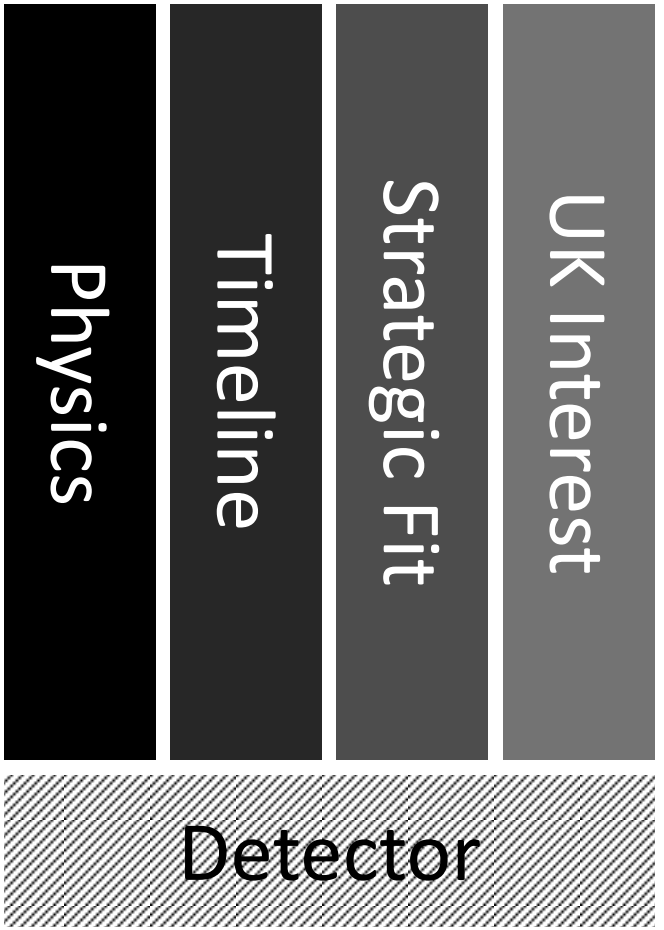
Precision Lepton Measurements

Physics to the PeV Scale

Themis Bowcock

Smörgåsbord

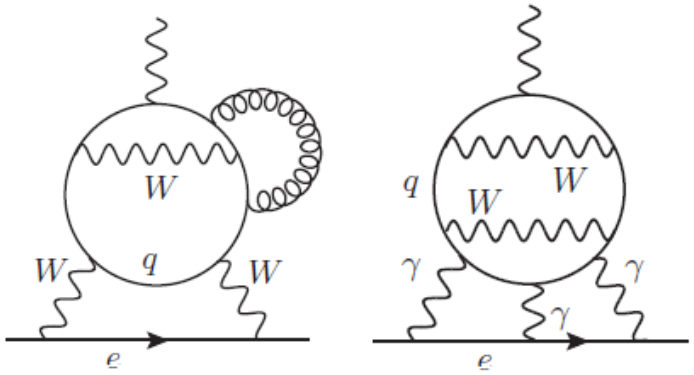
- srEDM
  - muEDM*
  - eEDM (prototype pEDM)
- Lepton Rare Decays
  - mu3e
  - mu2e*



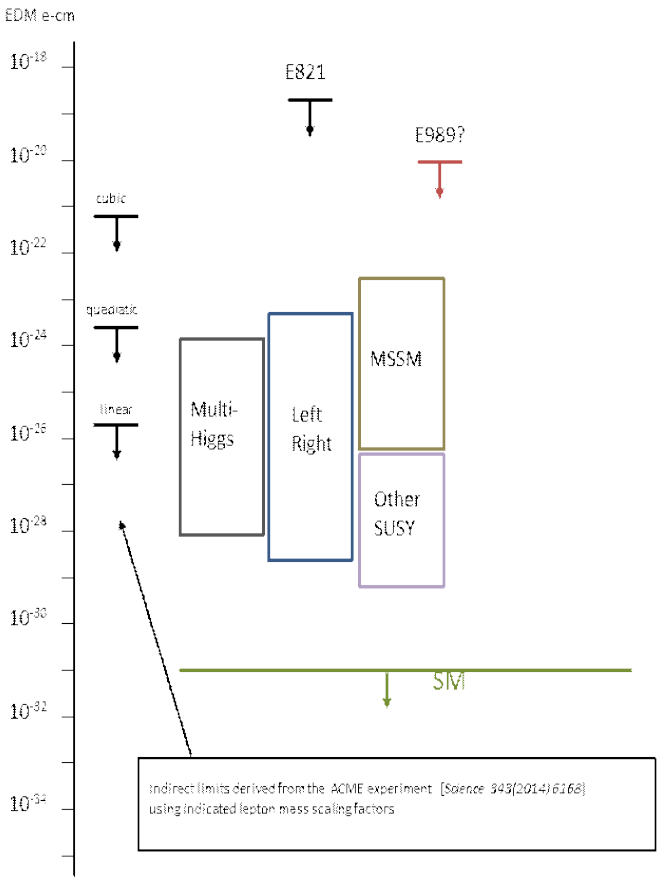
muEDM@FNAL

Physics

- Phase-I Part of g-2 experiment (first measurement)
  - No additional cost to STFC !
- see anything in muons, sign of new physics
- $|d_e| < 10^{-29}$ e cm, the current results, for 2nd generation muons 10 orders of magnitude worse, $|d_\mu| < 1.8 \times 10^{-19}$ e cm
- *g-2@FNAL will get improve this by two orders of magnitude*



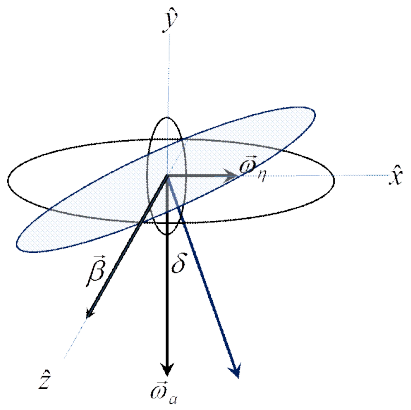
Examples of a 4-loop diagram, the lowest order contributing to lepton EDMs in the Standard Model, and 5-loop diagram

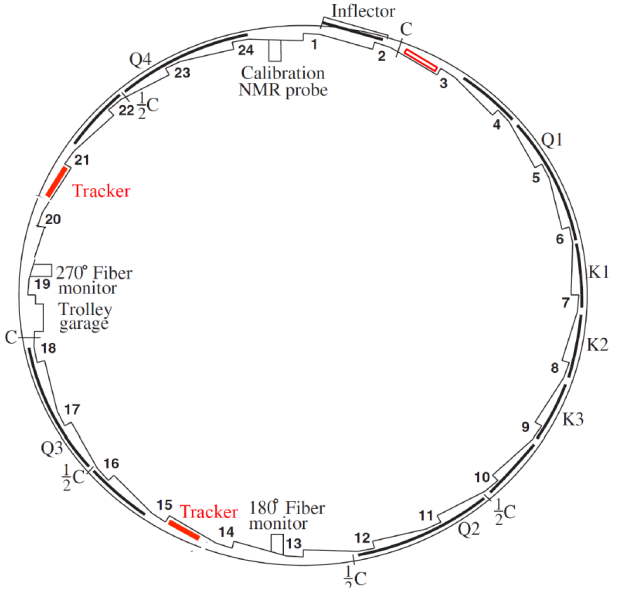


Workshop happening right now at Oxford!

