Particle Physics beyond the LHC

UNIVERSITY OF LIVERPOOL

Higgs-Maxwell Workshop

Muons

Themis Bowcock

THE ROYAL SOCIETY OF EDINBURGH

Experimental Particle Physics

- A little history ….
- What experiments & phenomenology?
  - g-2
  - Mu3e
  - Mu2e
  - (MuonE)
  - Theory
- UK effort
- Other muon measurements
- Why are we doing this now? Commentary
- Summary

Experimental Portfolio

2009

Experiment	Facility	Driver
ATLAS	CERN	Higgs/SUSY
LHCb	CERN	SUSY
T2K	J-PARC	ν Mixing

10 years preparing!

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2019

Experiment	Facility	Driver
ATLAS	CERN	Higgs/SUSY
LHCb	CERN	Top/LFV
T2K	J-PARC	ν Mixing
HK	Kamiokande	CP
DUNE	FNAL/Sanford	CP
LZ	Sanford	Direct DM
g-2	FNAL	*a*,*d*
Mu2e	FNAL	LFV
Mu3e	PSI	LFV
CTA/LSST		DM/DE
MAGIS	FNAL	DM/Gravity

Over 10 years

Two European Strategies worth

What has changed for PP?

1) Discovery of Higgs
2) No evidence to date of SUSY
3) Neutrino Physics
4) New technologies (Quantum)

Barometer from undergraduate teaching in UK – Zeitgeist

“what do PhD applicants find attractive?

IT COULD HAVE BEEN

DIFFERENT !

Disclaimer: Particle Physics Beyond the LHC

- We are in a European Strategy consultation

  Title does not imply *without* the LHC

- CERN remains a key part of our UK strategy delivering crucial physics, technology, R&D capability and training for fundamental physics
- Not discussing Future Colliders or CERNs strategy here
  - Prioritising and funding a diverse programme
  - Introducing new and dynamic ideas ;)
  - Informing future research at CERN

Experimental Portfolio

"SANS CERN" ACTIVITY

2009

Experiment	Facility	Driver
T2K	J-PARC	ν Mixing

2019

Particle Physics beyond the LHC

Experiment	Facility	Driver	
T2K	J-PARC	ν Mixing	
HK	Kamiokande	CP	
DUNE	FNAL/Sanford	CP	
LZ	Sanford	Direct DM	
g-2	FNAL	*a,d*	+Pheno
Mu2e	FNAL	LFV	
Mu3e	PSI	LFV	
CTA/LSST		DM/DE	
MAGIS	FNAL	DM/Gravity	

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Physics Drivers 2019

Junior Staff

Dark Matter

Neutrino Nature

SM Tests Collider

Higgs Properties

☆ **SM Tests Precision (LFV, g-2)**

SUSY

Dark Energy

Axions

Senior Staff

Dark Matter (SUSY)

Higgs Properties

SM Tests Collider

Neutrino Nature

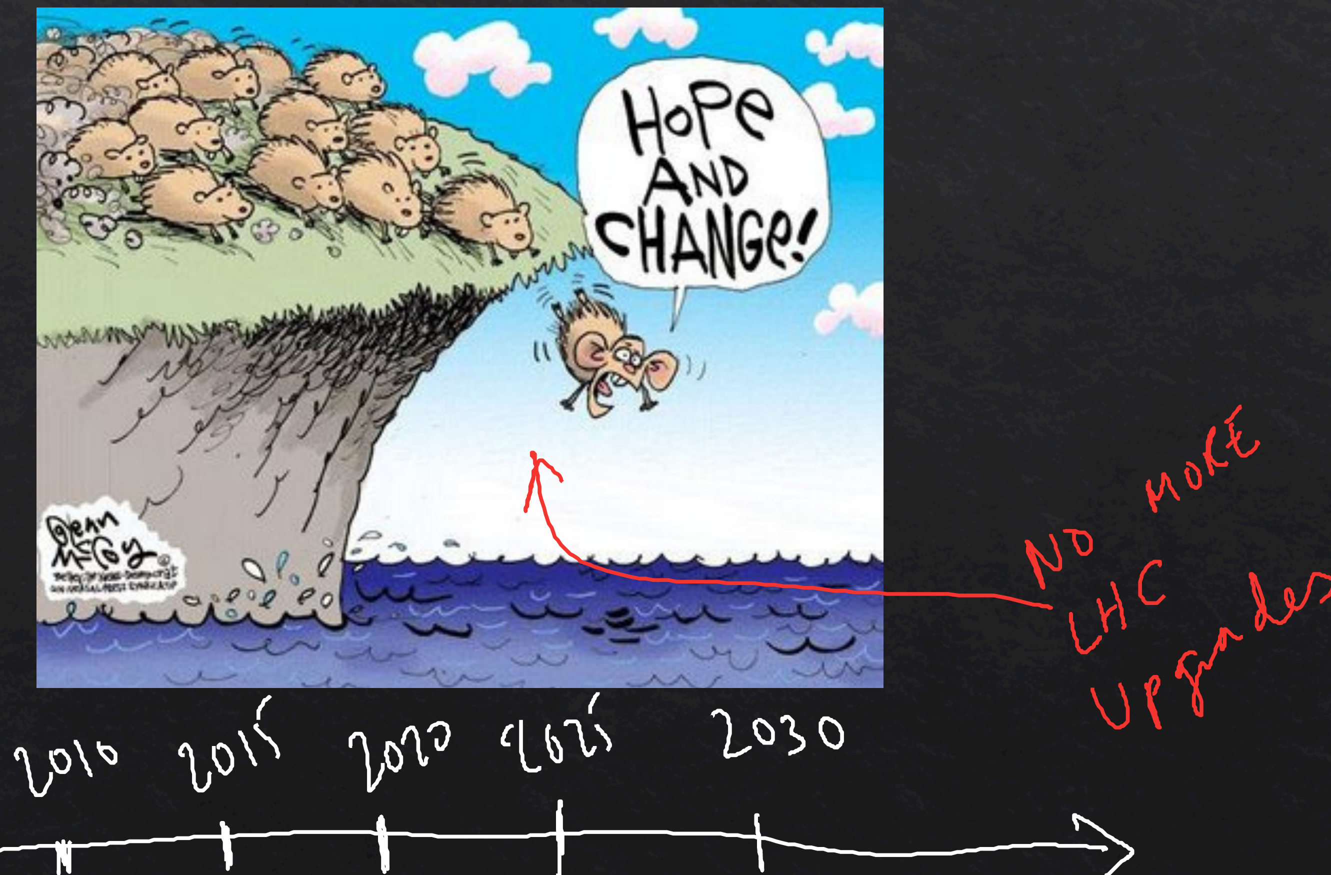
Quark CP

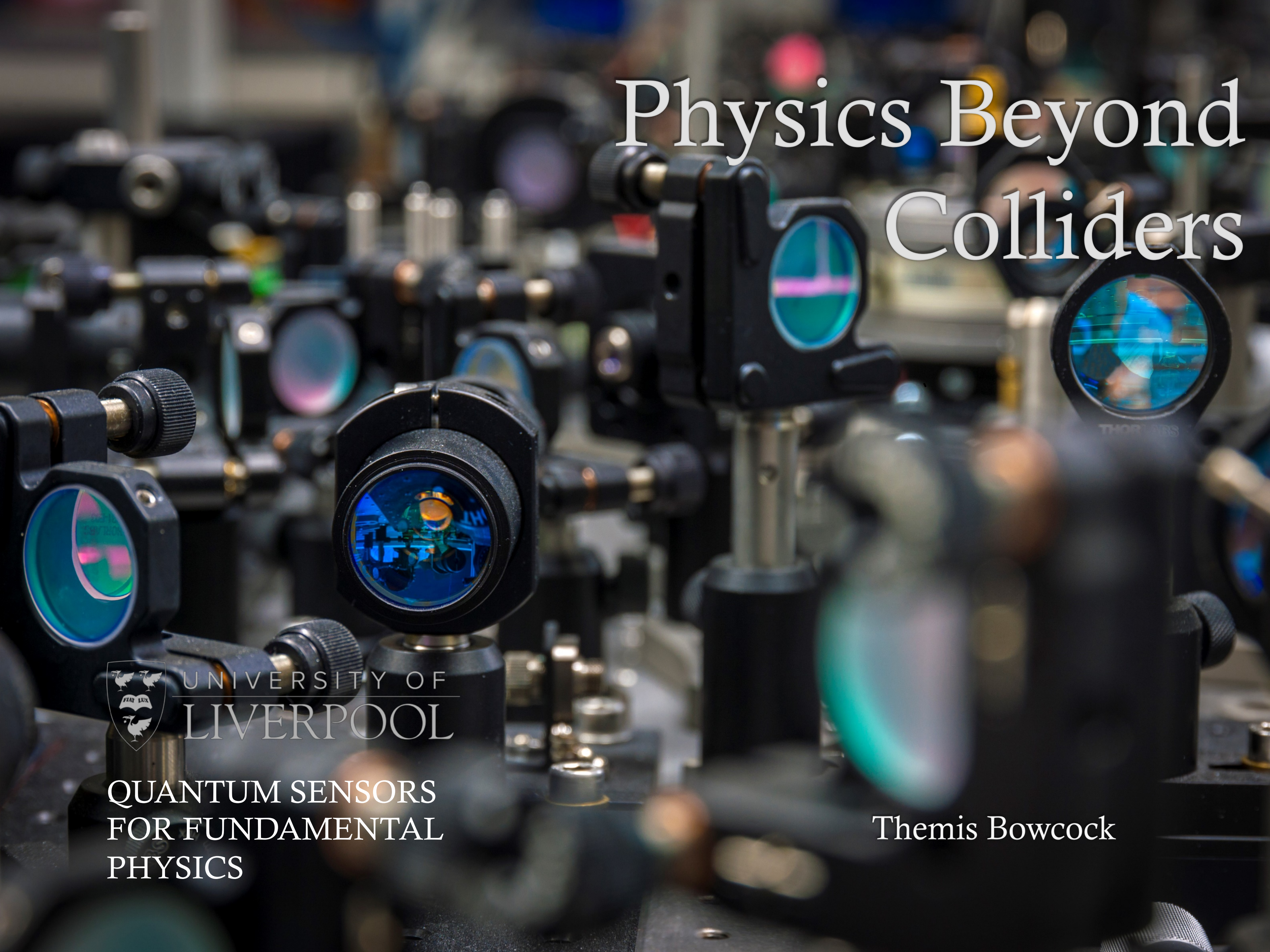
SM Tests Precision (LFV, g-2)

Dark Energy

Axions

The “cliff” …


HOPE AND CHANGE!
No more LHC upgrades
2010
2015
2020
2025
2030



Physics Beyond Colliders

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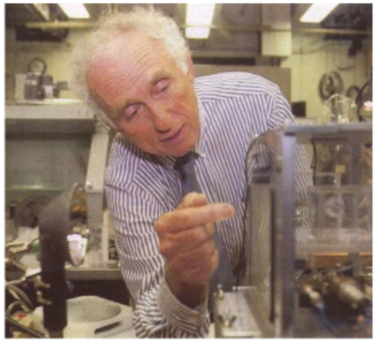
QUANTUM SENSORS FOR FUNDAMENTAL PHYSICS

Themis Bowcock

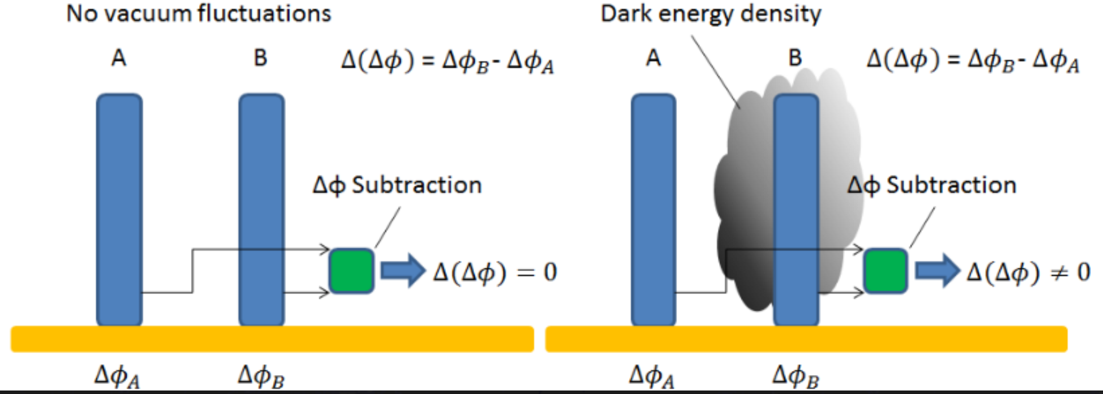
DEAI

Dark Energy

Work in Collaboration with late Martin Perl (Nobel Laureate, visiting professor @ U. Of Liverpool)



A terrestrial search for dark contents of the vacuum, such as dark energy, using atom interferometry (Ronald J.Adler, Holger Mueller and Martin L. Perl)



Liverpool Experiment

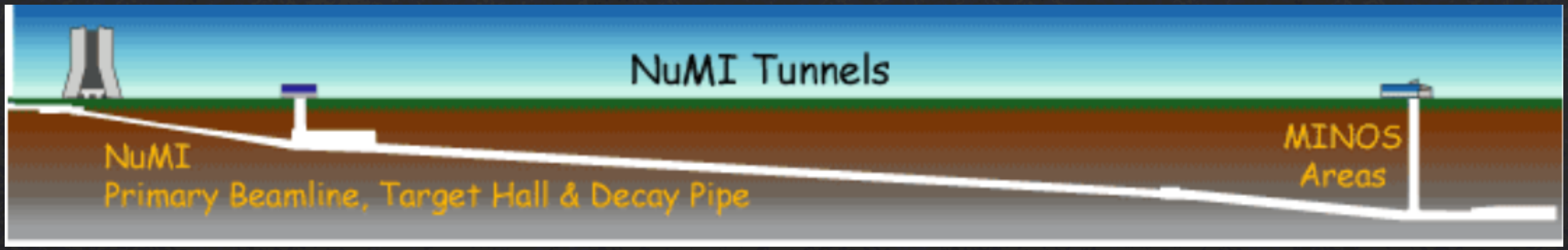
Since 2008

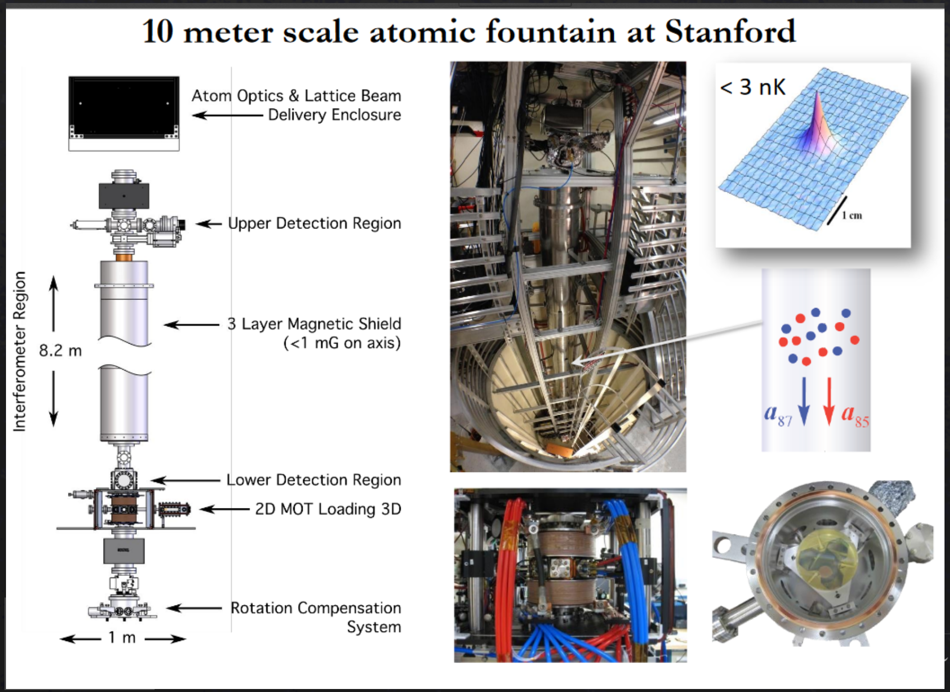
Led to QSFP Initiative

New Initiative-MAGIS-100

Stanford
Berkeley
FNAL
Liverpool

Magis-100





cosmic inflation in frequency range inaccessible to LIGO/LISA

Atomic interferometers can also be sensitive detectors of “dark” energy.

