Muon Physics

g-2, MUonE, Mu2e, COMET, Mu3e
…+ JPARC g-2, MEG

Not covering:
DeeMe, MuSEUM, HyperMu, MUSE, …

Motivation

We know new physics must be out there somewhere:

- dark matter, matter/antimatter asymmetry, …
- naturalness, structure of the Standard Model, …

No new physics directly observed at the LHC

…surprises have come from the lepton sector:

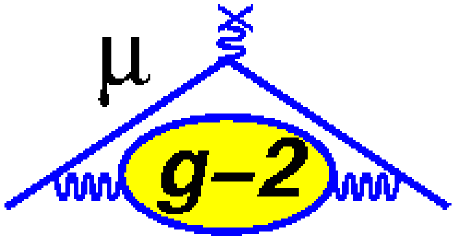
- neutrino oscillations
- some $>3\sigma$ effects: g-2, R(K), R(D)

Charged lepton flavour violation is possible / predicted in several BSM scenarios

- can be linked to leptogenesis of matter/antimatter asymmetry

The coming decade will see significant progress in experimental results

New Physics in Loops

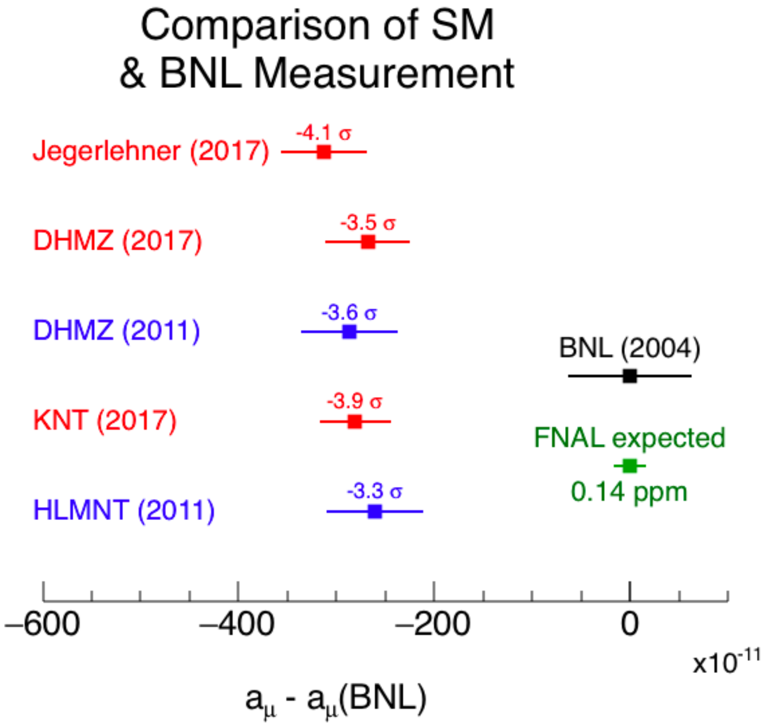


Anomalous contribution to magnetic moment:

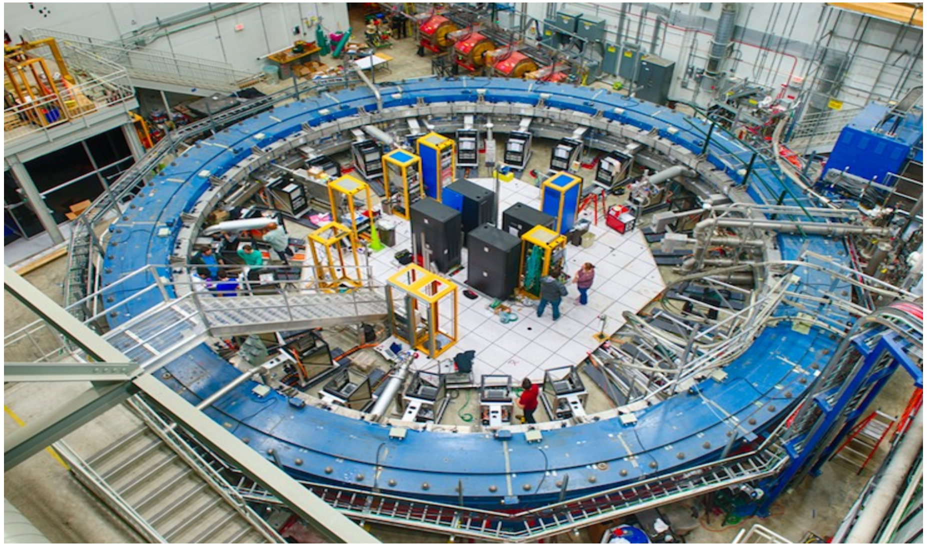
$$a_\mu = \left(\frac{g-2}{2}\right)$$

Brookhaven measurement ~3.6σ from prediction

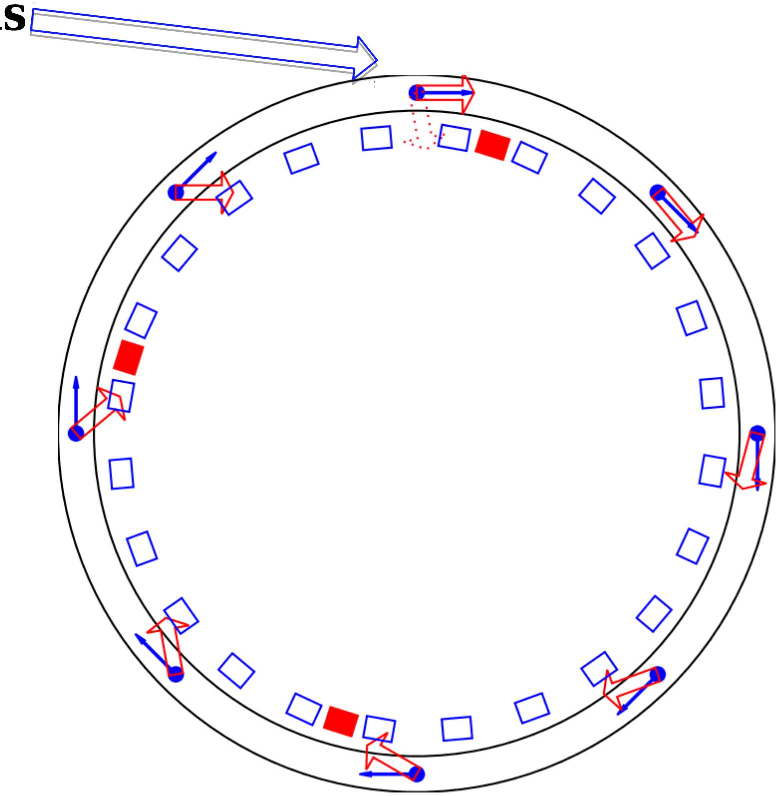
Muon g-2 experiment underway at Fermilab



Muon g-2



Inject muons at 3.09 GeV



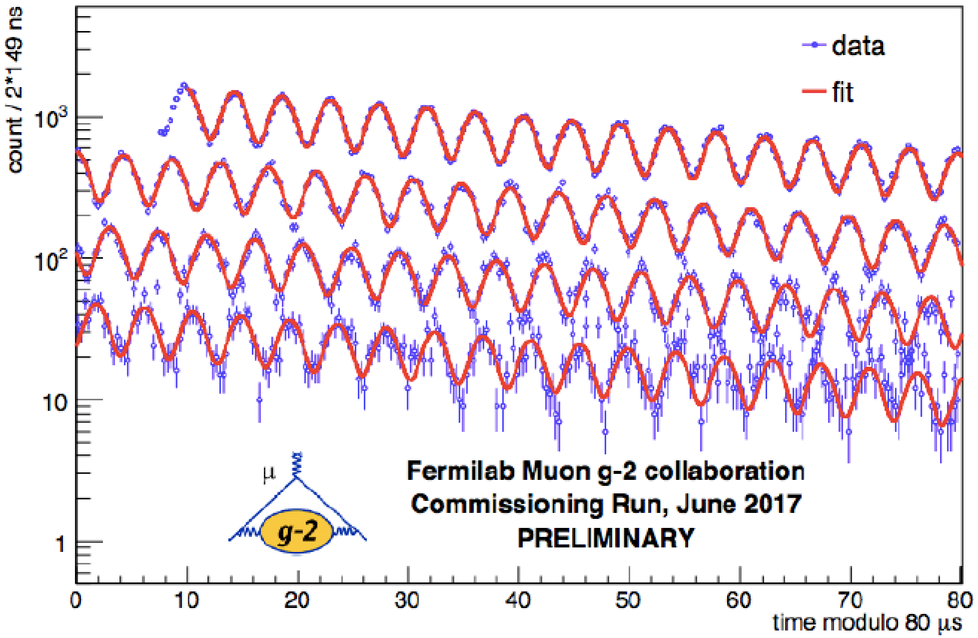
$$\omega = -\frac{q}{m}\left[a_\mu B - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\beta \times E}{c}\right]$$

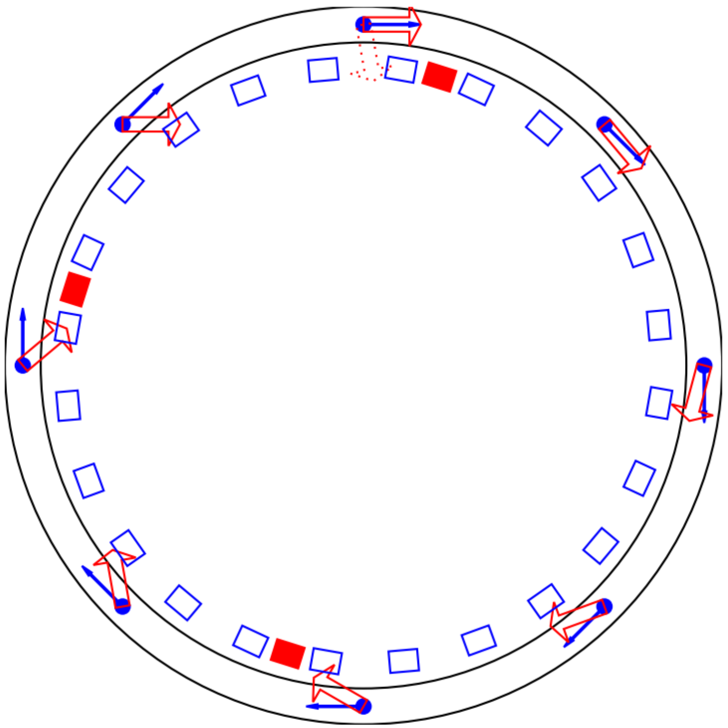
Use of “magic momentum” 3.09 GeV
→ direct access to a from precession freq.

