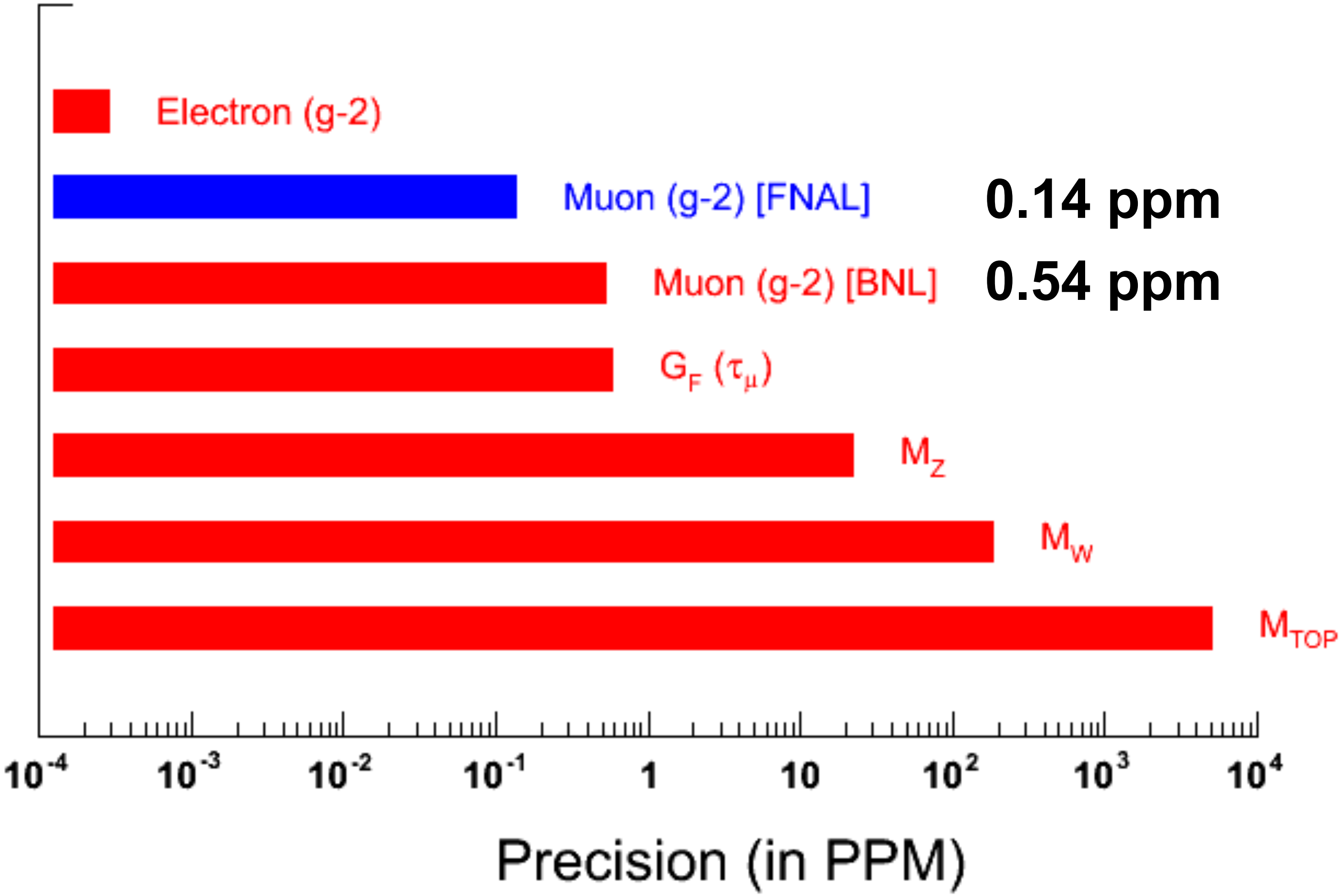
# The Fermilab Muon g-2 Experiment

*Becky Chislett*
UCL

# Aim of Experiment

Make a 0.14 ppm measurement



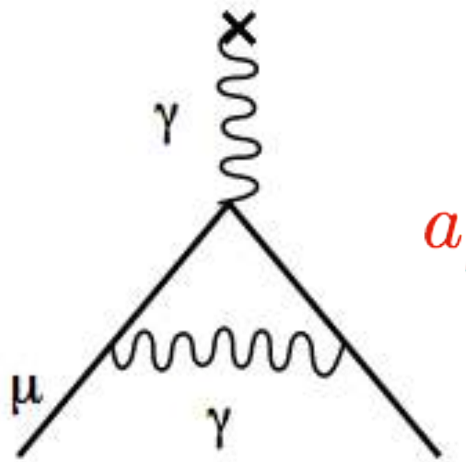
# Anomalous Contribution

Additional "loop" interactions give **a non g=2 contribution**

$$a_\mu = \left(\frac{g-2}{2}\right)$$

This is the so-called anomalous contribution

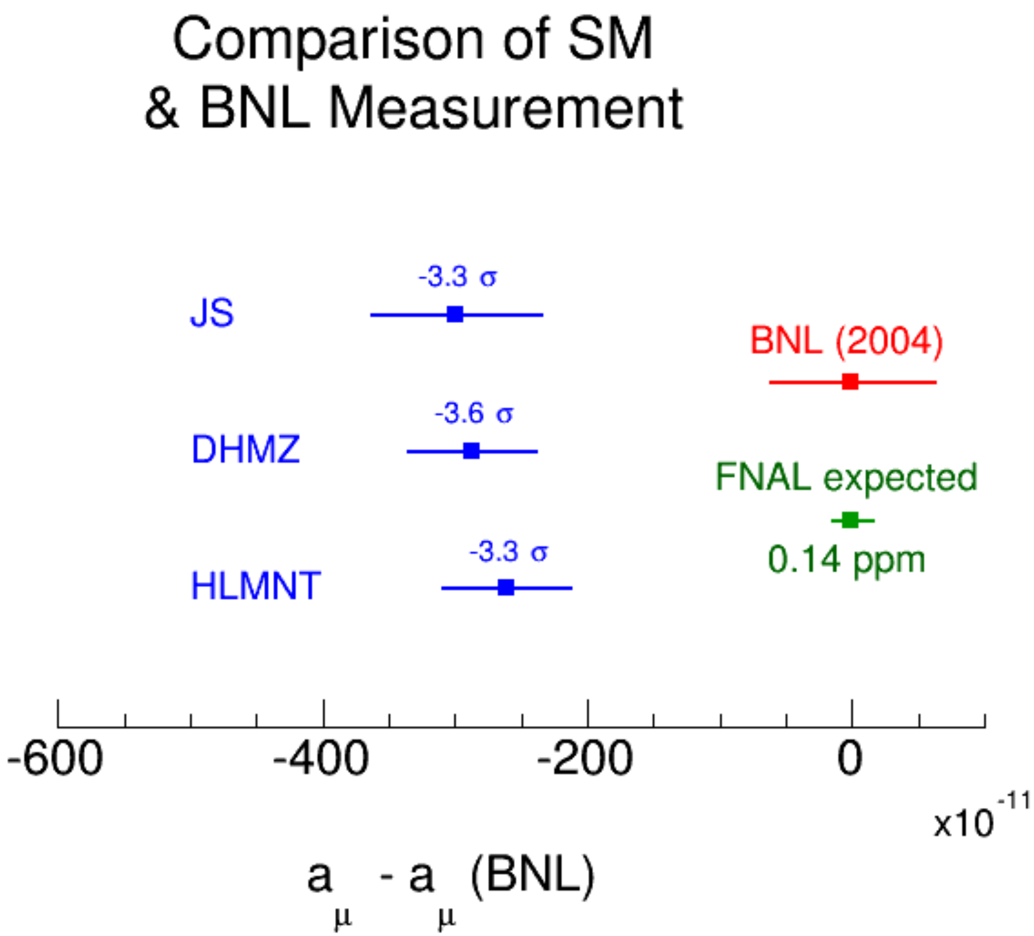
These interactions flip the chirality of the muon but conserve flavour and CP.




$$a_\mu = \frac{\alpha}{2\pi} = 0.00116\ 140980$$

$$= 0.00116\ 591792\ \text{(SM all loops)}$$

# Theory consensus

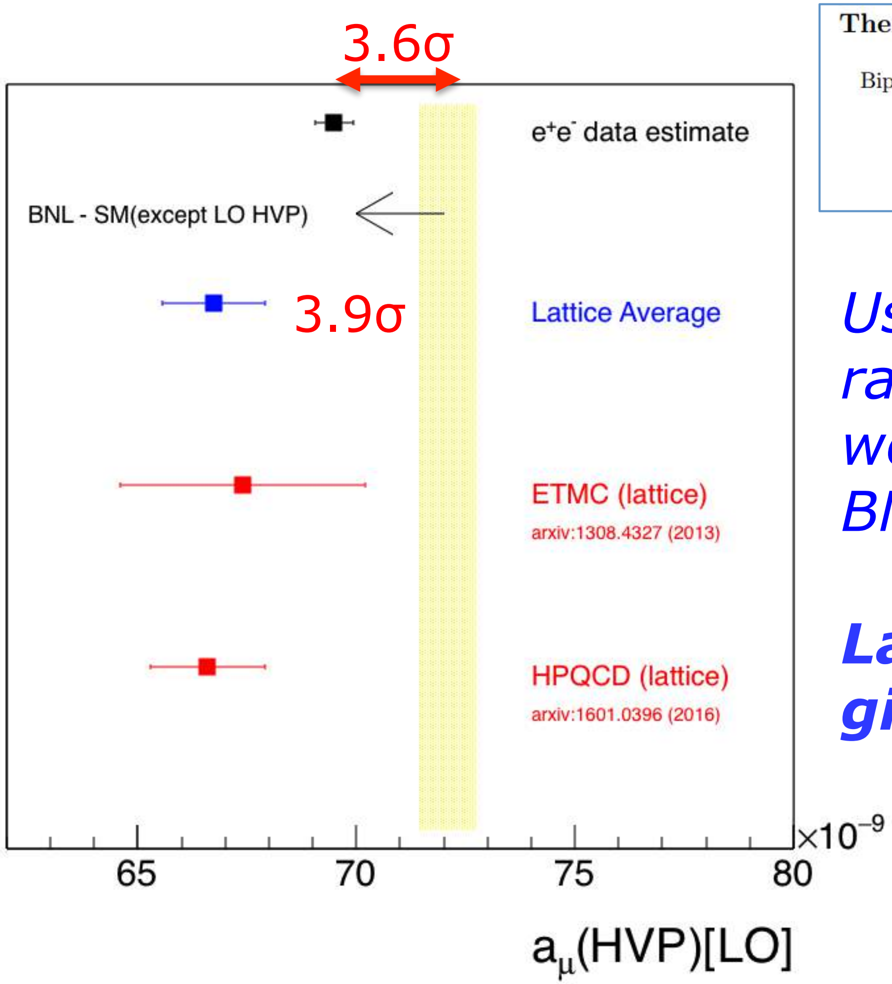



Present measurement is at odds with SM at 3.5σ level and now broad consensus on SM value

A 0.14 ppm measurement moves this to more than 5σ irrespective of theory.

