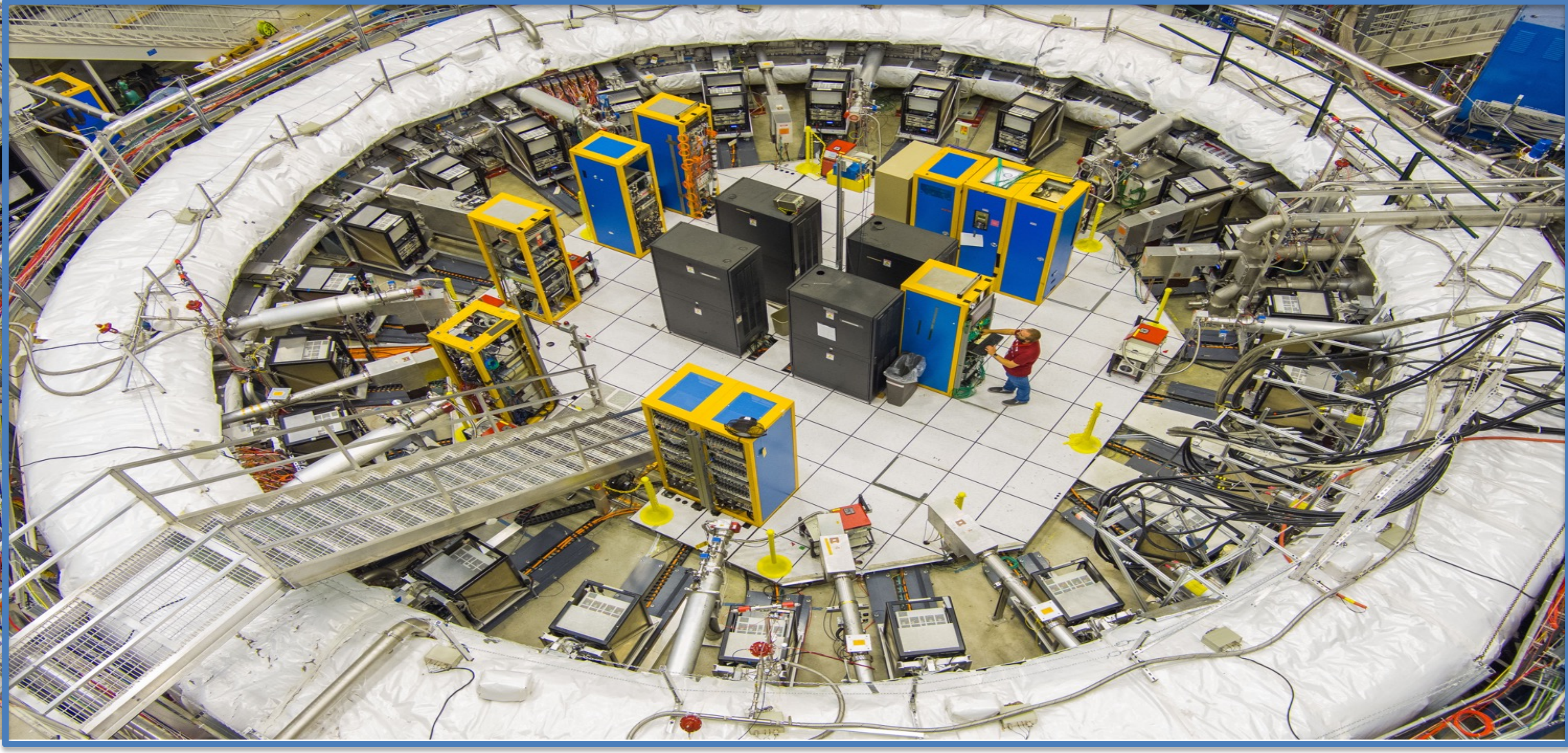


Muon g-2: Theory vs Experiment

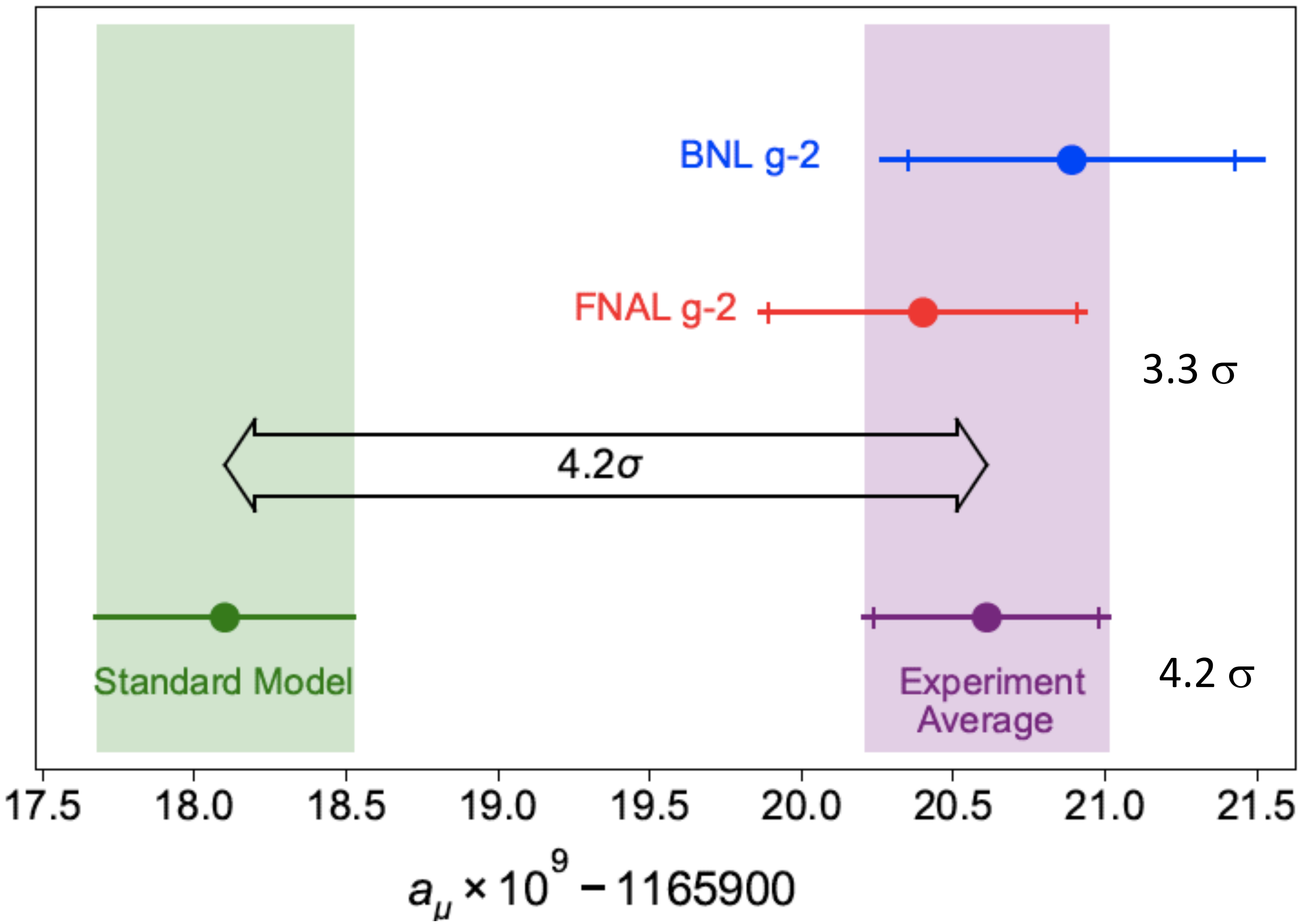
Graziano Venanzoni

University of Liverpool and Sezione INFN Pisa

Present and Future perspectives in Hadron Physics – LNF – 19 June 2024

April 7th 2021:
First results from the Muon g-2 experiment at FNAL

Muon g-2



3.7 σ

3.3 σ

4.2 σ

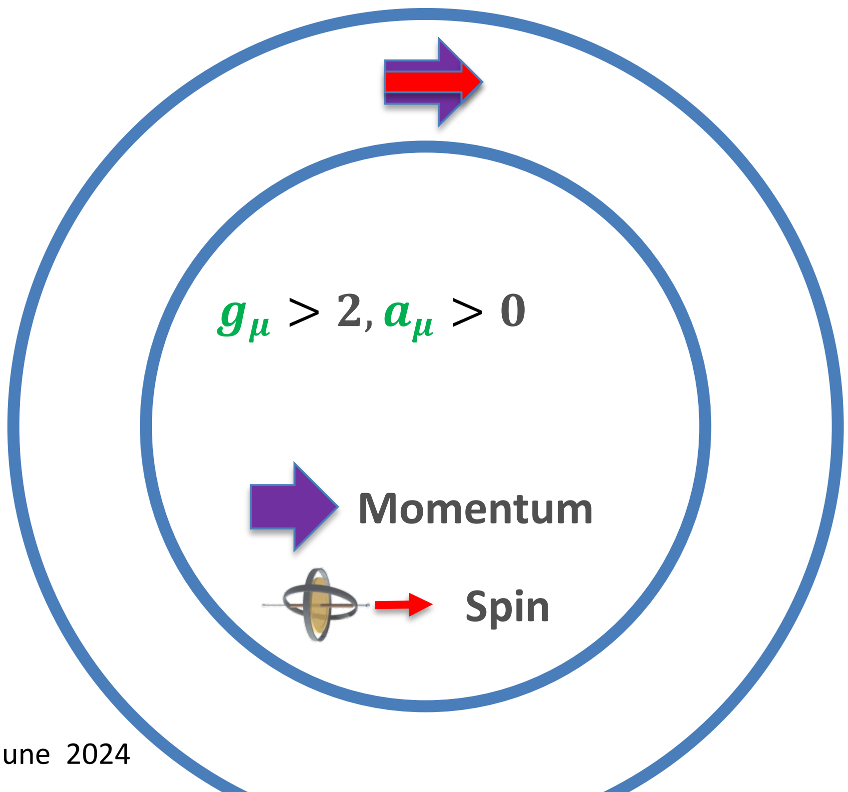
$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

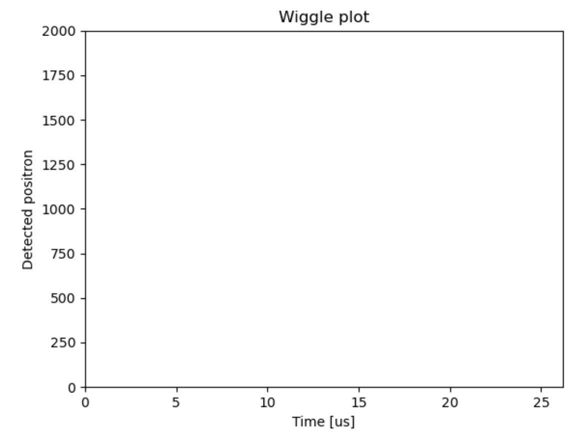
How to measure a_μ =(g-2)/2…

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g>2 (a>0) spin advances respect to the momentum



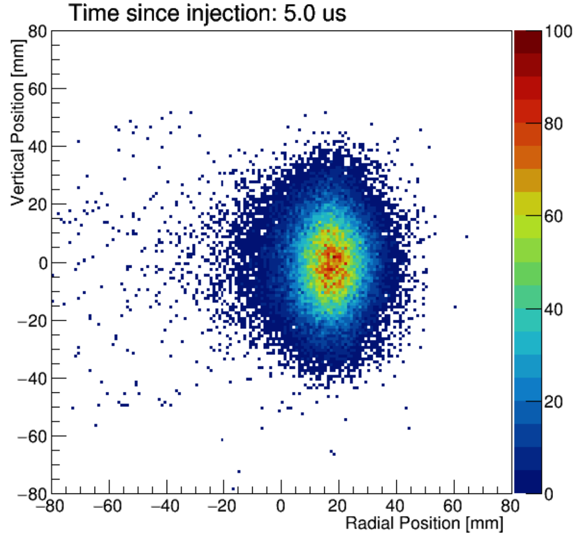


By measuring directly a_μ x800 more sensitive than an experiment which measures g

Current experiments δa_μ < 1ppm

However there are beam dynamics effects

- The muon beam oscillates and breathes as a whole
- The full equation is more complex and corrections due to radial (x) and vertical (y) beam motion are needed



$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c =$$

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

- Running at γ_{magic}=29.3 (p=3.094 GeV/c) this coefficient is null
- Because of momentum spread (<0.2%)→ **E-field Correction**

- Vertical beam oscillation → **Pitch correction**

Extracting a_μ

Corrections due to beam dynamics

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + \overbrace{C_e + C_p + C_{pa} + C_{dd} + C_{ml}}}{1 + \underbrace{B_k + B_q}}$$

Measured Values

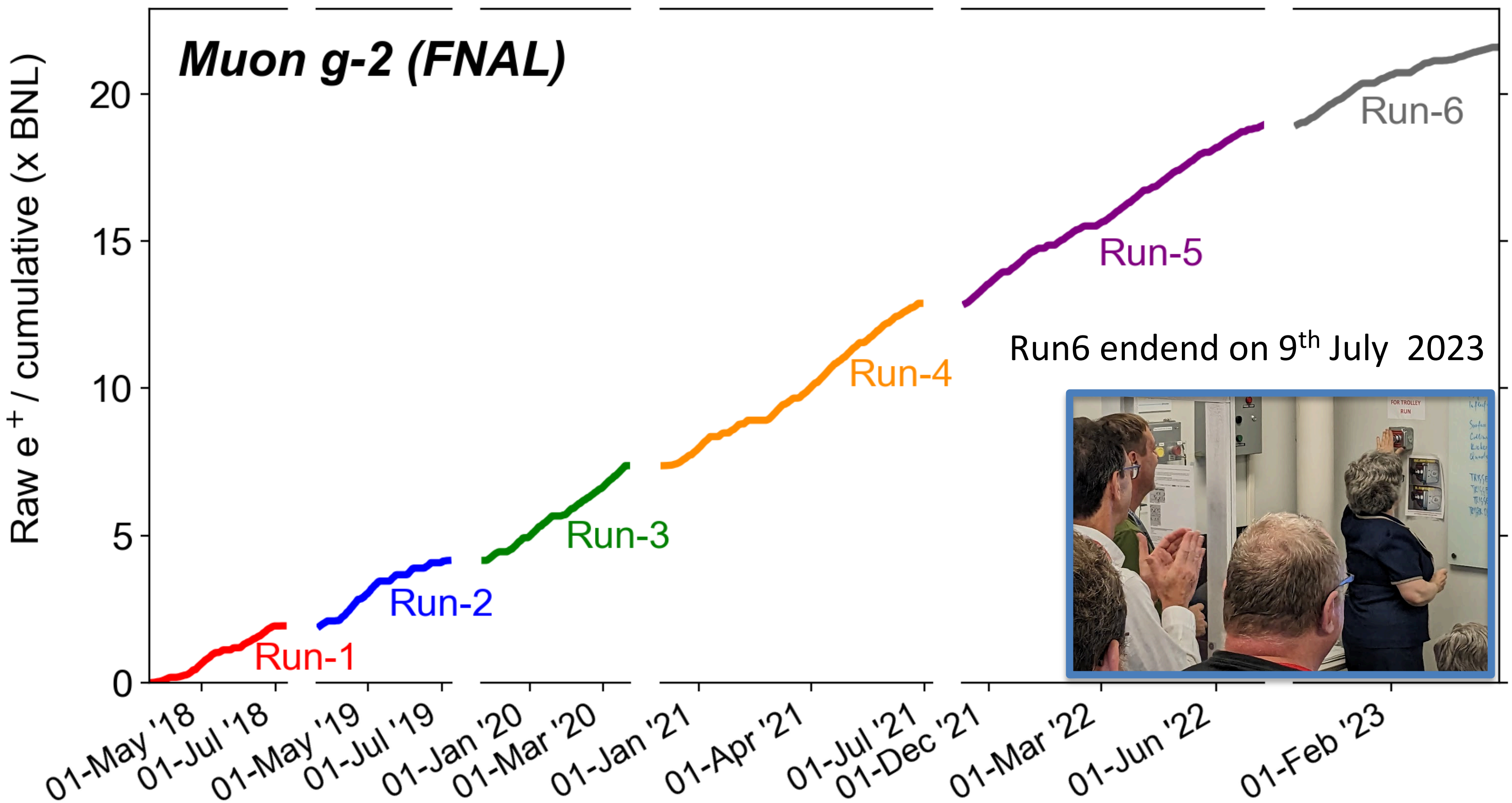
Corrections due to transient magnetic fields

