Updates and Perspectives on the Muon g-2 Experiment

A Muon g-2 storm seems to be brewing

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FPCP Meeting, 2 June 2023
Lyon (FR)

What is *"g-2"* ?

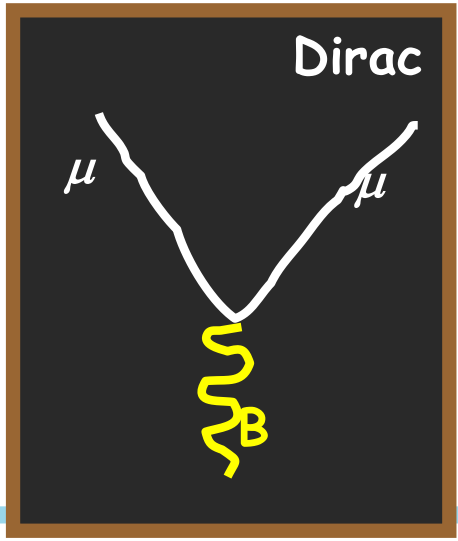
$$\vec{\mu}_p = -g_p \frac{e}{2m_p} \vec{S}$$

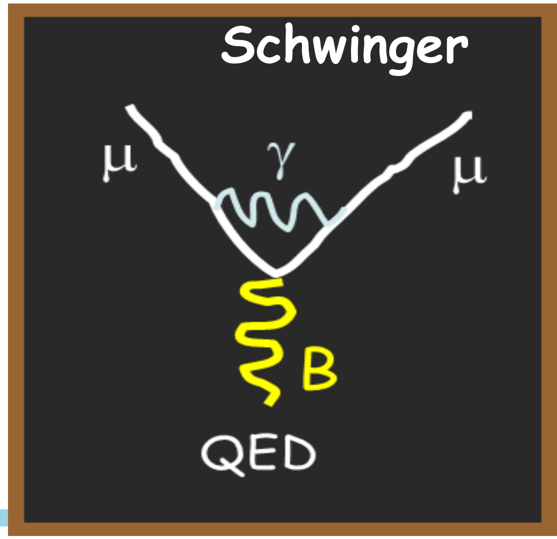
$$a_p = \frac{g_p - 2}{2}$$

- ***g$_P$*** : proportionality constant between spin and magnetic moment for particle P
- ***a$_P$*** : magnetic anomaly
- ***a$_P$*** = 0 at tree level (*purely Dirac particle*)

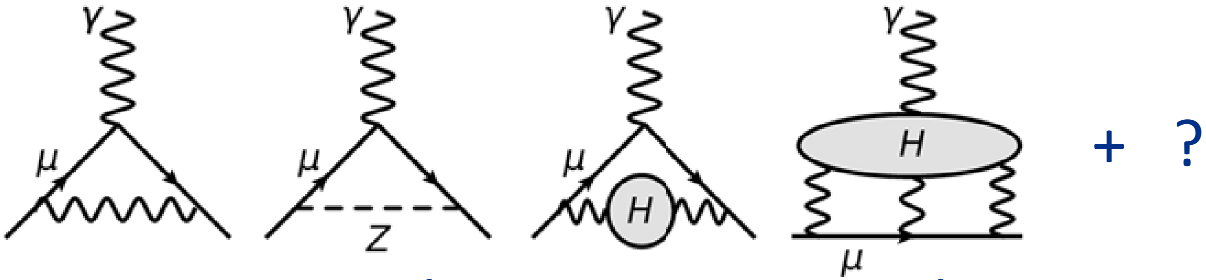
- Using modern language, the term (g-2)/2 reflects the magnitude of the Feynmann diagrams beyond leading order

$$a = 0 + \alpha/2\pi + \ldots.$$





Standard Model determination of a_μ



QED | Weak | HLO | HLbL | New Physics.

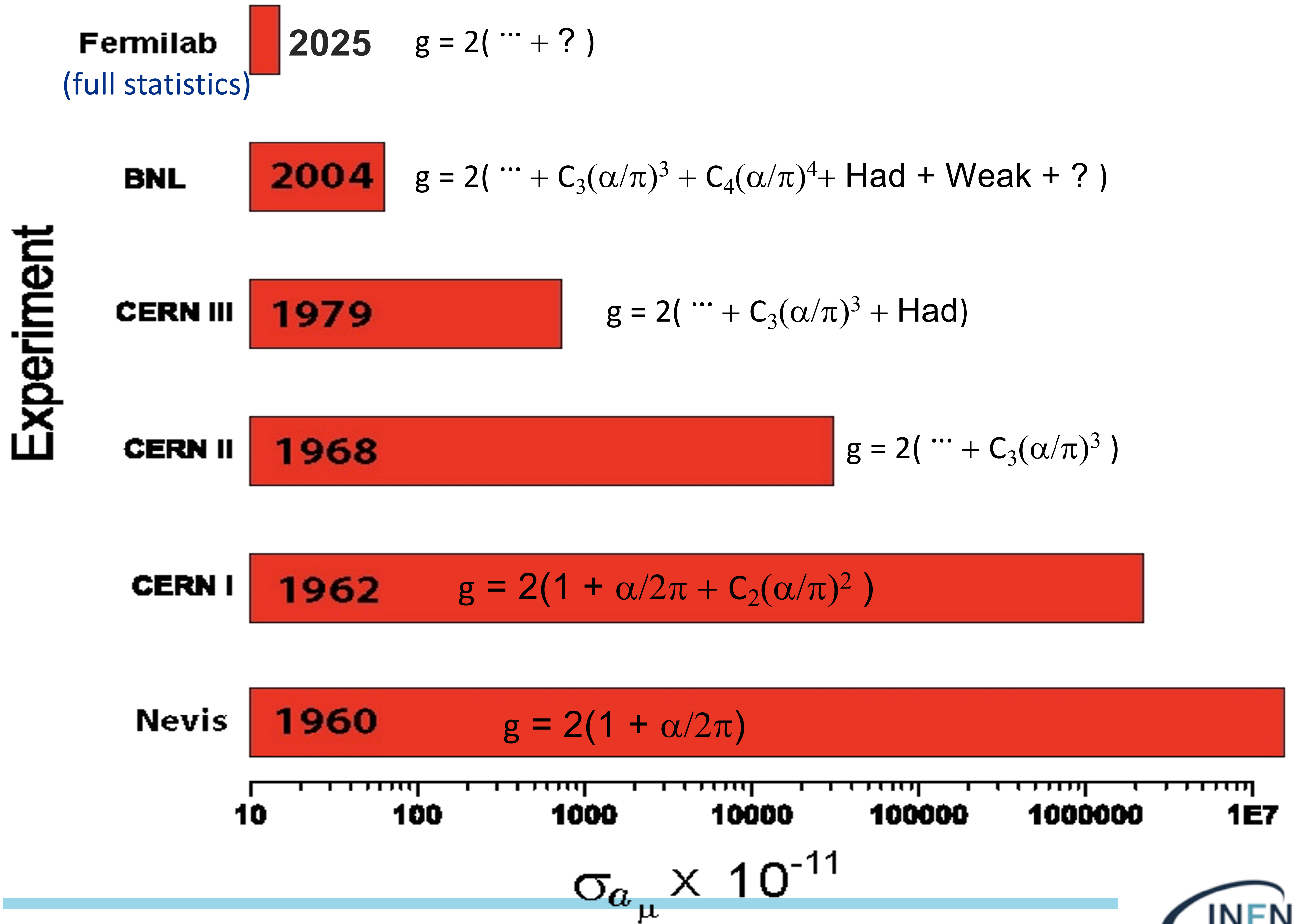
Known | Known | Data | Models/Lattice | ?

QCD

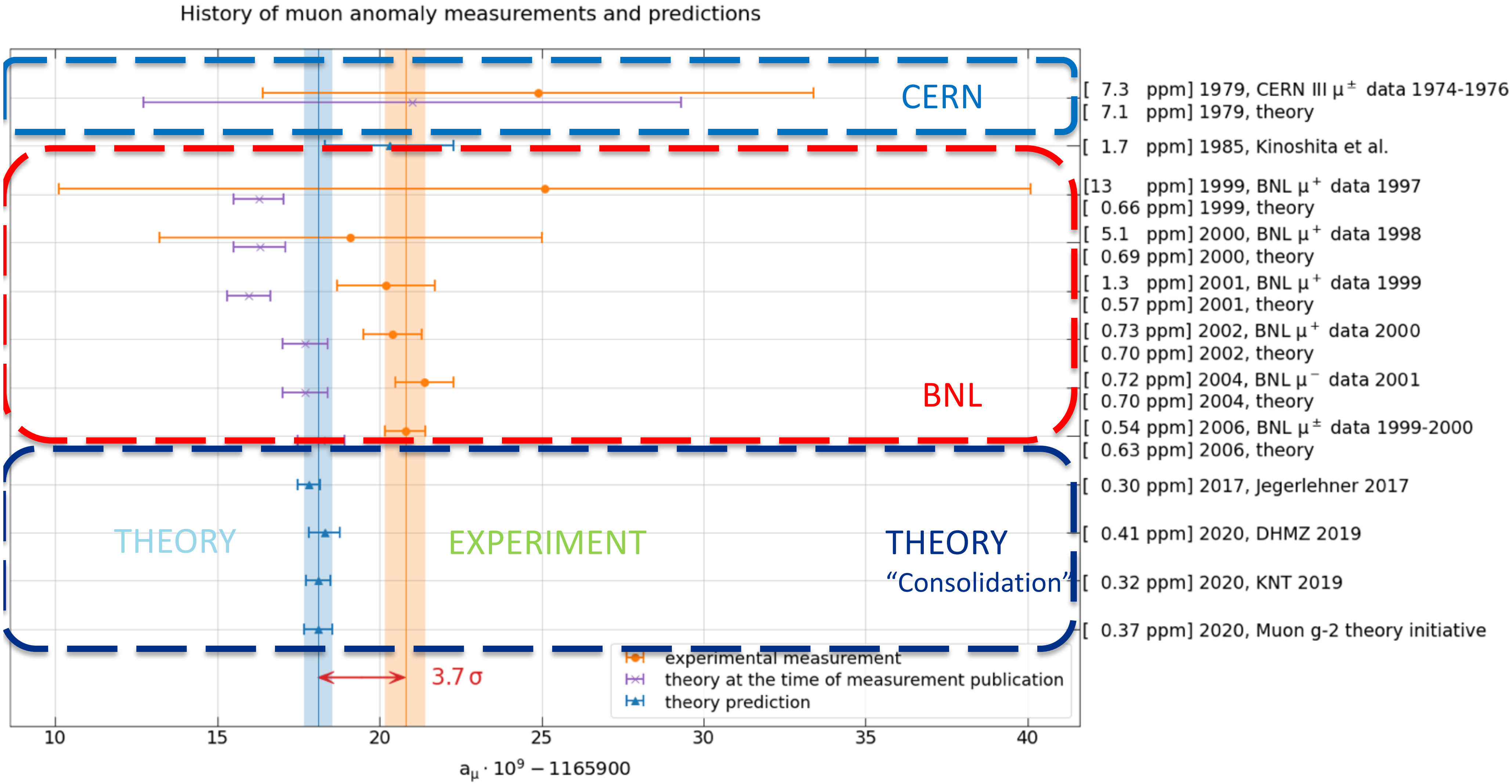
	Value ($\times 10^{-10}$) units
QED ($\gamma + \ell$)	$11\,658\,471.8951 \pm 0.0009 \pm 0.0019 \pm 0.0007 \pm 0.0077_\alpha$
HVP(lo) Davier17	692.6 ± 3.33
HLbL Glasgow	10.5 ± 2.6
EW	15.4 ± 0.1
Total SM Davier17	$11\,659\,181.7 \pm 4.2$

Theory Initiative White Paper (arXiv 2006:08443)

$$a_\mu = (116\,591\,810 \pm 43)\times 10^{-11} \rightarrow 370 \text{ ppb}$$


Experiment
Fermilab
(full statistics)
2025
g = 2(⋯ + ?)
BNL
2004
g = 2(⋯ + $C_3(\alpha/\pi)^3$ + $C_4(\alpha/\pi)^4$+ Had + Weak + ?)
CERN III
1979
g = 2(⋯ + $C_3(\alpha/\pi)^3$ + Had)
CERN II
1968
g = 2(⋯ + $C_3(\alpha/\pi)^3$)
CERN I
1962
g = 2(1 + $\alpha/2\pi$ + $C_2(\alpha/\pi)^2$)
Nevis
1960
g = 2(1 + $\alpha/2\pi$)
10
100
1000
10000
100000
1000000
1E7
$\sigma_{a_\mu} \times 10^{-11}$

