Intense Muon Physics Dipole Moments

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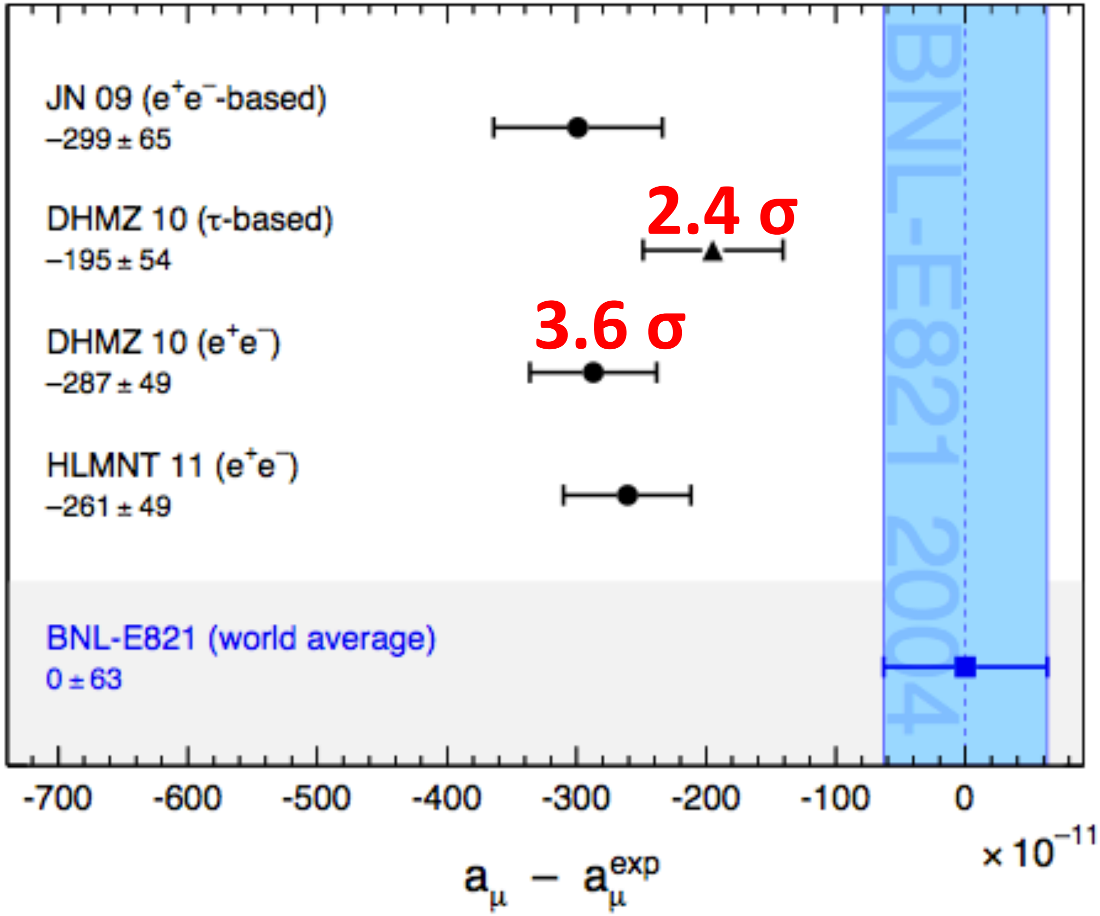
Magnetic Moments

"If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known"
W. Pauli

"No experiment is so dumb, that it should not be tried"
W. Gerlach

Magnetic Moment of the proton (1932)
first evidence for proton sub-structure.

Still Scope for Surprises ?



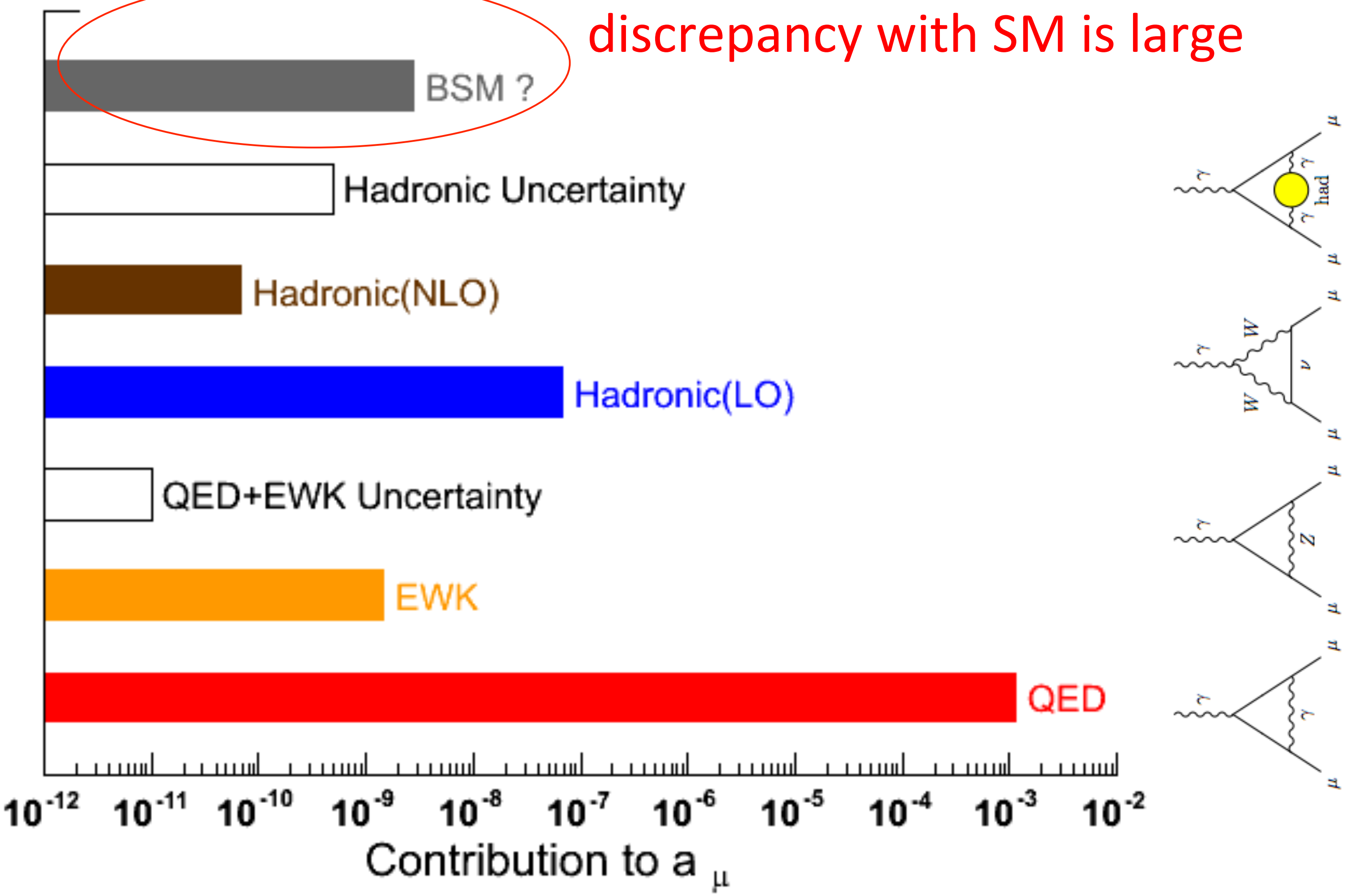
1,500+ citations

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

One of only a handful of measurements with ~ 3σ discrepancy wrt to SM

Why is one number interesting ?

Size of BSM effect to fix current discrepancy with SM is large



Scenarios

Anomaly IS new Physics

YES

LHC not sensitive to the new physics

g-2 is and so constrains possible BSM sources

LHC sees new physics

g-2 helps determine BSM pars & resolve model degeneracy

NO

g-2 anomaly was statistics

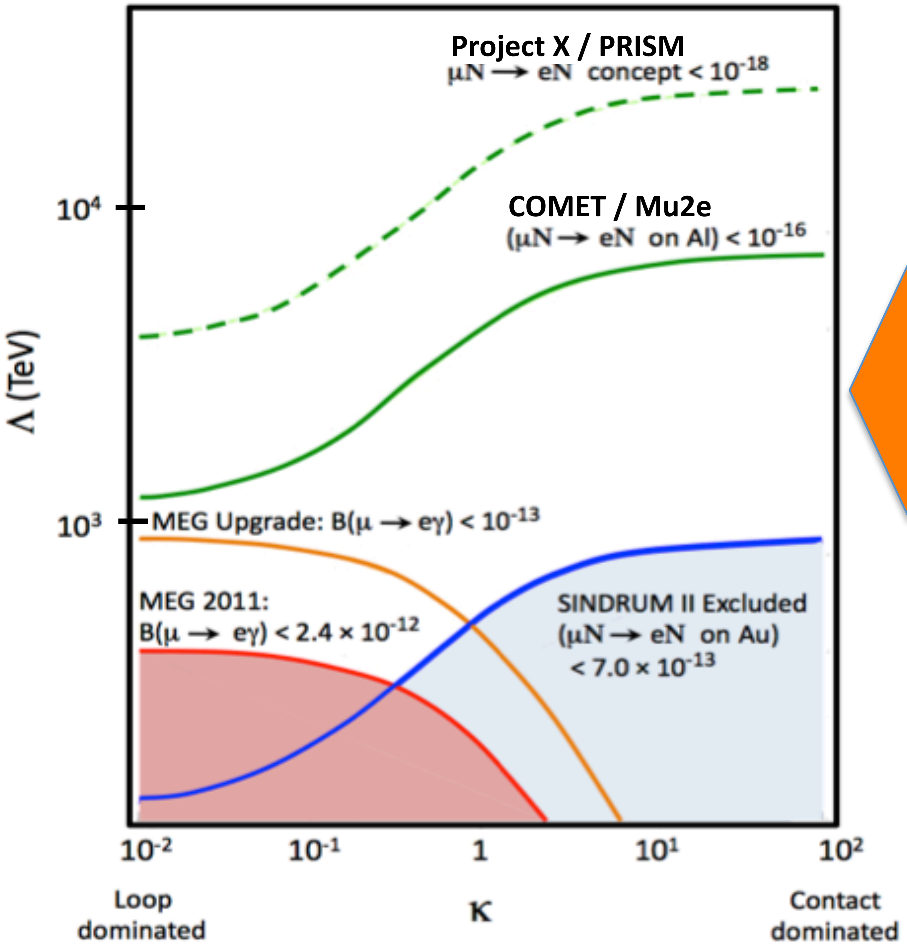
Back to drawing board…

g-2 anomaly was hadronic theory

Get to execute a few theorists !