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

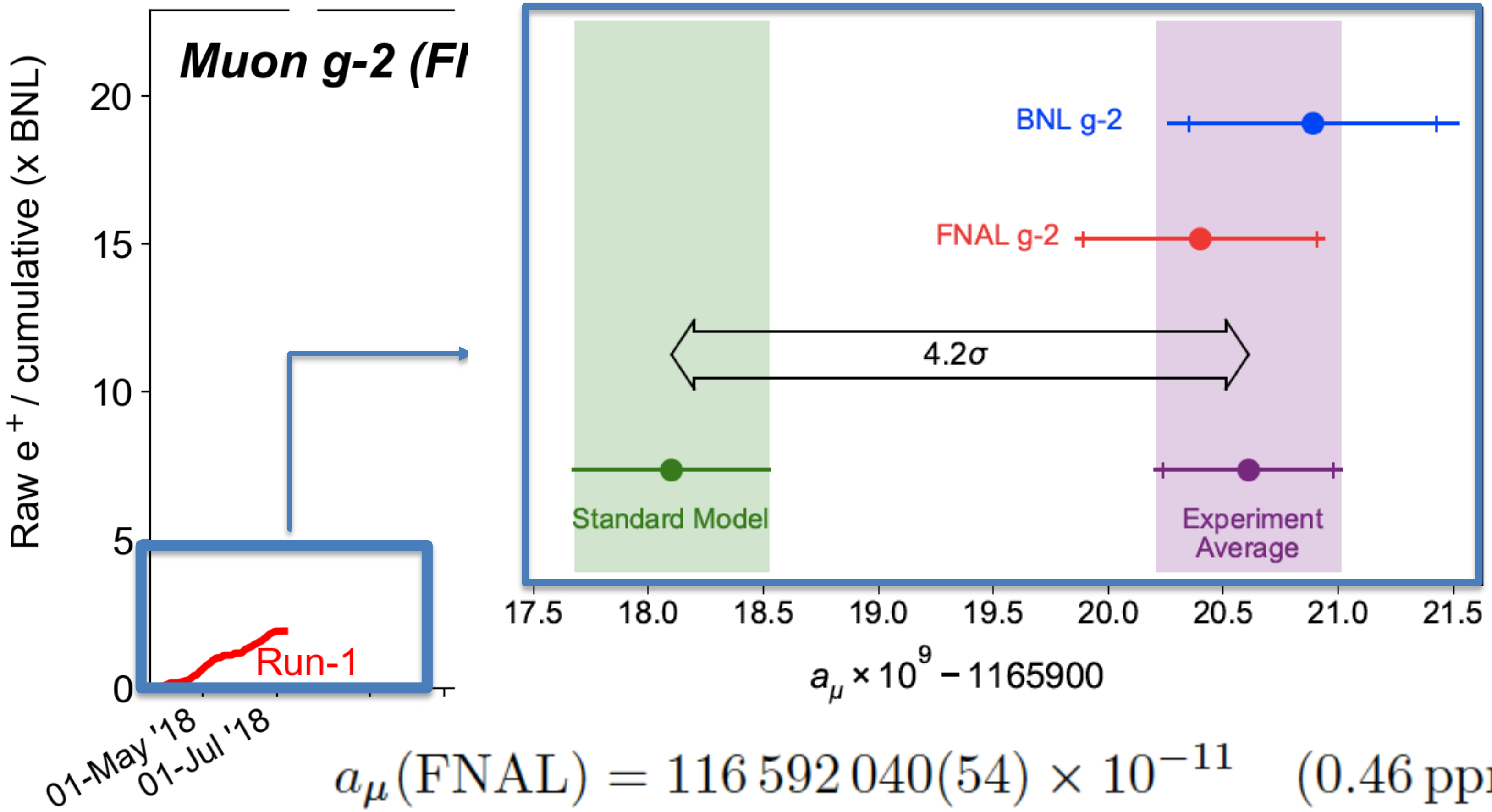
All these quantities have been evaluated throughout in the analysis of Run2/3 data: Total correction is **622 ppb**, dominated by **E-field & Pitch**

Collected statistics from Muon g-2: x21.9 BNL datasets

On 27 February 2023: proposal Goal of x21 BNL datasets!

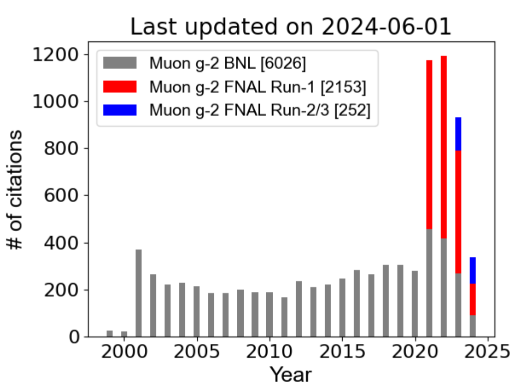


7 April 2021: We released our first result

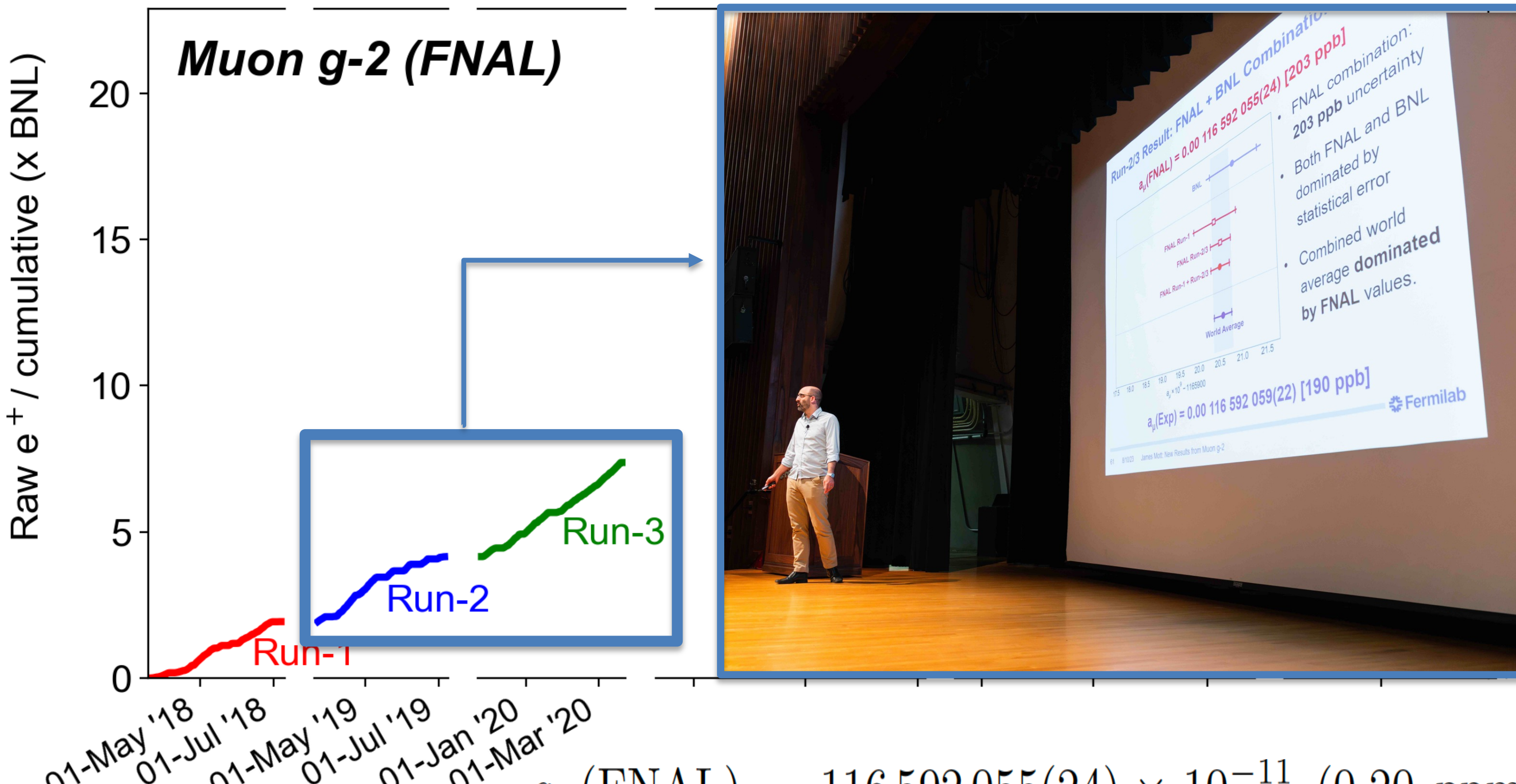


$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \qquad (0.46\,\mathrm{ppm})$$

4 Phys Rev journals on April 2021(>1700 citations)



10 August 2023: We released our new result



$$a_\mu(\mathrm{FNAL}) = 116\,592\,055(24) \times 10^{-11} \;\; (0.20\;\;\mathrm{ppm})$$

More than 4 times the statistics of Run1

submitted to PRL on 10 August 2023

Muon g-2

PRL

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm

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D. Flay,[32] S. B. Foster,[2] H. Friedsam,[7] N. S. Froemming,[20] C. Gabbanini,[10,j] I.
S. Ganguly,[7] A. Garcia,[36] J. George,[32,k] L. K. Gibbons,[6] A. Gioiosa,[25,l] K. L.
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O. Kim,[34] N. Kinnaird,[2] E. Kraegeloh,[33] V. A. Krylov,[15] N. A. Kuchinskiy,[15] K
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H. Nguyen,[7] Y. Oksuzian,[1] Z. Omarov,[16,5] R. Osofsky,[36] S. Park,[5] G. Pauletta,
R. N. Pilato,[30] K. T. Pitts,[28,u] B. Plaster,[29] D. Počanić,[35] N. Pohlman,[20] C. C. P
M. U. H. Qureshi,[14] S. Ramachandran,[1,k] E. Ramberg,[7] R. Reimann,[14] B. L.
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(The Muon $g-2$ Collaboration)

PRL 131 (2023) 16, 161802

PRD

Detailed Report on the Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm

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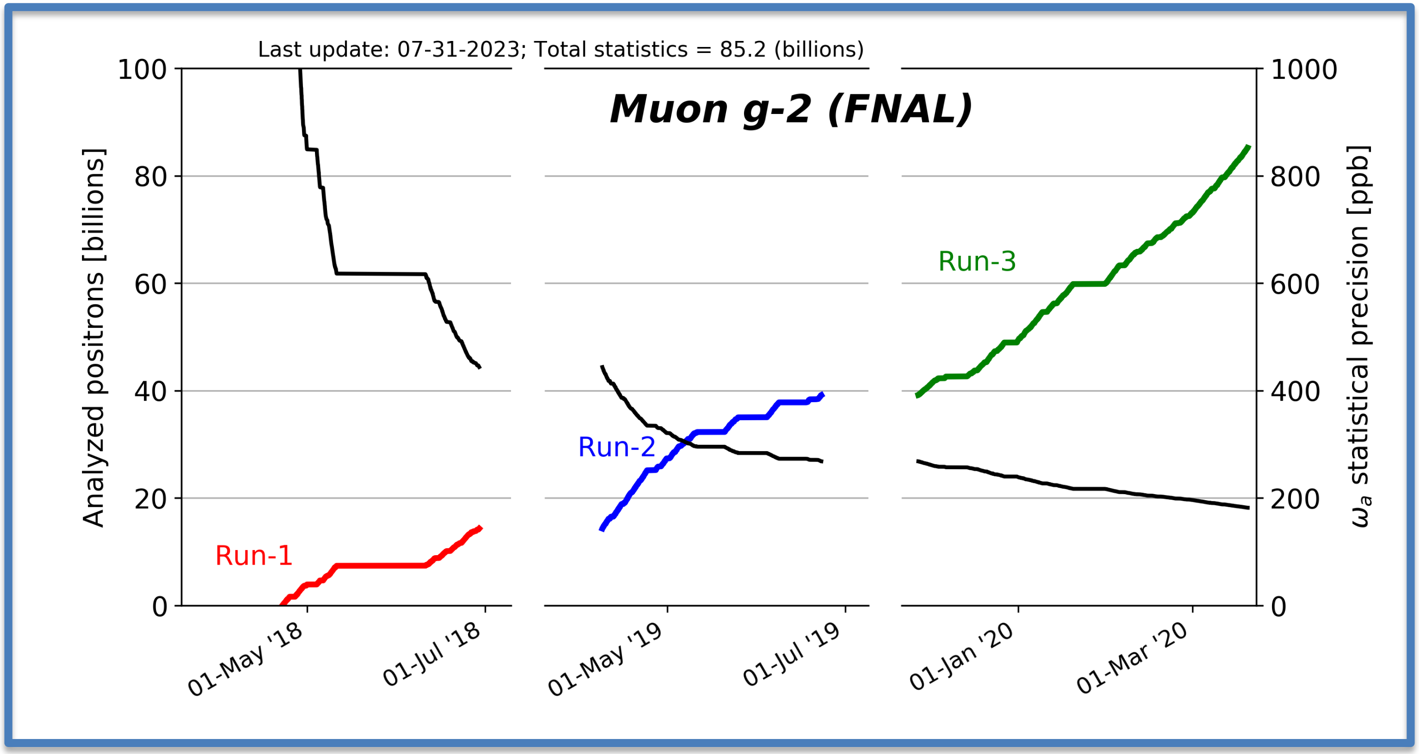
(The Muon $g-2$ Collaboration)

