The new muon g-2 experiment at Fermilab

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INFEIRI
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Today

- Motivation
  - brief g-2 history
  - measurement overview

- Muon storage, spin precession
  - beam dynamics systems
  - measurement of $d\vec{s}/dt$

- Magnetic field determination

- Current status, path forward

- Motivation
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The spinning muon

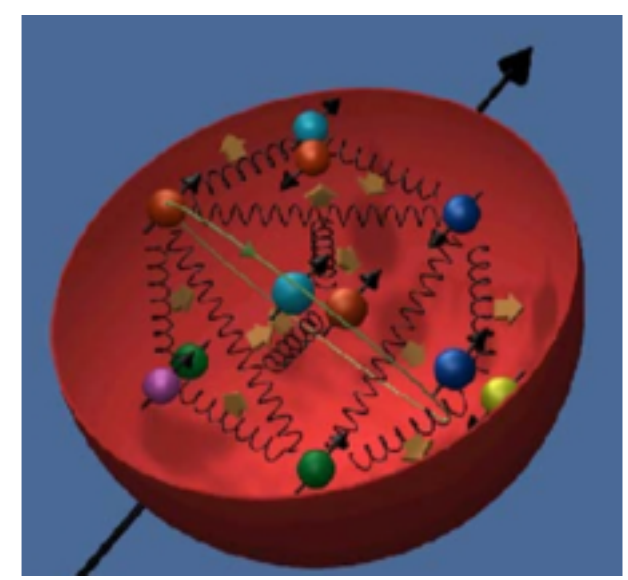
- Like every fundamental or system of particles, the muon has an intrinsic magnetic moment coupled to it's spin by the gyromagnetic ratio g.

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

- Interactions between the muon and virtual particles perturb this number, provides indirect measurement to wealth of physics:
  - internal structure
  - classes of interactions otherwise inaccessible

- For example, nucleon magnetic moments:
  - g_p (proton) ~ 5.6
  - g_n (neutron) ~ -3.8

$\Rightarrow$ nucleon substructure



Evolution of the SM muon magnetic moment

$$\vec{\mu} = \mathbf{g}\frac{e}{2m_\mu c}\vec{S}$$

Evolution of the SM muon magnetic moment

$$g_\mu = 2.$$

Evolution of the SM muon magnetic moment

P Dirac

1933

$$\left(\frac{1}{2m}(\vec{P}+e\vec{A})^2+\frac{e}{2m}\vec{\sigma}\cdot\vec{B}\right)\psi_A=(E-m)\,\psi_A$$

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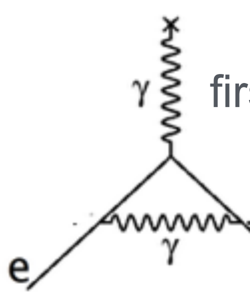
$$g_\mu = 2.002\ 3$$



first order QED

J Schwinger

1965

$$\frac{\alpha}{2\pi} = 0.00232$$

birth of QED!

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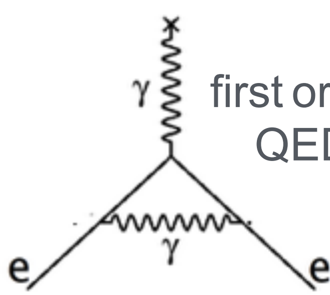

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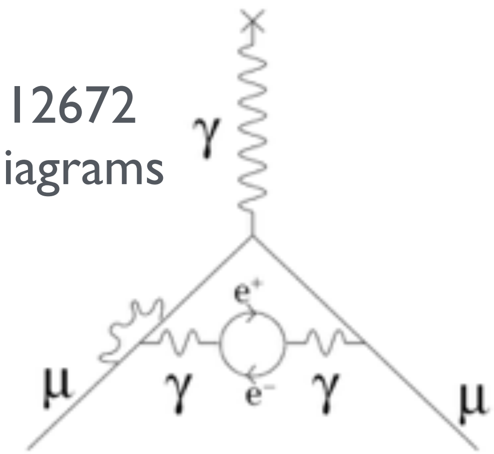
12672 diagrams



QED calculated to 10^{th} order

$$g_\mu = 2.002\ 331$$

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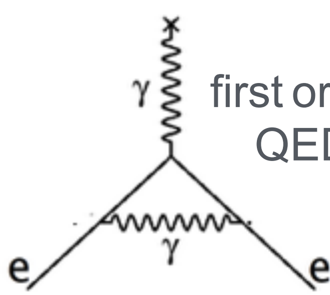

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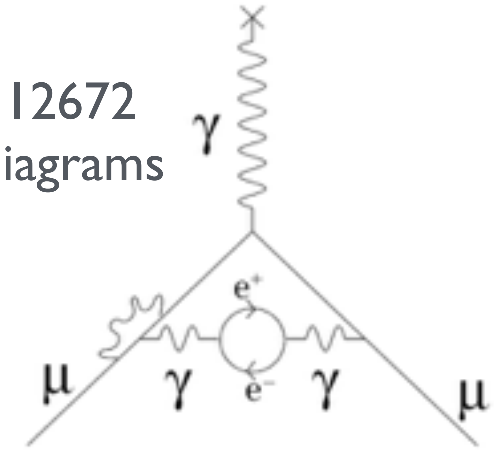

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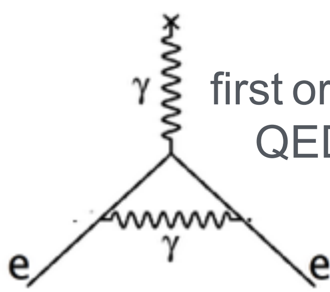

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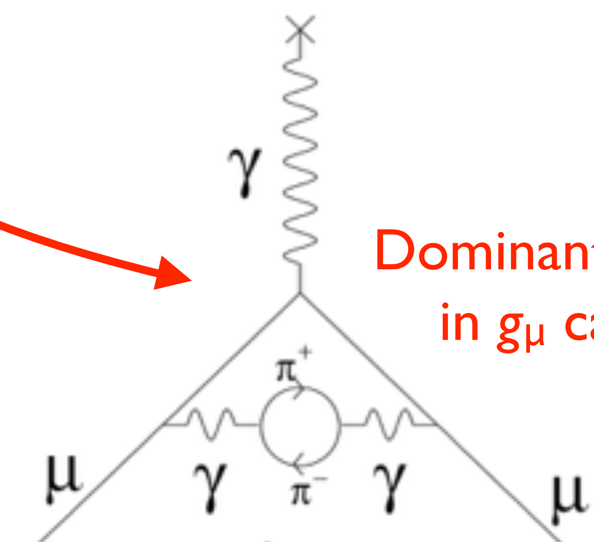

Hadronic

Dominant uncertainty in g_μ calculation!

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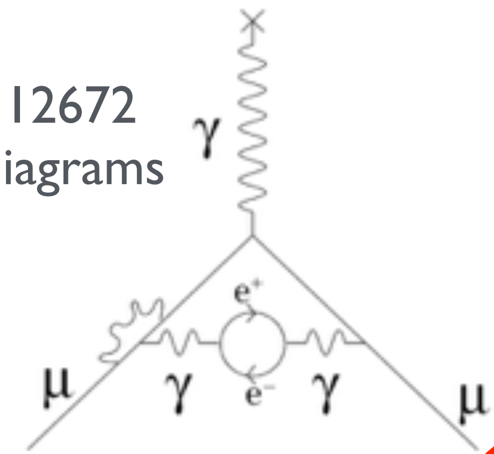

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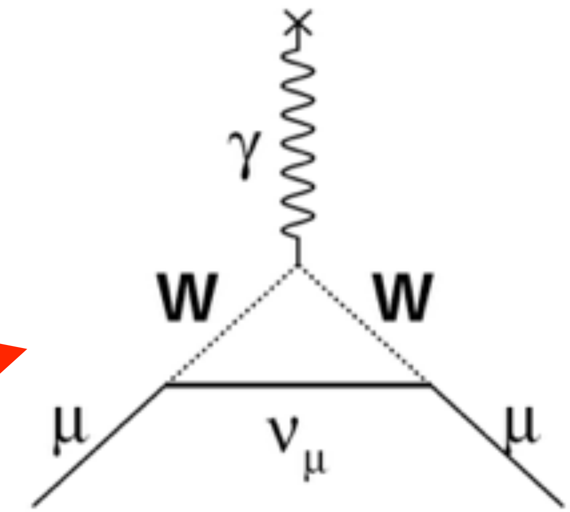
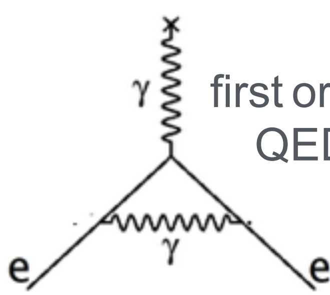


Electroweak

$$g_\mu = 2.002\ 331\ 841\ 7$$

J Schwinger



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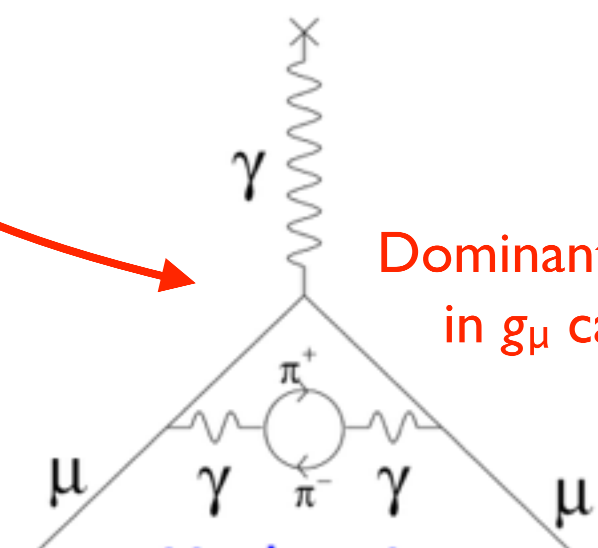

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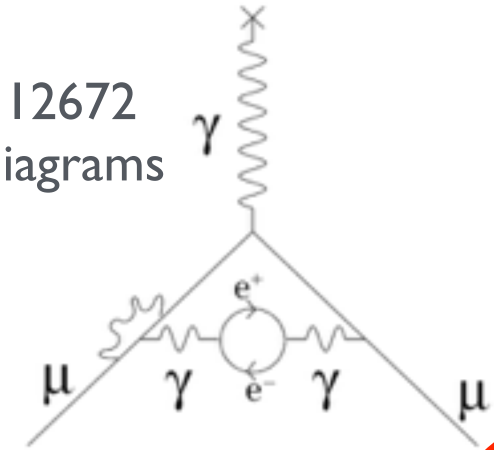

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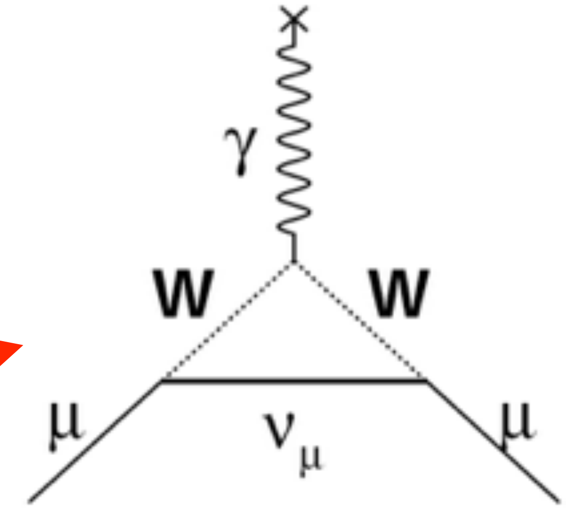

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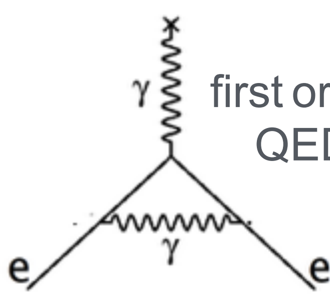

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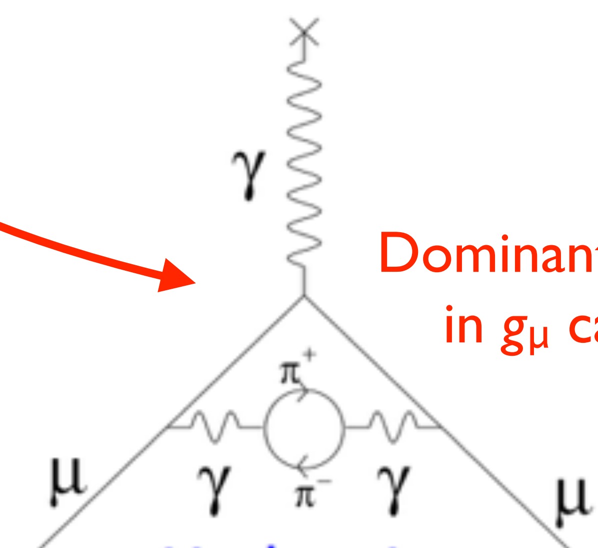


Hadronic

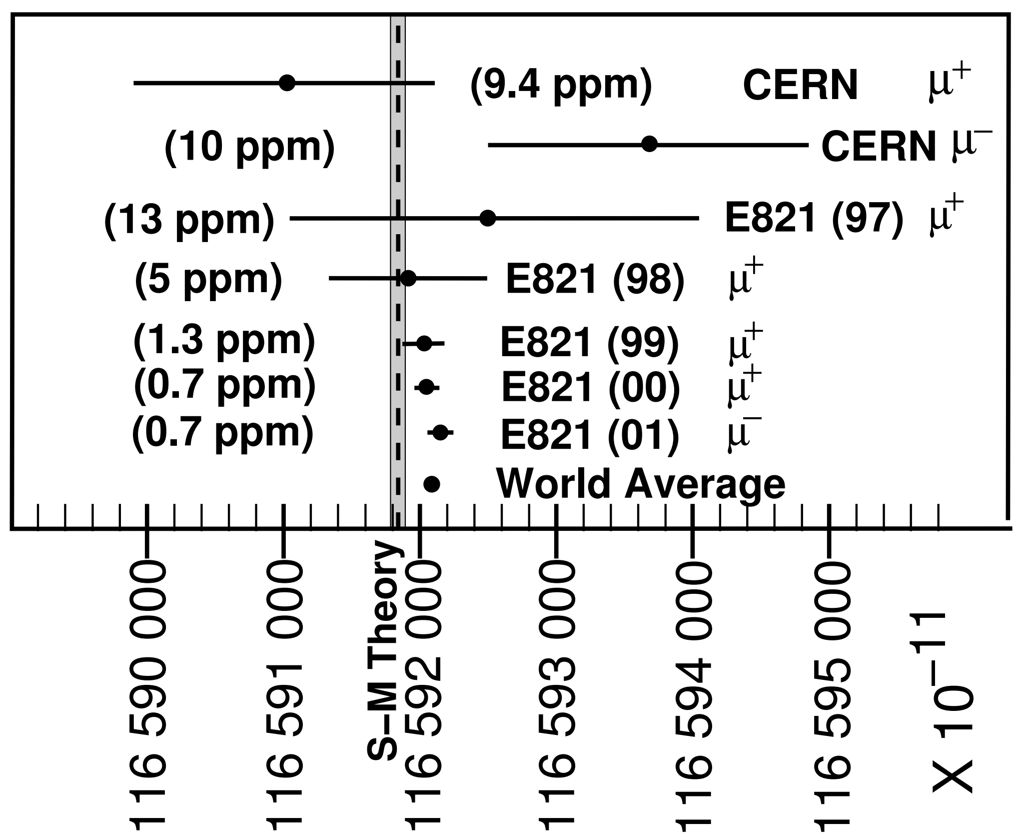
Dominant uncertainty in g_μ calculation!

History of experimental value

- In last 60 years, technology advancements has allowed enormous progress in experimentally measuring this quantity

- Each measurement gained sensitivity to additional interaction types

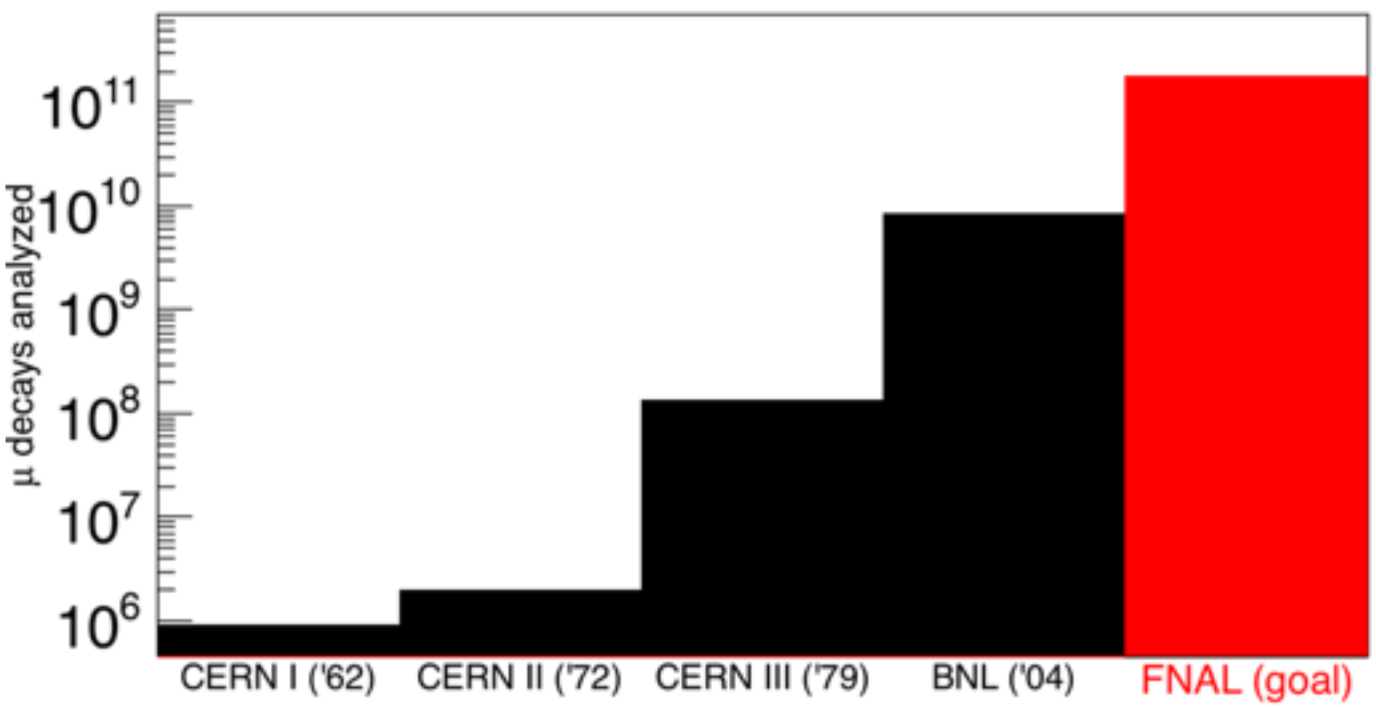
2004: Brookhaven measurement first to find robust discrepancy with SM value (~3.6σ)



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

Measurement improvements

- The BNL measurement (as with all previous *g*-2 expt's) was statistics-limited.
  - "just" need more muons!



Arguably the strongest existing hint of new physics, must be tested rigorously with more statistics, better control of systematic effects

- Strategy: reboot experiment, develop new muon beamline at Fermilab to deliver 21x statistics. 540 ppb (BNL meas) ⇒ 140 ppb (FNAL goal)
  - must reduce systematic uncertainty to fully exploit unprecedented stats

Experimental technique overview

- Motional muons in magnetic field:

  1. Cyclotron motion (momentum rotates)

$$\frac{d\vec{p}}{dt} = e\vec{v} \times \vec{B} \Rightarrow \omega_c = \frac{eB}{\gamma mc}$$

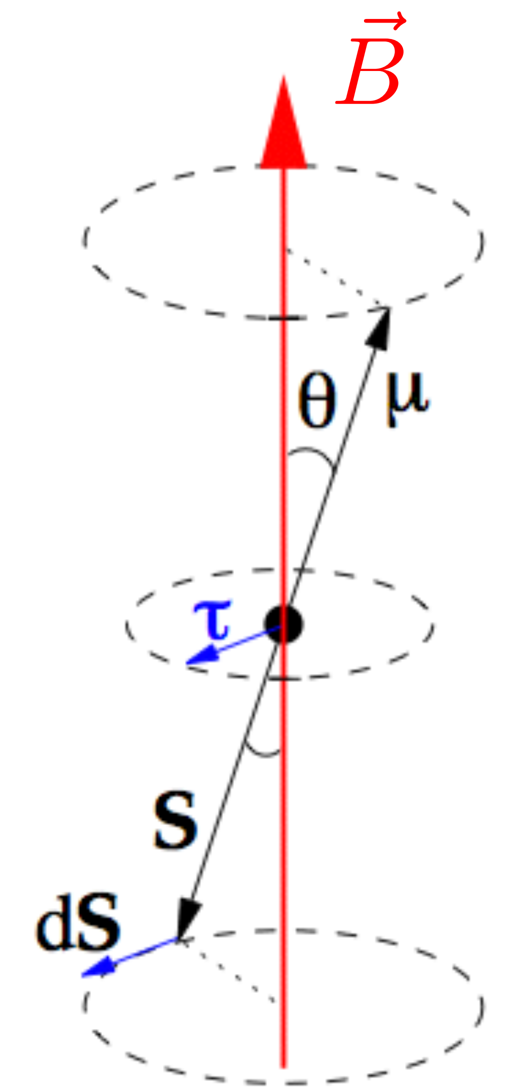
$$(\vec{v} \cdot \vec{B} = 0)$$

  2. Spin precession (spin rotates)

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} \Rightarrow \omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Larmor precession

Thomas precession

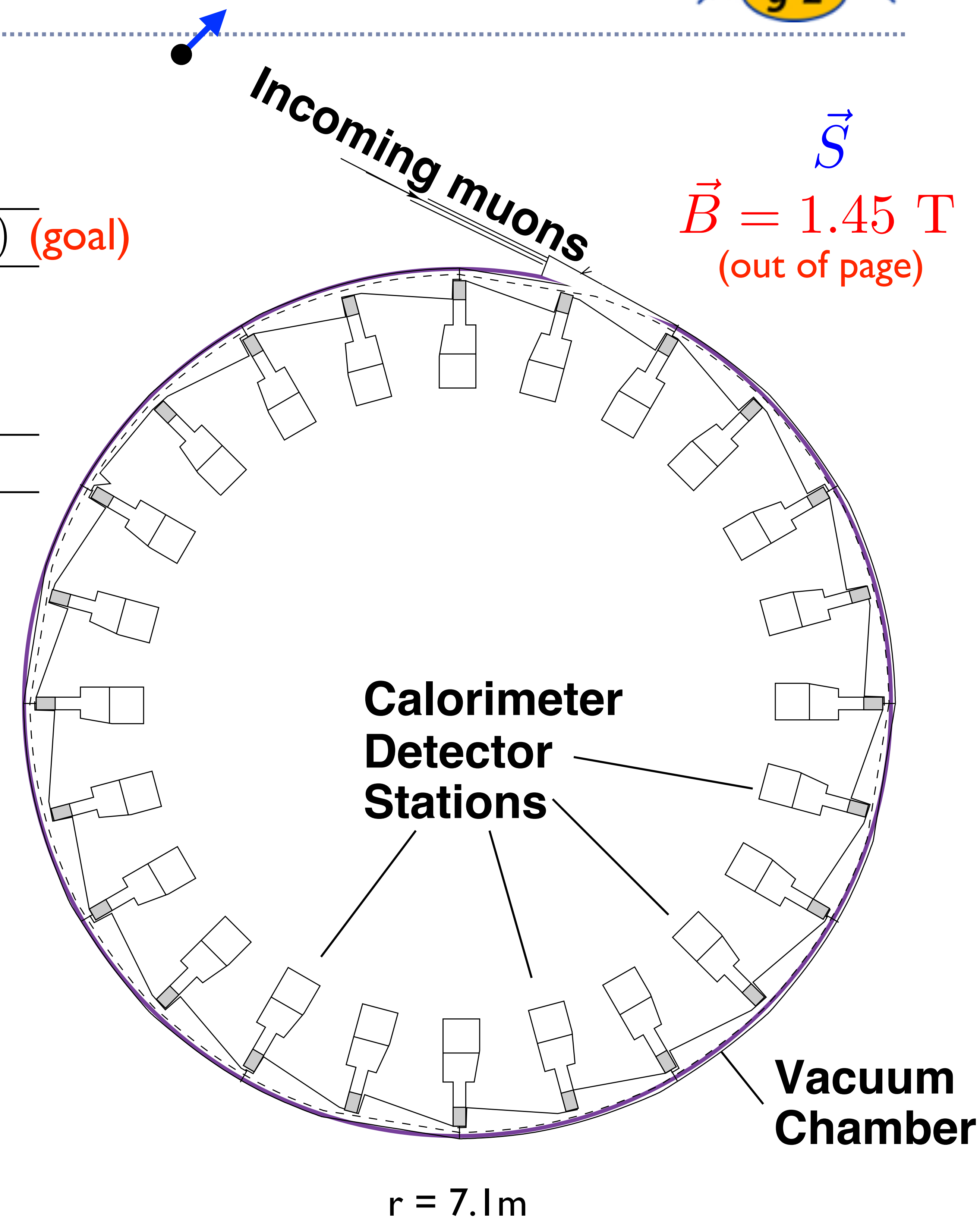


Difference frequency: $$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

Precision measurements of ω_a and B ⇒ a_μ

Experimental error overview

Unc. source	BNL (ppb)	FNAL (ppb) (goal)
spin precession stat.	480	100
spin precession syst.	180	70
magnetic field syst.	170	70
Total	540	140



- Spin precession statistics by far largest improvement
- To fully exploit statistics, need systematic improvement ~ factor 3

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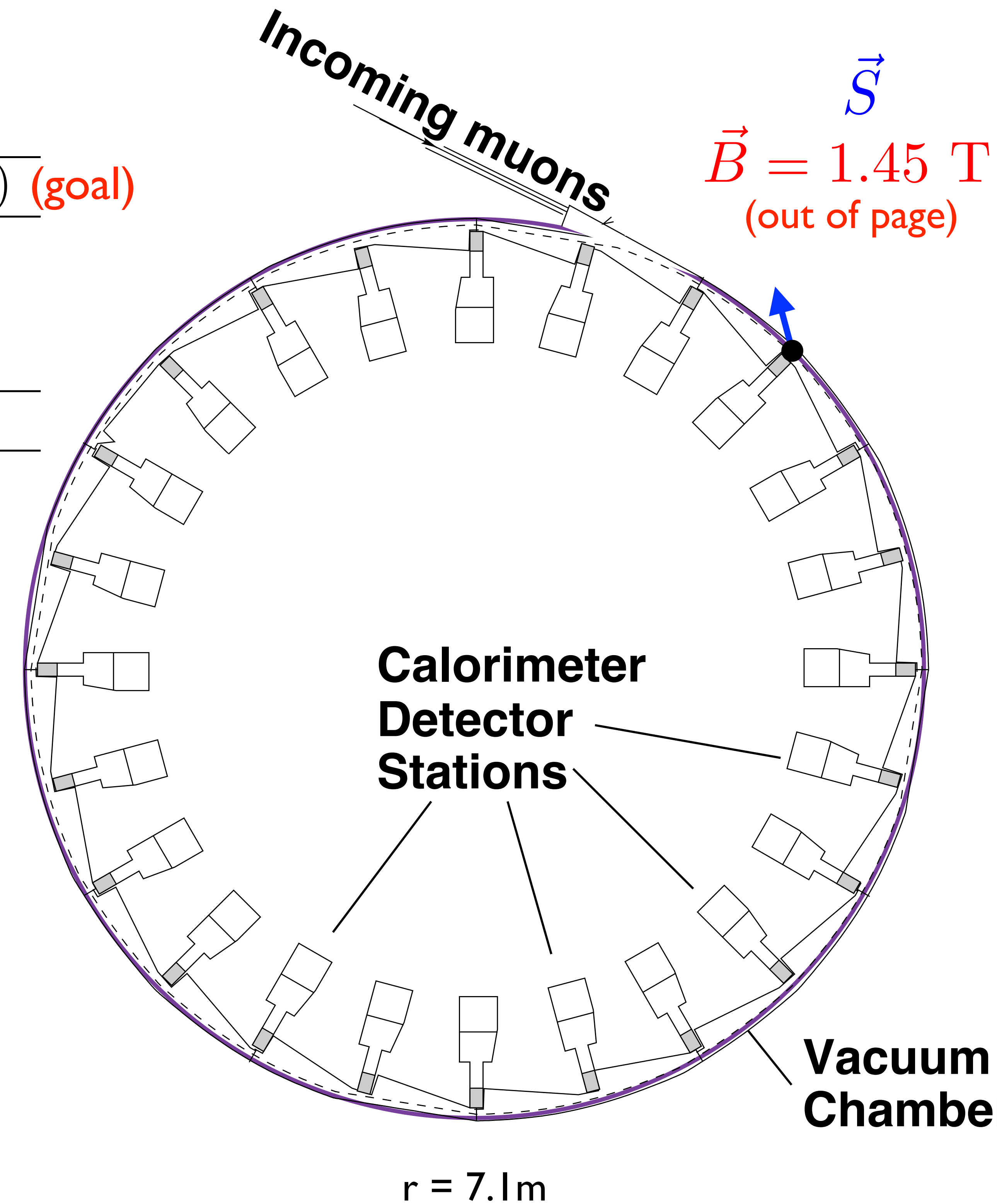

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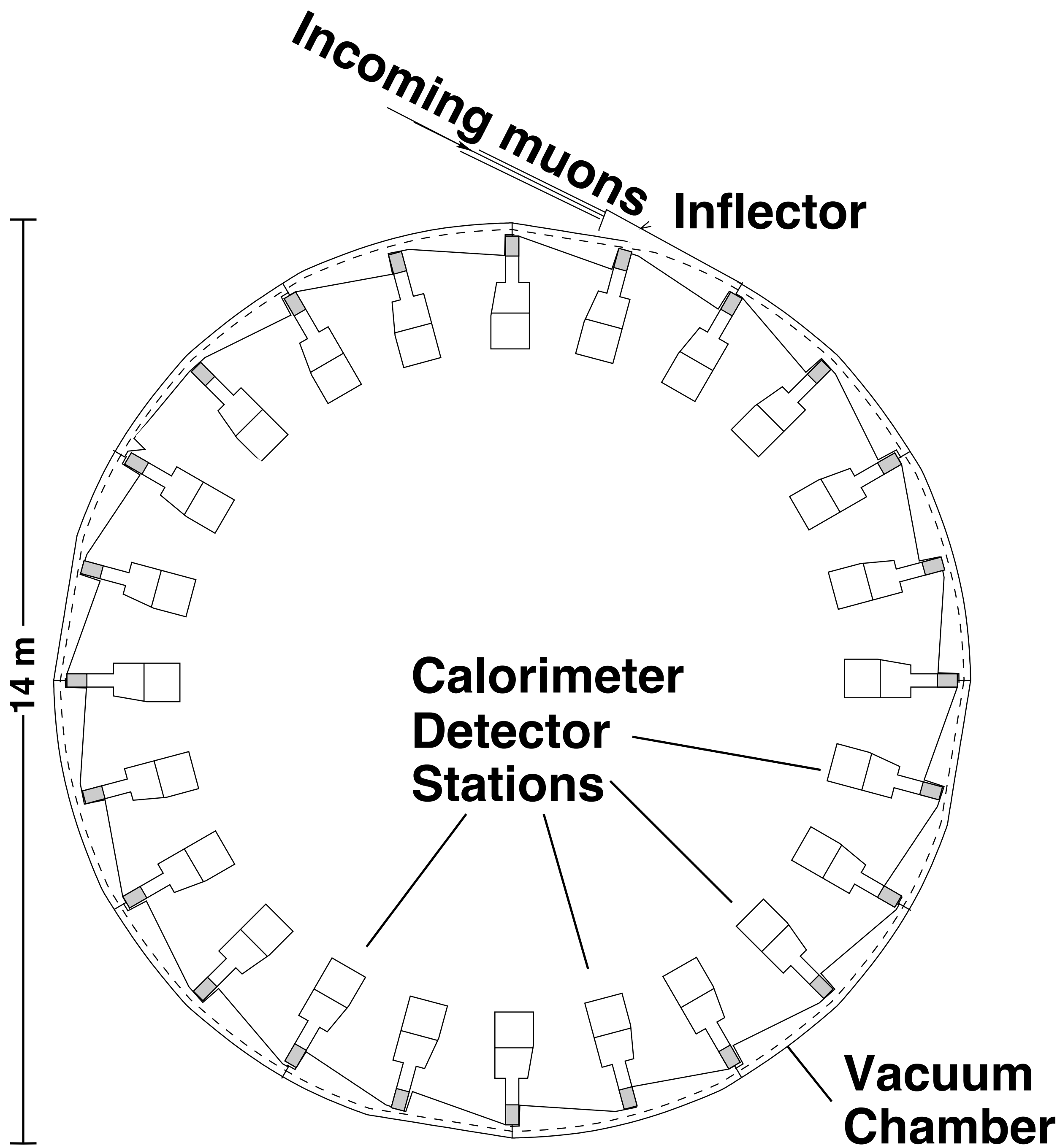
- **Magnetic field determination**
- Current status, path forward