Scenarios

BSM physics is beyond sensitivity of g-2 and LHC energy



cLFV new physics scale
1000 – 10000 TeV

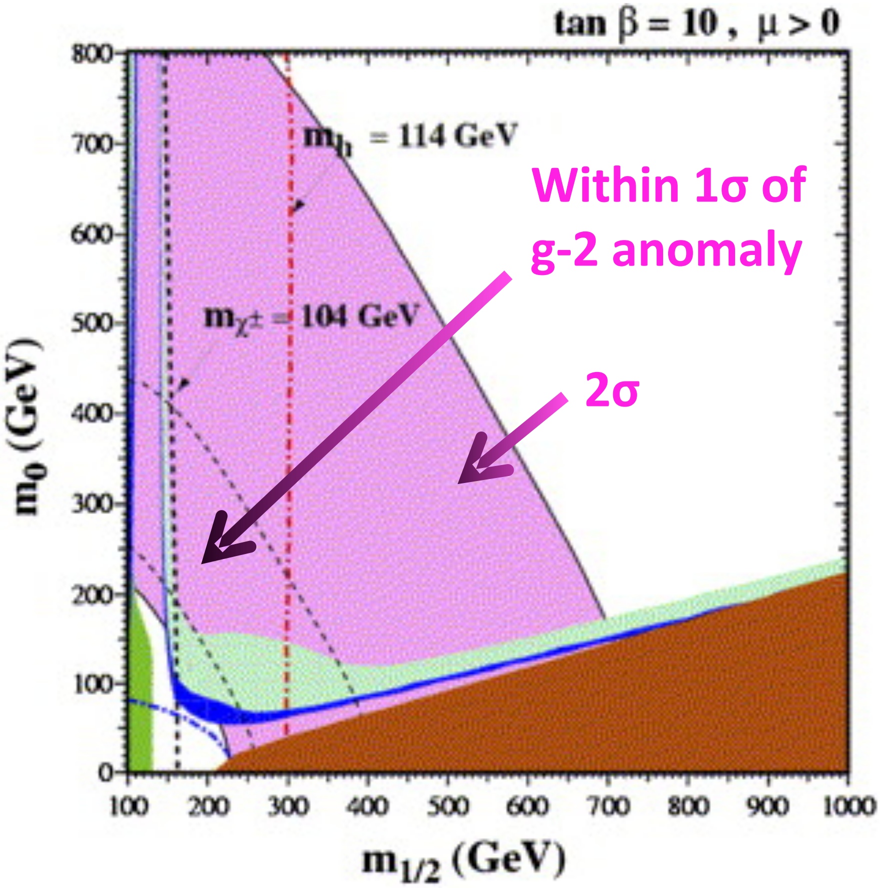
g-2 as probe of new physics

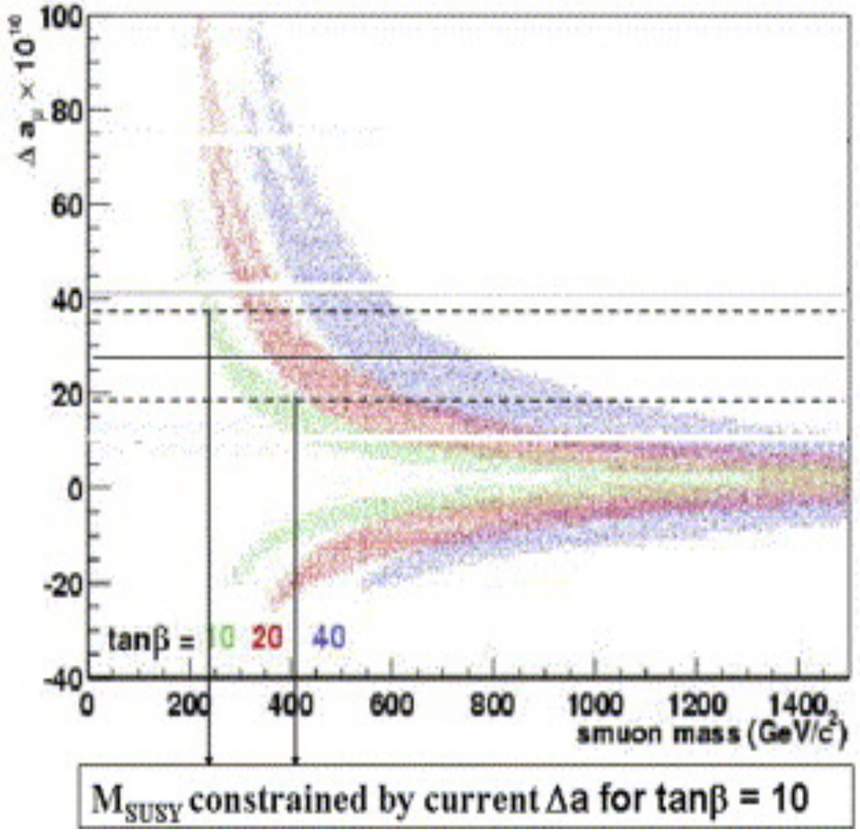
1,000+ papers exploring this and 35 alone in 2012 seeking to reconcile it with LHC (no low mass SUSY + Higgs) results.

Vanilla SUSY

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

g-2 as probe of new physics





Slepton limits from LHC are rather weak
and definitive limits still from LEP

SUSY Fits

Observable	$\Delta\chi^2$ CMSSM (high)	$\Delta\chi^2$ CMSSM (low)	$\Delta\chi^2$ NUHM1 (high)	$\Delta\chi^2$ NUHM1 (low)
Global	33.0	32.8	31.8	31.3
$BR^{EXP/SM}_{b\to s\gamma}$	1.15	1.19	0.94	0.18
$BR^{EXP/SM}_{B\to\tau\nu}$	1.10	1.03	1.04	1.08
$a_\mu^{EXP} - a_\mu^{SM}$	9.69	8.48	10.47	7.82
M_W [GeV]	0.10	1.50	0.24	1.54
R_ℓ	0.95	1.09	1.09	1.12
$A_{fb}(b)$	8.16	6.64	5.68	6.43
A_ℓ(SLD)	2.49	3.51	4.36	3.68
σ^0_{had}	2.58	2.50	2.55	2.50
ATLAS 5/fb jets $+ \not{E}_T$	0.09	1.73	0.02	1.18
$BR(B_s \to \mu^+\mu^-)$	2.52	1.22	1.59	1.70
XENON100	0.13	0.12	0.14	0.13

arxiv:1207.7315

Simple cMSSM struggling to describe all data.

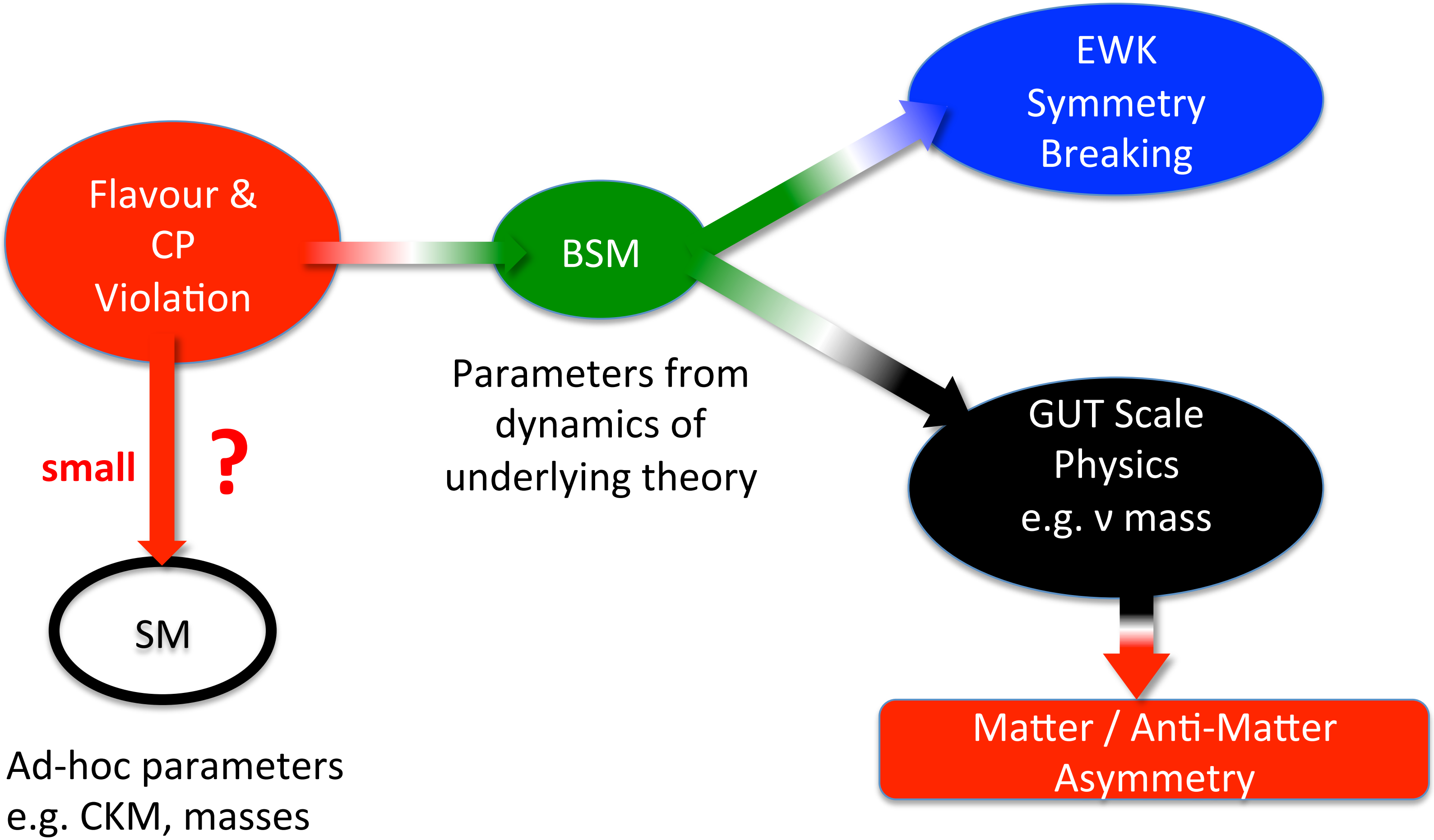
We need to cast the net as wide as we can

"Looking to (SUSY) models with a different connection between the coloured and uncoloured sector, not only seems timely now, but mandatory."

