Fundamental Symmetries and Precision Physics

David Hertzog
University of Washington

- **Lecture 1**
  - Motivations
  - Symmetries, Parity, and the Weak Interaction
  - The Fermi Constant
  - Muon Decay as a test of V-A theory
- **Lecture 2**
  - Neutron beta decay
  - Parity as a tool to probe matter: PVES
  - Highly sensitive low-energy probes of New Physics
  - CPV and Electric Dipole Moments
- **Lecture 3 (transition here at some point …)**
  - Charged Lepton Flavor Violation
  - Muon g-2
  - It's a wrap …

A question from Day 1

CPT Violation Implies Violation of Lorentz Invariance
O. W. Greenberg
Phys. Rev. Lett. **89**, 231602 – Published 18 November 2002

A interacting theory that violates CPT invariance necessarily violates Lorentz invariance. On the other hand, CPT invariance is not sufficient for out-of-cone Lorentz invariance. Theories that violate CPT by having different particle and antiparticle masses must be nonlocal.

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.89.231602

Topic 6

Charged Lepton Flavor Violation

Impressive sensitivity to new physics when the SM theory "is zero" (or sort of)

Progress in Particle and Nuclear Physics 71 (2013) 75–92

Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

Lepton flavor and number conservation, and physics beyond the standard model

CrossMark

André de Gouvêa[a,*], Petr Vogel[b]

[a] Department of Physics and Astronomy, Northwestern University, Evanston, IL, 60208, USA

[b] Kellogg Radiation Laboratory, Caltech, Pasadena, CA, 91125, USA

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ELSEVIER

Review

Flavour violating muon decays

CrossMark

T. Mori *, W. Ootani

International Centre for Elementary Particle Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

… those conservation laws again …

- Non-observation of decay $\mu \rightarrow e\gamma$ established that the muon was a distinct particle
- We have been stating for some time the reason …
  - Lepton Flavor is Conserved …

$$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$$

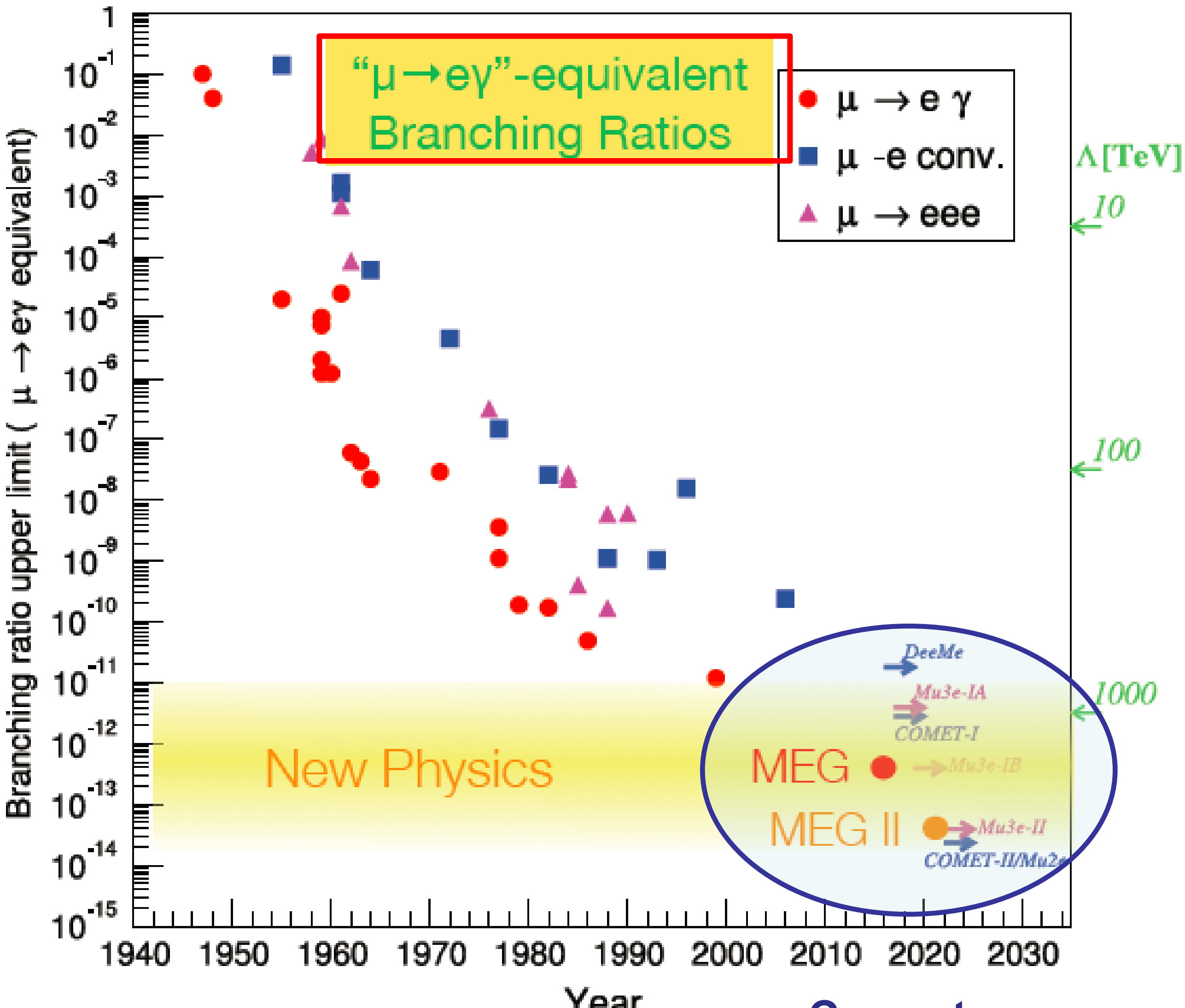
  - But we (now) know that neutrino flavors DO mix so …it must be the case that $\mu \rightarrow e\gamma$ is not truly forbidden, right?

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

Right. It's just impossibly small

Charged lepton flavor violation limits are impressive

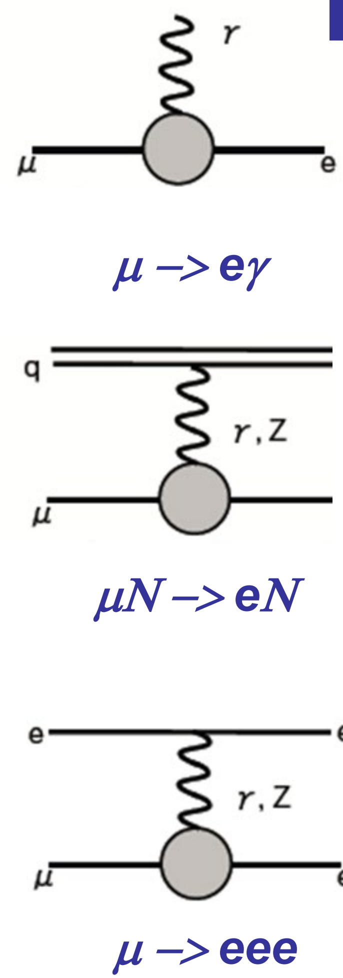
SM "allowed" but *Unobservable* *e.g.,* $\mu \to e\gamma$ BR: 10^{-54}



Current generation

For "dipole" like NP

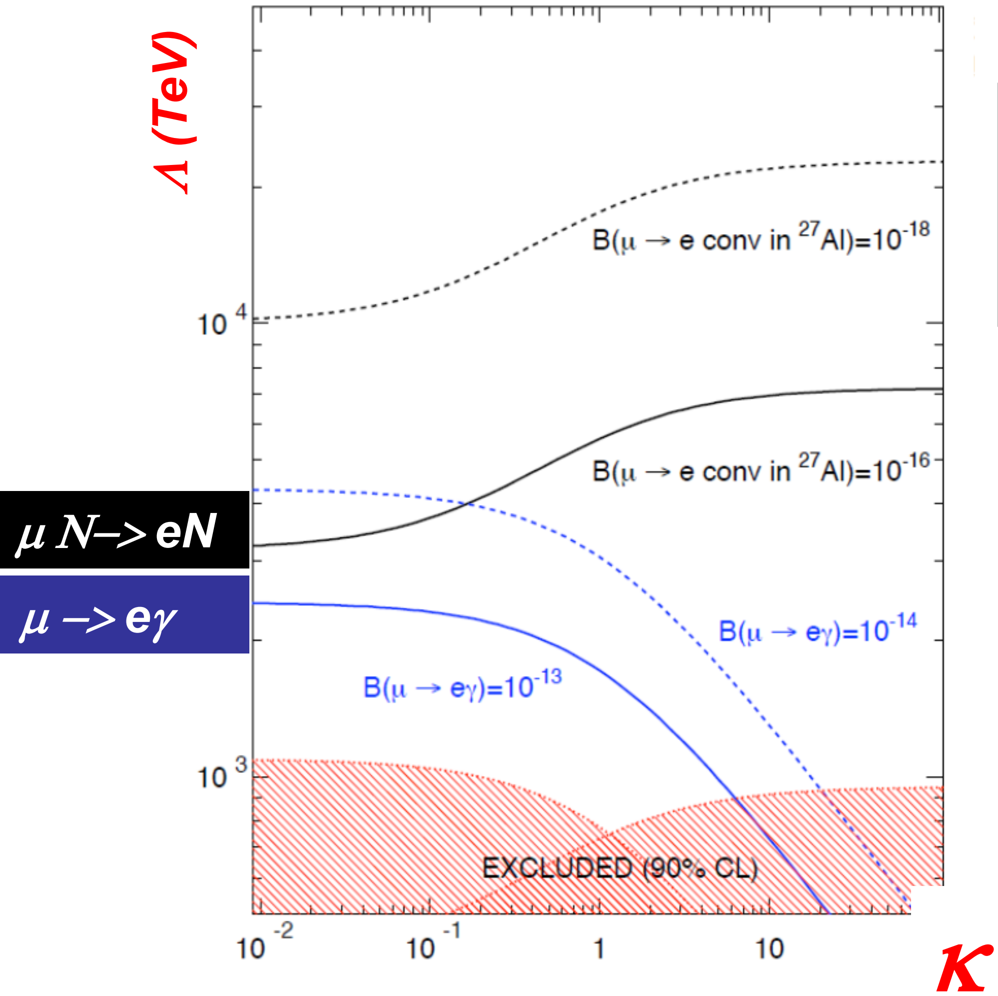
Ratios

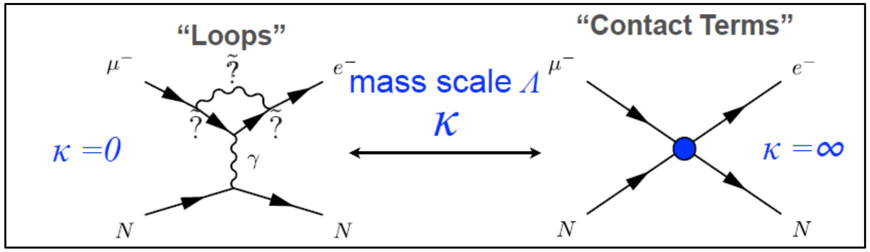


$\mu \to e\gamma$	1
$\mu N \to eN$	1/390
$\mu \to eee$	1/170

… but, life may not be just dipole

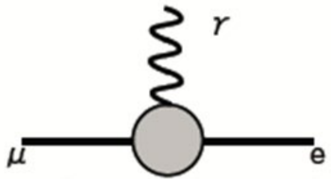
$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$



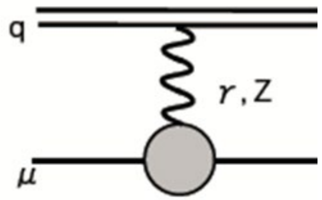


de Gouvěa

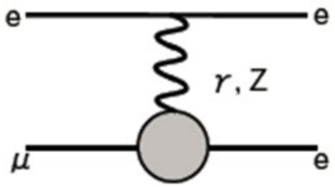
A comment about experimental design



$\mu \to e\gamma$



$\mu N \to eN$



$\mu \to eee$

- ***$\mu \to e\gamma$ is a coincidence experiment; you measure e and γ***
- ***$\mu N \to eN$ is a "singles" experiment. You only look for outgoing e***
- ***$\mu \to eee$ is a triple coincidence experiment. You need to see all three e at once***
- ***ALL THREE NEED HIGH STATISTICS***

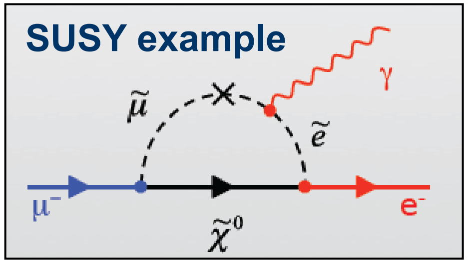
A comment about experimental design

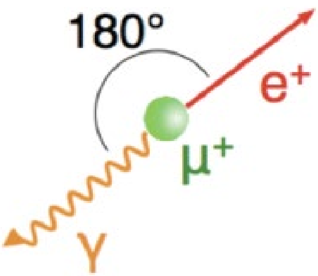
- Coincidence experiments need DC (continuous) beams to minimize PILEUP (event overlaps). Each event must be scrutinized to see it it follows the unique pattern: PSI for ~10^7 – 10^8 μ^+/s beams

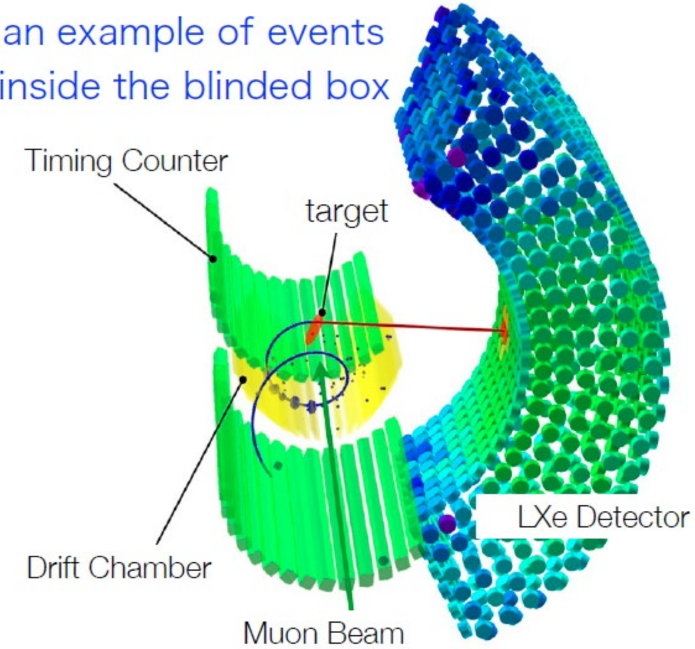
- Monoenergetic emission experiment needs PULSED beam to avoid overlap of "beam" related background with "quiet" measuring period background; eg. FNAL pulsed every 1.7 μs
  - It also allows for natural background subtraction periods
  - Examples from pulsed neutrino physics here …

MEG: μ → eγ

Signal is back-to-back 53 MeV γ and e⁺ from positive muons at rest







NEW 2016: BR(μ → eγ) < 4.2 x 10^{-13} @ 90% CL

x30 improvement compared to pre-MEG

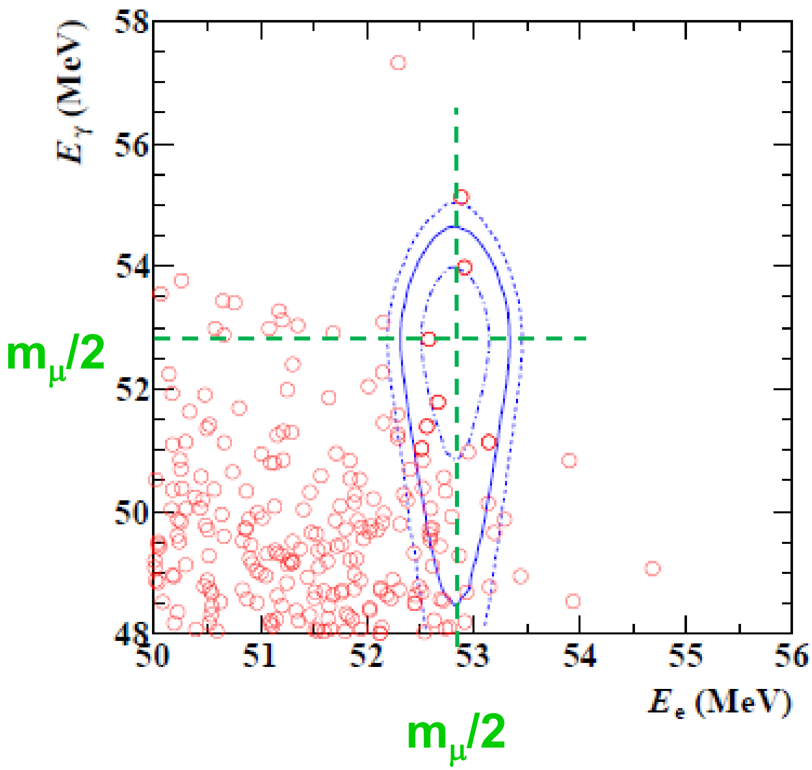
MEG II Upgrade approved at PSI: Expect to improve by another factor of 10 !

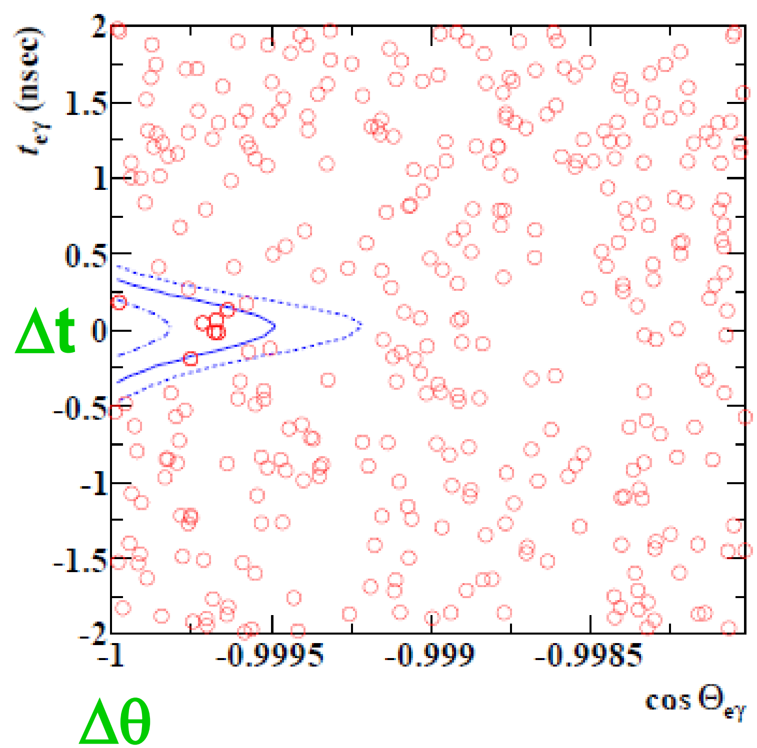
Eur.Phys.J. C76 (2016) no.8, 434

To give you a feeling: Event Search

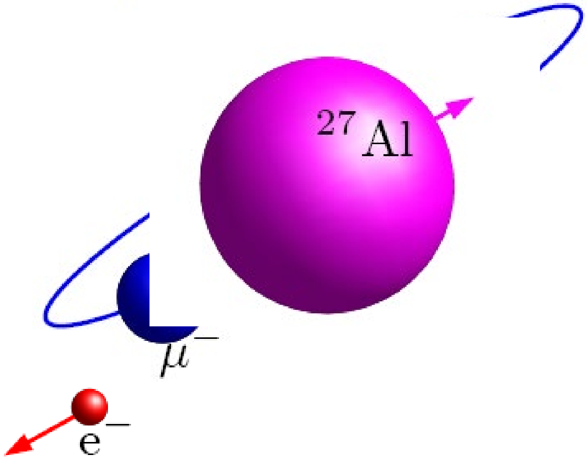
- **e** and **γ** are back-to-back, $\Delta\theta = 180°$
- **e** and **γ** are simultaneous, $\Delta t = 0$
- $E_e = E_\gamma = m_\mu/2$

4





Perhaps the most sensitive approach is coherent μ-to-e conversion



105 MeV
monoenergetic e-

$$\mu^- N \rightarrow e^- N$$

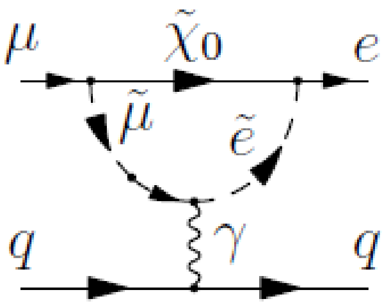
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

- This signature is quite unique
- Goal $R_{\mu\varepsilon}$ to < 6 x 10^{-17} (90% C.L.)
  - Present is < 7 x 10^{-13} → So this is very ambitious

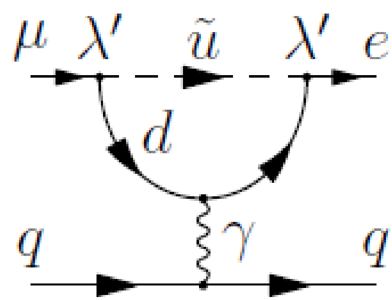
4 order of magnitude gain !!

