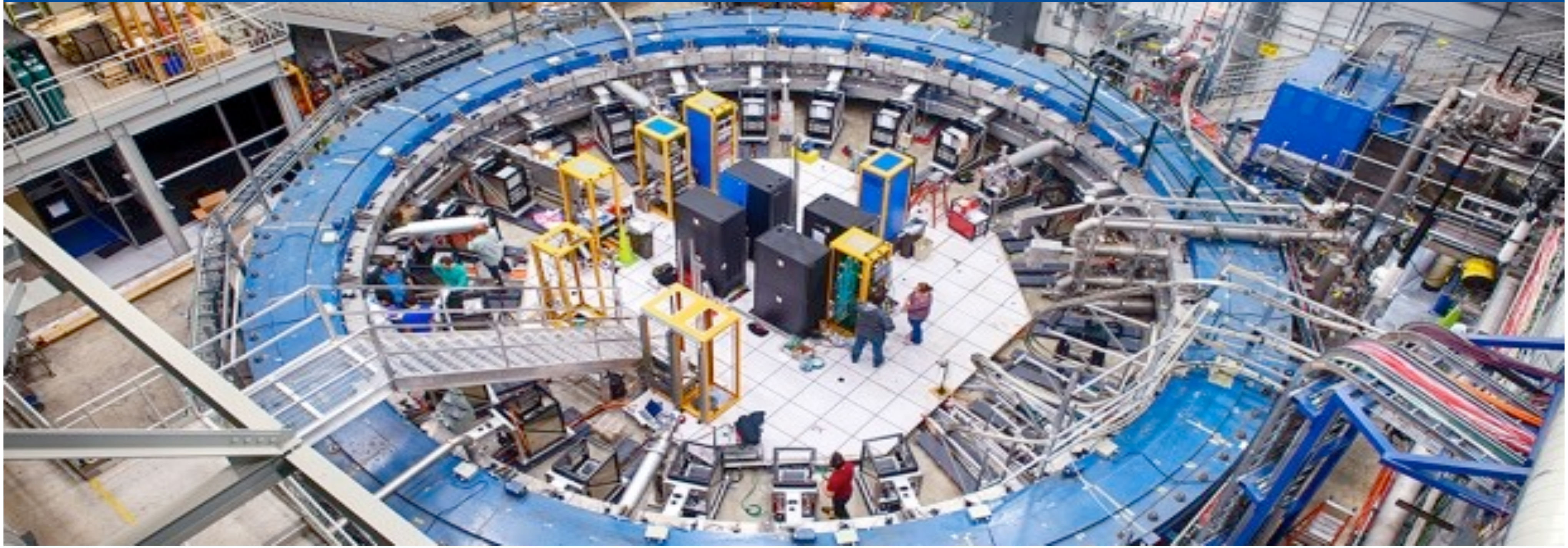


Measuring the muon magnetic anomaly a_μ with the *Muon g-2* experiment at Fermilab

INFN Pisa Seminar – 14 April 2021

Marco Incagli – INFN Pisa

What is "*g-2*"?

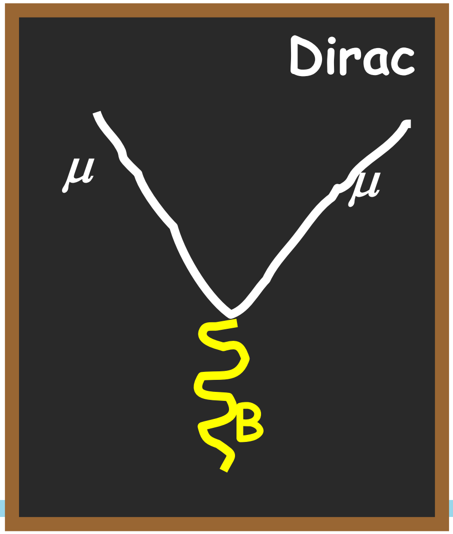
$$\vec{\mu}_p = -g_p \frac{e}{2m_p}\vec{S}$$

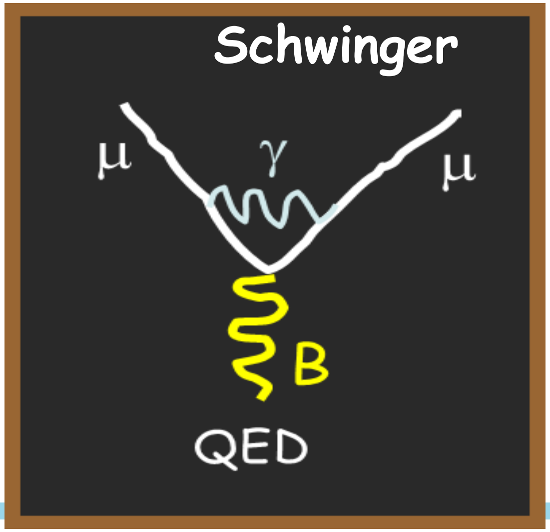
$$a_p = \frac{g_p - 2}{2}$$

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

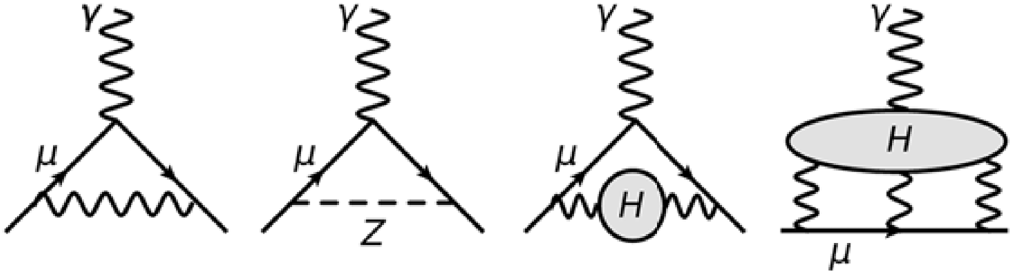
- The term (g-2)/2 reflects the magnitude of the Feynmann diagrams beyond leading order

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





Contributions to a_μ



+ ?

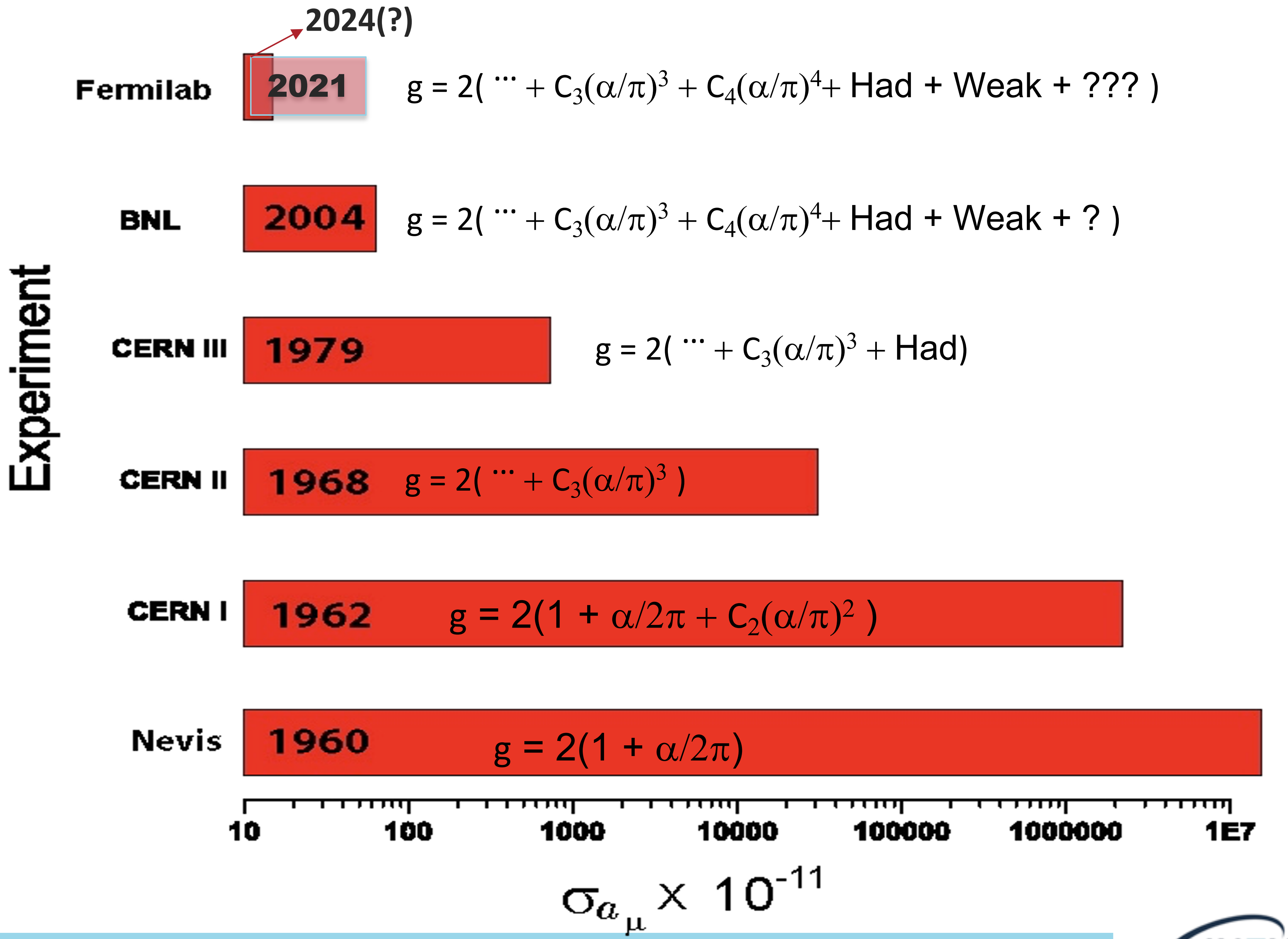
QED	Weak	HLO	HLbL	New Physics.
Known	Known	Data	Models/Lattice	?

HLbL = Hadronic Light by Light = Hadronic higher order

	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	$11\,659\,181.7 \pm 4.2$

686 ppt !!!

Theory initiative (June 2020) 11659181.0 ± 4.3 → 370 ppb



$g = 2(\cdots + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + \text{Had} + \text{Weak} + ???)$

$g = 2(\cdots + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + \text{Had} + \text{Weak} + ?)$

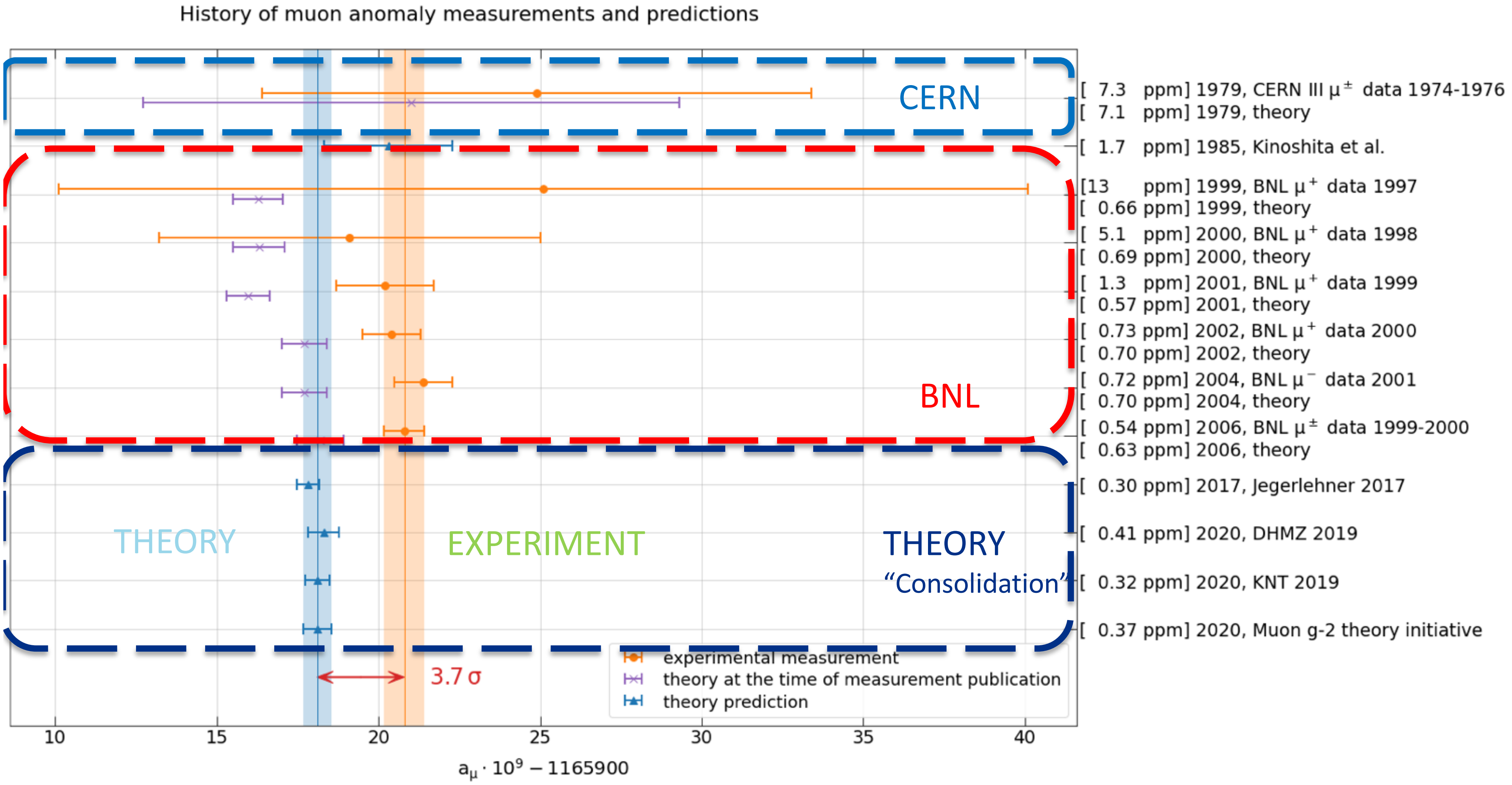
$g = 2(\cdots + C_3(\alpha/\pi)^3 + \text{Had})$

