The MUonE Project

Dimitris Loukas

The muon g-2 anomalous magnetic moment*

Why study the anomalous magnetic moment of the muon?

Because, is one of the most precisely measured quantities in particle physics.
It puts severe limits in deviations from the Standard Model and opens a window to new physics

An experimental measurement includes all effects, known and unknown, that exist in the real world (electromagnetic, weak, strong, gravitational plus any other unknown interaction)

On the theory side a considerable effort is underway in order to reduce the uncertainty In the Standard Model which is dominated by hadronic correction

The muon (g-2) is astonishing as an observable. It has a classical meaning but it It is a non trivial quantum structure.

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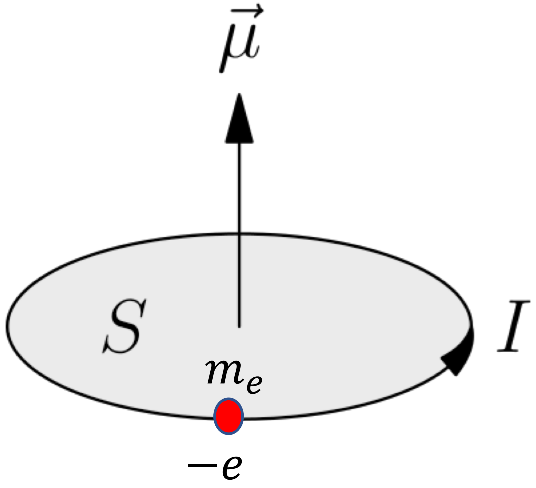
*Not an anomalous physical quantity but discrepancy between measurement and theory

