Status of the FNAL g-2 experiment

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on behalf of the g-2 collaboration

22nd June 2016
Virginia

Outline

- Introducing the anomaly
- Theoretical predictions
- Current experimental limits
- How to measure the anomaly
- Expected improvements at FNAL
- Time scale

Magnetic moments - QM

- 1928 - Dirac combined special relativity and quantum mechanics

$$(i\gamma^{\mu}\delta_{\mu} - m) = 0$$

- Led to reinterpretation of spin ½ particles as 4D spinors
  - Associated extra DOFs with spin, matter and anti-matter
- When placed in a field a potential-energy-like term appears, suggesting an intrinsic spin, the associated dipole moment is given by:

$$\vec{\mu} = g\frac{e}{2mc}\vec{S}$$

- g, the proportionality constant, is known as the gyromagnetic ratio
- Predicted by Dirac to be exactly 2 for spin ½ particles

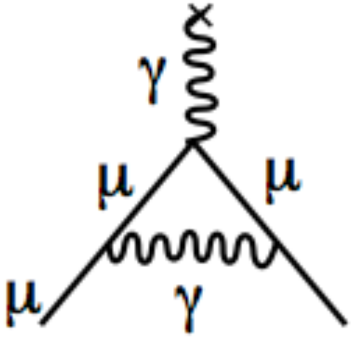
Introducing the anomaly

- 1947 Kusch-Foley experiment discovered an anomaly in the electron dipole moment
  - $g_e = 2.00238(6)$
- The anomaly is parameterised via:

$$a = \frac{g-2}{2}$$

- Within a year Schwinger had calculated the first order QED correction, for electrons, but applies to muons:

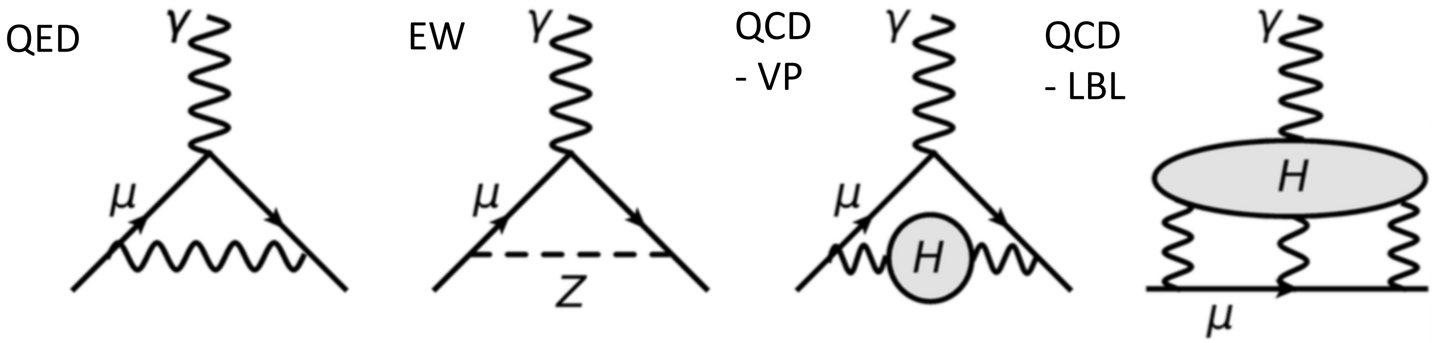
$$g = 2(1 + \frac{\alpha}{2\pi}) \approx 2.00232$$



DOI:http://dx.doi.org/10.1103/PhysRev.72.1256.2

Standard model predictions

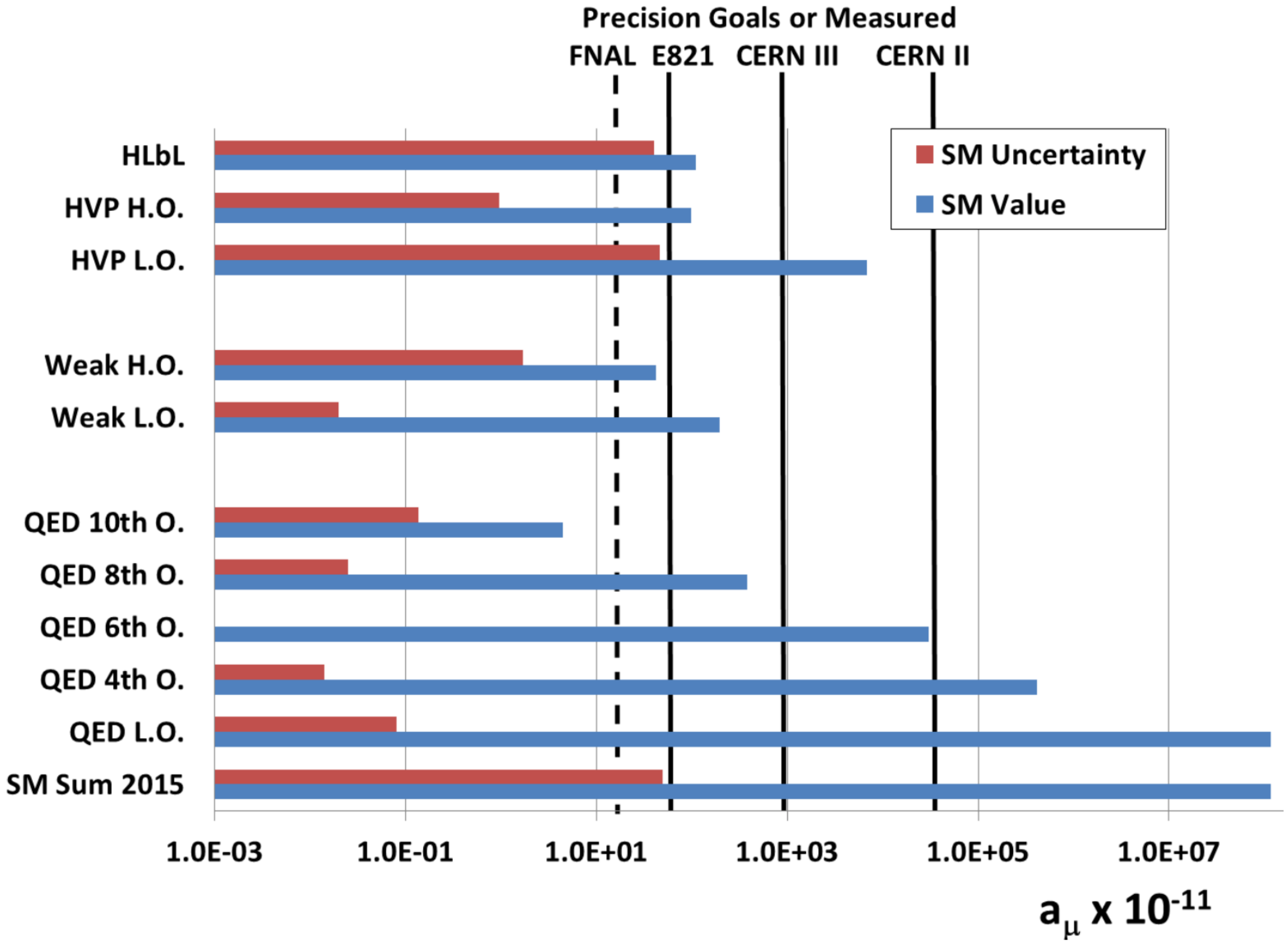
- There are higher order QED corrections, EW and QCD



- All diagrams need to be included in calculation
- So far the best prediction is:

$$g_\mu = \underbrace{2}_{\text{Dirac}}.00\underbrace{2\,3}_{\substack{\text{Schwinger}\\ \sim O(1)\text{ QED}}}\underbrace{3\,1}_{\substack{\text{Kinoshita}\\ \sim O(10)\text{ QED}}}\,\underbrace{8\,4}_{\text{Hadronic}}\overbrace{1\,7}^{\text{EW}}8(126)$$

SM uncertainties

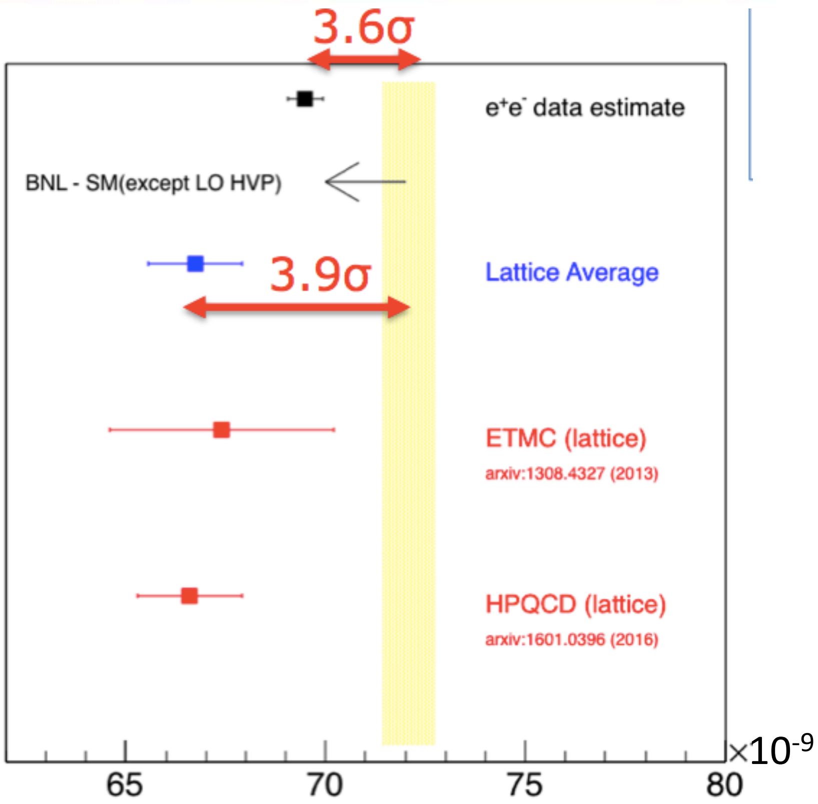


- SM uncertainty dominated by Hadronic - VP and LBL

HVP LO Davier et al, Eur. Phys. J. C(2011) 71:1515; HVP NLO Hagiwara et al, J. Phys. G38, 085003 (2001); HLbL Prades et al, Lepton Moments

Anticipated improvements to SM

- HVP can be tied to experimental data from e^+e^- collisions
  - New data expected from SND, CMD-3. BES-III, Belle-II…
  - Continuously updating SM prediction
- Alternative lattice calculation agrees with this prediction



- Hadronic light by light must be calculated by theory - lattice
- Factor of 2 improvement in SM calculation expected by end of data taking

Sensitivity to new physics

- Anomaly is due to vacuum interactions - sensitive to new physics
- But it hasn't shown up in a_e, why expect it in a_μ?
- Sensitivity to new physics proportional to squared mass of probe

$$\left(\frac{m_e}{m_\mu}\right)^2 \sim 4 \times 10^4$$

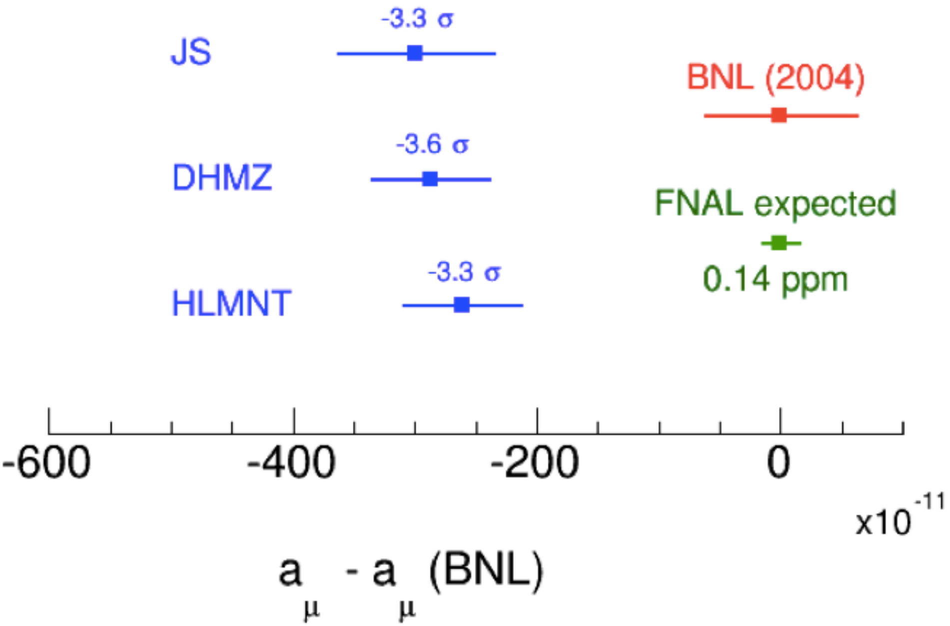
- For example EW contributes 1.3 ppm to a_μ, but only 26 ppt to a_e
- When using muons:
  - Relatively long lifetime means we can store muons
  - High production cross section
  - Relatively easy to polarise

Current experimental limits on a_μ

- Most precise measurement performed at BNL (1999-2001)
- Accuracy of ~0.5 ppm

$$a_\mu^{exp} = 116\,592\,089\,(0.54)_{st}(0.33)_{sy}(0.63)_{tot} \times 10^{-11}$$

- Uncertainty is dominated by statistics



- Measurement differs from theory by ~3.5 σ

$$\Delta a_\mu^{(\mathrm{today})} = (287 \pm 80) \times 10^{-11}$$

How to measure the anomaly

- Store longitudinally polarised muons in a dipole field
- Measure 2 quantities:
  - ω_a - the precession frequency
  - <B>, the average magnetic field sampled by the muon distribution

$$\boxed{\omega_a} = \omega_s - \omega_c = a_\mu \frac{e\boxed{< B >}}{m_\mu c}$$

