Muon g-2 experiments at FNAL and J-PARC

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on behalf of the g-2 and J-PARC collaboration

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CIPANP

Outline

- Introducing the anomaly
- Theoretical predictions
- How to measure the anomaly - J-PARC/FNAL
- FNAL data taking so far - early look at systematic measurements
- J-PARC time scale

Magnetic moments - QM

- 1928 - Dirac combined special relativity and quantum mechanics

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

intrinsic spin →

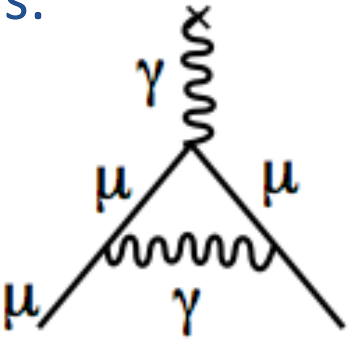
Magnetic Dipole moment

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

B-field

- g, the proportionality constant, is known as the gyromagnetic ratio
- Predicted by Dirac to be exactly 2 for spin ½ particles
- 1947 Kusch-Foley experiment discovered an anomaly in the electron magnetic dipole moment: $g_e = 2.00238(6)$
- Within a year Schwinger calculated the 1st order QED correction, for electrons, but applies to muons:

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

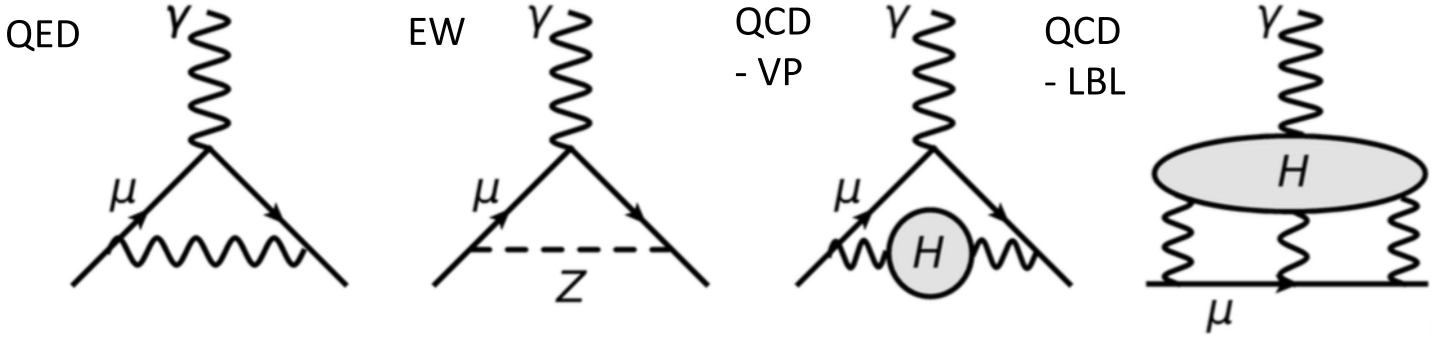


Parameterise anomaly

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

Standard model predictions

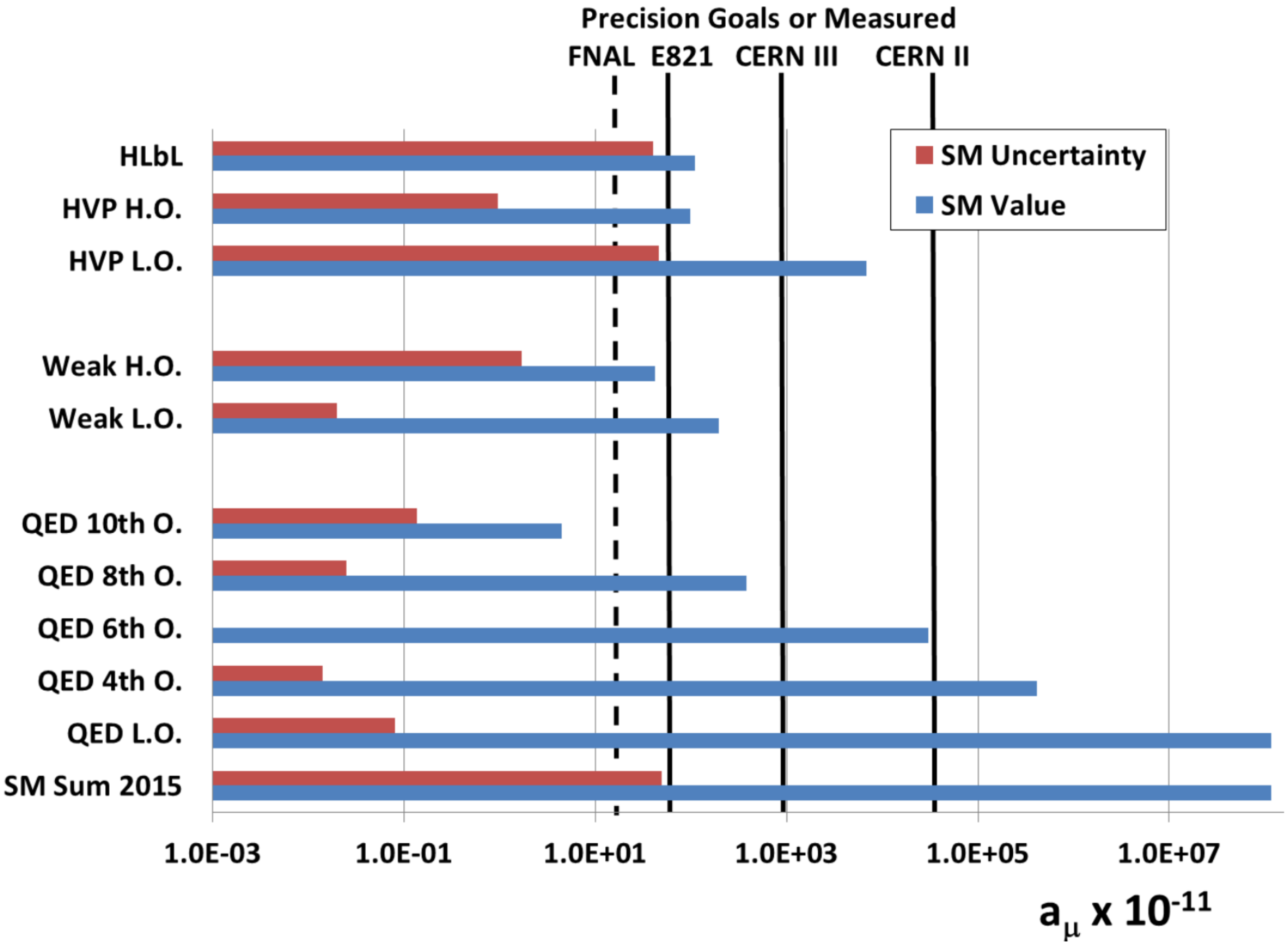
- There are higher order QED corrections, EW and QCD

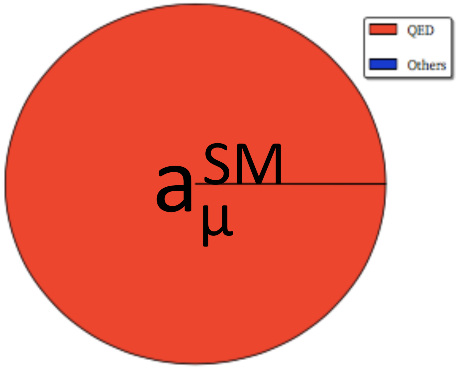


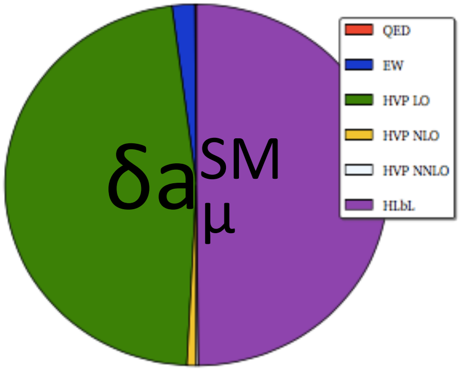
- All diagrams need to be included in calculation
- So far the best prediction is:

$$g_\mu = \underbrace{2}_{\text{Dirac}}.00\underbrace{2\,3}_{\text{Schwinger ~O(1) QED}}\underbrace{31}_{\text{Kinoshita ~O(10) QED}}\,\underbrace{84}_{\text{Hadronic}}\overbrace{1\,7}^{\text{EW}}8(126)$$

SM uncertainties





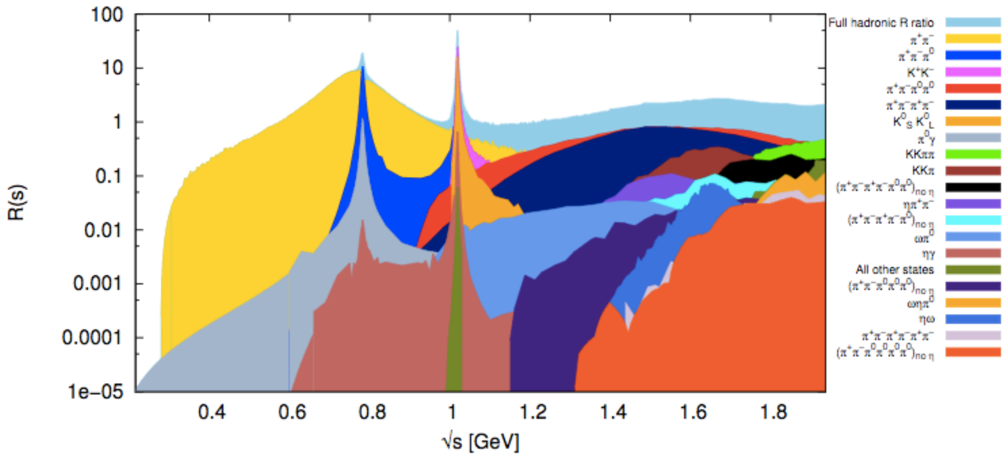


- SM uncertainty dominated by Hadronic - VP and LBL

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
HVP combination: https://arxiv.org/pdf/1802.02995.pdf

Improvements to SM

- HVP can be tied to experimental data from e^+e^- collisions
  - New data expected from SND, CMD-3, KLOE, BES-III, Belle-II…
  - Continuously updating SM prediction



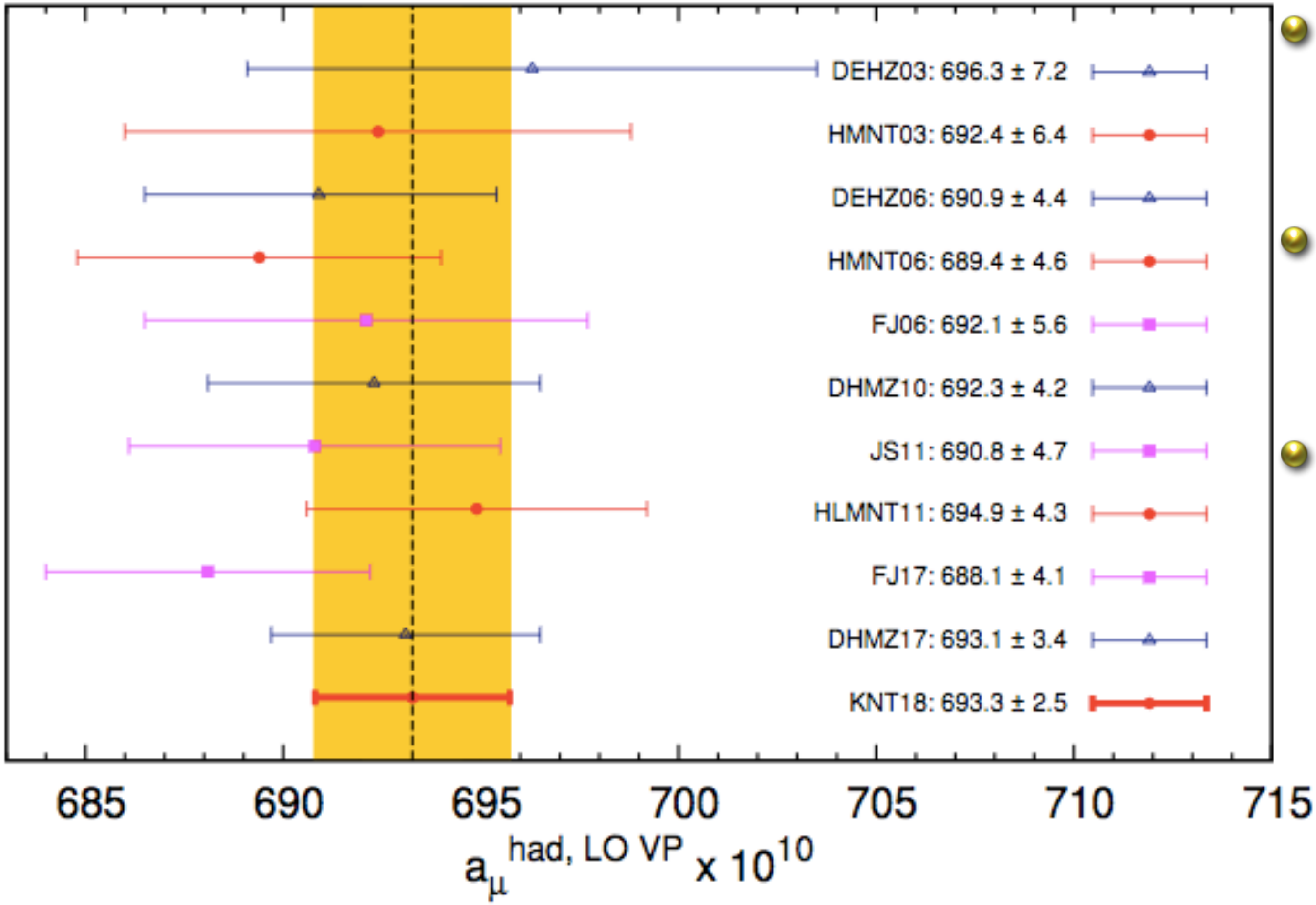
- Alternative lattice calculations used as cross check