The Basics

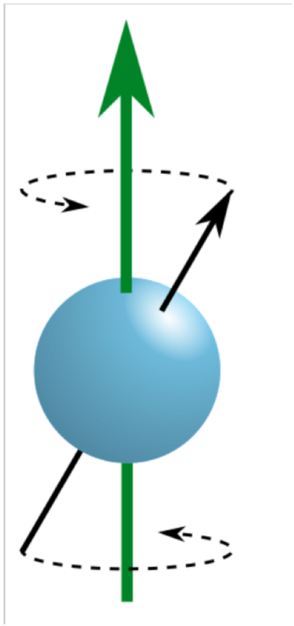
Orbiting electron



$$magnetic\ moment:\ \mu = \frac{-e}{2m_e} L$$

$$gyromagnetic\ ratio:\ \gamma \equiv \frac{\mu}{L} = \frac{-e}{2m_e}$$

Isolated electron



$$1935,\ Dirac\ (QM){:}\ \gamma_e = g_e \frac{-e}{2m_e}$$

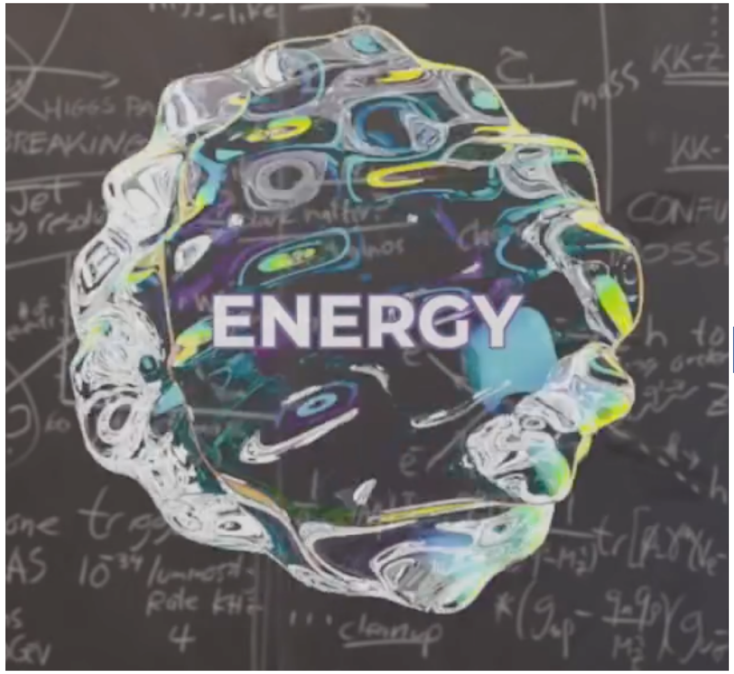
$$g_e = 2$$

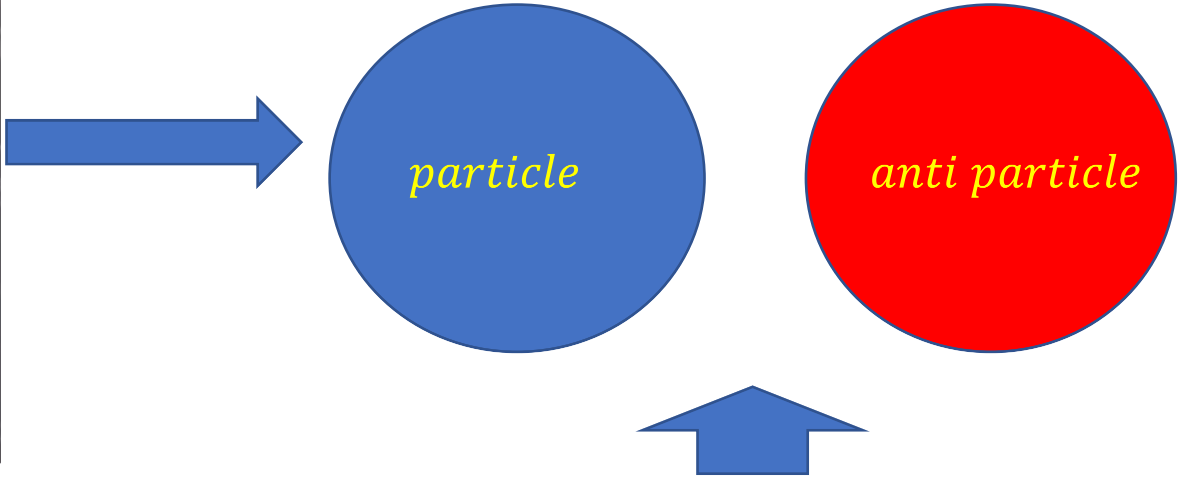
$$1948, QED : g_e = 2(1 + \frac{\alpha}{2\pi} + \cdots)$$

$$with\ a \approx \frac{1}{137}$$

$$g_e = 2.00238$$

The Basics





Strong energy around the electron

QED
Weak Forces
Strong Forces

Muon has a g_μ in analogy to the electron

STATUS in 2006

Experimental: $2.00233184160 \pm 0.00000000063$

Theoretical: $2.00233183608 \pm 0.00000000108$

Agreement in :

Experimental: $2.00233184160 \pm 0.00000000063$

Theoretical: $2.00233183608 \pm 0.00000000108$

Muon has a g_μ

Let's disentangle the part coming from the "cloud":

$$Fraction = \frac{(measured\ g) - (1935s\ prediction)}{(1935s\ prediction)} \quad \Rightarrow \quad \alpha = \frac{g-2}{2}$$

In terms of α:

Experimental: $0.00116592080 \pm 0.00000000031$

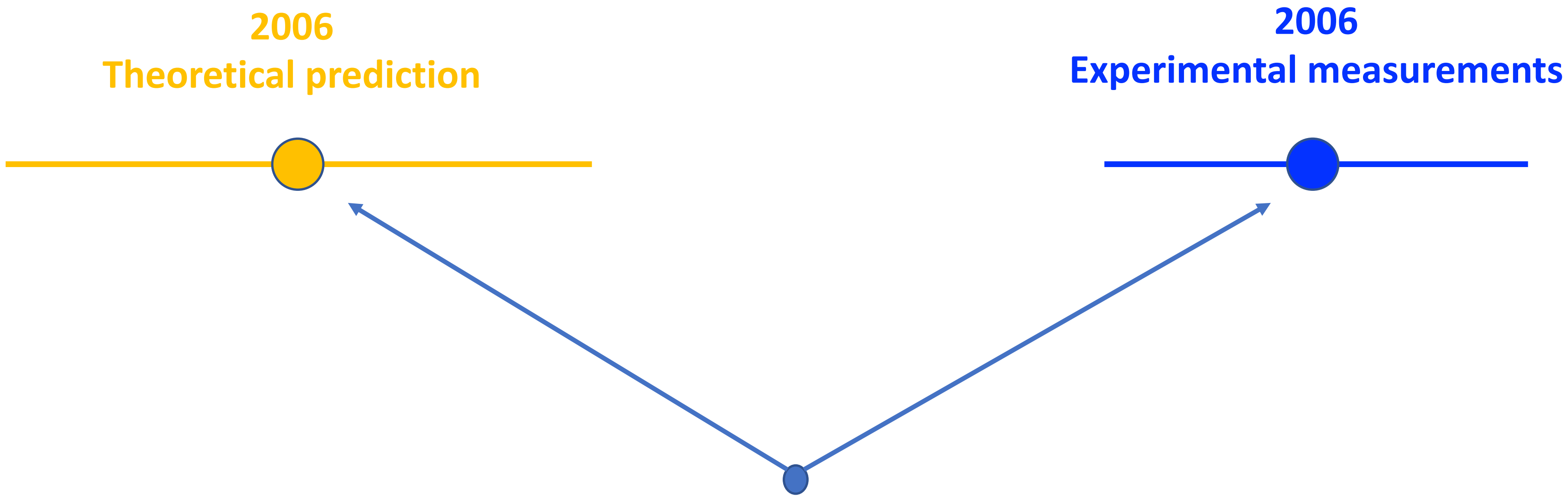
Theoretical: $2.00116591804 \pm 0.00000000054$

keep the part of disagreement

Exp: 2080 ± 31

Th: 1804 ± 54

Muon g_μ : situation in 2006

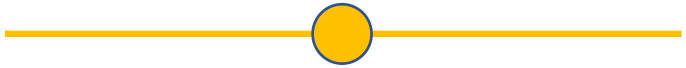


Options:

1. One of these is wrong
2. There are some physical phenomena that theory doesn't include

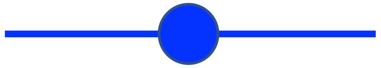
Muon g_{μ} : situation in 2021

2021
Theoretical prediction

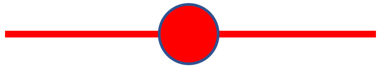


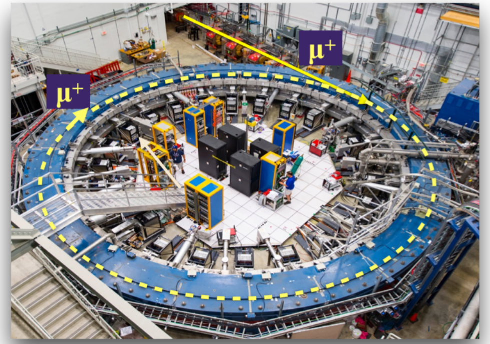
Not much change in theoretical calculations

2006
Experimental measurements



2021
New Fermilab experimental measurements



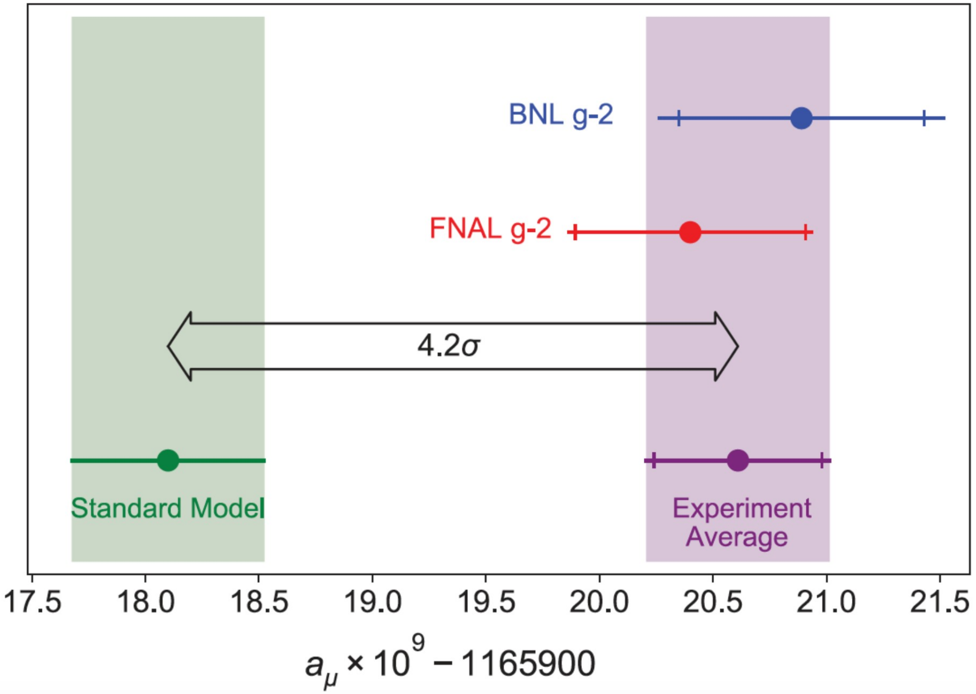


Muon g-2 measurements

Phys.Rev.Lett. 126 (2021) 141801

FNAL confirmed BNL: the experimental result is robust

SM: Muon g-2 Theory Initiative



3.7 σ

3.3 σ

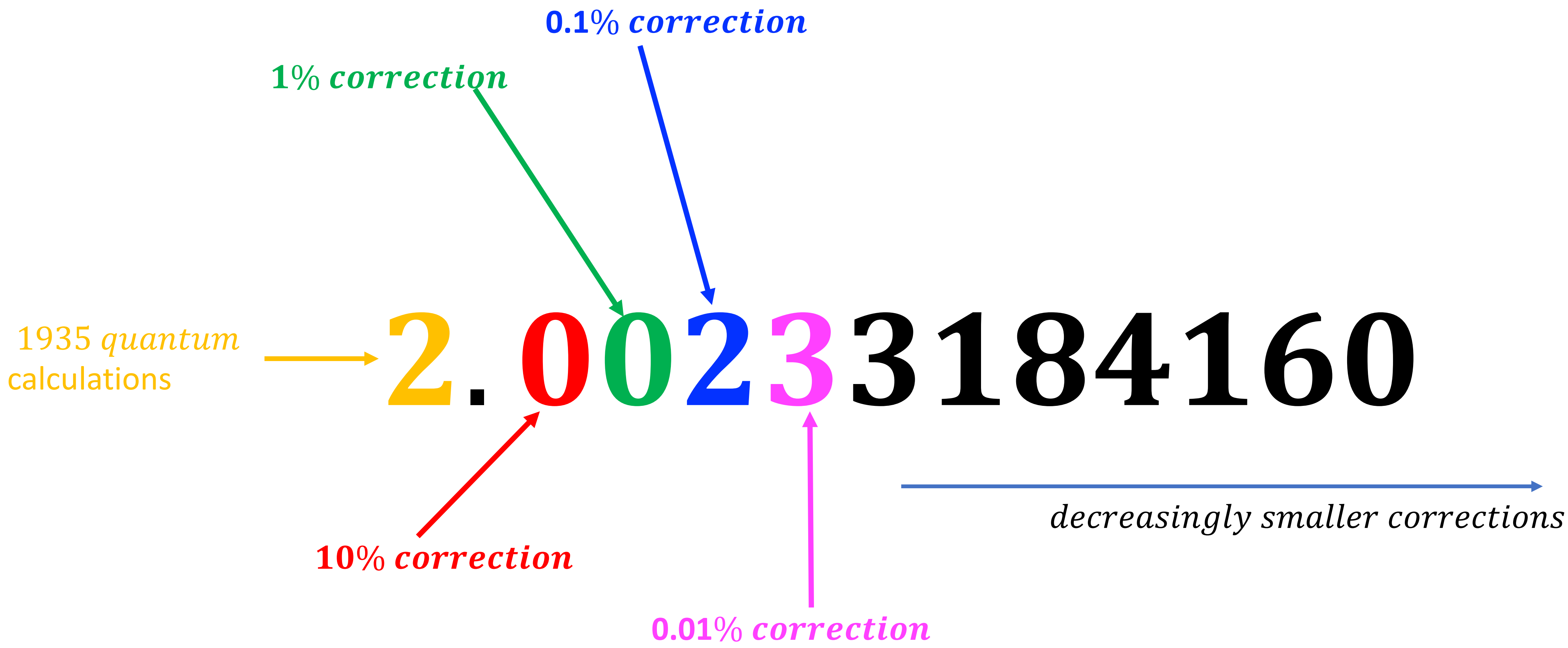
4.2 σ

BNL E821	$(116592089 \pm 63)\times 10^{-11}$	Dominant Statistical uncertainties
FNAL E989 Run 1	$(116592040 \pm 54)\times 10^{-11}$	
Weighted Average	$(116592061 \pm 41)\times 10^{-11}$	0.35 ppm

Expected improvements: factor 2 from FNAL Run 2+3; more from Run 4+5

Muon g_μ : situation in 2021

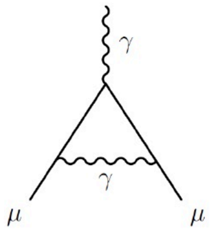
What does this discrepancy tell us?