What can Mu2e discover?

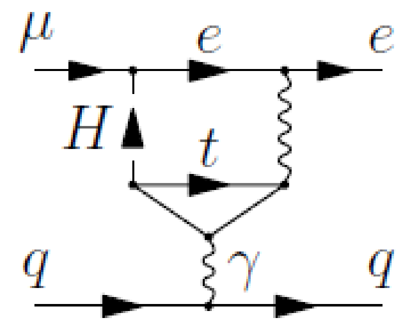
SUSY



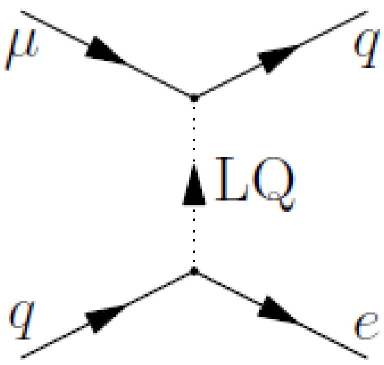
RPV SUSY



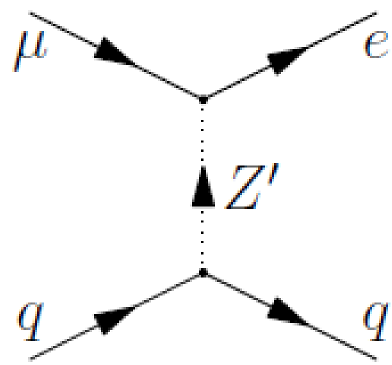
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Theory reviews:

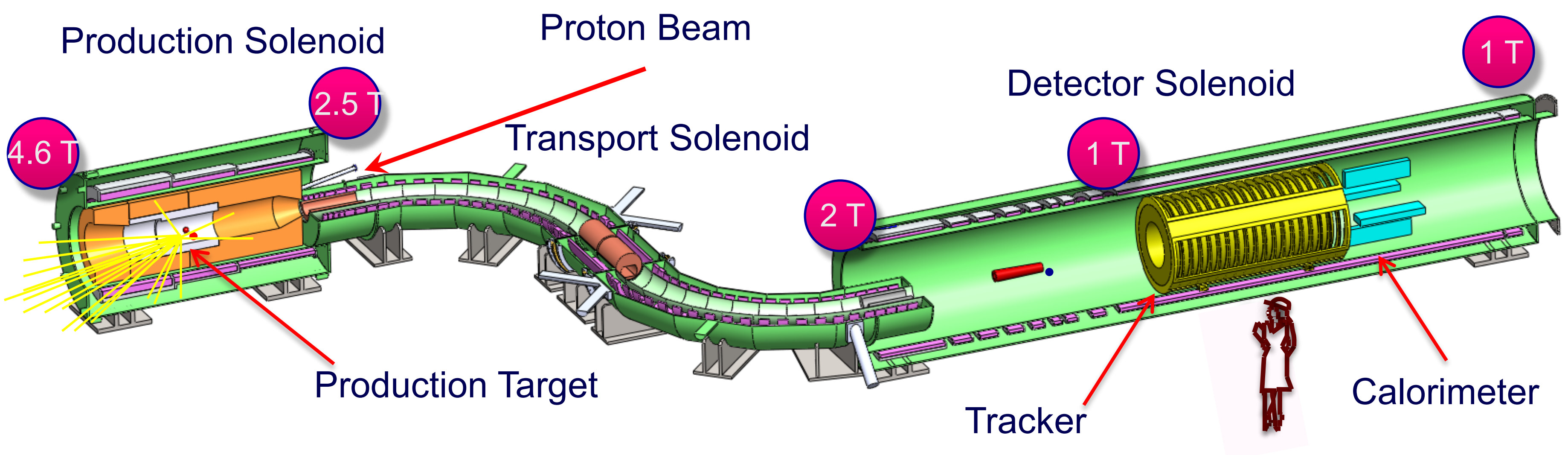
Y. Kuno, Y. Okada, 2001

M. Raidal *et al.*, 2008

A. de Gouvêa, P. Vogel, 2013

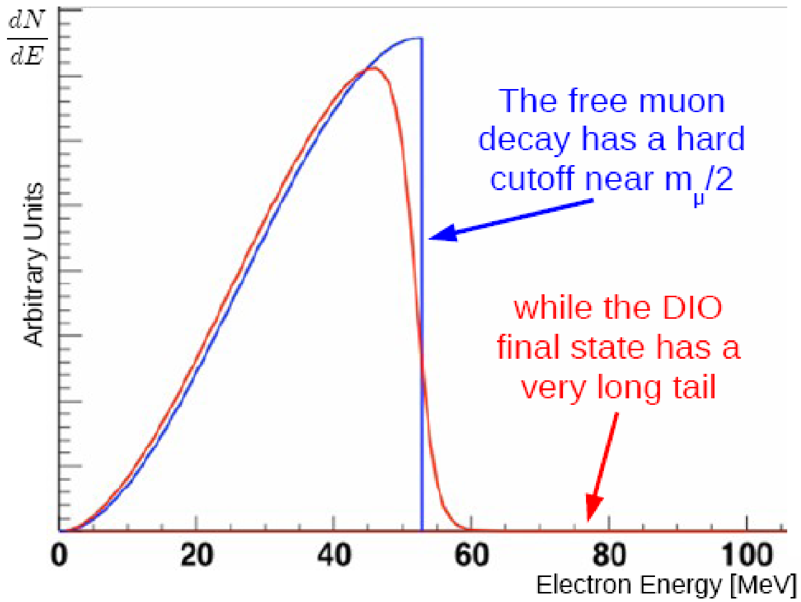
How it is done

- Need intense pulsed source of low-energy muons
- Stop in thin Al target
- Form muonic Al atoms.
- Observe
  - 40% will decay “in orbit”;
  - 60% will capture (hadronic junk emitted)

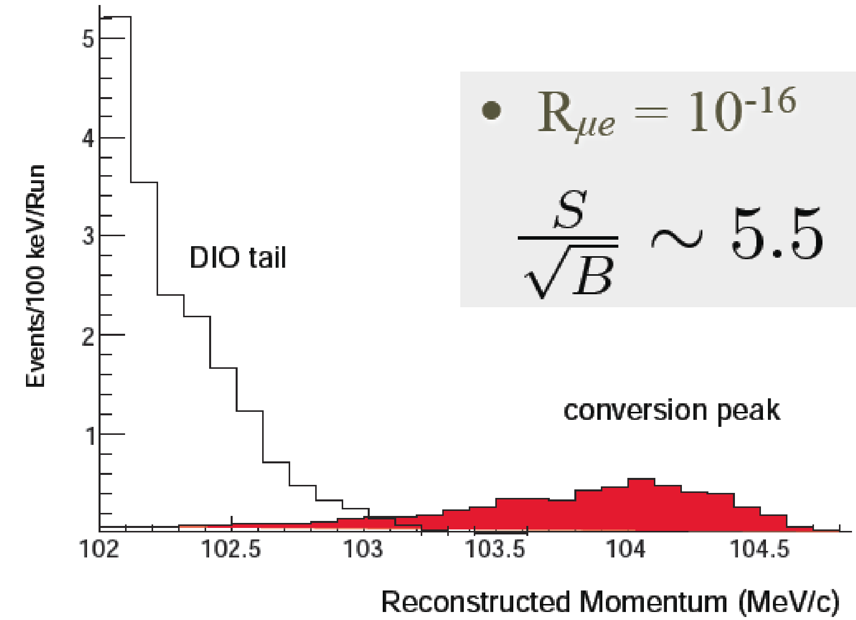


Challenge: find signal above "Decay in Orbit" tail

Tricky calculation; solved Czarnecki et al

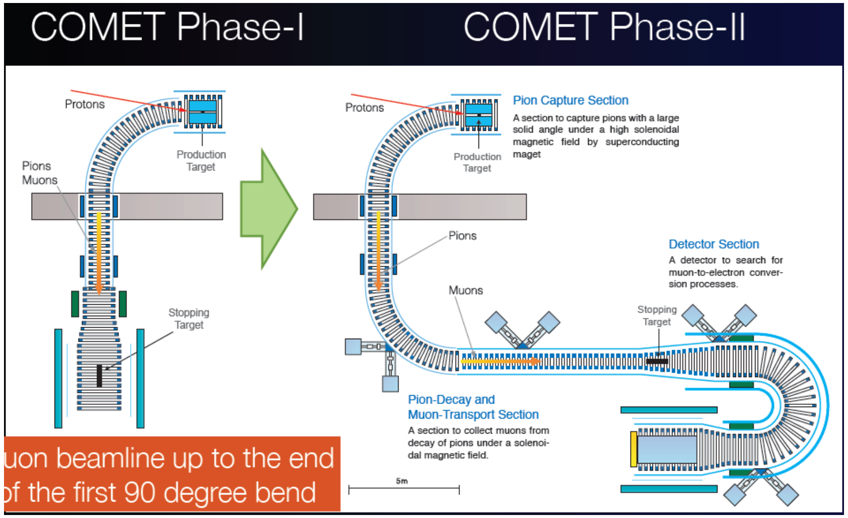


Resolution and Redundancy critical



- $R_{\mu e} = 10^{-16}$

$$\frac{S}{\sqrt{B}} \sim 5.5$$

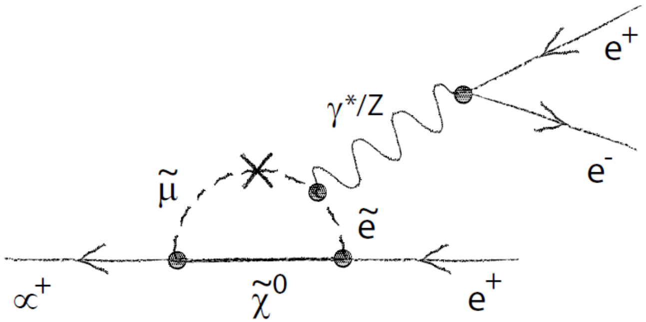


Similar: COMET in Japan

- Staged approach.
- Approved for Phase-1
  - Sensitivity: < 7×10^{-15}
- Full phase later, similar to Mu2e

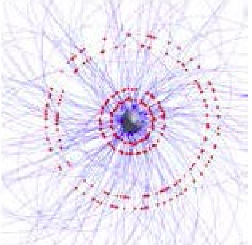
Next-generation: μ → eee

(2013: approved at PSI)

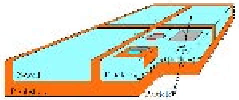


Typical comparison to $\mu \to e\gamma$ *without enhancement*

$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$



- **Goal:**
  - **Finding 1 in 10^{16} muon decays**



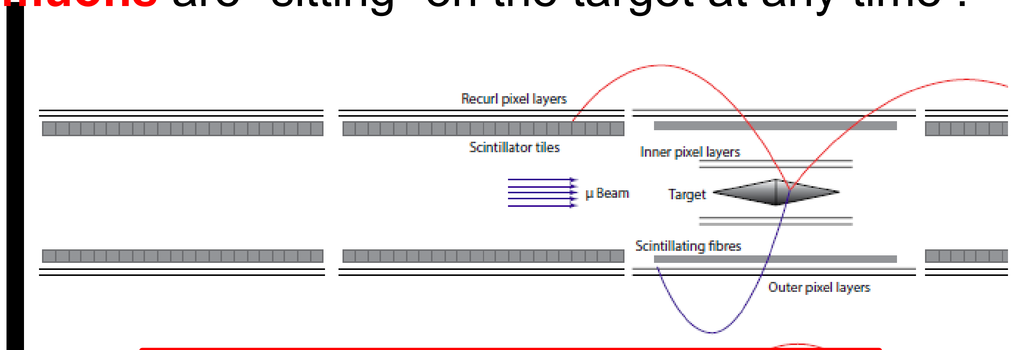
- **Special technique**
  - **High-voltage monolithic active pixel sensors**

- **The detector**
  - **Minimum material, maximum precision**

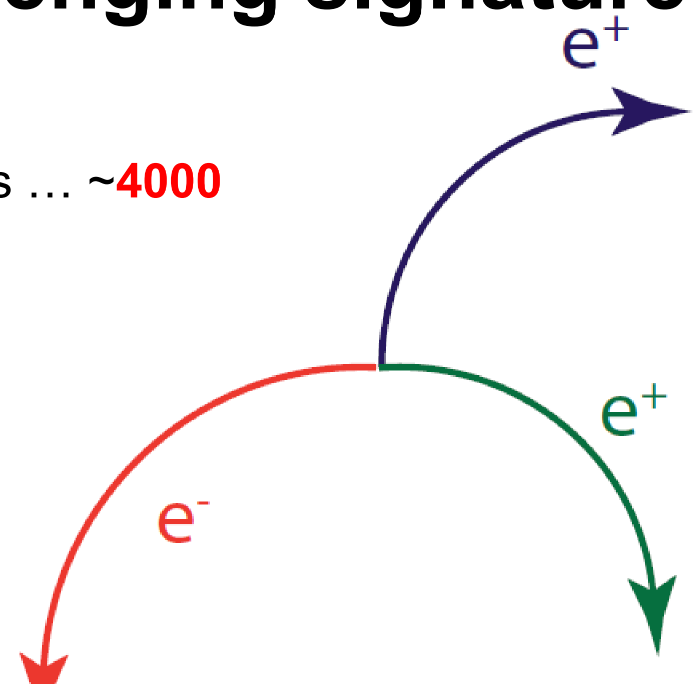
Again, a unique and challenging signature

A staged approach is starting now

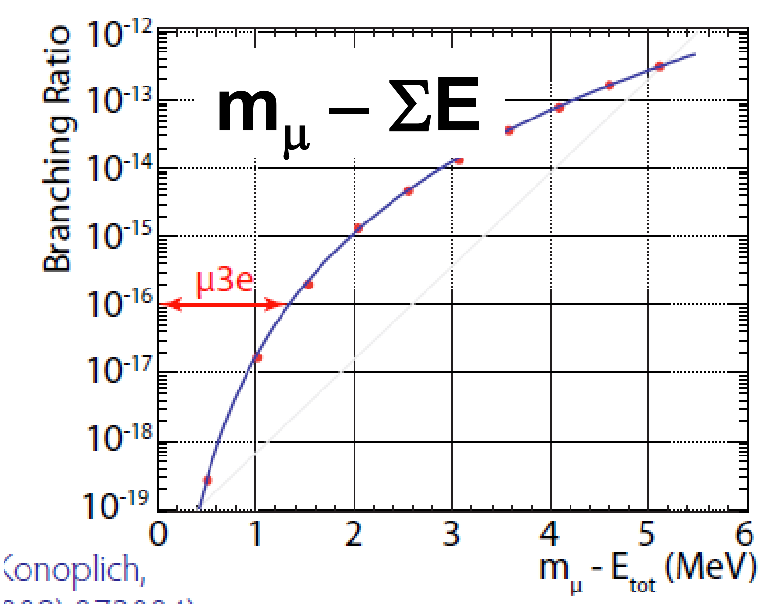
To achieve final statistics, extraordinary high rates … ~**4000 muons** are “sitting” on the target at any time !



10,000 times MuLan statistics
- **200 MHz muon rate**
- **Wow!!!**



- **$2\ e^+$, $1\ e^-$**
- **Common vertex**
- **Common time**
- **Σ energies = m_μ**
- **No energy > m_μ / 2**



Topic 7

The Muon's Anomalous Magnetic Moment

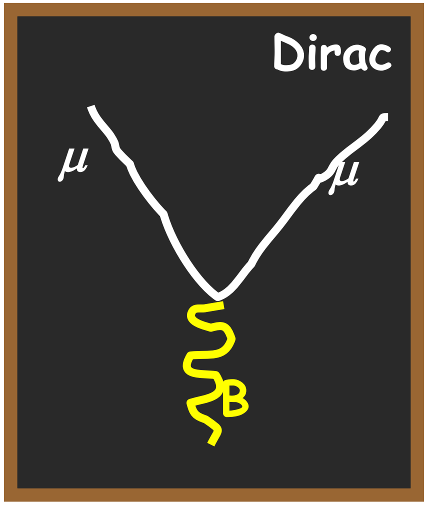
(finally, something I am doing)

… "*our future discoveries must be looked for in the sixth place of decimals.*"

It follows that every means which facilitates accuracy in measurement is a possible factor in a future discovery, and this will, I trust, be a sufficient excuse for bringing to your notice the various methods and results which form the subject matter of these lectures.

- Albert Abraham Michelson-

Dirac and beyond …

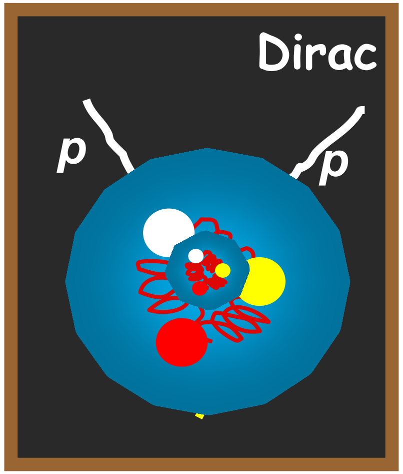


$$i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)$$

- 4-component (spinor) electron wave function Ψ in an EM potential (A_μ)
- Anticipates **antiparticles** (later found)
- Predicts **g = 2**, as observed in atomic fine-structure experiments for the **spin-1/2** electron magnetic moment (whereas an orbital picture → **g = 1**)

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}, \quad e > 0$$

- Allows for a so-called **Pauli interaction** term to accommodate **deviations of g from 2** (as we will see are very important !)