- Hadronic light by light must be calculated by theory - lattice
- Agreement with accepted model driven value
- Statistical uncertainty only working on systematic uncertainty
- Factor of 2 improvement in SM calculation expected

HVP combination: Keshavarzi, Nomura, Teubner - https://arxiv.org/pdf/1802.02995.pdf
Lattice predictions: T. Blum, *et al.*, *Phys. Rev. Lett.* **116**, 232002 (2016)
HLbL: T. Blum, et al., **Phys. Rev. Lett. 118, 022005**
HLbL: See yesterday's precision physics parallel session

Recent HVP improvements

- New combination shows improved in LO + NLO HVP measurements



- Improved correlation and in bias free fits
- Latest data continually added in
- Compare new theory prediction with BNL data

SM deviation

3.3σ ⟶ 3.7σ

HVP combination: Keshavarzi, Nomura, Teubner - https://arxiv.org/pdf/1802.02995.pdf

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

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

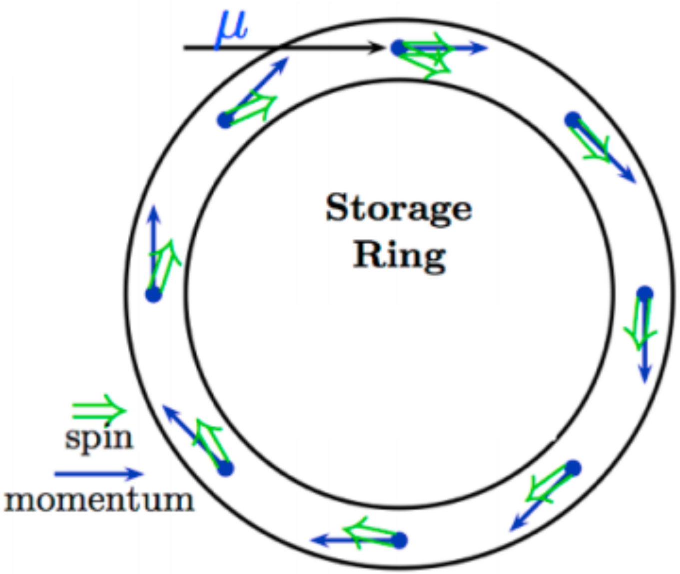
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Spin Precession frequency

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

Cyclotron frequency

~140ns @ FNAL ~149ns @ FNAL

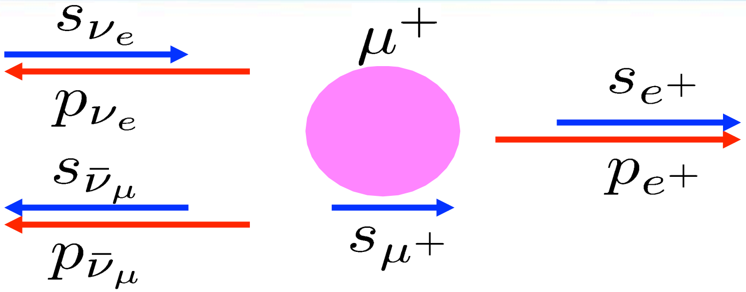


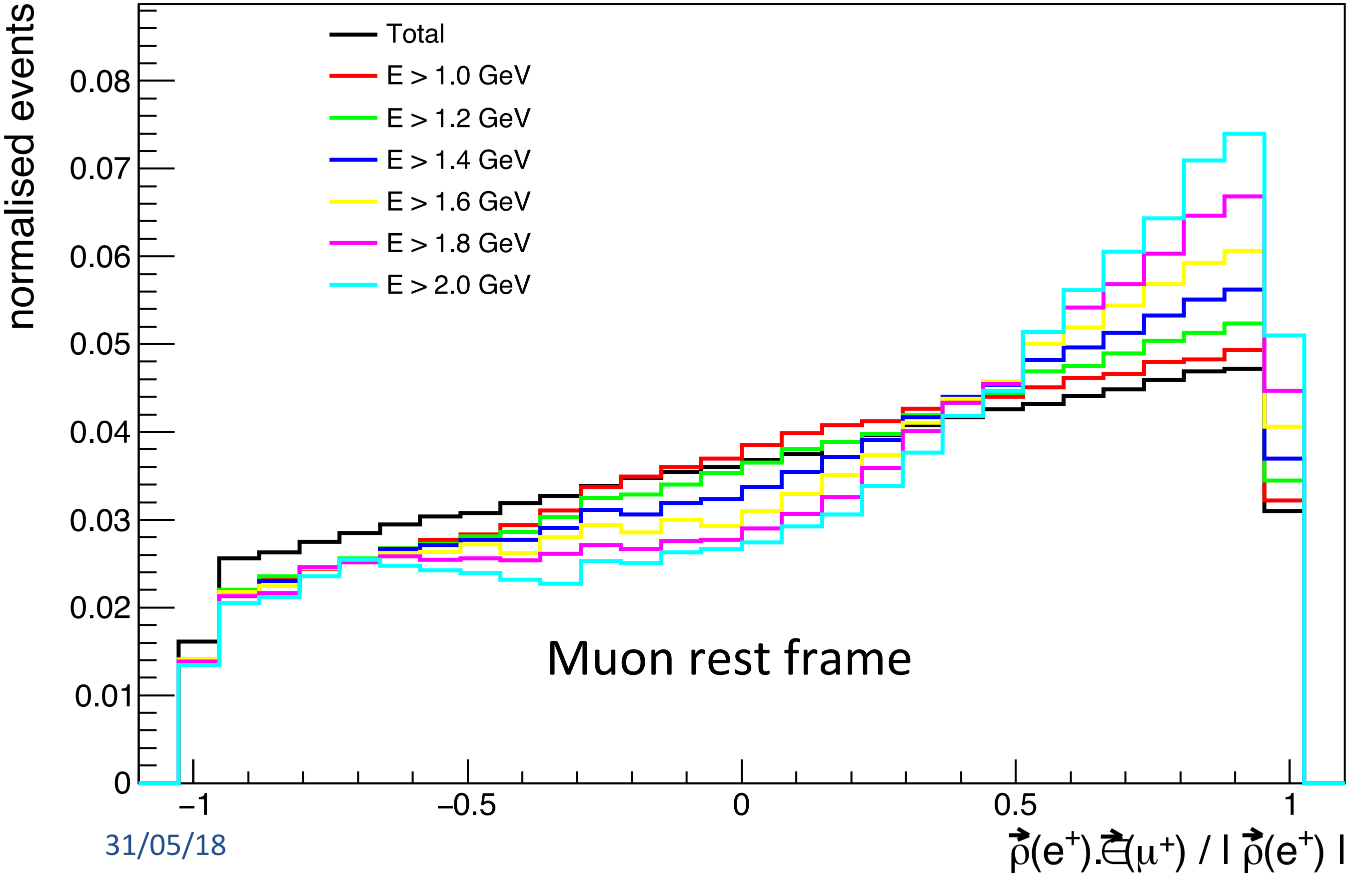
actual precession × 2

- Spin precession > 2π per cyclotron turn

μ^+ decay

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





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

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

Precession frequency

- Assuming velocity is perpendicular to E and B fields:

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

CERN/BNL/FNAL

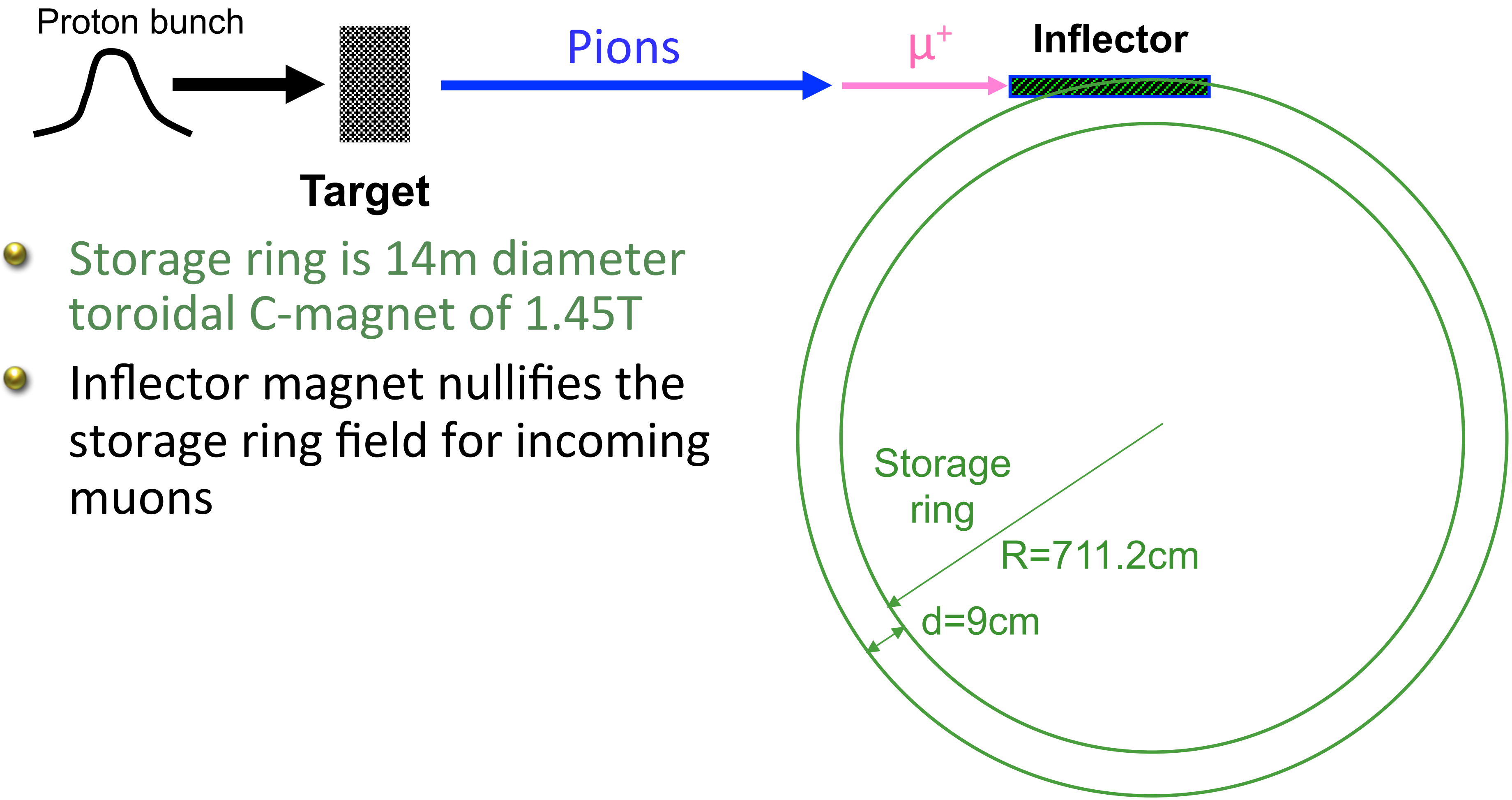
- Choose $\gamma = 29.3$, $p_\mu = 3.09$ GeV/c^2, β x E term is 0, $\tau_\mu = 64.4\ \mu s$
- Use E-field to vertically focus the beam to improve storage