# Theory consensus

SM estimate from $e^+e^-$ data is now being independently verified from lattice calculations.




**The hadronic vacuum polarization contribution to $a_\mu$ from full lattice QCD**

Bipasha Chakraborty,[1,*] C. T. H. Davies,[1,*] P. G. de Oliveira,[1] J. Koponen,[1] and G. P. Lepage[2]
(HPQCD collaboration)[†]
[1]*SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK*
[2]*Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, New York 14853, USA*
(Dated: January 14, 2016)

*Using lattice estimate of HVP (SM) rather than that based on $e^+e^-$ data would increase discrepancy of BNL result with SM from 3.6 to 3.9σ*

***Lattice calculation and $e^+e^-$ data give consistent result.***

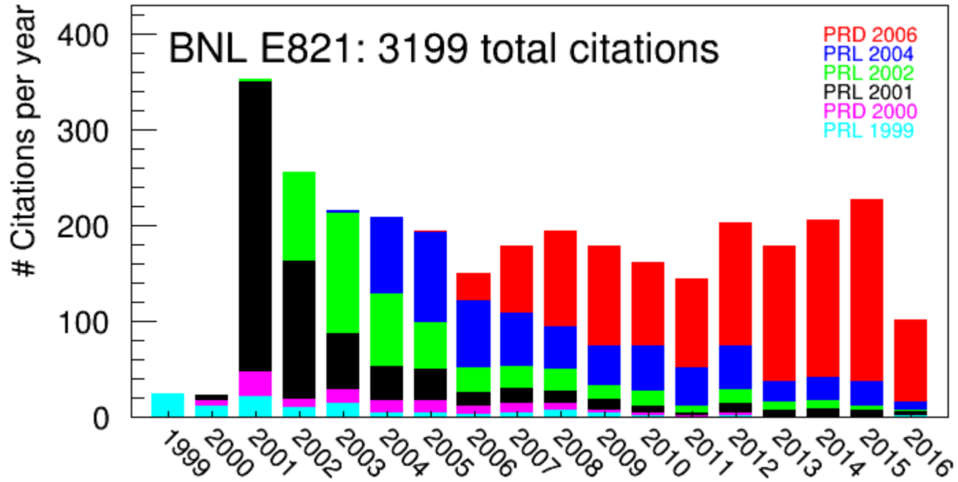
# BSM Landscape

Measurement probes much of the same TeV-scale BSM landscape as LHC.

**Large +ve anomaly wrt SM**

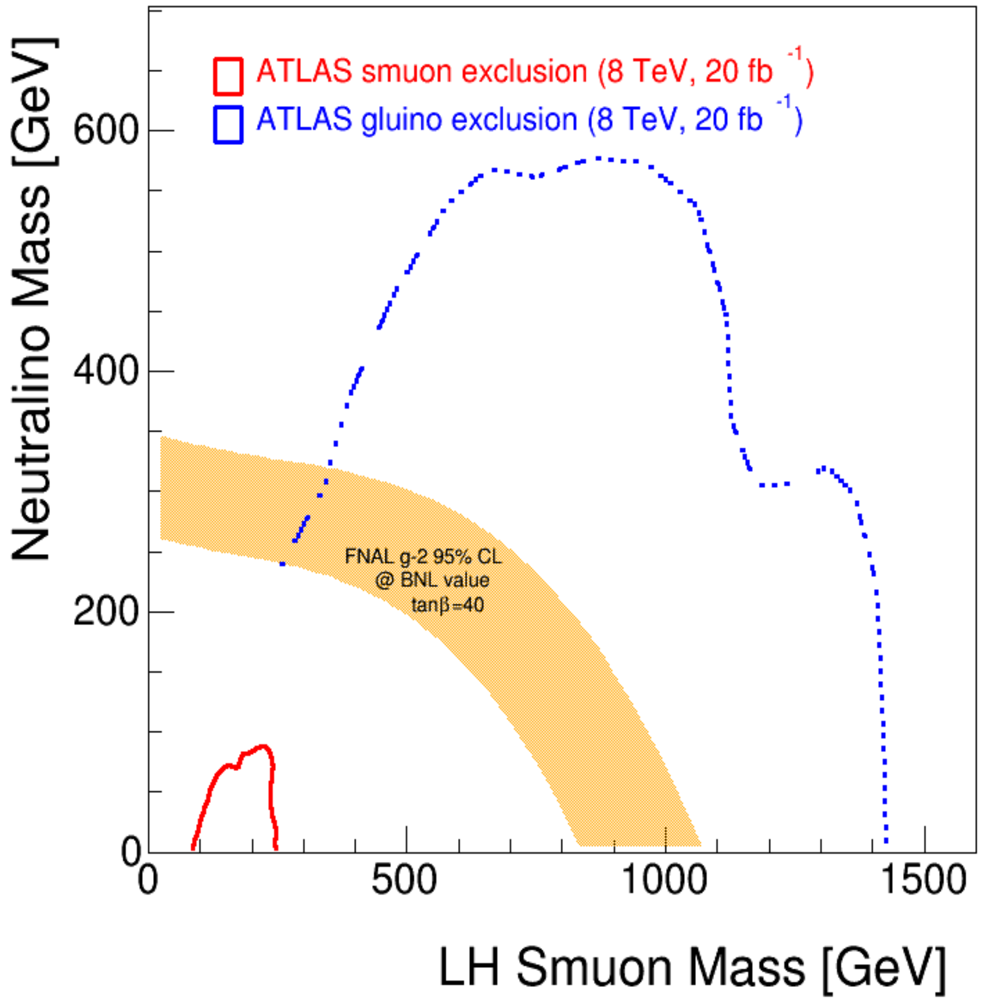
Extended technicolor (fermion masses)

SUSY, RS ED
Extra Higgs Doublet




Z', W', Little Higgs,
Universal ED

**Value consistent with SM**

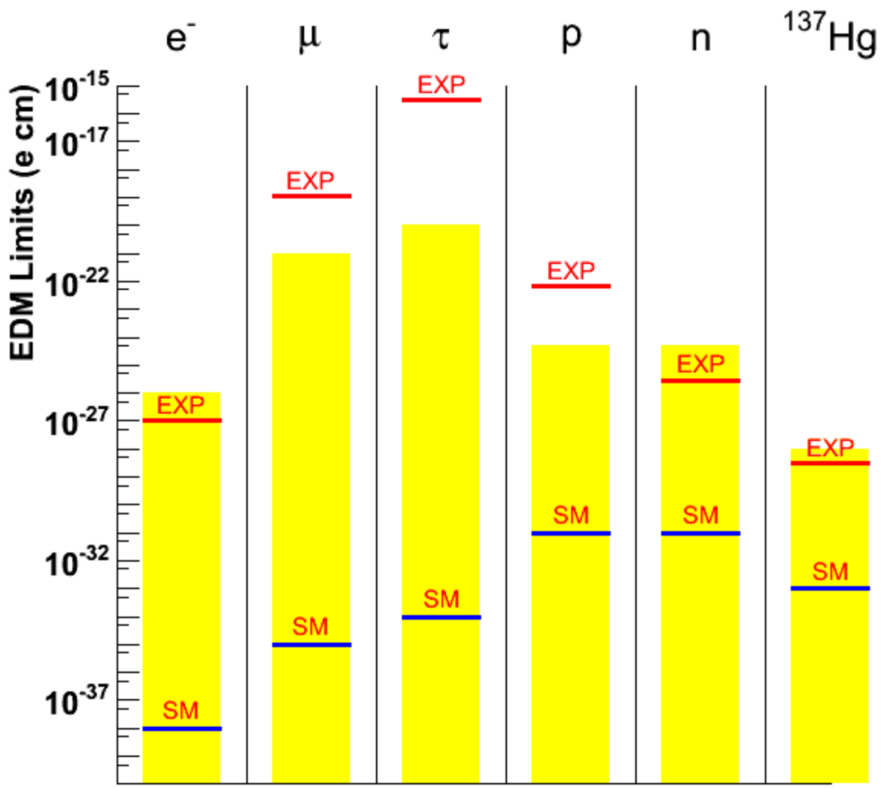



LHC cannot probe all of phase space e.g. small mass slepton/neutralino mass differences, high tanβ.

In event of LHC BSM observation g-2 measurement can resolve degeneracy in model pars & improve their determination e.g. tanβ.

# Muon : Electric Dipole Moment

Essentially zero in SM : any observation is new physics




Muon is the only 2nd flav. gen. measurement. and it's free of nuclear / molecular effects

BNL limit is $1.8 \times 10^{-19}$

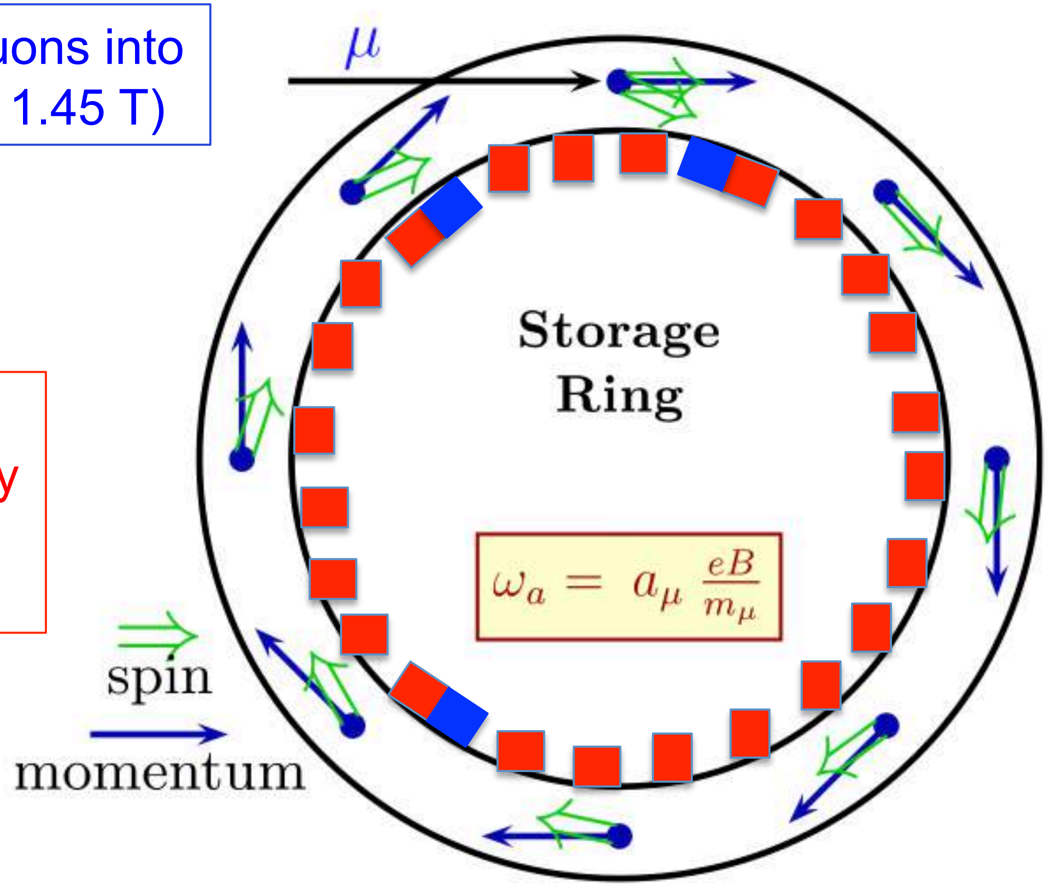
**Can quickly be improved by x10 and ultimately x100 to $10^{-21}$**

