Low-Energy Probes of the Standard Model II

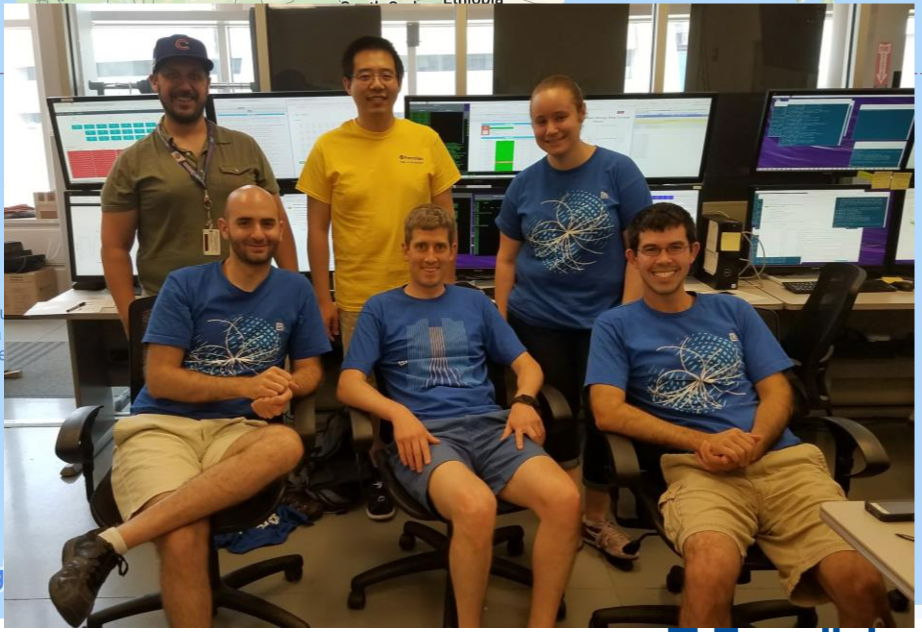
Brendan Kiburg, Fermilab

SLAC Summer Institute 2018

Standard Model at 50: Successes and Challenges

Aug 1, 2018

Introductions



Goals for this talk

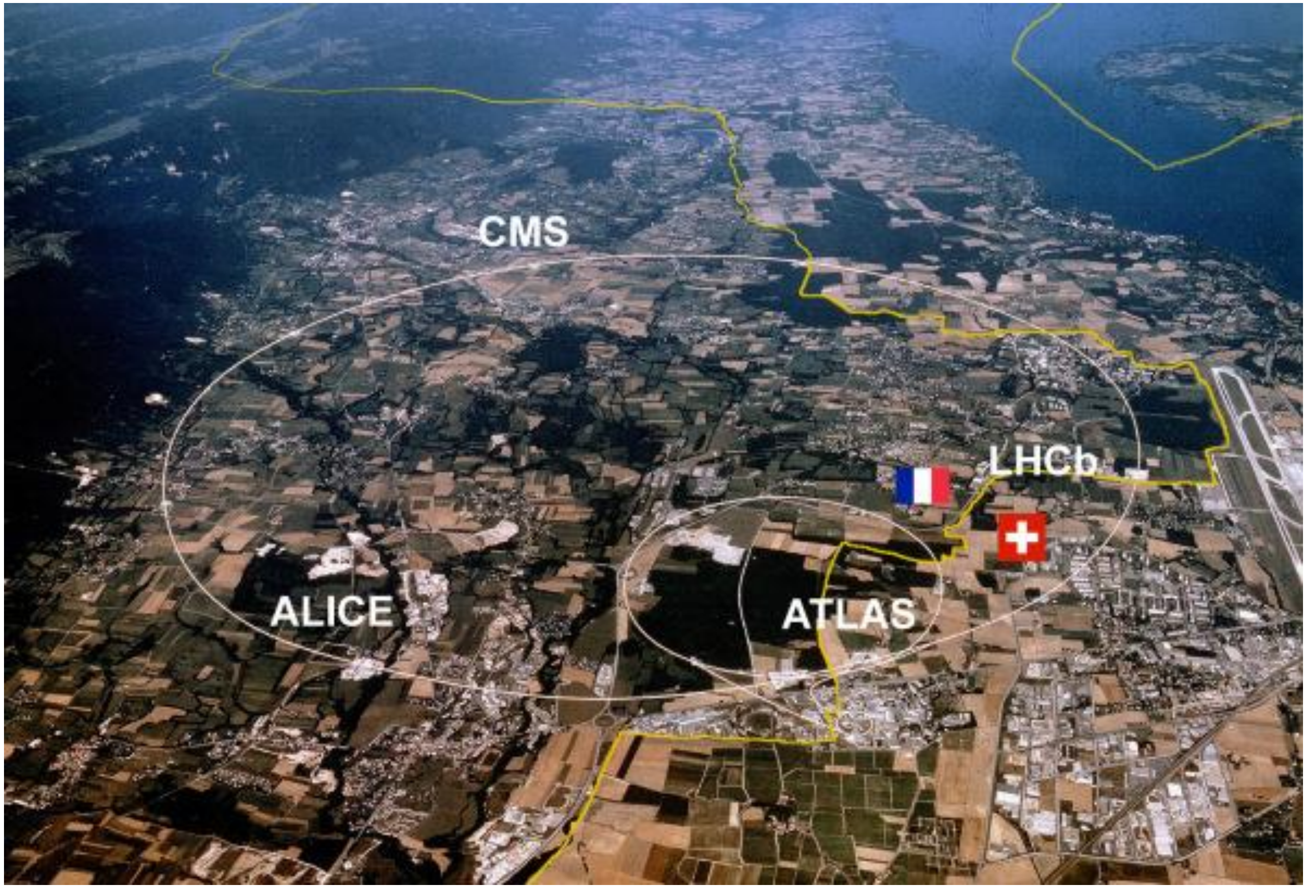
1. Why do we use muons to probe the Standard Model? How?

2. What details matter for precision experiments?

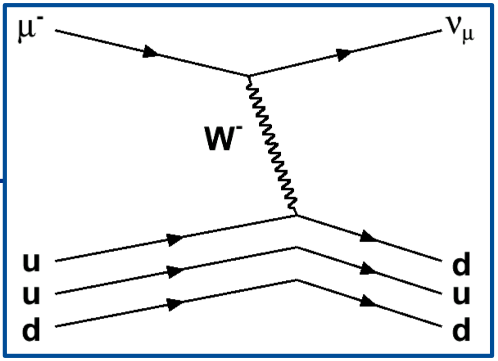
3. Where might we see the next cracks in the SM?

What details matter: Example from yesterday @ LEP

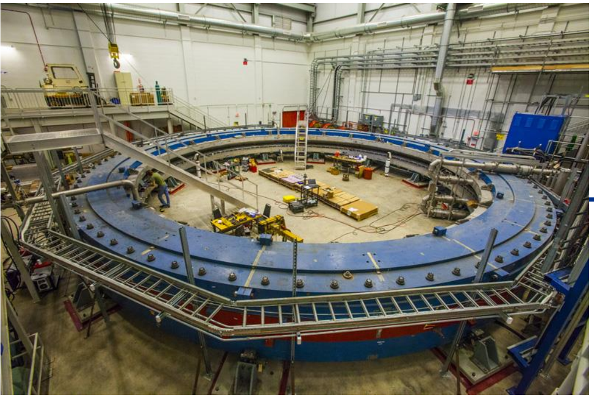
- LEP's energy measurement is sensitive to the orbit of the moon, the level of water in Lac Leman, and the departure of the TGV from Geneva station.



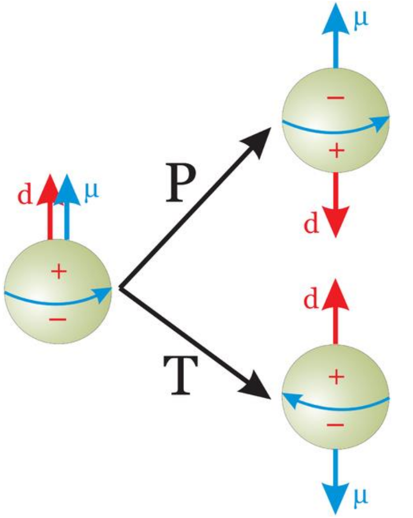
Overview



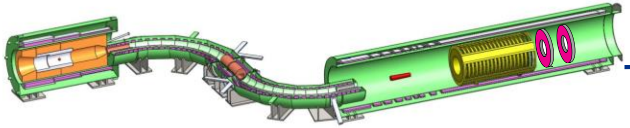
Muons as a SM Probe



SM/BSM: Muon g-2



BSM I: EDMS



BSM II: Mu2e

Conclusion


PHYSICS

We Asked Celeb Physicist Brian Cox About Flat Earth Conspiracies, the Multiverse, and Ghosts

Ryan F. Mandelbaum
7/11/18 12:00pm · Filed to: PARTICLE PHYSICS

Particle physicist and celebrity scientist Brian Cox

Precision Muon Physics: Why Muons?

- We have studied the muon since its discovery 80 years ago

- What useful properties do you know about muons?

Exceptionally Useful Probe	
Heavy, 2nd Generation Particle	$m_\mu \approx 207 \cdot m_e$
High Sensitivity to New Physics	$\propto (m_\mu / m_e)^2$
Produced and Decay via Weak Int	
• V-A structure in pion decay	$\nu \leftarrow \pi^+ \rightarrow \mu^+$
• Muon Decay	$\mu \rightarrow e\nu\nu$
Can produce hydrogen-like atoms	$\mu^- p\,,\ \mu^+ e^-\,,\ \mu^- \mu^+$
Muon lifetime is "just right" 2.2 μs	$10^{-9}\mathrm{s} << \tau_\mu << 1\mathrm{s}$

Global Precision Muon Physics Experiments

<u>RIKEN-RAL</u>
Materials – muSR
Techniques – LE beams

<u>PSI</u>
Lifetime – Fermi constant (MuLan, FAST)
Muon Capture – (Mucap, MuSun, AlCap)
Proton Radius – (mp/d Lamb Shift, CREMA, MuSE
CLFV - (MEG, MEG-II, mu3e)
Materials – muSR
Techniques – LE Beams, HI beams

<u>JPARC</u>
Muon g-2 (E34)
CLFV – COMET, DeeMee
Muonium Spectroscopy - MUSEUM

<u>TRIUMF</u>
Decay Parameters - TWIST
Materials - muSR

<u>RCNP</u>
HI Beams Facility – MUSIC

<u>Fermilab</u>
Muon g-2 (E989)
Muon eDM (E989)
CLFV – mu2e

Theoretical work also very widespread

Past Present Future

Precision Muon Physics to Establish the SM

- SM Electroweak Physics involves three parameters

Two gauge coupling constants: g, g'
Higgs vacuum expectation value: v

- Values fixed experimentally via precise determination of:

Fine structure constant α, known to 32 ppb
Z boson mass, known to 23 ppm
Fermi Coupling constant, G_F , known to 9 ppm (Giovanetti, 1984)

$$\frac{\delta G_F}{G_F} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau}{\tau}\right)^2 + \left(5\frac{\delta m_\mu}{m_\mu}\right)^2 + \left(\frac{\delta\Delta q}{\Delta q}\right)^2}$$

0.14 ppm contribution from radiative corrections (Pak & Czarnecki)

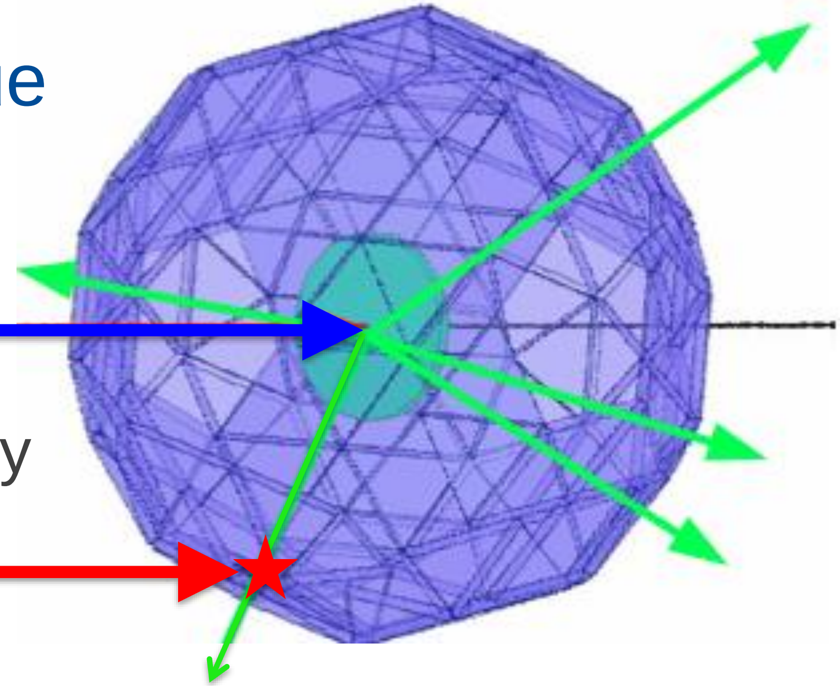
18 ppm contribution dominated uncertainty

0.09 ppm contribution

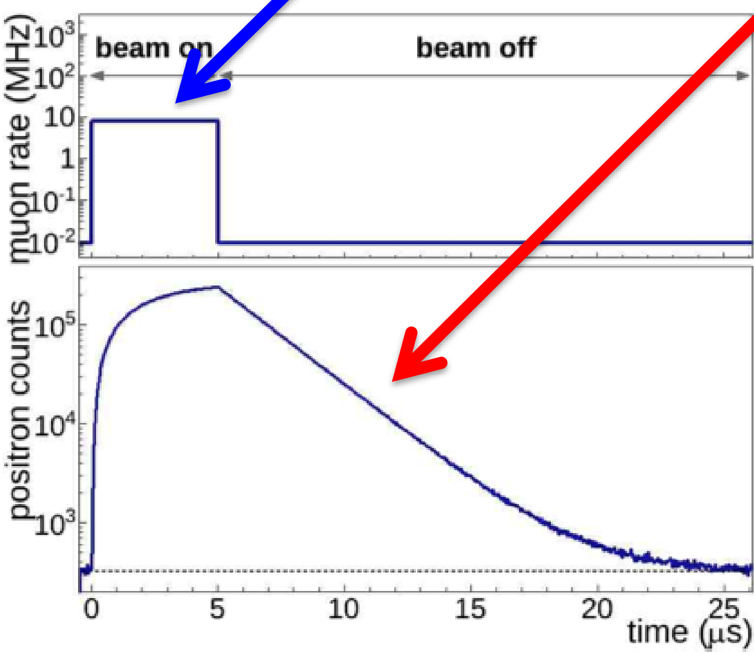
MuLan Experimental Technique

1. Prepare “radioactive source” of muons in a thin stopping target

μ^+ beam →



2. Detect decay positron



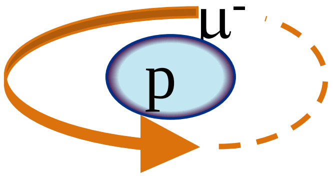
- Avoid “early-to-late” systematics
  - Gain Changes, Pileup

$$\tau_{\mu^+}^{\rm MuLan} = 2196980.3 \pm 2.2\text{ps}$$

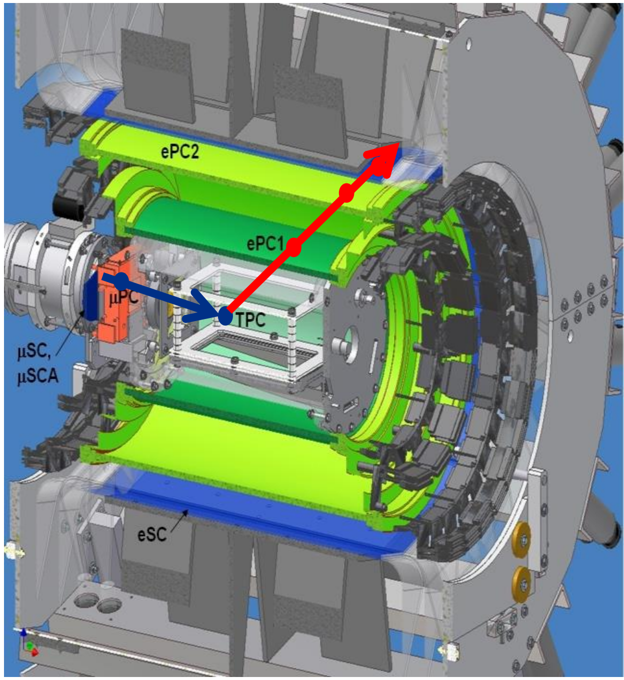
$$G_{\rm F}^{\rm MuLan} = 1.166\,378\,7(6) \times 10^{-5}\,\text{GeV}^{-2}$$

0.5 ppm!

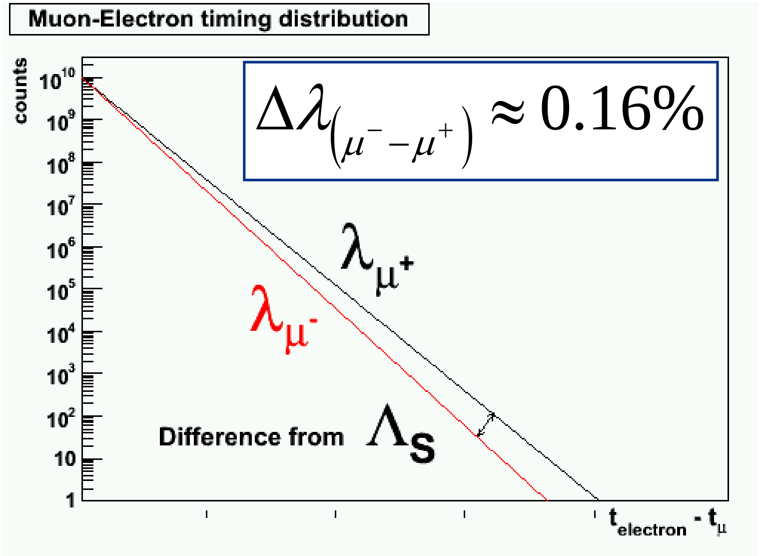
The Muon Lifetime: An Important Input to MuCap



1. Observe muons form Muonic Hydrogen Atoms in an ultra-pure protium TPC



2. Use Similar Technique: Measure μ^- disappearance rate



3. Compare μ^- disappearance (via $\mu \rightarrow e\nu\nu$) to μ^+ lifetime

4. Extract very different physics

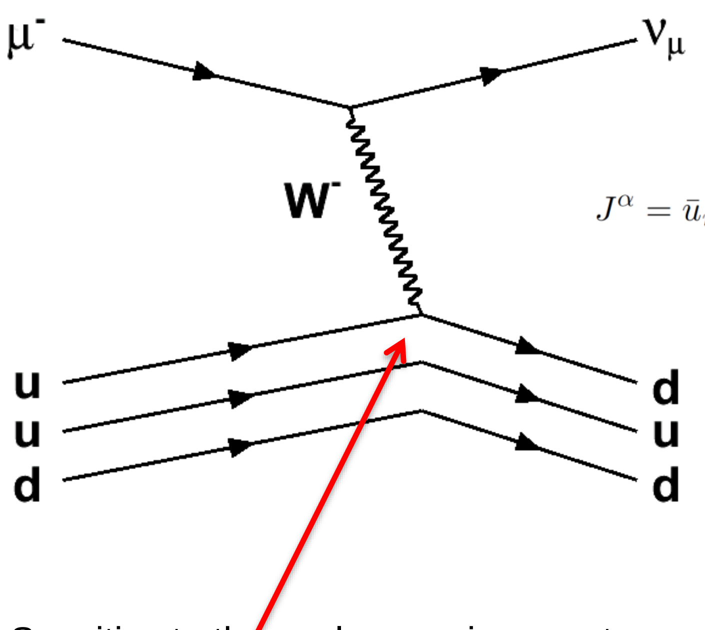
MuCap: Extracting the proton's pseudoscalar coupling, g_P

$$\mu^- + p \rightarrow n + \nu_\mu$$

$$M_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} L_\alpha J^\alpha$$

$$L_\alpha = \bar{u}_\nu \gamma_\alpha \left(1 - \gamma_5\right) u_\mu$$

$$J^\alpha = \bar{u}_n \left(\underbrace{g_V \gamma^\alpha + \frac{i g_M}{2 m_N} \sigma^{\alpha\nu} q_\nu + \frac{g_S}{m_\mu} q^\alpha}_{V^\alpha} - \underbrace{g_A \gamma^\alpha \gamma_5 - \frac{g_P}{m_\mu} q^\alpha \gamma_5 - \frac{i g_T}{2 m_N} \sigma^{\alpha\nu} q_\nu \gamma_5}_{A^\alpha} \right) u_p$$



Sensitive to the nuclear environment

g_P(Chiral Pert. theory) = 8.26 ± 0.23

g_P(MuCap) = 8.14 ± 0.55

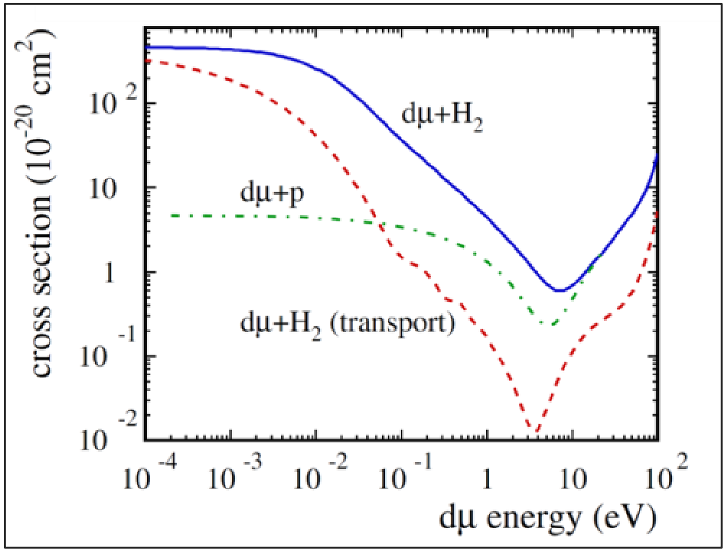
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.91.055502

Aside: Precision Measurements

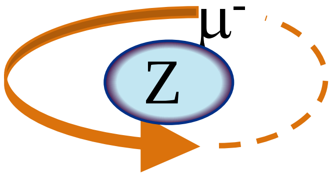
- Goal: ~10 ppm precision on muon disappearance rate

- Disappearance rate (decay) ~455,000 s^{-1}
- Capture rate on proton ~ 700 s^{-1}
- Capture rate on deuteron ~ 400 s^{-1}
- Capture rate on Aluminum ~705,000 s^{-1}

Stopping μ forms μd atom w/ ~45 eV

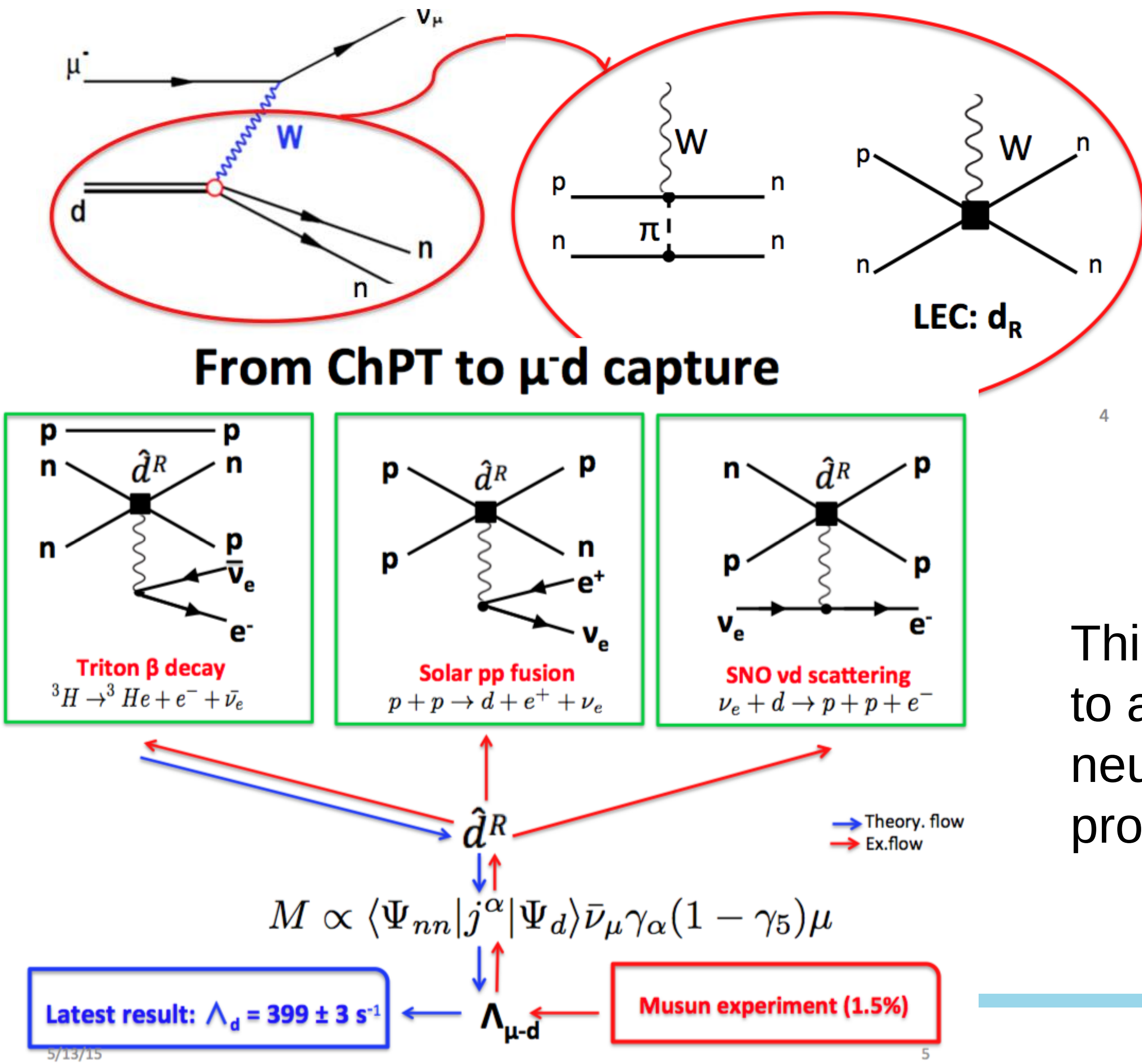


Ramsauer-Townsend minimum



- "Good" muon stop
- μd diffusion (cm / τ_μ)
- Finds a "high" Z material $\Lambda_Z \propto Z^4$

