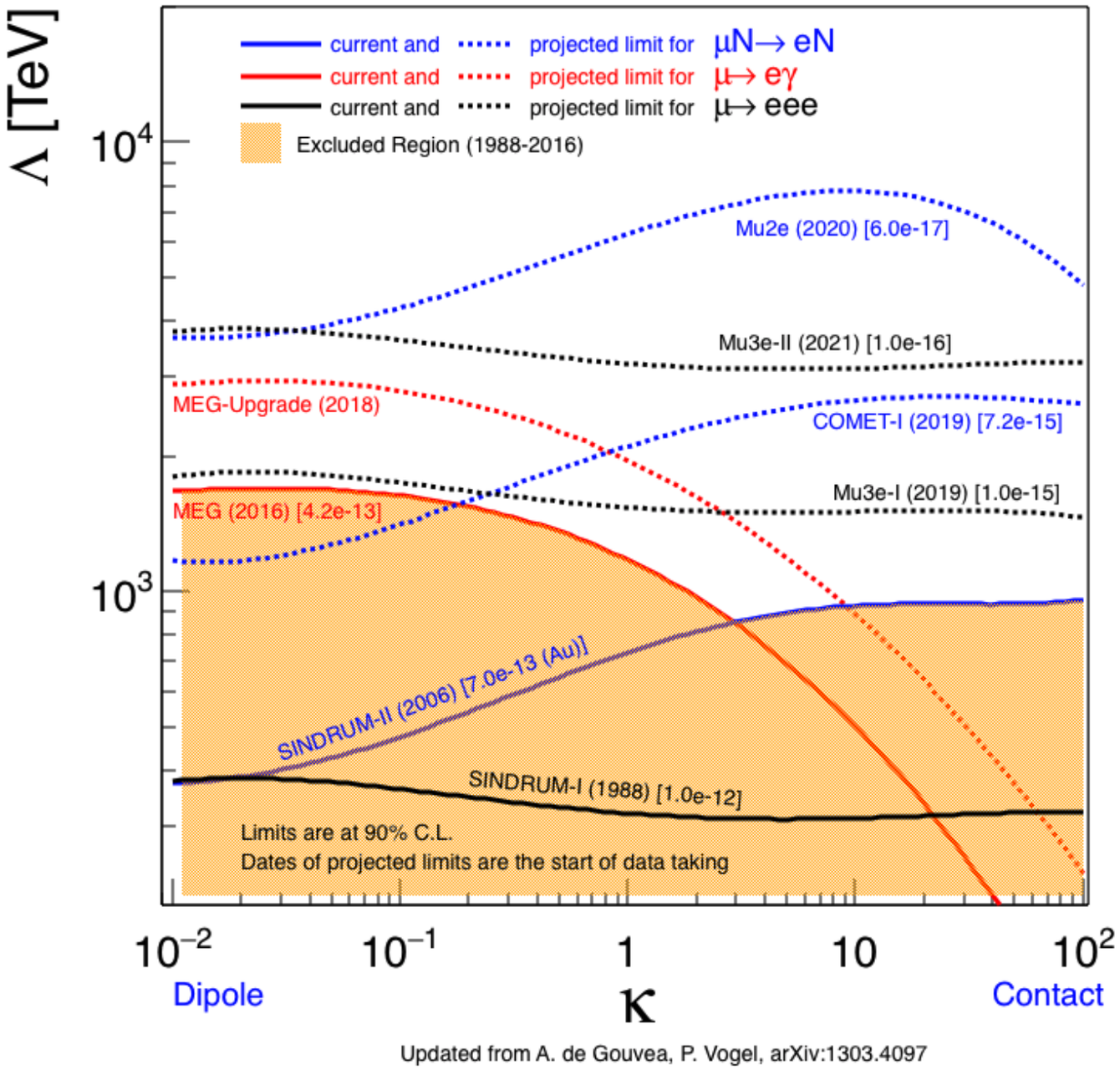
In light of ν-oscillations: is the lepton sector different ?



Gives a portal to the physics potentially explaining anti-matter asymmetry through leptogenesis

Why cLFV ?

