The New Muon g-2 Experiment

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On Behalf of E989 Collaboration

Precision Measurements in last year

arXiv.org > hep-ph > arXiv:1302.3794

High Energy Physics – Phenomenology

Higgs Precision (Higgcision) Era begins

30 %

arXiv.org > hep-ph > arXiv:1212.2355

High Energy Physics – Phenomenology

Precise charm–quark mass from deep–inelastic scattering

4 %

arXiv.org > hep-ex > arXiv:1212.4012

High Energy Physics – Experiment

Precision Measurement of the Ratio of the Charged Kaon Leptonic Decay Rates

0.4 %

arXiv.org > hep-ex > arXiv:1304.6865

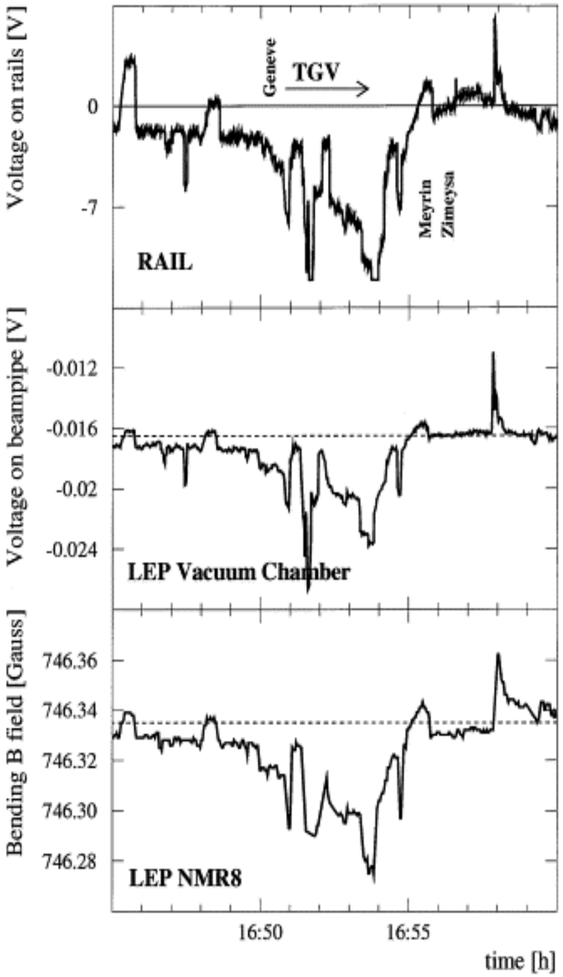
High Energy Physics – Experiment

Precision measurement of D meson mass differences

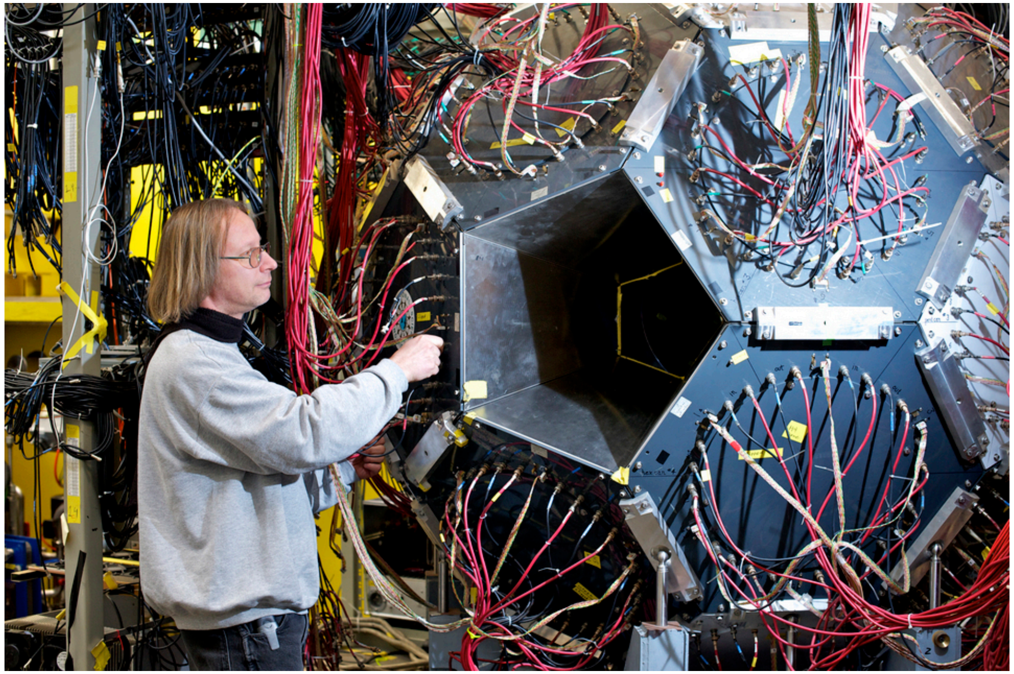
0.05%

500 ppm

Precision SM variables from accelerators



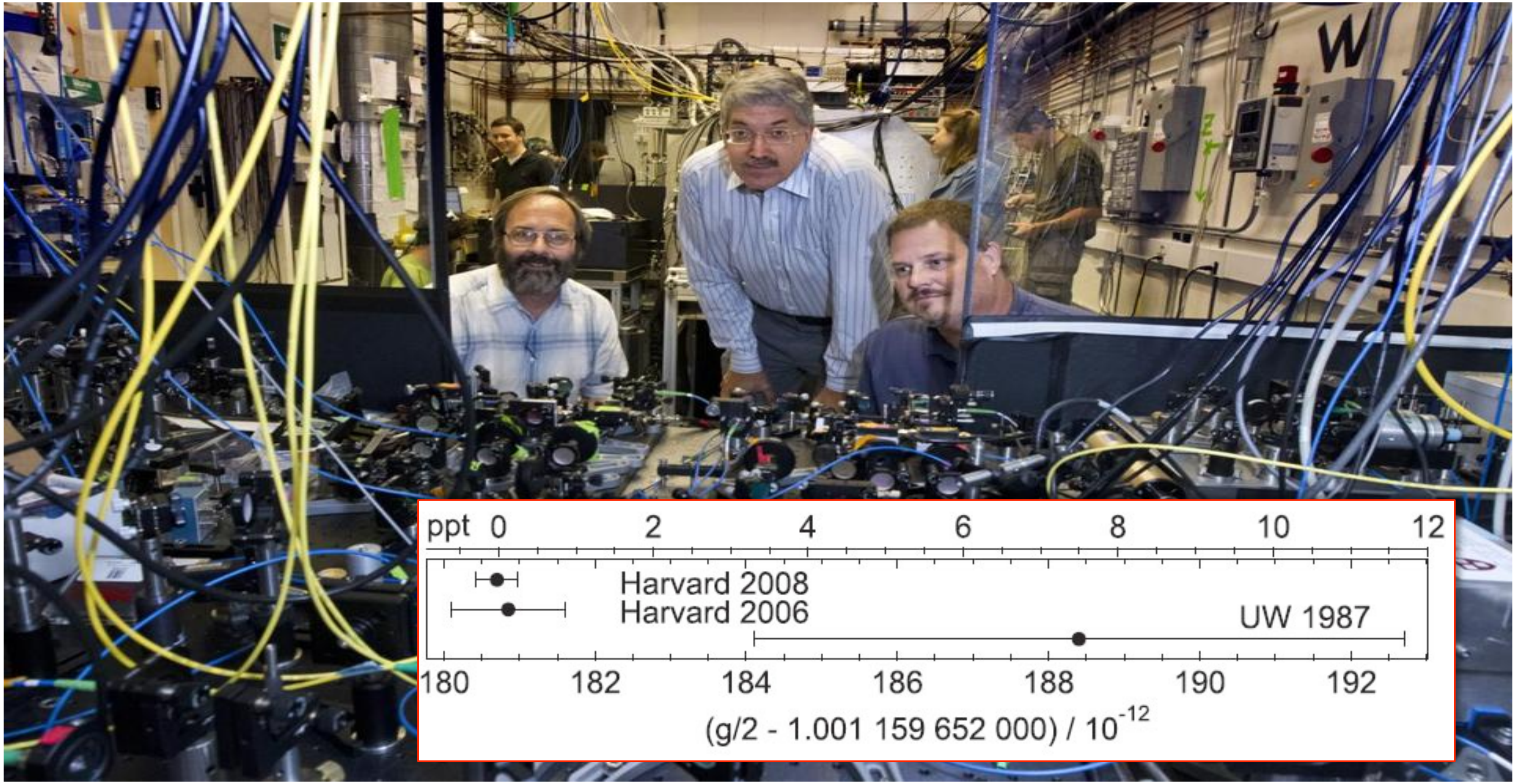
M_Z determined to 20 ppm



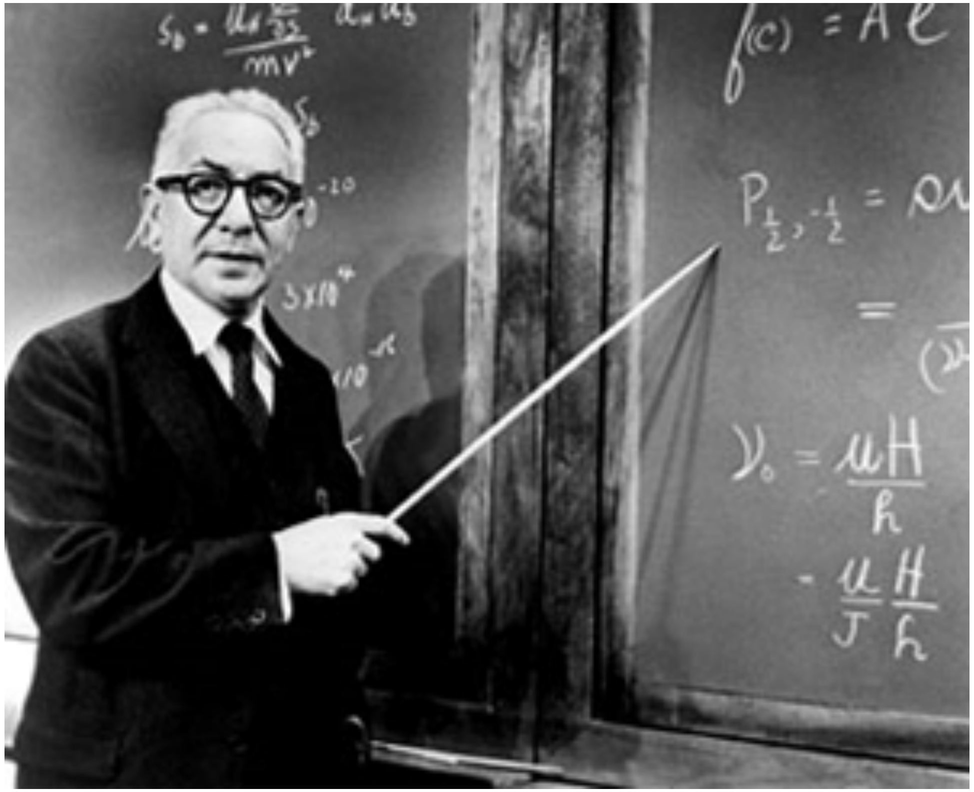
G_F (from τ_μ) determined to 0.6 ppm

Electron magnetic moment : 0.3 ppb

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



The precision mantra



1947 – 1948

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

All disagreed with Dirac theory…

"Never measure anything but frequency"

I. Rabi

Measuring Magnetic Moments Isn't Easy…

"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

Otto Stern **Wolfgang Pauli**

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

Evidence for proton structure in 1933 from its magnetic moment.

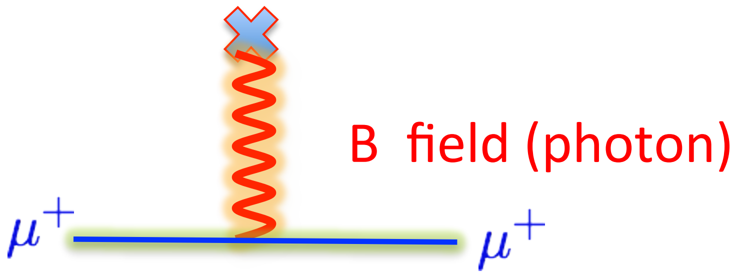
What is the magnetic moment / g-2

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

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

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

Spin **<u>precesses</u>** around B at a rate determined by "g"



Simplest "Dirac" interaction gives g=2

$$ieA_\mu\gamma^\mu$$

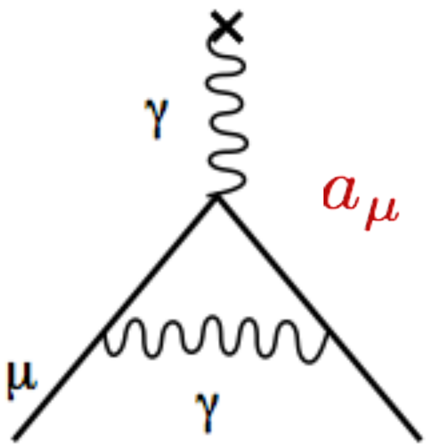
What's g-2

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

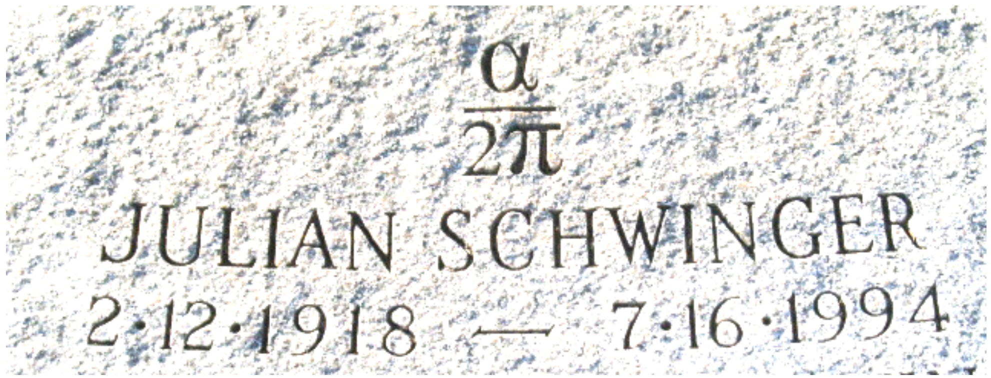
from loops give **a non g=2 contribution**.
This is the so-called anomalous contribution.

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

These interactions flip the chirality of the muon.



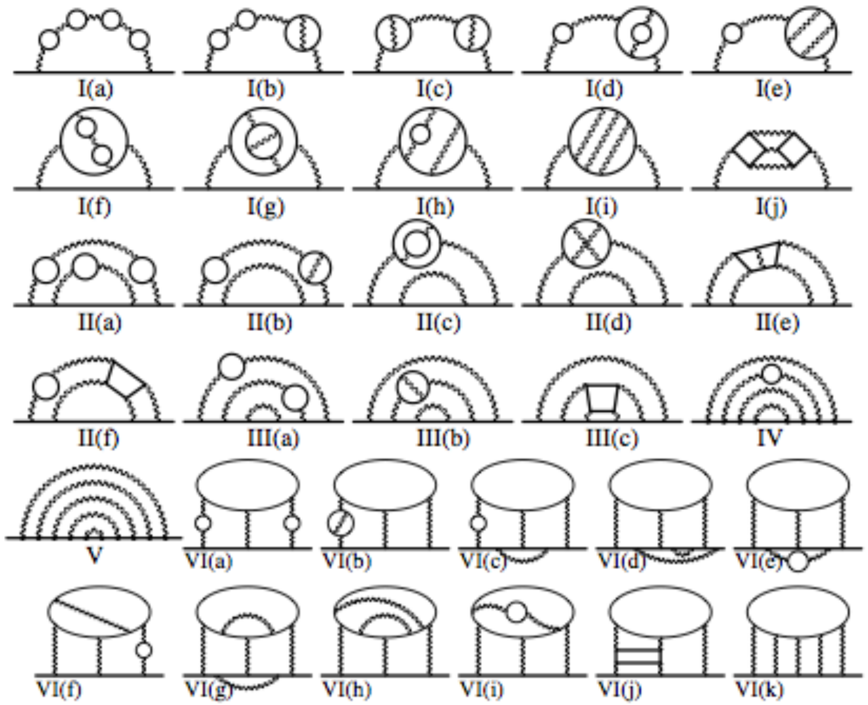
$$a_\mu = \frac{\alpha}{2\pi}$$



QED : 5 (NNNNLO!) contribution

arxiv:1205.5370
12,672 diagrams…

$$(753.29 \pm 1.04) \times \left(\frac{\alpha}{\pi}\right)^5$$

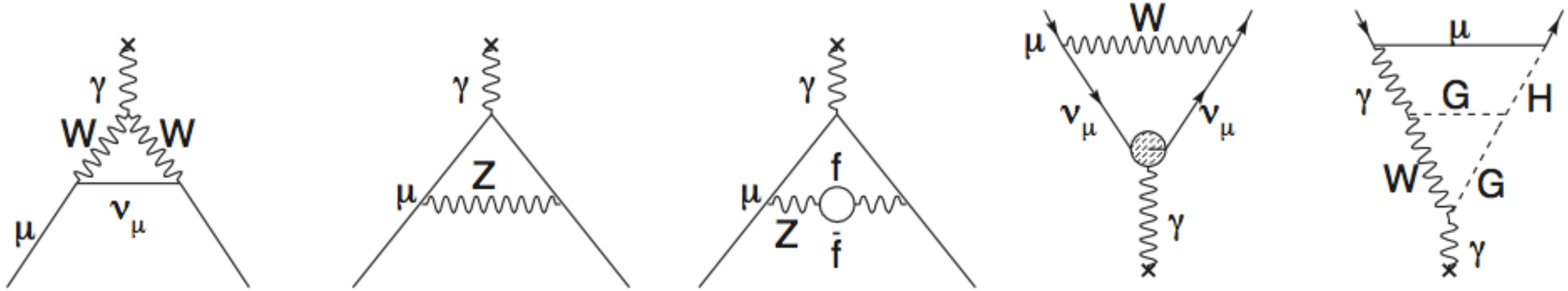


Known to 0.3 ppb (vs 0.5 ppm current experiment)

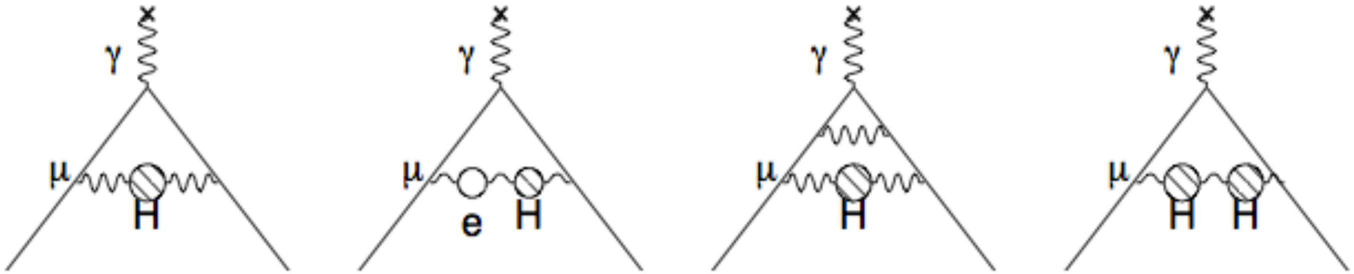
T. Kinoshita

SM (Non-QED) Contributions to g-2

Electroweak Contributions **(known to 0.01 ppm vs 0.5 ppm experiment)**

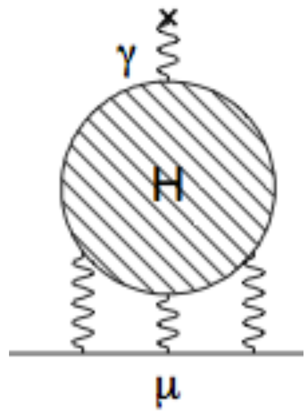


Hadronic Contributions (see talks tomorrow)



Hadronic Vacuum Polarisation (HVP)

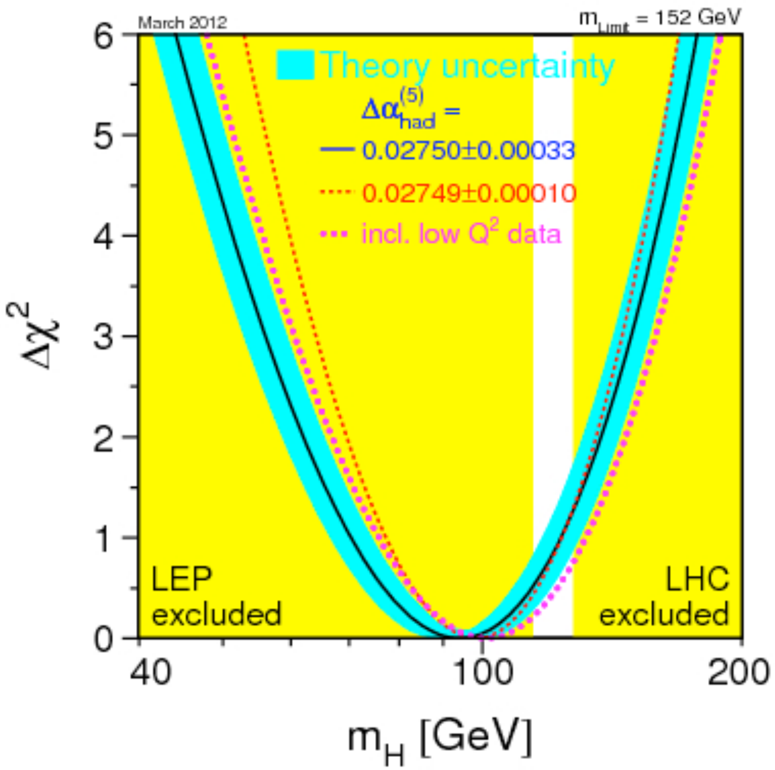
Hadronic Light-by-Light (HLBL)



Hadronic uncertainty : 0.42 ppm : comparable with current experimental uncertainty.