J-PARC

- E-field is 0, $p_\mu = 0.3$ GeV/c^2, $\gamma = 3.01$, $\tau_\mu = 6.6\ \mu s$

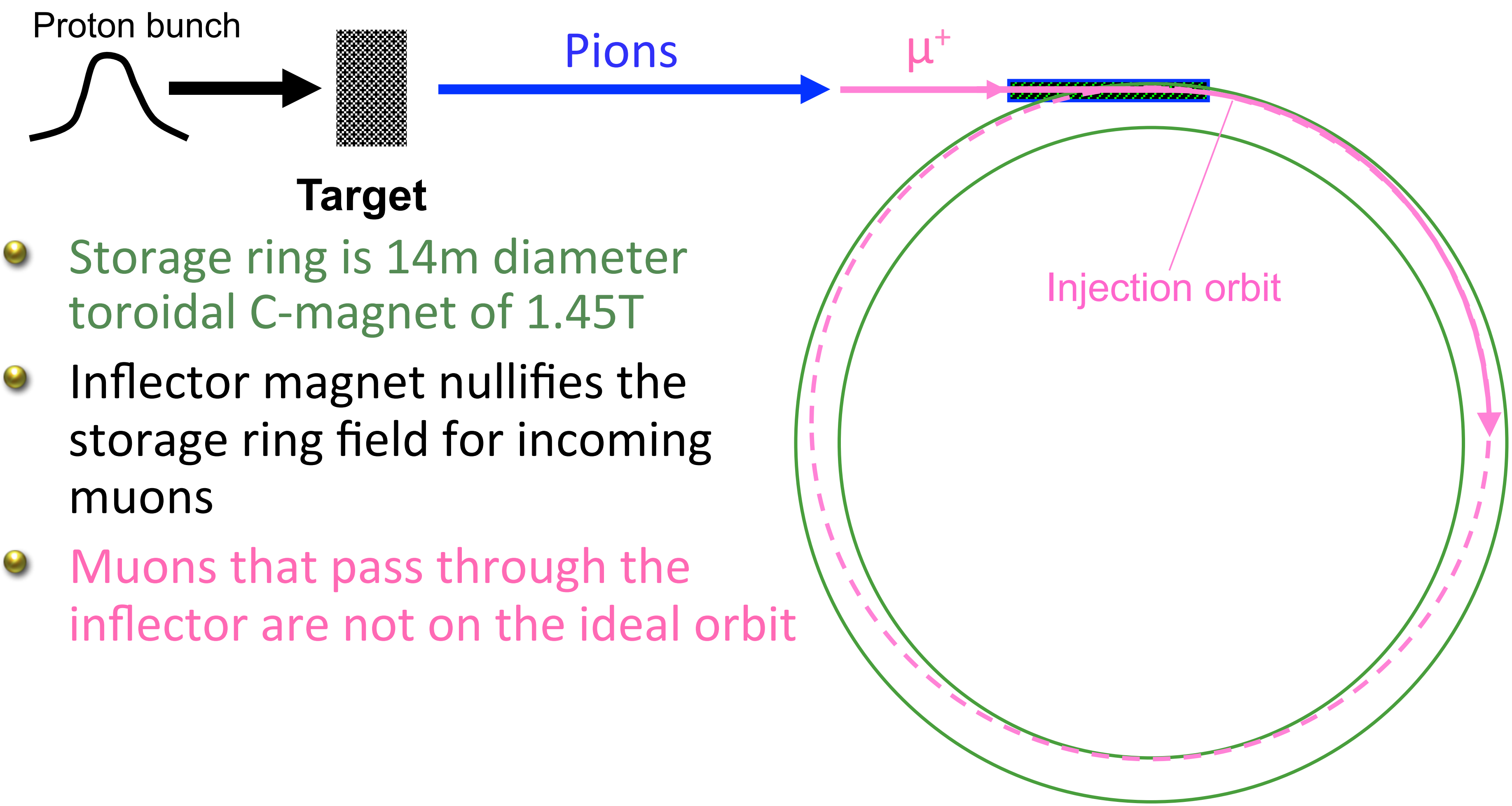
FNAL measurement

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



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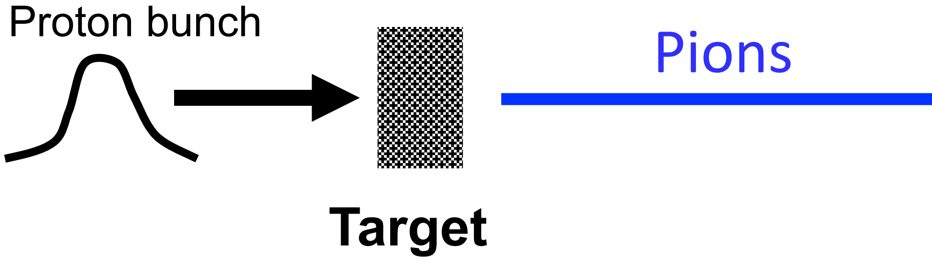
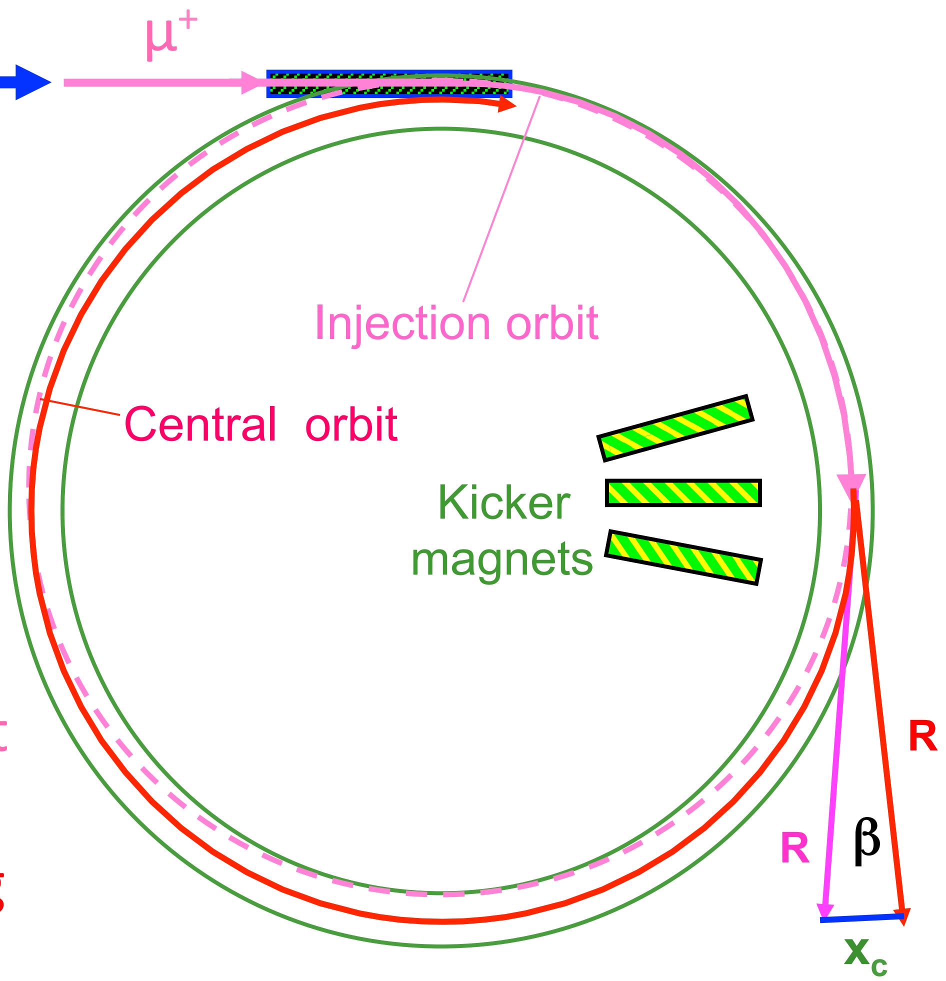
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are not on the ideal orbit

Supplying anti-muons

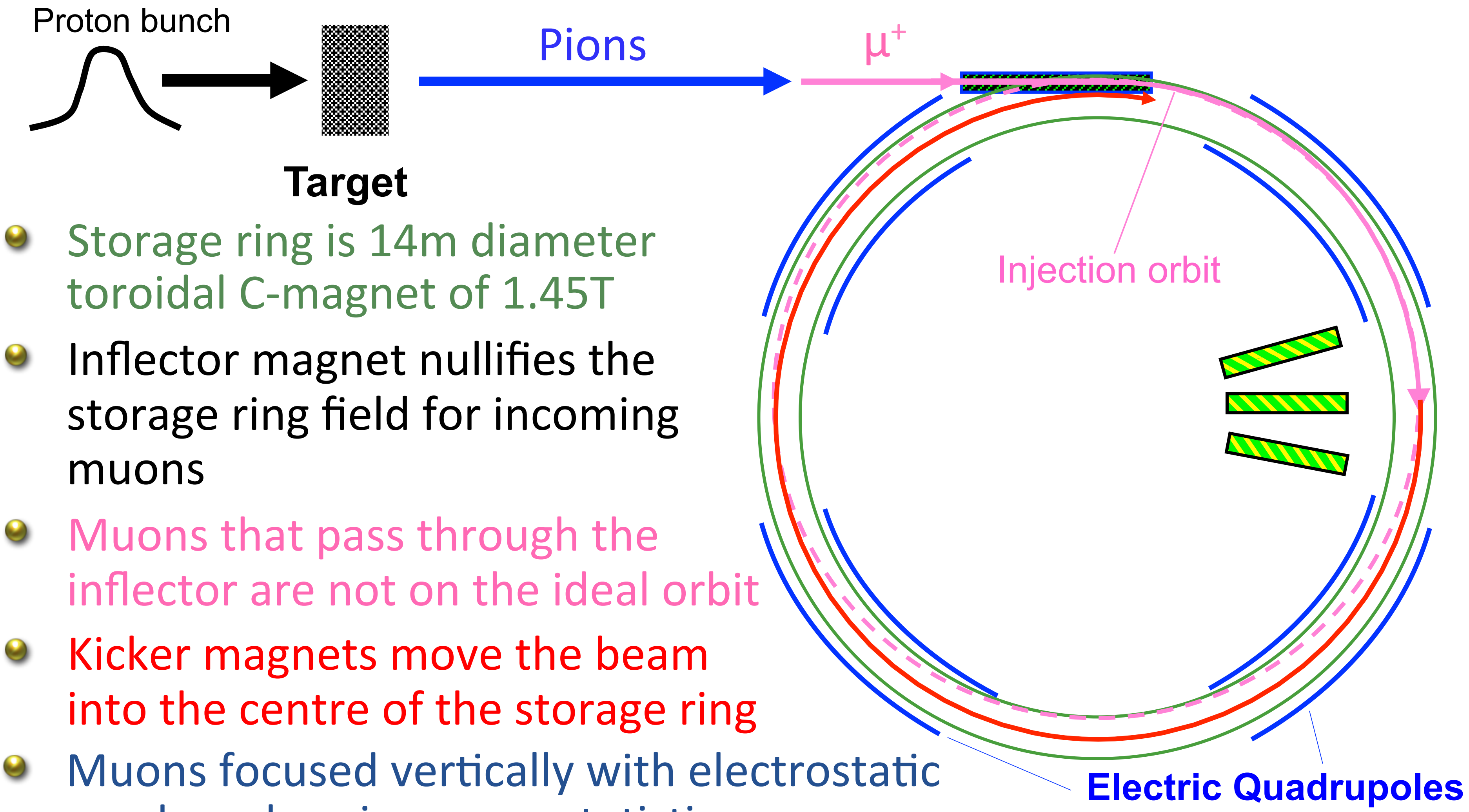




- Storage ring is 14m diameter toroidal C-magnet of 1.45T
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are not on the ideal orbit
- Kicker magnets move the beam into the centre of the storage ring

Xc ~ 77mm
β ~ 10mrad

Supplying anti-muons



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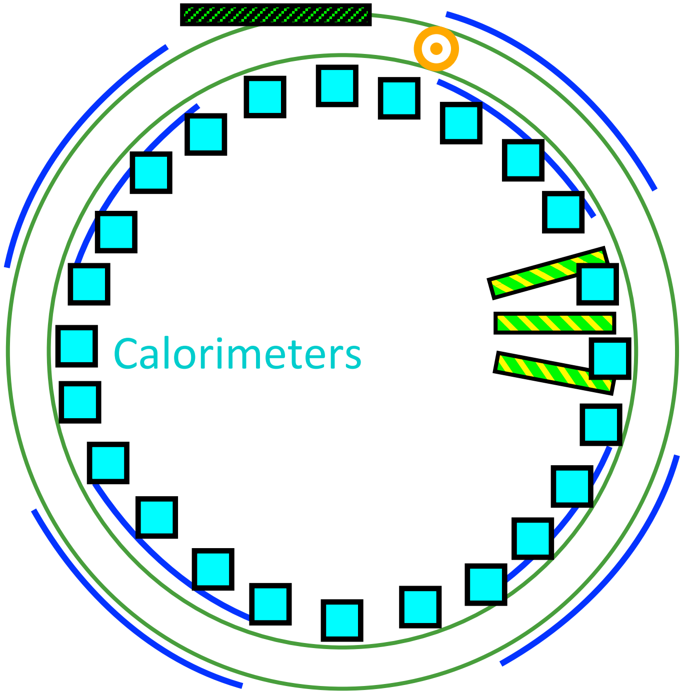
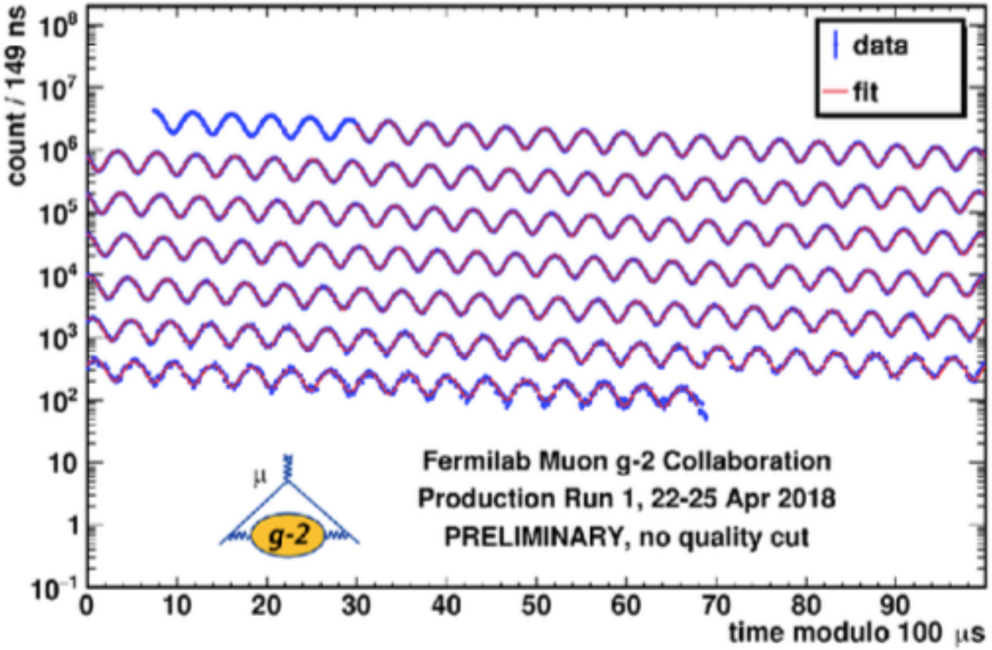
- Muons that pass through the inflector are not on the ideal orbit
- Kicker magnets move the beam into the centre of the storage ring
- Muons focused vertically with electrostatic quadrupoles - improves statistics

Calorimeters

- 24 calorimeters are placed around ring
- They measure the e^+ from the μ decay
- Number of high energy e^+ oscillates at spin precession frequency



