New Physics with Muons

g-2, CLFV and more

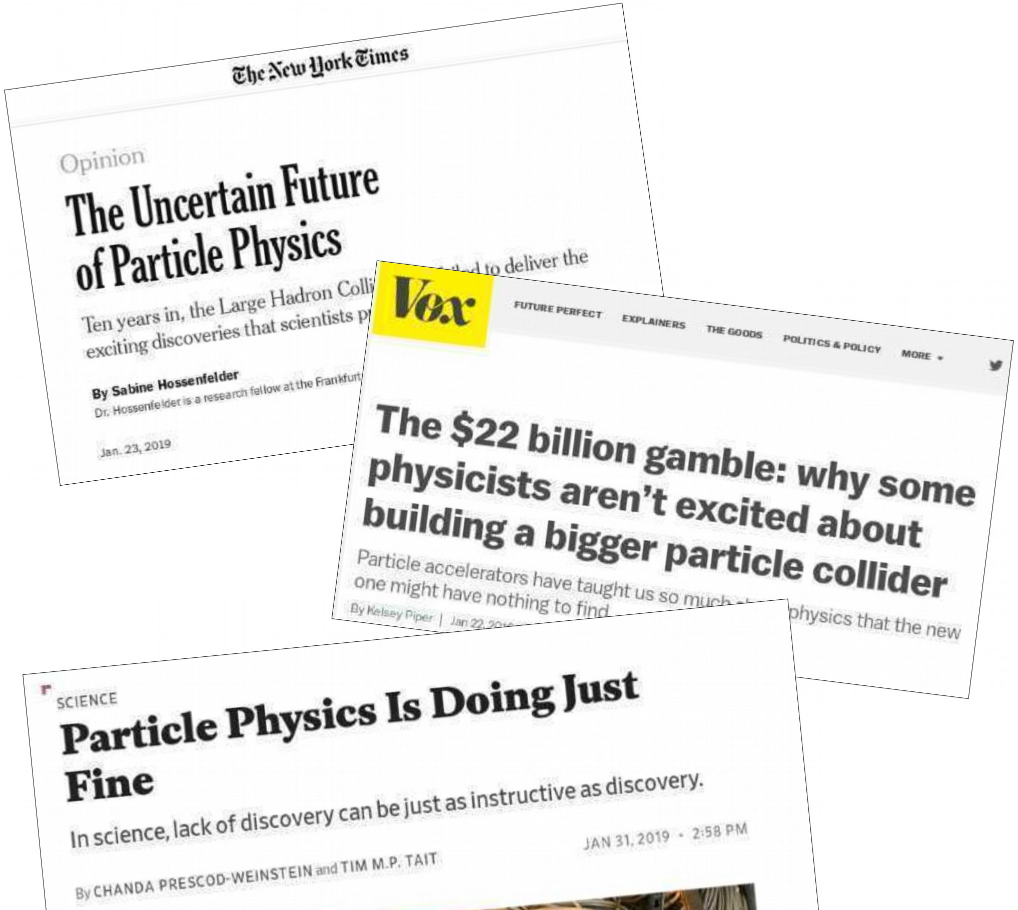
Gavin Hesketh
IoP HEPP Annual Meeting
8/4/19
Thanks to Becky Chislett, Mark Lancaster, Yoshi Uchida, Joost Vossebeld

…or: where is the New Physics?

New physics must exist:

- dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino masses, strong CP, gravity….

…but where is it?



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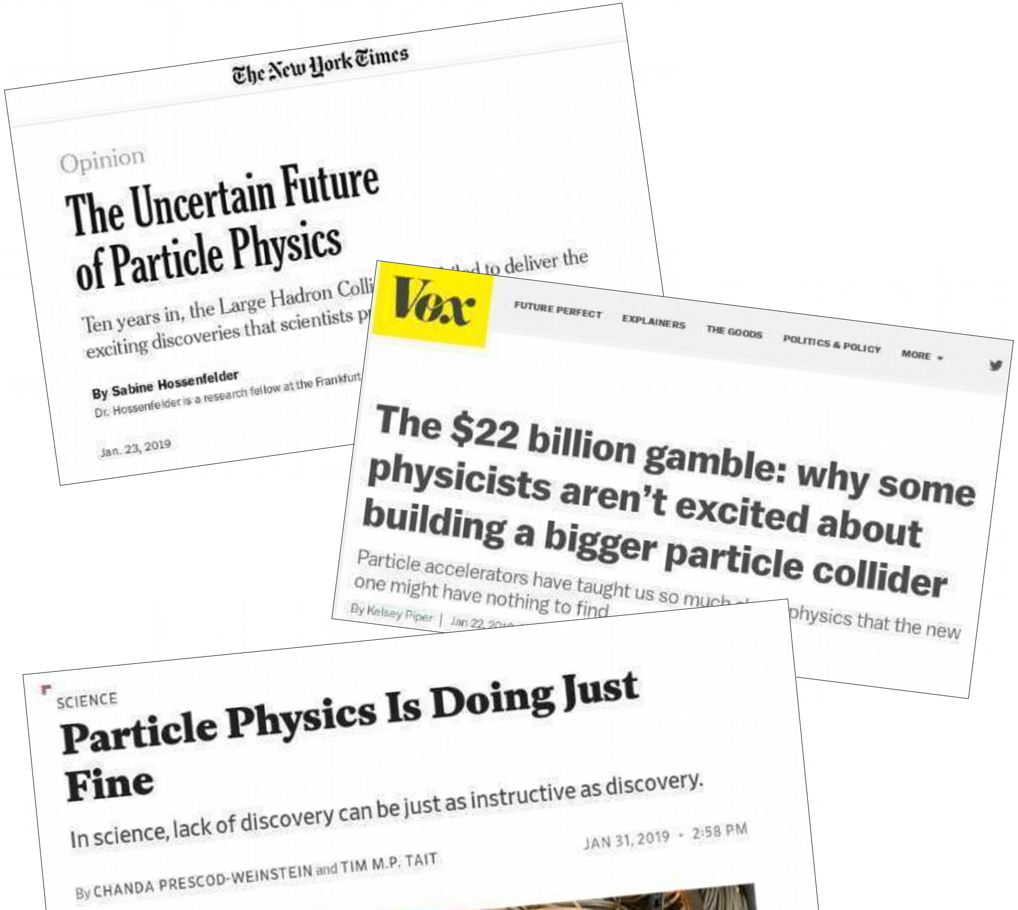
The New York Times
Opinion
The Uncertain Future of Particle Physics
Ten years in, the Large Hadron Colli… …iled to deliver the exciting discoveries that scientists p…
By Sabine Hossenfelder
Dr. Hossenfelder is a research fellow at the Frankfurt…
Jan. 23, 2019

Vox
FUTURE PERFECT EXPLAINERS THE GOODS POLITICS & POLICY MORE
The $22 billion gamble: why some physicists aren't excited about building a bigger particle collider
Particle accelerators have taught us so much… …physics that the new one might have nothing to find.
By Kelsey Piper | Jan 22, 201…

SCIENCE
Particle Physics Is Doing Just Fine
In science, lack of discovery can be just as instructive as discovery.
By CHANDA PRESCOD-WEINSTEIN and TIM M.P. TAIT
JAN 31, 2019 • 2:58 PM

There have been some surprises from the lepton sector:
- neutrino masses
- proton radius puzzle
- semi-leptonic hadron decays
- 3.7σ effect in muon g-2

Lepton g-2 & flavour violation in many BSM models
- linked to leptogenesis of baryon asymmetry

This talk:
- Fermilab Muon g-2
- CLFV: Mu2e, COMET, Mu3e
… + a few other experiments

Part 1: Muon g-2

GIZMODO

VIDEO REVIEW SCIENCE IO9 FIELD GUIDE EARTHER DESIGN PALEOFUTURE

PHYSICS

Why Particle Physicists Are Excited About This Mysterious Inconsistency

Ryan F. Mandelbaum
7/03/18 1:30pm
Filed to: PARTICLE PHYSICS

48.3K 10 9

Forbes

6,854 views | Sep 8, 2018, 10:00am

Ask Ethan: Does The Measurement Of The Muon's Magnetic Moment Break The Standard Model?

Ethan Siegel Senior Contributor
Starts With A Bang Senior Contributor
Science
The Universe is out there, waiting for you to discover it.

FRONTLINE

DISPATCHES
Demonetisation still hurts

SCIENCE & TECHNOLOGY

PHYSICS

Muon conundrum

R. RAMACHANDRAN

physicsworld MENU

particles and interactions

PARTICLES AND INTERACTIONS | RESEARCH UPDATE

Has the muon magnetic moment mystery been solved?

02 Feb 2018 Hamish Johnston

Gravitational effect: the g-2 magnet arrives at Fermilab to be installed experiment

Science

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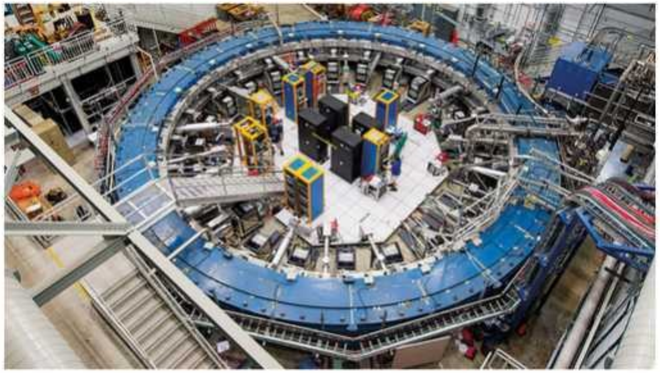


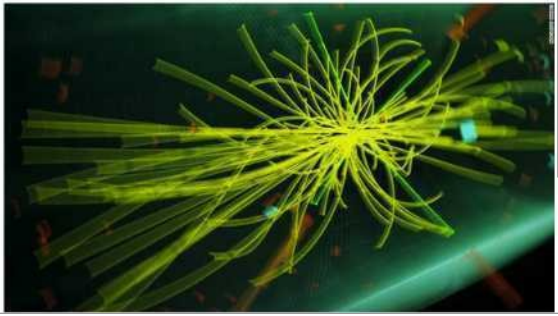
The magnetism of muons is measured as the short-lived particles circulate in a 700-ton ring. FERMILAB

Renewed measurements of muon's magnetism could open door to new physics

CNN Home

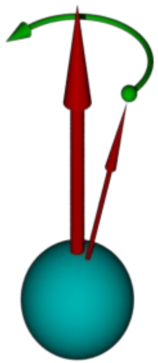
Scientific breakthrough could be as simple as measuring the wobble of a muon

By Don Lincoln
Updated 1648 GMT (0048 HKT) February 13, 2018



Fermilab @Fermilab · 3h
"If I were to put my money on something that would signal new physics, it's the g-2 experiment at Fermilab."

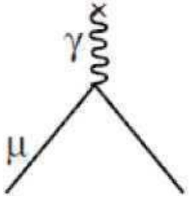
We Asked Celeb Physicist Brian Cox About Flat Earth Conspiracies, the ...
gizmodo.com



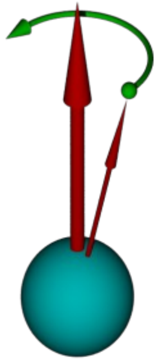
Spin precession of the magentic moment around external field:

$$\omega_s = \frac{gqB}{2\,m}$$

The g-factor of charged leptons:



- g = 2 (Dirac)



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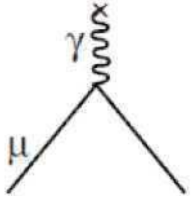

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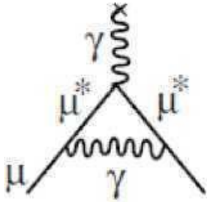
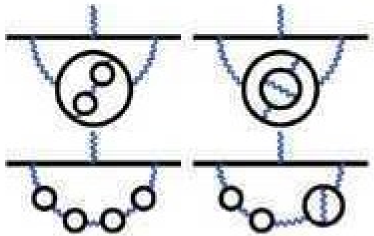


+ $\alpha/2\pi$ (Schwinger)



++...

+ *up to O(5) in QED*
12,672 diagrams! arXiv:1712.06060

Anomalous term, a=(g-2)/2, contains all loops – QED dominates for electrons

Recent measurement: $1/\alpha$=137.035999046(27) *Science, 13 V360, 6385, 2018*
→ new prediction: a_e = 0.00115965218161(23) PRD 97(2018)036001

Why Muons?

