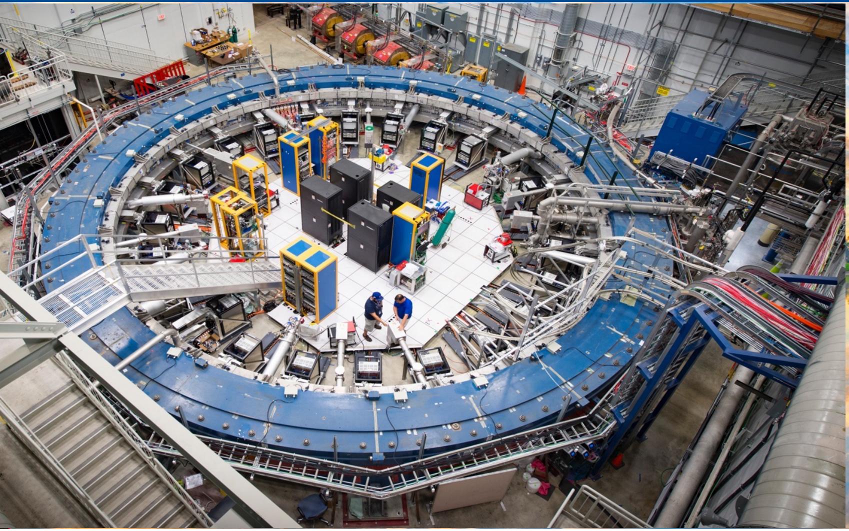


Big Questions in Muon g-2: Experimental Perspective

Brendan Kiburg, Fermi National Accelerator Laboratory

Snowmass Early Career Colloquium Series

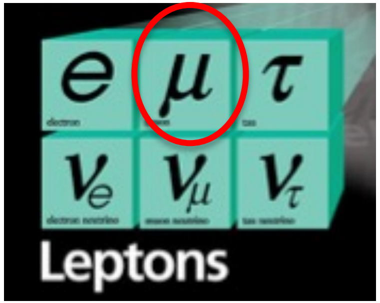
17 September 2021

Outline

- Muons probe the universe
- Status 2020
- Theory Calculations
  - Focus on the experimental inputs
- Fermilab Muon g-2
  - Experimental Recap
  - Status and Outlook
- Future Experimental Efforts

Big Question: What is responsible for the Muon g-2 discrepancy?

Our favorite probe: The muon



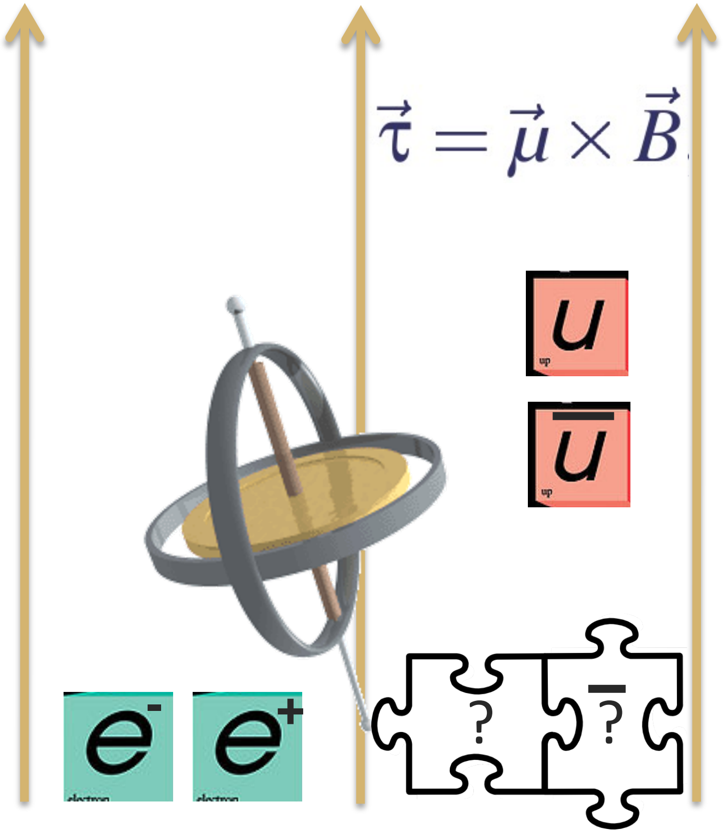
- Fortuitous lifetime = 2.2 μs
- Spin 1/2 particle
- Encodes information about spin in its decay

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

- This g-factor is the “g” in “g-2”
- g= 2 + contributions from virtual particles

Magnetic Field

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$



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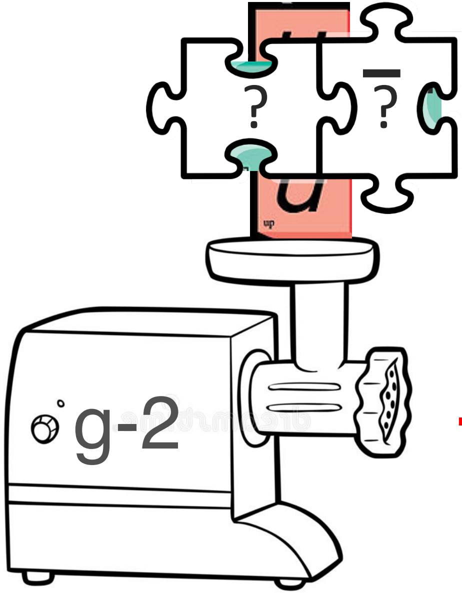
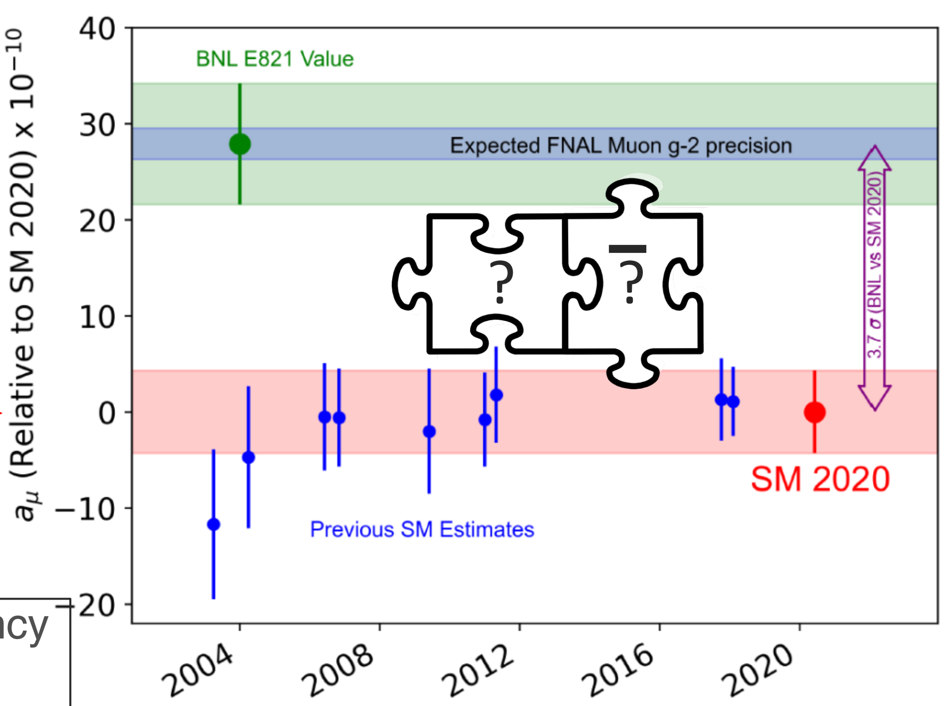
Motivation: Status of the muon anomaly before Fermilab Experiment





