Fermilab   Muon g-2

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

The new g-2 experiment is ramping up!

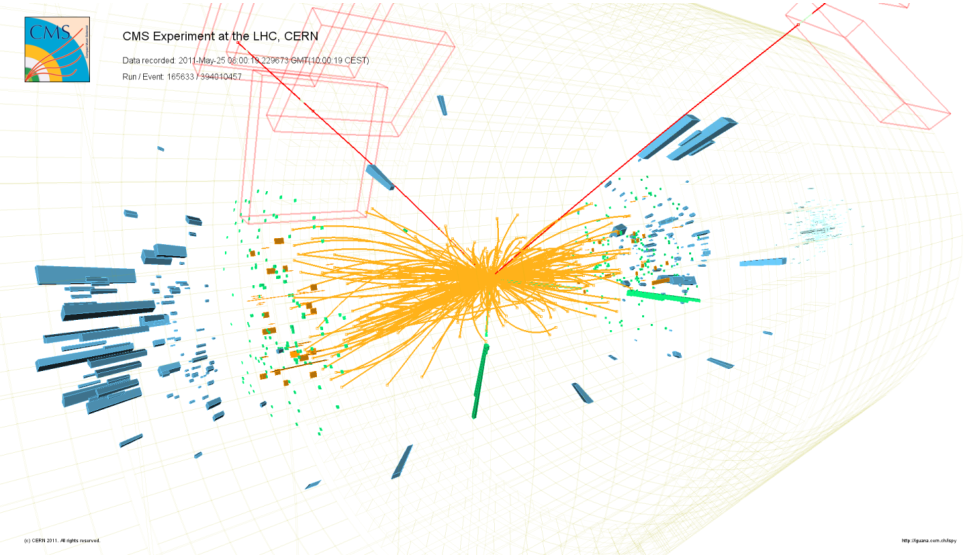
Renee Fatemi

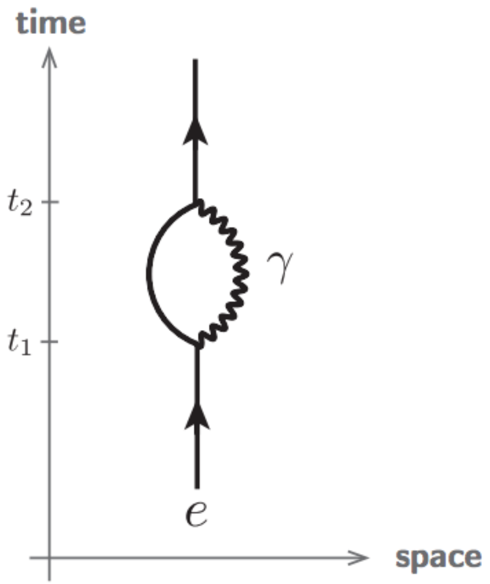
FNAL Users Meeting

June 10, 2015

The Standard Model is Incomplete

- What is dark matter?
- Why is the Higgs mass so light?
- Why is there more matter than anti-matter in the universe?





We can look for answers in high energy collisions.

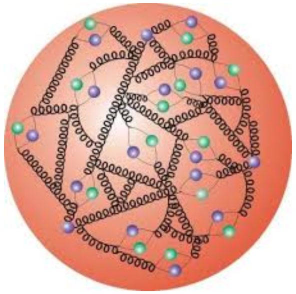
… or we can look for new particles in virtual loops!

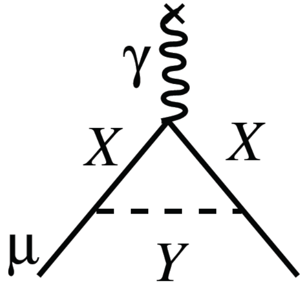
Anomalous Magnetic Dipole Moment

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

Dirac showed g = 2 for a point like spin ½ fermion.

Quark and gluon substructure reflected by proton g = 5.59





Structure may arise from virtual loops that encapsulate all possible interactions with an external field.

Anomalous Magnetic Dipole Moment

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

Why MUON a_μ?

τ

- \+ Sensitivity to new particles goes like M^2
- – Decays quickly ~10^{-13} seconds!
- – Small production cross-section

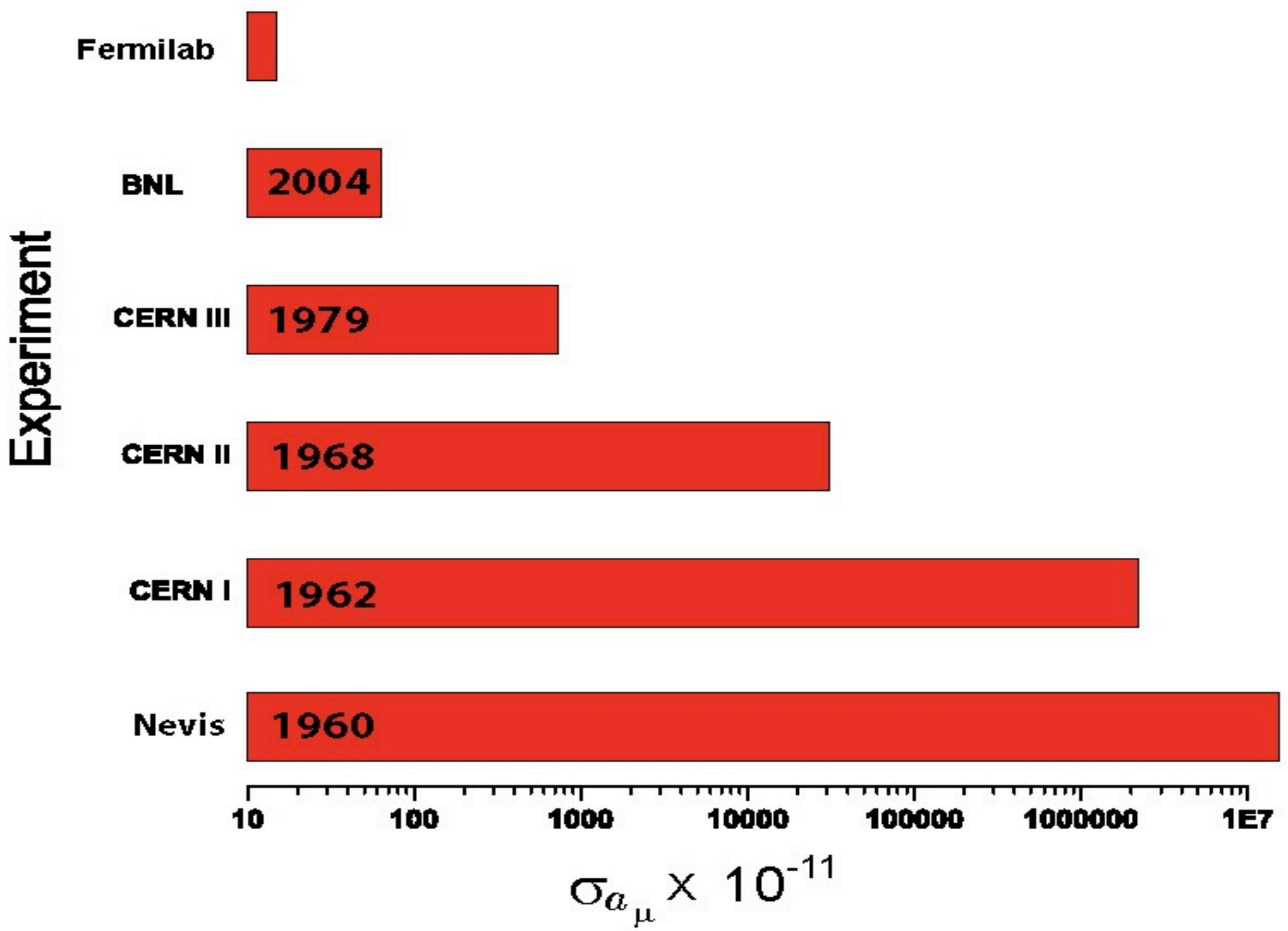
e

- \+ Abundant and stable
- \+ Measured to 240 parts per trillion!
- – Small mass means EW scale contributions are an order of magnitude smaller

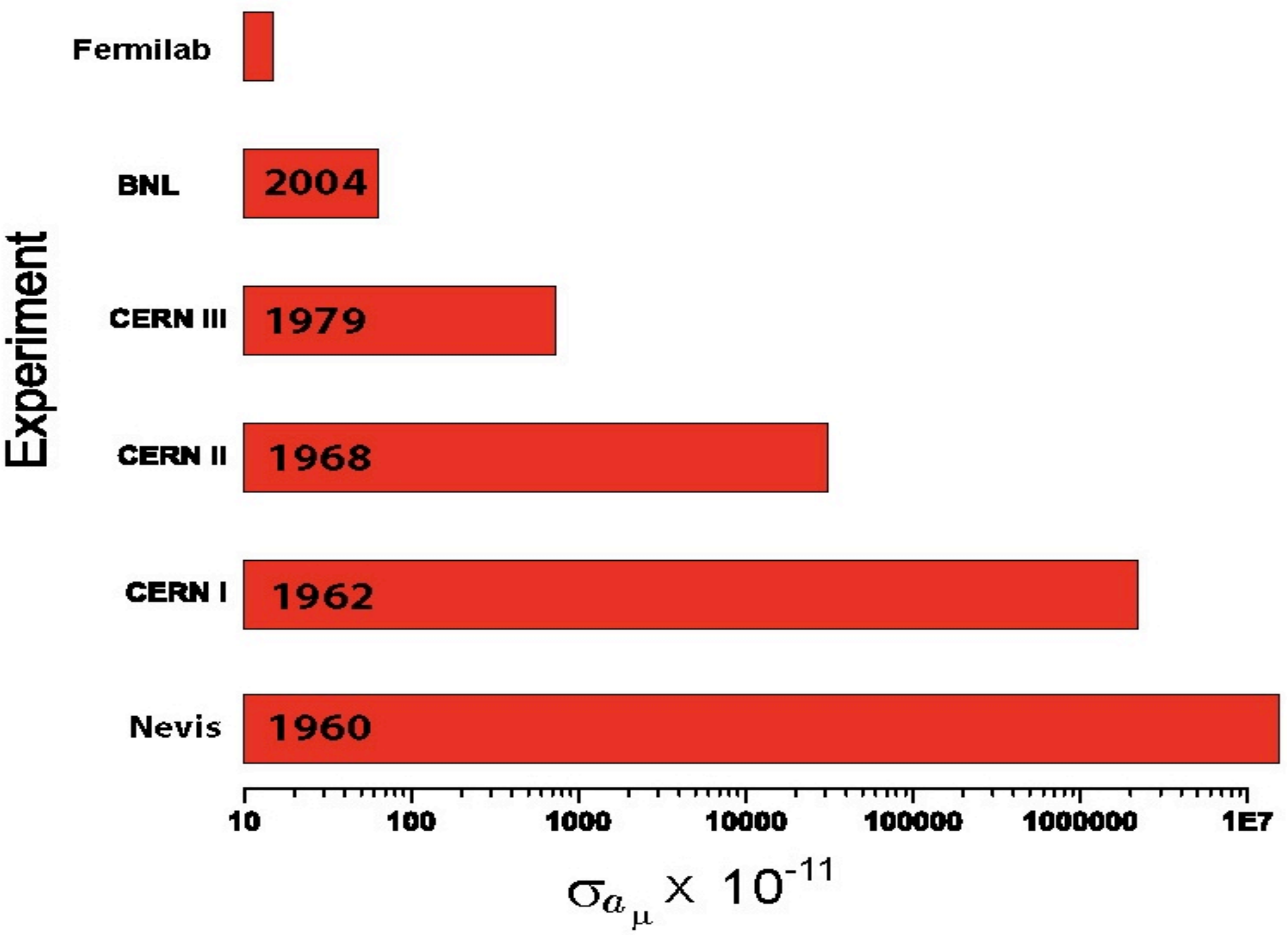
μ

- \+ Muon is a factor of 10^4 more sensitive than electron to new physics
- \+ Muon decays…
- \+ … but lifetime is ~10^{-6} seconds!

History of a_μ measurements



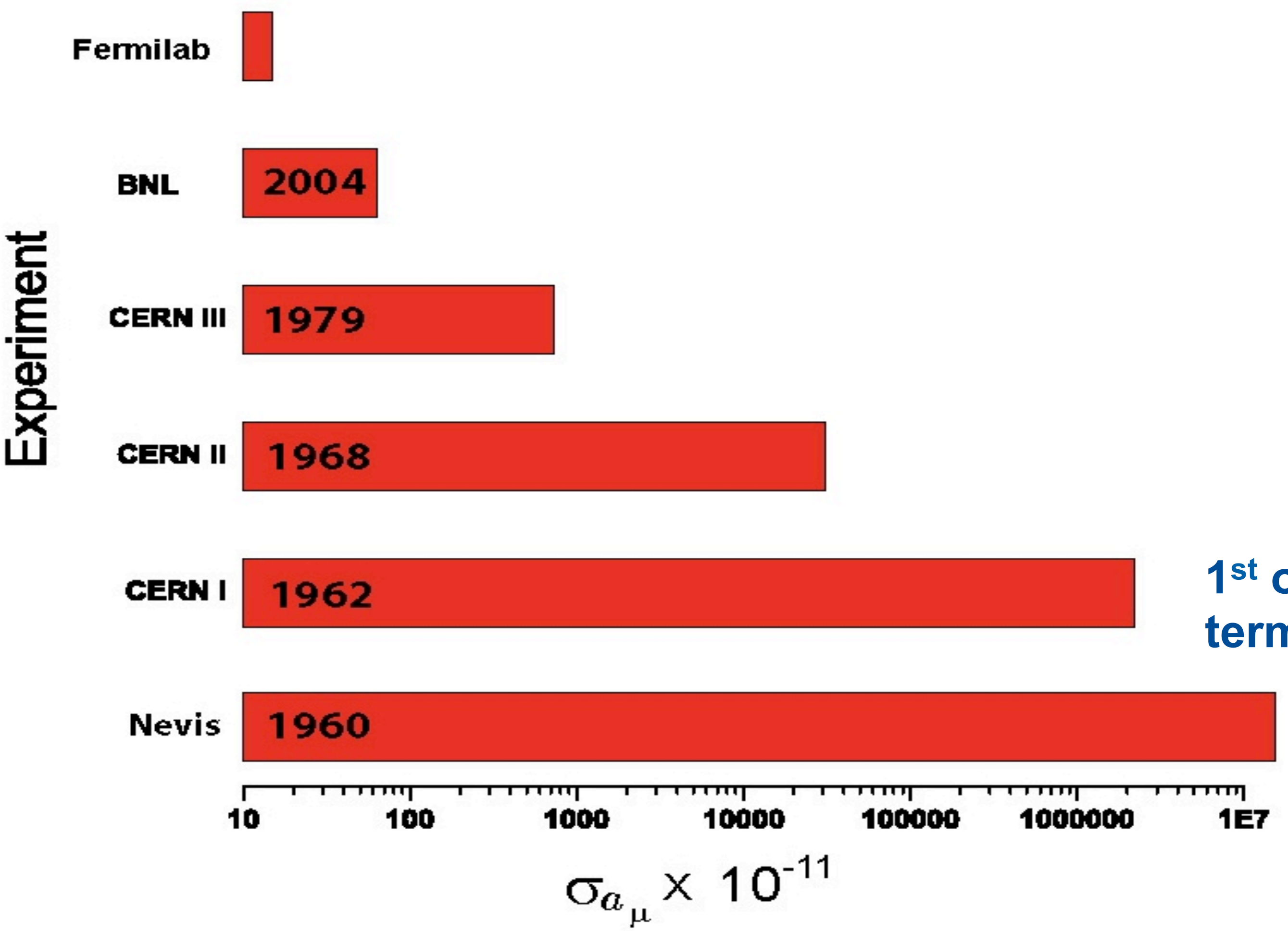
History of a_μ measurements



1^{st} experiment in 1957 determined

g = 2.00 ± 0.10!

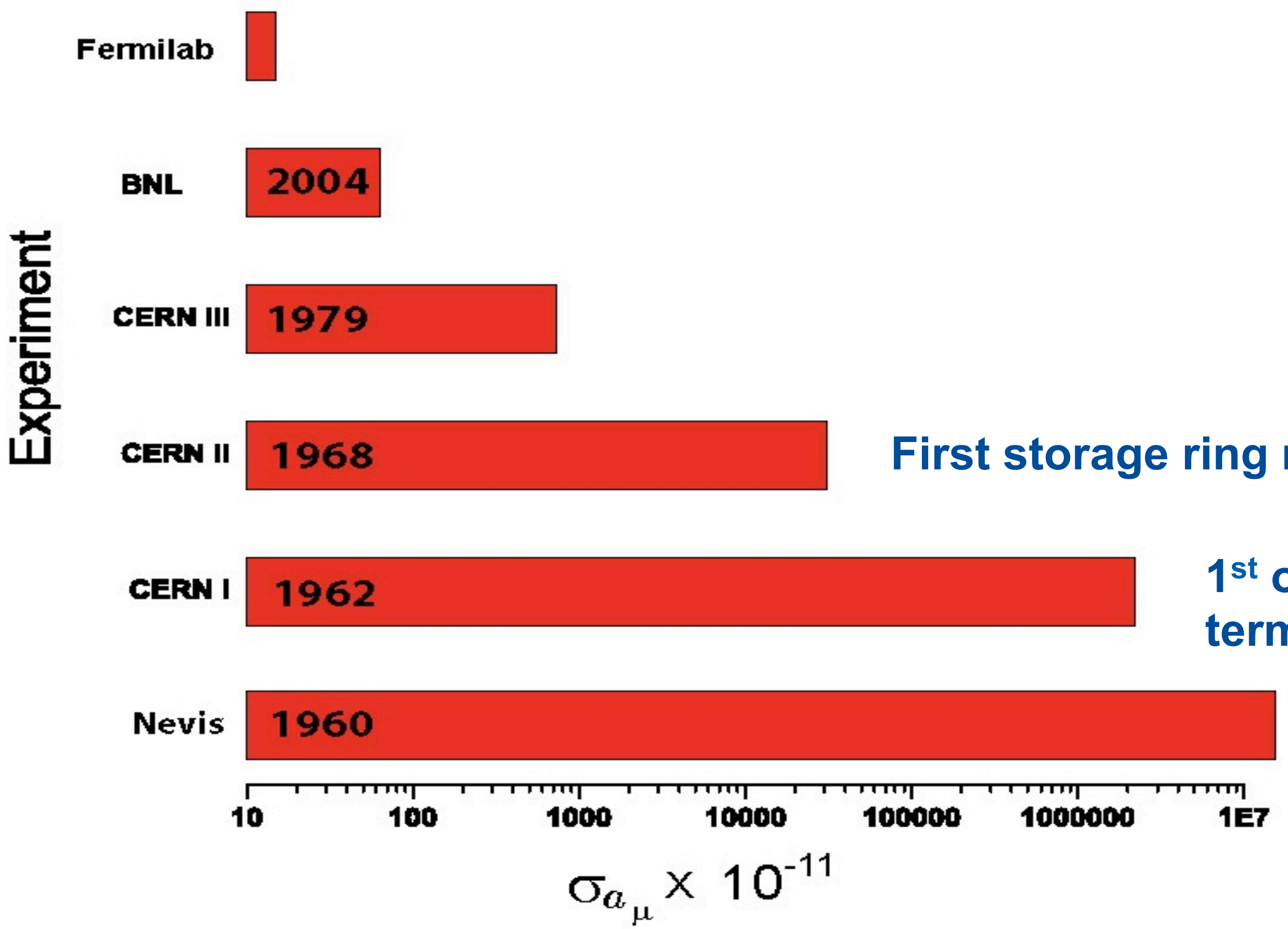
History of a_μ measurements



1[st] observation of $(\alpha/2\pi)^2$ term in QED expansion

1[st] experiment in 1957 determined
g = 2.00 ± 0.10!