Beam storage systems



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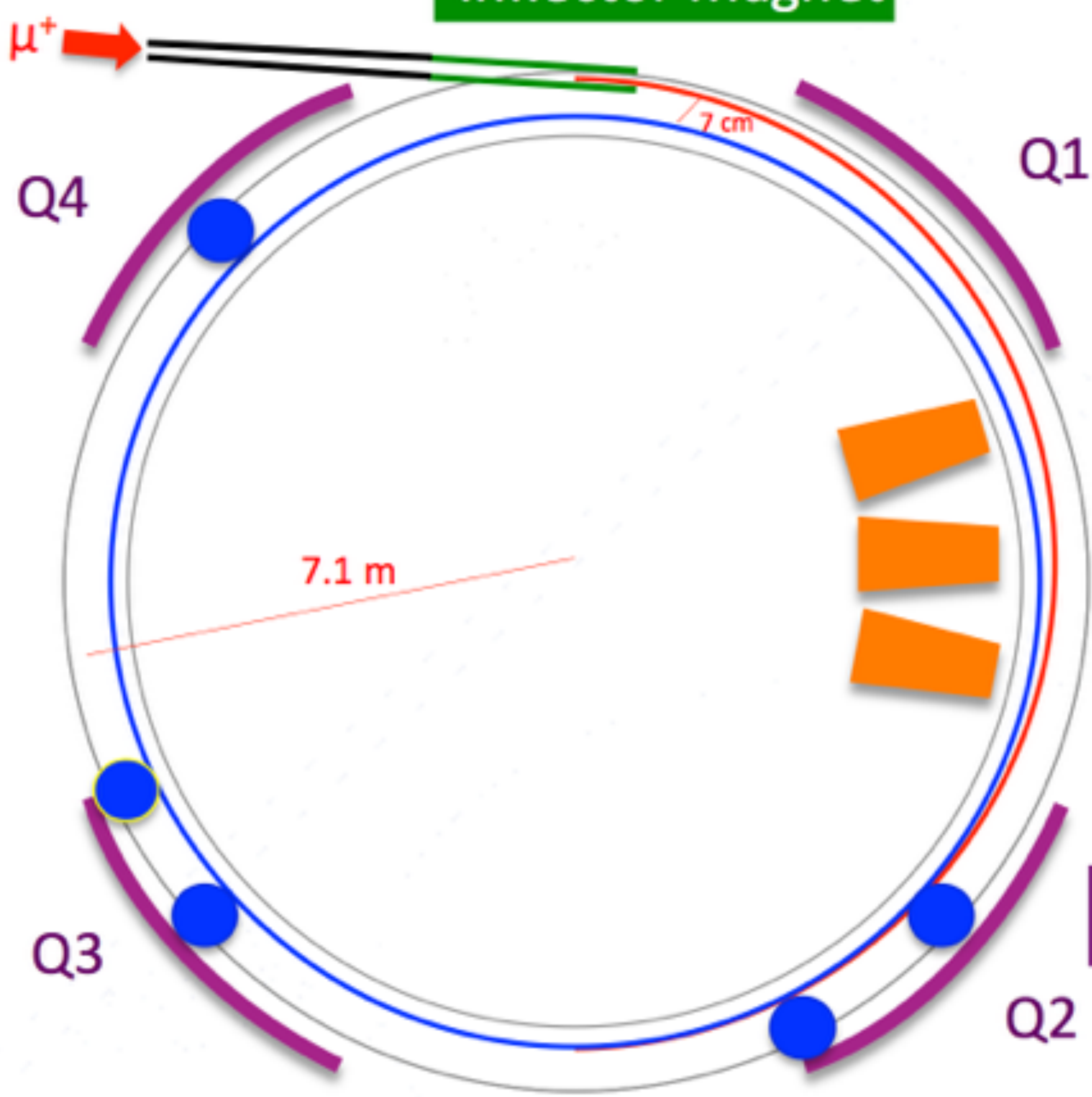


Inflector Magnet

Actively cancels magnet flux return so muons injected tangentially

Kicker magnets

Injected muons off-orbit. “Kicks” muons onto correct path

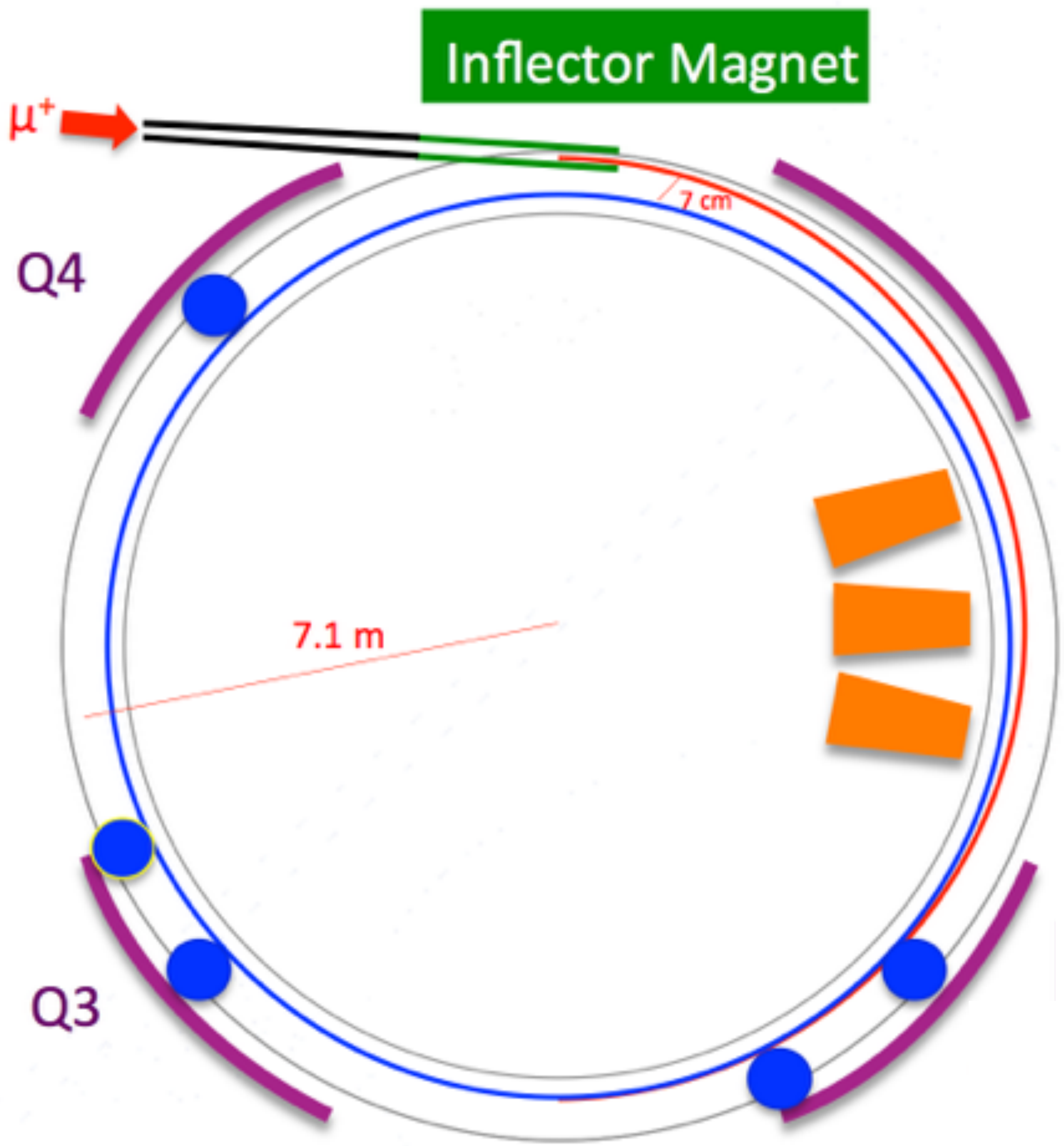
Focussing quads

Statistics, statistics, statistics…

Collimators

Helps eliminate off-momentum muons

Beam storage systems



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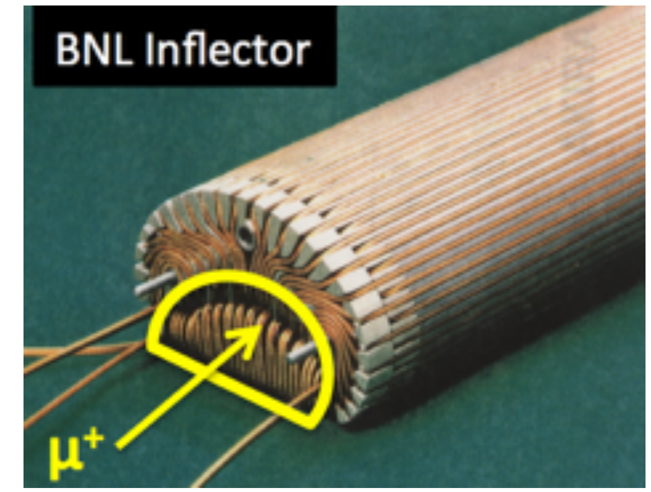

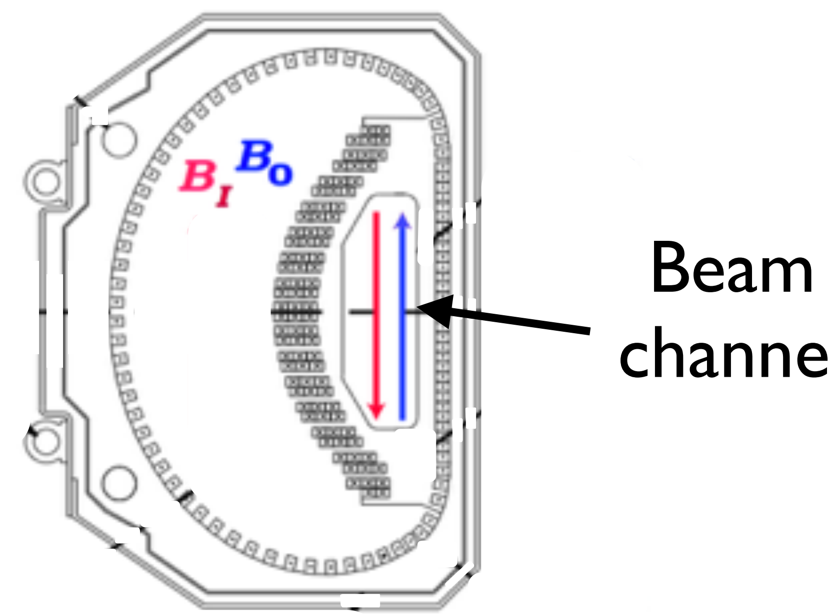

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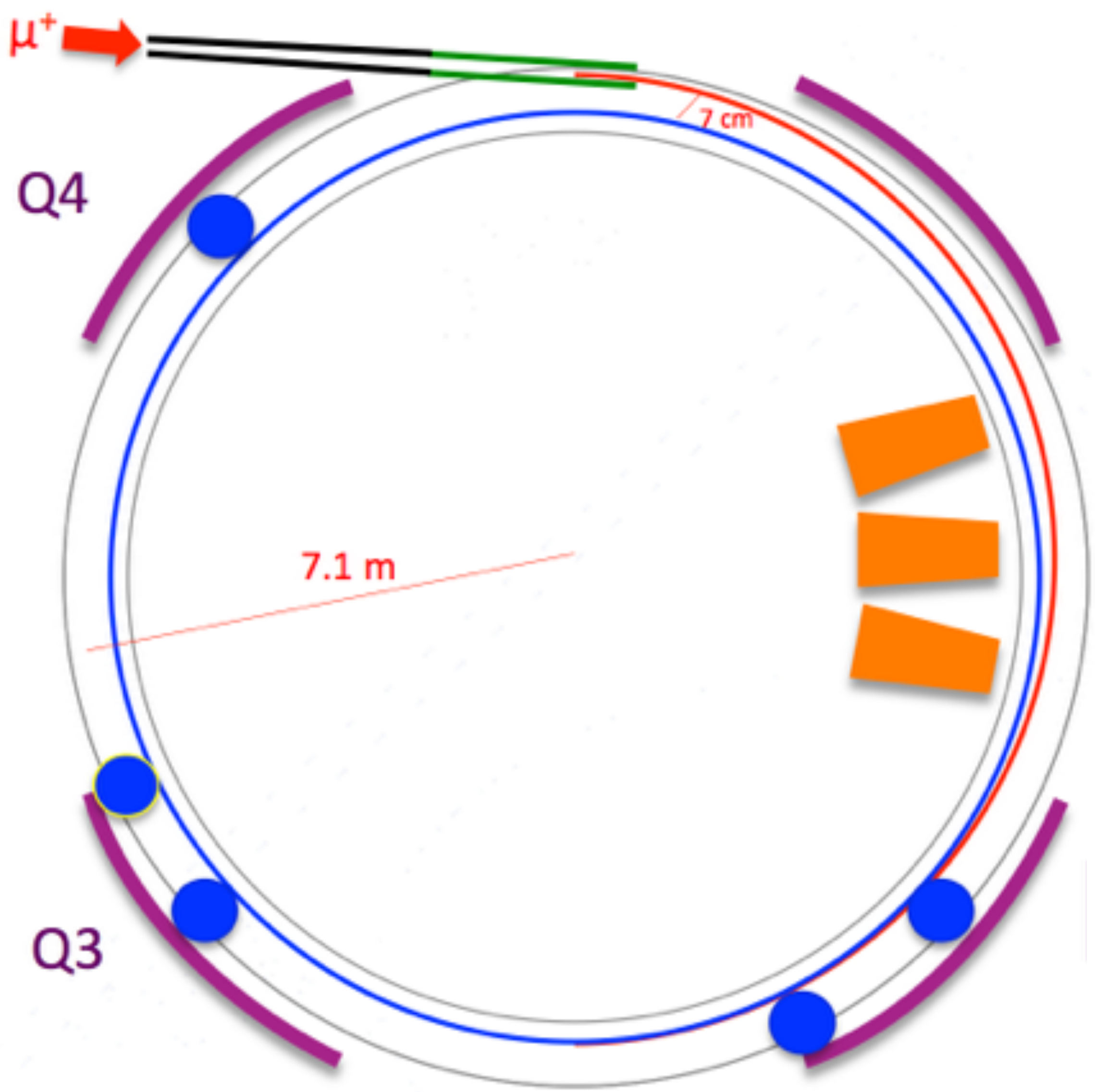
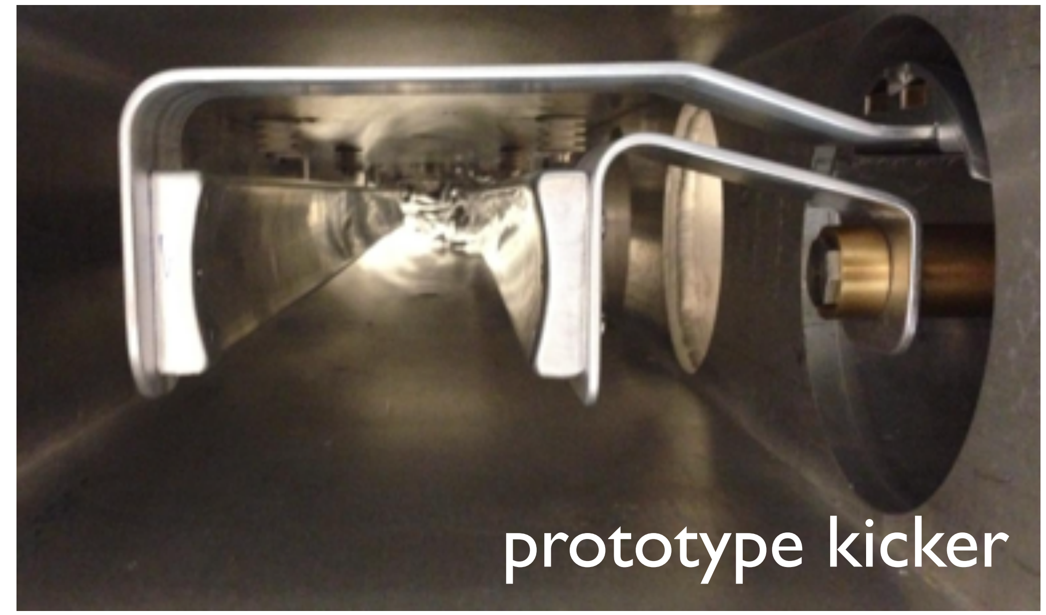




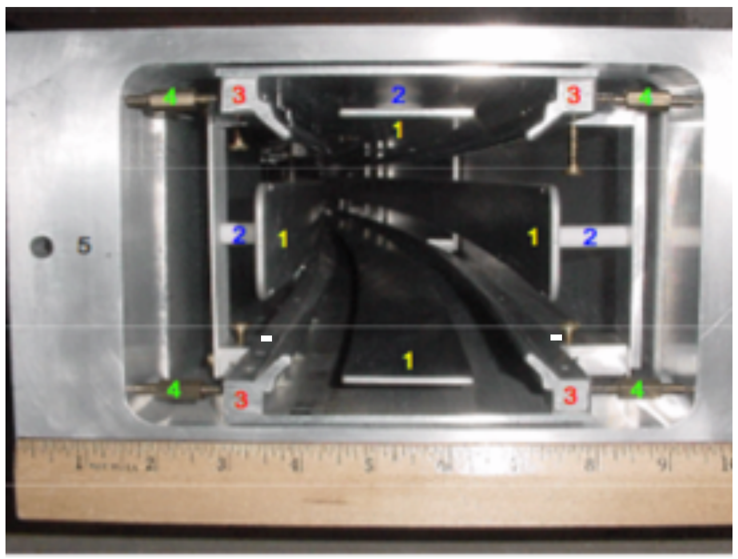
Kicker magnets

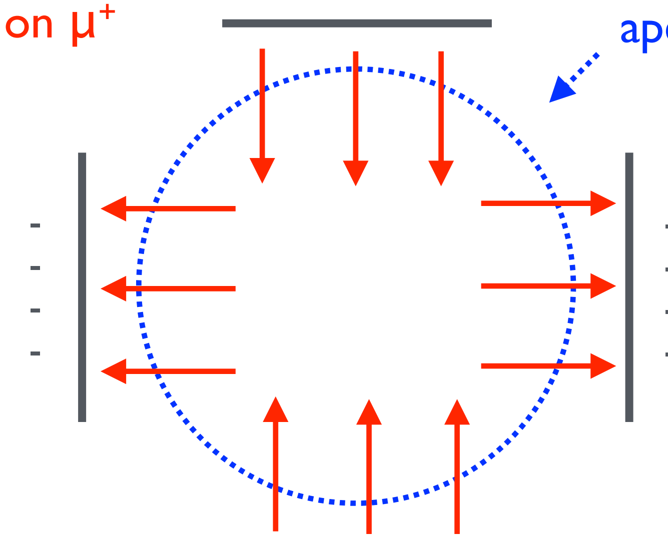
New with improved kick

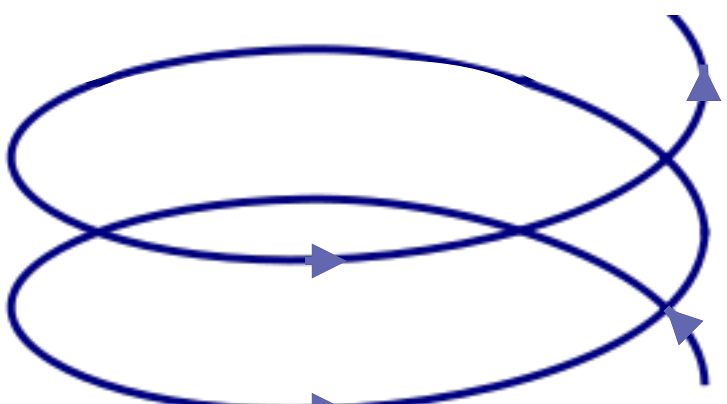
Injected muons off-orbit.
“Kicks” (10 mrad bend)
muons onto ideal orbit

Focusing quadrupoles

- Around 40% of storage volume equipped with electric focusing quadrupoles for vertical confinement
  - dramatically increases storage efficiency

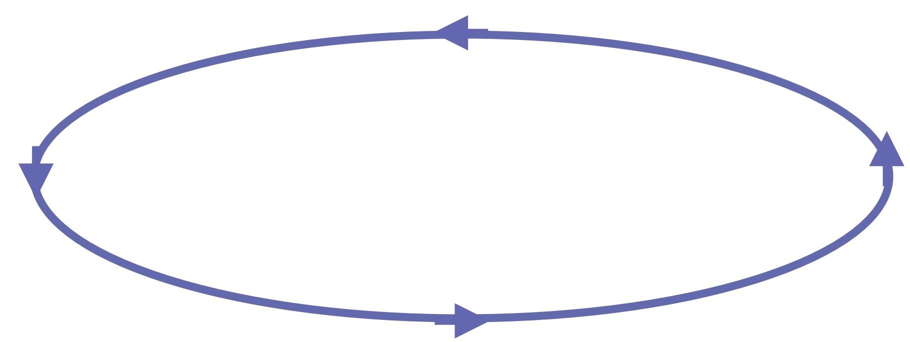






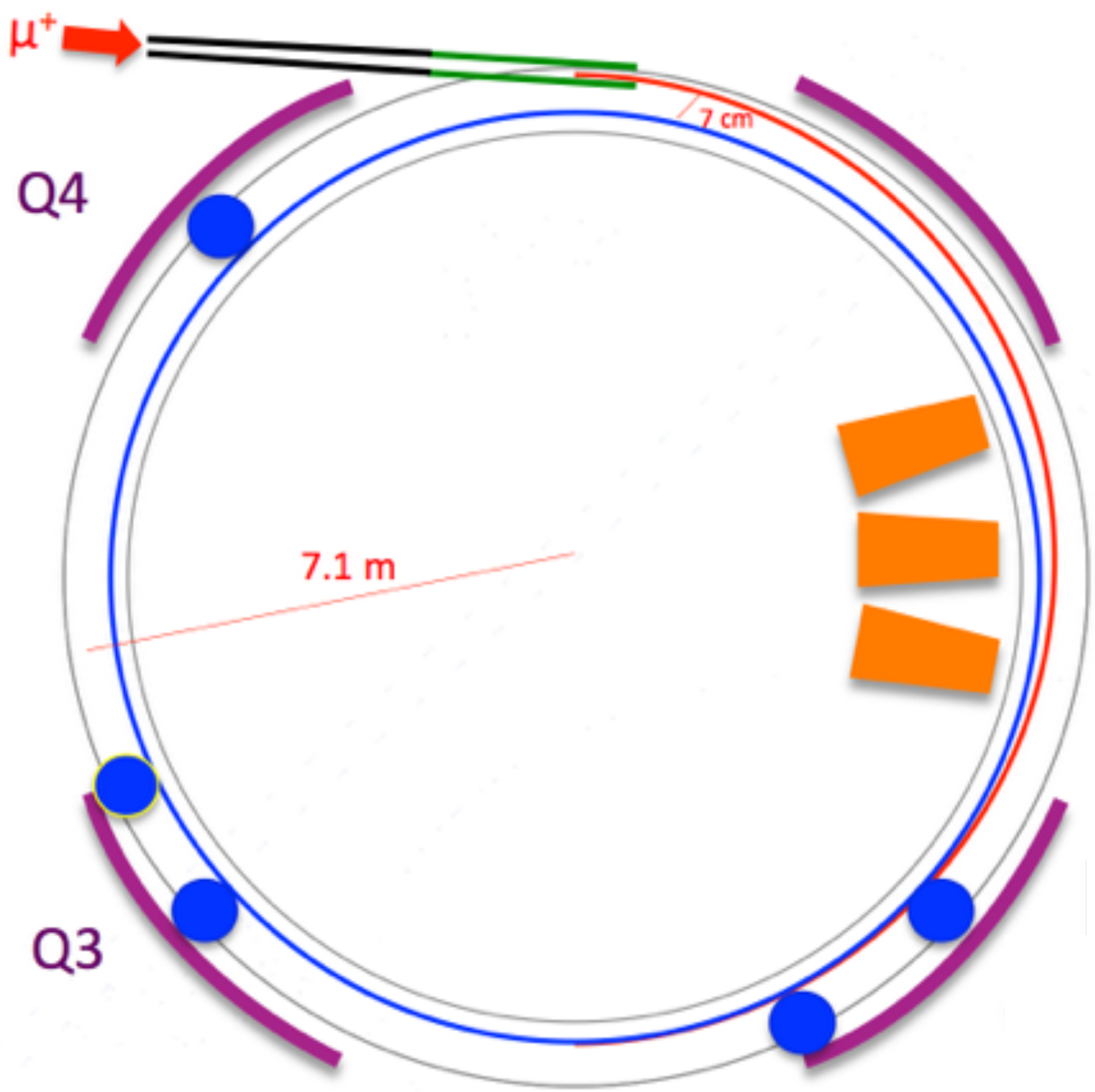
non-zero vertical momentum component without focusing

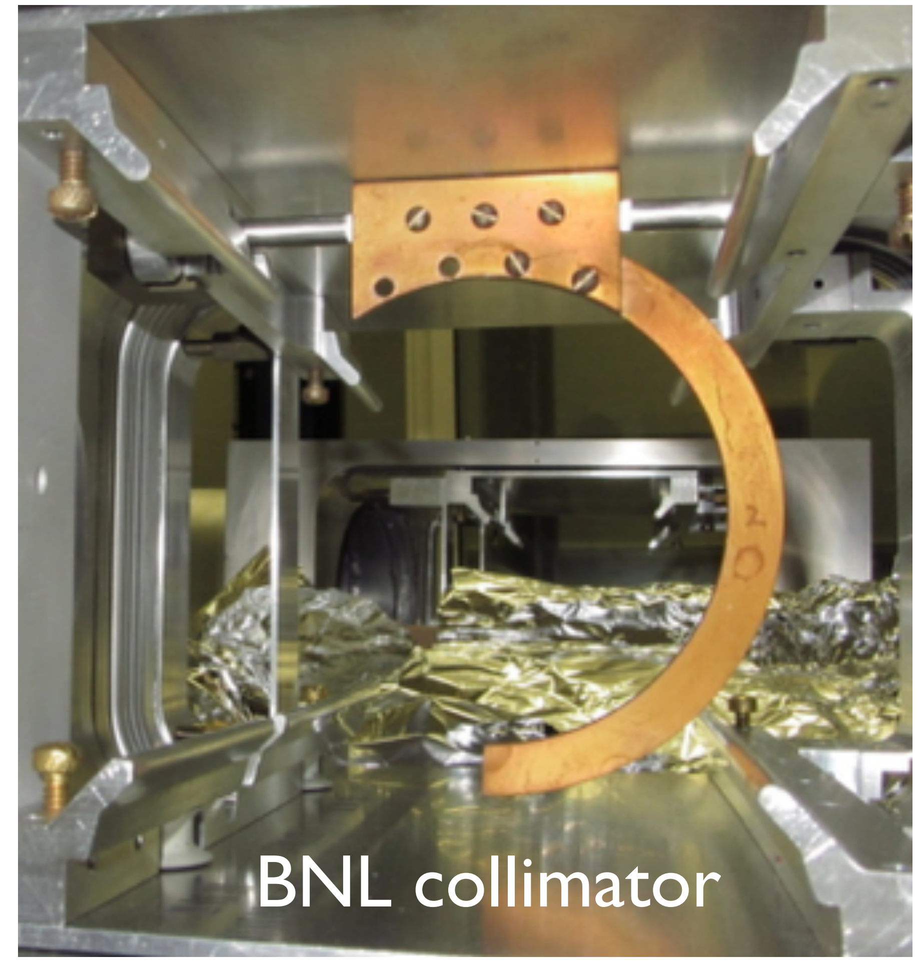
$\Rightarrow$



with focusing

Beam storage systems





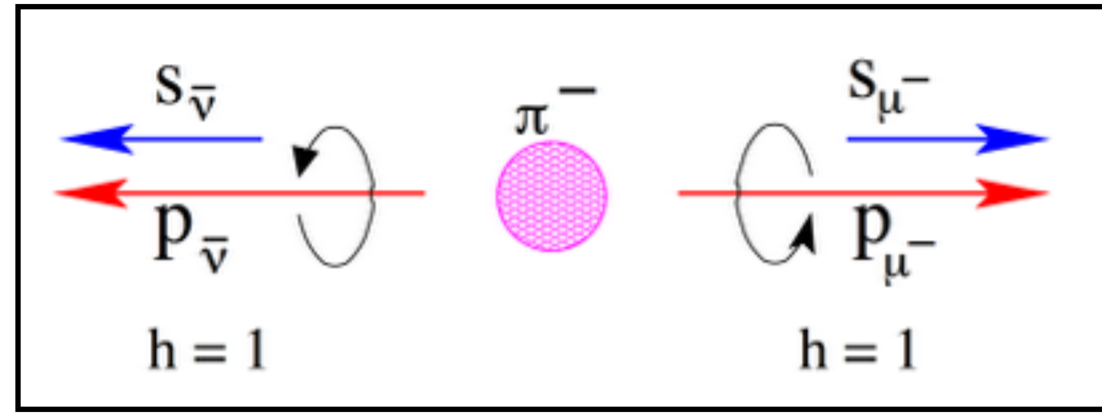
Produce new, thicker collimators for better beam cleaning efficiency

Collimators

Helps eliminate off-momentum muons

Experimental technique: ω_a (spin precession)

- Parity violation in weak interactions critical to experimental technique. Muons from DIF pions naturally polarized.
- Polarized muons injected into 7.1m storage ring



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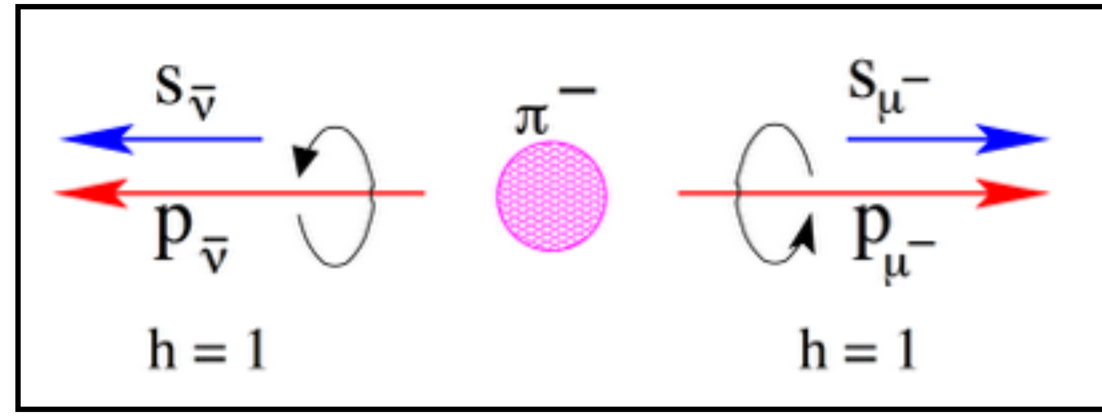
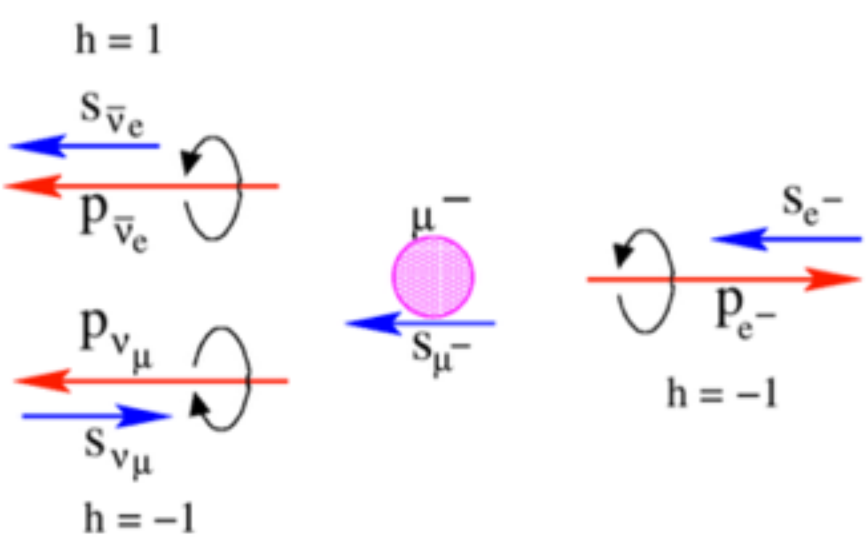
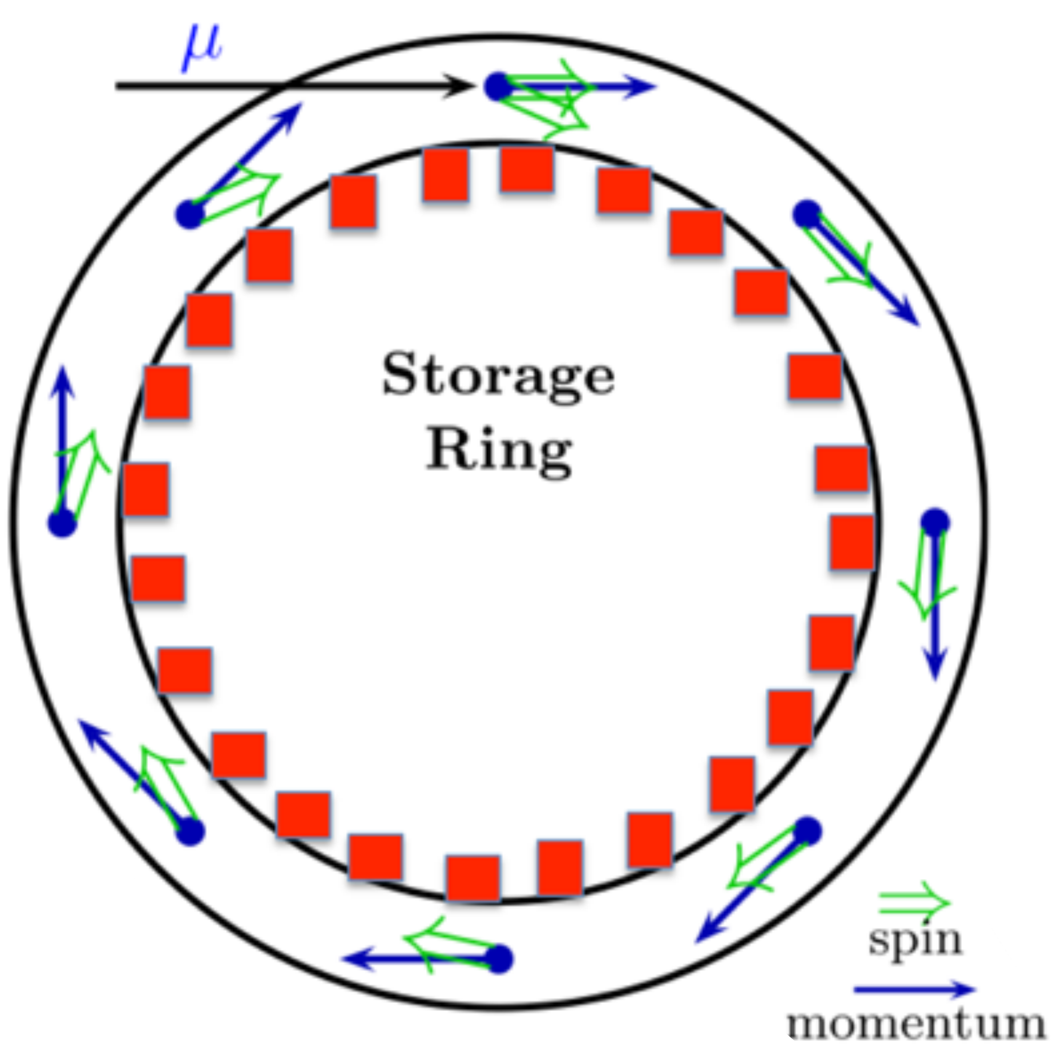