A rich history of g-2 Theory and Experiment



Situation before 2021: tension between theory and experiment

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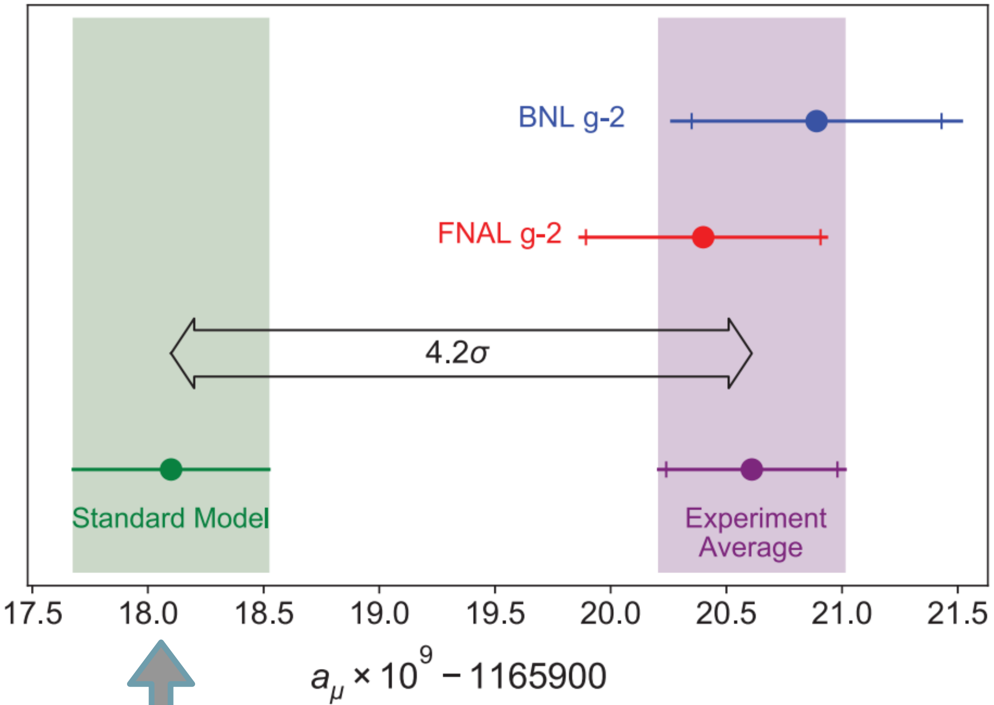
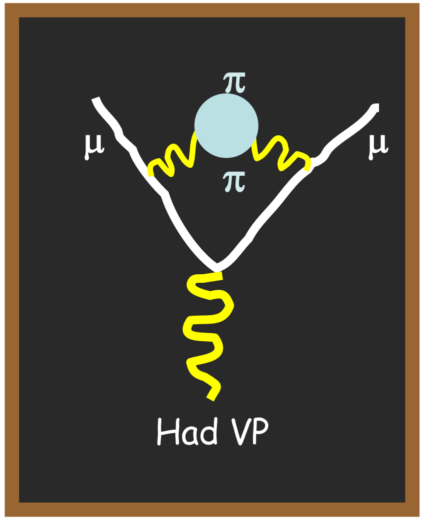
The 2021 Run1 g-2 result

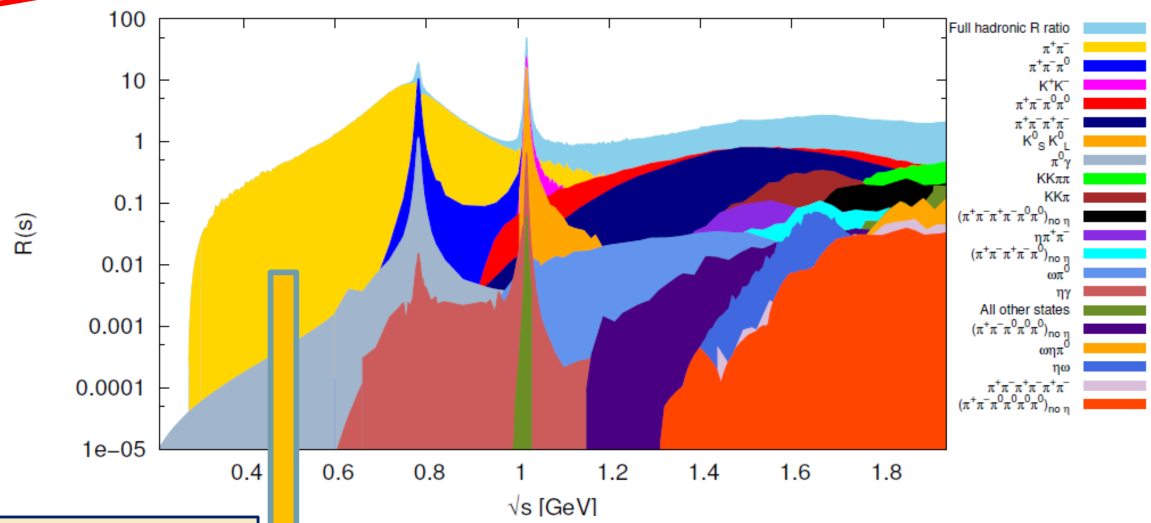


The uncertainty in the SM prediction is dominated by hadronic terms

- The 2021 Run1 g-2 result:
  - Confirmed the BNL result
  - Led to net increase in discrepancy with theory above 4 σ
  - Statistical uncertainty: 434 ppb; Systematics: 159 ppb)
  - World average uncertainty: 350 ppb
  - Represents only 5% of our data set

To date: recommended HVP value from e⁺e⁻ data

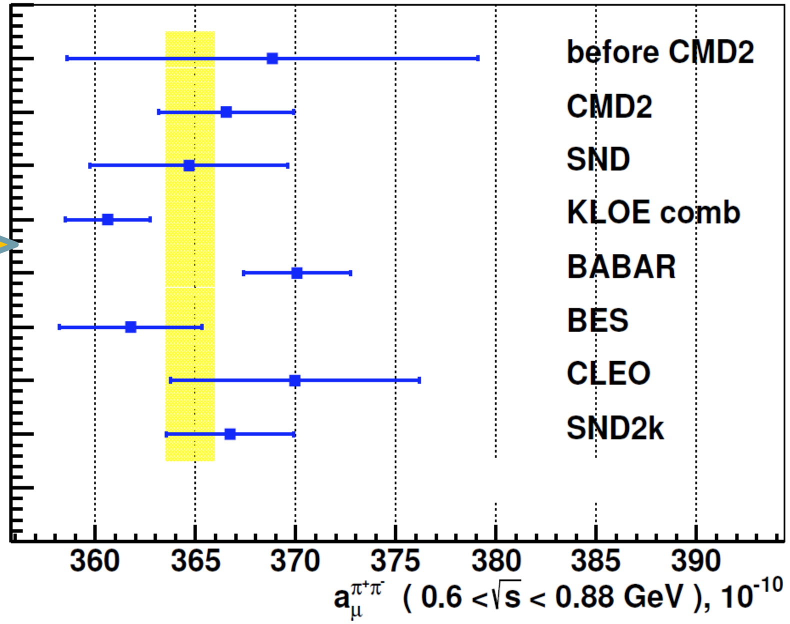




$$a_\mu^{\text{had,LO}} = \frac{\alpha^2(0)}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

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

ππ region



Here, **8** experiments contribute

I will return to this topic at the end

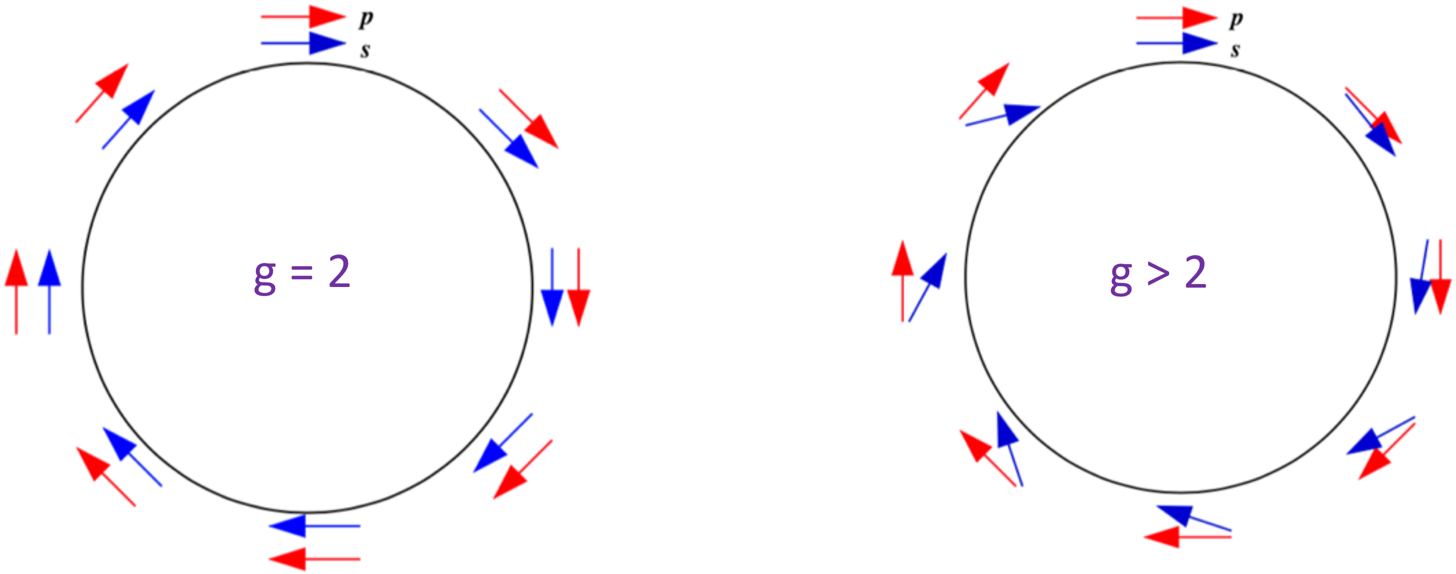
The Fundamental Experimental Principle

- Difference between spin precession and cyclotron revolution for a muon (charged particle with spin) in a magnetic field*:

$$\omega_a = \omega_s - \omega_c = g\frac{e}{2m}B - \frac{e}{m}B = \frac{g-2}{2}\frac{e}{m}B = a_\mu \frac{e}{m}B$$

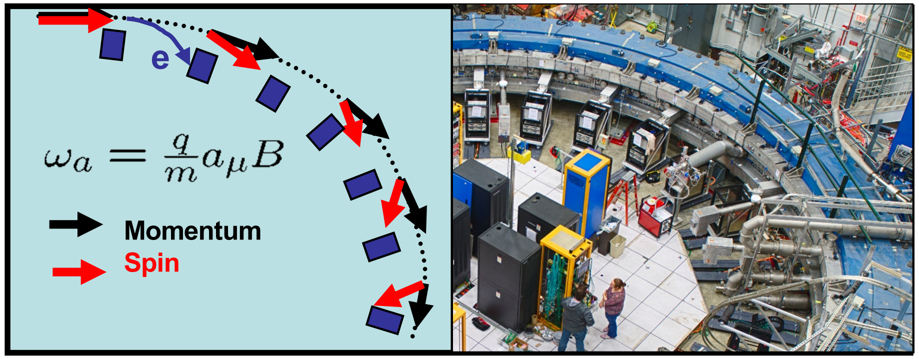
*s and p are assumed to be in a plane perpendicular to B

- simple classical calculation
- the relativistic approach provides the same result



From single muon to *muon beam*

- The expression is more complicated when you add in *E*-field focusing and out of plane oscillations



- **The motion is very nearly planar and the momentum is very nearly the ideal one, but both effects are not perfect and require corrections**