Hadronic Contribution & g-2

"We can't trust the hadronic calculations, so there is no point measuring g-2 !"



$$M_H = 94^{+29}_{-24}\ \text{GeV}$$

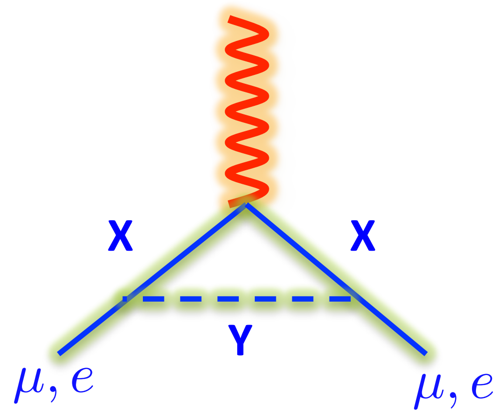
$$a_\mu^{HVP(LO)} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma(s)ds$$

Same low energy e^+e^- data

$$\Delta\alpha^{(5)}_{HAD}(M_Z) = \frac{M_Z^2}{4\alpha\pi^2} P\int_{4m_\pi^2}^{\infty}\frac{\sigma(s)}{M_Z^2 - s}ds$$

If we assume this is wrong then : $M_H = 94 \rightarrow 68$ GeV
and 95% upper limit in tension with observed 125 GeV state

New Physics Contribution to g-2



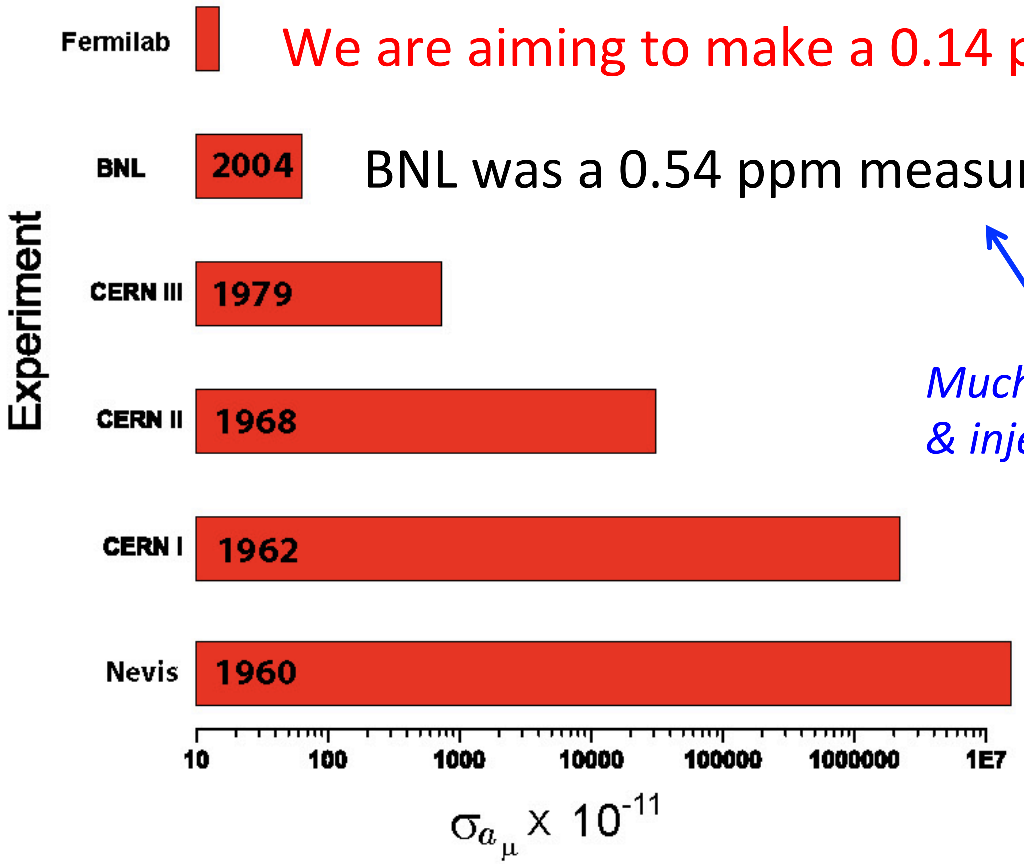
New physics as: $$\left(\frac{m_\ell}{M_{\mathrm{NEW}}}\right)^2$$

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

Ideally we'd like to measure tau g-2 but lifetime too short and the precision is not yet even sensitive to ($\alpha/2\pi$) QED contribution.

To probe TeV-scale physics need to measure muon g-2 to **high precision**

Precision of Muon g-2 Measurements



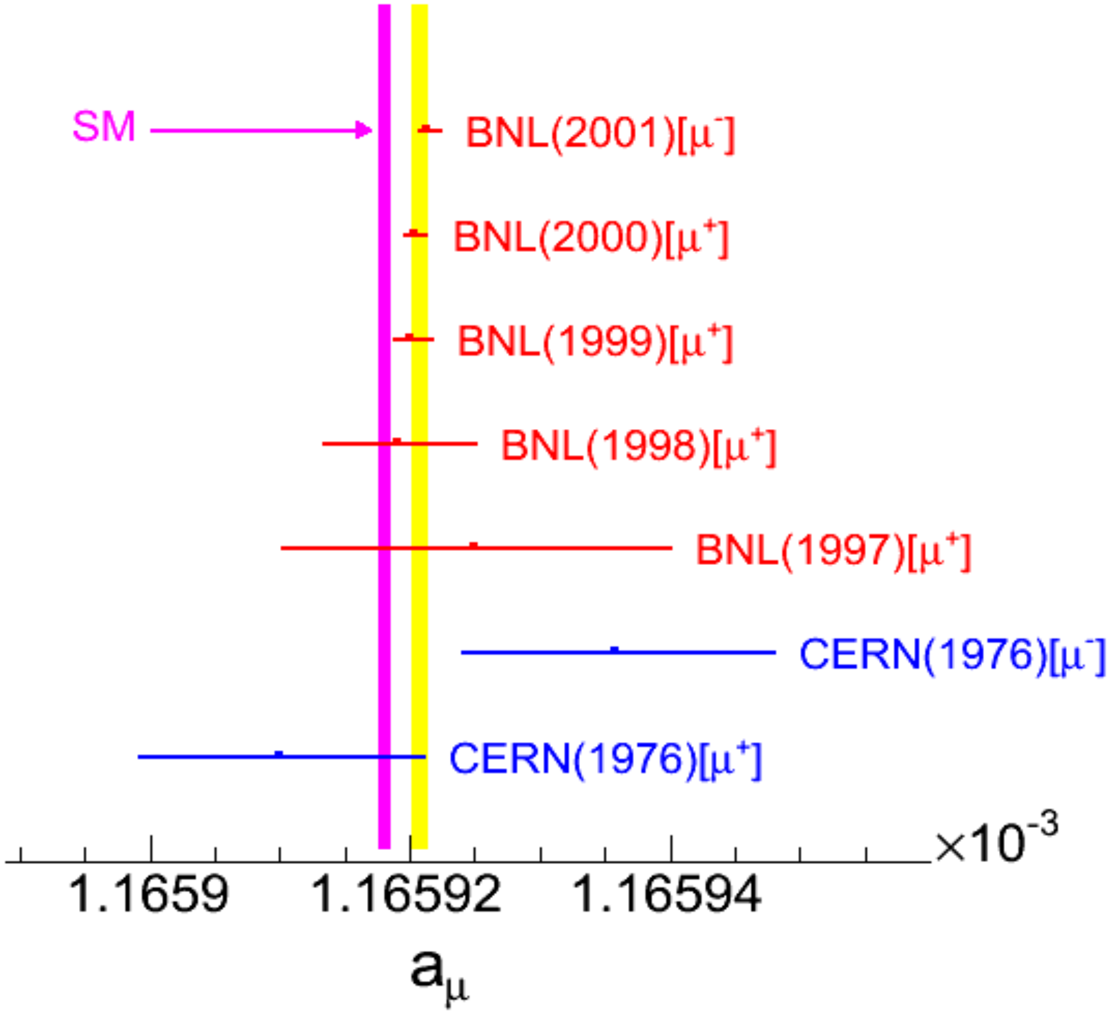
We are aiming to make a 0.14 ppm measurement

BNL was a 0.54 ppm measurement

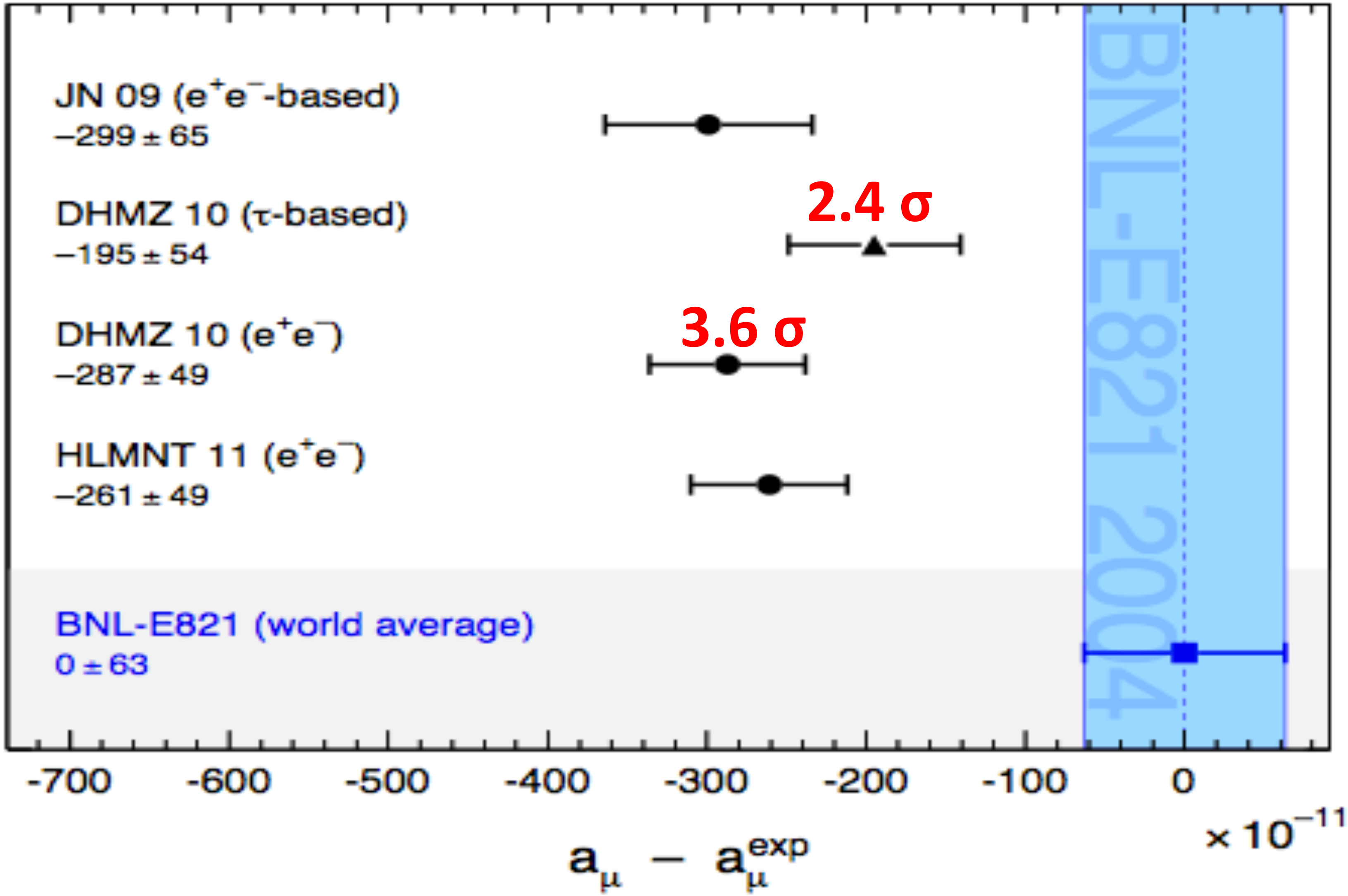
Much greater proton intensity & injected muons not pions

This precision at FNAL even with no improvement in SM prediction uncertainty **would establish BSM physics at beyond 5 σ** if BNL a_μ value confirmed.

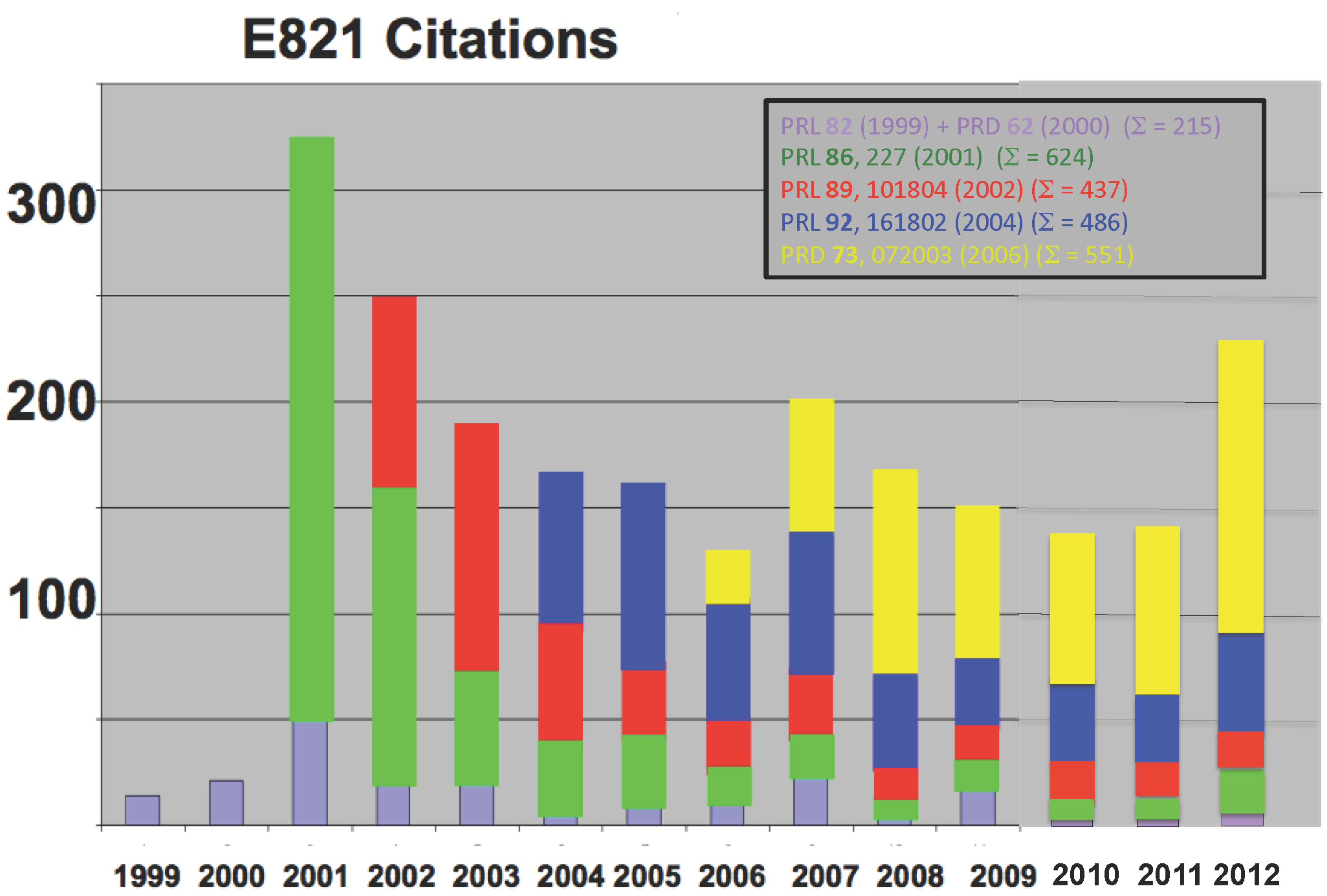
Muon g-2 Measurements



Why bother measuring it to 0.1 ppm ?