MuSun: Protium→Deuterium, Different Physics Goal

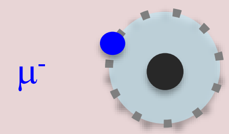


Simplest process on compound nucleus

Clean channel to determine Low Energy Constant in Effective Field Theories

This LEC directly relates to astrophysical and neutrino scattering processes

Proton Radius Puzzle



Muonic Hydrogen

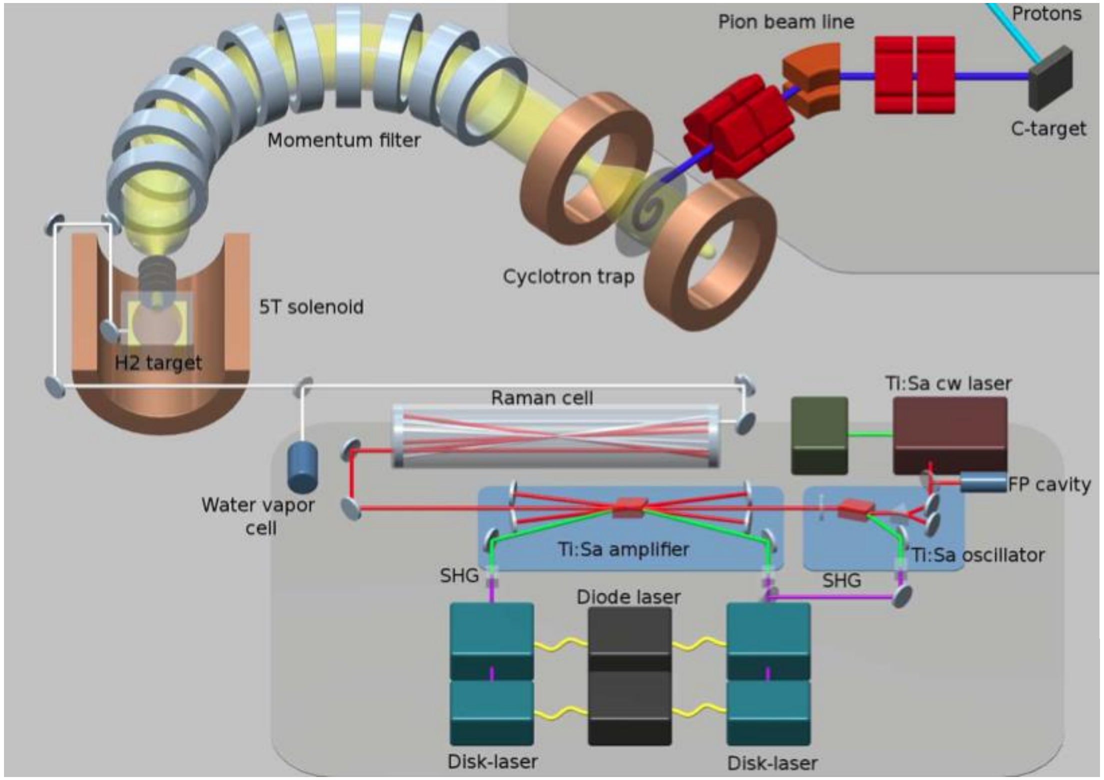
$$m_\mu \approx 207 \cdot m_e$$

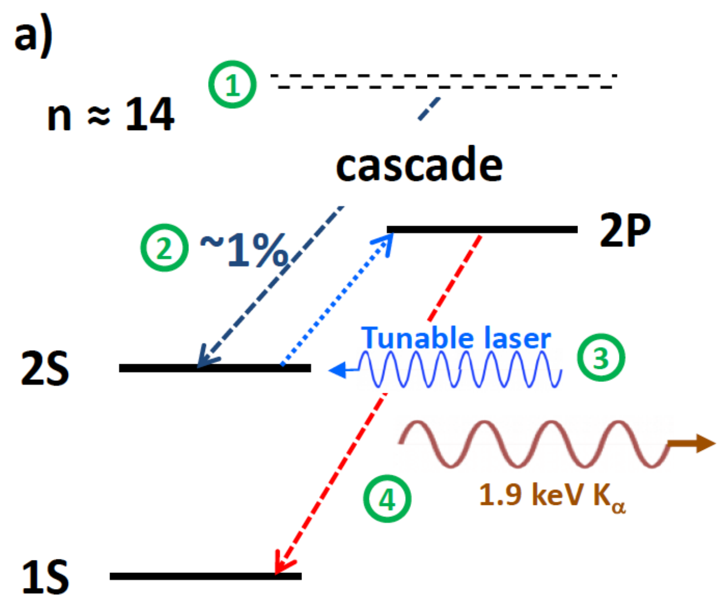
$$r_\mu \approx \frac{1}{186} \cdot r_e$$

$$\left(\frac{r_\mu}{r_e}\right)^3 \approx \left(\frac{1}{186}\right)^3 \approx 10^{-7}$$

- Muons probe the proton significantly deeper than electrons
- Improve precision of the proton charge radius

Muonic Hydrogen Lamb Shift Technique

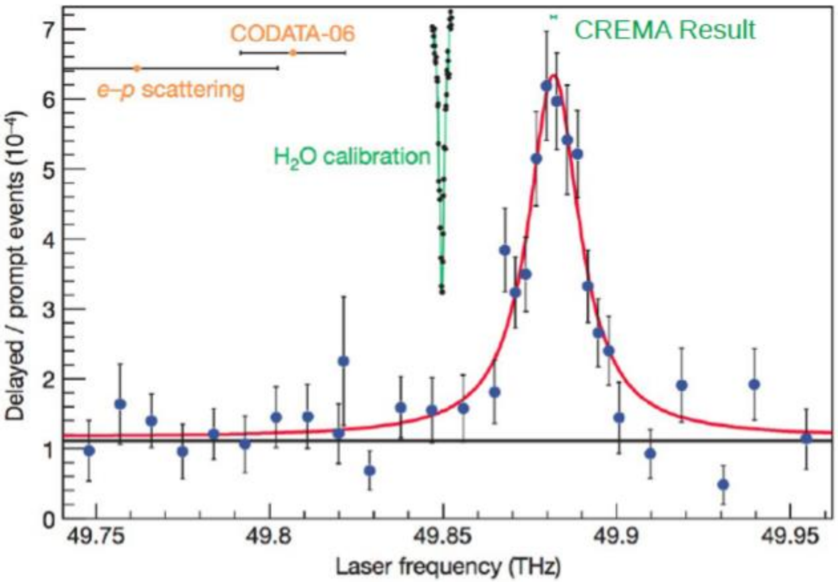


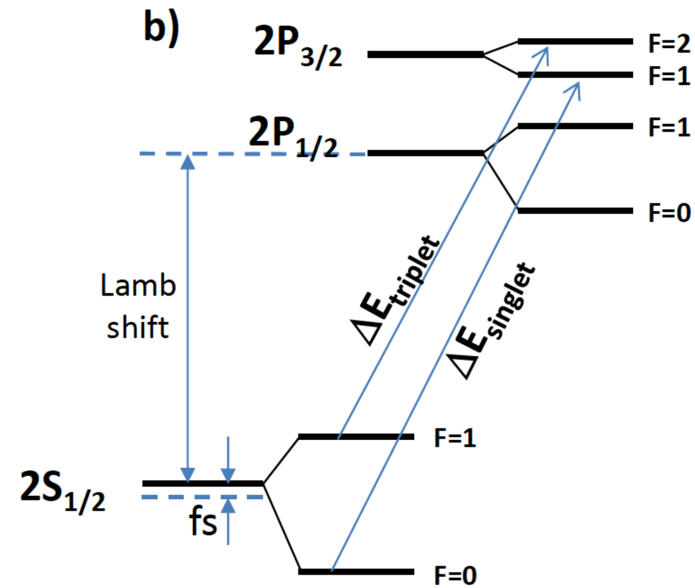


1. Form Muonic Hydrogen
2. About 1% of muons cascade to meta-stable 2S state
3. Use laser to induce 2S-2P
4. Measure 1.9 keV x-ray in 2P-1S transition

Muonic Hydrogen Lamb Shift Differs from Electronic Experiments

See: R. Pohl et al. Nature 466 (2010) 213.





$$\mu\text{p} \quad r_p = 0.8409(4)\text{fm}$$

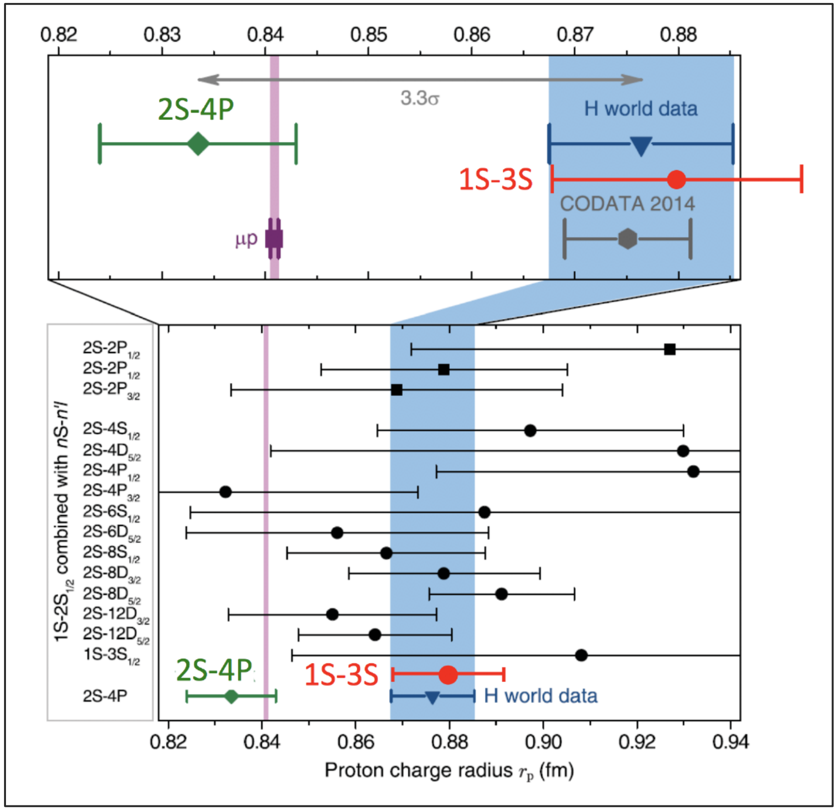
$$\text{e-p scat} \quad r_p = 0.8790(80)\ \text{fm}$$

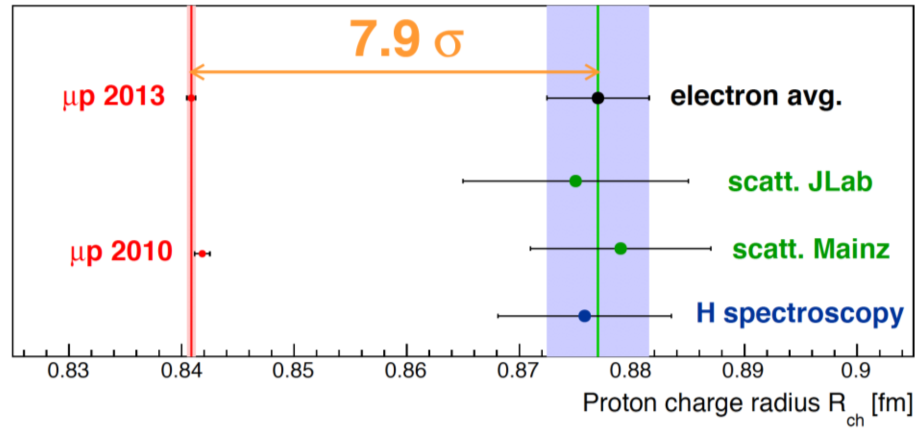
$$\frac{\left(\frac{d\sigma}{d\Omega}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}} = \frac{1}{\varepsilon(1+\tau)}\left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

$$R^2 = -6\,\frac{dG_e(q^2)}{dq^2}\bigg|_{q=0}$$

- Hard to build
- Easy to interpret
- μd Lamb shift confirms observation

Recent (2017,2018) Measurements Maintain the Tension





r_E (fm)	ep	μp
Spectroscopy	0.8758 ± 0.077	0.84087 ± 0.00039
Scattering	0.8770 ± 0.060	????

- Diversify e spectroscopy
- Pursue the missing quadrant (MUSE experiment)

SM So Far

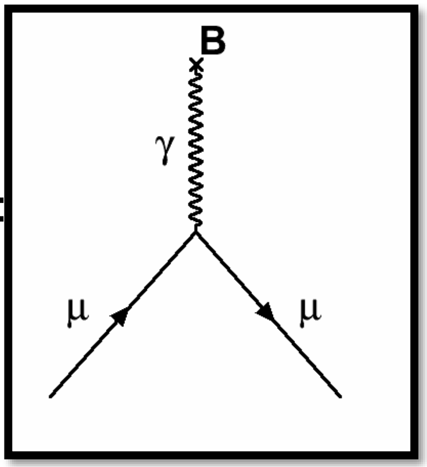
- MuLan → G_F – SM Electroweak Observable
- MuCap → g_p – Nucleon pseudoscalar coupling (ChPT predicts)
- MuSun → d_R – Low-energy Constants of EFT
- CREMA → r_p – Proton-radius

Precision measurements using the well-established muon as a probe continue to validate critical Standard Model parameters and sometimes reveal Puzzles

Muon g-2: The Basics

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

g =



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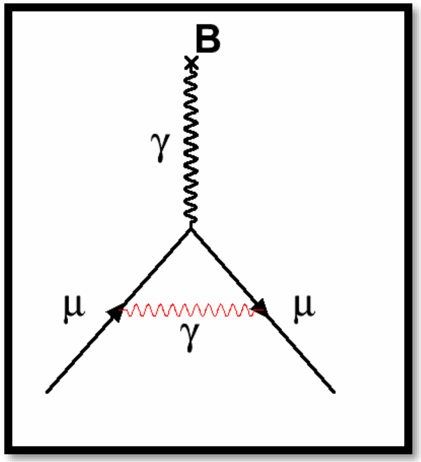

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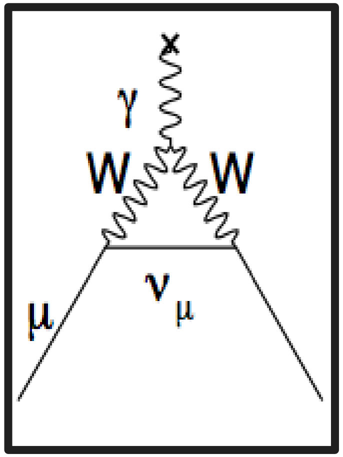

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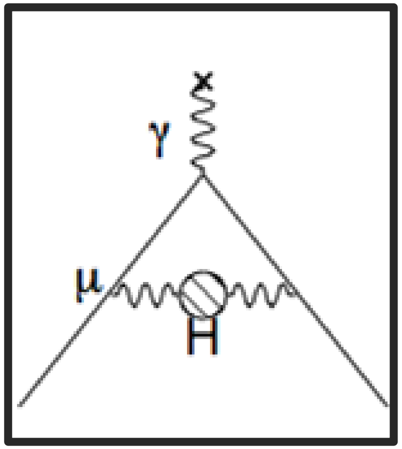


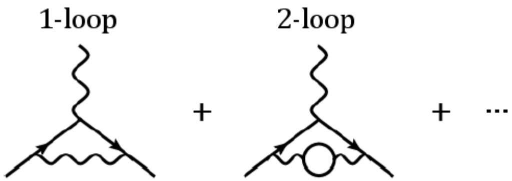
$$g = 2 + O(10^{-3})_{QED} + O(10^{-9})_{EW} + O(10^{-7})_{QCD}$$

$$a_\mu^{SM} = (g_\mu^{SM}-2)/2 = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$$

SM determination of a_μ

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had, VP}} + a_\mu^{\text{had, LbL}}$$

QED



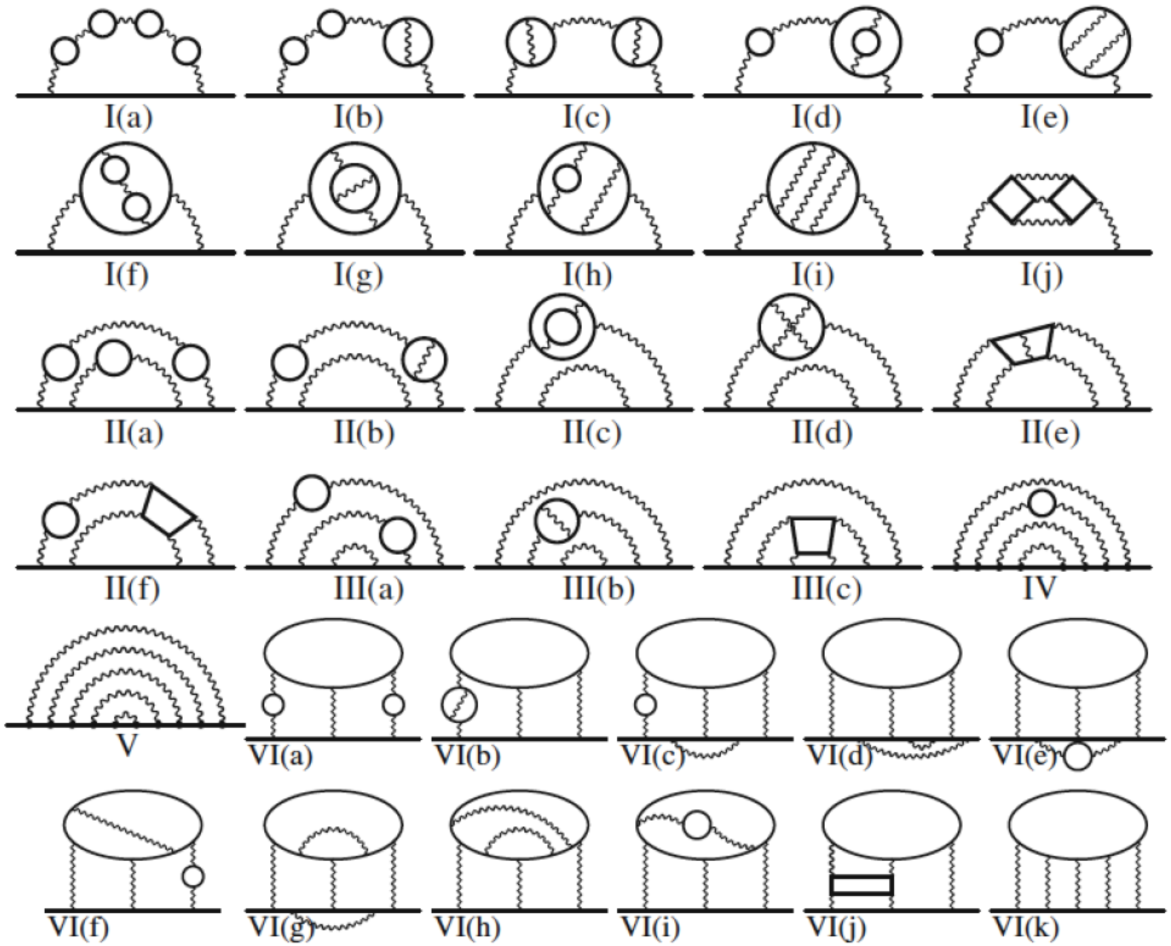
Known to five-loop (12,672 diagrams)

99.99% of a_μ^{SM} ~0.001% of δa_μ^{SM}

A Tour de force Standard Model Calc

- γ + leptons
- 12,762 5-loop diagrams!
- Kinoshita & independent cross-checks

Phys. Rev. Lett. 109 (2012) 111808, Phys. Rev. D 97 (2018) 036001.



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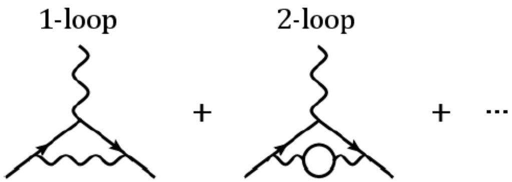
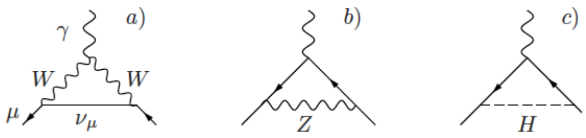


Known to five-loop (12,672 diagrams)

99.99% of a_μ^{SM} — $\sim$0.001% of δa_μ^{SM}

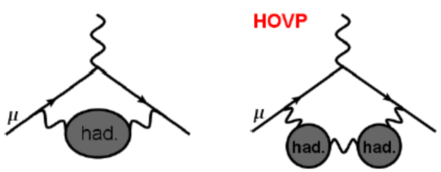
EW



Known to two-loop (with m_H known)

0.0001% of a_μ^{SM} — $\sim$0.2% of δa_μ^{SM}

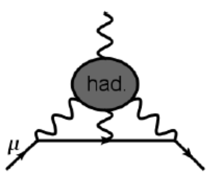
HVP



Non-perturbative (data input + lattice)

0.006% of a_μ^{SM} — $\sim$47% of δa_μ^{SM}

HLbL



Non-perturbative (data input + model/lattice)

0.0001% of a_μ^{SM} — $\sim$53% of δa_μ^{SM}

BSM

? ? ? ? ? ? ?

The Muon Theory Initiative

Great Progress with Lattice QCD

HVP: Improvements from e+e- data
Dispersion relations
Lattice QCD
Hybrid calculations

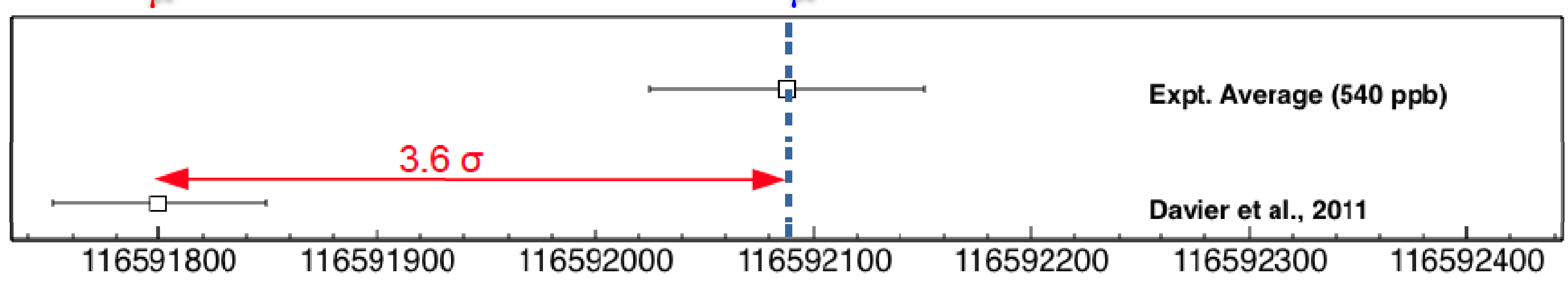
HLbL: Evaluation on parts on lattice
Dispersive approach
becoming possible

Conferences/Workshops

- Second plenary workshop of the Muon g-2 Theory Initiative at Mainz in June 18-22, 2018
- First Workshop of the Muon g-2 Theory Initiative at Q Center/FNAL in June 3-6, 2017

Theory and Experiment Disagree

a_μ^{SM} a_μ^{EXP}



a_μ [10^{-11}]

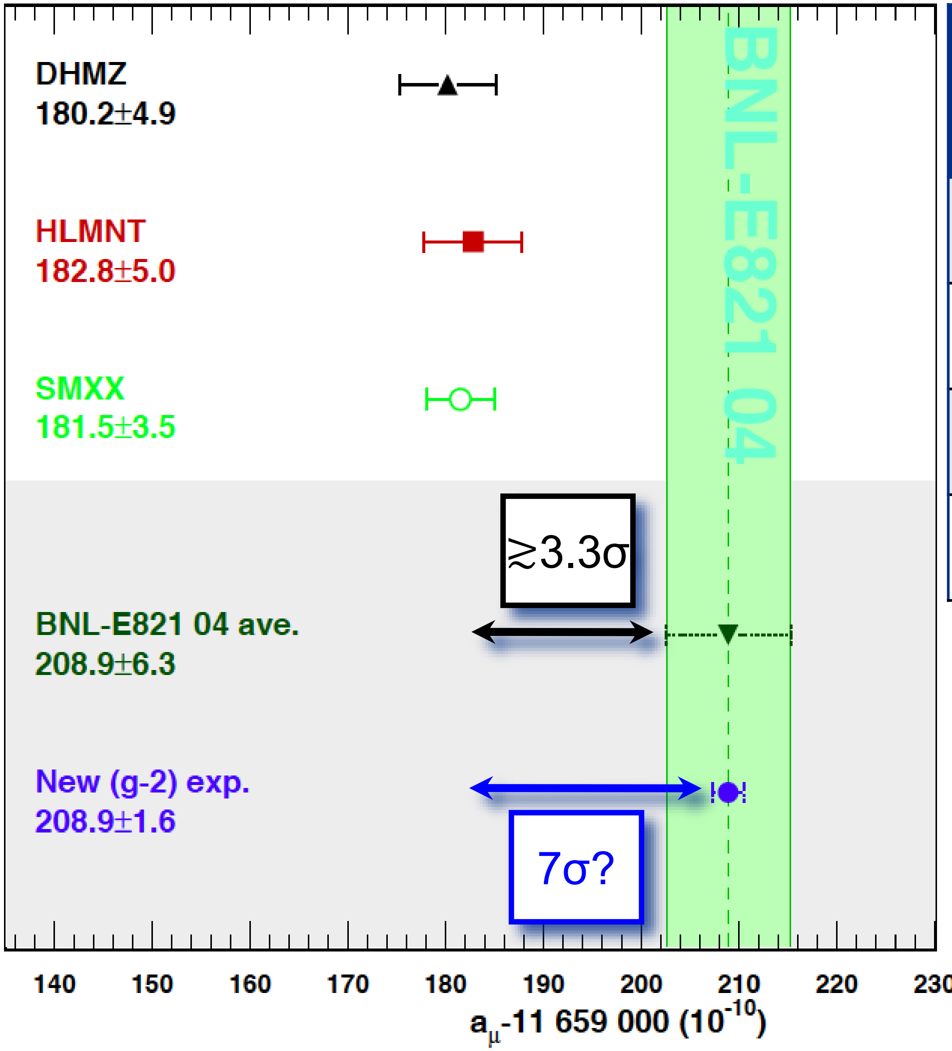
$$a_\mu^{EXP} - a_\mu^{SM} \stackrel{?}{=} a_\mu^{New\ Physics}$$

New Physics or missing systematics/statistics?