Muon EDM

What do we measure?
Tilt in precession plane





- Oscillations out of the plane
- Tracker Technique used by E821
- UK Trackers are a unique opportunity

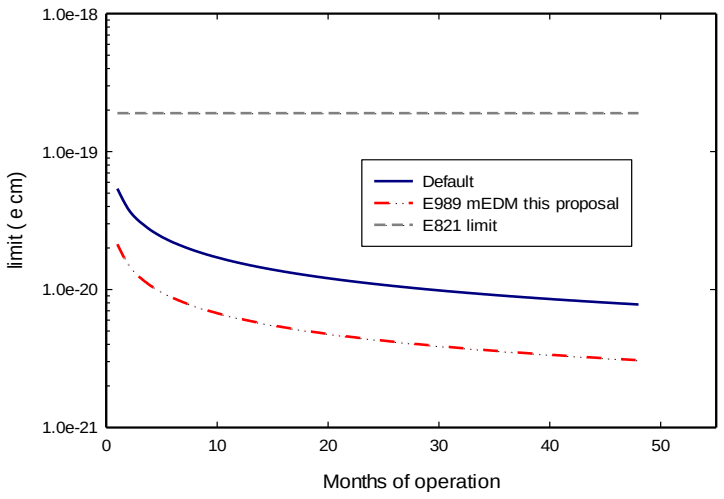
When?

- 2017 (first data) and updates BUT …
- Improvements (this method) depend on two factors (Phase II)
  i) Statistics (number of trackers)
  ii) Performance of the trackers

R&D for update

Timeline

- *Replace straws with ultra-compact tracking stations* (HV-CMOS) O(20) stations (from 3)
- Could also improve g-2 itself by 2018/2019



Improved systematics could yield almost an additional order of magnitude

Aim for $|d_\mu| < 10^{-21}$ e cm

Build prototype 2016

Why?

- HV-CMOS trackers of large interest for the future (ATLAS, ILC, …)
- This could be the first deployment in “anger”
- Improve existing amazing sensitivity to anomalous magnetic moment of muon and muon EDM.

Team

UK Interest

- For baseline mEDM (now)
  - Oxford
  - Liverpool
  - UCL
- Support from experiment extension with compact tracker(s)
  - All welcome!
  - UK could do it all

proton
storage ring
EDM

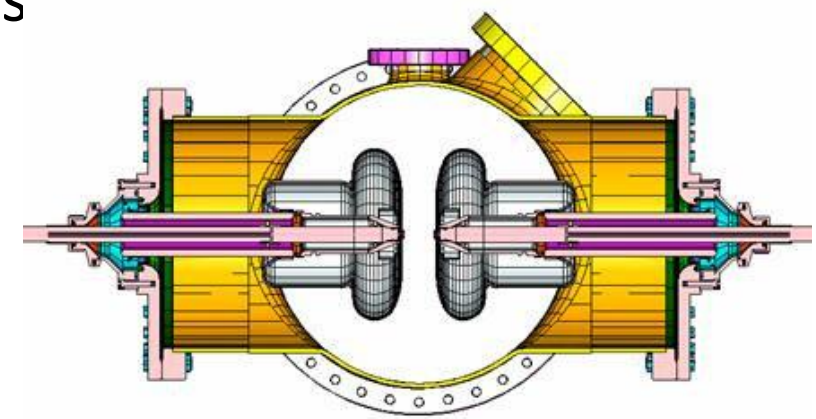
e(p)EDM

Detector

- eEDM is a prototype for a pEDM experiment
- Ideas from same original g-2 team
- pEDM “like” g-2 but ALL electric
  - Counter rotating beams enable huge cancellation of systematics
  - Study polarization of protons

2014 received P5 support under all scenarios

Marciano estimates physics reach ~ 3PeV

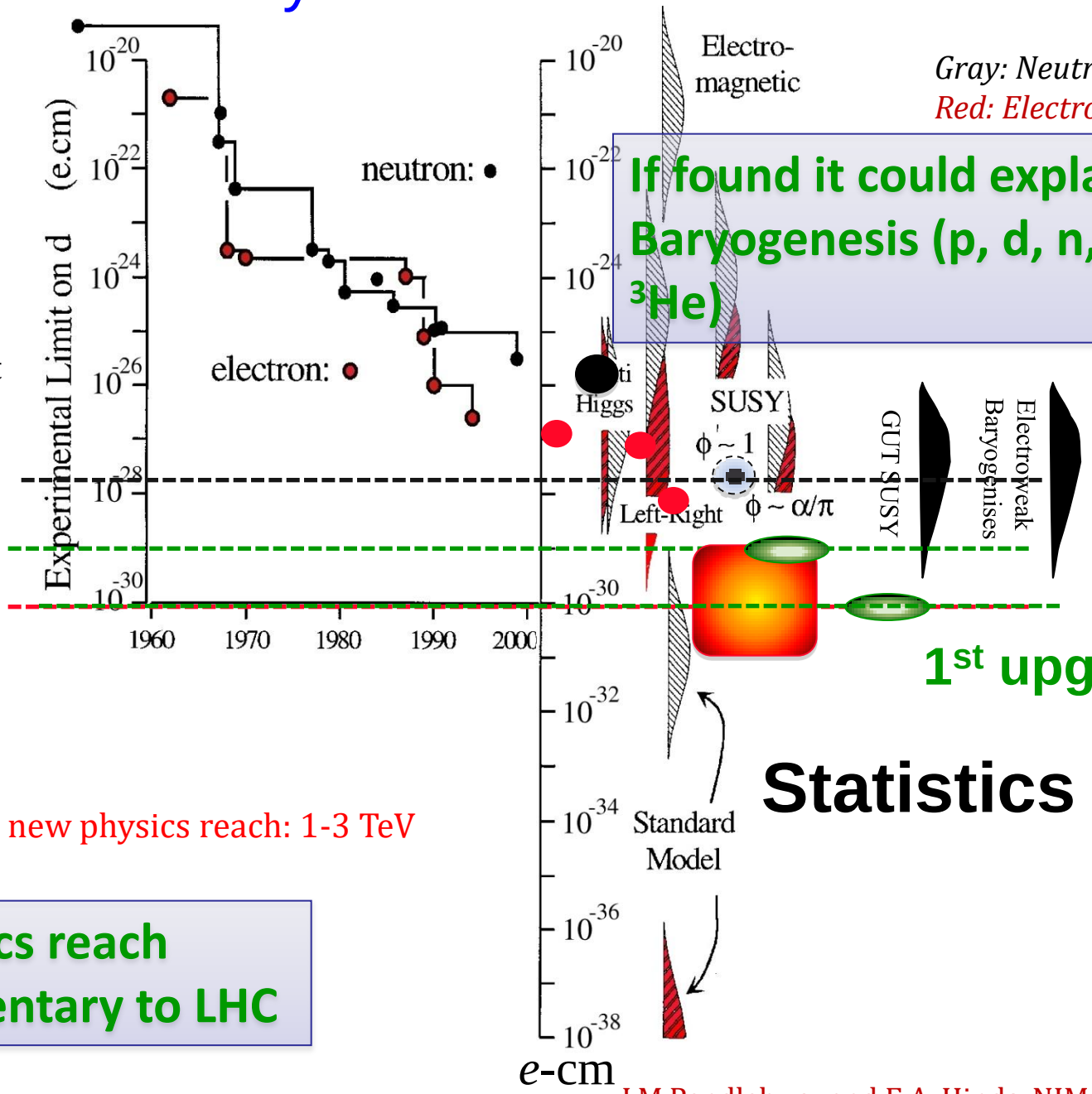


Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal [e·cm]	Neutron equivalent physics
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<3\times10^{-29}$	$<10^{-29}$	10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-29}$-10^{-31}	10^{-25}-10^{-27}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$<10^{-29}$	10^{-29}

Sensitivity to Rule on Several New Models

Physics



Gray: Neutron
Red: Electron

If found it could explain Baryogenesis (p, d, n, ^{3}He)