Electrons:

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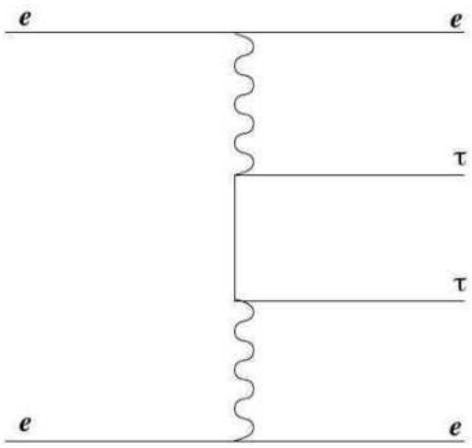
QCD and EWK loops become important for heavier leptons

... and new physics may enter @ $(m_{lepton} / M_{np})^2$



taus?

- prediction: $a_\tau = 0.00117721(5)$ Mod.Phys.Lett.A22:159-179,2007
- measured: $-0.052 < a_\tau < 0.013$

Delphi Collaboration, Eur.Phys.J.C35:159-170,2004

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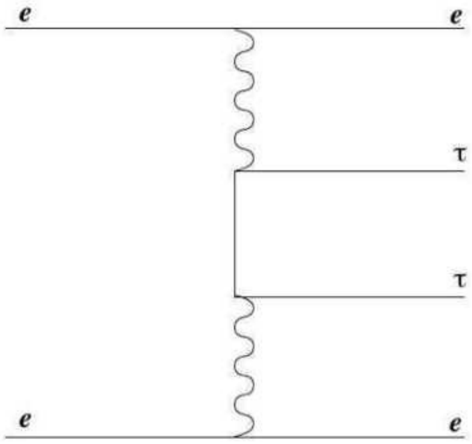

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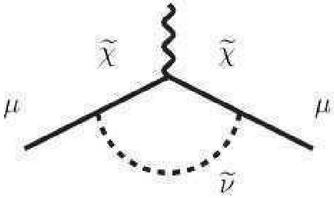
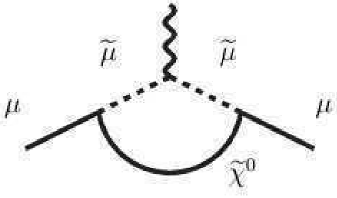
muons!
Long-standing tension:
- prediction: $a_\mu \sim 0.00116591821(36)$ KNT18, PRD97, 114025
- measured: $a_\mu = 0.00116592089(63)$ PRD 73(2006)072003

→ ***3.7σ difference***





Electrons:

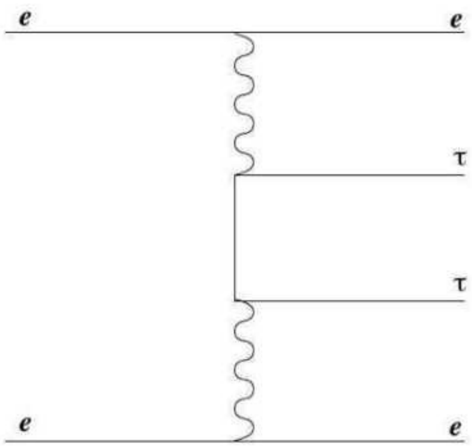
prediction: $a_e = 0.00115965218161(23)$ PRD 97(2018)036001

measured: $a_e = 0.00115965218073(28)$ PRL 100(2008)120801

→ 2.4σ difference

QCD and EWK loops become important for heavier leptons

... and new physics may enter @ $(m_{lepton} / M_{np})^2$



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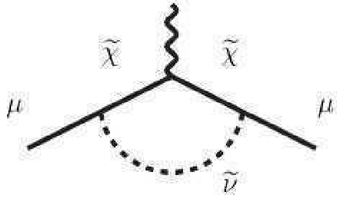
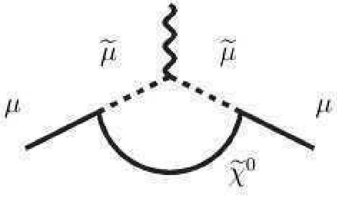
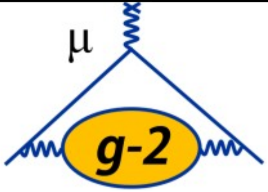




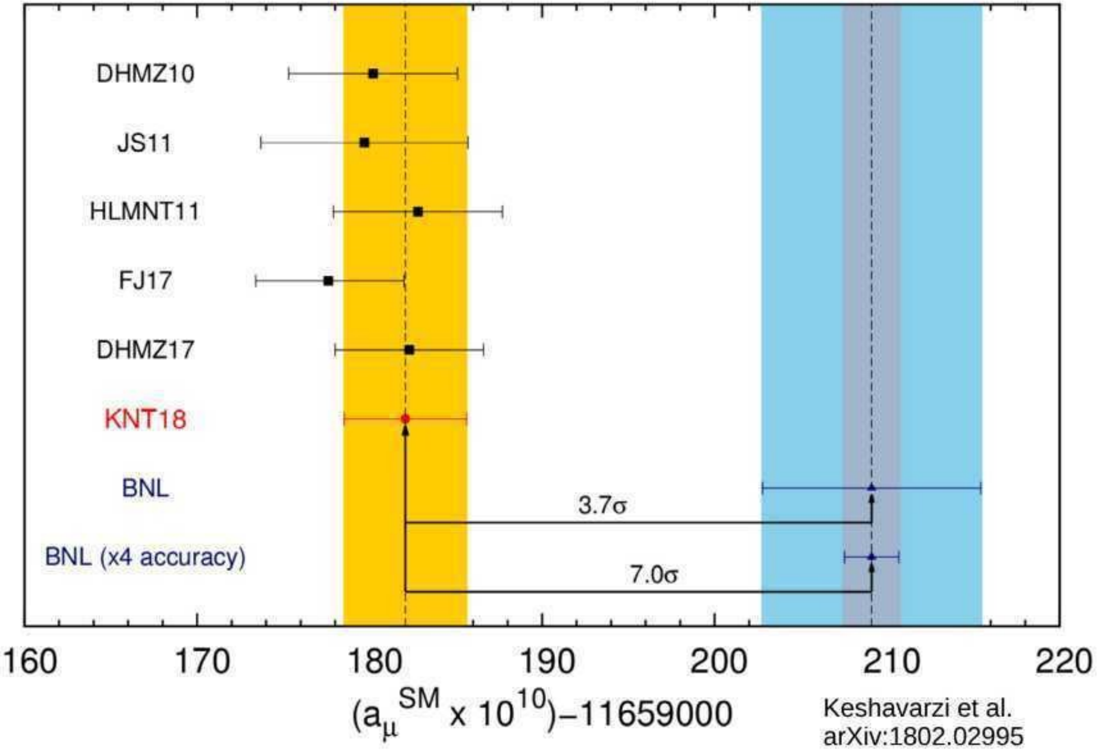


Fermilab Muon g-2 experiment (E989)

- factor 4 improvement over Brookhaven (E821) result
  - precision of 140 ppb

BNL → FNAL

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



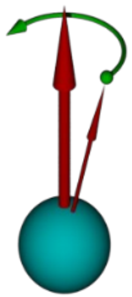
34 institutes, 185 collaborators

UK: Lancaster, Liverpool, Manchester, UCL

- *Spokesperson, Run Coordinator, DAQ experts*

Put muons in a magnetic field, measure precession frequency

$$\omega_s = \frac{gqB}{2m} = \frac{(2+2a_\mu)}{2}\frac{qB}{m} = (1+a_\mu)\frac{qB}{m}$$



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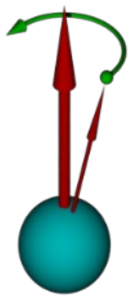
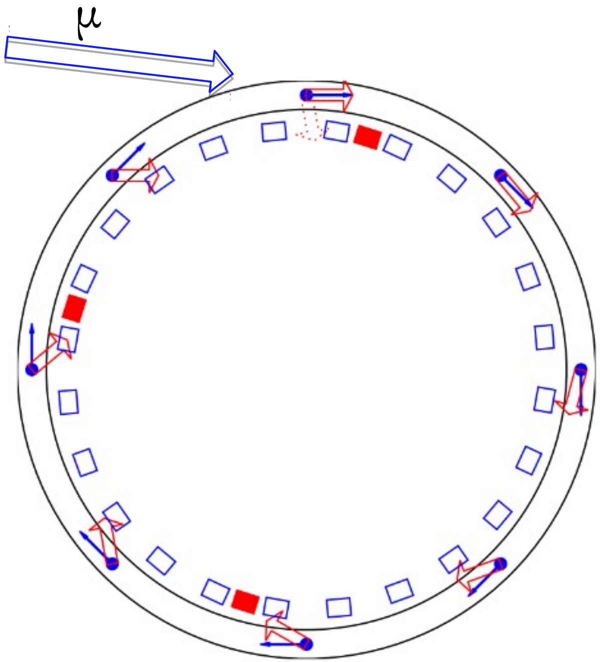


Storage ring cyclotron frequency:

$$\omega_c = \frac{qB}{m} \quad \Rightarrow \quad \boxed{\omega_a = \omega_s - \omega_c = a_\mu \frac{qB}{m}}$$

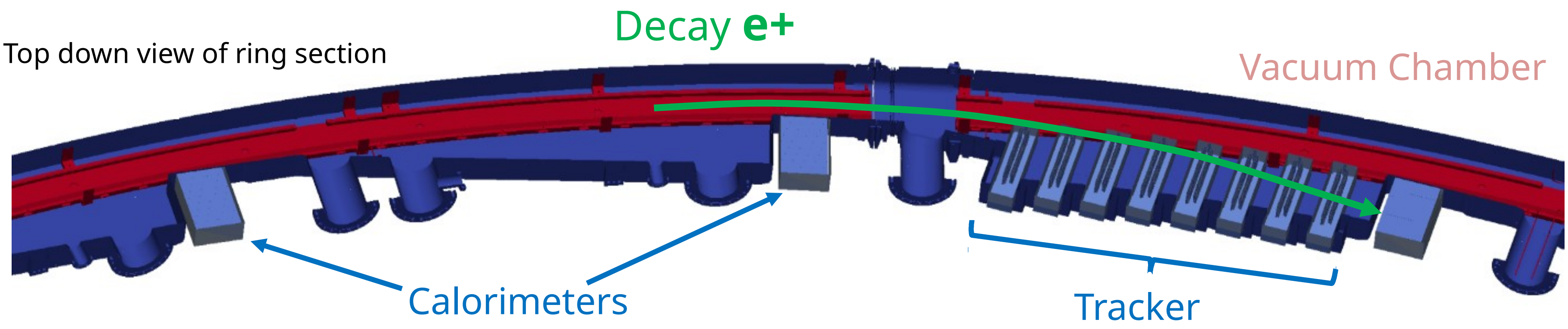


Electric focusing fields introduce further coupling:

Use "magic momentum" 3.09 GeV

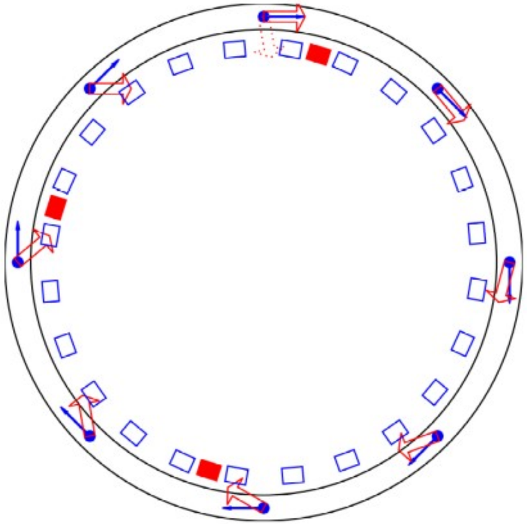
$$\omega_a = -\frac{q}{m}\left[a_\mu B - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\beta \times E}{c}}\right]$$

