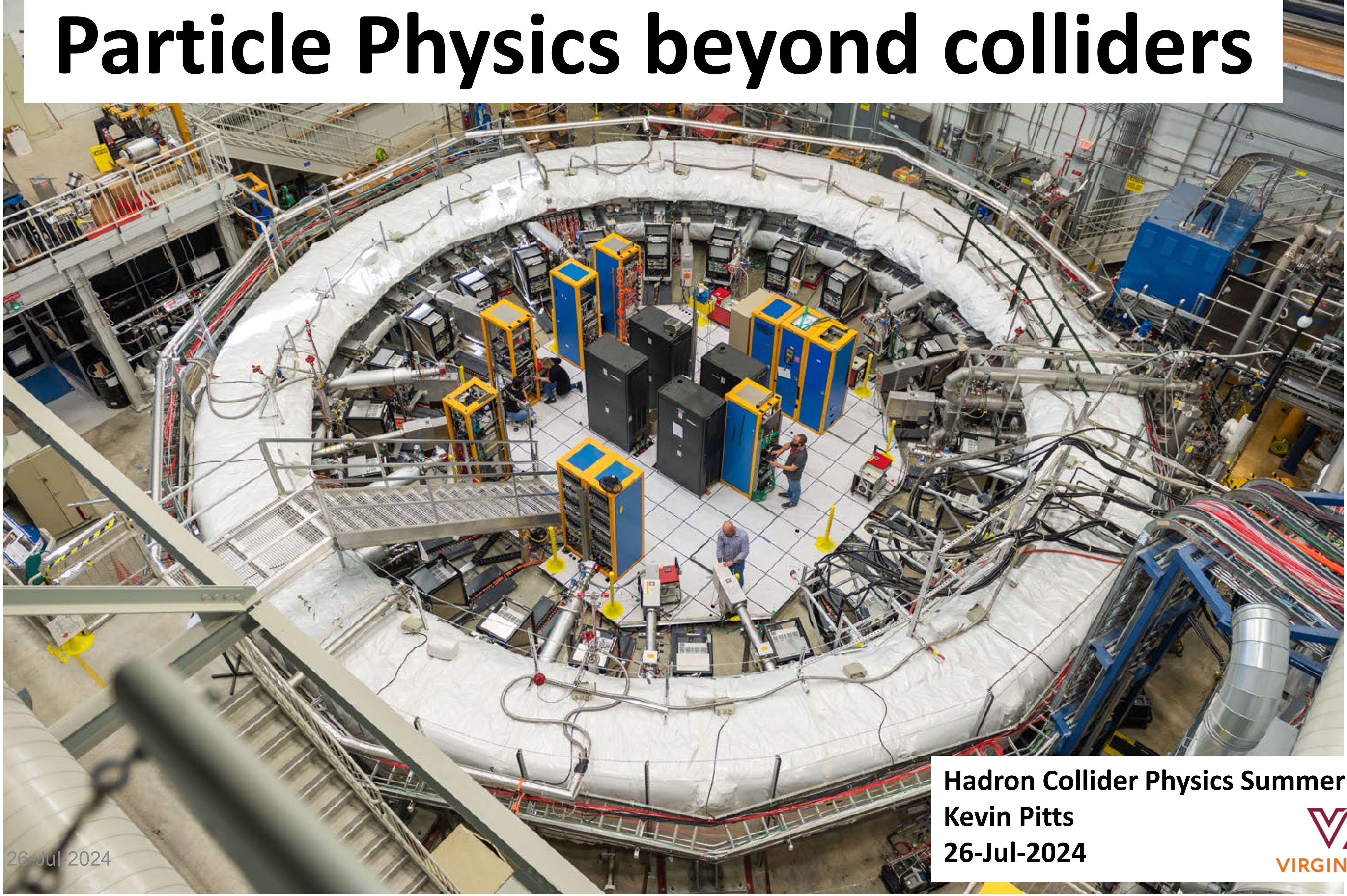
Particle Physics beyond colliders



Hadron Collider Physics Summer School
Kevin Pitts
26-Jul-2024

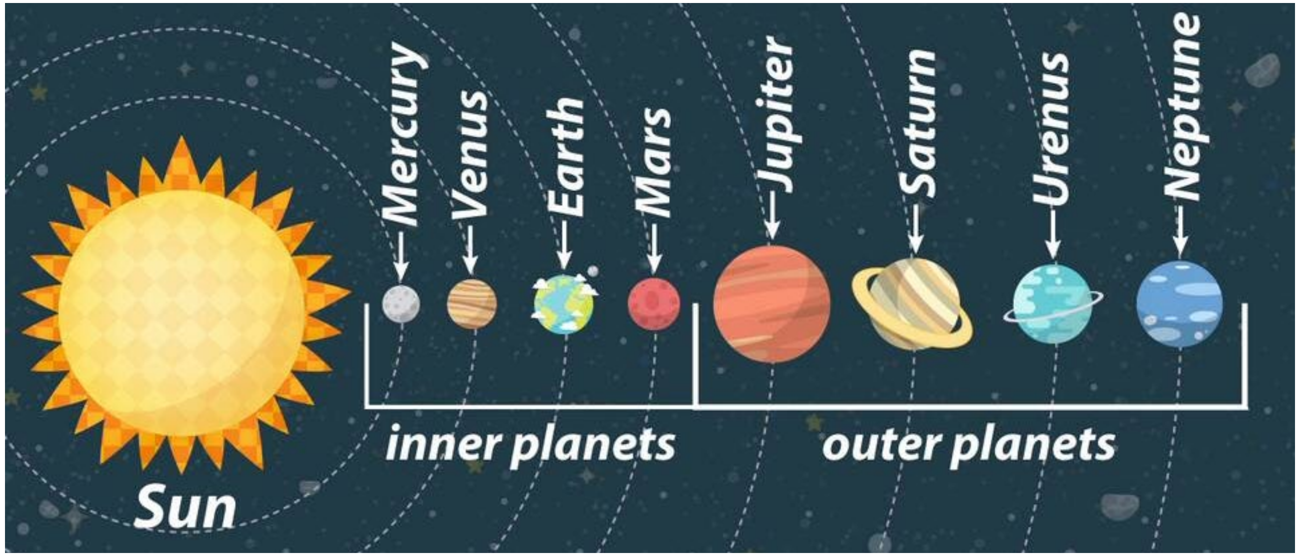
VIRGINIA TECH

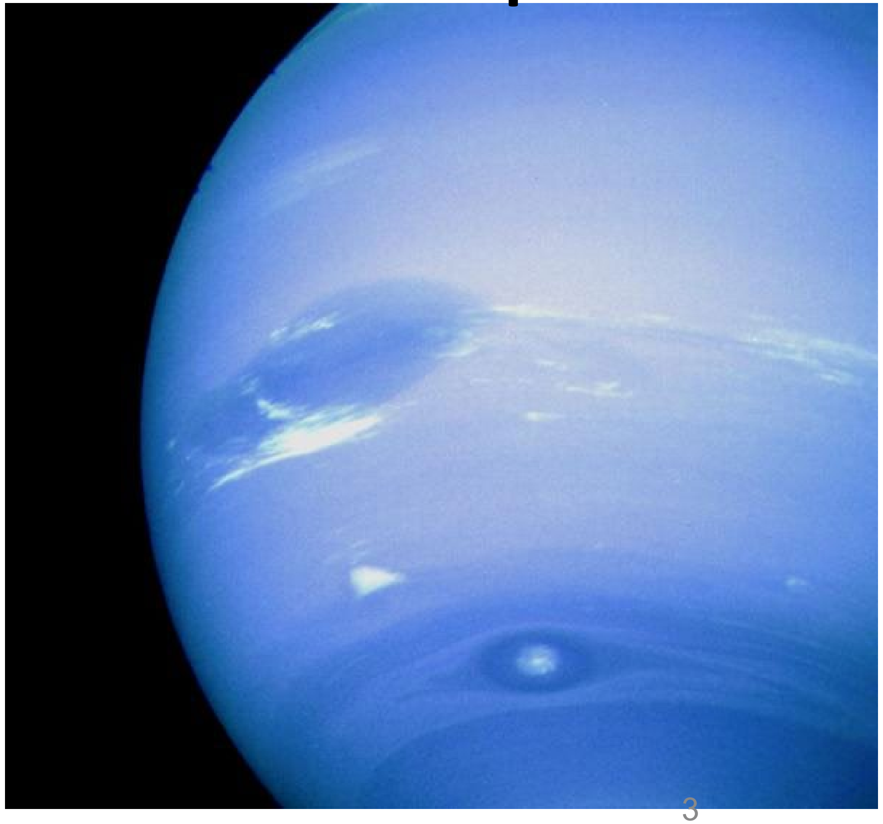
Outline

- Complementarity
  - Exploration & precision
  - Theory & experiment
  - Probes, techniques, sensitivity
- history, context, and comments
- Example: Muon g-2
- Summary

Indirect observation/prediction: Neptune

- Uranus discovered in 1781 (direct observation by telescope!)
  - Over many years, Uranus orbit appeared irregular
- Le Verrier & Adams independently calculate the effect of an 8th planet
  - Based upon understanding of Newtonian graviation
- Confirmed by direct observation in 1846





Particle Physics: A Sampling of Questions

- Higgs gives rise to mass, then
  - What about mass heirarchy?
  - Why is the top quark so heavy?
  - What about neutrino mass?
- Are quarks and leptons fundamental particles?
  - Why is $q_u = 2e/3$?
  - Is there something inside a quark? Inside a lepton?
- Why a matter/antimatter asymmetry in the universe?
- Why three generations of quarks and leptons?
- What about dark matter (is it from supersymmetry?)
- Are there other fundamental forces?
- Are there extra dimensions?
- Do all of the forces unify?

Complementarity

We are trying to answer BIG and HARD questions.

Must use a variety of tools & techniques:

- **Direct searches**
- **Precision measurements**
- **Different sources/probes (cosmic, accelerator)**
- **Different detection techniques**
- **New theoretical understanding/techniques**
- **Computational science**
- **New Technologies for all of the above**

AND we need to integrate the results.

Comment: Strengths & Weaknesses

My opinion, based upon history and experience. Feel free to argue…

We are good at:

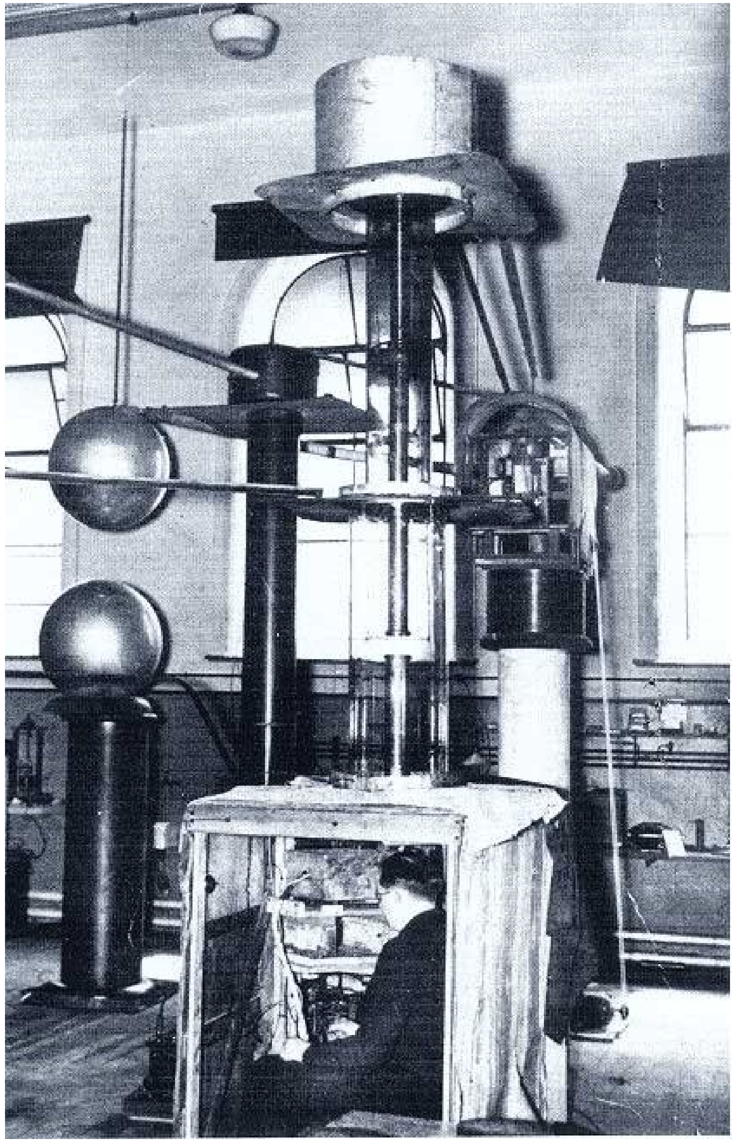
- **Embracing new technology (silicon, liquid argon)**
- **Taking a good idea and making it bigger and better (accelerators, computing)**
- **Technical training in foundational science**
- **Working in big teams (CMS, ATLAS)**

Where we could improve:

- **Looking to experts outside of our own field (e.g., materials science, computing)**
- **Thinking more broadly about impacts of our work**
- **Training young people for careers outside of research**
- **Communication – even within the discipline**
- **Inclusivity**

History
Embracing and advancing technology and ideas

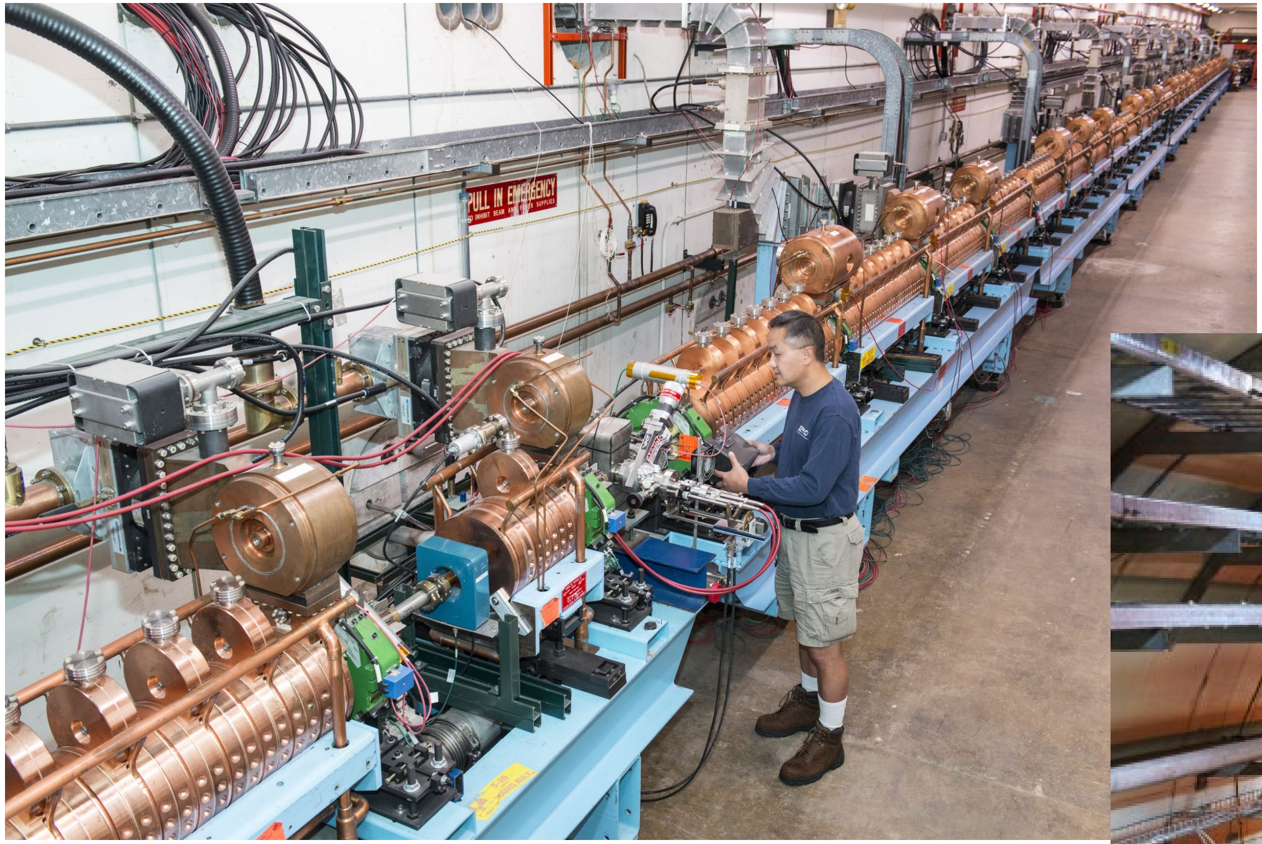
Particle accelerators, then:



Cockroft-Walton

60 inch cyclotron

Particle accelerators, now:

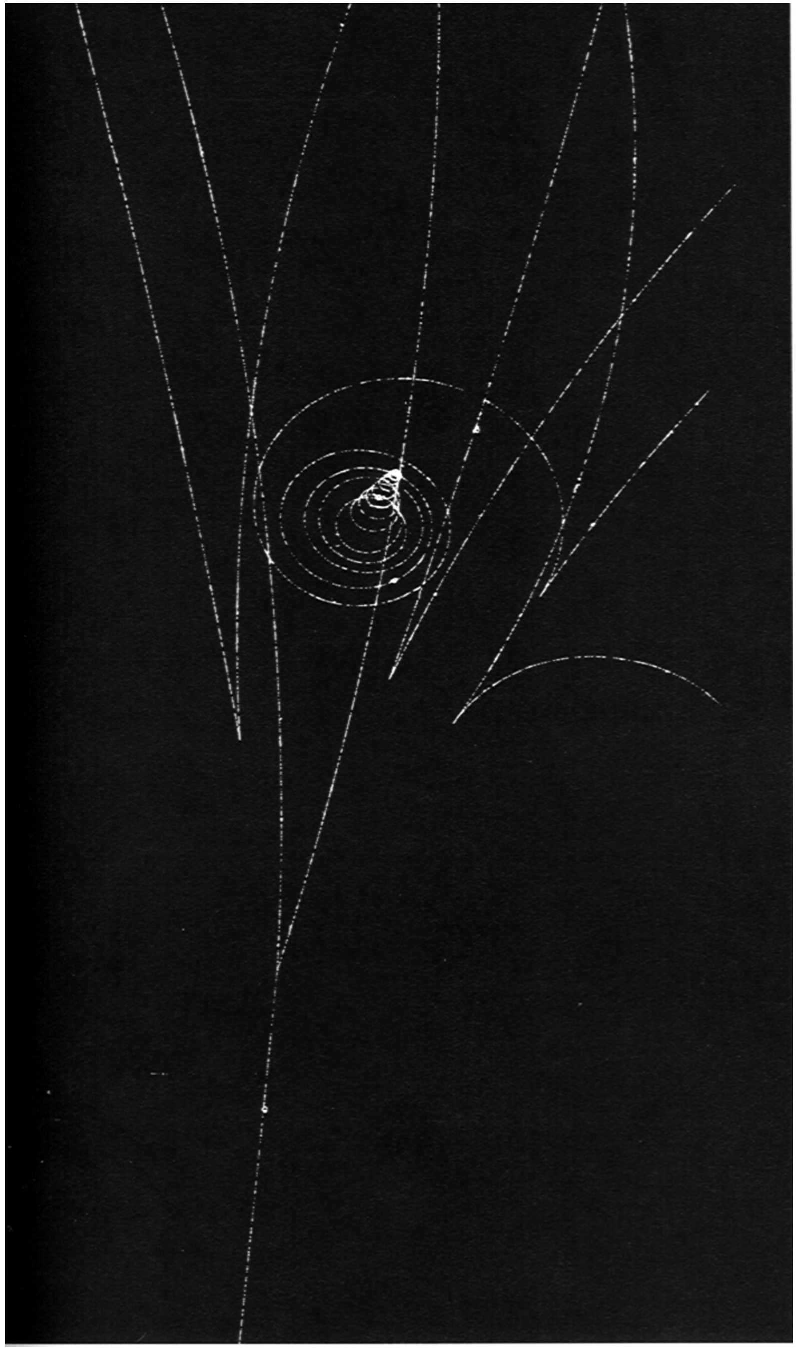


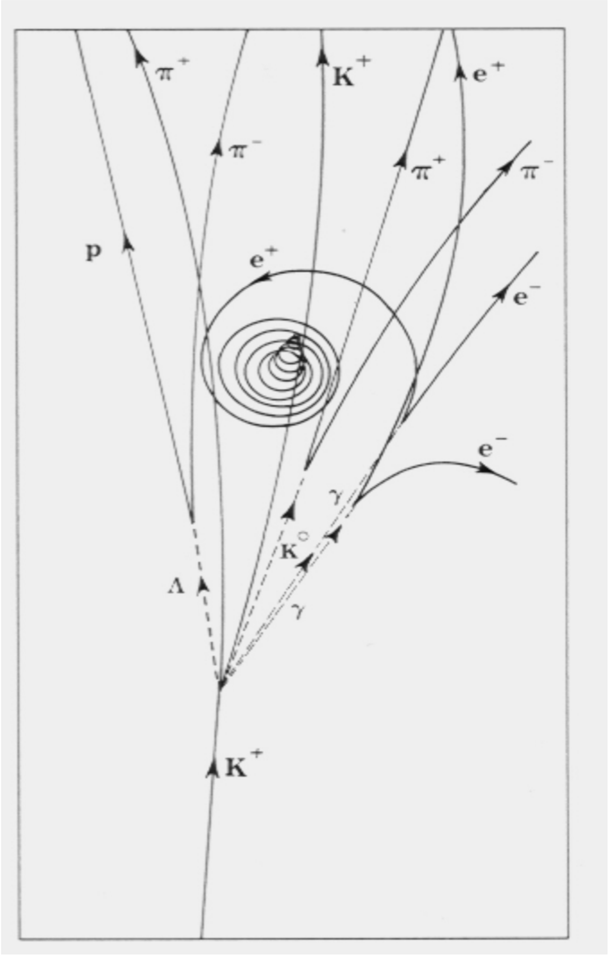
Fermilab linac

CERN LHC

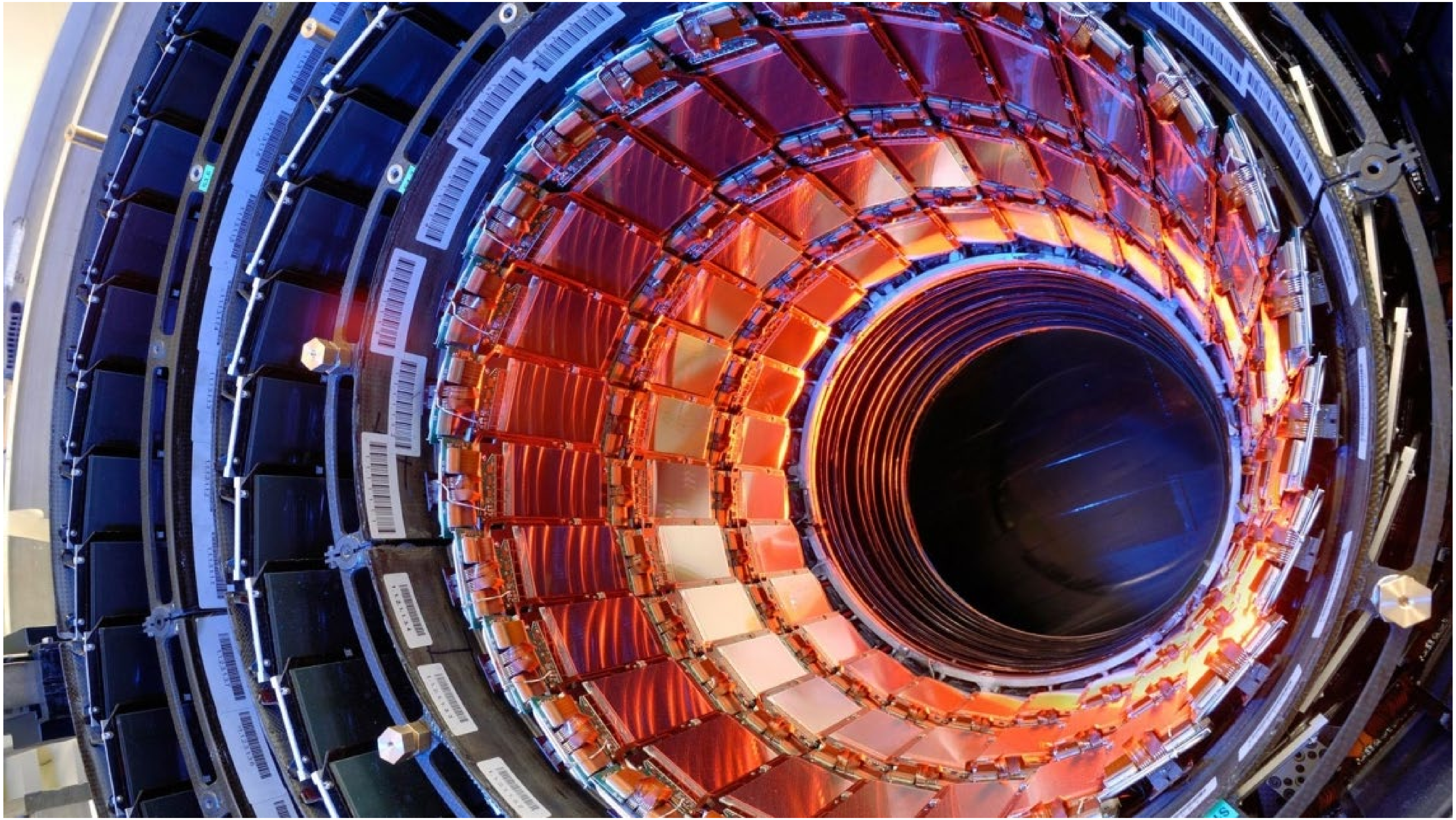
Detectors: then

Bubble chamber





Detectors: now

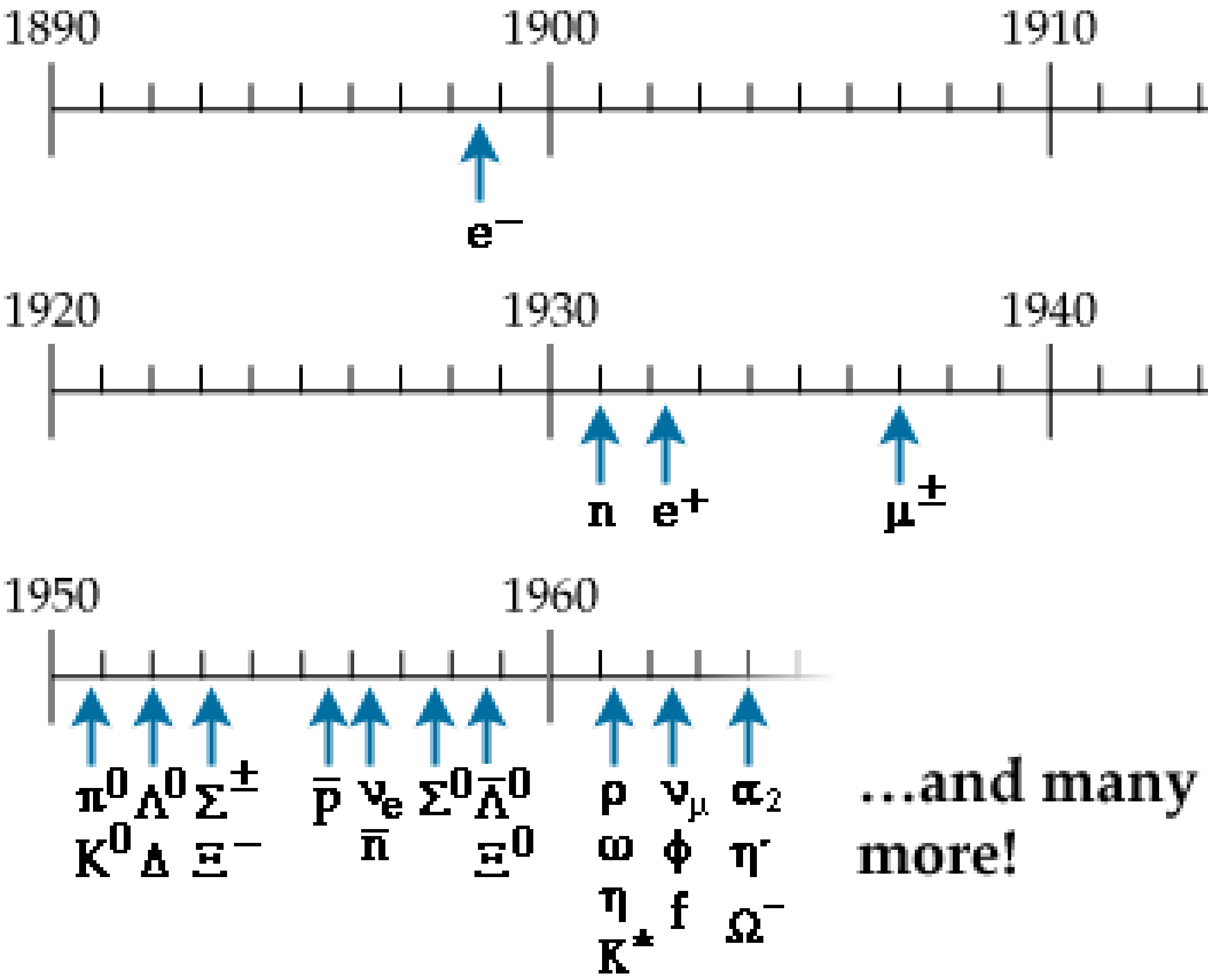


CMS Silicon Tracker

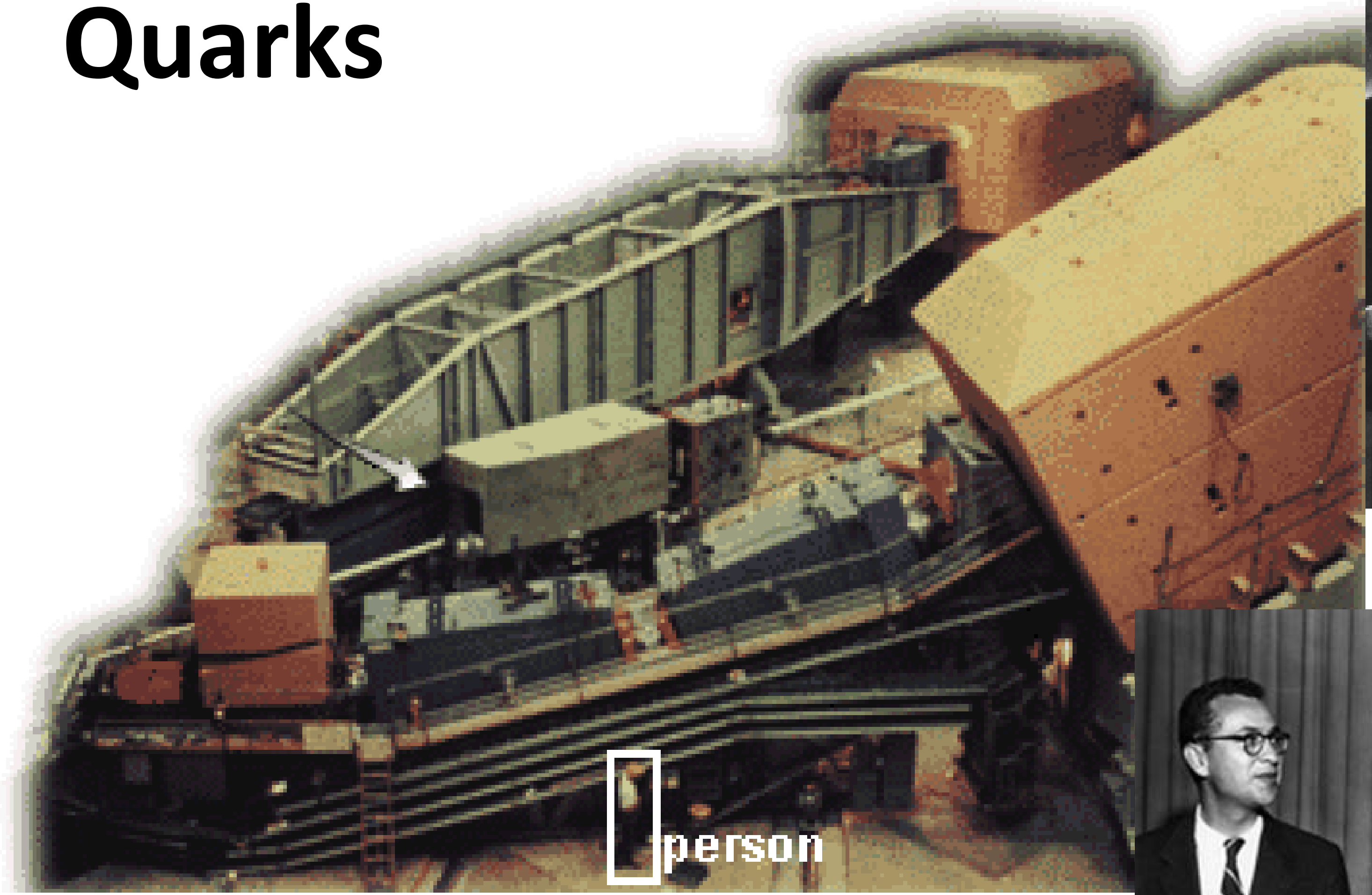
The last 125 years, oversimplified

- **Modern Physics** 1900-1930 relativity, quantum mechanics
- **The Nucleus** 1930-1950 neutron, fission, fusion
- **The Zoo** 1950-1970 Sigmas to Omegas, quarks
- **Foundations of SM** 1970-1990 GWS, Higgs, quarks, W/Z, gluon
- **Standard model and beyond** 1990-now
  - Flavor Physics charm, B, CP violation, mu, tau
  - Neutrinos mixing, solar, accelerators, reactors
  - Astrophysics dark energy, dark matter, CMB
  - Beyond SM searches (LEP/SLC, Tevatron, HERA, LHC)