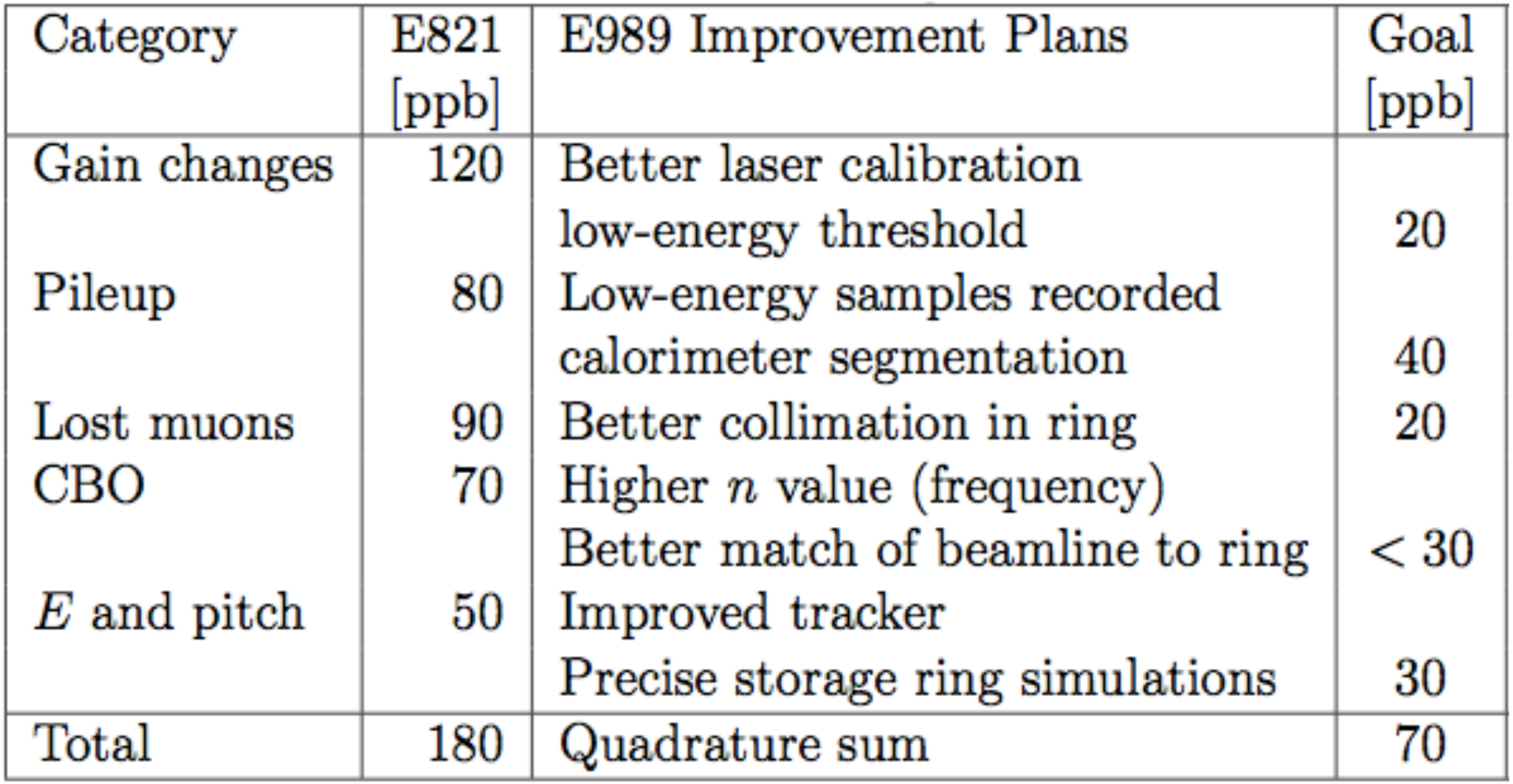


Fermilab Muon g-2 Collaboration
Production Run 1, 22-25 Apr 2018
PRELIMINARY, no quality cut

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

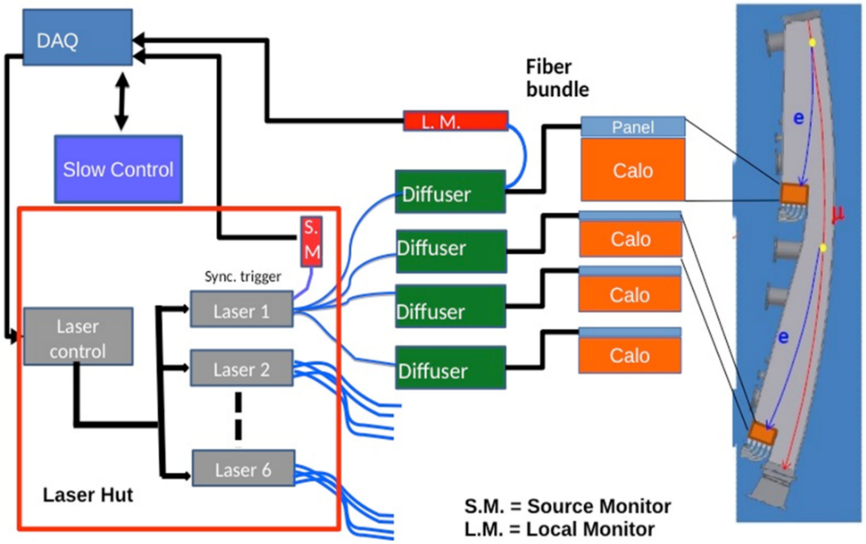
$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

Expected Improvements - ω_a



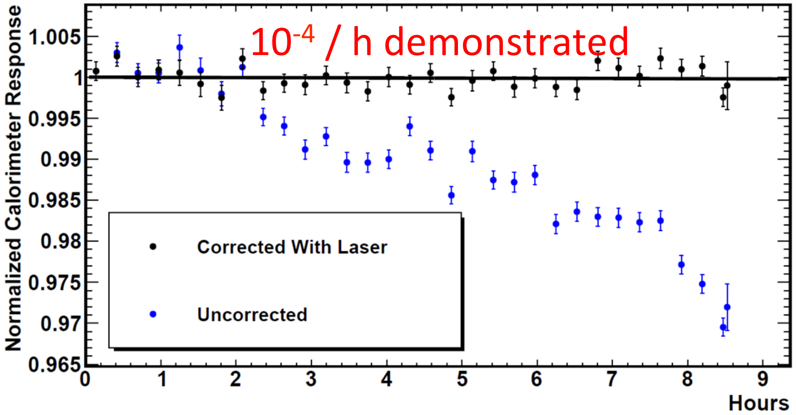
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to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

Gain variation - lasers



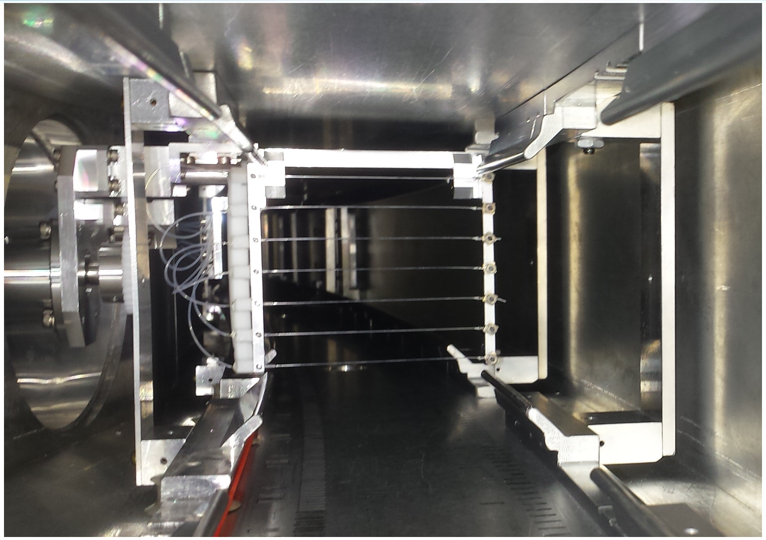
- Lasers measure gain variations in all 24 calorimeters
- Both in fill variations and long term trends
- Source monitors ensure laser remains constant

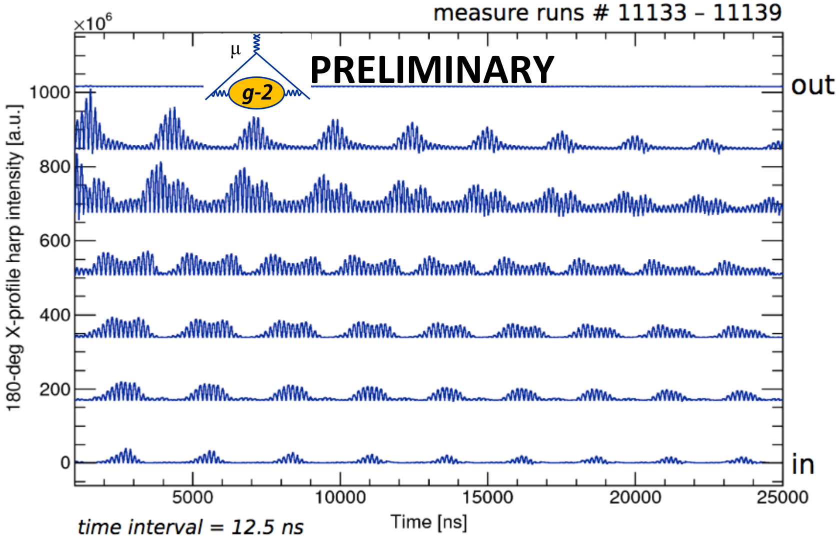
Test beam results



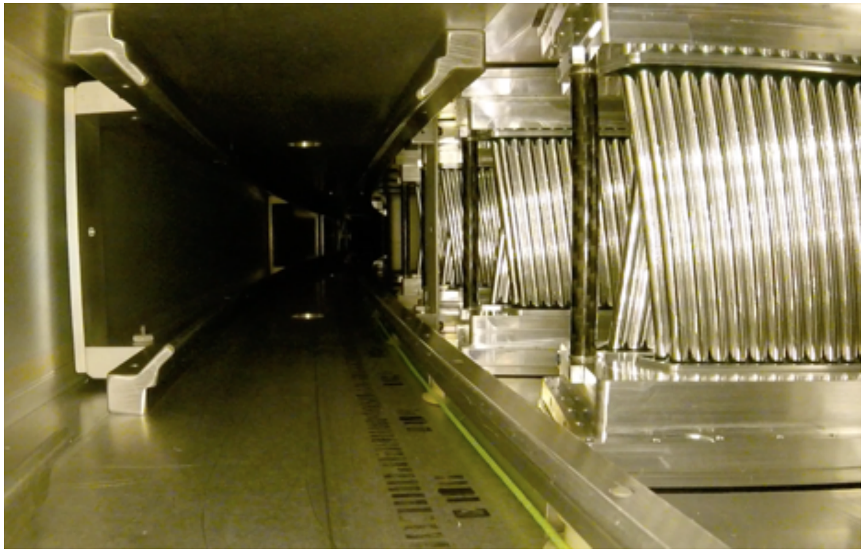
Beam oscillation (CBO) - detectors

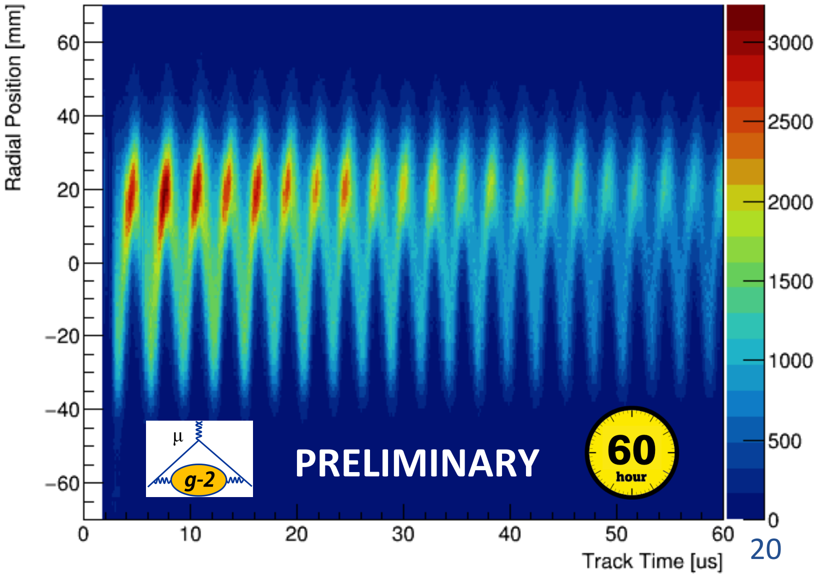
FIBER HARPS





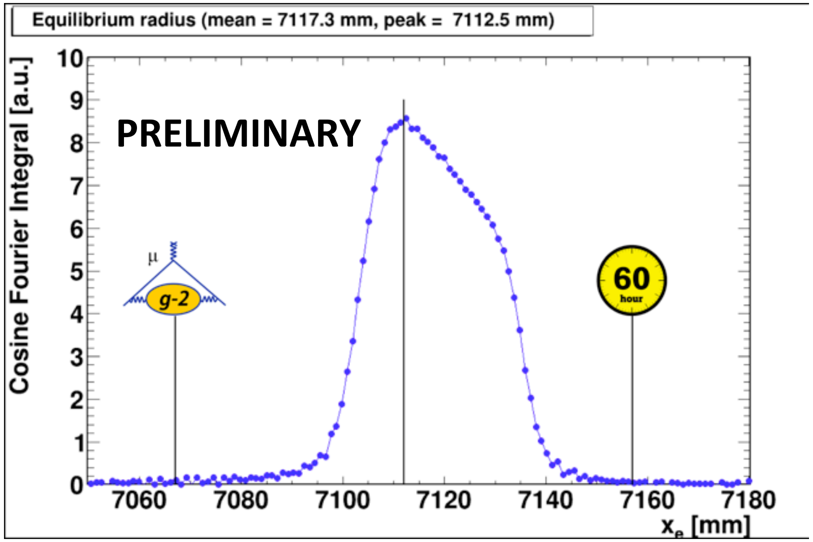
TRACKERS



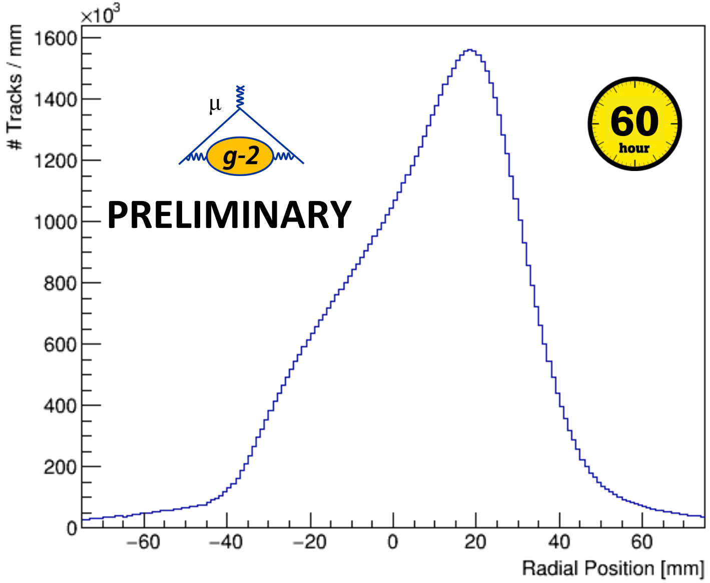


E-field correction

- E field correction for non magic momentum μ^+
- Off magic muons occupy different radii
- Radial position of beam measured 2 ways during fill
- Trackers using traceback to radial tangency point
- Calorimeters - low radius beam ‘laps’ high radius