Access to mass scales beyond that probed by ATLAS/CMS

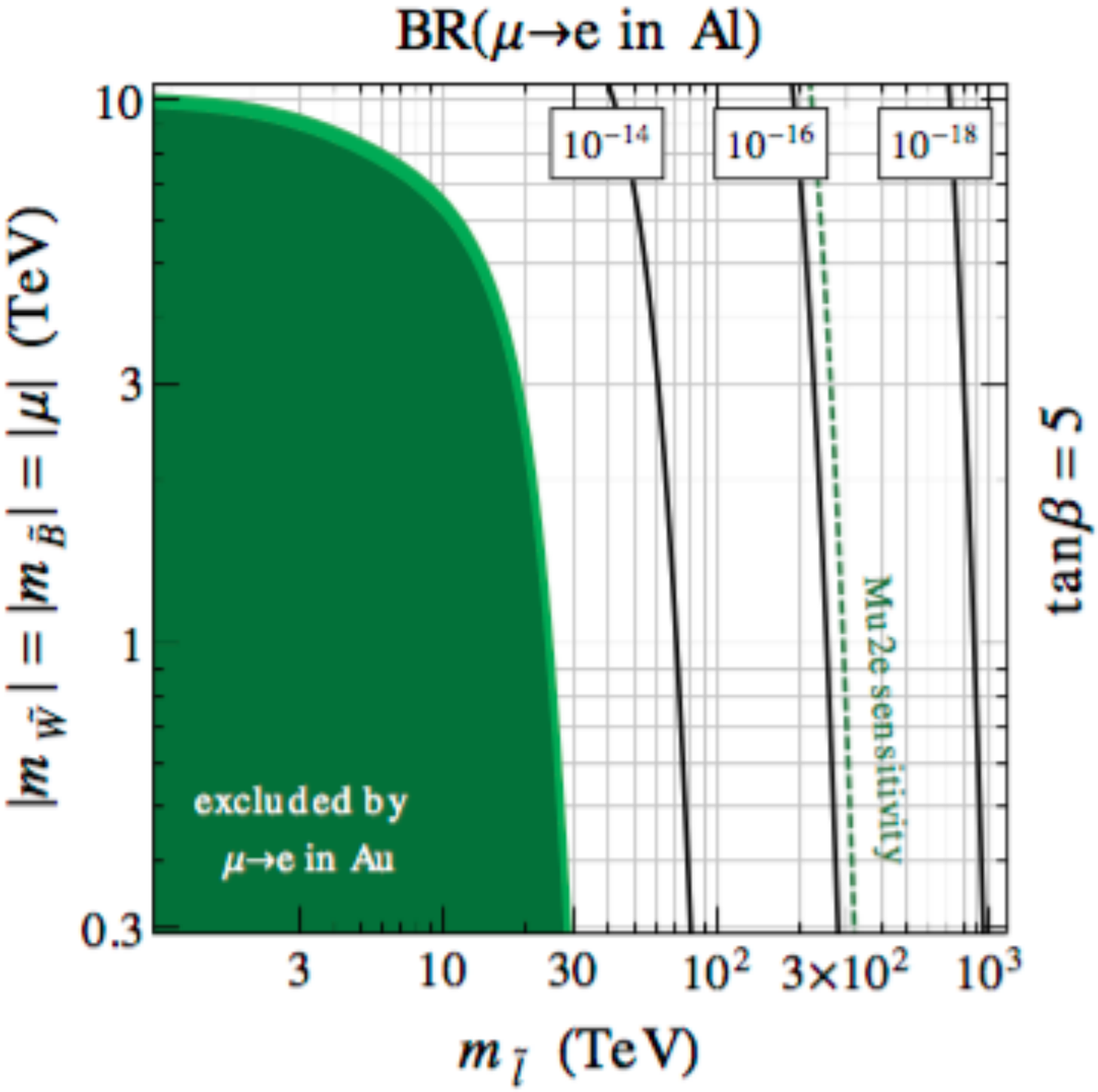


Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

Scales of upto 8000 TeV for unity coupling

Mu2e/Mu3e will extend mass reach by factor of 5 compared to MEG

An example: split SUSY



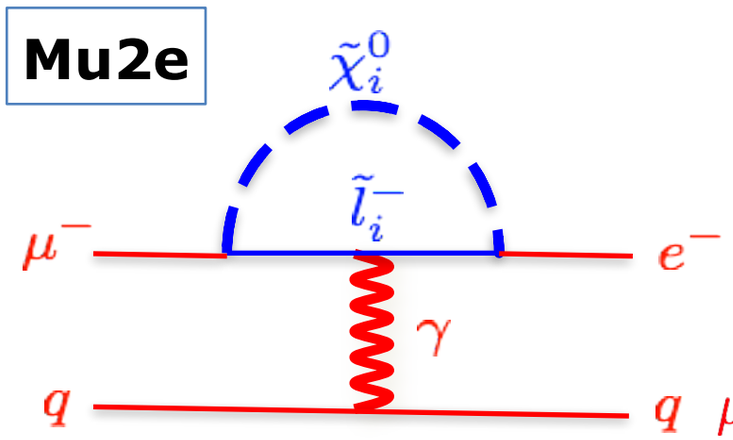
Slepton masses of 300 TeV probed in "Split-SUSY" model.