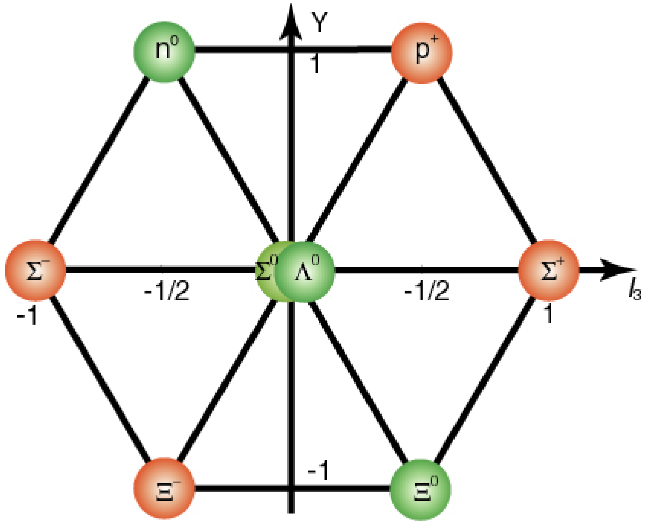
The Particle Explosion



Quarks


person


Scanned at the American
Institute of Physics

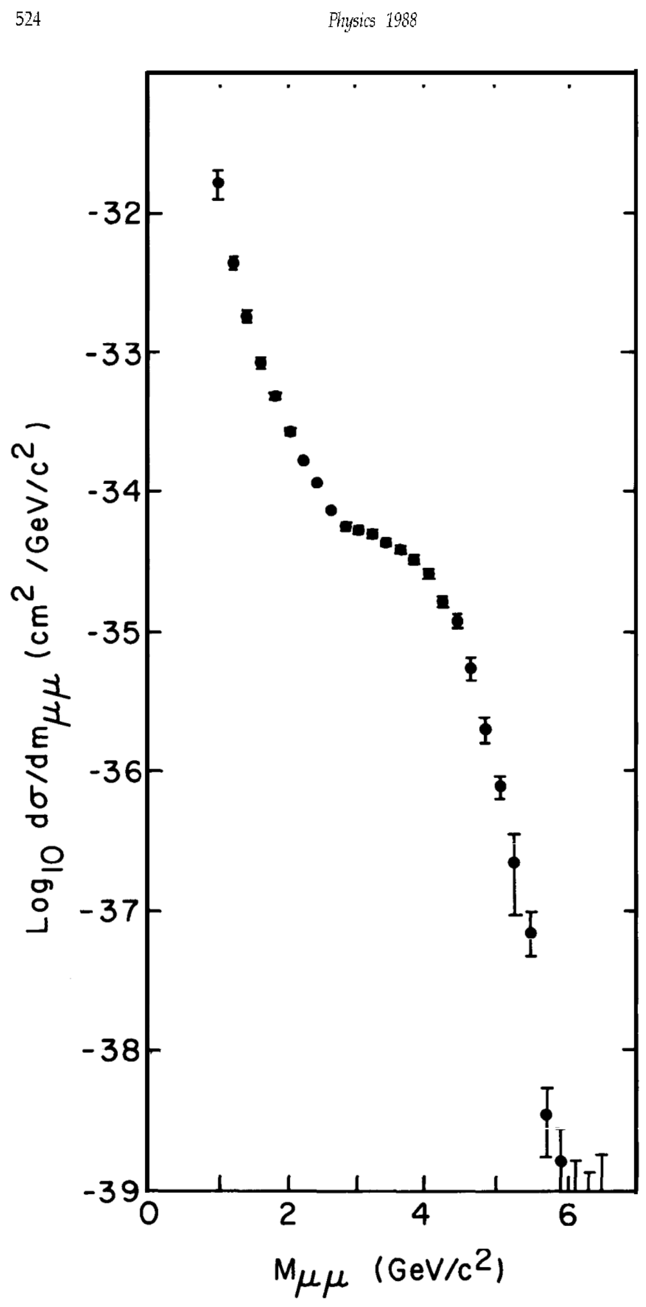

Y
n^0
p^+
1
Σ^-
Σ^0
Λ^0
Σ^+
-1/2
-1/2
-1
1
I_3
-1
Ξ^-
Ξ^0

Direct observation of…

- **Leon Lederman & team, looking at:**

  p + U $\rightarrow \mu^+ \mu^- X$

  (Brookhaven 30GeV protons, 1968)
- **Detector looking for the mass of the dimuon ($\mu^+ \mu^-$) system.**
- **Data showed funny "shoulder" around 3GeV/c^2.**
- **Problem: experiment did not have very good mass resolution.**



Discovery of the J/ψ

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \text{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

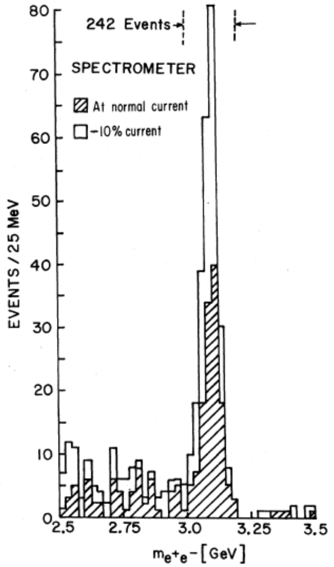
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

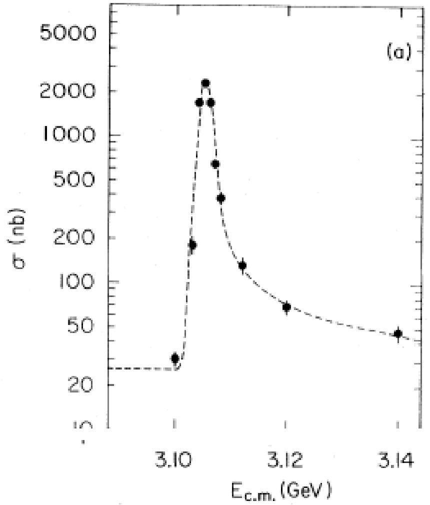
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

By studying the decay of strange particles, the existence of the charm and its properties (eg. mass, weak couplings) were predicted *before* its discovery – met with skepticism.



Brookhaven: J



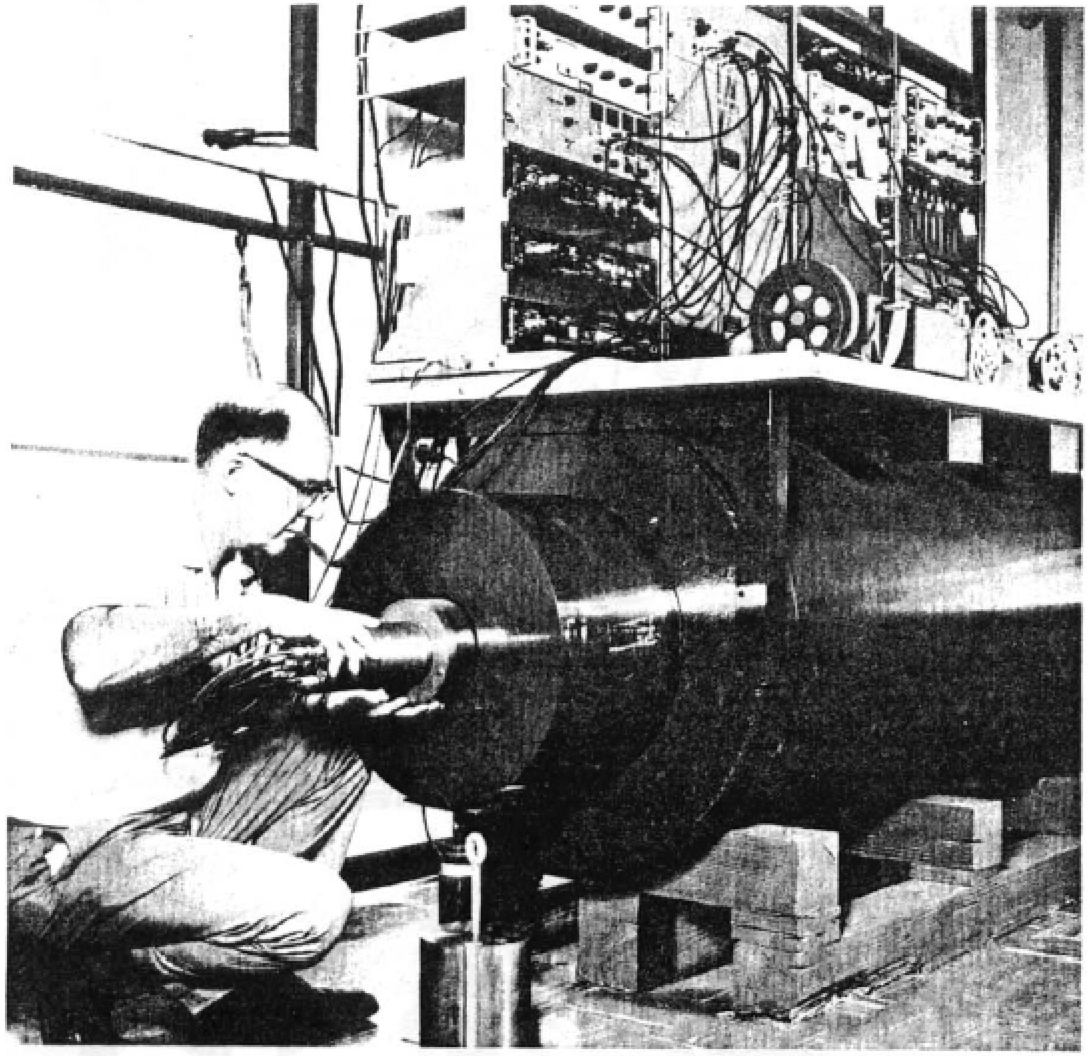
SLAC: ψ(3105)

Sam Ting and Burt Richter got the 1976 Nobel prize for their discovery

Volume 21, Number 36 Published by the BNL Public Relations Office

9-1307-66

Solar Neutrinos Are Counted At Brookhaven



Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar Neutrino Experiment.

Meanwhile, the Solar Neutrino Problem was starting.

Ultimately: neutrino oscillations, neutrino mass!