Measurements in coloured & uncoloured sector are mandatory….

Beyond Vanilla BSM (BVBSM)

Thrust is now in developing BSM models connecting flavor-mixing and fermion masses which are more nuanced than previous models.



Beyond Vanilla BSM (BVBSM)

BVBSM models tend to be characterised by large flavour symmetry and small SUSY breaking

Expect **SMALL** deviations from SM:

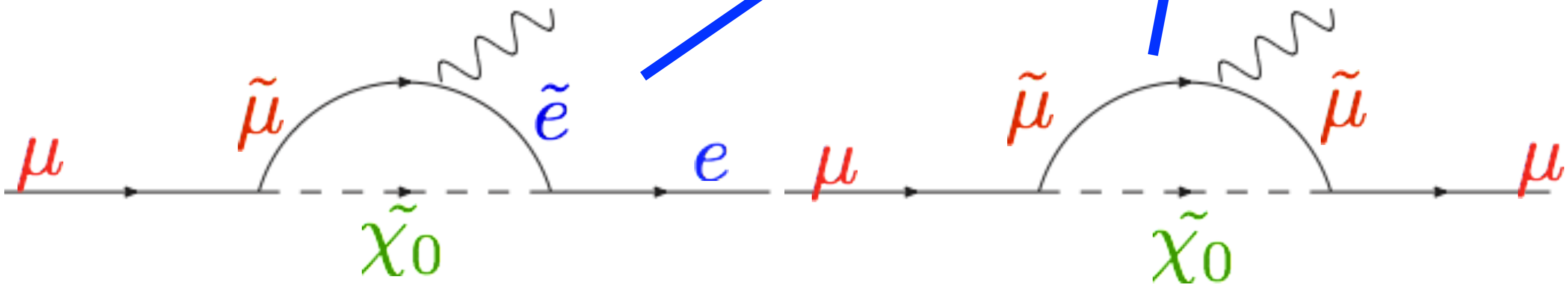
Michael's talk

- precision measurements : (g-2)
- processes that are zero in SM : **EDMs, cLFV**.

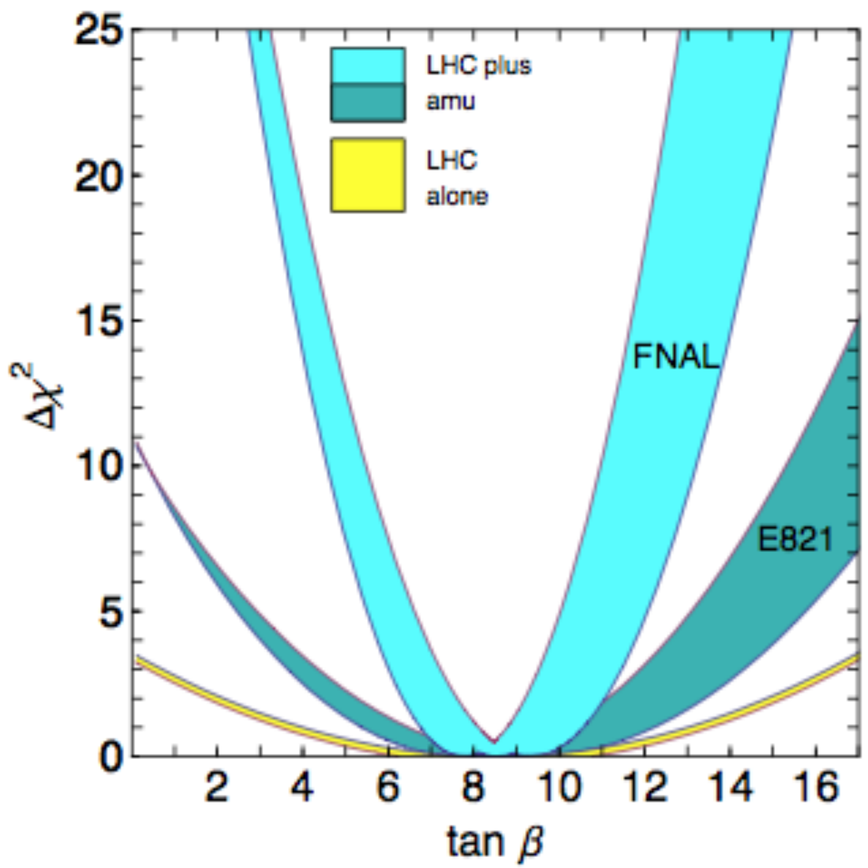
Yoshi's talk

In most BSM theories these three measurements are connected

$$\begin{pmatrix} \Delta m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & \Delta m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & \Delta m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$



Scenario that LHC sees BSM



LHC: 100 fb^{-1} at 14 TeV

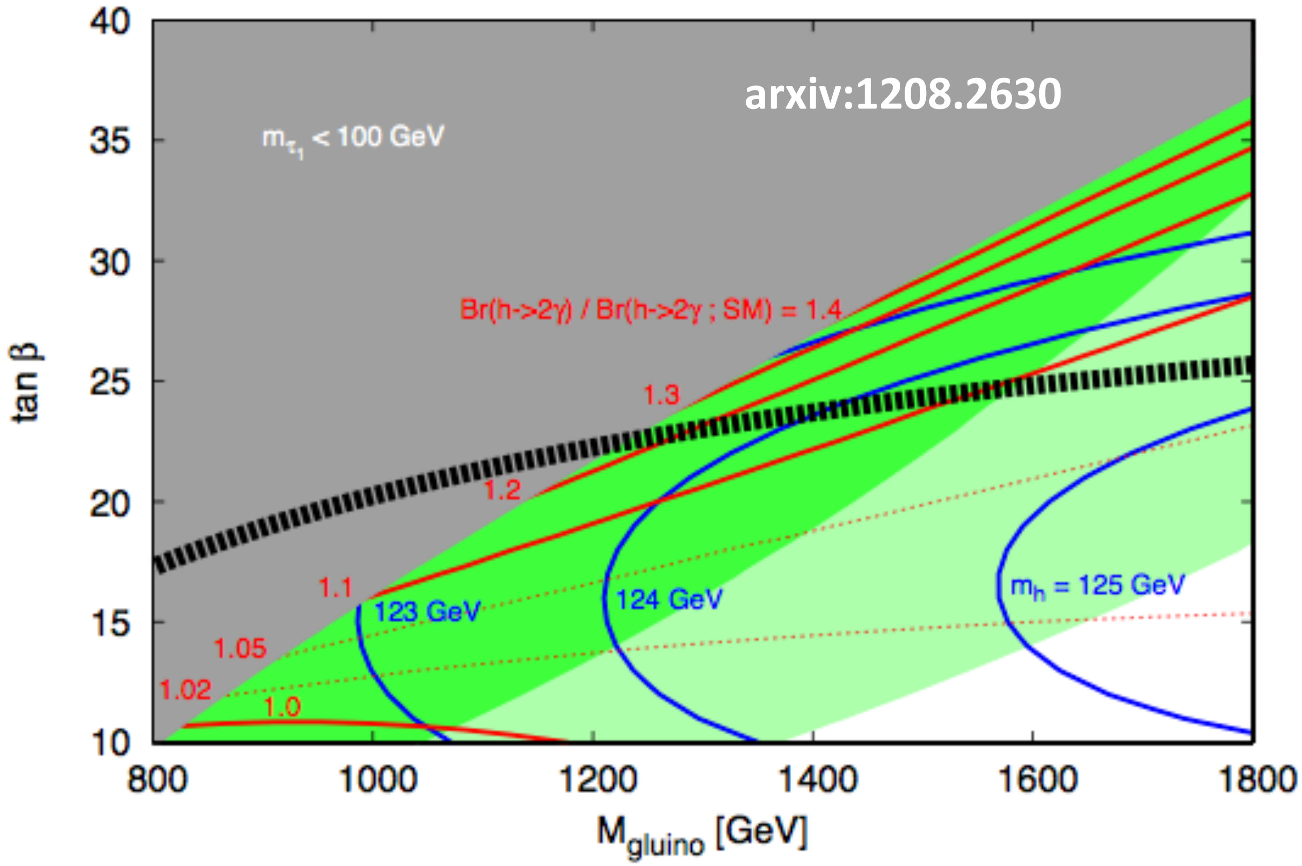
Sign of contribution of SUSY to (g-2) determined by sgn(μ)