Graphics from Themis Bowcock, PPAP 2017

Muon g-2

Direction of positron from muon decay strongly correlated with muon spin for highest energy positrons





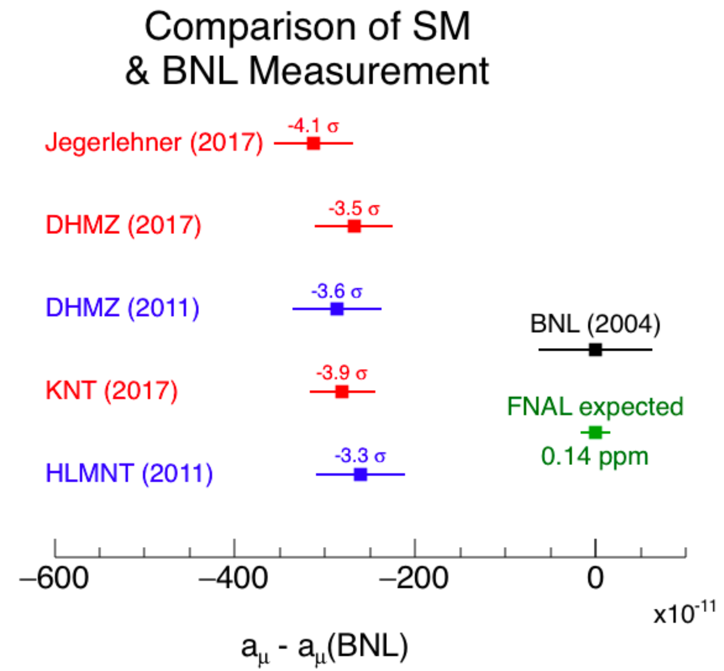
24 calorimeters and **3 straw-strackers (UK)** measure e^+ for O(1 ms) for spills separated by 10ms.

16,000 stored 3.09 GeV muons from 10^{12} protons per spill.

Muon g-2

BNL → FNAL

[50 (stat) + 33 (syst) → 11 (stat) + 11 (syst)] x 10^{-11}



Improvements:

- muon muons per proton, cleaner delivery
- detectors & modelling
- stored muon beam dynamics
- field uniformity & calibration

Expect ~1 - 2 x Brookhaven stats this year.

$$\vec{\omega} = -\frac{e}{m}\left\{\underbrace{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\vec{\omega}_a} + \underbrace{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\vec{\omega}_e}\right\}$$

Can also access muon EDM by looking for vertical oscillation

- zero in the SM (EDMs only possible with violation of *PT*)
- expect to suprpass Brookhaven limit very soon, then x100.

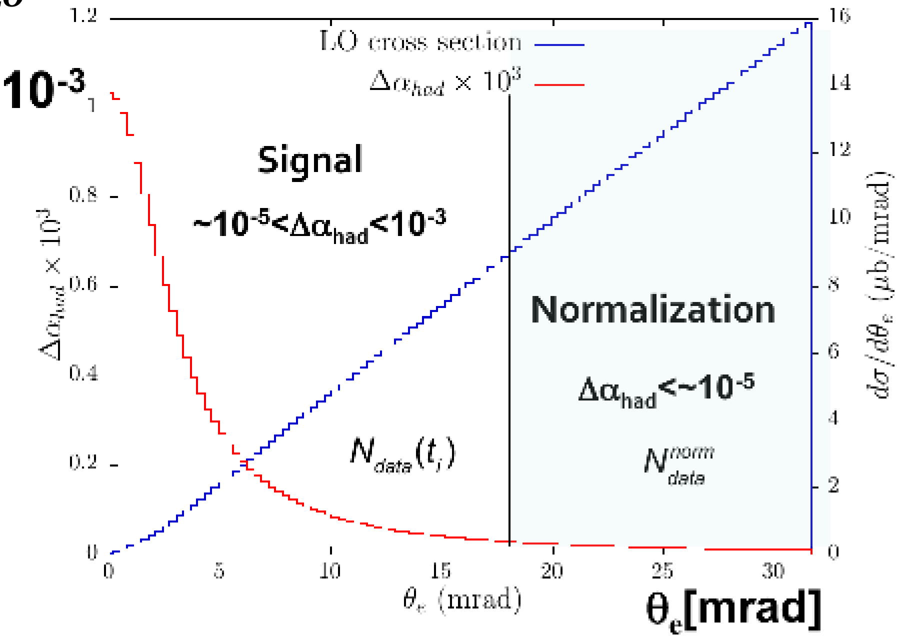
Theory limited by hadronic LO corrections, a_μ^{HNLO}

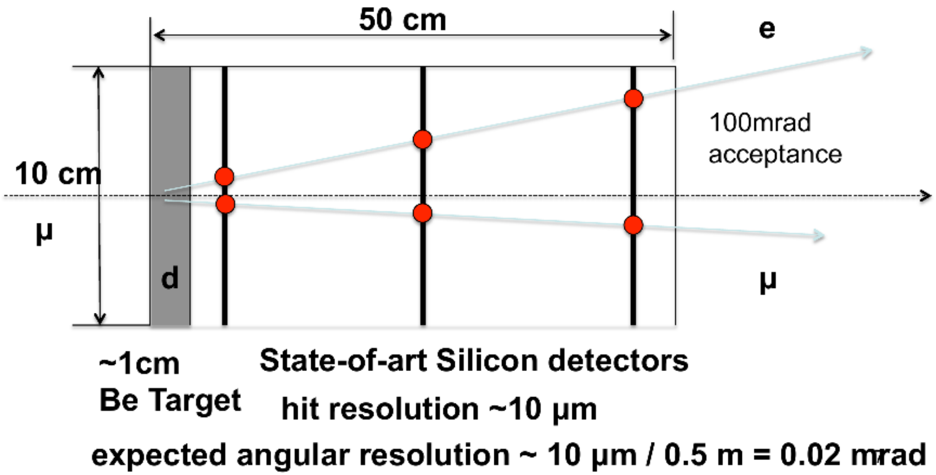
Traditional calculation from ee→hadrons
→ need x2 improvement to keep up with g-2

MUonE will measure space-like region:

→ scattering of high energy mu (150 GeV) on e

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}(t(x))dx$$



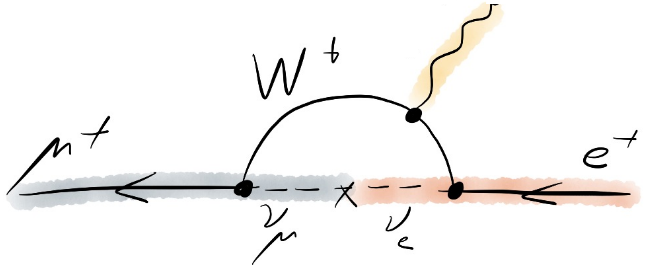


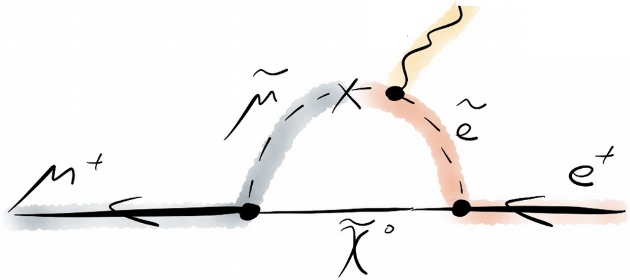
Schedule:

2017: test beam at CERN H8 Beam Line
2019: LOI to SPSC
2020/1: construction & installation
2022/4: (after LHC LS2) start data taking

Charged Lepton Flavour Violation

New Physics in Loops





Neutrinoless muon decay:

- possible in SM, suppressed by $\sim 10^{-54}$

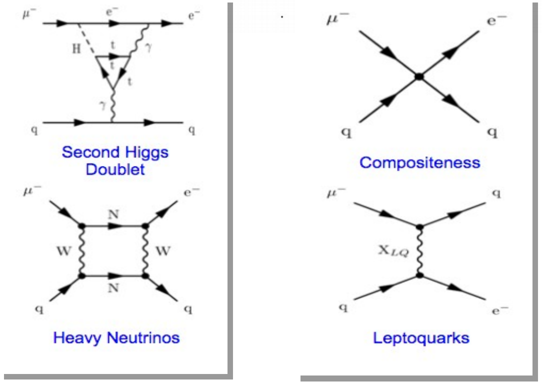
→ *any observation is new physics!*

Can put almost anything in the loop:

- heavy quarks, leptoquarks, compositness, second Higgs doublet, heavy neutrinos…

Different strategies:

- $\mu \rightarrow e\gamma$ MEG
- $\mu N \rightarrow eN$ Mu2e, COMET
- $\mu \rightarrow eee$ Mu3e



Synergy with g-2

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

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

New Physics in Loops

UCL

Effective Lagrangian for cLFV
(de Gouvea & Vogel)