Larmor Precession   Thomas Precession

$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

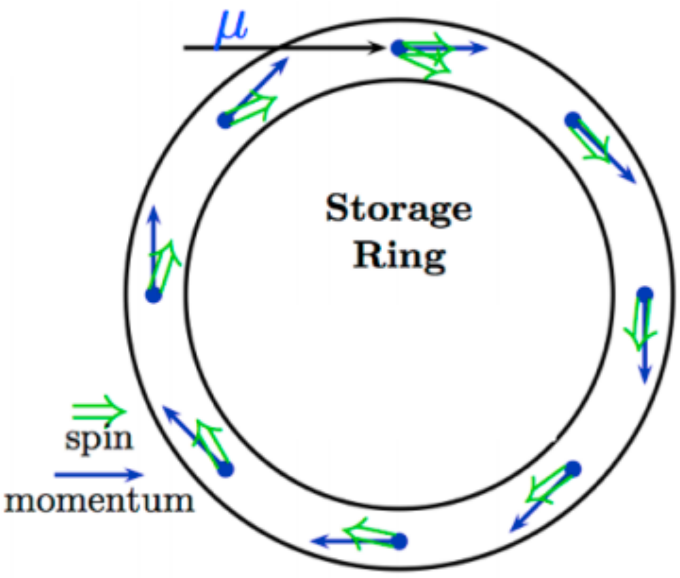
Spin Precession frequency

$$\omega_c = \frac{eB}{\gamma mc}$$

Cyclotron frequency

~140ns

~149ns



actual precession × 2

- Spin precessesion > 2π per cyclotron turn

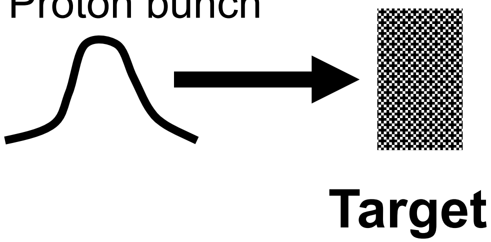
Magic momentum

- Electric quadrupoles used for vertical focusing seen as magnetic field in muon rest frame
- Assuming velocity is perpendicular to E and B fields:

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

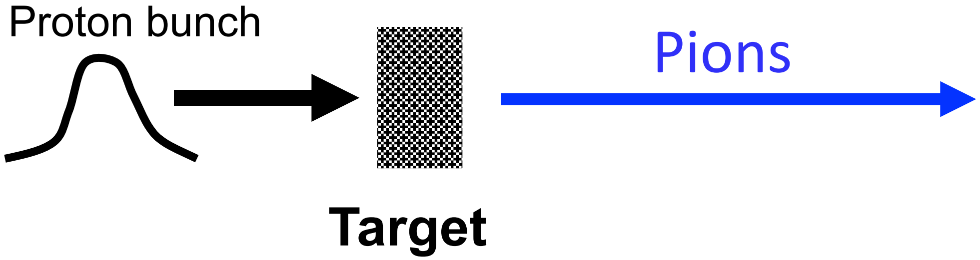
- By choosing $\gamma = 29.3$, $p_\mu = 3.09\ \mathrm{GeV}/c^2$, $\beta \times E$ term is 0
- At this momentum the magnetic field alone determines the precession frequency - only need to measure B and ω_a
- Dilated muon lifetime is 64.4 µs

Supplying anti-muons



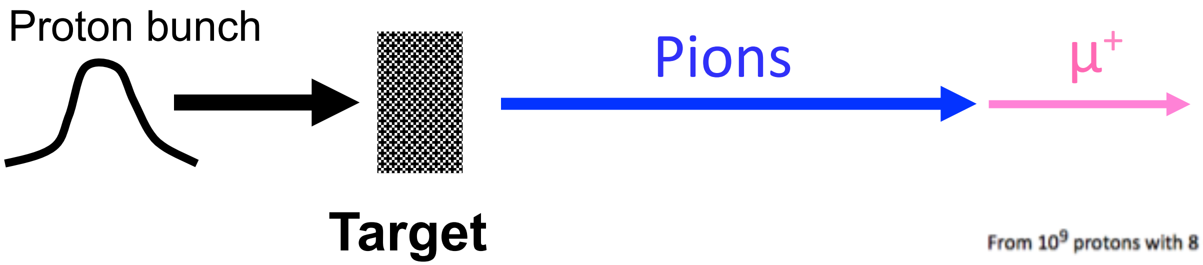
- Booster & Recycler supply 120 ns wide 8 GeV proton bunches
- Fired at pion production target

Supplying anti-muons



- Outgoing pions focused by a lithium lens and then momentum-selected, centred on 3.11 GeV
- The pions are then collected and sent towards the delivery ring

Supplying anti-muons



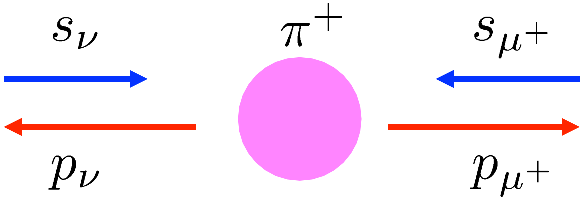
Proton bunch

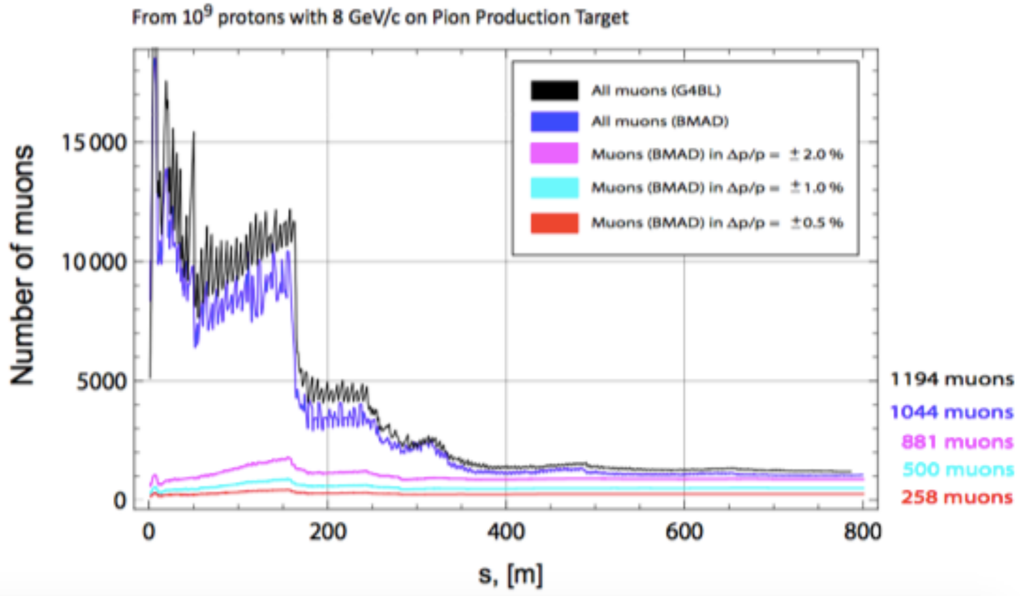
Pions

μ^+

Target

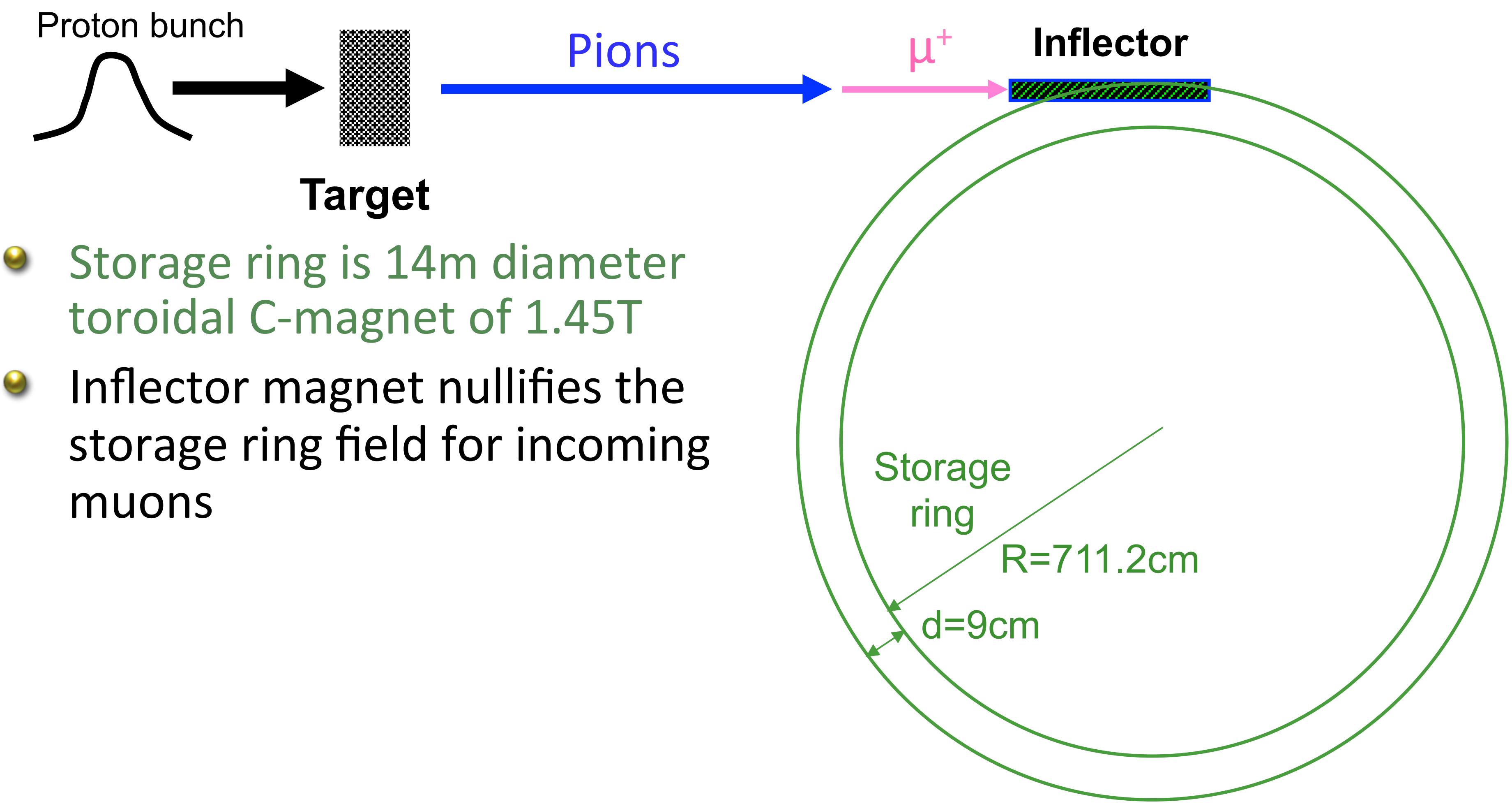
- In the delivery ring the pions decay to negative helicity anti-muons




From 10^9 protons with 8 GeV/c on Pion Production Target

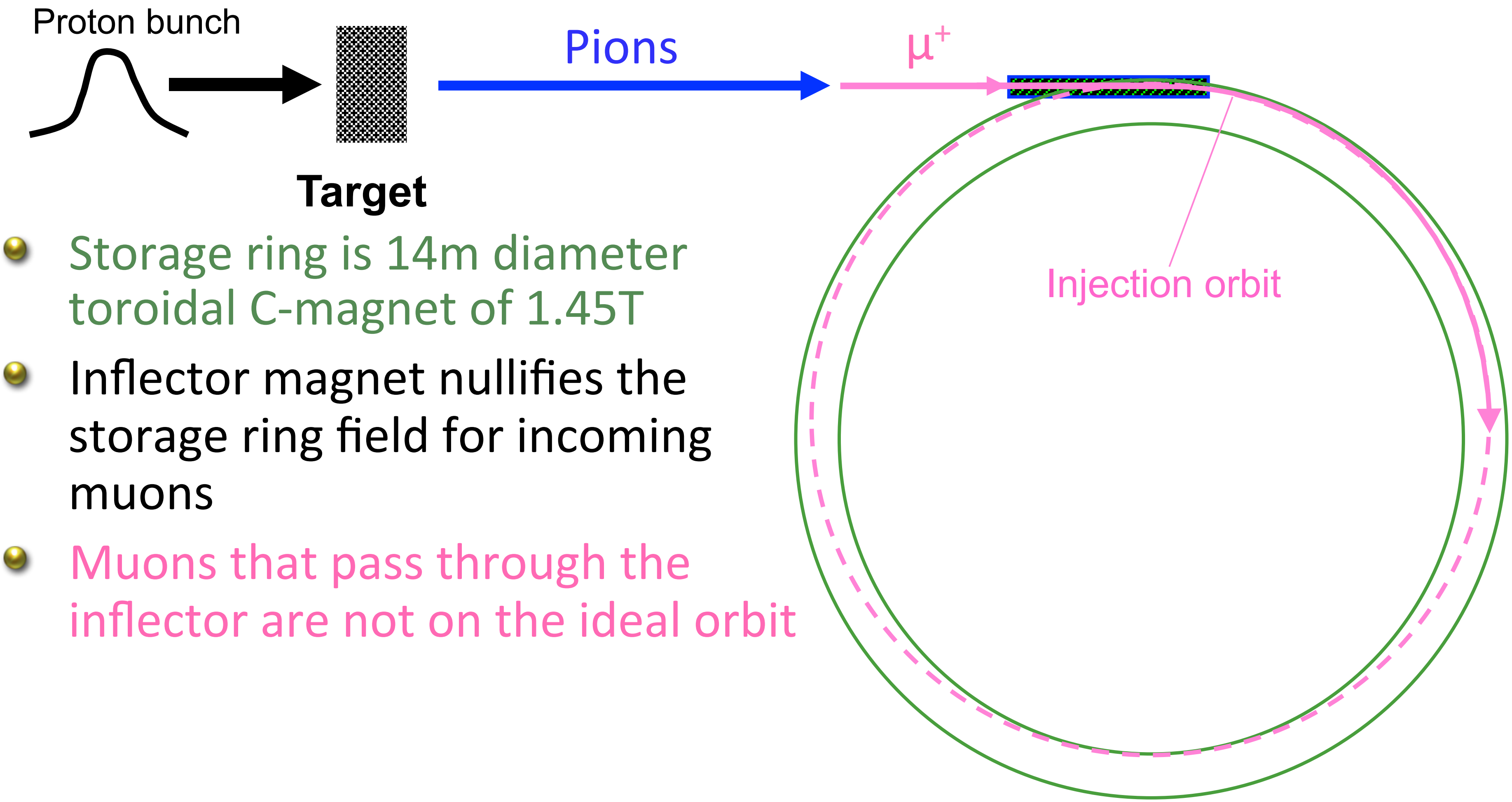
- 2 independent simulations of polarisation and phase space of beam

Supplying anti-muons



- Storage ring is 14m diameter toroidal C-magnet of 1.45T
- Inflector magnet nullifies the storage ring field for incoming muons