History of a_μ measurements

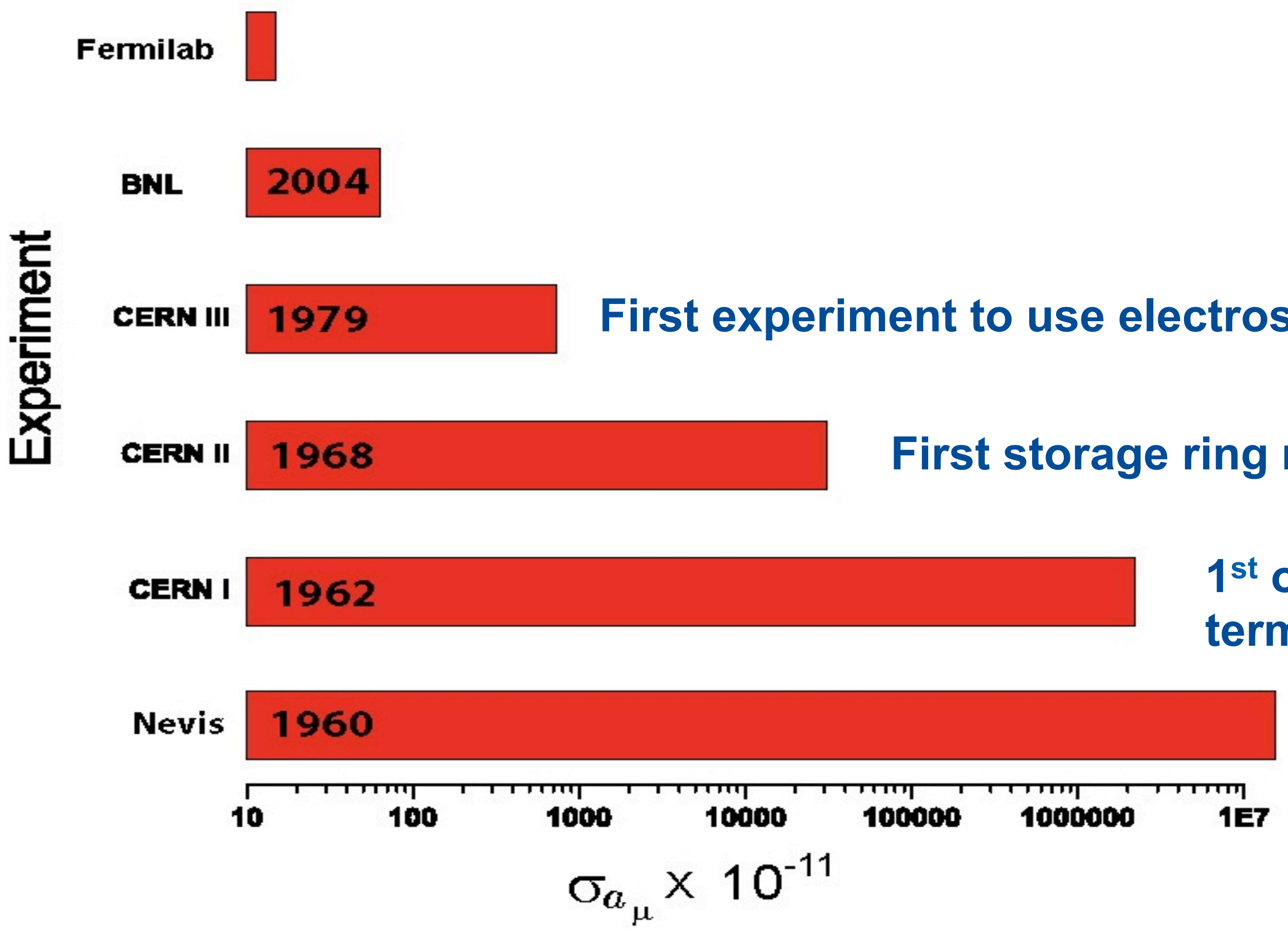


First storage ring measurement

1st observation of $(\alpha/2\pi)^2$ term in QED expansion

1st experiment in 1957 determined **g = 2.00 ± 0.10!**

History of a_μ measurements



First experiment to use electrostatic focusing

First storage ring measurement

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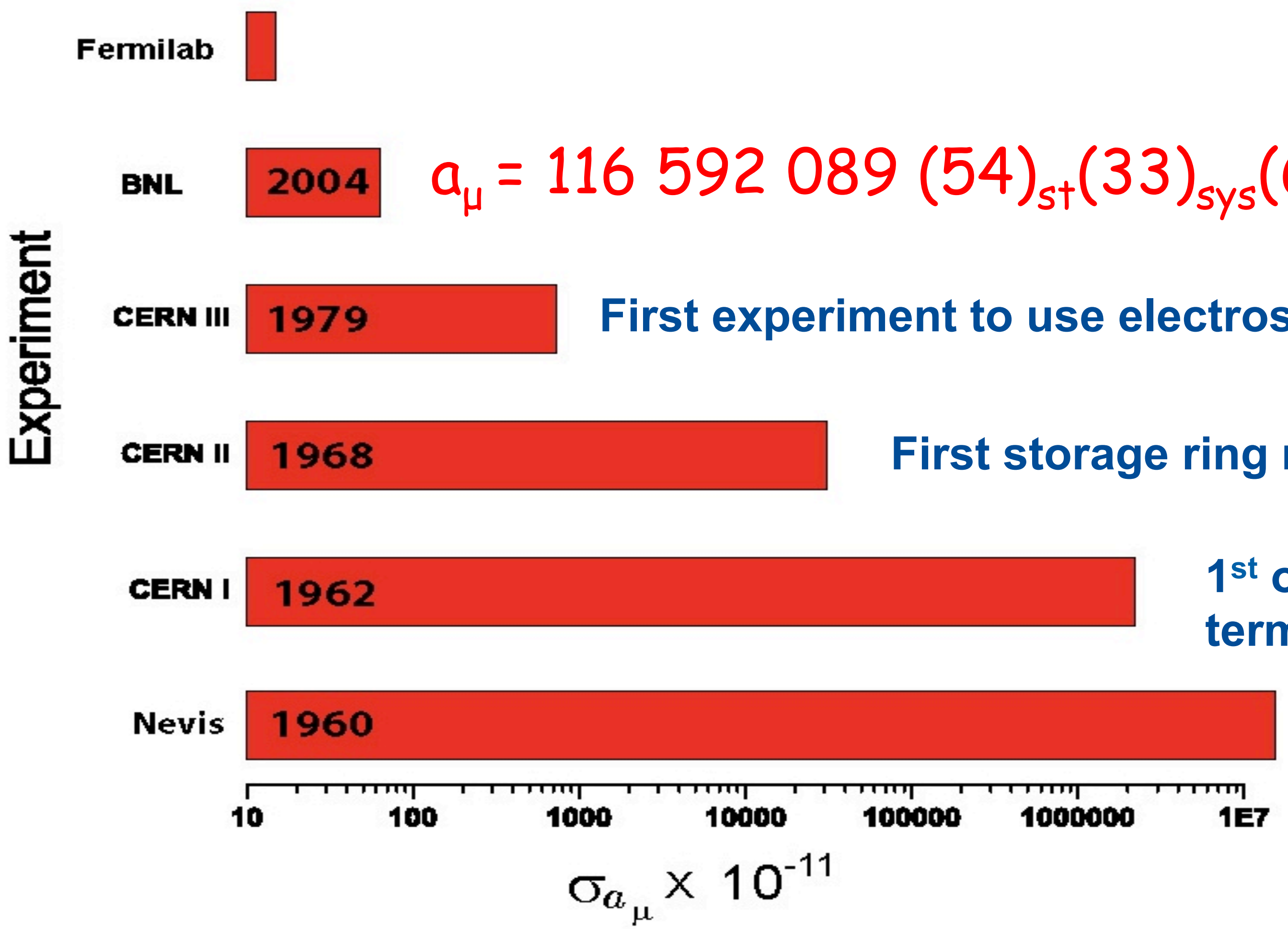
History of a_μ measurements



$a_\mu = 116\ 592\ 089\ (54)_{st}(33)_{sys}(63)_{tot} \times 10^{-11}$

First experiment to use electrostatic focusing

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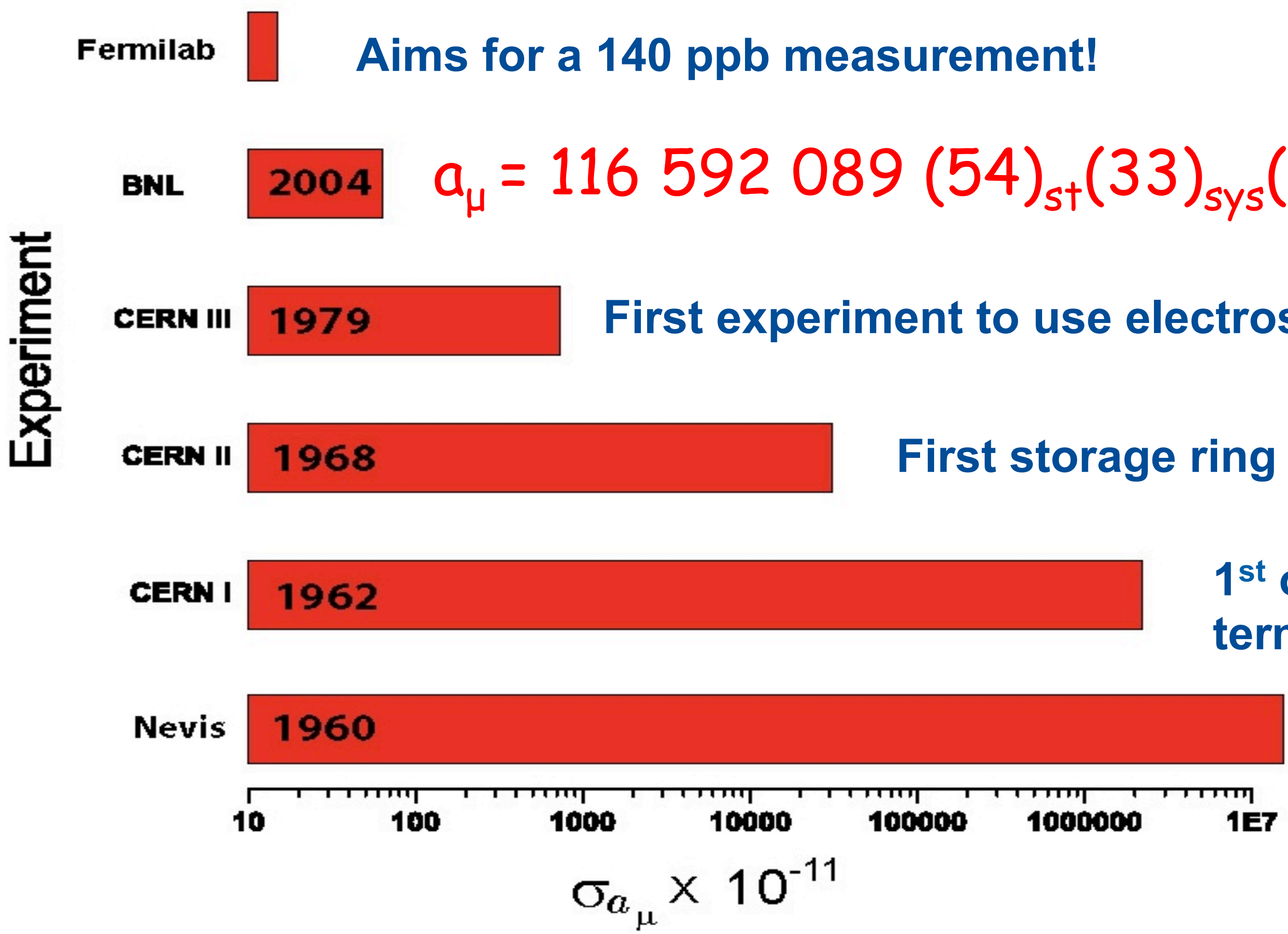
$g = 2.00 \pm 0.10$!

History of a_μ measurements



Aims for a 140 ppb measurement!

$a_\mu = 116\,592\,089\,(54)_{st}(33)_{sys}(63)_{tot} \times 10^{-11}$

First experiment to use electrostatic focusing

First storage ring measurement

1st observation of $(\alpha/2\pi)^2$ term in QED expansion

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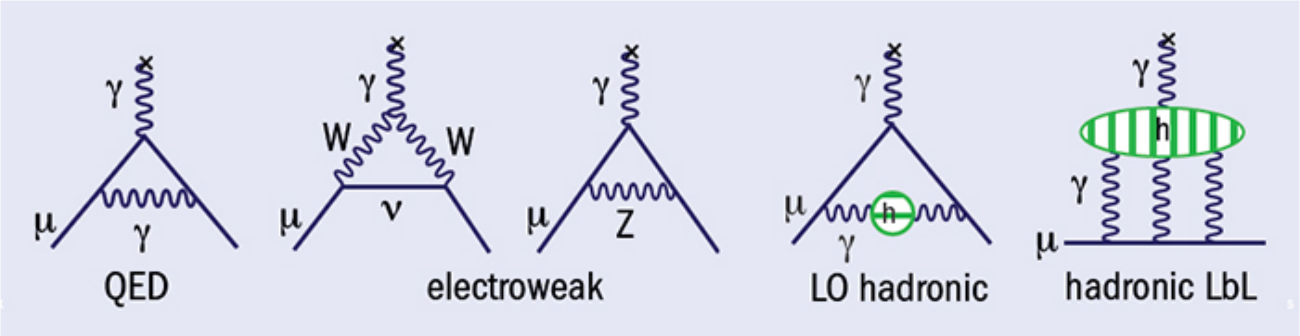
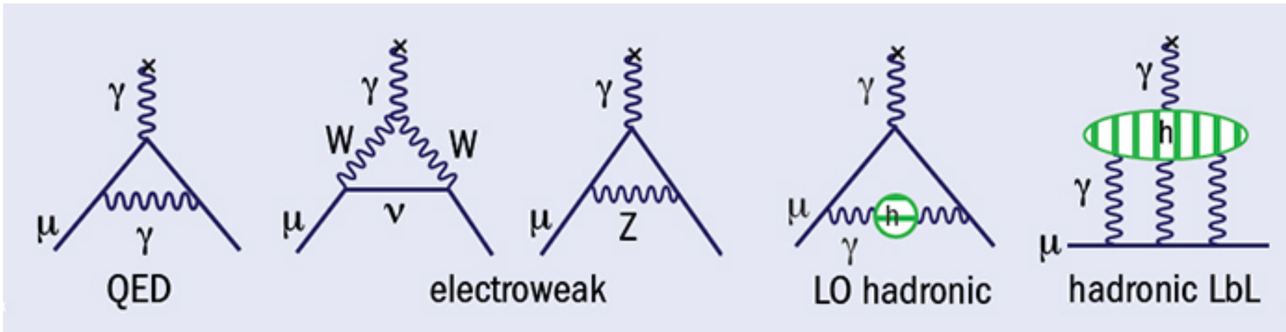
Standard Model Theory Predictions



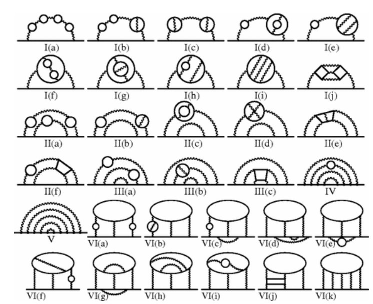
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

Standard Model Theory Predictions: QED



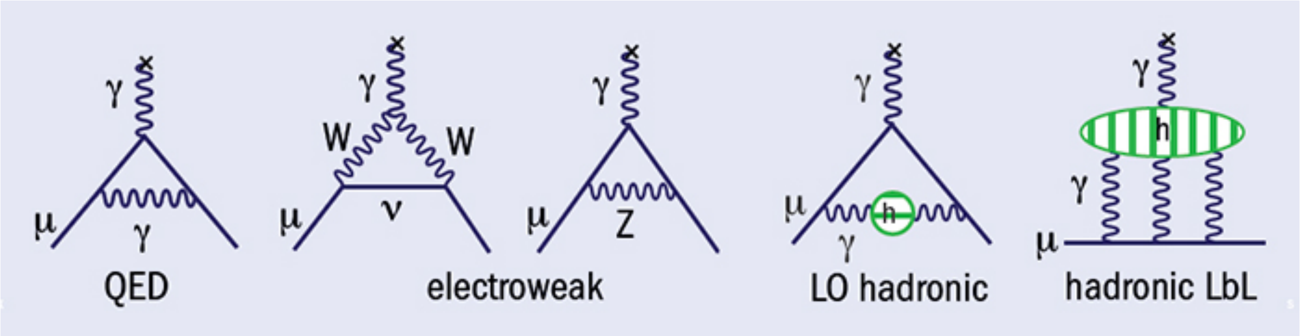
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

- Includes all photonic and leptonic loops
- Largest contribution from LO Schwinger term
- Calculated to five loops *Phys. Rev. Lett. 109 (2012) 111808.*



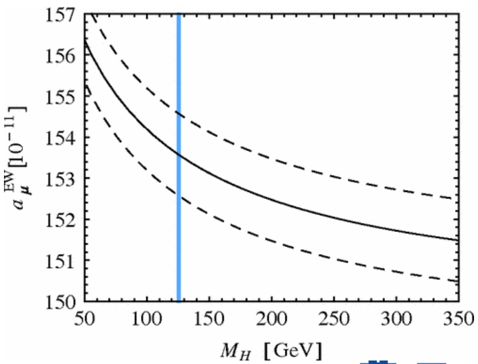
Fermilab

Standard Model Theory Predictions: QED

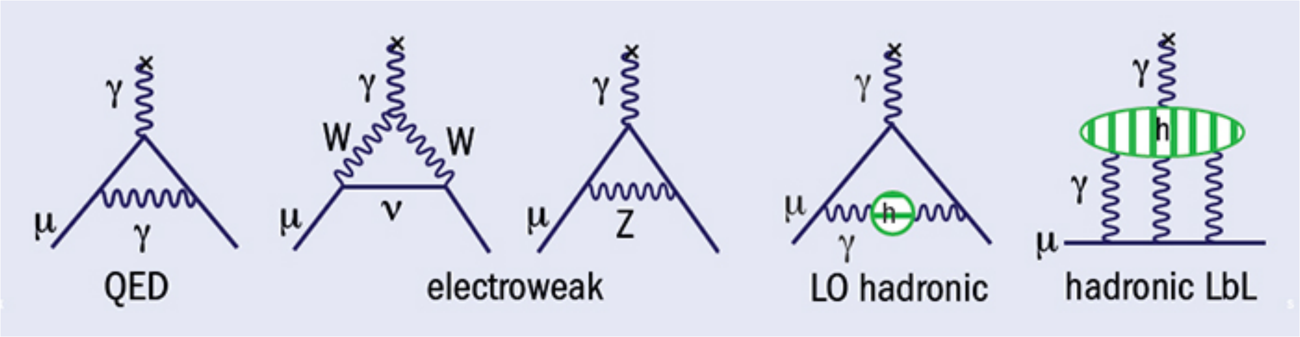


$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

- Includes all $W^{+/-}$, Z or Higgs loops.
- Calculated to two loops and re-evaluated using the LHC value of the Higgs mass *Phys.Rev.D 88, 053005 2013*

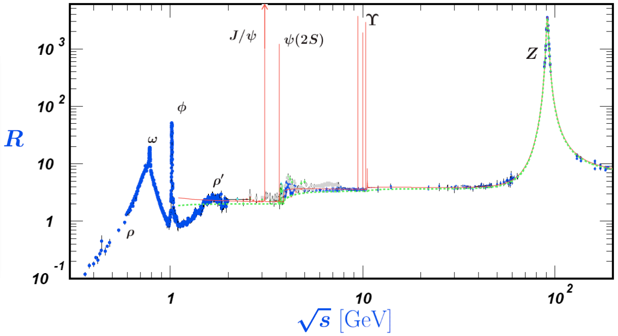


Standard Model Theory Predictions: Hadronic



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

- Includes quark and gluon loops
- Dominant source of theoretical error
- Relies on dispersion relationships and hadronic models *Eur.Phys.J. C71 (2011) 1515, Erratum-ibid. C72 (2012) 1874, J. Phys. G38 (2011) 085003*