Magis-100

Mid-band Gravitational Wave Detection

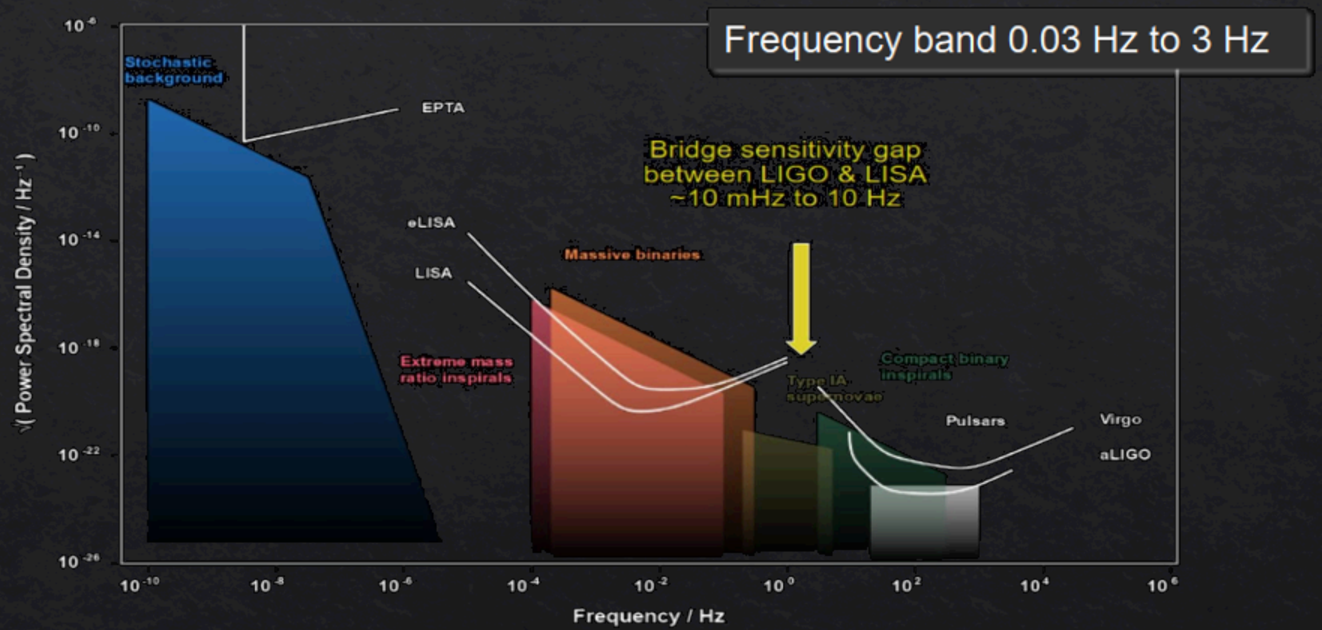


Figure: C. J. Moore et al., Class. Quantum Grav. **32**, 015014 (2015)

UKRI INITIATIVE

Many other things in QSFP

CONTACT ME

IAN SHIPSEY...

See Martin Bauer's talk…

But note … with QSFP style techniques we can probe new physics even up to Planck Scale (Beckenstein)

GREAT ENGAGEMENT WITH THEORY COMMUNITY...

EXCITEMENT & DYNAMISM

2013+ charged lepton programme

With Mark Lancaster (now spokesperson of g-2)

Joined and funded

g-2

Then (2016)

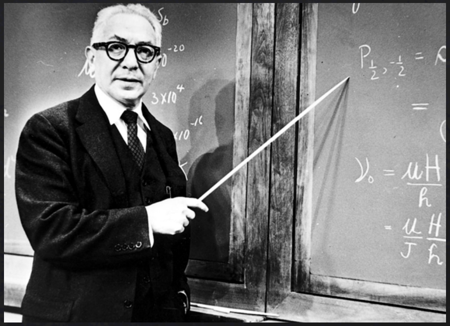
Mu2e/Mu3e

Future possibilities ….

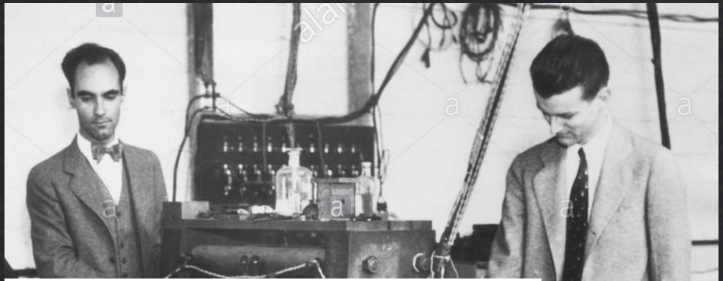
Why study them?

2019-1937 = 82 years

Positrons and then muons discovered in cosmic rays …



"Who ordered that?"

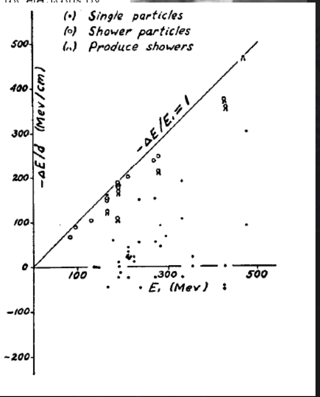


Seth H. Neddermeyer, Phys. Rev., **Vol. 51,** 884 **1937**

Note on the Nature of Cosmic-Ray Particles

SETH H. NEDDERMEYER AND CARL. D. ANDERSON
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

Measurements[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional to the incident energy and within the range of the measurements, up to about 400 Mev, is in approximate agreement with values calculated theoretically for electrons by Bethe and Heitler. These measurements were taken using (0.35 cm), and the observed individual losses were four amount below experimental detection up to the whole i particle, with a mean fractional loss of about 0.5. If thes correct it is evident that in a much thicker layer of heav losses should become much more important, and the prob a particle loss less than a large fraction of its initial ene small. For the purpose of testing this inference and al previous measurements[2] which had shown the presenc less massive than protons but more penetrating than ele Bethe-Heitler theory, we have taken about 6000 counter-t with a 1 cm plate of platinum placed across the center of This plate is equivalent in electron thickness to 1.96 c 1.86 cm of lead for a Z^2 absorption. The results of 55 particles in the range below 500 Mev are given in Fig. 1 distribution of particles is shown as a function of the frac The shaded part of the diagram represents particles wh



[1] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).
[2] Anderson and Neddermeyer, Report of London Conference, Vo

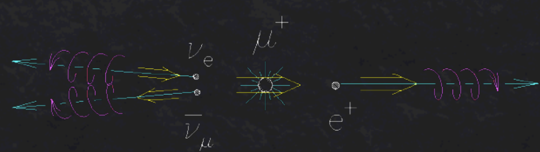
1

Properties

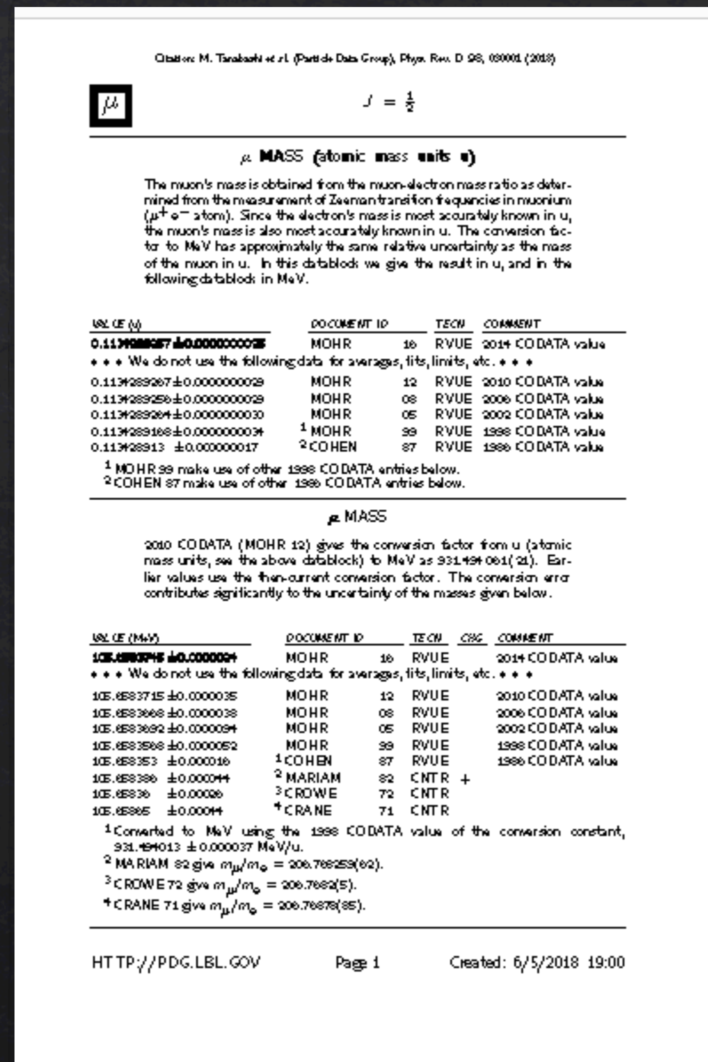
Well known!

Mass	(2016)	105.6583745 ± 0.0000024 MeV
τ	(2013)	2.1969811±0.0000022 μs
$\tau_{\mu^+}/\tau_{\mu^-}$	(1984)	1.000024±0.000078
a_μ	(2006)	11659208.9±5.4±3.3 (× 10^{-10})
d_μ	(2009)	11659208.9±5.4±3.3 (× 10^{-19} e cm)

Decays



	Mode		Fraction (Γ_i/Γ)
Γ_1	$e^-\overline{\nu}_e\nu_\mu$		≈ 100%
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$	[a]	$(6.0\pm0.5)\times10^{-8}$
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$	[b]	$(3.4\pm0.4)\times10^{-5}$



Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

μ $J=\frac{1}{2}$

μ MASS (atomic mass units u)

The muon's mass is obtained from the muon-electron mass ratio as determined from the measurement of Zeeman transition frequencies in muonium (μ^+e^- atom). Since the electron's mass is most accurately known in u, the muon's mass is also most accurately known in u. The conversion factor to MeV has approximately the same relative uncertainty as the mass of the muon in u. In this datablock we give the result in u, and in the following datablock in MeV.

VALUE (u)	DOCUMENT ID		TECN	COMMENT
0.1134289257±0.0000000025	MOHR	16	RVUE	2014 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.1134289267±0.0000000029	MOHR	12	RVUE	2010 CODATA value
0.1134289256±0.0000000029	MOHR	08	RVUE	2006 CODATA value
0.1134289264±0.0000000030	MOHR	05	RVUE	2002 CODATA value
0.1134289168±0.0000000034	[1] MOHR	99	RVUE	1998 CODATA value
0.113428913 ±0.000000017	[2] COHEN	87	RVUE	1986 CODATA value

[1] MOHR 99 make use of other 1998 CODATA entries below.
[2] COHEN 87 make use of other 1986 CODATA entries below.

μ MASS

2010 CODATA (MOHR 12) gives the conversion factor from u (atomic mass units, see the above datablock) to MeV as 931.494 061(21). Earlier values use the then-current conversion factor. The conversion error contributes significantly to the uncertainty of the masses given below.

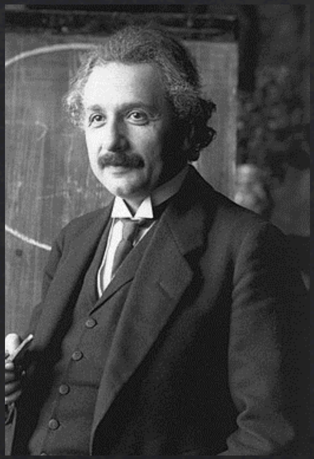
VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
105.6583745±0.0000024	MOHR	16	RVUE		2014 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.6583715±0.0000035	MOHR	12	RVUE		2010 CODATA value
105.6583668±0.0000038	MOHR	08	RVUE		2006 CODATA value
105.6583692±0.0000094	MOHR	05	RVUE		2002 CODATA value
105.6583568±0.0000052	MOHR	99	RVUE		1998 CODATA value
105.658353 ±0.000016	[1] COHEN	87	RVUE		1986 CODATA value
105.658386 ±0.000044	[2] MARIAM	82	CNTR	+	
105.65836 ±0.00026	[3] CROWE	72	CNTR		
105.65865 ±0.00044	[4] CRANE	71	CNTR		

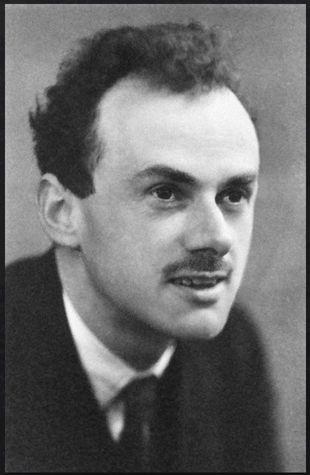
[1] Converted to MeV using the 1998 CODATA value of the conversion constant, 931.494013 ± 0.000037 MeV/u.
[2] MARIAM 82 give m_μ/m_e = 206.768259(62).
[3] CROWE 72 give m_μ/m_e = 206.7682(5).
[4] CRANE 71 give m_μ/m_e = 206.76878(85).

HTTP://PDG.LBL.GOV Page 1 Created: 6/5/2018 19:00

Spin ½ particle

$$i\hbar \partial\psi/\partial t = [p^2 /2m - e/2m\,(L+2S).B]$$





1948: Precise Measurement and Calculation (e)

Kusch and Foley measure g_e

$$g_e = 2.00238 +/- 0.00006$$

Anomalous Magnetic Moment

$$a\downarrow e = g - 2\ /2 = 0.00119 \pm 0.00003$$

PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY
Department of Physics, Columbia University, New York, New York
(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L = 1$ and $g_S = 2(1.00119 \pm 0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

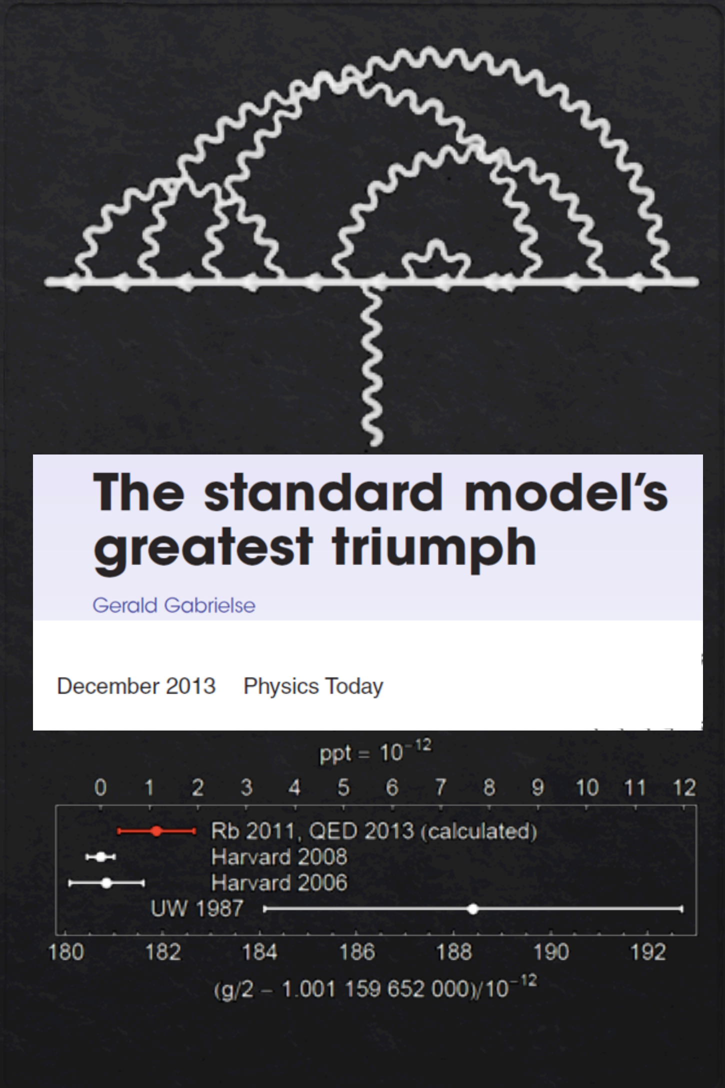
1947: QED

$$g_e \approx 2\left(1+\frac{\alpha}{2\pi}\right) \approx 2.00232$$

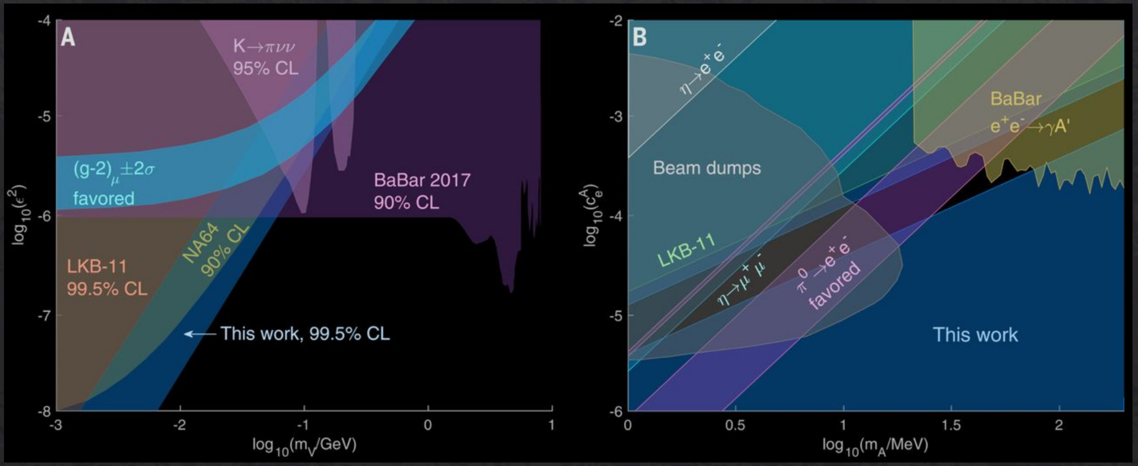
… and
Feynman and
Tomonaga ….

electron g-2 recently

Predicted: $\mu/\mu_B = -1.001\ 159\ 652\ 181\ 78\ (77)$
Measured: $\mu/\mu_B = -1.001\ 159\ 652\ 180\ 73\ (28)$



e
g-2 status



$1/\alpha = 137.035999046(27)$

Science, 13 Apr 2018: Vol. 360, Issue 6385, pp. 191-195

2.5 σ difference

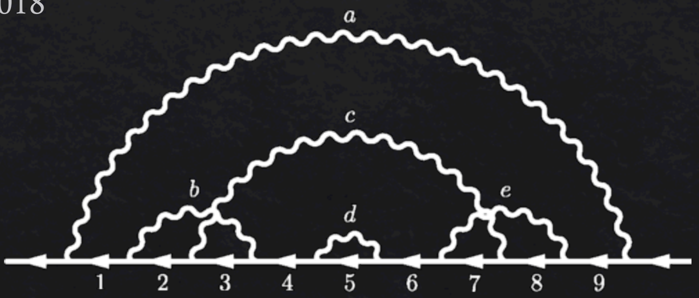
$a_e = 0.00115965218161(23)$

used matter-wave interferometry with a cloud of cesium atoms to make the most accurate measurement of α to date. QFSP

ATOM INTERFEROMETRY

Revised and improved value of the QED tenth-order electron anomalous magnetic moment
Tatsumi Aoyama, Toichiro Kinoshita, and Makiko Nio

Phys. Rev. D 97, 036001 – Published 8 February 2018



Garwin, Lederman, Weinrich
2.00+/-0.10
Phys Rev 105, 1415 (Jan 57) @
Columbia

…how about muons?