At first, g ≈ 2 was observed. But later, the proton …

$g_p = 5.59$

and then the neutron

$g_n = -3.8$

each showed large magnetic moments (g ≠ 2 by a lot)

The neutron? **It's not even charged!**

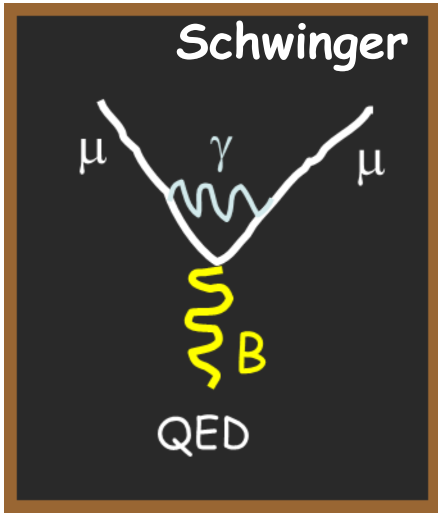
These are "Anomalous" magnetic moments owing to substructure

$$g = 2(1+a) \;\xrightarrow{\text{or}}\; a = \frac{(g-2)}{2}$$

In 1947, small deviations from g = 2 for the "pointlike" electron were observed at about the ~ 0.1% level

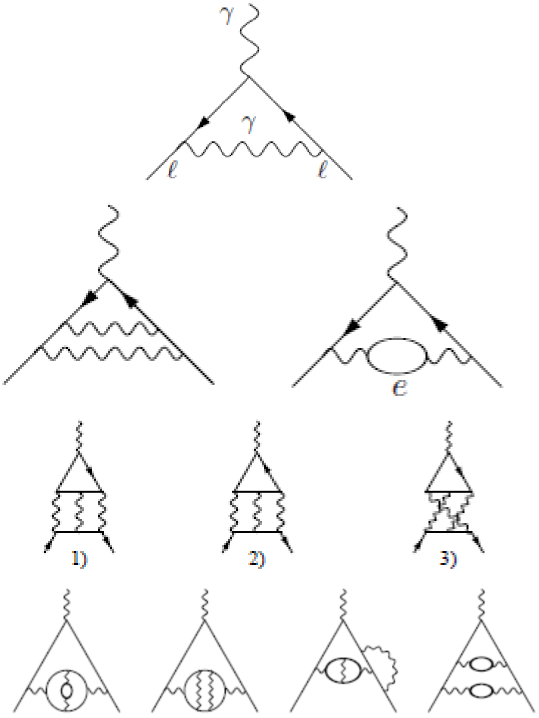
What is that ??

$$a_e = \frac{(g-2)}{2} \approx \frac{1}{2}\frac{\alpha}{\pi} \approx \frac{1}{800}$$



- Schwinger calculates 1st order radiative correction
- It agrees with experiment
- Higher-order terms are expansions in powers of α/π
- The set of radiative terms, represents the QED anomalous magnetic moment contribution for the leptons

$$a = \sum_{j=1} C_j \left(\frac{\alpha}{\pi}\right)^j$$



Another story, but a_e is calculated so precisely (and accurately) that we obtain the best α from it:

$$\frac{1}{\alpha}(a_e) = 137.035\,999\,085\,(12)(8x)(33)$$

QED recent update, including tenth-order terms ! 12,672 diagrams

Complete Tenth-Order QED Contribution to the Muon $g-2$

Tatsumi Aoyama,[1,2] Masashi Hayakawa,[3,2] Toichiro Kinoshita,[4,2] and Makiko Nio[2]

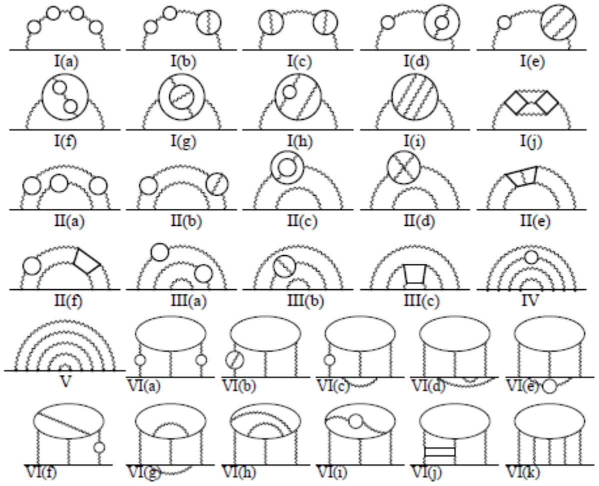
[1]*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan*
[2]*Nishina Center, RIKEN, Wako, Japan 351-0198*
[3]*Department of Physics, Nagoya University, Nagoya, Japan 464-8602*
[4]*Laboratory for Elementary Particle Physics, Cornell University, Ithaca, New York, 14853, U.S.A*

(Dated: May 29, 2012)

$$a_\mu(QED)^* = 116\,584\,718.09(14)(4)_\alpha \times 10^{-11}$$

Note: way better than expt.

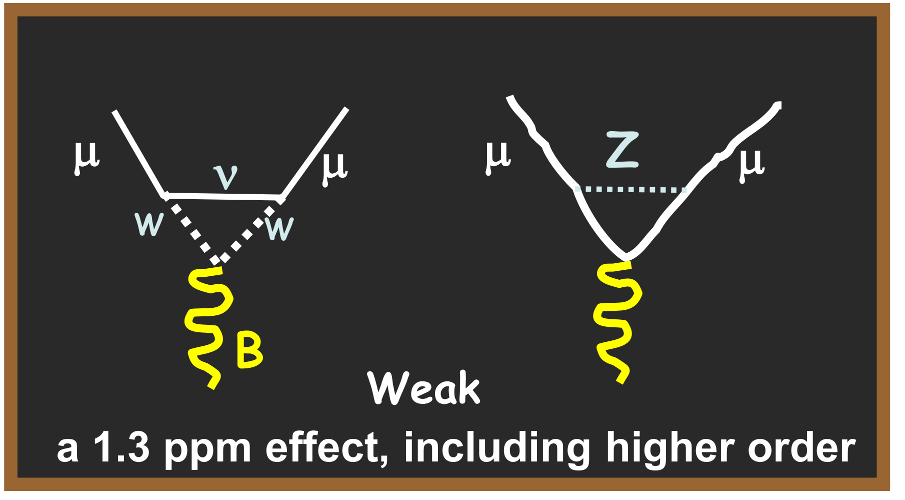
Do not try to calculate these at home:



arXiv:1205.5370v2 [hep-ph] 27 May 2012

* QED value here from 2010

The Electroweak theory says, e.g., we can replace any γ with a *Z* … and compute the Weak contribution to the anomaly

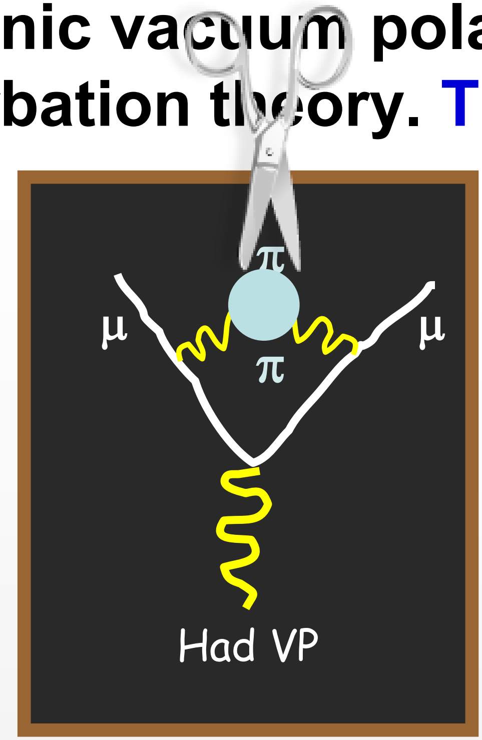


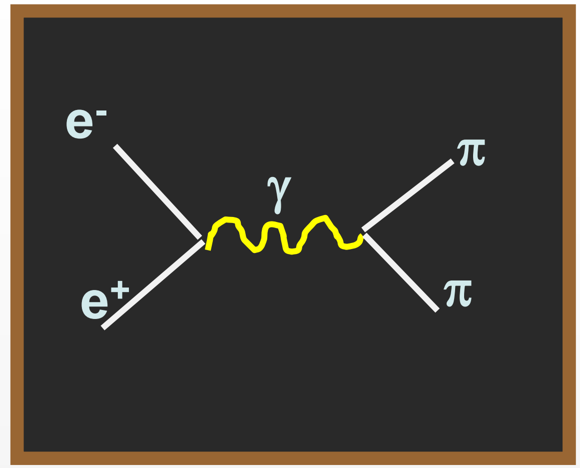
Known well, but wasn't easy

$$a_\mu(Weak) = 152(2)(1) \times 10^{-11}$$

Note: also way better than expt.

Hadronic vacuum polarization cannot be calculated using perturbation theory. The strong coupling is too large





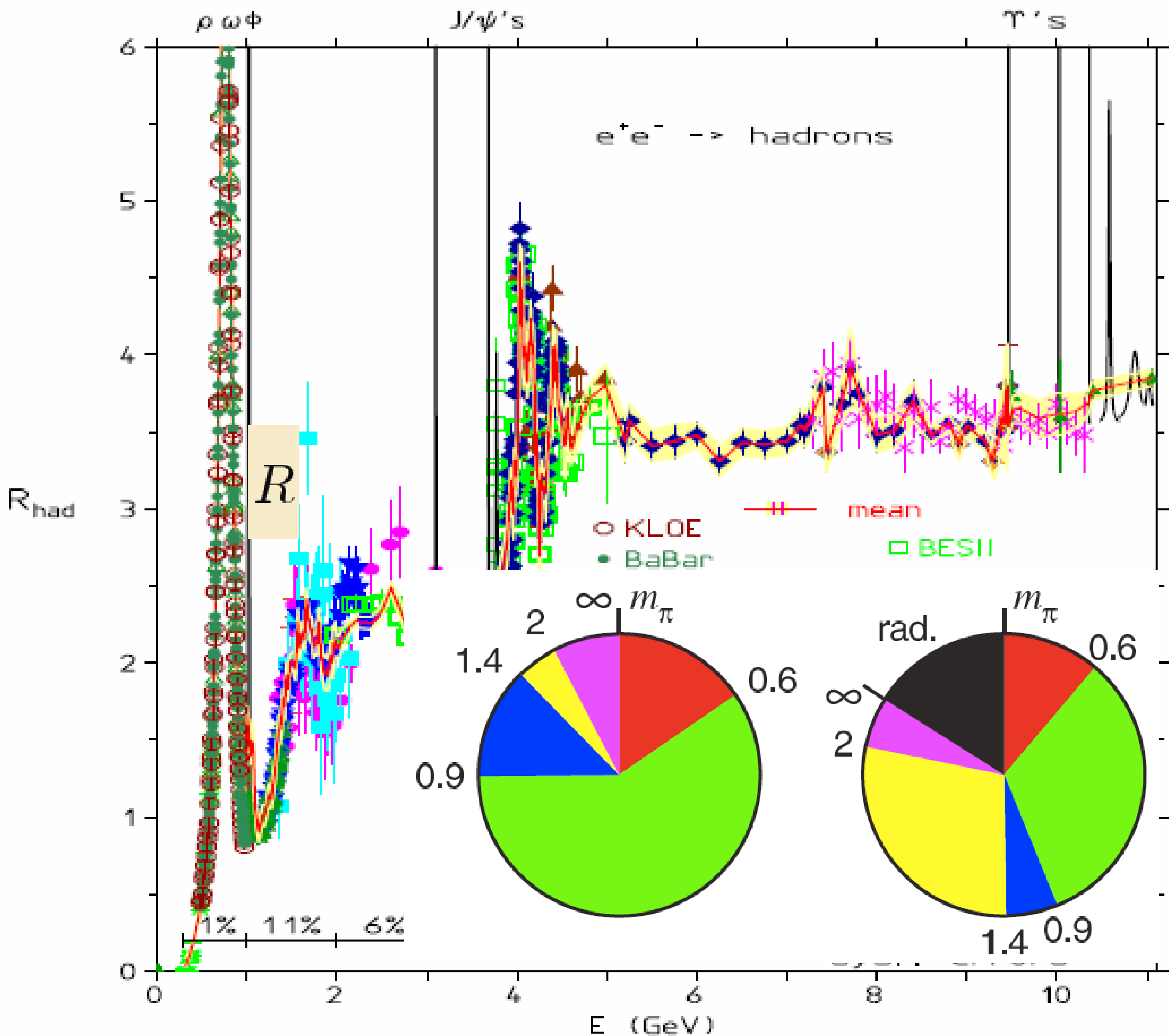
This contribution can be exactly linked to experimental data

1. Cut diagram down middle
2. Looks like $\gamma \rightarrow \pi\pi$
3. Dispersion relation connects $e^+e^- \rightarrow \pi\pi$ cross section measurement to anomoly contribution of 1st-order HVP

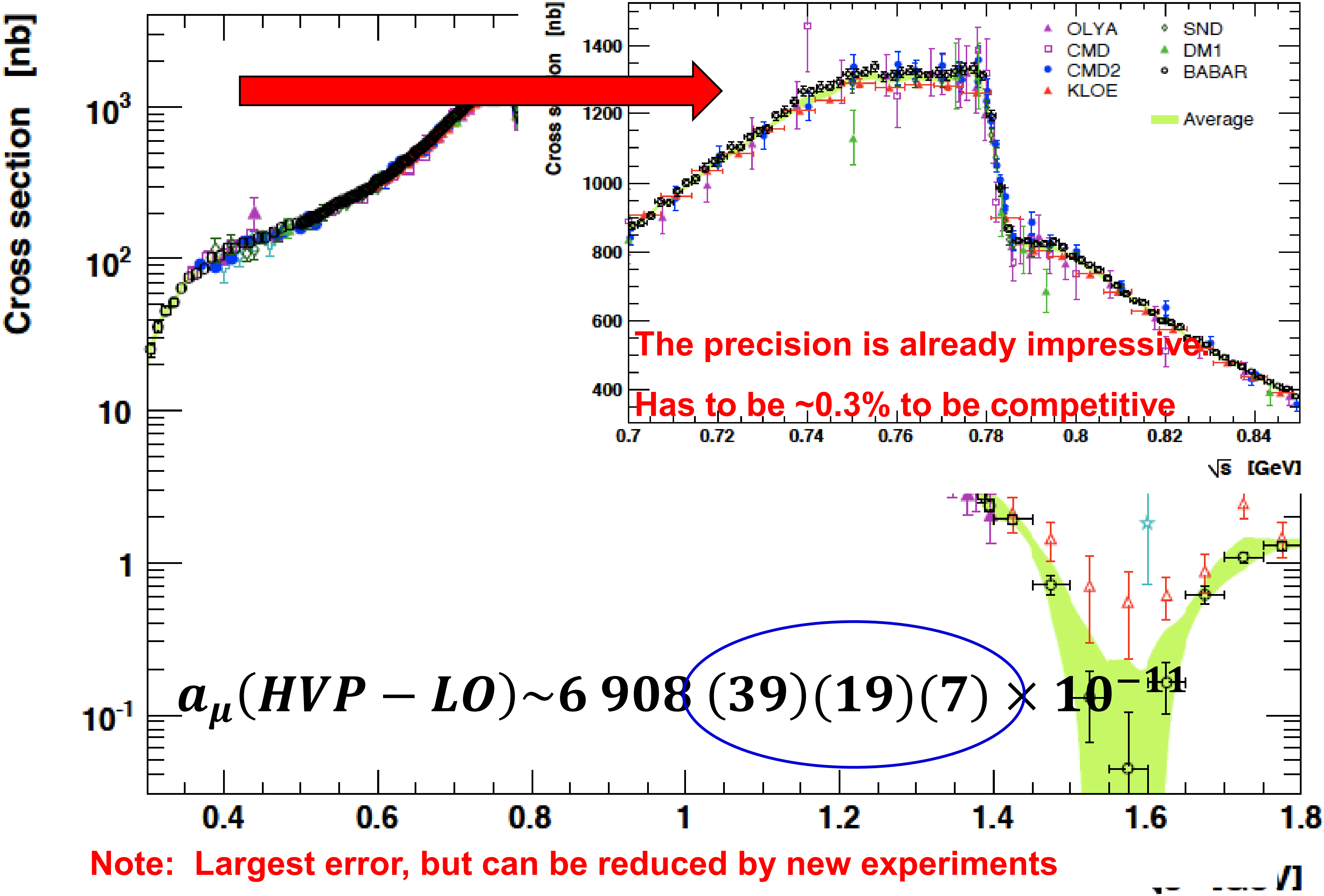
$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \rightarrow \mathrm{hadrons})}{\sigma(e^+e^- \rightarrow \mathrm{muons})}$$

The cross sections scan a wide range in energy



Most important is low energy: $e^+e^- \to \pi^+\pi^-$



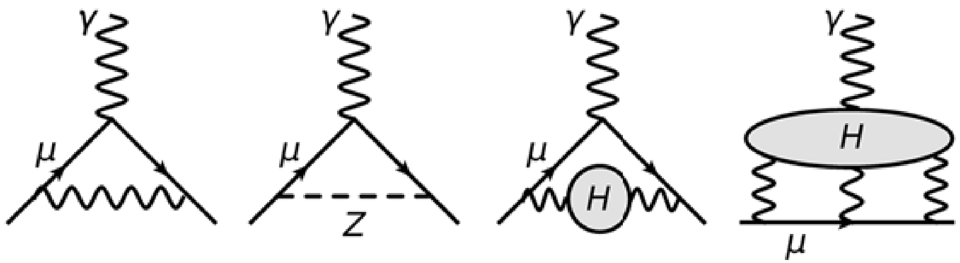
The precision is already impressive.

Has to be ~0.3% to be competitive

$$a_\mu(HVP-LO) \sim 6\,908\,(39)(19)(7) \times 10^{-11}$$

Note: Largest error, but can be reduced by new experiments

Standard Model contributions to a_μ … updates → 3.6 σ

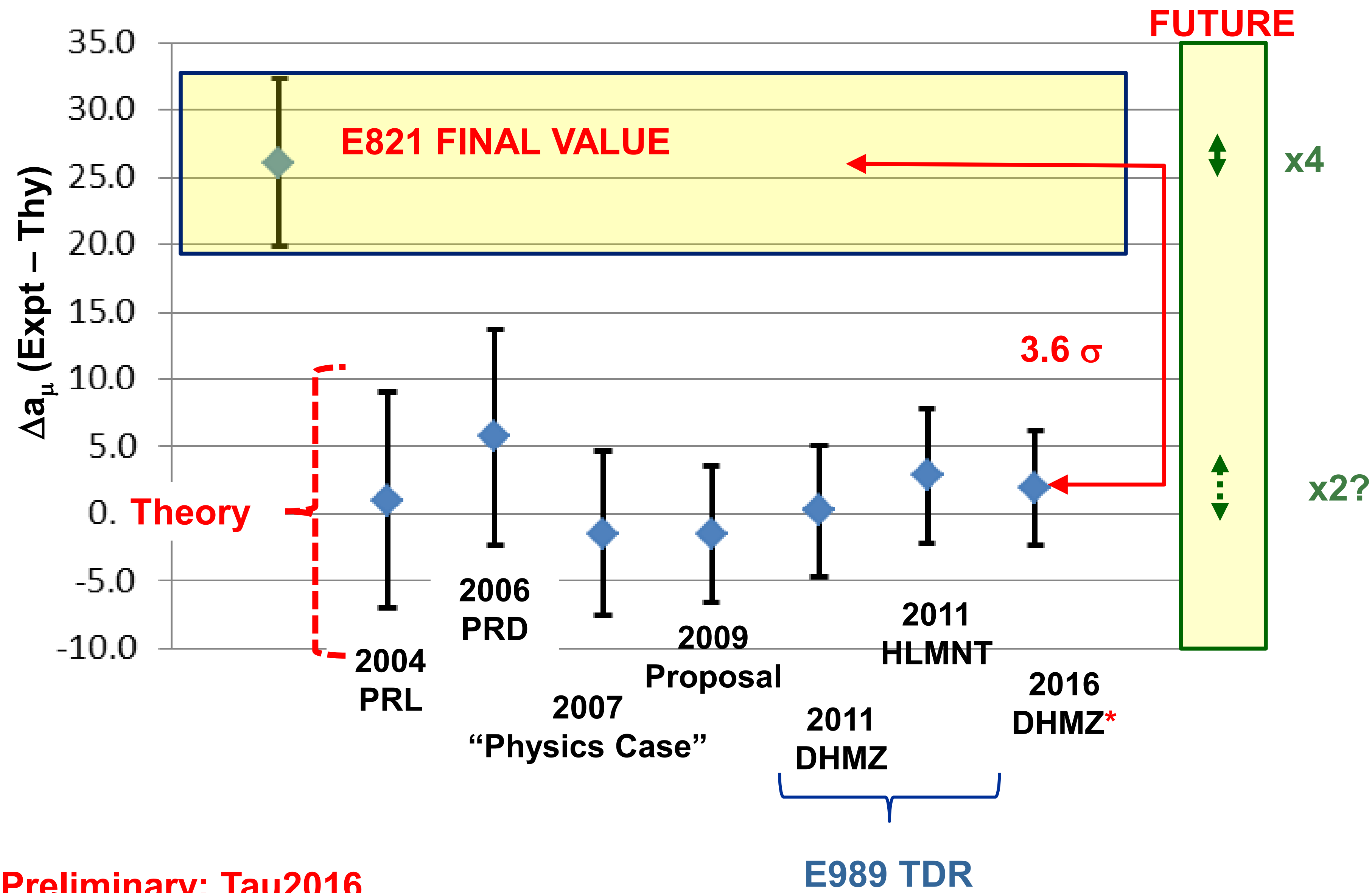


	Value ($\times 10^{-10}$) units
QED ($\gamma + \ell$)	$11\,658\,471.8951 \pm 0.0009 \pm 0.0019 \pm 0.0007 \pm 0.0077_\alpha$
HVP(lo) Davier17	692.6 ± 3.33
HVP(lo)KNT2017	693.9 ± 2.6
HVP(ho) KNT2017	-9.84 ± 0.07
HLbL Glasgow	10.5 ± 2.6
EW	15.4 ± 0.1
Total SM Davier17	$11\,659\,181.7 \pm 4.2$
Total SM KNT17	$11\,659\,182.7 \pm 3.7$

← This is a fancy guess; it will change →

BNL E821 δa_μ(Expt) = ± 6.3

In the 12 years since BNL E821, the "g-2 Test" has continued to point to something interesting

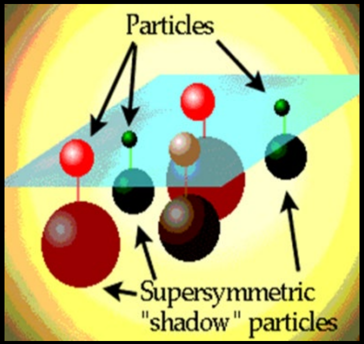


*Preliminary; Tau2016

What could it mean now?