$g = 2(\cdots + C_3(\alpha/\pi)^3)$

$g = 2(1 + \alpha/2\pi + C_2(\alpha/\pi)^2)$

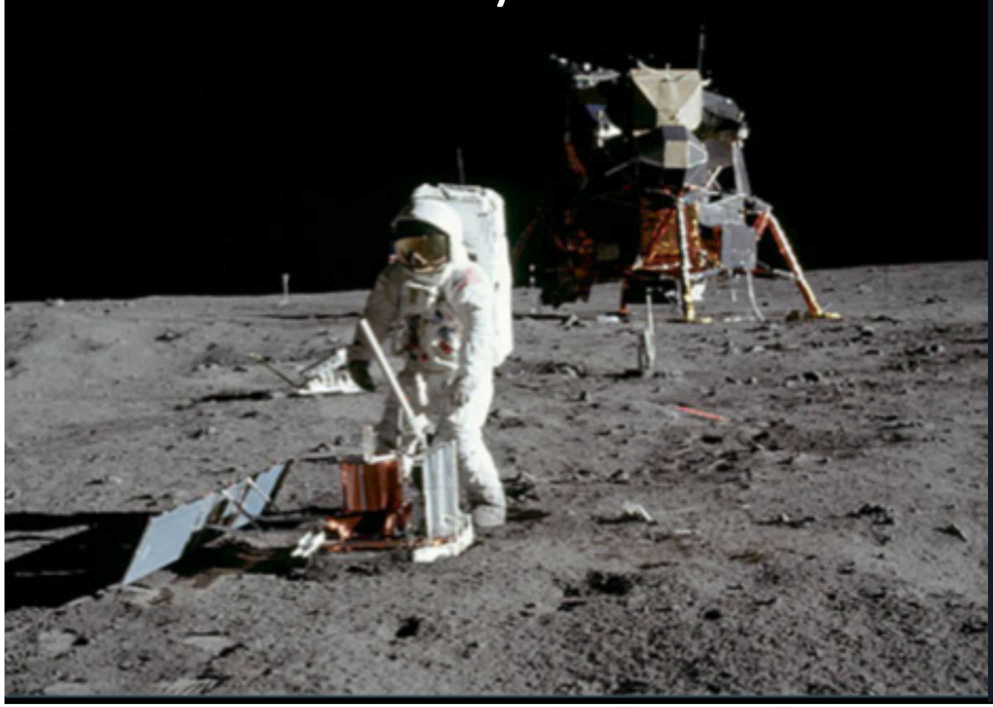
$g = 2(1 + \alpha/2\pi)$

A rich history of g-2 Theory and measurements

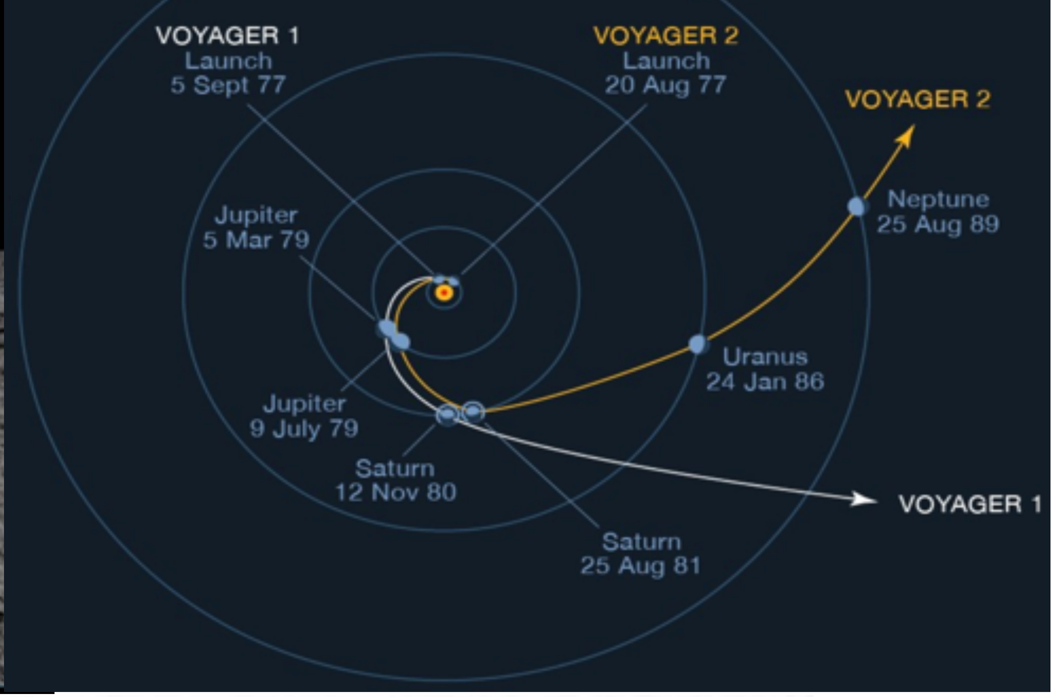


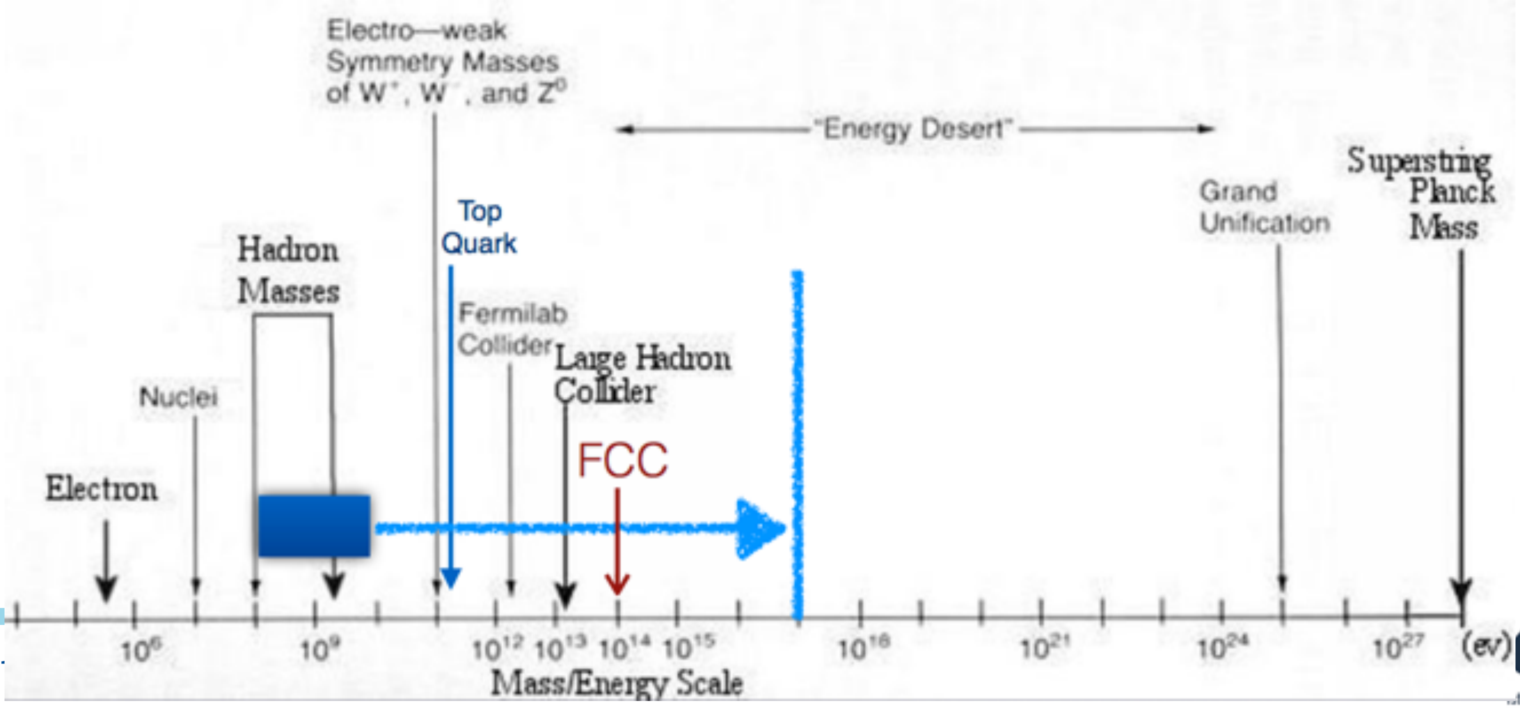
Tension between theory and experiment

HIGH ENERGY: systematic search



HIGH PRECISION: launching probes





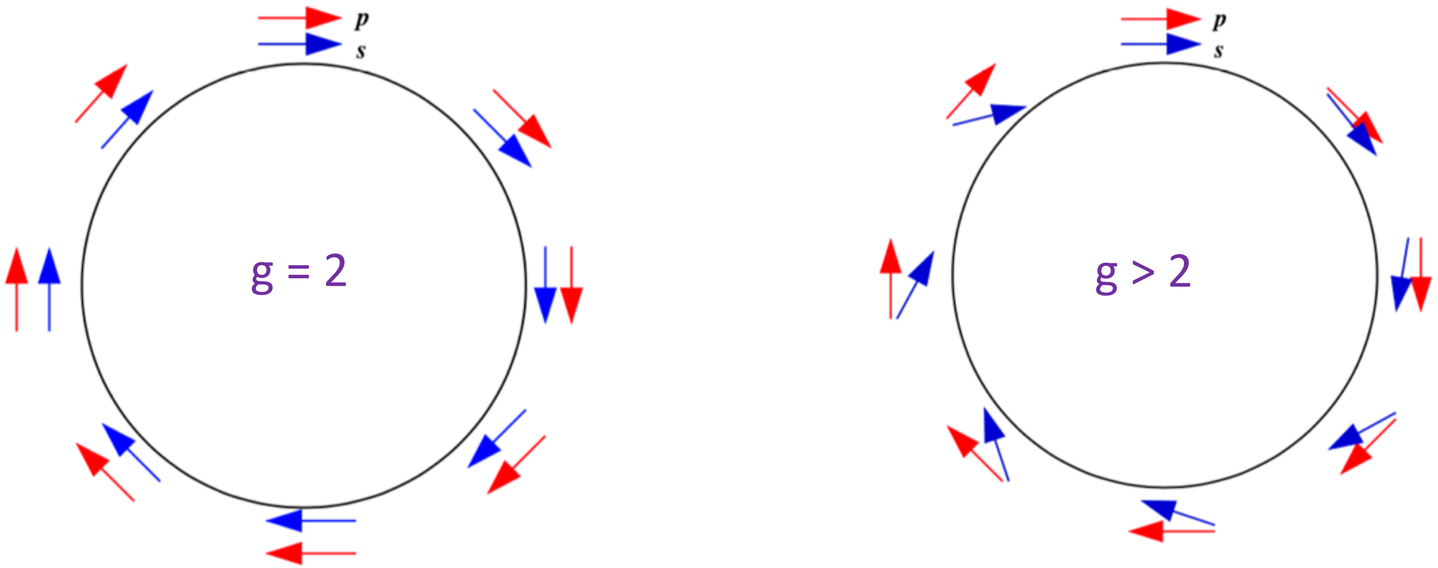
The Fundamental Experimental Principle

- 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 particle to beam

- It is not possible to follow the spin of a single muon, we can only have an *information of the spin direction when the muon is produced and when it decays* (see next slide)
- Need a **beam of muons** →
  - focusing elements: using *electrostatic quadrupoles*
  - betatron oscillations around ideal trajectory
- Additional terms in the muon precession complex

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

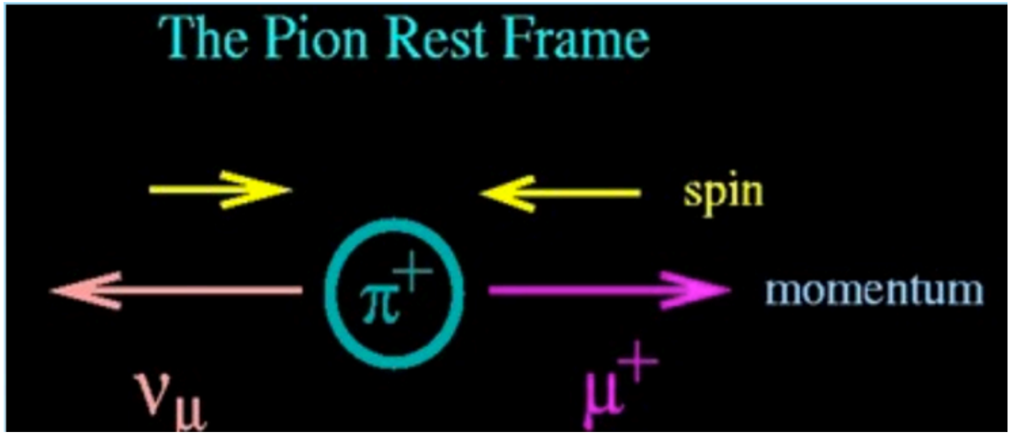
Term due to ElectroStatic Quadrupoles (ESQ)

Term due to beam vertical oscillations: pitch correction

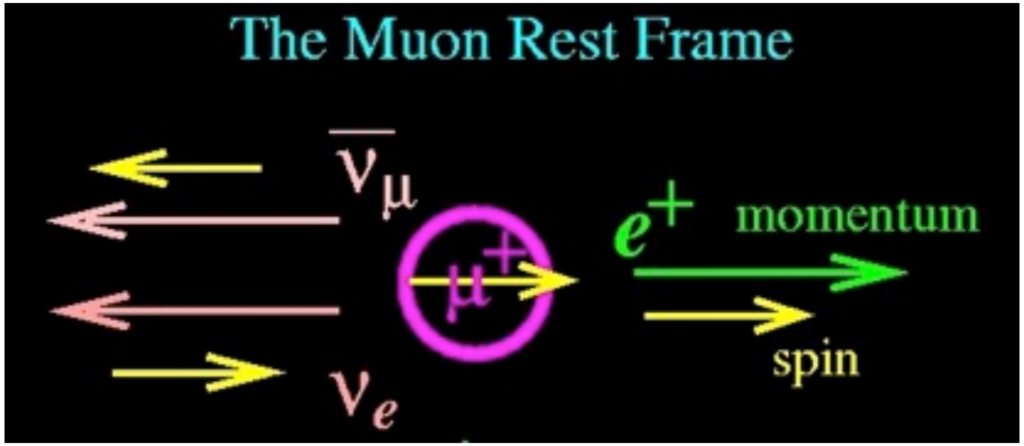
Becomes ~ 0 at “magic γ”~ 29.3
or $p \sim 3.1$ GeV/c

How do we measure the spin direction?