Needs non mass-scaling BSM effects to see anything given $e^-$ EDM limit

# FNAL g-2 Experimental Technique

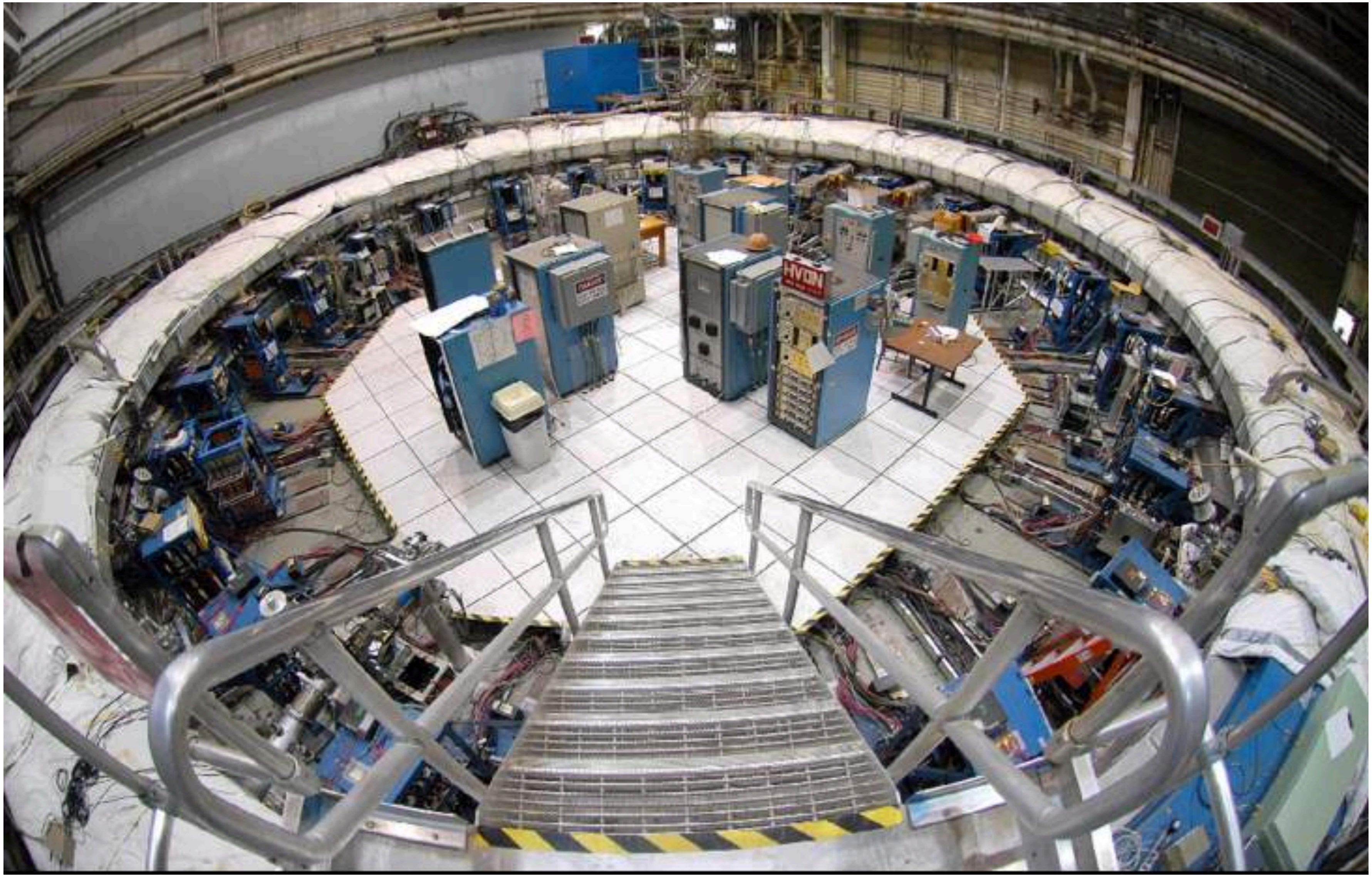
Inject 3.09 GeV muons into a storage ring (B = 1.45 T)

Exploit property that direction of $e^+$ from $\mu^+$ decay is strongly correlated with $\mu^+$ spin for highest energy $e^+$

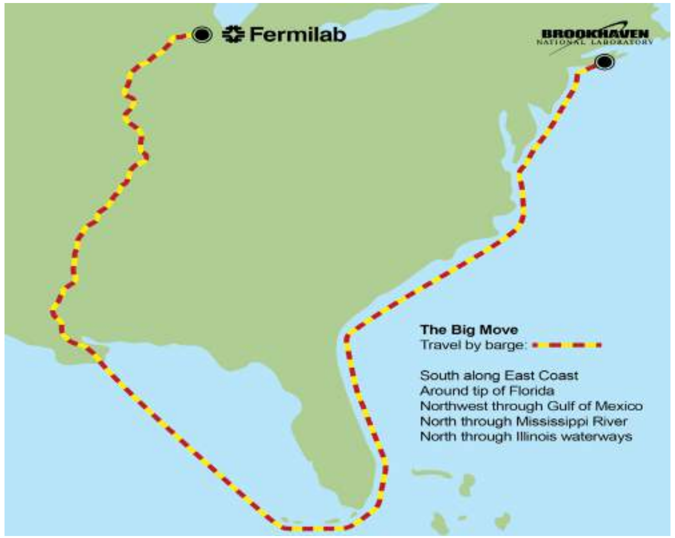



24 calorimeters and **3 straw-trackers (UK)** measure $e^+$ for O(1 ms) for spills separated by 10ms.
16,000 stored 3.09 GeV muons from $10^{12}$ protons per spill.

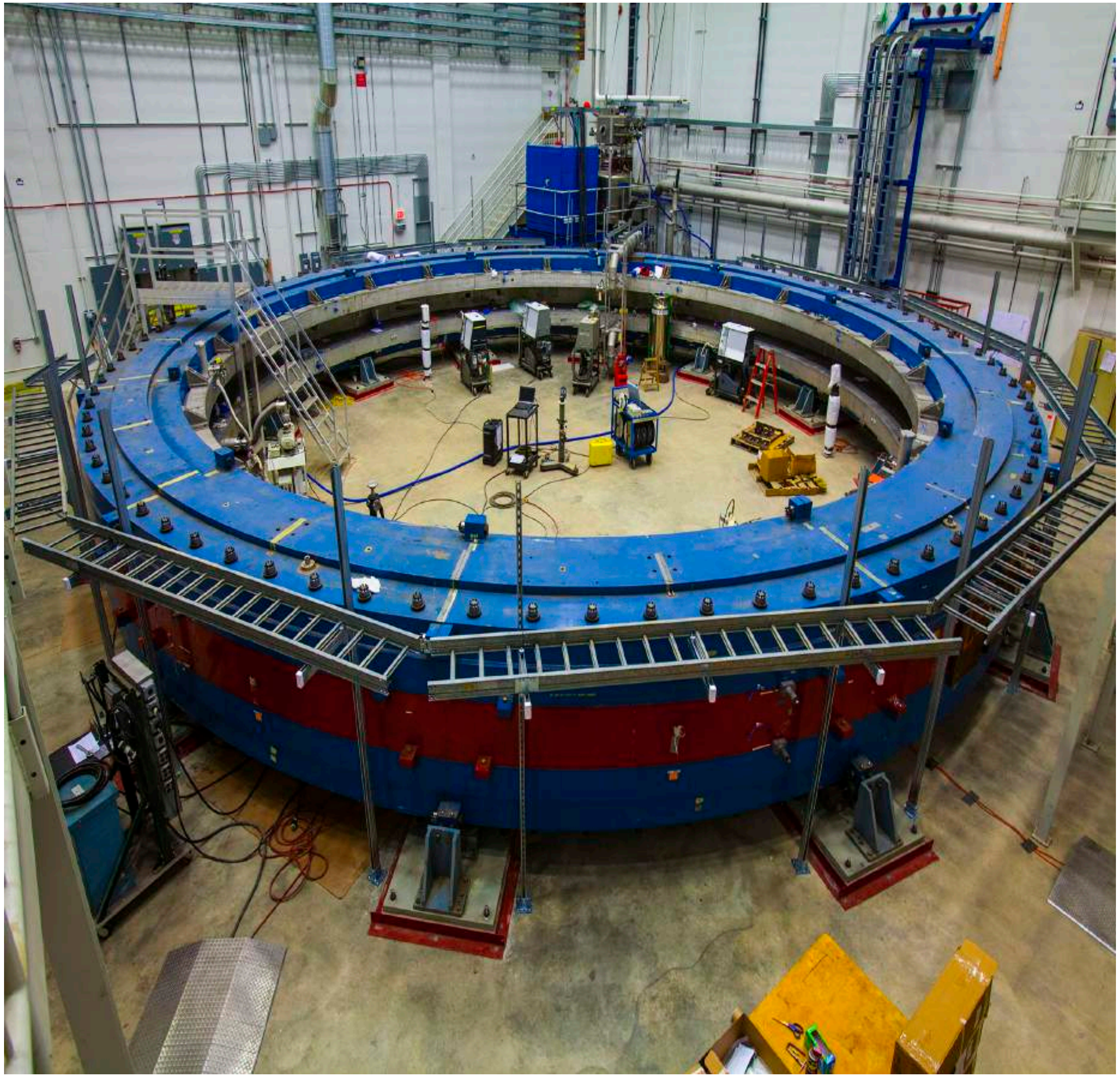
# Storage ring at BNL



# Storage Ring At FNAL







# Seven FNAL g-2 improvements

More μ per proton

Lower inst. rate

Fewer pions

Unique capabilities of FNAL accelerators

Improved detectors

Improved stored muon beam dynamics

Improved field uniformity, field measurement & calibration

Improved modeling of beam & detectors

$$\text{BNL} \rightarrow \text{FNAL}$$

$$[54\ (\text{stat.}) \oplus 33\ (\text{syst.}) \rightarrow 11\ (\text{stat.}) \oplus 11\ (\text{syst.})] \times 10^{-11}$$

