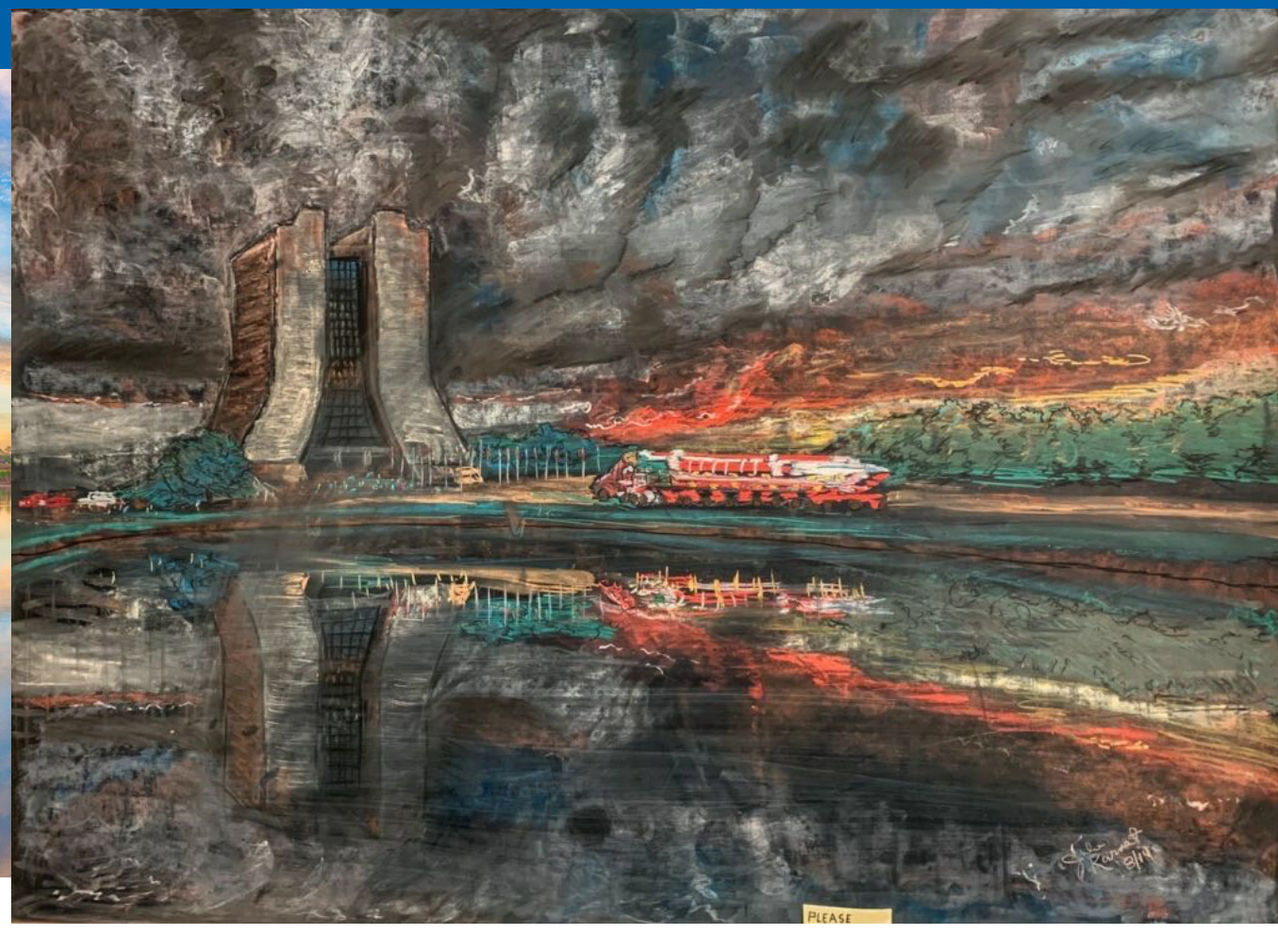
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

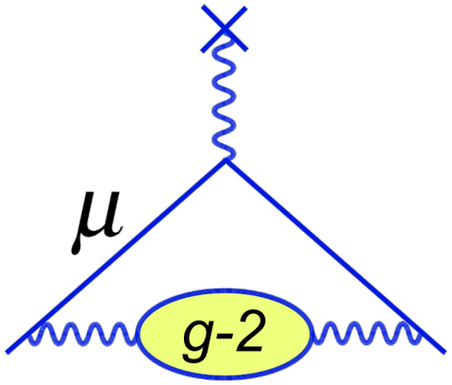


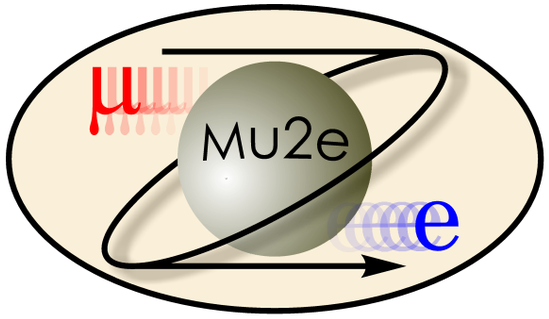
Precision Muon Physics at Fermilab

Manolis Kargiantoulakis

Neutrino Seminar Series

01/16/2020





Outline

Context and Motivation

- The Standard Model
- Why muons?

The Muon g-2 Experiment

- The anomaly and how to measure it
- a_μ ingredients
- Status

The Mu2e Experiment

- Charged lepton flavor violation
- Measurement principles
- Status

Status and Outlook

Outline

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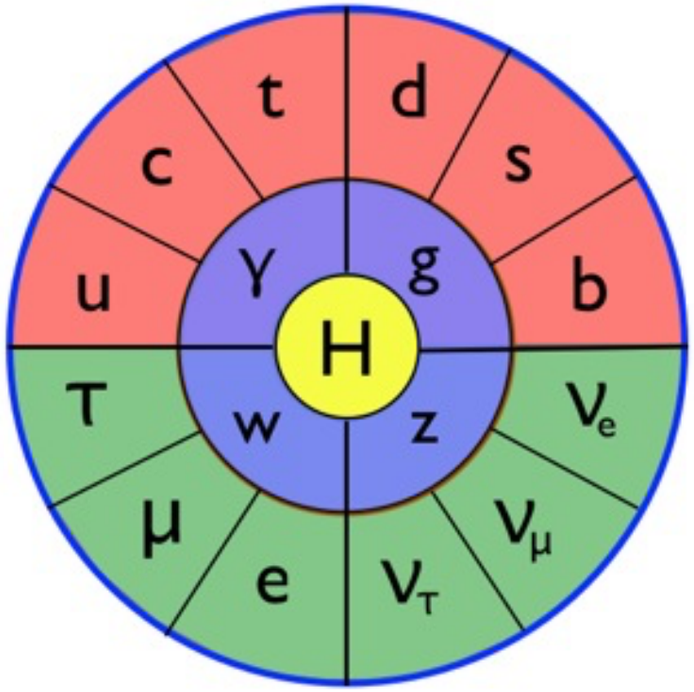
The Muon g-2 Experiment

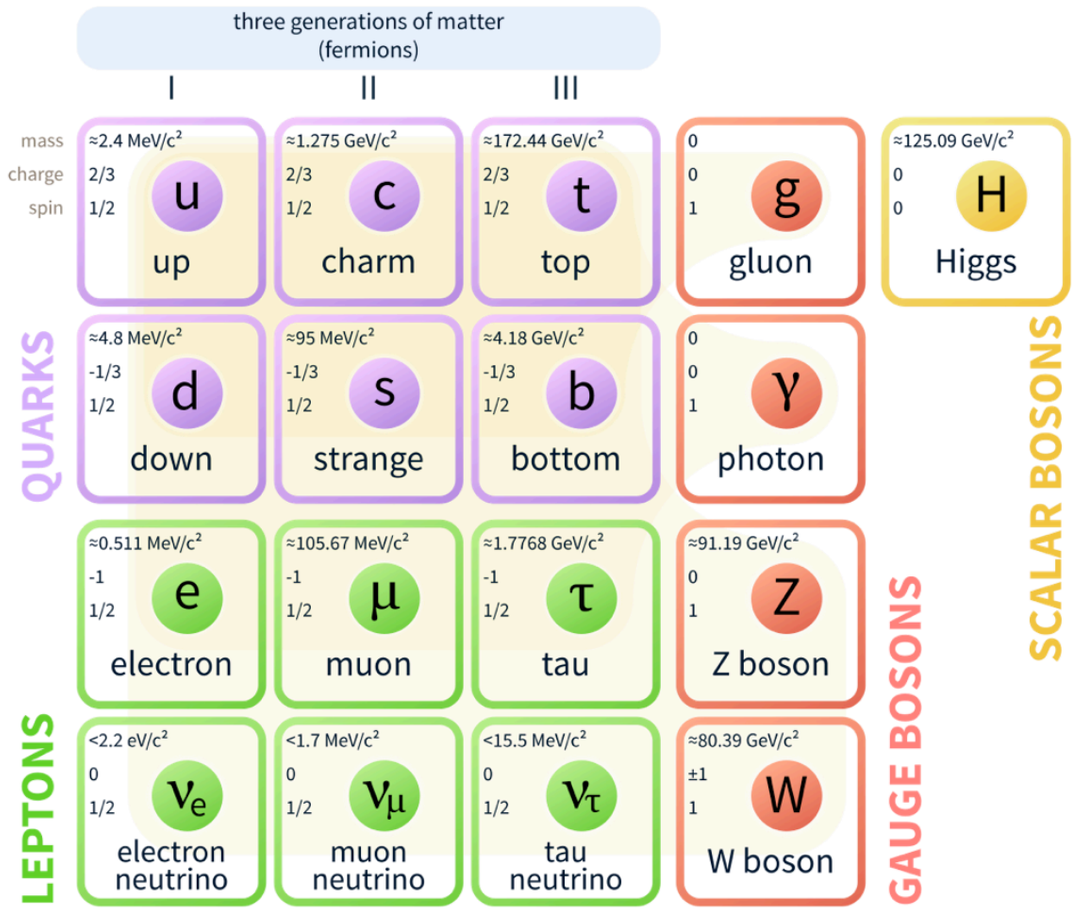
The Mu2e Experiment

Status and Outlook



The Standard Model of Physics

Our most fundamental, successful theory of nature

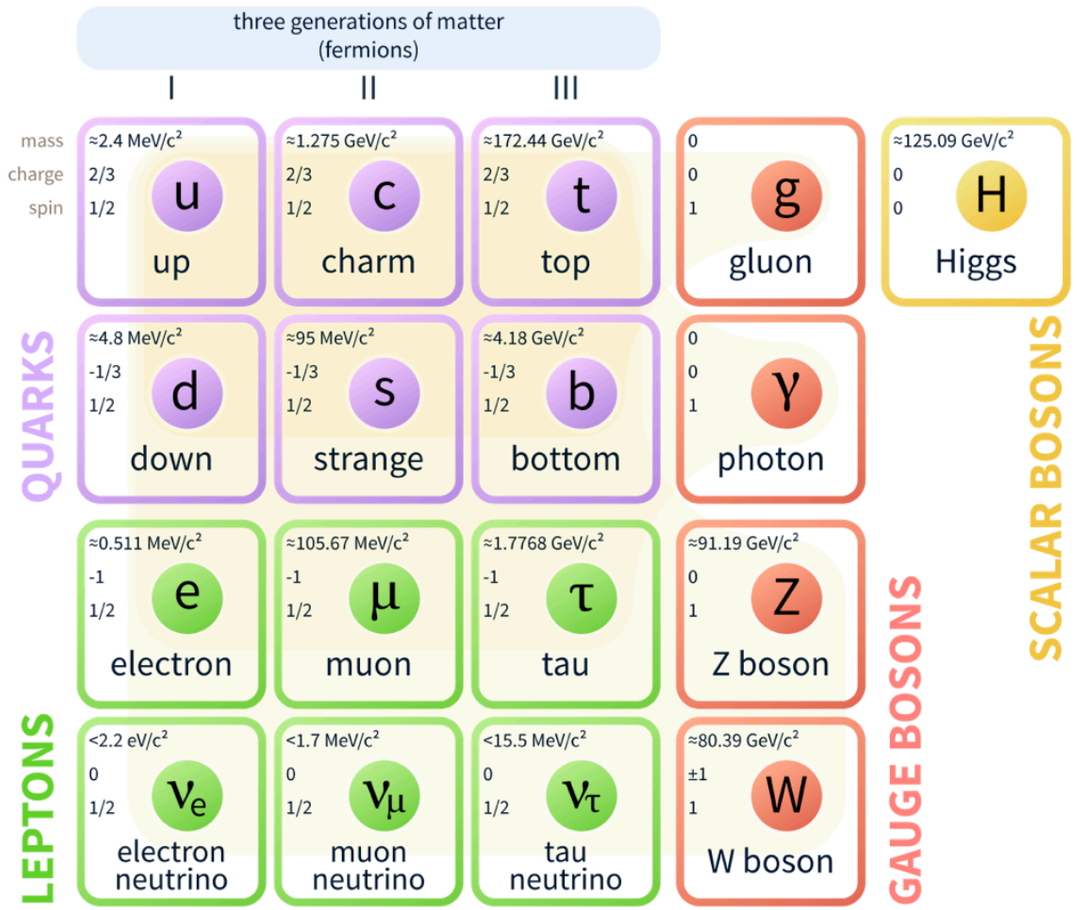


And yet, we know it to be incomplete

- No explanation for dark matter, no quantum picture of gravity, open neutrino questions
- Theoretical issues: hierarchies, instabilities

The Standard Model of Physics

Our most fundamental, successful theory of nature



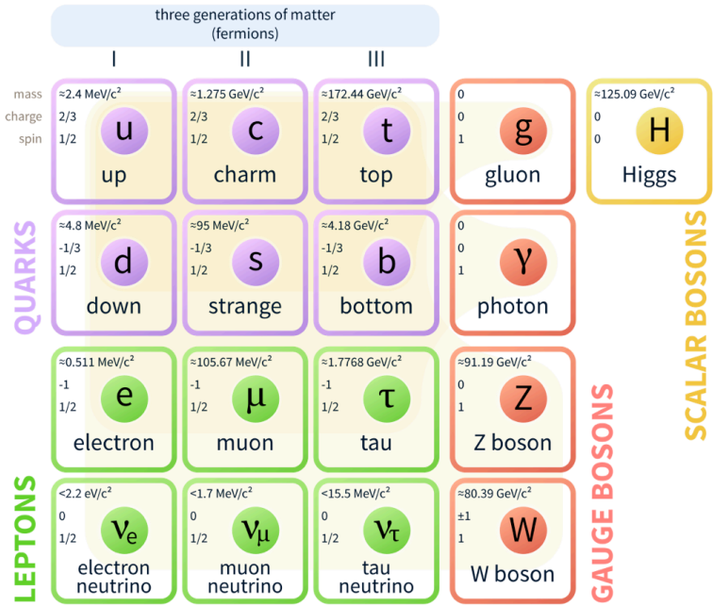
And yet, we know it to be incomplete

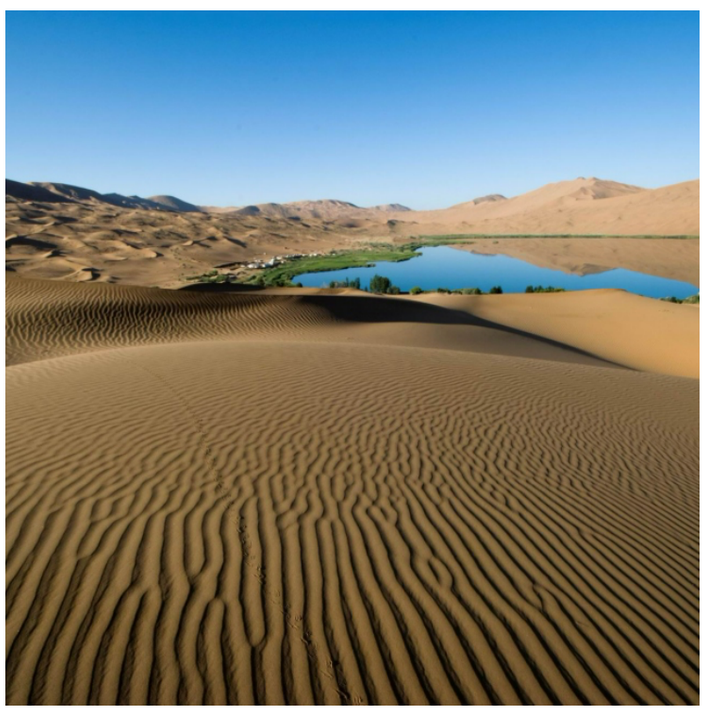
- No explanation for dark matter, no quantum picture of gravity, open neutrino questions
- Theoretical issues: hierarchies, instabilities

But still no new physics from high-energy machines

- Are we in a desert?

The Standard Model of Physics





- Ongoing efforts in Energy Frontier, intriguing results from Neutrino and Precision Frontiers
- Neutrino oscillations: extension to SM
  - Questions on neutrino nature and mass generation
- Precision Frontier: indirect access to higher energy scales or more weakly coupled interactions
  - Experimentally, significant deviations from SM:
    - Muon anomalous magnetic moment
    - Hints of lepton flavor non-universality
  - Connections to fundamental questions on flavor

LHC, DUNE, g-2, Mu2e are compelling and complementary approaches to moving Beyond the Standard Model

Why muons?

Properties of muons make them great tools for discovery

- Easy to produce
  - Natural product of pion weak decay
- Easy to control and manipulate
  - Charged, control with EM fields
  - Weak interaction Parity-Violating: emerges 100% polarized, decay is "self-analyzing"
- Sits at a lepton "sweet-spot"
  - More stable than τ → long enough lifetime to be manipulated for precision measurements (and still short enough for decays)
  - Lighter than pion → no hadronic decay → clean theoretical predictions
  - Heavier than e^- → more sensitive to heavy particles in loops by $(m_\mu/m_e)^2$

Muons offer unique advantages:

Readily available, experimentally versatile, theoretically clean, increased sensitivity to new physics

Fermilab Muon Campus

- Fermilab a global leader in muon physics
- Muon g-2 and Mu2e are among the most powerful probes of the SM

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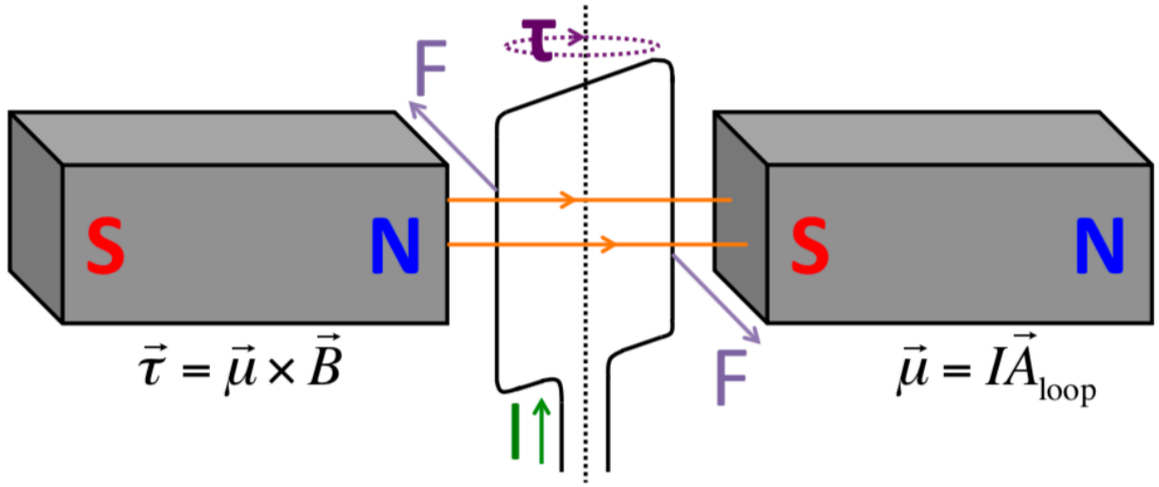
The Mu2e Experiment

Status and Outlook

Magnetic dipole moment

Classical Picture:



Quantum Picture:

g-factor:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

Dirac Equation for EM potential:

$$\left[i\gamma^{\mu}\left(\partial_{\mu} + ieA_{\mu}\right) - m\right]\psi = 0$$

- Spin-1/2 point particles
- Predicts g = 2

Larmor Precession (particle rest frame):

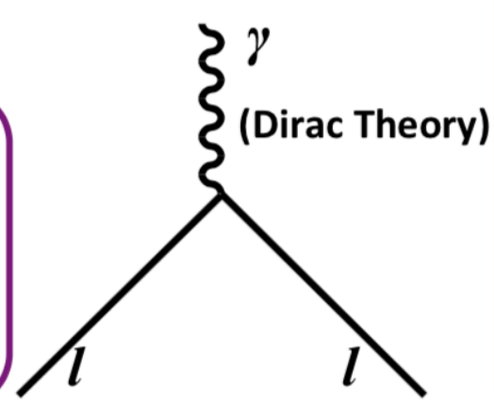
$$\frac{d\vec{s}}{dt} = \vec{\tau} = \vec{\mu} \times \vec{B} = g\left(\frac{q}{2m}\right)\vec{s} \times \vec{B}$$

Quantum Field Theory: Picture

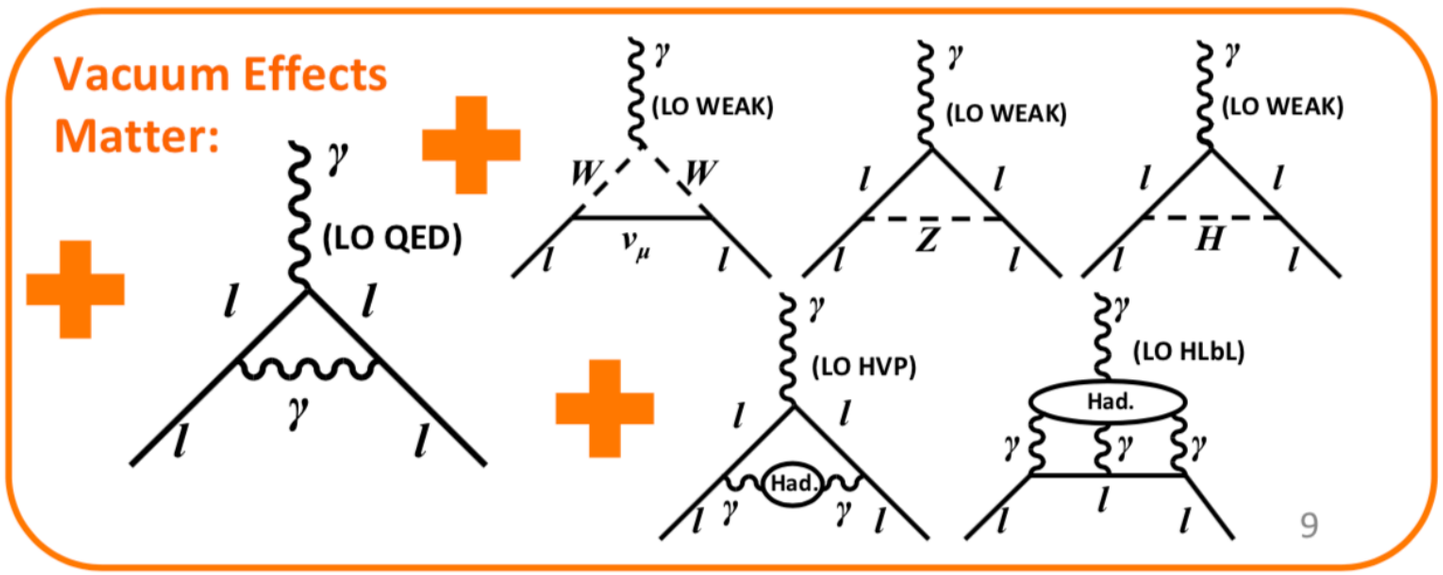
Anomaly:

$$a \equiv \frac{g-2}{2}$$

- Predicts g ≠ 2

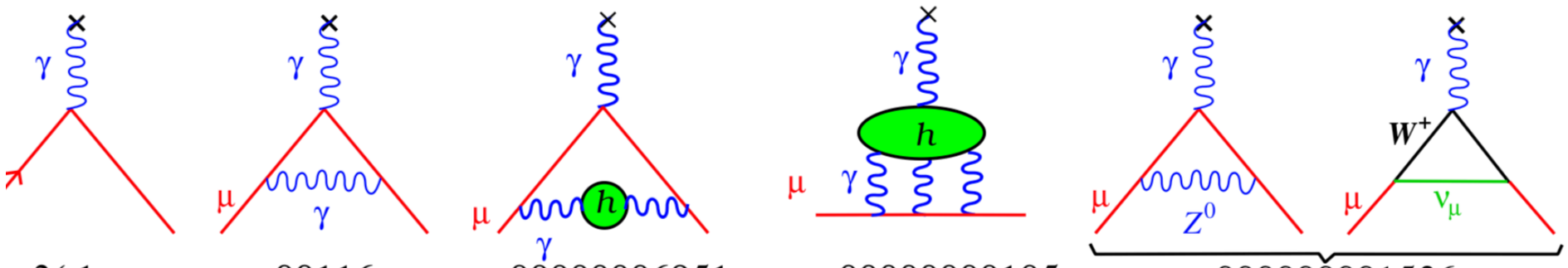


Vacuum Effects Matter:



Why measure g-2

QFT encodes our entire understanding onto g-2



$$g = 2(1 + .00116\ldots + .00000006951\ldots + .00000000105\ldots + .000000001536$$

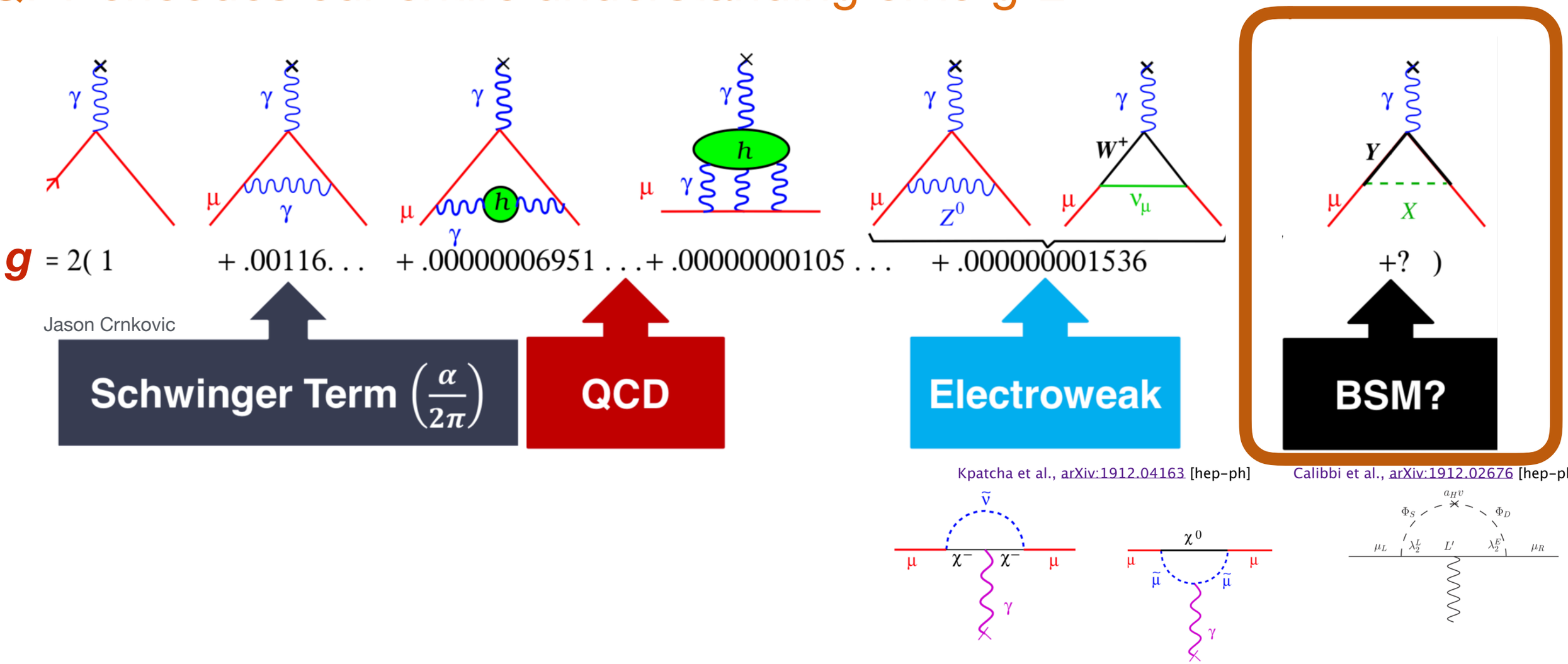
Jason Crnkovic

Schwinger Term $\left(\frac{\alpha}{2\pi}\right)$ | **QCD** | **Electroweak**

One of most accurate tests of SM validity

Why measure g-2

QFT encodes our entire understanding onto g-2



One of most accurate tests of SM validity

Sensitive to modifications from vast array of well motivated models

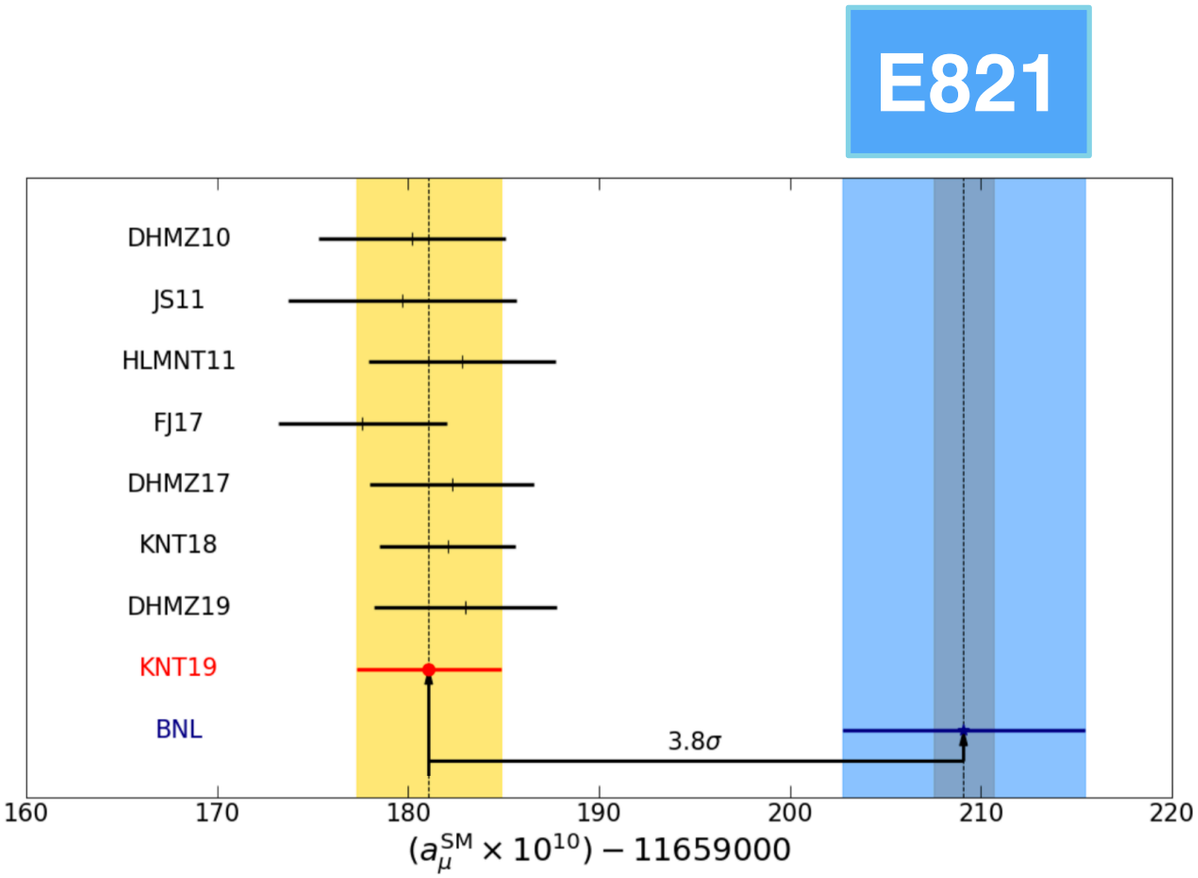
Muon *g*-2 enhanced sensitivity to heavy new physics

- $(m_\mu/m_e)^2 \sim 40{,}000$

a_μ from E821

The BNL E821 found significant discrepancy from SM prediction

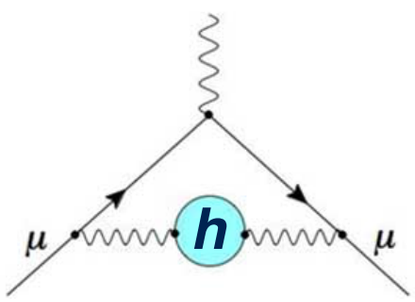
- Discrepancy has guided experiment and theory for nearly two decades



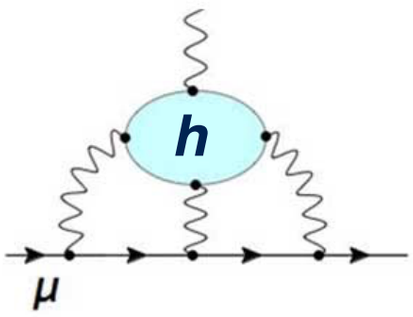
A. Keshavarzi, D. Nomura, T. Teubner, arXiv:1911.00367 [hep-ph]

Muon g-2 Theory Initiative:

- Global theory effort to improve SM determination
- Uncertainty dominated by hadronic VP and LbL contributions



Vacuum Polarization



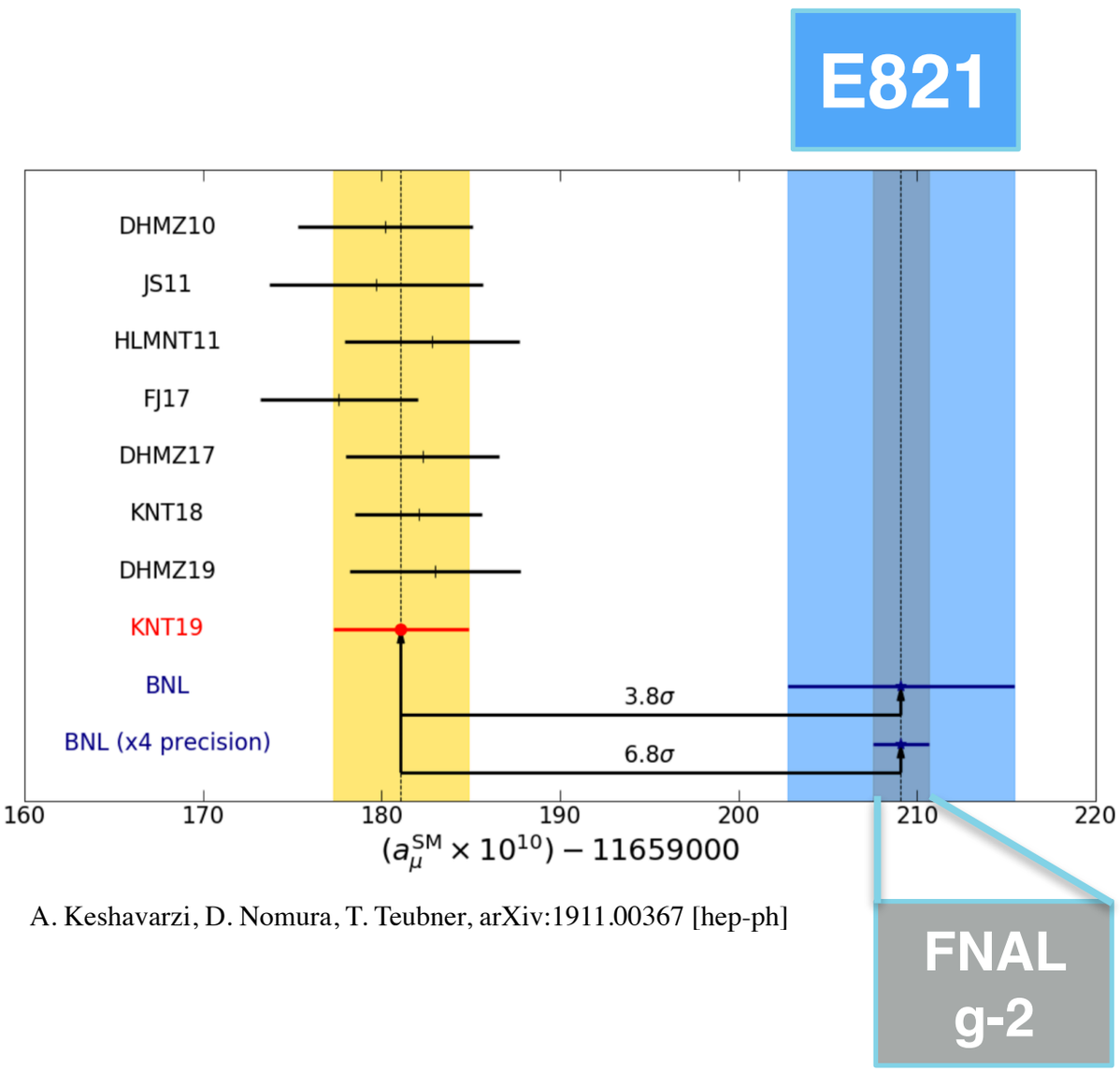
Light-by-light scattering

After latest re-evaluation, discrepancy stands at 3.8σ

a_μ from E821, E989

The BNL E821 found significant discrepancy from SM prediction

- Discrepancy has guided experiment and theory for nearly two decades

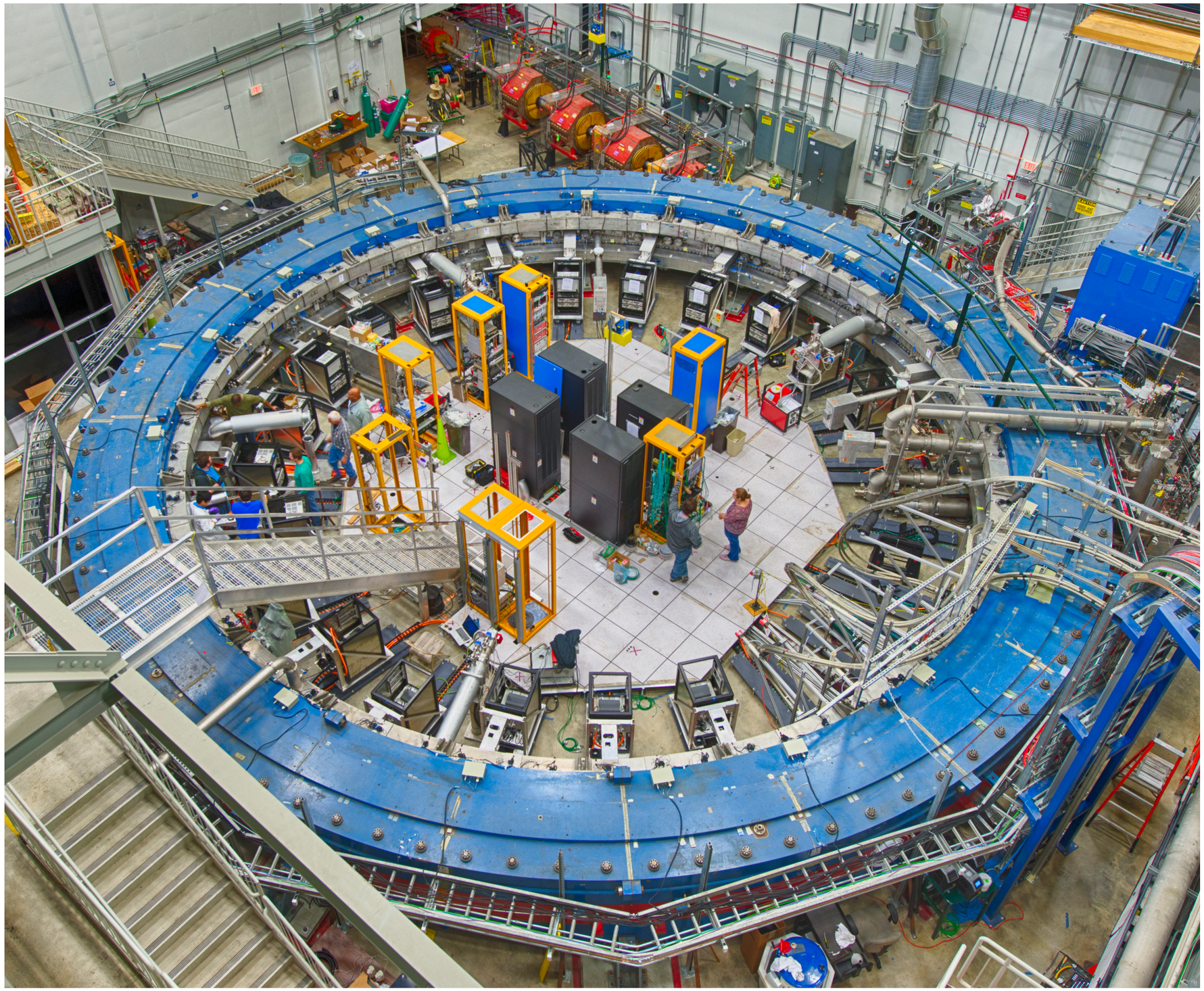


A. Keshavarzi, D. Nomura, T. Teubner, arXiv:1911.00367 [hep-ph]

Fermilab Muon g-2:

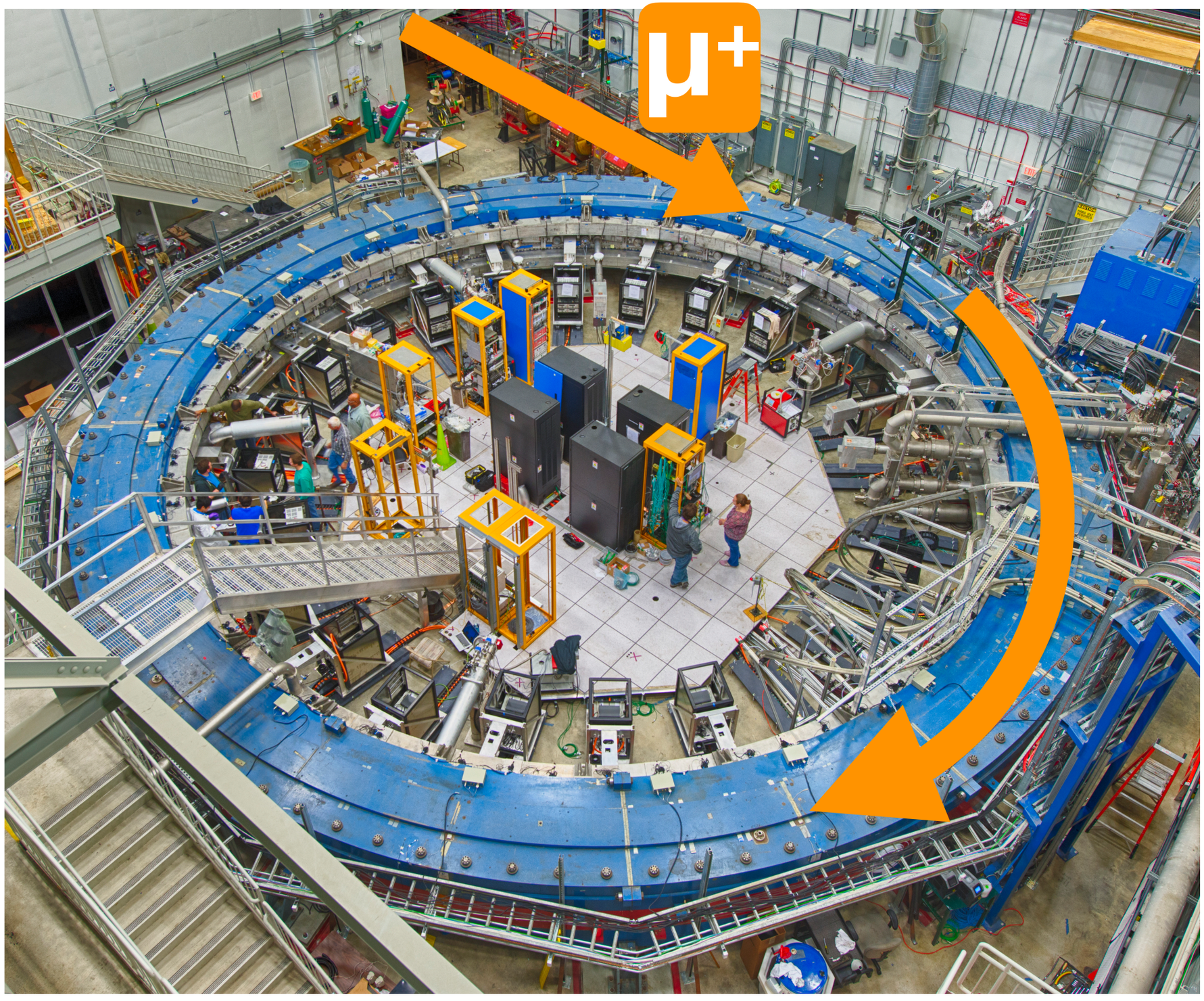
- Improve experimental precision by x4
- Potential for 7σ discrepancy

The g-2 experiment at Fermilab

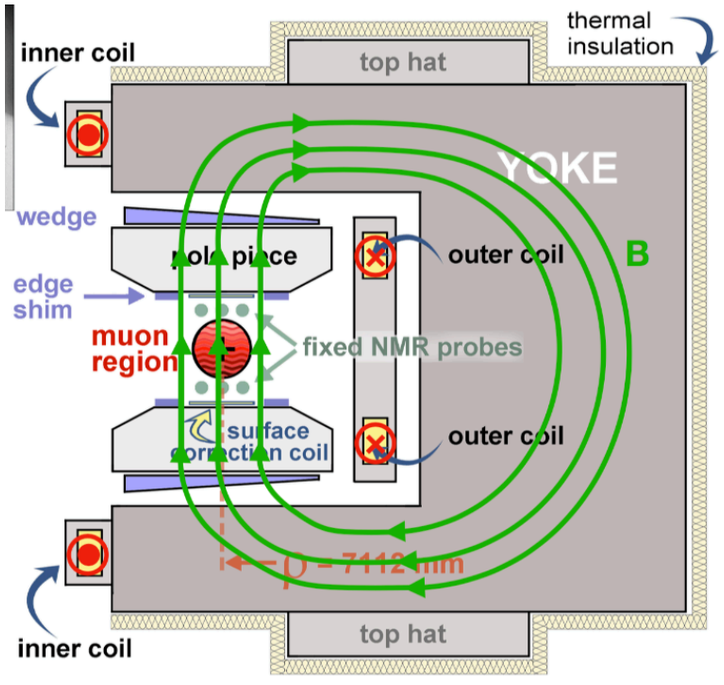


- Muon g-2 storage ring, located at Fermilab Muon Campus
- Brought from BNL, famous for its travels!

The g-2 experiment at Fermilab

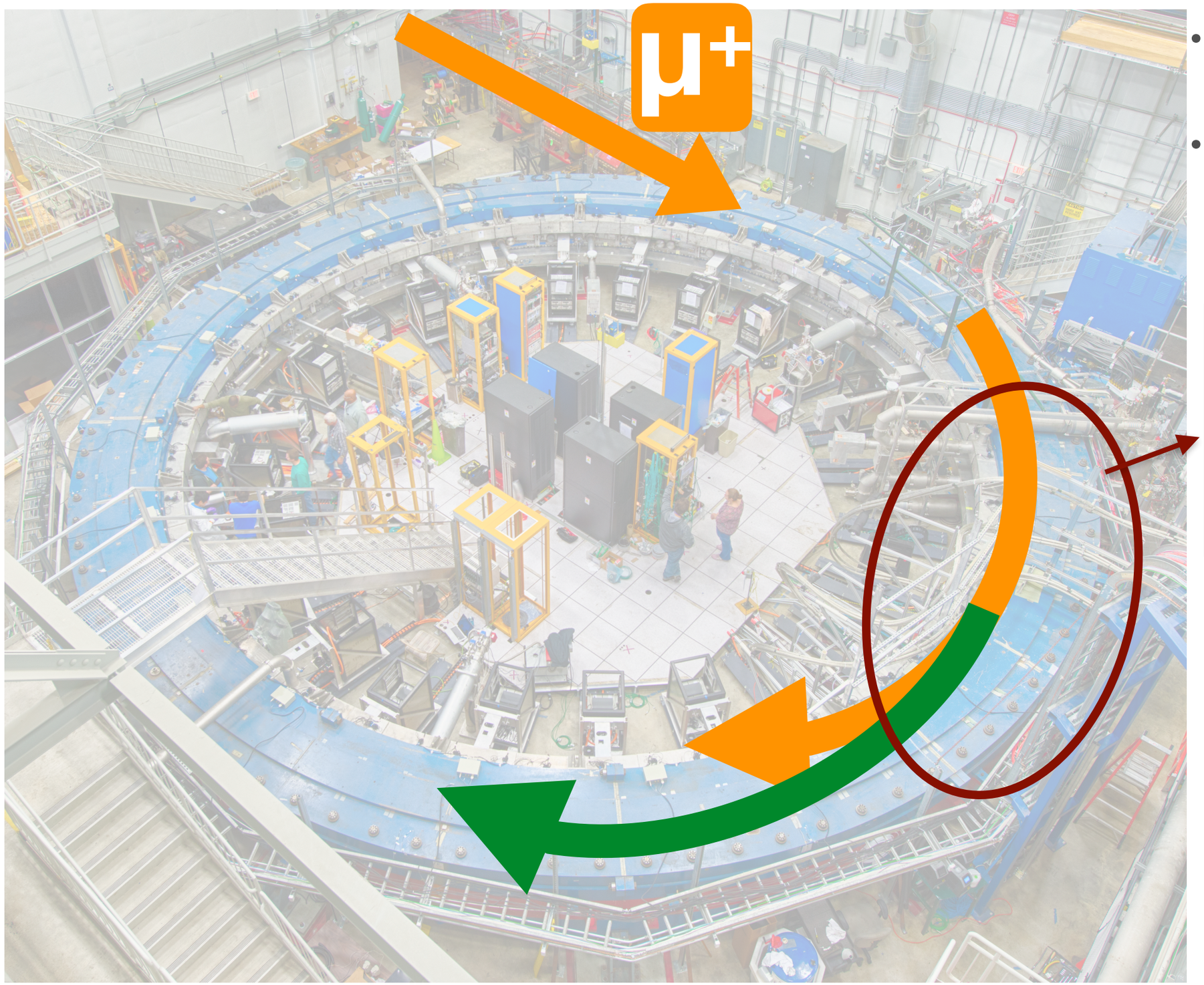


- 3.1 GeV/c muons injected into storage ring
- Highly longitudinally polarized muon beam from pion decay
- Muon spin precesses in 1.45T field
- Muon lifetime $\gamma\tau_\mu$ = 64.4 μs

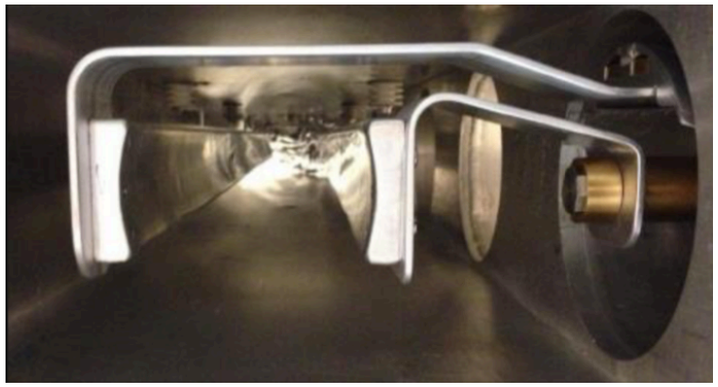


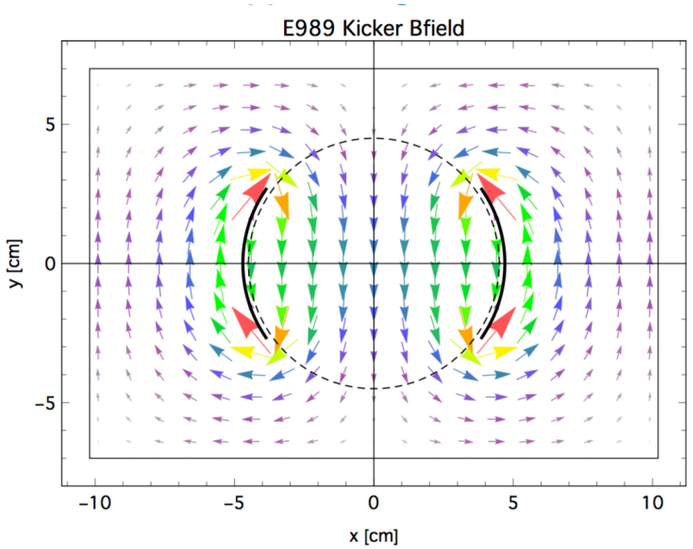
g-2 Magnet in Cross Section

The g-2 experiment at Fermilab

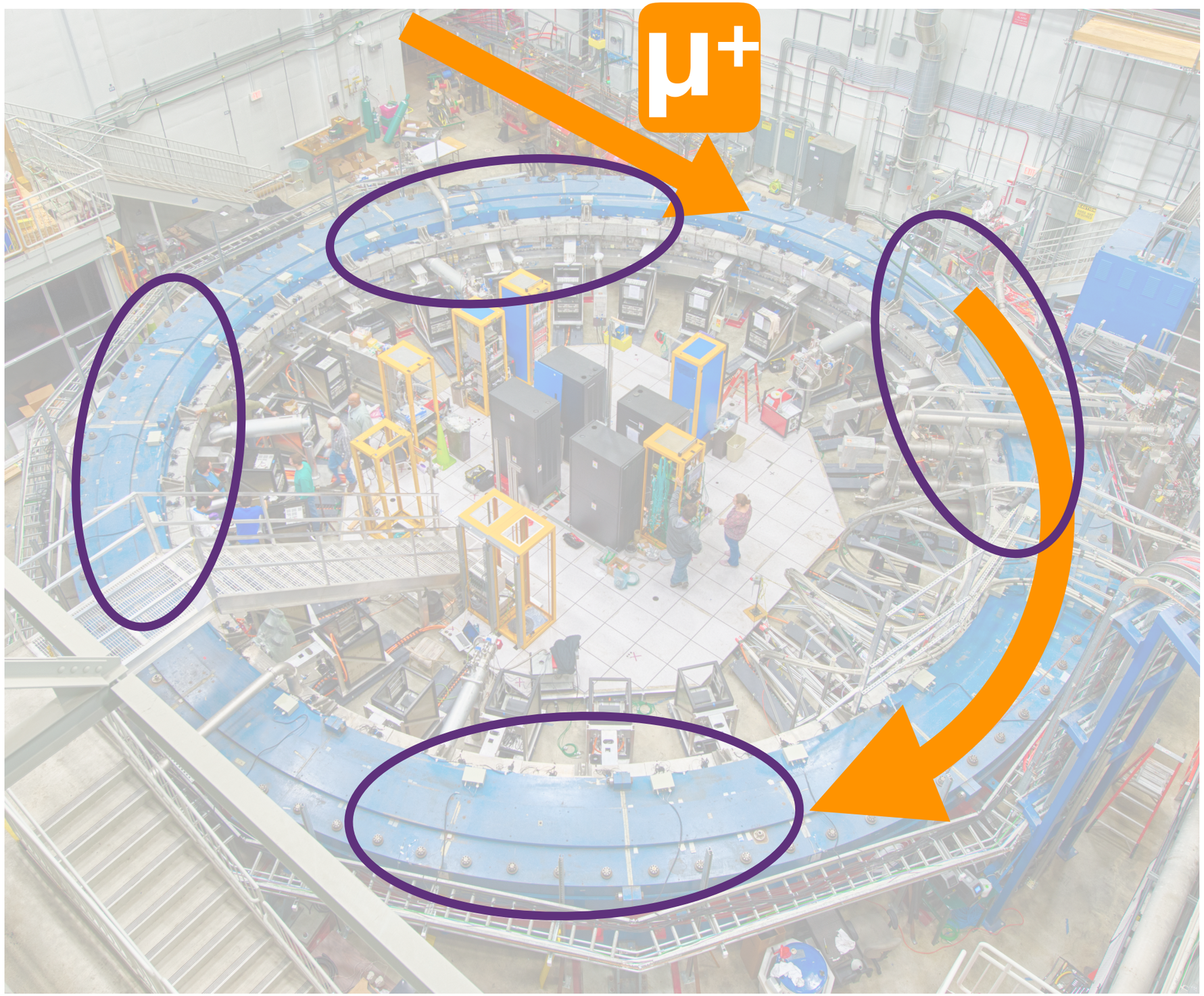


- Muons enter in "wrong orbit"
- Momentary kicker impulse puts them in correct orbit

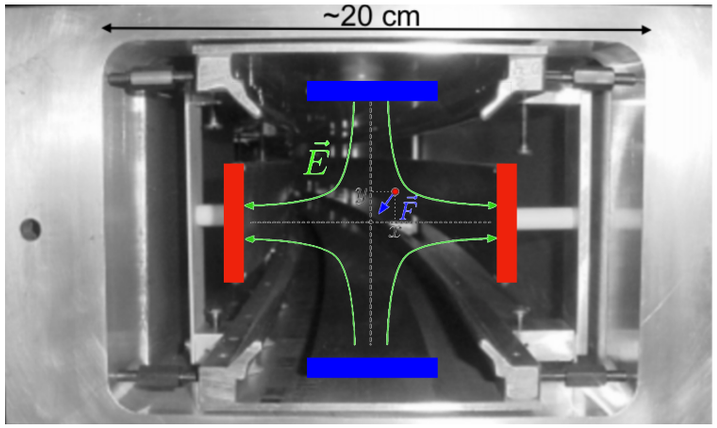


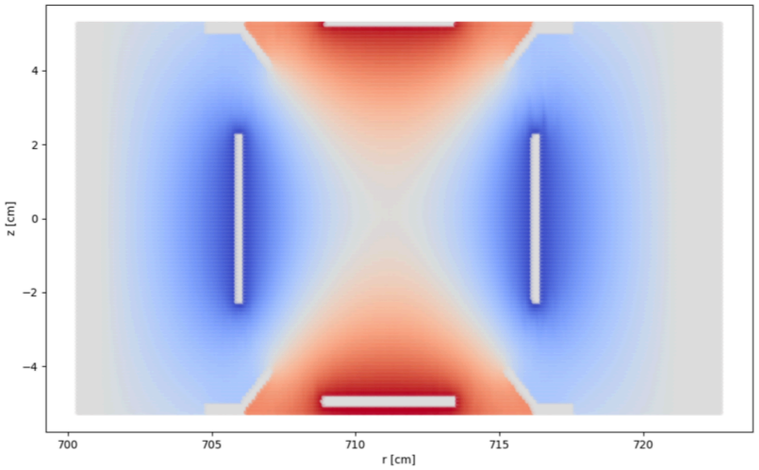


The g-2 experiment at Fermilab

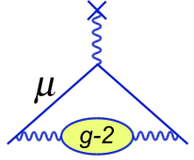


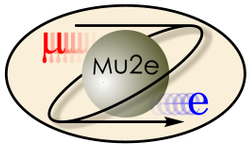
- 4 Electrostatic Quadrupole segments
- Provide vertical focusing to muons
- Integral to collective beam motion





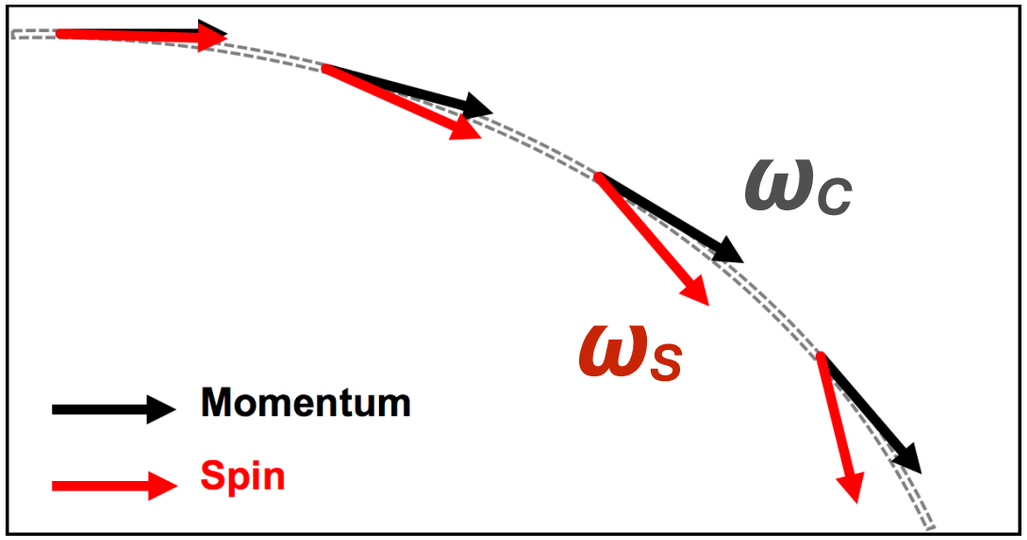
From a muon's eyes

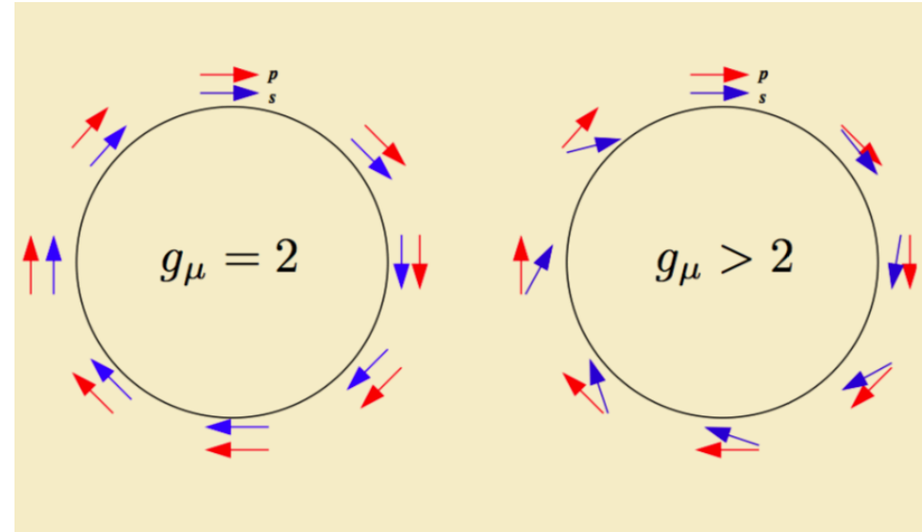




Will Turner

Spin precession





Anomalous precession due to g≠2

$$\vec{\omega}_s = -g_\mu \frac{q}{2m}\vec{B} - (1-\gamma)\frac{q}{\gamma m}\vec{B}$$

$\vec{\omega}_s$ = spin precession frequency

$\vec{\omega}_c$ = cyclotron frequency

$$\vec{\omega}_c = -\frac{q}{m\gamma}\vec{B}$$

$\vec{\omega}_a$ = anomalous precession frequency

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g_\mu - 2}{2}\right)\frac{q}{m}\vec{B} = -a_\mu \frac{q}{m}\vec{B}$$

Simple case of no E-field, constant B-field, and momentum perpendicular to B-field.

$$a \equiv \frac{g-2}{2}$$

$$\vec{\omega}_a = -\frac{q}{m} a_\mu \vec{B}$$

$$\vec{\omega}_a \approx -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

0 if $p = p_{\text{magic}} = mc/\sqrt{a_\mu} = 3.094\ \text{GeV}/c$

"Magic" momentum cancels Thomas precession term

Need measurement of ω_a, B

a_μ ingredients

- Recasting, a_μ can be measured from 5 inputs:

$$a_\mu = \frac{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\omega_a}{\langle \omega_p \rangle}}{\frac{\mu_e}{\mu_p}}$$

Need measurement of ω_a, B/ω_p

Get from CODATA[1]:

g_e = -2.002 319 304 361 82(52) (0.00026 ppb)

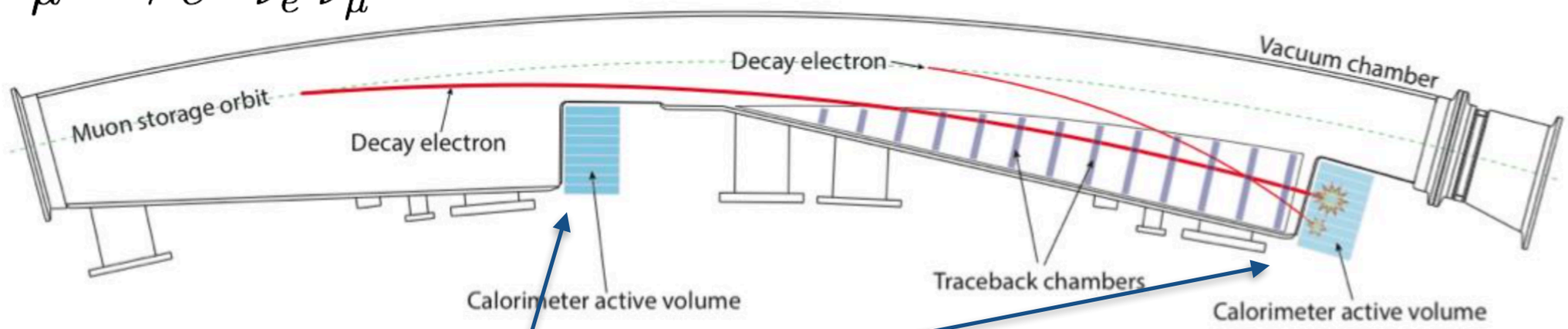
m_μ/m_e = 206.768 2826(46) (22 ppb)

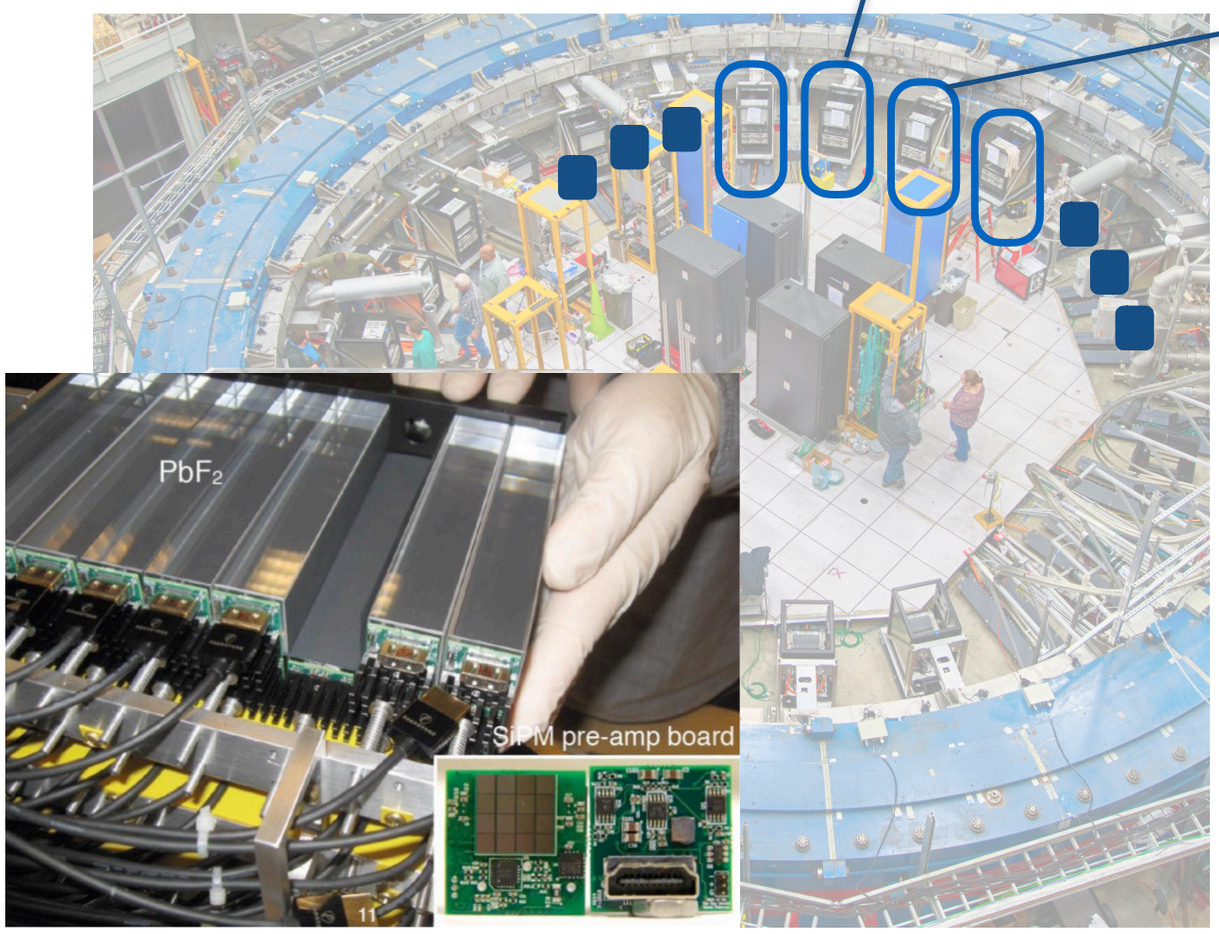
μ_e/μ_p = -658.210 6866(20) (3.0 ppb)

[1] Peter J. Mohr, David B. Newell, and Barry N. Taylor, Rev. Mod. Phys. **88**, 035009, DOI:https://doi.org/10.1103/RevModPhys.88.035009

Precession signal

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$$

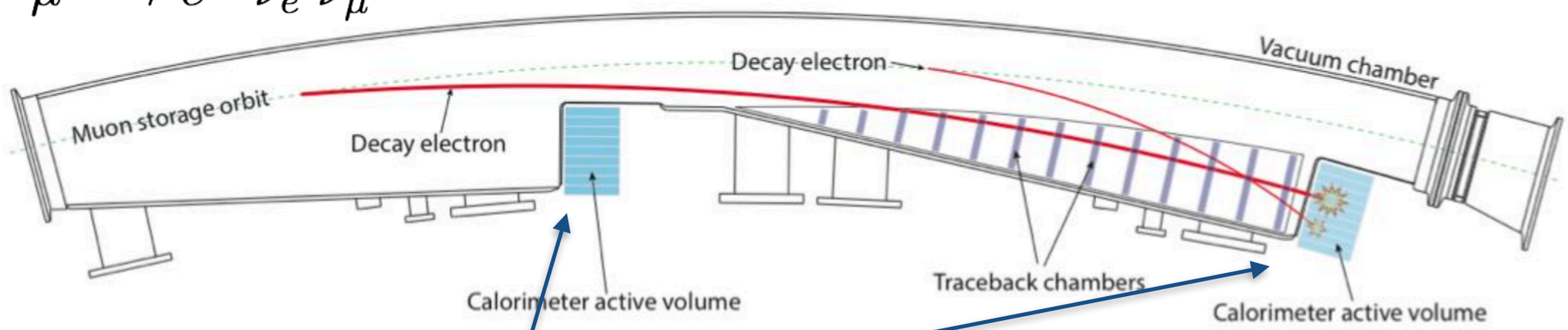


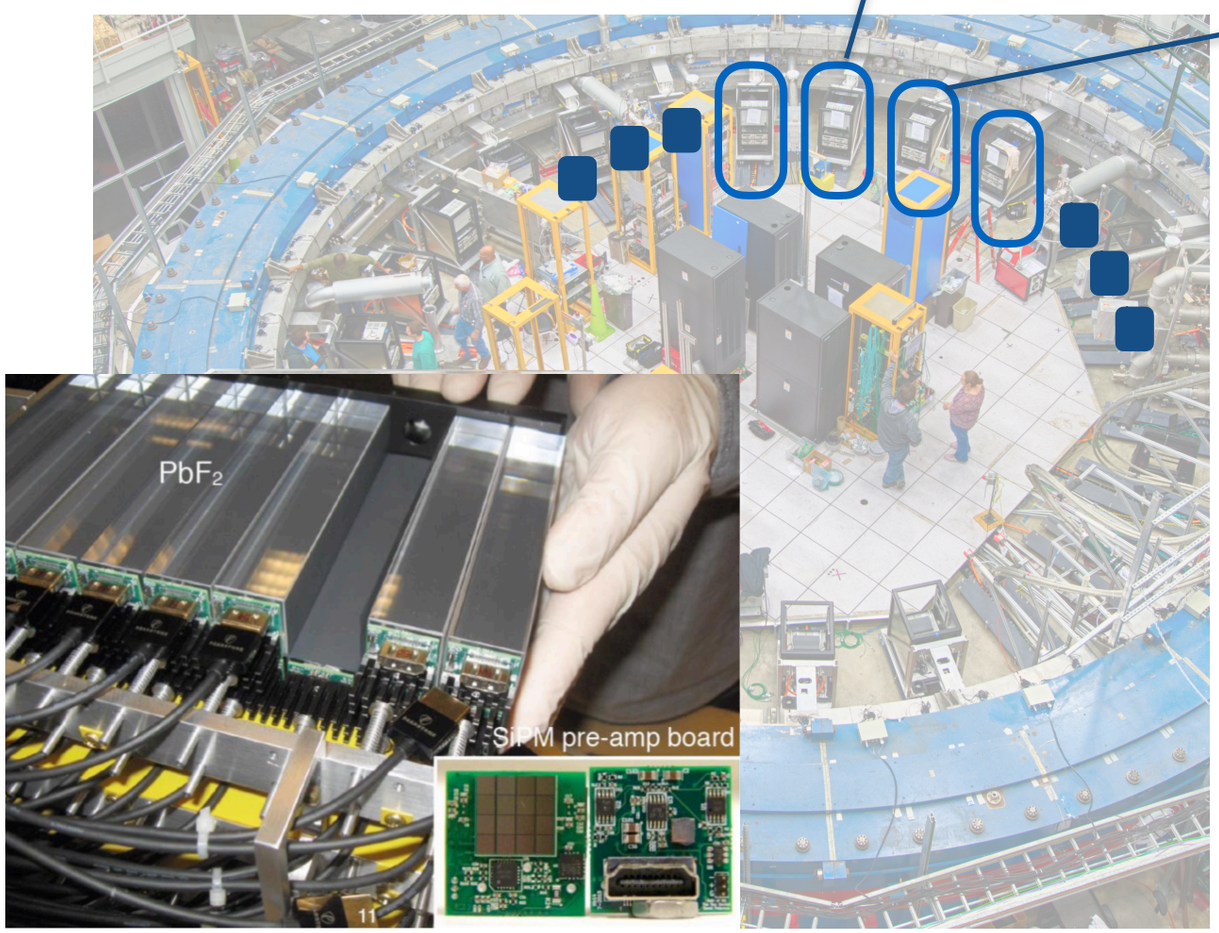


24 PbF_2 calorimeters monitor decays around the ring

Precession signal

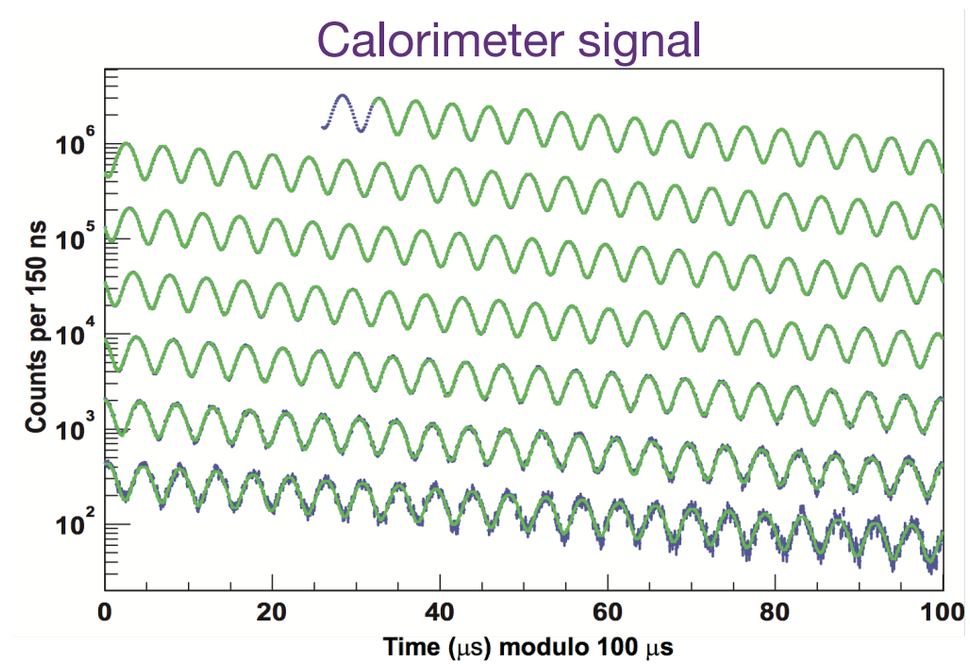
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$