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



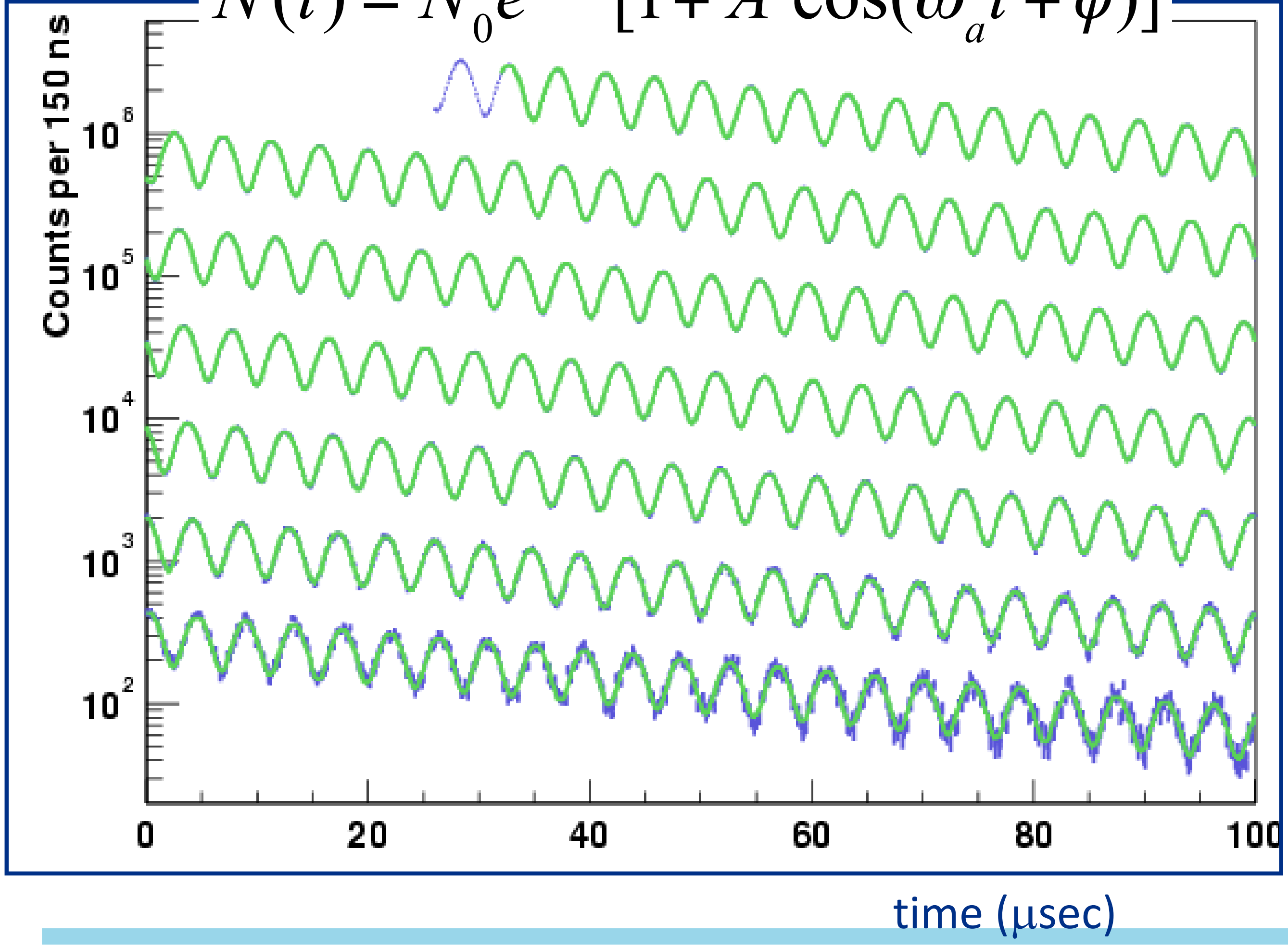
- ... and to measure the muon polarization looking for energetic positrons



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 → ~11 muon lifetimes*

Extracting a_μ(simplified)

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

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 (precise) data

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

ratio of muon to proton precession in the same magnetic dipole field

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

Extracting a_μ(more precise) left as reference

$$\frac{\mu_e(H)}{\mu'_p(T)}$$

Measured to 10.5 ppb accuracy at *reference temp.* $\boldsymbol{T_r = 34.7^oC}$

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)

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

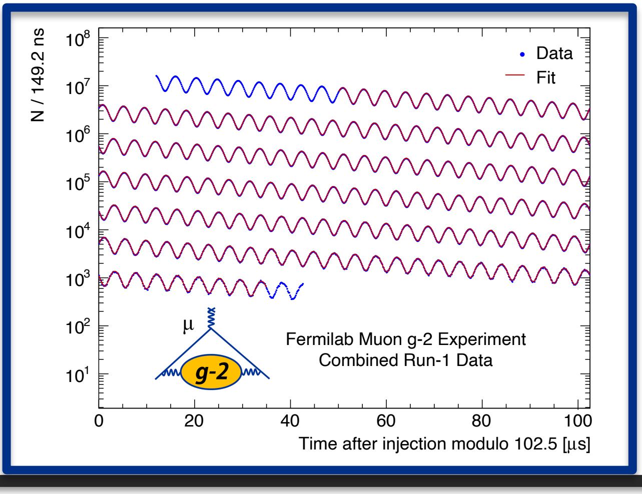
Total uncertainty of 25 ppb

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

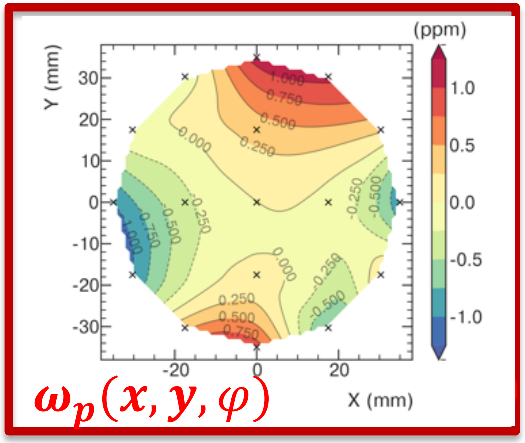
The key ingredients

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

ω_a

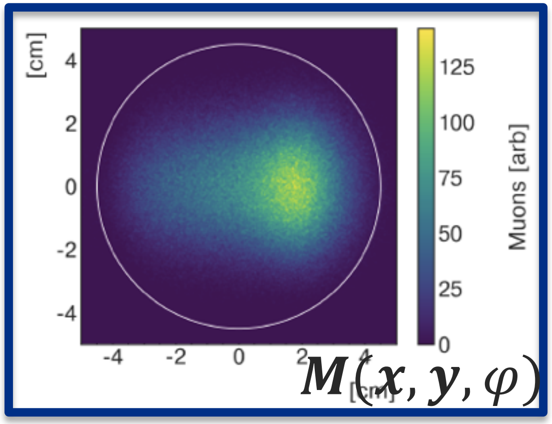


$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \sim$$



$\omega_p(x,y,\varphi)$

•



$M(x,y,\varphi)$

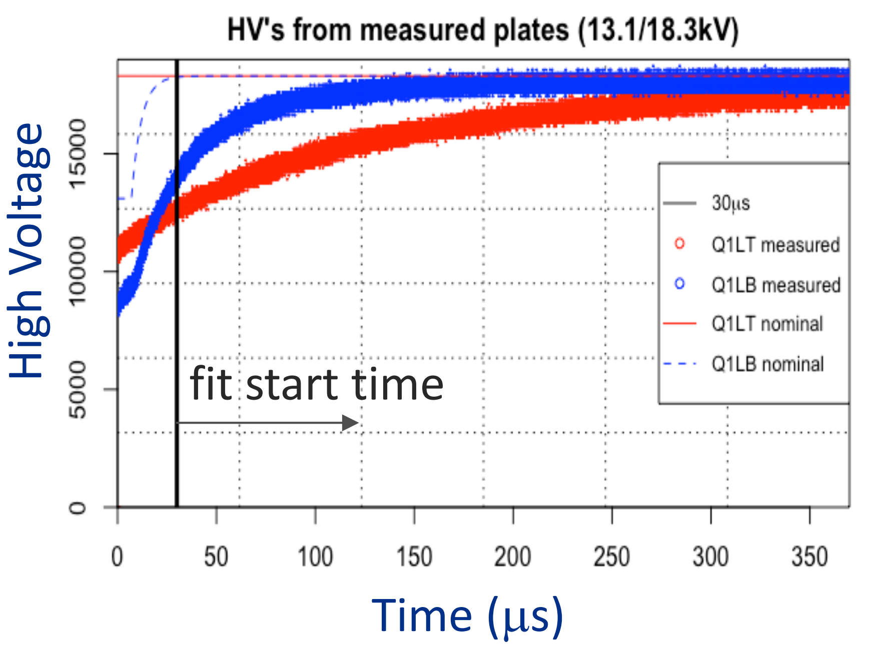
$$\tilde{\omega}_p{}' = \omega_p'(x,y,\varphi) \cdot M(x,y,\varphi)$$

ω_p=proton precession frequency

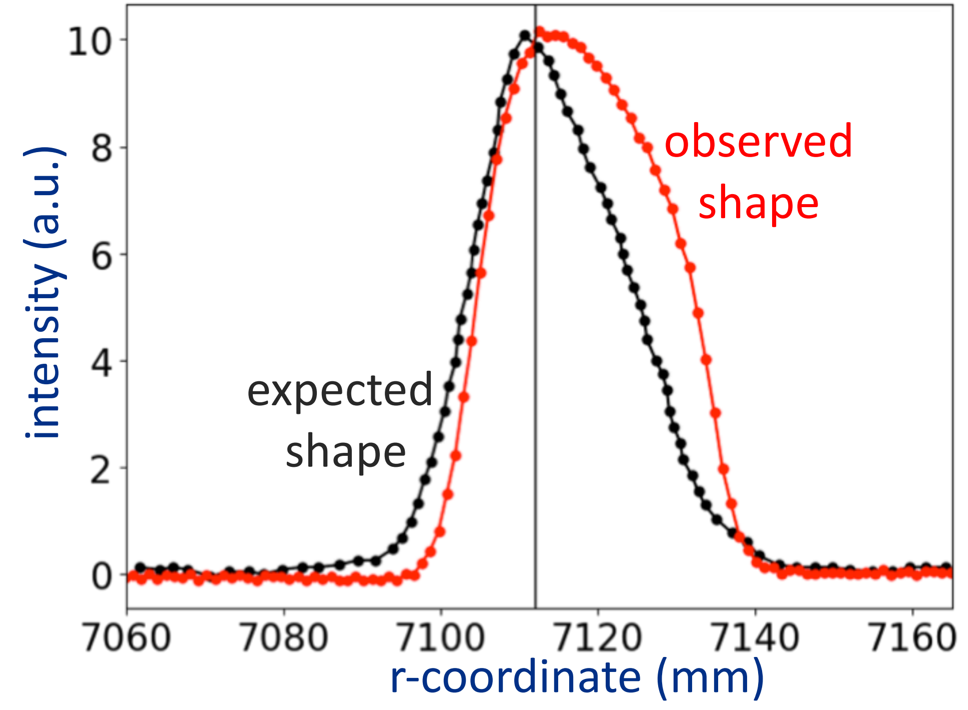
M=muon spatial distribution

Problems related to Storage Ring in Run1

- Two main problems observed in Run-1, fixed in Run-2:
  - bad resistors (QUADRUPOLES)
  - low current (KICKER)



Two resistors providing HV to the vertical plates of a QUADRUPOLE had a slow recovery time
The beam slowly moved vertically during fill.



Beam radial profile: ring acceptance Δp = ±0.5%
Asymmetry due to not perfect KICK

Additional (important) corrections

- On top of the *key ingredients* additional corrections due to beam dynamics and transient fields have to be included

$$R'_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{Corrections due to beam dynamics}})}{f_{calib} \cdot \omega'_p\,(x, y, \varphi) \cdot M(x, y, \varphi) \cdot (1 + \underbrace{B_k + B_q}_{\text{Corrections due to transient magnetic fields}})} \right)$$

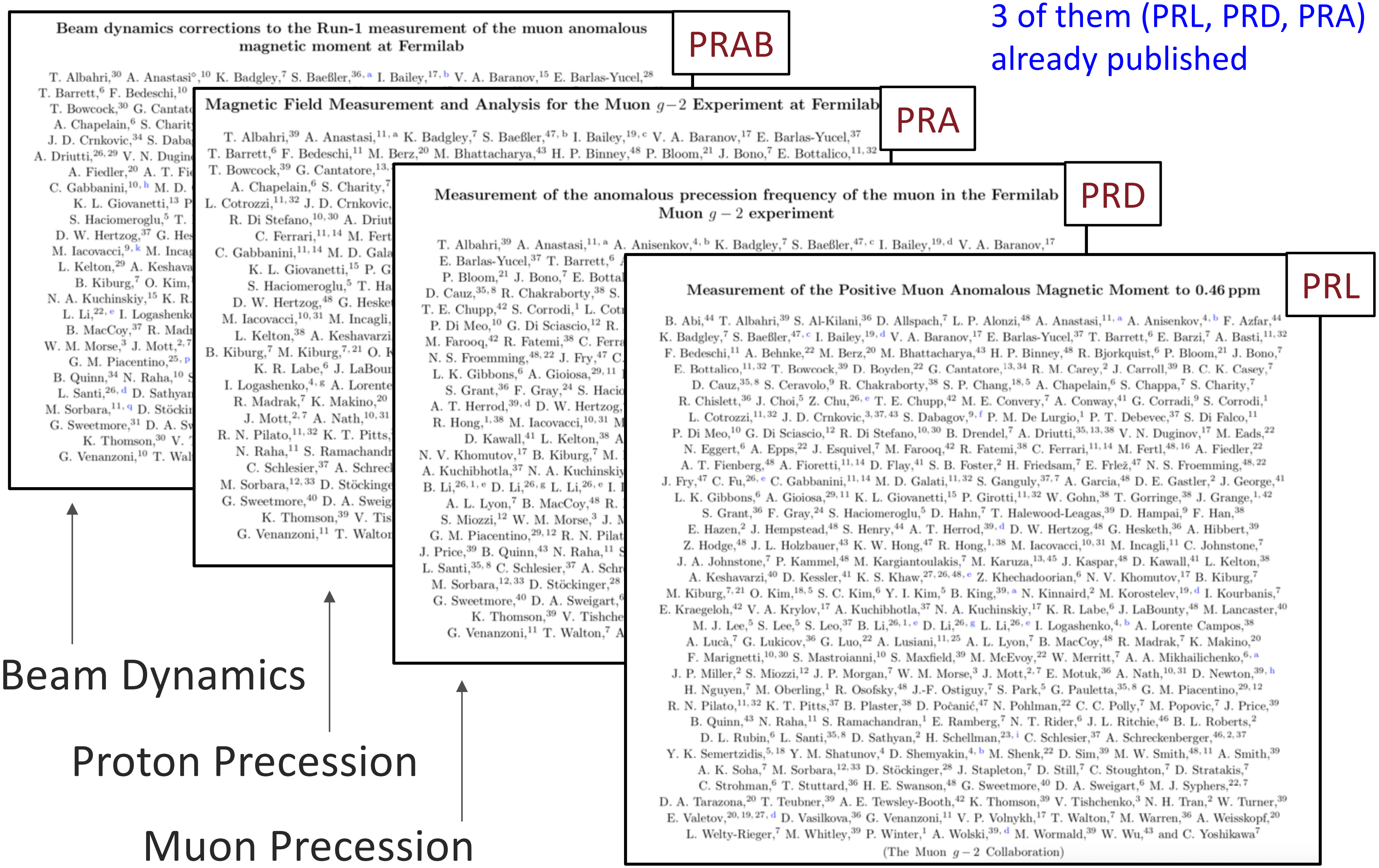
Measuring the ratio

- Contributo specifico dei gruppi italiani

$$\boxed{R'_\mu =}\left(\frac{f_{clock}\cdot\boxed{\omega_a^{meas}}\cdot(1+C_e+C_p+C_{ml}+\boxed{C_{pa}})}{f_{calib}\cdot\omega'_p(x,y,\varphi)\cdot M(x,y,\varphi)\cdot(1+\boxed{B_k}+B_q)}\right)$$

Four articles on arXiv for details

3 of them (PRL, PRD, PRA) already published



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

T. Albahri,[30] A. Anastasi°,[10] K. Badgley,[7] S. Baeßler,[36,a] I. Bailey,[17,b] V. A. Baranov,[15] E. Barlas-Yucel,[28]

Magnetic Field Measurement and Analysis for the Muon $g-2$ Experiment at Fermilab

T. Albahri,[39] A. Anastasi,[11,a] K. Badgley,[7] S. Baeßler,[47,b] I. Bailey,[19,c] V. A. Baranov,[17] E. Barlas-Yucel,[37]
T. Barrett,[6] F. Bedeschi,[11] M. Berz,[20] M. Bhattacharya,[43] H. P. Binney,[48] P. Bloom,[21] J. Bono,[7] E. Bottalico,[11,32]