hep-ex: 2402.15410 accepted per publication in PRD

Run-2/3 Improvement: Statistics

Muon g-2

Number of e^+
with $E > 1$ GeV
$t > 30\ \mu s$

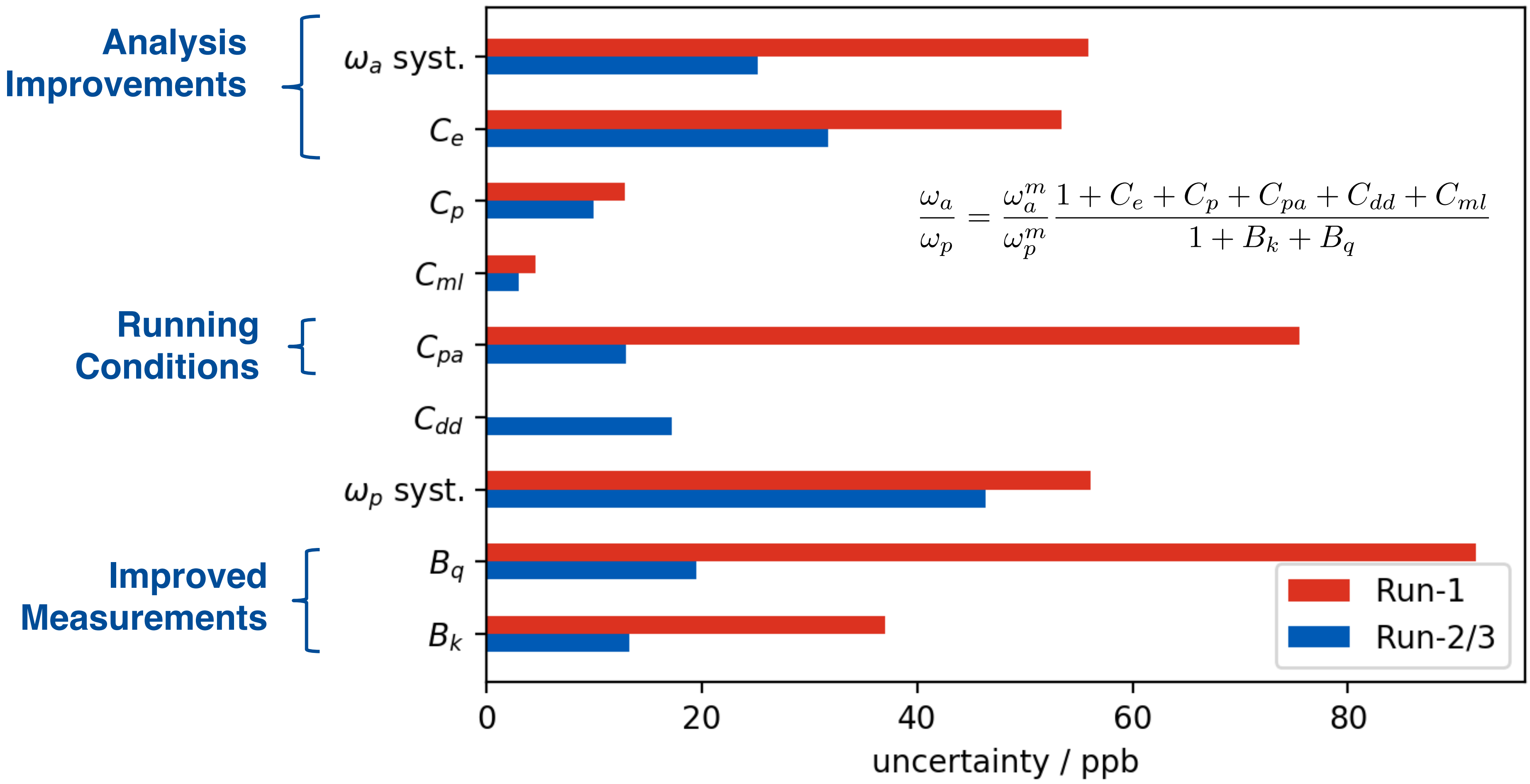


- Factor 4.7 more data in Run-2/3 than Run-1

Dataset	Statistical Error [ppb]
Run-1	434
Run-2/3	201
Run-1 + Run-2/3	185

Run-2/3 Improvement: Systematics

- Systematic improvements in **all parameters**



Run-2/3 Uncertainties

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

- Total uncertainty is **215 ppb**

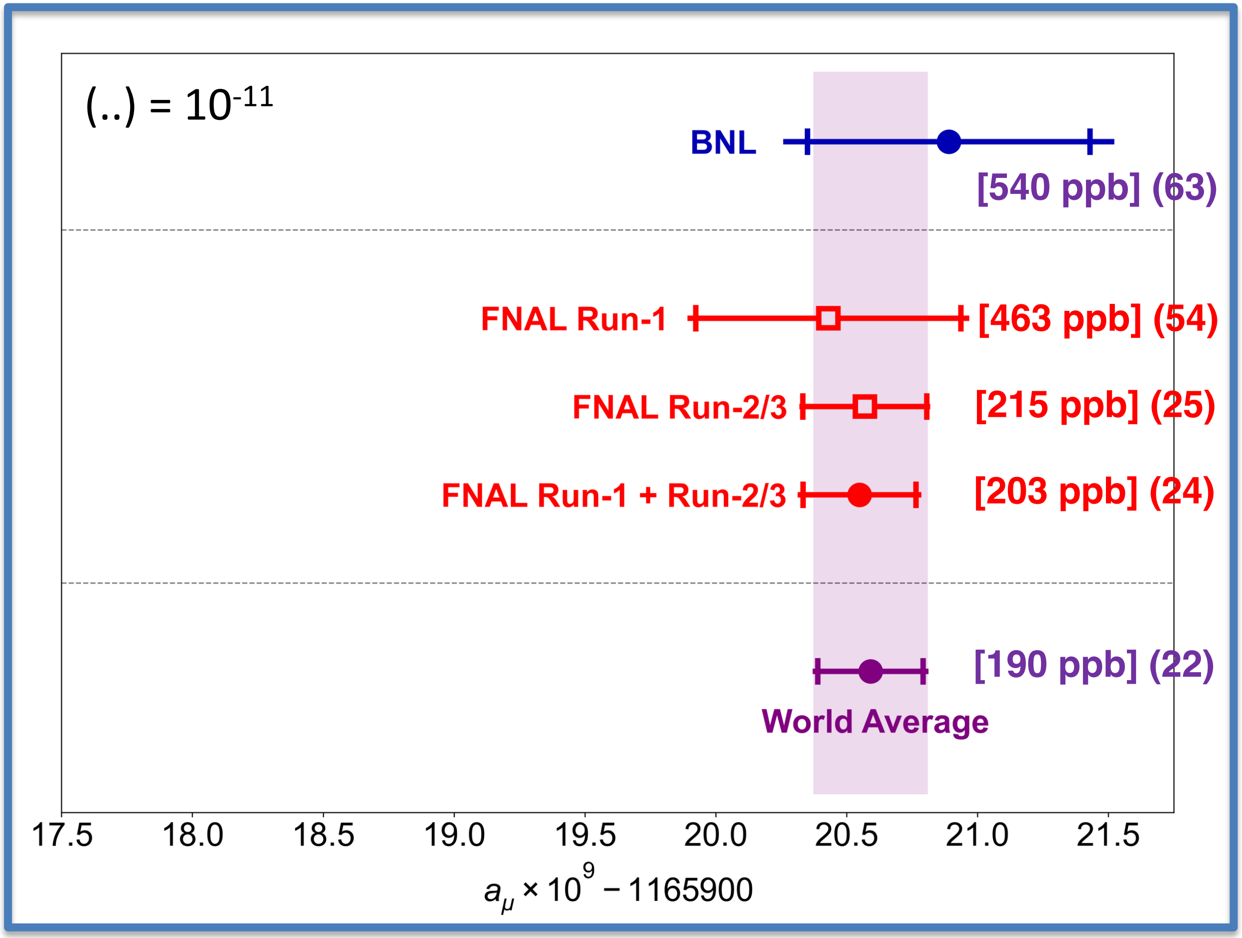
[ppb]	Run-1	Run-2/3	Ratio
Stat.	434	**201**	2.2
Syst.	157	**70**	2.2

- Near-equal improvement: We're still **statistically dominated**

Systematic uncertainty of 70 ppb surpasses our proposal goal of 100 ppb!

Run-2/3 Result: FNAL + BNL Combination

a_μ(FNAL) = 116 592 055(24) x10^{-11} [203 ppb]

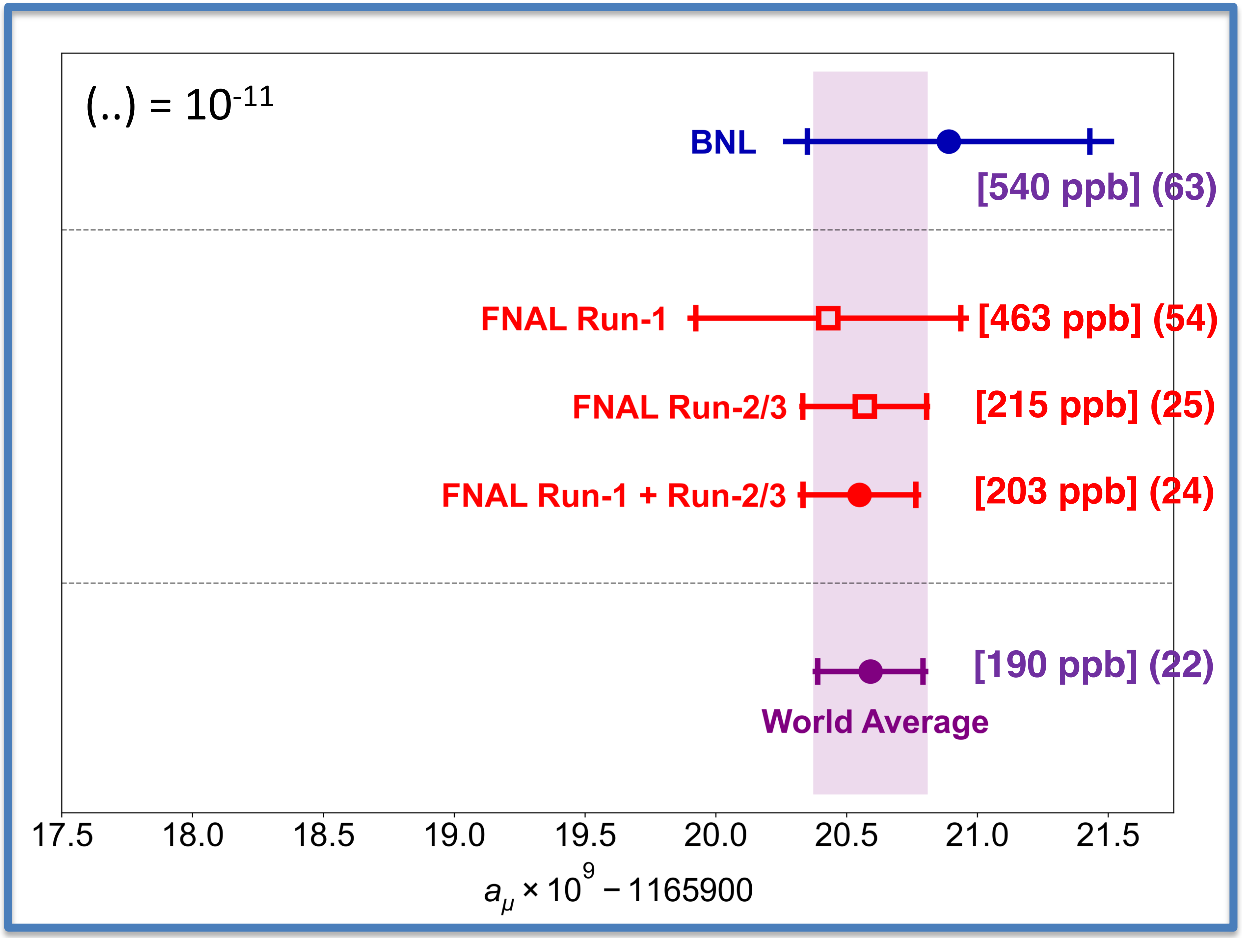


- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average **dominated by FNAL** values.

a_μ(Exp) = 116 592 059(22) x 10^{-11} [190 ppb]

Run-2/3 Result: FNAL + BNL Combination

a_μ(FNAL) = 116 592 055(24) x10^{-11} [203 ppb]



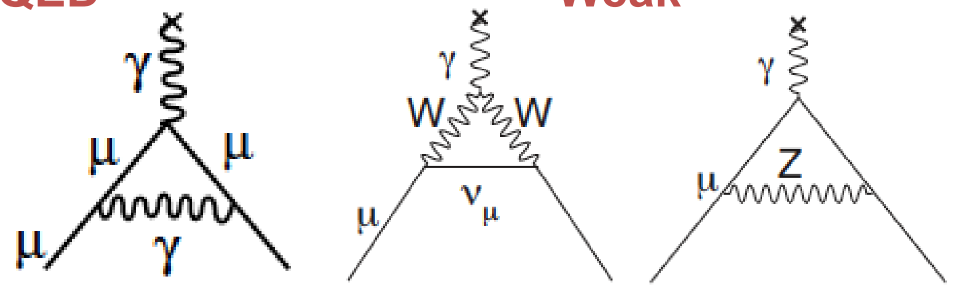
- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average **dominated by FNAL** values.

