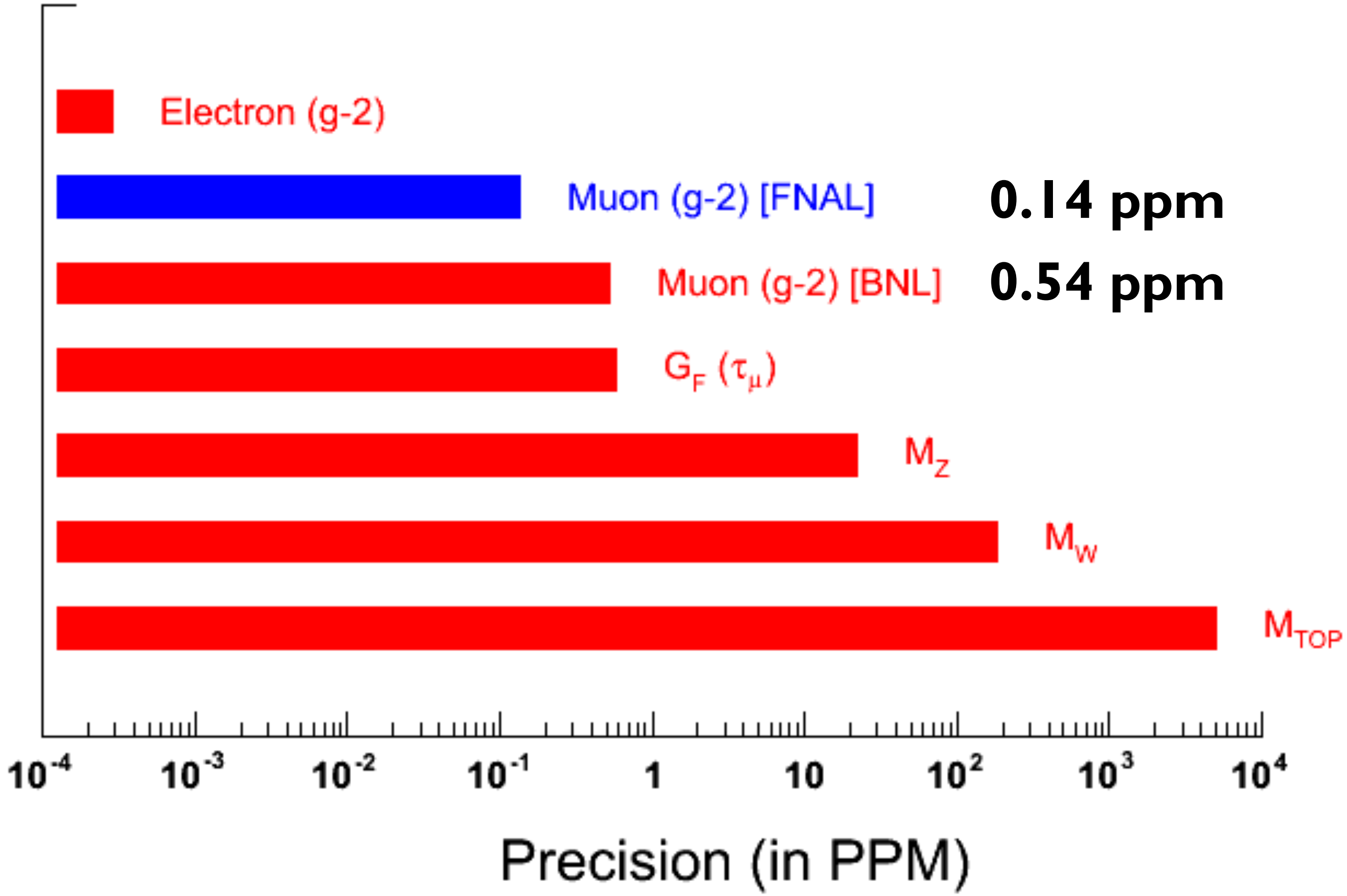
The Fermilab Muon g-2 Experiment

Mark Lancaster

UCL

Aim of Experiment

Make a 0.14 ppm measurement



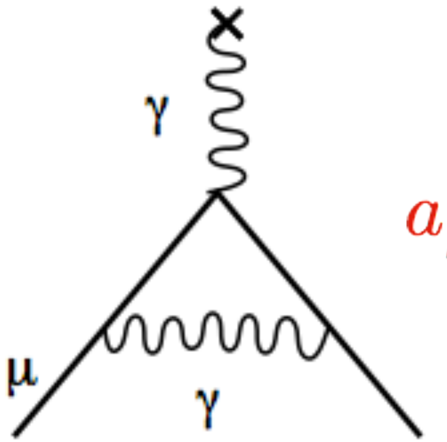
Anomalous Contribution

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

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

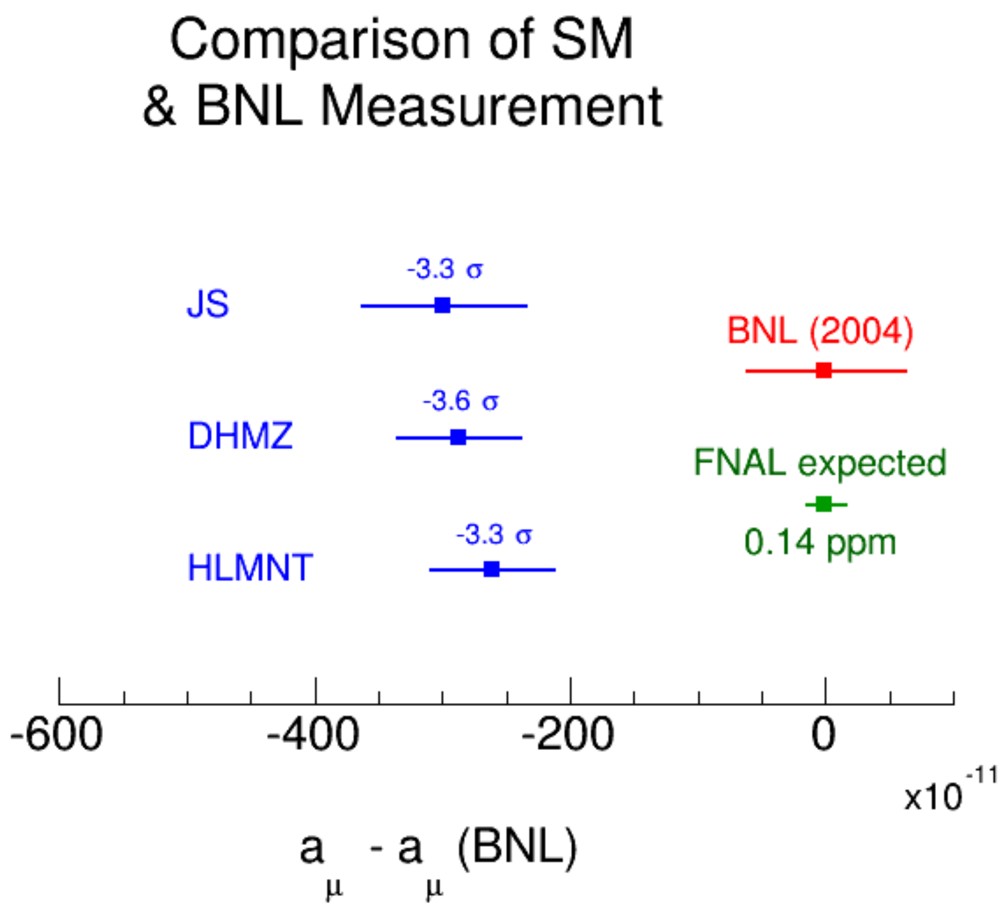
This is the so-called anomalous contribution

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

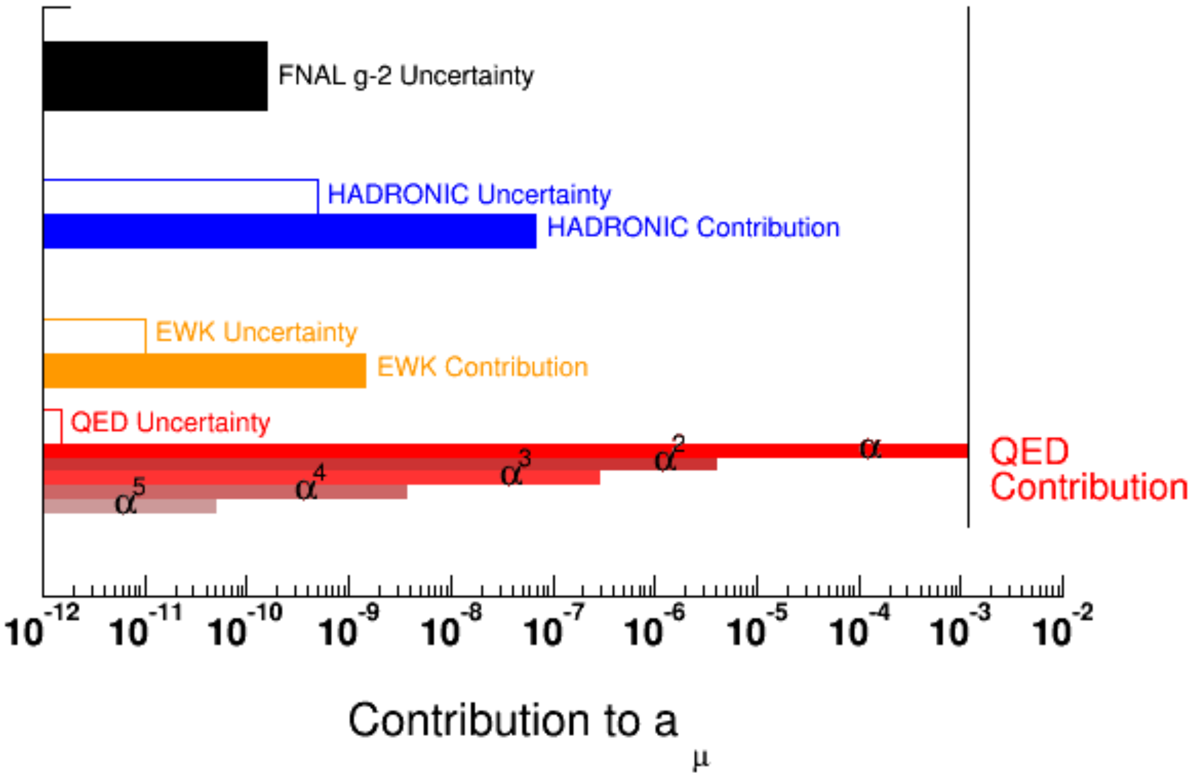


Present measurement is at odds with SM at 3.5σ level and now broad consensus on SM value

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

SM contribution

Hadronic, EWK and 5th order QED contributions are all in play.



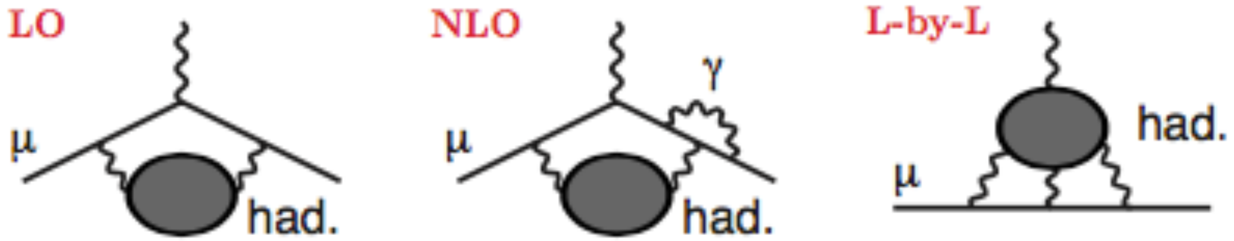
Uncertainty on EWK and QED is tiny and SM uncertainty is dominated by hadronic uncertainty.

Hadronic Uncertainty

Consensus average over several independent determinations a la PDFs at LHC.

Largest contribution to uncertainty is not theory but the precision, compatibility (and range) of low energy e^+e^- cross section data.