Logical Possible Explanations for 3.7σ discrepancy

1. Theory calculation is wrong
2. Experimental determination is wrong
3. New Physics Explains the gap
4. Some combination of the above

Theory WP: https://doi.org/10.1016/j.physrep.2020.07.006

Experimental Clues

Big Question:
Where can future experimental efforts help explain the muon g-2 discrepancy?

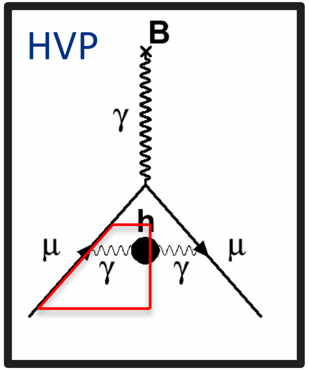
g-2 Theory

g-2 Experiment

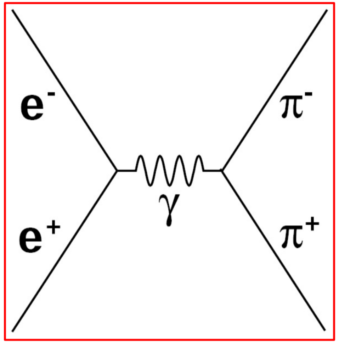
Other Experiments

Dispersive Theory Calculation is Driven by Experimental Input

Relates these terms

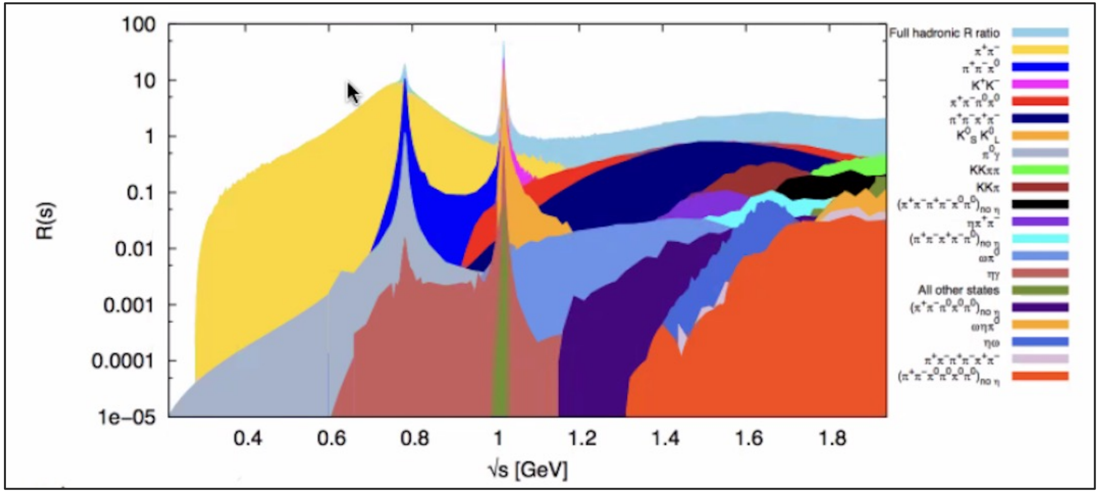


To observable processes like



$$\left(a_\mu^{\mathrm{HAD,LO}}\right) \propto \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) \equiv \frac{\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons})}{\sigma_{\mathrm{tot}}(e^+e^- \to \mu^+\mu^-)}$$



- Low-energy region dominates

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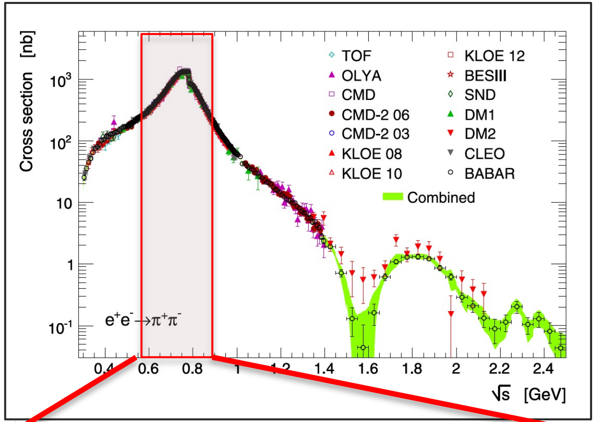
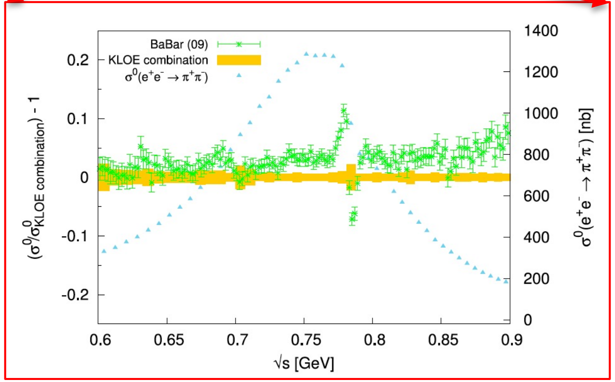
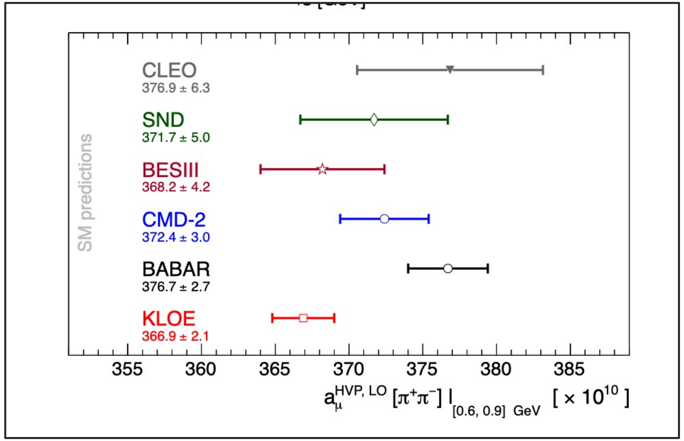
Dispersive Theory Calculation is Driven by Experimental Input

