The Fermilab Muon g-2 Experiment

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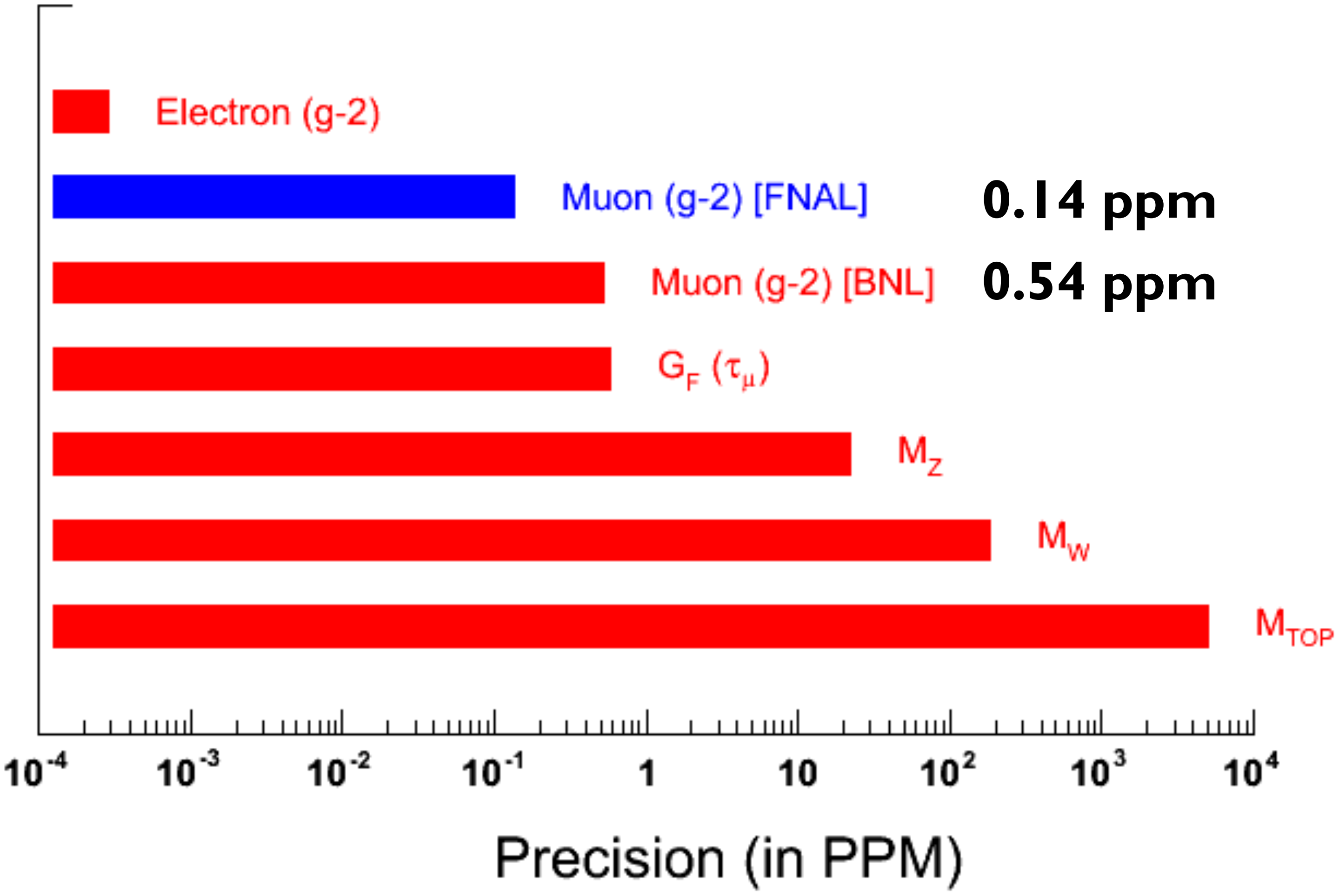
UCL

Aim of Experiment

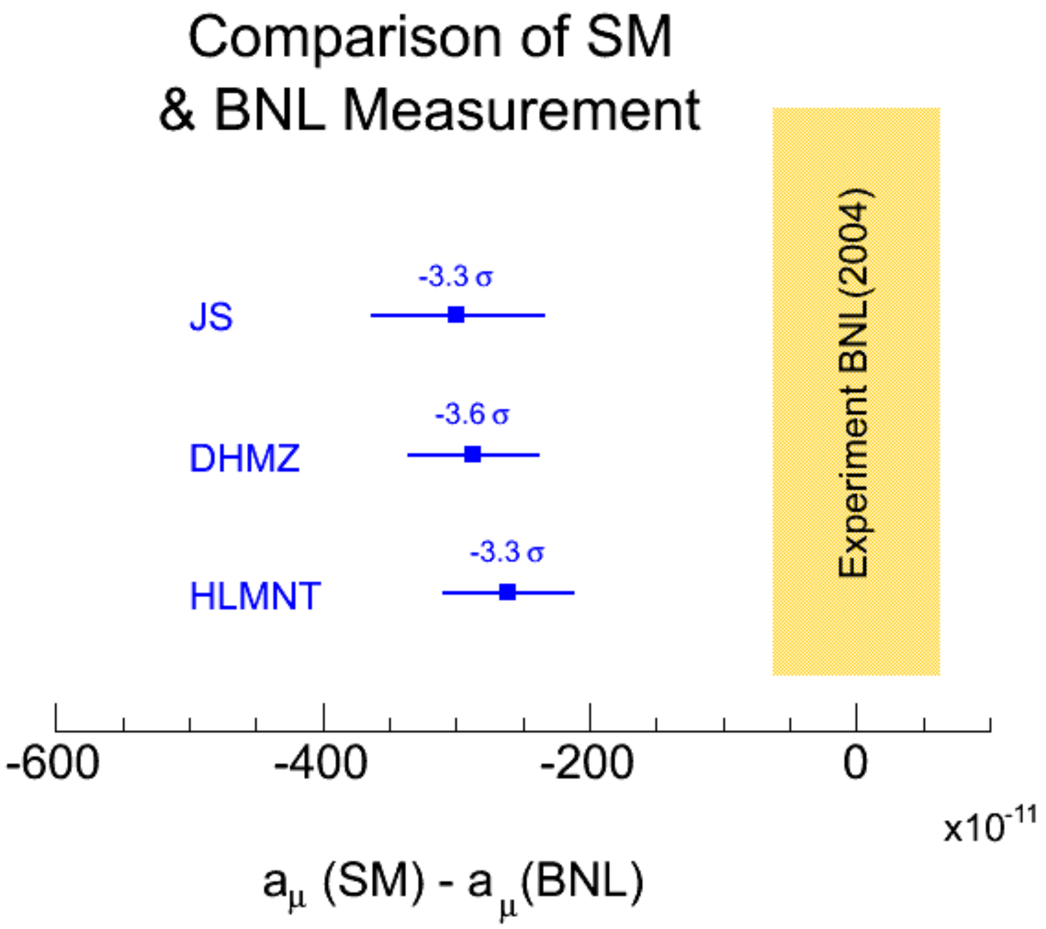
Make a 0.14 ppm measurement



0.14 ppm

0.54 ppm

Motivation

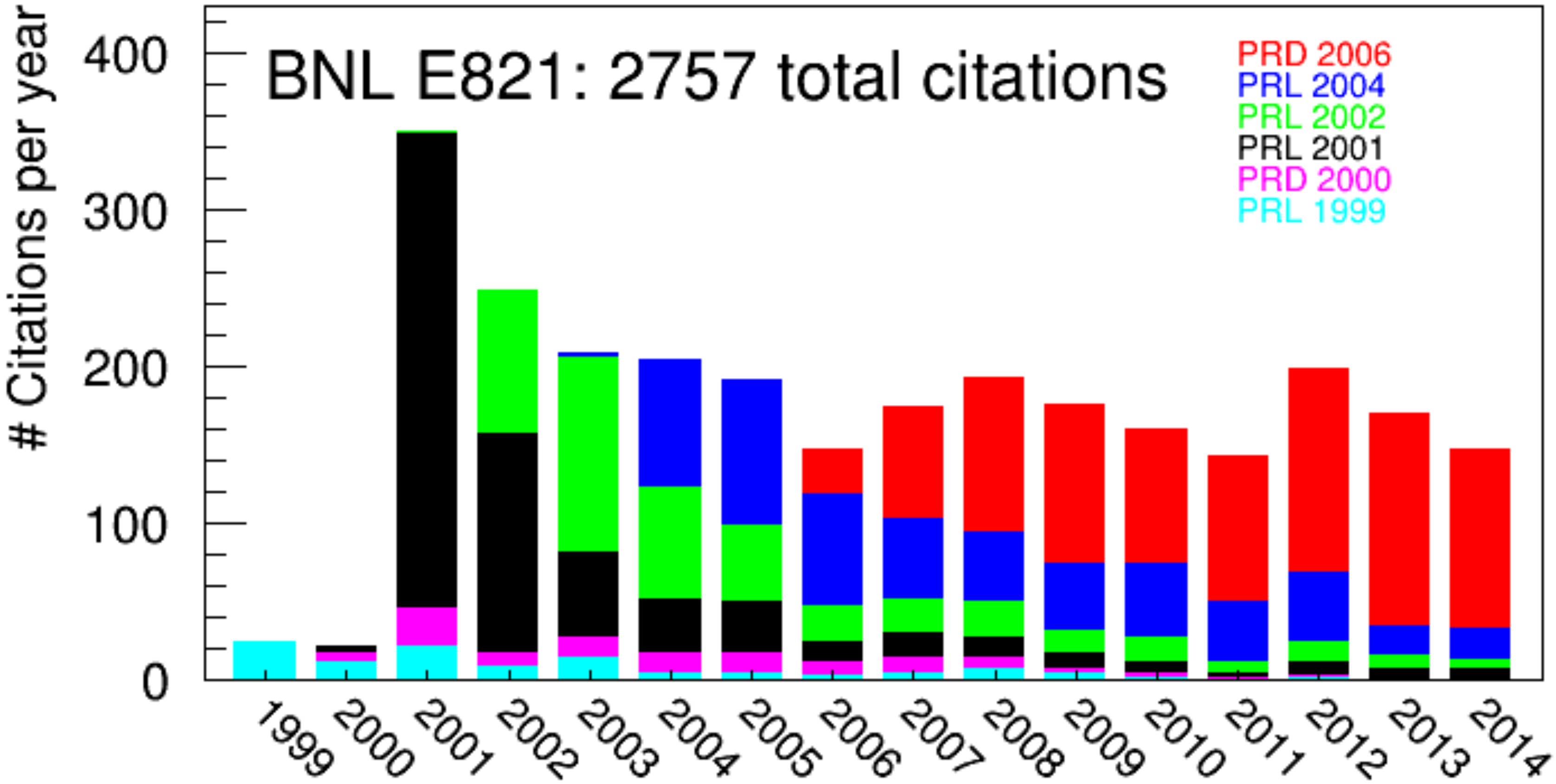


Present measurement is at odds with SM at 3.5σ level.

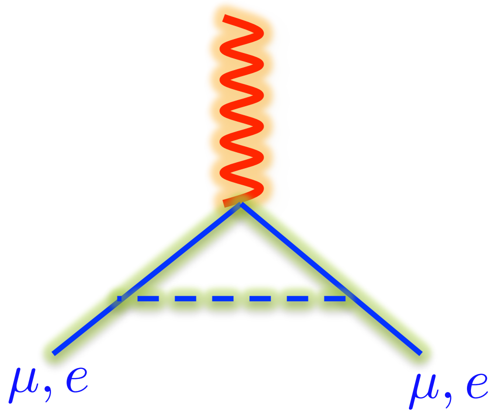
A 0.14 ppm measurement moves this to more than 5σ

Interest in this result

3rd most cited paper in experimental particle physics



Sensitivity to new physics



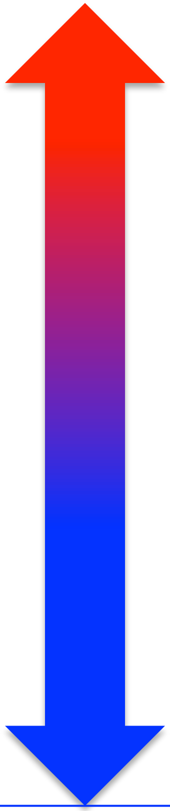
New physics as: $$\left(\frac{m_\ell}{M_{\rm NEW}}\right)^2$$

Muon sensitivity to BSM in 20 MeV (e.g. dark photons) to TeV region

Electron presently limited to BSM contributions from m < 100 MeV

BSM Landscape

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



Large +ve anomaly wrt SM

Extended technicolor (fermion masses)

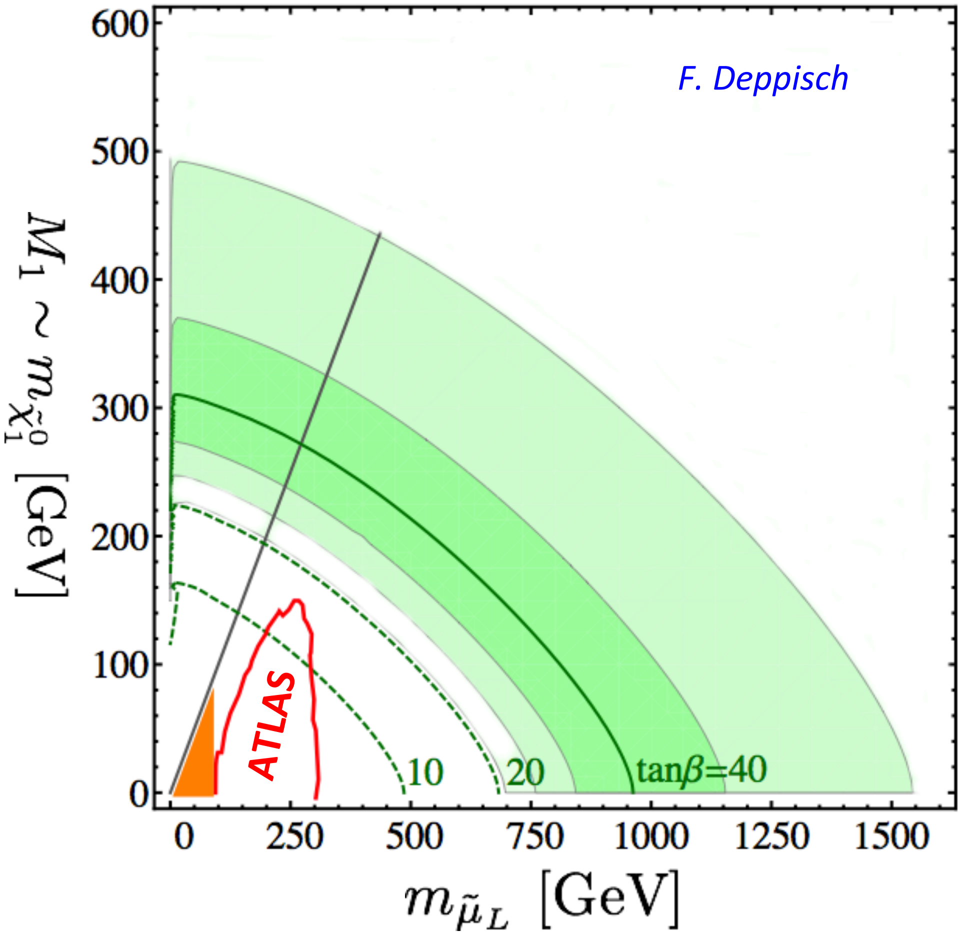
SUSY (natural, gauge-mediated, compressed), RS ED

Z', W', Little Higgs, Universal ED

Value consistent with SM

Complements LHC

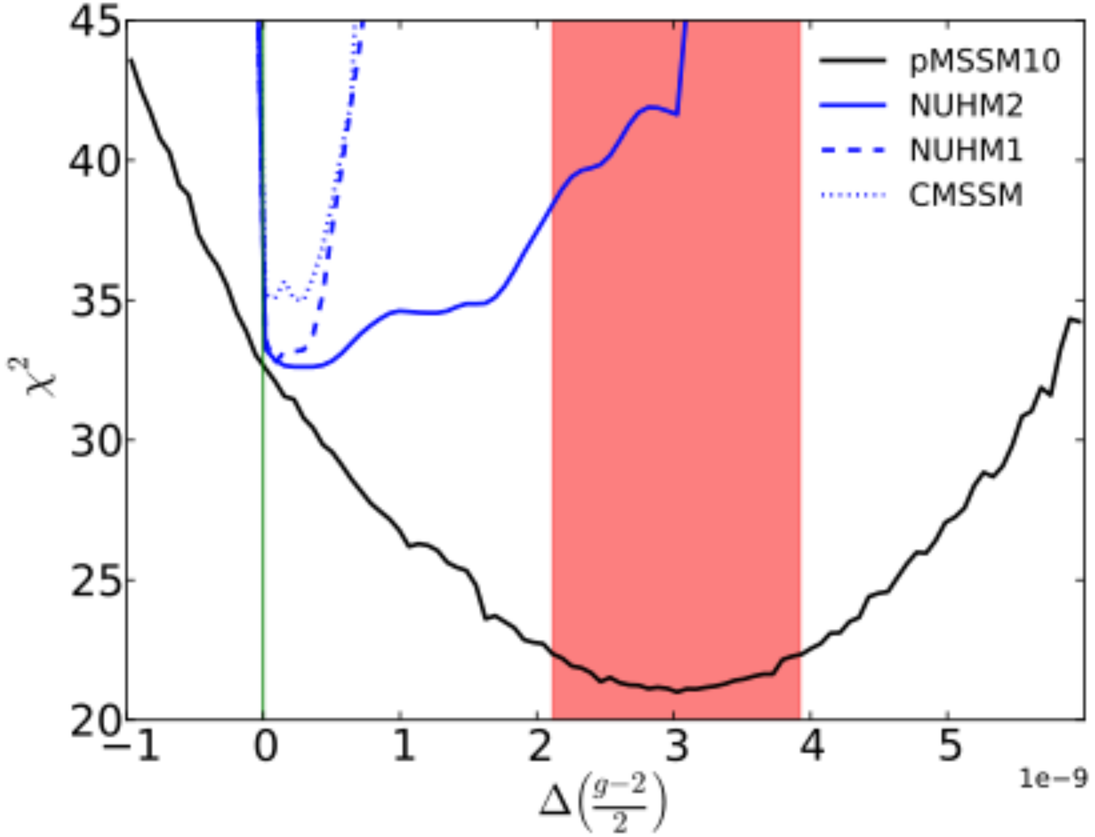
$$M_2 = \mu = 2M_1,\ m_{\tilde{\mu}_R} \gg m_{\tilde{\mu}_L}$$



BNL anomaly (if real) would be expected to produce a direct observable in 14 TeV LHC data in most TeV-scale models.

In this case the g-2 measurement can resolve degeneracy in model parameters & improve their determination e.g. tanβ.