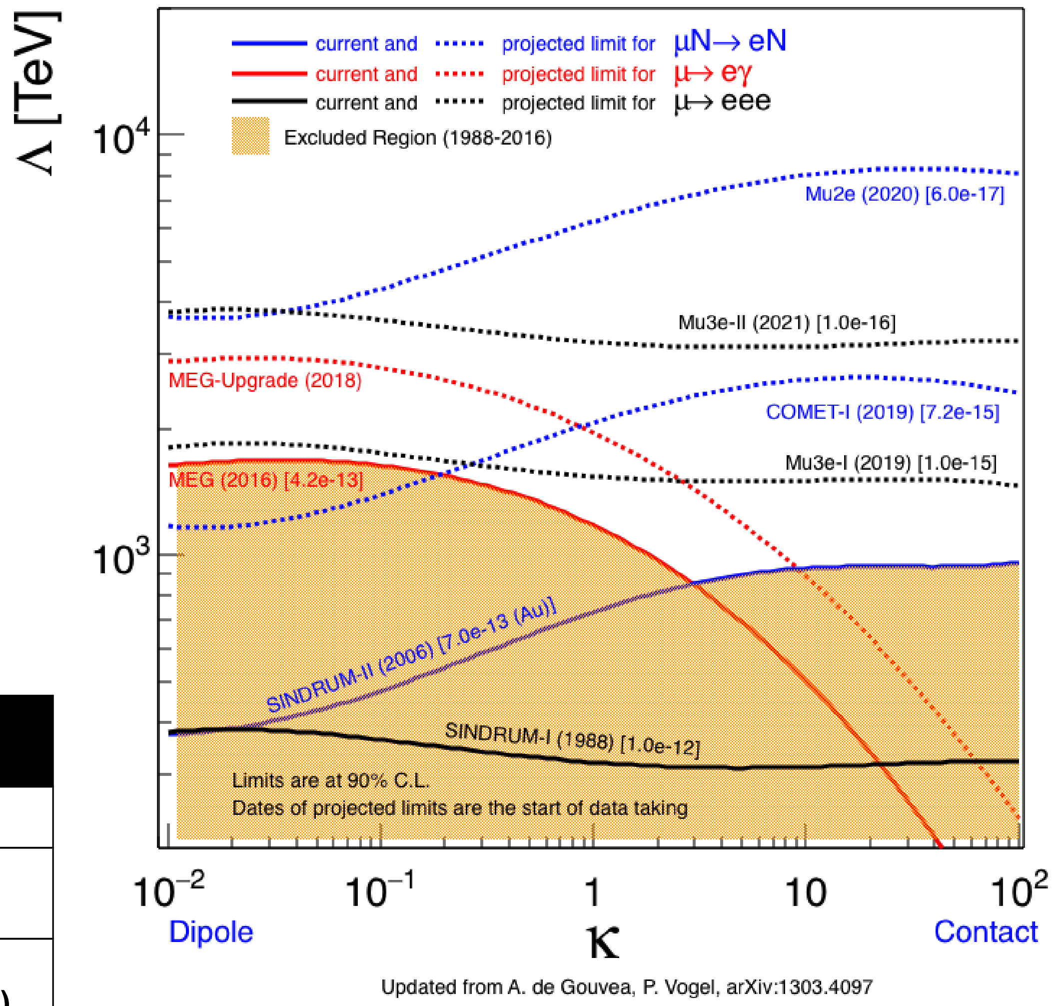
$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$

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

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

Extend sensitivity by 10^4

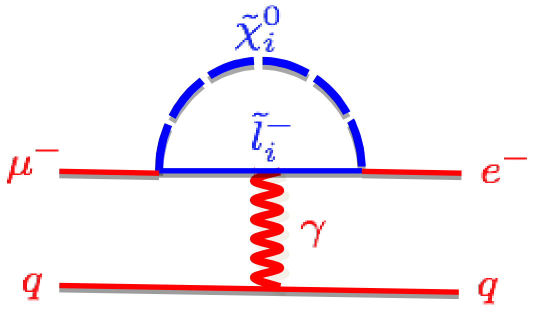
	Best limits	Projected sensitivities (90%CL)
μ→eγ	< 4.3×10^{-13} MEG (PSI)	4×10^{-14} MEG II (PSI)
μ→eee	< 1.0×10^{-12} SINDRUM (PSI)	1×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)
μN→eN	< 7.0×10^{-13} SINDRUM II (PSI)	6×10^{-17} Mu2e (FNAL) 7×10^{-15} COMET I (J-PARC) 6×10^{-17} COMET II (J-PARC)

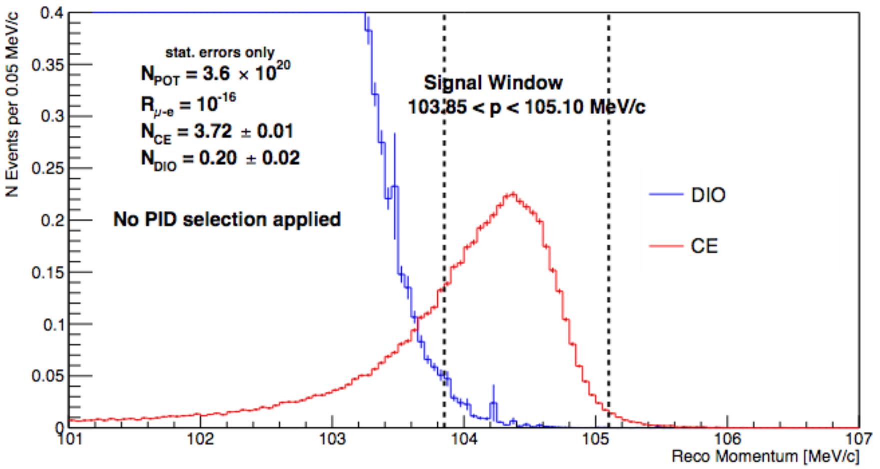


Updated figure from Mark Lancaster

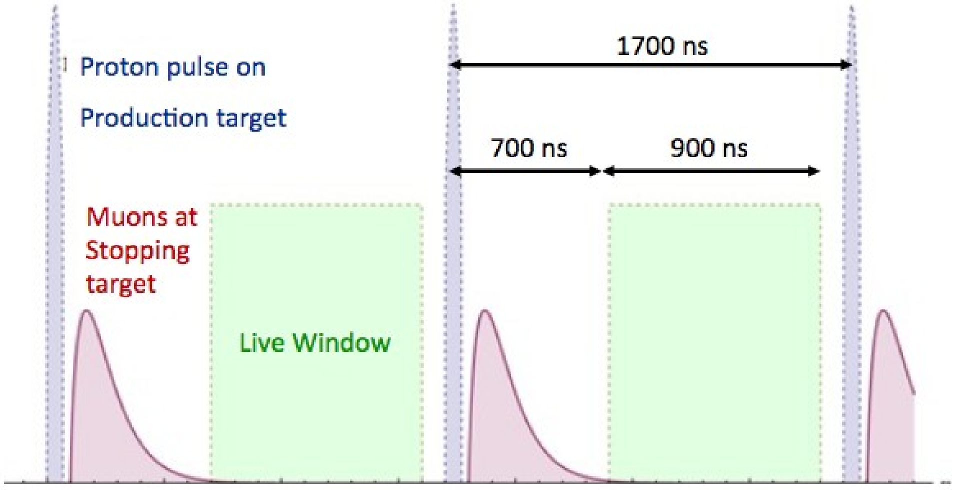
Mu2e

$\mu N \rightarrow eN$





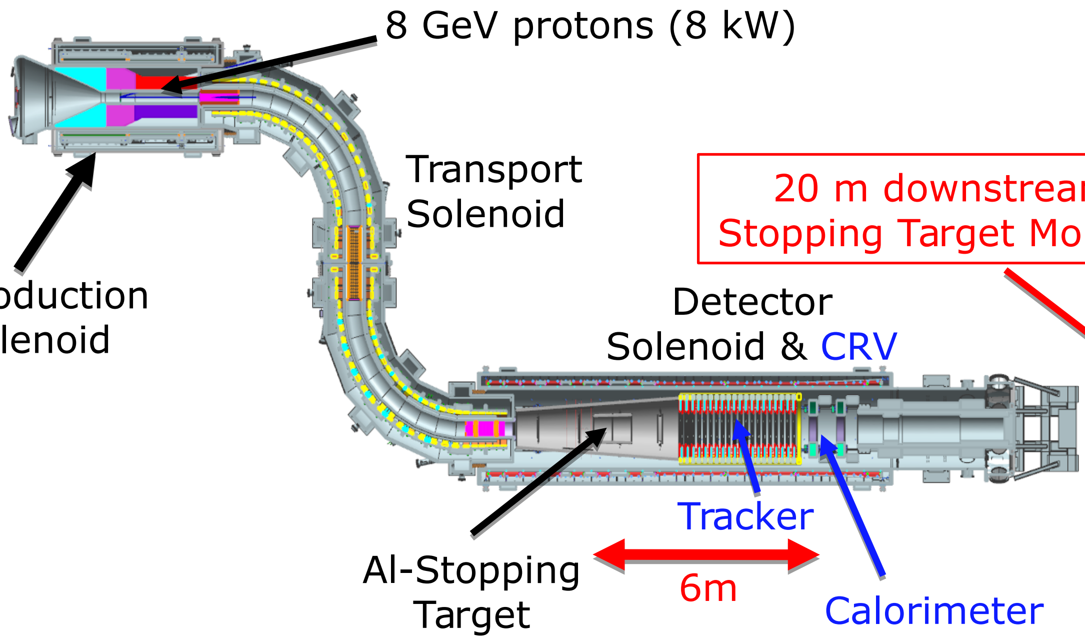
Stopped muons in orbit around nucleus.
- neutrinoless conversion of muon to electron
- mono-energetic electron (104.96 MeV for Al)
- delayed w.r.t. prompt particles (864 ns for Al)



Prompt backgrounds
(radiative nuclear capture, d.i.f., 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

Mu2e



220 members: 35 institutes.

HEPAP P5: 2014

Mu2e (& g-2) to be completed in all budget scenarios (as for HL-LHC, LBNF)

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

Beamline to Mu2e building completed.