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

T. Albahri,[39] A. Anastasi,[11,a] A. Anisenkov,[4,b] K. Badgley,[7] S. Baeßler,[47,c] I. Bailey,[19,d] V. A. Baranov,[17]

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

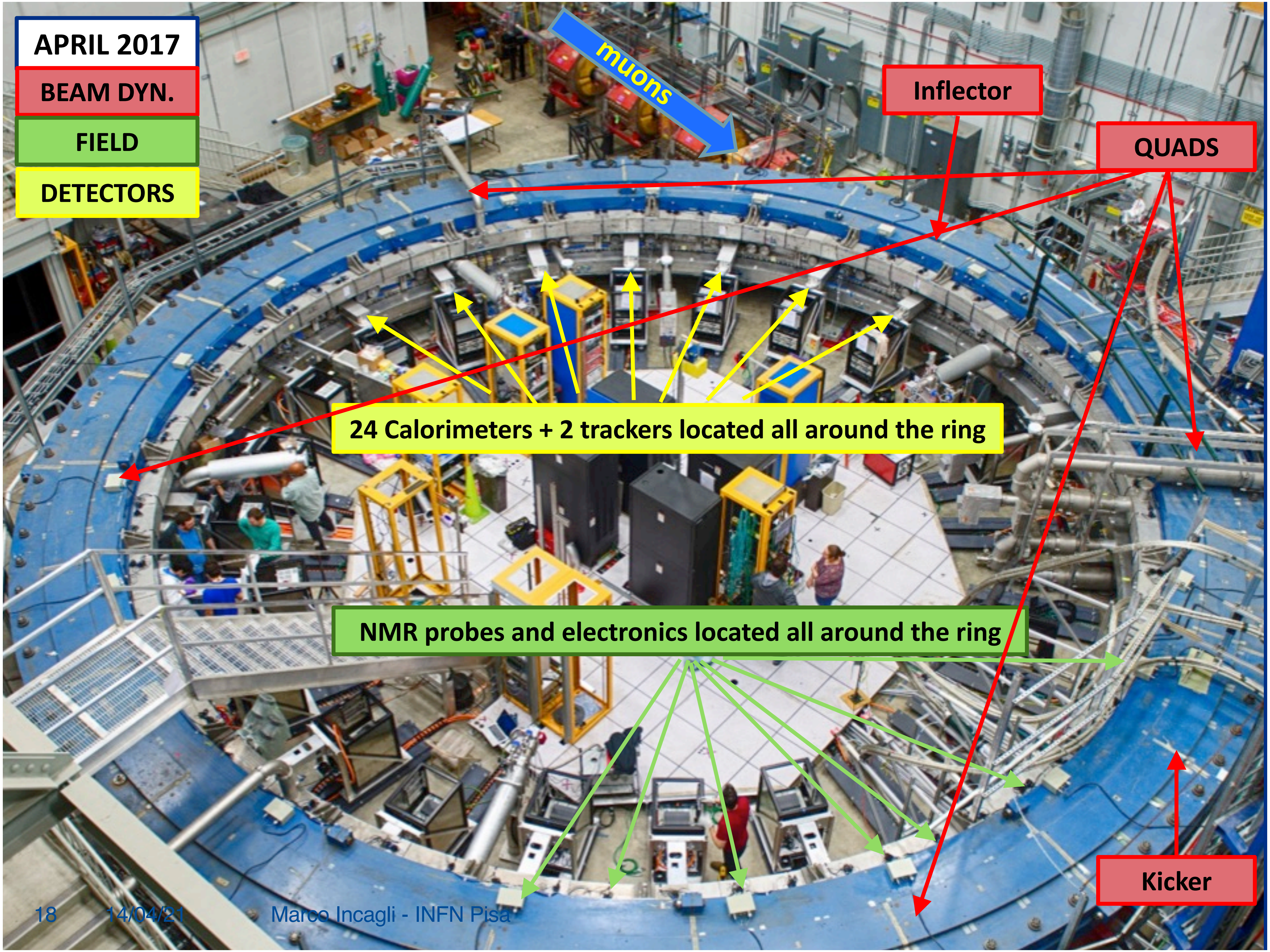
B. Abi,[44] T. Albahri,[39] S. Al-Kilani,[36] D. Allspach,[7] L. P. Alonzi,[48] A. Anastasi,[11,a] A. Anisenkov,[4,b] F. Azfar,[44] K. Badgley,[7] S. Baeßler,[47,c] I. Bailey,[19,d] V. A. Baranov,[17] E. Barlas-Yucel,[37] T. Barrett,[6] E. Barzi,[7] A. Basti,[11,32] F. Bedeschi,[11] A. Behnke,[22] M. Berz,[20] M. Bhattacharya,[43] H. P. Binney,[48] R. Bjorkquist,[6] P. Bloom,[21] J. Bono,[7] E. Bottalico,[11,32] T. Bowcock,[39] D. Boyden,[22] G. Cantatore,[13,34] R. M. Carey,[2] J. Carroll,[39] B. C. K. Casey,[7] D. Cauz,[35,8] S. Ceravolo,[9] R. Chakraborty,[38] S. P. Chang,[18,5] A. Chapelain,[6] S. Chappa,[7] S. Charity,[7] R. Chislett,[36] J. Choi,[5] Z. Chu,[26,e] T. E. Chupp,[42] M. E. Convery,[7] A. Conway,[41] G. Corradi,[9] S. Corrodi,[1] L. Cotrozzi,[11,32] J. D. Crnkovic,[3,37,43] S. Dabagov,[9,f] P. M. De Lurgio,[1] P. T. Debevec,[37] S. Di Falco,[11] P. Di Meo,[10] G. Di Sciascio,[12] R. Di Stefano,[10,30] B. Drendel,[7] A. Driutti,[35,13,38] V. N. Duginov,[17] M. Eads,[22] N. Eggert,[6] A. Epps,[22] J. Esquivel,[7] M. Farooq,[42] R. Fatemi,[38] C. Ferrari,[11,14] M. Fertl,[48,16] A. Fiedler,[22] A. T. Fienberg,[48] A. Fioretti,[11,14] D. Flay,[41] S. B. Foster,[2] H. Friedsam,[7] E. Frlež,[47] N. S. Froemming,[48,22] J. Fry,[47] C. Fu,[26,e] C. Gabbanini,[11,14] M. D. Galati,[11,32] S. Ganguly,[37,7] A. Garcia,[48] D. E. Gastler,[2] J. George,[41] L. K. Gibbons,[6] A. Gioiosa,[29,11] K. L. Giovanetti,[15] P. Girotti,[11,32] W. Gohn,[38] T. Gorringe,[38] J. Grange,[1,42] S. Grant,[36] F. Gray,[24] S. Haciomeroglu,[5] D. Hahn,[7] T. Halewood-Leagas,[39] D. Hampai,[9] F. Han,[38] E. Hazen,[2] J. Hempstead,[48] S. Henry,[44] A. T. Herrod,[39,d] D. W. Hertzog,[48] G. Hesketh,[36] A. Hibbert,[39] Z. Hodge,[48] J. L. Holzbauer,[43] K. W. Hong,[47] R. Hong,[1,38] M. Iacovacci,[10,31] M. Incagli,[11] C. Johnstone,[7] J. A. Johnstone,[7] P. Kammel,[48] M. Kargiantoulakis,[7] M. Karuza,[13,45] J. Kaspar,[48] D. Kawall,[41] L. Kelton,[38] A. Keshavarzi,[40] D. Kessler,[41] K. S. Khaw,[27,26,48,e] Z. Khechadoorian,[6] N. V. Khomutov,[17] B. Kiburg,[7] M. Kiburg,[7,21] O. Kim,[18,5] S. C. Kim,[6] Y. I. Kim,[5] B. King,[39,a] N. Kinnaird,[2] M. Korostelev,[19,d] I. Kourbanis,[7] E. Kraegeloh,[42] V. A. Krylov,[17] A. Kuchibhotla,[37] N. A. Kuchinskiy,[17] K. R. Labe,[6] J. LaBounty,[48] M. Lancaster,[40] M. J. Lee,[5] S. Lee,[5] S. Leo,[37] B. Li,[26,1,e] D. Li,[26,g] L. Li,[26,e] I. Logashenko,[4,b] A. Lorente Campos,[38] A. Lucà,[7] G. Lukicov,[36] G. Luo,[22] A. Lusiani,[11,25] A. L. Lyon,[7] B. MacCoy,[48] R. Madrak,[7] K. Makino,[20] F. Marignetti,[10,30] S. Mastroianni,[10] S. Maxfield,[39] M. McEvoy,[22] W. Merritt,[7] A. A. Mikhailichenko,[6,a] J. P. Miller,[2] S. Miozzi,[12] J. P. Morgan,[7] W. M. Morse,[3] J. Mott,[2,7] E. Motuk,[36] A. Nath,[10,31] D. Newton,[39,h] H. Nguyen,[7] M. Oberling,[1] R. Osofsky,[48] J.-F. Ostiguy,[7] S. Park,[5] G. Pauletta,[35,8] G. M. Piacentino,[29,12] R. N. Pilato,[11,32] K. T. Pitts,[37] B. Plaster,[38] D. Počanić,[47] N. Pohlman,[22] C. C. Polly,[7] M. Popovic,[7] J. Price,[39] B. Quinn,[43] N. Raha,[11] S. Ramachandran,[1] E. Ramberg,[7] N. T. Rider,[6] J. L. Ritchie,[46] B. L. Roberts,[2] D. L. Rubin,[6] L. Santi,[35,8] D. Sathyan,[2] H. Schellman,[23,i] C. Schlesier,[37] A. Schreckenberger,[46,2,37] Y. K. Semertzidis,[5,18] Y. M. Shatunov,[4] D. Shemyakin,[4,b] M. Shenk,[22] D. Sim,[39] M. W. Smith,[48,11] A. Smith,[39] A. K. Soha,[7] M. Sorbara,[12,33] D. Stöckinger,[28] J. Stapleton,[7] D. Still,[7] C. Stoughton,[7] D. Stratakis,[7] C. Strohman,[6] T. Stuttard,[36] H. E. Swanson,[48] G. Sweetmore,[40] D. A. Sweigart,[6] M. J. Syphers,[22,7] D. A. Tarazona,[20] T. Teubner,[39] A. E. Tewsley-Booth,[42] K. Thomson,[39] V. Tishchenko,[3] N. H. Tran,[2] W. Turner,[39] E. Valetov,[20,19,27,d] D. Vasilkova,[36] G. Venanzoni,[11] V. P. Volnykh,[17] T. Walton,[7] M. Warren,[36] A. Weisskopf,[20] L. Welty-Rieger,[7] M. Whitley,[39] P. Winter,[1] A. Wolski,[39,d] M. Wormald,[39] W. Wu,[43] and C. Yoshikawa[7]

(The Muon $g-2$ Collaboration)

Beam Dynamics

Proton Precession

Muon Precession



APRIL 2017

BEAM DYN.

FIELD

DETECTORS

muons

Inflector

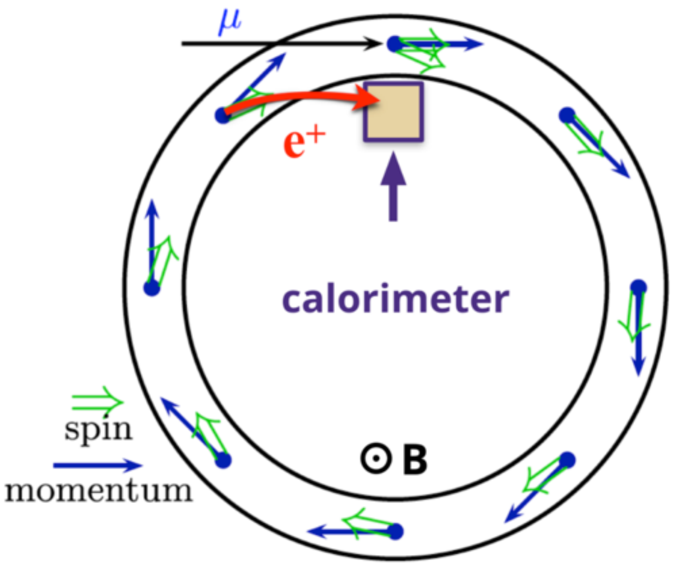
QUADS

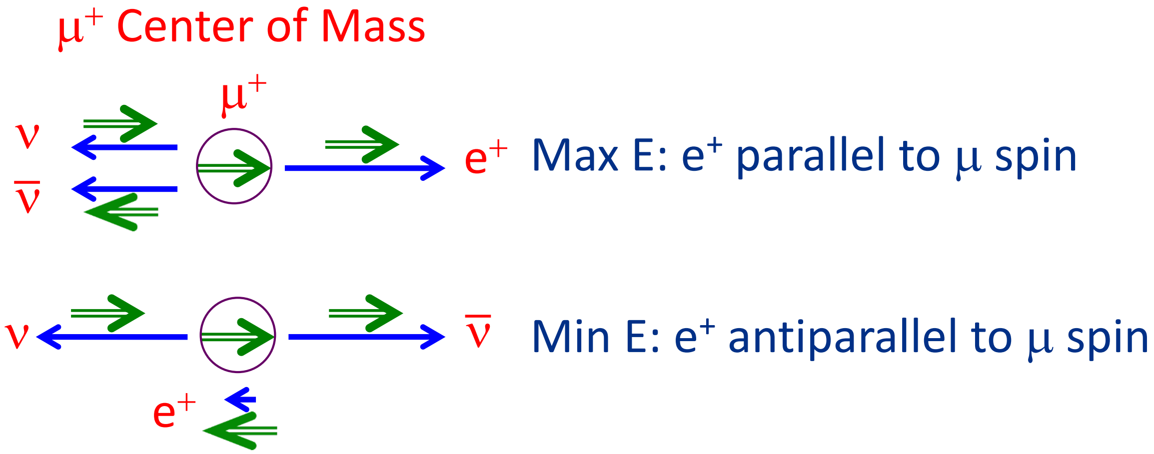
24 Calorimeters + 2 trackers located all around the ring