24 PbF_2 calorimeters monitor decays around the ring

Self-analyzing decay: highest-*E* e^+ emitted preferentially along μ^+ spin

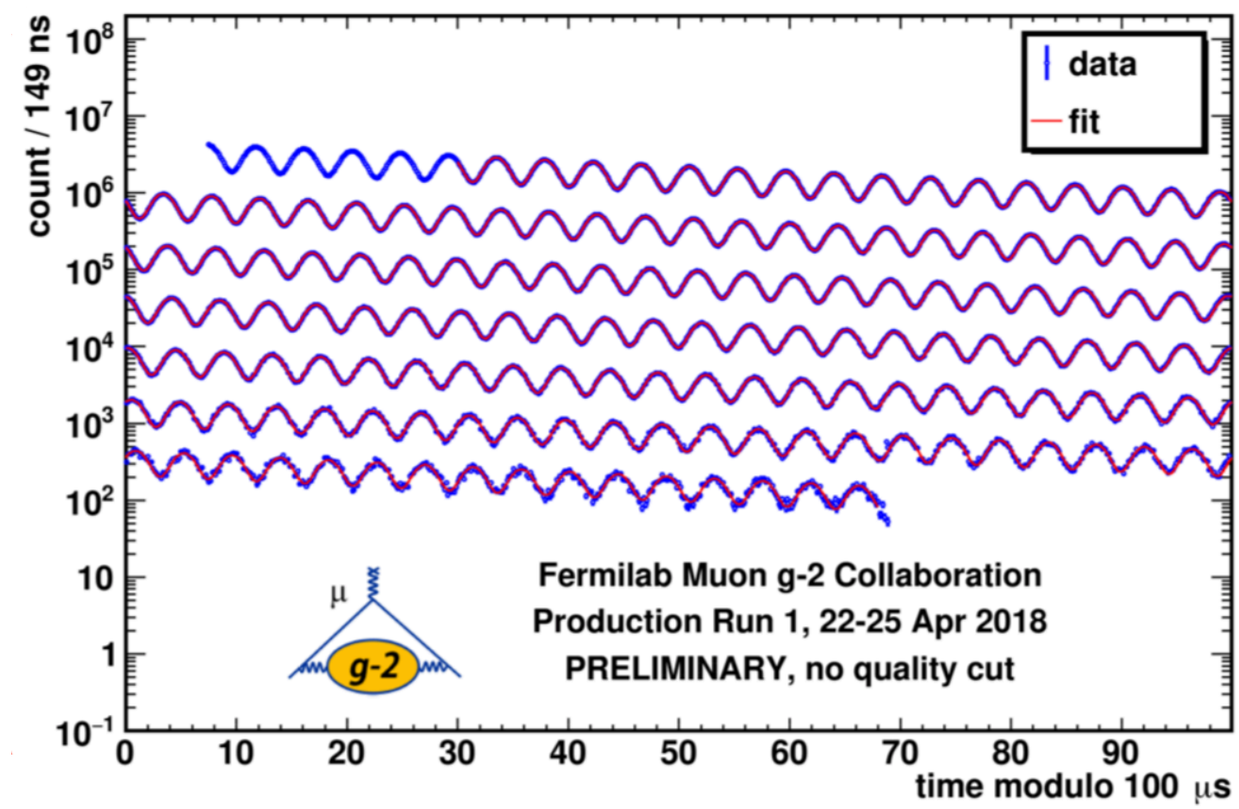


(Muon decay) × (Oscillation due to precession)

a_μ ingredients: ω_a

$$a_\mu = \frac{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\omega_a}{\langle \omega_p \rangle}}{\frac{\mu_e}{\mu_p}}$$

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



ω_a extracted from fit to calorimeter signal

a_μ ingredients: ω_p

$$a_\mu = \frac{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\omega_a}{\langle \omega_p \rangle}}{\frac{\mu_e}{\mu_p}}$$

ω_p: free proton precession frequency

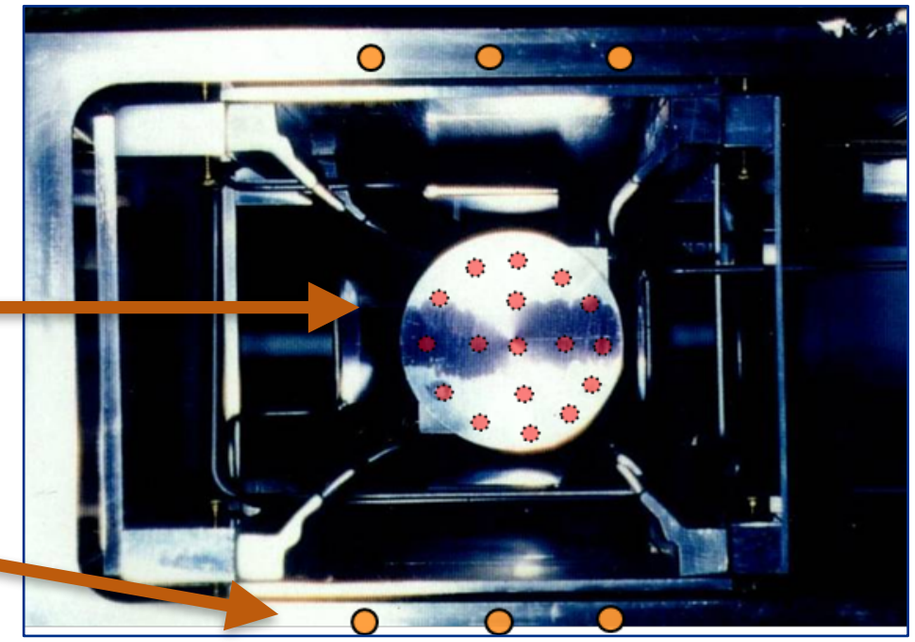
Encodes B field (using NMR probes)

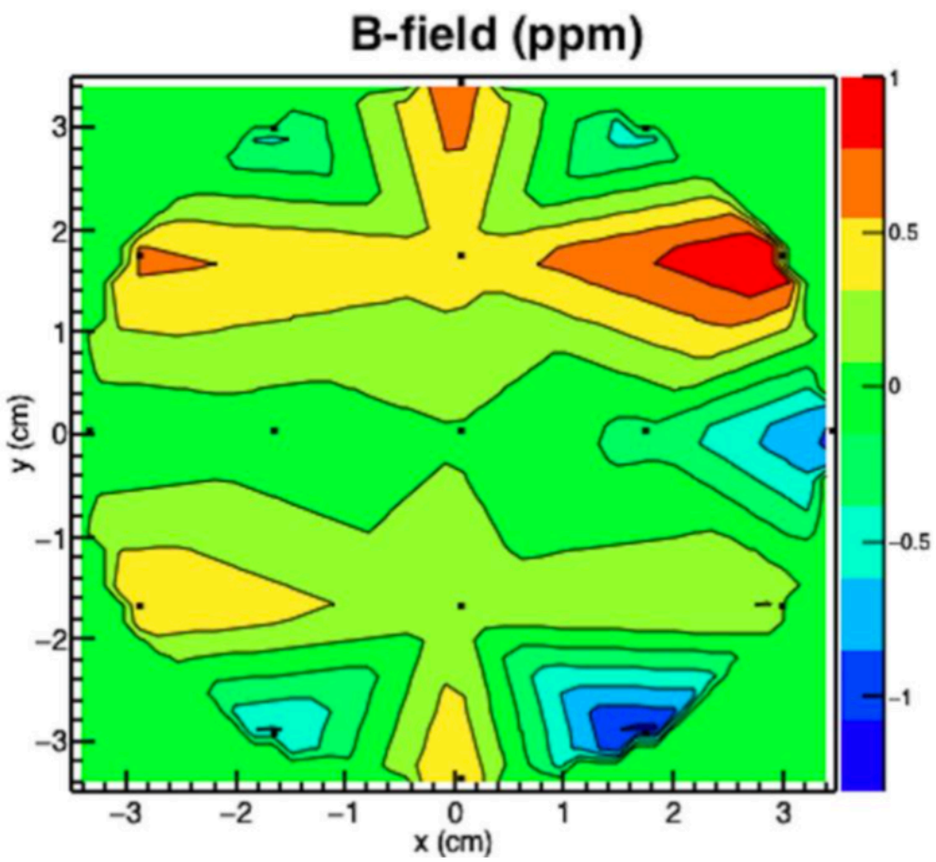
as experienced by muons distribution

Magnetic field

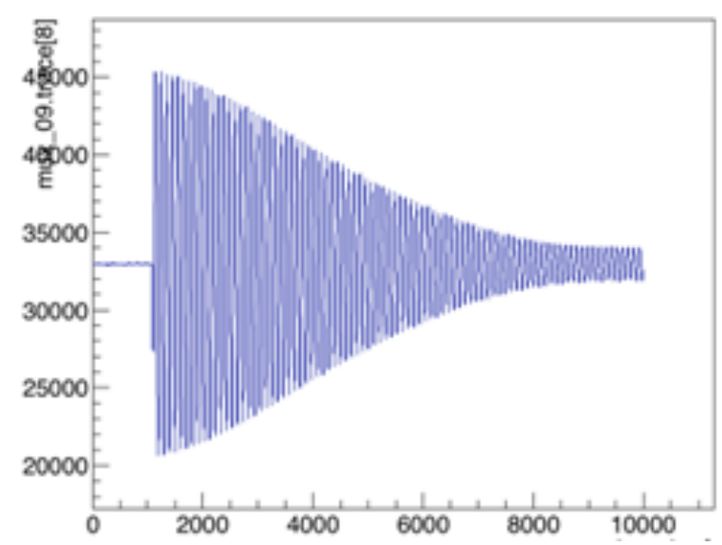
B field monitored with NMR probes

- Pulsed NMR, proton free induction decay
- Probes pulled in trolley for measurement in muon region (~3 days)
- Fixed probes for interpolation

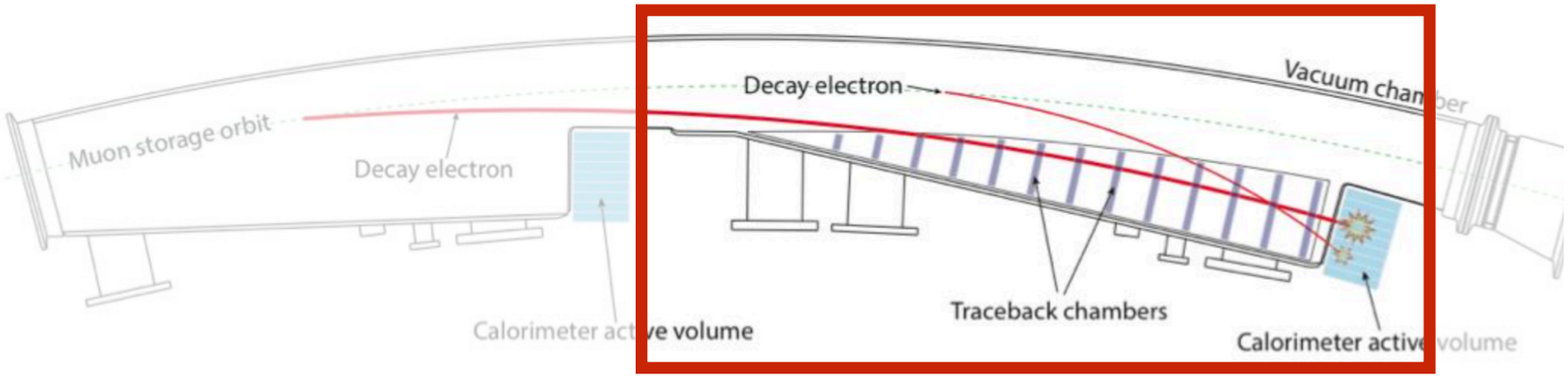


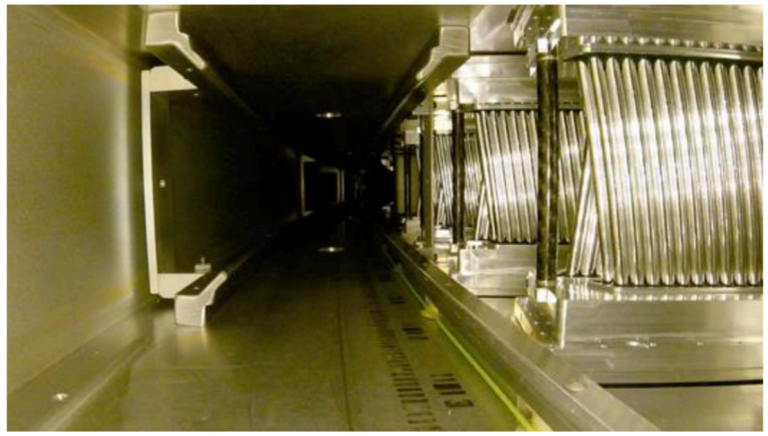


FID signal

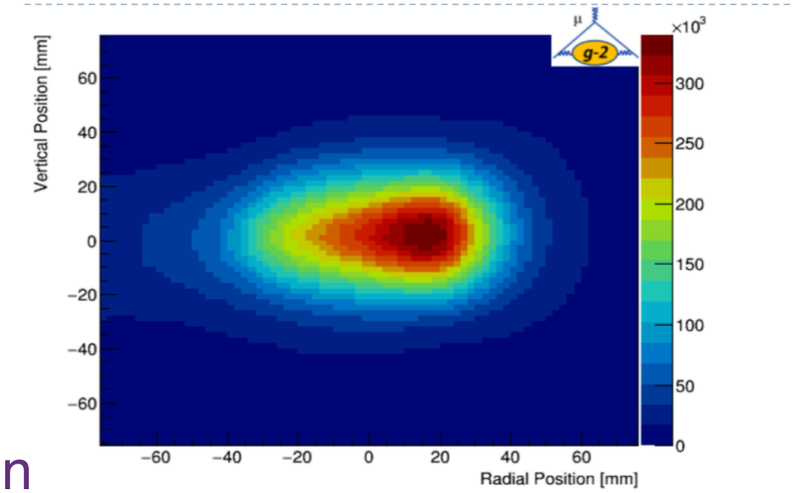


Muon distribution



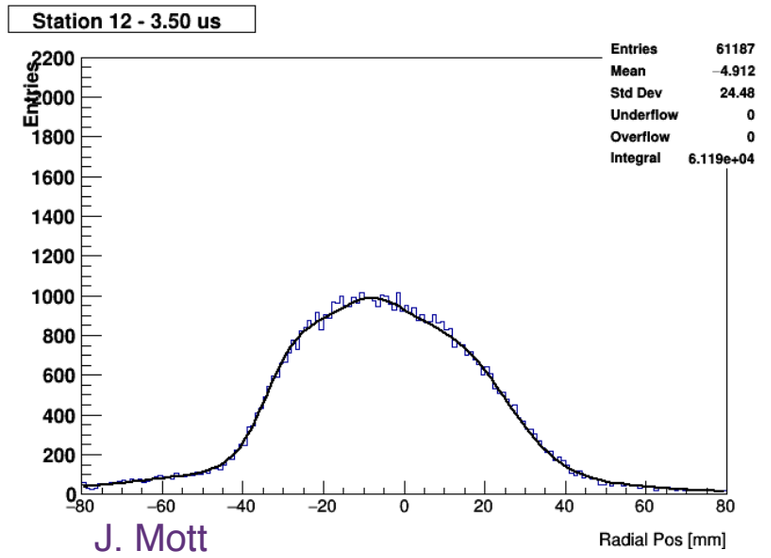


Straw trackers reconstruct muon distribution and determine the complex beam dynamics

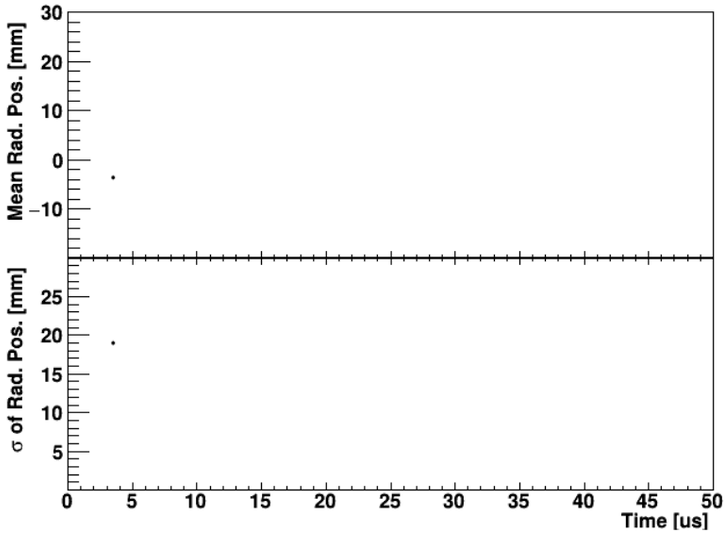


Muon distribution,
Coherent betatron motion

Needed for convolution with field, but also for ω_a fit corrections

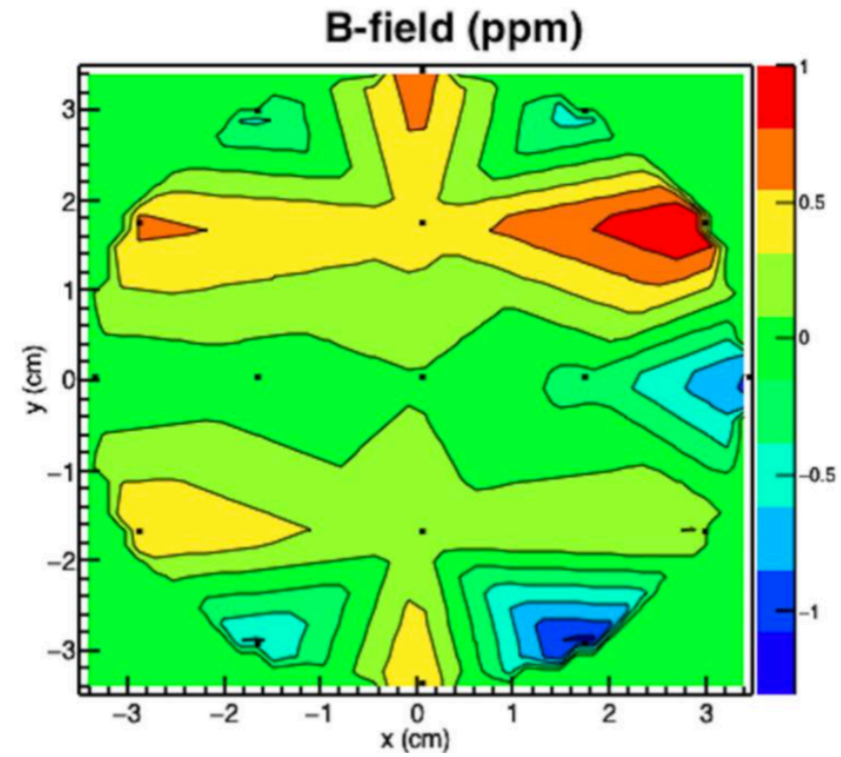


J. Mott

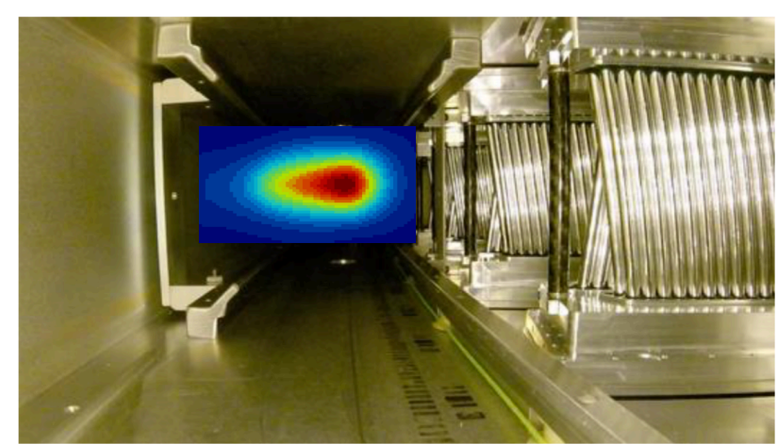


a_μ ingredients: ω_p

$$a_\mu = \frac{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\omega_a}{\langle \omega_p \rangle}}{\frac{\mu_e}{\mu_p}}$$



convolution ⊛



Muon distribution

Improving from BNL

ω_a **systematic uncertainty summary**[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Gain Changes	120	20
Pileup	80	40
Lost Muons	90	20
CBO	70	< 30
E-field & Pitch Corrections	50	30
Total (Quadrature Sum)	190	70

New instrumentation for ω_a, better control of beam dynamics

$\langle\omega_p\rangle$ **(B-field) systematic uncertainty summary**[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Absolute Field Calibration	50	35
Trolley Probe Calibrations	90	30
Trolley Measurements Of B_0	50	30
Fixed Probe Interpolation	70	30
Muon Distribution	30	10
Time-dependent External Magnetic Fields	-	5
Others (Collective Smaller Effects)	100	30
Total (Quadrature Sum)	170	70

More uniform field, better measured

[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].

Improving from BNL

ω_a **systematic uncertainty summary**[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Gain Changes	120	20
Pileup	80	40
Lost Muons	90	20
CBO	70	< 30
E-field & Pitch Corrections	50	30
Total (Quadrature Sum)	190	70

~21x BNL statistics

a_μ **uncertainty summary**[1,2].

Category	BNL [ppb]	FNAL Goal [ppb]
Total Statistical Uncertainty	460	100
Total Systematic Uncertainty	280*	100
Total (Quadrature Sum)	540*	140

* The net systematic is across 3 running periods.

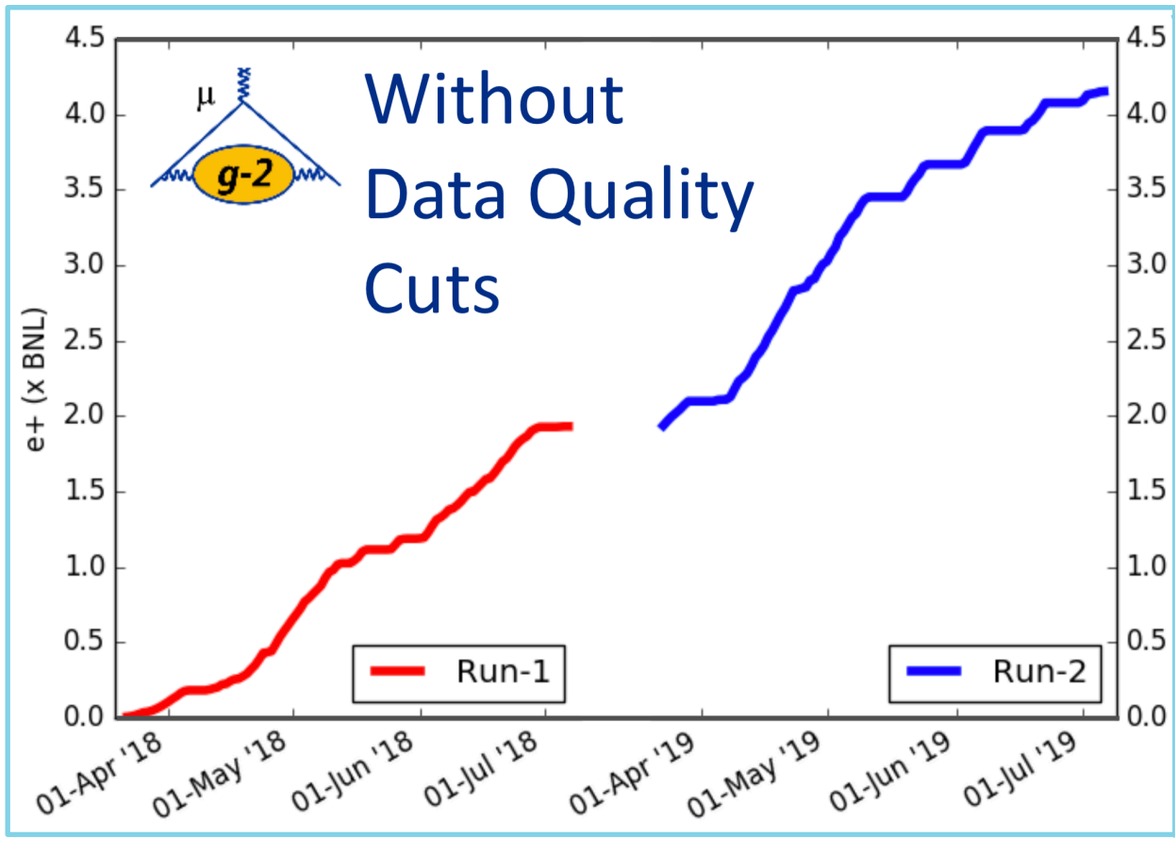
$\langle\omega_p\rangle$ **(B-field) systematic uncertainty summary**[1].

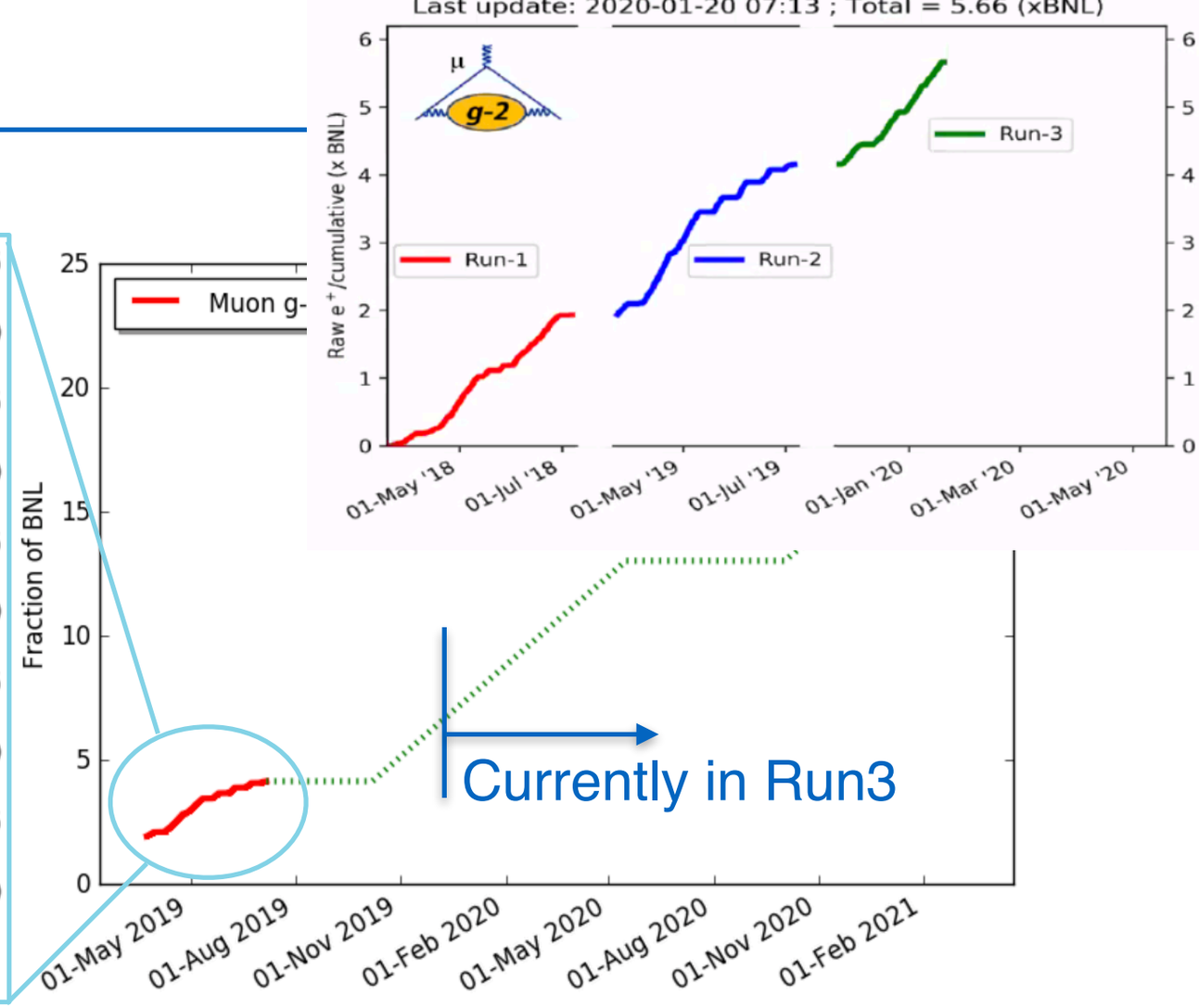
Category	BNL [ppb]	FNAL Goal [ppb]
Absolute Field Calibration	50	35
Trolley Probe Calibrations	90	30
Trolley Measurements Of B_0	50	30
Fixed Probe Interpolation	70	30
Muon Distribution	30	10
Time-dependent External Magnetic Fields	-	5
Others (Collective Smaller Effects)	100	30
Total (Quadrature Sum)	170	70

Overall uncertainty reduction x4

[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].
[2] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

Current status





1st publication (> 1x BNL stats)

Intermediate publications (3x, 10x BNL stats)

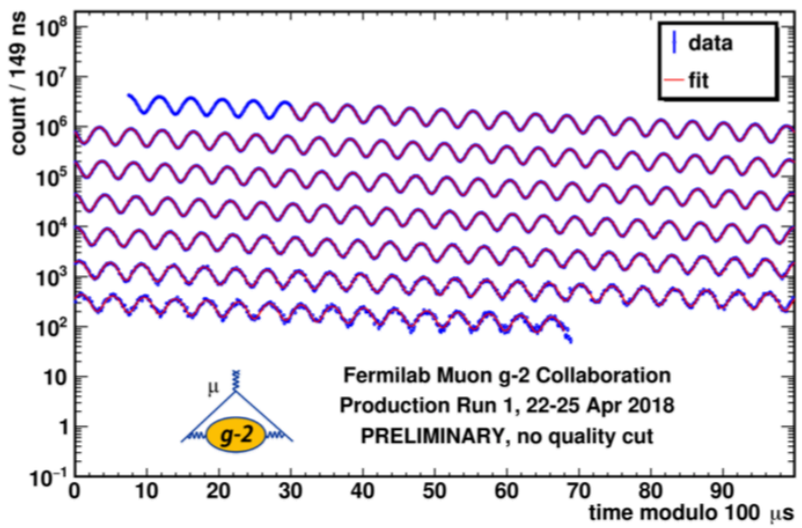
Final publication

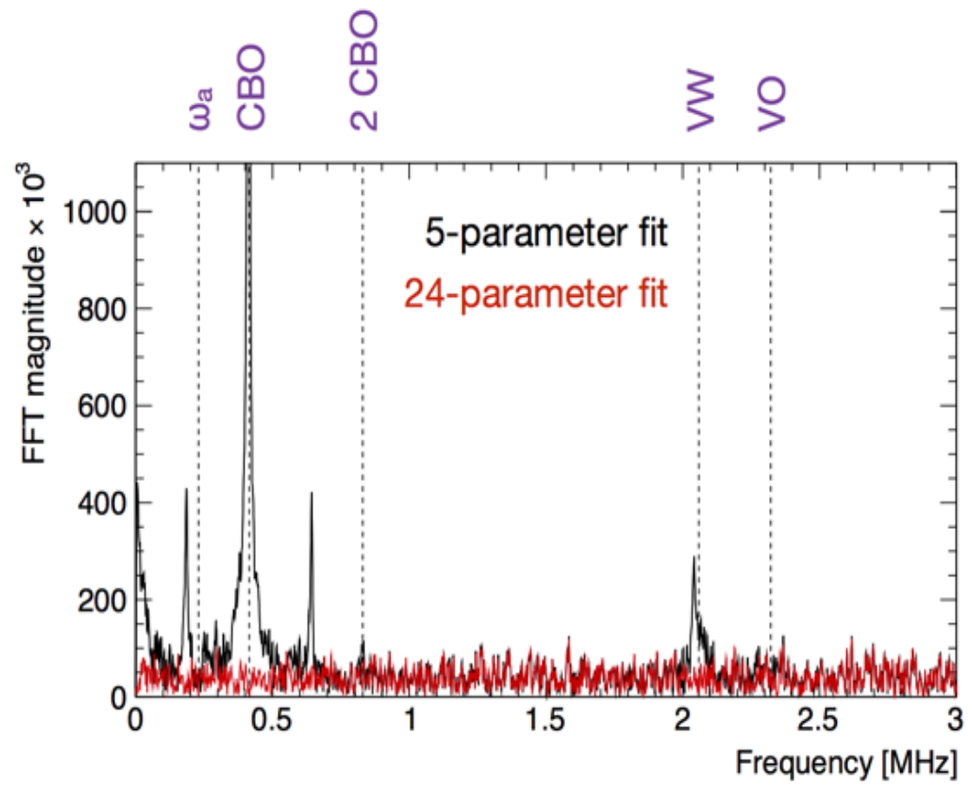
CY18 → CY19 → CY20 → CY21 → CY22

Run1 result expected in few months

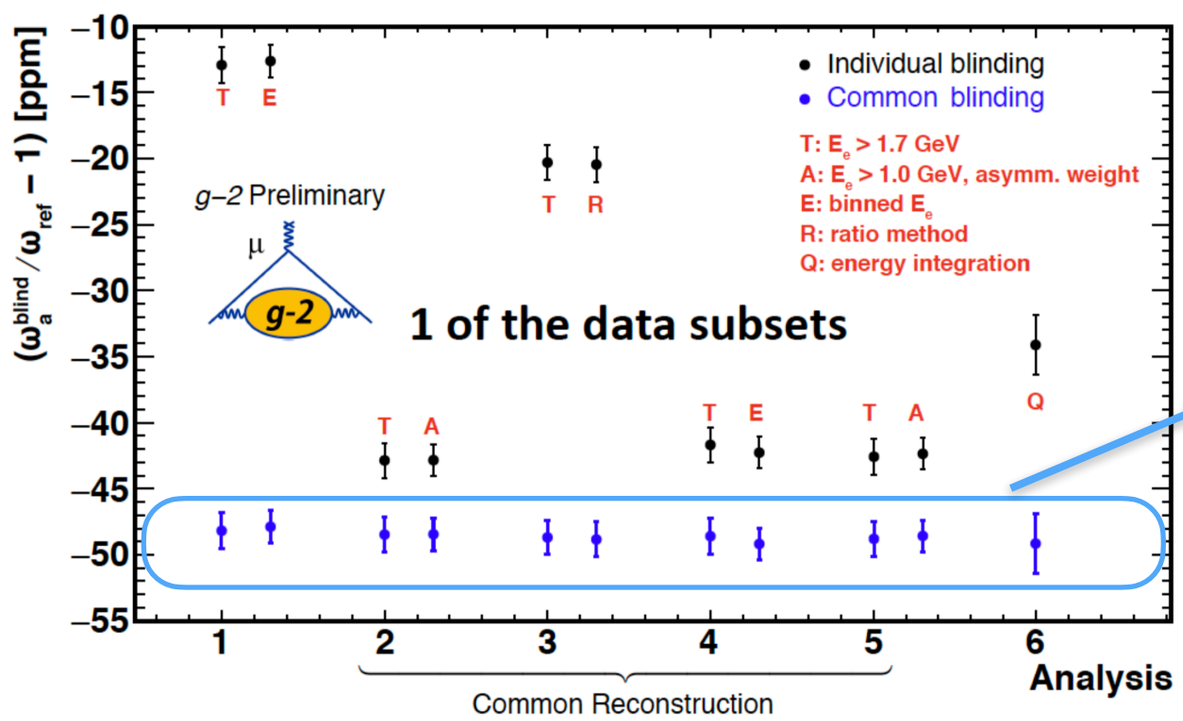
Run1 ω_a analysis

$$N(t) = N_0 \Lambda(t) N_{cbo}(t) N_{vw}(t) e^{-t/\tau}$$
$$\cdot\left\{1 + A_0 \cdot A_{cbo}(t) \cdot \cos\left[\omega_a(R) \cdot t + \phi_0 + \phi_{cbo}(t)\right]\right\}$$



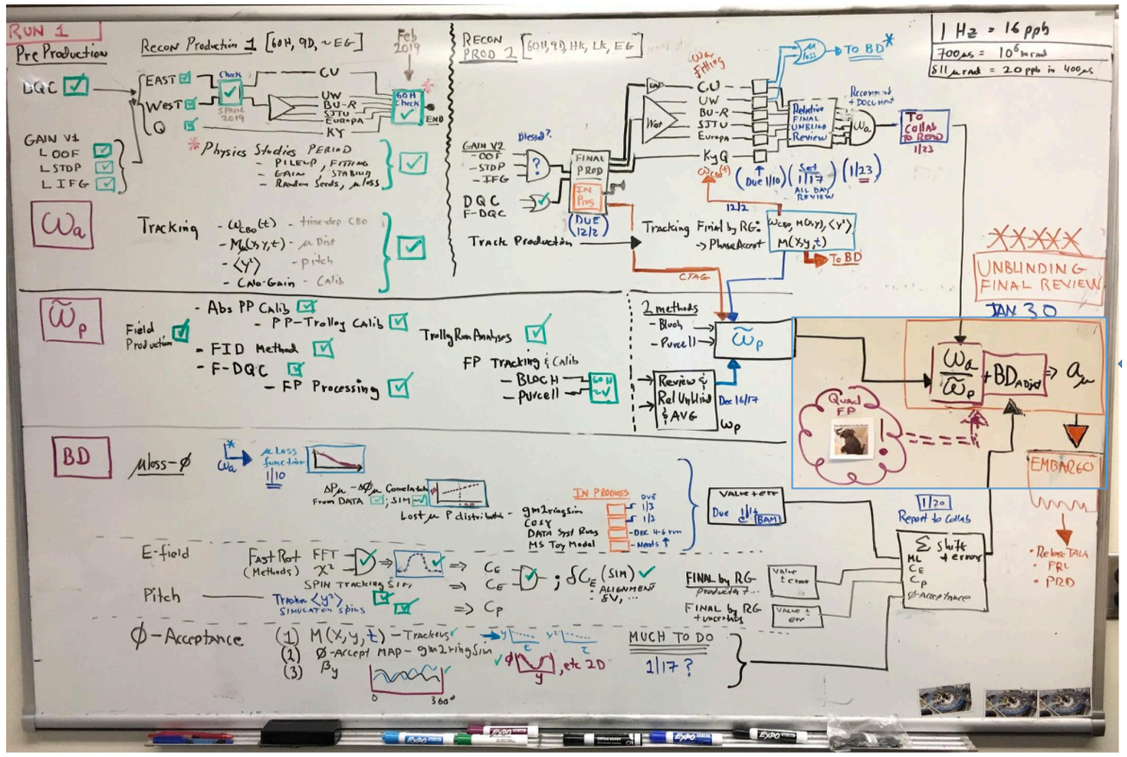


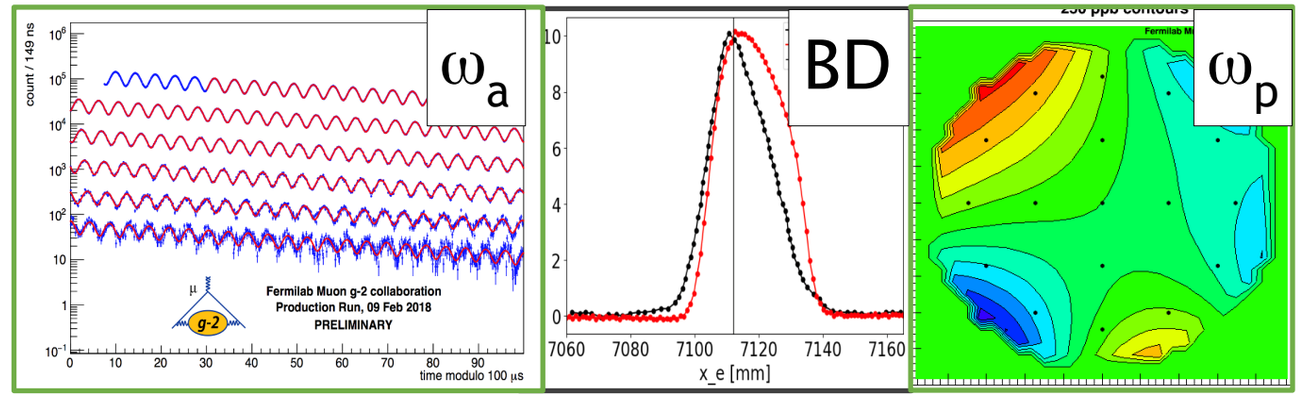
FFT of residuals flat, after accounting for beam dynamics effects on ω_a.