1st upgrade

Statistics limited

Electron EDM new physics reach: 1-3 TeV

high physics reach
Complementary to LHC

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

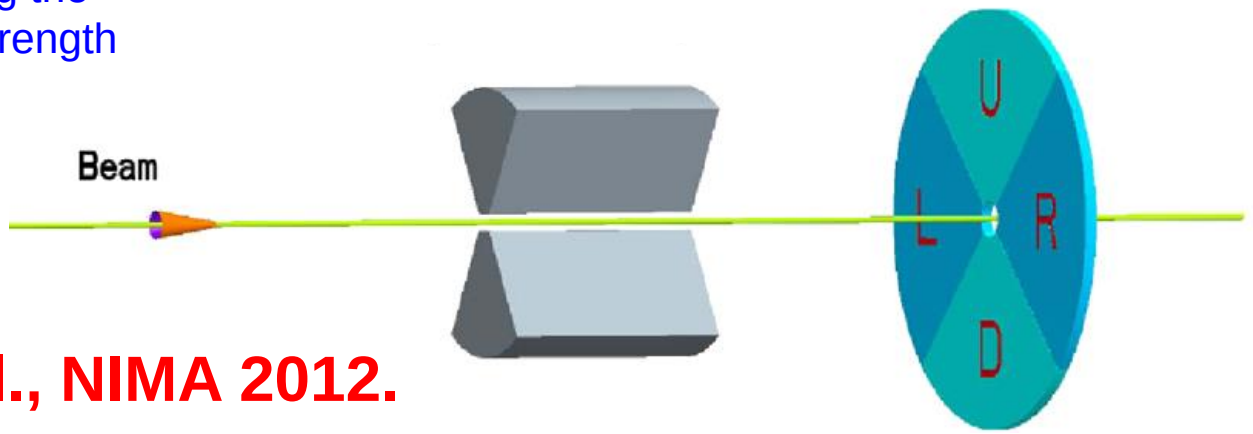
proton storage ring EDM

pEDM polarimeter principle (placed in a straight section in the ring): probing the proton spin components as a function of storage time

Detector

"defining aperture" polarimeter target

Extraction: lowering the vertical focusing strength



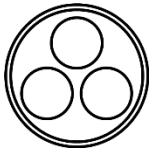
Brantjes et al., NIMA 2012.

$$\varepsilon_H = \frac{L-R}{L+R}$$

carries EDM signal
increases slowly with time

$$\varepsilon_V = \frac{D-U}{D+U}$$

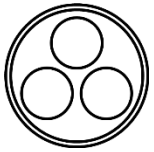
carries in-plane (g-2) precession signal



proton
storage ring
EDM

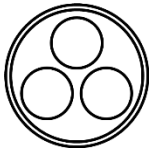
Timeline

- "All" technical problems solved for pEDM (TDR writted)
- Host (*was* to be BNL)
  - $50M
  - Could be built in 5-10 years
  - Discussions with labs
- Demonstrator with electrons (few $M) Mostly for electric deflectors & sextupoles, control system,
  - eEDM (mixed electric/magnetic)
  - Compact (room size)
  - But only gets to 10^{-29}ecm



What's in it for the UK

- Physics
- For a low cost (one or two staff) we could land the contract (>> $10M) for the electrostatic deflectors
  - HV technology (for accelerators)
- The active element (polarimeter) in pEDM case can be Si and have huge technical advantage over existing COSY@Juelich device
  - "Simple". Can be delivered in months.



proton
storage ring
EDM

New idea in UK

- pEDM (Cockcroft, Liverpool, UCL)
  - All welcome (invite Yannis Semertzides)
- eEDM
  - Very recent idea (Royal Holloway, +…)
  - (Special polarimeter non-suitable for Si)

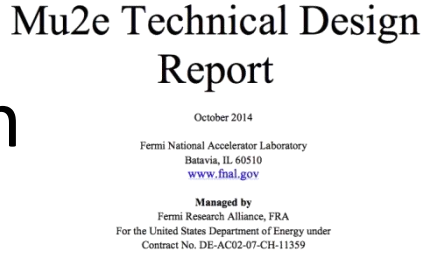
CLFV/mu2e

Physics

What is Mu2e?

A search for Charged-Lepton Flavor Violation

$\mu^- N \rightarrow e^- N$



U.S. DEPARTMENT OF ENERGY | Office of Science INFN Fermilab

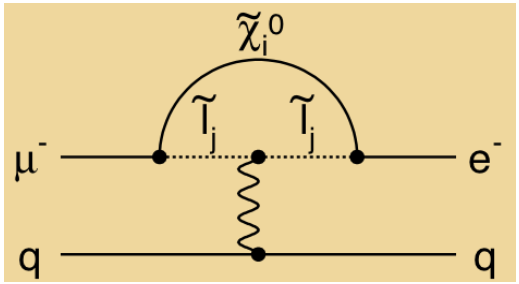
FLV in the field of a nucleus

Use *current* Fermilab accelerator complex to reach a sensitivity 10 000 better than current world's best