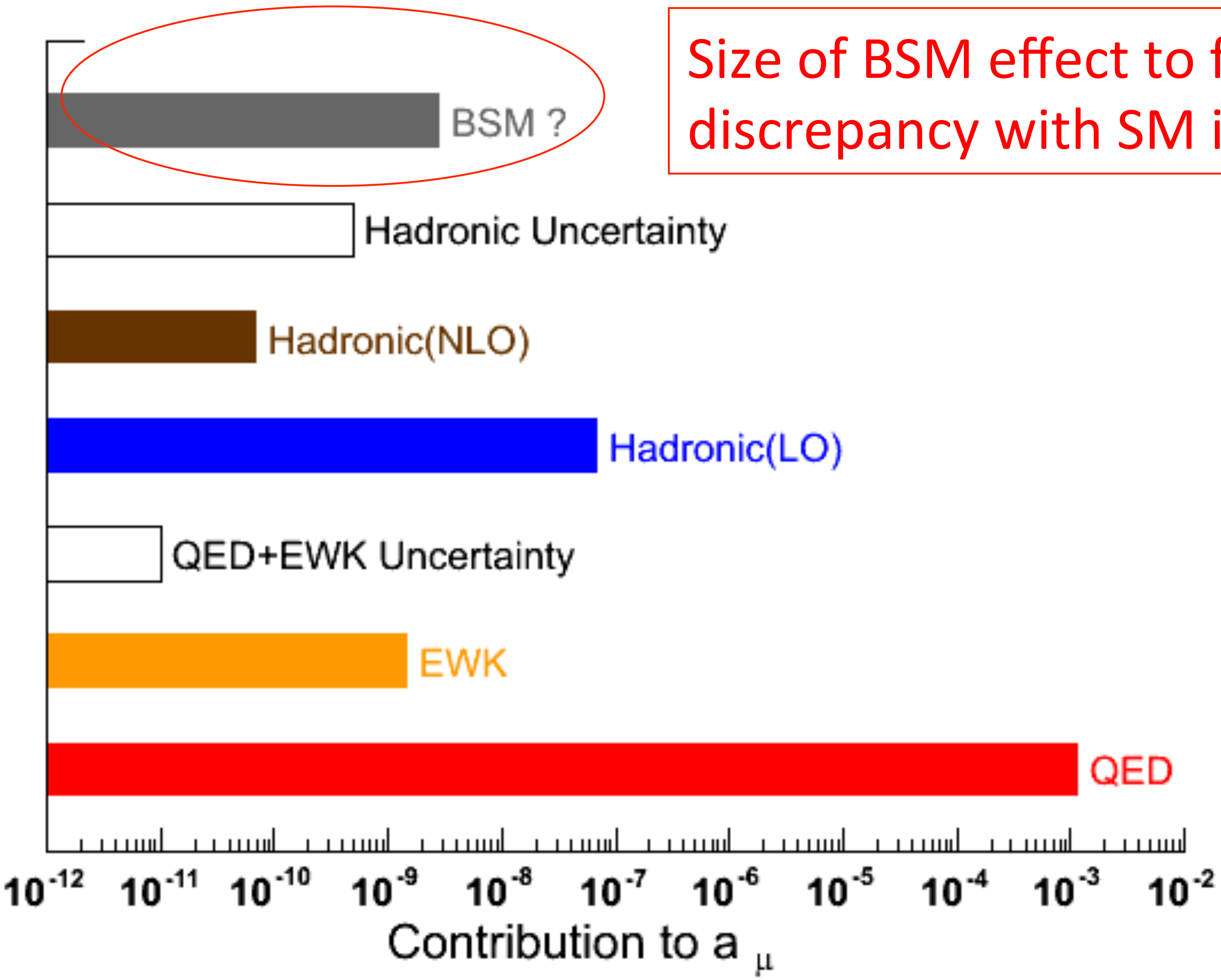
It's clearly of interest



2098 citations

2[nd] most cited paper in experimental particle physics

Why is this one number so interesting ?



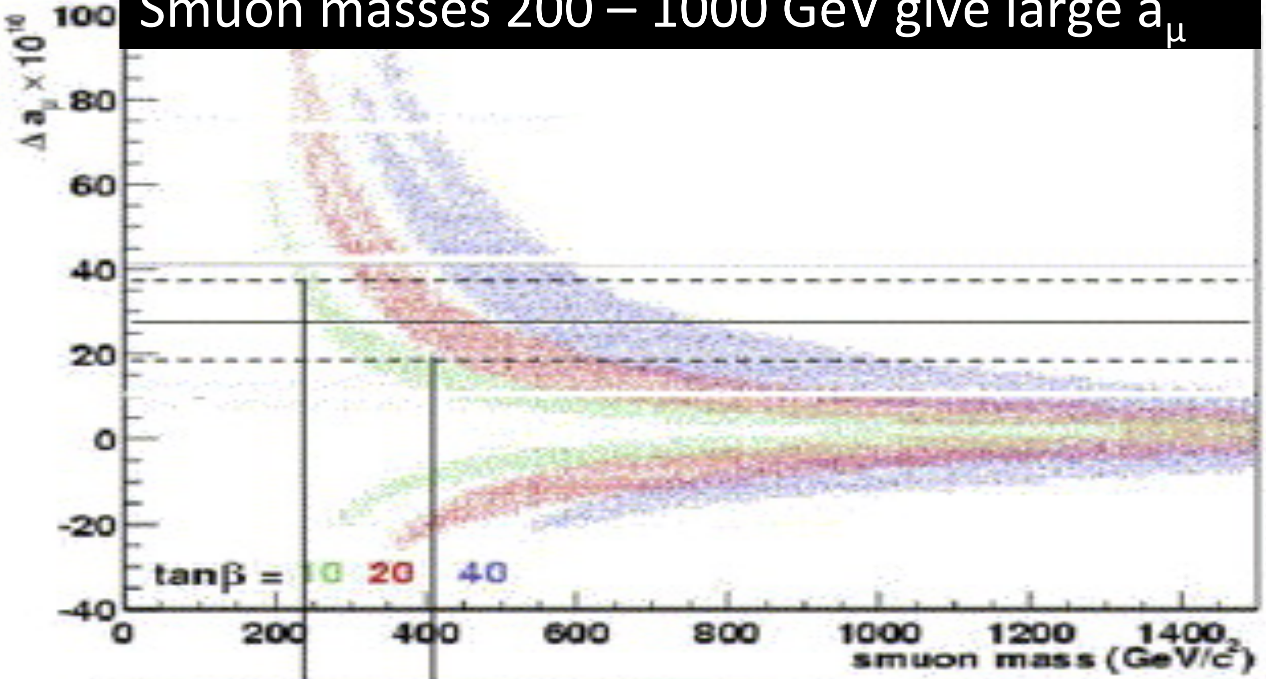
Size of BSM effect to fix current discrepancy with SM is large

Mantra pre-LHC

Vanilla SUSY

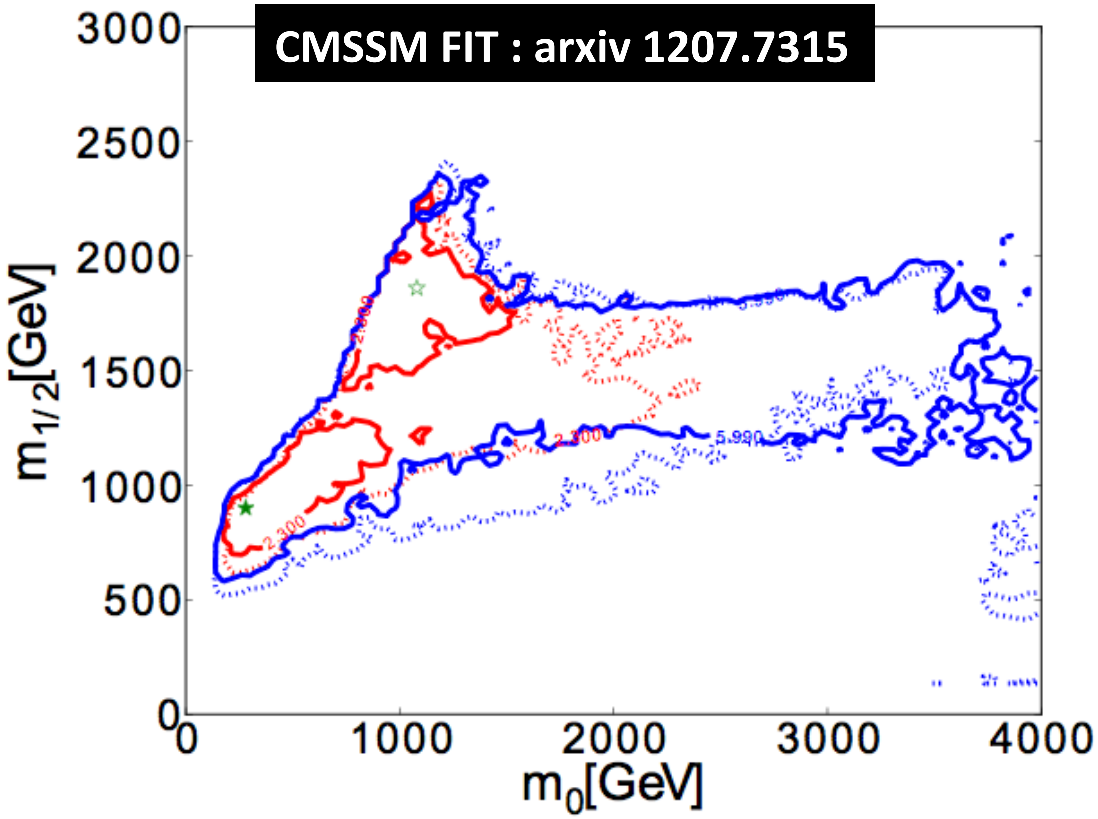
$$a_\mu^{\mathrm{SUSY}} \sim \pm\, 130 \times 10^{-11} \cdot \left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2 \tan\beta$$

Smuon masses 200 – 1000 GeV give large a_μ



M_{SUSY} constrained by current Δa for $\tan\beta = 10$

Coloured vs Non-Coloured Sector



SUSY masses allowed by ATLAS/CMS+XENON @ 68% C.L (95 % C.L)

Data (at least in coloured sector) is dis-favouring light SUSY.

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

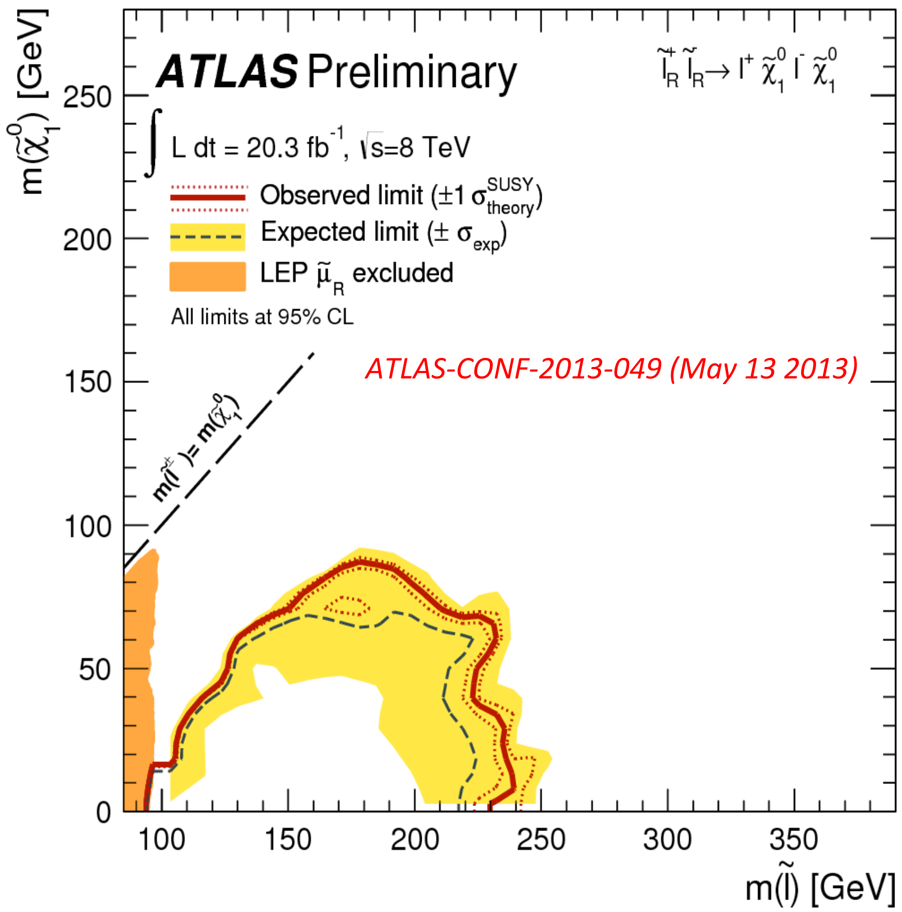
arxiv:1207.7315

Simple cMSSM struggling to describe all data.

g-2 is the result with largest tension against simplest SUSY models

This could be a fluctuation or could be telling us something

LHC Smuon limits



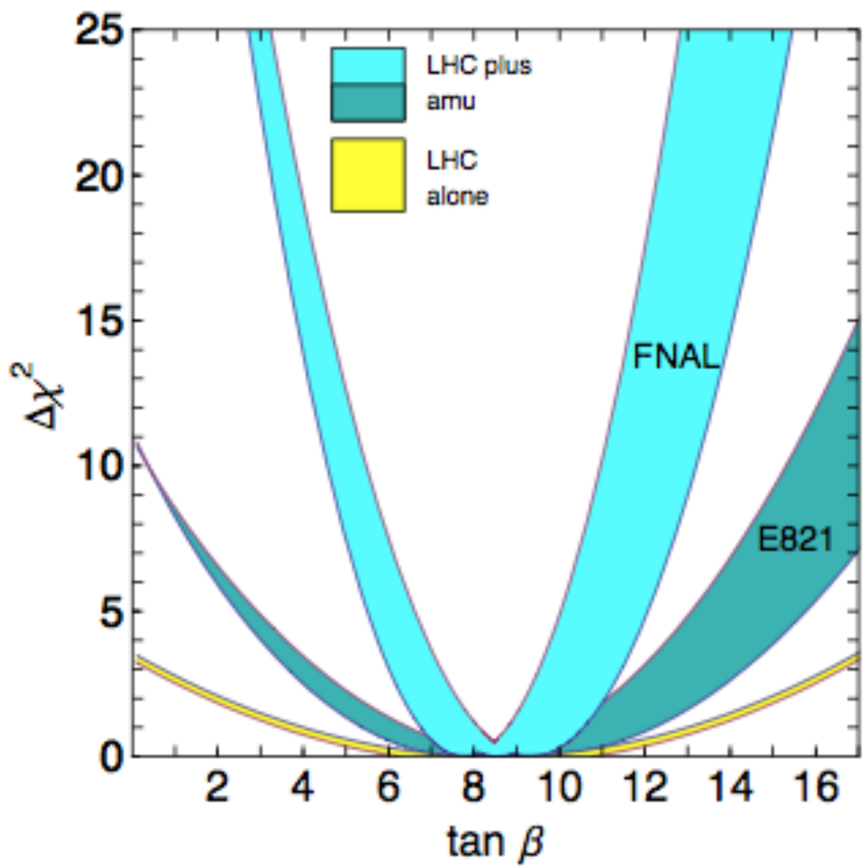
At LHC slepton sector is not as well explored as squark/gluino sector

"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

Much of phase space that gives the large a_{μ} of BNL is not covered by LHC

Scenario that LHC sees BSM



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

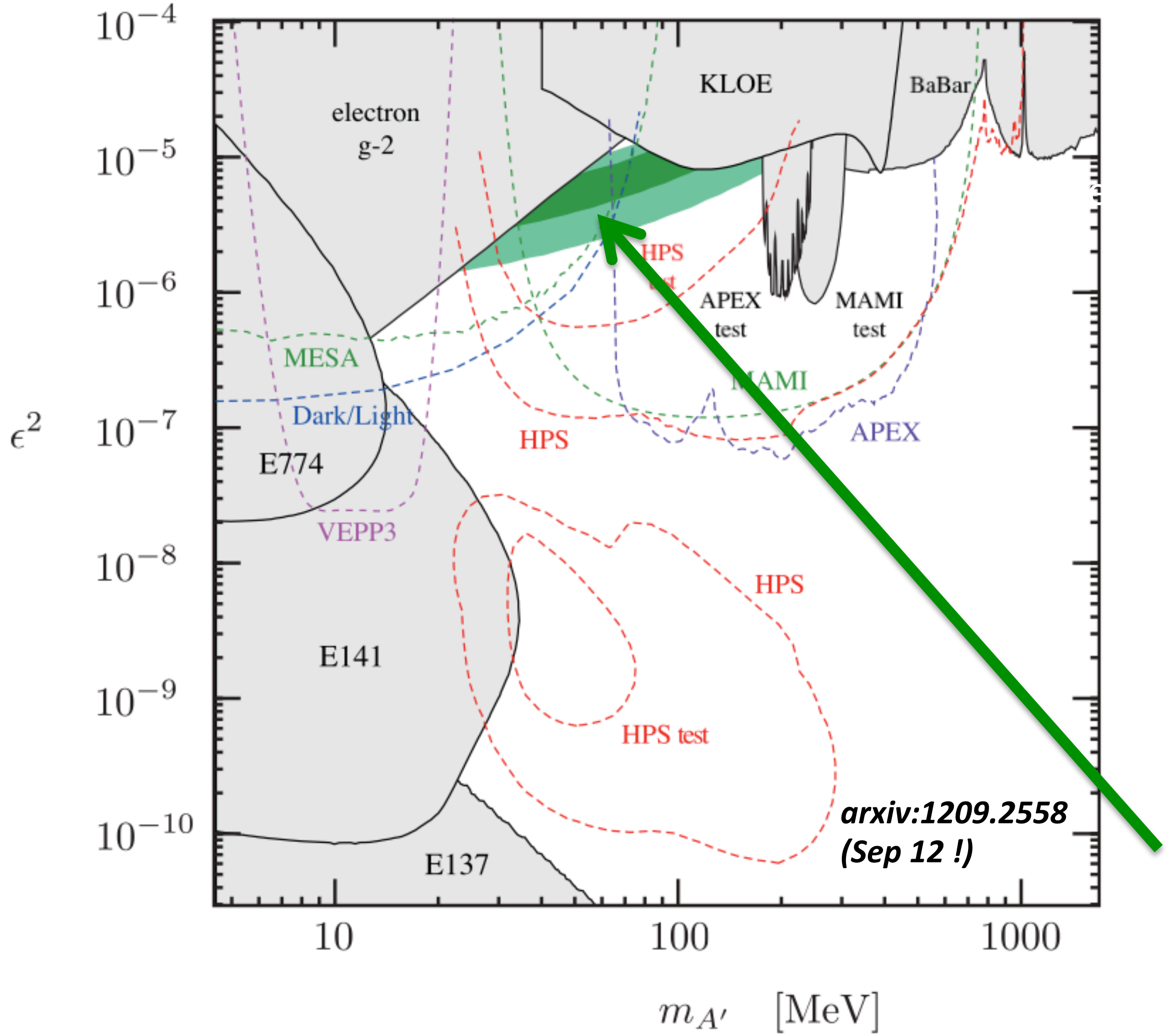
Sign of contribution of SUSY to (g-2) determined by sgn(μ)

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

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

g-2 and LHC results can complement each other and resolve model degeneracy

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

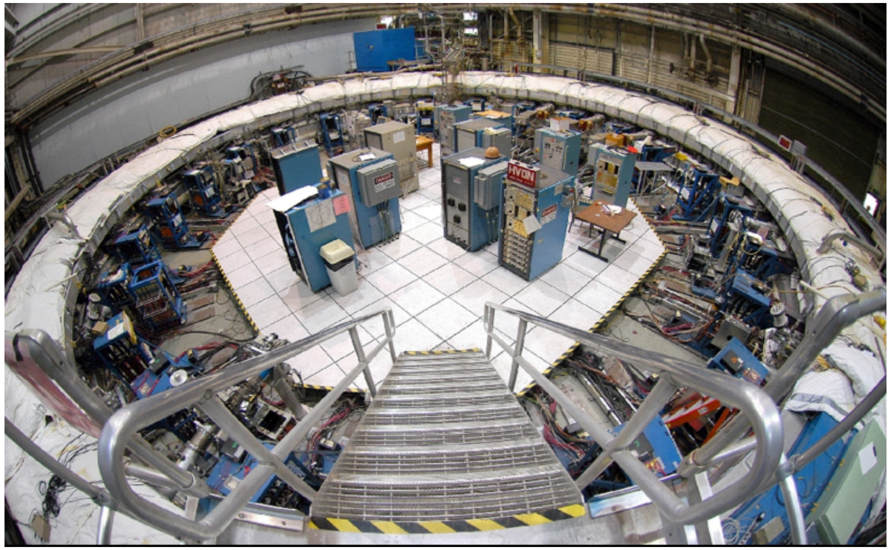
g-2 will complement direct searches at JLAB, Mainz

Explains large BNL g-2

The new g-2 experiment @ FNAL (E989)

Aiming to reduce experimental uncertainty by factor of 4 with respect to BNL exp.