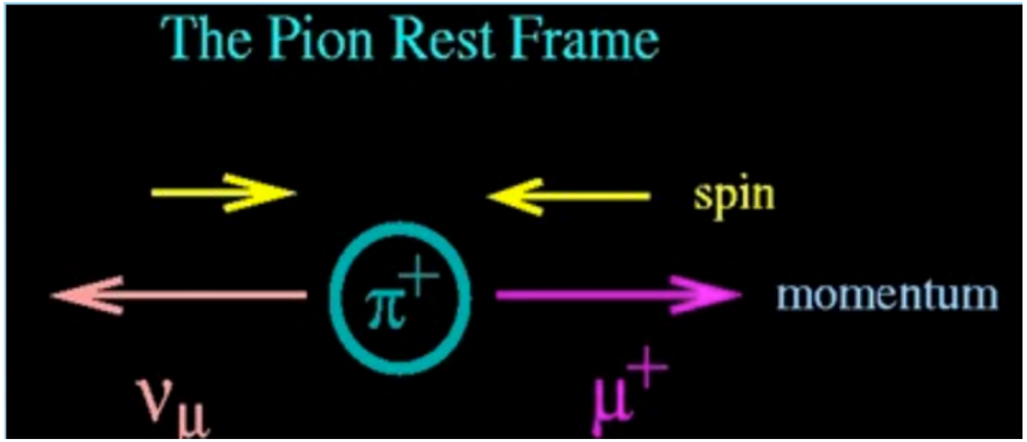
$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)\cancel{(\vec{\beta}\cdot\vec{B})}\vec{\beta} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}\frac{\vec{\beta}\times\vec{\mathcal{E}}}{c}\right]$$

0 if "in plane"

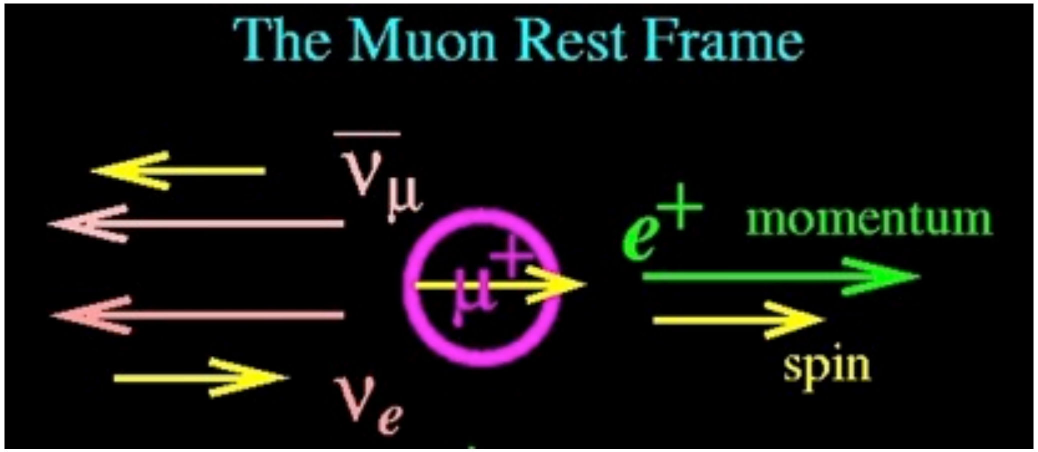
Term cancels at 3.094 GeV/c, the "Magic γ"

How do we measure the spin direction?

- Use V-A structure of weak decays to build a polarized beam...



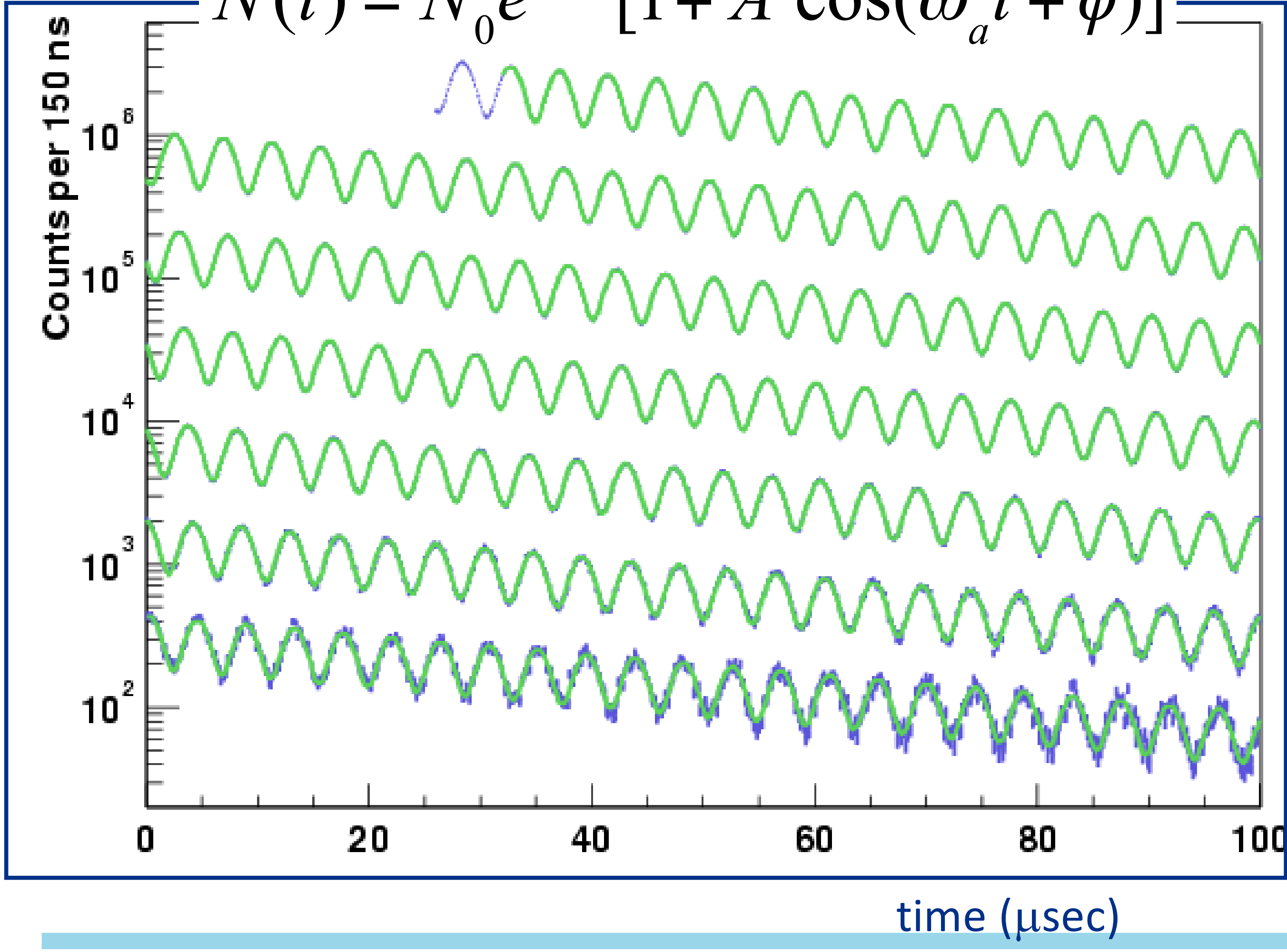
- ... and to measure the muon polarization looking for energetic positrons



Measuring the spin precession

- The number of observed positrons above a threshold energy oscillates with the $\omega_a/2\pi$ frequency due to spin precession

$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$



- exponential decay modulated by spin precession
- *note that the x-axis "wraps up" every 100 μsec for a total of ~700 μs → ~10 muon lifetimes*

Extracting a_μ(simplified)

$$\boldsymbol{\omega_a = a_\mu\,(e/m)\,B} \rightarrow \boxed{\boldsymbol{a_\mu = \omega_a/B\,(m/e)}}$$

by expressing B in terms of the (shielded) proton precession frequency:
$(B = \hbar\omega'_p/2\mu'_p)$:

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p}} \cdot \frac{\mu'_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2} = \boxed{R'_\mu} \cdot \boxed{\frac{\mu'_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}}$$

What we measure

External data

$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p}$$

ratio of muon to proton precessions in the same magnetic field

$\tilde{\omega}'_p$ = (shielded) Proton angular velocity **weighted for the muon distribution**

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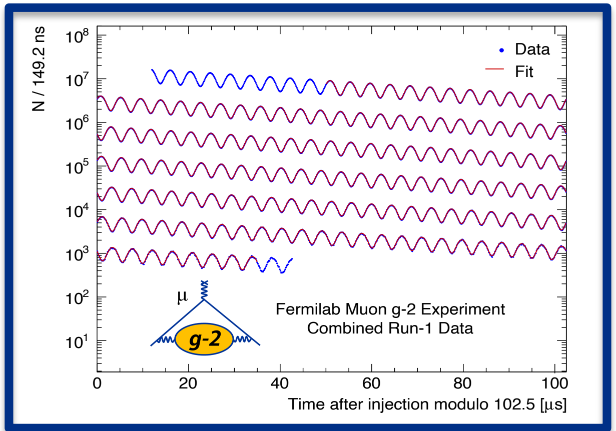
The key ingredients

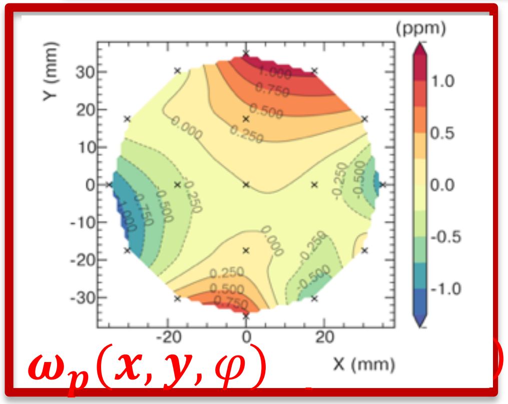
- Neglecting corrections like *E-field, out-of-plane, etc*, the three *key ingredients* to measure the muon magnetic anomaly are:

ω_a=muon spin precession respect to momentum (in B field)

$\boldsymbol{\omega_a}$



$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \sim$$



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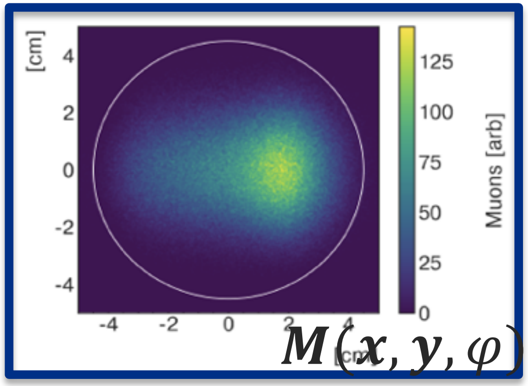
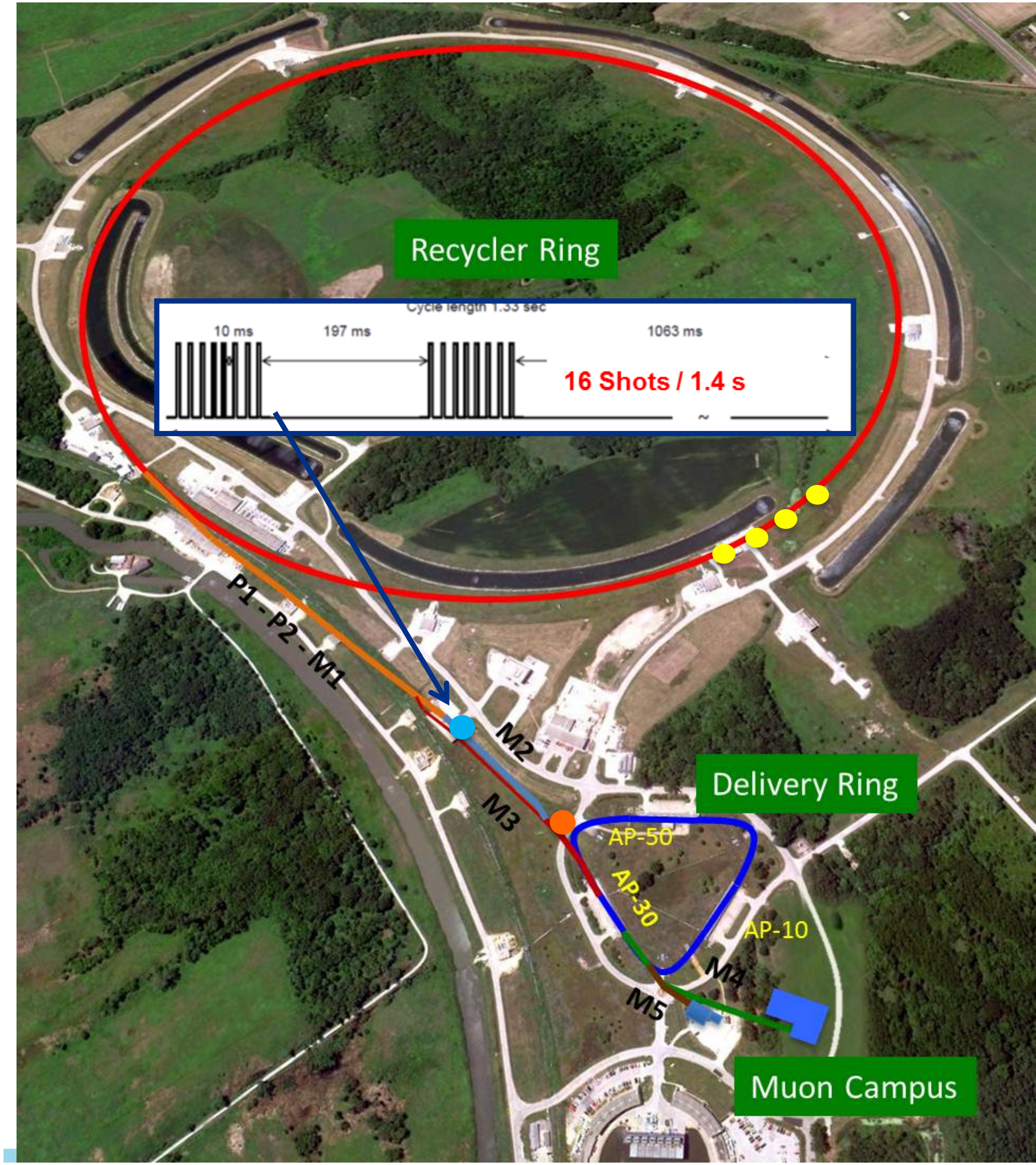