Supplying anti-muons



Proton bunch

Target

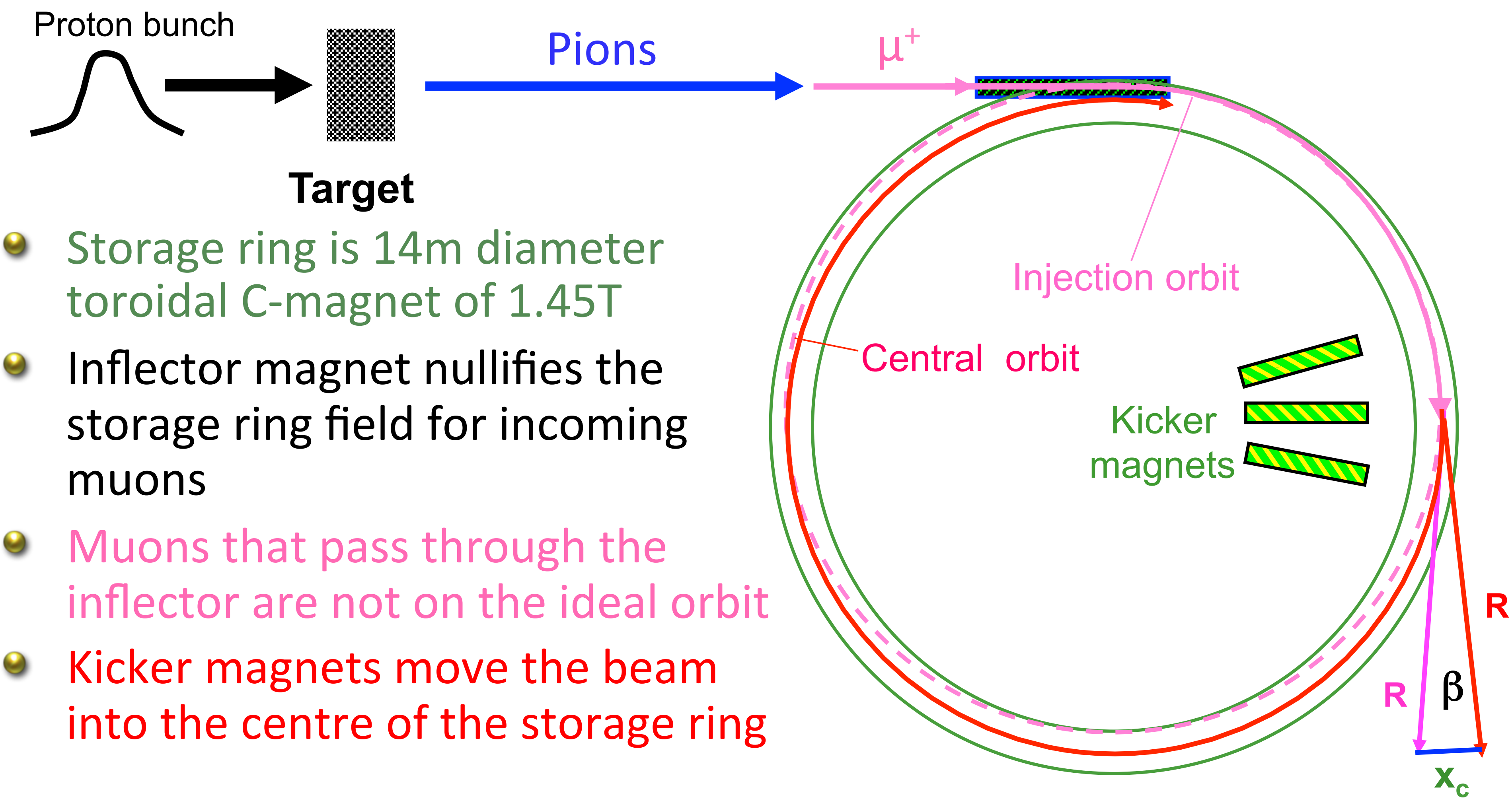
Pions

μ^+

Injection orbit

- Storage ring is 14m diameter toroidal C-magnet of 1.45T
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are not on the ideal orbit

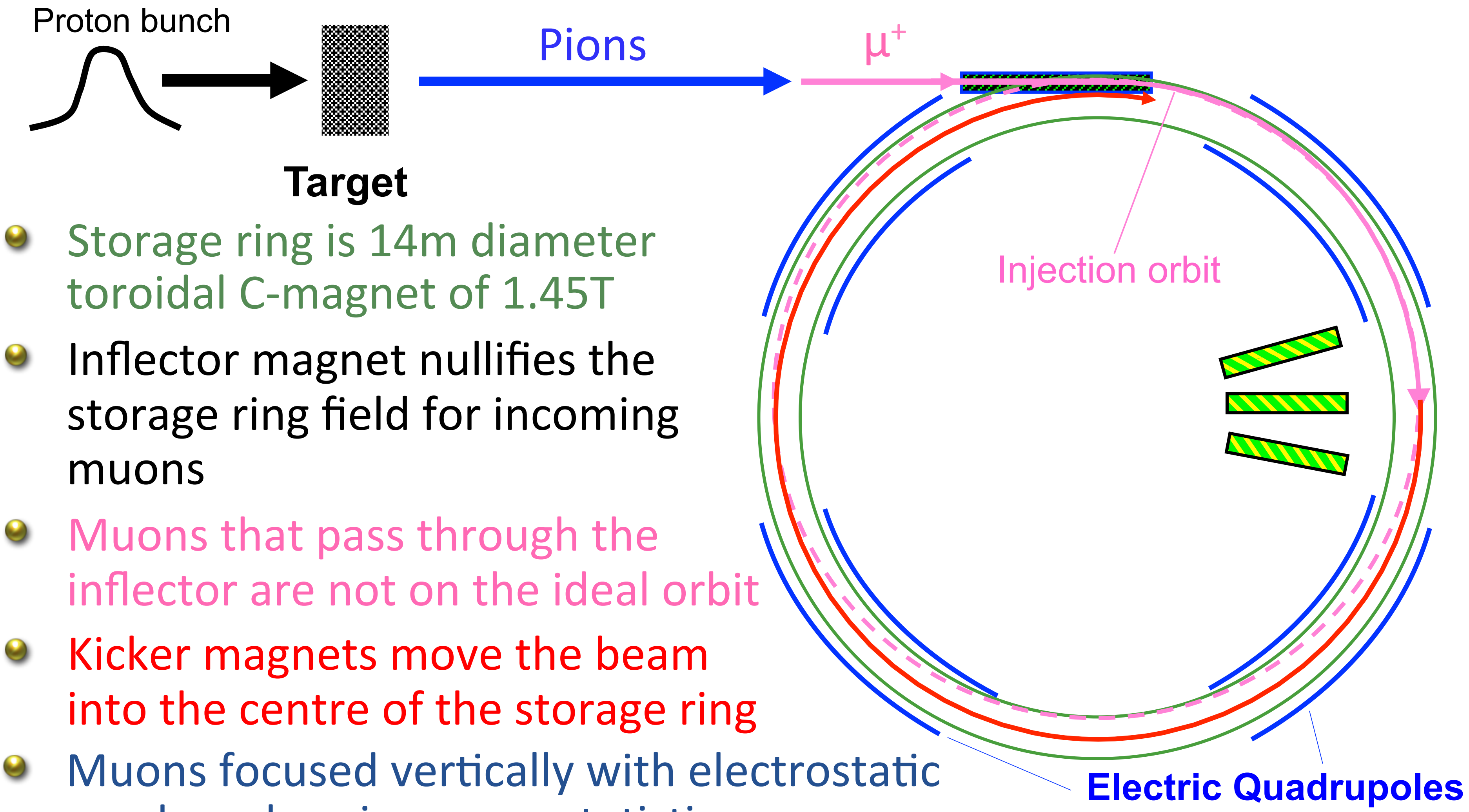
Supplying anti-muons



- Storage ring is 14m diameter toroidal C-magnet of 1.45T
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are not on the ideal orbit
- Kicker magnets move the beam into the centre of the storage ring

Xc ~ 77mm
β ~ 10mrad

Supplying anti-muons



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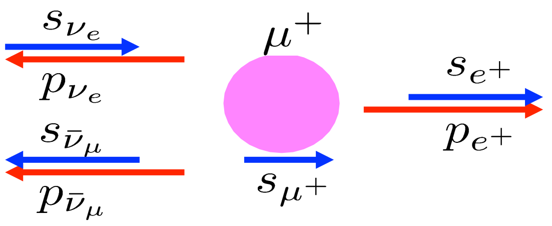
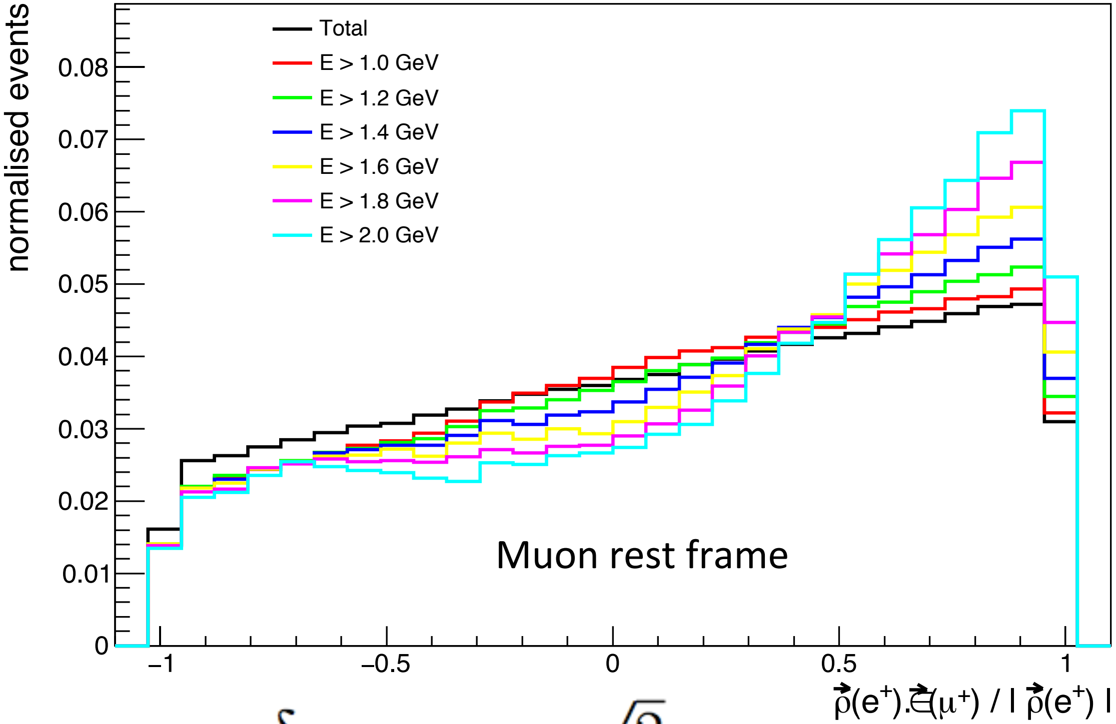
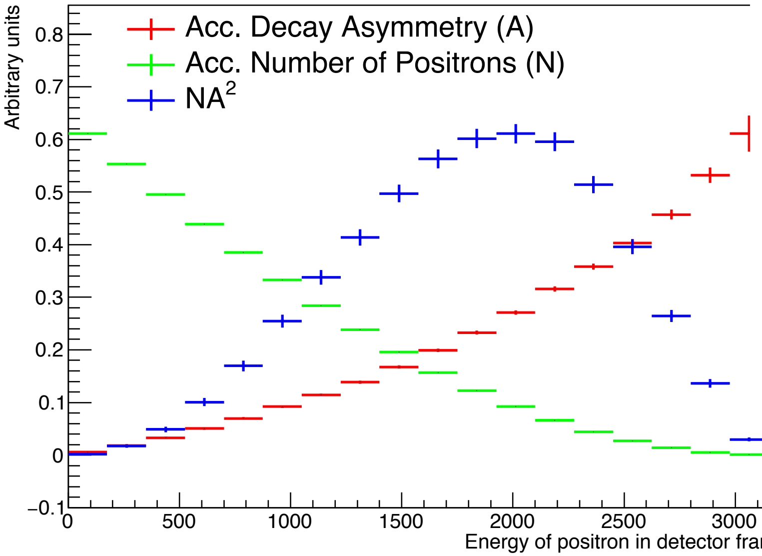
- Muons that pass through the inflector are not on the ideal orbit
- Kicker magnets move the beam into the centre of the storage ring
- Muons focused vertically with electrostatic quadrupoles - improves statistics

Muon decay

- e^+ preferentially emitted in direction of the μ^+ spin





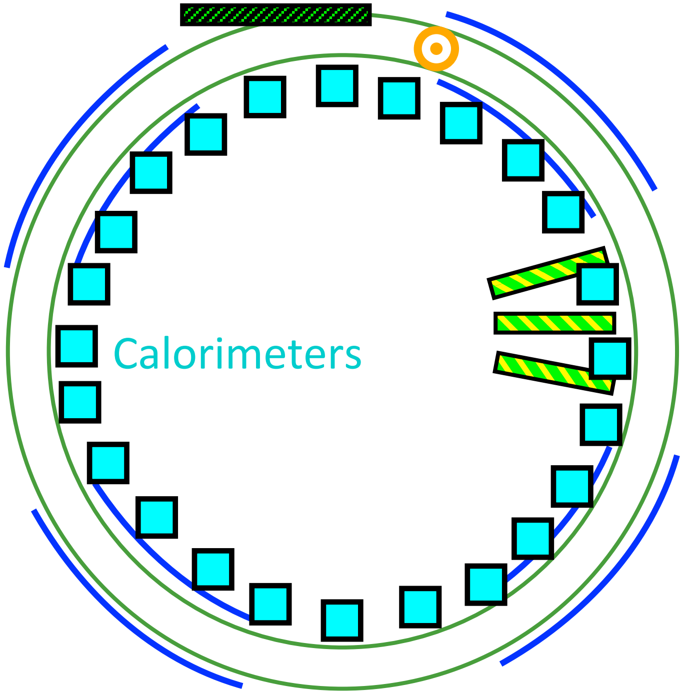


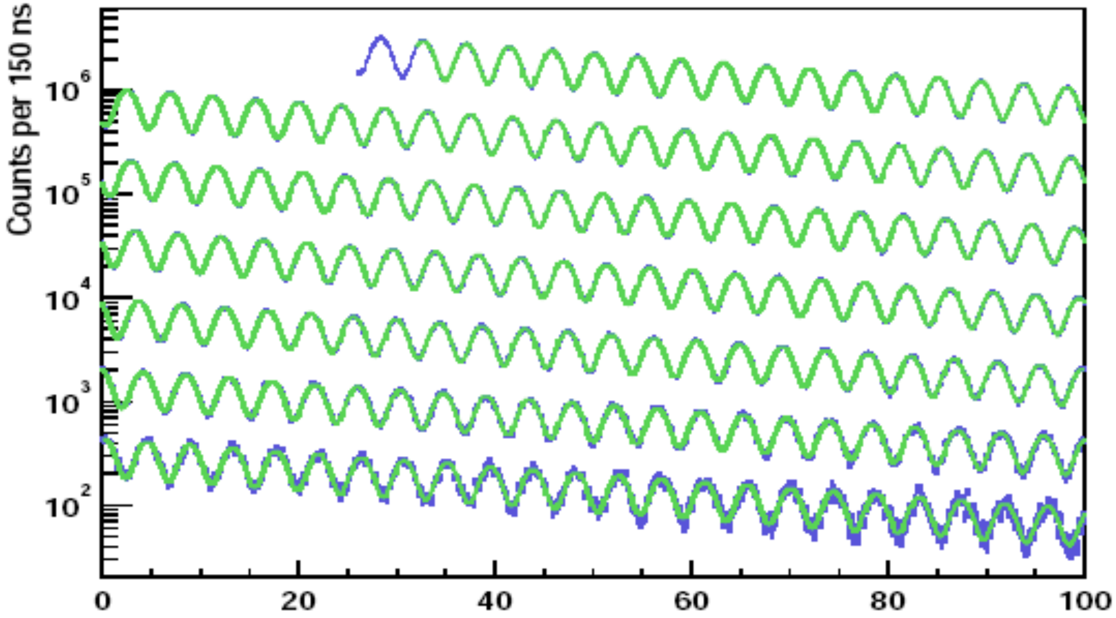
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu \sqrt{NA^2}}$$