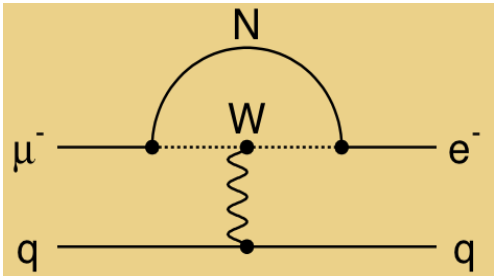
Contributions to μN → eN

Physics

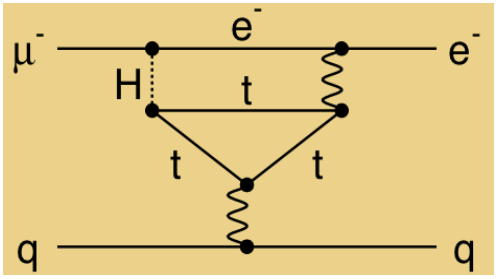
Loops



Supersymmetry

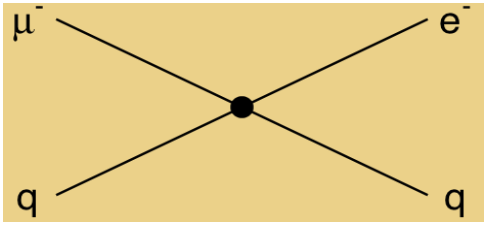


Heavy Neutrinos

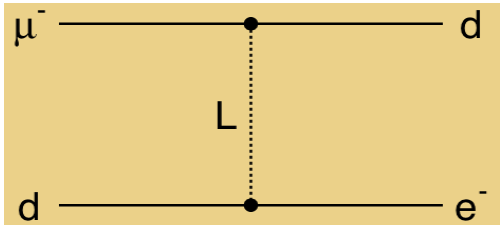


Two Higgs Doublets

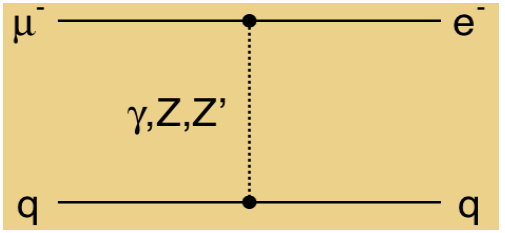
Contact Terms



Compositeness



Leptoquarks

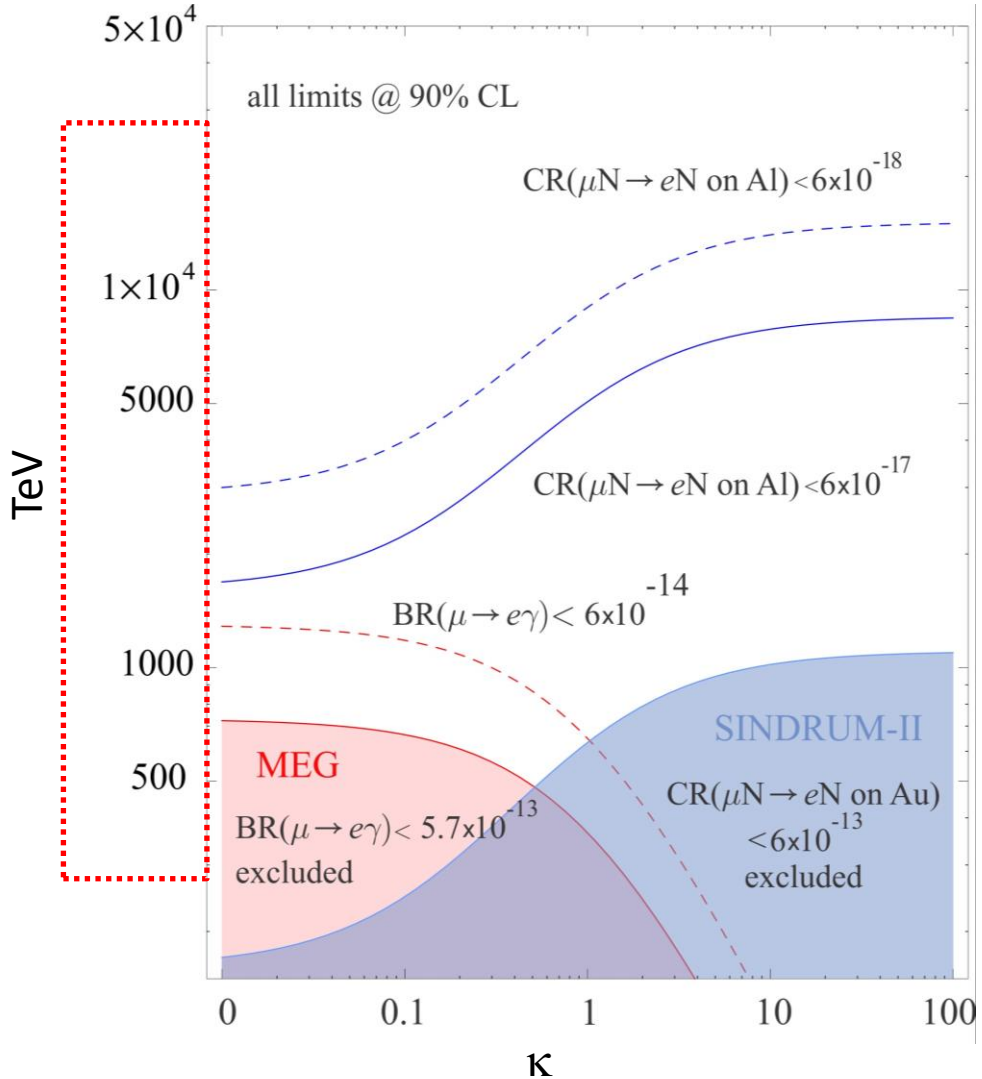


New Heavy Bosons / Anomalous Couplings

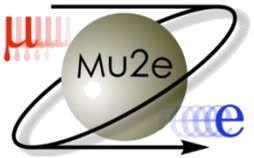
μN → eN sensitive to wide array of New Physics models

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$

Magnetic moment op. contact term



Mu2e extends beyond MEG for all BSM interaction types and conversion process has sensitivity to non-dipole BSM that MEG doesn't.



Basics

- Generate a beam of low momentum muons (μ^-)
- Stop the muons in a target
  - Mu2e plans to use aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
- The stopped muons are trapped in orbit around the nucleus
  - In orbit around aluminum: τ_μ^{Al} = 864 ns
  - Large τ_μ^{N} important for discriminating background
- Signature an Experimental signature is an electron and nothing else
  - Energy of electron: $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$
  - For aluminum: E_e=104.96 MeV
- Measure the rate compare to “normal” captures.

Total number of stopped muons

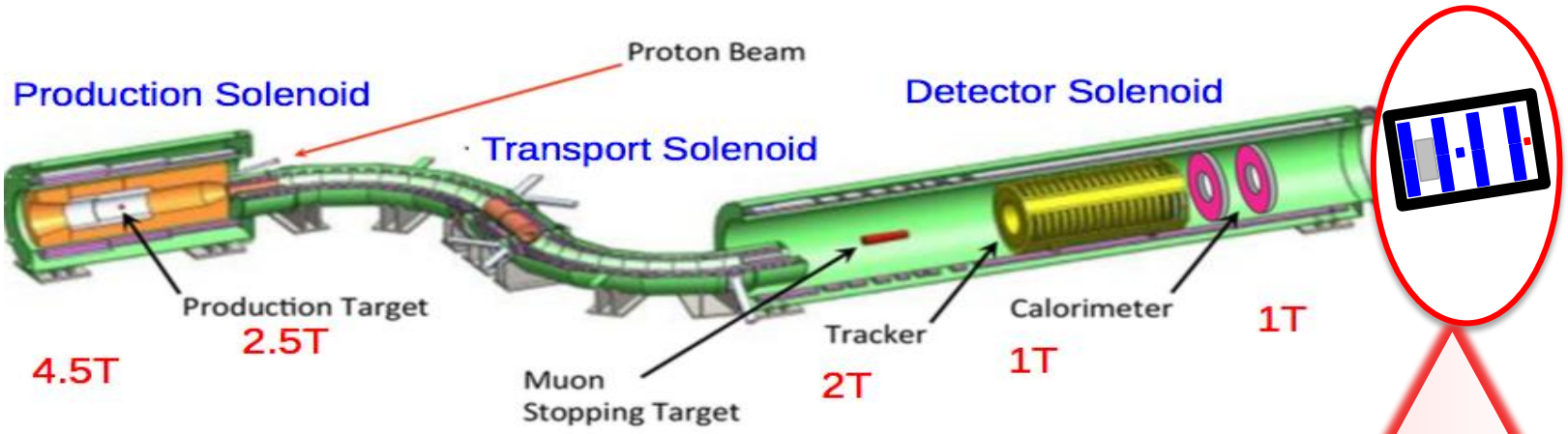
1,000,000,000,000,000,000

Some Perspective

1,000,000,000,000,000,000

= number of stopped Mu2e muons

= number of grains of sand on earth's beaches



Detector

Four critical elements:

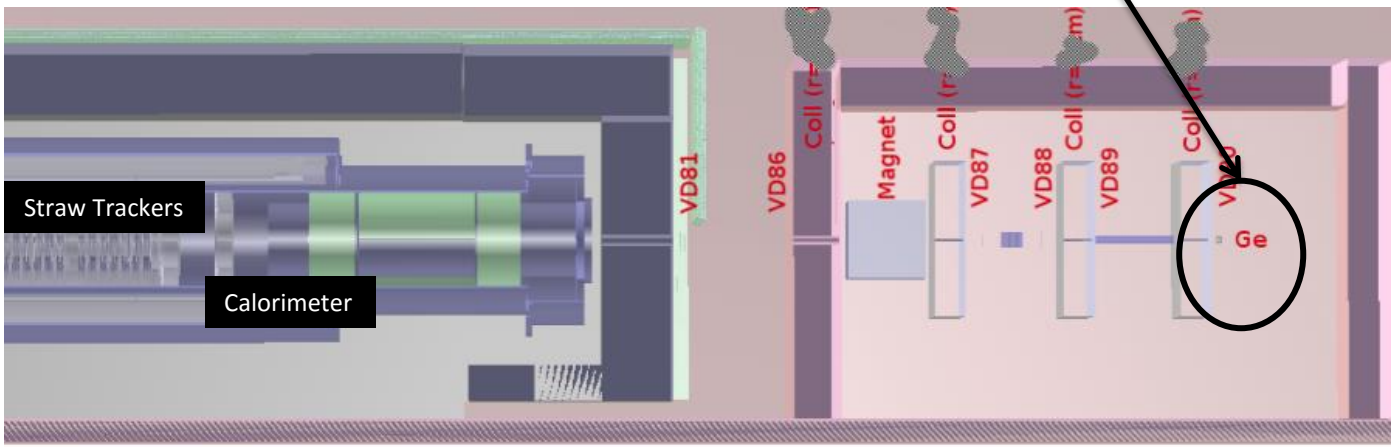
- solenoids (USA)
- straw tracker (USA)
- calorimeter (Italy)
- X ray detector (UK proposal)

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

This provides 10^{10} stopped muons/sec !