$$\tilde{\omega}'_p = \omega'_p(x,y,\varphi)\cdot M(x,y,\varphi)$$

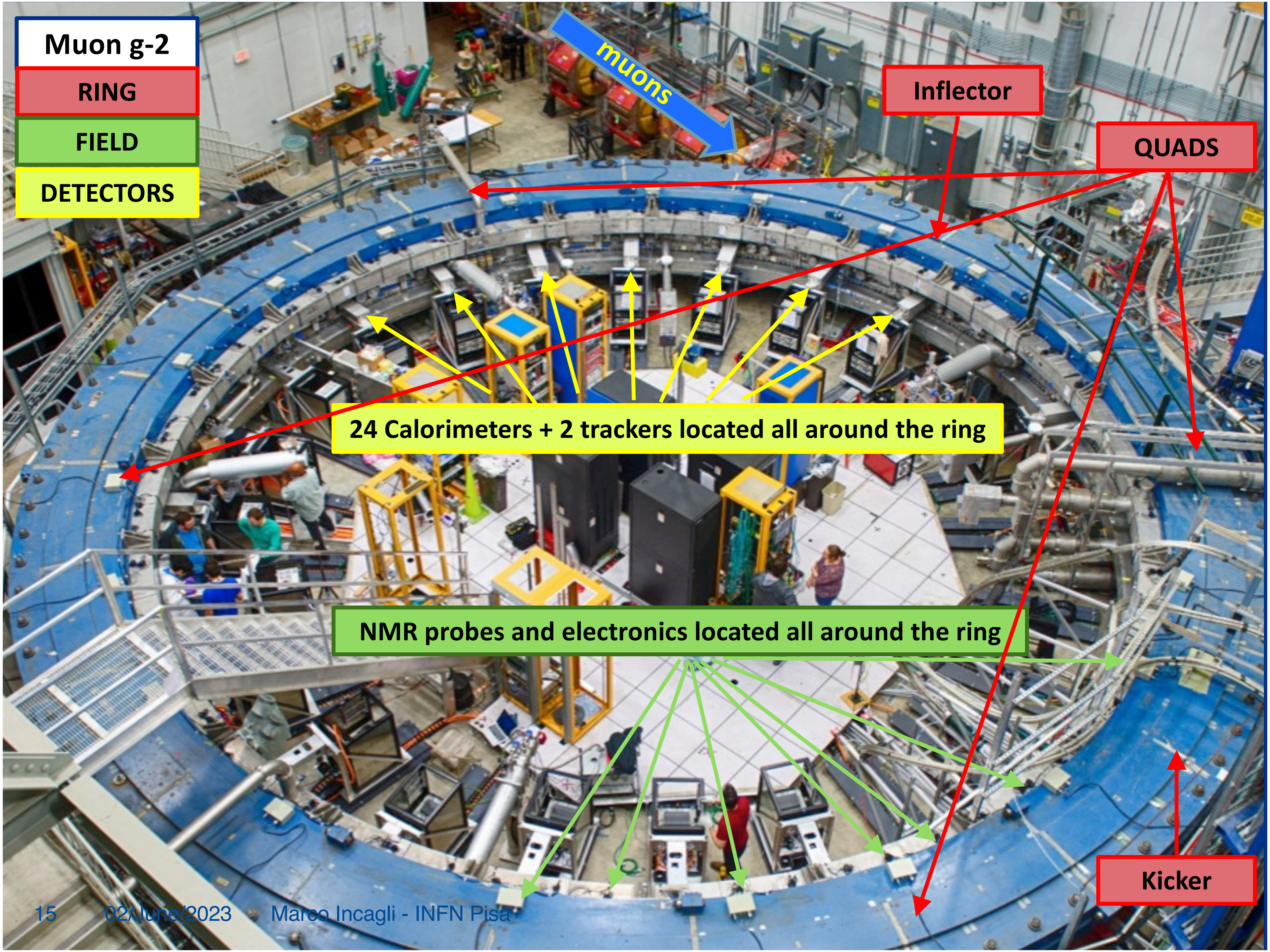
ω'_p=proton precession frequency

M=muon spatial distribution



Creating the Muon Beam for g-2:

- 8 GeV protons into the Recycler
- Target for pion production
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- pions decay in ~2km channel
- μ enter storage ring


Muon g-2
RING
FIELD
DETECTORS
muons
Inflector
QUADS
24 Calorimeters + 2 trackers located all around the ring
NMR probes and electronics located all around the ring
Kicker

Additional corrections

- The ratio R'_μ requires additional corrections related to beam dynamics and to magnetic transient fields:

$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \cdot \frac{1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{Corrections due to beam dynamics}}}{1 + \underbrace{B_k + B_q}_{\text{Corrections due to transient magnetic fields}}} \cdot f_{clock}$$

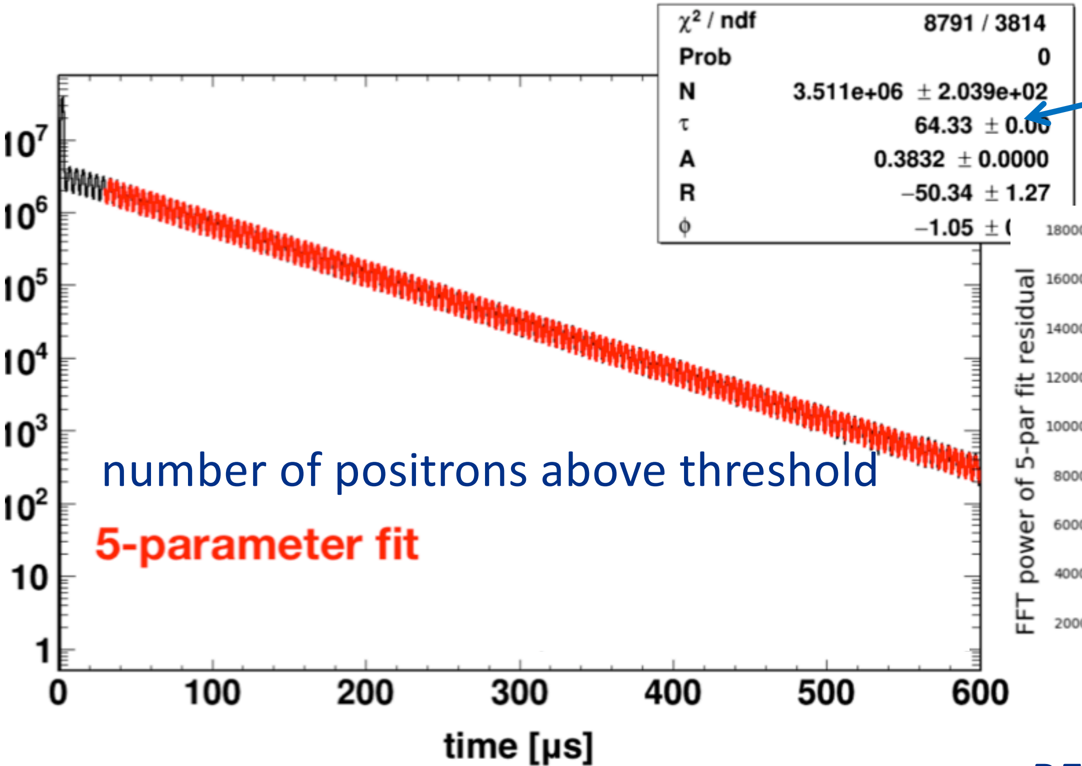
- f_{clock} = *blinding frequency* (see later)

Measuring ω_a : 5 parameters fit function

- Fit with simple positron oscillation:

$$N_e(t) = N_0 \exp\left(-t/\tau_{\mu}\right)\left[1 + A\cos(\omega_a t + \varphi)\right]$$

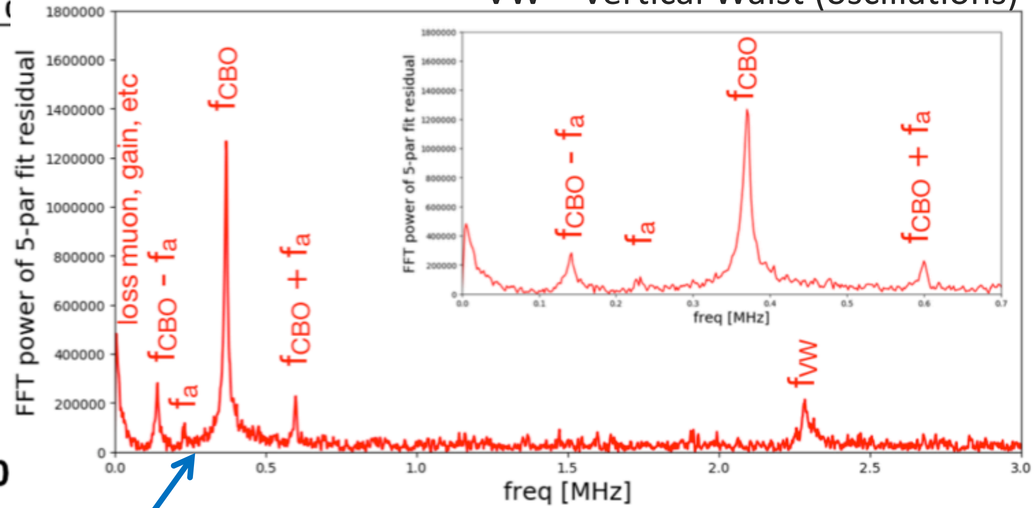
- This simple fit is clearly not sufficient and well defined resonances are observed in the residuals



muon lifetime: $\tau_\mu = \gamma\tau_{0\mu}$ = 64.33 μsec

CBO = Coherent Betatron Ocillations

VW = Vertical Waist (oscillations)



RESIDUALS (in frequency space)