- Many Possible Models
  - ~~Dark Photons~~ (most var)
  - SUSY (~~many~~ variations)

$$a_l - a_l^{SM} \propto (m_l^2/\Lambda_{NP}^2)$$

More precise comparison of SM and experimental values of g-2 needed to reveal new physics

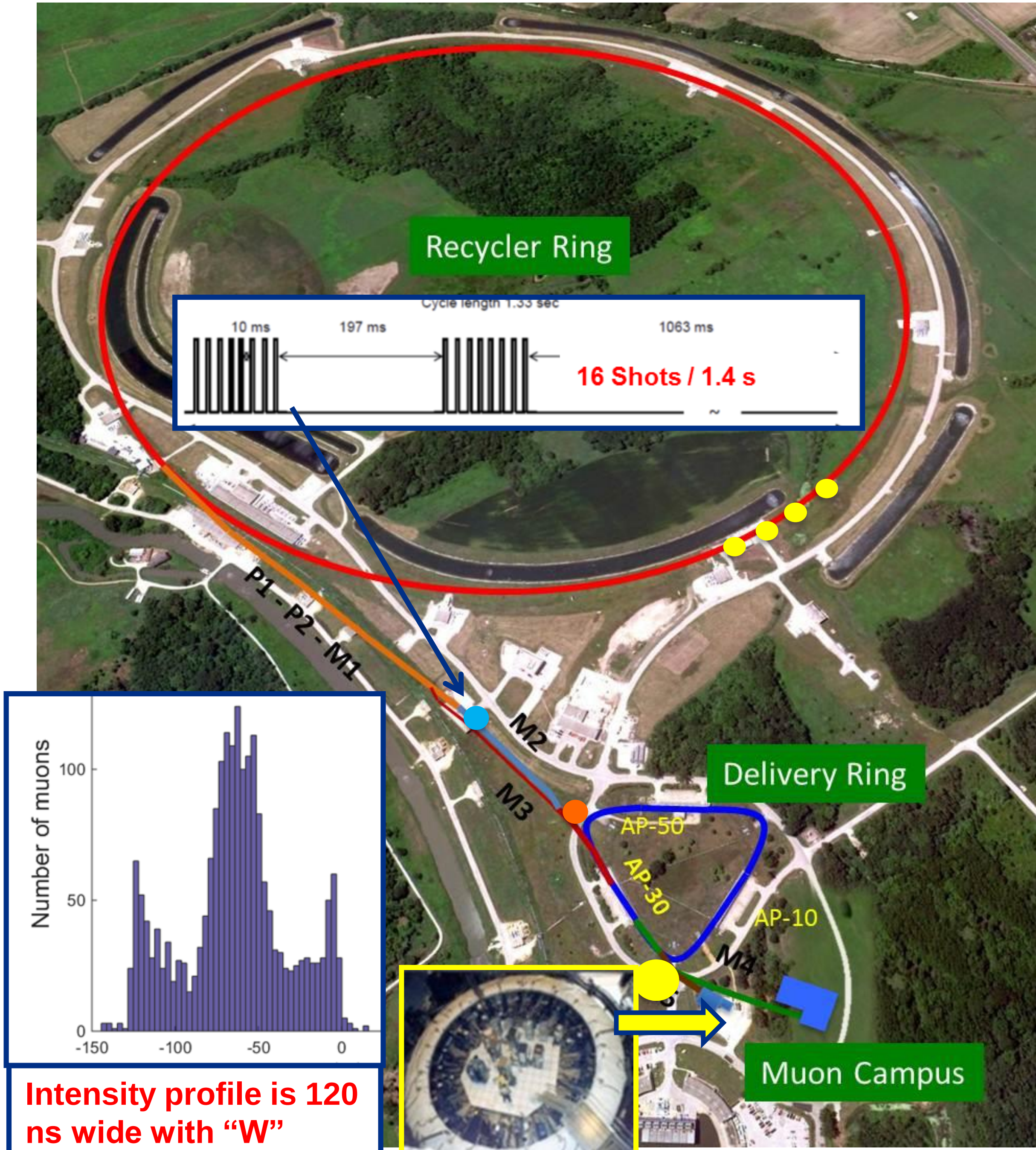


[Blum et al.,arXiv:1311.2198]

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	240?
HVP	360	215
HLbL	225	100?
Total Exp.	540	**140**

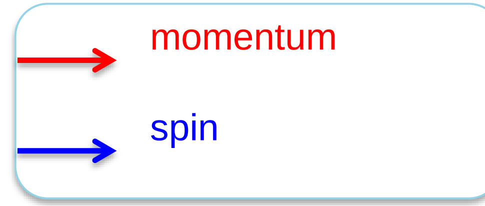
- **Combined updates expected as output of summer work**
- **Results expected in 2018**

Creating the Muon Beam for g-2



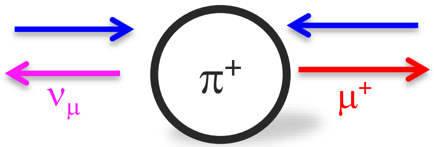
Intensity profile is 120 ns wide with "W" shape

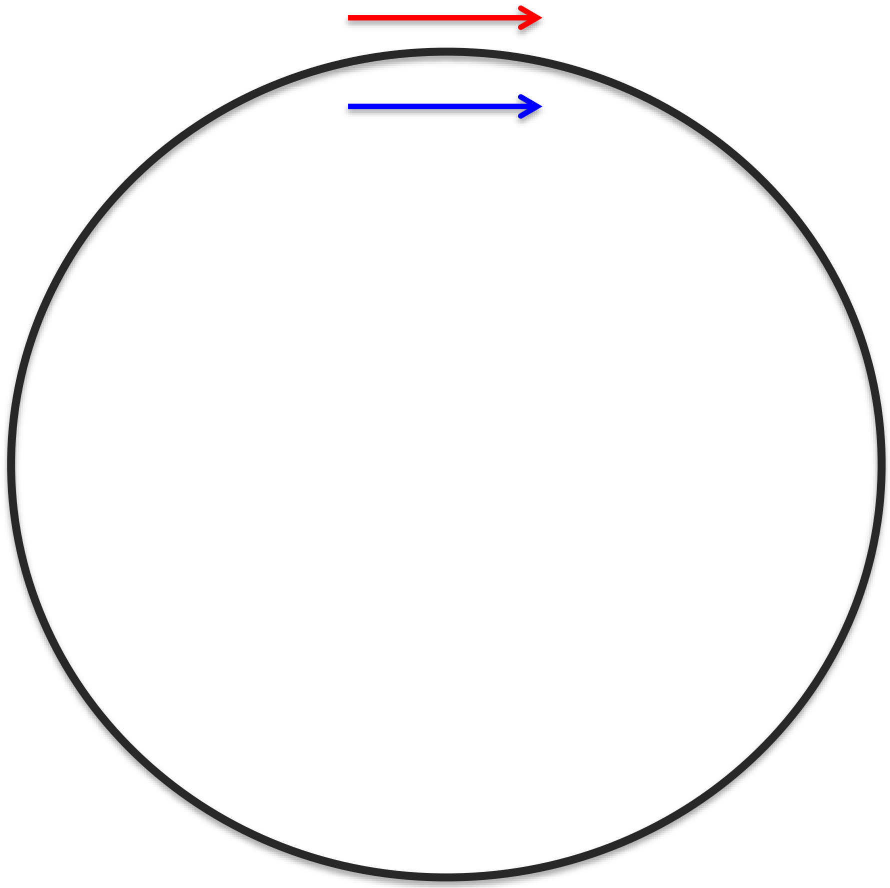
- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract each bunch to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- **~10,000 μ stored in ring per pulse (goal)**

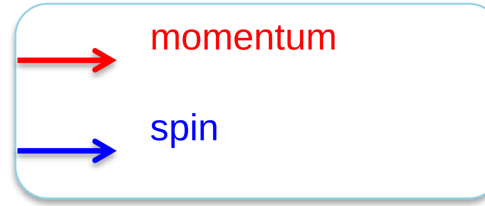


Experiment Basics: Muons in a storage ring

1. Start with polarized muon beam (from pion decay)







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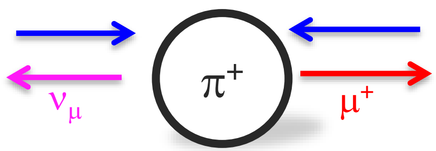
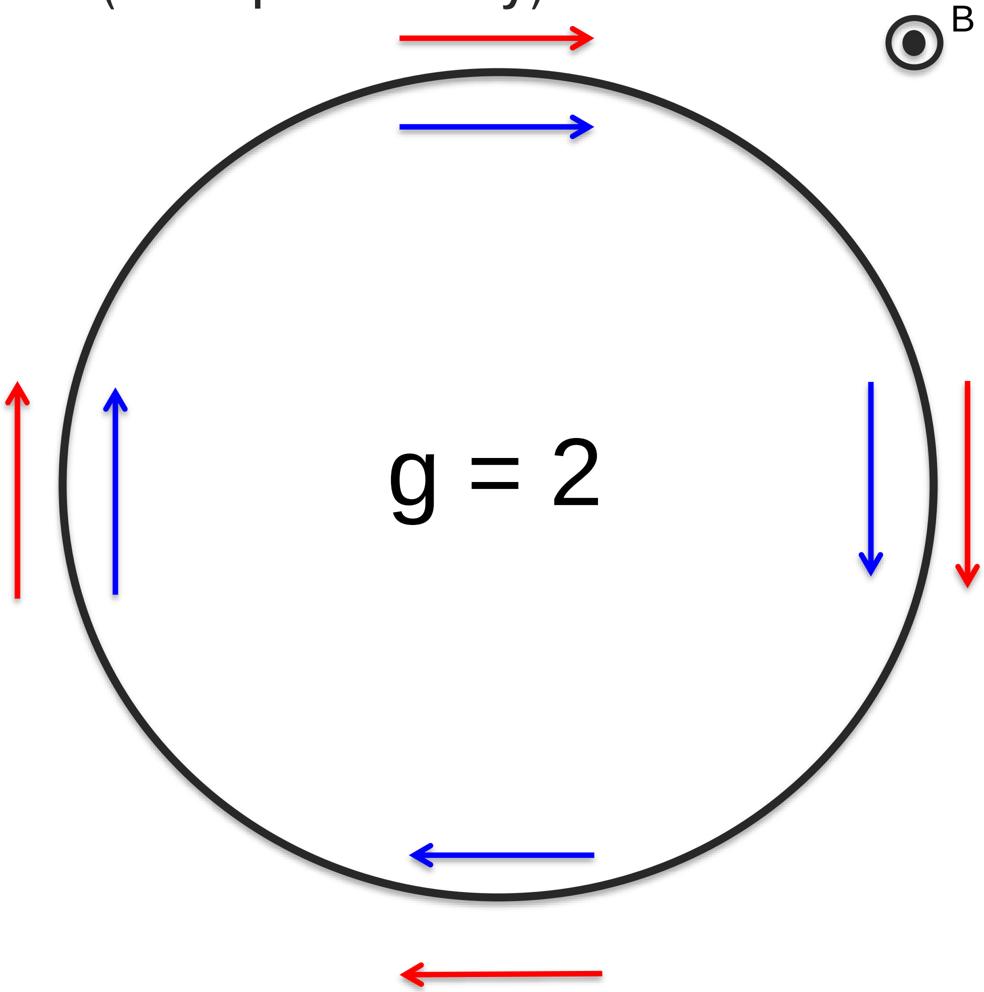


2. Cyclotron frequency :

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

3. Spin precession frequency :

$$\omega_S = \frac{e}{m\gamma} B\left(1 + \gamma a_\mu\right)$$



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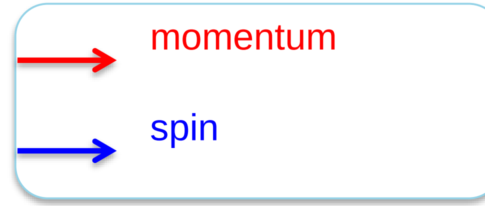

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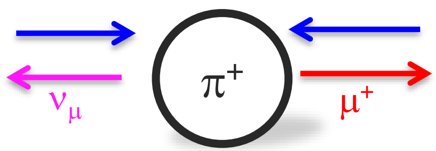

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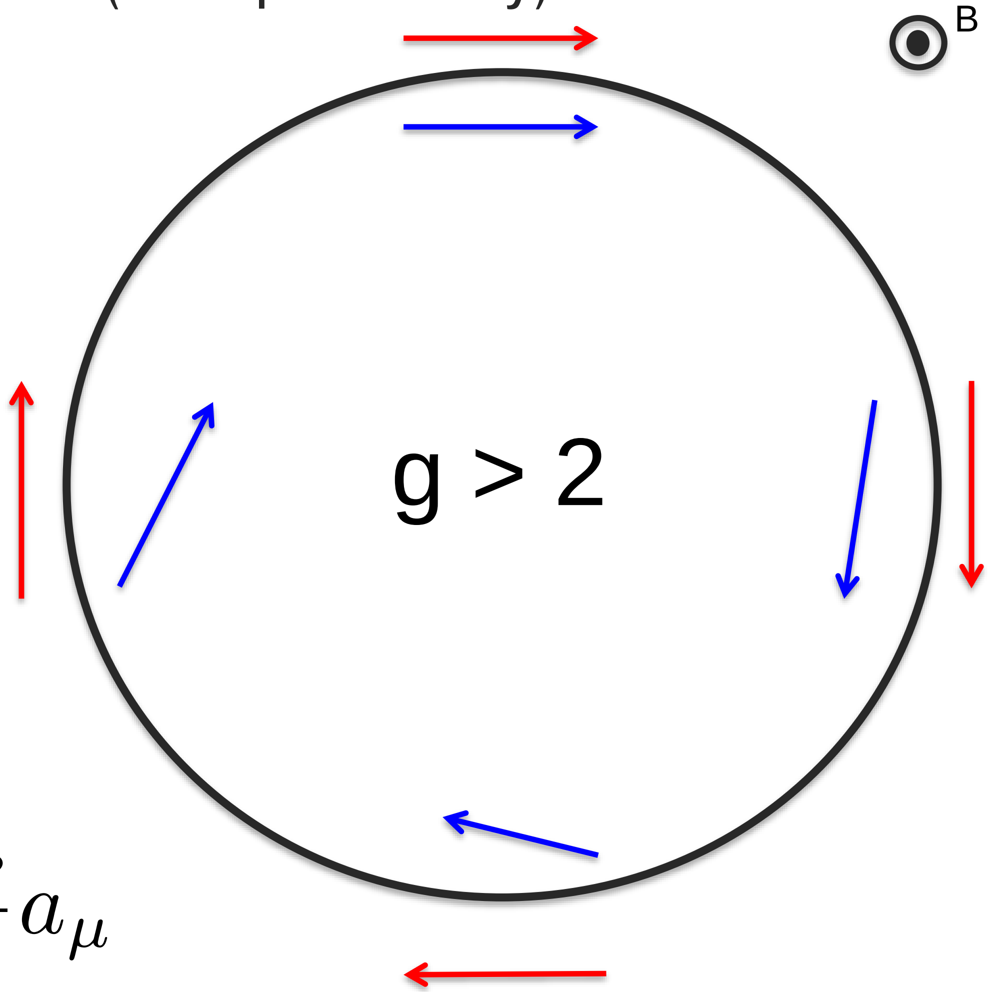


$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$

Muon g-2 Measurements

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

B via NMR → ω_p proton precession frequency,

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$$\delta\left(\frac{m_\mu}{m_e}\right) \sim 25\,\text{ppb}$$

$$\delta\left(\frac{\mu_e}{\mu_p}\right) \sim 8\,\text{ppb}$$

$$\delta\left(\frac{g_e}{2}\right) \sim 0.3\,\text{ppt}$$

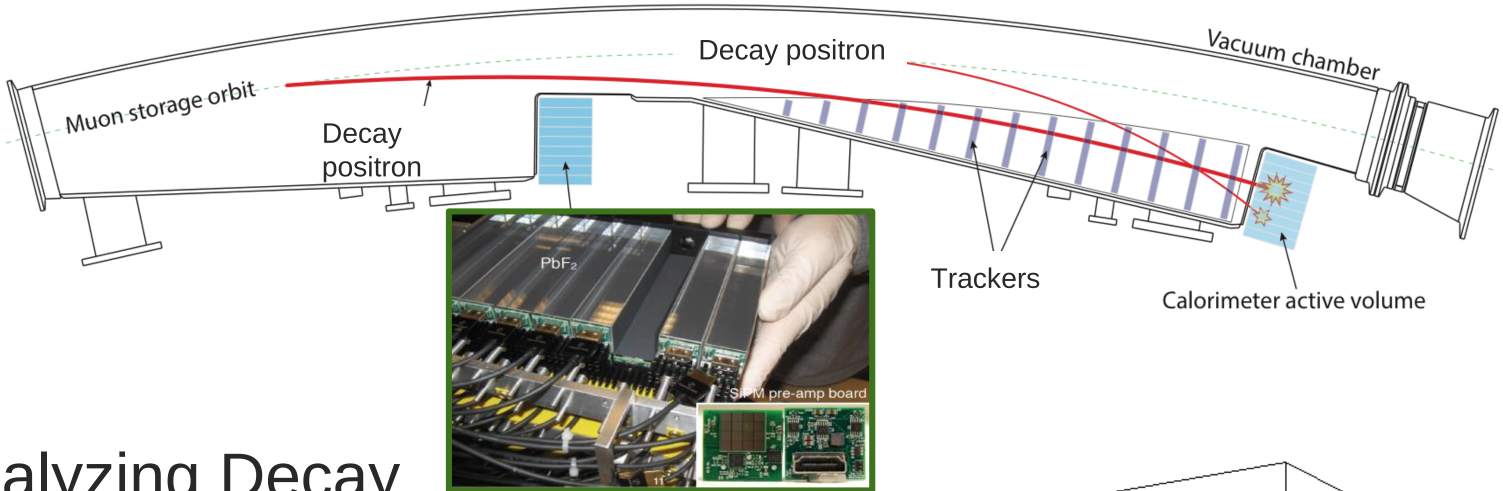
Muon g-2 Measurements

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

B via NMR → ω_p proton precession frequency,

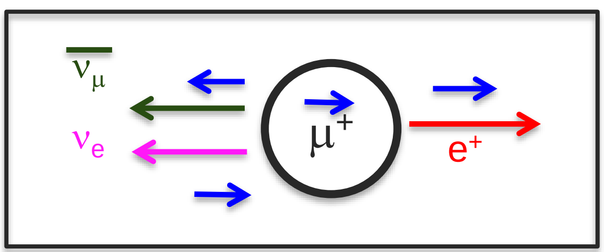
$$a_\mu\,(Expt) \approx \frac{\boldsymbol{\omega_a}}{\boldsymbol{\omega_p} \otimes \boldsymbol{\rho}(\boldsymbol{r})}$$

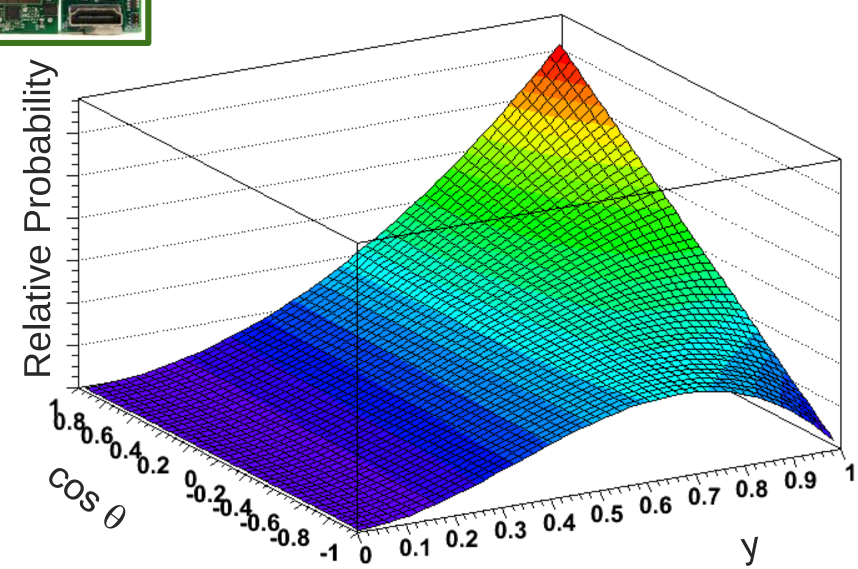
Muon spin precession frequency



Self-Analyzing Decay

- Energy Direction Correlation



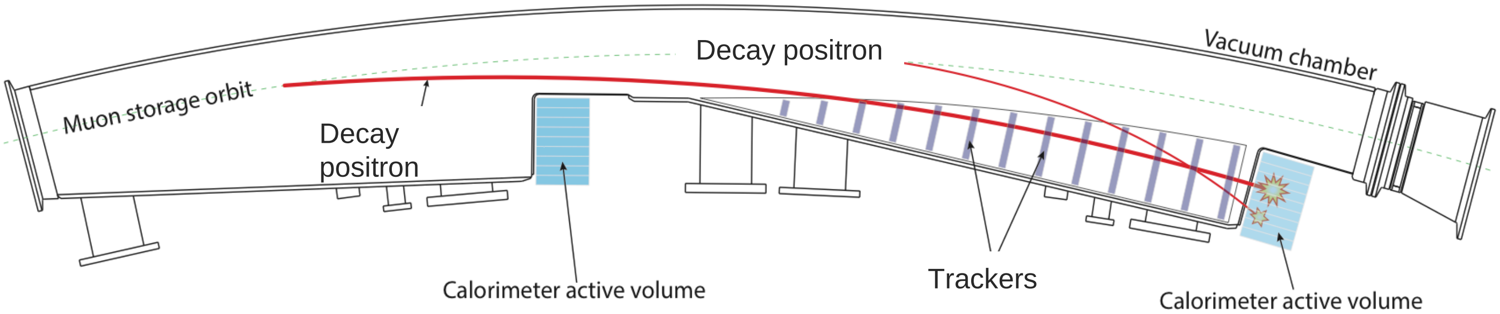


$$dP(y,\theta) \propto n(y)[1 \pm A(y)cos\theta]dyd\Omega$$

$$\theta = \cos^{-1}(\hat{p}_e \cdot \hat{s})$$

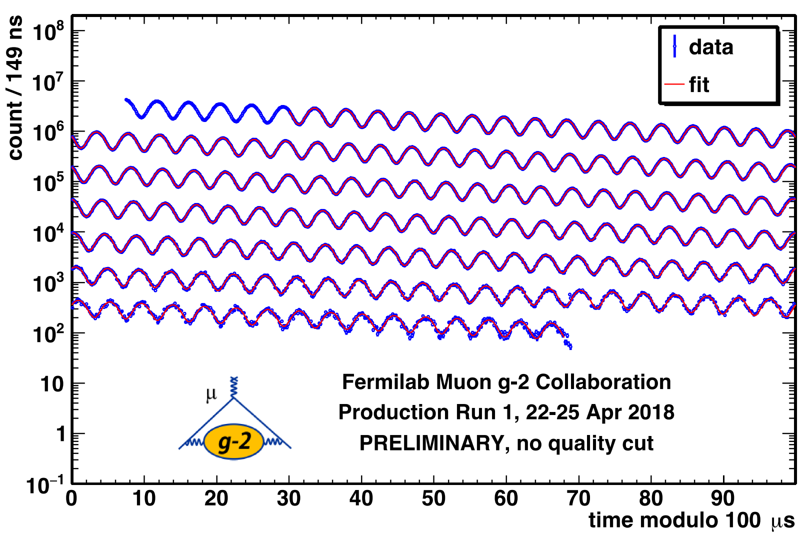
$$y = E_e/E_e\max$$

Muon spin precession frequency



E989 data: e^+ with E > 1.8 GeV

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



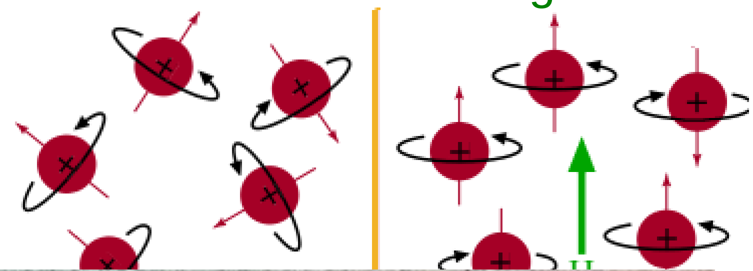
$$N(t) = N_0 e^{-t/\tau} \left(1 + A cos(\omega_a t + \phi)\right)$$

