Probing New Physics with Muon g-2

Mark Lancaster
University College London

Some Muon History : Despair

*"As you undoubtedly know, theoretical physics –
what with the haunting ghosts of neutrinos,
the Copenhagen conviction,*

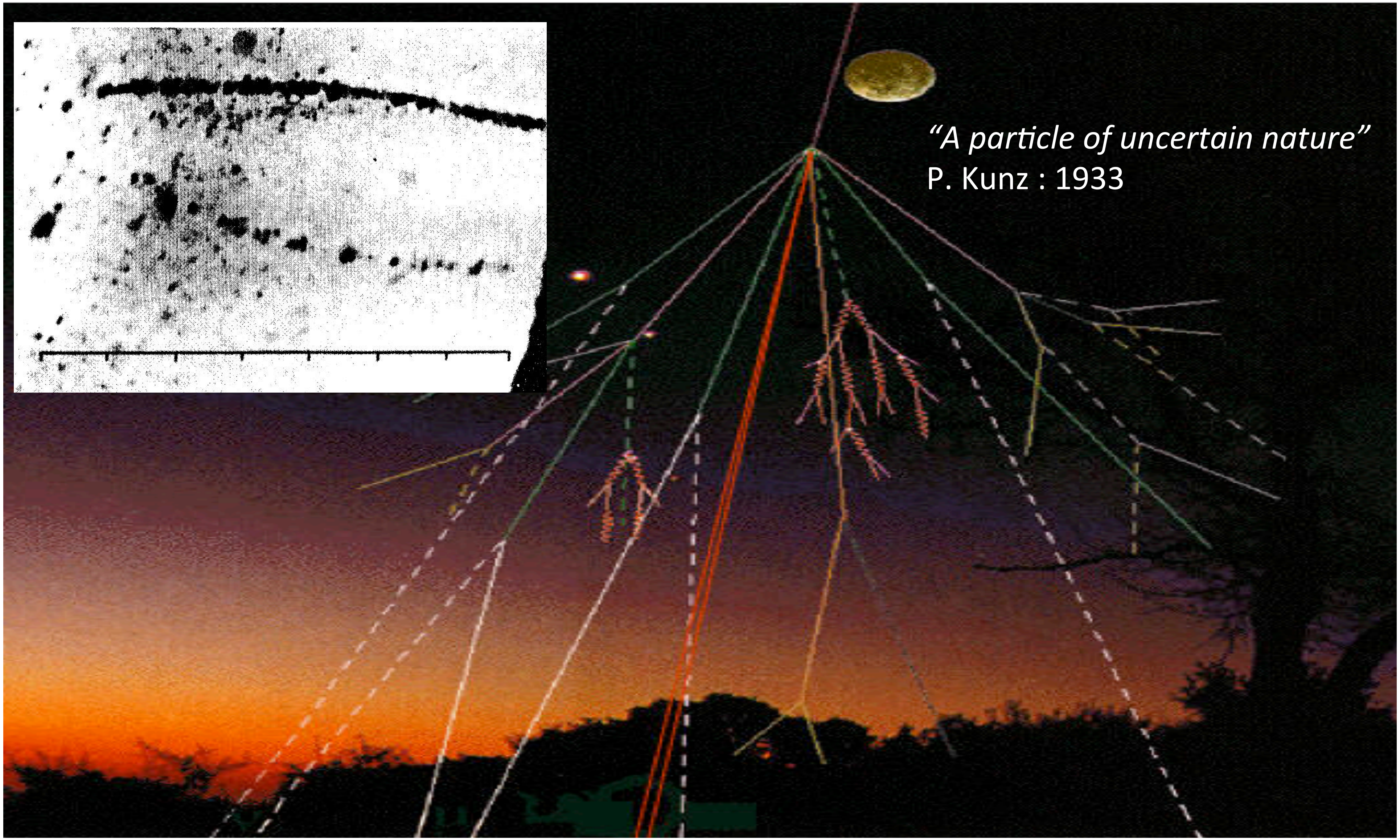
***against all evidence,
that cosmic rays are
protons***

*Born's absolutely unquantizable field theory,
the divergence difficulties with the positron
and the utter impossibility of making a rigorous
calculation at all*

– is in a hell of a way"

June 1934

The problem



"A particle of uncertain nature"
P. Kunz : 1933

Nutters

Late 1920s developed a theory: the "Birth Cry of Atoms"
- Religion inspired fusion model forming atoms that also emitted photons.
- Primary cosmic rays were photons of discrete energies

With a dodgy theory and dubious fits to the ionisation data of cosmic rays – he claimed he could explain all the data !

Millikan ignored warnings from Oppenheimer and got his **PhD student** to make more measurements to prove "The Birth Cry"

Robert Millikan

Nobel Prize 1923

Fisticuffs

Millikan ignored the fact that if primary cosmic rays were **not** photons then there would be a **"lattitude effect"** due to the earth's magnetic field.

Millikan failed to measure the **"lattitude effect"** Compton did and the two Nobel Prize winners had several public spats.

Millikan and Anderson continued to ignore QM and believed e^- and e^+ existed in the nucleus and were knocked out by the "Birth-Cry" cosmic ray photons.

They rejected the Dirac theory of "pair creation" since more e^- were observed than e^+

It was in the Cavendish (Blackett, Rossi, Occhialini) where e^-e^+ pair-creation coincidence measurements were made and which vindicated Dirac.

Soon after Anderson distanced himself from Millikan and continued his work solo…

Apples

"I've put a poisoned apple on Blackett's desk and I've got to go back and see what happened"
- Oppenheimer (1925)

Form

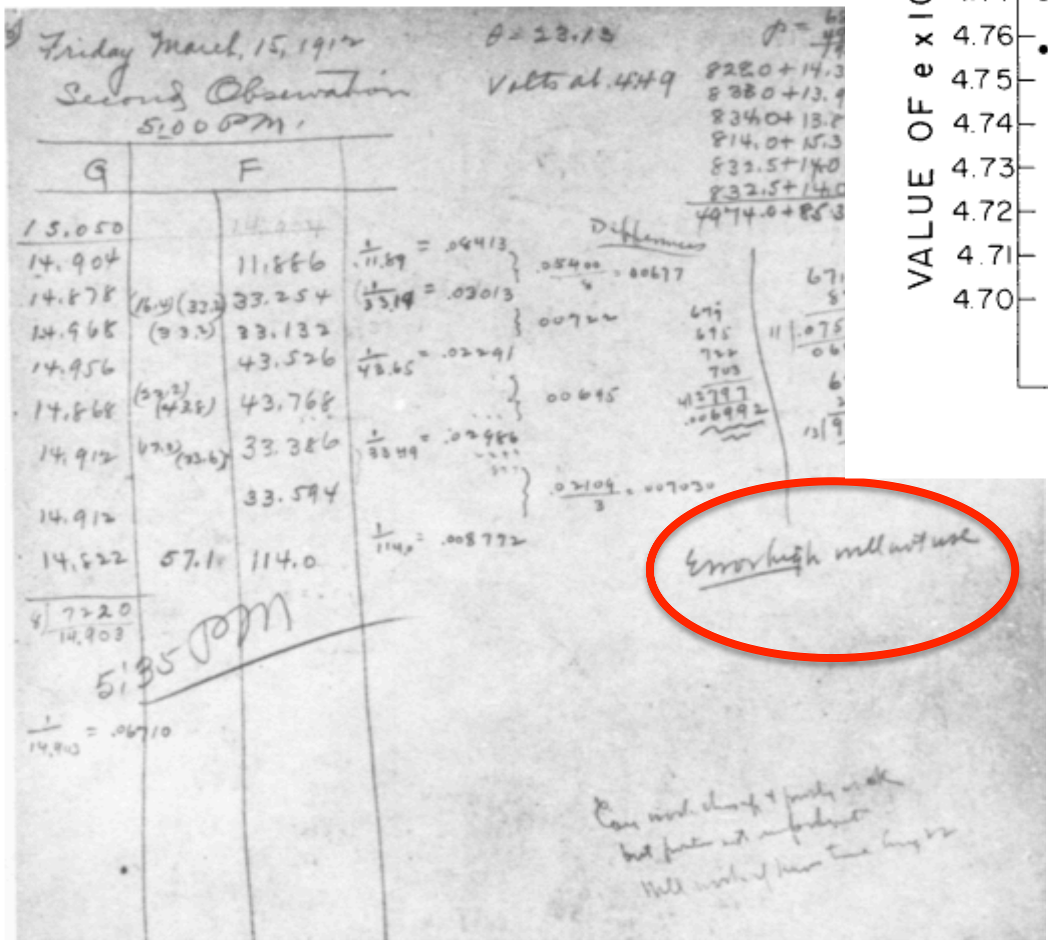
Millikan's notebook for the oil-drop measurements determining "e"

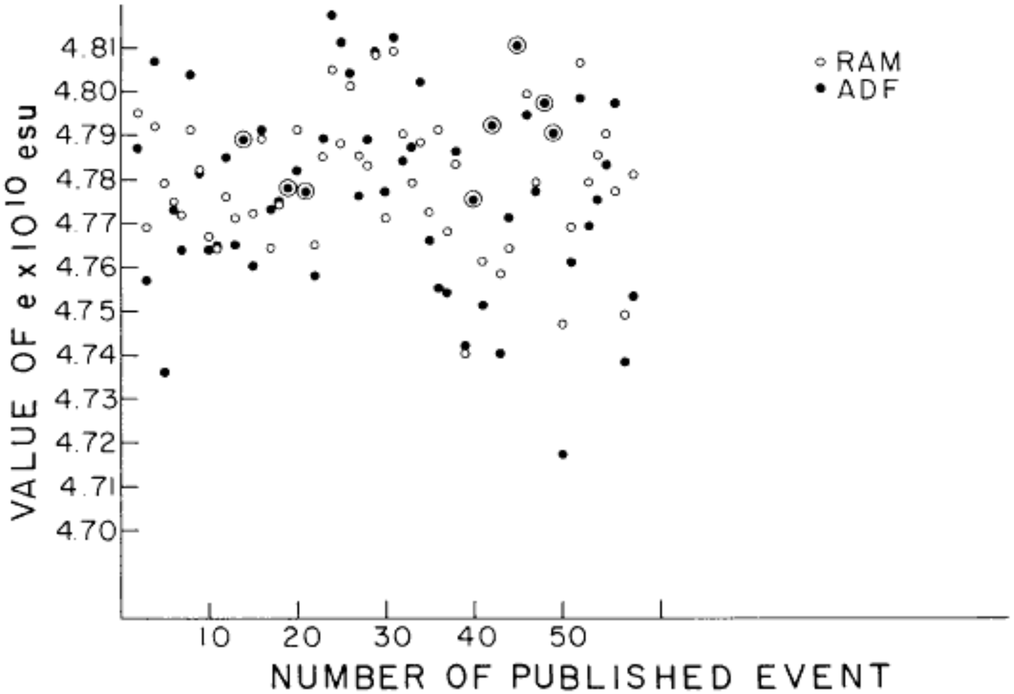
This is almost exactly right & the best one I ever had!!! [20 December 1911]
Exactly right [3 February 1912]
Publish this Beautiful one [24 February 1912]
Publish this surely / Beautiful !! [15 March 1912, #1]
Error high will not use [15 March 1912, #2]
Perfect Publish [11 April 1912]
Won't work [16 April 1912, #2]
Too high by 1½% [16 April 1912, #3]
1% low
Too high e by 1¼%

The published paper only had 58 "selected" measurements from 175.

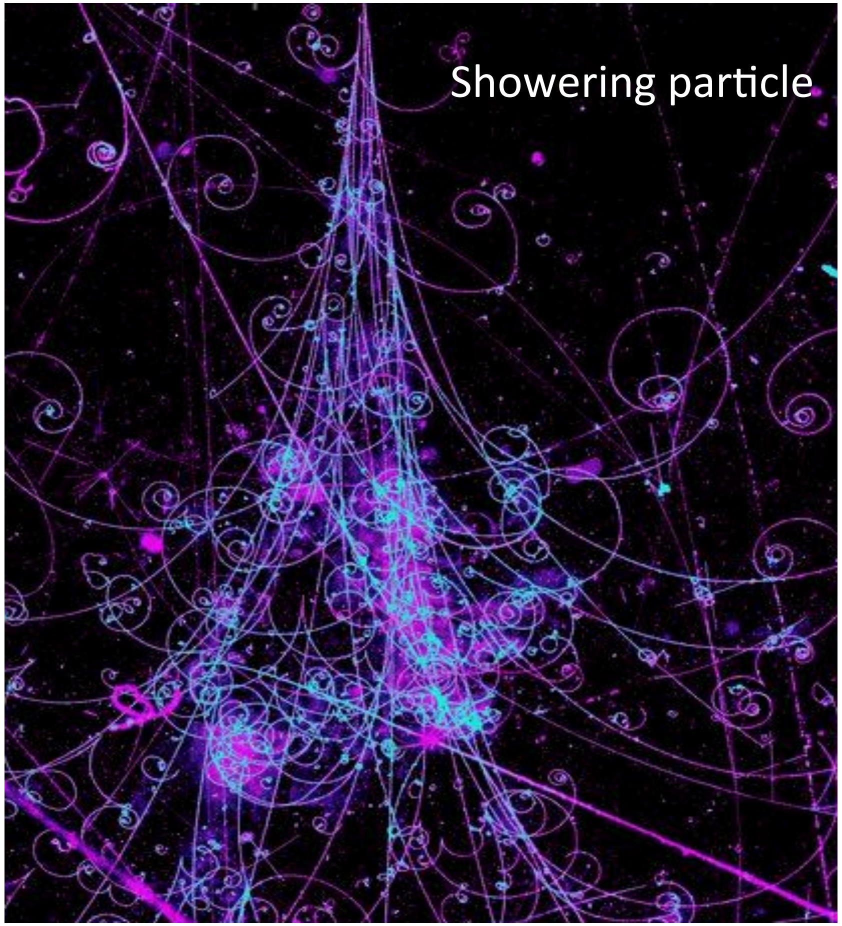
"These drops represent all of those studied for 60 consecutive days, no single drop being omitted."

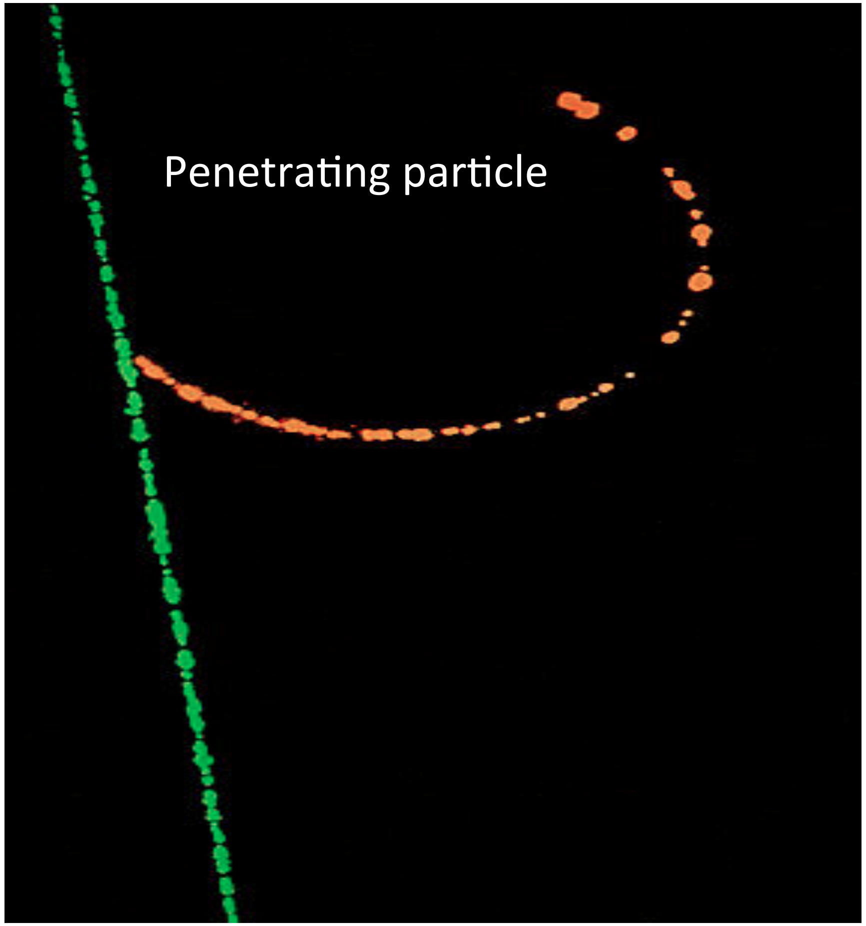
Form


Friday March 15, 1912
Second Observation
5:00 PM
G
F
5:35 PM
Error high will not use


VALUE OF e x 10^{10} esu
NUMBER OF PUBLISHED EVENT
RAM
ADF

Two types of particle seen





Showering particles believed to be electrons but only after a lot of theoretical work by Bethe, Heitler, Oppenheimer, Carlsson in developing QED of e^+e^- pair creation

Red and Blue Electrons !

But no tweaks to the theory could explain why e^- would be penetrating.

For a time the theorists toyed with the idea of the cosmic-ray particles being protons.

They then rejected that in favour of a model of “red” and “blue” electrons : one type showering and one type penetrating !

These rather embarrassing conjectures were quickly swept under the theorist’s carpet when the experimentalists started measuring masses and charges of the penetrating particles.

Chronology

1935 : Yukawa proposes a "mesotron" to explain the finite range of the nuclear force. A particle with mass between e^- and p

March 1937 : Anderson, Neddermeyer (CalTech)
± particles with mass between e and p

April 1937 : Street, Stevenson (Harvard)
mass (+) = (130 ± 30) m_e

August 1937 : Nishina, Takeuchi, Ichimiya (Tokyo)
mass(+) = (220 ± 40) m_e

June 1938 : Anderson, Neddermeyer
mass (+) ~ 240 x m_e

Jan 1939 : Nishina, Takeuchi, Ichimiya
mass(-) = (170 ± 10) m_e; mass(+) = (180 ± 20) m_e

Everybody goes off with "Oppie" to Los Alamos to build a bomb

The 1947 Consensus : Muon and Pion

After the war was still believed that what had been observed was Yukawa's mesotron.

1947 : Conversi, Pancini and Piccioni showed that interactions of the negative mesotron with the nucleus were not "strong" but "weak"

1947 : Weisskopf, Teller and Fermi noted that the decay time of mesotrons in matter was 10^{12} longer than for the "Yukaka mesotron".

The negative mesotron was then given the symbol : μ.

1947 : Lattes, Muirhead, Occhialini and Powell find μ^- arise from decay products of another cosmic ray mesotron that they give the symbol π.

It was finally realised the μ wasn't a meson but the name "mu-meson" persisted for many years with "muon" only being widely adopted in the 1960s.

Yukawa's mesotron was christened the pi-meson in 1947 and latterly the pion.

Nobel Problems

Muon was “discovered” by 5 sets of experimentalists and cogent interpretation wouldn’t have been possible without the theory input.

Arguably the Japanese had the most incisive measurement.

The data and its interpretation took 15 years to be accepted.

Solution – no Nobel Prize for the Muon Discovery !

- Keep the Japanese happy : Yukawa (1949) gets a prize for the pion theory
- Keep the USA happy : Anderson already got the prize for e^+ (1936) and gets the credit for the muon but not a second prize
- Keep the Brits happy : Powell (1950) for the experimental discovery of the pion and Blackett (1948) for cloud chamber.
- Italians not happy and the 1st observation was by a German !

ATLAS, CMS, Englert, Guralnik, Hagen, Higgs, Kibble, ….

More problems

Three initial problems of QM:

- identity of strong force carrier
- composition of cosmic rays
- magnetic moments/spin and infinities in Dirac theory.

First two solved with pion and muon (1932 – 1948)

Last took longer but also concluded in 1948.

Began with Stern/Gerlach : seeking to measure "spatial quantization" of Bohr/Sommerfeld orbits at a time when nothing known about "spin"

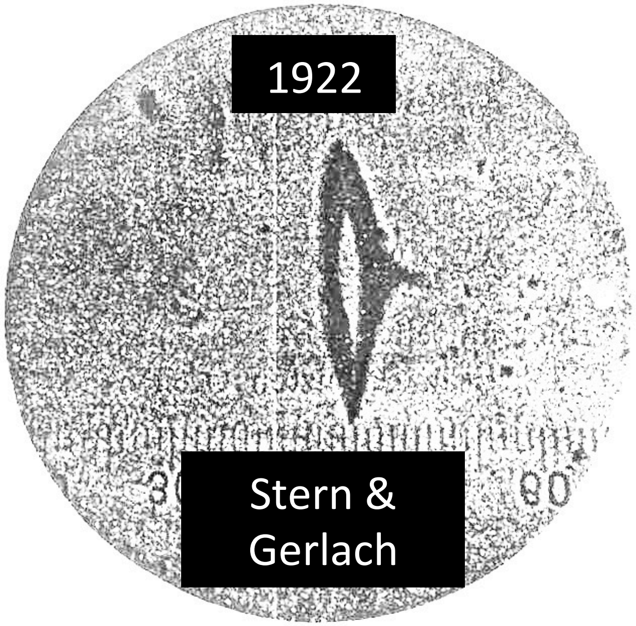
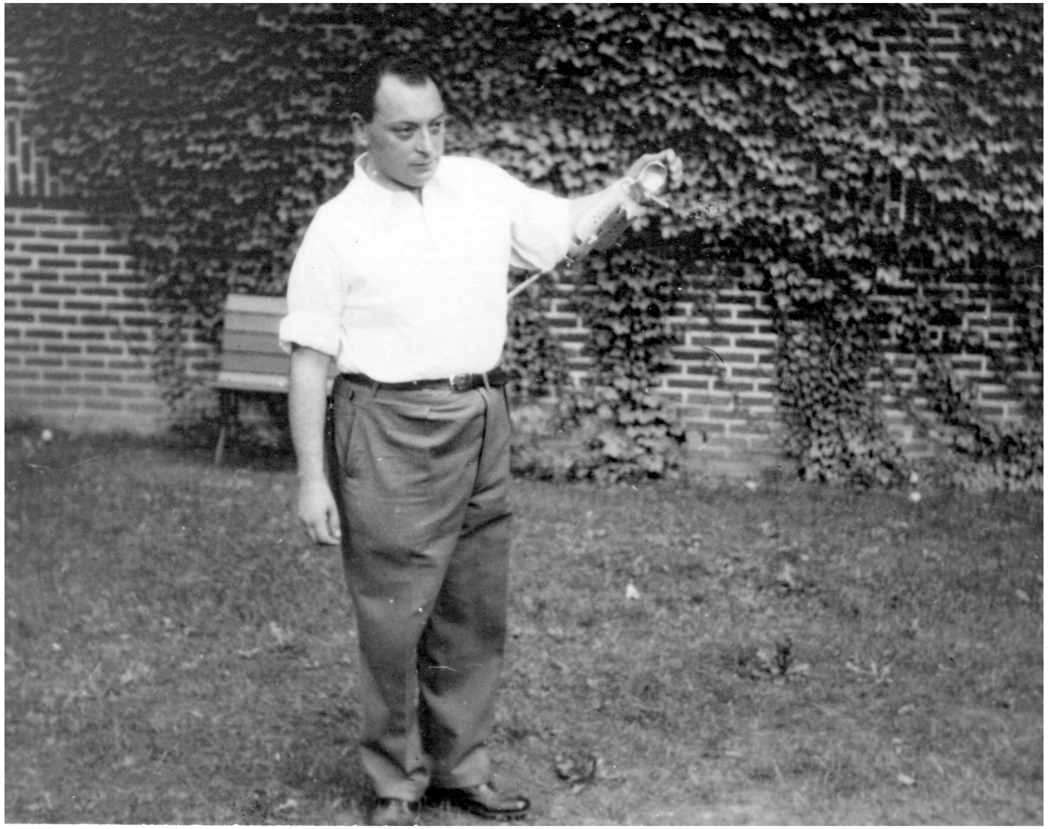


Fig. 3.

Not a lot in the way of theory

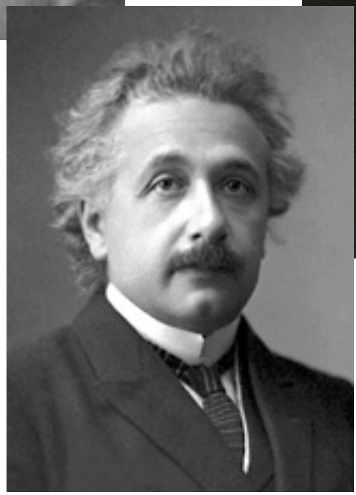
"You look very unhappy,"

"How can one look happy when he is thinking of the anomalous Zeeman effect?"



Experimentalists also unhappy since they had no money…

Max Born & Bankers to the rescue



A little luck

Sulphide from his cheap cigars blackened the glass plates and revealed new method to view the beam.

Experiments moved to Hamburg where with Frisch/Esterman
Stern set about trying to measure proton & deuteron magnetic moments.

By this time Dirac had his equation and with Pauli's proposed spin + work by Uhlenbeck, Goudsmit, Thomas *things were beginning to make sense*
(fine structure of spectra, Stern-Gerlach)

BUT Magnetic Moment of the Proton

"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" : Pauli

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

The assumption was that the proton would behave just like the electron

Magnetic Moment of the Proton

Fiendishly tricky since affect is 1/1836 that of atom (electron)

1st evidence of quarks ~ 40 years before "direct" experimental discovery.

Magnetic Moment of the Proton

1947 – 1948 : 3 "precision" measurements to change everything.