- 6 independent teams/algorithms
- Excellent agreement in subset where relative unblinding tested

Run1 result expected soon!





Tremendous work done, many checks and cross-checks

Brian Cox: … if I were to put my money on something that would signal new physics, it's the g-2 experiment at Fermilab.

Run1 result, highly anticipated by global community, is expected in few months!

nature

The science events to watch for in 2020

One of only 2 PP events to be included

Outline

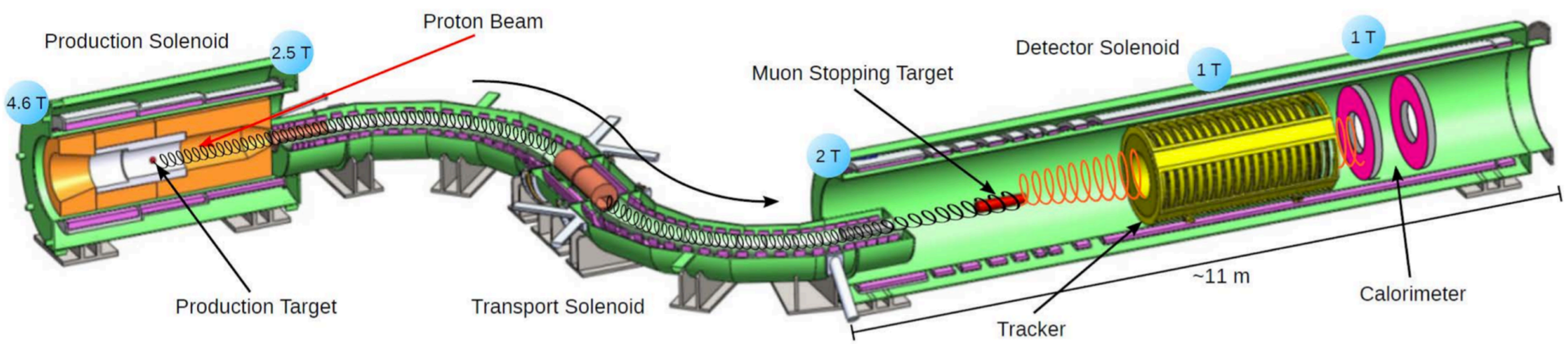
Context and Motivation

The Muon g-2 Experiment

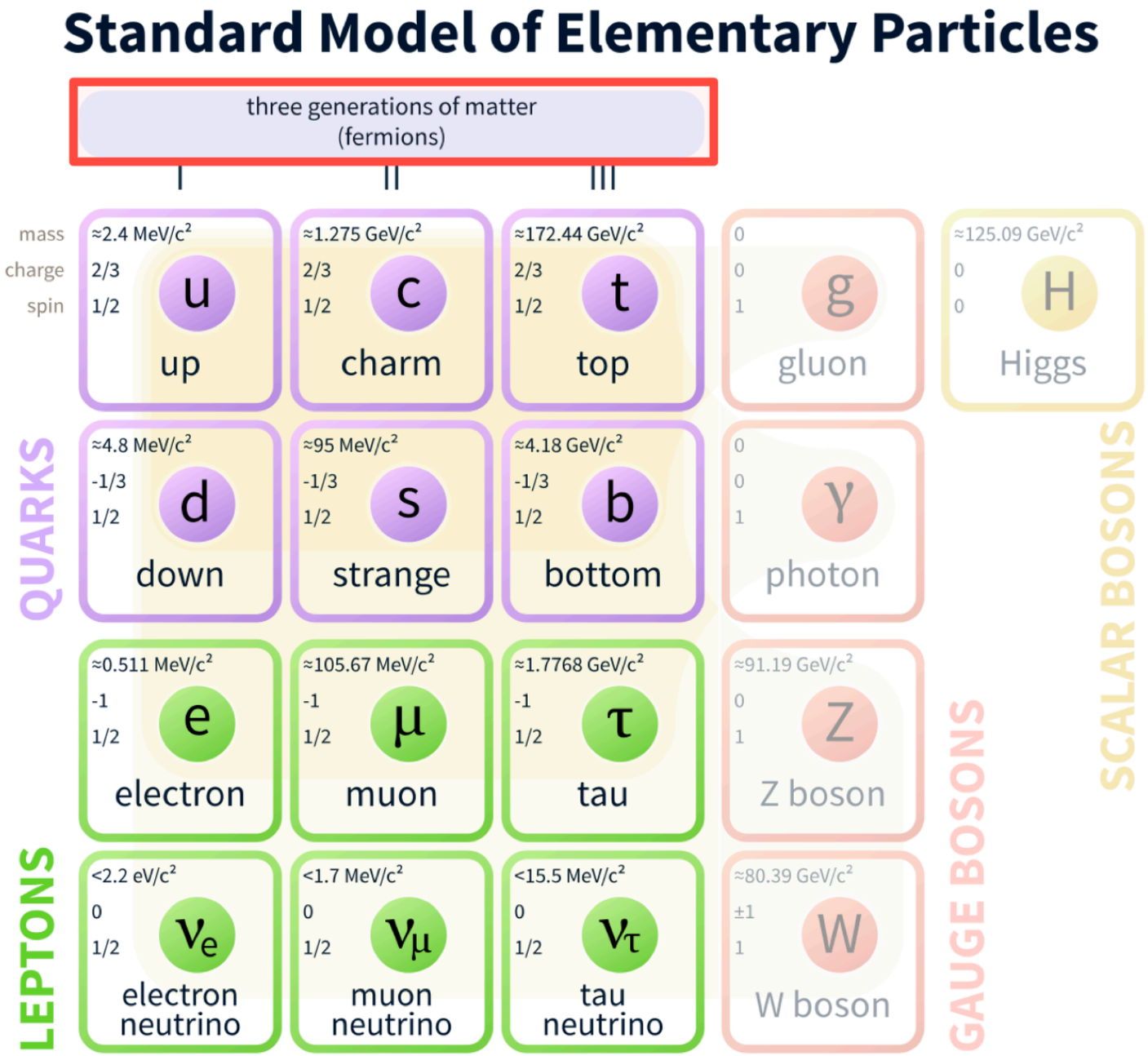
The Mu2e Experiment

- Charged lepton flavor violation
- Measurement principles
- Status

Status and Outlook



Flavor in the SM

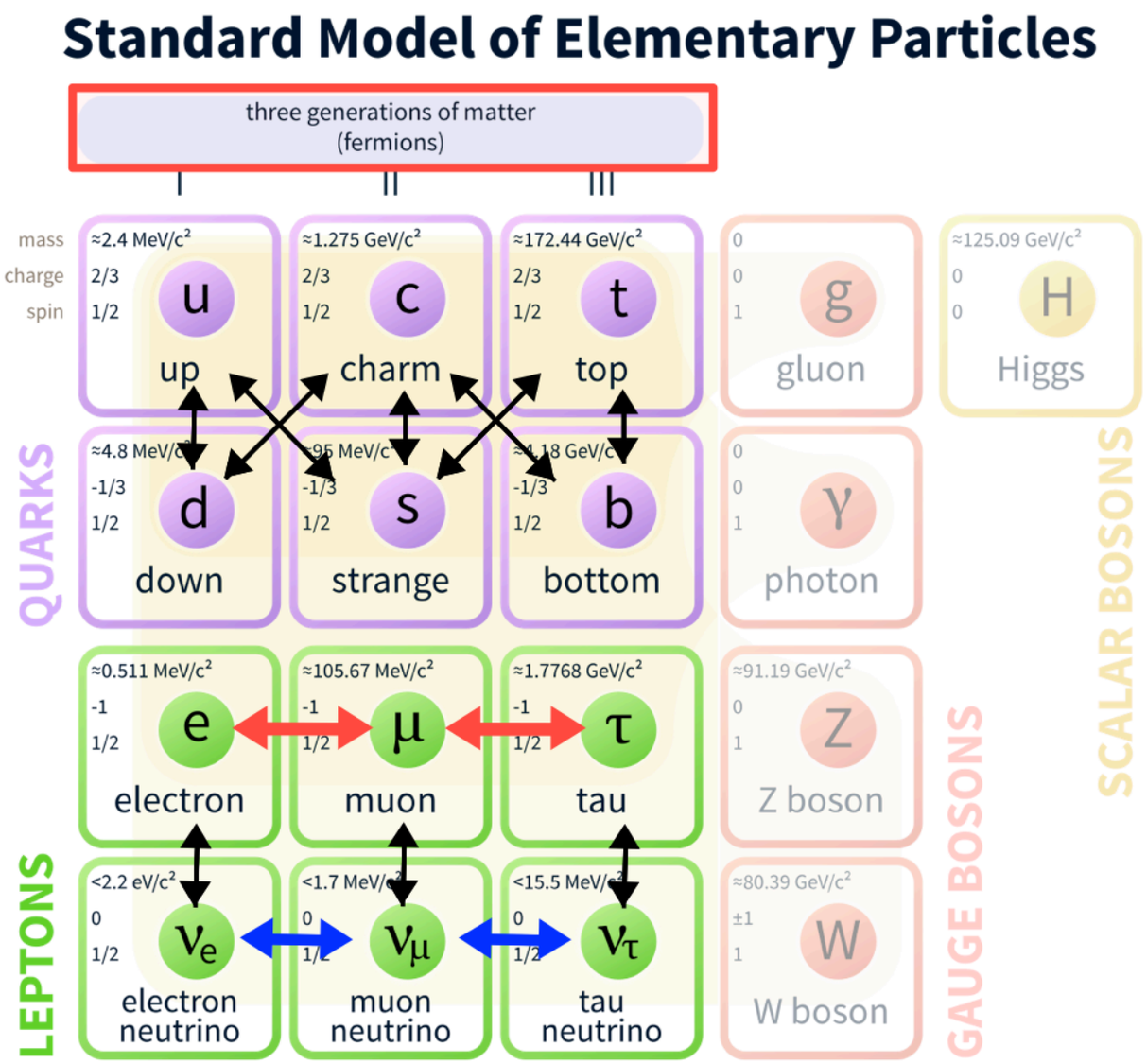


The SM flavor puzzle

- Why 3 generations of matter?
  - Rabi encapsulated the issue well:

- What defines hierarchy of masses and couplings?
- What is the origin of lepton asymmetry in the universe
  - Is lepton *number* conserved?
- Is mixing allowed between generations/flavors?

Flavor in the SM



Mixing between flavors

- Quarks mixing, CKM mechanism
- Leptons weak decay

- Neutrino oscillations
  - Lepton flavor violated!

- Mixing between charged leptons: never observed
  - Powerful probe of flavor models
  - Especially well motivated given ν-oscillations, LFU-violation

Any observation of Charged-Lepton Flavor Violation (CLFV) would be evidence of New Physics

The charged-lepton analog to neutrino oscillations

CLFV processes

Broad global interest in CLFV searches:

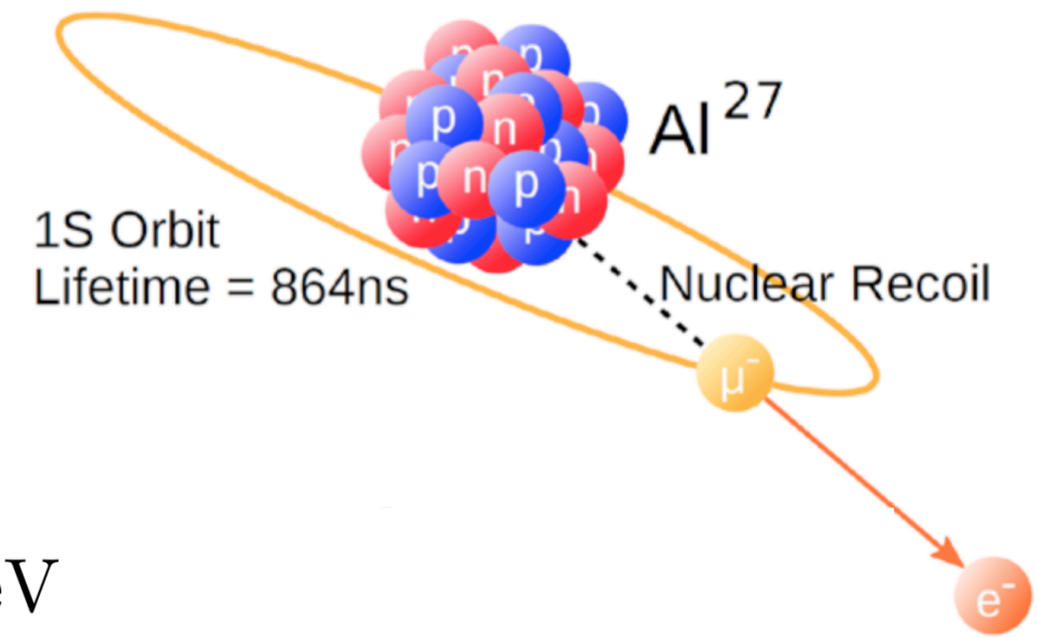
Process	Current limit	Planned Next Gen Experiment
$Z \to e\mu$	$\mathrm{BR} < 7.5 \cdot 10^{-7}$	
$\tau \to eee$	$\mathrm{BR} < 2.7 \cdot 10^{-8}$	10^{-9}, BELLE-II
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 2.1 \cdot 10^{-8}$	
$\tau \to \mu ee$	$\mathrm{BR} < 1.5 \cdot 10^{-8}$	
$\tau \to \mu\eta$	$\mathrm{BR} < 6.5 \cdot 10^{-8}$	
$\tau \to e\gamma$	$\mathrm{BR} < 3.3 \cdot 10^{-8}$	
$\tau \to \mu\gamma$	$\mathrm{BR} < 4.4 \cdot 10^{-8}$	
$K_L \to e\mu$	$\mathrm{BR} < 4.7 \cdot 10^{-12}$	
$K^+ \to \pi^+ e\mu$	$\mathrm{BR} < 1.3 \cdot 10^{-11}$	
$B^0 \to e\mu$	$\mathrm{BR} < 7.8 \cdot 10^{-8}$	
$B^+ \to K^+ e\mu$	$\mathrm{BR} < 9.1 \cdot 10^{-8}$	
$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \to e^+e^-e^+$	$\mathrm{BR} < 1.0 \cdot 10^{-12}$	10^{-16} (Mu3e)
$\mu^- A \to e^- A$	$\mathrm{R}^{\mathrm{Au}}_{\mu e} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

- Most stringent limits come from the muon sector
- The $\mu\mathrm{A} \to e\mathrm{A}$ process offers greatest potential sensitivity
  - Best control of backgrounds

μ -> e conversion: The Mu2e search

Coherent conversion $\mu \rightarrow e$ in the field of a nucleus

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$



Clean experimental signature

- mono-energetic e^- – for Al:

$$E_{\mu e}(\mathrm{Al}) = m_\mu - E_\mathrm{b} - E_\mathrm{rec} = 104.97\,\mathrm{MeV}$$

Current limit: $R_{\mu e} < 7\times10^{-13}$ [SINDRUM II]

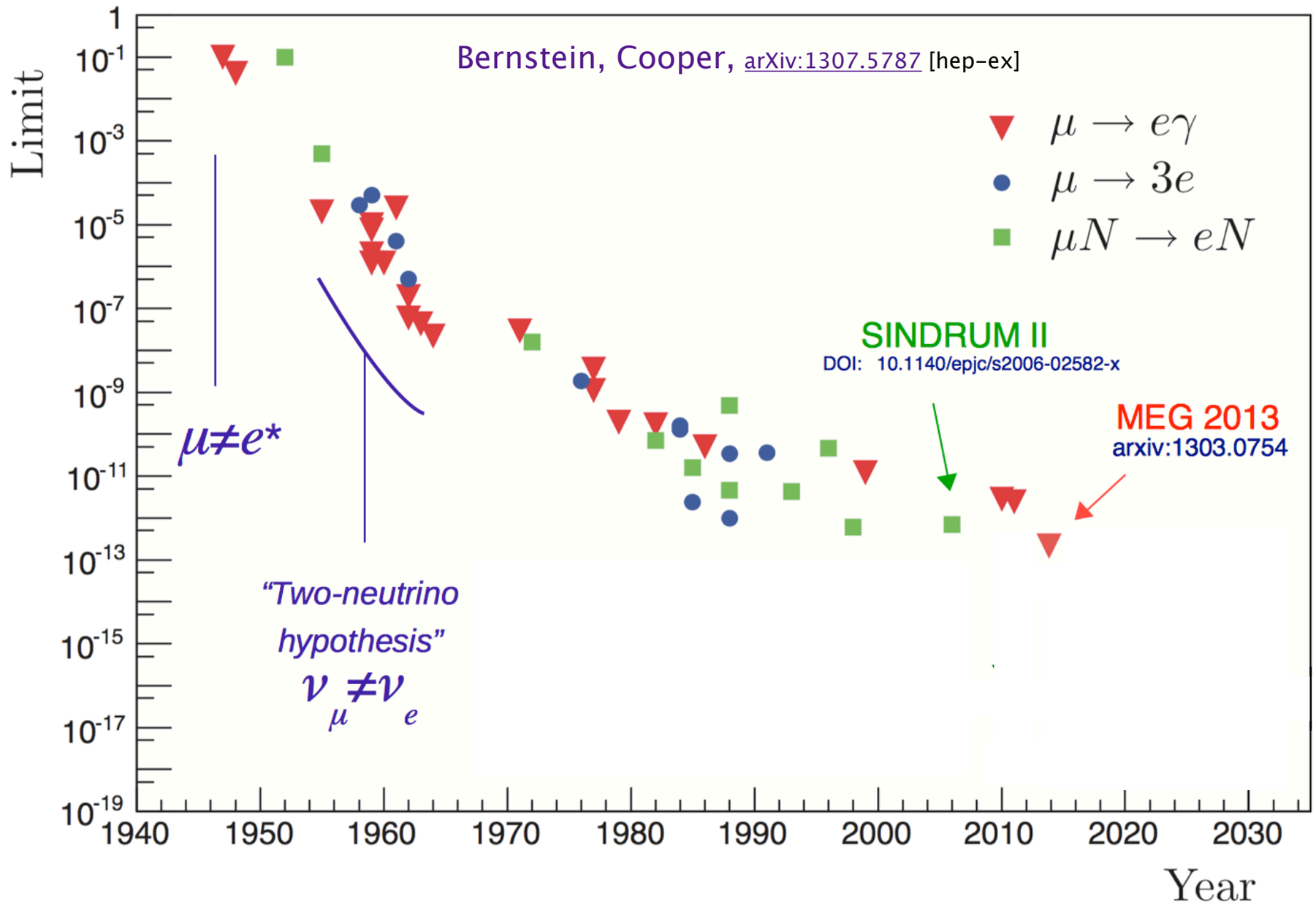
$$R_{\mu e} = \frac{\mu^- + N \rightarrow e^- + N}{\mu^- + N \rightarrow \text{nuclear capture}} < 7 \times 10^{-13}.$$

Conversion process normalized to nuclear capture

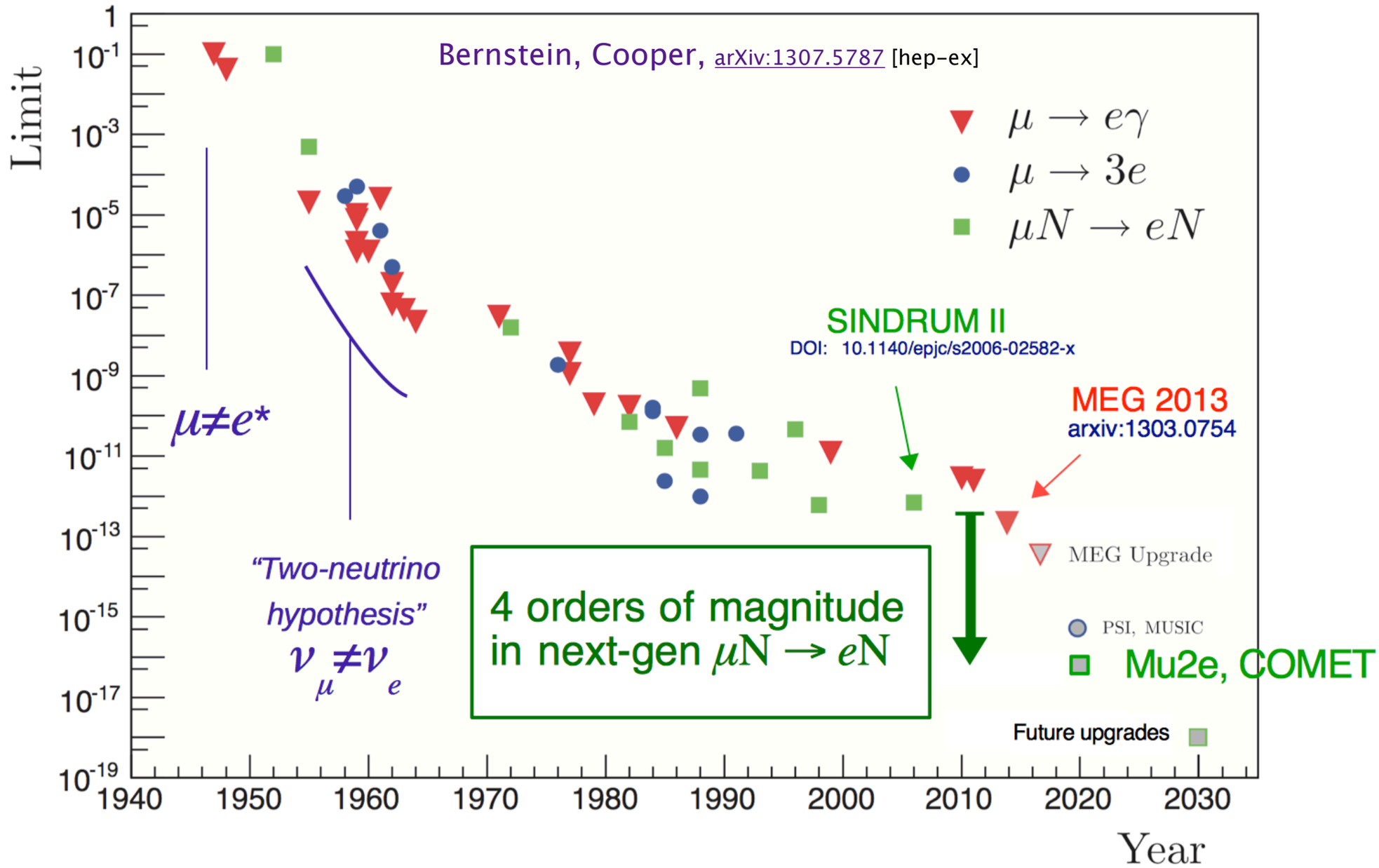
The Mu2e experiment will probe $R_{\mu e}$ at the level of $<3\times10^{-17}$ (SES)

- 4 orders of magnitude improvement – a rare opportunity!

History of CLFV searches



History of CLFV searches



- Dramatic improvement in next generation experiments, especially $\mu N \to eN$
- Exploring unconstrained phase space favored by many New Physics models

$\mu \rightarrow e$ conversion processes

Effective Lagrangian:

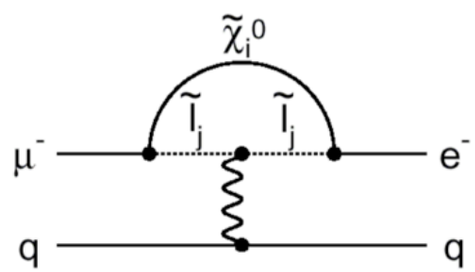
$$\mathcal{L}_{\mathrm{CLFV}} = \underbrace{\frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{“Loop”}} + \underbrace{\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)}_{\text{“Contact”}}$$

Λ: effective mass parameter

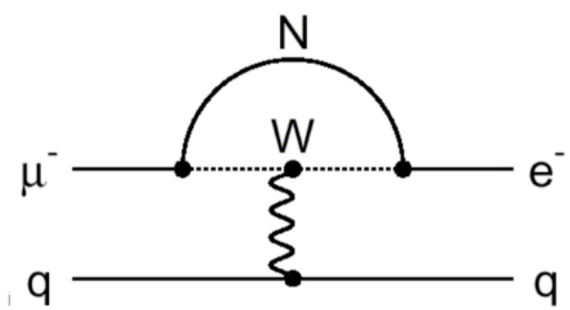
κ: relative strength of loop- and contact-dominated terms

Loop terms:

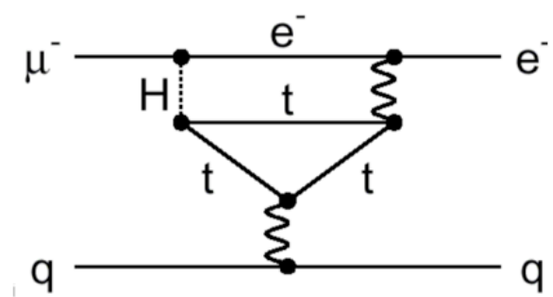
- Also mediate $\mu \rightarrow e\gamma$



Supersymmetry



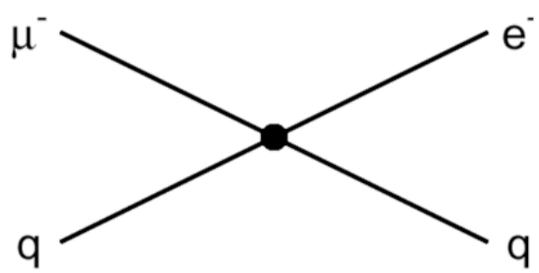
Heavy neutrino



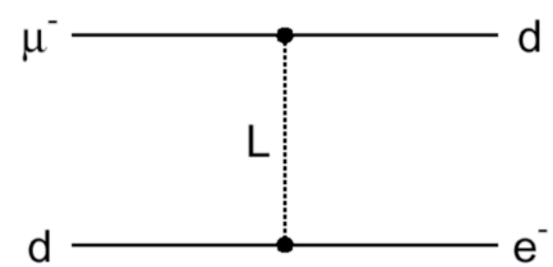
Two Higgs doublets

Contact terms:

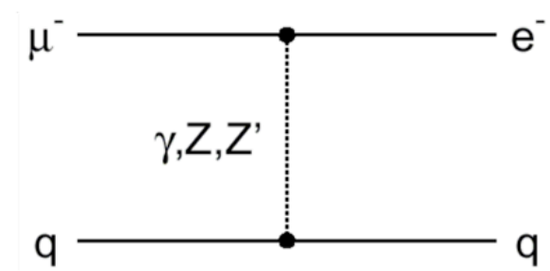
- Only mediate $\mu N \rightarrow eN$



Compositeness

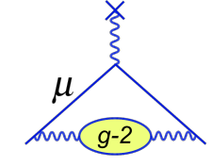


Leptoquarks



New heavy bosons/ anomalous couplings

Connections to g-2



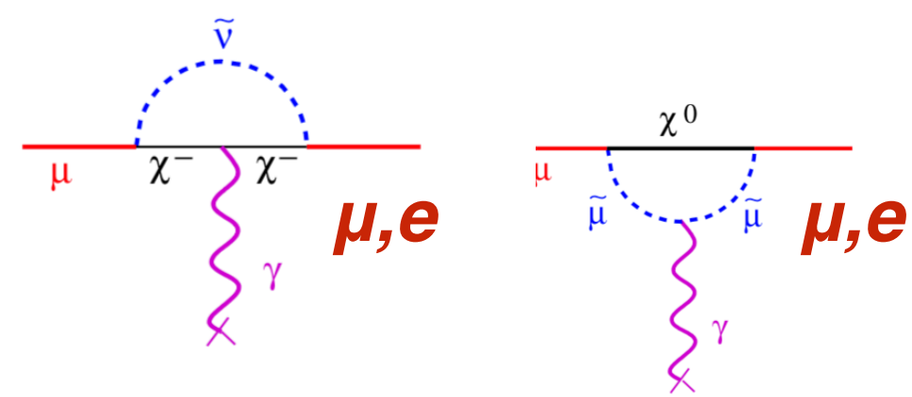
Effective Lagrangian:

$$\mathcal{L}_{\mathrm{CLFV}} = \underbrace{\frac{m_\mu}{(1+\kappa)\,\Lambda^2}\,\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu}}_{\text{“Loop”}}$$

Unsurprisingly, “magnetic dipole”-like operator relates to Muon g-2

- The CLF-violating part of any New Physics that modifies g-2 would give Mu2e events
- MEG constraints then already limit Λ~800 TeV, or NP not very CLF-violating

Kpatcha et al., arXiv:1912.04163 [hep-ph]

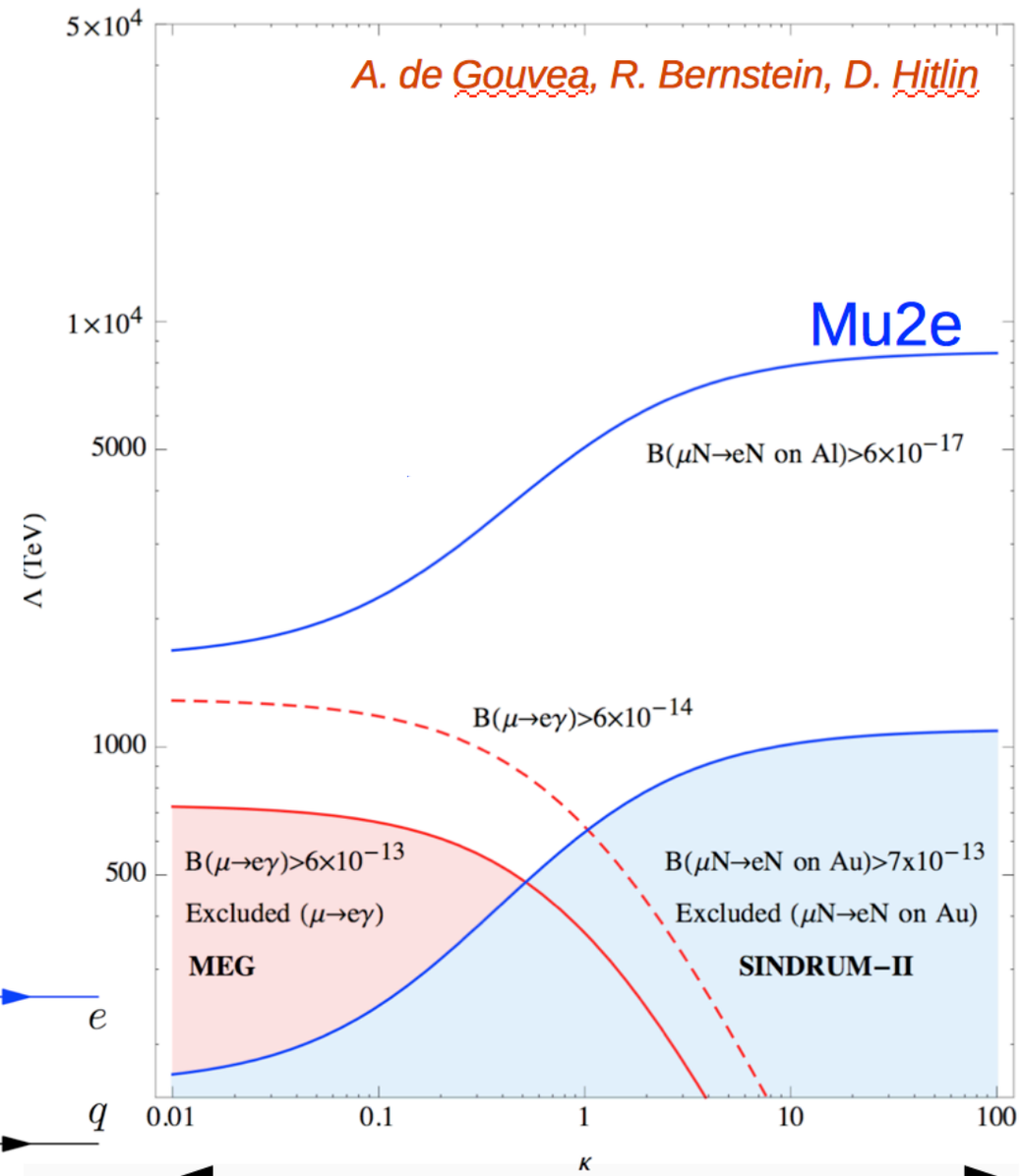


Physics reach

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

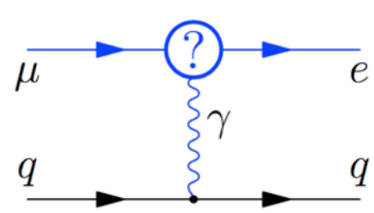
Λ: effective mass parameter

κ: relative strength of loop- and contact-dominated terms

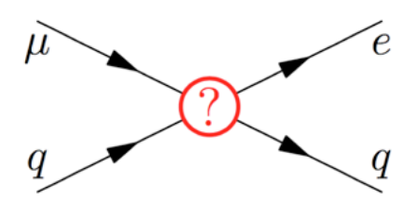


Mu2e improves sensitivity in all New Physics scenarios

Effective mass scale reach up to 10^4 TeV, well beyond the direct reach of current or future colliders



Loop-dominated



Contact-dominated

These "golden" search channels provide complementary sensitivity to new sources of cLFV since the relative rates depend on the details of the underlying new physics model. Thus, it is important to pursue a programme with experiments exploring all three μ → e cLFV transitions to maximize discovery potential, and, in the event of discovery, to help differentiate the various BSM models through a comparison of the rates.