Proton Precession Frequency: How We Measure

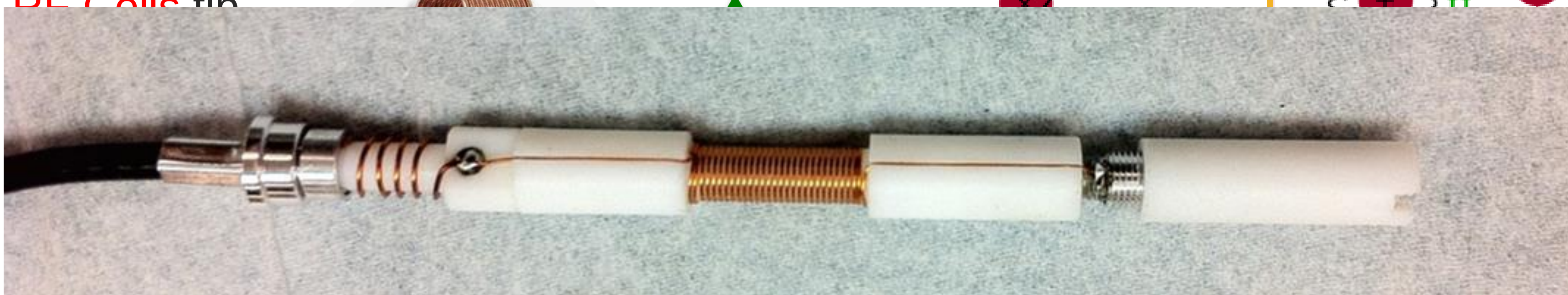
- Nuclear Magnetic Resonance (NMR)
  - Extremely Precise (~10 ppb)
  - Measures Total Field

Proton-rich sample

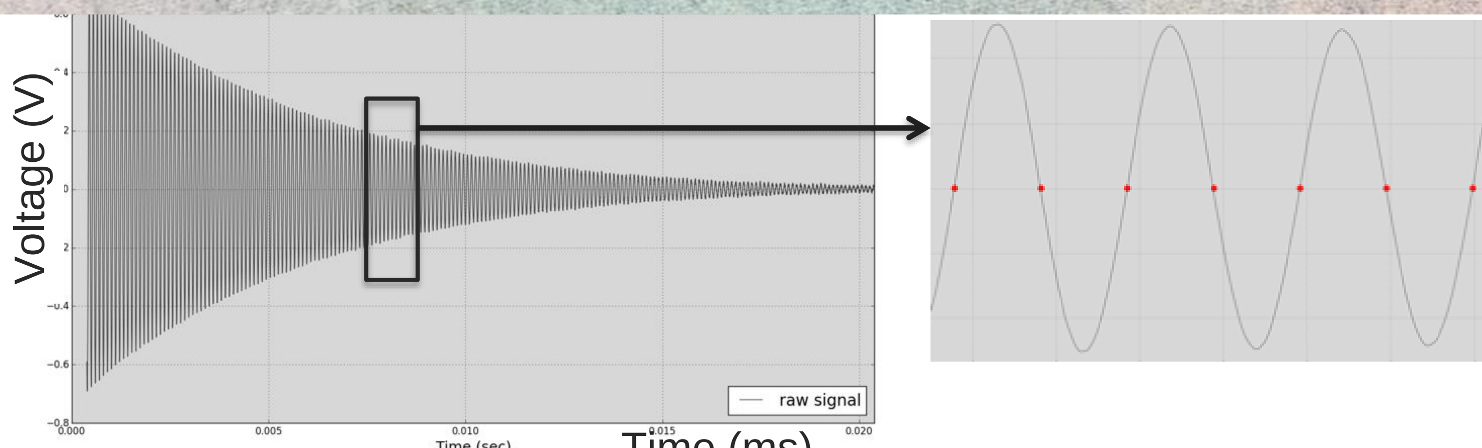
- Turn on magnetic field



RF Coils tip

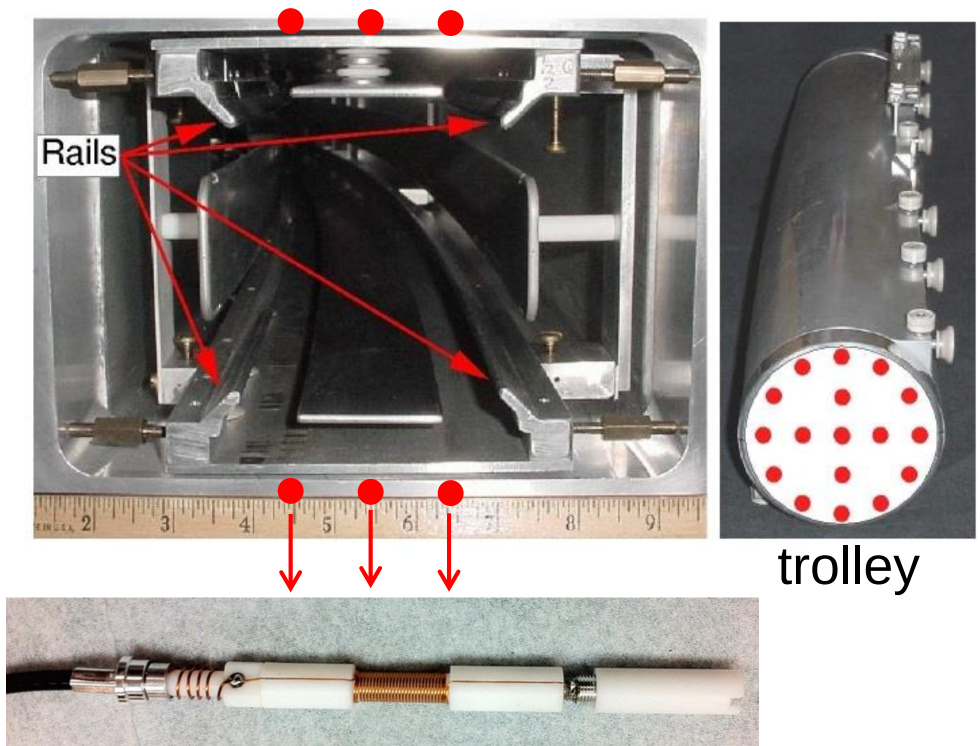


Digitize to extract ω_p



Measurement principle for the magnetic field

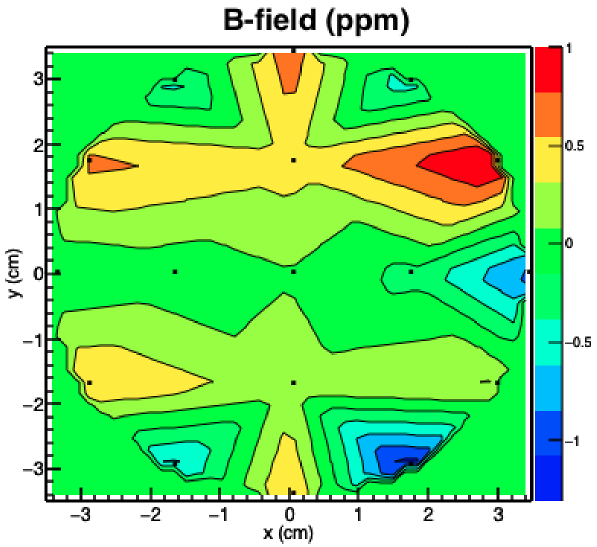
- Map the storage field regularly during beam off periods with trolley
- Monitor the field with 400 fixed NMR probes around the ring



trolley

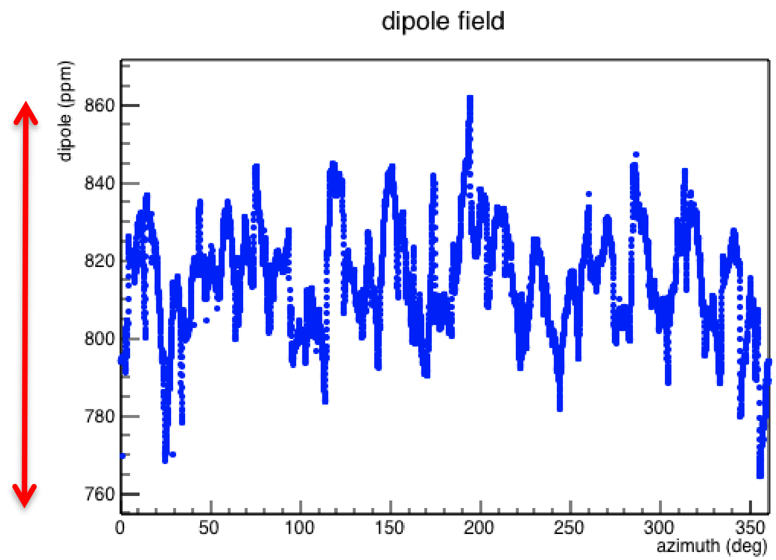
Fixed NMR probes

Field: Production Trolley Runs



	Norm	Skew
Quad	-0.19	0.28
Sext	0.05	0.27
Octu	-0.07	0.25
Decu	0.23	0.07
Dipole	-0.0	

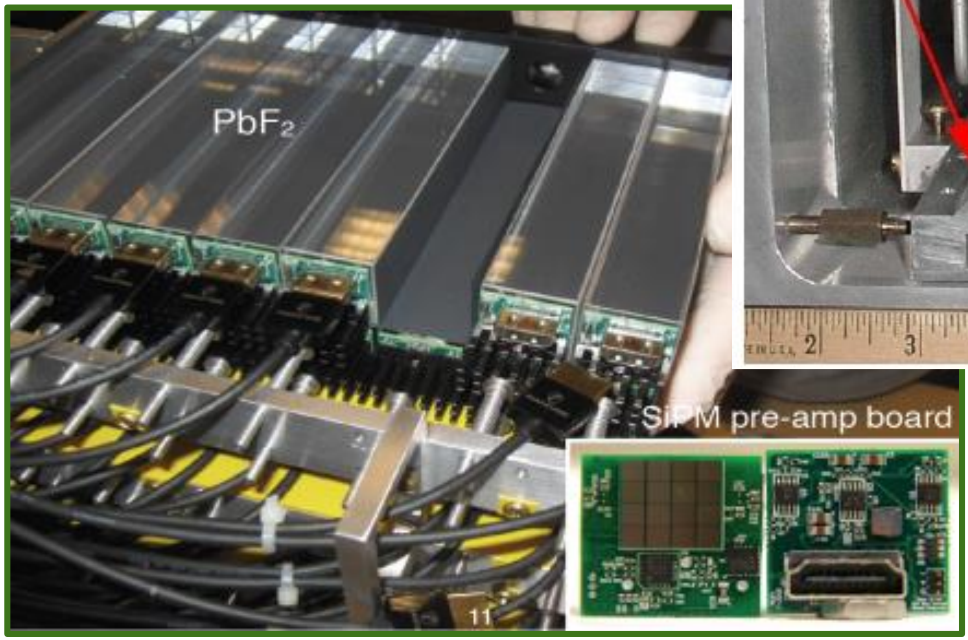
100 ppm

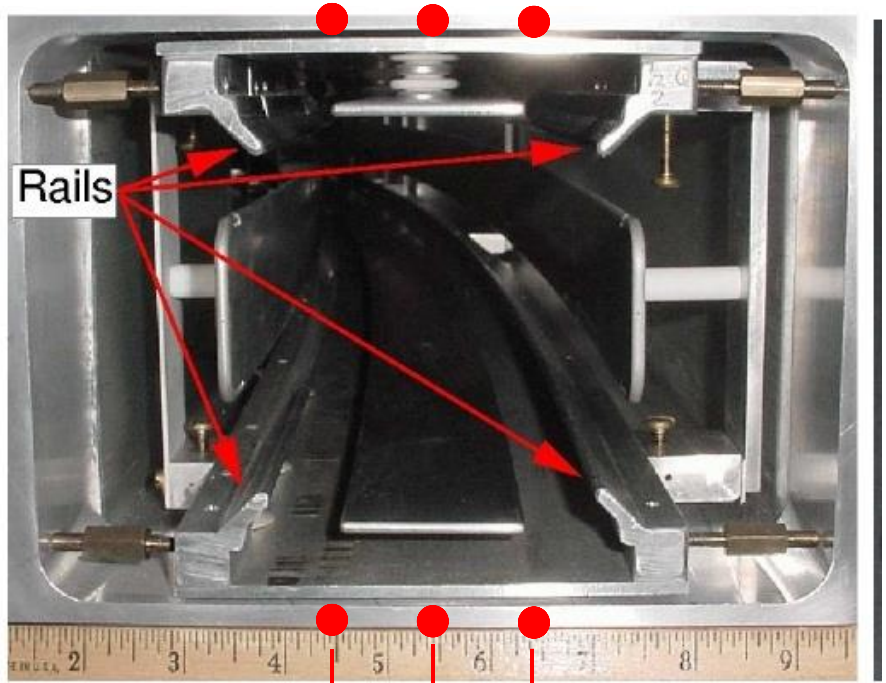


- Moments all < 0.28 ppm! Goal was < 0.5 ppm
- Variation of field +/-1ppm over storage region
- BNL +/-2 ppm

- **Dipole RMS =14.2 ppm**
- BNL RMS = 29 to 39 ppm

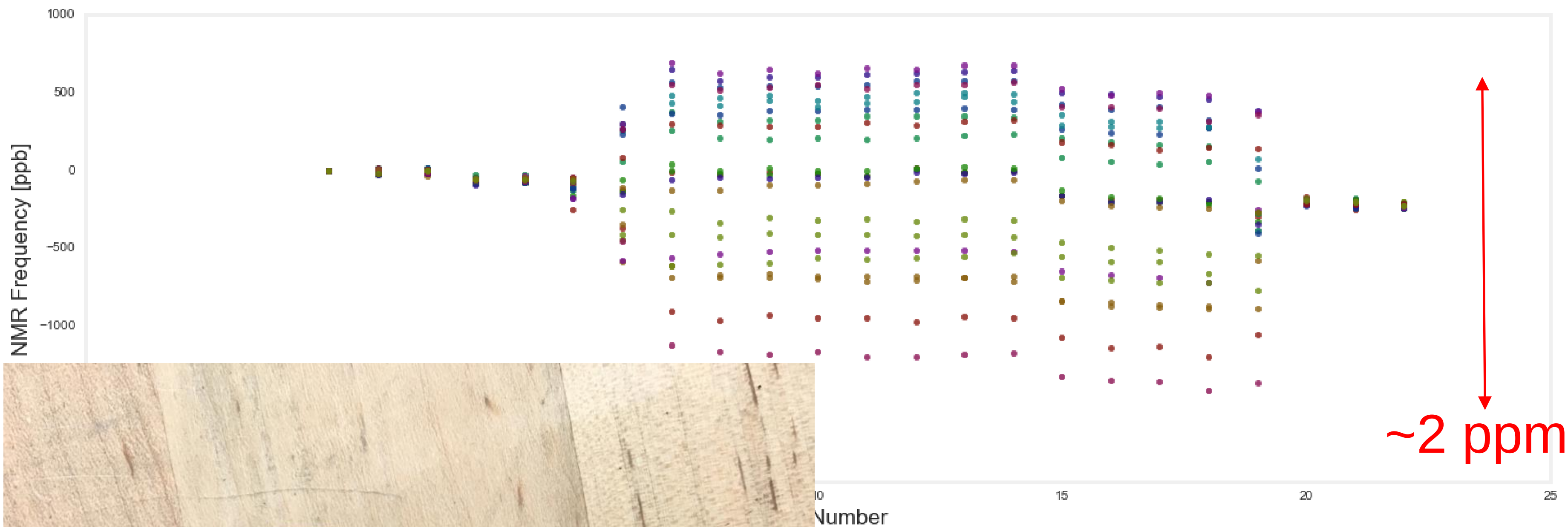
Aside: Precision Measurements





< 10 cm

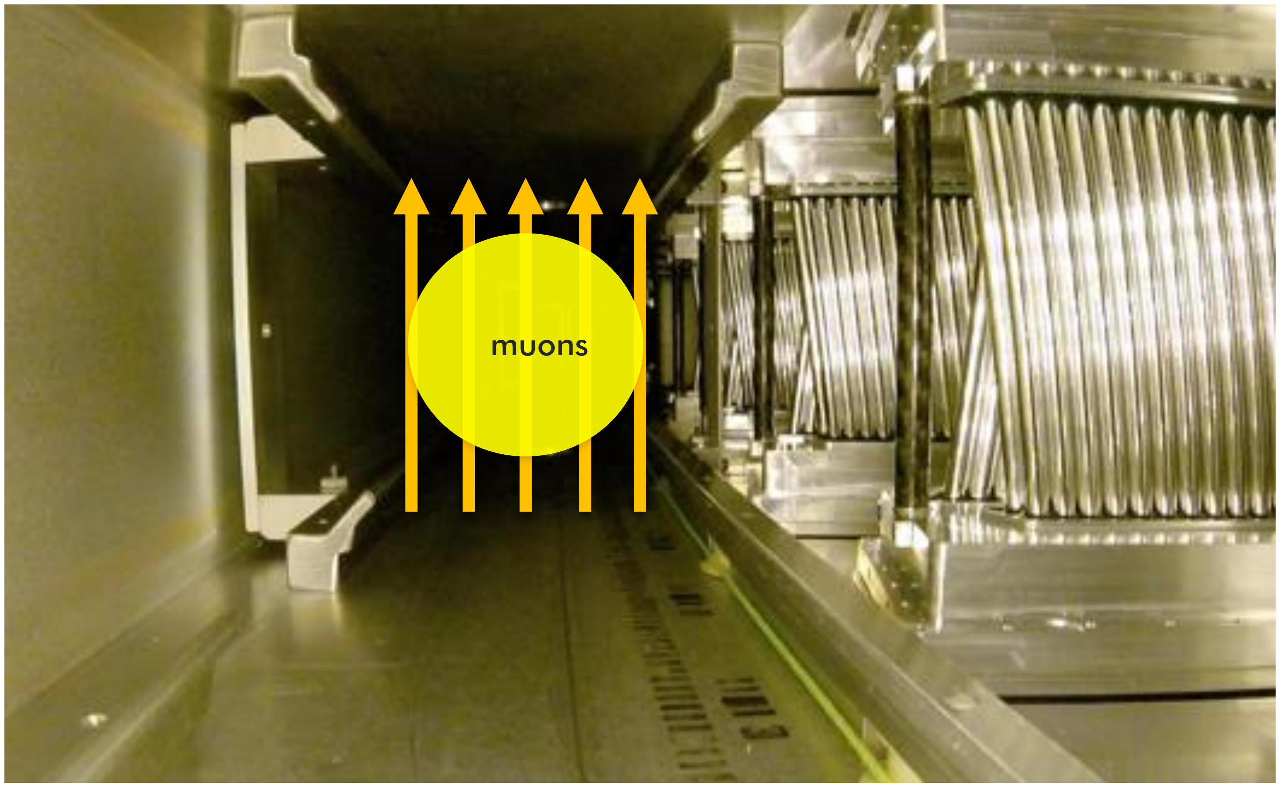
Aside: Precision Measurements → Calculate or Measure!



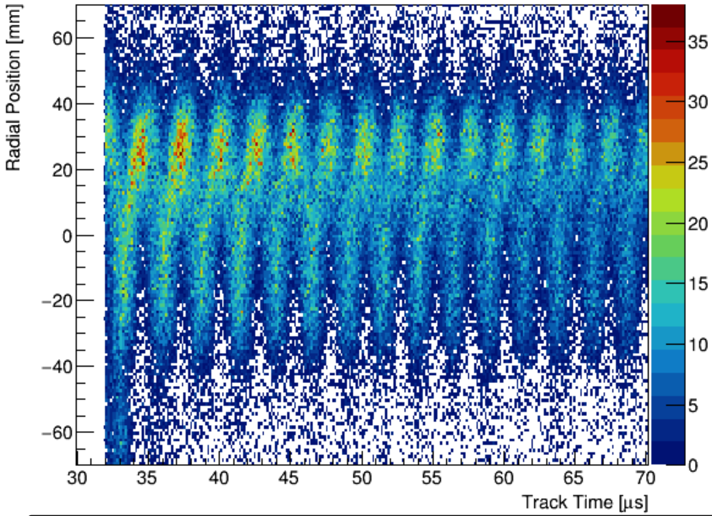
$$a_\mu\ (Expt) \approx \frac{\omega_a}{\omega_p \otimes \rho(r)}$$

B-field = 1.45 T

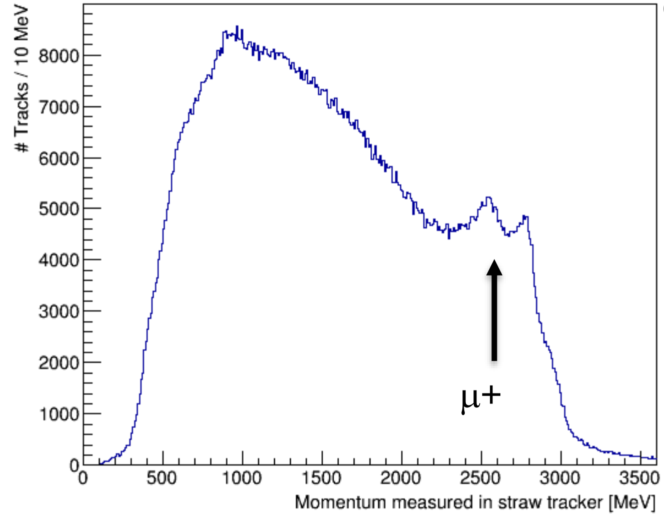
Tracking detectors measure the muon beam.