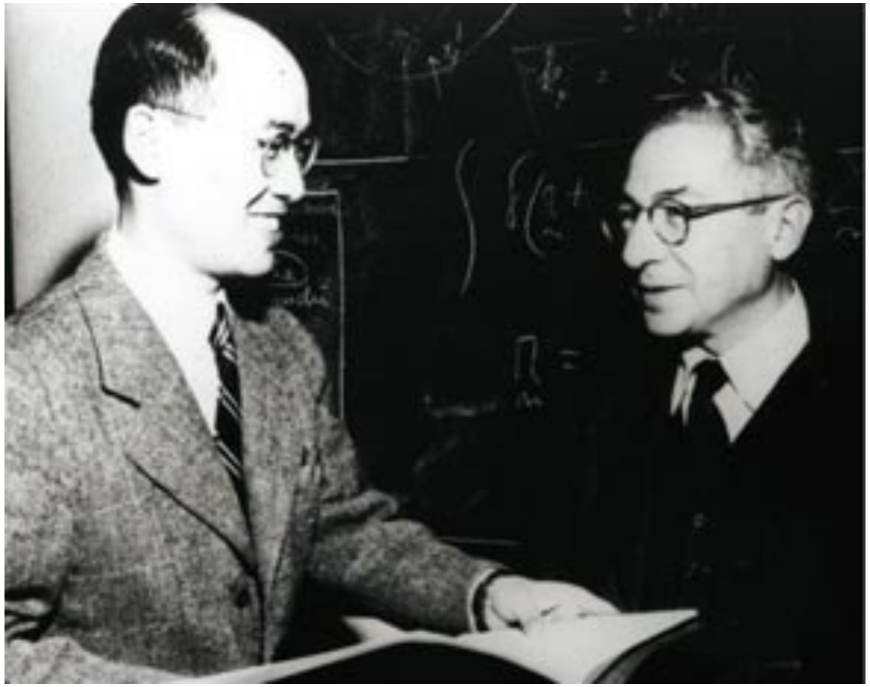
1. Hyperfine splitting in hydrogen : Lamb shift.
2. Hyperfine structure of hydrogen + deuterium : Rabi *et al.*
3. Kusch & Foley : precision magnetic moment of electron: (g-2)

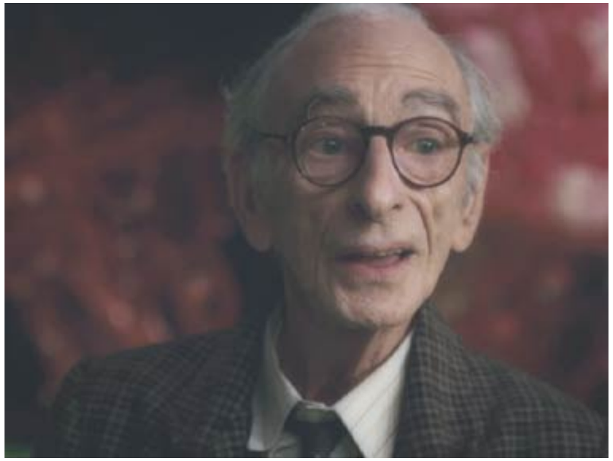
None of these measurements agreed with Dirac theory ……..

"Never measure anything but frequency"

I. Rabi

Who ordered that ?





One of 1st CERN experiments was Lederman's muon magnetic moment experiment (1959) using the 600 MeV accelerator

Why all this history ?

1. Never believe the theorists, particularly if they say the experiment is irrelevant or the result is already known.

2. Even if the experiment seems impossible : try it.

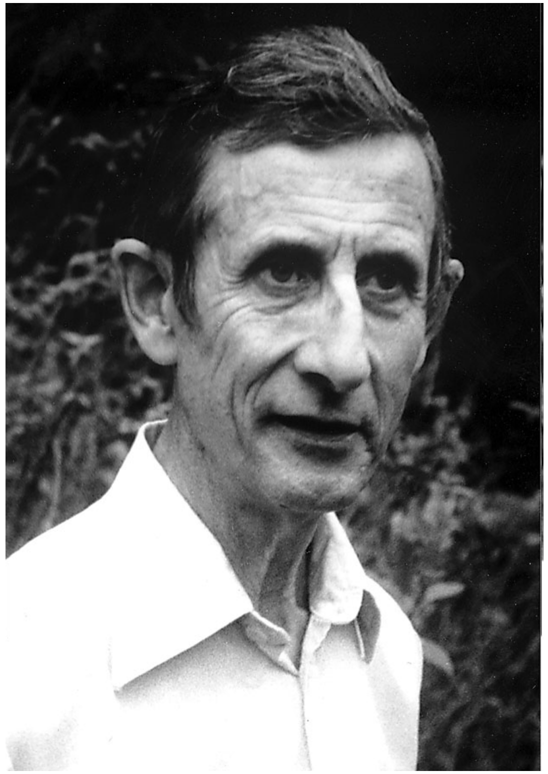
3. It's not all about high energy.
High precision arguably been of more value in the development of physics.

4. Expect a surprise even at low energy that can affect fundamental physics

Why Precision

"The results of my survey are then as follows: four discoveries on the energy frontier, four on the rarity frontier, eight on the accuracy frontier. *Only a quarter of the discoveries were made on the energy frontier, while half of them were made on the accuracy frontier*. For making important discoveries, high accuracy was more useful than high energy."

Freeman Dyson



Go to Birmingham

In 1948 Freeman Dyson received offers from Birmingham, Bristol & Cambridge.

Oppenheimer advised:

"Birmingham has much the best theoretical physicist, Peierls;

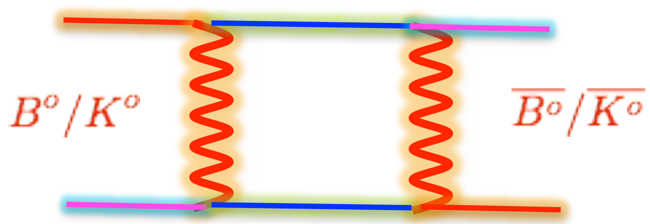
Bristol has much the best experimental physicist, Powell;

Cambridge has some excellent architecture"

Why Precision ?

Historically small deviations have been as insightful as new particles in developing a self-consistent (Standard) model.

1. Precise measurement of Kaon-mixing : **prediction of charm quark.**



2. Rare Kaon decays : **first observation of CP-violation**
   : **requirement of CKM and a 3rd generation of quarks**
   - *first input into explaining universe's baryon asymmetry.*

3. Precise measurement of B-mixing **: prediction of large top quark mass.**

Outside of HEP : tiny deviations in Mercury's orbit : vindication of General Relativity.

Low Energy Surprises

Published online 7 July 2010 | Nature | doi:10.1038/news.2010.337

News

The proton shrinks in size

Tiny change in radius has huge implications.

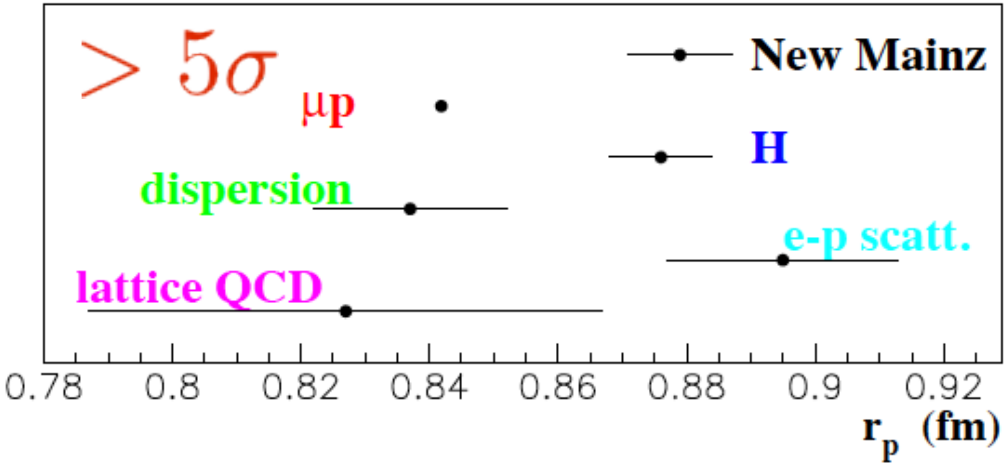
Geoff Brumfiel

The proton seems to be 0.00000000000003 millimetres smaller than researchers previously thought, according to work published in today's issue of *Nature*[1].

Measurements with las
revealed that the proto
touch smaller than predicted by current theories.
PSI / F. Reiser

The difference is so infinitesimal that it might defy belief that anyone, even physicists, would care. But the new measurements could mean that there is a gap in existing theories of quantum mechanics. "It's a very serious discrepancy," says Ingo Sick, a physicist at the University of Basel in Switzerland, who has tried to reconcile the finding with four decades of previous measurements. "There is really something seriously wrong someplace."

Muonic hydrogen
- originally missed it !



Rp = 0.84184 (67) fm (muons)
Rp = 0.8768 (69) fm (electrons)

$$\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0346 r_p^3 \ \ \text{meV}$$

Low Energy Surprises

NATURE | NEWS

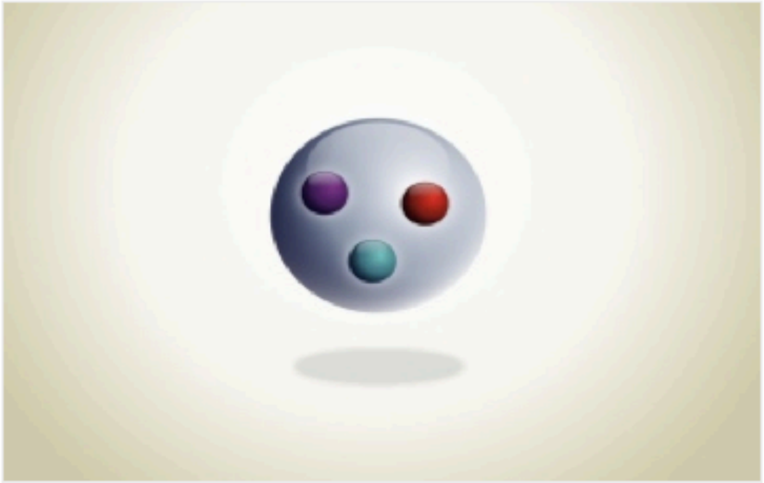
Shrunken proton baffles scientists

Researchers perplexed by conflicting measurements.

Geoff Brumfiel

24 January 2013

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.

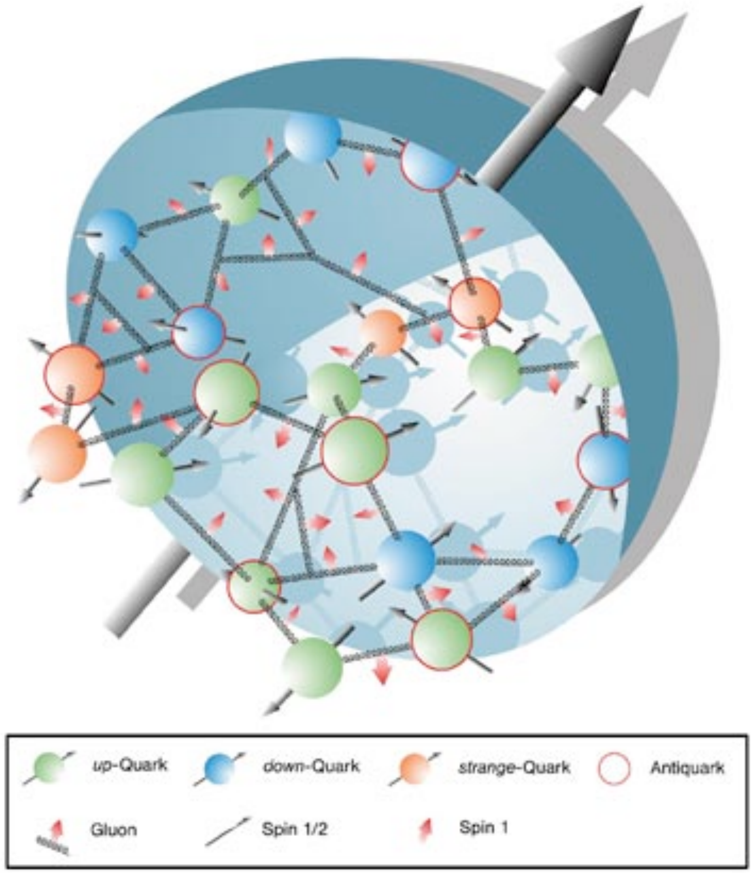


The proton's three quarks are (mostly) confined within a region 0.87 femtometres wide — or is it 0.84?

WESLEY FERNANDES

An experiment published today in *Science* [1] only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

Proton's Angular Momentum



Naively expect sea & gluons ~ 0
and be simply spin of 3 valence quarks

Observe that 2/3 of J NOT carried by spin of quarks and there is a large contribution from quark L and some from gluons…

Predicting the proton's magnetic moment from QCD remains unsolved.

$$\mu_p = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d$$

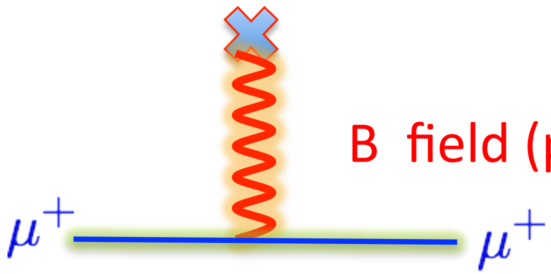
is NR, assumes spin carried by valence quarks of mass 300 MeV…

What's g-2

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

$\vec{\mu} \times \vec{B}$ Interaction between magnetic moment (spin) with B-field.

Spin precesses around B at a rate determined by "g"



Simplest "Dirac" interaction gives g=2 $ieA_\mu\gamma^\mu$

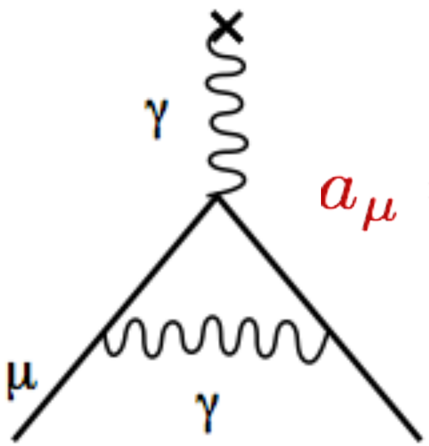
What’s g-2

Additional “Pauli-term” interactions $(g-2)F_{\mu\nu}\sigma^{\mu\nu}$

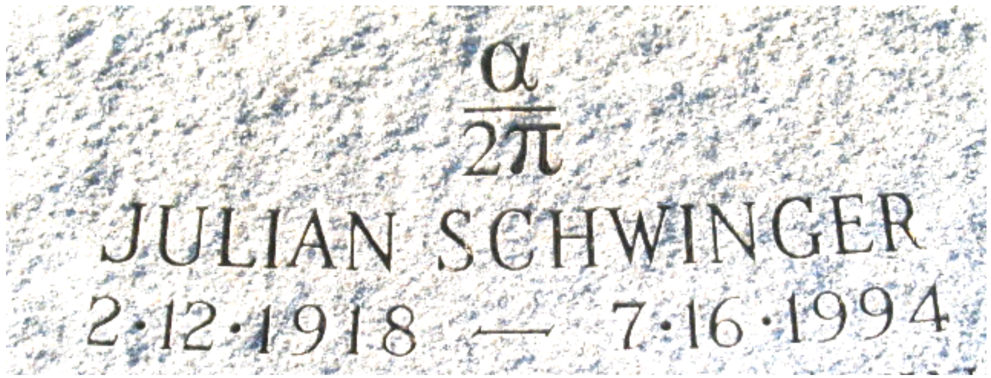
from loops give **a non g=2 contribution**.
This is the so-called anomalous contribution.

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

These interactions flip the chirality of the muon.

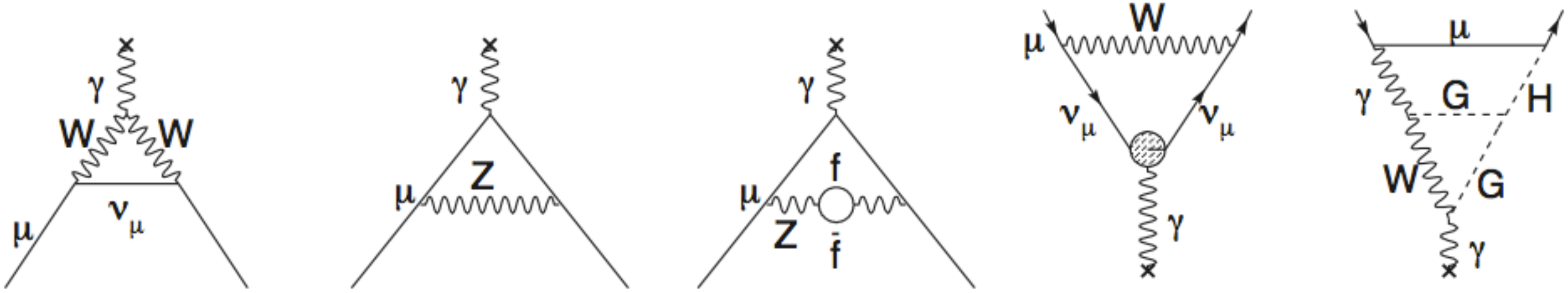


$$a_\mu = \frac{\alpha}{2\pi}$$

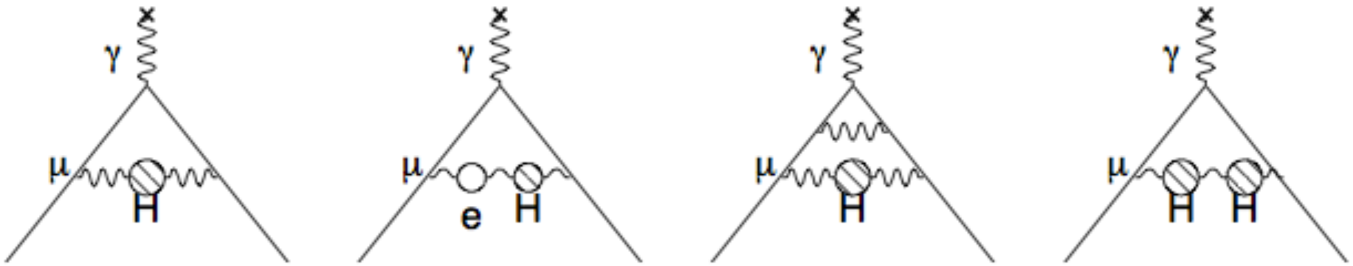


Contributions to g-2

Electroweak Contributions

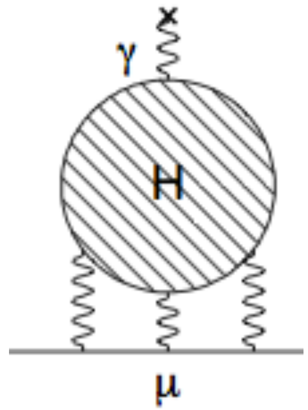


Hadronic Contributions

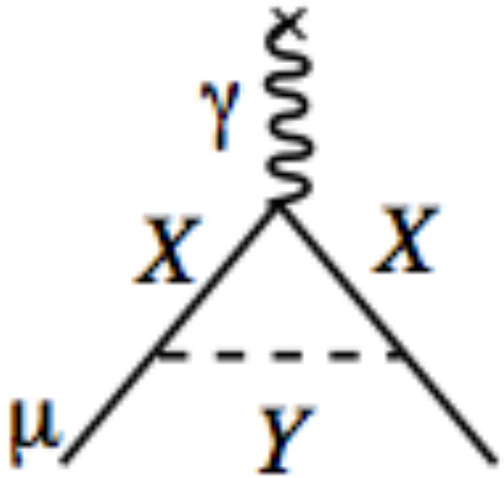


Hadronic Vacuum Polarisation (HVP)

Hadronic Light-by-Light(HLBL)



New Physics Contribution to g-2



New physics as: $$\left(\frac{m_\mu}{M_{\mathrm{NEW}}}\right)^2$$

Although precision of electron g-2 measurement is phenomenal
it does not have sensitivity to new physics except at very low masses.

To probe upto TeV-scale physics need to measure muon g-2.

Electron g-2

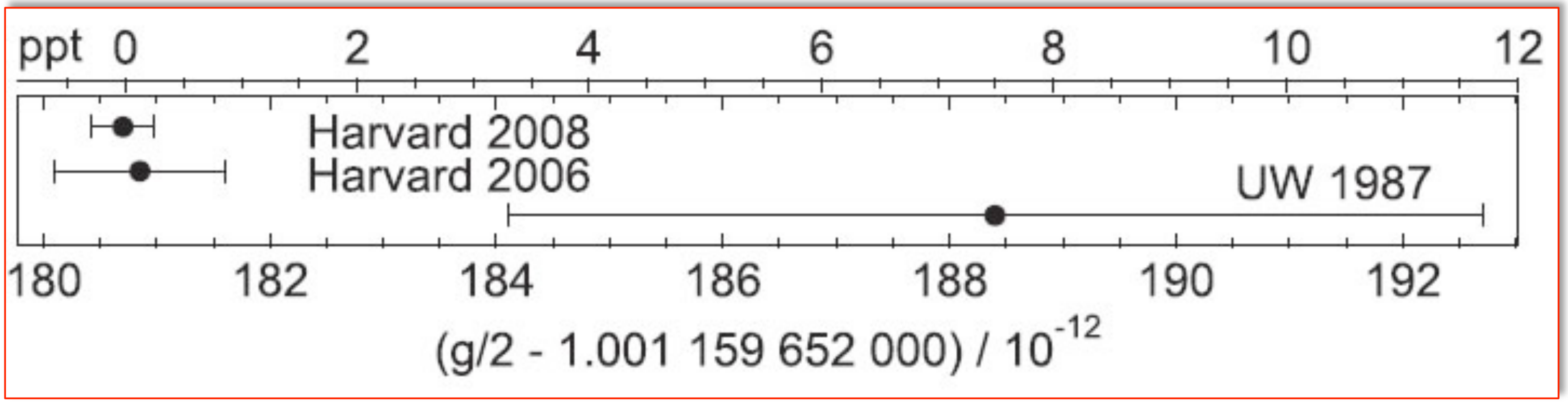
Electron g-2 is ostensibly a QED probe and yields most precise α_{EM}

We need α_{EM}/ $(g\text{-}2)_e$ to make the QED prediction for (g-2)μ and any other EWK parameter e.g. the Higgs Mass…..

Gerald Gabrielse

g-2 electron

Measured to 3 parts in 10^{13} !!!



QED (5th order) at 13th dp.

$$g - 2 = 0.00231930436146 \pm 0.00000000000056$$

Hadronic at 12th dp.

EWK beyond exp. precision

QED : 5 (NNNNLO!) loop for (g-2) of electron

arxiv:1205.5368
12,672 diagrams…

$$(9.2 \pm 0.6) \times \left(\frac{\alpha}{\pi}\right)^5$$

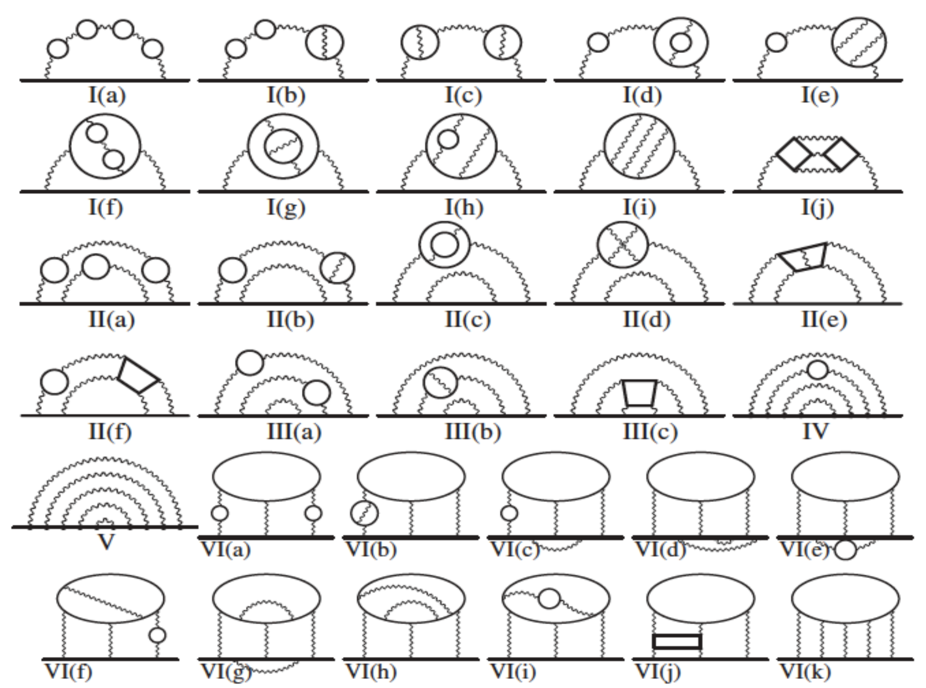


FIG. 2. Typical self-energy-like diagrams representing 32 gauge-invariant subsets contributing to the tenth-order lepton $g-2$. Solid lines represent lepton lines propagating in a weak magnetic field.

T. Kinoshita

Magnetic Moment of Anti-Proton (2013)

ATRAP Collaboration

arxiv: 1301.6310 : single anti-proton, uncertainty reduced by a factor of 680 !

