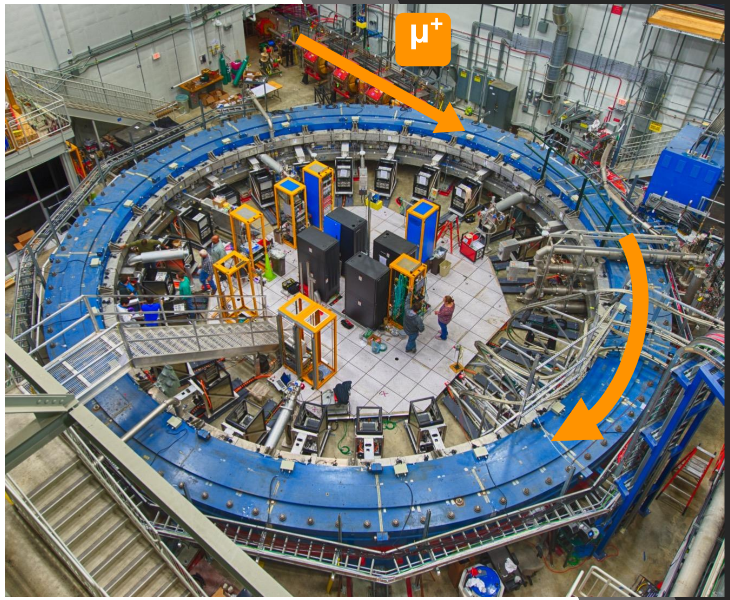
Lepton Flavour Universality and g-2



Themis Bowcock

UNIVERSITY OF LIVERPOOL

Birmingham University
Seminar 26/05/2021

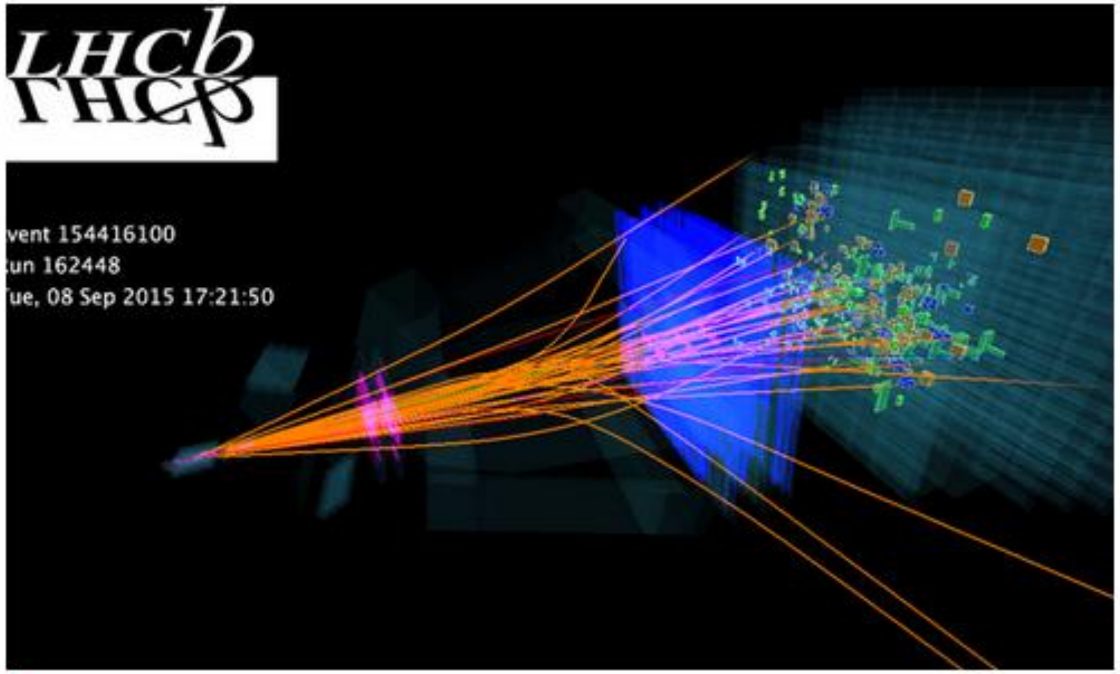
Slides: many thanks
J. Price, B. Casey, B. Quinn, D. Herzog, T. Teubner…

Lepton Universality

- Lepton universality is the idea that all three types of charged lepton particles – electrons, muons and taus – interact in the same way with other particles.
- As a result, the different lepton types should be created equally often in particle transformations, or “decays”, once differences in their mass are accounted for.

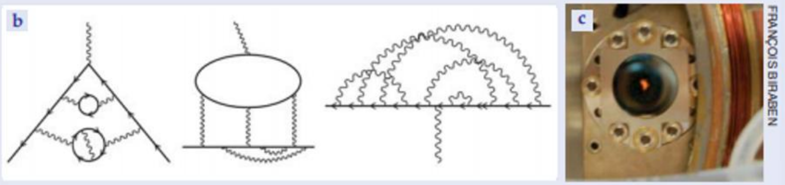
Straws in the LHC wind: Lepton universality and an update on "that bump"

As new data continue to be collected at CERN, another look at some of the straws in the wind, otherwise known as “hints of new physics”, that might develop into exciting breakthroughs



▲ A display of a proton-proton collision event in LHCb, from the 2015 13 TeV data. The interactive, live event display can be found here. Photograph: LHCb/CERN

Single electron trapped for months



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

Unprecedented confrontation of theory and experiment. **(a)** Our Penning trap shown here suspended a single electron for the months it took to measure its magnetic moment **μ**—the most precisely measured property of an elementary particle. **(b)** The magnetic moment is also the quantity most precisely predicted by the standard model of particle physics. The prediction requires the calculation of nearly 14 000 integrals. These Feynman diagrams represent three of those. **(c)** Fluorescing rubidium atoms are used to measure the fine-structure constant α, which gives the strength of the electromagnetic interaction. The measured α and the standard-model calculation are the essential inputs for the precise prediction. **(d)** The predicted and measured values of μ agree to an astounding part per trillion. Both values shown here are divided by the Bohr magneton μ_B defined in the text. Parentheses denote uncertainties in the rightmost two digits.

quick study

The standard model's greatest triumph

Gerald Gabrielse

The standard model predicts the electron magnetic moment to an astonishing accuracy of one part in a trillion.

Gerald Gabrielse is the George Vasmer Leverett Professor of Physics at Harvard University in Cambridge, Massachusetts.

The electron is amazing. The particle whose orbits give size to atoms may actually have no size. We only know that its radius must be less than 2×10^{-20} meters to explain why more high-speed positrons do not bounce backward when they collide with electrons. The "spin-½" electron has angular momentum $\mathbf{S} = \frac{1}{2}\hbar\hat{\mathbf{S}}$, as Otto Stern and Walther Gerlach famously demonstrated, even though it has no size and nothing is rotating.

The electron, though, does have the magnetism that we might expect if charge displaced from the electron's center rotates to make current loops. Insofar as the electron has a simple internal structure, that magnetic moment $\boldsymbol{\mu}$ is parallel to its spin: $\boldsymbol{\mu} = \mu\hat{\mathbf{S}}$. To measure μ, a single electron is suspended for months at a time in a strong magnetic field **B**. A weak electric field (henceforth to be ignored, since it adds no fundamental complication) keeps the electron from leaving the measurement apparatus—the Penning trap shown in panel a of the figure.

that is, $\boldsymbol{\mu}$ is antiparallel to the spin—because the electron charge is negative. In terms of the famous electron g value, $\mu/\mu_B = -g/2$.

Other critical experimental methods can only be mentioned, given space constraints. Using only the lowest cyclotron states eliminates the necessity to make a relativistic correction that depends on velocity. We obtain the fraction of a second needed to observe a one-quantum cyclotron excitation by using a cylindrical trap cavity that inhibits the spontaneous emission that otherwise would radiate away the energy of the excited state before it could be observed. So-called quantum nondemolition detection keeps repeated observations of the lowest quantum states from causing transitions.

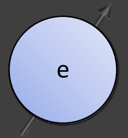
The resulting electron magnetic moment, $\mu/\mu_B = -1.001\ 159\ 652\ 180\ 73\ (28)$, is the most precisely measured property of any elementary particle. The uncertainty, in parentheses for the rightmost two digits, is only 2.8 parts in 10^{13}. For comparison, the muon magnetic moment has been measured only about 1/2500 as precisely.

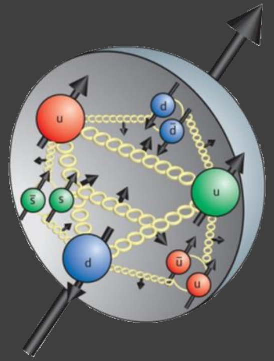
The standard-model calculation

In 1928 Paul Dirac introduced the famous relativistic wave equation that describes an electron and other spin-½ particles. The Dirac equation prediction, $\mu/\mu_B = -1$, is the first and largest of four standard-model contributions that together may be written $-\mu/\mu_B = 1 + a_{QED} + a_{hadronic} + a_{weak}$.

Moments

- Electric and Magnetic
  - Leptons v baryon





- Electron: "…magnetic moment is the most precisely calculated property of an elementary particle" (parts per trillion)
  - Gabrielse Physics Today 66(12), 64 (2013);
- Theory of the Anomalous Magnetic Moment of the Electron:
  - Kinoshita et al. see e.g. *Atoms* 7 (2019) 1, 28

Magnetic moments

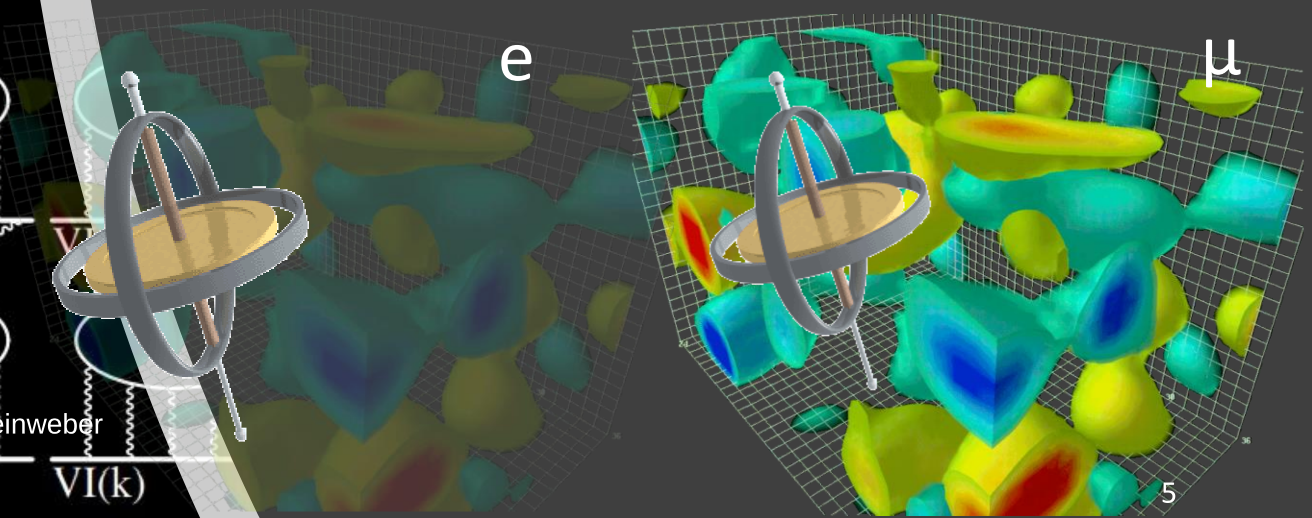
- The muon has an intrinsic magnetic moment that is coupled to its spin via the gyromagnetic ratio *g*: $\vec{\mu} = g \frac{e}{2m_\mu} \vec{S}$

- Magnetic moment (spin) interacts with external B-fields

- Makes spin precess at frequency determined by *g*

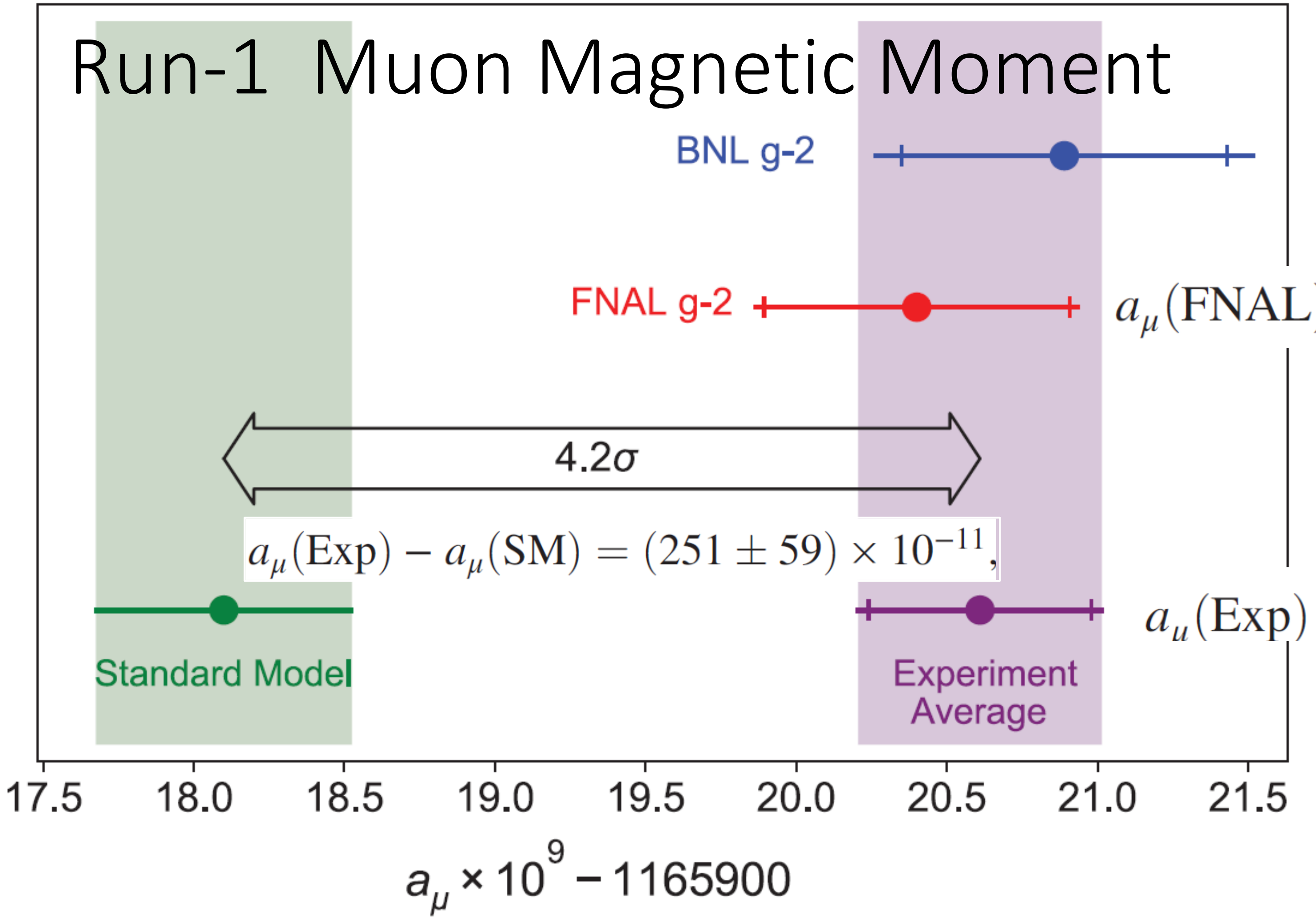
Confronting Magnetic Moments of Muon

- g-2 results
  - n.b. lattice “BMW” argument
  - Anomaly persists (dispersive calculation of HVP)
- This is of interest because the (heavier) muon is more sensitive to the vacuum
  - Lamor precession in field
  - Possible explanations: … Z’, ALPs, LQ etc.



Vacuum: Derek Leinweber

Run-1 Muon Magnetic Moment



$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\text{ ppm})$$

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11},$$

$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\text{ ppm})$$

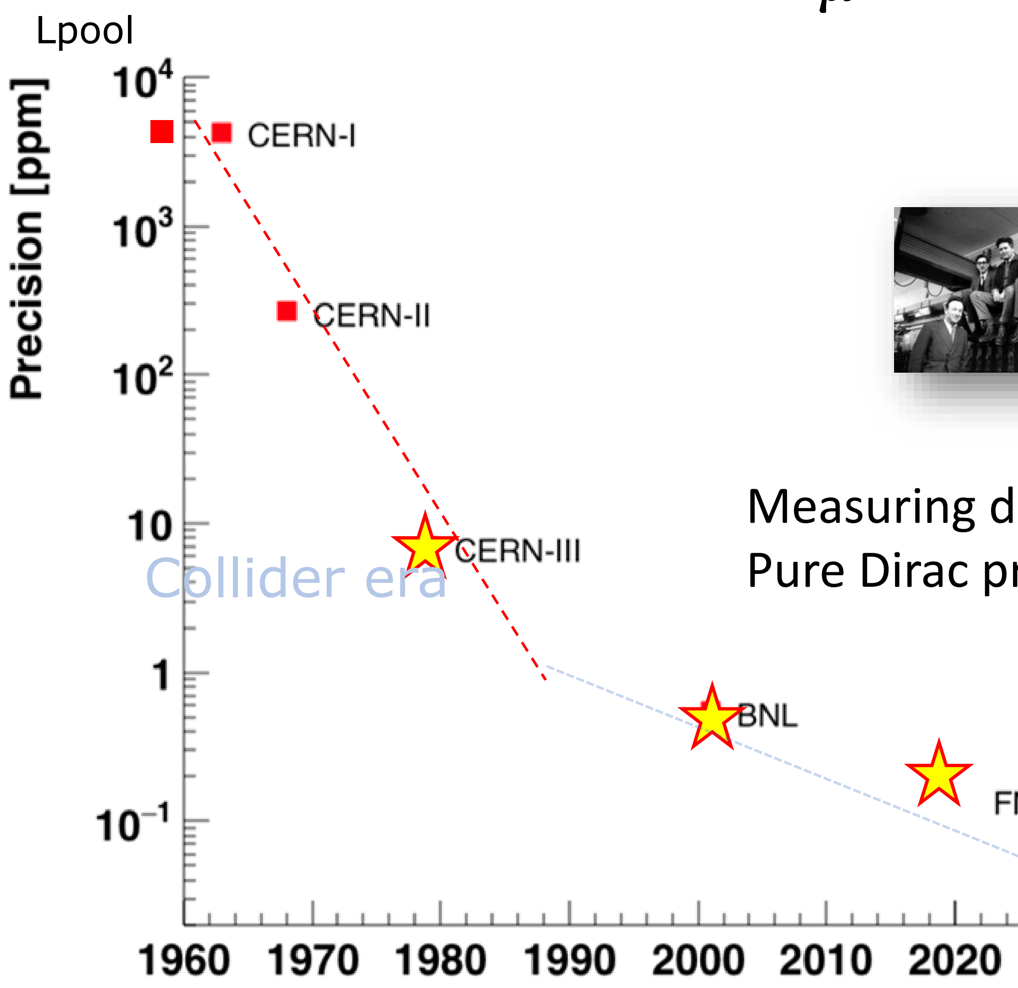
Outline

- Muon g-2
- Interpretation and Theory
- Context
- Other Experiments

Precision g-2

Evolution

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



Measuring deviations from Pure Dirac prediction

History g-2

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

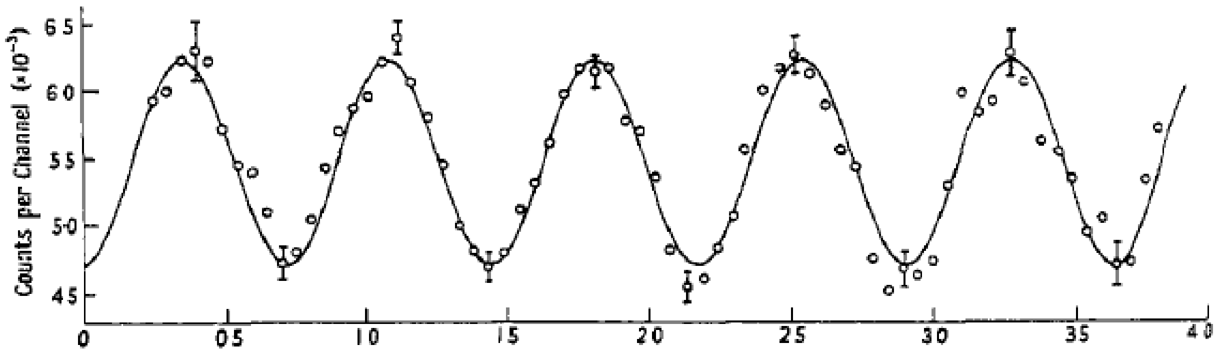


Figure 2. Time distribution of forward electrons from positive muons stopped in copper (87%) and carbon (13%). The magnetic field was 101·9 gauss. The exponential decay factor has been removed, and the first few points have been corrected for a slight non-linearity in the time analyser. Note the displaced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

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

g=2.004 ± 0.014 (0.6%)

In 1959 CERN launched the g-2 experiment aimed at measuring the anomalous magnetic moment of the muon. The measures were studied using a magnet 83cm x 52cm x 10cm borrowed from the University of Liverpool.

In 1962 this precision had been whittled down to just 0.4%.