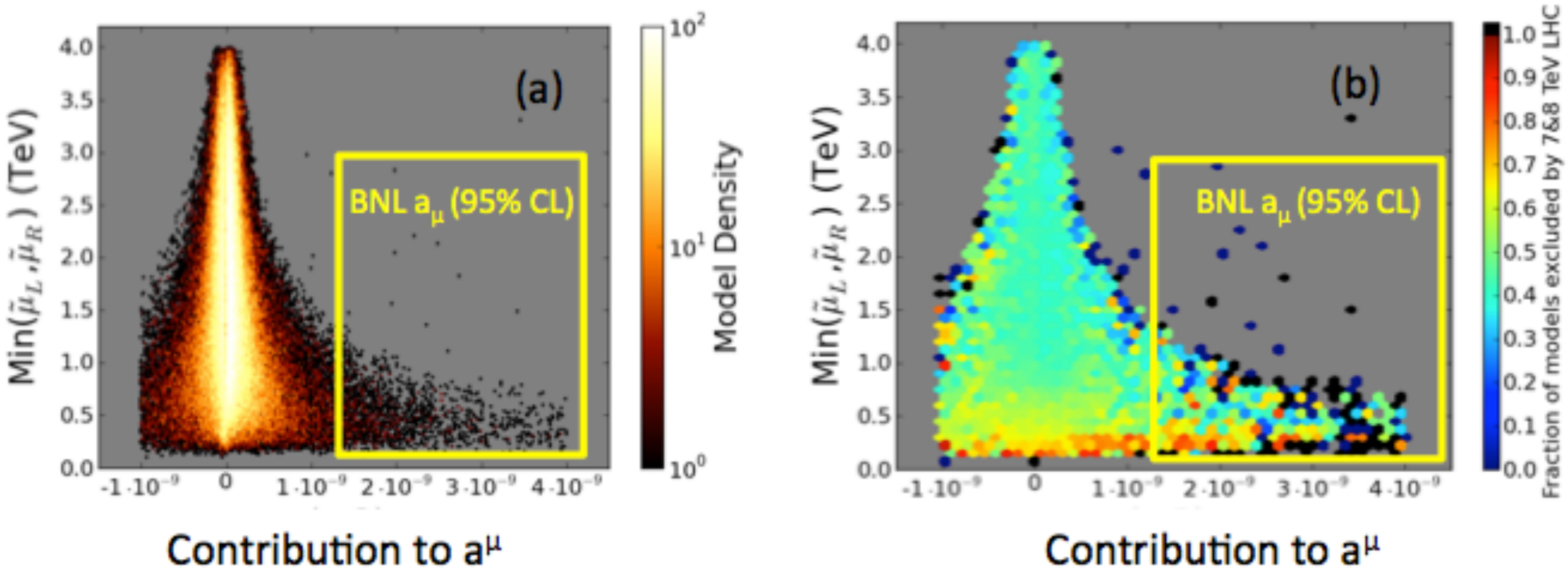
pMSSM Models



Mastercode collaboration arXiv:1410.6755

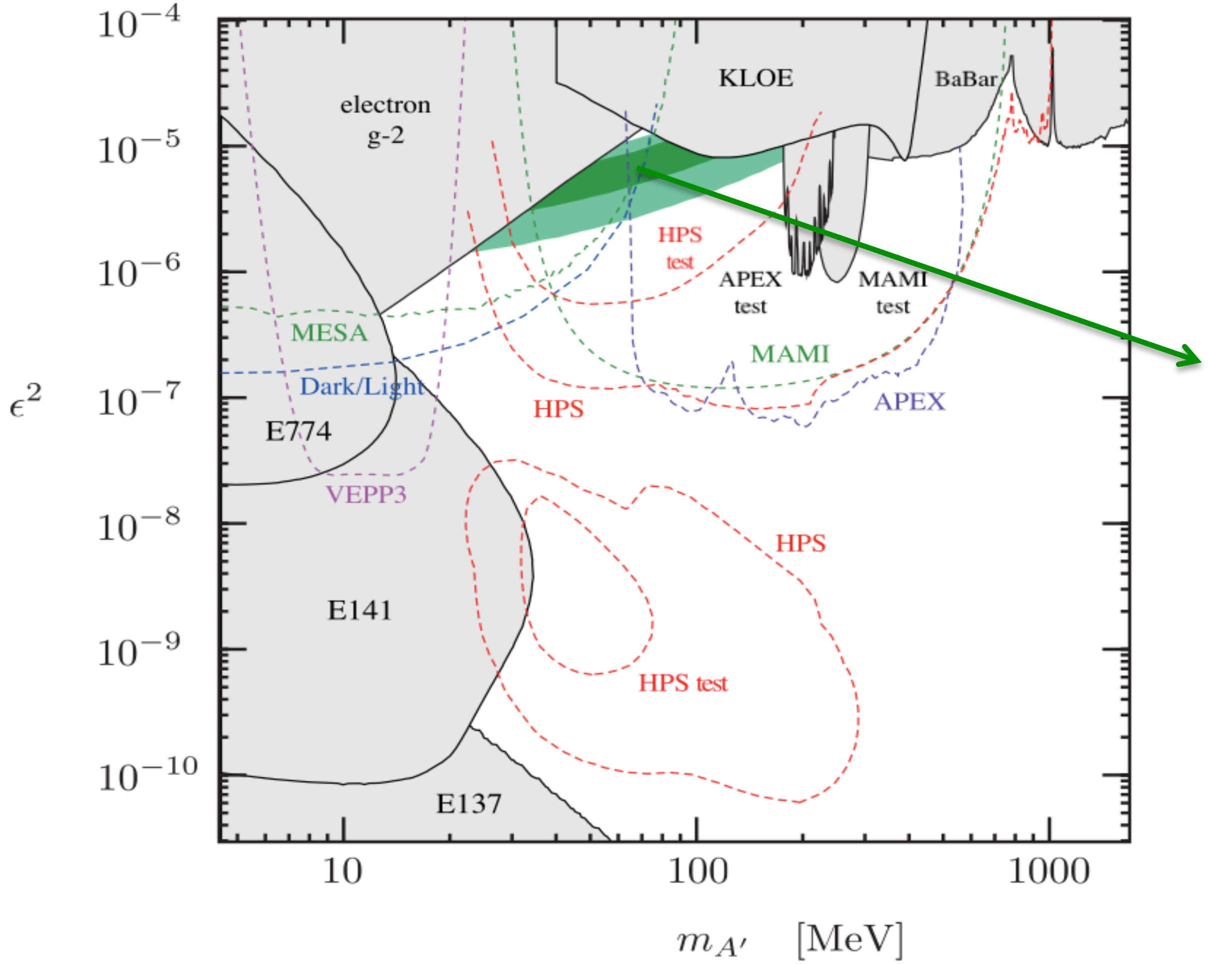
pMSSM Models

Sampling of pMSSM phase space



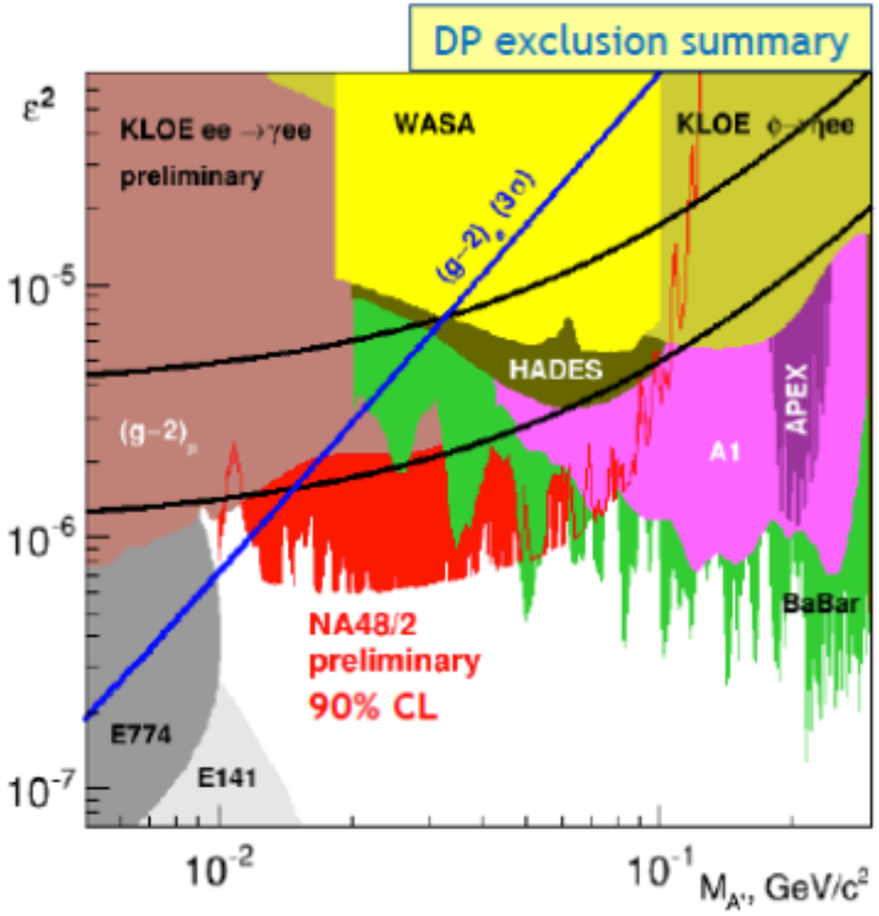
M. Cahill-Rowley et al., Eur. Phys. J72, 2156 (2012); Phys. Rev. D 88, 035002 (2013).

Dark Photons



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

New results from NA48



How to achieve 0.1 ppm

“Never measure anything but frequency”

I. Rabi

Spin Equation

Measure rate at which muon spin turns relative to momentum vector

$$\omega_a = \omega_s - \omega_c$$

This is determined by (g-2) and the EM fields and energy of the muon

$$a_\mu = \frac{1}{2}(g-2)$$

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

FNAL/BNL approach : effect of focussing E-field cancelled by using "magic" 3.09 GeV momenta muons.

J-PARC approach : 300 MeV beam with v. low transverse momenta requiring no E-field to focus.

Spin Equation

$$a_\mu = \boxed{\omega_a}\frac{m\boxed{B}}{e}$$

Two measured quantities : ω_a and B

B is measured using NMR in terms of the proton Larmor frequency : ω_p

$$a_\mu = \frac{\omega_a/\omega_p}{\lambda_+ - \omega_a/\omega_p} \; ; \; \lambda_+ = \mu_{\mu^+}/\mu_p$$

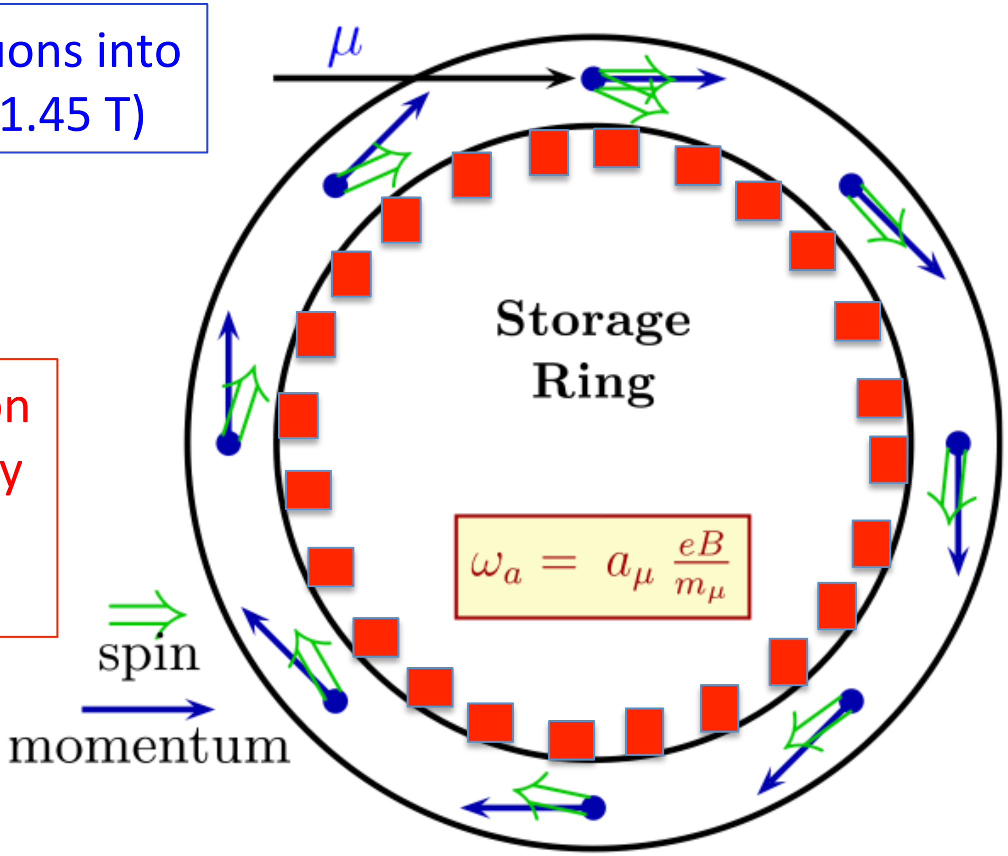
λ_+ measured from muonium hyperfine structure

Uncertainty in a_μ determined by precision of ω_p and ω_a measurements

FNAL g-2 Experimental Technique

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

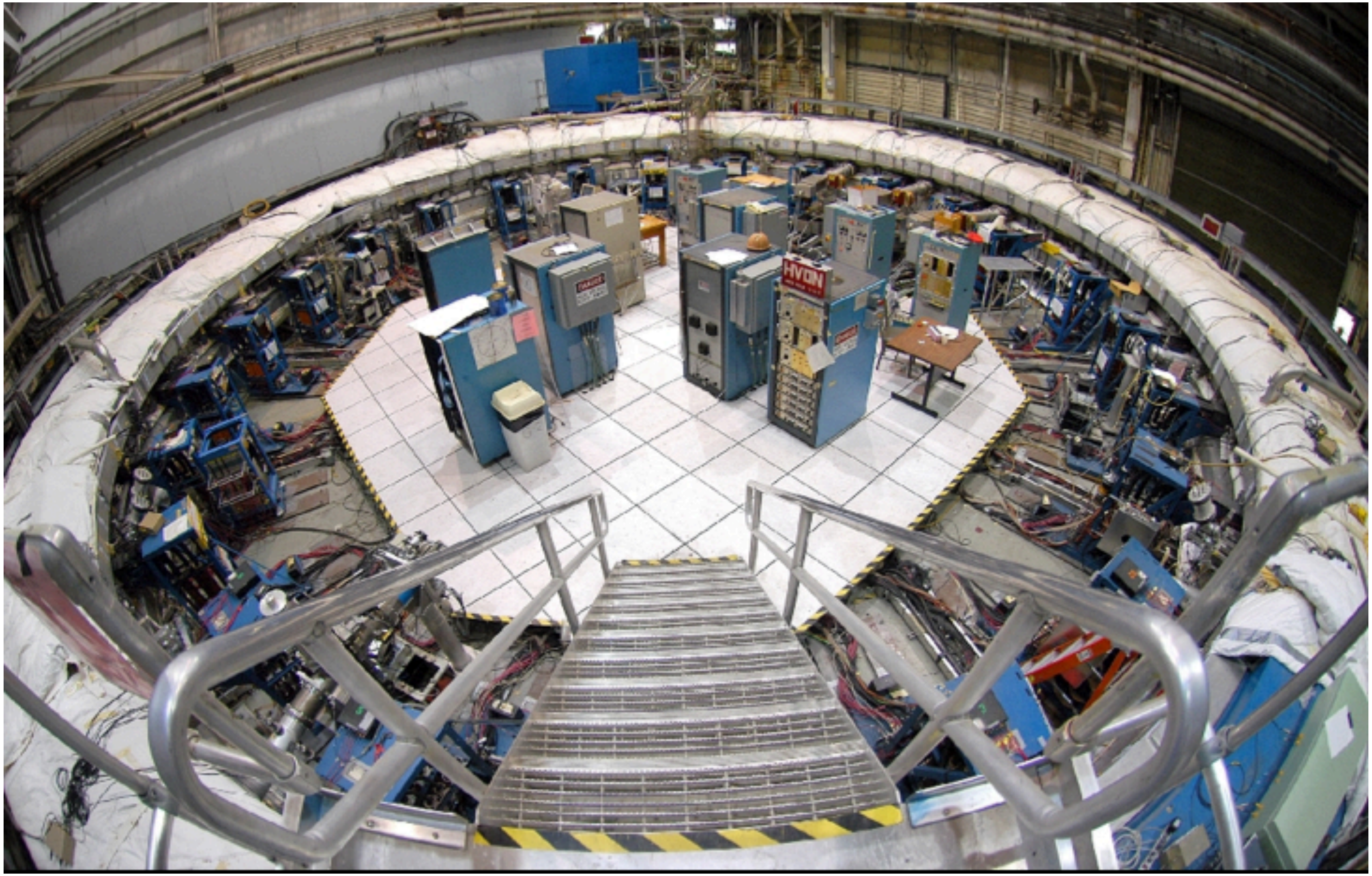
Exploit property that direction of e^+ from μ^+ decay is strongly correlated with μ^+ spin for highest energy e^+



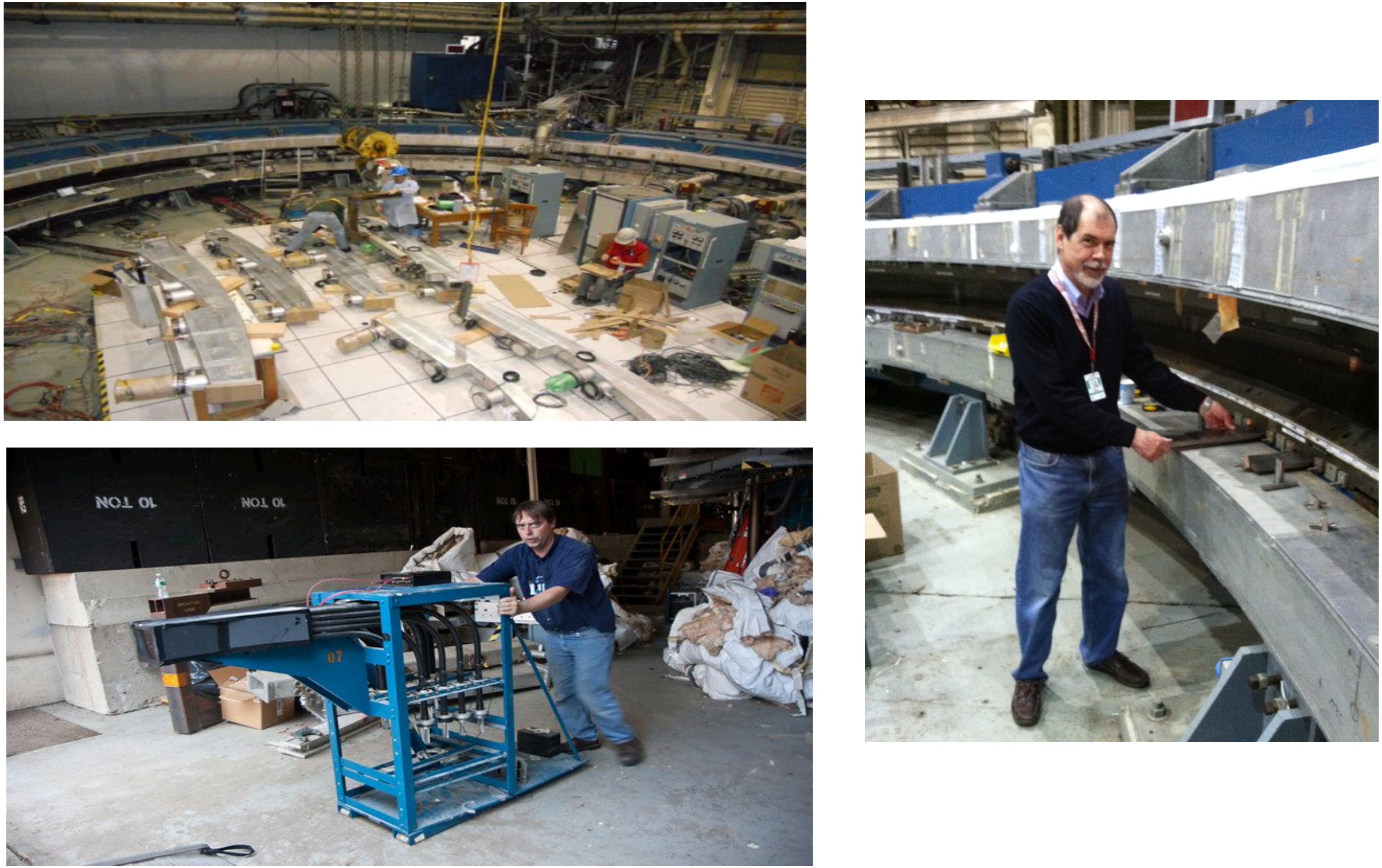
In g-2 experiment : cyclotron period is 149 ns

Spin precesses around momentum direction once every 30 turns (4.3 us)

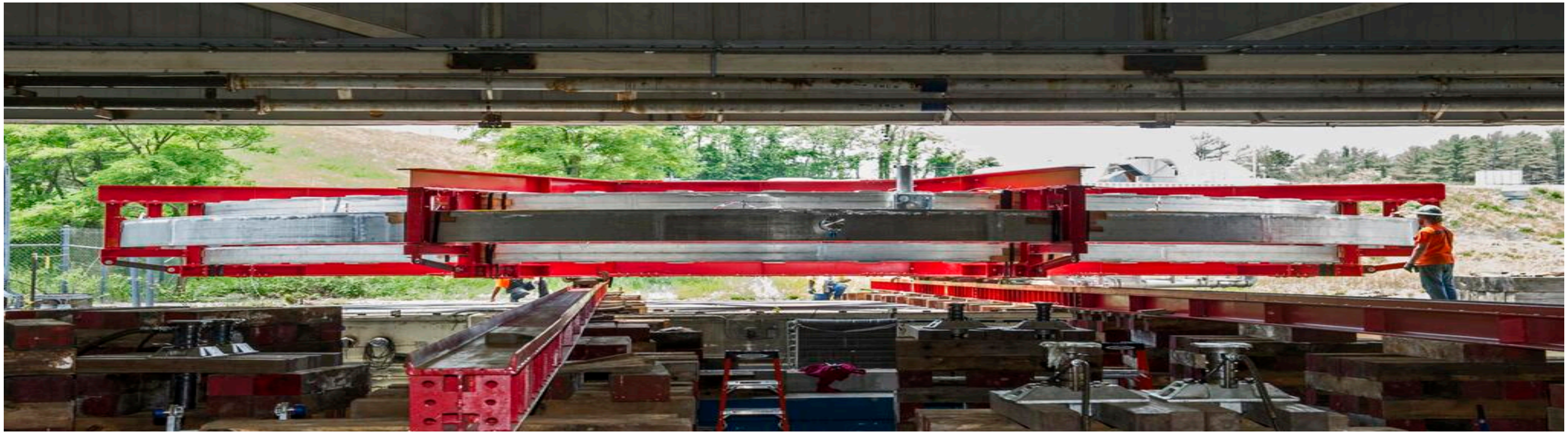
Storage ring at BNL

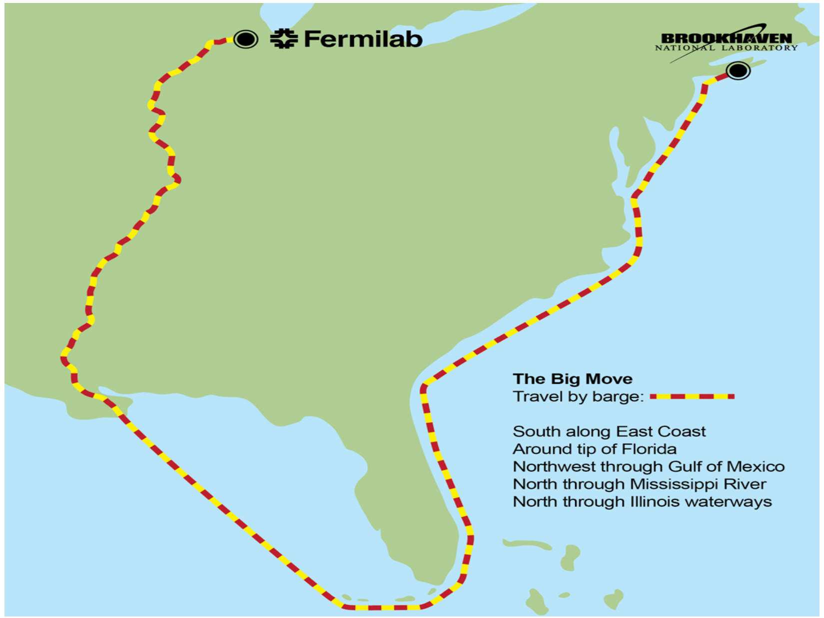


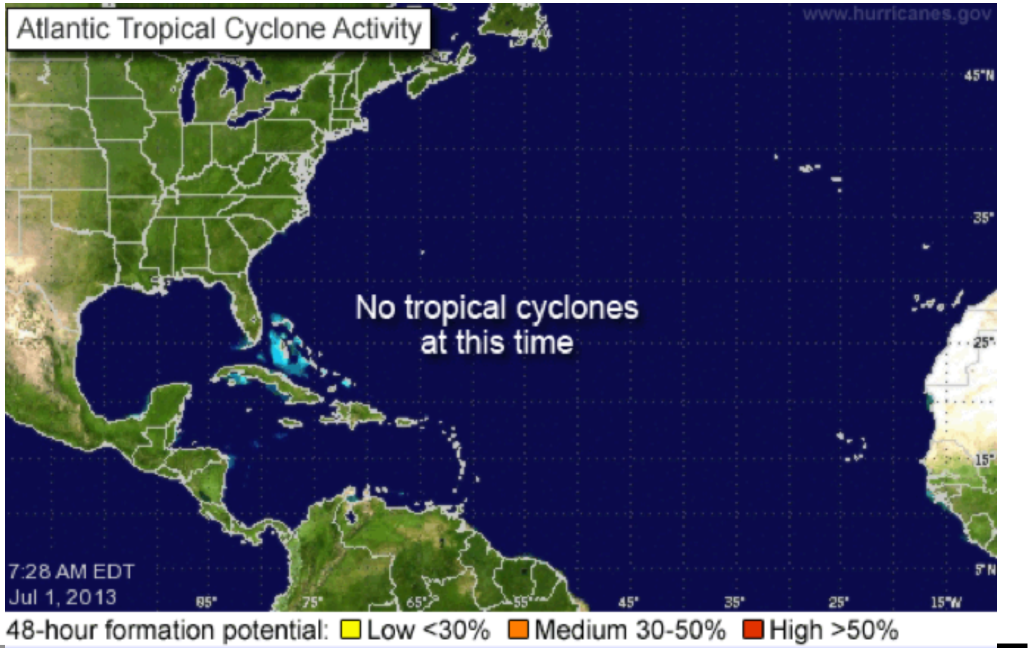
The Small Move



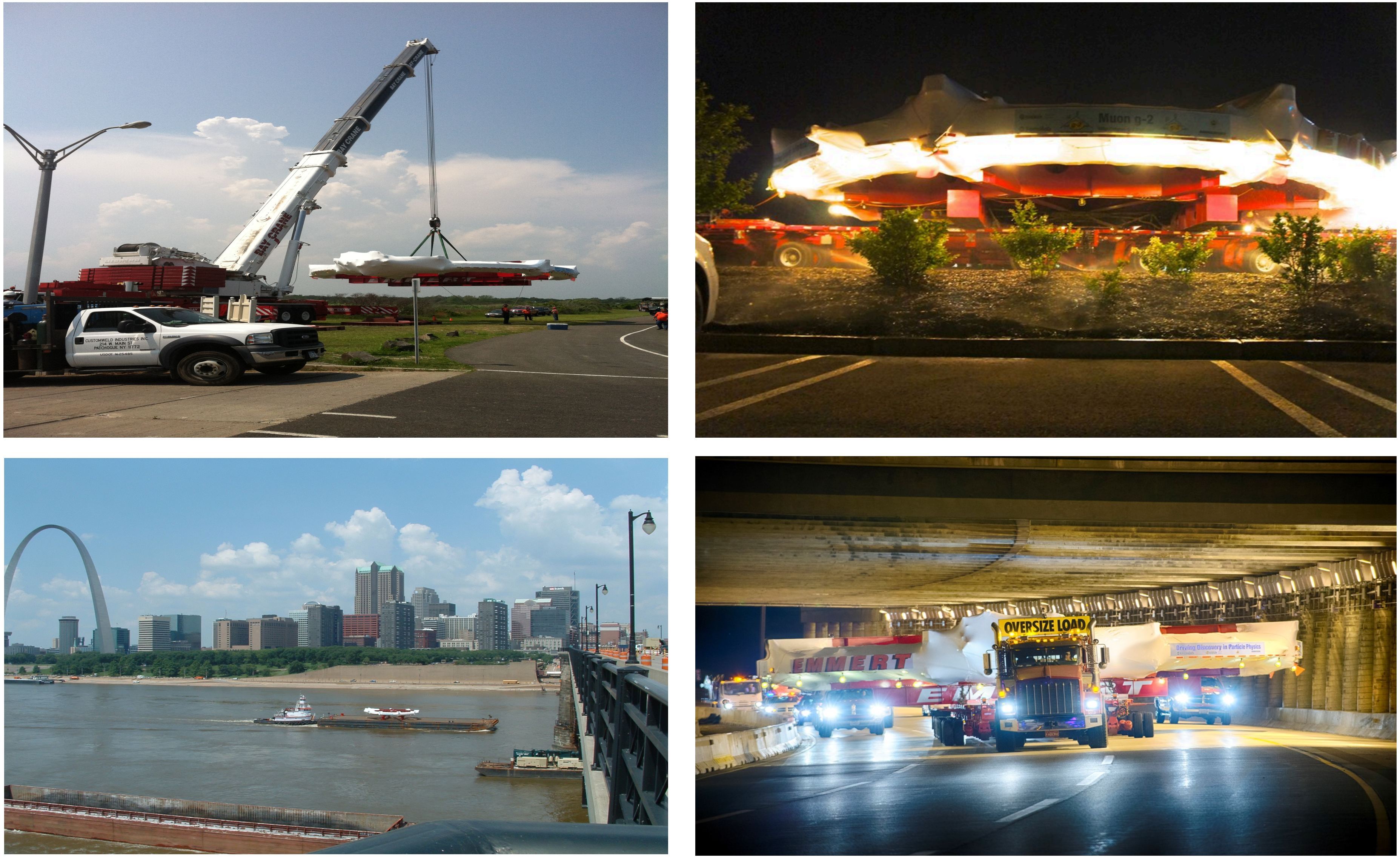
The Big Move




Fermilab
BROOKHAVEN NATIONAL LABORATORY
The Big Move
Travel by barge:
South along East Coast
Around tip of Florida
Northwest through Gulf of Mexico
North through Mississippi River
North through Illinois waterways