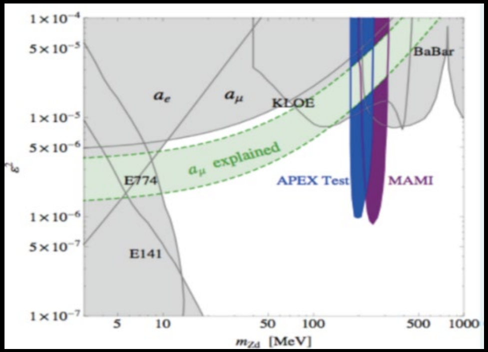
Some things "seen" just wash away …

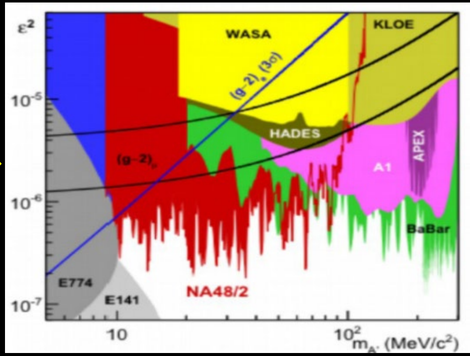
And some things are under Tension



LHC limits growing, but SUSY, if exists, is hiding well

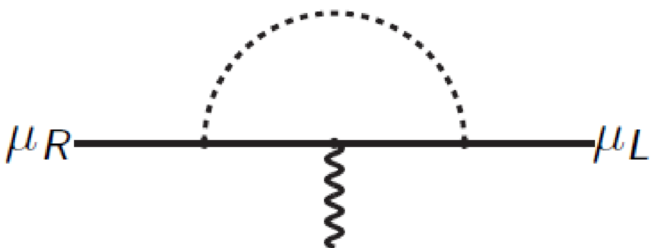
And some things don't' seem to be so …

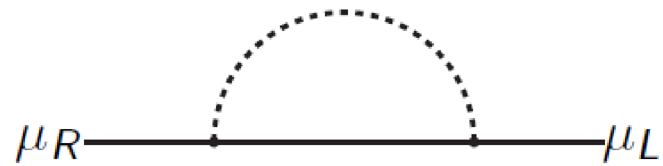


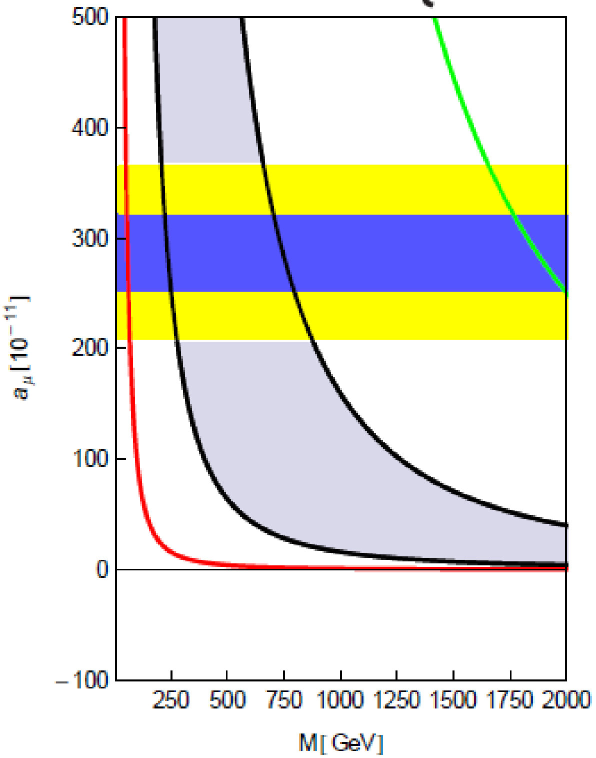


In a generic sense, these are "loop effects" that couple to the muon mass and moment in similar fashion, characterized ▯ *C*, a coupling:

$$\mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2 \qquad\qquad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$



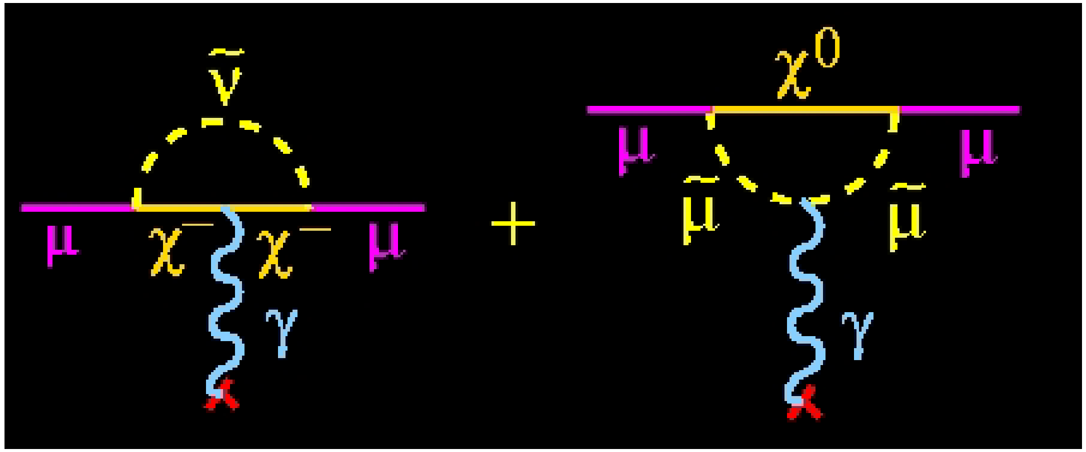




$\mathcal{O}(1)$	radiative muon mass generation . . . [Czarnecki,Marciano '01] [Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry (tan β) vectorlike fermions . . .
$\mathcal{O}(\frac{\alpha}{4\pi})$	SM: Z, W. New physics: Z', W'. . .
$< \frac{\alpha}{4\pi}$	2-Higgs doublet model, dark photon .

Following Czarnecki, Marciano, and Stockinger

SUSY contribution to a_μ:



Difficulty to measure at the LHC

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \tan\beta \; \mathrm{sign}(\mu) \left(\frac{100\text{ GeV}}{M_{SUSY}}\right)^2$$

Recall, the deviation between Experiment and Theory is ~280 x 10^{-11}, so the above calculation is interesting if you put in M_{SUSY}, and tanβ

tanβ? Ratio of the two vacuum values of the 2 neutral Higgses, typically estimated in range from 3 to 55

A few key numbers determine the precision of the g-2 Test:

$$a_\mu(\text{New Physics}) \equiv a_\mu(\text{Expt}) - a_\mu(\text{SM})$$

- $a_\mu(SM) = a_\mu(QED) + a_\mu(Weak) + a_\mu(HVP) + a_\mu\,(Had\;HO) + a_\mu\,(HLbL)$

✓ ✓ ✓

A few remarks here

In E821 **≡** $\mathcal{R}_\mu(\text{E821}) = 0.003\,707\,206\,4(2\,0)$ **[0.54 ppm]**

- $a_\mu(\text{Expt}) = \frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

-.001519270384(12) [8 ppb]

206.768 2843(52) **[25 ppb]**

Spin motion for a particle *moving* in a magnetic field

$$\omega_C = \frac{eB}{mc\gamma}$$

Momentum turns at ω_c cyclotron frequency

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Spin turn depends on g and on ω_c with $1-\gamma$ factor

If g = 2 exactly, then the difference between SPIN and MOMENTUM vectors

$$\omega_S - \omega_C = \left[\frac{eB}{mc} + \frac{eB}{mc\gamma} - \frac{eB}{mc}\right] - \frac{eB}{mc\gamma} = 0$$

Spin motion for a particle *moving* in a magnetic field

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \qquad \omega_C = \frac{eB}{mc\gamma}$$

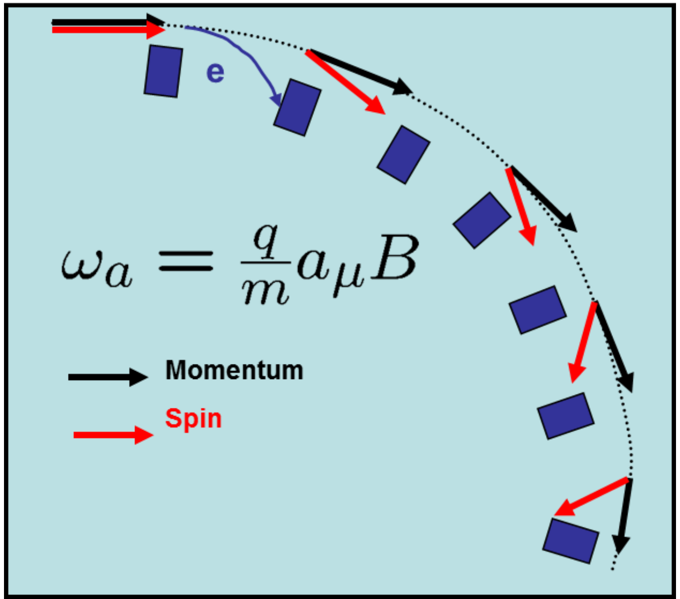
The **Spin** frequency relative to the **Cyclotron** frequency is the "anomalous precession frequency", ω_a

Does **NOT** depend on γ !

Proportional to g - 2 and ***B*** !

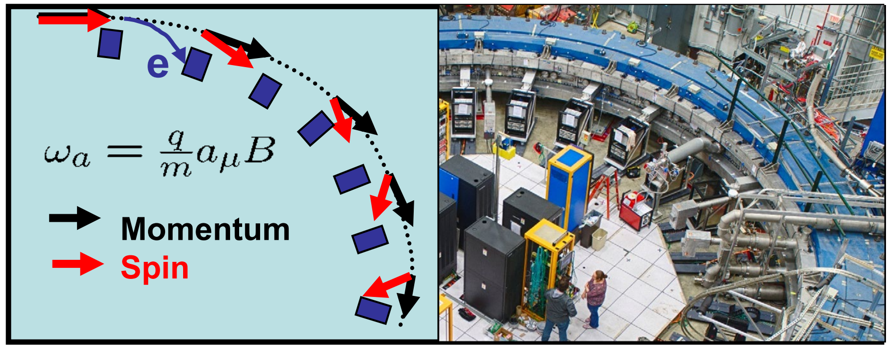
$$\omega_a = \omega_S - \omega_C$$

$$= \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$



Measurement of Muon g-2 and μEDM

Goal: 140 ppb
X 4 improvement



Determine difference between spin precession and cyclotron motion for a muon moving in a magnetic field:

The expression including E-field focusing and possible EDM

Get a_μ

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

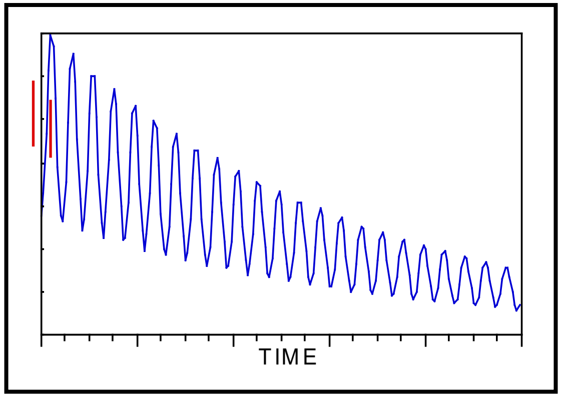
Magic γ

EDM

Measure these

$$\vec{\omega}_{net} = \vec{\omega}_a + \vec{\omega}_{EDM}$$

Two "blinded" frequency measurements are made. The ratio gives $a_\mu \equiv (g-2)/2$

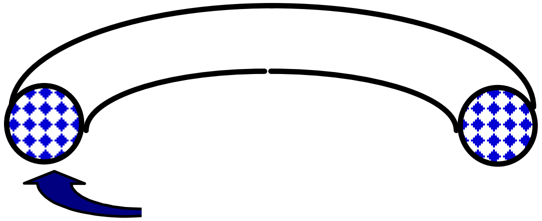


(1) Precession frequency

- (1) Calorimeters

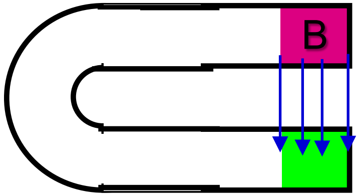
(2) Muon distribution

- (2) Trackers & Models



(3) Magnetic field

- (3) proton pNMR



$$(g-2) \propto \frac{(1)}{\left\langle \int (2)(3) \right\rangle}$$

How do we get each of these?

Systematic error projections in-line with statistical goal

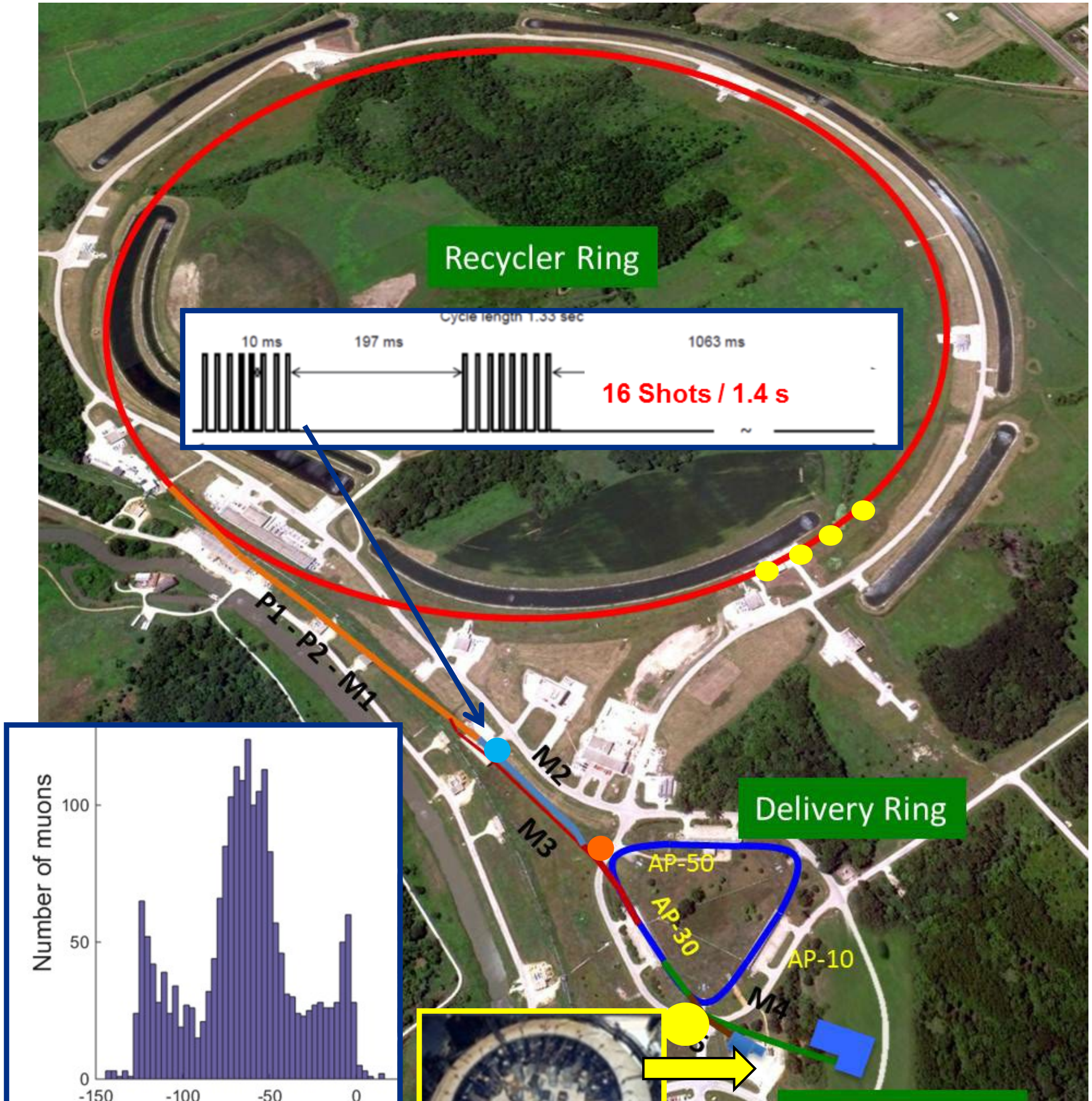
Precession

E821 Error	Size [ppm]	Plan for the New $(g-2)$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

Magnetic field

Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	-
Uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Others		0.15	0.10	0.10	0.05
Total systematic error on ω_p	0.5	0.4	0.24	0.17	0.11