Storage Beam Method

- Store muons in a ring
- The spins precess like a top about the magnetic field as they circulate around the ring

Muons in ring (I)

The **anomalous magnetic moment** is roughly proportional to the **anomalous precession frequency**

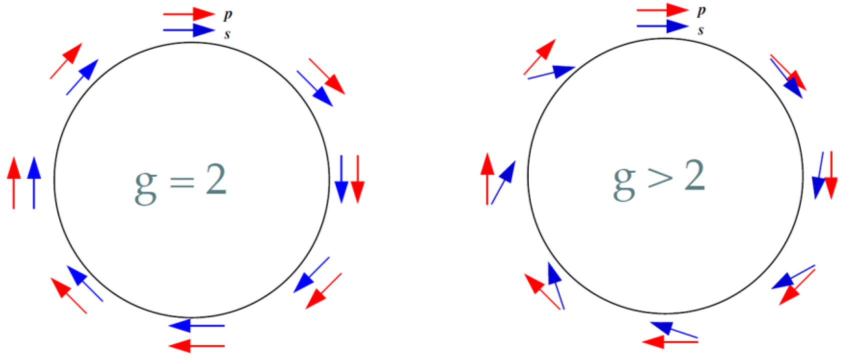
Spin precession freq: $\omega_s = \frac{g_\mu e B}{2 m_\mu c} + (1-\gamma)\frac{eB}{m_\mu c \gamma}$

Cyclotron (mom. precession) freq: $\omega_c = \frac{eB}{m_\mu c \gamma}$

Anomalous precession freq: $\boldsymbol{\omega_a} = \omega_s - \omega_c = \boldsymbol{a_\mu} \frac{e}{m_\mu c} \boldsymbol{B}$

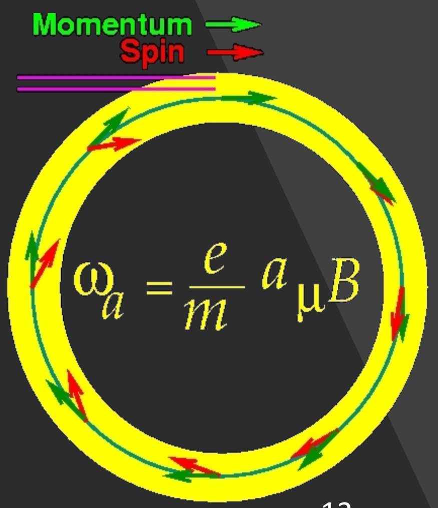
(simplified)

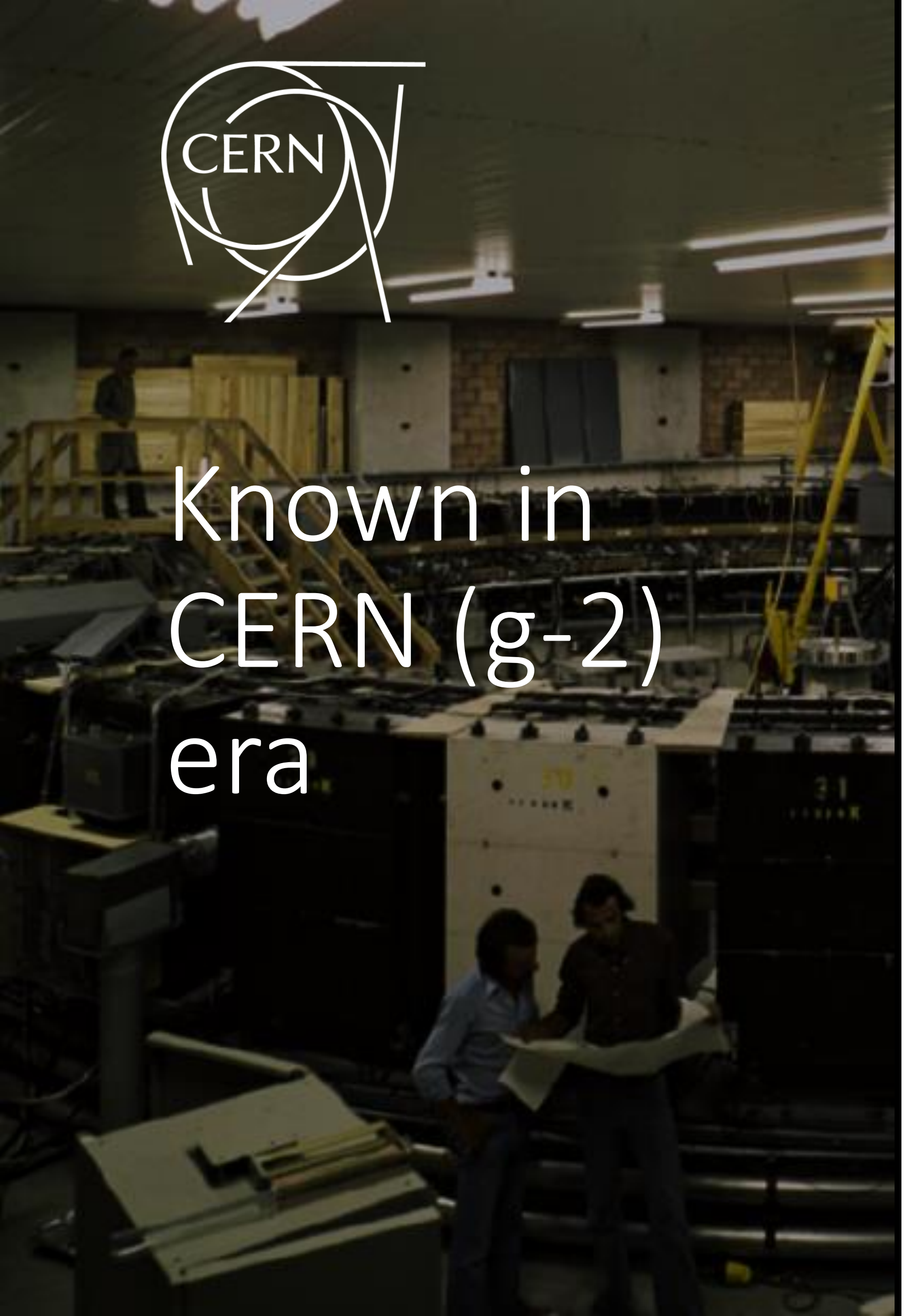
800x more sensitive than rest muon experiments that measure *g*



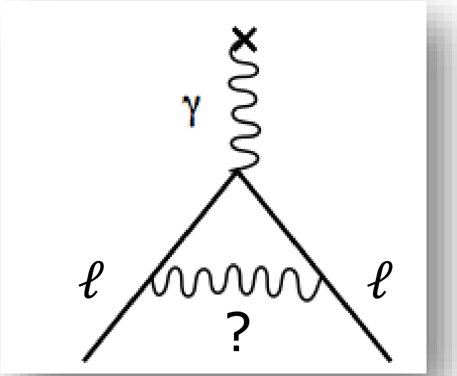
Muons in ring(2)

- $\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{mc}\left[a_\mu \vec{B} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)(\vec{\beta}\times\vec{E})\right]$
- There is *some* vertical beam motion, so **need** to use electric quadrupole fields to contain the beam vertically (the *B* field holds them in horizontally). But these facts complicate the expression for the **anomalous precession frequency**
- At "**magic**" momentum ($\gamma = 29.3, p_\mu = 3.09\ \mathrm{GeV}/c$), last term cancels!
- Note 2nd and 3rd terms, due to beam "imperfections" are not exactly zero
- CERN-III miracle





Known in CERN (g-2) era



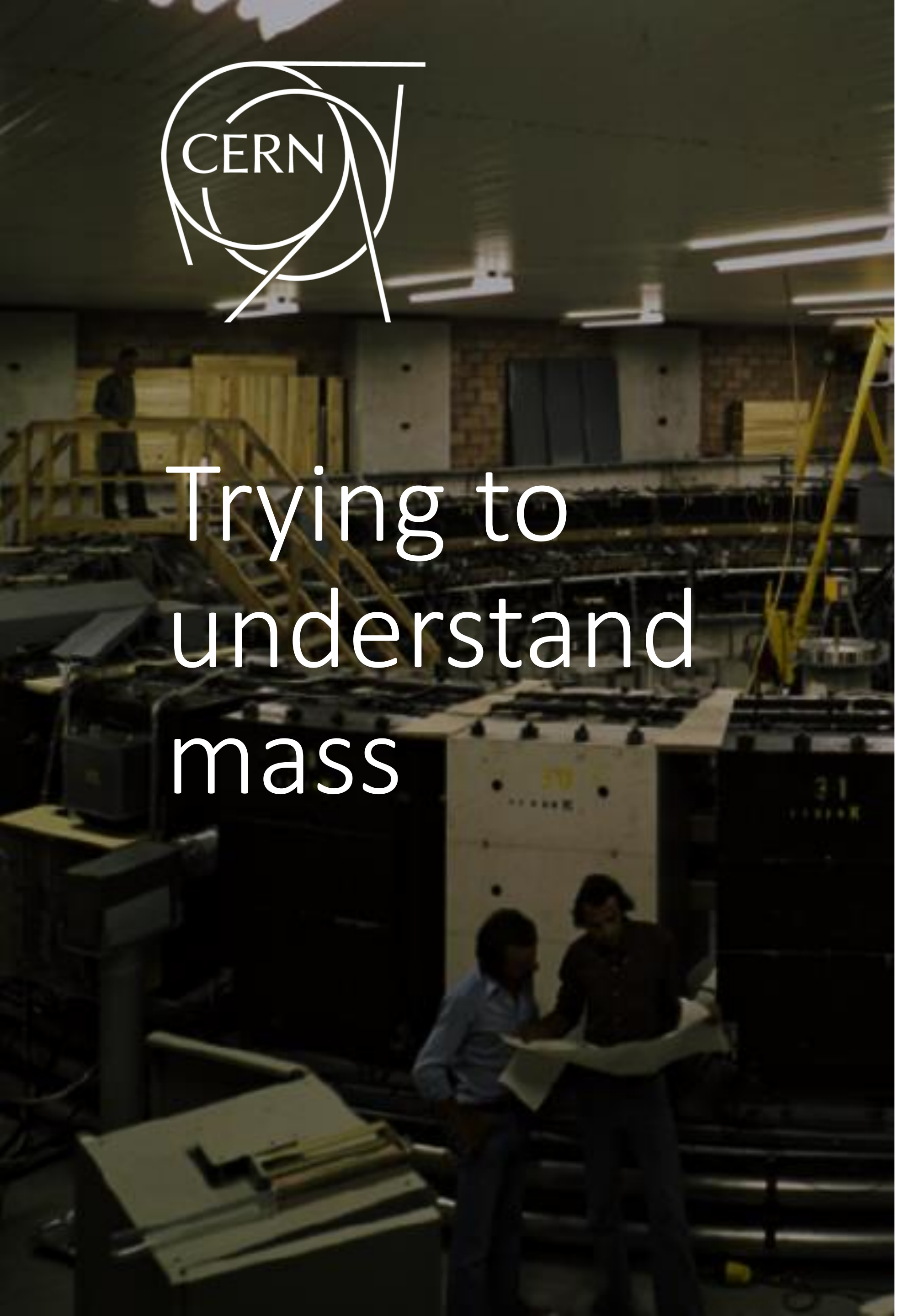
New physics contributes as:

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

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. 2^{nd} Generation Leptons v. useful.

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

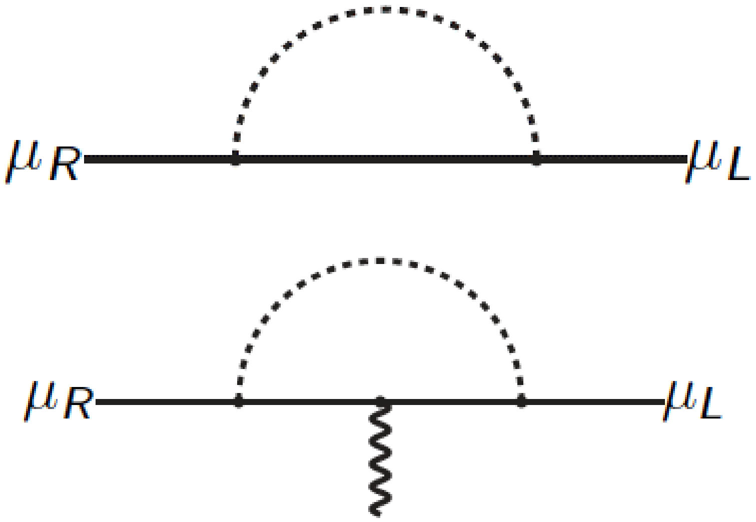


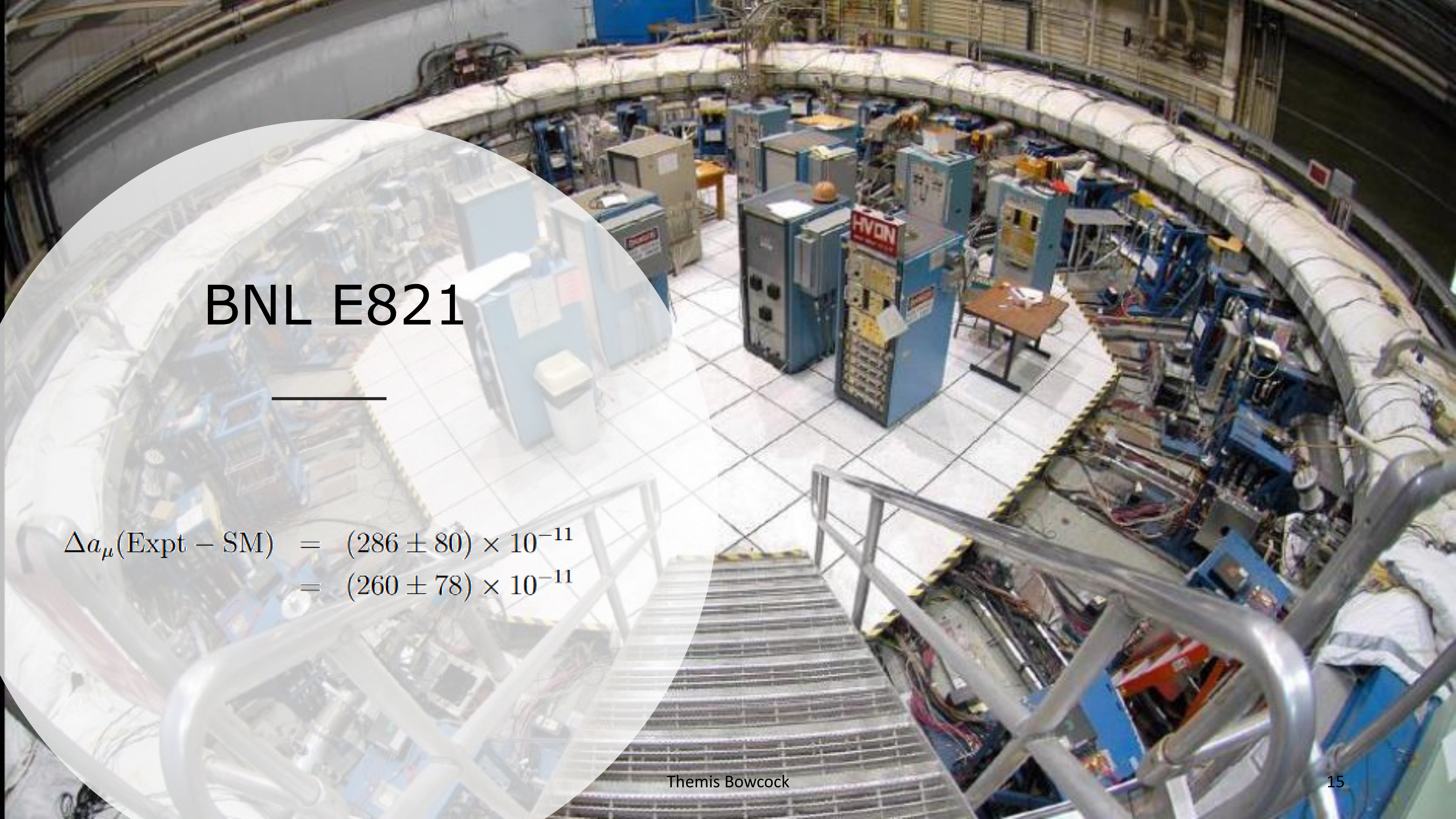
Trying to understand mass

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

m_μ in loops

a_μ in loops





BNL E821

$$\begin{aligned}\Delta a_\mu(\mathrm{Expt}-\mathrm{SM}) &= (286 \pm 80) \times 10^{-11} \\ &= (260 \pm 78) \times 10^{-11}\end{aligned}$$

"Never measure anything but frequency"

I. Rabi (Schawlow)

- g-2 Experiment at FNAL

Fermilab

- *…can we resolve the E821 anomaly?*

Muon Production (above ground)

- Muon g-2 Collaboration
  - >200 collaborators, 35 institutes, 7 nations
  - Particle, Nuclear, Atomic, Optical, Accelerator, Theory
  - Experienced BNL E821 veterans, and lots of new young (and some old…) talent

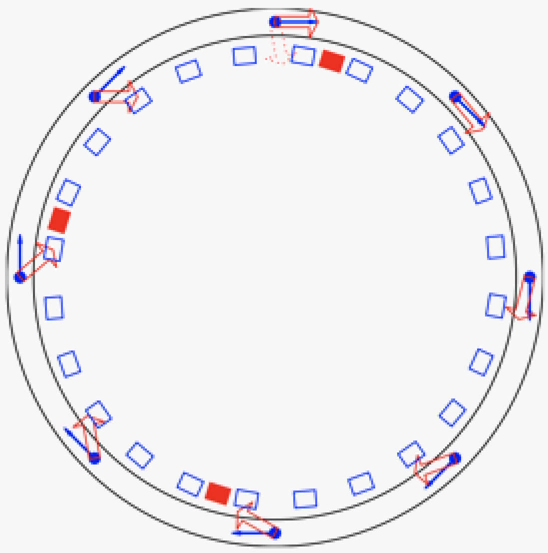
Fermilab Muon g-2 Experiment (E989)

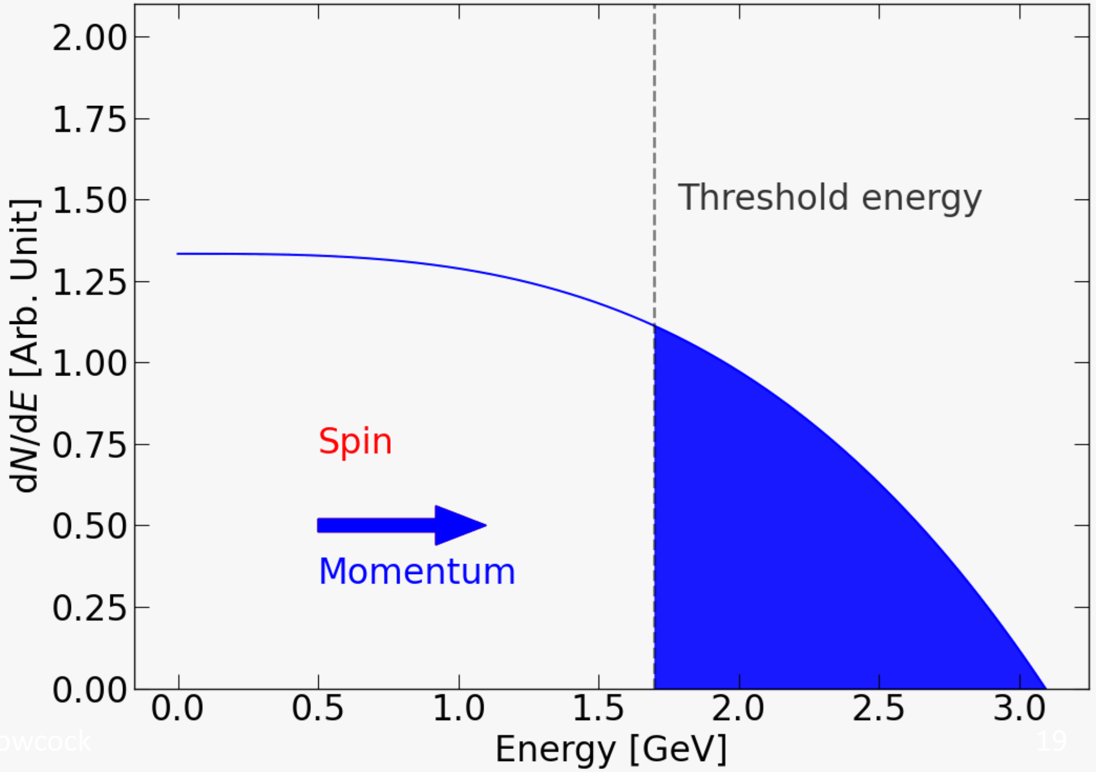
- Rebuild the BNL experiment at Fermilab, but "*Better, Stronger, Faster than before*" (OK, maybe not faster…)
- Start with the original core foundation
  - Reuse the BNL storage ring – move it to FNAL
- Power with Fermilab's more intense, cleaner beams
- 4x reduction in uncertainty (540 ppb→140 ppb)
  - 20x more muons (stat.unc. 460 ppb→100 ppb)
  - Improvements/upgrades (syst.unc. 280 ppb→100 ppb)

Measuring ω_a

The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency

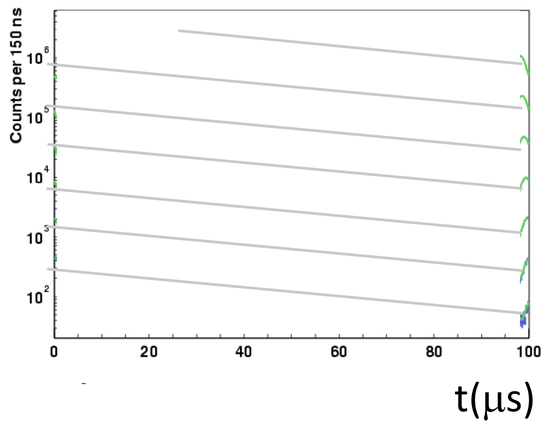
Simply measure the time and energy of decay positrons and count the number above an energy threshold



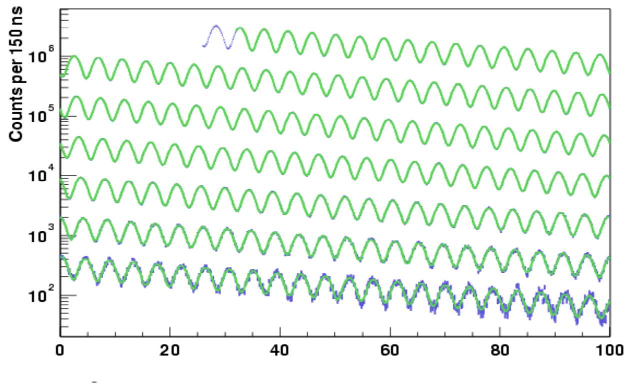


Muon precession frequency measurement

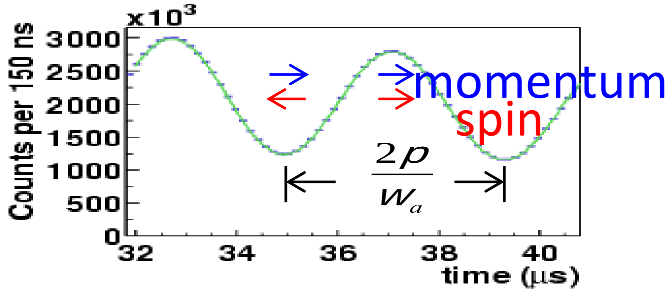
- What data looks like if g-2 = 0



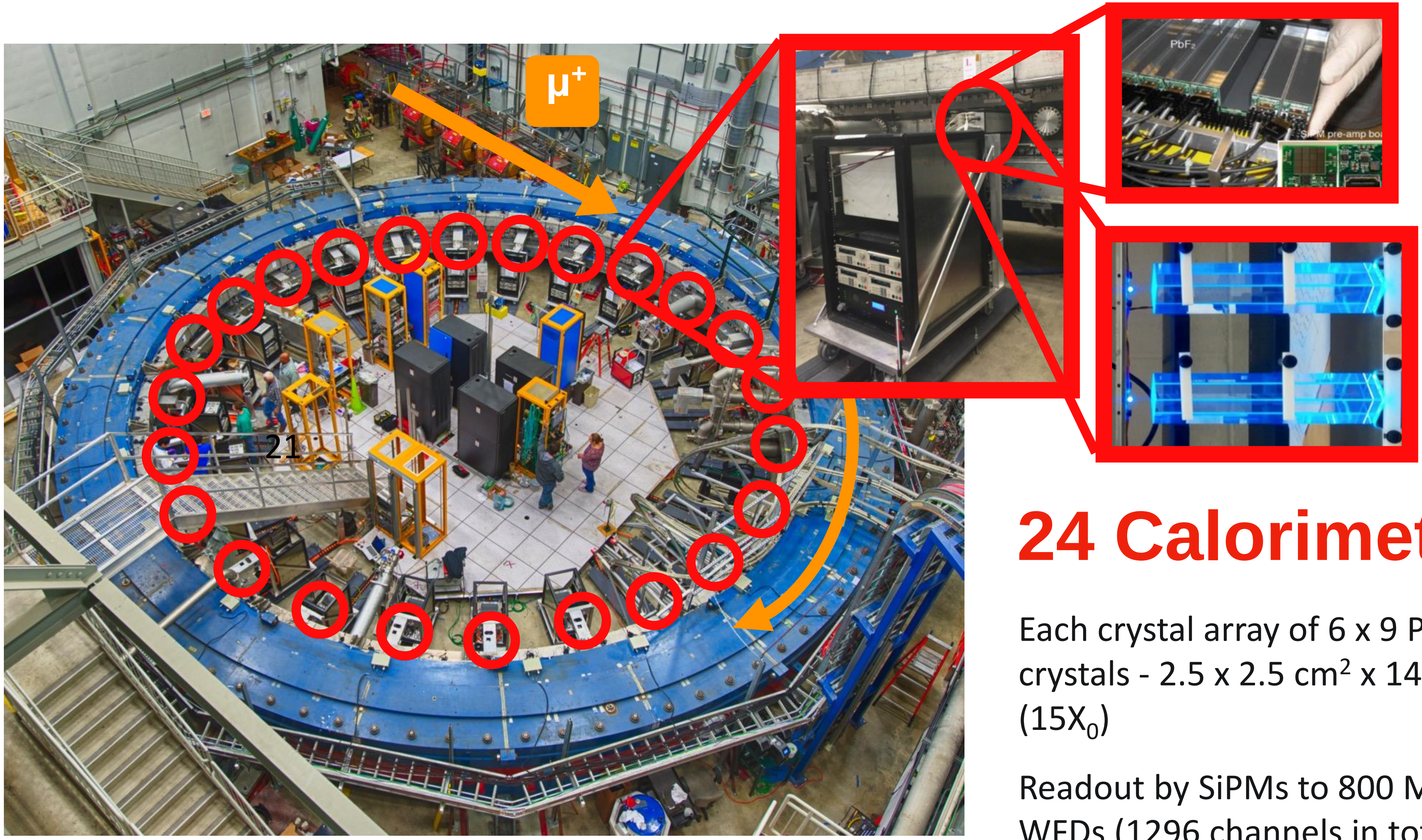
- What data looks like if g-2 = 0.002



high energy positrons versus time



Calorimeters



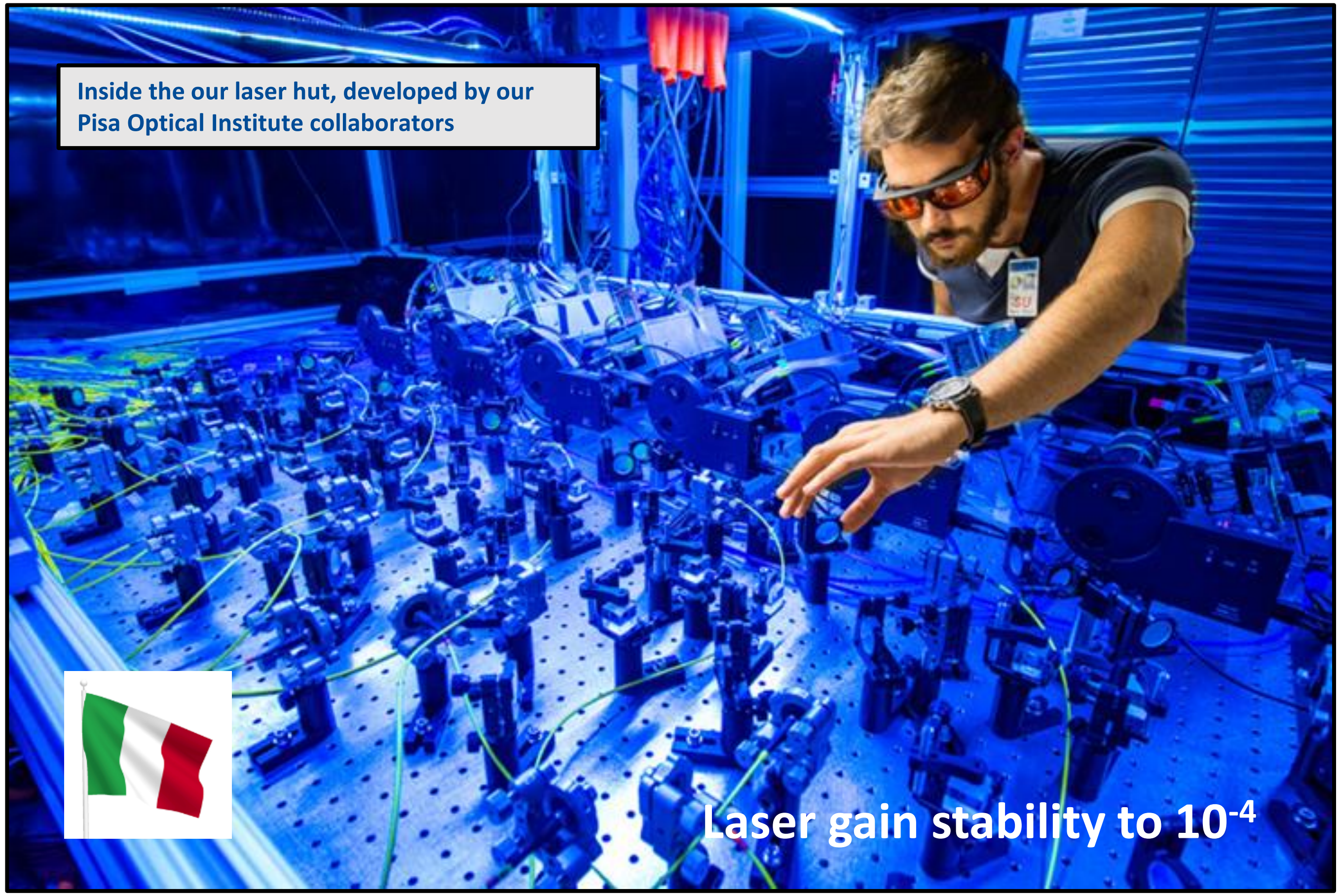
24 Calorimeters

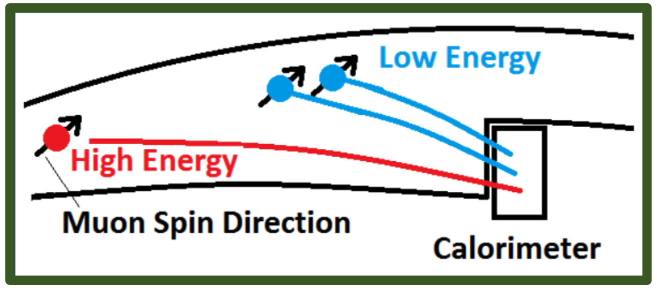
Each crystal array of 6 x 9 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)