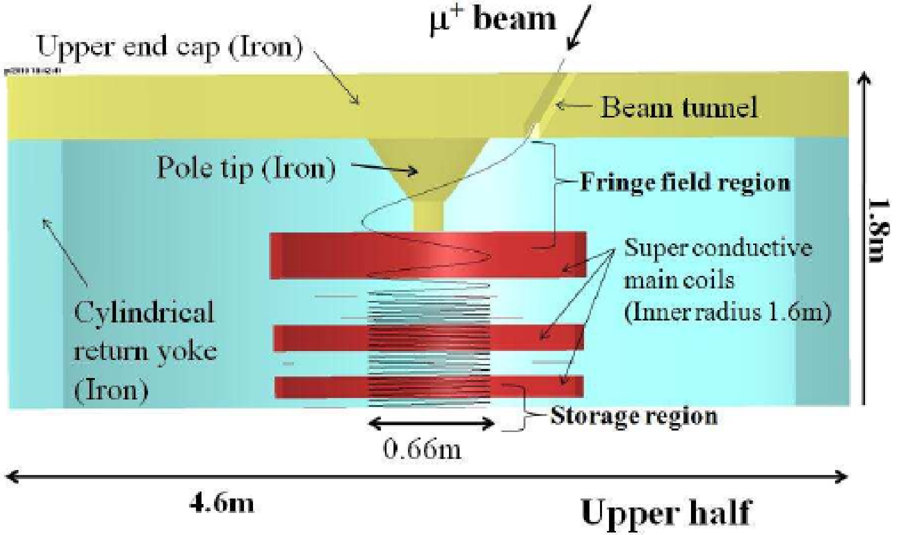
Most accelerator mods also needed by g-2

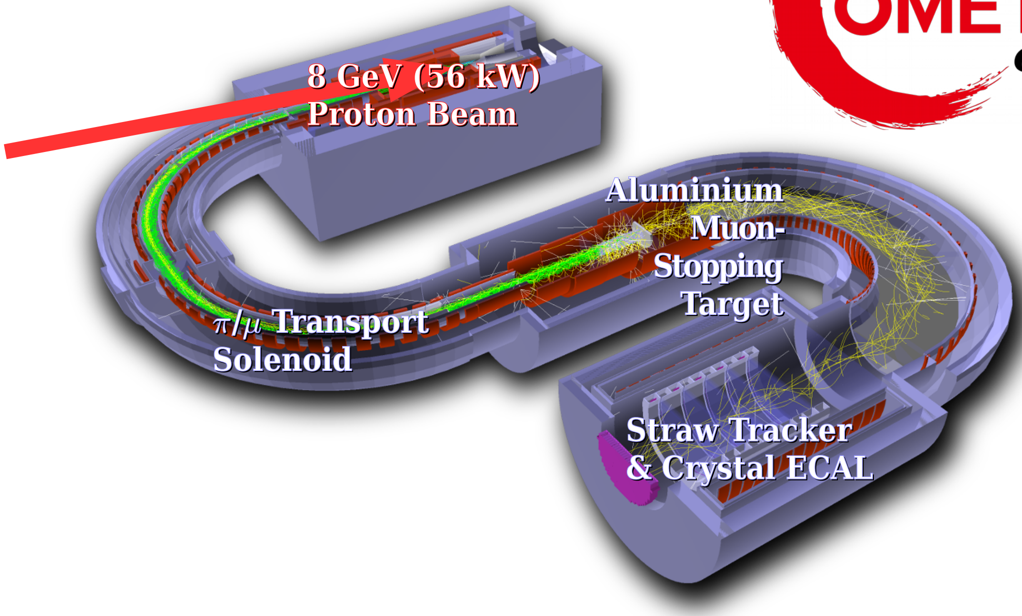
First beam in 2020, data-taking through 2025

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

- to be finalised in 2020 HEPAP P5.

Proposed g-2 / EDM experiment at J-PARC
- Innovative design
- currently in R&D phase
- would see beam, after Fermilab g-2
    - provide important cross-check



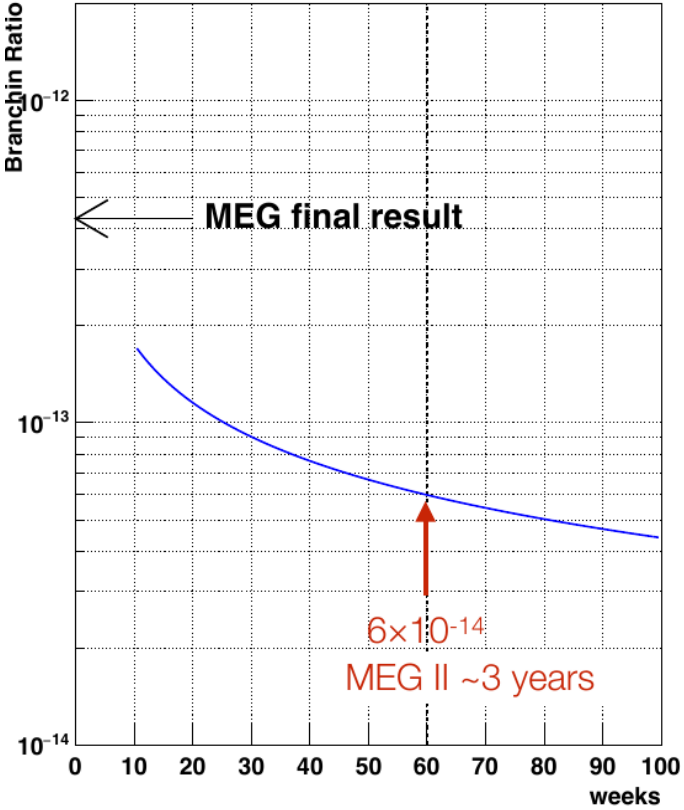


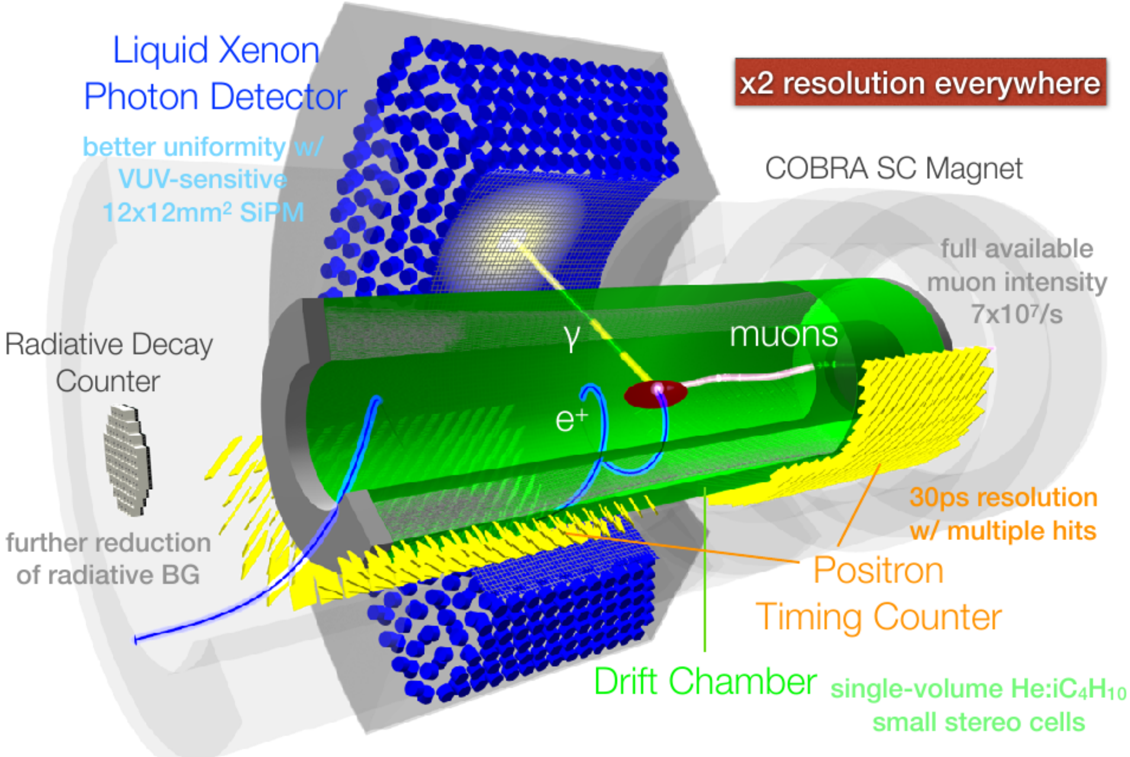
Targeting same process as Mu2e
COMET Phase 1 approved
- beam in ~4 years (?), sensitivity 10^{-15}
Phase 2 (full detector)
- ~2 yrs after phase 1, sensitivity 10^{-17}

Upgraded MEG experiment at PSI

- looking for $\mu \rightarrow e\gamma$

Limited by photon E & pos^n resolution



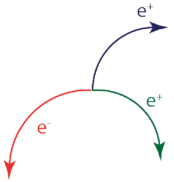


Current limit ~$4\text{x}10^{-13}$, aiming for x10 improvement

Complete installation & engineering run 2018.

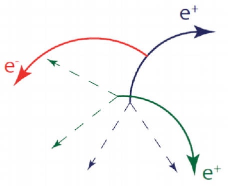
The mu3e experiment at PSI

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



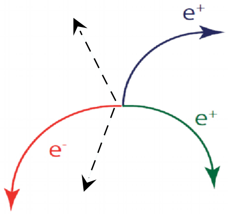
Combinatorics, Michel decay + photon conversion:

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



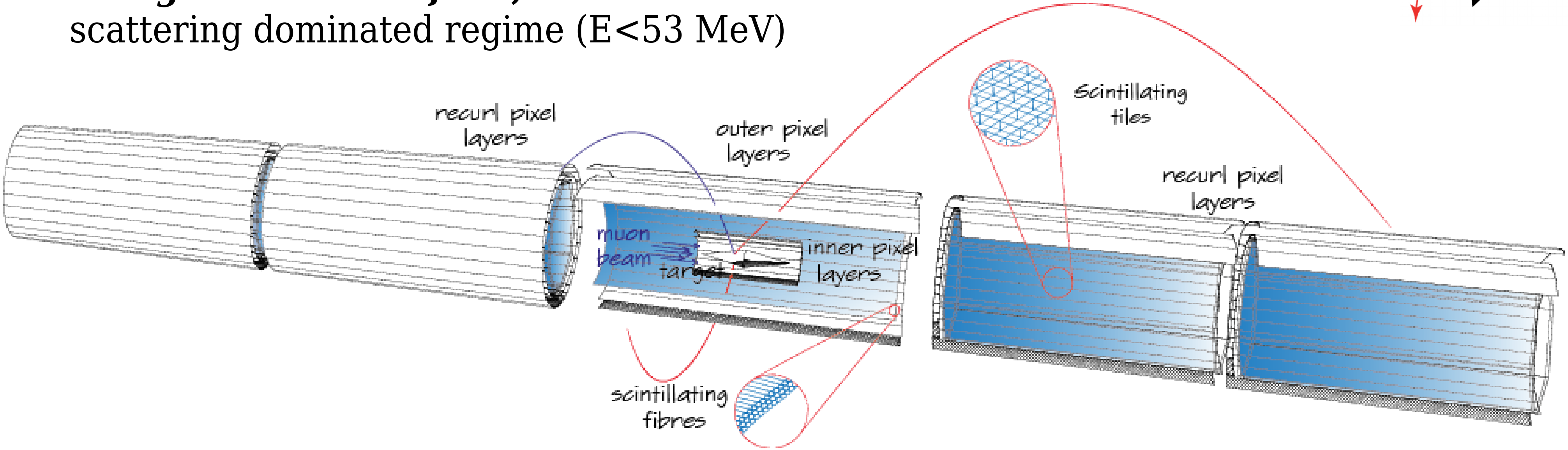
Michel decay + internal conversion

- momentum resolution 0.5 MeV



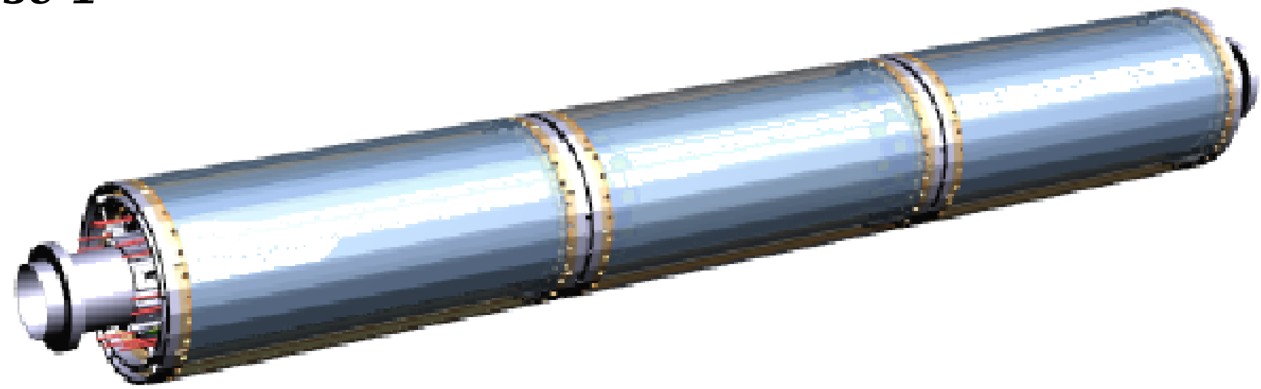
Recurling tracks in 1T field,

scattering dominated regime (E<53 MeV)



MuPix outer pixel layers for Phase 1

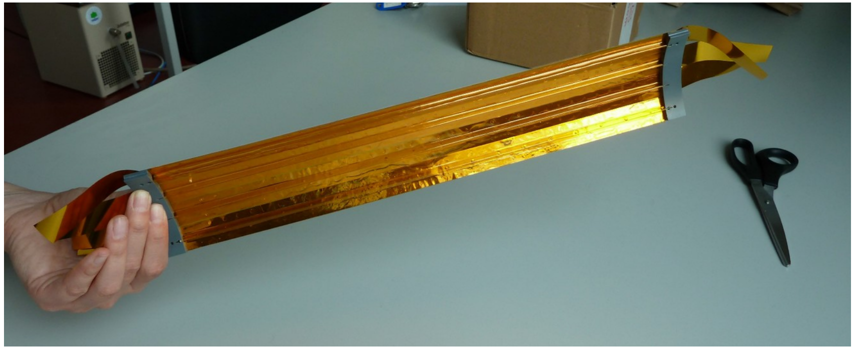
1.1 m^2 HV-MAPS pixel tracker



Material budget critical:

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

→ 0.1% X_0 per tracking layer



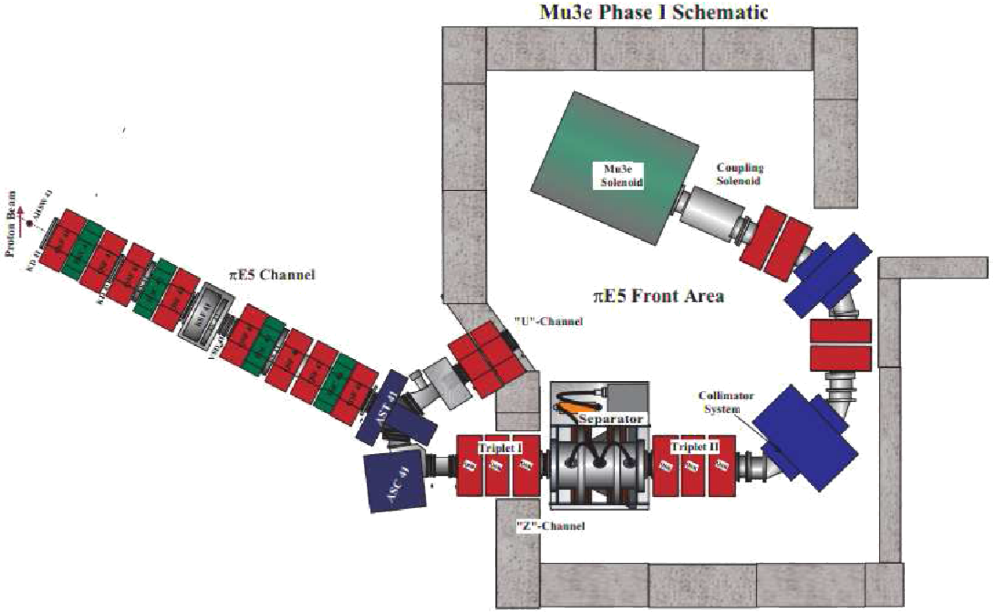
UK Deliverables

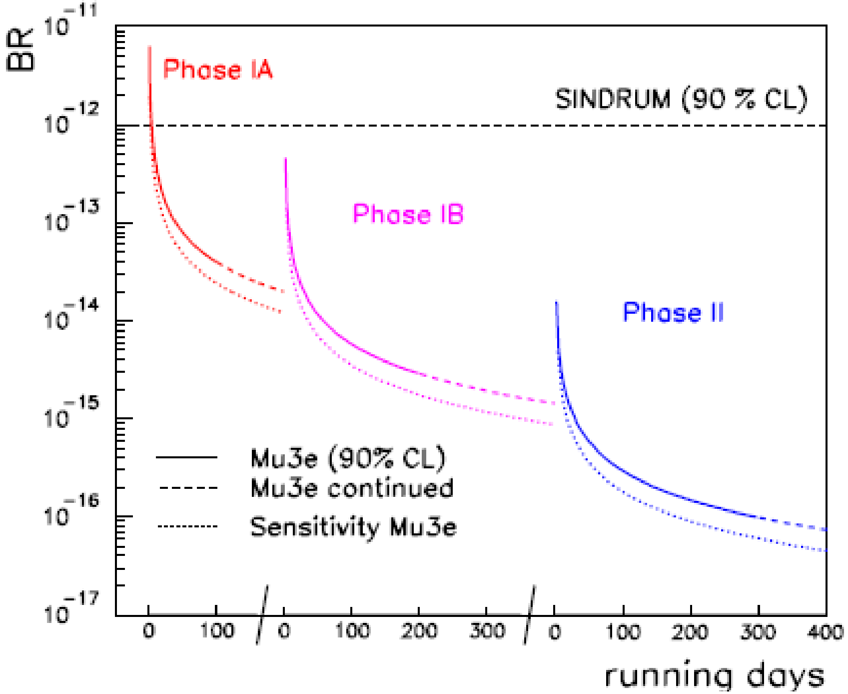
- Participate in final pre-production of MuPix chip
- Tooling for chip-to-ladder assembly, ladder prototype production.
- Assembly of all Phase 1A outer tracker (Spring 2019).
  & Phase 1B recurl layers (Spring 2020).
- Design and deliver clock and control system (Spring 2019)

Mu3e

Phase 1A and 1B (2020-2022): Br(μ→eee) < 10^{-15}

- Approved (2013) and funded. PSI πE5 beam, shared with MEG.
- 10^8 μ/s on target for Mu3e demonstrated.





Phase 2 (2022/23): Br(μ→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

Summary

From 2013: Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.

g-2 @ FNAL: Liverpool, Lancaster, Manchester, UCL

Interest in MUonE @ CERN:

- start in 2022, reduce theory uncertainties on g-2, critical if Brookhaven result confirmed

Mu2e @ FNAL: Liverpool, Manchester, UCL

- fully funded, will follow g-2

Mu3e @ PSI: Bristol, Liverpool, Oxford, UCL

- commissioning in 2019, first data in 2020

COMET @ J-PARC: Imperial

- Phase 1 approved, expecting beam in ~2-4 years, Phase 2 approval to follow

Muon physics complements and extends major research themes:

- BSM searches, CPV in the neutrino sector and leptogenesis of matter-antimatter asymmetry

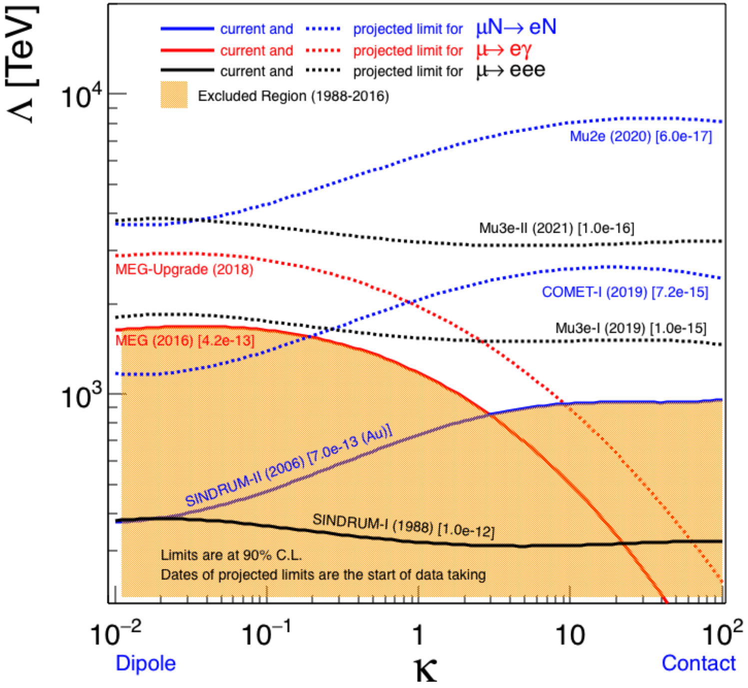
..and should play an important role in European strategy

Talking Points

There is still a lot of phase space to explore: cLFV limits will reach 10^{-16}, SM ~ 10^{-50}!