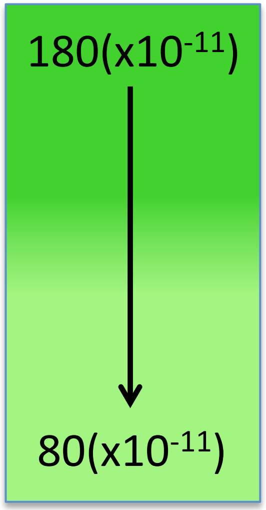
$$g-2 : \tan\beta = 9 \pm 1$$

$$\mathrm{LHC} : \tan\beta = 9 \pm 5$$

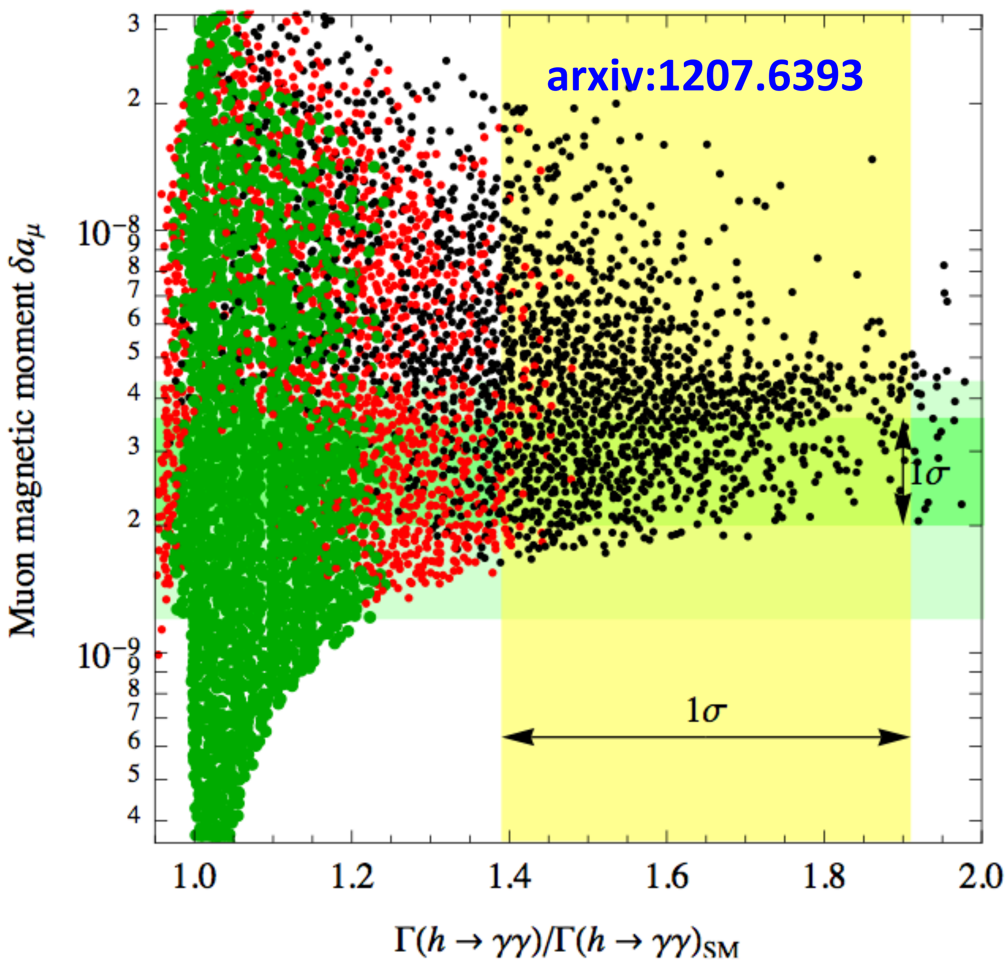
Synergy with LHC

Gauge mediated SUSY breaking models with enhanced $h \to \gamma\gamma$



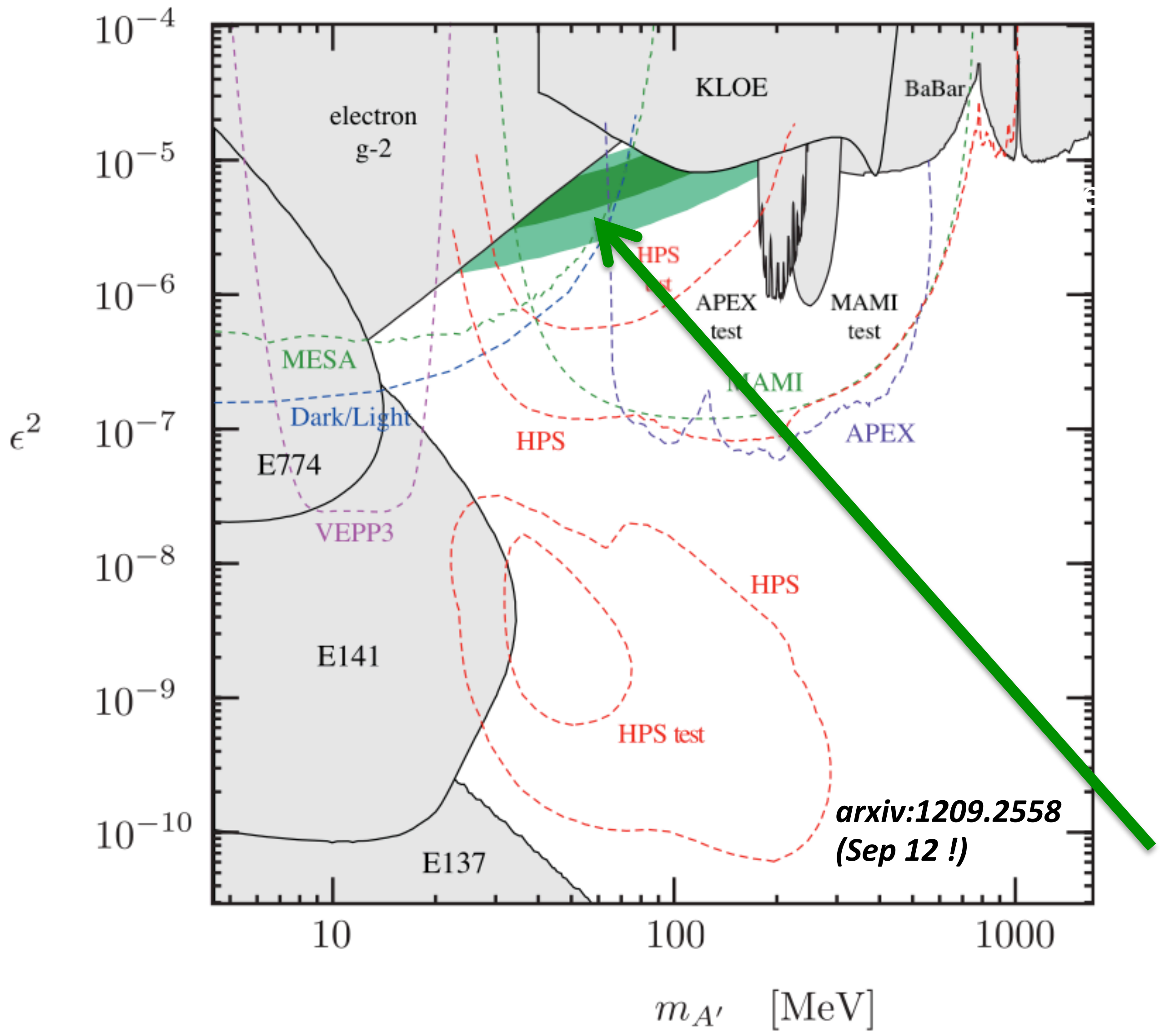


Synergy with LHC



A larger $h \longrightarrow \gamma\gamma$
and (g-2) points to light staus
that are quasi degenerate to
neutralino (evading LEP)

New Physics that LHC cannot detect



Dark photons aka light Z'

$$a_\mu = \frac{\alpha}{2\pi}\epsilon^2 F\left(\frac{m_V}{m_\mu}\right)$$

Motivated to explain PAMELA excess

g-2 will complement direct searches at JLAB, Mainz

Fixes up g-2

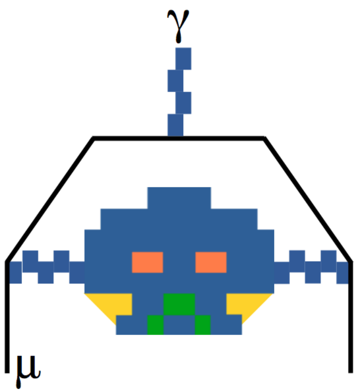
What about the hadronic corrections ?

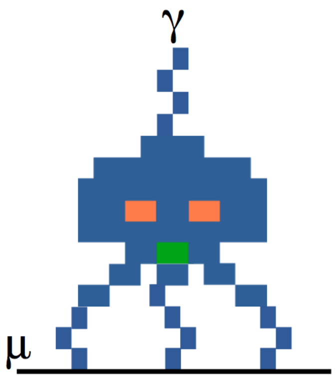
This is a nice problem to have … other similar measurements are yet to need this level of (0.5 ppm) understanding or benefit from this level of scrutiny…

If current anomaly persists then with precision of FNAL g-2 ***and even without any further progress*** on hadronic contributions.

$$3.6\sigma \rightarrow 5.6\sigma$$

But **progress on precision of hadronic corrections expected** $\rightarrow \sim 9\sigma$





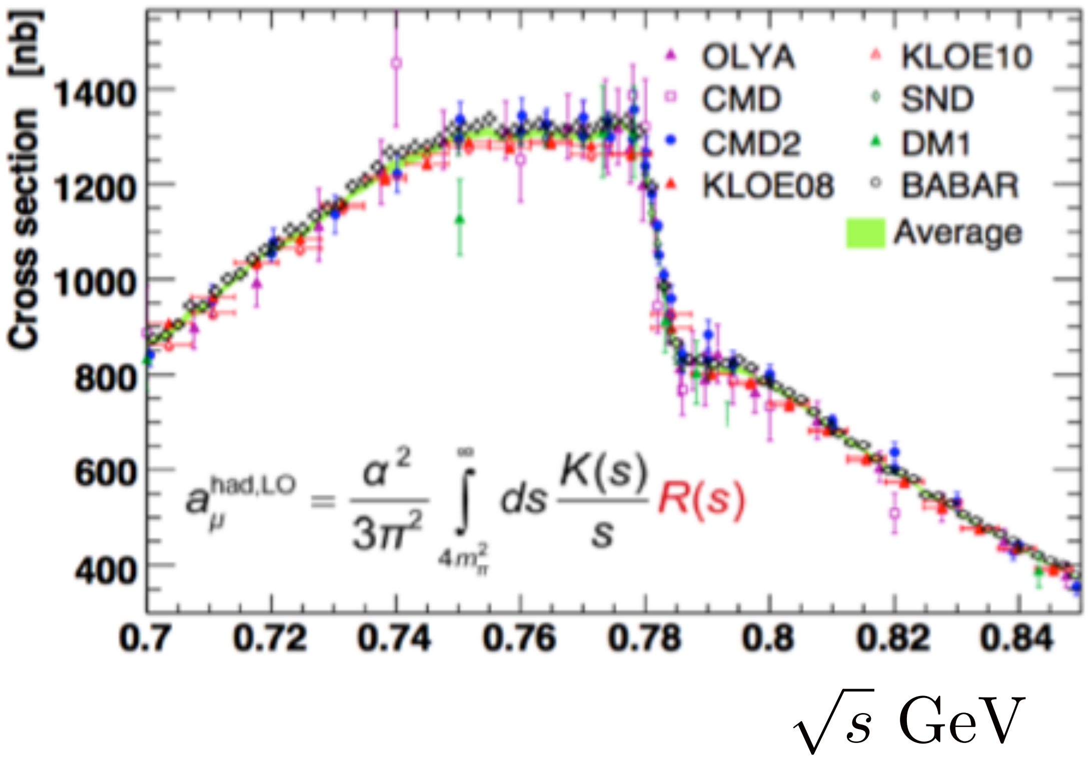
Progress on Hadronic Contribution

This has been spurred by announcement that FNAL g-2 is seeking to reduce the experimental uncertainty by a factor of 4.