Many detailed measurements lead to precise theory calculation

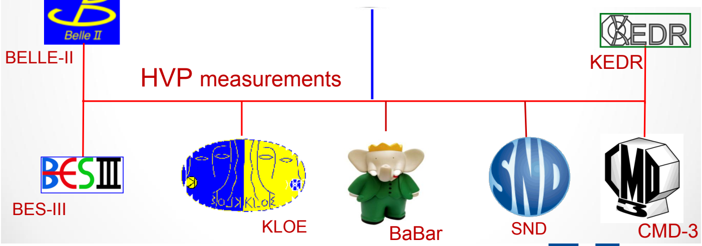




The combination uncertainty is driven by tension in low-energy region



Many machines/exp pushing to improve to sub % precision



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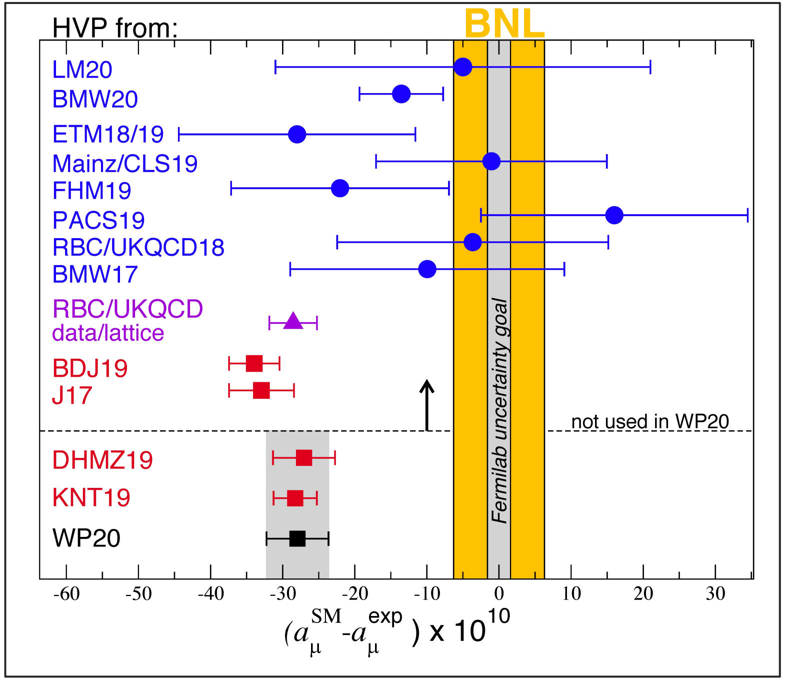
Theory WP: https://doi.org/10.1016/j.physrep.2020.07.006

New Lattice Calculations are in tension with Dispersive Calculations

- Most results statistically limited
- First precise LQCD result in (BMW20) in tension with dispersive result

- Important to see how story evolves
  - Will other lattice calculations look similar with improved precision?
  - Will a particular region or window show tension between the various groups?
  - Could the lattice results end up shifting the focus to understanding the discrepancy between lattice and e+/e- data?



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Additional Experimental handle being pursued: MUonE at CERN

- A novel approach to determine the leading hadronic contribution via a very precise measurement of the shape of the differential cross section of μe elastic scattering

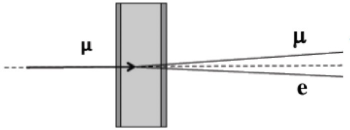
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

- Be scattering target
- Tracking via silicon strip detectors
- Status
  - Scattering test beam studies 2017-2018
  - Test run in 2021/2022
- Goal: 3 years of running → 0.3% precision on a_μ^{HLO}

The MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the «shape» of the $\mu^+ e^- \rightarrow \mu^+ e^-$ elastic differential cross section

$\mu\, e \rightarrow \mu\, e$

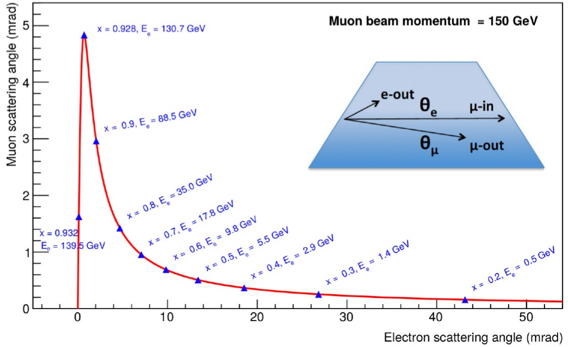


$$\frac{d\sigma_{data}/dt}{d\sigma_{MC}^{\text{no VP}}/dt} = \frac{1}{|1-\Delta\alpha_{lep}(t)-\Delta\alpha_{had}(t)|^2}$$

From theoretical calculation

To be measured

- A beam of 160 GeV muons allows to cover the whole a_μ^{HLO}.
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production).
- Boosted kinematics: θ_μ < 5 mrad, θ_e < 32 mrad.



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G. Venanzoni, TI Meeting, KEK, 29 Jun 2021

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Experimental Clues

Big Question:
Where can future experimental efforts help explain the muon g-2 discrepancy?