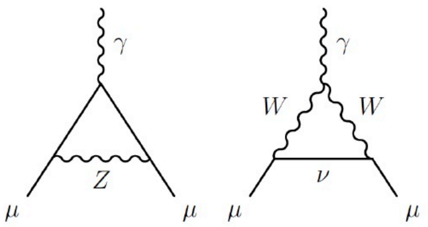

0.1% correction
1% correction
1935 quantum calculations
2.00233184160
10% correction
0.01% correction
decreasingly smaller corrections

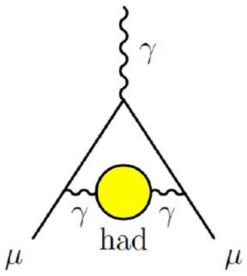
Muon anomalous magnetic moment

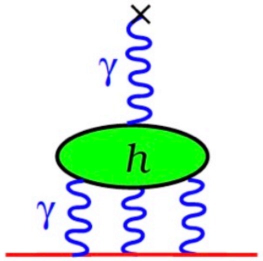
Currently accepted Standard Model prediction:
White Paper of the Muon g-2 Theory Initiative
Aoyama et al., Phys.Rept.887(2020)1

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{had}$$









	QED	EWK	HADRONIC: VP	HADRONIC: Light-By-Light
Order	$\mathcal{O}(\alpha)$	$\mathcal{O}(G_F m_\mu^2) = \mathcal{O}(\frac{\alpha}{s_W^2}\frac{m_\mu^2}{M_W^2})$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha^3)$
SIZE	10^{-3}	10^{-9}	7×10^{-8}	10^{-9}
Uncertainty	10^{-12}	10^{-11}	$\mathbf{4\times10^{-10}}$	2×10^{-10}

Hadronic contributions
-not calculable by pQCD-

QED LO term (Schwinger) = $\alpha/2\pi$ ~ 0.00116
QED corrections known up to 5 loops,
uncertainty related to missing 6 loops!