1933: Stern and Esterman g_p=5.6

Rabi g_n=-3.8

New heavy particle….

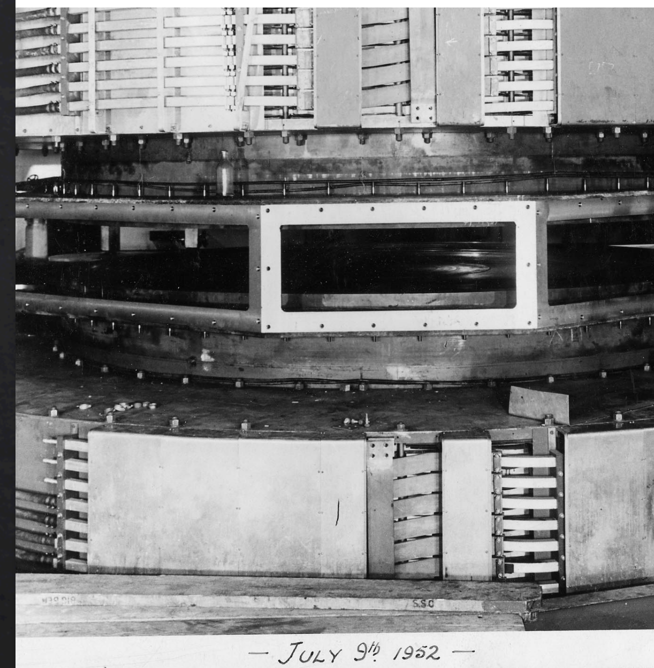
$g=2.004 \pm 0.014$ (0.6%)

$a=0.002 \pm 0.007$

1957 Proc. Phys. Soc. A 70 543

Experiments with a Polarized Muon Beam

By J. M. CASSELS, T. W. O'KEEFFE, M. RIGBY, A. M. WETHERELL AND J. R. WORMALD
Nuclear Physics Research Laboratory, University of Liverpool



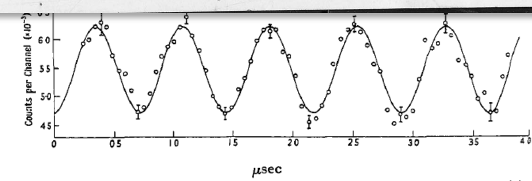
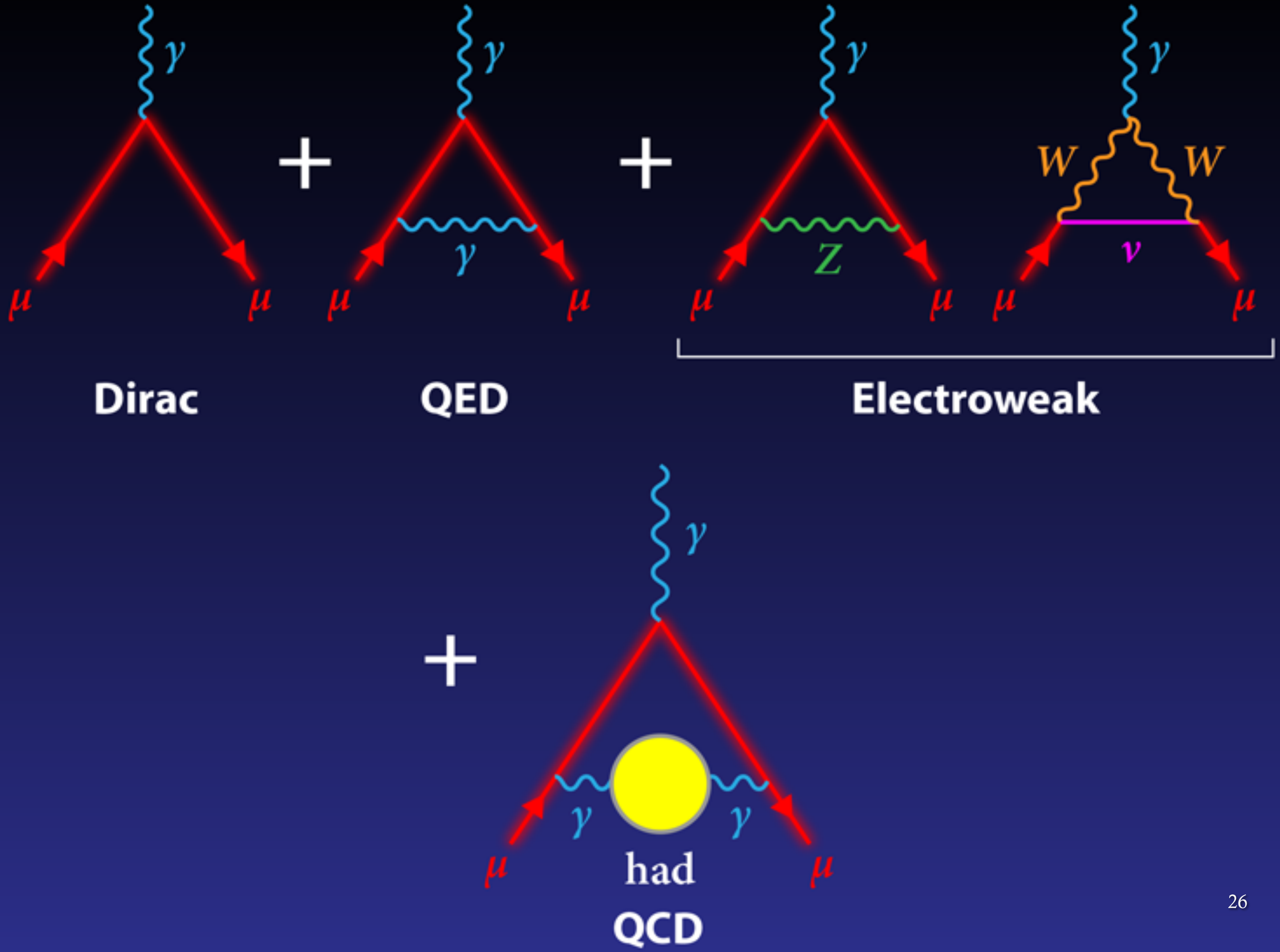


Figure 2. Time distribution of forward electrons from positive muons stopped in copper (87%) and carbon (13%). The magnetic field was 101·9 gauss. The exponential decay factor has been removed, and the first few points have been corrected for a slight non-linearity in the time analyser. Note the displaced zero

Today

June 25, 2018• *Physics* 11, 65

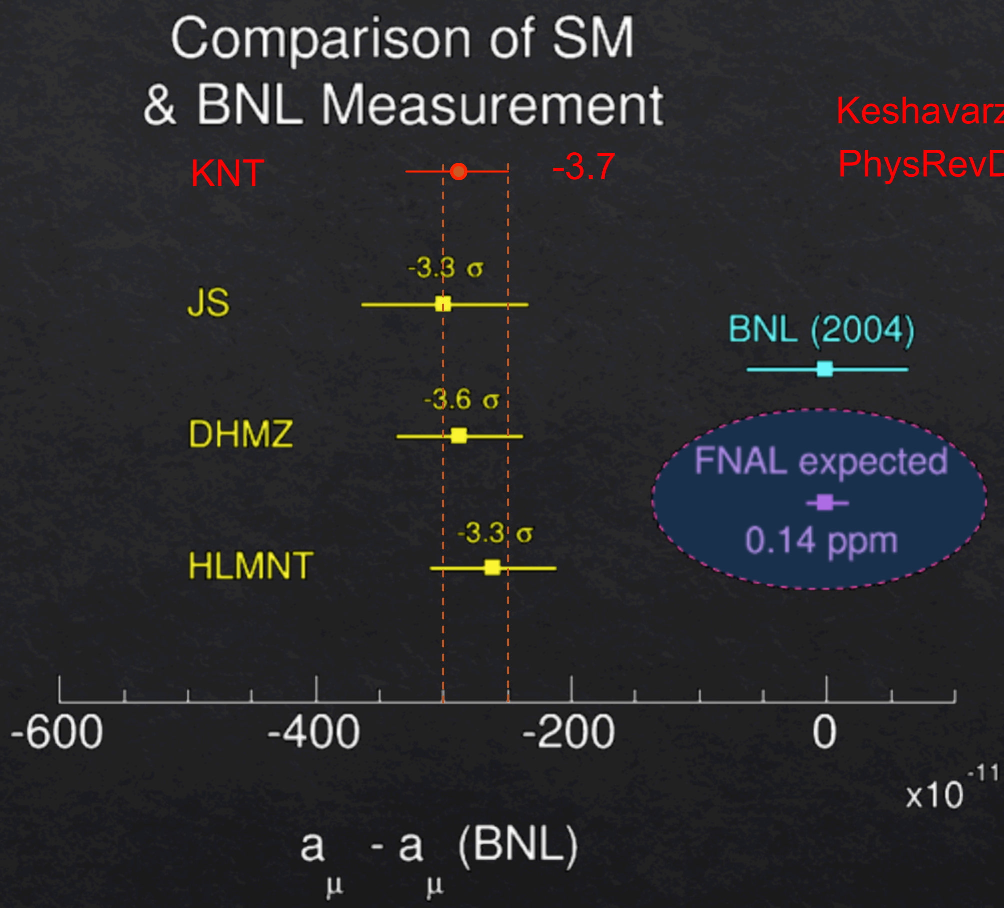
“The muon anomalous magnetic moment important and unique quantity in subatomic physics, since its value represents a sum over all known standard model physics. This wide sensitivity exists because the anomalous moment depends on all particles in nature that can couple to the muon, including as-yet-undiscovered ones.”


γ
μ
Dirac
QED
Z
W
ν
Electroweak
had
QCD

W. Bennett *et al.*, "Final Report of the E821 Muon Anomalous Magnetic Moment Measurement at BNL," Phys. Rev. D **73**, 072003 (2006).21

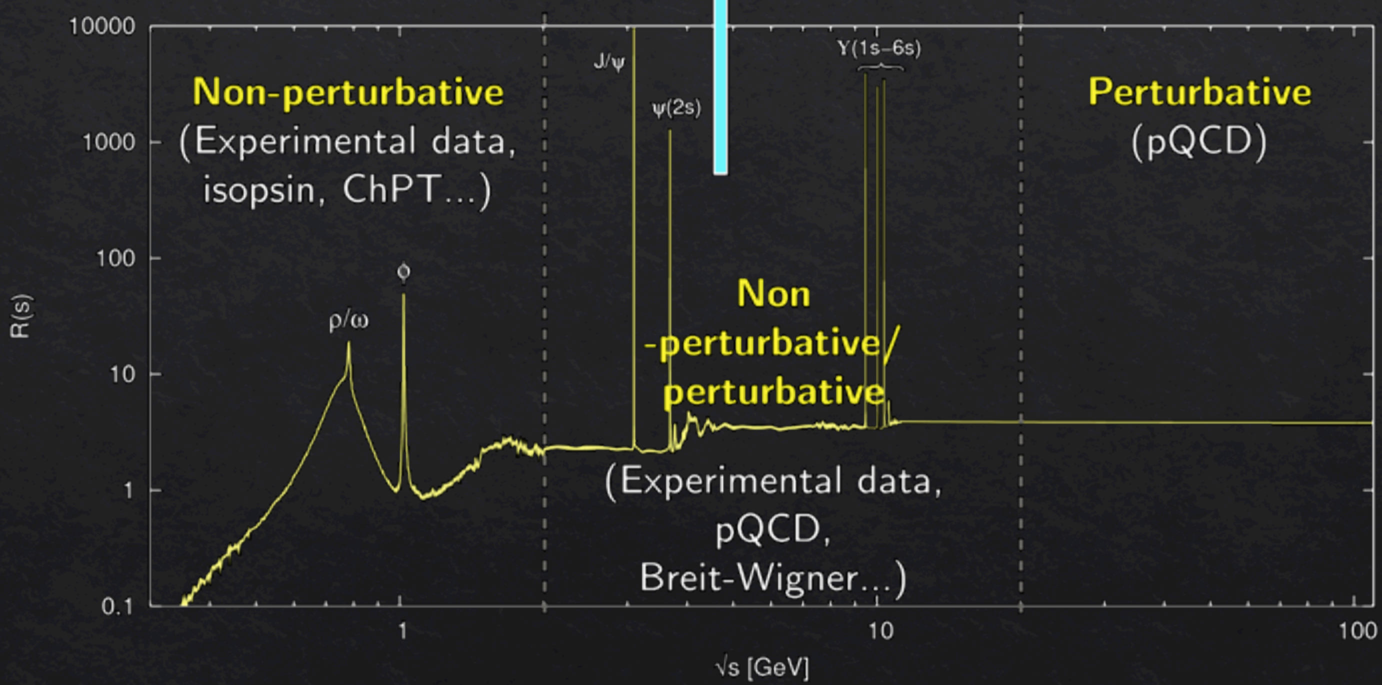
a_{μ}(Expt)=11659208.0(5.4)(3.3)×10−10

$$\Delta a_\mu = (27.06 \pm 7.26) \times 10^{-10}$$



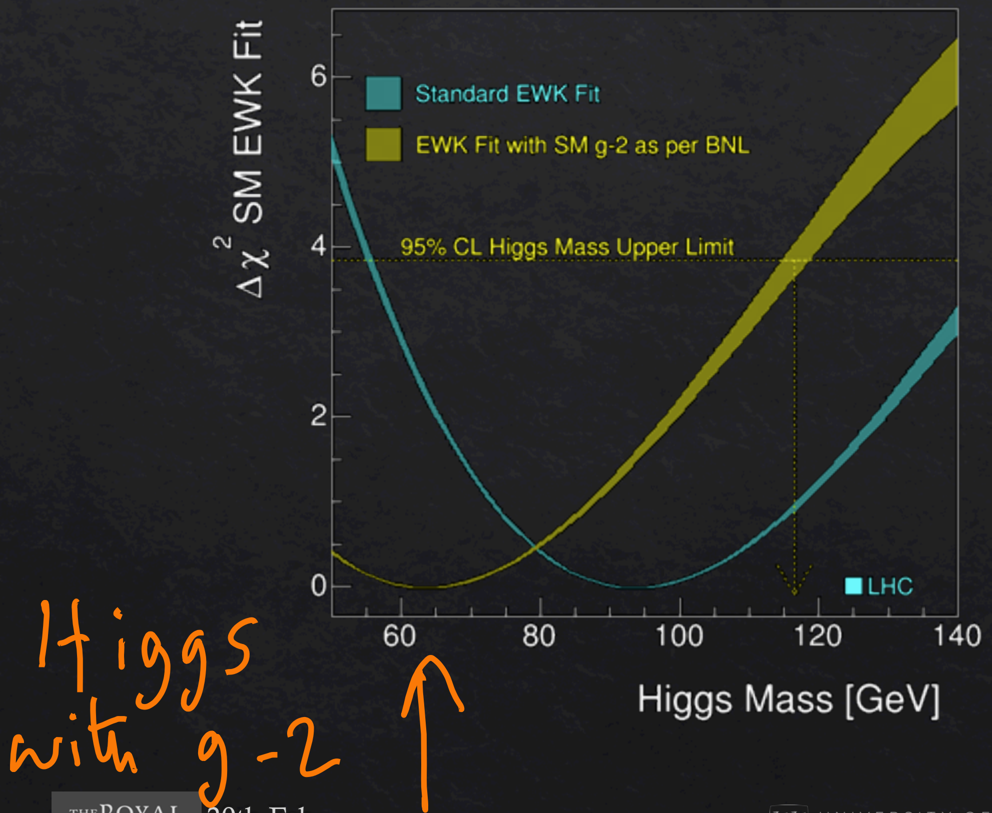
Keshavarzi, Nomura, Teubner
PhysRevD.97.114025

$$a_\mu^{\text{had, LO VP}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{ds}{s}R(s)K(s),\ \text{where}\ R(s) = \frac{\sigma^0_{\text{had},\gamma}(s)}{4\pi\alpha^2/3s}$$



Hadronic Corrections

For the BNL result to match the SM prediction then the SM hadronic estimate would need to be wrong by 6 σ v

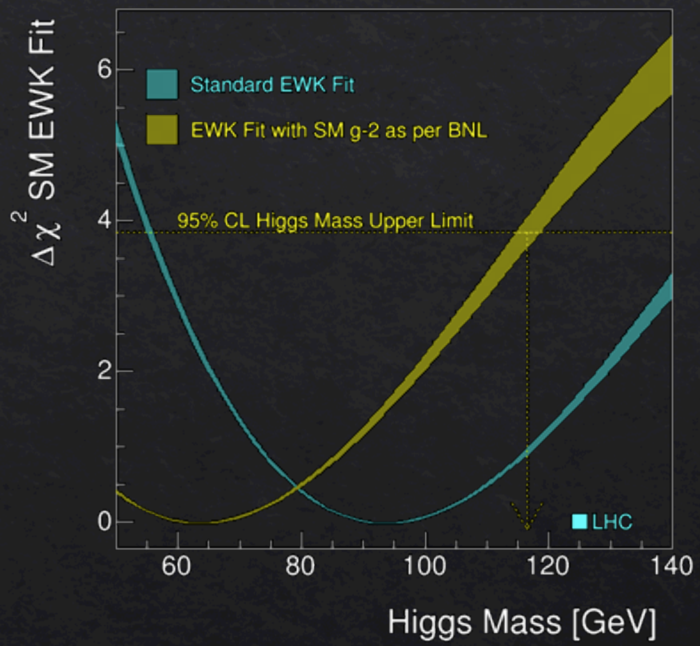


The beauty of the SM is that everything is related …..