Improvement vs time →

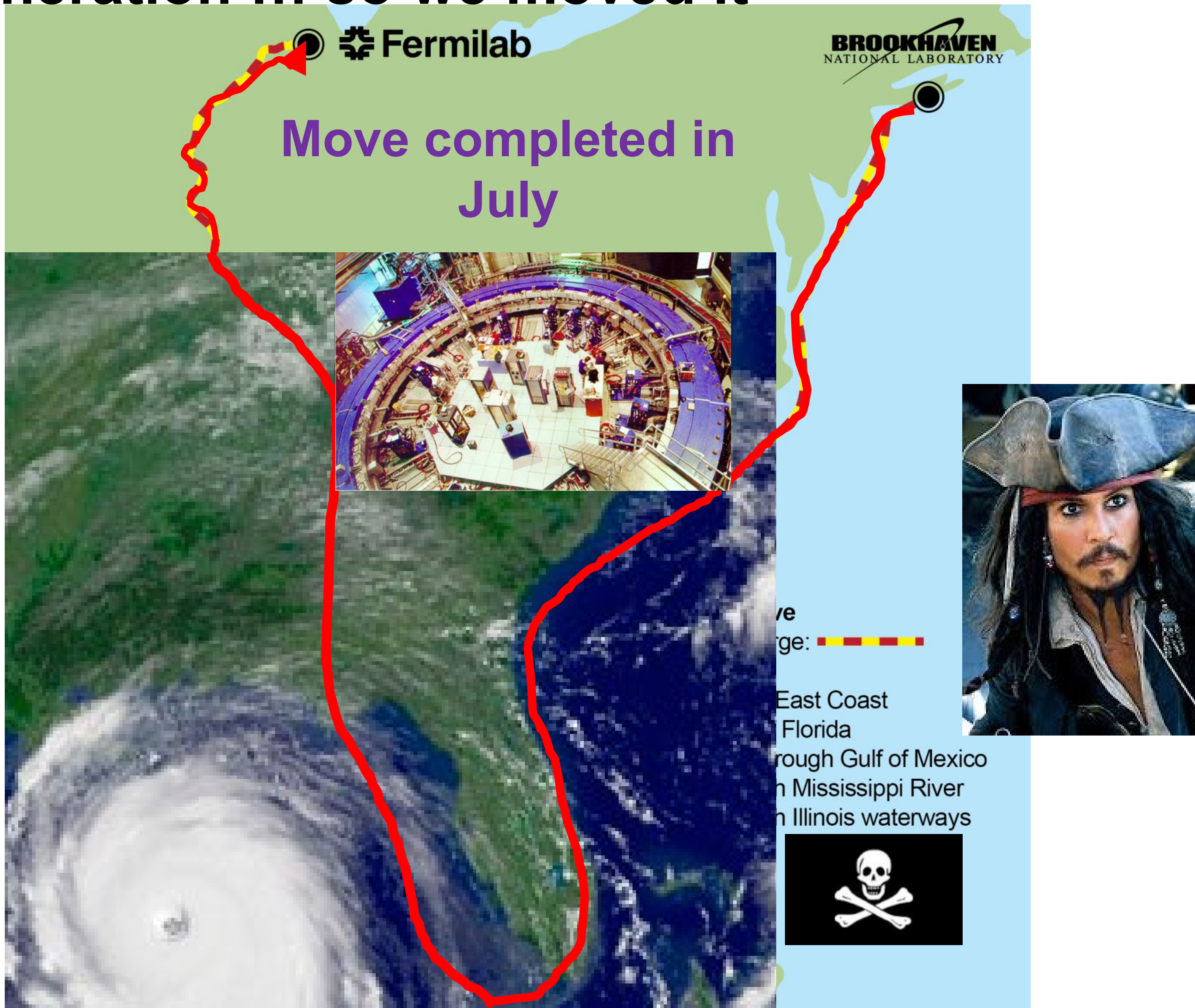


Intensity profile is 120 ns wide with "W" shape

Creating the Muon Beam for g-2

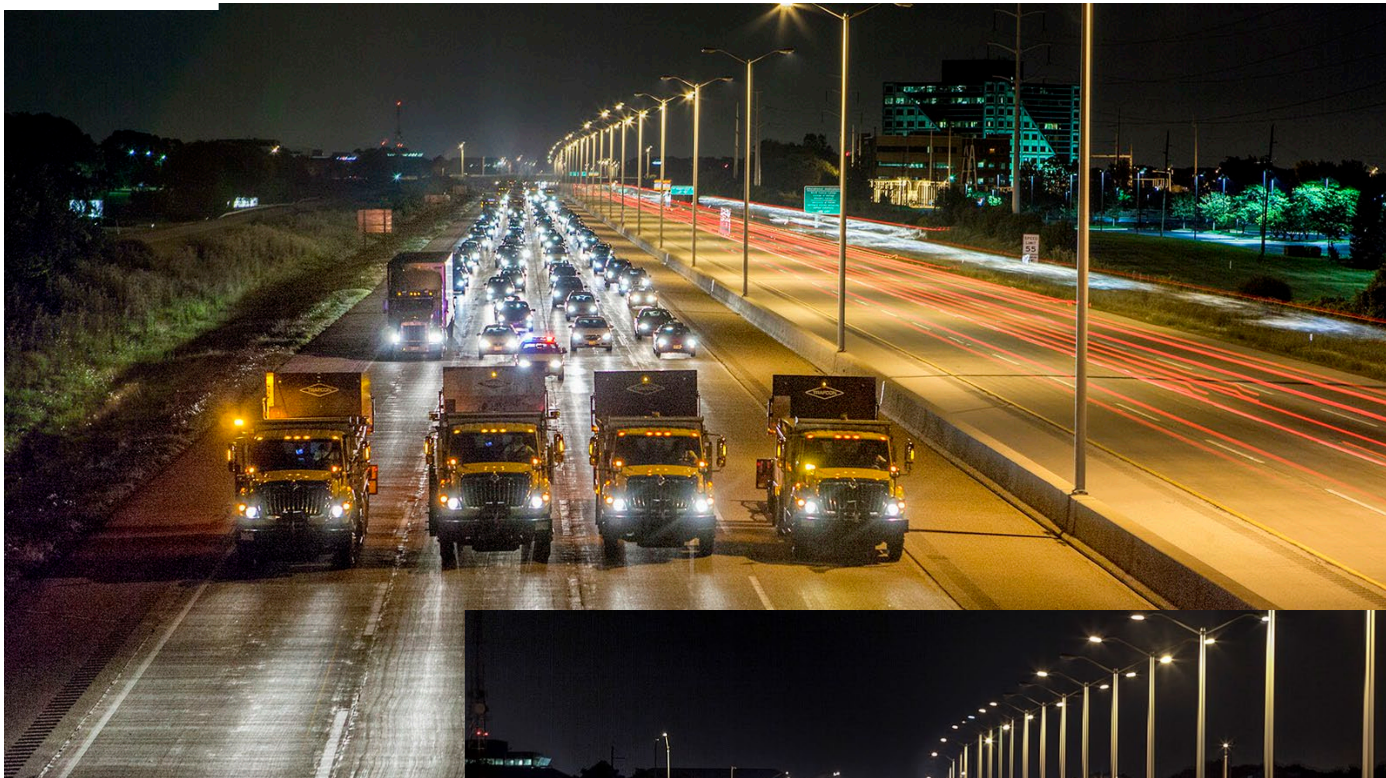
- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- **μ enter storage ring**

The *MAGNET* is the centerpiece and worthy of the next generation … so we moved it



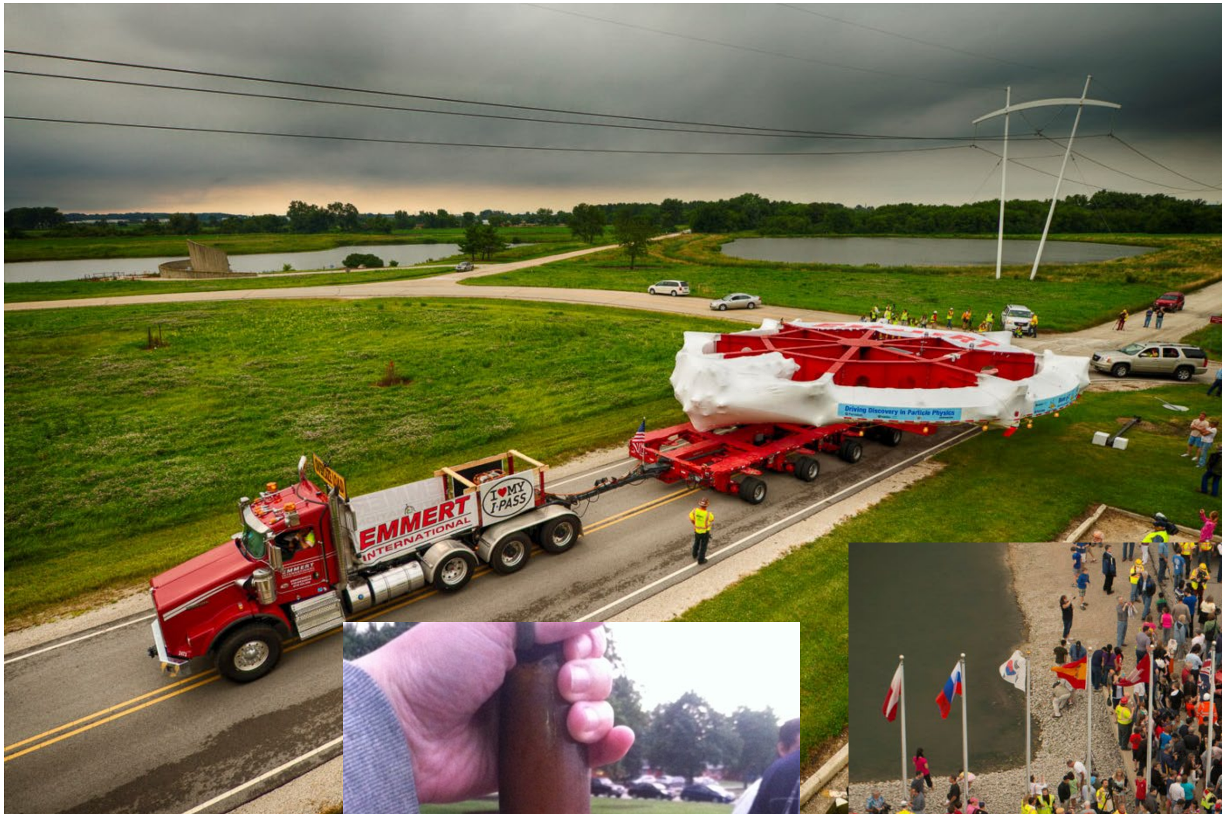
Leaving BNL and loading the barge

30 police cars escort it and close interstate

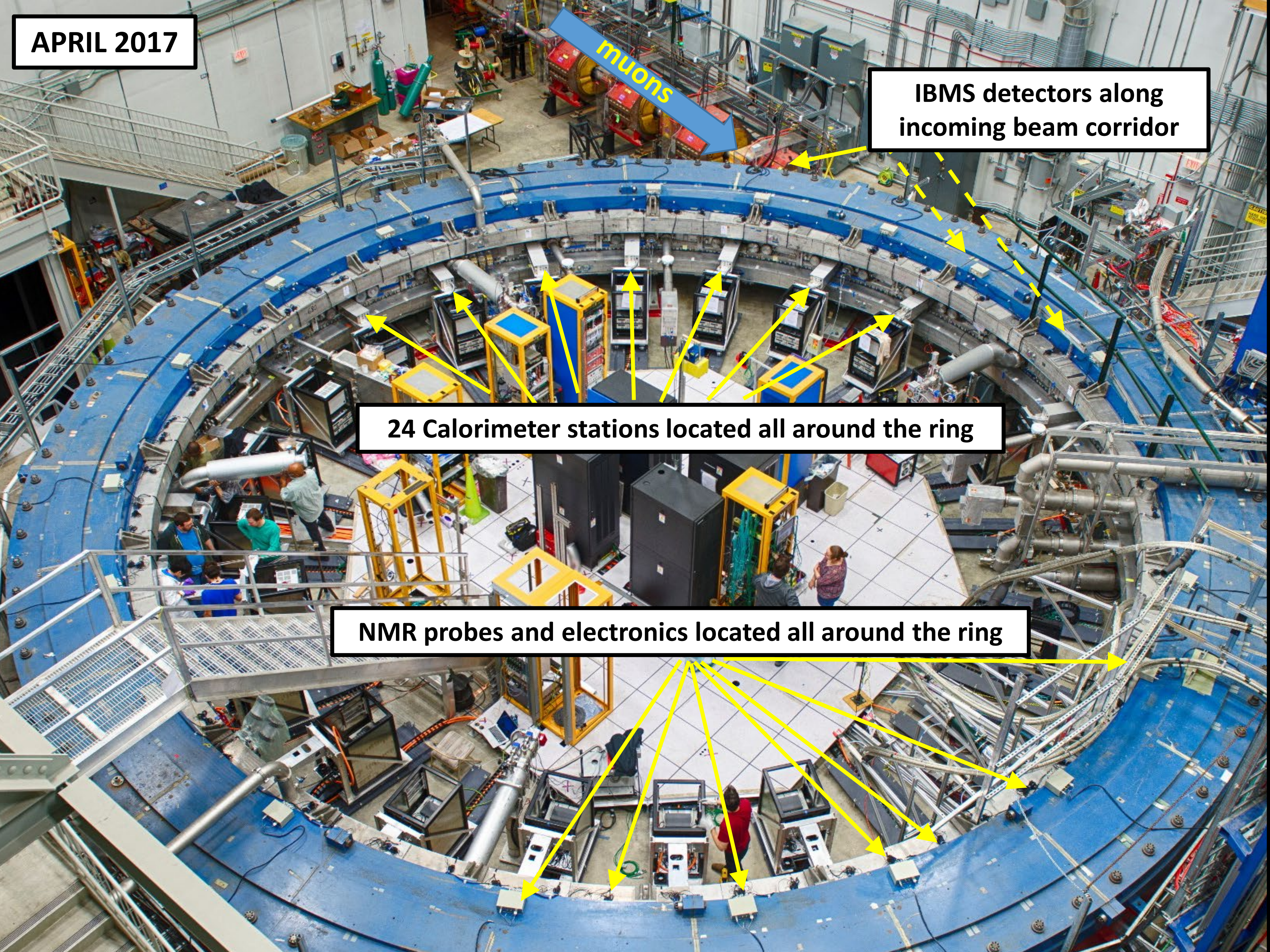


Squeezing through the I-355 tollbooth and a tight underpass

Arriving at FNAL to a huge crowd

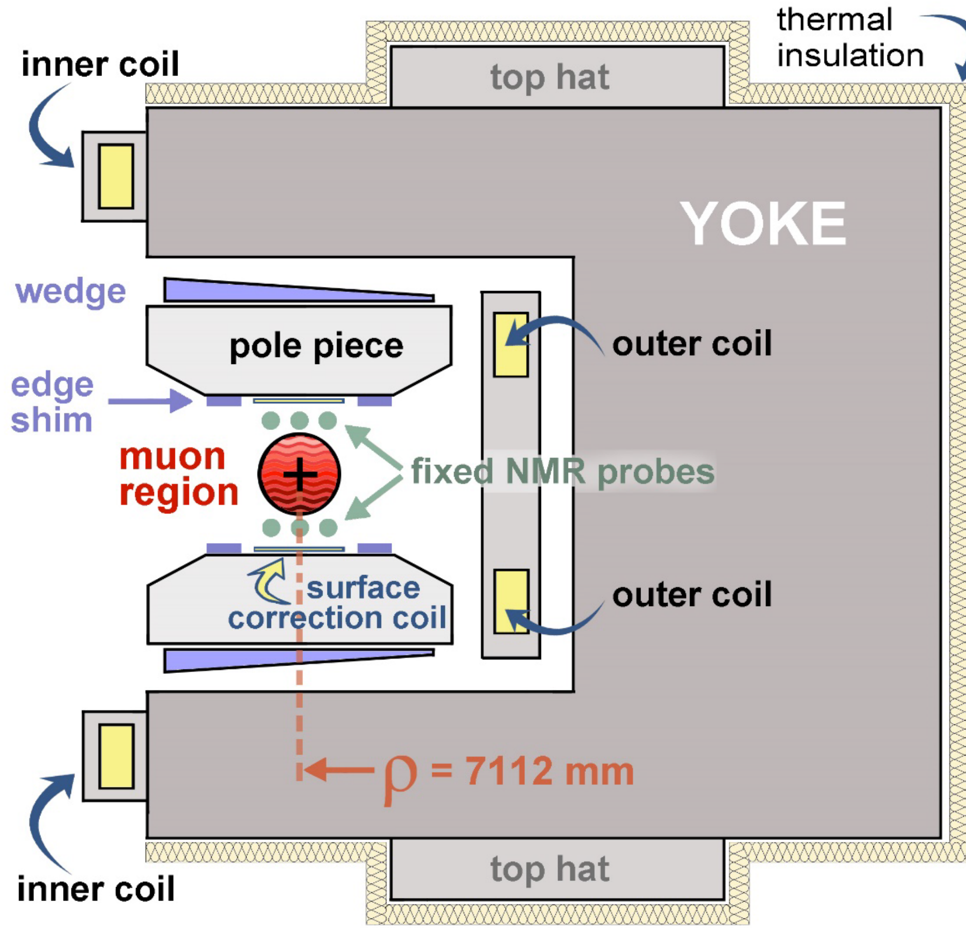


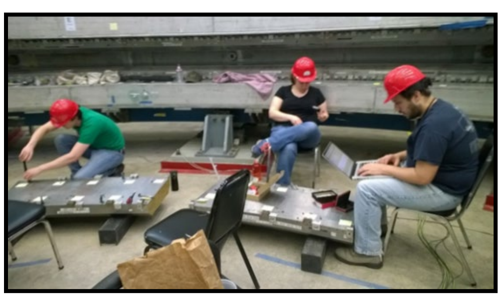
Magnetic Moment Beer

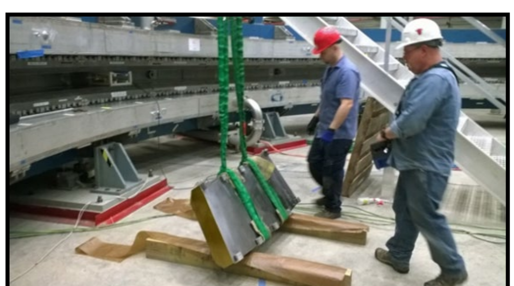

APRIL 2017
muons
IBMS detectors along incoming beam corridor
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring

The storage ring magnet is built and shimmed

- **B Field** 1.45T
- **12 Yokes**: C shaped flux returns
- **72 Poles**: shape field
- **864 Wedges:** angle - quadrupole (QP))
- **24 Iron Top Hats**: change effective mu
- **Edge Shims**: QP, sextapole (SP)
- **8000 Surface iron foils**: change effective mu locally
- **Surface coils**: will add average field moments (360 deg)



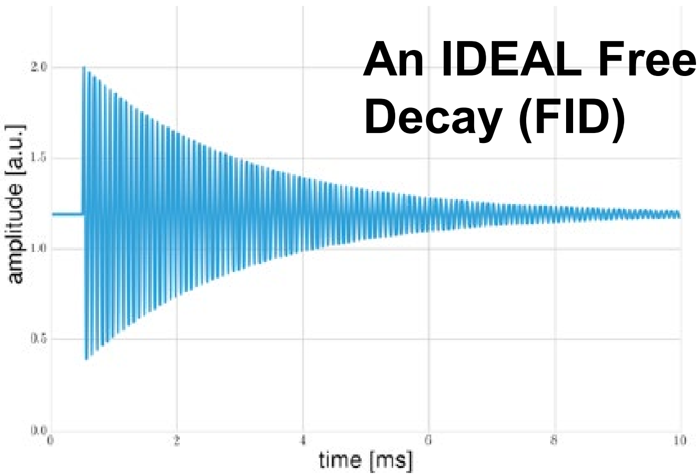




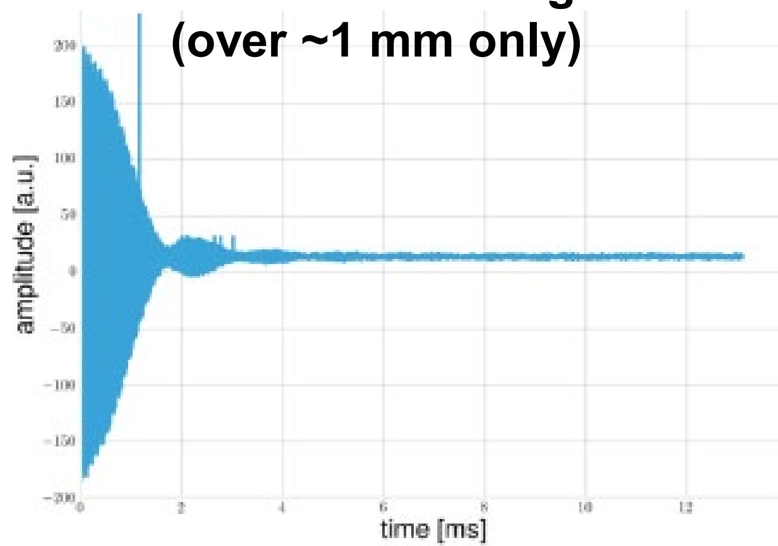
g-2 Magnet in Cross Section

Field measured using a proxy: pulse NMR of protons

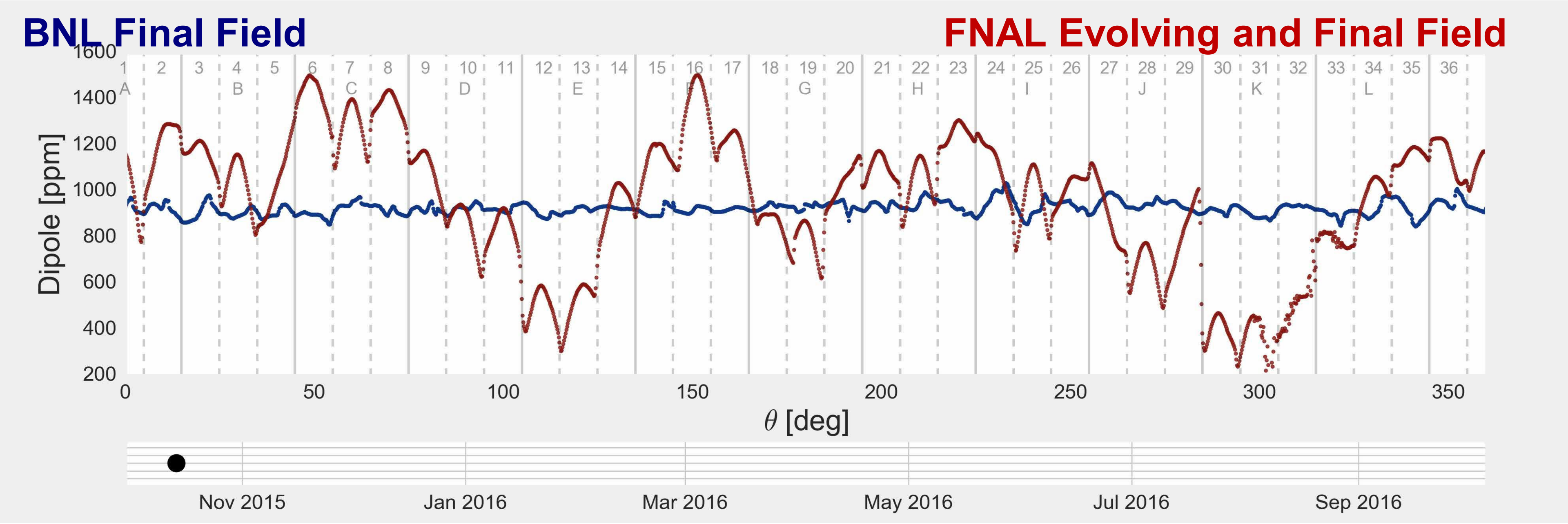
An IDEAL Free Induction Decay (FID)