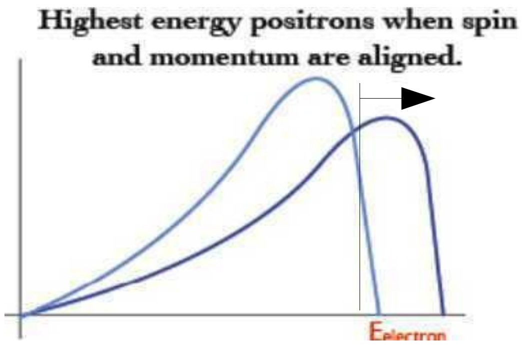
Wiggle plots

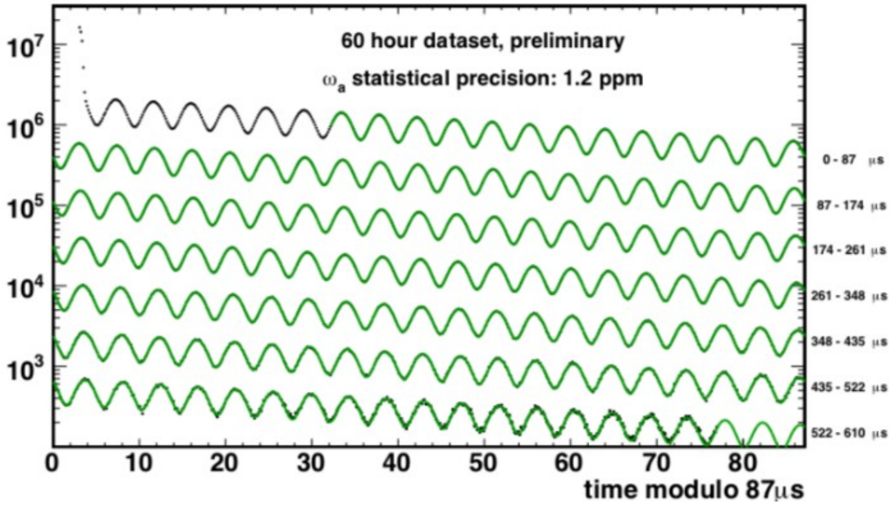


Main energy measurement made using 24 calorimeters

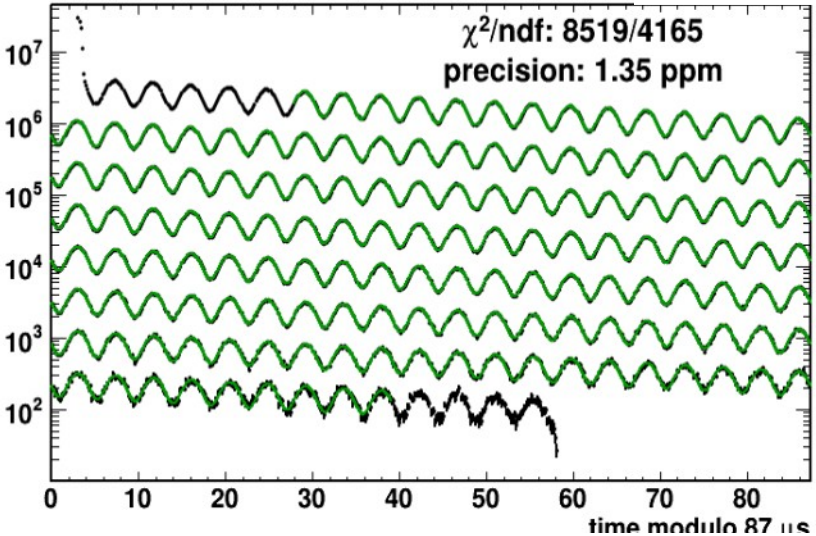
- fast response lead-flouride Cherenkov crystals (9x6 crystals, each 25 x 25 x 140 mm), resolution 2.3% at 3 GeV

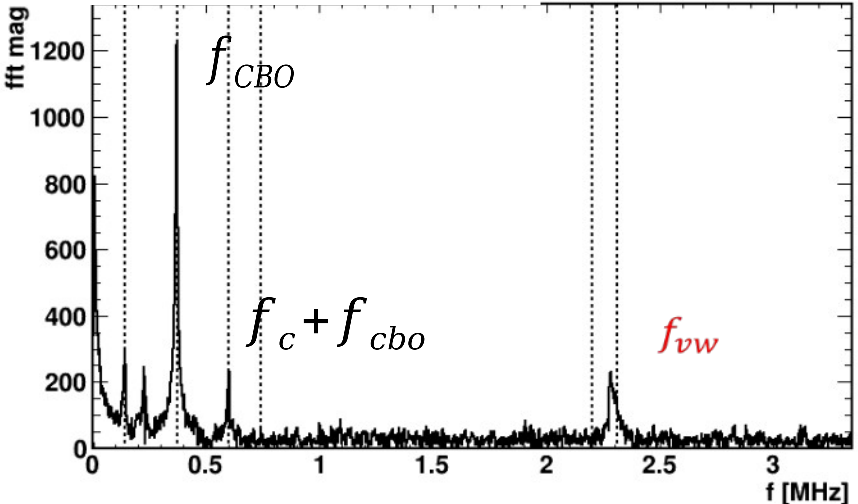






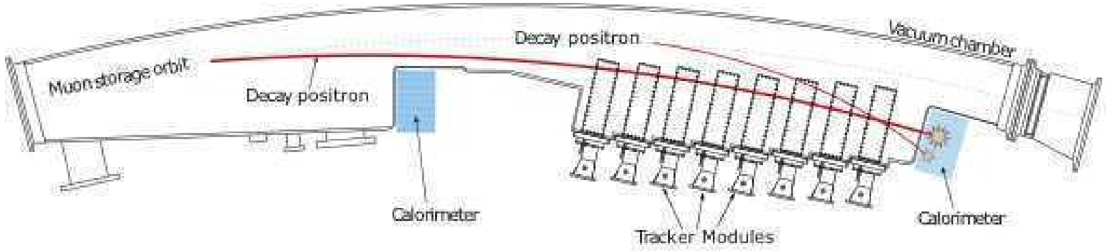
Improved Wiggle

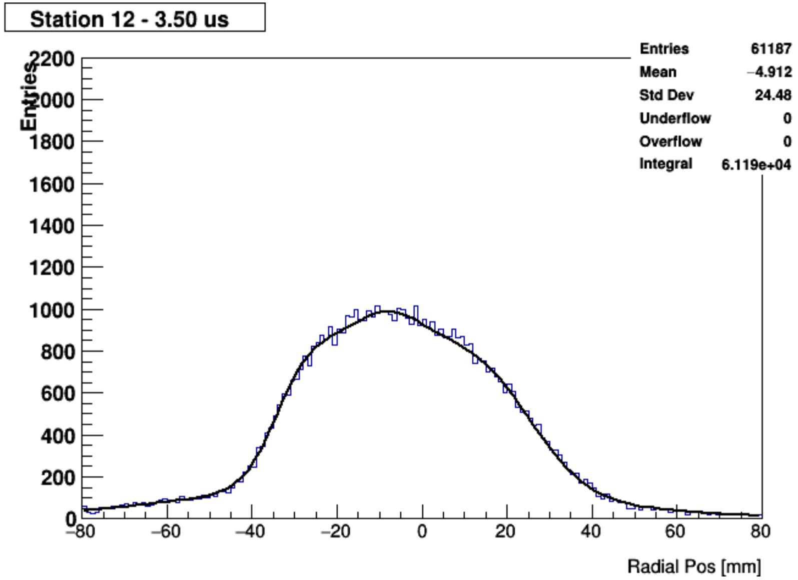




UK contributed new tracking detectors in front of two calorimeters

- 8 modules, 4 rows (2 x stereo) per module, 32 straws per row





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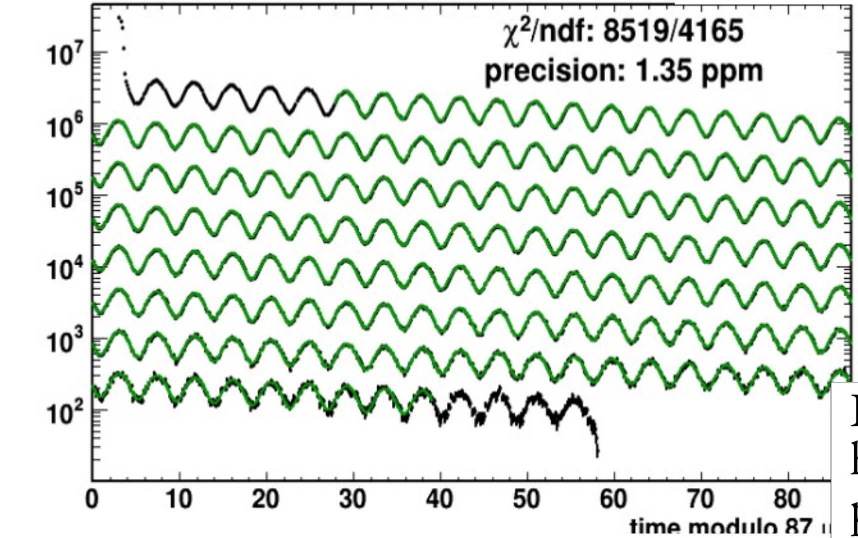
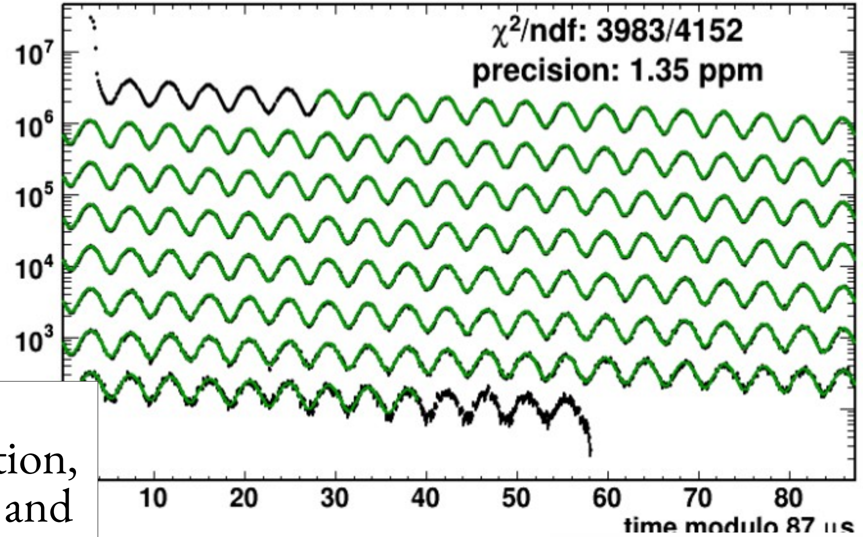
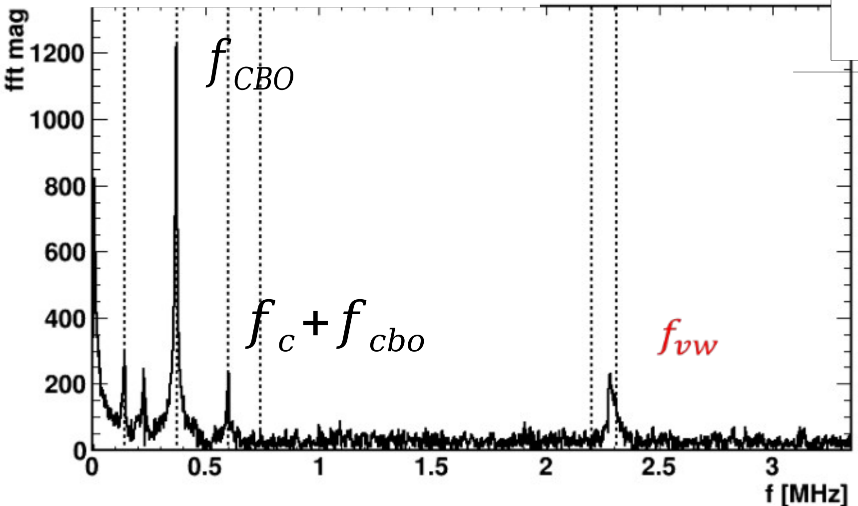
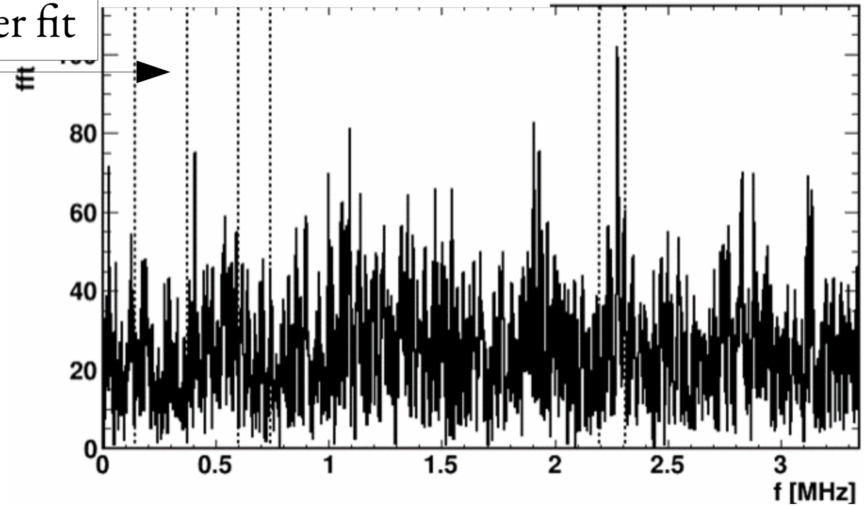