Two theoretical uncertainties

HVP (45×10^{-11}) + **HLBL** (26×10^{-11})

52×10^{-11} (25%)



HVP uncertainty

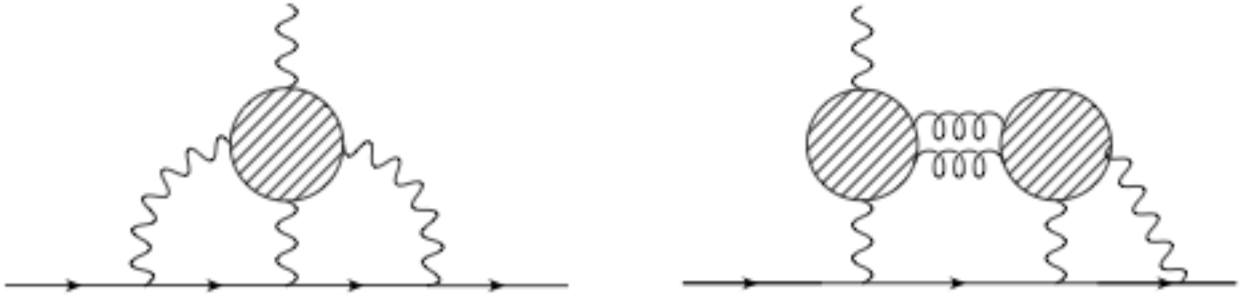
* Consensus now emerging on $\tau^+\tau^-$ vs e^+e^- discrepancy
* New data/analysis from BaBar, Belle, BES, VEPP2000
* Lattice uncertainty (5% → 1.5%)

Should be reduced by factor of two

UK Lattice QCD Community

Progress on Hadronic Contribution

Contribution of HLBL uncertainty is ½ that of the HVP uncertainty but more tricky



Uses models (informed by data) + independently lattice QCD.

Moving forward on two fronts:

- anticipated new (PrimEx, KLOE) data for the models and use of lattice QCD to verify the $(\pi^0 \to \gamma^{(*)}\gamma^*)$ models
- progress on pure lattice QCD calculation *(lattice QED calculation has demonstrated integrity of approach)*

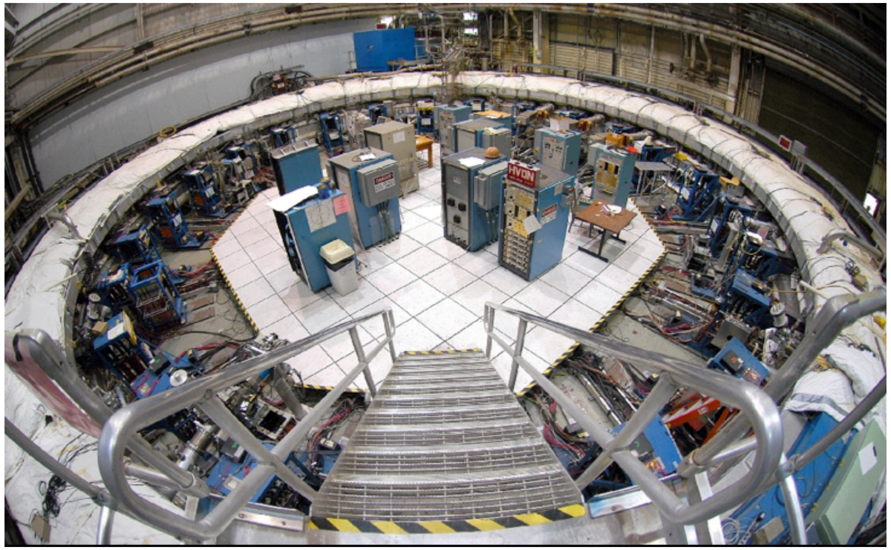
Expect HLBL uncertainty to reduce from 25% to 10%

Hadronic uncertainty will reduce by ½ on timescale of FNAL g-2 result

Experimental Uncertainty

Having established theoretical motivation how do we get x4 reduction in experimental uncertainty.

1. Use established technique (& apparatus)
2. Increase # muons by factor of 21
   to reduce statistical error by over 4.
3. Reduce systematics by factor of 3.



$$54\ (\mathrm{stat}) \oplus 33\ (\mathrm{sys}) \rightarrow 11\ (\mathrm{stat}) \oplus 11\ (\mathrm{sys})$$

Experimental Uncertainty

Ring disassembly at BNL begun. Most small kit already at FNAL

Experimental Uncertainty

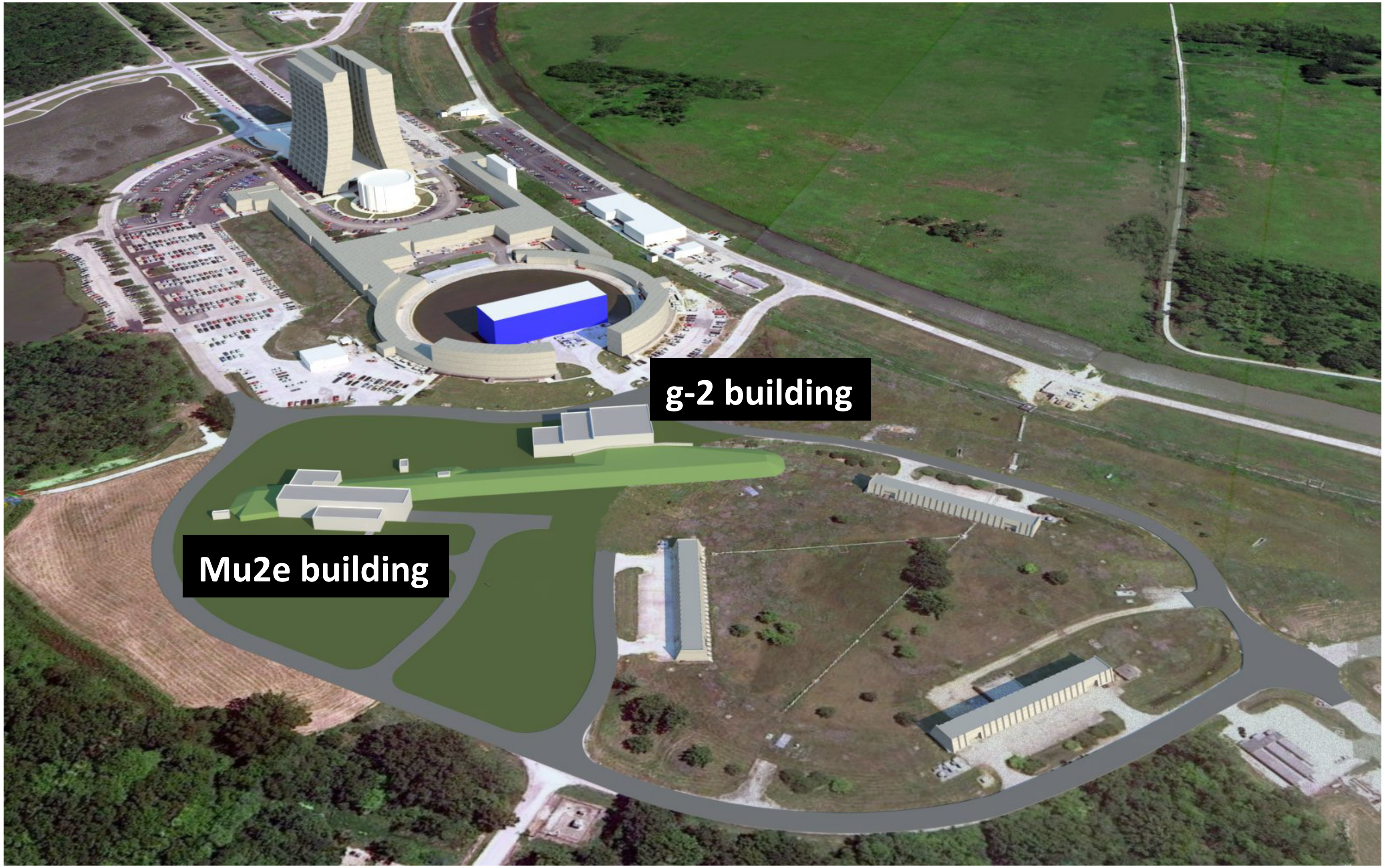
Ring shipping scheduled for summer 2013 to arrive before rivers freeze !