Possible Mu2e upgrade (2020 HEPAP P5), give ~x10
- could make use of FNAL PIP-II beam
  - 100kW pulsed beam at 800 MeV

Discussions beginning between Mu3e/Mu2e/MEG/COMET
→ ***single experiment doing all 3 cLFV modes,***
→ push sensitivity by further x10.
- would happen after MEG-II and Mu3e Phase 2 (ie >2025?)
- possibly at FNAL, use PIP-II beams



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

Talking Points

Renewed interest in EDMs

- g-2 measurement of the muon EDM will improve limit by ~x100
- possibility to upgrade g-2: replace straw trackers with silicon
  → further x10 in limit

Plan for a demonstrator proton EDM @ CERN

- requires new proton/deuteron storage ring
- can already improve on the present limit

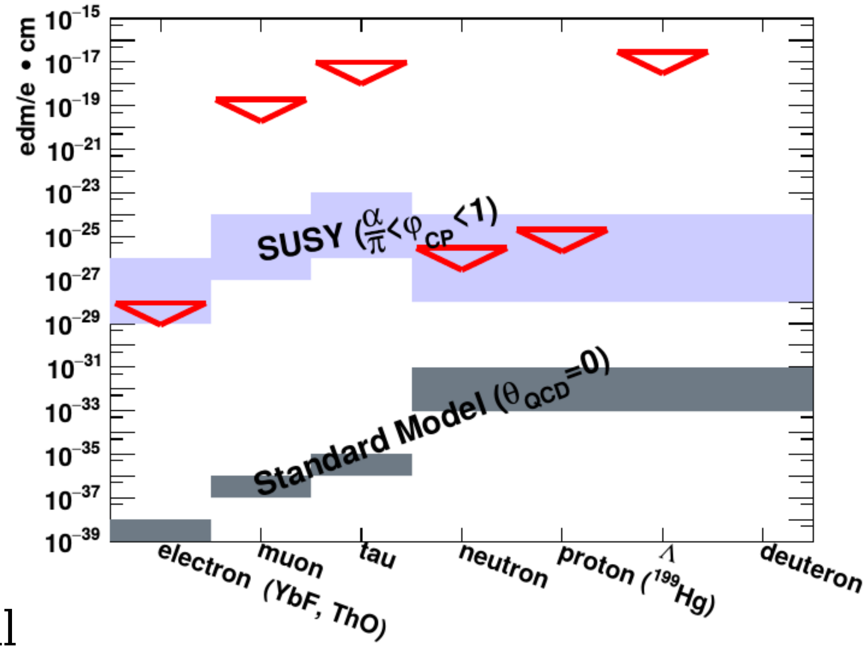
...before full-scale experiment

- $x10^5$ improvement in limit ($7x10^{-25} \rightarrow 10^{-29}$)

See CERN "*Physics Beyond Colliders*" workshops:

- eg Jorg Pretz, Nov 2017
  https://indico.cern.ch/event/644287/timetable/#all

...and talk by Claire Burrage yesterday.



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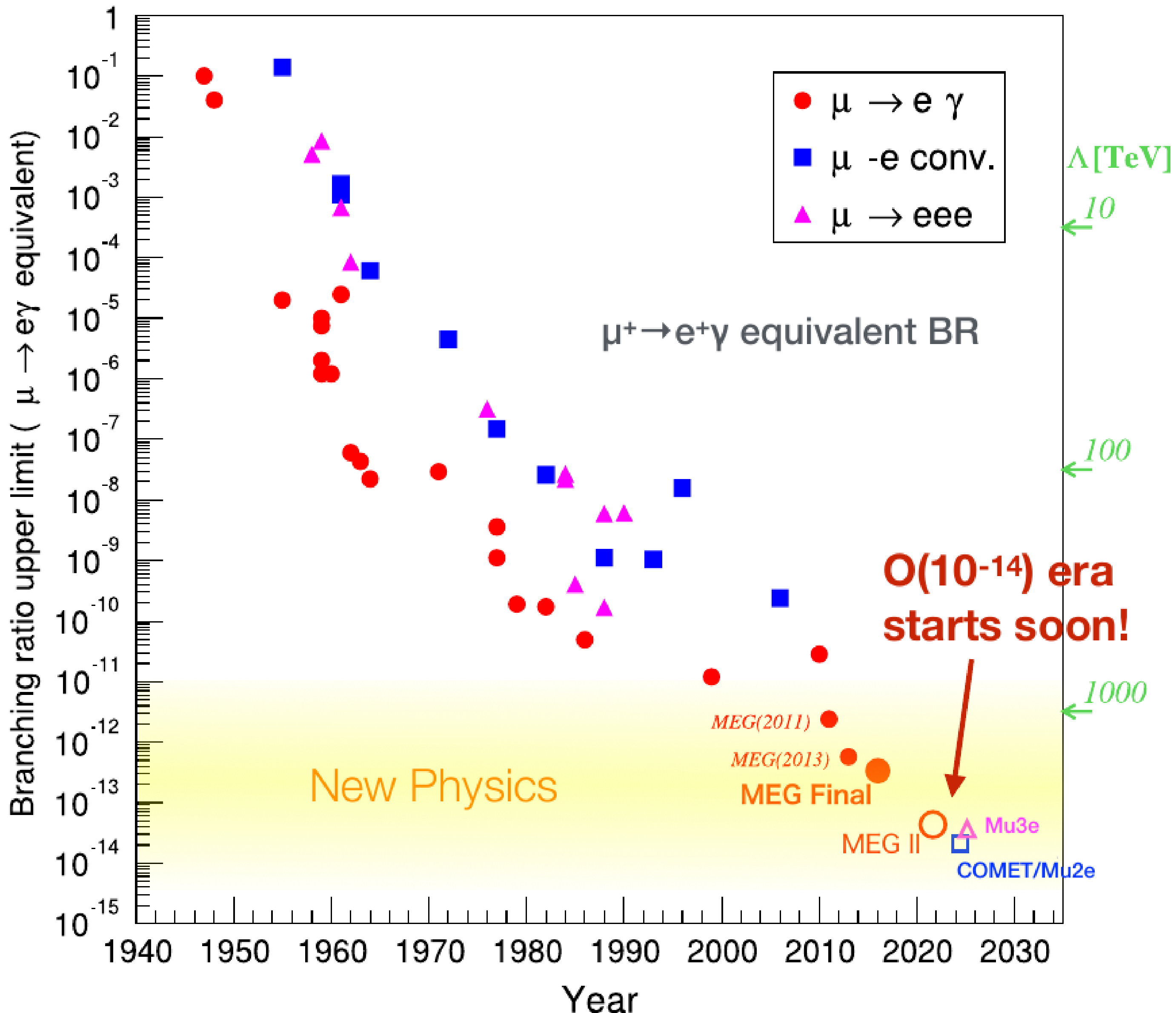
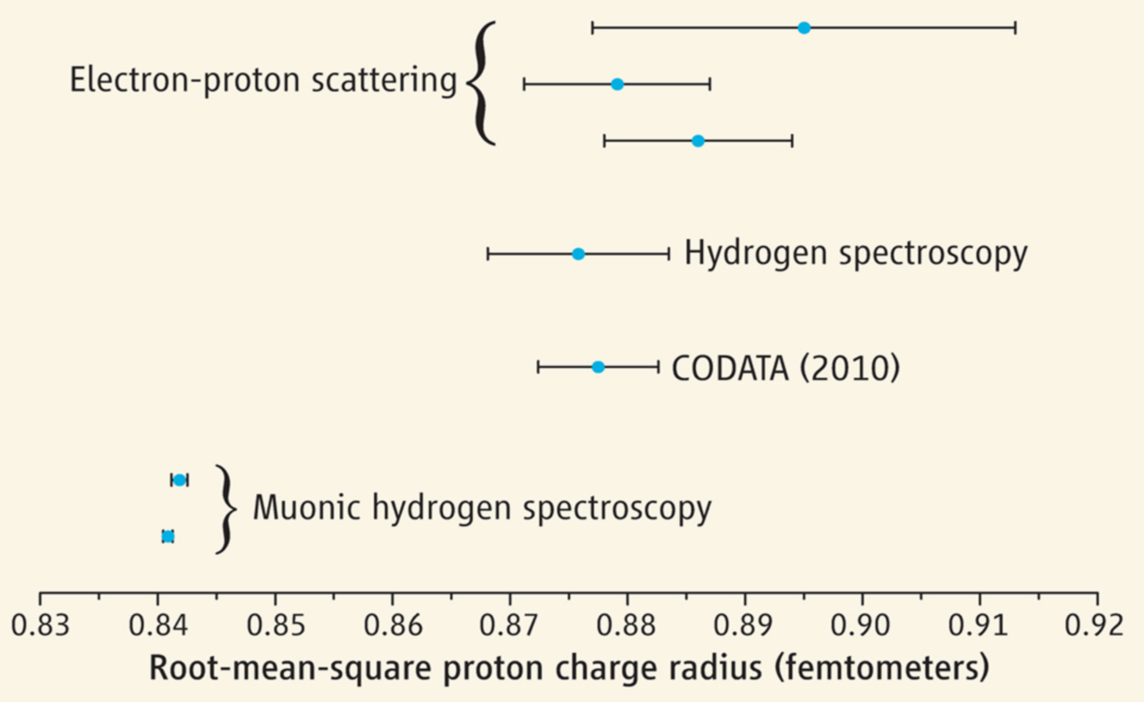
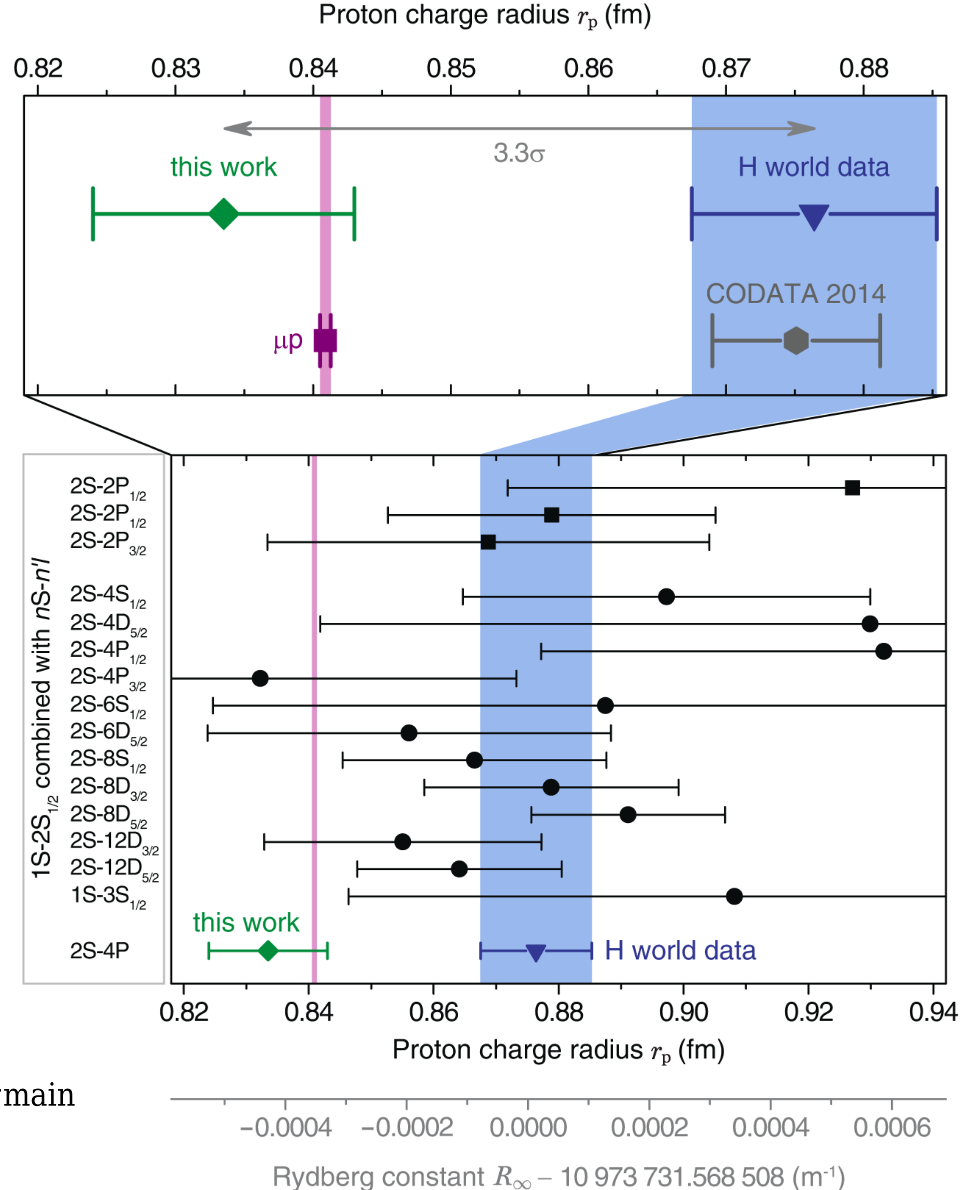