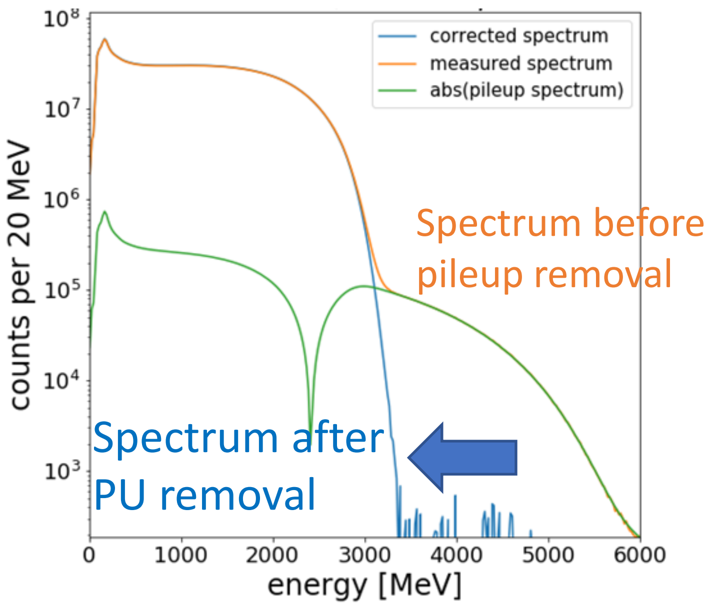
Readout by SiPMs to 800 MHz WFDs (1296 channels in total)

The e^+ time histograms are prepared with exquisite gain (energy) control

They also require pileup removal to avoid an important systematic

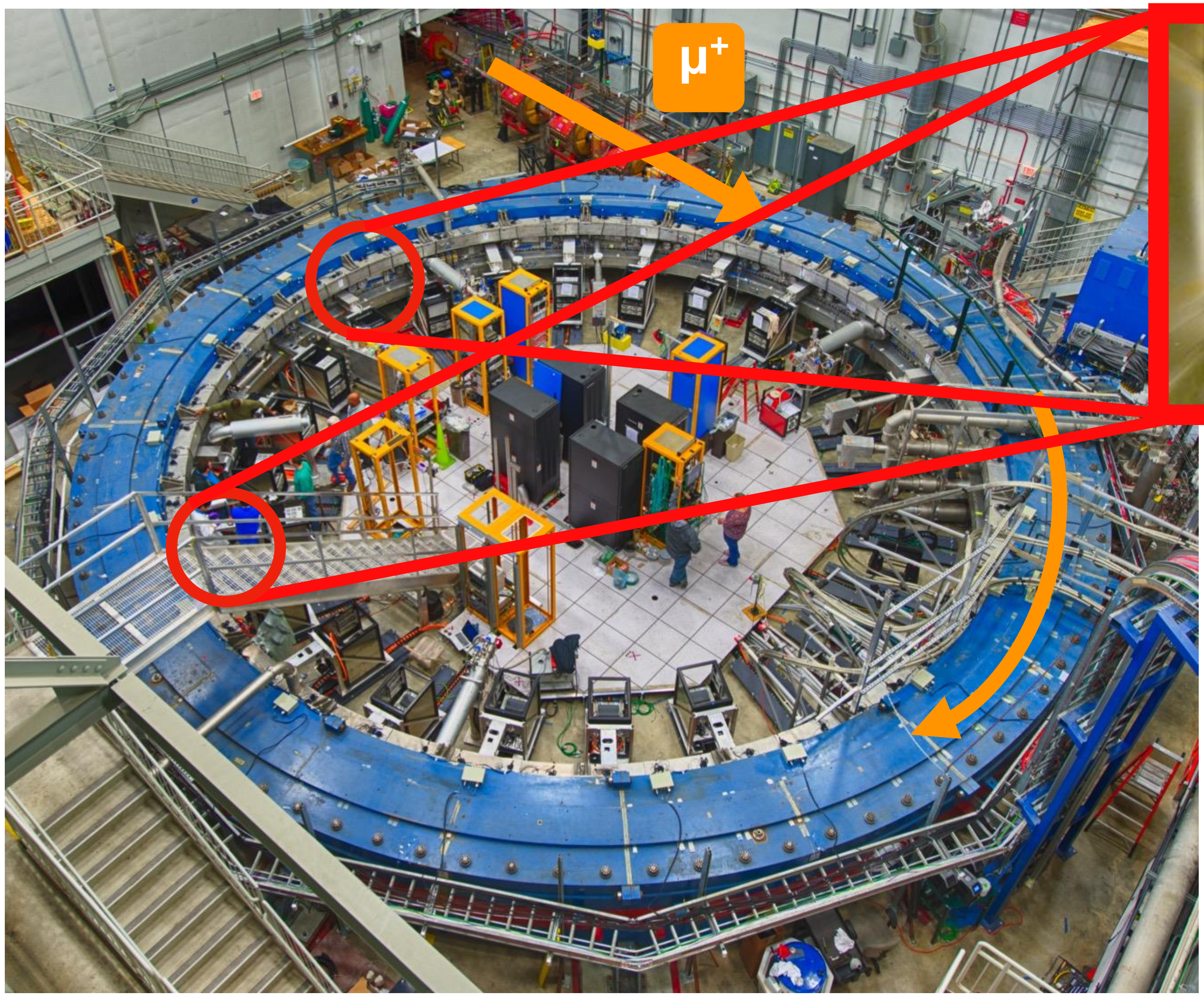


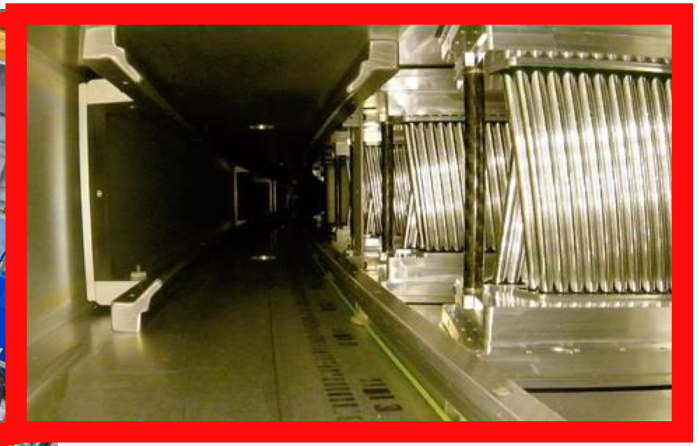


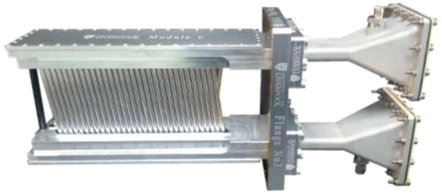


1296 PbF_2 crystals with individual laser calibrations into each channel

Tracking Detectors







2 Tracking stations

Each contain 8 modules

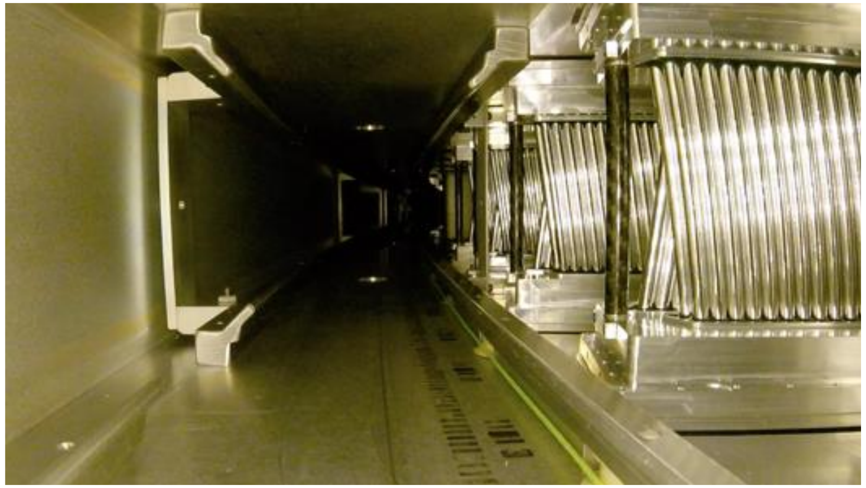
128 gas filled straws in each module

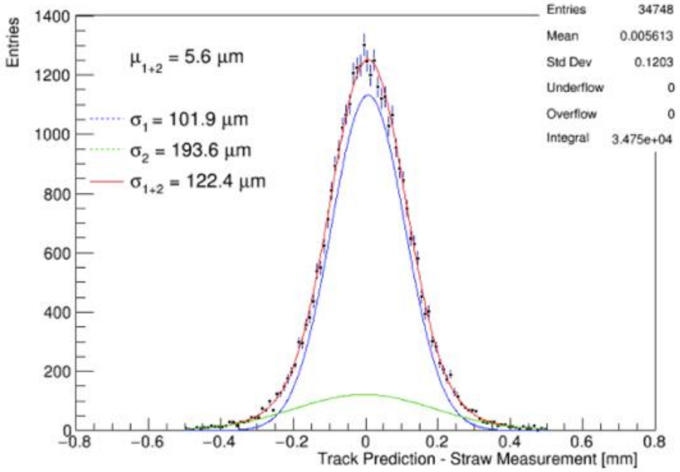
Traceback positrons to their decay point

Trackers

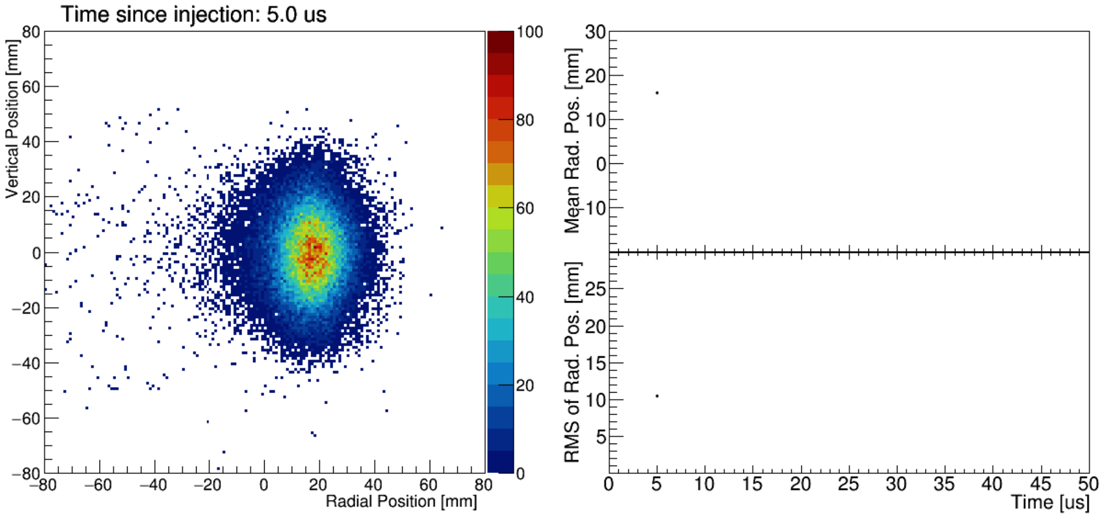
Doublet layers of 5µm diameter, 15µm wall thickness straws with UV layers at 7.5 degrees stereo angles

Located in front of two calorimeters at ~180 degrees and ~270 degrees.

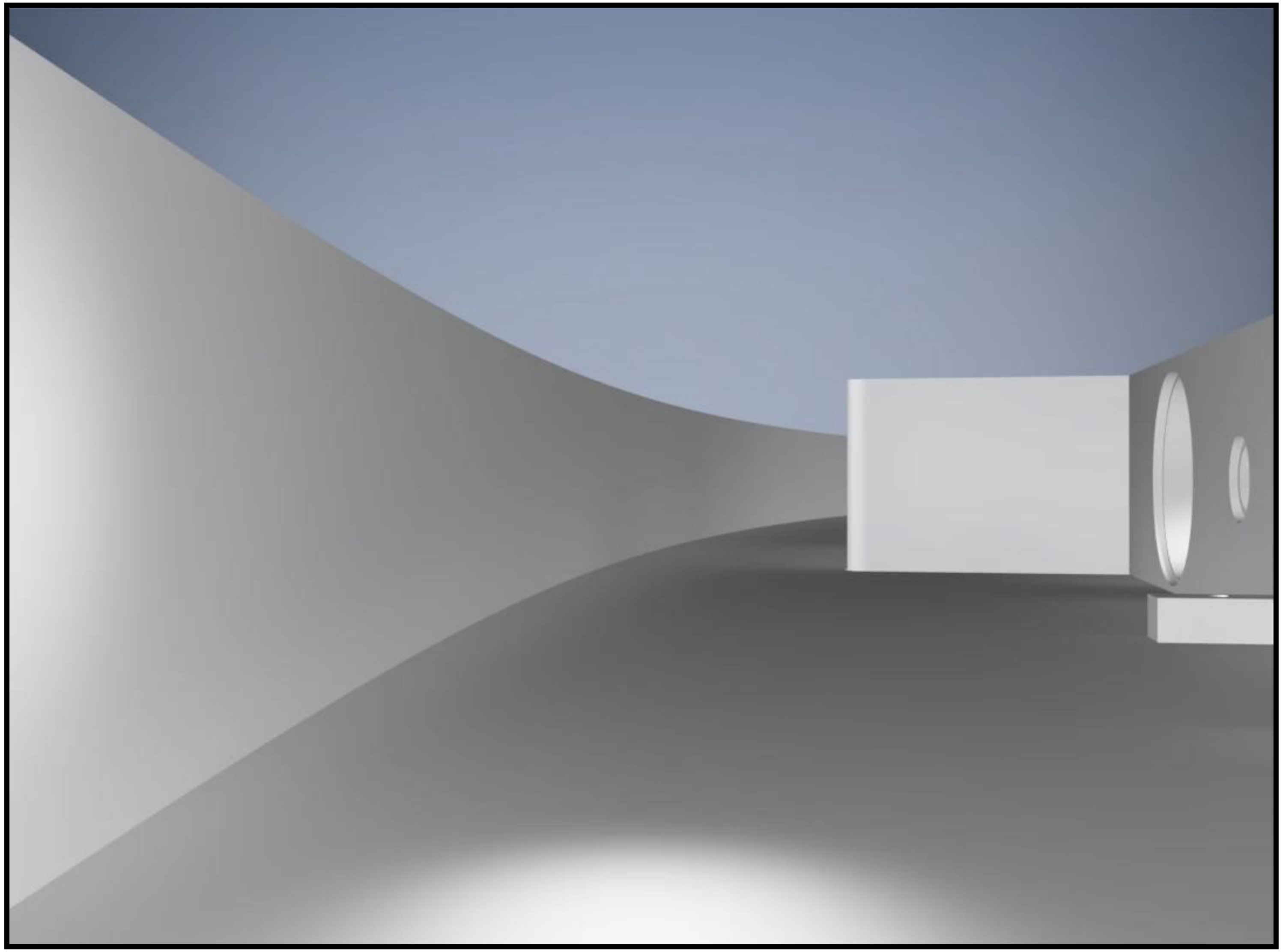




125 µm hit resolution and sub mm resolution on beam location



Drive around inside the ring …



You can spot …

1) Quads
2) Kicker
3) Straw Trackers

Spoiler Alert!!

- The biggest uncertainty is the statistics !!!
- There are corrections (known) and will reduce in future

Fitting Wiggle (5 param)

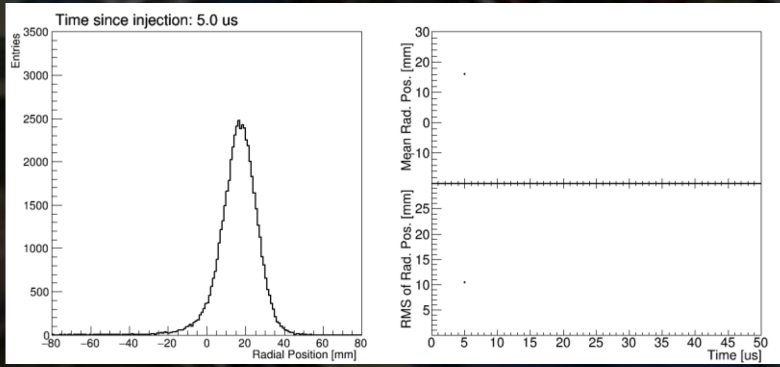
$$a_\mu \propto \frac{\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Wiggle plot is fit to exponential decay and anomalous precession oscillation

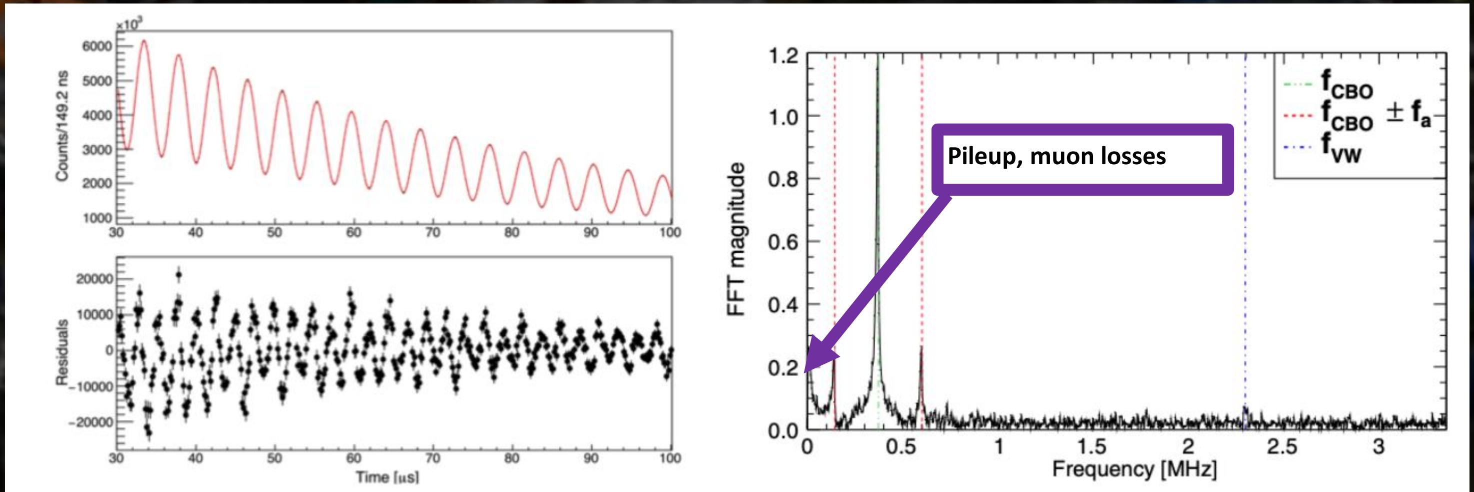
Try simple 5-parameter fit:

$$N(t) = N_0 e^{-t/\tau_\mu} \left[1 + A\cos(\omega_a t + \phi_0)\right]$$

- Simple model is missing several effects
  - Radial and vertical beam motions (e.g. Coherent Betatron Oscillations, or CBO)
  - Early-to-late slow effects (e.g. Pileup, Muon Losses)



$$\chi^2/\mathrm{ndf} = 9500/4150$$

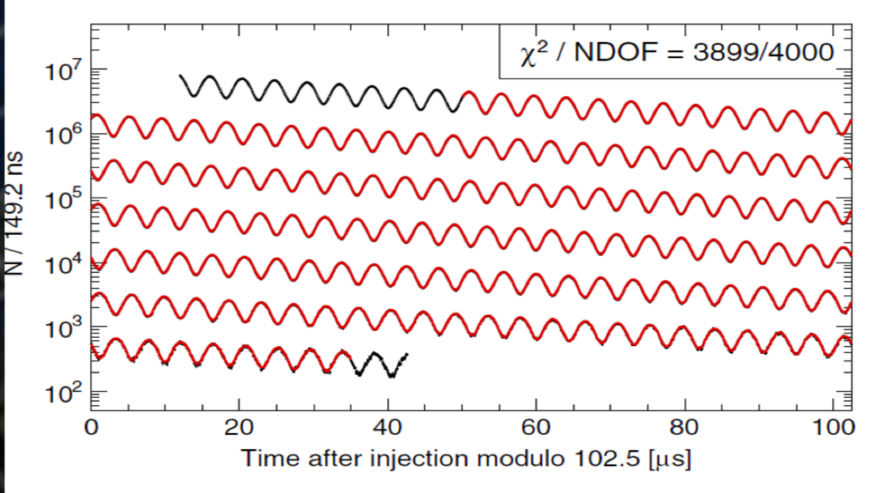


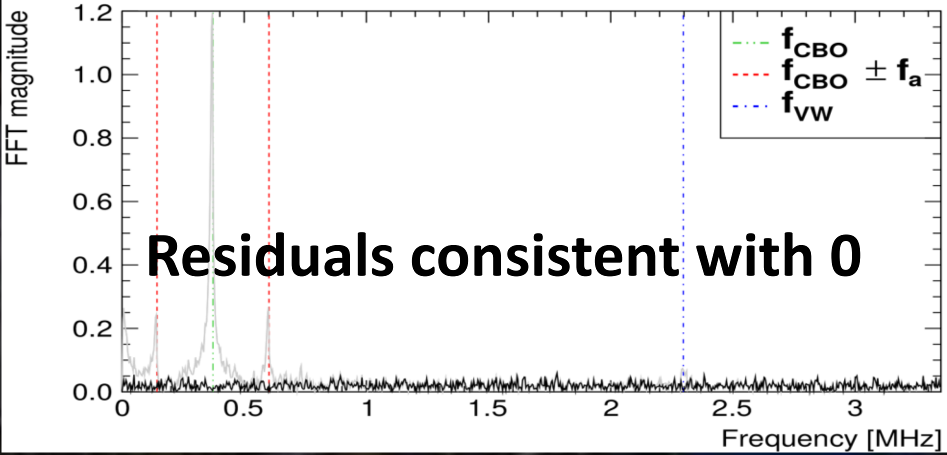
Could just do with CBO! (Just with tracker correction)

Fitting Wiggle (21 param)

Now try a more complex 21-parameter fit with terms covering each of those effects.

$$a_\mu \propto \frac{\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$





With this fit quality, the (blinded) fitted ω_a is ready

Proportionality

$$a_\mu \propto \frac{\omega_a^m\left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle \left(1 + B_k + B_q\right)}$$

$\frac{\mu_e(H)}{\mu'_p(T)}$ Measured to 10.5 ppb accuracy at T = 34.7℃
Metrologia **13**, 179 (1977)

$\frac{m_\mu}{m_e}$ Known to 22 ppb from muonium hyperfine splitting
Phys. Rev. Lett. **82**, 711 (1999)

$\frac{\mu_e}{\mu_e(H)}$ Bound-state QED (exact)
Rev. Mod. Phys. **88** 035009 (2016)

$\frac{g_e}{2}$ Measured to 0.28 ppt
Phys. Rev. A **83**, 052122 (2011)

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Correction: E field

$C_e = 489$ ppb
$\delta C_e = 53$ ppb

$$a_\mu \propto \frac{\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

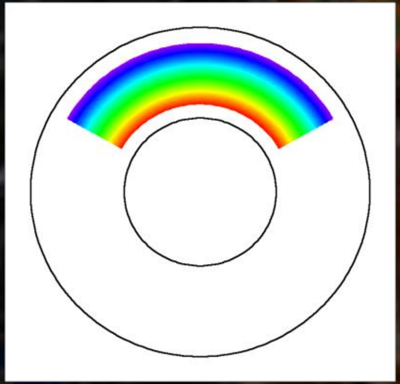
Electric field correction compensates for motional magnetic field "(v x E)" for off-momentum muons

$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E} - a_\mu\left(\frac{\gamma}{\gamma + 1}\right)\left(\vec{\beta}.\vec{B}\right)\vec{\beta}\right]$$

Momentum time dependence, kick of early muons v late. Being improved. Use trackers early v late.