The complete 22 parameters fit function

ω_y, ω_{VW} vertical oscillations
ω_{CBO}, ω_{2CBO} radial oscillations

$$\boxed{N_0\, e^{-\frac{t}{\gamma\tau}}\,(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t)))\cdot N_{\mathrm{CBO}}(t)\cdot N_{\mathrm{VW}}(t)\cdot N_y(t)\cdot N_{2\mathrm{CBO}}(t)\cdot J(t)}$$

$$A_{\mathrm{BO}}(t) = 1 + A_A \cos(\omega_{\mathrm{CBO}}(t) + \phi_A)e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$\phi_{\mathrm{BO}}(t) = 1 + A_\phi \cos(\omega_{\mathrm{CBO}}(t) + \phi_\phi)e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{CBO}}(t) = 1 + A_{\mathrm{CBO}} \cos(\omega_{\mathrm{CBO}}(t) + \phi_{\mathrm{CBO}})e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{2\mathrm{CBO}}(t) = 1 + A_{2\mathrm{CBO}} \cos(2\omega_{\mathrm{CBO}}(t) + \phi_{2\mathrm{CBO}})e^{-\frac{t}{2\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{VW}}(t) = 1 + A_{\mathrm{VW}} \cos(\omega_{\mathrm{VW}}(t)t + \phi_{\mathrm{VW}})e^{-\frac{t}{\tau_{\mathrm{VW}}}}$$

$$N_y(t) = 1 + A_y \cos(\omega_y(t)t + \phi_y)e^{-\frac{t}{\tau_y}}$$

Red = free parameters
Blue= fixed parameters

$$J(t) = 1 - k_{LM}\int_{t_0}^{t} \Lambda(t)dt$$

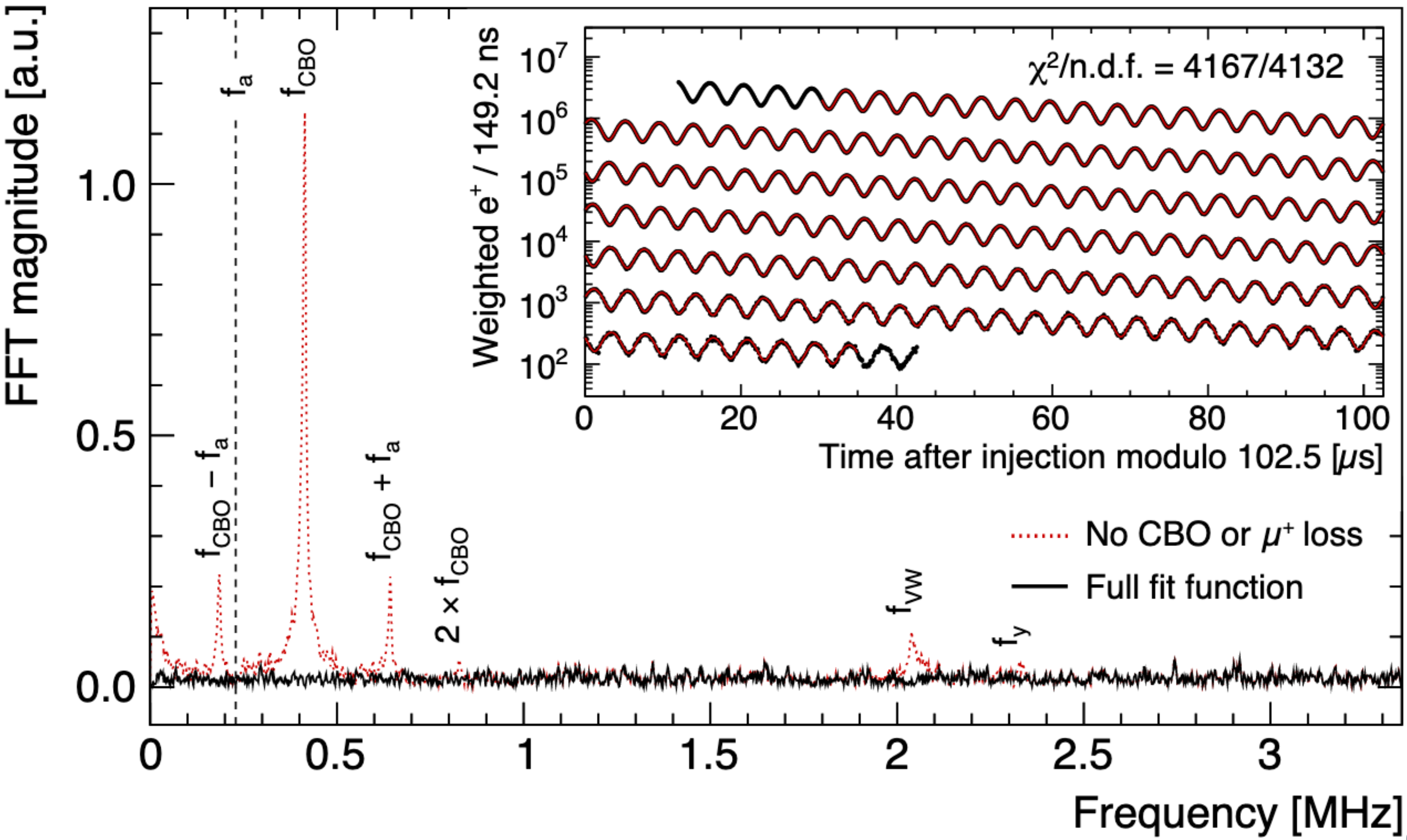
Lost muons (μ hitting collimators)

$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + Ae^{-\frac{t}{\tau_A}} + Be^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F\omega_{\mathrm{CBO}(t)}\sqrt{2\omega_c/F\omega_{\mathrm{CBO}}(t) - 1}$$

$$\omega_{\mathrm{VW}}(t) = \omega_c - 2\omega_y(t)$$

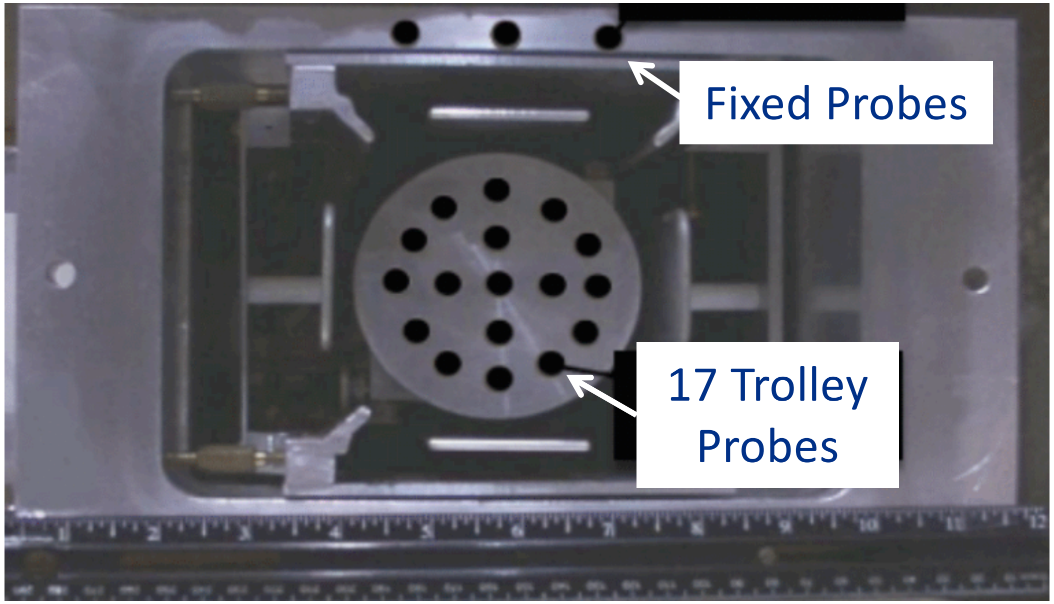
Final fit to get ω_a



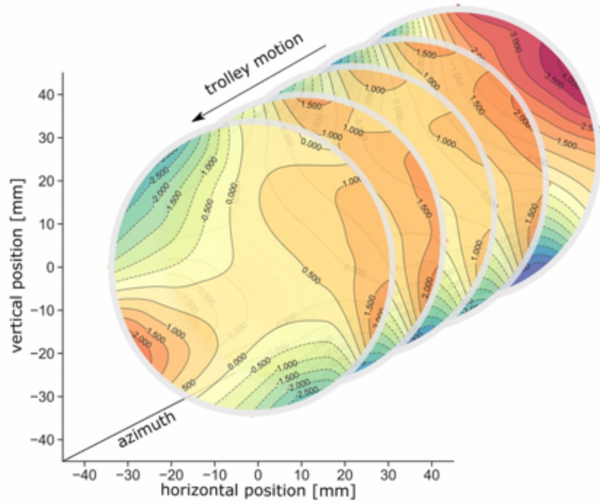
Magnetic field $\vec{B}$ determination

The “trolley”

The "trolley" inside the beam "pipe”



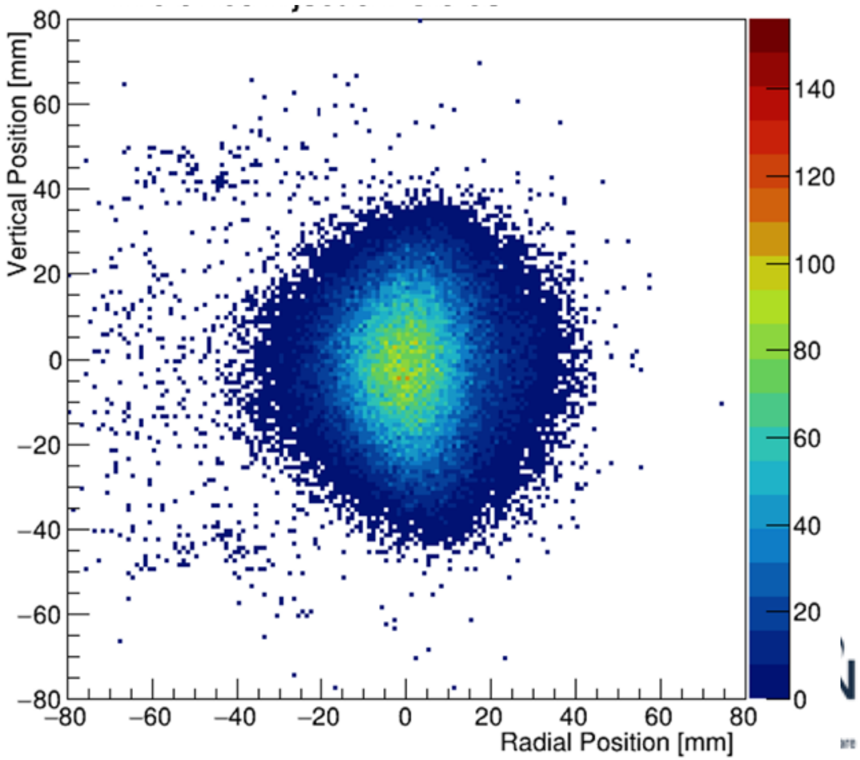
The map



- A Cylinder with 17 **NMR probes** (“trolley”) runs inside the ring every 2-3 days to map the field experienced by muons
- A set of 378 **fixed probes**, located in 72 azimuthal positions, continuosly measures the field
- Absolute probes for calibration tested at Argonne (ANL) magnet

$\omega'_p \to \tilde{\omega}'_p$: muon distribution inside the Ring

- Two tracker stations, made of straw tube modules, placed at $\phi \sim 180^o$ and $\phi \sim 270^o$, are used to trace back positrons and get the muon distribution
- Use Beam Dynamics models to extrapolate the distribution all around the ring
- Systematic uncertainties mostly due to Beam Dynamics models used for extrapolation and to tracker alignment



The blinding

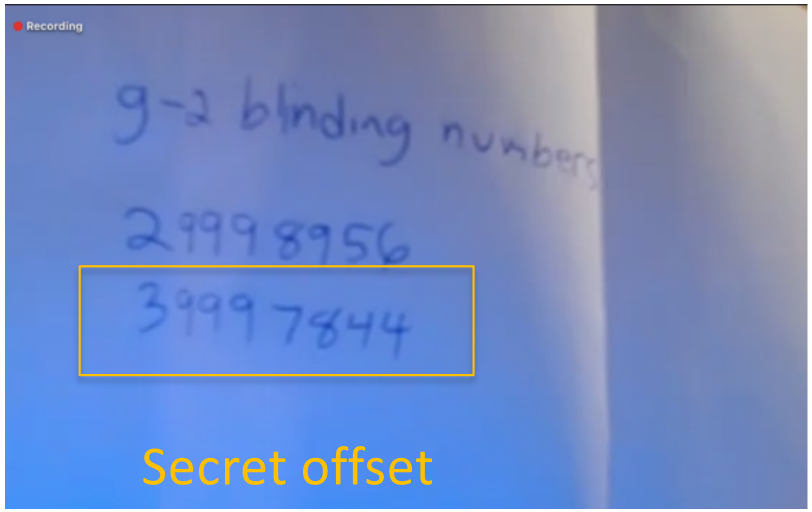
$$R'_\mu = \boxed{f_{clock}} \cdot \frac{\omega_a}{\tilde{\omega}'_p} \cdot \frac{1 + C_e + C_p + C_{ml} + C_{pa}}{1 + B_k + B_q}$$