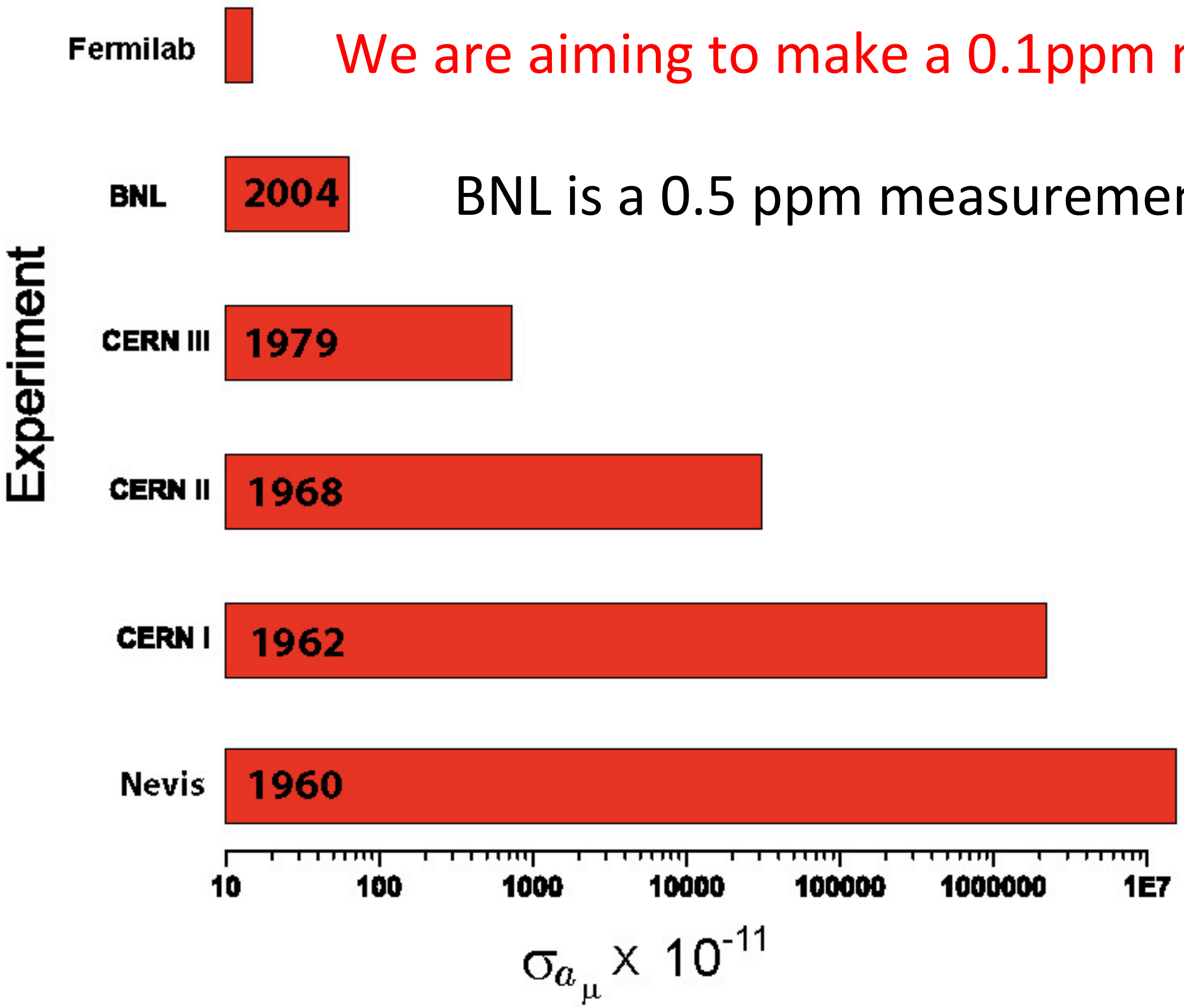
$$\frac{\mu_{\overline{p}}}{\mu_p} = -1.000000 \pm 0.000005 \quad (5\text{ppm})$$

5×10^{-17} torr Penning trap

Claim that precision can be improved further by a factor of $10^{3\text{-}4}$

Complementary test of CPT compared to H/anti-H and e^-/e^+
and for p/p-bar from q/m (precision 1 p in 10^{10})

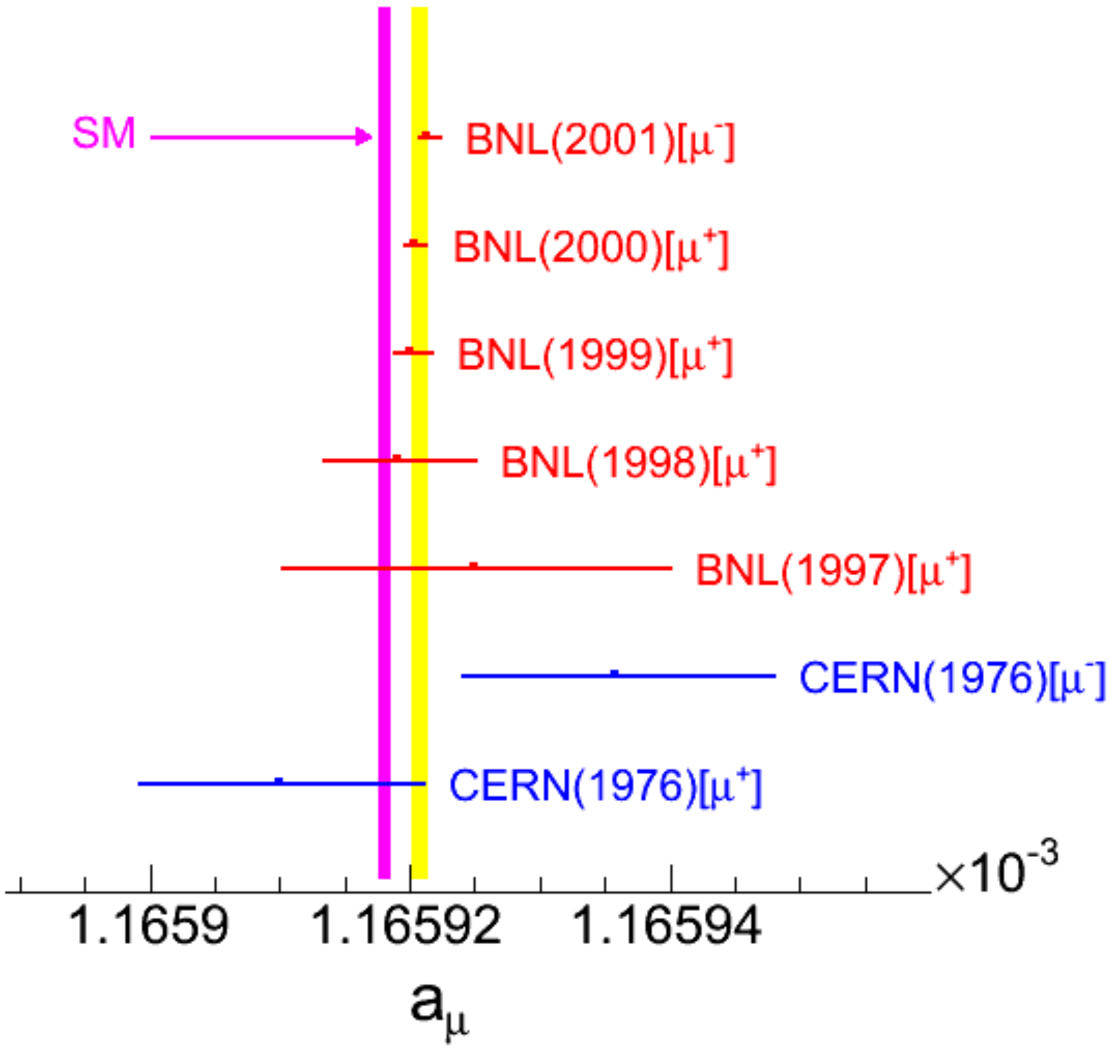
Muon g-2 Measurements



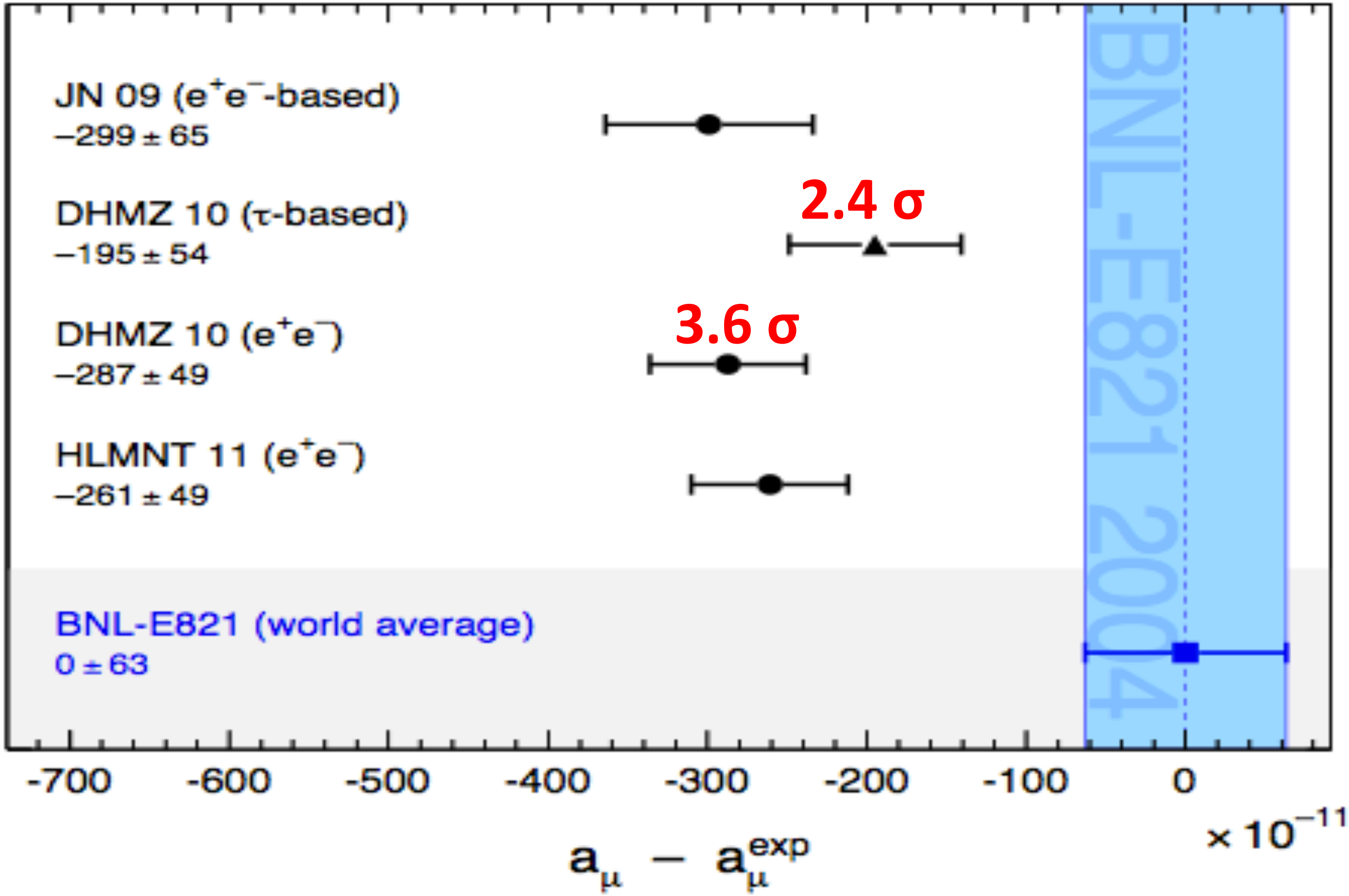
We are aiming to make a 0.1ppm measurement

BNL is a 0.5 ppm measurement

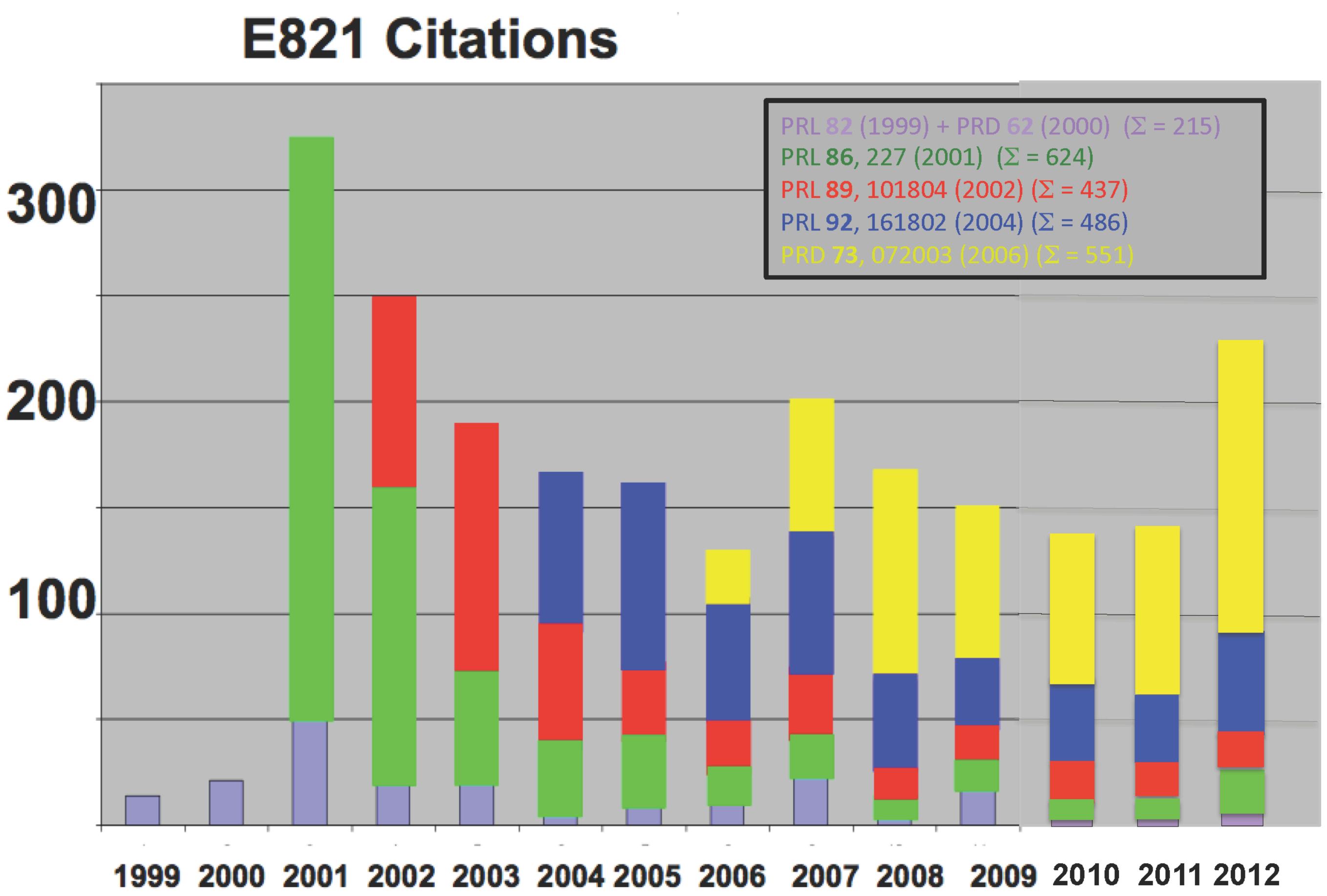
Muon g-2 Measurements



Why bother measuring it to 0.1 ppm ?



Citations of g-2 BNL result



2098 citations

Top 100 "Spires" Citations

95 on astrophysics (CMB etc) + particle theory

Only 5 from experimental particle physics

3478 : Super K : neutrino oscillations (1998)

2098 : BNL g-2 (2001)

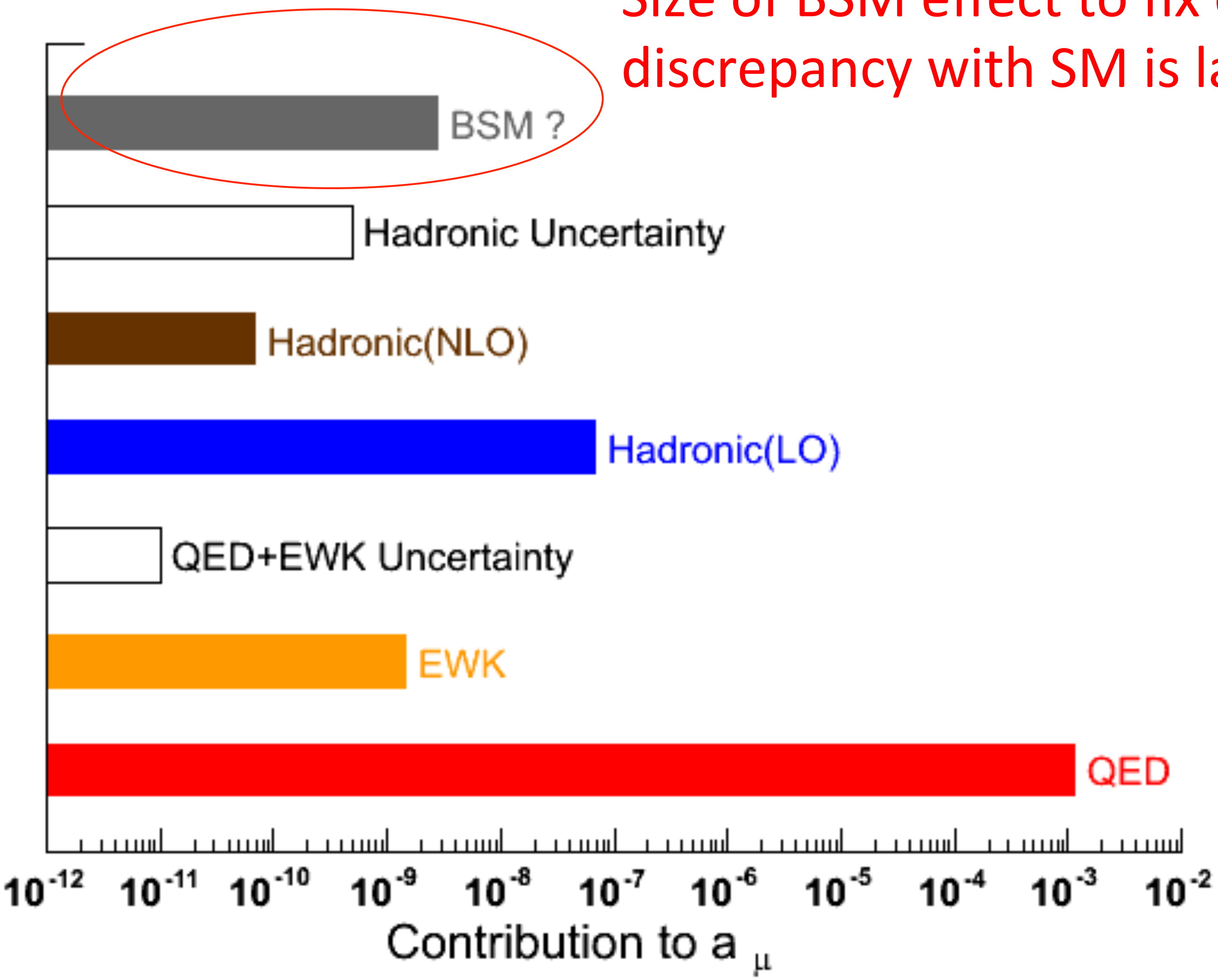
1808 : CP violation in Kaon decays (1964)

1771 : CDF top quark discovery (1995)

1765 : J/ψ discovery (1974)

Why is this one number interesting ?

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



Physics is in a "hell of a way"

Need new physics to:

1. Give mass to the neutrino and explain why $m_\nu/m_t = 10^{-12}$
2. Give significant CP violation to explain matter anti-matter asymmetry but also to explain why there is zero CP in QCD : axion !!!
3. Explain dark matter
4. Develop a quantum theory of gravity

The LHC cannot do all of this and may do none of it.....

Current sightings of new physics

1. Neutrino oscillations : >> 5σ
2. (g-2) of muon : 3.6σ

3. D0 like-sign dimuon asymmetry : 3.9σ but with LHCb results requires a highly-tweaked theory to explain
4. DAMA/COGENT/CRESST : 10 GeV dark matter : not confirmed.
5. LHCb/CDF CP violation in D mesons : 3.8σ

6. ALEPH 4 jet events : 12σ

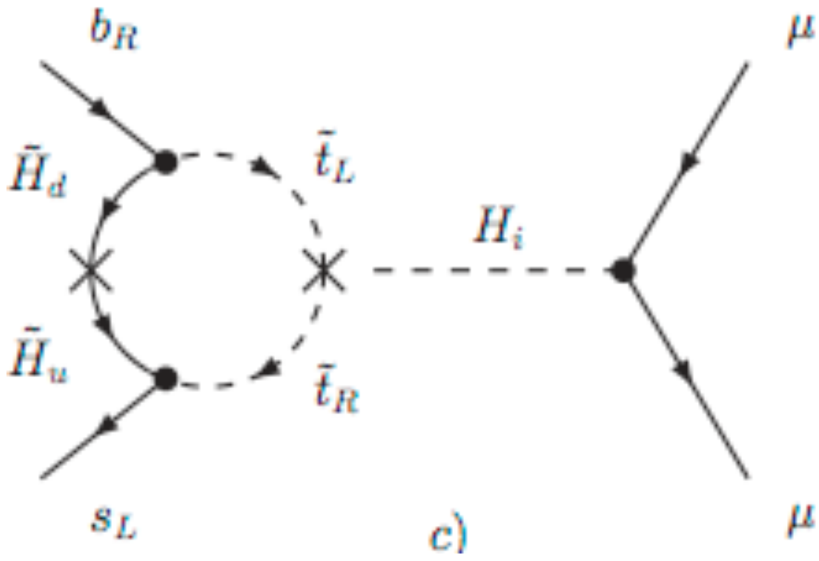
Lack of significant BSM in B → μμ or direct SUSY ….

Coloured vs Non-Coloured Sector

Insufficient SM or BSM CP-violation in the quark sector
→ **We need CP-violation in the neutrino sector**

No obvious "(s)colour" loops
→ **Are there (s)lepton loops ?**

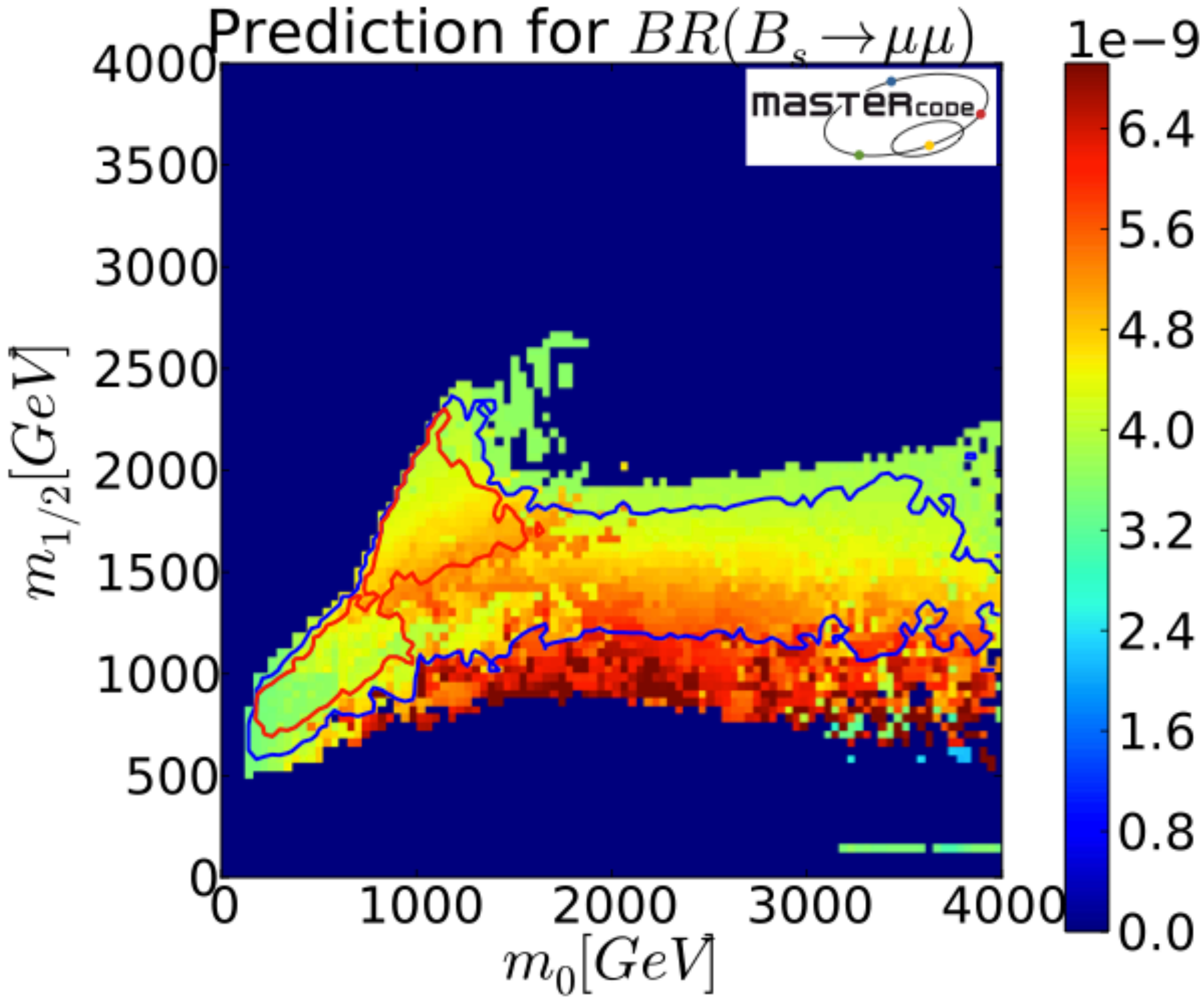
No obvious 0.1 – 2 TeV particles ?
→ **Probe higher energy**



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

John Ellis et al., arxiv:1207.7315

Coloured vs Non-Coloured Sector



95% allowed
by ATLAS/CMS+XENON

LHCb
Measurement

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
$BR_{b\to s\gamma}^{EXP/SM}$	1.15	1.19	0.94	0.18
$BR_{B\to\tau\nu}^{EXP/SM}$	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
$A_\ell(SLD)$	2.49	3.51	4.36	3.68
σ_{had}^0	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

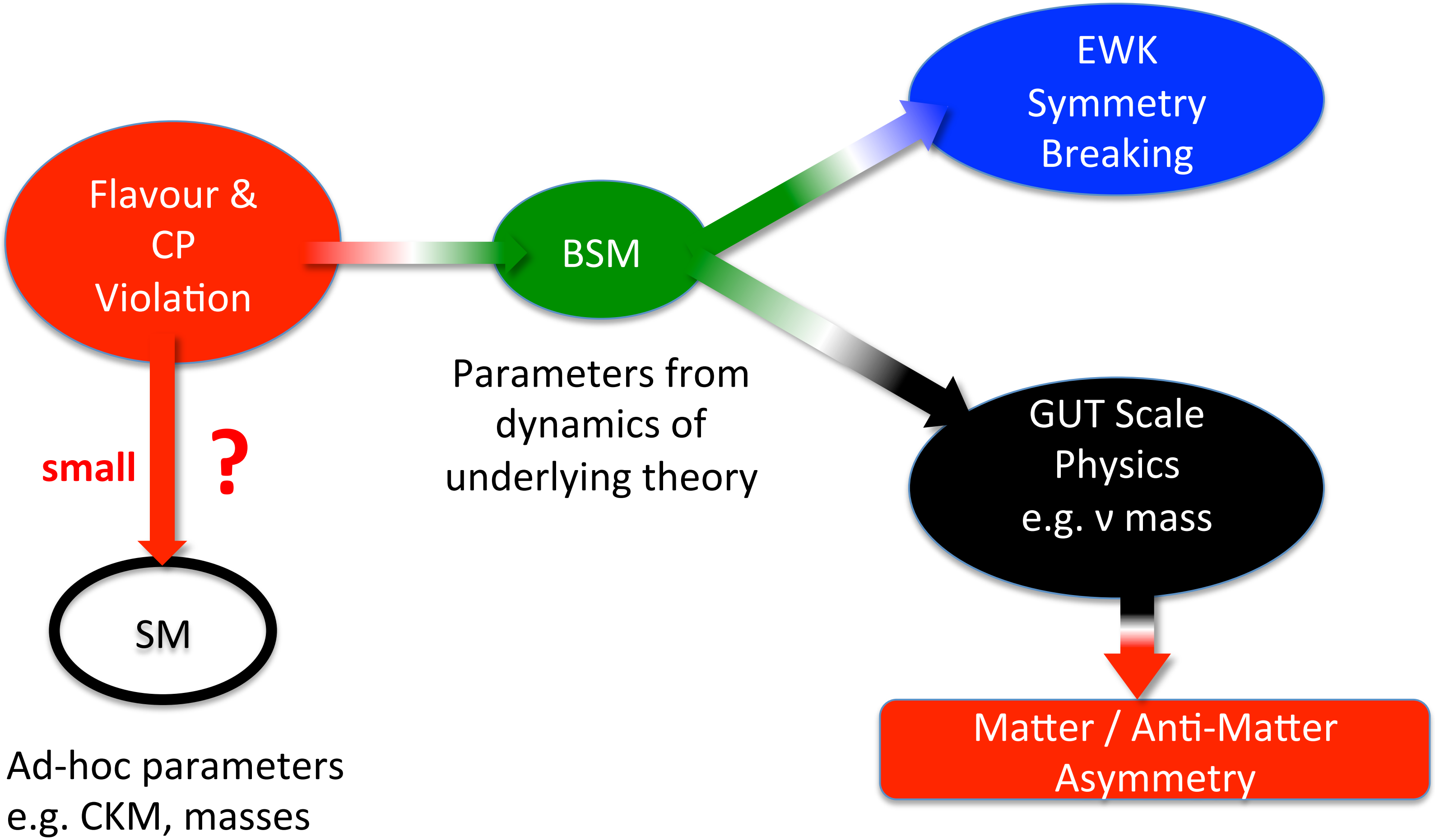
Simple cMSSM struggling to describe all data.