Dominant Theoretical uncertainty
LO Hadronic Vacuum Polarization
Relative uncertainty: 0.6%

New Lattice QCD result for $a_\mu^{HVP,LO}$

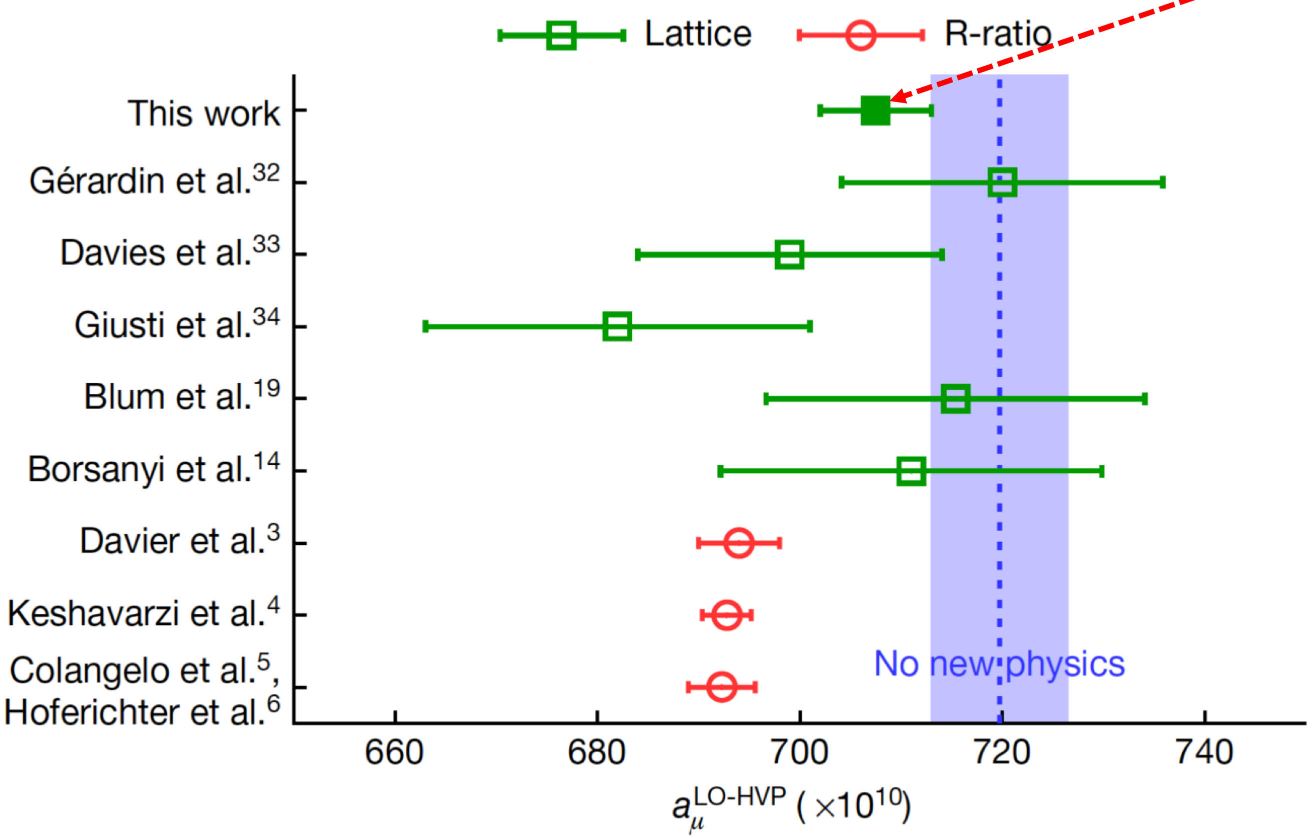
Great progress: the BMW collaboration reached 0.8% precision

It weakens the discrepancy with the measurement

tension ~2σ with the standard dispersive approach

Should be checked by other independent calculations

Borsanyi et al., Nature 593 (2021)



BMW(Lattice QCD): $a_\mu^{HVP,LO} = (7075 \pm 55) \times 10^{-11}$

WP20(R-ratio): $a_\mu^{HVP,LO} = (6931 \pm 40) \times 10^{-11}$

The MuonE project

Measure the effective electromagnetic coupling in the space like region via scattering data* :

Scatter a 150 GeV muon beam on a Graphite (or Beryllium) fixed target

$$\mu^{\pm}(p_1)e^{-}(p_2) \rightarrow \mu^{\pm}(p_3)e^{-}(p_4)$$

* C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni, Phys. Lett. B 746 (2015) 325, http://dx.doi.org/10.1016/j.physletb.2015.05.020 , arXiv:1504.02228 [hep-ph].