- Asymmetry is larger for higher energy positrons
- Optimal cut at ~E > 1.8 GeV

Calorimeters

- 24 calorimeters are placed around ring
- They measure the e^+ from the μ decay
- Number of higher energy positrons oscillates as spin points towards/away from calorimeters

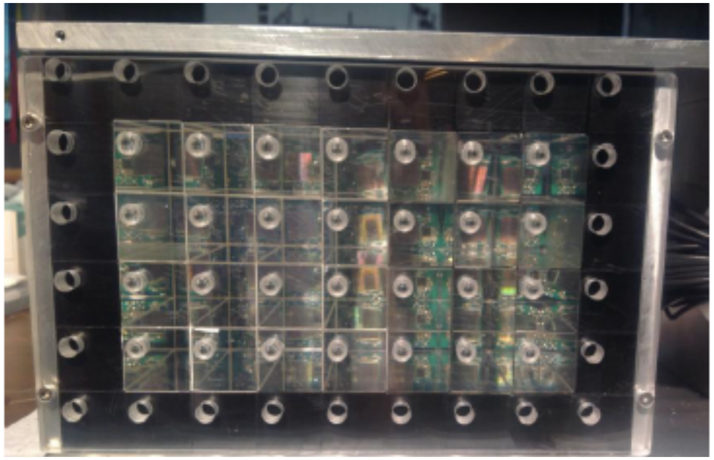


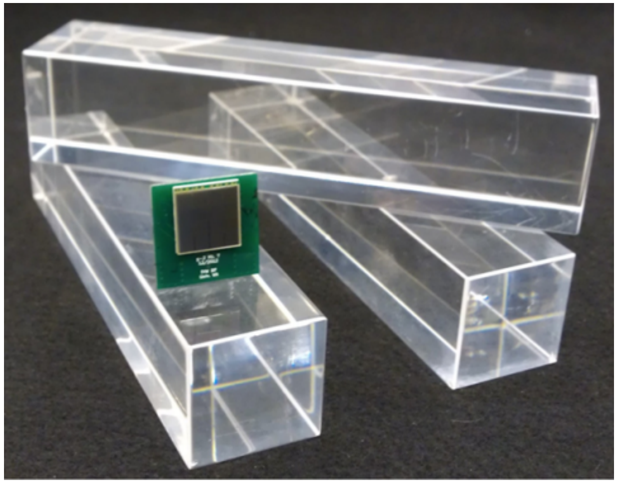


- Perform 5 parameter fit to arrival time spectrum - same as in BNL experiment

$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

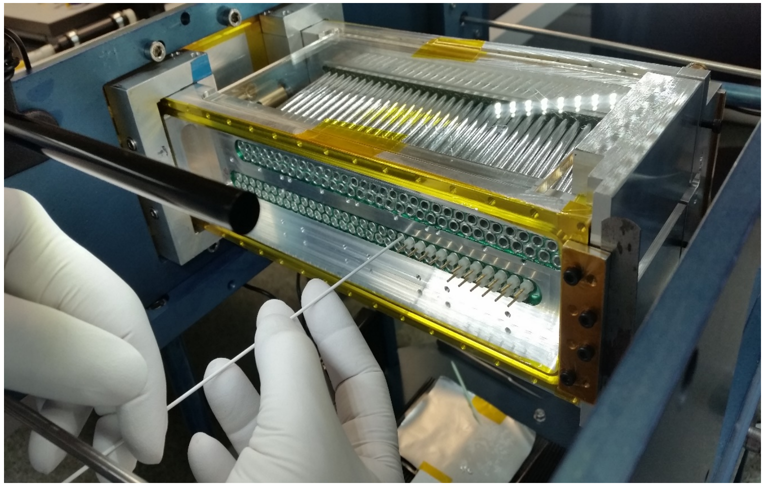
Calorimeters

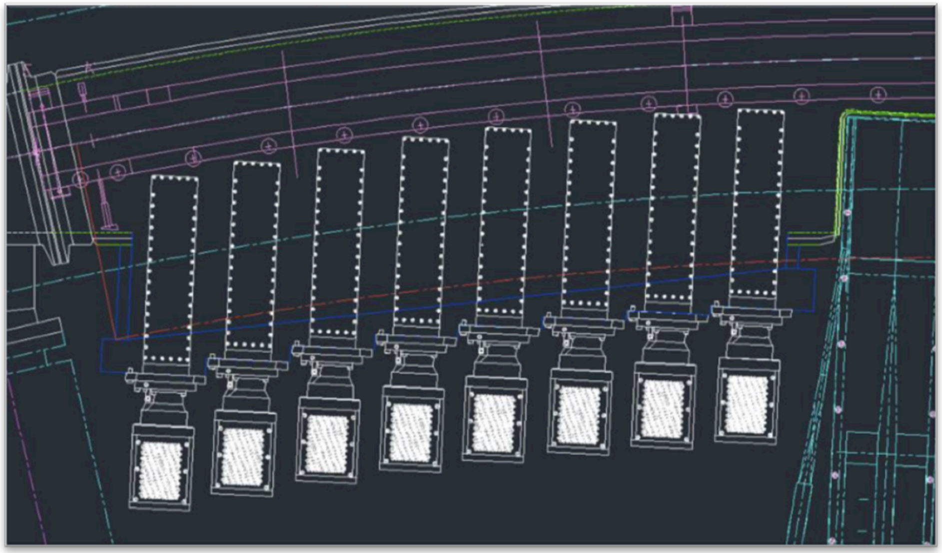




- Each consists of 6 by 9 array of PbF_2 crystals
  - Multiple test beams at SLAC with 28 crystals
- Each crystal is 2.5 x 2.5 x 14cm ~ ($15X_0$)
- Improvement in gain - event rate changes 4 orders of magnitude over 700 μs fill
- Increased segmentation reduces pile up
- Readout by SiPM

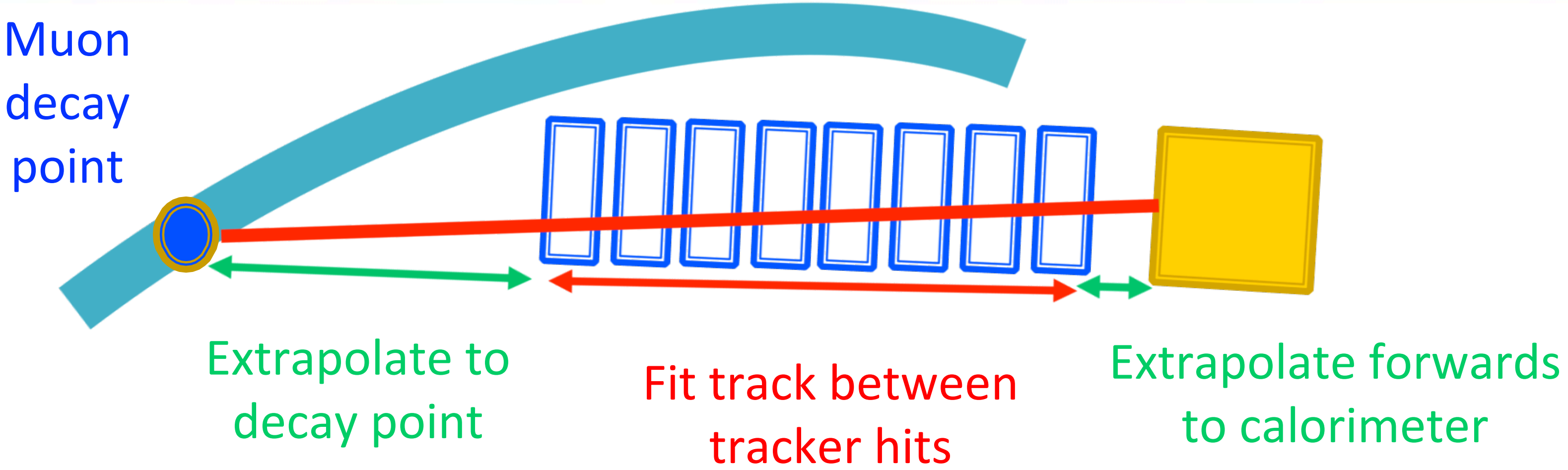
Trackers





- 3 trackers - each with 8 modules
- Placed in front of calorimeters
- Each module 128 straws filled with Ar-Ethane
- ~100 µm radial resolution
- Major improvements on tracking for E989
  - Allow extrapolation to decay point / into calorimeters

Improvements from trackers



- Measuring beam profile during spill allows reduction in several key systematics:

Decay point

- Magnetic field seen by muons
- Beam dynamics corrections
- Precession plane tilt

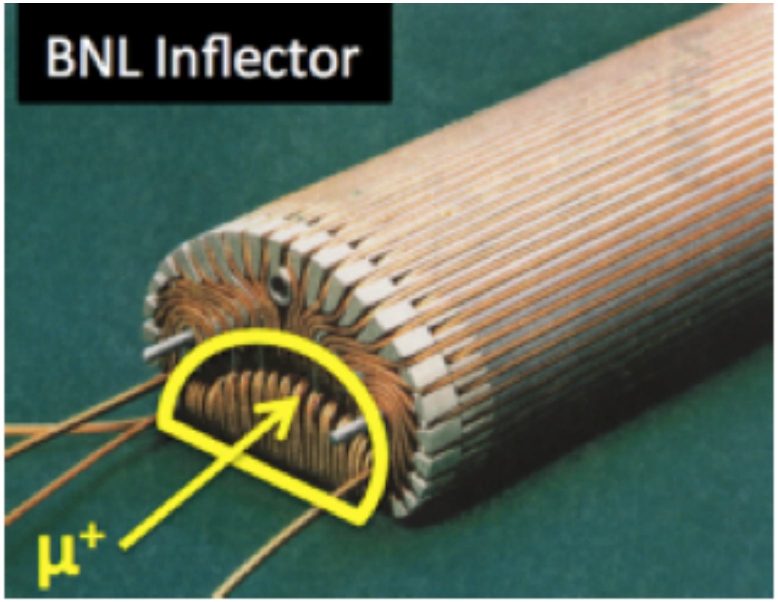
Calorimeter matching

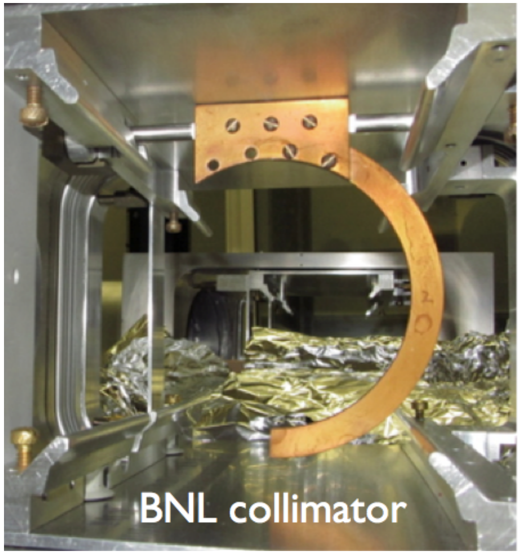
- Pileup correction
- Calorimeter gain stability

- Additional improvement in vertical measurement - EDM

Inflector / collimator

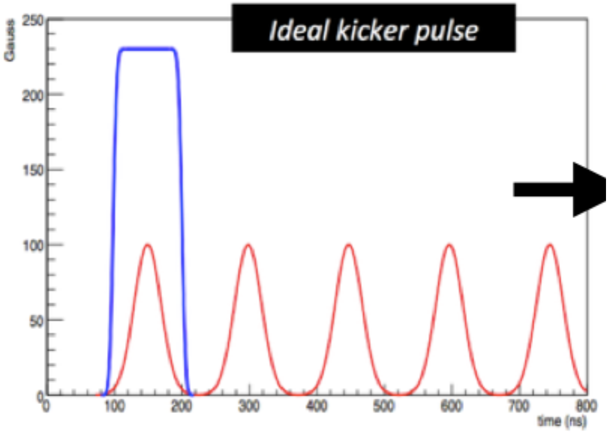
- Inflector actively cancels magnetic fringe field so that muons are injected tangentially
- New inflector scheduled for 2018 running period

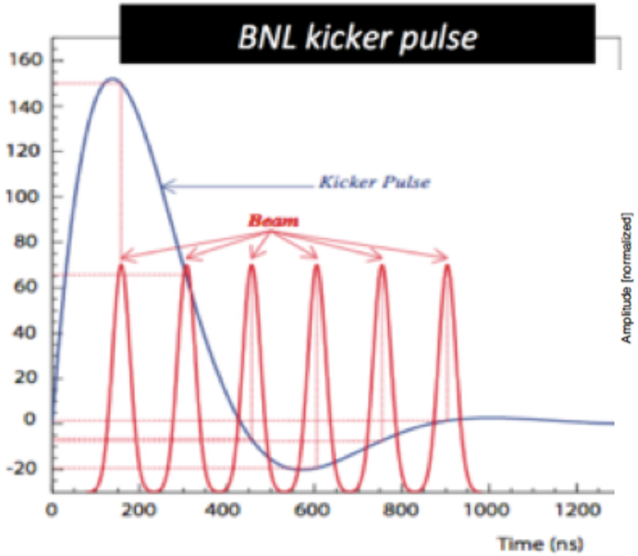


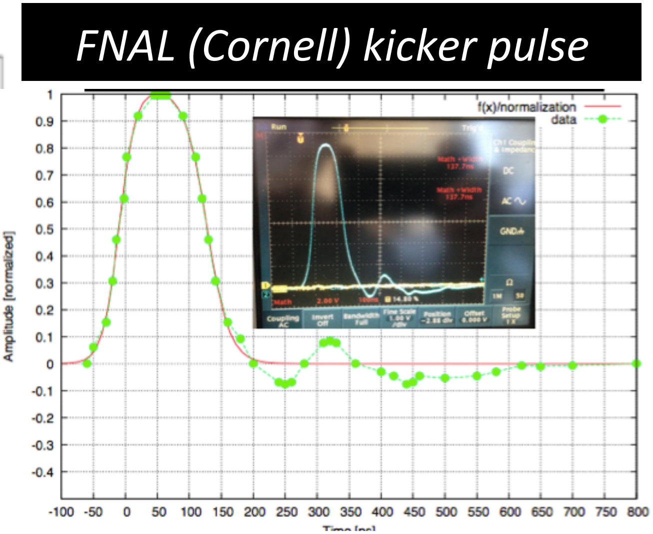


- Collimators help eliminate off magic momentum muons
- Increased thickness of collimators w.r.t E821 for better beam cleaning efficiency