Fermilab

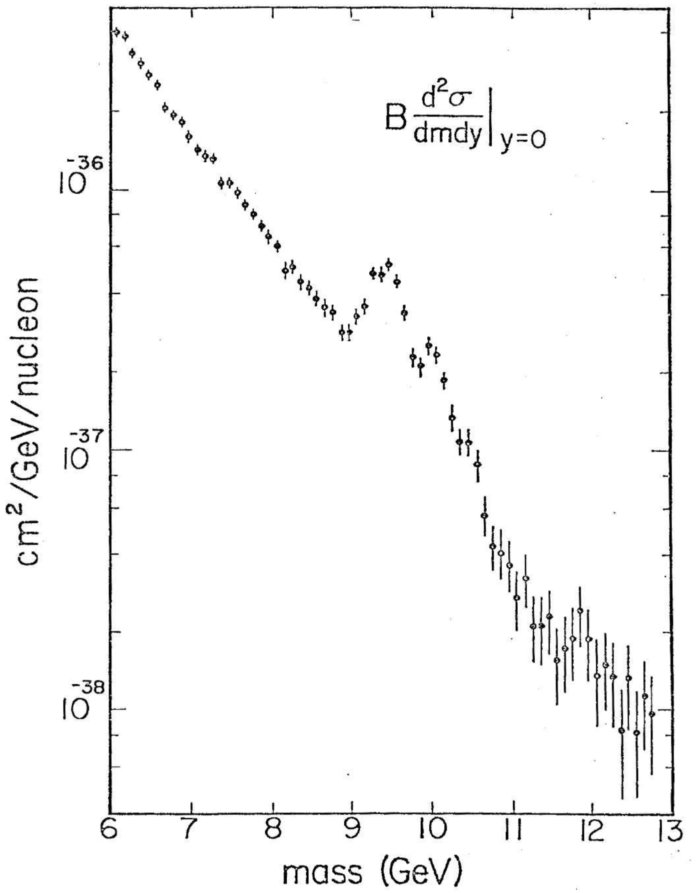
Early 1970's

Main ring proton accelerator

Originally 200 GeV, later 400 GeV

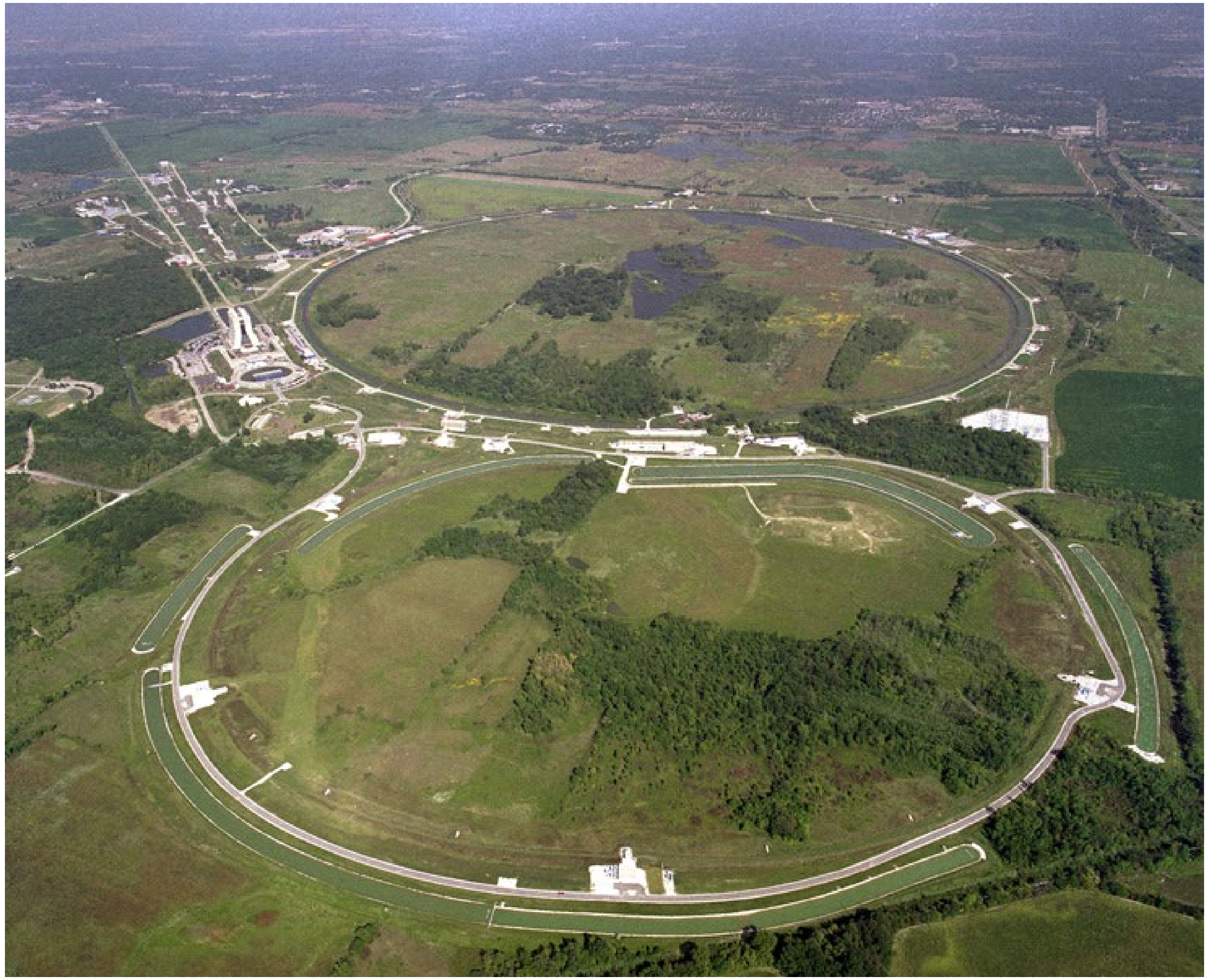
Fermilab

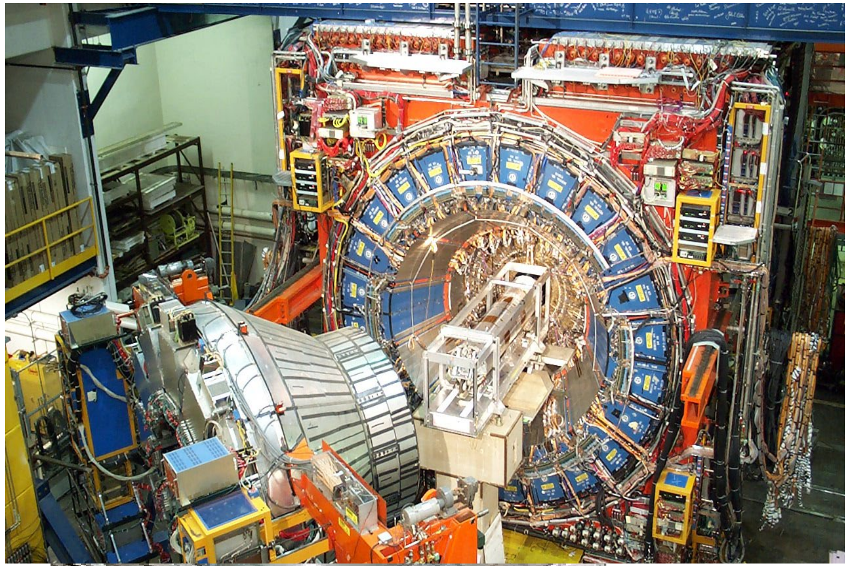
1977 E288 discovers b



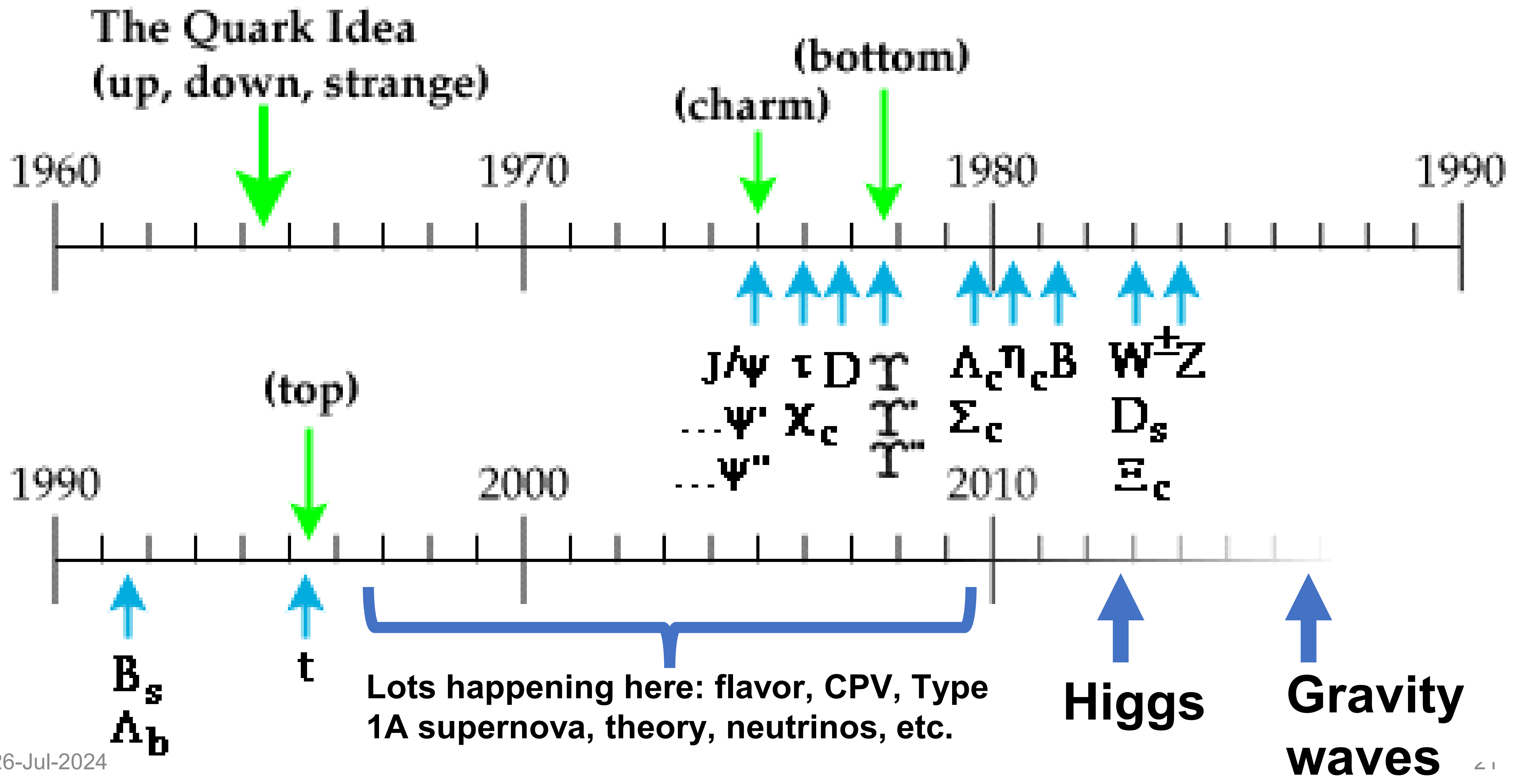
Press release: An experimental group at the Fermi National Accelerator Laboratory announced recently that it has discovered a new particle. The new particle has a mass of 9.5 GeV. It is 10 times heavier than the proton and is the heaviest sub-nuclear particle ever seen. The new particle -- which the group has named "Upsilon" -- is interpreted by theorists to be the first hint of a whole new family of subnuclear particles.

Tevatron (Main Injector foreground)





Slightly more recently…



A Sampling of Questions

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A Sampling of Questions

- Higgs gives…
-
- W…
- W…
- Wh…
- Are…
- Are t…
- Do all…

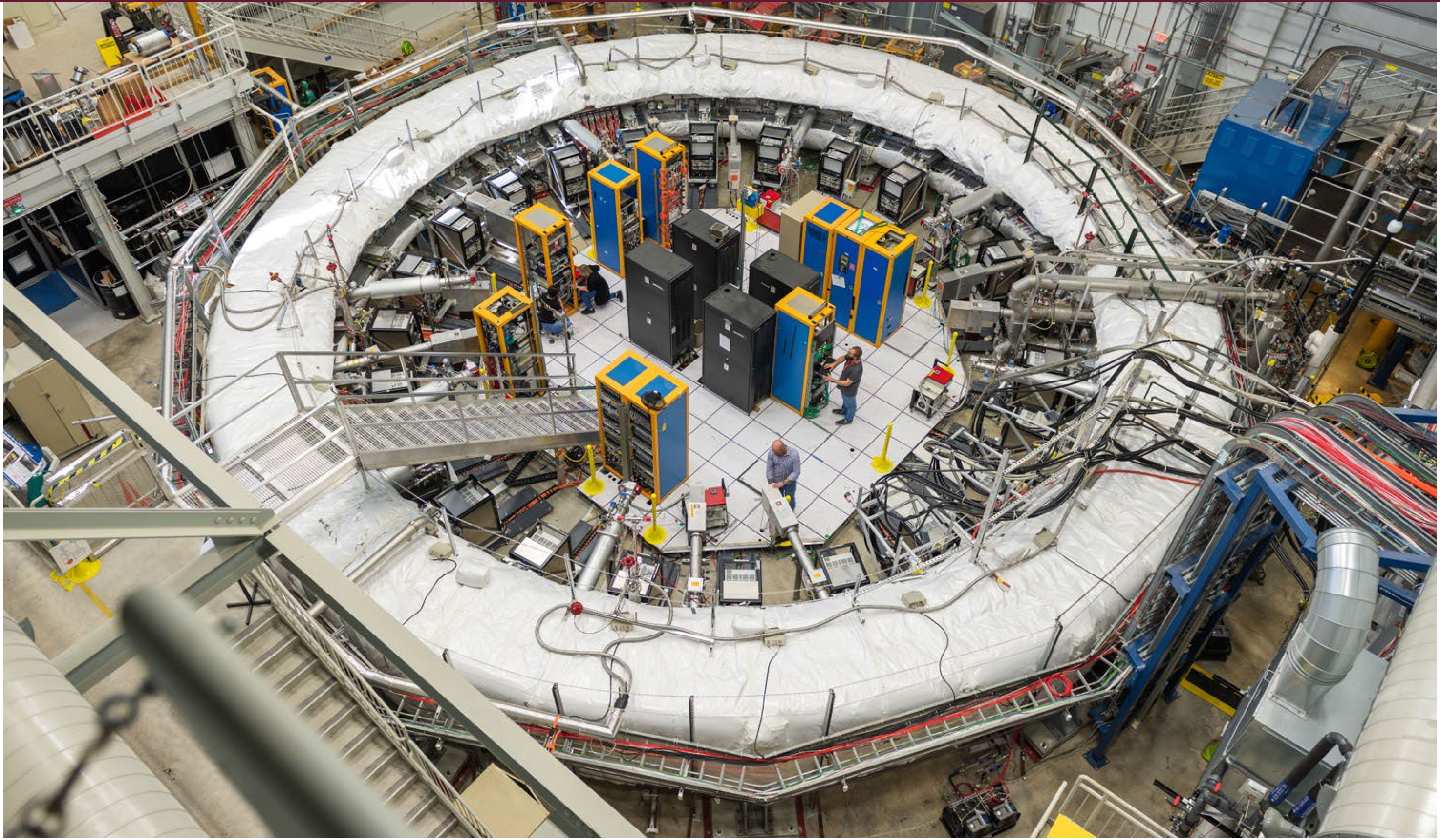
Difficult questions!

We need every tool in the toolkit:

- Colliders
- Fixed target
- Cosmic rays
- Theoretical calculations
- Computational Science
- New techniques
- …

To find answers to these questions!!!

Beyond colliders: the Muon g-2 Experiment



Context within this talk

Muon g-2 ultra-high precision. Uncertainties in the range of

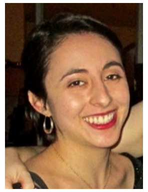
100 parts per billion (ppb)

- Indirect search for new physics
- Quantity that can be measured with high precision
- Quantity that can be predicted with high precision
- Comparison is very interesting/enlightening

The UIUC Muon g-2 Team

Murong Cheng
Graduate student

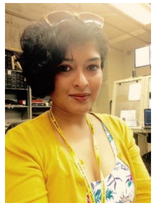
Esra Barlas Yucel
Postdoc



Cristina Schlesier
- Cornell University
- Former grad student

Adam Schreckenberger
- Scientist at Fermilab
- Former postdoc

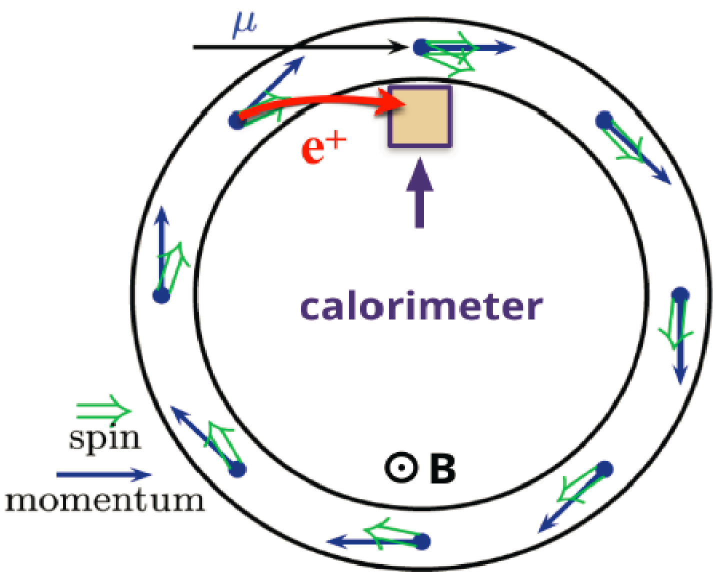
Adi Kuchibhotla
- University of Georgia
- Former grad student



Sudeshna Ganguly
- Scientist at Fermilab
- Former postdoc

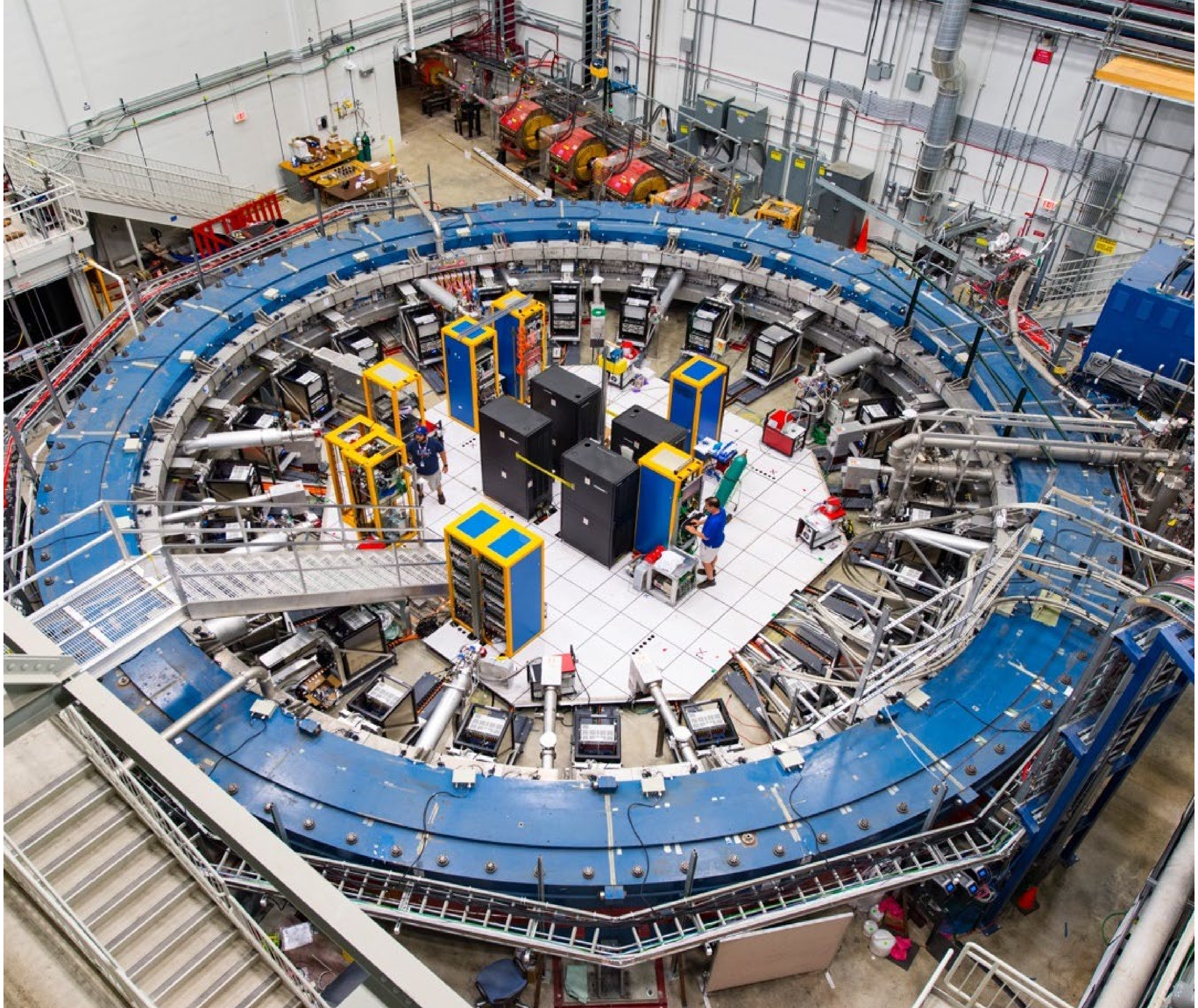
Jason Crnkovic
- Scientist at Fermilab
- Former postdoc

Sabato Leo
- Fressnapf Holding
- Former postdoc



Big Picture up front

1. Make lots and lots of muons
2. See how they wobble in a magnetic field
   - Do it with an amazing level of precision
3. Calculate how they should wobble in a magnetic field
   - Do it with an amazing level of precision
4. Marvel that you can do both to this level of precision (<1 ppm)
5. See if theory and experiment agree…
6. Get back to work



The Big Move June-July 2013

Leaving Brookhaven National Laboratory

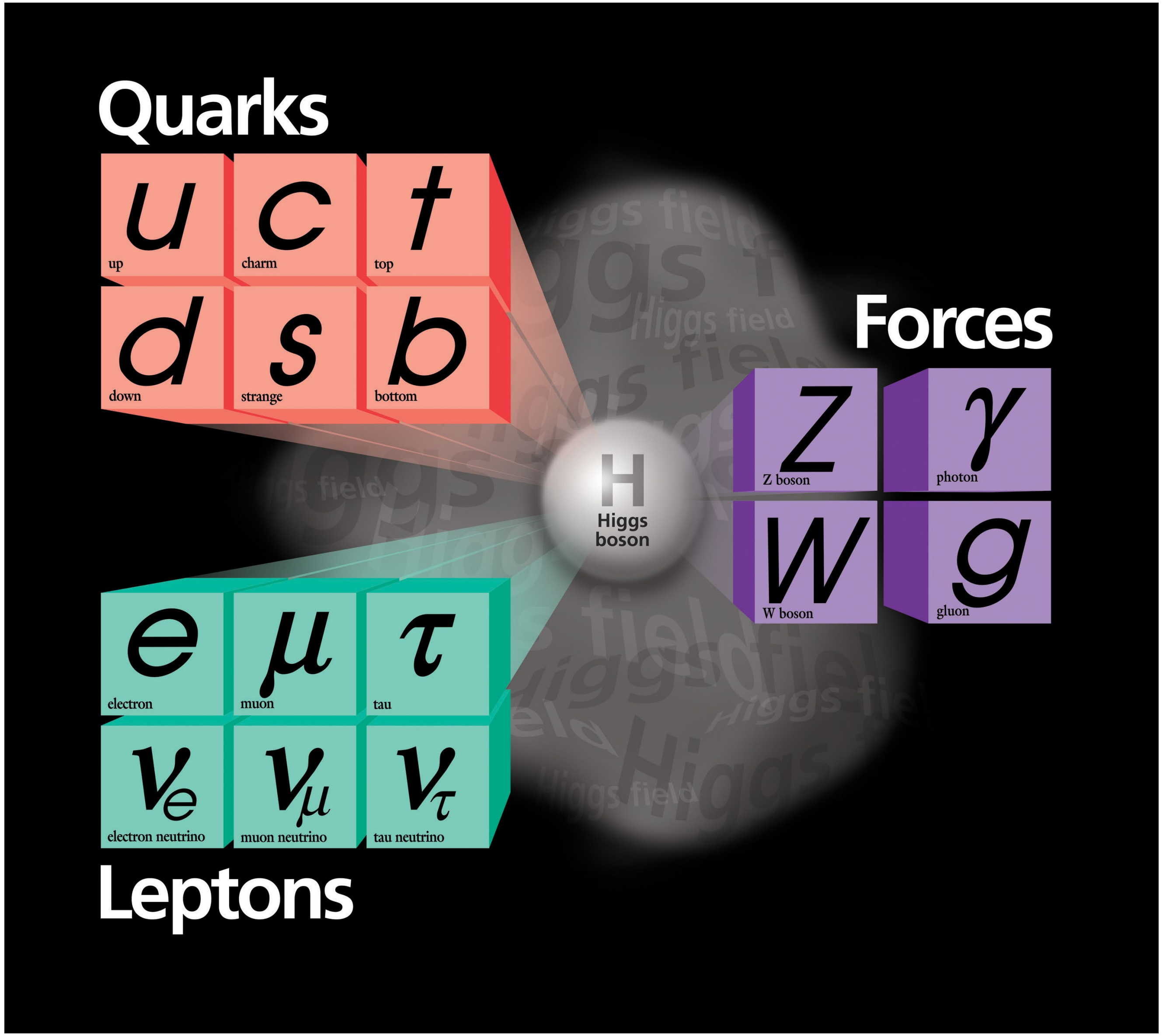
On Illinois tollway towards Fermilab

GPS record of barge carrying magnet


μ
g-2
Photo: Hogan Nguyen

Fermilab Muon Campus

Muons: What & Why?