Result with largest tension against simplest SUSY models i.e. it favours low mass SUSY is the muon magnetic moment

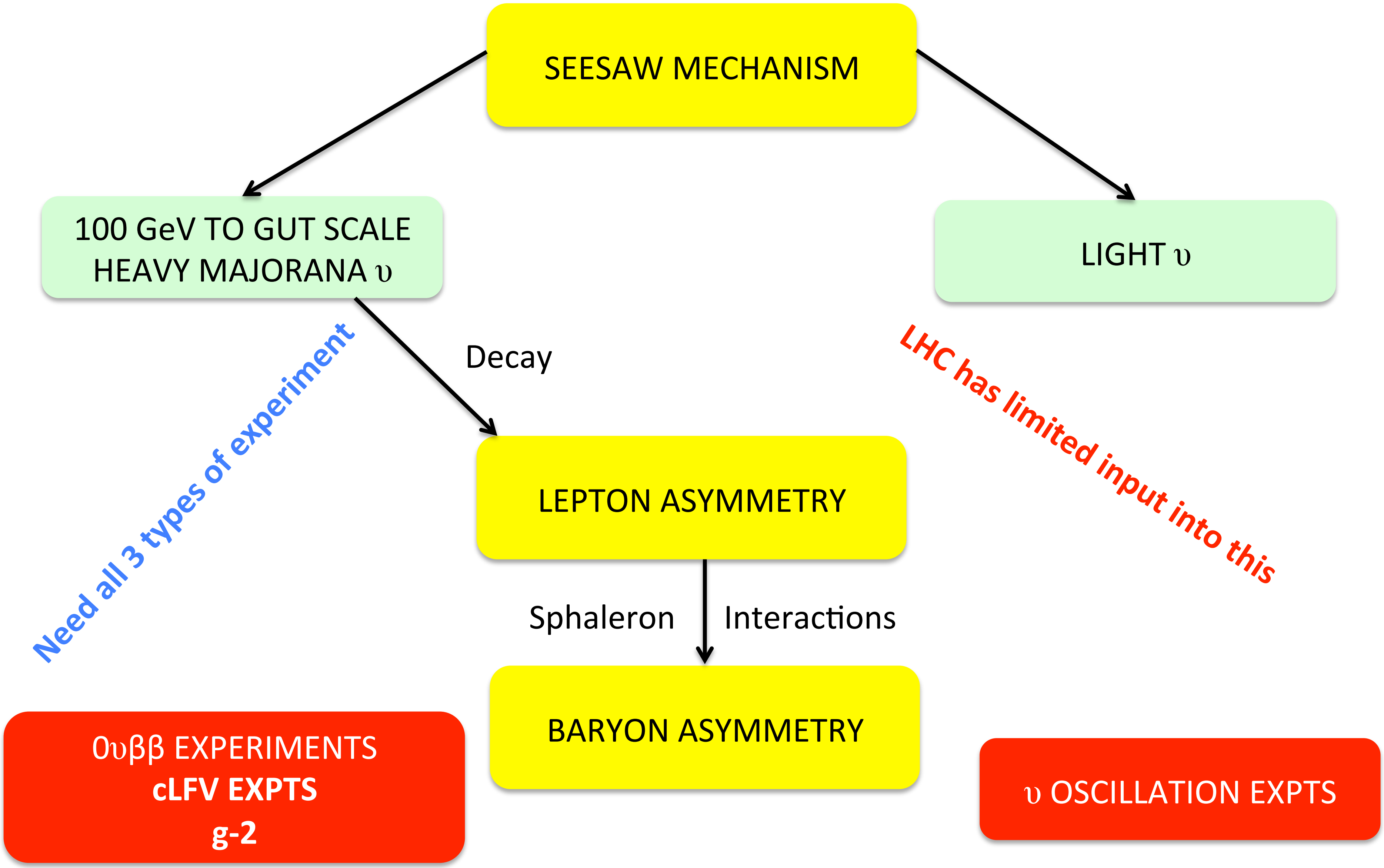
Could be a fluctuation or could be telling us something

Beyond Vanilla BSM (BVBSM)

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



Matter Anti-Matter / Neutrino Synergy



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

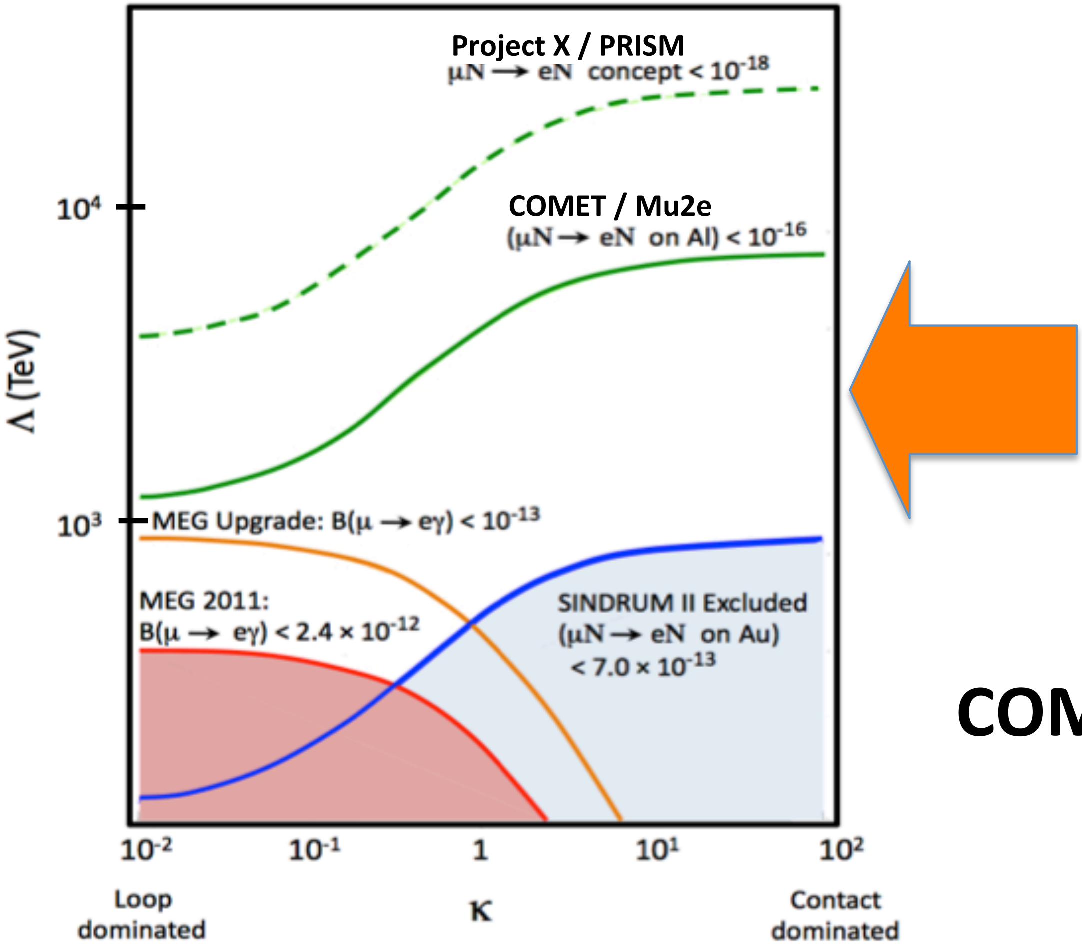
Back to drawing board...

g-2 anomaly was hadronic theory

Get to execute a few theorists !

Probing beyond LHC reach with muon CLFV

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



cLFV new physics scale
1000 – 10000 TeV

COMET / Mu2e experiments

g-2 as probe of new physics

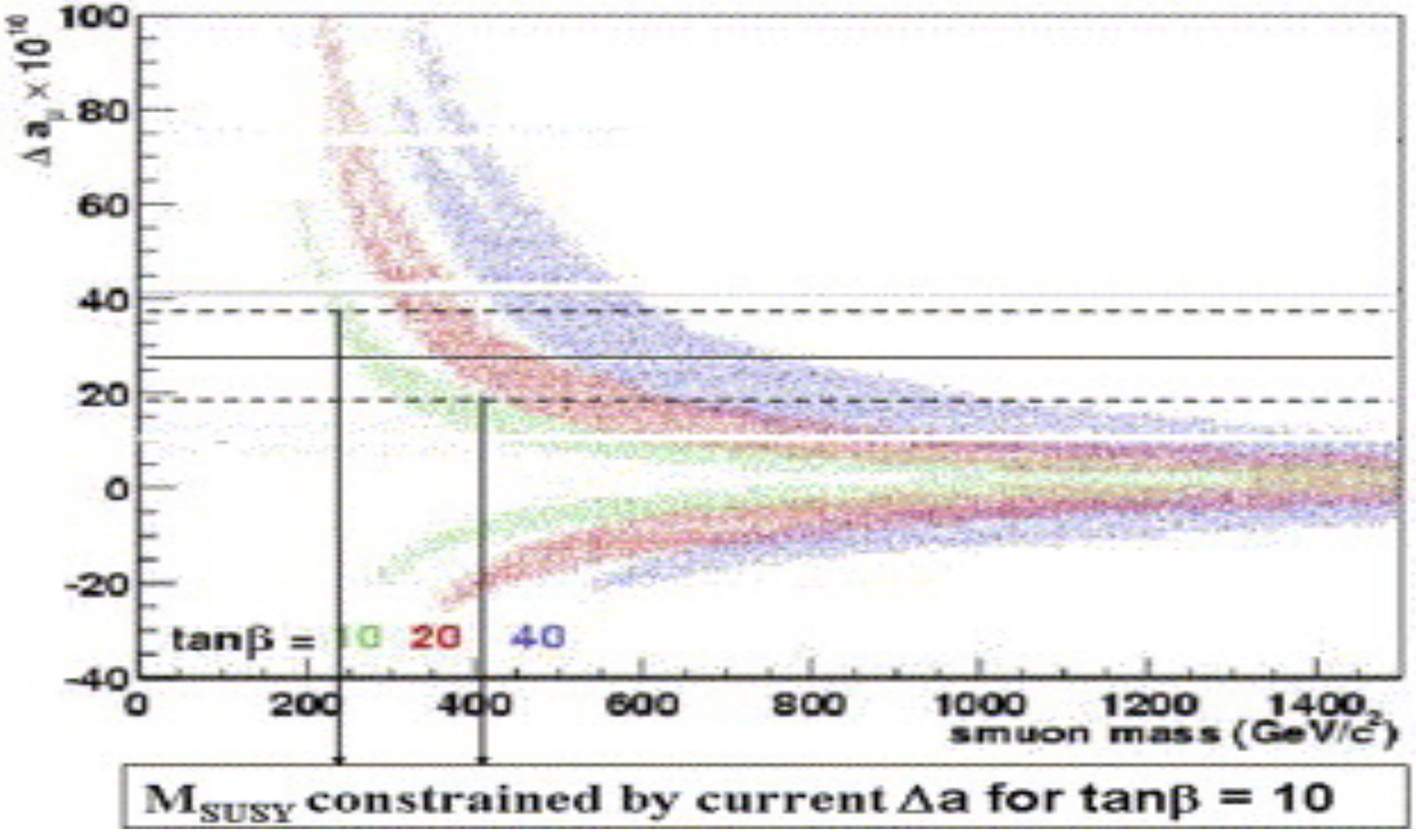
2,000+ papers exploring this and 200+ alone in 2012 seeking to reconcile it with LHC i.e. 125 GeV Higgs + no low mass results.

Vanilla SUSY

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

Generic picture that BSM comes in as $1/m^2$

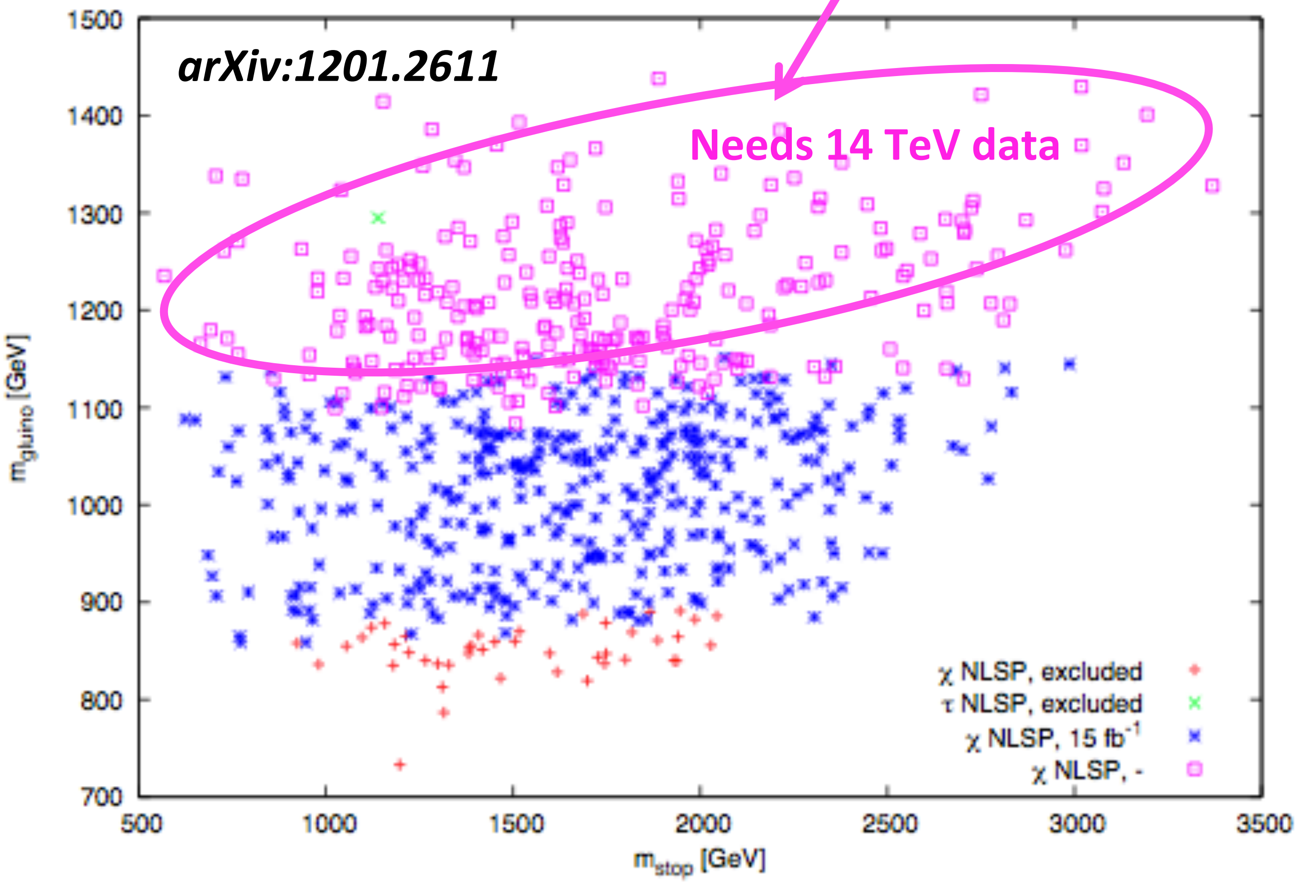
g-2 as probe of new physics



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

g-2 as probe of new physics

Consistent with current g-2 measurement at 95% CL



Beyond Vanilla BSM (BVBSM)

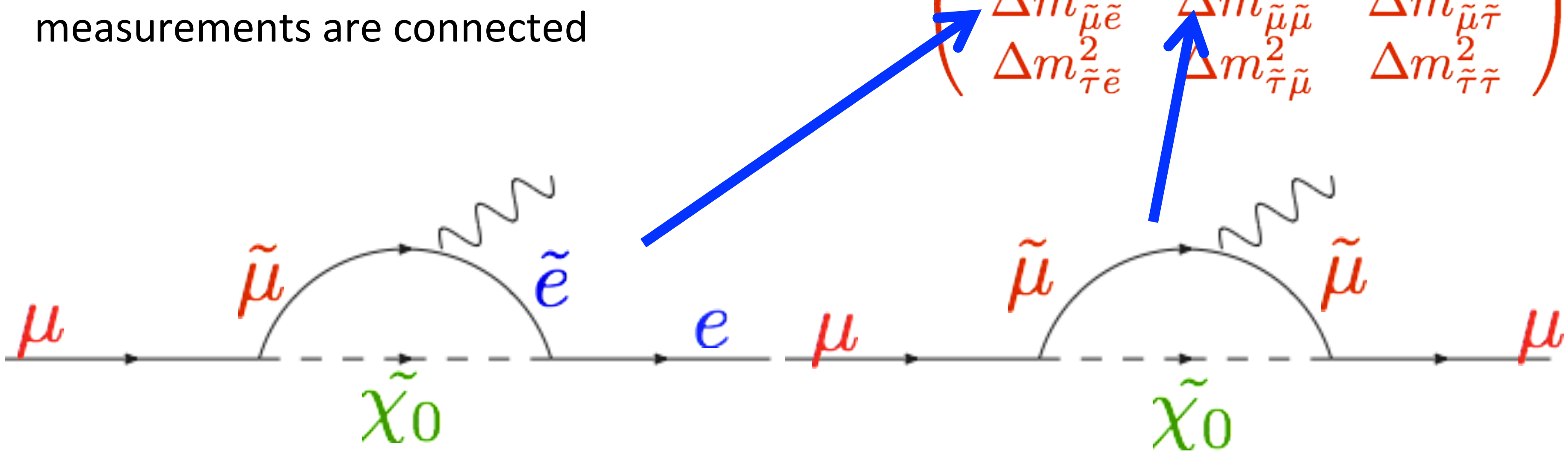
BVBSM models tend to be characterised by large flavour symmetry and small SUSY breaking

Expect **SMALL** deviations from SM:

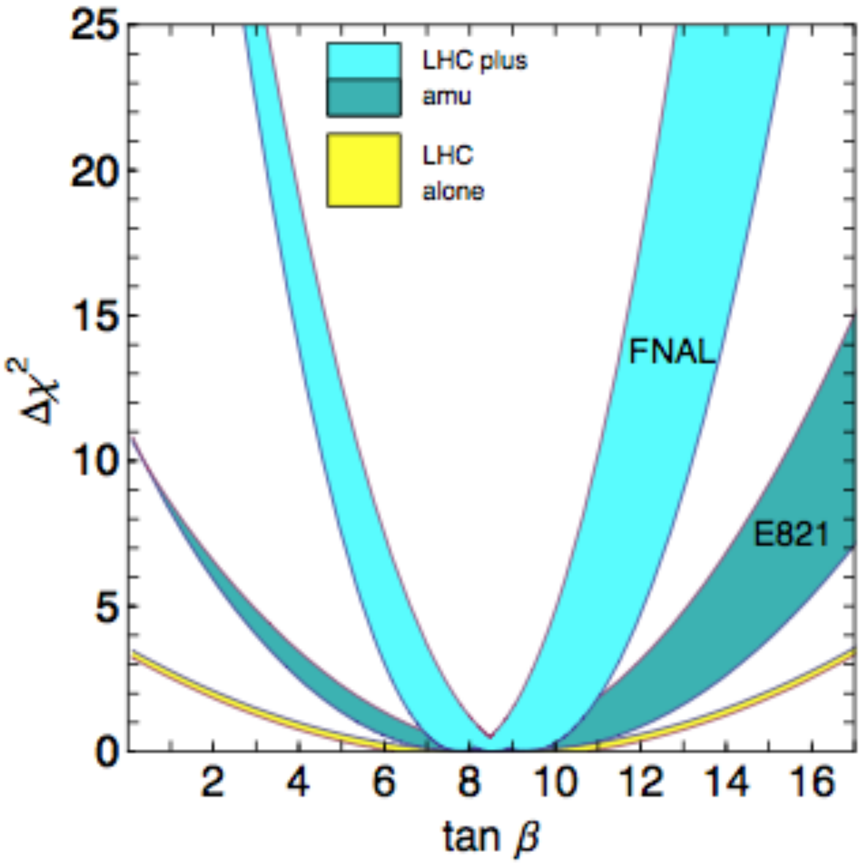
- precision measurements : (g-2)
- processes that are zero in SM : **EDMs, cLFV**.

