The new g-2 Experiment at Fermilab

Andrea Fioretti, *CNR-INO and INFN, Pisa Italy*

on behalf of the g-2 collaboration

EXA 2017 , Wien, August 14th, 2017

Outline

- Introduction and motivations
- Principle of the experiment
- Experimental overview
- Status of the experiment
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The magnetic moment of particles

A particle with spin has a magnetic moment $\vec{\mu}$ directed along its spin $\vec{S}$,

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

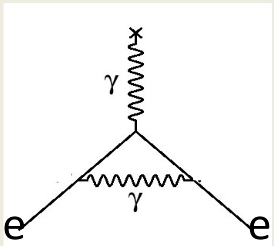
the g-factor relates the magnetic moment to the angular momentum.

Dirac's equation predicts $g = 2$ but quantum fluctuations produce an anomaly

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

Example: Electron anomaly: its value has been accurately reproduced by QED calculations (from Schwinger on…)

a_e = 0,001 159 652 181 64 (76) (thy, 10th order)
a_e = 0,001 159 652 180 73 (28) (exp, 24 ppb)



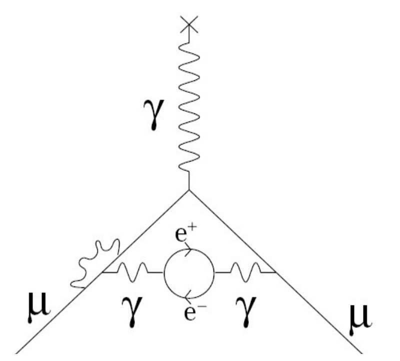
+ ....

The magnetic moment of the muon

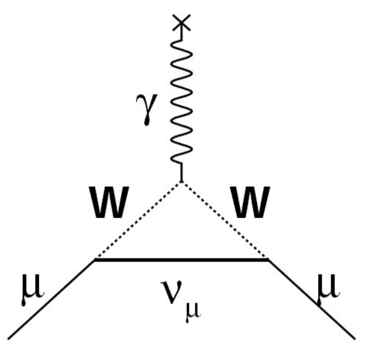
a_μ much more sensitive than a_ε to massive particles in loops:

$$\left({}^{m_\mu}/_{m_e}\right)^2 \cong 43000$$

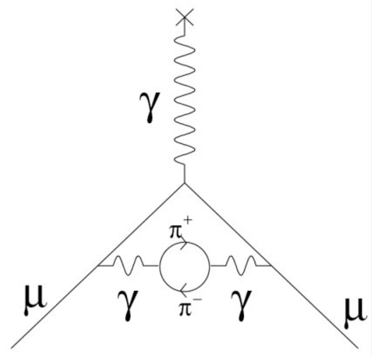
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HAD}$$



QED



Electroweak



Hadronic

example graphs for the three above contributions to a_μ

INO-CNR ISTITUTO NAZIONALE DI OTTICA

Muon anomaly: theory

From: T. Blum *et al*. (2013), https://arxiv.org/abs/1311.2198

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW (*)	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

- HVP (lo/ho): Hadronic Vacuum Polarization, low/high order
- HLbL: Hadronic Light-by-Light

[20] M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. **C71** (2011) 1515, Erratum-ibid. **C72** (2012) 1874.

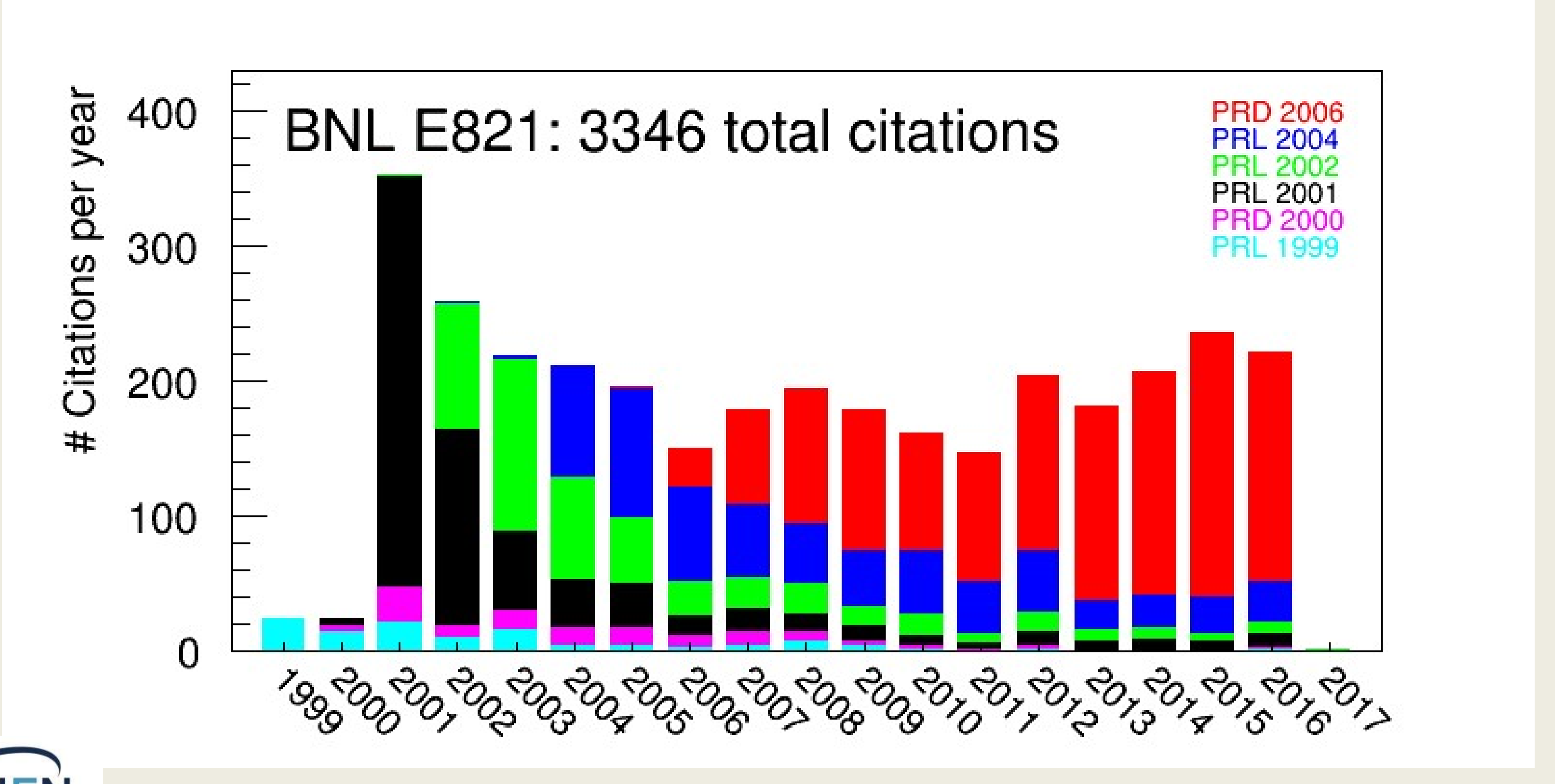
[21] K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, J. Phys. **G38** (2011) 085003.

(*) Glasgow consensus, 2007, http://www.ippp.dur.ac.uk/old/MuonMDM/

Experiment vs theory

E821 experiment at BNL has generated a large interest:

$$a_\mu^{exp} = 1\ 165\ 920\ 89\ (63) \quad \times 10^{-11} \quad (\pm 0.54\ \text{ppm})$$



Experiment vs theory

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$$a_\mu{}^{exp} = 1\ 165\ 920\ 89\ (63) \quad \times 10^{-11} \quad (\pm 0.54\ \text{ppm})$$

$$a_\mu{}^{th} = 1\ 165\ 918\ 02\ (49) \quad \times 10^{-11} \quad (\pm 0.42\ \text{ppm})$$

There is a tantalizing **~3.3σ deviation** with SM prediction (persistent >10 years):

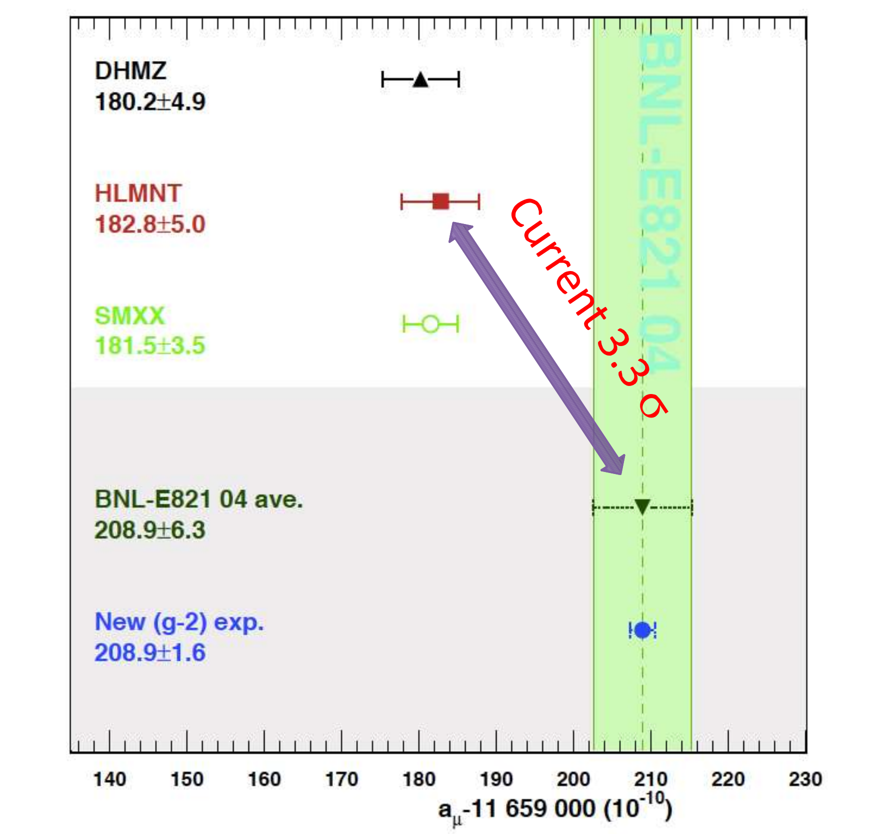
$$\boxed{a_\mu{}^{exp} - a_\mu{}^{SM} = 261\ (or\ 287)\ \pm 80 \times 10^{-11}}$$

Current discrepancy limited by:

- Experimental uncertainty→ New experiments at FNAL and J-PARC x4 accuracy
- Theoretical uncertanty→ limited by hadronic effects

Goal of the new E989 experiment

- Reduce the experimental error bar in a_μ by a factor 4
- Resolve the long-standing E821 *g*-2 discrepancy



$\delta\omega_a$(statistics) at 100 ppb level

~ 1.5 x 10^{11} events in the final fit

Multiple independent blind analyses

Multiple sorting and fitting methods

Net Systematics error to 100 ppb (x 3 improvement)

Leading issues

Pileup

Gain (energy scale) stability

Muon losses

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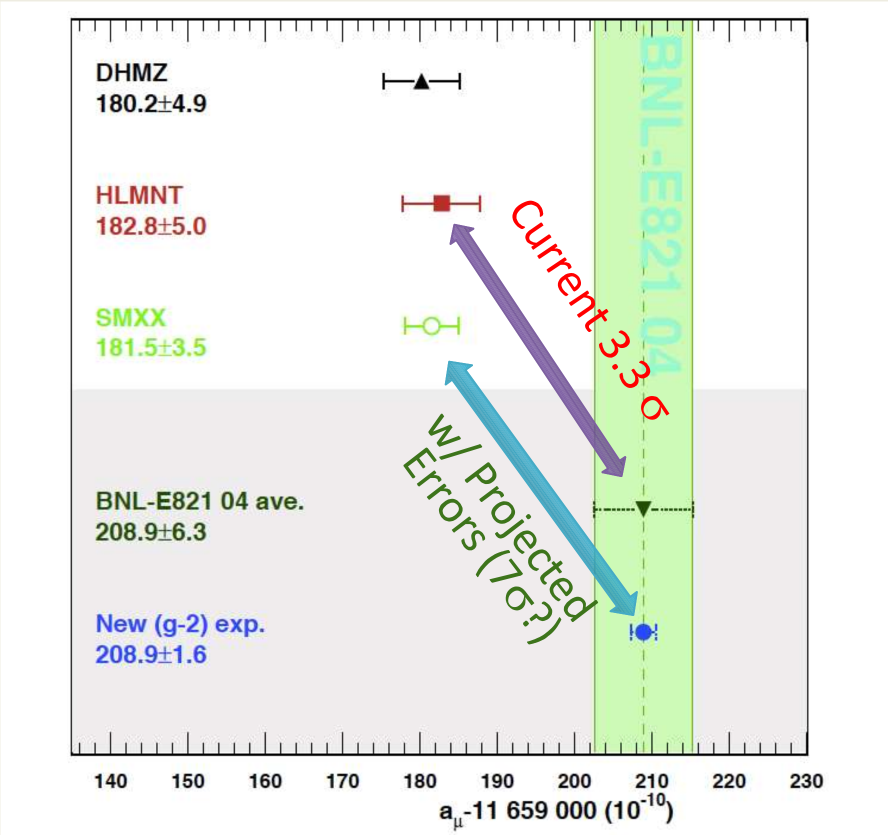

- With new e+e- → hadron data samples and improvements on LbL contribution theory error should come down by about 30% in the next 5 years
- Lattice community provides avenues to independent calculations
- If current discrepancy persists, significance will be pushed beyond 5σ discovery threshold
- Anticipated theoretical improvement could lead to >7σ discrepancy

Possible cracks in the Standard Model?

- New massive particles appearing in loops
- Dark Matter/Dark Photons
- Supersymmetry

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Principle of the experiment

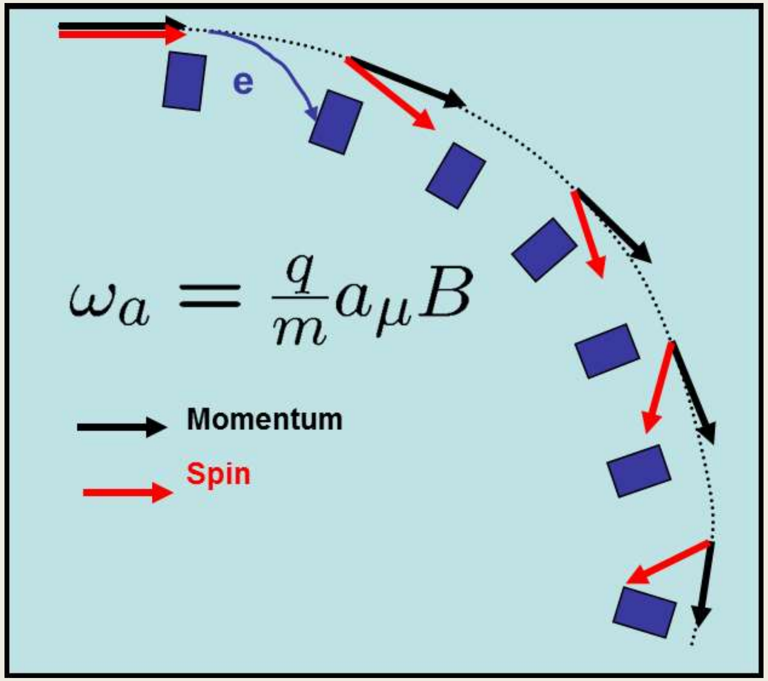
Store longitudinally polarized muons in a ring and observe their decay product (positrons). If $g \neq 2$ then the spin $\vec{S}$ rotates faster than momentum $\vec{p}$.