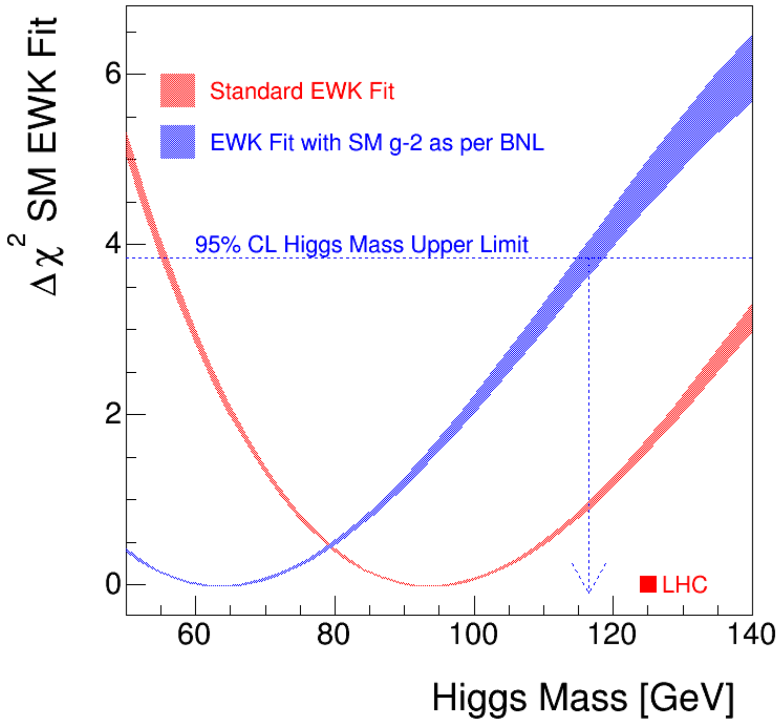
$$a_\mu^{\text{had}} = a_\mu^{\text{had,VP LO}} + a_\mu^{\text{had,VP NLO}} + a_\mu^{\text{had,Light-by-Light}}$$



Contribution to hadronic uncertainty	75%	~ 0%	25%

SM Hadronic Uncertainty

While there are tensions amongst the various e^+e^- datasets reflected in a conservative error these are far from sufficient to explain away the BNL anomaly.



The SM hadronic estimate would need to be wrong by 6σ and this would shift α_{EM} and the EWK fit of the Higgs mass.

You cannot cook-up a zero g-2 SM anomaly and be consistent with the LHC Higgs mass !

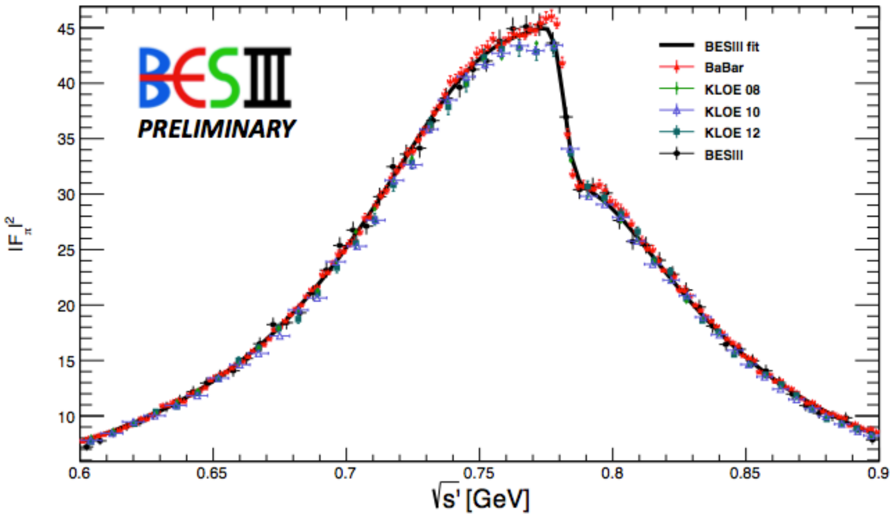
SM Hadronic Uncertainty

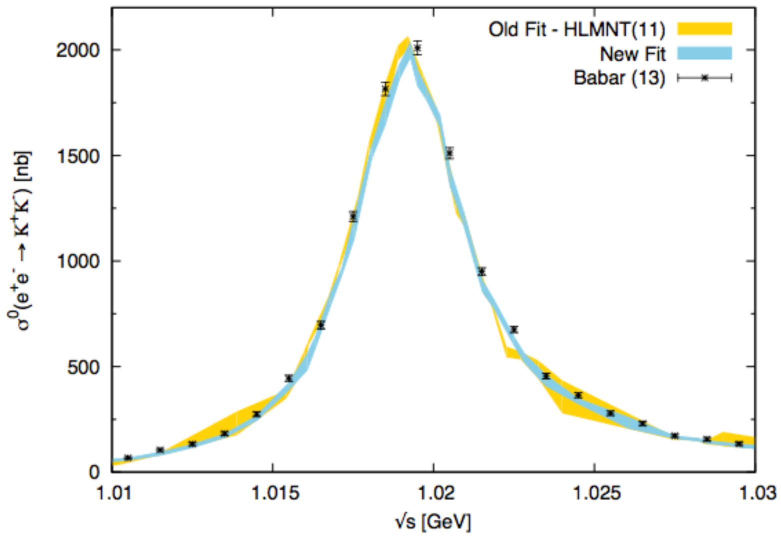
Expect that hadronic estimate will be improved by a factor of 2 in time for FNAL g-2 result from:

- more precise data with more channels and ISR vs direct-scan from BES-3, SND, CMD-3, KLOE-2, final BaBar and then Belle-2

- lattice calculations of the HLBL

This would mean a 5.5σ significance from the experimental improvement becomes 9.7σ.





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

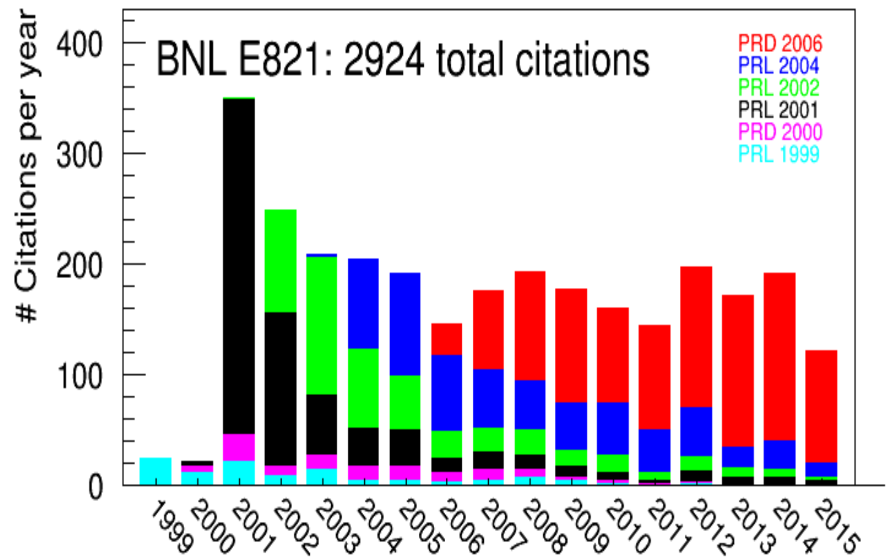
Large +ve anomaly wrt SM

Extended technicolor (fermion masses)

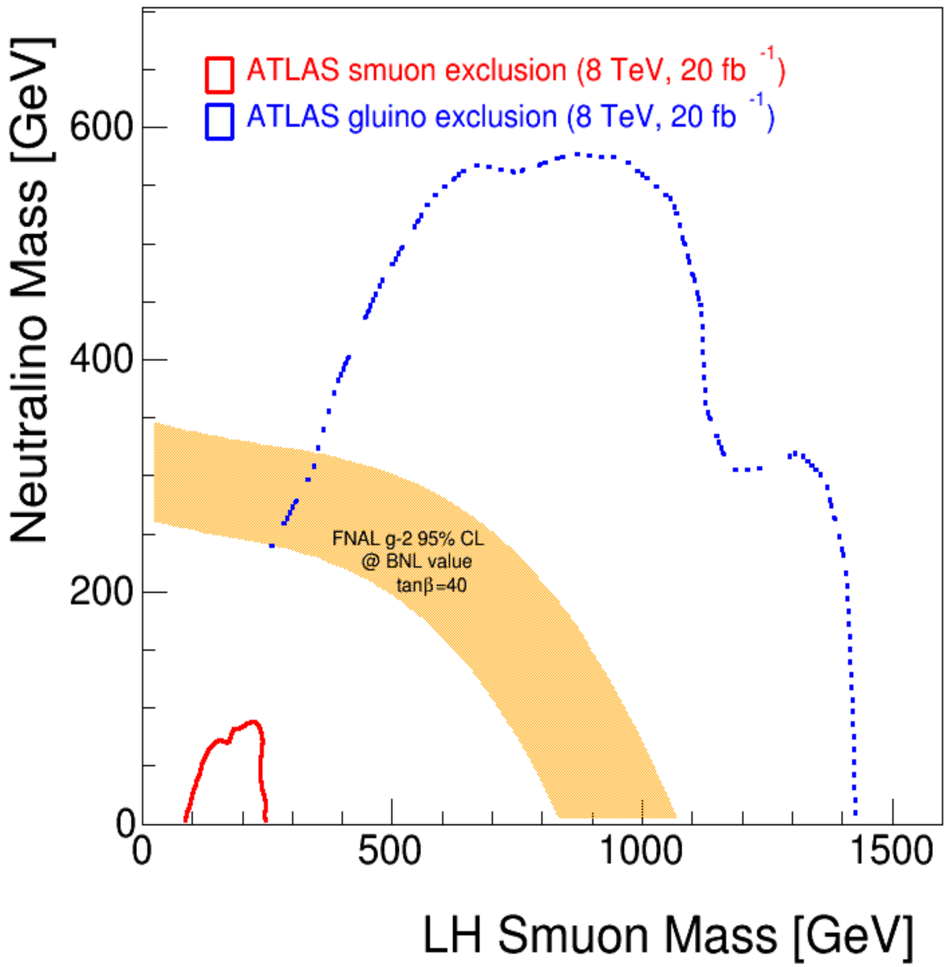
SUSY, RS ED
Extra Higgs Doublet

Z', W', Little Higgs,
Universal ED

Value consistent with SM



Complements LHC

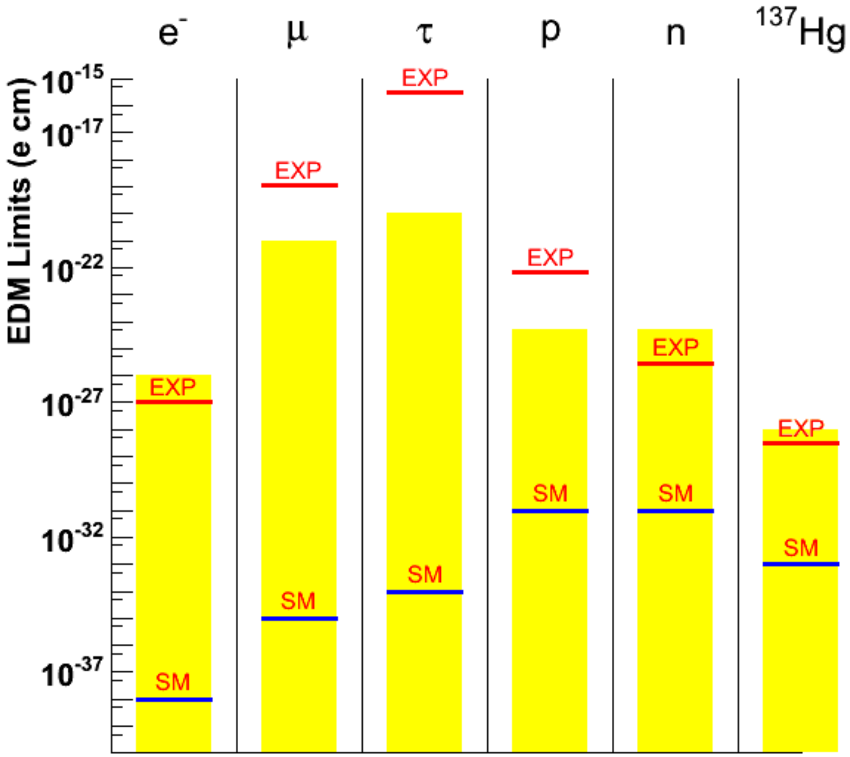


LHC cannot probe all of phase space e.g. small mass slepton/neutralino mass differences, high tanβ.