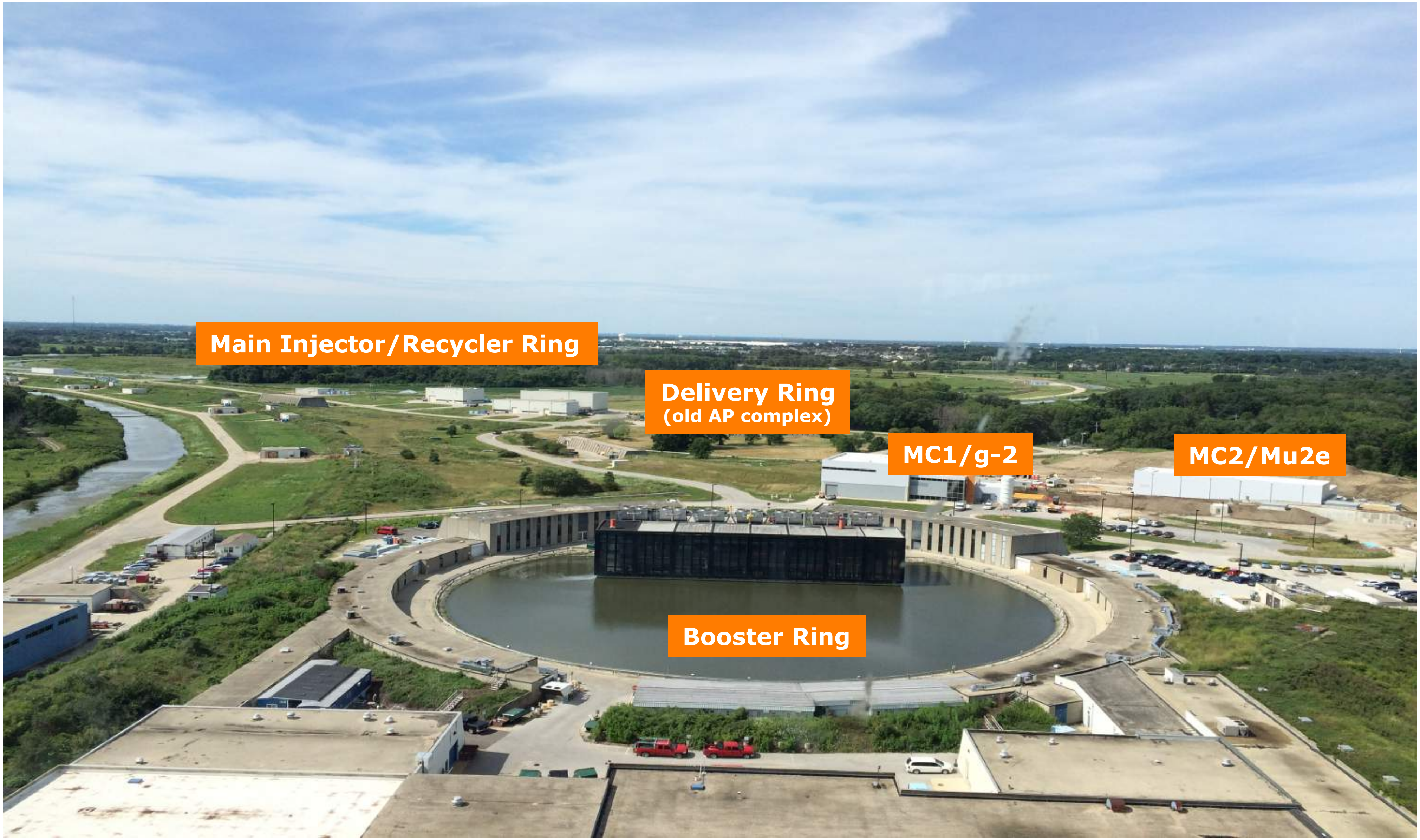
$$0.54\ \text{ppm} \rightarrow 0.14\ \text{ppm}$$

New / improved technologies

Additional collaborators

Building on wealth of experience from BNL E821 & other expts

# Muon Campus at FNAL

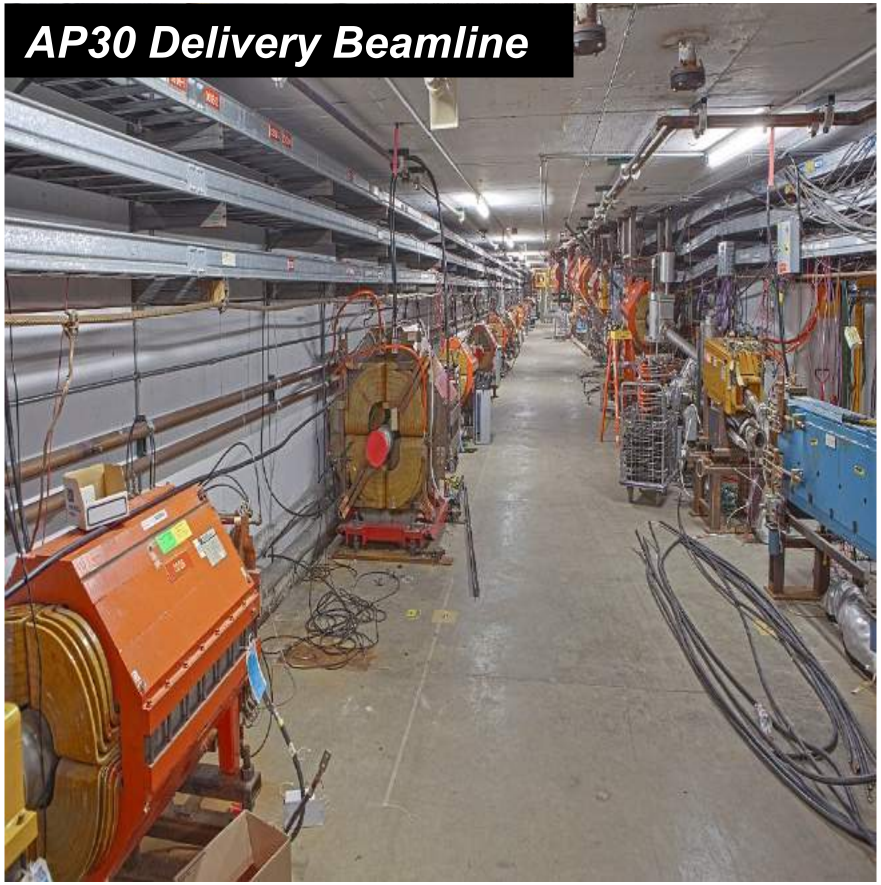


# Status

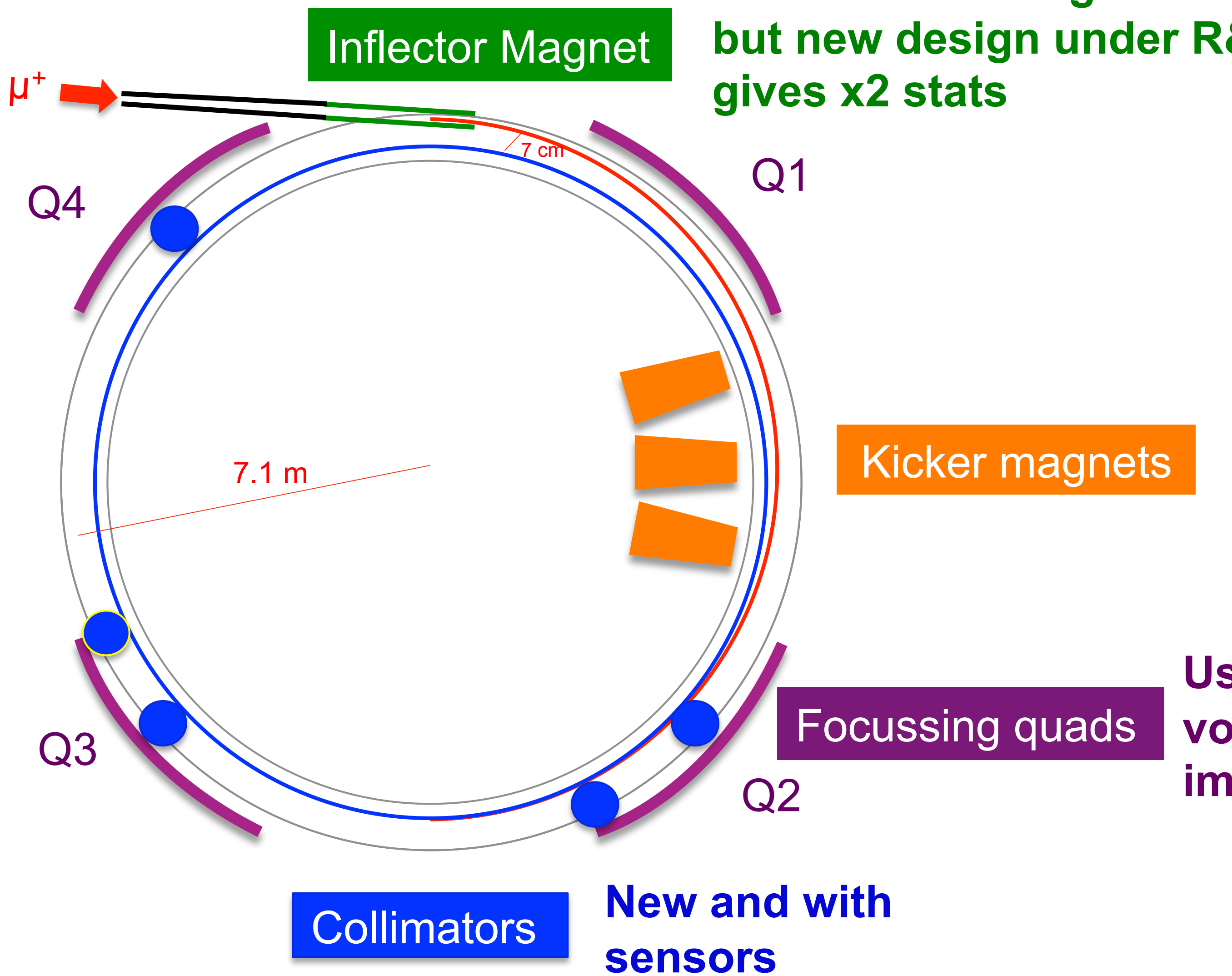
**75% of beam/accelerator work complete.**
**Remaining infrastructure work in 2016 summer shutdown**

**First beam Q2 2017.**


*Beam Quads Into g-2 Ring*


*AP30 Delivery Beamline*

# Improvements to injection system




**Baseline: existing BNL inflector but new design under R&D which gives x2 stats**

**New with improved kick**

**Using higher voltage for improved tune**

**New and with sensors**

# Magnet on : shimming almost done


Magnet has been on OK
at 1.45T (4.5k) for 10 months.