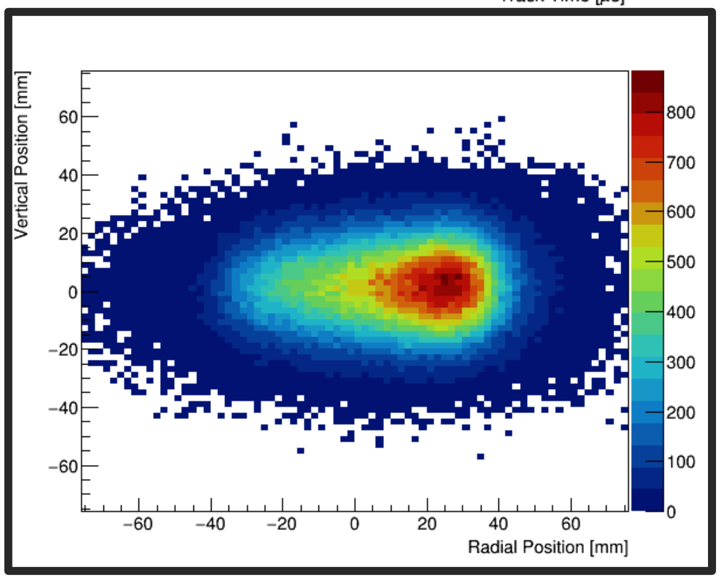


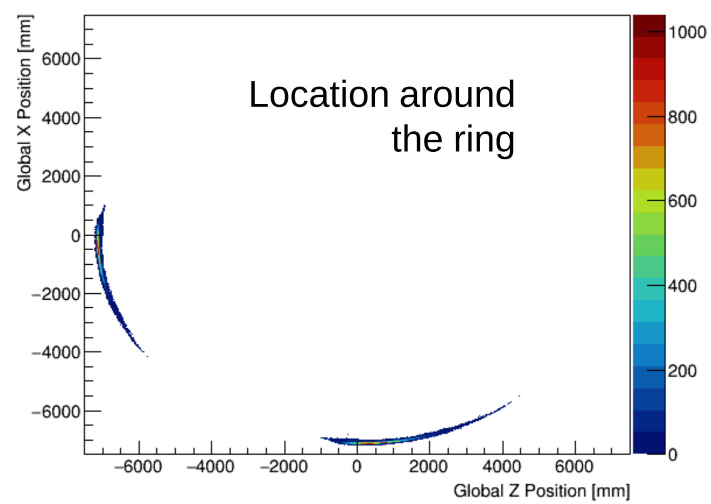
Detector: Offline+OnlineTrackers



e+ momentum dist

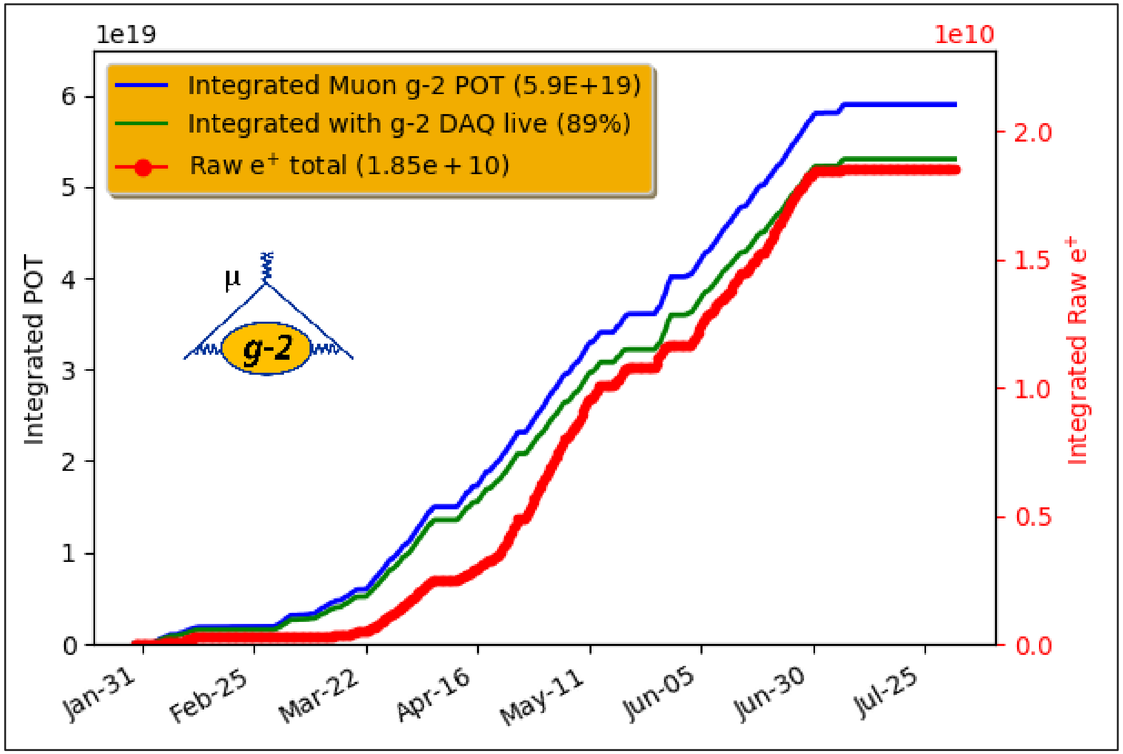






Plots from J. Mott

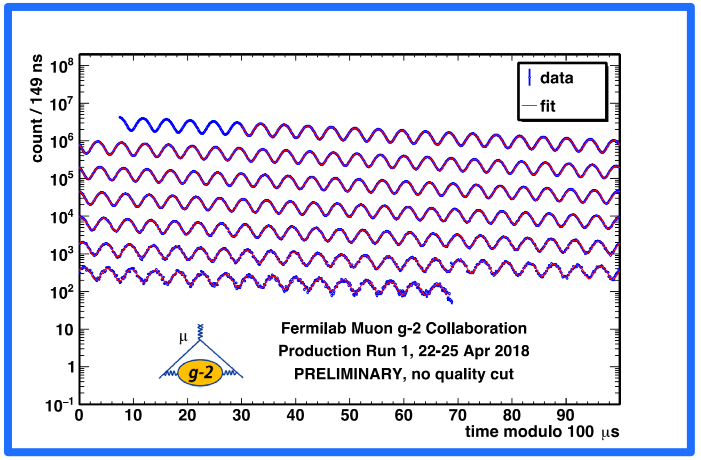
Performance

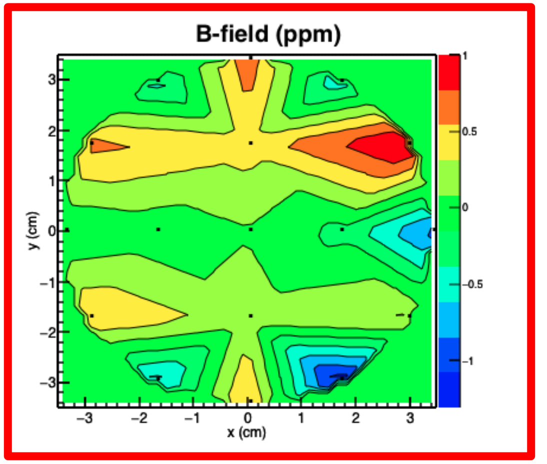


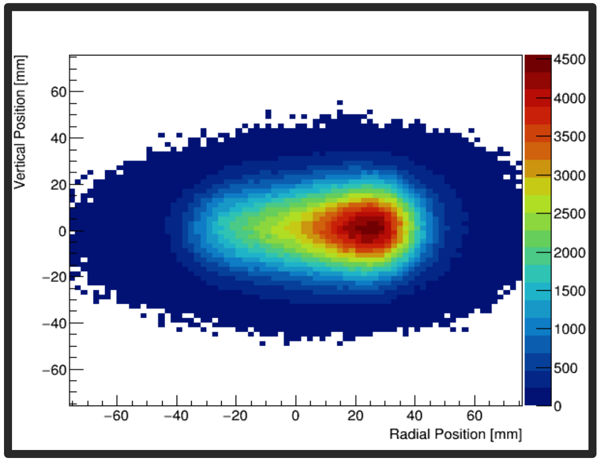
- Commissioning Nov → Feb
- Started full running w/ all systems installed Mar 22 2017
- Accumulated 1.85e10 raw decay positrons!
  - BNL 0.939e10 total w/ quality cuts [raw e^+ now ~2x BNL]

g-2 Summary

$$a_\mu(\mathrm{Expt}) \approx \frac{\omega_a}{\omega_p \otimes \rho(r)}$$







- The Muon g-2 Experiment @ FNAL is underway
  - Collected raw stats ~2x BNL
  - Analyses are well underway
  - Projected first results in 2019
- We are very excited to hear updates on the theory progress
  - Great progress on lattice
  - Improvements in dispersive approach for both HVP and HLbL

Baryon Asymmetry of Universe

- Observed asymmetry:

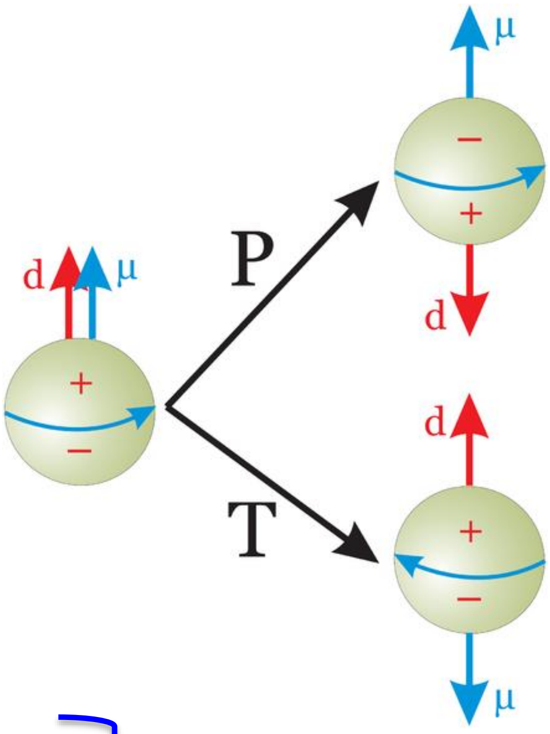
$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10}$$

- Existing CP-Violation insufficient to explain observation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

- Assuming asymmetry not present at the Big Bang, looking for New sources of CP-Violation
  - neutrinos, permanent EDMs, etc…

EDM Basics



- Permanent Electric Dipole Moments are good candidates
  - T- & P-Violating
  - → CP-Violating (Assuming CPT)

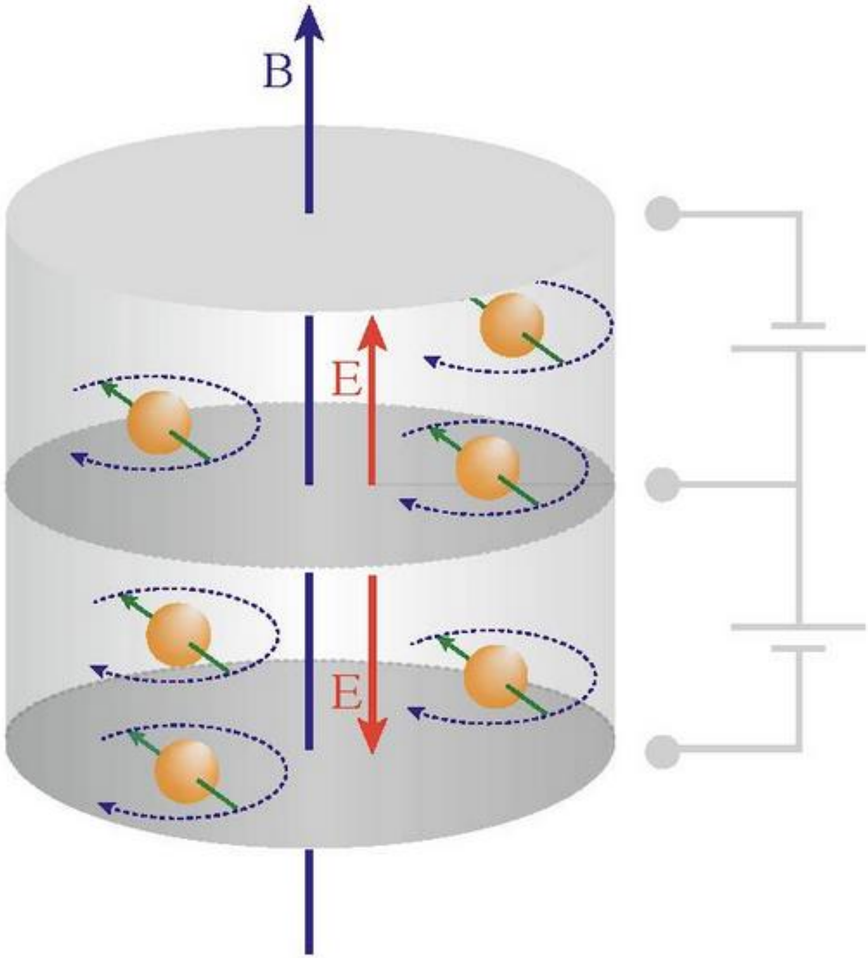
- Types of EDMs
  - Nucleon EDM (n,p)
  - Bare lepton (e, μ)
  - Paramagnetic Atoms/Molecules → Electron EDM, nuclear-spin independent coupling
  - Diamagnetic Atoms → Nuclear Shiff moment, nucleon EDM, or nuclear-spin-dependent electron-nucleon interaction

Theory must interpret

- ANY detection of an EDM would be very significant
  - So far, experiments have set impressive limits

Ref: Theory: Engel, Musolf arXiv:1303.2371.
Exp: Chupp, Fierlinger, Musolf, Singh https://arxiv.org/abs/1710.02504

Typical EDM Technique



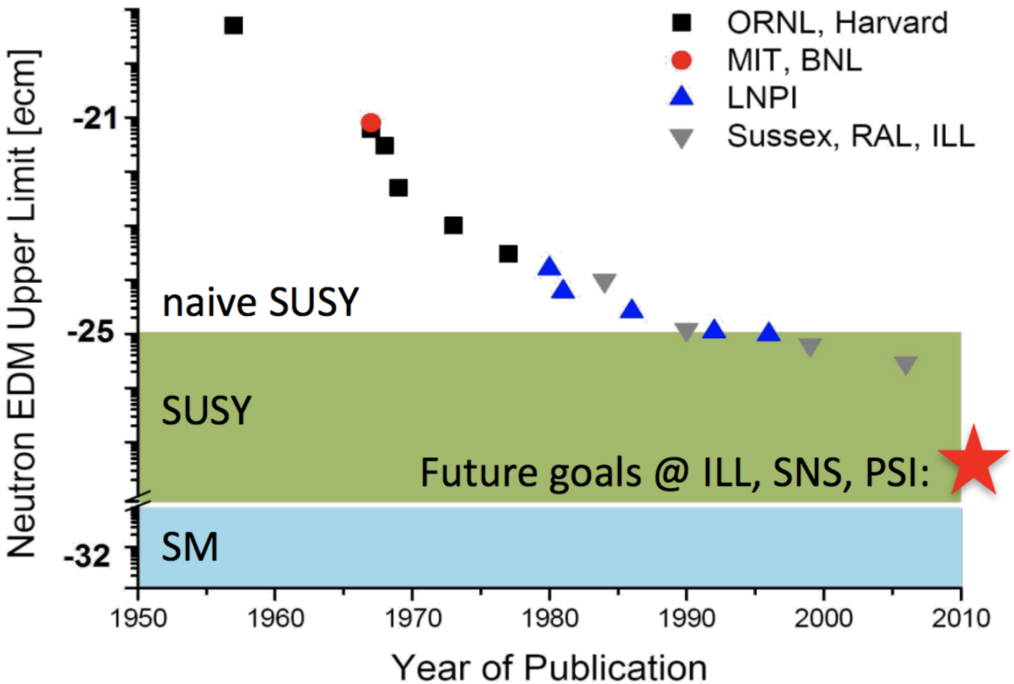
1. Set up constant magnetic field
2. Bring neutral particle into the field
3. Rotate particle so that it precesses about the B-field
4. Add Electric field Parallel to field (alternate aligned/anti-aligned)
5. A permanent intrinsic EDM will manifest as a difference in the Larmor precession frequencies

$$\omega(E\uparrow, E\downarrow) = 2\mu B \pm 2dE$$

$$\Delta\omega = 4dE$$

6. Steps 6-100: Systematic variations of all of the knobs

Neutron EDM projections as of Dec 2017



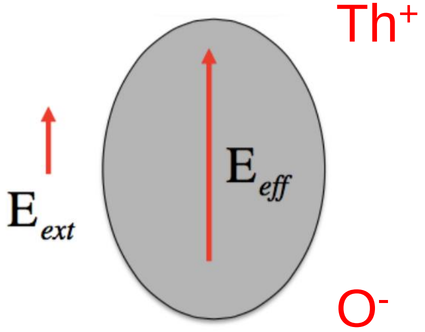
Component demo

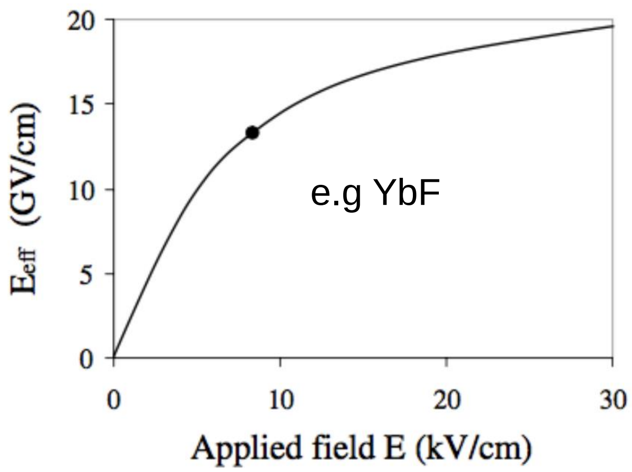
Project	Status	Sensitivity goal (E-27 *ecm*)	Schedule (start data-taking)
LANL	2017:UCN source upgrade finished	UCN density sufficient for O(1)	2019
TUM-ILL	TUM apparatus moves to ILL	O(0.1)	2019
PNPI	At PNPI 2020	PNPI: 0.5	PNPI later
SNS	Critical component demonstration concluded	0.2	2022
TRIUMF	2017: first UCN 2-3 years for experiment	O(1)	2019
PSI	Phase(1) data-taking concluded Phase(2) construction	Phase 1: O(10) Phase 2: O(1)	Phase(2): 2020
ESS	Demonstration phase at ILL	O(0.1) ?	2025

EDMs of Paramagnetic Polar Molecules

- Schiff Enhancement → Amplify external E field → Extreme internal fields

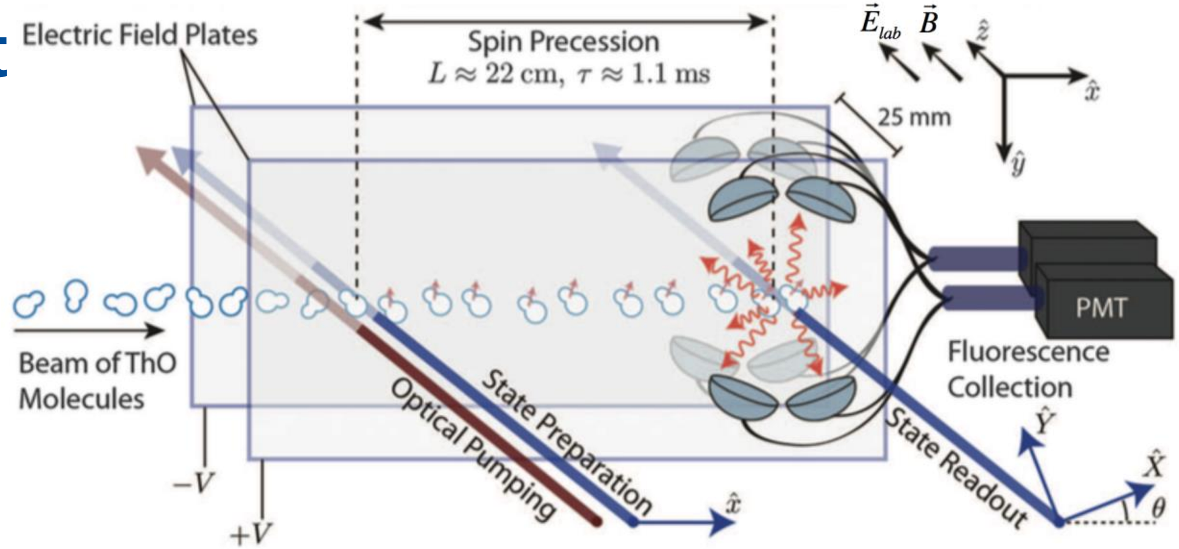
$$\Delta E \simeq E_{eff}(E_{ext})\, d_e$$

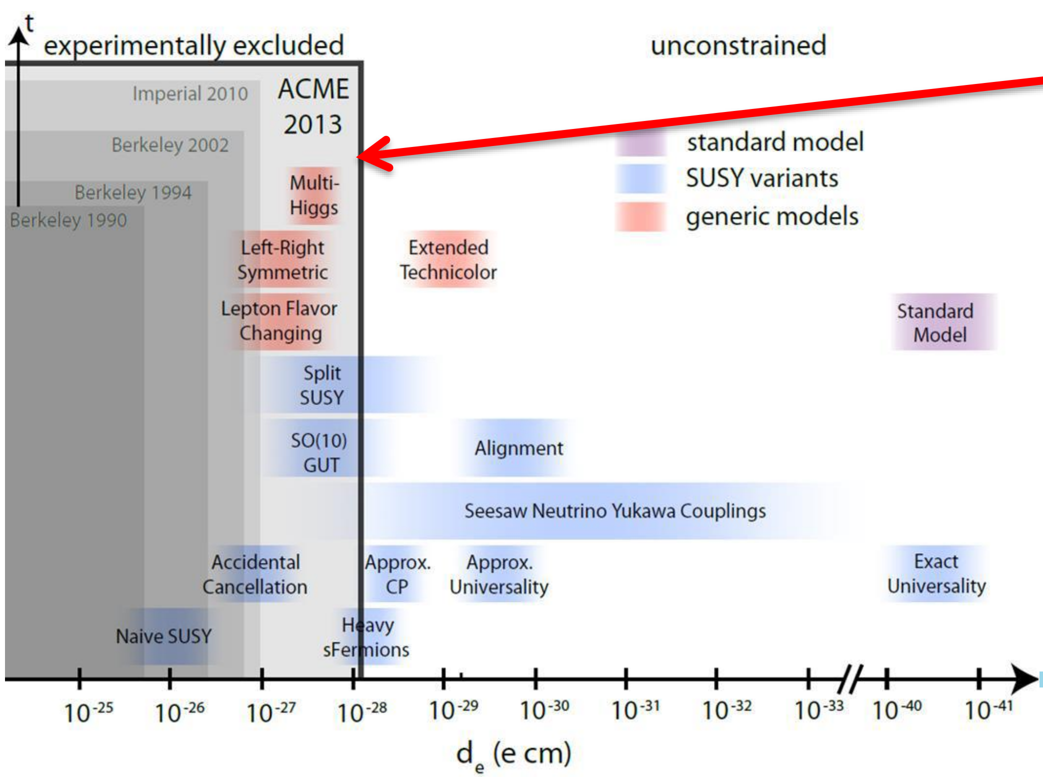




For ThO: E_{ext} ~ 10 V/cm → E_{eff} ~ 80 GV/cm !

ACME Experiment





Impressive new limit

$$|d_e| < 1 \times 10^{-28}\ e{\cdot}\mathrm{cm}$$

(90 % CL)

Models constrained

10x improvement (or detection??) in preparation

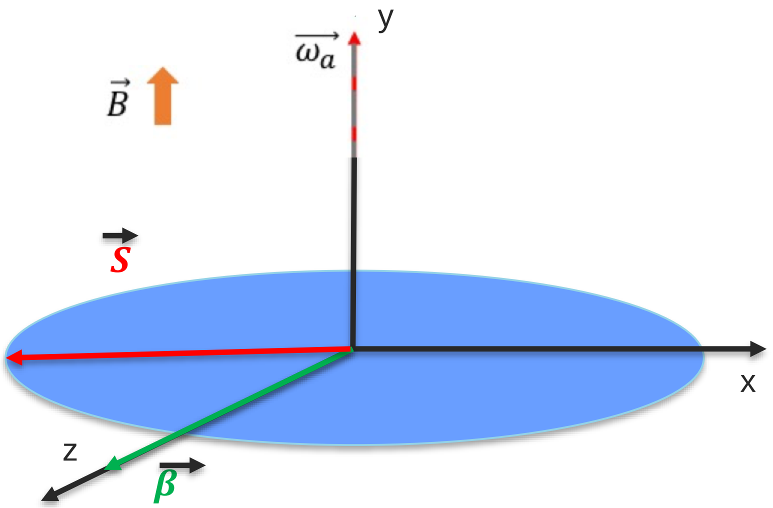
A Muon EDM modifies the muon precession

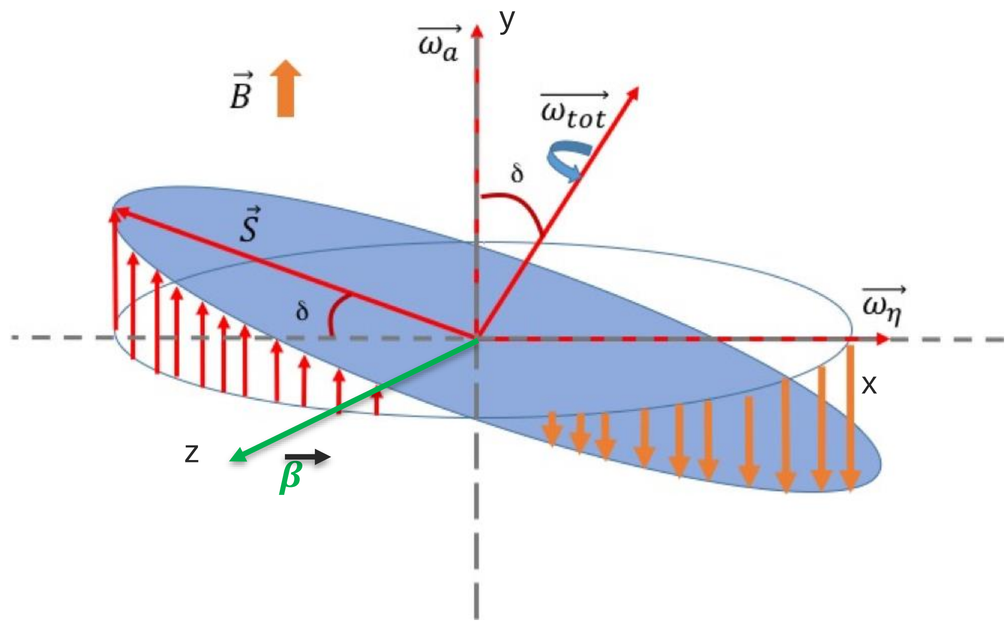
$$\boldsymbol{\omega}_{tot} = \boldsymbol{\omega}_a + \boldsymbol{\omega}_\eta = \frac{e}{mc}\left[a_\mu \boldsymbol{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\boldsymbol{\beta} \times \boldsymbol{E}\right] + \eta \frac{e}{2m}\left[\frac{\boldsymbol{E}}{c} + \boldsymbol{\beta} \times \boldsymbol{B}\right]$$