Kickers

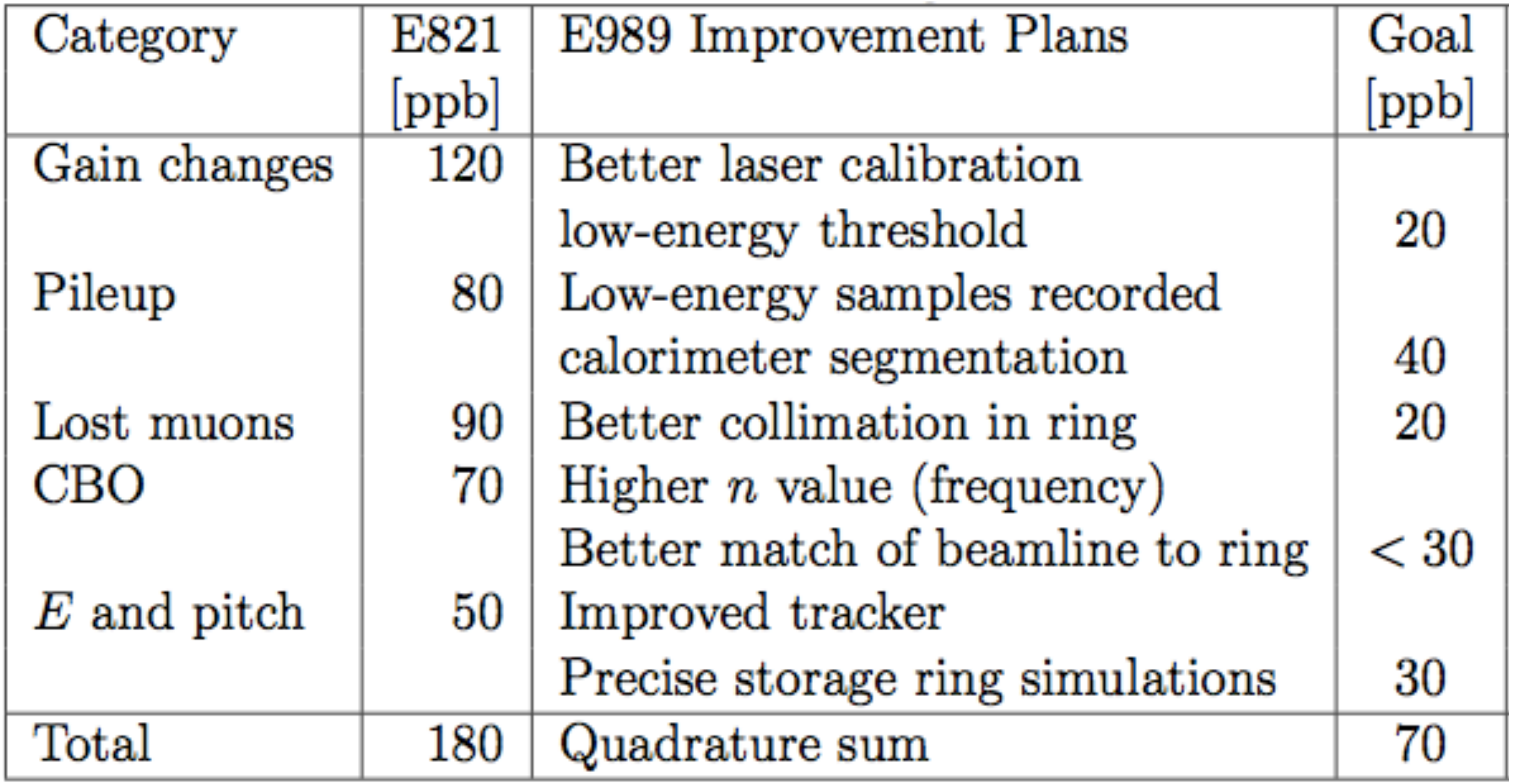

Ideal kicker pulse


BNL kicker pulse


FNAL (Cornell) kicker pulse

- Muon beam does not enter ring in central orbit
- To place the beam into the central orbit a quick magnetic field burst (kick) is supplied
- Change in angle of ~10.8 mrad
- Pulse must be shorter than 149ns - orbit time
- Vacuum chambers with kickers being installed this summer/fall

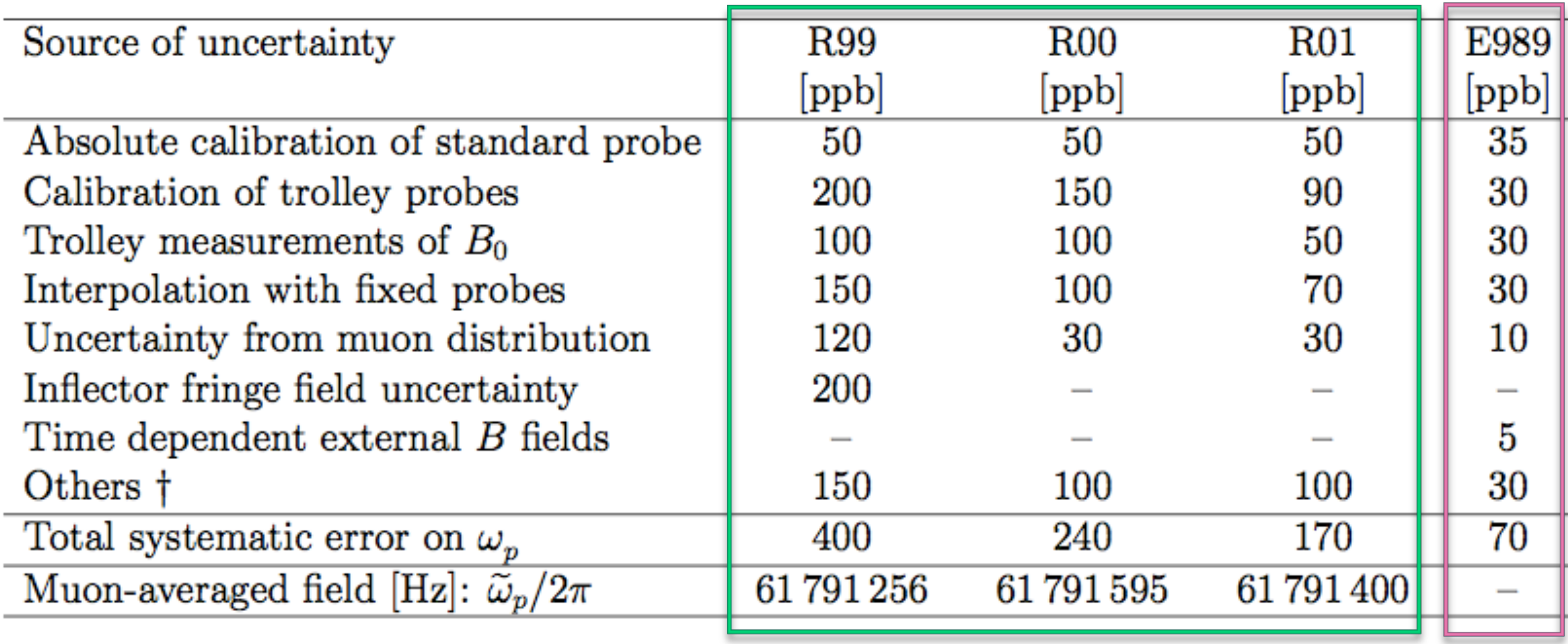
Improvements summary - ω_a



Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

Magnetic field - goals

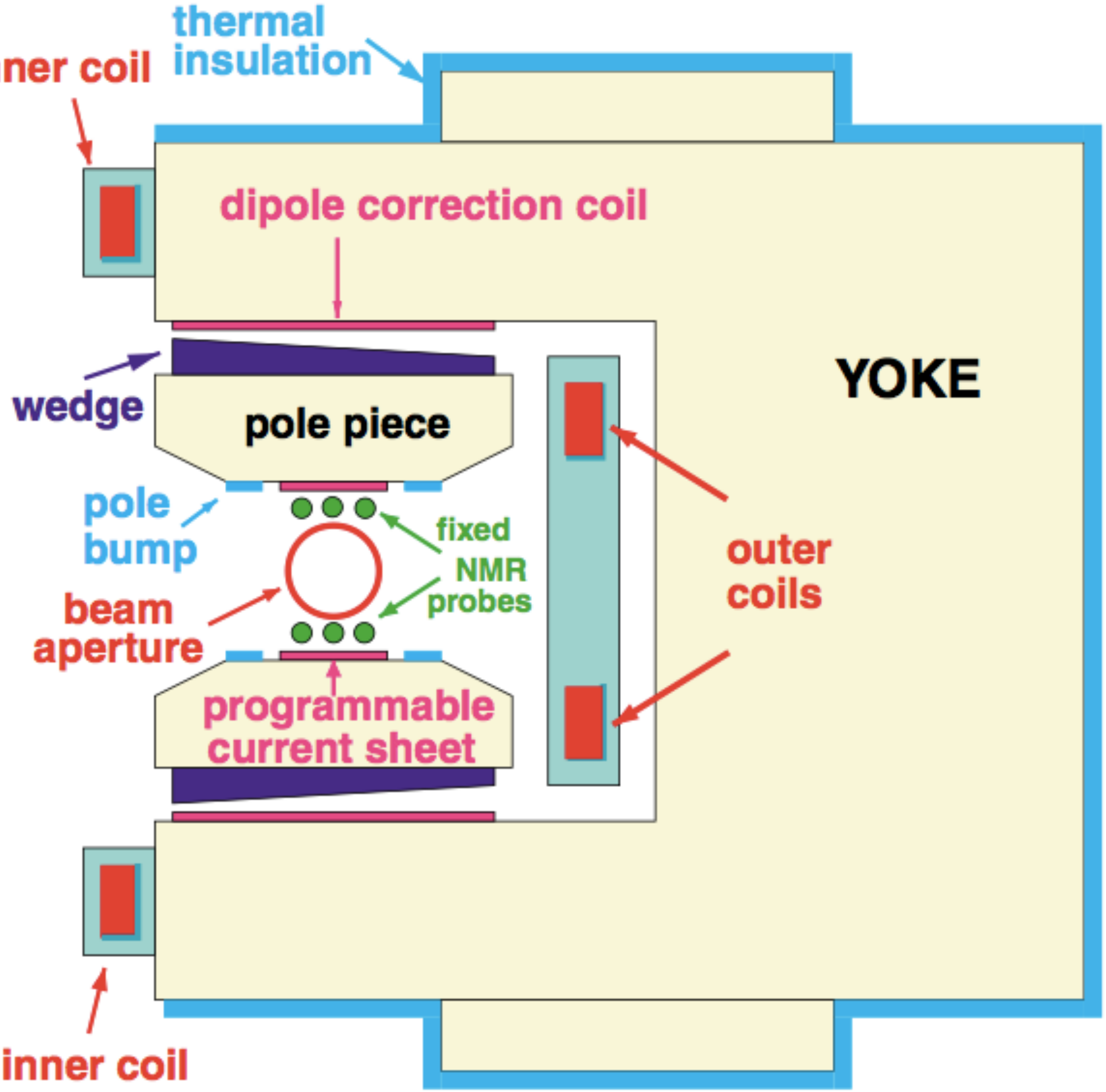
- BNL achieved ~1-2ppm deviation when averaged around azimuth
- FNAL aiming for factor of 2 improvement in homogeneity



Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	50	50	35
Calibration of trolley probes	200	150	90	30
Trolley measurements of B_0	100	100	50	30
Interpolation with fixed probes	150	100	70	30
Uncertainty from muon distribution	120	30	30	10
Inflector fringe field uncertainty	200	–	–	–
Time dependent external B fields	–	–	–	5
Others †	150	100	100	30
Total systematic error on ω_p	400	240	170	70
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–

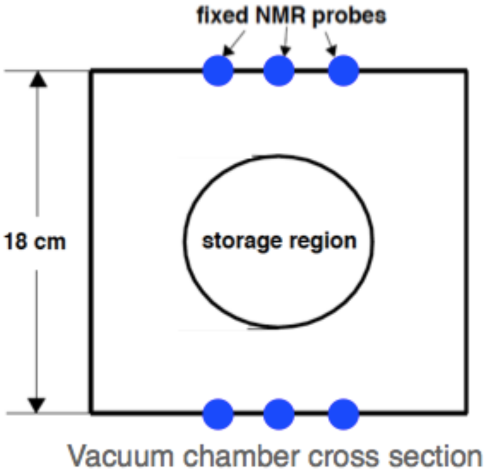
Magnetic field - shimming

- Multiple passive and active shimming tools
- Insert thin wedges into air gap to distort field
- Use to adjust field shape up to the decupole term
- ±1°C gives ± 40 ppm field strength change - so temperature monitored precisely

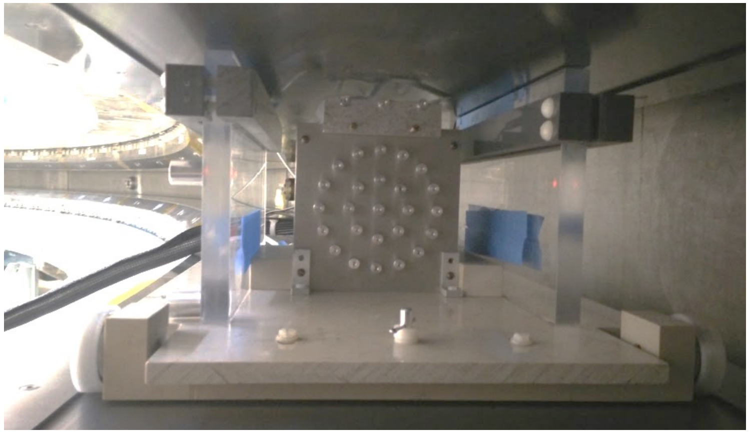


Magnetic field - monitoring

- Field monitored by fixed NMR probes and NMR trolley



- ~400 probes constantly monitor field just outside storage region (in air)
- Insensitive to field shape drifts inside SR