Branching ratio upper limit (μ → eγ equivalent)
Year
μ → e γ
μ -e conv.
μ → eee
Λ[TeV]
10
100
1000
μ⁺→e⁺γ equivalent BR
O(10⁻¹⁴) era
starts soon!
MEG(2011)
MEG(2013)
MEG Final
MEG II
Mu3e
COMET/Mu2e
New Physics

Proton radius puzzle no more...





http://www2.mpq.mpg.de/~haensch/hydrogen/index.php/Research/H2SnP#main

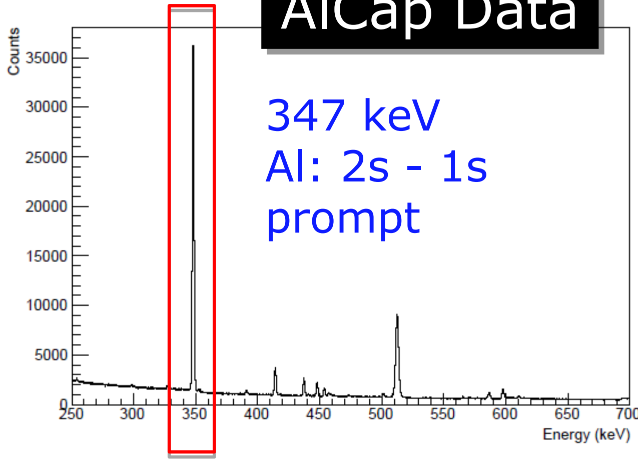
UK contribution (Liverpool, Manchester, UCL): STM

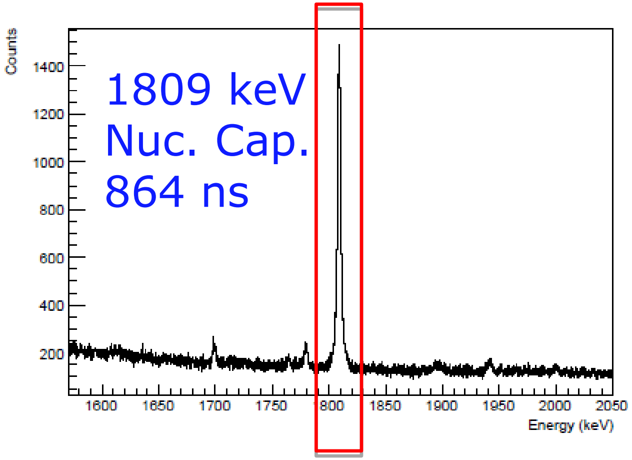
$$\text{Conversion BR} = \frac{\#\mu \rightarrow e}{\#\text{ captured } \mu}$$

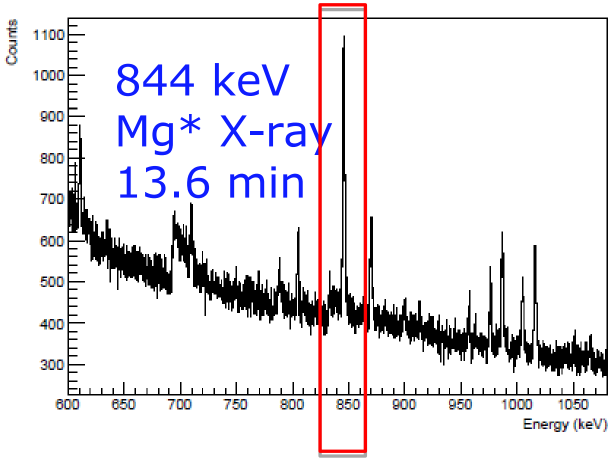
cf luminosity at collider

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

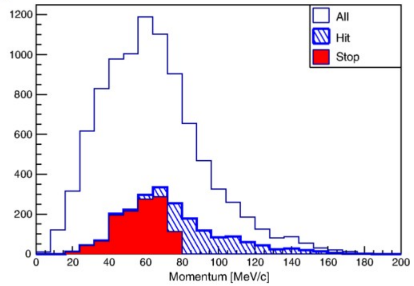
AlCap Data







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

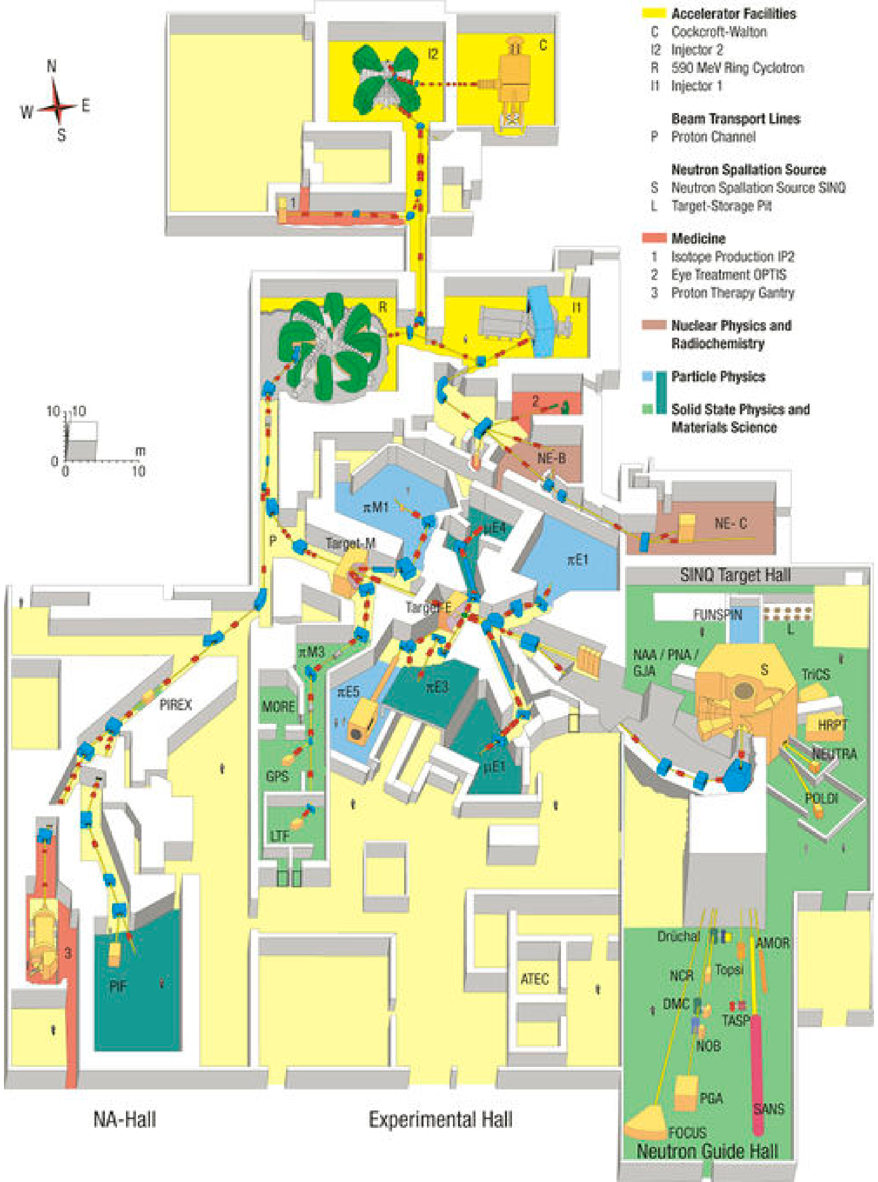


Delivering the world's most intense muon beam

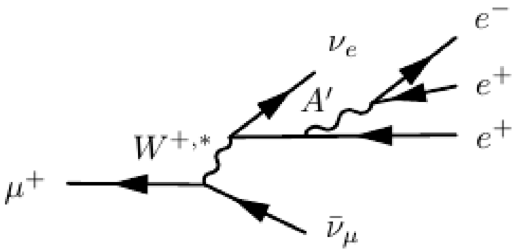
S. Cook, R. D'Arcy, A. Edmonds, M. Fukuda, K. Hatanaka, Y. Hino, Y. Kuno, M. Lancaster, Y. Mori, T. Ogitsu, H. Sakamoto, A. Sato, N. H. Tran, N. M. Truong, M. Wing, A. Yamamoto, and M. Yoshida