Include vertical and horizontal beam motion, pile-up, muon losses and energy scale:
→ 9 or 13 parameter fit





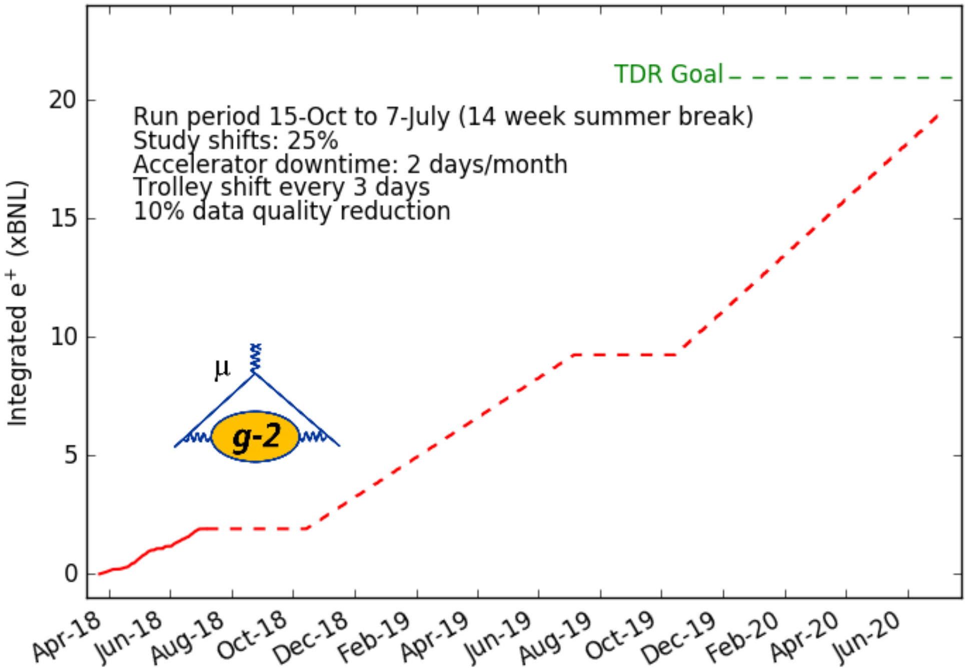
Status

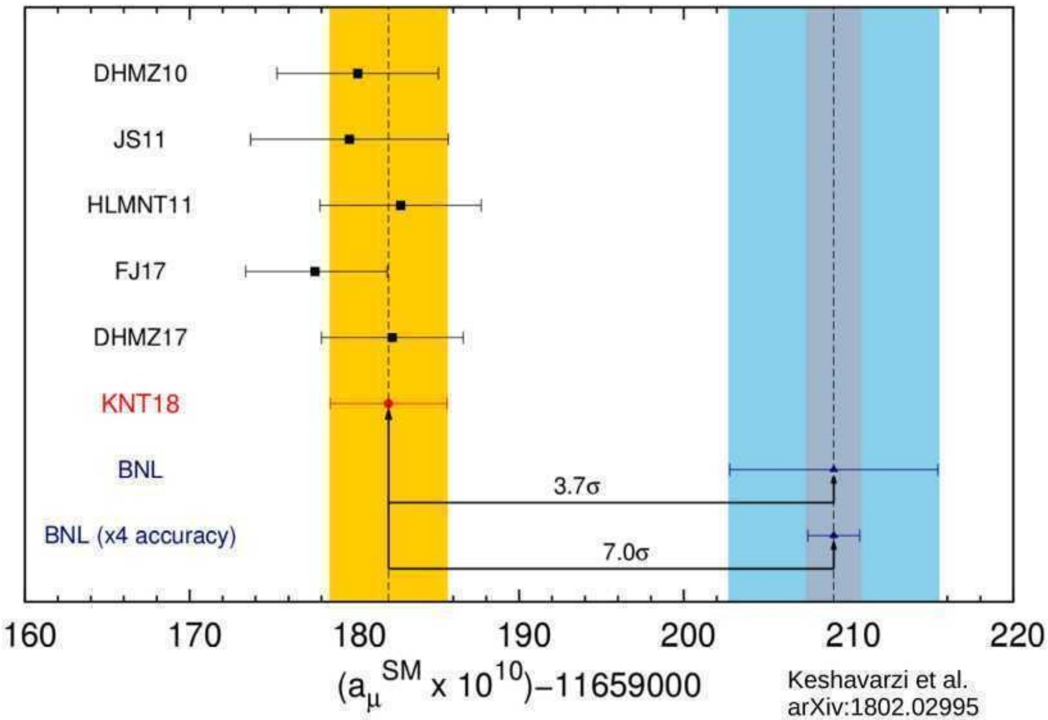
First data-taking run complete:

- 5 months running, > 2x Brookhaven stats (took 5 years!)
- publish in 2019 (currently still blinded)
- run 2 underway

Target for end 2020: 20 x BNL

→ could push significance to ~5-10σ



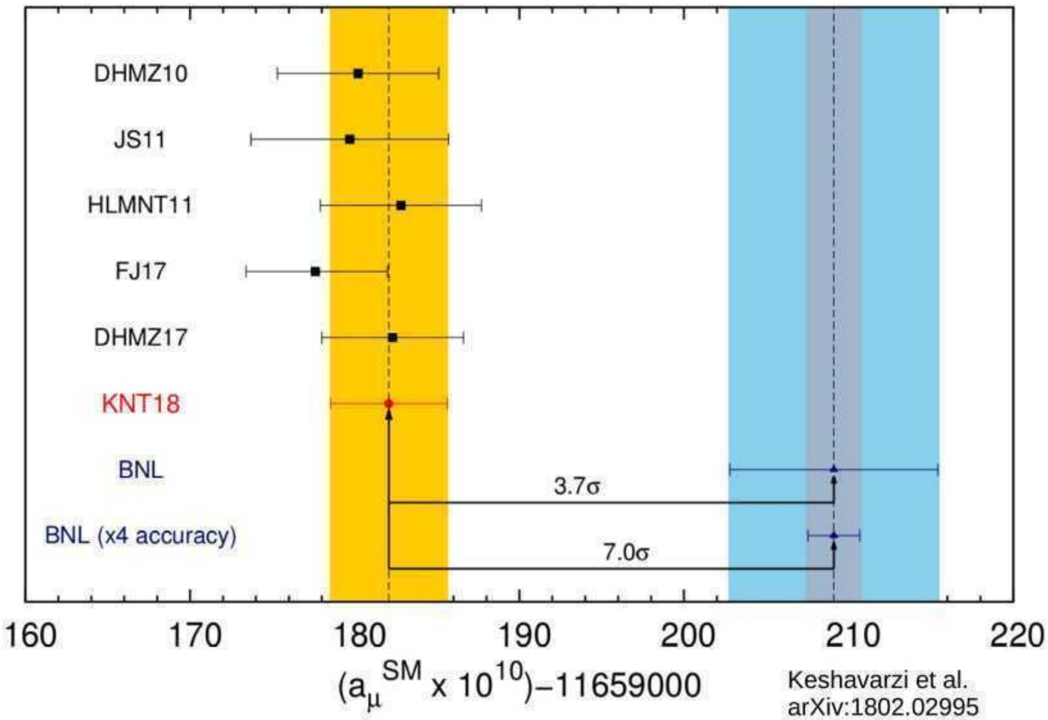


What would it mean..?

Further experimental confirmation?

→ *Planned g-2 experiment at J-PARC*

- different techniques, different systematics



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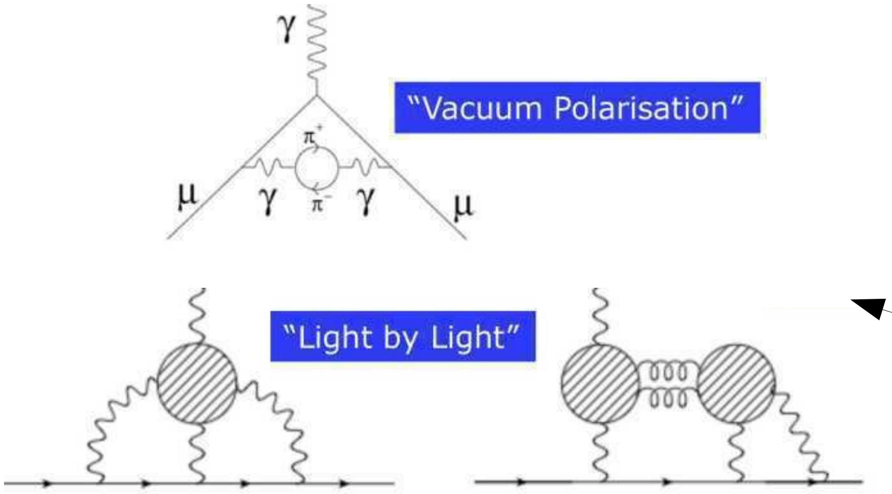
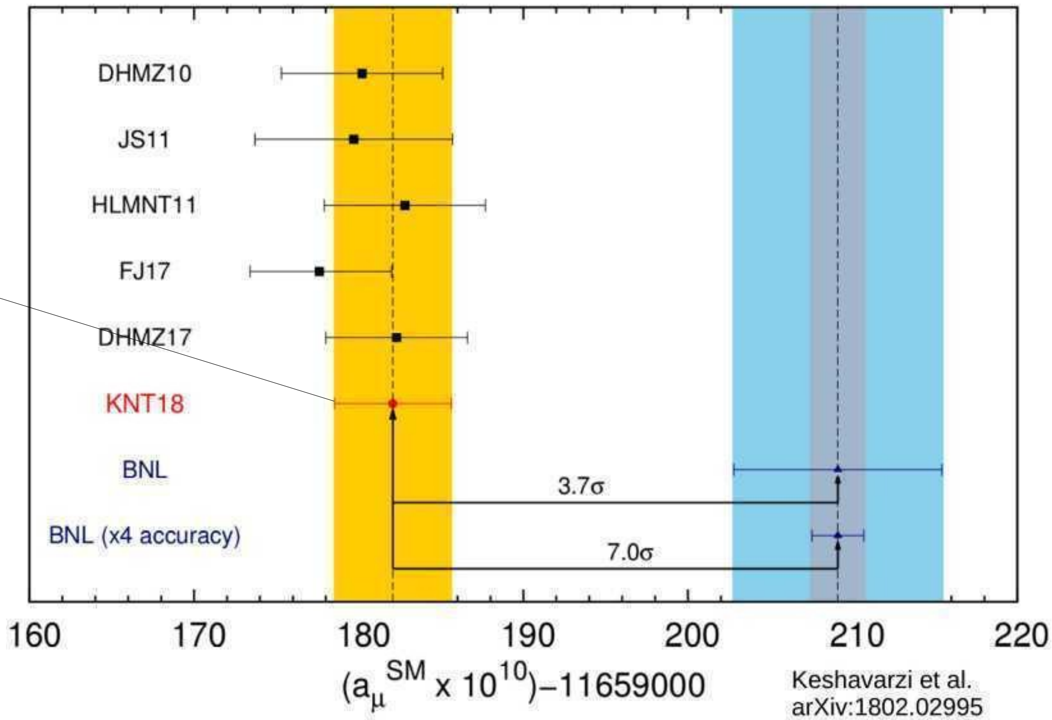
Muon g-2 theory initiative underway:

https://indico.him.uni-mainz.de/event/11/overview



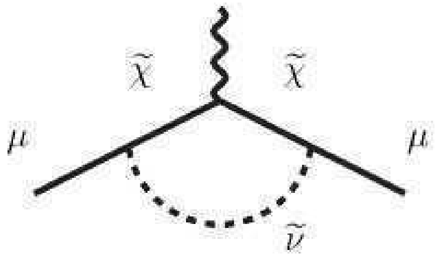


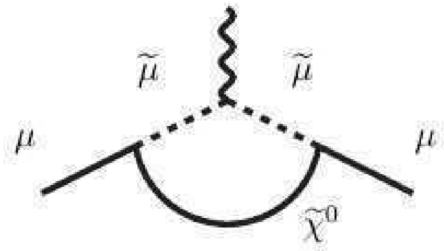
Low energy QCD...

- input from ee→hadrons
- proposed MUonE experiment at CERN

...or lattice calculations

g-2: new physics?





SUSY?