Size of $a_\mu^{EW} = 153.6(1.0) \times 10^{-11}$

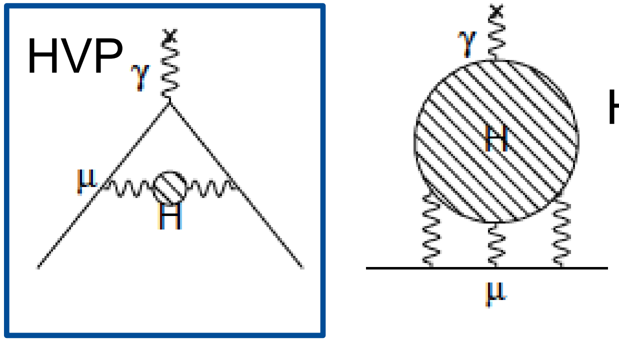
SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$

Muon g-2

QED **Weak**



Hadronic contribution



Precisely known

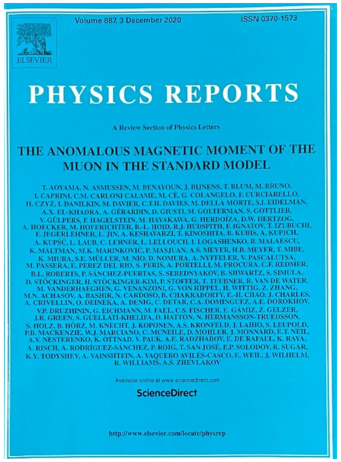
Large uncertainty

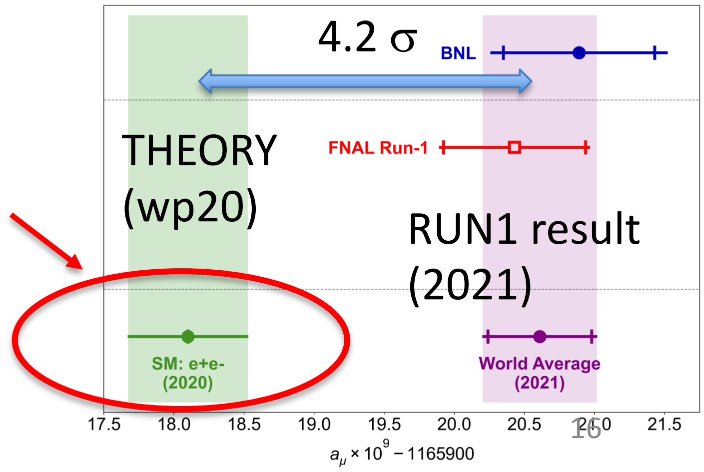
$$\boxed{a_\mu(\mathrm{SM}) = 116\,591\,810(43) \times 10^{-11} \quad (0.37\,\mathrm{ppm})}$$

SM Prediction in 2020

Theory Initiative **(wp20):**
T. Aoyama et al. Phys. Rept. 887 (2020)

HVP based on e+e- hadronic cross section data

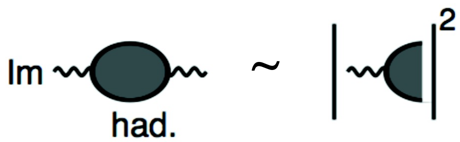

Volume 887, 3 December 2020 ISSN 0370-1573
PHYSICS REPORTS
A Review Section of Physics Letters
THE ANOMALOUS MAGNETIC MOMENT OF THE MUON IN THE STANDARD MODEL
ScienceDirect



HVP Calculation: Dispersive (e^+e^-) Method

Muon g-2

- Calculated from data for $\sigma(e^+e^- \to \text{hadrons})$



Analyticity & Unitarity

$$a_\mu^{\text{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty} \frac{K(s)}{s} R(s)\, ds$$

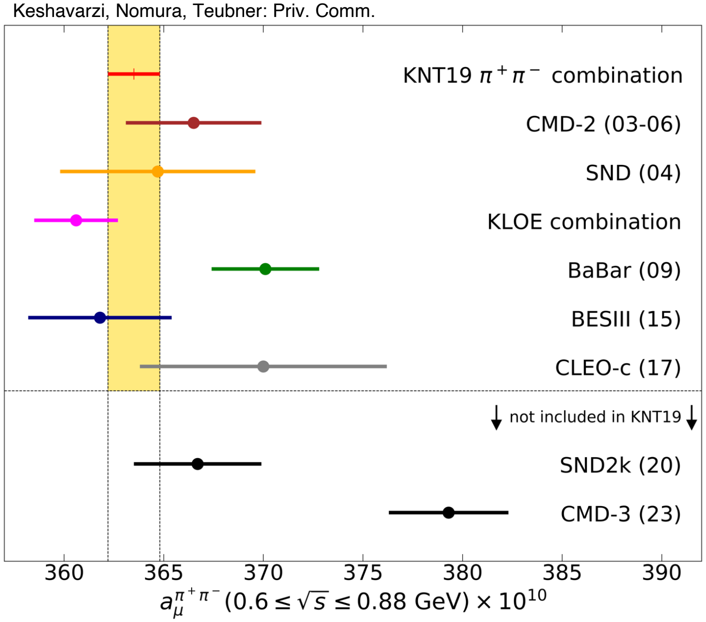
K(s) ~1/s

Hadronic R-ratio (Data Driven)

- Uses **data** from different experiments from **20+ years**
- 1/s weights low energy strongly: 73% from $\boldsymbol{\pi^+\pi^-}$ **channel**

$$\mathbf{R(s)} = \frac{\boldsymbol{\sigma^0(e^+e^- \to \gamma \to \text{hadrons})}}{\boldsymbol{4\pi\alpha^2/3s}}$$

Keshavarzi, Nomura, Teubner: Priv. Comm.



inc. in wp20

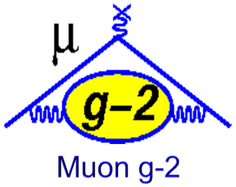
NOT inc. in wp20

- Data from **CMD-2, SND, KLOE, BaBar, BESIII** and **CLEO-C** were included in wp20

$$\boxed{a_\mu^{HVP;LO} = 6931\,(40) \times 10^{-11} (0.6\%) \quad \text{(wp20)}}$$

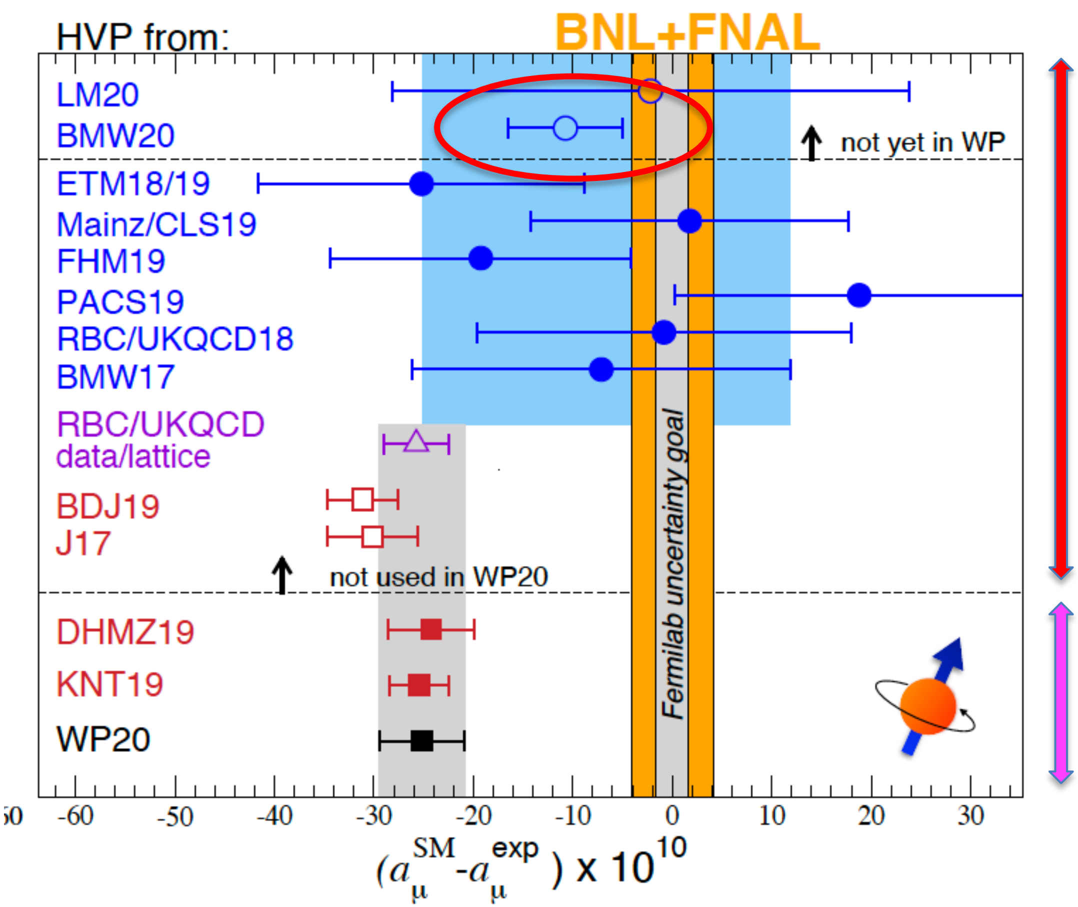
- New results from **SND2k** and **CMD-3** after wp20
- **CMD-3 is different from all the other data**

HVP Calculation: Lattice QCD Method



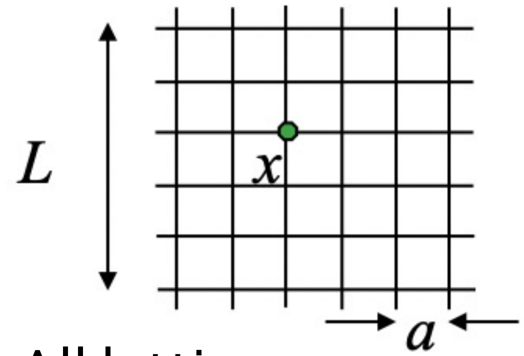
- ***Ab-initio*** calculation of HVP on lattice

G. Colangelo et al.
https://arxiv.org/pdf/2203.15810.pdf



NOT inc. in wp20

inc. in wp20



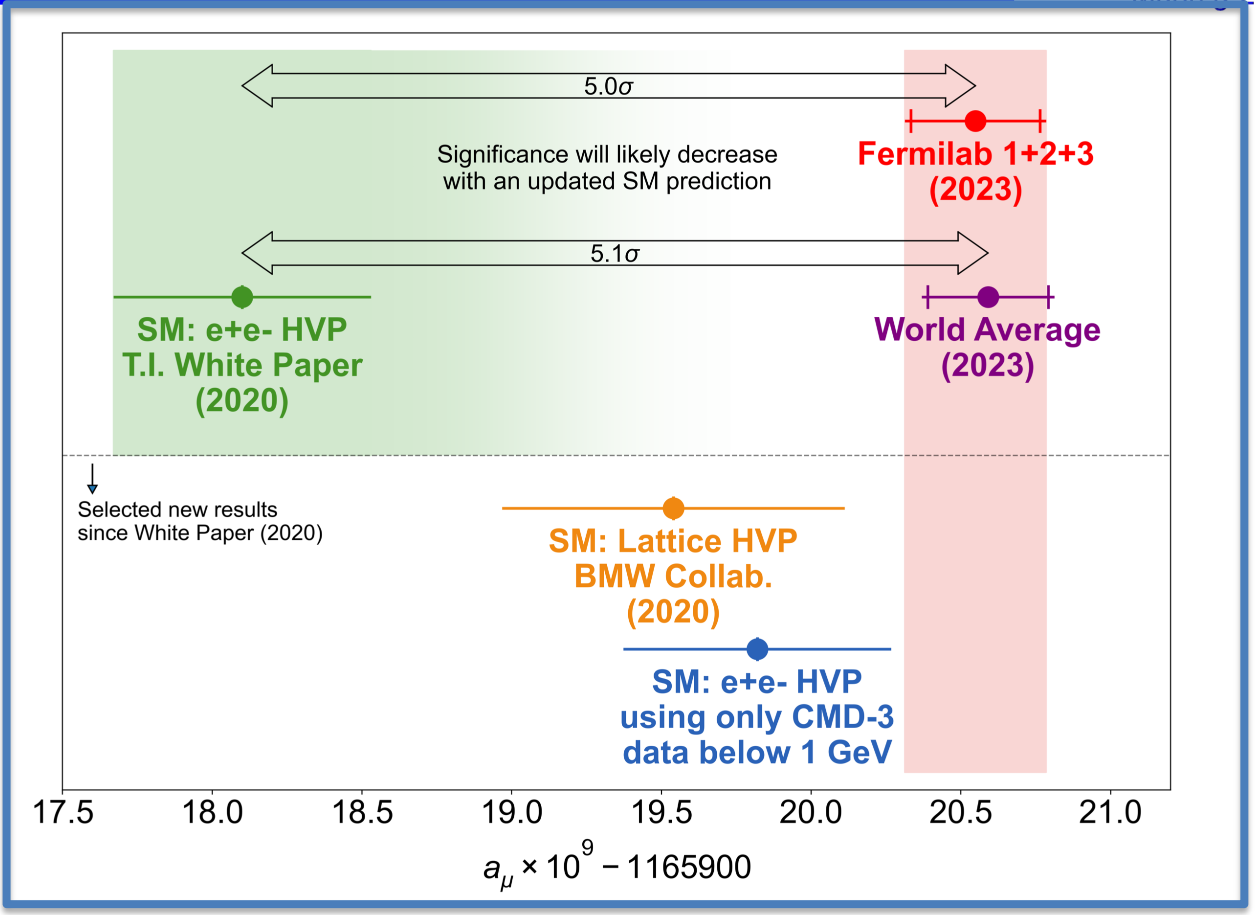
- All lattice calculations were not included in wp20
- **BMW** is only high precision calculation: closer to exp. Result

Comparison with SM prediction (2023)

Comparison with wp20

New results after 2020

Disclaimer: prediction from Lattice taken from Lattice 2023 talk; prediction from CMD3 based on our specific assumption

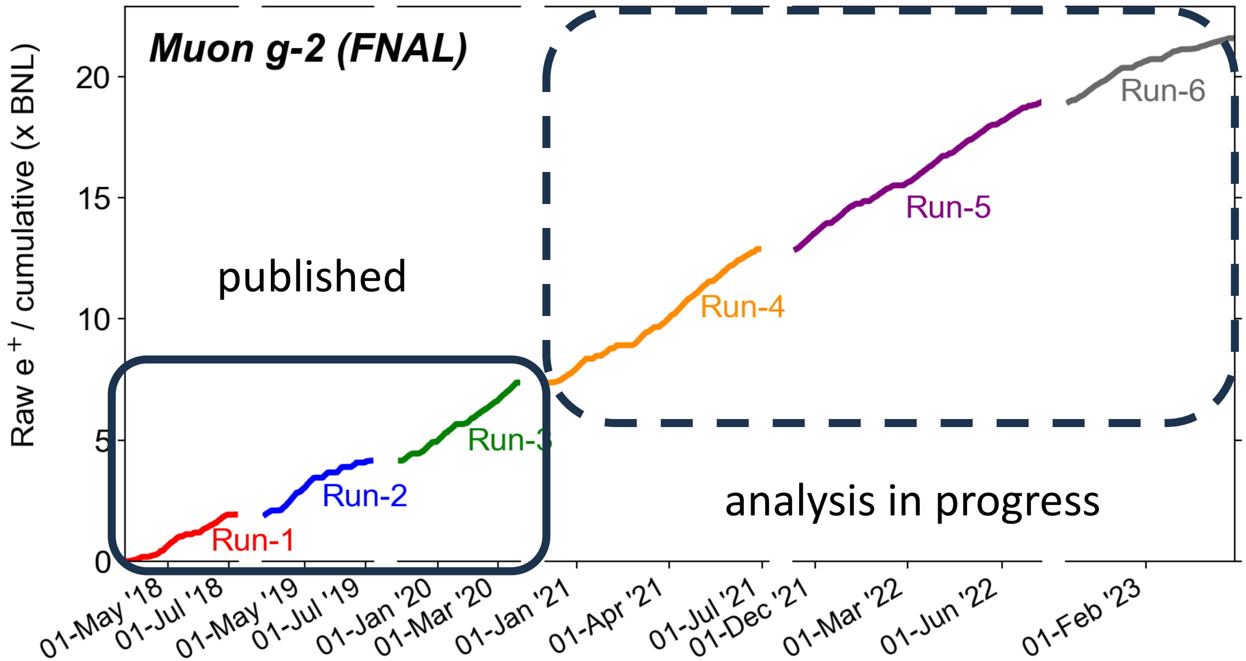


- Comparison of FNAL Run1-3 result with the Theory Initiative's calculation **wp20** is at **5 sigma**

- Waiting for a clarification of the theory

Prospects: Experiment

Data from **Run-4/5/6 fully produced** and analysis making good progress
With more than 21x BNL statistics on tape we will likely surpass total precision of **140ppb**