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

Proposed UK X-ray detector



Investigating several options

- Prompt Al 2p-1s muon transitions
- Delayed (864 ns) gamma from muon nuclear capture
- Slow (9-min) gamma from Mg*

With shuttered or highly collimated detector (Ge/LaBr(Ce)) in a high radiation environment (~ 1000 n/s/cm^2)

US Support

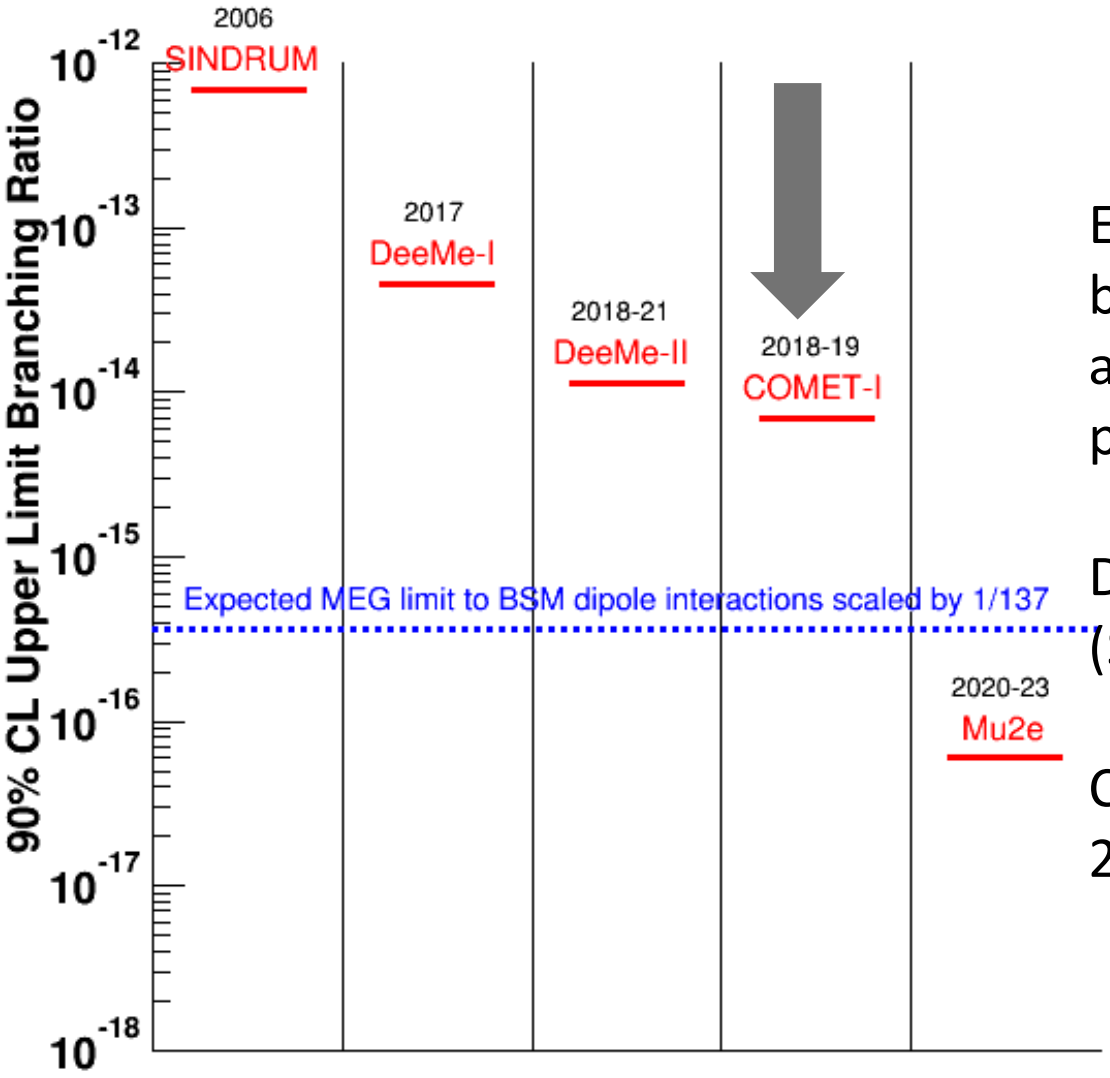
In 2013 the Facilities Panel gave Mu2e the highest endorsement:

> "The science of Mu2e is *Critical* to the DOE OHEP mission and is *Ready to Construct*."

In the 2014 P5 report Mu2e is strongly supported:

> Recommendation 22, "Complete the Mu2e and Muon (g-2) Projects."

Timeline



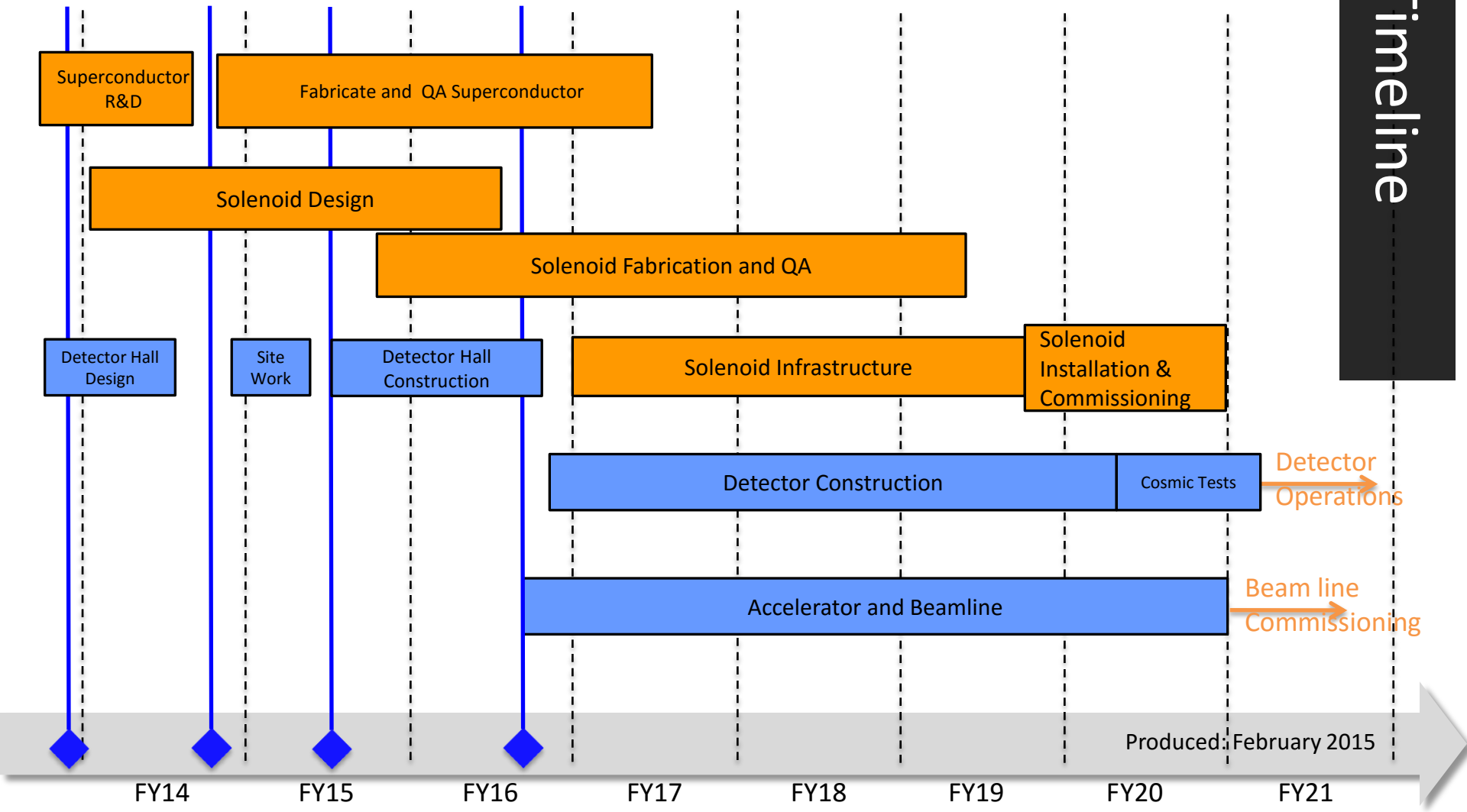
Extends significantly beyond the approved J-PARC programme