g-2 Theory

g-2 Experiment

Other Experiments

Muon g-2 basics in a storage ring

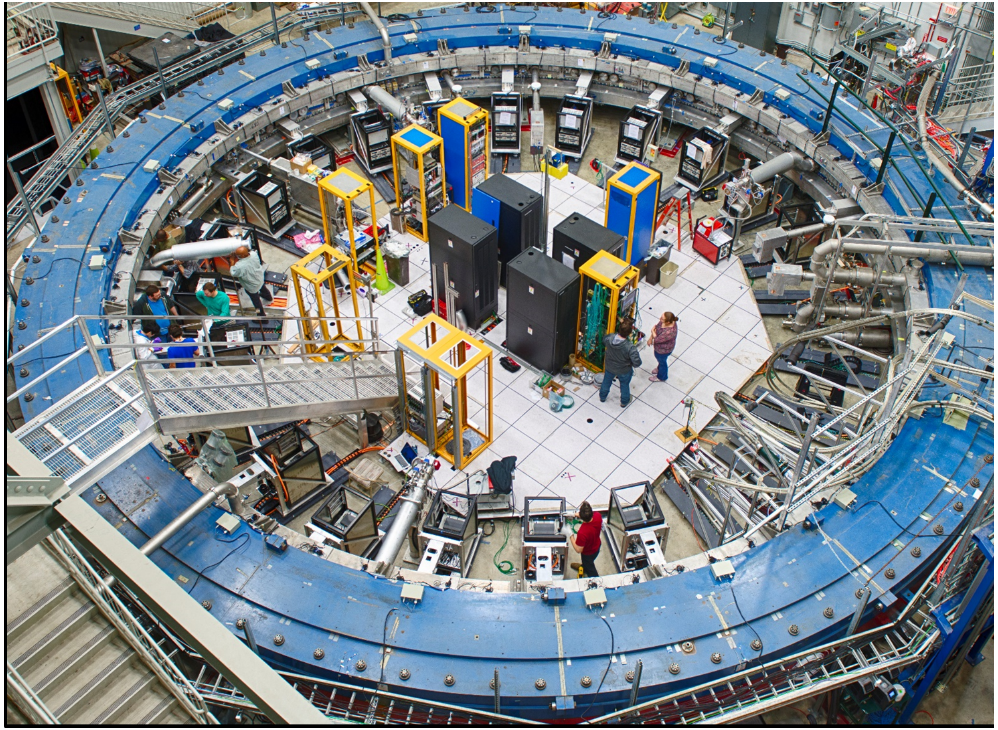
$$\omega_a = \frac{eB}{m} a_\mu$$

A precision measurement of the muon's anomalous spin-precession frequency in a well-measured magnetic field will tell us how muons see the universe.

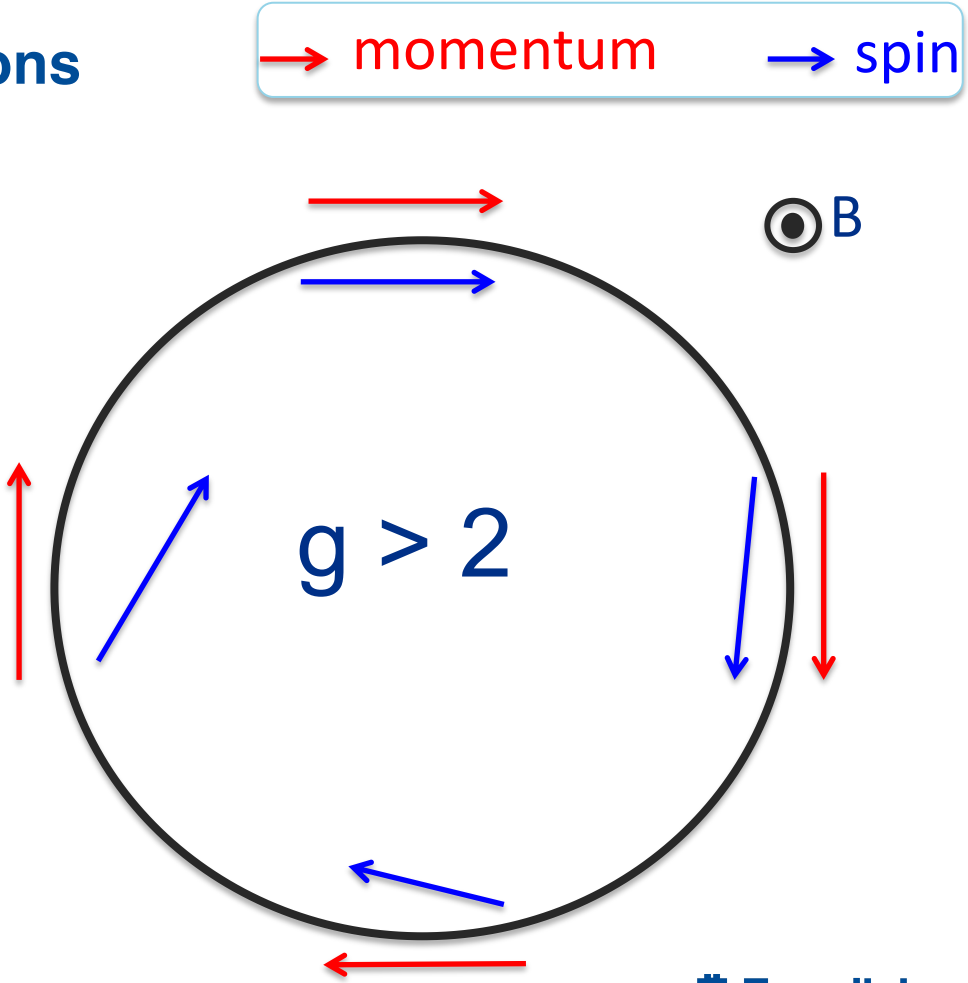
What are the main experimental steps to get a_μ ?

$$\omega_a = \frac{eB}{m} a_\mu$$

1. Inject and store polarized muons
2. Measure the decay electrons to determine the muons' properties
3. Map and track the magnetic field



1. Inject and store polarized muons



1. Cyclotron frequency:

$$\omega_c = \frac{e}{m\gamma} B$$

2. Spin precession frequency

$$\omega_s = \frac{e}{m\gamma} B \left(1 + \gamma \frac{g-2}{2}\right)$$

$$\omega_s - \omega_c \equiv \omega_a = \frac{eB}{m}\frac{g-2}{2} = \frac{eB}{m} a_\mu$$

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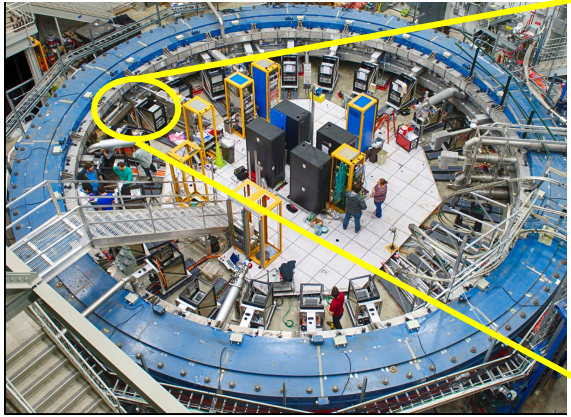
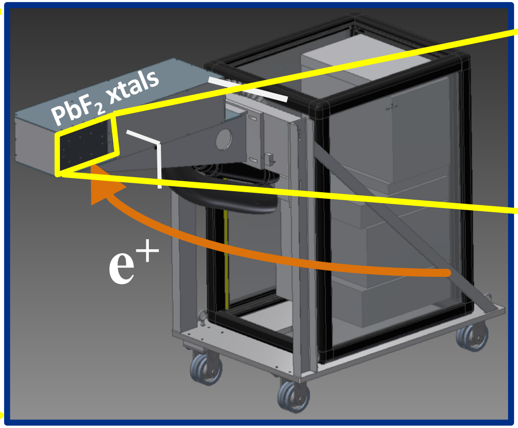
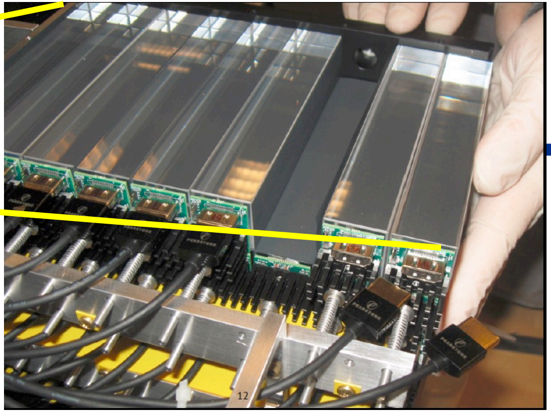
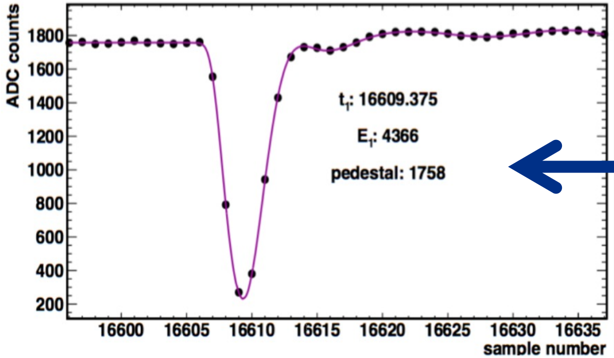
2. Measure decay electrons to determine the muons' properties