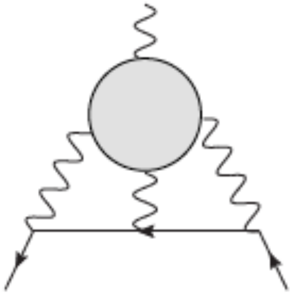


~25% of total statisics ~75% of total statisics

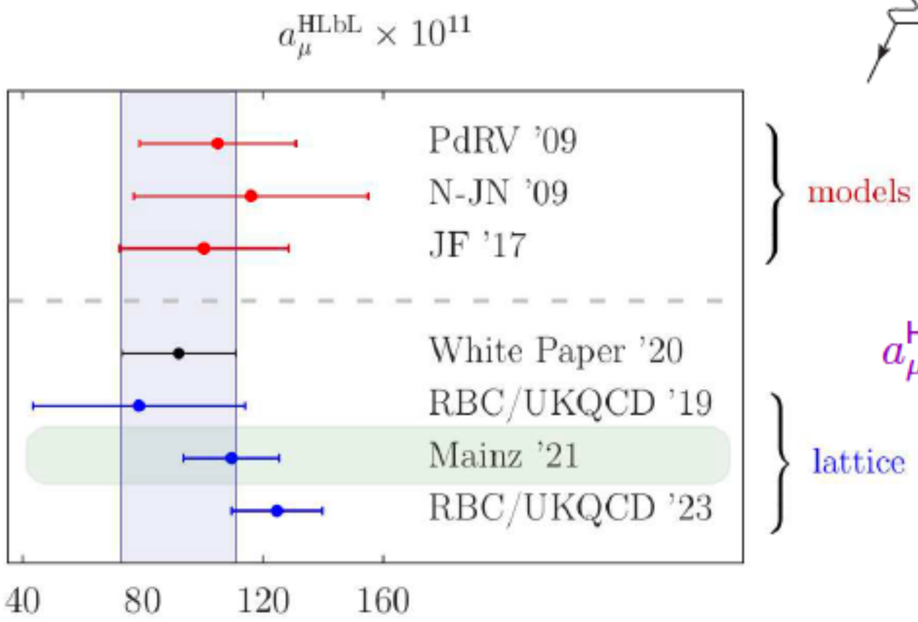
Plan to **publish result of the full dataset in 2025** with twice improved statistical precision

Prospects: Theory: HLbL

QCD contribution: HLbL



Two main approaches:
- Dispersion relations
- Lattice simulations



$$a_\mu^{\mathrm{HLxL}} = 92(19) \cdot 10^{-11} \quad \text{[WPsummary]}$$

$$a_\mu(\mathrm{SM}) = 116\,591\,810(43) \times 10^{-11}$$

(wp2020)

RBC-UKQCD 19: PRL 124, 132002 (2020)

Mainz 21: Eur. Phys. J. C 81, 651 (2021); C 82, 664 (2022)

RBC-UKQCD 23: arXiv:2304.04423

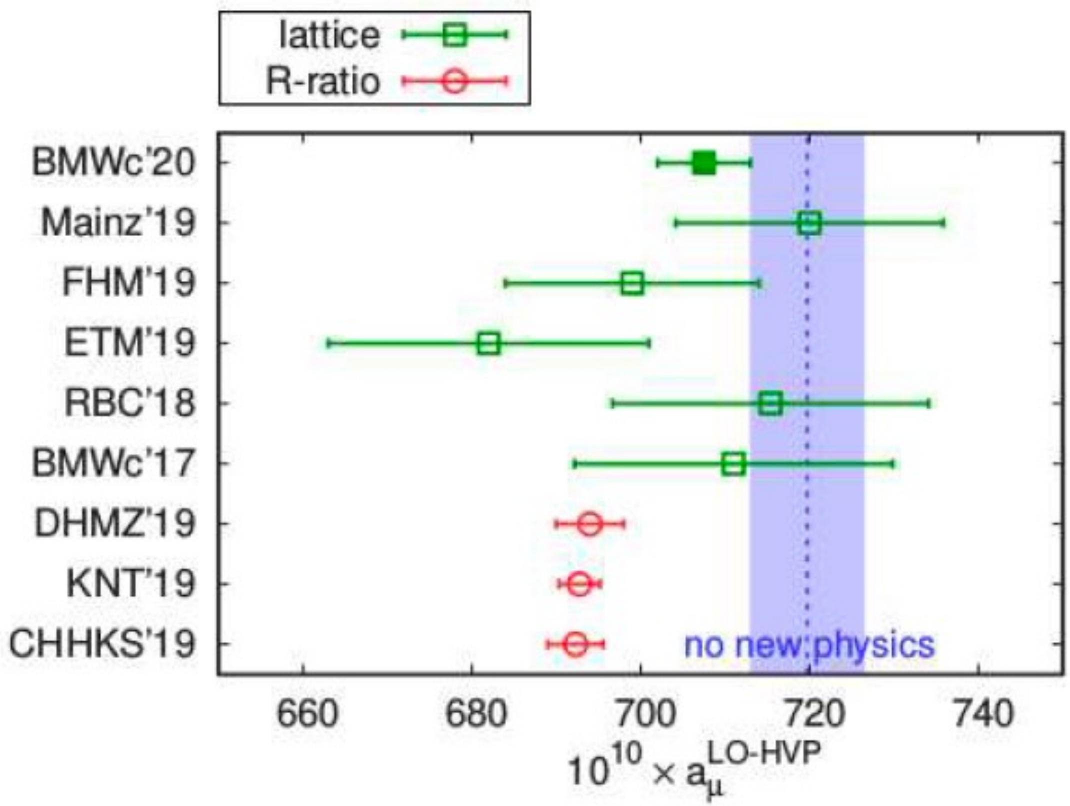
WP update: expect (cf. lattice results) some upward shift of central value, precision < 15%

Prospects: Theory: HVP - Lattice

New lattice QCD result for HVP from BMWc (2020) with 0.8% accuracy

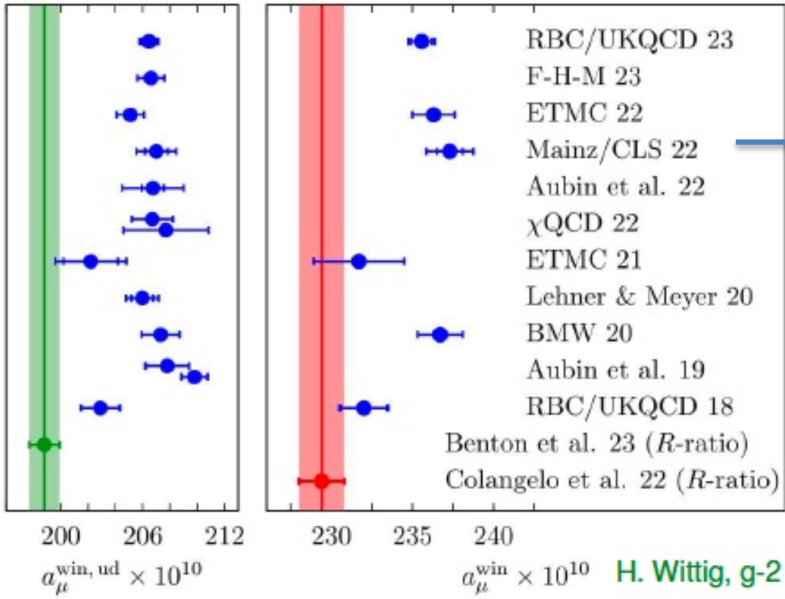
$$a_\mu^{\mathrm{HVP;LO}} = 7075(55) \cdot 10^{-11}$$

S. Borsanyi et al., Nature 593, 7857 (2021)

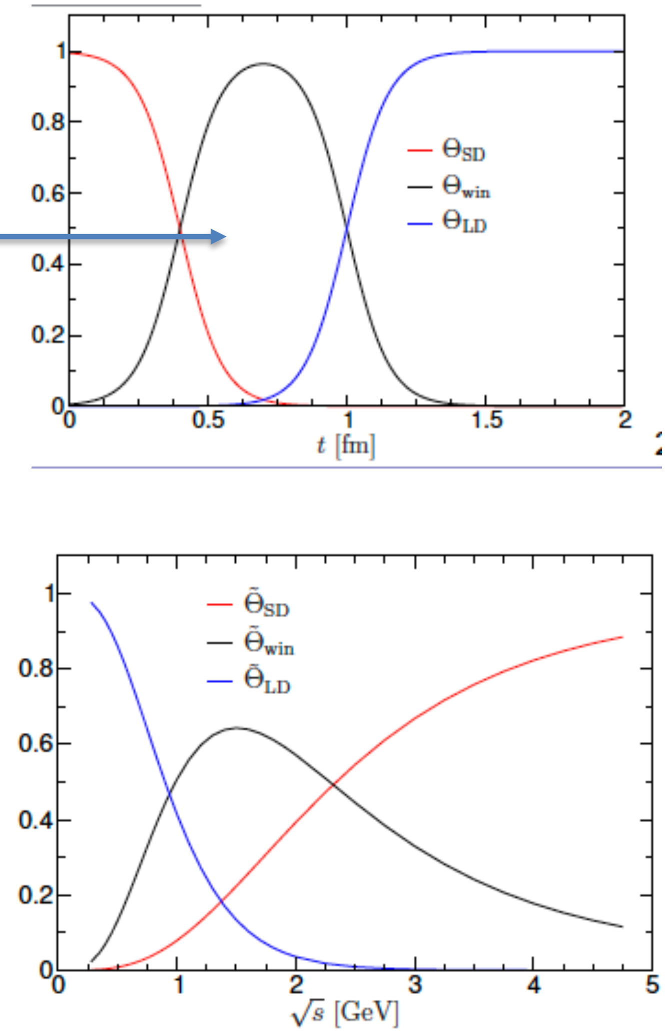


Prospects: Theory: HVP - Lattice

Several confirmations of BMWc result in the intermediate and short-distance windows



H. Wittig, g-2 TI Worsho



$$a_\mu^{\rm SDW} \sim 10\% \text{ of } a_\mu^{\rm HVP;LO}$$

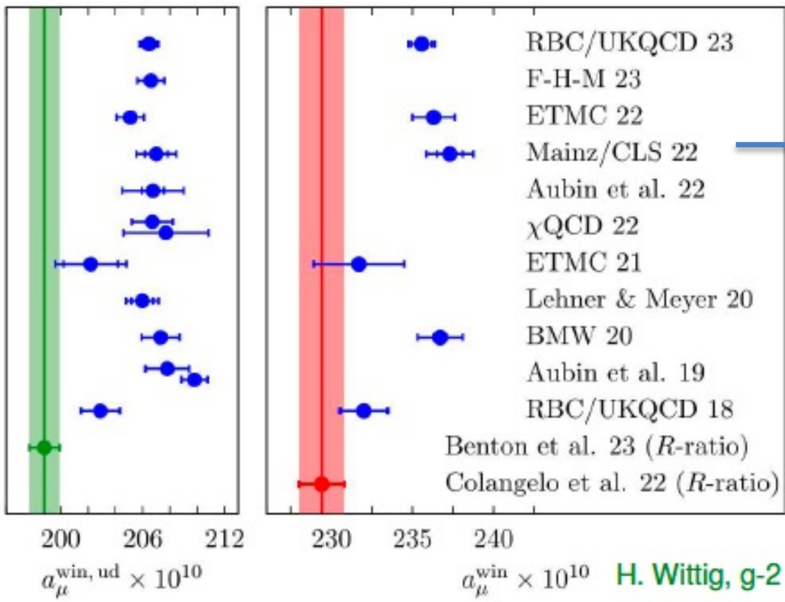
$$a_\mu^{\rm IW} \sim 30\% \text{ of } a_\mu^{\rm HVP;LO}$$

$$a_\mu^{\rm LDW} \sim 60\% \text{ of } a_\mu^{\rm HVP;LO}$$

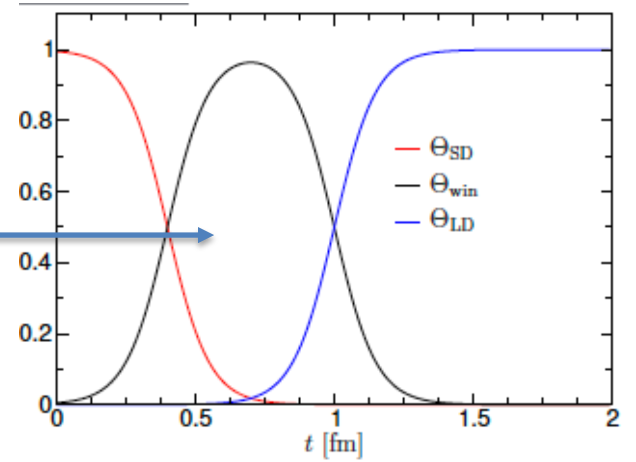
$$a_\mu^{HVP;LO} = 6931\ (40) \times 10^{-11} (0.6\%) \ \text{(wp20)}$$

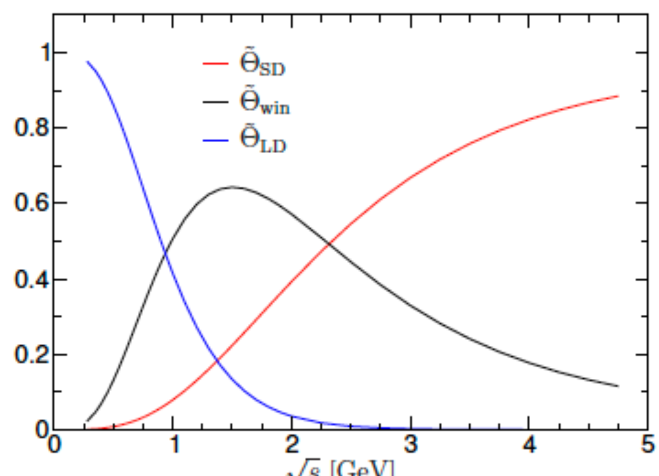
Prospects: Theory: HVP - Lattice

Several confirmations of BMWc result in the intermediate and short-distance windows