NMR probes and electronics located all around the ring

Kicker

ω_a principle of measurement



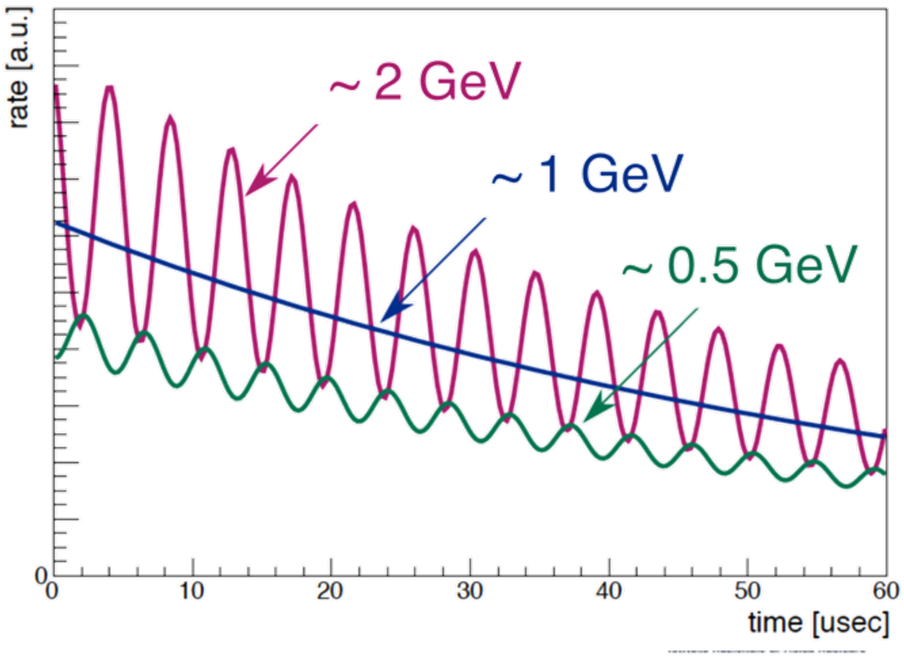


Max E: e^+ parallel to μ spin

Min E: e^+ antiparallel to μ spin

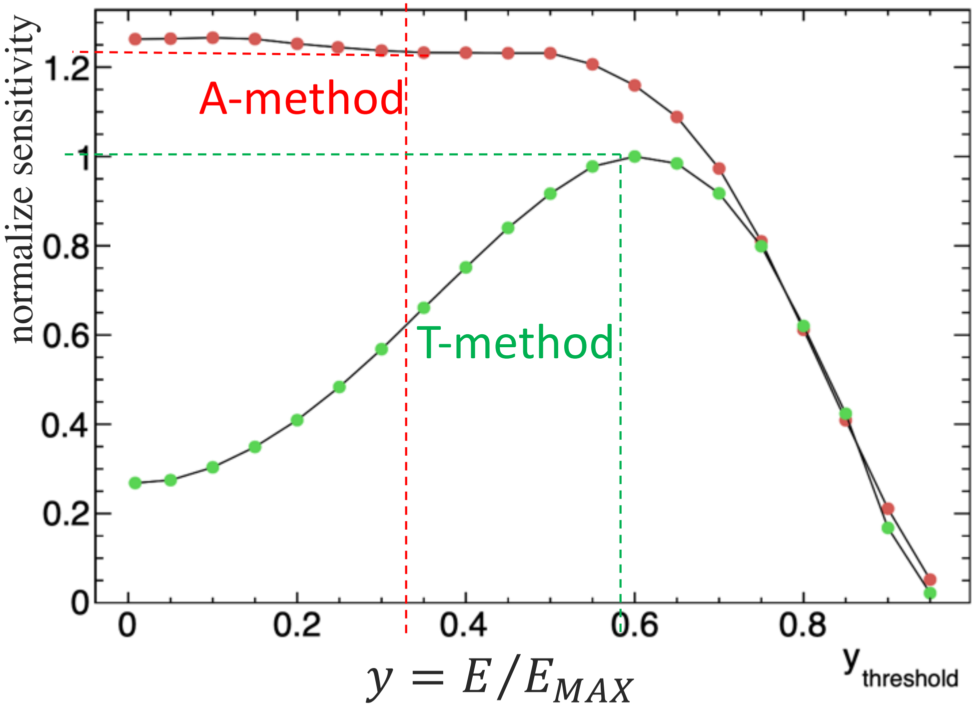
$$N(t) = N_0 e^{-t/\tau}\left(1 + A\cos(\omega_a t + \varphi)\right)$$

- positron direction correlated with muon spin direction
- correlation depends on *positron energy* : the Asymmetry A(E) can be positive, null or negative



Optimizing the statistical sensitivity

- **T-method** = counting positrons above E_{thr} vs time
  - by decreasing the threshold the asymmetry decreases but the number of events increases → *max sensitivity for E_{thr}~1.7 GeV*
- **A-method** = each positron is *weighted by the value of its asymmetry A(E)*
  - optimize statistical sensitivity
- In theory the A-method can use *all decay positrons*, in practice, due to calorimeter acceptance and to low A(E) value at low energies, only positrons with *E_{thr}>1.1 GeV (y>0.3) are used*



$y = E/E_{MAX}$

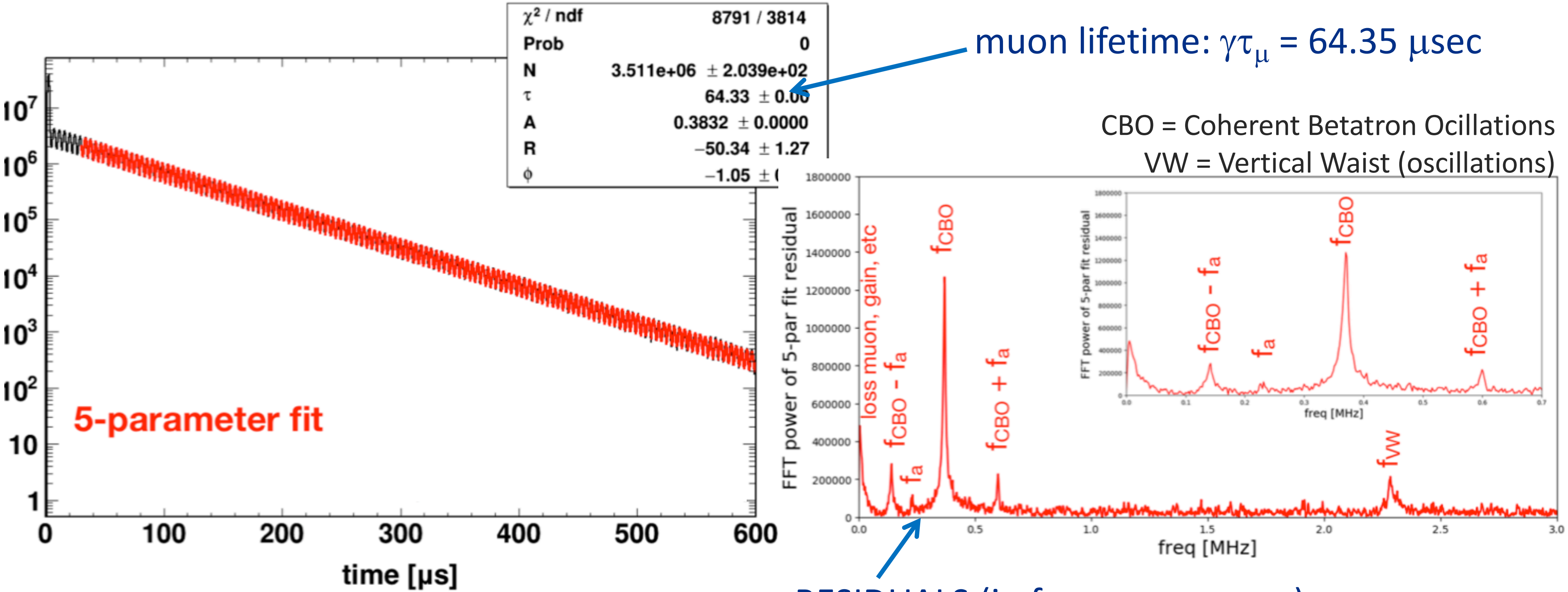
$(E_{MAX} = 3.1GeV)$

Measuring ω_a : 5 parameters fit function

- Fit with simple positron oscillation:

$$N_{ideal}(t) = N_0 \exp(-t/\tau_{\mu})\,[1 + A\cos(\omega_a t + \varphi)]$$

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



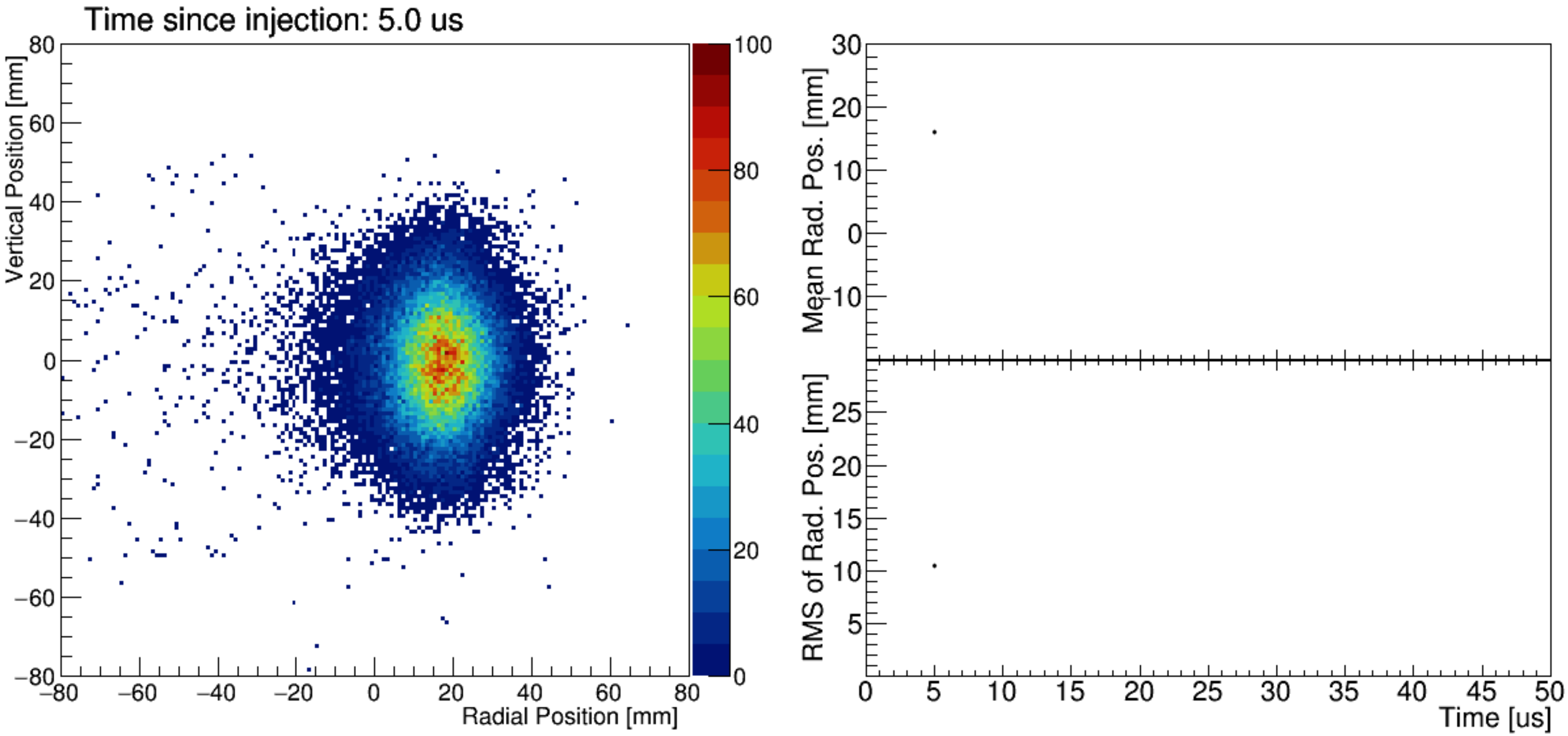
muon lifetime: $\gamma\tau_{\mu}$ = 64.35 μsec

CBO = Coherent Betatron Ocillations
VW = Vertical Waist (oscillations)

RESIDUALS (in frequency space)

Beam oscillations

- Beam oscillations are accurately measured by the tracker and folded into the fit function



The complete 22 parameters fit function

ω_y, ω_{VW} vertical oscillations

ω_{CBO}, ω_{2CBO} radial oscillations

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

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

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

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

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

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

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

Red = free parameters

Blue= fixed parameters

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

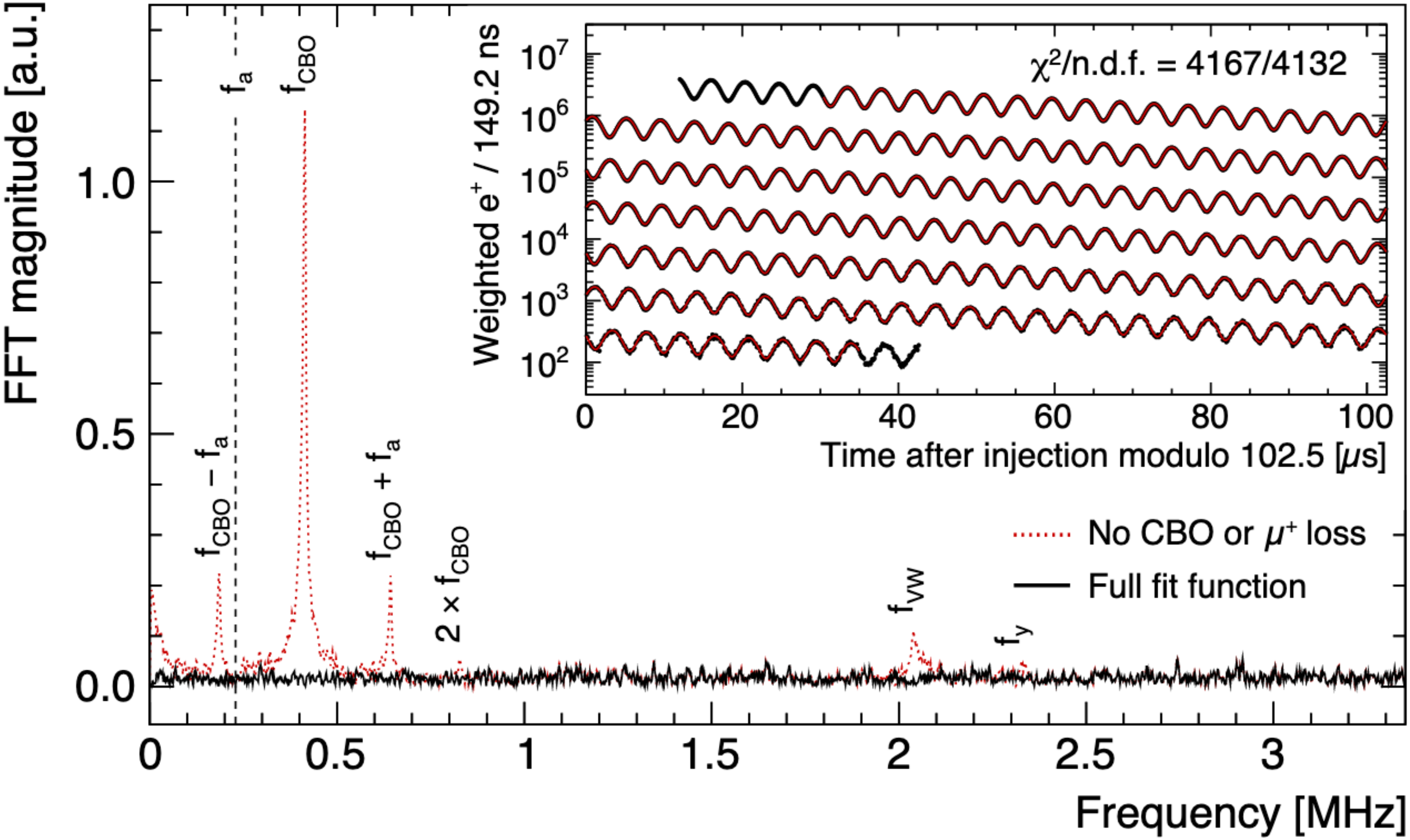
Lost muons (μ hitting collimators)