DOE CD3b approved ($274M)

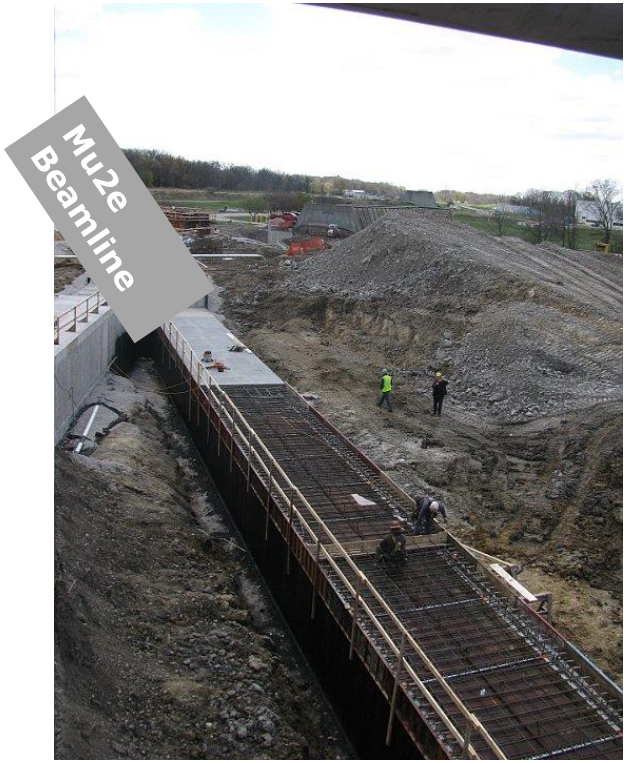
Construction began in 2014.

Schedule

Timeline

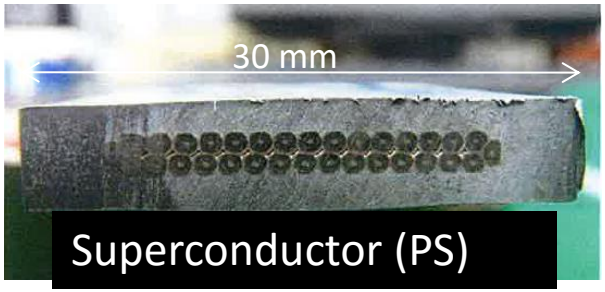


Beamline excavation done and Mu2e experimental hall will be complete in summer of 2016



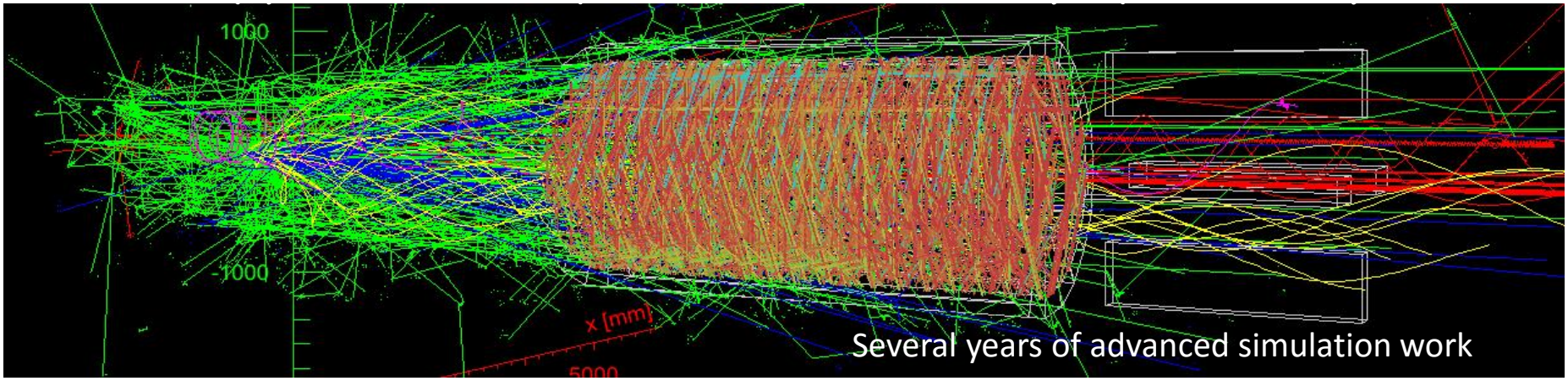
0.12 MeV resolution at 105 MeV for straws

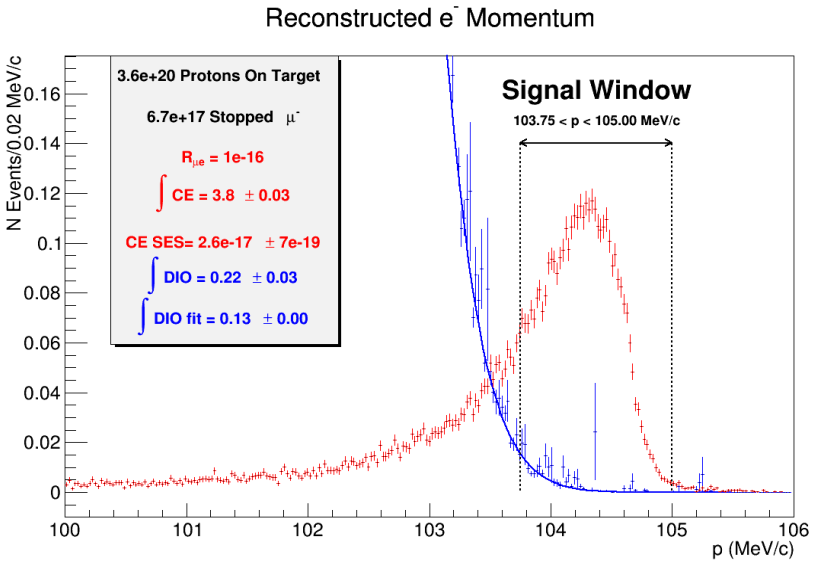
Detector and solenoid prototypes now under test at FNAL



50% (40 km!) of superconducting cable for solenoids is fabricated and required performance demonstrated.