- Needs $\mu>0$, 'light' SUSY-scale (Λ) and/or large tan β

…already ruled out by the LHC?

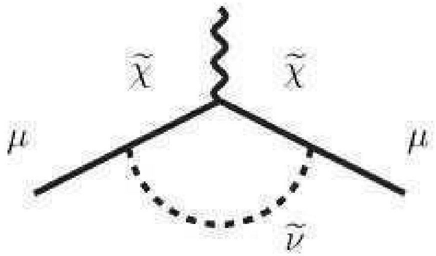
$$a_\mu^{\text{SUSY}} \simeq sgn(\mu)\, 130 \times 10^{-11} \tan\beta \left(\frac{100\,\text{GeV}}{\Lambda_{\text{SUSY}}}\right)^2$$

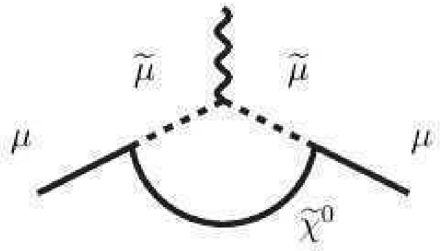
Many other ideas out there, eg:

- 1 TeV Leptoquark Bauer + Neubert, PRL 116 (2016)
- 2 Higgs doublet model Stockinger et al., JHEP 1701 (2017) 007
- axion-like particle Marciano et al, PRD 94 (2016) 115033
- dark photon eg Feng et al, PRL 117 (2016) 071803

See also Thomas Teubner's talk at UK HEP Forum, Nov 2018

g-2: new physics?





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Complementary measurements needed to resolve model dependency if signal confirmed

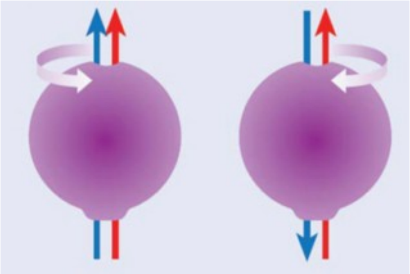
If tension resolved, will set tight limits on these new physics scenarios

- will also want experiments that can probe higher mass scales in search for new physics

→ EDMs, CLFV experiments

Part 2: Electric Dipole Moments

Fundamental particles can also have an EDM
- zero at tree level in SM
- can be boosted by BSM loops



Existence of EDM → additional source of CP violation

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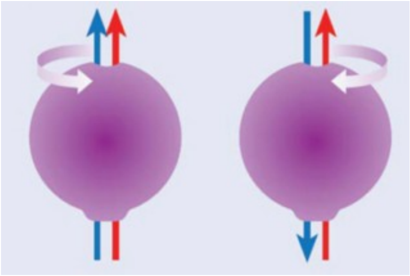
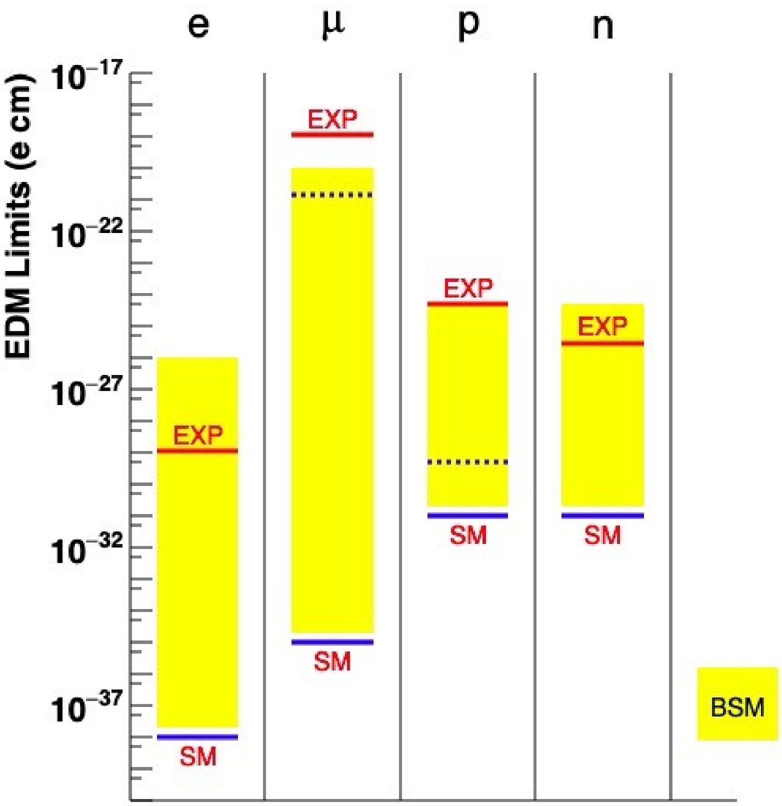


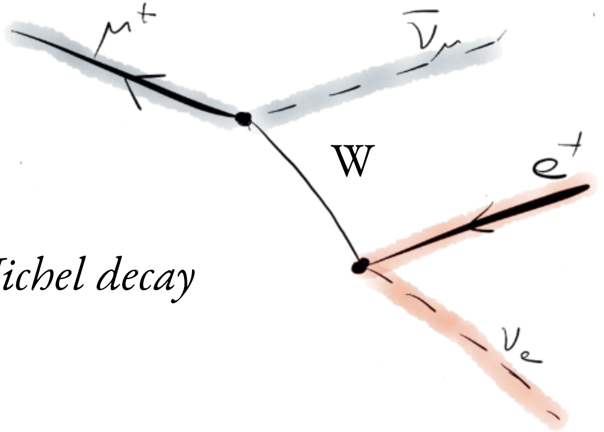
Existence of EDM → additional source of CP violation

→ Fermilab g-2 will give 100x improvement in muon EDM limit
- non-zero EDM would cause to out-of-plane precession
- an upgrade (24 x new trackers) would push limit further…

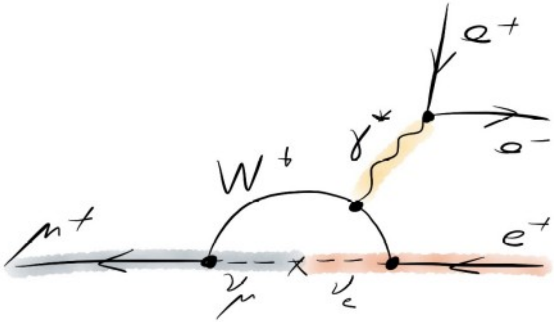
Development work for proton EDM ring underway
- part of CERN's "*Physics Beyond Colliders*" programme.



Part 3: Charged Lepton Flavour Violation



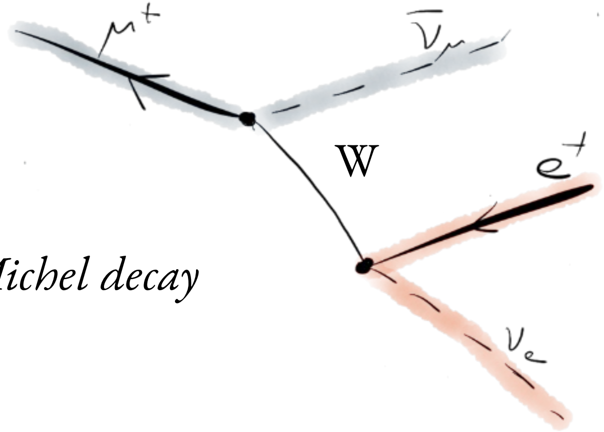
Michel decay



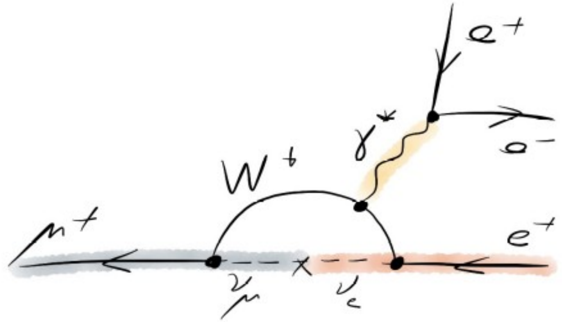
CLFV decay

Neutrino oscillations violate lepton flavour conservation
→ technically possible in charged lepton sector
  …but suppressed by ~10^{-50}

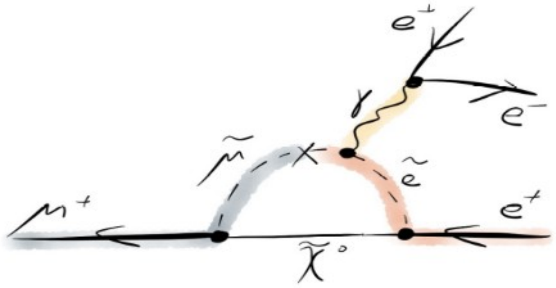
Part 3: Charged Lepton Flavour Violation



Michel decay



CLFV decay



Neutrino oscillations violate lepton flavour conservation
→ technically possible in charged lepton sector
...but suppressed by ~10^{-50}

Put BSM physics in the loop → increase the rate

Any observation of CLFV is new physics!

Could show limits on:

- *leptoquarks, compositeness, Higgs doublets, heavy neutrinos...*

Instead, parametrise using an effective Lagrangian

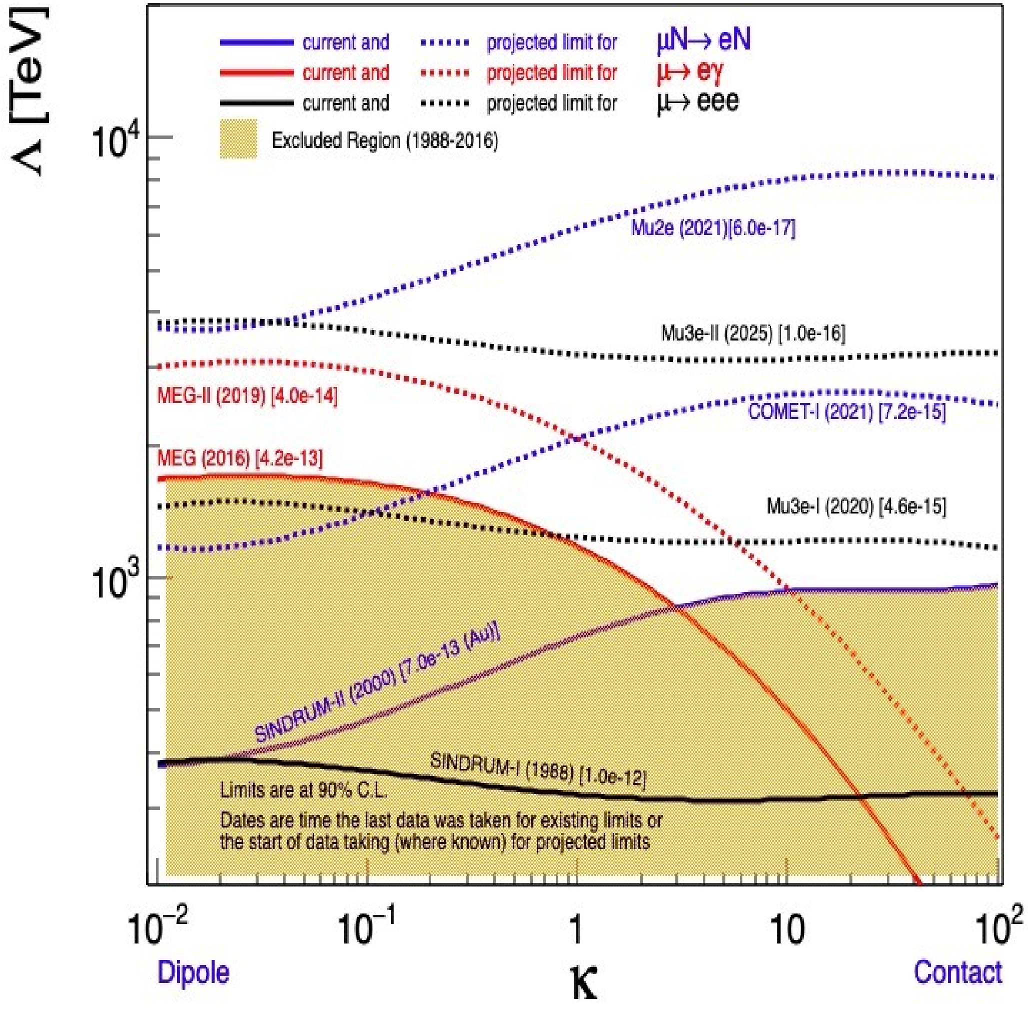
de Gouvea & Vogel, arXiv 1303.4097

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

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

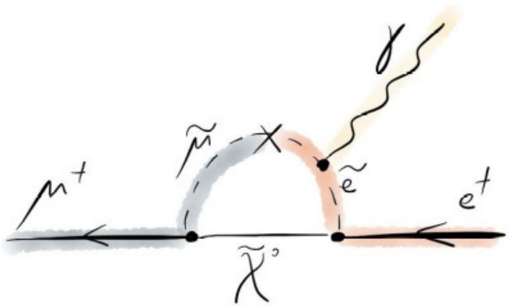
Step-change in sensitivity in coming years