$$\omega_{\rm CBO}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

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

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

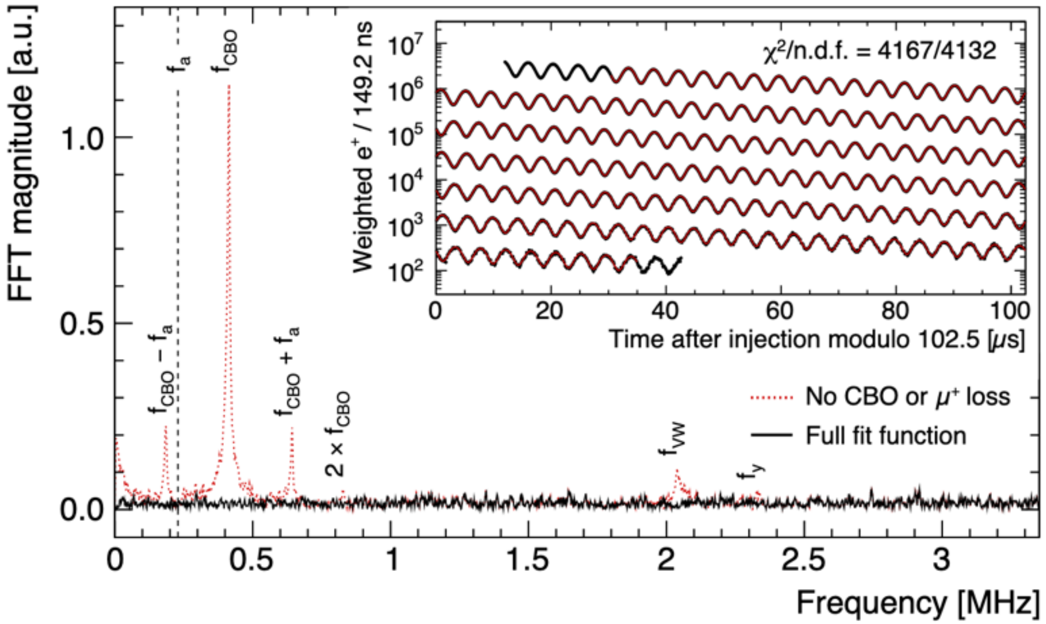
Final fit



FFT magnitude [a.u.]
1.0
0.5
0.0
0
0.5
1
1.5
2
2.5
3
Frequency [MHz]
f_a
f_{CBO}
$f_{CBO} - f_a$
$f_{CBO} + f_a$
$2 \times f_{CBO}$
f_{VW}
f_y
No CBO or μ^+ loss
Full fit function
Weighted e^+ / 149.2 ns
10^7
10^6
10^5
10^4
10^3
10^2
χ^2/n.d.f. = 4167/4132
0
20
40
60
80
100
Time after injection modulo 102.5 [μs]

Final fit

- Four datasets in Run-1
- ω_a value expressed in terms of a "blinded" (see later) parameter R
- Four independent analyses used for the final result



- The analyses are strongly correlated, although not identical, and contribute to the robustness of the final result

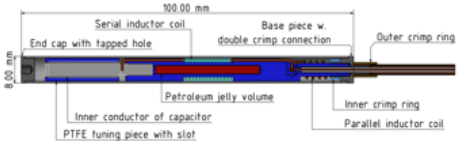
			R [ppm] for each dataset			
Recon.	Method	Pileup	Run-1a	Run-1b	Run-1c	Run-1d
global	A	empirical	-82.98 ± 1.21	-81.70 ± 1.03	-82.30 ± 0.82	-82.34 ± 0.68
local	A	shadow	-83.23 ± 1.20	-81.77 ± 1.02	-82.35 ± 0.82	-82.48 ± 0.67
local	A	shadow	-83.17 ± 1.21	-81.84 ± 1.03	-82.50 ± 0.83	-82.45 ± 0.68
local	A	pdf	-83.39 ± 1.22	-81.72 ± 1.04	-82.32 ± 0.83	-82.42 ± 0.68

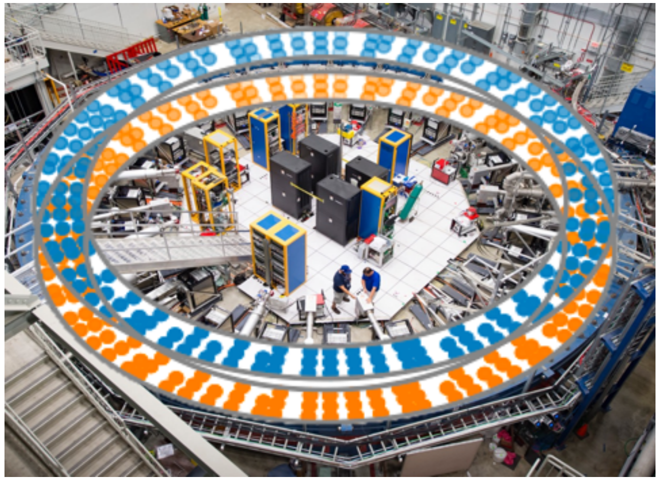
We also need B to determine a_μ

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

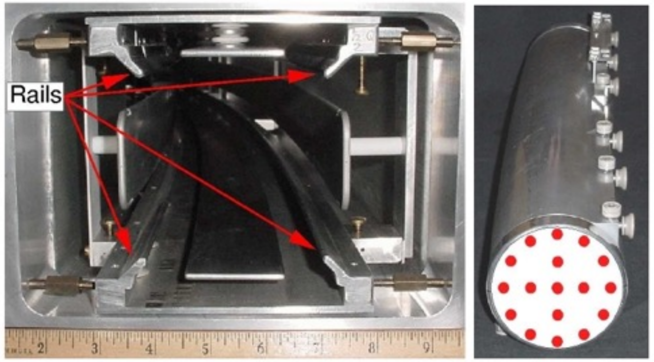
- Use NMR to find B-field in terms of proton precession frequency ω_p (comagnetometer)

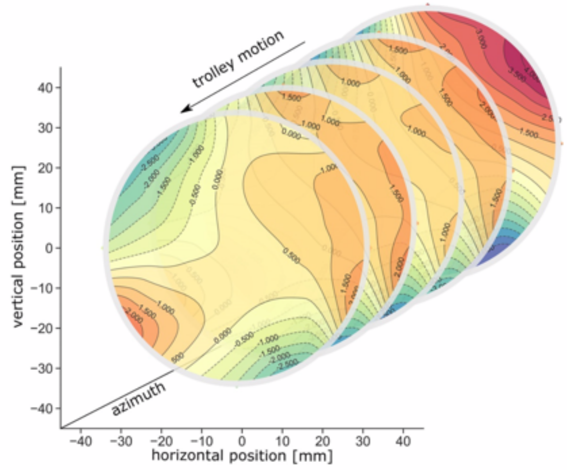
378 fixed probes monitor 24/7



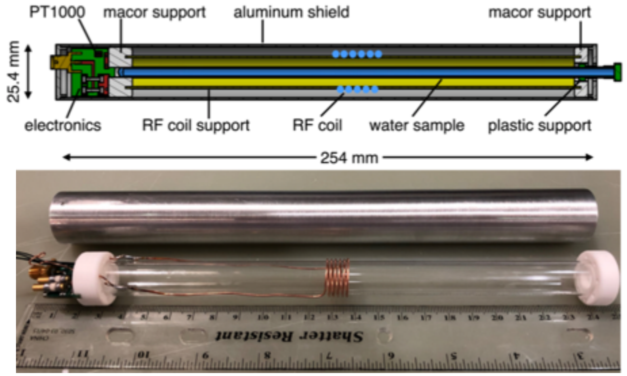


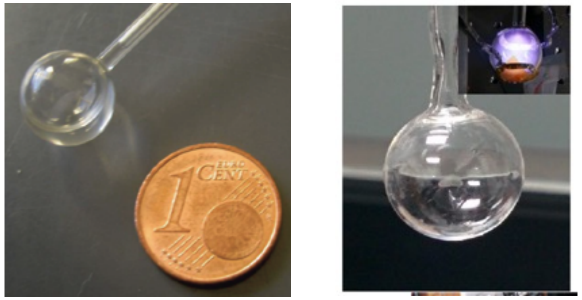
NMR trolley maps field every 3 days





Trolley cross-calibrated to absolute probes





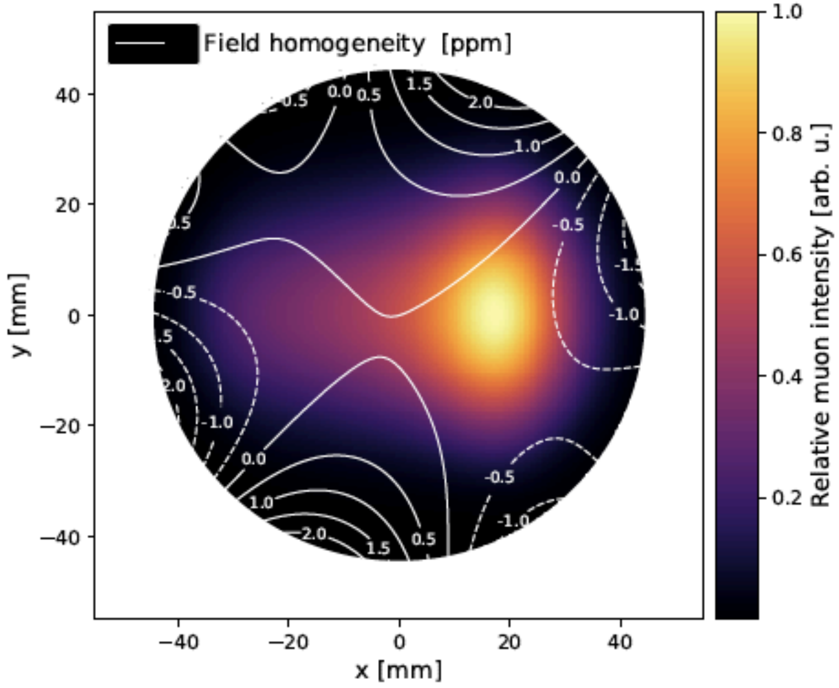
Absolute probes all cross-calibrated at ANL test magnet

$\omega'_p \rightarrow \tilde{\omega}'_p$: muon weighted average

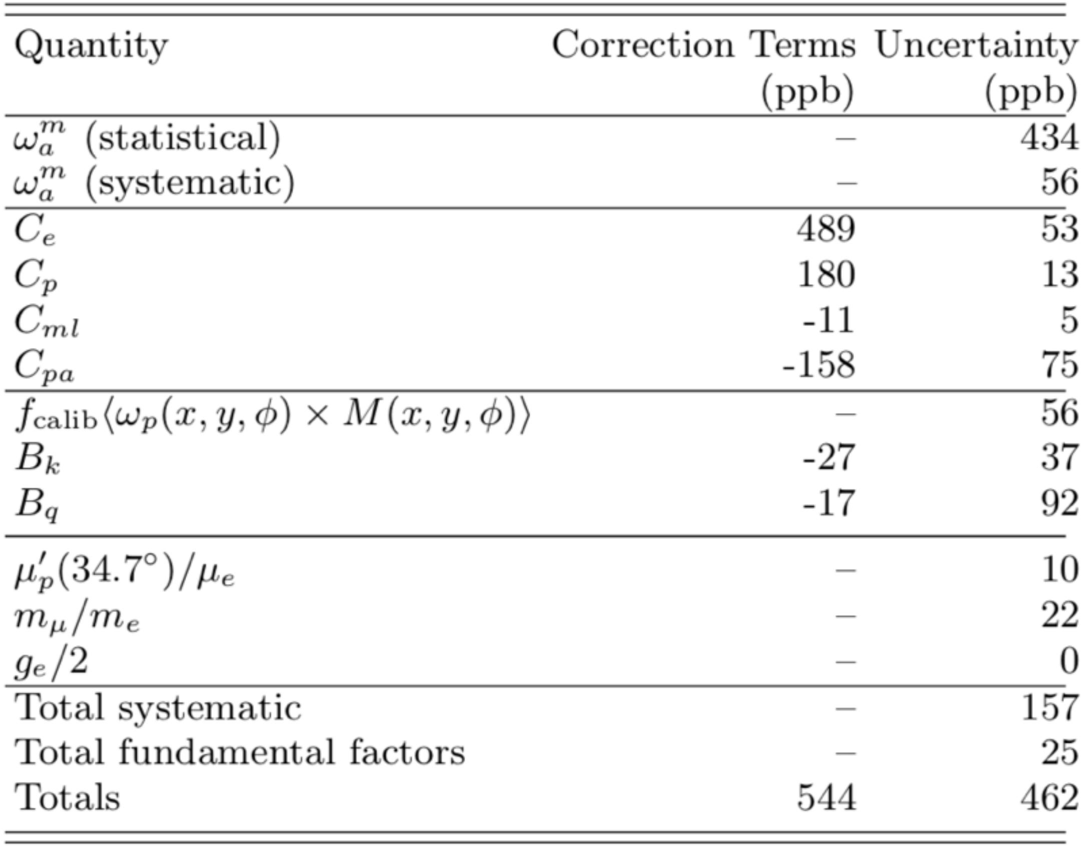
- Need field experienced by muons
- Use tracker to recostruct e+ track and muon vertex in storage ring
- Use beam dynamics models, tuned to the tracker data, to extrapolate the distribution all around the ring
- Systematic uncertainties mostly due to Beam Dynamics models used for extrapolation, to field map and to tracker alignment

$$\boxed{\delta_{\tilde{\omega}'_p} \sim 56\ ppb}$$

Muon’s view of a tracker



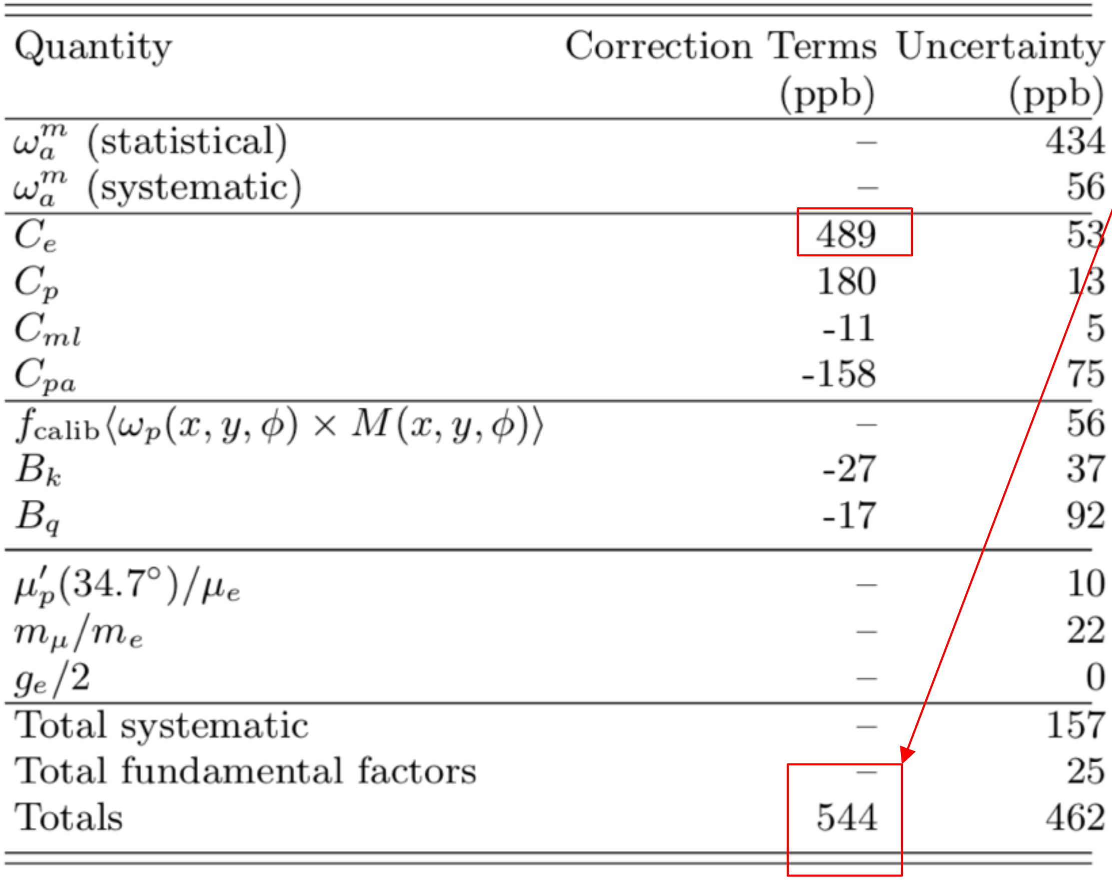
Final uncertainties from Run 1



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
$f_{\text{calib}}\langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle$	–	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