- measure the uniform magnetic field $\vec{B}$
- measure the "anomalous" precession $\omega_a = \omega_S - \omega_C$

} get a_μ

$$\omega_S = g_\mu \frac{eB}{2m} + (1-\gamma)\frac{eB}{\gamma m} \qquad \omega_C = \frac{eB}{m\gamma}$$

$$\frac{g_\mu - 2}{2} = a_\mu = \omega_a \frac{m}{eB}$$



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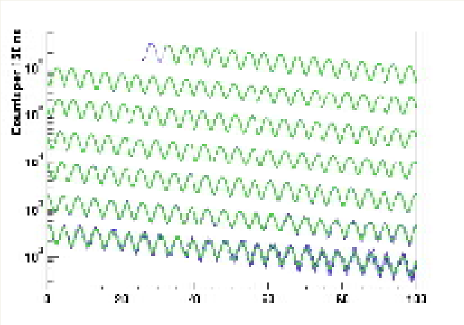
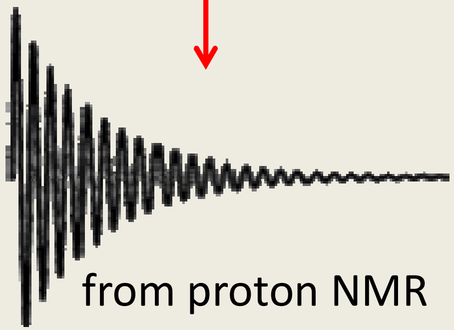
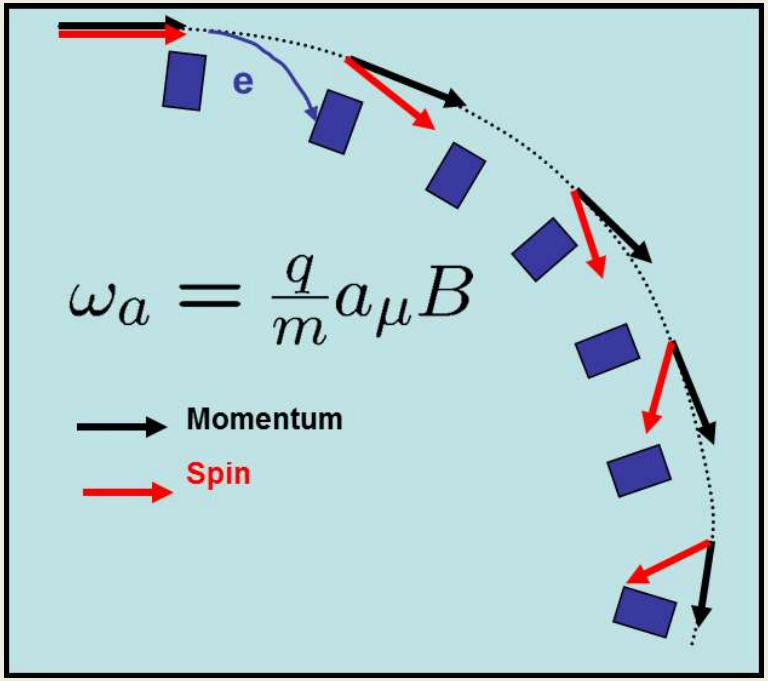
$$\frac{\boldsymbol{g_\mu - 2}}{\boldsymbol{2}} = \boldsymbol{a_\mu} = \boldsymbol{\omega_a}\frac{\boldsymbol{m}}{\boldsymbol{eB}}$$



N posit. with $E > E_{th}$ vs time



from proton NMR



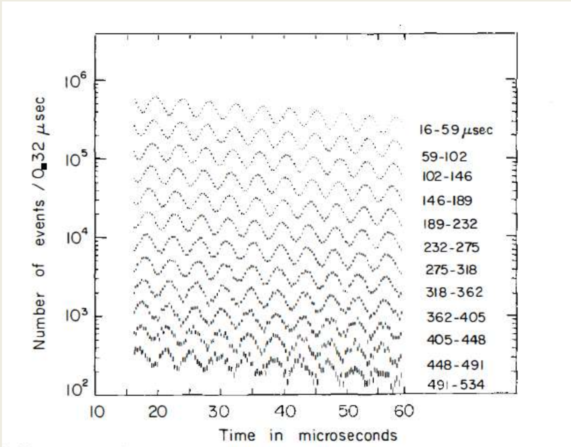
The magic momentum

An Electric field is necessary for vertical focusing of the beam so:

$$\overrightarrow{\omega_a} = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}}\right]$$

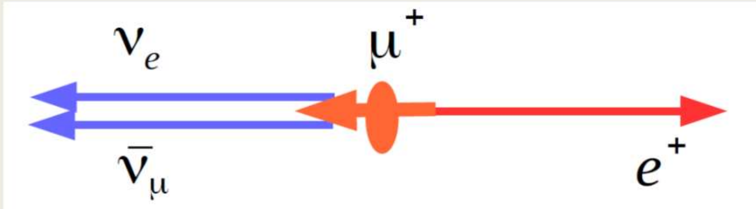
The extra term is zero for $\gamma = 29{,}3$ ($P_\mu = 3.09$ GeV/c)

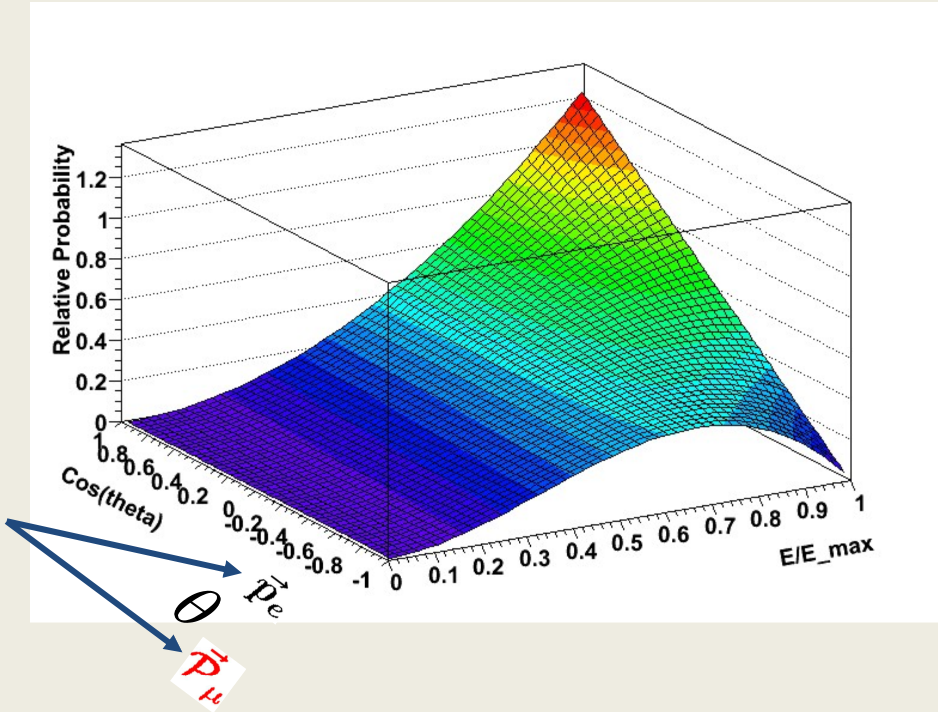
CERN III
(1979)



Analyzing the muon spin

- Parity violation in muon decay → highest energy decay positron emitted opposite of muon spin
- When spin is aligned/anti-al. with momentum, the boost subtracts/adds, and the decay positron energy is reduceded/increased in the lab frame
- This results in a modulation of the energy spectrum at the g-2 frequency

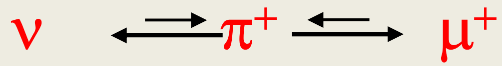


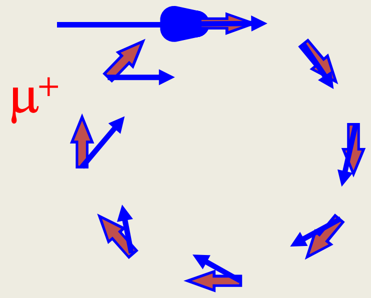


Recap the 4 key elements

(1) **Polarized muons**

~ 97% polarized for forward decays

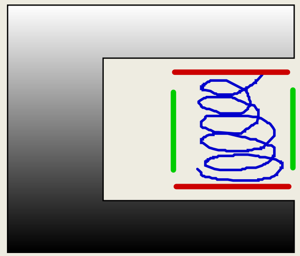




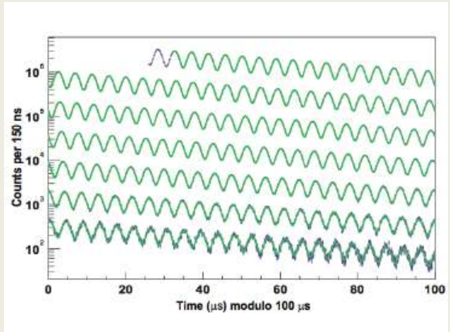
(2) **Precession proportional to (*g*-2)**

(3) **P_μ magic momentum = 3.094 GeV/c**

No *E* effect on precession when γ = 29.3



(4) **Parity violation in the decay gives average spin direction.** The number of higher energy positrons is modulated at ω_a



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The *g-2* Collaboration

The Big Move of the Ring (2013)

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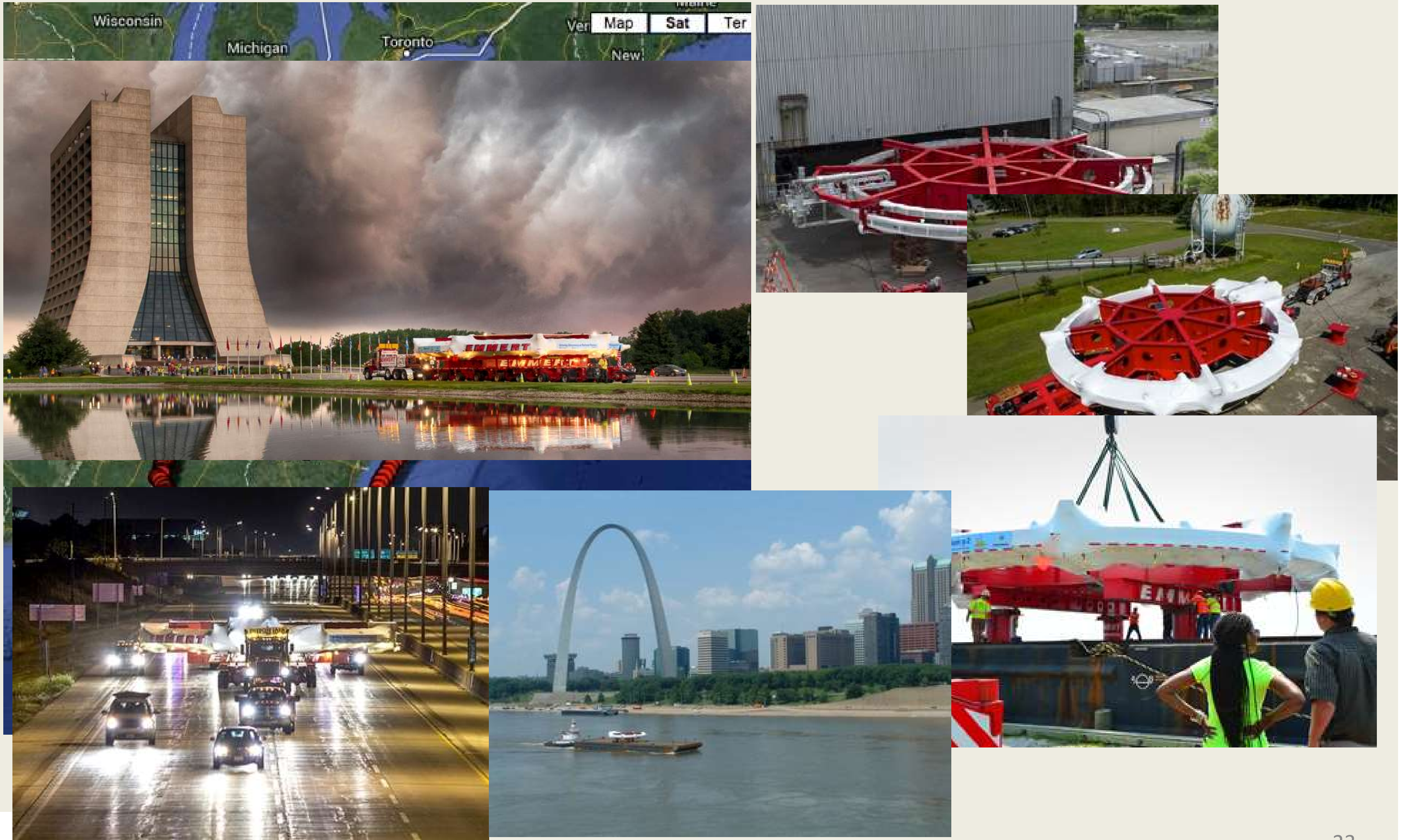
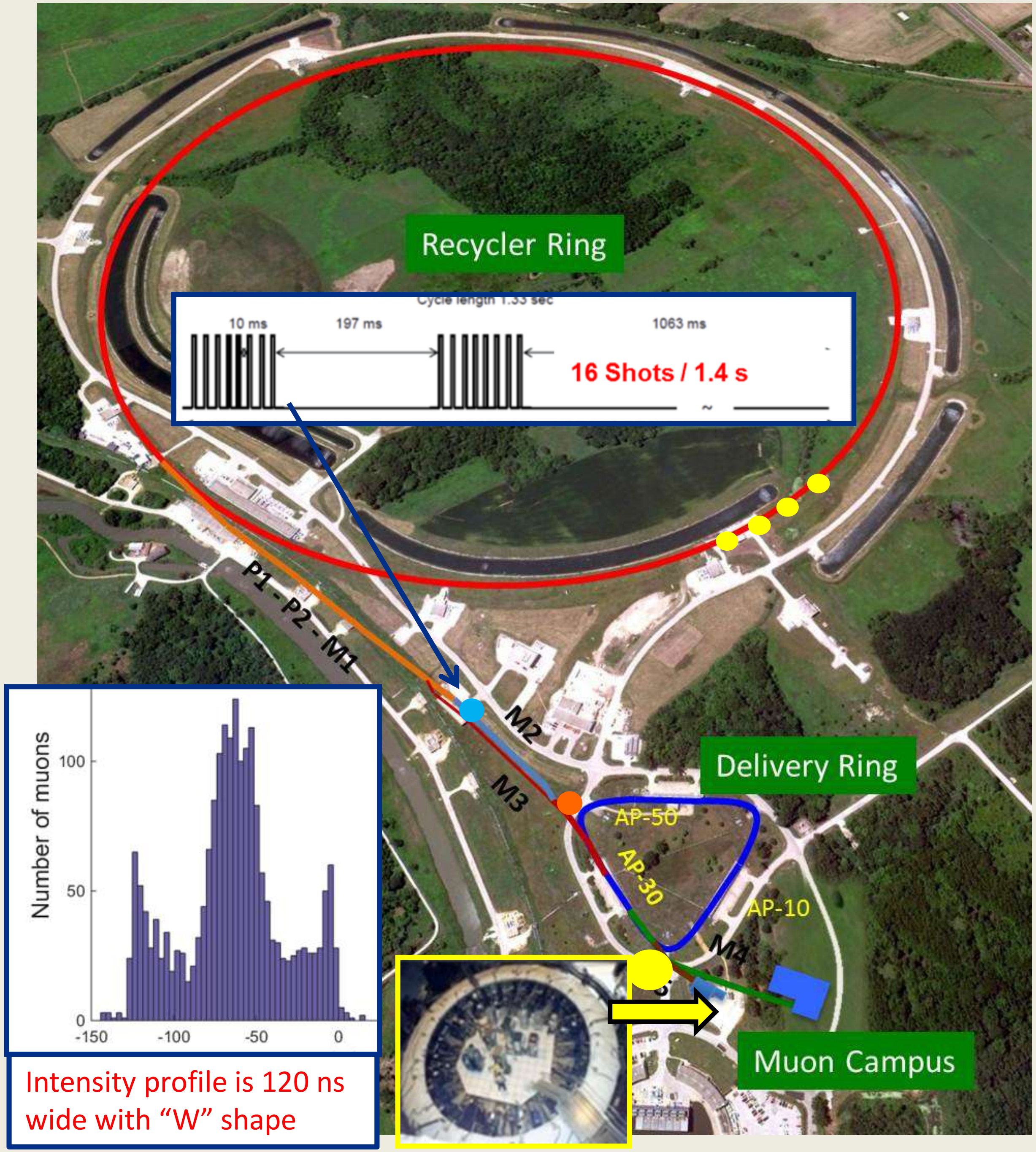
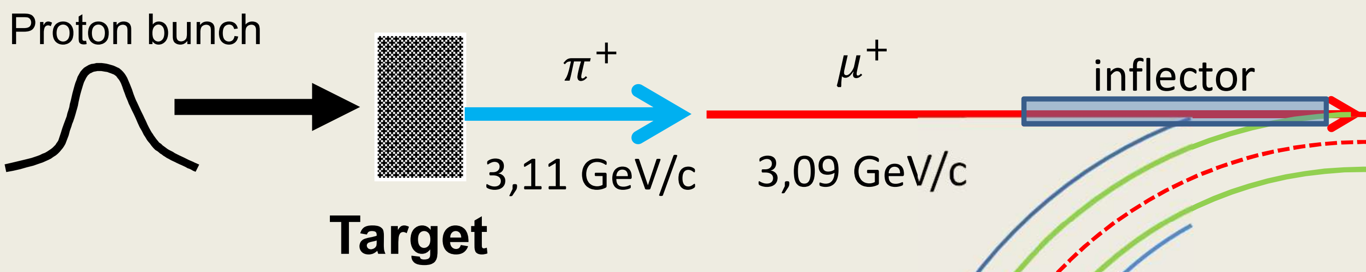


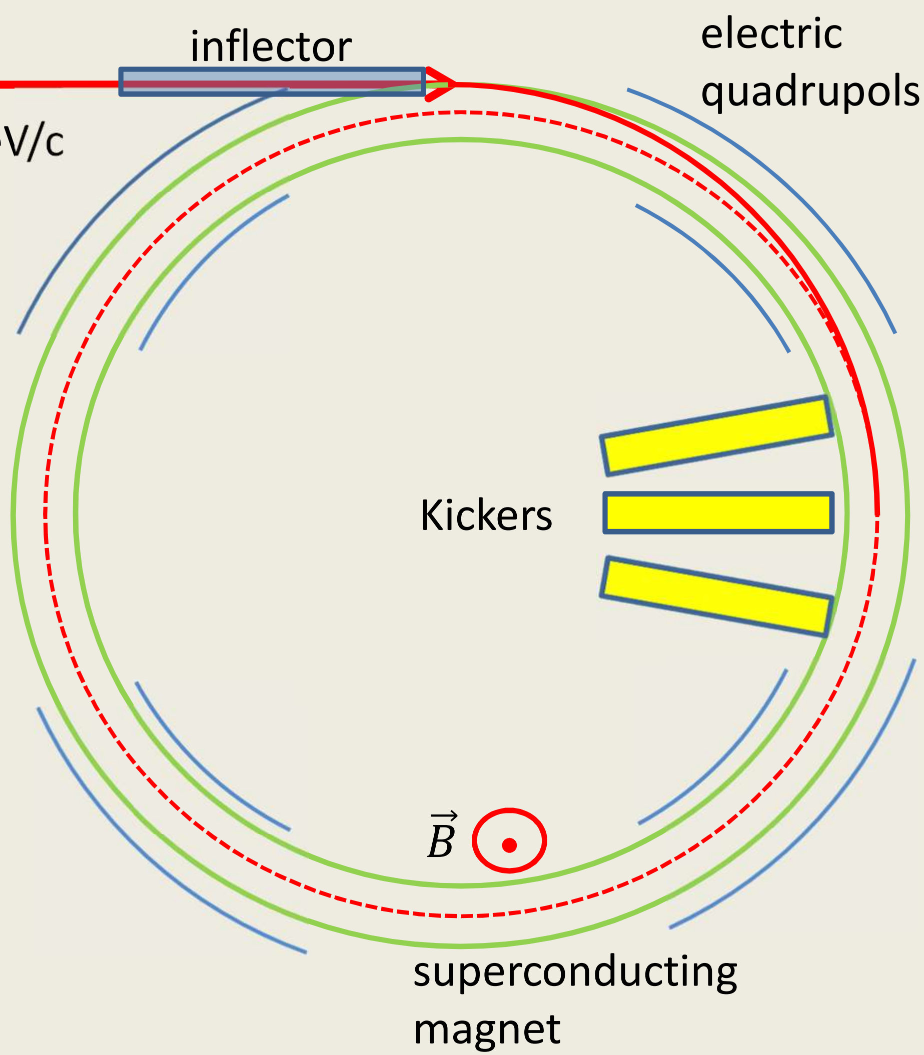


Creating the Muon Beam for g-2

- 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/π/μ beam enters DR; protons kicked out; π decay away
- μ enter storage ring