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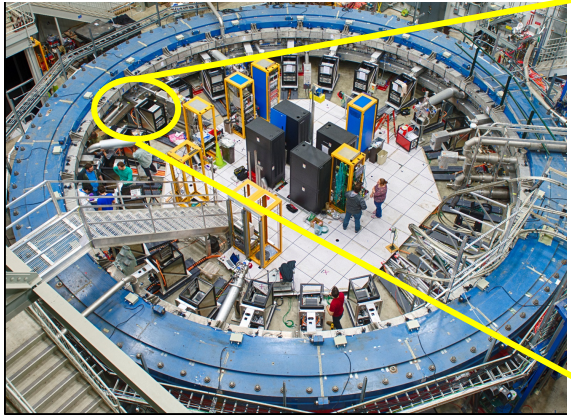
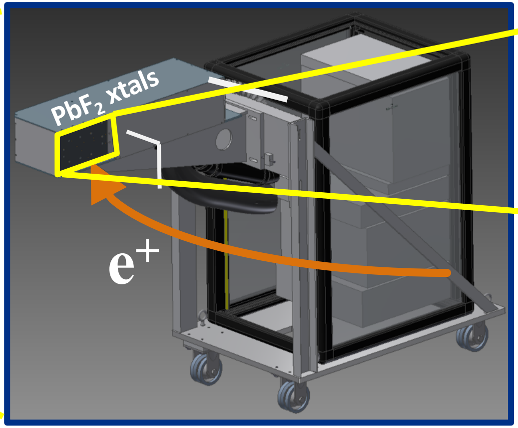
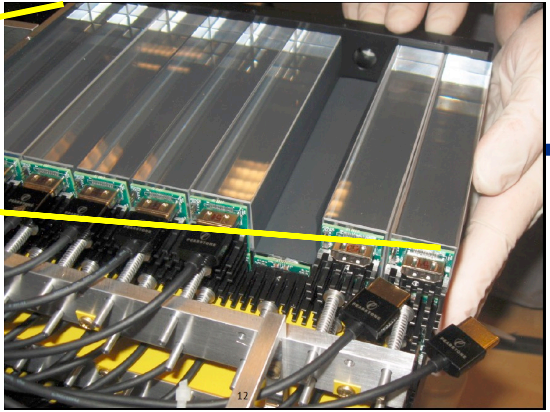
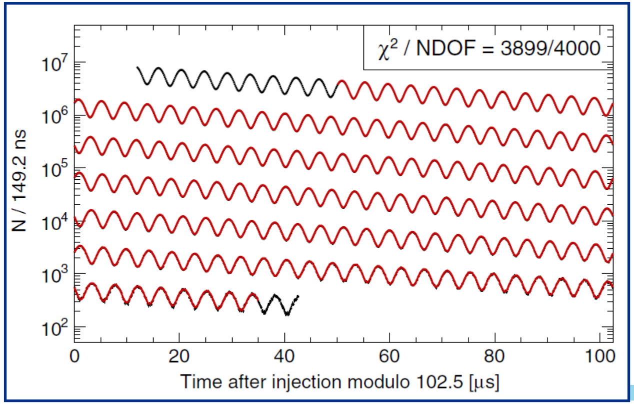
2. Measure decay electrons to determine the muons' properties

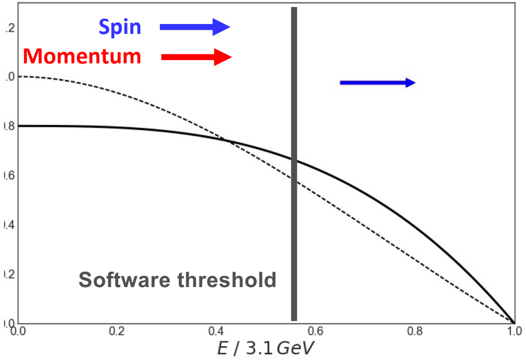


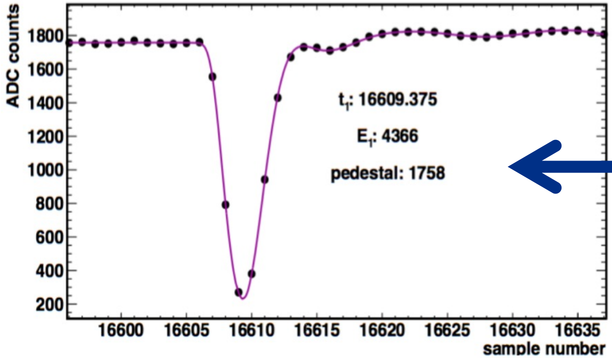




Events above threshold







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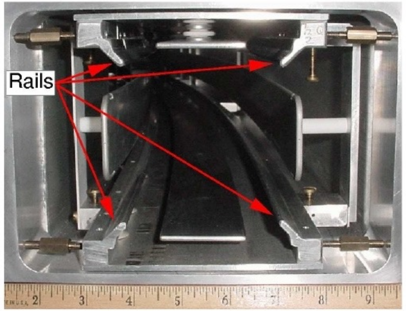
3. Map and track the magnetic field

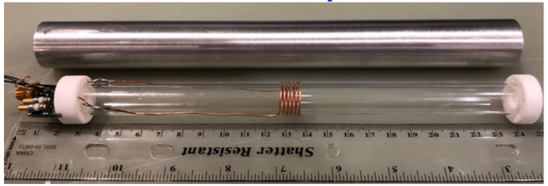
- Use Nuclear Magnetic Resonance (NMR)
  - Determine the B-field in terms of the proton precession frequency ω_p