- 462 ppb overall error
  - 434 ppb statistical
  - 157 ppb systematic
  - 22 ppb external inputs
- Results for Run 1 are vastly dominated by statistical error
- At 157 ppb systematic error
  - Nearly half of BNL
  - Not quite to 100 ppb goal

Final uncertainties from Run 1



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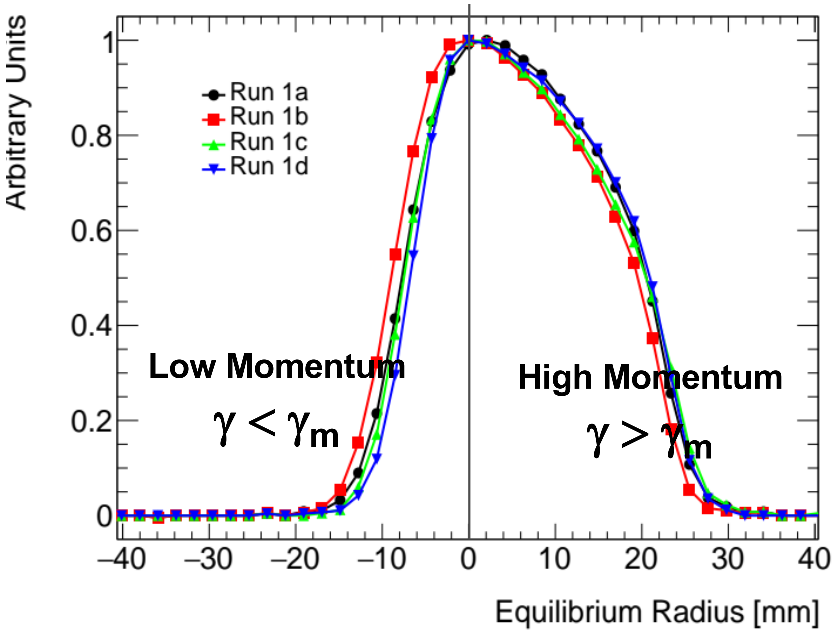
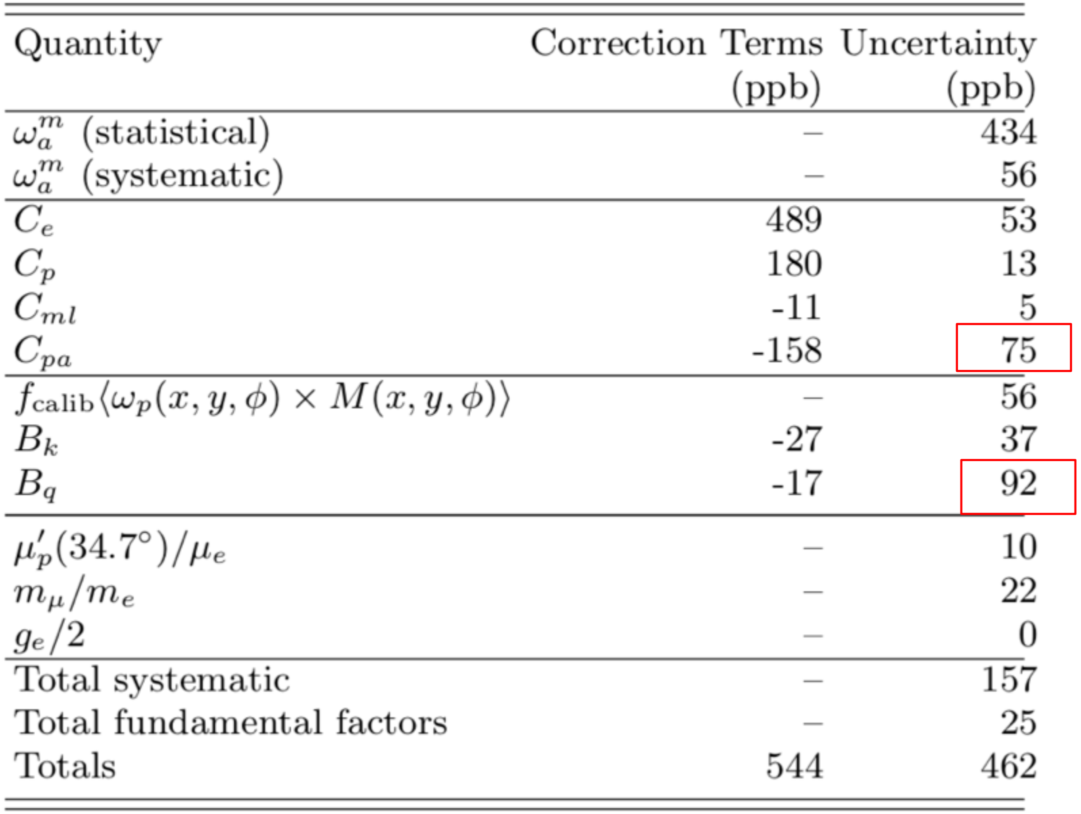
$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu\vec{B} - \boxed{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}\vec{\beta}\times\vec{E}\right]$$

(..) = 0 for $\gamma = \gamma_{magic}$

- Correction terms larger than total error
- Dominated by Electric Field corrections C_E
- Related to non-centered radial distribution
- Fixed in Run-2



Final uncertainties from Run 1



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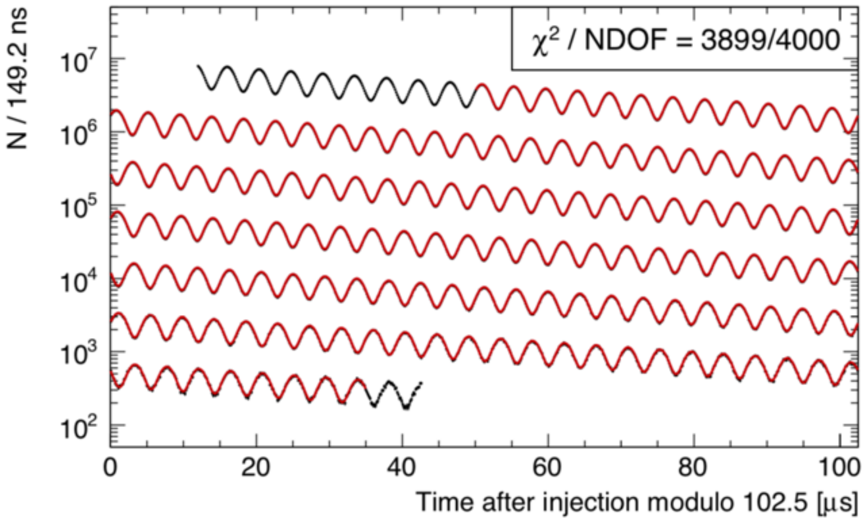
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

- Two largest systematics:
  - *phase acceptance*
  - *quadrupole field*

C_{PA} – Phase acceptance error

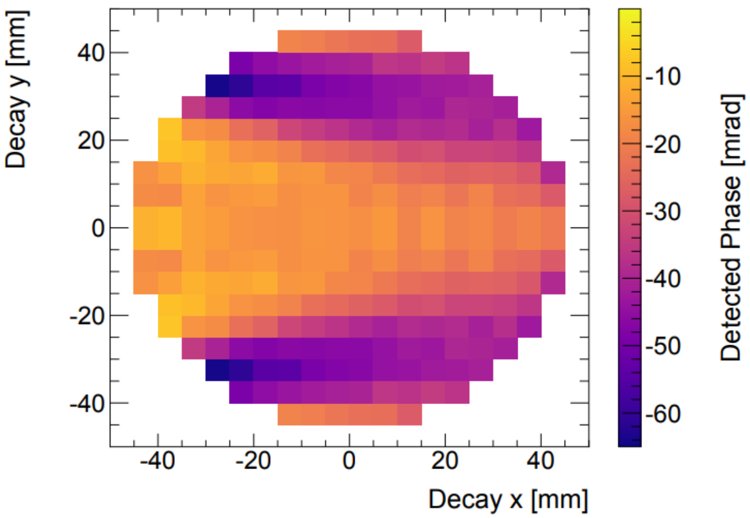


$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

But what if the phase of the muon population changes in time $\phi(t)$?

$$\begin{aligned} cos(\omega_a t + \phi(t)) &= cos(\omega_a t + \phi_0 + \phi' t + ...) \\ &= cos((\omega_a + \phi')t + \phi_0 + ...) \end{aligned}$$

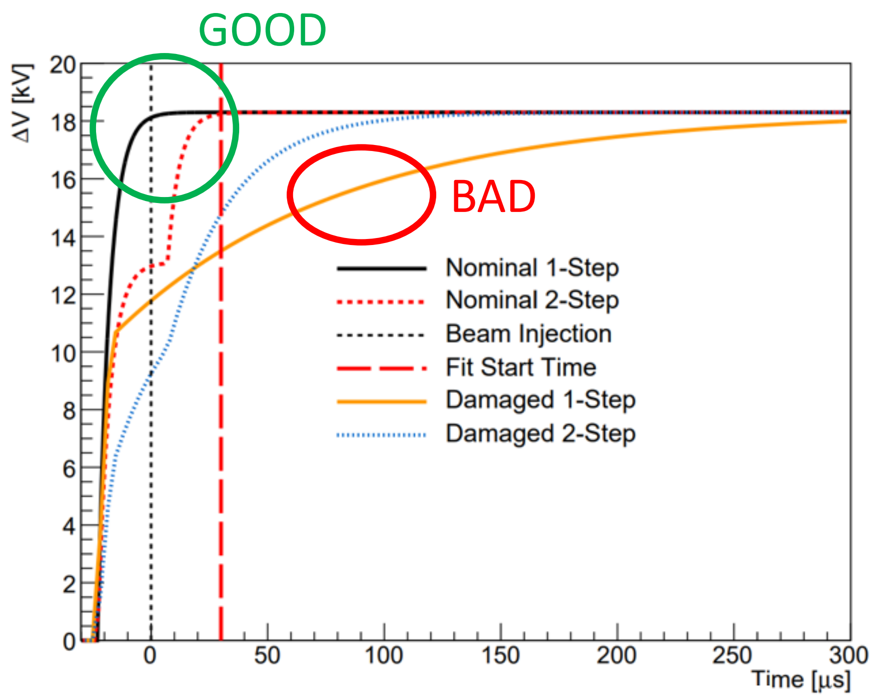
The extracted ω_a is shifted by ϕ' 😬

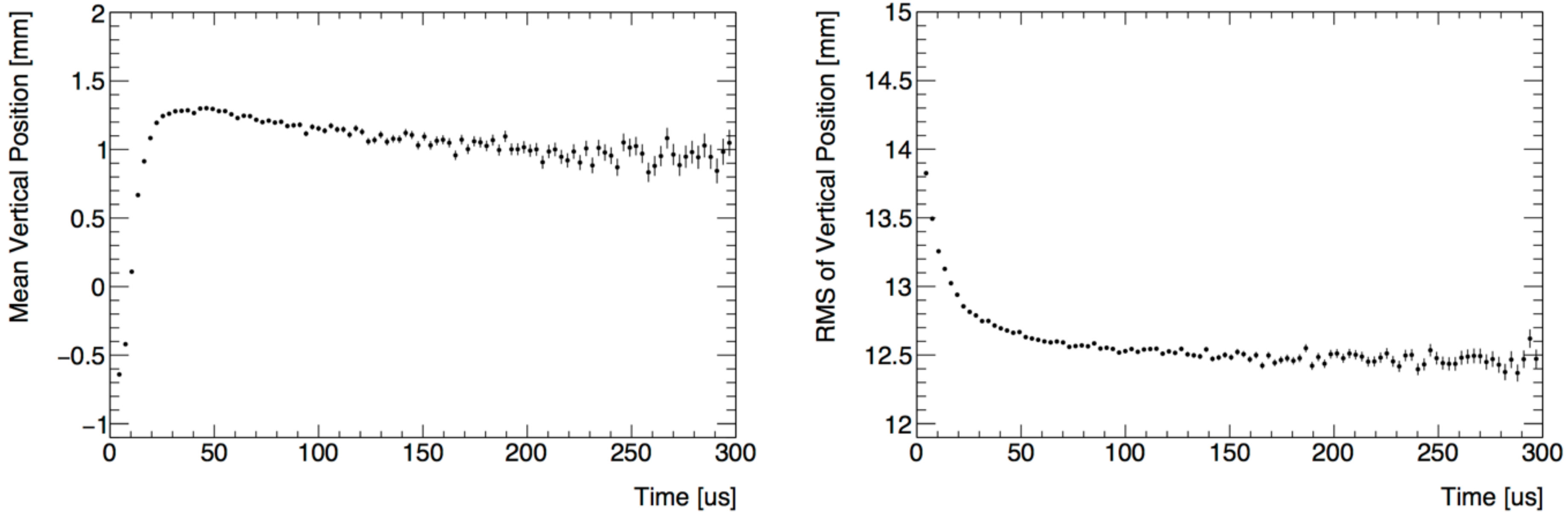


- The decay positrons we detect carry a particular phase
- That phase depends on muon decay position (x,y) and energy E
- Not a big issue if the muon distribution remains stable in the gap

C_{PA} – Phase acceptance error

- HV resistors failed → changing E-field → beam vertical mean and width changed
- $C_{PA} = -158\,ppb,\;\; \delta_{PA} = 75\,ppb$
- Faulty resistors fixed before Run-2