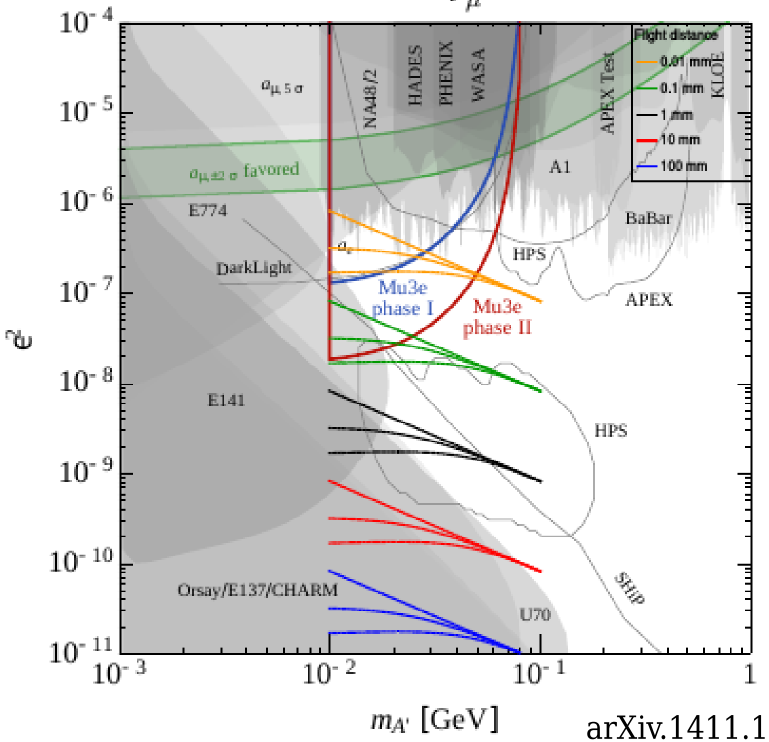
Phys. Rev. Accel. Beams **20**, 030101 – Published 15 March 2017

UK



Dark photons at mu3e



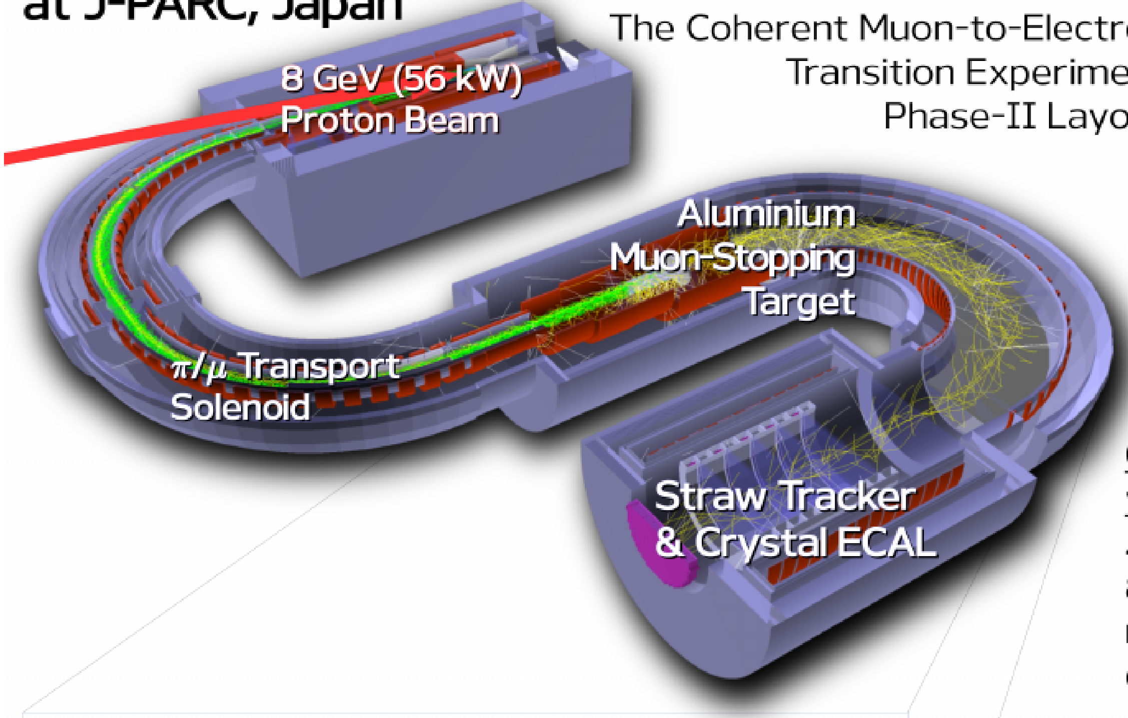


arXiv.1411.1770

The COMET Experiment

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

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



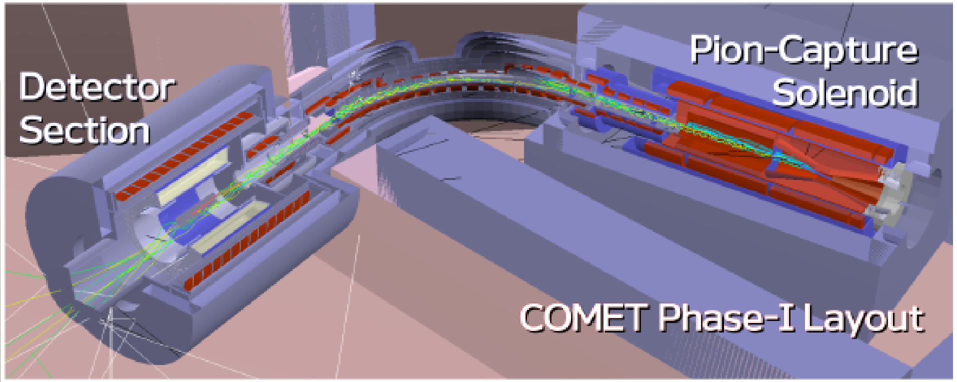
Signal electron density along curved beam line

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

<u>56 kW proton beam:</u> Seven times the muon production rate of Mu2e

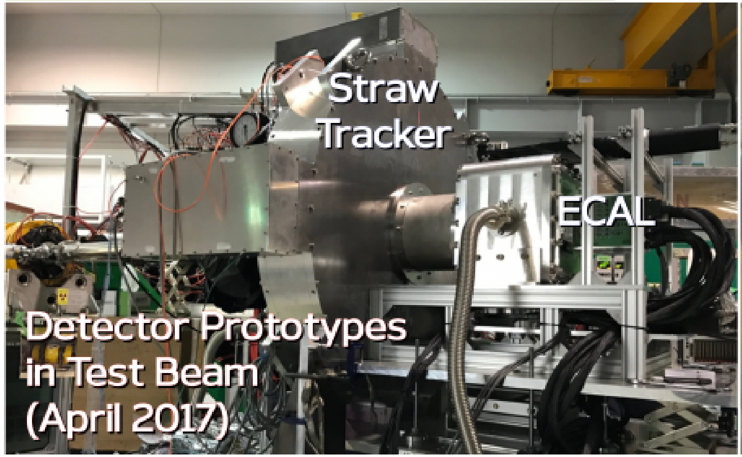
Fully physics study by Ben Krikler (PhD Thesis, 2016)

COMET Phase-I

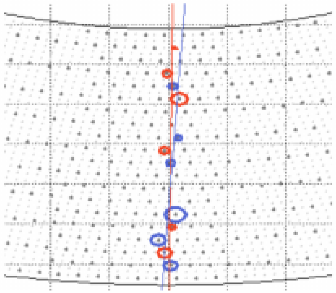


Very high-rate/rare signal experiment

- 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

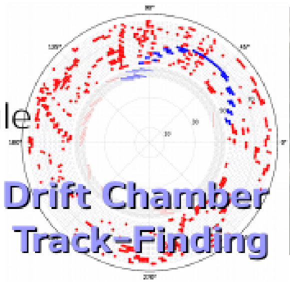
More than 150 collaborators from 32 institutions in 15 countries

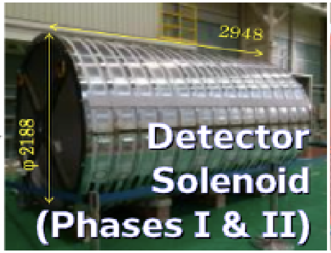
UK leadership includes:

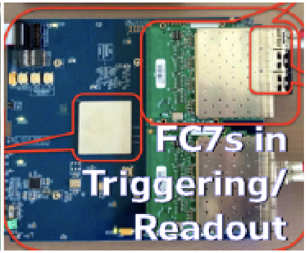
- Founding member, participation since 2006
- Collaboration Board Chair
- Physics and Software Coordinator
- Lead Editor of TDR
- Online/Offline Software, Data Processing
- Triggering/DAQ Electronics and Firmware
- Detector Raw Data Interface
- Triggering, Tracking and Reconstruction

COMET Phase-I

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







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 $B(\mu \to e) = 3 \times 10^{-17}$, but aim to improve using knowledge from Phase-I