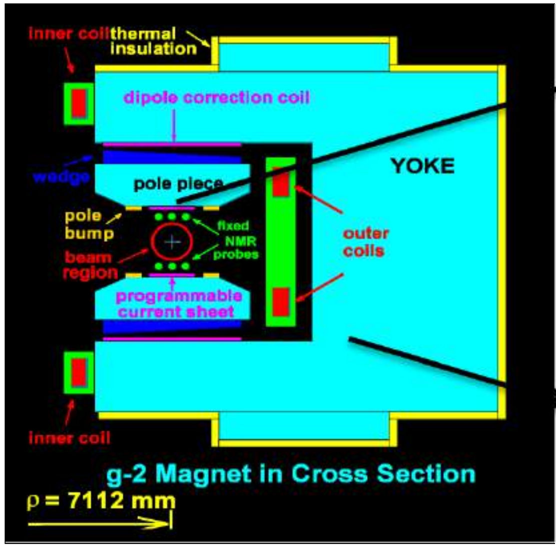
**Shimming of magnet** has been going on for 10 months

Improved field uniformity by a factor of 100.

Now well below required uniformity of 25 ppm azimuth average

These shims are thinner than a human hair….

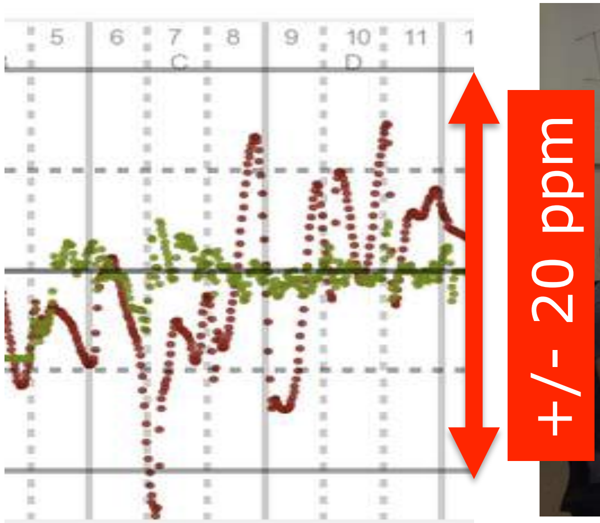
# Field Uniformity is excellent

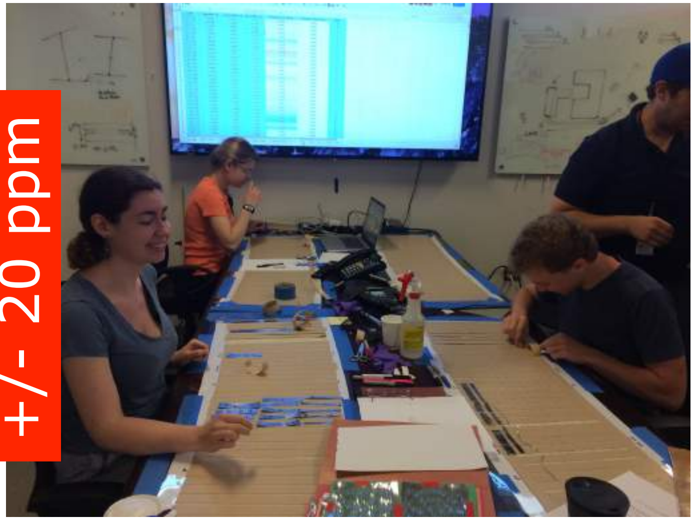


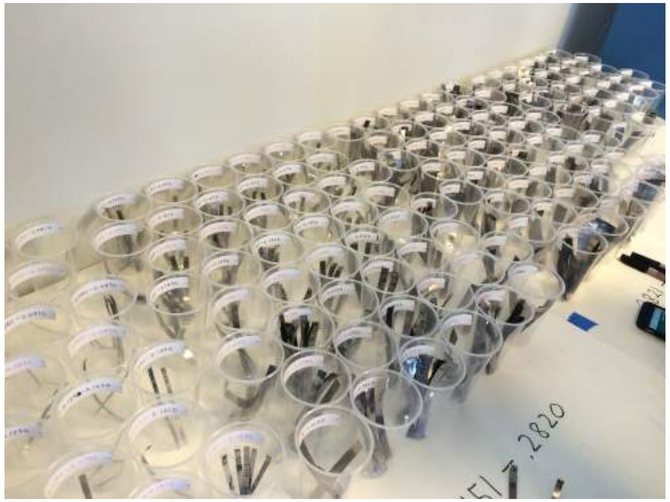

to 10 microns

Tilt to 5

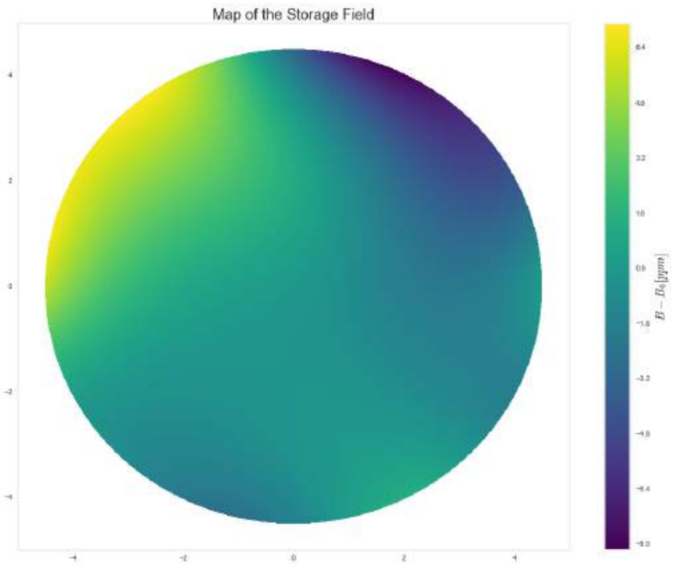
26 tons to 125 microns



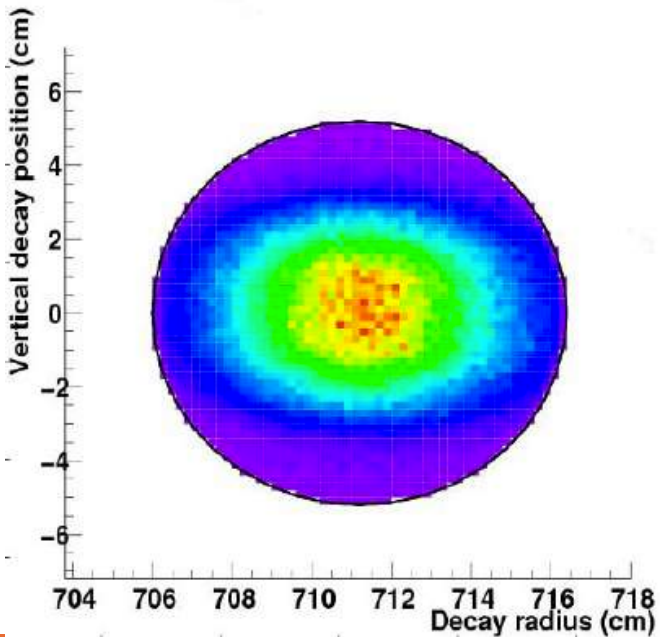





# Field Uniformity




Field uniformity in storage region < 0.1 ppm

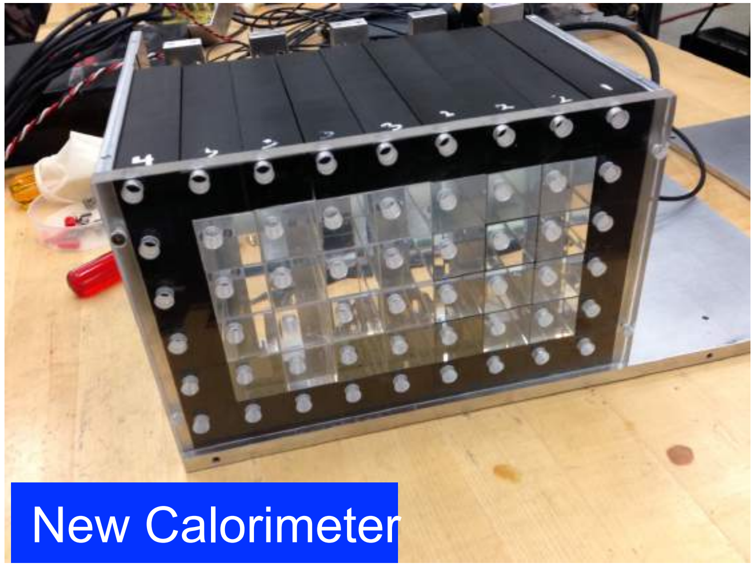



Muons are distributed over storage volume

B-field is not uniform over this volume

Need to convolute the two : **use trackers**

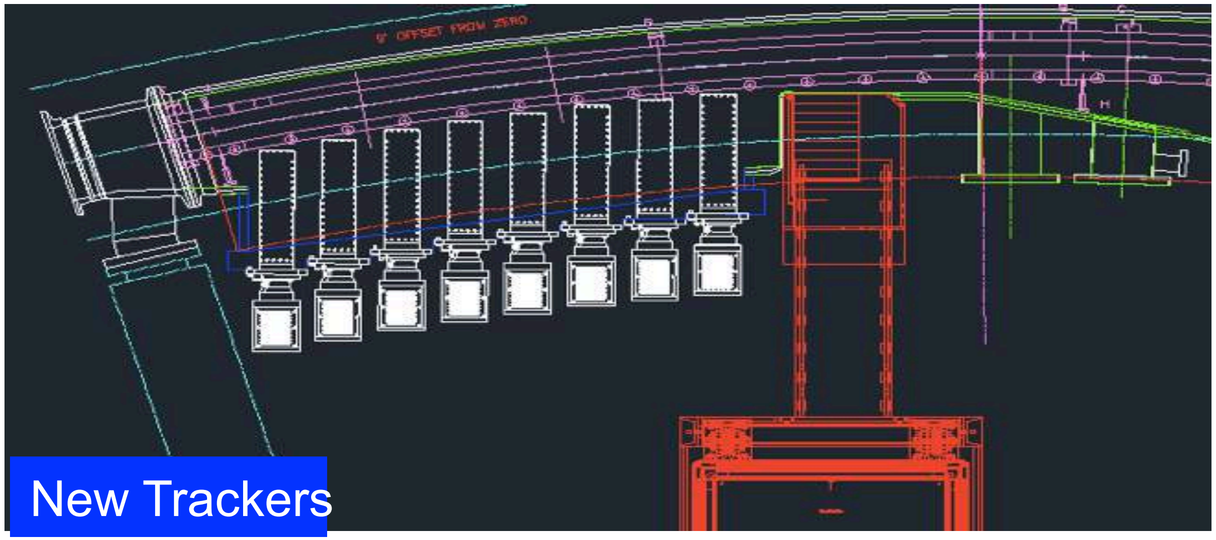
# New Detectors



New Calorimeter

**Calorimeter ($PbF_2$ + SiPMT)**

- more segmented.
- x2 sampling (800M/s) vs BNL
- quicker response (5 ns)
- improved energy resolution