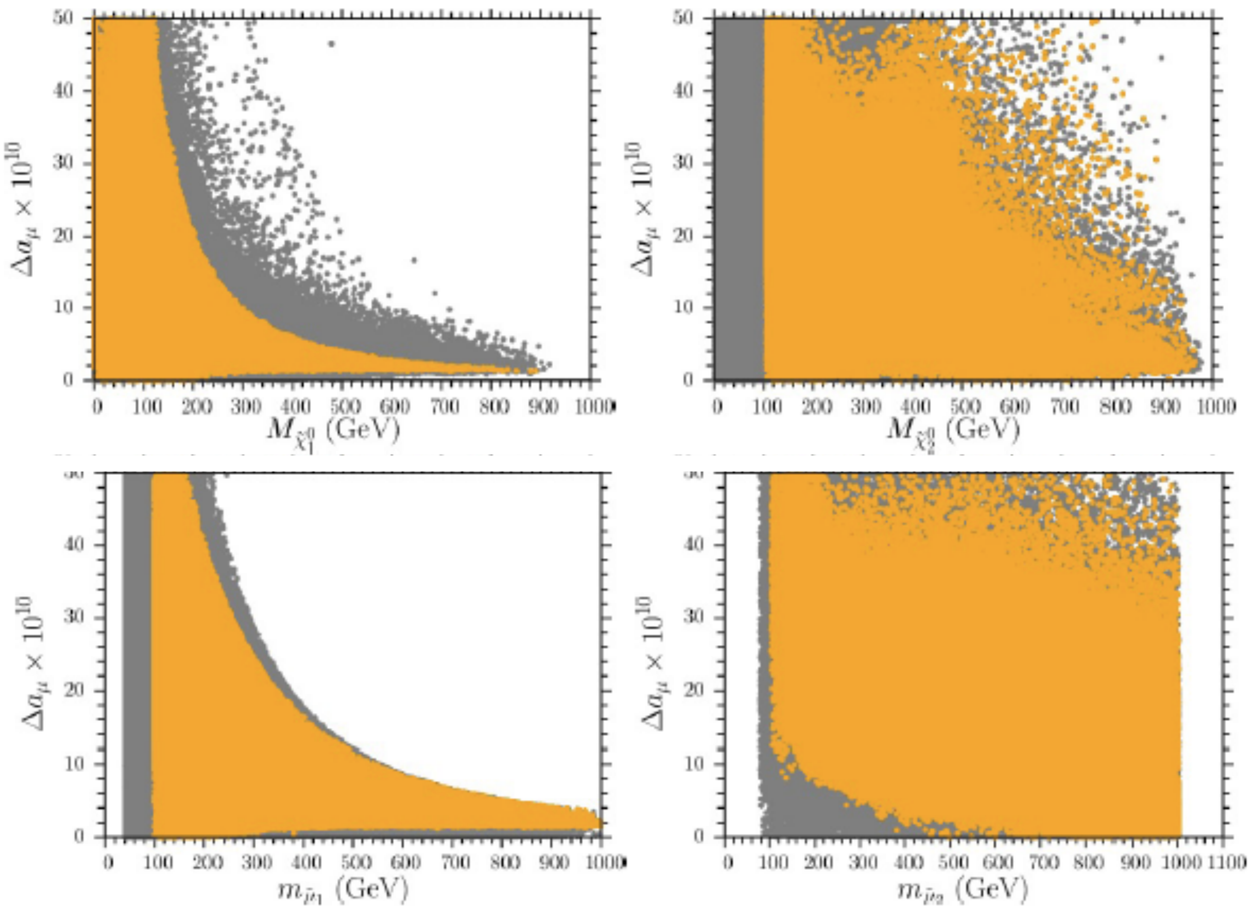
Experiment – Theory Comparison

Contribution	a_μ Result x 10^{-11}	
QED	116 584 718.951 ± 0.080	Smallest
EW	153.6 ± 1	
HVP (LO)	6 949 ± 43	Largest
HVP (NLO)	-98.4 ± 1	
HLbL	105 ± 26	
SM	116 591 828 ± 50	
Exp-SM	261 ± 80	3.3σ

Improvements in theory alone are expected to decrease error on (Exp – SM) by factor of 2!

SUSY Parameter Space still allowed by LHC and a_μ

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



For tan(β) = 10 the lightest neutralinos are restricted to be < 300/900 GeV

For tan(β) = 10 the smuon is required to be < 300 GeV

Ajaib, Dutta, Ghosh, Gogoladze, Shafi arXiv:1505.05896v1

Making the measurement : Big Picture

- Store longitudinally polarized muons with momentum 3.09 GeV/c in a magnetic dipole field B.

- Measure anomalous precession frequency ω_a

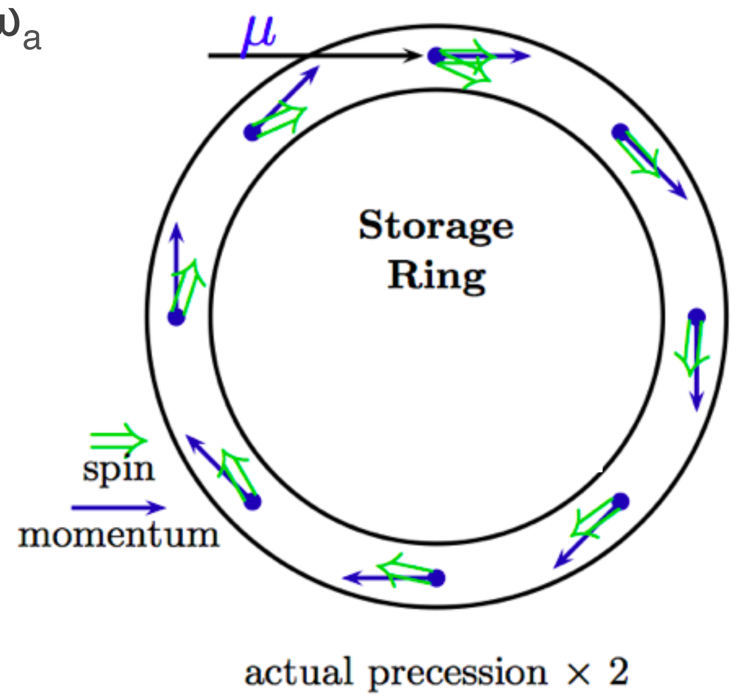
$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e}{mc} B$$

Spin Precession Frequency

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

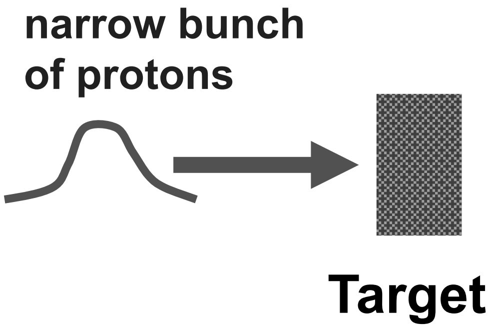
Cyclotron Frequency

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



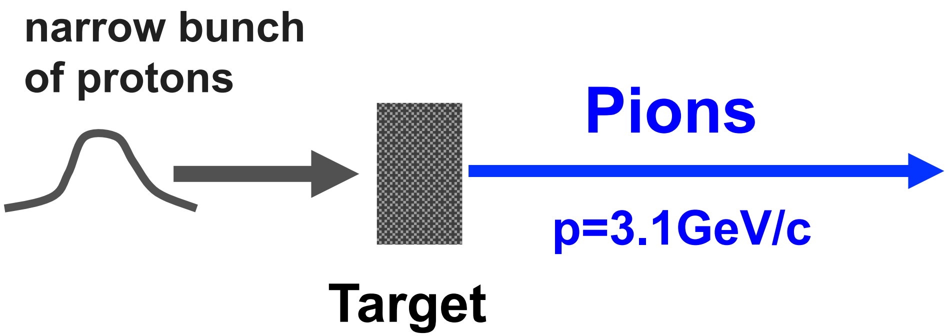
- Measure the magnetic field **B** seen by the muons

Making the measurement : Muon production



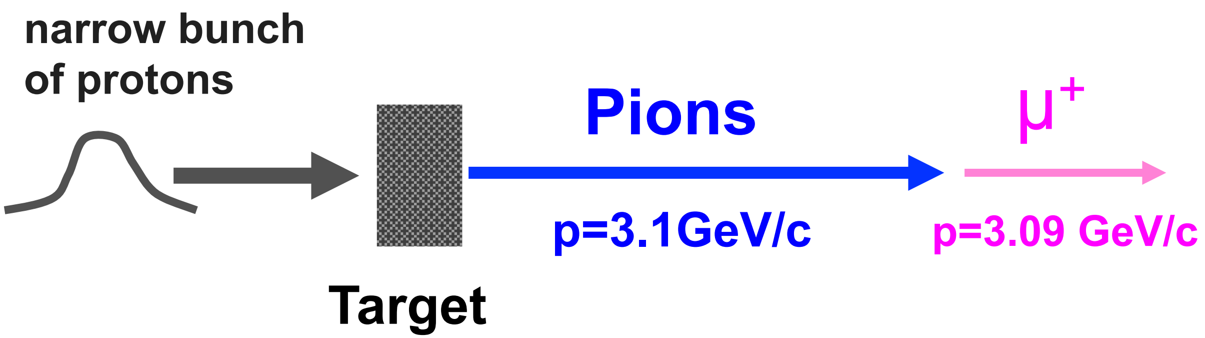
120 ns wide bunch of protons from 8 GeV Booster collide with target used for Tevatron Run-II anti-proton production.

Making the measurement : Muon production



Pions with p = 3.11 GeV/c
are collected from target
and sent to beamline.

Making the measurement : Muon production

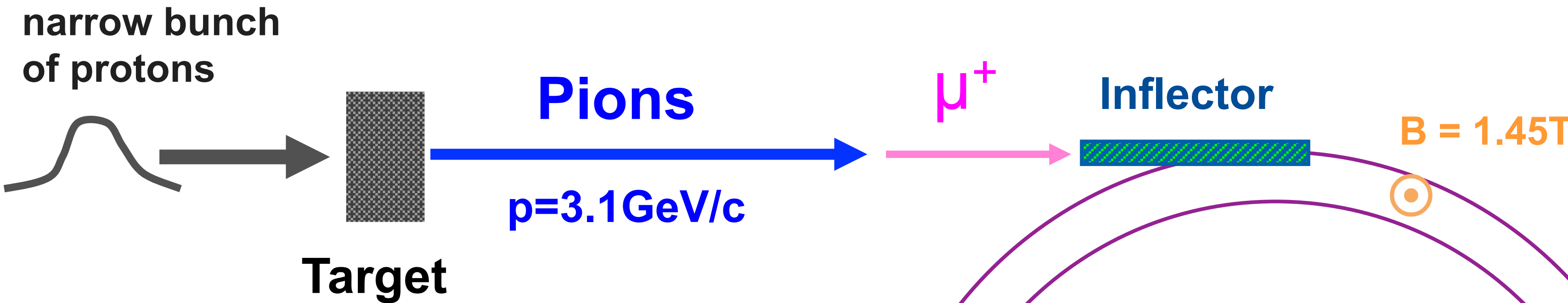


Pions decay into left-handed μ^+

$$\pi^+ \rightarrow \mu^+ + \upsilon_\mu$$

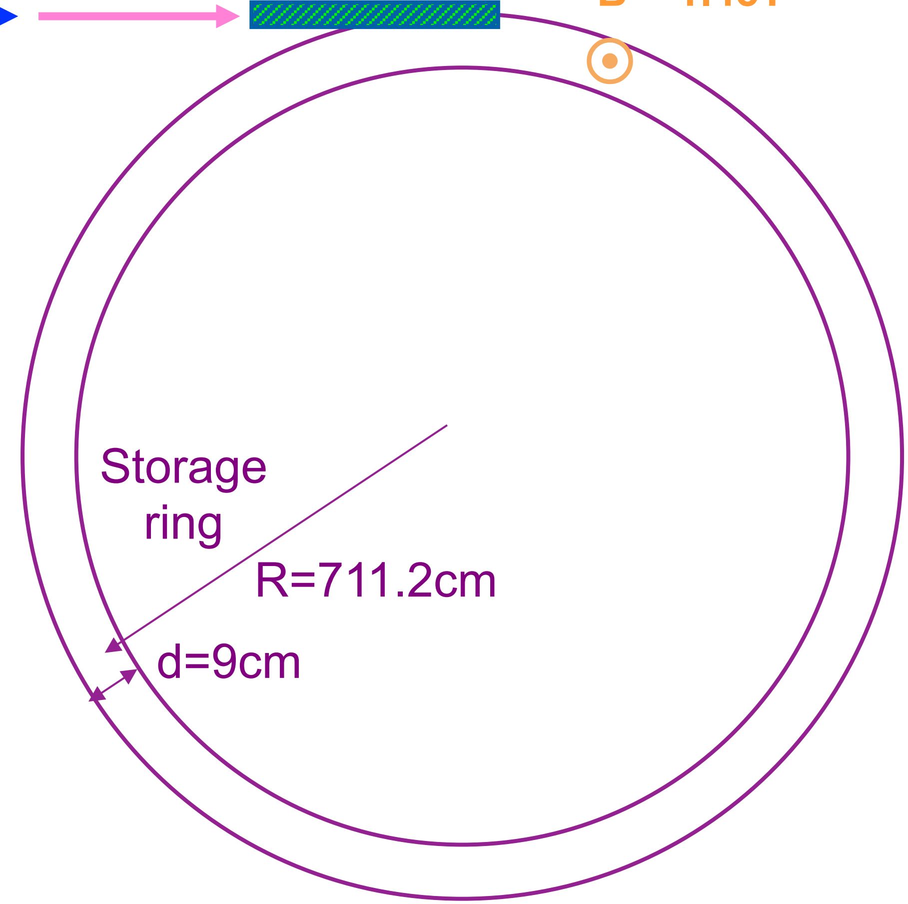
Create ~90% polarized beam by selecting highest energy μ^+

Making the measurement : Ring

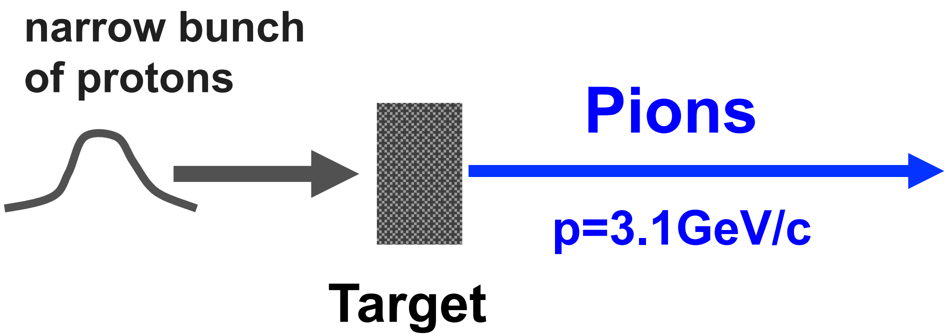


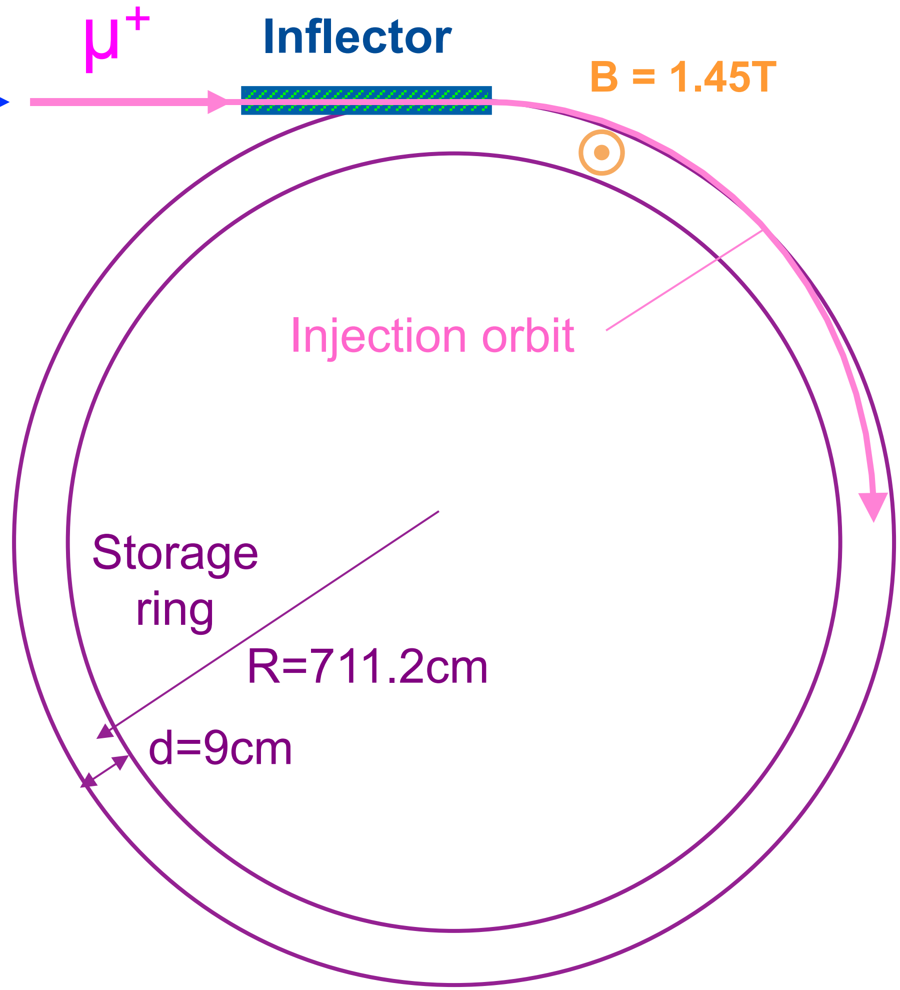
Muon storage ring

- Three superconducting coils provide 1.45 T field
- Vacuum chamber reduces particle interactions

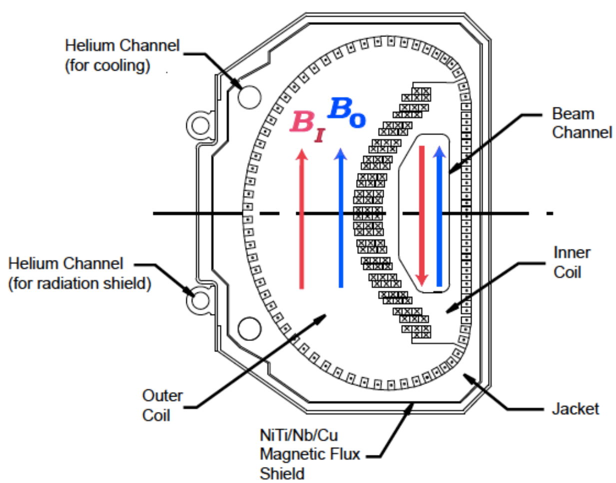


Making the measurement : Inflector

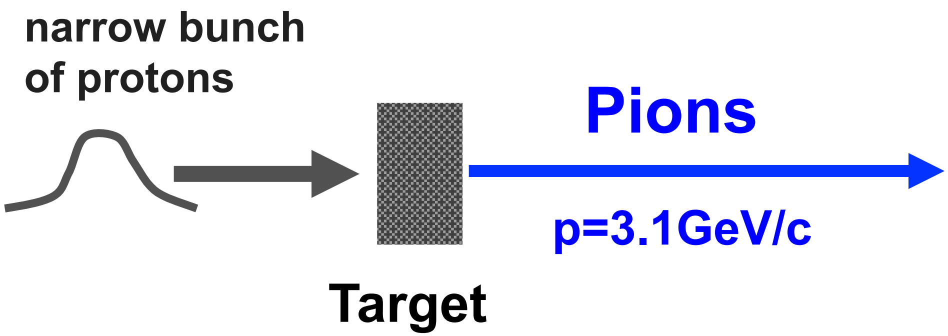


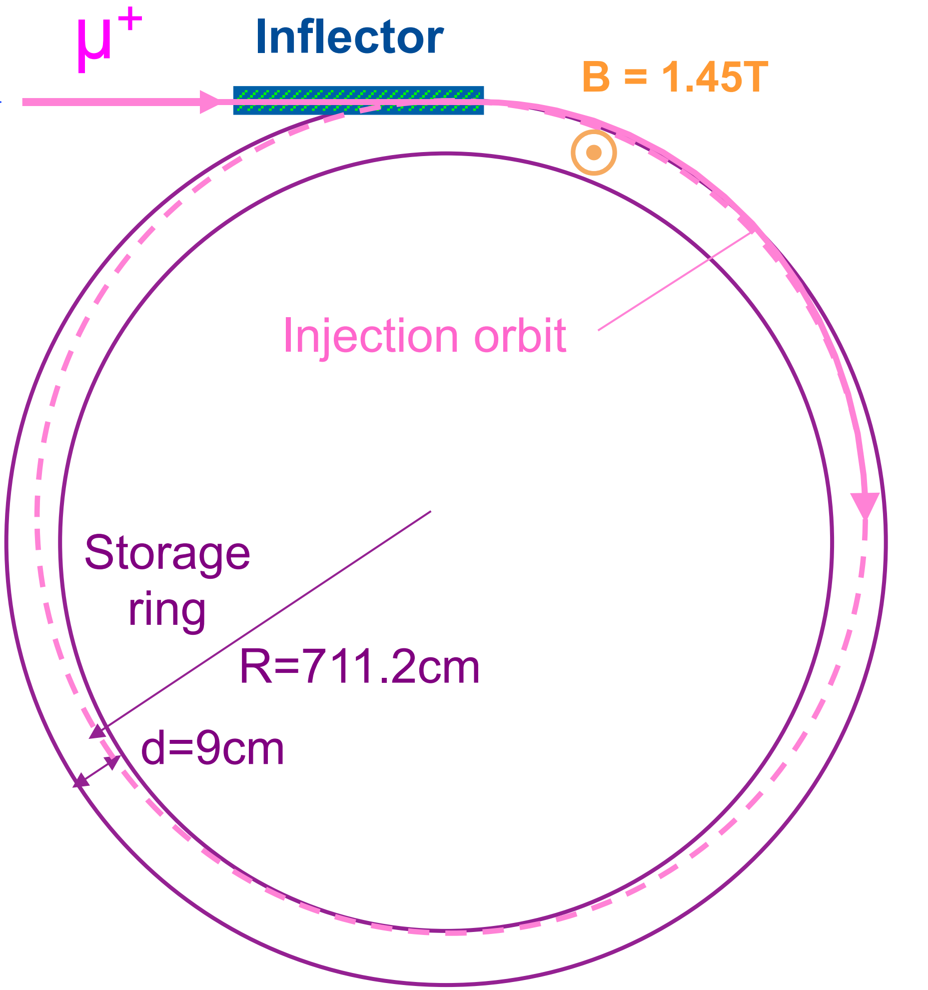


Inflector magnet provides a nearly field free region for muons to enter the ring.