Choose $\gamma = 29.3$ → coefficient vanishes

Electrostatic quads vertically contain μ

$$\vec{d}_\mu = \frac{\eta}{2}\frac{e\hbar}{2m_\mu c}\vec{S}$$





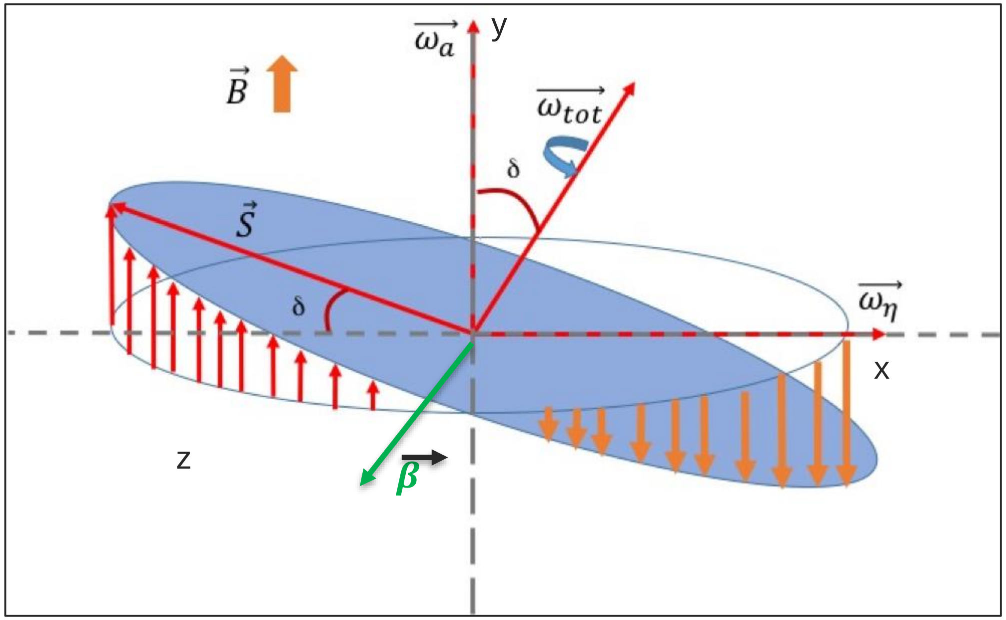
- With just MDM in uniform B field, the spin precesses around B field

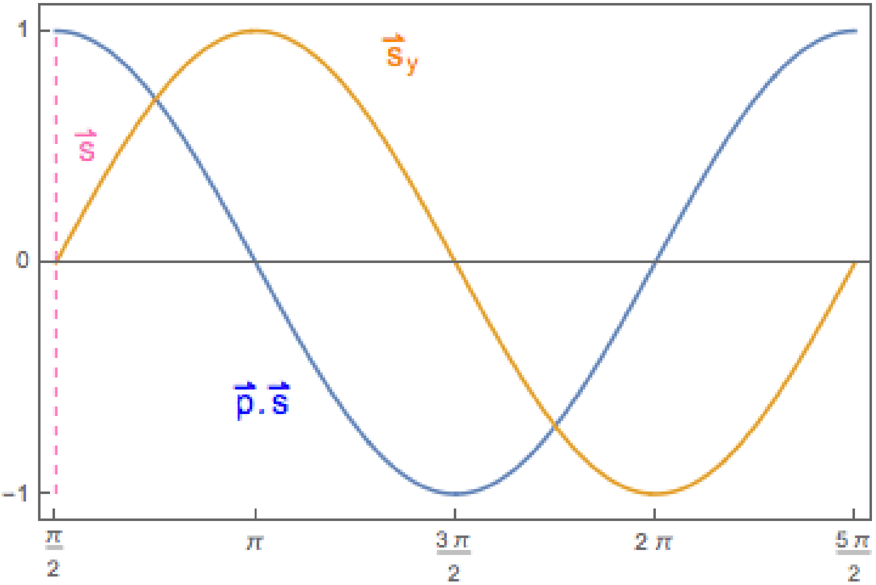
- An EDM tips the spin precession plane, modifies $\boldsymbol{\omega}_{tot}$

Muon EDM Signal

- Muon polarization has vertical component S_y

Maximized when $\boldsymbol{\beta} \cdot \boldsymbol{S} = 0$





EDM signal: an oscillation with in the average vertical angle of the e+ that:

- has frequency ω_{tot} (~ ω_a)
- is 90° out of phase with g−2 oscillation
- has amplitude ∝ EDM magnitude

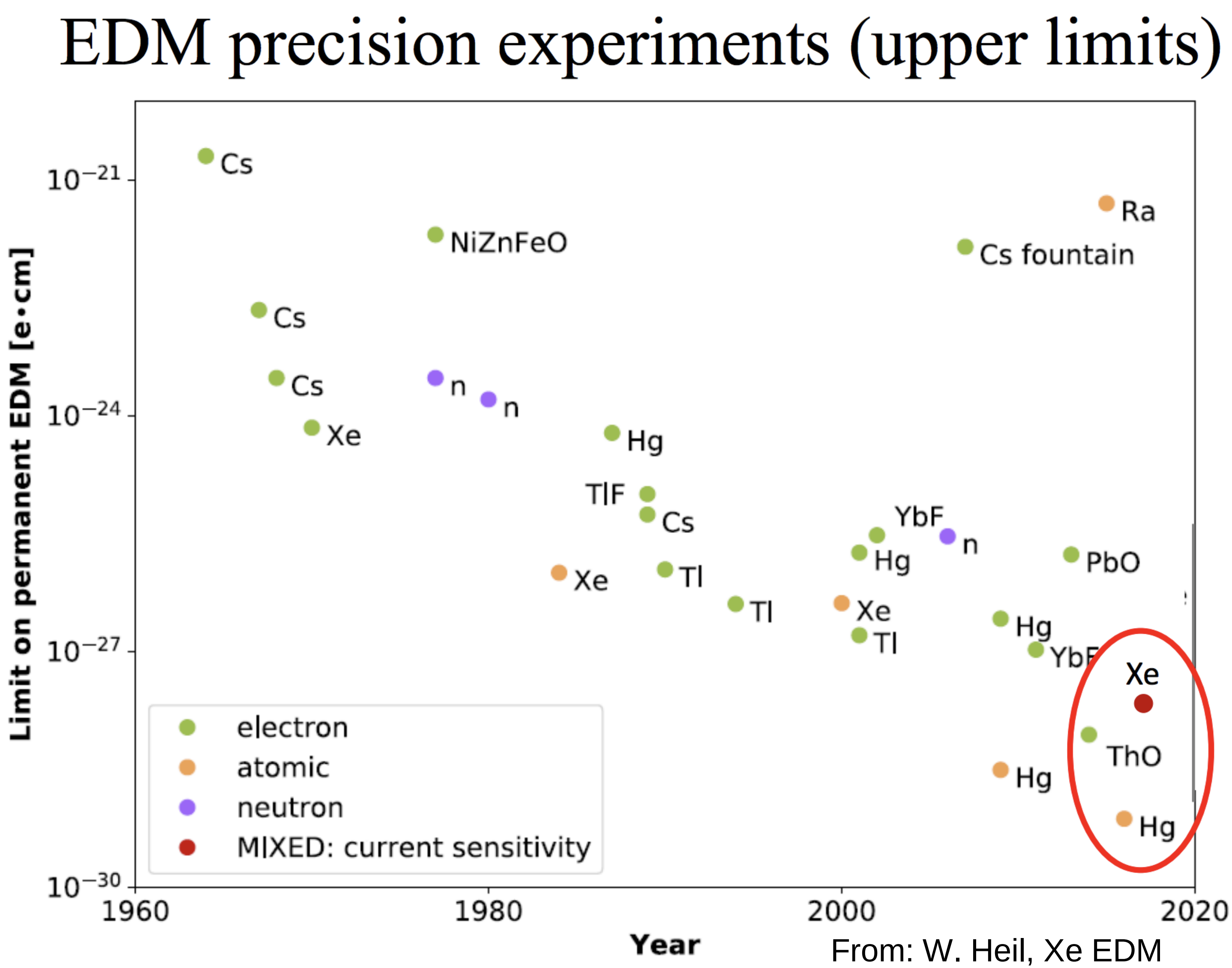
Experimental Summary of muon EDM bounds

SM pred ~10^-36 e-cm
SM EDM scales with lepton mass

Source	d_μ Limit (e-cm)	Note
CERN III	< 1.05 x 10^-18	Bailey (1978)
BNL	< 1.8 x 10^-19	Bennett (2009)
FNAL	< ~10^-21	Projection
JPARC	< ~10^-21	Projection
eEDM	< 1.8 x 10^-26	Naïve SM scaling* from Baron (2014) ACME
eEDM	< ~1.8 x 10^-27	ACME update (Projection assuming limit)

Muons are curious particles → Keep looking for clues

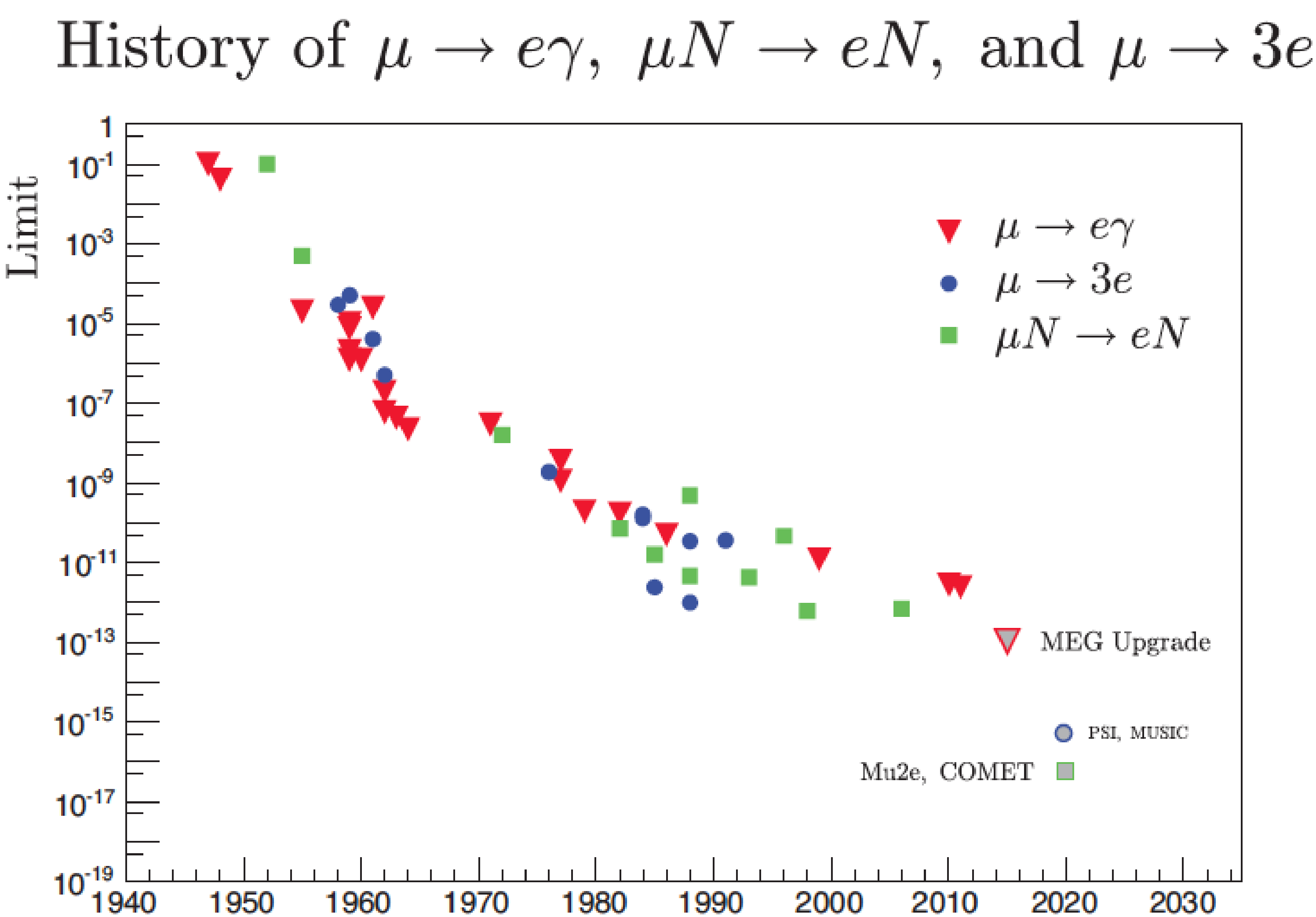
The Evolution of Precision: EDM limits



From: W. Heil, Xe EDM

Fermilab Muon Campus: The Stage for Mu2e

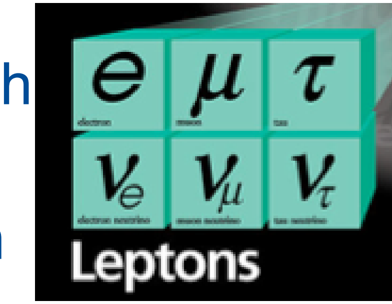
The Evolution of Precision: CLFV



R. Bernstein, P. Cooper , arXiv:1307.5787v3

Mu2e conversion

- Charged Lepton Flavor Conservation
  - Processes that start with "electron-ness", end with "electron-ness"
  - Empirically observed, but no known conservation "Law" yet



- What e
  - Ene

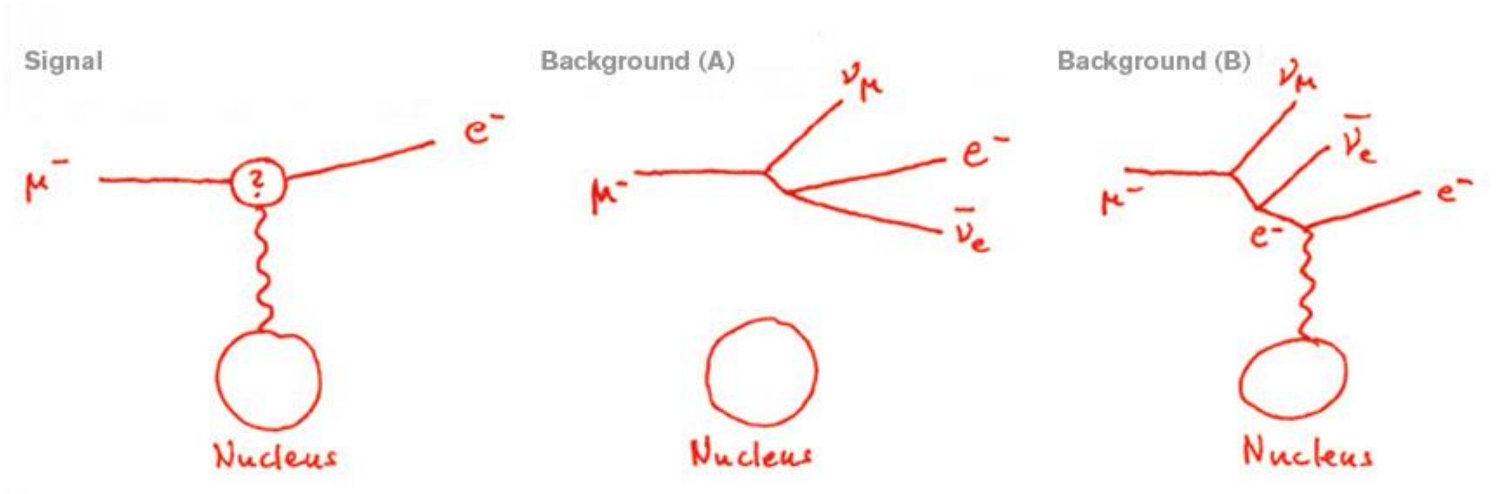
  - Having a nucleus to recoil against allows for conservation of E and p

The Search for Mu2e

- Mu2e searches for charged lepton flavor violation (CLFV) in muons:

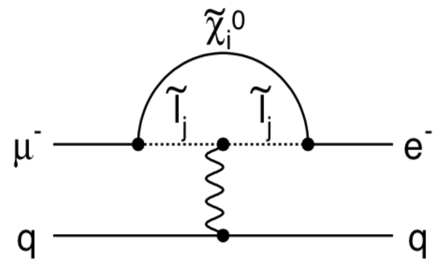
$$\mu^- + \mathbf{Al} \rightarrow e^- + \mathbf{Al}$$

- The Standard Model (with neutrino masses) predicts fewer than 1 in 10^{50} muons to convert
- **An observed signal means unambiguous new physics.**
- The experimental signature? **Electron with 105 MeV!**

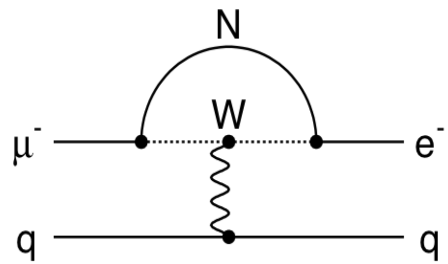


Lots of Possibilities for New Physics

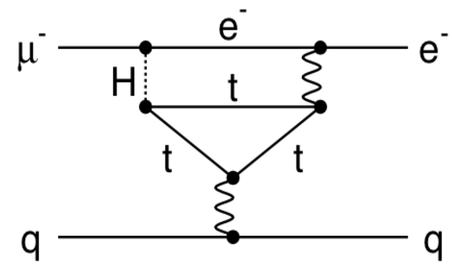
Loops



Supersymmetry

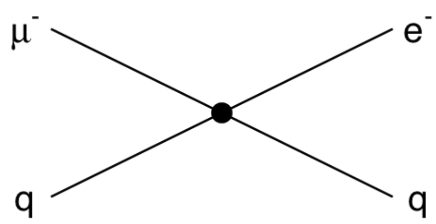


Heavy Neutrinos

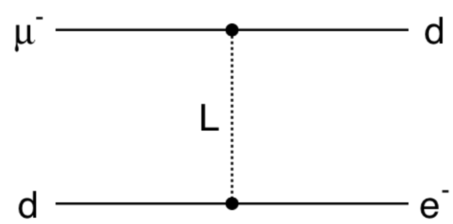


Two Higgs Doublets

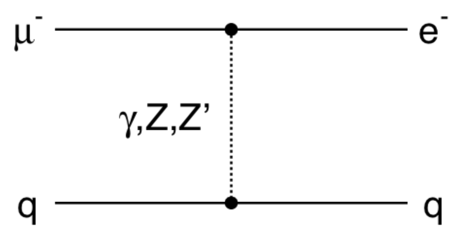
Contact Terms



Compositeness



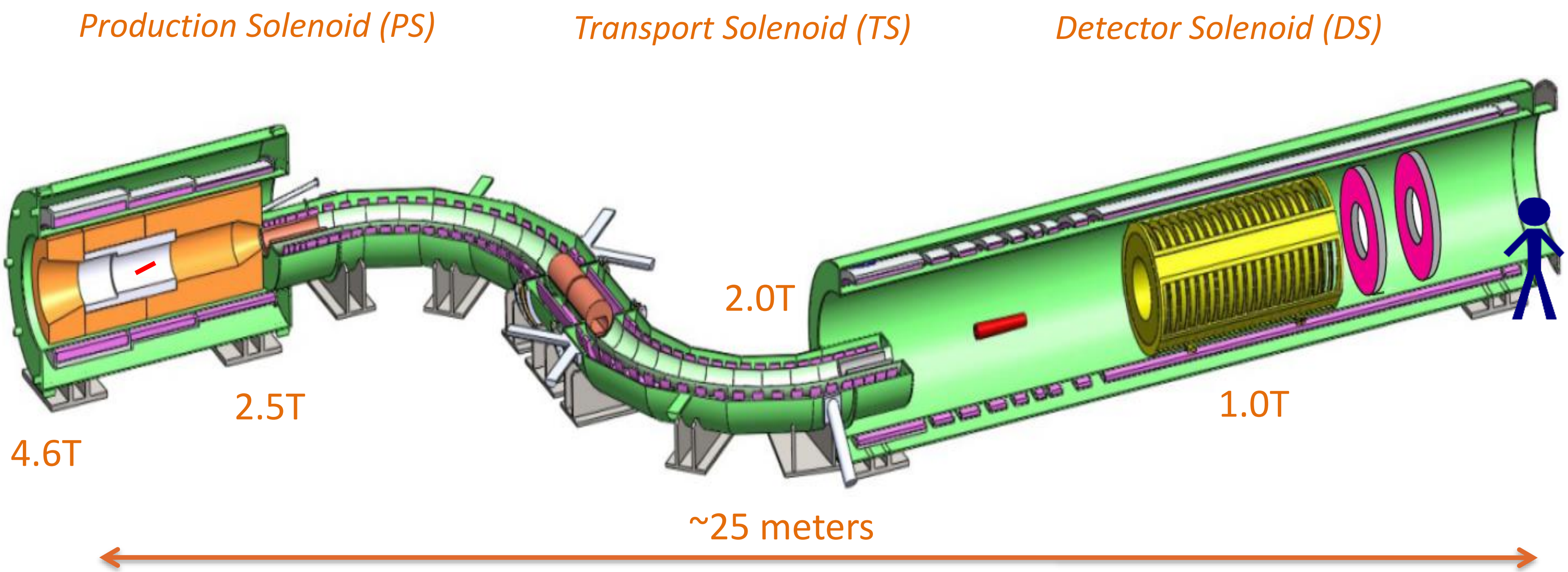
Leptoquarks



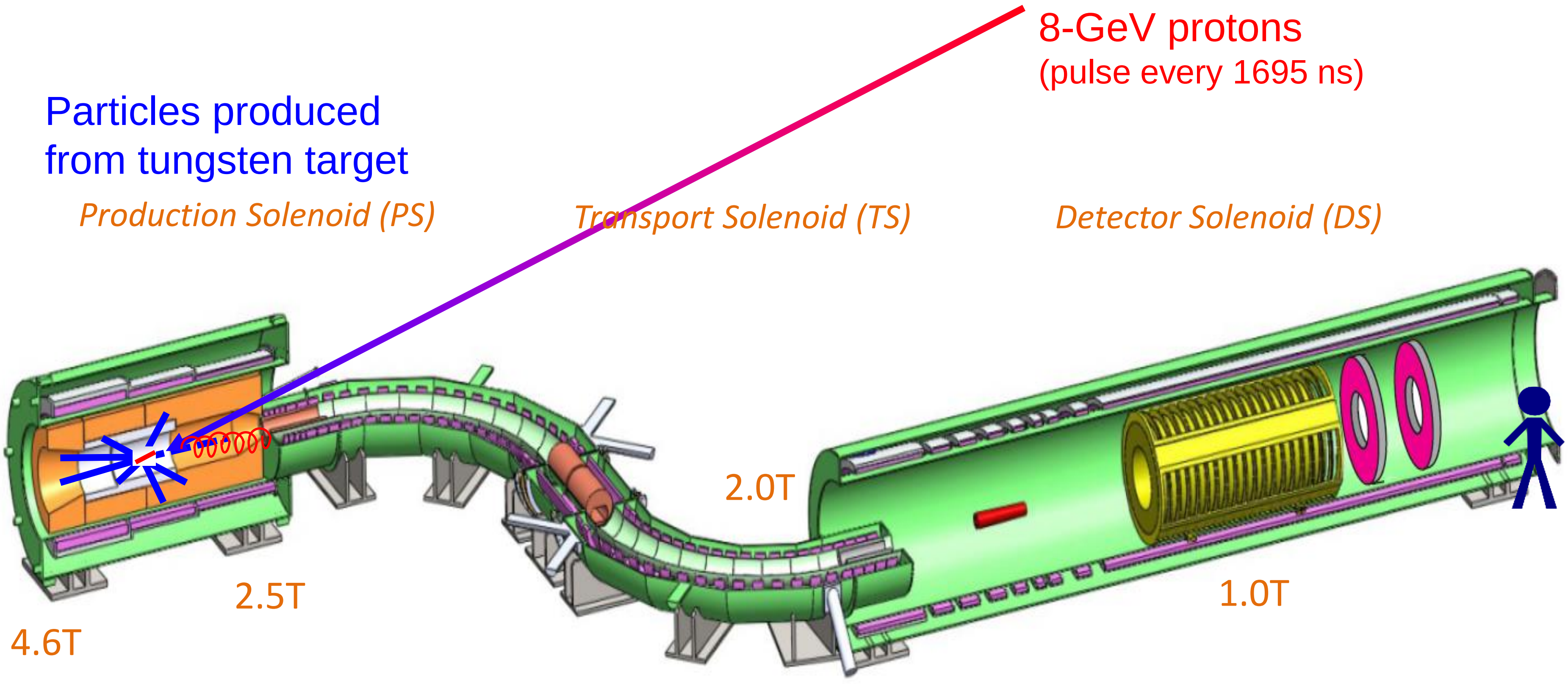
New Heavy Bosons / Anomalous Couplings

- Muon-to-electron conversion allowed via loop diagrams **or** contact terms.
  - cf: $\mu \rightarrow e\gamma$ happens via loops.
- Muon-to-electron conversion enables discovery sensitivity over broad swath of BSM parameter space.