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

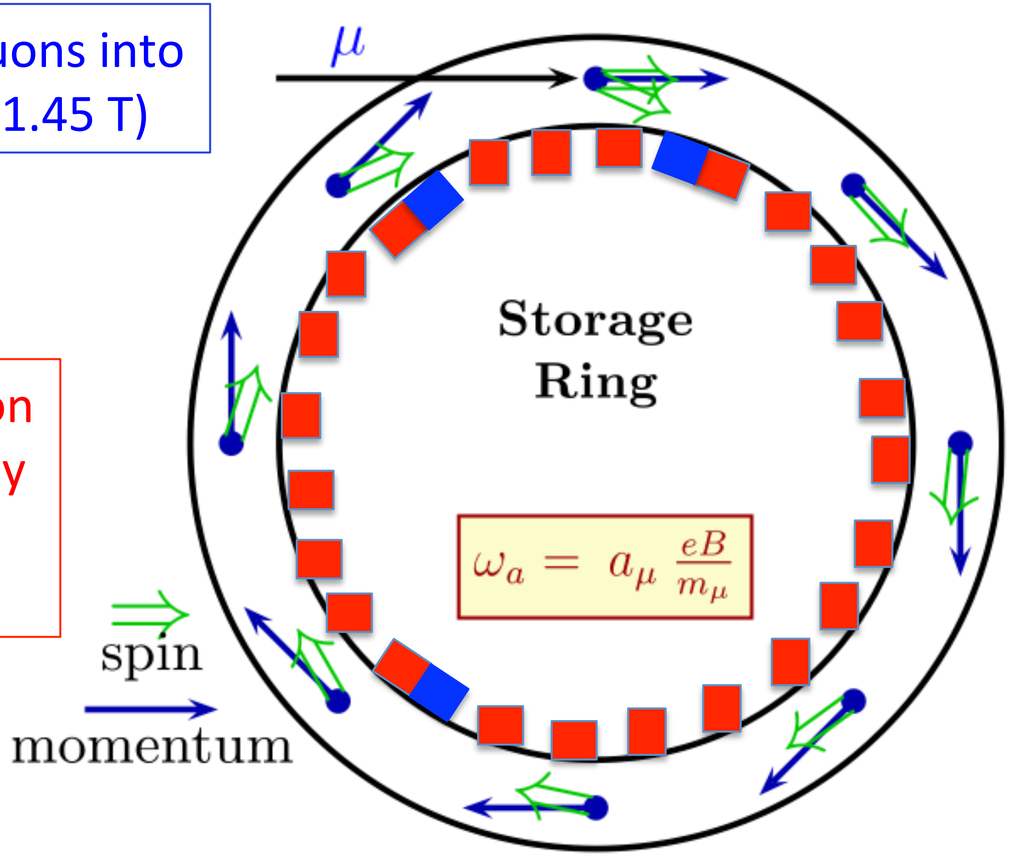
BNL limit is 1.8×10^{-19}

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

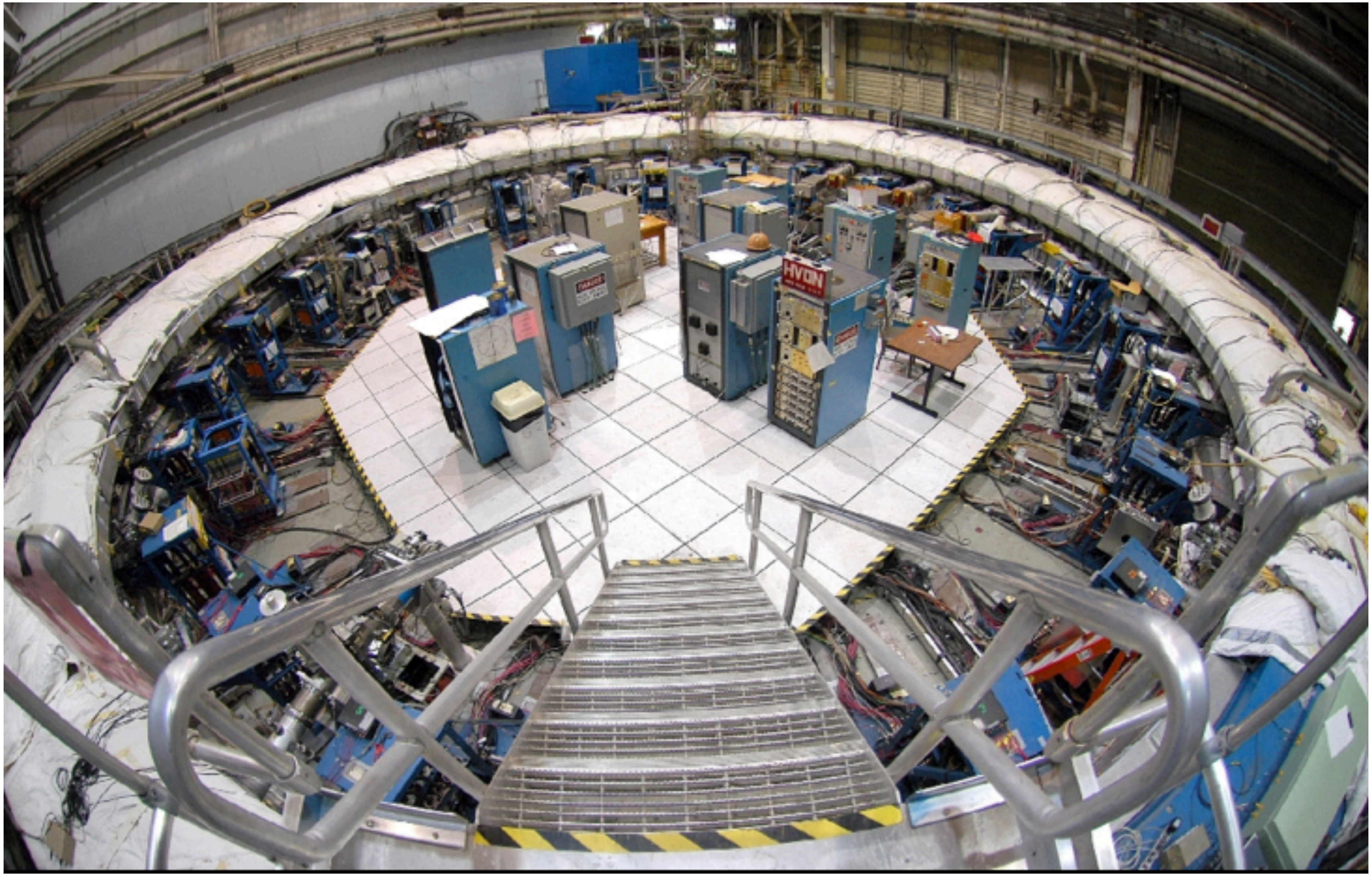
Inject 3.09 GeV muons into a storage ring (B = 1.45 T)

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

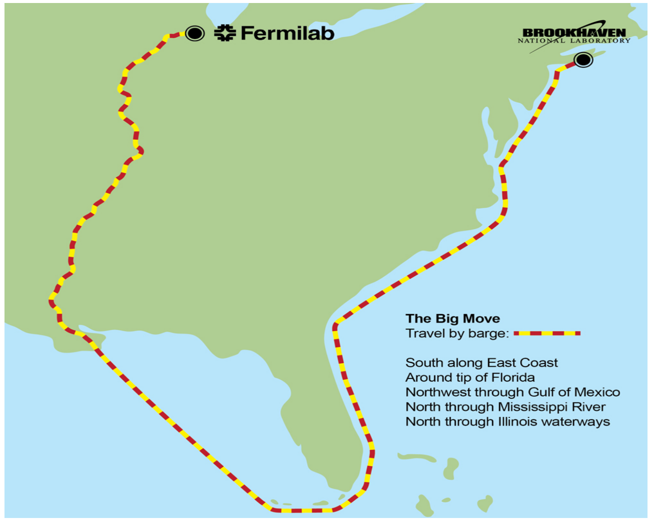


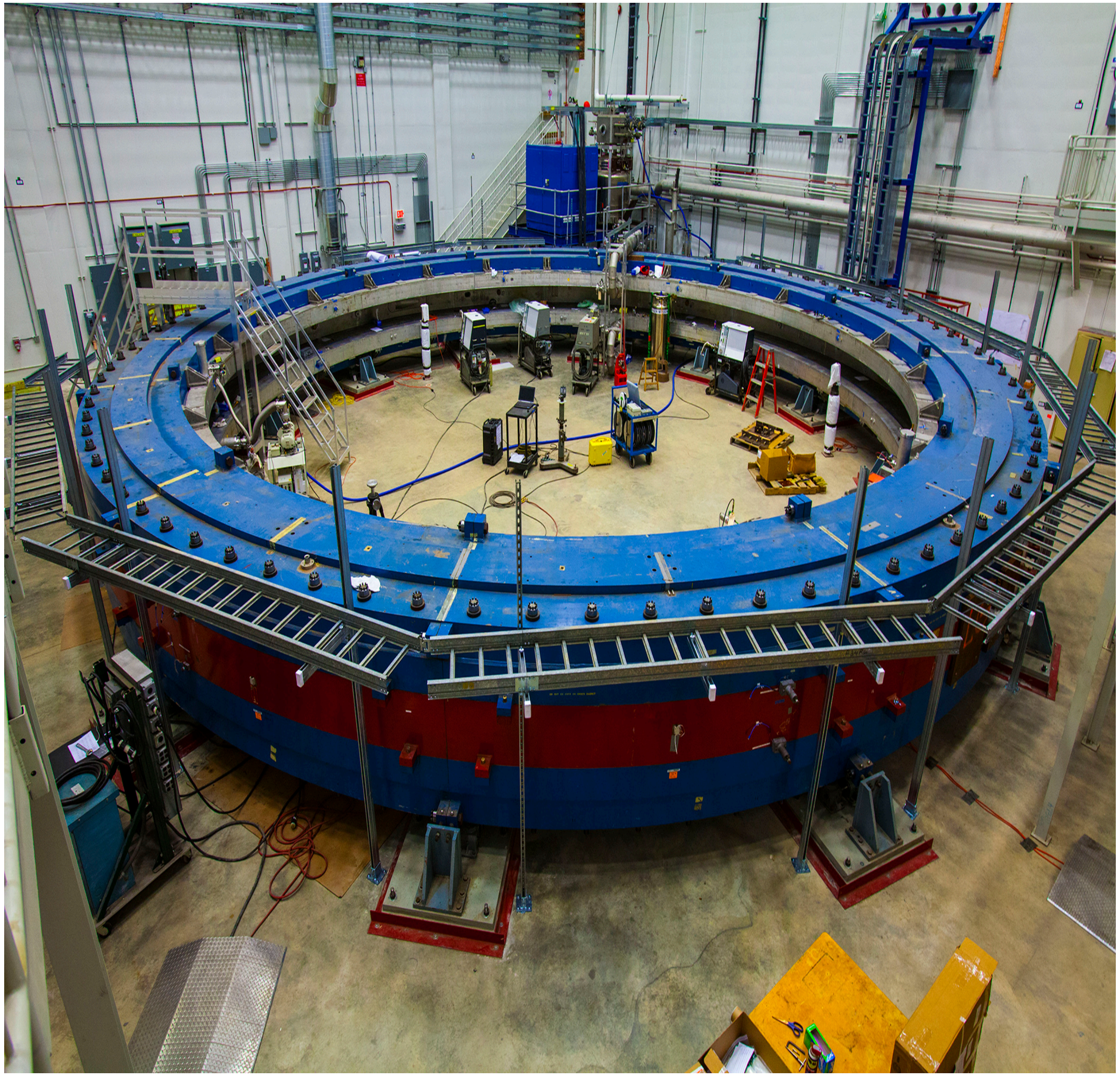
24 calorimeters and **3 straw-strackers (UK)** measure e^+ for O(1 ms) for spills separated by 10ms.
16,000 stored 3.09 GeV muons from 10^{12} protons per spill.