"You cannot cook-up a zero g-2 SM anomaly and be consistent with the LHC Higgs mass!"

SM in action…

For the BNL result to match the SM prediction then the SM hadronic estimate would need to be wrong by 6 σ



Any new physics that contributes to the muon mass can contribute to a_μ

m_μ in loops

a_μ in loops

Why μ not e?

Electron g-2 is presently measured x 2,000 better than muon g-2

But $\left(\frac{m_\mu}{m_e}\right)^2$ is 44,000.

2nd Generation Leptons v. useful.

Muon has sensitivity to new physics from < MeV to TeV.

New physics contributes as:

$$\left(\frac{m_\ell}{M_{\mathrm{NEW}}}\right)^2$$

Difficult to use taus!

Any ideas for Z's ???

Many BSM studies use g-2 as constraint or even motivation

SUSY could easily explain g-2

- Main 1-loop contributions:

- Simplest case:

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

- Needs $\mu>0$, \`light' SUSY-scale Λ and/or large $\tan\beta$ to explain 281×10^{-11}

- This is already excluded by LHC searches in the simplest SUSY scenarios (like CMSSM); causes large χ^2 in simultaneous SUSY-fits with LHC data and g-2

- However: * SUSY does not have to be minimal (w.r.t. Higgs),
  * could have large mass splittings (with lighter sleptons),
  * be hadrophobic/leptophilic,
  * or not be there at all, but don't write it off yet…

MANY THEORETICAL STUDIES

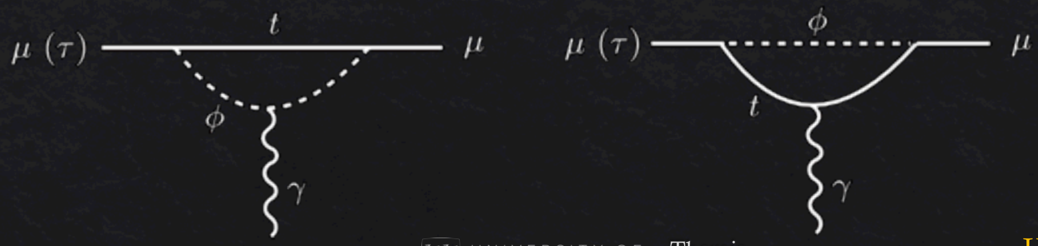
- Don't have to have full MSSM (like coded in GM2Calc [by Athron, ..., Stockinger et al., EPJC 76 (2016) 62], which includes all latest two-loop contributions), and

- extended Higgs sector could do, see, e.g. Stockinger et al., JHEP 1701 (2017) 007, `The muon magnetic moment in the 2HDM: complete two-loop result'

➔ lesson: 2-loop contributions can be highly relevant in both cases; one-loop analyses can be misleading

- 1 TeV Leptoquark Bauer + Neubert, PRL 116 (2016) 141802

one new scalar could explain several anomalies seen by BaBar, Belle and LHC in the flavour sector (e.g. violation of lepton universality in B -> Kll, enhanced B -> Dτν) and solve g-2, while satisfying all bounds from LEP and LHC



How to measure the anomaly

- Store longitudinally polarised muons in a dipole field
- Measure 2 quantities:
  - ω_a the precession frequency
  - <B> the average magnetic field sampled by the muon distribution

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e < B >}{m_\mu c}$$

Larmor Precession Thomas Precession

$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

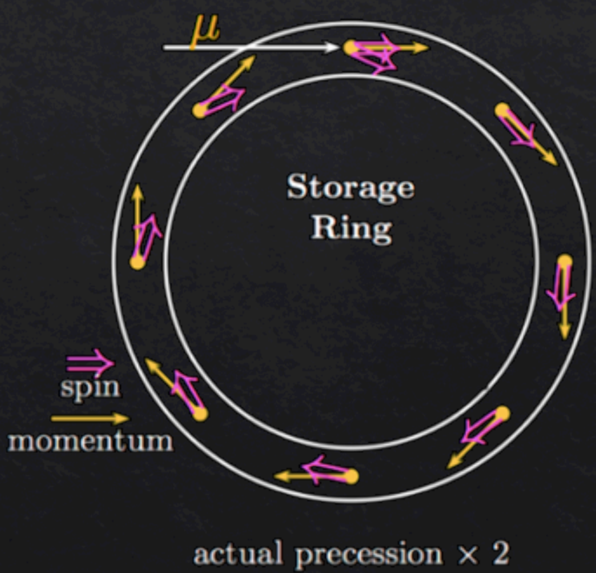
Spin Precession frequency

~140ns

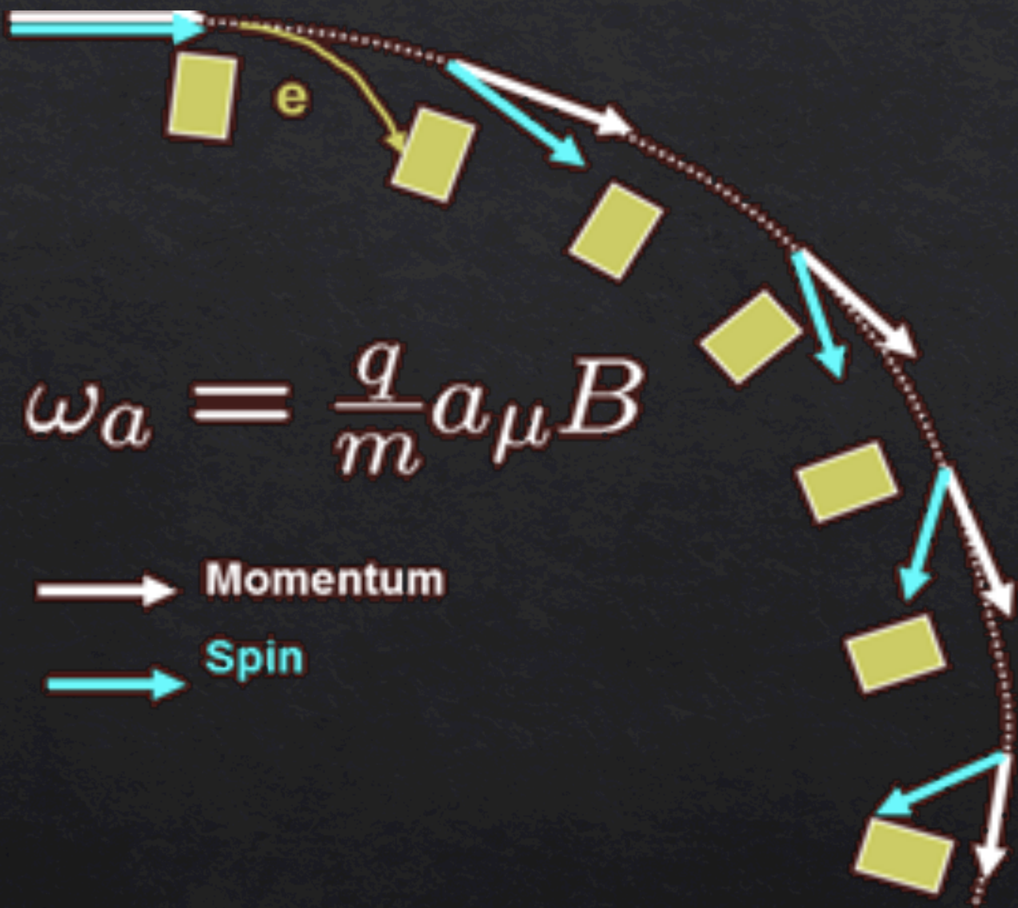
$$\omega_c = \frac{eB}{\gamma mc}$$

Cyclotron frequency

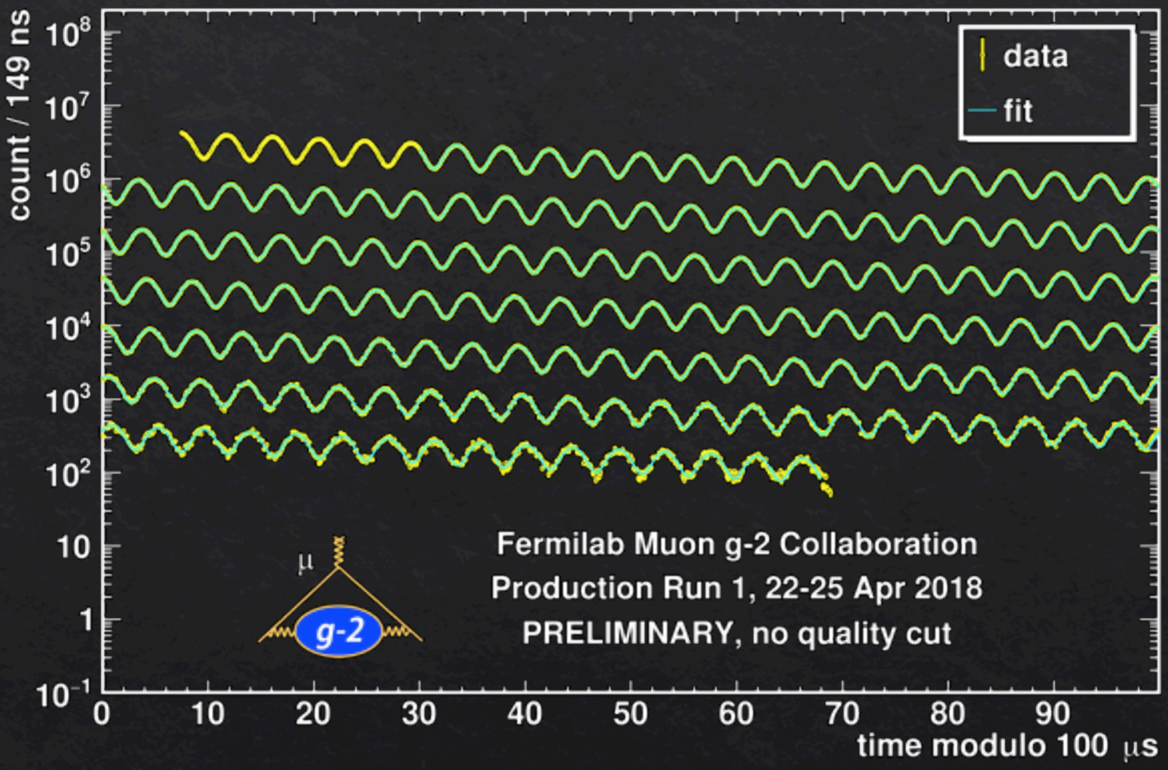
~149ns



"LIGHTHOUSE ON A CAROUSEL"

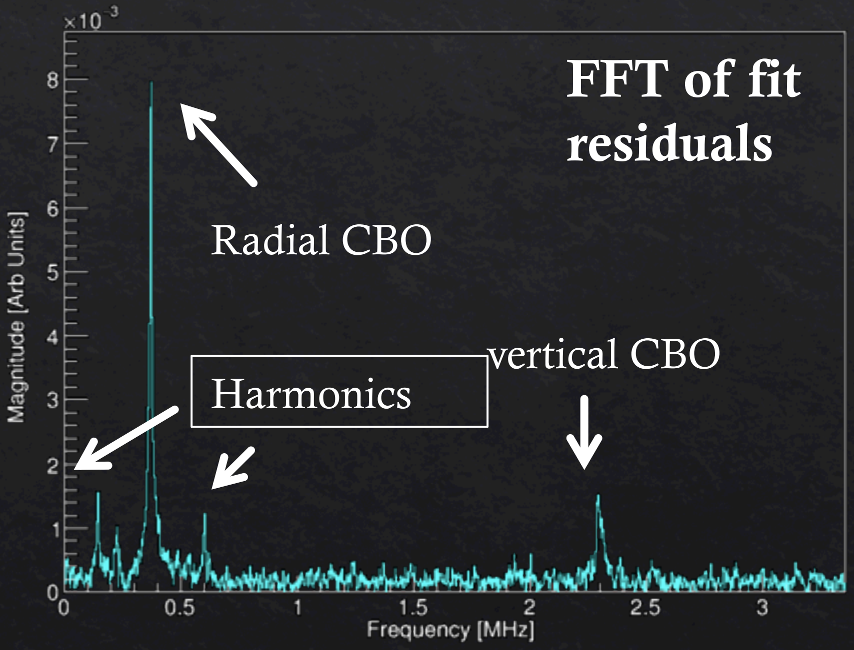


Measuring the precession



Beam oscillations

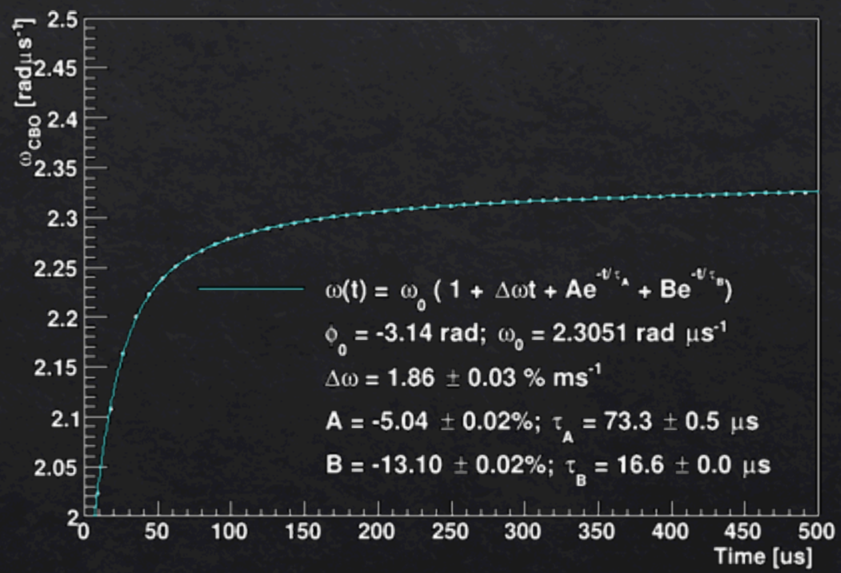
- Beam oscillations introduce additional fluctuations in the e^+ arrival spectrum that need to be accounted for
- Measured using the Liverpool-built tracking detectors



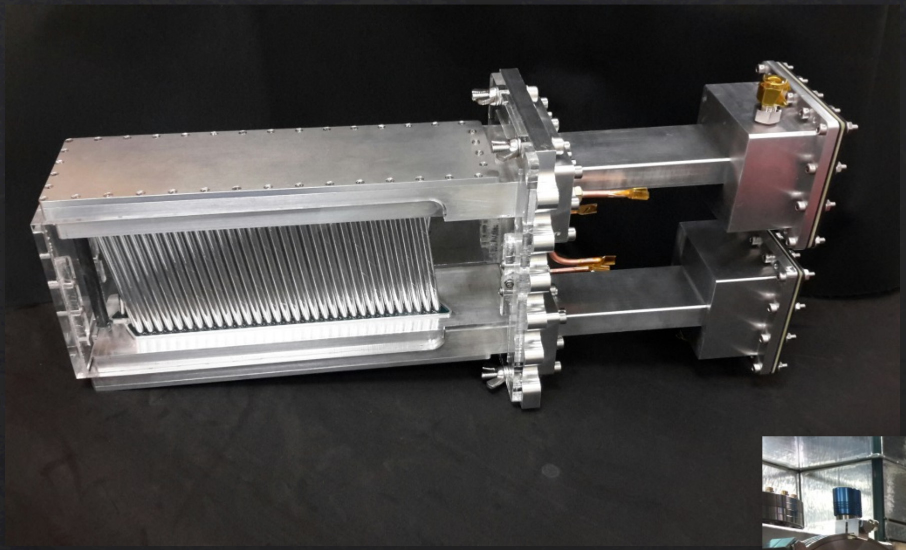
Changing frequency

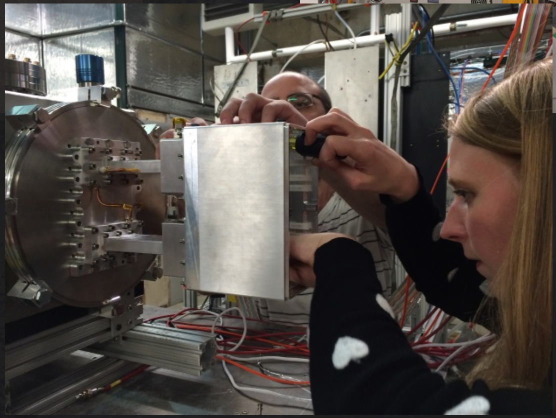
UK CONTRIBUTIONS CRITICAL....