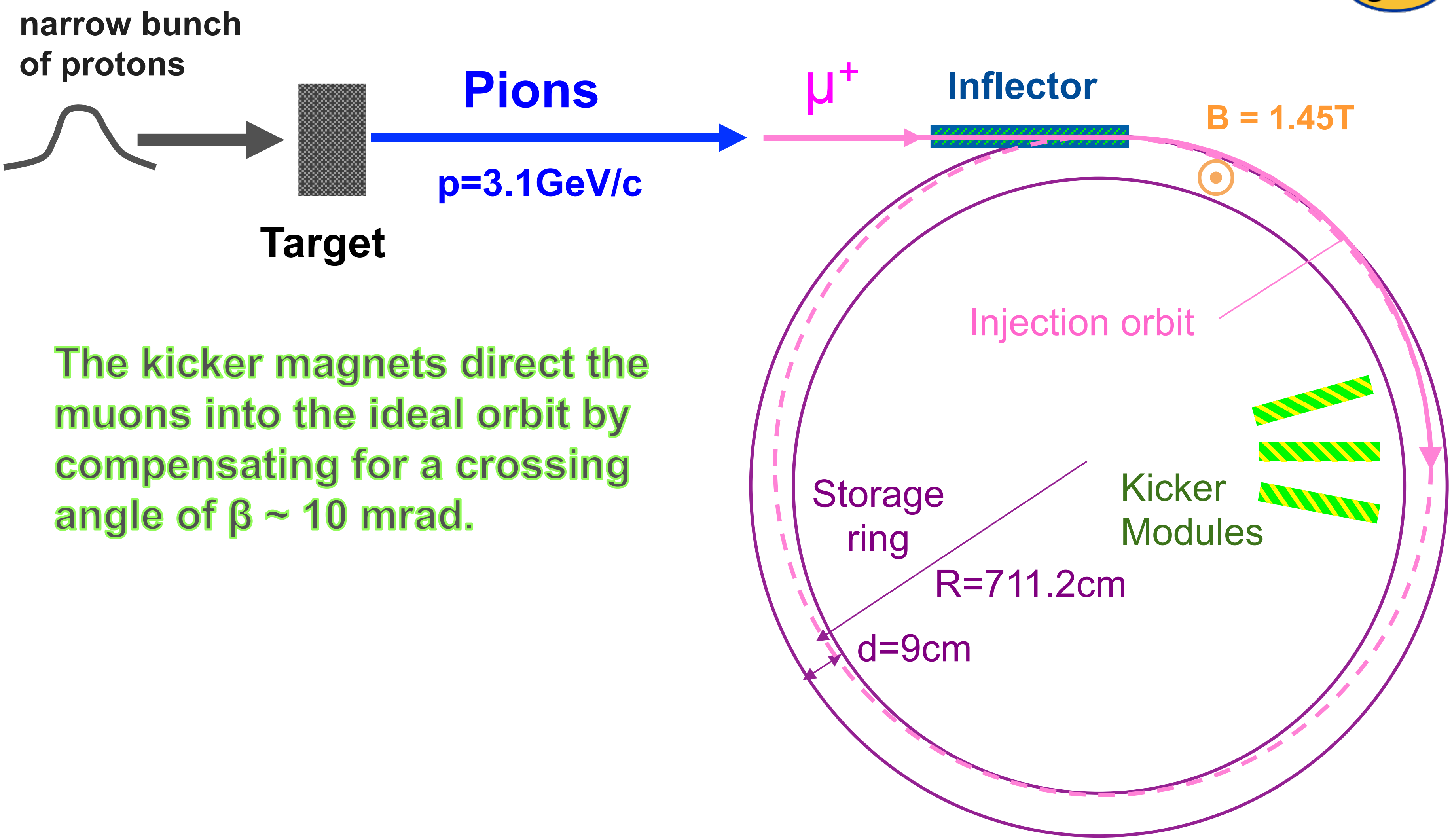
Making the measurement : Injection





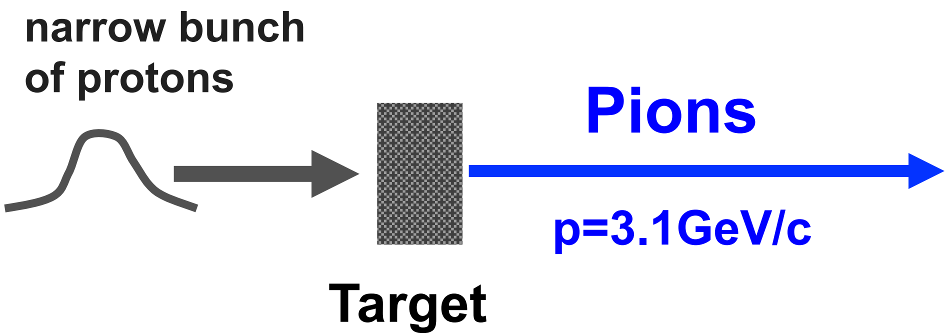
Injection orbit steers muons back into the inflector. Need to put muons into stable orbit.

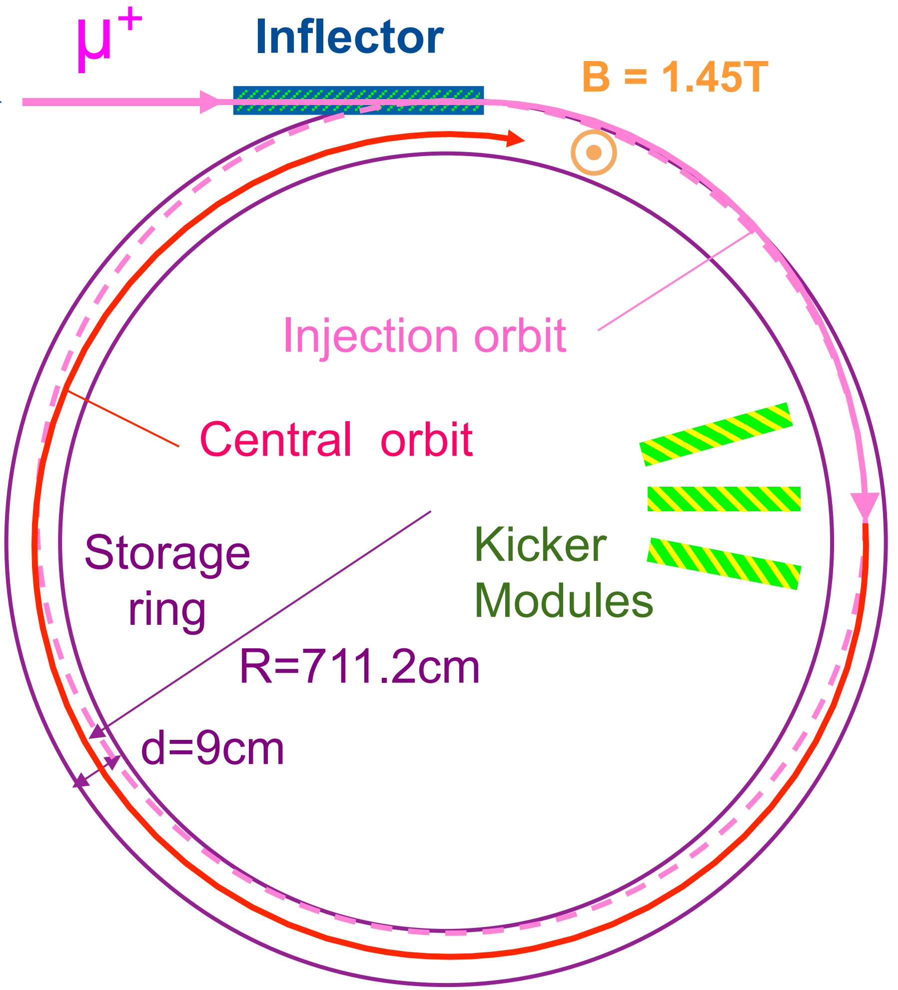
Making the measurement : Kickers



The kicker magnets direct the muons into the ideal orbit by compensating for a crossing angle of β ~ 10 mrad.

Making the measurement : Central Orbit





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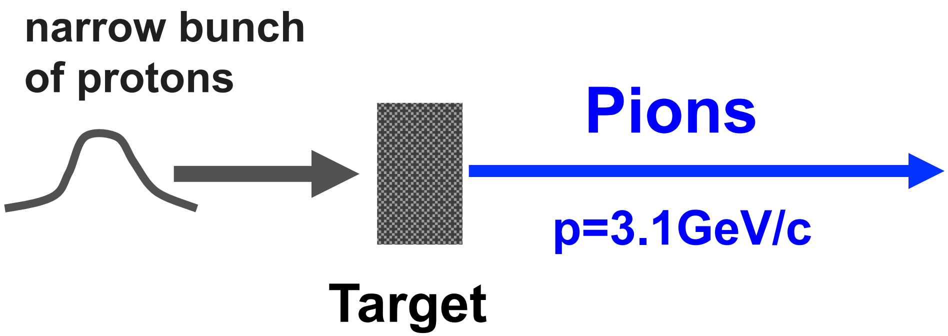
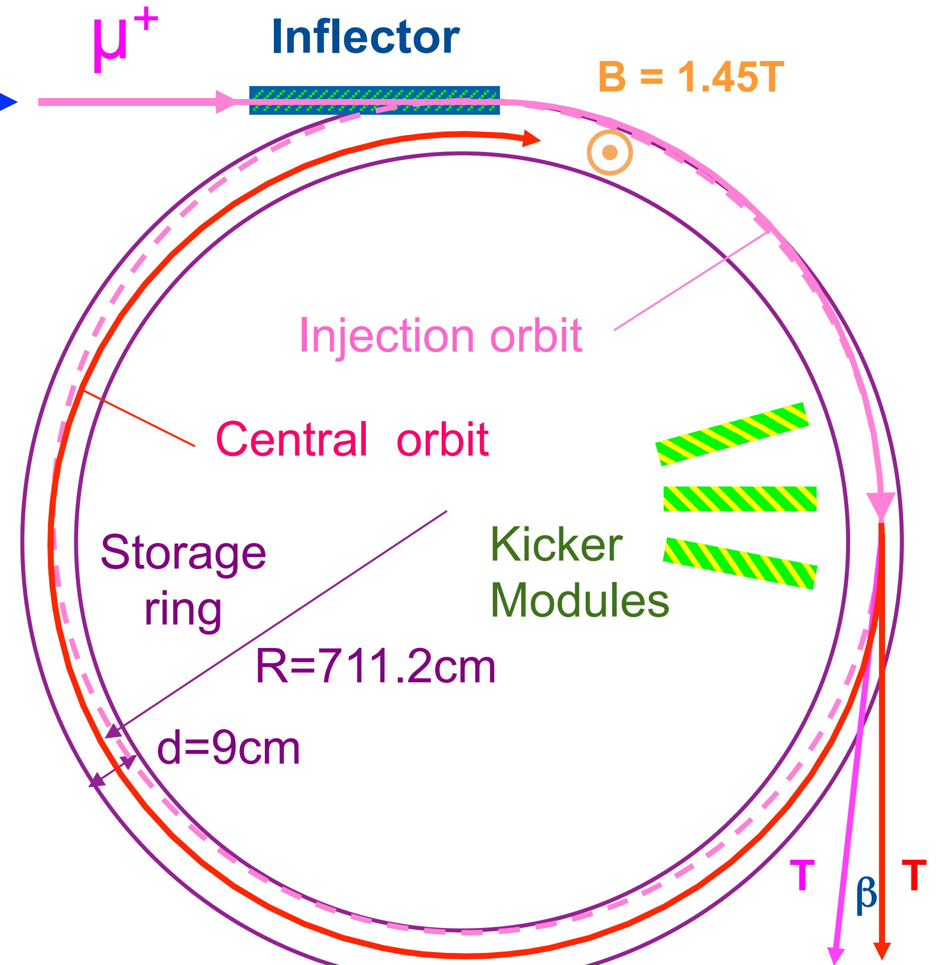
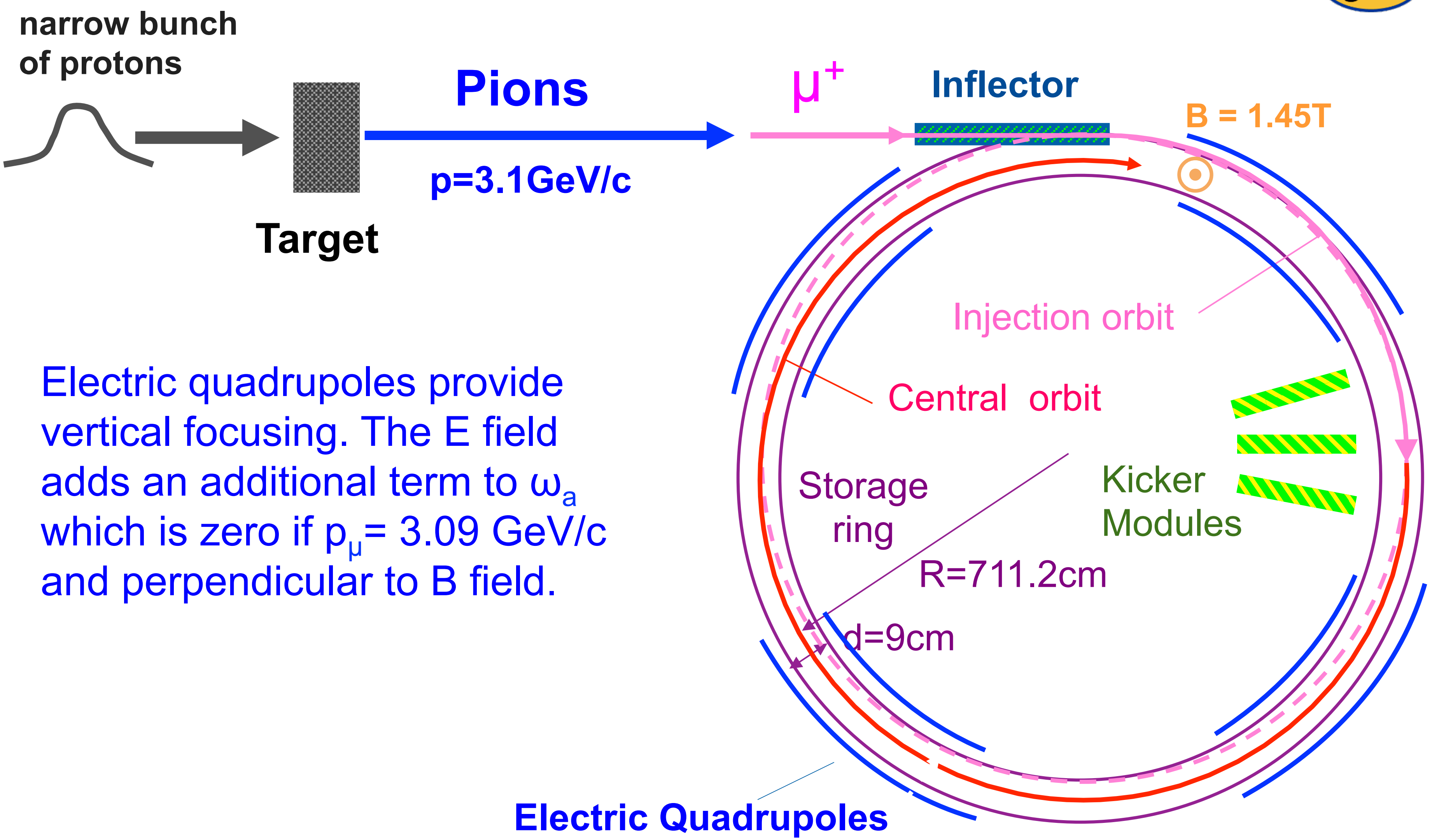




The kicker magnets direct the muons into the ideal orbit by compensating for a crossing angle of β ~ 10 mrad.

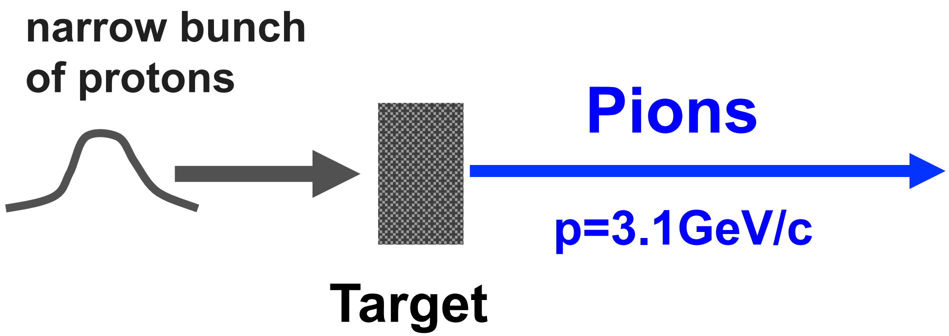
The kicker pulse should be shorter than 149 ns, the cyclotron period.