Timeline





Single event sensitivity of 2.6×10^{-17}
100 more sensitive than COMET-I

Data taking to begin in 2020 for 3-4 years: immediately after the g-2 running.

There is a window for the UK to produce one of the major systems for the experiment in the next 4 years. UK/STFC is expert in Ge technology.

Ensures UK has a prominent in the Intensity Frontier/FNAL programme before DUNE and continuing from successful CDF/D0 – MINOS – Nova - g-2 involvement and the UK's investment in the FNAL Muon Campus.

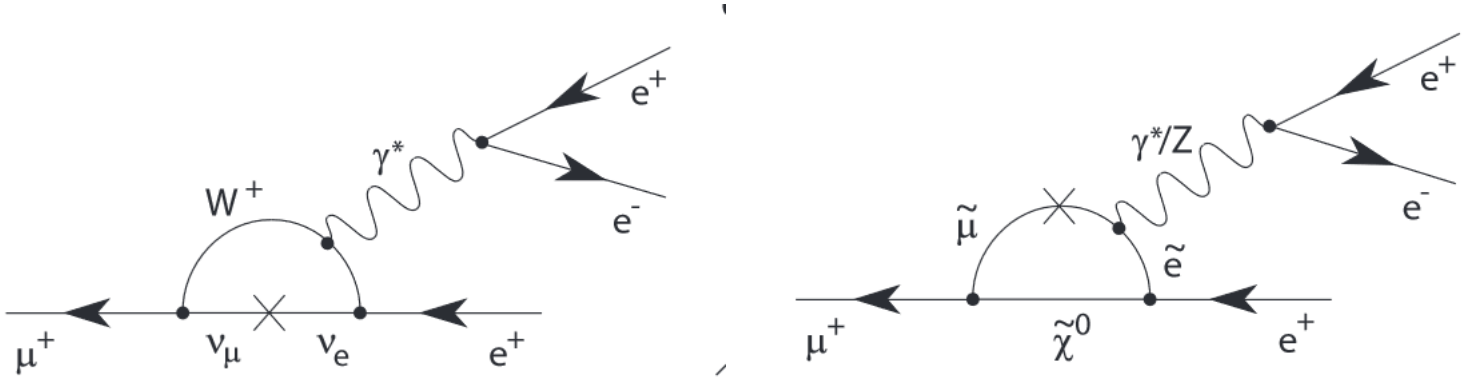
Interest

- Liverpool
- UCL
- Manchester
- Edinburgh(?)

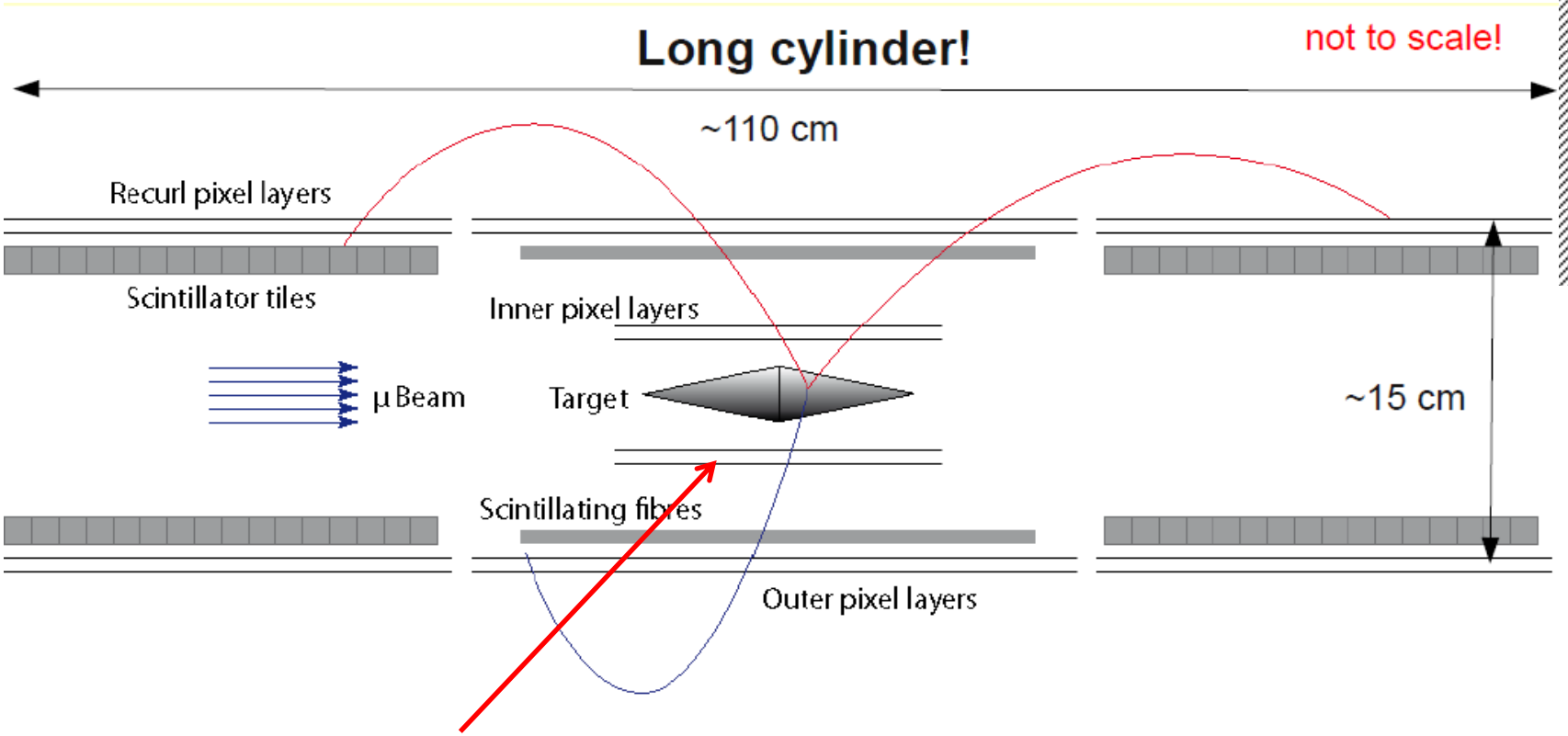
UK Interest

mu3e

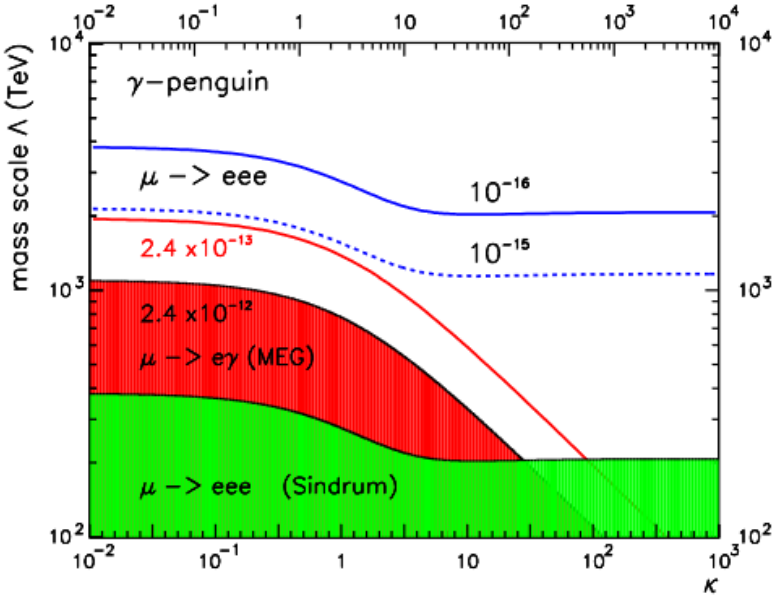
- Similar physics to mu2e (PSI experiment)
- Look at 1 in 10^{16} decays (10^4 better than before)
  - (MEG), Sindrum
- CFLV with $\mu \rightarrow eee$