Storing muons

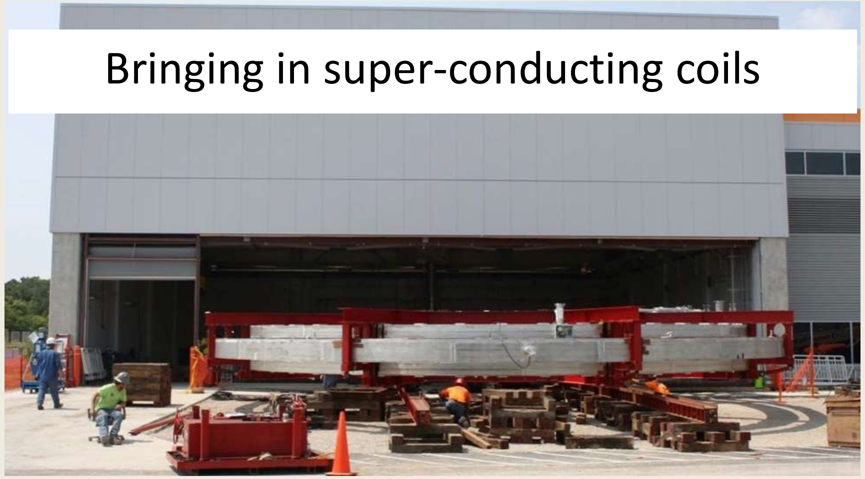




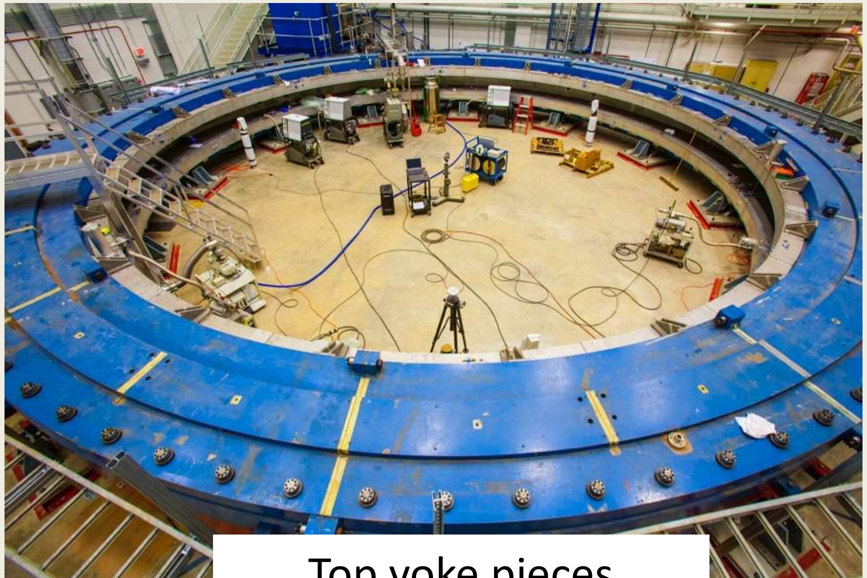
- 120 ns wide bunch of 10^{12}, 8 GeV protons from Booster & Recycler
- Fired at pion production target (Inconel (Ni-Cr))
- Outgoing pions focused by a lithium lens and then momentum-selected, centred on 3.11 GeV
- In DR pions decay into polarized muons
- Muons are stored in a 14m diameter ring with 1.45 T *B* field

The magnetic field


Bottom yoke pieces

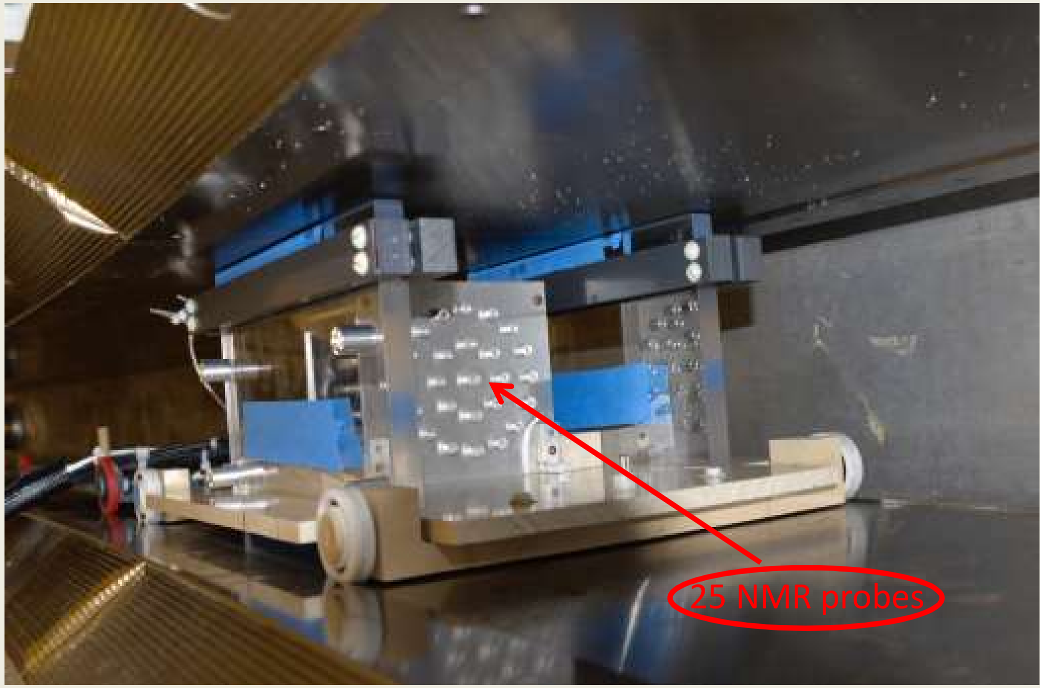

Bringing in super-conducting coils


SC coils installed


Top yoke pieces

The magnetic field

- Regularly map field inside vacuum chamber with NMR probe trolley
- Monitor field during data-taking with fixed probes and interpolate
- Shimming trolley contains array of probes that map whole storage volume
- Field in storage volume is measured using pulsed proton NMR (<10ppB single shot precision)



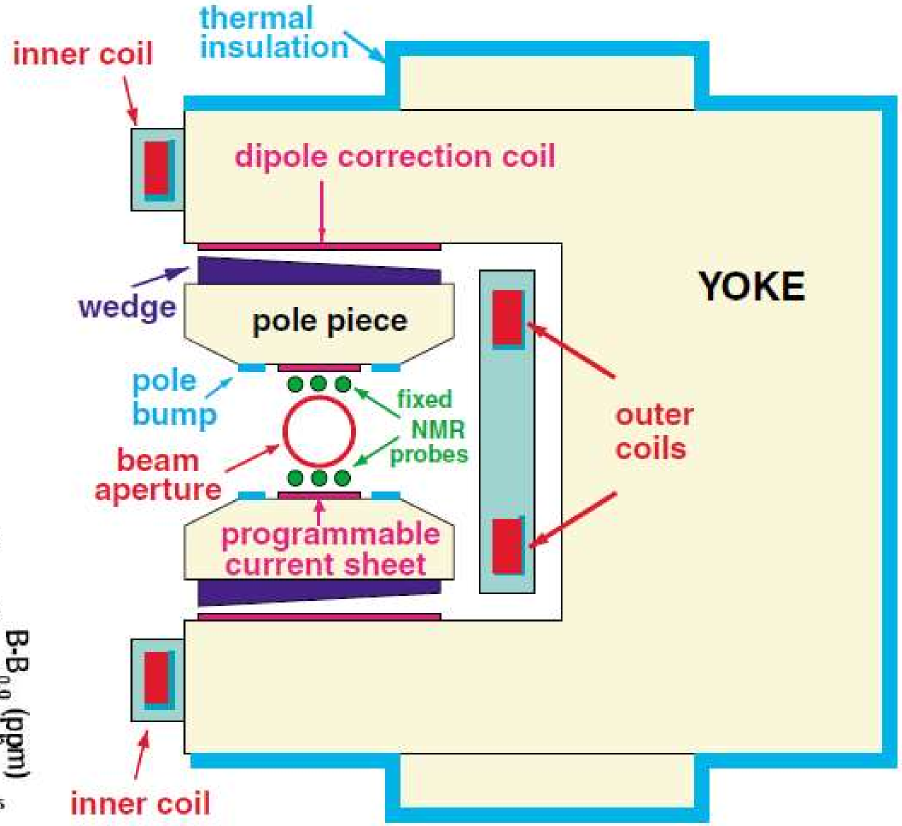
- BNL E821 result:
  - 1 ppm (azimuth average)
  - 100 ppm (local variations)
- FNAL E989 goal:
  - 1 ppm (azimuth average)
  - 50 ppm (local variations)

The magnetic field

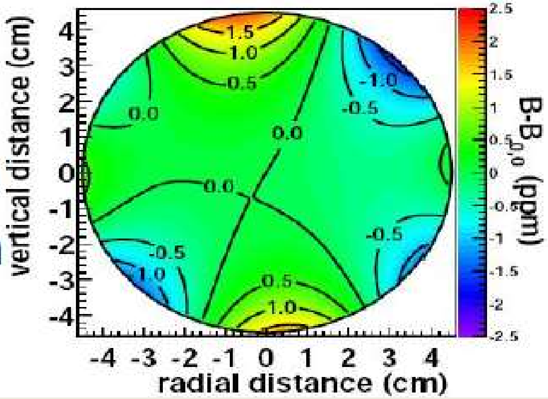
- Many passive and active shimming tools to achieve unprecedented field homogeneity for such a large volume.
- Each "knob" adjusts nearly orthogonal components of the field shape

Passive shims
- Iron wedges
- Pole tilt
- Iron pole bumps

Active shims
- Dipole correction coils
- Surface correction coils



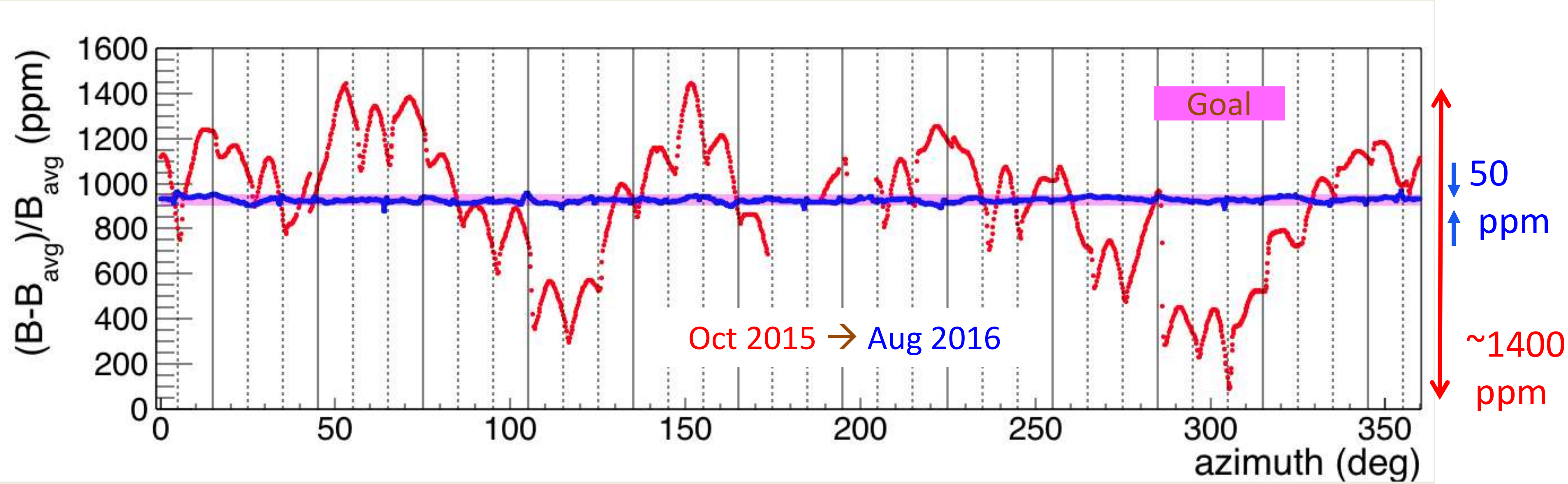
FNAL goal is x2 improvement in homogeneity



Slide credits: Joe Grange, Argonne Nat. Lab

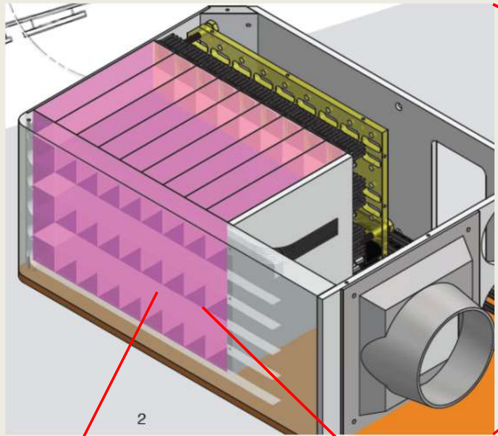
The magnetic field: shimming results

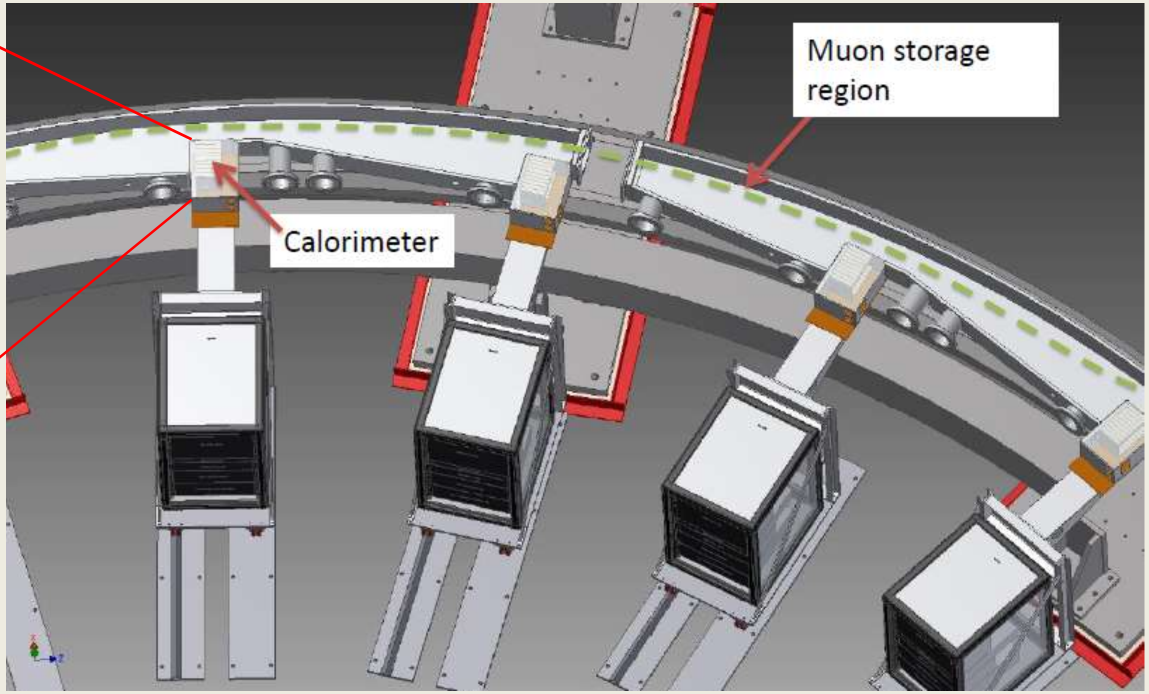
- August 2016: completed addition of surface foils & achieved 50 ppm goal for rough shimming:

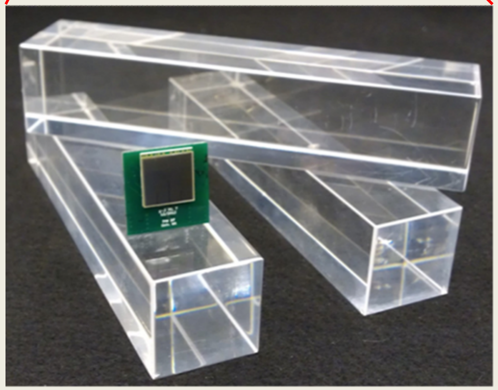


	RMS (ppm)	p-p (ppm)
FNAL (Rough shimmed)	10	75
BNL (Typical scan)	30	230

The detectors: calorimeters

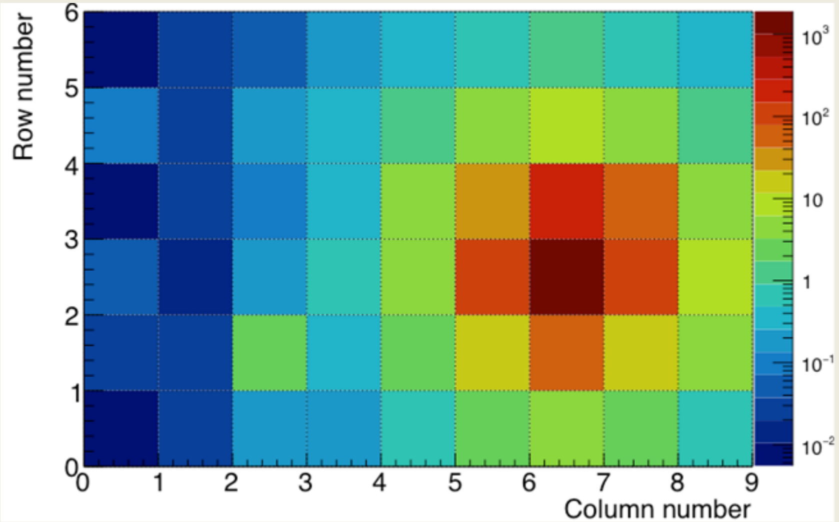


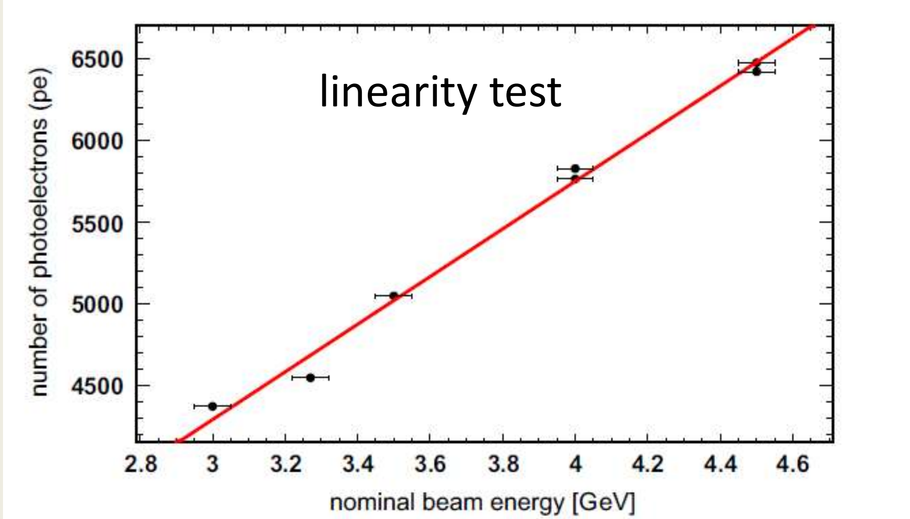




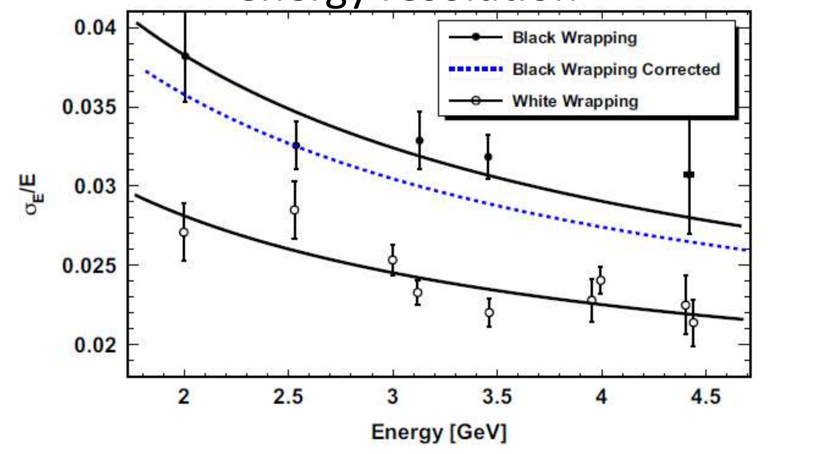
Energy and time of positrons is measured with 24 calorimeters, each one segmented in 54 channels. Each PbF_2 crystal is read out by a Silicon Photomultiplier (SiPM)

The detectors: calorimeters

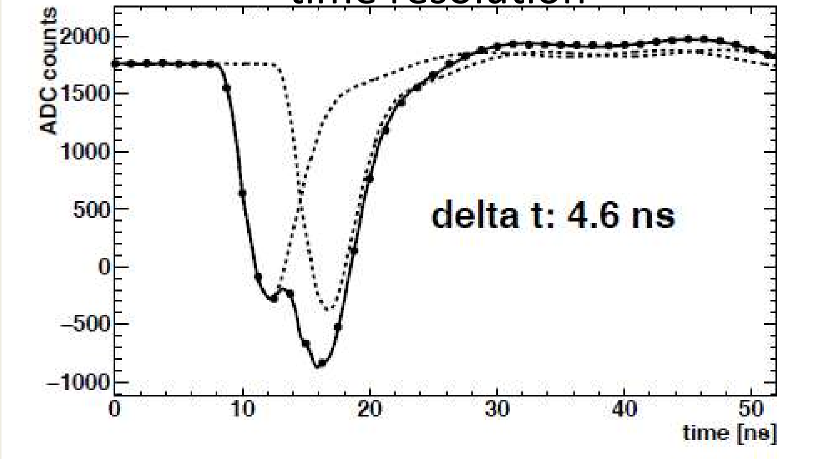




energy resolution



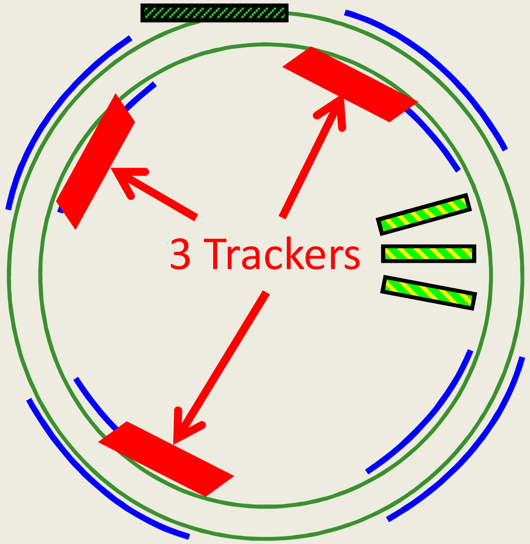
time resolution

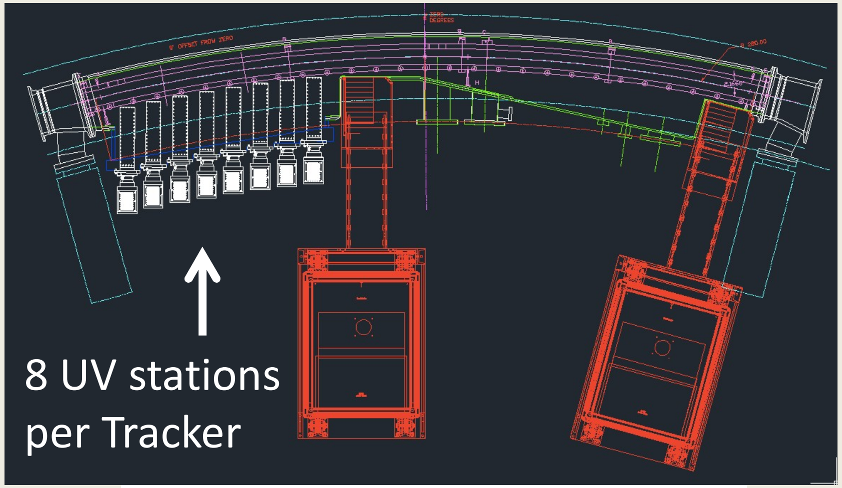


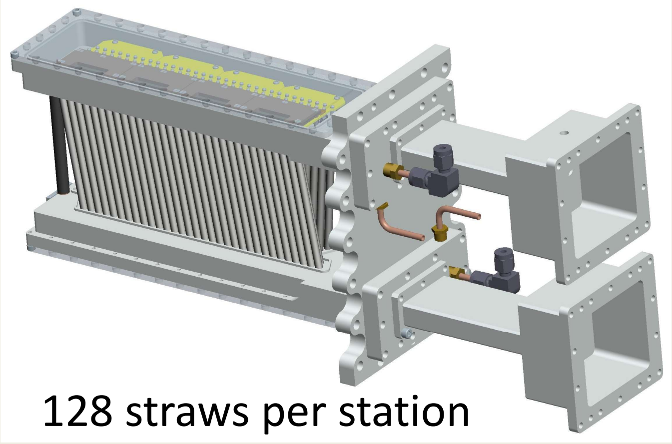
A. Fienberg, NIM A 783, 12 (2015); J. Kaspar, Jinst (2017)

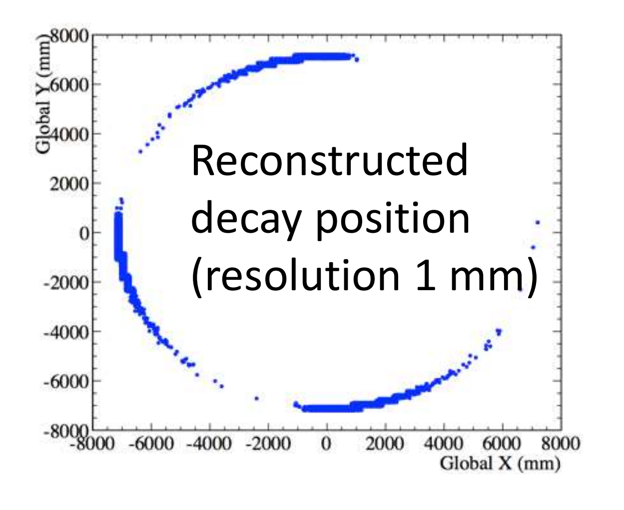
The detectors: trackers

They are used to determine beam position vs time



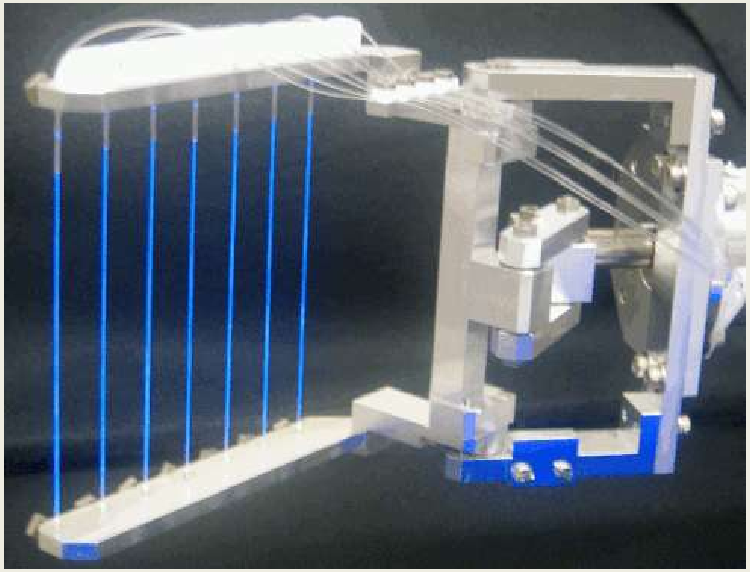






Aux detectors: harps and counters

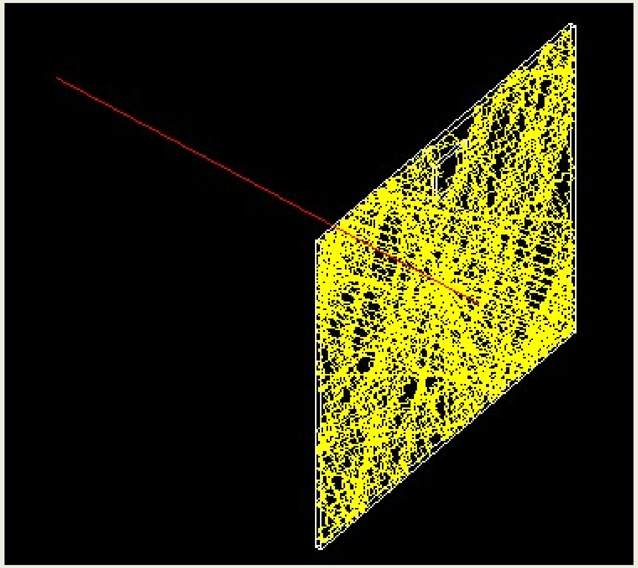
Fiber Harps



2 locations, 2 axis

- used to monitor the muon beam entrance position and angle during commissioning
- measures betatron oscillations during run

Entrance counters



outside the inflector

- gives relative intensity of fill
- timing of the fill (resolution << 150ns, cyclotron period)

The laser calibration system

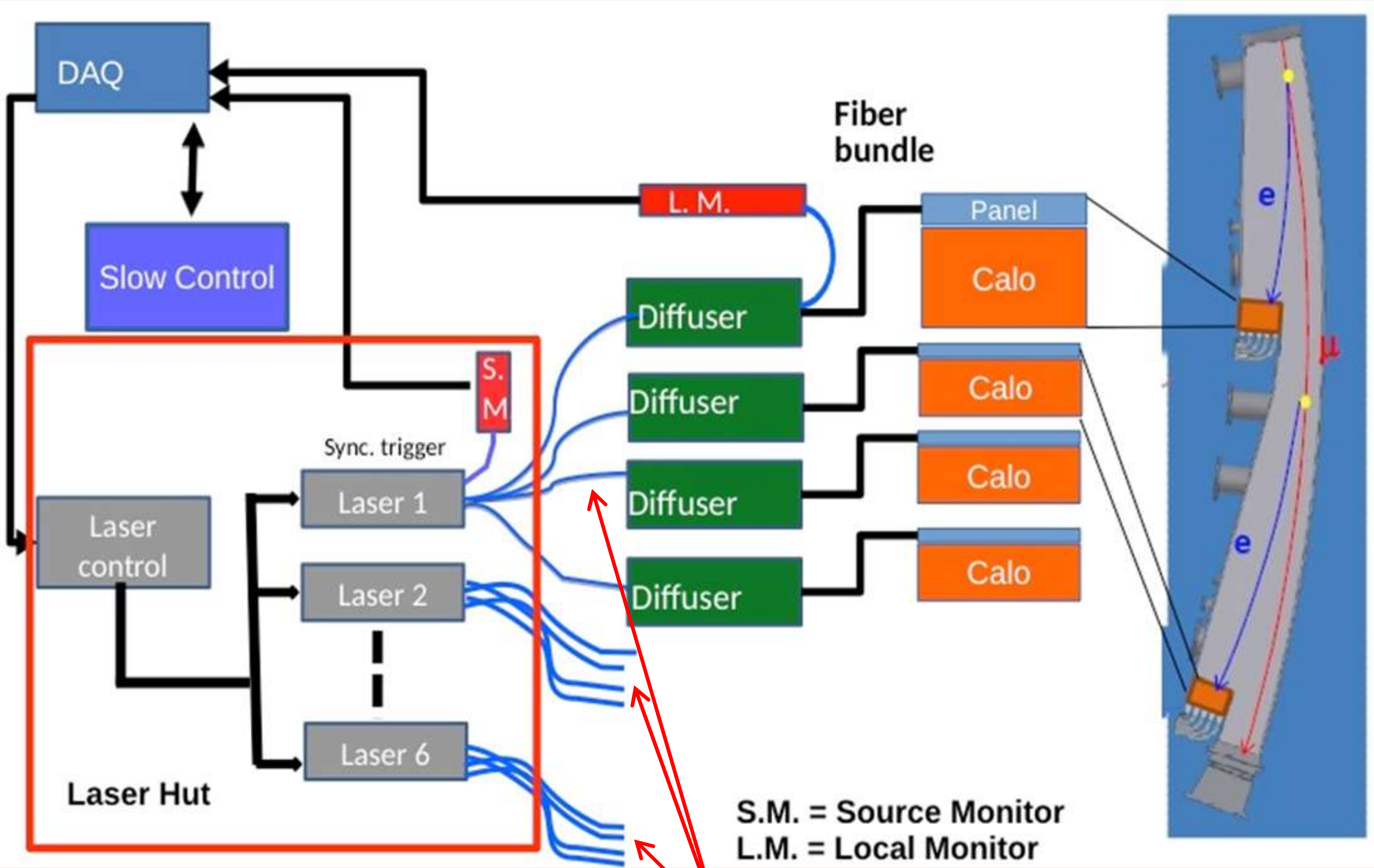
Idea:

- Send trains of laser pulses on known intensity synchronously on all calorimeters' channels

Goals:

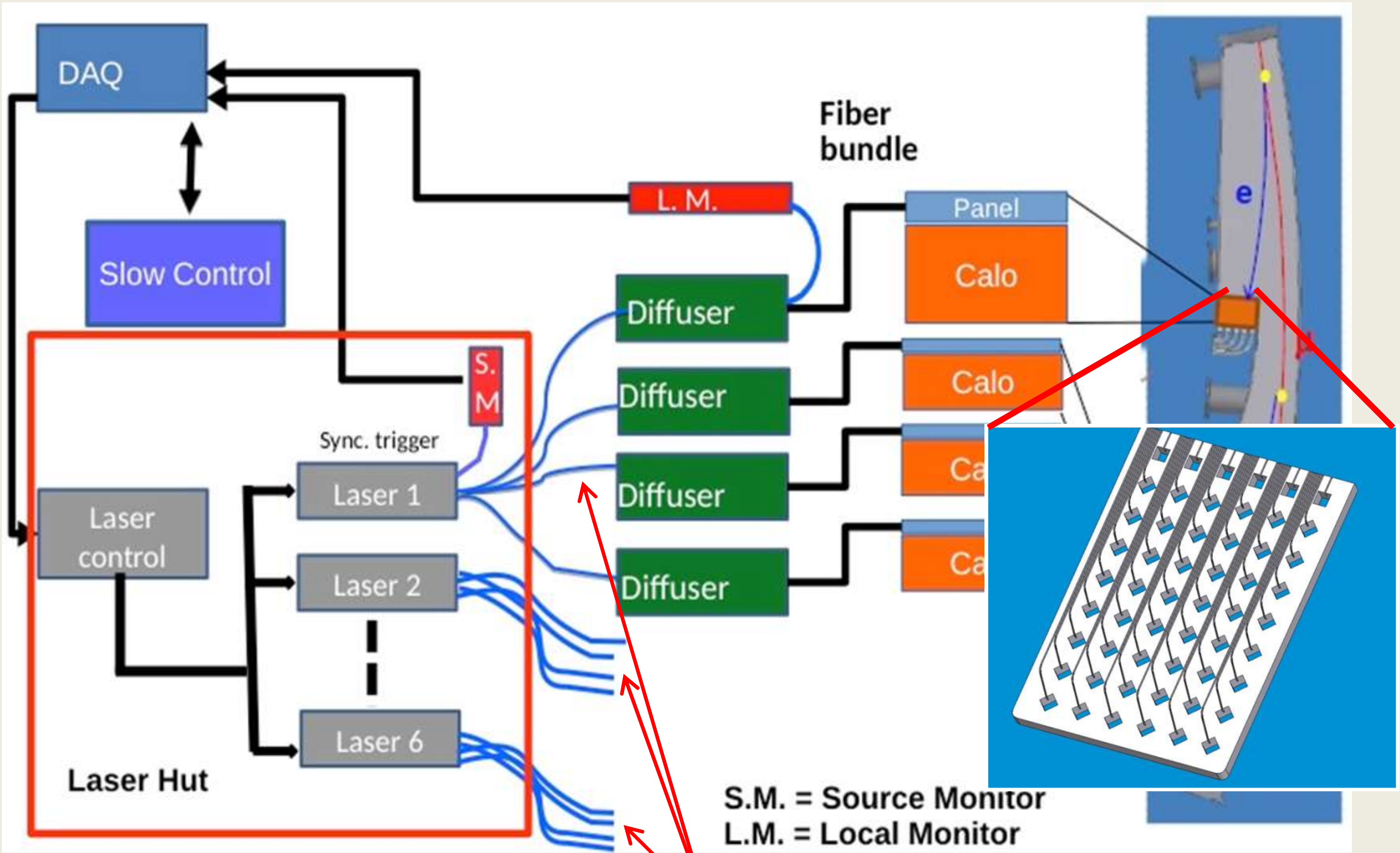
- Absolute calibration of the SiPMs response (photoelectrons/photons response)
- Provide **short term** (in fill, gain saturation) and **long term** (bias and temperature variations) calibration of the of the SiPM gain function
- debugging of Calorimeters and Data Acquisition System (DAQ debugging) by providing physical signals
- provide additional synchronization signals

The laser calibration system



25m silica fibers

The laser calibration system



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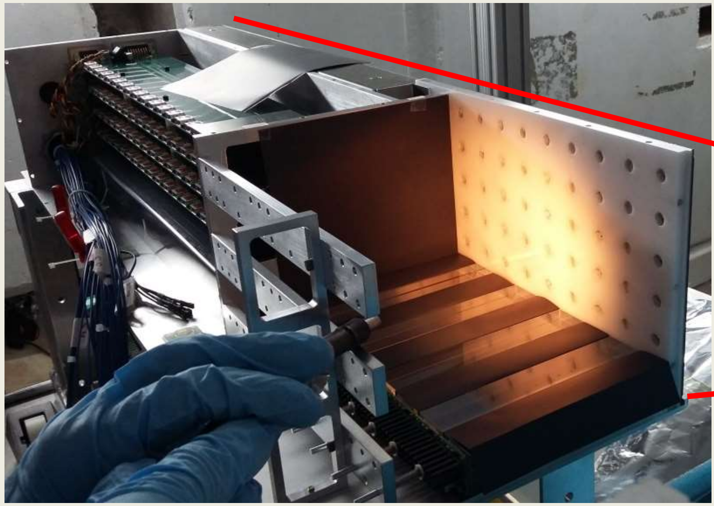

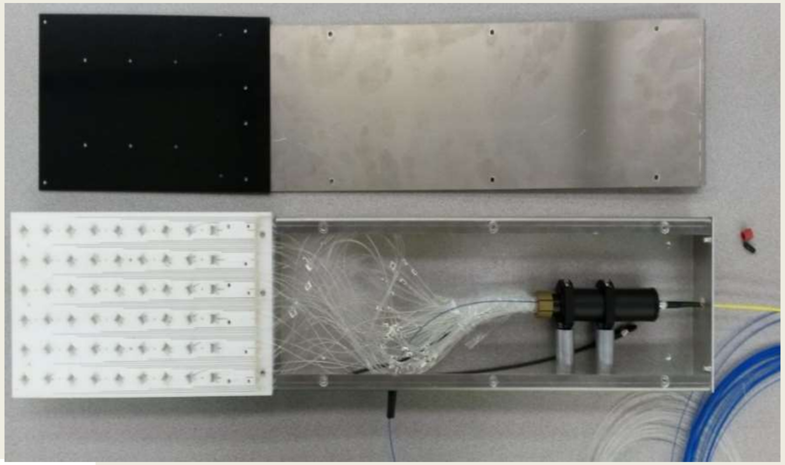

The laser calibration system

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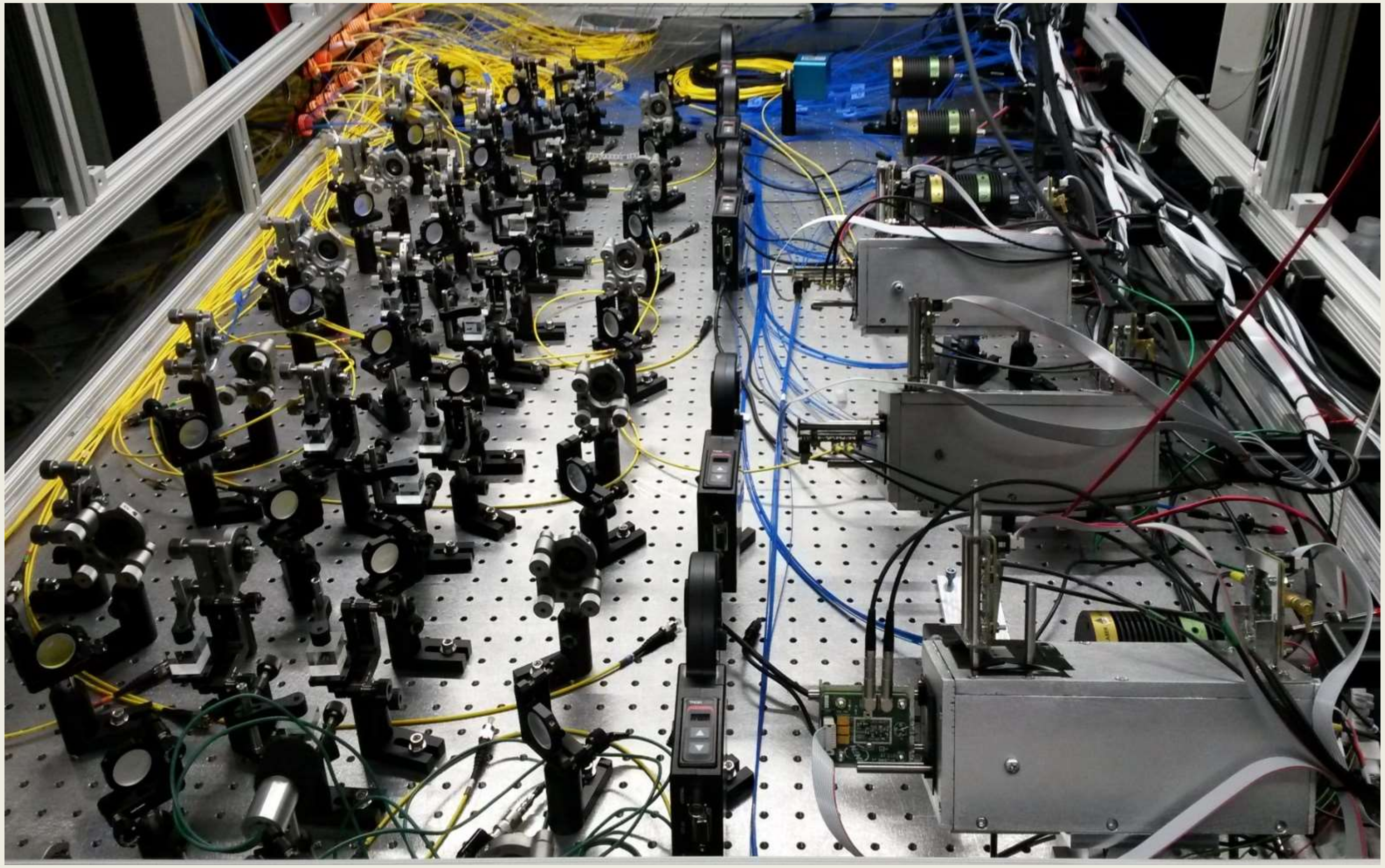

Laser diodes @405nm, 600ps, 1nJ/pulse, 0-40 MHz rep. rate

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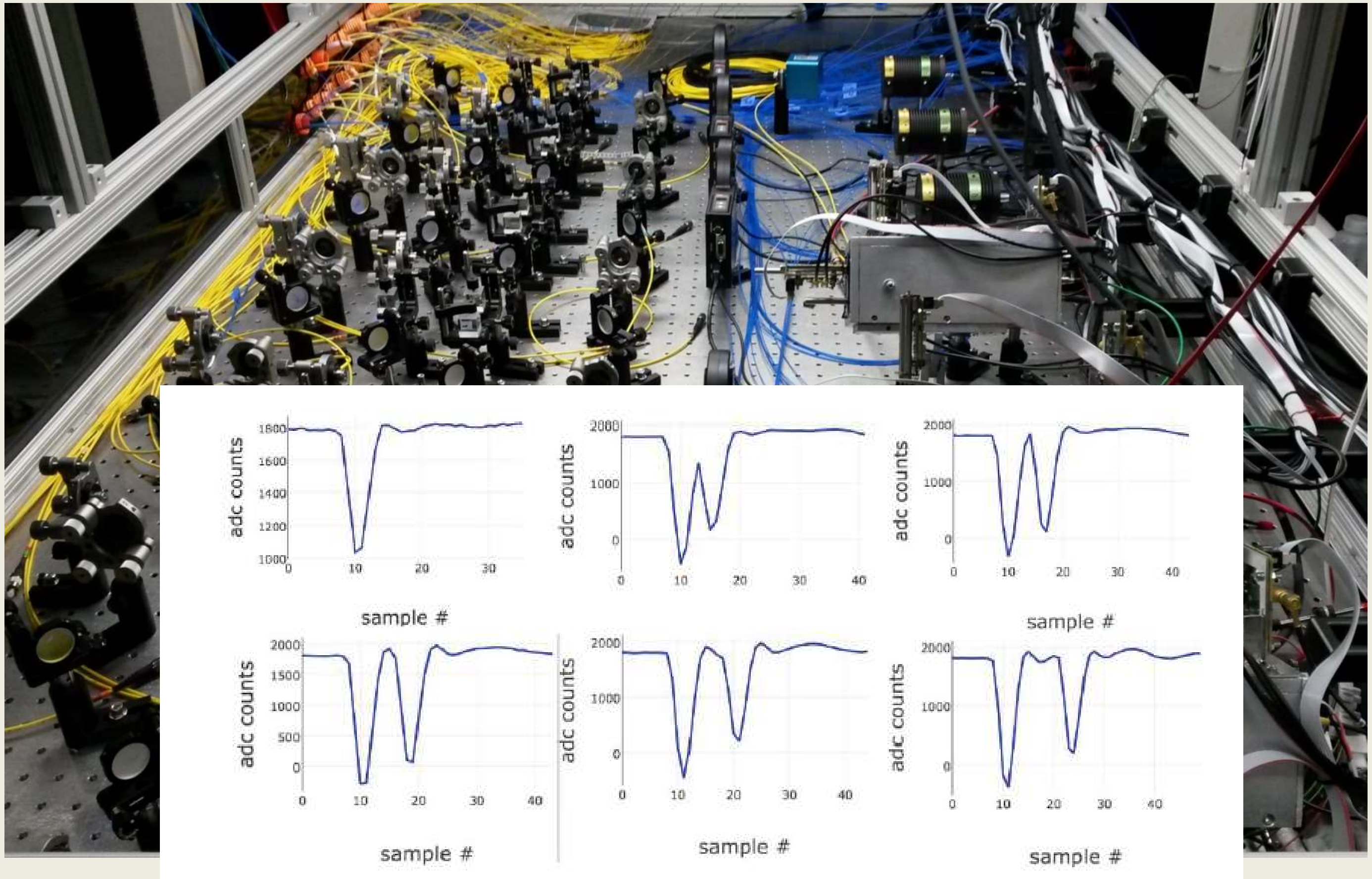
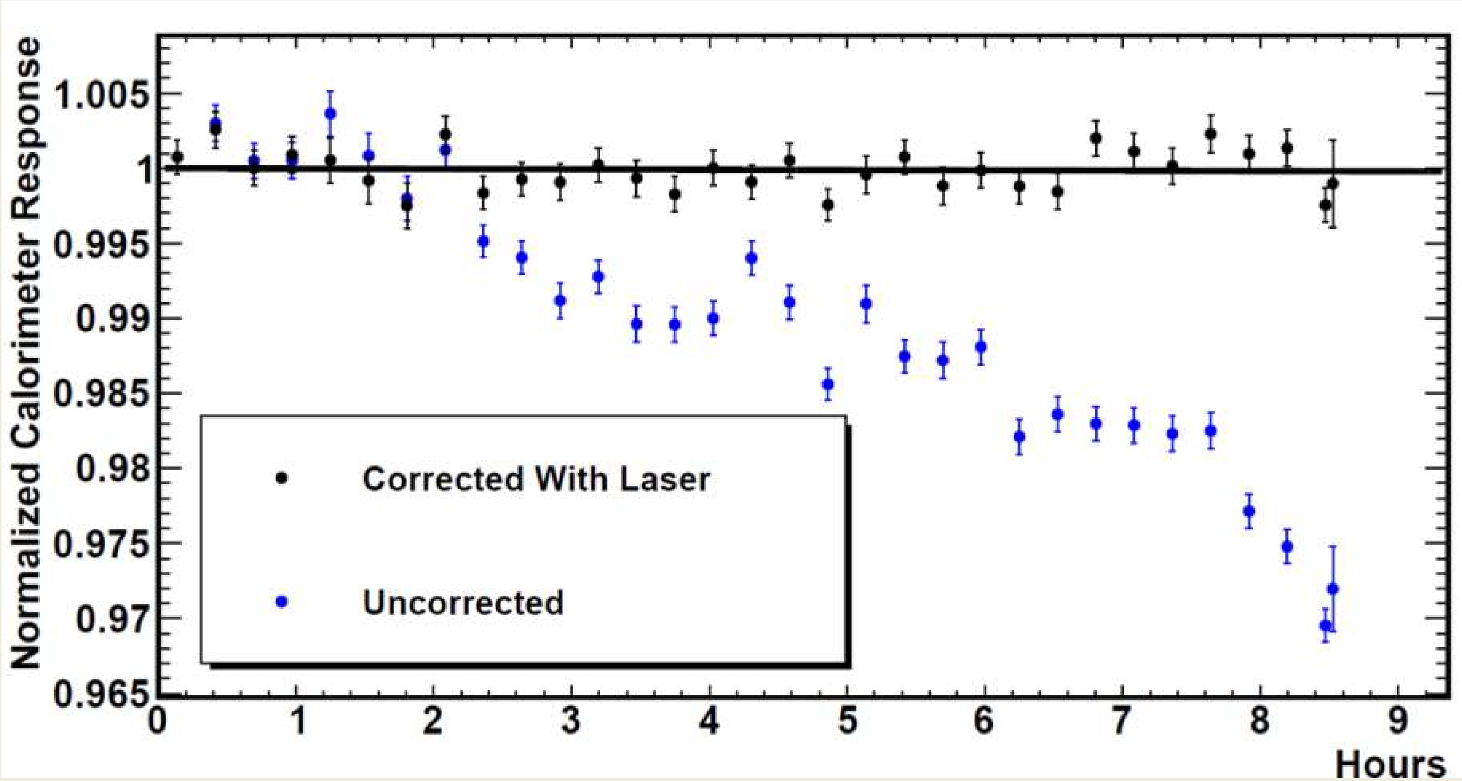


