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

Lomonosov Conference – 21 August 2021

Marco Incagli – INFN Pisa

What is *"g-2"* ?

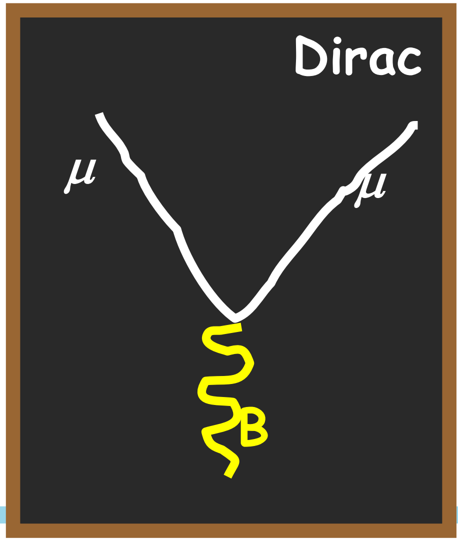
$$\vec{\mu}_p = -g_p \frac{e}{2m_p} \vec{S}$$

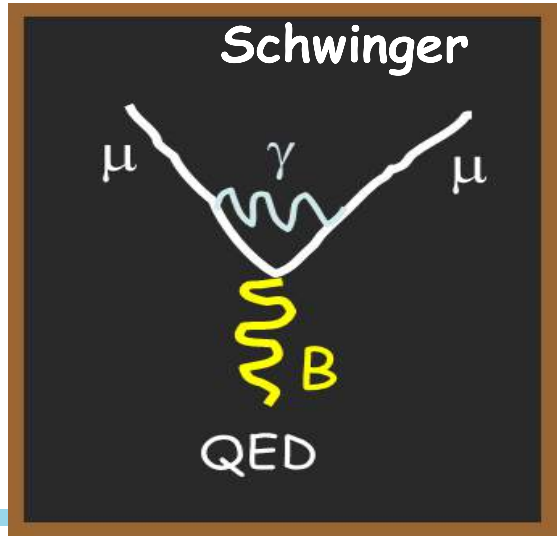
$$a_p = \frac{g_p - 2}{2}$$

- ***g_P*** : proportionality constant between spin and magnetic moment for particle P
- ***a_P*** : magnetic anomaly
- ***a_P*** = 0 at tree level (*purely Dirac particle*)

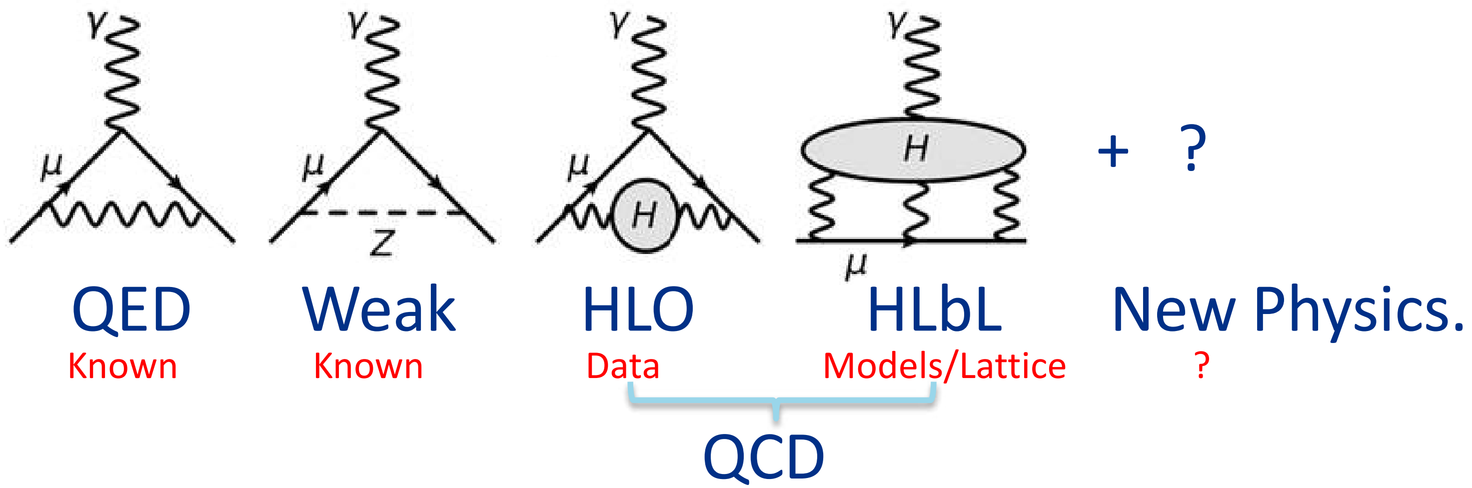
- Using modern language, the term (g-2)/2 reflects the magnitude of the Feynmann diagrams beyond leading order

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





Standard Model determination of a_μ

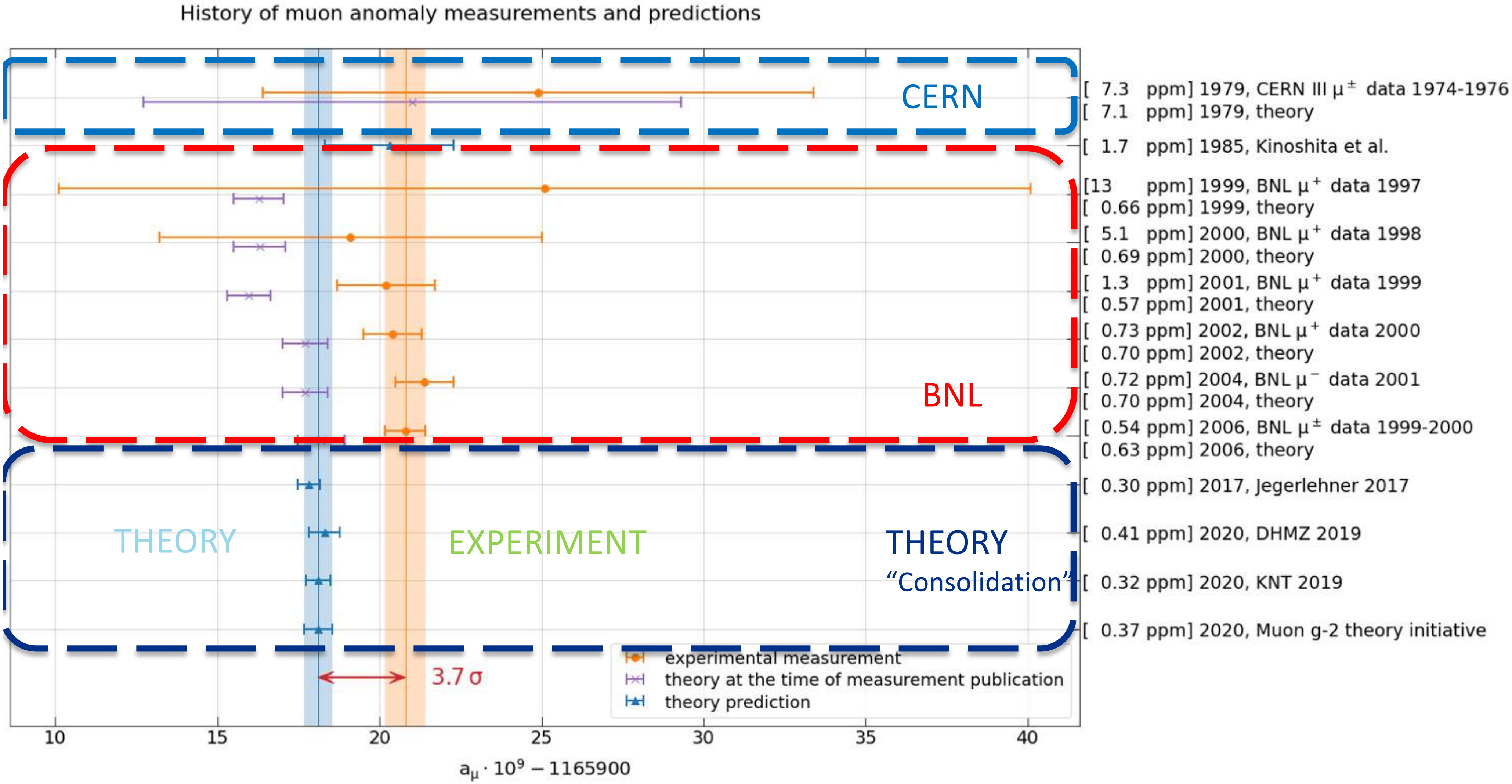


	Value ($\times 10^{-10}$) units
QED ($\gamma + \ell$)	$11\,658\,471.8951 \pm 0.0009 \pm 0.0019 \pm 0.0007 \pm 0.0077_\alpha$
HVP(lo) Davier17	692.6 ± 3.33
HLbL Glasgow	10.5 ± 2.6
EW	15.4 ± 0.1
Total SM Davier17	$11\,659\,181.7 \pm 4.2$

Theory Initiative White Paper (arXiv 2006:08443)