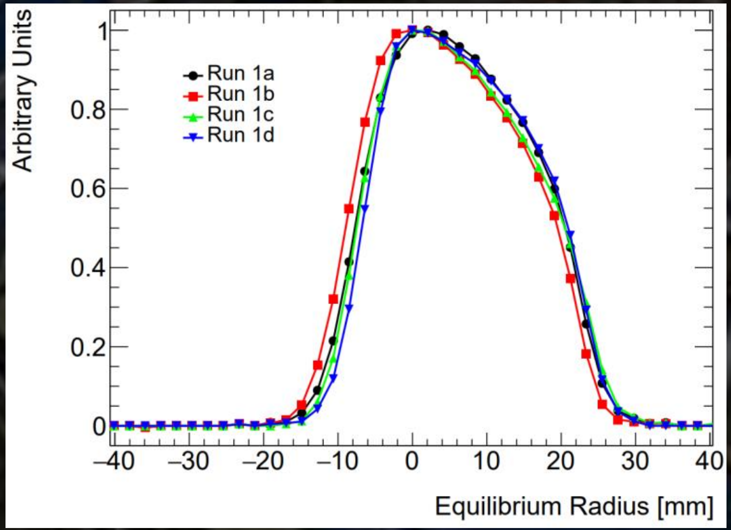
Correction: E field

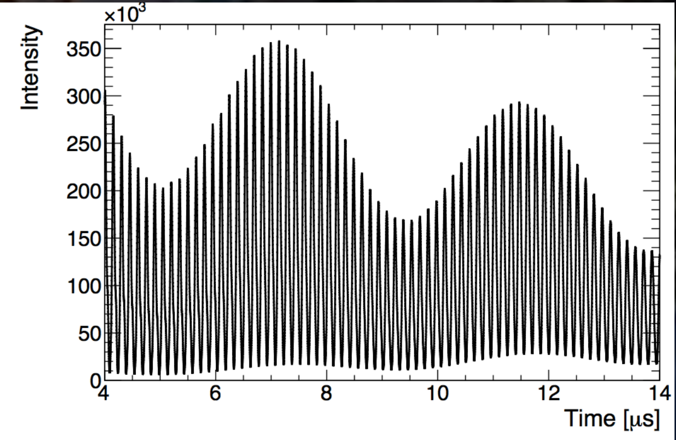
$C_e = 489$ ppb
$\delta C_e = 53$ ppb



$$a_\mu \propto \frac{\omega_a^m\left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle \left(1 + B_k + B_q\right)}$$

- ~0.1% spread in momentum in the ring
- <R> of stored muons depends on *p*
- Fourier analysis to determine equilibrium positions





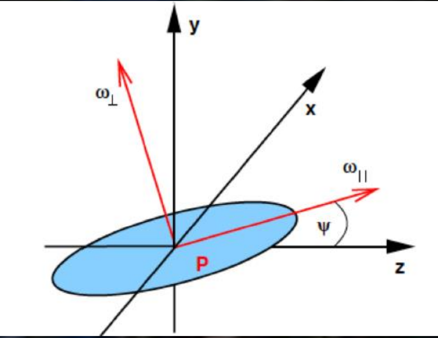
Path difference beats the velocity

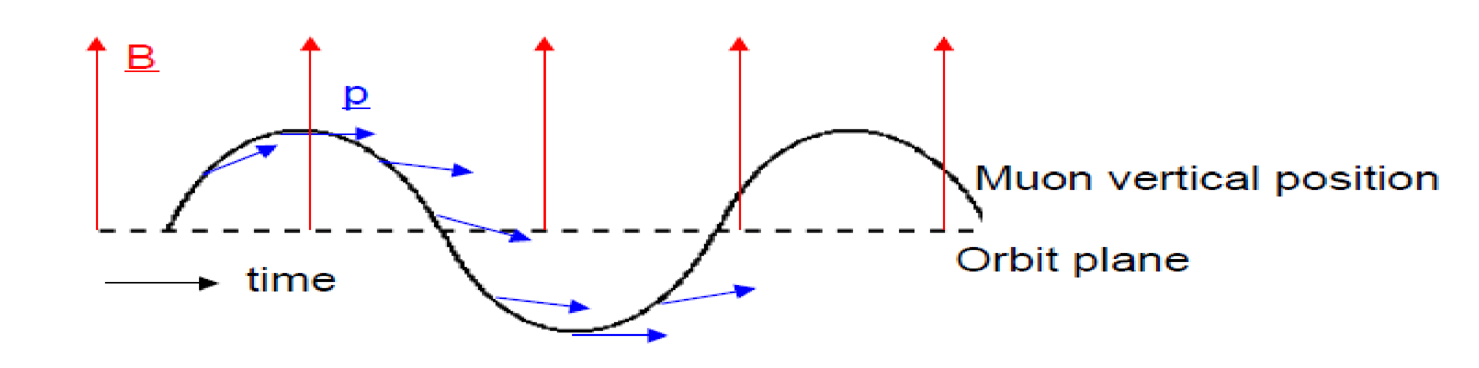
Tends to kill the CBO

Correction: Pitch

$C_p = 180 \text{ ppb}$
$\delta C_p = 13 \text{ ppb}$

$$a_\mu \propto \frac{\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$





- Component of momentum parallel to field due to focusing
- Effectively reduces B field
- Use tracking detectors to measure the vertical width of the beam

$$C_p = \frac{n}{2}\frac{\langle y^2 \rangle}{R_0^2} = \frac{n}{4}\frac{\langle A^2 \rangle}{R_0^2}$$

Correction: Muon Loss

$\boldsymbol{C_p = -11\ \mathrm{ppb}}$
$\boldsymbol{\delta C_p = \quad 5\ \mathrm{ppb}}$

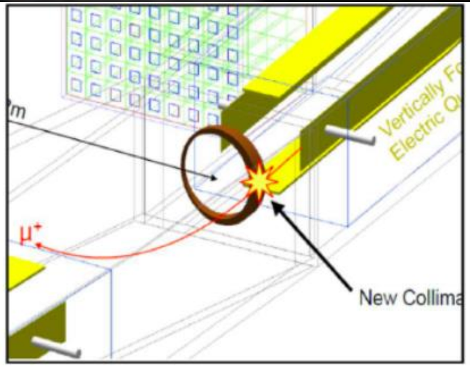
$$a_\mu \propto \frac{\omega_a^m\left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle \left(1 + B_k + B_q\right)}$$

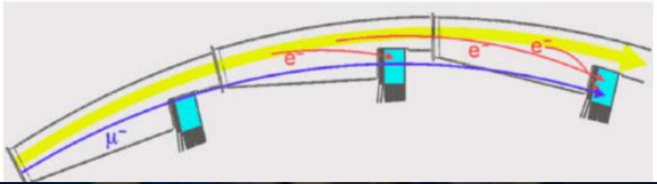
Lost muons have a different phase than the muons that remain
Phase and loss are momentum dependent

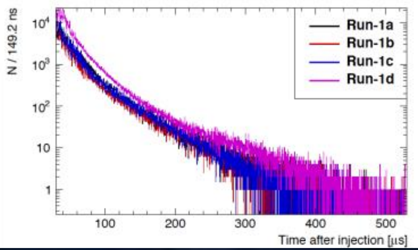
- Muon losses distort the exponential decay of the number of stored muons
- Muon Loss term :

$$J(t) = 1 - K_{LM}\int_0^t e^{\frac{t'}{\tau}} L(t')dt'$$

- $L(t)$ measured from the detection of Minimum Ionizing Particles in the calorimeters







Correction: Phase Acceptance

$C_{pa} = -158$ ppb
$\delta C_{pa} = \;\; 75$ ppb

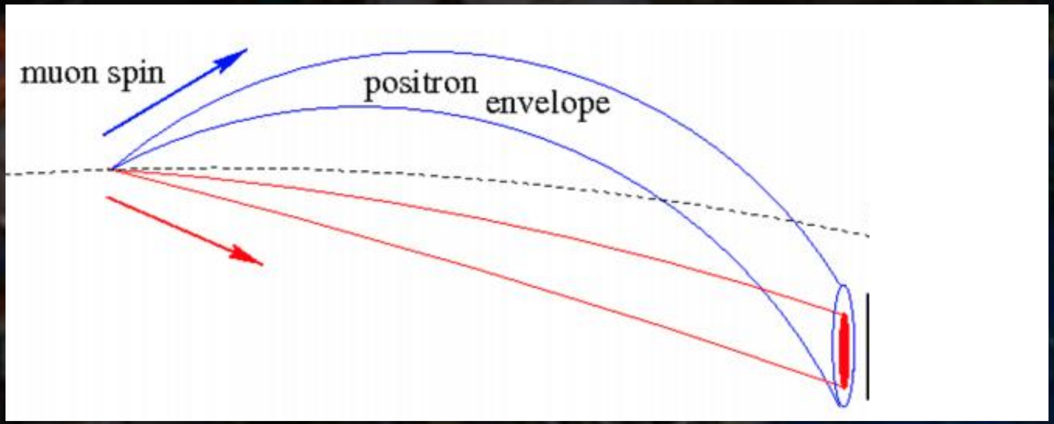
$$a_\mu \propto \frac{\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

$\cos(W_a t + f)$

Phase between the muon spin and momentum

Phase advance between decay time and detection time due to path length

If the beam is moving, this phase advance is changing



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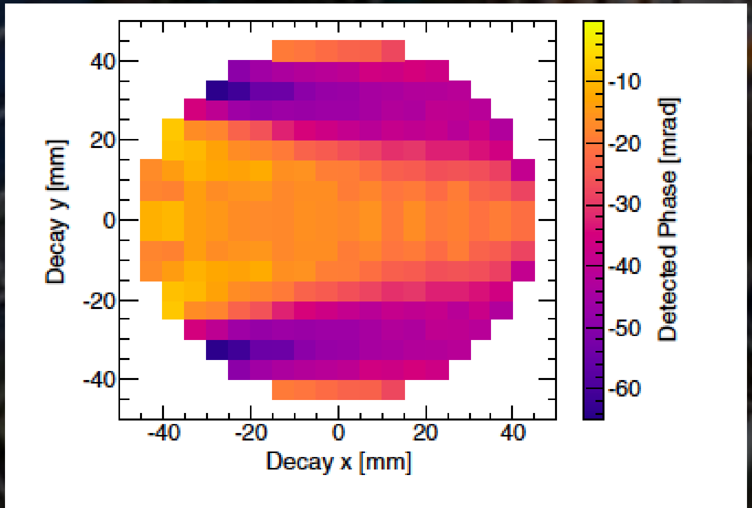
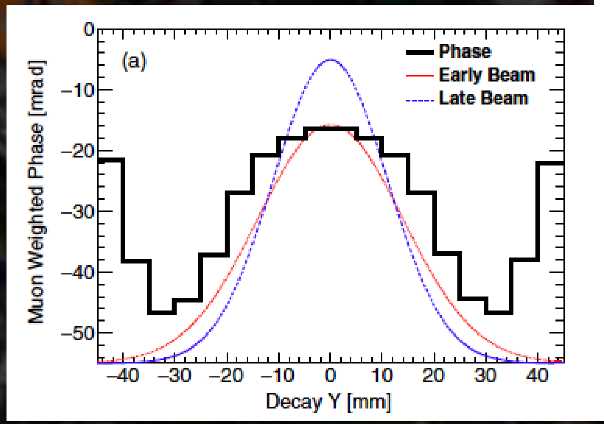
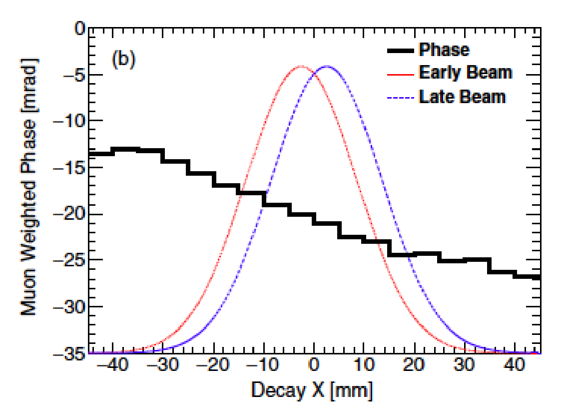


Phase at calorimeter depending on muon decay point

Vertical decay position



Horizontal decay position



For final run period:

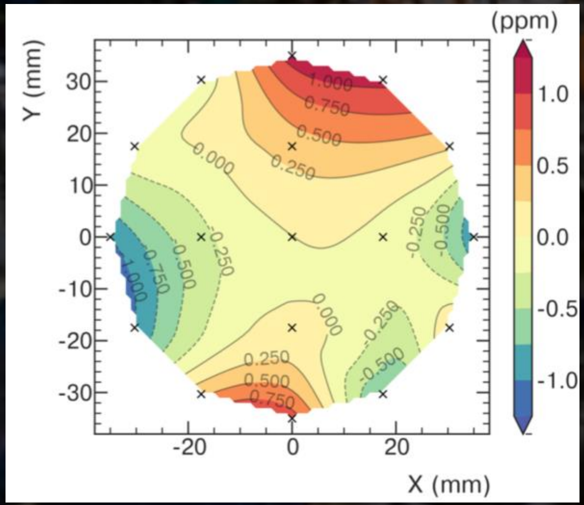
$$\frac{\Delta\omega_a}{\omega_a} = -164 \pm 80\, ppb$$

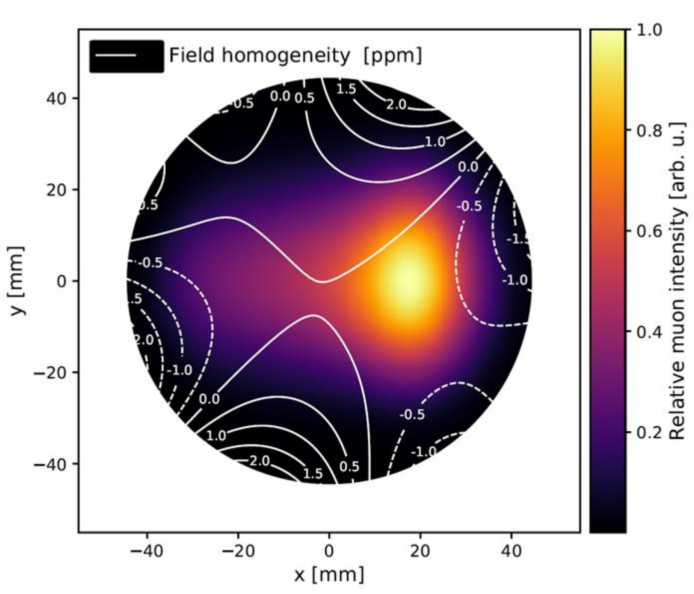
Beam currently reduces in size (optics now fixed), C_{pa} will reduce.

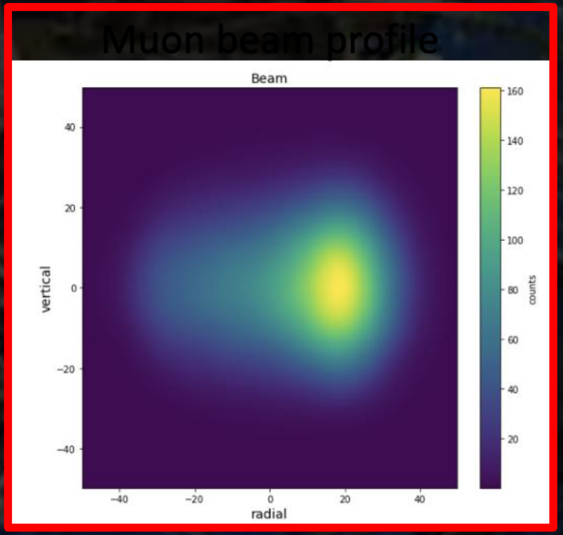
Field Measurement

$\boldsymbol{\delta = \quad 56\ \mathrm{ppb}}$

$$a_\mu \propto \frac{\omega_a^m\left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle \left(1 + B_k + B_q\right)}$$





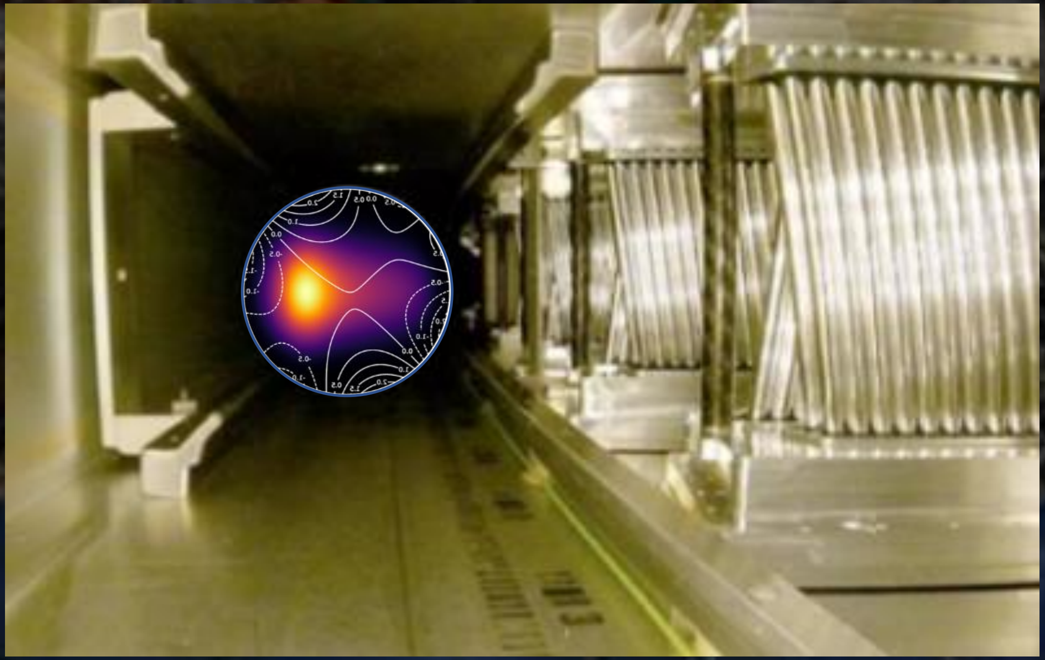


Weighted Field - NMR

$\delta = \quad 56\ \mathrm{ppb}$

$$a_\mu \propto \frac{\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Under kicked optics δ will reduce

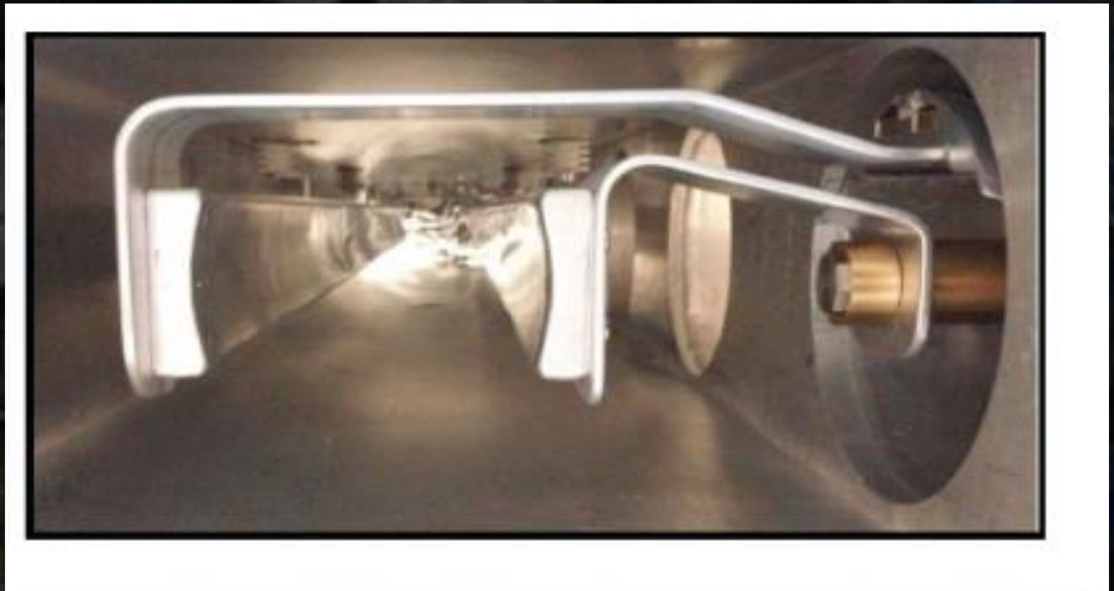


Correction: Kicker Transients

$\boldsymbol{B_k = -27\ \mathrm{ppb}}$
$\boldsymbol{\delta B_k = 37\ \mathrm{ppb}}$

$$a_\mu \propto \frac{\omega_a^m\left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{\left\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\right\rangle\left(1 + B_k + B_q\right)}$$

Eddy Currents When Kicker Fire
Produce magnetic fields (30ppb)
Kicker performance



Correction: Quadrupole Transients

$B_q = -17$ ppb
$\delta B_q = 92$ ppb

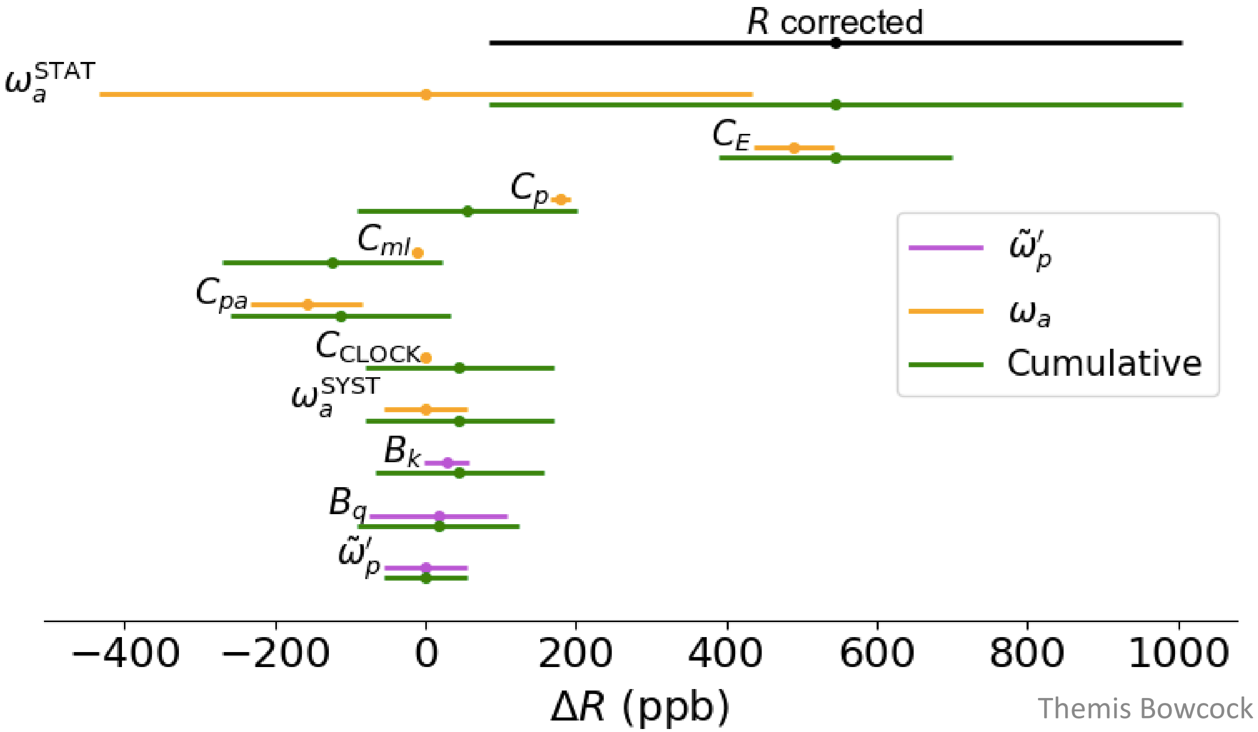
$$a_\mu \propto \frac{\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

ESQ mechanical vibrations give rise to B fields

Optics modified. δB_q will reduce with more data.