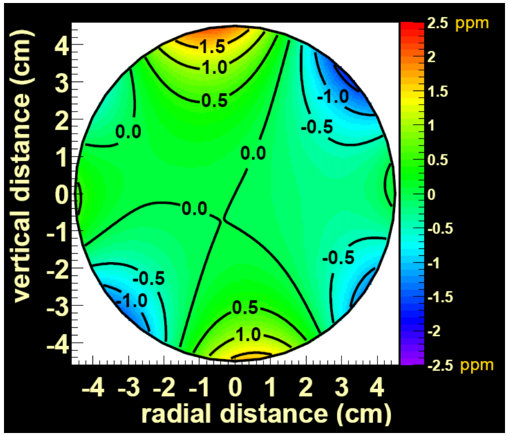


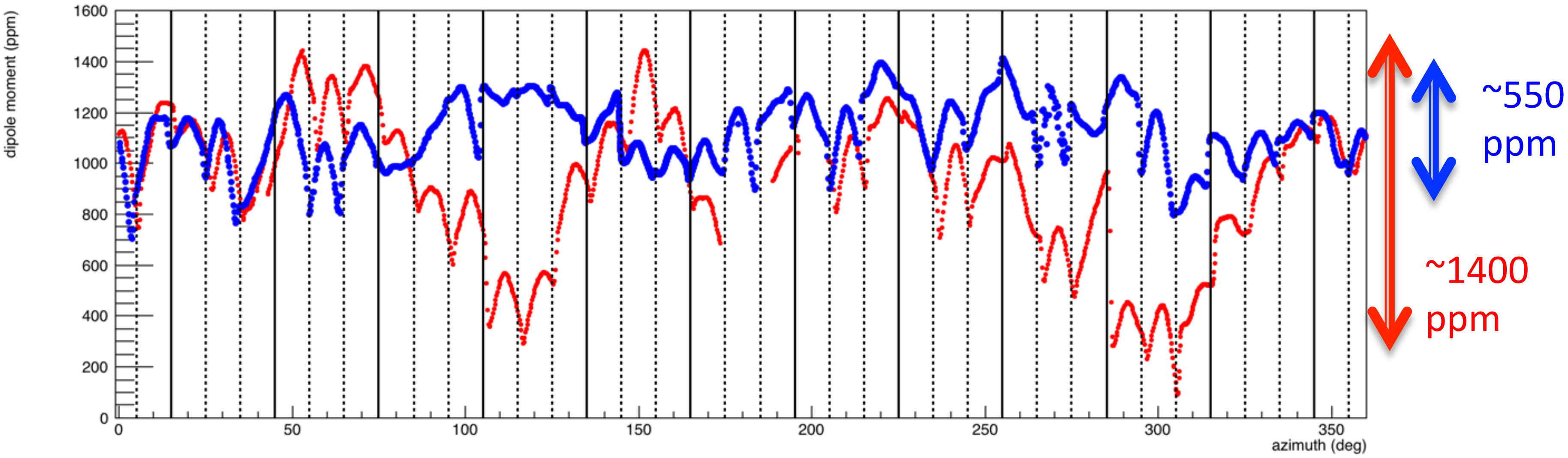
- Matrix of 25 NMR probes pulled around ring to measure field as felt by muons
- 4 Position censors give 25 μm resolution

- Overall calibration with MRI facility (Argonne) via spherical probe

Current status - field

- Target level of <1 ppm in uniformity
- Coarse shimming complete - Variation down from 1400 ppm (October) to 550 ppm (Feb)
- Fine tuning completed end of summer

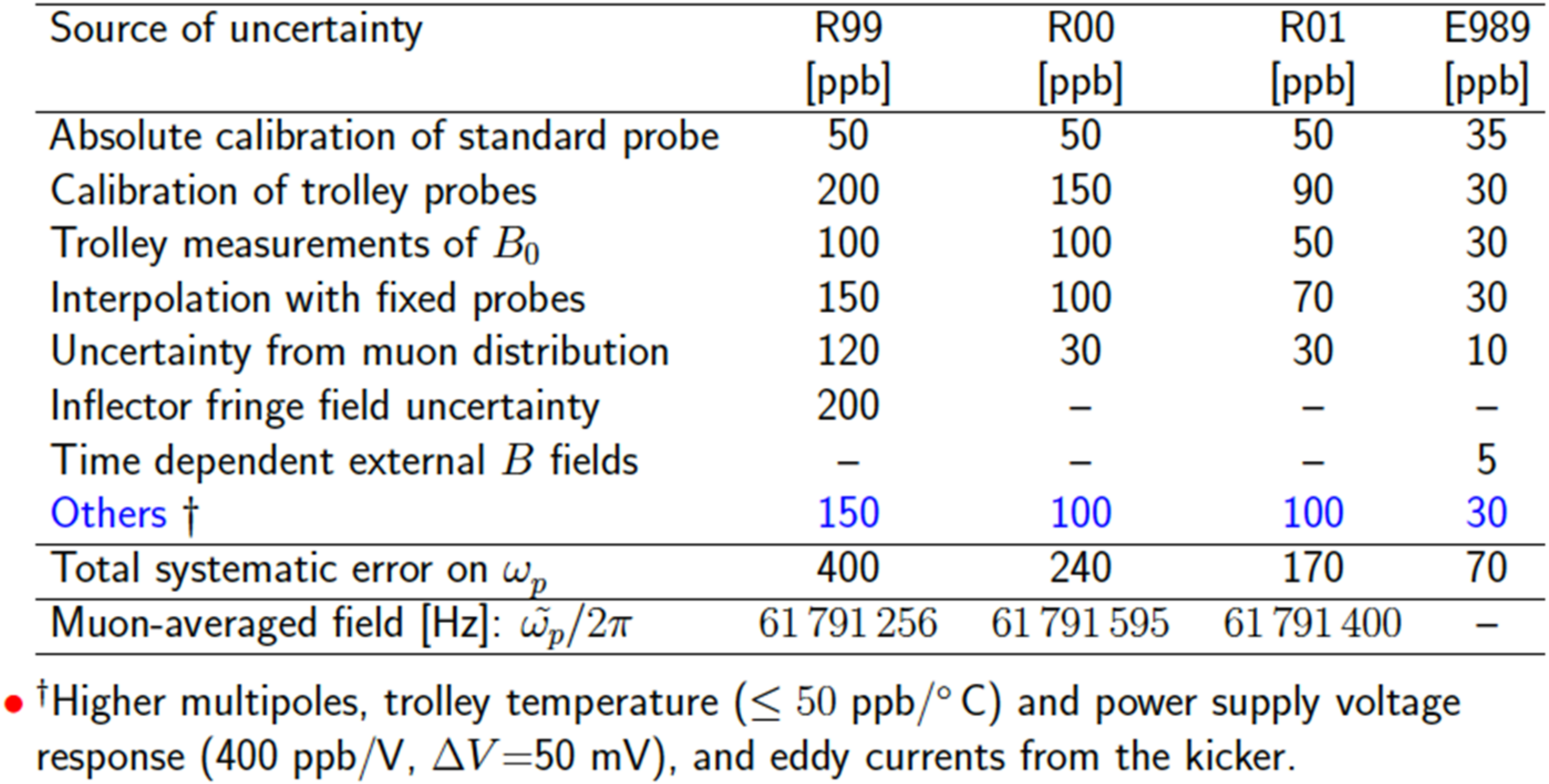




~550 ppm

~1400 ppm

Uncertainty budget - ω_p



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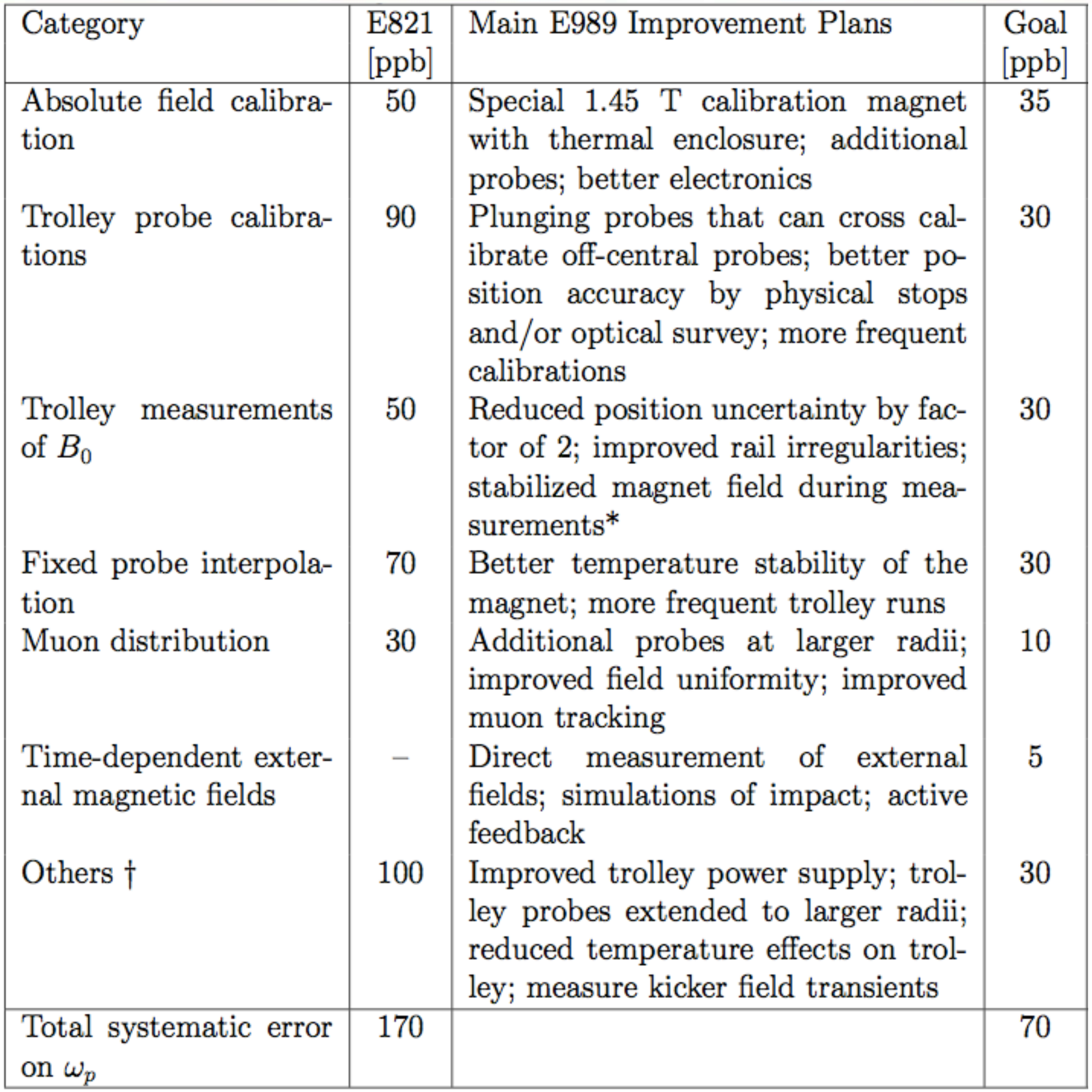
- †Higher multipoles, trolley temperature (≤ 50 ppb/° C) and power supply voltage response (400 ppb/V, ΔV=50 mV), and eddy currents from the kicker.

- 0.17 ppm will be reduced to 0.07 ppm

Improvements summary - ω_p



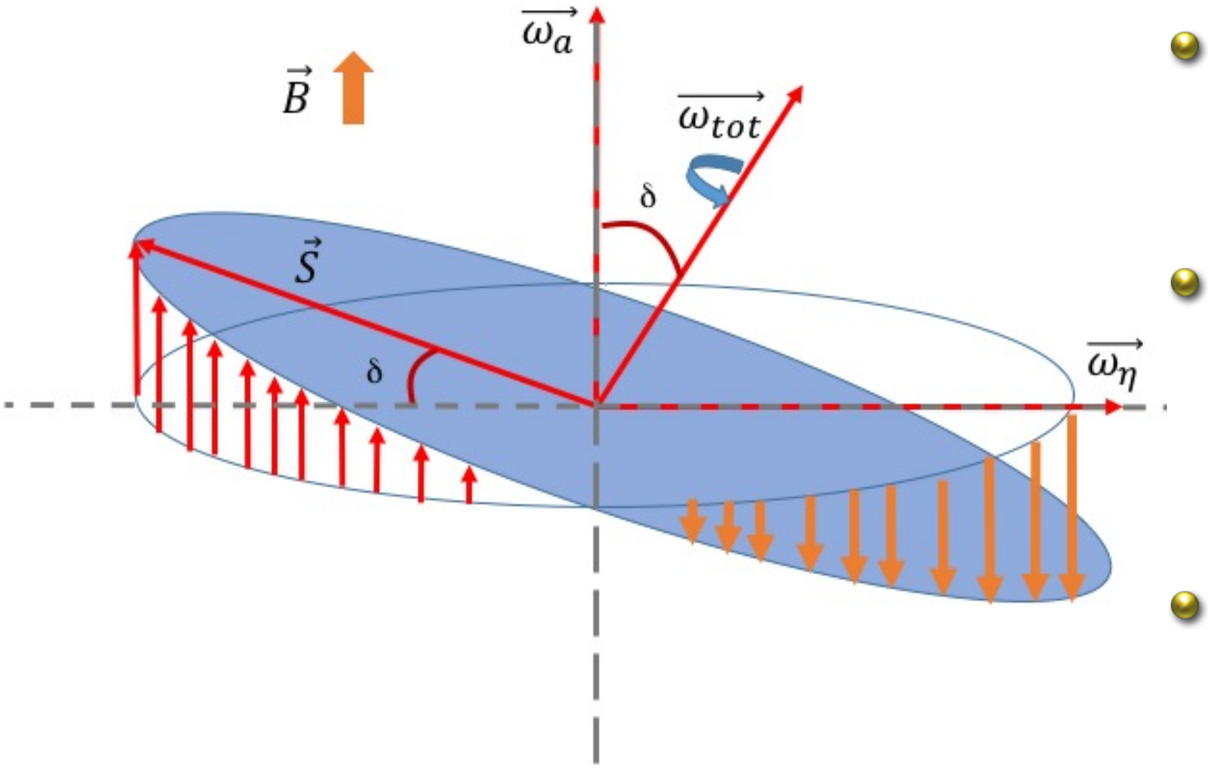
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
Trolley probe calibrations	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30
Total systematic error on ω_p	170		70

- *Improvements due to more uniformally shimmed magnetic field
- Others - higher multipoles, temperature unc., voltage response and eddy current from kickers

Additional measurements

- As well as measuring the anomalous magnetic moment can additionally search for electric dipole moment

$$\vec{d}_\mu = \frac{\eta}{2}\frac{e\hbar}{2m_\mu c}\vec{S}$$



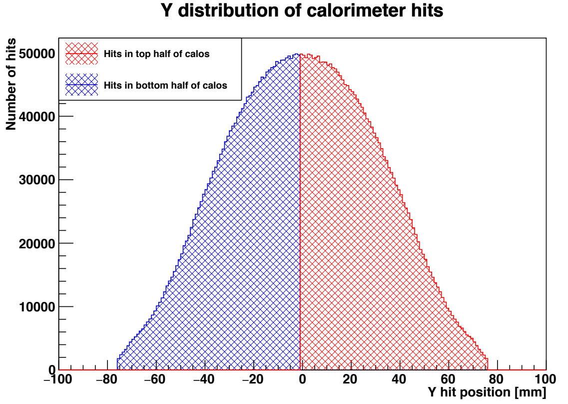
- Precession plane tilts towards centre of ring