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

A rich history of g-2 Theory and Experiment



Tension between theory and experiment

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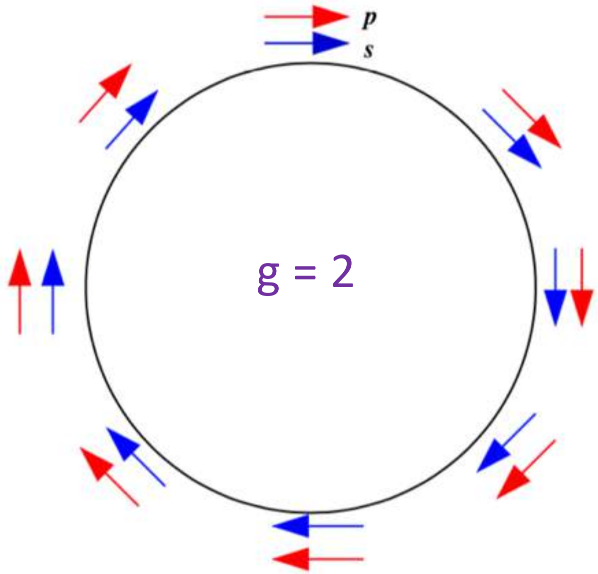
The Fundamental Experimental Principle

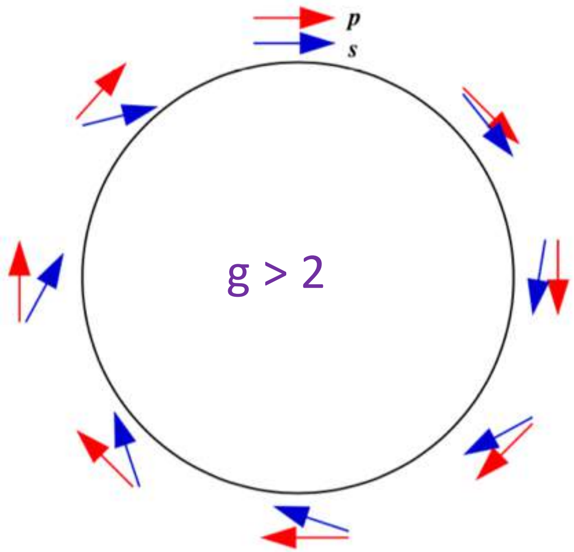
- Difference between spin precession and cyclotron revolution for a muon (charged particle with spin) in a magnetic field*:

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

*$\mathbf{s}$ and $\mathbf{p}$ are assumed to be in a plane perpendicular to $\mathbf{B}$

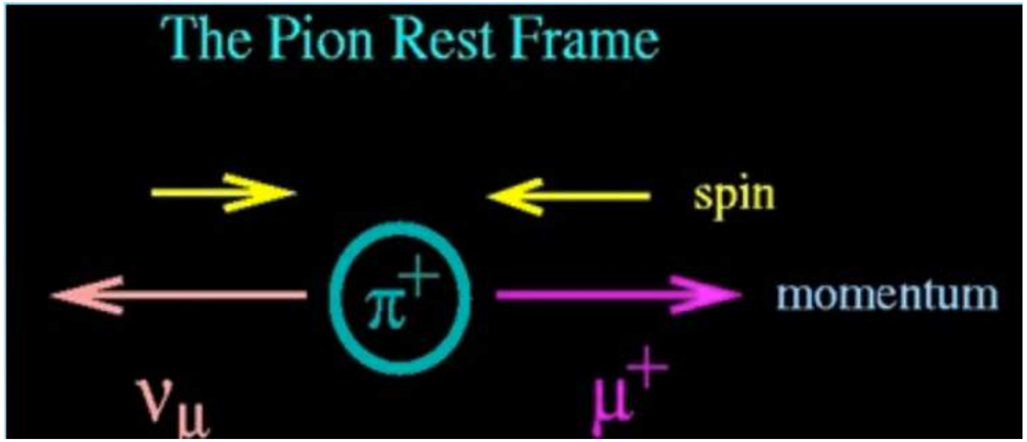
- simple classical calculation
- the relativistic approach provides the same result



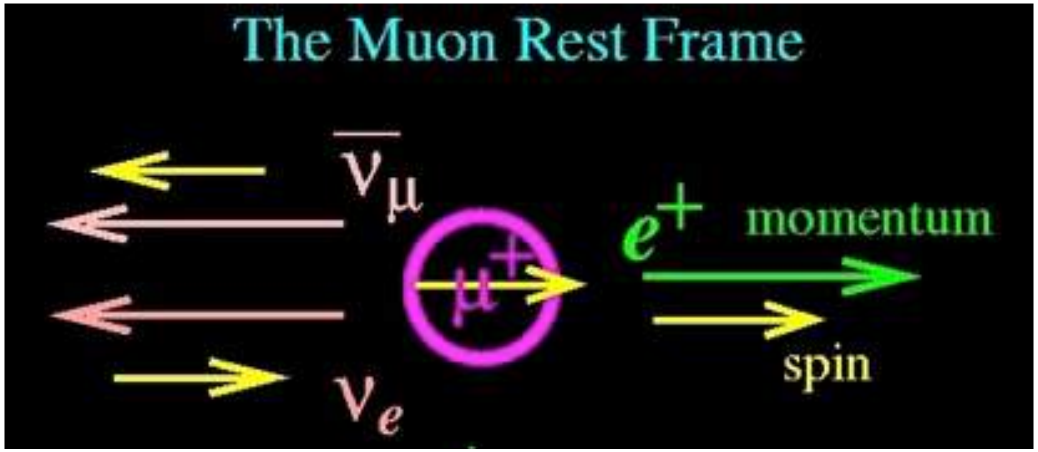


How do we measure the spin direction?

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



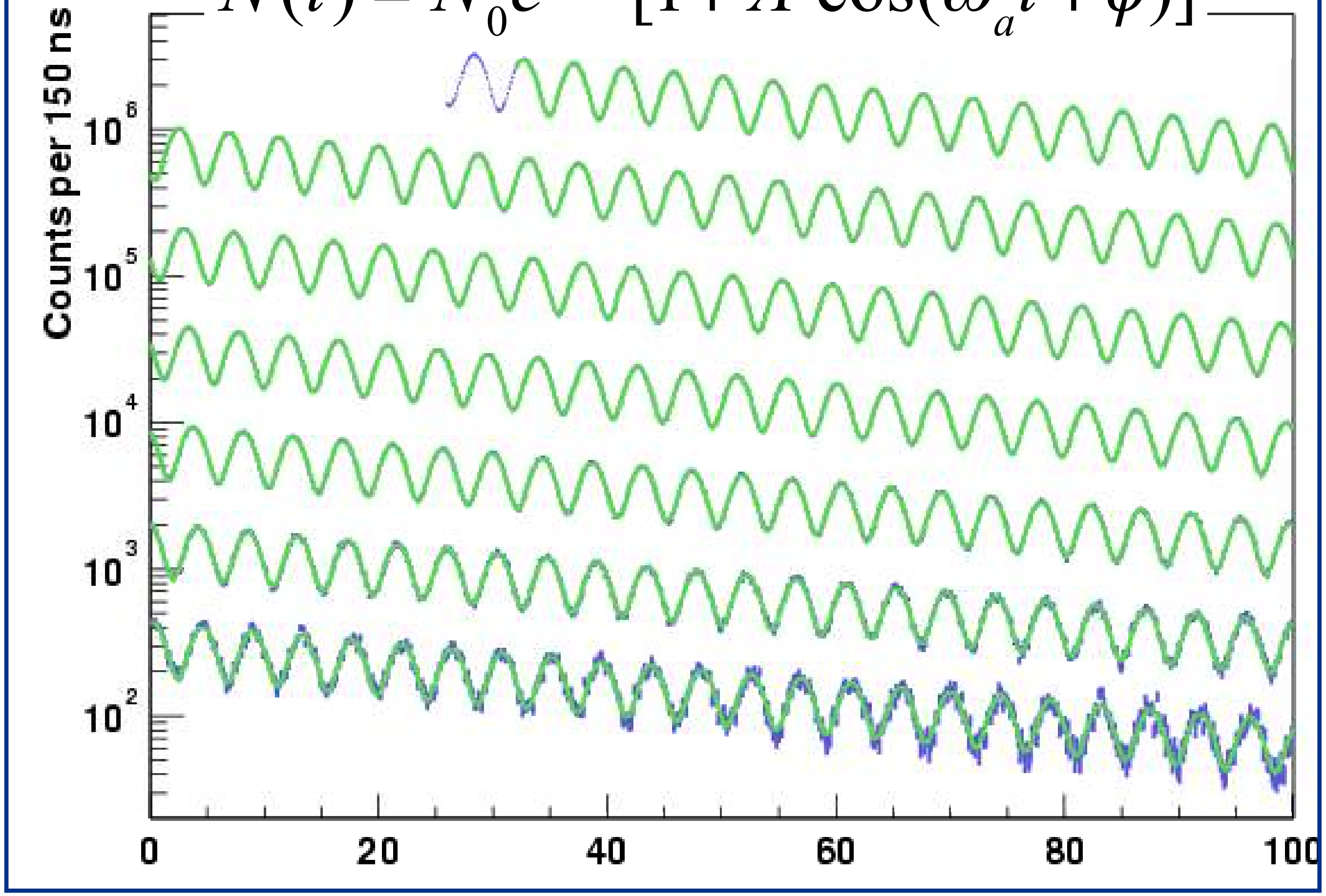
- ... and to measure the muon polarization looking for energetic positrons



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

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



time (μsec)

- 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)

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

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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Additional corrections

- A **beam of muons**
  1. requires focusing elements → *electrostatic quadrupoles*
  2. undergoes *betatron oscillations* around the ideal trajectory
- Additional terms have to be considered in the muon precession formula:

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

Term due to ElectroStatic Quadrupoles (ESQ)

Term due to beam vertical oscillations: *pitch correction*

Becomes ~ 0 at magic $\gamma \sim 29.3$ or $p \sim 3.1$ GeV/c

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* ; described later in the talk

Four articles on PRx and on arXiv for details

PRAB

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

PRA

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

PRD

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

PRL

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)