Atlantic Tropical Cyclone Activity
www.hurricanes.gov
No tropical cyclones at this time
7:28 AM EDT
Jul 1, 2013
45°N
35°
25°
15°
5°N
85°
75°
65°
55°
45°
35°
25°
15°W
48-hour formation potential: 🟨 Low <30% 🟧 Medium 30-50% 🟥 High >50%

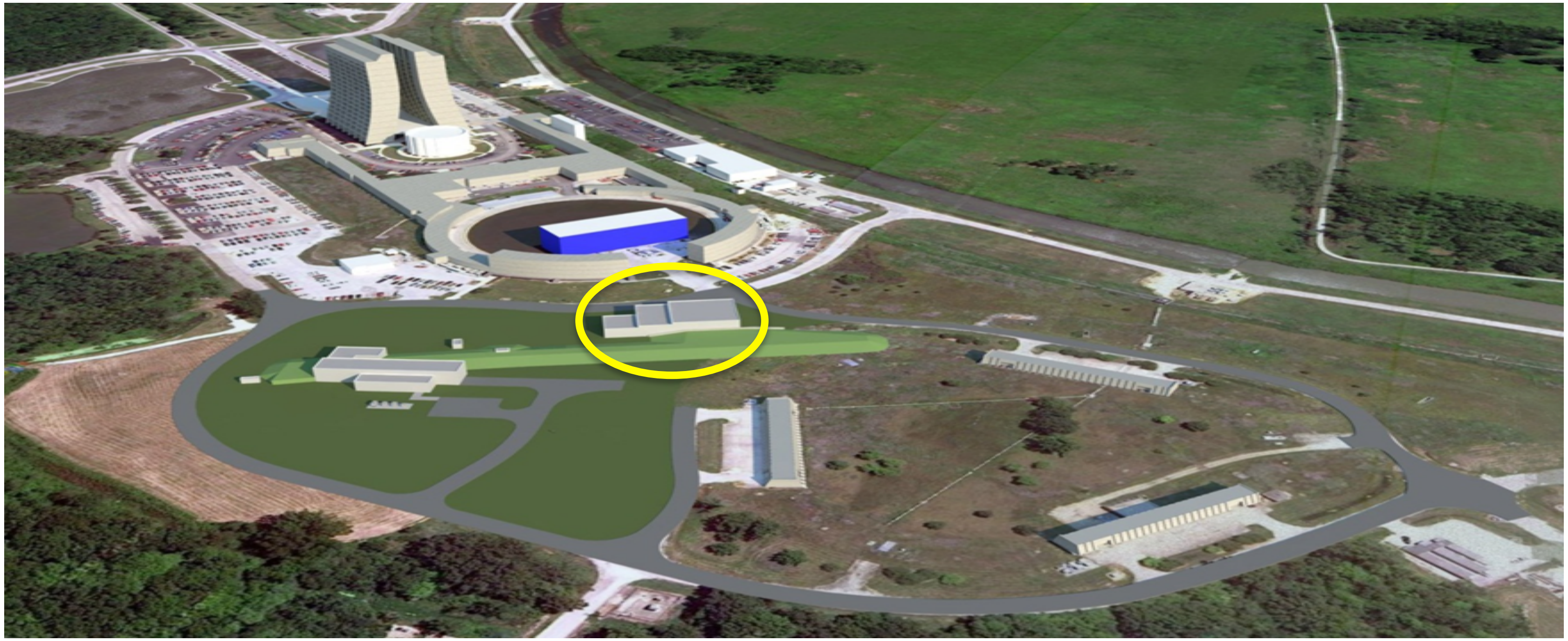
The Big Move


BAY CRANE
Muon g-2
OVERSIZE LOAD
EMMERT
Driving Discovery in Particle Physics

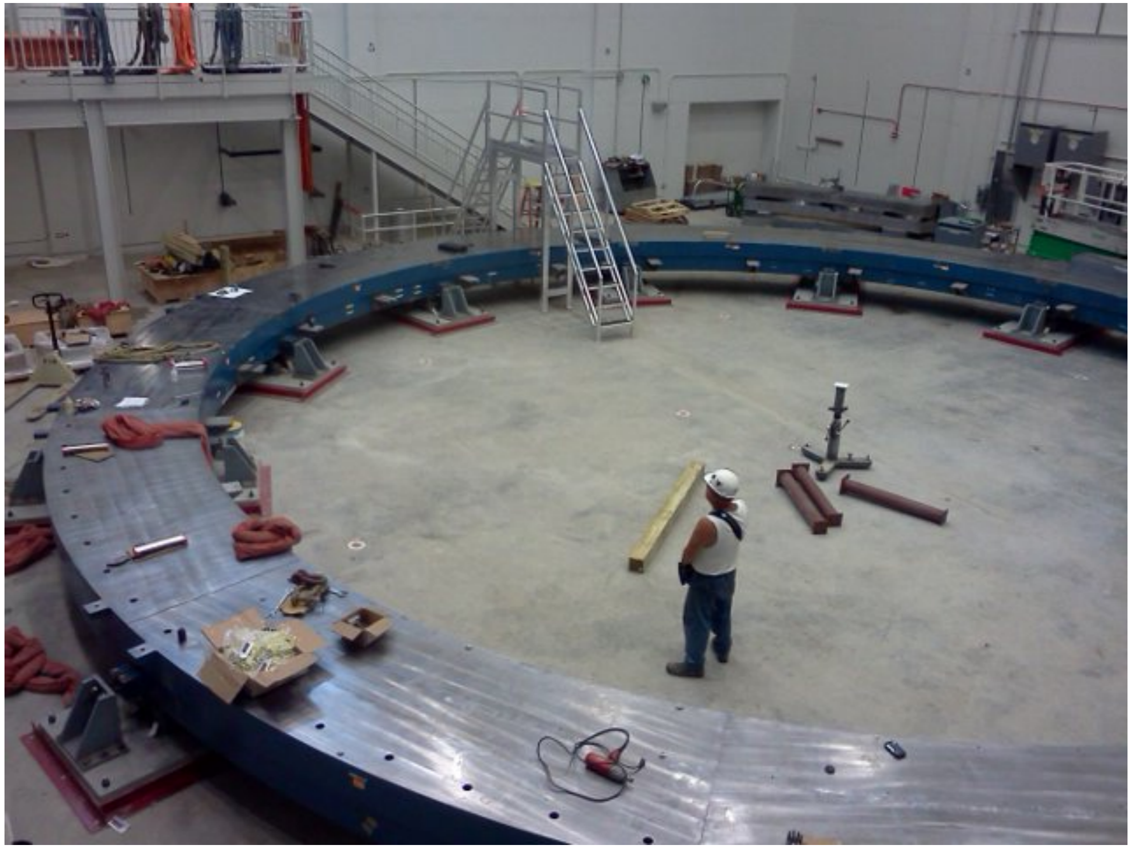
Arrival at FNAL

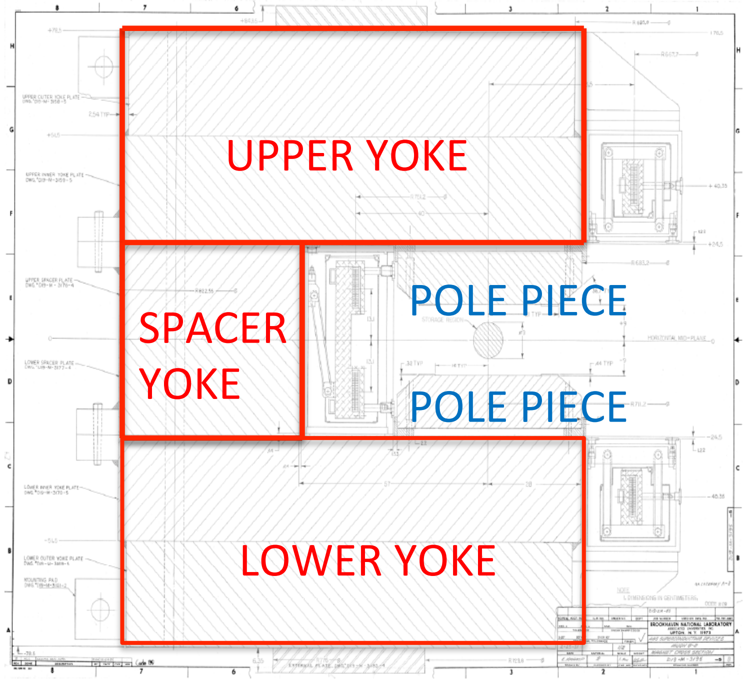
Long Live The Risk Register

Muon Campus at FNAL

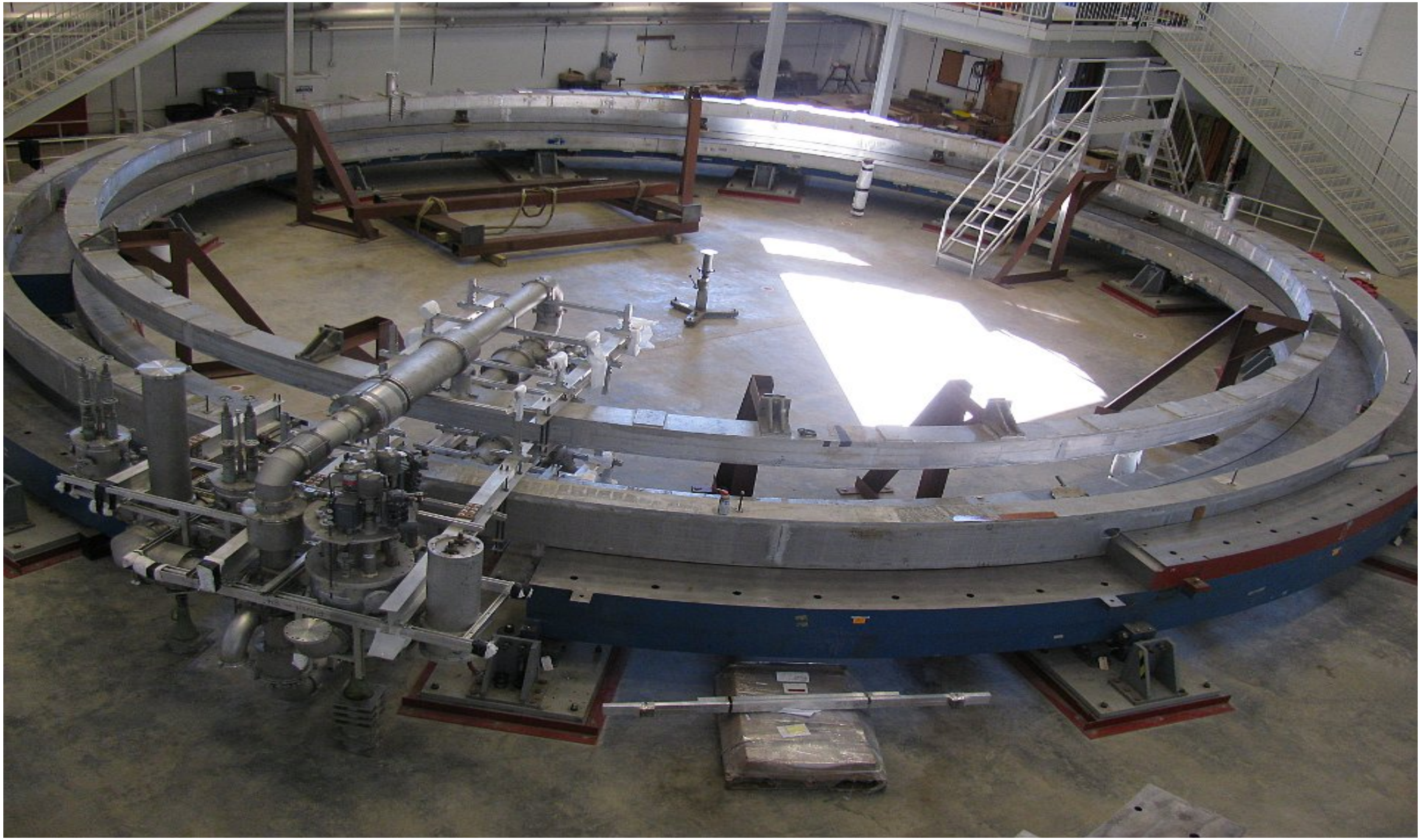


Lower Yoke installed






EMMERT

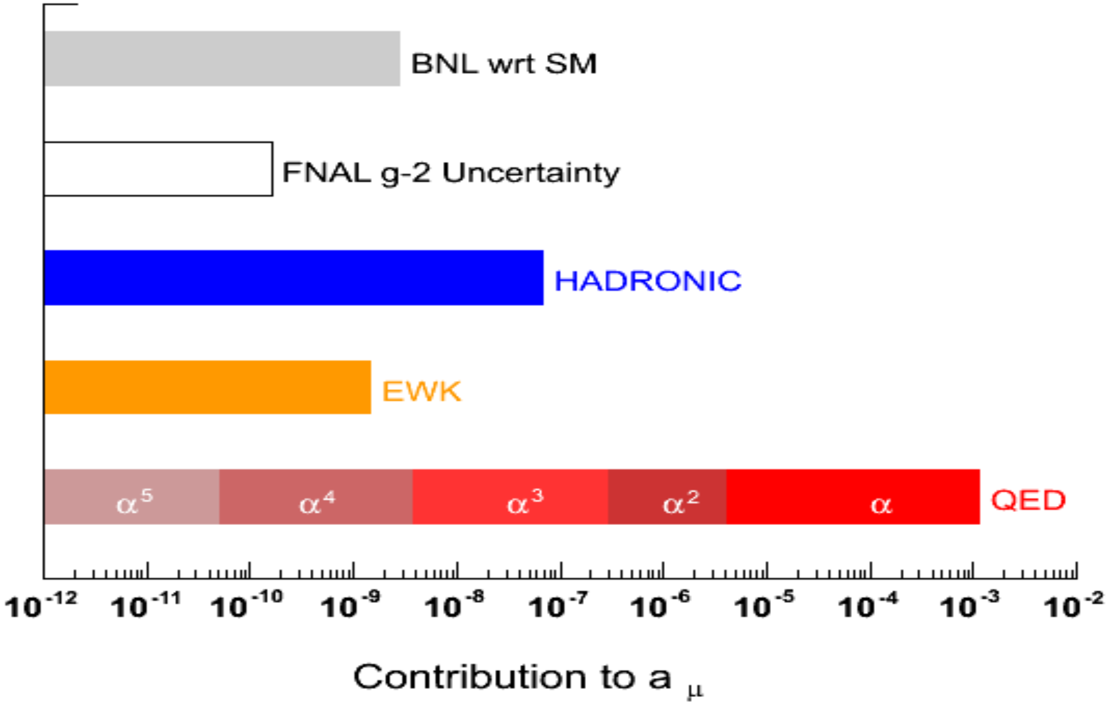


2nd Challenge

$$\text{BNL} \to \text{FNAL}$$

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

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



Seven FNAL g-2 improvements

- More μ per proton
- Lower inst. rate
- Fewer pions

Unique capabilities of FNAL accelerators

- Improved detectors
- Improved stored muon beam dynamics
- Improved field uniformity, field measurement & calibration
- Improved modeling of beam & detectors

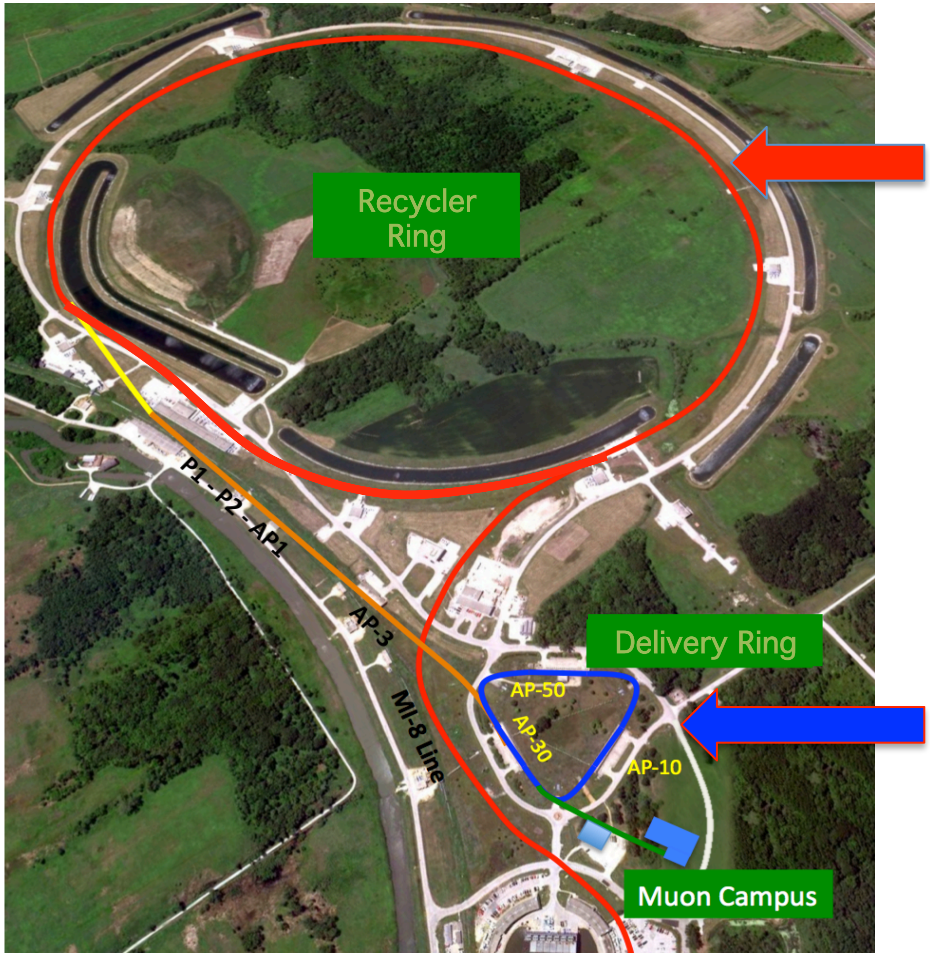
New / improved technologies

Additional collaborators

Building on wealth of experience from BNL E821 & other expts

Accelerator Modifications

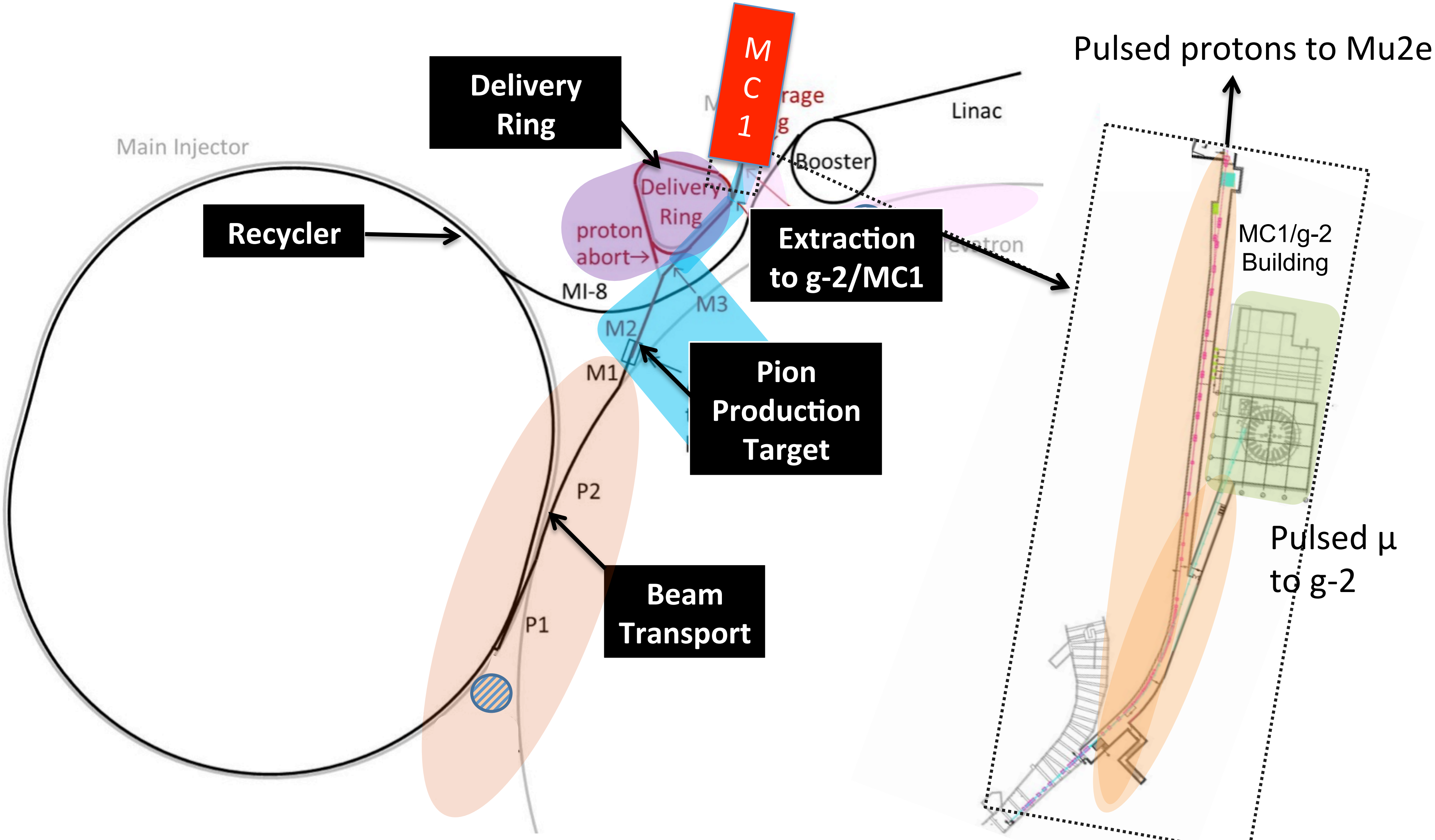
To provide x20 more muons at lower inst. rate with much reduced pion contamination compared to BNL.