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

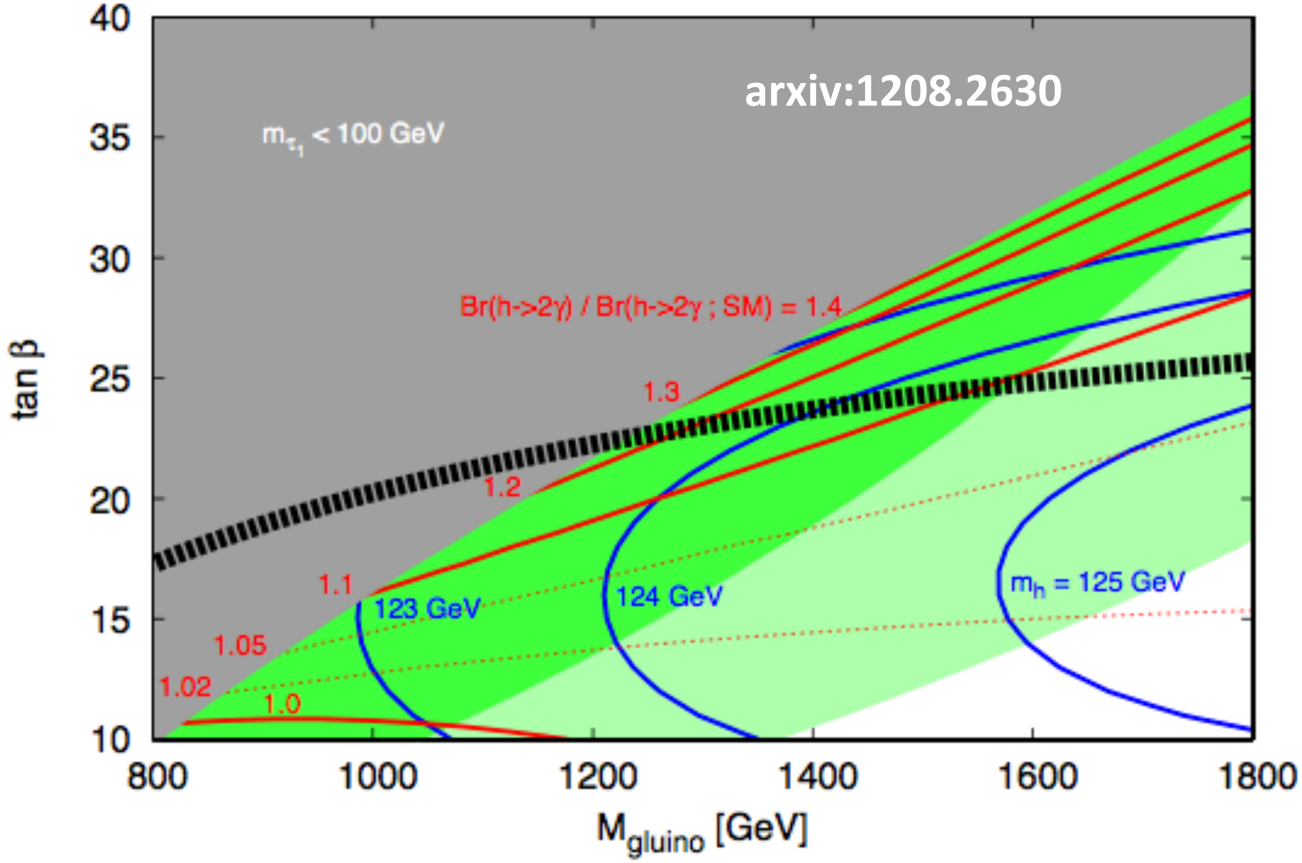
Sign of contribution of SUSY to (g-2) determined by sgn(μ)

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

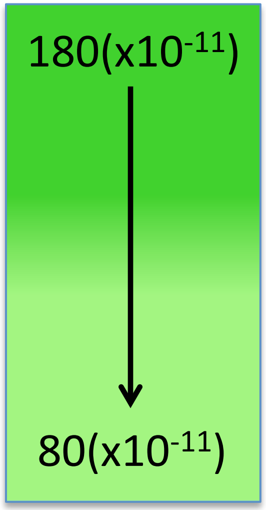
$$\mathrm{LHC} : \tan\beta = 9 \pm 5$$

Synergy with LHC

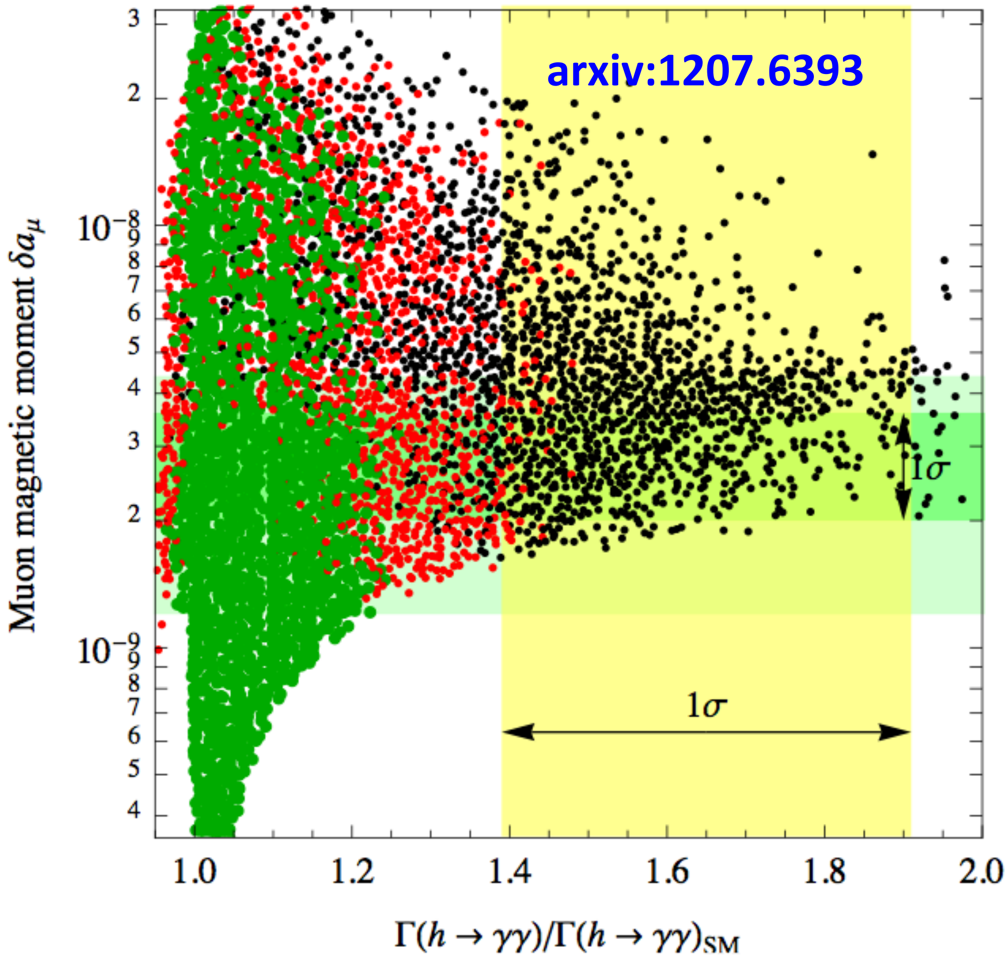
Gauge mediated SUSY breaking models with enhanced $h \rightarrow \gamma\gamma$



Contribution to a_μ

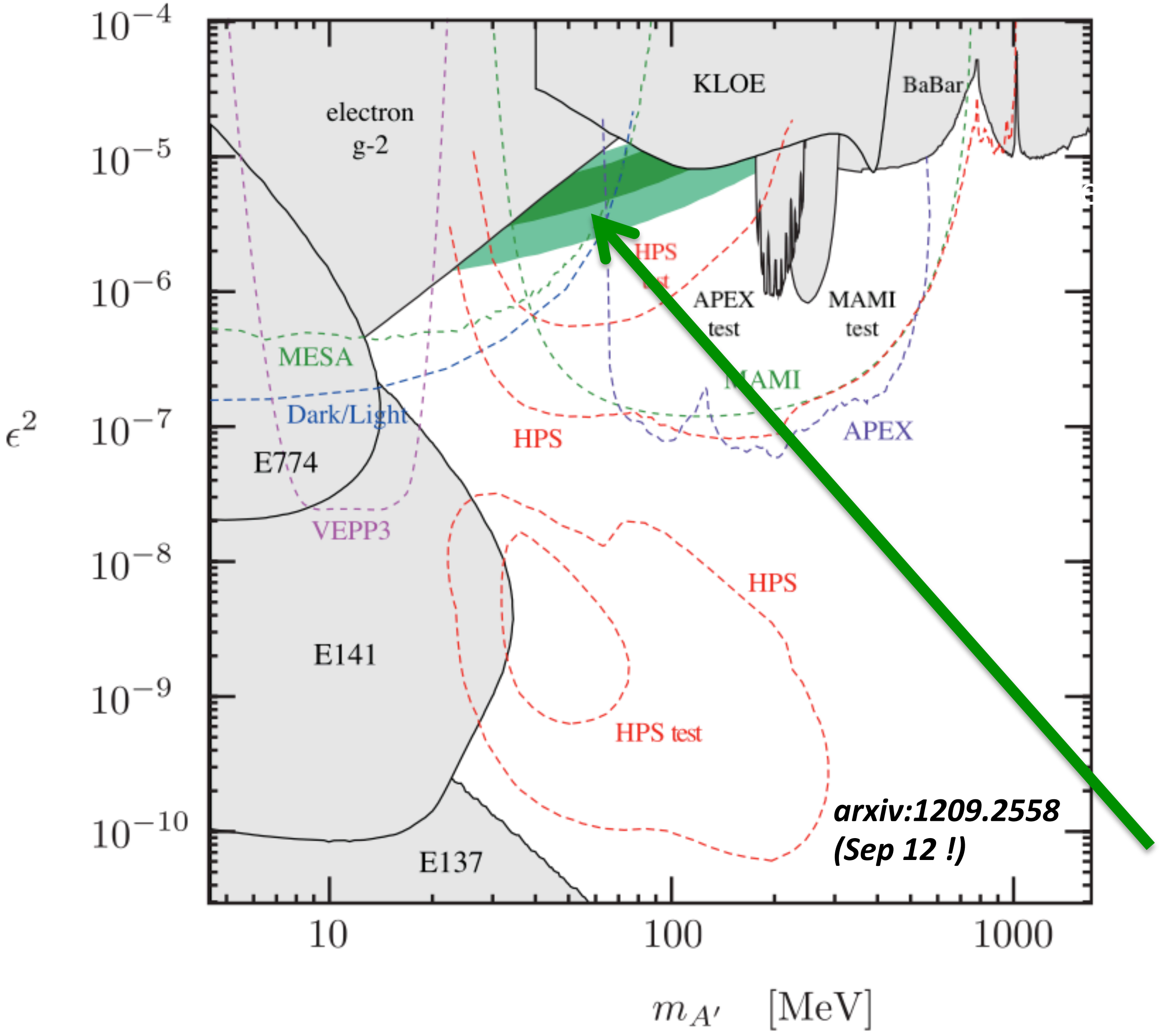


Synergy with LHC



A larger $h \to \gamma\gamma$
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'

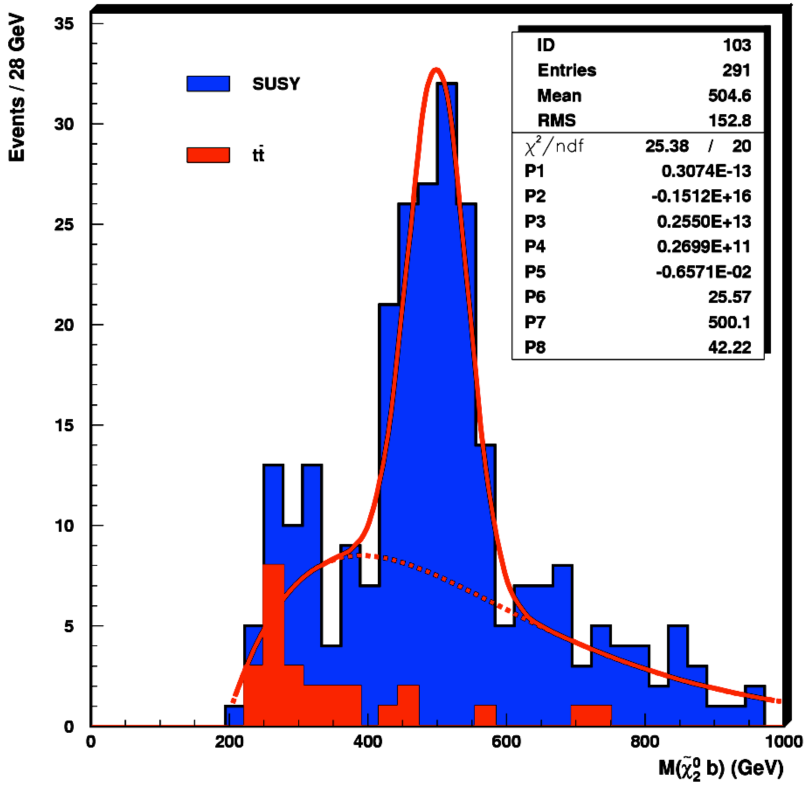
$$a_\mu = \frac{\alpha}{2\pi}\epsilon^2 F\left(\frac{m_V}{m_\mu}\right)$$

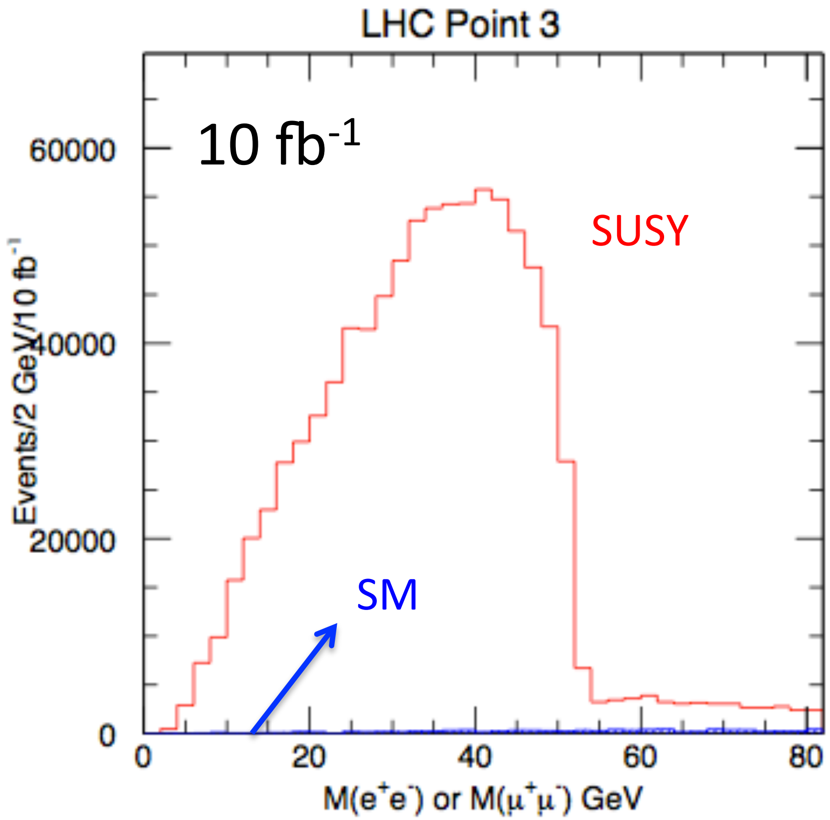
Motivated to explain PAMELA excess

g-2 will complement direct searches at JLAB, Mainz

Fixes up g-2

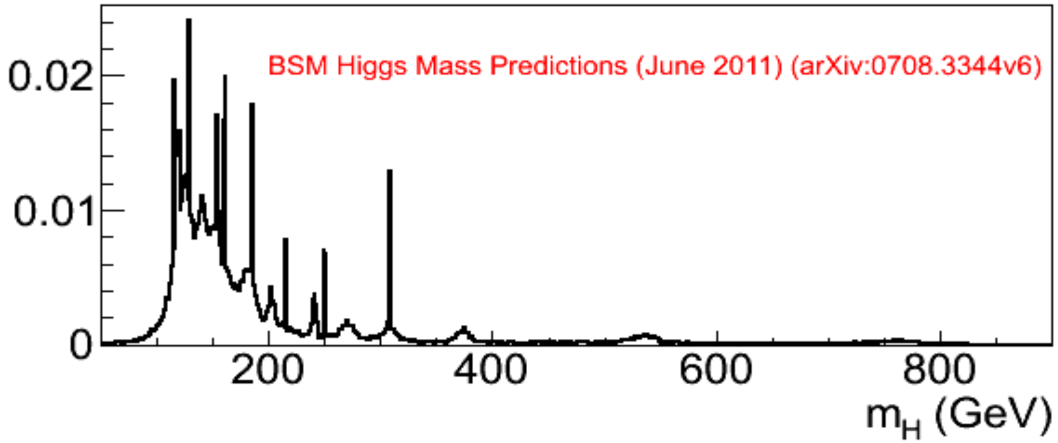
Lest We Forget

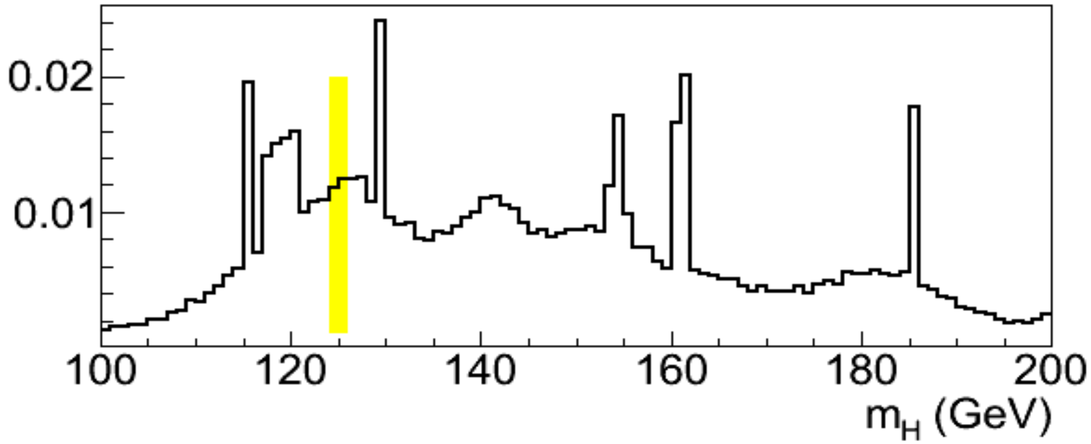




This is what we should have seen at the LHC .....

Beware of Theory Predictions….





10+ years of Higgs Mass Predictions

Beware of Theory Predictions….

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13 ✓
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09 ✓
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08 ✓
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3 × 2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

3 correct predictions from 28…

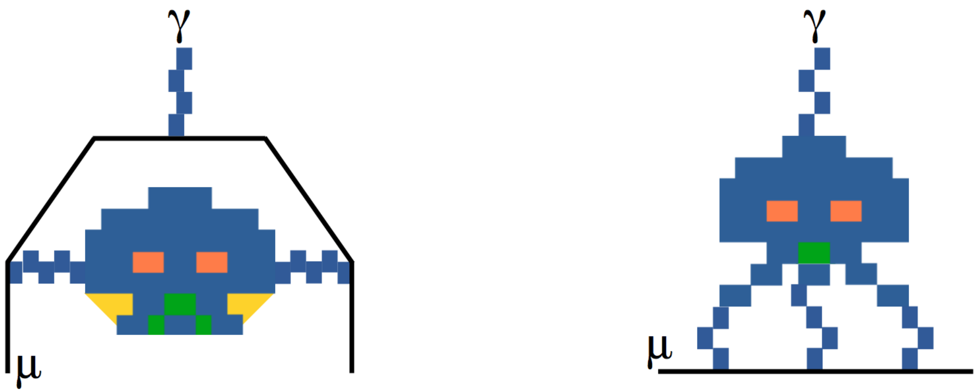
What about the hadronic contribution ?

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.

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

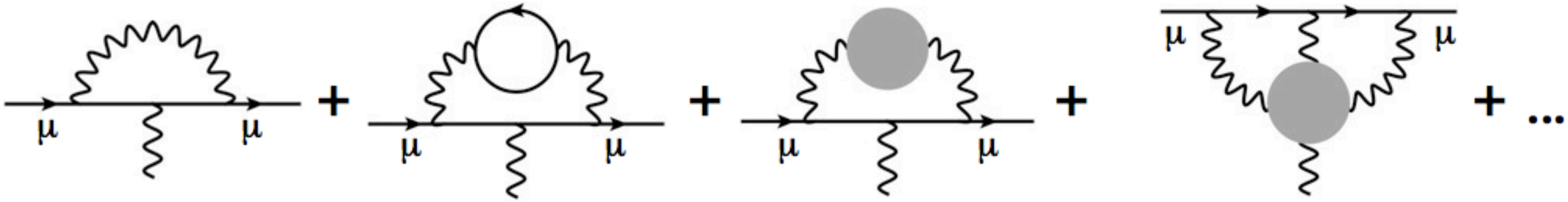
But **progress on precision of hadronic contribution expected** $\longrightarrow \sim 9\sigma$



What about the hadronic corrections ?

Hadronic vacuum polarization (HVP):

Hadronic light-by-light (HLbL):



QED (4 loops) & EW (2 loops)

from experimental result for $e^+e^- \rightarrow$ hadrons plus dispersion relation

estimated from models such as large N_c, vector meson dominance, χPT, etc...

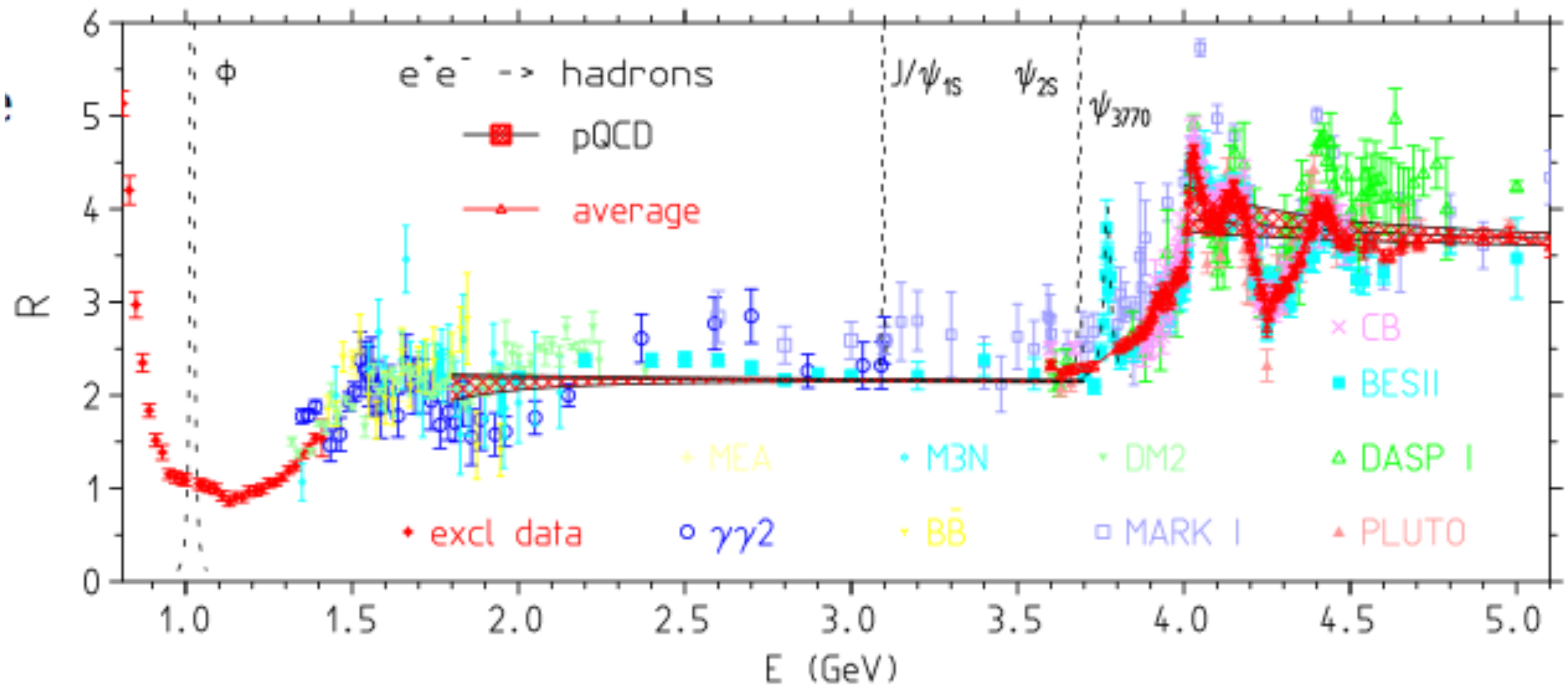
Contribution	Result ($\times 10^{11}$)		Error
QED (leptons)	116 584 718 ± 0.14	± 0.04_α	0.00 ppm
HVP(lo) [1]	6 923 ± 42		0.36 ppm
HVP(ho)	-98 ± 0.9_{exp}	± 0.3_{rad}	0.01 ppm
HLbL [2]	105 ± 26		0.22 ppm
EW	154 ± 2	± 1	0.02 ppm
Total SM	116 591 802 ± 49		0.42 ppm

[1] Davier, Hoecker, Malaescu, Zhang, Eur.Phys.J. C71 (2011) 1515

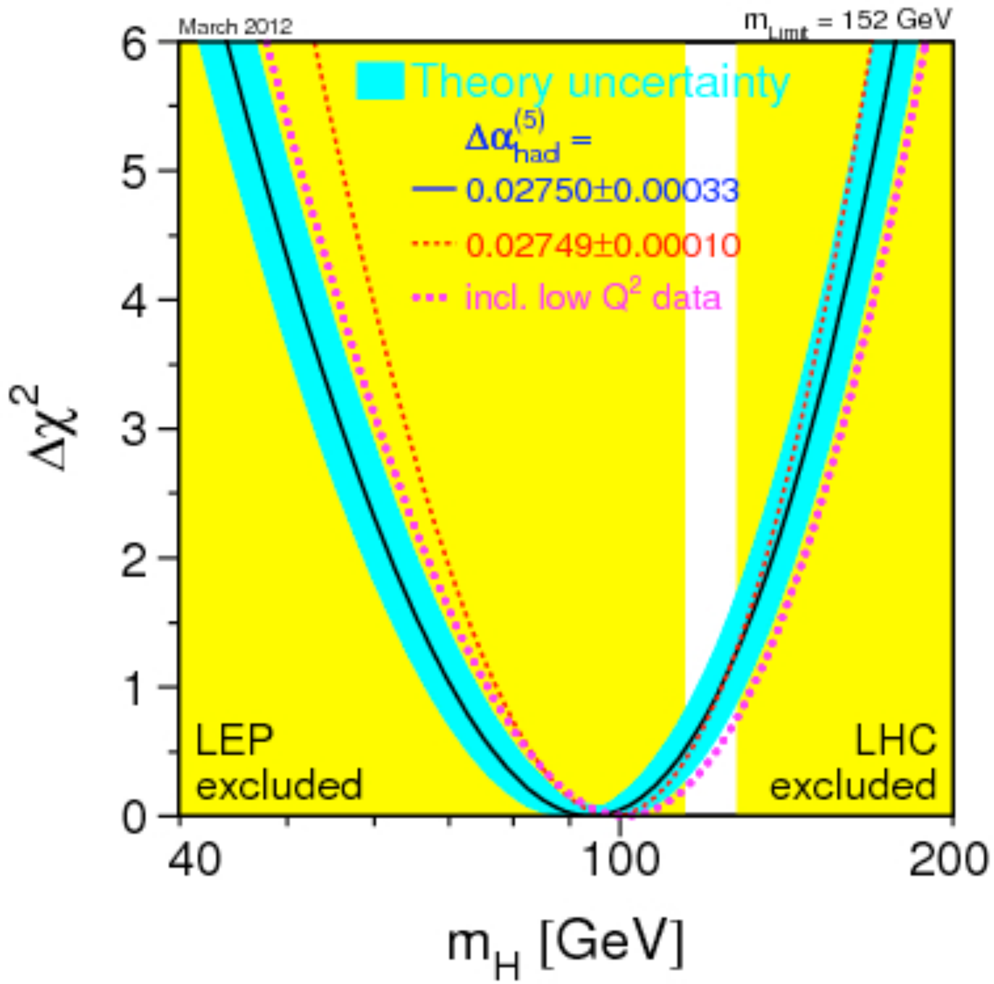
[2] Prades, de Rafael, Vainshtein, 0901.0306

Hadronic Vacuum Polarisation (HVP)

$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} \mathrm{d}s \frac{R(s)K(s)}{s^2} \qquad R \equiv \frac{\sigma_{\mathrm{total}}(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



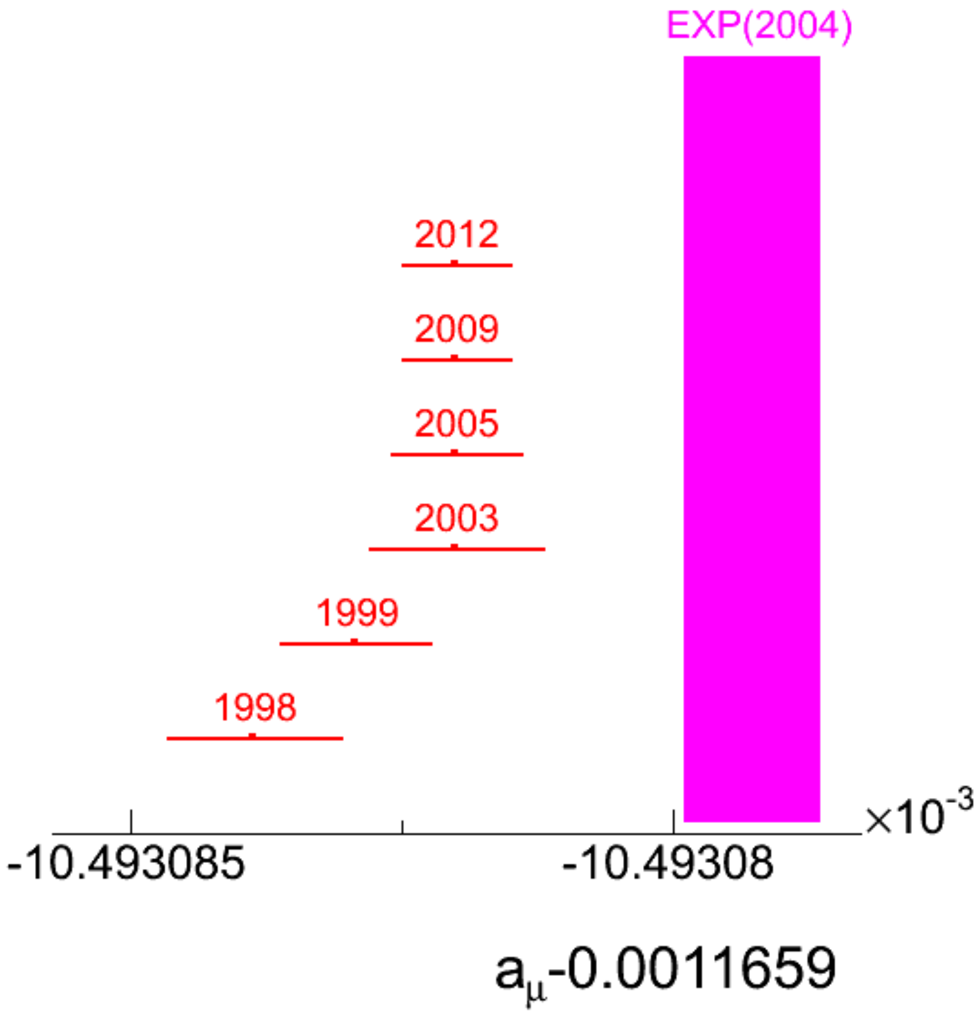
If these are v. wrong : so is the Higgs Mass



If change hadronic corrections to make a_μ agree with SM

Then M_H prediction reduces by 20 GeV and is then in tension with the measured value…

SM Prediction



SM prediction has been stable over 10 years.