- Frequency observed to change during fill
- Must be accounted for in fits
- Crucial measurement from the trackers!



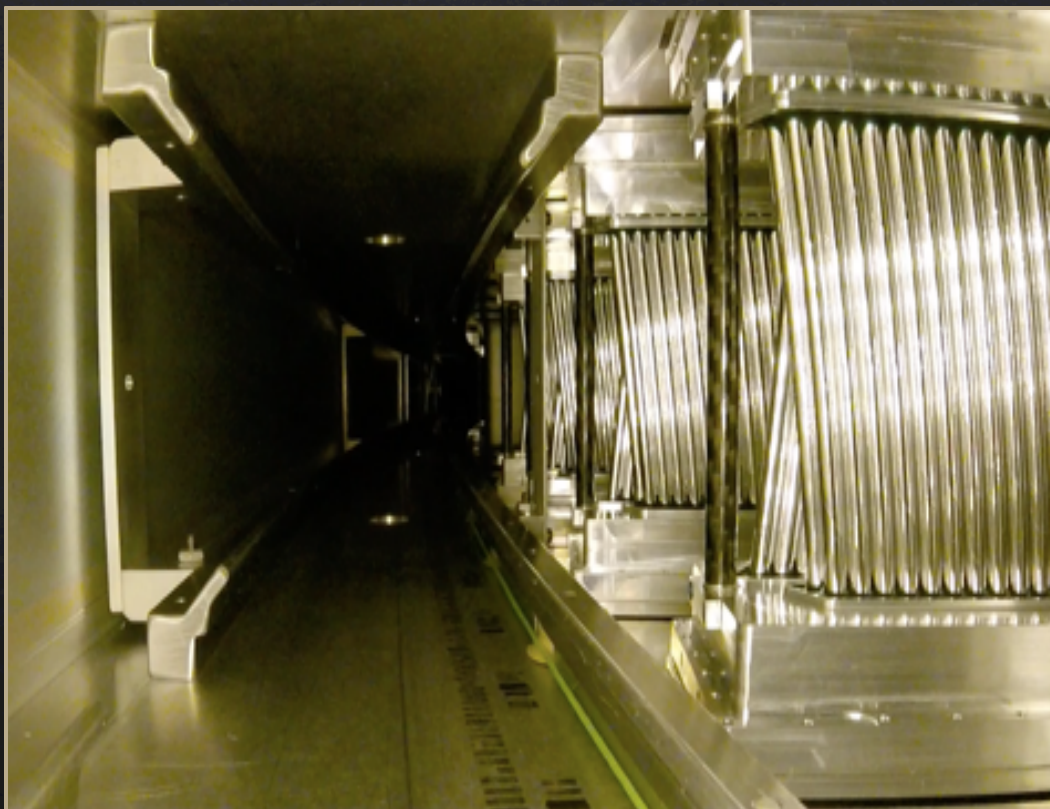
Straw trackers

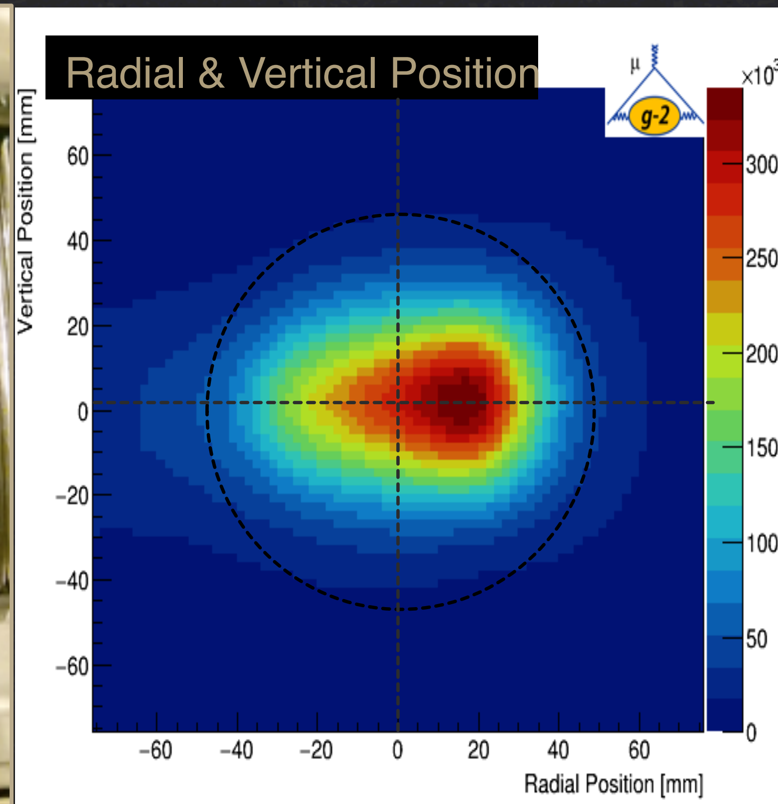




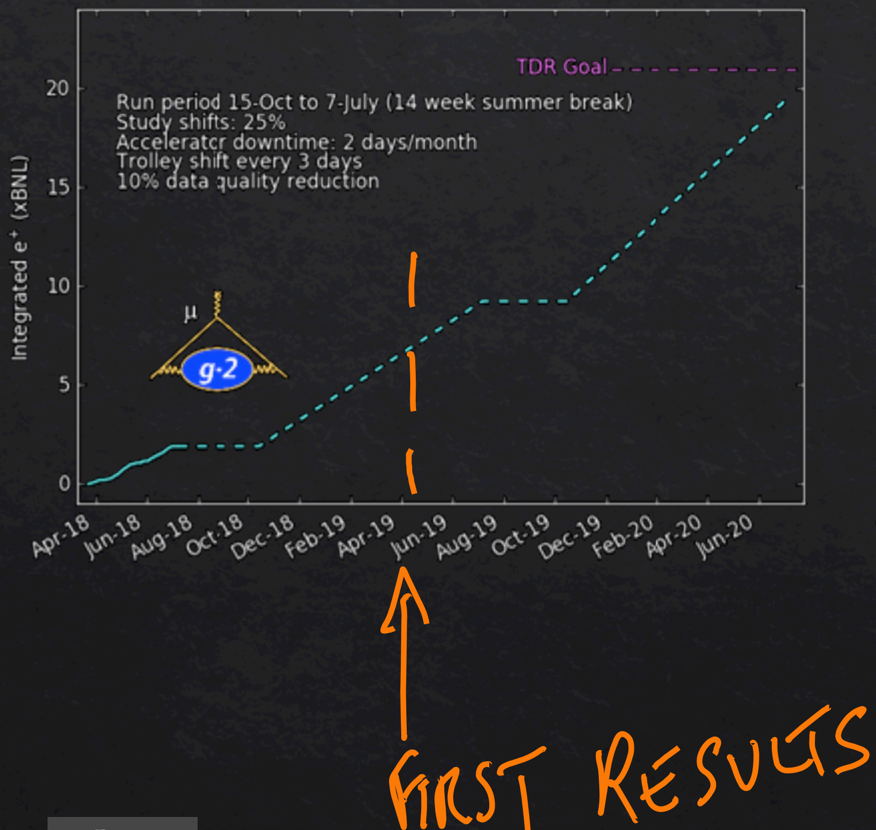
100 µm radial resolution achieved

Tracking detectors

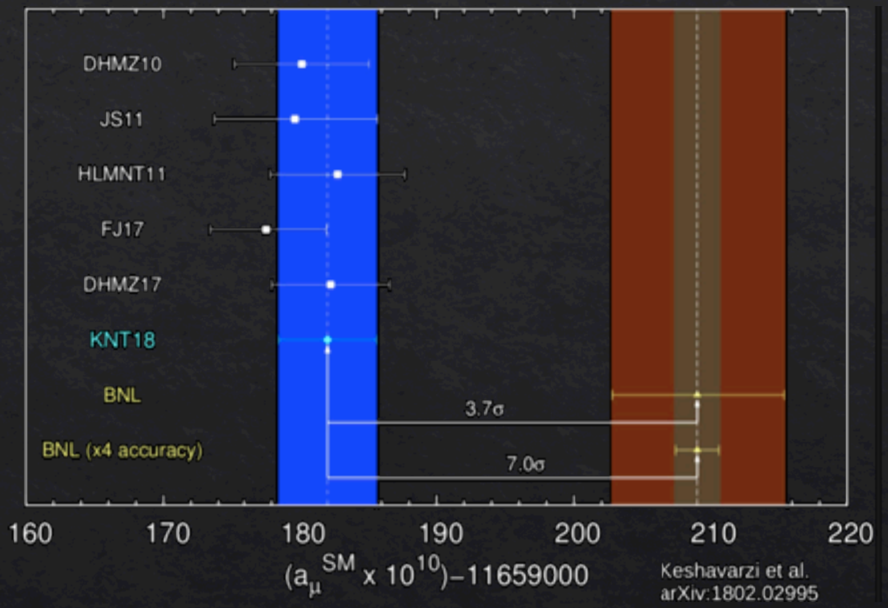




Data Collection



Significance gap



... a lepton-flavour violating dark photon..?

...a model with a large muon EDM..?

arXiv:1807.1148

Combined explanations of $(g-2)_{\mu,e}$ and implications for a large muon EDM
Andreas Crivellin, Martin Hoferichter, Philipp Schmidt-Wellenburg

Fortunately UK using g-2 to make a 1-2 order magnitude improvement in muEDM!

Explaining electron and muon anomalies

New

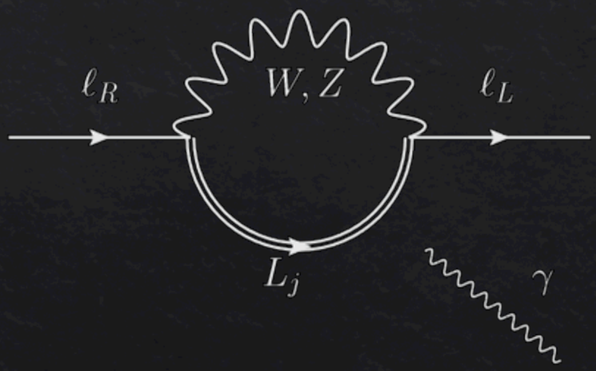
Crivellin + Hoferichter + Schmidt-Wellenburg, arXiv:1807.11484

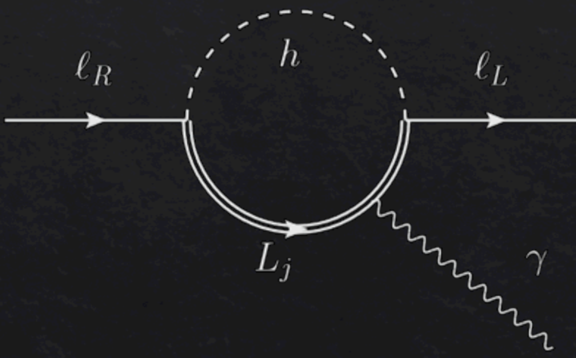
`Combined explanation of $(g-2)_{\mu,e}$ and implications for a large muon EDM'

discuss UV complete scenarios with vector-like fermions (not minimally flavor violating) which solve both puzzles and at the same time give sizeable muon EDM contributions,

$|d_\mu| \sim 10^{-23}$-10^{-21},

but escaping constraints from $\mu \to e\,\gamma$.



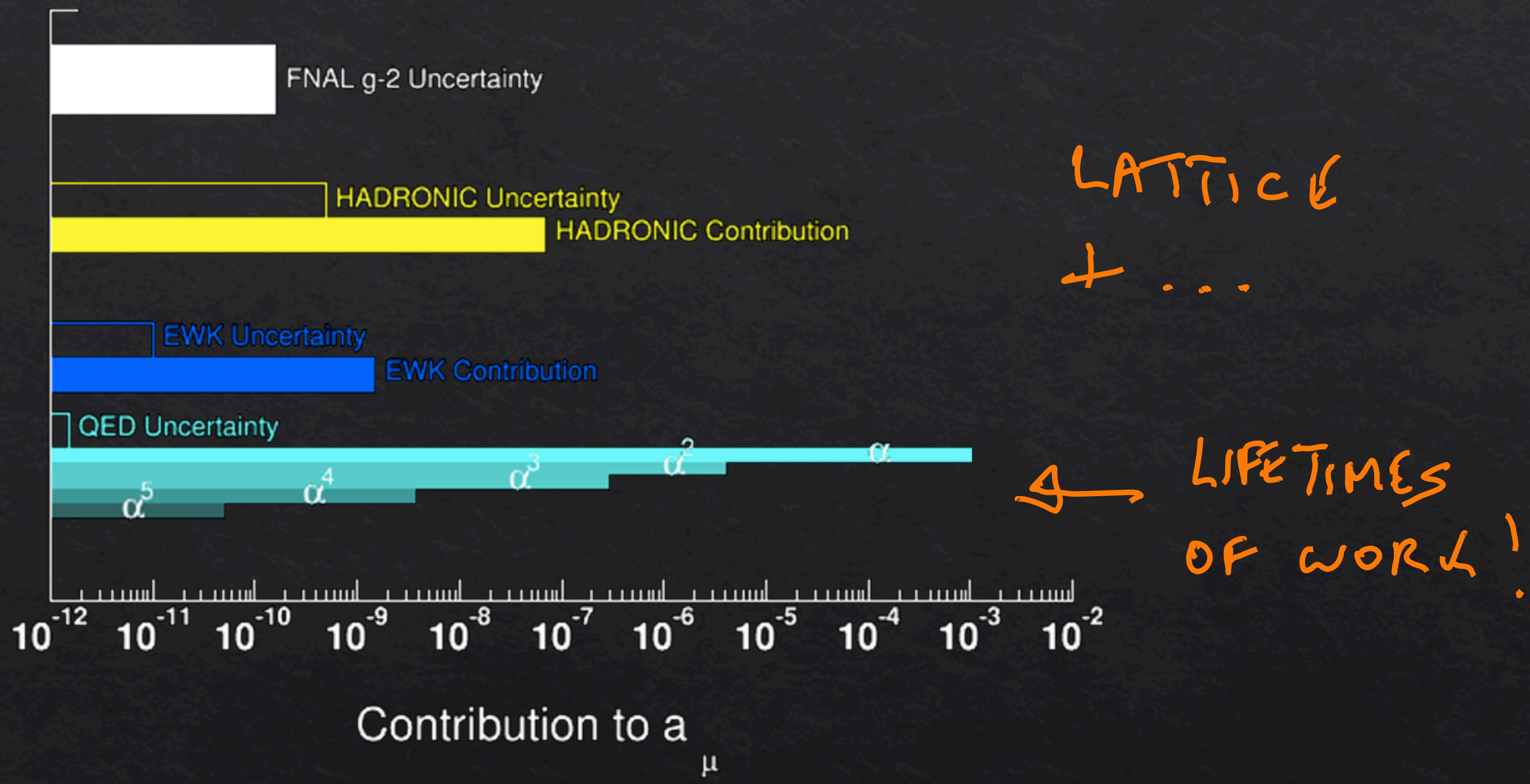


Explaining electron and muon anomalies

- Davoudiasl + Marciano, `A Tale of Two Anomalies', PRD96(2018)096018

  use one singlet real scalar Φ with mass ~ 250-1000 MeV and couplings ~10^{-3} and ~10^{-4} for μ and e, in one- and two-loop diagrams

Summary of g-2 SM corrections/uncertainities



EDM

Purcell and Ramsey

On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. PURCELL AND N. F. RAMSEY
Department of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

IT is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

One form of the argument against the possibility of an electric dipole moment of a nucleon or similar particle is that the dipole's orientation must be completely specified by the orientation of the angular momentum which, however, is an axial vector specifying a direction of circulation, not a direction of displacement as would be required to obtain an electric dipole moment from electrical charges. On the other hand, if the nucleon should spend part of its time asymmetrically dissociated into opposite magnetic poles of the type that Dirac[2] has shown to be theoretically possible, a circulation of these magnetic poles could give rise to an electric dipole moment. To forestall a possible objection we may remark that this electric dipole would be a polar vector, being the product of the angular momentum (an axial vector) and the magnetic pole strength, which is a pseudoscalar in conformity with the usual convention that electric charge is a simple scalar.