Run1 Result

Beam Dynamics

Proton Precession

Muon Precession

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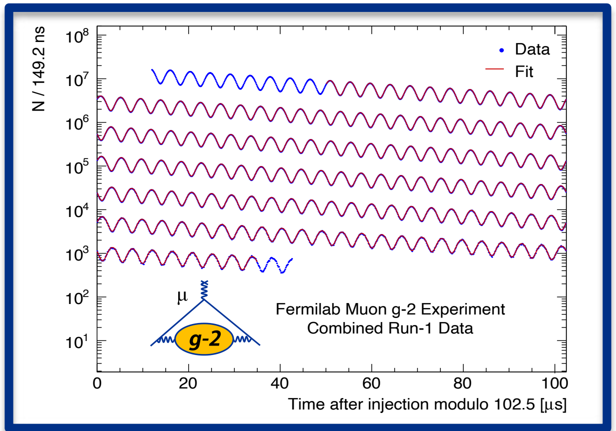
The key ingredients

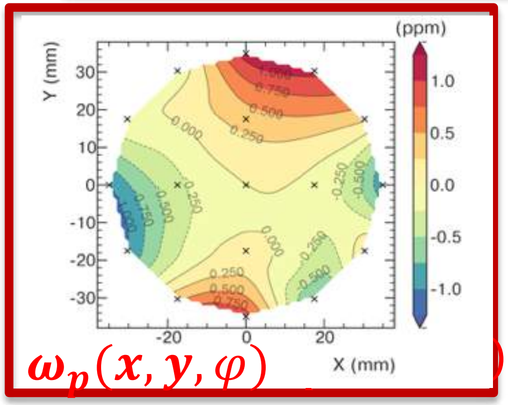
- Neglecting the corrections, the three *key ingredients* to measure the muon magnetic anomaly are:

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

$$\omega_a$$

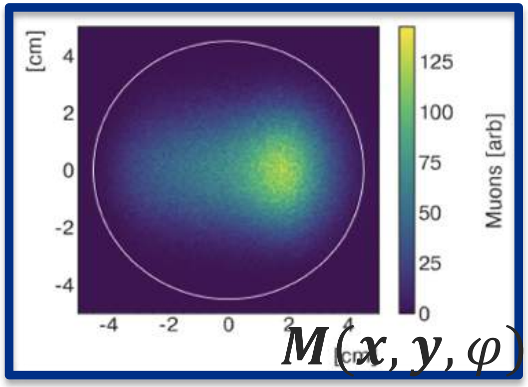


$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \sim$$



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

$\cdot$

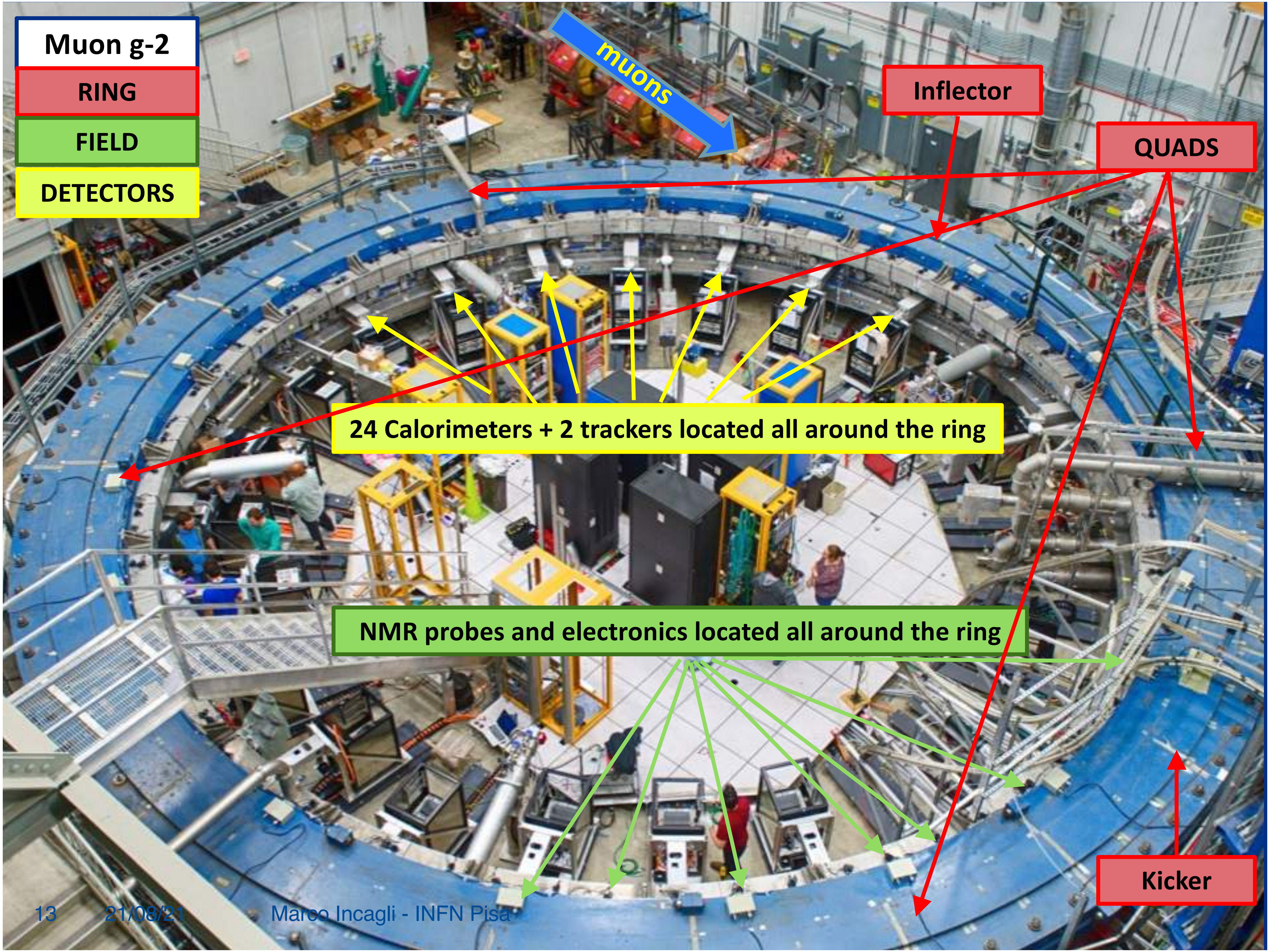


$M(x, y, \varphi)$

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

ω'_p=proton precession frequency

M=muon spatial distribution

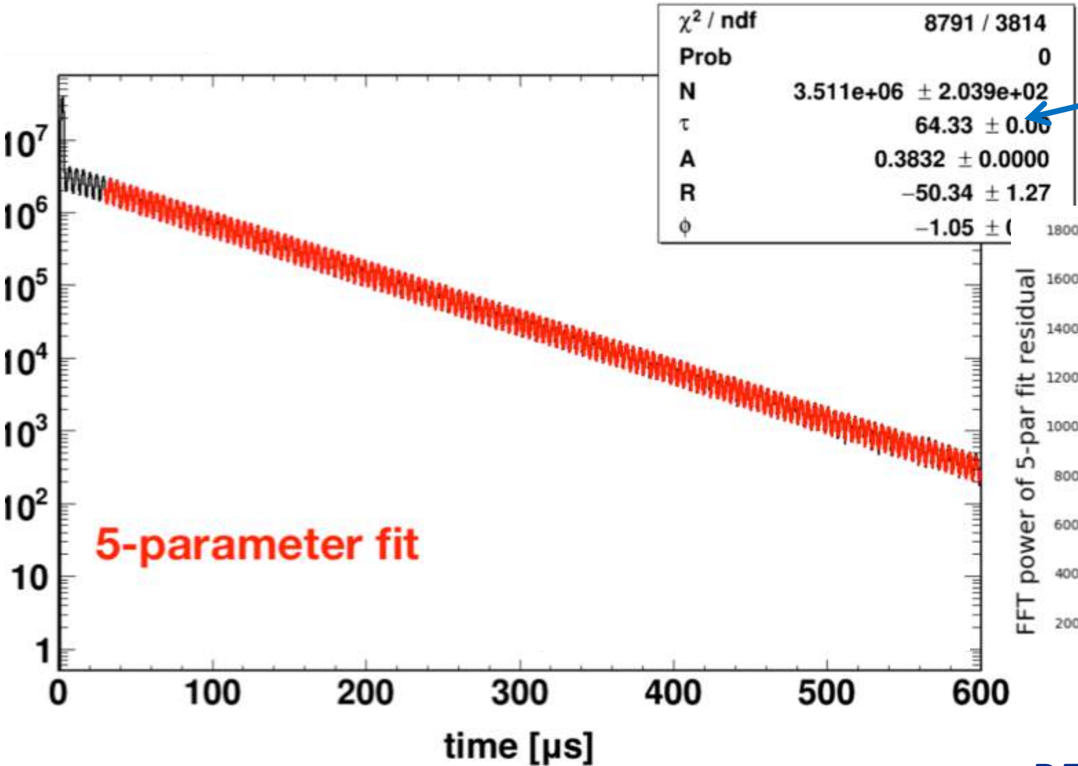

Muon g-2
RING
FIELD
DETECTORS
muons
Inflector
QUADS
24 Calorimeters + 2 trackers located all around the ring
NMR probes and electronics located all around the ring
Kicker

Measuring ω_a : 5 parameters fit function

- Fit with simple positron oscillation:

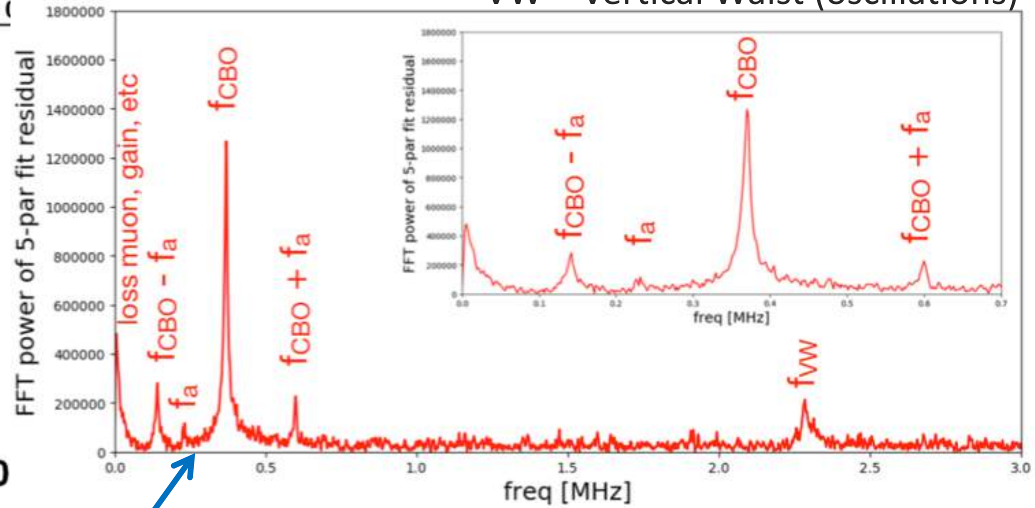
$$N_e(t) = N_0 \exp(-t/\tau_\mu)\,[1 + A\cos(\omega_a t + \varphi)]$$

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



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

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

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

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

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

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

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

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

Red = free parameters
Blue= fixed parameters

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

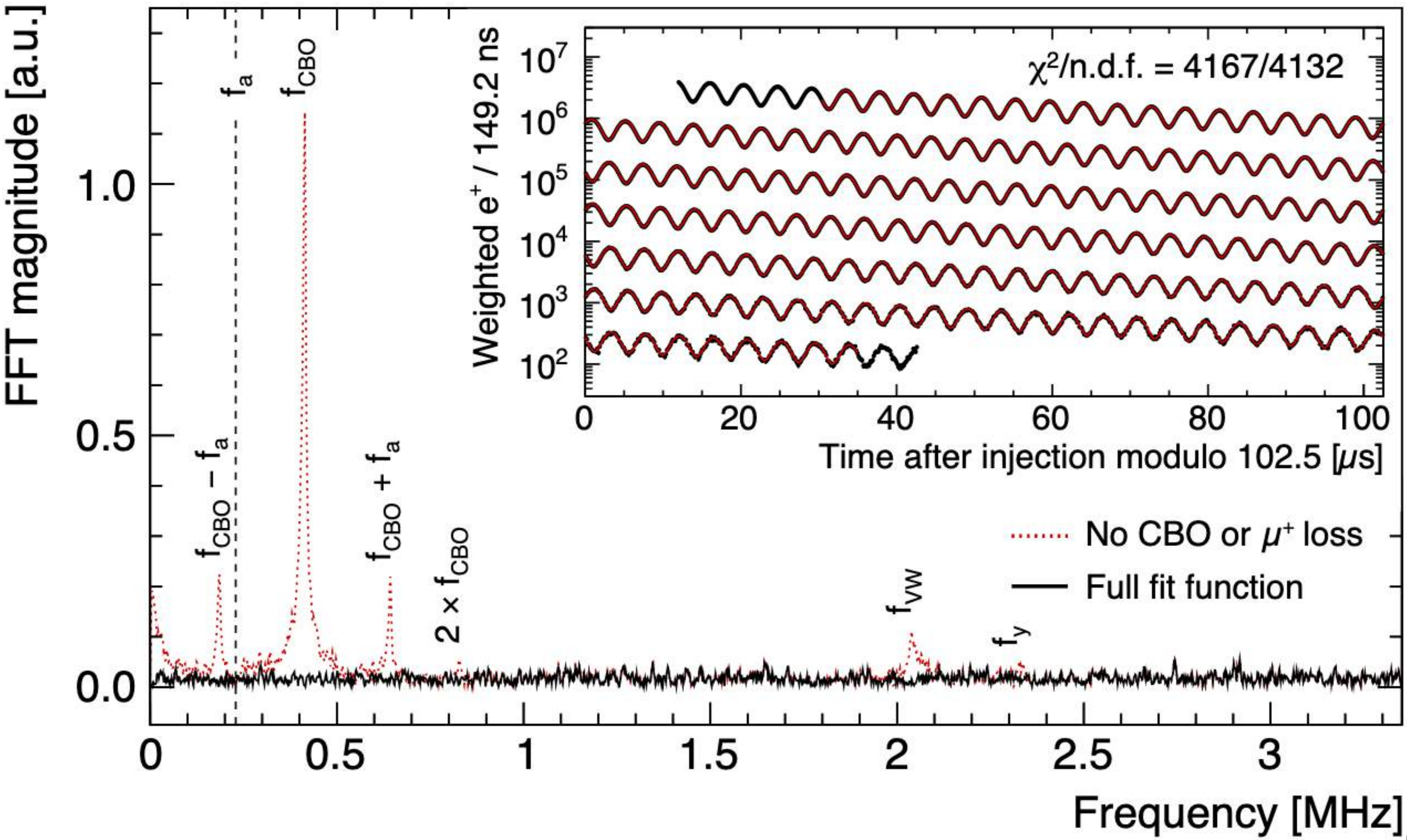
Lost muons (μ hitting collimators)

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

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

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

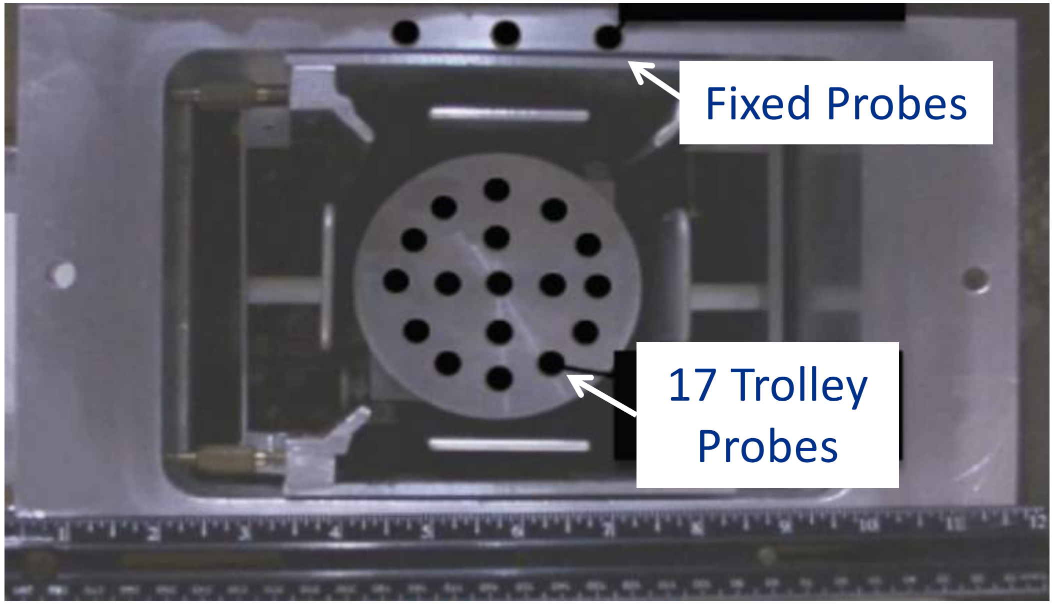
Final fit to get ω_a



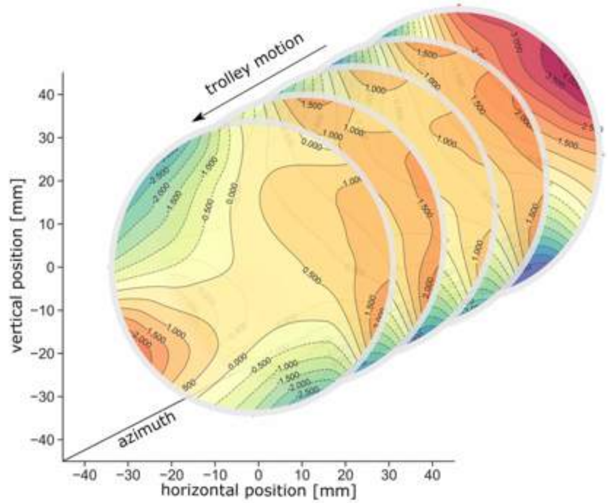
Magnetic field $\vec{B}$ determination

The “trolley”

The "trolley" inside the beam "pipe”