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.



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

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

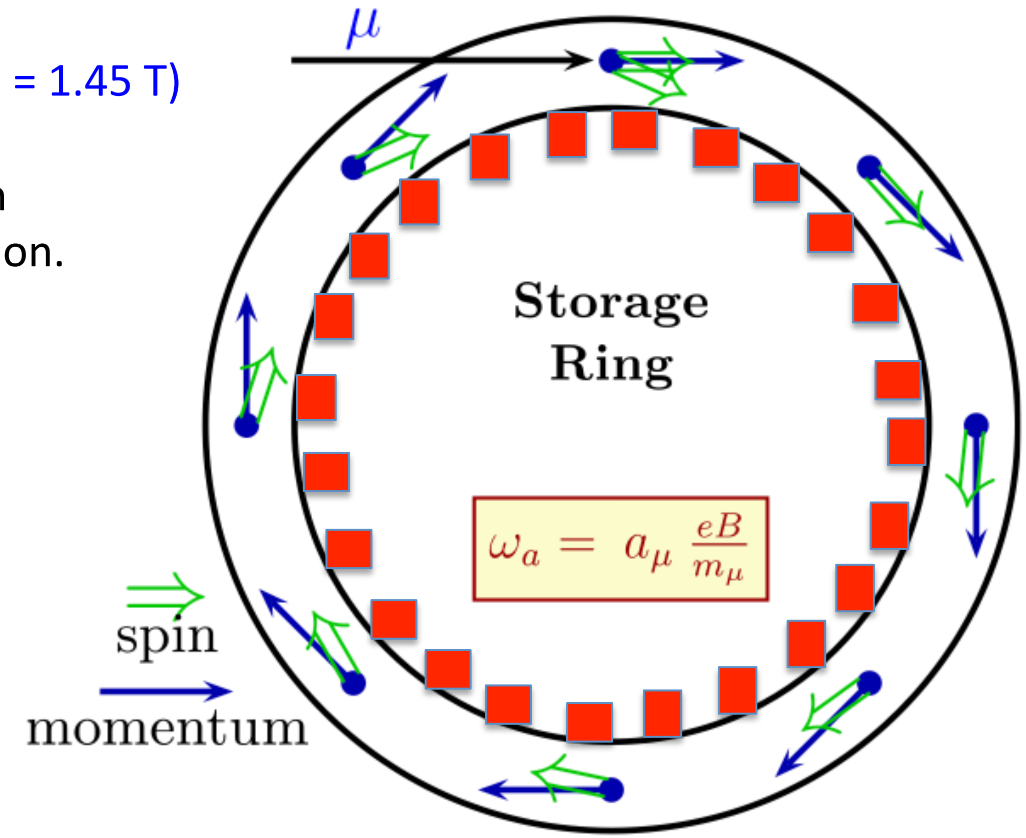
BNL Storage Ring

Experimental Technique

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

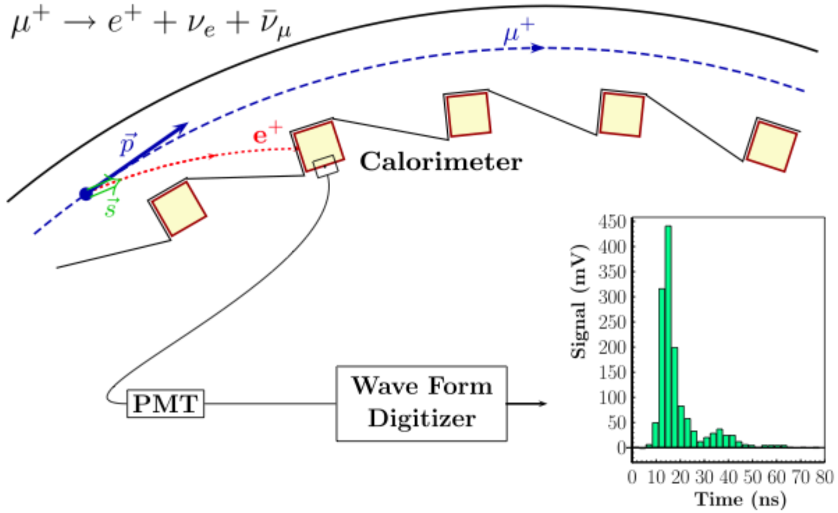
Measure rate of precession of spin
with respect to momentum direction.

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



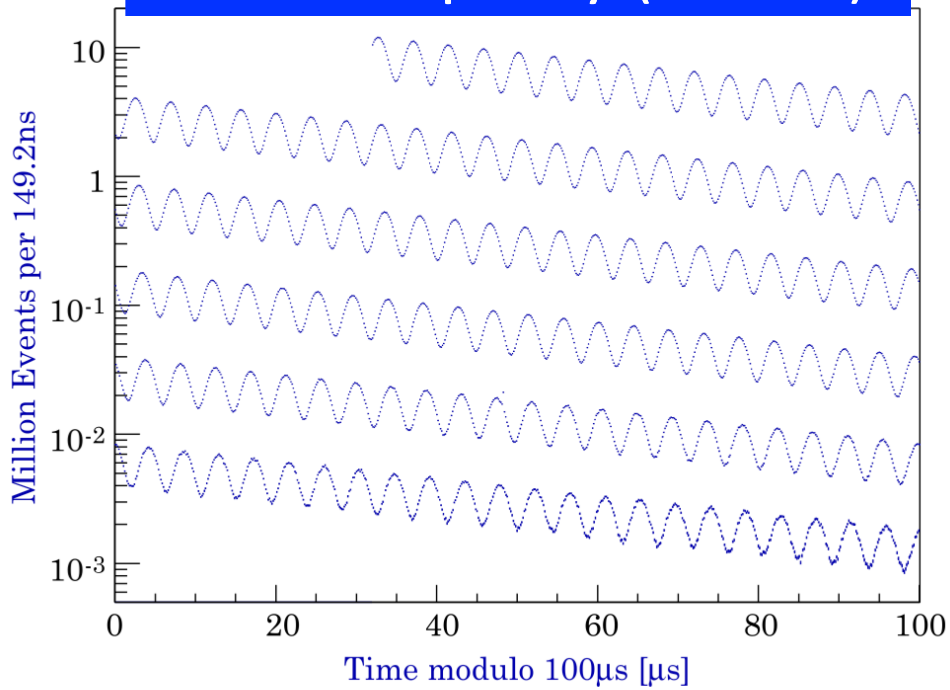
1. **Measure e^+ with E > 1.9 GeV in 24 calorimeters vs time (30 μs after injection)**
2. **Measure B field to a precision of 0.1 ppm**

The data



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

BNL 3.6 billion μ⁻ decays (2001 data)



$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

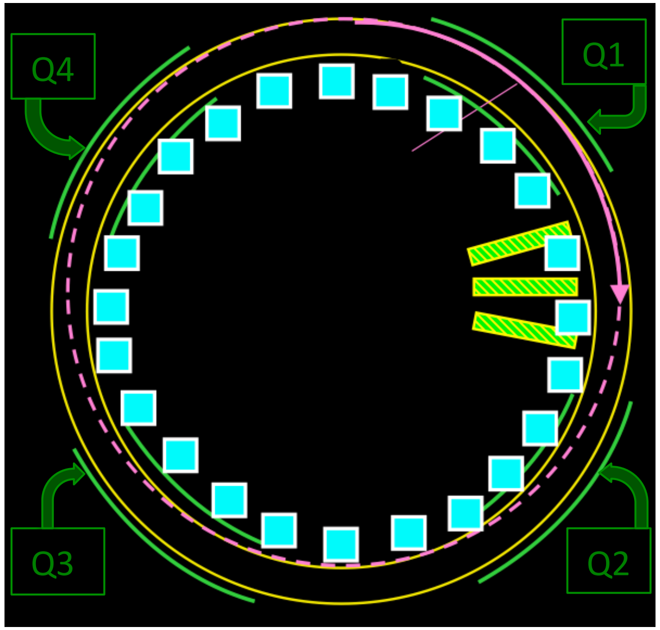
A, ϕ : known functions of e^+ energy

Experimental Technique

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

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

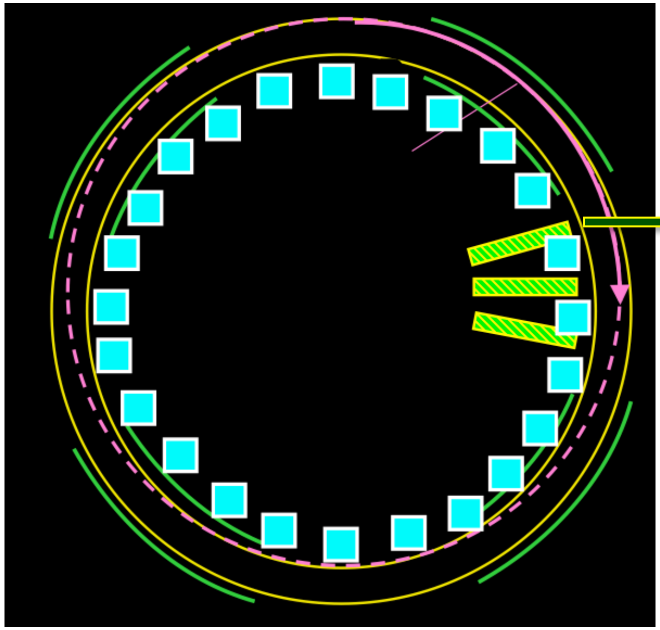
4 electric quadrupoles for focussing

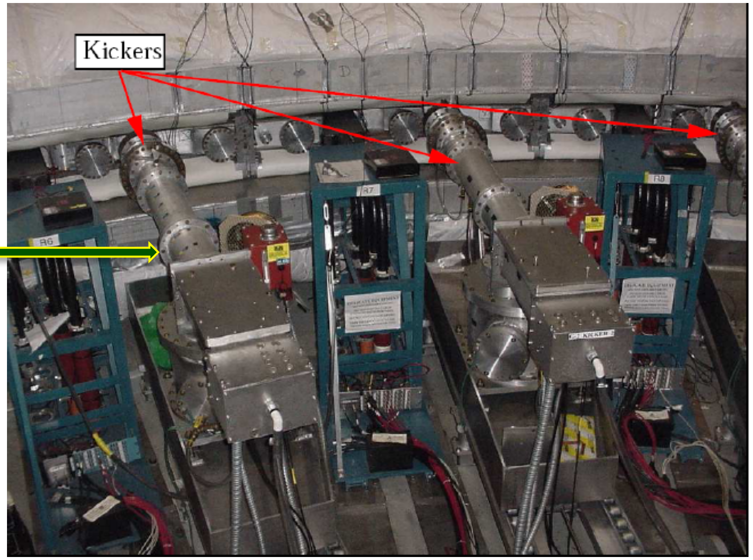


Cancel the E-field contribution by judicious choice of γ : the "magic momentum" : 3.094 GeV

Kicker

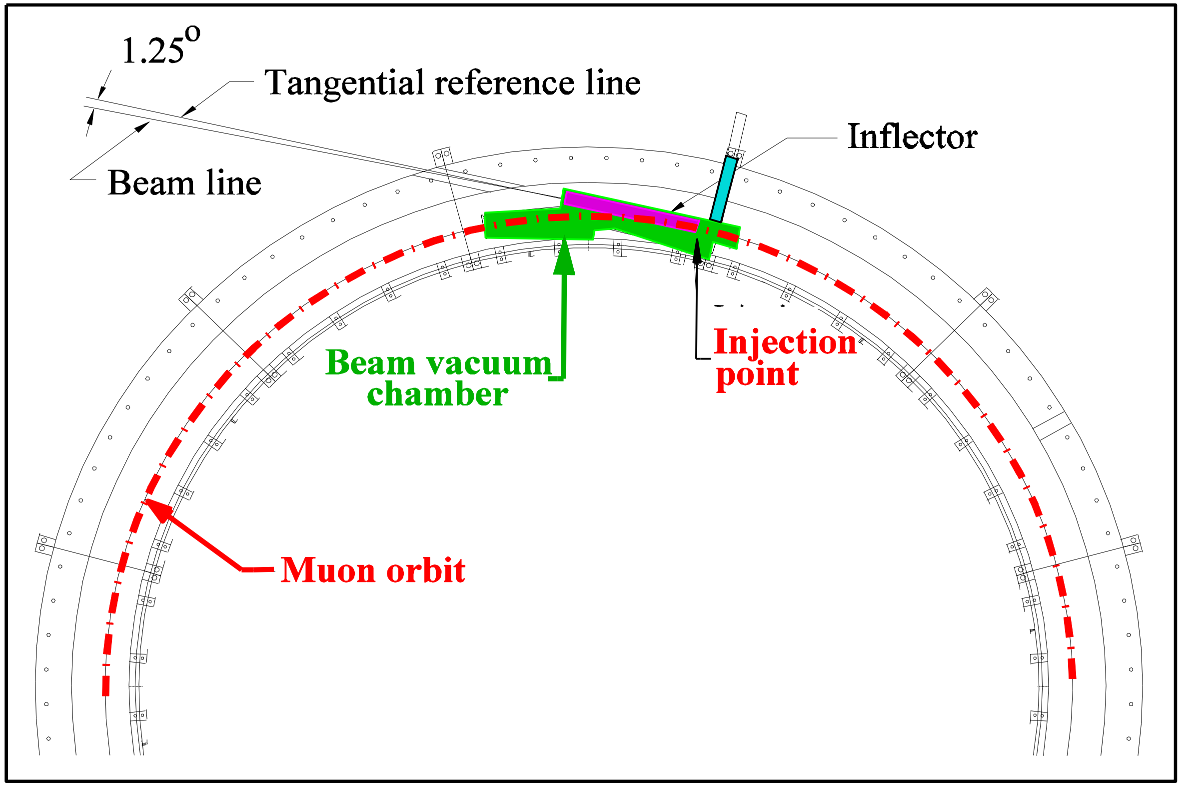
3 kickers to put beam "on orbit"

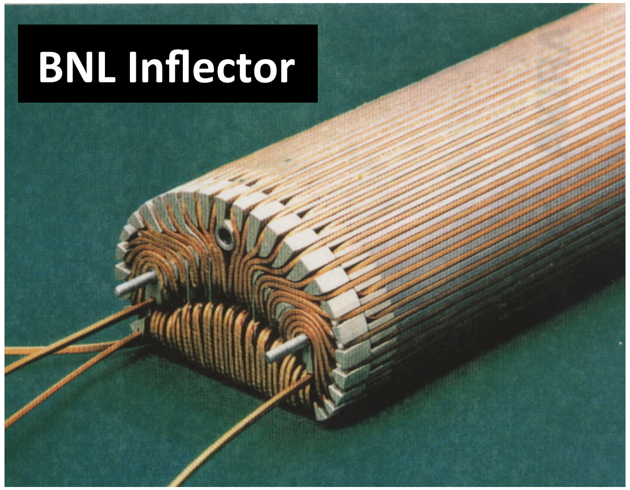




These are being replaced to have a "kick" over a smaller time period to produce a more stable beam.

Inflector





1.7m superconducting magnet with superconducting flux shield

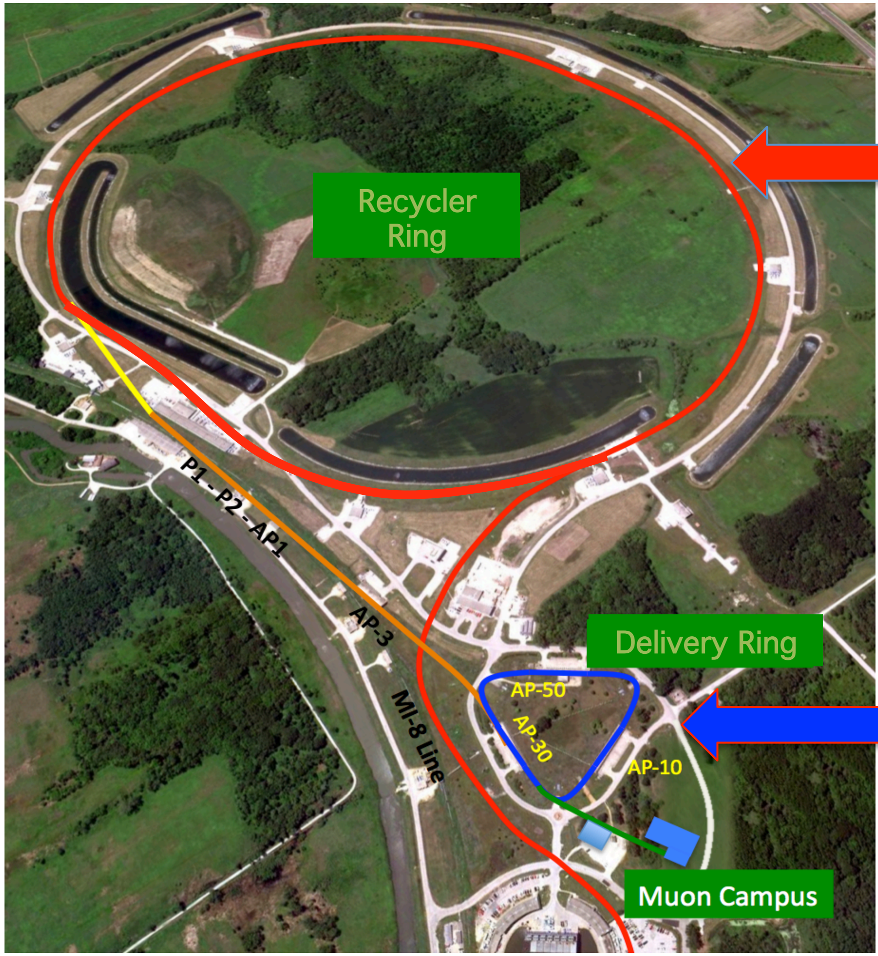
Cancels main storage ring B-field by providing “cancelling” field BUT only at the injection point

This will be replaced with a new “open-end” design that increases muon acceptance and orbit stability over BNL experiment.