The Fermilab Mu2e experiment

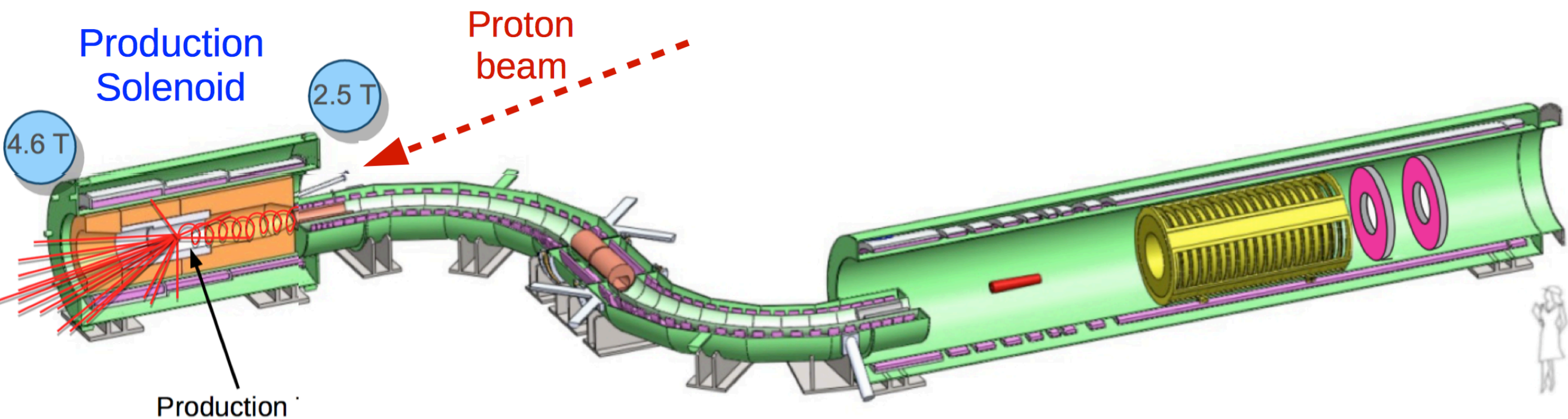
Scheduled to start after Muon g-2, currently in construction phase

To achieve 4 orders of magnitude improvement, Mu2e must:

- Create world's most intense muon beam
- Identify 105 MeV electron with high precision
- Suppress all possible backgrounds

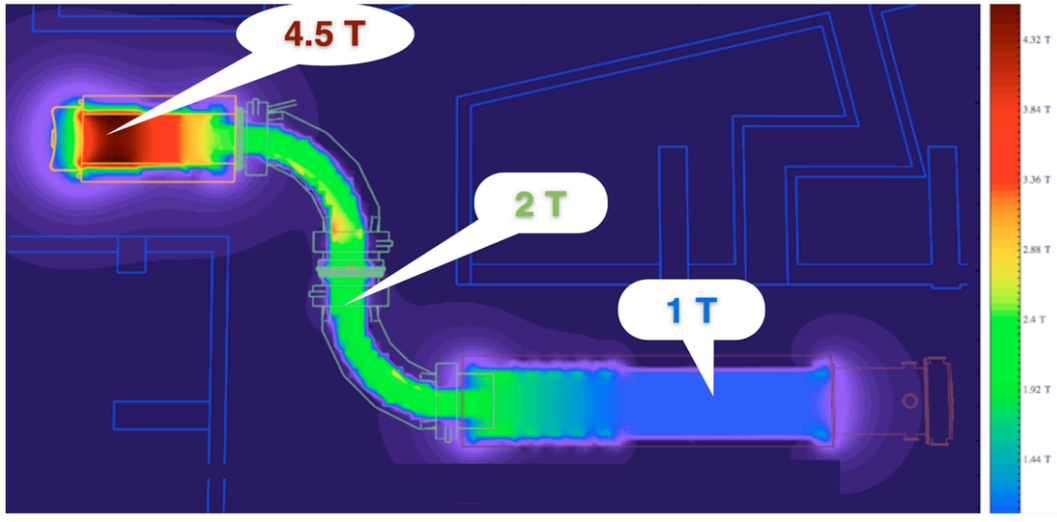
Mu2e solenoids: Production

Creating world's most intense muon beam



System of 3 functional solenoid units

- x10^4 improvement in μ production per p



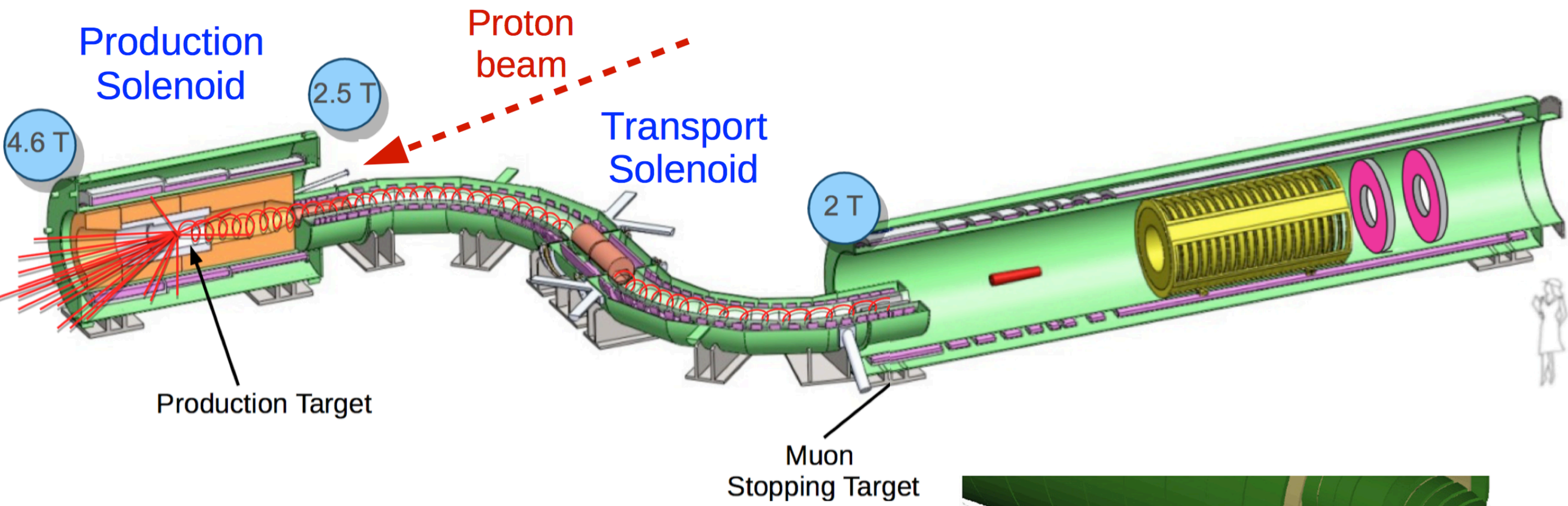
Production solenoid:

8GeV pulsed beam, 1.7 μs between pulses

~7×10^{12} protons/s on tungsten production target

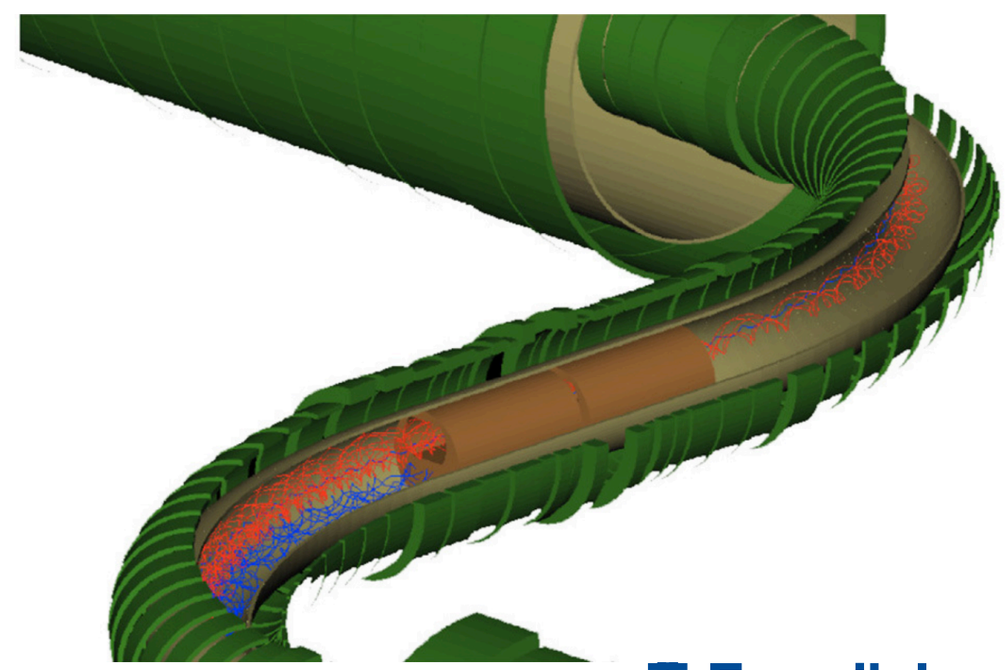
Mu2e solenoids: Transport

Creating world's most intense muon beam



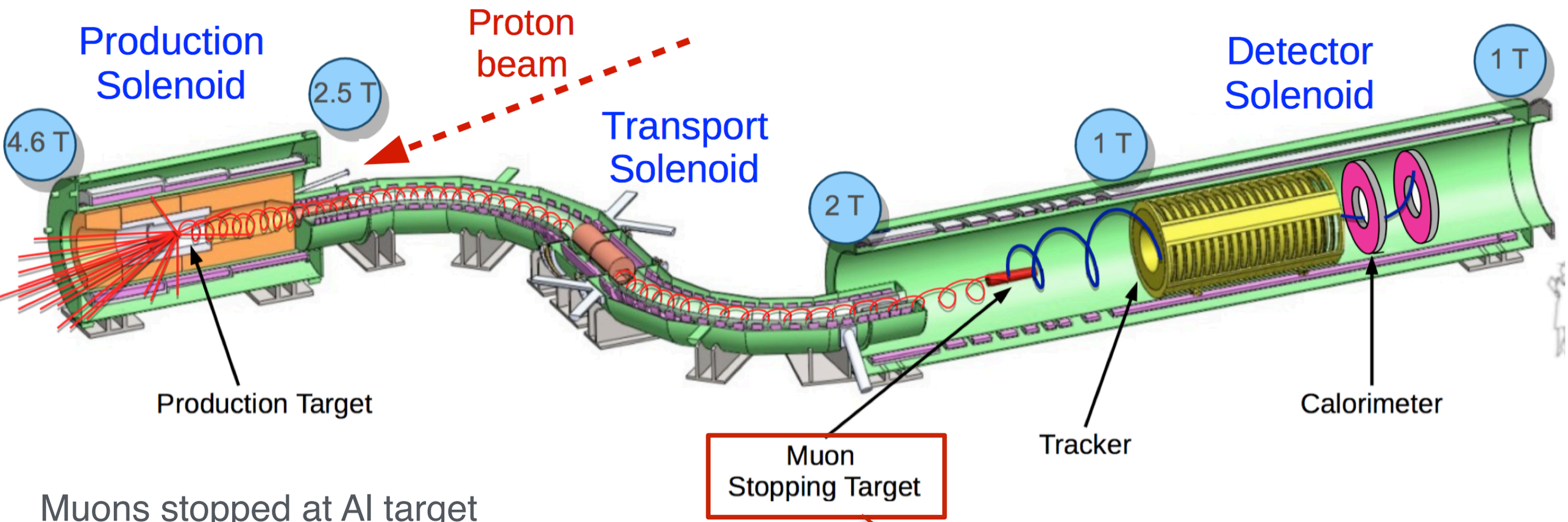
S-shape solenoid eliminates line-of sight backgrounds.

Curvature drift and collimators select sign and momentum of muon beam, transport to stopping target.



Mu2e solenoids: Detector

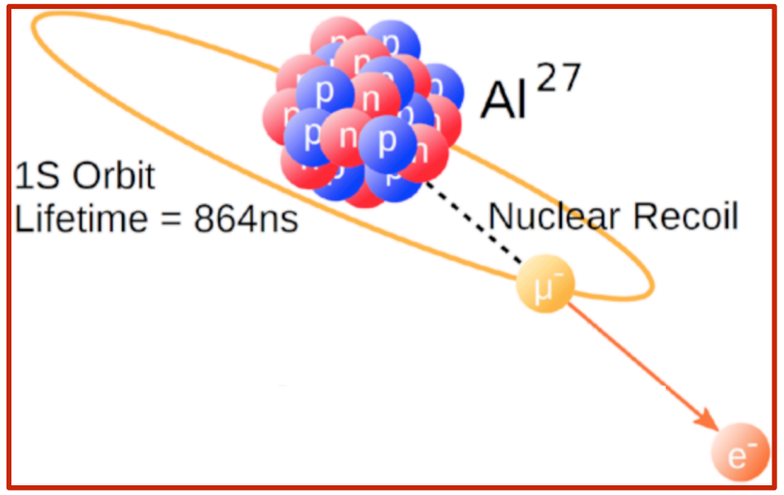
Creating world's most intense muon beam



Muons stopped at Al target

10^{10} stopped μ/s, ~10^{18} total over 3 years

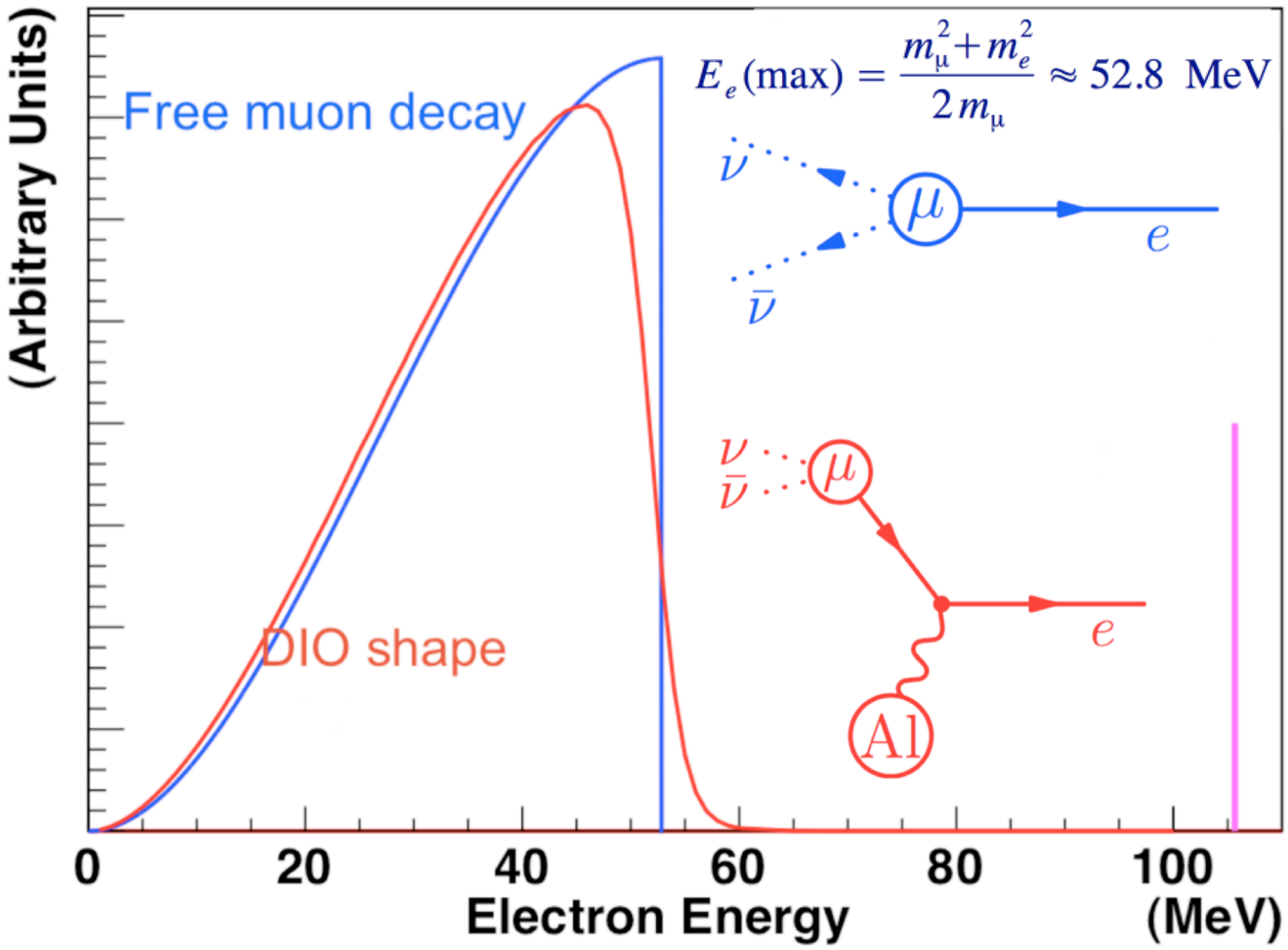
→ World's most intense muon beam



Detector system must identify and reconstruct a 105 MeV conversion electron, while rejecting backgrounds from conventional processes

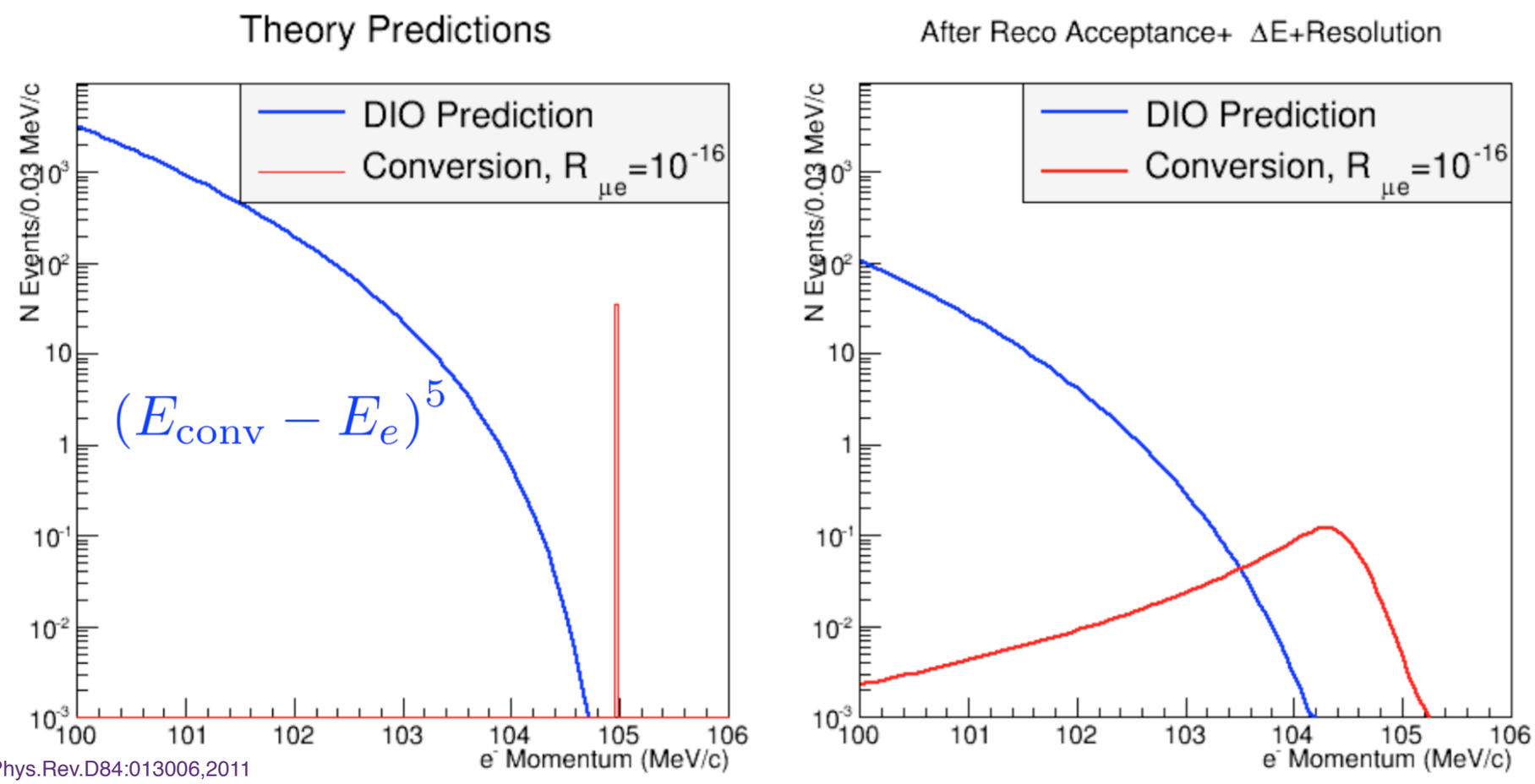
Background process: Decay-in-Orbit (DIO)

Michel spectrum of Ee after free muon decay, or modified in field of nucleus



Conversion electron energy far from Michel peak

Background process: DIO



Czarnecki et al., Phys.Rev.D84:013006,2011
Szafron and Czarnecki, 10.1103/PhysRevD.94.051301

Nuclear modification pushes DIO spectrum near conversion electron energy

Overlap after energy loss in material and detector resolution

DIO electron only differs from signal through its momentum

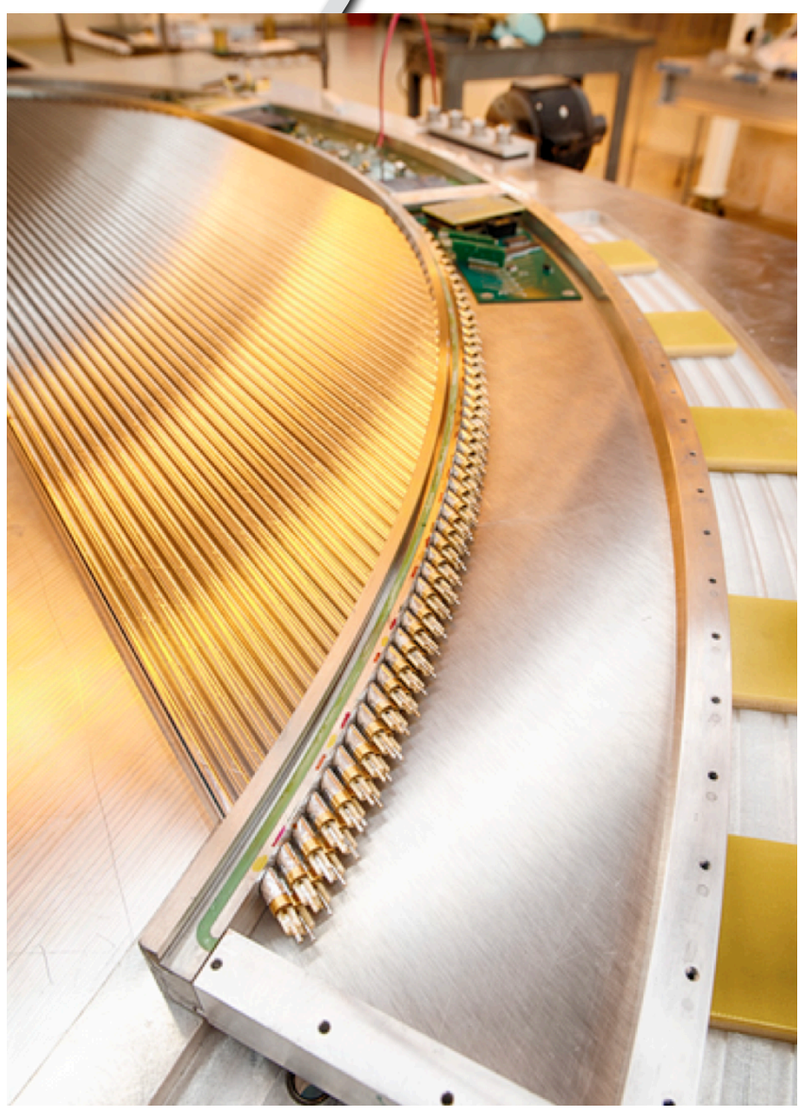
→ Low-mass detector with good resolution needed

Straw tracker

5mm diameter straw drift tubes

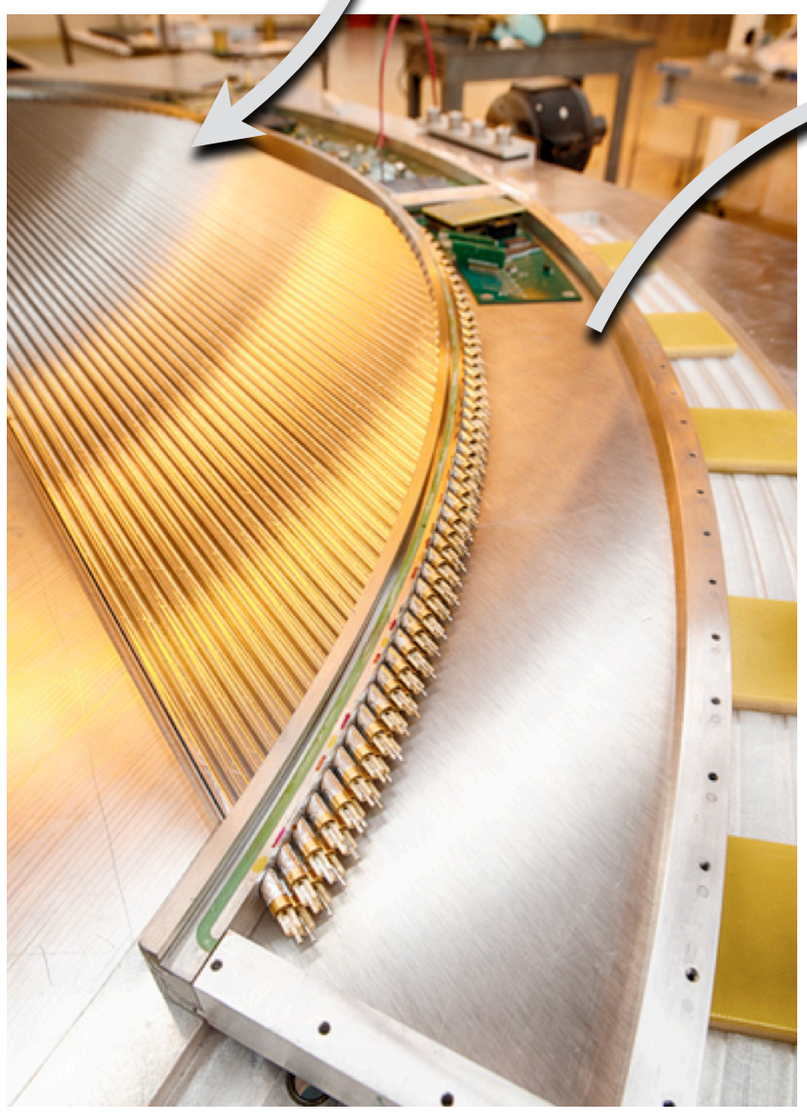
Ultra low mass, minimize multiple scattering and E-loss

Same construction as g-2 straws, just longer



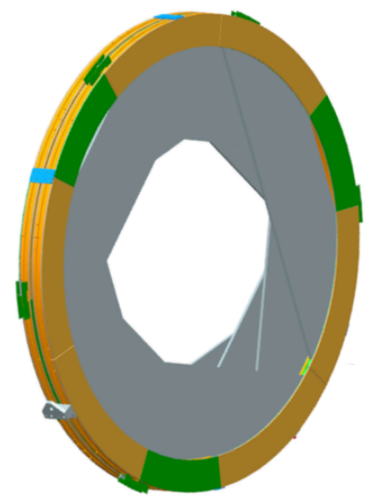
120° panel of 2x48 straws, two staggered layers

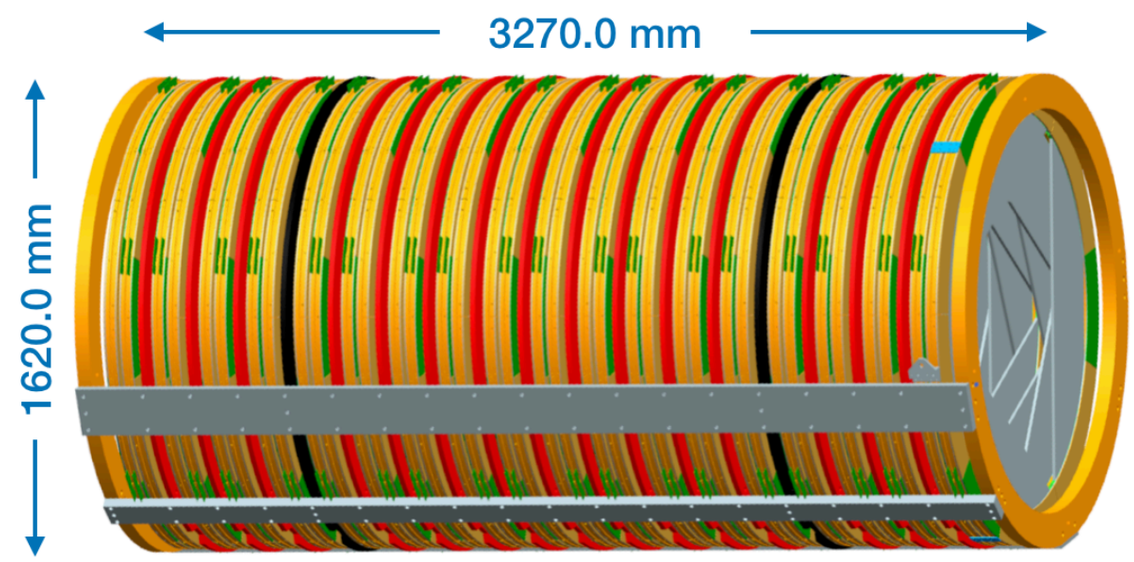
Straw tracker



3 panels for 360° ring

Repeating in successive staggered planes for optimal trajectory reconstruction

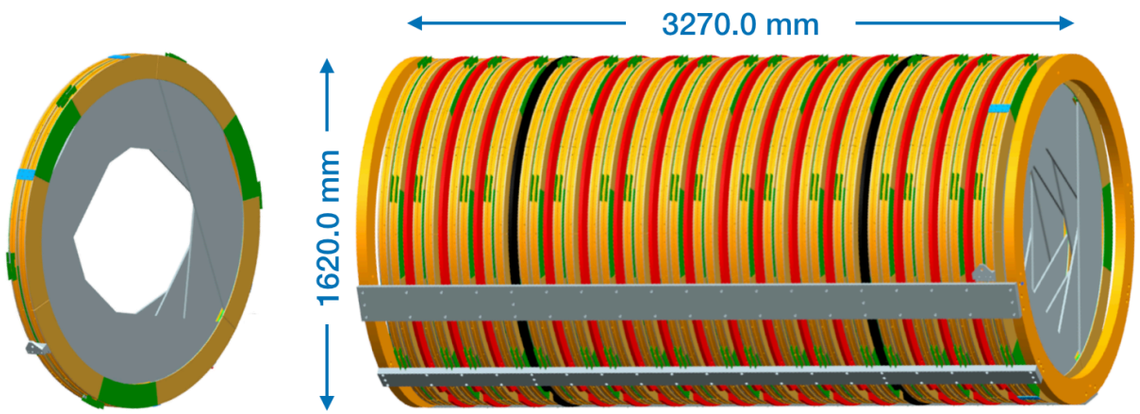


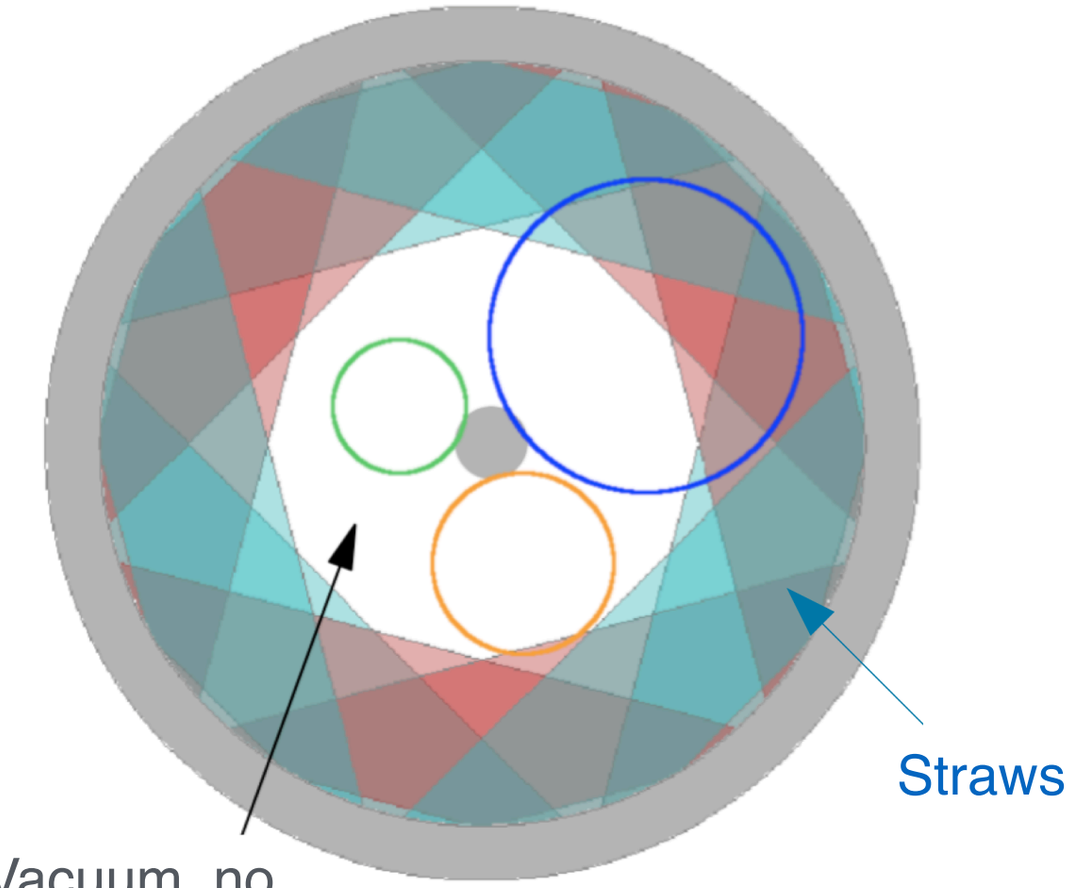


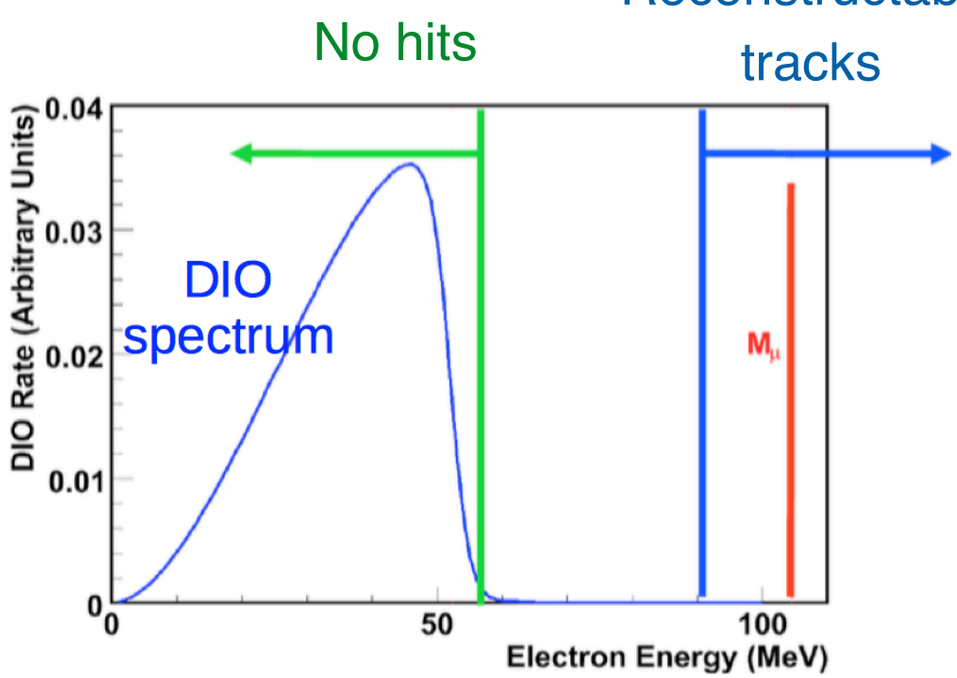
21,000 straws over ~3.3m → high segmentation