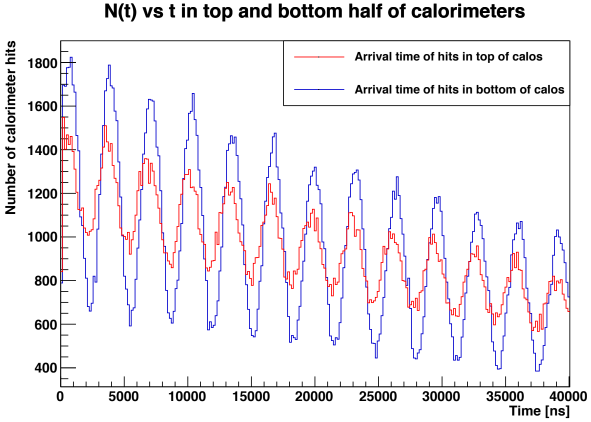
- Increase in precession frequency

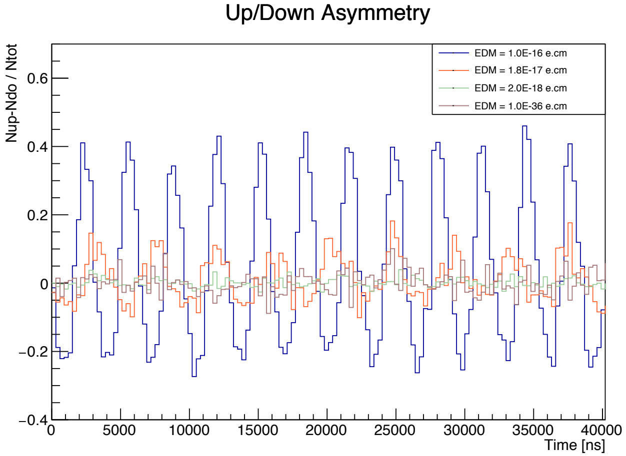
$$\omega_{tot} = \sqrt{{\omega_a}^2 + {\omega_\eta}^2}$$

- Vertical oscillation is 90° out of phase with a_μ oscillation

EDM sensitivity



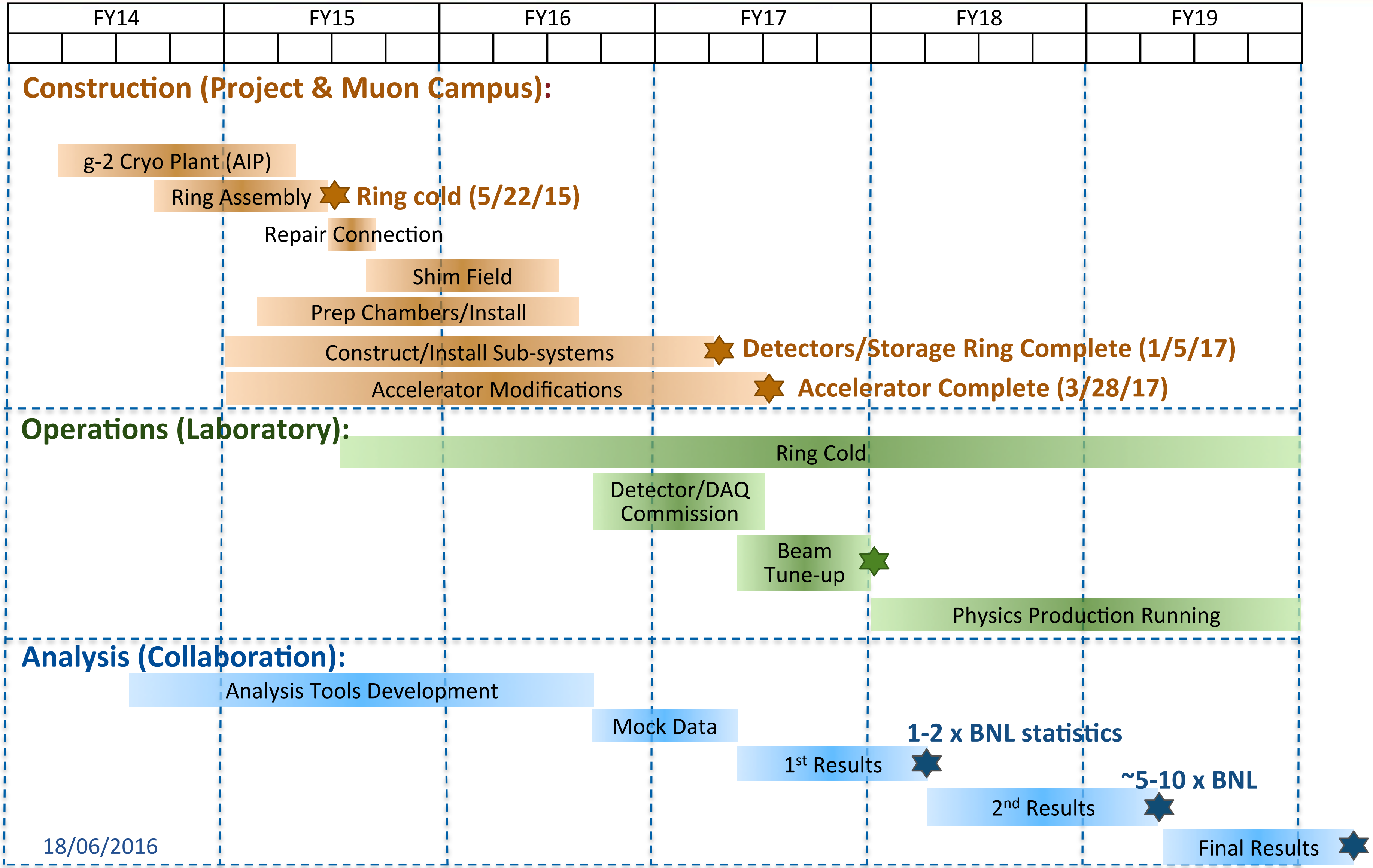




- Amplitude of vertical oscillation proportional to d_μ
- Current limit $|d_\mu| < 1.8\times10^{-19}$ e.cm
- Improvement from statistics compared to BNL
  - Trackers operational for full early part of spill
- Vertical position from trackers
- Aiming for sensitivity at $|d_\mu| \sim 10^{-21}$ e.cm

BNL limit : http://dx.doi.org/10.1103/PhysRevD.80.052008

Schedule



Construction (Project & Muon Campus):

- g-2 Cryo Plant (AIP)
- Ring Assembly ✶ **Ring cold (5/22/15)**
- Repair Connection
- Shim Field
- Prep Chambers/Install
- Construct/Install Sub-systems ✶ **Detectors/Storage Ring Complete (1/5/17)**
- Accelerator Modifications ✶ **Accelerator Complete (3/28/17)**

Operations (Laboratory):

- Ring Cold
- Detector/DAQ Commission
- Beam Tune-up ✶
- Physics Production Running

Analysis (Collaboration):

- Analysis Tools Development
- Mock Data
- 1st Results ✶ **1-2 x BNL statistics**
- 2nd Results ✶ **~5-10 x BNL**
- Final Results ✶

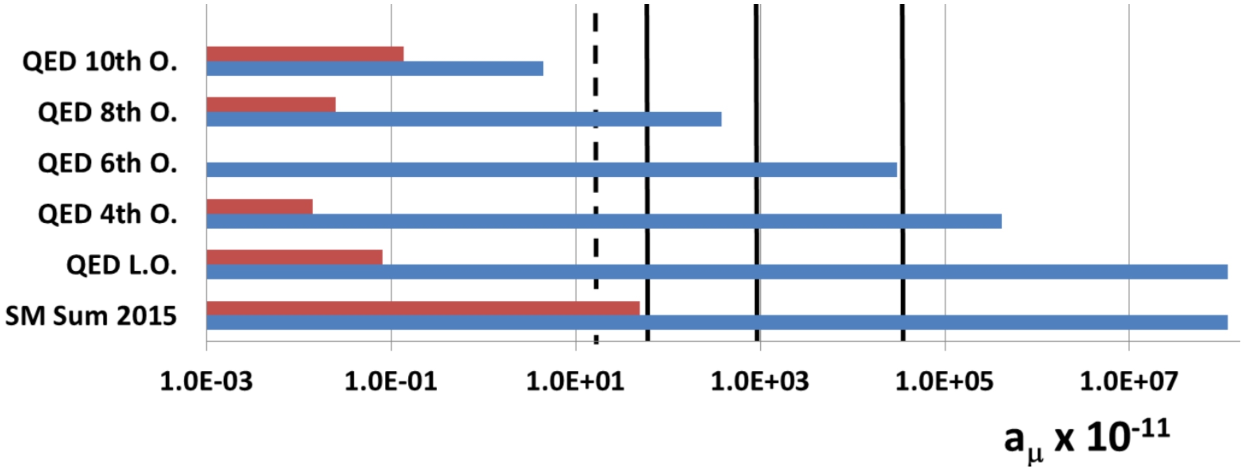
18/06/2016

Summary

- a_μ sensitive to new physics
- Discrepancy shows no signs of going away with improved theory
- Main experimental improvement from increased stats
  - Expecting 21 times more data ~ 1.5 x 10^{11} muons
  - Available due to improved facilities at FNAL
- Additional improvements in experimental uncertainties
  - Improved uniformity in B field, calibration procedures, …
  - New calorimeters, trackers, kickers, …
- Data taking starts in summer 2017

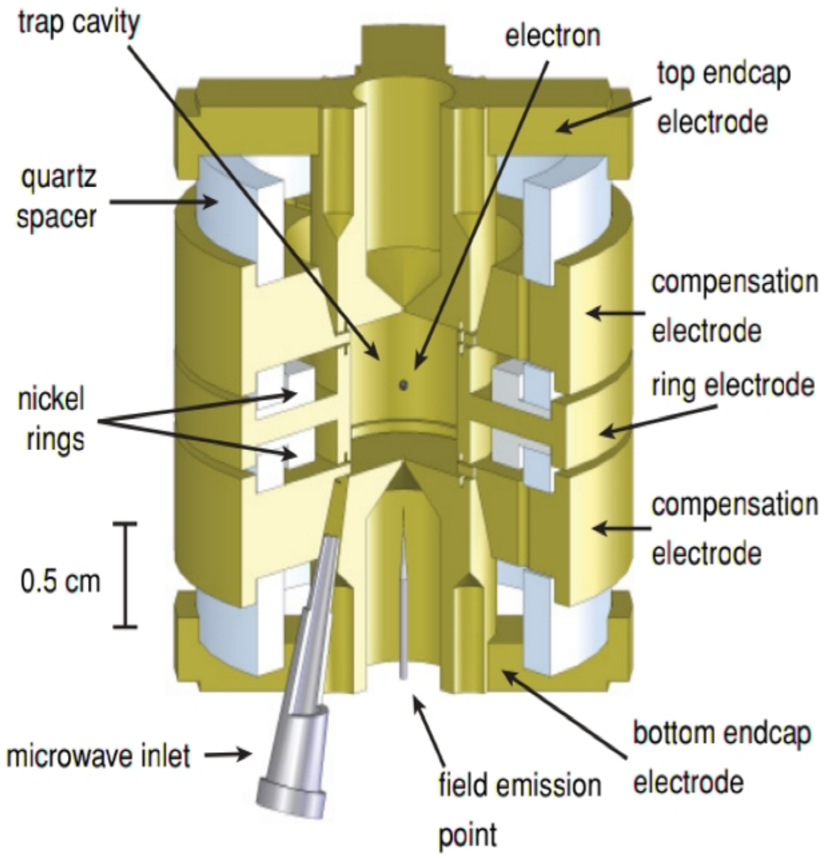
- backups…

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_{\alpha}$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$



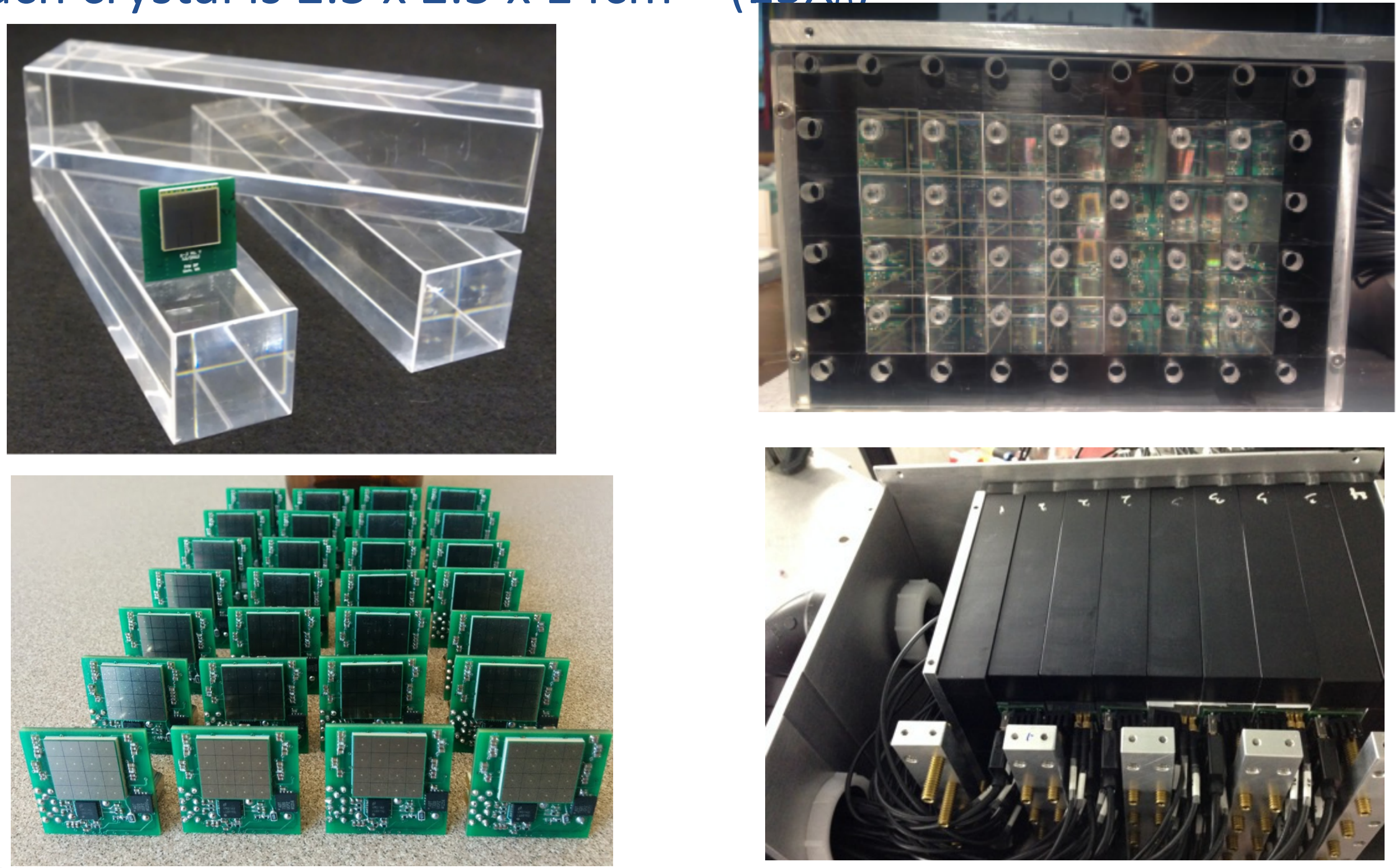
Electron anomaly

- Measurement of a_e is measured to ~1ppb
- Experiment utlzed Penning trap - homogeneous axial B field quadrupole E field
- One of the most precisely measured properties in fundamental particle physics
- Excellent agreement with SM