Correcting Final Value

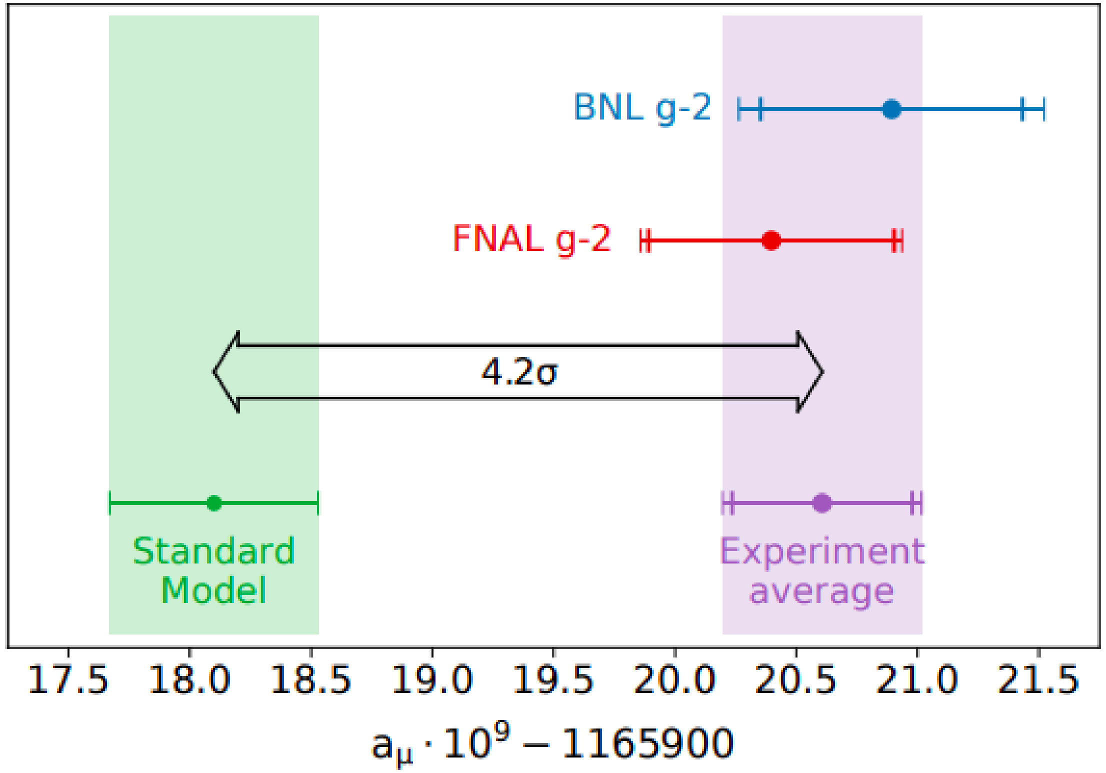
$$a_\mu \propto \frac{\omega_a^m\left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle \left(1 + B_k + B_q\right)}$$

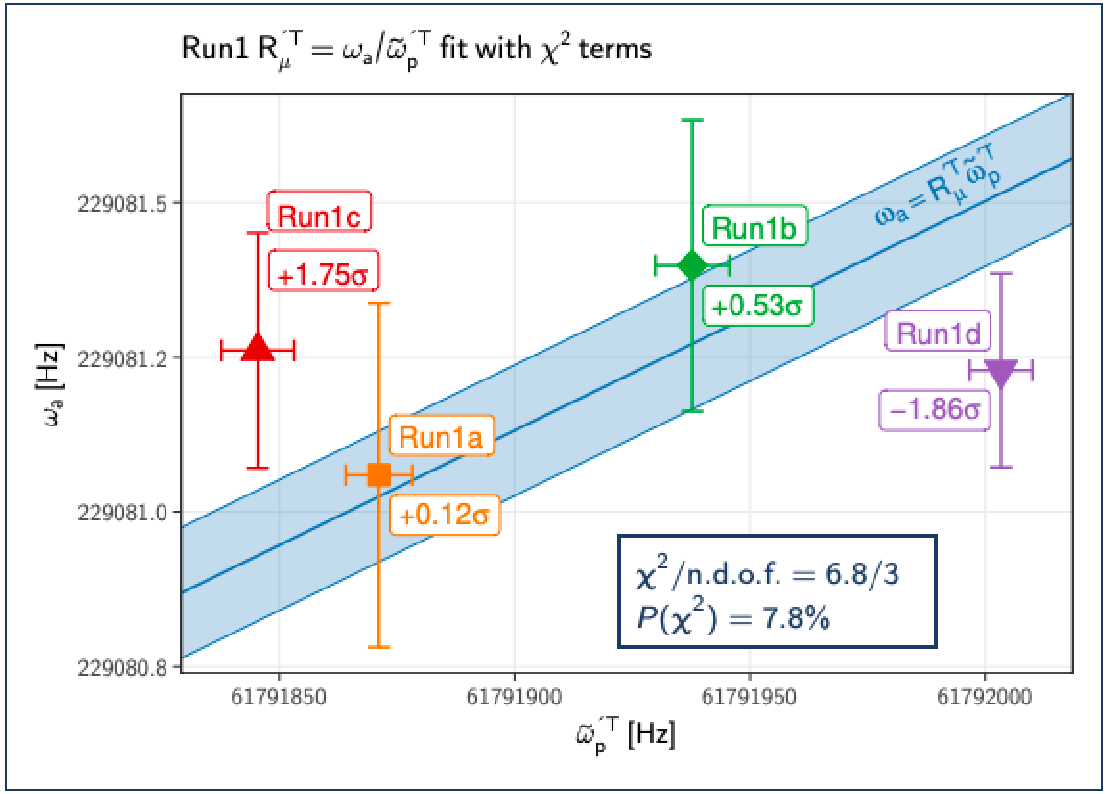


Run 1 Results

g_μ(Theory Initiative) = 2.00233183620(86)

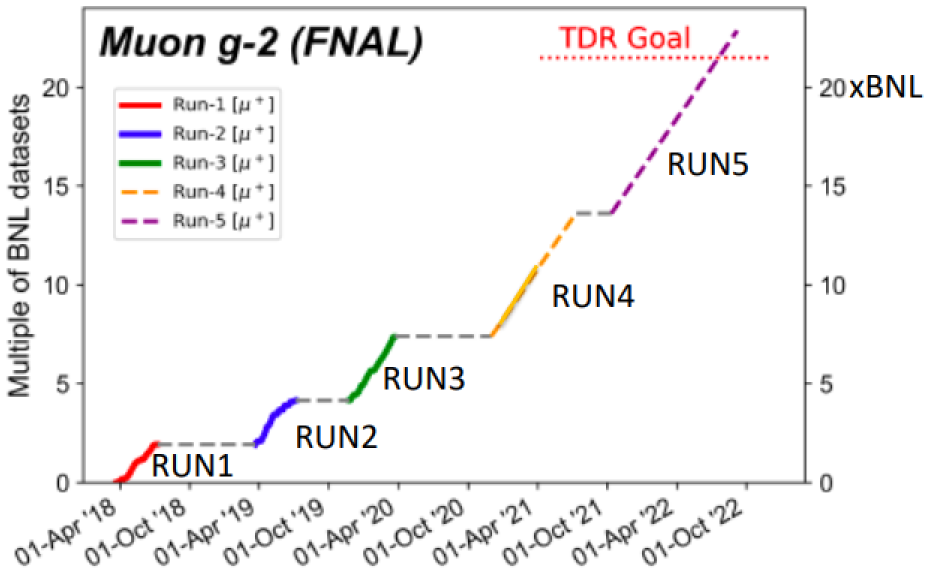
g_μ(BNL + Fermilab) = 2.00233184122(82)



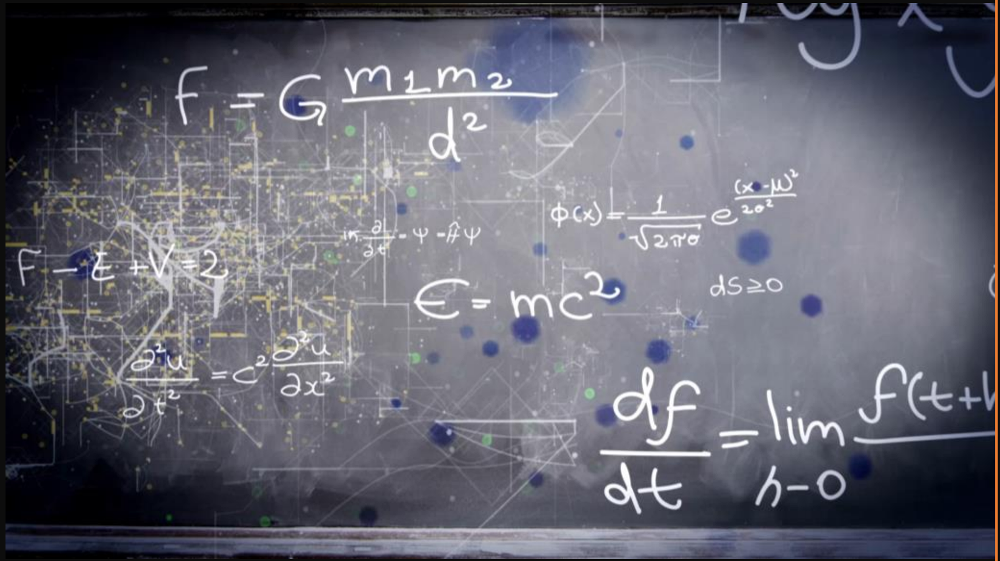


More Data

- RUN1 is only 6% of the final dataset
- Analysis of RUN2/3 (expect an improvement of a factor ~2 in precision)
- RUN4 (November 2020-July 2021) is expected to bring the statistics to ~13 BNL
- RUN5 in 2021-2022 should allow to achieve the x20 BNL project goal



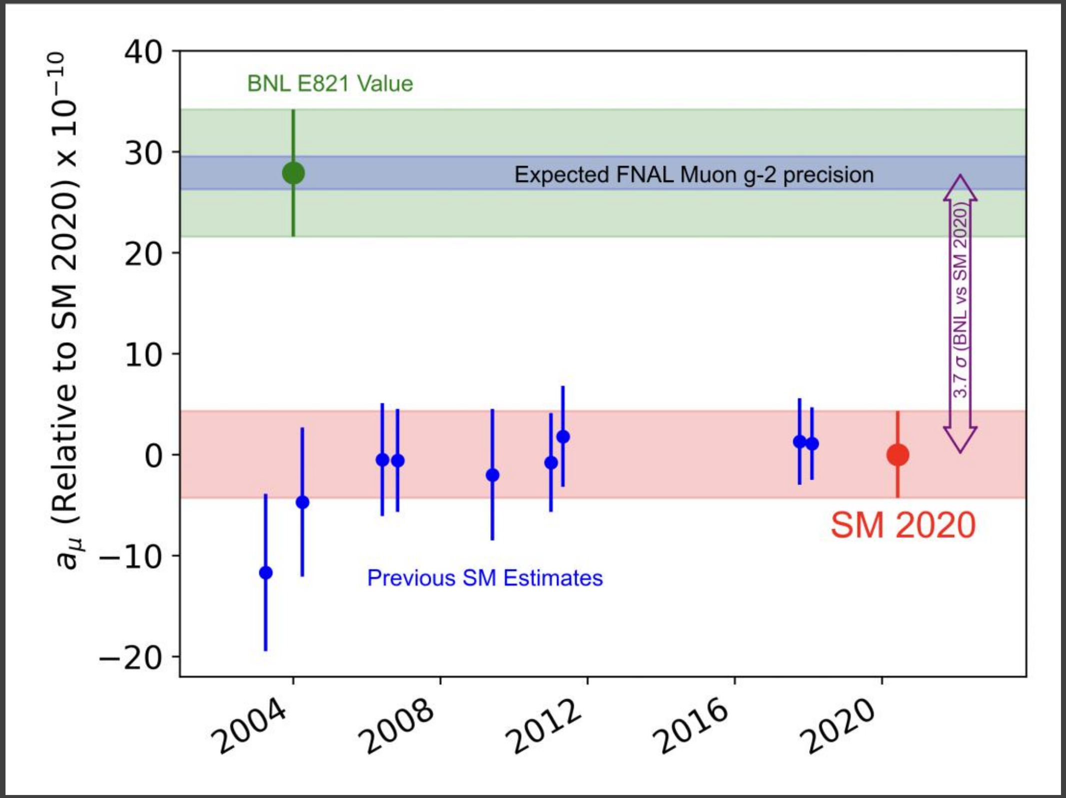
Interpretation and Theory



Chris Polly: ``monsters lurking''

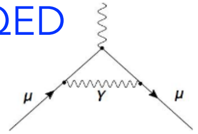
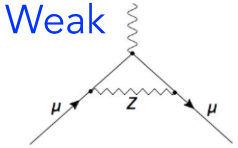
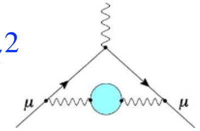
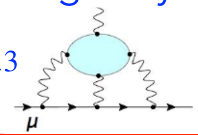
SM theory vs. Experiment

- SM theory vs. Experiment
- If the two don't match, something may be missing in the SM
- Precision measurements + precision theory
- Discovery potential for **New Physics**
- **N**eed for consolidated & reliable SM prediction



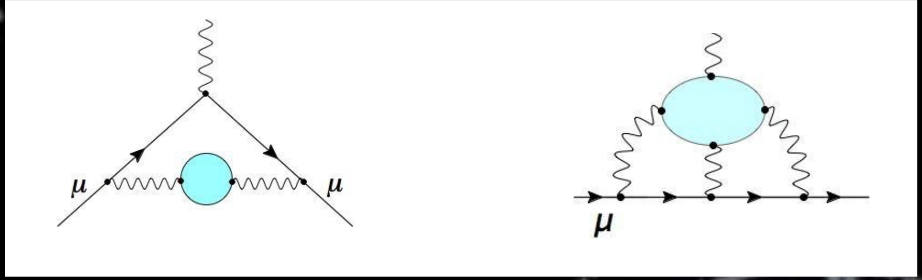
$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}} + a_\mu^{\text{NP?}}$$

SM 2020' prediction from the TI White Paper

QED 	$+\ldots$	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
Weak 	$+\ldots$	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
Hadronic…			
…Vacuum Polarization (HVP) α^2 	$+\ldots$	$6845\,(40) \times 10^{-11}$ [0.6%]	0.34 ppm
…Light-by-Light (HLbL) α^3 	$+\ldots$	$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm

➤ Uncertainty completely dominated by hadronic contributions

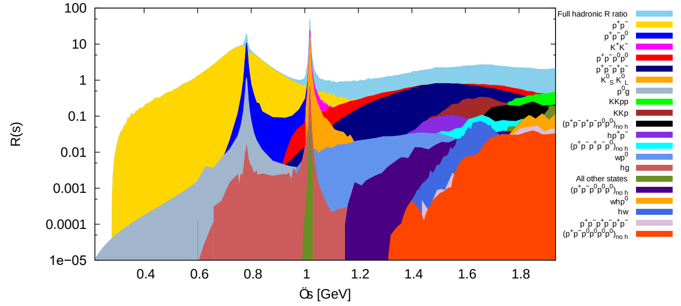
a_μ hadronic : non-perturbative, the limiting factor of the SM prediction

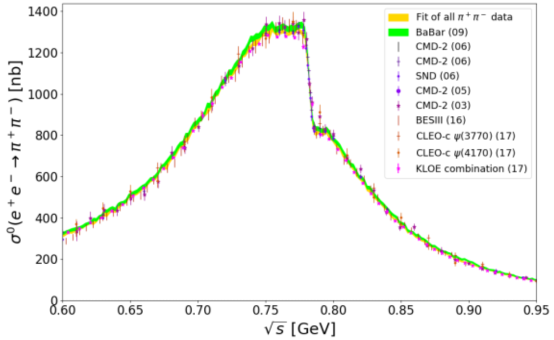


- Q: What's in the hadronic (Vacuum Polarisation & Light-by-Light scattering) blobs?
- A: Anything `hadronic' the virtual photons couple to, i.e. quarks + gluons + photons
- But: low q2 photons dominate loop integral(s) cannot calculate blobs with perturbation theory
- Two very different strategies:
  - use wealth of hadronic data, `data-driven dispersive methods' (more details for VP later):
    - data combination from many experiments, radiative corrections required
  - simulate the strong interaction (+photons) w. discretised Euclidean space-time, `lattice QCD':
    - finite size, finite lattice spacing, artifacts from lattice actions, QCD + QED needed
    - numerical Monte Carlo methods require large computer resources

$$a_\mu^{\text{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

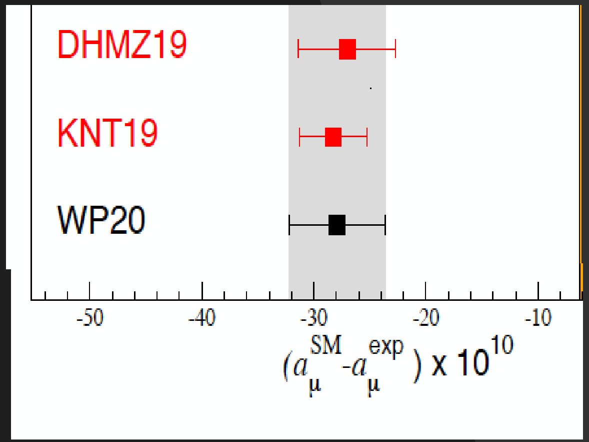
$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$





a_μ^{HVP} : Landscape of $\sigma_{had}(s)$ data & most important $\pi^+\pi^-$ channel

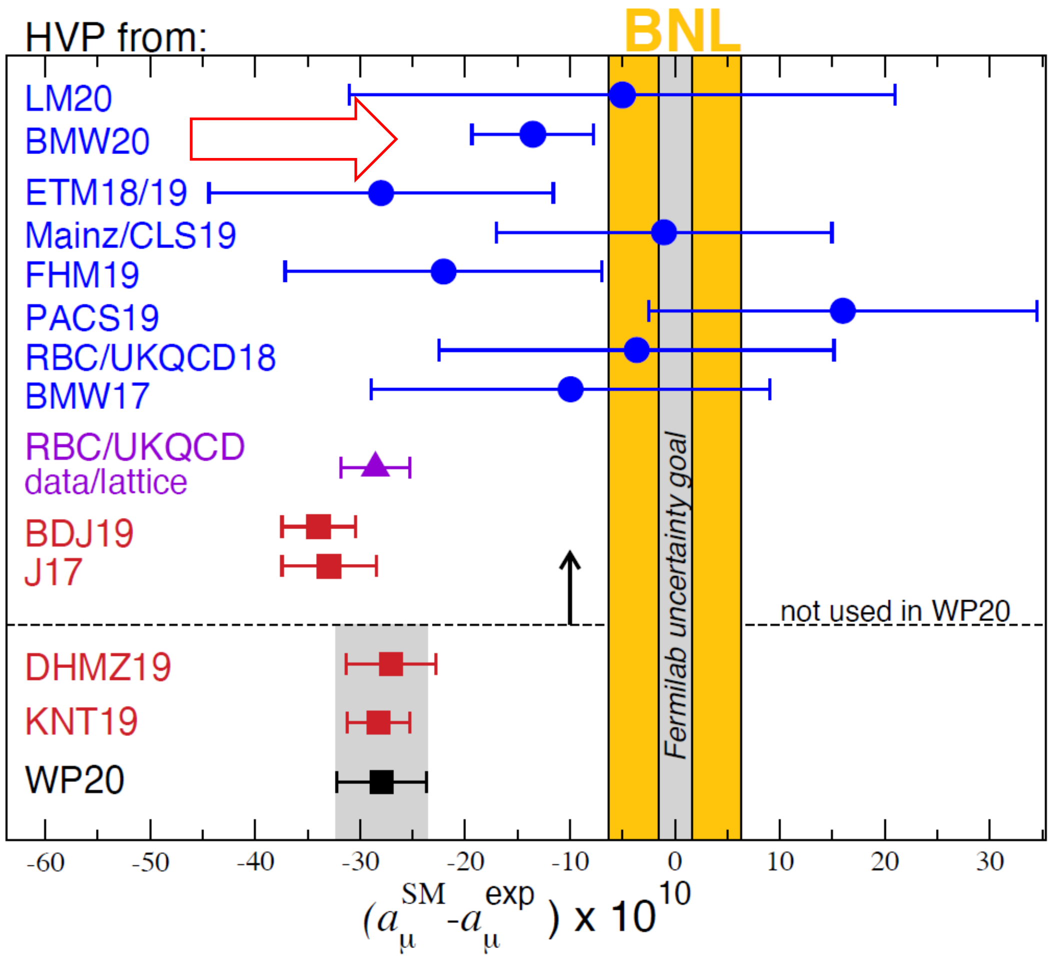
Data Driven (KNT)



- Combination of >30 data sets, >1000 points, contributing >70% of total HVP
- Precise measurements from 6 independent experiments with different systematics and different radiative corrections
- Data sets from Radiative Return dominate
- Some tensions in data accounted for by local χ^2_{min} inflation and via WP merging procedure

What about that new Lattice result?

- *The BMW collaboration's result is the first of its kind at sub-percent precision; it is compared to decades of expt. results*
- *We look forward to continued efforts by all lattice groups as we require the SM precision to increase over time*



Ab-initio lattice QCD(+QED) calculations are maturing

Difficult problem: scales from $2m_\pi$ to several GeV enter; cross-checks needed at high precision

Hybrid window method restricts scales that enter from lattice/dispersive data

Dispersive, $e^+e^- \rightarrow$ hadrons (20+ years of experiments)

Article

Leading hadronic contribution to the muon magnetic moment from lattice QCD

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The standard model of particle physics describes the vast majority of experiments and observations involving elementary particles. Any deviation from its predictions would be a sign of new, fundamental physics. One long-standing discrepancy concerns the anomalous magnetic moment of the muon, a measure of the magnetic field surrounding that particle. Standard-model predictions[1] exhibit disagreement with measurements[2] that is tightly scattered around 3.7 standard deviations. Today, theoretical and measurement errors are comparable; however, ongoing and planned experiments aim to reduce the measurement error by a factor of four. Theoretically, the dominant source of error is the leading-order hadronic vacuum polarization (LO-HVP) contribution. For the upcoming measurements, it is essential to evaluate the prediction for this contribution with independent methods and to reduce its uncertainties. The most precise, model-independent determinations so far rely on dispersive techniques, combined with measurements of the cross-section of electron–positron annihilation into hadrons[3–6]. To eliminate our reliance on these experiments, here we use ab initio quantum chromodynamics (QCD) and quantum electrodynamics simulations to compute the LO-HVP contribution. We reach sufficient precision to discriminate between the measurement of the anomalous magnetic moment of the muon and the predictions of dispersive methods. Our result favours the experimentally measured value over those obtained using the dispersion relation. Moreover, the methods used and developed in this work will enable further increased precision as more powerful computers become available.

The muon is an ephemeral sibling of the electron. It is 207 times more massive, but has the same electric charge and spin. Similarly to the electron, it behaves like a tiny magnet, characterized by a magnetic moment. This quantity is proportional to the spin and charge of the muon and inversely proportional to twice its mass. Dirac's relativistic quantum mechanics predicts that the constant of proportionality, g_μ, should be equal to 2. However, in a relativistic quantum field theory such as the standard model, this prediction receives small corrections due to quantum vacuum fluctuations. These corrections are called the anomalous magnetic moment and are quantified by $(g_\mu - 2)/2$. They were measured to a precision of 0.54 ppm at the Brookhaven National Laboratory in the early 2000s[2], and have been calculated with a comparable precision (see ref. [7] for a recent review).

At this level of precision, all of the interactions of the standard model contribute. The leading contributions are electromagnetic and described by quantum electrodynamics (QED), but the one that dominates the theoretical error is induced by the strong interaction and requires solving the highly nonlinear equations of QCD at low energies. This contribution is determined by the LO-HVP, which describes how the propagation of a virtual photon is modified by the presence of quark and gluon fluctuations in the vacuum. Here we compute this LO-HVP contribution to $(g_\mu - 2)/2$, denoted by a_μ^{LO-HVP}, using ab initio simulations in QCD and QED.