Laser diodes @405nm, 600ps, 1nJ/pulse, 0-40 MHz rep. rate

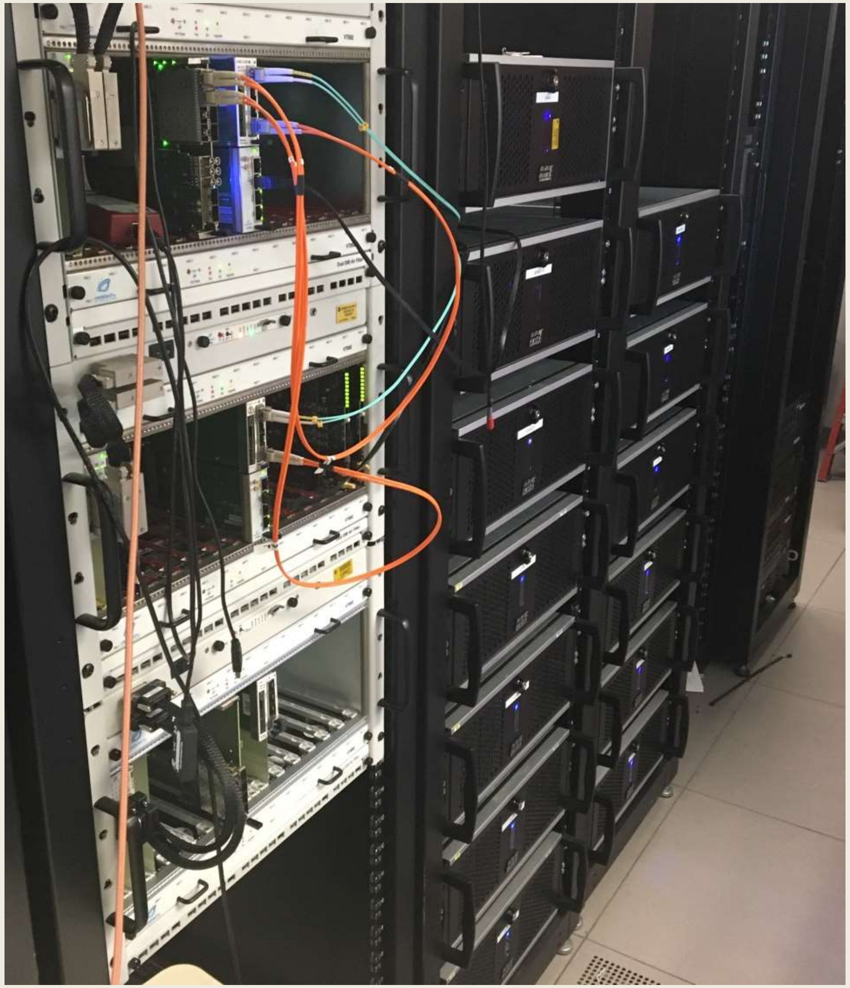
The laser calibration system



10^{-4} / h stability demonstrated
with mono-energetic test beam at SLAC

Data Acquisition System

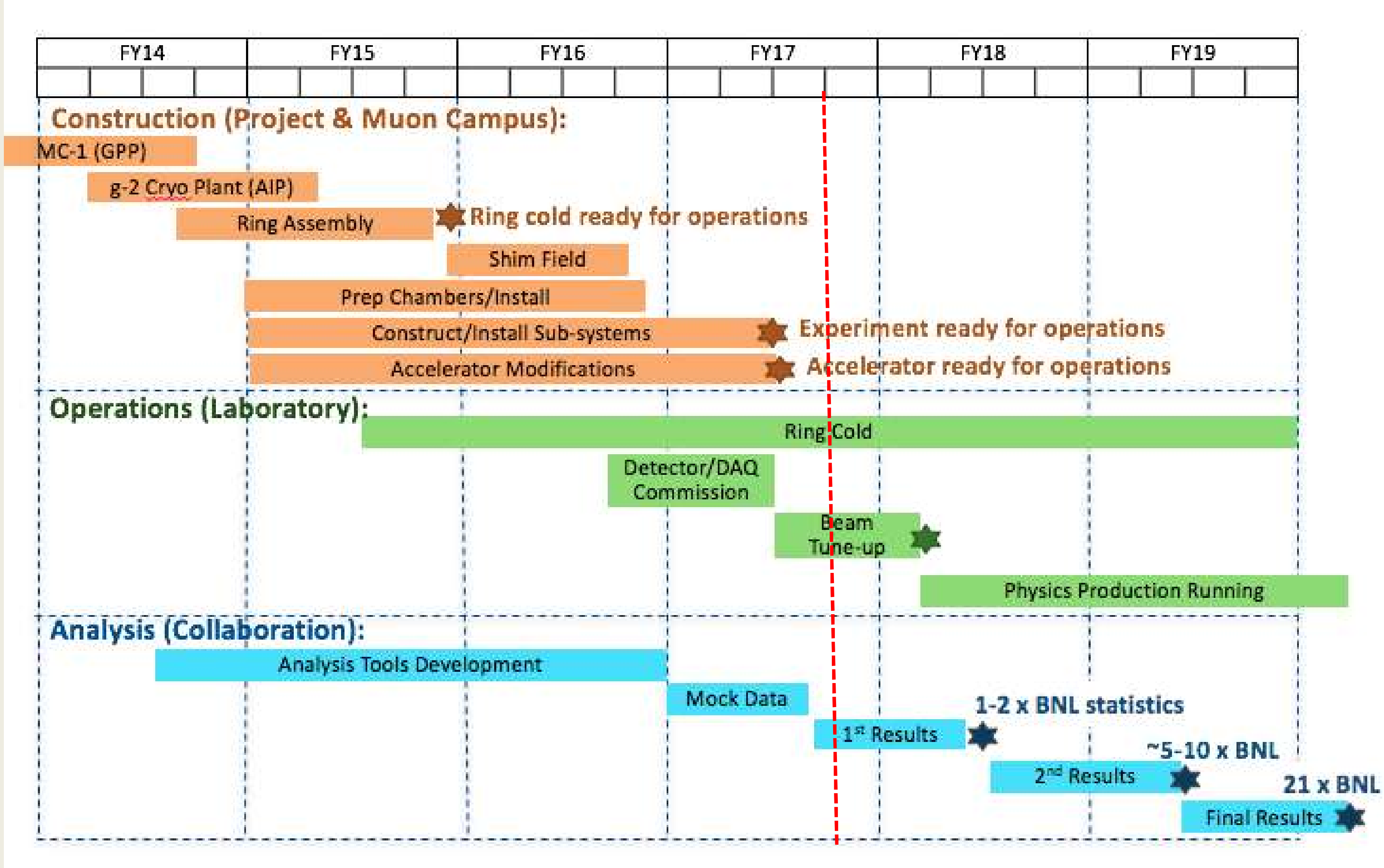
- Calorimeters, trackers and the laser monitoring system are read out by custom 800 MSPS waveform digitizers.
- The DAQ produces a deadtime-free record of each 700 μs muon fill. We get 12 fills per second, providing a total data rate of 20 GB/s.
- Data from each calorimeter is processed by an NVidia Tesla K40 GPU, which processes 33M threads per event.
- Data is sorted by T-method (chopped islands) and Q-method (current integrated) data, from which timing info can be extracted.
- The DAQ software is MIDAS based



Outline

- Introduction and motivations
- Principle of the experiment
- Experimental overview
- Status of the experiment
- Conclusions

Status of the experiment

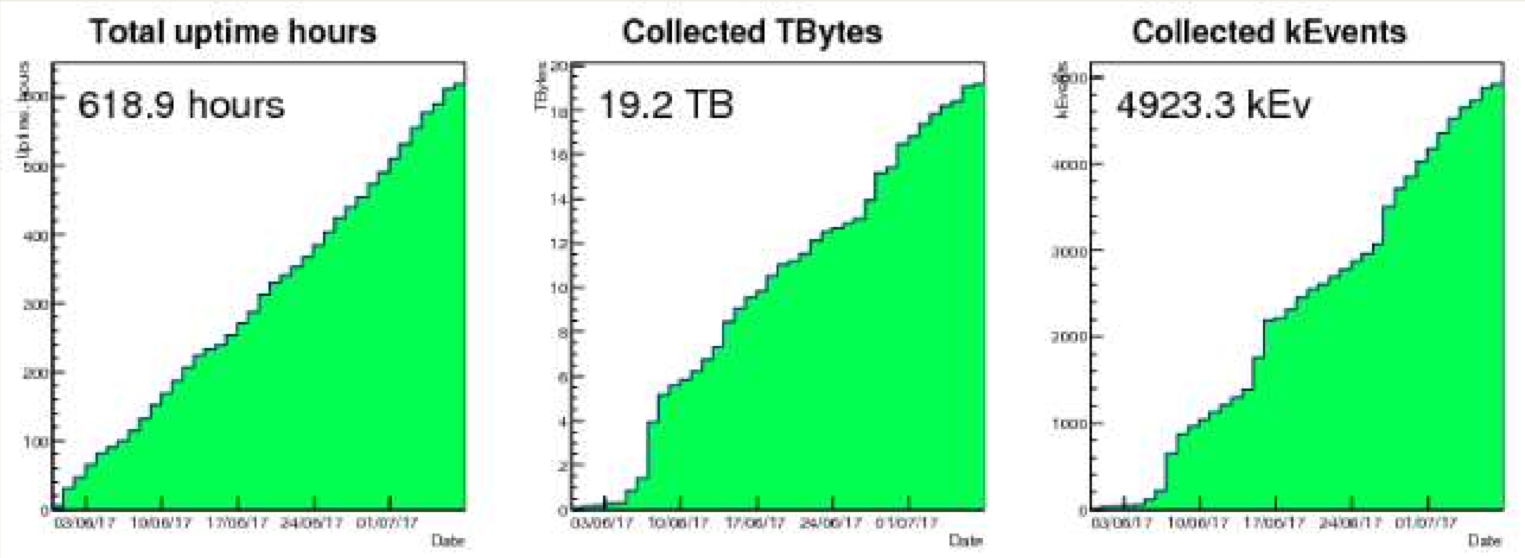


Status of the experiment

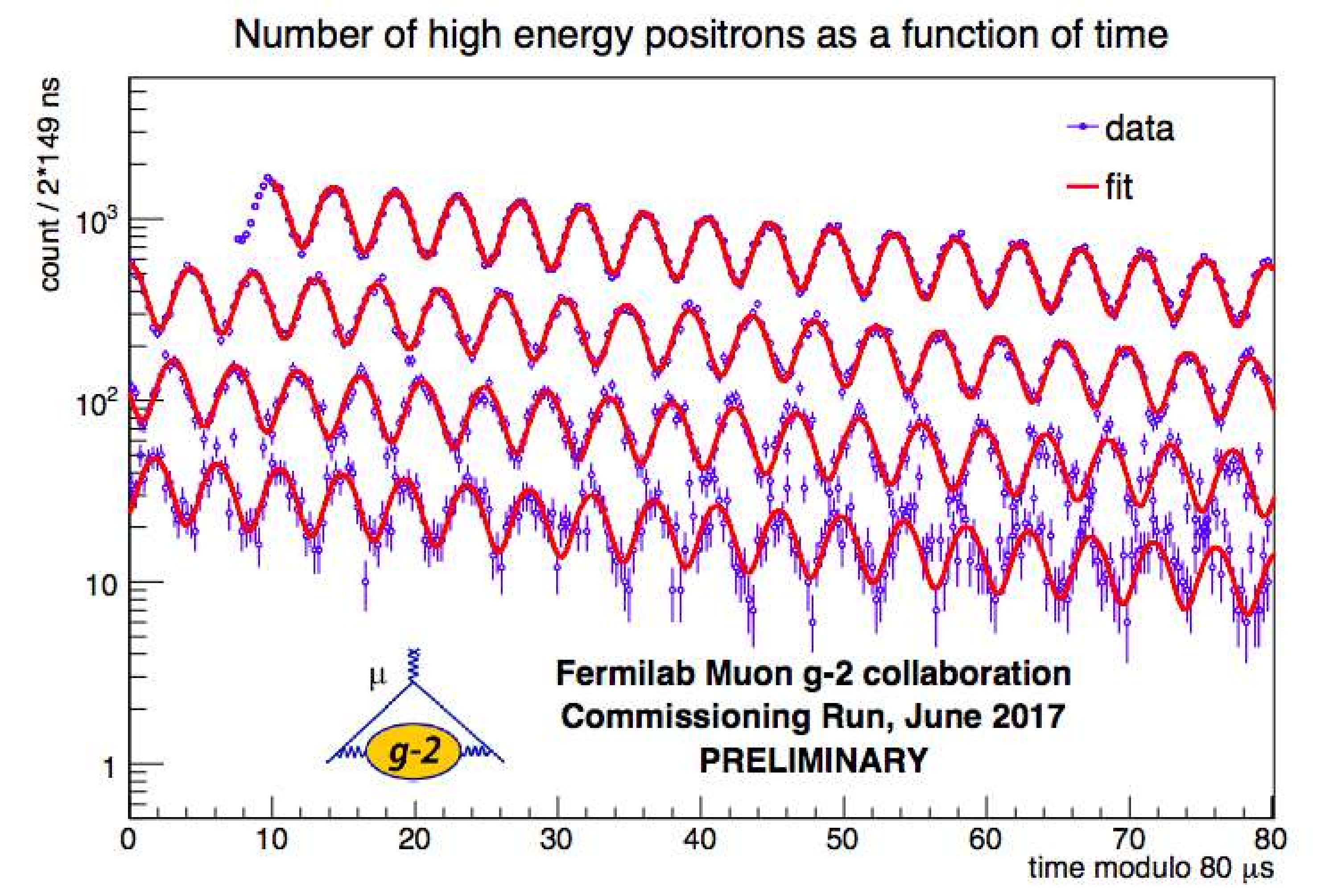
- Almost all different sub-systems already in place and in operation
- First beam injected into ring on May 31, 2017
- Beam (protons and muons) stored for several hundred turns.
- in July 2017 completed commissioning run (10^{16} proton on target, 3billion muons delivered to ring)
- first wiggle plot ready!
- shut-down for Beam/Systems tune-up : ready for next commissioning run, October 1st

Results of the commissioning run

- Received 5 weeks of beam during June-July 2017.
- Mostly protons with 1% muons.
- Fill rate of 0.1 Hz (nominal rate of 12 Hz expected)



Results of the commissioning run



$$N_e(E_e > E_{thr}) = N_0(E_{thr})e^{-t/\gamma\tau}[1 + A(E_{thr})\cos(\omega_a t + \phi(E_{thr}))]$$

Conclusions and outlook

Nature, April 11th 2017

- The new E989 experiment at Fermilab will measure the anomaly a_μ of the muon to 4x the precision of the previous BNL measurement (0.54 ppm)
- If the BNL value holds, this could provide a 7σ discrepancy with the Standard Model and plenty of room for New Physics.
- A 5 weeks commissioning run just completed successfully. Next run scheduled for October 1st, 2017
- Our goal is to reach the BNL level precision by end 2018, and the final 0,14 ppm result measurement in 2020. This will require a total of 1.5×10^{11} collected events.

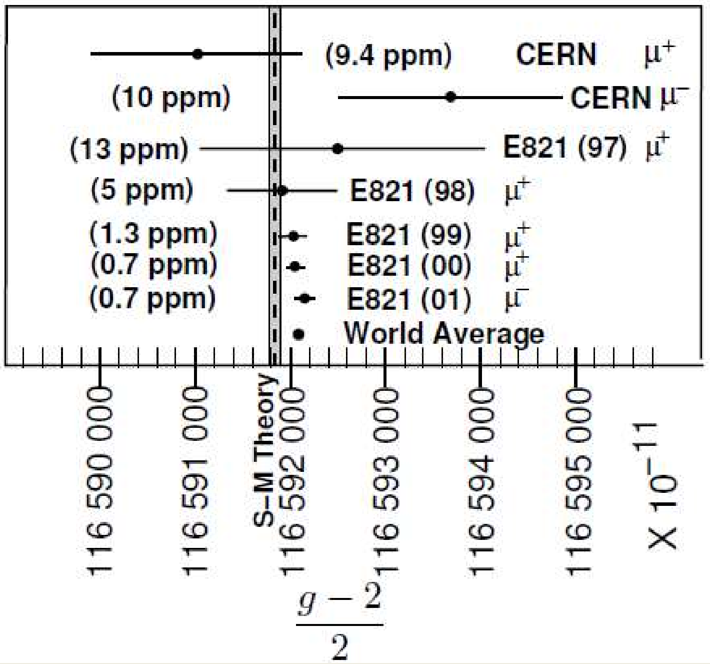
Thank you for your attention

Backup

History of a_μ experimental value

- In last 60 years, technology advancements has allowed enormous progress in experimentally measuring this quantity
- Each measurement gained sensitivity to additional interaction types

2004: Brookhaven measurement first to find robust discrepancy with SM value (~3.6σ)