Proton accelerator modifications (Recycler & Booster)

Old Pbar complex being re-configured to provide muons. **aka "The Delivery Ring"**

Accelerator Modifications



Delivery Ring

Recycler

Extraction to g-2/MC1

Pion Production Target

Beam Transport

Pulsed protons to Mu2e

MC1/g-2 Building

Pulsed μ to g-2

Many of these modifications are also required by Mu2e

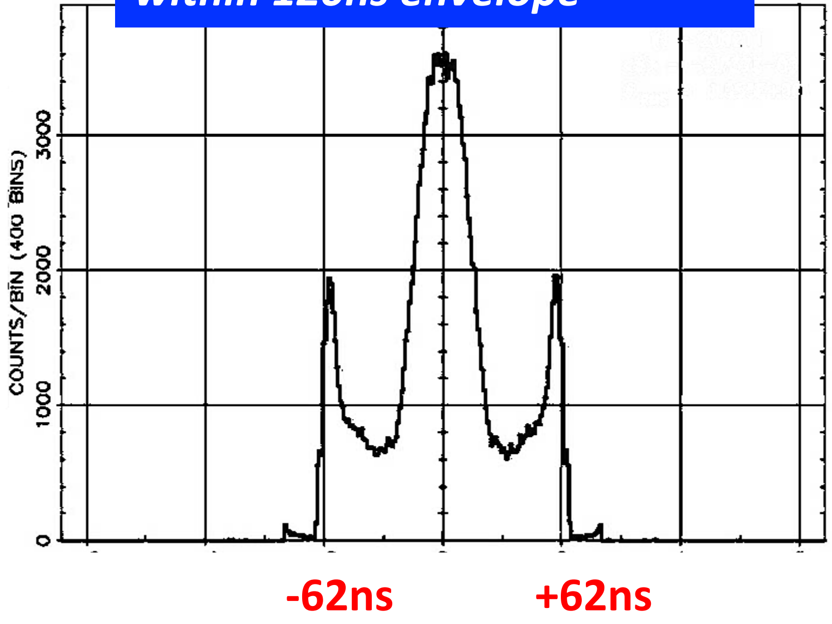
Accelerator Requirements

- 4 proton pulses of 10^{12} @ 8 GeV separated by 10ms (av rate 12 Hz)
- pulse duration to be less than cyclotron period (149ns)

- dispersion in pion momentum < 2%

- long pion decay beamline

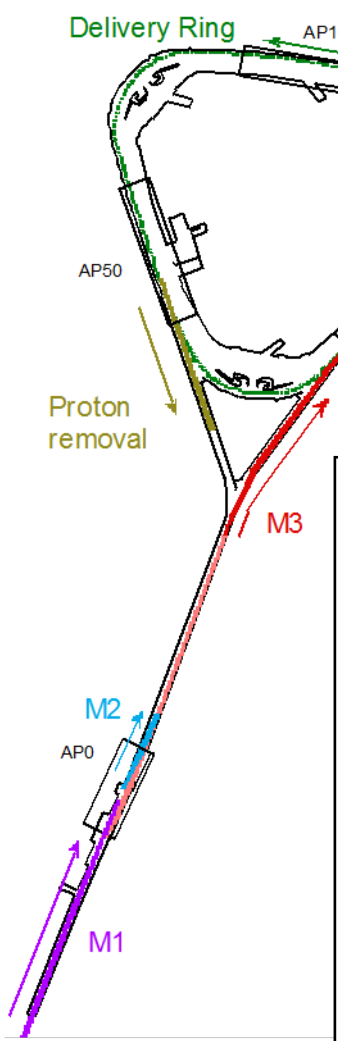
Re-uses much of current infrastructure but requires new beamlines, kickers, power supplies, controls etc

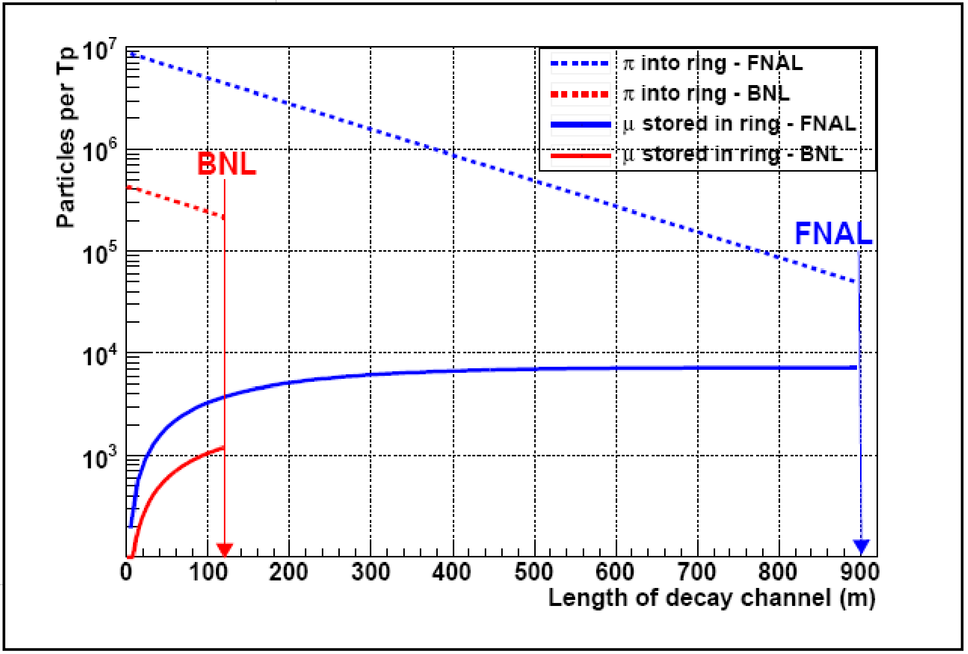


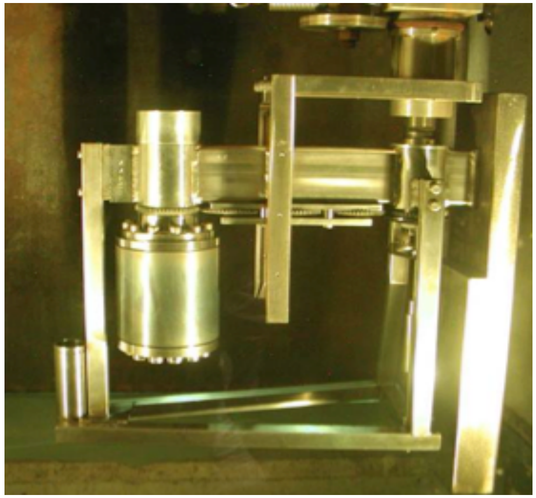
95% of protons from Recycler within 120ns envelope

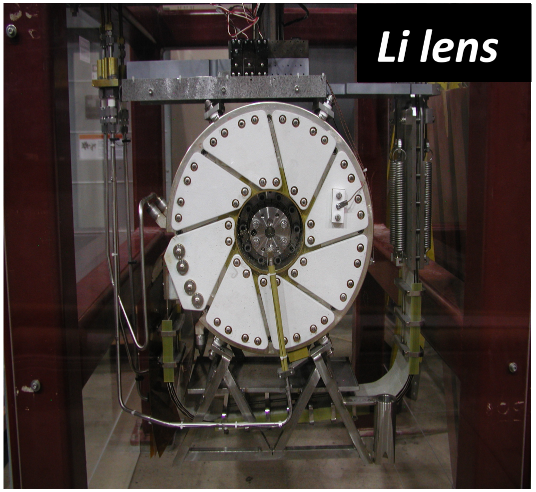
Each 10^{12} proton pulse results in ≈ 16,000 stored 3.09 GeV muons in g-2 ring

Accelerator Modifications









Lens tested at required 12 Hz rate

Accelerator Modifications


Existing AP30 section being re-configured (D30) : critical path task

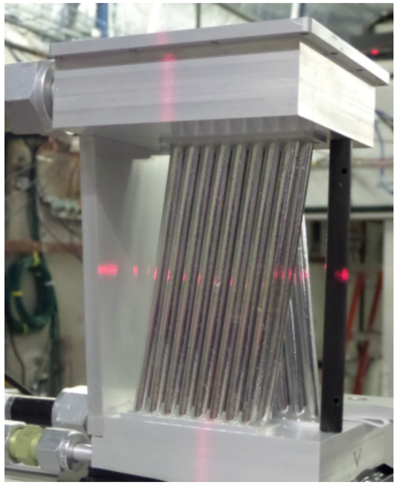
Schedule is funding-constrained.

Beamlines will be ready for operation in April 2017.

Accelerator mods : x20 in stats

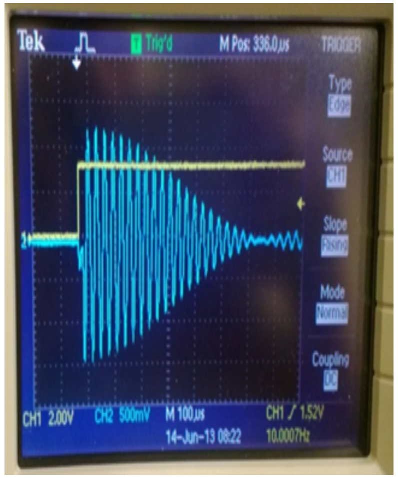
Final challenge : reduce systematics by factor of ~ 3.

B-field systematic (ω_P) from 0.17 ppm -> 0.07 ppm
Precession systematic (ω_a) from 0.2 ppm -> 0.07 ppm

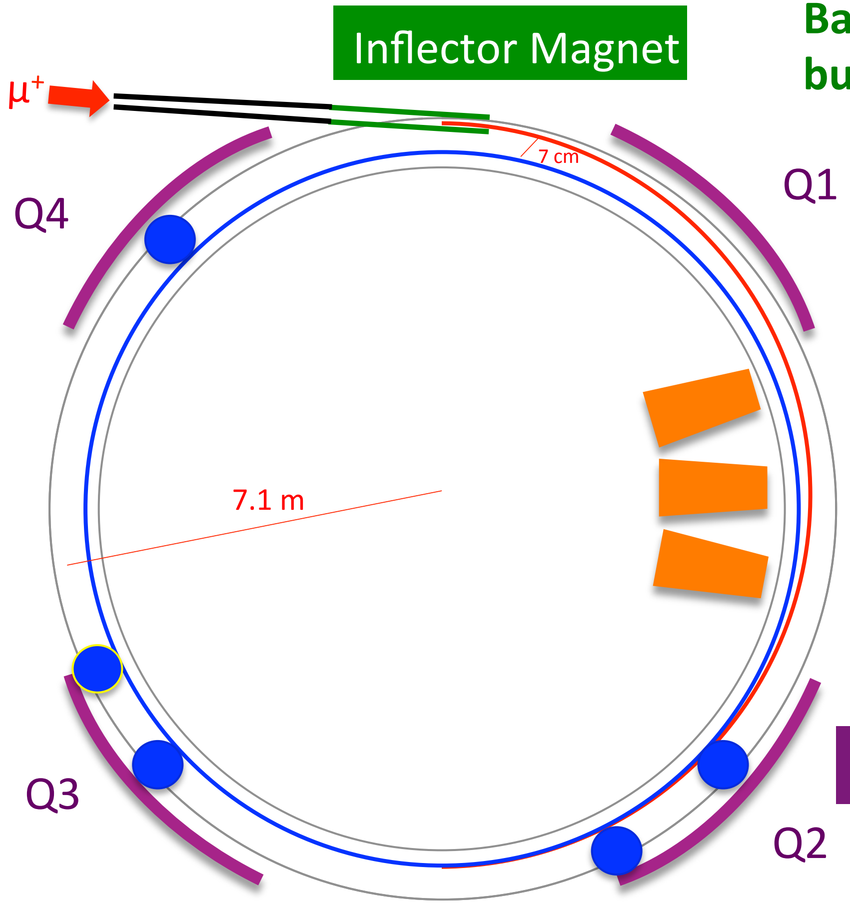


Many aspects to achieving this:

- New, improved detectors, calibration & readout systems
- Improved beam stability/monitoring e.g. new kicker
- Improved calibration/shimming/readout of B-field
- End to end simulation of both accelerator,
  storage ring and detectors



Improvements to injection system



Inflector Magnet

Baseline: existing BNL inflector but new design under R&D

Kicker magnets

New with improved kick

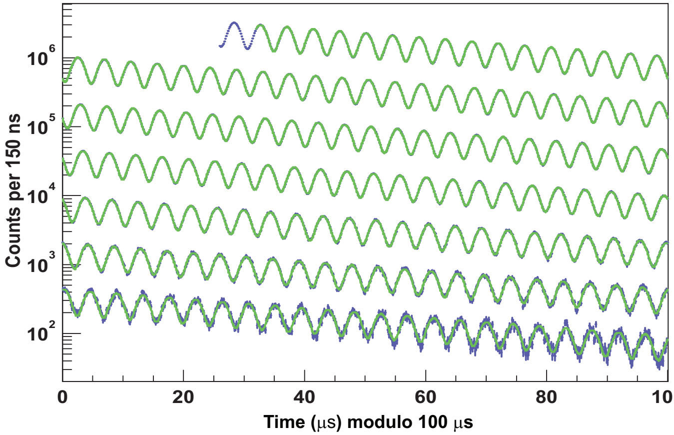
Focussing quads

Collimators

New and with sensors

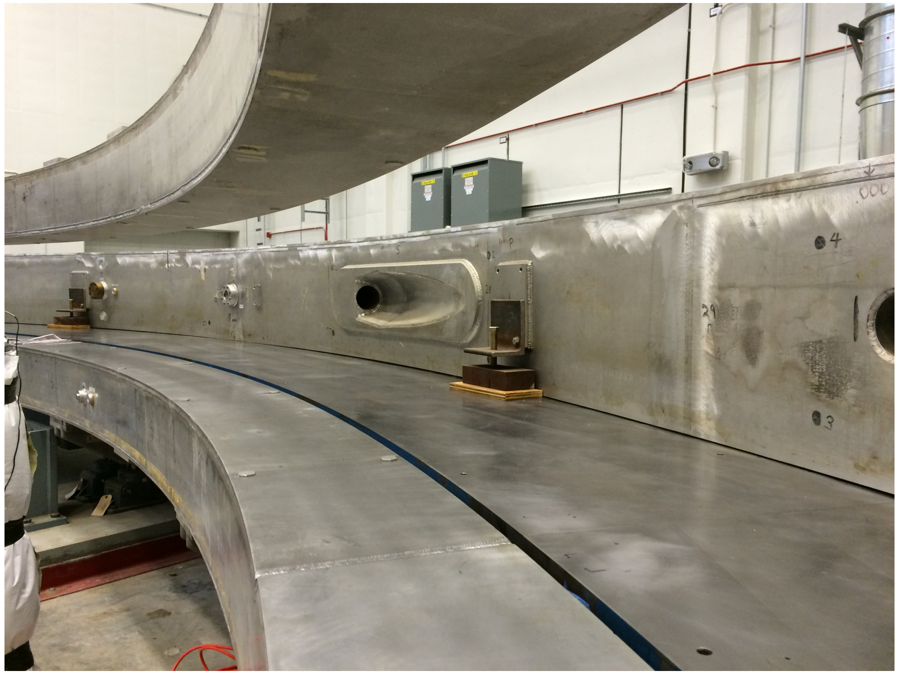
Improvements to injection system

Injection, beam orbit / stability important to:

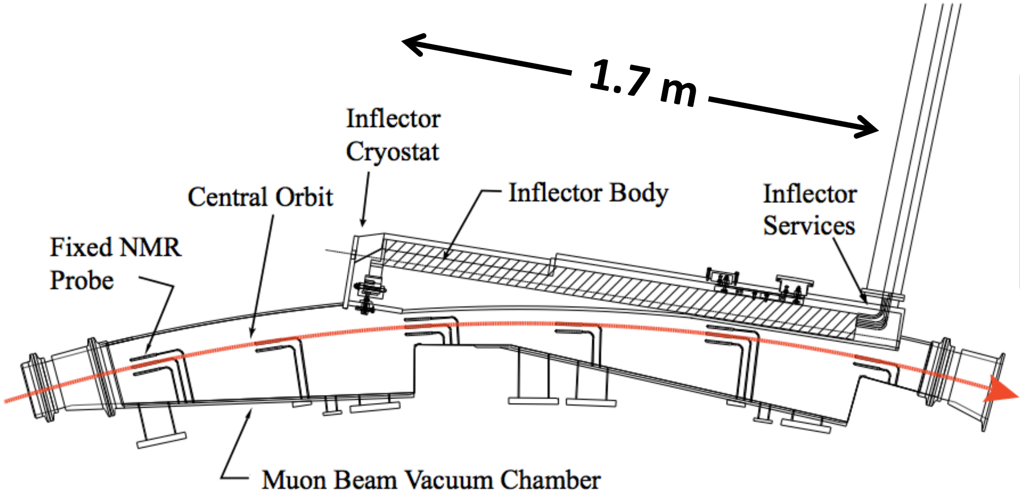


- minimise muon losses
    - *maximise statistics*
    - *minimise impact of losses that are time dependent*
- minimise corrections to the “spin equation”
    - vertical betatron oscillations mean : v.B ≠ 0 (aka “pitch correction”)
    - ± 15 MeV variance in beam momentum (aka “E-field correction”)
- ensure beam traverses known/consistent path in B-field

Inflector system



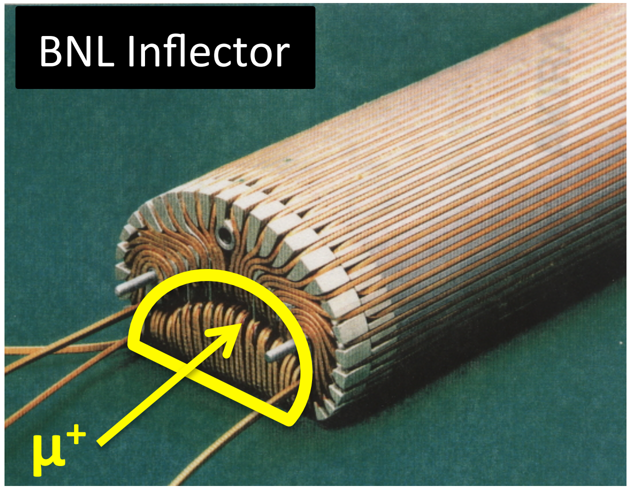
Inflector system



Nulls 1.45 T field at point of injection
Static and non ferromagnetic
Cannot leak flux into storage ring

Both magnet and shield

BNL Inflector



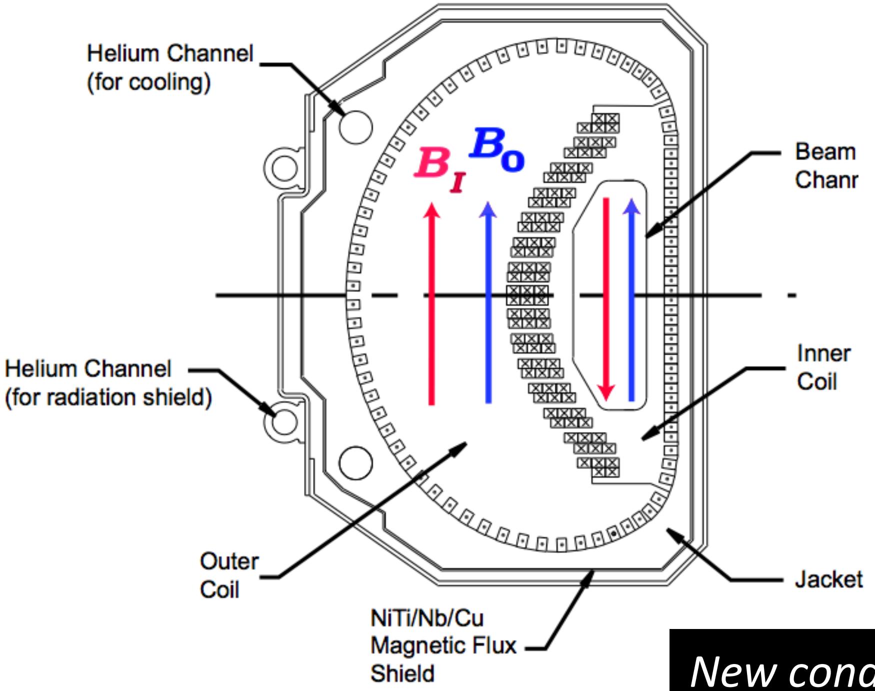
R&D into an open-end design:

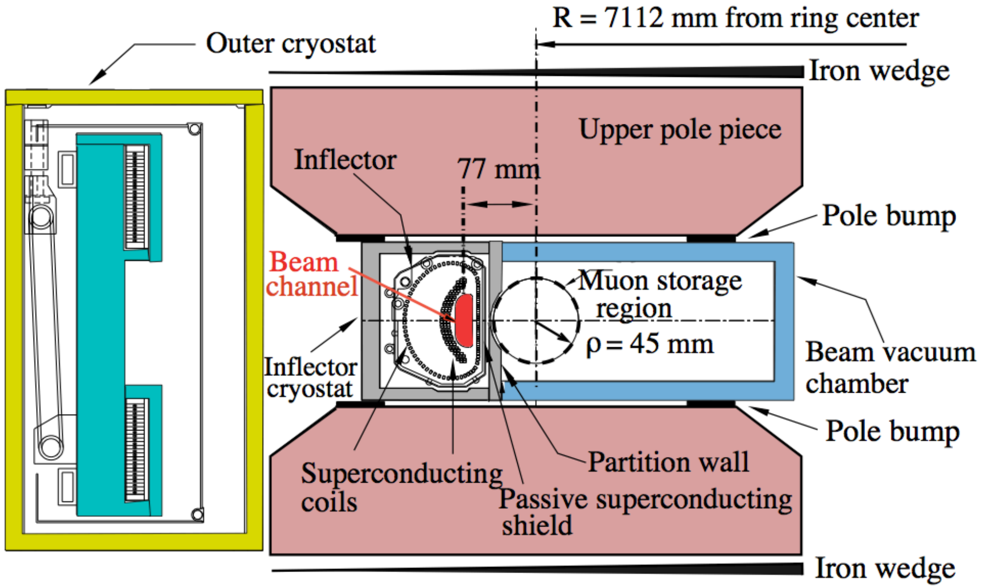
- less scattering
- x2 more muons
- better matched

Test facility in MC1

Inflector

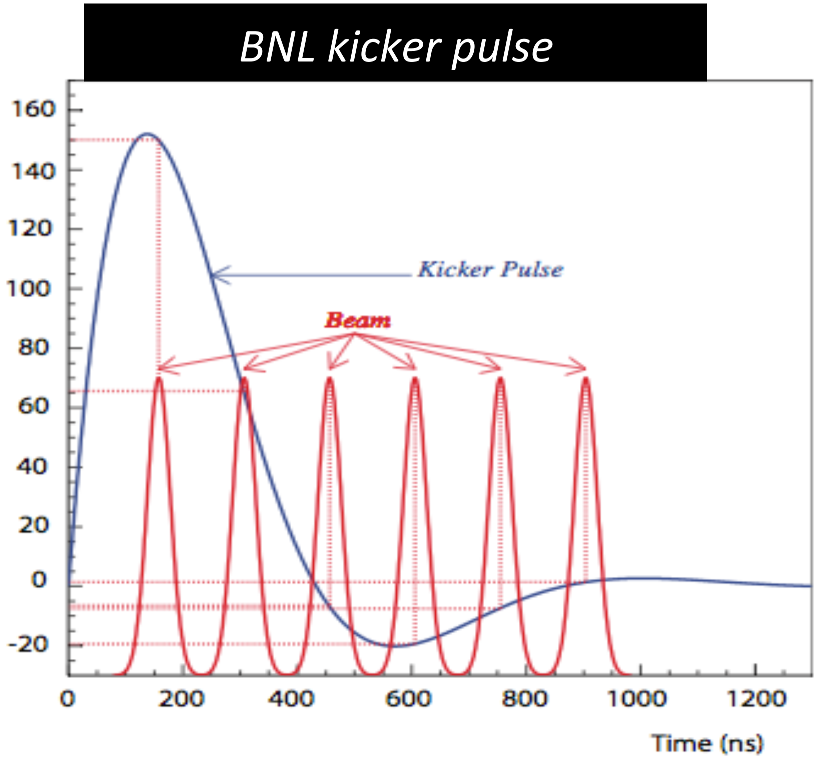
Two double (truncated) cosθ magnets that trap their own flux.