QCD is a generalized version of QED. The Euclidean Lagrangian for this theory is $\mathcal{L} = [1/(4e^2)]F_{\mu\nu}F_{\mu\nu} + [1/(2g^2)]\mathrm{tr}(G_{\mu\nu}G_{\mu\nu}) + \Sigma_f \bar{\psi}_f[\gamma_\mu(\partial_\mu + iq_f A_\mu + iB_\mu) + m_f]\psi_f$, where γ_μ are the Dirac matrices, f runs over the 'flavours' of quarks, m_f are the masses and the q_f are the charges of quarks in units of the electron charge, e. Moreover, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu + [B_\mu, B_\nu]$ and g is the QCD coupling constant. In electrodynamics the gauge potential A_μ is a real-valued field, whereas in QCD B_μ is a 3 × 3 Hermitian matrix field. The different flavours of quarks are represented by independent fermionic fields, ψ_f. These fields have an additional 'colour' index in QCD, which runs from 1 to 3. In this work, we include both QED and QCD, as well as four non-degenerate quark flavours

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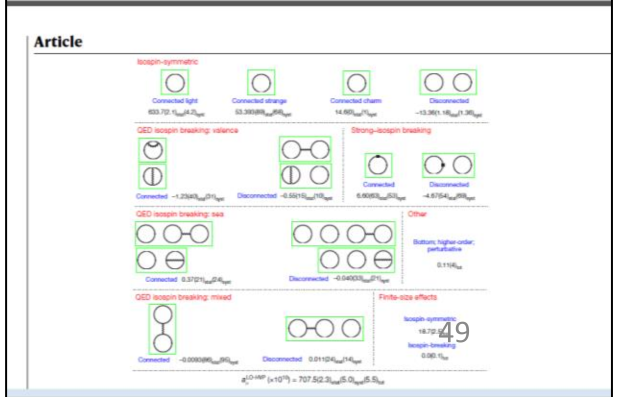
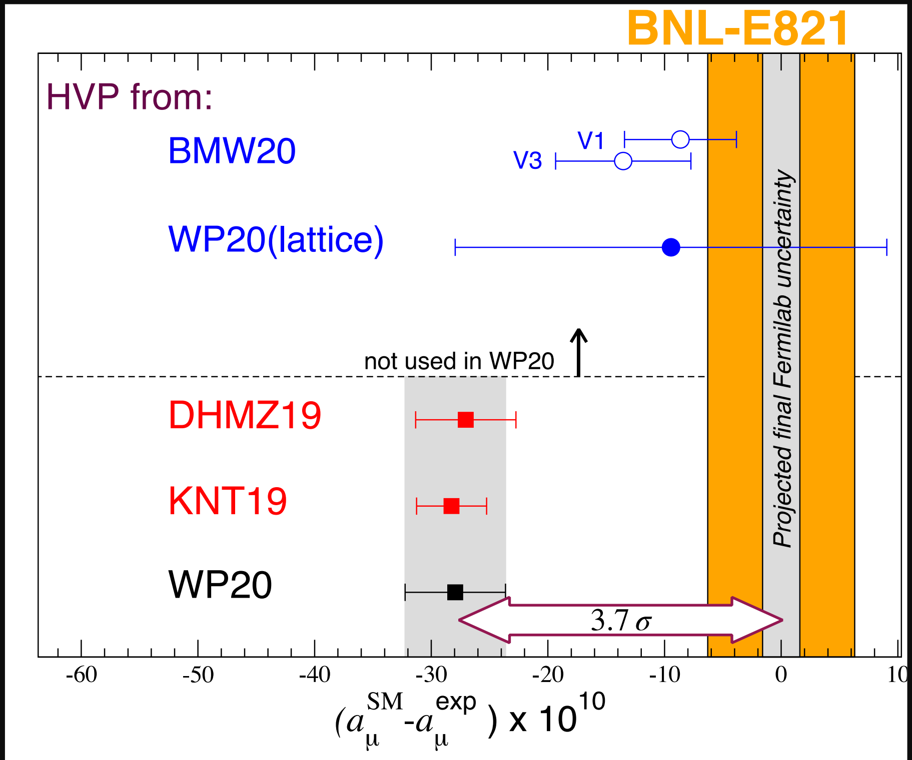


Now first published lattice result with sub-percent precision available (BMW20), cross-checks are crucial to establish or refute high-precision lattice methodology (same situation as for HLbL) $\Rightarrow$ Theory Initiative as a platform to do this

What about that new Lattice result?




Article

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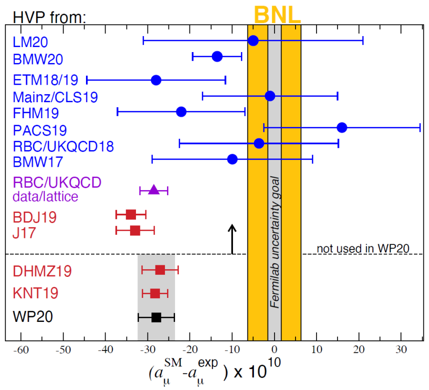

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HVP: Connection between g-2 and $\Delta\alpha(M_Z^2)$

- Precision observable $\alpha(M_Z^2) = \alpha/(1-\Delta\alpha(M_Z^2))$ as a sensitive test of HVP
- content by Massimo Passera

- **Can Δa_μ be due to hypothetical mistakes in the hadronic $\sigma(s)$?**
- **An upward shift of $\sigma(s)$ also induces an increase of $\Delta\alpha_{had}^{(5)}(M_Z)$.**
- **Consider:**

$a_\mu^{HLO} \rightarrow \quad a = \int_{4m_\pi^2}^{s_u} ds\, f(s)\,\sigma(s), \qquad f(s) = \frac{K(s)}{4\pi^3},\ s_u < M_Z^2,$

$\Delta\alpha_{had}^{(5)} \rightarrow \quad b = \int_{4m_\pi^2}^{s_u} ds\, g(s)\,\sigma(s), \qquad g(s) = \frac{M_Z^2}{(M_Z^2 - s)(4\alpha\pi^2)},$

Note the very different energy-dependent weighting of the integrands…

and the increase

$$\Delta\sigma(s) = \epsilon\sigma(s)$$

ϵ>0, in the range:

$$\sqrt{s} \in [\sqrt{s_0} - \delta/2, \sqrt{s_0} + \delta/2]$$

HVP: Connection between g-2 and $\Delta\alpha(M_Z^2)$

- Marciano, Passera, Sirlin (2008):
  - changing the hadronic cross section at higher energies significantly upwards leads to tensions in EW precision fits of the SM.
  - not easy to reconcile g-2 without running into problems with $\Delta\alpha(M_Z^2)$

- Crivellin et al, PRL125(2020)9,091801:
  - shifts in HVP make fit based on HEPFitter worse, but they can not rule out shifts at low energies as obtained by the BMW lattice analysis
- Keshavarzi et al, PRD102(2020)3,033002:
  - updating Marciano et al, again find significant tensions with Gfitter if shifts in HVP were to explain g-2, unless they are below ~0.7 GeV
  - However, the low energies hadronic cross section measurements (mainly 2pi) are most precise there.

What do TI think?

- Expect another major update once results are available from the VEP2000 experiments and the flavor factories and when the BMW lattice result is confirmed
- After a ton of work by a ton of people, the QCD contribution and all other SM contributions are mainly unchanged!

BSM Implications

If it's real, what are general take-home remarks (D. Stockinger)

- The deviation is larger than the SM EW contributions and hence "large" and not obviously easy to explain in BSM

- a_μ is a loop-induced, CP- and flavor-conserving, and chirality-flipping
  - (an inclusive probe of essentially all particles/interactions)
  - The chirality flip implies interesting correlations to the muon mass
    - fundamental questions like Higgs/electroweak symmetry breaking and Yukawa couplings/connection to flavor structure/origin of three generations

- Many BSM scenarios *can give* large contributions, but
  - they either involve a chirality flip enhancement (connections to deep physical properties)
  - or rather light, neutral new particles (dark matter?)
  - In virtually all cases there are strong parameter constraints from LHC, dark matter, LEP, flavor experiments etc.

Typically one is forced into *non-traditional parameter regions*.

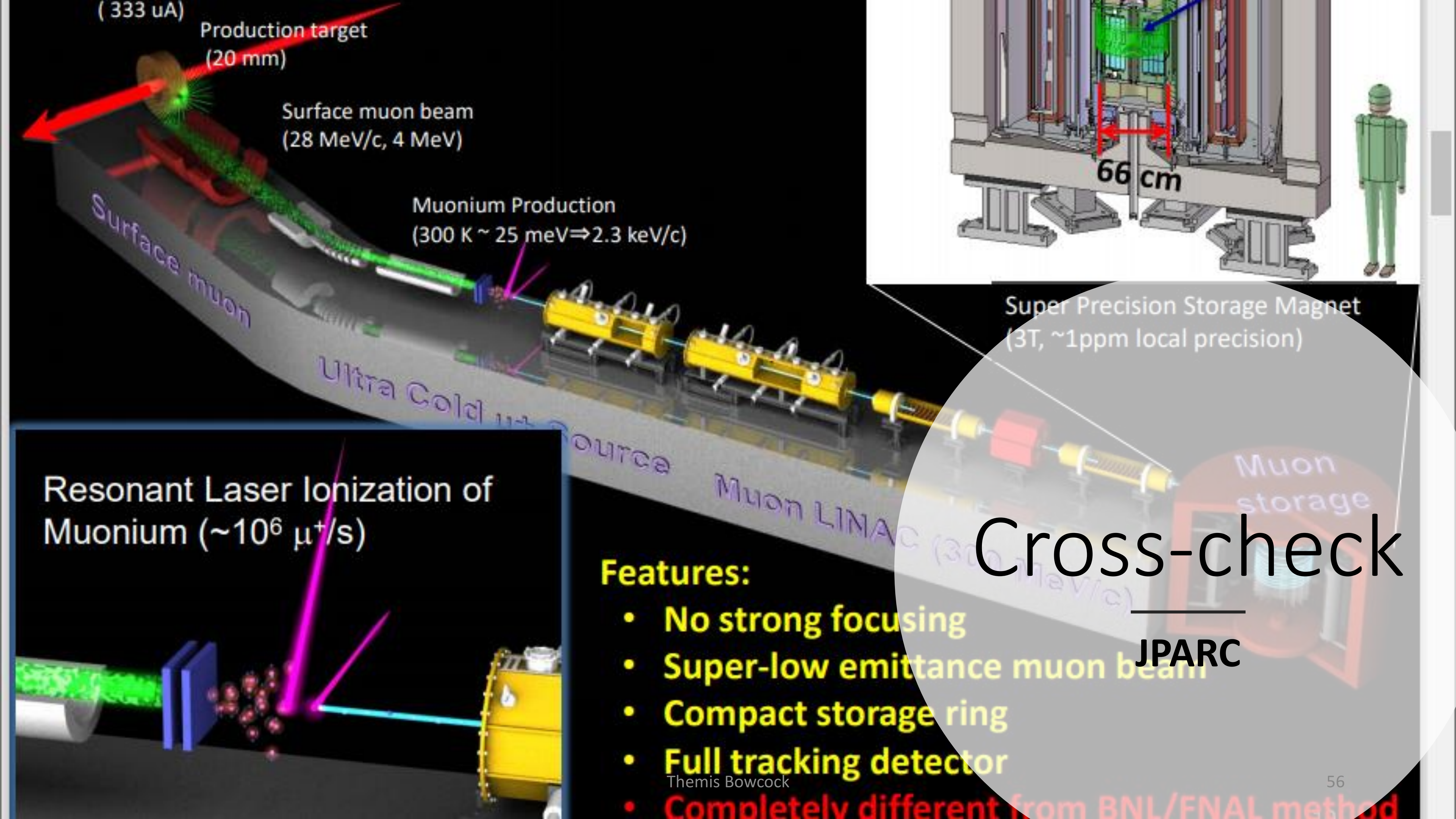
Electron g-2

Does not (so obviously) show a discrepancy

Can we see LFUV elsewhere????

Cross-check

JPARC

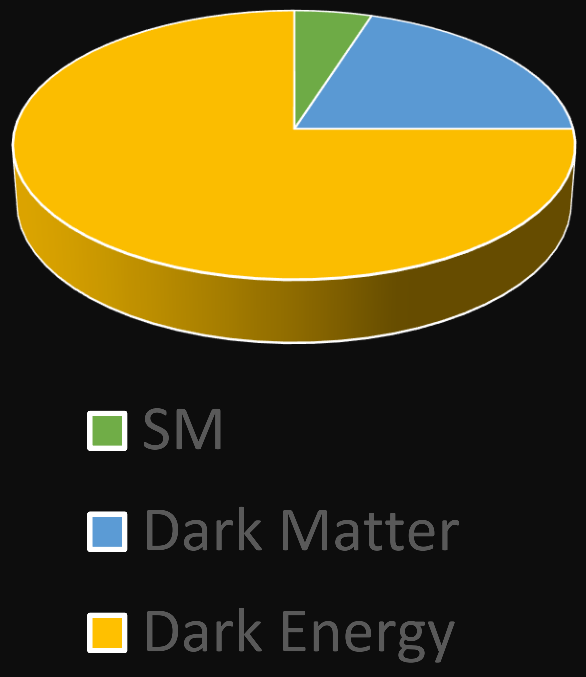


Wider Context

Based on slides by Andreas Crivellin

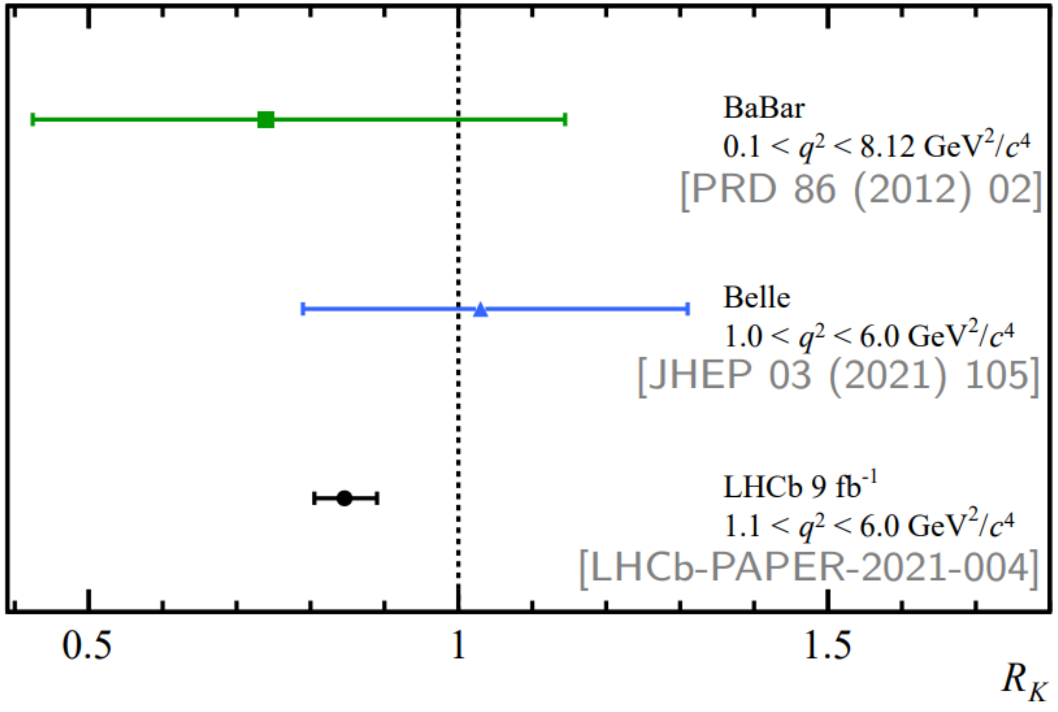
Physics Beyond the Standard Model

- Dark Matter existence established at cosmological scales
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions
- The SM must be extended!
  What is the underlying fundamental theory?

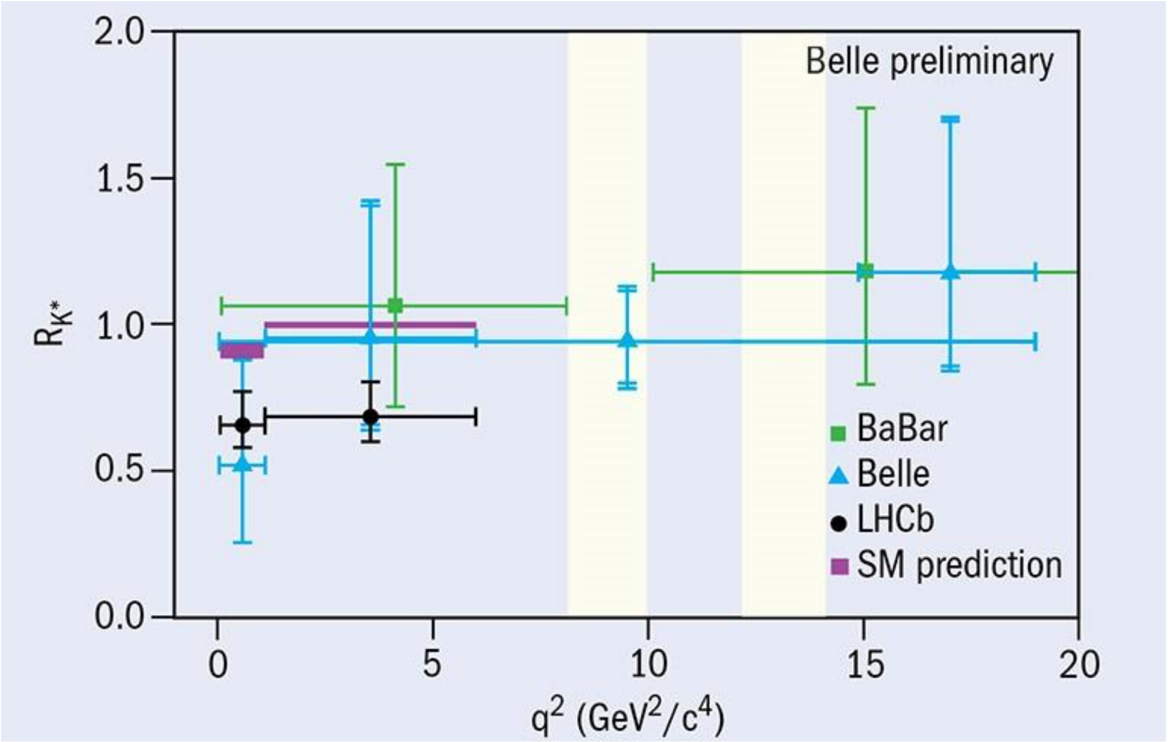


Lepton Flavour Violation in B decays?

- Theoretically absolutely clean observable (in the SM)



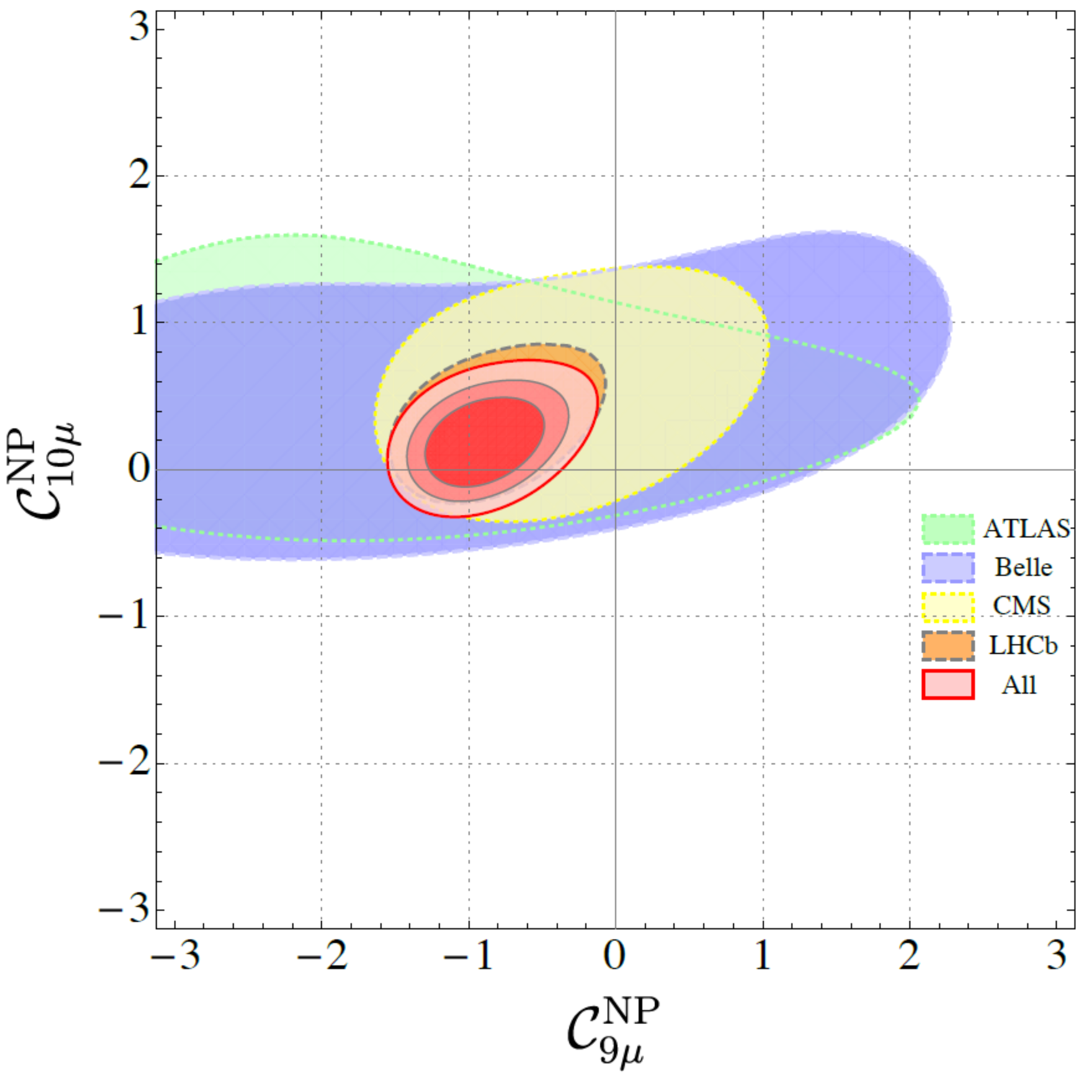
$R(K) = B \to K\mu^+\mu^- / B \to Ke^+e^-$



$R(K^*) = B \to K^*\mu^+\mu^- / B \to K^*e^+e^-$

Global Fit to $b \rightarrow s\mu^+\mu^-$ Data

- Perform global model independent fit to include all observables (≈150)
- Several NP hypothesis give a good fit to data significantly preferred over the SM hypothesis
- Fit is 5-6 σ better than the SM



$\tau \to \mu\nu\nu$

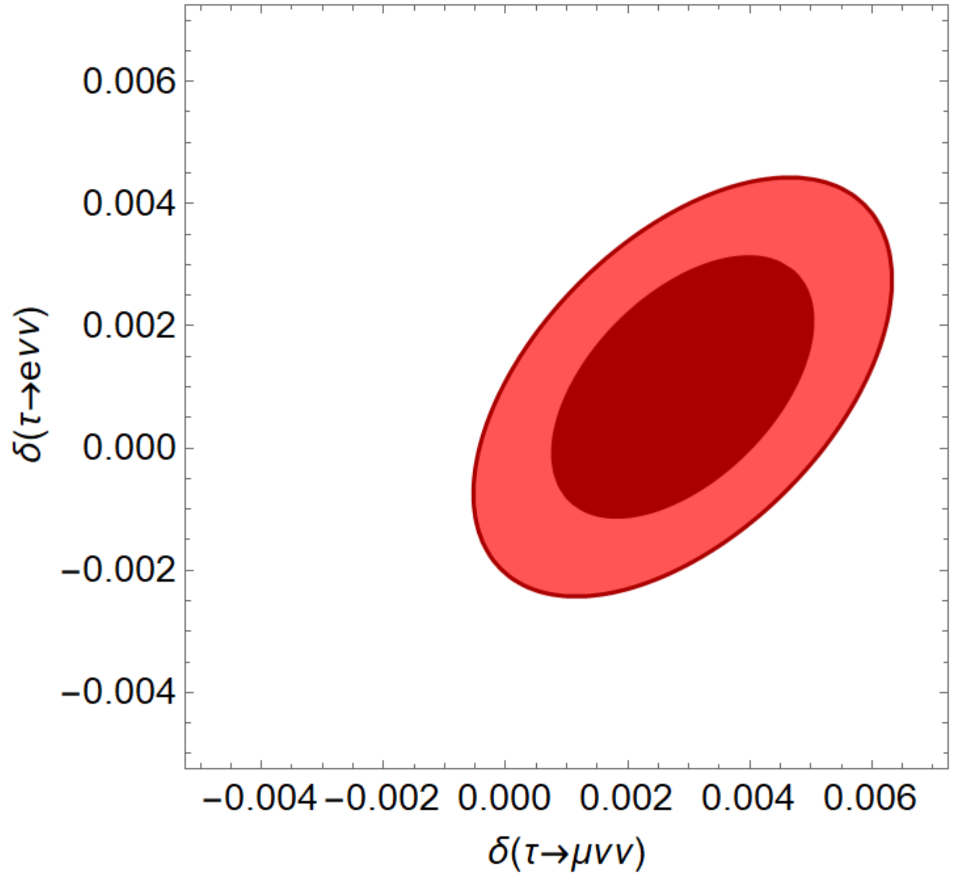
- Ratios of leptonic tau decays

$$\frac{A_{EXP}(\tau \to \mu\nu\bar{\nu})}{A_{SM}(\mu \to e\nu\bar{\nu})} = 1.0029 \pm 0.0014$$

$$\frac{A_{EXP}(\tau \to \mu\nu\bar{\nu})}{A_{SM}(\tau \to e\nu\bar{\nu})} = 1.0018 \pm 0.0014$$