NMR trolley **maps** field every 3 days



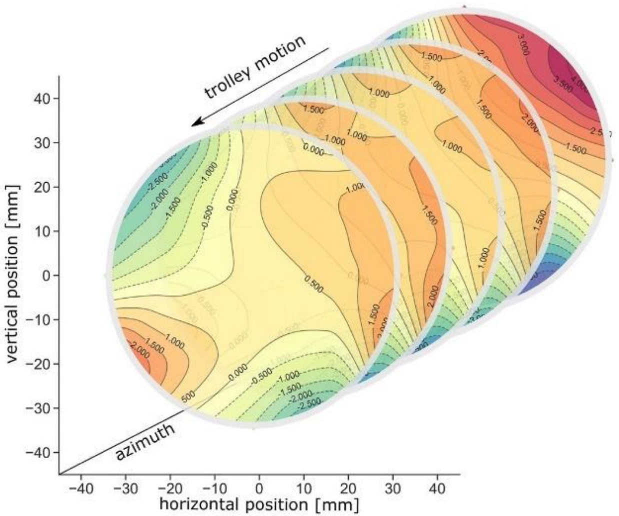
378 fixed probes **monitor** continuously

Trolley cross-**calibrated** to absolute probes



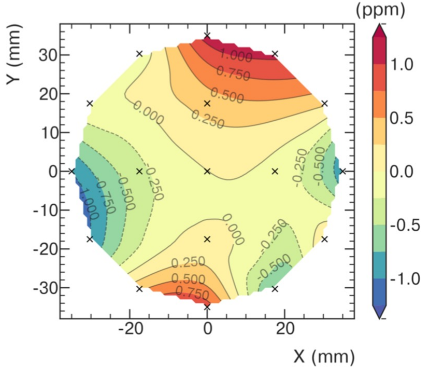
Trolley Magnetic Field Maps

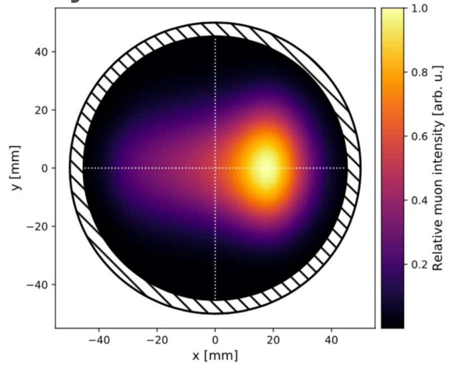
- Create a highly uniform field
- Trolley has 17 probes, produces map at 8000 azimuthal locations
- Determines strength of the field vs space



Produce azimuthally averaged field

Field maps are weighted by muon distribution





We relate our observables to the quantities that determine a_μ

$$\omega_a = \frac{eB}{m} a_\mu$$

$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Building confidence in experimental result

- Run 1 Result Statistically limited
- Improvements implemented to reduce uncertainties to 100 ppb syst, 100 ppb stat
- Technique same as BNL, but most systems are new (different), e.g. trackers, calos, field probes, electronics, etc..

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
$\mu'_p(34.7°)/\mu_e$	⋯	10
m_μ/m_e	⋯	22
$g_e/2$	⋯	0
Total systematic	⋯	157
Total fundamental factors	⋯	25
Totals	544	462

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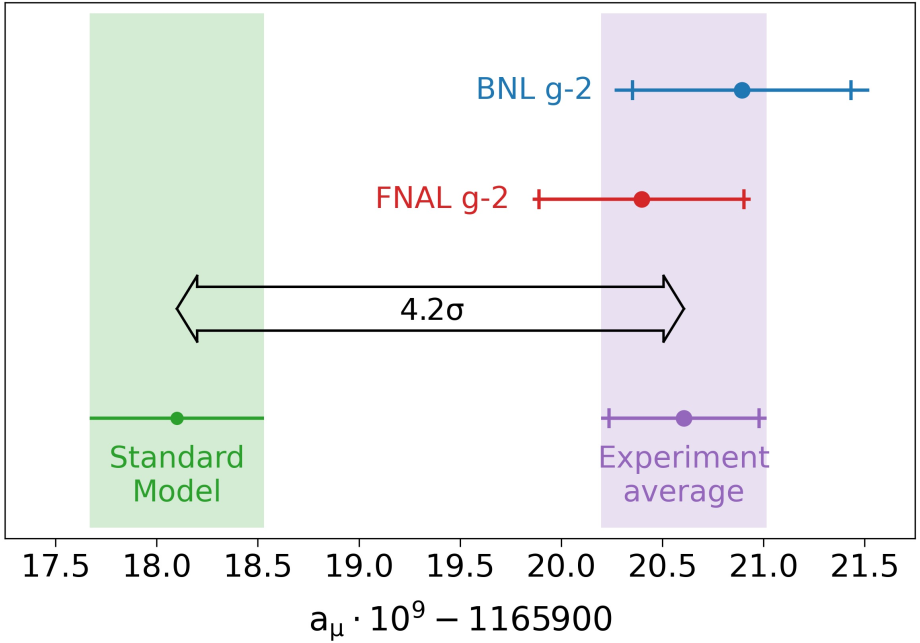
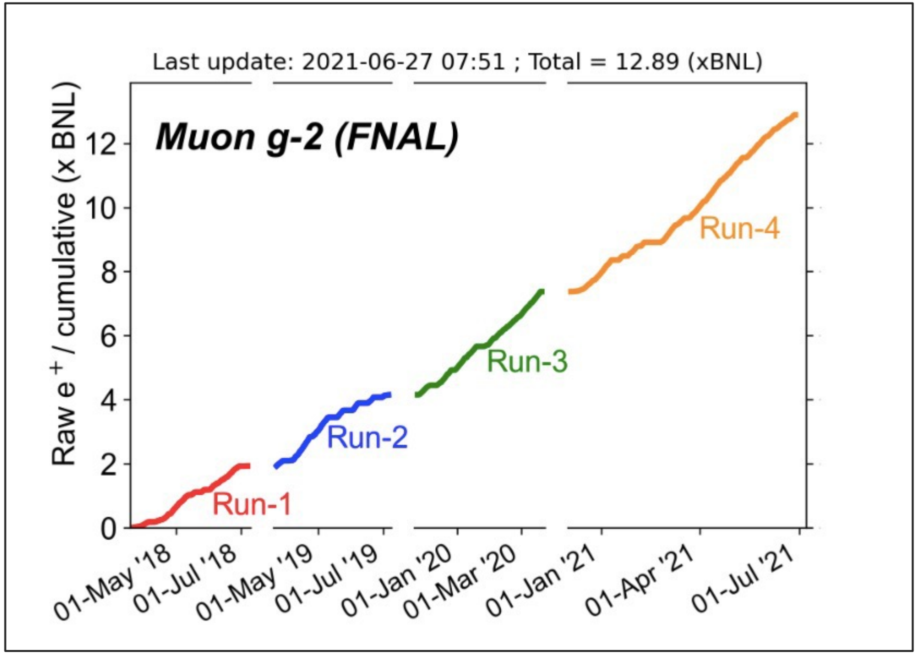
Run 1 Muon g-2 Results





- Published 6%, collected > 50% of goal
- Additional long Run 5 coming up
- Where will the experimental result settle?
- Important to push this precision

Experimental Clues

Big Question:
Where can future experimental efforts help explain the muon g-2 discrepancy?

g-2 Theory

g-2 Experiment

Other Experiments

What is next?