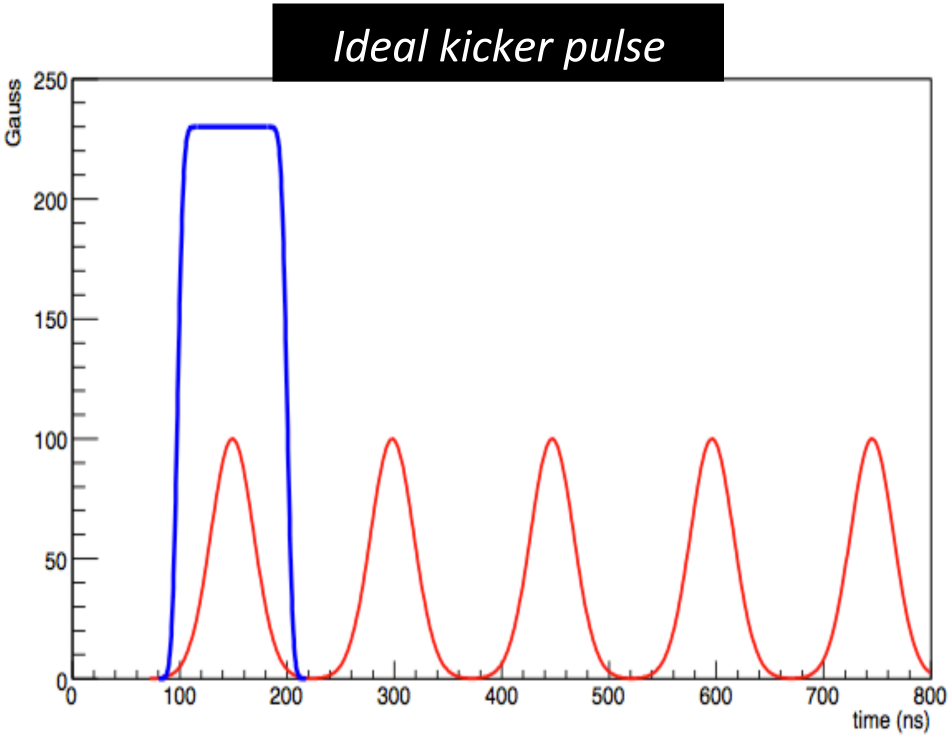




New conductor under R&D at FNAL

New Kicker



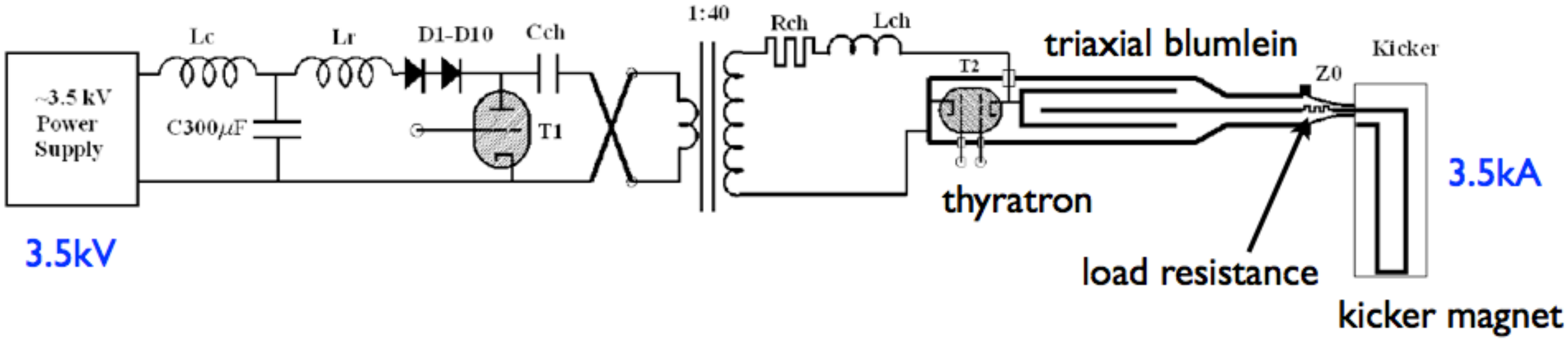


No (or known) eddy currents during measurement period (30us after injection)

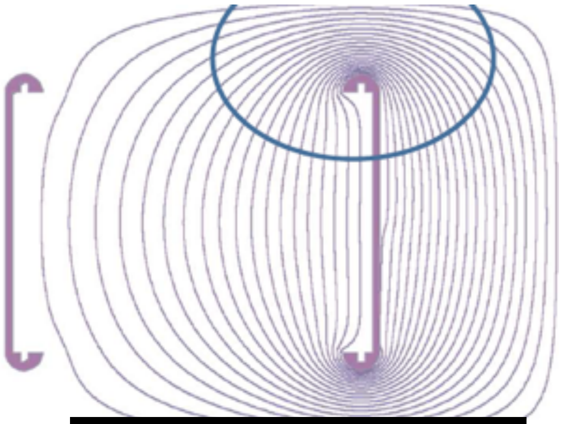
No ferrite materials that can affect the storage ring field

New Kicker Magnet

Blumlein double transmission line to form the pulse into the kicker plate

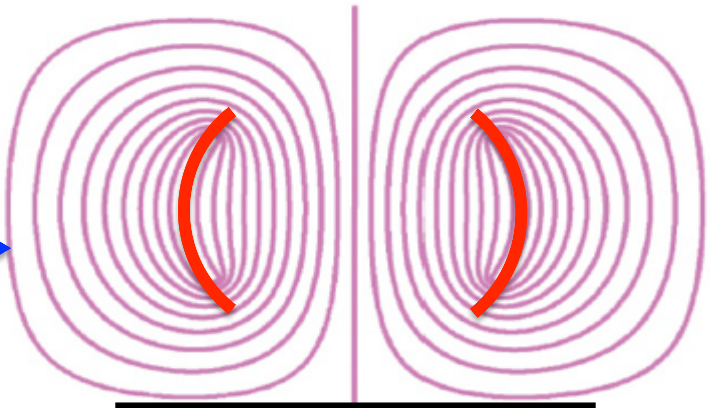


Stronger field between plates with reduced field at edge of plots



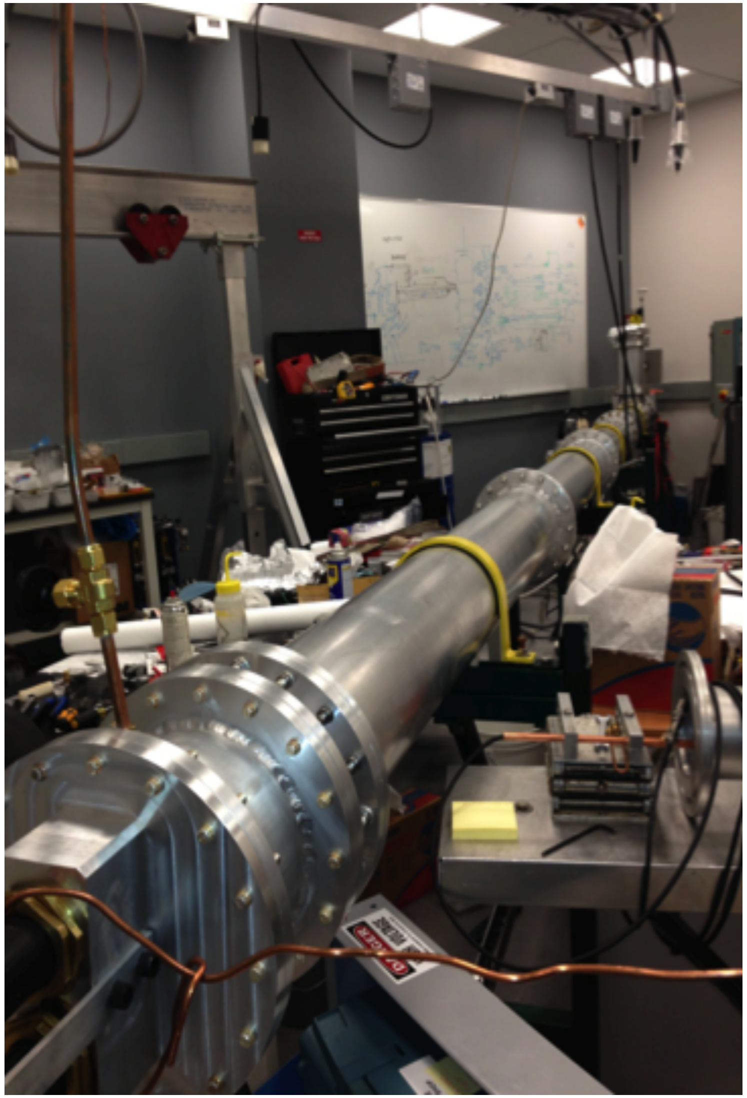
BNL kicker geometry

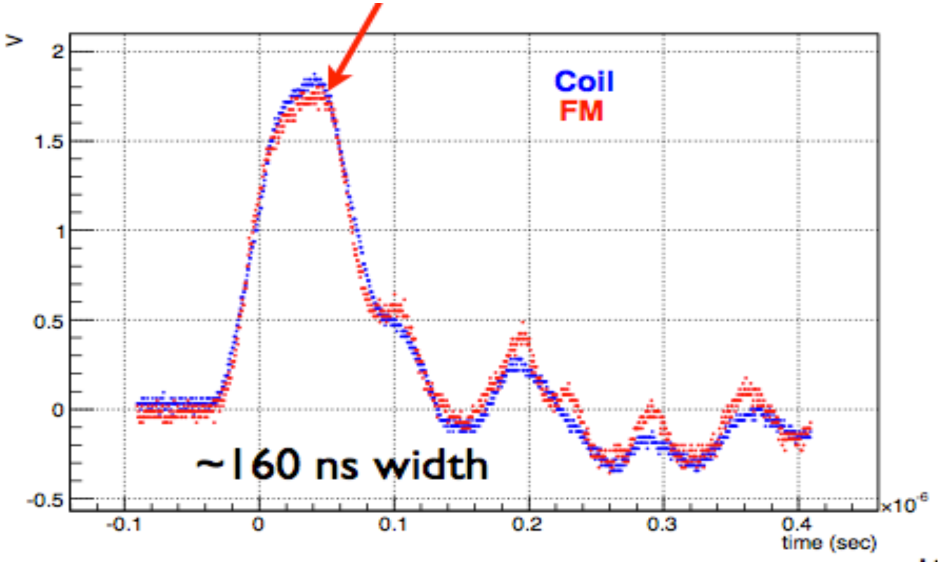
New geometry →



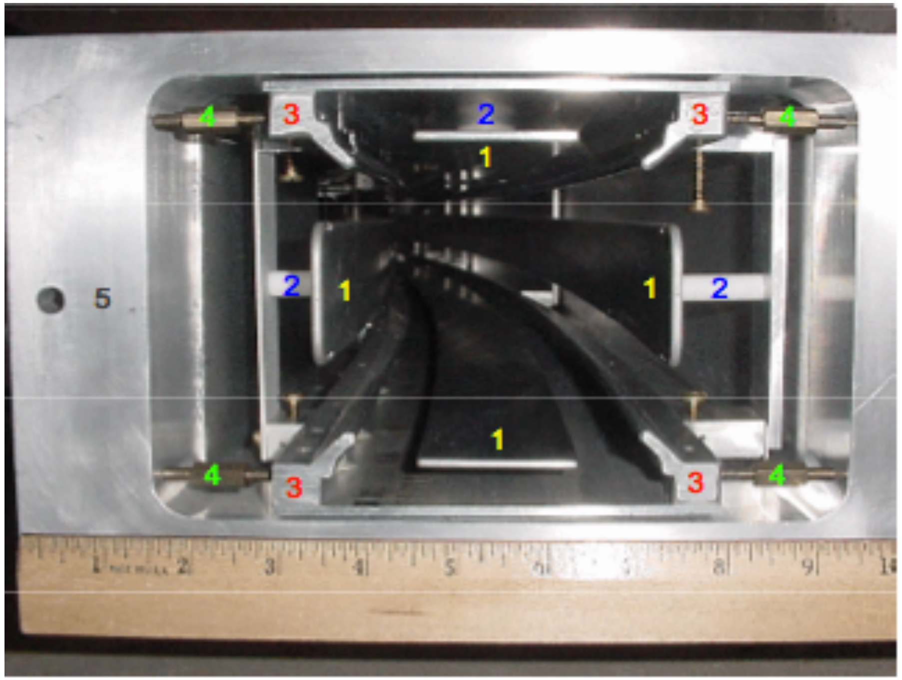
FNAL kicker geometry

New Kicker Magnet





Electrostatic Focussing Quadrupoles



(1) plates, (2) HV standoffs, (3) trolley rails, (4) adjustment screws, (5) vacuum chamber

Provide vertical focussing of beam

4 (non-ferrite) metal plates under HV

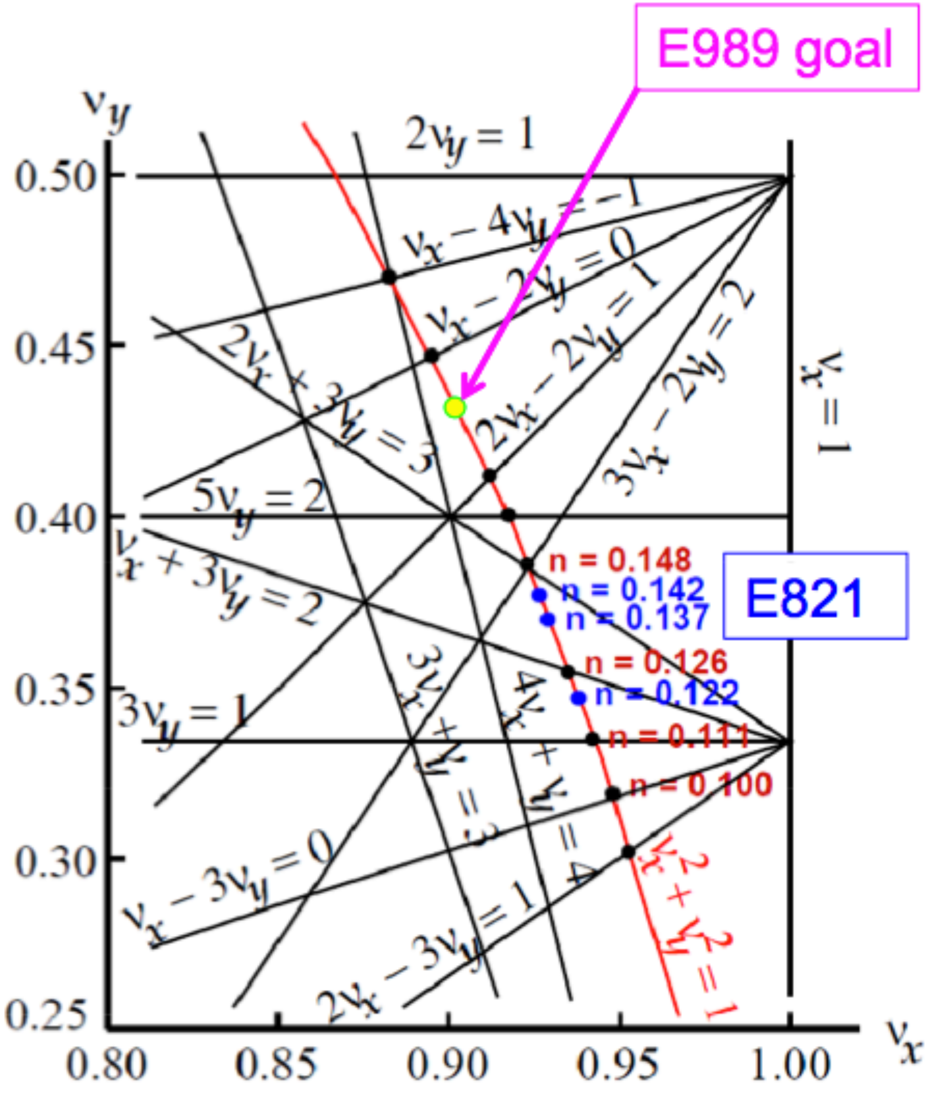
Influences:

- # lost muons
- E field correction
- ω_P (orbit distortion)

Dipole B-field & quadrupole E-field means beam undergoes **SHM (betatron) oscillations** in vertical and radial direction.

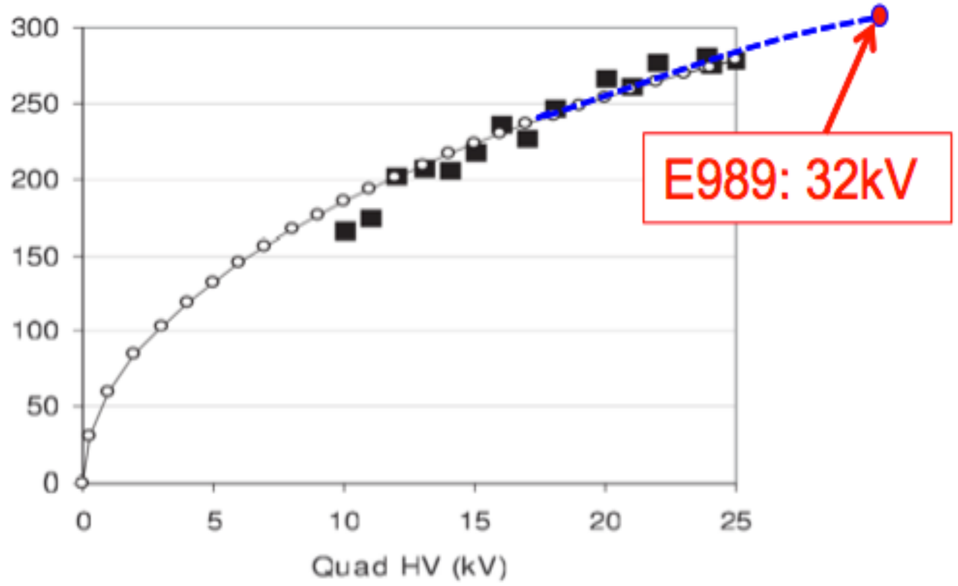
Radial : affects detector acceptance.
Vertical : lowers ω_a since v.B ≠ 0 (pitch correction)