- Polarized muons injected into 7.1m storage ring

- Muon decay self-analyzing: electron direction follows μ spin





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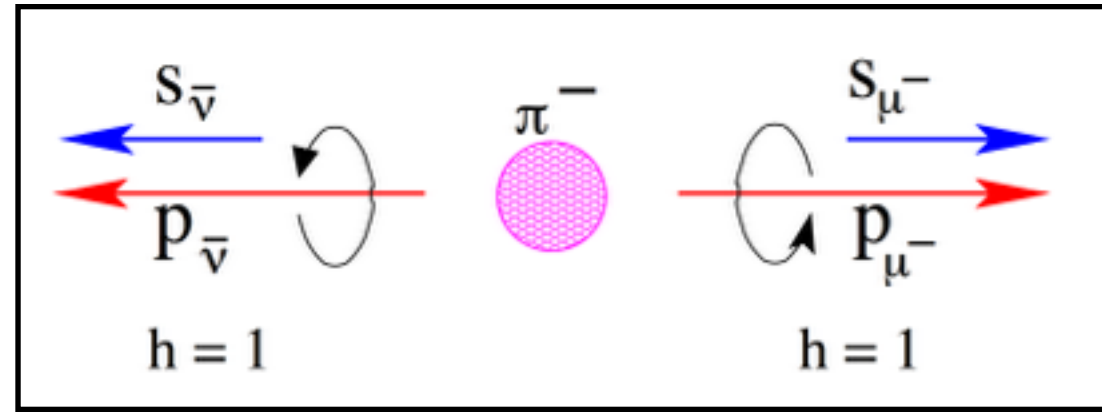

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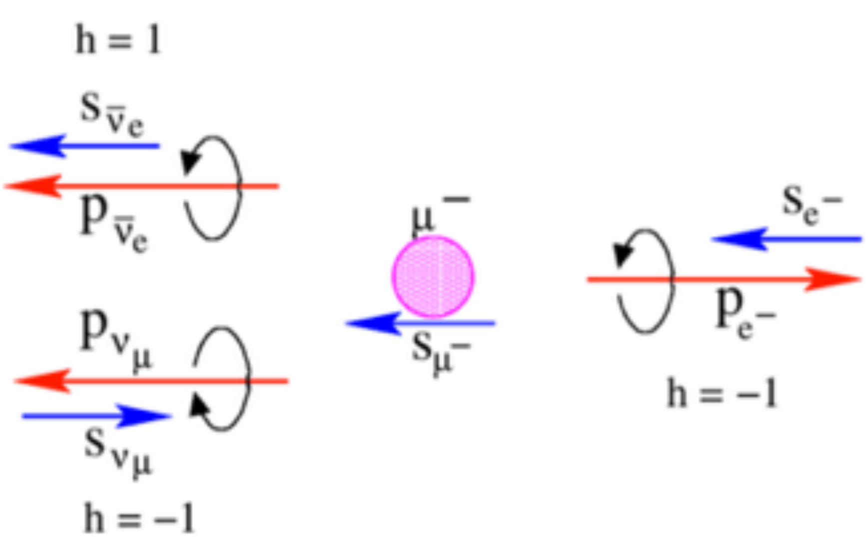

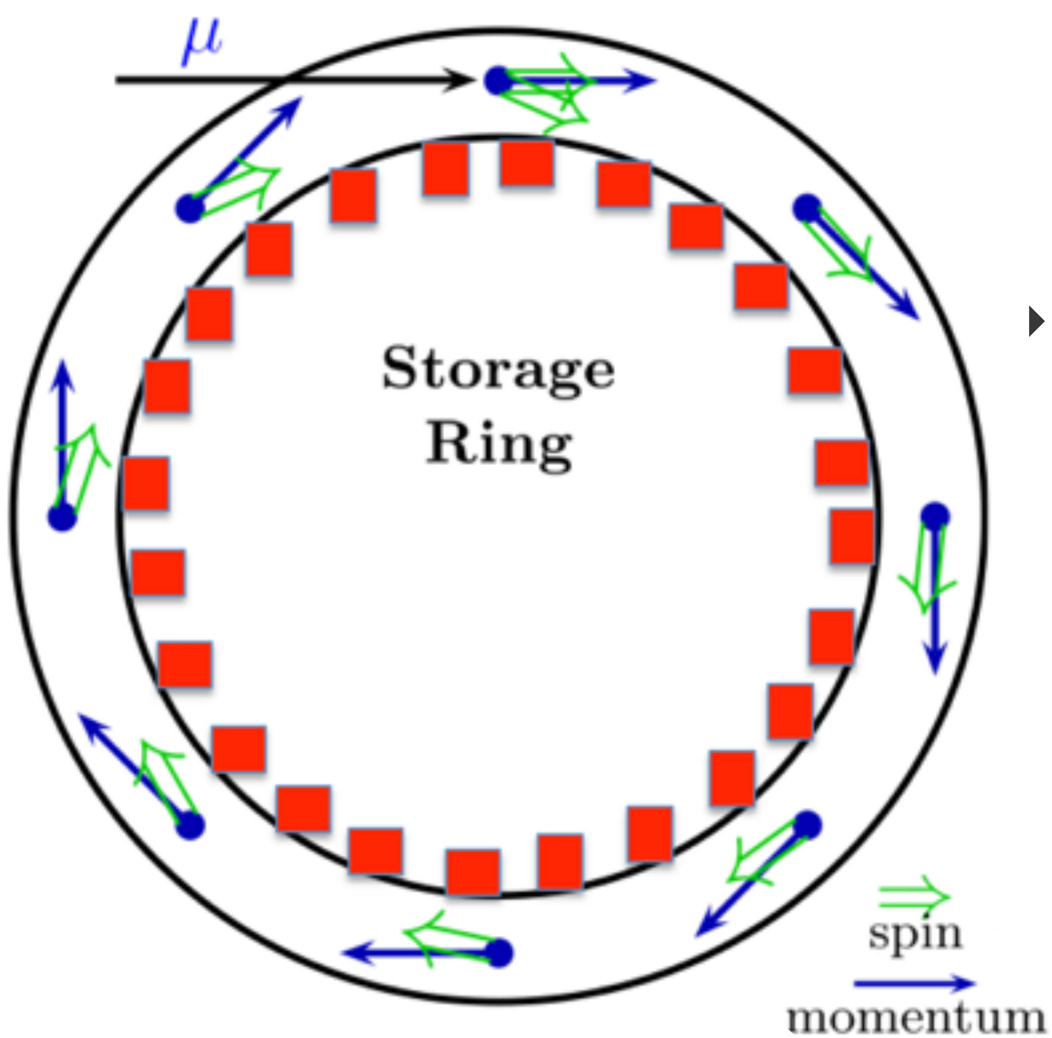

- 24 calorimeters (■) observe electron direction, energy for ~10 muon lifetimes

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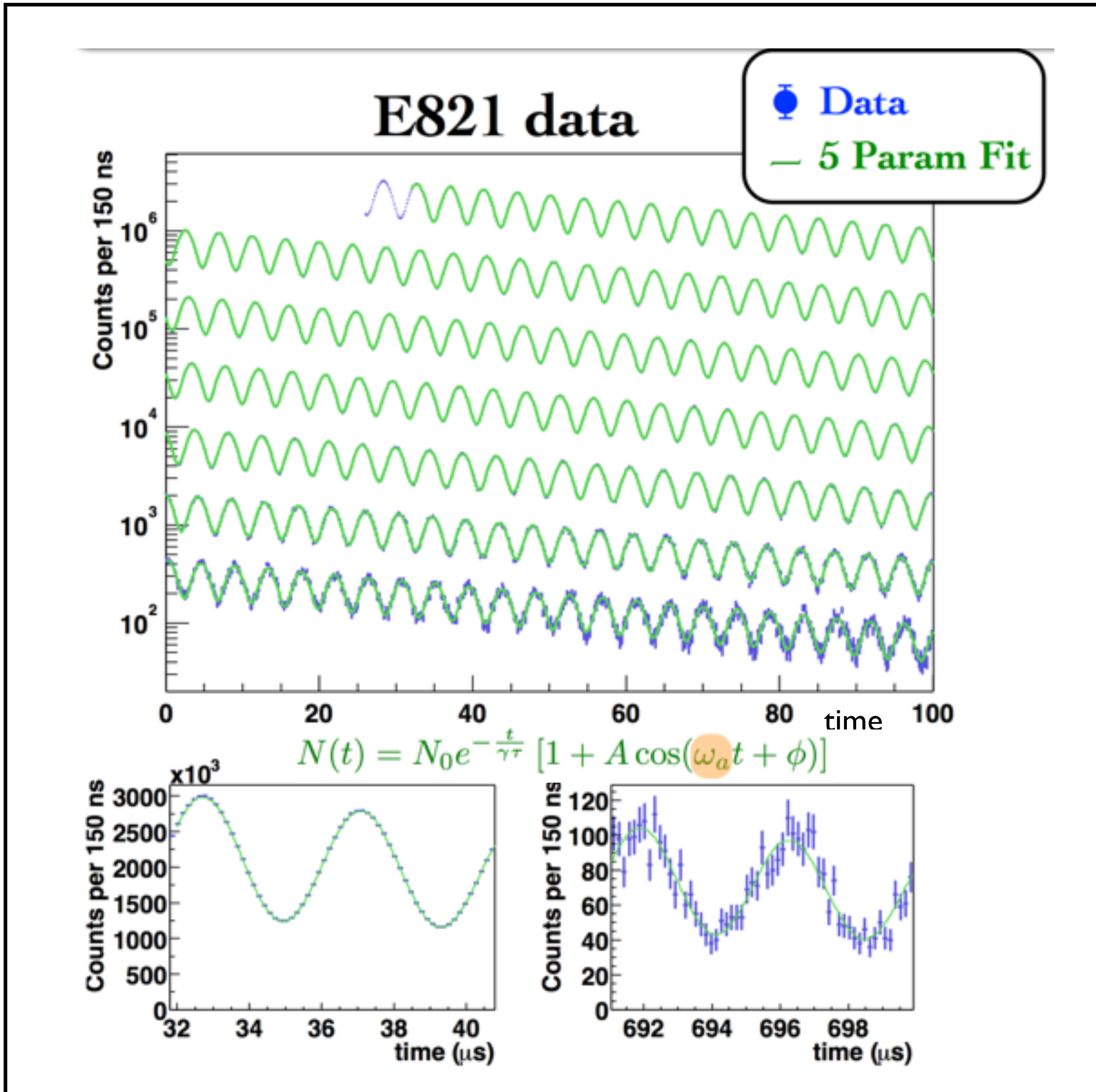

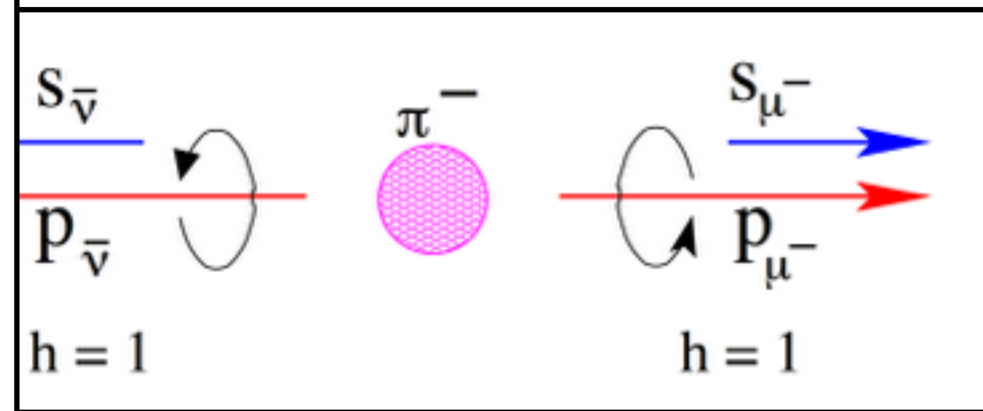

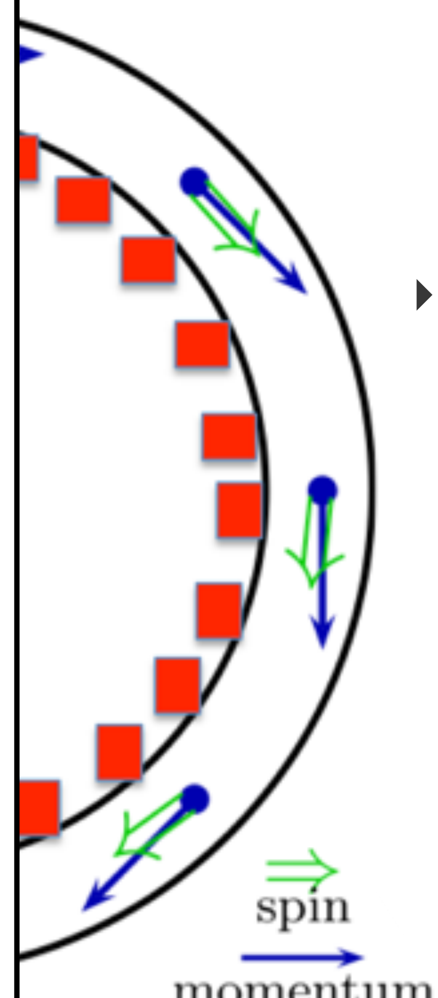

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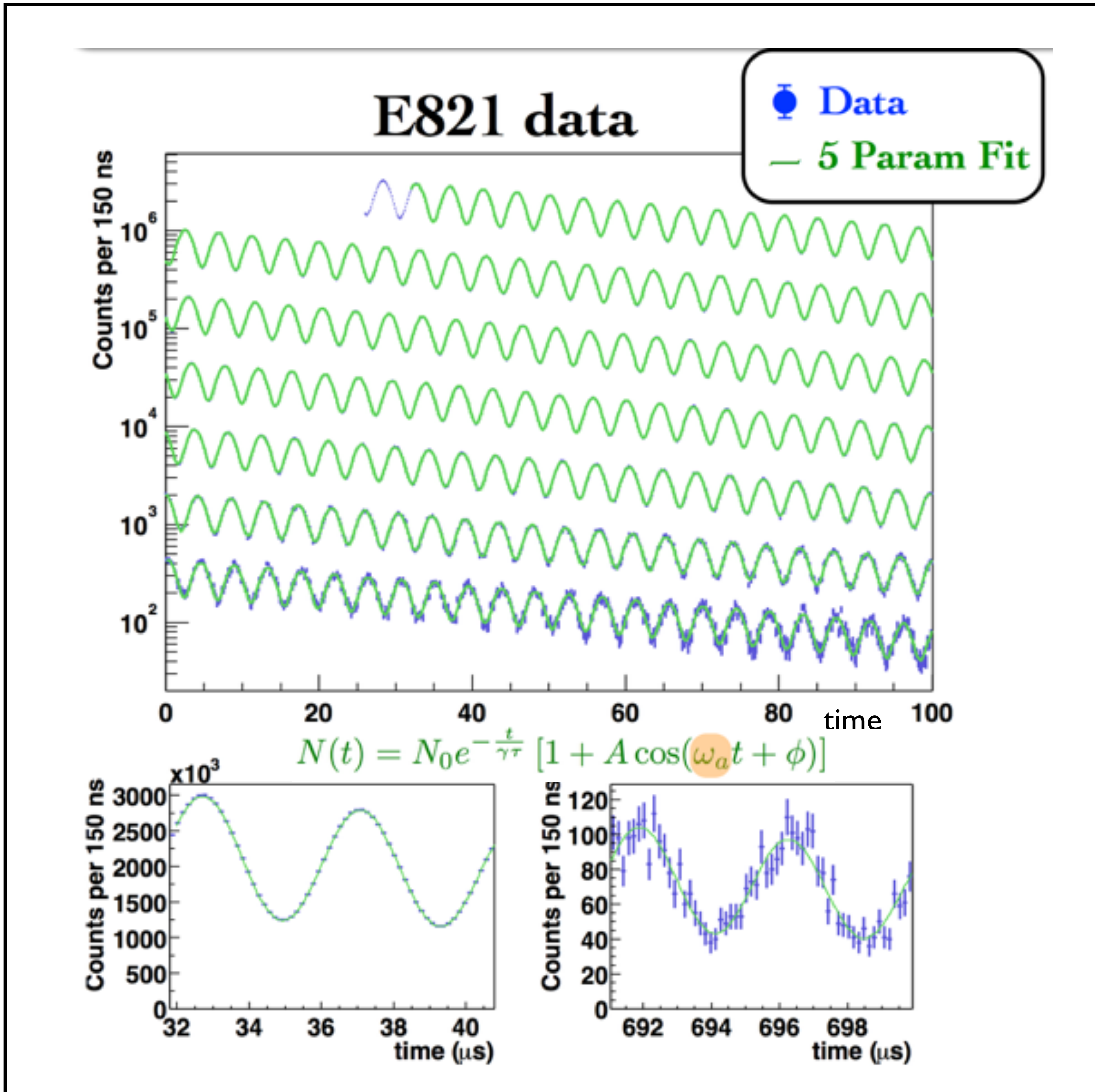

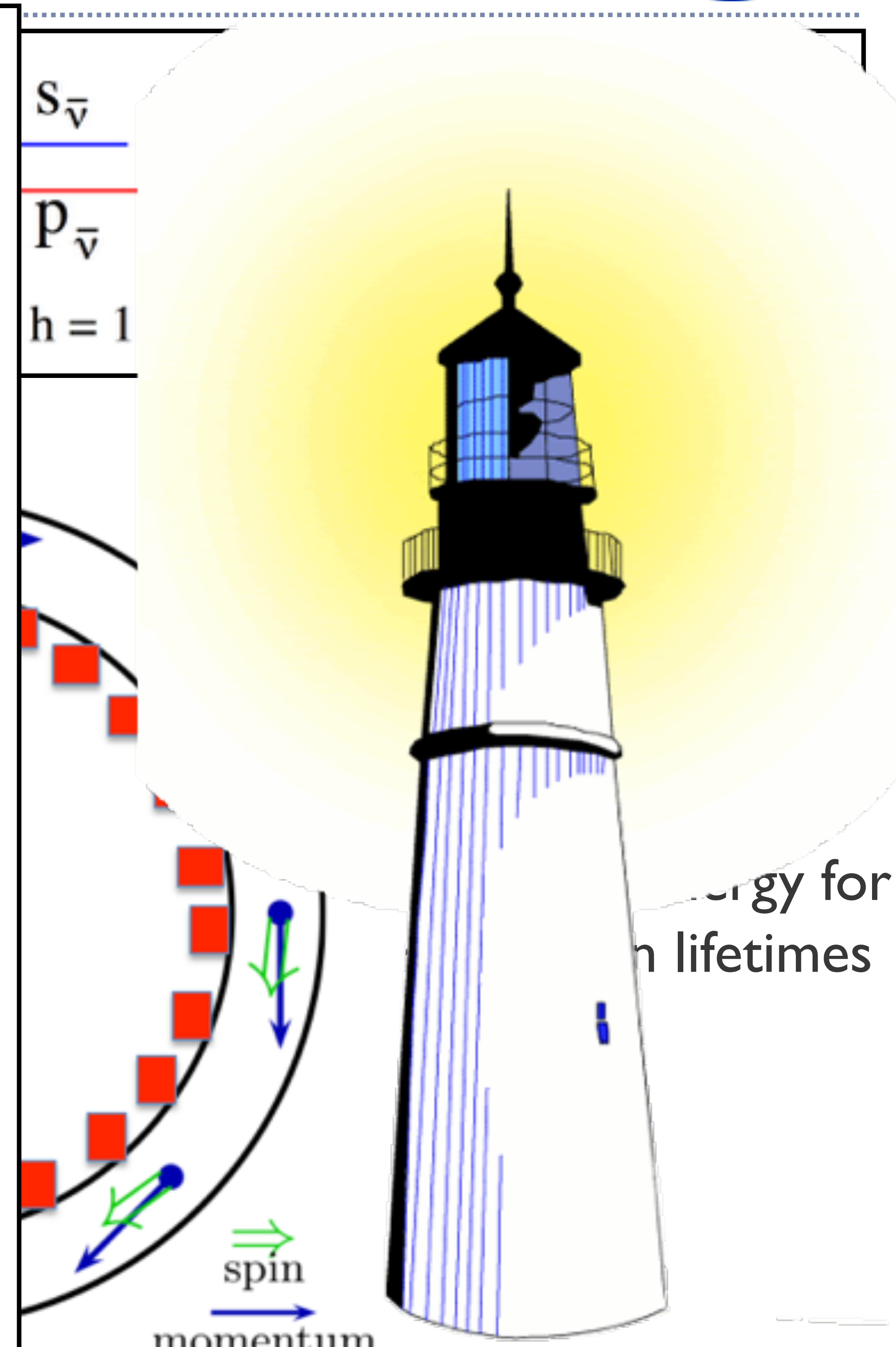

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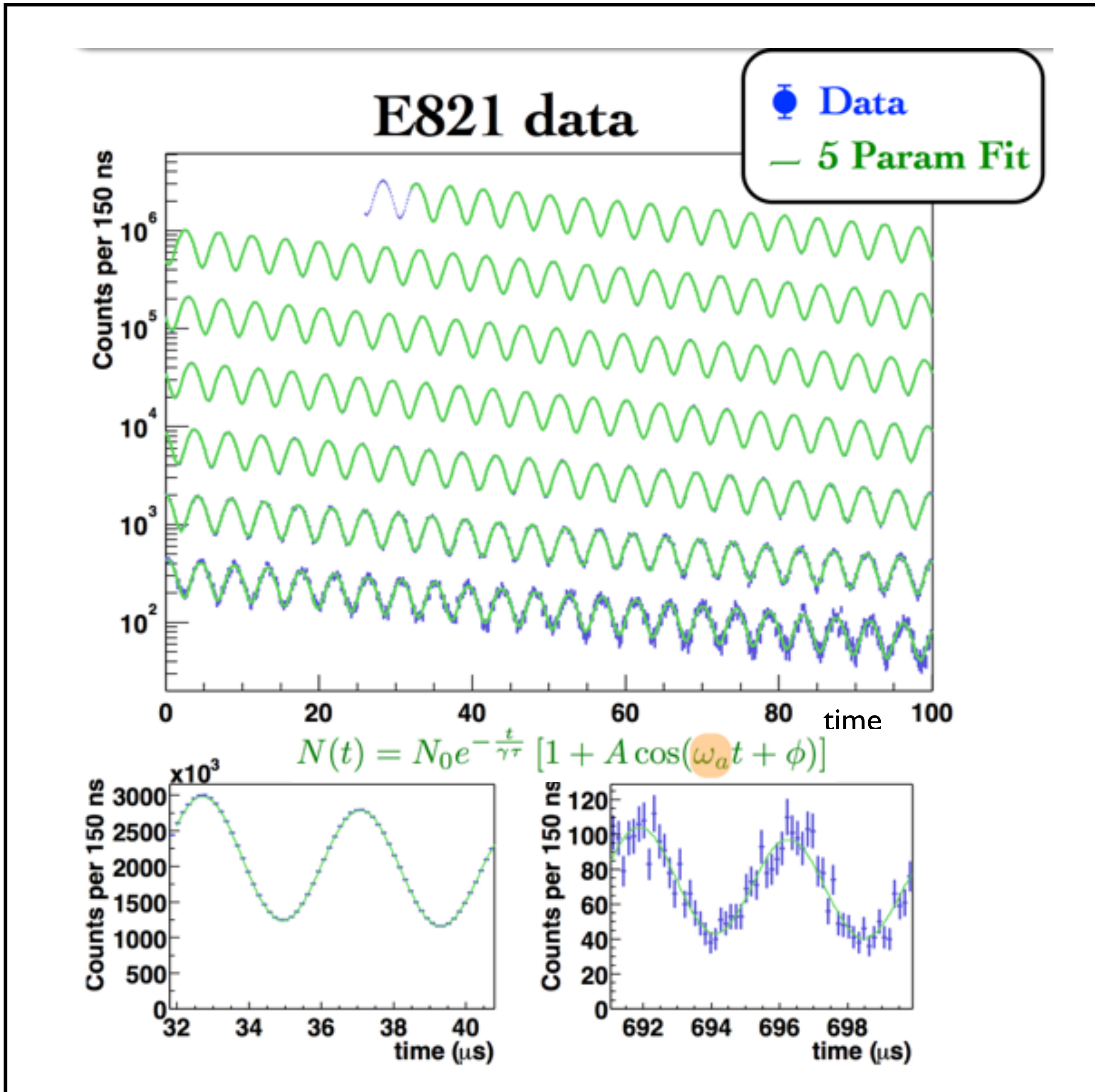

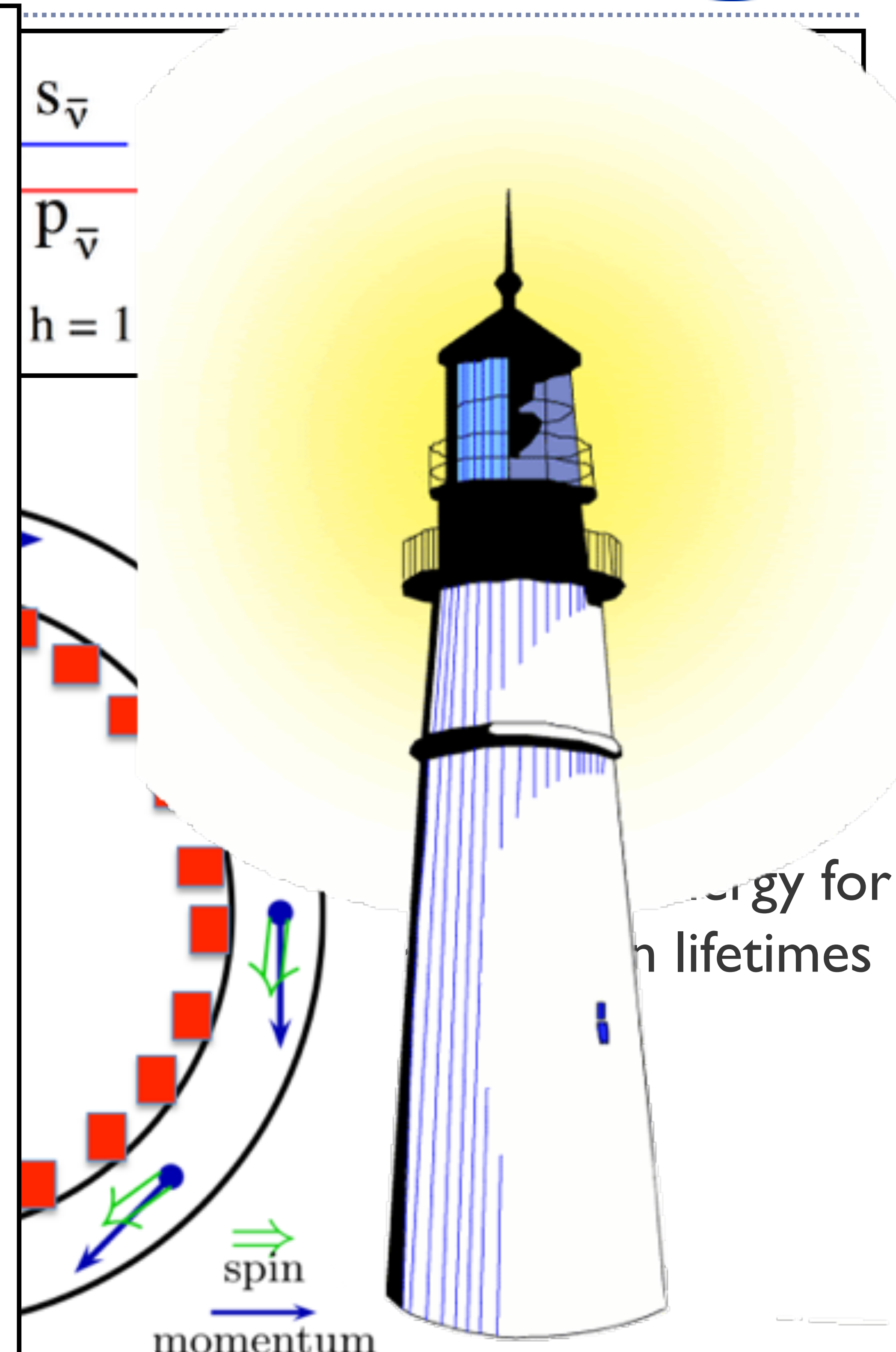

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- Motivation
  - brief g-2 history
  - measurement overview

- Muon storage, spin precession

- **Magnetic field determination**
  - absolute calibration
  - production tools
  - semi-*in situ* calibration

- Current status, path forward

What's needed from field measurements

- Recast a_μ in fundamental constants:

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

$$\mu_e = \frac{g_e \hbar}{4 m_e} \qquad B = \frac{\hbar \omega_p}{2 \mu_p}$$

Expression used in final analysis

$$a_\mu = \frac{\omega_a}{\omega_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

g-2 observables:

ω_a: measured directly.