Uncertainty has been reduced by 50% since first BNL measurement

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

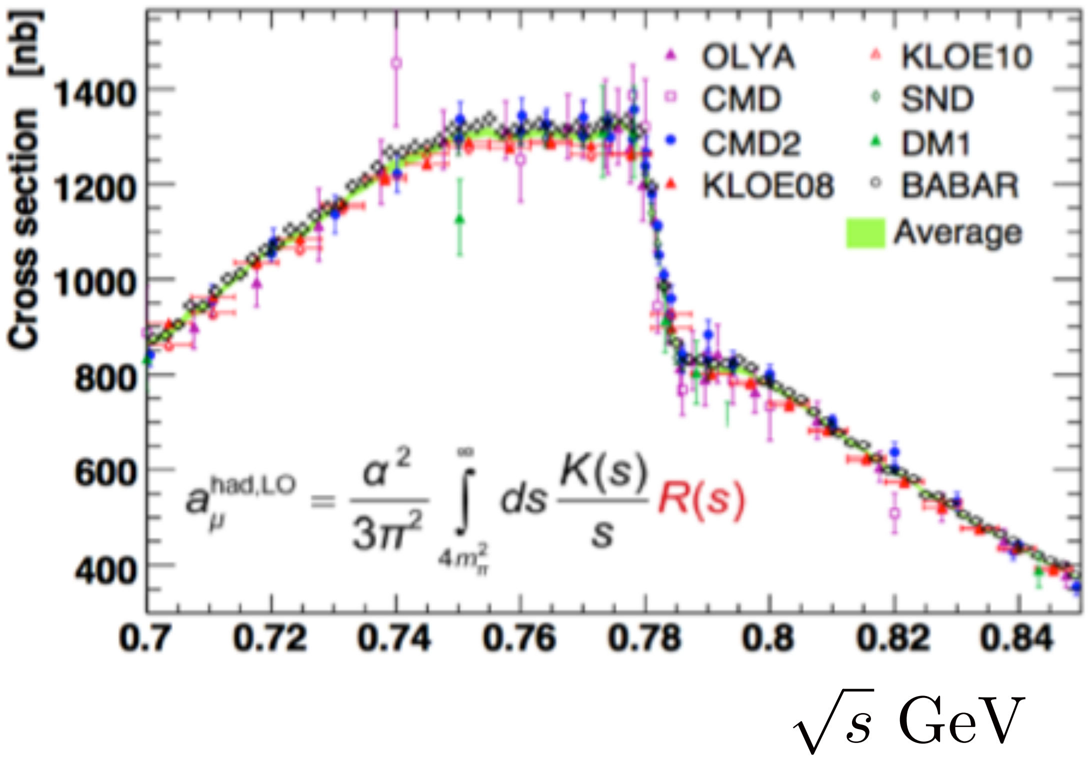
HVP (42×10^{-11}) + **HLBL** (26×10^{-11})

49×10^{-11} (20%)

HVP uncertainty

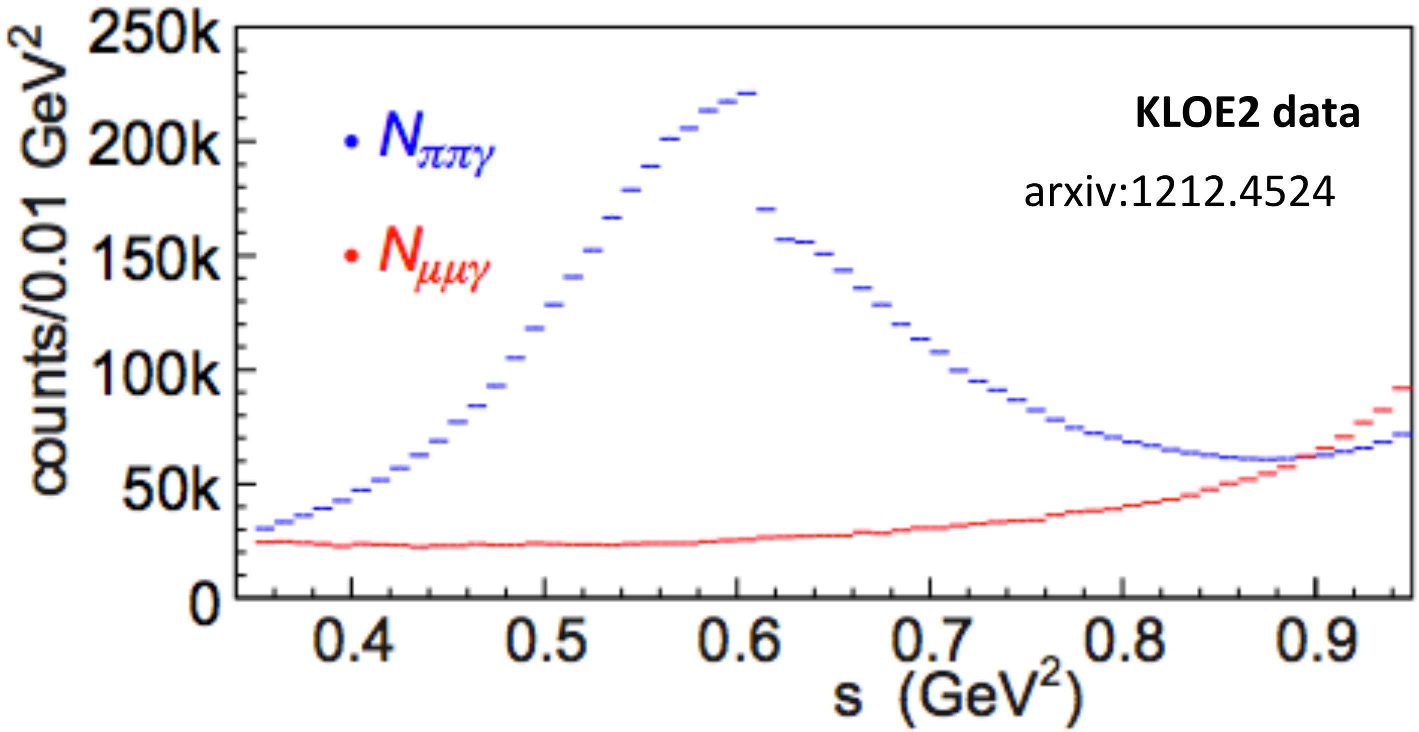
* Consensus now emerging on $\tau^+\tau^-$ vs e^+e^- discrepancy
* New data/analysis from BaBar, Belle, BES, VEPP2000
* Lattice uncertainty (5% → 1.5%)

Should be reduced by factor of two



UK Lattice QCD Community

New KLOE analysis for HVP

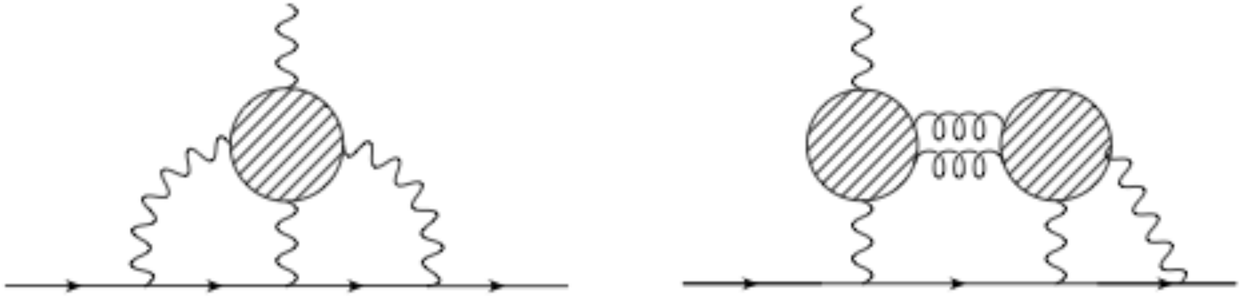


By measuring ratio many systematics cancel.
Particularly theory uncertainty is reduced by 70%.

New hadronic (HVP) estimate unchanged but uncertainty reduced by 20%.

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 $(\pi^0 \rightarrow \gamma^{(*)}\gamma^*)$ models
- progress on pure lattice QCD calculation *(lattice QED calculation has demonstrated integrity of approach)*

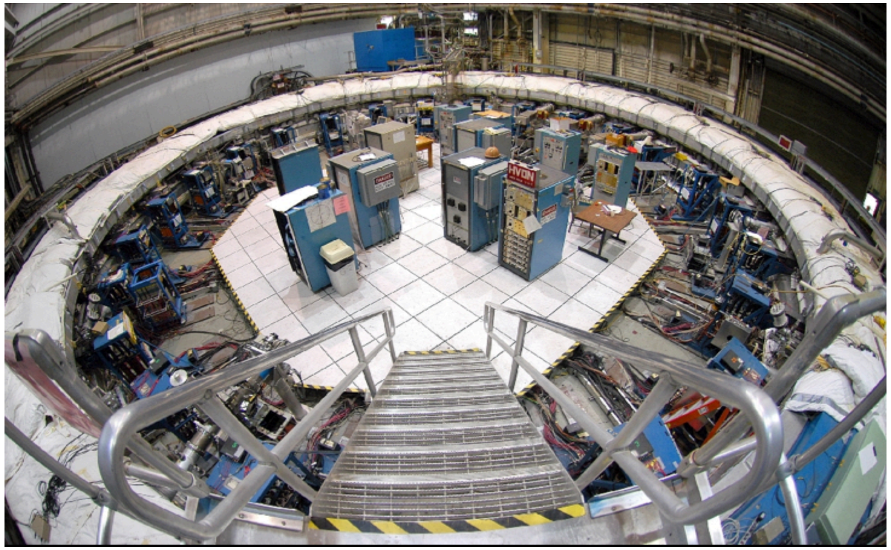
Expect HLBL uncertainty to reduce from 25% to 10%

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.

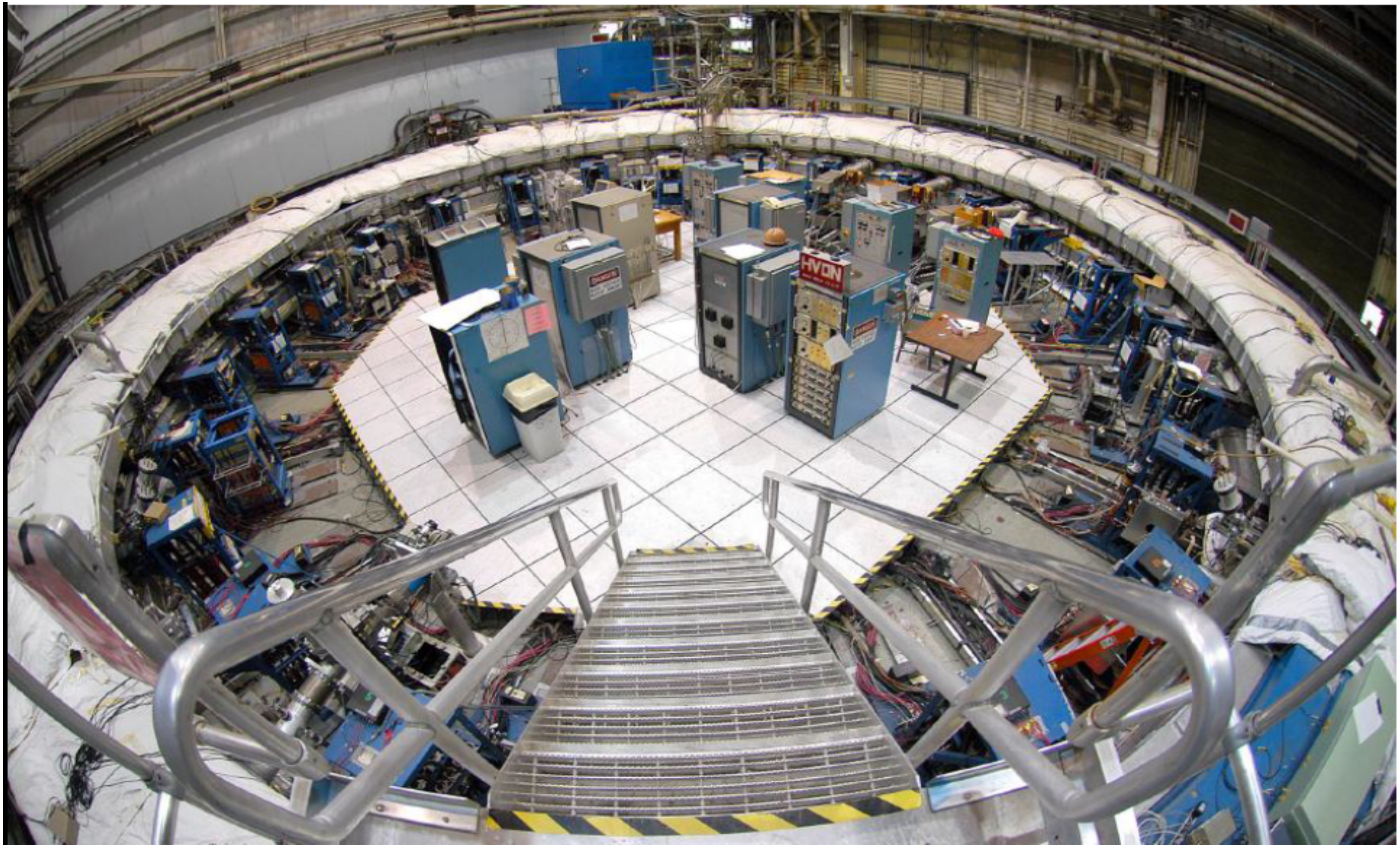
1. Use established technique (& apparatus)
2. Increase # muons by factor of 21
   to reduce statistical error by over 4.
3. Reduce systematics by factor of 3.



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

$$42\ (\text{HVP}) \oplus 26\ (\text{HLBL}) \rightarrow 15 \oplus 15$$ (theory)

BNL Storage Ring (1999-2012)



Call U-Haul and willing PhD students

And Spokesperson

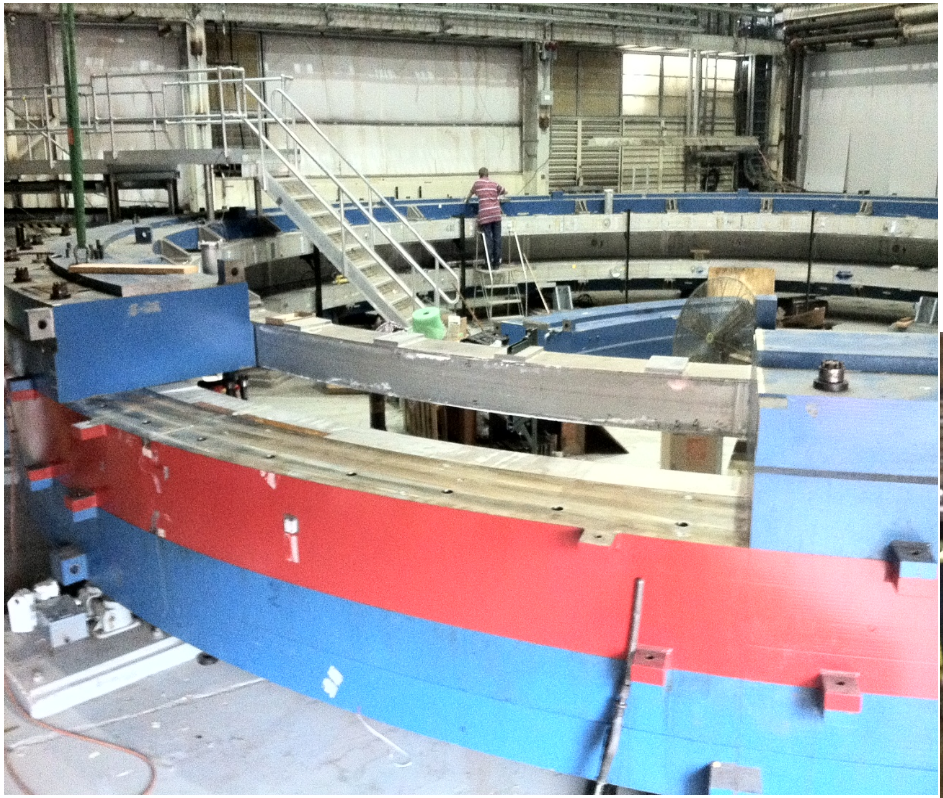
Ring disassembly at BNL completed. Most small kit already at FNAL

Spokesperson (Lee Roberts)