Present ATLAS direct search limit is 0.6 TeV

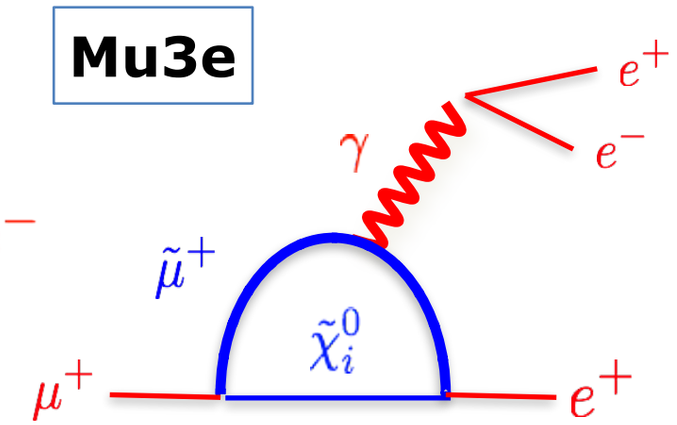
Complements LHC at higher scale

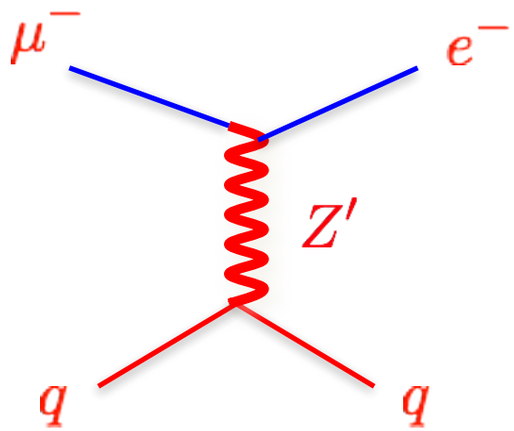
Probing similar range of BSM interactions as LHC