The argument against electric dipoles, in another form, raises directly the question of parity. A nucleon with an electric dipole moment would show an asymmetry between left- and right-handed coordinate systems; in one system the dipole moment would be parallel to the angular momentum and in the other, antiparallel. But there is no compelling reason for excluding this possibility. It would not be the only asymmetry of particles of ordinary experimence, which already exhibit conspicuous asymmetry in respect to electric charge. Although magnetic poles were used above as an illustration of a particular mechanism by which a nuclear electric dipole could arise, this is, of course, not the only possibility.

The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle in view of the above becomes a purely experimental matter. The evidence from most past experiments on molecules, atoms, nucleons, and elementary particles is not as conclusive as one might suppose. Most past experiments are in fact very insensitive to the effects of a nuclear electric dipole, because of the smallness of the electric field at the position of a charged nucleus or the antisymmetric nature of the electric dipole potential. We have analyzed a number of experiments including conversion of ortho- to parahydrogen, depolarization of neutron beams, ionization by neutrons, relaxation times of nuclei in liquids, nuclear scattering of neutrons, hyperfine structure studies, the Lamb-Retherford experiment, and the experiments on the interaction of electrons and neutrons. Non-scattering experiments on charged nuclei are particularly insensitive to the existence of an electric dipole moment and even the most favorable would not have revealed an electric dipole moment smaller than the charge of the electron multiplied by a distance D less than 10^{-13} cm. The scattering experiments[3,4] to detect an electron-neutron interaction are by far the most sensitive; the results of Havens, Rabi, and Rainwater[3] would correspond to a D of 3×10^{-18} cm if they were due to an electric dipole moment.

We are now undertaking, in collaboration with Mr. James H. Smith, an experiment which should directly measure the electric dipole moment of the neutron if it has a value of D of approximately the above magnitude. The experiment will utilize a neutron beam magnetic resonance[5] apparatus of high resolution[6] to detect a possible shift of the neutron precession frequency upon the application of a strong electric field.

The authors wish to thank Mr. Smith for suggesting an important correction to our original calculation on the neutron-electron interaction experiment.

[1] A typical argument is given by H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York).
[2] P. A. M. Dirac, Phys. Rev. **74**, 817 (1948).
[3] Havens, Rabi, and Rainwater, Phys. Rev. **72**, 634 (1947).
[4] E. Fermi and L. Marshall, Phys. Rev. **72**, 1139 (1947).
[5] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1940).
[6] N. F. Ramsey, Phys. Rev. **76**, 996 (1949).

Supernovae*

L. B. BORST
Brookhaven National Laboratory, Upton, Long Isl
April 27, 1950

SUPERNOVAE of type I are charact
intensity maximum of 20 to 30 d
ponential tail to the light curve of ha
±0.0012 magnitudes per day;[1] (c
emission of nearly 10^{49} ergs;[1] (d)
hydrogen content expanding at
radiating 10^{38} ergs/sec. visible

These characteristics ma
proposed mechanism. Th
sun, e.g., $15M_\odot$, underg
its hydrogen. As th
perature will rise u
of 2 to 3×10^{9} °C
between alpha-

This r
rapid
by m
is a n

where Z is th
number of partic
the alpha-particle (
reaction threshold; k is
perature. It may be note
volume increases as the squa
exponentially with the temperat
accelerate under conditions of gravi
star may collapse in a time approaching

The reaction will proceed until there are s
of the reaction products to produce the re
expression at equilibrium may be given

$$K=[Be^7][n]/[He]^2,$$

where the entries denote atomic concentrations per unit v
Since neutrons will be absorbed rapidly in a system contai

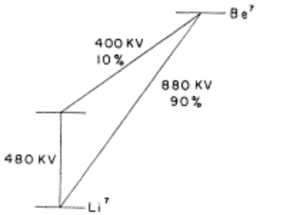
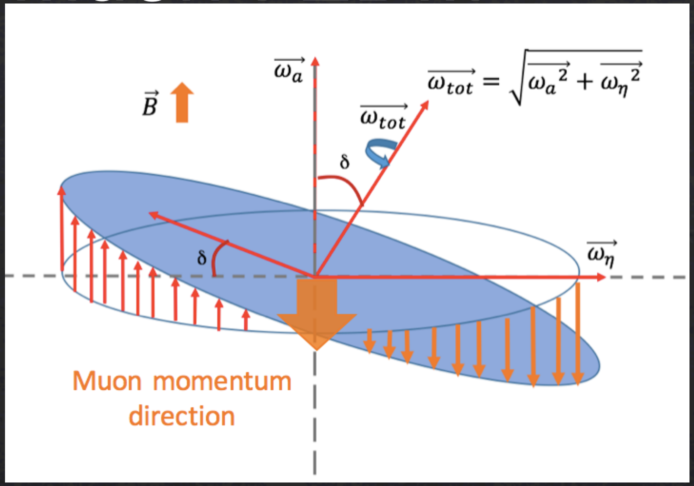
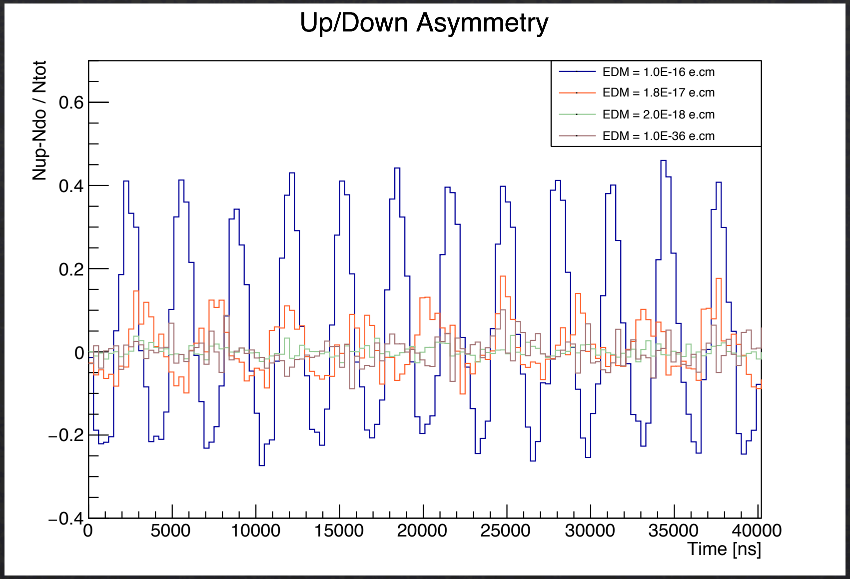


FIG. 1. Decay scheme of Be⁷.

Muon : EDM





O(1M) events in trackers (few weeks)
--> sensitivity at 10^{-19} [BNL]

Expect several billion events in the trackers and so reach 10^{-21}

- Precession plane tilts towards center of ring
- Causes an increase in muon precession frequency
- Oscillation is 90° out of phase with the a_μ oscillation

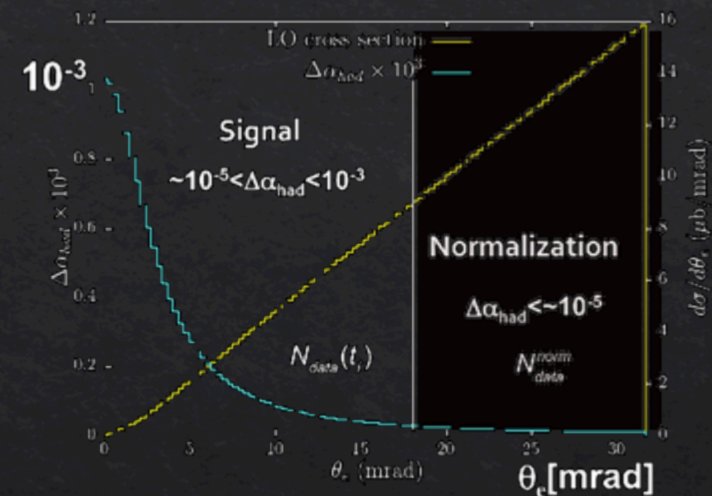
MuonE

WE COULDN'T GET THIS FUNDED (YET)

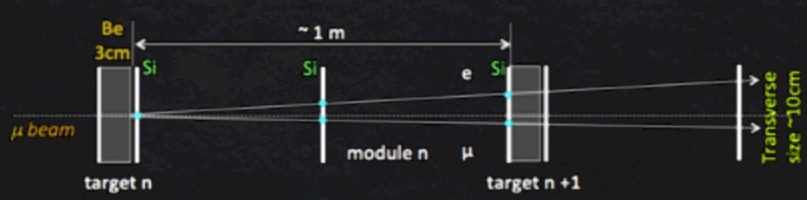
Theory limited by hadronic LO corrections, a_μ^{HNLO}
Traditional calculation from ee→hadrons
→ need x2 improvement to keep up with g-2

MUonE will measure space-like region:
→ scattering of high energy mu (150 GeV) on e

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



Up to 20 Be targets + Si detectors
downstream calorimeters + muon PID



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

Outlook/Conclusions

- ~1.4 x BNL dataset taken during run 1 after quality cuts
- Liverpool-built trackers crucial component of measurement
- Currently analysing - hardware and software blinded in both frequency and field measurements
- Expect unblinding in early summer 2019

- Run 2 underway - aiming for 3 times more data this year
- Additional tracking station being added summer 2019

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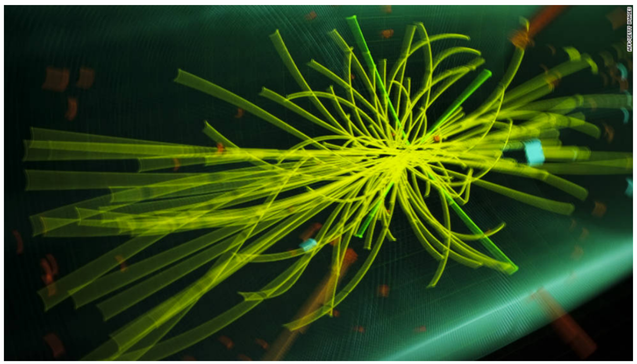
Scientific breakthrough could be as simple as measuring the wobble of a muon

By Don Lincoln

Updated 1648 GMT (0048 HKT) February 13, 2018



Fermilab @Fermilab · 3h

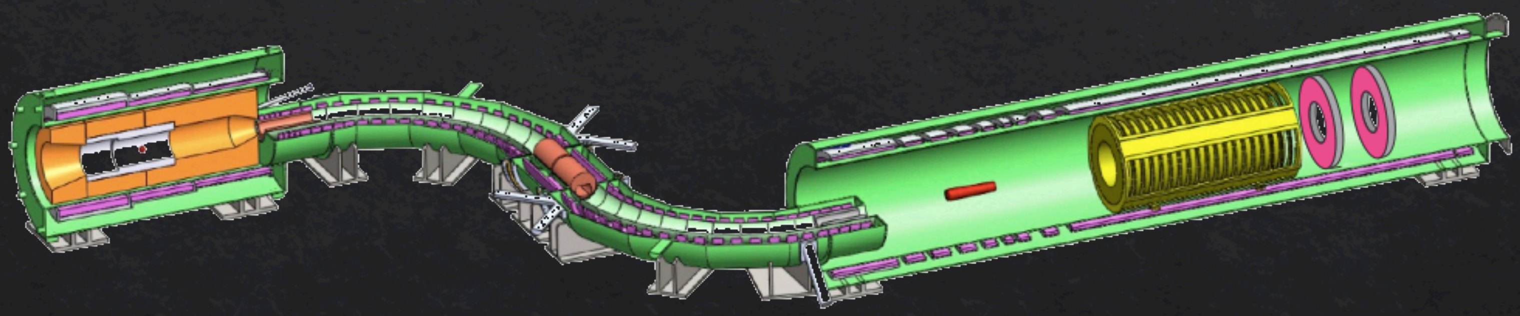
"If I were to put my money on something that would signal new physics, it's the g-2 experiment at Fermilab."

PHYSICS REPORTS (Review Section of Physics Letters) 68, No. 2 (1981) 93–119. North-Holland Publishing Company

After some 21 years of (g-2) measurements on the muon at CERN, a great deal of territory has been brought within the civilized domain of QED theory, and the precision of the most recent result defines the limits within which that domain is secure against any future theoretical excursions. As we have stressed above, any modification to the photon propagator or new coupling common to both muons and electrons would imply a perturbation of a_μ by a factor $(m_\mu/m_e)^2$ larger than for a_e. Thus in the absence of possible coupling particular to the electron, the present muon result ensures that a_e is a "pure QED quantity" down to the level of three parts in 10^{10}.

However, all the effort expended in this activity has brought us no nearer to understanding the mystery of the muon mass. No evidence of a special coupling to the muon has been found. On more general observational grounds it is known that the neutrinos distinguish between the charged leptons. The neutrinos clearly know the difference in the sense that the electron, the muon and the new lepton of mass 1.8 GeV/c^2, discovered by Perl et al. [68], each have their own associated neutral massless fermion; perhaps it is in this area that enquiry should be made for an answer to the charged lepton mass splittings.

For the present, however, the thread which has linked many experimenters together in the common cause of measuring the muon (g-2) factor at CERN is now broken and those who have shared this experience have gone their separate ways. It remains to be seen whether or not future refinement of the theory of the weak, electromagnetic, and strong interactions will call for the discerning scrutiny of further measurements of even greater precision.



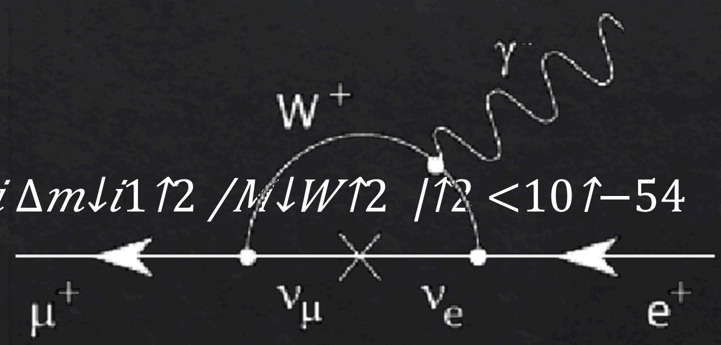
Lepton Flavour Violation

15 year programme ...

CFLV

In SM

$$Br(\mu\to e\gamma)=\frac{3\alpha}{32\pi}\left|\sum_{i=2,3}U_{\mu i}^{*}U_{ei}\frac{\Delta m_{i1}^{2}}{M_W^{2}}\right|^{2}<10^{-54}$$

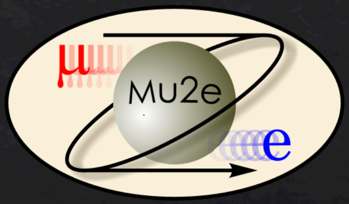


Other possible decays

$\mu \rightarrow e\gamma$

$\mu \rightarrow eee$

$\mu N \rightarrow eN$



point.[4] I[…] the con- centratio[…]0°K, was immeasu[…]ibly zero. The high[…]o residual gas from[…]

In vie[…]mple 3, it appears […] apparatus could be[…]

* The w[…]ce of Naval Research u[…]y of Minne- sota by gra[…]uate School.
[1] See Po[…]John Wiley and Sons, […]m Professor Pollard th[…]anck, Phys. Rev. 70, 5[…]
[2] J. G. D[…]h, and A. O. Nier, Phys[…]
[3] J. G. D[…]n. Phys. 15, 759 (1947)[…]
[4] H. A. […] Nier, Phys. Rev. 73, 2[…]

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. Hincks and B. Pontecorvo
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
December 9, 1947

THE meson decay process which is identified by a mean life of 2.2 microseconds[1] has been usually thought of as consisting of the emission of an electron and a single neutrino, as suggested by the well-known Yukawa explanation of the ordinary beta-process in nuclei. However, the Yukawa theory is at variance with the results of the experiment of Conversi, Pancini, and Piccioni,[2] and since there remains no strong justification for the electron-neutrino hypothesis,[3] a direct experiment to test an alternative hypothesis—*that the decay process consists of the emission of an electron and a photon, each of about 50 Mev*—has been performed.

The apparatus, illustrated in Fig. 1, consists of three rows of Geiger-Müller counters, A, B, and C, each having an effective area of approximately 38 cm×20 cm. Above A there are 15 cm of lead, and between A and B, 1.5 cm of lead. Mesons traversing A and B, and stopped in a graphite absorber 38 cm×19 cm×5 cm thick, produce decay electrons which may be detected in either B or C. Decay photons, if present, could also be detected in B or C, whose efficiency for gamma-radiation was increased by introducing 2.1 mm of lead between the graphite and both B and C. The twofold function of B—first, detection of the passage of a meson by a coincidence with A (event "(A, B)"), and second, detection of a decay electron (or photon) following "(A, B)"—is permitted by the circuit design. Although one of the eight counters of B (that through which the meson passed) is insensitive to the decay particle because of the long counter dead time, the use of B in this manner allows an advantageous geometry. The outputs of the three rows are mixed by circuits whose function is schematically shown in the diagram, and the following delayed events are finally recorded:

Table I. Delayed single and coincidence counting rates.