ω_p: *free proton precession frequency.* "how quickly would the spin of a free proton rotate in the g-2 ring?"

$$\delta\left(\frac{\mu_e}{\mu_p}\right) \sim 8\,\text{ppb}$$

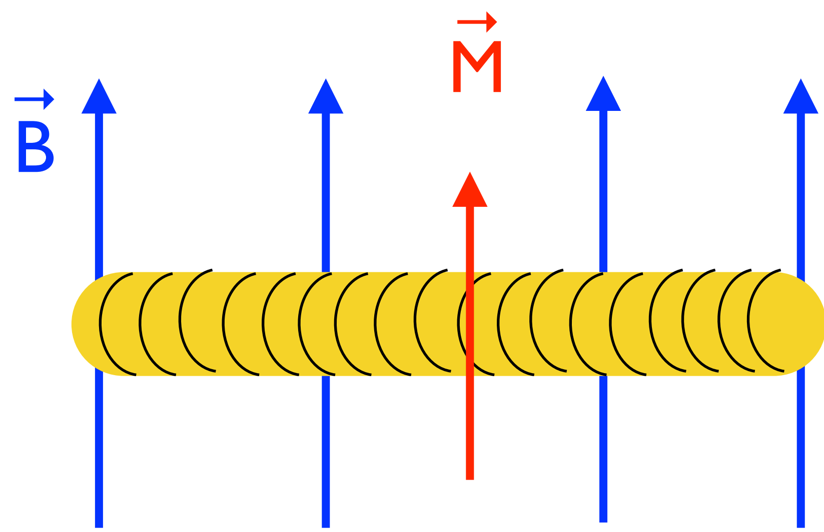
$$\delta\left(\frac{m_\mu}{m_e}\right) \sim 25\,\text{ppb}$$

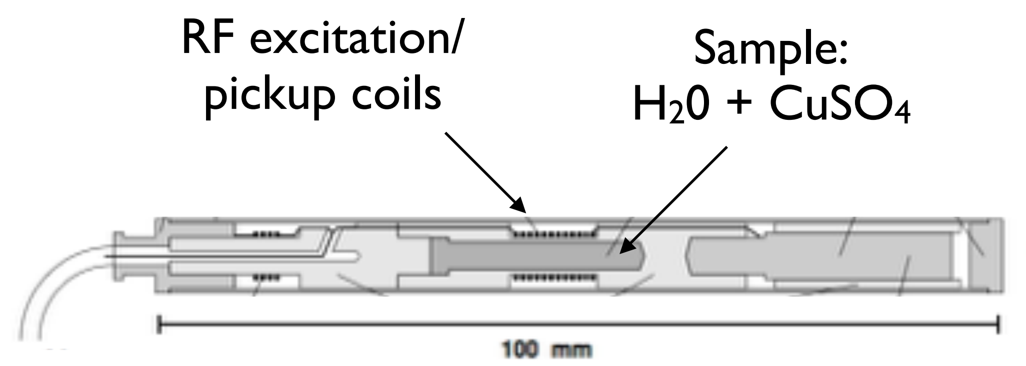
$$\delta\left(\frac{g_e}{2}\right) \sim 0.3\,\text{ppt}$$

Magnetometer

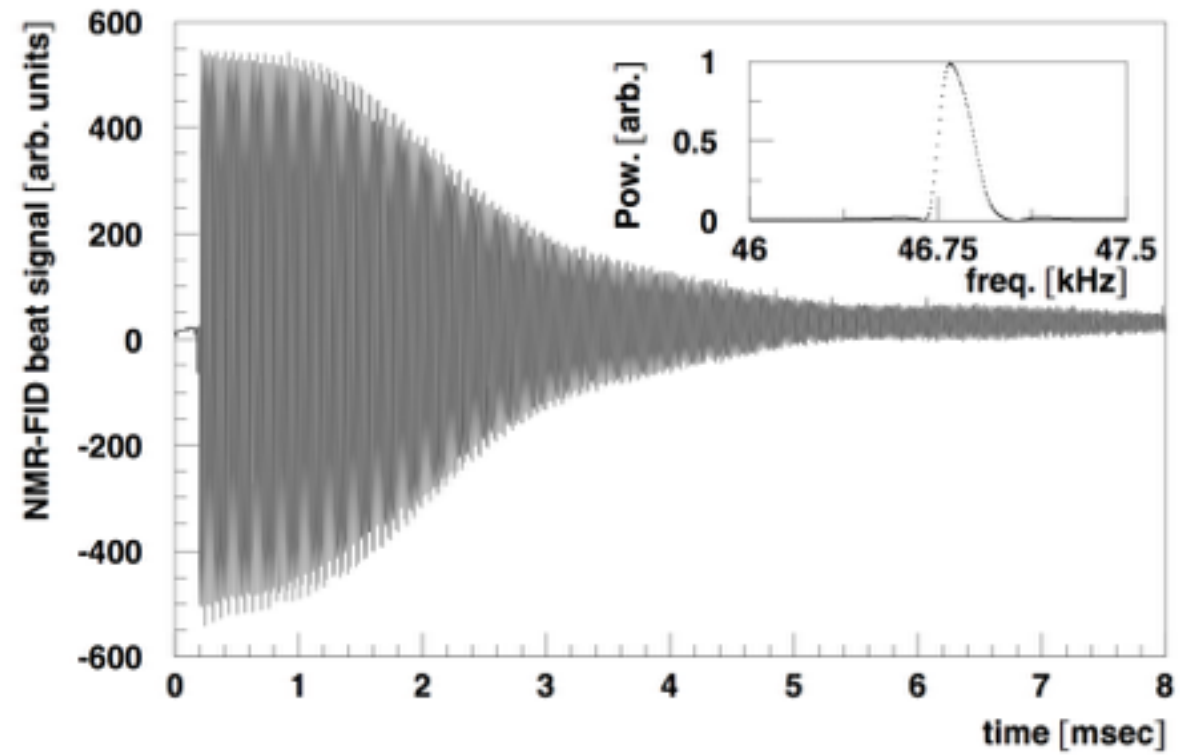
- Pulsed Nuclear Magnetic Resonance (NMR):
  - RF signals tip bulk magnetization vector of NMR sample by π/2

Sample with bulk magnetization M surrounded by RF coils





- spin precession picked up by same RF coils proportional to |B| (via Fourier transform)
- *excellent* precision: ~ 20 ppb
- sample is *not* free protons: typically water based, doped with $CuSO_4$ to reduce relaxation time → increase repetition rate



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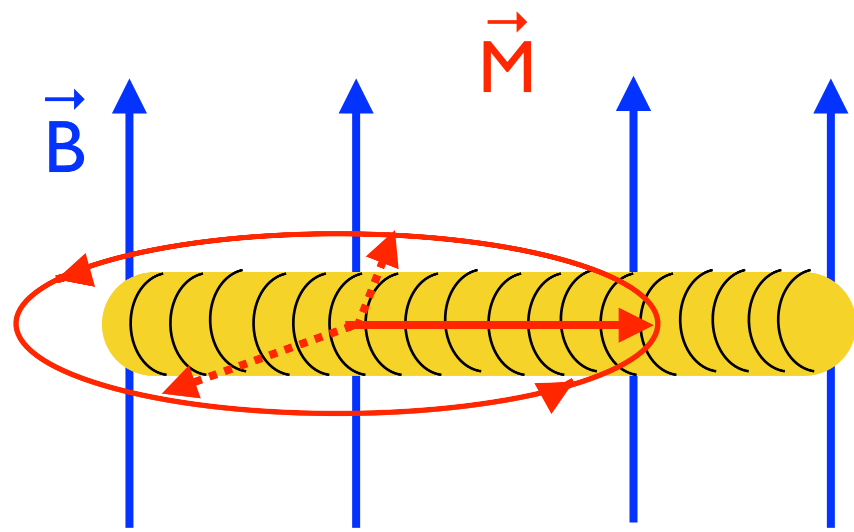
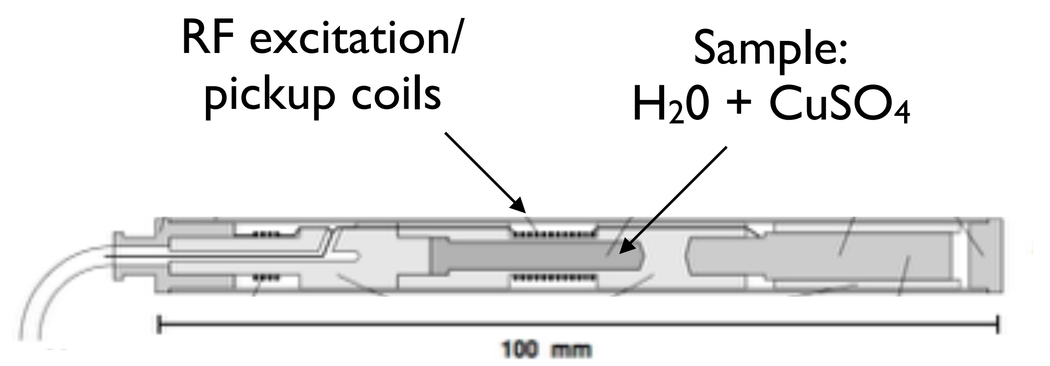
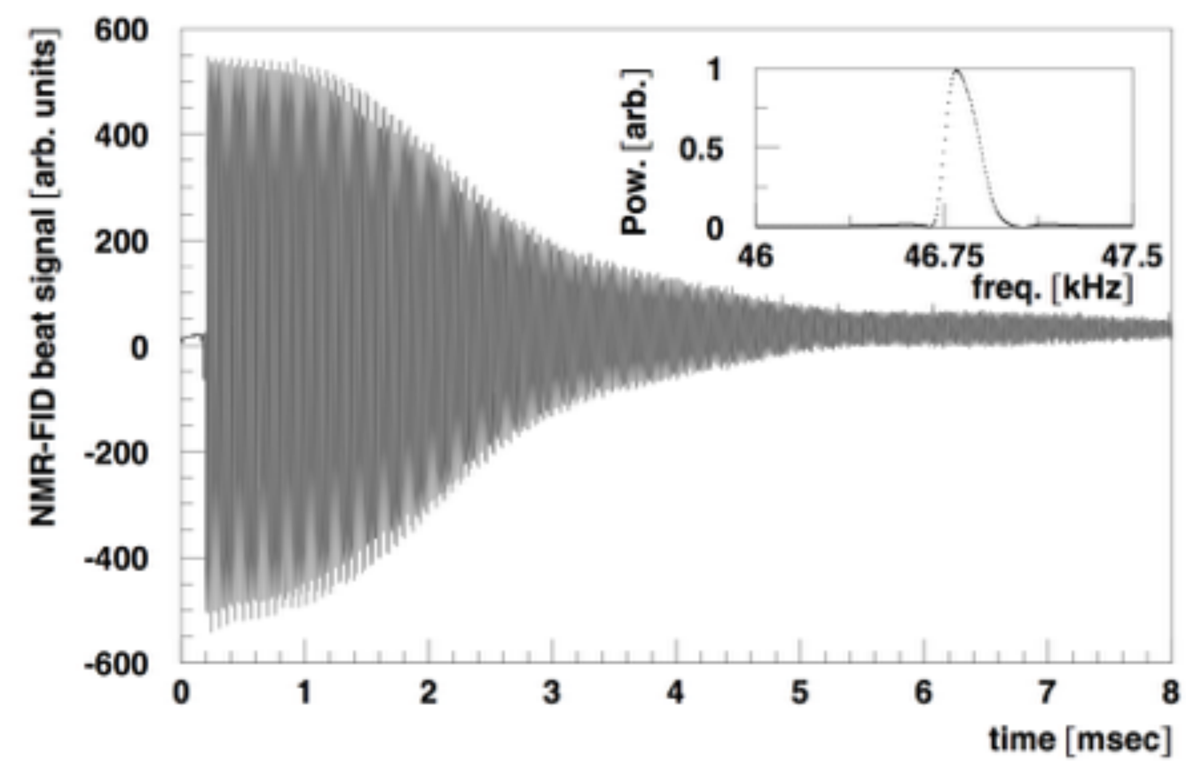
Sample with bulk magnetization M surrounded by RF coils





- spin precession picked up by same RF coils proportional to |B| (via Fourier transform)
- *excellent* precision: ~ 20 ppb
- sample is *not* free protons: typically water based, doped with $CuSO_4$ to reduce relaxation time → increase repetition rate



Water-based NMR probe calibration

- Shift from field felt by free proton (*fp*) compared to protons in water (*p*):

Measure with NMR

$$B_p = (1 - \delta_t) B_{fp}$$

External information

remaining unknown

diamagnetic shielding

paramagnetic impurities

$$\delta_t = \sigma(H_2 0) + \delta_b + \delta_p + \delta_s$$

shape-dependent bulk diamagnetism

additional diamagnetic materials in probe structure

- Absolute calibration steps for g-2:
  1. Need independent measurements of $\sigma(H_2 0)$
  2. Record it’s NMR signals in highly uniform, stable magnetic field
  3. Transfer calibration to ~400 probes in g-2 exp’t

Homogeneous, stable field

- High uniformity inside g-2 ring, but demand even better for delicate, critical calibration
- Developing new magnet test facility at Argonne to produce enormously homogeneous, stable field

Bore size (without active coils)	Homogeneity	Drift
68 cm (90 cm)	7ppb/cm	~90ppb/hr

OR66 specifications at 4T

0-4 Tesla hospital-style MRI magnet at Argonne

- Can also test various systematic effects
  - e.g., temp dependence, material influence
- Plan to cross-calibrate with J-PARC g-2
- Also investigating using He-3 probe
  - different systematics

Magnetic field summary

Calibration flow

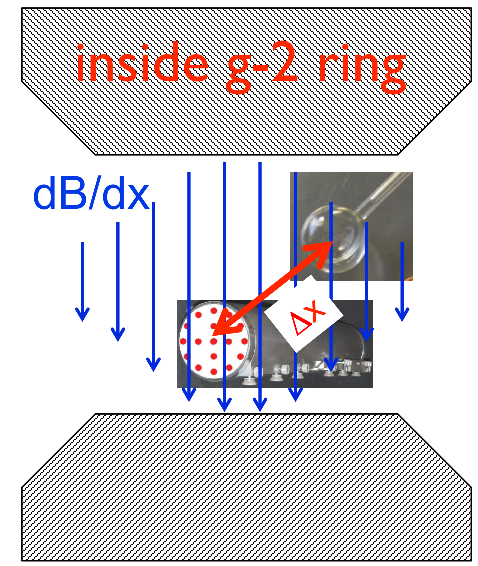
Absolute calibration

$$B_p = (1 - \delta_t)B$$

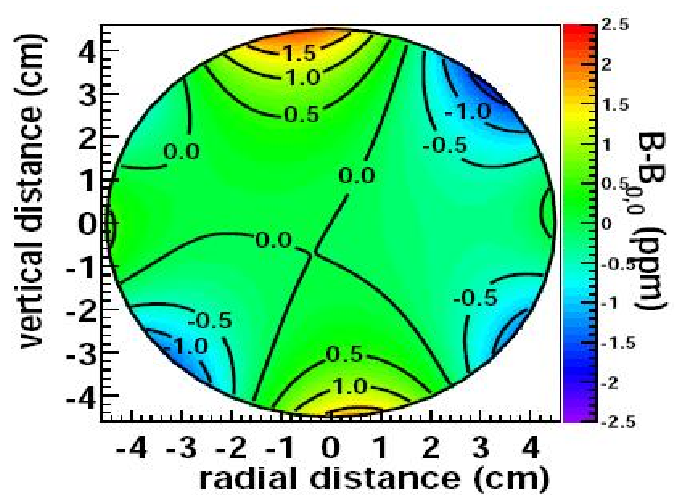
$$\delta_t = \sigma(H_20) + \delta_b + \delta_p + \delta_s$$

Measured — Minimize in calibration probe

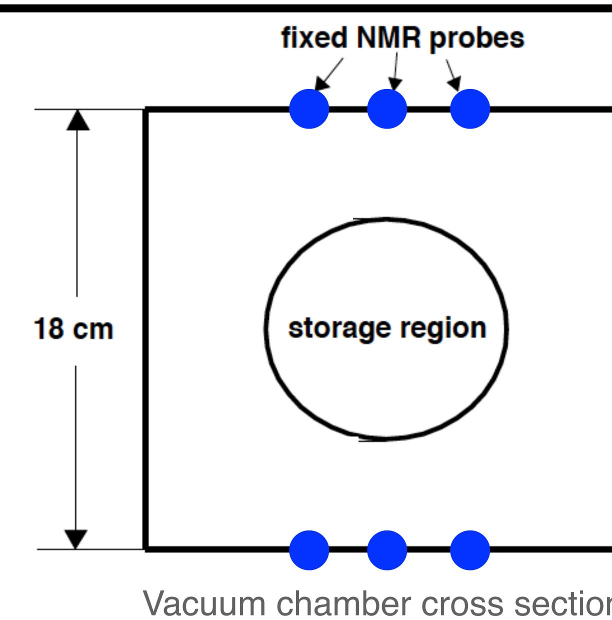
Trolley relative calibration



Trolley measures field in storage volume, calibrates stationary probes

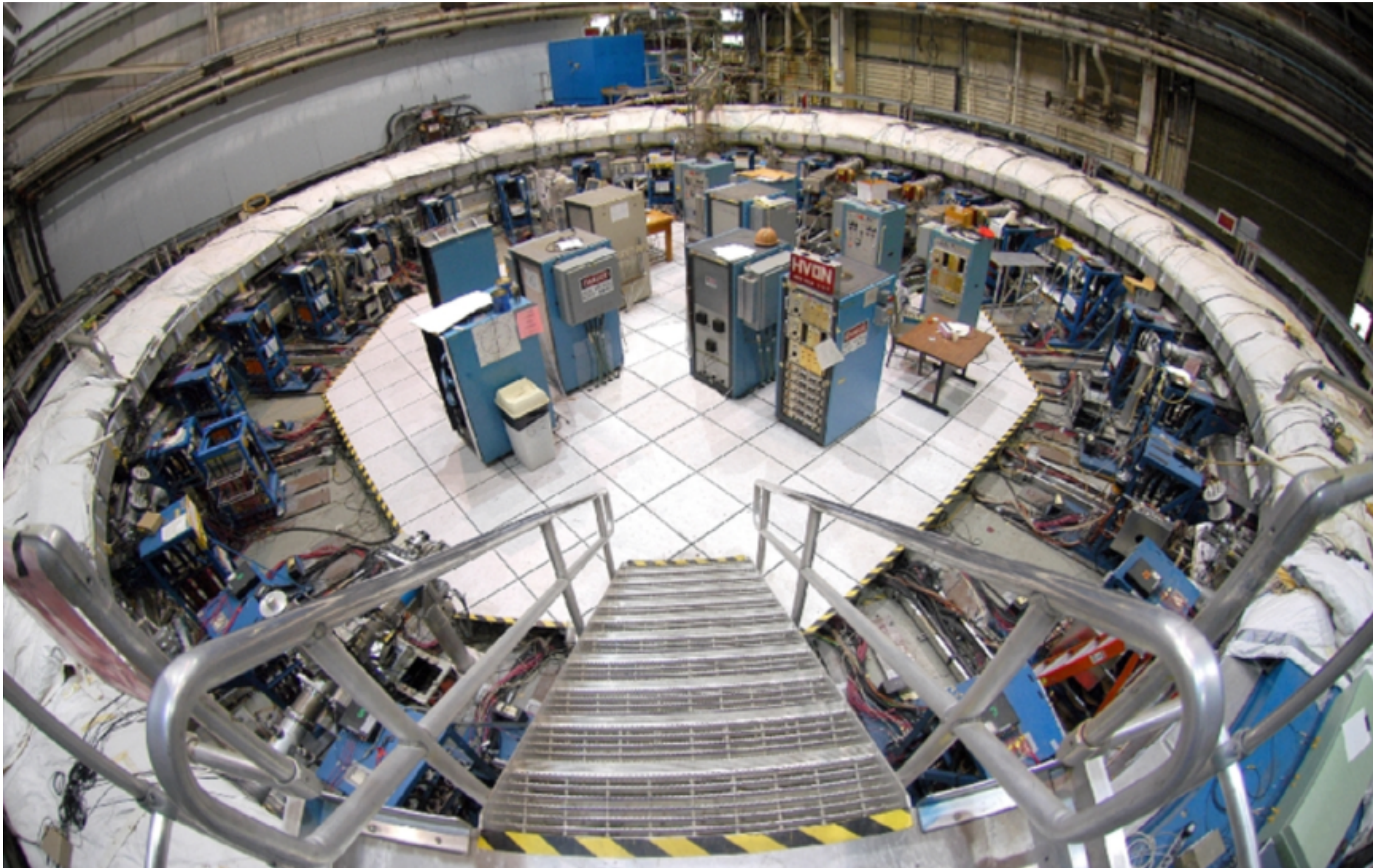


Fixed probes monitor field during muon storage



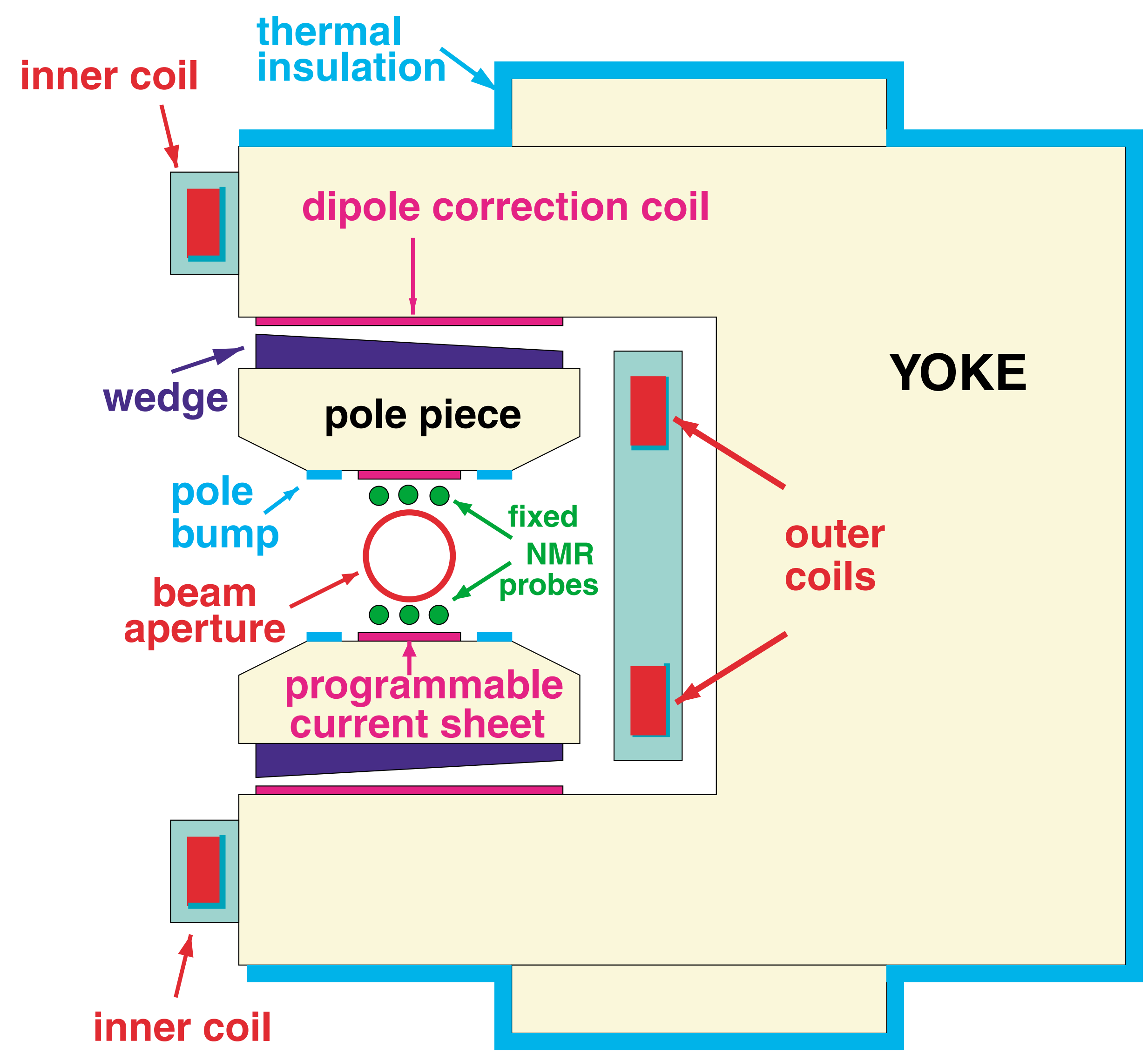
Field homogeneity, stability critically affect uncertainty in these processes

Shimming the magnetic field



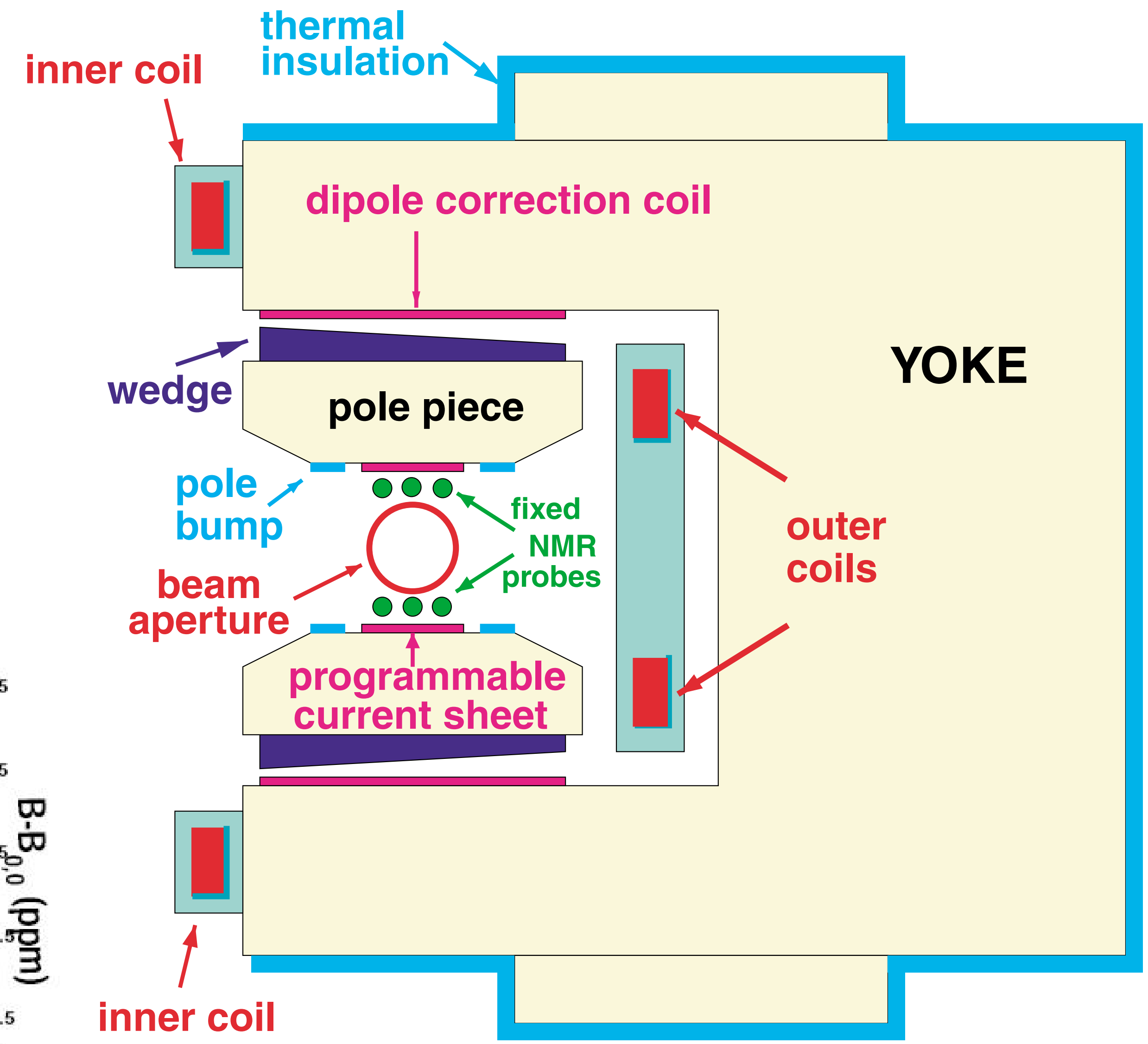
Shimming the magnetic field

Shimming the magnetic field



Shimming the magnetic field

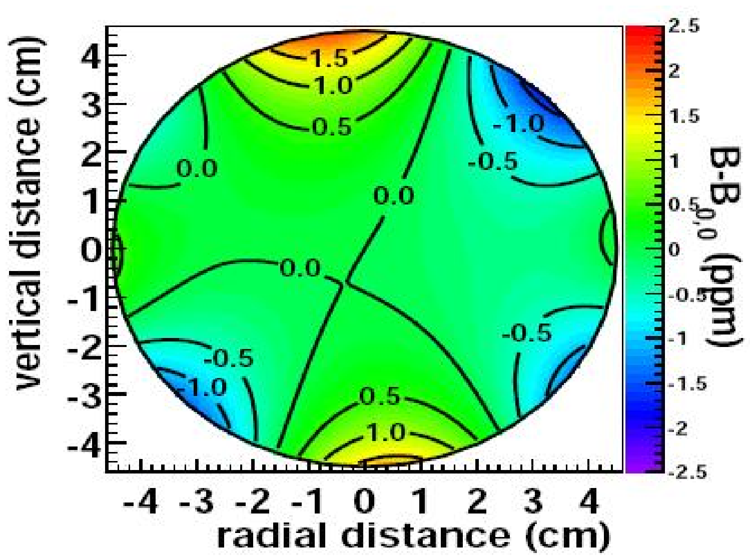
- Many passive and active shimming tools to achieve unprecedented field homogeneity for such a large volume.
- Each "knob" adjusts nearly orthogonal components of the field shape



Passive shims
- **Iron wedges**
- **Pole tilt**
- **Iron pole bumps**

Active shims
- **Dipole correction coils**
- **Surface correction coils**

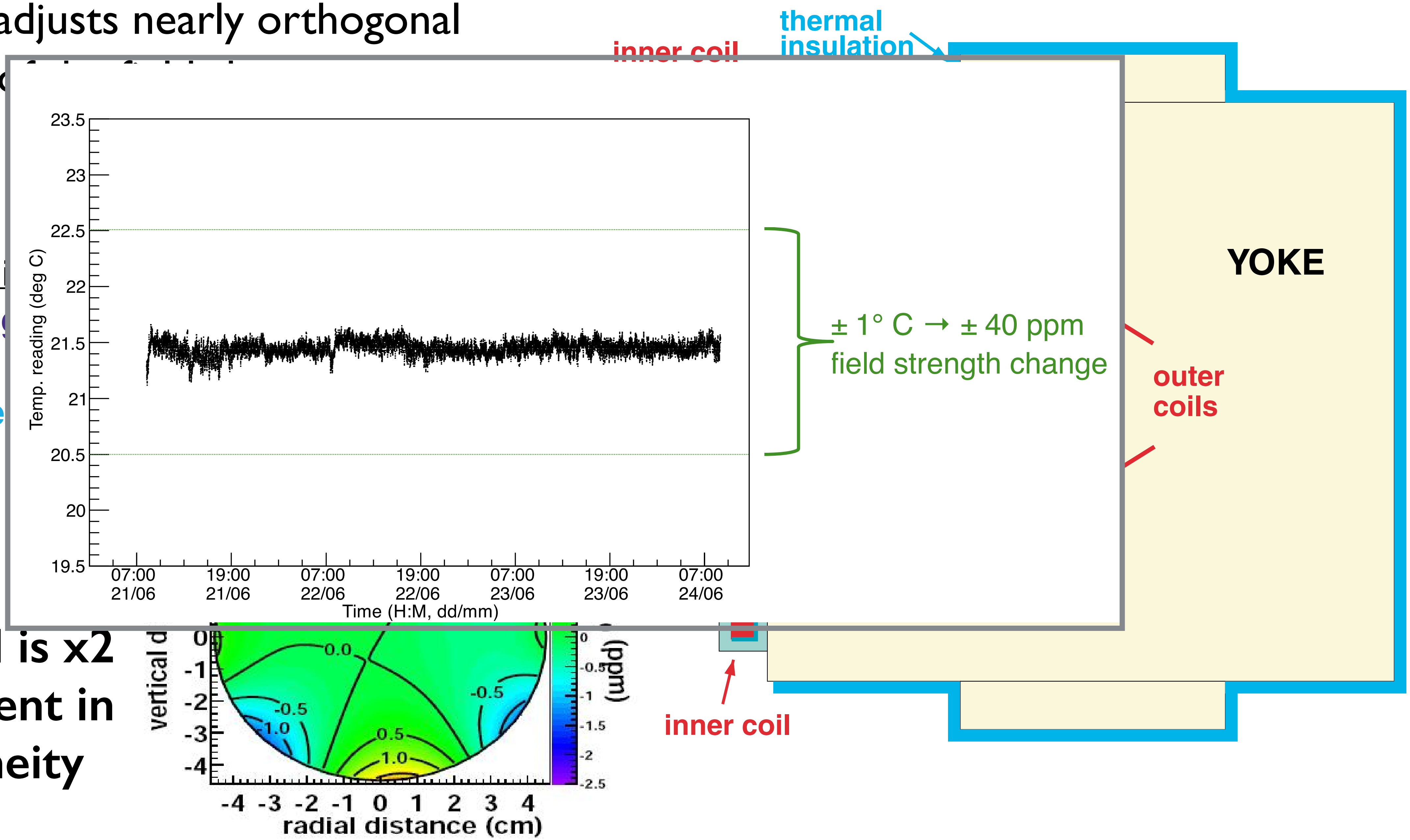
FNAL goal is x2 improvement in homogeneity



Shimming the magnetic field

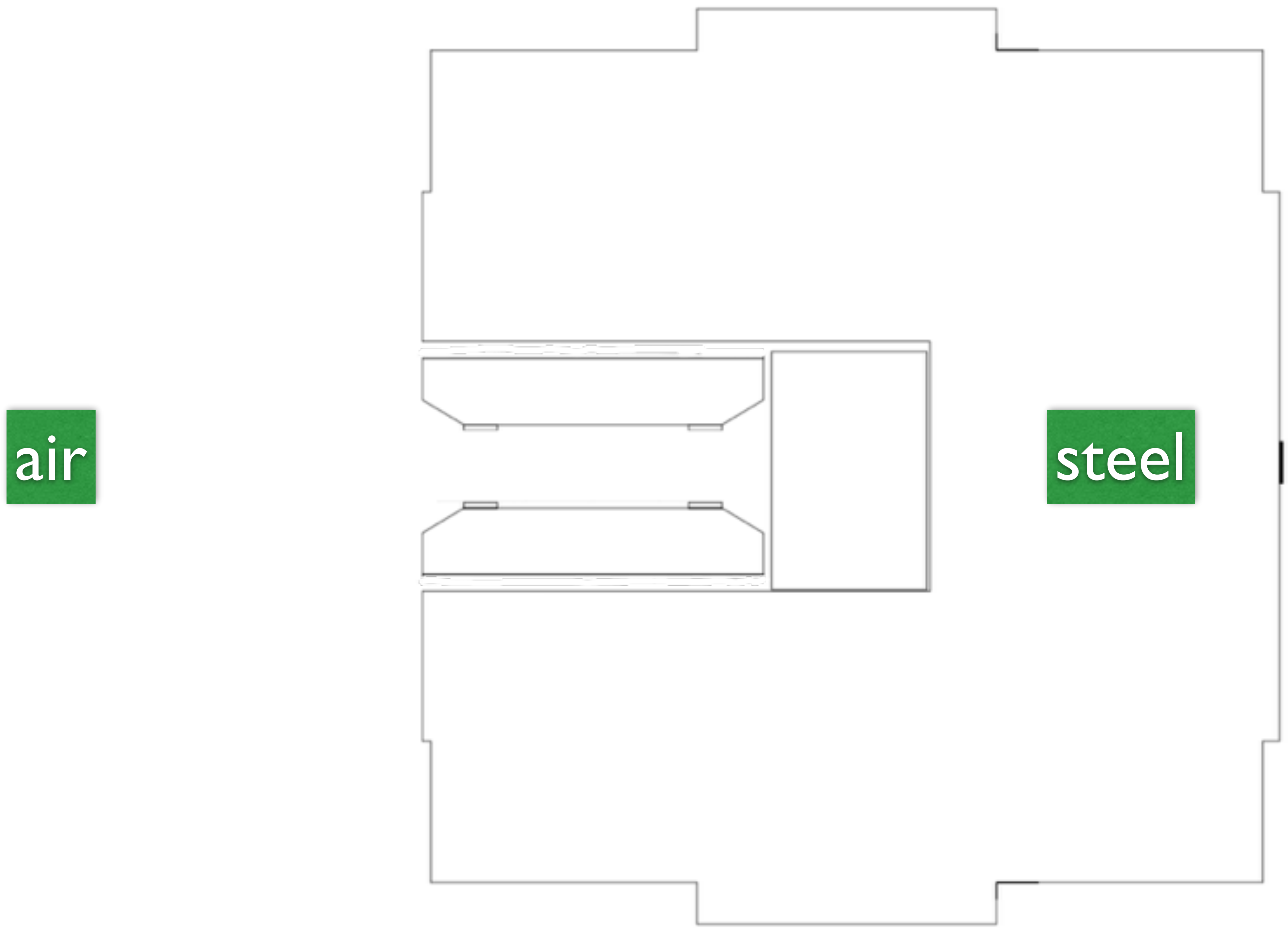
- Many passive and active shimming tools to achieve unprecedented field homogeneity for such a large volume.
- Each "knob" adjusts nearly orthogonal components o