Mu2e

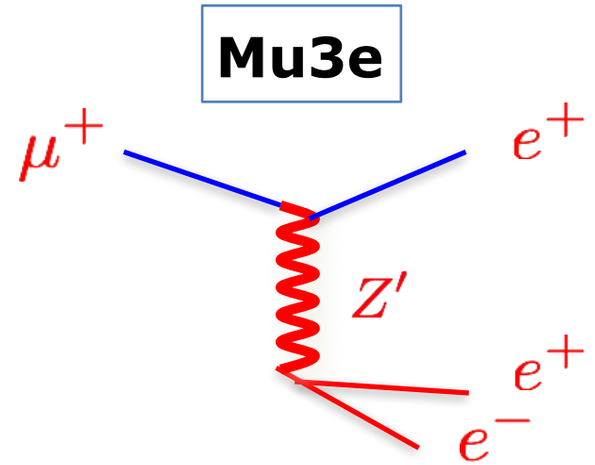


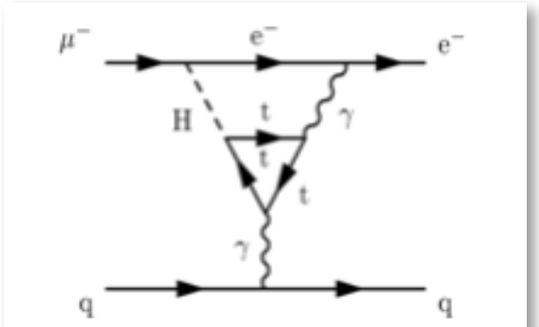
Mu3e



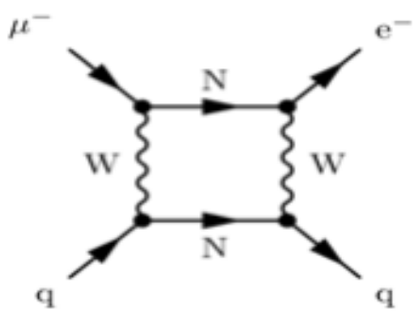


Mu3e





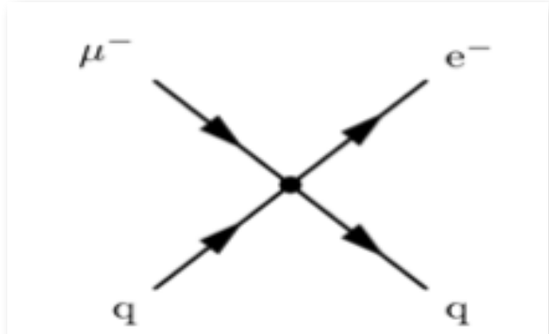
Second Higgs Doublet



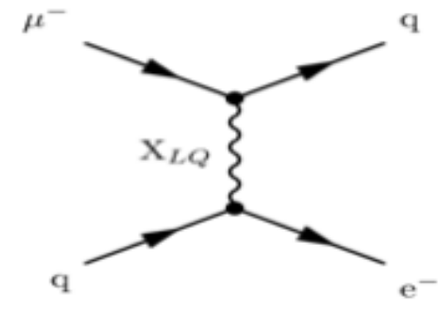
Heavy Neutrinos

Mu2e

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



Compositeness



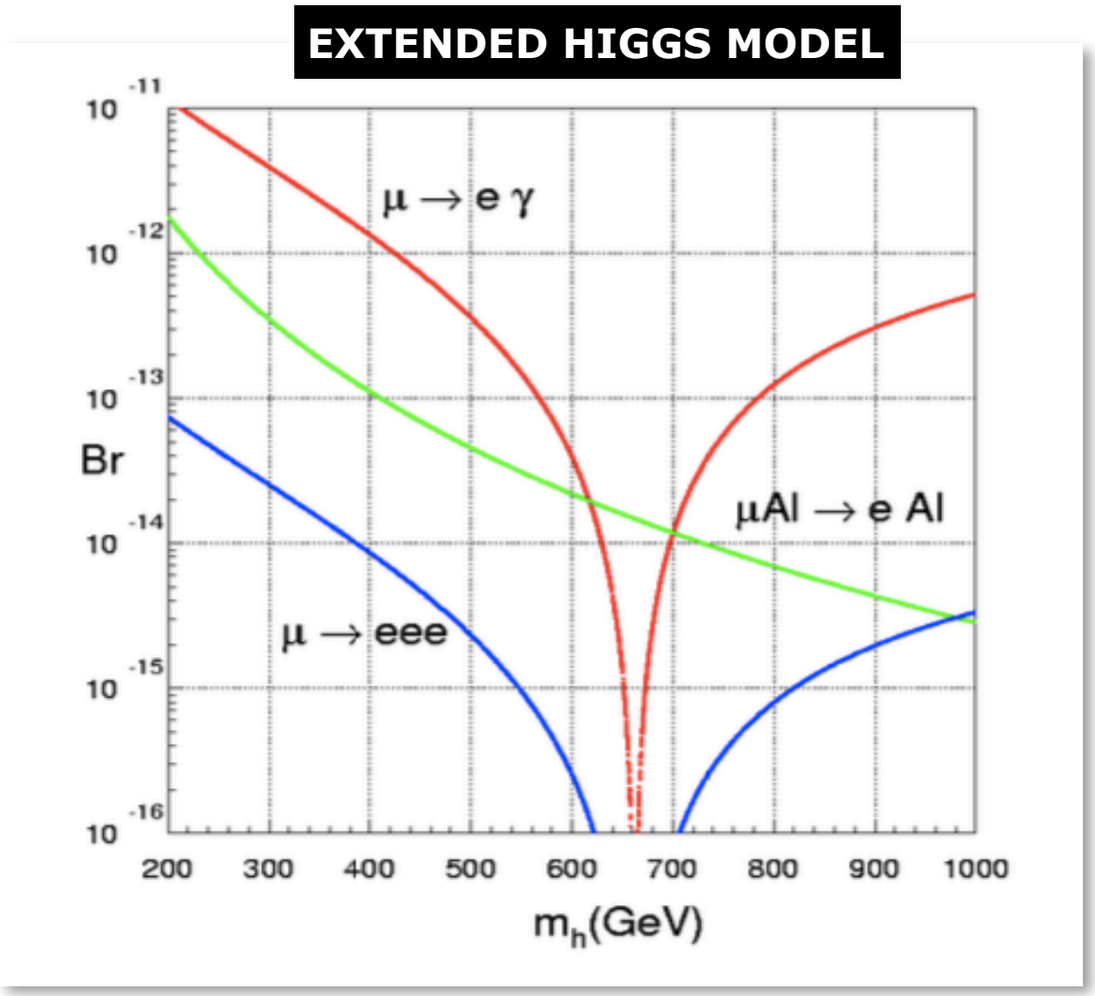
Leptoquarks

Why MEG, Mu2e and Mu3e ?

Ratio of the 3 different CLFV processes is model dependent and BR (ratios) depend on model parameters.

Mu2e probes: lepton and quark BSM couplings; Mu3e only lepton

Both probe non-dipole/loop interactions that MEG doesn't.