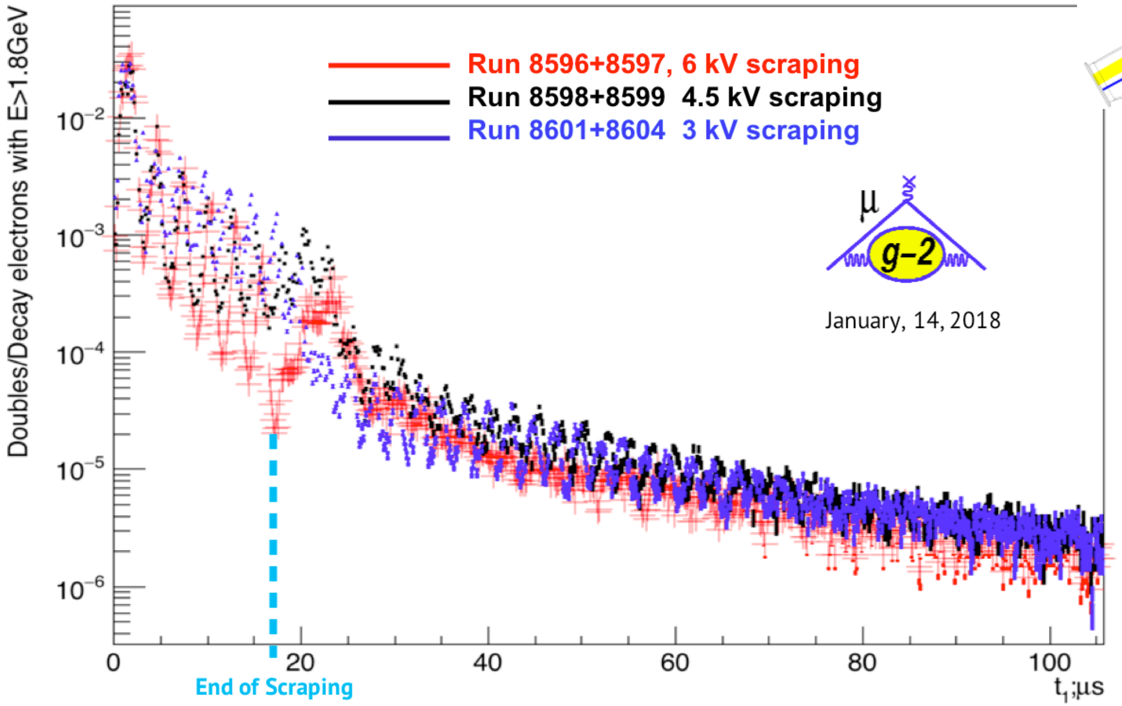
average radial position

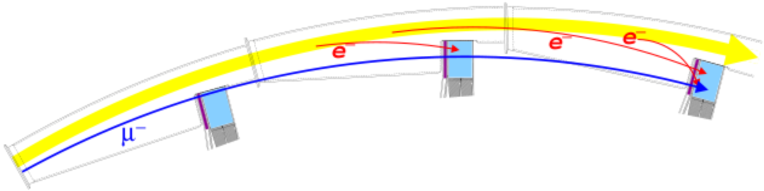


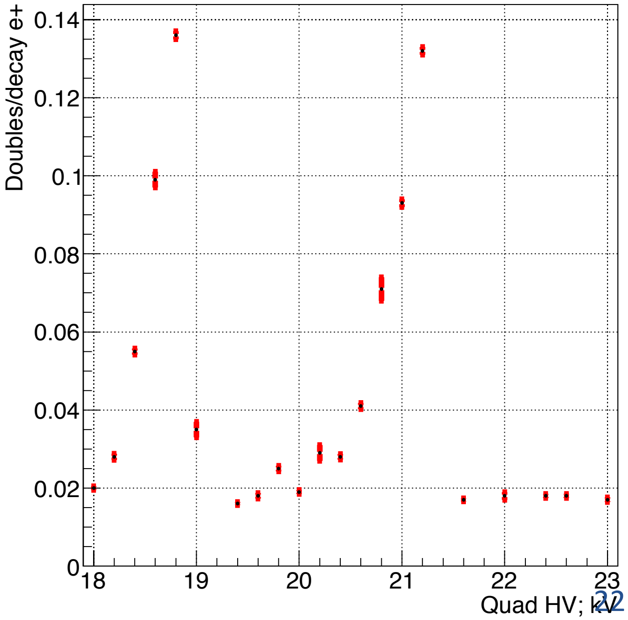
radial position at approximate point of decay (includes CBO)

Lost muons

- Muons punch through calorimeters, leaving a small energy deposit
- Robust analysis using double coincidences in calorimeters
- Vary voltage on the focusing quadrupoles to pick out lost muon resonances and avoid them in nominal data taking

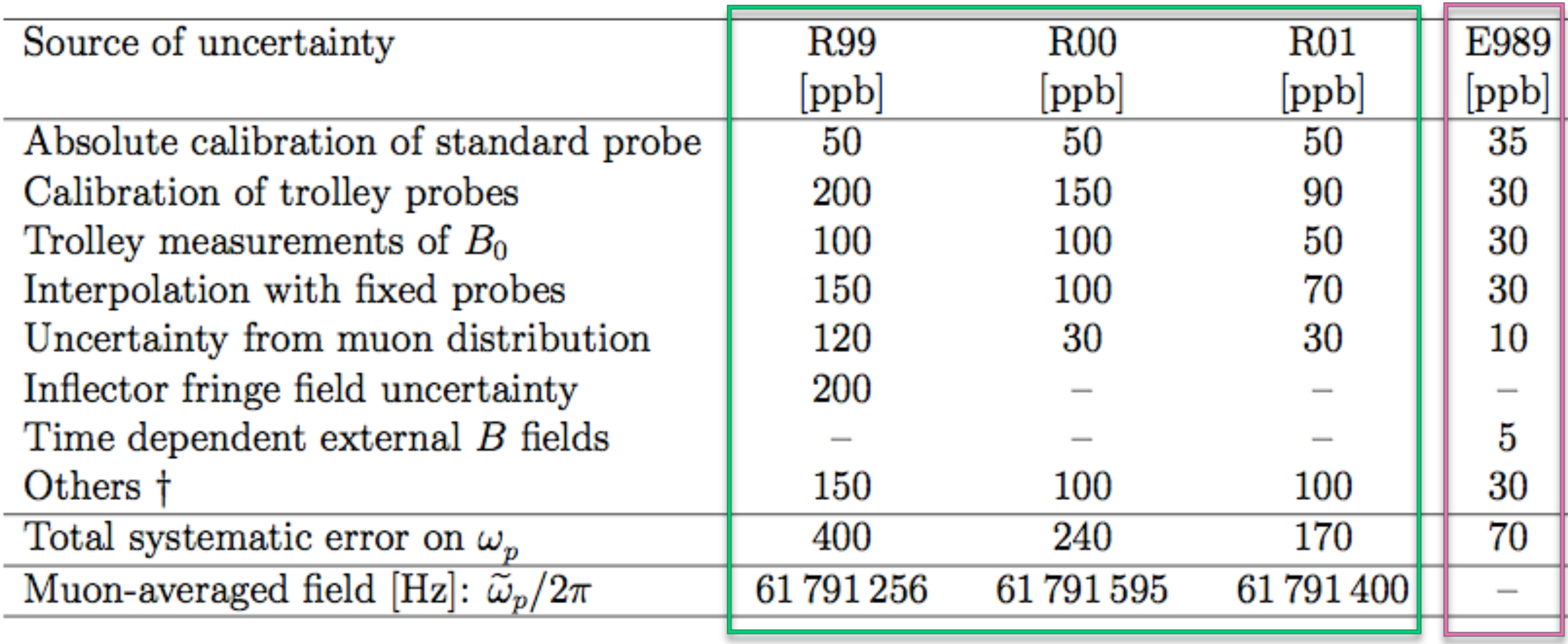






Magnetic field - goals

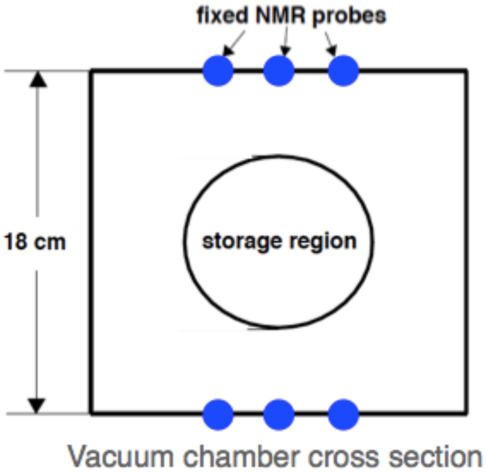
- BNL achieved ~1-2ppm deviation when averaged around azimuth
- FNAL aiming for factor of 2 improvement in homogeneity



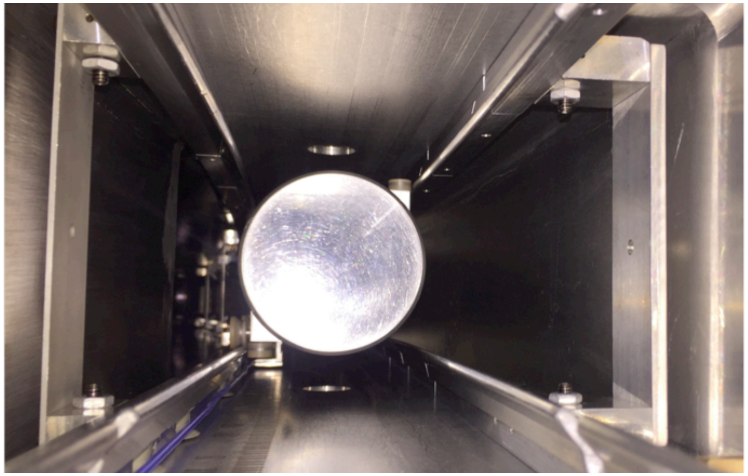
Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	50	50	35
Calibration of trolley probes	200	150	90	30
Trolley measurements of B_0	100	100	50	30
Interpolation with fixed probes	150	100	70	30
Uncertainty from muon distribution	120	30	30	10
Inflector 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 - monitoring

- Field monitored by fixed NMR probes and NMR trolley



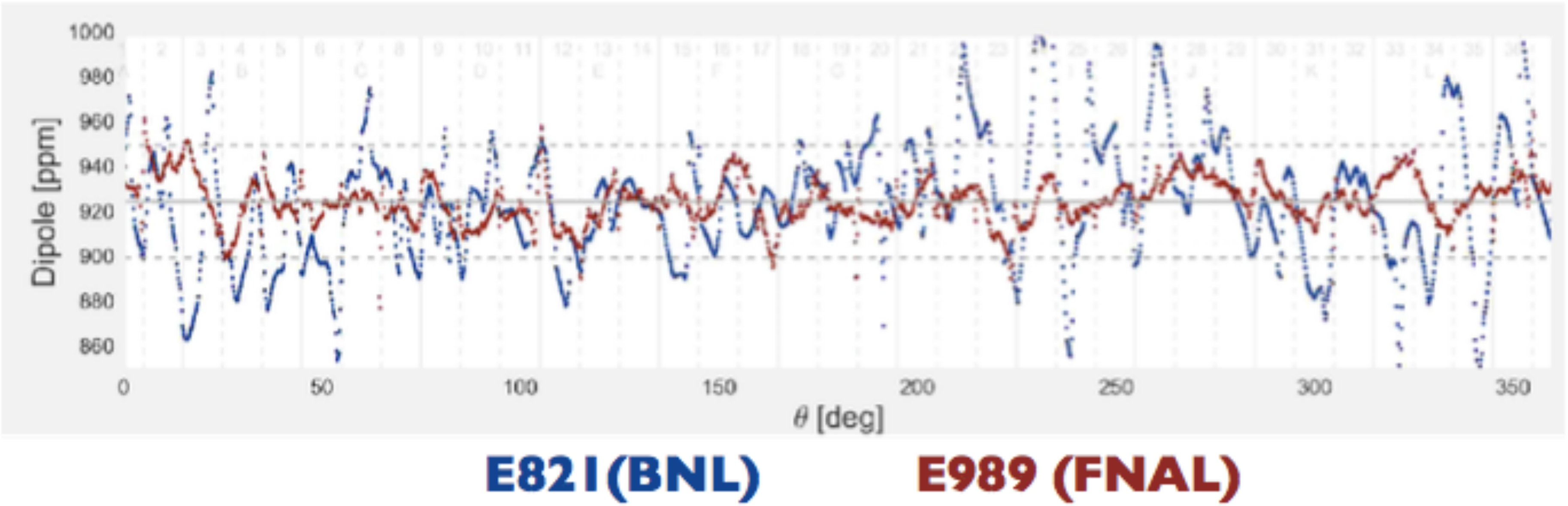
- ~400 probes constantly monitor field just outside storage region (in air)
- Insensitive to field shape drifts inside SR