Passive shi
- Iron wed
- Pole tilt
- Iron pole

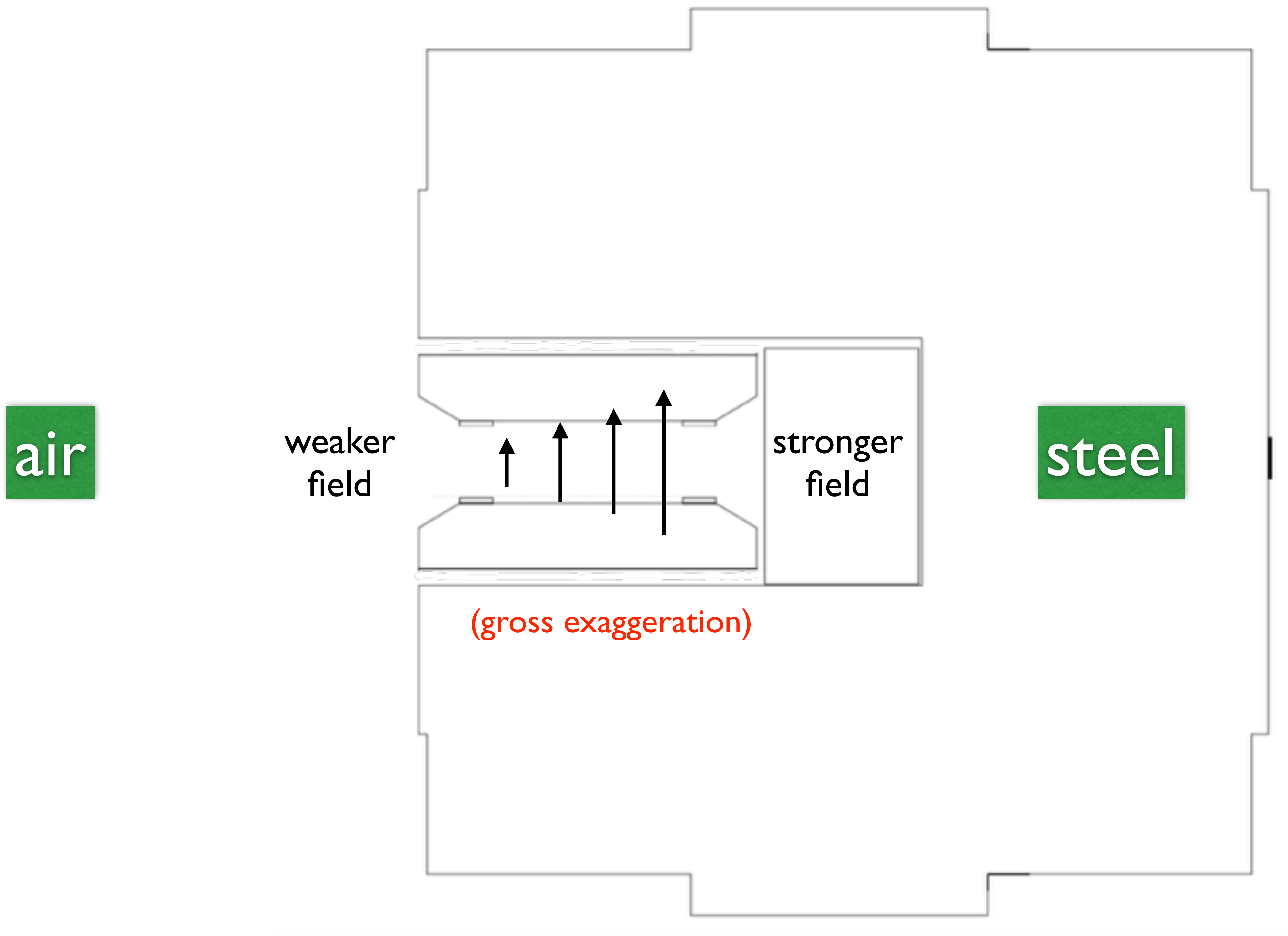


FNAL goal is x2 improvement in homogeneity

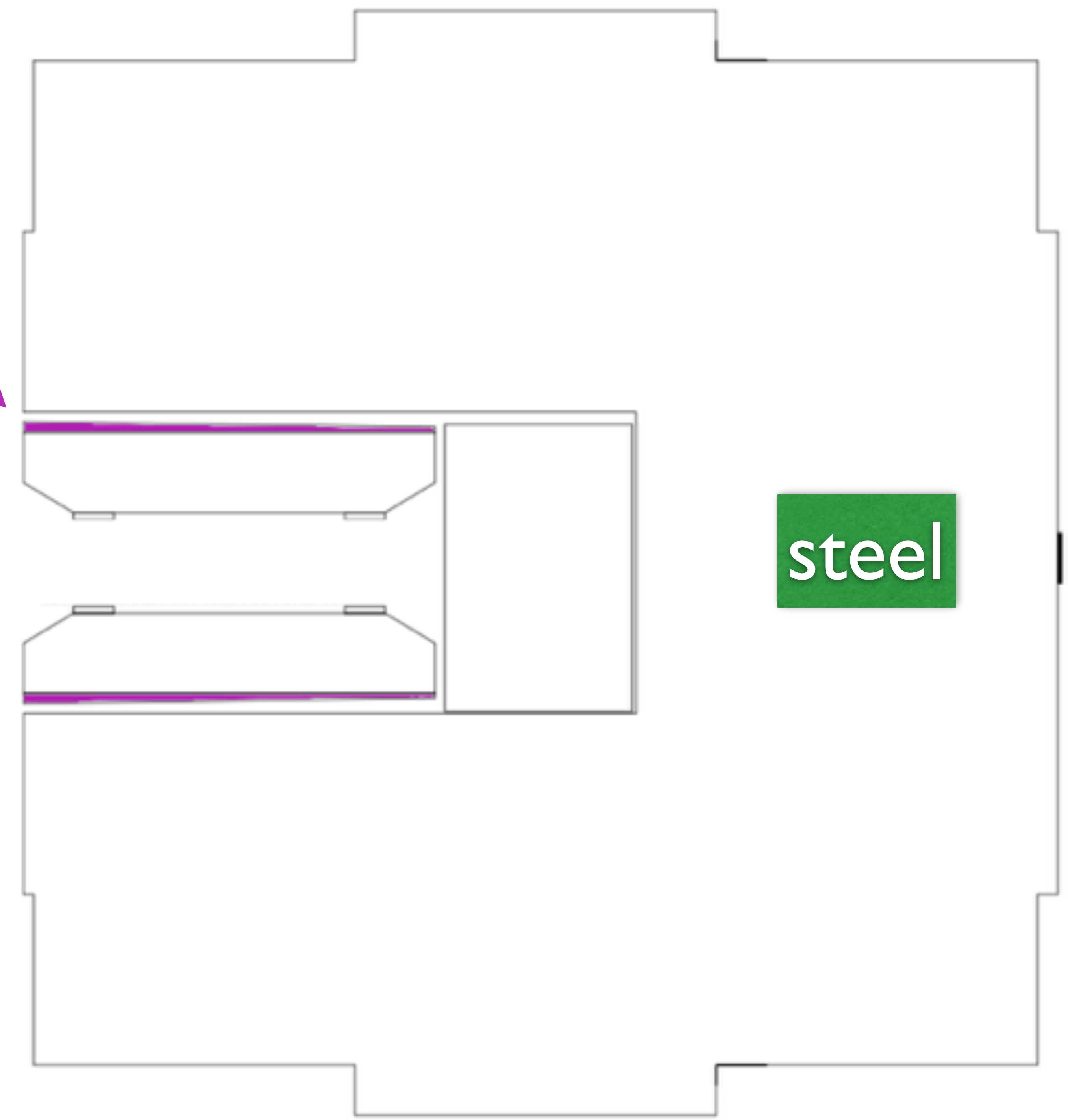
Passive shimming example



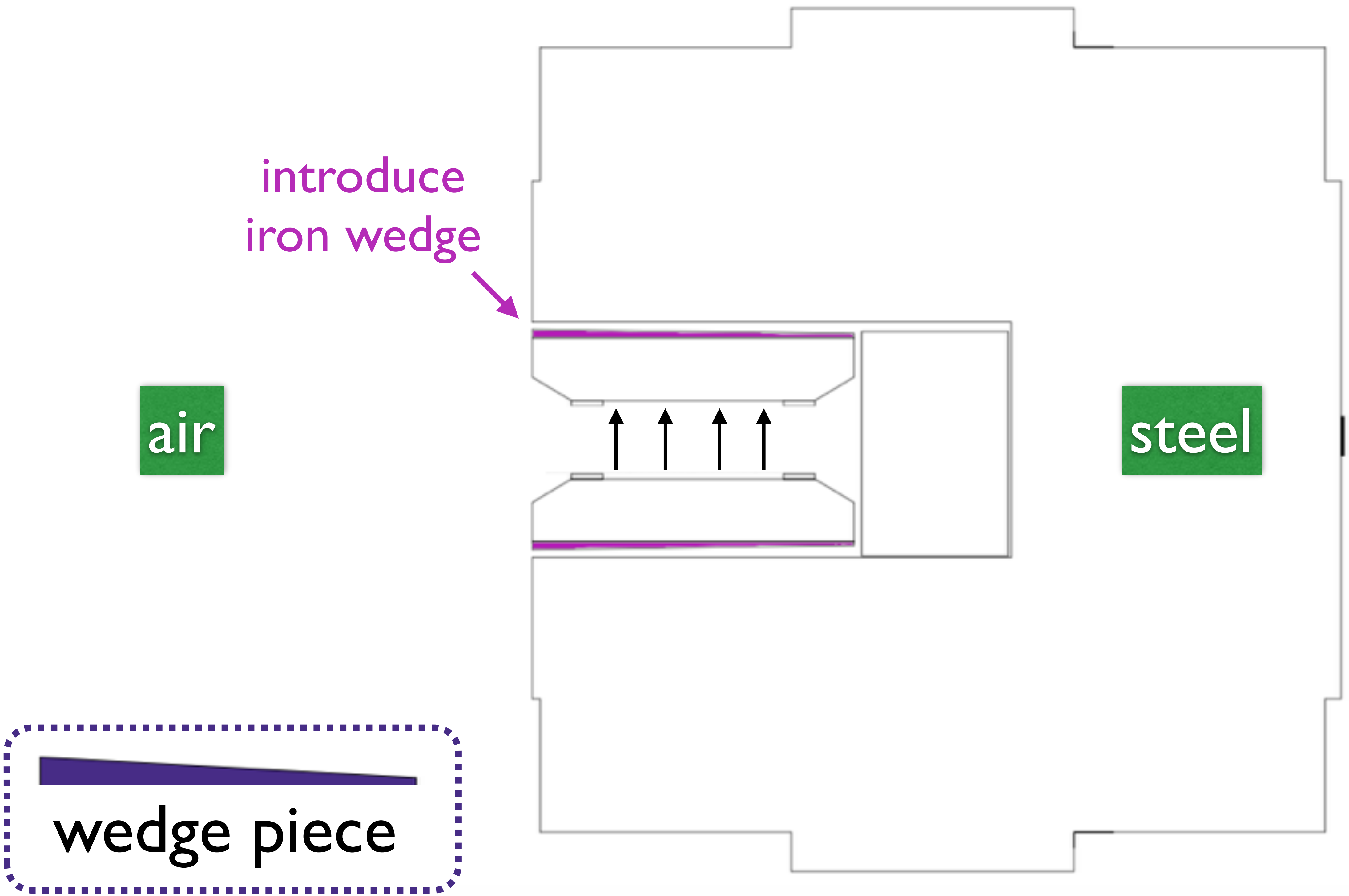
Passive shimming example



Passive shimming example



Passive shimming example



- Motivation
  - brief g-2 history
  - measurement overview

- Muon storage, spin precession
  - beam dynamics systems
  - determine spin precession

- **Magnetic field determination**

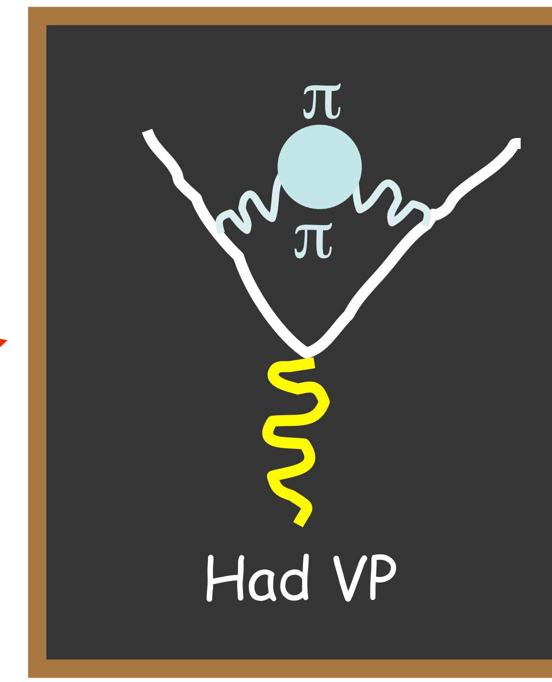
- Current status, path forward

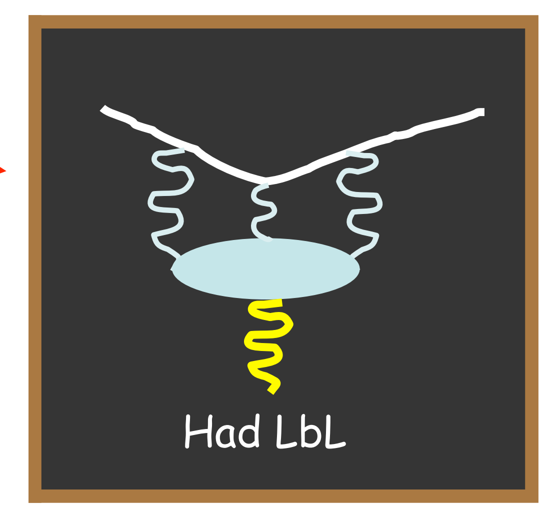
Current status of SM value

- Culmination of incredible amount of theoretical work, challenges remain to push forward

	$a_\mu \equiv \frac{g-2}{2}$ Value (x 10^{-11})
QED	116 584 718.951 ± 0.009 ± 0.019 ± 0.007 ± 0.077
HVP (lo)	6949 ± 42
HVP (ho)	-98.4 ± 0.7
HLBL	105 ± 26
EW	154 ± 1
Total SM	116 591 802 ± 49

$\delta(a_\mu^{th})$ = 420 ppb





- Uncertainty dominated by hadronic interactions
  - principally by hadronic vacuum polarization
  - hadronic "light-by-light" uncertainty also important
- Various improvements → optimistic factor 2 reduction in uncertainty on exp't timescale

3.5 years since groundbreaking

3.5 years since groundbreaking

Building finished early 2014

May 2013

3.5 years since groundbreaking

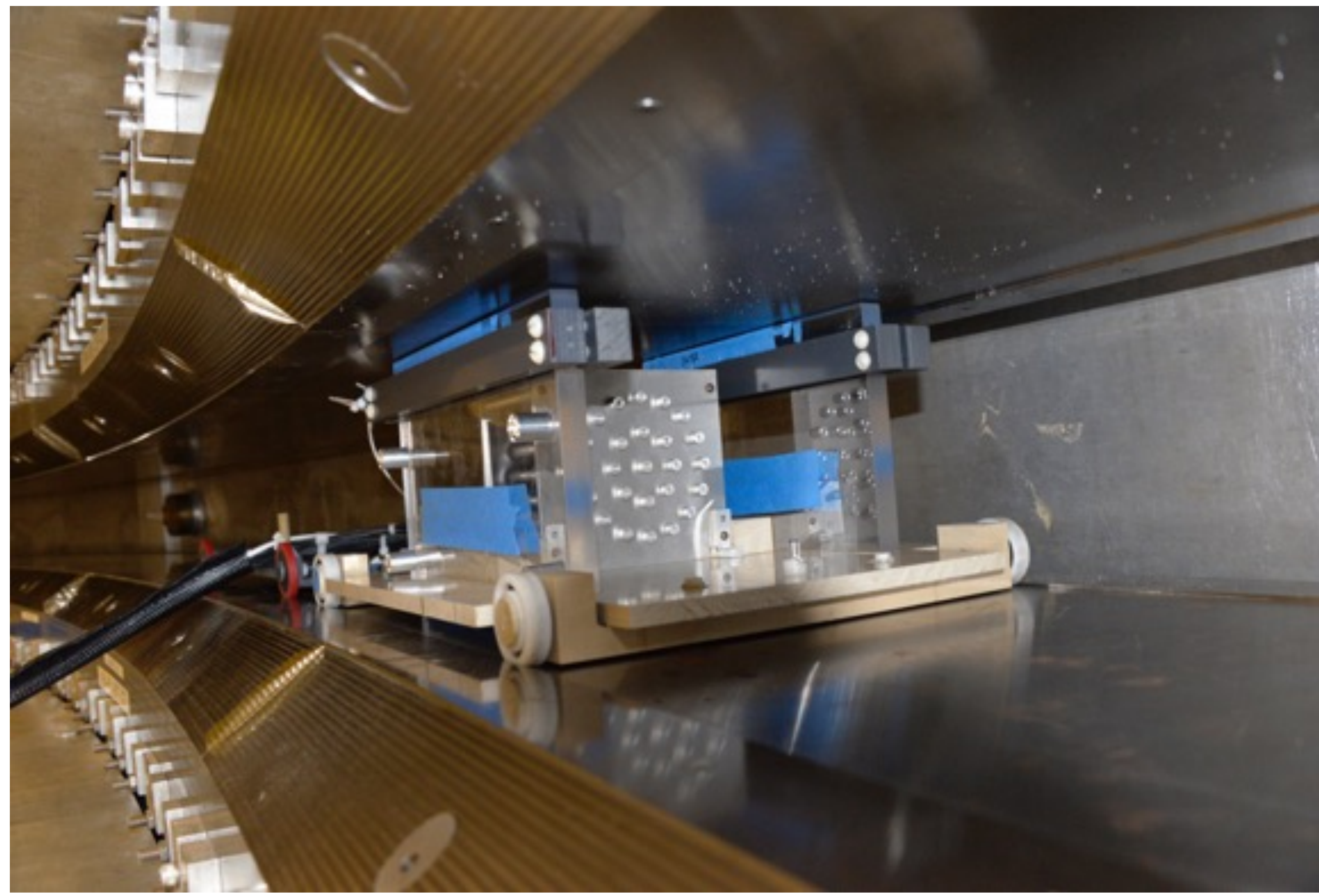
3.5 years since groundbreaking

Courtesy Fermilab Visual Media Services

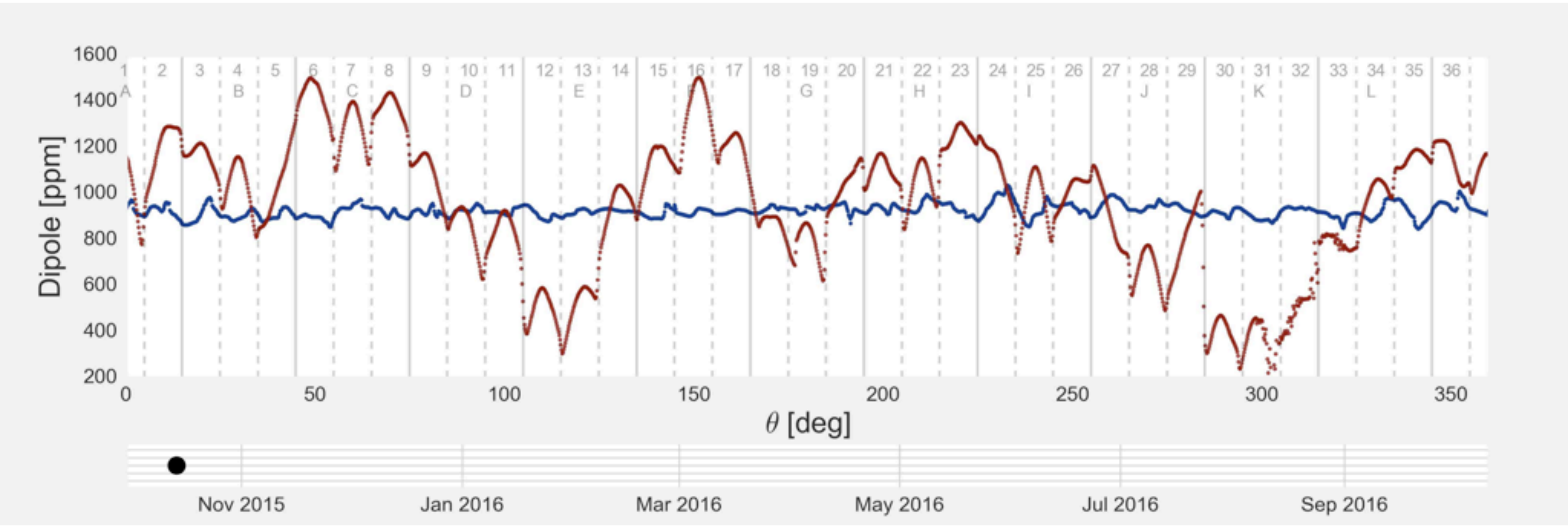
Courtesy Fermilab Visual Media Services

Field shimming

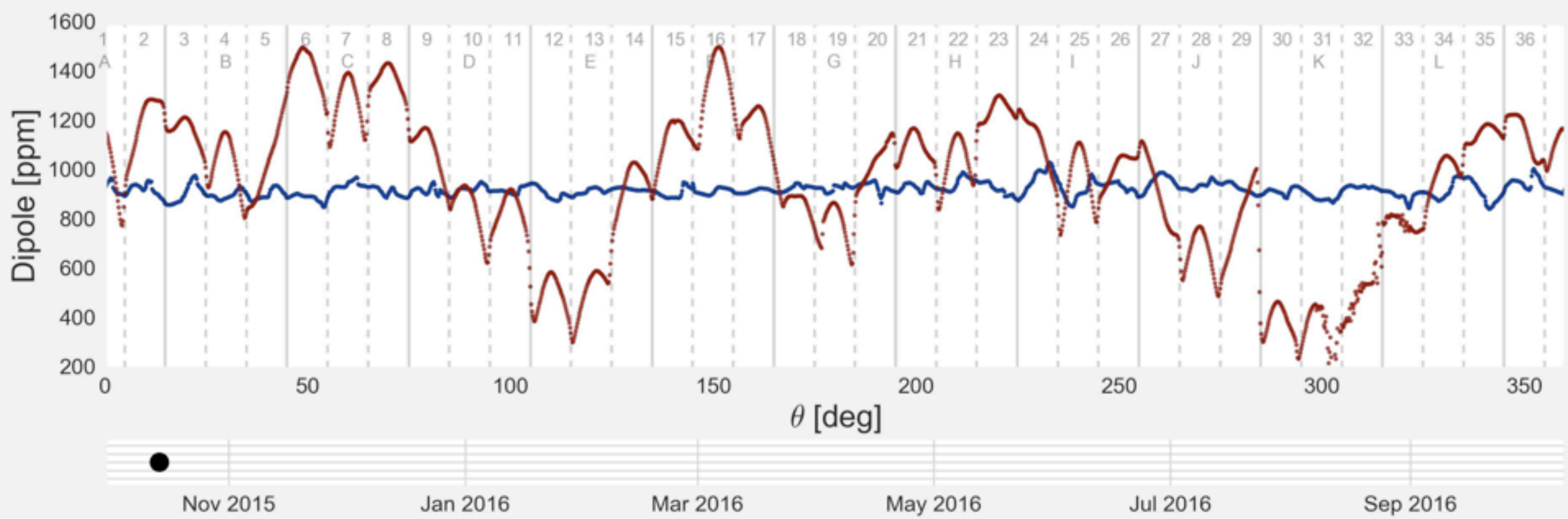
- Sept 22, 2015: **first full power since 2001!**
  - entire ring at 4 K, 5200 Amps in SC circuit
- Pre-vacuum chamber trolley commissioned to take first measurements. On board:
  - 25 NMR probes
  - 4 contact-less gap sensors
  - temperature sensor
- Map field in all three dim of storage volume: using a stepper motor, measure-pull-measure sequencing



Field evolution in the last year



Field evolution in the last year



Summary

- New muon g-2 experiment at Fermilab will exploit new infrastructure in development at Fermilab to increase statistics by > factor 20.

- Must reduce systematic uncertainties by ~ factor 3 to avoid systematic limitation. To understand the magnetic field at this level, better homogeneity and stability will be critical.

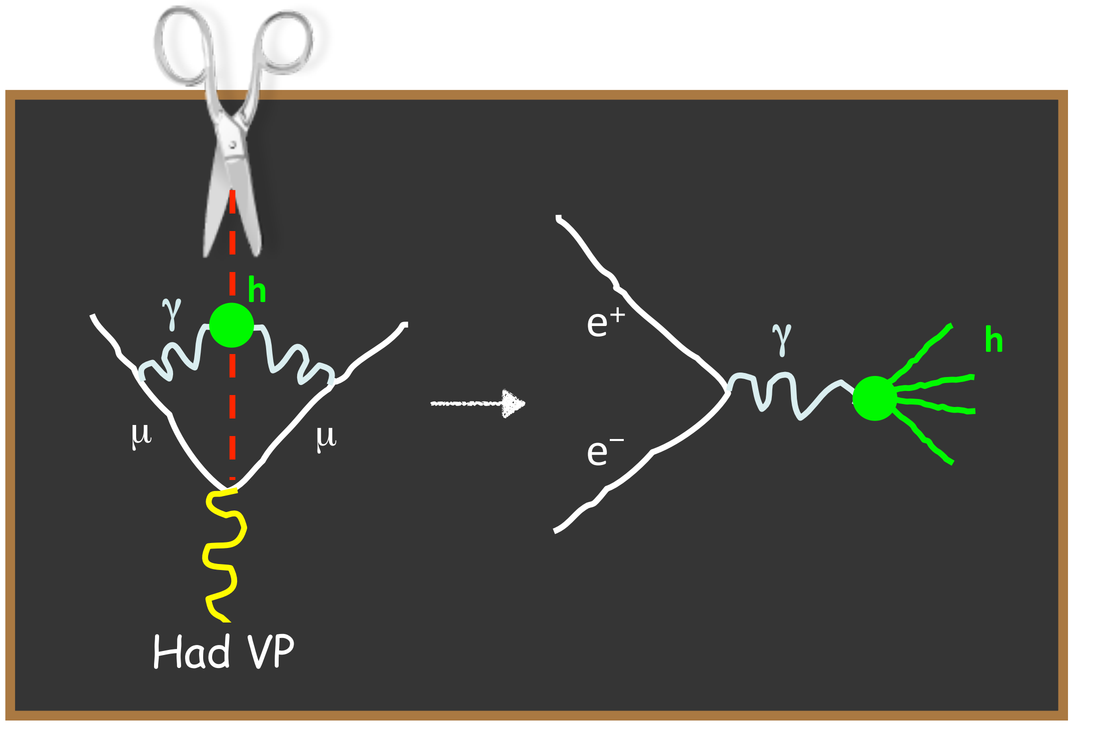
- We have challenging and exciting work ahead of us. In coming years, will test if current g-2 SM-exp't discrepancy holds up to increased scrutiny.

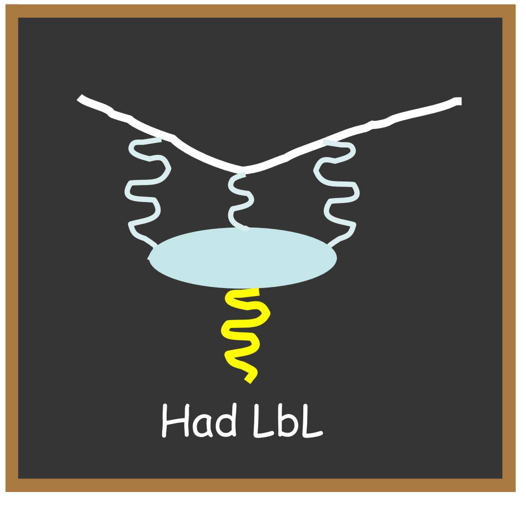
Thanks for your attention!

backup

Anticipated improvements to the SM

- Hadronic vacuum polarization can be tied to experimental data from e^+e^- colliders
  - data already in hand to improve this calculation (analysis underway)
  - lots of planned improvements from VEP-2000, KLOE, BaBar, Belle, Novisibirsk, BES-III, …



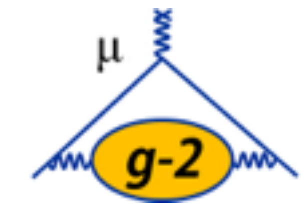


- Hadronic light-by-light must be calculated by theory. Model dependent, challenging…
  - getting more attention lately
  - workshops in 2011, 2014 by leading experts

Lattice-QCD also progressing on both fronts

- Theory anticipated to improve by factor 2 on the experiment timescale
- Without theory improvements, discrepancy reaches > 5σ (for same central values)

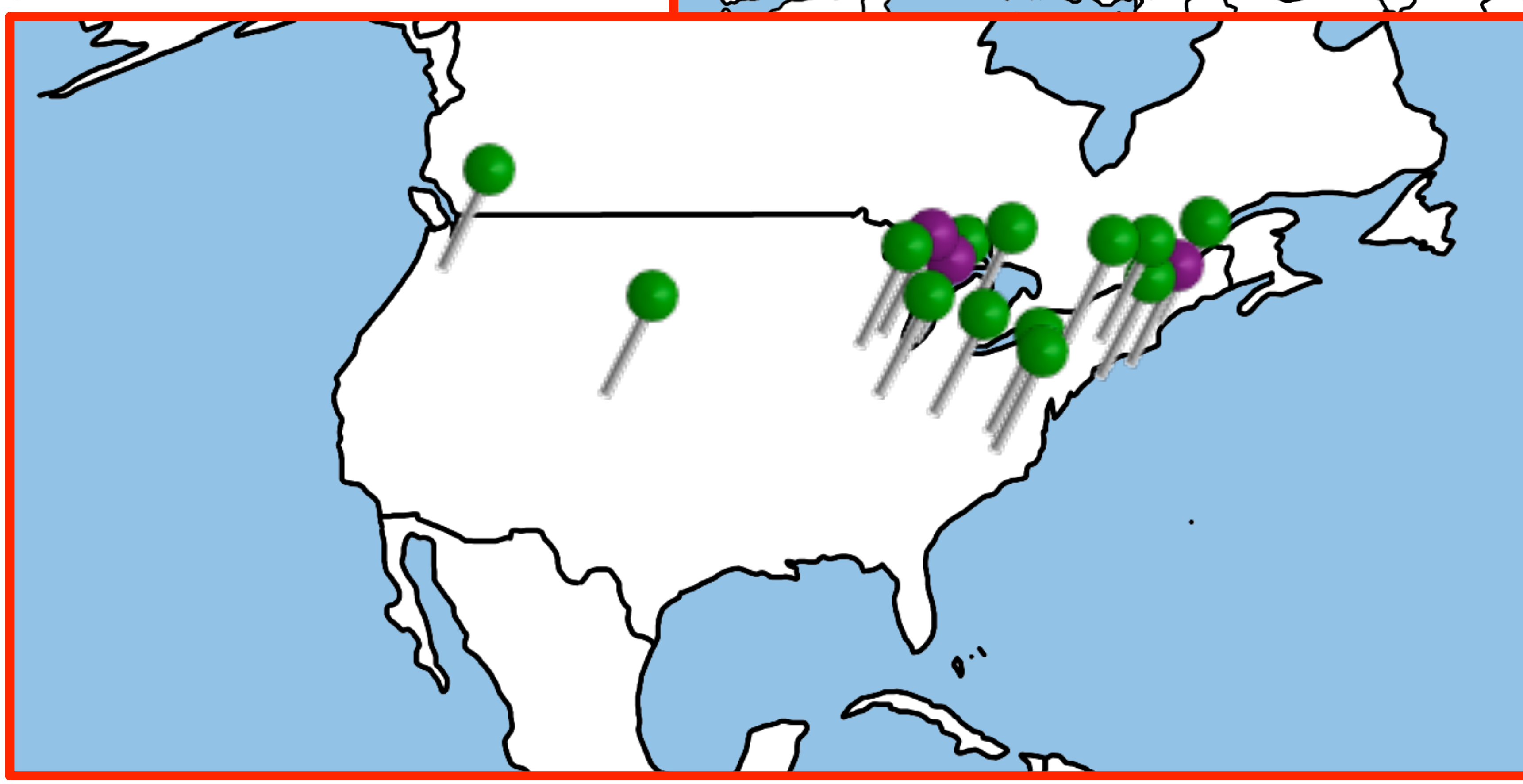
New g-2 collaboration



16 international institutions from 7 countries

13 US institutions

3 national labs



150+ collaborators

Strong mix of BNL g-2 members and new collaborators

Accelerator rates, efficiencies

Table 5.1: Event rate calculation using a bottom-up approach.