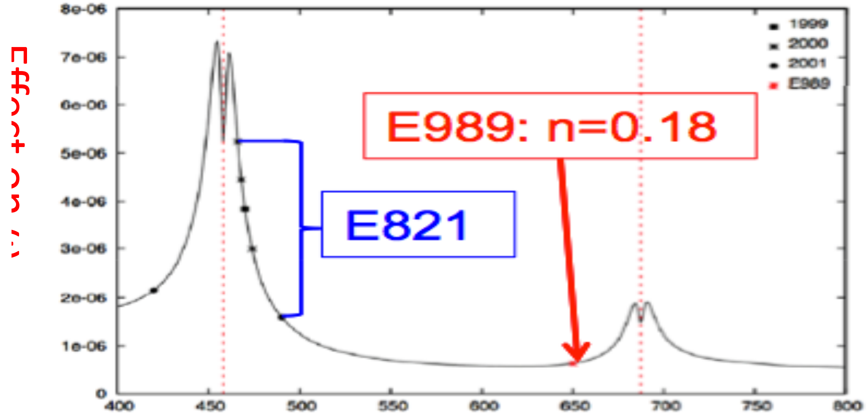
Quadrupoles and n-value



Avoid resonances & minimise CBO impact

Increase "n" by increasing quad field

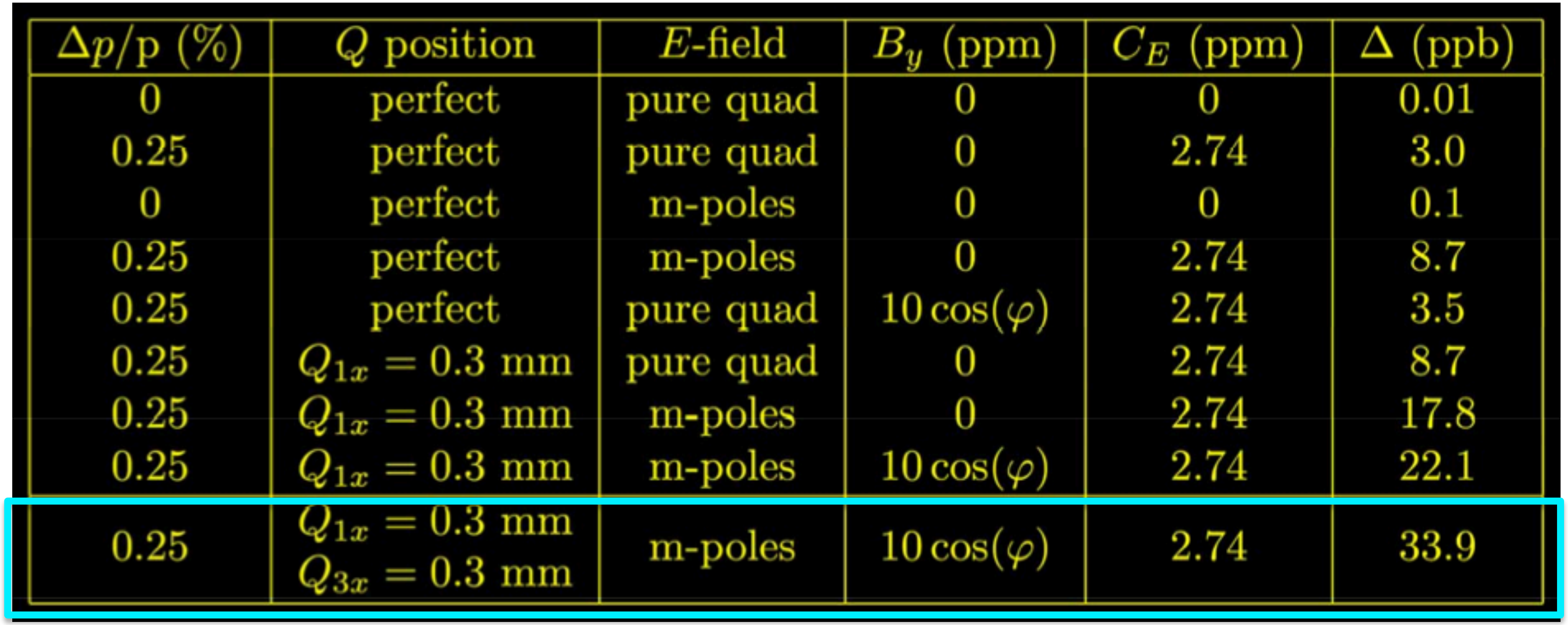




SHM (CBO) frequency

Impact of Quad field, position on ω_a

$$\frac{\Delta\omega_a}{\omega_a} = -2\frac{\beta E_r}{cB_y}\left(\frac{\Delta p}{p_m}\right) = -2n(1-n)\beta^2\langle x_e^2\rangle R_o^2$$

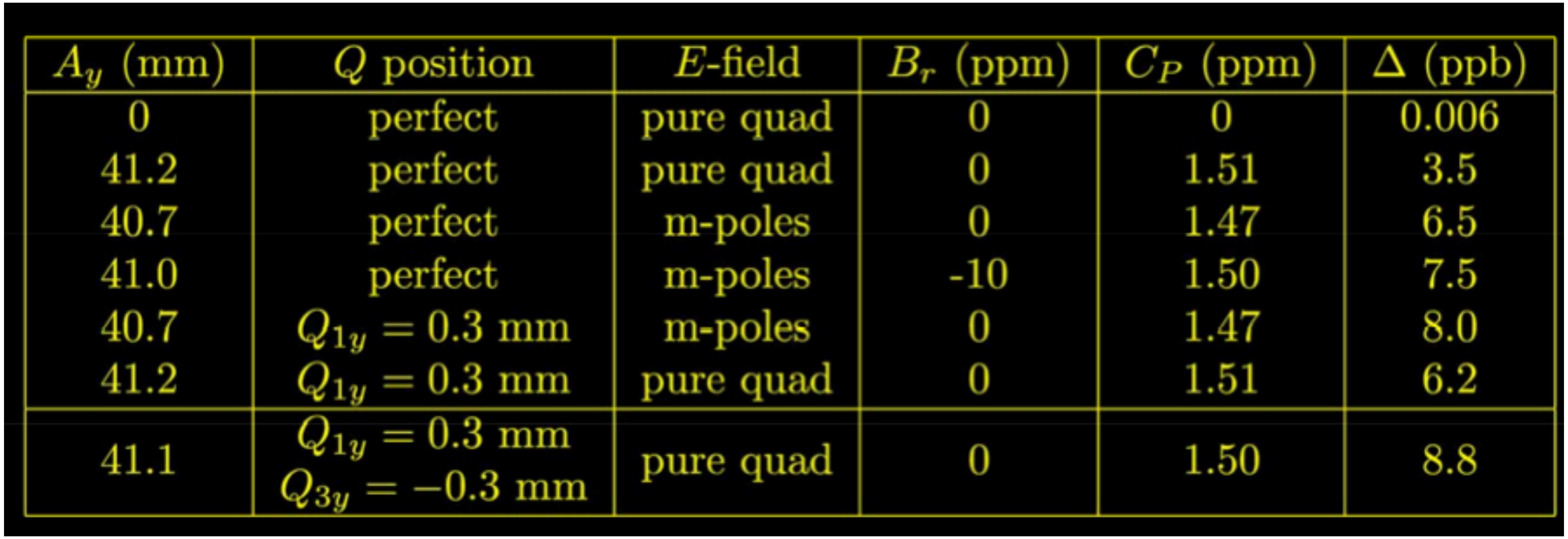


$\Delta p/\mathrm{p}$ (%)	Q position	E-field	B_y (ppm)	C_E (ppm)	Δ (ppb)
0	perfect	pure quad	0	0	0.01
0.25	perfect	pure quad	0	2.74	3.0
0	perfect	m-poles	0	0	0.1
0.25	perfect	m-poles	0	2.74	8.7
0.25	perfect	pure quad	$10\cos(\varphi)$	2.74	3.5
0.25	$Q_{1x} = 0.3$ mm	pure quad	0	2.74	8.7
0.25	$Q_{1x} = 0.3$ mm	m-poles	0	2.74	17.8
0.25	$Q_{1x} = 0.3$ mm	m-poles	$10\cos(\varphi)$	2.74	22.1
0.25	$Q_{1x} = 0.3$ mm $Q_{3x} = 0.3$ mm	m-poles	$10\cos(\varphi)$	2.74	33.9

0.03 ppm is FNAL aim. BNL achieved 0.065 ppm

Quad affect on “pitch correction”

Smaller than E-field correction but again requires precise alignment of quads
Again it systematically lowers ω_a



A_y (mm)	Q position	E-field	B_r (ppm)	C_P (ppm)	Δ (ppb)
0	perfect	pure quad	0	0	0.006
41.2	perfect	pure quad	0	1.51	3.5
40.7	perfect	m-poles	0	1.47	6.5
41.0	perfect	m-poles	-10	1.50	7.5
40.7	$Q_{1y} = 0.3$ mm	m-poles	0	1.47	8.0
41.2	$Q_{1y} = 0.3$ mm	pure quad	0	1.51	6.2
41.1	$Q_{1y} = 0.3$ mm $Q_{3y} = -0.3$ mm	pure quad	0	1.50	8.8

A_Y : Amplitude of vertical betatron oscillation

B-field measurement

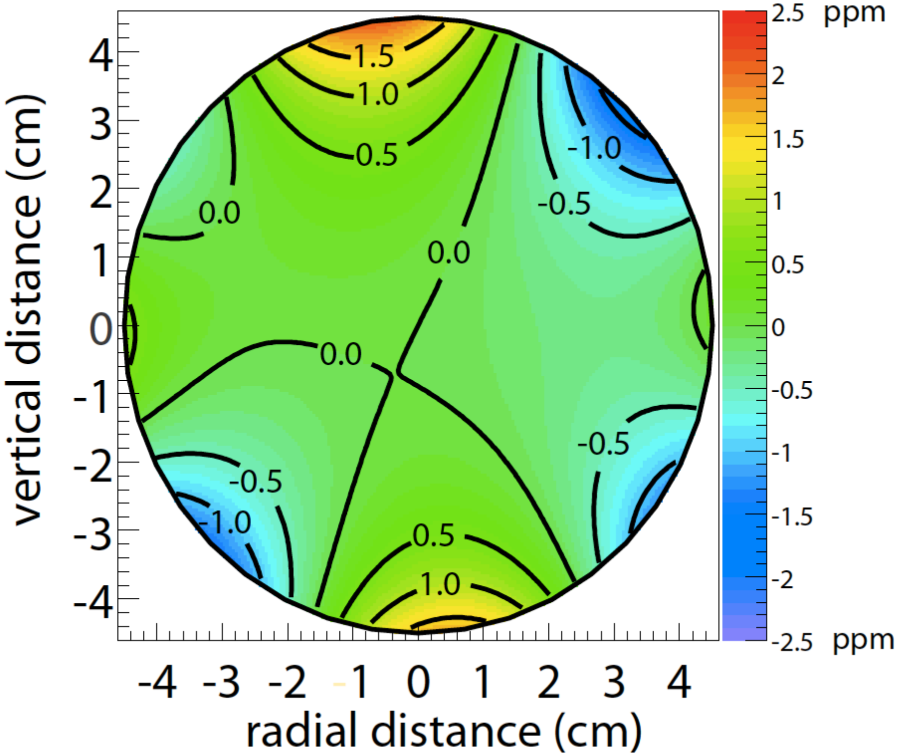
ω_p systematics need to be reduced by a factor of 2.5

Better run conditions, e.g. temperature stability.

Improved shimming of magnetic field to high uniformity

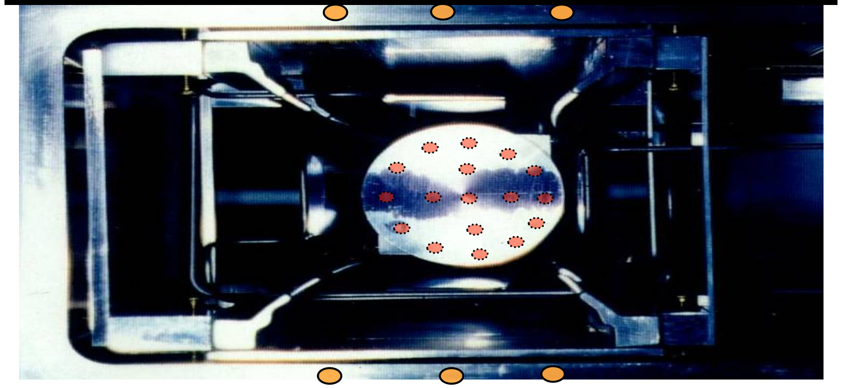
Smaller stored muon distribution

Hardware and simulation improvements

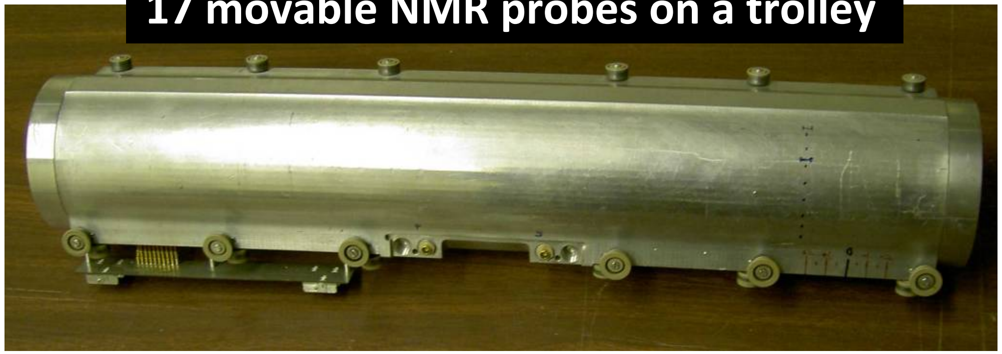


B-field measurement

300+ NMR probes in vacuum tank walls



17 movable NMR probes on a trolley



Map field at 6,000 locations every 2 hrs (vs 2 days BNL)

Much improved temp. control

B-field measurement

Bar codes every 2.5mm to track location of trolley

Large bore solenoid now at ANL to test all NMR components to better than 20 ppb.

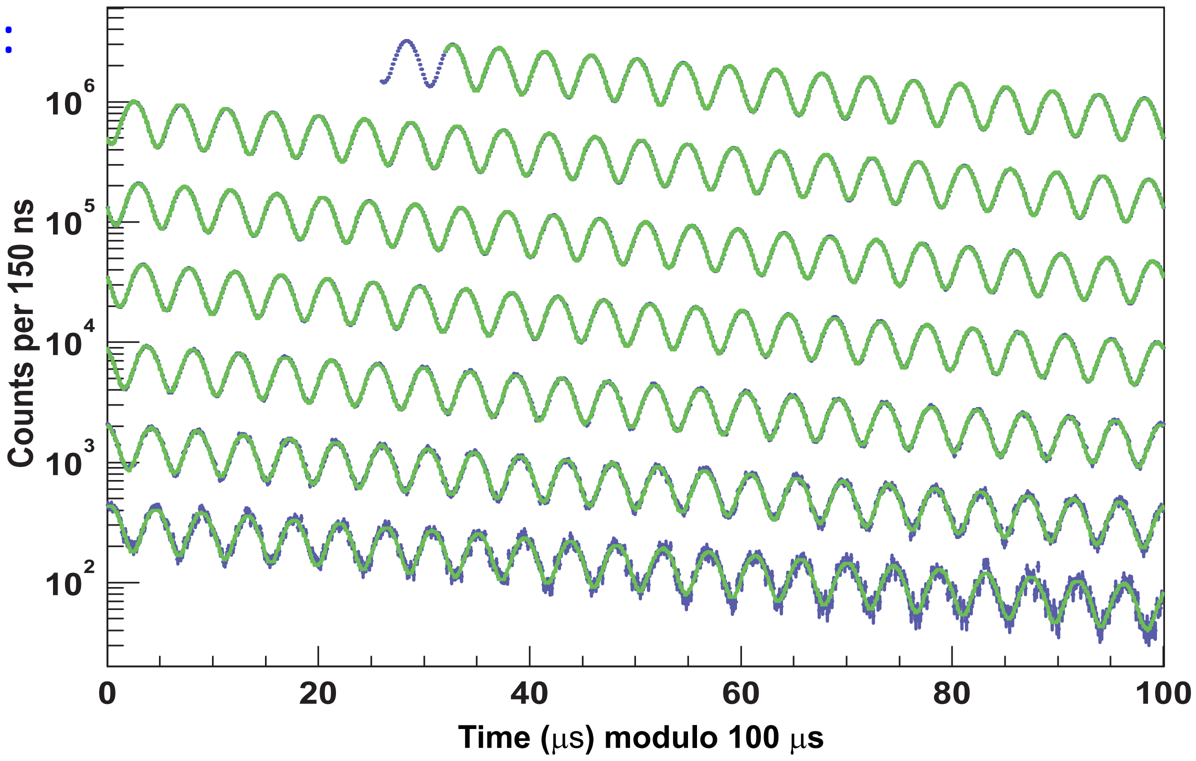
ω_a measurement

Syst. from lost muons, CBO, E & pitch-corrections : mitigated by quads, ring but detectors provide the input / diagnostics

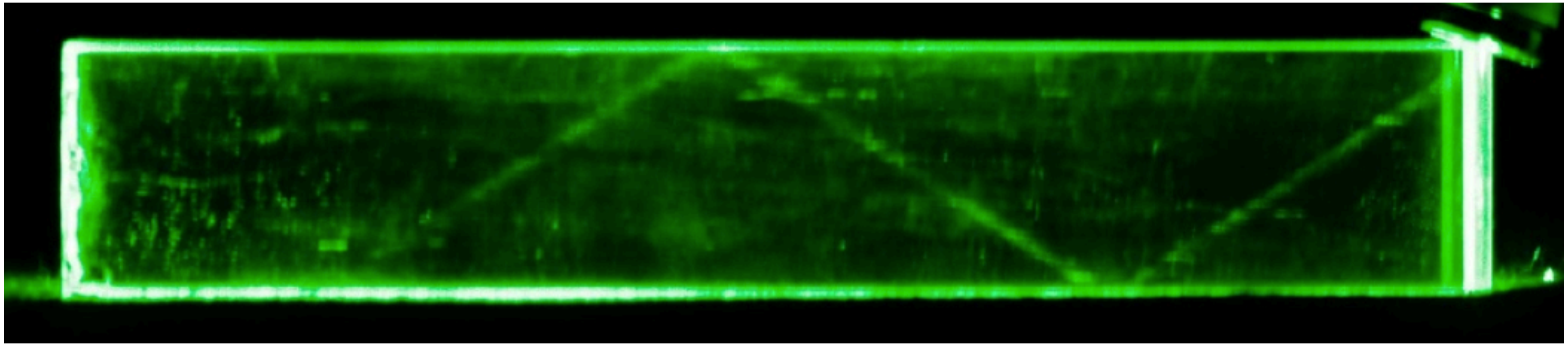
Detectors also the key in the other ω_a systematics & provide the “money-plot”

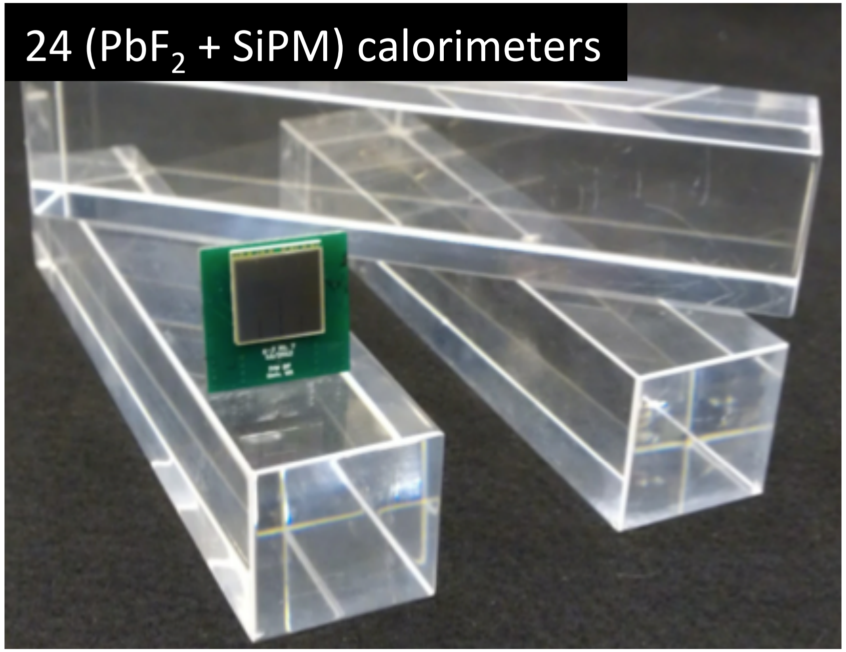
Key systematics to control:

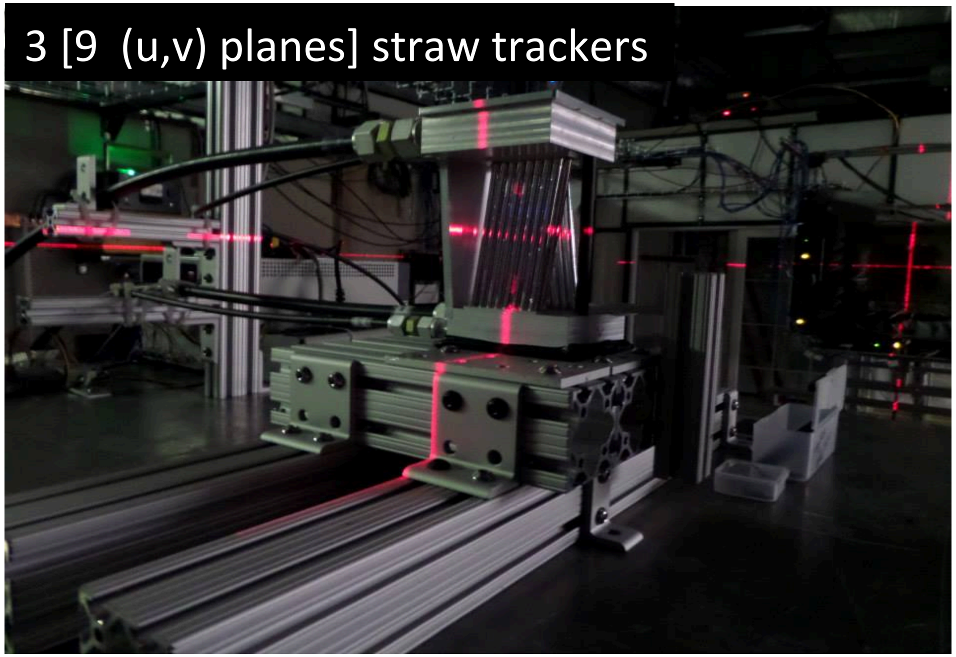
- Gain changes
- Pileup



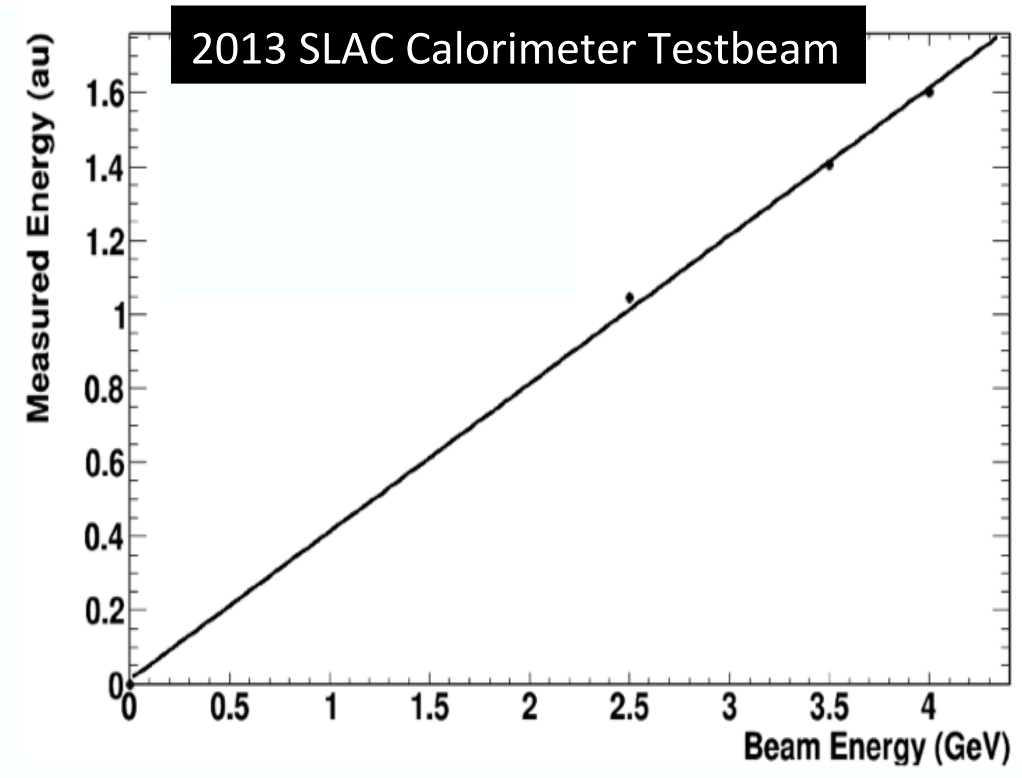
ω_a measurement

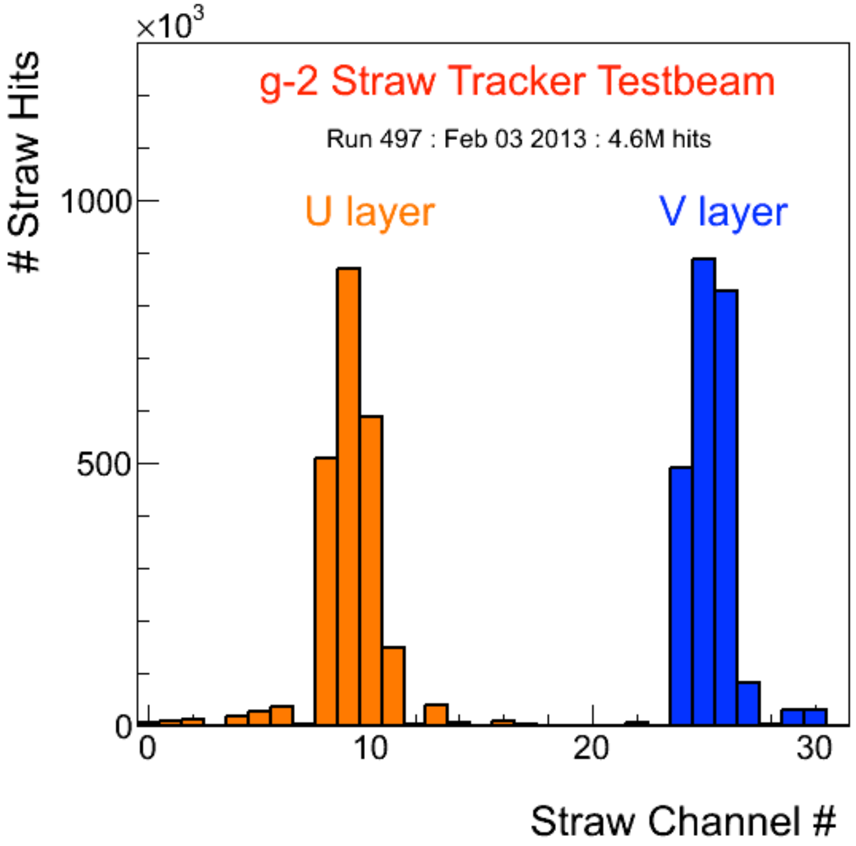



24 (PbF_2 + SiPM) calorimeters


3 [9 (u,v) planes] straw trackers

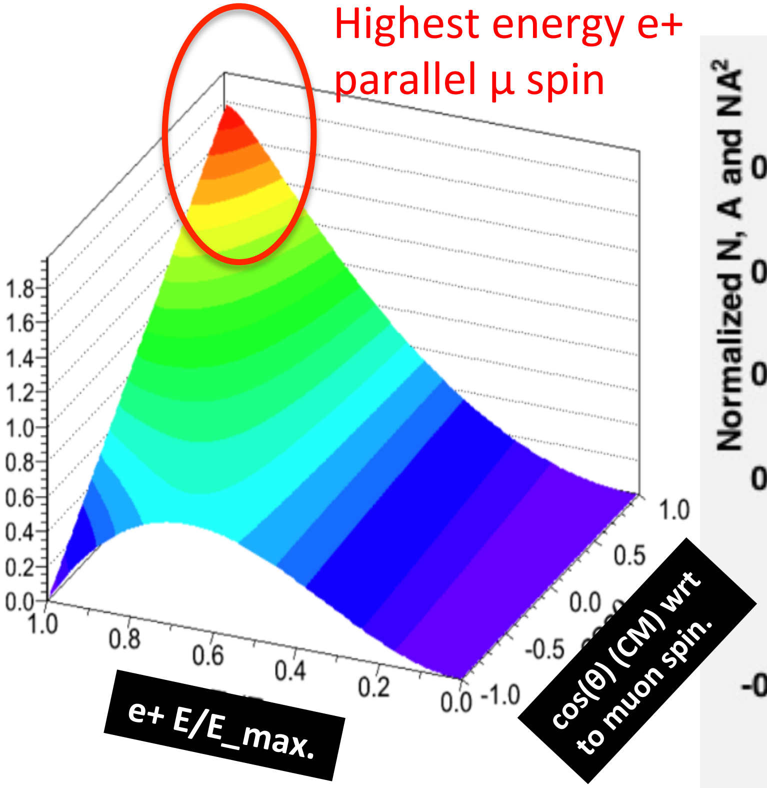
ω_a measurement



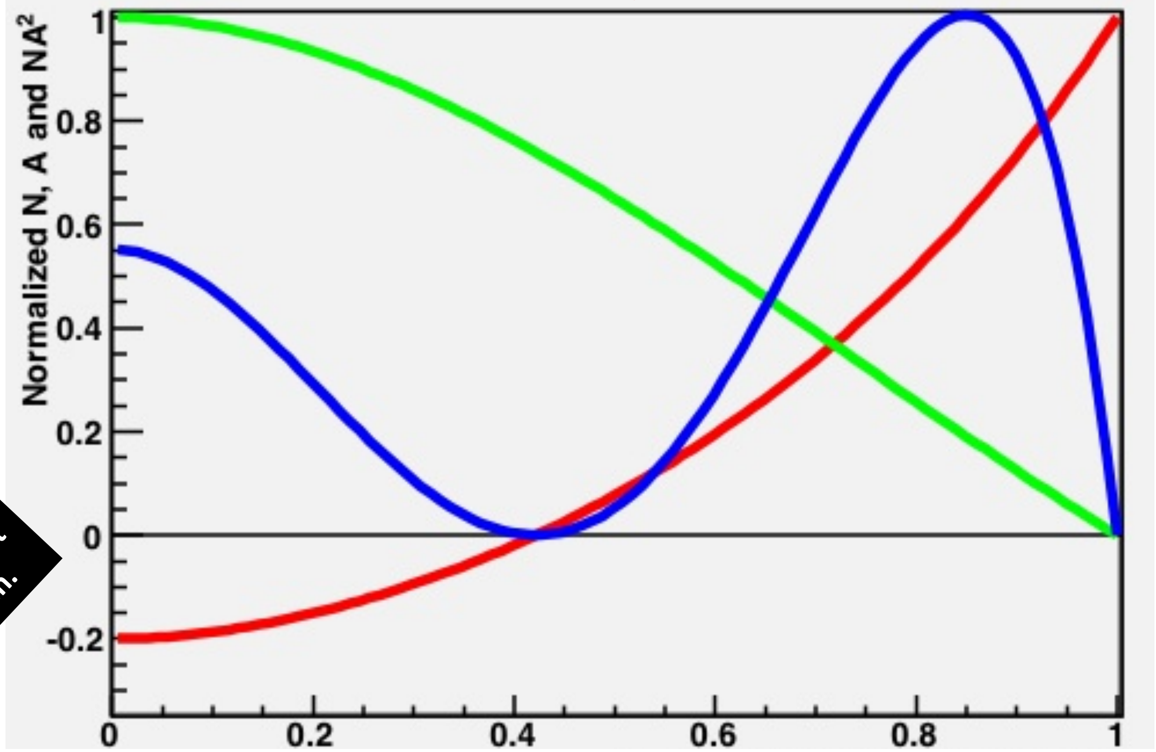


Working prototypes of both detector systems
Final versions of the detectors to be constructed in 2015/16.

ω_a measurement



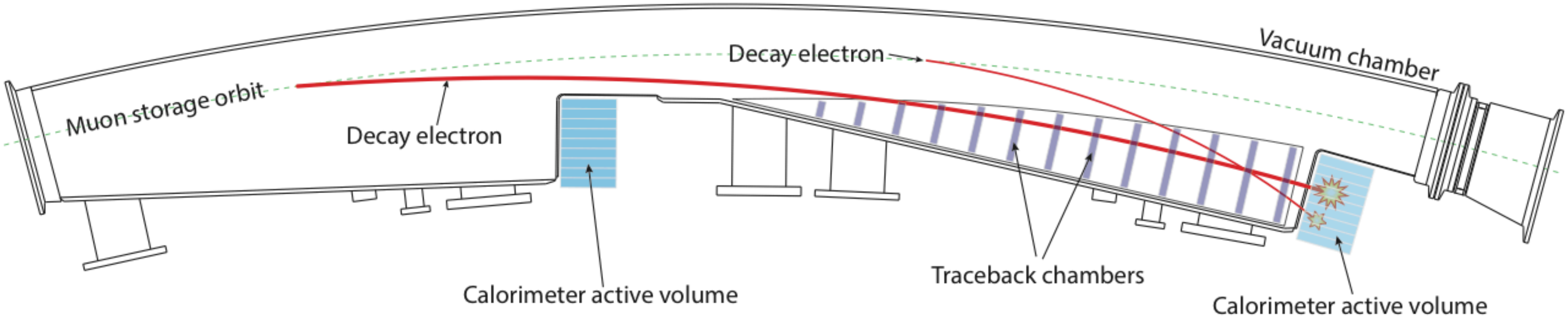
DIFFERENTIAL QUANTITIES

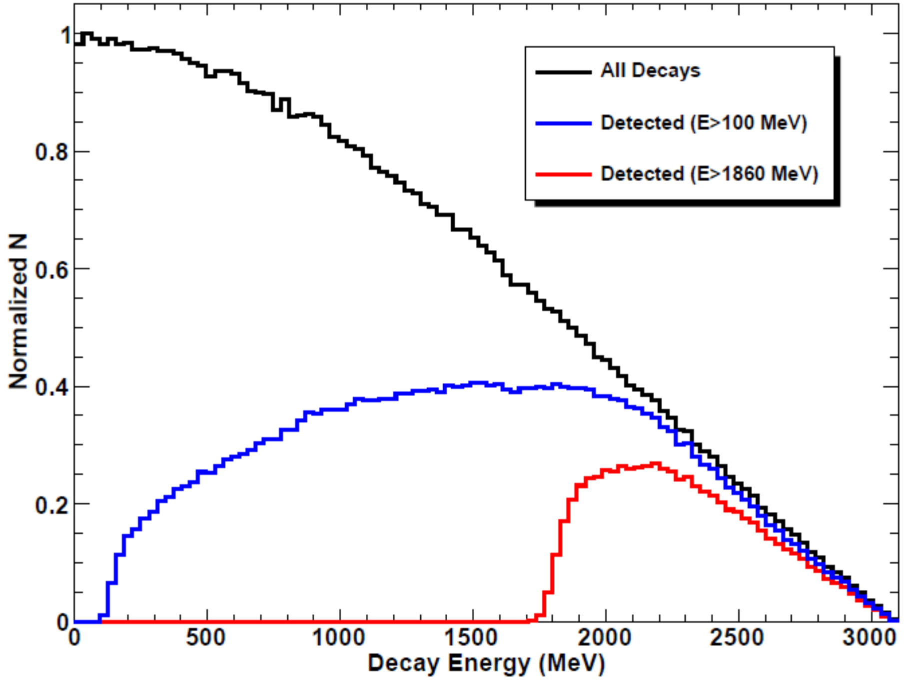


3.1 GeV

We select positrons above E = 1.86 GeV : maximises sensitivity.

ω_a measurement



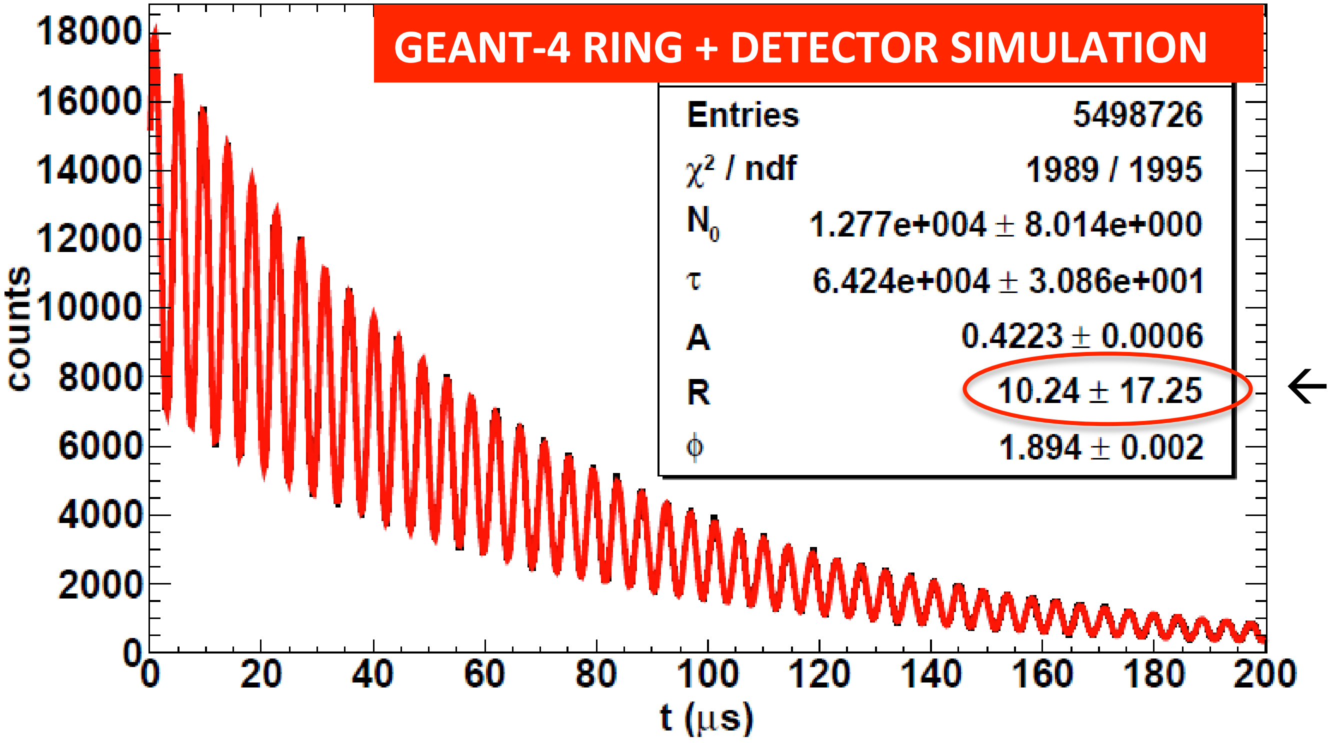


11% of positrons are above threshold and detected (~ 2k/fill)

ω_a measurement

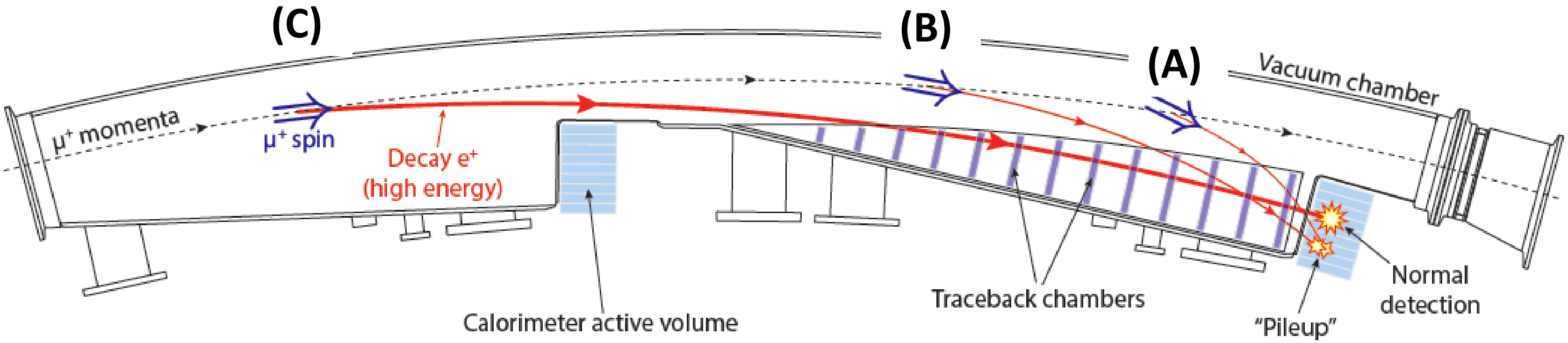
Simply plot of time of positrons above threshold and perform 5-par fit

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



← ω_a(meas)-ω_a(MC) ppm

ω_a measurement

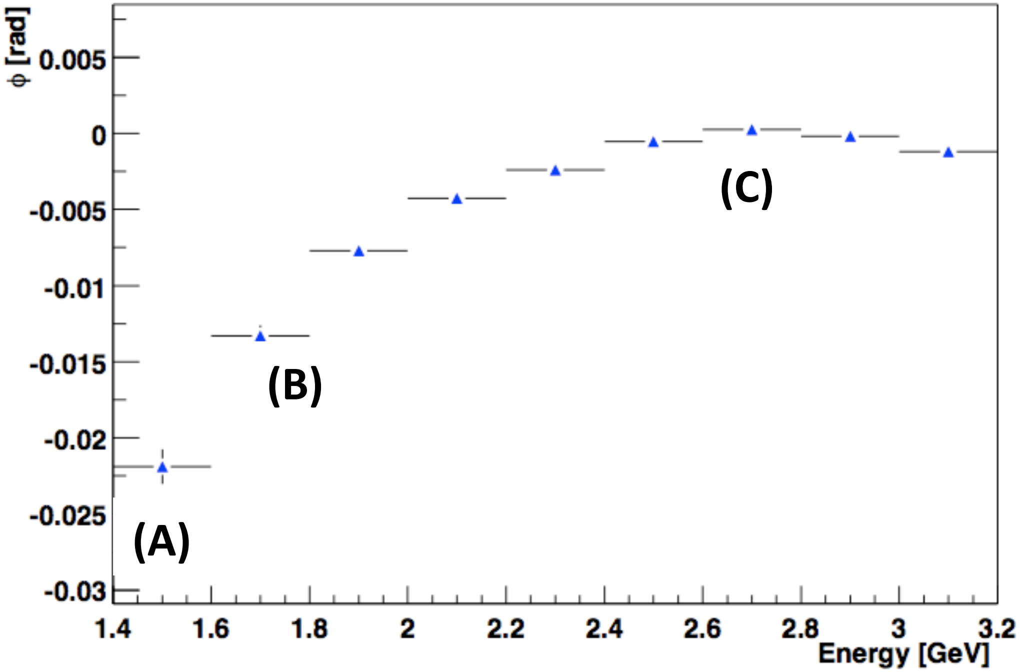


Calorimeter:

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

Tracker:

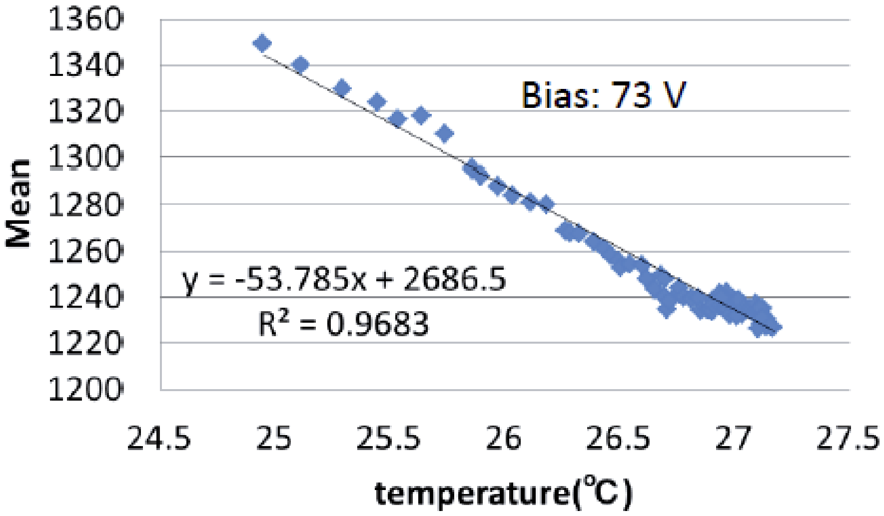
- authenticate pileup
- measure muon profile
- measure EDM

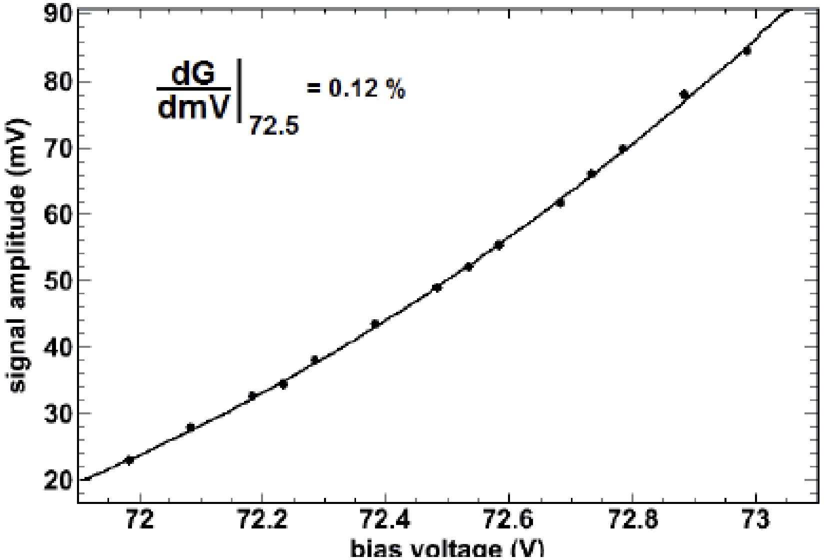


ω_a measurement

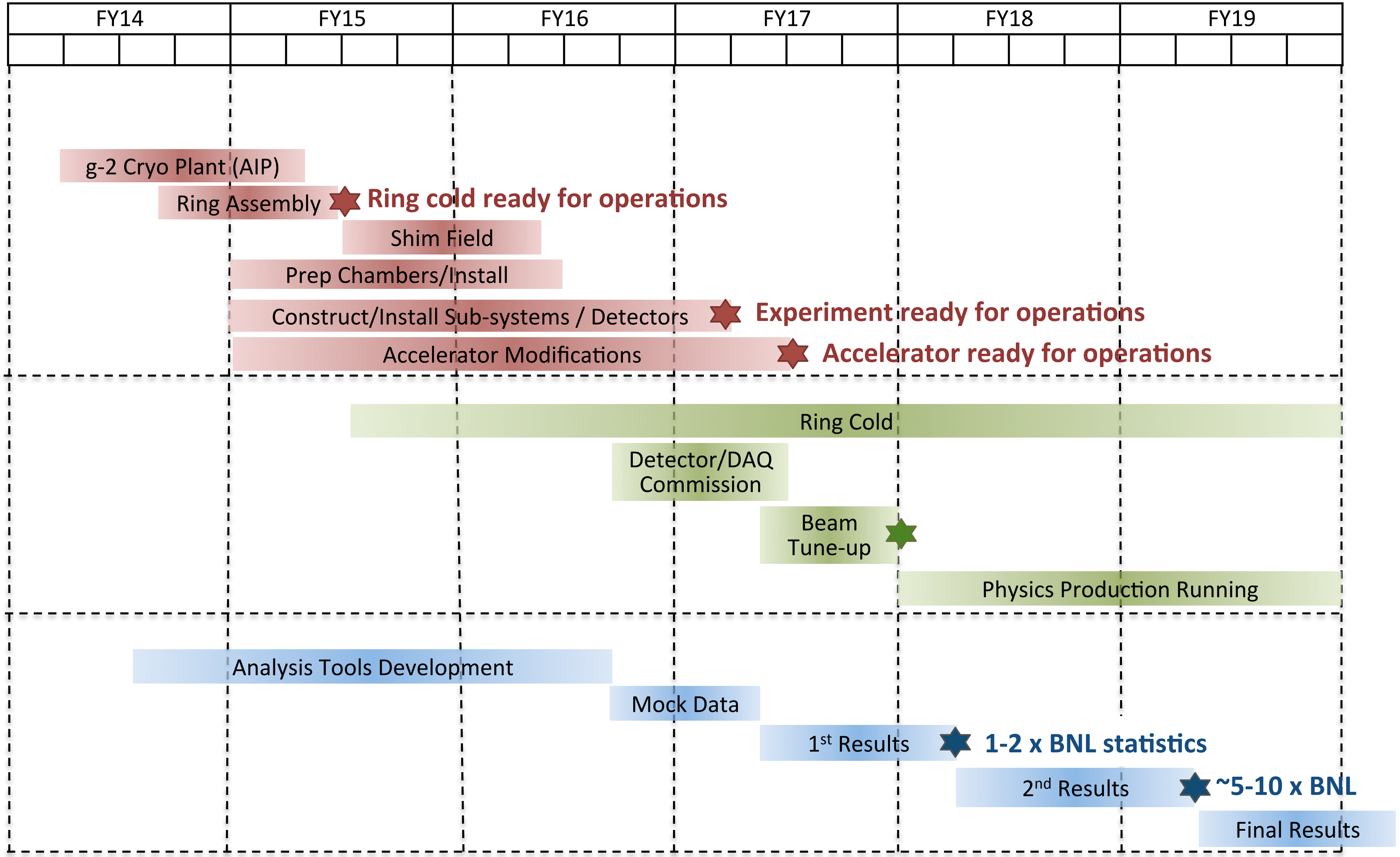
Particularly attention is being paid to gain of calorimeter.