4 Key Improvements over BNL experiment

1. **Accelerator before storage ring**

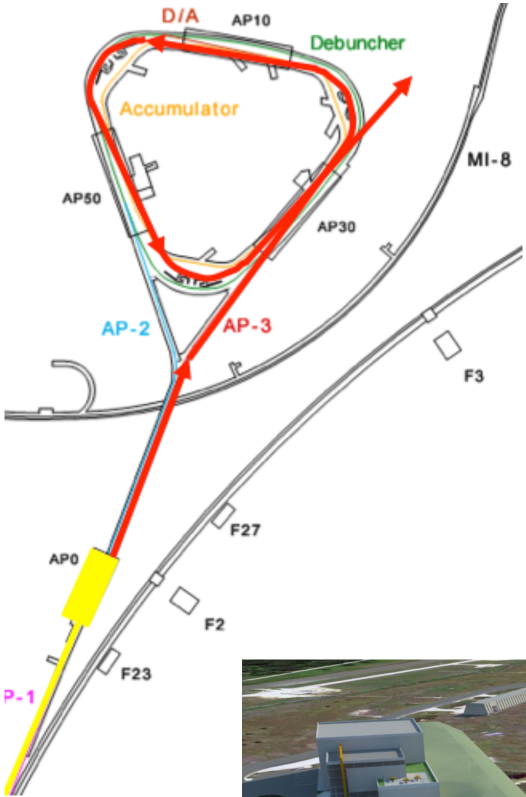
   More muons at lower inst. rate with much reduced pion contamination

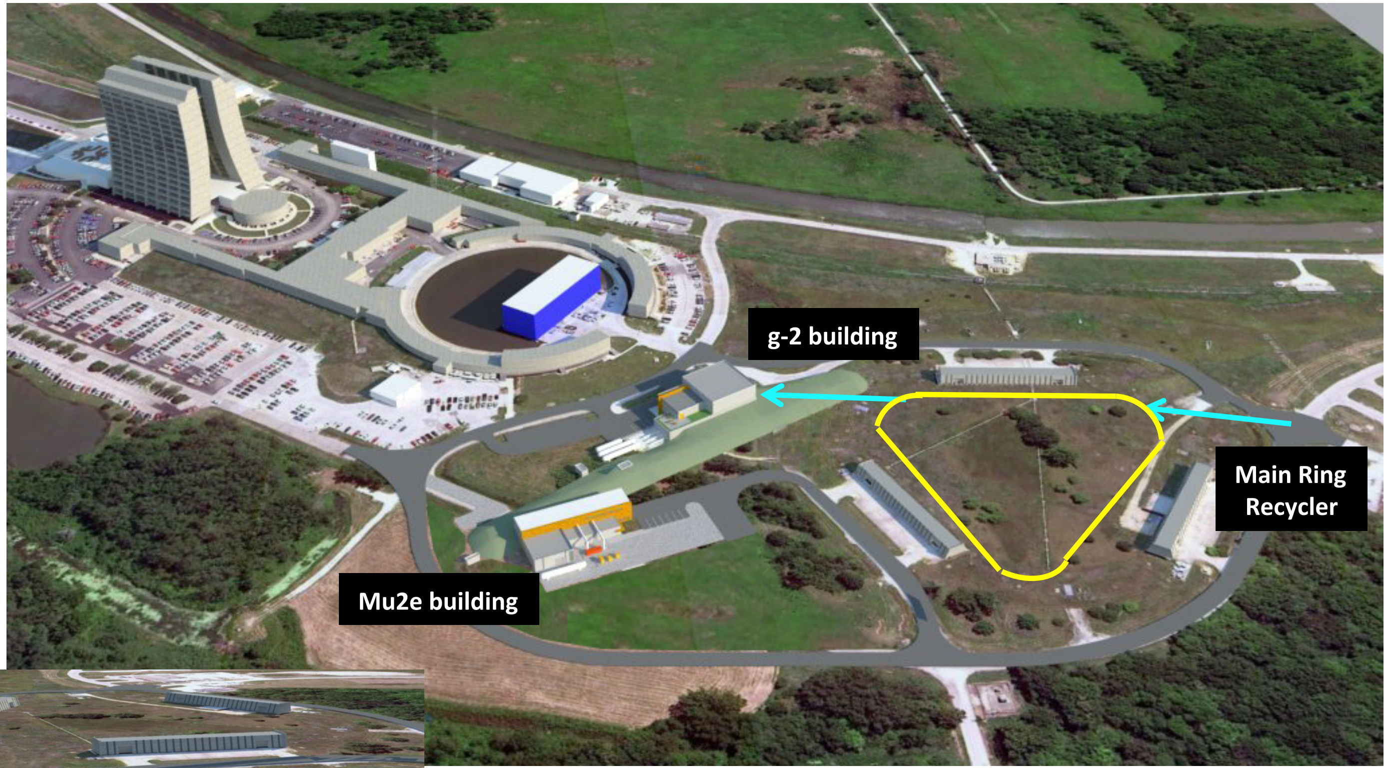


Proton accelerator mods almost complete since needed for NoVa.

Pbar accelerator complex being re-configured to provide muons.

Improvements over BNL experiment



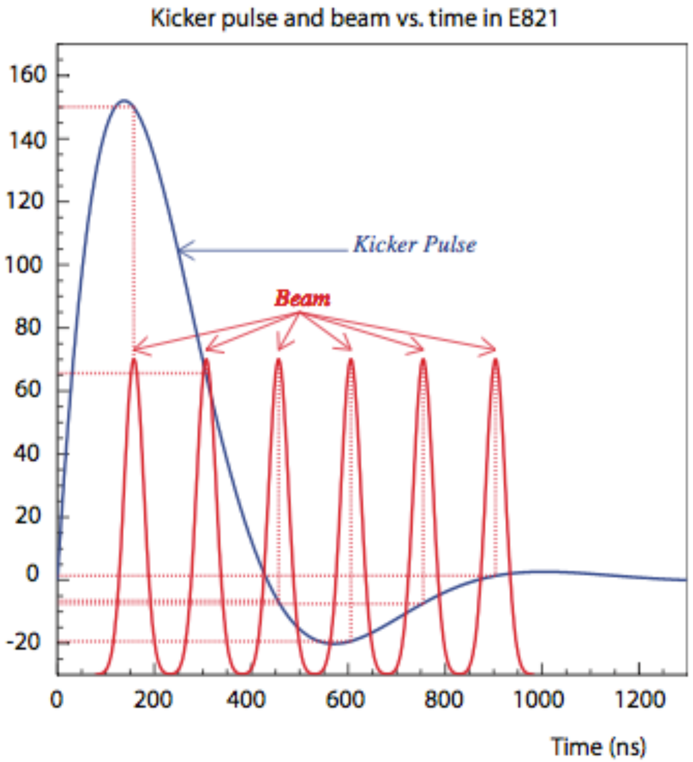


Muon campus groundbreaking

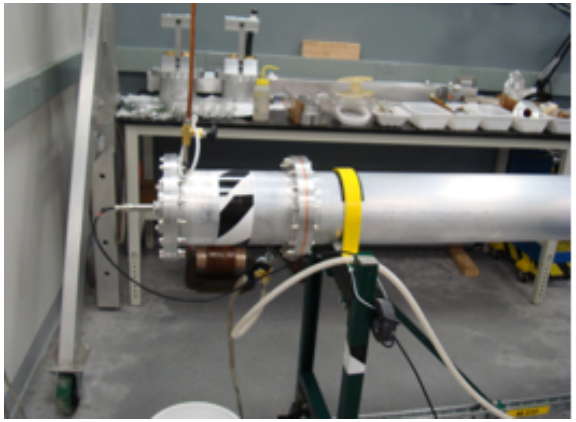
May 10 2013

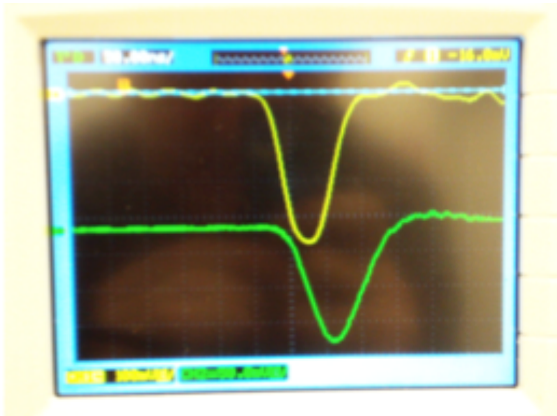
Improvements

2. New inflector magnet, better kicker, better CBO damping



Kicker use Blumlein triaxial transmission line to reduce kick to < 100 ns.

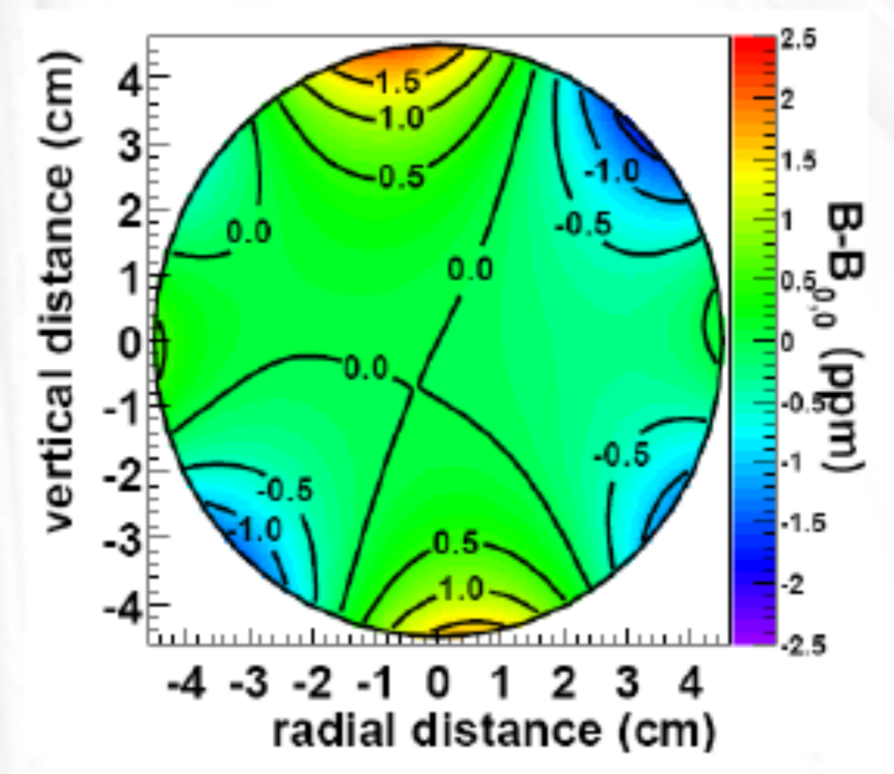




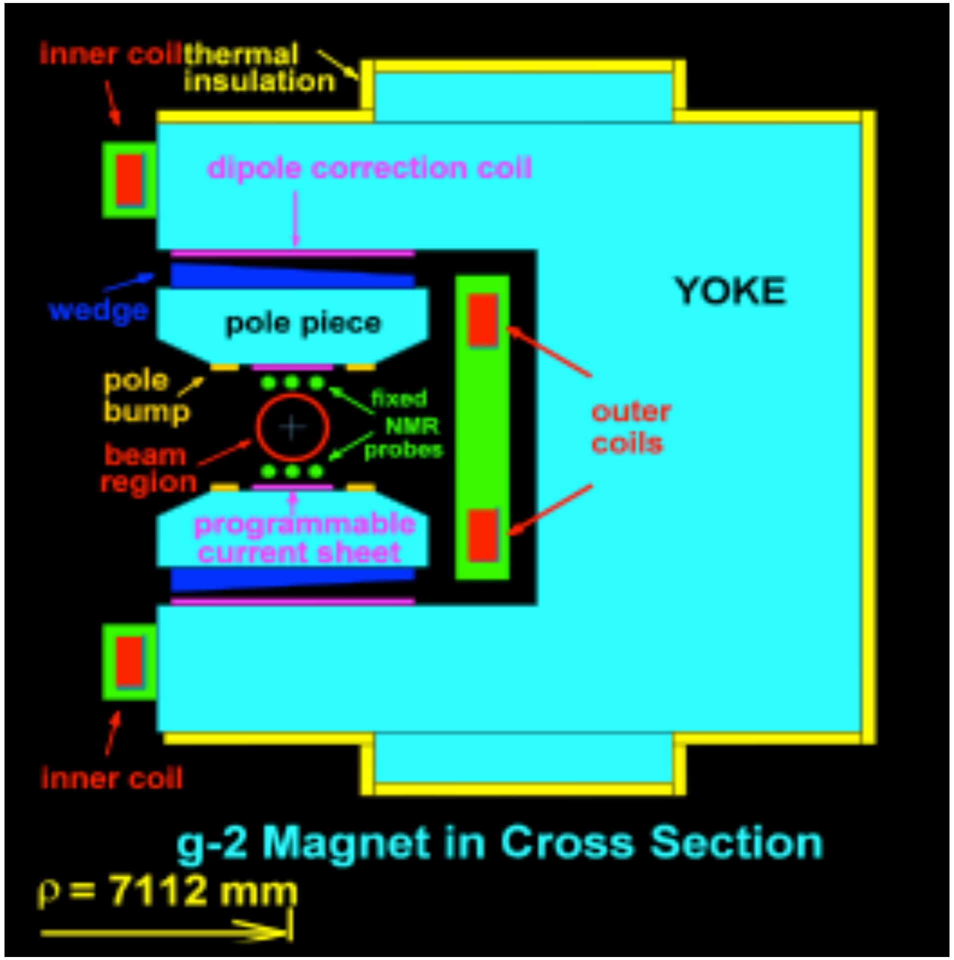
- coupled with improved beam modeling

Improvements

3. B-field : uniformity and calibration will be improved



Additional field shimming,
more frequent field mapping.



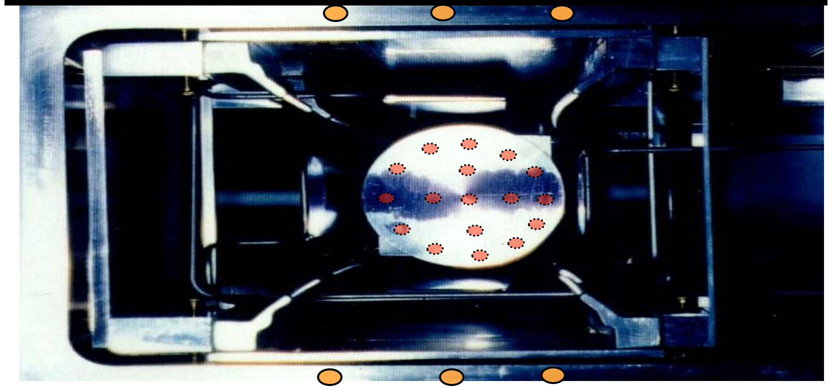
B-field improvements

Better knowledge of muon beam profile (simulation and straw trackers)

Improvements in trolley probes (position) & environment

H_20-based ref. NMR probe -> ^{3}He

300+ NMR probes in vacuum tank walls



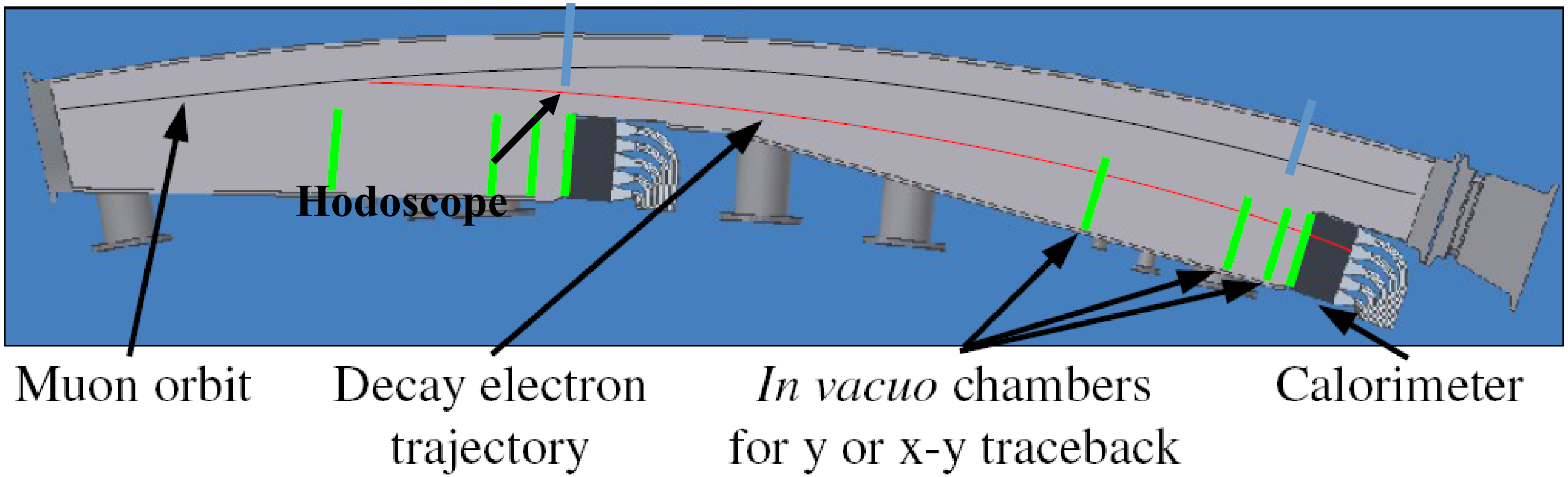
H_20 reference probe

17 movable NMR probes on a trolley

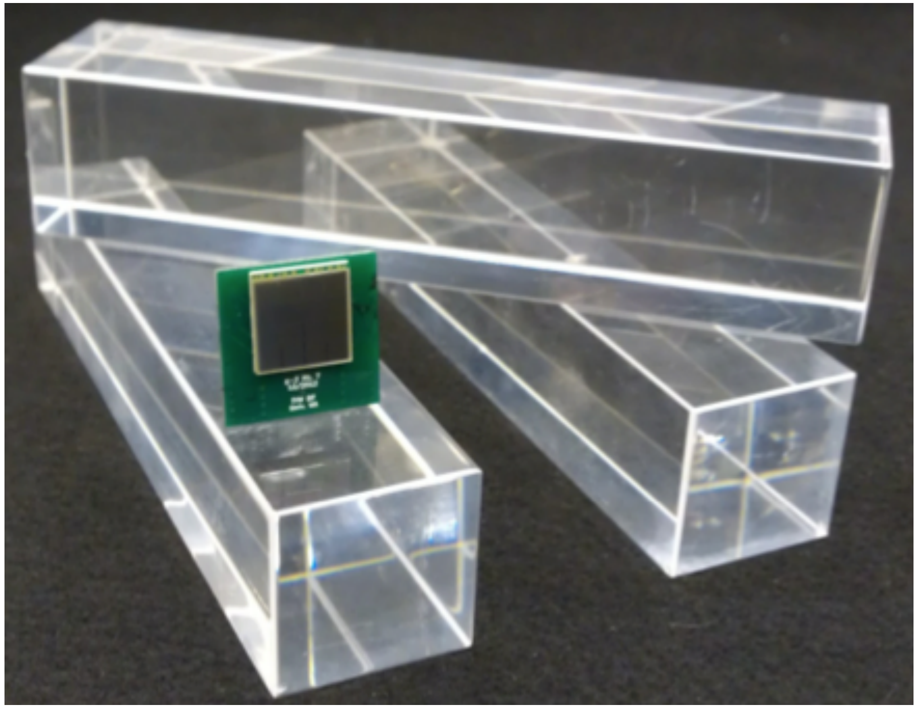
Improvements

4. New detectors: improved stability, better handling of pileup

- Improved tracking (straws in vacuum)
- New segmented calorimeter
- New calibration system