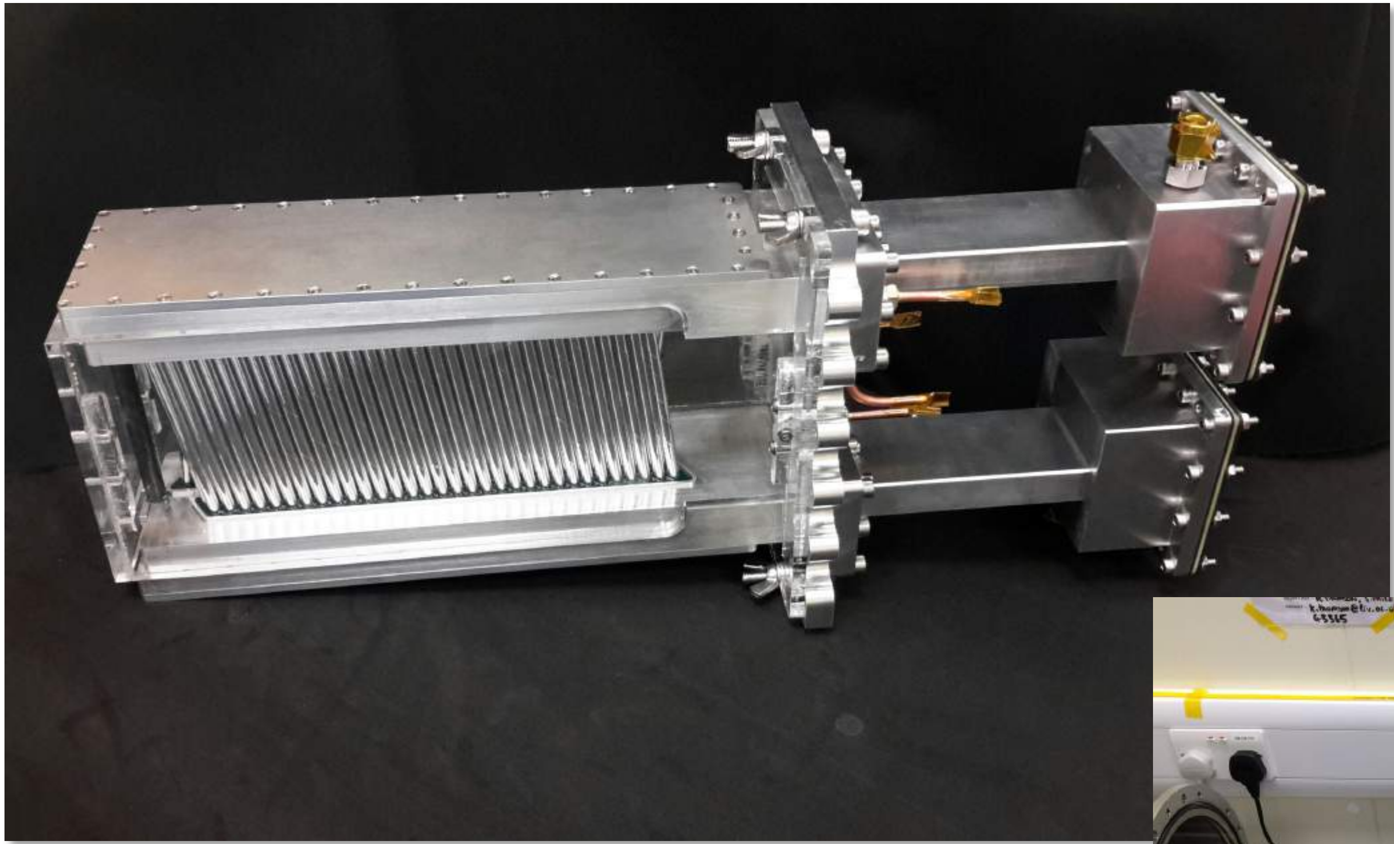


New Trackers

**Straw Trackers (UK)**

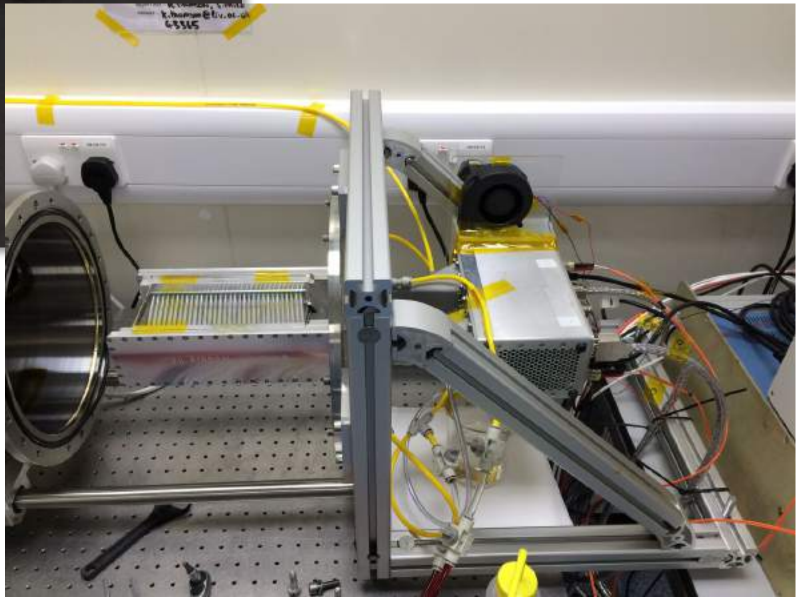
- authenticate pileup
- measure muon profile
- identify lost muons
- calibrate calorimeter
- measure EDM

# Straw Trackers



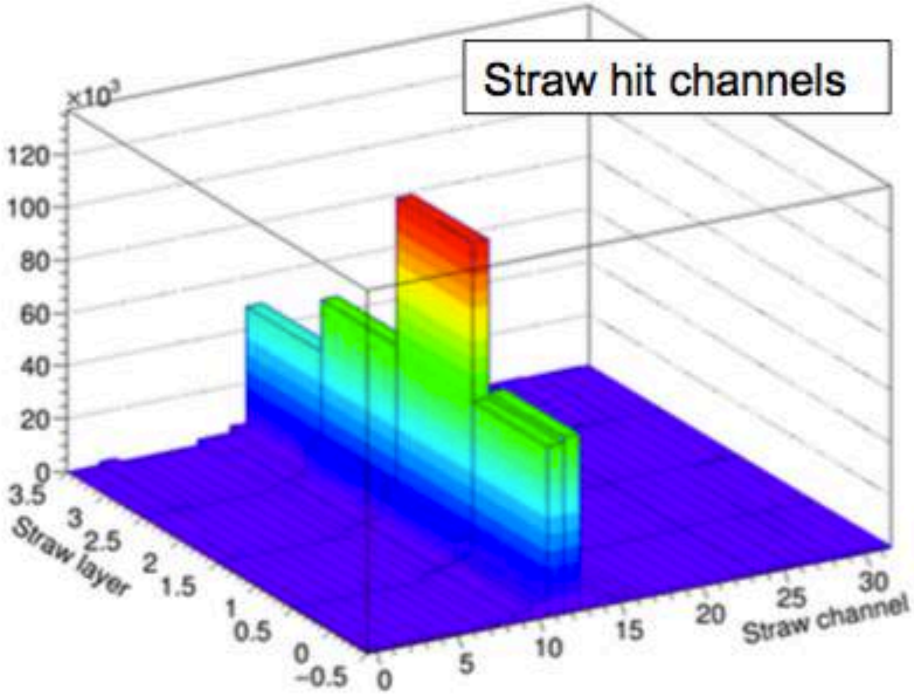
UK building
24 trackers
+ spares

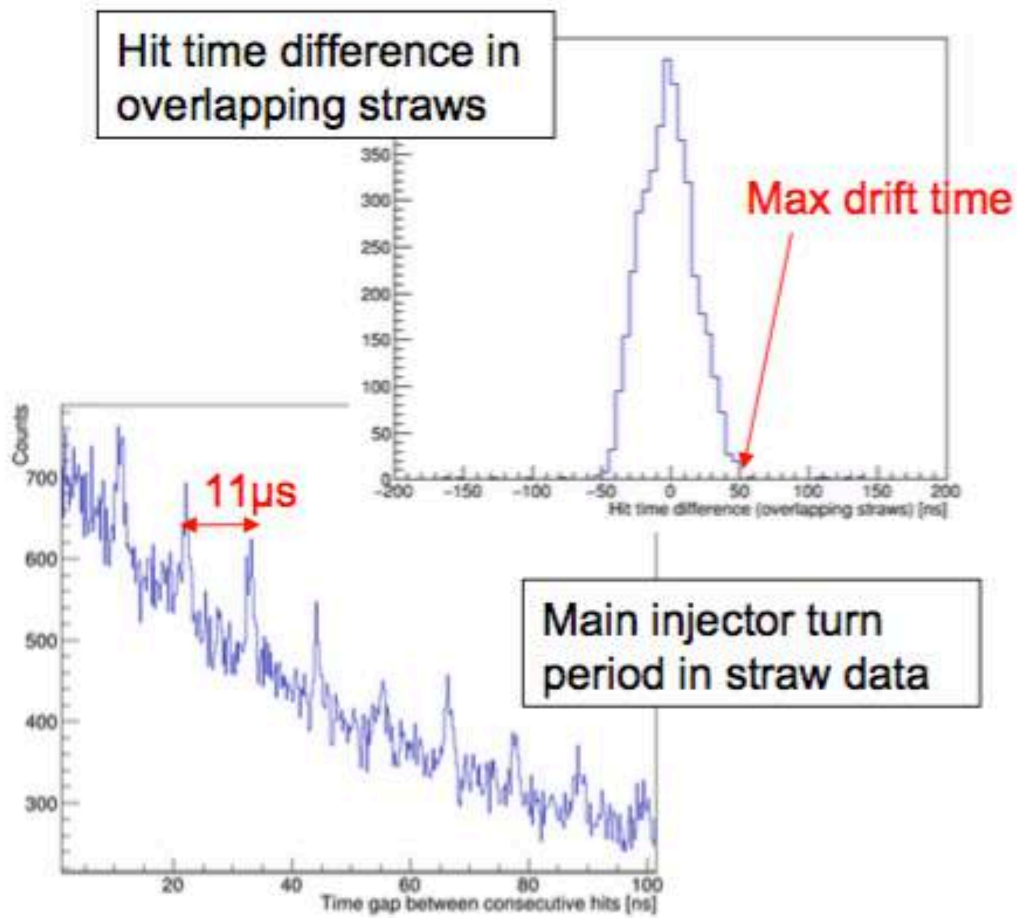
Funding for
2 RAs + techs.
£1M PPRP.



And off detector electronics, DAQ
DQM & offline tracker software.