2^{nd} **generation** elementary particle

Broadly similar to electrons, but

- **200x more massive**
- **Unstable**: decay to $e^-, \bar{\nu}_e, \nu_\mu$

2.2 μs lifetime: easy to make and manipulate at accelerators

$\beta\gamma = p/m$=3.1GeV/0.106 GeV = 29

τ_{lab} = $\tau\gamma$ = 2.2μs * 29 = 64μs

- **"Goldilocks" Mass:**
  - Heavier than electron more sensitive to virtual particles
  - Lighter than pion so no hadronic decays
- Have a property called **spin** that rotates in a magnetic field

Muon Magnetic Moment

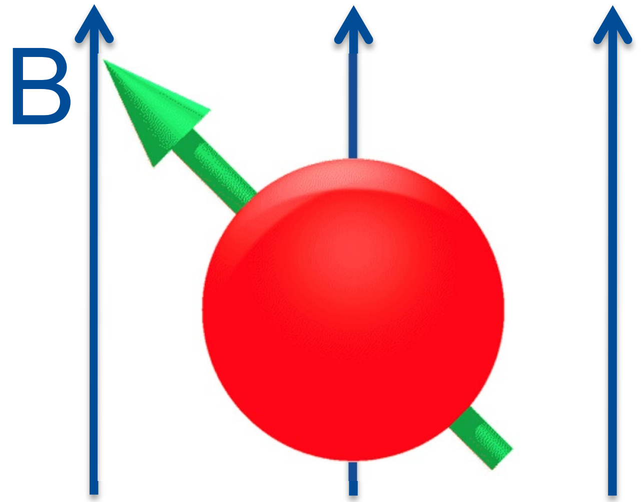
- ***g*** determines spin precession frequency in a magnetic field

Torque in B-field

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

Magnetic Moment

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



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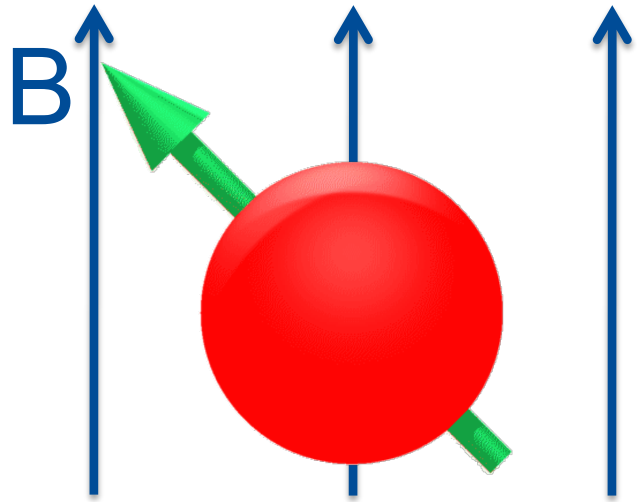
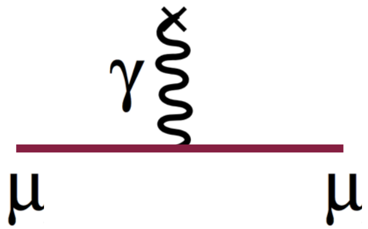
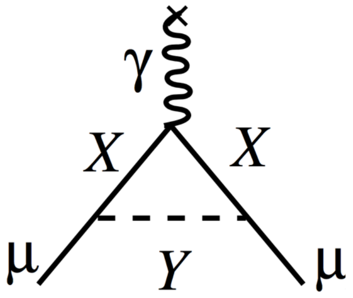


$g = 2$



- For a pure Dirac spin-½ charged fermion, *g* is exactly 2

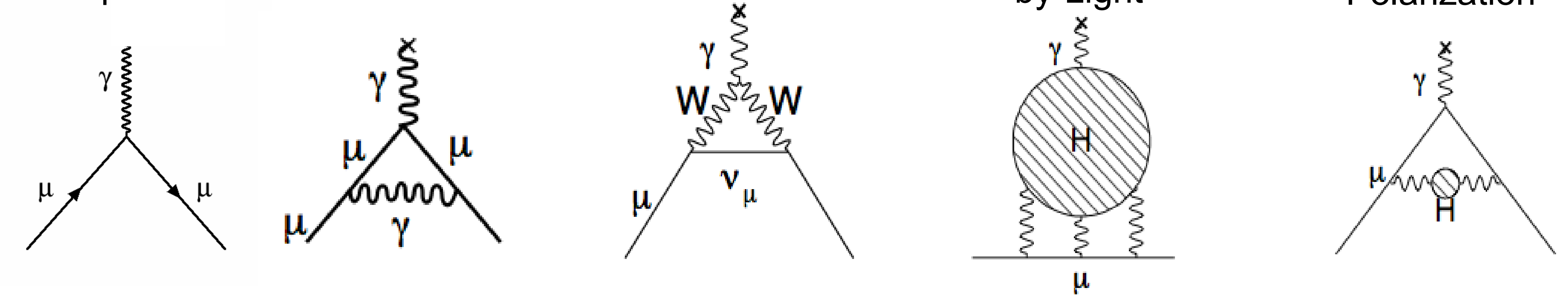
$g > 2$



- Interactions between the muon and **virtual particles** alter the value: X & Y particles could be SM or new physics

Standard Model Components of g_μ

Dirac Equation | QED | Electroweak | Hadronic Light-by-Light | Hadronic Vacuum Polarization



- SM values taken from the **Muon g-2 Theory Initiative**

2018: Mainz, Germany

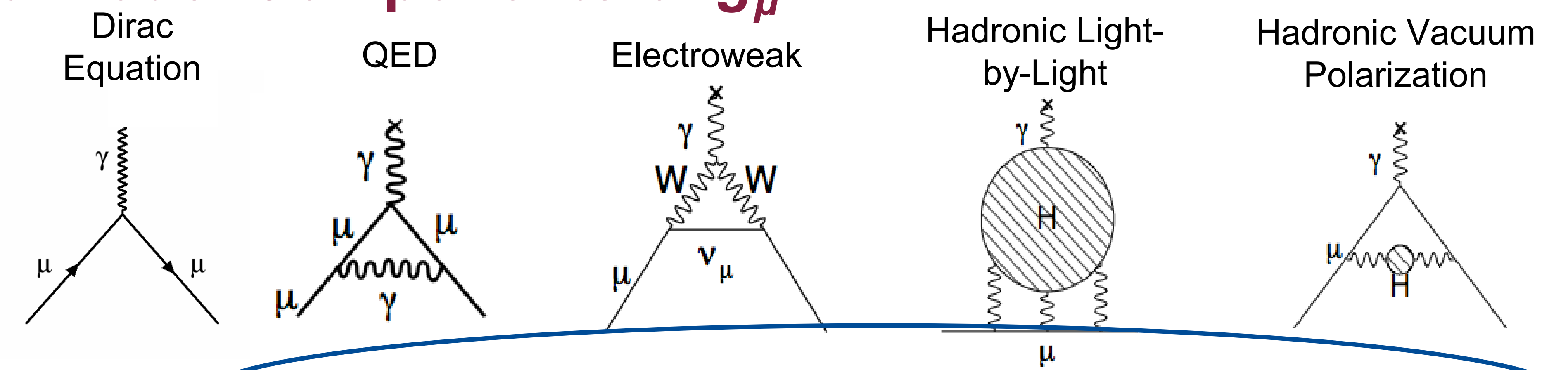
- **Consortium of 100+ theorists who calculate, compile theoretical inputs and provide recommendations**

- Last compilation in **2020**:

White Paper: Phys. Rept. 887 (2020) 1-166
https://doi.org/10.1016/j.physrep.2020.07.006

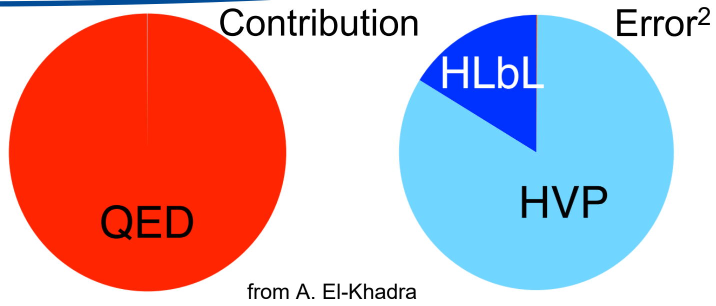
https://muon-gm2-theory.illinois.edu/

Standard Model Components of g_μ



$$g_\mu = 2(\quad 1 \quad + 0.00116584719 \quad + 0.00000000154 \quad + 0.00000000092 \quad + 0.00000006845)$$

- **QED** dominates the value itself
- Uncertainty is dominated by **QCD**, in particular **HVP**



from A. El-Khadra

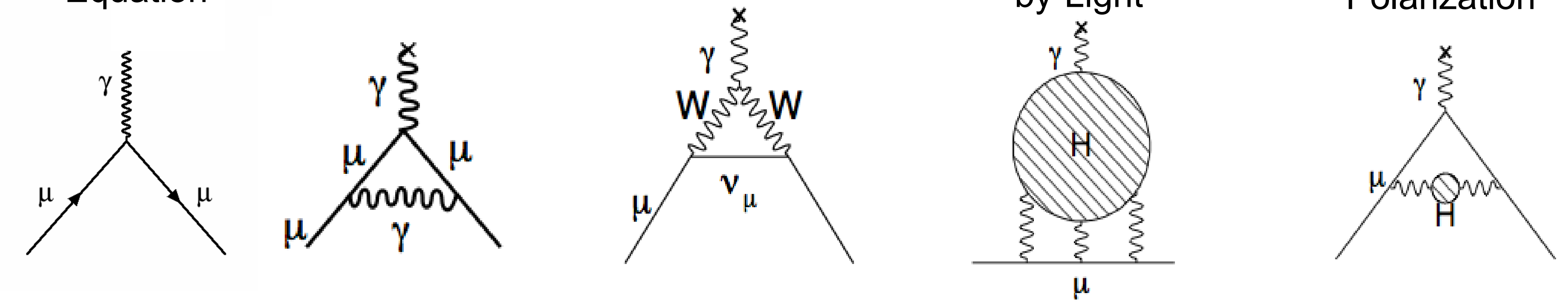
- All the interesting physics is in the loop terms, so we define

$$a_\mu = \frac{g-2}{2}$$

Muon magnetic anomaly
or anomalous magnetic moment

Standard Model Components of g_μ

Dirac Equation | QED | Electroweak | Hadronic Light-by-Light | Hadronic Vacuum Polarization



$$g_\mu = 2(\quad 1 \quad + 0.00116584719 \quad + 0.00000000154 \quad + 0.00000000092 \quad + 0.00000006845)$$

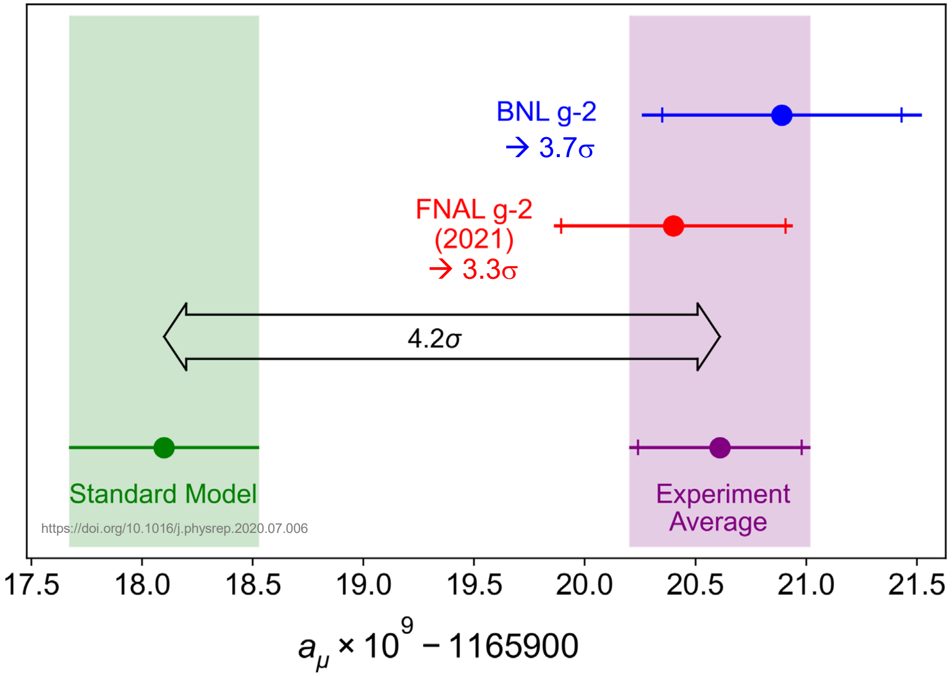
- Everything in SM needs to be included here: but are we sensitive to some **physics beyond the SM**?
- We can compare **experimental & predicted** values and ask:

"Is there some New Physics in our experiment that isn't in the Standard Model?"

Fermilab Run-1 Result (2021)

- BNL E821 (2004) disagreed with SM prediction:

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.141801



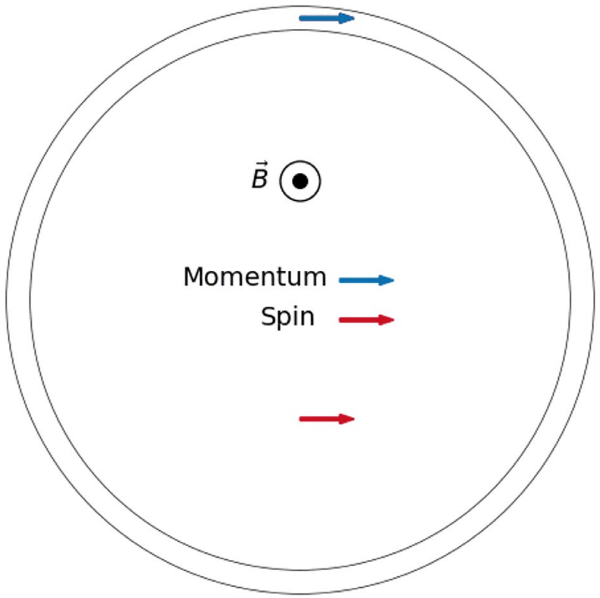
- 7-Apr-2021, **Run-1** result
- Using 5% of our data, we **confirmed BNL** value
- FNAL+BNL average stood **4.2σ** from Theory Initiative White Paper (2020)

Measurement Principle

- Store **polarized muons** in ring with **dipole B-field**
- Both **spin** and **cyclotron** frequencies are proportional to **B**

Difference frequency ω_a is prop. to a_μ (and B)

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



- **Spin rotates ahead of momentum** as muon orbits the ring

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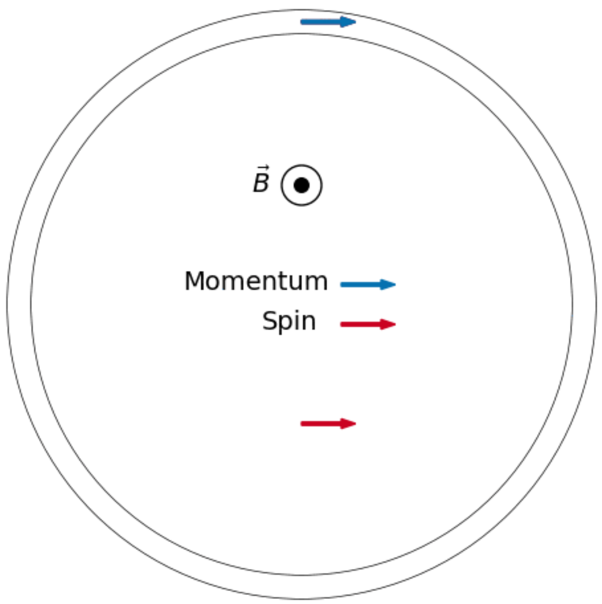

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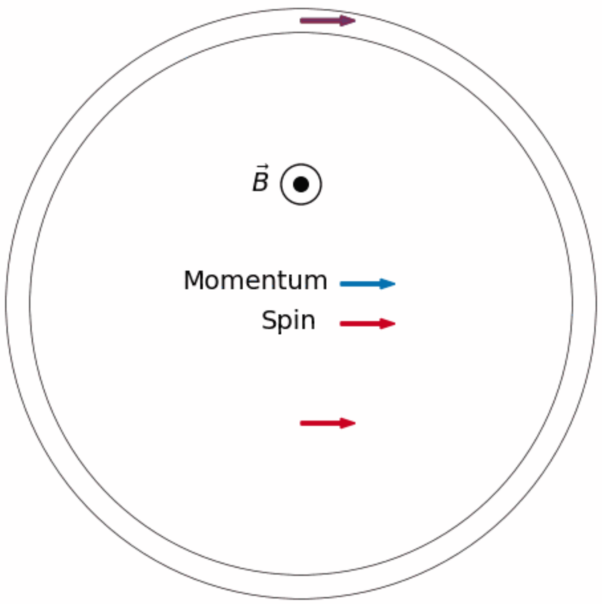