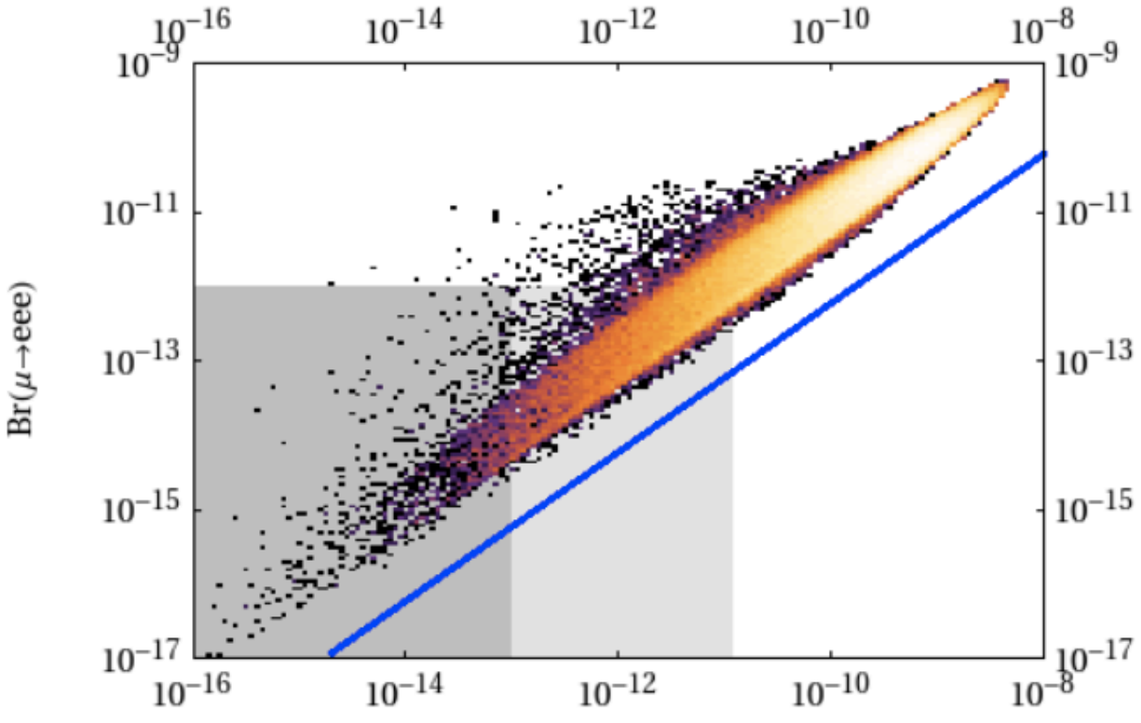


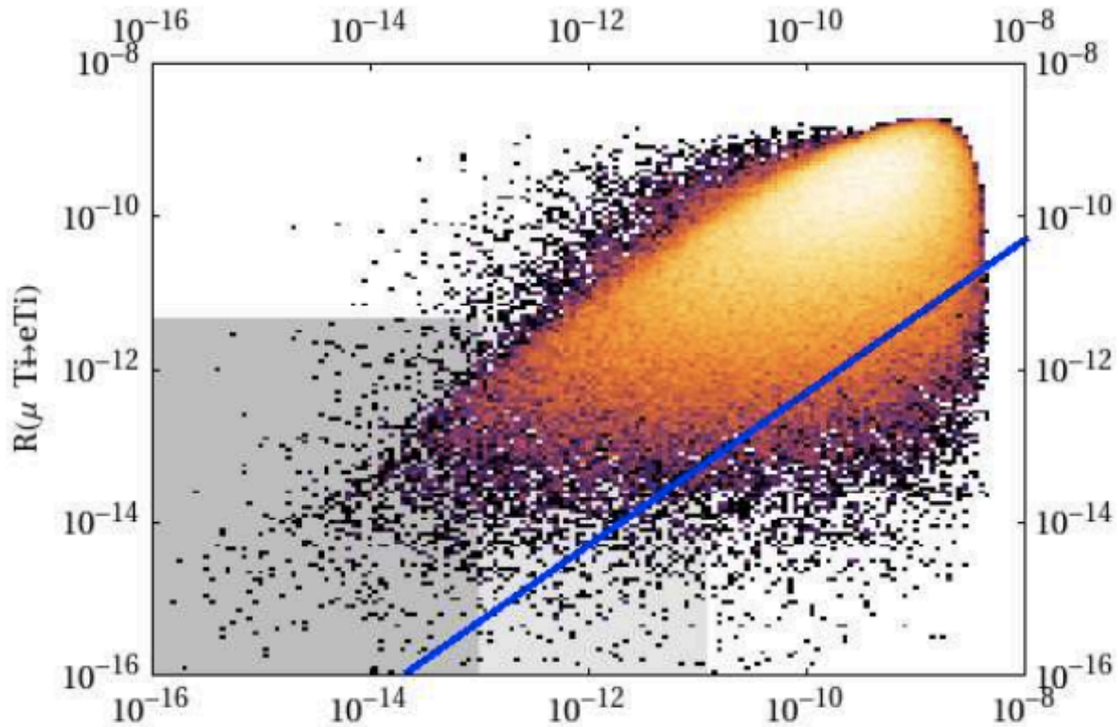
Important to make all 3 CLFV measurements.

Mu2e and Mu3e together provide the most detailed study of cLFV in next 10 years.