Storage ring at BNL



Storage Ring At FNAL





Muon Campus 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

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

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

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

New / improved technologies

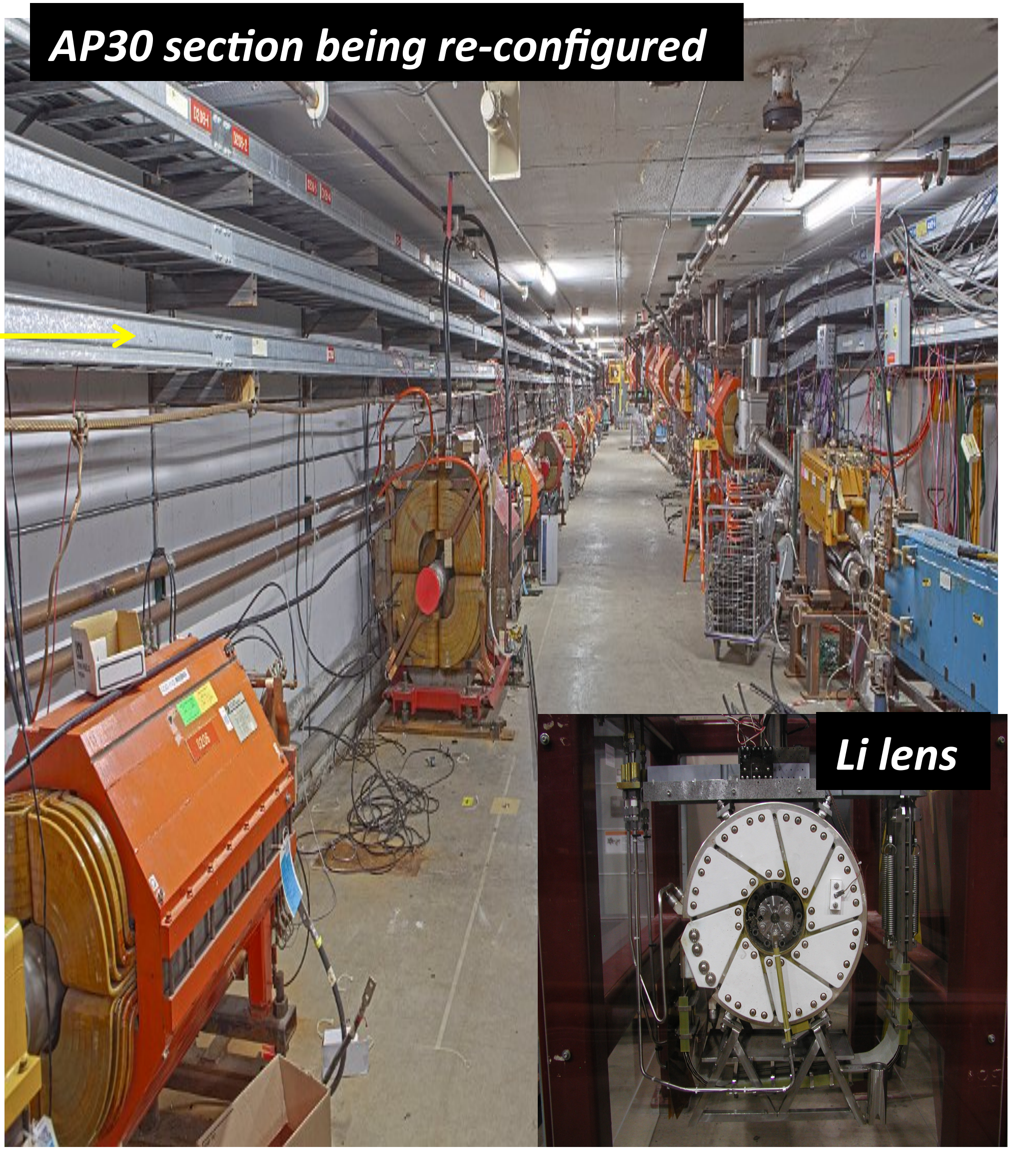
Additional collaborators

Building on wealth of experience from BNL E821 & other expts

Status

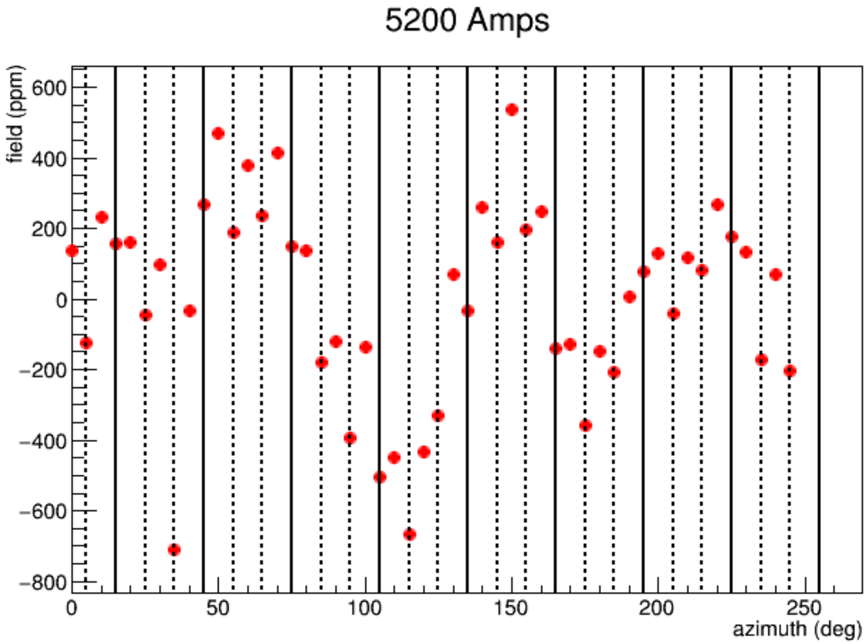
UCL


Both g-2 and Mu2e beamlines
from delivery ring to experimental
halls are complete
g-2
Mu2e


AP30 section being re-configured
Li lens

Muon focussing Quads

Ring has been cooled & powered

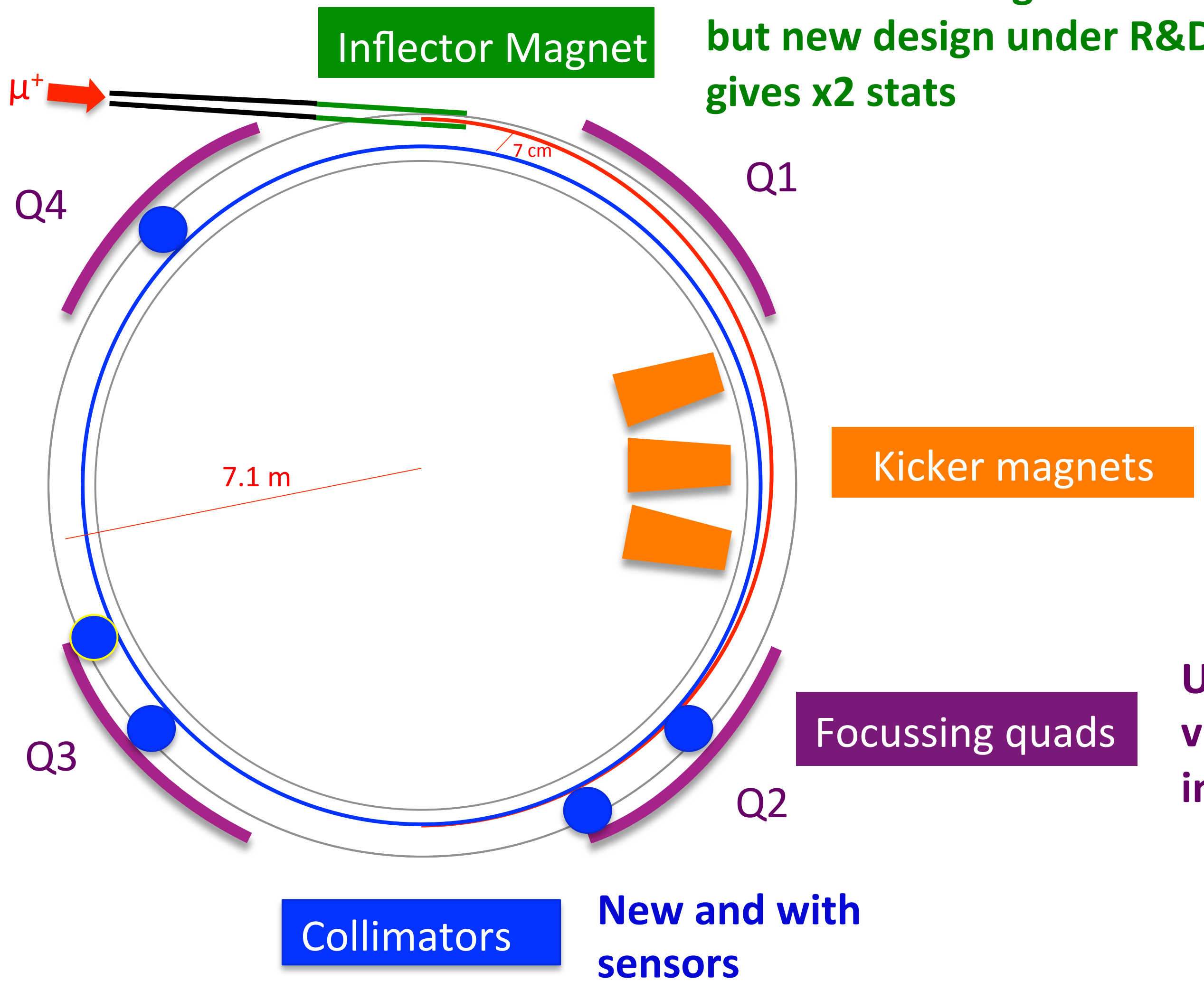


Magnet now on at 1.45T (4.5k) : start of B-field data-taking.

Measured mechanical strains/motion as expected from BNL.

Shimming of magnet for next 9 months to improve field uniformity by a factor of 100 prior to installation of detectors.

Improvements to injection system



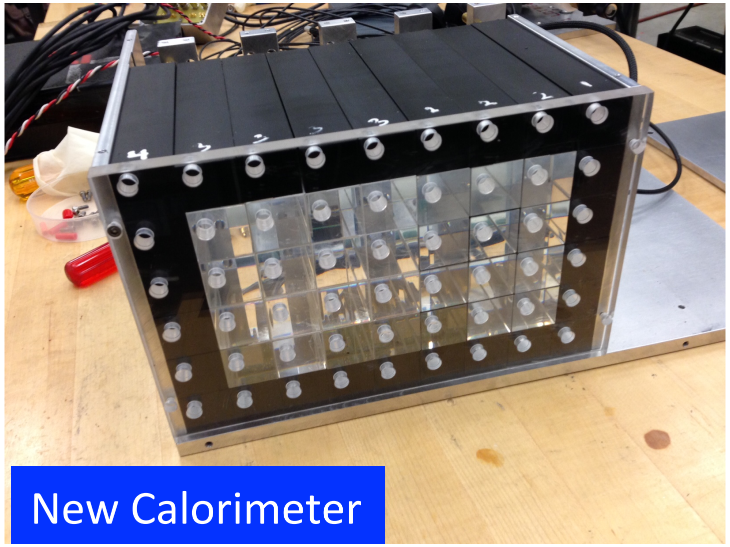
Baseline: existing BNL inflector but new design under R&D which gives x2 stats

New with improved kick

Using higher voltage for improved tune

New and with sensors

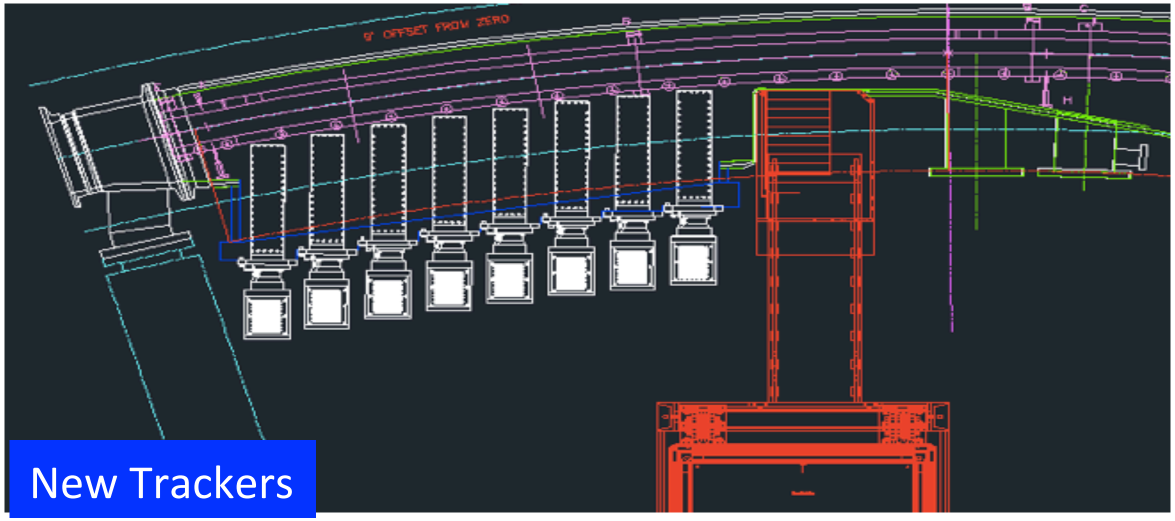
New Detectors



New Calorimeter

Calorimeter (PbF_2 + SiPMT)