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Diffe

ω_a

Measure

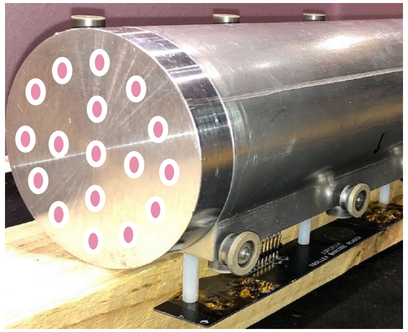
$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

Extract

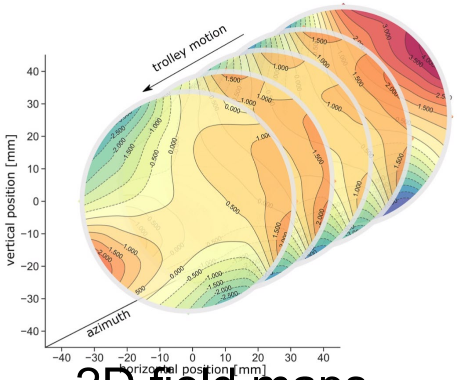
- **Spin rotates ahead of momentum** as muon orbits the ring

Measuring the Field: NMR Probes

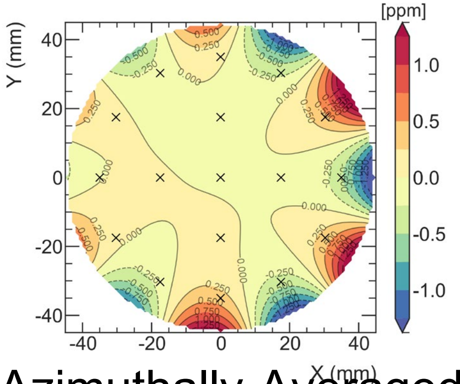
- In-vacuum NMR trolley **maps field every ~3 days**



17 petroleum jelly NMR probes



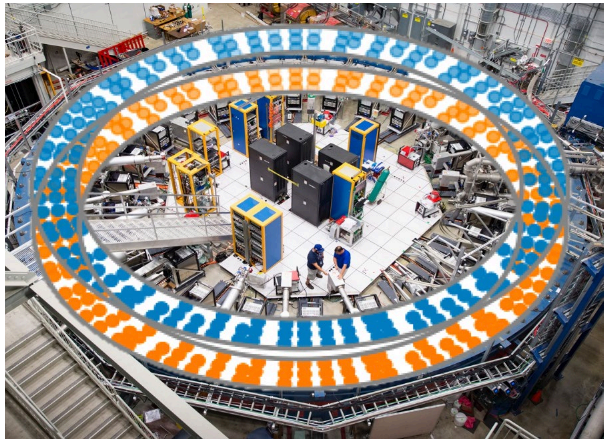
2D field maps (~8000 points)

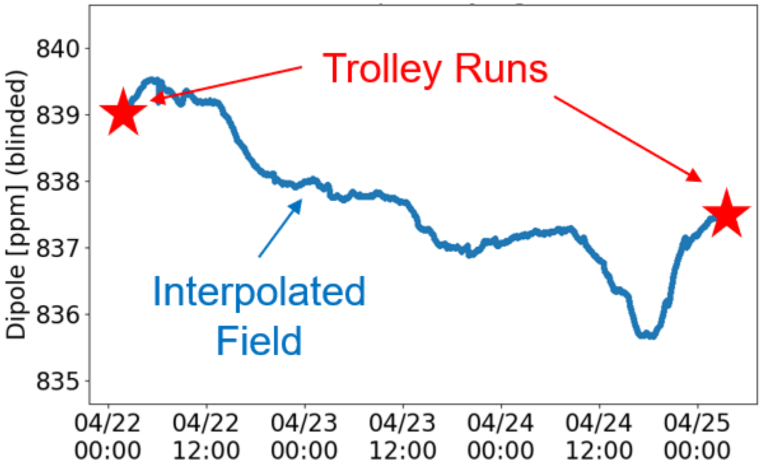


Azimuthally-Averaged
Variation < 1 ppm

- **378 fixed probes** monitor field during muon storage at 72 locations

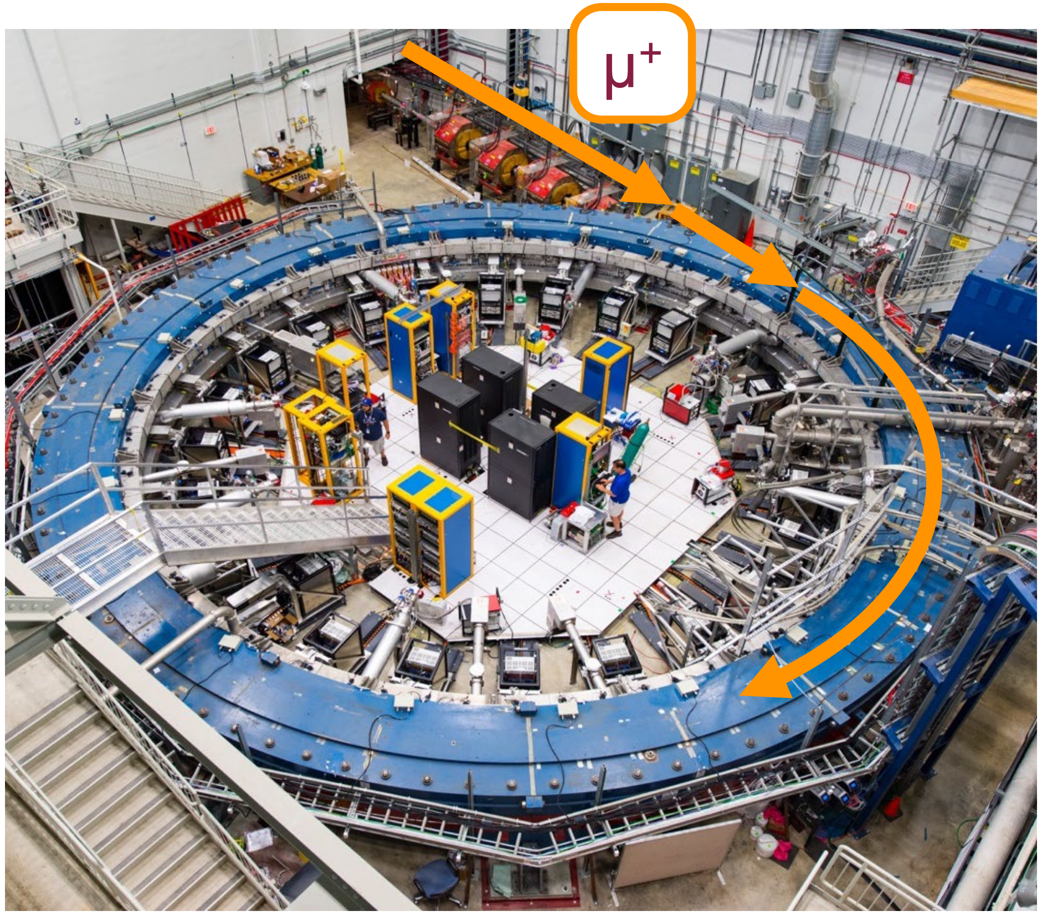
Fixed probes above/below muon storage region





Muon Injection

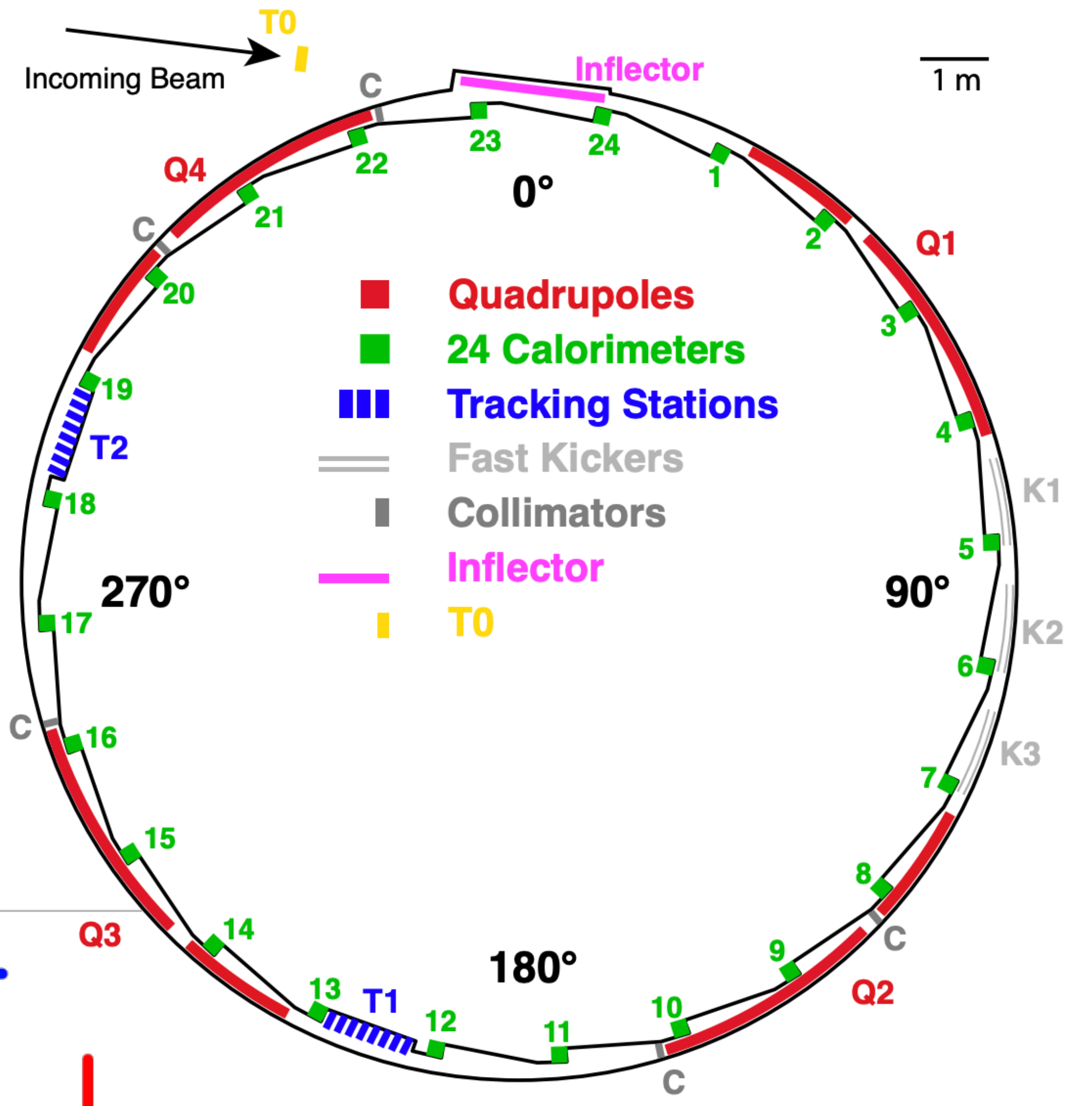
- Muons are injected into storage ring & bend in the *B* field

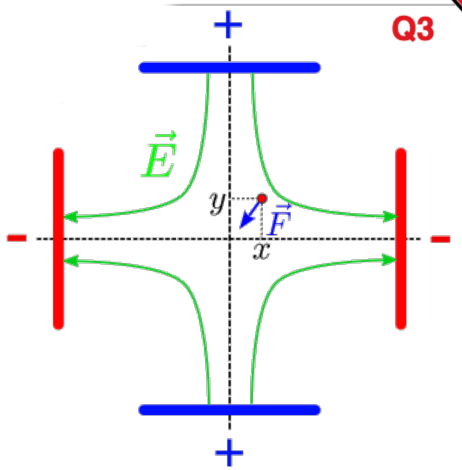


Electrostatic Quadrupoles

- **Cover 43% of the storage ring**
- Provide vertical beam focusing while magnet contains radial focusing
- Runing at “magic” momentum of p=3.094 GeV/c minimizes electric field contribution

Captured with trolley

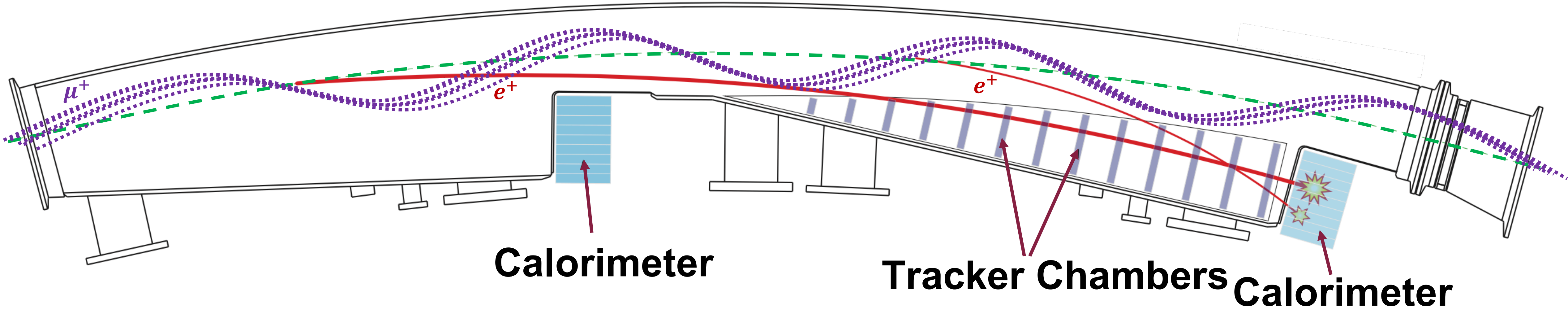




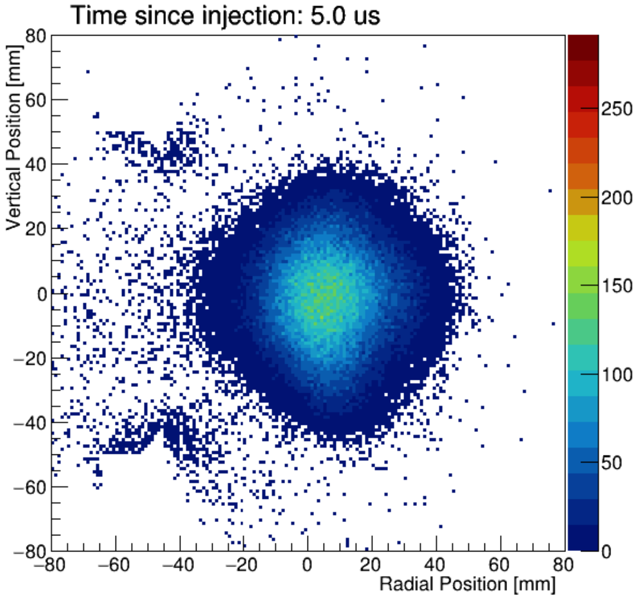
Beam orbit

Coherent oscillation effects must be included in fits to positron spectra!

- Beam mean position oscillates.
- Beam width oscillates.
- Cyclotron motion creates an effective sample rate.
    - Detectors can measure alias frequencies.
- Oscillations decohere over time.