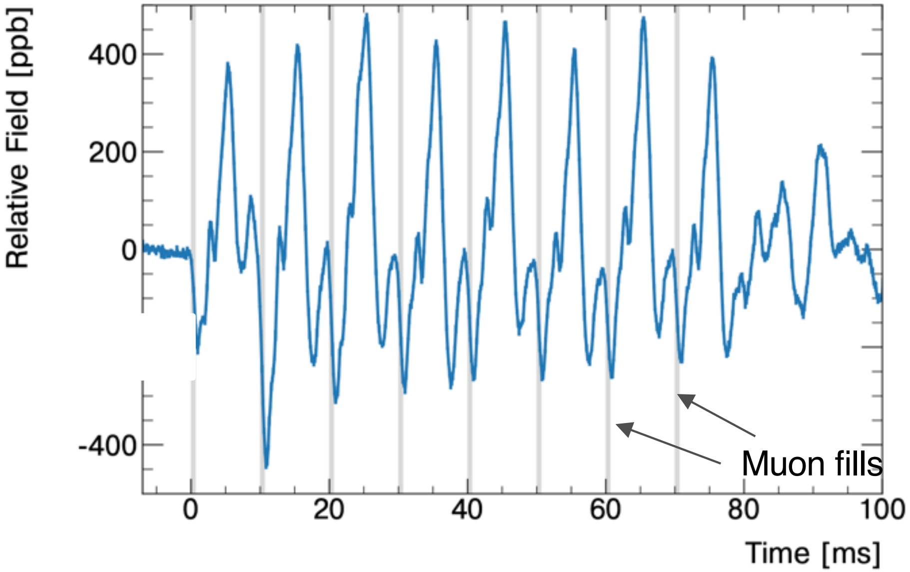
ElectroStatic Quadrupoles transient field B_q

- The ESQ are charged/discharged every muon fill (700ms)
- The electric pulse induces mechanical vibrations in the plates which generate magnetic perturbations
- Special NMR probes measured B_q at several positions

$$B_q \sim 20\ ppb, \delta_{B_q} \sim 90\ ppb$$

- Uncertainty dominated by limited number of measurements in Run-1, reduced in Run-2 by more measurements

Quad Plates inside Vacuum Chamber



The blinding

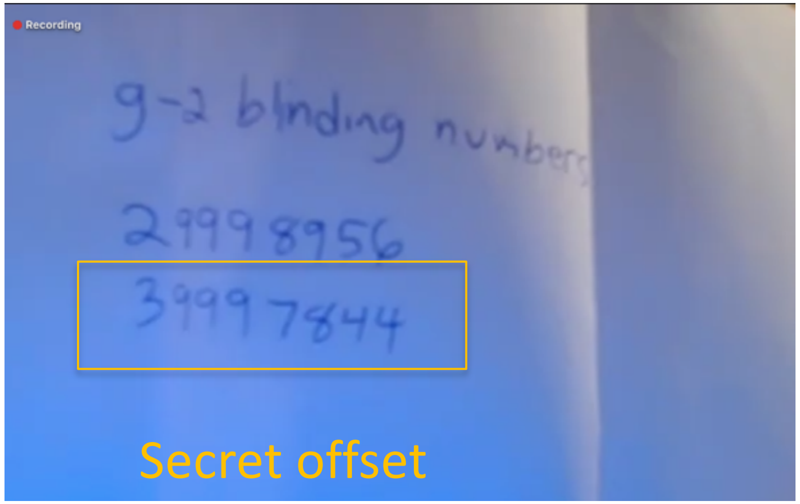
$$R'_\mu = \left(\frac{\boxed{f_{clock}} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\varphi) \cdot M(x,y,\varphi) \cdot (1 + B_k + B_q)} \right)$$

- 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 the collaboration met for the unblinding:

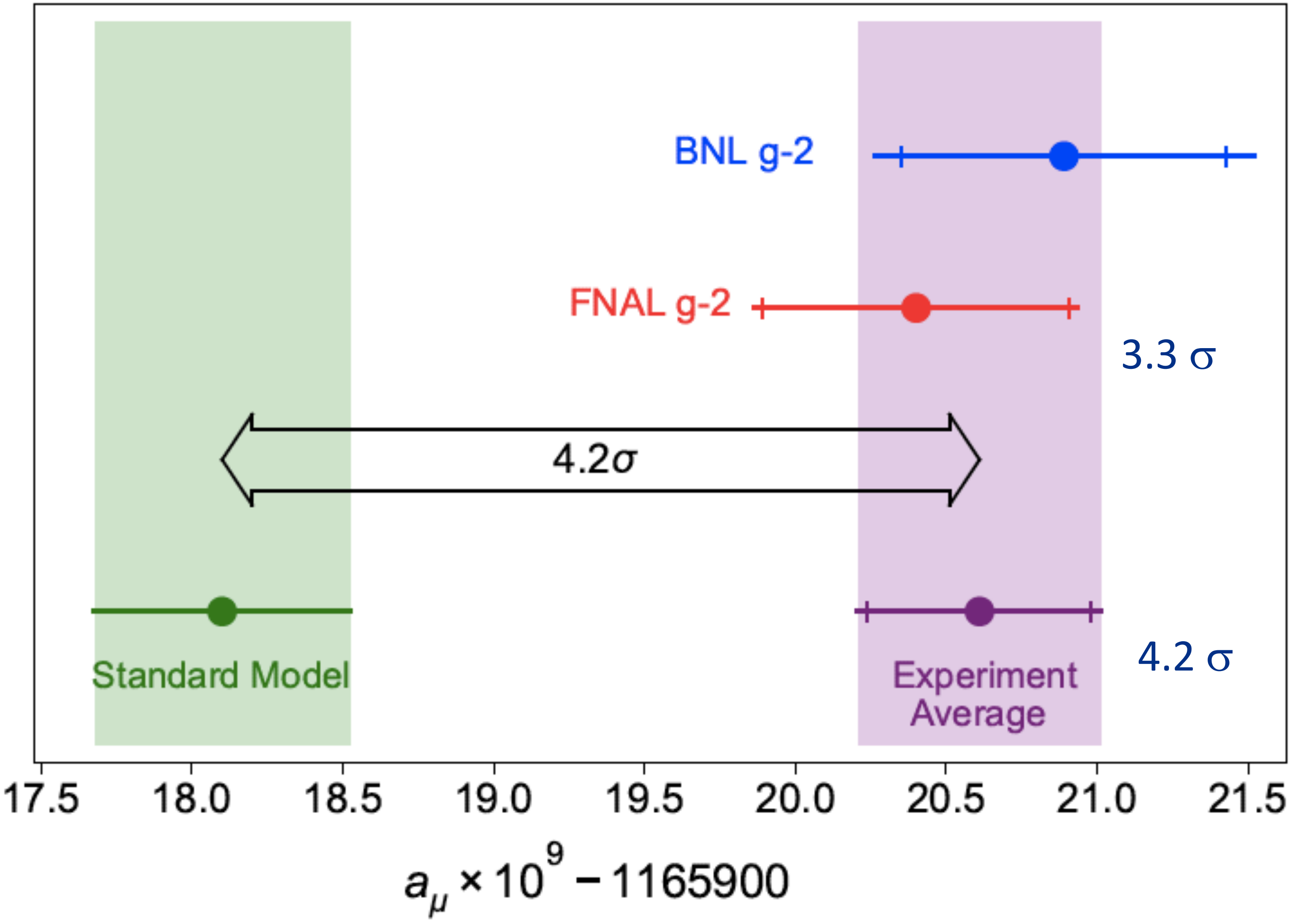
1) The *box* (envelope) was opened
2) The number was plugged into two independent programs
3) And the result was….



Secret offset

Are we ready to unblind?

a_μ: Unblinding



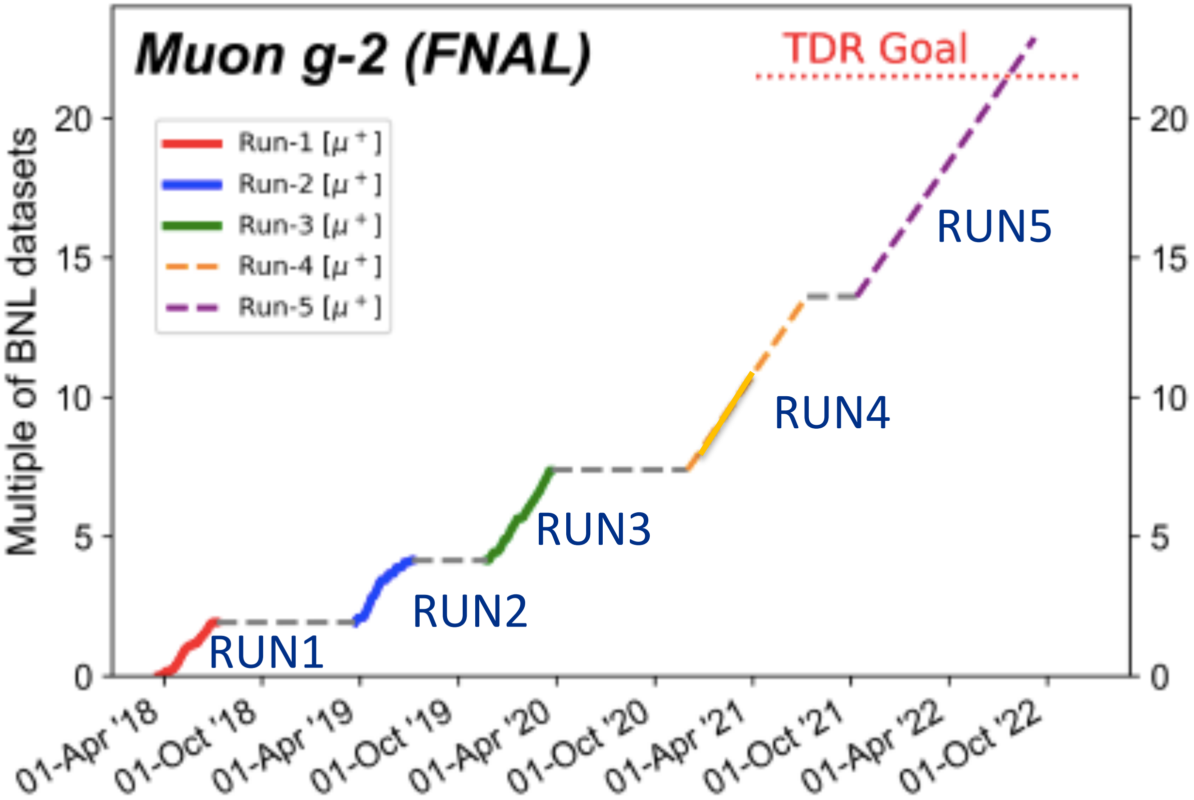
3.7 σ

3.3 σ

4.2 σ

The future of E989 *Muon g-2 (Fnal)*

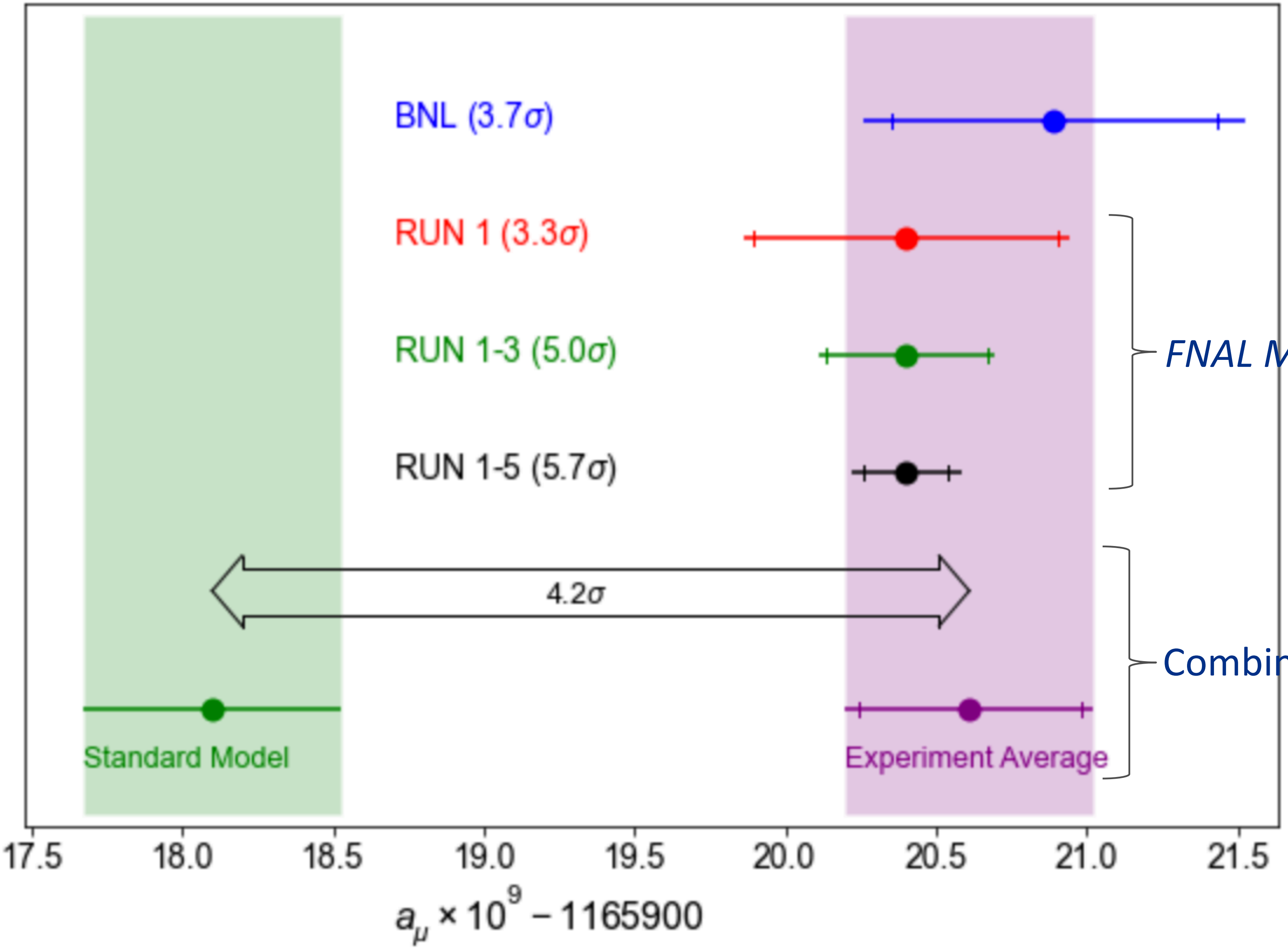
- RUN-1 is only 6% of the final dataset
- Analysis of RUN-2/3 in progress (factor ~2 in precision)
- RUN-4 (November 2020-July 2021) is expected to bring the statistics to ~12 times the Run-1 dataset



- RUN-5 in 2021-2022 should allow to achieve the project goal which will allow to reduce by a factor ~4 current total error

Future

- Discovery potential of *FNAL Muon g-2*, for same central value as Run-1 and same SM prediction



FNAL Muon g-2 alone

Combined (Apr 2021)

Conclusions

- We have presented the first measurement of a_m at 0.46 ppm
- Our result is consistent with the BNL one (within one standard deviation) with slightly better precision

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

- The discrepancy with the Standard Model prediction of the g-2 by the Theory Initiative is 4.2σ
- We expect an improvement in precision of a factor 2 from the RUN2/3 data and more from Run4 and 5.