Performing as expected in three testbeams at FNAL

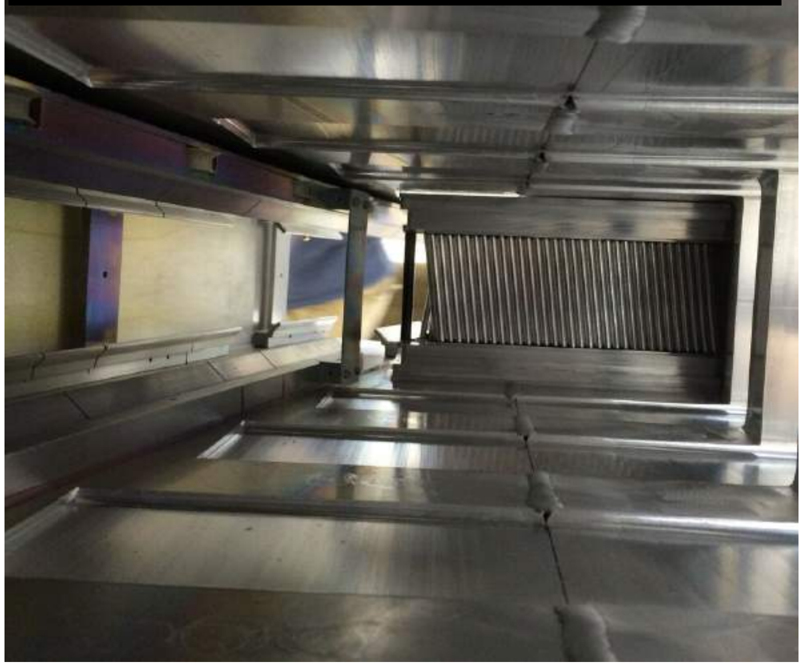


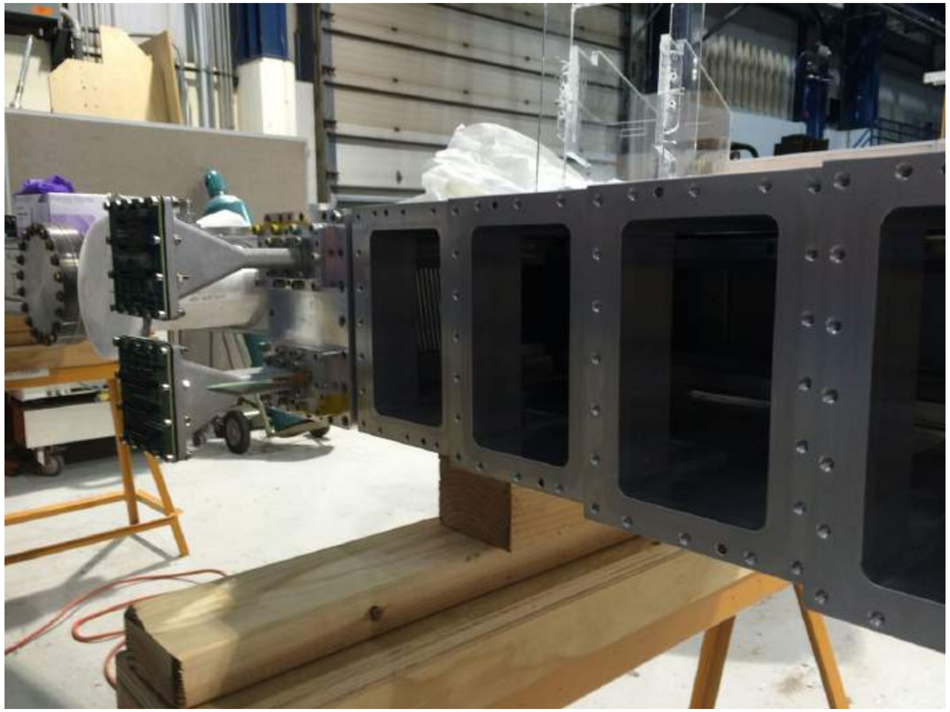

UK is leading offline and online analysis

# Straw Trackers

Mass production well underway at Liverpool and trackers arriving every 2 weeks at FNAL.



*Tracker in FNAL vacuum chamber*



1st 8 station tracker will be installed in November.
$2^{nd}/3^{rd}$ trackers before beam in June 2017.

# Schedule & Competition

Project has remained on-budget and on-schedule since 2013.

UK deliverables on track : project grant ends April 2017.

1st data-taking in 2017 when expect stats similar to BNL.

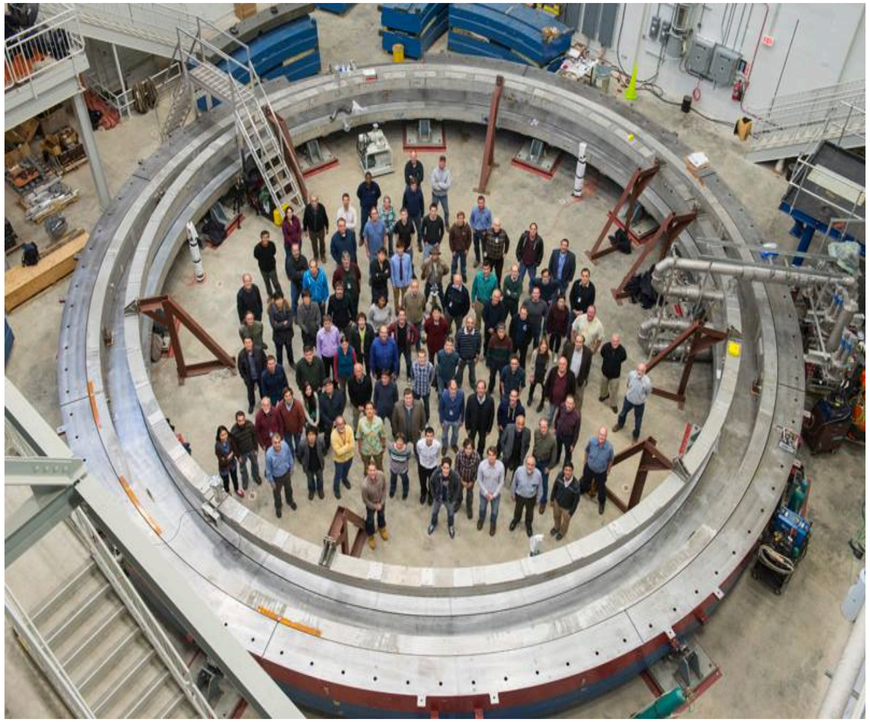
x20 BNL stats to be accumulated in 2018-2019.

RAs, M&O funded by STFC CG through to Sep 2019
- expect analysis to be conclude in subsequent CG-period.

**Competition**: J-PARC g-2

Still in R&D phase and not yet fully approved.
Will ultimately provide very valuable orthogonal measurement using a very different (and challenging !) technique

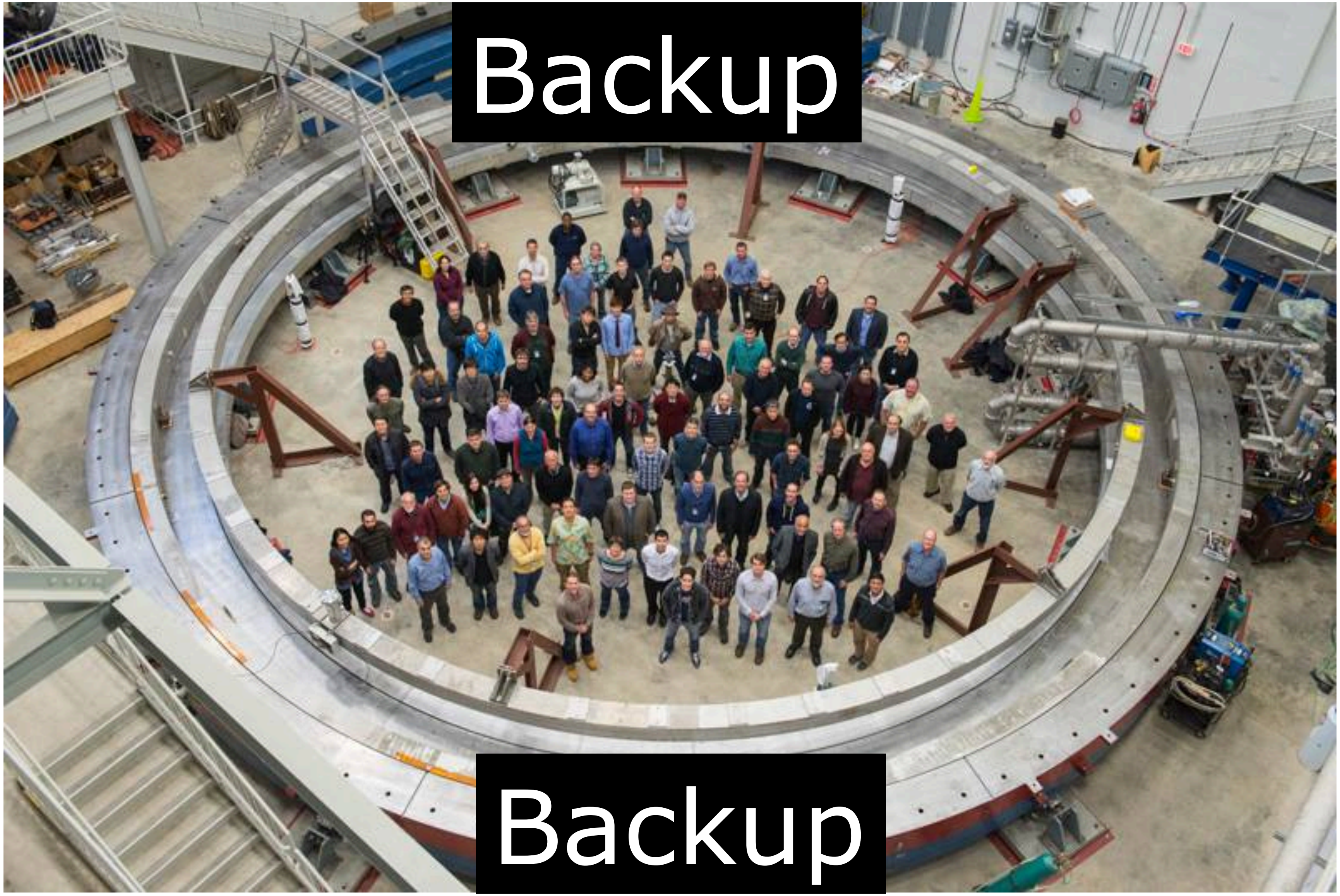
# Conclusion



g-2 is a critical measurement in establishing (or not) integrity of BSM models in concert with LHC: particularly the non-colour sector

UK making most significant contribution to experiment outside of US.