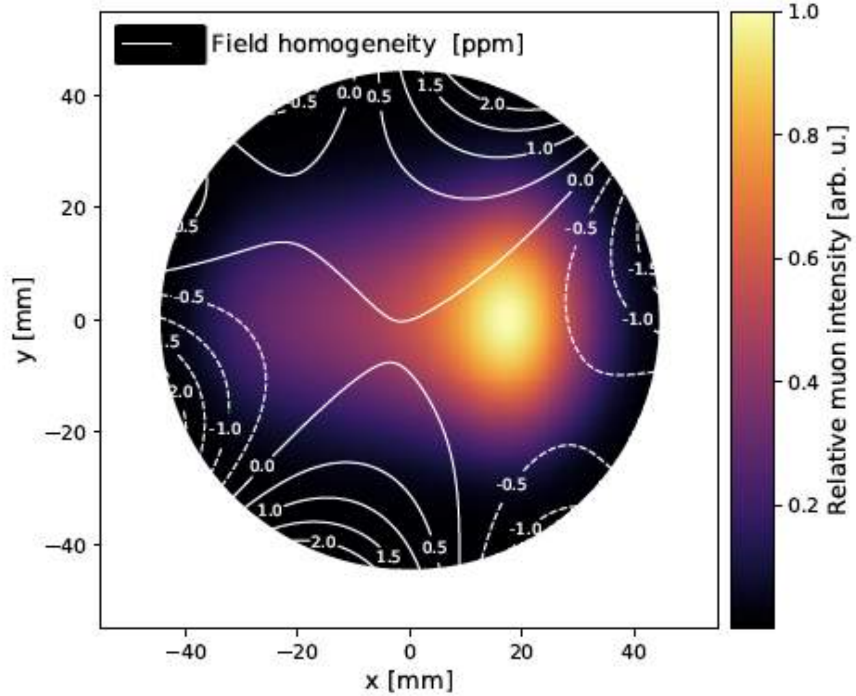
The map



- A ***Trolley*** (Cylinder with 17 NMR probes) 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



Final uncertainties from Run 1, ~8×10⁹ positrons

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

- 462 ppb overall error
  - 434 ppb statistical
  - 157 ppb systematic
    - 25 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

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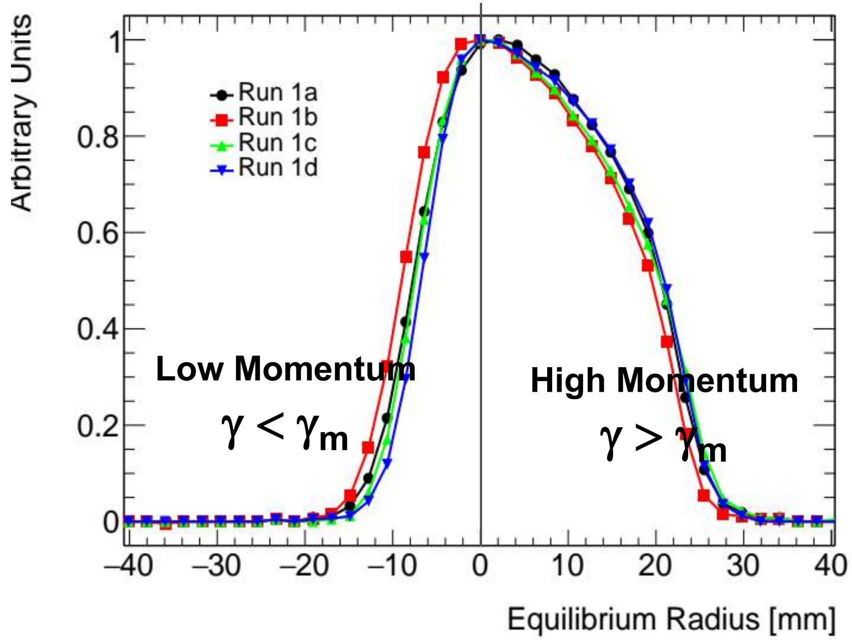
- Correction larger than total error
- Dominated by Electric Field correction C_e
- Related to non-centered radial distribution due to low kicker field (sparks!)
- Fixed in Run-2

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

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



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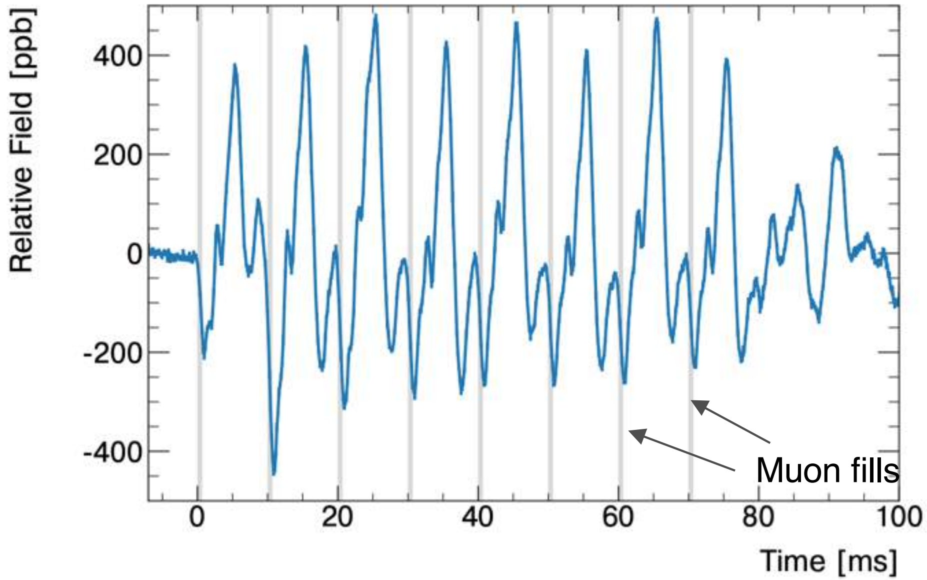
- Two largest systematics:
  - *phase acceptance*
  - *quadrupole field*

ElectroStatic Quadrupoles (ESQ) transient field B_q

- *Mechanical vibration in the plates due to the ESQ charge/discharge which generates magnetic perturbations*
- Special NMR probes measure the perturbation B_q at several positions
- Uncertainty dominated by limited number of measurements in Run-1
- Reduced in Run-2 by more measurements

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

Quad Plates inside Vacuum Chamber



The blinding

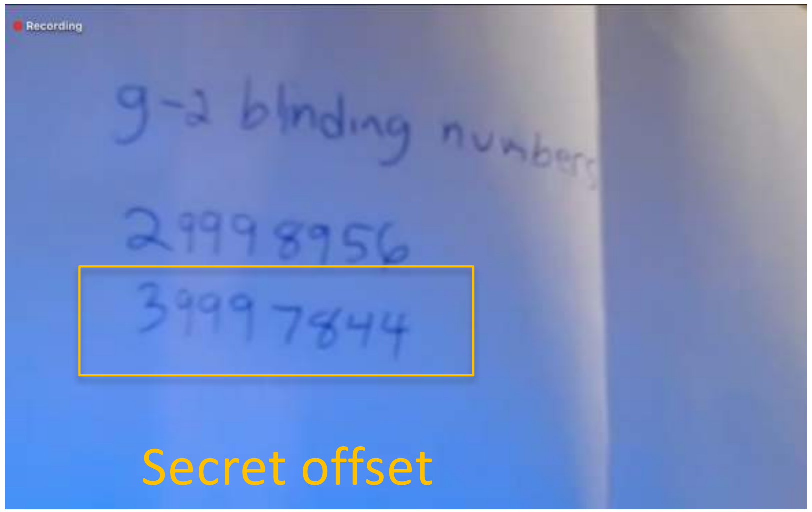
$$R'_\mu = \boxed{f_{clock}} \cdot \frac{\omega_a}{\tilde{\omega}'_p} \cdot \frac{1 + C_e + C_p + C_{ml} + C_{pa}}{1 + B_k + B_q}$$