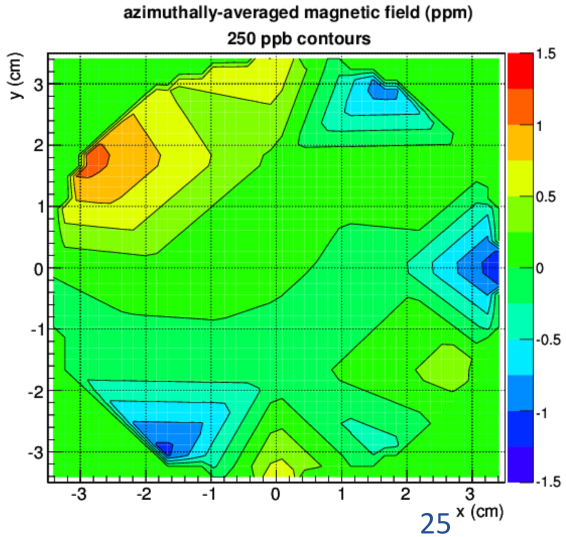
- Matrix of 17 NMR probes pulled around ring to measure field as felt by muons
- 1 mm position accuracy - reads bar codes inside ring

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

Field - Dipole moment

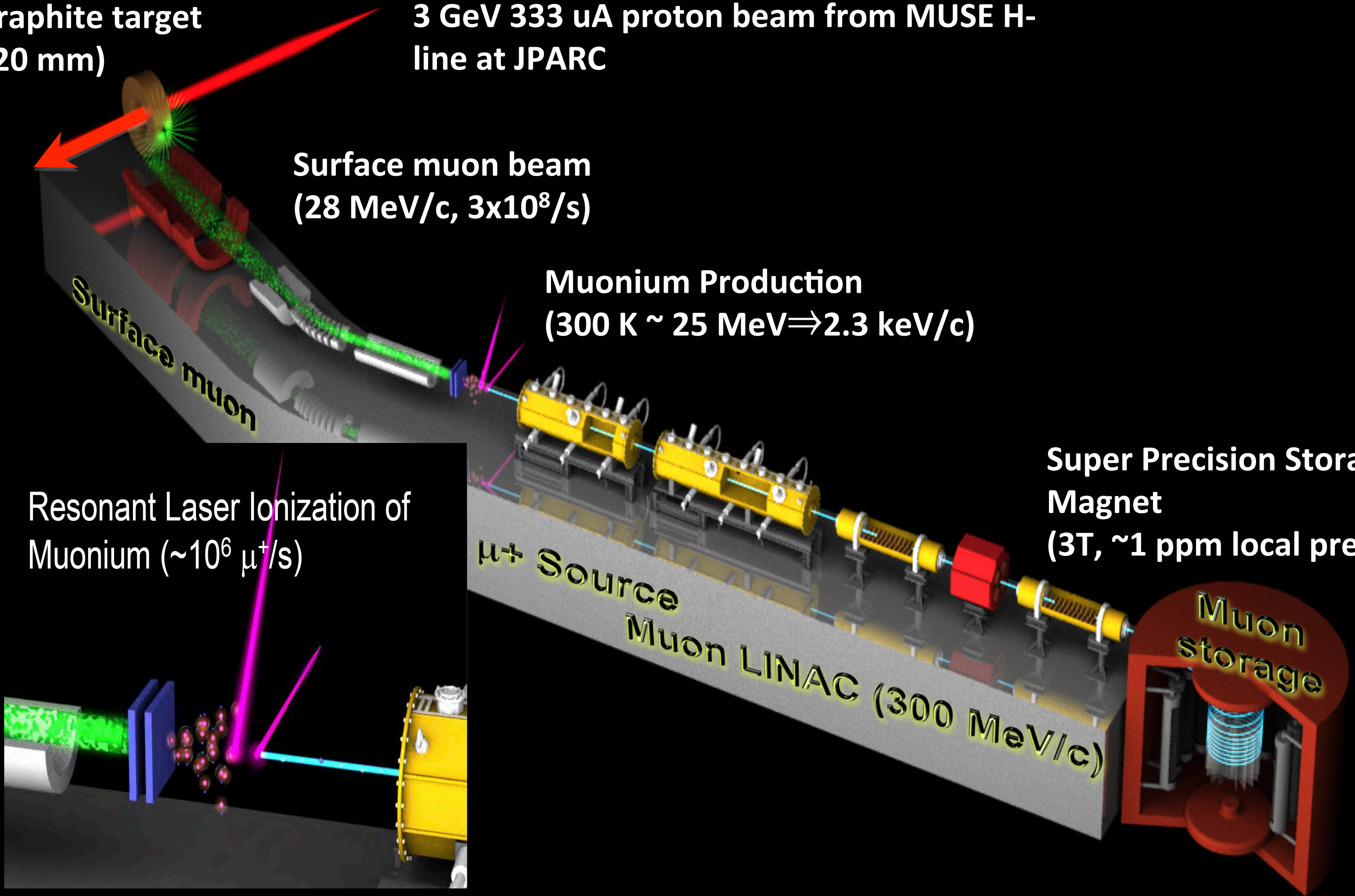


- All stored muons (magic momentum or otherwise) need to see the same field
- Extensive shimming program from 2015-2016 to reduce azimuthal fluctuations around the ring
- 3 times more uniform than BNL



J-PARC

New Muon g-2 Experiment- JPARC



Graphite target
(20 mm)

3 GeV 333 uA proton beam from MUSE H-line at JPARC

Surface muon beam
(28 MeV/c, 3x10^{8}/s)

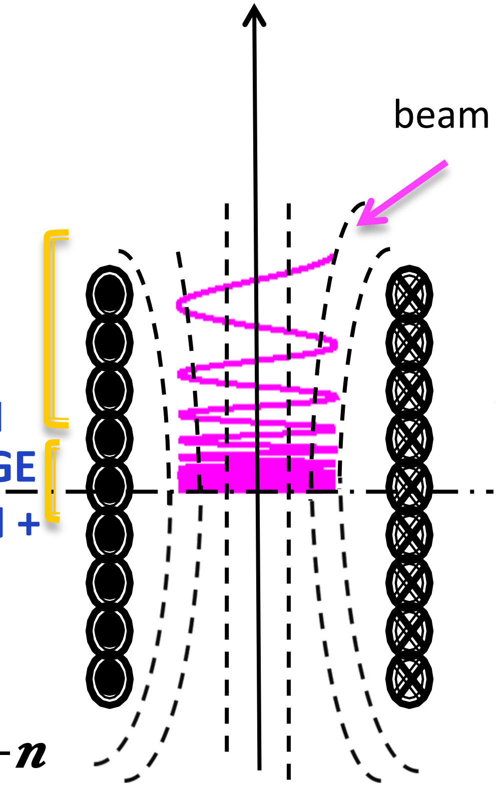
Muonium Production
(300 K ~ 25 MeV⇒2.3 keV/c)

Resonant Laser Ionization of Muonium (~10^{6} μ^{+}/s)

Super Precision Storage Magnet
(3T, ~1 ppm local precision)

Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

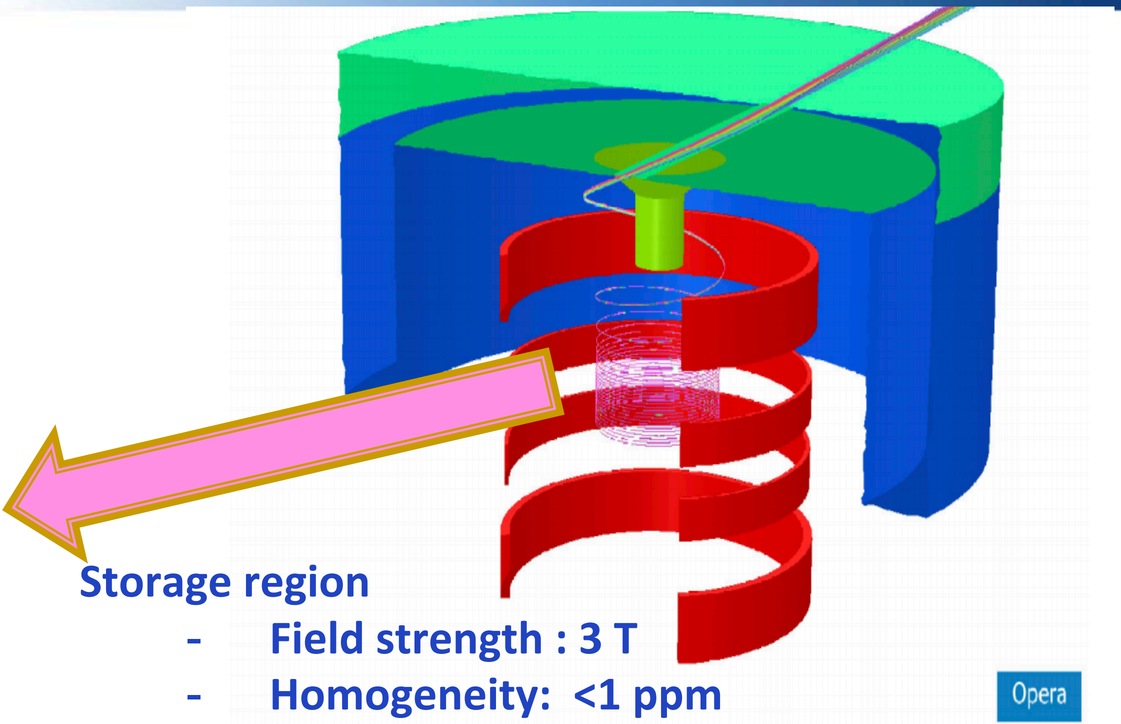
JPARC muon storage



INJECTION REGION

STORAGE REGION + WEAK FOCUS FIELD

$B_{r} = -n \frac{B_{0}}{R} z$



Storage region

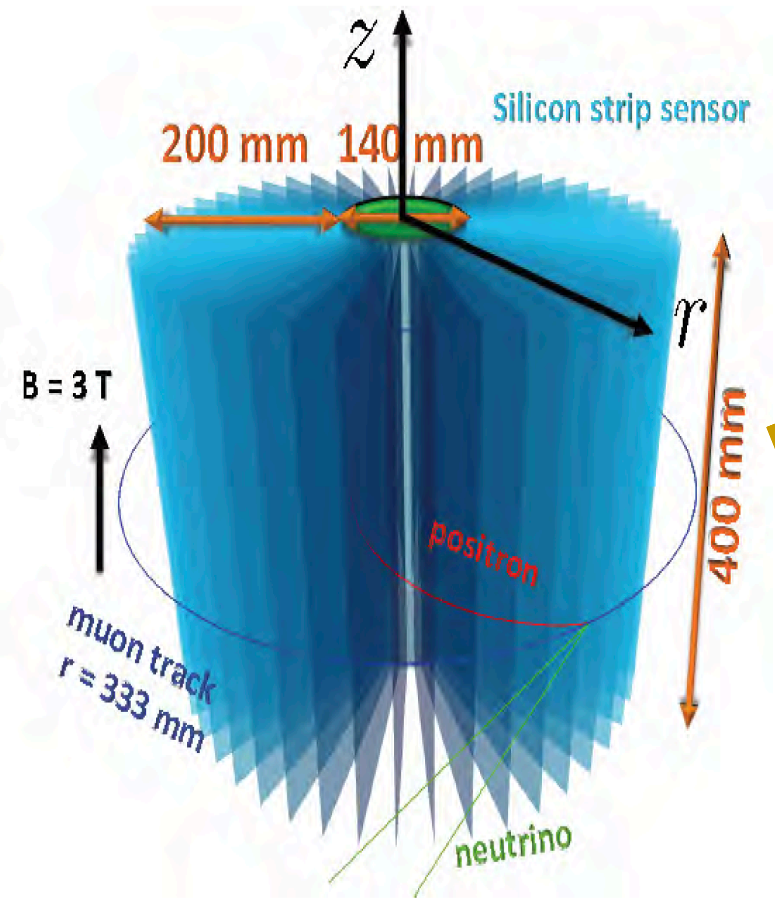
- Field strength : 3 T
- Homogeneity: <1 ppm locally
- radius: 33.3 cm
- height: ±5 cm