Experimental Uncertainty

Still some magnet alignment problems @ FNAL

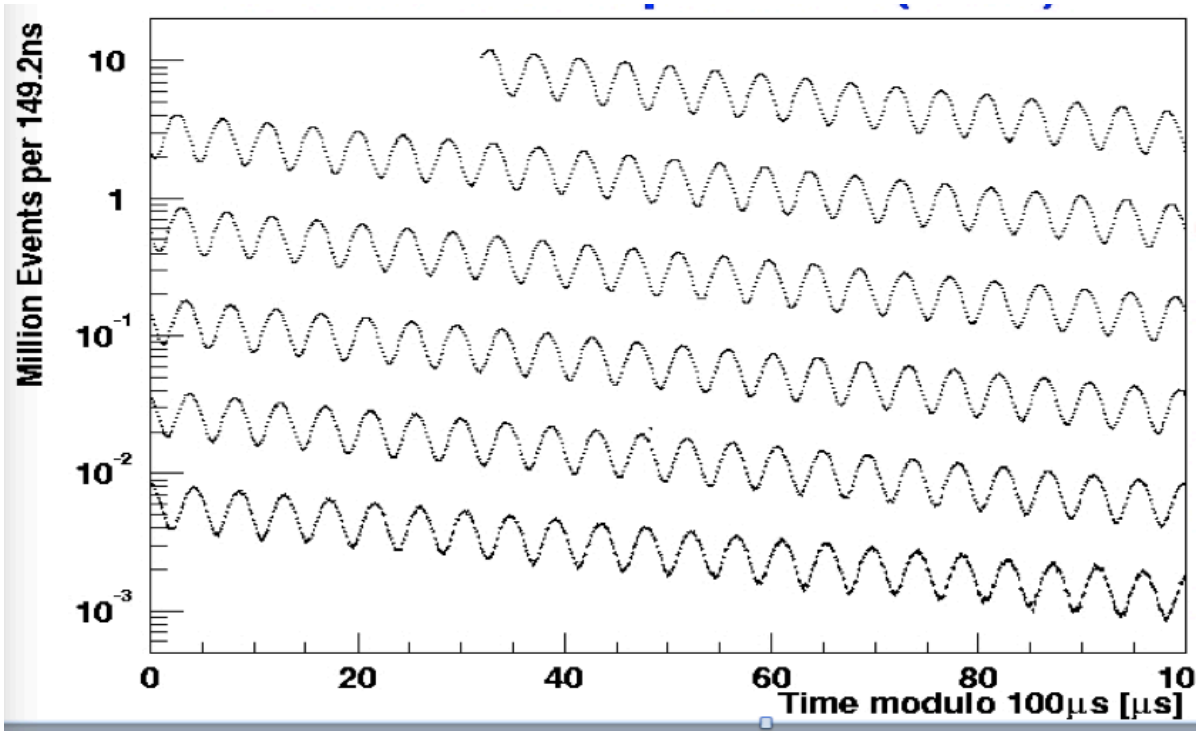
FNAL Muon Campus

Obligatory picture of someone from the DOE with a shovel : Nov 2012



Experimental Uncertainty

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



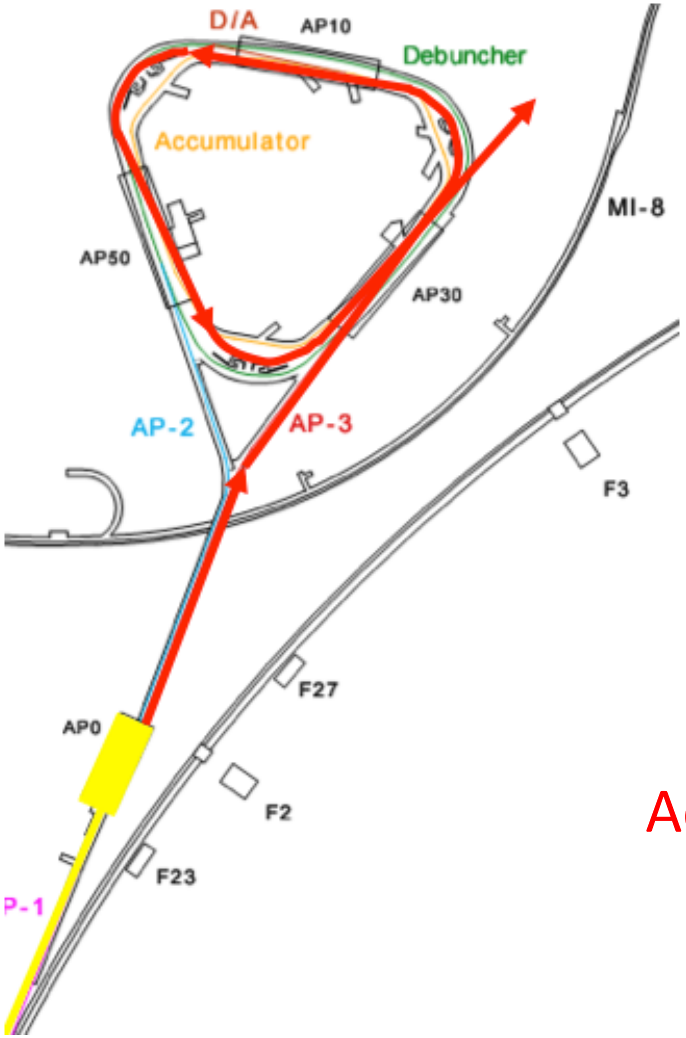
Measure at spin precession at “magic” p (3.1 GeV) to ameliorate B from E.

Count # of positrons above 1.8 GeV vs time

Measure B-field to 0.1ppm

Statistics

x20 (vs BNL) using FNAL booster with fewer pions (x10 decay length)



Accelerator infrastructure shared between Mu2e and (g-2) but cannot run both experiments concurrently.

(g-2) will run first.

Accelerator modifications have begun

Systematics

key accelerator area where UK can take a lead

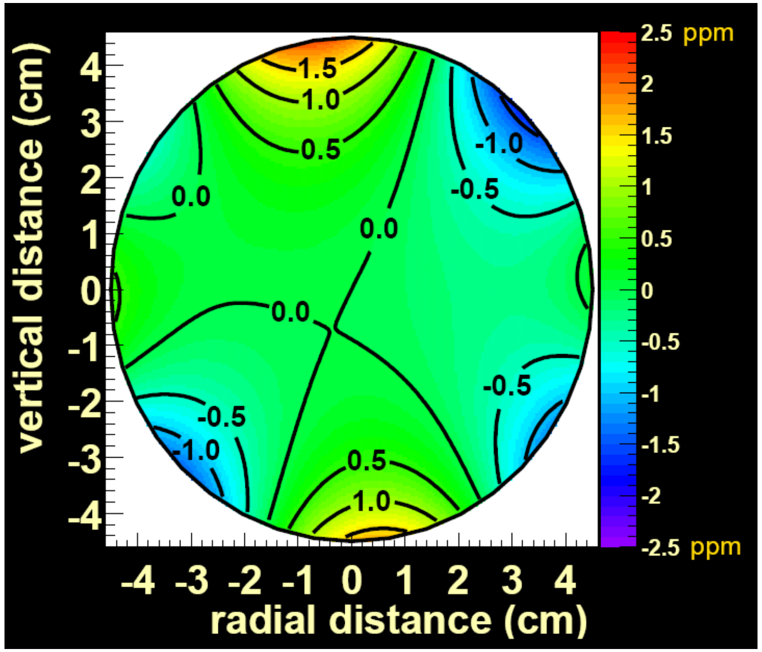
E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme;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

Systematics : B field

300+ fixed NMR probes and 17 portable probes

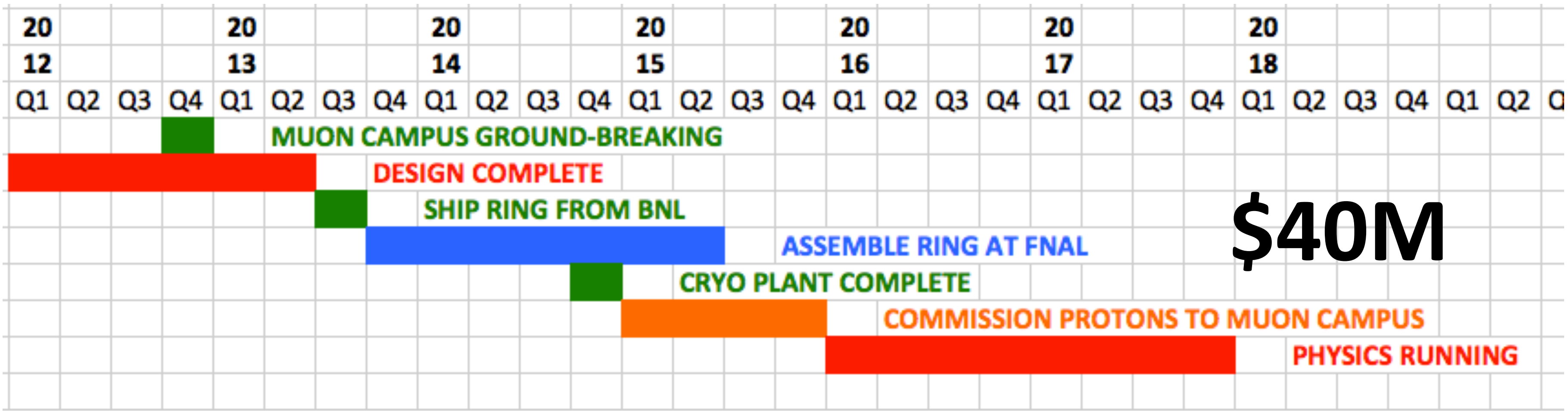
Another area of UK expertise via cryoEDM

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



Additional field shimming, more frequent field mapping,
improved temperature control. more precise location of NMR probes

Timeline



UK has been invited to join the collaboration

A UK Muon Programme To Search For New Physics

P. Dauncey, P. Dornan, K. Long, J. Nash, J. Pasternak, Y. Uchida (Imperial); R. Appleby, W. Bertsche, M. Gersabeck, H. Owen, (Manchester); F. Azfar, M. John, (Oxford); C. Densham (RAL/STFC); S. Boogert (RHUL); S. Jolly, M. Lancaster, M. Wing (UCL).

Much synergy with UK COMET activities.

If we are to take a defining and leading role then speed is of the essence
- MOUs have been / are being signed NOW.

Conclusion

Yes this is a single number experiment but some single numbers are important
- neutrino mass, Majorana neutrino, m_W, m_t, m_H.

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

It's clear that the path to a credible BSM theory isn't as smooth as some had anticipated.
We need to cast the net wide to establish a credible BSM theory.

This is $40M experiment. Per number this is bargain-basement….

A modest UK investment can utilise existing expertise and establish leadership in a new area for the UK with potential physics significant returns.

If current anomaly persists we are looking at BSM at 9 σ
Join US !!

If have strategy ennui could I suggest

ILC-UK discussion, supported by Age UK: Is Social Exclusion still important for Older People?

Wednesday, 19 September 2012 from 08:15 to 09:30 (BST)
London, United Kingdom

International Longevity Center !

BACKUP

UK g-2 Role

Reducing the systematic from the CBO

Precision mapping of B-field

Construction of straw trackers (for the EDM measurement)