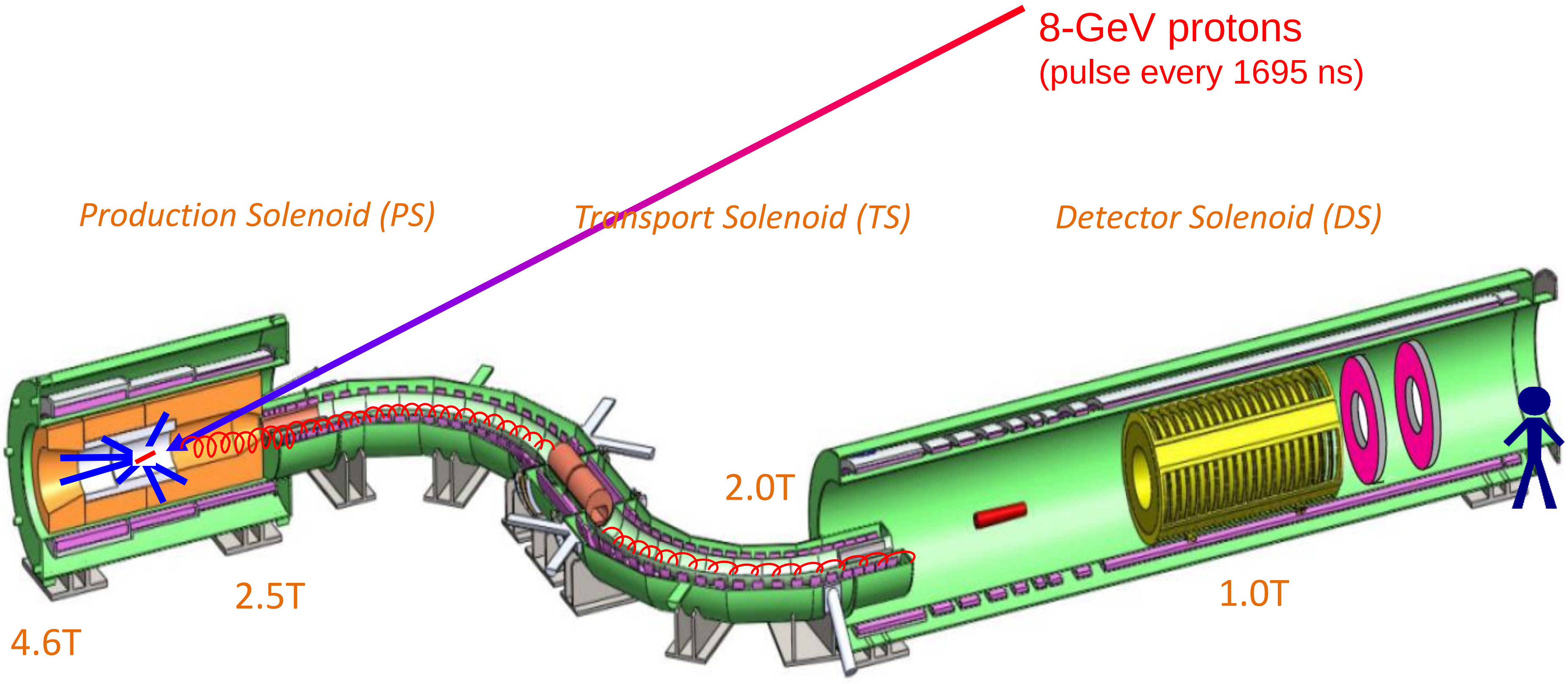
Mu2e apparatus



Mu2e apparatus



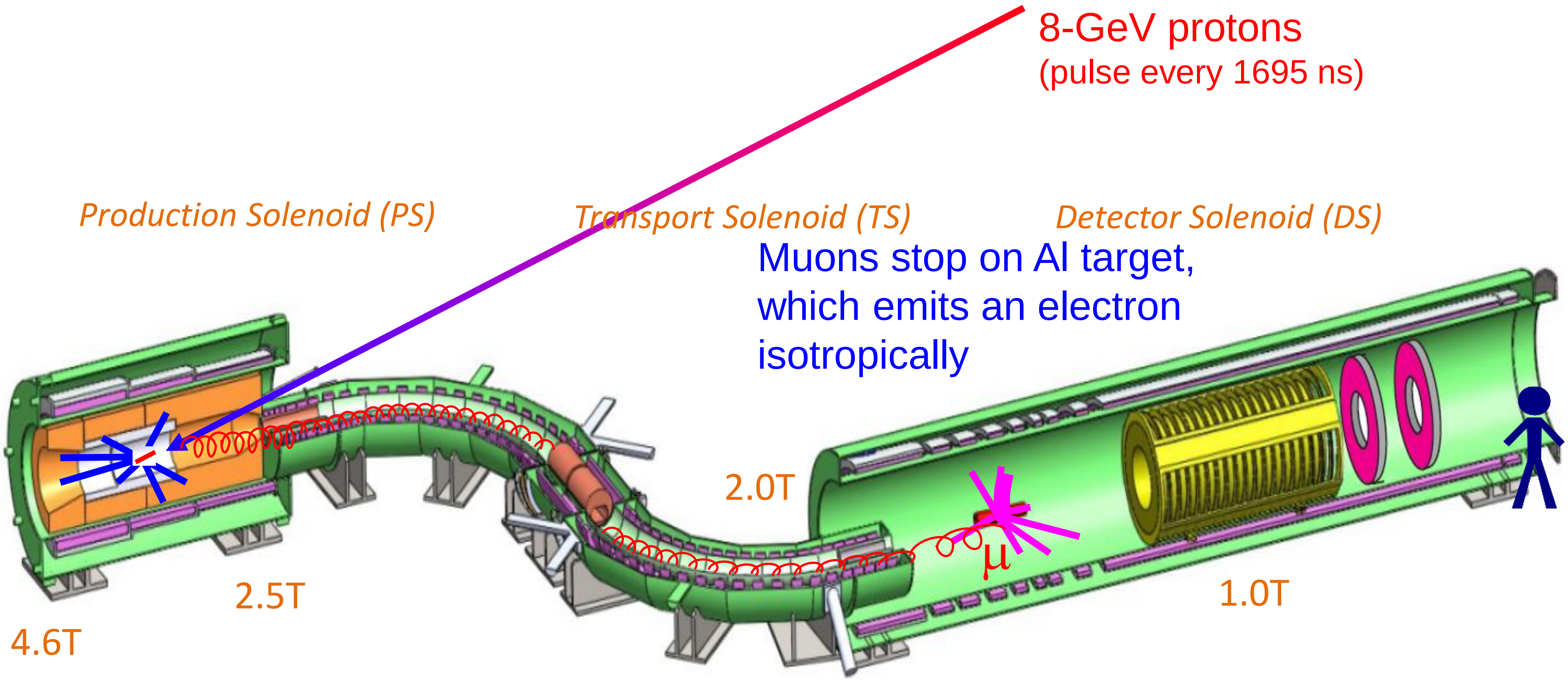
Mu2e apparatus



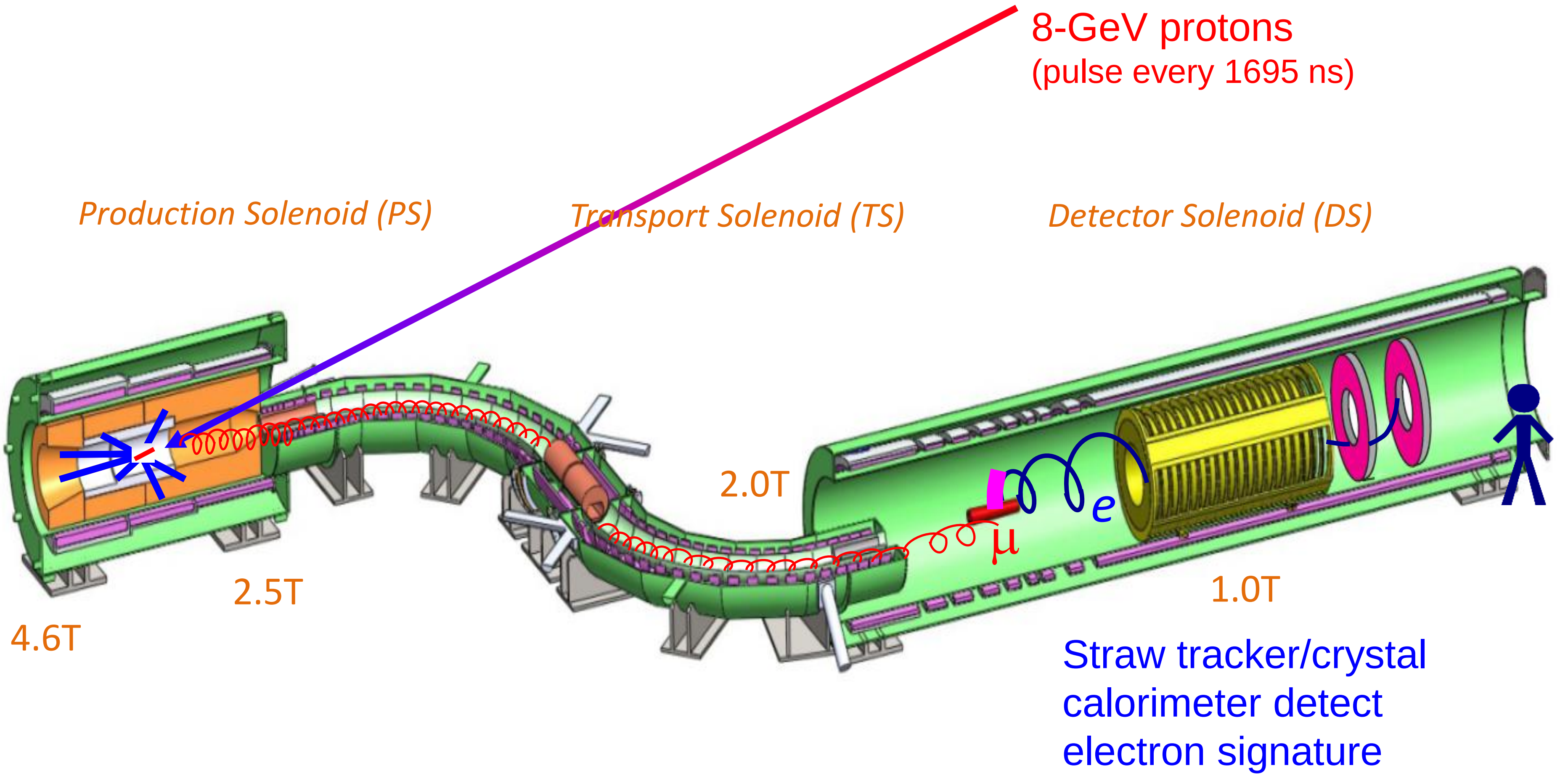
S-shaped solenoid:

- collimator selects negatively-charged particles
- transports particles to detector area, and
- allows remaining pions to decay to muons

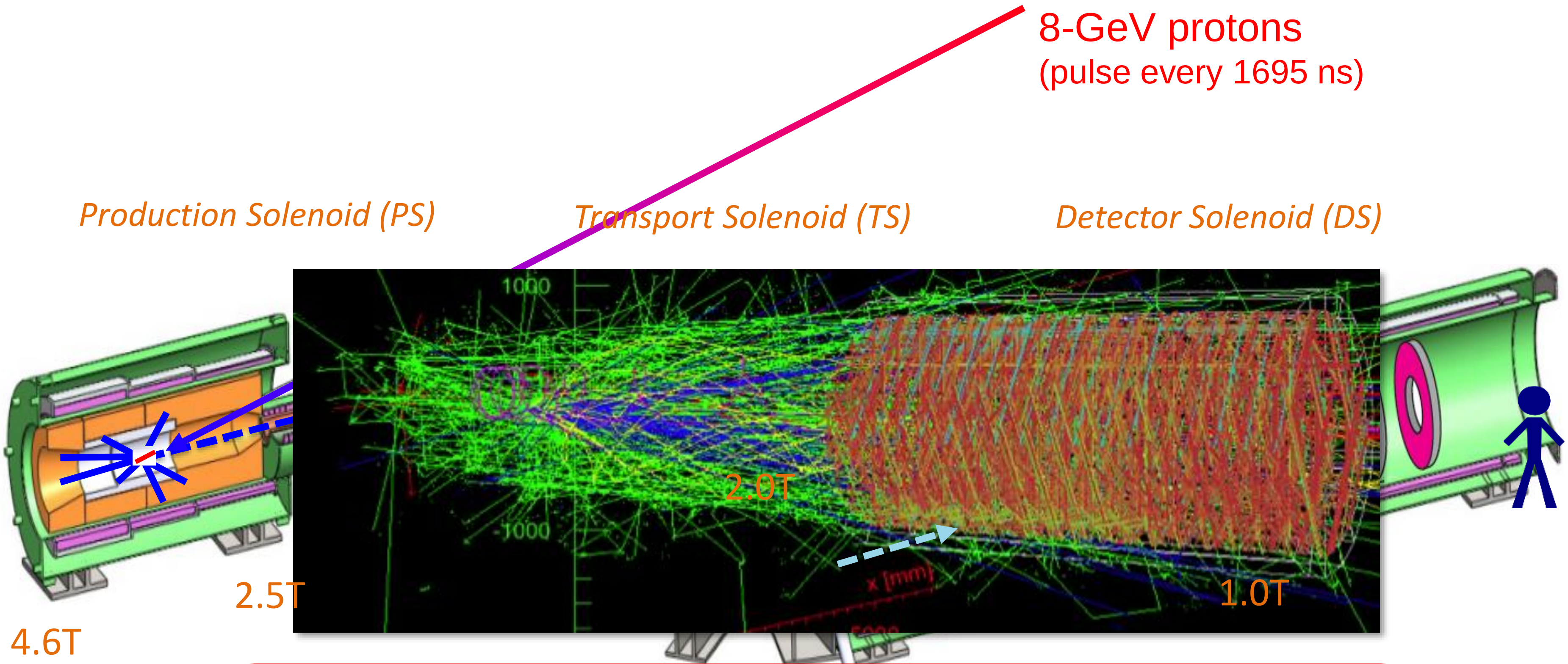
Mu2e apparatus



Mu2e apparatus



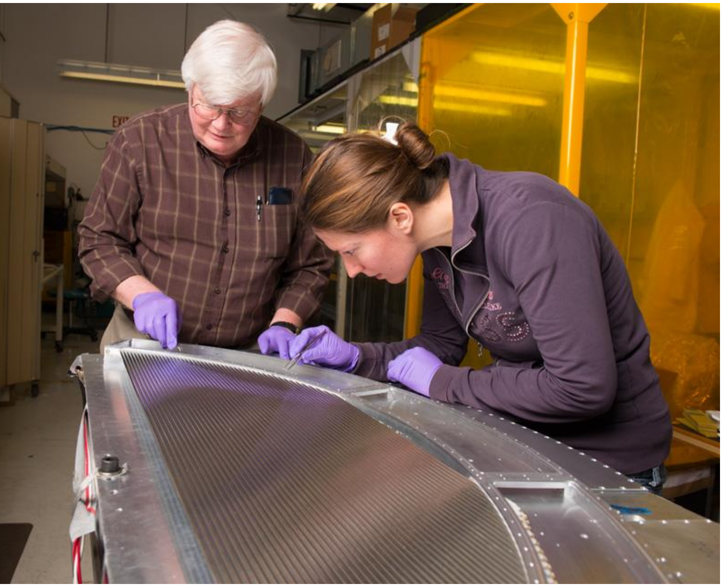
Mu2e apparatus

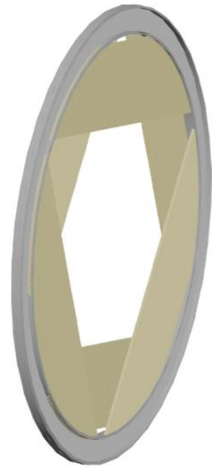


Factor of 10,000 improvement due to:

1) *Pulsed beam, with protons delivered every 1695 ns*
2) *Solenoids used to efficiently create secondary muon beam*

Mu2e Tracker

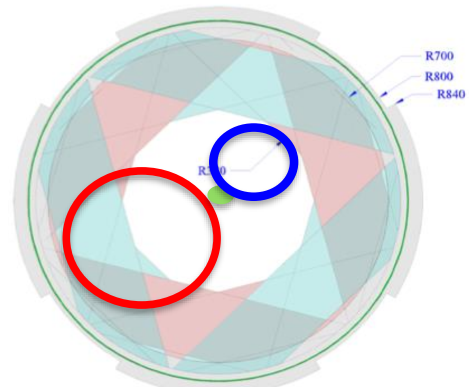


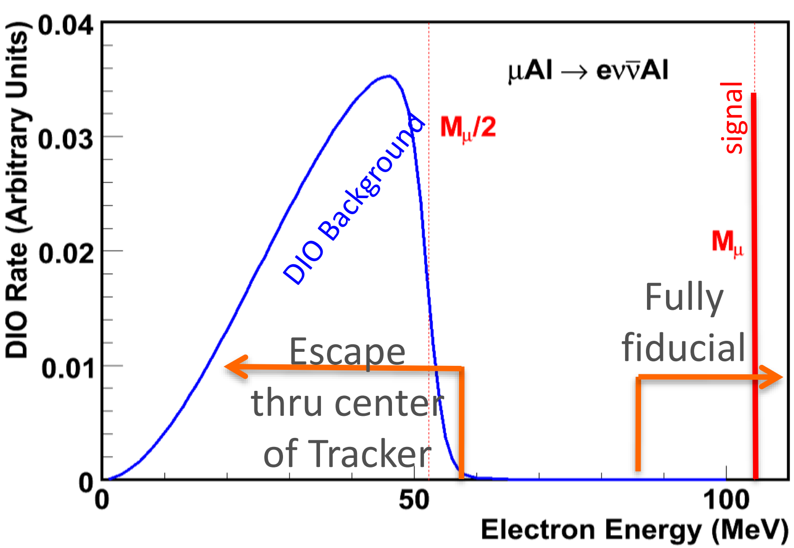


20k Straw tubes transverse to beam

High efficiency, excellent resolution

Momentum resolution 120 keV/c core for 105 MeV electrons



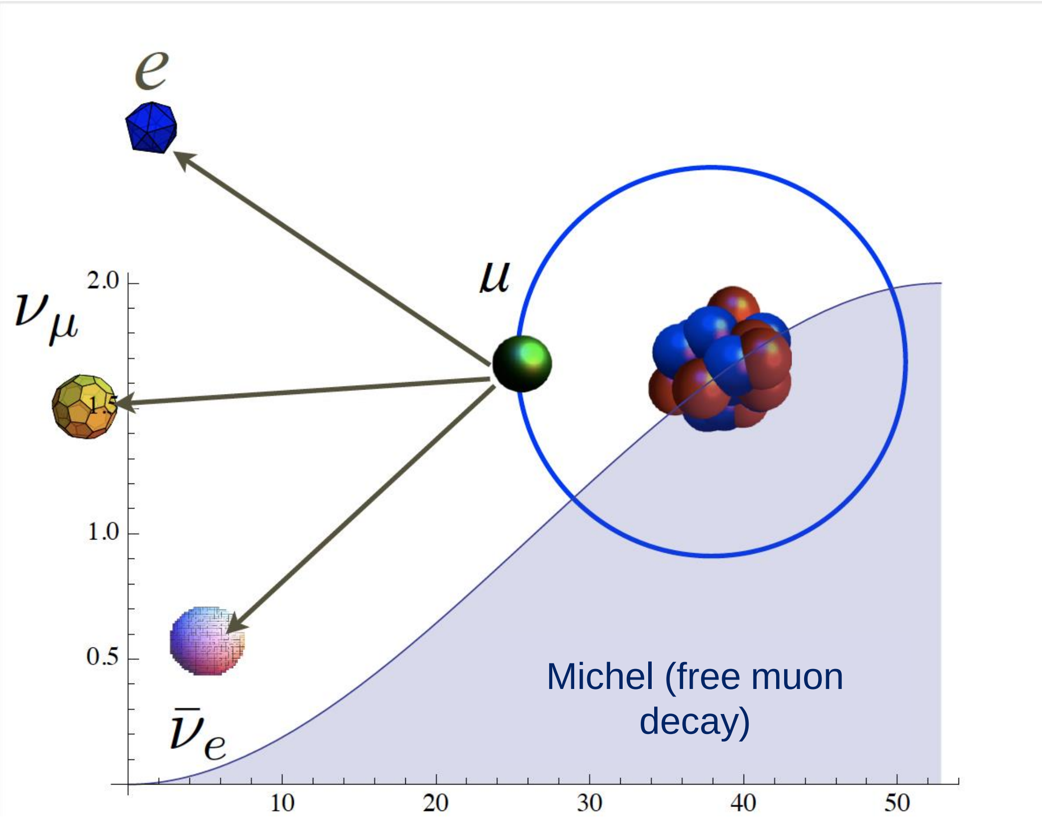


Inner 38 cm is purposefully un-instrumented

- Blind to beam flash
- Blind to >99% of Decay In Orbit (DIO) spectrum

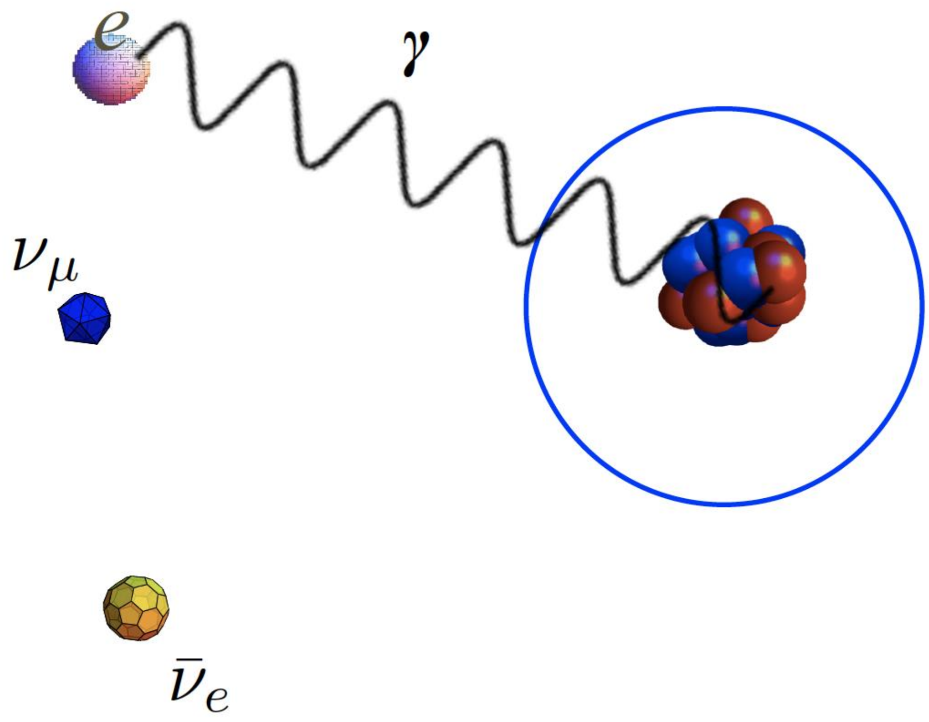
Decay-In-Orbit (DIO)

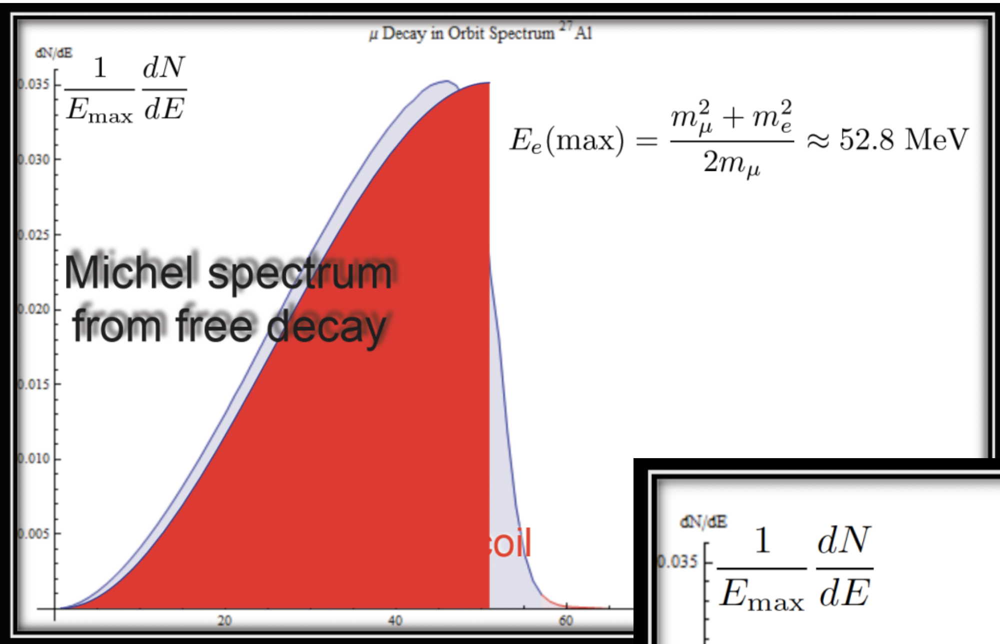
- Peak and Endpoint of free muon decay ~ 52.8 MeV
- Detector blind to these electrons
- Conversion signal at 105 MeV >> 52.8 MeV