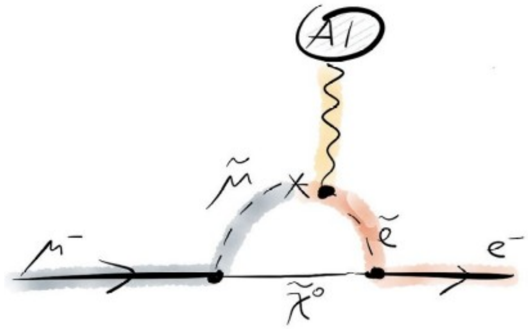
...probing mass scales up to 10,000 TeV

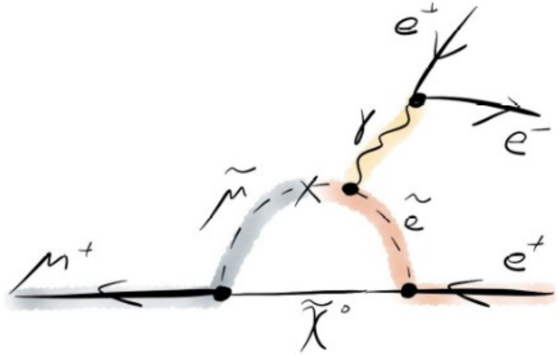


Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

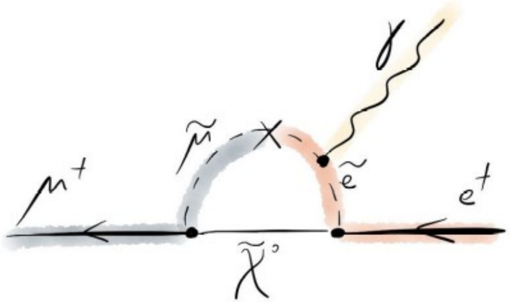
CLFV

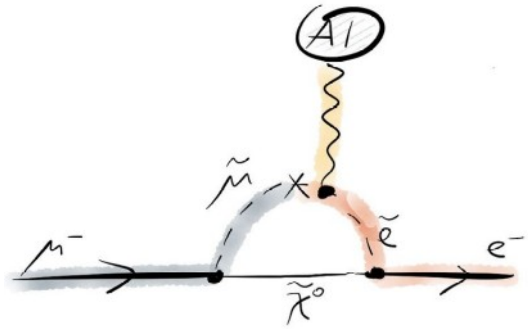


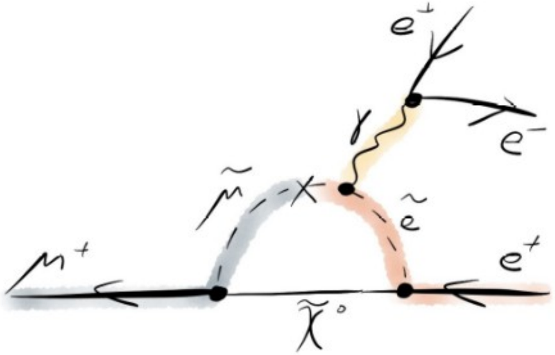




MEG-II @ PSI:
- physics in 2019
- x10 on limit
→ 10^{-14} after 3 years
11 institutes, 75 collaborators
- no UK involvement







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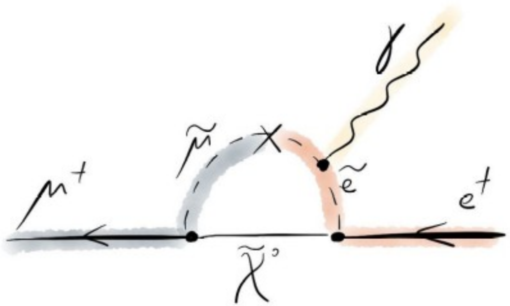
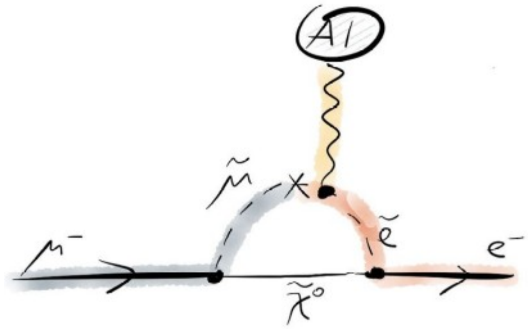
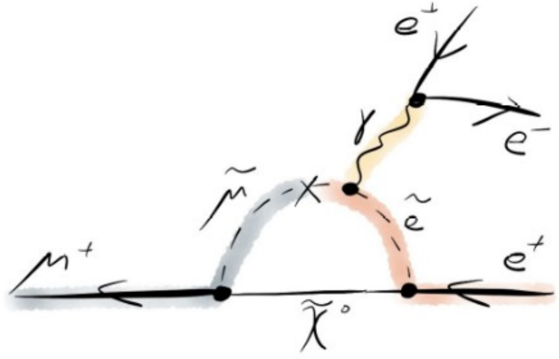
Mu2e @ FNAL
COMET @ JPARC
- starting 2022 /2020
- x10^{4} on limit
→ 10^{-17} 4 yrs, COMET phase 2

Mu2e:- L'pool, Manchester, RAL, UCL
COMET: Imperial

CLFV







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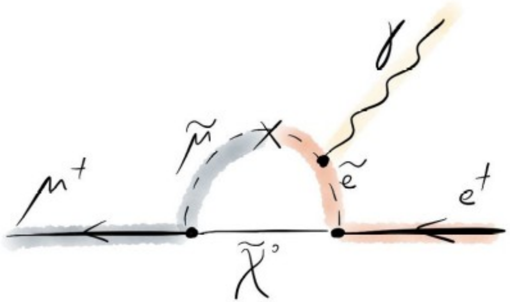
COMET: Imperial

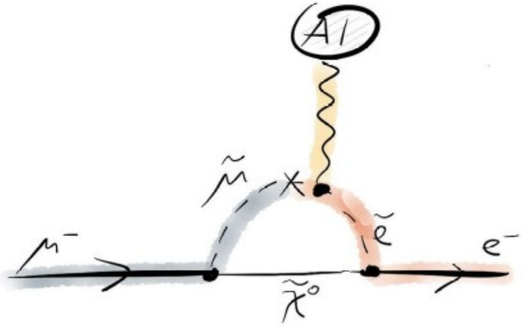
Mu3e @ PSI
- phase 1 (2020) & 2 (2025)
- x10^4 on limit
→ 10^{-16} after phase 2
11 institutes, 60 collaborators
- Liverpool, Bristol, Oxford, UCL

CLFV



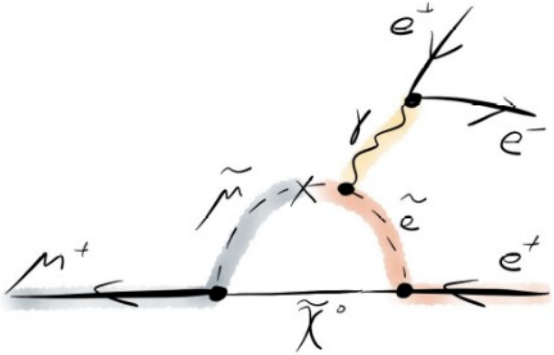
MEG-II @ PSI:
- physics in 2019
- x10 on limit
  → 10^{-14} after 3 years

11 institutes, 75 collaborators
- *no UK involvement*



Mu2e @ FNAL
COMET @ JPARC
- starting 2022 /2020
- x10^4 on limit
  → 10^{-17} ~4 yrs, COMET phase 2

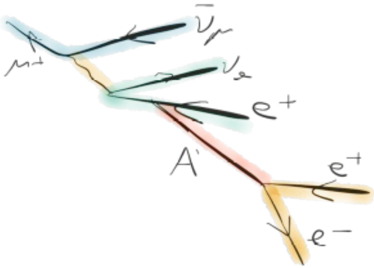
Mu2e:- L'pool, Manchester, RAL, UCL
COMET: Imperial



Mu3e @ PSI
- phase 1 (2020) & 2 (2025)
- x10^4 on limit
  → 10^{-16} after phase 2

11 institutes, 60 collaborators
- Liverpool, Bristol, Oxford, UCL

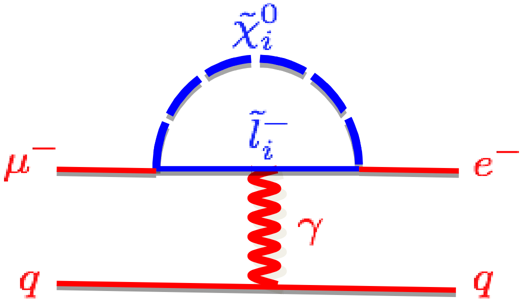
Complementary experiments:
- Mu2e/COMET: quark and lepton couplings
- Mu3e purely leptonic, can also search for dark photons, ALPS, etc



One CLFV interaction in 10^{17} muon decays is like…

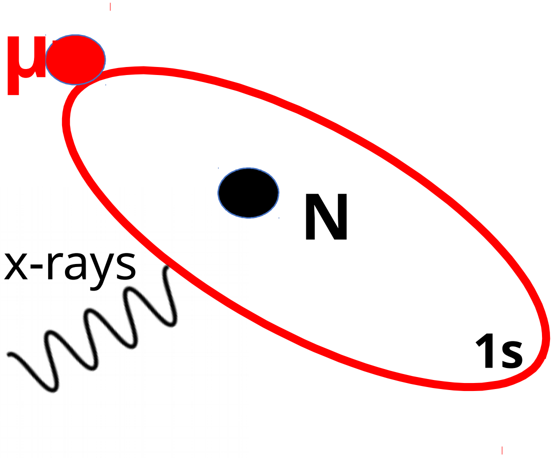
looking for one specific grain of sand

μN → eN



Stop muons on an Al target

- x-ray emission from capture → normalisation

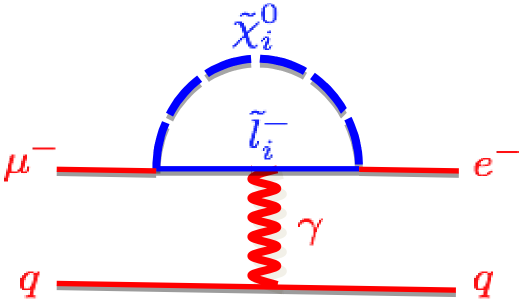


$$E_e = m_\mu - E_{bind} - E_{recoil}$$
$$= 105.67 - 0.47 - 0.22\ MeV$$
$$= 104.98\ \mathbf{MeV}$$