Big Question:
What if the discrepancy is real? Where could we look?

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

Muon g-2 Collaboration • B. Abi (Oxford U.) Show All(237)
Apr 7, 2021

11 pages
Published in: *Phys.Rev.Lett.* 126 (2021) 14, 141801
e-Print: 2104.03281 [hep-ex]
DOI: 10.1103/PhysRevLett.126.141801 (publication)
Report number: FERMILAB-PUB-21-132-E
Experiments: FNAL-E-0989
View in: OSTI Information Bridge Server, ADS Abstract Service

pdf links cite 286 citations

A flurry of activity in the last 5 months to attempt to answer those questions

Anomalies popping up in the flavor sector

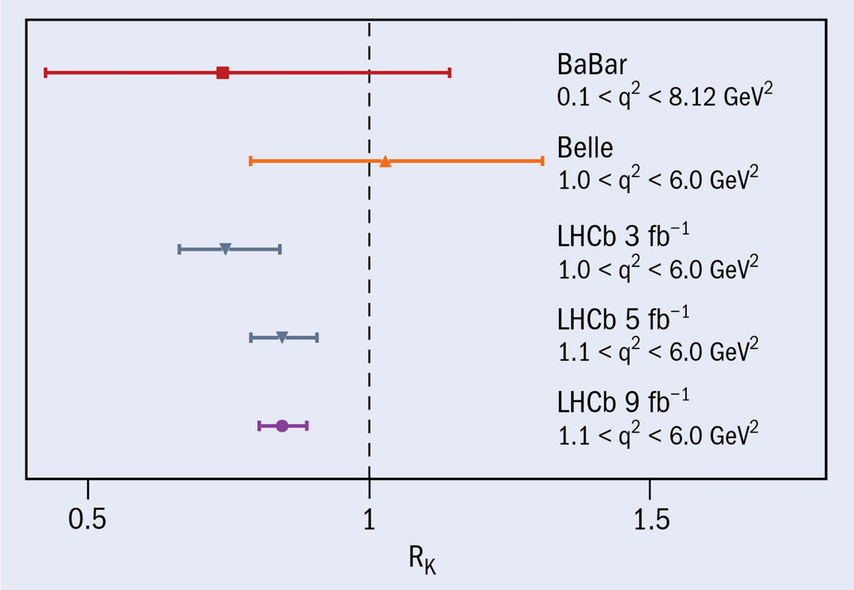
LHCB presented a recent update with the Run1 and Run 2 LHC data this spring:

- R_K probes the ratio of B-meson decays to muons vs electrons:

  $$R_K = BR(B^+ \rightarrow K^+\mu^+\mu^-) / BR(B^+ \rightarrow K^+e^+e^-)$$

- Hints that lepton flavor universality is violated: $R_K = 0.846^{+0.044}_{-0.041}$, 3.1σ
- Several other anomalies at the 2^+ σ level

- Challenging for theorists to construct models that accommodate all anomalies and g-2
- But perhaps NP sees muons differently



https://cerncourier.com/a/new-data-strengthens-rk-flavour-anomaly/

LHCB: arXiv:2103.11769v1

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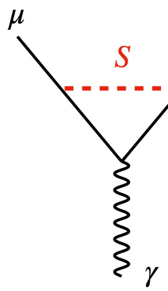
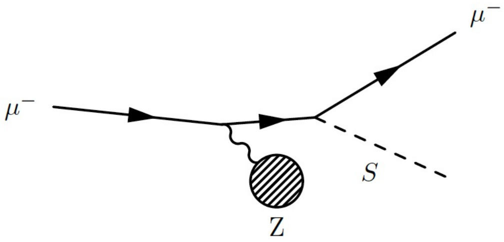
Searches for Muonphilic dark bosons

- Light (sub-GeV) new boson that couples preferentially to muons
  - Would need significant coupling strength to explain muon g-2 discrepancy
  - Would be produced with large production rates in muon beam experiments

If diagrams like this exist



…then one should be able to detect signatures like…

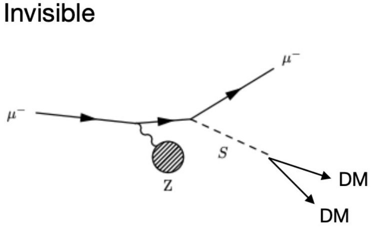


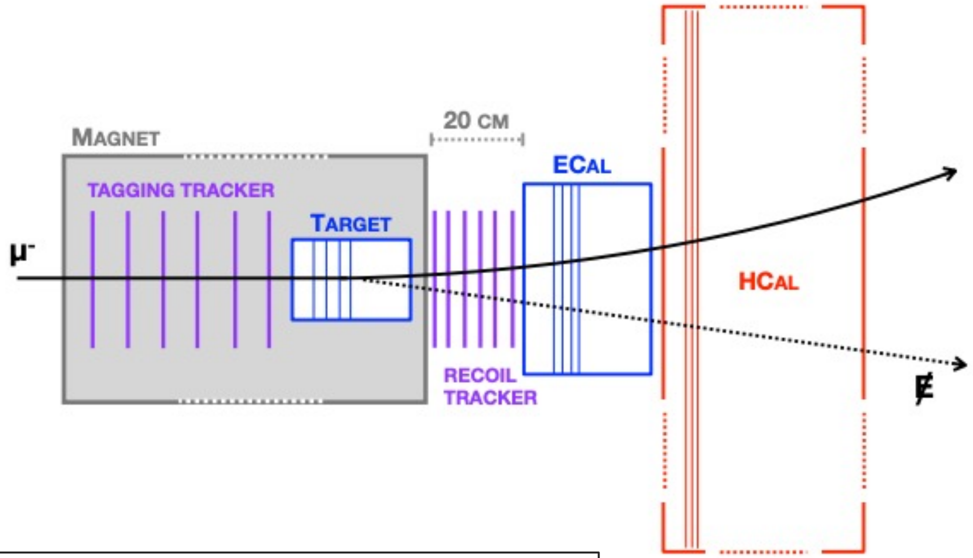
- Experimental design depends on manner in which new particle decays
  - Invisibly to our detectors
  - Decaying to detectable SM particles

Diagrams from talks by Y. Kahn, B. Batell: https://indico.fnal.gov/event/48469/contributions/214613/attachments/143550/181654/M3.pdf

Technique to identify Missing Momentum processes

- Track individual muons
- Scatter on target, new muonphilic particle takes away momentum
  - $\mu N \to \mu N \not{E}$
- Track the momentum of the outgoing muon
- Ensure "missing momentum" is not hiding in SM processes / detector inefficiencies