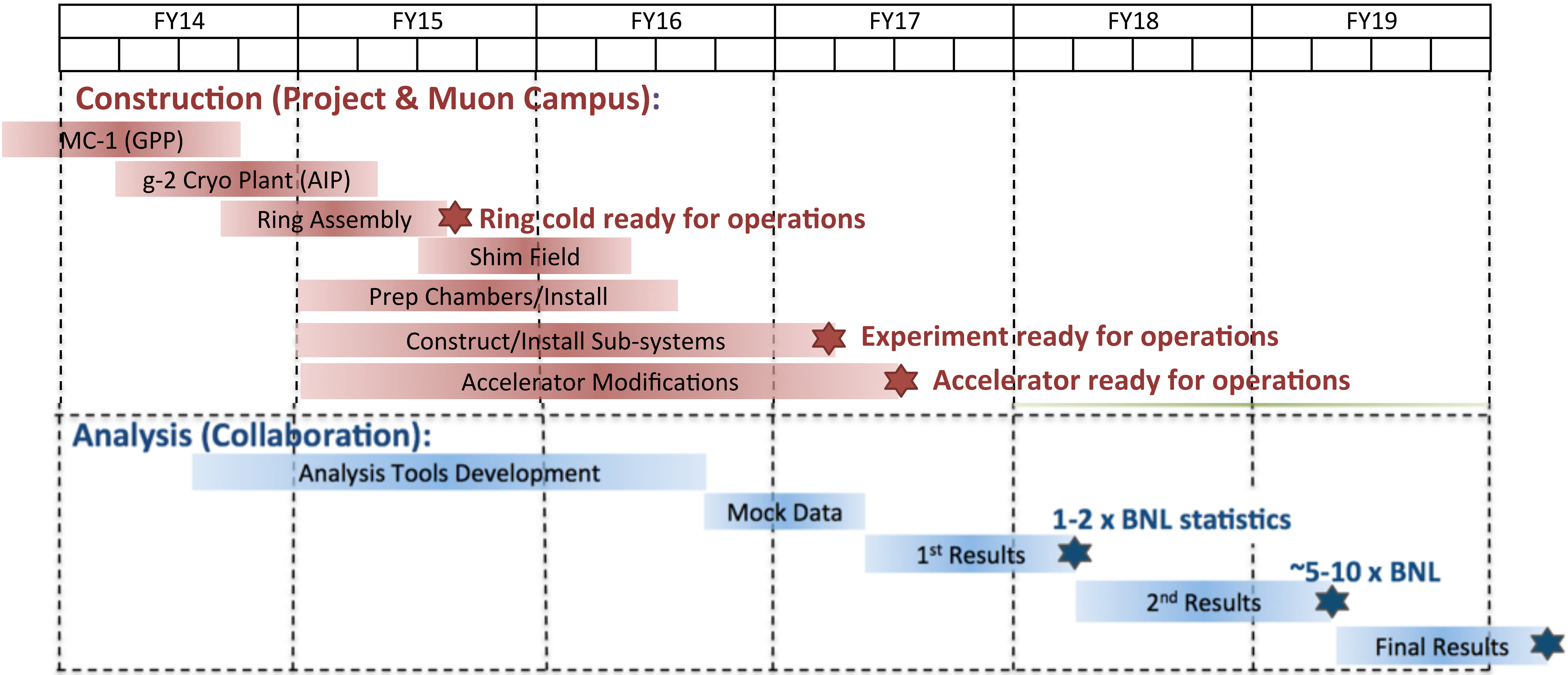
Item	**Factor**	**Value per fill**
Protons on target		10^{12} p
Positive pions captured in FODO, $\delta p/p = \pm 0.5\%$	1.2×10^{-4}	1.2×10^{8}
Muons captured and transmitted to SR, $\delta p/p = \pm 2\%$	0.67%	8.1×10^{5}
Transmission efficiency after commissioning	90%	7.3×10^{5}
Transmission and capture in SR	$(2.5 \pm 0.5)\%$	1.8×10^{4}
Stored muons after scraping	87%	1.6×10^{4}
Stored muons after 30 μs	63%	1.0×10^{4}
Accepted positrons above E = 1.86 GeV	10.7%	1.1×10^{3}
Fills to acquire 1.6×10^{11} events (100 ppb)		1.5×10^{8}
Days of good data accumulation	17 h/d	202 d
Beam-on commissioning days		150 d
Dedicated systematic studies days		50 d
Approximate running time		402 ± 80 d
Approximate total proton on target request		$(3.0 \pm 0.6) \times 10^{20}$

ω_a improvements

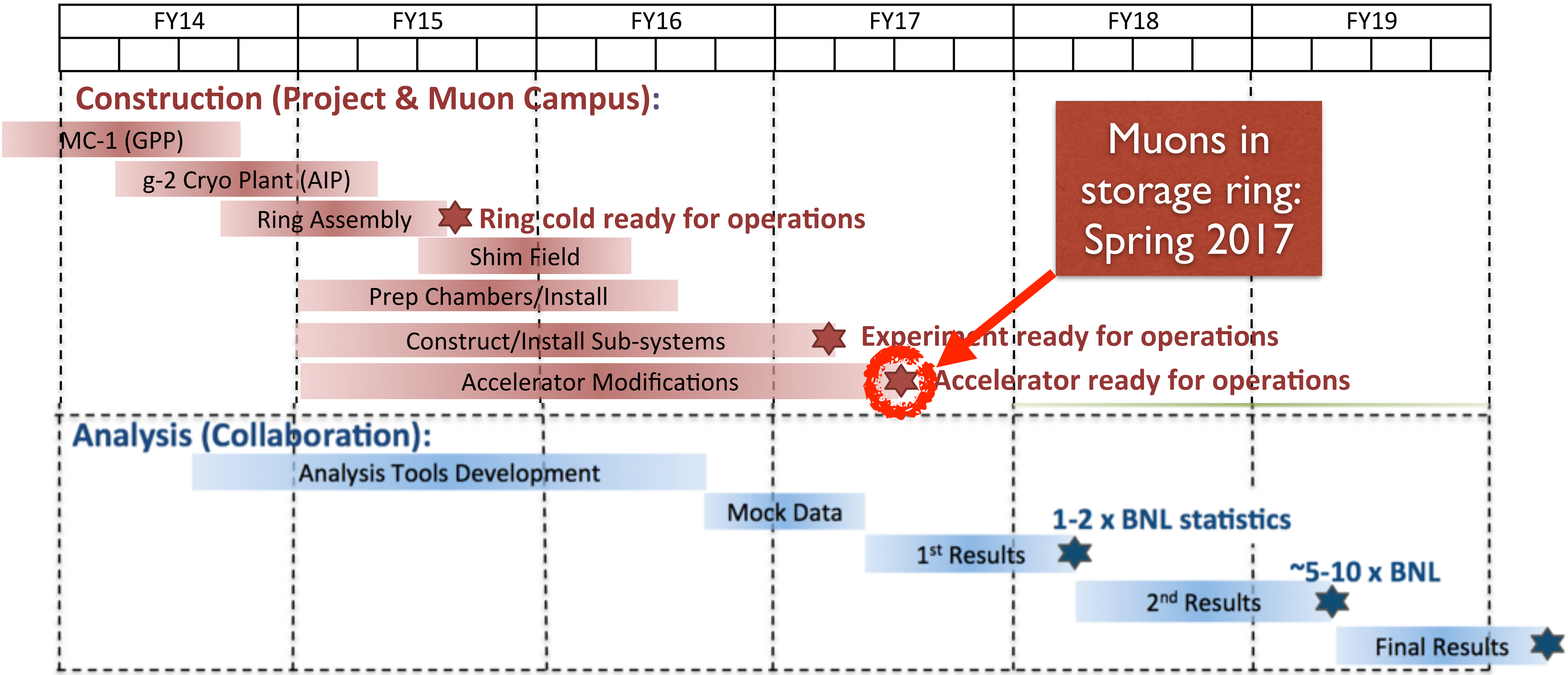
Table 5.2: The largest systematic uncertainties for the final E821 ω_a analysis and proposed upgrade actions and projected future uncertainties for data analyzed using the T method. The relevant Chapters and Sections are given where specific topics are discussed in detail.

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]	Chapter & Section
Gain changes	120	Better laser calibration		
		low-energy threshold	20	16.3.1
Pileup	80	Low-energy samples recorded		
		calorimeter segmentation	40	16.3.2
Lost muons	90	Better collimation in ring	20	13.10
CBO	70	Higher n value (frequency)		
		Better match of beamline to ring	< 30	13.9
E and pitch	50	Improved tracker		
		Precise storage ring simulations	30	4.4
Total	180	Quadrature sum	70	

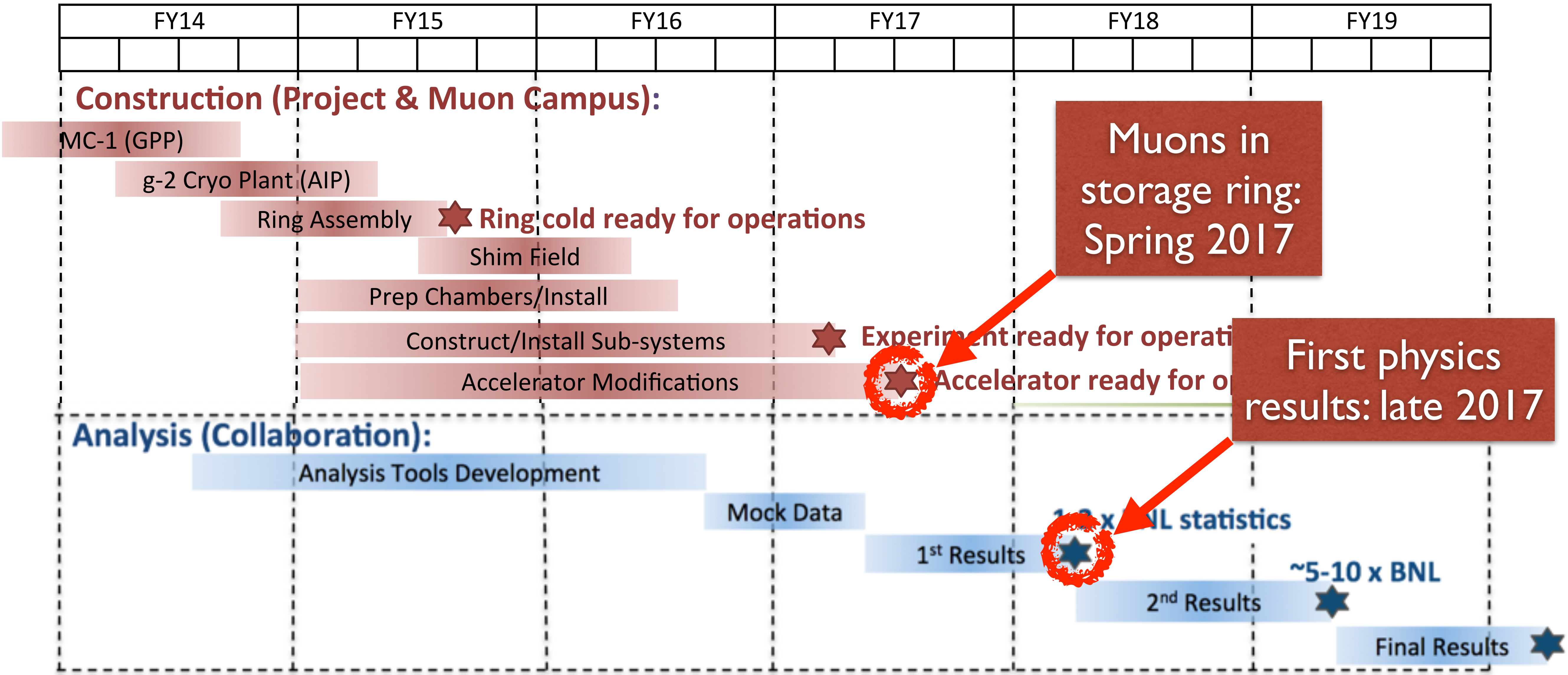
Experiment schedule



Experiment schedule



Experiment schedule



ω_p improvements

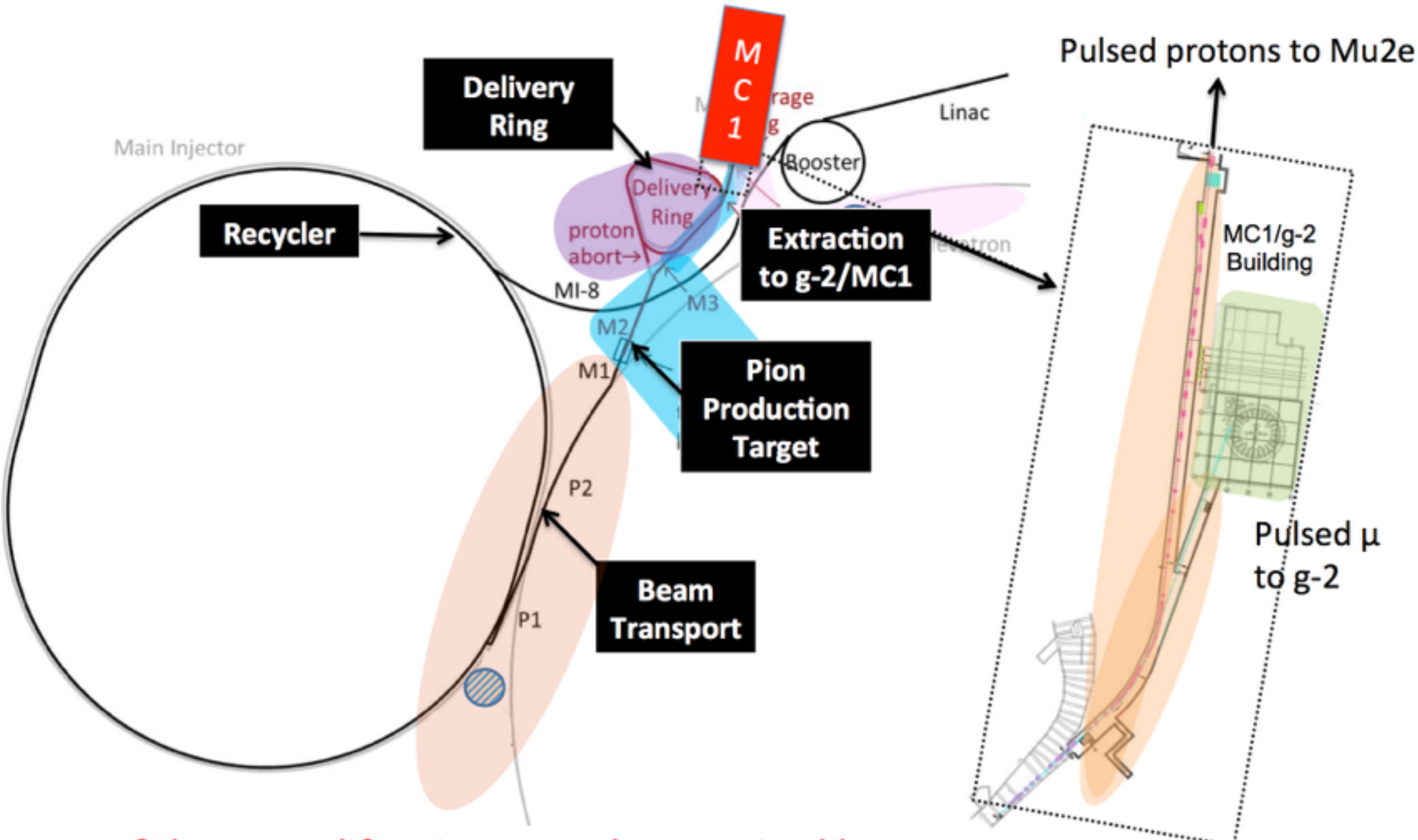
Table 5.3: Systematic uncertainties estimated for the magnetic field, ω_p, measurement. The final E821 values are given for reference, and the proposed upgrade actions are projected. Note, several items involve ongoing R&D, while others have dependencies on the uniformity of the final shimmed field, which cannot be known accurately at this time. The relevant Chapters and Sections are given where specific topics are discussed in detail.

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]	Chapter
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35	15.4.1
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	15.4.1
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30	15.3.1
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30	15.3
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10	15.3
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5	15.6
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30	15.7
Total systematic error on ω_p	170		70	15

*Improvements in many of these categories will also follow from a more uniformly shimmed main magnetic field.

†Collective smaller effects in E821 from higher multipoles, trolley temperature uncertainty and its power supply voltage response, and eddy currents from the kicker. See 15.7.

Accelerator modifications

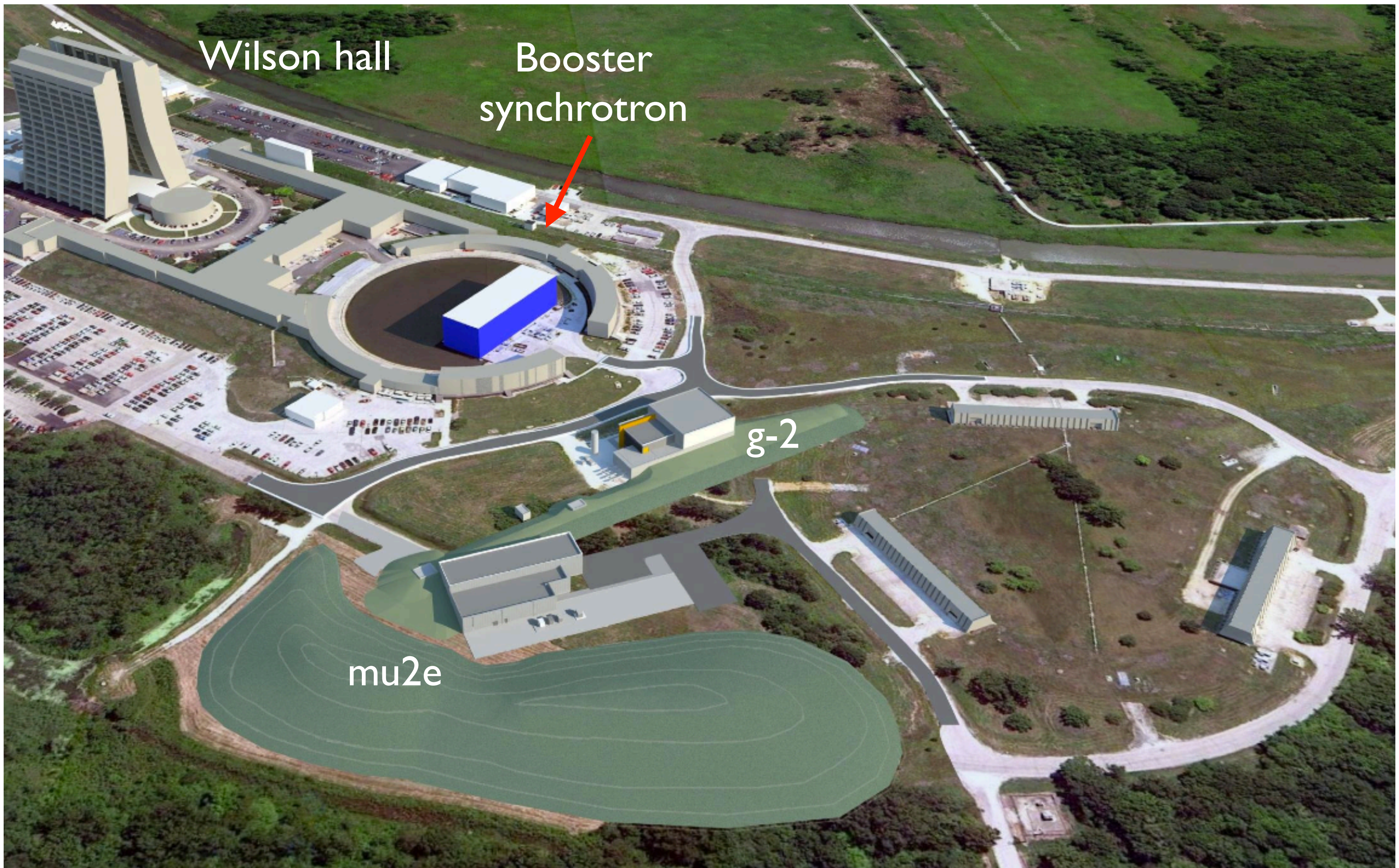


Many of these modifications are also required by Mu2e

FNAL accelerator complex

- Proven technique, statistics limited, tantalizing discrepancy…

Evolved into FNAL "muon campus" plan: g-2, mu2e first users



Must find "B_μ"

- Critical quantity is field experienced by the muons. Along with NMR trolley measurements, need beam optics and muon momentum distribution.
- Muons make ~400 revolutions per lifetime → field average is important
- Must interpolate average field value between trolley runs

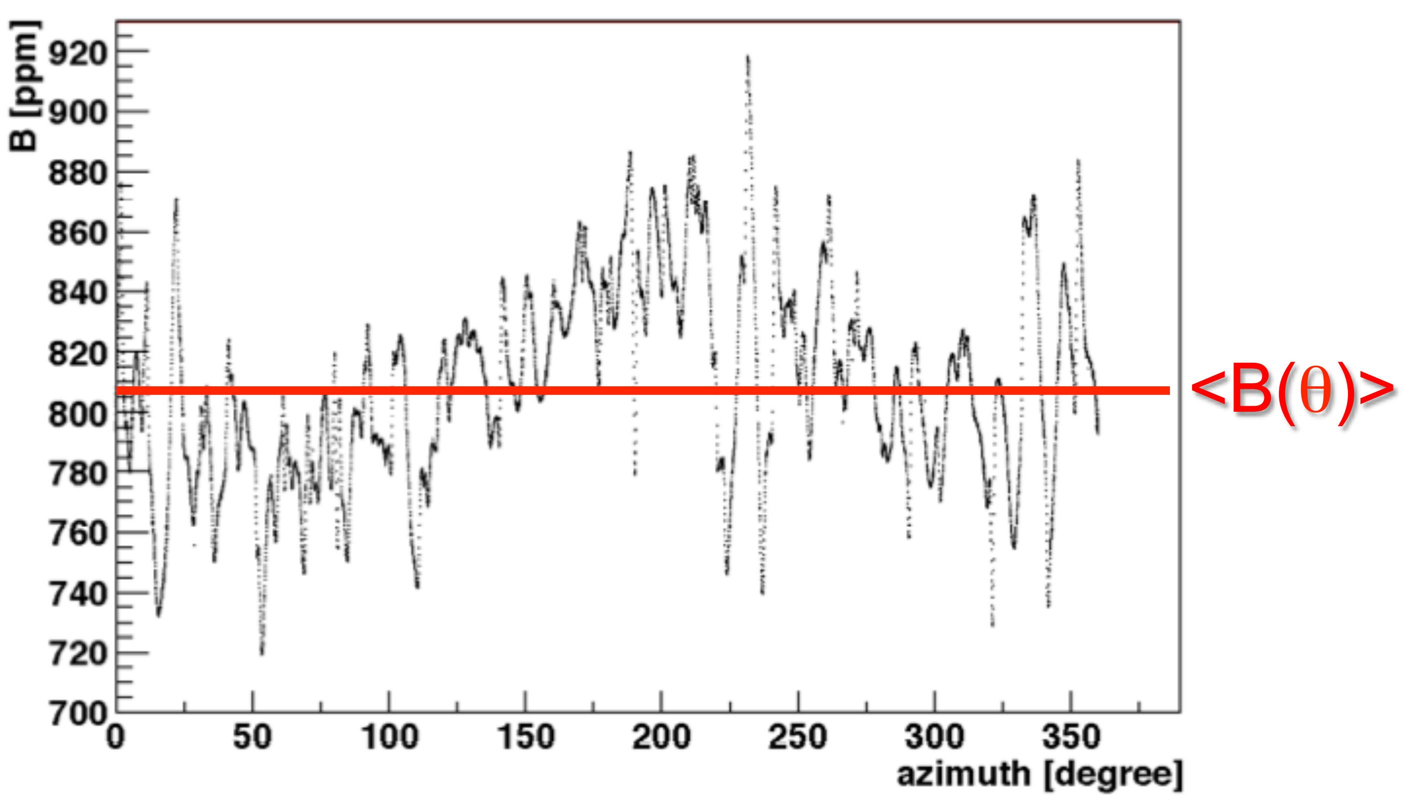


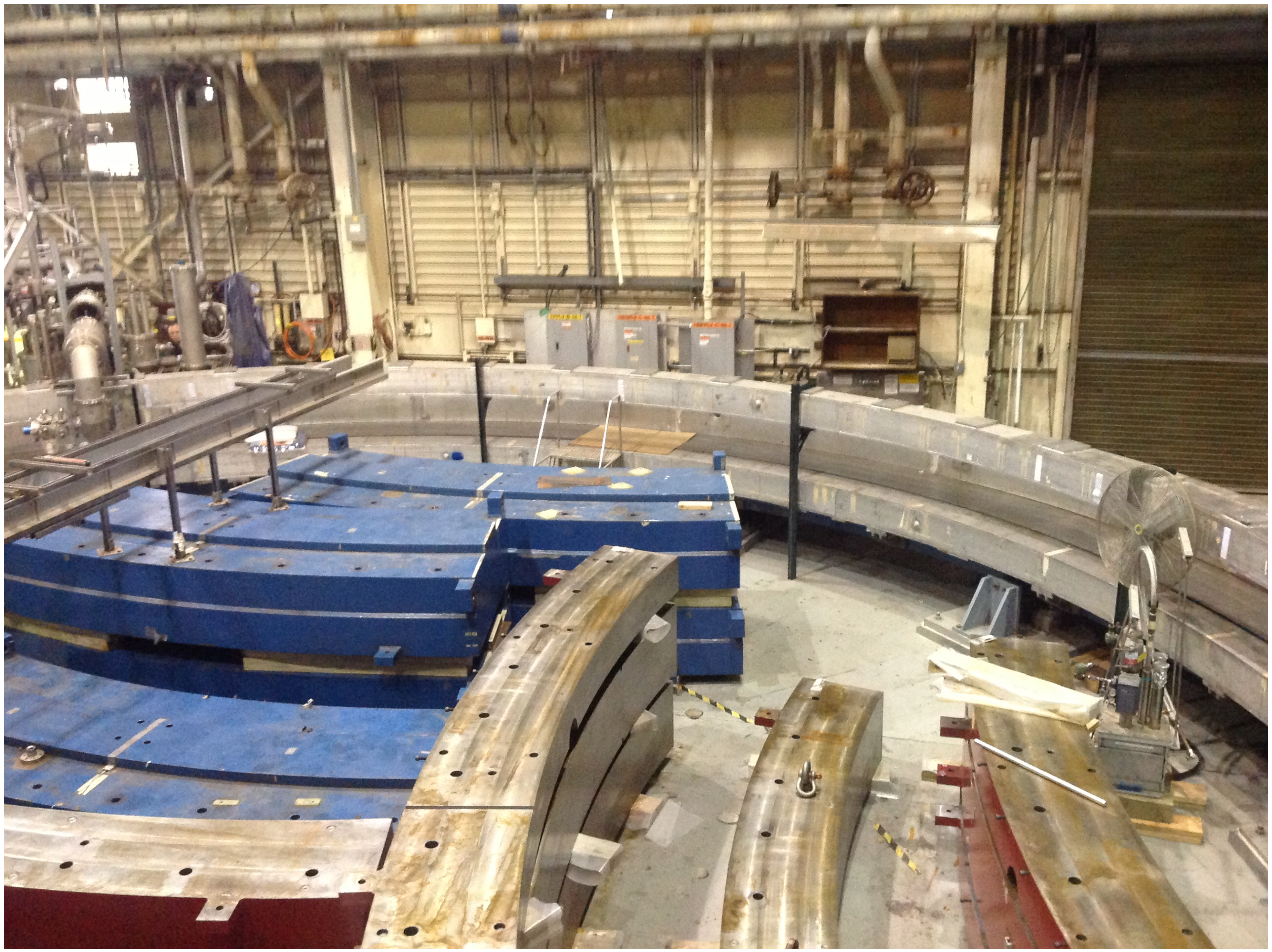
Figure 18: The magnetic field vs. azimuth at the center of the storage region.

Magnetic field uncertainty summary

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

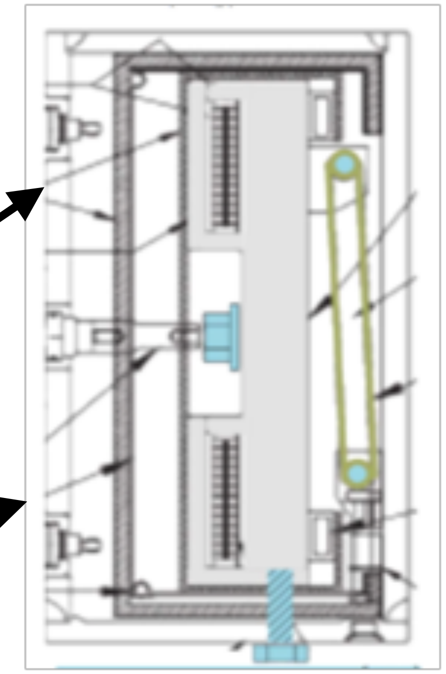
Towards getting the ring to FNAL

- Steel pieces come apart, able to transport in trucks

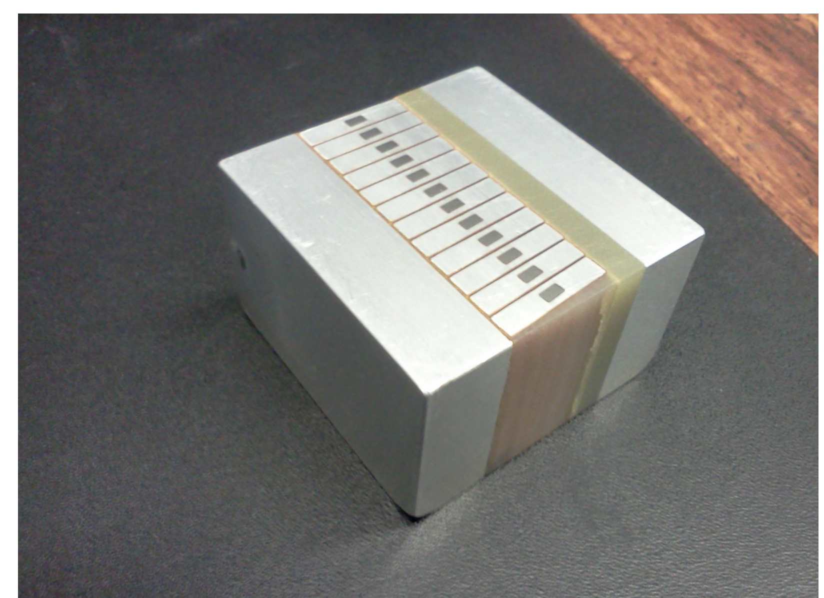


Towards getting the ring to FNAL

- Not the superconducting rings though…

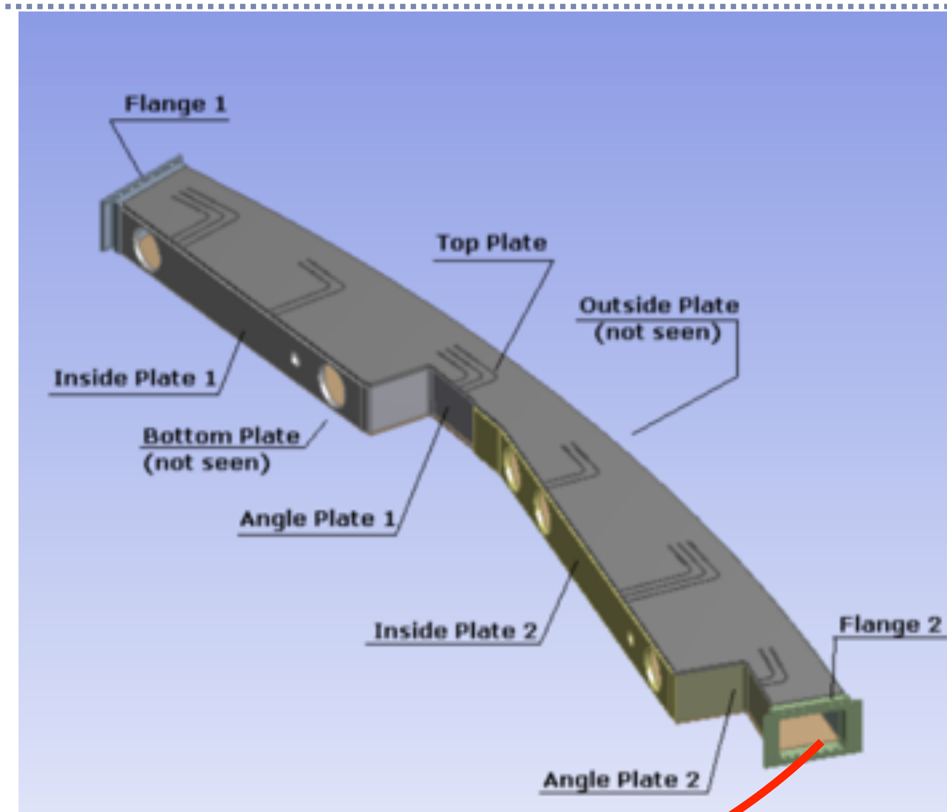


Many, many windings epoxied in place…
can't unwind, can't cut.