Mu2e, COMET

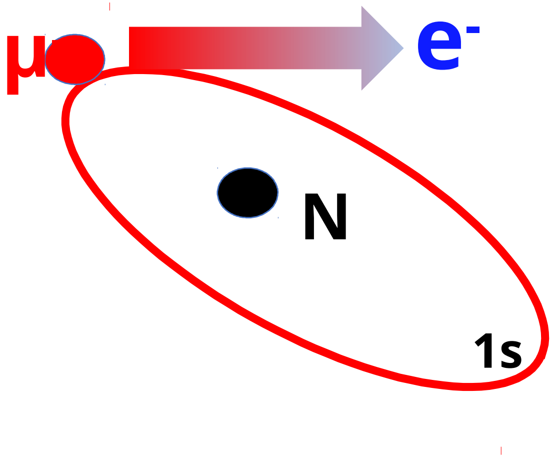
UCL

$\mu N \to eN$



Stop muons on an Al target
- x-ray emission from capture → normalisation

Signal of neutrino-less conversion:
mono-energetic electron



$$E_e = m_\mu - E_{bind} - E_{recoil}$$
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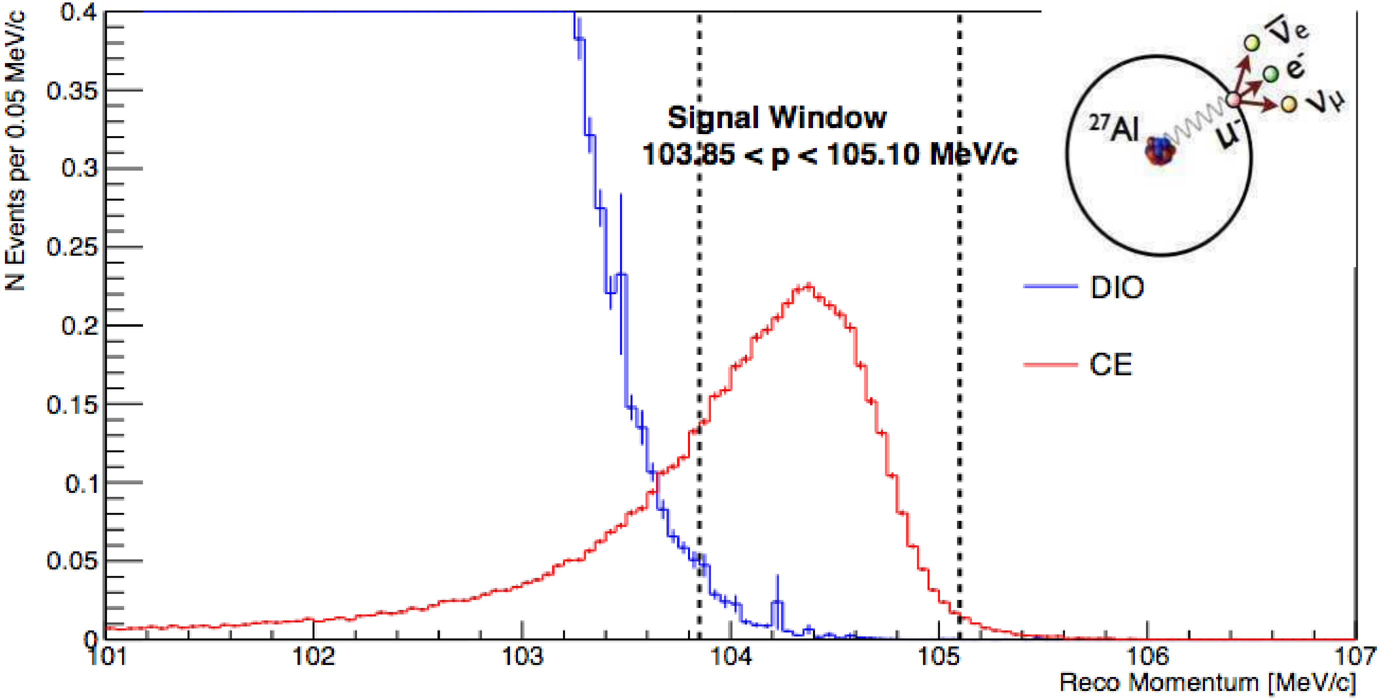
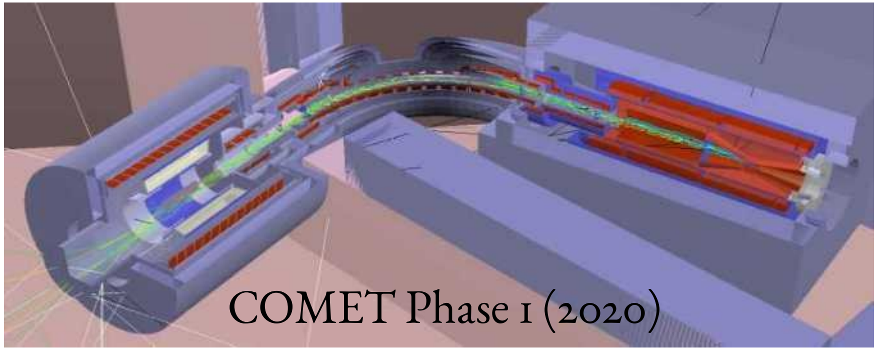
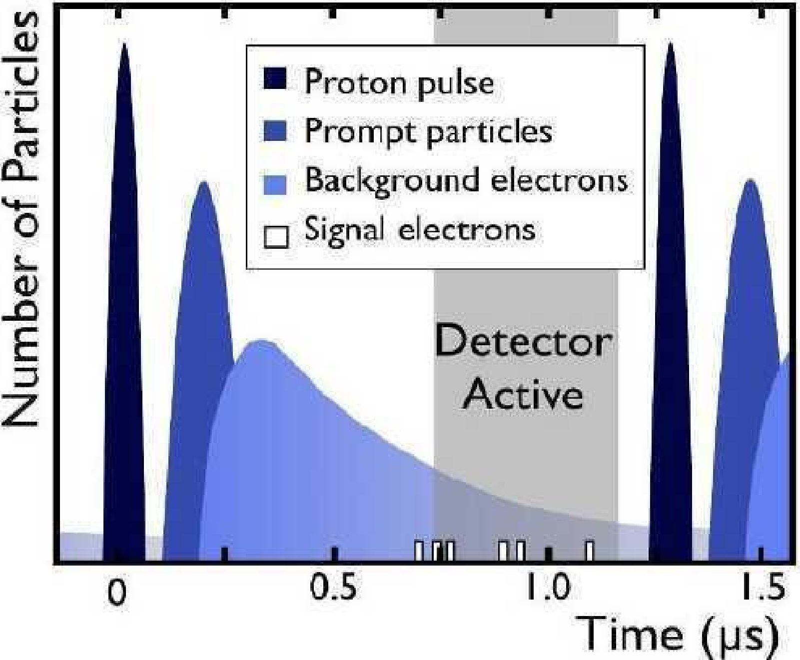


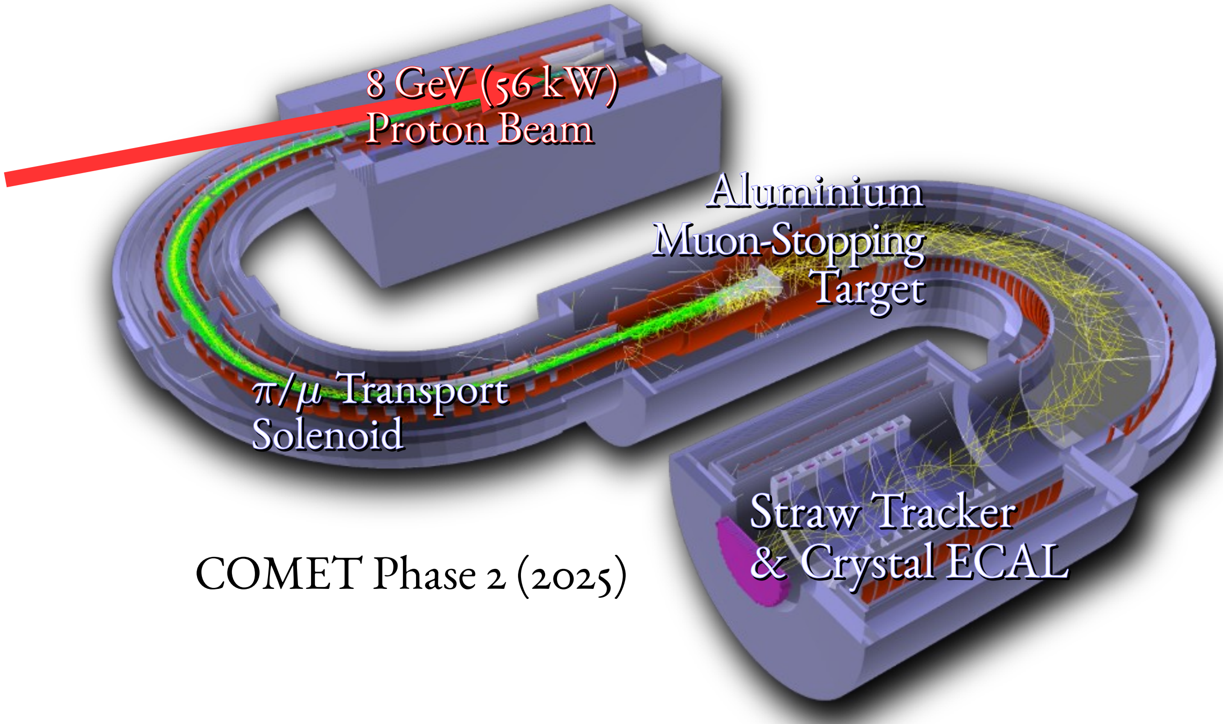
COMET

Muon lifetime on Al: 864 ns

Prompt backgrounds:
- Curved solenoid transport channel
- Pulsed beam with strong extinction factor ($<10^{-9}$)

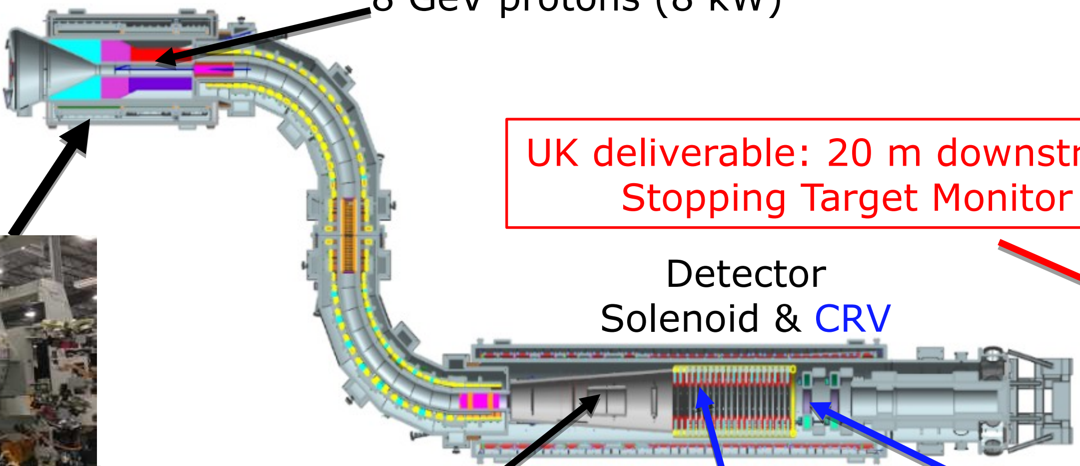






Production Target

Production Solenoids

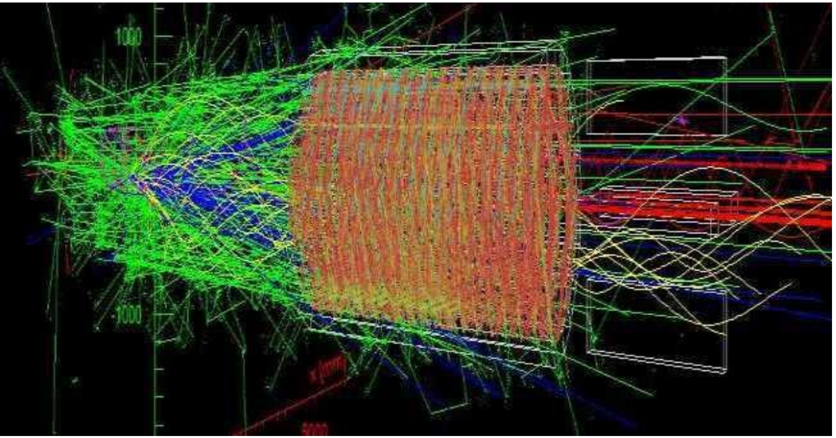


UK deliverable: 20 m downstream
Stopping Target Monitor

Mu2e follows g-2: 2021

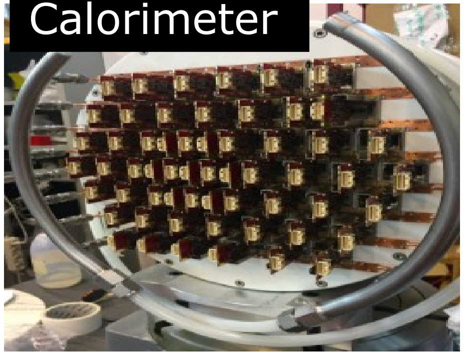
Mu2e-II:

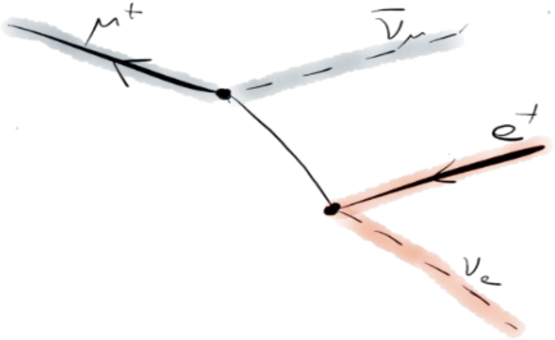
- use PIP-II beam
  100 kW @ 800 MeV
- further x10 on limit
- part of 2020 P5