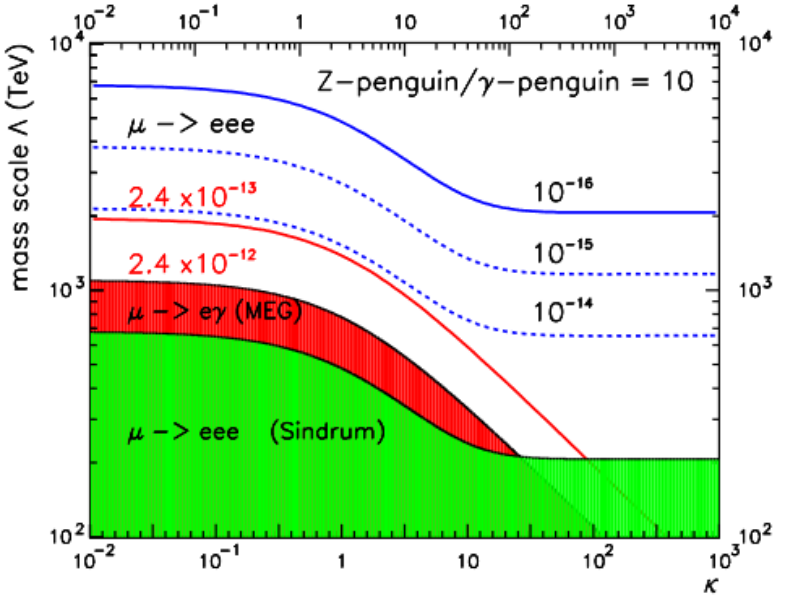


Heavily suppress $\mu \rightarrow eee\nu\nu$ (over 16 orders magnitude with kinematic cuts) (and timing)

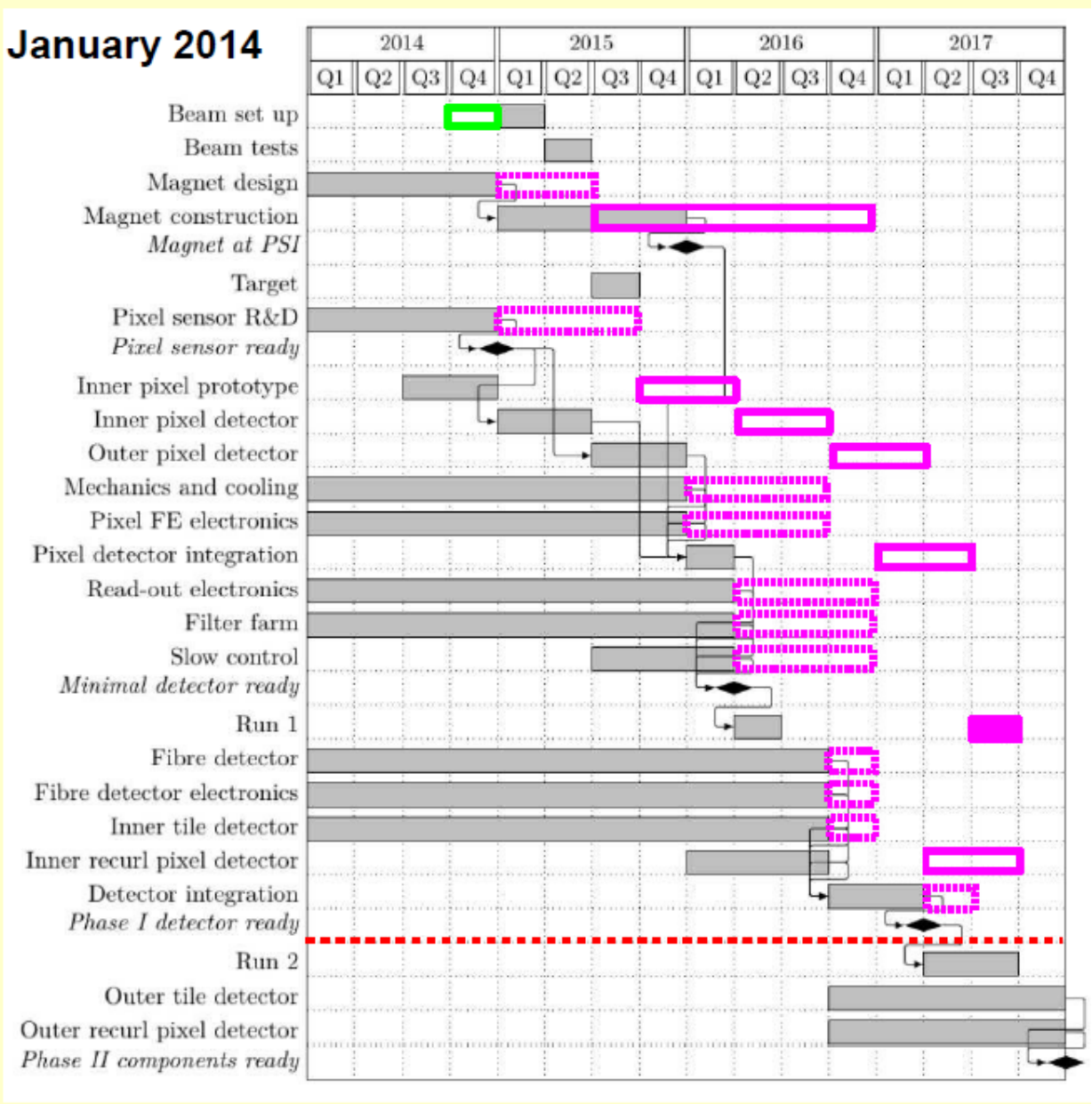


HV-CMOS detectors (Peric) – 50um resolution


γ−penguin
μ −> eee
10^-16
10^-15
2.4 x10^-13
2.4 x10^-12
μ −> eγ (MEG)
μ −> eee (Sindrum)
mass scale Λ (TeV)
κ


Z−penguin/γ−penguin = 10
μ −> eee
2.4 x10^-13
10^-16
10^-15
10^-14
2.4 x10^-12
μ −> eγ (MEG)
μ −> eee (Sindrum)
mass scale Λ (TeV)
κ

Timeline


January 2014
2014
2015
2016
2017
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Beam set up
Beam tests
Magnet design
Magnet construction
Magnet at PSI
Target
Pixel sensor R&D
Pixel sensor ready
Inner pixel prototype
Inner pixel detector
Outer pixel detector
Mechanics and cooling
Pixel FE electronics
Pixel detector integration
Read-out electronics
Filter farm
Slow control
Minimal detector ready
Run 1
Fibre detector
Fibre detector electronics
Inner tile detector
Inner recurl pixel detector
Detector integration
Phase I detector ready
Run 2
Outer tile detector
Outer recurl pixel detector
Phase II components ready

- HV-CMOS (now!) (Theme???)
- Perfect fit to UK technical capabilities
- Little investment needed
- UK needed …

Summary

- Timely interest in this sort of experiment
  - In context of Bs and neutrinos & direct searches
  - Theoretical support
  - International community interest
- Windows to the PeV scale
- UK strategic opportunities in short, medium and long term
  - HV-CMOS
  - Accelerator Physics (STFC business)
- Not necessarily a high cost for entry
- Potential high payoff
- Classic (beautiful) measurements & good training ground for next generation of physicists