	$(B)_{del}$ (Counts/hr.)	$(C)_{del}$ (Counts/hr.)	$(B)_{del}+(C)_{del}$ (Counts/hr.)	$(B, C)_{del}$ (Counts/hr.)
With graphite plus lead—(104.2 hours of observation)	11.93±0.34	12.26±0.34	24.19±0.48	0.21±0.05
Without graphite plus lead—(77.2 hours of observation)	6.48±0.29	4.64±0.25	11.12±0.38	0.43±0.08
Net effect due to decay electrons from graphite plus lead	5.45±0.45	7.62±0.42	13.07±0.62	

1. "$(B)_{del}$;" discharges of B occurring between 0.6 and 5.3 microseconds after "(A, B),"
2. "$(C)_{del}$;" discharges of C occurring between 0.6 and 5.3 microseconds after "(A, B),"
3. "$(B, C)_{del}$;" coincidences of B and C occurring between 0.6 and 5.3 microseconds after "(A, B)."

Runs were made with and without the graphite plus lead between B and C, and the results are presented in Table I. Other runs with graphite only, with lead only, and with other thicknesses of graphite and lead, were performed and these will be reported in a more complete account of the experiment. Check runs with a 1.6- to 6.3-microsecond delay gave results consistent with a mean life of 2.2 microseconds.

The observed rate $(B, C)_{del}$ could be due to the following causes:

(i) genuine electron-photon coincidences from the meson decay,
(ii) single decay electrons which traverse both B and C,
(iii) casual events.

The casual rate (iii), which is due essentially to mesons traversing B and C between 0.6 and 5.3 microseconds after an event "(AB)," has been estimated from the measured double and triple coincidence rates and from the characteristics of the circuits to be 0.22±0.02 counts per hour. It is independent of the presence or absence of graphite plus lead. Effect (ii) should be detected only in absence of graphite plus lead, since otherwise the total thickness of material between B and C is of the order of the expected range of the electrons. We observe, in fact, that $(B, C)_{del}$ increases appreciably when the graphite plus lead is removed. The presence of this effect was verified by a sub-

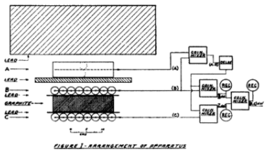
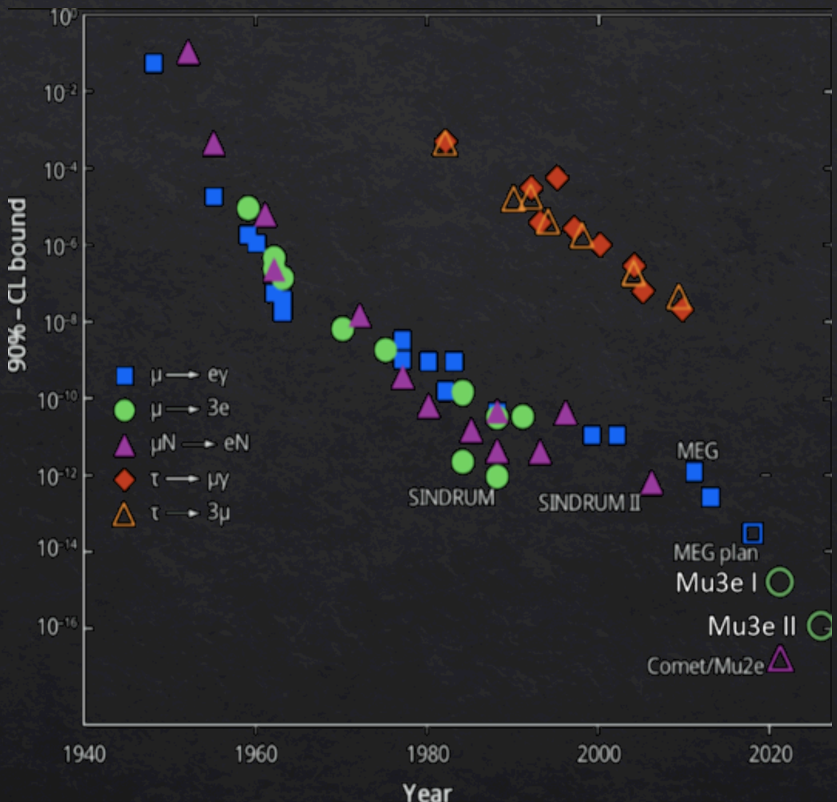


Fig. 1. Arrangement of apparatus.



Now

Other CLFV searches

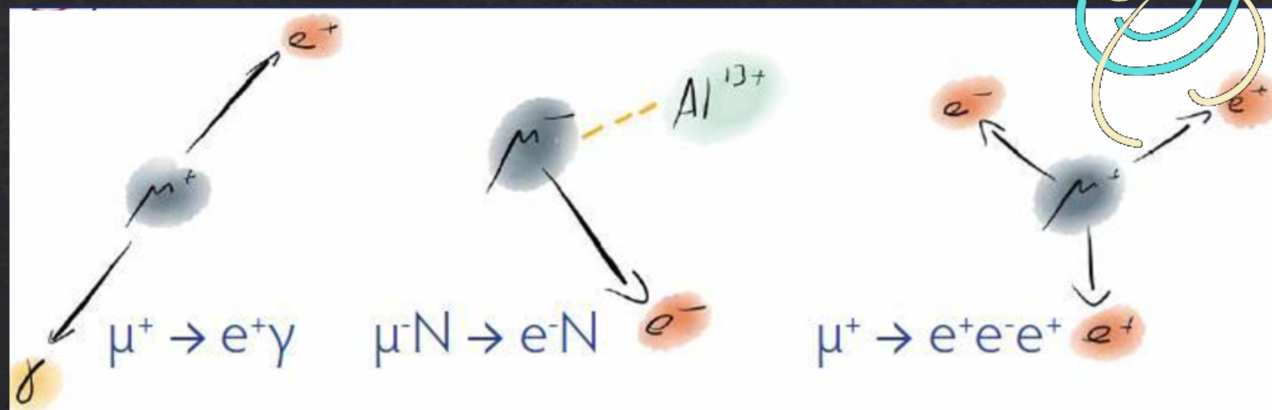
At e+e- or pp GPDs:

- $Z \to e\mu, \tau\mu, e\tau,$
- $H \to e\mu, \tau\mu, e\tau$

In flavour experiments:

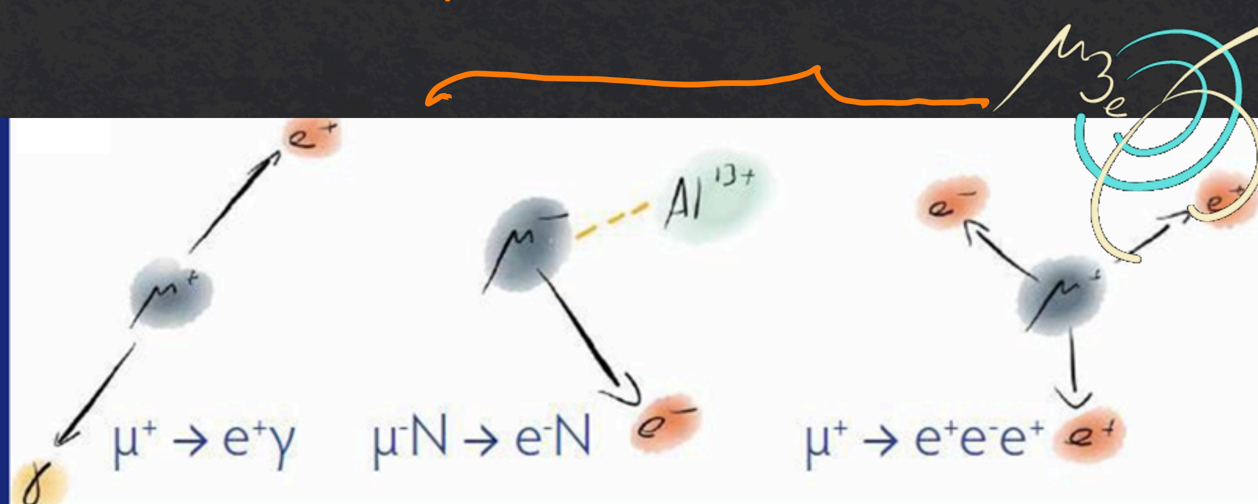
- LFV in hadron decays

MEG μ2e (COMET) μ3e

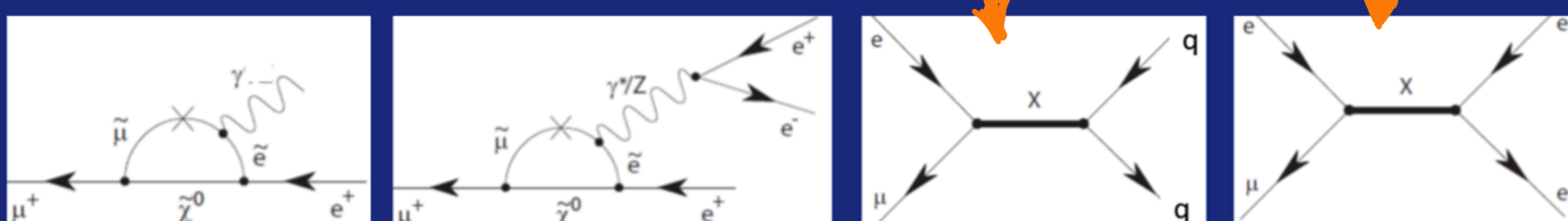


back-to-back electron and photon **$E_\gamma = E_e = ½ m_\mu$**	**Muon decay from muonic atom. Monochromatic electron** **$E_e = m_\mu - E_{binding} - E_{recoil}$**	**3 co-planar electrons** **$\Sigma P_e = 0, \Sigma E_e = m_\mu$**
Radiative decay: **$\mu \rightarrow e\nu\nu\gamma$** **Accidental backgrounds:** **$\mu \rightarrow e\nu\nu$ + conversion or Bhabha electrons**	**Muon Decay in orbit beam related: prompt antiprotons, pions,..**	**Radiative decay ($\mu \rightarrow ee e\nu\nu$);** **Accidental backgrounds** **$\mu \rightarrow e\nu\nu$ + conversion or Bhabha pairs**

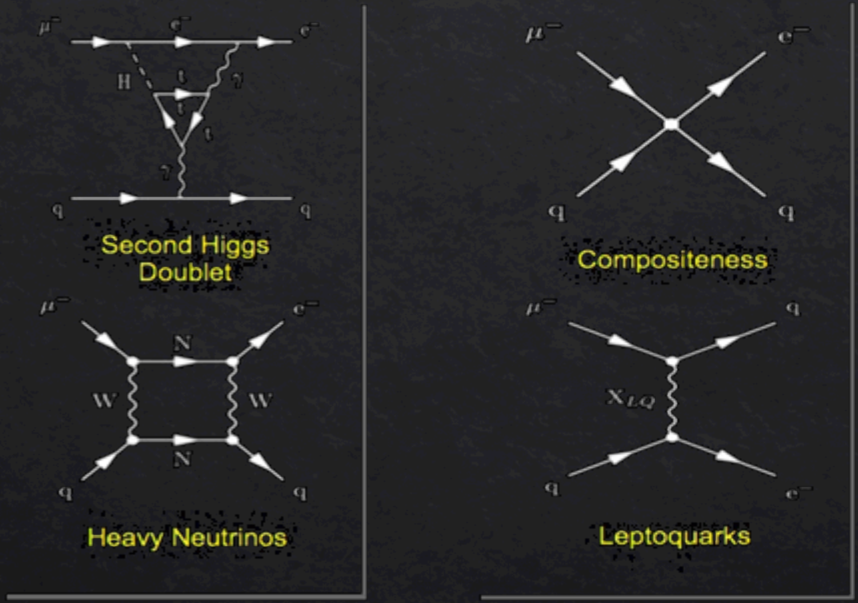
LIVERPOOL DOES BOTH

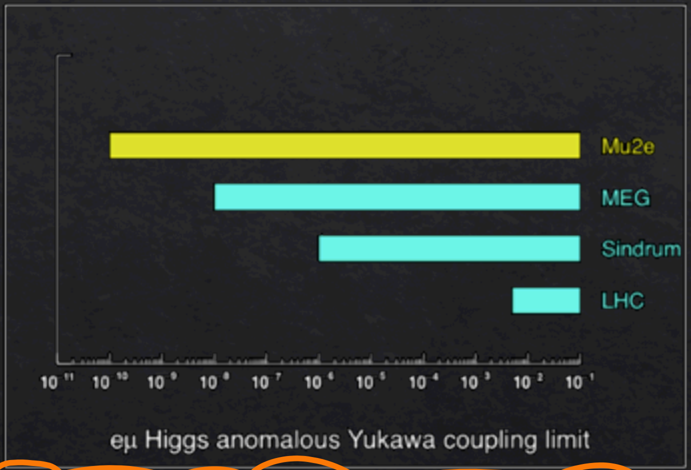


Sensitive to loop diagrams (coupling to γ)	**Sensitive to loops (coupling to γ*/Z, Z',..) and tree diagrams (qqeμ)**	**Sensitive to loops(coupling to γ*/Z, Z',..) and tree diagrams (eeeμ)**



Many BSM models include charged lepton flavour violation
- leptoquarks, compositeness, Higgs doublets, heavy neutrinos…
…or invoke it for leptogenesis of matter-antimatter asymmetry



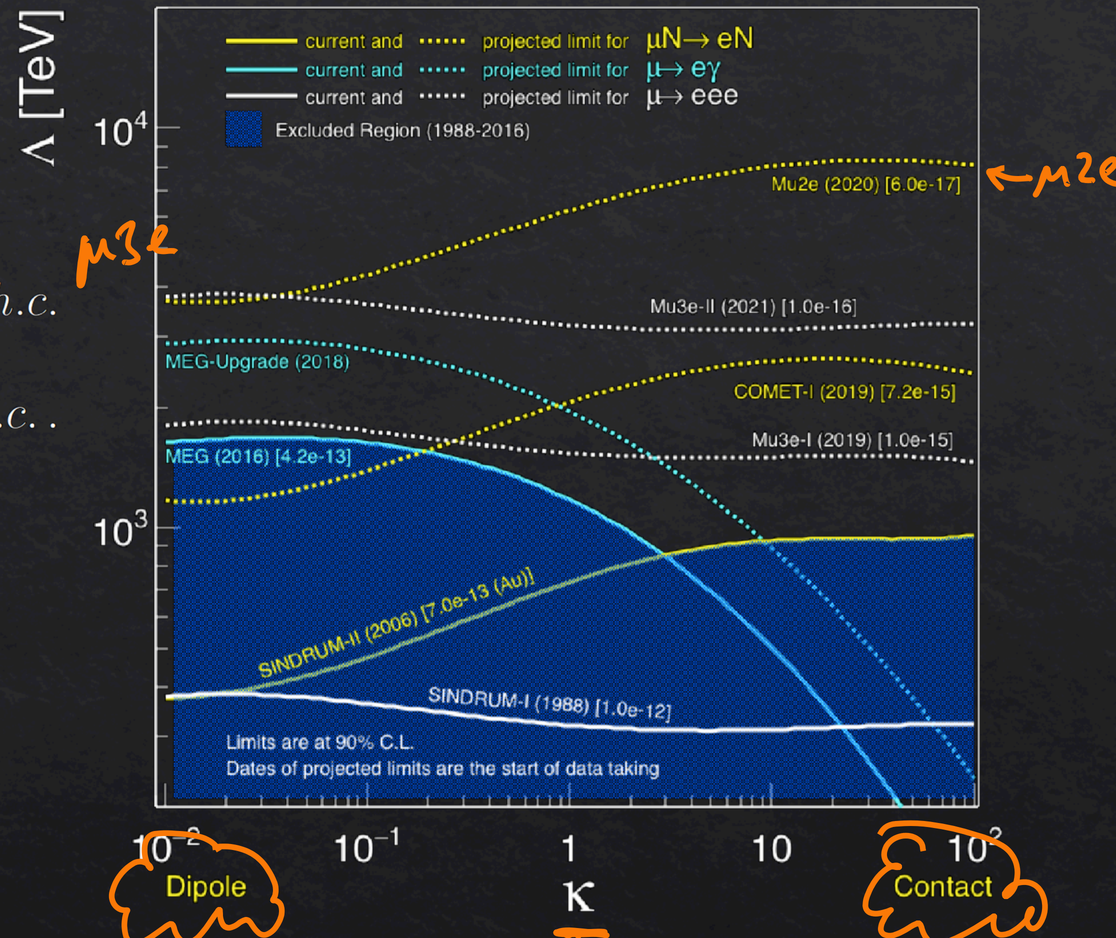


Probe LQ masses up to 300 TeV
cf 1 (120) TeV at HL-LHC (LHCb)

Sensitivity to flavour-violating Higgs couplings

Update from de Gouvea & Vogel, Prog. in Part. and Nucl. Phys. 71 (2013).