An FID with of a gradient field (over ~1 mm only)



The x3 improved field uniformity compared to BNL was achieved by tuning knobs and *calculation*



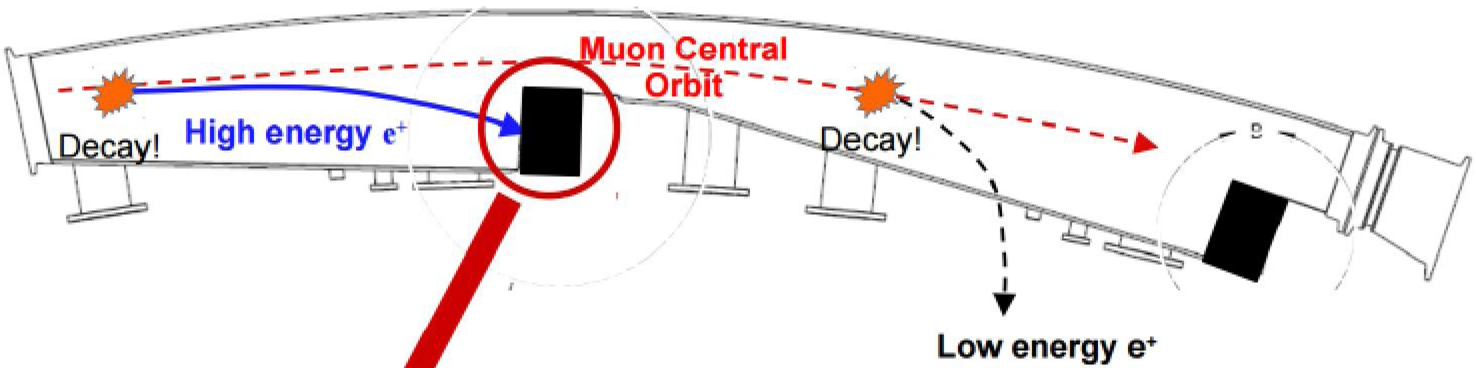
Evolution from “as built” → rough shimmed

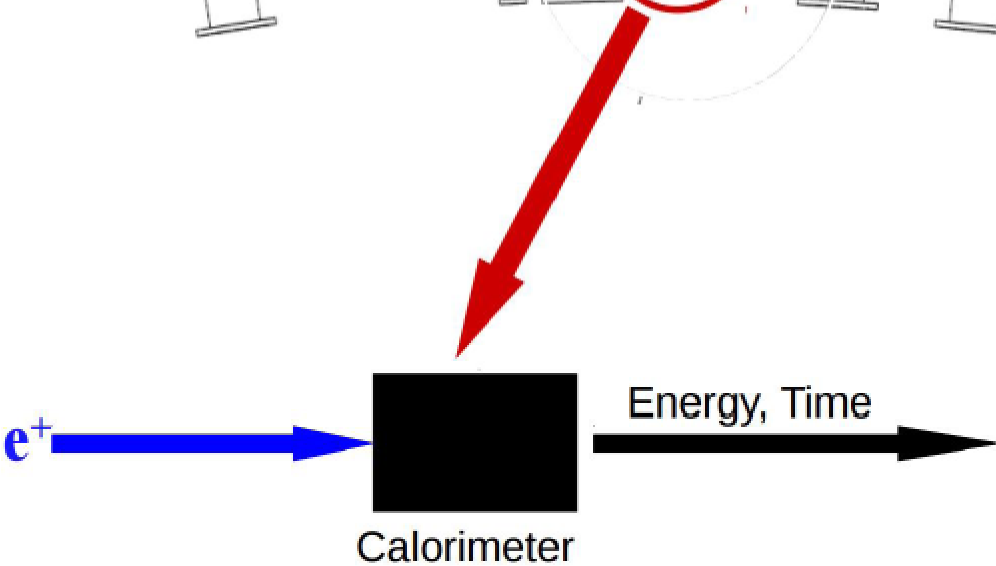
Measures of the Average Dipole Field from 0 – 360 degrees vs MONTHs of effort

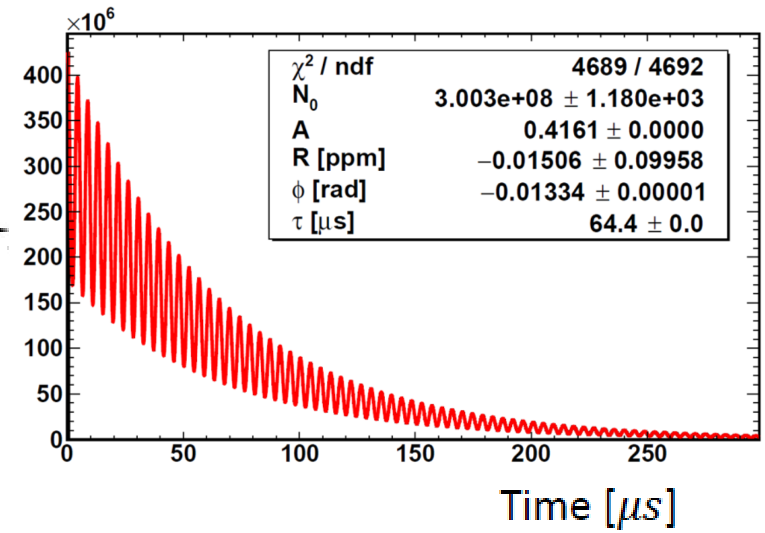
The result is 3 times better than BNL; +/- 10 ppm typically all the way around the 44 m circumference

Detector

… record muon decay times and energies, determine stored beam parameters …





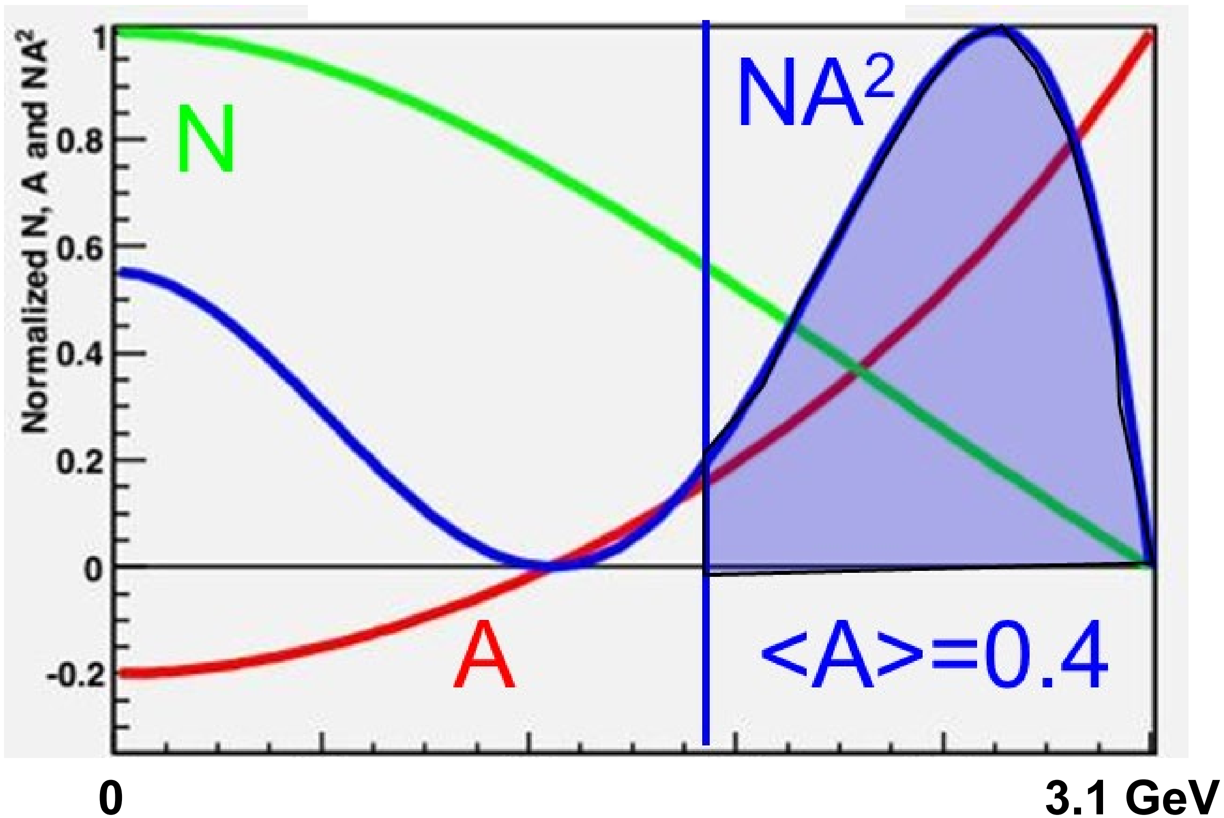


- Time and energy measurement
- Over-threshold events added to time histogram
- 700 μs muon "fills", ~10,000 stored muons/fill

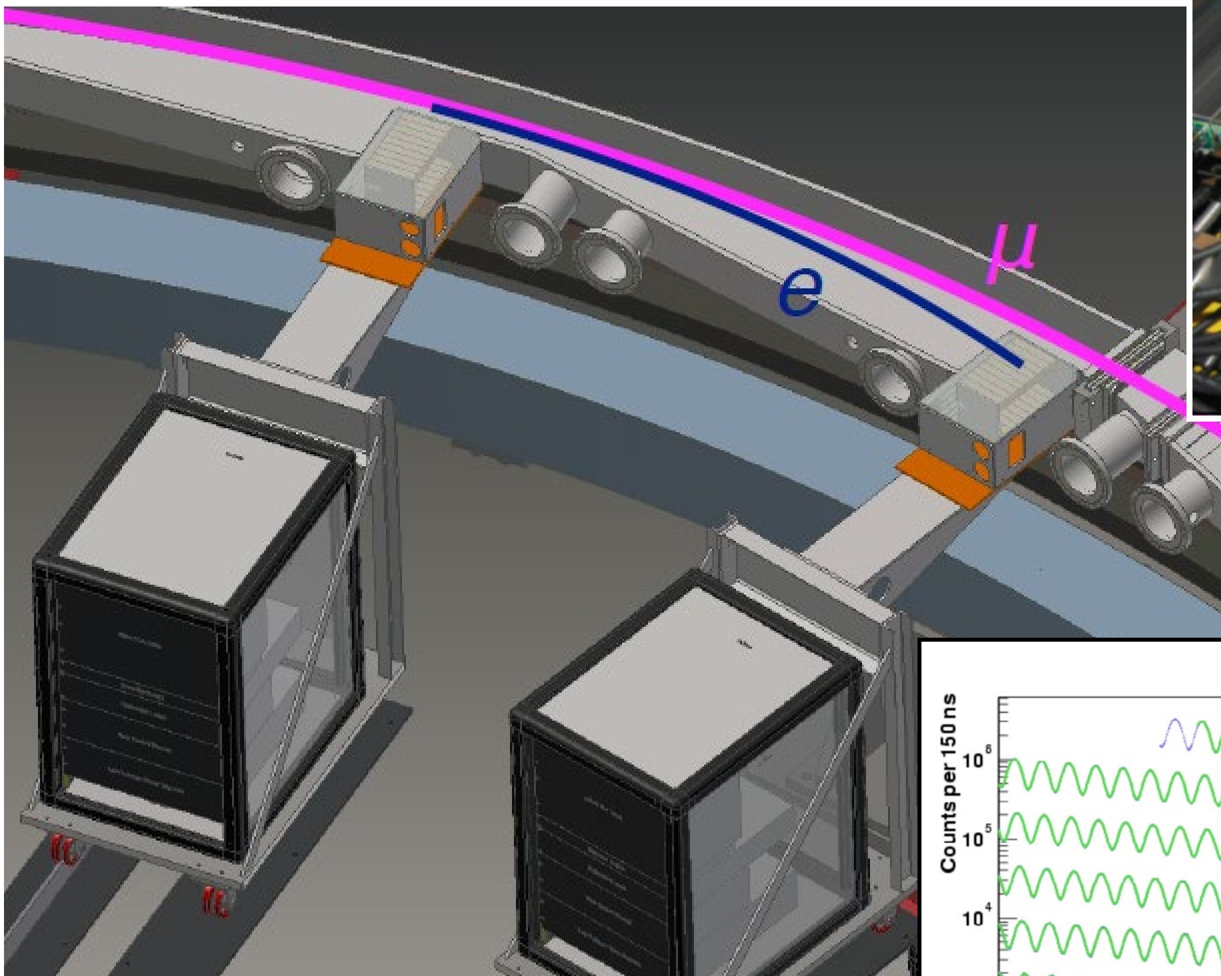
Time distribution of over-threshold decays for three thresholds

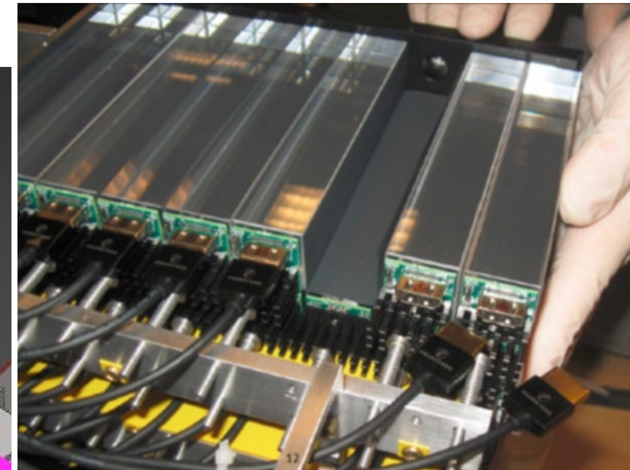
Optimizing Statistical Error

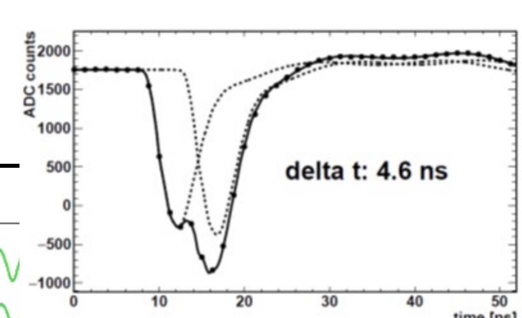
$$\delta\omega_a = \frac{1}{\gamma\tau_\mu}\sqrt{\frac{2}{NA^2}}.$$

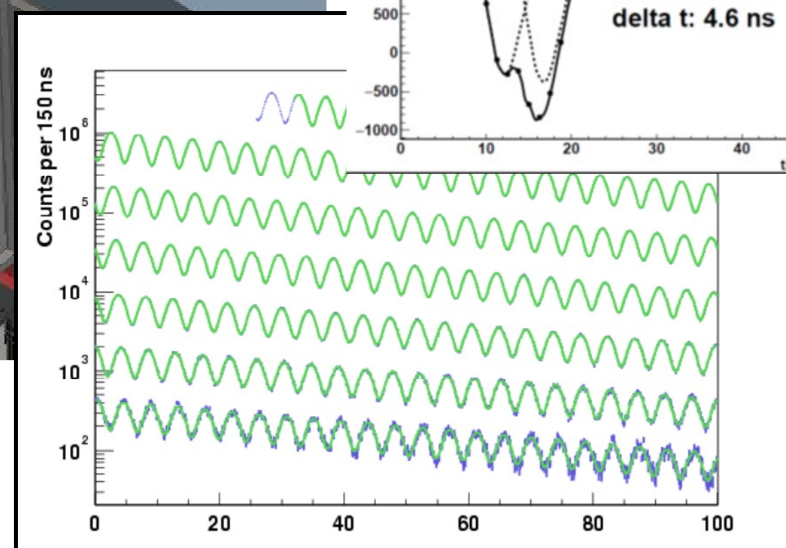


Ultra-fast PbF2+SiPM calorimetry used to record e^+ times and energies; energy correlates with μ^+ spin