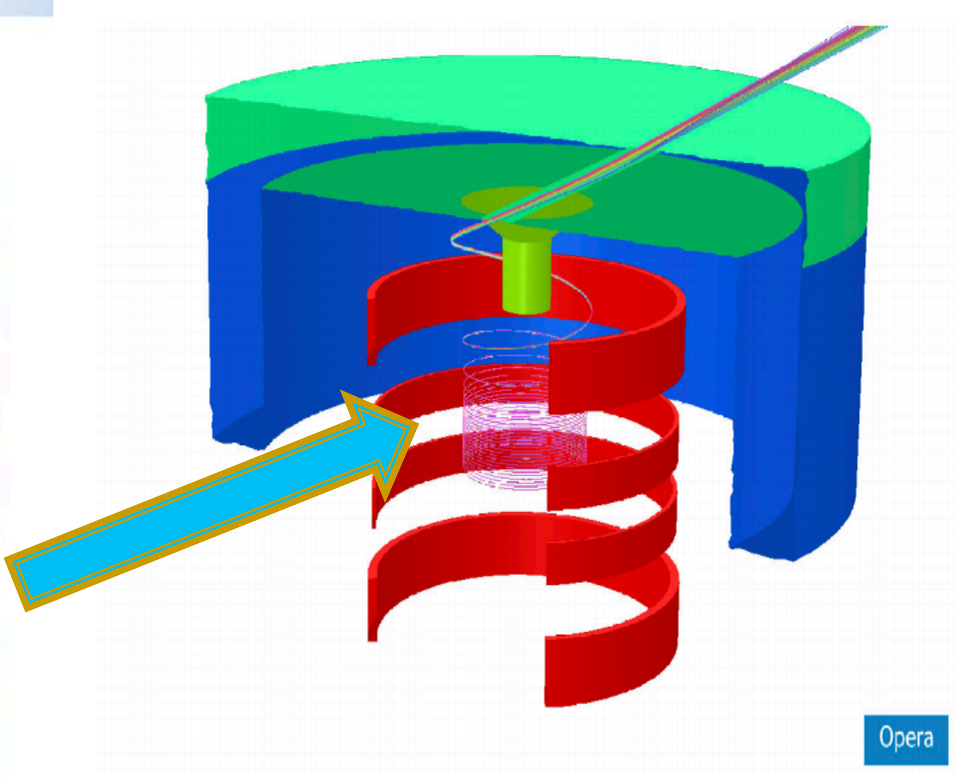
Injection region

- $B_r \times B_z > 0$
- B_r changes smoothly along the beam orbit

Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

JPARC e^+ detection





- **48 silicon tracking vanes inserted into the storage region.**
- **Radius = 70-270 mm**
- **Height = +/- 200 mm**
- **Segmentations allows for time tracking of the beam - reduces pileup effects.**

Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

JPARC- Timeline

- July 2009 Letter of Intent
- 2012 Conceptual Design Report and Stage 1 approval
- May 2015 Technical Design Report
- Nov 2016 TDR review
- 4 years for construction once budget fully approved.
- Two year run ~0.35 ppm measurement (statistical)
- Novel approach significantly reduces several of the largest systematic errors in E821.
- New experiments always bring new surprises …
- An important effort and complementary to new g-2 FNAL experiment.

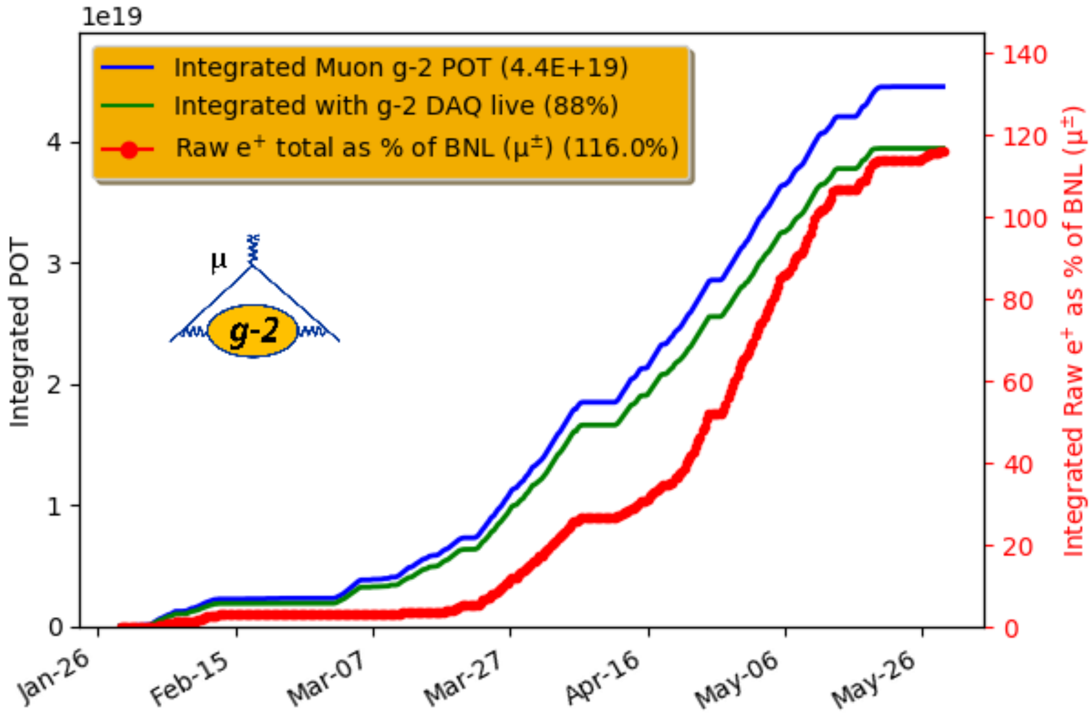
ERROR	**BNL (ppm)**	**JPARC (ppm)**	**ω_a Systematics**
Pileup	0.08	<0.05	Tracking rather than calorimeter
Beam background	-	-	Only stored muons
Lost muons	0.09	<<0.09	Requires low emittance beam
Timing shifts	-	<<0.1	No PMTs
E-field, pitch	0.05	<<0.01	No E field, small divergence
Fitting/binning	-	<<0.1	Fewer oscillations cycles
CBO	0.07	<<0.1	Small focusing fields
Track Reconstruction	-	<<0.1	Need to maintain rate independence
Gain changes	0.12	<<0.1	Access with spin flip
Others	-	TBD	Simulation studies started
TOTAL	**0.180**	**<0.1**	

ω_p systematic error expected to be similar for JPARC and FNAL ~ 0.07 ppm

Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

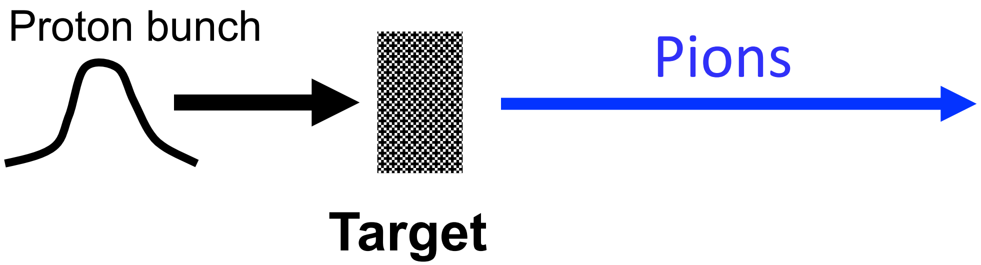
Conclusions

- New data and improved combination reducing major theoretical uncertainties and improving BNL limit
- FNAL g-2 measurement underway
- Detectors working well - refining systematic uncertainty analyses
- J-PARC on track to make complimentary measurement



- backups…

Supplying anti-muons



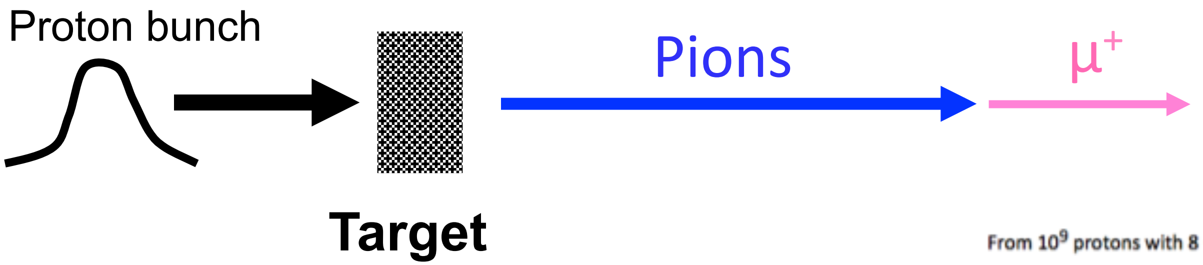
Proton bunch

Pions

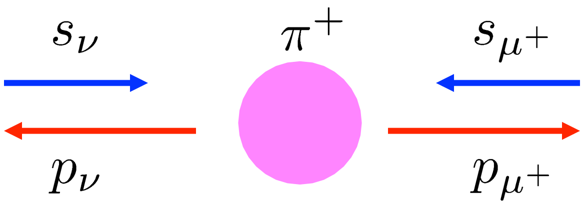
Target

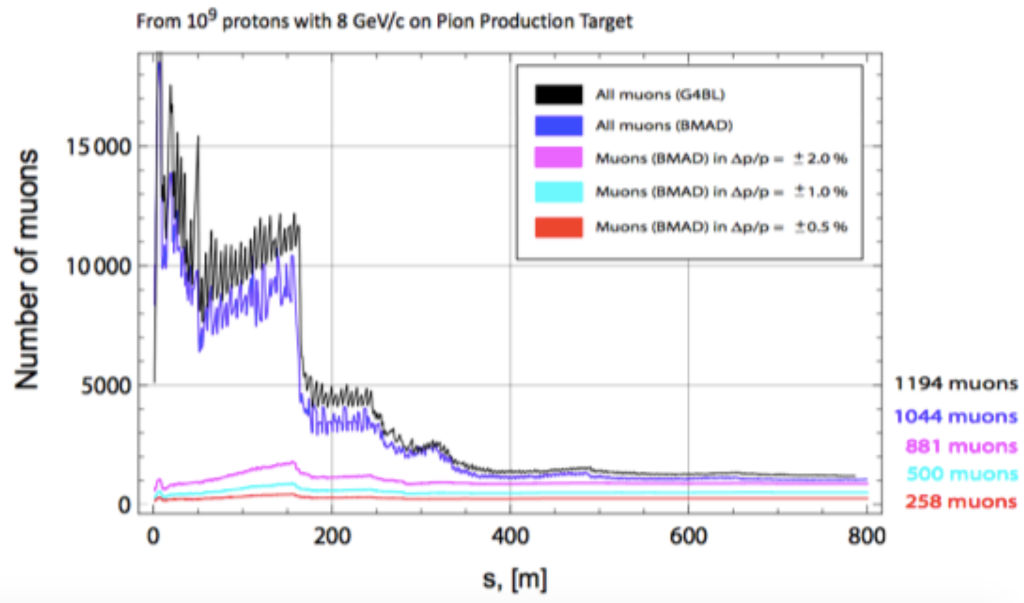
- Outgoing pions focused by a lithium lens and then momentum-selected, centred on 3.11 GeV
- The pions are then collected and sent towards the delivery ring

Supplying anti-muons



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



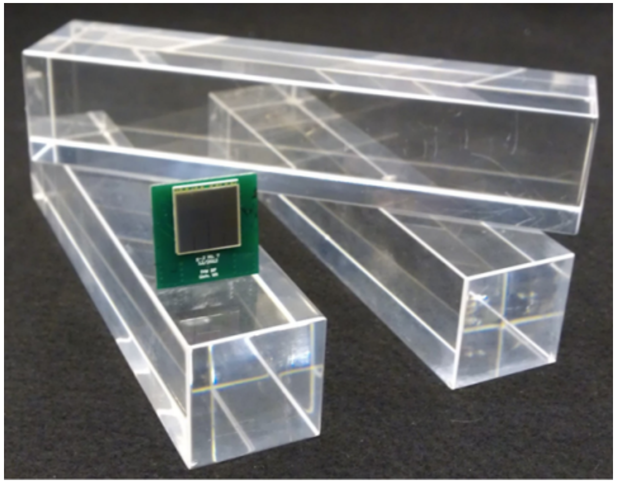


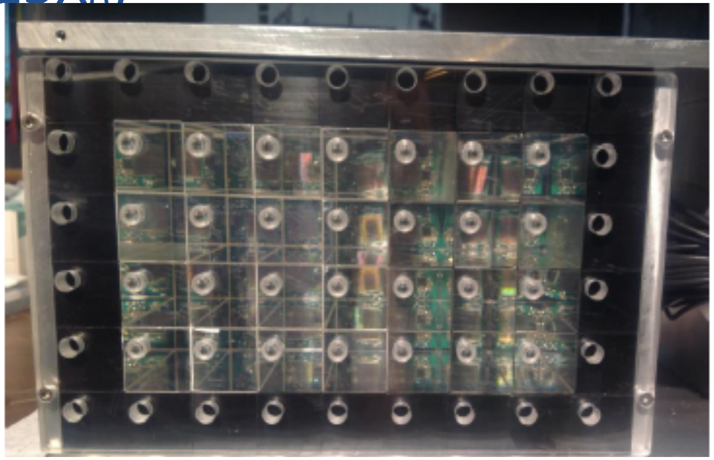
- 2 independent simulations of polarisation and phase space of beam

- JPARC ref:
- http://iopscience.iop.org/article/10.1088/1742-6596/295/1/012032/pdf