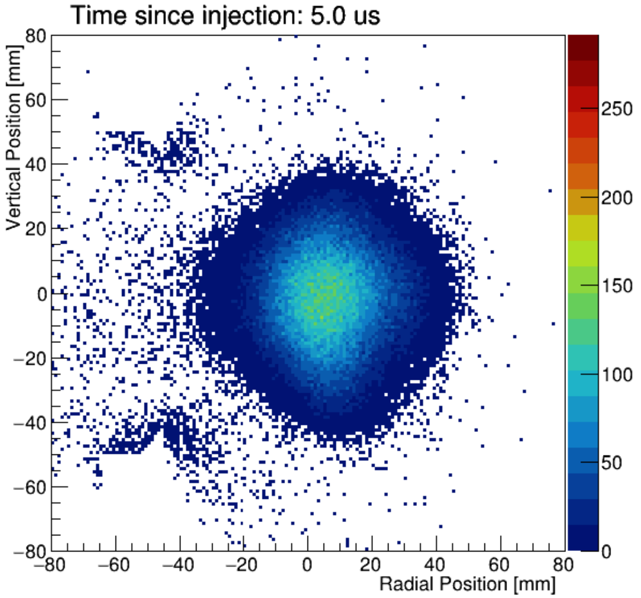


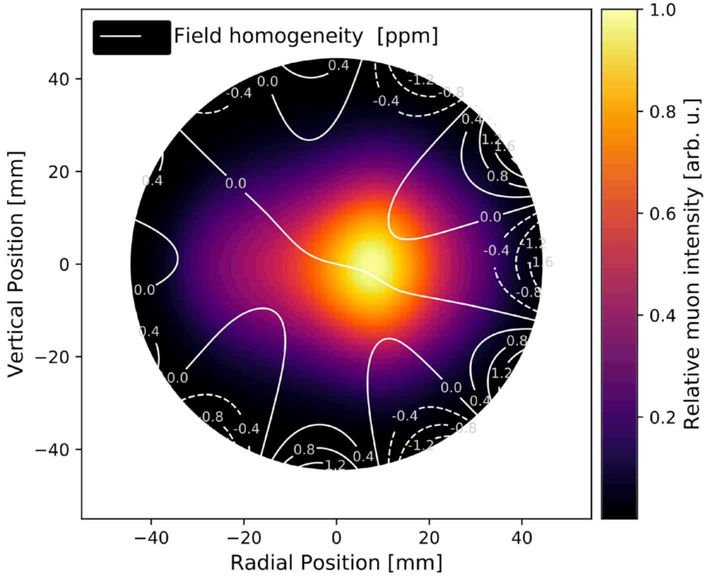
Muon Distribution from Trackers:



- Measure **beam oscillations** directly
  - Beam-dynamics corrections
  - Tuning simulations
  - Optimizing experiment running

Muon Distribution from Trackers:



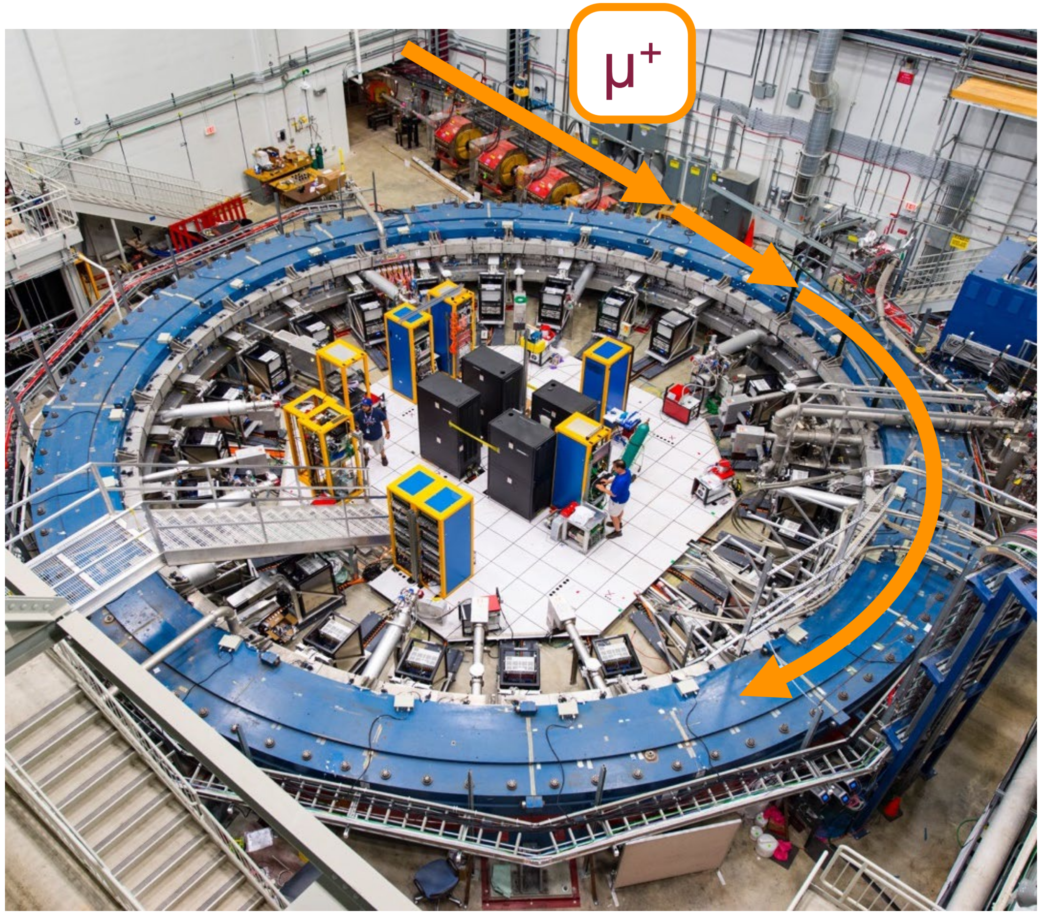


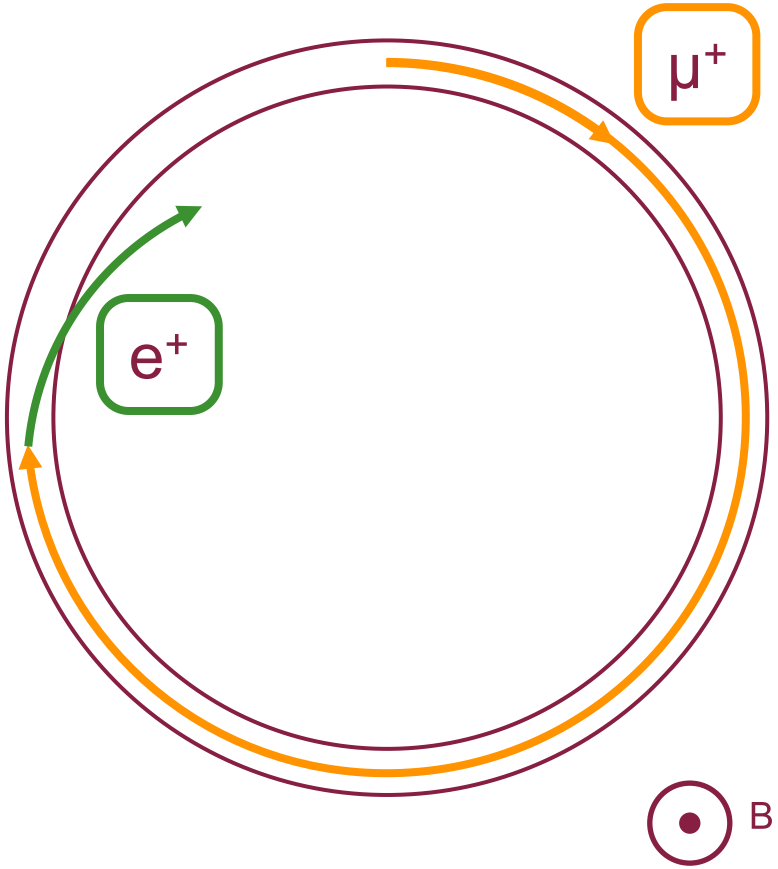
- Measure **beam oscillations** directly
  - Beam-dynamics corrections
  - Tuning simulations
  - Optimizing experiment running

- Use distribution to weight the field maps by where the muons live

Decay Positrons

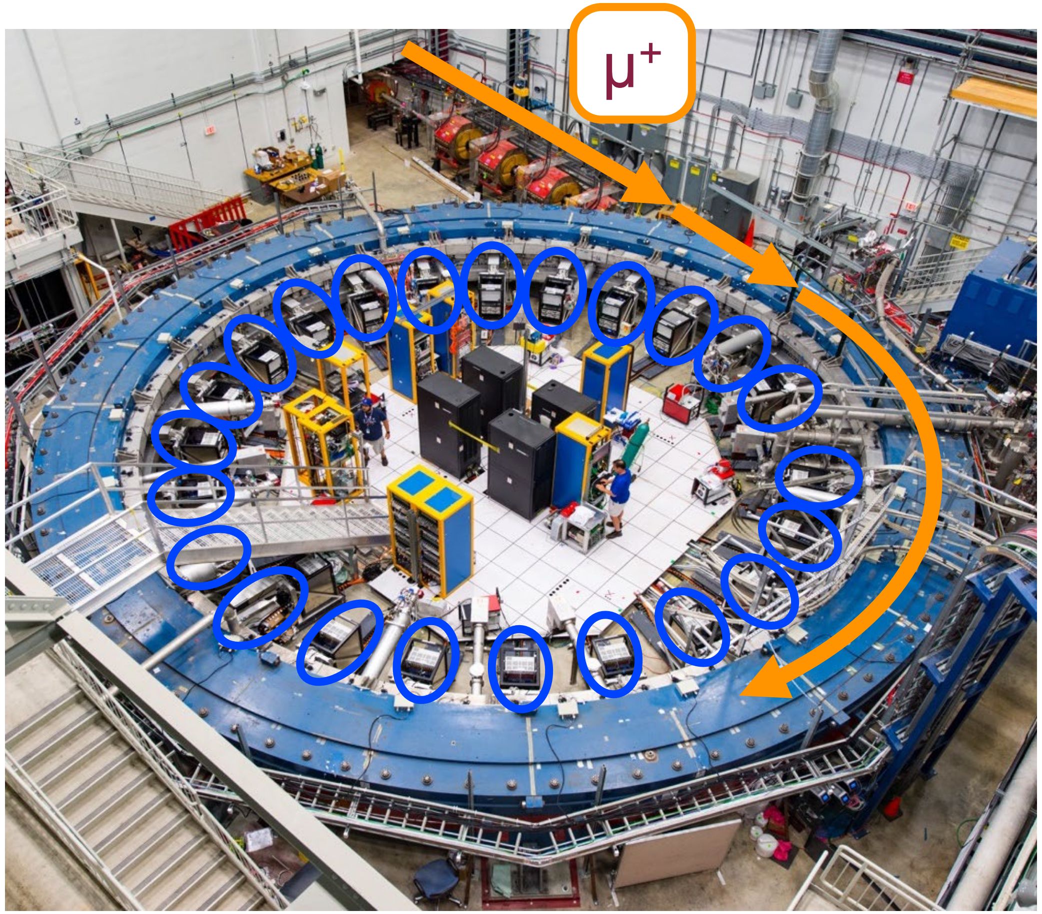
- Experiment measures decay e^+ which curl inwards as they have lower momentum

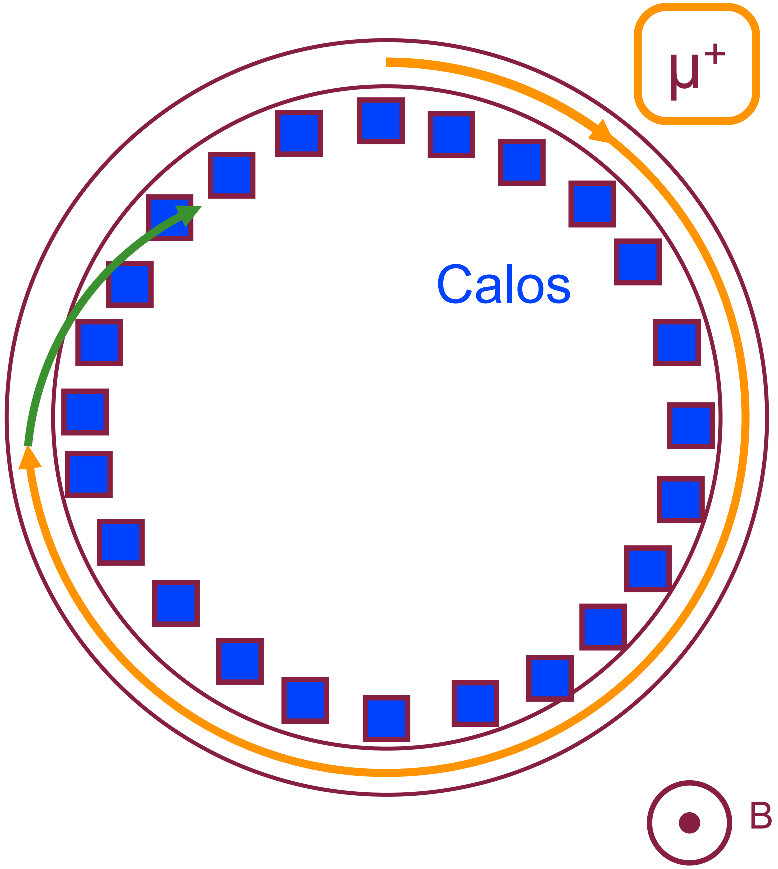




Calorimeters

- Time & energy of decay e^+ are measured by **24 calorimeters**

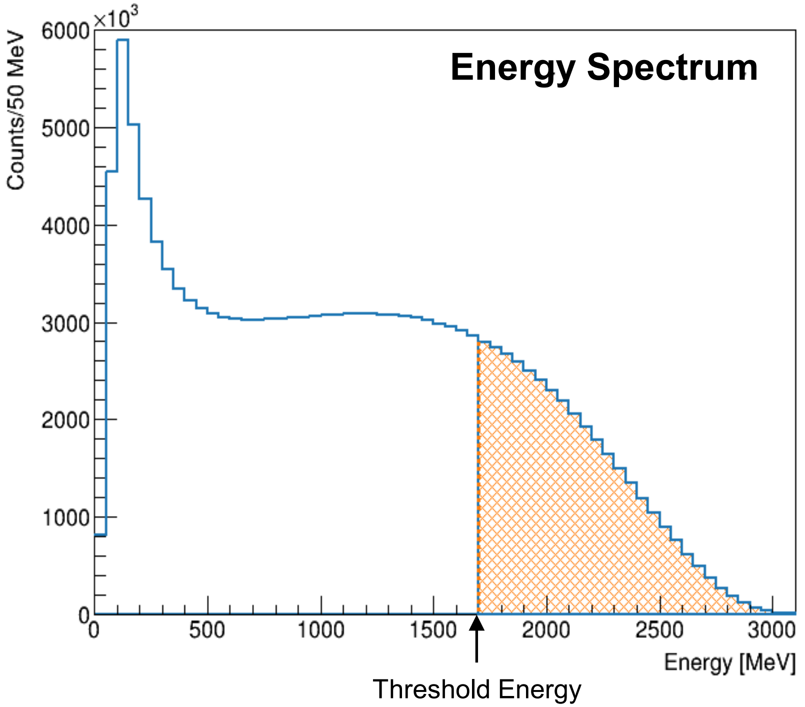


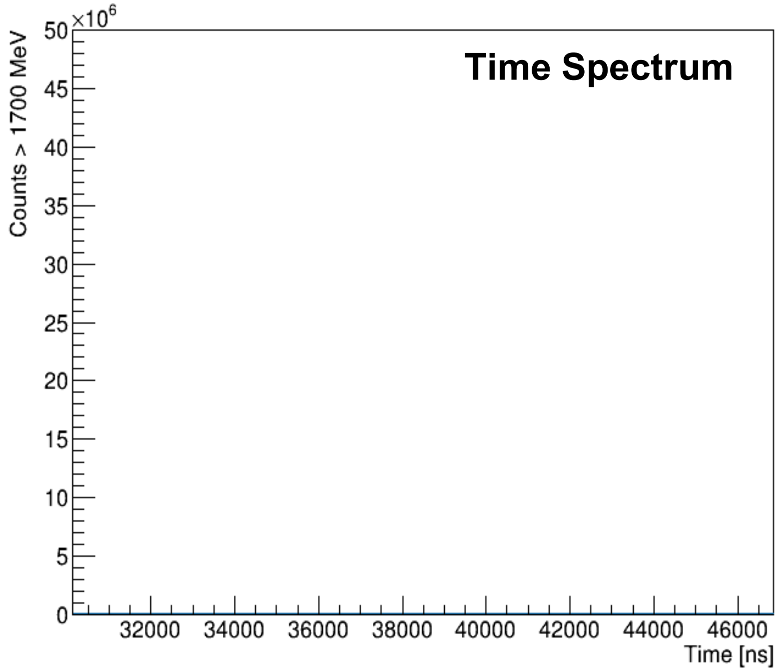


Measuring Spin Precession (ω_a)

	In COM:	In LAB:
Right-handed μ^+	**$\Rightarrow$ e^+ forward**	**$\Rightarrow$ higher energy**
Left-handed μ^+	**$\Rightarrow$ e^+ backward**	**$\Rightarrow$ lower energy**

- Due to **parity violation**, as the **μ^+ spin** points towards & away from calos the number of **high energy e^+ oscillates**

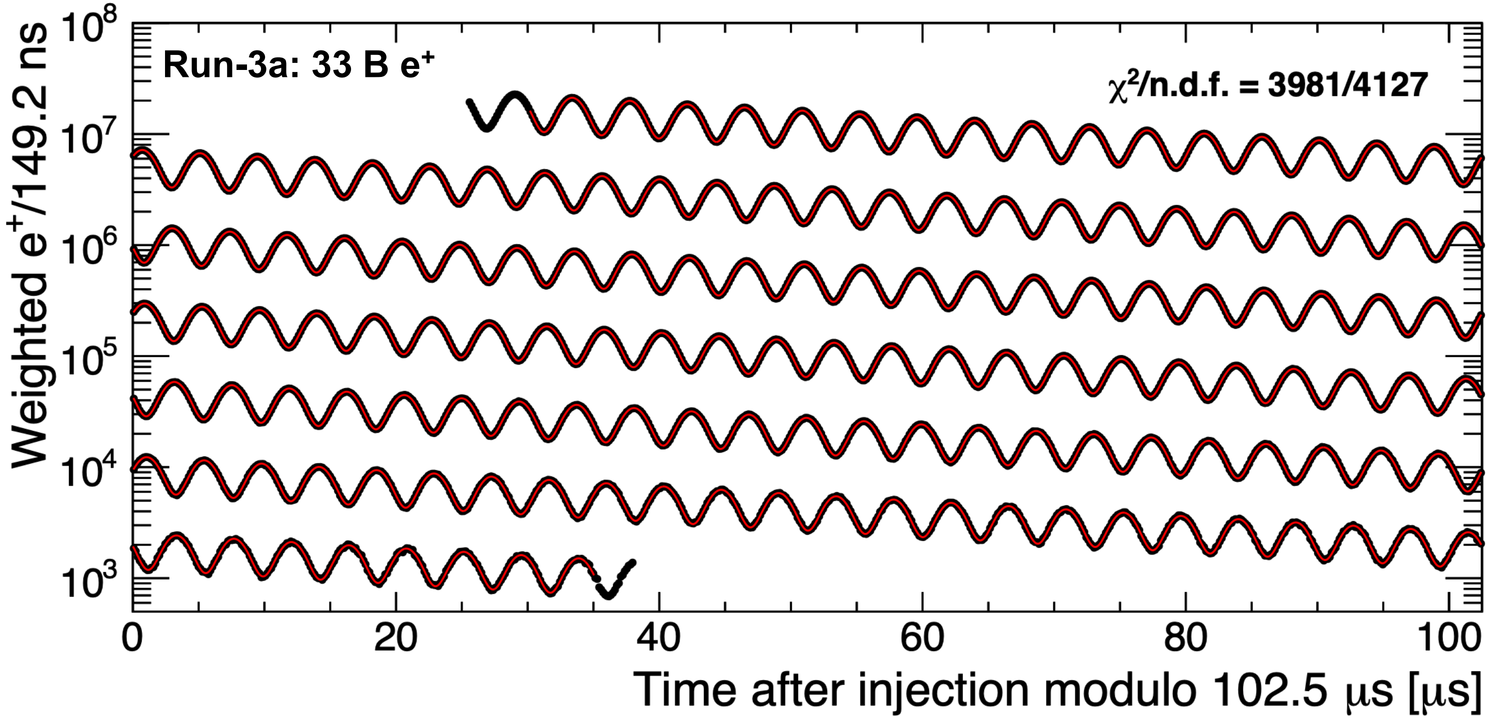




Real Data (Run-3a)