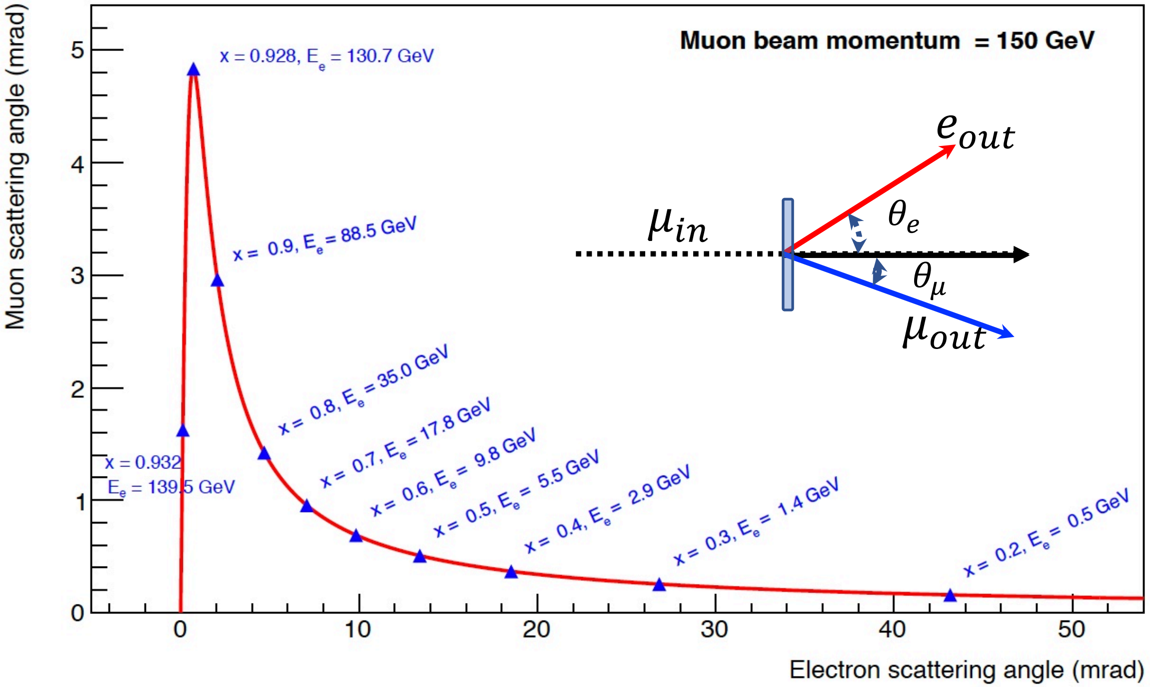
The fundamental constrain

For elastic μe scattering

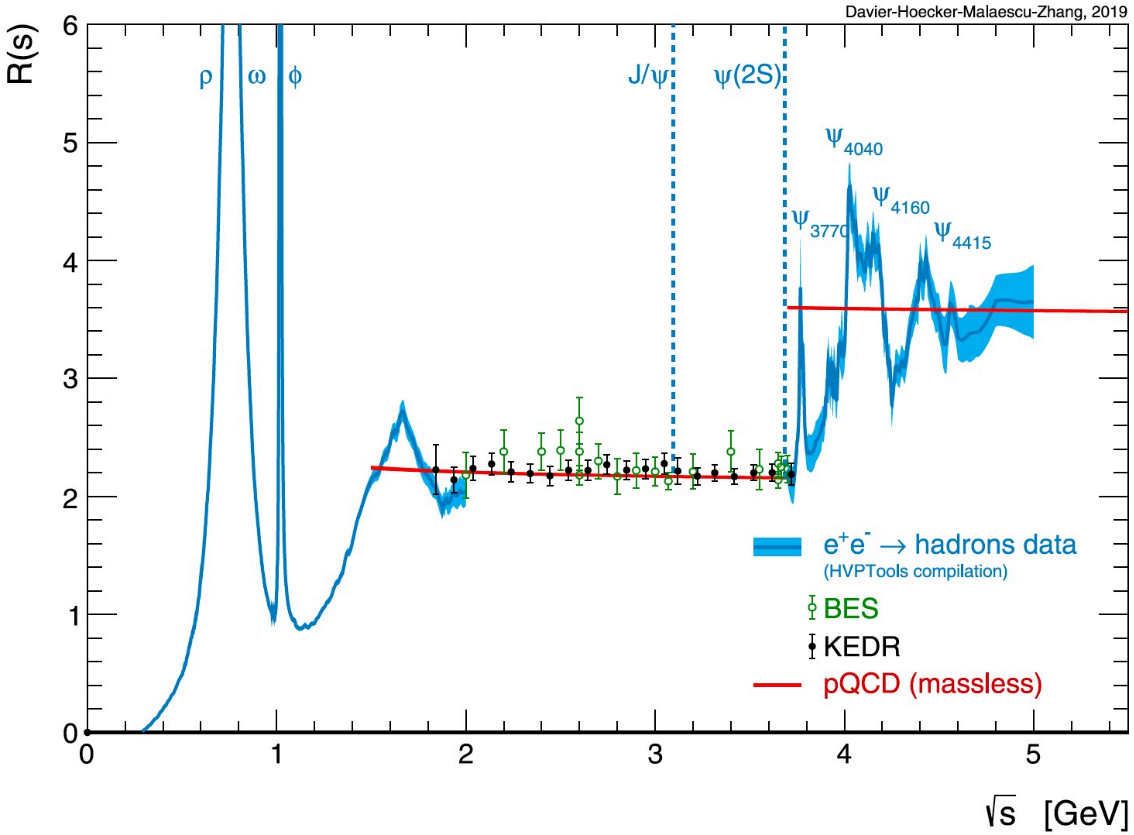
$$tan\theta_{\mu} = \frac{2tan\theta_e}{(1+\gamma^2 tan^2\theta_e)\left(1+\frac{E_1 m + M^2}{E_1 m + m^2}\right) - 2}$$

1. This is the fundamental constraint to discriminate elastic scattering events from the background of radiative events and inelastic processes.