Resolution <180 keV @ 105 MeV , <0.18%

Straw tracker





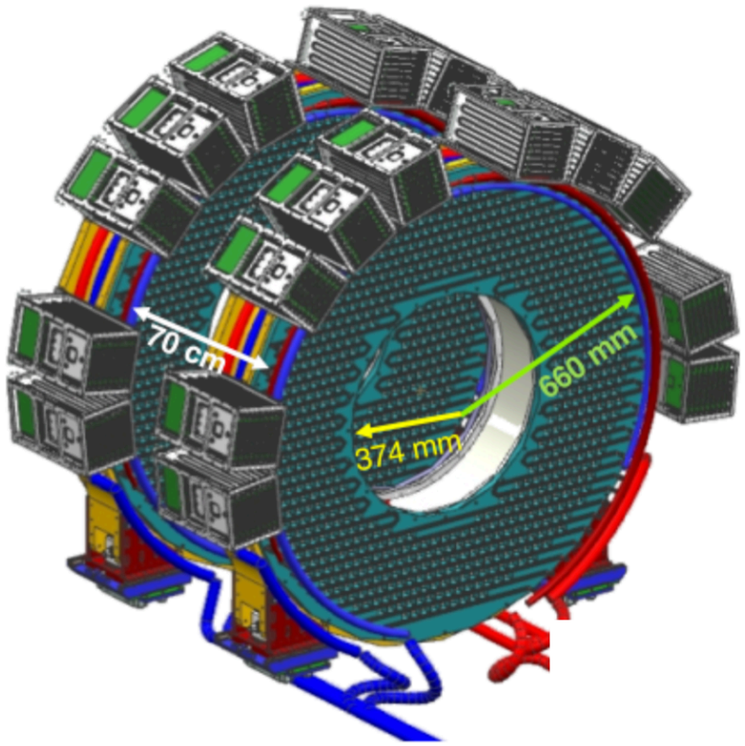


Hole-in-center annular design

Tracker is blind to nearly all DIO spectrum

Only e^- with p_T>~90 MeV have reconstructable tracks

Calorimeter



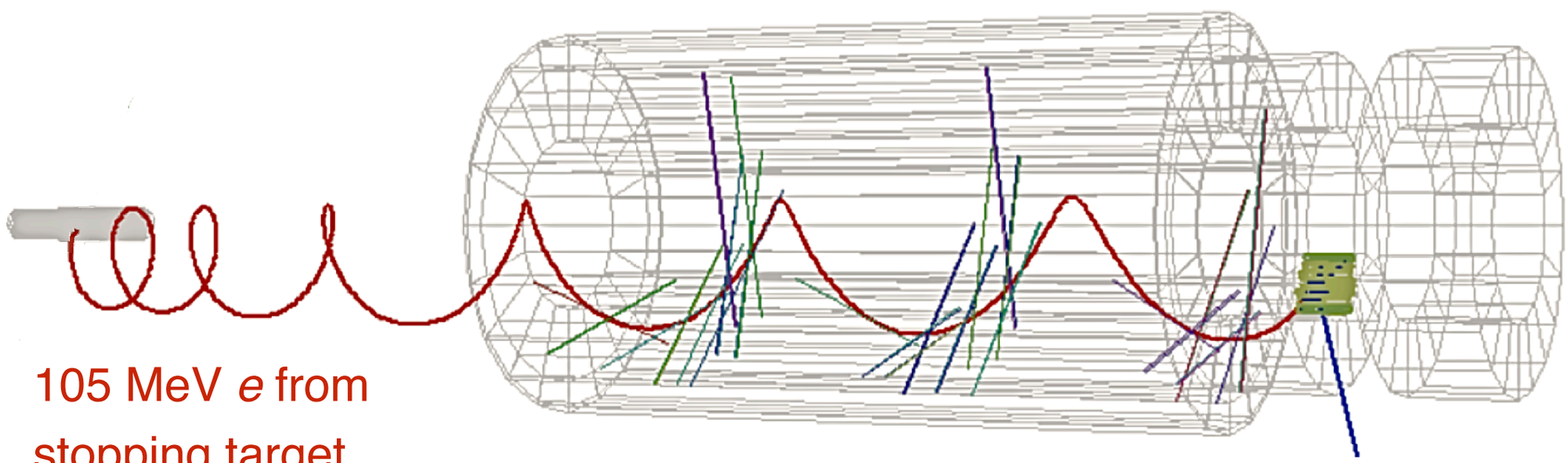
Tracker followed by calorimeter

~1,350 CsI crystals arranged in two disks

Redundant *E*, *t*, position measurement to tracker

Calorimeter information can be combined with tracker

- Remove backgrounds, guard against mis-reconstruction

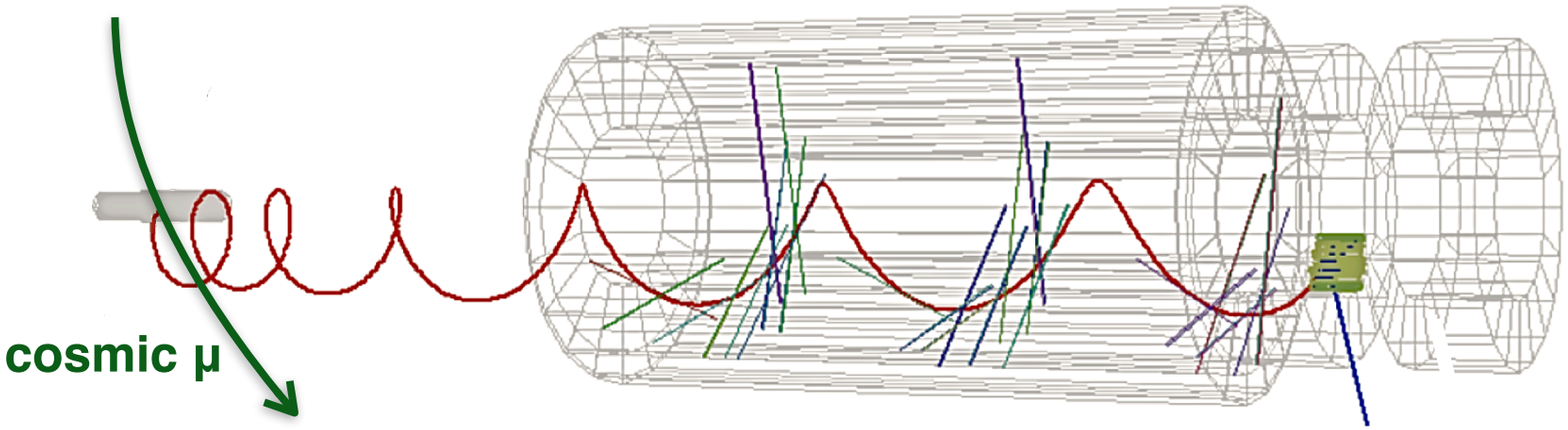


105 MeV *e* from stopping target

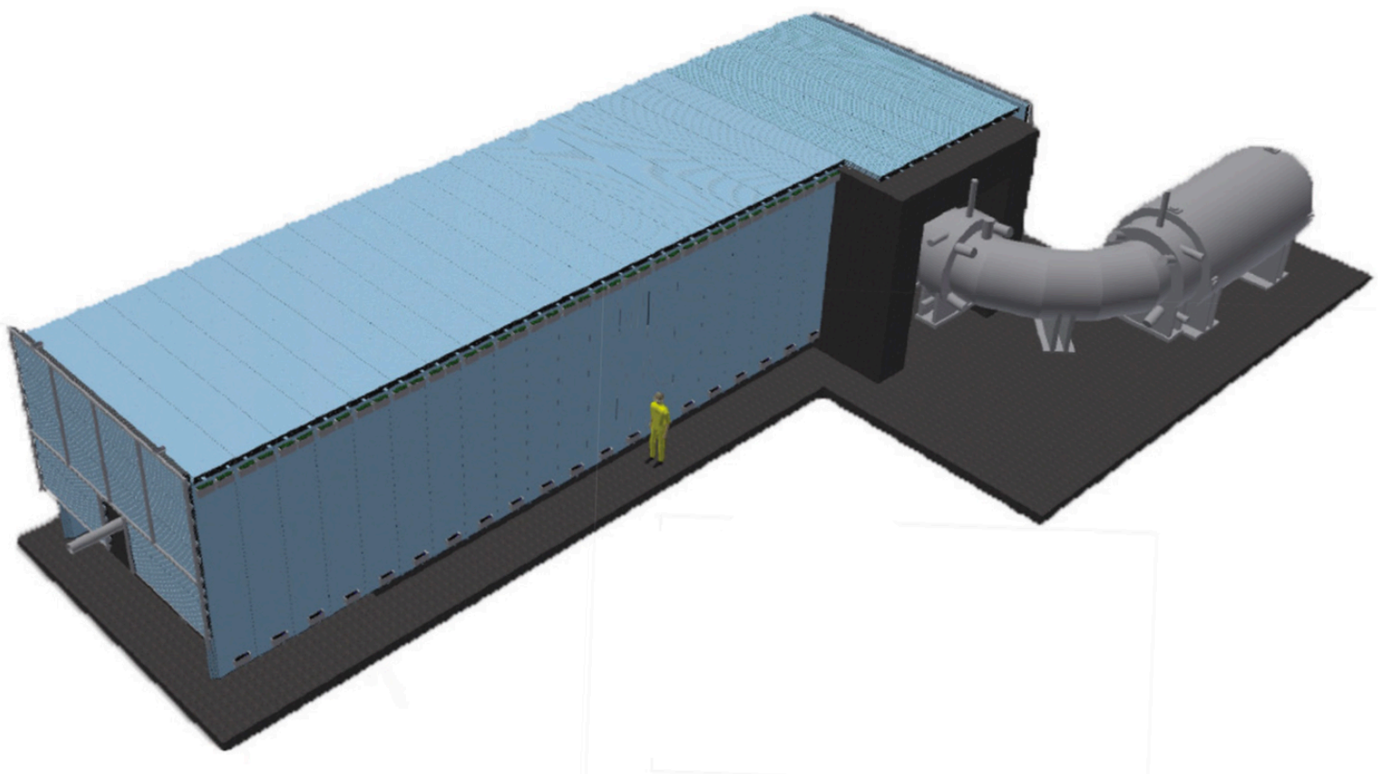
Tracker straw hits

Calorimeter hit

Cosmic backgrounds



105 MeV *e* could have been generated from cosmic event!

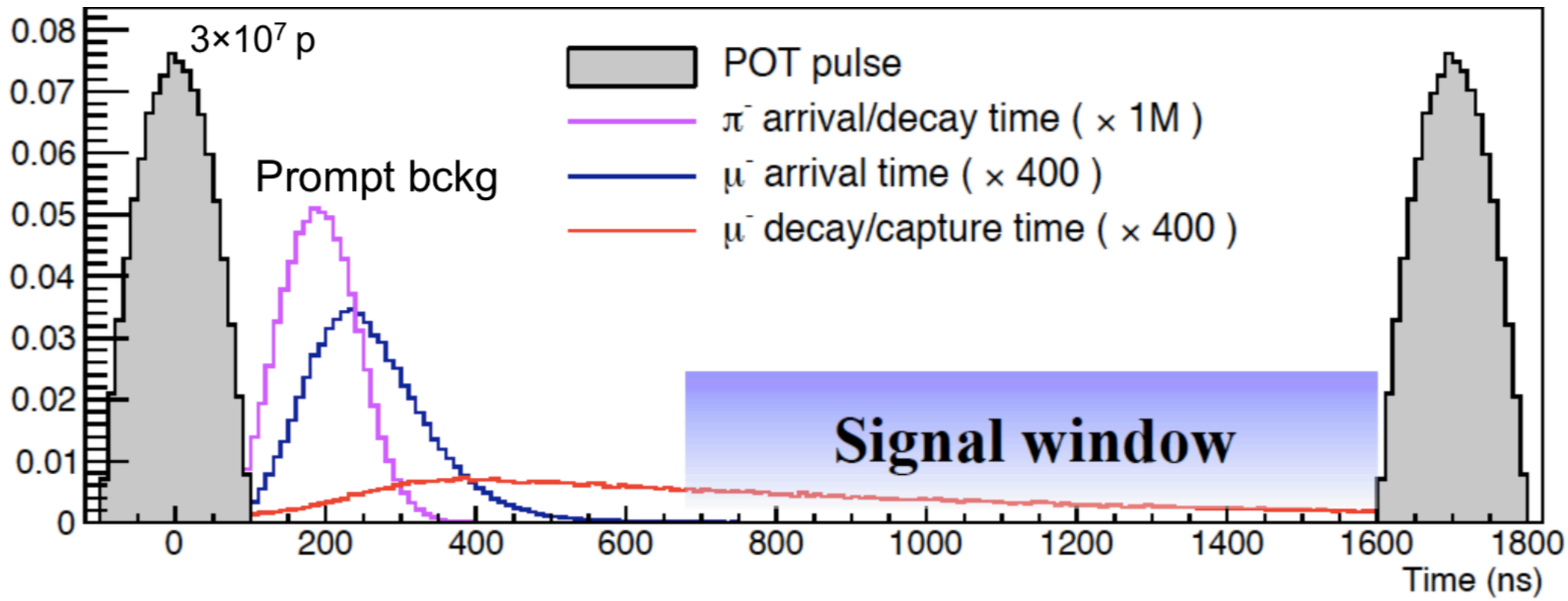


Cosmic ray veto system encases PS and downstream TS

4 stacked layers of extruded polystyrene

99.99% efficiency requirement

Mu2e time structure



Several prompt background sources could give 105 MeV *e*

Characteristic: pion lifetime 26 ns

Example:

Radiative pion capture

$$\pi^- N \rightarrow \gamma N$$

$$\gamma \rightarrow e^- e^+$$

Concept: Simply wait for prompt bkgds to decay

- Delayed signal window by 700 ns
- Proton pulse period 1695 ns
- Muonic Al lifetime 864 ns

Time structure eliminates prompt backgrounds

Background budget

Expected total number of background events from each source, over entire Mu2e:

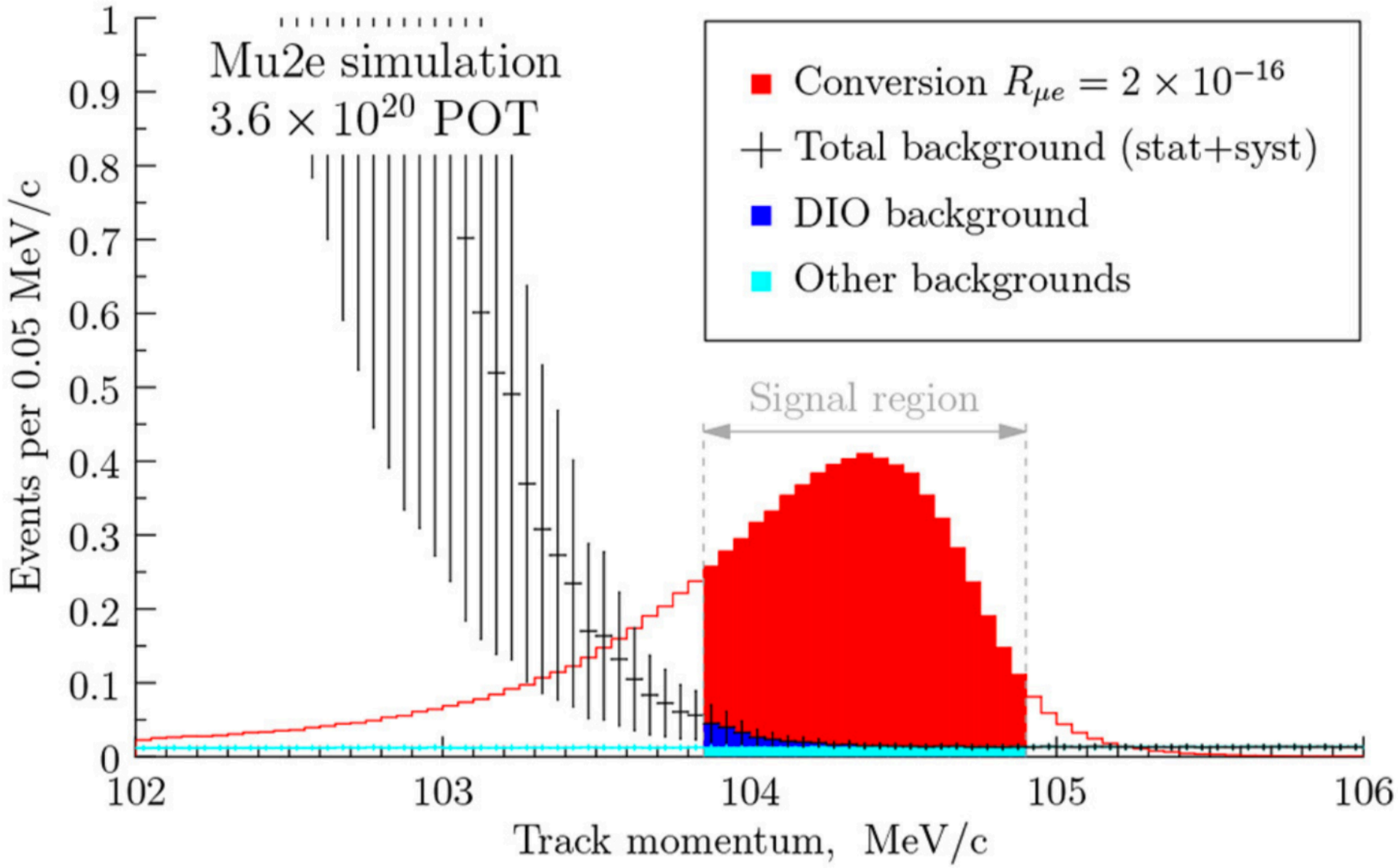
3 years at 1.2×10^{20} protons/year (8 kW beam power)

Background process		Expected events
Cosmic ray muons		$0.21 \pm 0.02 \pm 0.055$
Intrinsic	DIO	$0.14 \pm 0.03 \pm 0.11$
	RMC	$0.000^{+0.004}_{-0.000}$
Prompt, late-arriving	RPC	$0.021 \pm 0.001 \pm 0.002$
	Muon DIF	< 0.003
	Pion DIF	$0.001 \pm < 0.001$
	Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Antiproton-induced		$0.04 \pm 0.001 \pm 0.02$
Total		**0.41 ± 0.03 (stat+syst)**

Expect <0.5 background event in 3 years

Any observation will be strong evidence for CLFV

Signal sensitivity



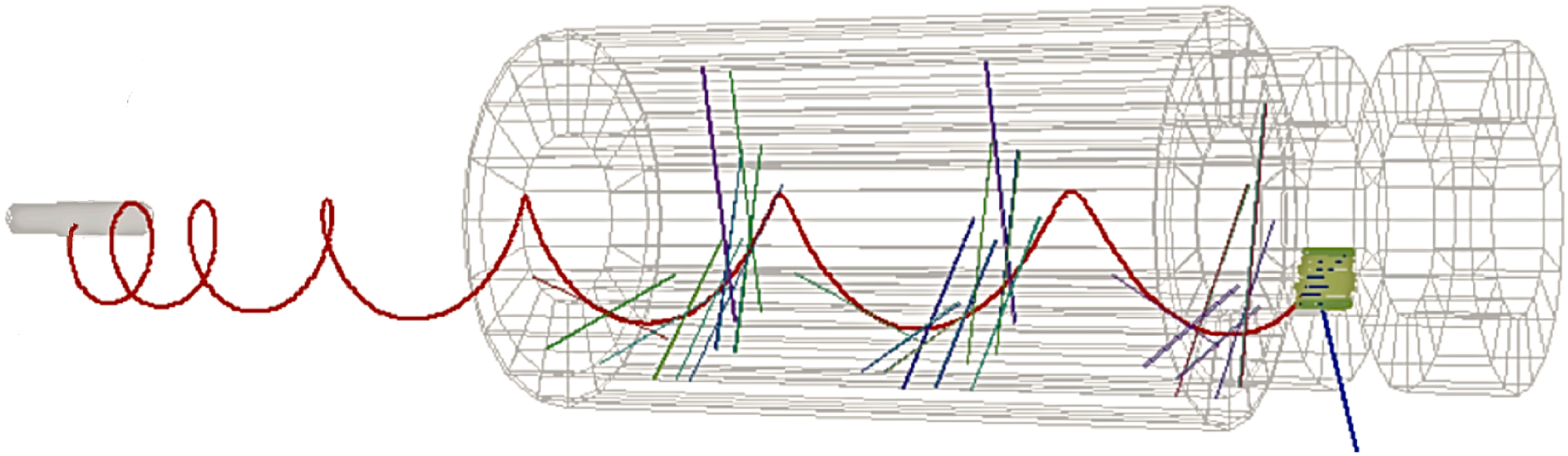
Expectation of 7.5 events in signal window against 0.41 bkgd events:

5σ discovery sensitivity at $R_{\mu e}=2\times10^{-16}$

- *orders of magnitude beyond currently constrained*
- Single-event sensitivity at $R_{\mu e}=3\times10^{-17}$

→ Real discovery potential

Lepton number violation search



Tracker straw hits

Calorimeter hit

Note charge symmetry of detector

Reconstruction of e^+ as well as e^-

Allows Lepton Number Violation search $\mu^- N \rightarrow e^+ N'$ with $\Delta Z = 2$

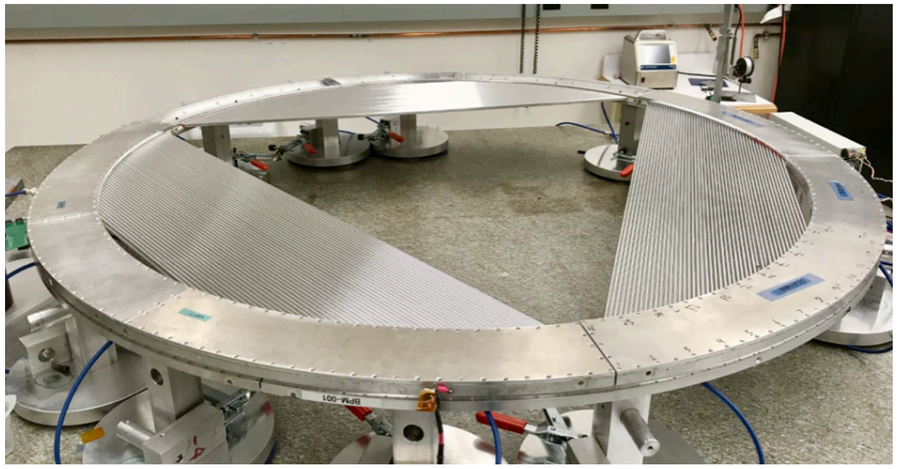
Guaranteed to occur if Majorana neutrino

Complementary measurement to $0\nu\beta\beta$

Status

All solenoids and sub-systems currently under construction

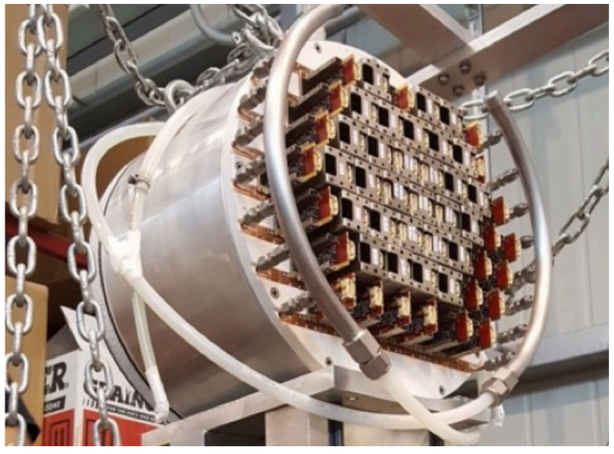
- Several components successfully prototyped, or already delivered and being tested



Tracker panel prototypes

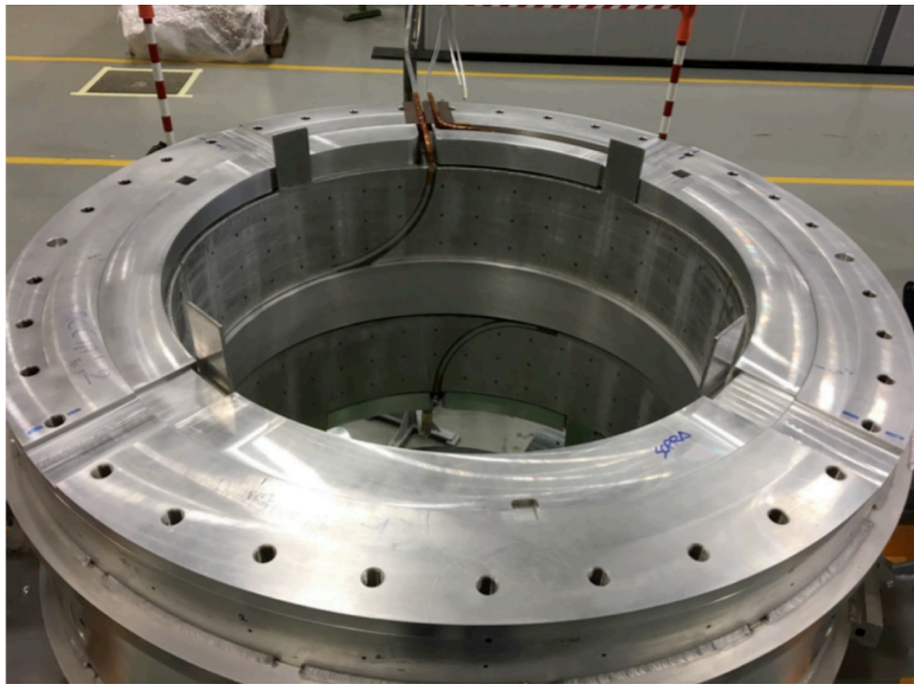
Solenoids are schedule driver

Commissioning expected in 2022



Calo prototype

CRV module

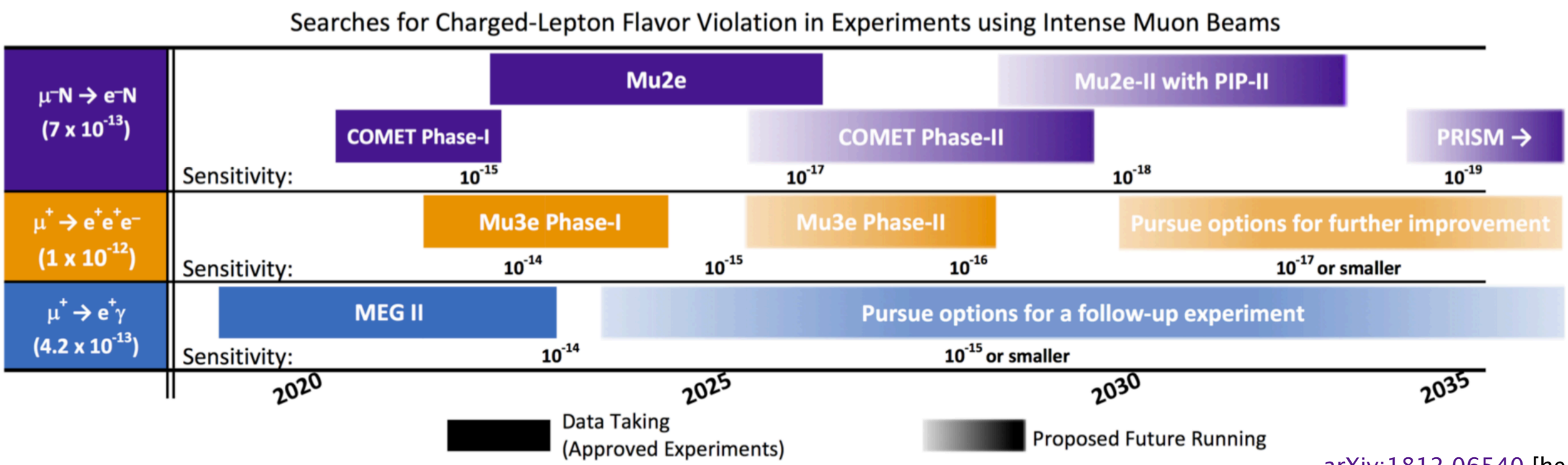


TS coil module

Outlook - CLFV

Our sensitivity to CLFV will improve by orders of magnitude in next few years

- MEG-II, Mu3e-I, COMET-I, Mu2e

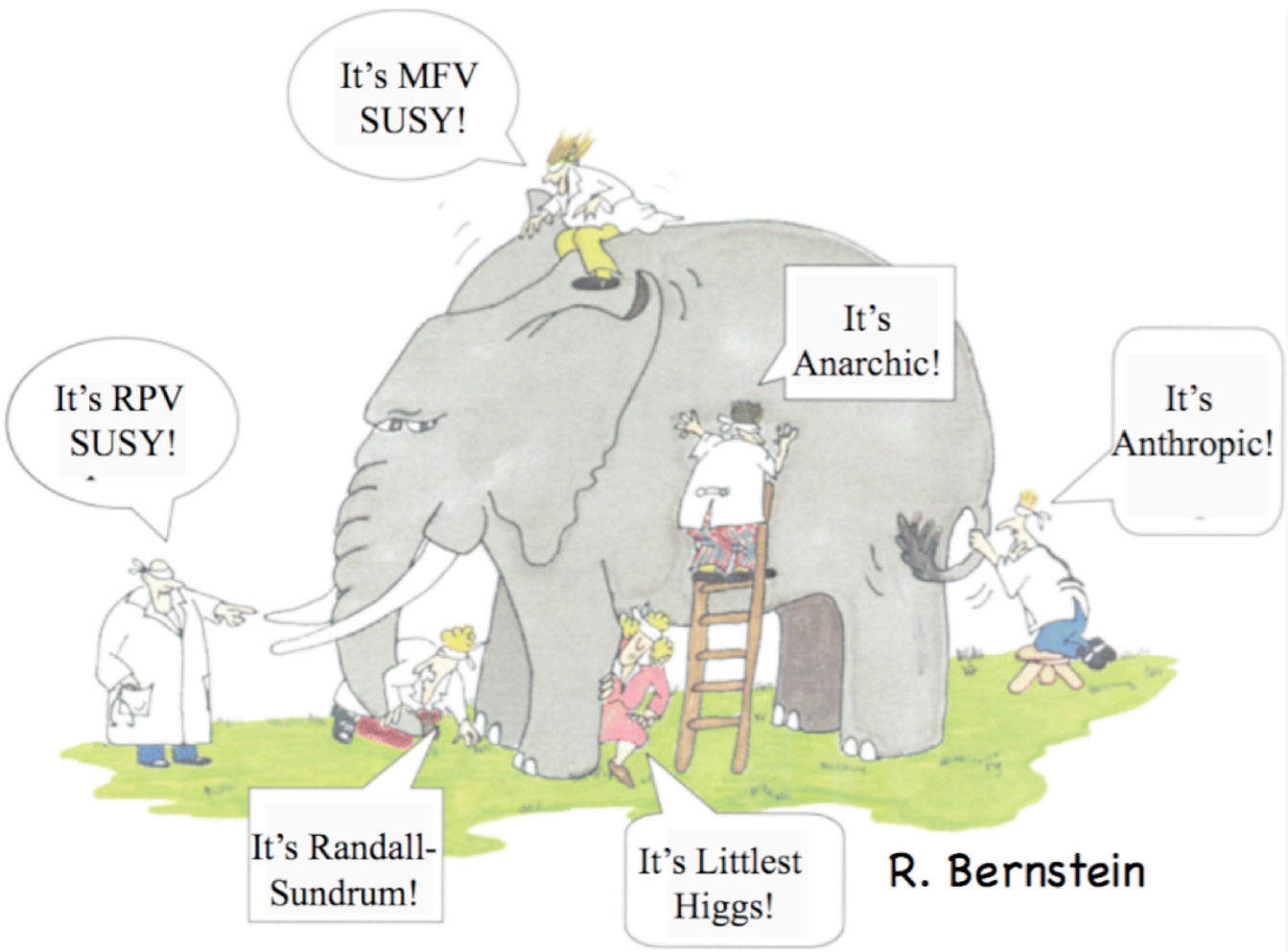


arXiv:1812.06540 [hep-ex]

A very well motivated set of searches with real discovery potential

Outlook

What if g-2 or Mu2e observes a signal?



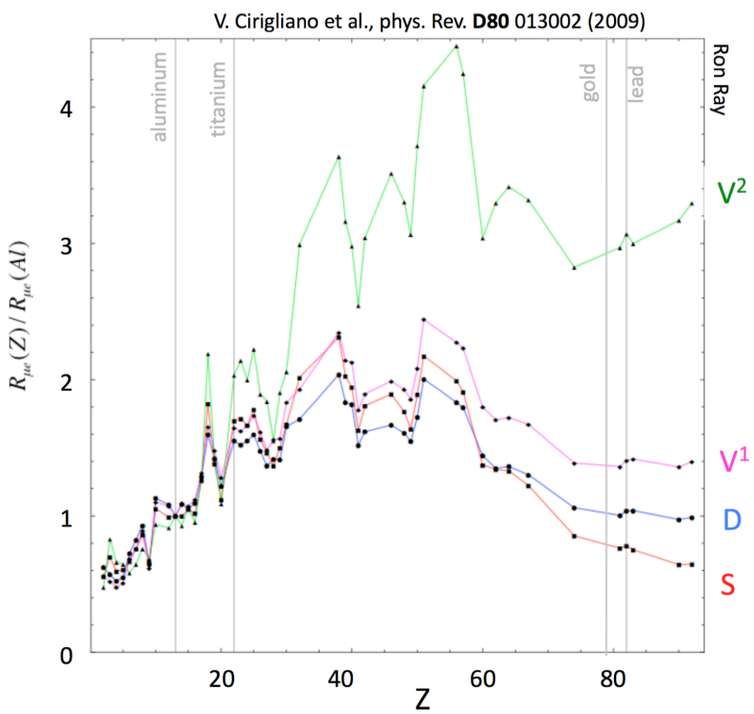
- Hugely important input for BSM
- But limited information on exact nature of New Physics

- Complementary input and more sensitive future searches needed
  - Complementarity with other CLFV, neutrino programme, …

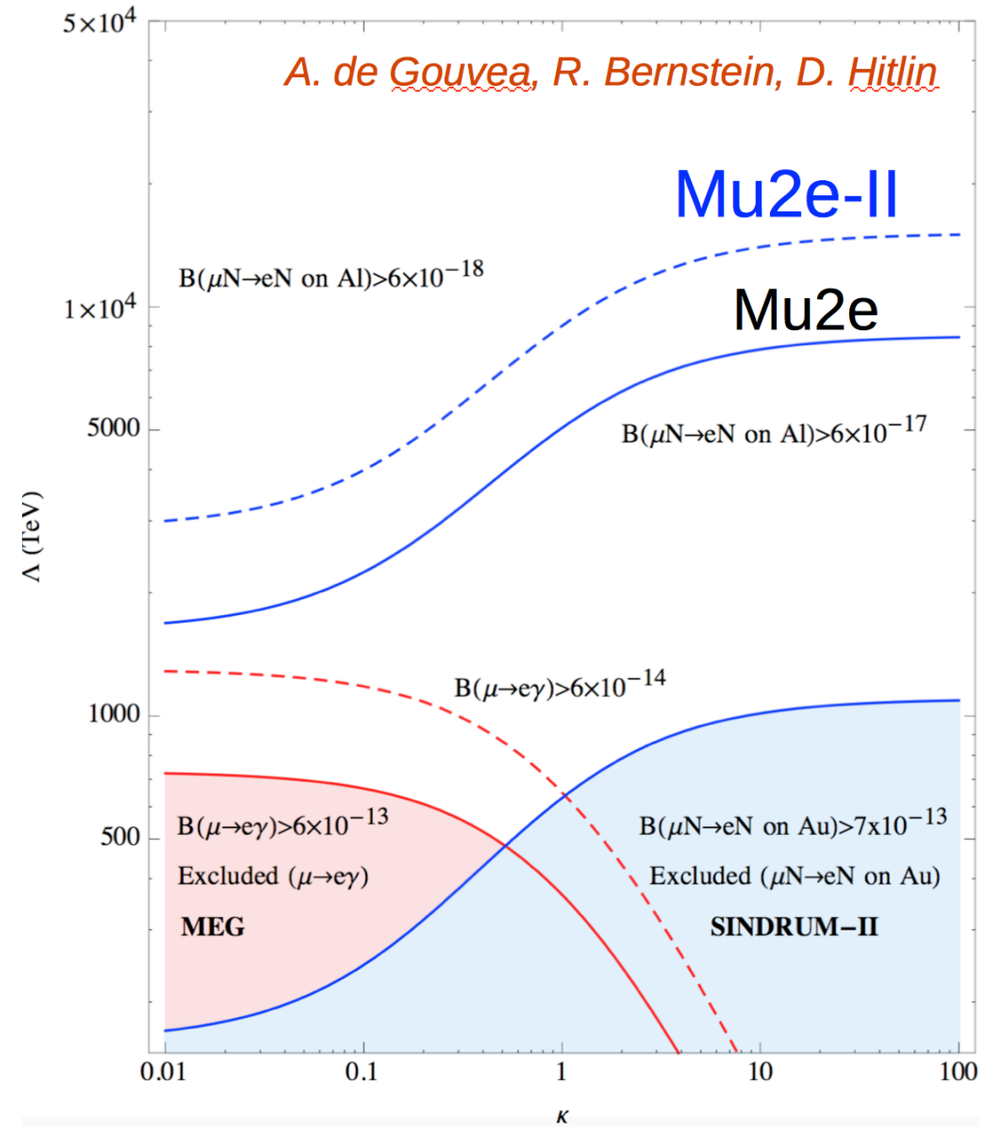
Future precision searches at Fermilab

Mu2e-II, evolution to Mu2e

- improving sensitivity by extra order of magnitude
- Most sensitive CLFV probe for foreseeable future
- Powerful in any scenario, PAC-endorsed



Model discrimination on underlying physics by comparing CLFV rates on different stopping targets, channels



Several other ideas for PIP-II -era precision science

- Storage ring EDMs
- Future CLFV all-channels, lepton flavor universality
- Fixed target Dark Matter search

Summary

Precision Muon Physics:

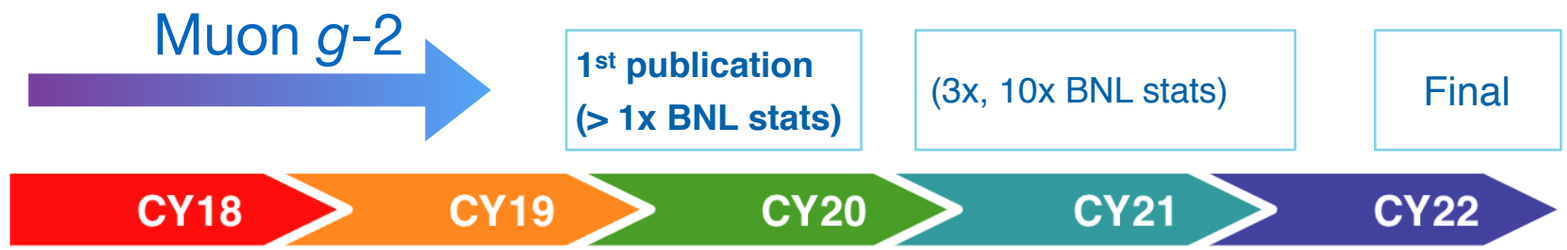
A powerful tool with unique advantages

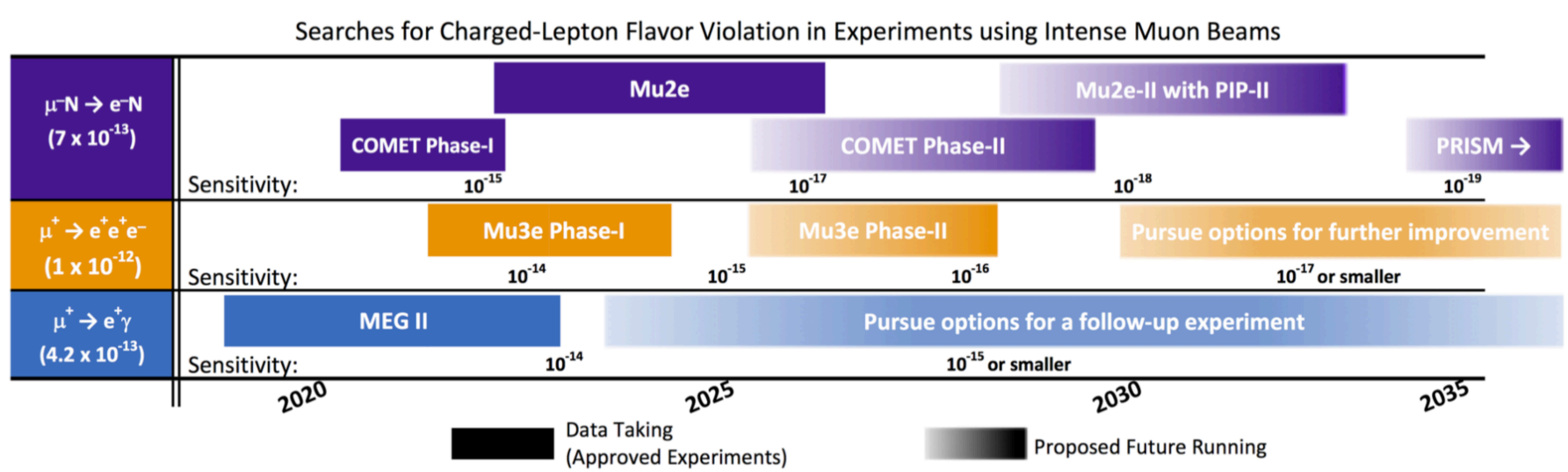
Fermilab a global leader

Muon g-2, Mu2e: two of the most sensitive tests to SM

Landmark results expected soon, and over next years

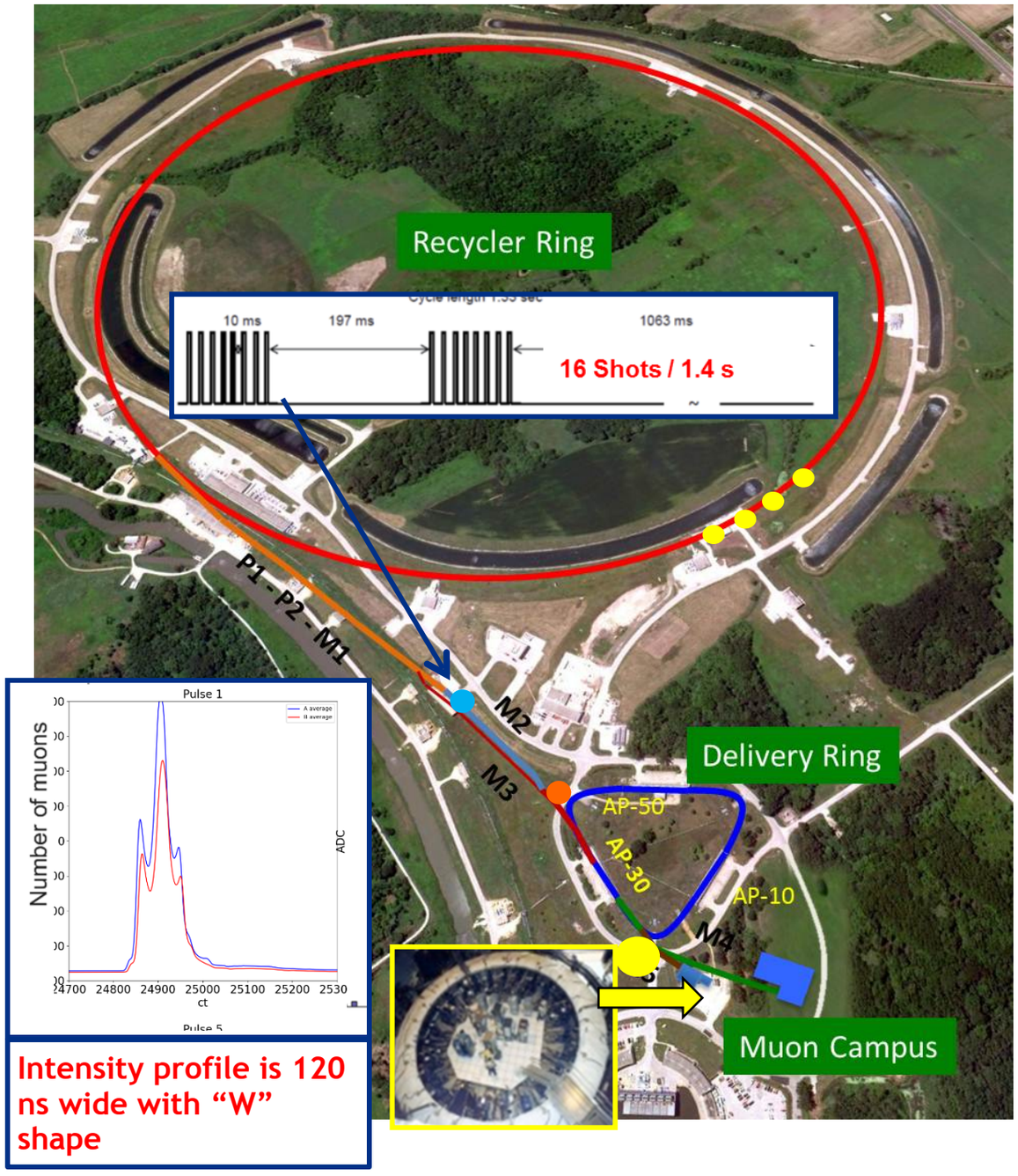
Stay tuned!