Detector improvements

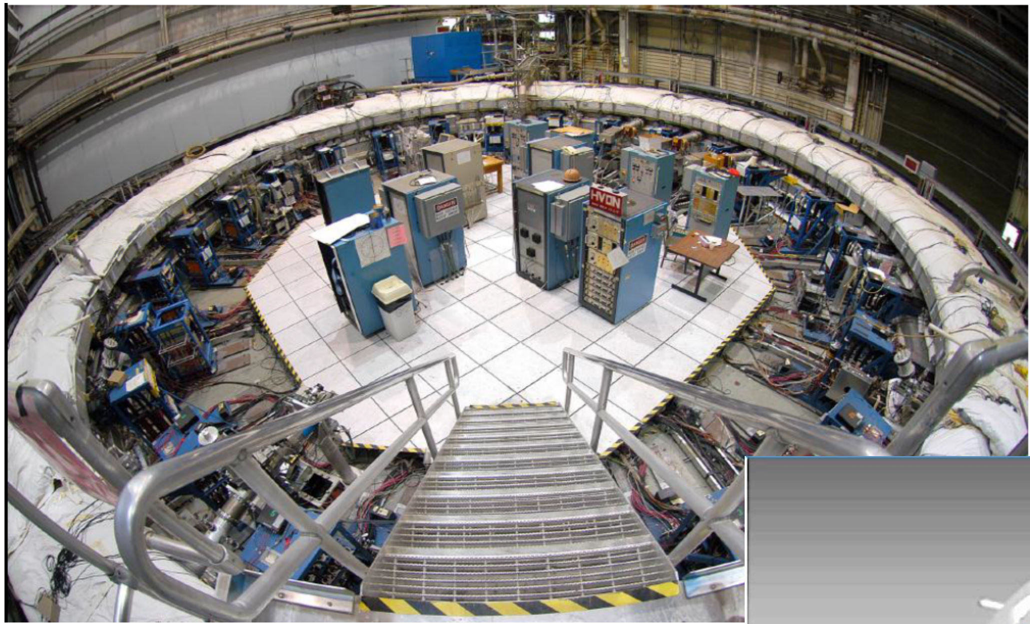


PbF_2 + 16-channel MPCC

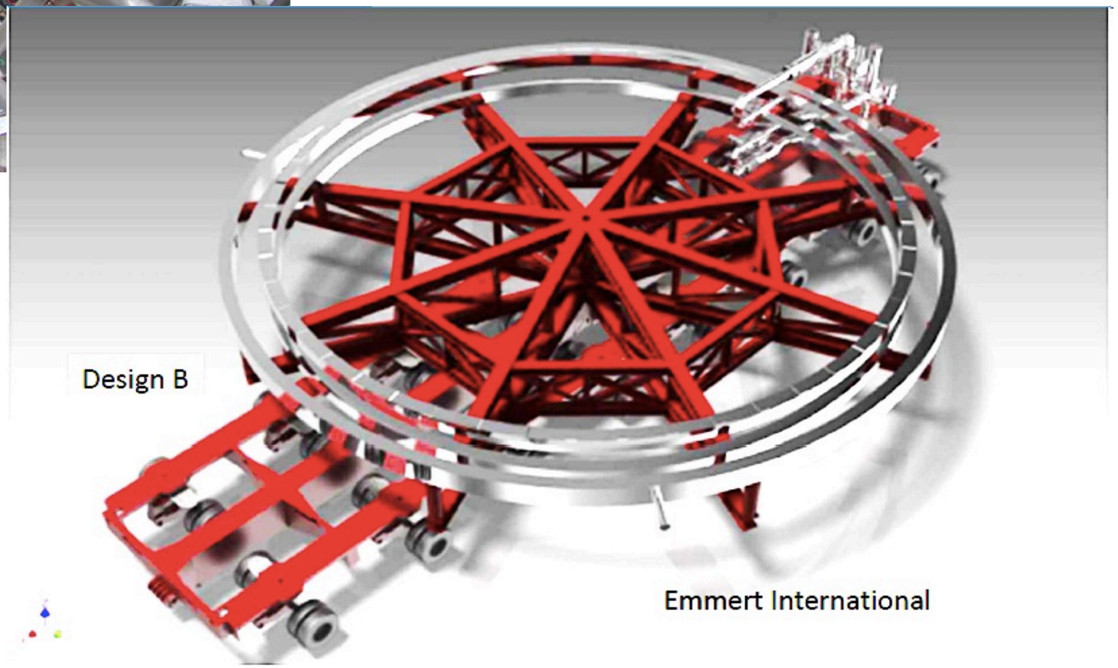
Straw tracker

- **coupled with improved detector modeling**

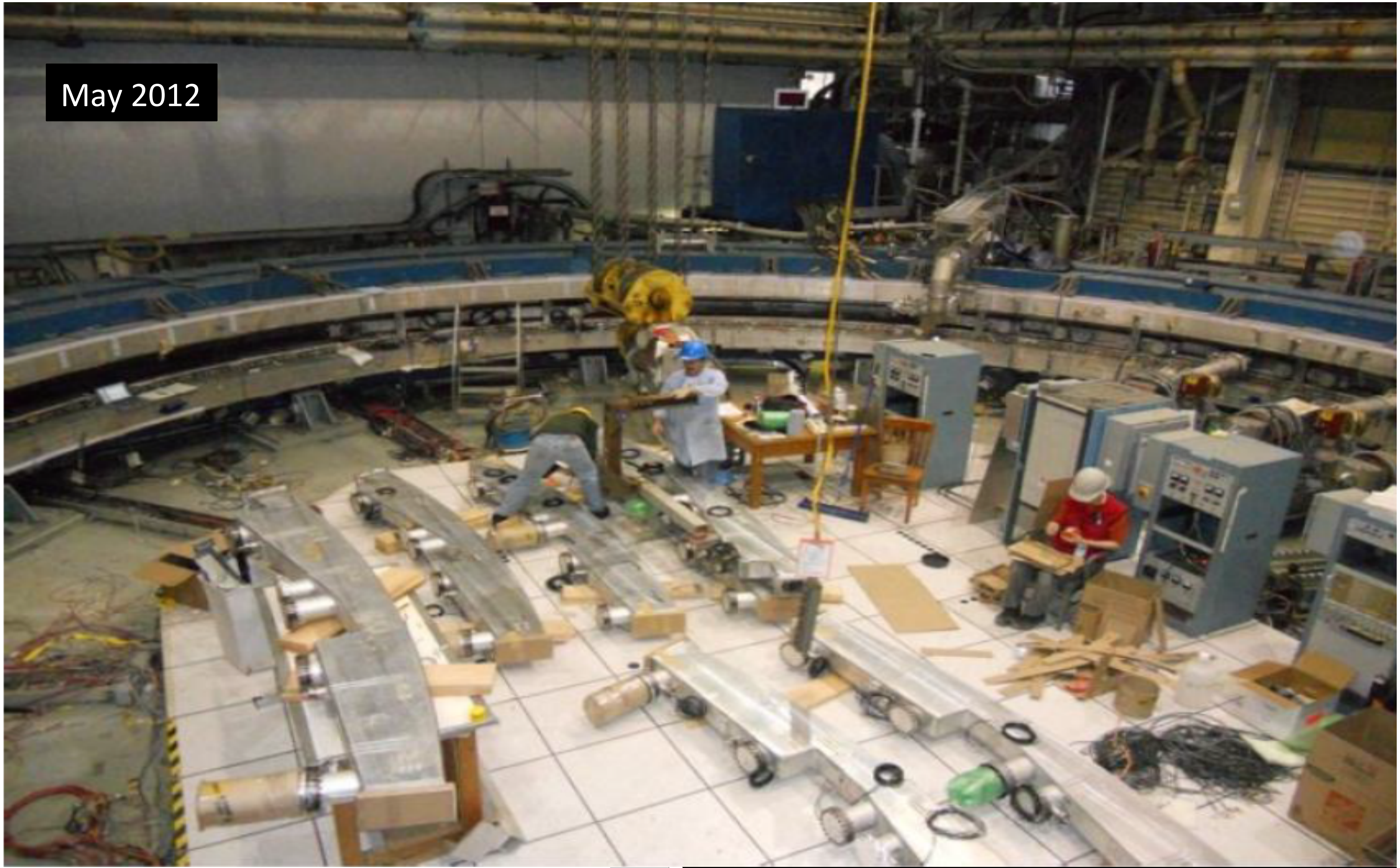
Movement of the ring from BNL to FNAL



Must be shipped in one piece !



Stage-1: Call U-Haul & willing PhD students



And Spokesperson & Project Manager

Most small kit already at FNAL

Larger Kit

Yokes etc arriving at FNAL now

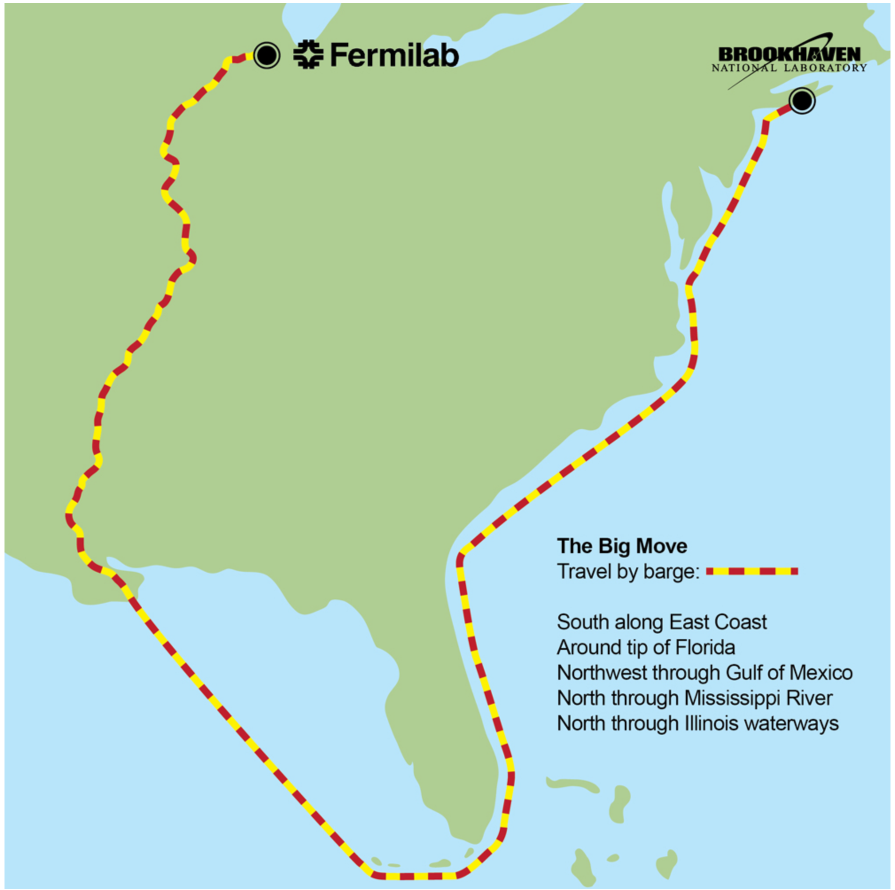
Ring Removal

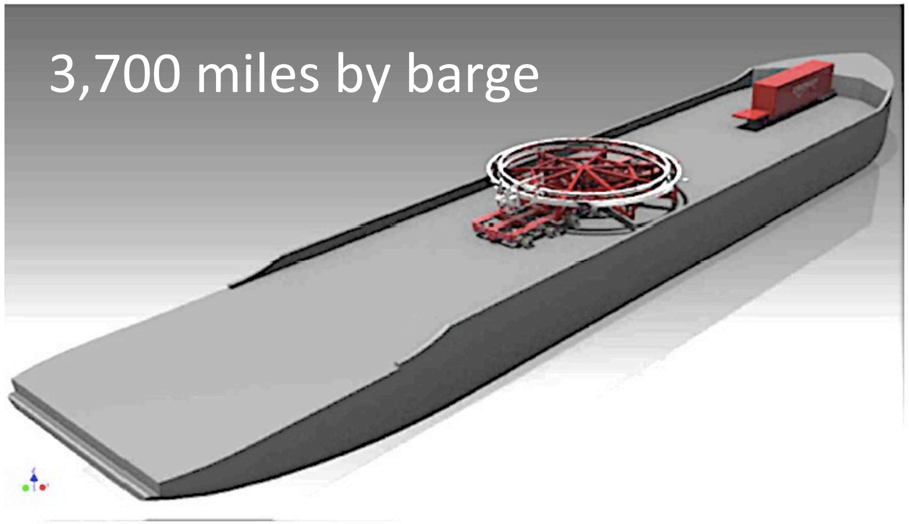
5 miles by road on Long Island

Ring Removal : Plan-A

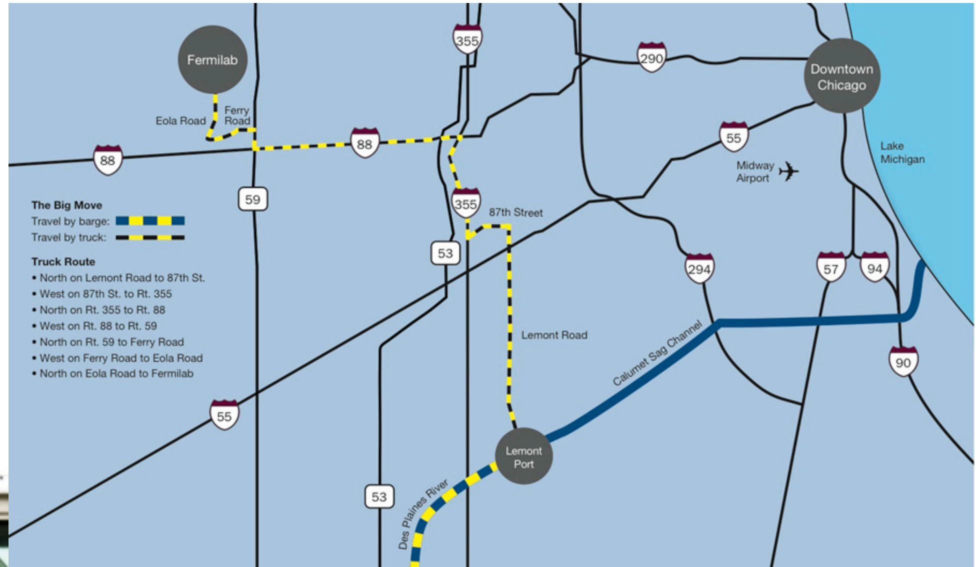
Not selected !

Ring Removal : Plan-B



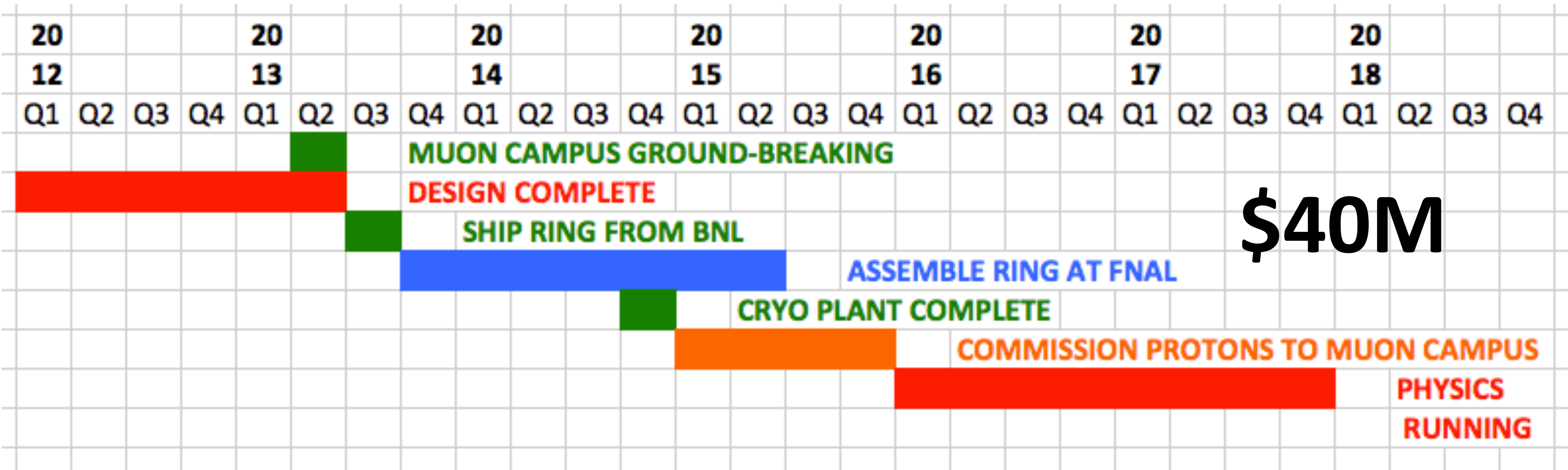


30 miles by road to FNAL ….



Timeline

Ring shipment begins in June



80 collaborators in 16 US institutes + 30 (Germany, Netherlands, China, Russia, Italy, UK)

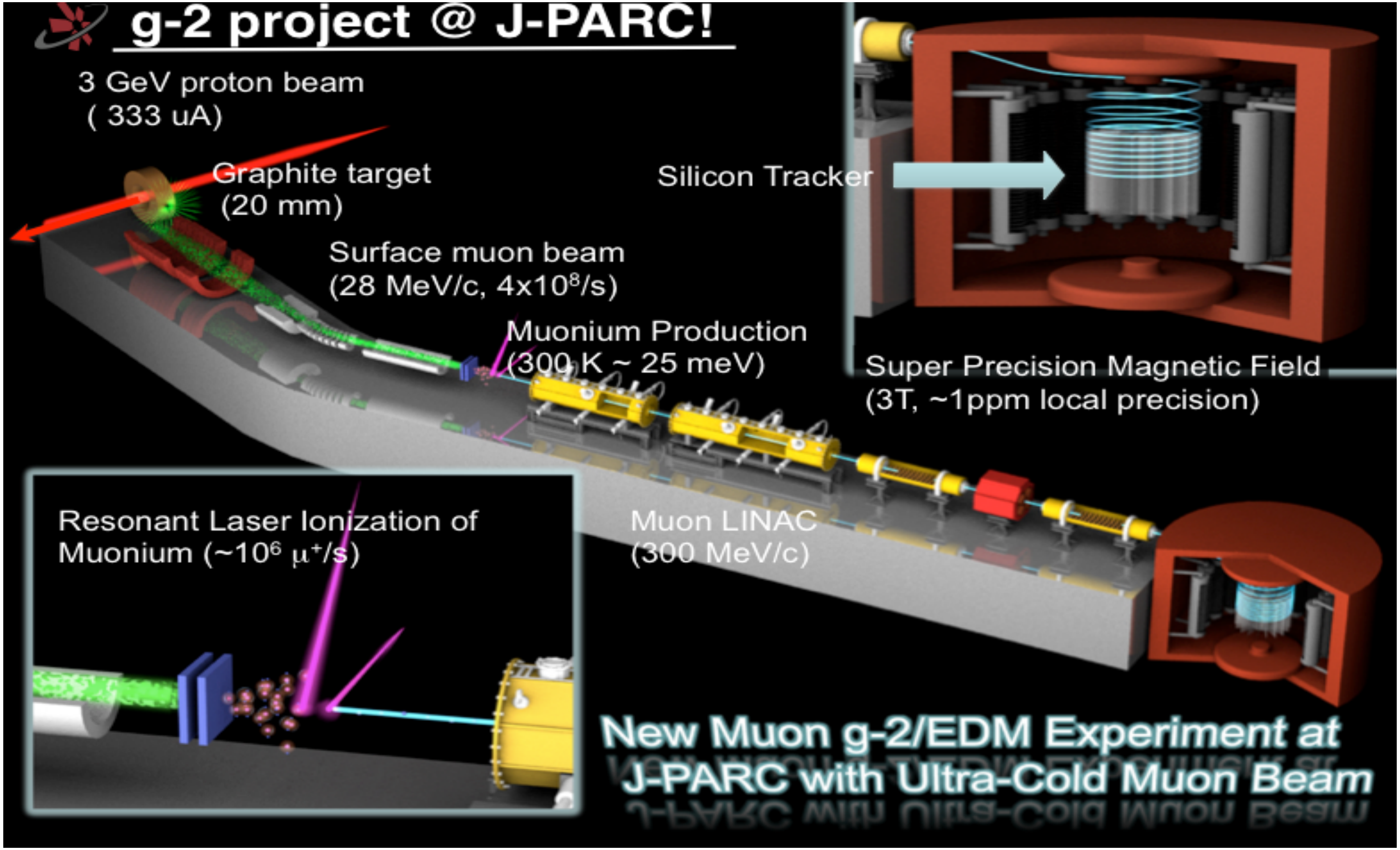
J-PARC Muon g-2

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

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)