Calorimeters

- Each consists of 6 by 9 array of crystals
- Each crystal is 2.5 x 2.5 x 14cm ~ (15X_0)



Magnetic moments - Classical

- A magnetic moment in a magnetic field will experience a torque

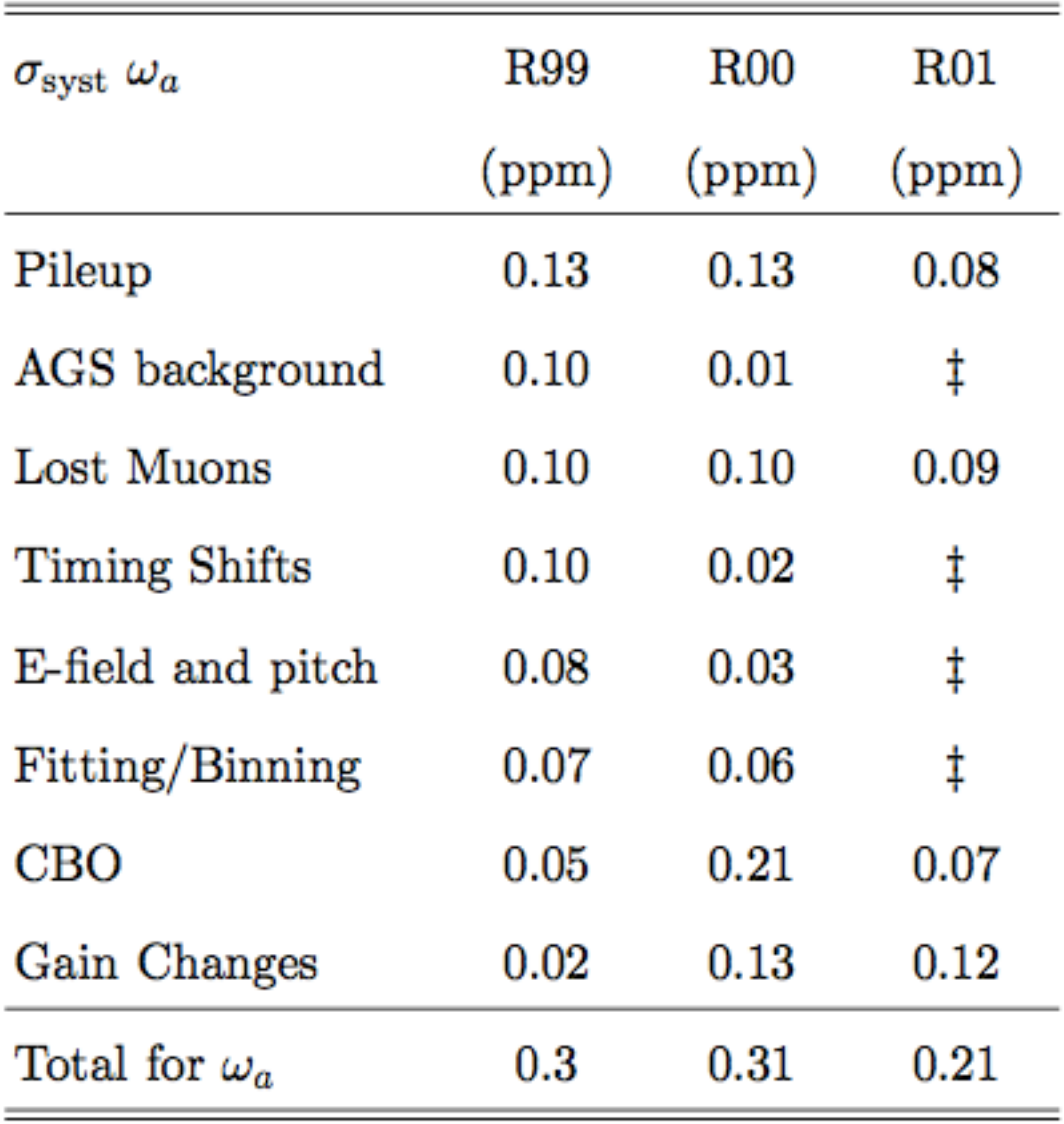
$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

$$\vec{F} = \nabla \vec{\mu}.\vec{B}$$

$$U = \vec{\mu}.\vec{B}$$

$$\vec{\mu} = \frac{e}{2mc}\vec{L}$$

Brookhaven systematics - ω_a



$\sigma_{\text{syst}}\ \omega_a$	R99 (ppm)	R00 (ppm)	R01 (ppm)
Pileup	0.13	0.13	0.08
AGS background	0.10	0.01	‡
Lost Muons	0.10	0.10	0.09
Timing Shifts	0.10	0.02	‡
E-field and pitch	0.08	0.03	‡
Fitting/Binning	0.07	0.06	‡
CBO	0.05	0.21	0.07
Gain Changes	0.02	0.13	0.12
Total for ω_a	0.3	0.31	0.21

- For R01 the AGS, timing shifts, E field and vertical oscillations and fitting/binning equaled 0.11ppm

Brookhaven systematics - ω_p

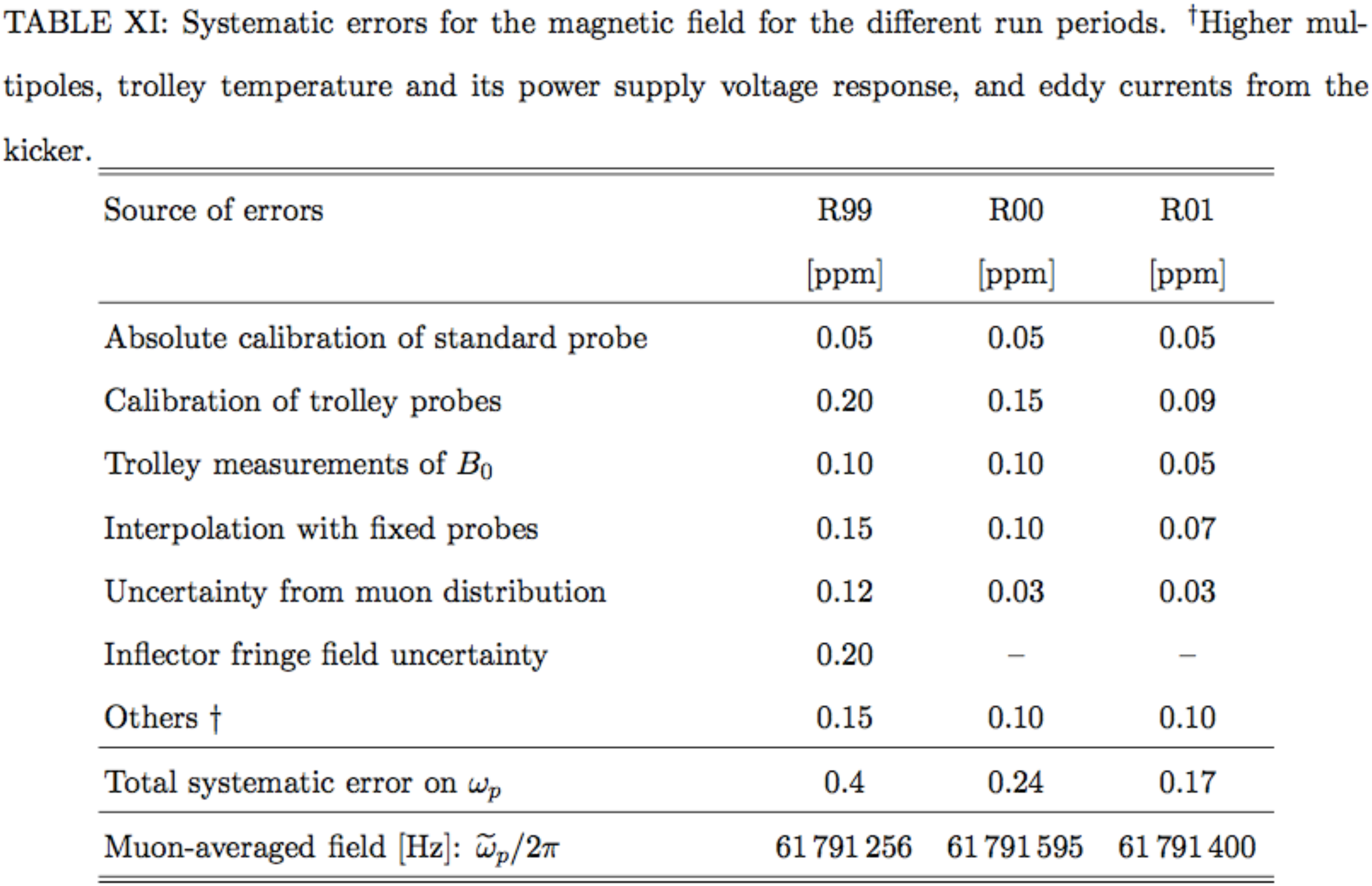
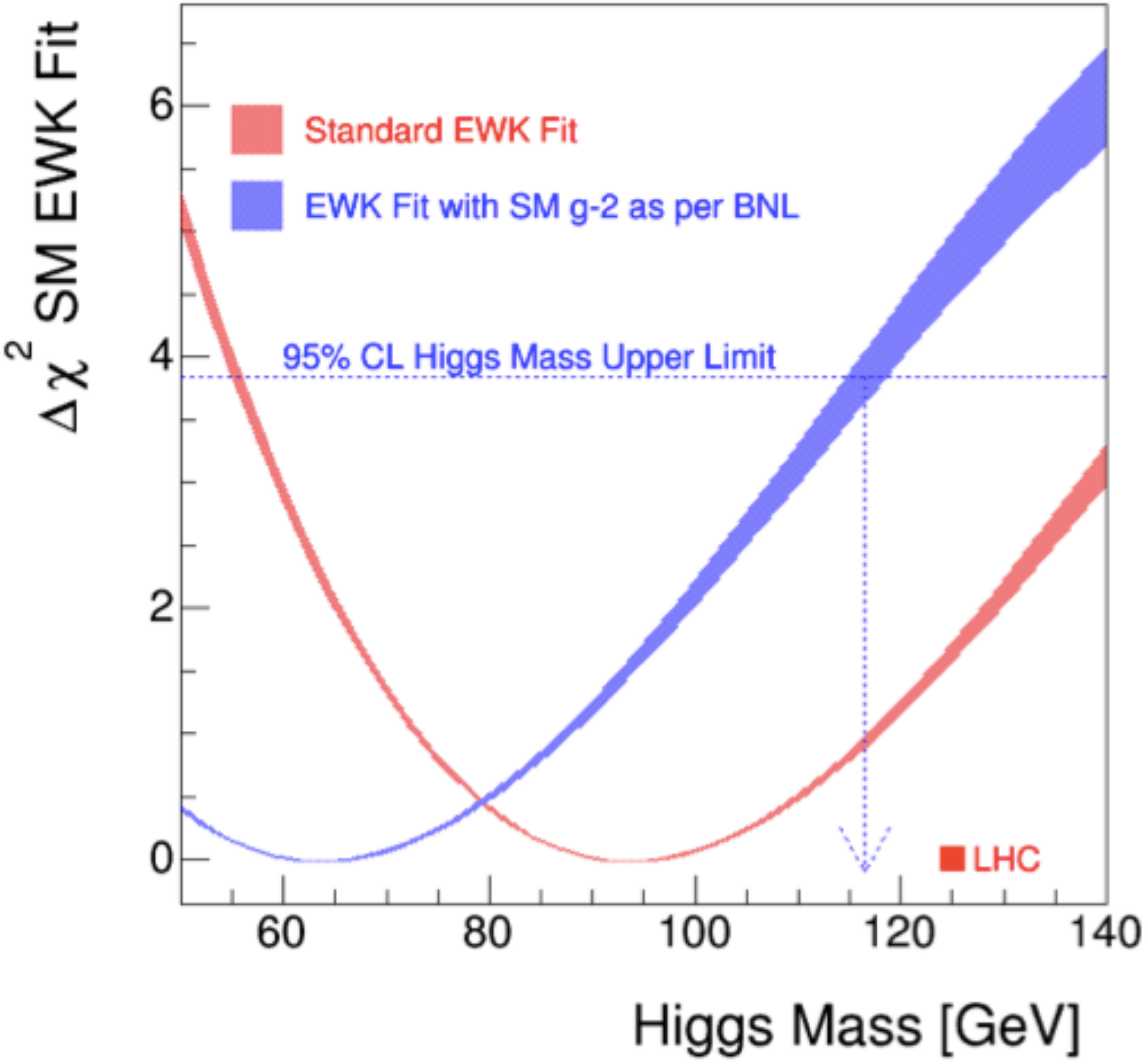


TABLE XI: Systematic errors for the magnetic field for the different run periods. †Higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

Source of errors	R99 [ppm]	R00 [ppm]	R01 [ppm]
Absolute calibration of standard probe	0.05	0.05	0.05
Calibration of trolley probes	0.20	0.15	0.09
Trolley measurements of B_0	0.10	0.10	0.05
Interpolation with fixed probes	0.15	0.10	0.07
Uncertainty from muon distribution	0.12	0.03	0.03
Inflector fringe field uncertainty	0.20	–	–
Others †	0.15	0.10	0.10
Total systematic error on ω_p	0.4	0.24	0.17
Muon-averaged field [Hz]: $\widetilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400

HVP

- Same data for α_{EM} calculation in SM fits as for HVP
- For the BNL result to match the SM prediction Hadronic estimate would have to be incorrect by 6σ
- If HVP was out by 6σ then Higgs mass starts to become incompatible



based on arxiv: 0809:4062