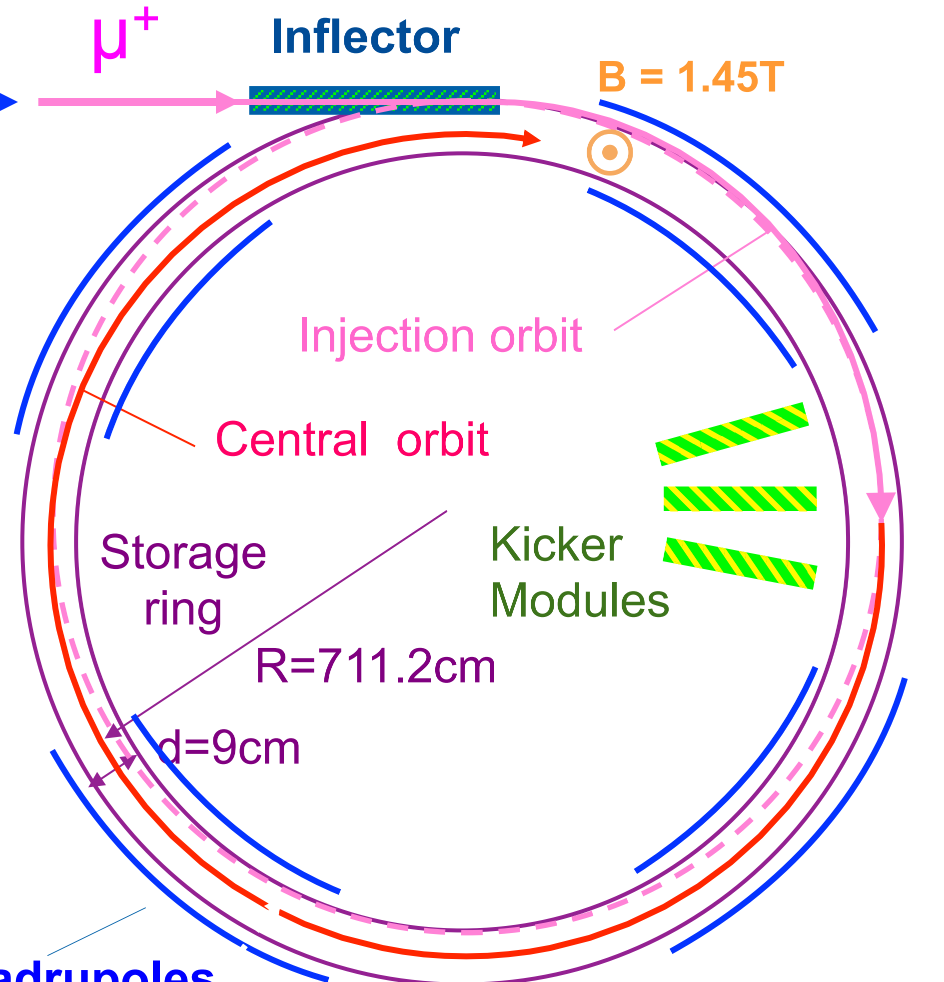
Making the measurement : Quadrupoles

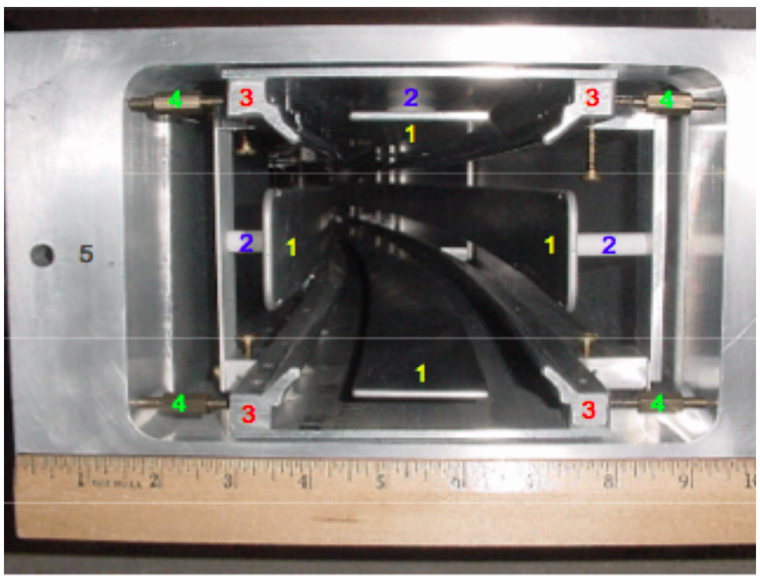


Electric quadrupoles provide vertical focusing. The E field adds an additional term to ω_a which is zero if p_μ= 3.09 GeV/c and perpendicular to B field.

Making the measurement : Quadrupoles



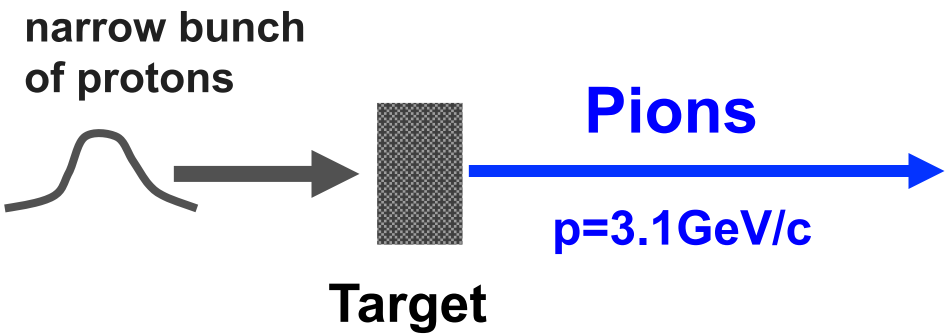


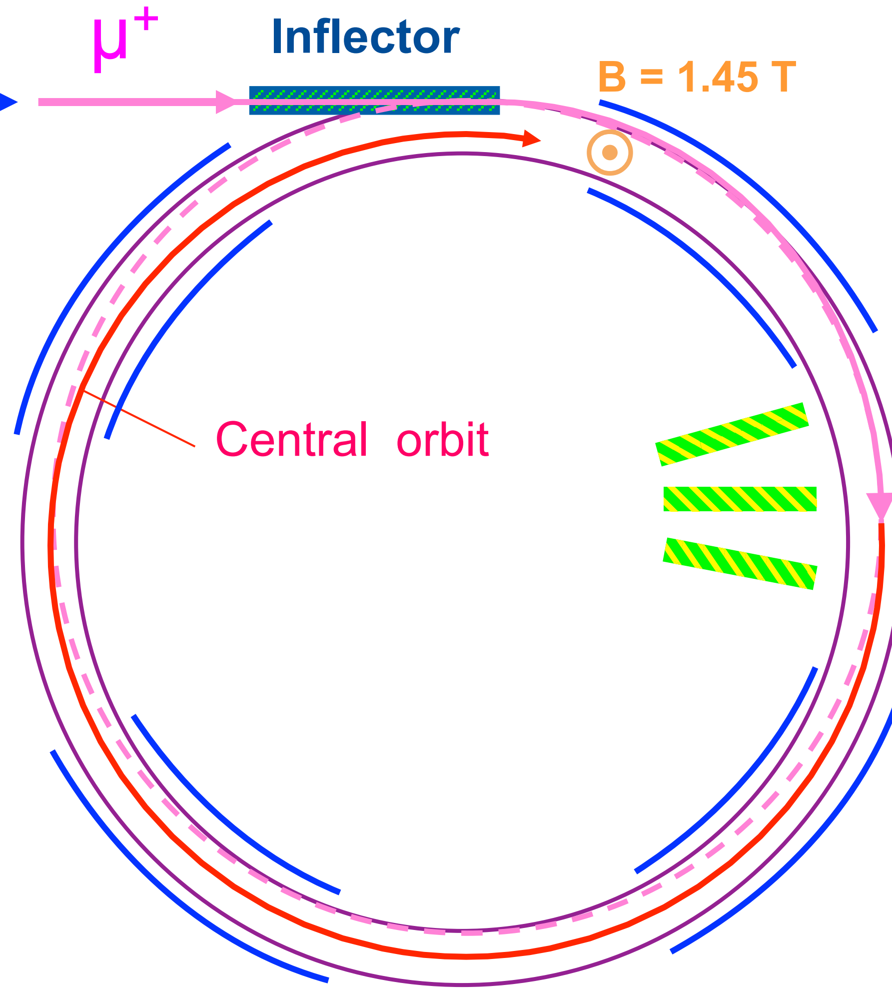


(1) plates, (2) HV standoffs, (3) trolley rails, (4) adjustment screws, (5) vacuum chamber

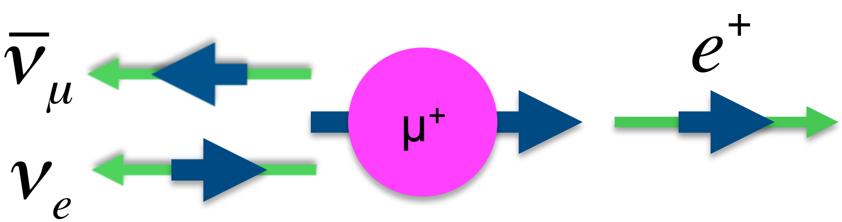
Electric Quadrupoles

Making the measurement : Muon Decay

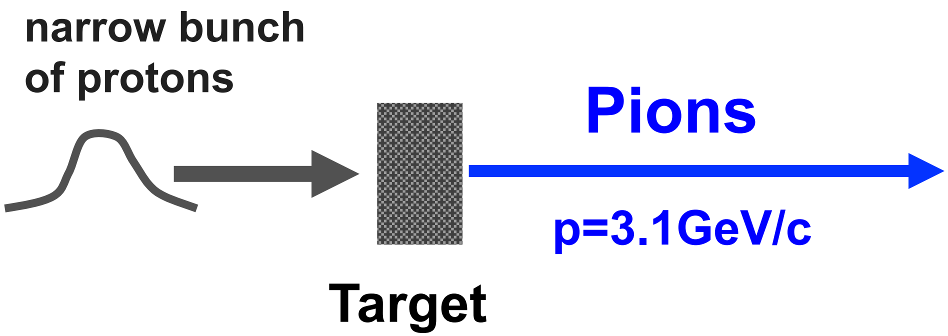


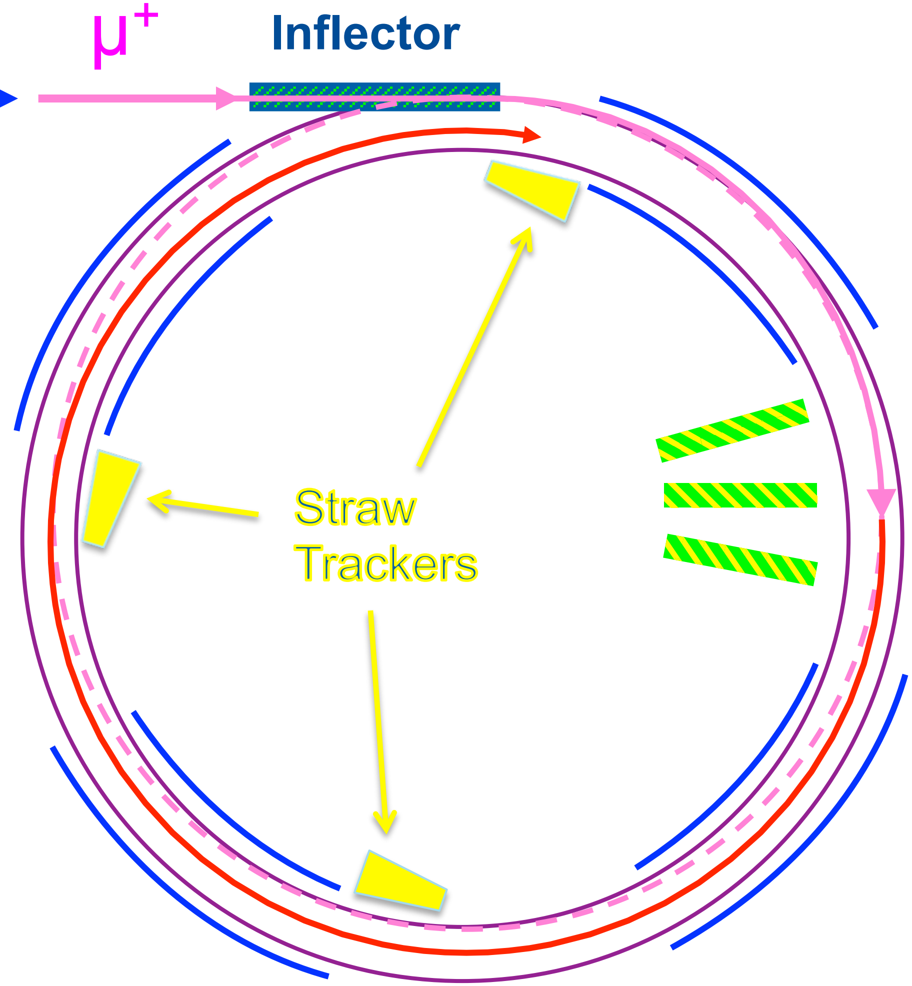


In μ^+ decay the highest energy e^+ are emitted parallel to the μ^+ spin

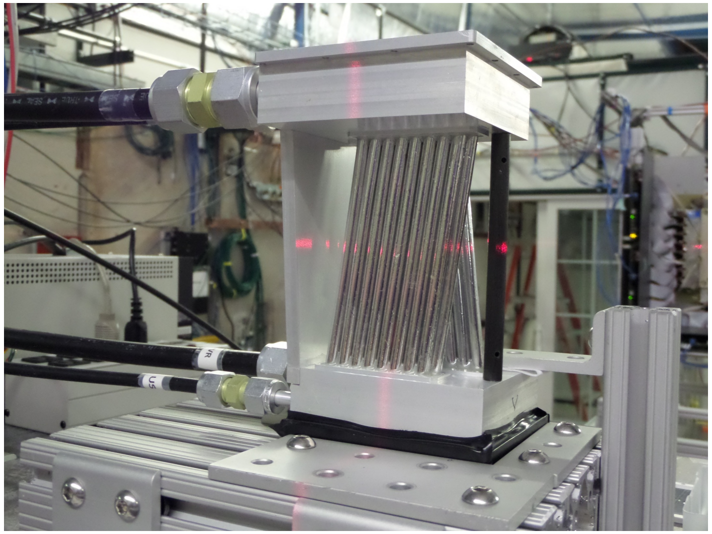


Making the measurement : Straw trackers

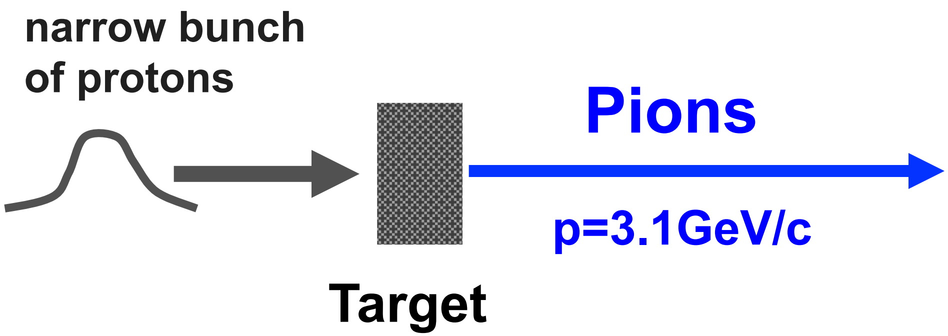


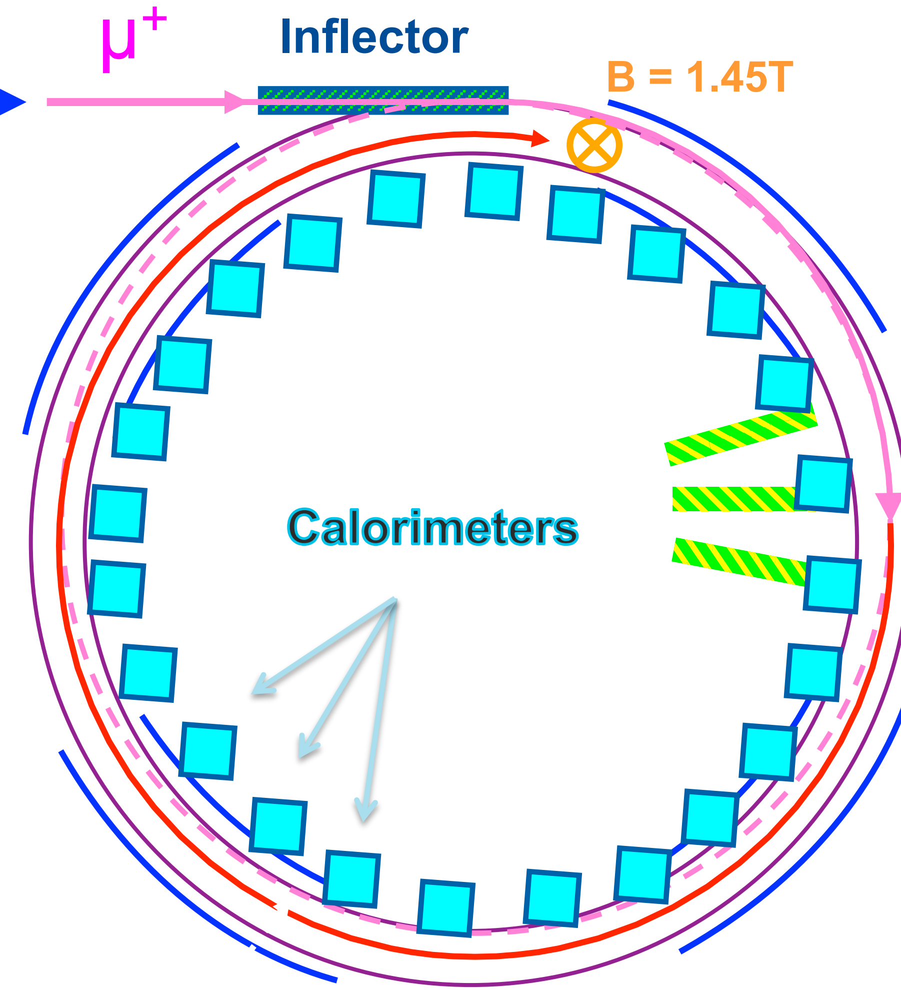


Straw trackers measure the vertical and radial profile of the muon beam to < 1 cm