Improved wrt to BNL through: better temperature control & much reduced hadronic-flash negating the need for gated operation





Timeline


FY14
FY15
FY16
FY17
FY18
FY19
g-2 Cryo Plant (AIP)
Ring Assembly
Ring cold ready for operations
Shim Field
Prep Chambers/Install
Construct/Install Sub-systems / Detectors
Experiment ready for operations
Accelerator Modifications
Accelerator ready for operations
Ring Cold
Detector/DAQ Commission
Beam Tune-up
Physics Production Running
Analysis Tools Development
Mock Data
1st Results
1-2 x BNL statistics
2nd Results
~5-10 x BNL
Final Results

Conclusion

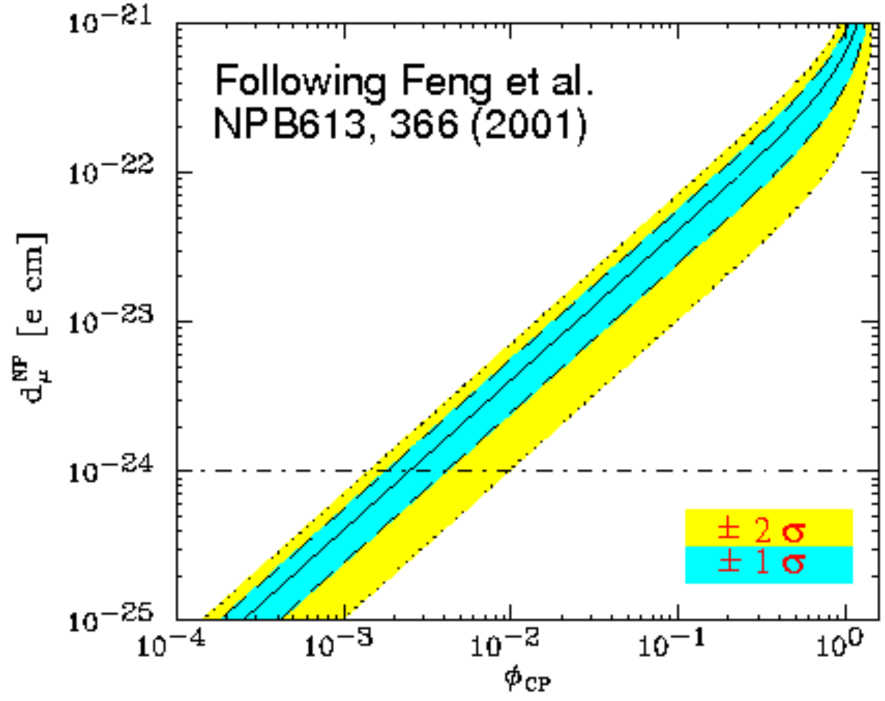
"If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known" : Pauli

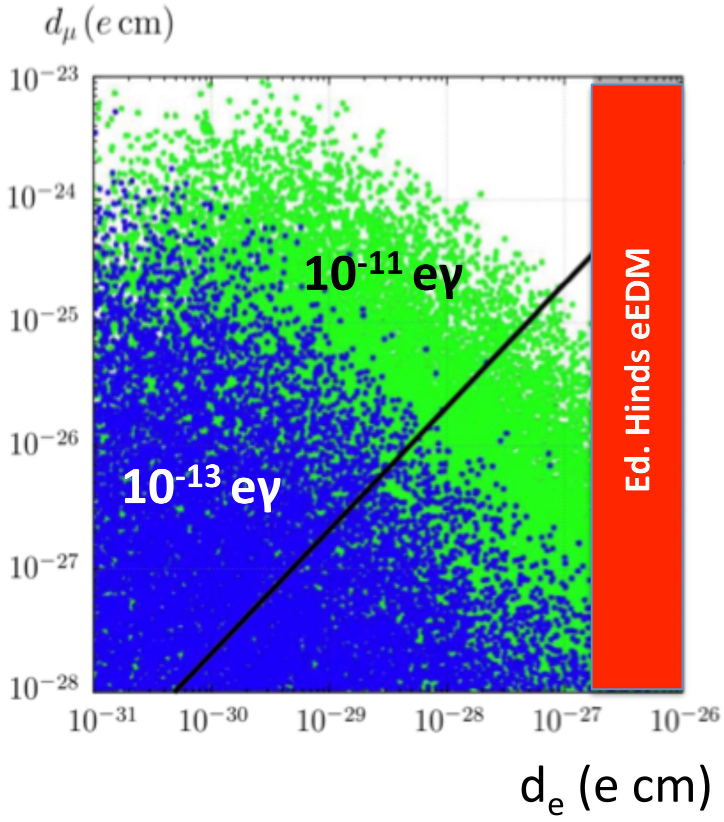
"No experiment is so dumb, that it should not be tried" : Gerlach

BACKUP

Muon EDM

Muon EDM in two BSM models.

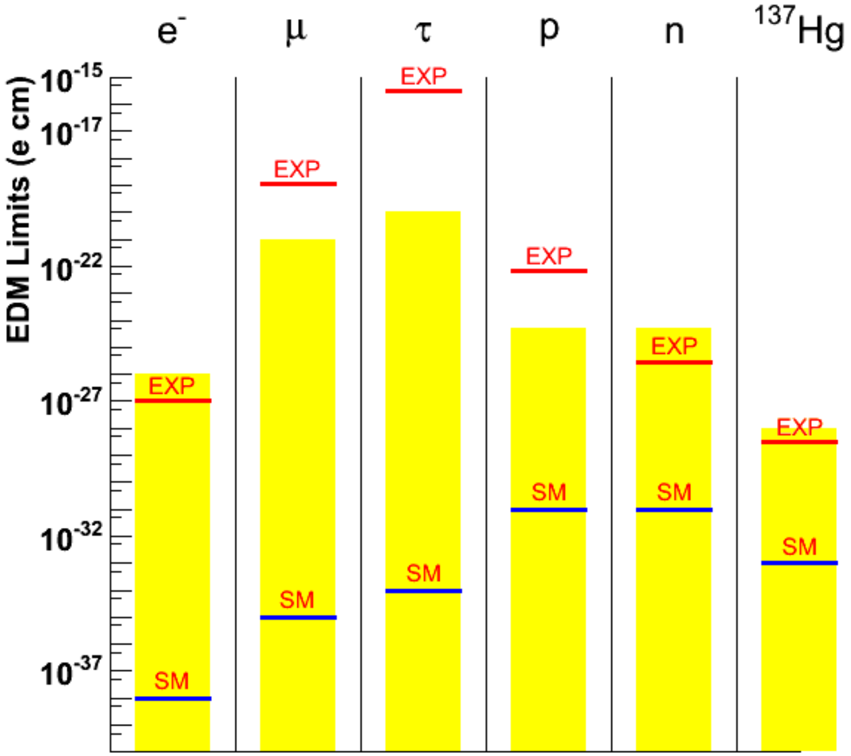




BSM predictions range from: 10^{-21} to 10^{-28}

Muon EDM

Essentially zero in SM : any observation is new physics



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

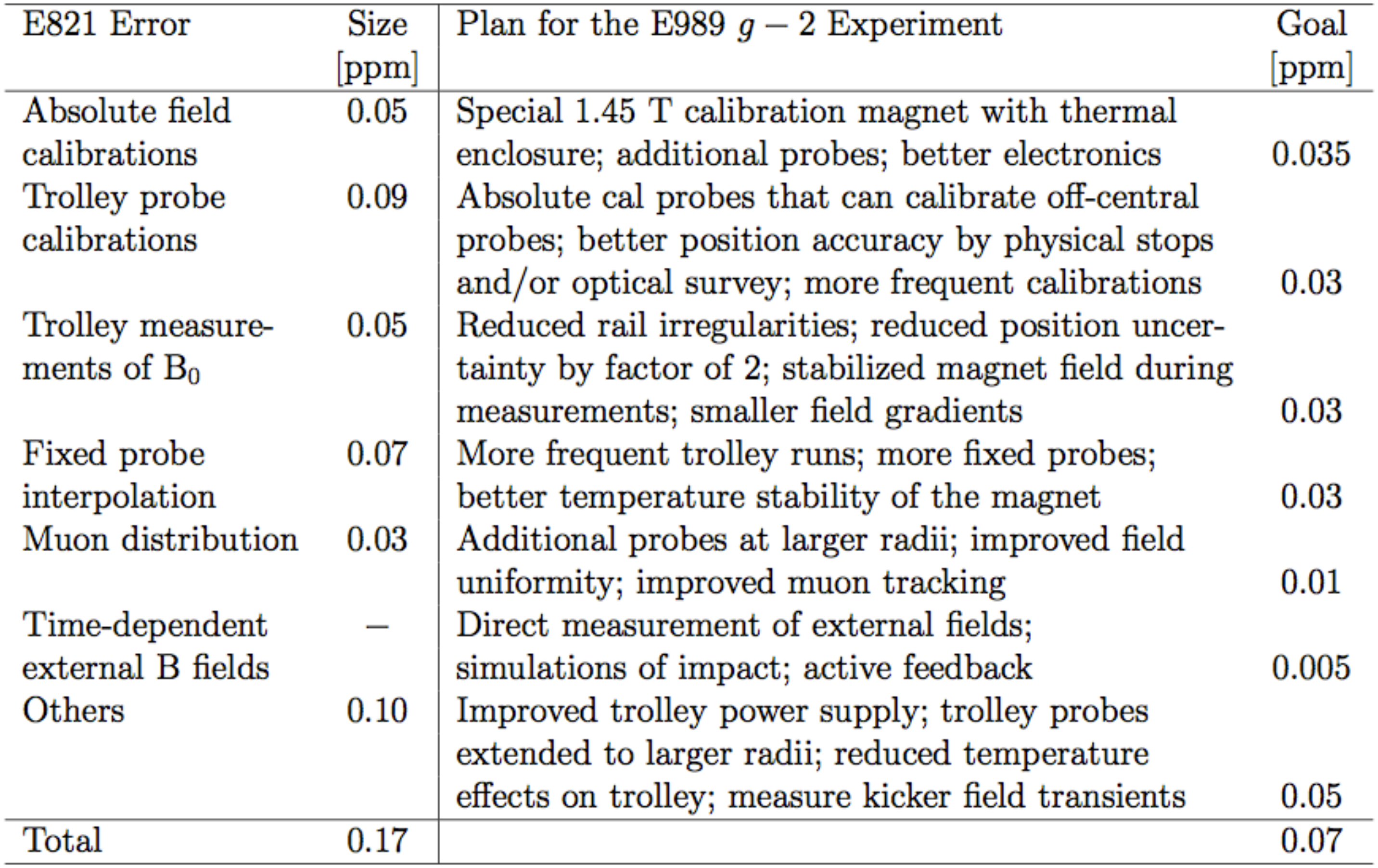
BNL limit is 1.8 x 10^{-19}

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

If there are non mass-scaling BSM effects then 10^{-21} becomes competitive

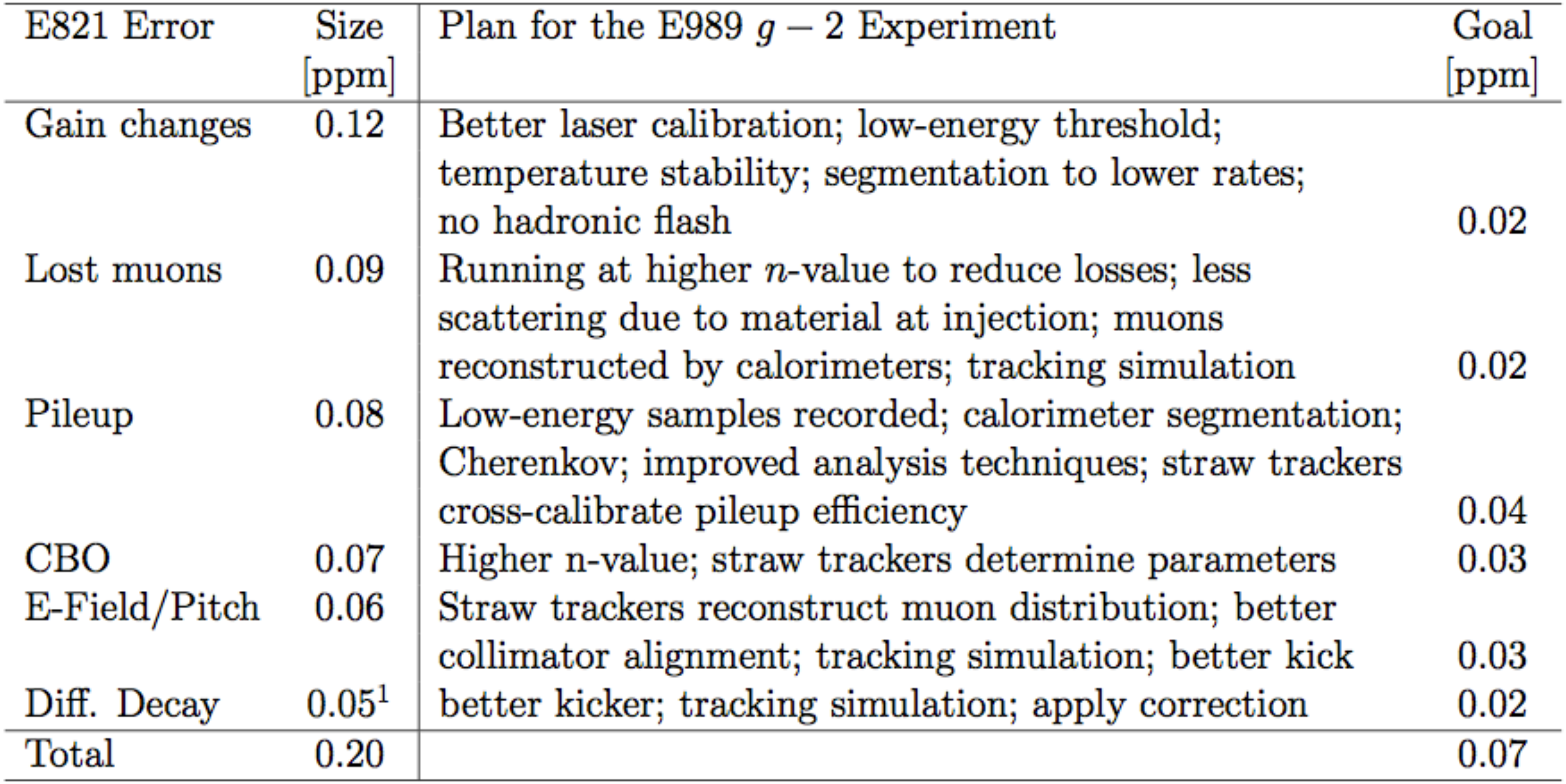
Measurement can only be performed using the tracking detectors

B-field / ω_p systematics



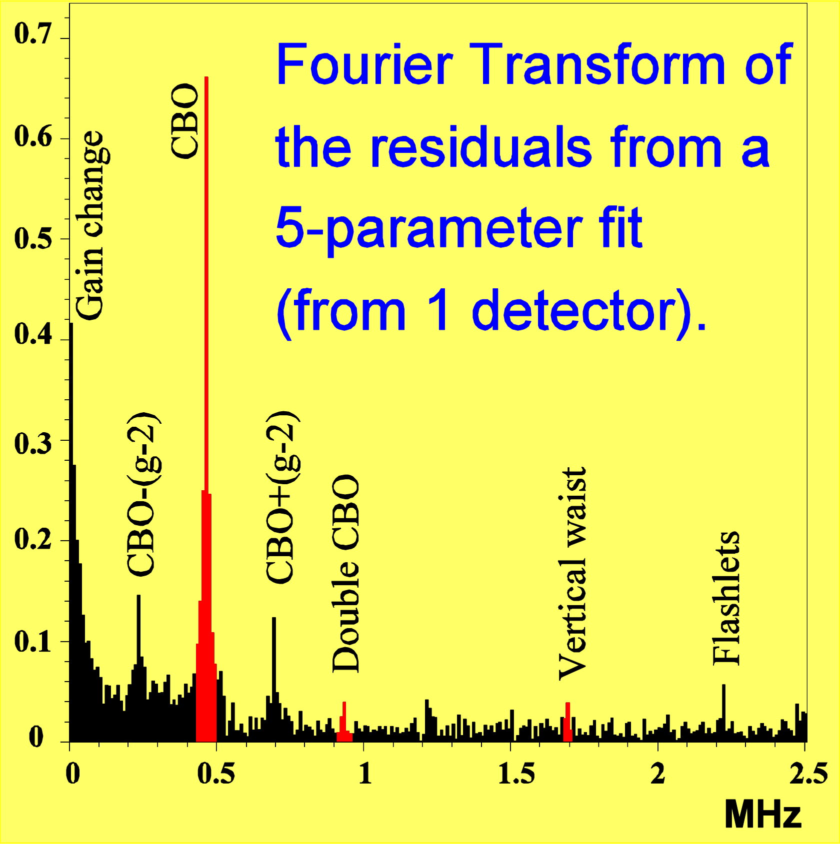
E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better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

ω_a systematics



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

CBO



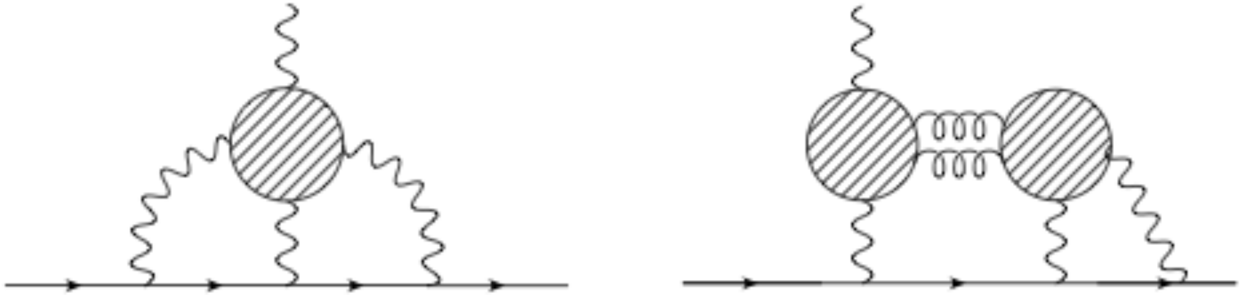
CBO means B.β not zero and adds frequency component to ω_a

Hadronic Corrections

Hadronic Vacuum Polarisation (HVP)

0.36 ppm

Hadronic Light-by-Light (HLBL)

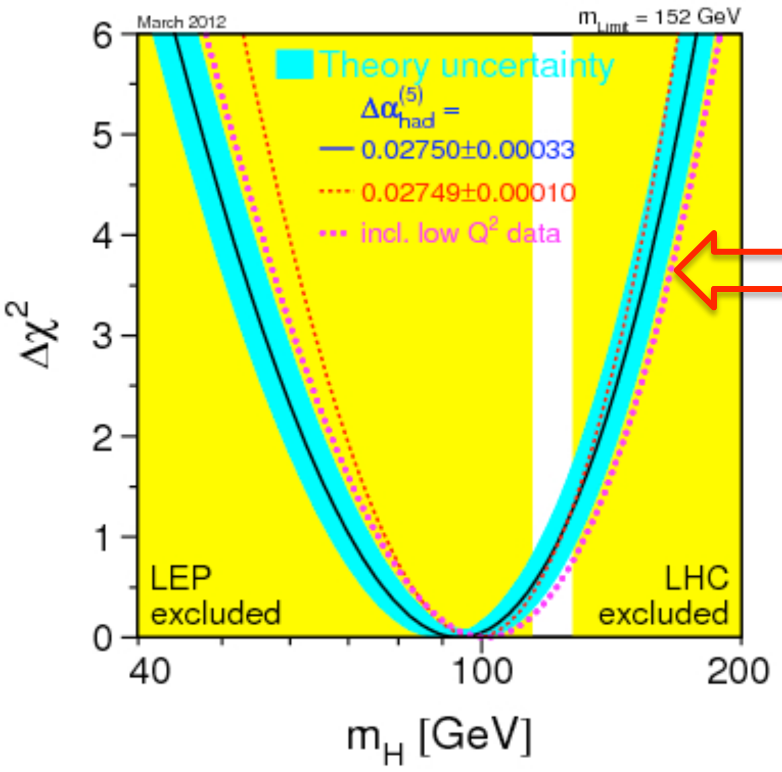


0.22 ppm

Reducing this 0.42 ppm to ensure 0.14 ppm FNAL measurement has maximum impact is a high priority.

Is this hadronic estimate reliable ?

97% of the hadronic estimate is **data-driven** and it can now be cross checked by the measured Higgs Mass



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

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

This HVP value (+ other EWK data) gives

$$M_H = 94^{+29}_{-34}\ \mathrm{GeV}$$

Assume HVP is wrong by 6 σ (so BNL = SM)

$$M_H = 68^{+29}_{-34}\ \mathrm{GeV}$$

Use M_H = 125 GeV for HVP **increases significance** of BNL discrepancy wrt SM