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

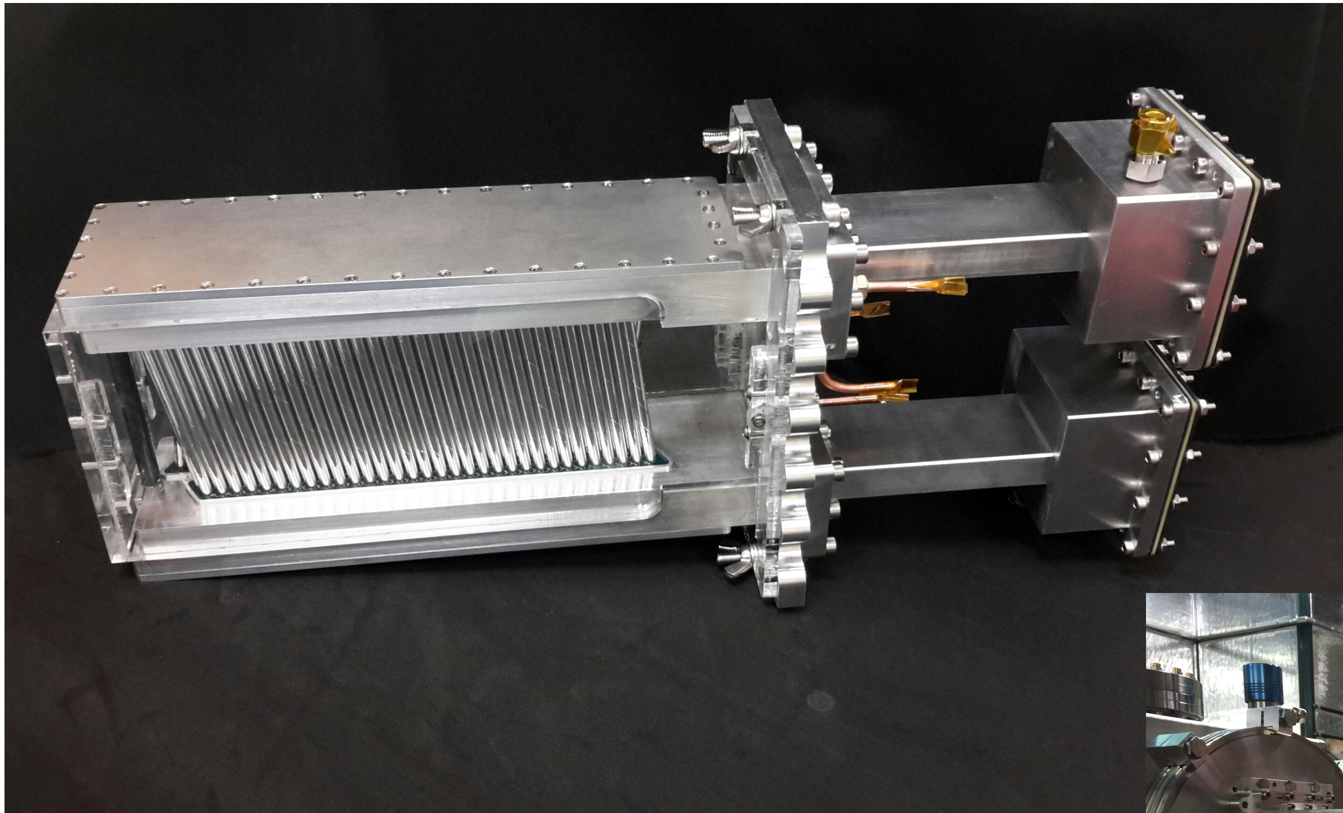


New Trackers

Straw Trackers (UK)

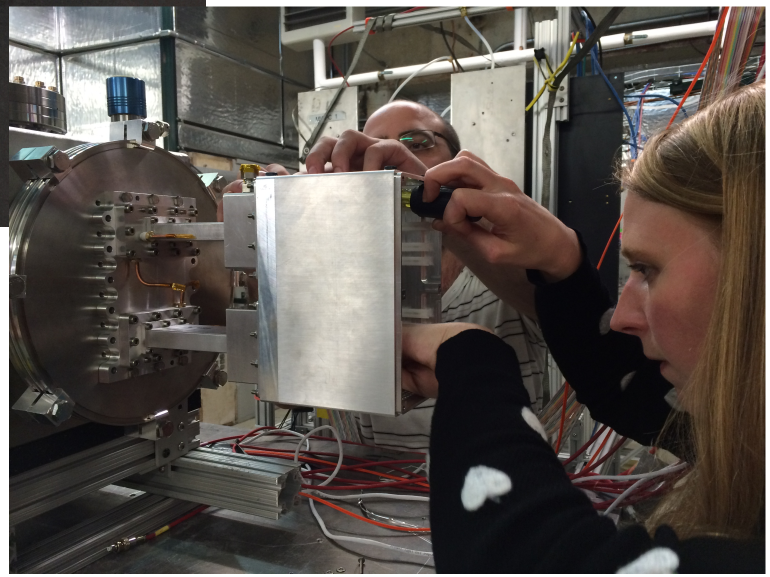
- authenticate pileup
- measure muon profile
- identify lost muons
- calibrate calorimeter
- measure EDM

Straw Trackers



UK building
24 trackers
+ spares

Funding for
2 RAs + techs.
£1M PPRP.

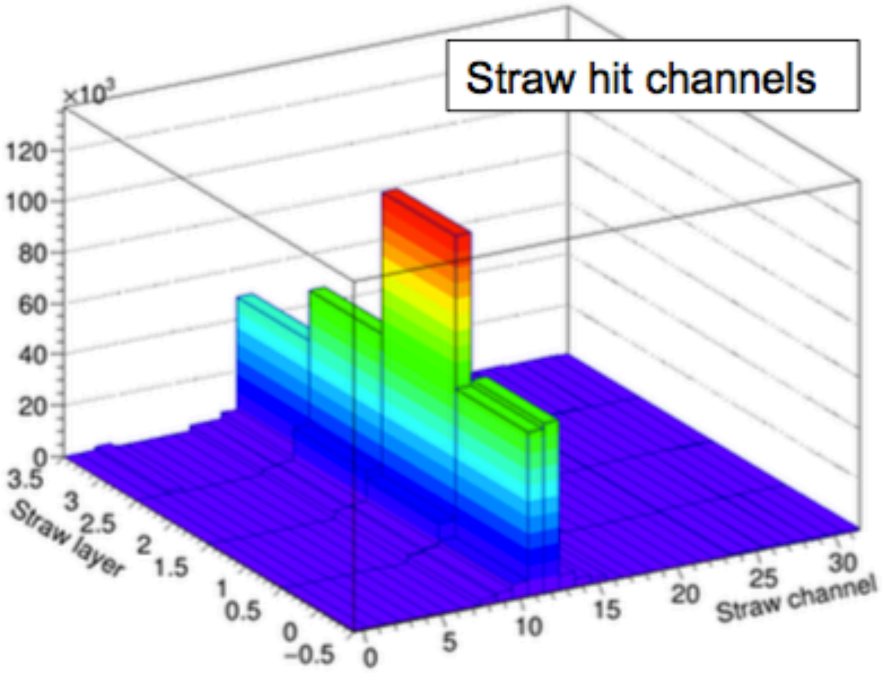


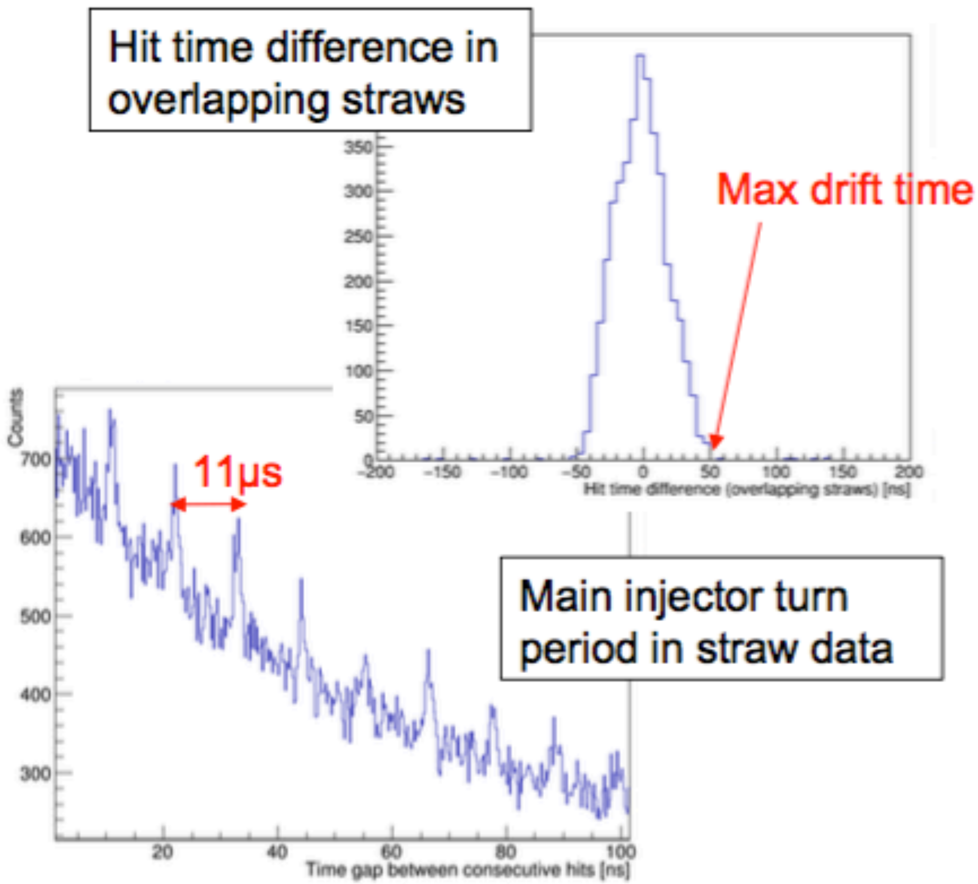
And off detector electronics, DAQ
DQM & offline tracker software.