Extra slides

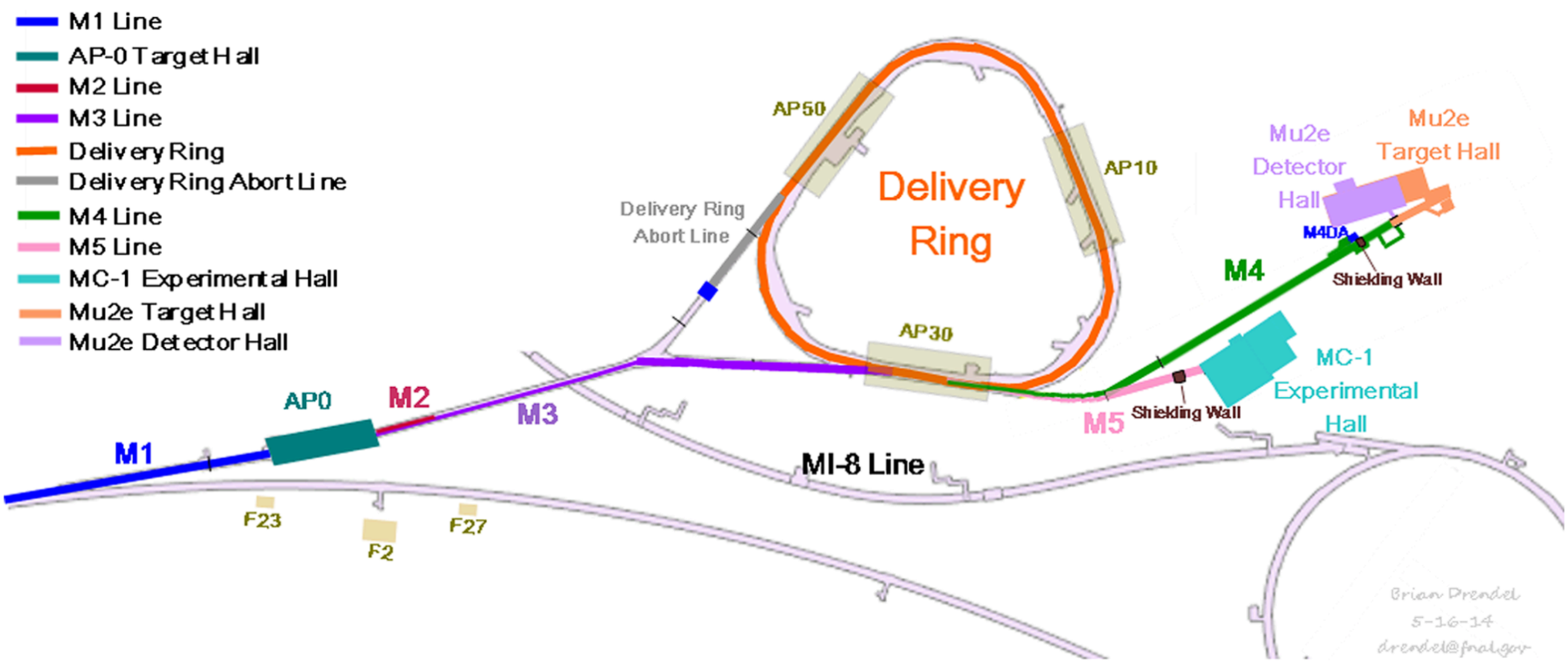
g-2 Fermilab beam



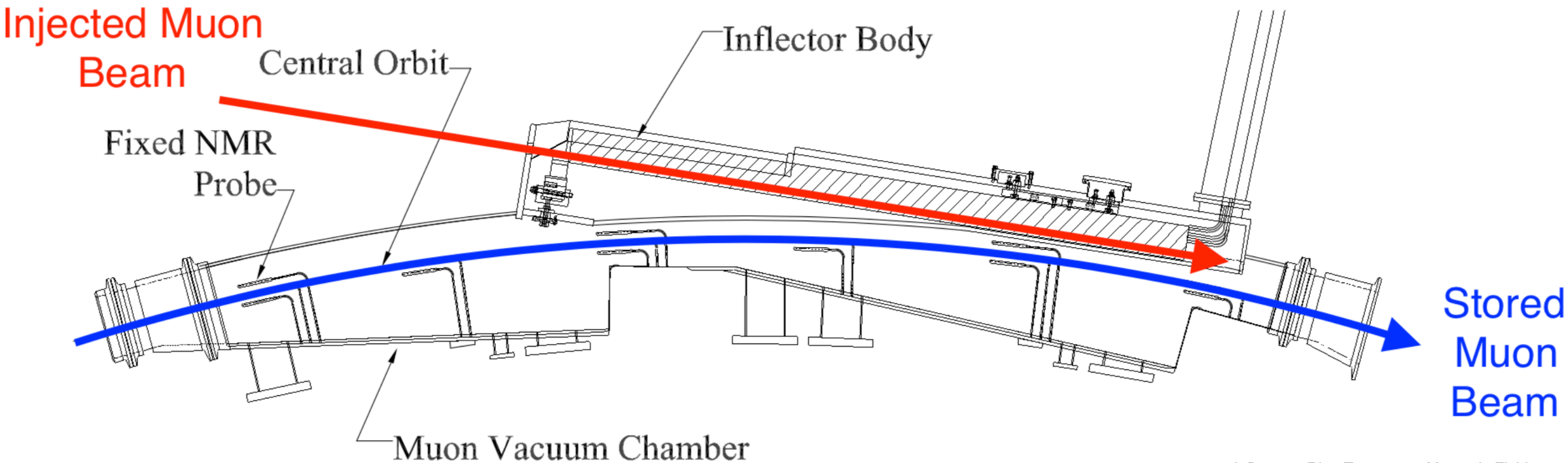
Creating the Muon Beam for g-2

- 8 GeV protons
- Divide in 4 bunches
- Extract each to strike target
- Magnetic lenses collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters Delivery ring - protons get kicked out; pions decay away
- **And only muons enter storage ring**

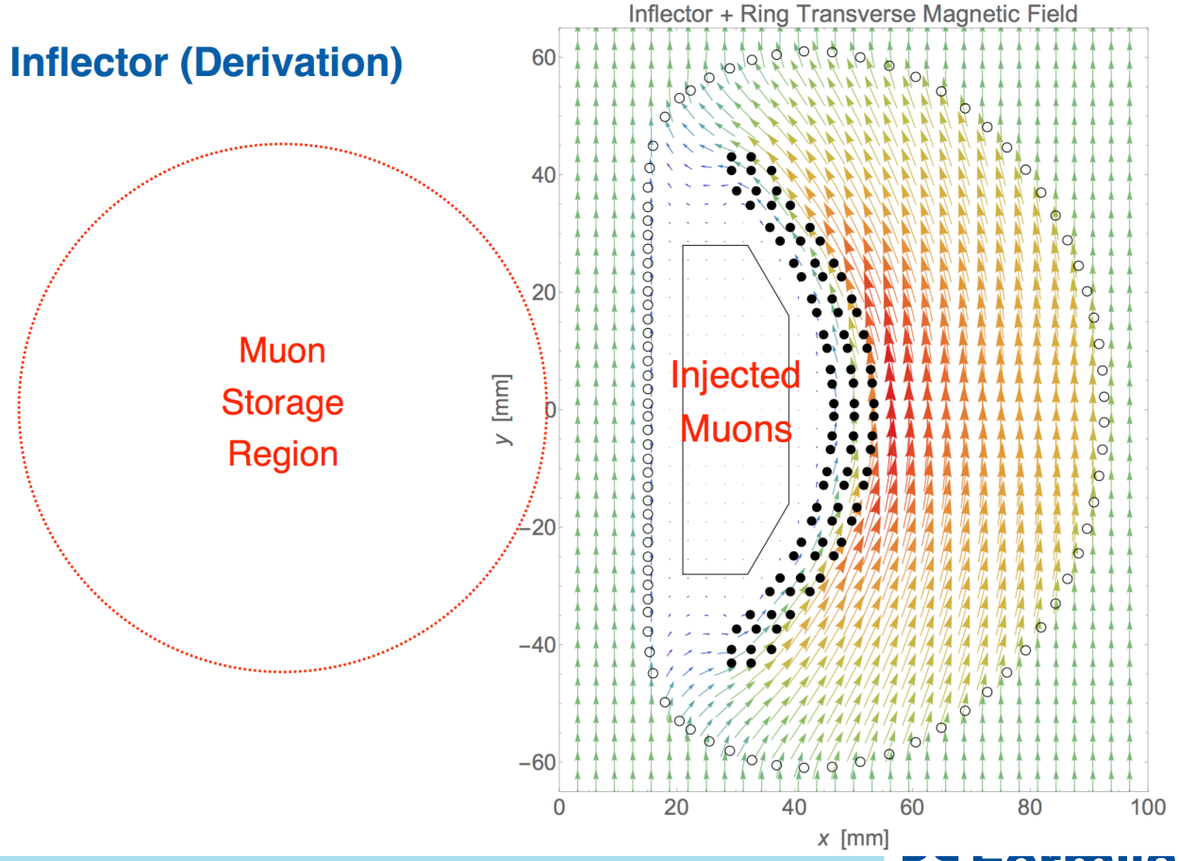
Beam to Muon Campus



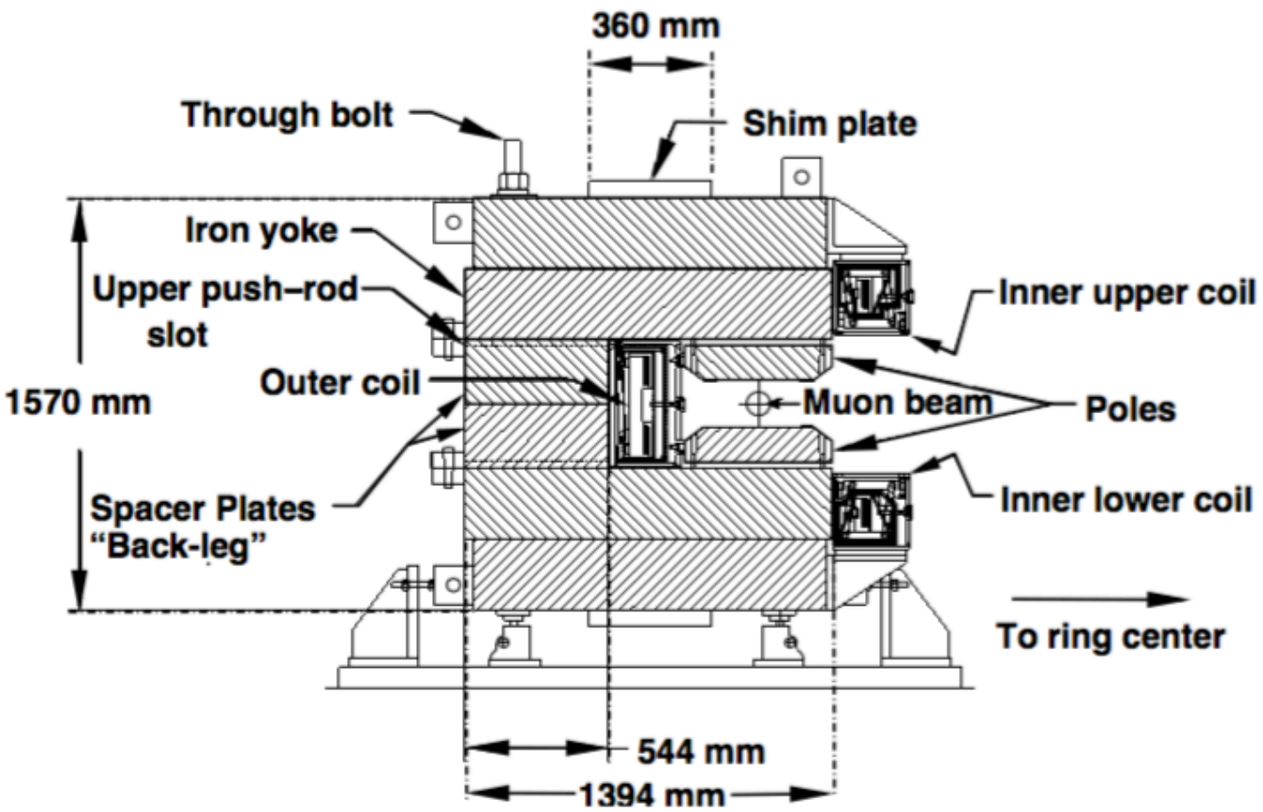
Inflector

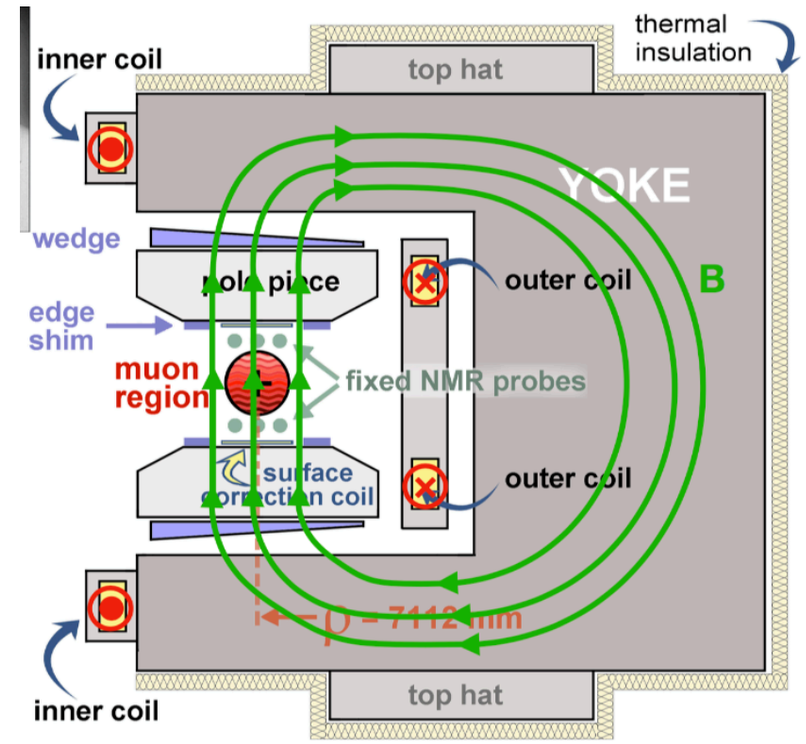


Inflector (Derivation)

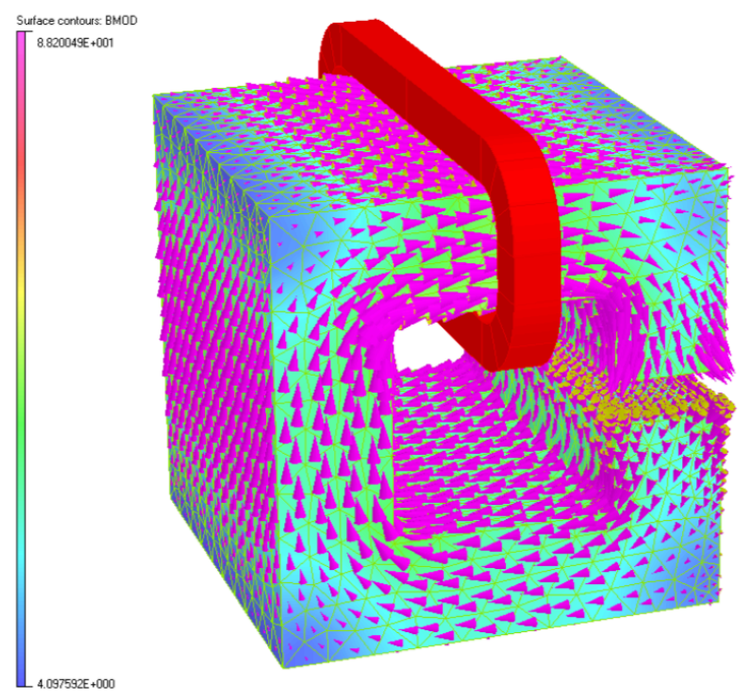


Storage ring field





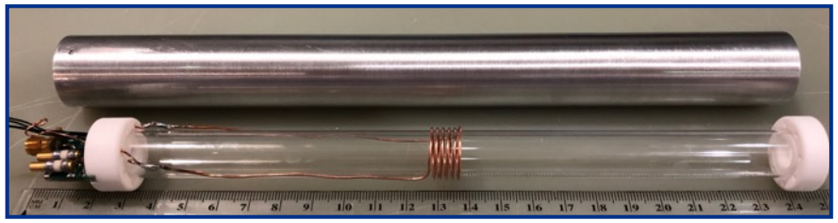
g-2 Magnet in Cross Section



Field

Absolute field calibration in great shape

- Same BNL H_2O probe, also used in LANL muonium hyperfine compared to our new probes
- We developed a new cylindrical plunging probe (smaller shape corrections)
- We developed a new He-3 standard probe (smaller corrections)
- We built a dedicate cross-calibration facility at ANL to make all tests under highly controlled conditions

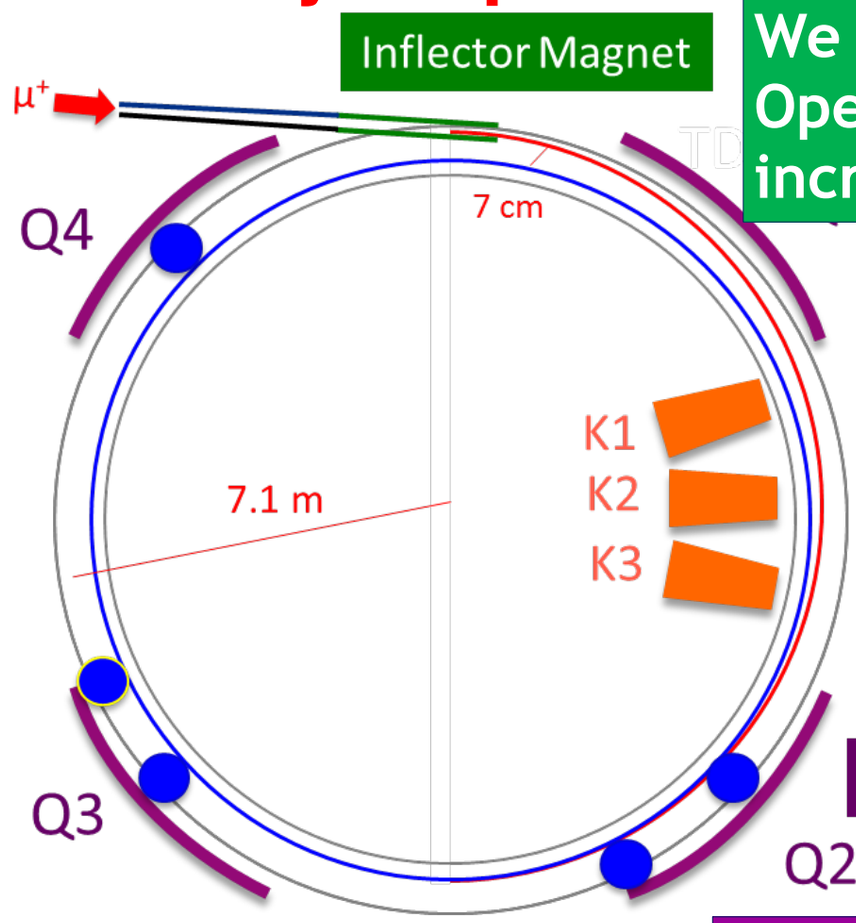


Cylindrical plunging probe

Developed He-3 as a new standard

3) There are also challenges:

Reminder of Injection and storage components because that's where we are not yet optimized



We would like to put in new Open Ended next summer to increase the Rate by 30%

We continue to improve this challenging system to increase Kick

radially centers beam

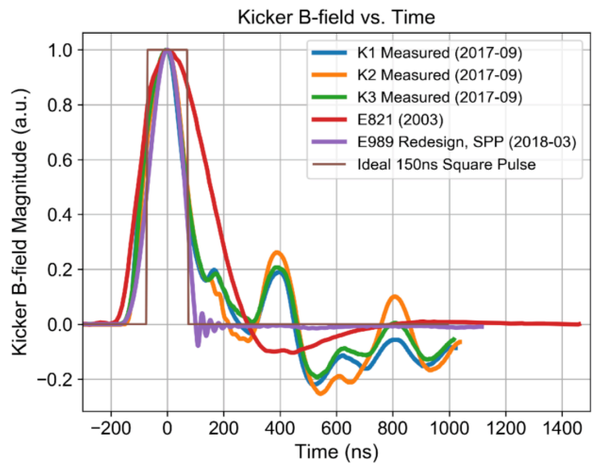
Focusing quadrupoles

15-28 kV

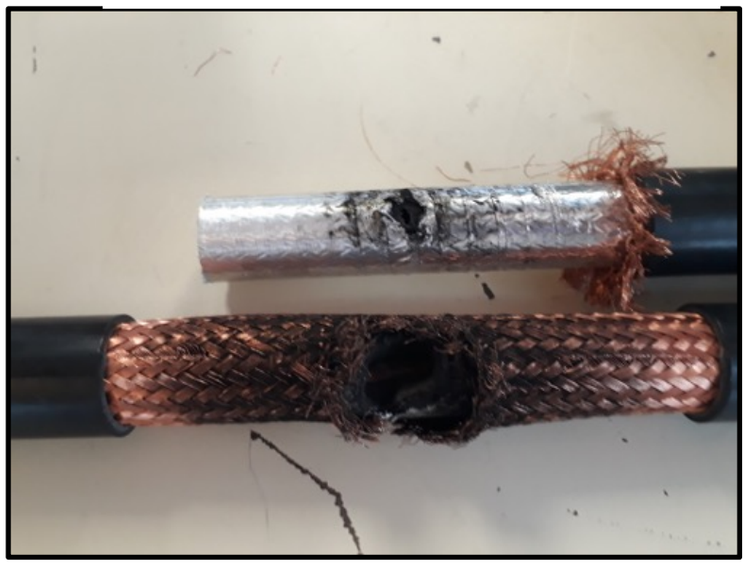
vertically focuses beam

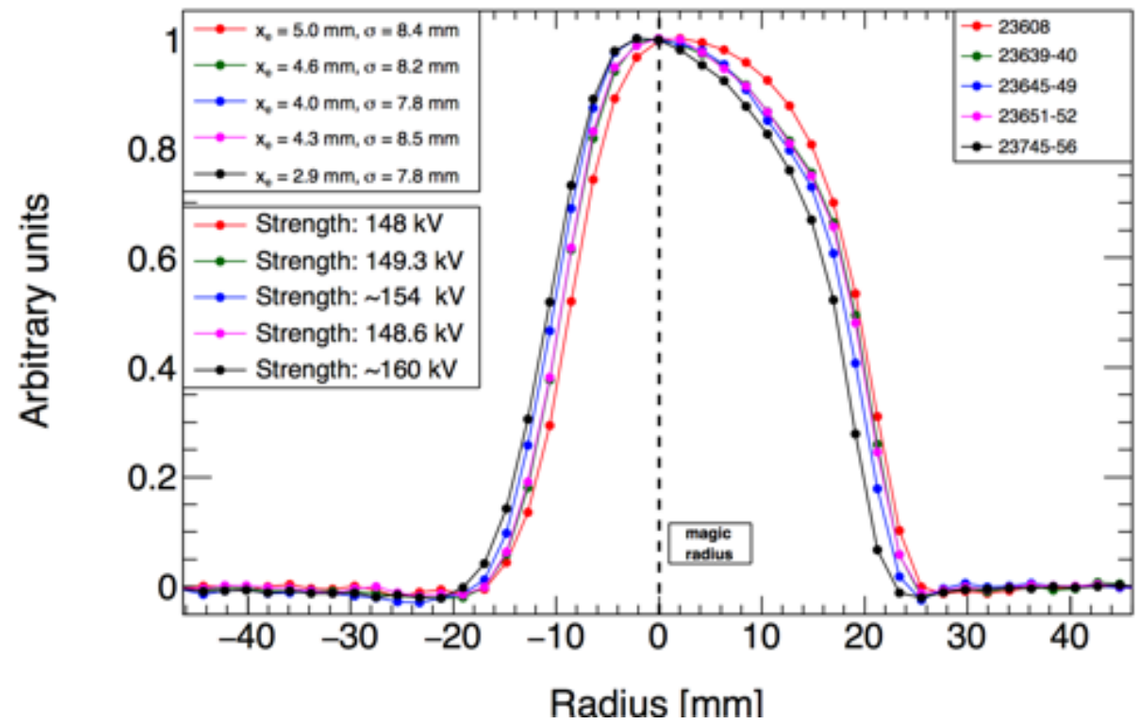
Working on increasing max Voltages and adding Novel RF system for scraping and CBO reduction

3X Kicker Pulse Shapes



The (magnetic) Kicker needs to create a ~11 mrad deflection of the incoming beam on the first turn, and then "get out of the way" before the beam returns. This is an engineering challenge that was never fully realized for BNL … and not yet for us.





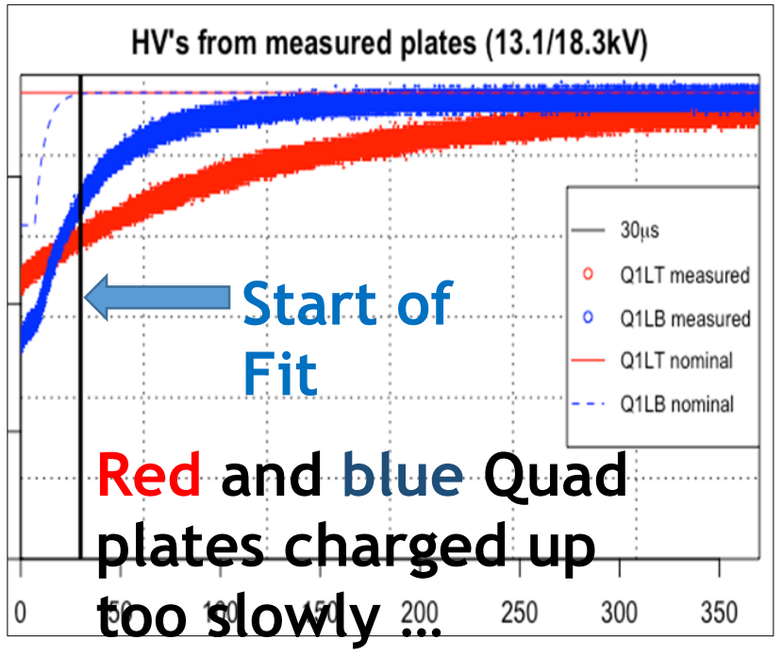
If the kicker voltage is set too high, current-carrying cables can burn so we had to back off a bit to avoid that.

These are distributions of the beam in the ±45 mm radial coordinate. It's well contained, but not quite centered. The colors represent different kick strengths

Important takeaway for now. We can live with this. We just don't like it

During Run-1, 2 of 32 HV resistors on the Quad plates were flawed. This meant they did not stabilize prior to “fit start time” and thus …

- **Vertical Muon distribution mean moves down by 0.6 mm**
  - We are investigating its impact on ω_a extraction
- **Muon Loss fraction ~10x greater than Run 2**
  - This can cause a “phase shift” if the lost muons have a different average phase compared to the non-lost muons.



EXAMPLE of how we approach determining the Muon Loss impact

1. **Determined Momentum-Phase correlation** in Stored Muon distribution from Simulation ***AND*** directly by a special measurement where we exaggerated the effect significantly. This is known well.
2. **Determined Muon Loss Fraction** in context of Precession fits. This is known well.
3. **Determining correlation** between Lost muons and their momentum. In progress.
   - We made a special systematic run to bias the momentum distributions high and low to test ML rate
   - Multiple beam storage simulation programs being tuned to study lost muon event momenta
4. In the end, we take **the most conservative information** to estimate the systematic.

(Remember, this was a Run-1 problem only. These resistors were replaced before Run-2

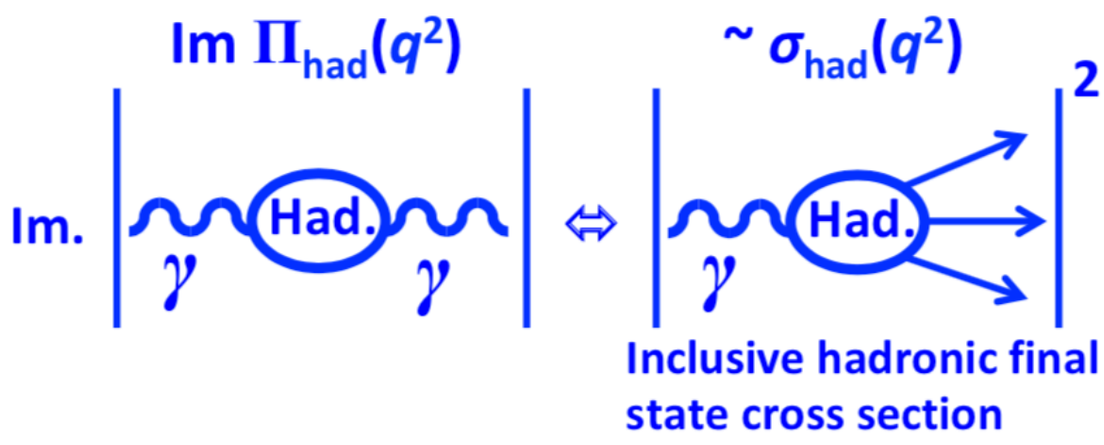
Non-perturbative QCD dominates SM muon g-2 uncertainty.

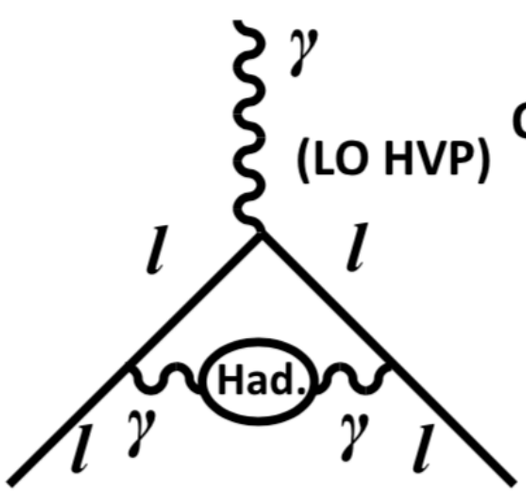
[1]

Contribution	a_μ [$\times 10^{-11}$]	δa_μ [$\times 10^{-11}$]
QED incl. 4-loops + 5-loops	116 584 718.86	0.03
hadronic LO VP	6 894.6	32.5
hadronic LbL	103.4	28.8
Hadronic HO VP	-87.0	0.6
Weak to 2-loops	153.6	1.1
Theory	116 591 783	43
Experiment	116 592 091	63
The. − Exp. (4.0σ difference)	-306	76

Largest source of SM error

Optical Theorem





Analyticity & Optical Theorem

$\Leftrightarrow$

$$a_\mu^{\text{had. LO VP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} R(s)\hat{K}(s)$$

Can obtain from data for low energies

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

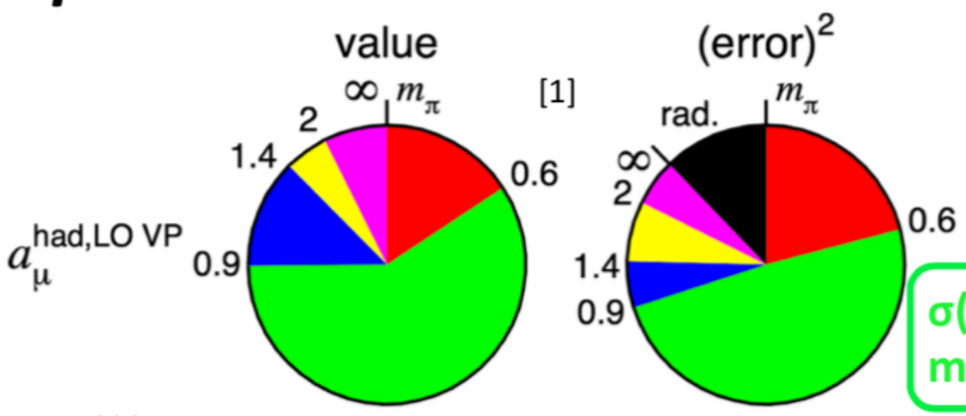
$\sigma(e^+e^- \to \mu^+\mu^-)$ at tree level

$$\hat{K}(s) = \frac{3s}{m_\mu^2}\int_0^1 dx \frac{x^2(1-x)}{x^2 + \left(s/m_\mu^2\right)(1-x)}$$

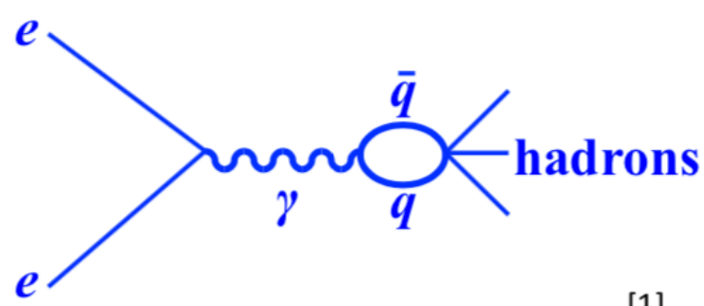
Amplifies low energy $\sigma(e^+e^- \to \text{hadrons})$

[1] F. Jegerlehner, arXiv:1804.07409 [hep-ph].

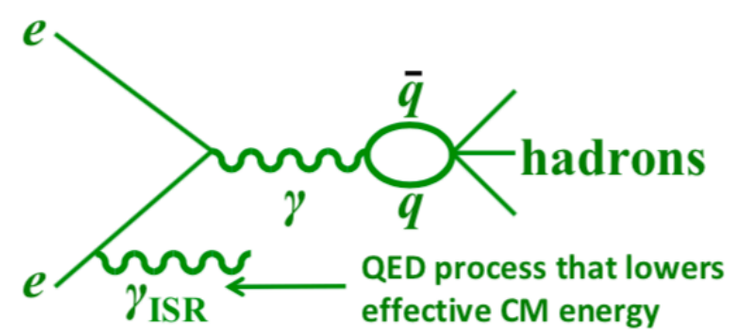
Work continues on improving the precision of $a_\mu^{\text{had. LO VP}}$.