NA64 @ CERN gearing up for LHC Run 3, 160 GeV
M^3 (Muon Missing Momentum) proposal @ FNAL, few-10s GeV

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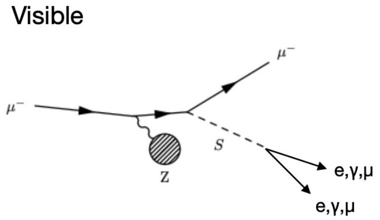
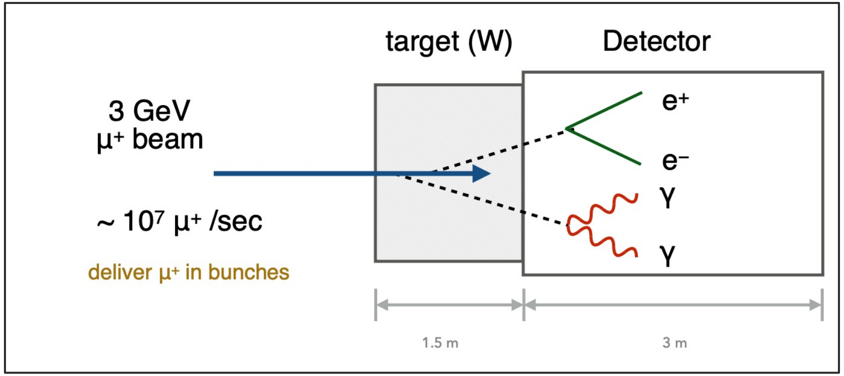
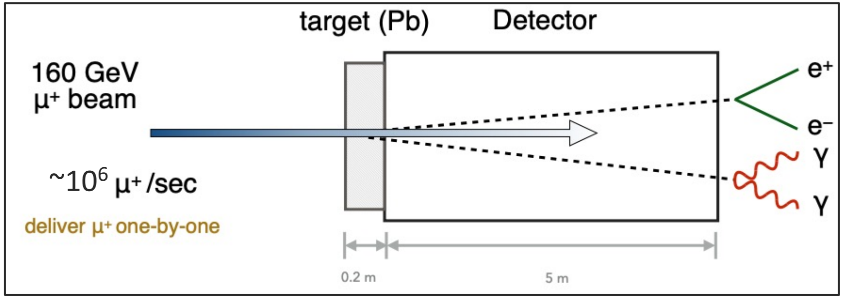
Diagrams from talks by N. Tran, C.M. Suarez
https://indico.fnal.gov/event/48936

Beam-dump proposals

- If the new particle couples preferentially to muons (and not quarks/electrons) and decays visibly
  - Can also account for muon g-2 anomaly
  - Can manifest as a displaced vertex
- Fully stop low-energy muon beam in target
  - Look for a displaced vertex / anomalous energy deposit in adjacent detector
- Or, produce particle in target with higher-energy muon beam
  - Displaced vertex occurs beyond detector
  - Observe large missing momentum







Diagrams from Y. Zhong: arXiv:1701.07437

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Ongoing and Future Efforts

- Muon g-2
  - Improve precision of existing FNAL Muon g-2 data
  - JPARC g-2 – cold μ^+ beam, tracking detector
  - Direct DM search in g-2 data by analyzing (long) time-variations in g-2 signal
- Lepton Universality
  - b physics experiments @ colliders to improve precision in rates and properties of b decays
  - Pion Decay proposal – Direct study of ratio of pion decay to muons vs electrons, extremely precisely calculated
- Charged Lepton Flavor Violation Program (CLFV)
  - mu3e/Meg-II@PSI, mu2e @FNAL, COMET @ JPARC
  - mu2e-II could probe the operators driving muon to electron conversion if found
  - ENIGMA: nExt geNeration experIments with hiGh intensity Muon beAms – a proposal to build a CLFV program investigating/measuring multiple channels

Ongoing and Future Efforts

- Fixed-Target Dark Matter Searches
  - NA64 @ CERN, M^3 @ FNAL, DarkQuest and LongQuest
- HL-LHC
  - Broad program that extends existing investment
  - Extends reach of SUSY searches into allowed regions that could also explain g-2 discrepancy
- Muon Collider
  - Lepton interactions, significant physics reach at “modest” energies
  - Needs efficient creation, collection, acceleration of muons
  - Proposed “no-lose theorem” to discover NP if the muon g-2 discrepancy is real (see: https://arxiv.org/abs/2101.10334)

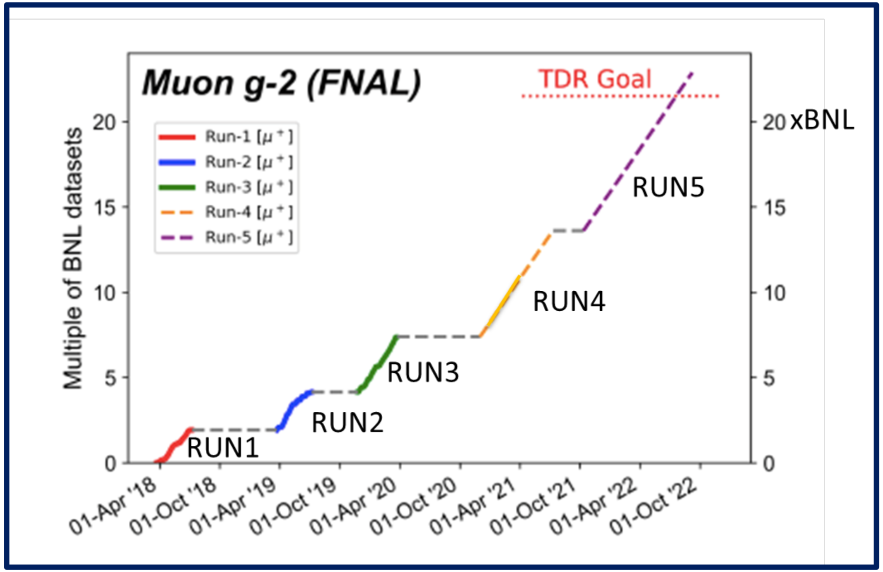
Snowmass Process

Big Question:
Where do *you* think the solution to the muon g-2 discrepancy is lurking?

- Snowmass 2022 is a great opportunity to present physics arguments and develop community consensus to pursue interesting ideas
- Early-career researches are pushing many of these efforts and defining the direction of the field

Summary and Outlook

- Theory needs experimental input to improve precision
  - e+/e- input to dispersive calculation
  - Lattice QCD comparisons
  - MUonE scattering effort
- Experiment
  - First result with 6% total data confirms BNL
  - 10x data collected, being analyzed
- Future Efforts
  - Maximize output from existing facilities
  - Is flavor trying to tell us something?
  - Can we utilize fixed-target muon experiments?
  - What big machine would help?



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