- 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

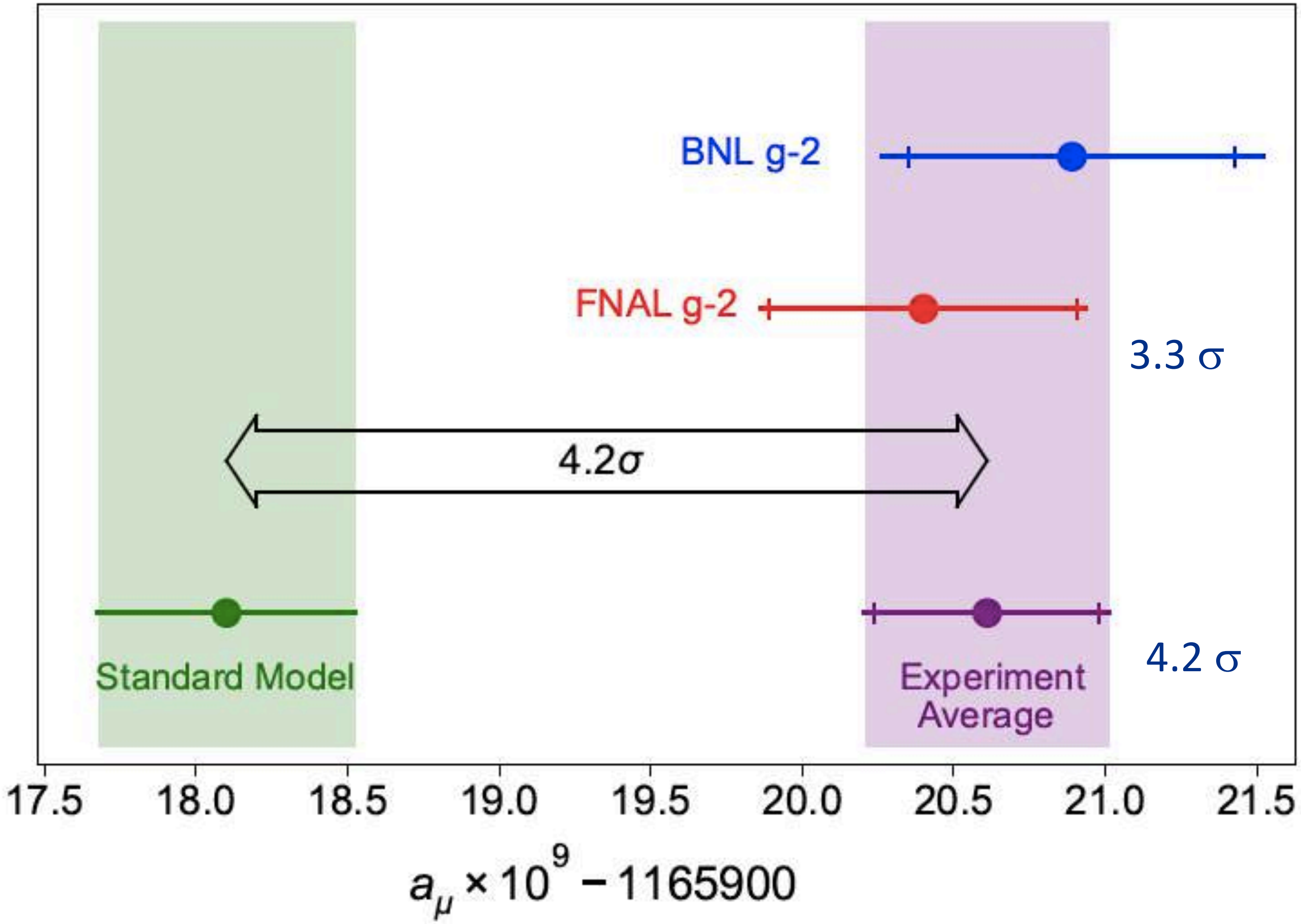
a_μ: Unblinding

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



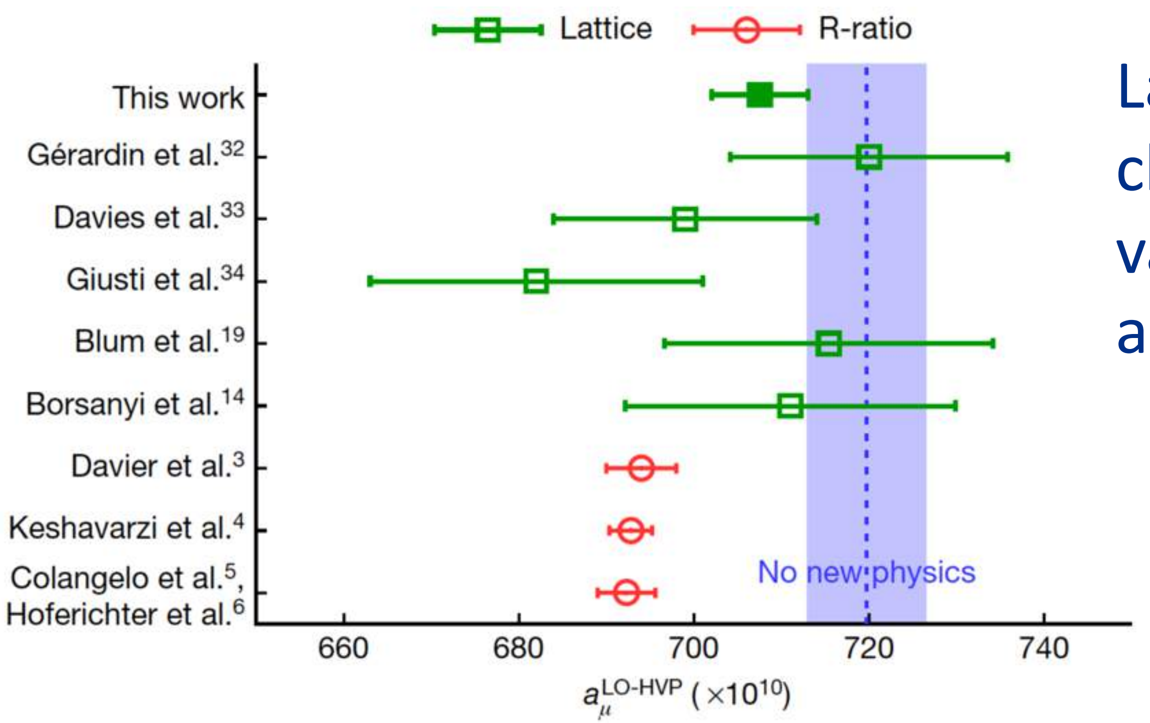
3.7 σ

3.3 σ

4.2 σ

A new prediction based on lattice

- a recent (published April 7!) result has reduced the uncertainty of the lattice calculation from 2-3% to 0.8%!
- breakthrough which requires further scrutiny
- uncertainty similar to the standard approach based on e^+e^- →*hadrons* data via dispersion relation (0.6%)



Lattice calculation closer to experimental value than standard approach

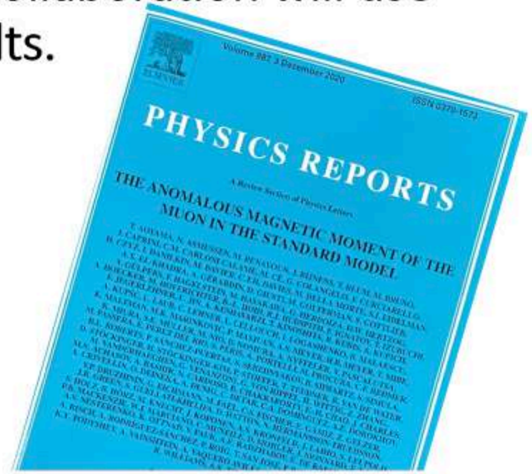
Borsanyi et al (BMWc), Nature 2021

The Theory Initiative

- ~130 physicists collaborated for 3 years [June 2017 – June 2020] in seven workshops to produce a reference number for am to be used by FNAL g-2 experiment as a benchmark

Muon g-2 Theory Initiative defines SM benchmark value that our collaboration will use for comparison. We don't "pick and choose" other individual results.

Group photo from the Seattle workshop in September 2019, https://indico.fnal.gov/event/21626/

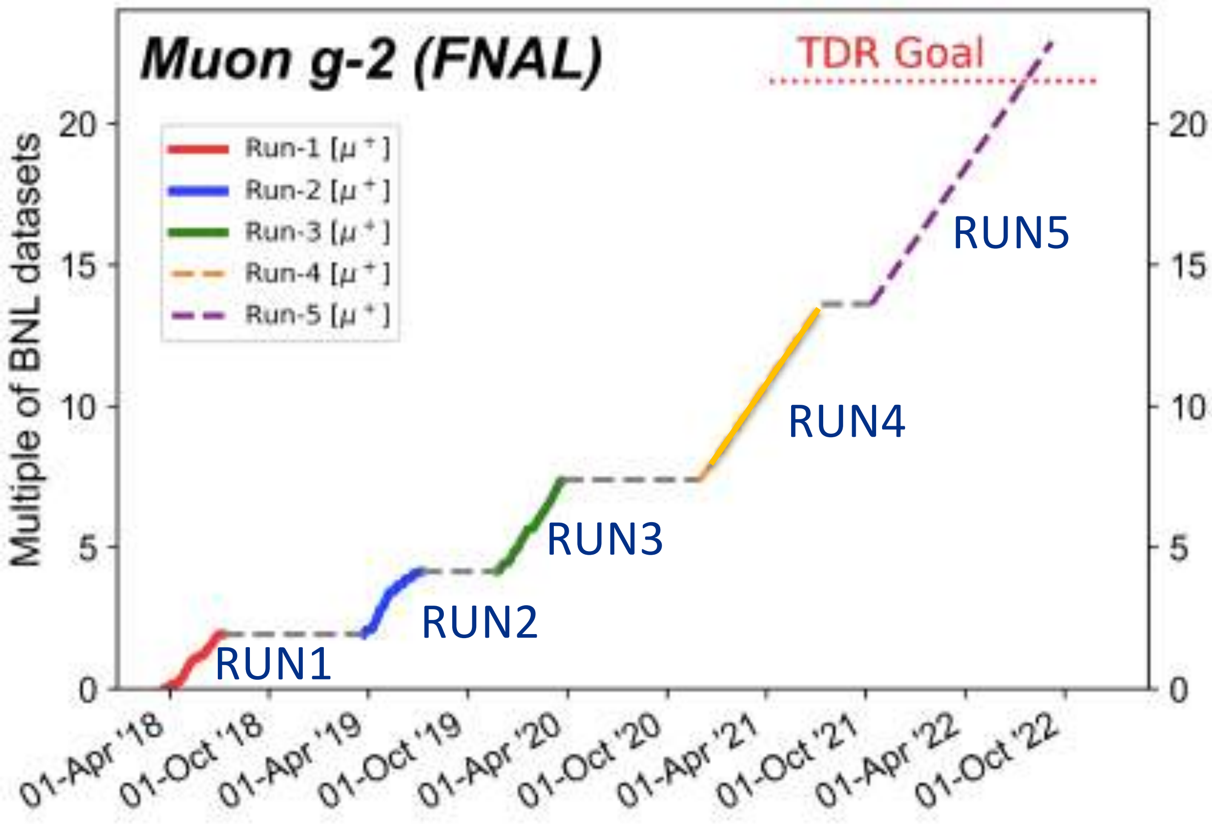


Organizers:
Aida El-Khadra
Martin Hoferichter
DWH

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	Sec. 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	Sec. 2.3.8	Eq. (2.34)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	Sec. 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, *udsc*)	Sec. 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Sec. 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Sec. 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, *uds*)	Sec. 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Sec. 8	Eq. (8.10)	90(17)	Refs. [18–30, 32]
QED	Sec. 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33, 34]
Electroweak	Sec. 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35, 36]
HVP (e^+e^-, LO + NLO + NNLO)	Sec. 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Sec. 8	Eq. (8.11)	92(18)	Refs. [18–32]
WP20 Total SM Value	Sec. 8	Eq. (8.12)	$\boxed{116\,591\,810(43)}$	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	Sec. 8	Eq. (8.14)	279(76)	