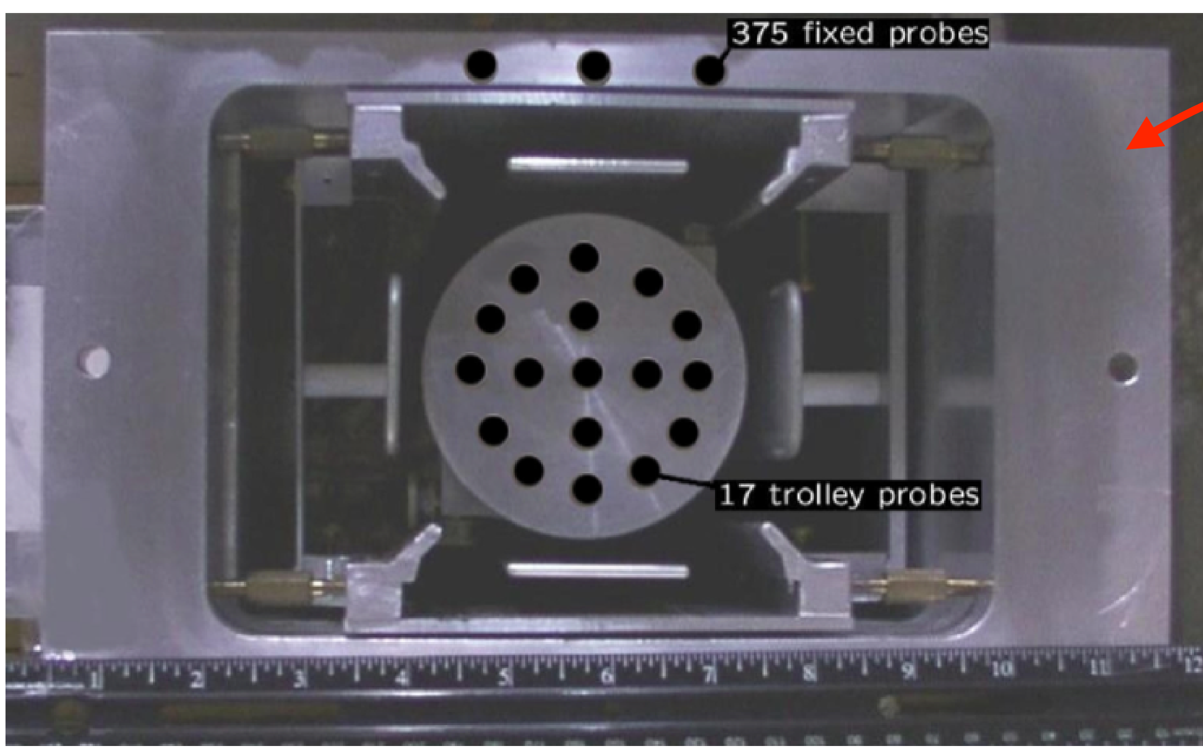


Vacuum chambers

- 12 independent 4m-long aluminum vacuum chambers
  - no ferrous material!



- Many access ports for hardware, visual access, feedthroughs, etc.



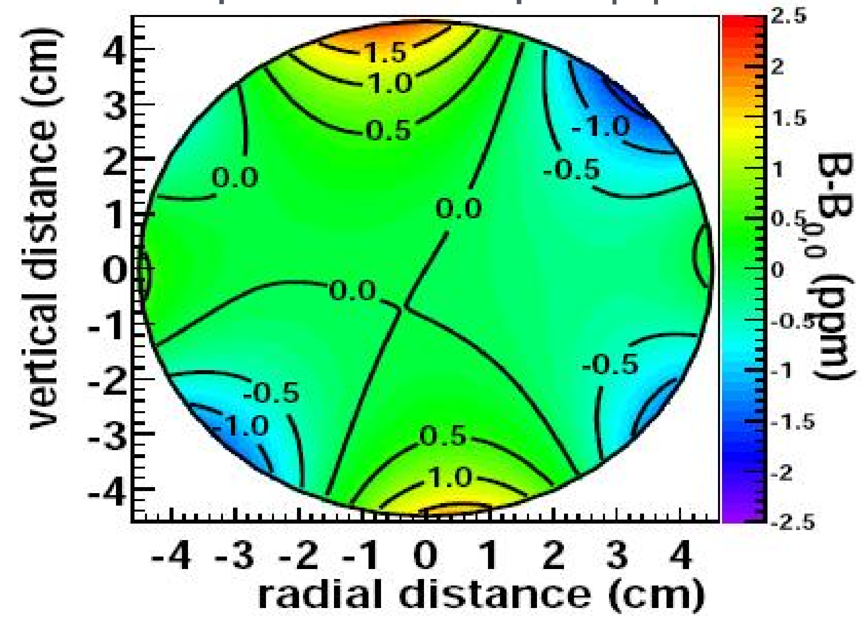
- Houses entire NMR system:
  - mobile "trolley" with 17 probes stored in vacuum
  - 375 in-air fixed probes evenly distributed around ring on top and bottom of chamber

Calibration transfer

Magnet test facility ⇒ NMR trolley

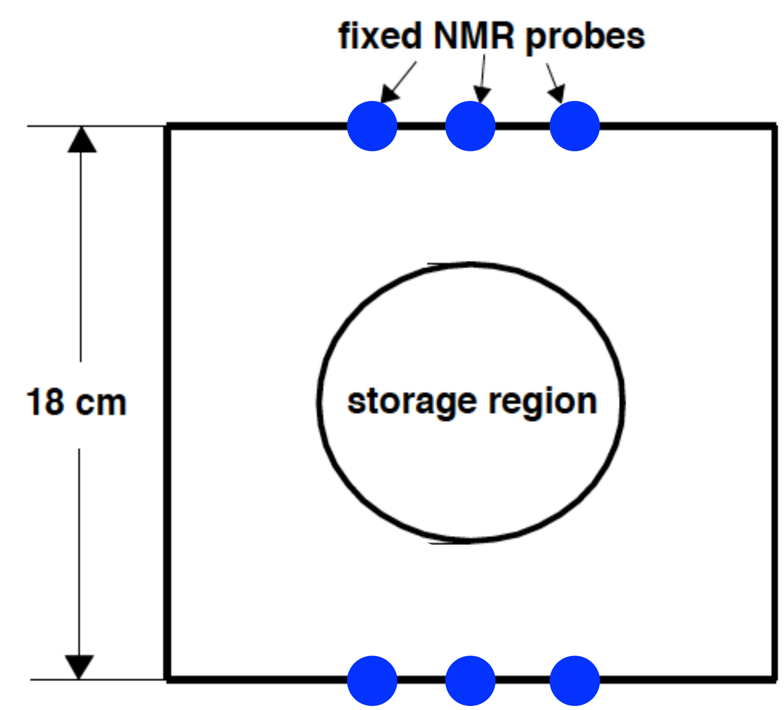
- Matrix of 17 NMR probes pulled around ring as needed (~daily during beam-off conditions)
- Calibrated in MRI magnet and specially shimmed region in g-2 ring
- Directly measures "B_μ", the average field felt by stored muons

precise 3D map of |B|



NMR trolley ⇒ stationary NMR probes

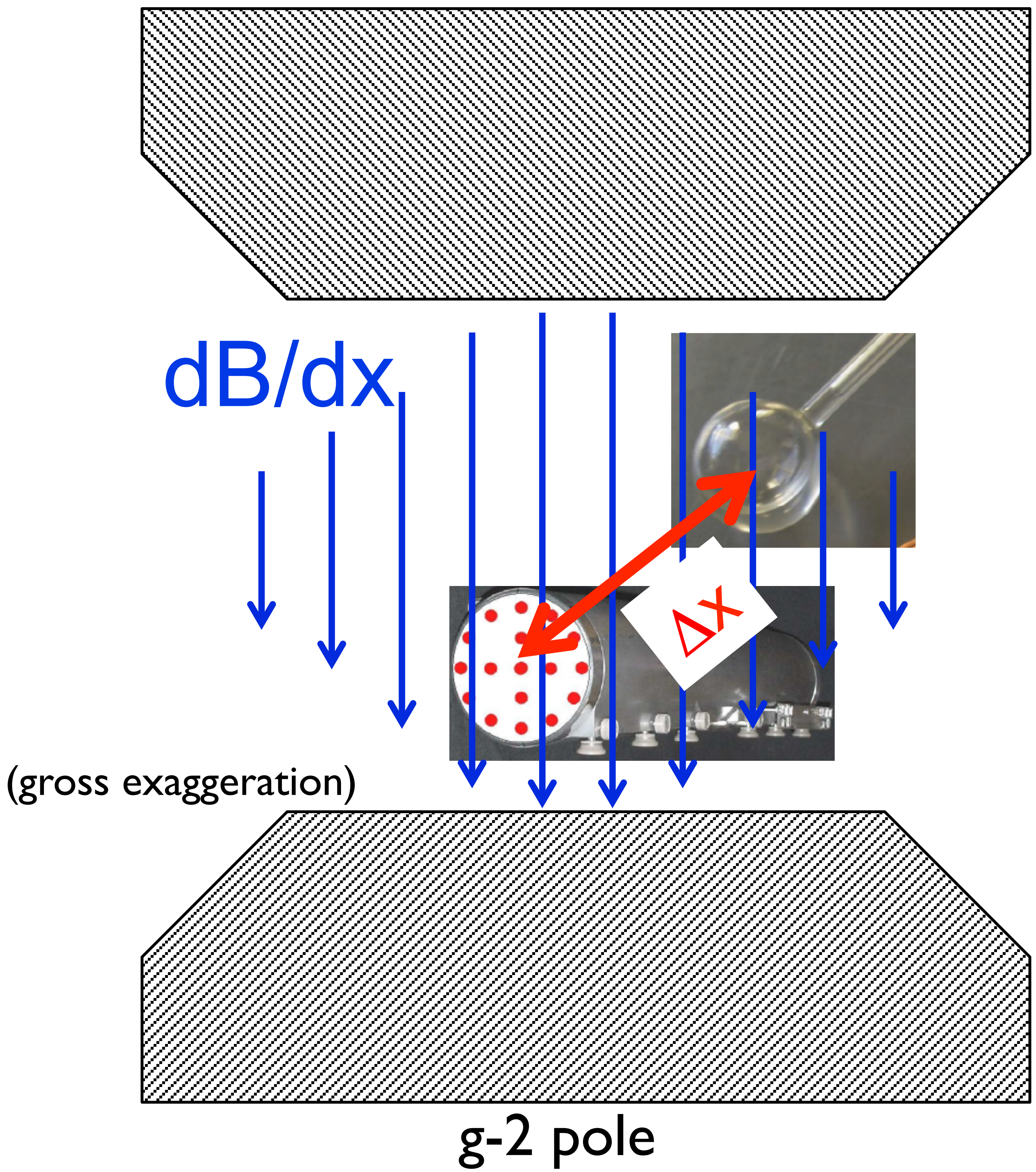
- 375 NMR probes constantly monitor field just outside μ storage region, individually calibrated as trolley passes its position
- Sole ω_p observable during muon precession runs
- Field shape drifts inside storage volume
  - invisible to fixed probes



Vacuum chamber cross section

Calibration worries: position, gradients, stability

- Extra shimming attention paid to specific "calibration region" in g-2 ring.



Want:

$$\Delta B = B_{abs} - B_{trolley}$$

But:

$$\Delta B_{meas} = \Delta B + dB/dx^{*}\Delta x + dB/dt^{*}\Delta t$$

Systematics

gradients position stability calib. time

- Combination of all effects led to ~90 ppb magnetic field uncertainty
  - FNAL goal: 30 ppb

Magnetic field summary

Calibration flow

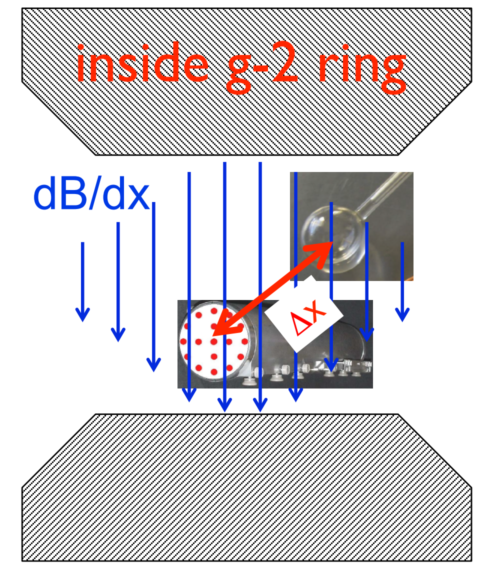
Absolute calibration

$$B_p = (1 - \delta_t)B$$

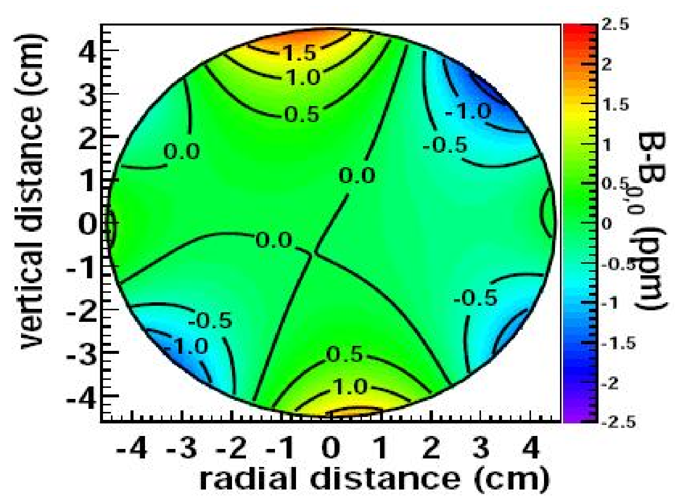
$$\delta_t = \sigma(H_20) + \delta_b + \delta_p + \delta_s$$

Measured — Minimize in calibration probe

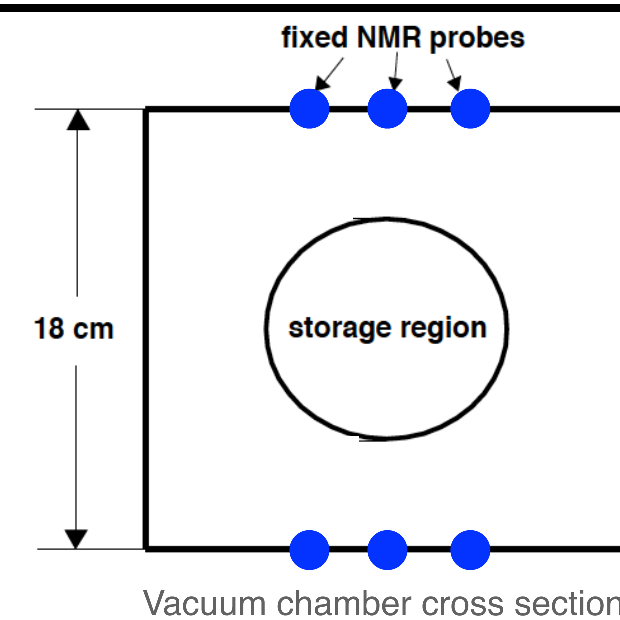
Trolley relative calibration



Trolley relatively calibrates fixed probes, **measures B_μ.**



Fixed probes monitor field during muon storage

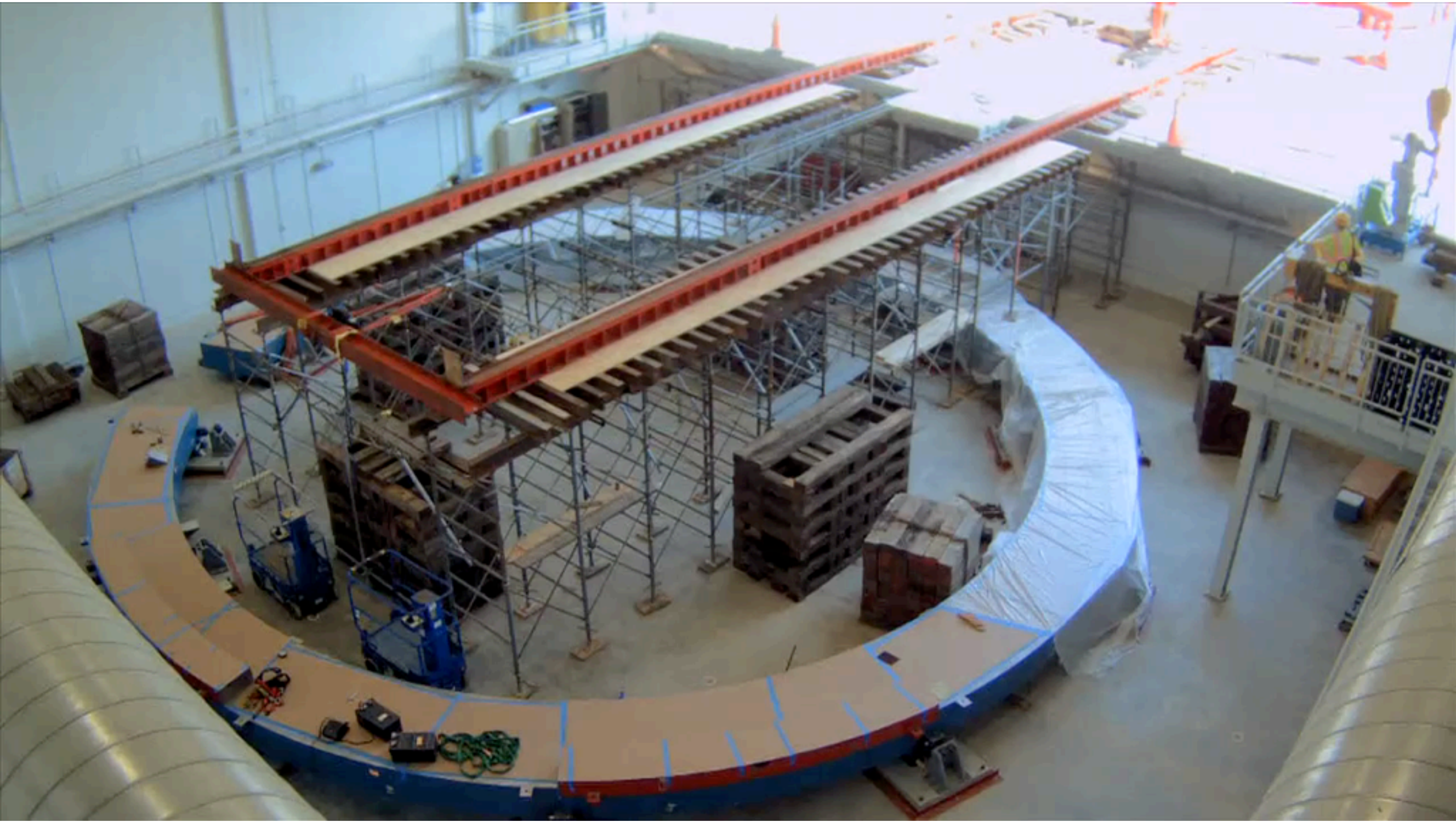


Field homogeneity, stability critically affect uncertainty in these processes

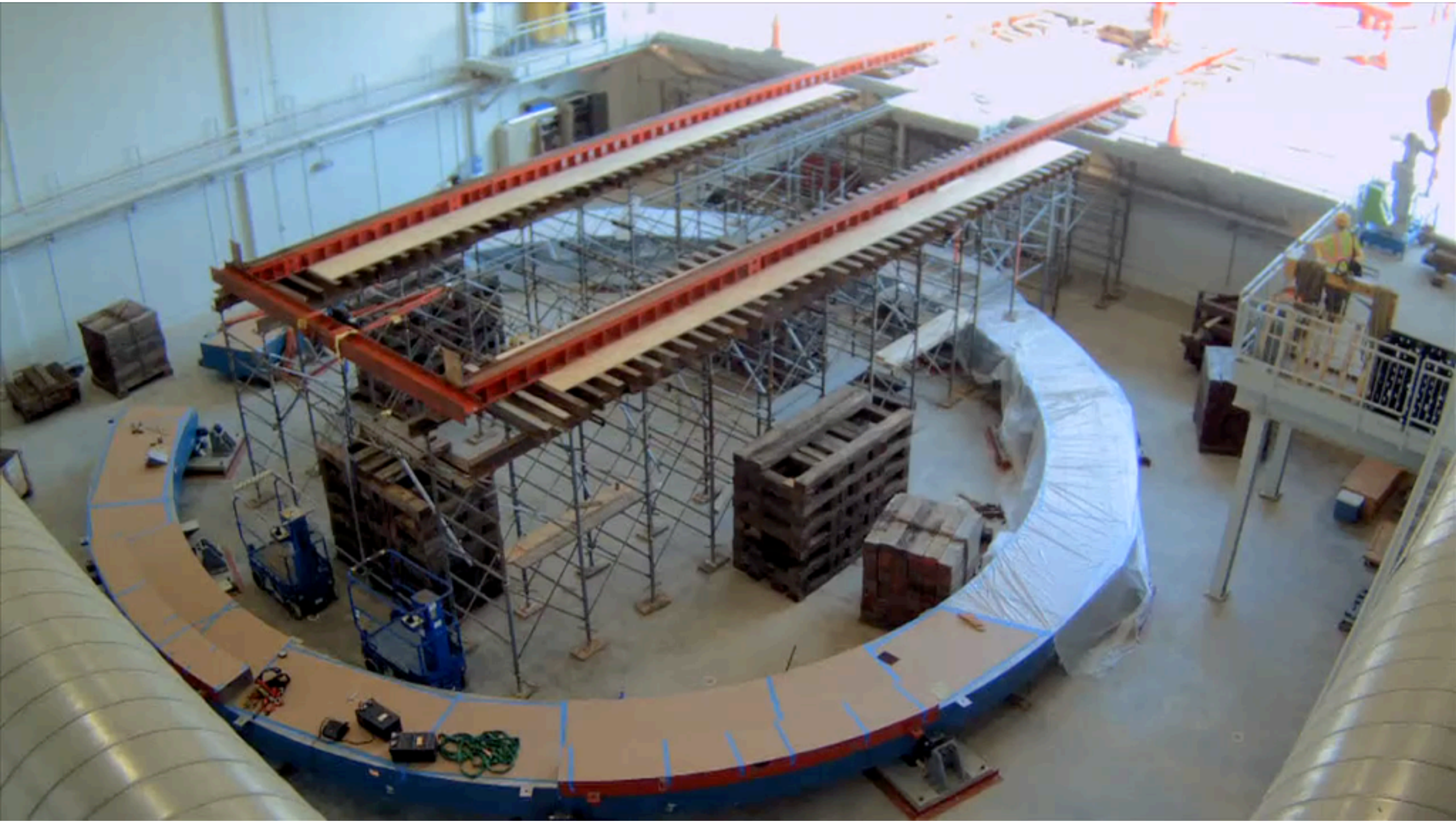
Had to transport as one piece (summer '13)

Illinois roads

New home for the ring (summer '14)

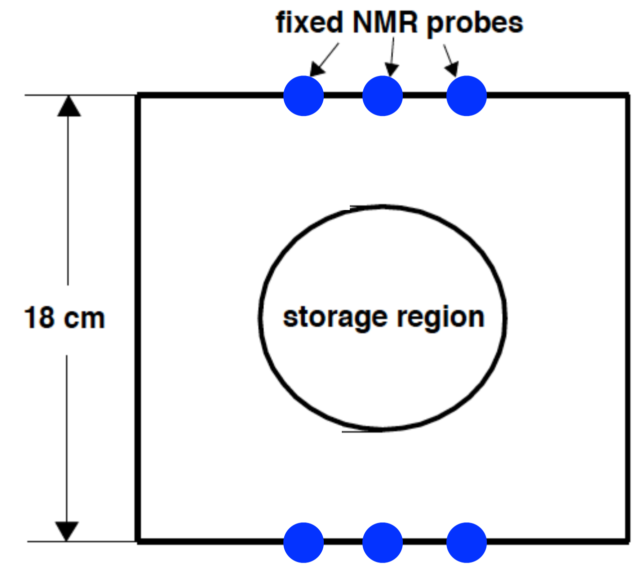


New home for the ring (summer '14)



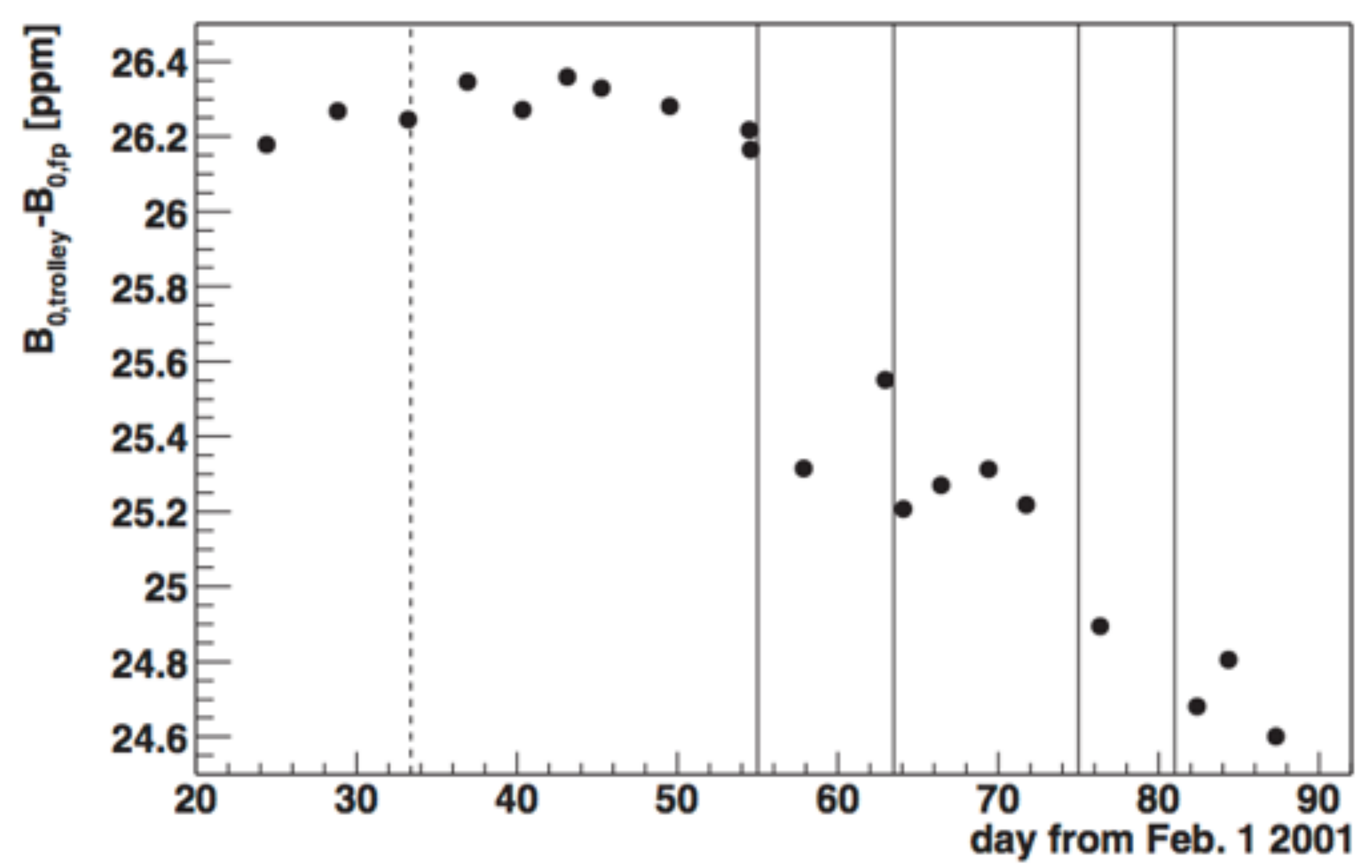
Calibrating the fixed probes

- Due to distance from storage volume, can only grossly track field.
- Trolley runs simultaneously directly measure field felt by muons and calibrates fixed probe readings.
- As magnet drifts, so does field shape and fixed probes lose calibration



Vacuum chamber cross section

- Trolley measurements interpolated into muon precession data with 70 ppb uncertainty
- Better magnet stability and more frequent trolley runs will reduce this substantially for FNAL g-2
  - FNAL goal: 30 ppb



MRI solenoid req's

	Requirement for E989	Oxford OR66 magnet
Magnetic field	1.45 T	$\leq$ 4 T
Stability	< 200 ppb/hr	90 ppb/hr
Homogeneity at center	< 200 ppb/cm	~10 ppb/cm
Bore diameter	> 60 cm	68 cm (with gradient coils) 90 cm (w/o gradient coils)

Absolute calibrations

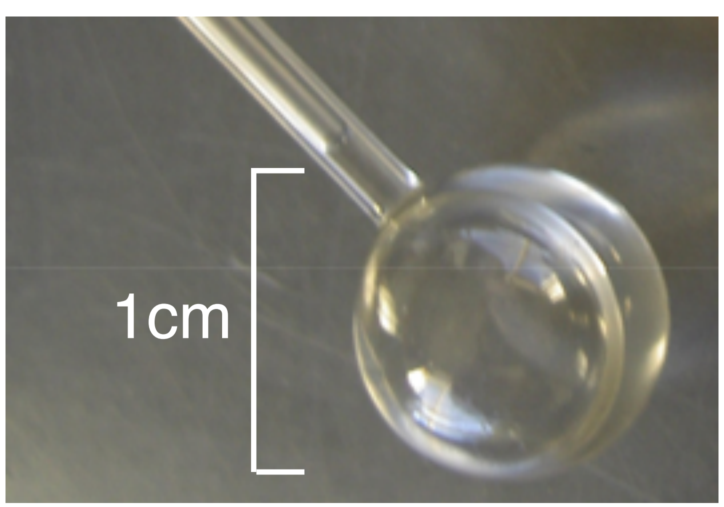
- NMR probes typically precise to ~20 ppb. However, accuracy for water-based probes shifted from true value by 10's of ppm
  - correction dominated by diamagnetic shielding (~25 ppm)

- Strategy:
  1. place NMR probe with high-purity spherical water sample in stable and homogeneous magnetic field (e.g. MRI solenoid)
  2. cross-calibrate various g-2 NMR probes in both MRI magnet and a special region in g-2 ring (again shimming is critical!)

$$B_p = (1 - \delta_t) B_{fp}$$

$$\delta_t = \sigma(H_2 0) + \delta_b + \delta_p + \delta_s$$

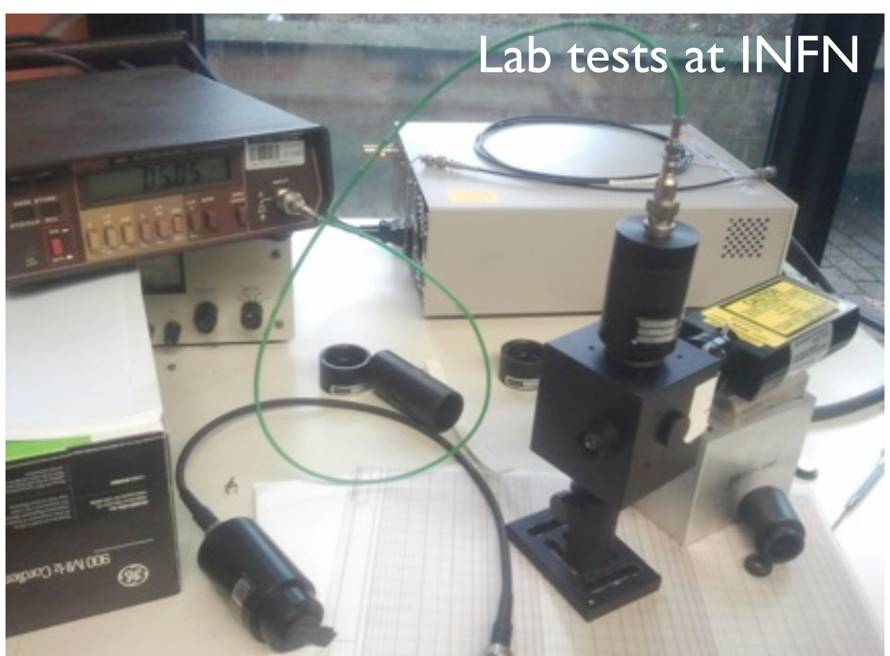
- $\sigma(H_2 0)$: diamagnetic shielding
- δ_b: shape-dependent bulk diamagnetism (zero for perfect sphere)
- δ_p: paramagnetic impurities
- δ_s: additional diamagnetic materials in probe structure

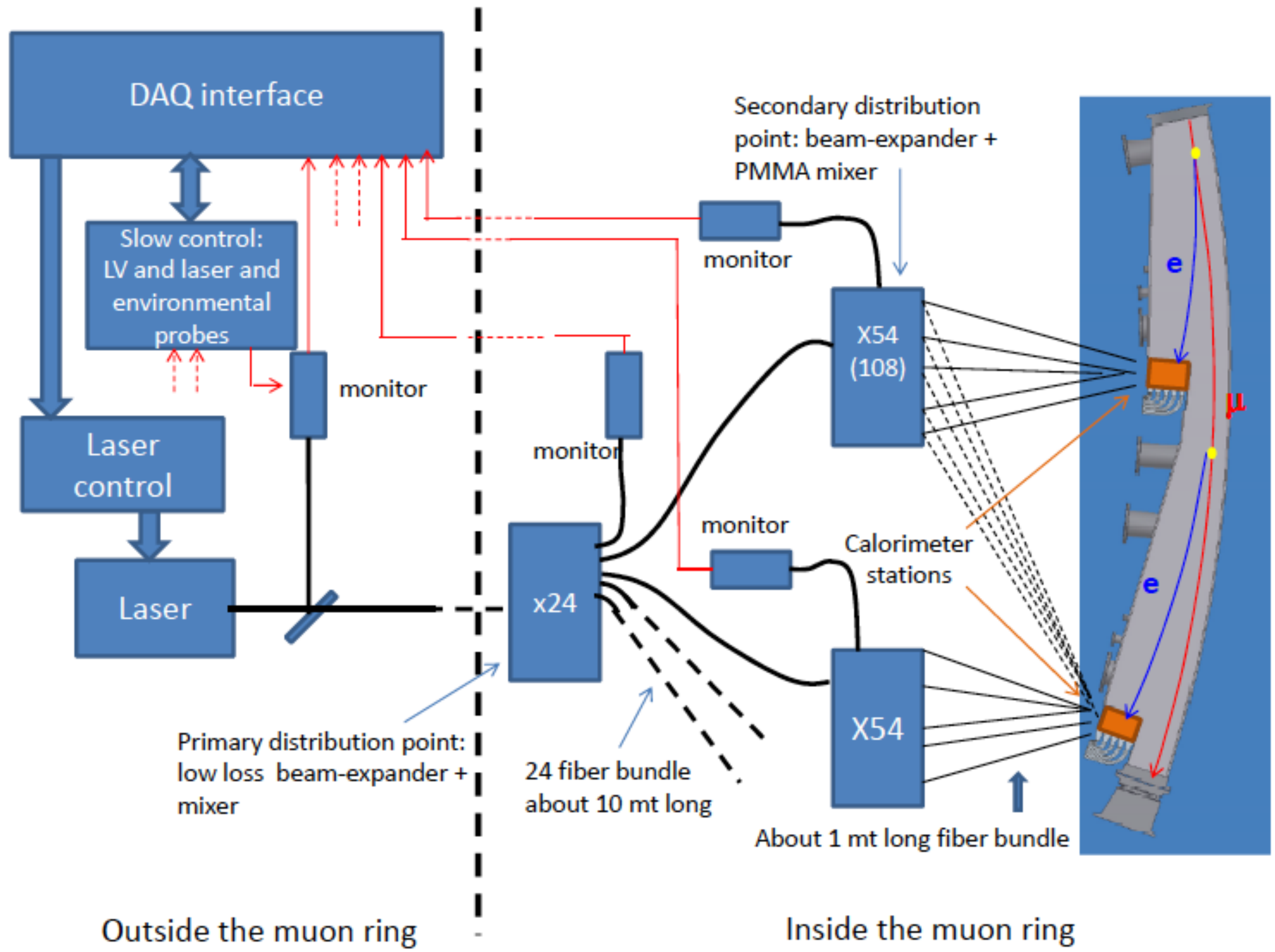


BNL g-2 absolute probe

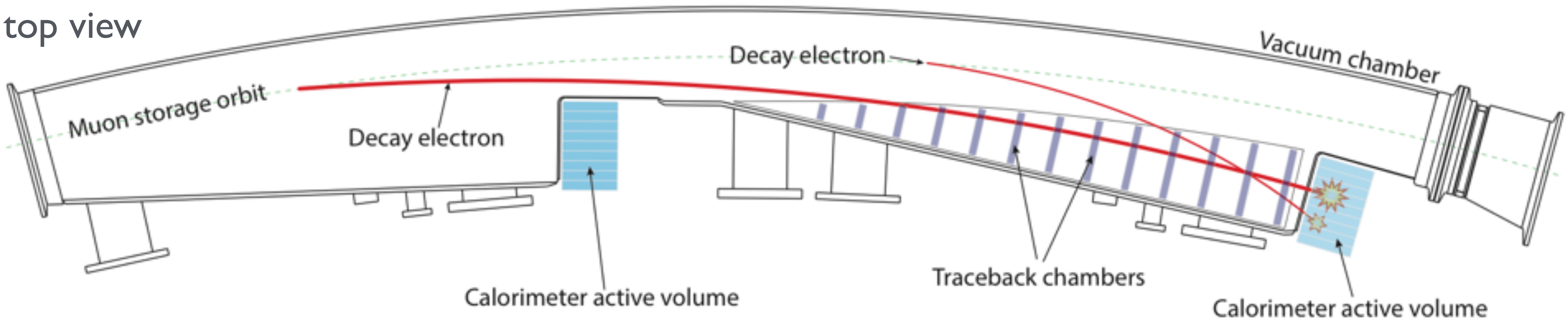
Calorimeter calibration

- Early-to-late gain changes can pull precession frequency
- Four orders of magnitude rate change throughout muon fill!
  - gain must be stable to within 10^{-3}