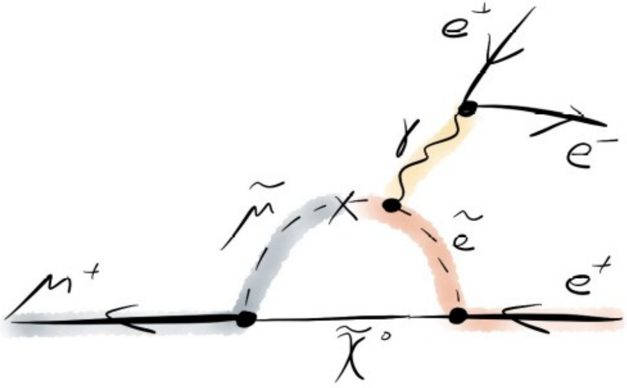
Tracker

Calorimeter



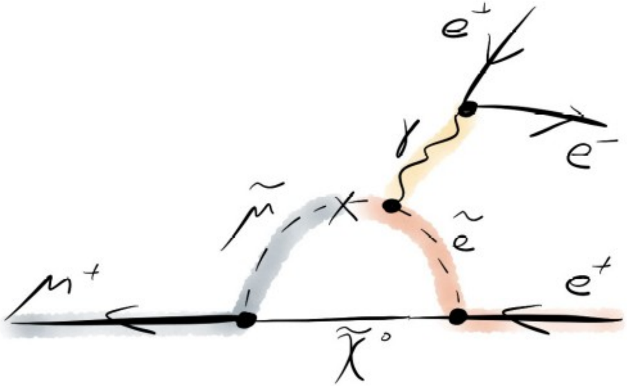


Michel Decay
- rate: ~ 1



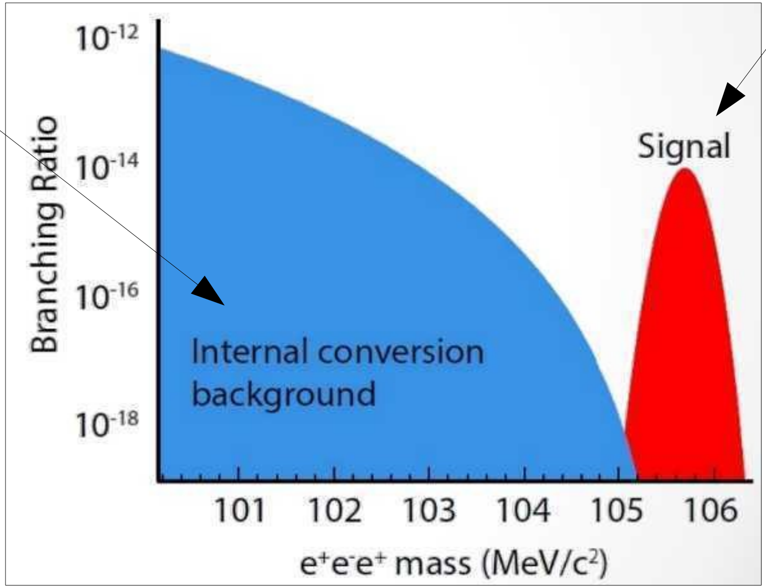
Signal
- push limit to 10^{-16}

Mu3e



Michel Decay + Conversion
- rate: 10^{-5}

Signal
- push limit to 10^{-16}



Mu3e @ PSI

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

- Scintillating fibres (<1ns) and tiles (<100ps) to time-slice the data
- online reconstruction using GPU farm

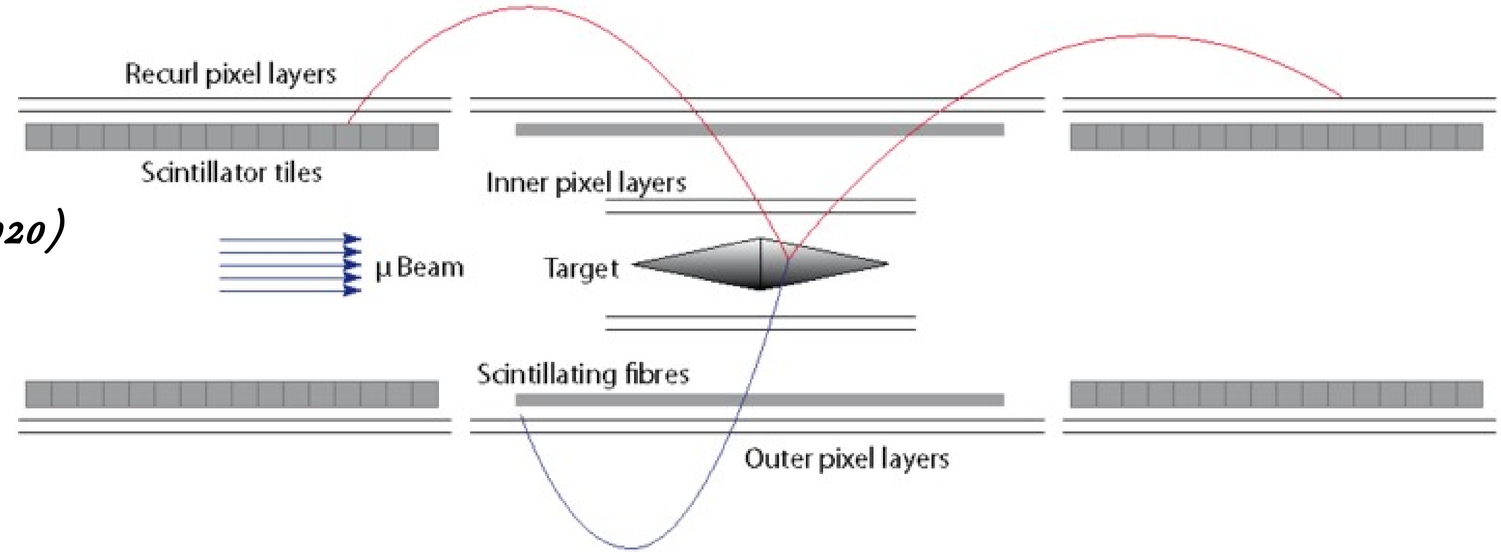
- vertex resolution 200 μm
- momentum resolution 0.5 MeV
  ...in the scattering-dominated regime (E<53 MeV)

→ HV-MAPS sensors, thinned to 50 μm; 0.1%X_0 per layer

UK deliverables:

- outer layers of tracker
- clock and control system
- *Pixel Detector Coordinator*

Mu3e Phase-1 (2020)



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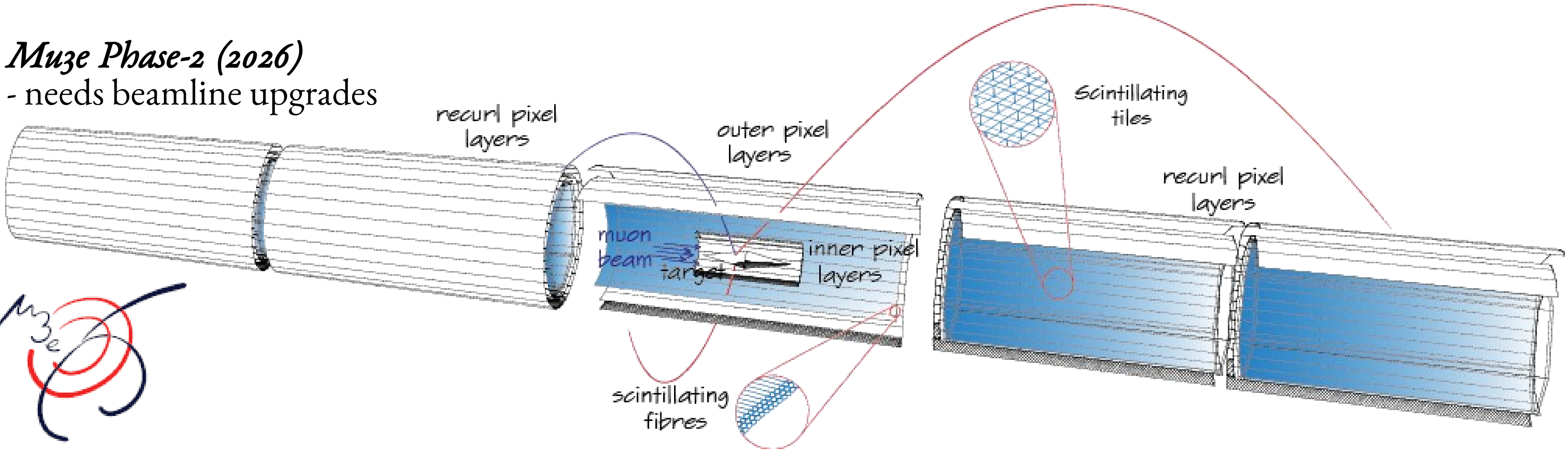
Mu3e Phase-2 (2026)

- needs beamline upgrades

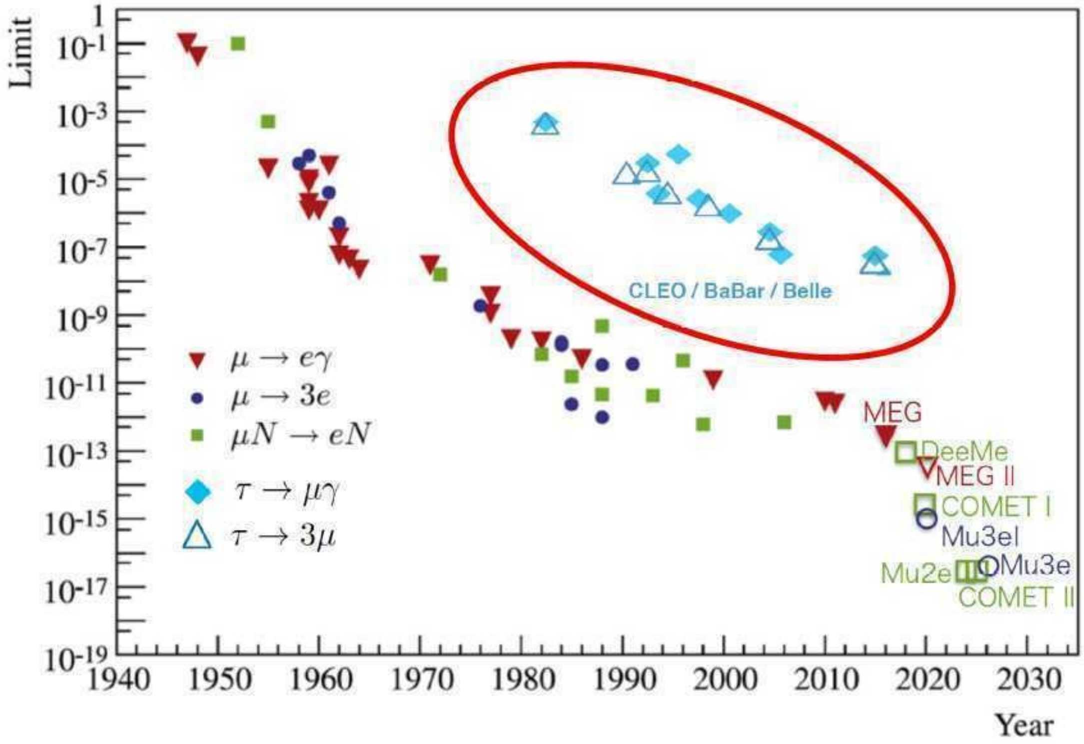


Best limits on τ → μμμ and τ → μγ from B-factories

- Belle-II expect to reach 10^{-9} in coming decade

TauFV at CERN:

- proposed detector at SPS beam dump (parasitic to SHiP)
- could reach 10^{-10} for $\tau \rightarrow \mu\mu\mu$, possibly further for $\tau \rightarrow \mu\mu e$



Conclusion

New physics must be out there... but where?

→ reach further testing loop effects with high precision measurements

Muon physics complements and extends major research themes:

- BSM searches, CPV in the lepton sector and leptogenesis of matter-antimatter asymmetry
  - → input to European Strategy: arXiv:1812.06540

Muon g-2:

- first publication planned in 2019, running for 2 more years to reach 20x BNL stats.
- EDM and μ^- measurements
- options for extended / upgraded running, and follow-on measurements

CLFV with muons:

- Mu2e, COMET and Mu3e aiming for 10^4 improvement in sensitivity over current limits
  - probe mass scales up to ~10^4 TeV
- complementary physics, and complementary to g-2 & LHC

Going to be an exciting few years!