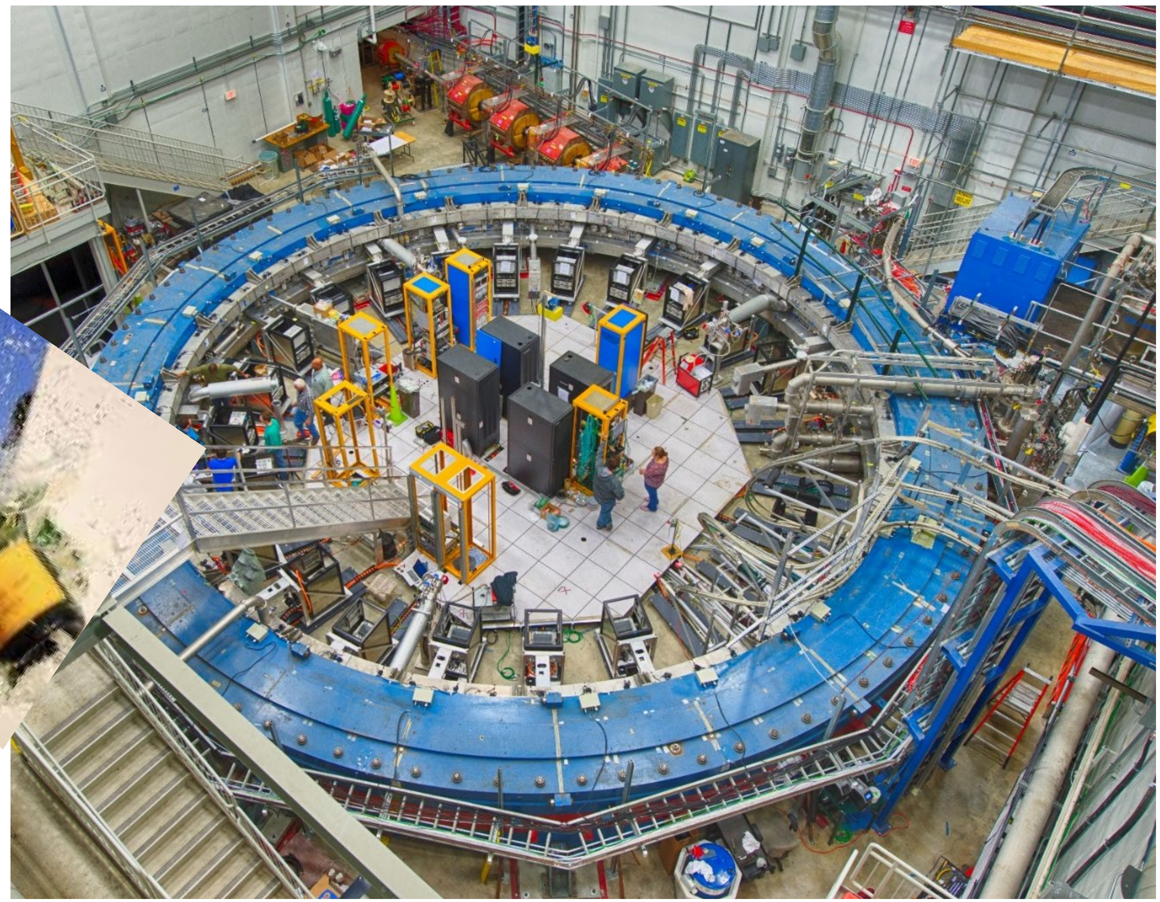




BREAKING NEWS

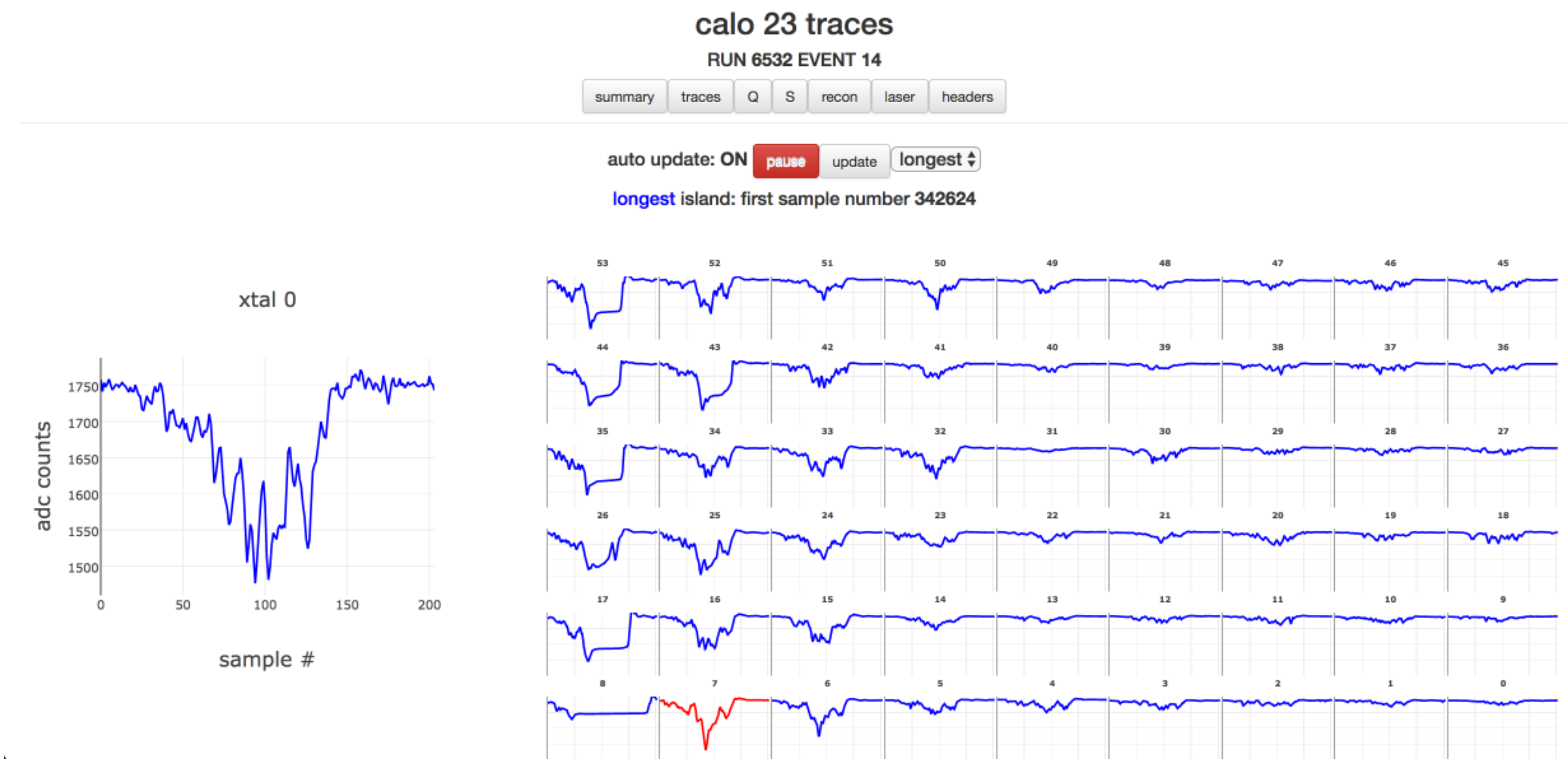
The experiment just finished a 6-week commissioning run

Let's change up a moment and let me describe the (rare) process of christening a battleship … that is, launching a new experiment



Finding a beam is hard. When? How much?

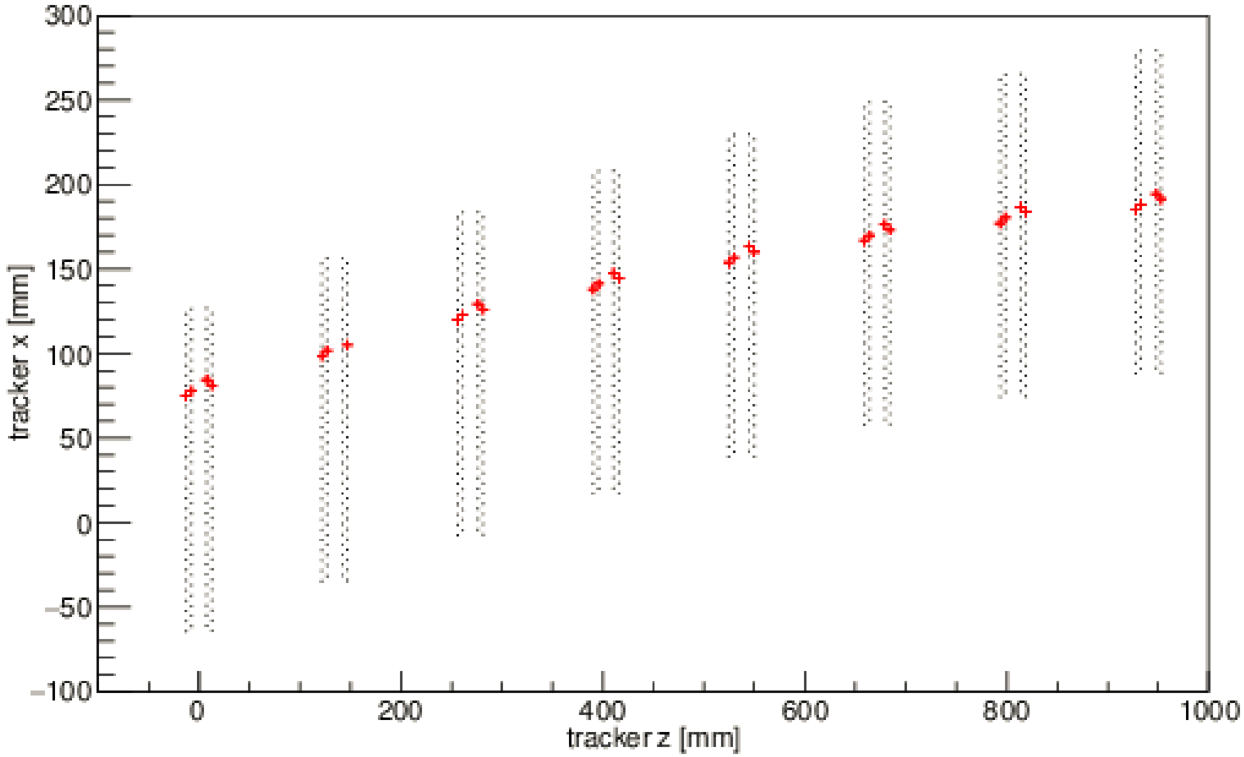
First Beam *Crashes* into Calorimeters



Do any of the particles find stable orbits? How about protons? Here's one that hung around a long time

First evidence of stored protons from some hand-selected events

Image from Tracker of escaping proton at late times



How do tune up the storage? In real time?

Sweep the following to optimize Storage of Protons (muons)

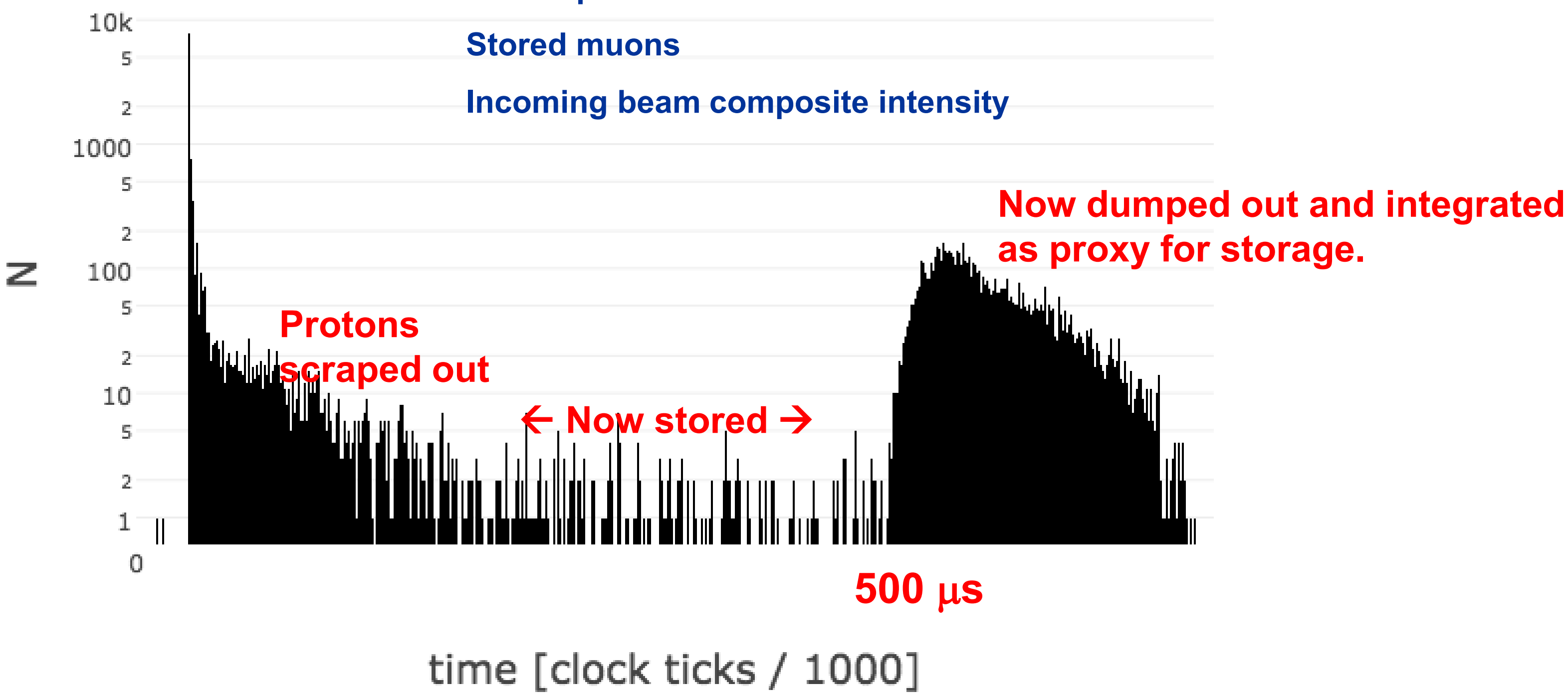
- Kicker timing
- Quad strength
- Inflector current
- Incoming beam x,x', y,y'
- Incoming beam focus parameters

We have online monitors of:

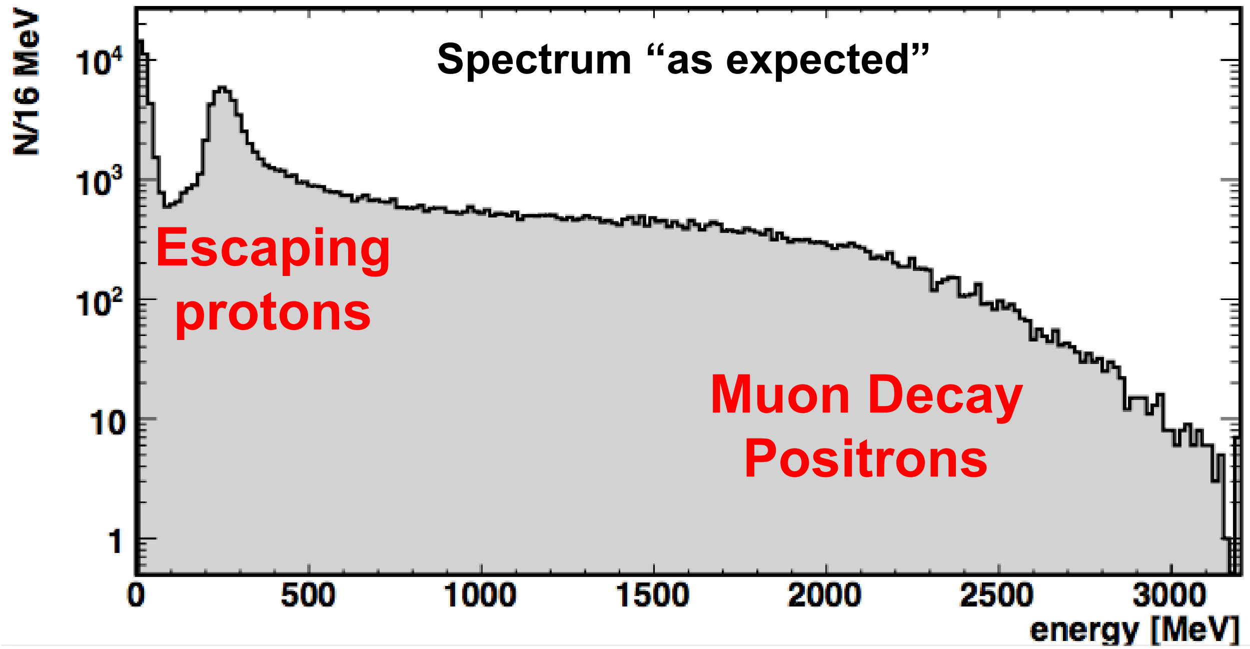
Stored protons

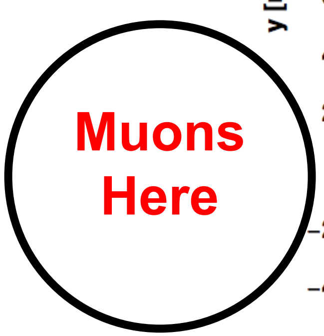
Stored muons

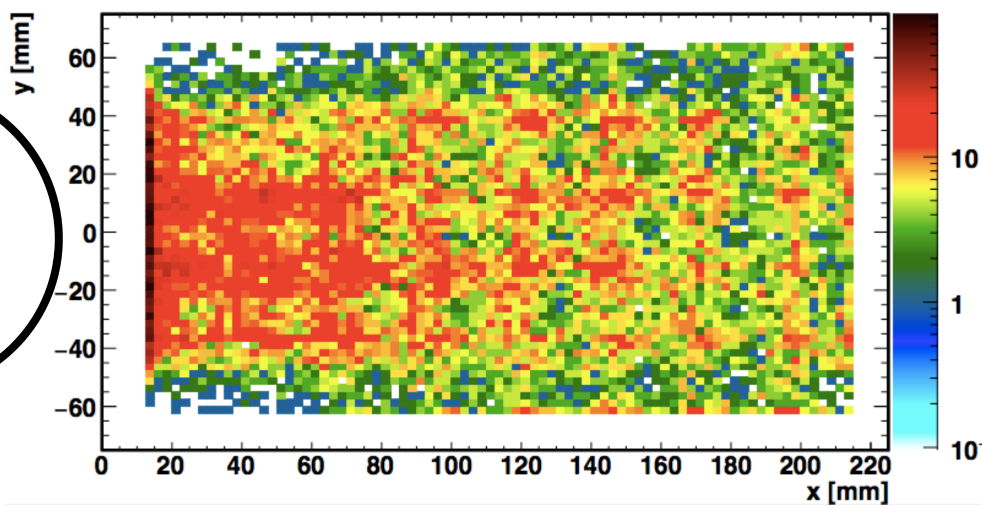
Incoming beam composite intensity



Do the energy spectra look like those beautiful Monte Carlo plots you made for years?



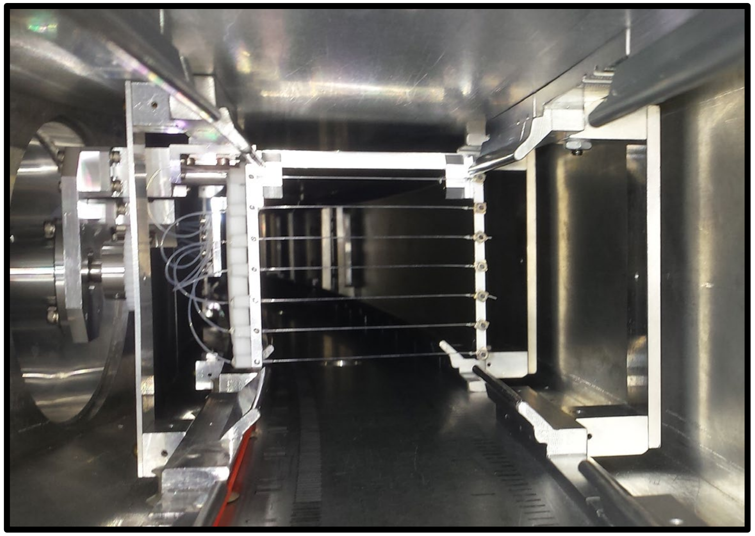




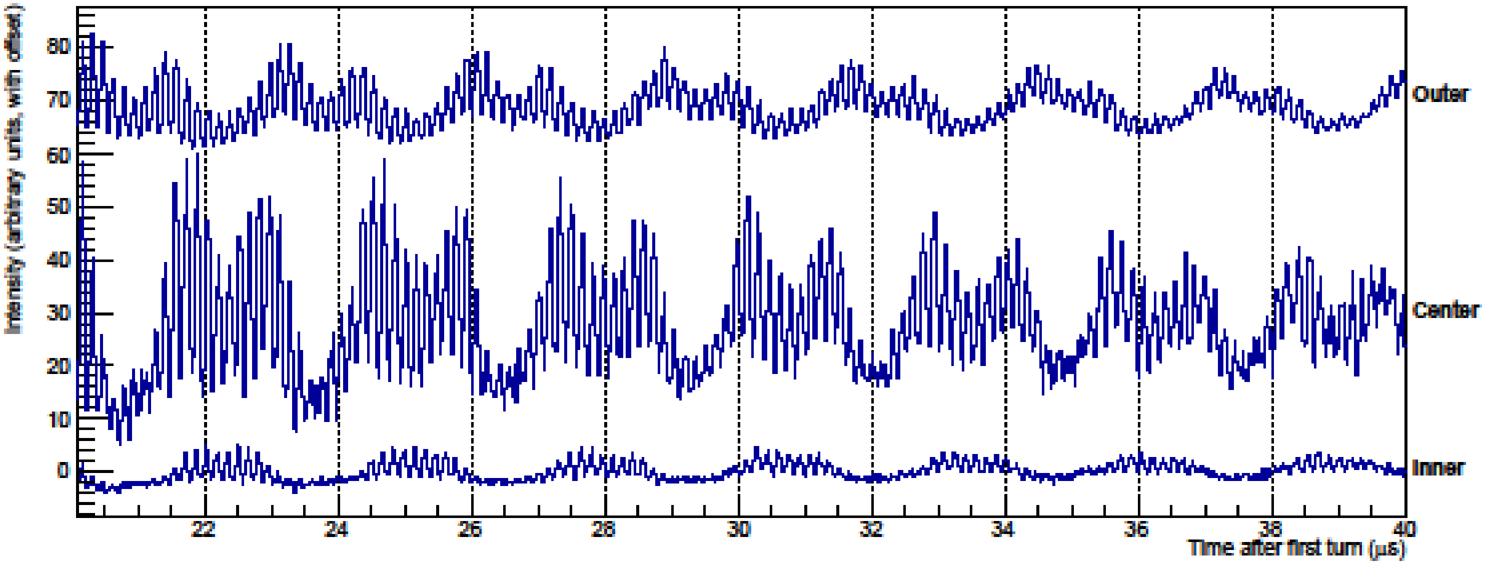
Hit positions “as expected”