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

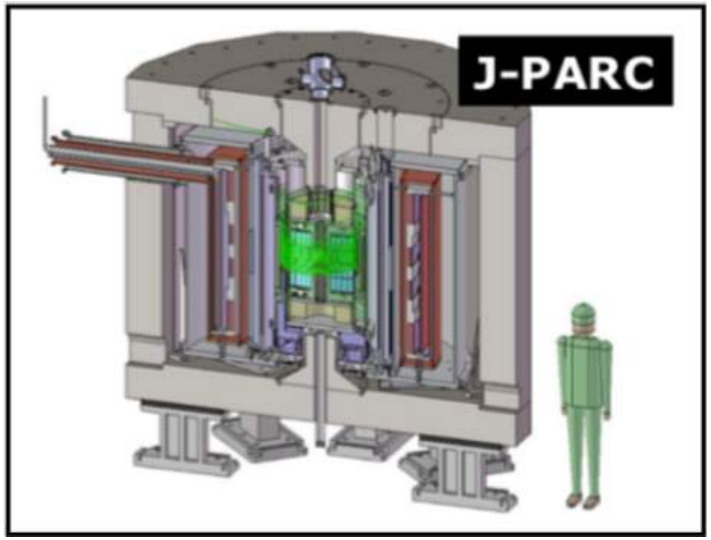
- RUN-1 is only 6% of the final dataset
- Analysis of RUN-2/3 in progress (factor ~2 in precision)
- RUN-4 (November 2020-July 2021), which was recently completed, and Run5 (2021-2022) will allow to reduce by a factor ~4 current error



Conclusions: experiment

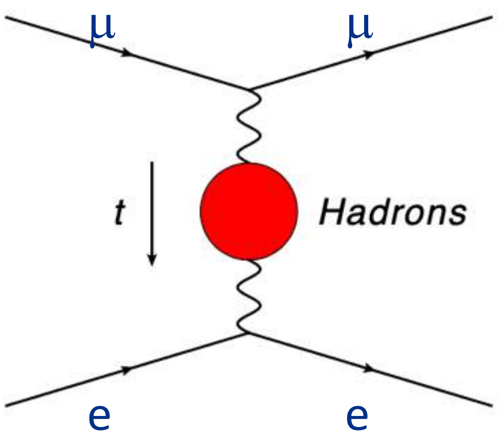
1. FNAL Muon g-2 :
   - **a_μ measured at 0.46 ppm → 4.2σ discrepancy!**
   - data already available to reduce error to ~0.25 ppm
   - Run4 (just finished) and Run5, starting later this year 2021, will allow to reach ~0.15 ppm

2. A new type of experiment projected at J-Parc using low energy muons (p~300 MeV/c)
   - new technique
   - under construction
   - final goal ~0.4 ppm



Conclusions: theory

1. close scrutiny of lattice calculations to establish its solidity
   - how to reconcile it with dispersion approach? and with Standard Model global EW fit? → *next talks*
2. Use the dispersive approach with t-channel data (*muon-electron* scattering), instead of the standard s-channel
   - Letter Of Intents submitted at CERN: *Muone (mu-on-e scattering)*



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

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

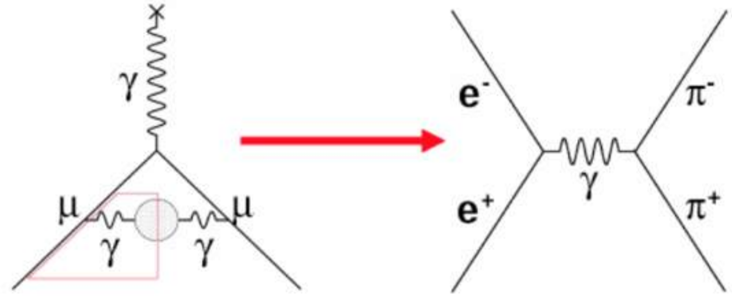
Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the spacelike region: a_μ^{HLO} can be extracted from scattering data!

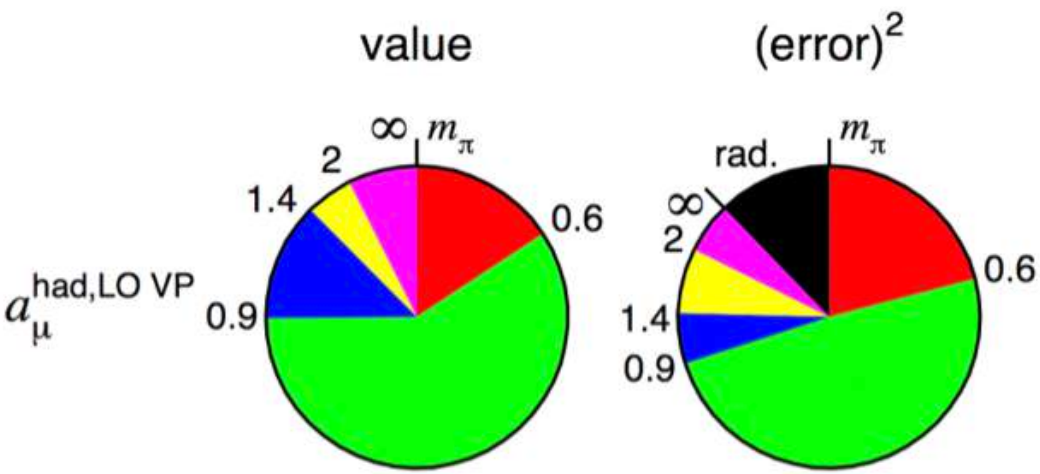
BACKUP SLIDES

a_μ^{HLO} : dispersion integral

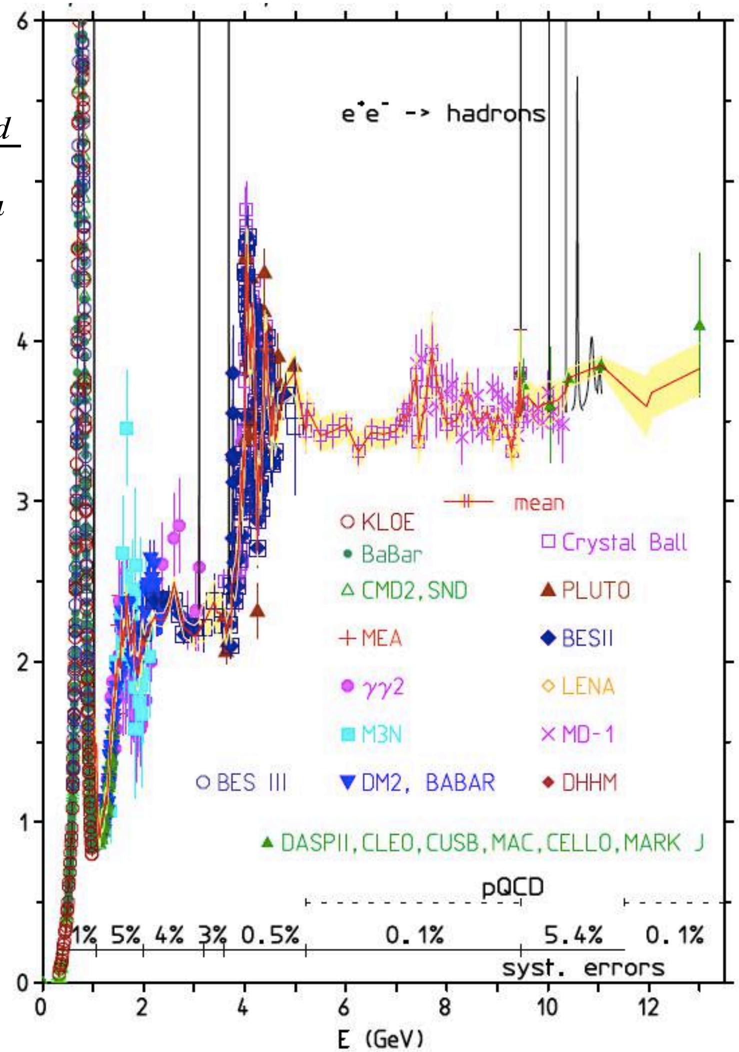
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^- \to hadr}(s)K(s)\,ds$$



- Kernel function: $K(s) \propto {}^{1}/_{s}$
- Due to the 1/s term, the low energies most important

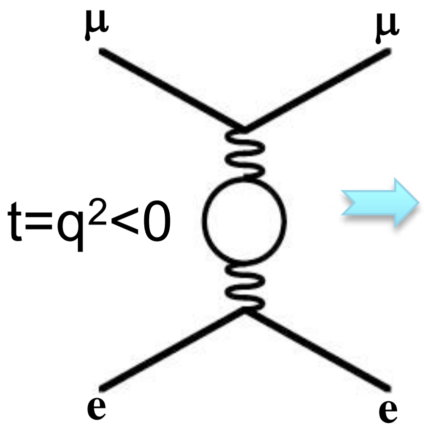


$$R = \frac{\sigma_{had}}{\sigma^0_{\mu\mu}}$$



a_μ^{HAD} from $\mu + e \rightarrow \mu + e$ scattering

- NEW IDEA:
  - measure a_μ^{HAD} using $\mu e \rightarrow \mu e$ (t-channel) instead of $ee \rightarrow \pi\pi$!