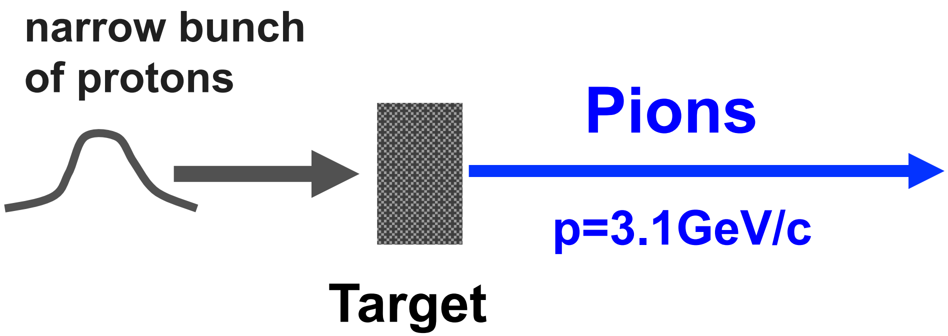
Making the measurement : Calorimeters

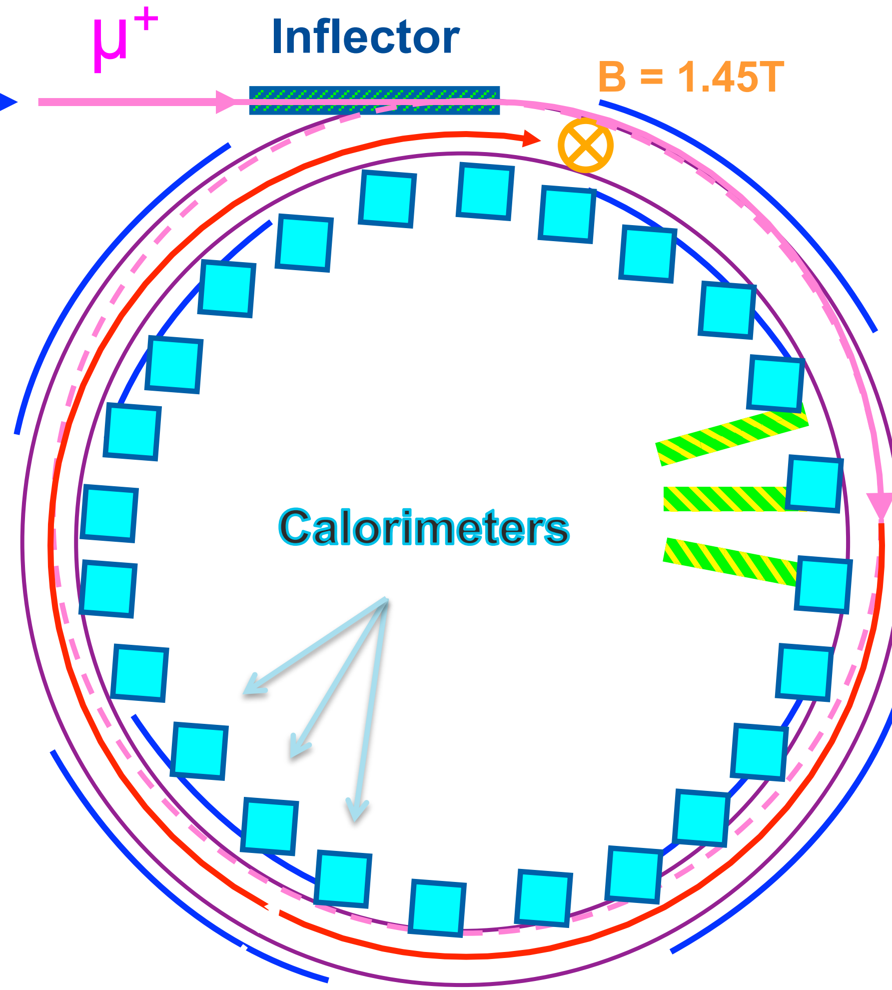


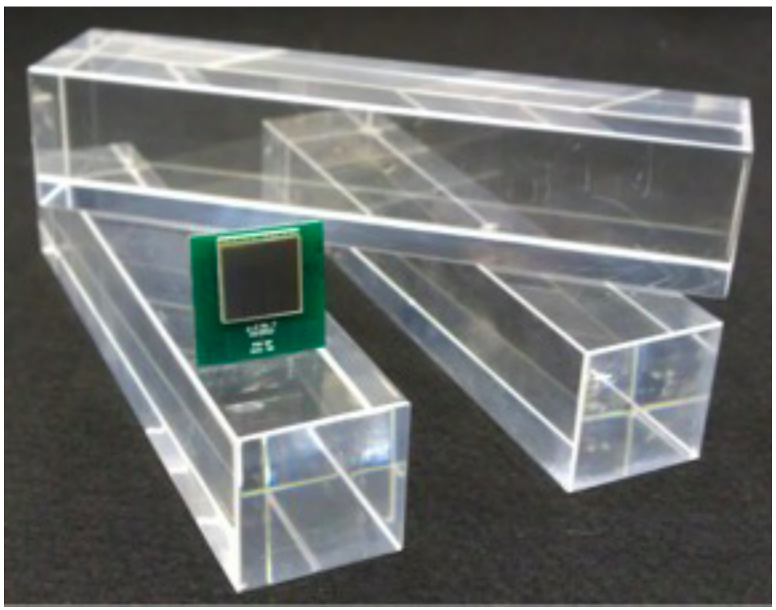


24 PbF_2 electromagnetic calorimeters read out by silicon photo-multiplies detect the energy and arrival time of the decay positrons. Fast response time of PbF_2 and SiPM essential for reduction of pile-up.

Making the measurement : Calorimeters

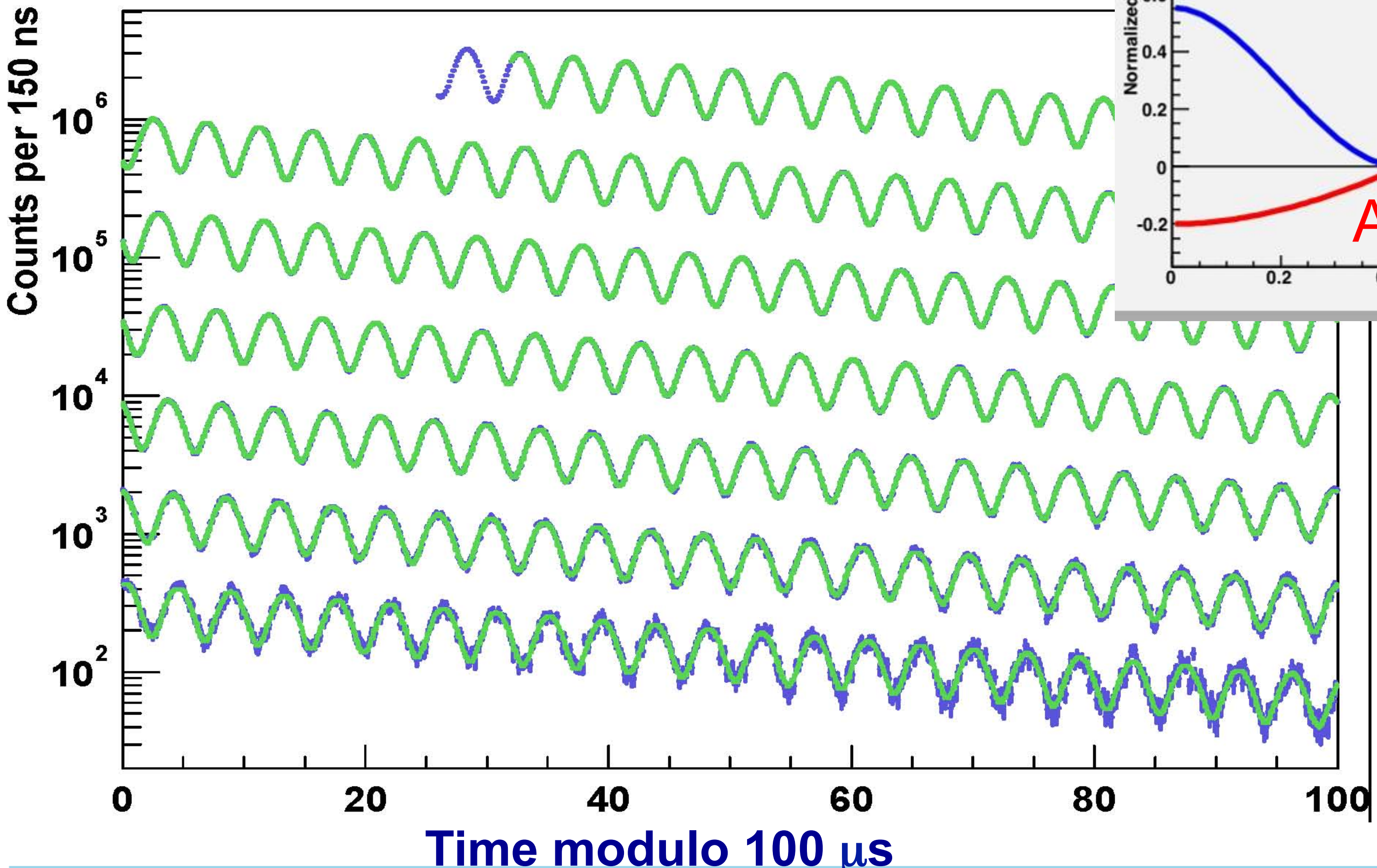


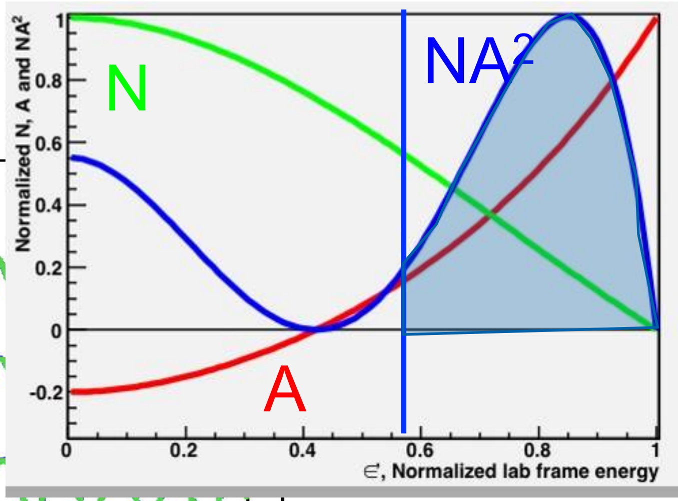




Making the measurement : Extracting ω_a

$$N_e(t) = N_0 e^{-t/\gamma\tau}\left[1 - A\cos(\omega_a t + \phi_a)\right]$$

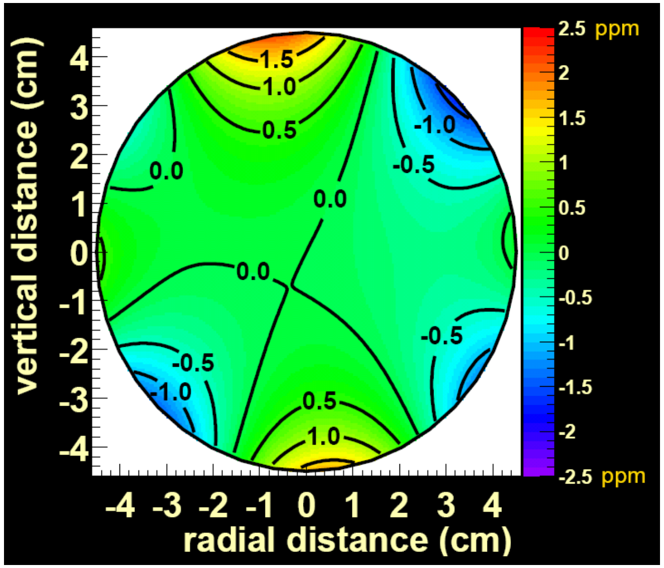




Making the measurement : B field

Map field using relationship between B and precession frequency of free proton ω_p.

$$\omega_a = a_\mu \frac{e}{m_\mu c} B = a_\mu \frac{e}{m_\mu c}\left(\frac{\hbar\omega_p}{2\mu_p}\right)$$



Rewrite anomalous magnetic moment in terms of terms of ω_p, ω_a, μ_u, μ_p:

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Making the measurement : B field

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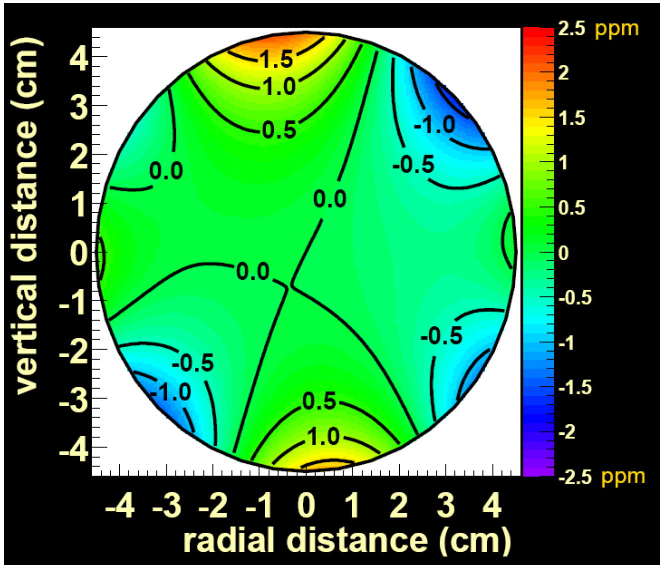

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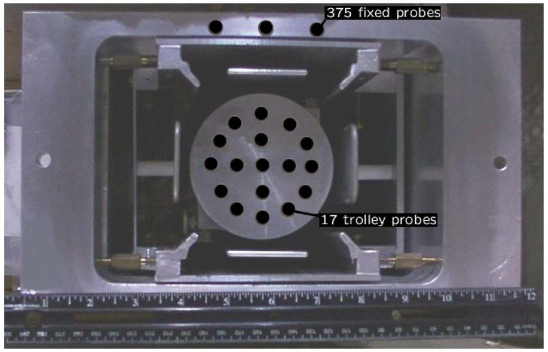
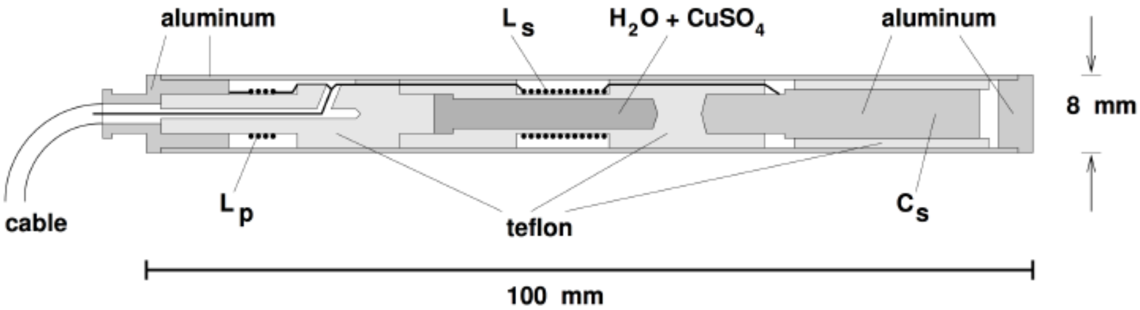
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Zeeman ground state hyperfine transitions in Muonium

Making the measurement : B field

378 NMR probes fixed at 78 locations in azimuth continuously monitor the field.





- Probes are filled with pure water and $CuSO_4$ to increase relaxation time
- Trolley with 17 probes measures field at 6000 points while ring is empty
- Trolley data is cross-referenced with static probe data
- Static probe data is calibrated against a set of probes with spherical water sample. This is the same design used to measure μ_p/μ_μ.

Fermilab

The road to 140 ppb

Planned Improvements for E989 at Fermilab:

- Increase statistics by x21 -> ±100 ppb
- All pions will decay and protons will be removed, so only inject muons into ring. No hadronic flash!
- Reduce systematic errors to 70 ppb separately for ω_a and ω_p
- New calibration probes and refurbished NMR Trolley
- Longer shimming time to improve field uniformity
- Improved laser system for gain tracking (stability ~ 0.1%) in calorimeters
- Improved calorimeters and trackers will reduce systematic errors associated with pileup.

Milestones from the last year

① Building is complete

Milestones from the last year

① Building is complete

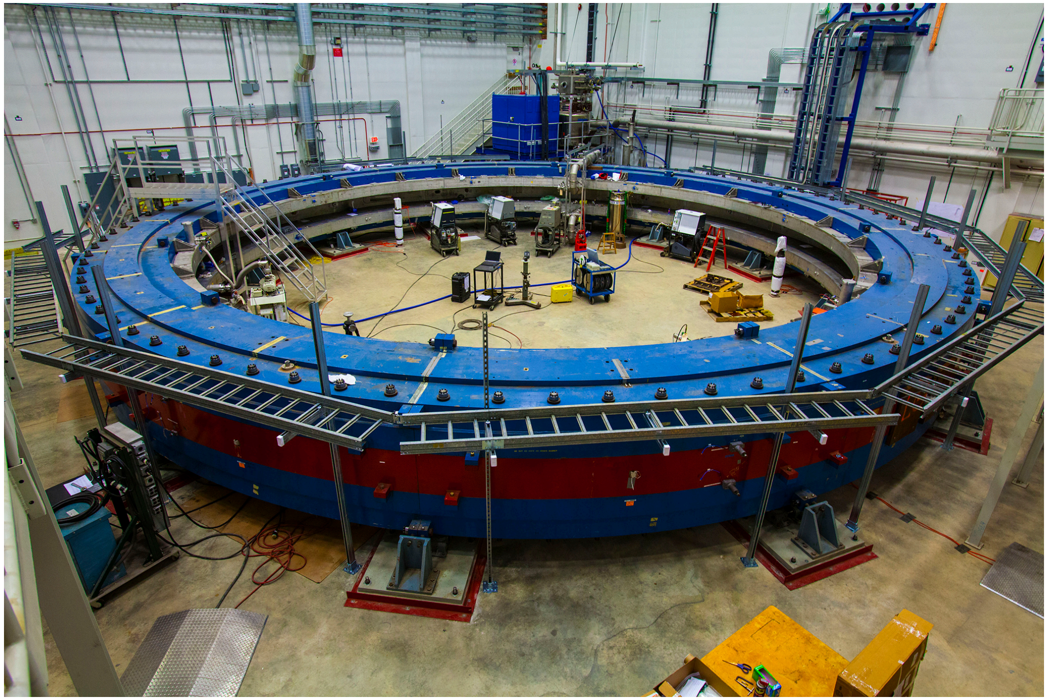
② Cryostat is operational

Milestones from the last year

① Building is complete

② Cryostat is operational

③ Ring is in the building and reassembled



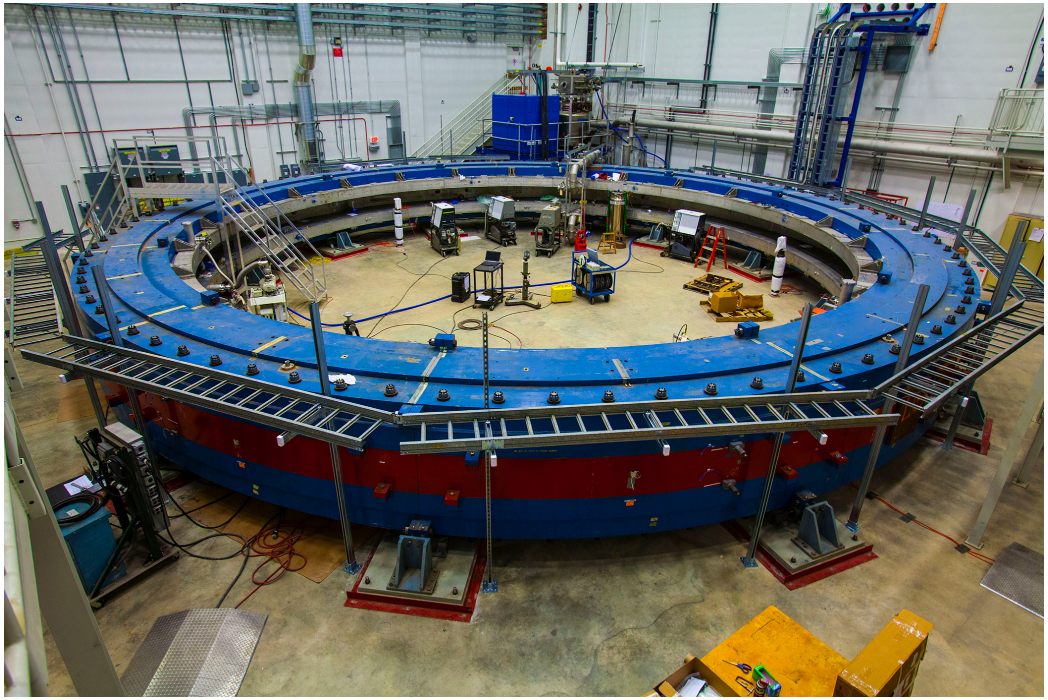
Milestones from the last year

① Building is complete

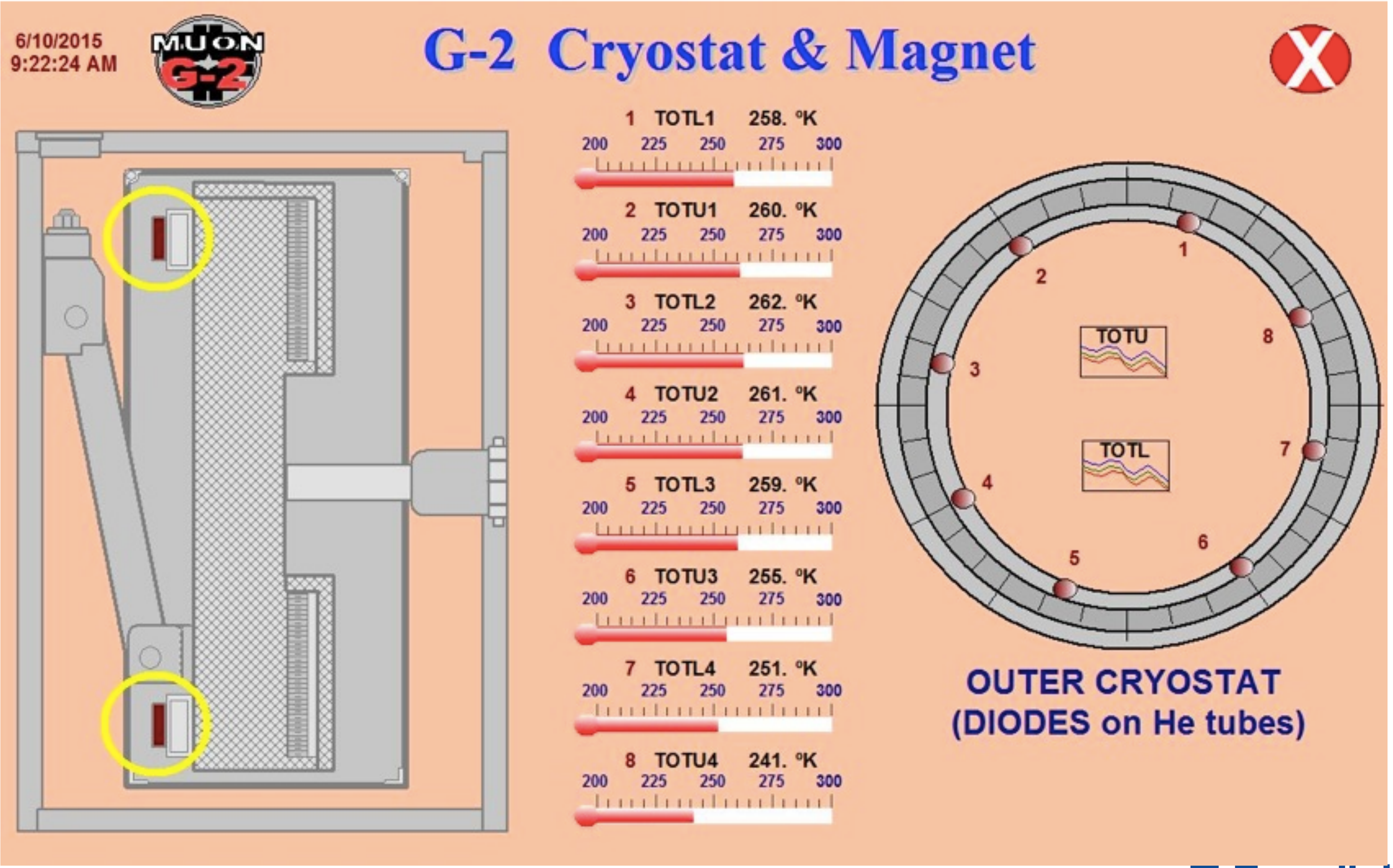
② Cryostat is operational

③ Ring is in the building and reassembled

④ Cool down of the ring started on June 4th. Expected to be at 115K by the 15th and operating temperature by the 19th.