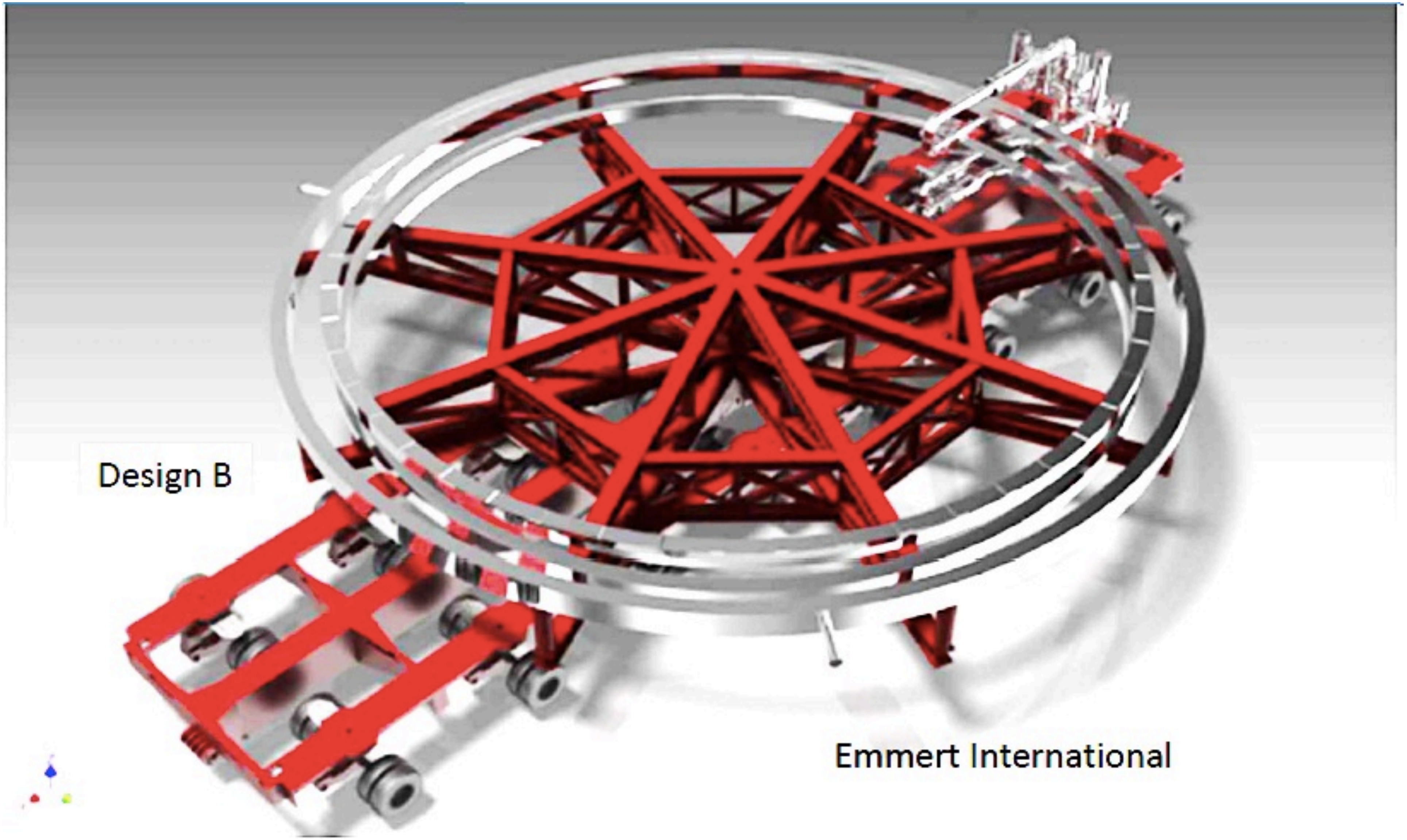
And Project Manager

Project Manager : Chris Polly

Yoke Removal : Sep 2012

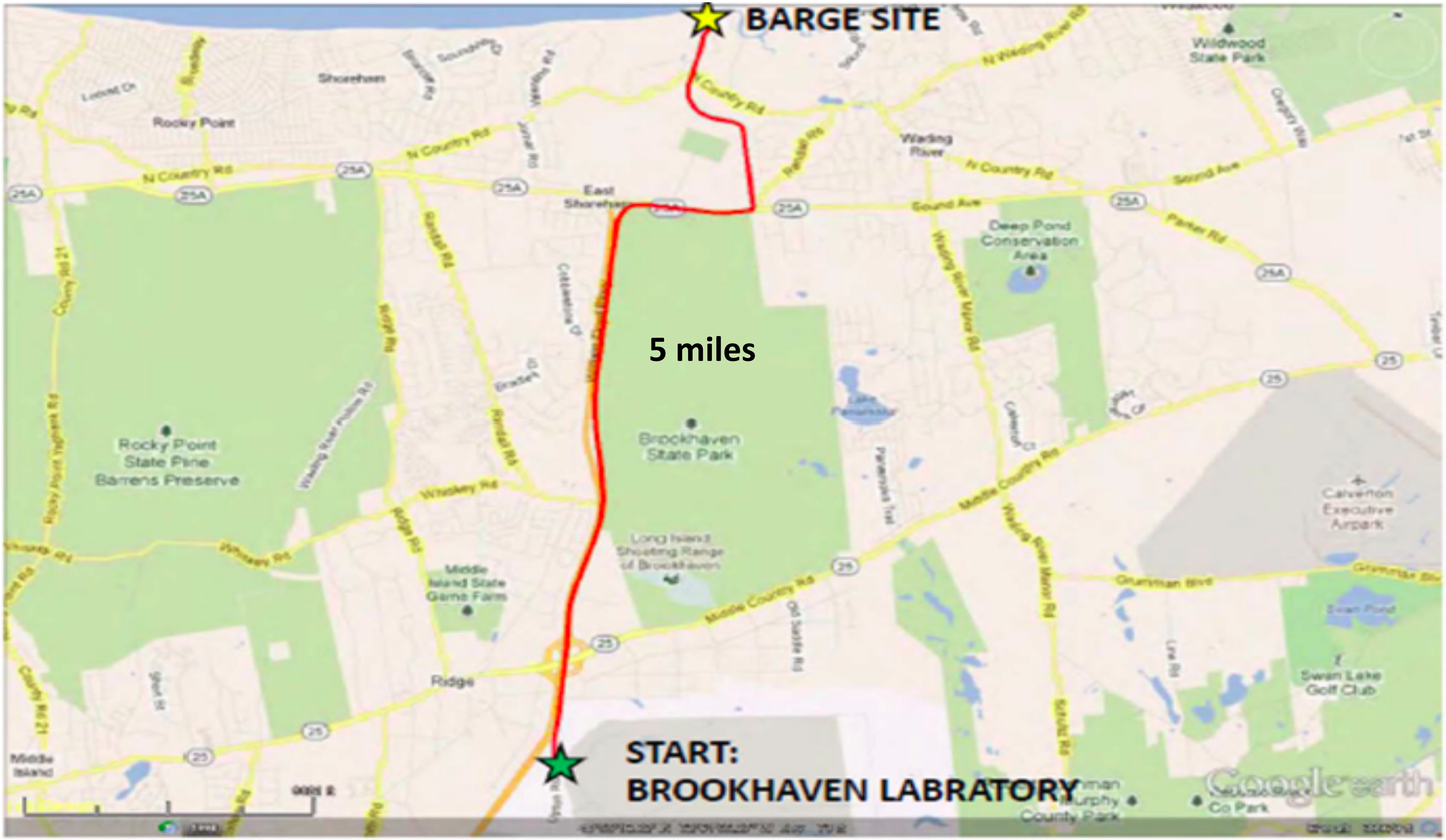


From Long Island to Fermilab

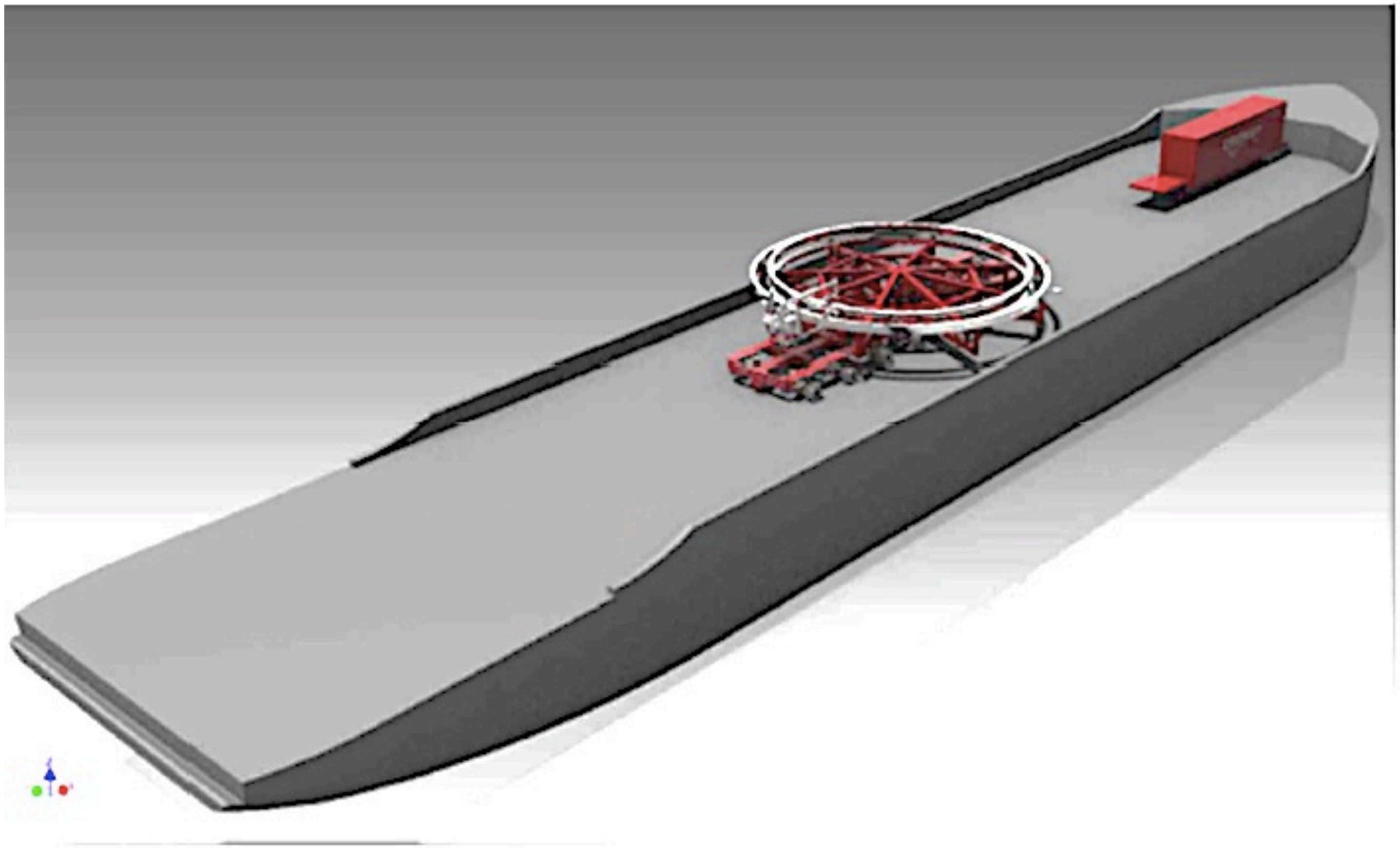


On Truck to Barge Port on L. Island

Easy Bit

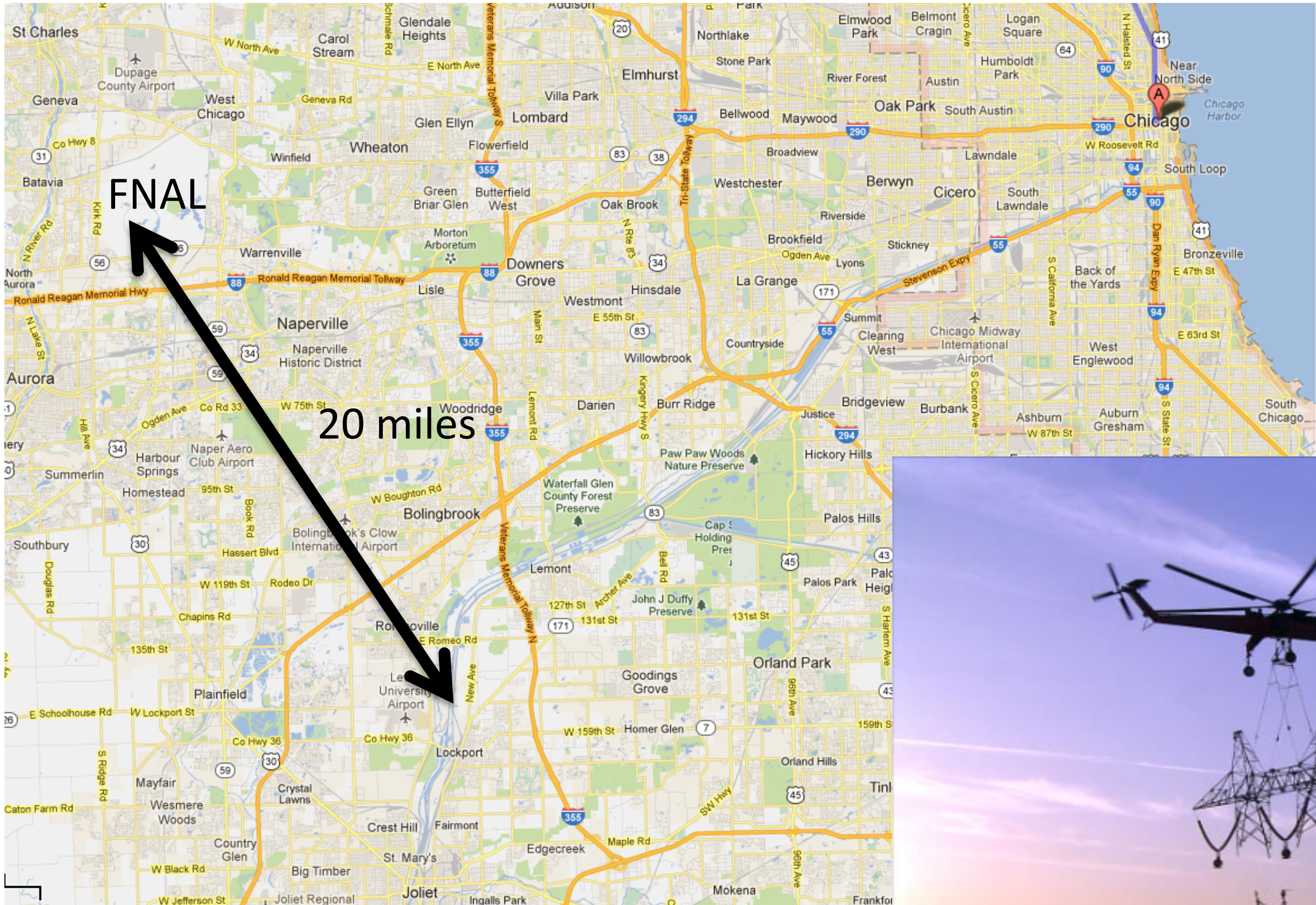


The Barge



Not as the crow flies….

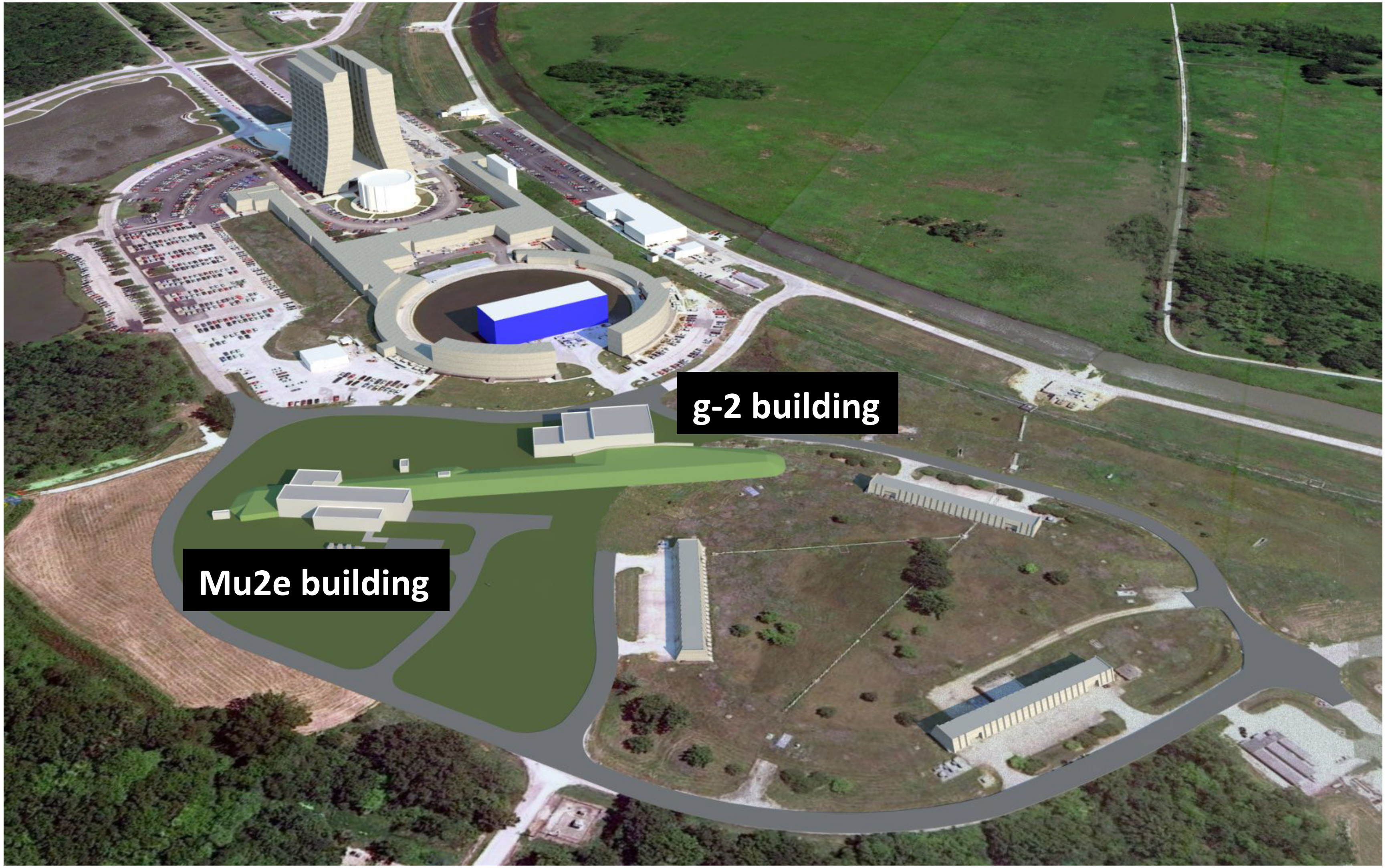
Getting to FNAL : Plan-A



Getting to FNAL : Plan-B

Plan-B

FNAL Muon Campus

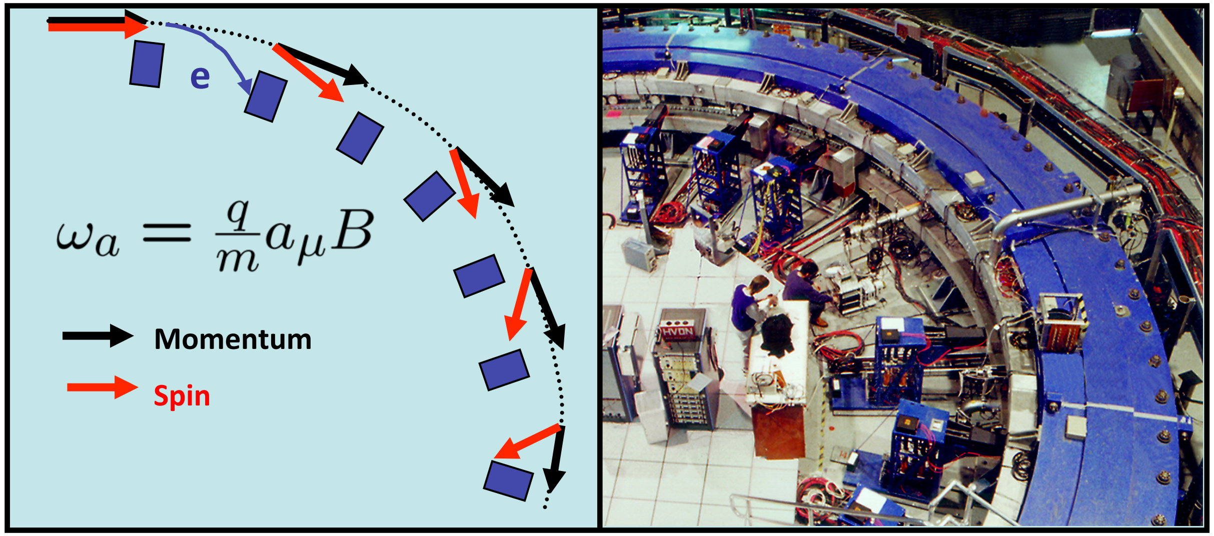


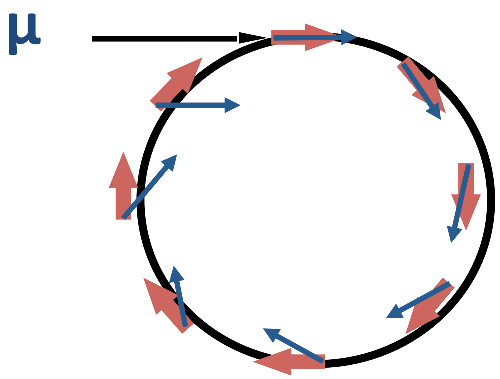
FNAL Muon Campus : Jan 2013

Storage Ring Location

Still some magnet alignment problems @ FNAL

Experimental Method





$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

But….

But particle trajectory in B-field is a spiral and need E-field to keep in orbit

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

Cancel the E-field contribution (E-field cannot measure precisely enough) by judicious choice of γ : the "magic momentum" : 3.094 GeV

Then just need to:

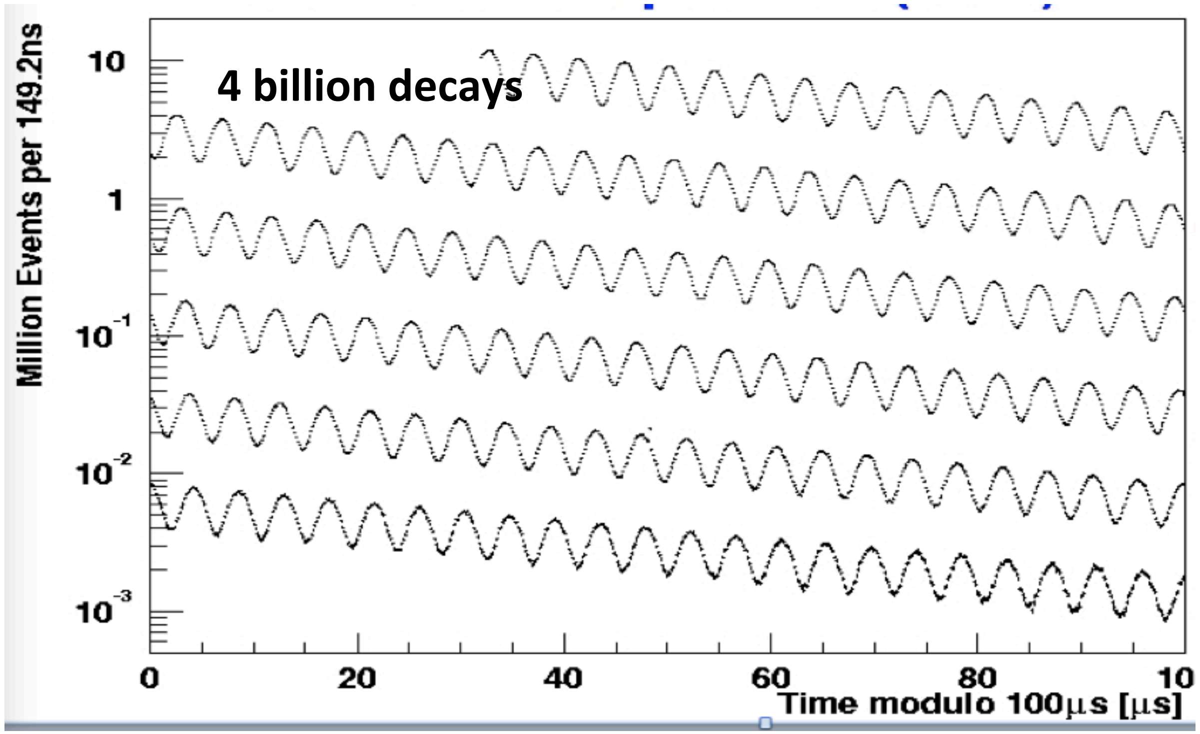
- know and map B-field to 0.1 ppm
- measure spin direction of decay positrons vs time

and be insane….

Parity Violation to the rescue

The muons we use are 97% polarised (by selecting forward decays of pion)

Decay positron direction is strongly correlated with muon spin direction and for high energy positrons it is in the opposite direction.

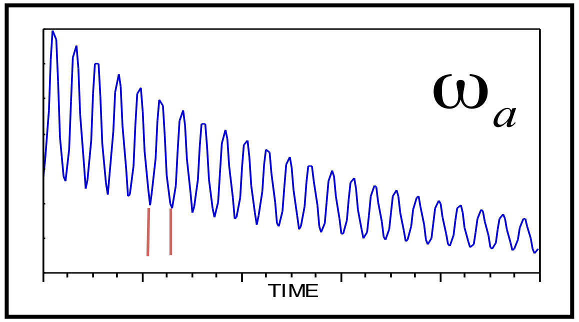


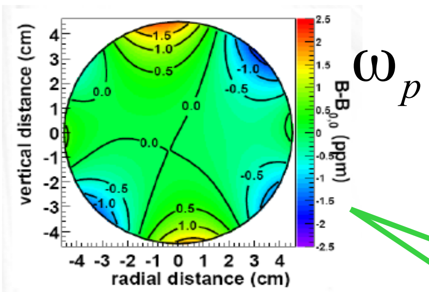
Select decay positrons above 1.9 GeV and count them vs time.

Need three measurements

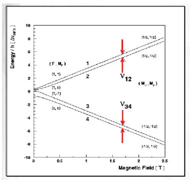
$$N(t) = N_0 \exp(-t/\gamma\tau_\mu)\,[1 - A\cos(\omega_a t + \phi)]$$

A, Φ known (depend on E_{e+})





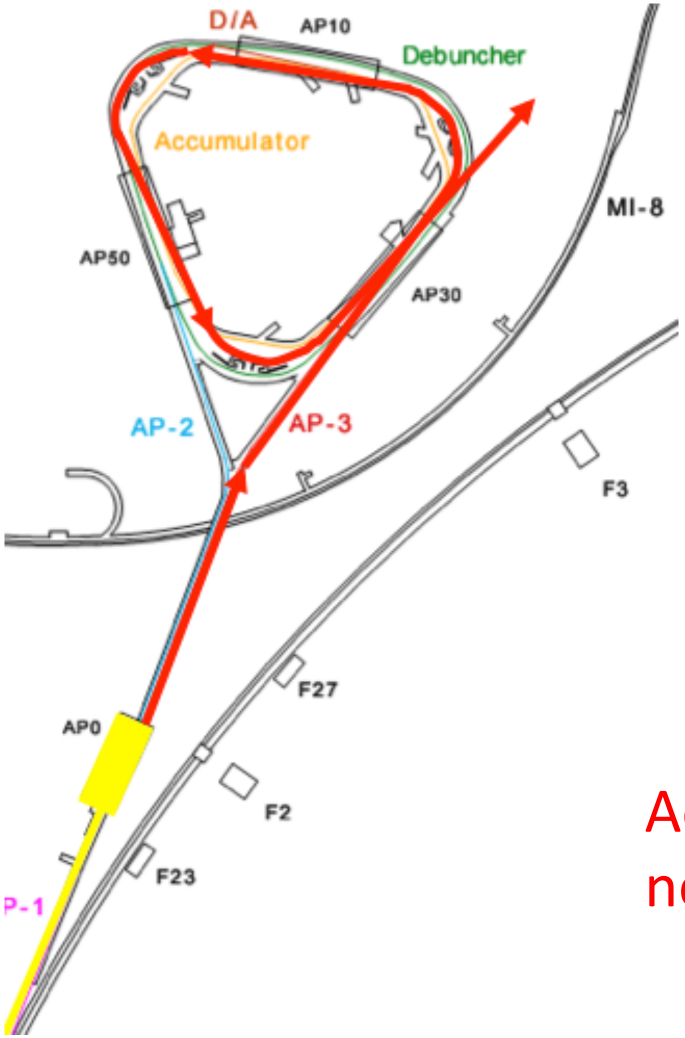
$$a_\mu = \frac{\dfrac{\omega_a}{\omega_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\omega_p}}$$



μ_μ/μ_p = 3.183 345 24(37) (120 ppb)
= *3.183 345 39(10) (31 ppb)*

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.

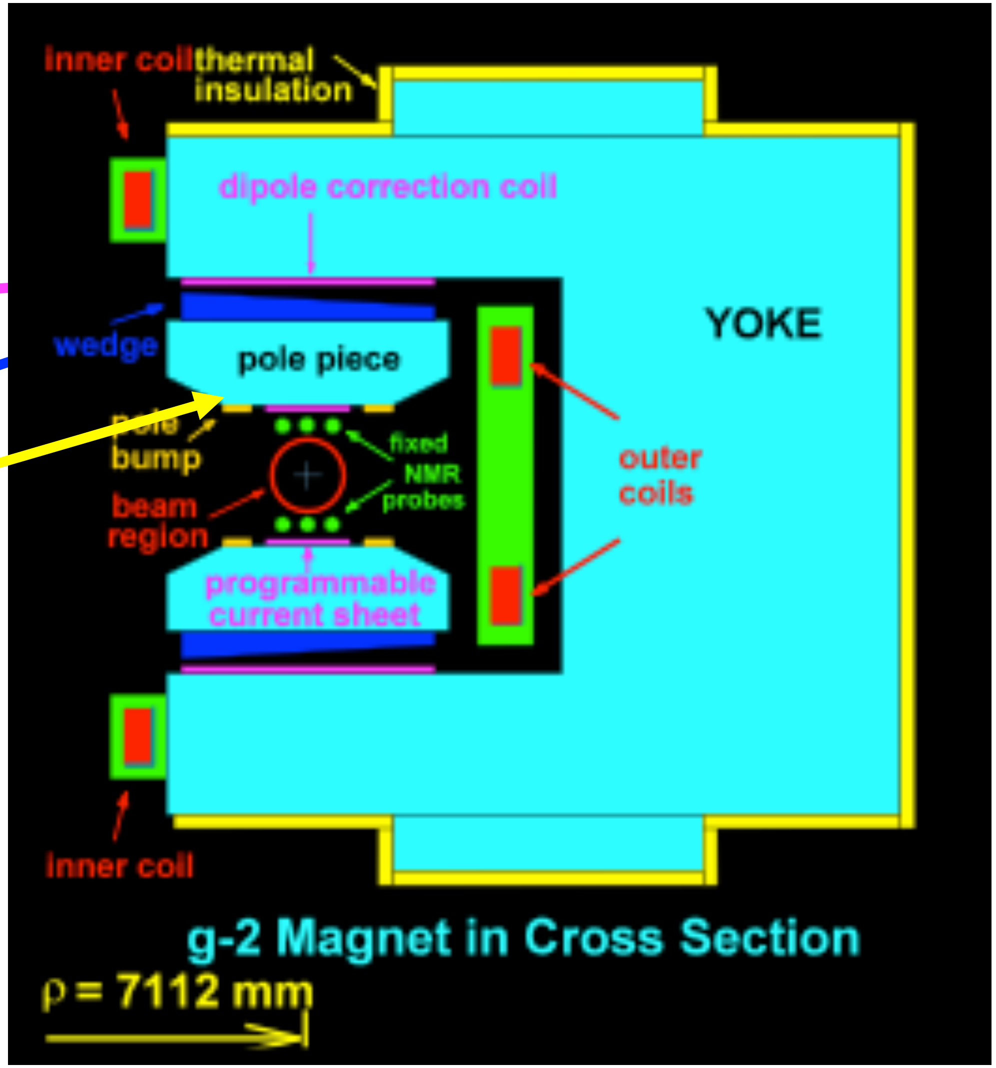
Accelerator modifications began since needed for Nova

9 months of shimming….