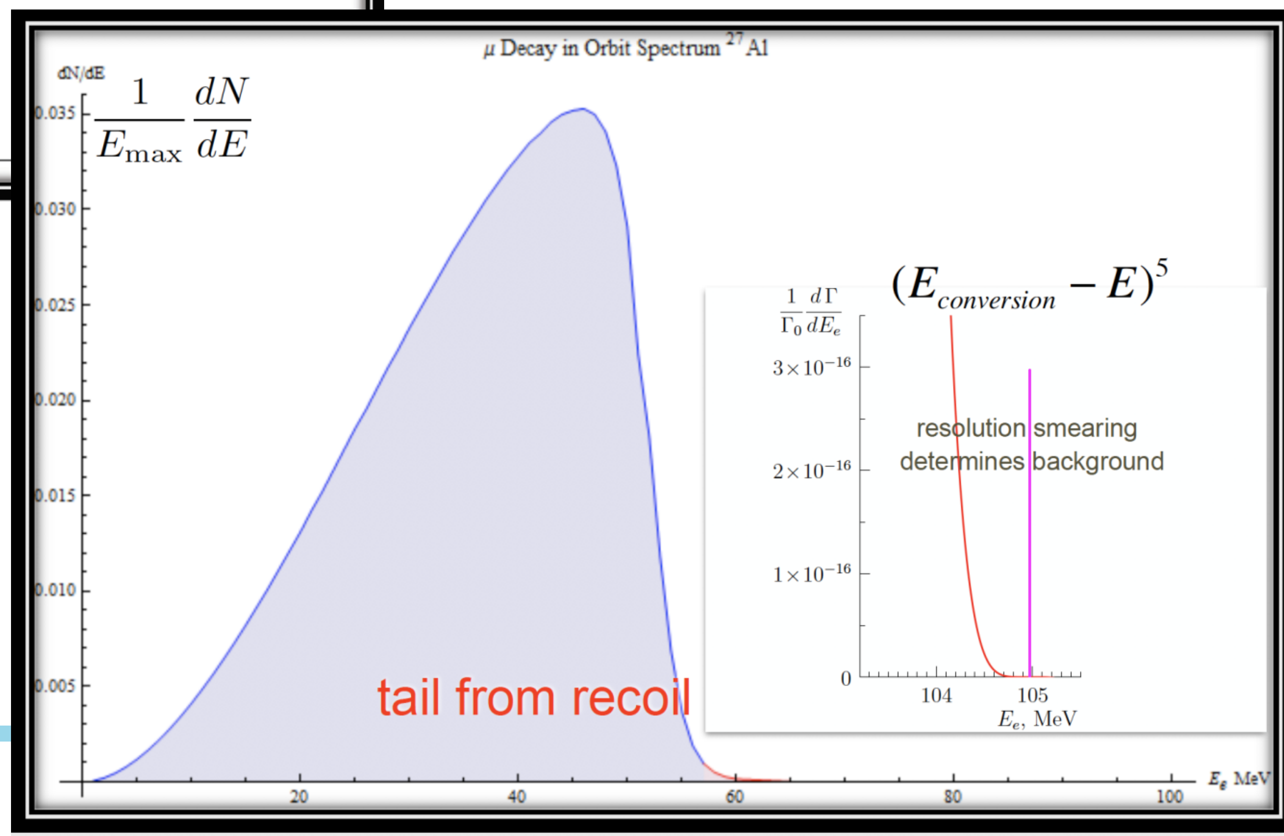


Decay-In-Orbit (DIO) Background

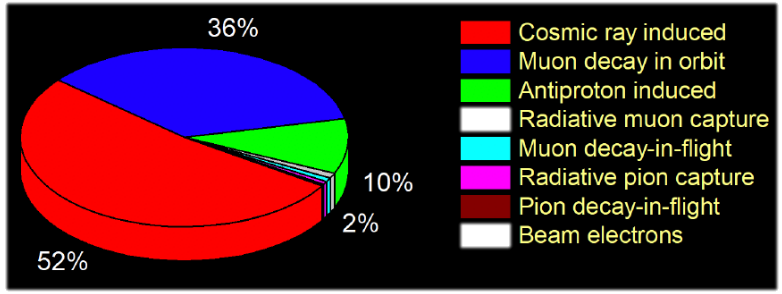
- Consider the recoil off the nucleus
- When neutrinos are at rest, the DIO electron can be at the conversion energy (minus the tiny neutrino mass)




μ Decay in Orbit Spectrum 27 Al
dN/dE
$\frac{1}{E_{\max}}\frac{dN}{dE}$
$E_e(\max) = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8\ \mathrm{MeV}$
Michel spectrum
from free decay
0.035
0.030
0.025
0.020
0.015
0.010
0.005
20
40
60


μ Decay in Orbit Spectrum 27 Al
dN/dE
$\frac{1}{E_{\max}}\frac{dN}{dE}$
0.035
0.030
0.025
0.020
0.015
0.010
0.005
20
40
60
80
100
E_e MeV
tail from recoil
$(E_{conversion} - E)^5$
$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_e}$
3×10^{-16}
2×10^{-16}
1×10^{-16}
0
104
105
E_e, MeV
resolution smearing
determines background

Expected backgrounds



Process	Expected Number
Cosmic Ray Muons	0.25 ± 0.026
DIO	0.14 ± 0.09
RPC	0.025 ± 0.003
Antiprotons	0.047 ± 0.024
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam Electrons	$< 5 \times 10^{-4}$
Total	0.46 ± 0.03

Single Event Sensitivity

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \text{all muon captures})}$$

- Designed for SES of ~3 x 10^{-17}
- Online in ~2021
- Detection would usher in new era of precision measurements
- Setting 10,000x improved limit would be tremendous too
- Upgrades → 10^{-18} underway

Probability of...	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

What's Next?

PHYSICS

We Asked Celeb Physicist Brian Cox About Flat Earth Conspiracies, the Multiverse, and Ghosts

Ryan F. Mandelbaum
7/11/18 12:00pm • Filed to: PARTICLE PHYSICS

Particle physicist and celebrity scientist Brian Cox

RFM: And finally, what do you think are the most important outstanding mysteries in physics?

BC: The LHC hasn't taken nearly as much data as it can, and it's also being upgraded to get many more collisions. It will be a big surprise if all [we find] is the Standard Model Higgs particle. People were expecting we'd see supersymmetry that would have given us an idea of what dark matter is.

One of the biggest discrepancies in particle physics at the moment is the g-2 experiment. It's a measurement of the way the muon behaves in a magnetic field. The experiment shows a significant discrepancy with the Standard Model that's getting more significant with time. It's a low-profile experiment, but it's extremely sensitive to new physics. It's still running, but if I were to put my money on something that would signal new physics, it's the g-2 experiment at Fermilab. I think it's really fascinating.

The other thing is gravitational waves. The point was not to discover gravitational waves—everyone was pretty sure they existed. The point is that we now have an observatory that can watch the collisions of black holes and neutron stars. Thinking that LIGO was built to discover gravitational waves is like saying we build telescopes to look at one star. Of course not. It completely revolutionized astronomy.

Goals for this talk

1. Why do we use muons to probe the Standard Model? How?

   Muons have very useful properties

   We design clean, precision experiments to carefully expose cracks (Muon g-2, EDM, Mu2e, etc...)

2. What details matter for precision experiments?

   Until you have calculated/simulated/measured, everything you can think of. And probably some things you didn't!

3. Where might we see the next cracks in the SM?

   I can't answer your contest question for you, but I hope I left a few clues about my opinions ☺

Suggested Readings

Precision Muon Physics

- "Low-energy precision tests of the standard model: a snapshot" D. Hertzog. Ann. Phys. (Berlin), 1–8 (2015) / DOI 10.1002
- Gorringe, Hertzog. *Precision Muon Physics.* Prog. Part. Nucl. Phys. **84** p.73-123 (2015).
- Kammel, Kubodera, *Precision Muon Capture.* Ann. Rev. Nucl. Part. Sci. **60** p.327-353 (2010).

EDMs

- Engel, Ramsey-Musolf, van Kolck, *Electric dipole moments of nucleons,nuclei, and atoms: The Standard Model and Beyond.* Prog. Part. Nucl. Phys. **71** p.21-74 (2013).
- Chupp, Ramsey-Musolf, *Electric dipole moments: A global analysis.* Phys. Rev. C **91** 035502 (2015).
- Chupp, Fierlinger, Musolf, Singh. *Electric Dipole Moments of the Atoms, Molecules, Nuclei and Particles.* Rev. Mod. Physics https://arxiv.org/abs/1710.02504

- Baron et al. *Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron* Science **343** p.269-272 (2014).

Acknowledgments

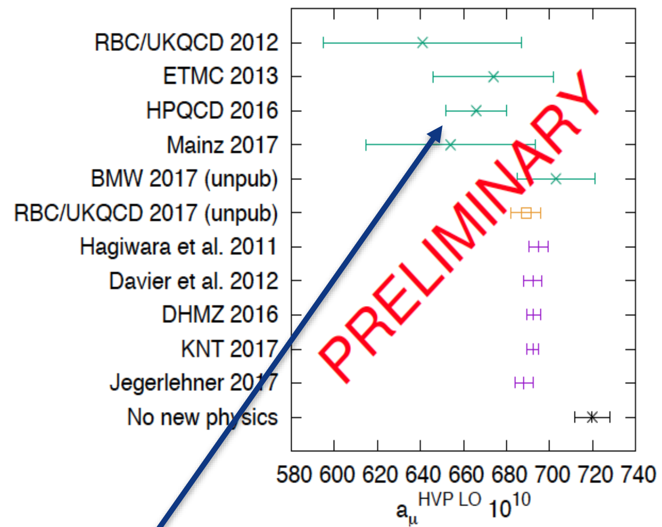
Many thanks to the folks who aided in conversation and in providing plots:

- **Muon g-2**: Alex Keshavarzi, Tammy Walton, James Mott, Chris Polly, Dave Hertzog, Kim-Siang Khaw, Erik Swanson, Peter Winter, Ran Hong, David Flay, and more
- **EDM**: Saskia Charity, Adam Ritz, Gerry Gabrielse, Tim Chupp
- **Proton Radius**: Jan Bernauer, Randolph Pohl
- **Mu2e:** Doug Glenzinski, Bob Bernstein

Great Progress with Lattice QCD

- 2016-17: physical pions, u,d,s,c connected loops

2% Precision (Models 0.7%)



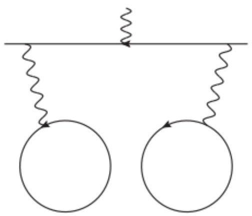
From talk by C. Lehner at Lattice 2017

3.5σ from lattice alone!

- Lattice Calculation
- Dispersion Relation
- Both

https://arxiv.org/pdf/1710.06874.pdf

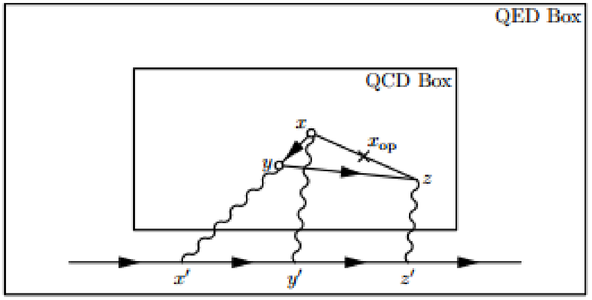
- Dec 2015: disconnected loops
  – Small contribution
  – First calculation



disconnected diagram (gluons not shown)

Blum et al, http://arxiv.org/pdf/1512.09054.pdf

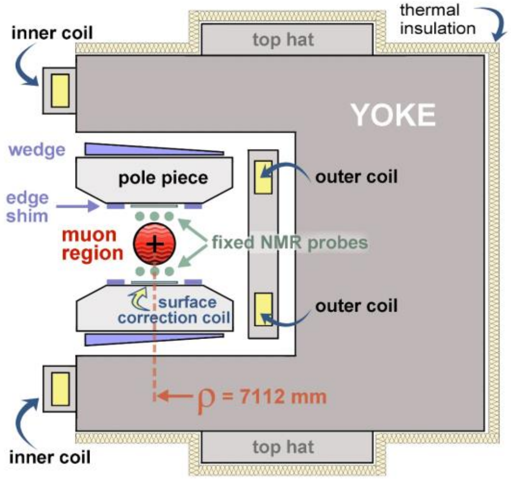
- Nov 2015: hadronic light-by-light
  – Needed to avoid becoming dominant theory uncertainty



QCD Box in a QED Box to manage finite volume effects

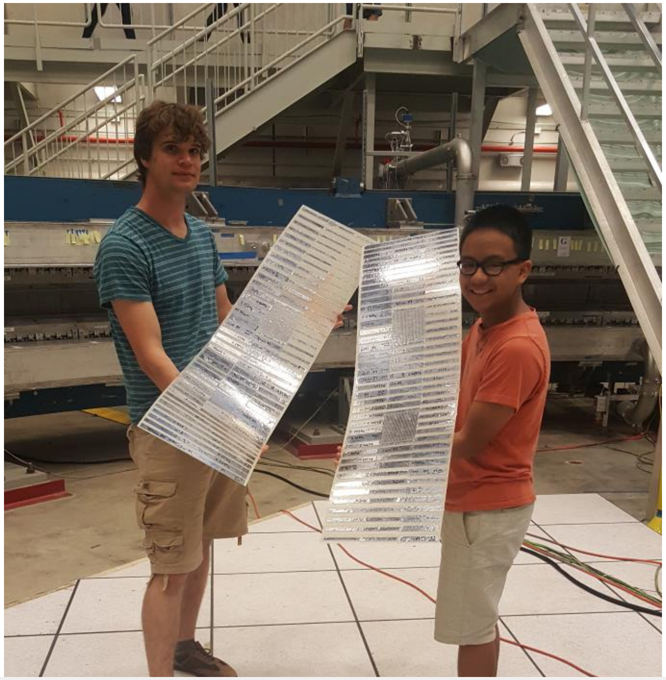
Jin et al, http://arxiv.org/pdf/1511.05198v1.pdf

Muon g-2 Field

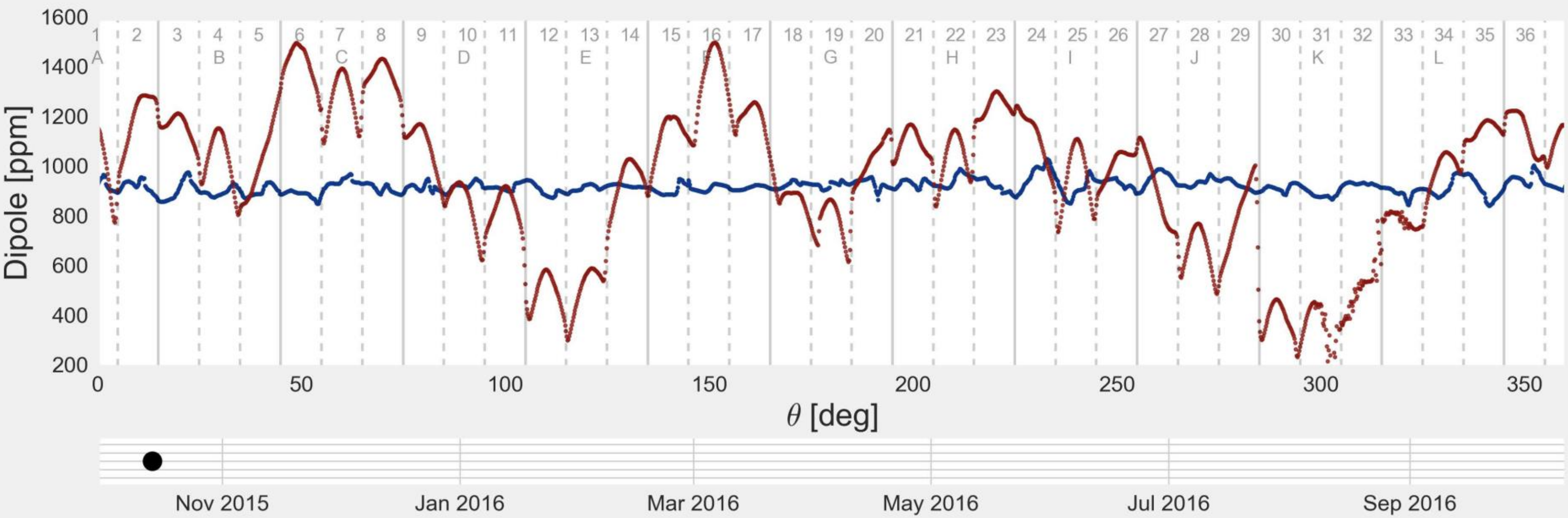


g-2 Magnet in Cross Section

Superb Intrinsic Shim Kit
Added iron laminations for x3 improvement in field uniformity



BNL FINAL → FNAL Shimming Effort



Muon g-2 Running Outlook

- Will need FY2020 running
- Running about 50% of design rate, making great progress
- Started summer shutdown to upgrade various components

		FY 2017	FY 2018	FY 2019	FY 2020	
		Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	
NuMI	MI	MINERvA	MINERvA	MINERvA ?	OPEN	ν
		NOvA	NOvA	NOvA	NOvA	
BNB	B	MicroBooNE	MicroBooNE ?	SBN: MicroBooNE	SBN: MicroBooNE	
		SBN: ICARUS	SBN: ICARUS	SBN: ICARUS / SBN: ICARUS	SBN: ICARUS	
		SBN: SBND	SBN: SBND	SBN: SBND	SBN: SBND	
Muon Campus		g-2	g-2	g-2	OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	
SY 120	MT	FTBF - MTEST	FTBF - MTEST	FTBF - MTEST	FTBF - MTEST	p
	MC	OPEN / LArIAT	FTBF - MC	FTBF - MC	FTBF - MC	
	NM4	SeaQuest	OPEN	OPEN	OPEN	
		Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	

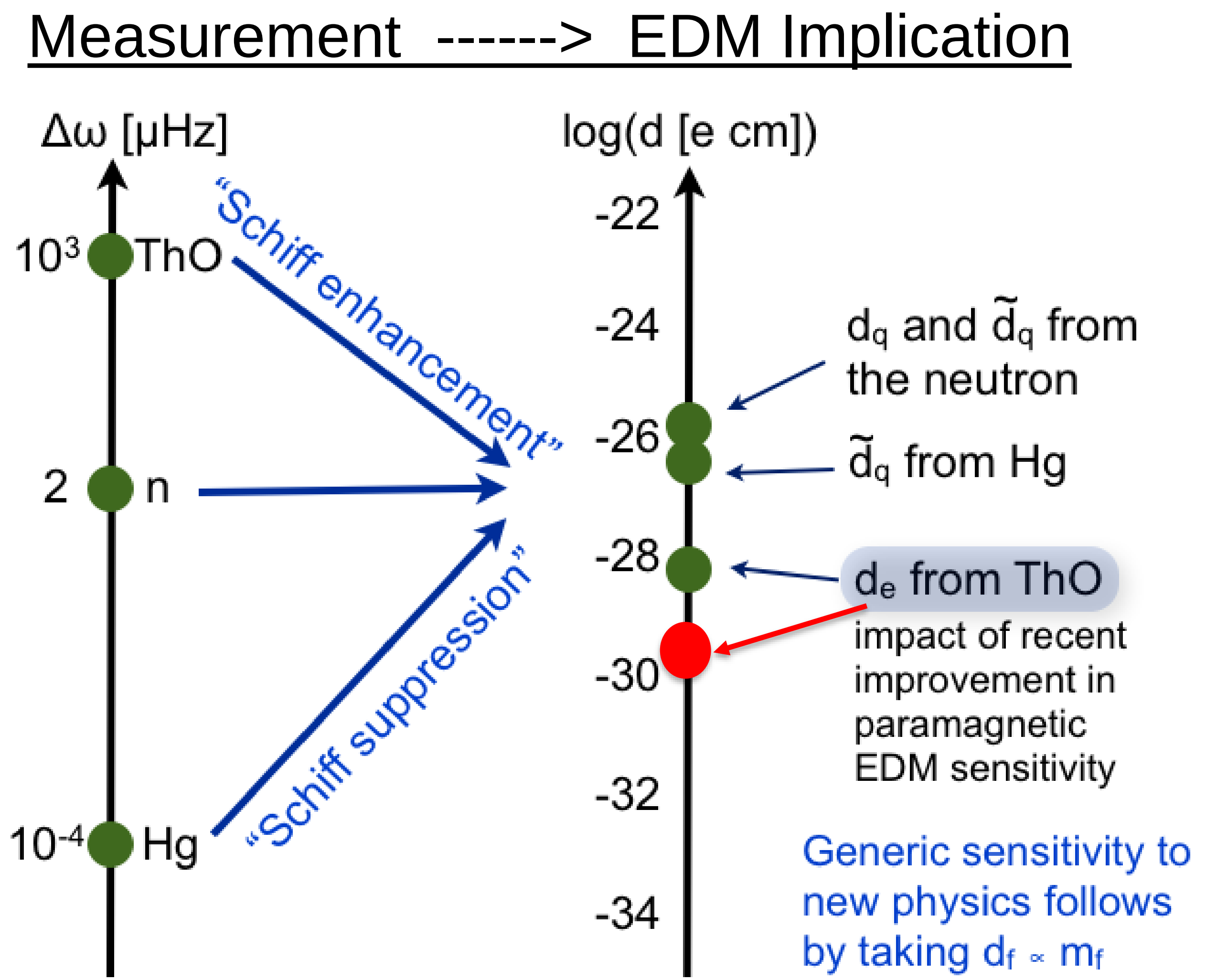
1st publication (>1 x BNL statistics)

2nd publication (5-10 x BNL statistics)

3rd publication (>20 x BNL statistics)

CY18 | CY19 | CY20 | CY21

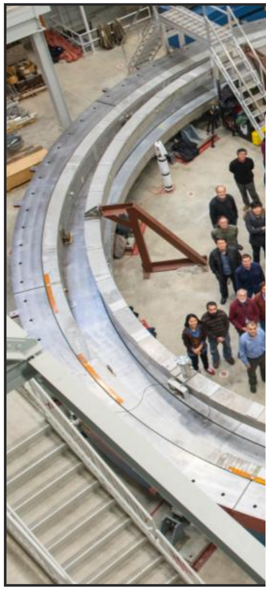
Experimental Summary of EDM bounds

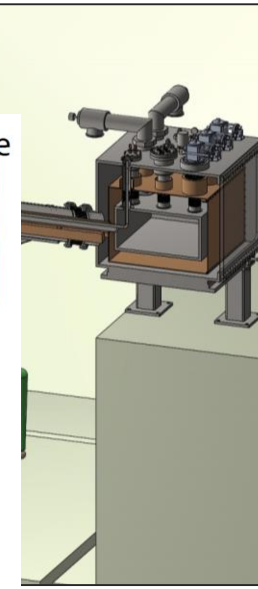


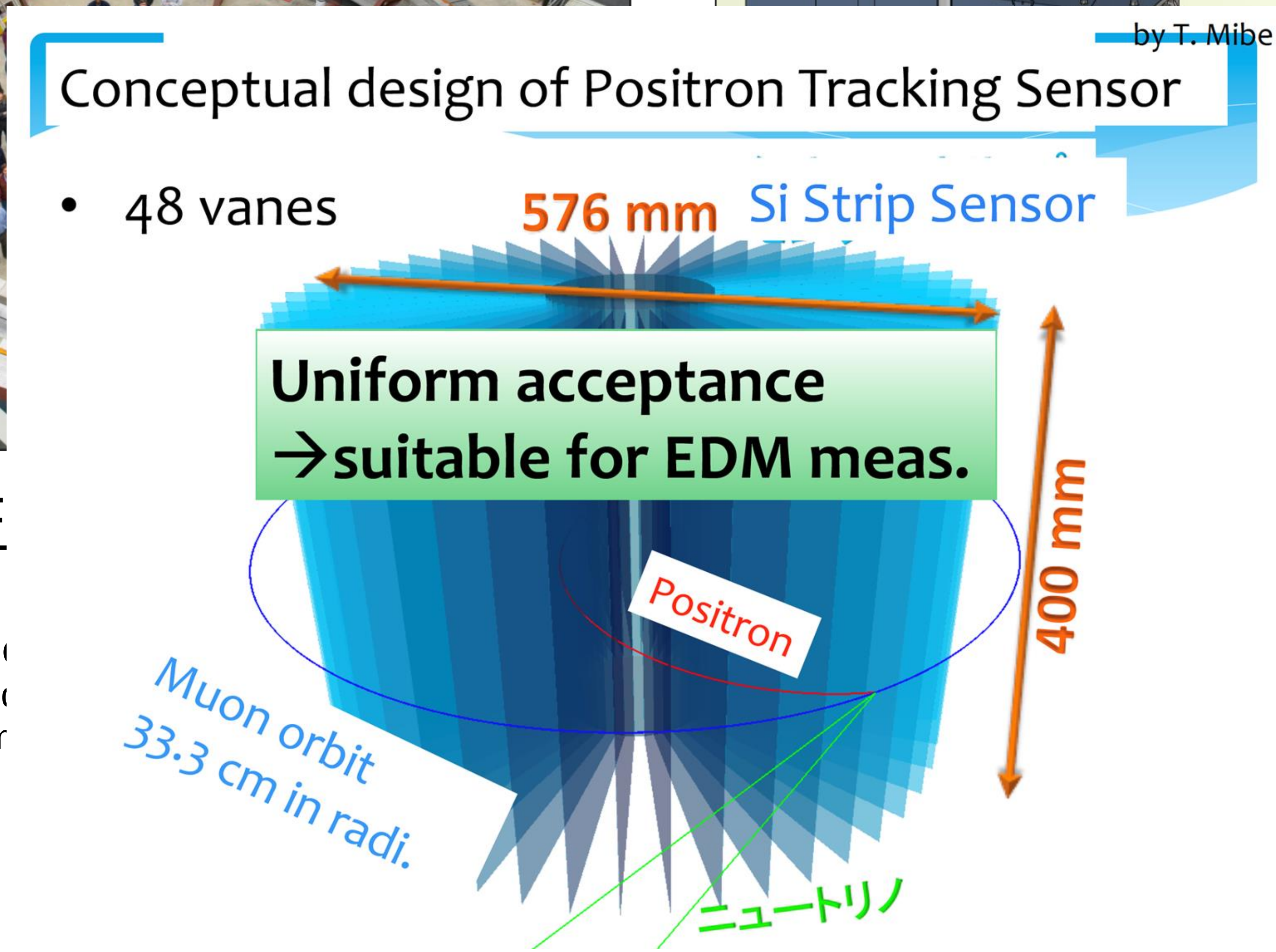
Significant experimental progress in last few years

Courtesy: A. Ritz

Next-Generation Muon MDM+EDM Experiments







F

•High-rate 3.09
•Highly polarize
•1.45 Tesla, 7-m

.3 GeV/c muon

g

Novel Beamline Design

Pulsed proton beam, ~250 ns wide , ~1695 ns apart
Delay live gate ~700 ns
Suppress prompt backgrounds (beam electrons and pion interactions)