- Clock frequency f_{clock} uncalibrated by Joe Lykken and Greg Bock (FNAL Directorate) Feb 22 2018
  - stop in each week to check clock and sealing
- Secret envelopes kept until physics analysis complete and ready to be revealed Feb 25 2021

a_μ: Unblinding

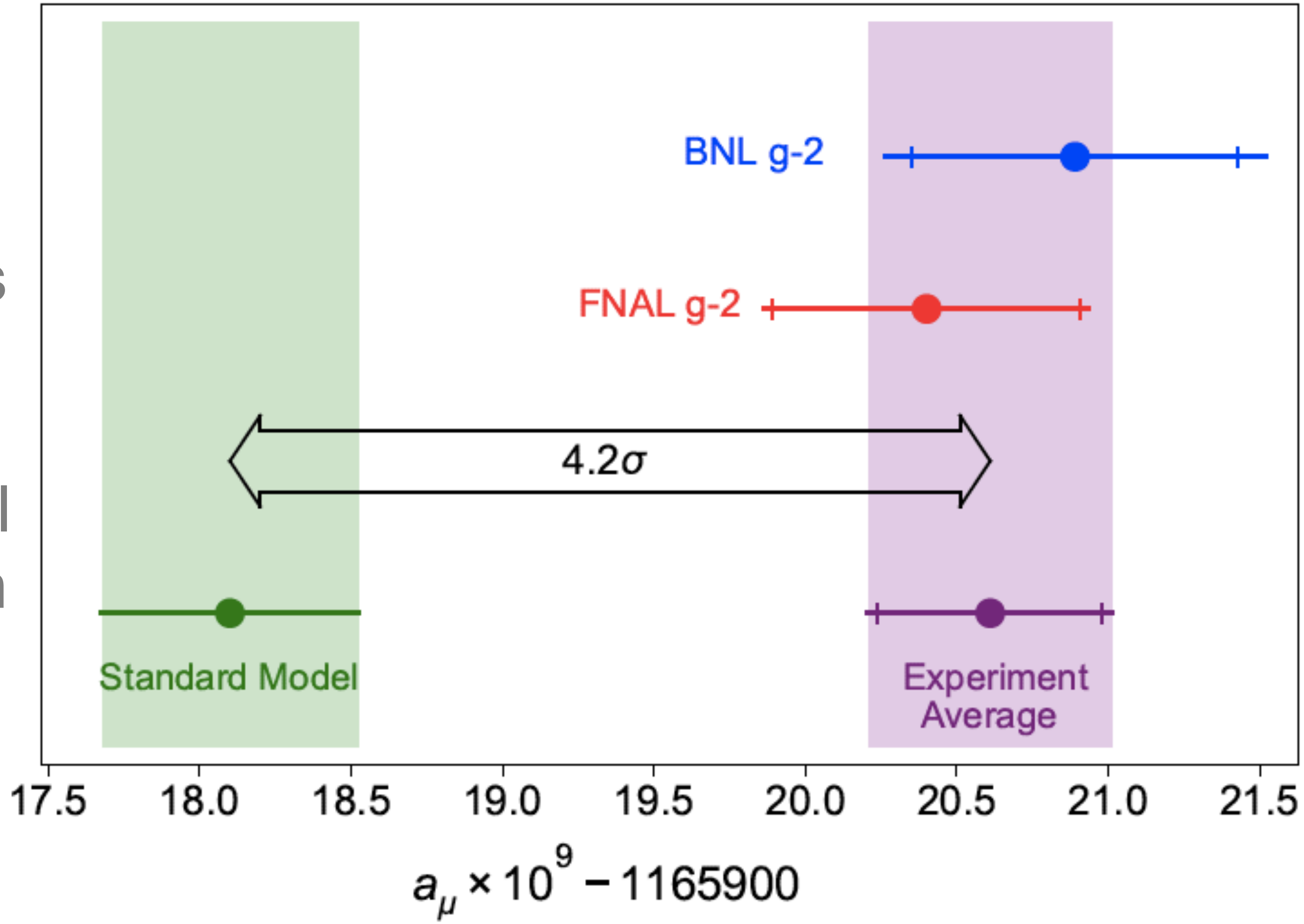
On February 25 2021 the Collaboration met for the unblinding:

1) The *box* (envelope) was opened
2) The number was plugged into two independent programs
3) And the result was….



a_μ: Unblinding and result

- ***462 ppb total uncertainty***
- The combined a_μ value shows a 4.2σ tension with the standard model 2020 prediction *in the* **Theory Initiative Group White Paper**



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Final uncertainties from Run 1

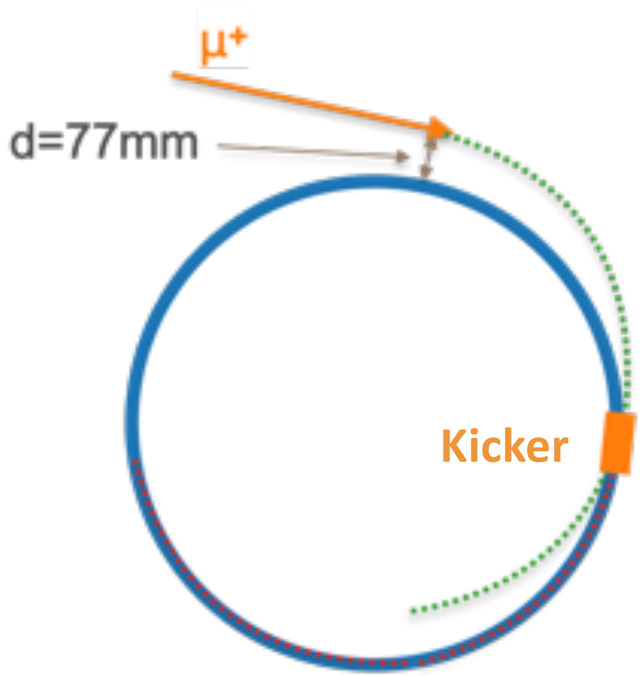
Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\mathrm{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

Largest corrections and systematics:

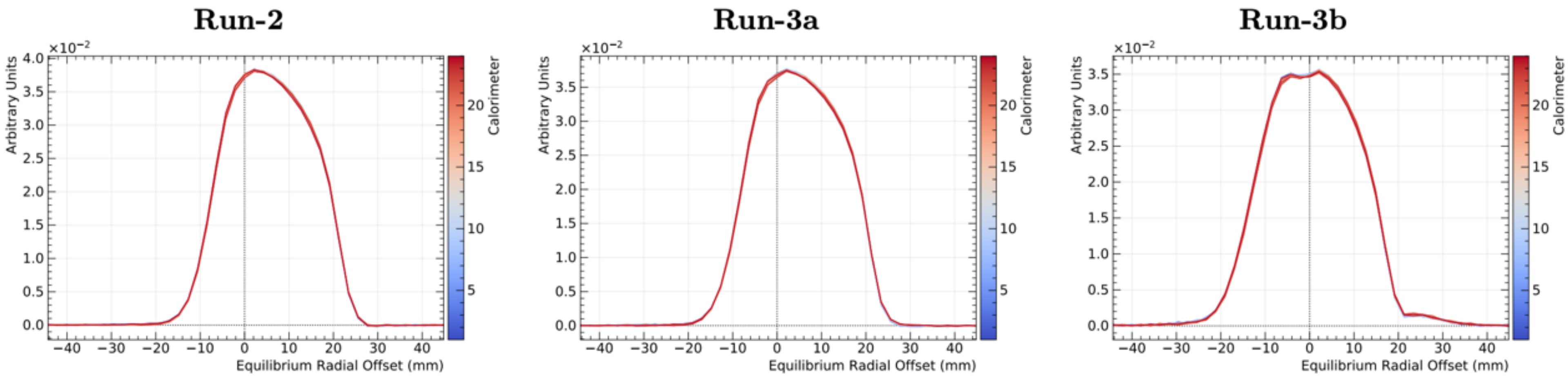
- correction due to beam not perfectly centered in Run 1 → modified kicker field
- *transient fields:* large currents are produced in the quadrupole and kicker plates → *ad hoc* campaigns to reduce the error budget

Final Run1 uncertainty = ±462 ppb

Major post Run 1 improvements – kicker strength

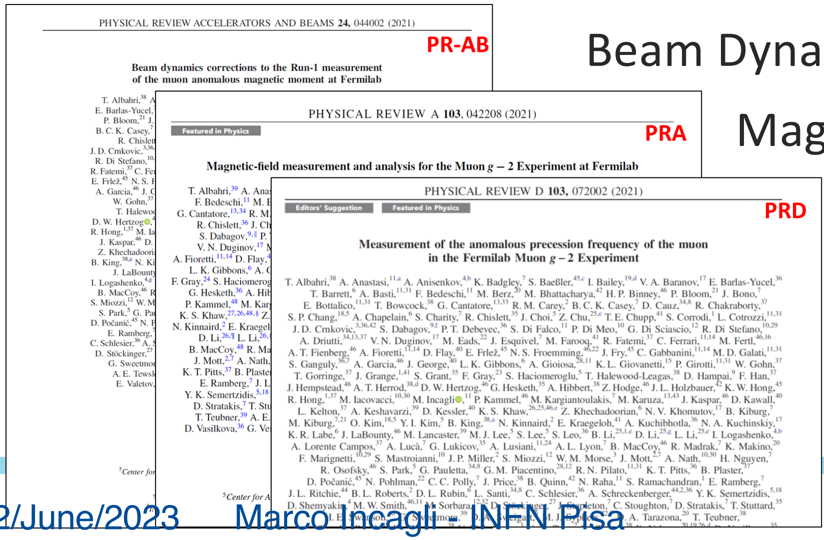


- R1: Kickers did not center beam
- Negative impacts
  - Larger CBO amplitude
  - Muons live in less uniform B field
  - Off-center → off-momentum → large E-field corrections
- Major upgrade campaign completed by end of Run 3



Toward the Run-2/3 Release …

1. It's a lot of data, taken in 2019 and 2020 …until the Covid shutdown → current release date August/September 2023
2. Many improvements leading to final "ideal" conditions only in Run 3b (Feb. 2020)
   1. Muon kicker gradually upgraded to center beam & minimize CBO amplitudes (previous slide)
   2. Ring and Hall temp stabilized; significant for magnet and detector stability
   3. ... many other small (and not so small) improvements


PHYSICAL REVIEW ACCELERATORS AND BEAMS 24, 044002 (2021)

PR-AB

Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

PHYSICAL REVIEW A 103, 042208 (2021)

PRA

Magnetic-field measurement and analysis for the Muon $g-2$ Experiment at Fermilab

PHYSICAL REVIEW D 103, 072002 (2021)

PRD

Measurement of the anomalous precession frequency of the muon in the Fermilab Muon $g-2$ Experiment

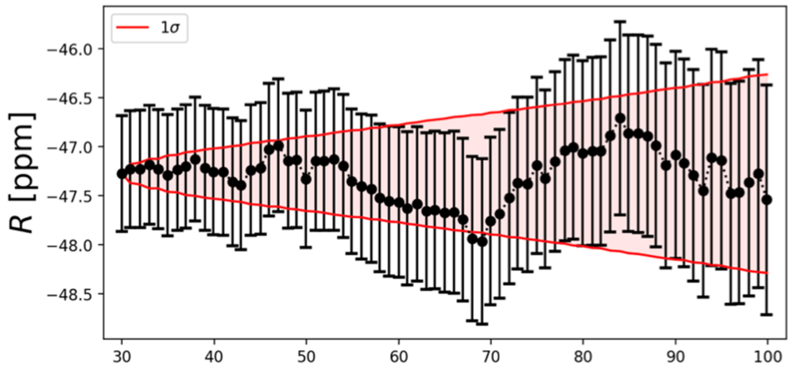
Beam Dynamics Corrections

Magnetic Field Status

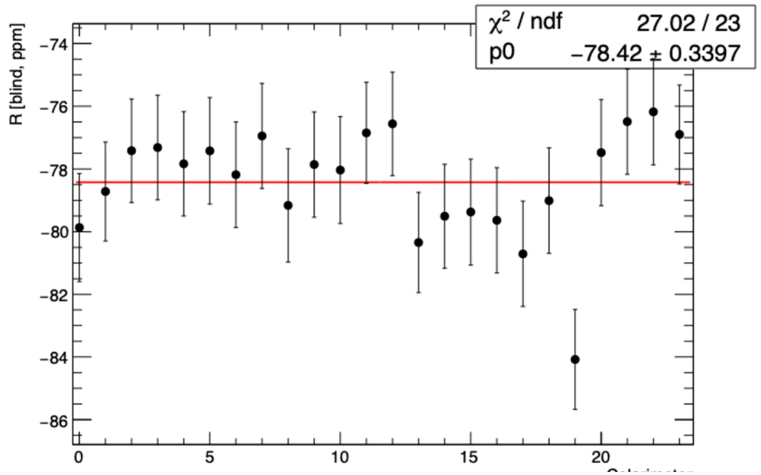
Muon Precession Frequency Status

Ancillary papers published for Run1 (on top of main article on Phys. Lett.)