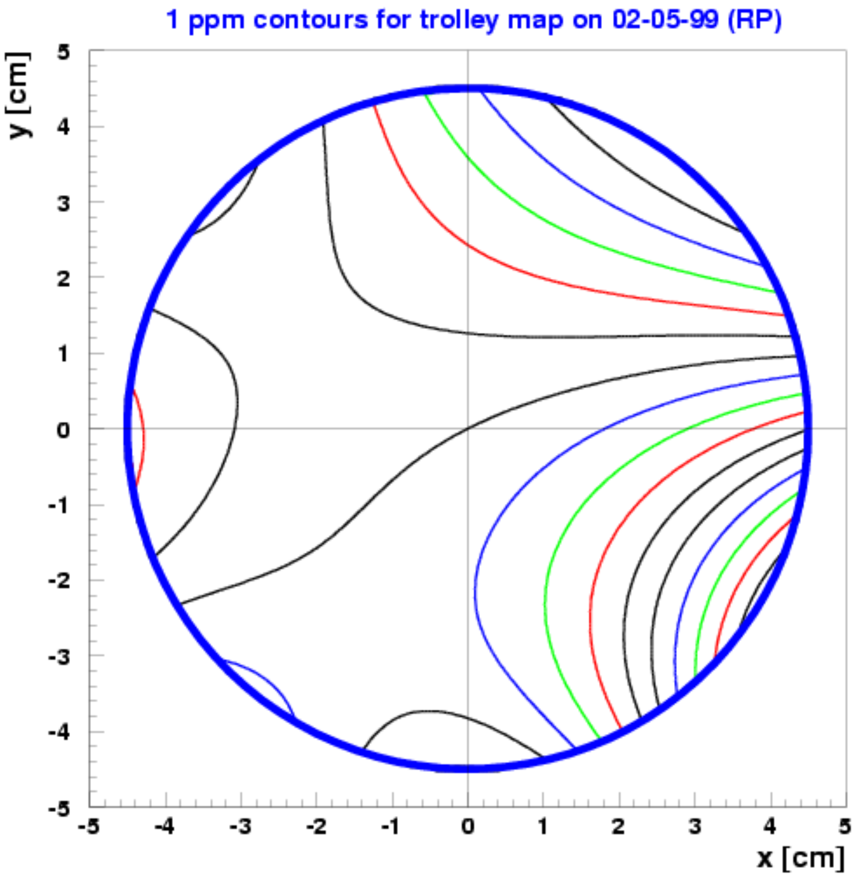
dipole,

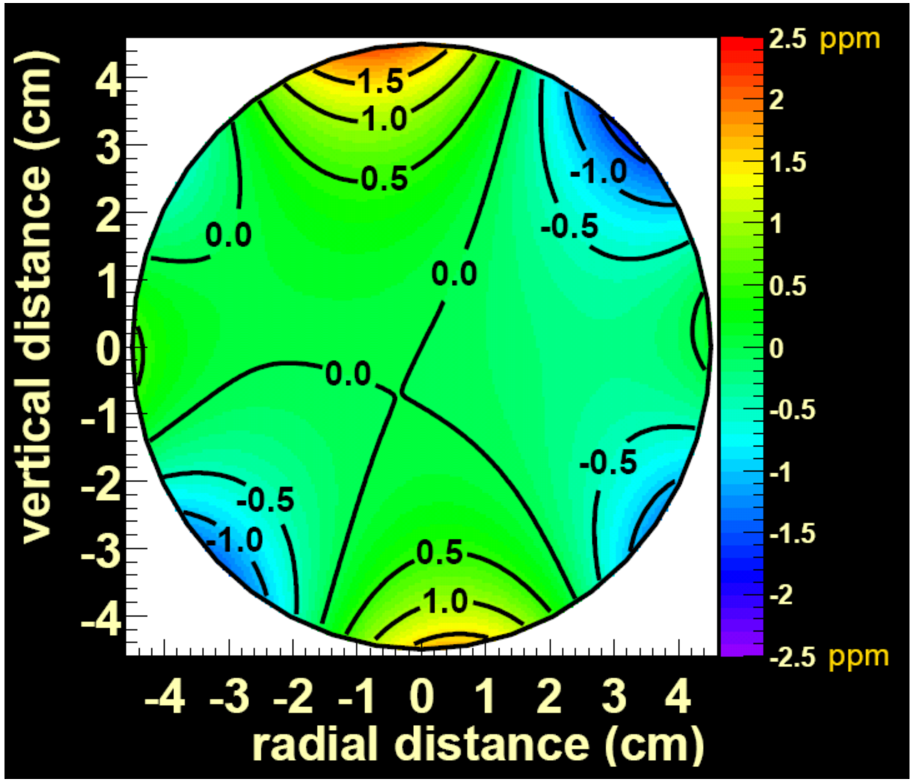
quadrupole

sextupole



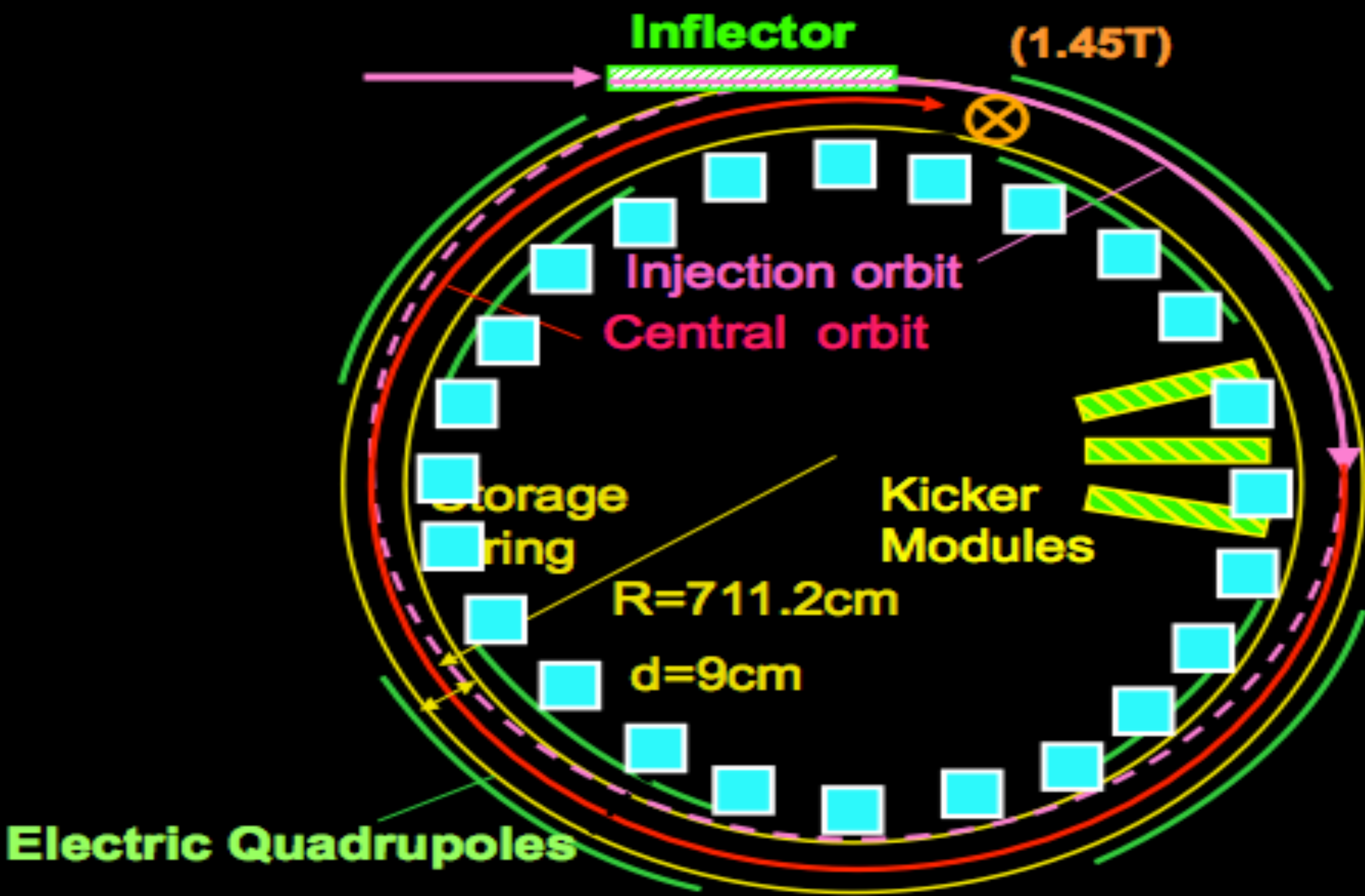
All about systematics : magnetic field





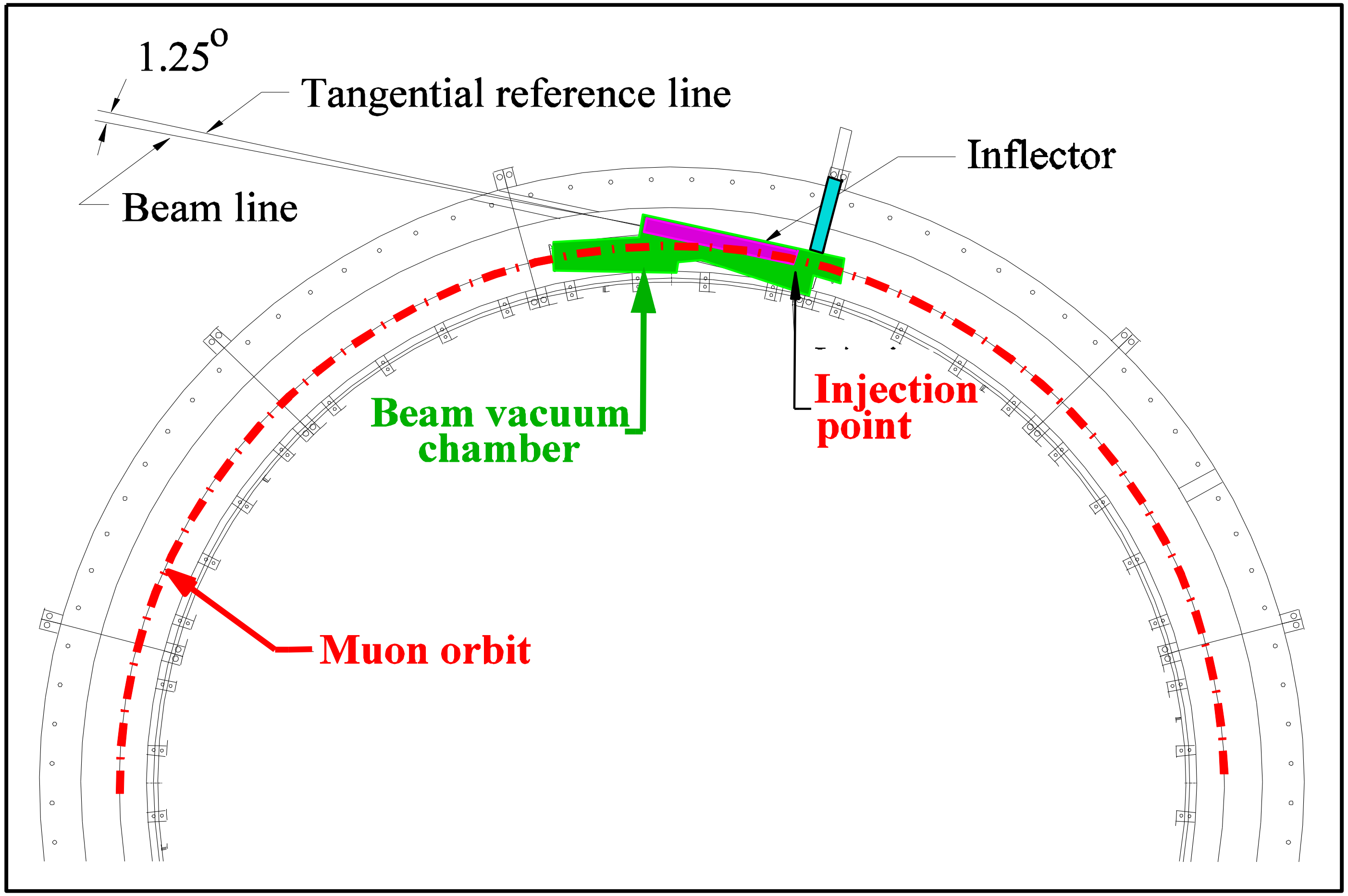
With this uniformity : trajectory less critical …

All about systematics : muon trajectory



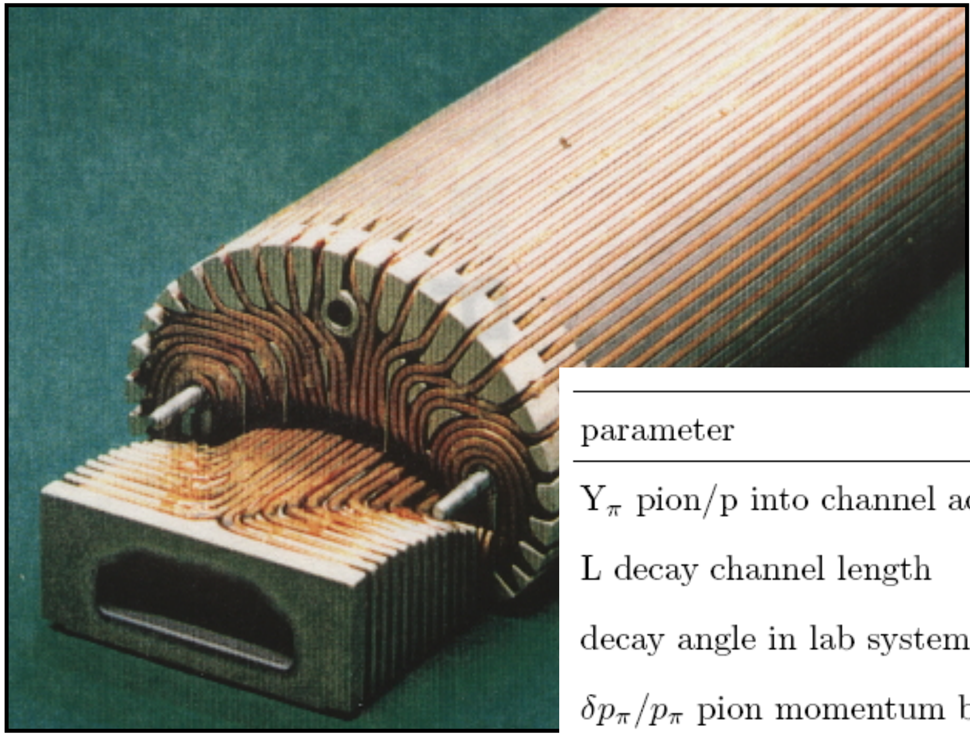
All about systematics : injection

Injected through yoke using non-ferrous s/c (1.45 T) magnet



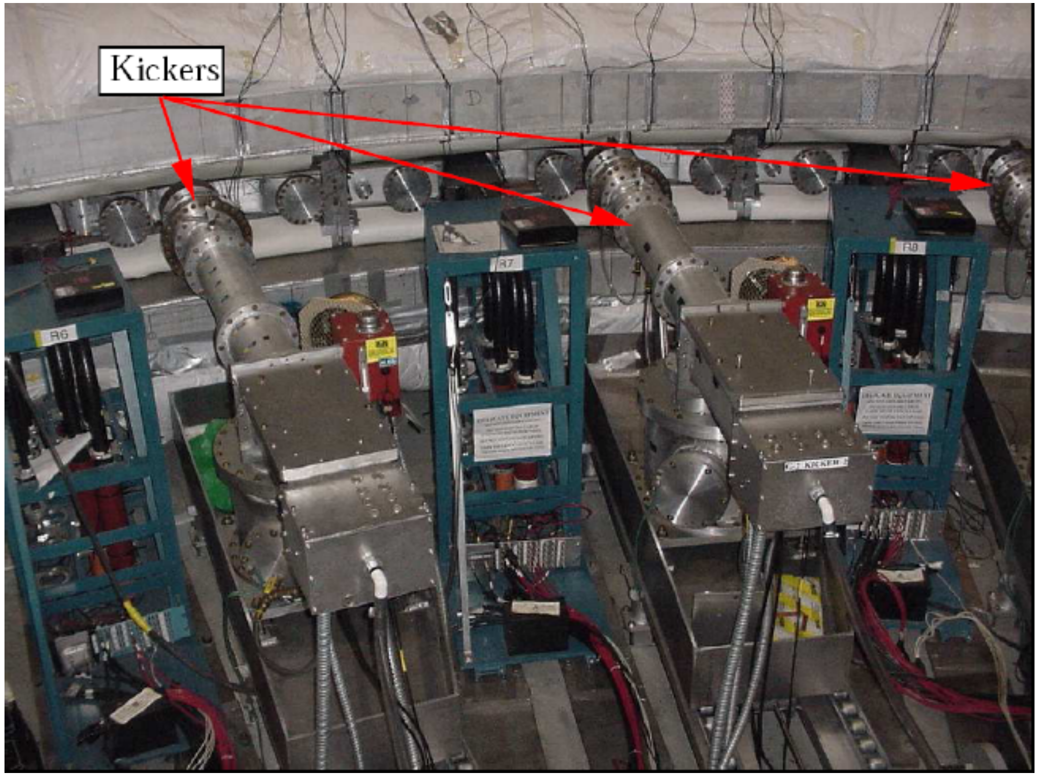
All about systematics : injection

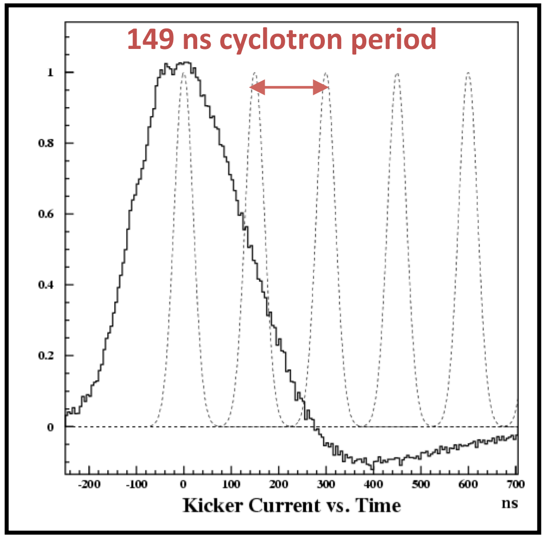
Present inflector scattered away 50% of muons
R&D on "open-end" design



parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

All about systematics : kicking

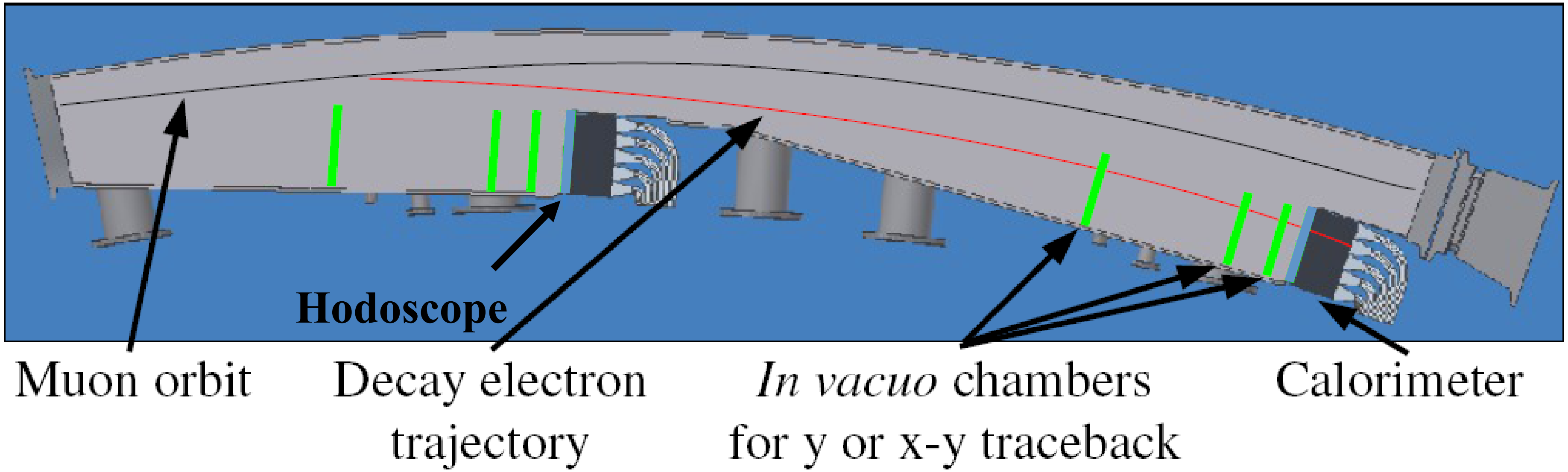




BNL kicker was too slow. New one being designed.

Detectors

24 calorimeters and n (TBD) straw trackers



Systematics

Correct / control using information from straw trackers (UK)

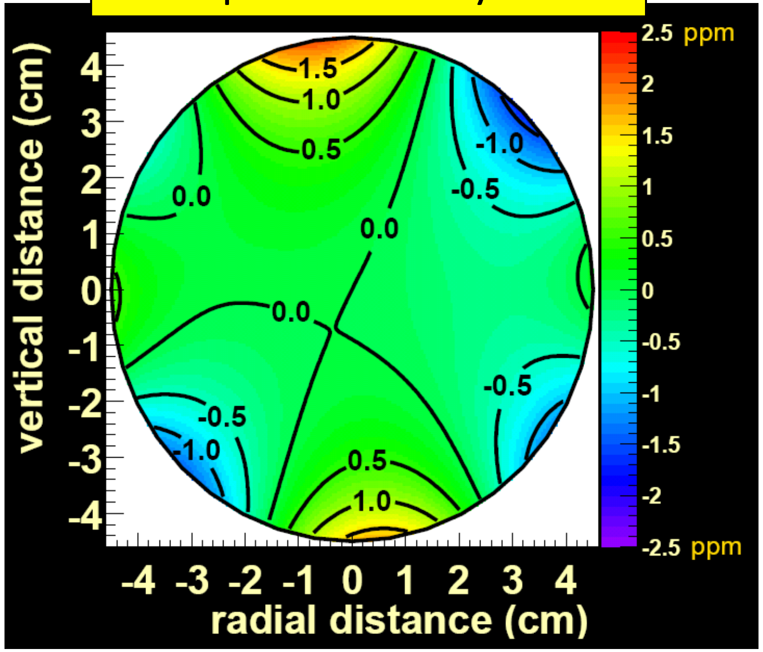
E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; 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

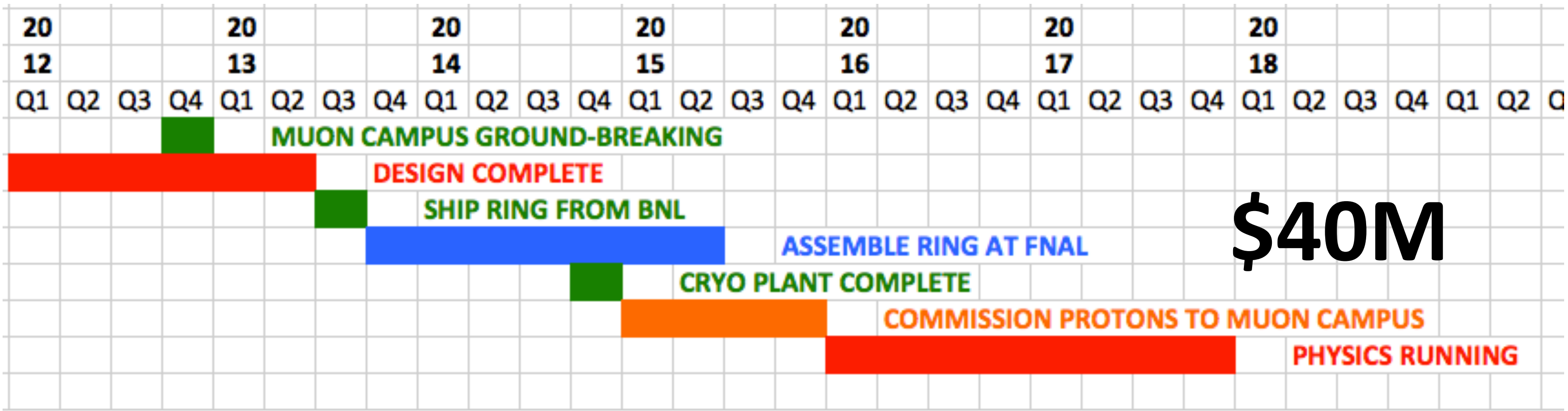
Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe 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

UK expertise via cryoEDM



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.

MOUs have been / are being signed NOW.

UK g-2 Role

Construction of inflector : RAL

- to improve muon transmission efficiency into storage ring and beam orbit.

Precision mapping of B-field using ^{3}He magnetometer : Oxford

- to map B-field to 0.07 ppm building on cryo-nEDM SQUID expertise

Construction of straw trackers : Liverpool

- to measure pileup and muon's orbit

- also make measurement of muons electric dipole moment

Trigger / DAQ : Oxford/UCL

- 10 kHz of decay positrons & data volumes 5 Gb/sec.

Simulation : Oxford/UCL

- e.g. to optimise the kicker waveform, affect of stray accelerator B-fields

Cost to the UK

CERN/LHC-EXP : £128M
THEORY : £6M
NEUTRINOS : £3M
ASTRO-PARTICLE : £4M
MUONS : £0.2M

A UK MUON (COMET/g-2) PROGRAMME CAN BE ESTABLISHED FOR £15M (£6M g-2) OVER NEXT 6-12 YEARS.

Committed STFC funding pending outcome of programmatic review.

By April 2014 the g-2 construction project is 50% complete …. data taking starts in 3 years…

Bigger Picture

STFC PP Advisory Panel

*"There is a **strong science case for precision muon experiments** and the emerging **UK community interest should be supported.**"*

CERN/European Strategy

*"Experiments studying quark flavour physics **investigating dipole moments**, searching for charged- lepton flavour violation and performing other precision measurements at lower energies, such as those with neutrons, **muons** and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. Experiments in Europe with unique reach should be supported, as well **as participation in experiments in other regions, especially Japan and the US.**"*

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 a $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