Cool down status



Milestones from the last year

① Building is complete

② Cryostat is operational

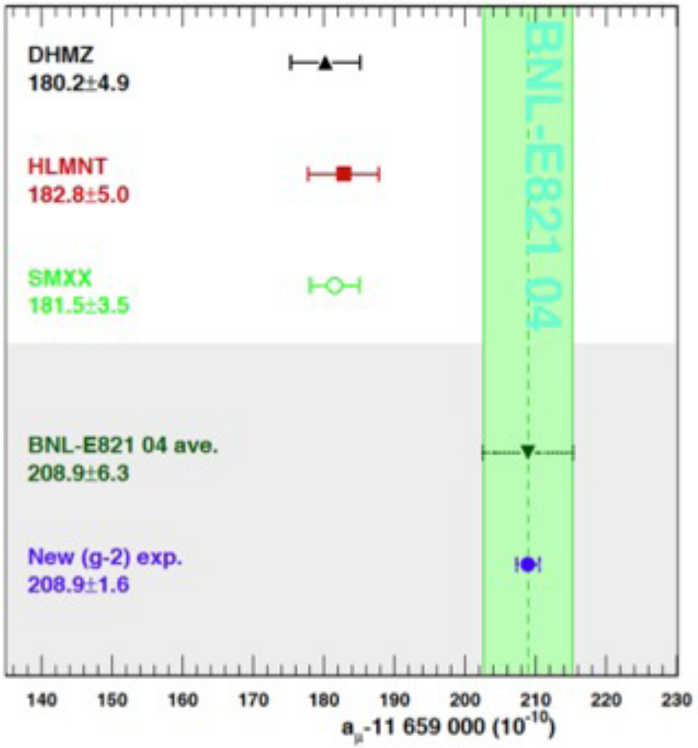
③ Ring is in the building and reassembled

④ Cool down of the ring started on June 4th. Expected to be at 115K by the 15th and operating temperature by the 19th.

⑤ Tunnel that connects g-2 to accelerator is being constructed

Looking Forward

- Fermilab muon g-2 aims to measure the muon anomalous magnetic moment to **140 ppb**.
- 140 ppb is **discovery** level sensitivity.
- Ring is being **cooled down** as we speak! Plan to ramp magnets by end of the month.
- Shimming the field, construction of calorimeters, trackers, NMR probes and DAQ, as well as simulation verification are focus for upcoming year.



- First beam planned for **early 2017**. Running will continue through 2019 and possibly early 2020.

Fermilab E989 Collaboration

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Massachusetts
- Mississippi
- Kentucky
- Michigan
- Michigan State
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

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

China:

- Shanghai

The Netherlands:

- Groningen

Germany:

- Dresden

Japan:

- Osaka

Russia:

- Dubna
- PNPI
- Novosibirsk

England

University College London

Liverpool

Oxford

Rutherford Lab

Korea

KAIST

Korea Univesity

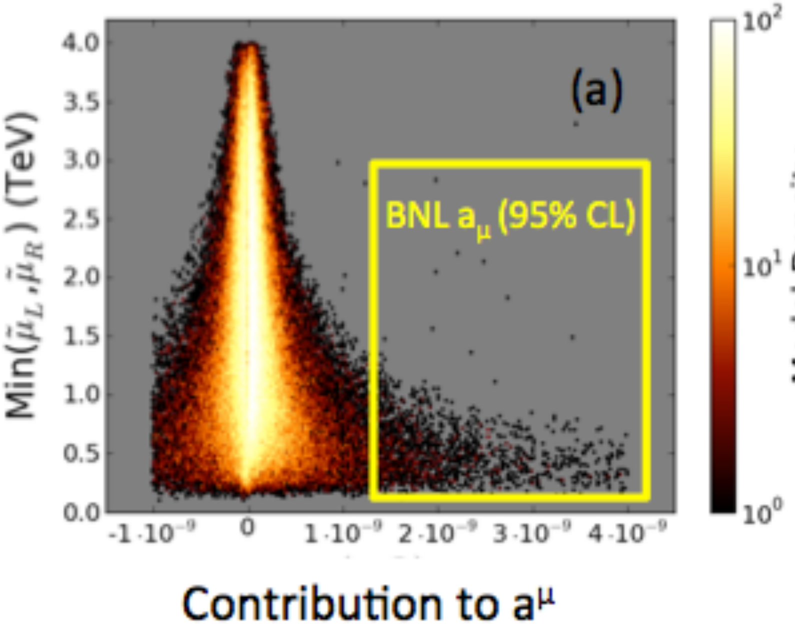
D.W. Hertzog, Co-Spokesperson
B.L. Roberts, Co-Spokesperson
C. Polly, Project Manager

You want to see more?

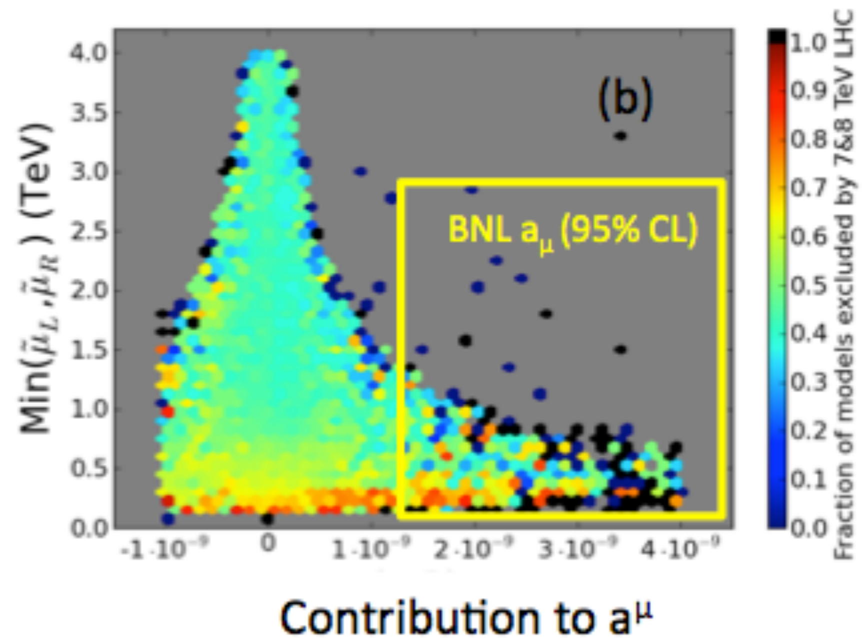
SUSY Parameter Space still allowed by LHC and a_μ

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

Density of Models



Fraction of Models Excluded

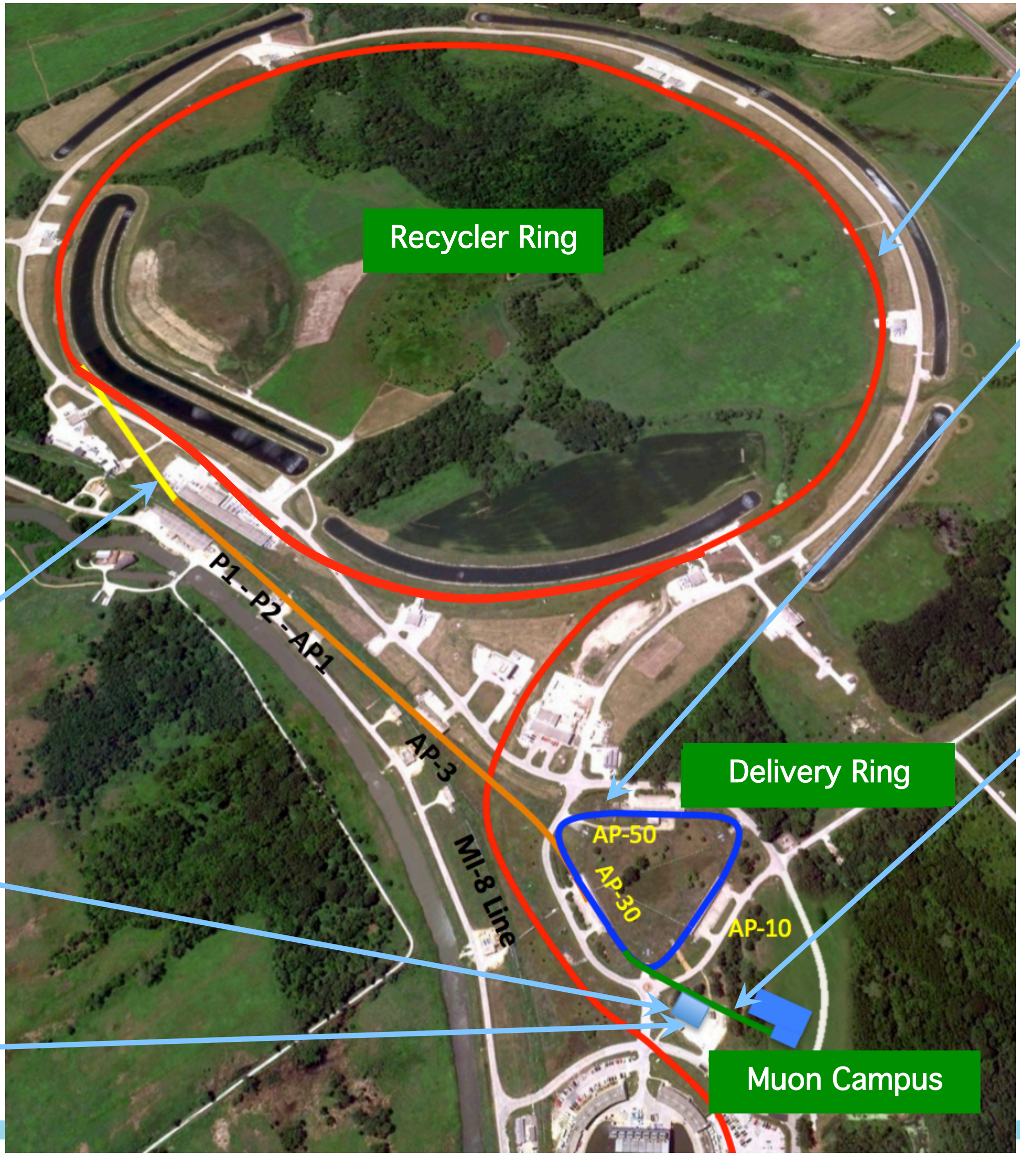


Plots courtesy of Tim Rizzo

Cahill-Rowley, Hewett, Hoeche, Ismall, Rizzo Eur. Phys. J. C (2012) 72:2156

Cahill-Rowley, Hewett, Ismall, Rizzo PRD 88, 035002 (2013)

The Muon Campus GPPs/AIPs



Recycler RF AIP:
Adds RF capability to Recycler meeting g-2/Mu2e specifications

Delivery Ring AIP:
Modify Delivery Ring to deliver custom beams to the muon experiments

Beamline Enclosure GPP:
New tunnel to Muon Campus

Infrastructure Upgrades:
Cooling for A0 compressors, MI-52 building extension, added feeder if needed

Beam Transport AIP:
New connection from Recycler to Delivery Ring, improve apertures

MC-1 Building GPP:
Houses cryo plant, power supplies for beams, g-2

Cryo Plant AIP:
Cryogenics to both experimental halls

Muonium HFS and μ_μ/μ_p ratio (MuSEUM)

- Future g-2 experiments (~0.1ppm) require more precise determination of magnetic moment ratio μ_μ/μ_p (current uncertainty : 0.12ppm)
- An improved measurement of Mu-HFS and μ_μ/μ_p is in preparation at J-PARC lead by K. Shimomura et al.

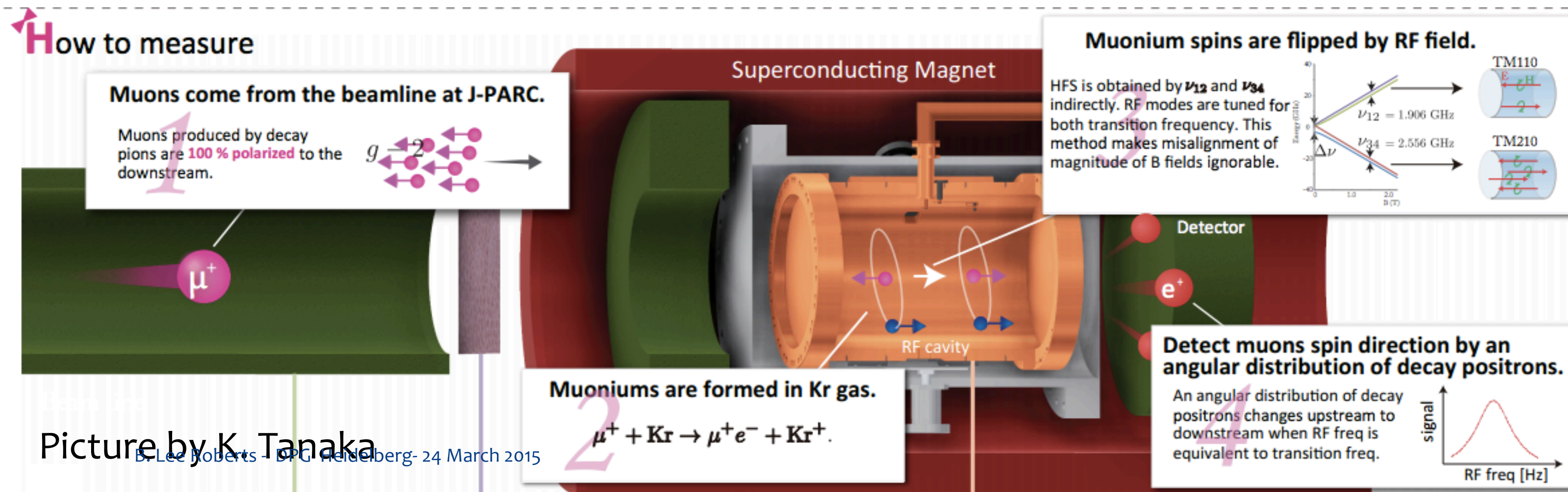
$$a_\mu = \frac{R}{\lambda - R}$$

$$R \equiv \frac{\omega_a}{\omega_p}$$

From g-2 measurement

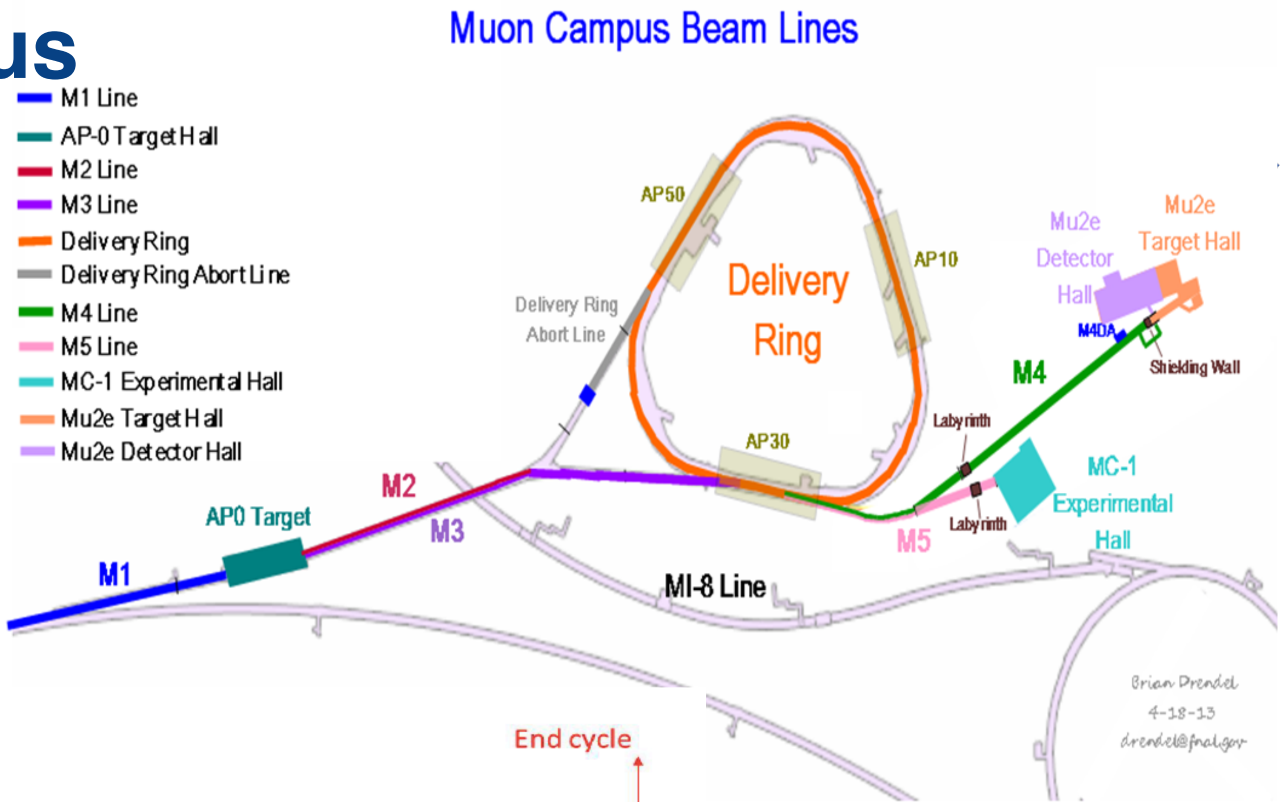
$$\lambda \equiv \frac{\mu_\mu}{\mu_p}$$