H. Wittig, g-2 TI Worsho



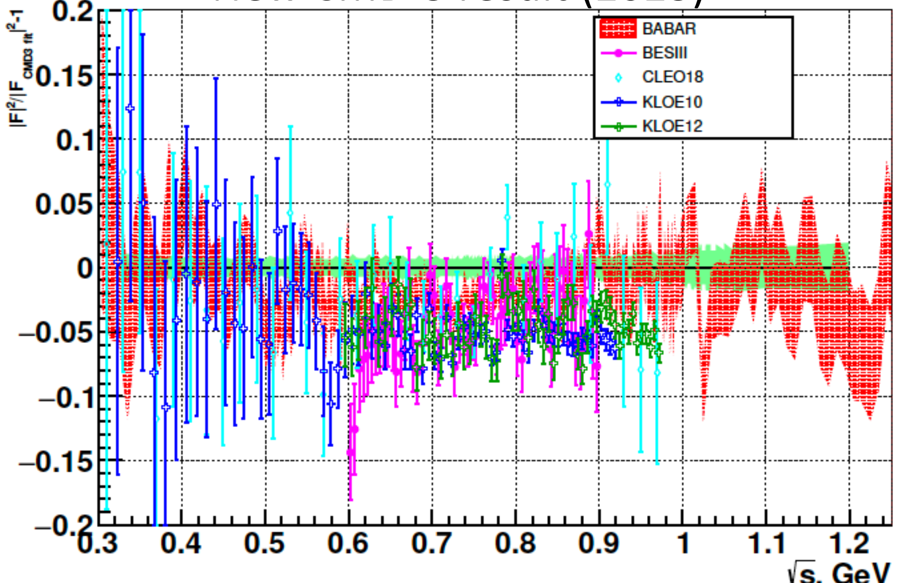


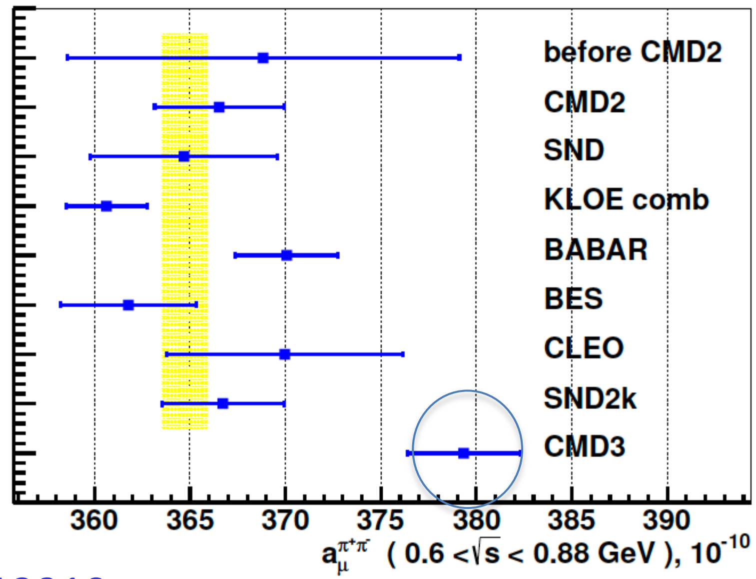
To date, no other complete lattice evaluation of the total HVP contribution at the same level of precision as BMWc…

$$a_\mu^{HVP;LO} = 6931\ (40) \times 10^{-11} (0.6\%)\ \ (\text{wp20})$$

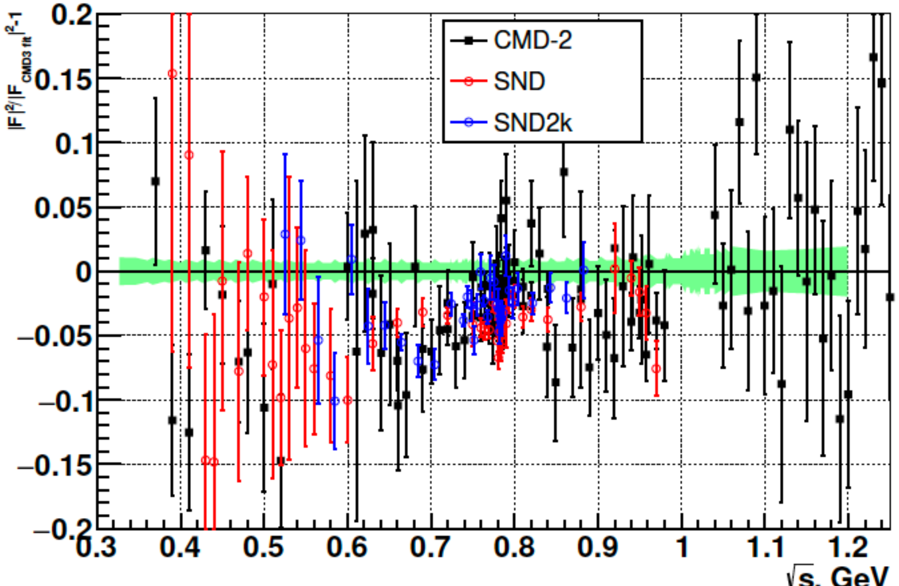
Prospects: Theory: HVP – e^+e^- data

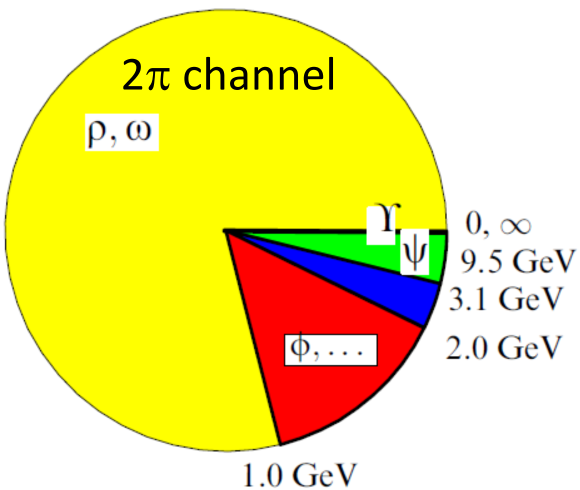
New CMD-3 result (2023)





arXiv: 2302.08834, 2309.12910



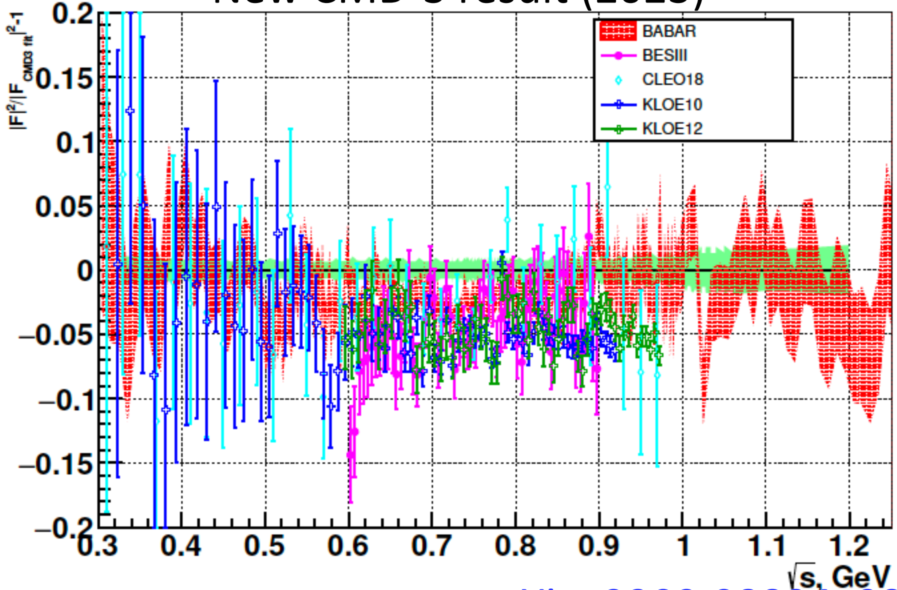


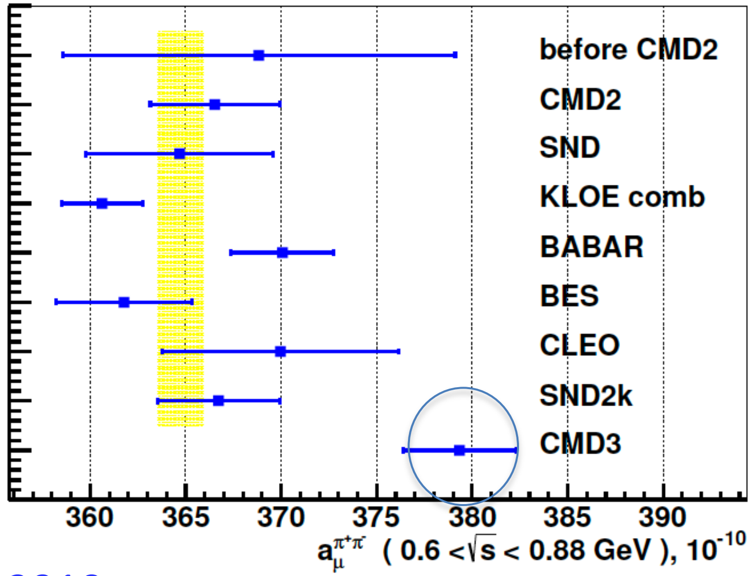
Contribution to HVP

Prospects: Theory: HVP – e^+e^- data

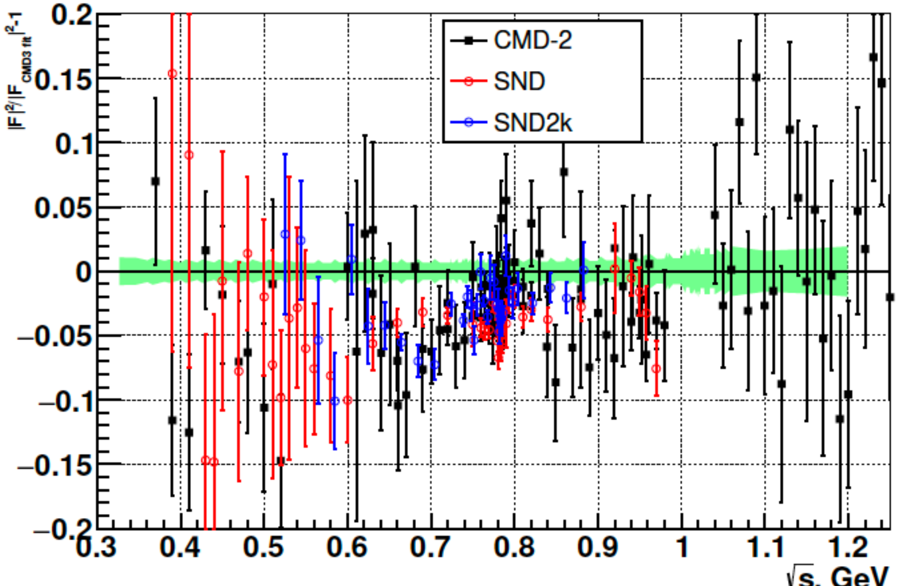
Muon g-2

New CMD-3 result (2023)





arXiv: 2302.08834, 2309.12910



2π channel contribute to ~73% of total HVP

No explanation for the discrepancy of CMD3 with previous e+e- experiments so far

Perspectives: $e^+e^- \to \pi^+\pi^-$

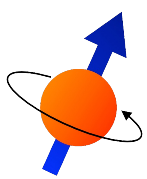
•**BaBar**: a new analysis of $\pi^+\pi^-$ cross section using ISR based on the full statistics (x7) with new analysis technique. A dedicated study of RC show difference with Phokhara MC generator, with possible impact on other experiment. Final results are expected in 2024.

•**SND 2020**: analysis of $e^+e^-\to\pi^+\pi^-$ on full statistics (x10) is in progress.

•**BESIII**: Analysis of the $e^+e^-\to\pi^+\pi^-$ cross section using ISR with ~x6 statistics in progress. Normalization of the di-pion event yield by di-muon events.

• **KLOE**: analysis of x7 larger statistics in progress with improved versions of the Monte Carlo generators for radiative corrections and modern analysis techniques. To avoid possible biases with published KLOE or other experiments the analysis will be blinded.

•**Belle-II**: measurement of the $e^+e^-\to\pi^+\pi^-$ cross section, based on the current full data set, is expected by 2025 with a precision comparable to the BABAR 2009 result.



(for more details see https://muon-gm2-theory.illinois.edu)

Other e+e- channels

Muon g-2

NEW

Hadronic Cross Section Data after 2020 Whitepaper

23

- BESIII $\pi^+\pi^-$ (600 < √s < 900) MeV, update of covariance matrix → central value unchanged
- Energy scan measurements above 2 GeV of multi-hadronic channels (spectroscopy)
- Total hadronic cross section measurement above 2 GeV

- New SND scans of $\pi^+\pi^-4\pi^0$ above 1 GeV (> 3% uncertainty)
- New SND scan of $\pi^+\pi^-$ channel, (525 < √s < 883) MeV
  → systematic uncertainty > 600 MeV: 0.8%; after publications issues found

- New BABAR ISR data on $\pi^+\pi^-4\pi^0$, $2(\pi^+\pi^-)3\pi^0$, $KK\pi\pi\pi$
- New BABAR ISR analysis of $\pi^+\pi^-\pi^0$ channel, (0.62 < √s < 3.5) GeV
  → systematic uncertainty: > 1.3%
  → fit to $M_{3\pi}$ including $\omega(782)$, $\omega(1420)$, $\omega(1680)$, $\phi(1020)$, $\rho(770)$

- First BELLE-II ISR analysis of hadronic process: $\pi^+\pi^-\pi^0$ channel, (0.62 < √s < 1.8) GeV
  → systematic uncertainty: >2.2%
  → integral value higher by 2.5 sigma than BABAR
- Main limitation (~1.2% error): NLO rad. correction → confirmation of BABAR findings

Achim Denig   Status of e^+e^- hadronic cross section experiments

A. Denig, *MITP Topical Workshop, June 4-7, 2024*

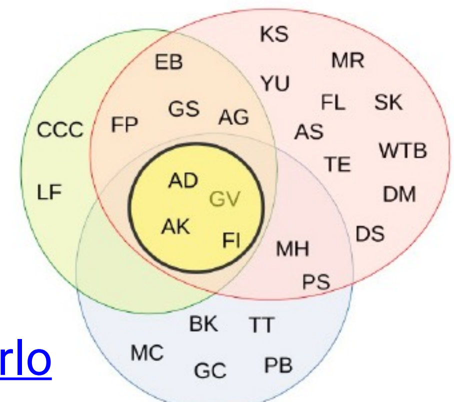
Perspectives: radiative corrections

Muon g-2

- Recent effort on MC (arXiv:2201.12102) and analyses at BaBar [PRD108 11, L111103 (2023)] and CMD-3 [PLB 833 137283 (2022)] have shown the importance of improved treatment of RC and hadron-photon modelization.
  - **Renovated effort** on RC and MC tools towards NNLO MC $\sigma(e+e- \rightarrow$ *hadrons* $(+\gamma)) \rightarrow$ report by 2024

Team: P. Beltrame, E. Budassi, C. Carloni Calame, G. Colangelo, M. Cottini, A. Driutti, T. Engel, L. Flower, A. Gurgone, M. Hoferichter, F. Ignatov, S. Kollatzsch, B. Kubis, A. Kupsc, F. Lange, D. Moreno, F. Piccinini, M. Rocco, K. Schönwald, A. Signer, G. Stagnitto, D. Stöckinger, P. Stoffer, T. Teubner, W. Torres Bobadilla, Y. Ulrich, G. Venanzoni

WP1:	QED for leptons at NNLO
WP2:	Form factor contributions at N^3LO
WP3:	Processes with hadrons
WP4:	Parton showers
WP5:	Experimental input



A. Signer, Jun 2023 – p.5/16

5th Workstop / Thinkstart: Radiative corrections and Monte Carlo tools for Strong 2020, 5-9 June 2023, Zurich

Conclusions

Muon g-2

- FNAL-E989 $(g-2)_\mu$ result at 0.20 ppm (<1/6 of EW contribution) and on the right course to achieve a measurement at 0.14ppm

- Theory situation at the moment limits the comparison:
- Tensions at the level of HVP:
  - between KLOE and BABAR
  - between CMD-3 and earlier experiments (incl. CMD-2!)
  - between BMWc and data-based evaluations (except CMD-3)
- Results on HLbL at ≤15% within reach

- More data are being analyzed (BaBar, KLOE) or will become available in the future (BESIII, BelleII,…)

Conclusions

- Important to have independent confirmation of the full BMWc result

- Possibility (in future) for inclusive measurements of HVP in the space-like region (MUonE at CERN)

- Reappraisal of τ -data-based evaluation of HVP

[M. Davier, A. H¨ocker, A. M. Lutz, B. Malaescu, Z. Zhang, arXiv:2312.02053]

- Next milestone on the theory side: updated WP: to be ready before release of FNAL-E989 final analysis (Spring 2025?)