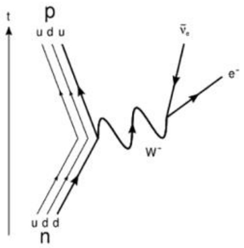
$$\frac{A_{EXP}(\tau \to e\nu\bar{\nu})}{A_{SM}(\mu \to e\nu\bar{\nu})} = 1.0010 \pm 0.0014$$

$$\rho = \begin{pmatrix} 1.00 & 0.49 & 0.51 \\ 0.49 & 1.00 & -0.49 \\ 0.51 & -0.49 & 1.00 \end{pmatrix}$$

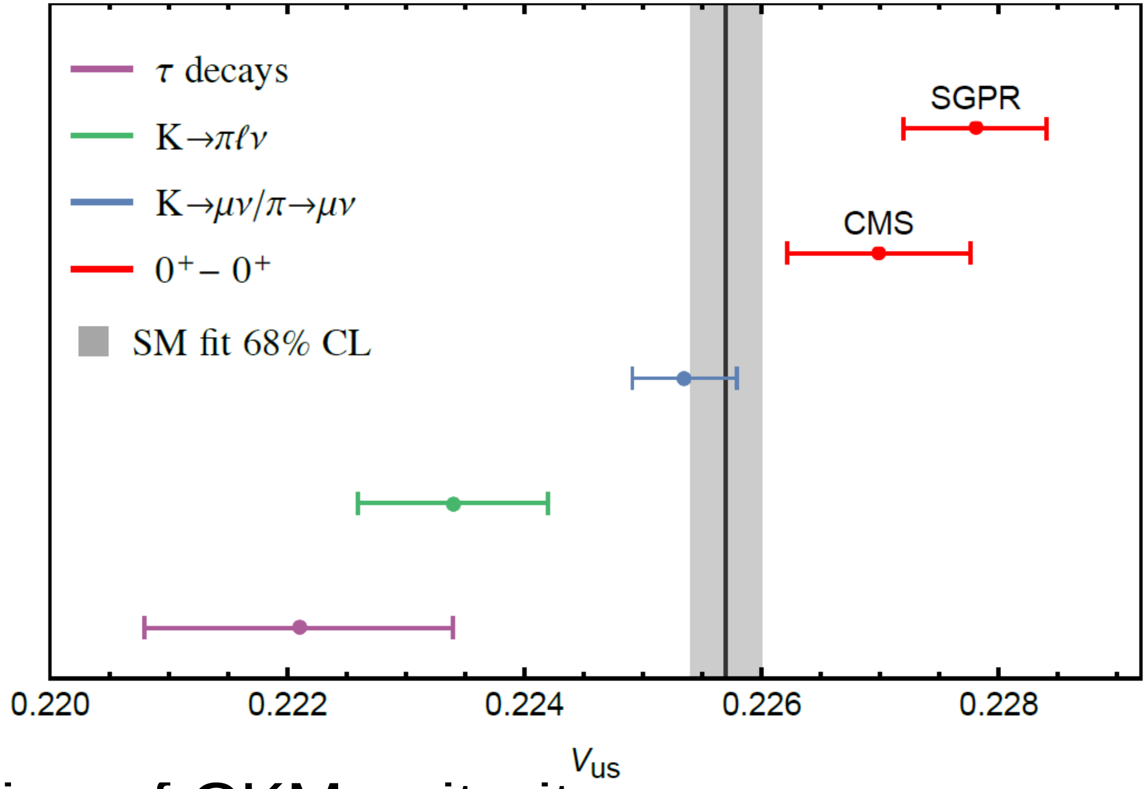


≈2σ hint for LFUV in tau decays

Cabibbo Angle Anomaly



- V_{ud} from super-allowed beta decays
- V_{us} from Kaon and tau decays
- Disagreement leads to a (apparent) violation of CKM unitarity

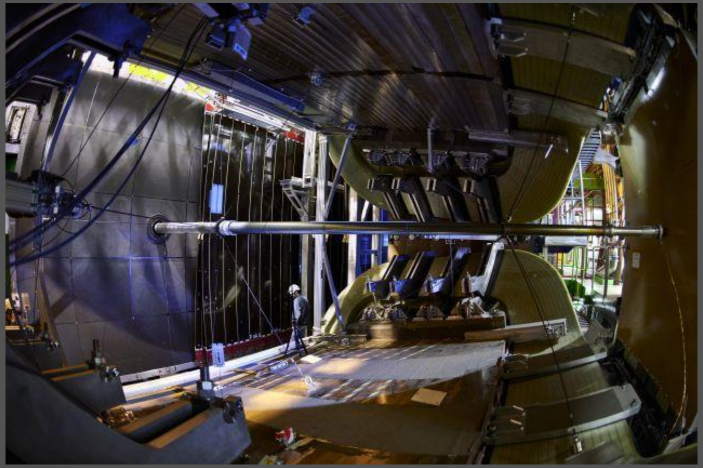


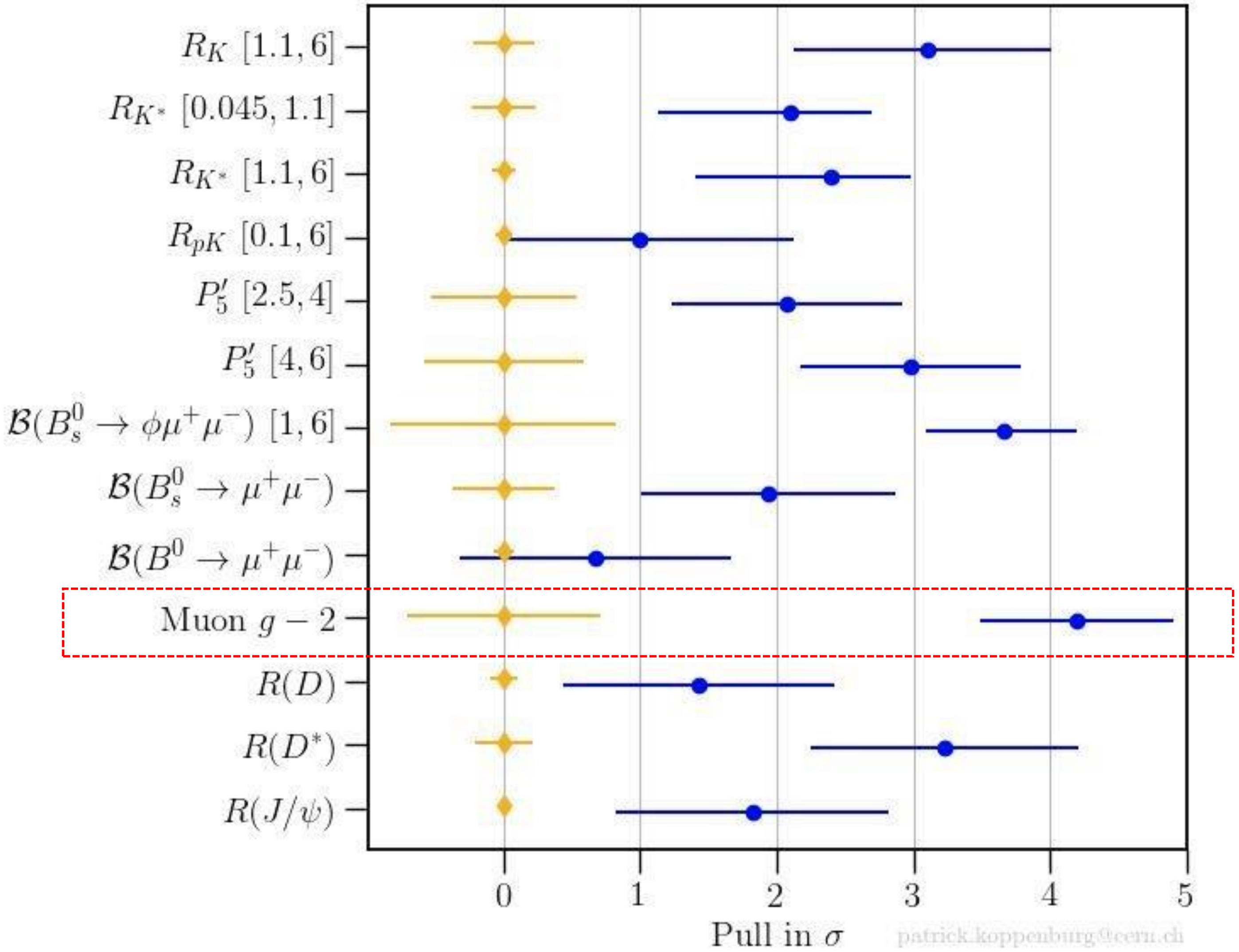
$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005\,(\text{PDG})$$

CMS, SGPR: radiative corrections

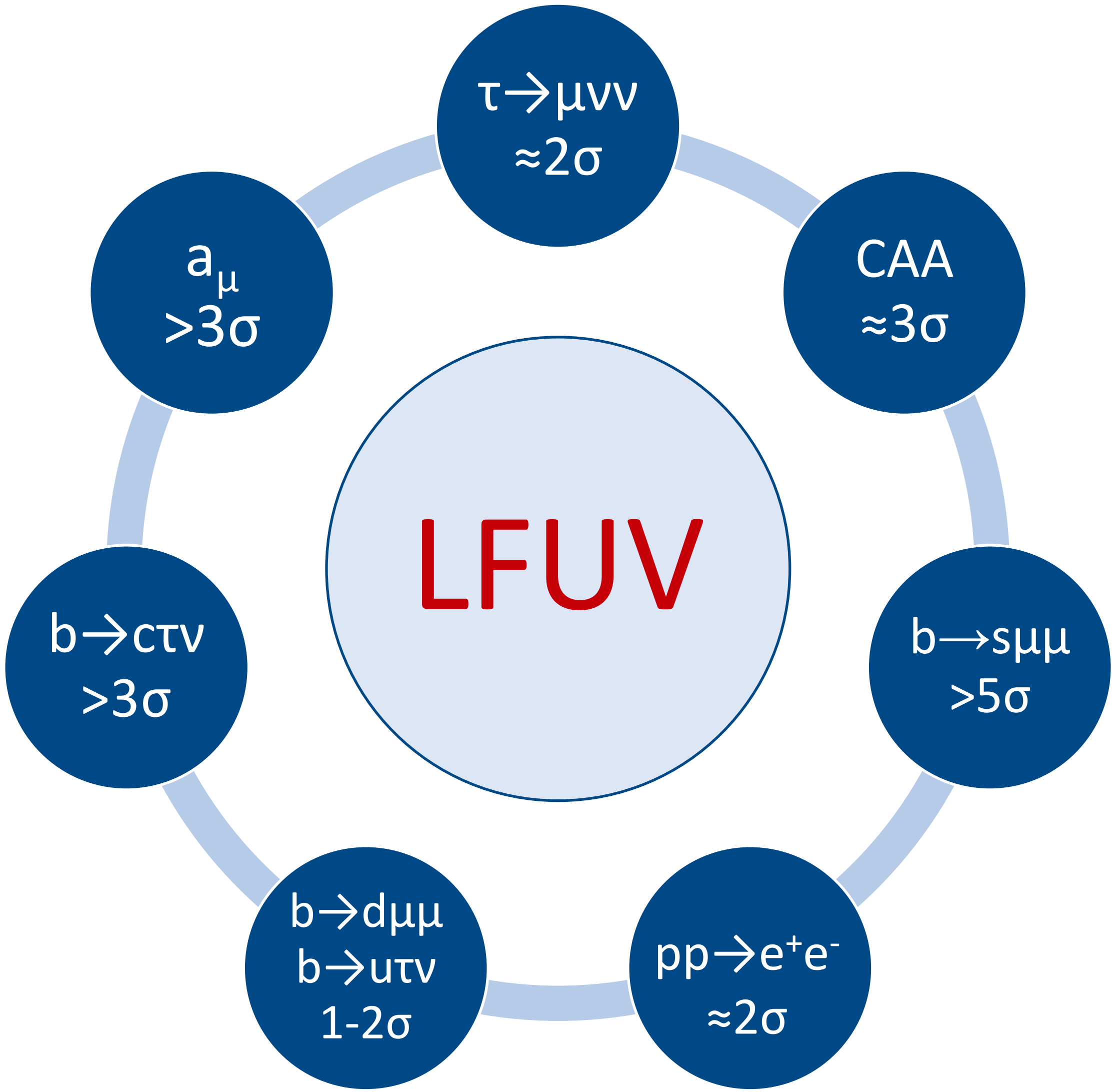
≈3σ hint for LFUV in the charged current

From LHCb (P. Koppenberg)



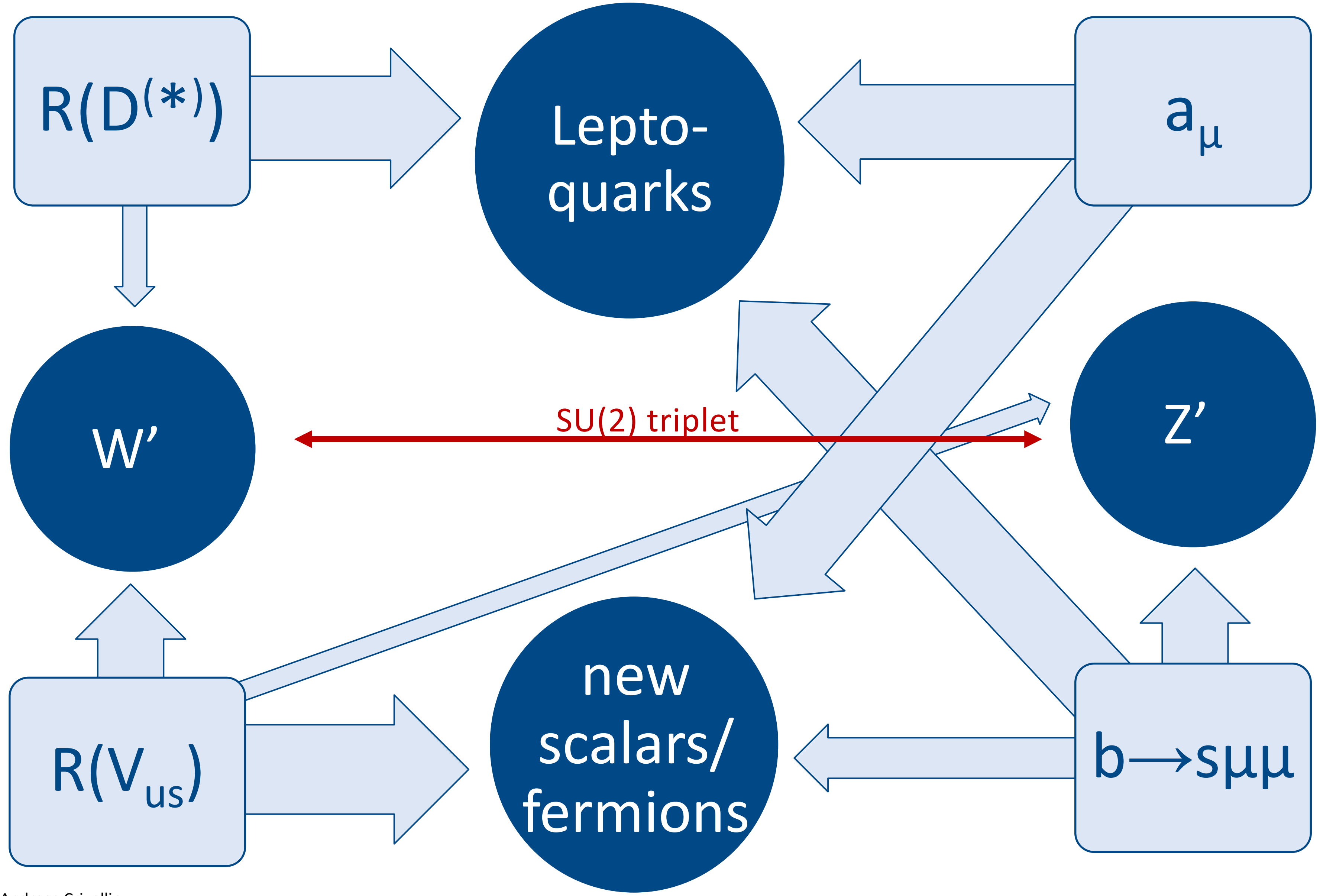


Hints for New Physics



Conclusions

- Flavour Anomalies require NP at the TeV scale



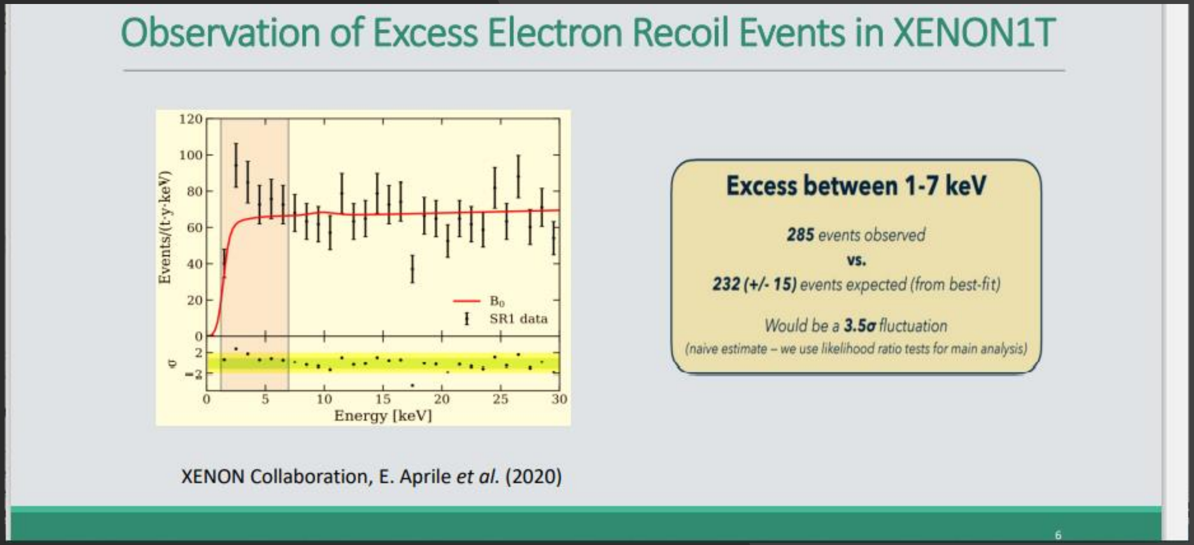
And … finally

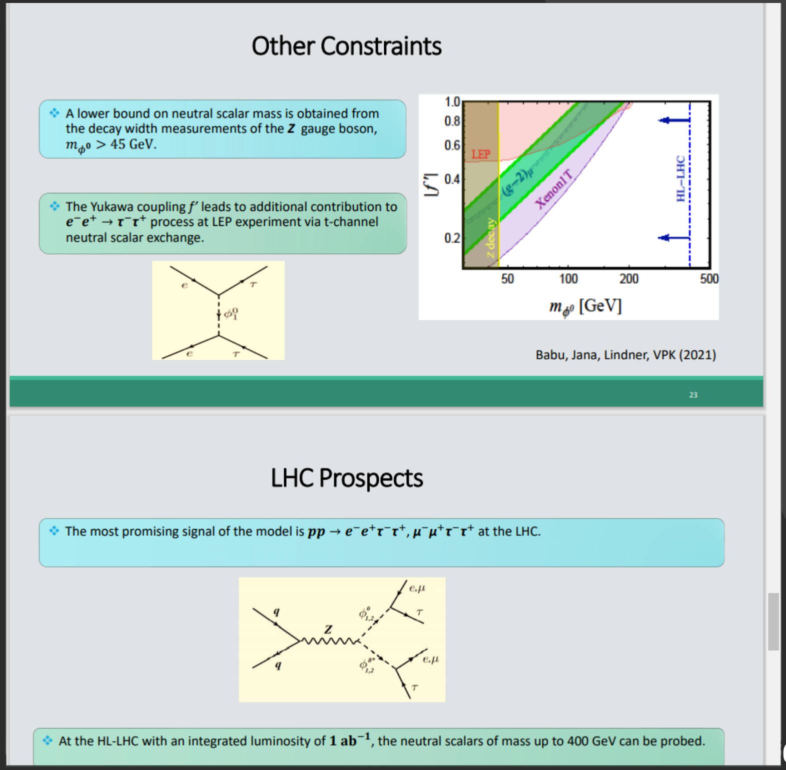
Muon g−2 Anomaly and Neutrino Magnetic Moments

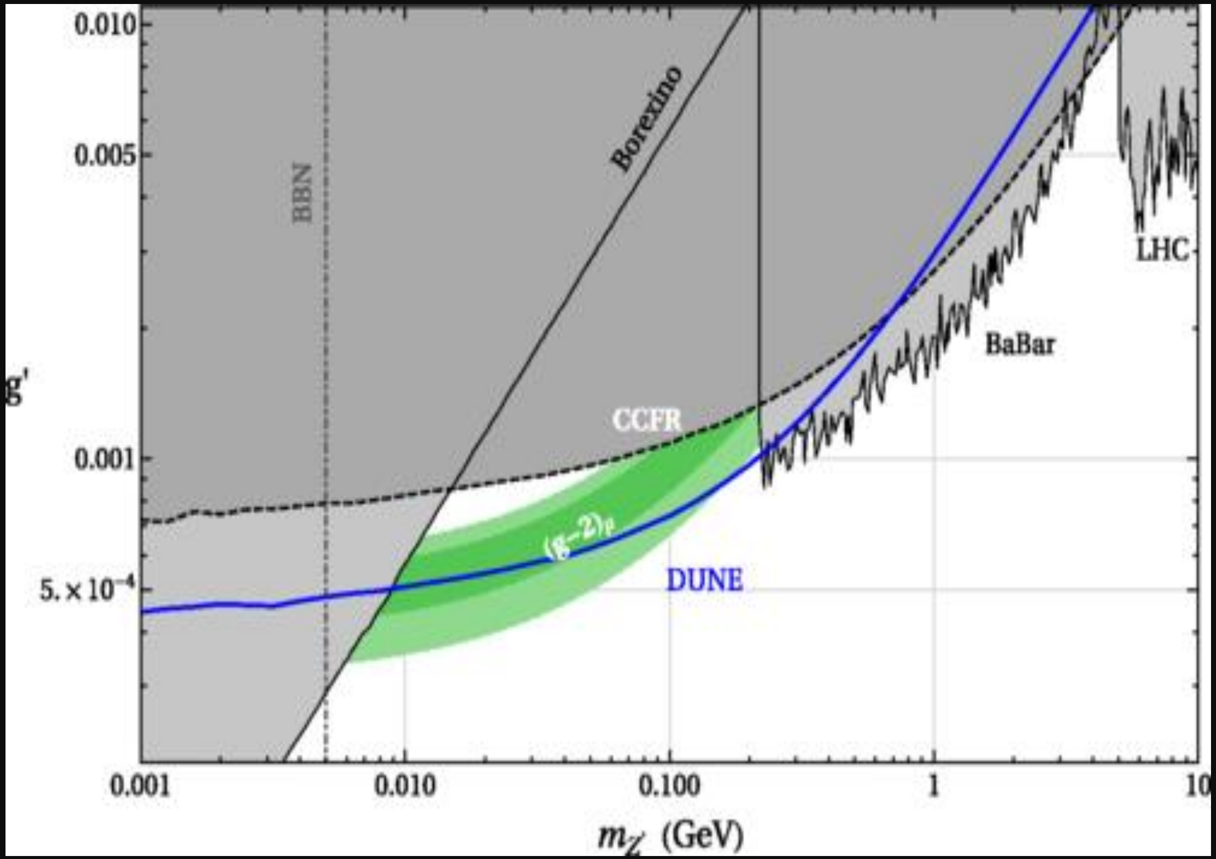
Authors: [K. S. Babu](), [Sudip Jana](), [Manfred Lindner](), [Vishnu P. K]()

Abstract: We show that a unified framework based on an SU(2)H horizontal symmetry which generates a naturally large neutrino transition magnetic moment and explains the XENON1T electron recoil excess

also predicts a positive shift in the muon anomalous magnetic moment. This shift is of the right magnitude to be consistent wit… ∇ More







Flavour Violating Low mass Z' More neutrinos

Evading the LHC?!!!