History of a_μ experimental value

Authors	Year/Lab	a_μ	δa_μ
Garwin *et al.*	'60 CERN	0.001 13(14)	124 ppt
Charpak *et al.*	'61 CERN	0.001 145(22)	19 ppt
Charpak *et al.*	'62 CERN	0.001 162(5)	4.3 ppt
Farley *et al.*	'66 CERN	0.001 165(3)	2.7 ppt
Bailey *et al.*	'68 CERN	0.001 166 16(31)	270 ppm
Bailey *et al.*	'79 CERN	0.001 165 923 0(84)	8 ppm
Brown *et al.*	'00 BNL μ^+	0.001 165 919 1(59)	
Brown *et al.*	'01 BNL μ^+	0.001 165 920 2(14)(6)	
Bennett *et al.*	'02 BNL μ^+	0.001 165 920 4(7)(5)	
Bennett *et al.*	'04 BNL μ^-	0.001 165 921 4(8)(3)	
BNL E821 & CODATA 2010	'06 BNL	0.001 165 920 91(63)	0.54 ppm
WA (CODATA 2008)		0.001 165 920 89(63)	0.54 ppm

a_μ determination

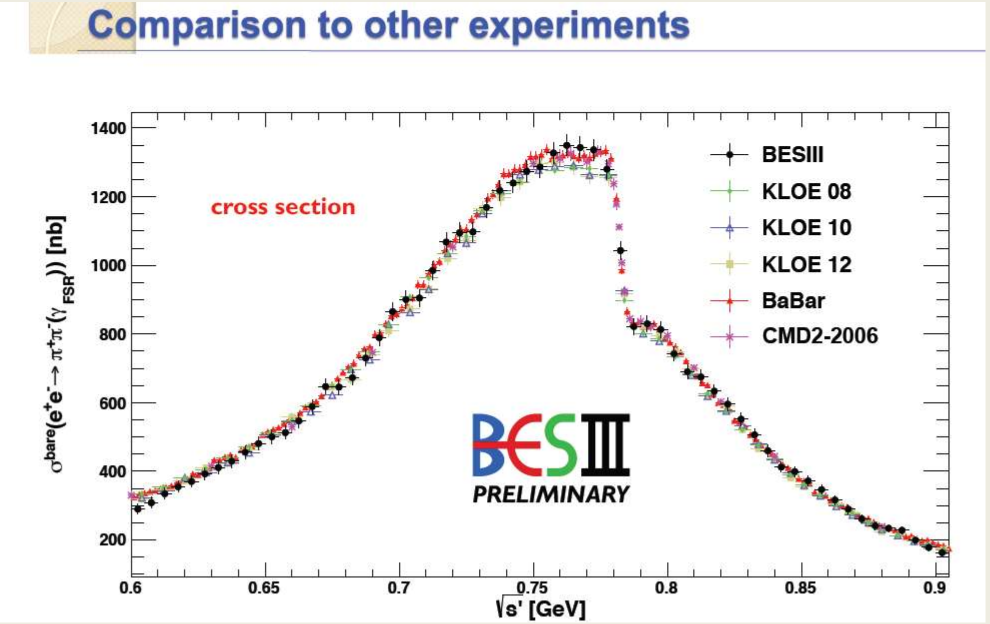
- $\vec{\omega}_s = -\frac{gq\vec{B}}{2m} - (1-\gamma)\frac{q\vec{B}}{\gamma m}$
- $\vec{\omega}_c = -\frac{q\vec{B}}{\gamma m}$
- $\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{q\vec{B}}{m} = -a_\mu \frac{q\vec{B}}{m}$
- average B in muon orbit measured with proton spin precession frequency $\tilde{\omega}_p$

a_μ^{exp} determination

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

- $\omega_a/\tilde{\omega}_p$ (540 ppb) from muon $g-2$ exp WA
- g_e (0.0003 ppb) from a_e measurements
- m_μ/m_e (22 ppb) from CODATA 2014
- μ_p/μ_e (3 ppb) from CODATA 2014

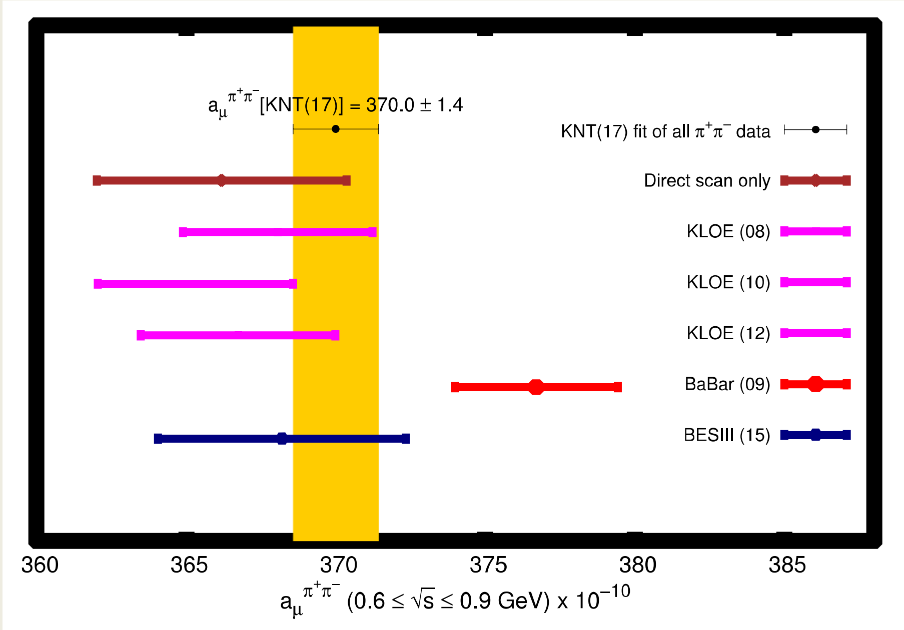
The theory error in HVP(lo) is exp



$$a_{\mu}^{had,1} \propto \int_{2m_{\pi}}^{\infty} ds \frac{K(s)}{s} R(s)$$

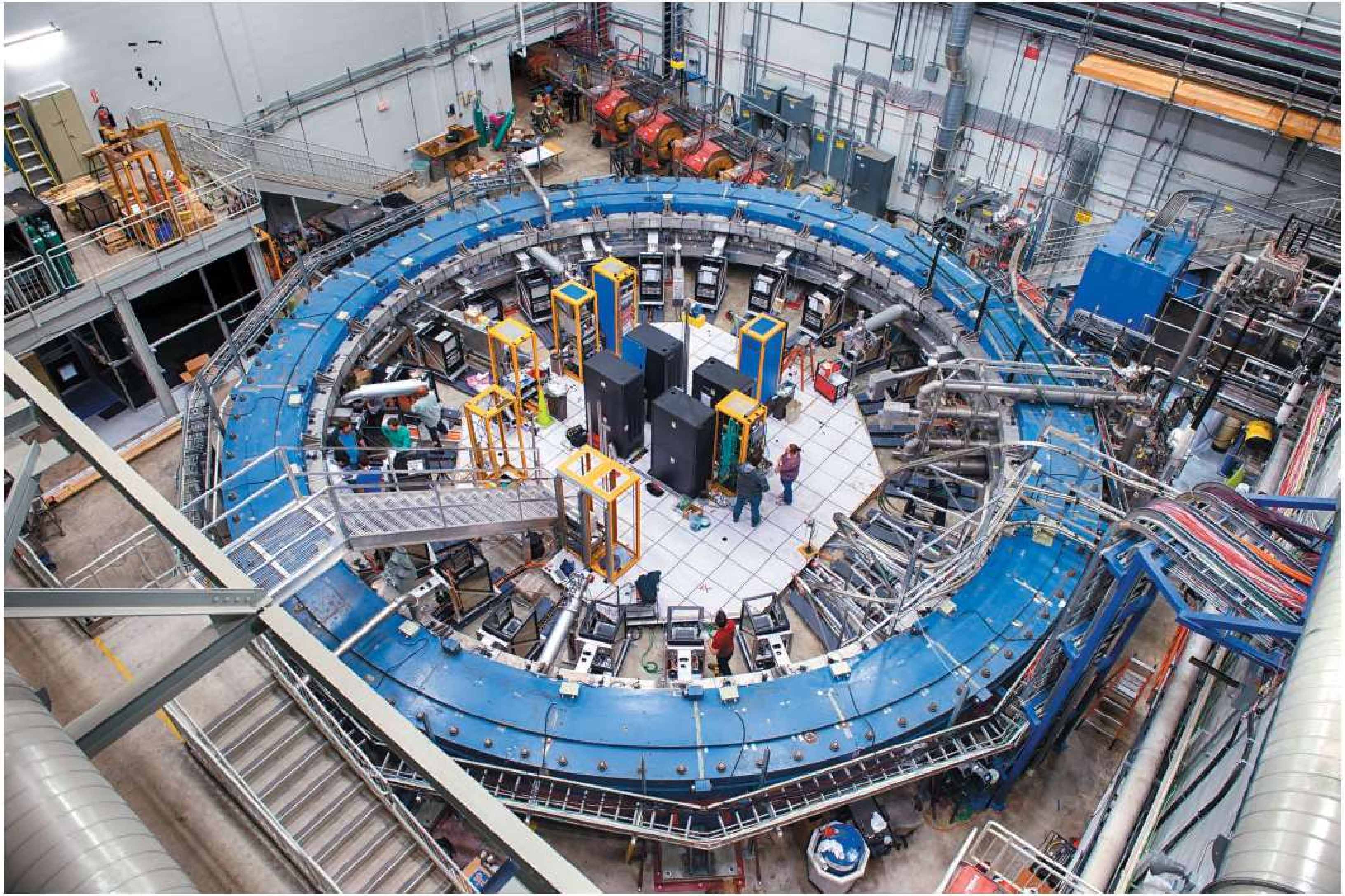
$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \text{muons})}$$

Low order Hadronic contribution
is determined by cross-sections knowledge



Nature, April 11th 2017

FERMILAB



The Muon g−2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

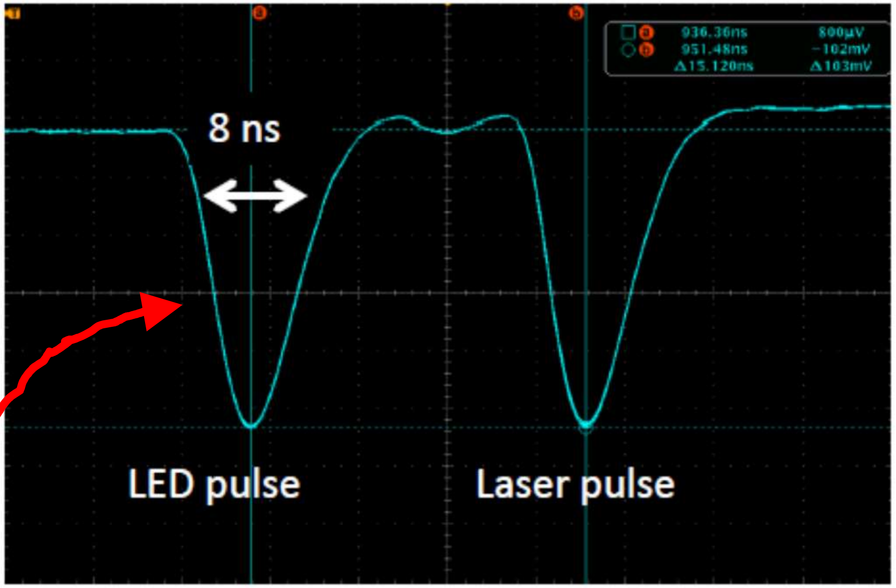
PARTICLE PHYSICS

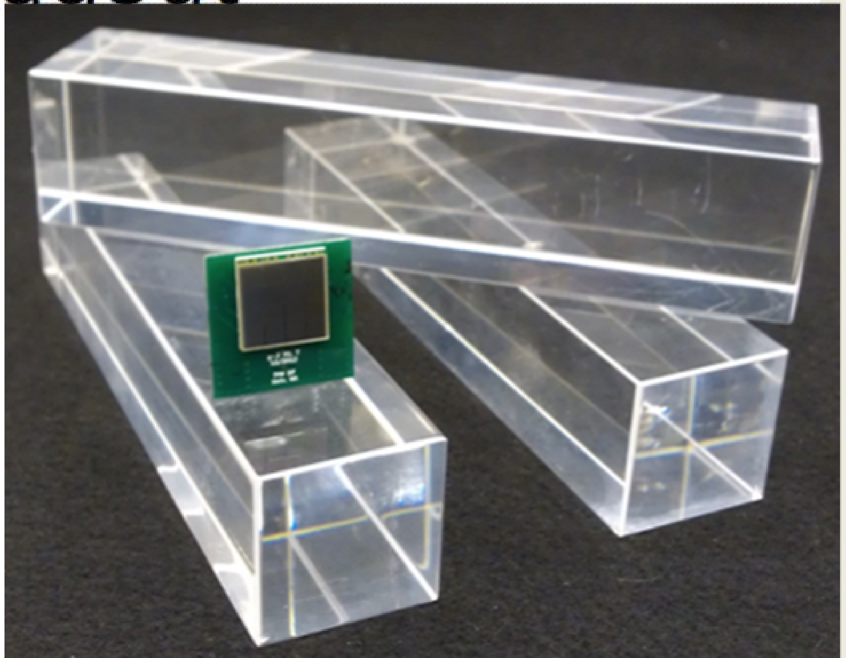
http://www.nature.com/news/muons-big-moment-could-fuel-new-physics-1.21811

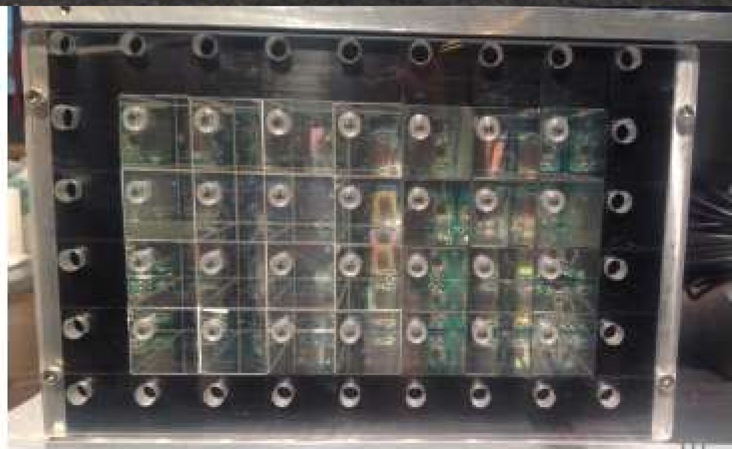
Muons' big moment

Segmented PbF_2 Calorimeter with SiPM Readout

SiPM boards optimized to produce PMT-like pulses to exploit short pulse duration of Cherenkov crystals (relevant: pileup)







28-channel prototype calorimeter tested at SLAC

E989: 38 institutes, >150 members

- Domestic Universities
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Massachusetts
  - Mississippi
  - Kentucky
  - Michigan
  - Michigan State
  - Mississippi
  - Northern Illinois University
  - Northwestern
  - Regis
  - Virginia
  - Washington
  - York College
- National Labs
  - Argonne
  - Brookhaven
  - Fermilab
- Consultants
  - Muons, Inc.

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Japan:
- Osaka

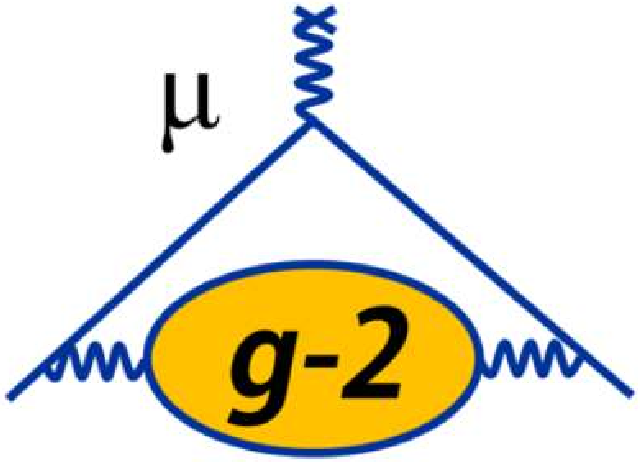
Russia:
- Dubna
- PNPI
- Novosibirsk

UK

University College London
Liverpool
Oxford
Rutherford Lab

Korea

KAIST

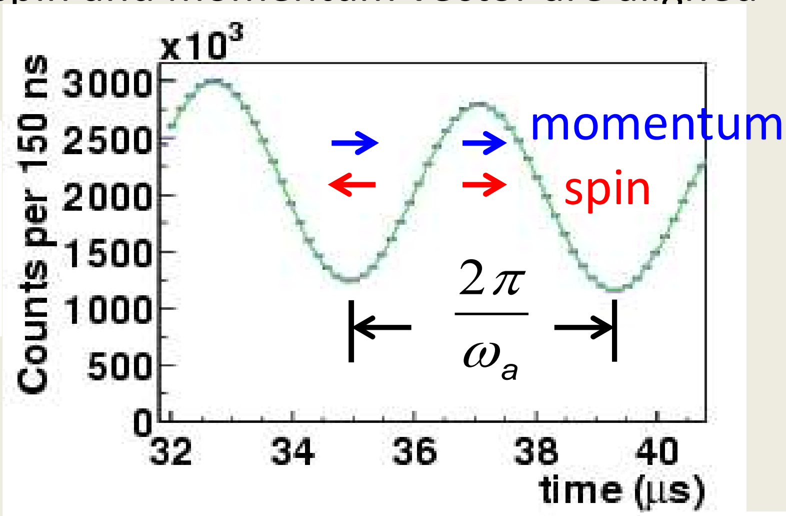


D.W. Hertzog, Co-Spokesperson, hertzog@uw.edu
B.L. Roberts, Co-Spokesperson, roberts@bu.edu
C. Polly, Project Manager

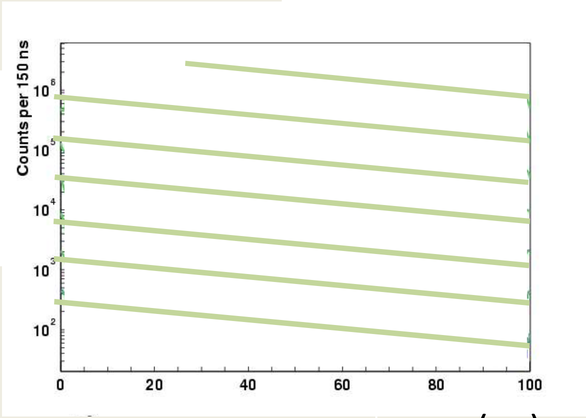
Muon precession frequency

V-A decay, positron follows spin direction, and highest energy positrons occur when spin and momentum vector are aligned

high energy positrons versus time

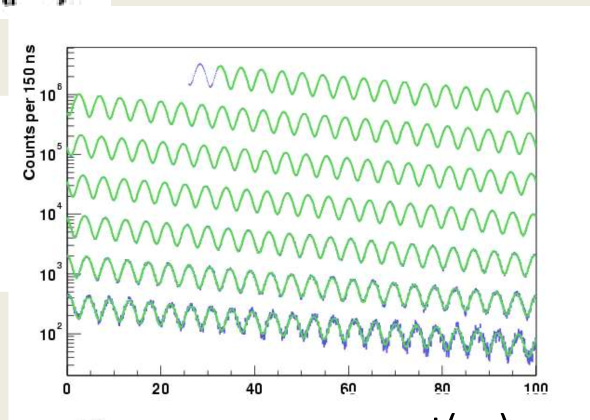


What data looks like if g-2 = 0



t(μs)