Direct Scan Method:

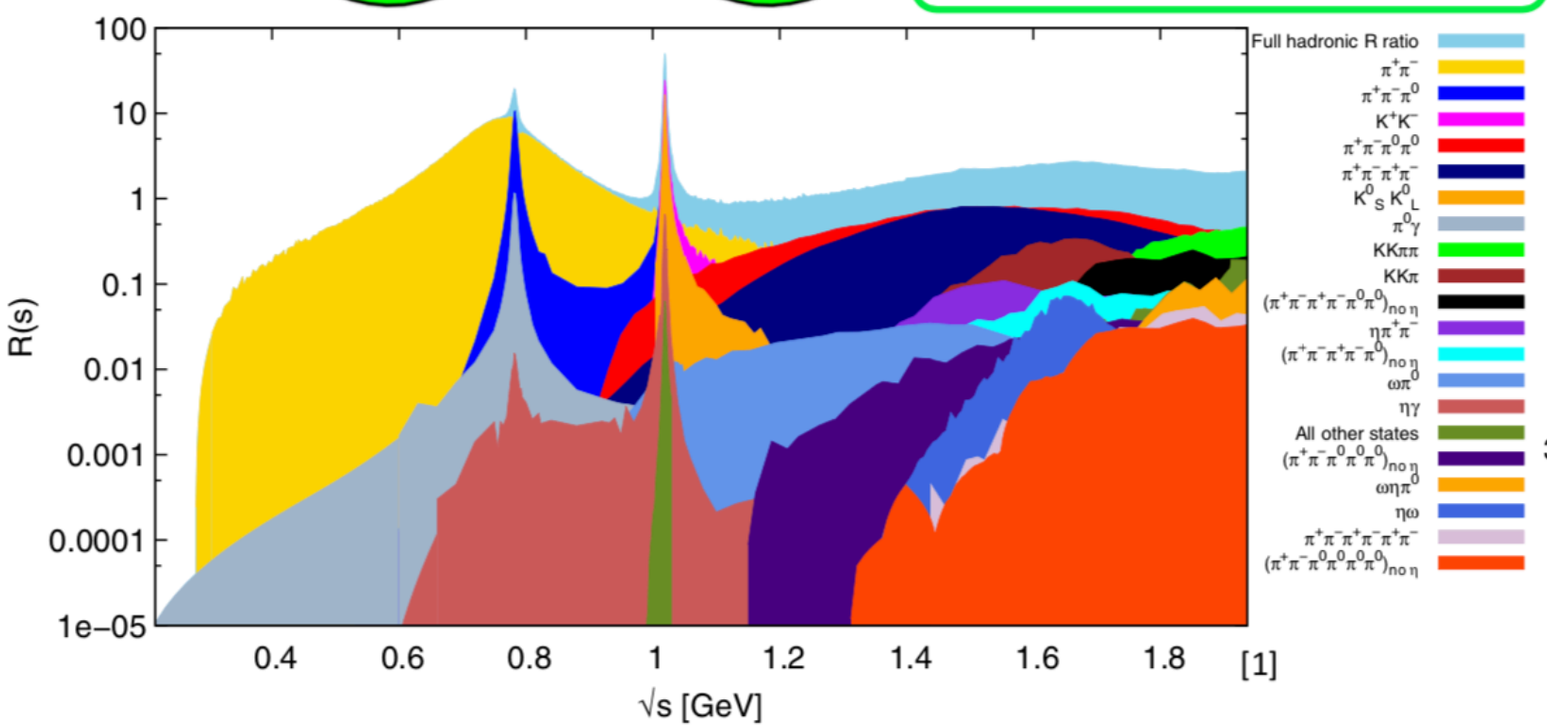


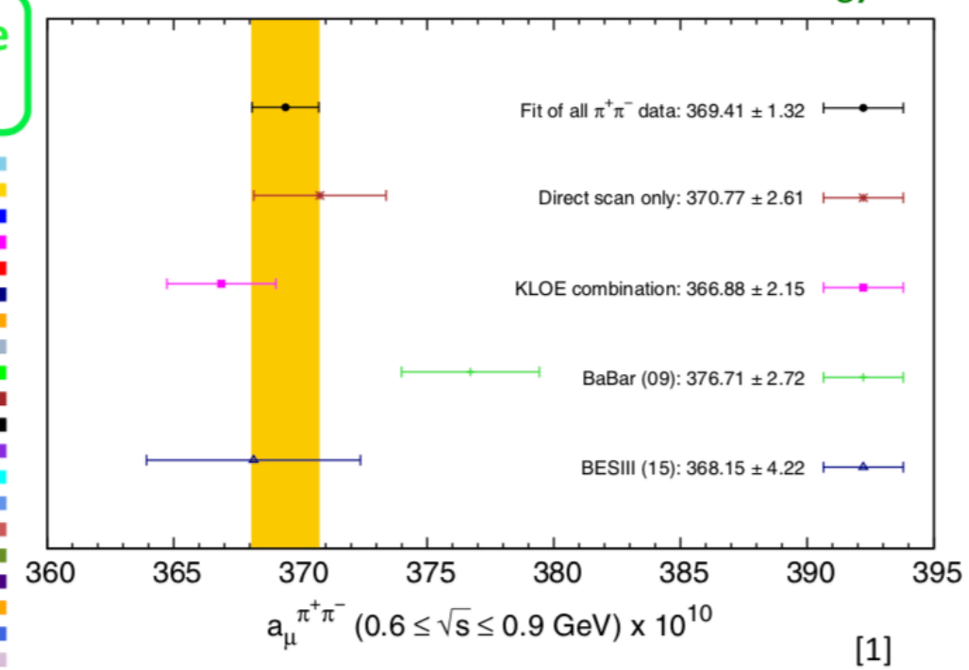
Initial State Radiation (ISR) method:
(suitable for Phi- and B-factories)

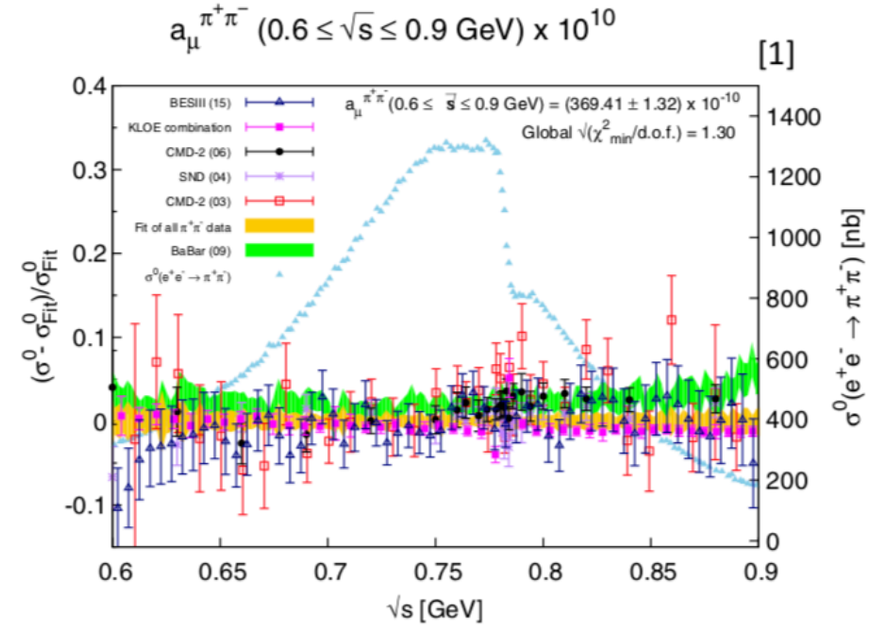


QED process that lowers effective CM energy

$\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ contributes the most to the value and error





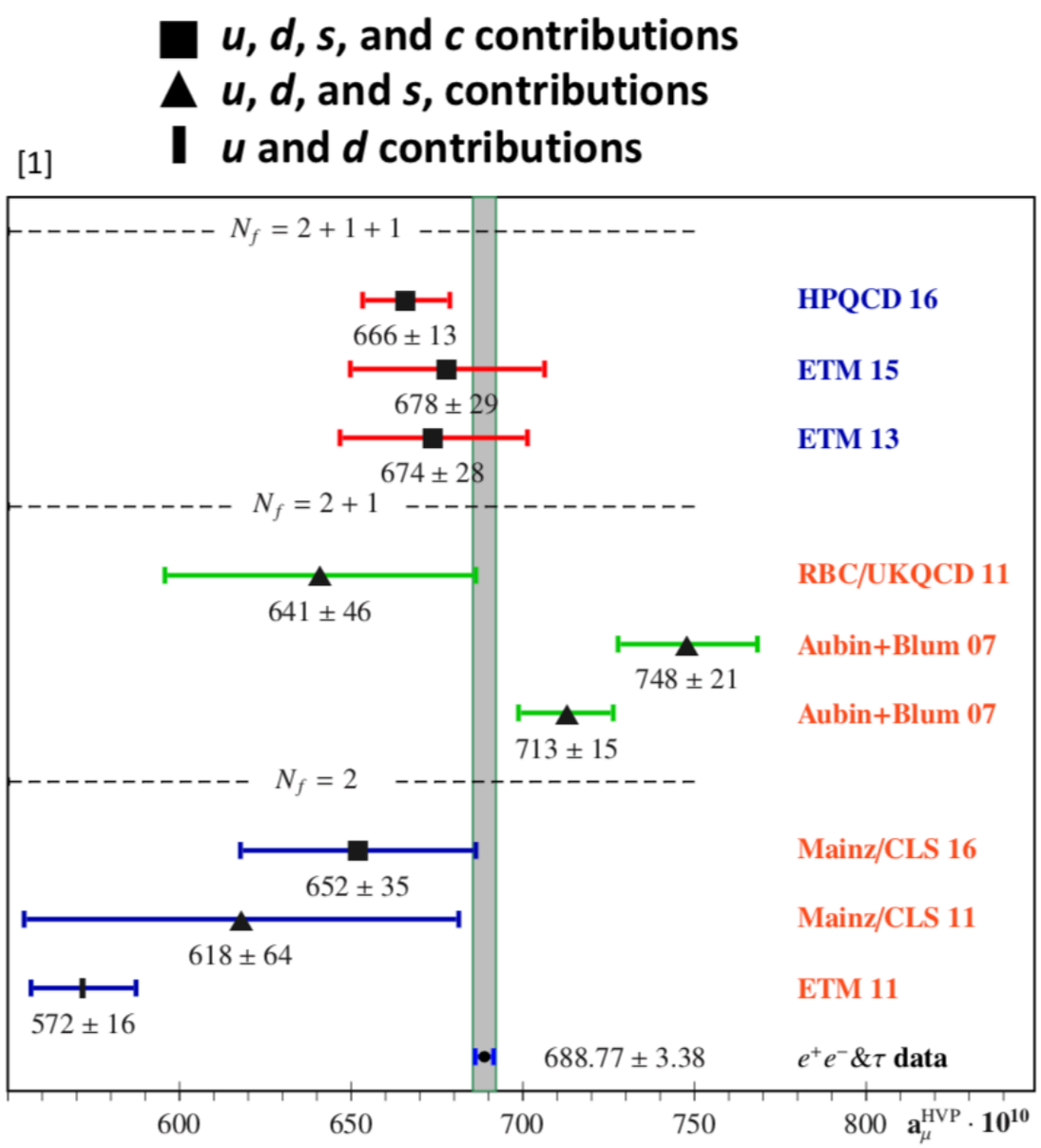


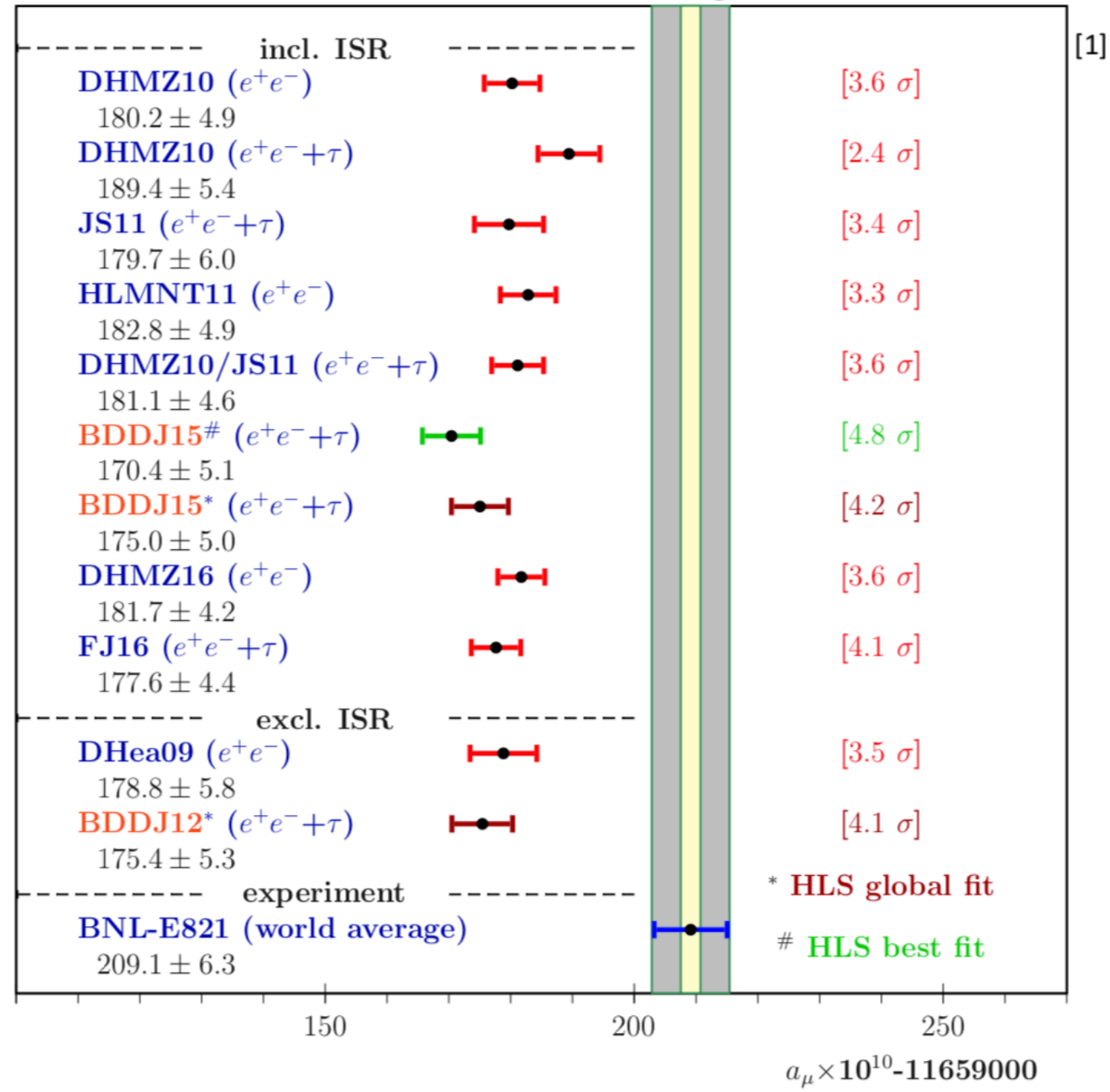
From a recent hadronic VP contributions to muon g-2 workshop[2]:

- Belle II studying an $e^+e^- \rightarrow \pi^+\pi^-$ measurement (Maeda Yosuke)
- BABAR working on $e^+e^- \rightarrow \pi^+\pi^-$ measurement using full BABAR data set (Michel Davier)
- BESIII preliminary $e^+e^- \rightarrow \pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$, and $\pi^+\pi^-3\pi^0$ measurements (Christoph Florian Redmer)

[1] A. Keshavarzi, D. Nomura and T. Teubner, Phys. Rev. D **97**, no. 11, 114025 (2018) doi:10.1103/PhysRevD.97.114025 [arXiv:1802.02995 [hep-ph]].
[2] Workshop on hadronic vacuum polarization contributions to muon g-2, KEK, Tsukuba, Japan, Feb. 12th to 14th (2018):

BNL muon anomaly measurement and SM prediction differ by greater than 3σ.





- Historical e^+e^- and τ data discrepancy resolved by including effects such as ρ−γ mixing (important isospin breaking effects): DHMZ10 (e^+e^- + τ) does not have ρ−γ mixing correction
- BDDJ15# excludes while BDDJ15* includes BABAR $\pi^+\pi^-$ data
- If central values do not move, achieving Fermilab error goal will lead to a greater than 5σ difference

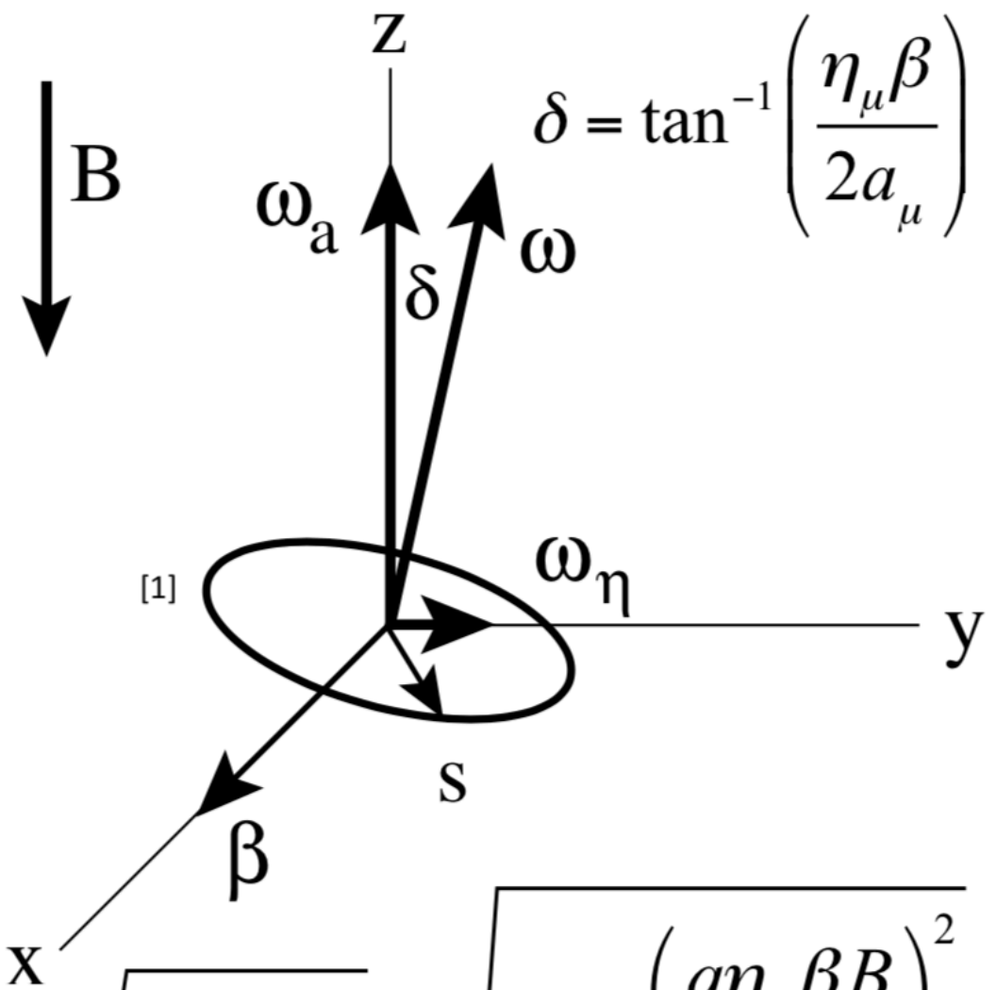
Work continues with LQCD $a_\mu^{\text{had. LO VP}}$ calculations

[1] F. Jegerlehner, EPJ Web Conf. **166**, 00022 (2018) doi:10.1051/epjconf/201816600022 [arXiv:1705.00263 [hep-ph]].

Muon electric dipole moment (EDM) will tilt the spin precession plane.

[1]

- Muon EDM will violate P, T, and CP symmetries.
- Experiment only measures one precession frequency!
- To a good approximation, $\vec{\omega}_a$ is parallel to $\vec{B}$ and $\vec{\omega}_\eta$ points radially in the storage ring.
- Straw Tracker Detectors can measure a tilt in the spin precession plane.
  - From a radial or longitudinal magnetic field component.
  - From a muon EDM.
  - A tilt in the precession plane leads to an up-down asymmetry in the positron angle.



$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2} \approx \sqrt{\omega_a^2 + \left(\frac{q\eta_\mu \beta B}{2m}\right)^2}$$

B-field contribution dominates over E-field contribution in storage ring.

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta \approx -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right] - \eta_\mu \frac{q}{2m}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)$$

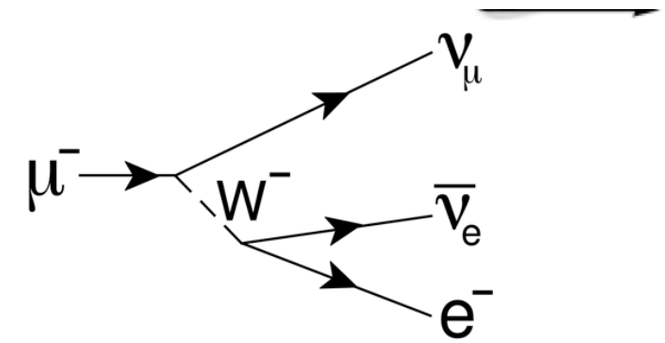
[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].

CLFV

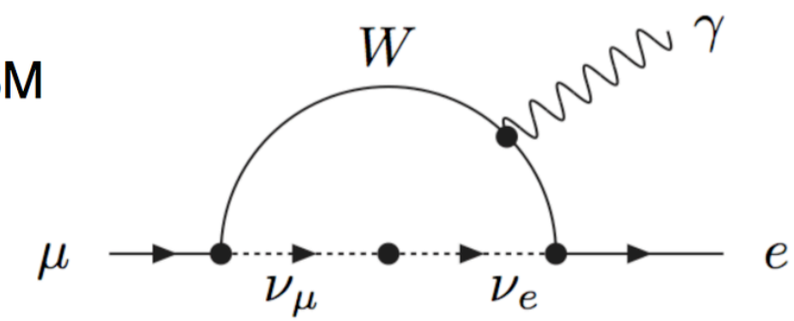
Ordinary muon decay conserves lepton flavor:

$$\mu^- \rightarrow e^- \, \bar{\nu}_e \, \nu_\mu$$

L_μ	1	0	0	1
L_e	0	1	-1	0



Violation of charged lepton flavor "forbidden" in SM



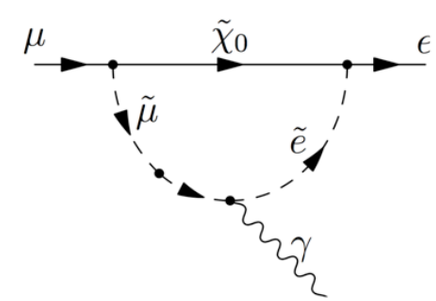
Loophole: neutrino oscillations

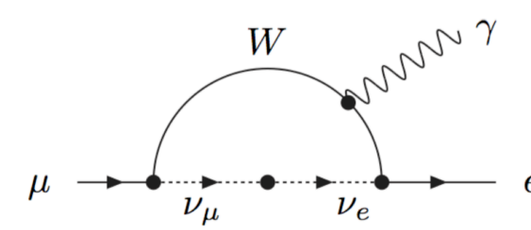
- Some CLFV *must occur*
- But rate is vanishingly small, $<10^{-50}$

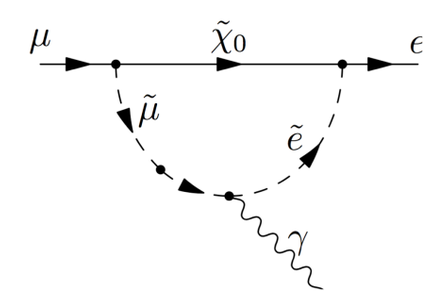
$$\mathrm{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

Any CLFV observation would be evidence that rate is enhanced by new physics

- A search for rare forbidden processes at the Intensity Frontier
- Complementarity and synergy with LHC





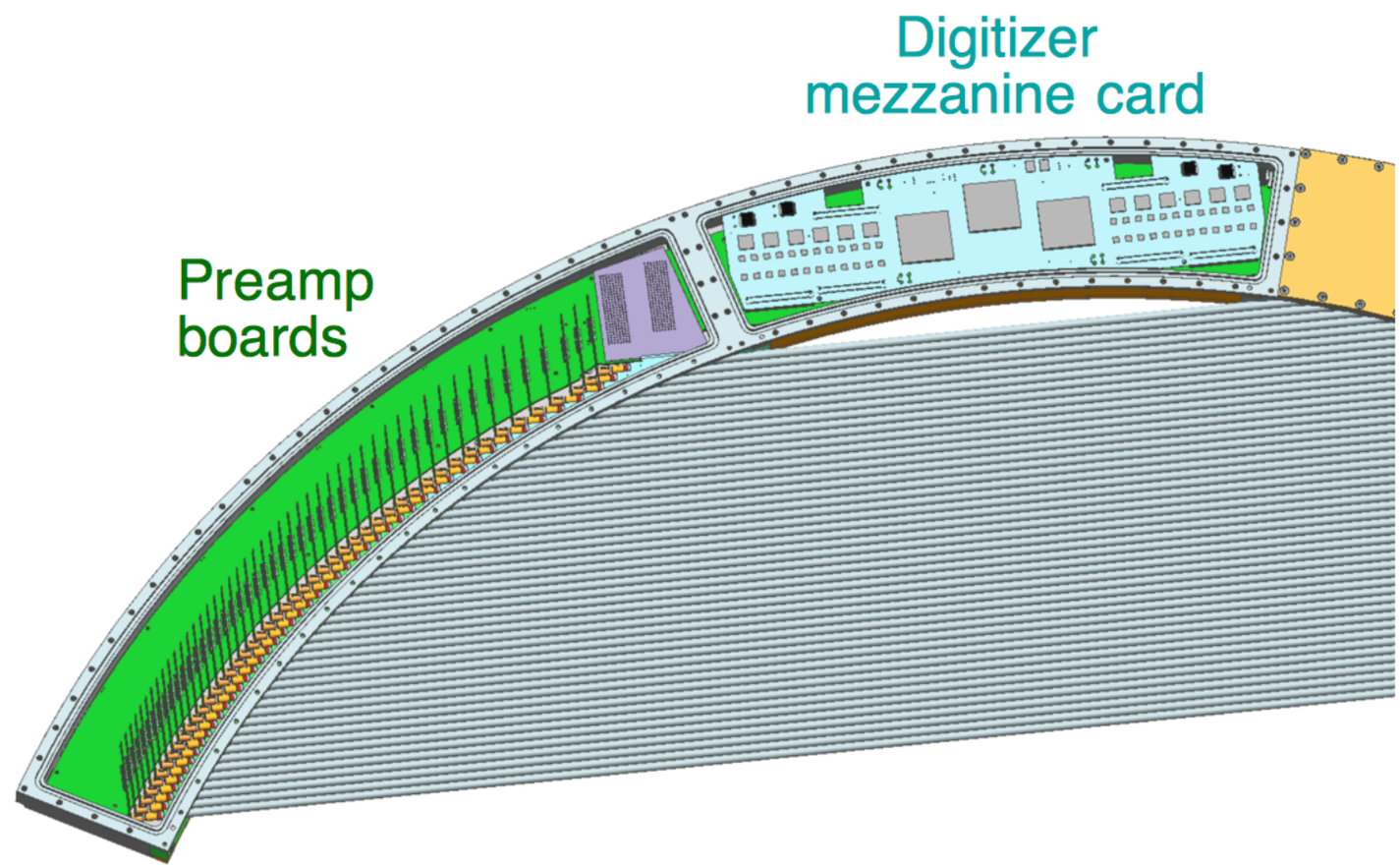


- The charged-lepton analog to neutrino oscillations!

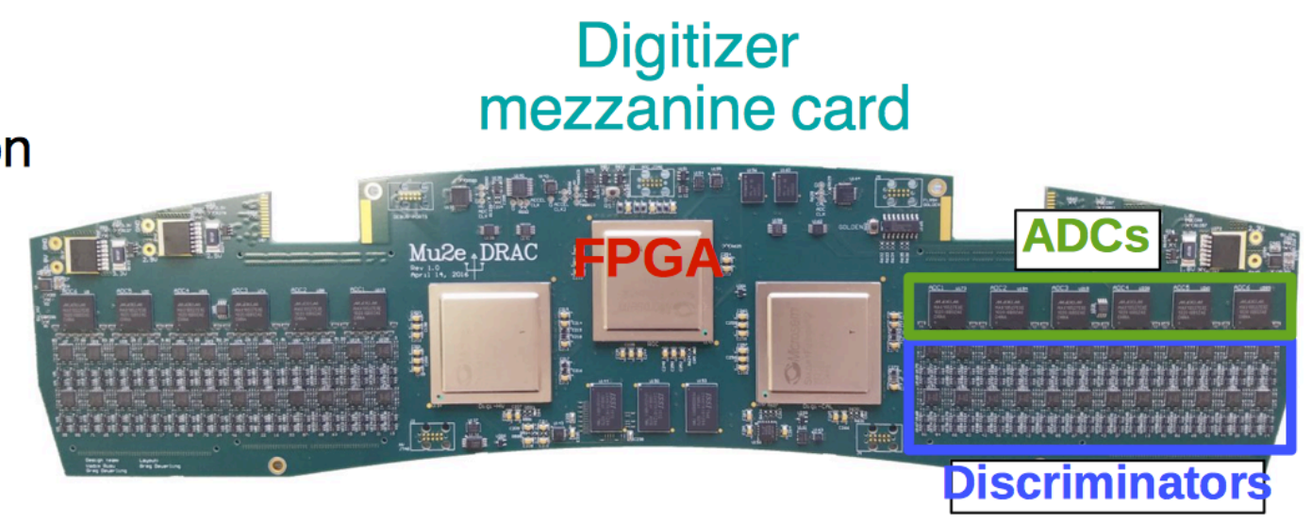
Tracker from-end electronics

Electronics volume 71<r<80 cm
- on every panel inside cryostat

Readout at both ends of straw, preamp and digitization
- Drift time resolution: 2ns (100μm drift radius)
- Time difference resolution: 4cm along straw axis
- ADC for dE/dx measurement to identify highly-ionizing proton hits



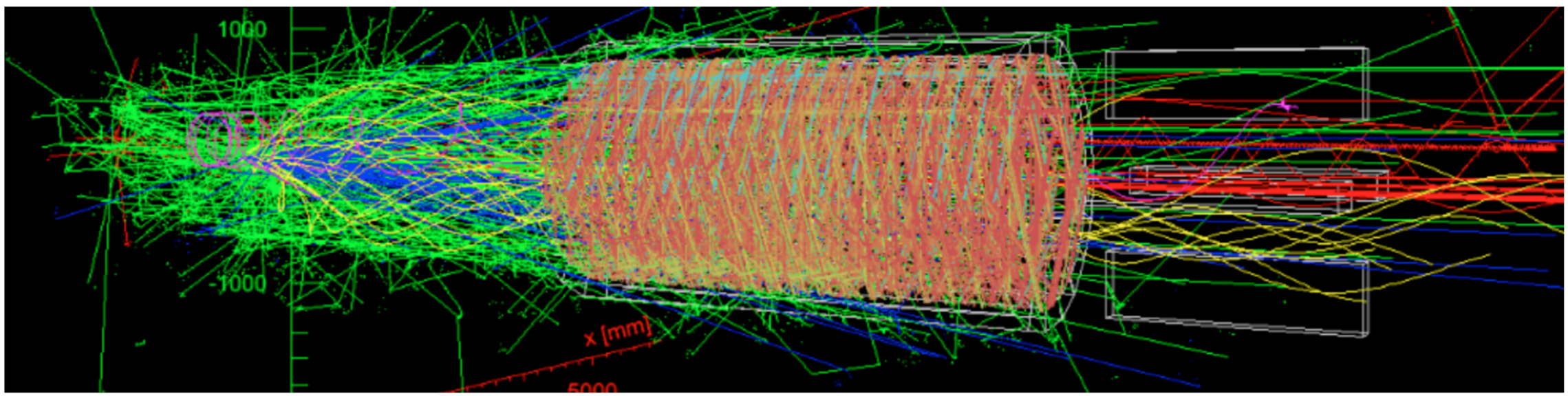
Requirements:
- Supply HV to straws (and remote disconnect)
- B-field perturbation <1G in active detector region
- Low power <10kW within cooling capabilities
- Sustain radiation damage from target
- <12×96 dead channels in 5 yrs at 90% CL



Tracker analysis

From individual straw hits in tracker we need to:

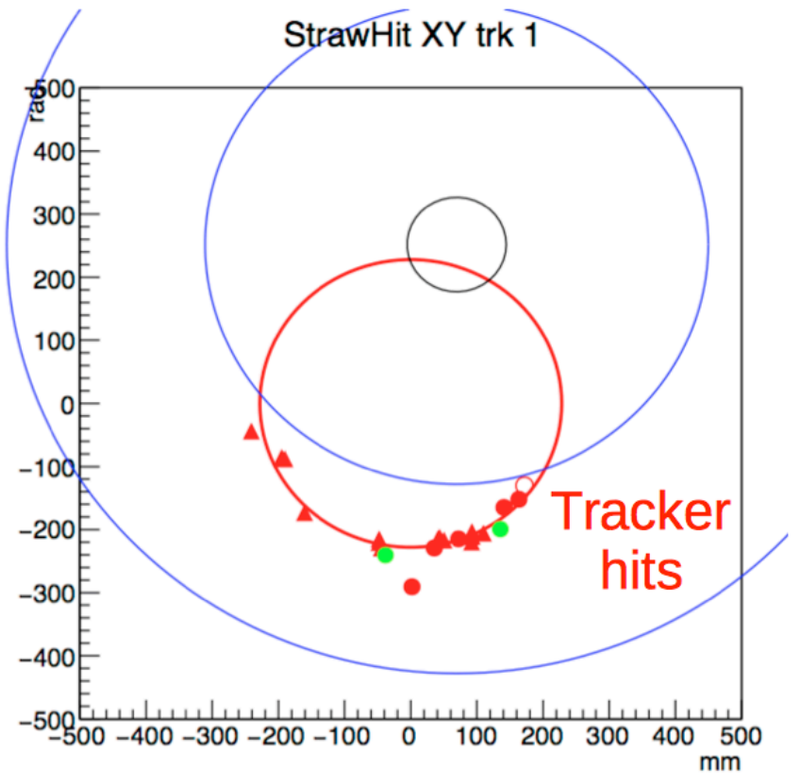
- Remove background hits
- Identify hits from single particle (pattern recognition)
- Reconstruct particle's trajectory (helix fitting)

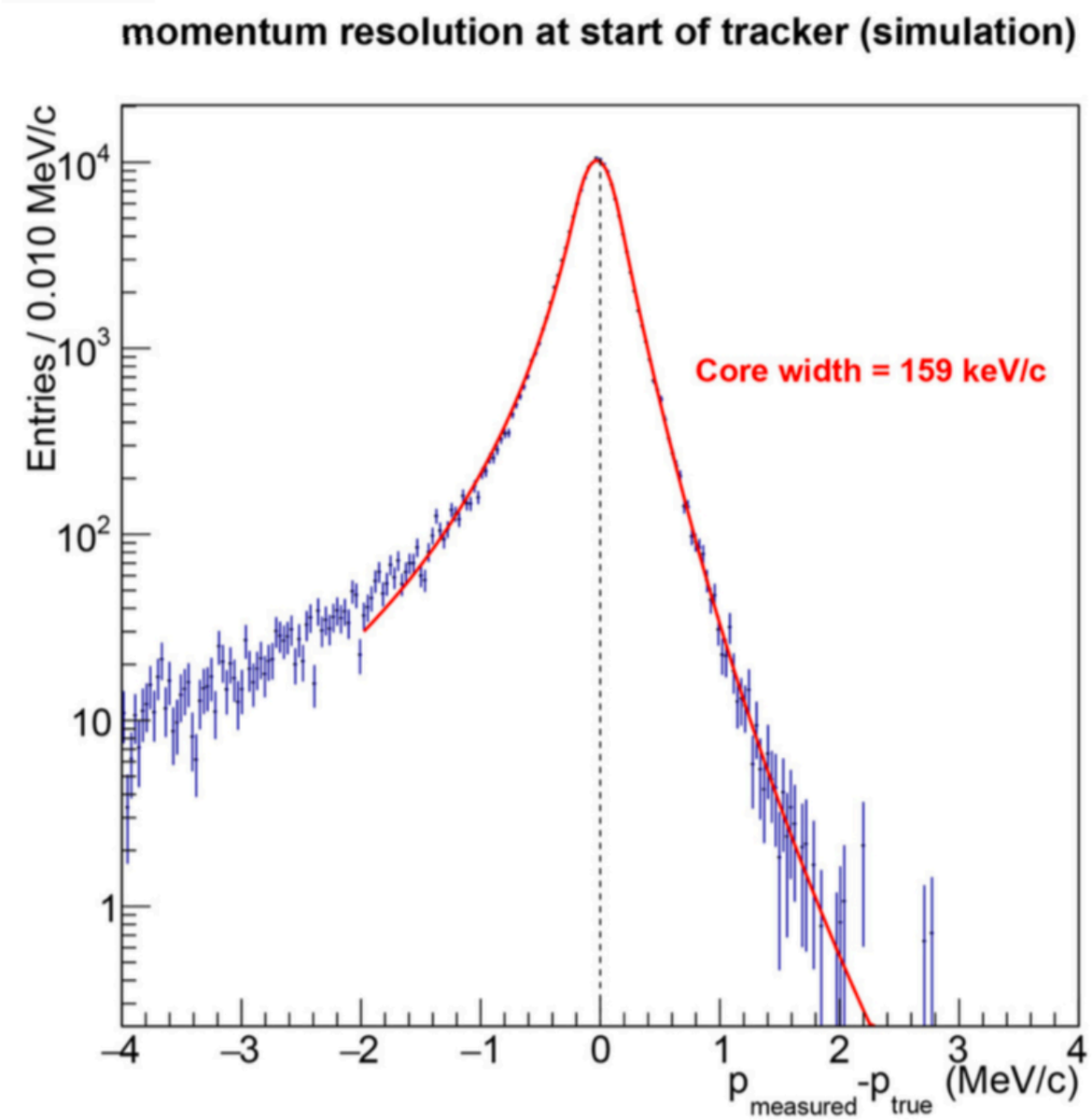


Signal electron + all hits over 500-1695 ns window

Detailed G4 model: straws, electronics, supports, B-fields

Tracker analysis

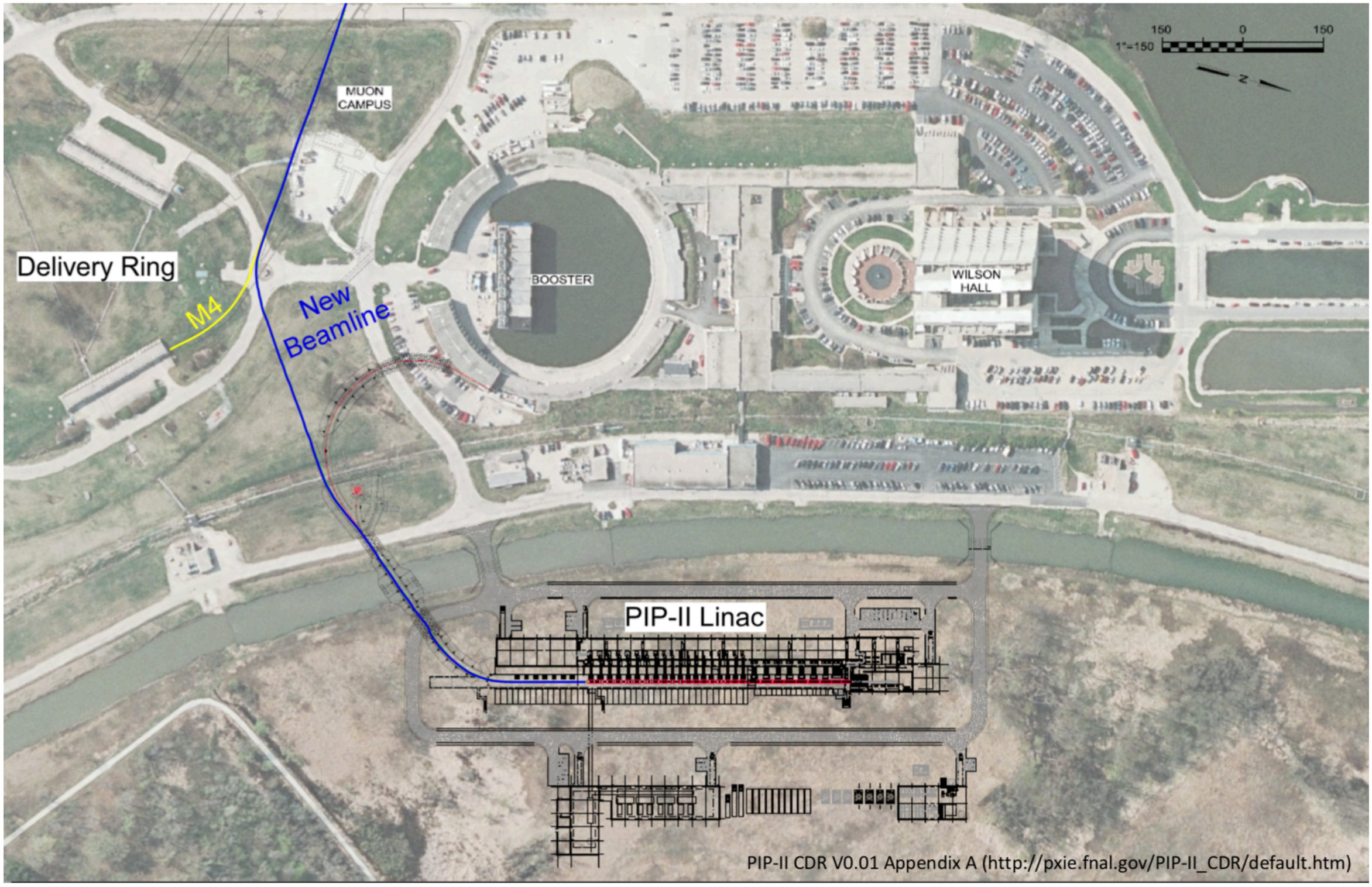




Helix fit, least squares fit, followed by iterative Kalman Filter track fit

Tracker momentum resolution requirement:
σ_p/p<0.2% for a 105 MeV electron, or σ_p<180 keV/c

PIP-II beamline for Mu2e-II



PIP-II CDR V0.01 Appendix A (http://pxie.fnal.gov/PIP-II_CDR/default.htm)