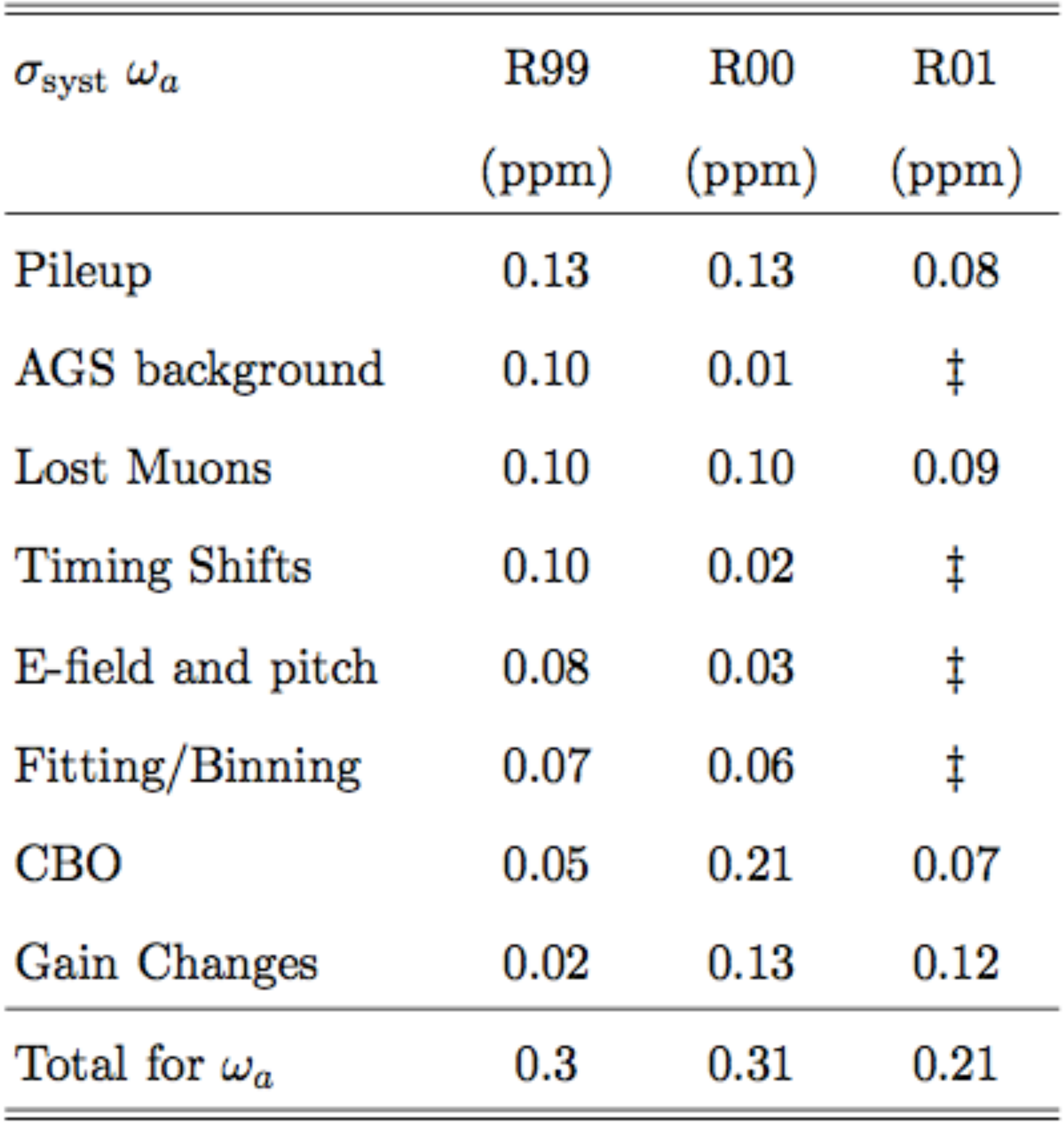
Calorimeters

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





Brookhaven systematics - ω_a



σ_{syst} ω_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

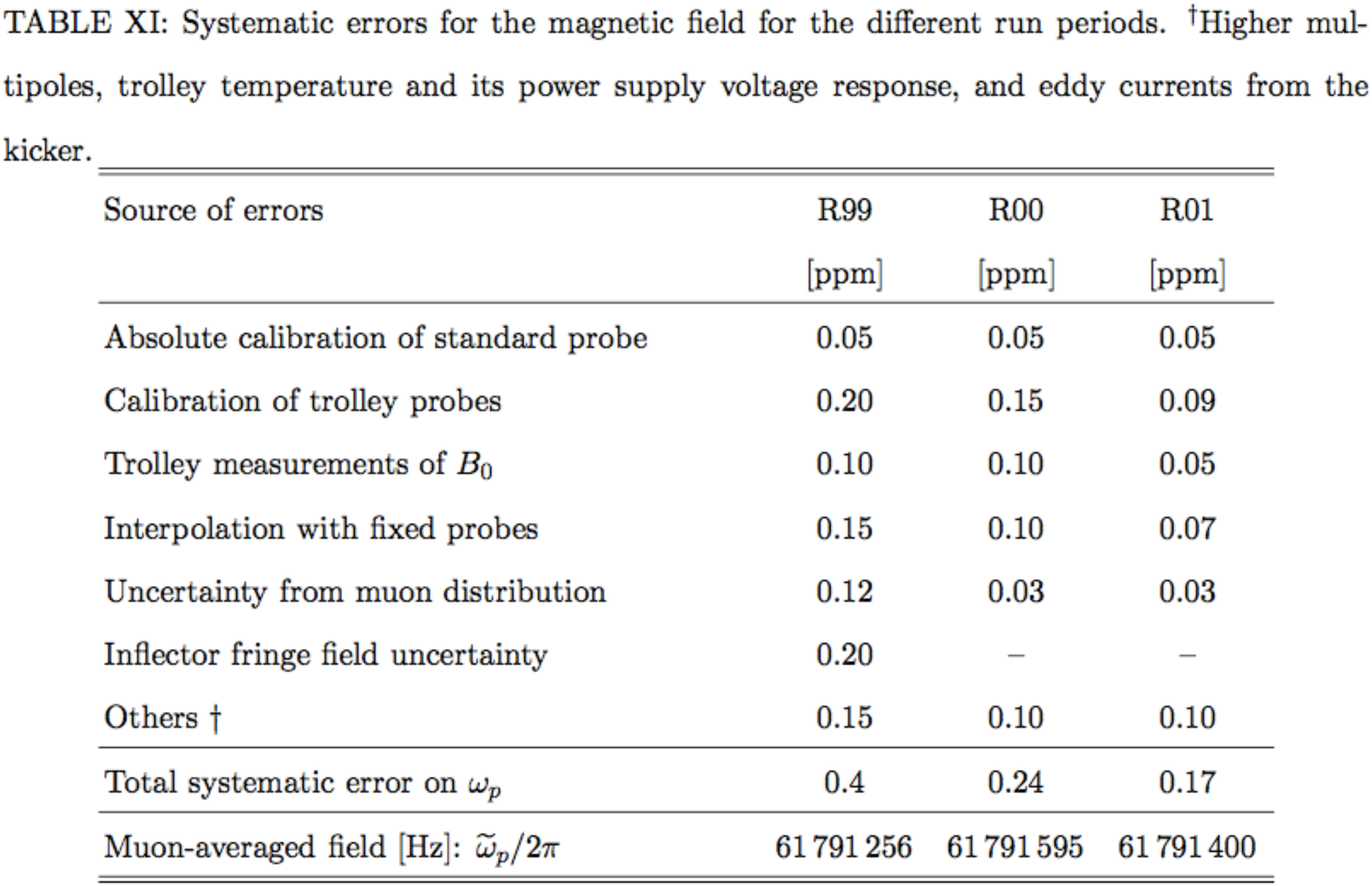


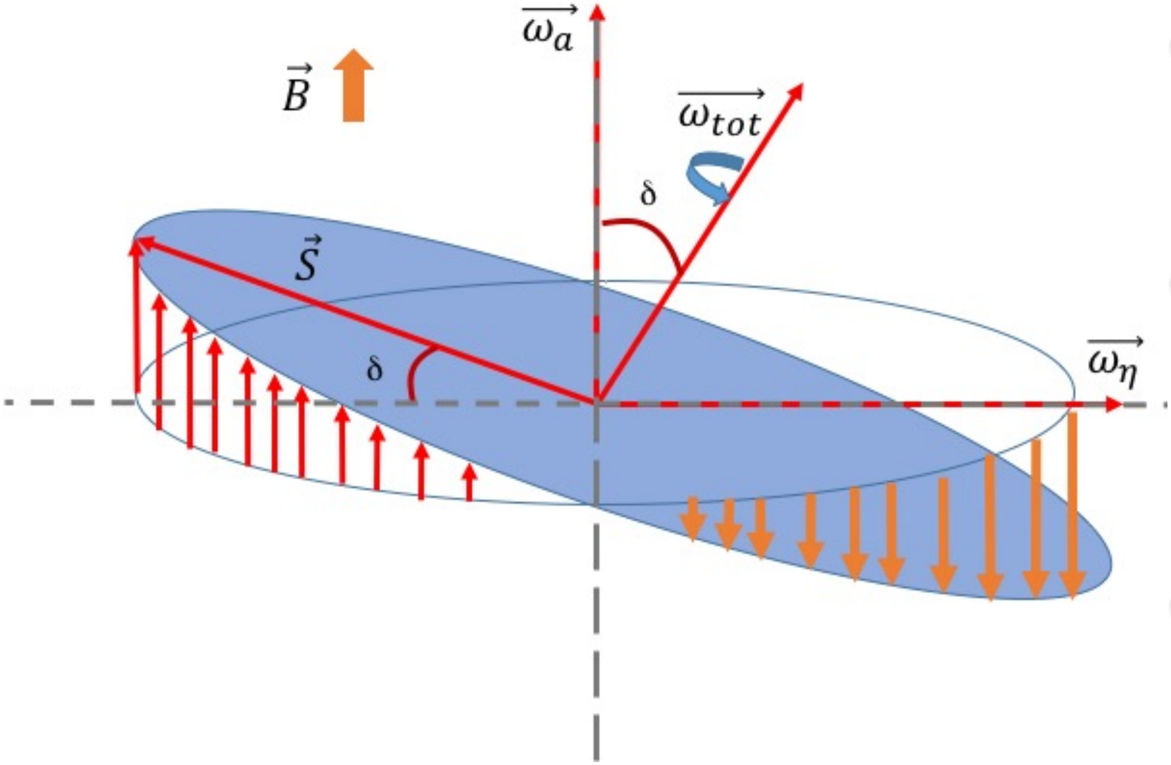
TABLE XI: Systematic errors for the magnetic field for the different run periods. [†]Higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

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

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

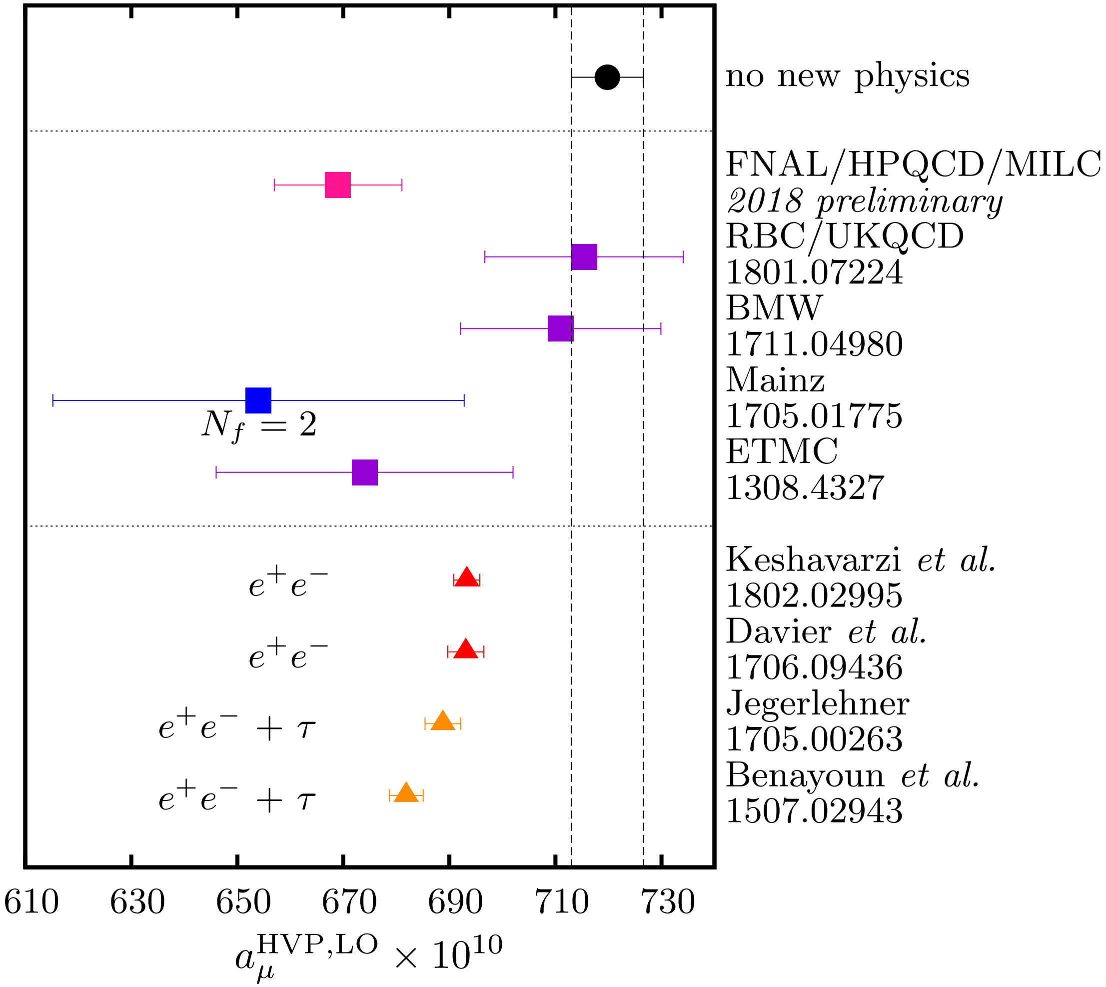
- Increase in precession frequency

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

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

Lattice QCD

- higher lattice values missing some components but agree with KNT



Ruth Van De Water (FNAL/HPQCD/MILC), presented at Muon g-2 theory initiative workshop, KEK, Japan, Feb 2018