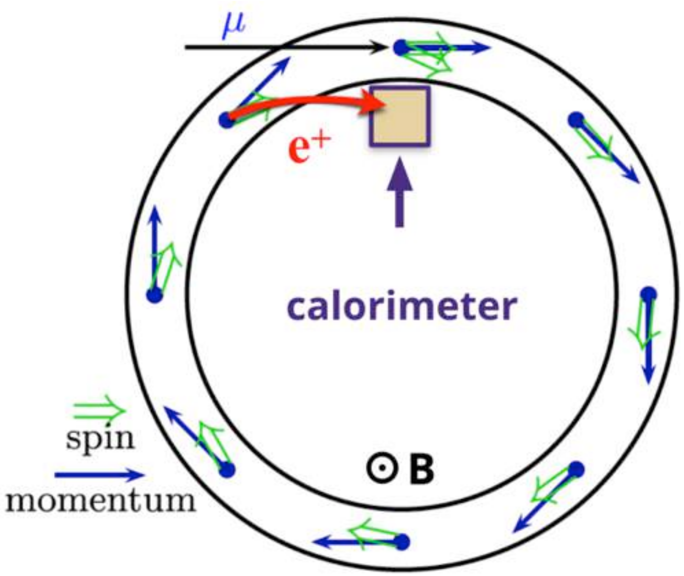
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \Rightarrow \alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha_{LEP}(t) - \Delta\alpha_{HAD}(t)}$$

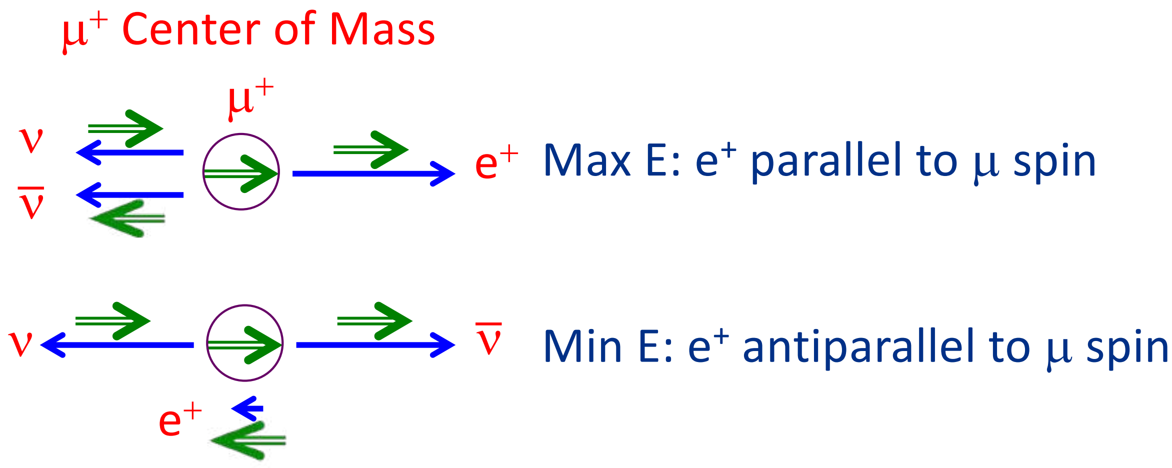
$$\boxed{a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}(x)dx}$$

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

$t=0$ $t=-\infty$

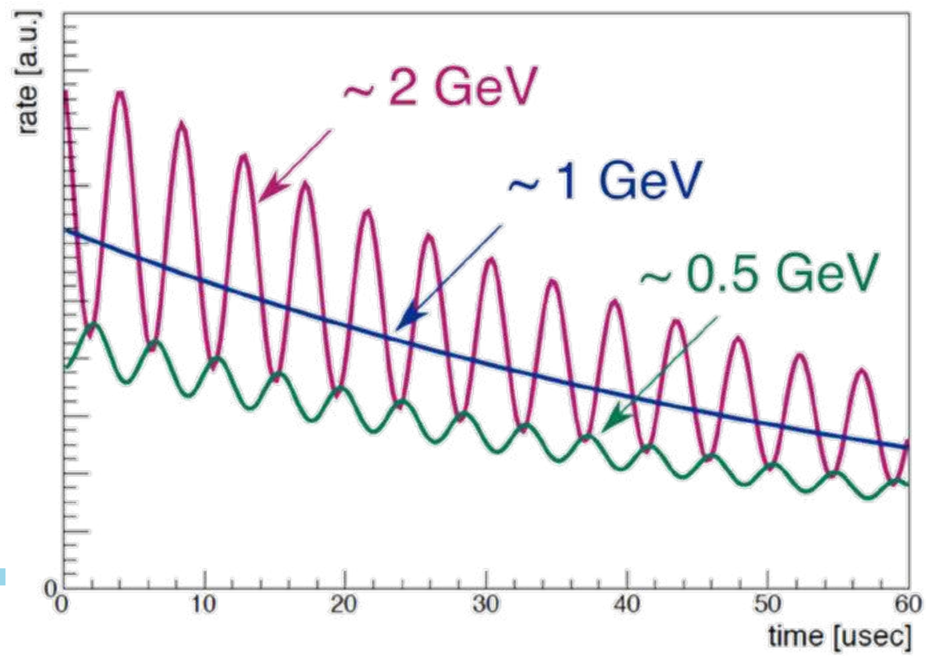
ω_a principle of measurement





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

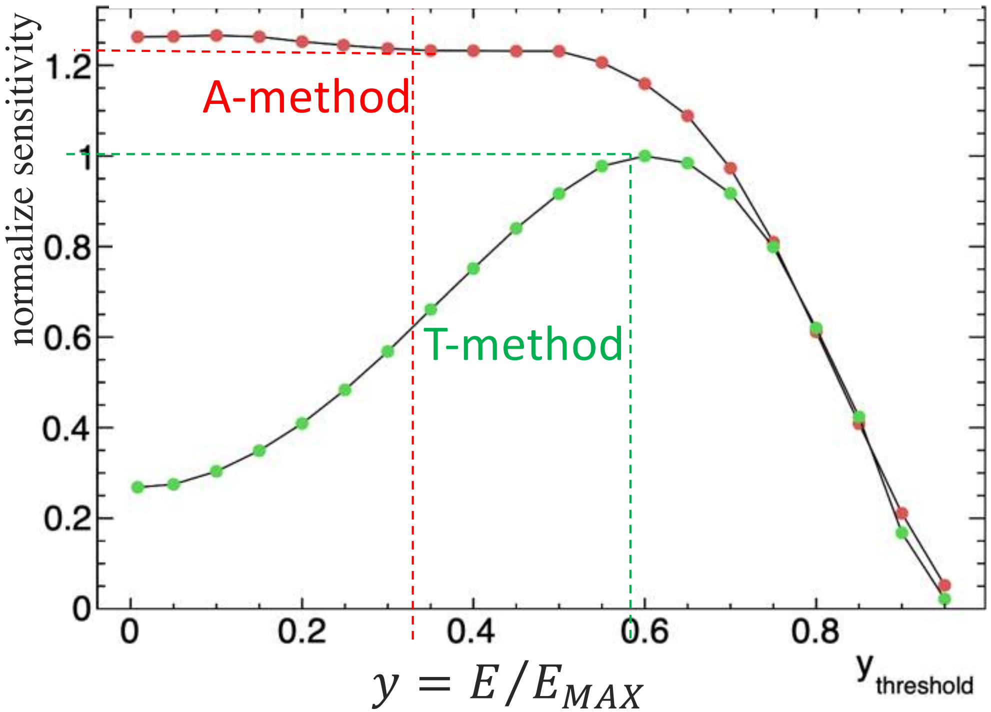
- positron emission correlated with muon spin direction
- correlation depends on *positron energy* : the Asymmetry A(E) can be positive, null or negative



Optimizing the statistical sensitivity

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

- **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



$y = E/E_{MAX}$
$(E_{MAX} = 3.1 GeV)$

- 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*

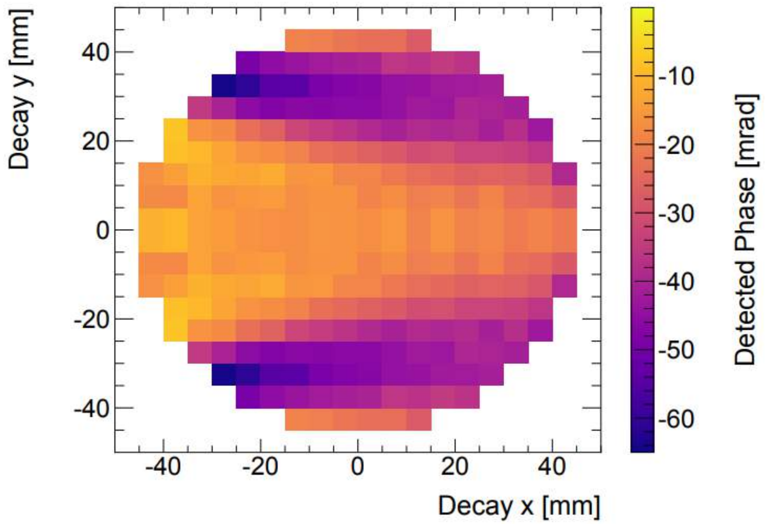
C_{PA} – Phase acceptance error

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

- But if the phase of the muon population changes in time :

$$\cos(\omega_a t + \phi(t)) \approx \cos(\omega_a t + \phi' t + \phi_0) = \cos((\omega_a + \phi')t + \phi_0)$$

- The extracted ω_a is shifted by ϕ' !



- The phase depends on the muon decay position (x,y)
- Not a big issue if the muon distribution remains stable with time

C_{PA} – Phase acceptance error

- 2 quadrupoles 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