What data looks like if g-2 = 0.002



t(μs)

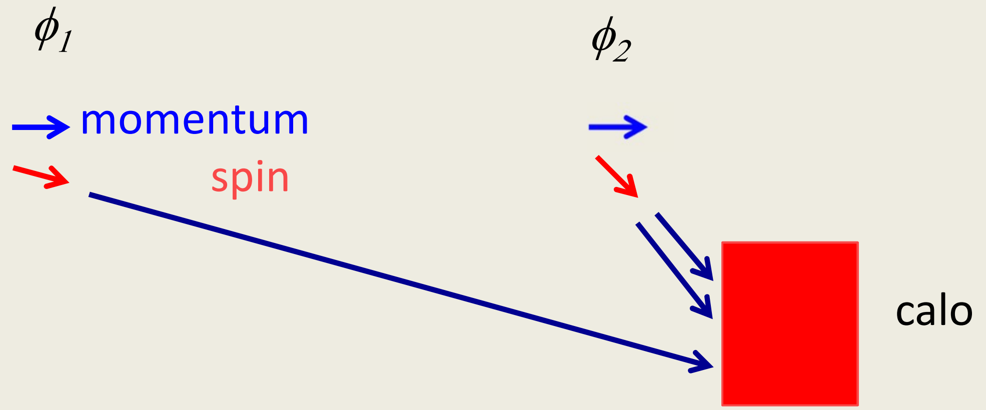
from B. Casey, FNAL

Systematics

Pileup: two low energy positrons fake a high energy positron
(happens early, not late)

$\phi_{early} \sim \phi_1 + \phi_2$

$\phi_{late} \sim \phi_1$

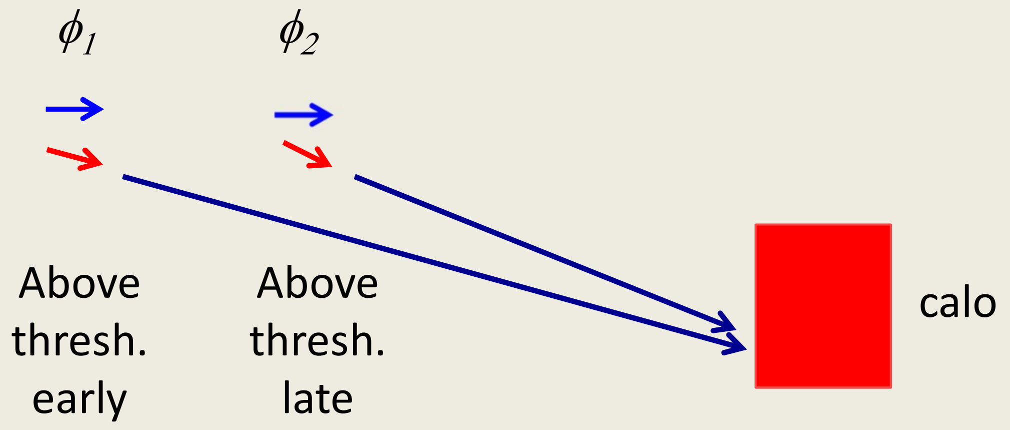


Gain change:
example: saturation (happens early, not late)

$\phi_{early} \sim \phi_1$

$\phi_{late} \sim \phi_2$

$\boxed{\Delta\omega \sim \Delta\phi}$



Design not driven by absolute performance, but relative stability early to late

Know how well we did on these for BNL experiment. Need to do better by a factor of 4. Detector package designed to contain the tools to enable this.

from B. Casey, FNAL

Muon $g-2$ SM test uncertainties summary

Quantity	Uncertainty $\times 10^{-11}$	$\delta a_\mu / a_\mu$ (ppb)
ω_a statistical	53	458
ω_a systematic	24	210
$\tilde{\omega}_p$ systematic	20	170
CODATA m_μ / m_e	2.6	22
CODATA μ_p / μ_e	0.35	3
Electron g factor, g_e	0.000035	0.0003
QED	0.08	0.7
EW	1	8.6
hadLBL	26	223
hadLO	33	280
hadNLO	0.9	7.6
hadNNLO	0.1	0.86

Uncertainty of E821 ω_a measurement

Statistical uncertainty

- fit $N_e(E_e > E_{thr}) = N_0(E_{thr}) e^{-t/\gamma\tau} [1 + A(E_{thr}) \cos(\omega_a t + \phi(E_{thr}))]$
- $\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau_\mu} \sqrt{\frac{2}{NA^2P^2}}$ N = number of muons, P = muon polarization, A = asymmetry
  - improves with B field since $\omega_a \propto B$
  - improves with number of muons, asymmetry, polarization
  - improves with muon momentum (γ)

Systematic uncertainty

	E821 [ppb]
detector gain variation	120
event pileup	80
lost muons	90
coherent betatron oscillations	70
electric-field and pitch corrections	50

Reduce statistical $\delta\omega_a$ from 458 ppb to 100 ppb

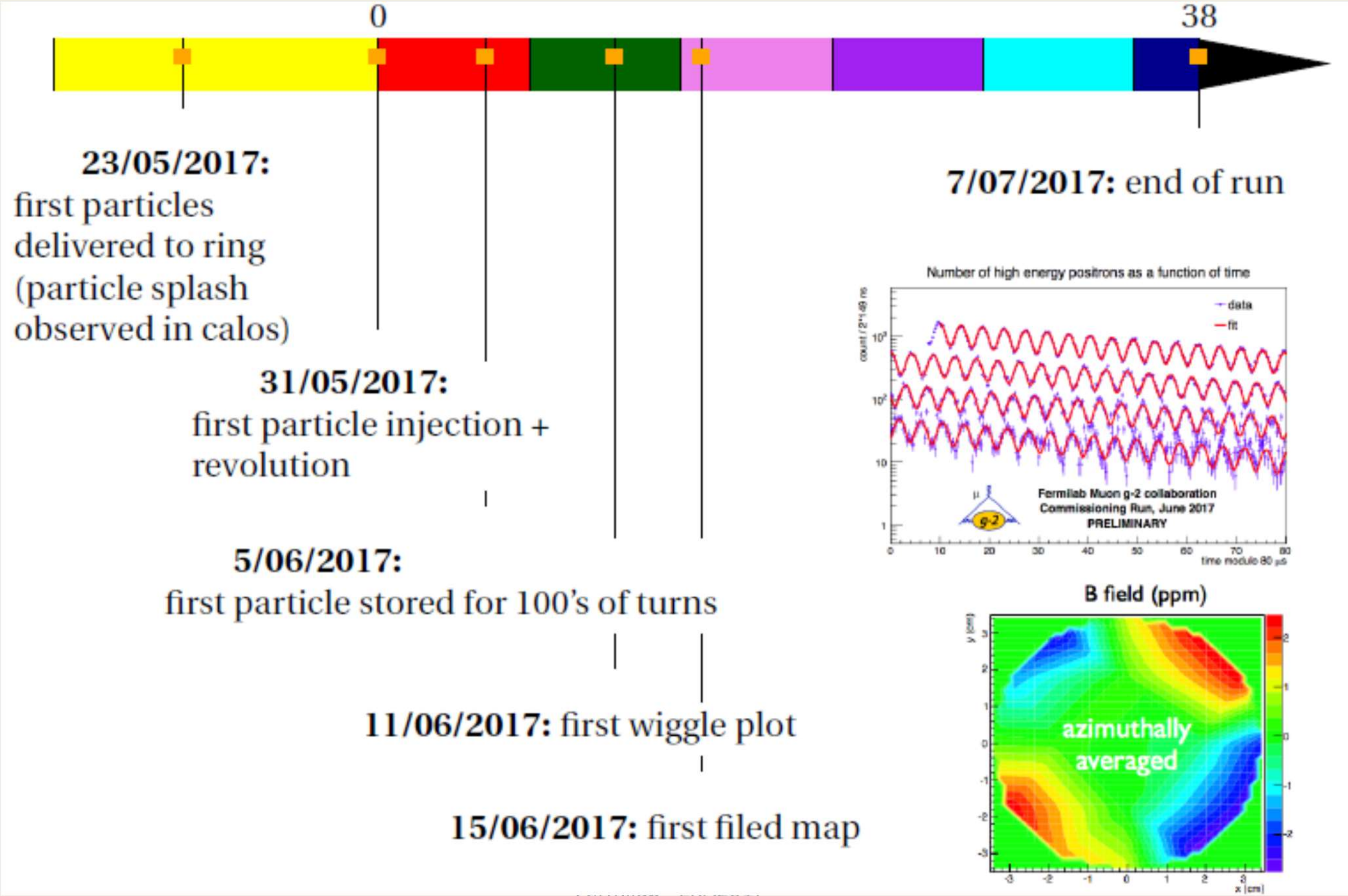
- just need 21 times more muons, $1.5 \cdot 10^{11}$

Item	Estimate
Protons per fill on target	10^{12} p
Positive-charged secondaries with $dp/p = \pm 2\%$	4.8×10^7
π^+ fraction of secondaries	0.48
π^+ flux entering FODO decay line	$> 2 \times 10^7$
Pion decay to muons in 220 m of M2/M3 line	0.72
Muon capture fraction with $dp/p < \pm 0.5\%$	0.0036
Muon survive decay 1800 m to storage ring	0.90
Muons flux at inflector entrance (per fill)	4.7×10^4
Transmission and storage using $(dp/p)_\mu = \pm 0.5\%$	0.10 ± 0.04
Stored muons per fill	$(4.7 \pm 1.9) \times 10^3$
Positrons accepted per fill (factors 0.15 x 0.63)	444 ± 180
Number of fills for 1.8 $\times 10^{11}$ events	$(4.1 \pm 1.7) \times 10^8$ fills
Time to collect statistics	(13 ± 5) months
Beam-on commissioning	2 months
Dedicated systematic studies periods	2 months
Net running time required	17 ± 5 months

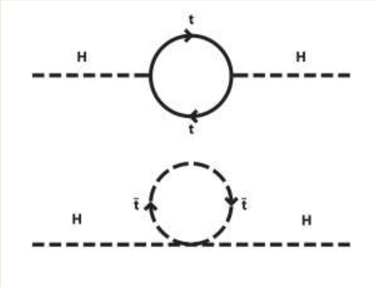
Reduce systematic $\delta\tilde{\omega}_p$ from 170 ppb to 70 ppb

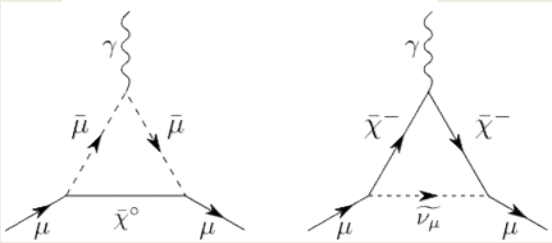
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes	30
Trolley measurements of B_0	50	Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	30
Fixed probe interpolation	70	Better temp. stability of the magnet, more frequent trolley runs, more fixed probes	30
Muon distribution	30	Improved field uniformity, improved muon tracking	10
External fields	–	Measure external fields; active feedback	5
Others †	100	Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce O_2 and image effects	30
Total syst. unc. on ω_p	170		70

2017 commissioning run highlights

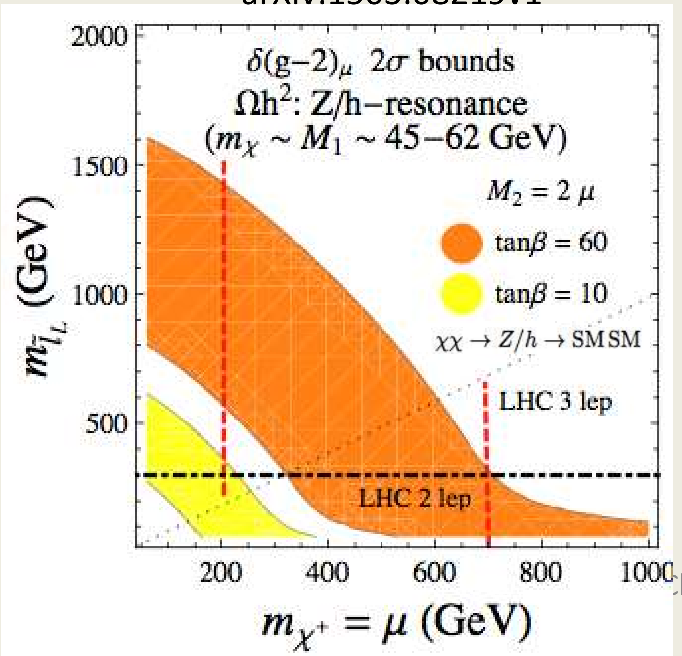


What monsters might there be? SUSY





arXiv:1503.08219v1

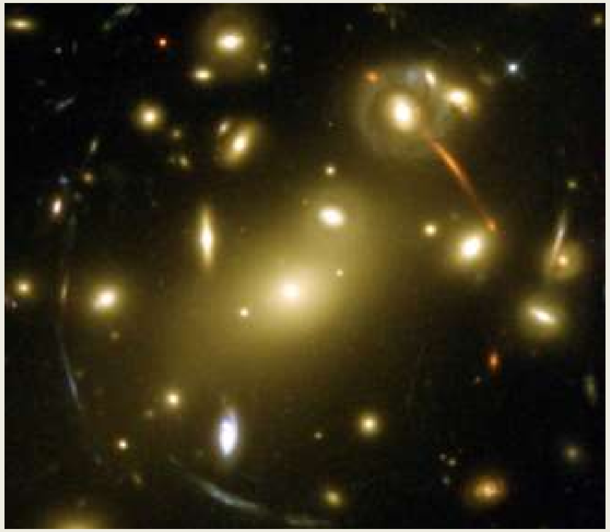


- The Higgs mass has now been measured at the LHC (and predicted long before that due to precision electroweak fits) to be ~125 GeV
- Theoretically, expectation is that the Higgs should acquire a much heavier mass from loops with heavy SM particles, e.g. top quark
- Supersymmetry postulates a new class of particles who can enter the loops and effectively cancel the

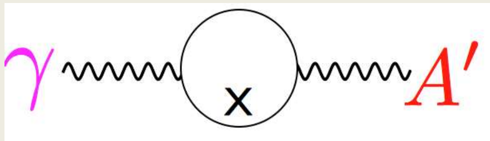
$$a_\mu(SUSY) \approx (\mathrm{sgn}\mu)130 \times 10^{-11} \tan\beta \left(\frac{100\mathrm{GeV}}{\tilde{m}}\right)^2$$

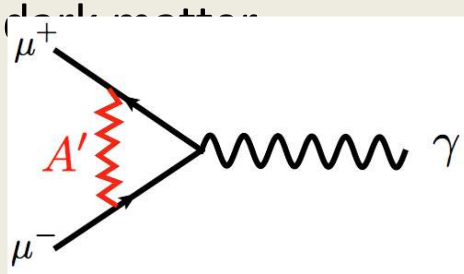
- Complementary to direct searches at the LHC
  - Sensitive to sgn μ and tan β
  - Contributions to g-2 arise from charginos and sleptons while LHC direct searches are most sensitive to squarks and gluinos

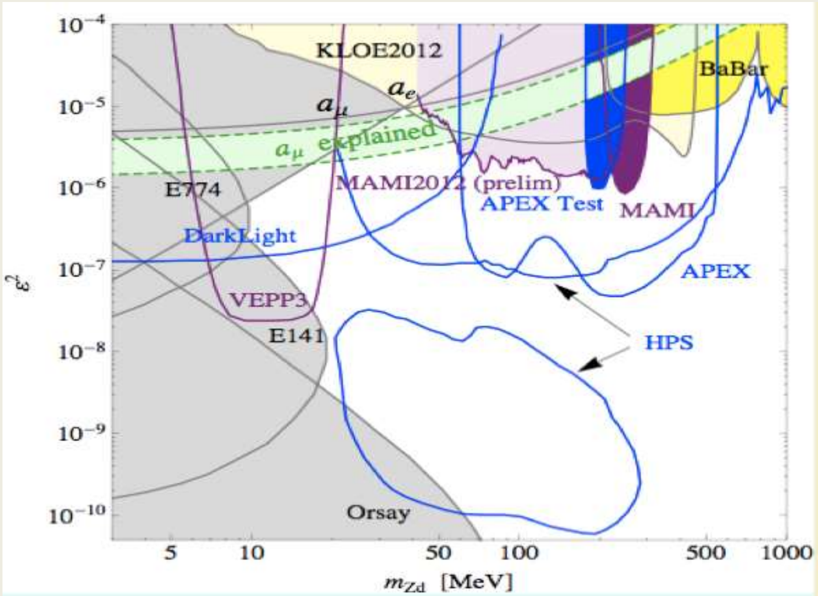
What monsters might there be? Dark Matter



- Through cosmological observations, e.g. galaxy rotation curves, lensing, there appears to be much more mass in the universe than expected
- Many theories arising to explain the dark matter
- One example is the dark photon, which is a new U(1) gauge symmetry that would weakly couple standard model particles to







- Dark photon can also impact the magnetic moment of the muon
- Many search underway for direct production