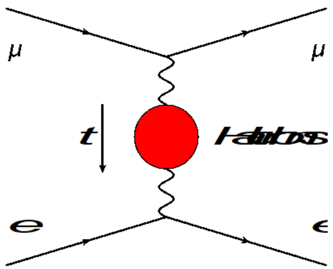
New Experiments

To check g-2 or investigate leptons

errors biggest towards x=1

HVP from electron-muon scattering in the space-like regime

M. Passera @HVP KEK 2018 [A. Abbiendi et al, arXiv:1609.08987, EPJC 2017]



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

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the space-like region. It can be extracted from scattering data!

- use CERN M2 muon beam (150 GeV)
- Physics beyond colliders program @CERN
- LOI June 2019
- Jan 2020: SPSC recommends pilot run in 2021
- goal: run with full apparatus in 2023-2024

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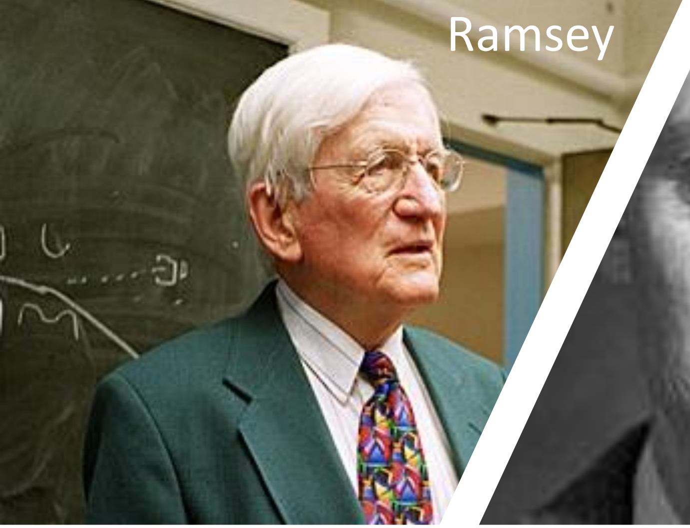
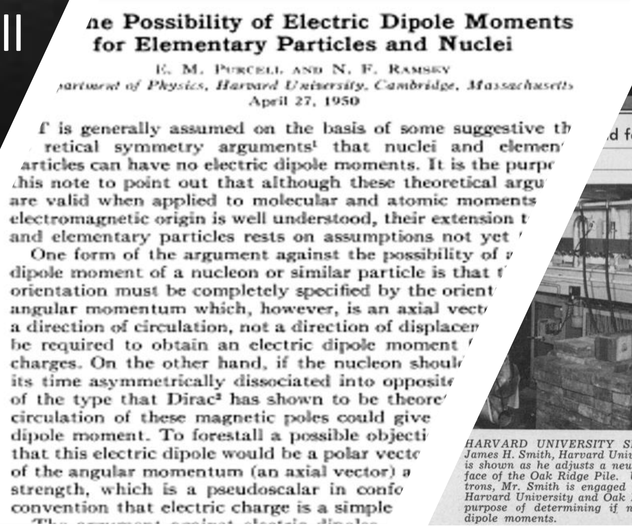




ne Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

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

f is generally assumed on the basis of some suggestive th retical symmetry arguments[1] that nuclei and elemen articles can have no electric dipole moments. It is the purp his note to point out that although these theoretical argu are valid when applied to molecular and atomic moments electromagnetic origin is well understood, their extension t and elementary particles rests on assumptions not yet

One form of the argument against the possibility of dipole moment of a nucleon or similar particle is that orientation must be completely specified by the orient angular momentum which, however, is an axial vect a direction of circulation, not a direction of displacen be required to obtain an electric dipole moment charges. On the other hand, if the nucleon shoul its time asymmetrically dissociated into opposit of the type that Dirac[2] has shown to be theore circulation of these magnetic poles could give dipole moment. To forestall a possible objecti that this electric dipole would be a polar vect of the angular momentum (an axial vector) a strength, which is a pseudoscalar in confo convention that electric charge is a simple

RIDGE NATIONAL LABORATORY NEWS

d for the ORNL Employees of Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation

OAK RIDGE, TENNESSEE — Friday, September 29, 1950

HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

Harvard University Conducts Important Research at ORNL

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a

DR. TAYLOR

ACS Lectureship Set For October 26, 27

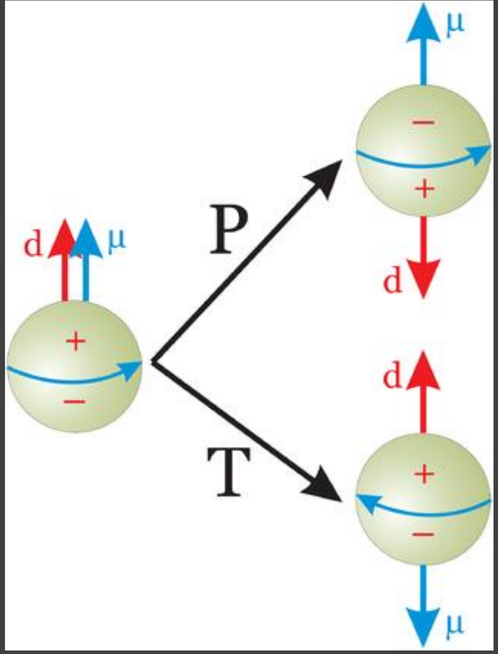
The East Tennessee Section of the American Chemical Society will have its Annual East Tennessee Lectureship this year in two sessions, according to plans re-

Dr. Ellison Taylor Appointed Chem. Division Director

Effective October 1, Dr. Ellison H. Taylor will assume the duties of Director of the Chemistry Division. In this capacity he will succeed Dr. John A. Swartout, who was recently elevated to the position of Assistant Research Director of Oak Ridge National Laboratory.

Dr. Taylor's present connection with the Chemistry Division is that of Associate Director of the Division and Group Leader of the Radiation Chemistry Group, in which capacities he has served since June, 1948. Previously, he had been Assistant Director of the Division, from June, 1946, to February, 1948, and was Acting Di-

Electric Dipole Moments



P changes sign of EDM but not spin.

System under **P** or **T** is not symmetric with respect to the initial system

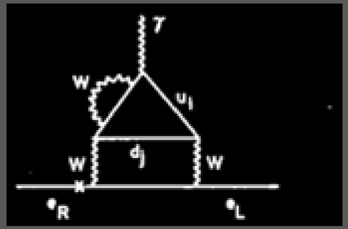
T reversal changes spin but not EDM

EDM of non-composite particle aligned with spin

Having CPT symmetry, the combined symmetry

CP is violated

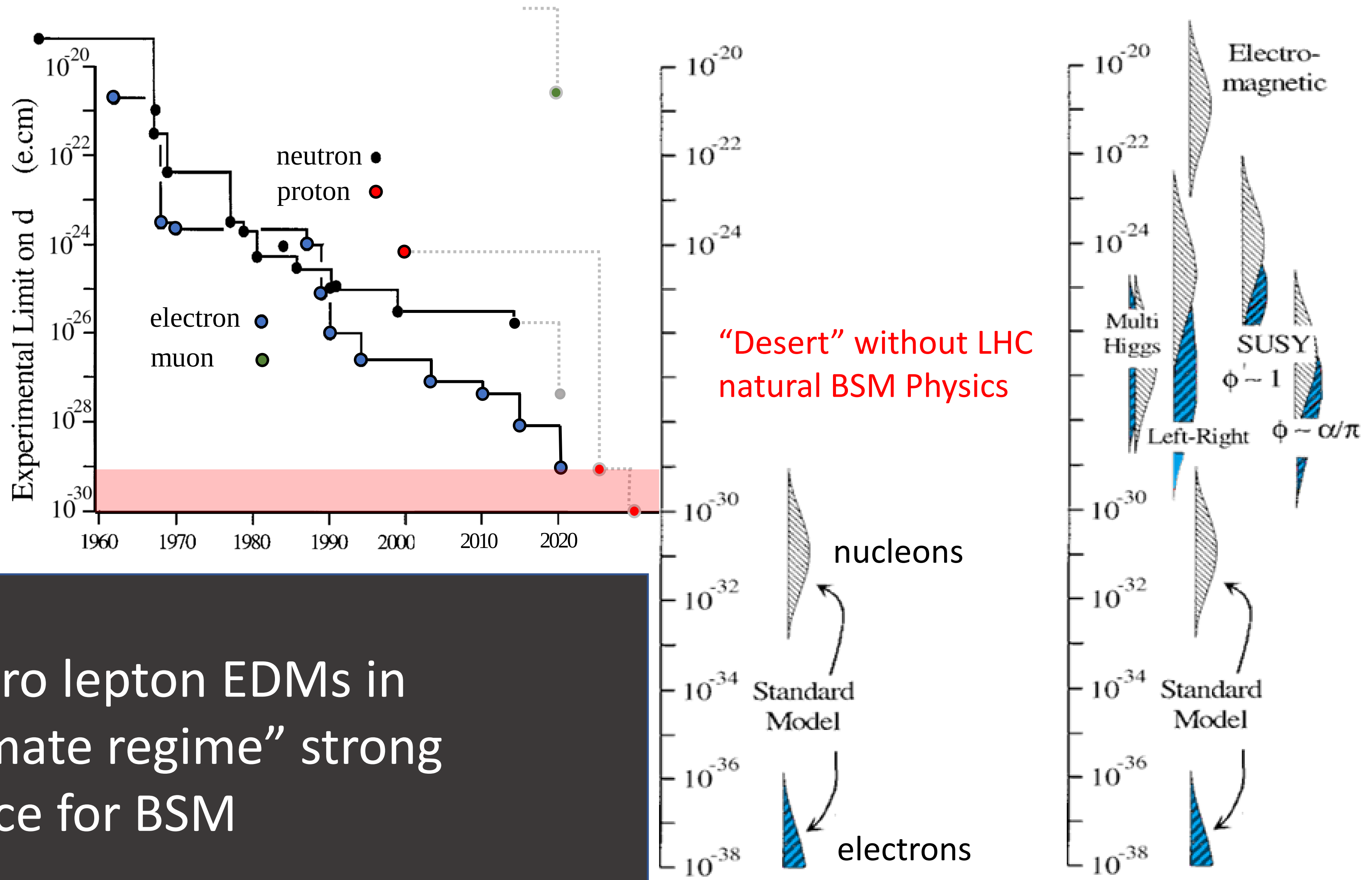
SM value for electron/muon CP/EDM v. small



EDMs arising from the CKM-matrix vanish up to three loops for the electron (Bernreuther and Suzuki, 1991)

Baryon Asymmetry of the Universe needs more than CKM

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



"Desert" without LHC natural BSM Physics

Non-zero lepton EDMs in "proximate regime" strong evidence for BSM

Need to measure Muon EDM

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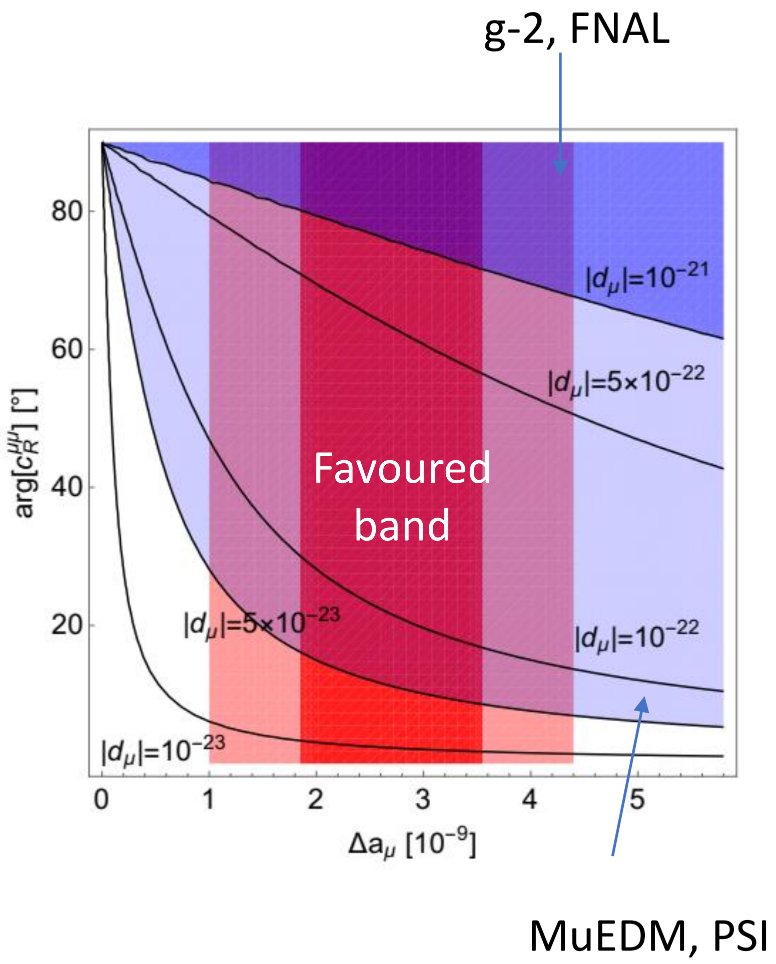
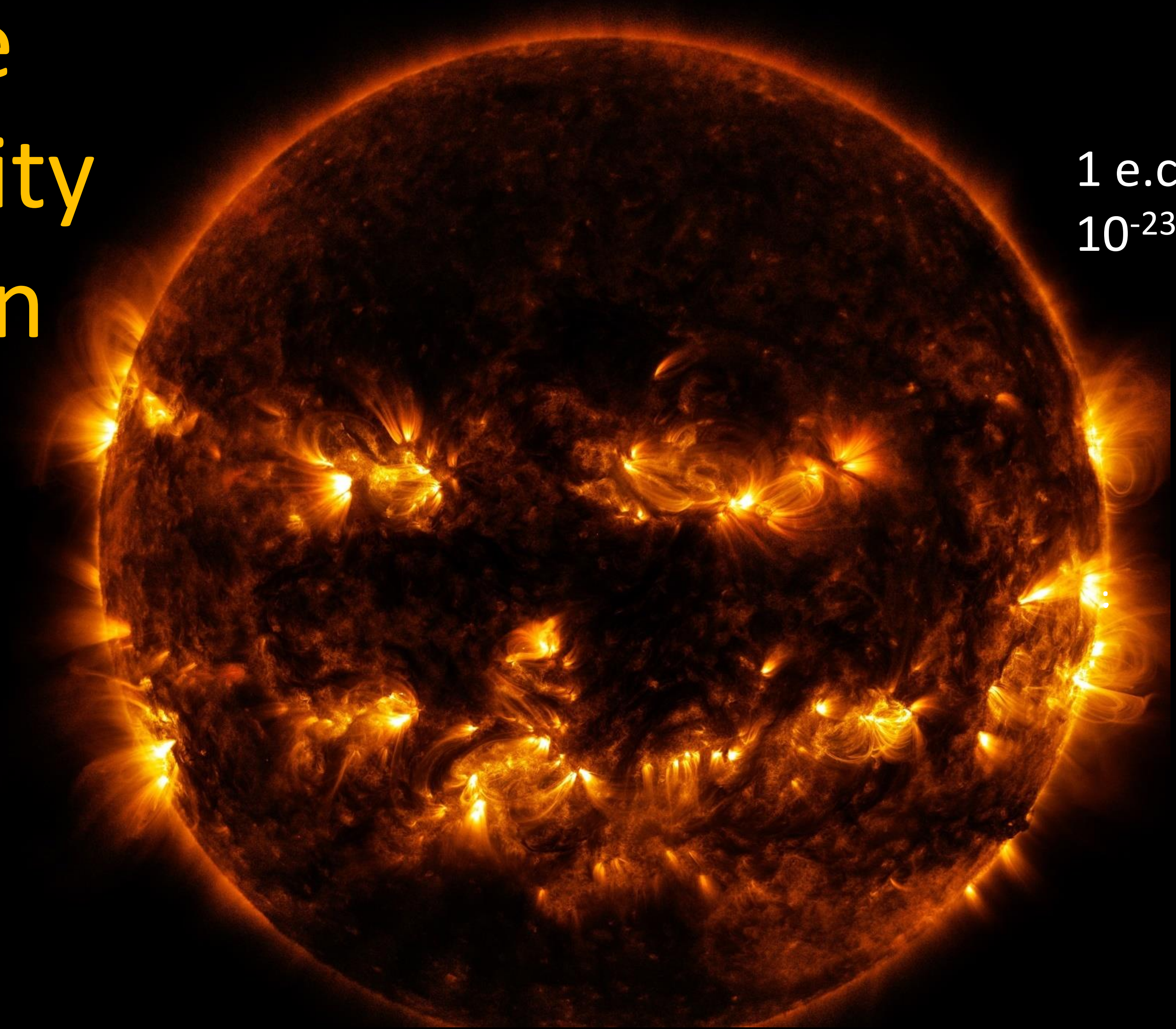
- muEDM Proposal (2021, PSI)
  - In past eEDM scaled to muEDM by ratio of masses (squared). Only results less than 10^{-27} ecm thought "useful". (LFU, MFV etc.)
  - New results from LHCb, g-2, and lack of naturalness challenges these assumptions
  - *"While some of the parameter space for d_μ favored by a_μ could be tested at the $(g-2)_\mu$ experiments at Fermilab and J-PARC, a dedicated muon EDM experiment at PSI would be able to probe most of this region" (Crivellin, Hoferichter* arXiv:1905.03789



Extreme
Sensitivity
Precision



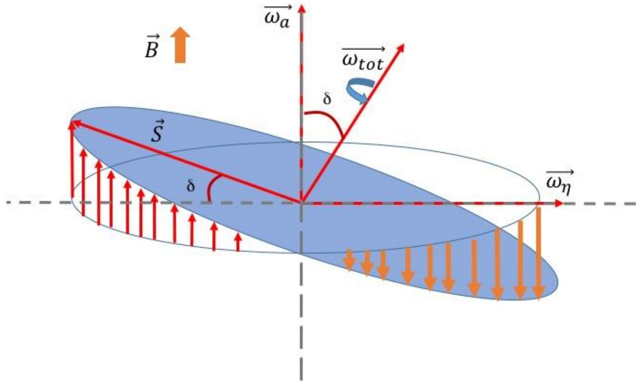
1 e.cm $\propto$ Sun Radius
10^{-23} e.cm $\propto$ 1000 fm

Can also measure the Muon EDM at g-2

- Causes an increase in muon precession frequency
- Precession plane tilts towards center of ring
- Vertical oscillation is 90^o out of phase with the a_m oscillation

$$\omega_{tot} = \sqrt{{\omega_a}^2 + {\omega_\eta}^2}$$

$$\vec{d} = \eta \left(\frac{Qe}{2mc} \right) \vec{s}$$



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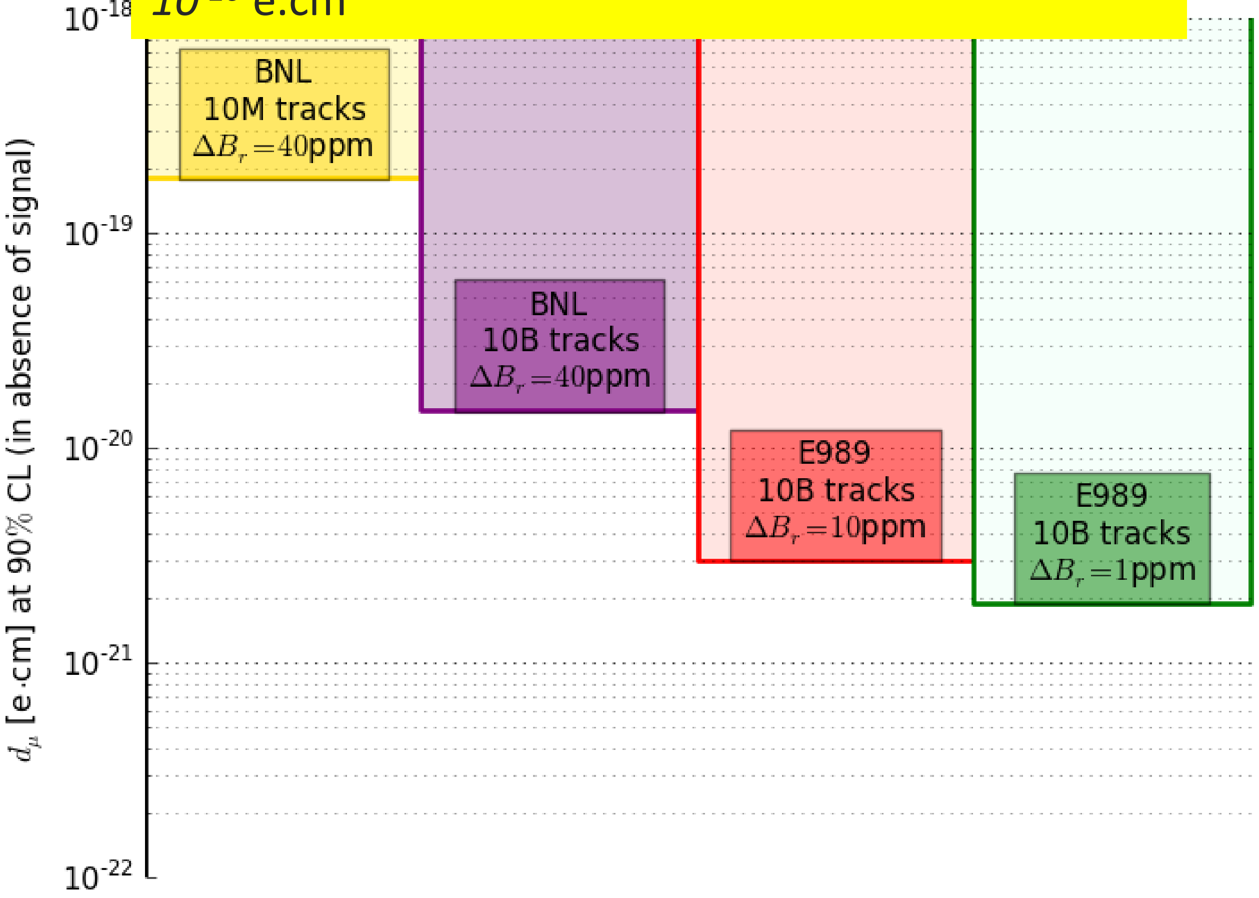
EDM Projected Limits

Current worlds best limit is from BNL: $|d_\mu| > 1.9 \times 10^{-20}$ e.cm



Had BNL had enough tracking statistics would have set:

$|d_\mu| \approx 2 \times 10^{-20}$ e.cm

With $\sigma_{|Br|}$ = 10ppm FNAL can improve the EDM limit:

$|d_\mu| \approx 3.0 \times 10^{-21}$ e.cm

Target of $\sigma_{|Br|}$ = 1ppm is difficult, and requires new dedicated B_r apparatus

Would improve E989 the limit:

$|d_\mu| \approx 1.9 \times 10^{-21}$ e.cm

Lepton Flavour Violation

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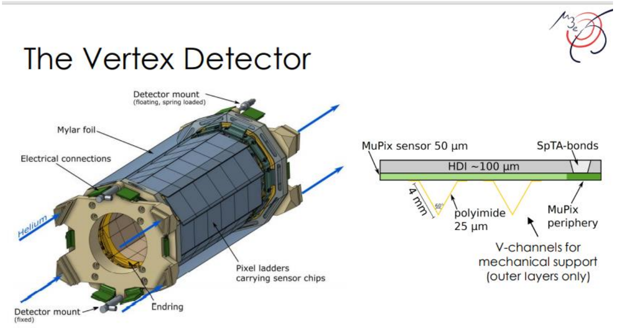
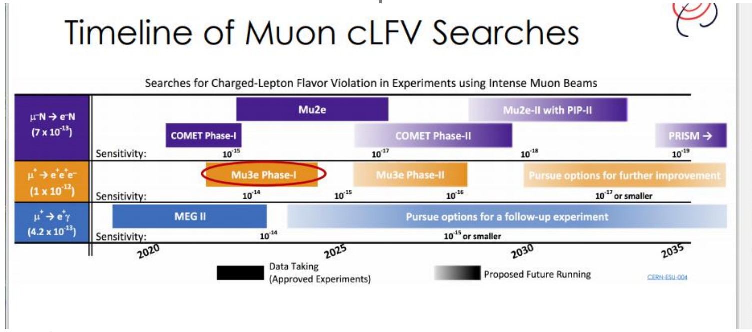
- Mu2e @ FNAL

- Mu3e @ PSI





Summary

- **g-2 indicates strong evidence for non SM behaviour of magnetic moment**
  - If confirmed this will be in contrast to electron
- **There is evidence of LFUV in flavour experiments**
  - Together is this over 5 sigma?
- Many phenomena remain to explained and need BSM

- Theory requires continued searches at LHC and beyond
  - No obvious “elegant” solution
- New Generations of Lepton Experiments are being planned