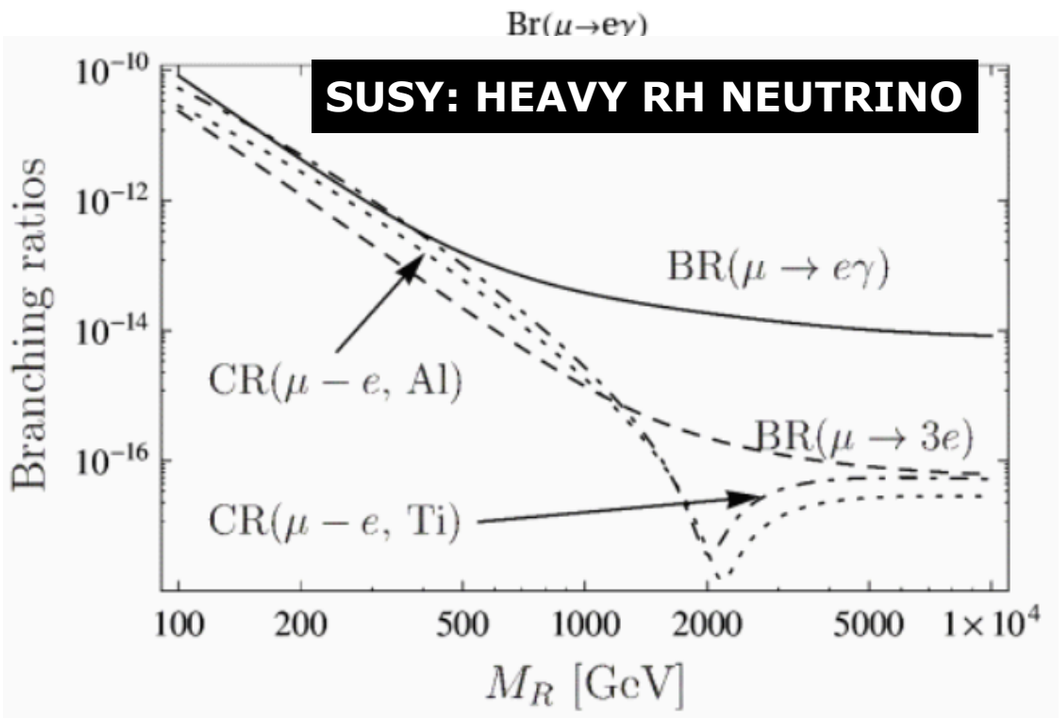
Model Dependence

LITTLE HIGGS MODEL

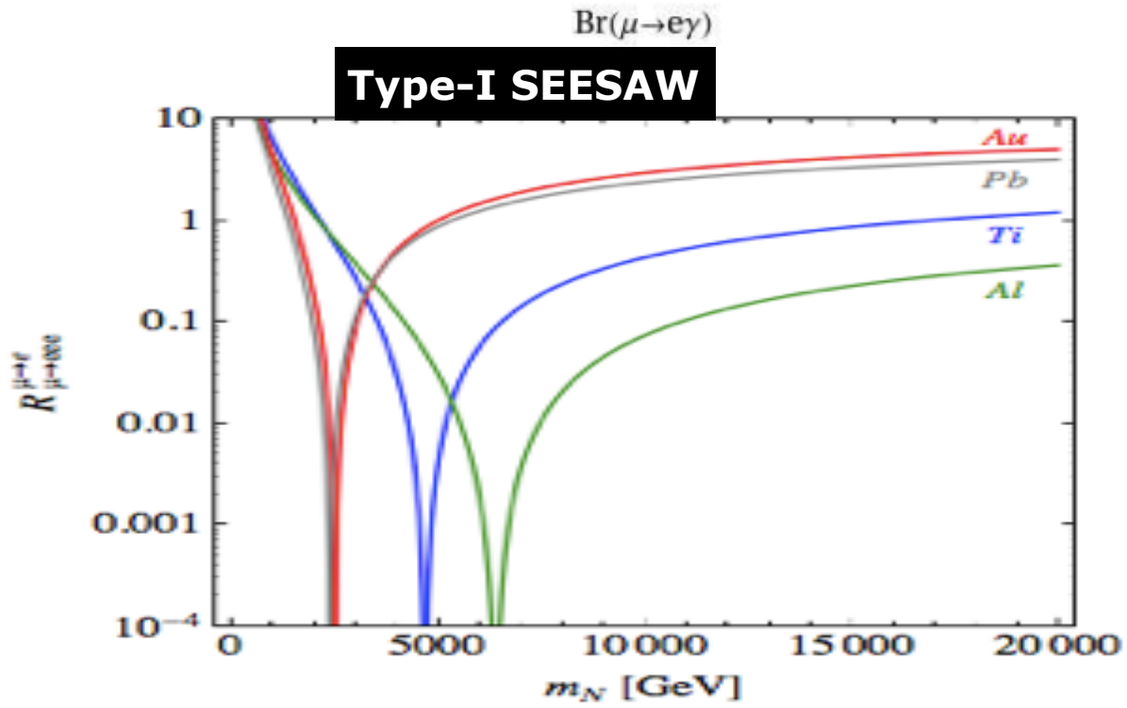




SUSY: HEAVY RH NEUTRINO

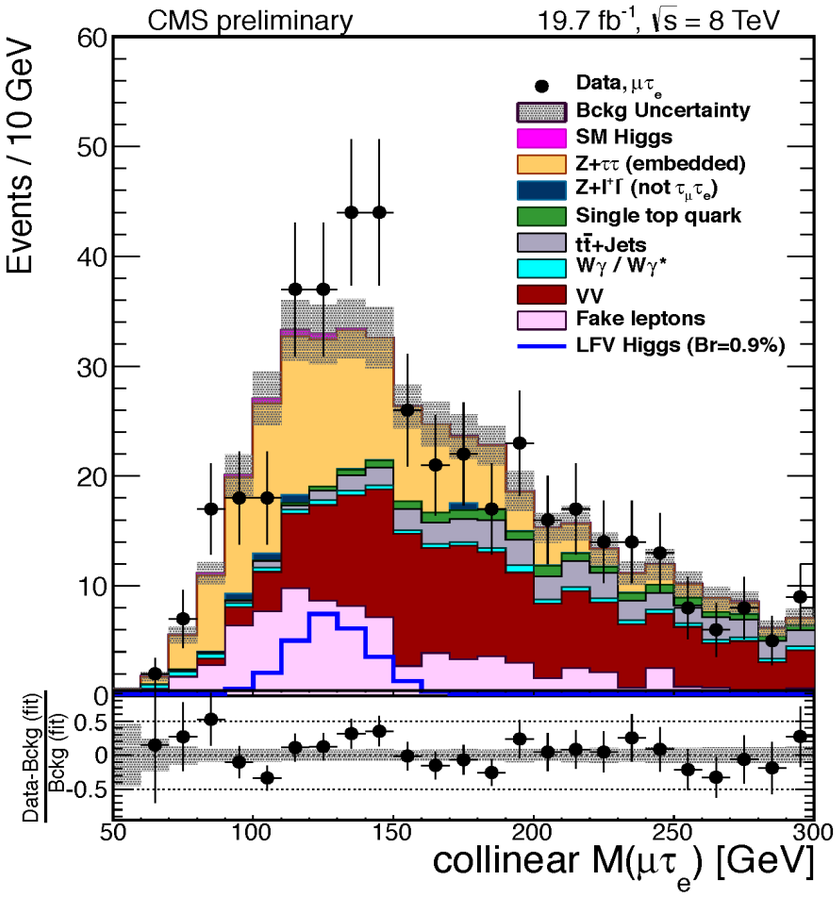


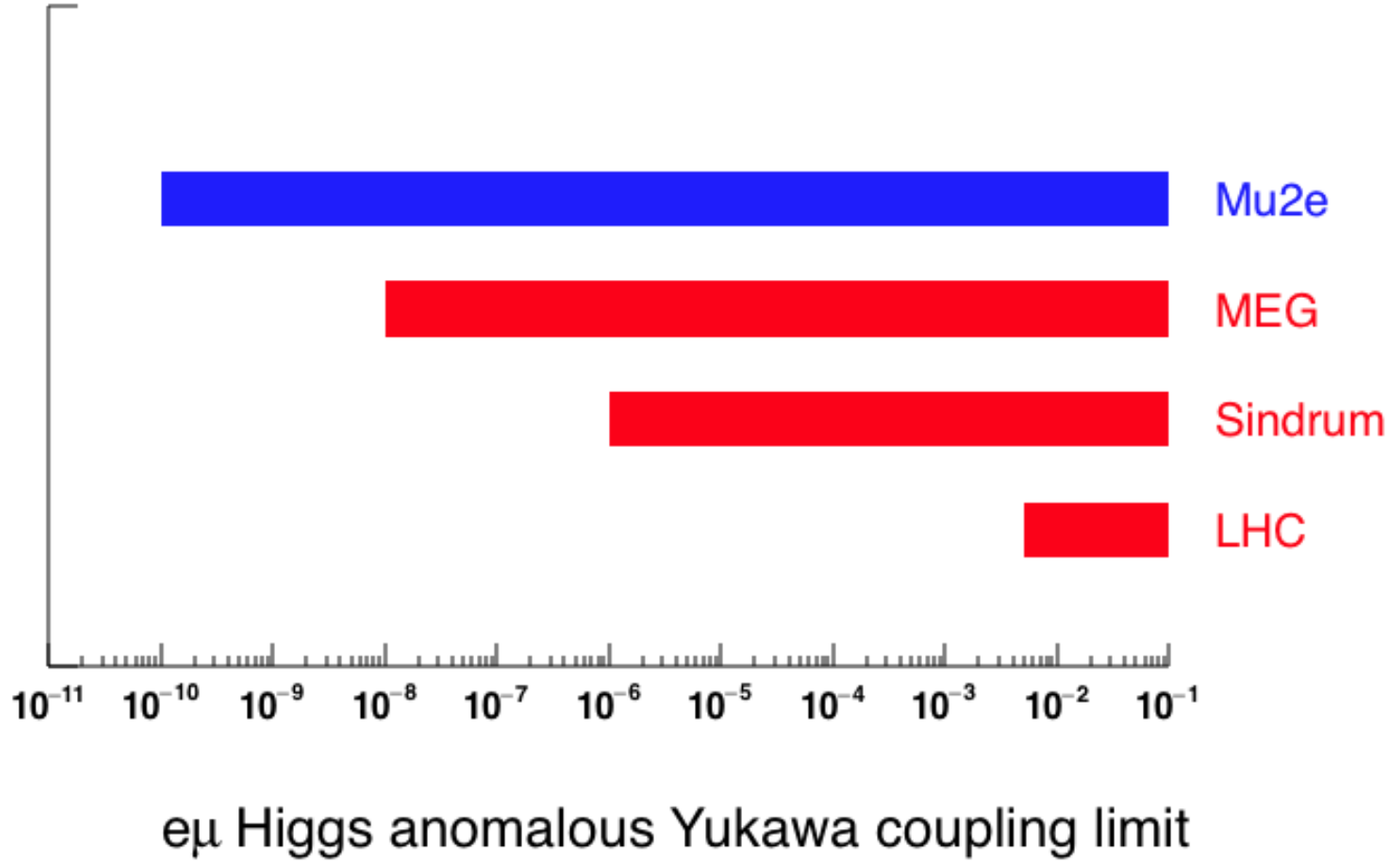
Type-I SEESAW



Anomalous Higgs Couplings

Aswell as probing extended Higgs: also probe FV Higgs couplings





Possible since Mu2e/Mu3e utilise 10^7 – 10^{10} muons/sec

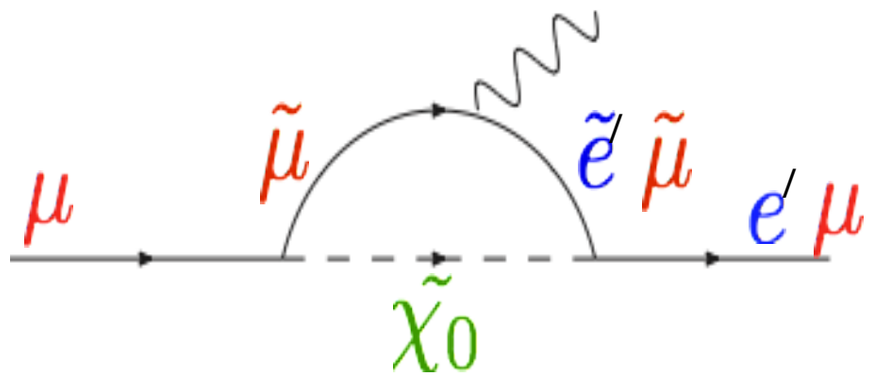
Extend sensitivity by 8 orders of magnitude vs LHC

Synergy with g-2