From Muonium HFS measurement

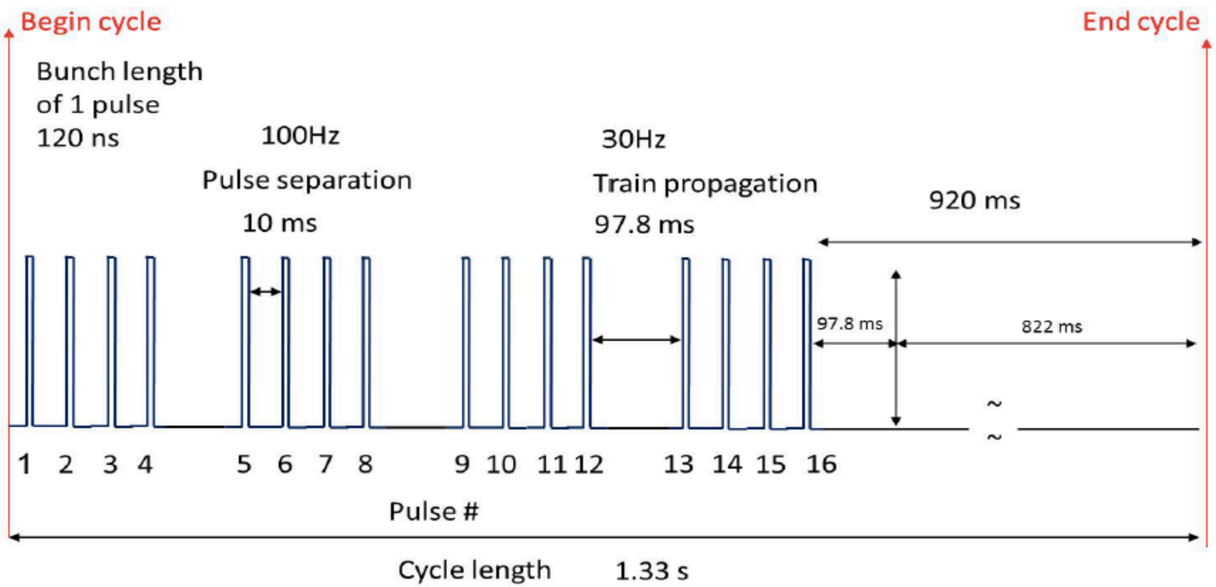


Picture by K. Tanaka

Muon Campus



Muon Campus Beam Lines
M1 Line
AP-0 Target Hall
M2 Line
M3 Line
Delivery Ring
Delivery Ring Abort Line
M4 Line
M5 Line
MC-1 Experimental Hall
Mu2e Target Hall
Mu2e Detector Hall
AP50
AP10
AP30
Delivery Ring
Delivery Ring Abort Line
Mu2e Detector Hall
Mu2e Target Hall
M4DA
Shielding Wall
M4
Labyrinth
MC-1 Experimental Hall
M2
AP0 Target
M3
M1
M5
MI-8 Line
Brian Drendel
4-18-13
drendel@fnal.gov



Begin cycle
End cycle
Bunch length of 1 pulse 120 ns
100Hz
Pulse separation 10 ms
30Hz
Train propagation 97.8 ms
920 ms
97.8 ms
822 ms
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Pulse #
Cycle length 1.33 s

Electric Dipole Moment

- The electric dipole moment of a fundamental particle like the muon must be aligned with the spin of the particle.

$$\vec{d} = n\frac{Qe}{2mc}\vec{S}$$

n is a dimensionless constant analogous to g in the magnetic dipole moment

- In principle an EDM term is added onto ω_a:

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

- However SM muon EDMs are predicted by the standard model to be < 10^{-38}.

- Measurement of a non-SM EDM would point to a new source of CP violation, a necessary component in explaining the current matter – anti-matter asymmetry.

Errors from BNL and projected at Fermilab

Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	50	50	35
Calibration of trolley probes	200	150	90	30
Trolley measurements of B_0	100	100	50	30
Interpolation with fixed probes	150	100	70	30
Uncertainty from muon distribution	120	30	30	10
Inflector fringe field uncertainty	200	–	–	–
Time dependent external B fields	–	–	–	5
Others †	150	100	100	30
Total systematic error on ω_p	400	240	170	70
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–

- †Higher multipoles, trolley temperature (≤ 50 ppb/° C) and power supply voltage response (400 ppb/V, ΔV=50 mV), and eddy currents from the kicker.

Systematic Errors on ω_a (ppb)

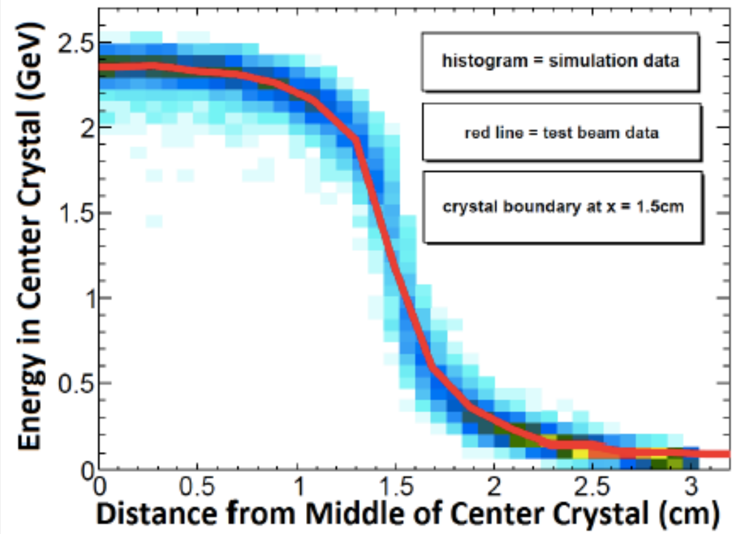
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

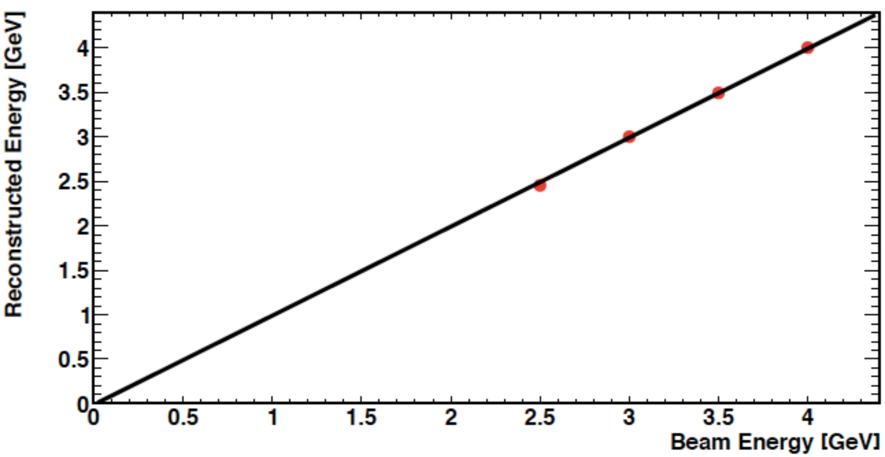
B Field Uncertainties for BNL and Fermilab

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

Calorimeters

- δE/E < 5% at 2 GeV. Achieved 2.8% in SLAC beam tests.
- Timing resolution < 100ps for E >100 MeV



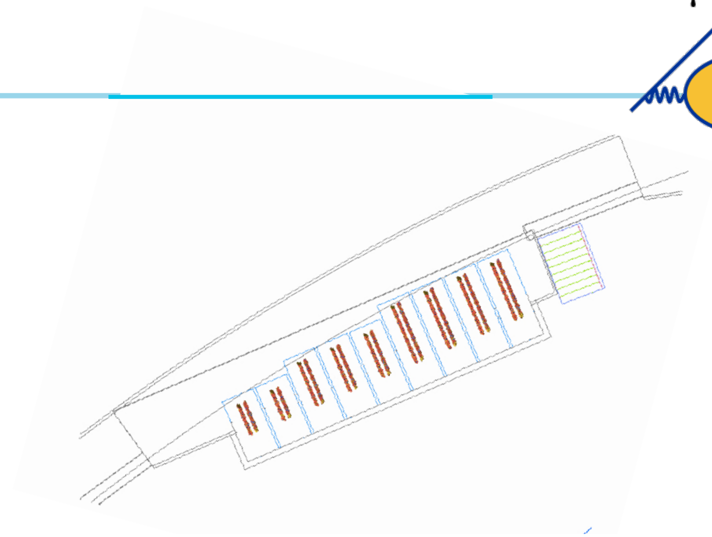


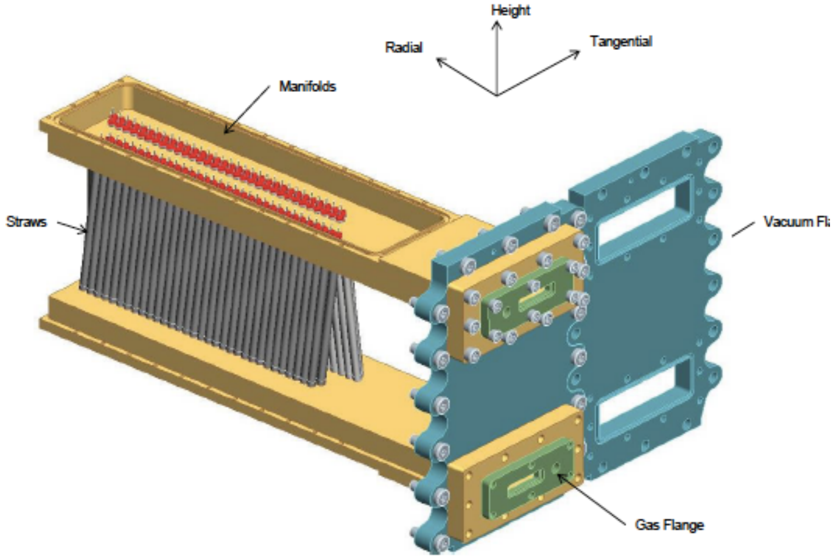
- Must be able to resolve two positrons arriving 5 ns apart. Drives choice of PbF_2 crystals and SiPM tubes.
- Calibration and gain tracking with laser system. Demonstrated ability to track gains to relative precision of 10^{-4} per hour.

Fermilab

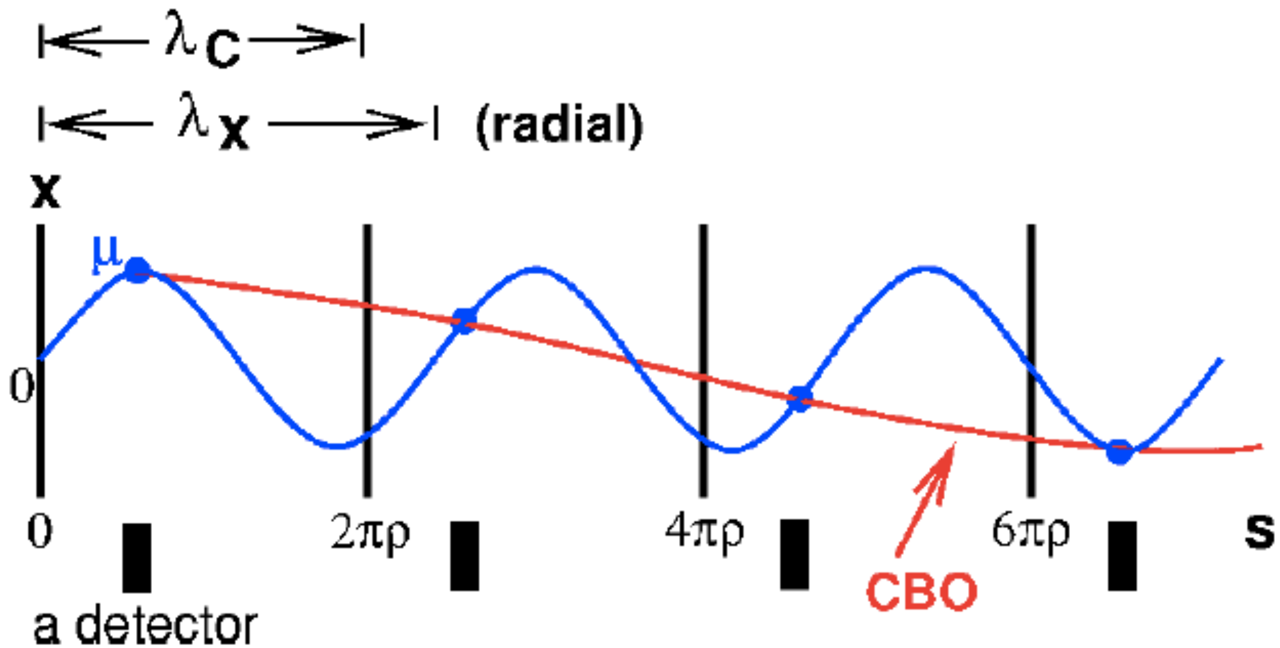
Strawtrackers

- Momentum spread and betatron motion of the beam lead to ppm level corrections to the muon ω_a associated with the fraction of muons that differ from 3.09 GeV/c and the fraction of time the muons momentum is not perpendicular B.
- Betatron motion of the beam causes acceptance changes in the calorimeters that must be included in the fitting functions used to extract the precession frequency.
- The muon spatial distribution must be convoluted with the measured magnetic field map in the storage region to determine the effective field seen by the muon beam.
- Help identify and characterize pile up events in the calorimeters.
- Detect permanent EDM which manifests as a tilt in the muon precession plane away from vertical which leads to an up/down asymmetry that can only be measured with the straw trackers.





Coherent Betatron Motion

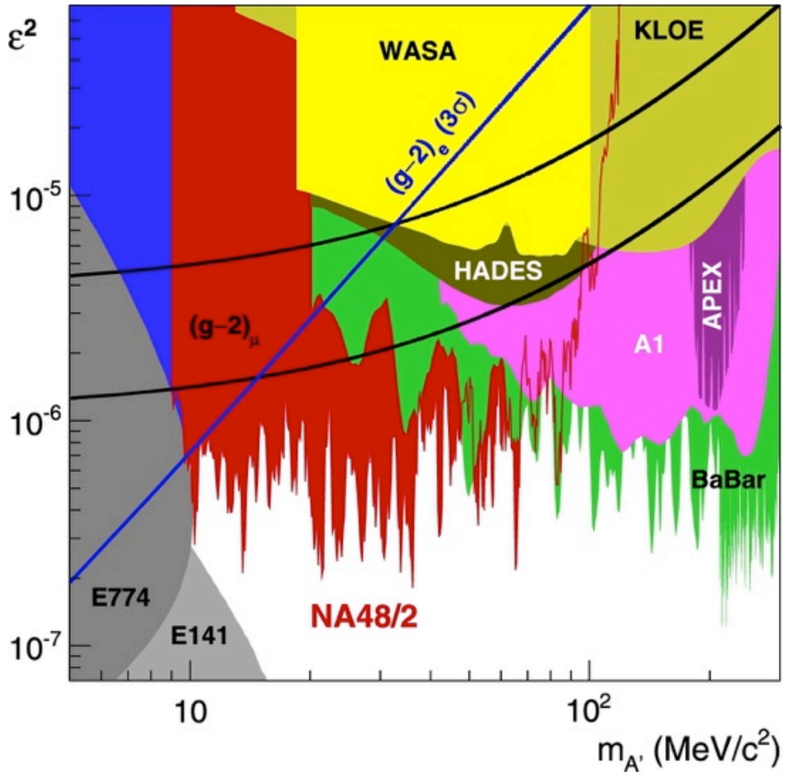


A cartoon of the coherent betatron motion (CBO). The radial CBO oscillation is shown in blue for 3 successive betatron wavelengths, the cyclotron wavelength (the circumference) is marked by the black vertical lines. One detector location is shown. Since the radial betatron wavelength is larger than the circumference, the detector sees the bunched beam slowly move closer and then further away. The frequency that the beam appears to move in and out is fCBO

Beyond the Standard Model Contributions?

DARK PHOTON

Phys.Lett. B746 (2015) 178-185



The dark photon is a light (10-100 MeV) weakly interaction new

Models are barely constrained by LHC. However PHENIX, NA48/2, Babar and the electron g-2 have nearly eliminated available phase space.

Summary of J-PARC E34

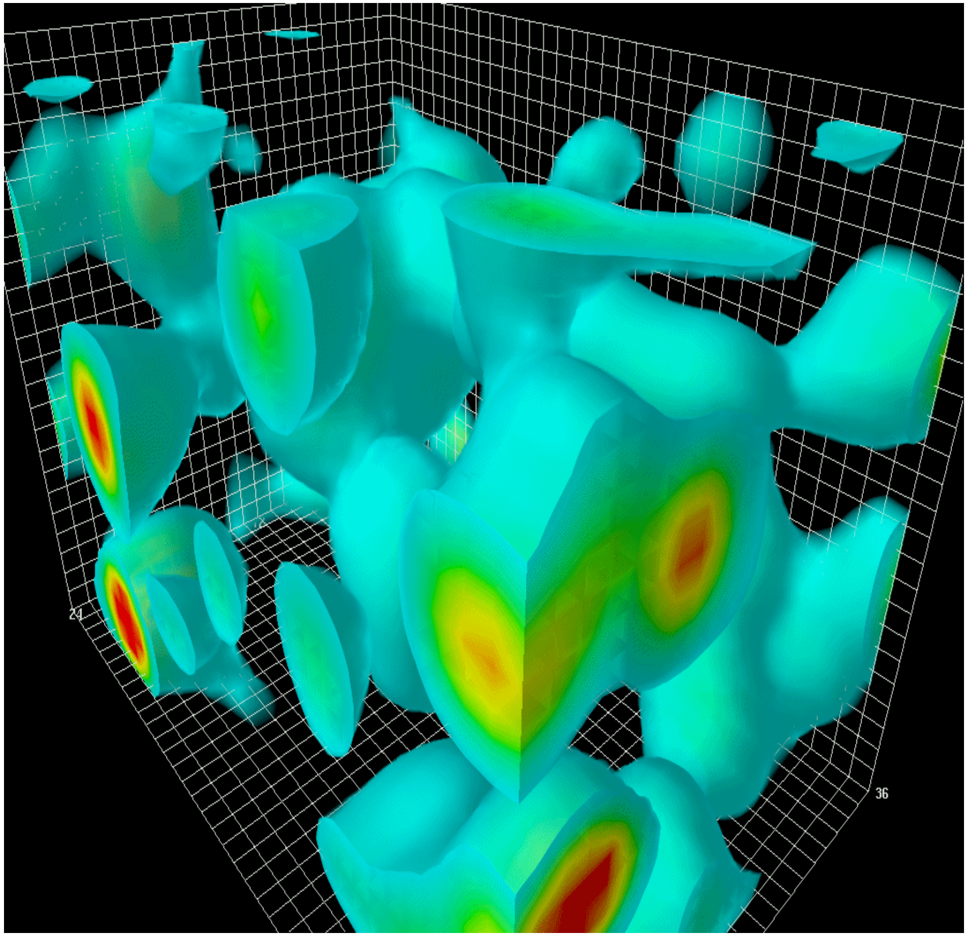
- **Experimental principle of J-PARC E34 with ultra-cold muon is completely different from BNL E821/FNAL E989.**
- **Projected sensitivity on a_μ :**
  - **0.5ppm (initial stage) → 0.1ppm (final goal)**
- **Full tracker covering entire azimuth providing 100% acceptance for an EDM measurement. FNAL g-2 has only 3/24 tracker coverage.**
- **50% polarization. FNAL g-2 has ~90% polarization**
- **Technical Design Report is under preparation.**
- **Four years to start running (technically-driven schedule)**

Comparison of experiments

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		**0.3 GeV/c**
gamma	29.3		**3**
Storage field	B=1.45 T		**3.0 T**
Focusing field	Electric quad		**Very weak magnetic**
# detected μ+ decays	5.0E9	1.8E11	**1.5E12**
# detected μ- decays	3.6E9	-	**-**
Target Precision (stat)	0.46 ppm	0.1 ppm	**0.5* ppm**
Muon Polarization	90%	90%	**50%**
Spin flip	No	No	**Yes**

*x5 improvements in muonium yield may result in 0.1 ppm result.

QCD Vacuum



D. Leinwebar