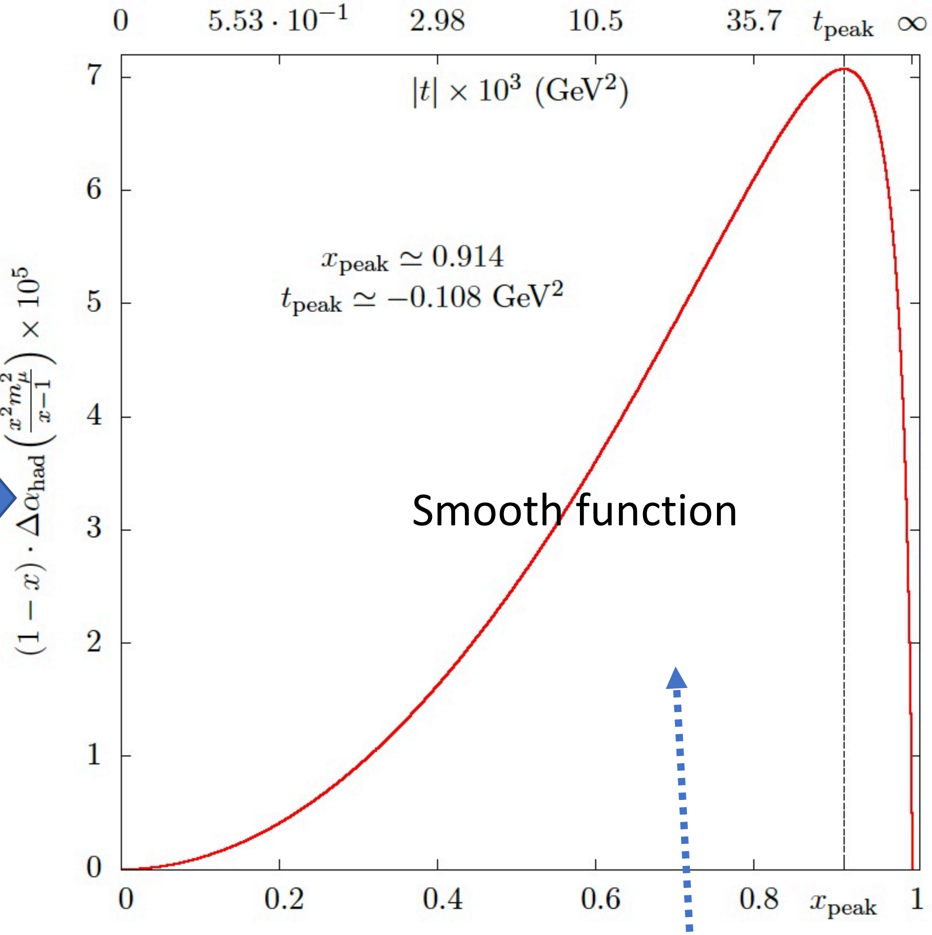
2. At the same time, due to the small angles between the incoming muon and the the outgoing electron, a detector of medium to small transverse surface will suffice.



$$a_\mu^{had,LO} = \frac{\alpha}{3\pi}\int_0^\infty \frac{ds}{s} K_\mu^2(s) R(s)$$



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



a_μ^{HLO} Is the total area under this curve

How to…

In principle :

Assuming a 150 GeV muon beam with intensity 1.3 x 10^7 muons/s (presently available at CERN) incident on a Beryllium or Graphite target (40 layers, each 1.5 cm thick) and three years of data taking, one can reach an integrated luminosity of 1.5 x 10^7 nb^{-1} , which would correspond to a statistical error of 0.3% on the value of $a_\mu^{HVP,LO}$. This will consolidate the muon g-2 and allow a firmer interpretation of upcoming measurements at Fermilab[1] and J-PARC[2].

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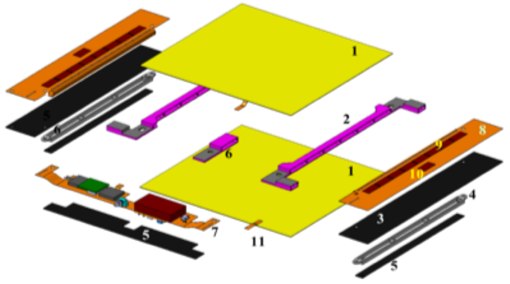
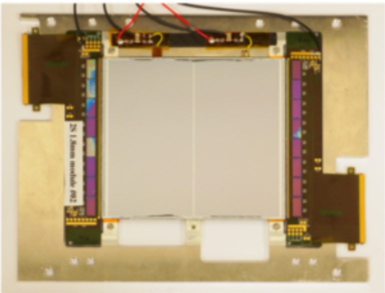
1. Fermilab Muon g-2 Collab, http://muon-g-2.fnal.gov
2. J-PARC g-2/EDM Collab, http://g-2.kek.jp

*How to...