- **Count e^+** hitting calos **above threshold** (or weight the hits)
- We measure the oscillation frequency $\boldsymbol{\omega_a}$

Spin Precession (ω_a): "Wiggle Plot"



- Fit the time spectrum to **extract ω_a**, accounting for:
- **Beam oscillations** – couple to acceptance & modulate signal
- **Muon losses** – affects decay time spectrum

Real World Complications: Corrections

- We need to make corrections for seven small effects:

E-field & Up/Down motion: Spin precesses slower than in basic equation

Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses

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

Measured Values

Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current,

- Total correction is **622 ppb**, dominated by **E-field & Pitch**
- Corrections are small, but dominated Run-1 systematics…

Run-2/3 Uncertainties: Final Values

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
$\mu'_p(34.7°)/\mu_e$	–	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**

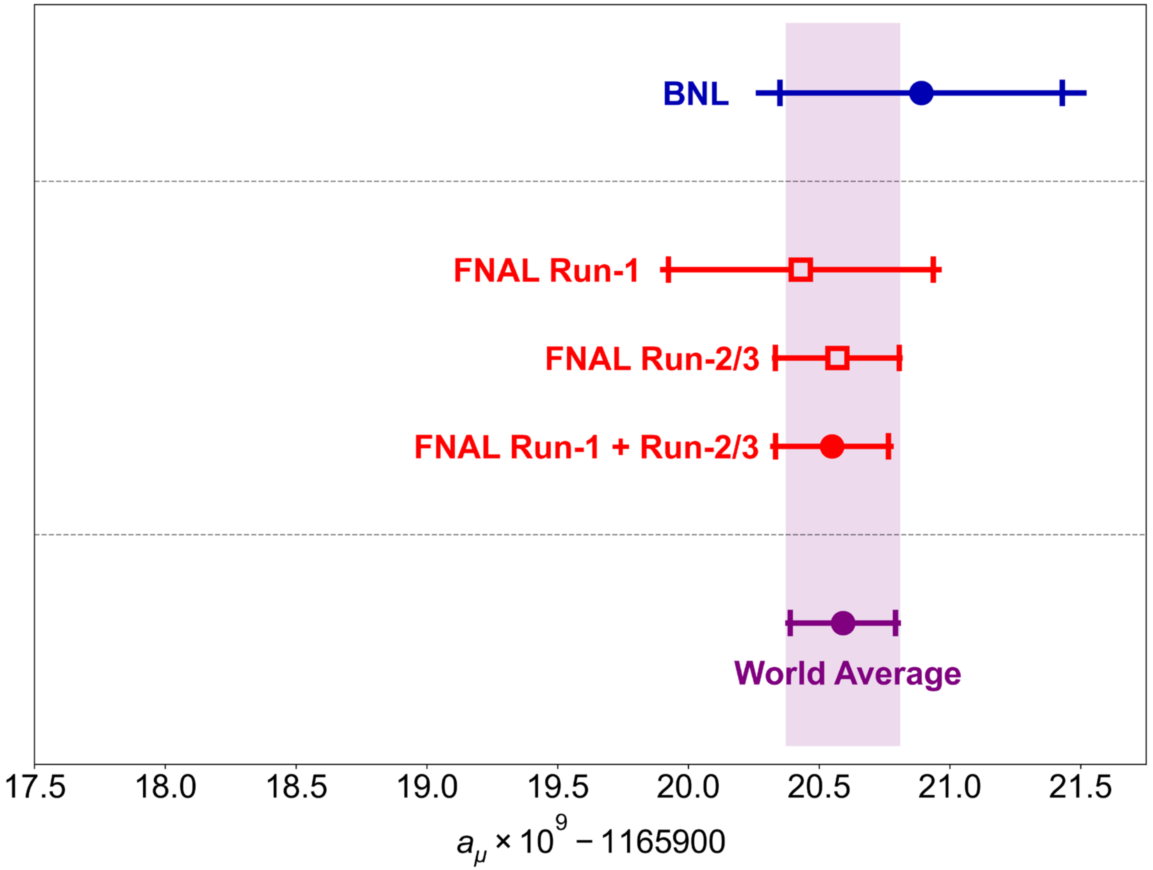
[ppb]	Run-1	Run-2/3	Ratio
Stat.	434	**201**	2.2
Syst.	157	**70**	2.2

- 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) = 0.00 116 592 055(24) [203 ppb]



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

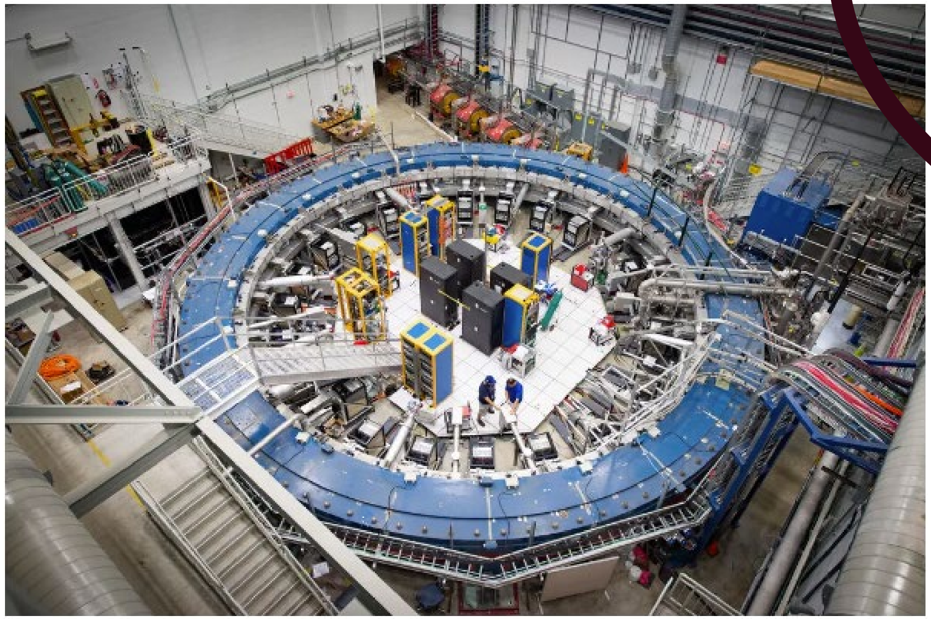
a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

The New York Times

Physicists Move One Step Closer to a Theoretical Showdown

The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.

Share full article 480



The Muon g-2 ring at the Fermilab particle accelerator complex in Batavia, Ill. Reidar Hahn/Fermilab, via US Department of Energy

By Katrina Miller
Katrina Miller, a science reporter, recently earned a Ph.D. in particle physics from the University of Chicago.

"The result has a precision of 0.2 parts per million. That's like measuring the distance between New York City and Chicago with an uncertainty of only 10 inches, Dr. Pitts said."

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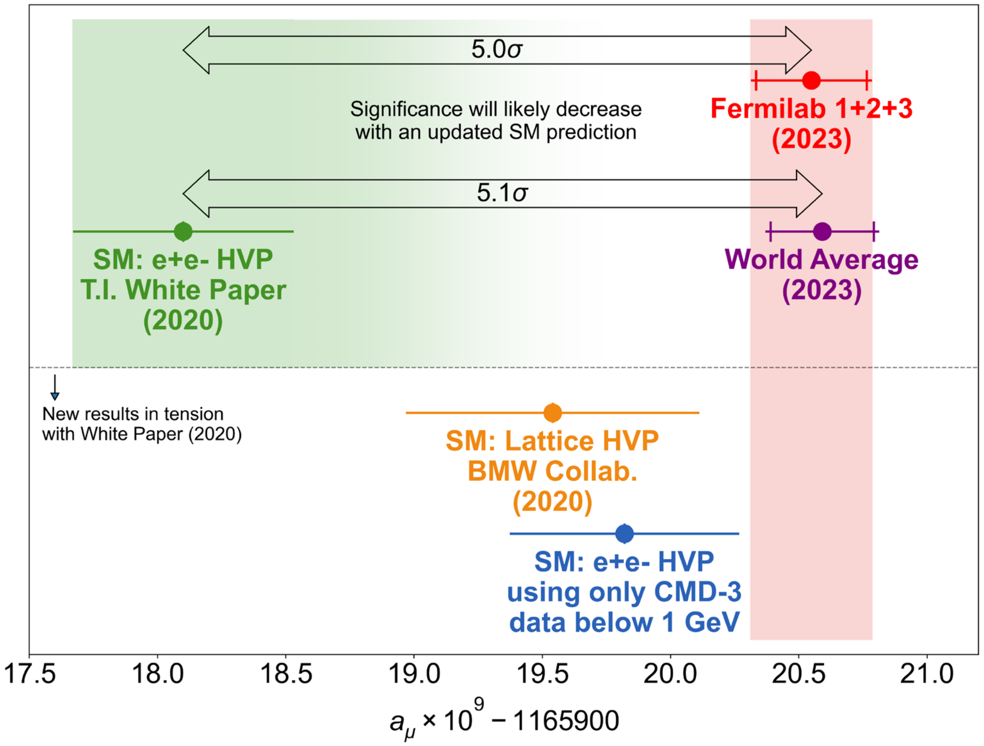
Experiment vs Theory Comparison

- Theory prediction is less clear now, but we can still compare



Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

Following A. Keshavarzi at Lattice 2023…

- Substitute **CMD-3** data for HVP below 1 GeV
- Cherry-picking one experiment but gives a bounding case
- **SND2k** cannot be processed in this way, but would fall closer to WP (2020).
- Many **parallel efforts are underway** to resolve the theoretical ambiguity…new results just out…

A Sampling of Questions

- Higg…
- …
- W…
- W…
- W…
- Ar…
- Are…
- Do a… …es unify?

Difficult questions!

We need every tool in the toolkit:

- **Colliders**
- **Fixed target**
- **Cosmic rays**
- **Theoretical calculations**
- **Computational Science**
- **New techniques**
- **…**

To find answers to these questions!!!

Acknowledgements

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Royal Society (UK),
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European Union's Horizon 2020,
Strong 2020 (EU),
German Research Foundation (DFG),
National Natural Science Foundation of China,
MSIP, NRF and IBS-R017-D1 (Republic of Korea)

Techniques

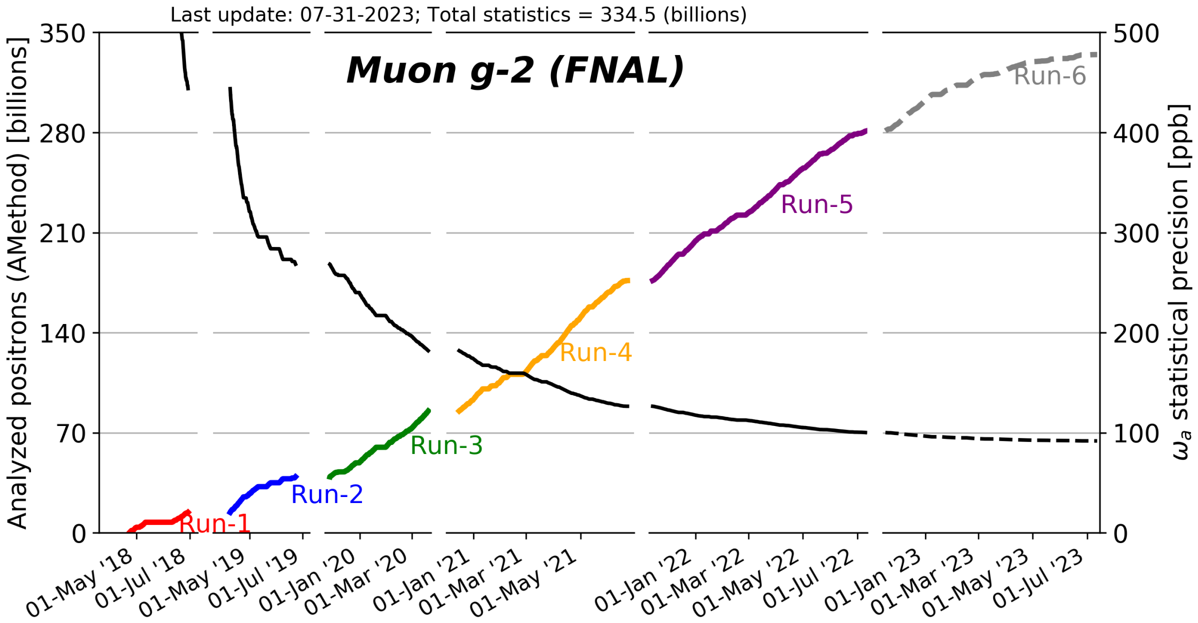
“Probes”

- Cosmic rays
- “natural” accelerators (radioactive decay)
- Particle accelerators:
  - Fixed target
  - Colliders

“Detectors”

- Bubble chambers (human scanning)
- Drift chambers, time projection chambers
- Silicon detectors
- Calorimetry
- Cerenkov detectors

Outlook: Muon g – 2



- Future is bright – there's much more data still to analyze!
- Now: **beat our systematics goal;** future: **surpass statistical goal**.
- Expect **theory improvements** on a similar timescale.

A bit of history

Particle	Year discovered	Comment
Electron*	1897	JJ Thomson
Nucleus*	1911	Rutherford
Positron*	1932	Cosmic rays
muon	1937	Cosmic rays
Electron neutrino*	1953	Reactor experiment
Anti-proton*	1955	Bevatron
Muon neutrino*	1962	Brookhaven AGS
Charm quark*	1974	SLAC and BNL
Tau lepton*	1975	SLAC
Bottom quark	1977	Fermilab
Gluon	1979	Petra
W boson*	1983	CERN SppS
Z boson*	1984	CERN SppS
Top quark	1994	Fermilab
Higgs	2012	CERN LHC

Last 35 years

Comments:

1. Discovery ≠ understanding (much to learn about particles discovered years ago)

2. Much of what we know to be the "Standard Model" has been unearthed in the last 50 years.

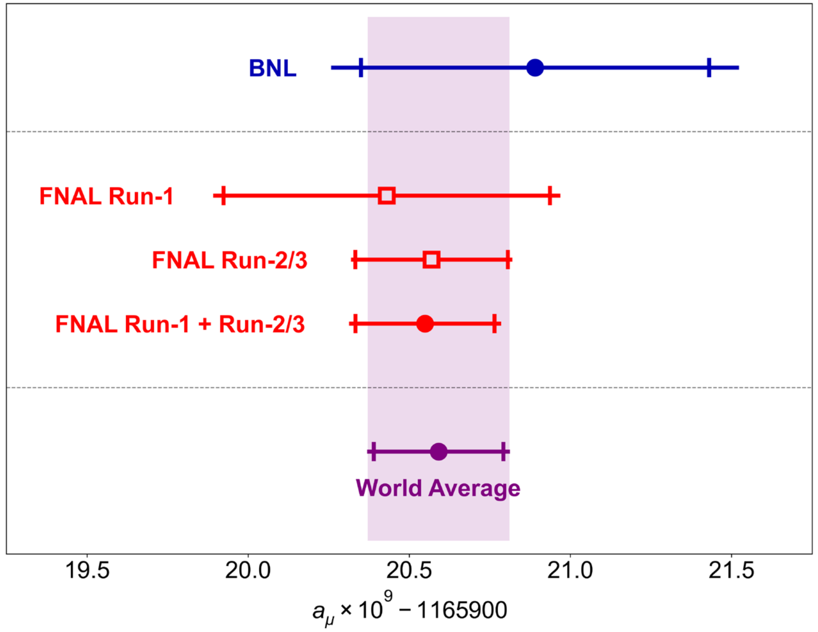
3. The picture is incomplete, there are *many* outstanding questions.

*Nobel prize

This can't be the whole story….

Conclusions

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



- New result is in **excellent agreement** with **Run-1 & BNL**
- More than **halved the total uncertainty** from Run-1
- **Beat our design goal** with systematic uncertainty of **70 ppb**.

- There's **more data** to analyze and we'll squeeze uncertainty down further in our future results!

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