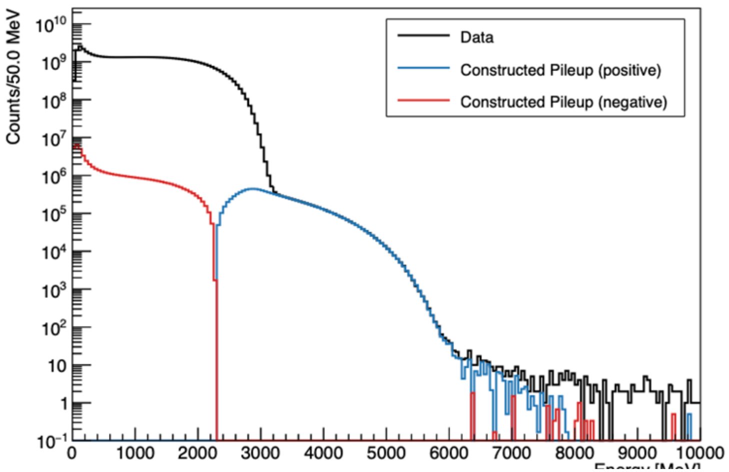
Overall message: Results are consistent and are supported by many quality control checks



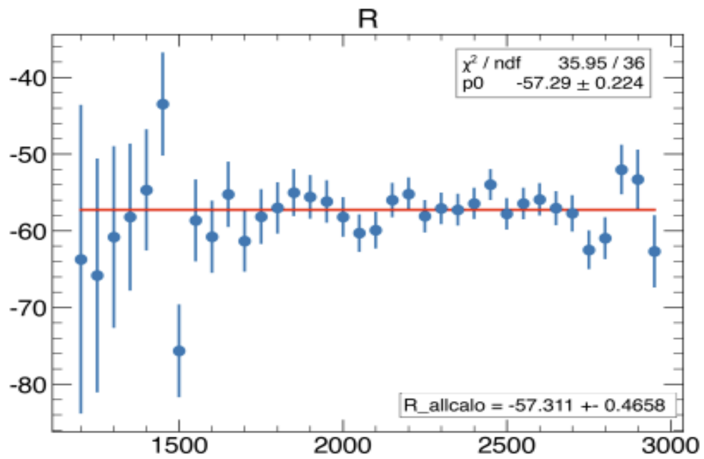
ω_a vs Start of Fit in Fill



ω_a vs Calorimeter



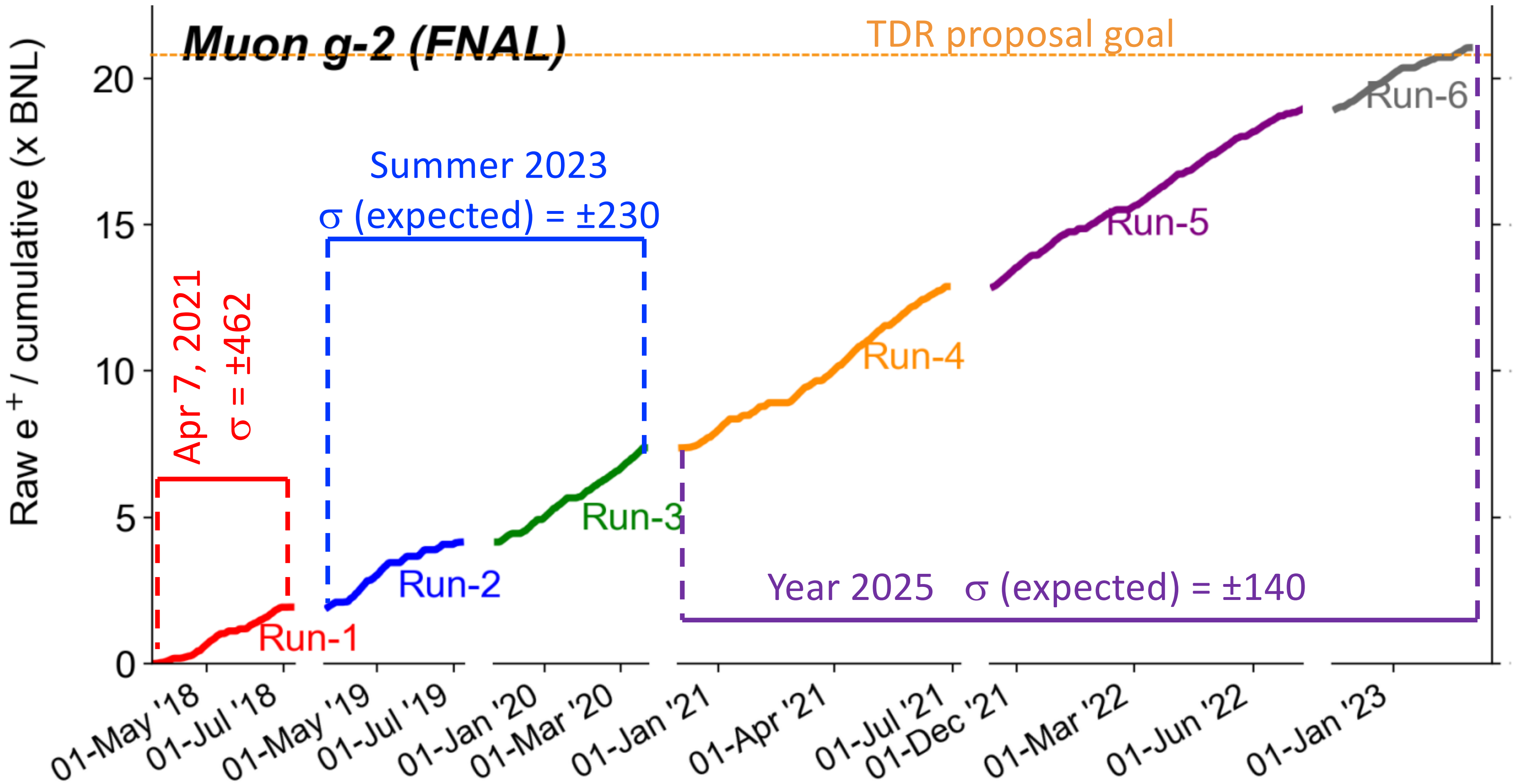
Raw Energy spectrum: Pileup Correction



ω_a vs Energy Bin

Etc, millions more…

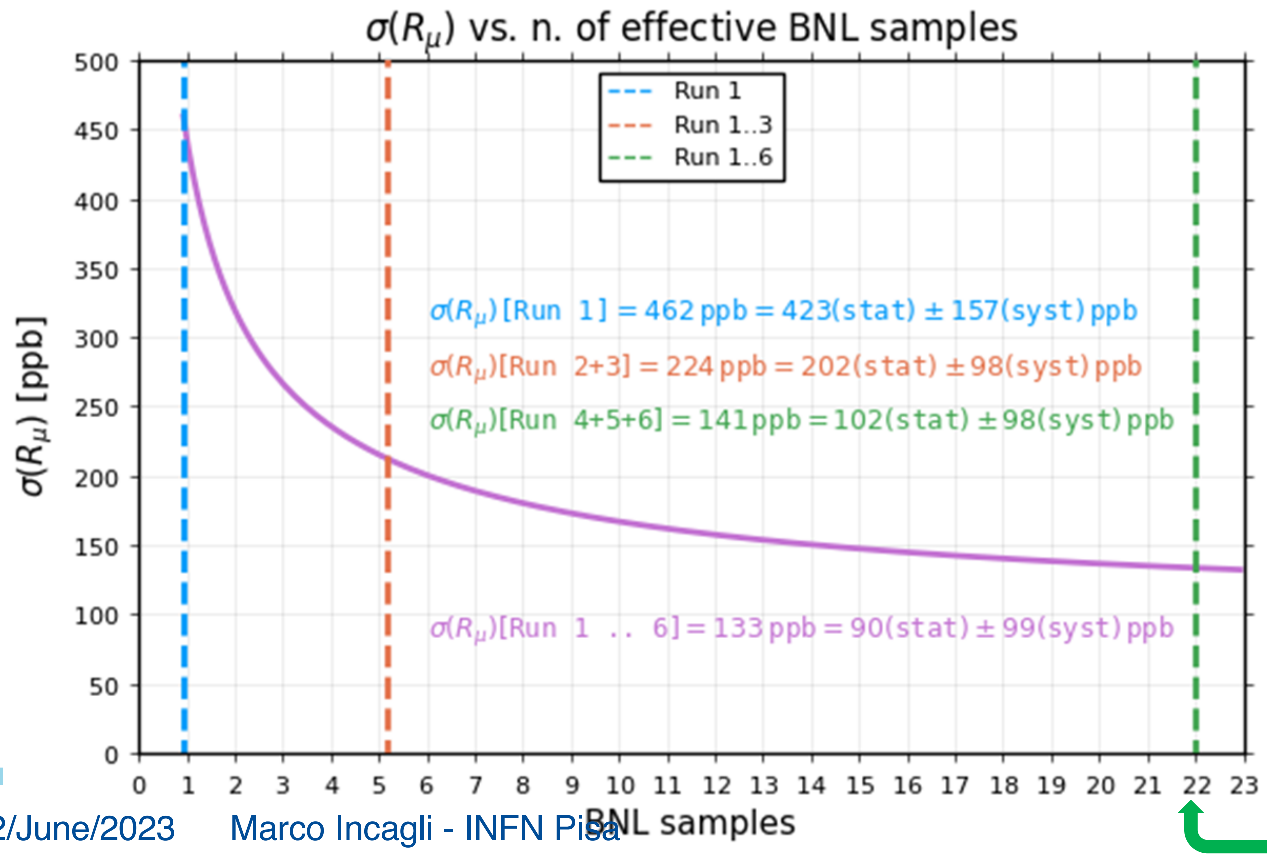
Data collected met proposal goals … “21 BNLs”



(each publication will include the average with previous runs)

Original Goals and Where we are trending

- TDR (2012) goal: δa_μ = 140 ppb (maybe slightly less)
  - Statistics 100 ppb (probably ok)
  - Precession systematics 70 ppb (maybe slightly less)
  - Field systematics 70 ppb (maybe slighbtly less)
  - Not thought of then 0 ppb (... maybe slightly more!)

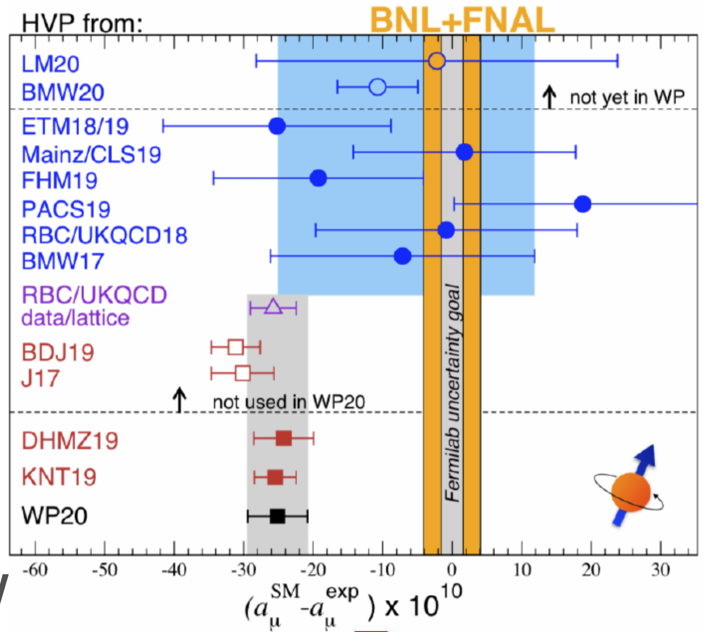


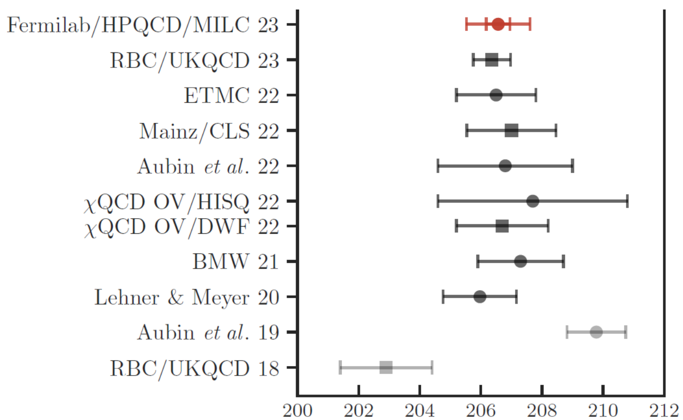
~133 ppb?