Also prototyping ^{3}He magnetometer

Straw Tracker

Performing as expected in three testbeams at FNAL

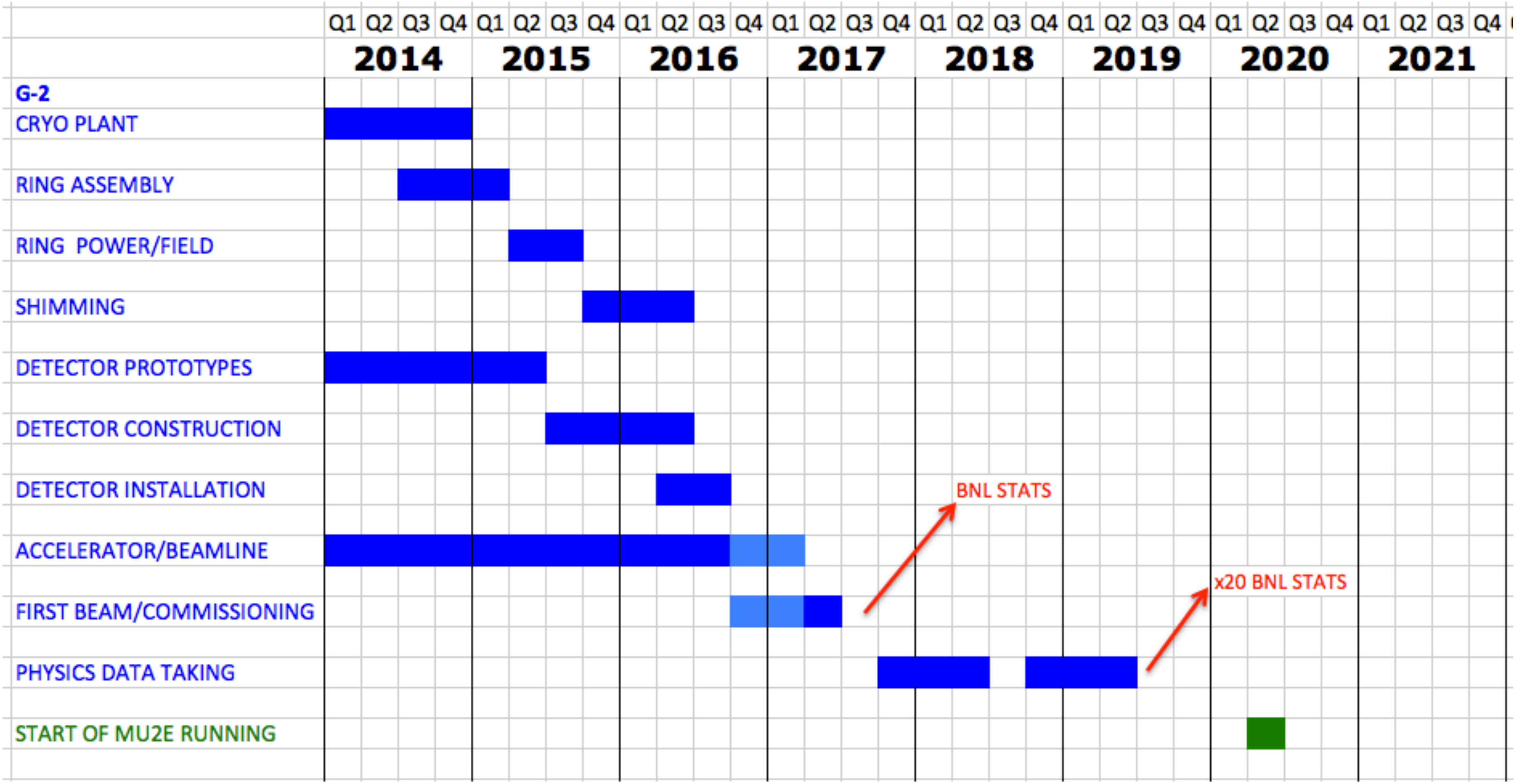




UK is leading offline and online analysis

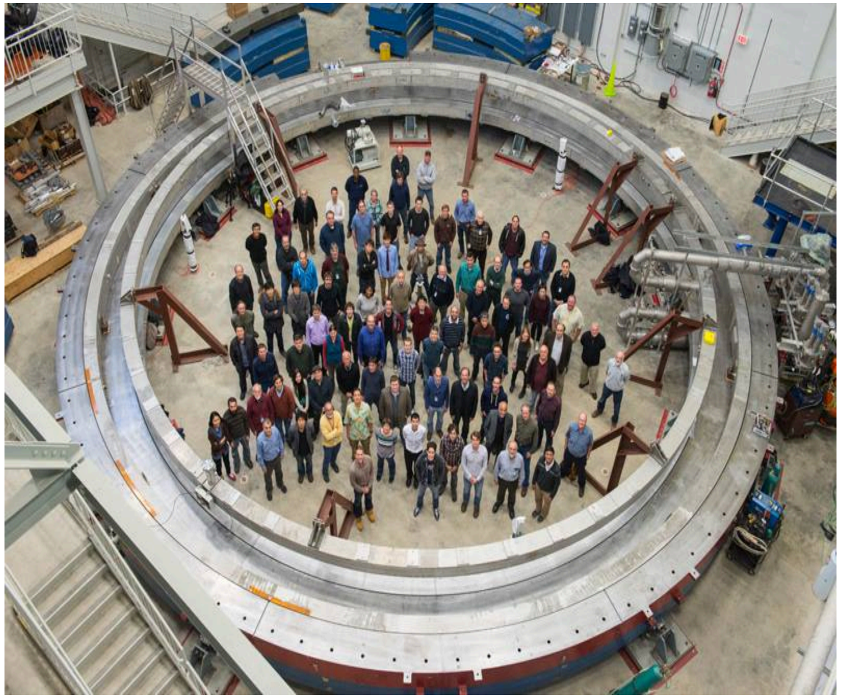
Schedule

CD2/3 approved and fully funded ($47M)



Schedule unchanged since 2013: 1st data taking period will end in 2017

Conclusion

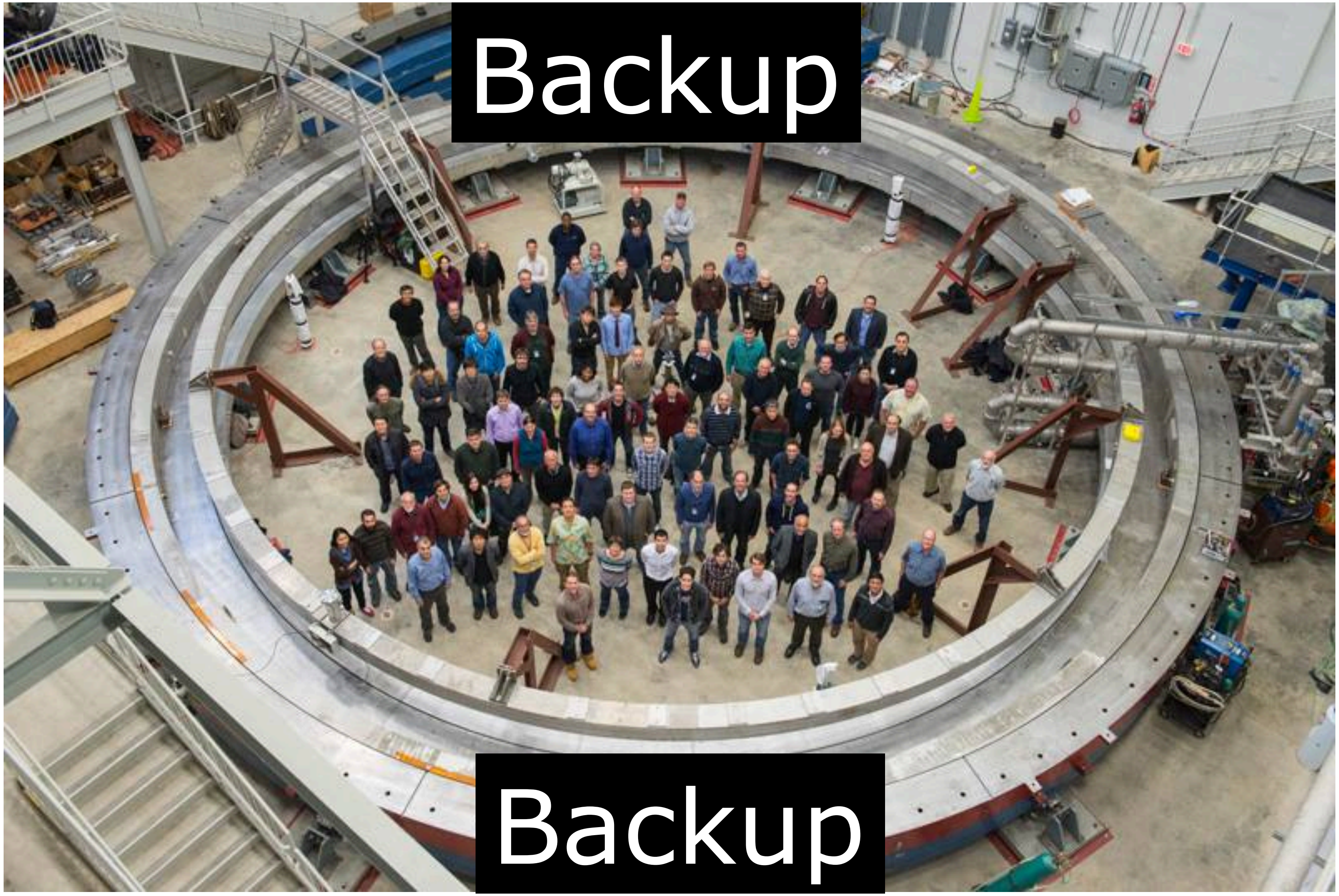


g-2 is a critical measurement in establishing (or not) integrity of BSM models in concert with LHC: particularly the non-colour sector

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



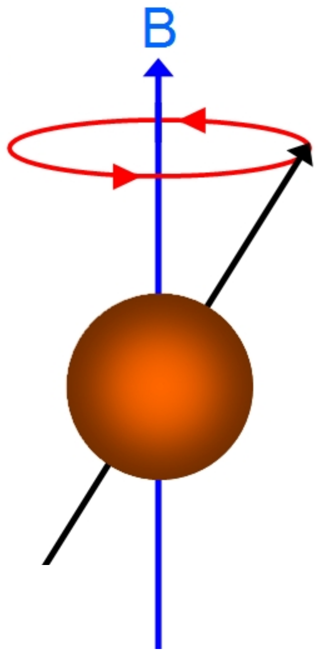
Backup

Methodology

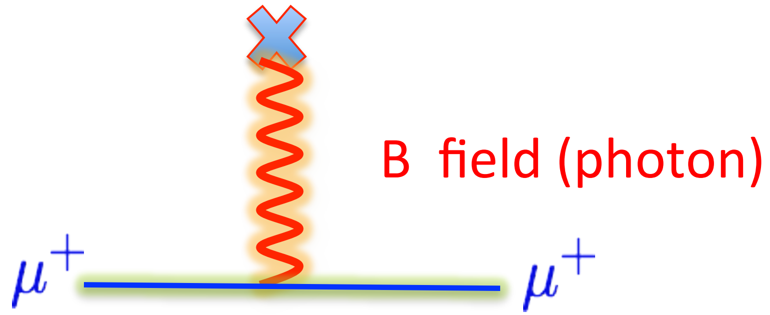
$$\vec{\mu} = g\frac{Qe}{2m}\vec{s}$$

Interaction between
magnetic moment (spin) with B-field.

$$\vec{\mu} \times \vec{B}$$

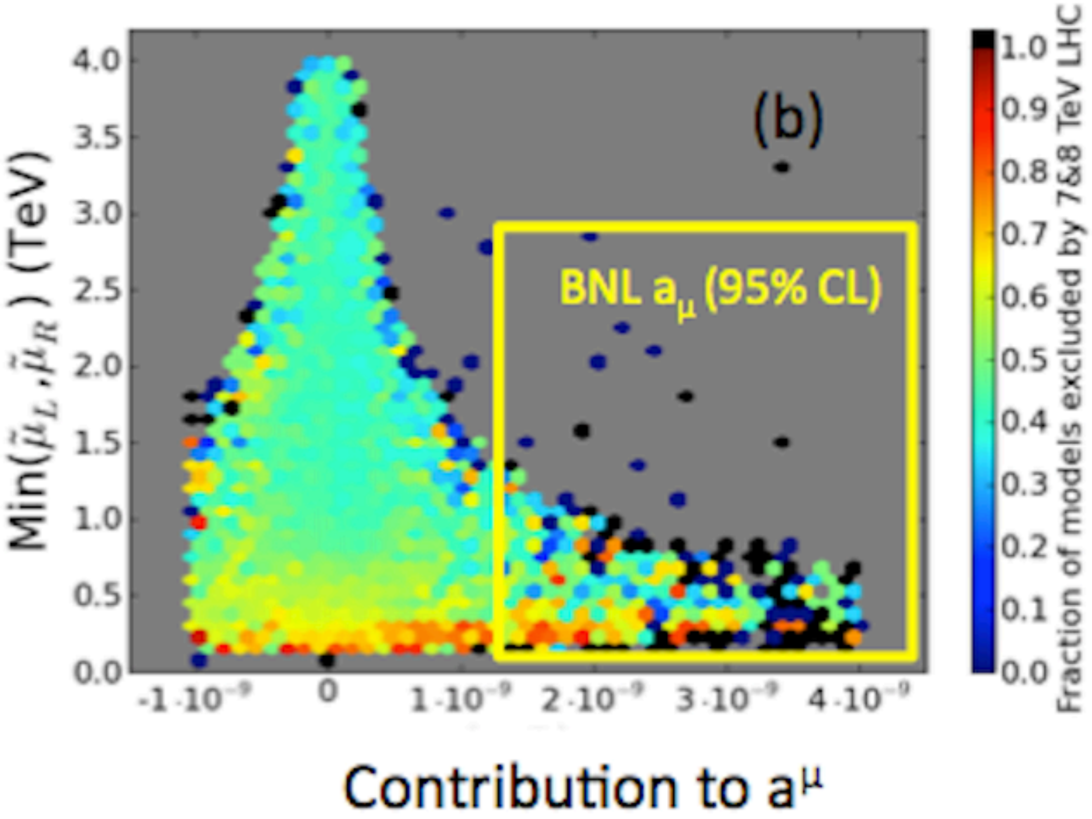


Spin **precesses** around B at
a frequency determined by “g”