Personal note

- I was very saddened by the news of Carlo. I was lucky to known Carlo since more than 20 years and I was always impressed by his scientific curiosity, his mild and gentle manner, his contagious smile, and his willingness to give his time with great ease. I remember Carlo with great affection and I miss him very much

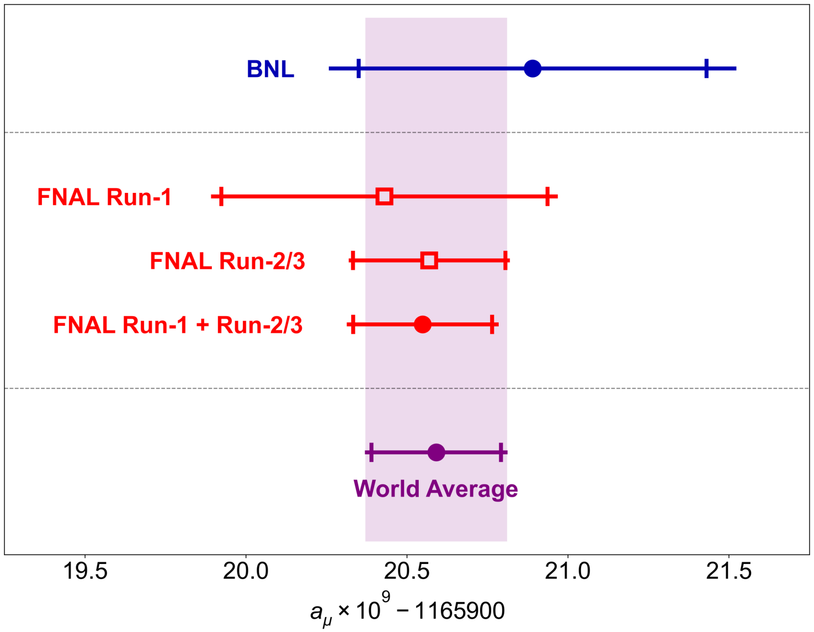
Thanks Carlo for all your advice, support and friendship!

END

t [μs]

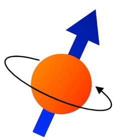
Conclusions

- We've measured a_μ to an unprecedented **203 ppb** precision



- New result is in **excellent agreement** with **Run-1 & BNL → ** new **world average** has an uncertainty of **190 ppb**
- More than **halved the total uncertainty** from Run-1
- **Went beyond our design goal** with systematic uncertainty of **70 ppb**.

- A factor ~ x 3 **data** from Run4-6 with a projected twofold improvement on the uncertainty (analysis should be completed by 2025)
- Expect **theory improvement** on a similar timescale (https://muon-gm2-theory.illinois.edu/)
- Look out for other analyses too: **EDM, CPT/LV** and **Dark Matter** searches.



Muon g-2 Collaboration

Muon g-2

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

181 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS
- KAIST

Ru
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

Muon g-2 Collaboration Meeting @ Elba, May 2019

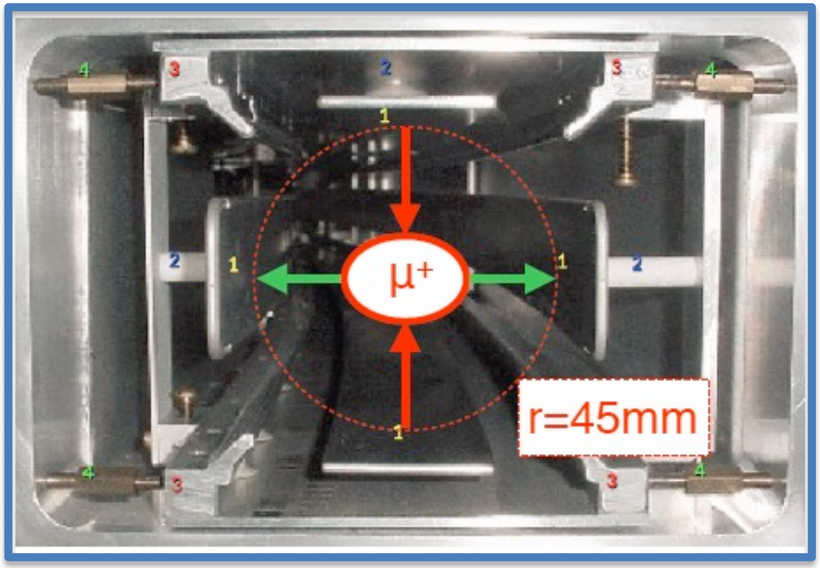
Muon g-2 Collaboration (2023)

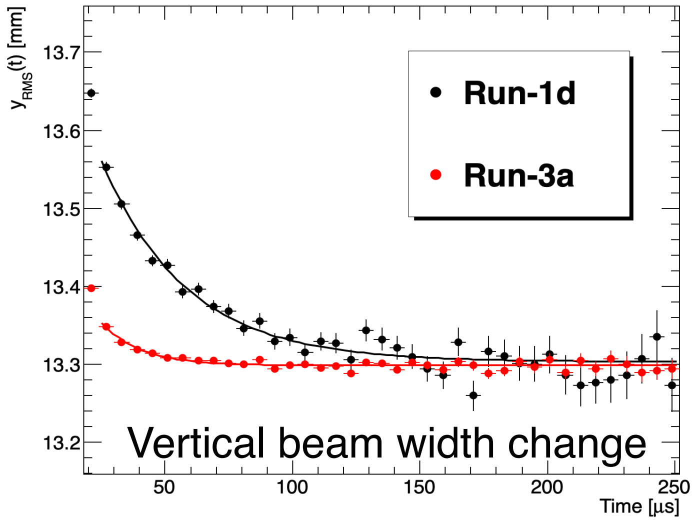
Muon g-2

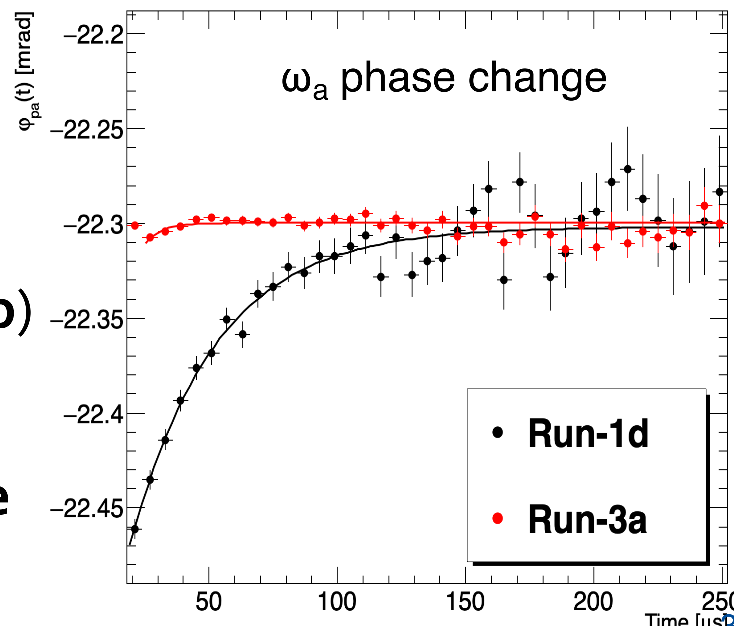
Summer Collaboration meeting at University of Liverpool July 24-28, 2023

Running Conditions: Damaged Quad Resistors

- Run-1 had **damaged resistors** in 2/32 quad plates leading to **unstable beam storage**
- Resistors **replaced before Run-2**







- C_{pa} uncertainty is reduced (**75 ppb → 13 ppb**) thanks to a more stable beam
- Beam **oscillation frequencies** are also **more stable**

Other systematic improvements

- **Running conditions:**
  - Improved cooling of the hall and added insulation of the magnet which made the magnetic field more stable
  - Improved kicker strength which made the orbit more centered and reduced the E-field correction
- **Improved measurements:**
  - Extensive measurement of vibration the quadrupoles in multiple locations around the ring
  - Reduced vibration noise for kicker transient field measurement
- **Analysis improvements:**
  - Improved treatment of the pileup for ω_a analysis
  - Improved analysis of E-field correction including correlations between momentum & time of injection.

July 24th 2023: Unblinding

- Muon g-2 analysis has **software & hardware blinding**
- Unblinding meeting in Liverpool:

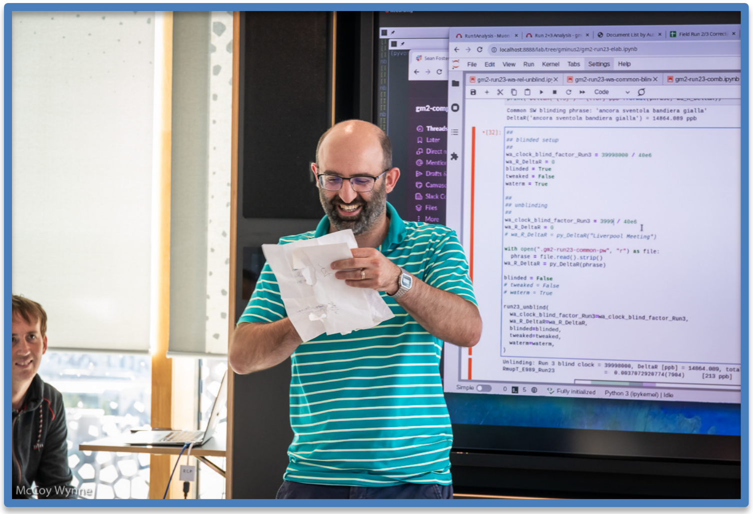


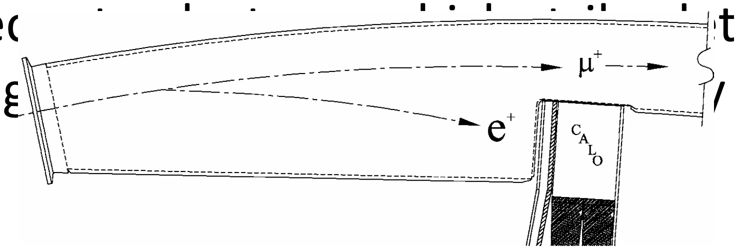
Photo credits: McCoy Wynne

- Unanimous vote from all collaborators to unblind!
- Secret envelopes were finally opened to reveal the hidden clock frequencies and the result…