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

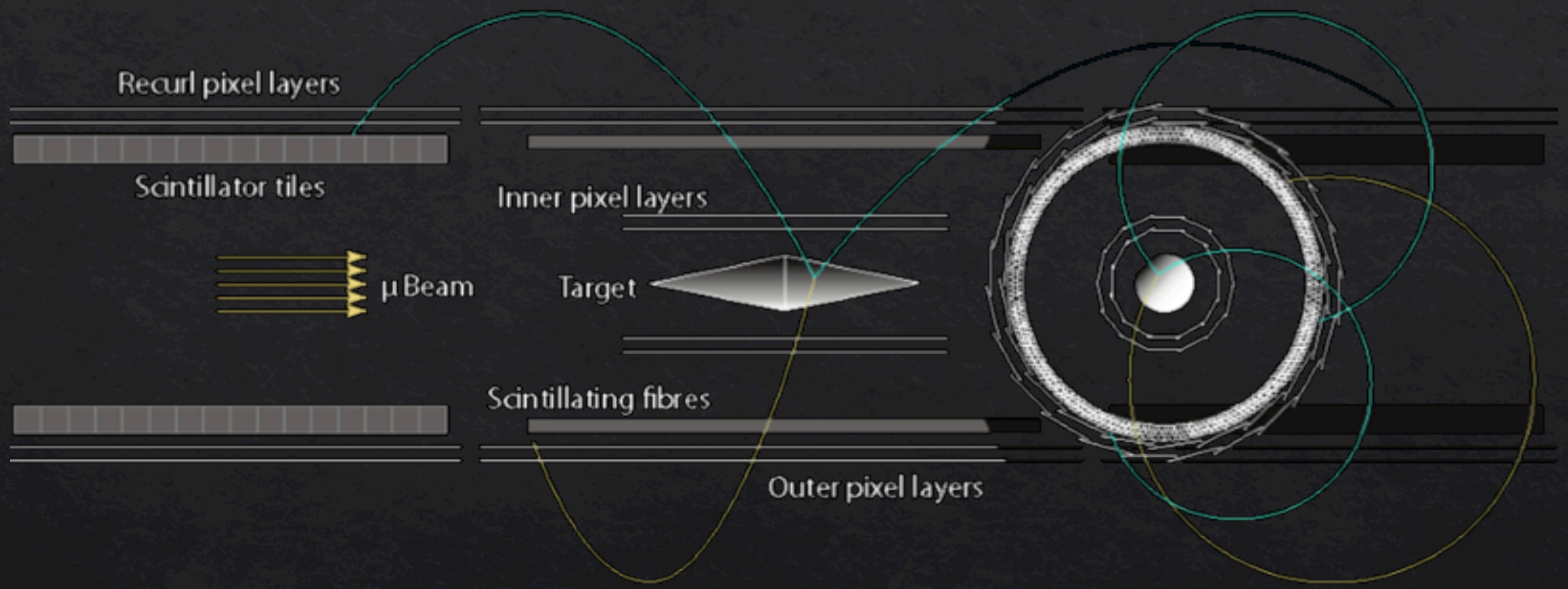


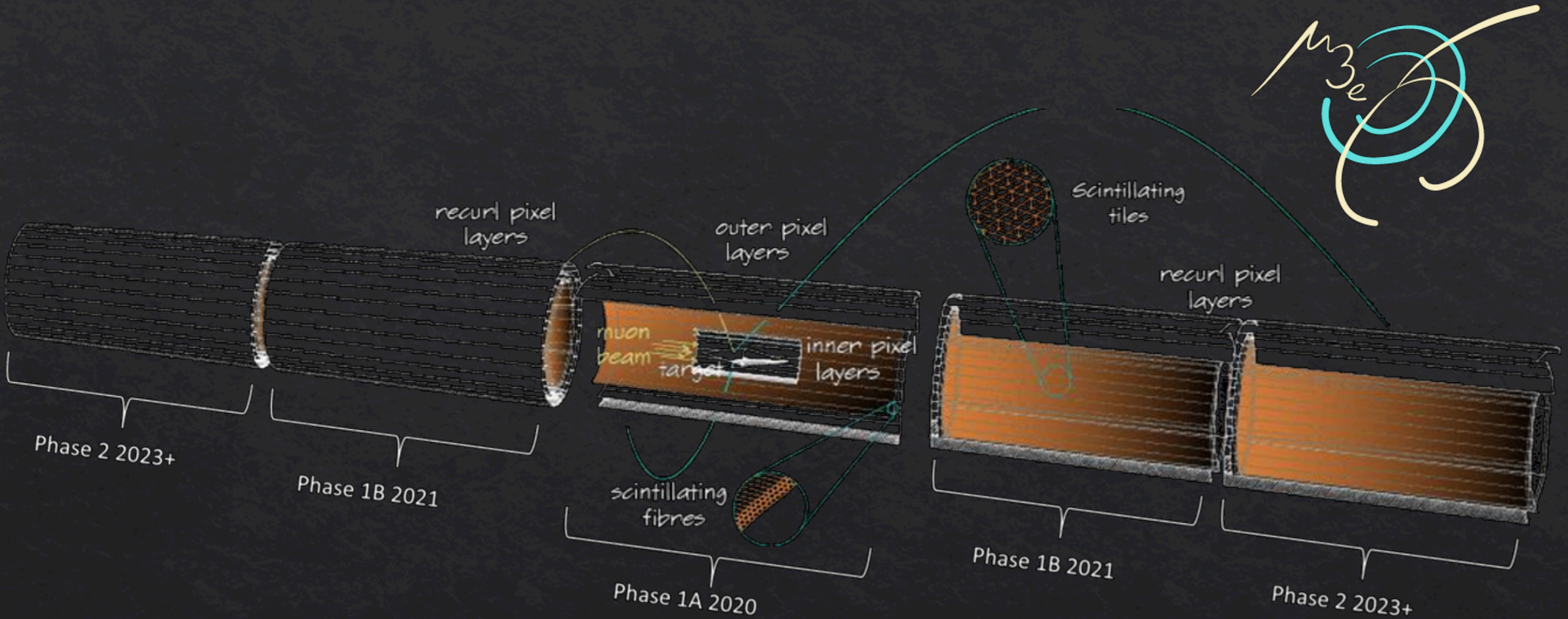
κ « 1, loop diagrams dominate

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

κ » 1 , tree level diagrams dominate

Mu3e


Recurl pixel layers
Scintillator tiles
Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers



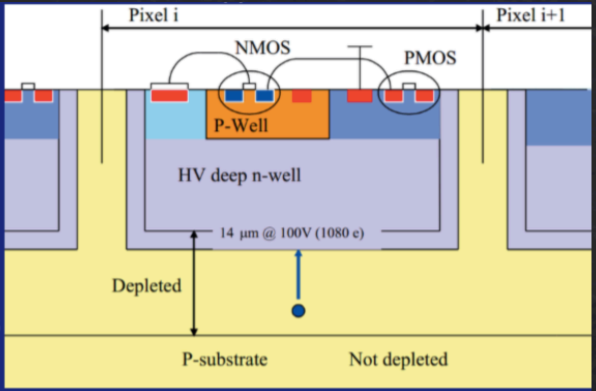
Phase 1A/1B: BR (μ→ eee) < 4×10^{-15} , ~3 years running at 10^8 μ/s from PSI πe5 Compact Muon Beam Line
Phase 2: BR (μ→ eee) < 10^{-16} , ~3 years running with extended acceptance detector at 2×10^9 μ/s from planned High Intensity Muon Beam (HIMB)

UK deliverables (Phase 1)

- Assembly off all outer pixel layers of the MuPix tracker
- Mu3e clock-and-control system for the time-slice based DAQ

UNIVERSITY OF LIVERPOOL

HV-MAPS sensors

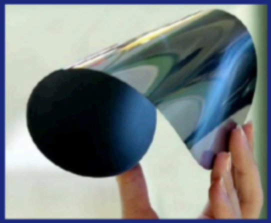


Adaptation from CMOS-MAPS using high-voltage compliant CMOS processes.

- Specific is deep N-well that collects charge and includes analogue and digital circuits. (no parasitic collection)
- N-well is biased to > 80 – 200 V giving 10 - 30 µm depletion in bulk.
- High signal and fast charge collection, *combining compactness of CMOS with performance of hybrid planar silicon sensors.*

<u>*Critical properties for Mu3e:*</u>

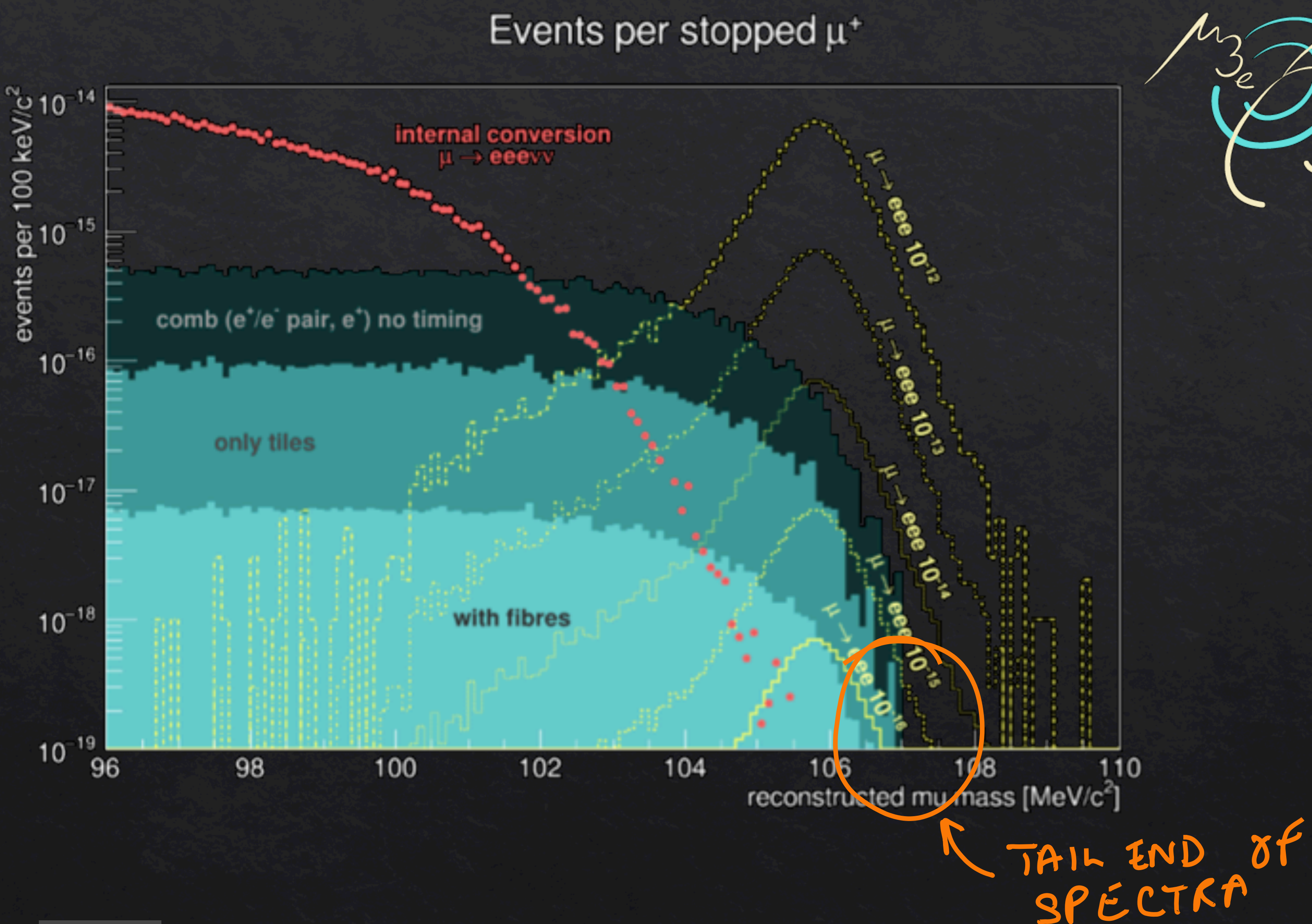
- Sensors can be thinned to 50 µm without signal loss.
- Sensors can operate in a high rate environment (σ(t) < 25 ns)



Mu3e is the first PP experiment to employ HV-MAPS in a tracker

Mu3e would not be possible without this new technology! (sensitivity ~ $(X/X_0)^3$

GREAT TECHNOLOGY
– MORE ADVANCED THAN LHC


Events per stopped μ+
events per 100 keV/c2
internal conversion
μ → eeeνν
comb (e+/e- pair, e+) no timing
only tiles
with fibres
μ → eee 10-12
μ → eee 10-13
μ → eee 10-14
μ → eee 10-15
μ → eee 10-16
reconstructed mu mass [MeV/c2]
TAIL END OF SPECTRA

One CLFV interaction in 10^{16} muon decays is like…

looking for one specific grain of sand

CLFV

- If g-2 confirmed CFLV checks whether NP has a lepton mixing angle
- Particular sensitivity to 4 fermion contact terms
- Mu3e can search for dark photons
- UK on mu2e (with upgrade options) and mu3e

Other muon experiments

- muEDM – parasitically at g-2 and upgrade
- Dedicated experiment for muEDM
- J-PARC experiments
- Proton radius
- ….

A few comments

- There is a great richness and elegance in these experiments
- Creativity and training
- Whatever the outcome of ES this diversity should be preserved
- Enthusiasm of students and teams working on this
- Cheap (UK resource CLFV minimal)
- But major contributions to all experiments so far
  - g-2: Theory, Hardware, Analysis, Leadership
  - Mu3e: building vertex detector
  - Mu2e: STM

Moments …

"If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known" : Pauli

"No experiment is so dumb, that it should not be tried" : Gerlach

"the Muon obeys QED.
g-2 is correct to 0.5%.
In my opinion, it will be
right to any accuracy. <u>So it's not worth doing the experiment</u>"

Head of CERN Theory at time of CERN EDMs

"would you like to predict the result ?" : F. Farley FRS

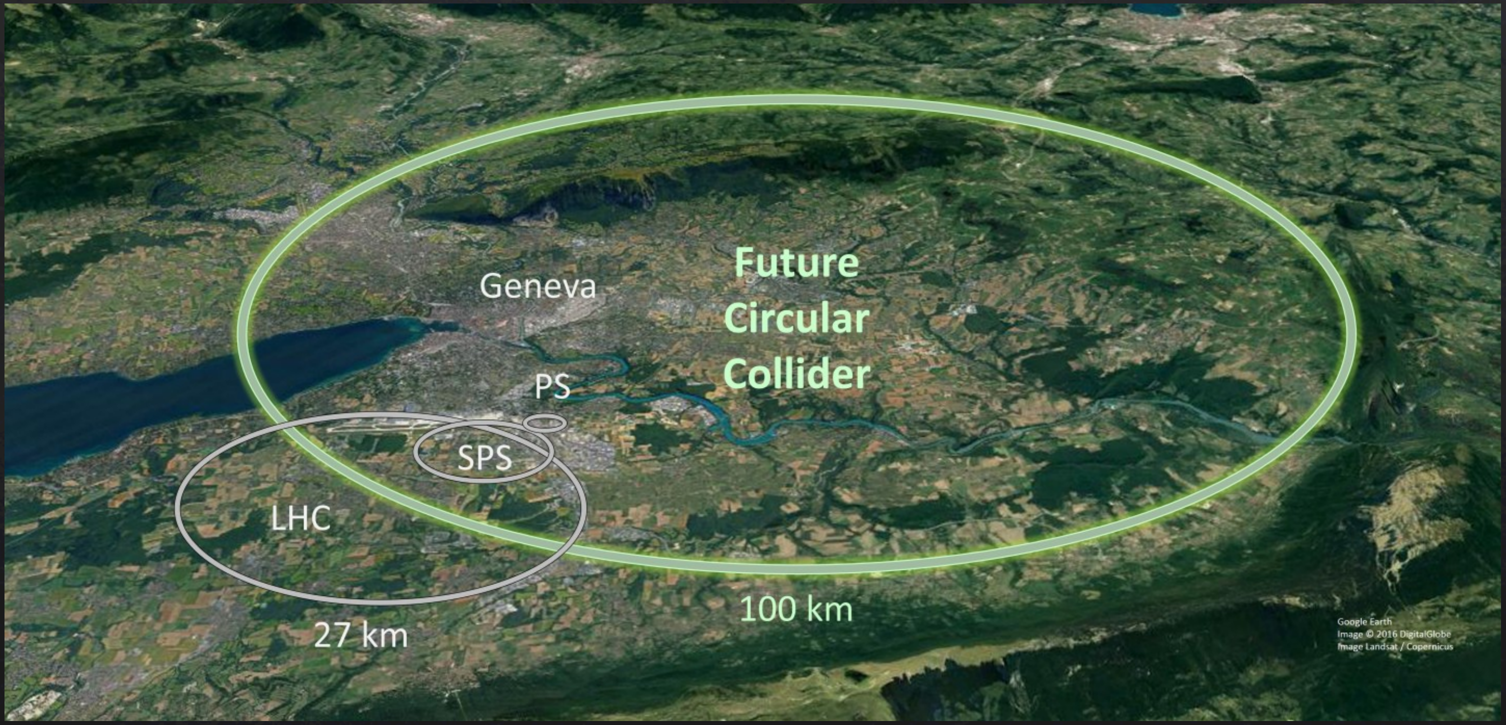
Muons

- Why Liverpool and UK joined
- Part of UK strategy …
- Partial snapshot
- Missed out muons at LHCb
    - Universality etc

Physics Beyond the LHC is exciting!

Access to PeV in the next decade

Can we do physics with loops? Existential question….



Theory

CRITICAL TIME FOR SUBJECT

– LEADERSHIP & IDEAS

BUILD 95 km AND INVEST IN THEORY ?
(AND PBC?) !