*easy to fix after run ends and we have access

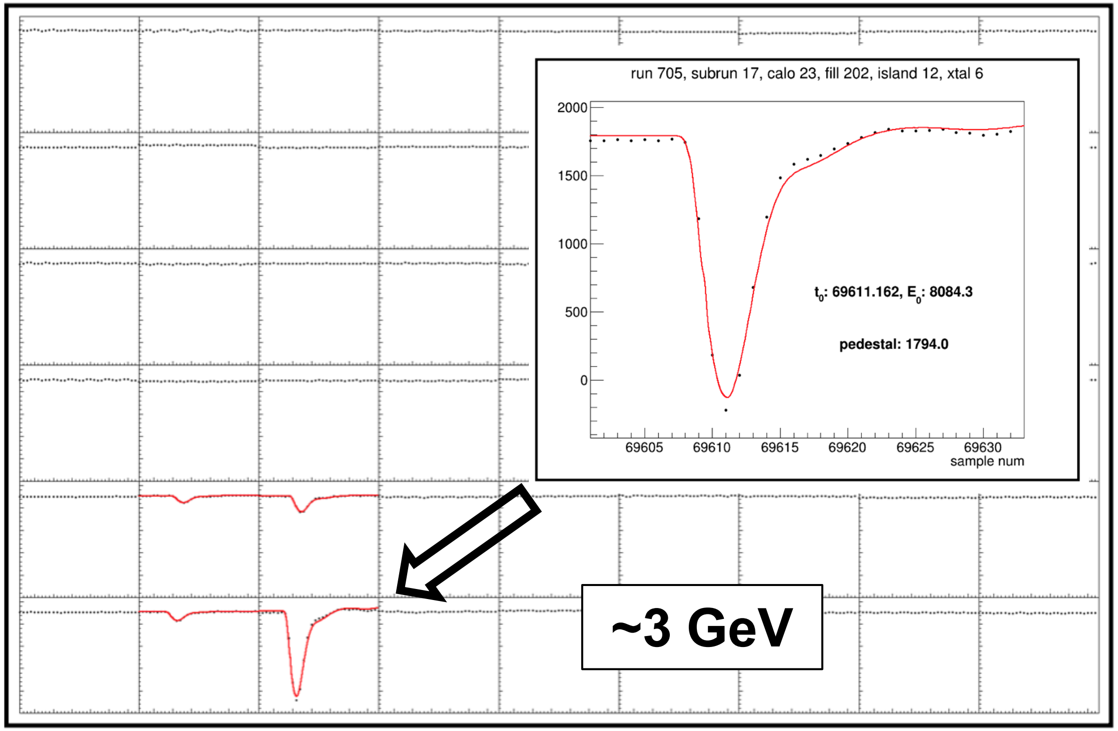
Imaging a beam is tricky; It also destroys it

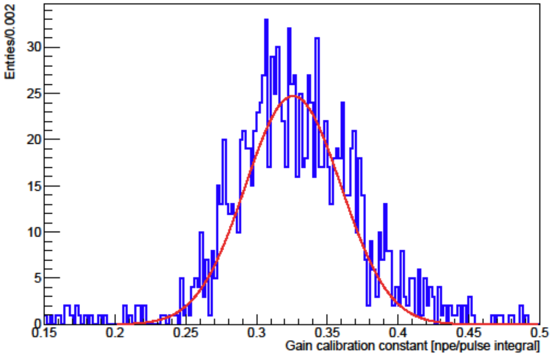


Looking downstream as a Muon or Proton would



What a high-energy positron looks like in our calorimeter

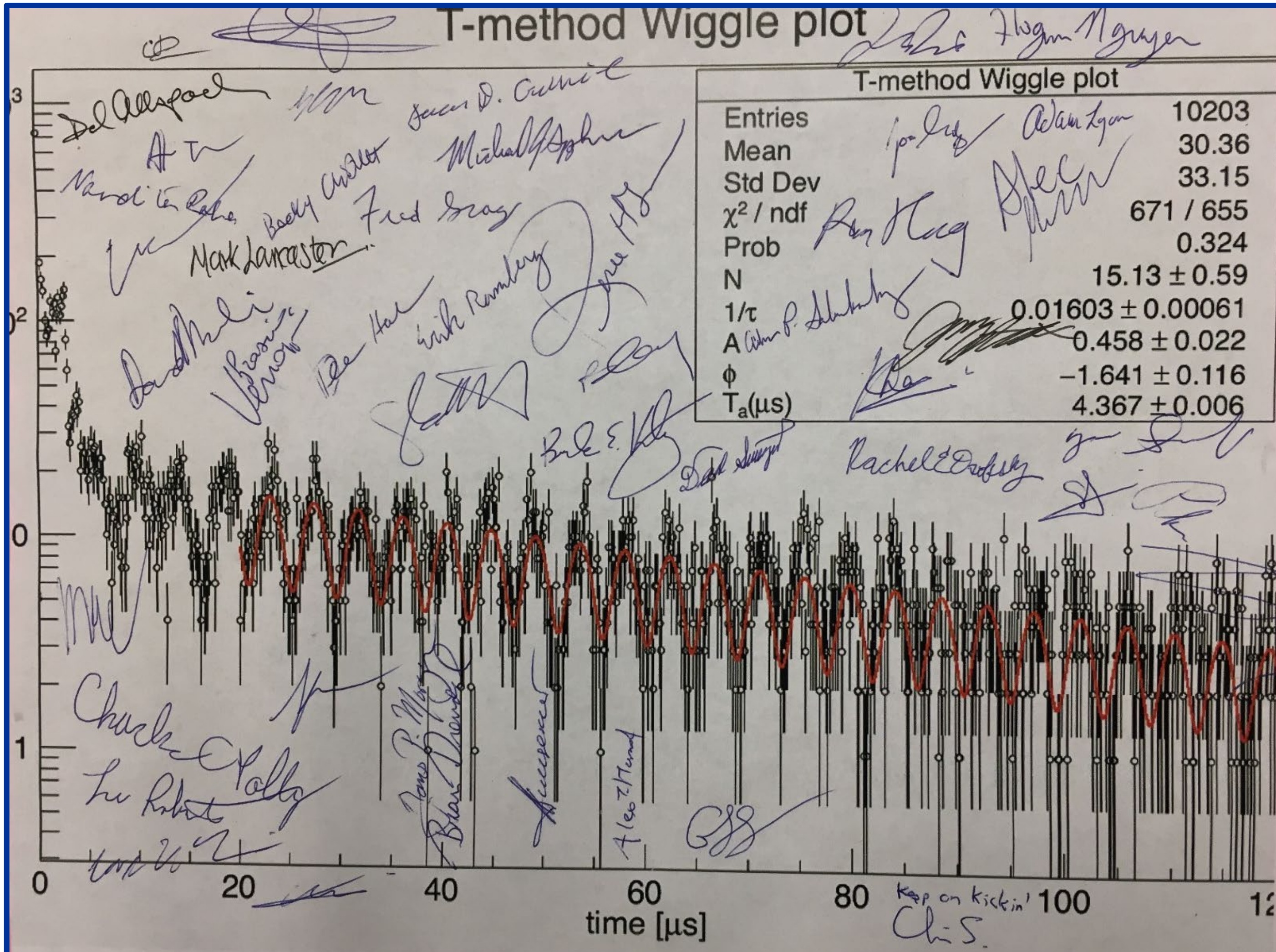




Online pre-calibration gain of 1294 crystals using Laser system for absolute PE / pulse integral

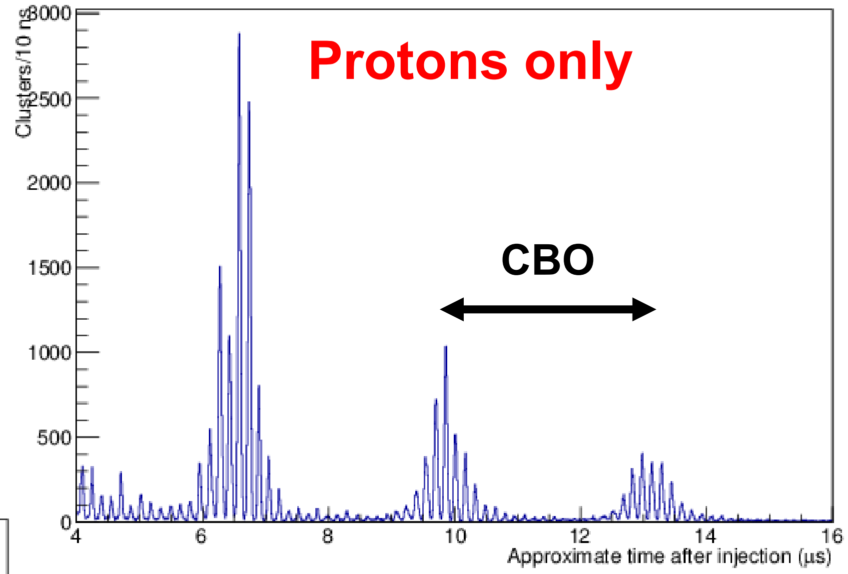
You have your moments ….

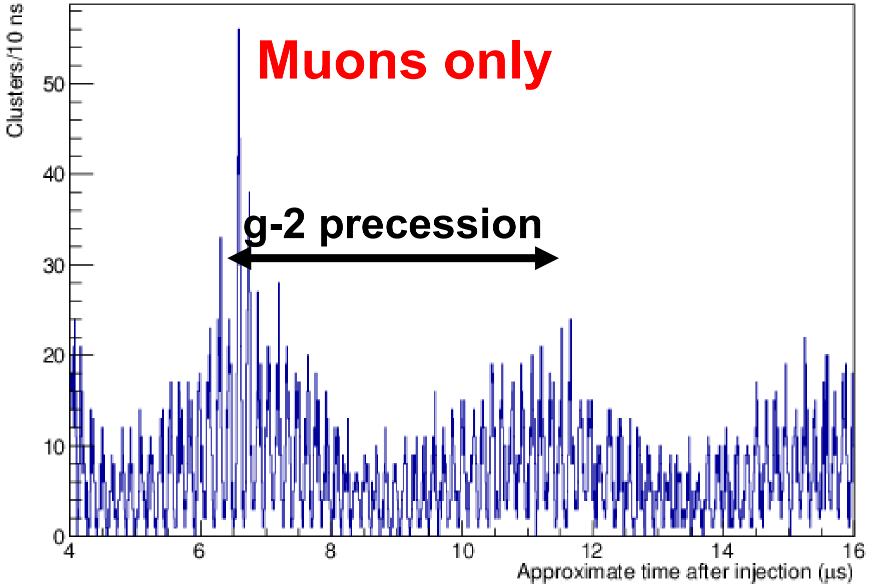
First evidence of stored muon precession



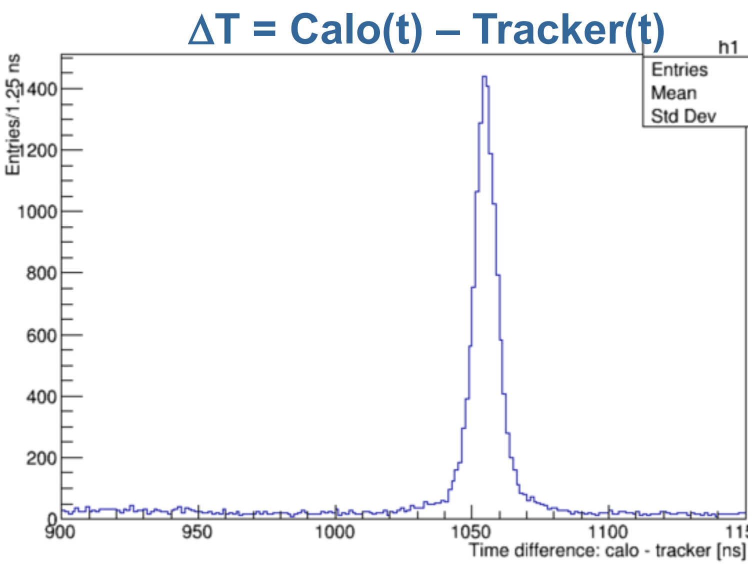
Proton and Muon Fast Rotation in calorimeters

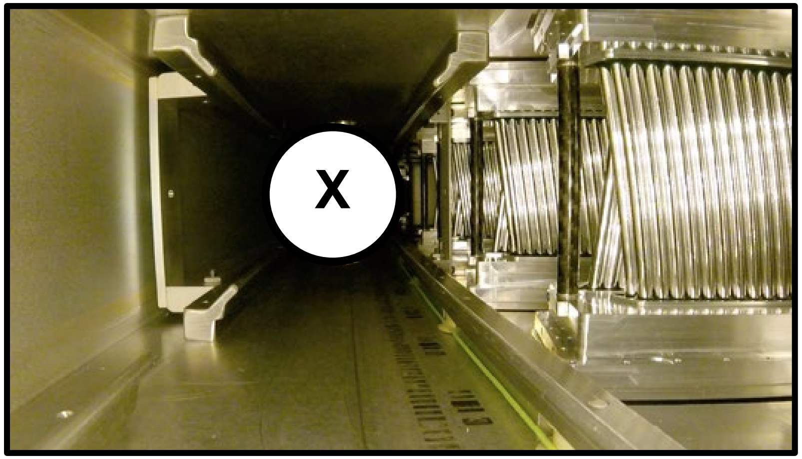
(could not see this at BNL so easily)

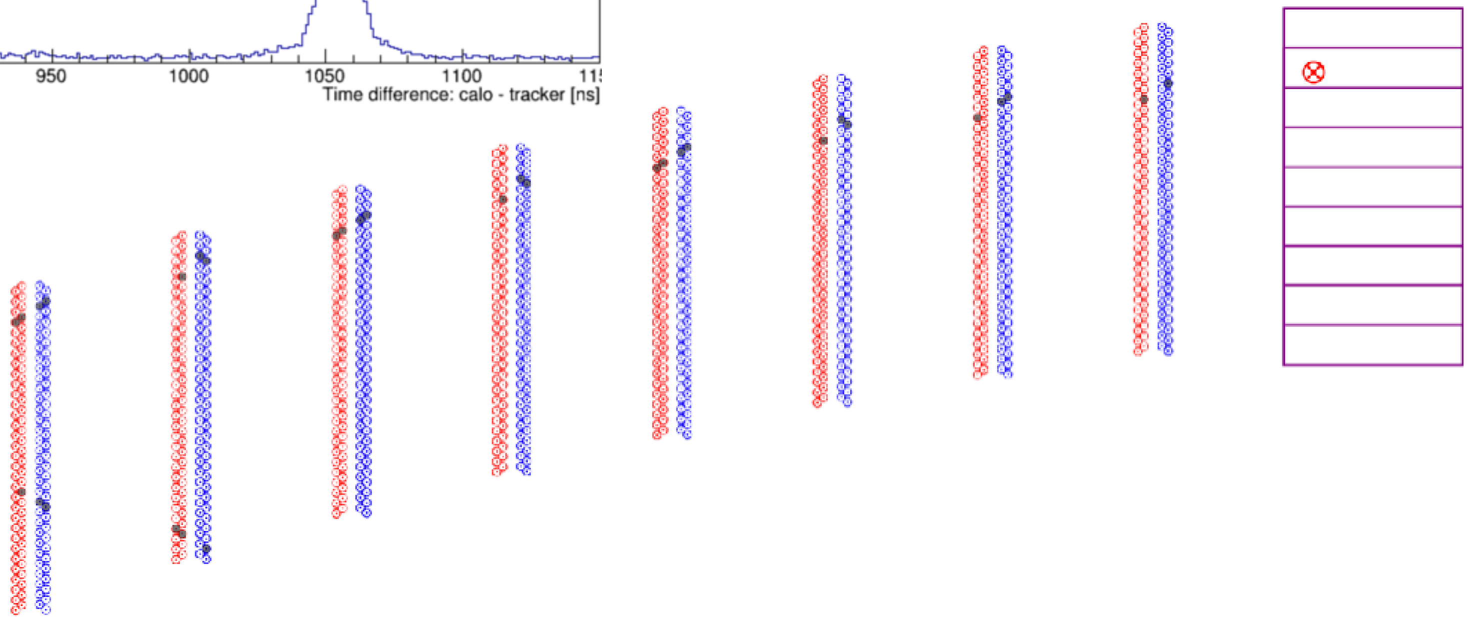




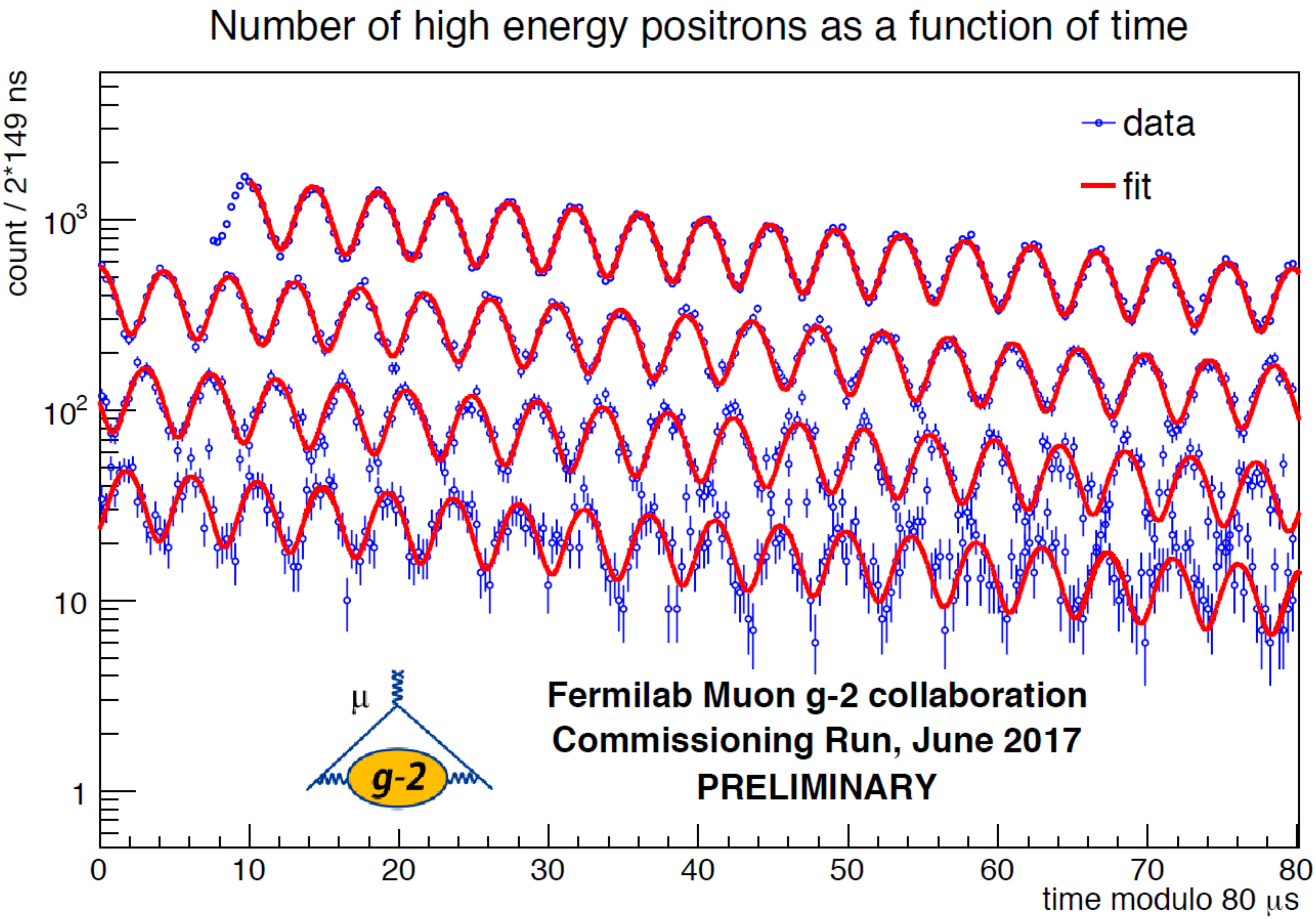
Tracker & Calorimeter working together







Getting better … : June 25



Okay, enough of that …

- **Lessons (possibly learned)**
  - The Field of Fundamental Symmetries (and later, neutrinos) has a finite number of rather specialized experiments that generally aim to do just one thing very well
  - They take time
  - They take ingenuity and patience
  - They require a particular attention to systematics and details
- **The Physics case is rather profound**
  - We aim to shake up the foundations of what is now just believed
  - We KNOW there must be new physics out there … back to Lecture 1, or else ???
- **THEORY plays a vital role in these missions**
  - The known but hard: radiative corrections, hadronic effects
  - The interpretations and vision: What if? And what else? And, does the idea survive the many tests as HIGH and LOW energies already?

My predictions … (totally biased)

- Muon g-2 is next most important one to watch.
  - The 3.6 σ deviation is either a bad luck fluke or it's telling us something. The next experiment has started.
- EDMs are super promising.
  - Watch out for all systems, Hg, n, atoms, molecules, …
- cLFV experiments are very sensitive to BSM now
  - New Mu2e here and MEG II in Switzerland to watch
  - Muons are much more sensitive than B factories (or future ones)
- Neutrons mostly "self consistency" issues
  - new generation experiments seem to be converging and the story will be looking good. There is little room for NP right now
- I didn't mention nuclear beta decays.
  - The He-6 system has promise but goal posts for this and other measurements ~x10 beyond where experiments are now
- PVES has a unique reach
  - watch for imminent announcement by Qweak; keep eye on progress of MOLLER

The Final Stopping Point !

David Hertzog
hertzog@uw.edu