J-PARC Muon g-2



J-PARC g-2 : Several Challenges

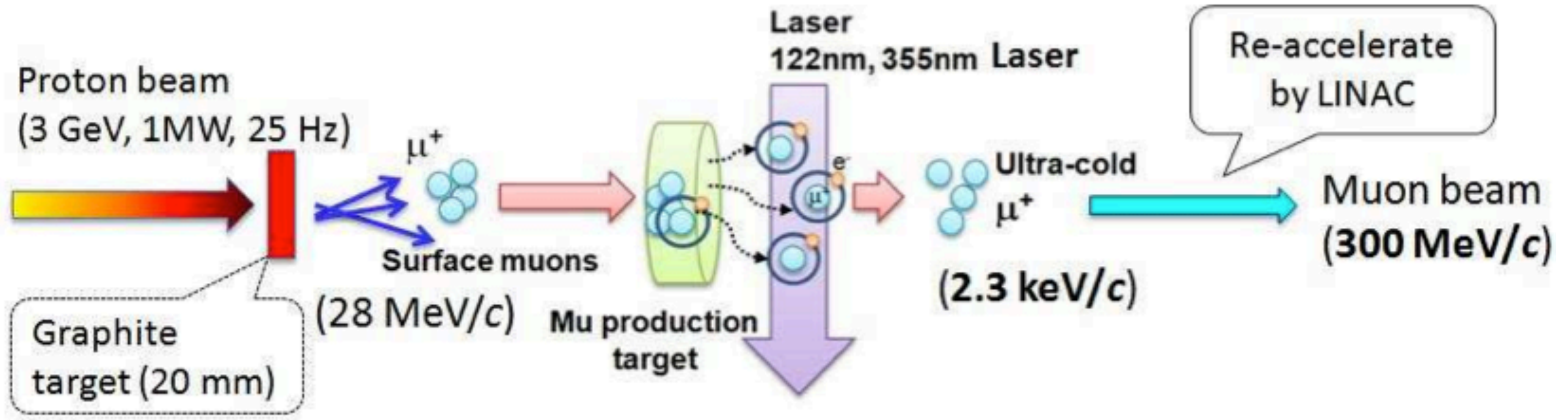
Getting a sufficient rate of ultra cold muons (require 10^6 /sec and 10^{12} e^+)

Avoiding pile-up issues in detector with the high rate

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

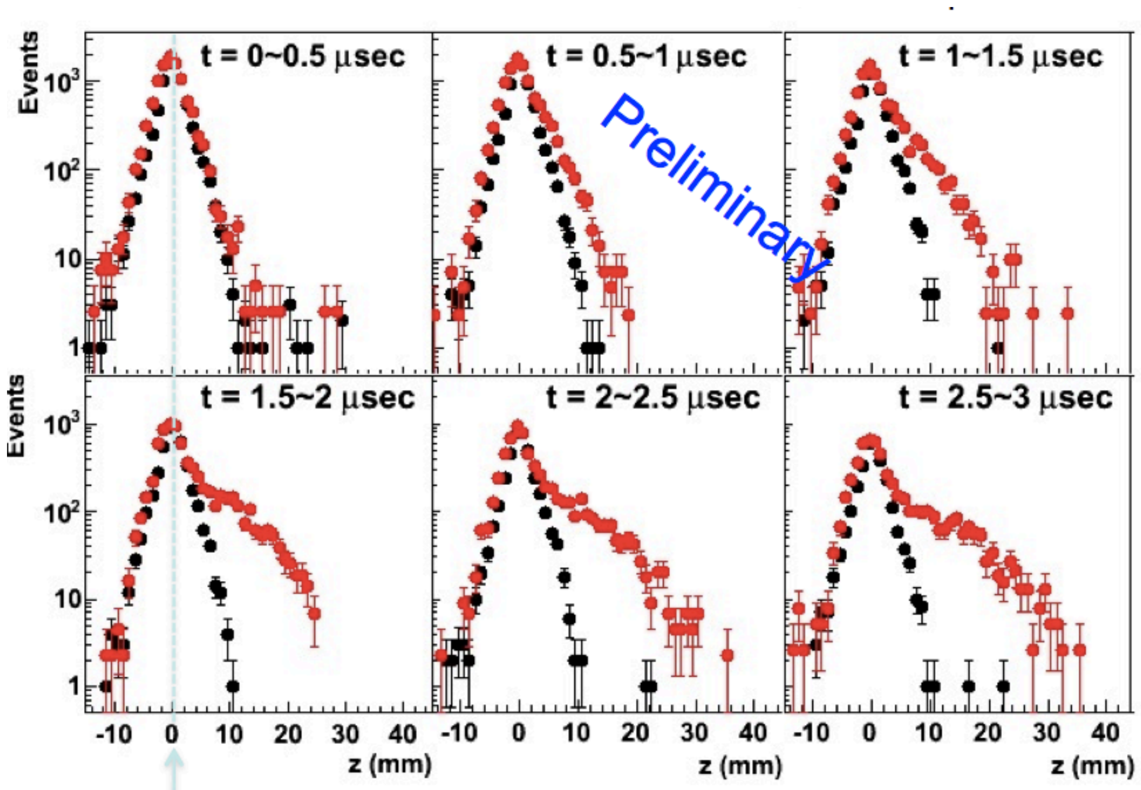
Requires advances in "muonium" production

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



JPARC g-2

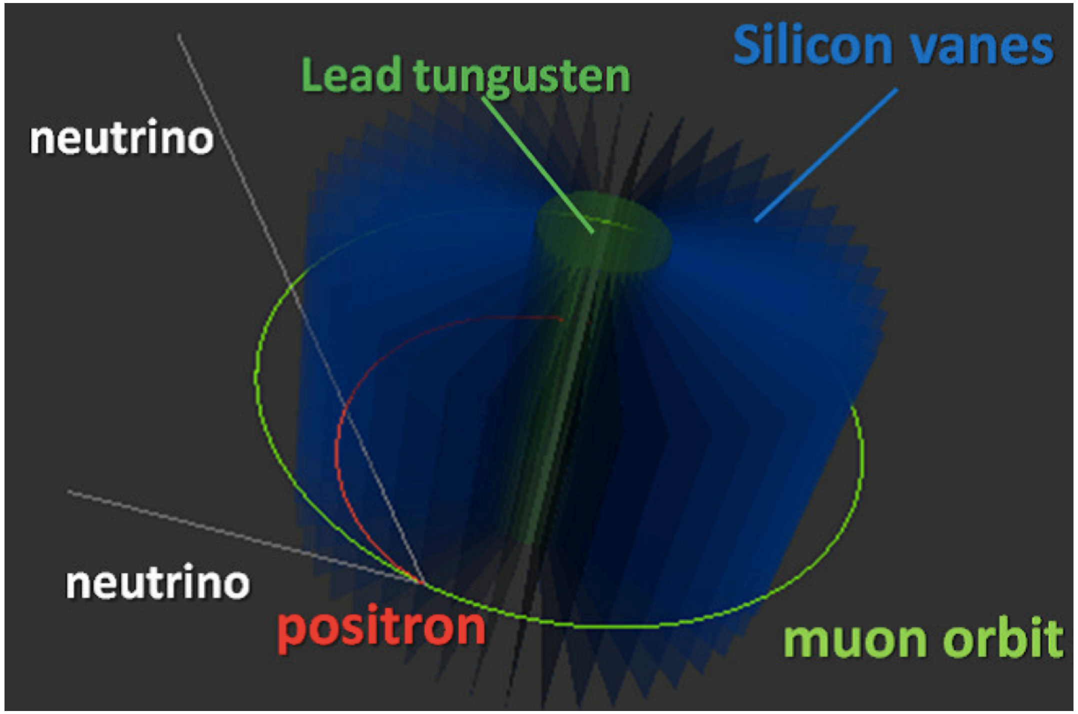
R & D continuing on cold muon yield and ionisation efficiency

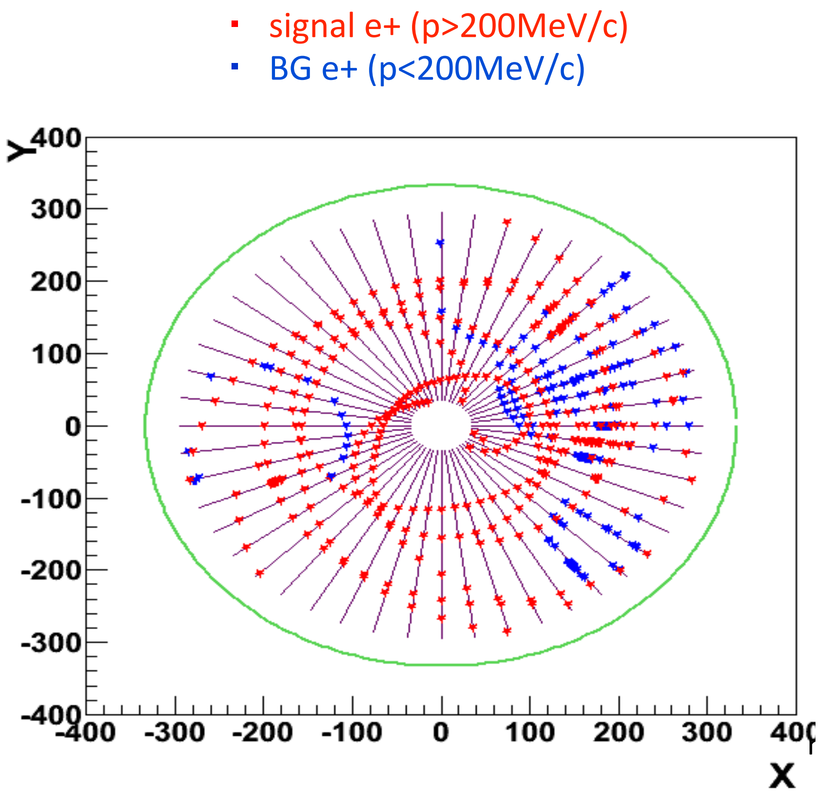


Potential to achieve same precision as FNAL **<u>with very different systematics</u>** but likely on a timescale after the FNAL experiment.

JPARC g-2 Silicon Tracker

High granularity Silicon vane tracker (exploiting (Super)KEKB electronics))
Event rate : 1 MHz
Need to reconstruct e+ track from lots of hits, particularly for earliest events.





Conclusion

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.

Muon g-2 is a critical number in establishing (or not) integrity of BSM models in concert with the LHC : particular the non-coloured sector + BSM that flips chirality.

The new FNAL experiment will take data in 2016 and measure g-2 to a precision of 0.14 ppm. The most precise accelerator-based measurement in particle physics.

If present anomaly persists it could establish BSM physics at 5-9 σ

BACKUP

Precession Systematics

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

B field Systematics

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

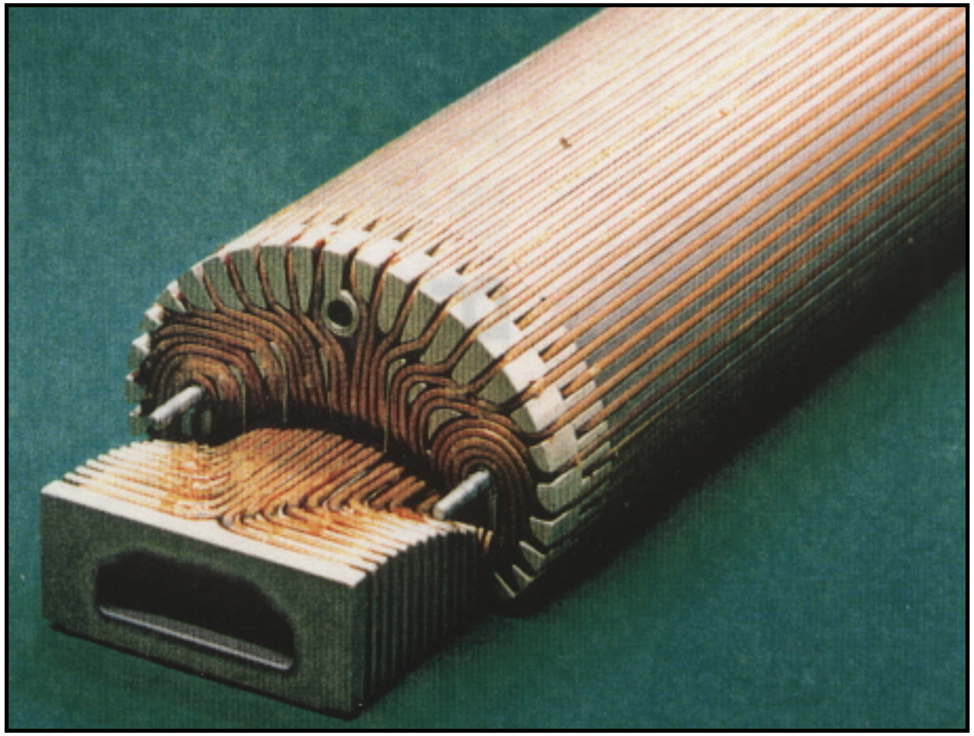
initial

↓

0.07 ppm

All about systematics : injection

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



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.**"*

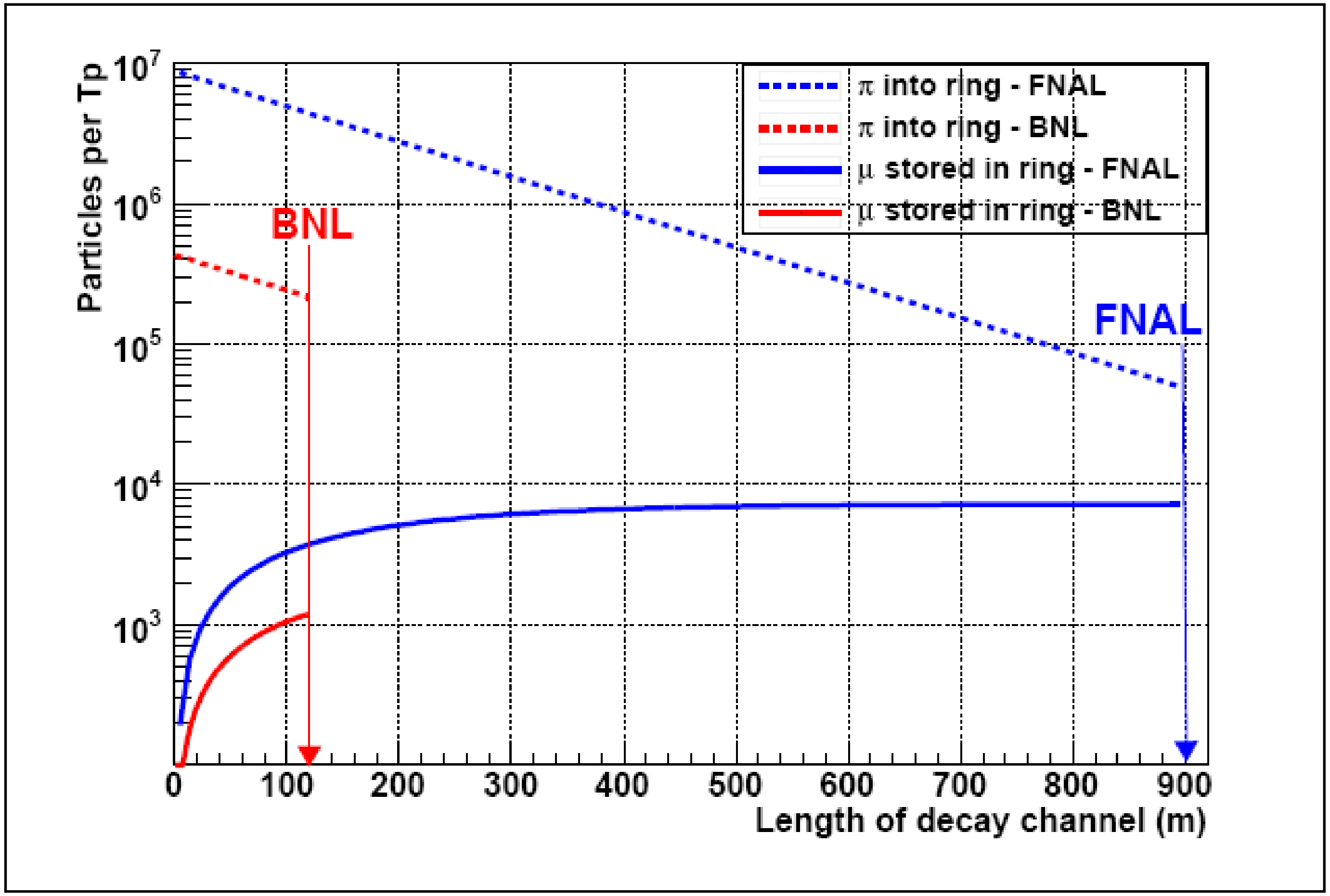
J-PARC Muon g-2

	BNL-E821	Fermilab	This Experiment
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		none/very weak
# of detected e^+	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected e^-	3.6×10^9	–	–
Statistical precision	0.46 ppm	0.1 ppm	0.1 ppm

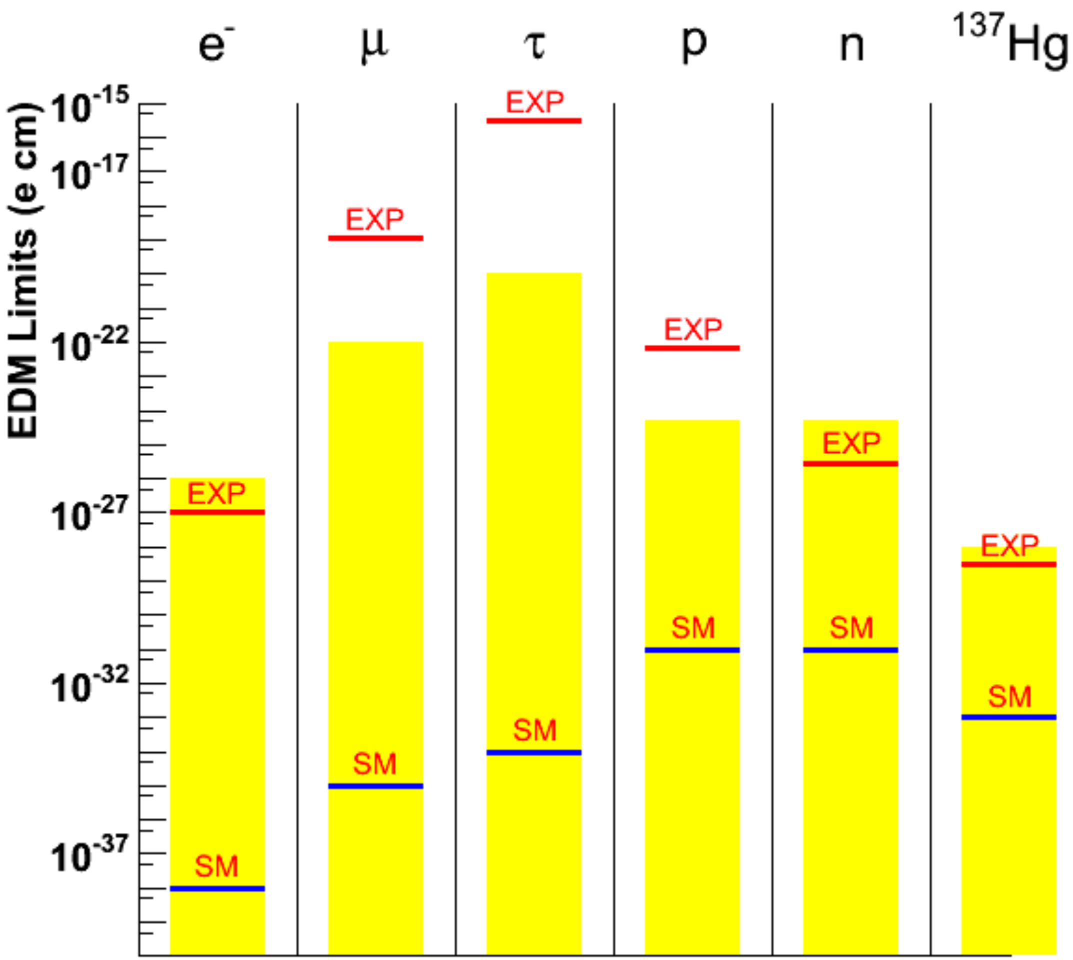
Clearly Pros and Cons of two approaches:

Cold muons : no pion contamination, no coherent betatron oscillations
BUT : μ^+ only and as yet unproven method
"Hot" muons : proven technology, utilising existing accelerator etc

FNAL vs BNL : more muons, fewer pions



EDMs



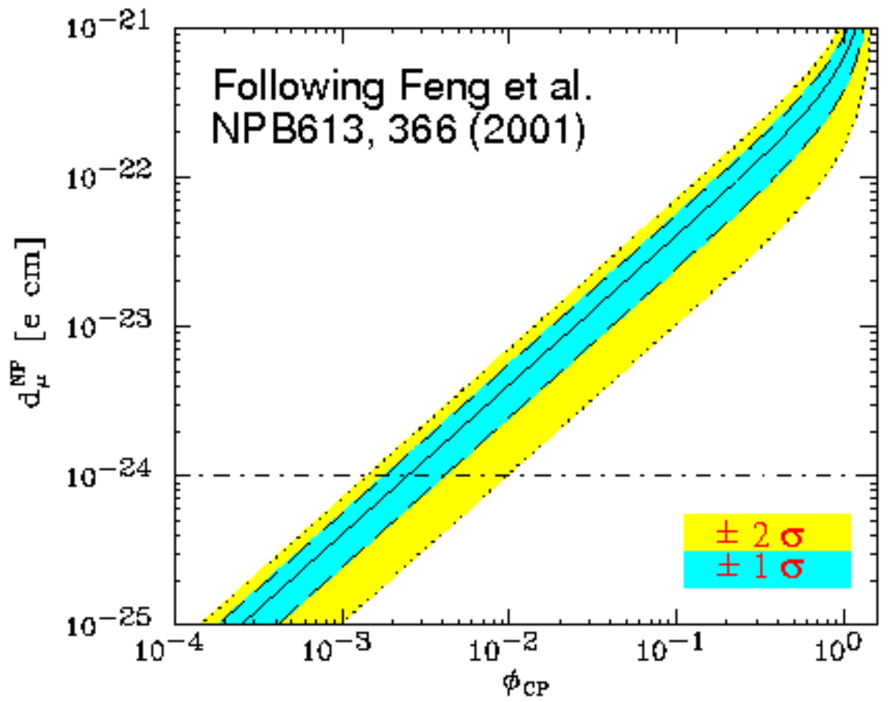
BSM

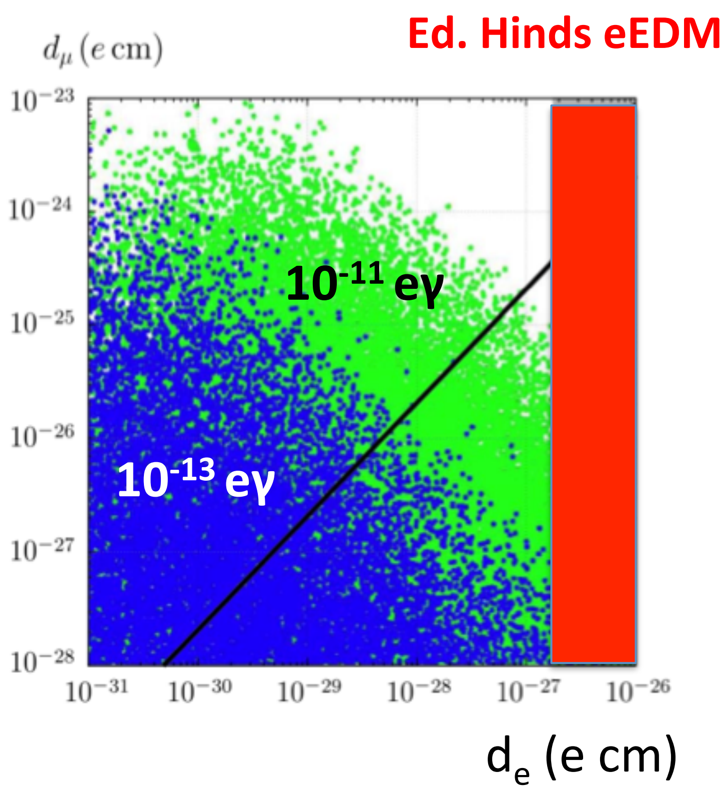
Neutron EDM is one nearest to reaching SM prediction while also being in the "BSM" region.

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 @ E989





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

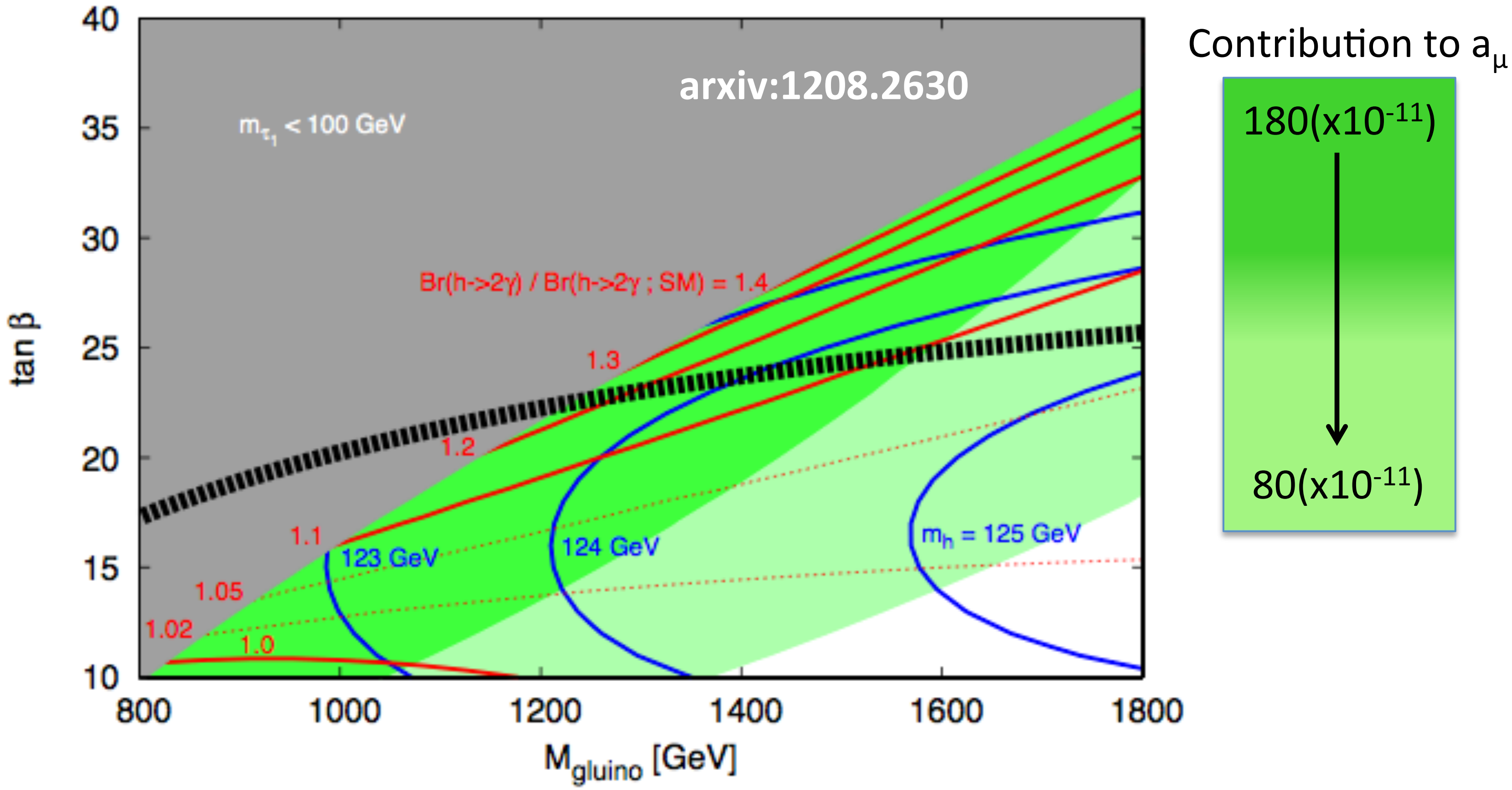
Present limit (BNL) is 1.8 x 10^{-19}.

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

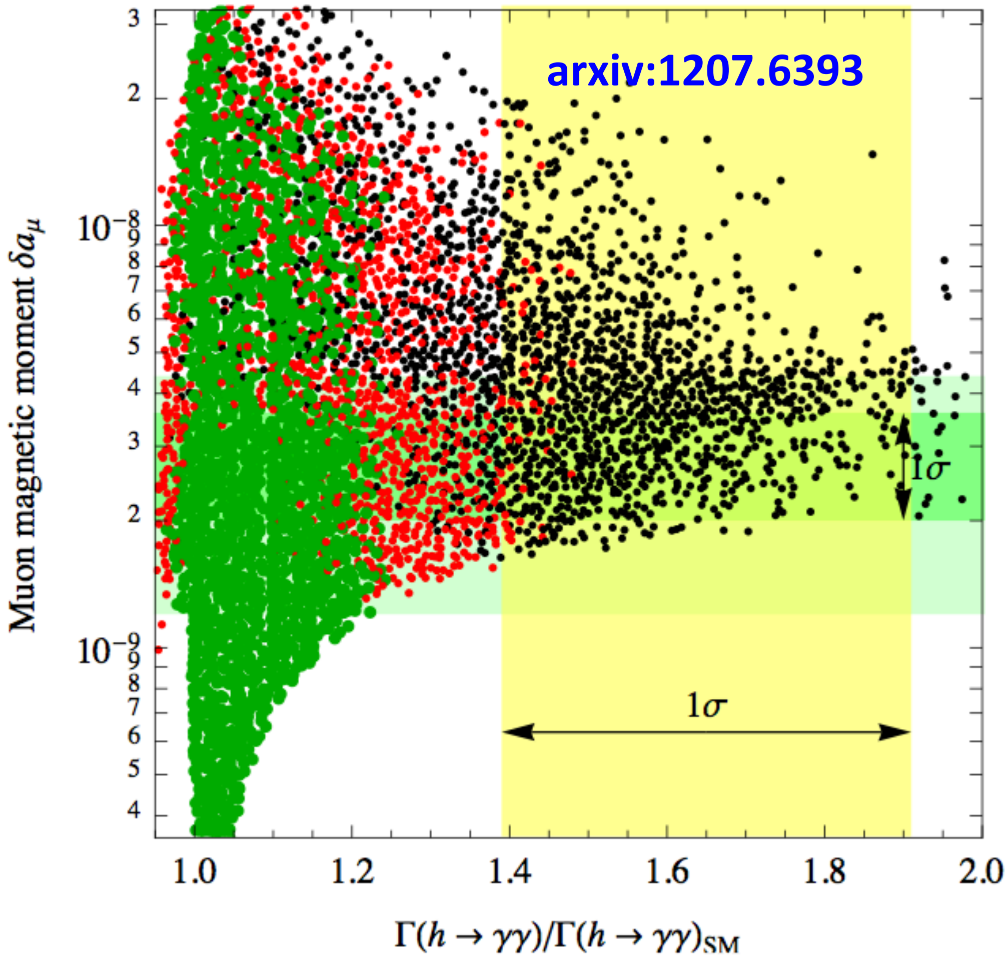
Muon unique since 2nd generation & it's a single particle measurement unlike e/n EDM.

Synergy with LHC

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



Synergy with LHC



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

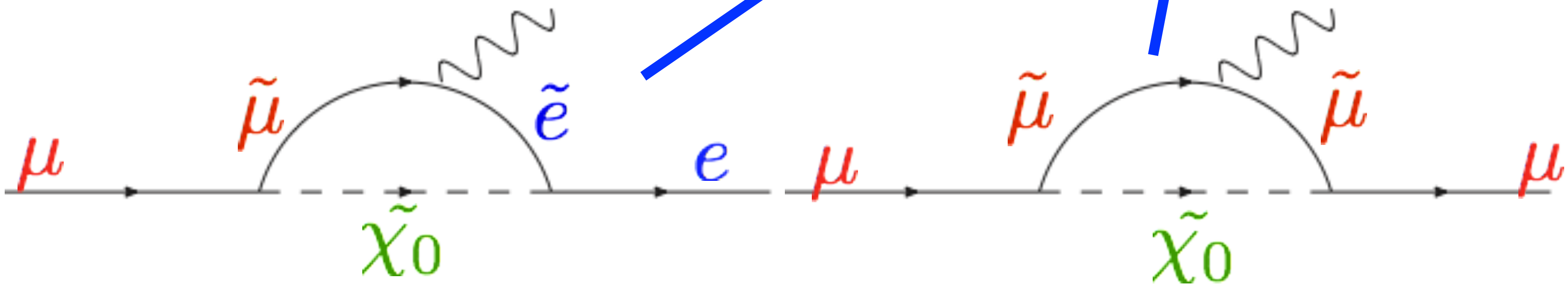
Beyond Vanilla BSM models tend to be characterised by large flavour symmetry and small SUSY breaking

Expect **SMALL** deviations from SM:

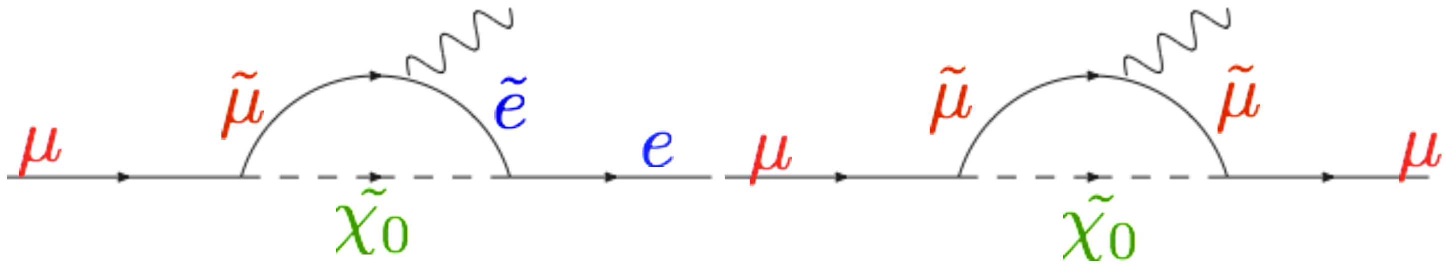
- precision measurements : (g-2)
- processes that are zero in SM : **EDMs, cLFV**.

In most BSM theories these three measurements are connected

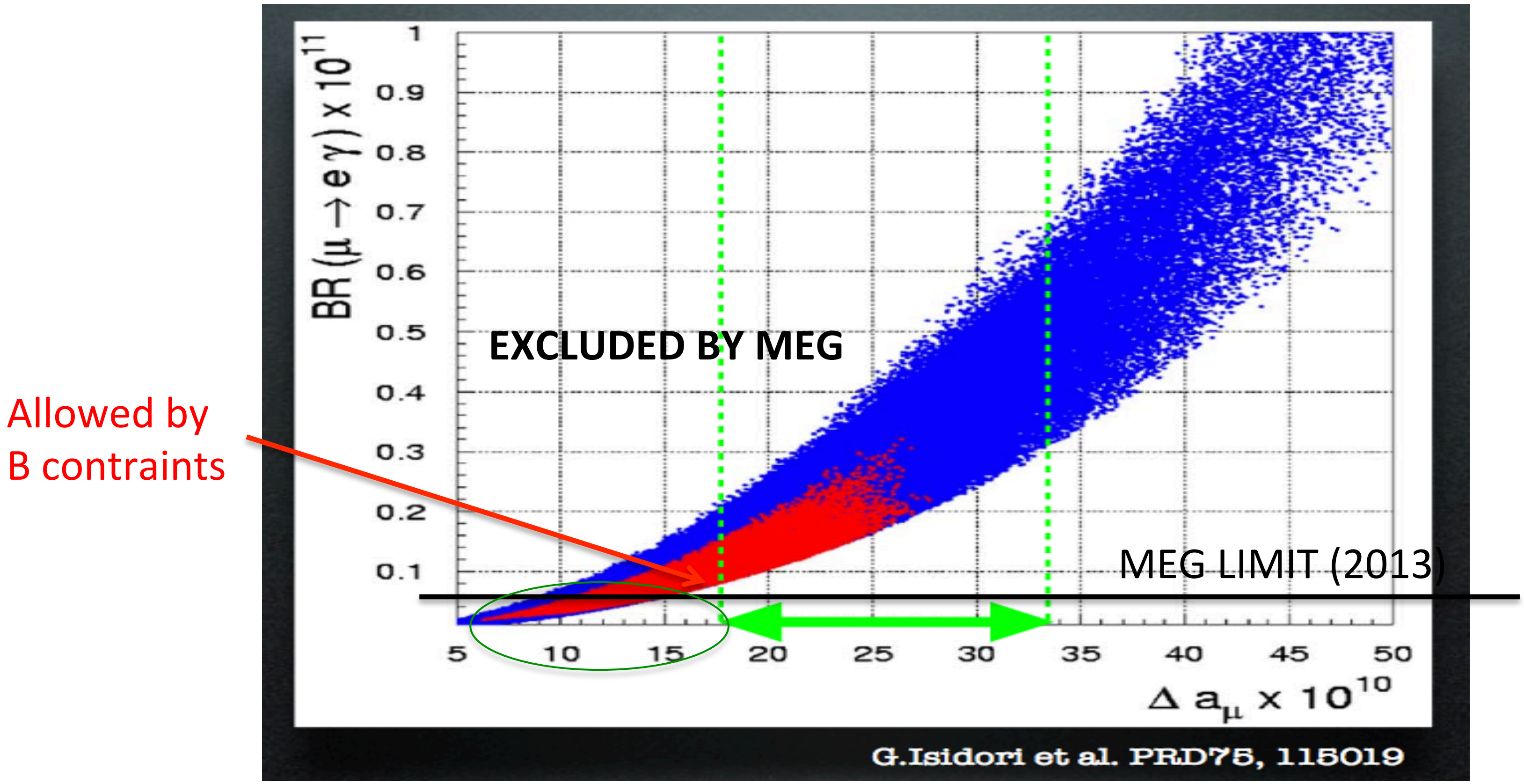
$$\begin{pmatrix} \Delta m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & \Delta m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}}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



cLFV and g-2



μ
$\tilde{\mu}$
$\tilde{e}$
e
$\tilde{\chi}_0$
μ
$\tilde{\mu}$
$\tilde{\mu}$
μ
$\tilde{\chi}_0$



Allowed by
B contraints
EXCLUDED BY MEG
MEG LIMIT (2013)
BR ($\mu \rightarrow e\gamma$) x 10^{11}
$\Delta a_\mu \times 10^{10}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
5
10
15
20
25
30
35
40
45
50
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