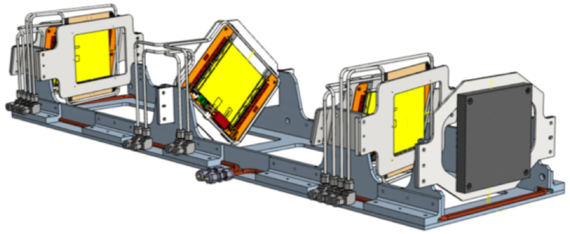
In practice :

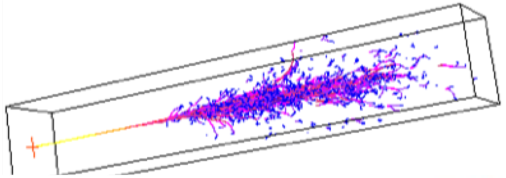
1. Get profit of current R&D for the CMS Phase II Outer Tracker



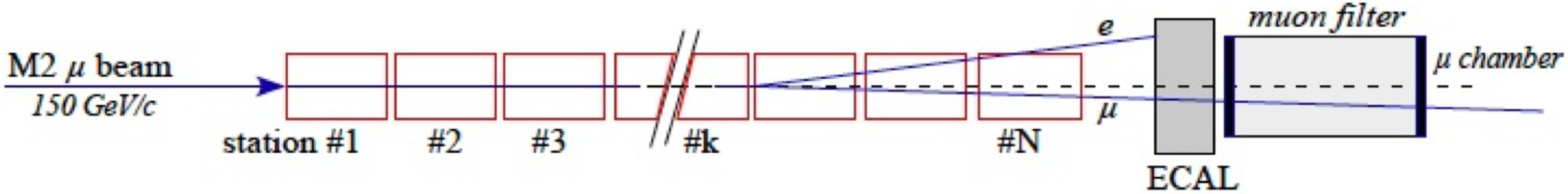


2. 40 stations: CMS modules (10 cm x 10 cm) equipped with plates of 1.5 cm Graphite each one, and spaced by 1 m





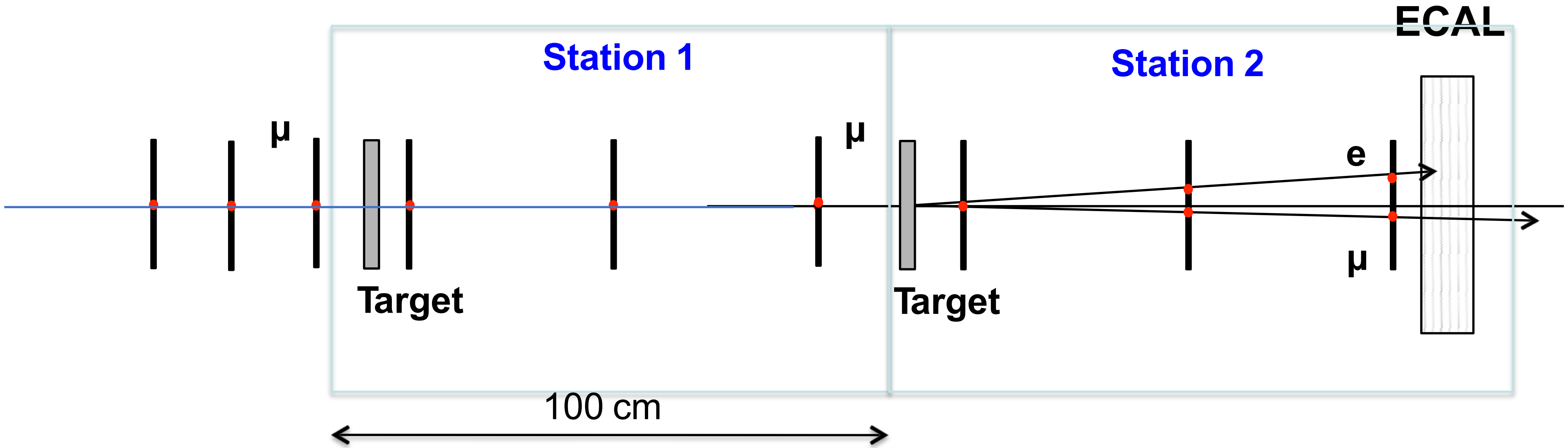
3. With an electromagnetic at the end a muon detector at the end



Letter of Indent https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf

The MUonE Test Run (2021)

Test run set up :



Tracker: **18** **CMS 2Smodule ~95 mm x 95 mm**

Calorimeter: **25** **PbWO4 crystal , ~140 x 140 mm**

total length ~ 4-5 m + services

- **the apparatus will be in a thermalized volume**
- **will run with 2 full stations plus 3 tracking planes for the incoming μ**

The INPP MUonE Group

We jointed the MUonE in summer 2020

Members of the INPP group

Panagiotis	Assiouras
Giannis	Kazas
Dimitris	Loukas
Kostas	Papadopoulos
Aristotelis	Kyriakis