pMSSM Models

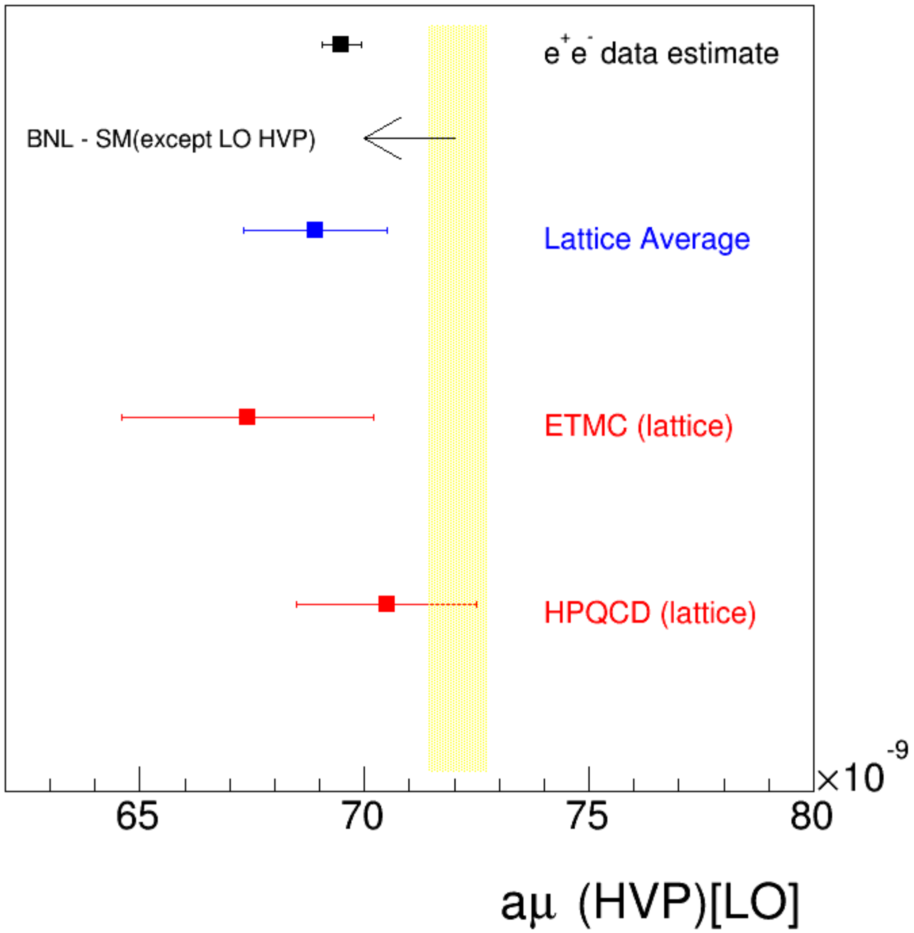
CMSSM cannot accommodate BNL result since assumes slepton masses are TeV+ like the excluded squarks/gluons.



Approx 50% of models predicting large g-2 not yet ruled out by LHC data.

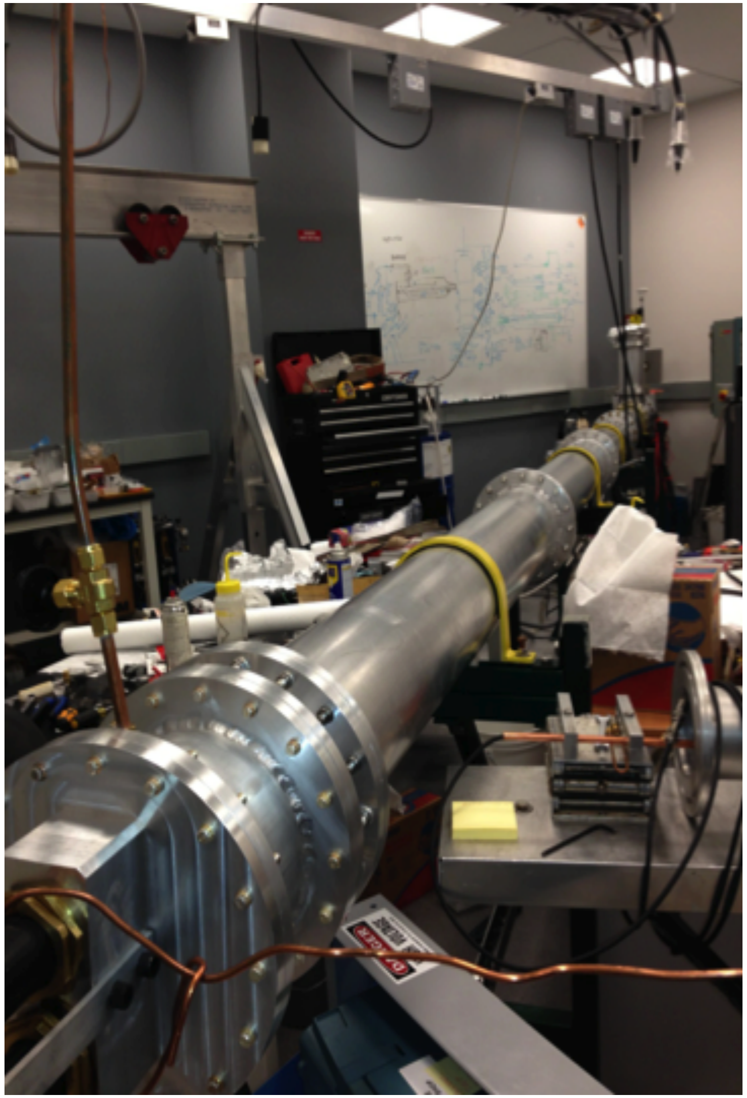
M. Cahill-Rowley et al., Eur. Phys. J72, 2156 (2012); Phys. Rev. D 88, 035002 (2013).

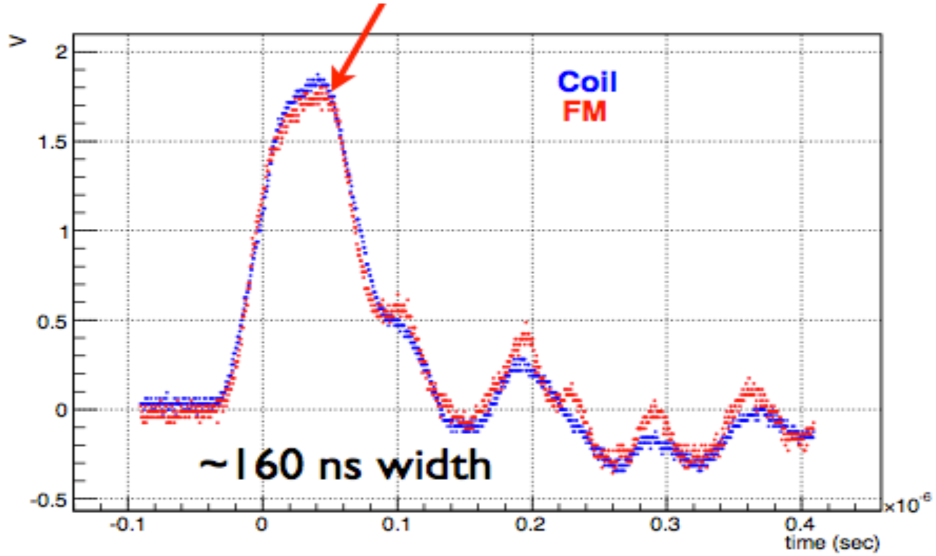
HVP estimate is now being independently verified from lattice calculations.



Presently shows nothing seriously wrong with e^+e^- data estimate but lattice uncertainty needs to come down by a factor-2 to be insightful.

New Kicker Magnet





B-field / ω_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

ω_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

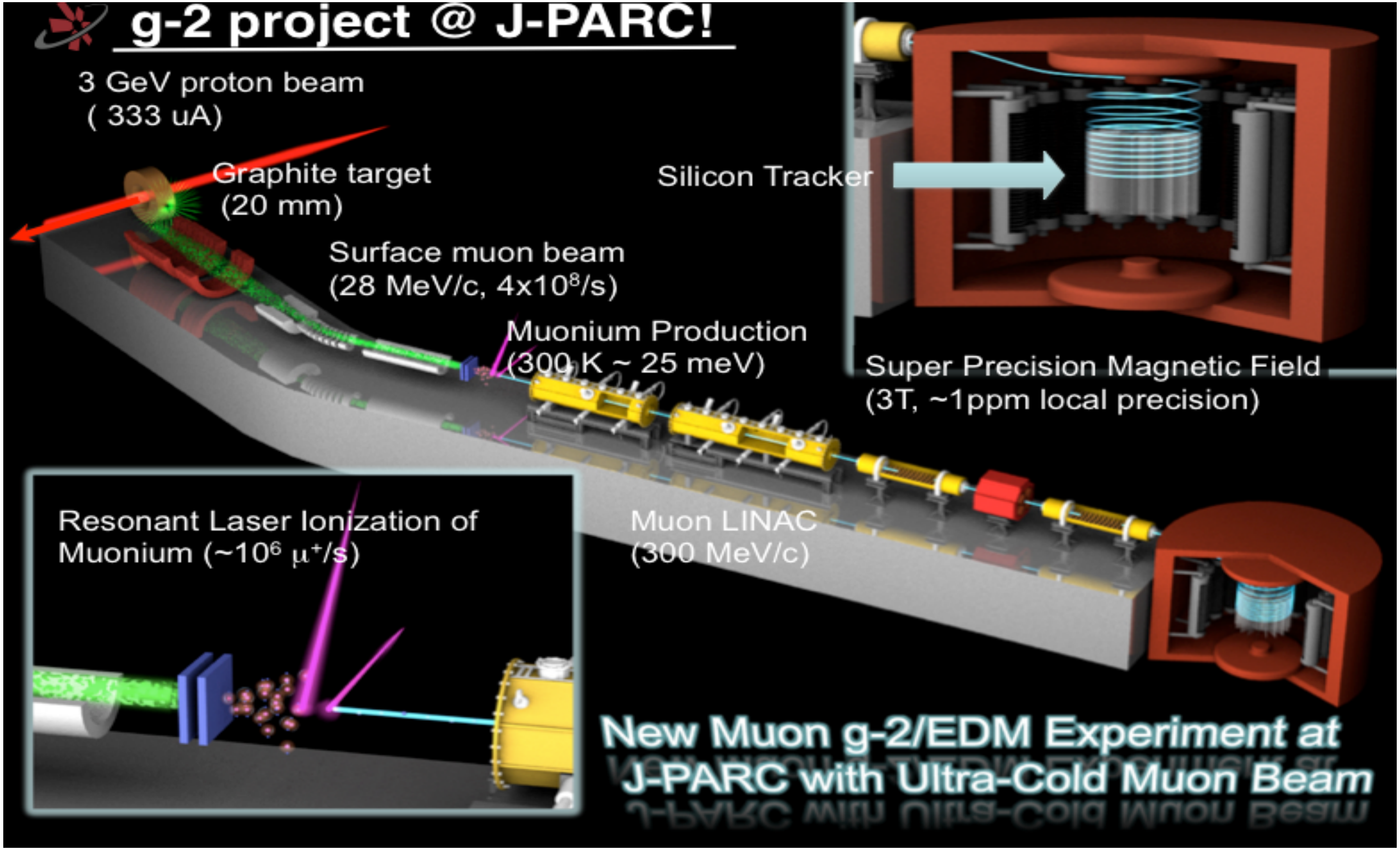
$$\omega_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

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**

J-PARC g-2

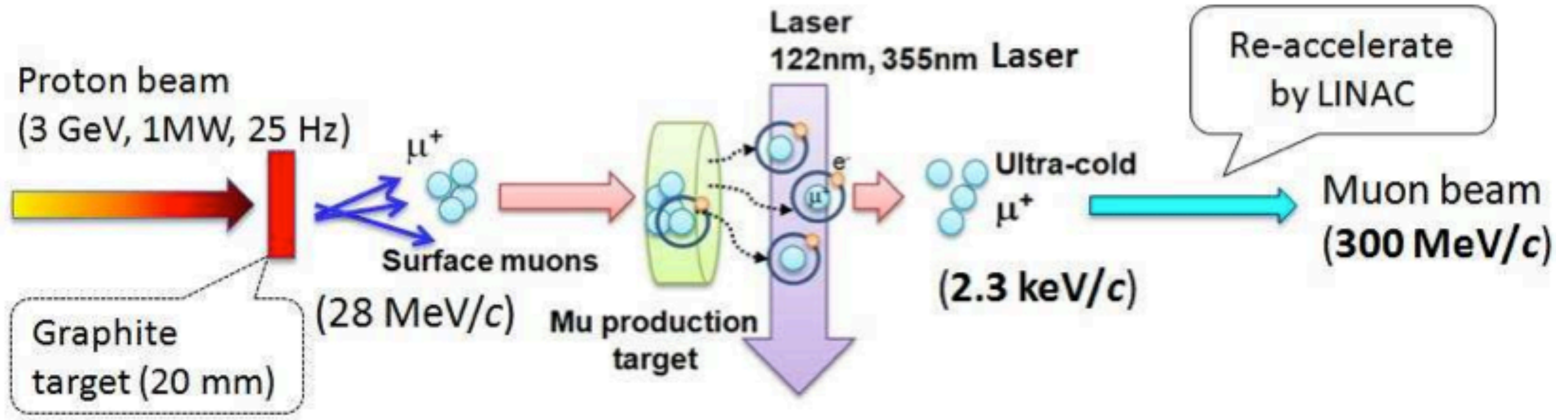

g-2 project @ J-PARC!
3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10⁸/s)
Muonium Production
(300 K ~ 25 meV)
Silicon Tracker
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10⁶ μ⁺/s)
Muon LINAC
(300 MeV/c)
New Muon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