Trigger / DAQ

Simulation

Physics Analysis

J-PARC Muon g-2

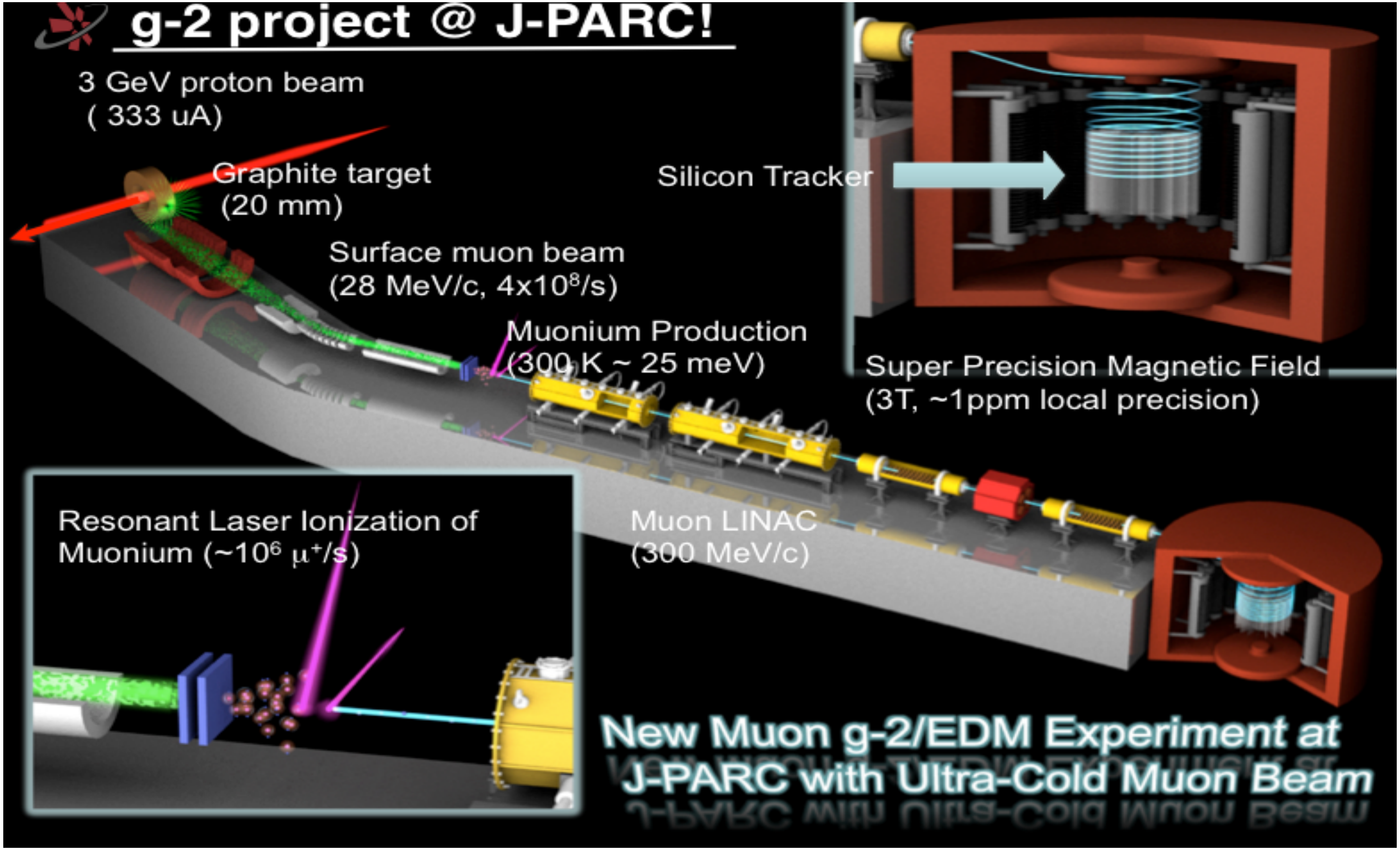
$$\omega = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Traditional approach : use magic γ (29.3), p = 3.09 GeV muons.

- BNL measurement and proposed FNAL g-2 measurement

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

J-PARC Muon g-2



Several Challenges

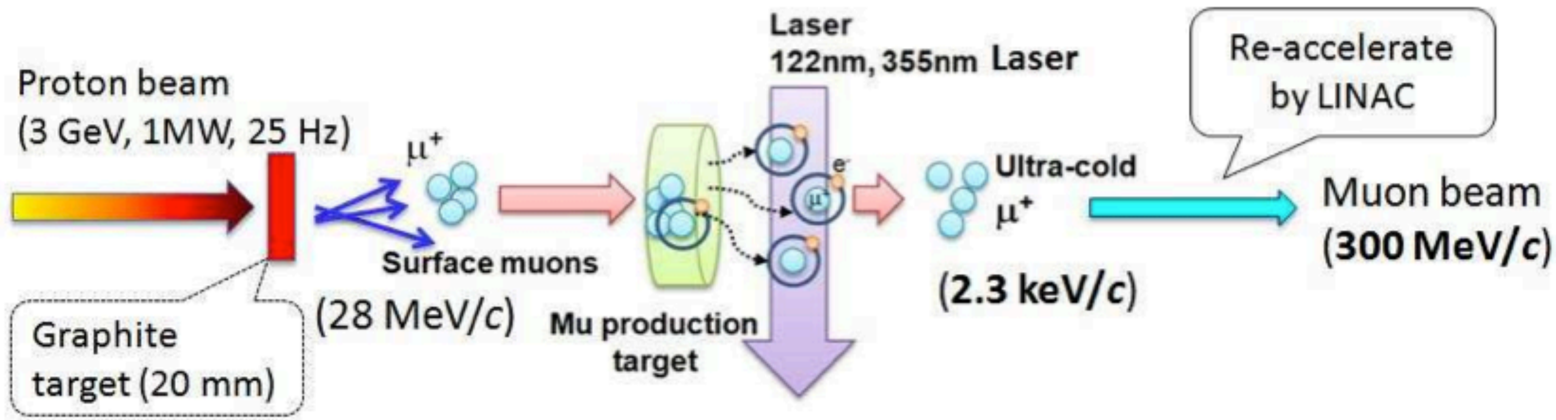
Getting a sufficient rate of ultra cold muons (require 10^6 /sec and 10^{12} e^+)

Avoiding pile-up issues in detector with the high rate

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

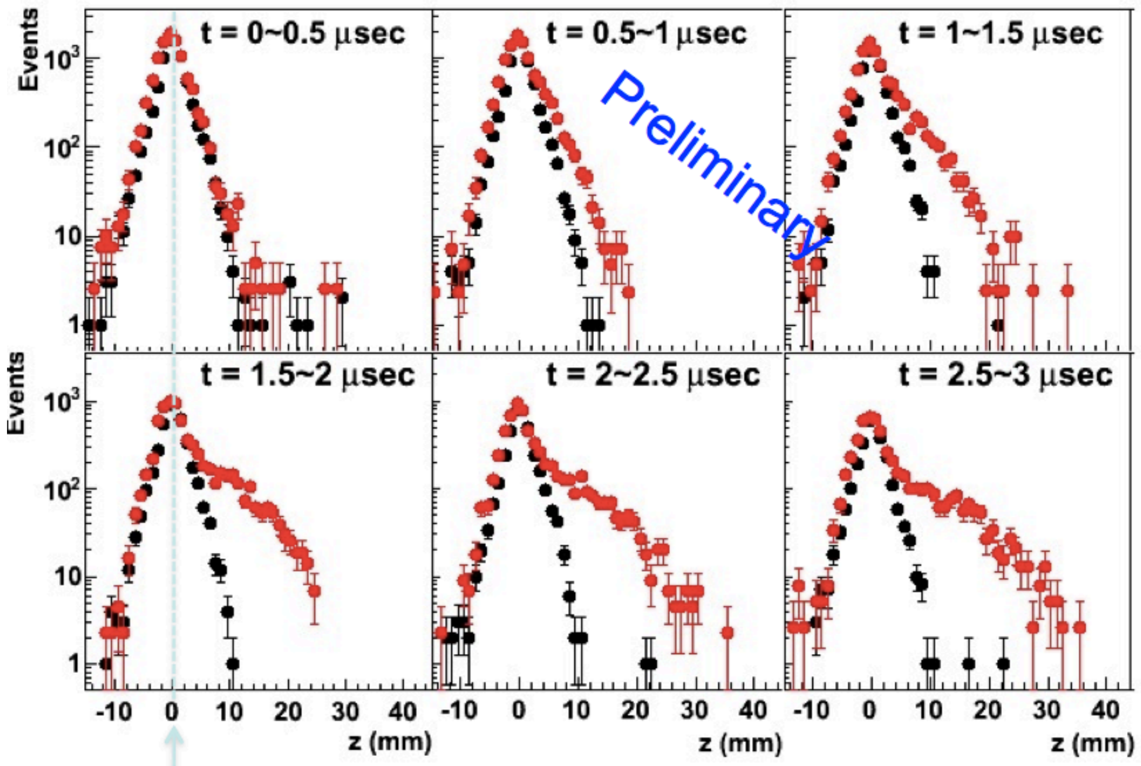
Requires advances in "muonium" production

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



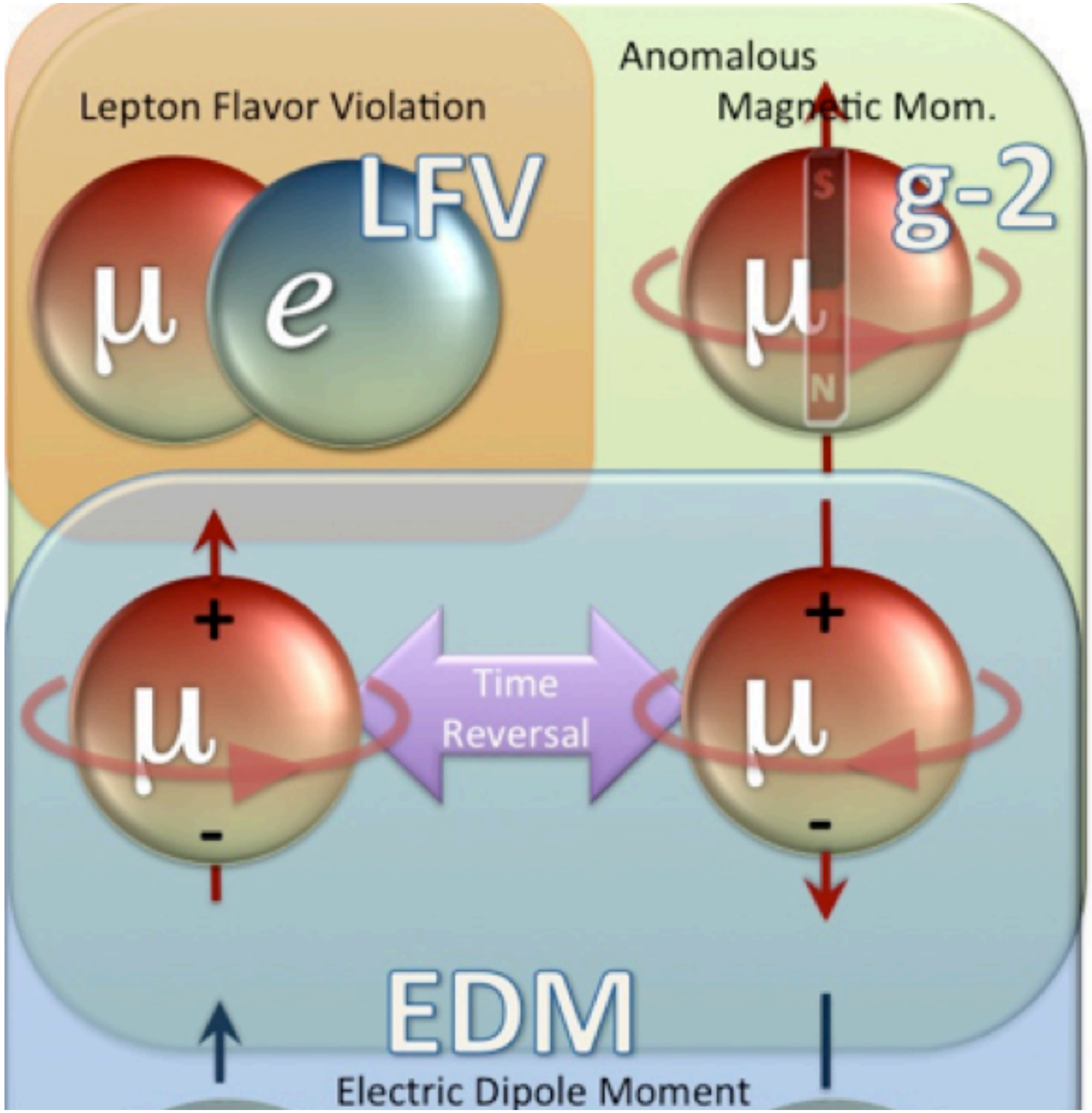
JPARC g-2

- Much challenging R&D still to be completed.
- Cold muon yield and ionisation efficiency presently significantly below required level to provide 10^6 mu/sec