For BSM dipole interactions e.g. SUSY

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

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



But no theoretical motivation for any particular $\theta_{e\mu}$ value.

If g-2 anomaly is confirmed then we have evidence for a BSM Muon interaction

Need **both** measurements to resolve model degeneracy

Reconciling $(g-2)_\mu$ and charged lepton flavor violating processes through a doubly charged scalar

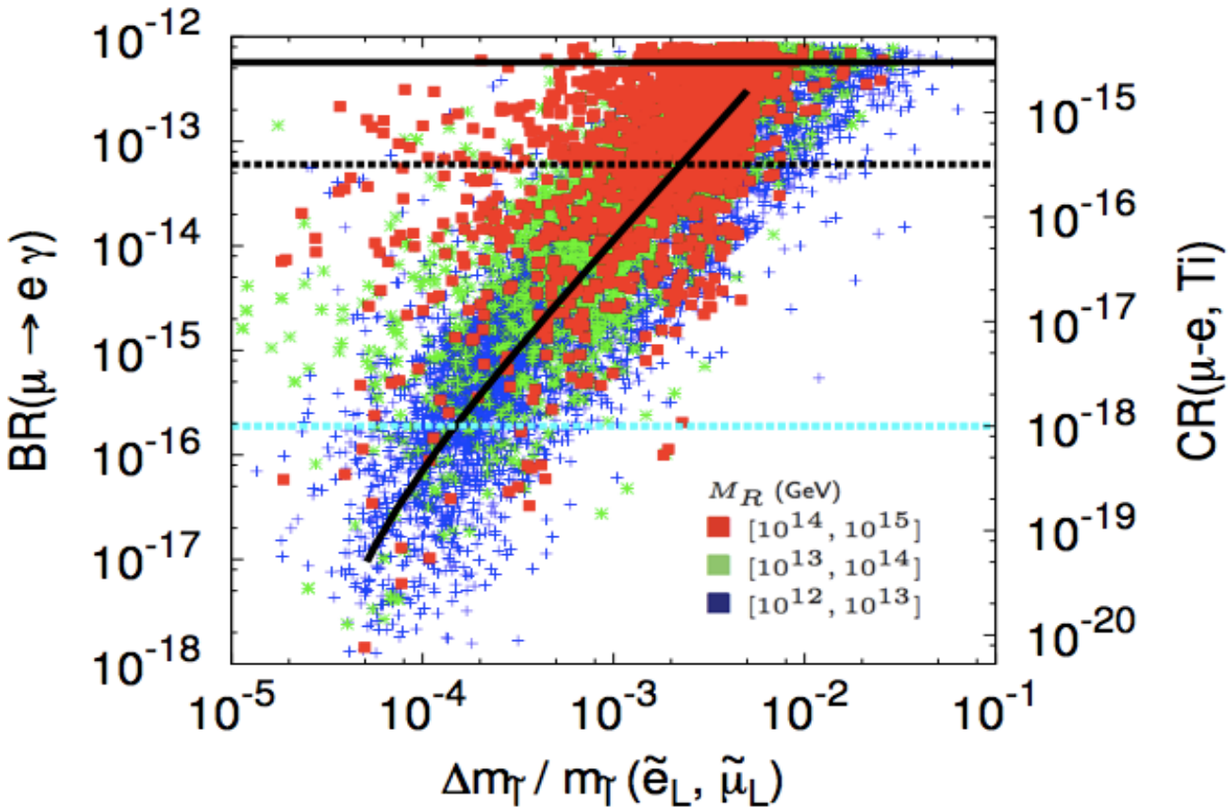
Joydeep Chakrabortty, Pradipta Ghosh, Subhadeep Mondal, and Tripurari Srivastava
Phys. Rev. D **93**, 115004 – Published 3 June 2016

Physics summary

The two major research themes in the UK:

- BSM searches and Higgs physics at the LHC
- Neutrino mass hierarchy and CPV in neutrino sector

are <u>both</u> extended and complemented by Mu2e/Mu3e



If new physics is observed at the LHC, Mu2/3e is critical to elucidating degenerate models

If the new physics is at a higher scale then Mu2/3e can probe it

Imperial College London

COMET Update for PPAP/

July 2018

Yoshi Uchida