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

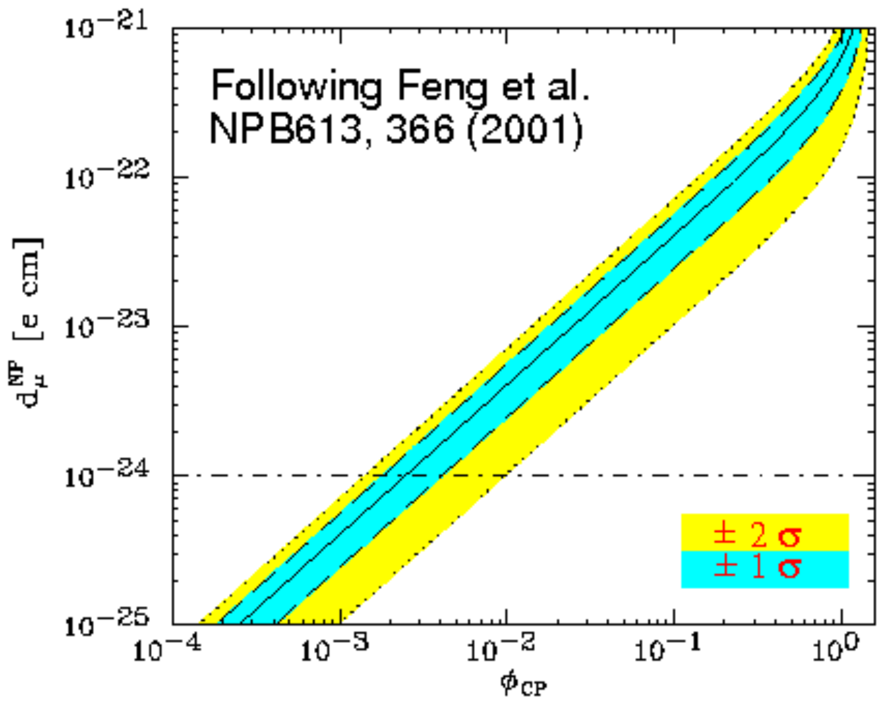
Achieving v. small vertical beam divergence : $\Delta p_T/p_T = 10^{-5}$

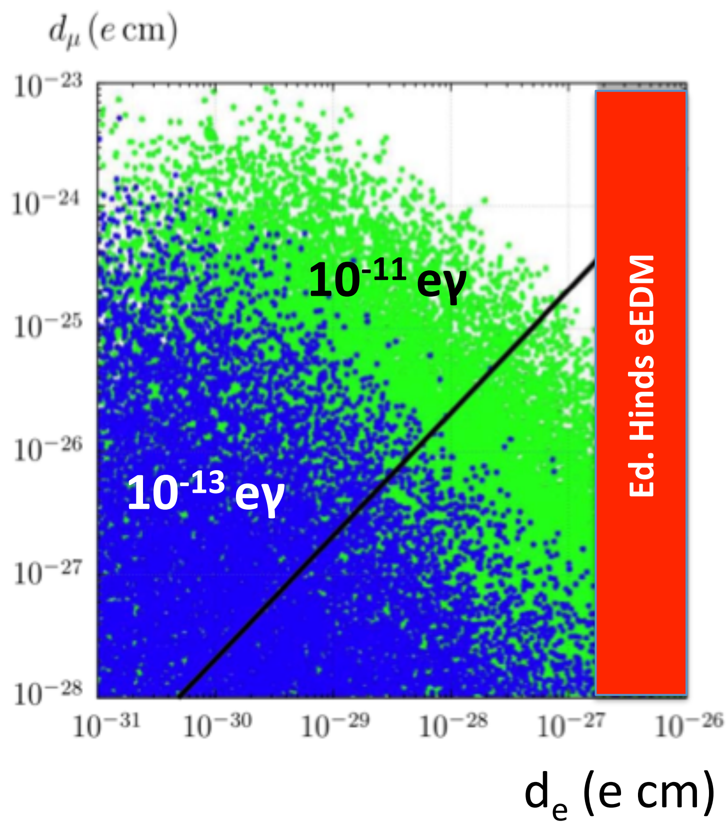
Requires advances in "muonium" production
- target materials e.g. nano-structured SiO_2
- lasers (pulsed 100 μJ VUV) to ionise muonium (x100)



Muon EDM

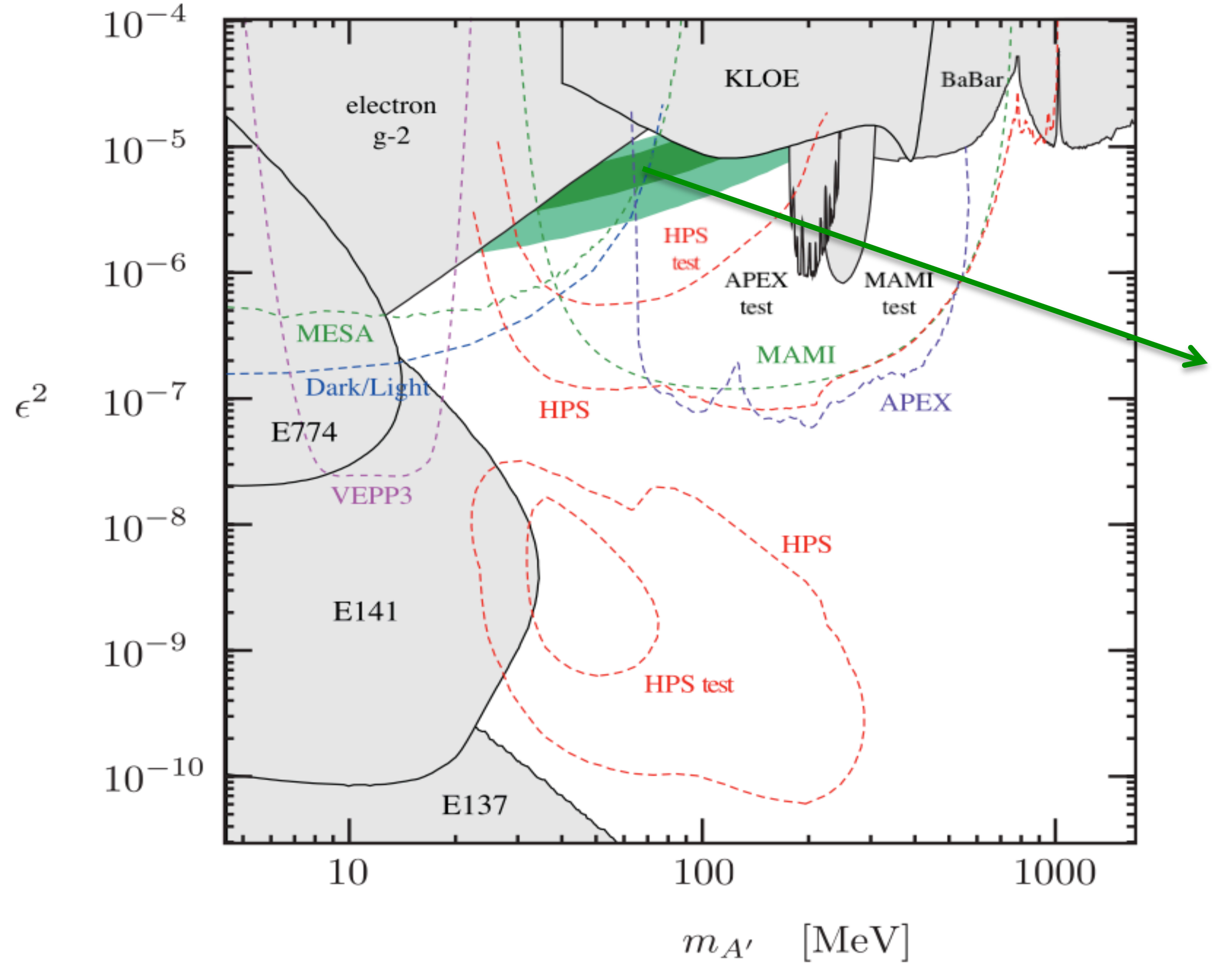
Muon EDM in two BSM models.





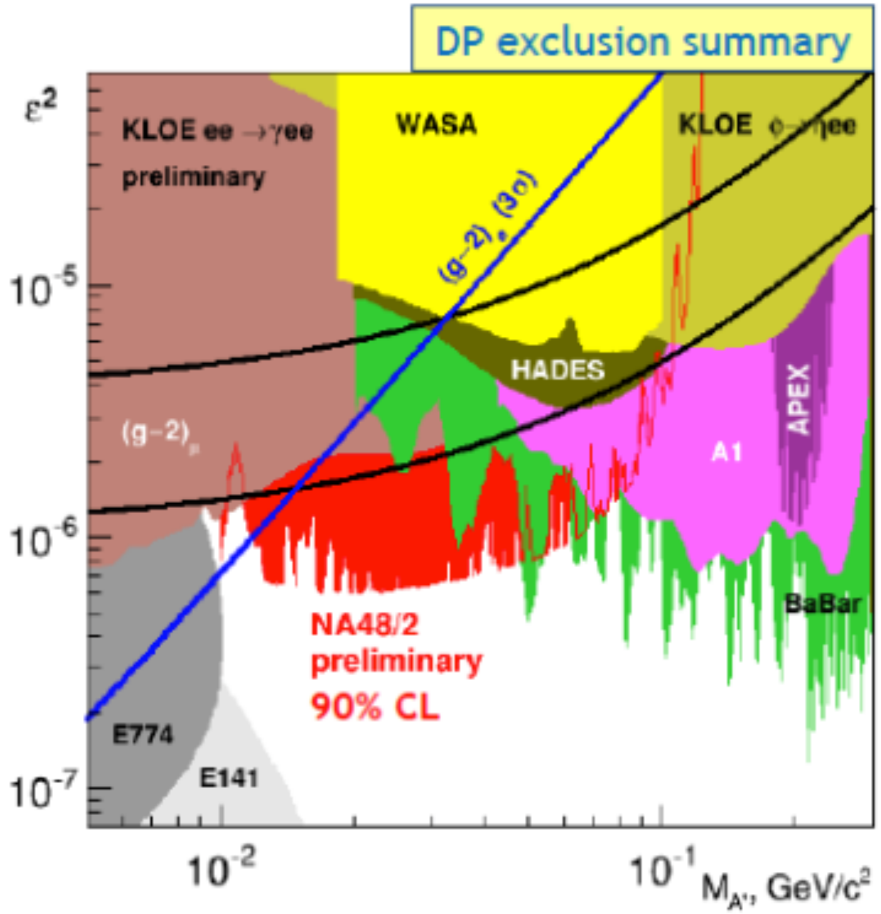
BSM predictions range from: 10^{-21} to 10^{-28}

Dark Photons



Dark photon contribution of 280±80 x 10^{-11} to a_{μ}

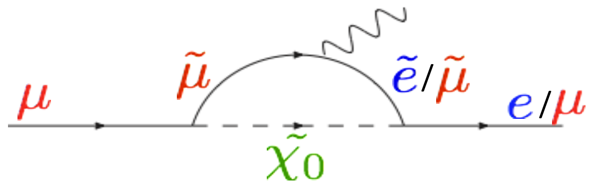
New results from NA48



Complementarity with Mu2e

For BSM dipole interactions e.g. SUSY

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



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

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

Need **both** measurements to resolve model degeneracy