Ultimately could achieve same precision as FNAL with very different systematics but on a timescale **AFTER** the FNAL experiment has completed

Muon EDM



$$\mathrm{EDM} \propto \mathrm{Im}(m^2_{\tilde{\mu}\tilde{\mu}})$$

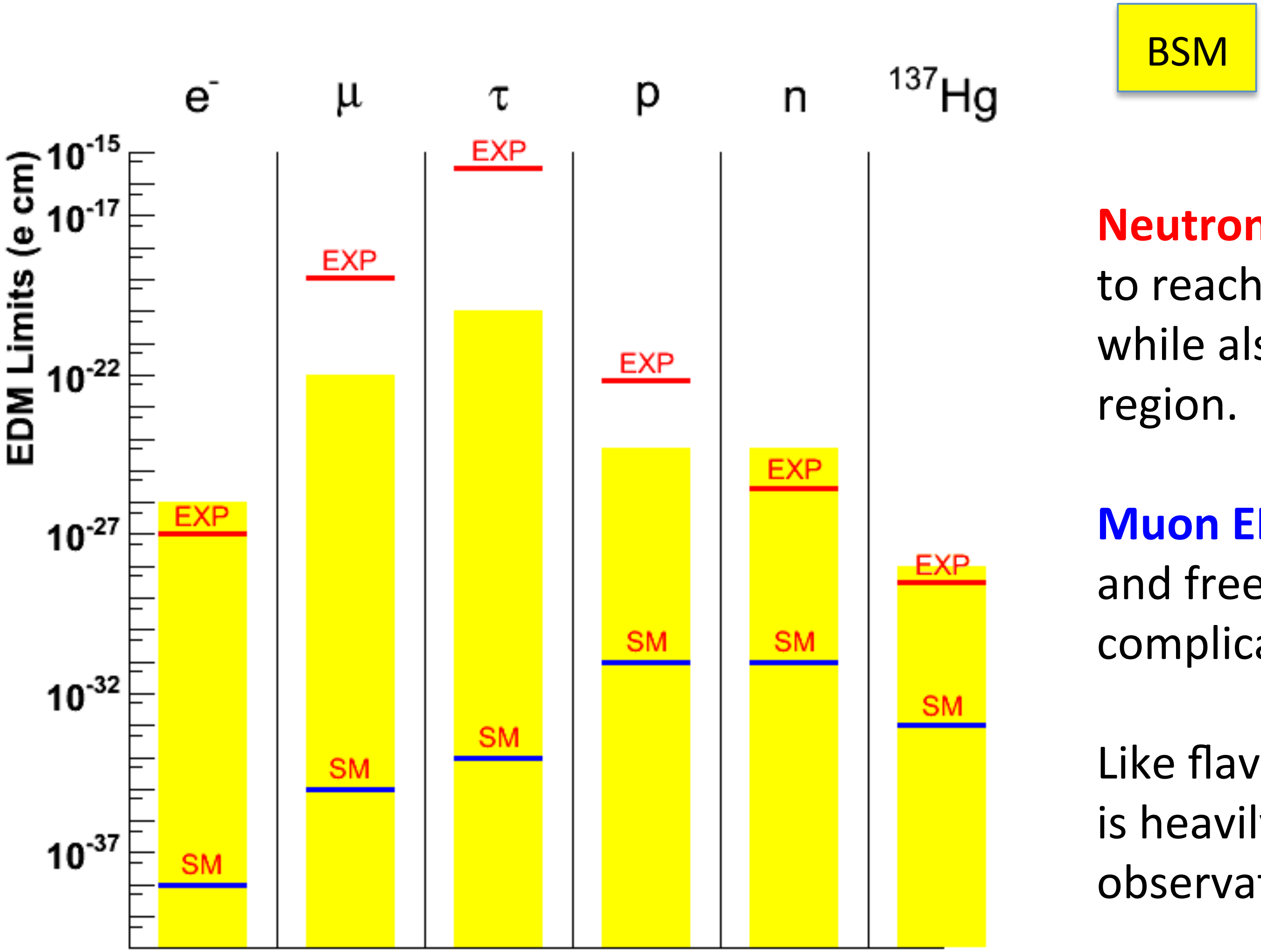
$$\mathrm{cLFV} \propto \Delta m^2_{\tilde{e}\tilde{\mu}} + \Delta m^2_{\tilde{\mu}\tilde{e}}$$

$$\mathrm{g-2} \propto \mathrm{Re}(m^2_{\tilde{\mu}\tilde{\mu}})$$

$$M^2_{\tilde{l}\tilde{l}'} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

SUSY Mass Matrix

EDMs

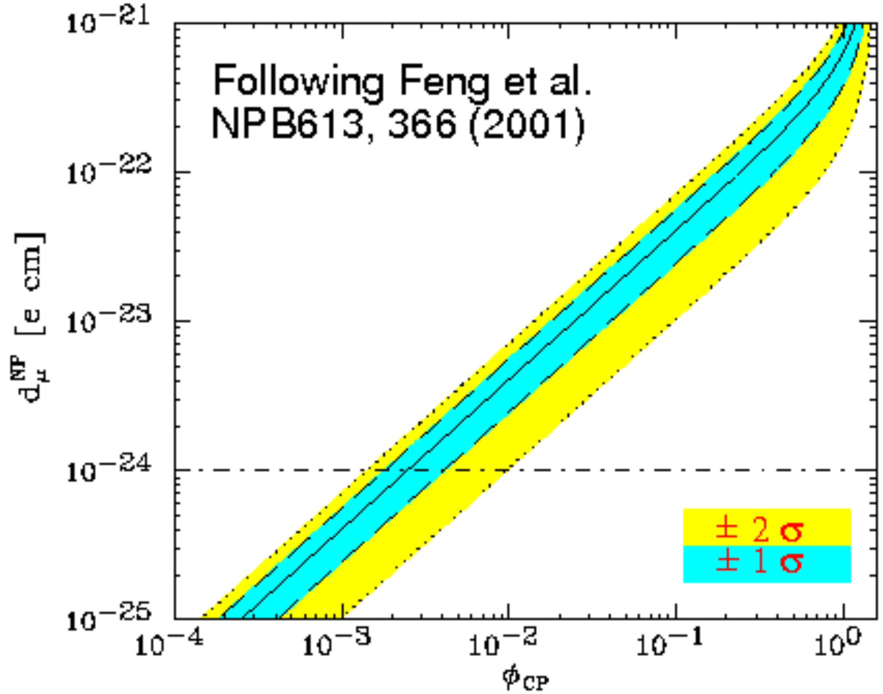


Neutron EDM is one nearest to reaching SM prediction while also being in the "BSM" region.

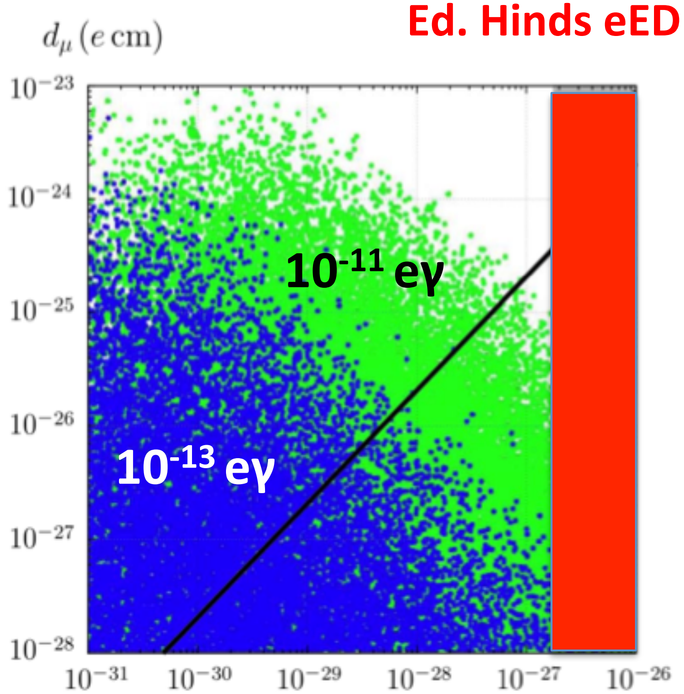
Muon EDM is 2nd generation and free of nuclear/molecular complications.

Like flavour violation, since SM is heavily suppressed any observation is new physics.

Muon EDM



Ed. Hinds eEDM



Expect muon EDM below 10^{-22} and likely below 10^{-24} (SM = 0)

Present limit (BNL) is 1.8 x 10^{-19}.

FNAL (g-2) should reach 10^{-21} looking at vertical angle, 90^0 out of phase with g-2 modulation

Muon unique since 2nd generation & it's a single particle measurement unlike e/n EDM.

J-PARC Muon EDM beyond 10^{-21}

Parasitic EDM has intrinsic limitation at ~ 10^{-21-22}

To go below this : use so-called **"Frozen Spin" technique**
- judicious E and B to cancel magnetic moment contribution

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

Radial E-field without any residual vertical field.

LOI to J-PARC in 2003 to use dedicated 11m FFAG ring with sensitivity @ 10^{-24}
Proof of principle proposed at PSI (2006-2010) with 42cm ring with sensitivity @ 5×10^{-23}
- challenging .....

J-PARC PAC / IPNS favours nEDM (E33) experiment over μEDM although nEDM has not yet got stage-1 approval.