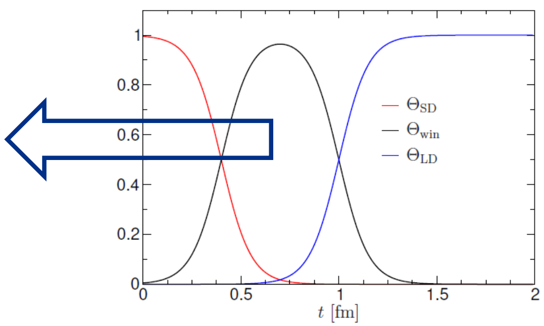
We are here now

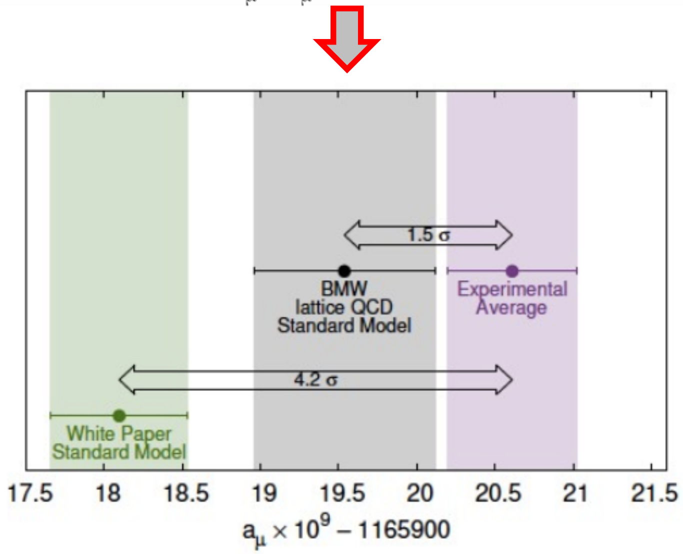
And now back to SM: is lattice the most precise HVP method?

- Not yet included in the Theory Initiative recommendation.
- The 2021 BMW HVP publication is an impressive, sub-percent calculation.
- Since then, lattice groups trying to find common values to compare
- Step 1: "Intermediate" Euclidian Window









Looks consistent

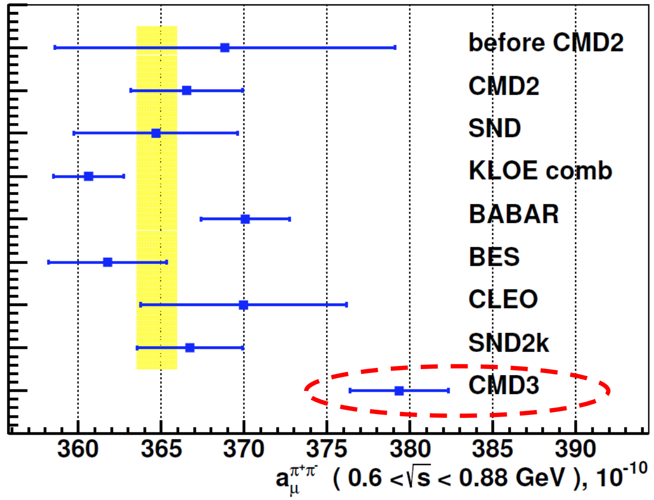
Now back to the SM ...

- The CMD-3 "February Surprise" [F. Ignatov et al, arXiv:2302.08834]

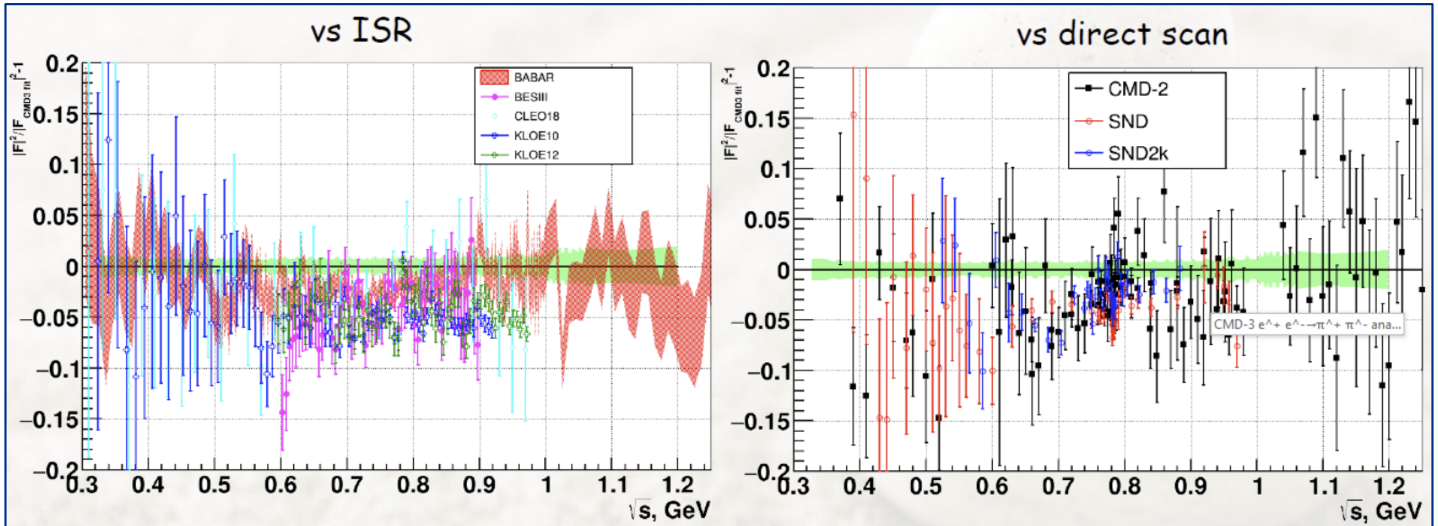
  $e^+e^- \rightarrow \pi^+\pi^-$ disagrees with all other results by many σ!
  - What might they have wrong?
  - How rigorously were results vetted?
  - Did older exeriments miss something big and common?

  After lengthy seminar/panel discussion, nothing is obviosly wrong on new or old results and methods

  This is a big PUZZLE that must get resolved, …



$\boldsymbol{\sigma(e^+e^- \rightarrow \pi^+\pi^-)}$
fractional difference
CMD-3 vs older exps



Hadronic cross section

- Is it possible that old experiments made a mistake in $\sigma^{had}(s)$ of $e^+e^- \rightarrow hadrons$ channels?
- Yes (e.g.: experimental cuts) but
  - many different experiments should have same bias
  - an upward shift in $\sigma^{had}(s)$ induces an increase of $\Delta\alpha^{had}(M_Z)$

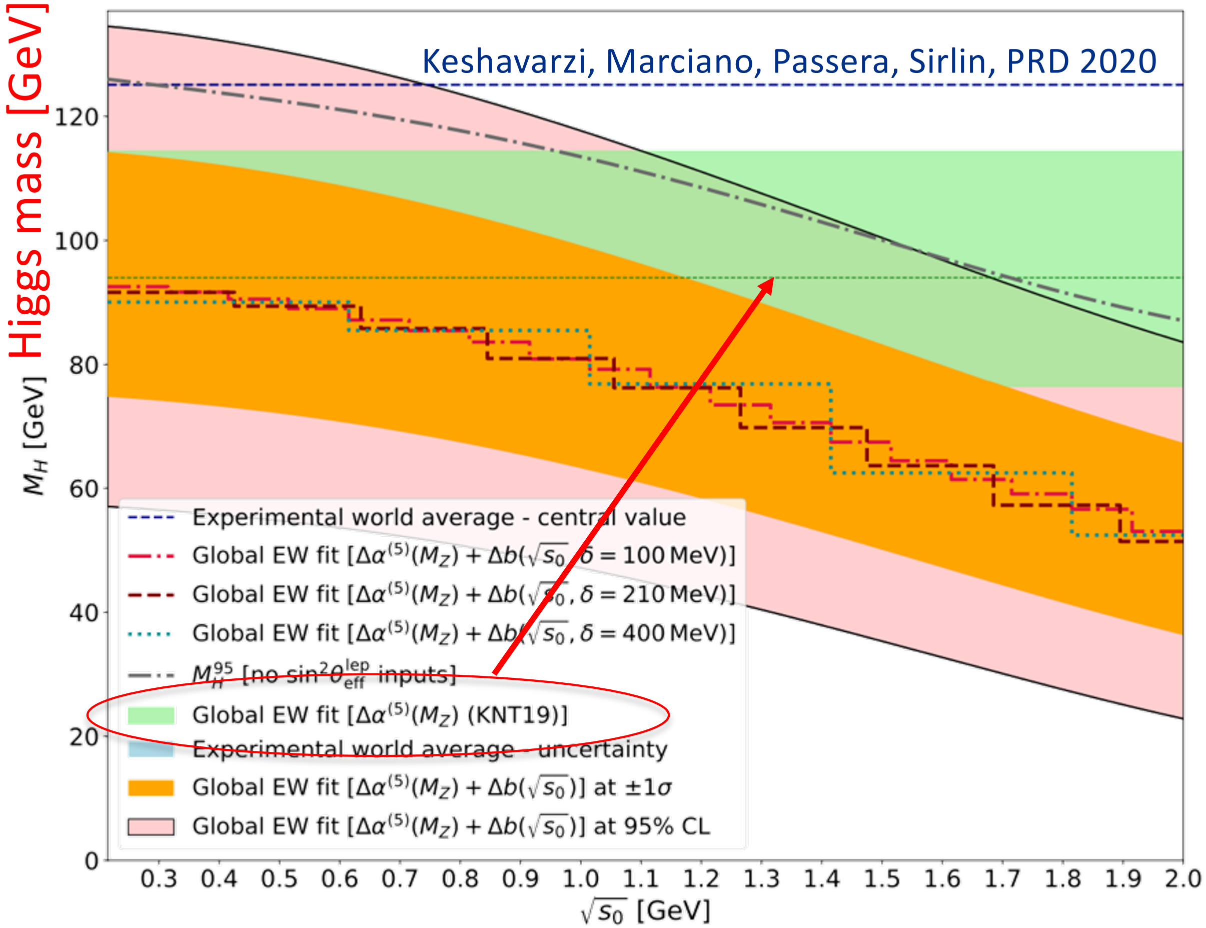
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} K(s)\sigma^{had}(s)ds \;\; ; \;\; with \;\; K(s) \propto \frac{1}{s}$$

$$\Delta\alpha^{had} = \int_{m_\pi^2}^{\infty} g(s)\sigma^{had}(s)ds \;\; ; \;\; with \;\; g(s) \propto \frac{M_Z^2}{M_Z^2 - s}$$

- Similar dispersion integral with a different kernel function

Hadronic cross section and fine structure constant

- An upward shift in the hadronic cross section to move the theoretical prediction towards the lattice one, or towards the exp. value, also “pulls down” the preferred Higgs Mass value in the global electroweak fit (green band)



The experimental landscape will improve …

Ongoing work in experimental inputs on *hadronic cross section*

- BaBar: new analysis of large $\pi\pi$ data set with better detector
- KLOE: new analysis of 7x larger $\pi\pi$ set
- SND: new results for $\pi\pi$ channel
- BESIII: new results for $\pi\pi$ channel and $\pi\pi\pi$
- Belle II: promising greater statistics than BaBar or KLOE and similar or better systematics for low-energy cross sections

If the differences between experiments are resolved:
data-driven evaluations of HVP with $\sim 0.3\,\%$ feasible by ~2025

See Aida El-Khadra's P5 presentation, March 2024 for lots of details on the g-2 Theory Initiative and the recent lattice efforts related to HVP

… and, then ?

- We are all excited to see the next next g-2 result with ~½ and the final with ~¼ the current uncertainty
- JParc g-2 experiment building up: less precision then Fermilab g-2, but different systematic effects
- But, to what SM value can we compare it to this time?

  A) The “recommended” 2020 Theory Initiative value remains a standard

  B) But the situation is dynamic and could greatly change

    - The CMD-3 result is a true outlier right now, but that does not imply it is wrong. Fortunately a lot of new data is being analyzed so we have a “wait and see” situation
    - new full lattice calculations expected
- “Discovery” takes time.
  - We do not know the final implications of our measurements of g-2.
  - We can only control the quality of the effort and analysis.

Clearly there is something going on there.

Our task: reduce as much as possible the experimental uncertainty on *g-2* !

Why muons and not electrons?

- electron magnetic anomaly known at the ppt level!
- ... but
- a possible new interaction mediated by a *Z-like* vector boson is favoured in the muon channel by a factor

$$\left(\frac{m_\mu}{m_e}\right)^2 \sim 4 \cdot 10^4$$

- due to helicity (quasi) conservation

- → muons have a higher potential in New Physics discovery