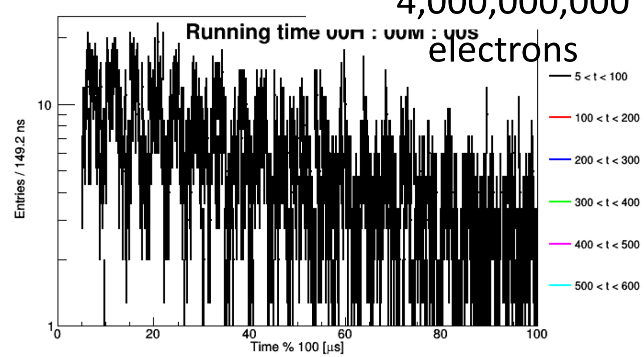
Measuring the wobble frequency

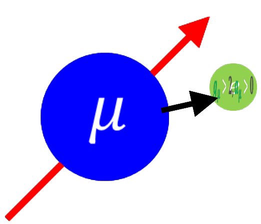
Muons dec

Flash of Lig

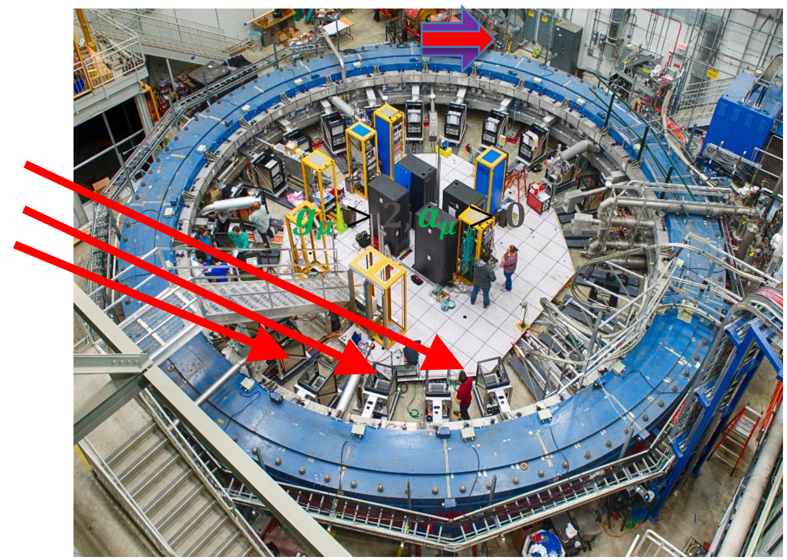


~4,000,000,000 electrons





Electromagnetic Calorimeter

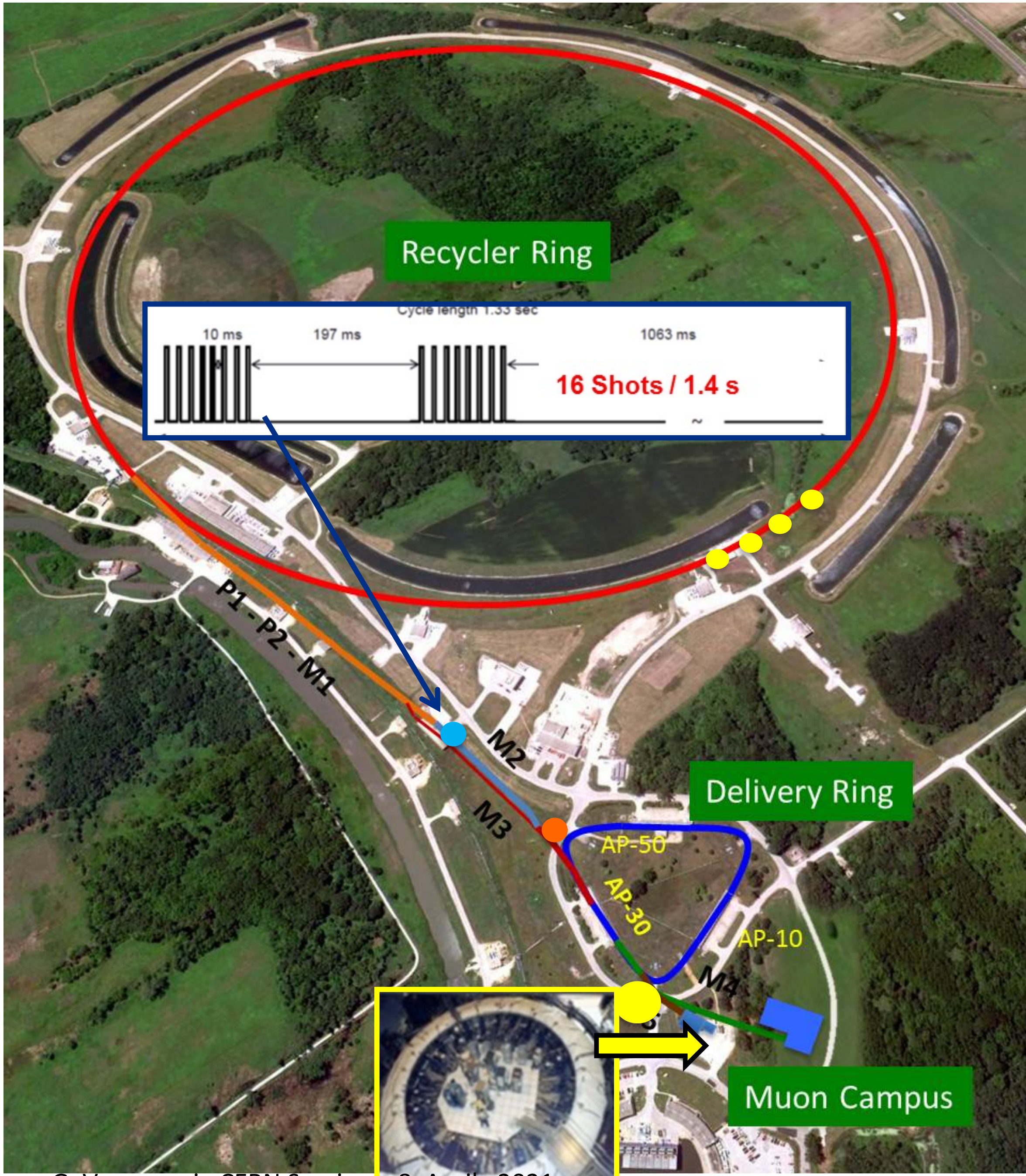


SM prediction

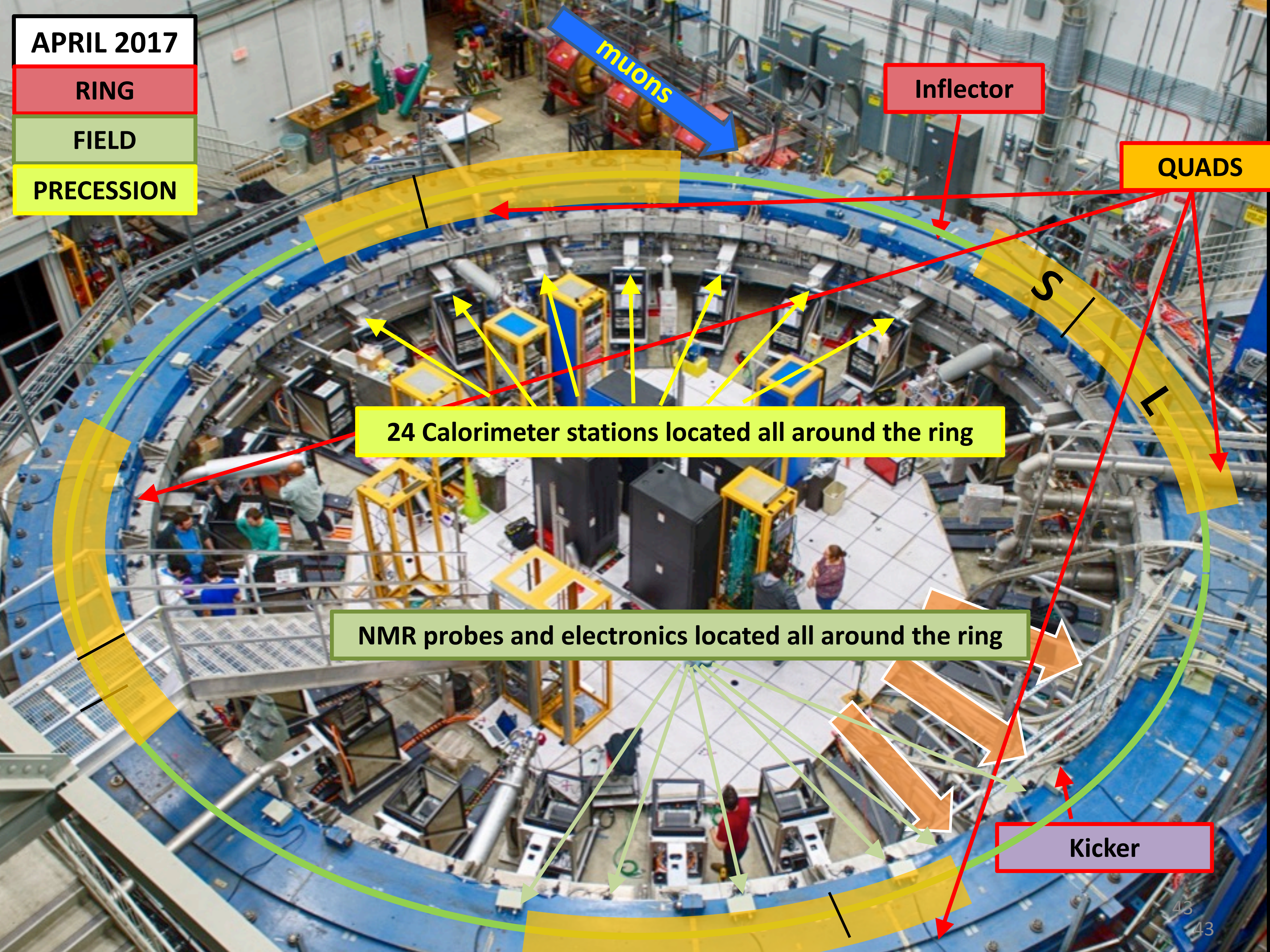
Muon g-2

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]
Total SM Value	Sec. 8	Eq. (8.12)	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)	

Creating the Muon Beam for g-2



- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- p/π/μ beam enters DR; protons kicked out; π decay away
- μ enter storage ring


APRIL 2017
RING
FIELD
PRECESSION
muons
Inflector
QUADS
S
L
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring
Kicker

43

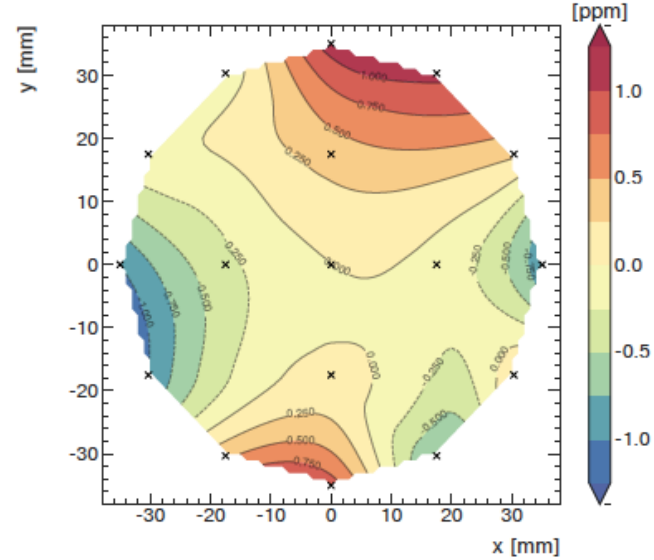
ω'_p measurement

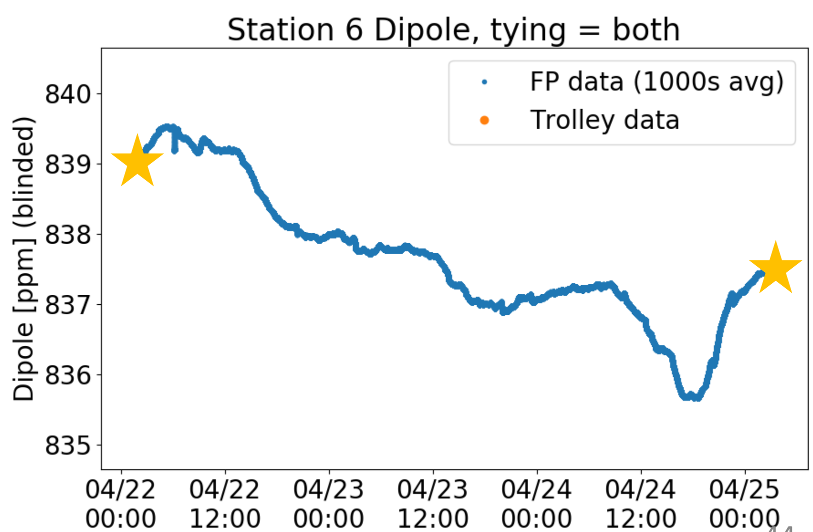
- Trolley maps of the magnetic field at about 9000 locations over the entire azimuth every 3 days
- Fixed probes at 72 locations to interpolate the field during muon storage between the trolley runs
- Need calibration to convert the 17 NMR trolley to water sample

$$\boxed{\delta_{\omega'_p} \sim 48ppb}$$

Uncertainty due to:

1. Temperature Corrections
2. Configuration Corrections
3. Trolley Map Systematics
4. Fixed Probe Systematics
5. Tracking Drift Uncertainty



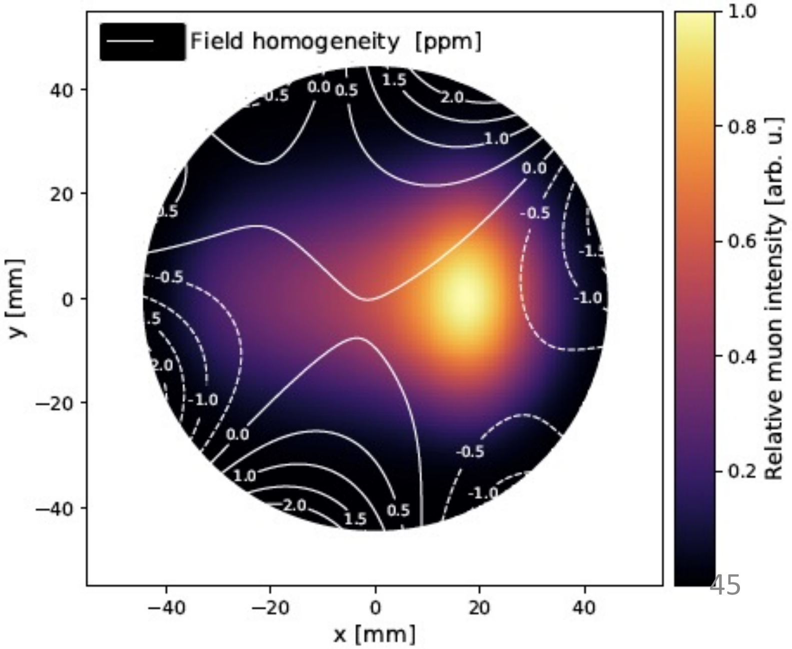


$\omega'_p \rightarrow \tilde{\omega}'_p$: muon weighted average

- Need field actually experienced by muons
- Muon decay point estimated from e+ track reconstructed by the two straw trackers inside storage vacuum
- Use beam dynamics models, tuned to the tracker data, to get distribution all around the ring
- Systematic uncertainty due to probe calibrations, field map, tracker alignment and BD model

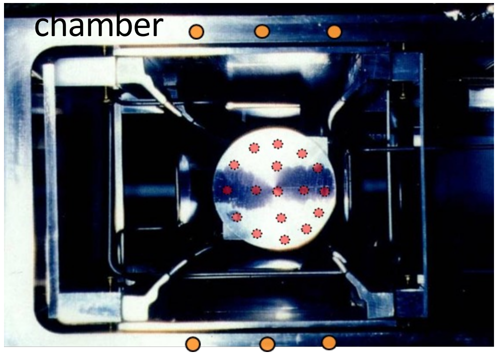
$$\boxed{\delta_{\widetilde{\omega'}_p} \sim 56\ ppb}$$

Muon's view of a tracker

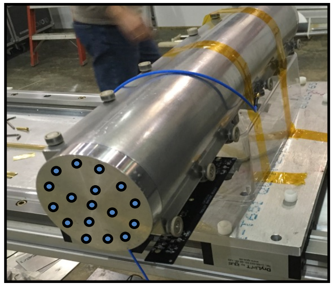


The magnetic field is measured using pulsed-proton NMR where the proton “wobble” frequency ω_p is measured

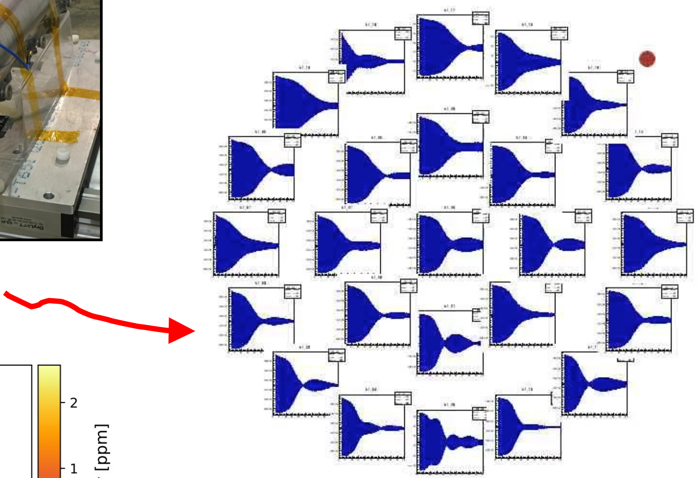
Fixed NMR around the vacuum chamber

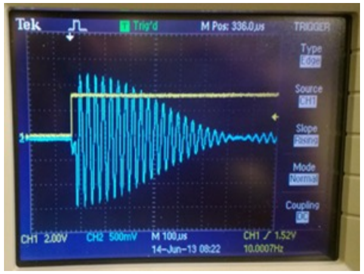


NMR trolley

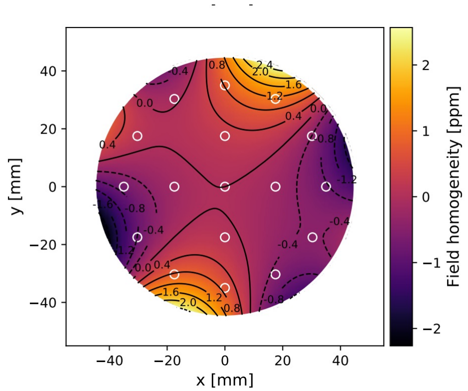


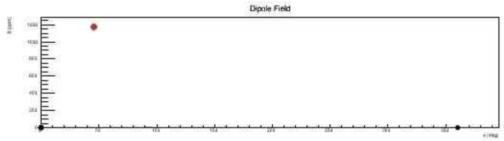
We built a little “NMR Trolley” that goes around the ring and maps the field





Free induction decay signal of the probes digitized and analyzed





The Final Field is VERY uniform