We need to cast the BSM-search net wide: if the current anomaly persists then FNAL g-2 would establish BSM at 9σ


Backup
Backup

# B-field / $\omega_p$ systematics

| E821 Error | Size [ppm] | Plan for the E989 $g-2$ Experiment | Goal [ppm] |
|---|---|---|---|
| Absolute field calibrations | 0.05 | Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics | 0.035 |
| Trolley probe calibrations | 0.09 | Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations | 0.03 |
| Trolley measurements of $B_0$ | 0.05 | Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients | 0.03 |
| Fixed probe interpolation | 0.07 | More frequent trolley runs; more fixed probes; better temperature stability of the magnet | 0.03 |
| Muon distribution | 0.03 | Additional probes at larger radii; improved field uniformity; improved muon tracking | 0.01 |
| Time-dependent external B fields | – | Direct measurement of external fields; simulations of impact; active feedback | 0.005 |
| Others | 0.10 | Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients | 0.05 |
| Total | 0.17 | | 0.07 |

# $\omega_a$ systematics

| E821 Error | Size [ppm] | Plan for the E989 $g-2$ Experiment | Goal [ppm] |
|---|---|---|---|
| Gain changes | 0.12 | Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash | 0.02 |
| Lost muons | 0.09 | Running at higher $n$-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation | 0.02 |
| Pileup | 0.08 | Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency | 0.04 |
| CBO | 0.07 | Higher n-value; straw trackers determine parameters | 0.03 |
| E-Field/Pitch | 0.06 | Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick | 0.03 |
| Diff. Decay | 0.05[1] | better kicker; tracking simulation; apply correction | 0.02 |
| Total | 0.20 | | 0.07 |

# Competition: J-PARC Muon g-2

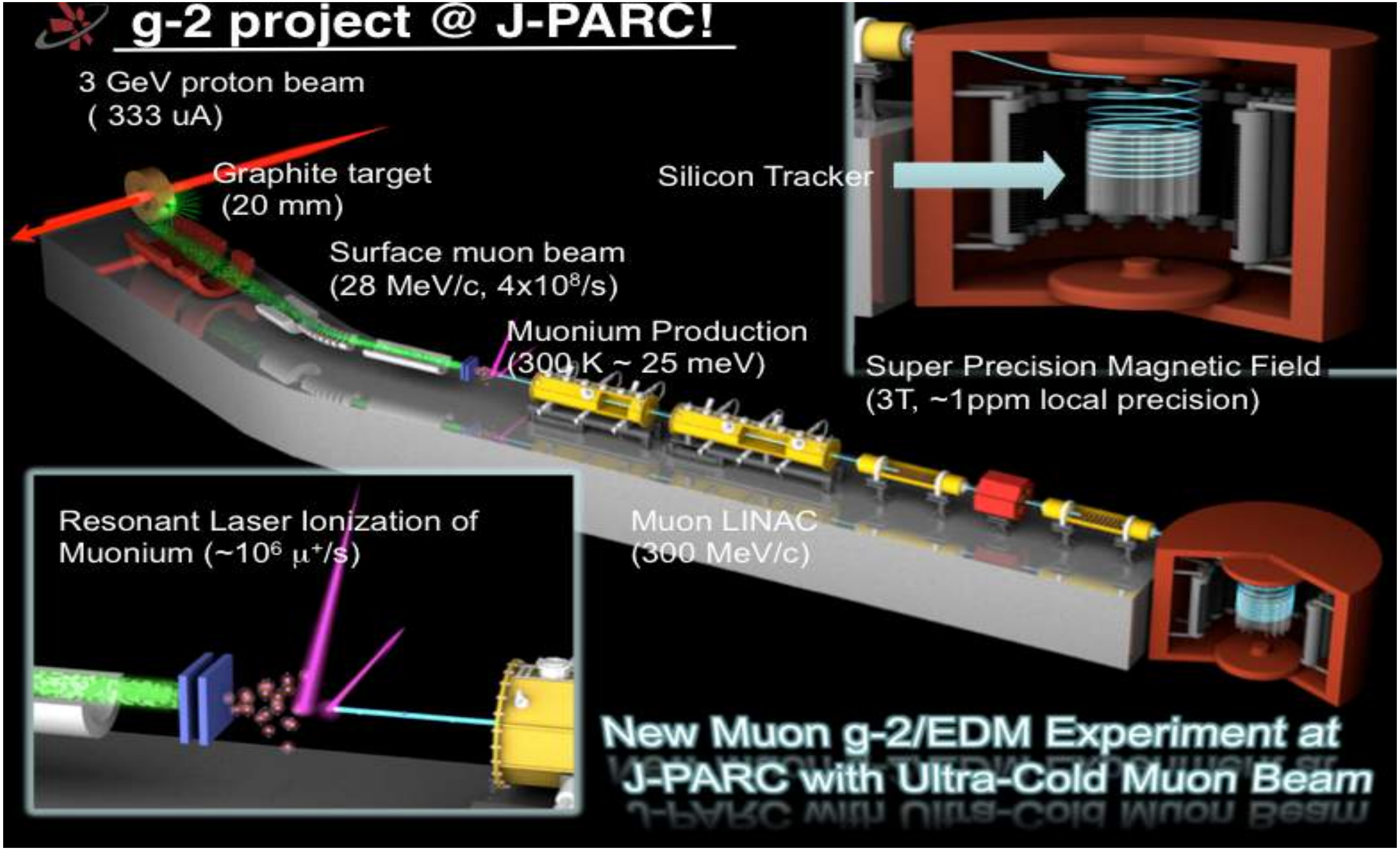
UCL

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

FNAL/BNL approach : use magic γ (29.3), p = 3.09 GeV muons.

J-PARC proposal : use E ~ 0
: ultra-cold muons (low β)
: larger (and more uniform) B (3T MRI magnet)

Unlike FNAL/BNL approach. This technique **has yet to be proven to work**


g-2 project @ J-PARC!
3 GeV proton beam
( 333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10⁸/s)
Muonium Production
(300 K ~ 25 meV)
Silicon Tracker
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10⁶ μ⁺/s)
Muon LINAC
(300 MeV/c)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

# J-PARC g-2 : Several Challenges

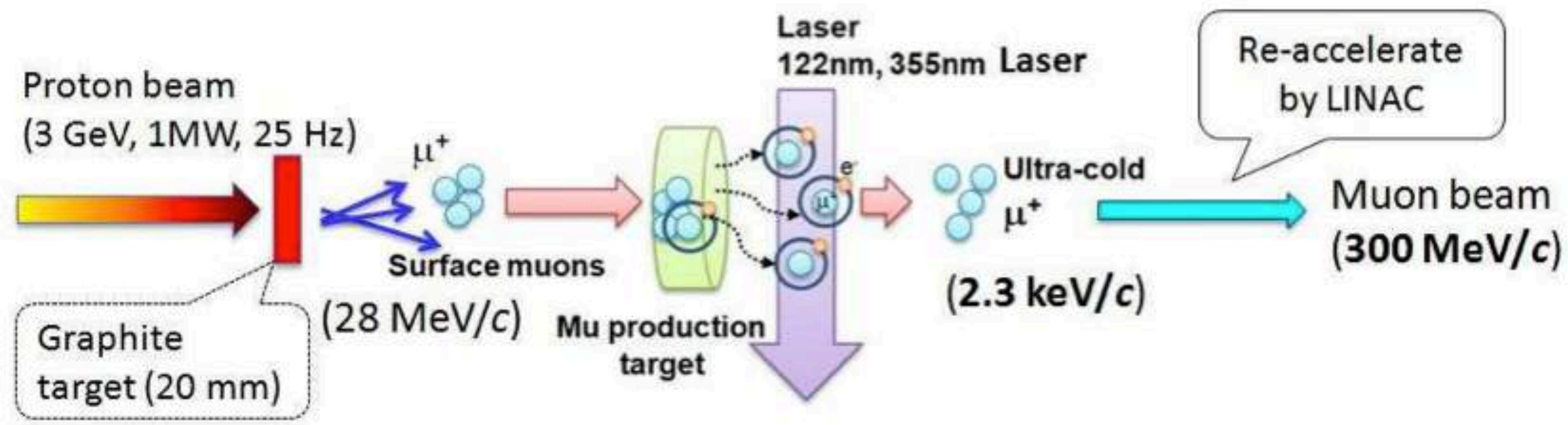
Getting a sufficient rate of ultra cold muons (require $10^6$ /sec and $10^{12}$ e+

Avoiding pile-up issues in detector with the 1 MHz rate

Achieving v. small vertical beam divergence : $\Delta p_T/p_T = 10^{-5}$

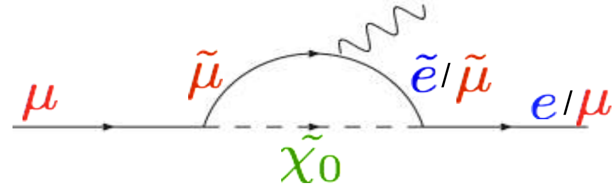
Requires advances in "muonium" production

- target materials e.g. nano-structured $SiO_2$
- lasers (pulsed 100 μJ VUV) to ionise muonium (x100)



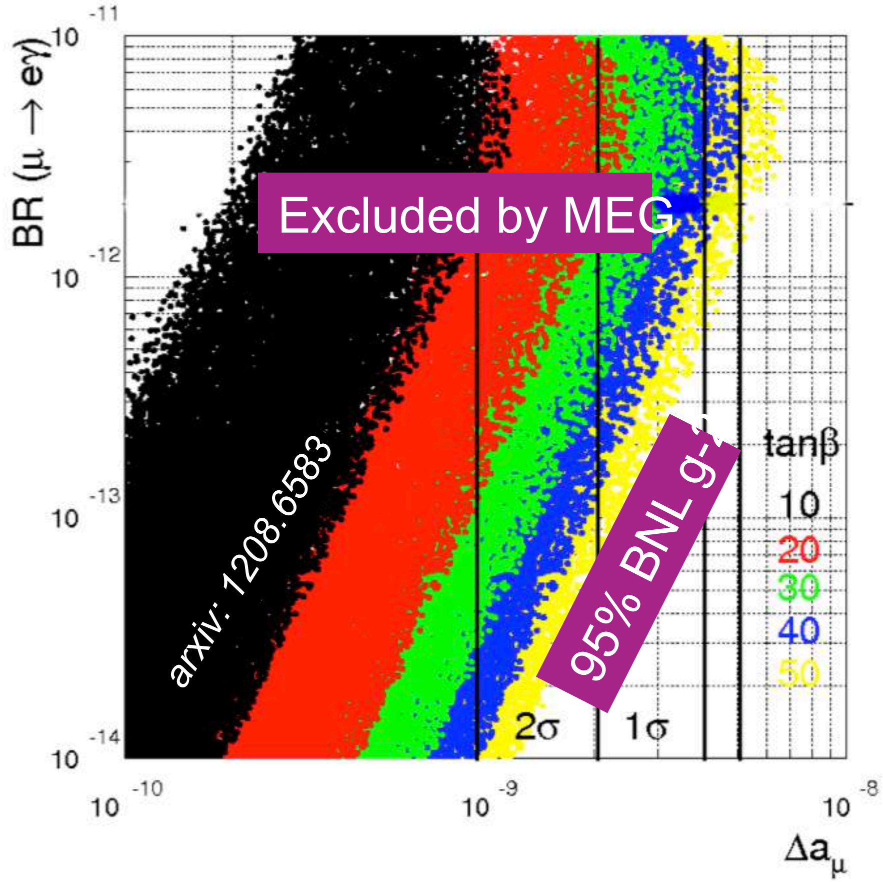
For BSM dipole interactions e.g. SUSY

$$\mathrm{Rate\ (CLFV)} \sim g^2 \times \theta_{e\mu}^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$




$$a_\mu \sim g^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$

But no theoretical motivation for any particular $\theta_{e\mu}$ value.




Need **both** measurements to resolve model degeneracy