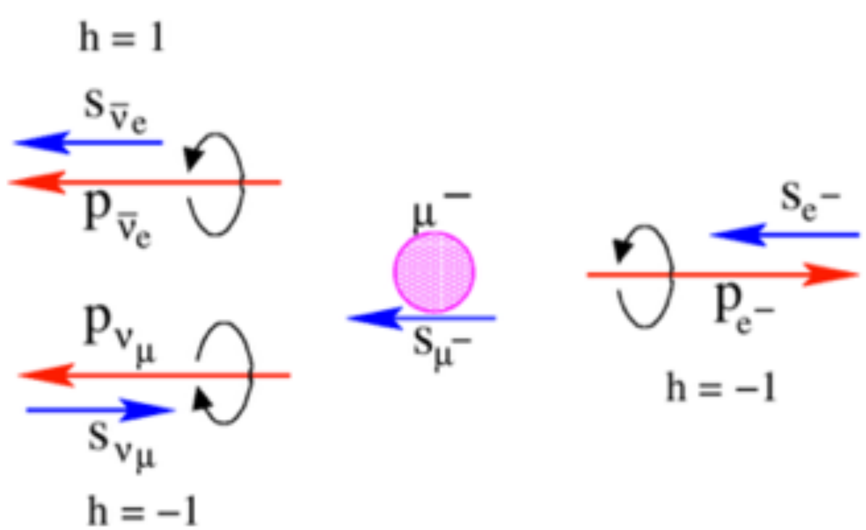




Pileup



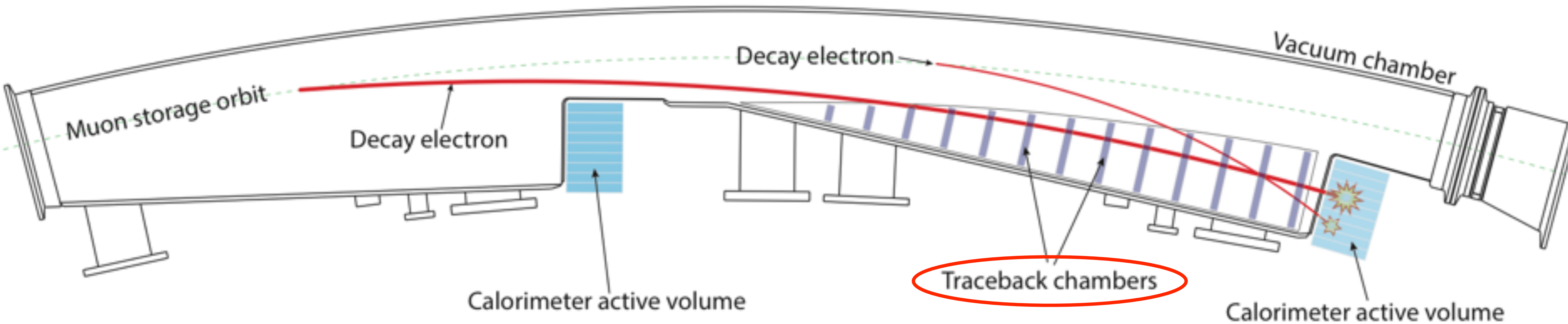
- Recall self-analyzing μ decay



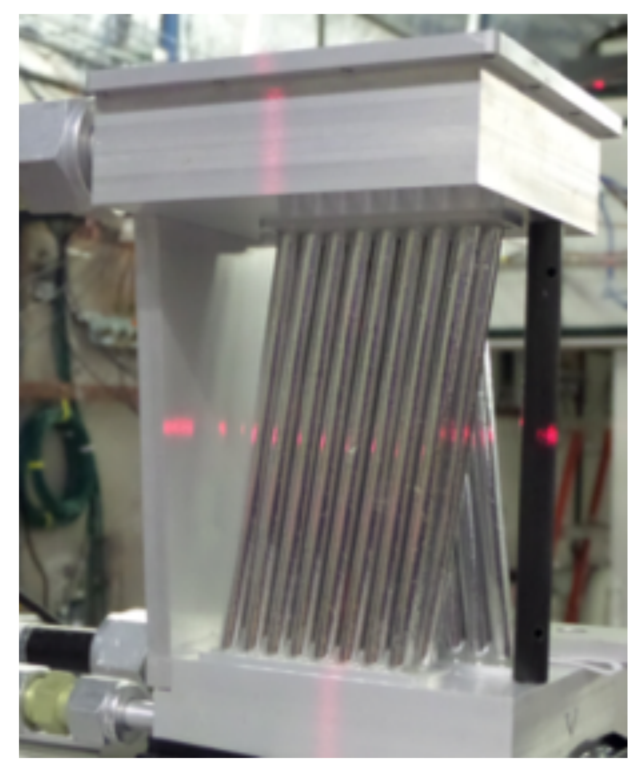
Strategy: calorimeters with higher segmentation, straw trackers further resolve ambiguities

- Correlation strongest at high momentum. Pileup of two low E e^+ may fake high E e^+.

Straw tracker



- Nearly massless (~10^{-3} X_0) detectors measure full beam profile at three locations in ring. Beam profile monitors:
  - betatron motion
  - momentum spread
  - magnetic field variations (indirect)
- Few mm resolution for pileup detection
- Better energy resolution than calorimeter allows verification of gain measurements



Prototype at FNAL test beam

Straw tracker

- Also affords sensitivity to additional physics: muon electric dipole moment (EDM)

size of μ EDM

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{EDM}} = \vec{\omega}_a - \frac{q\eta}{2m}(\vec{\beta} \times \vec{B}) \qquad \vec{d}_\mu = \eta \frac{e}{4mc} \vec{S}$$

"radial"
spin precession

- Non-zero EDM observable in up-down asymmetry in spin precession

- BNL: $|\vec{d}_\mu| < 1.8 \times 10^{-19} e \text{ cm}$

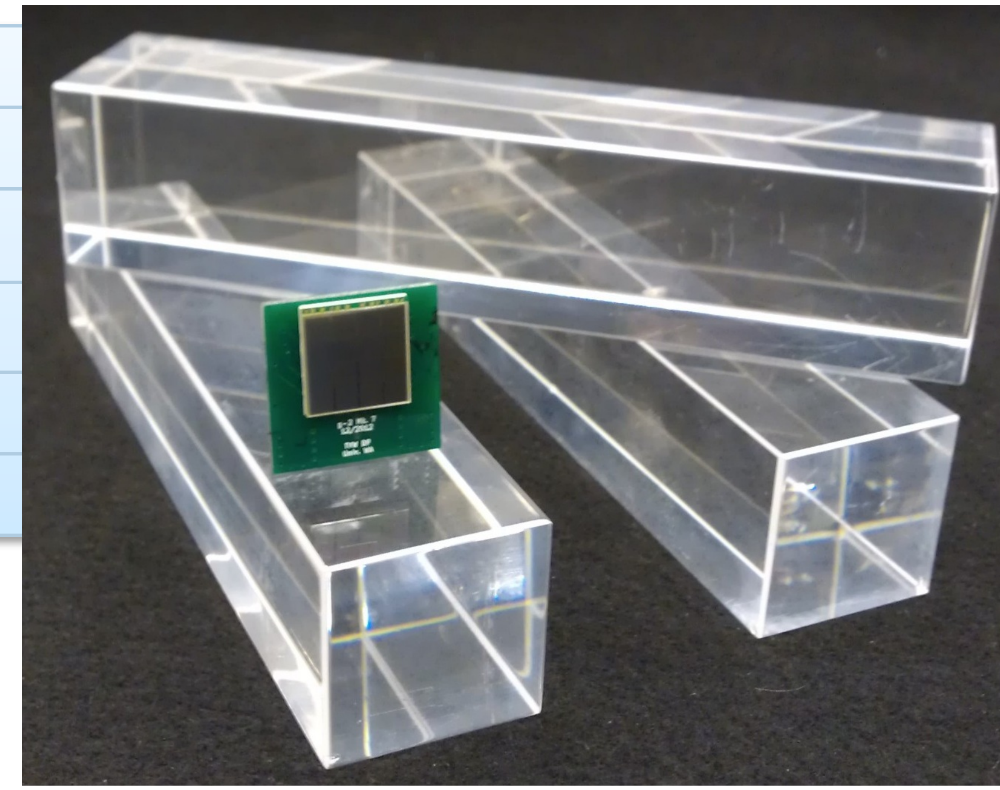
  Phys. Rev. D 80, 052008 (2009)

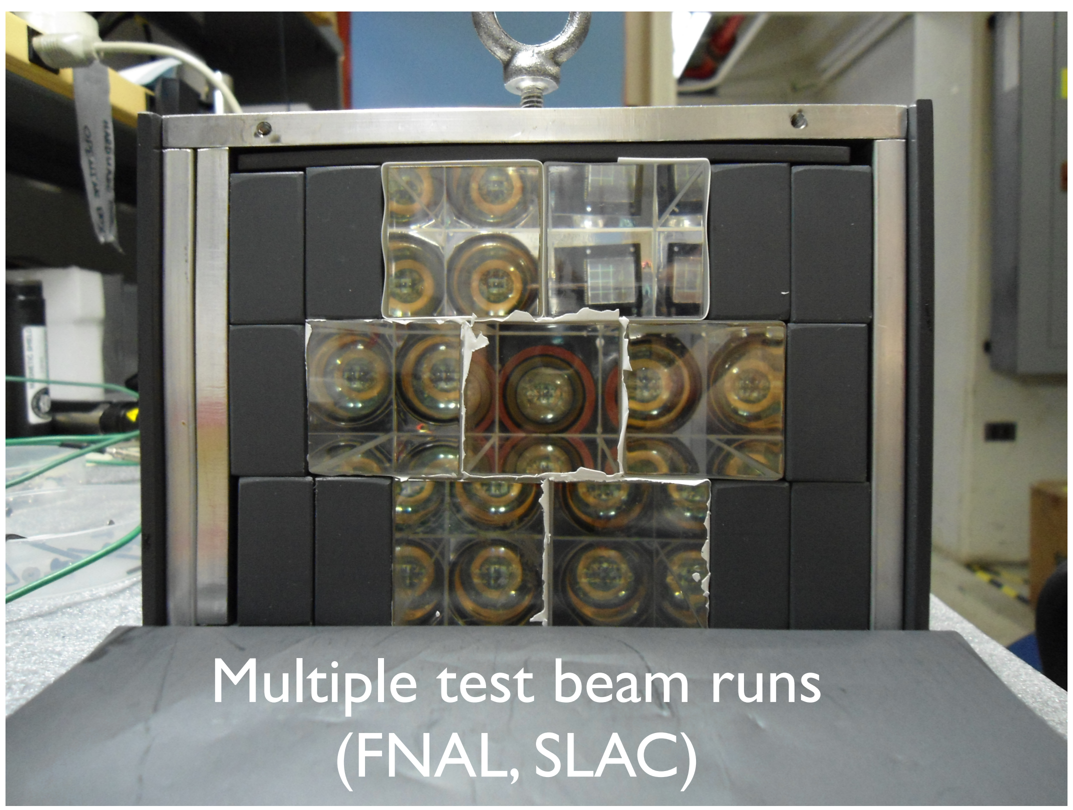
- Goal is order of magnitude improvement

NIU g-2 group heavily involved. Future colloquium by Prof. Eads with more on straw trackers.

Calorimeter improvements

Size	2.5 x 2.5 cm
Thickness	14 cm (> 15 X_0)
Segmentation	6 x 9
Radiation length	0.93 cm
Moliere radius R_M	2.2 cm
Moliere radius R_M (Cerenkov)	1.8 cm





Multiple test beam runs (FNAL, SLAC)

- Much greater segmentation
- Dense medium (PbF_2)
- SiPM readout operates in fringe field
  - waveform fully digitized
- Needs stable bias voltage

from D. Kawall,
UMass Amherst

E821/E989 Absolute Calibration Probe

- Have probe calibrated in terms of free proton frequency at level of 34 ppb by LANL E1054 (muonium hyperfine experiment)
- Details of probe in X. Fei *et al.*, Nucl. Instr. Meth. A **394**, 349 (1997).
- BNL E821 had 50 ppb accuracy (due in part to temperature uncertainties)

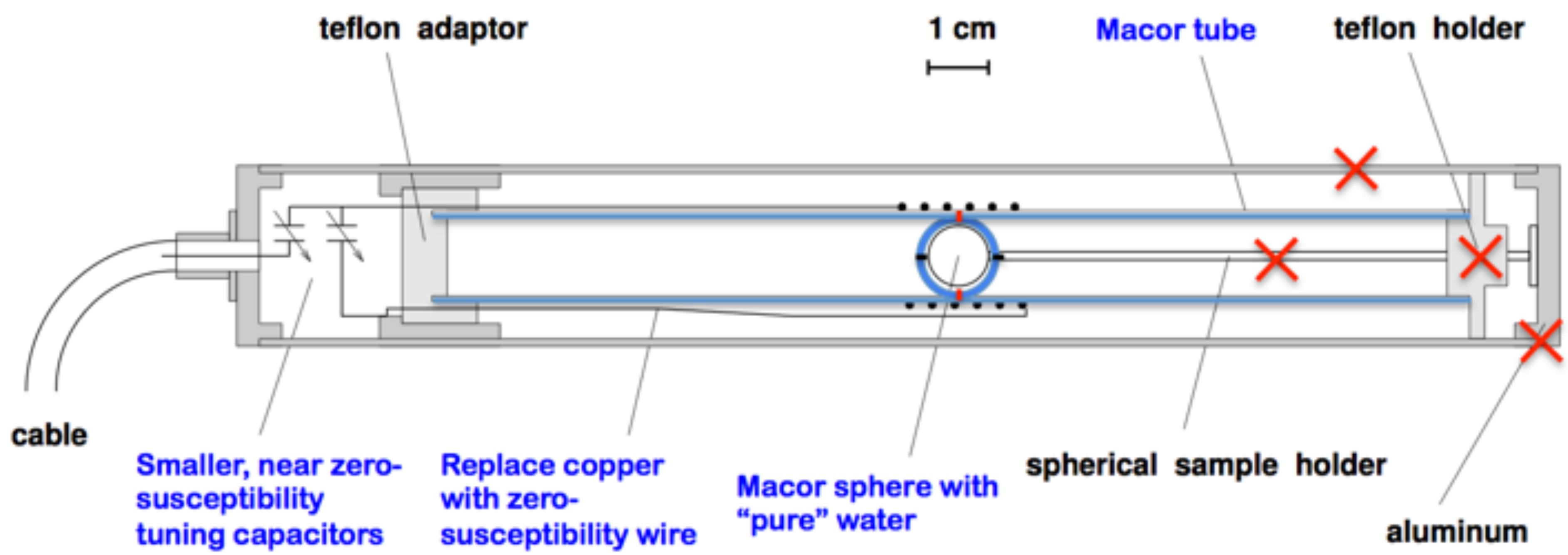
Source of error	Uncertainty
NMR detection and measurement	1.5×10^{-8}
Field homogeneity	1.0×10^{-8}
Materials outside the probe	1.5×10^{-8}
Water/sample holder shape	1.5×10^{-8}
Probe materials	1.0×10^{-8}
Diamagnetic shielding (H_2O)	1.4×10^{-8}
Temperature effect	1.0×10^{-8}
Total:	3.4×10^{-8}

- We will use the existing absolute calibration probe, develop a 2nd probe
- Will repeat E1054 calibration studies in MRI solenoid at Argonne at 1.45 T in 2015
- Develop thermal enclosure, probe platform with minimal influence on measurements
- Reduce calibration uncertainty from 50 ppb in E821 to 35 ppb

from D. Kawall, UMass Amherst

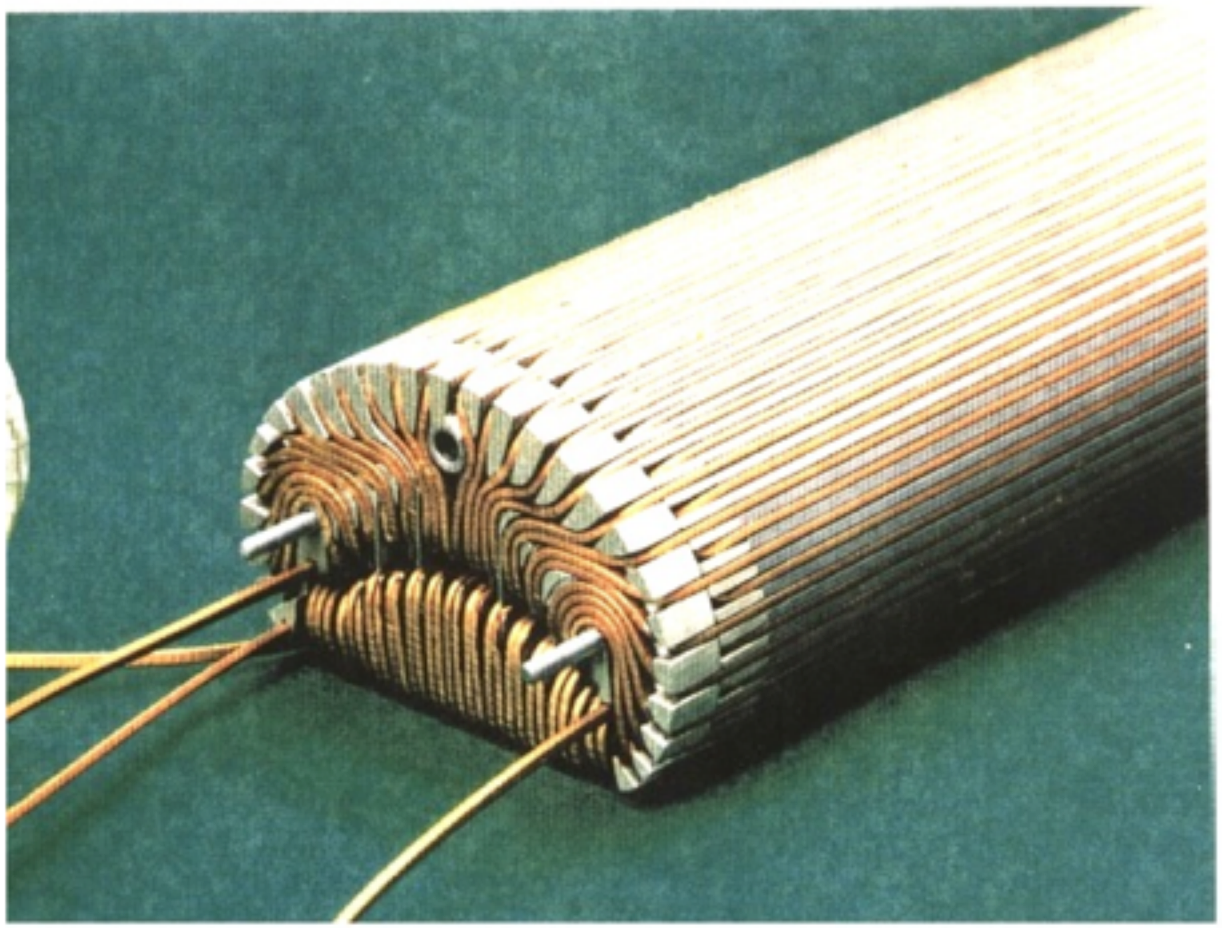
Development of Second Absolute Calibration Probe

- Second probe will provide redundancy, a cross-check, lower systematic uncertainties
- New probe spherical sample holder from machined Macor (mica+borosilicate glass) hemi-spheres 1 mm thick

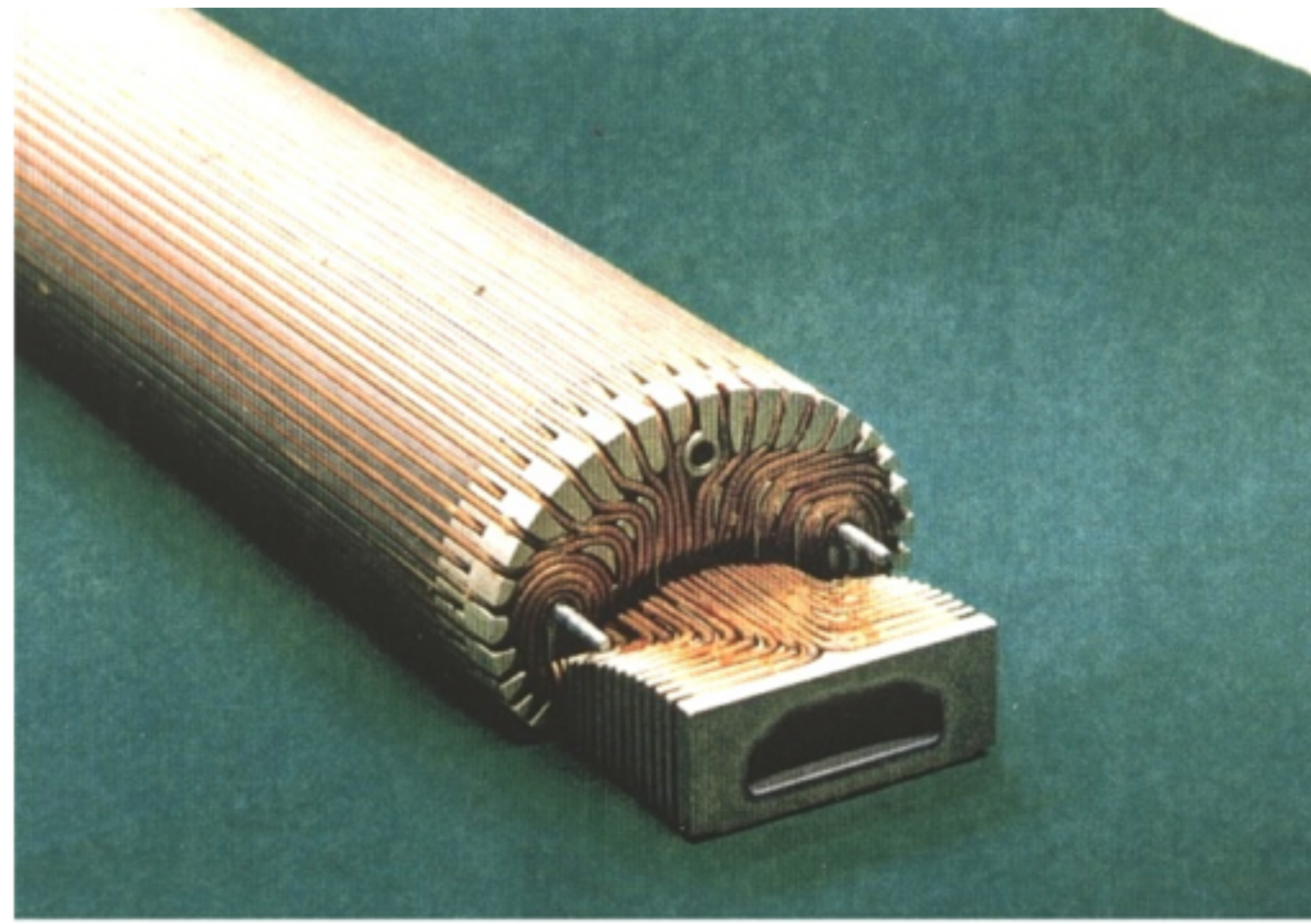


- Eliminate/use zero-susceptibility combination of Al and Cu for shell, reduces δ_s and image effects
- Zero-susceptibility coil wire (Doty Scientific) will reduce δ_s and image effects
- More spherical water sample, no stem which leads to asymmetric NMR line
- Smaller, near-zero suceptibility tunable capacitors
- Homogeneity of RF field ($> 90\%$) by non-uniform coil winding

Closed vs. open inflector



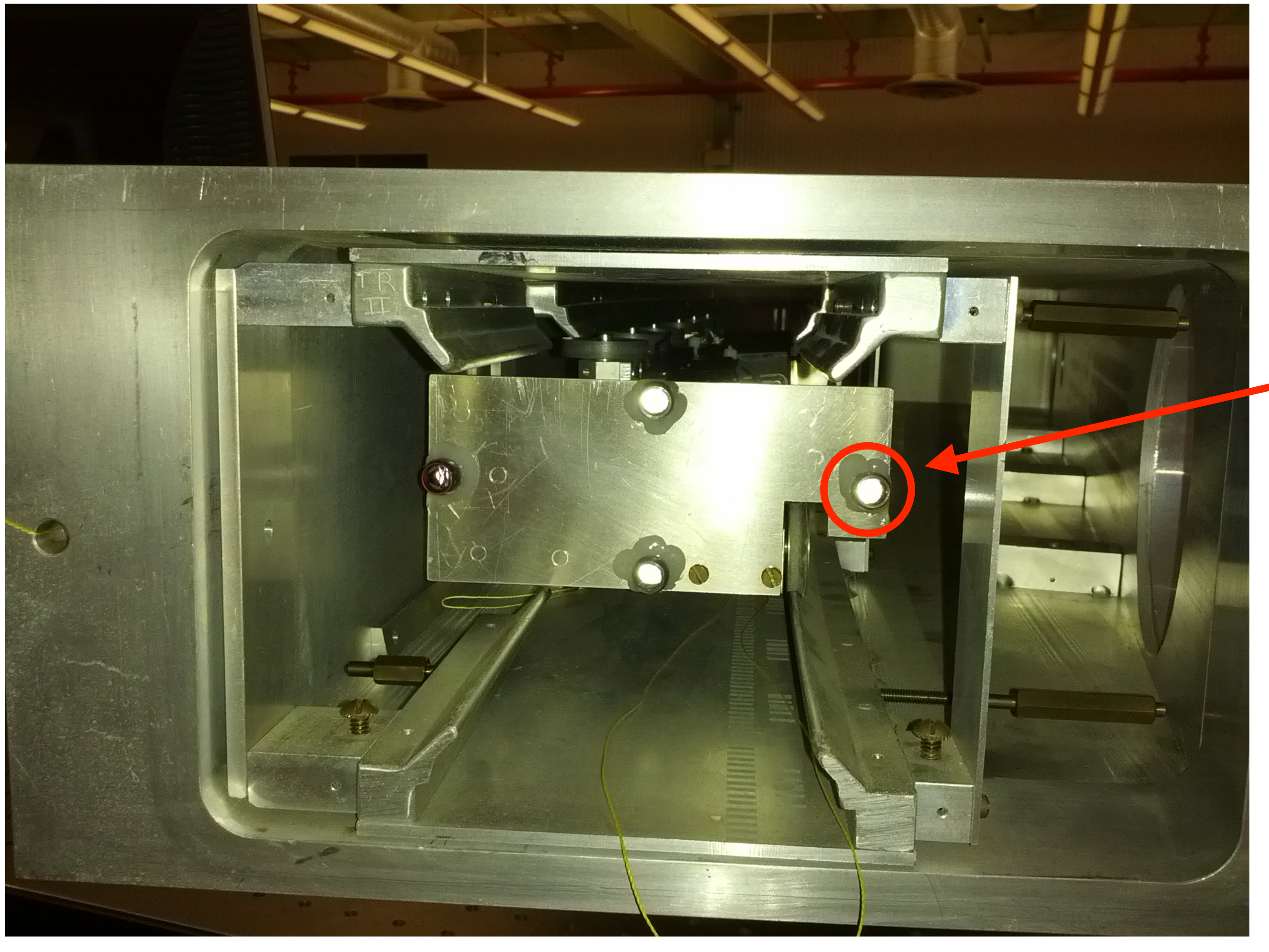
(a) Closed Inflector End



(b) Open Inflector End

Trolley position uncertainty: transverse

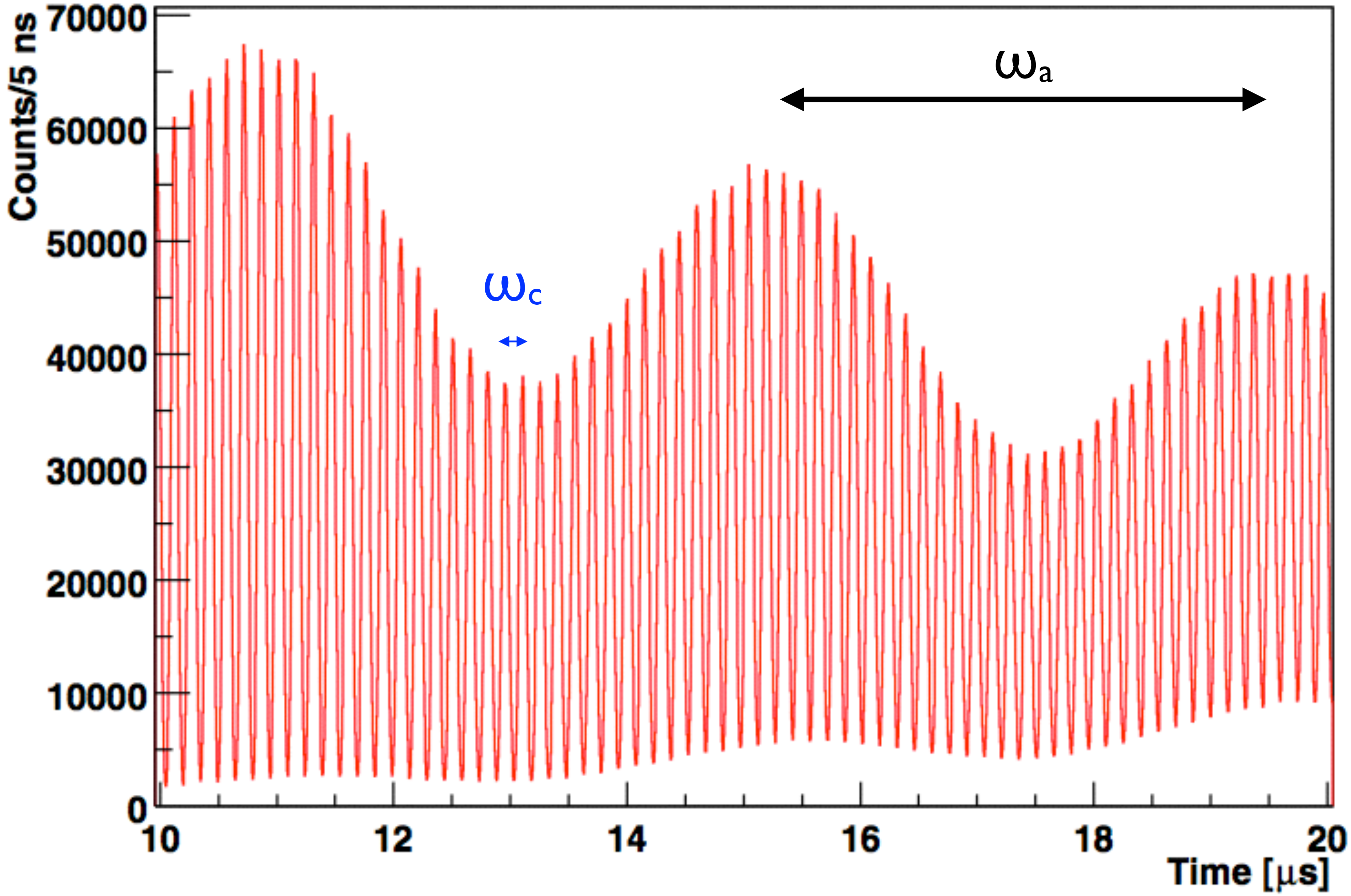
- Solution for FNAL: better field homogeneity and measure rail "swimming" with laser system
  - could make correction



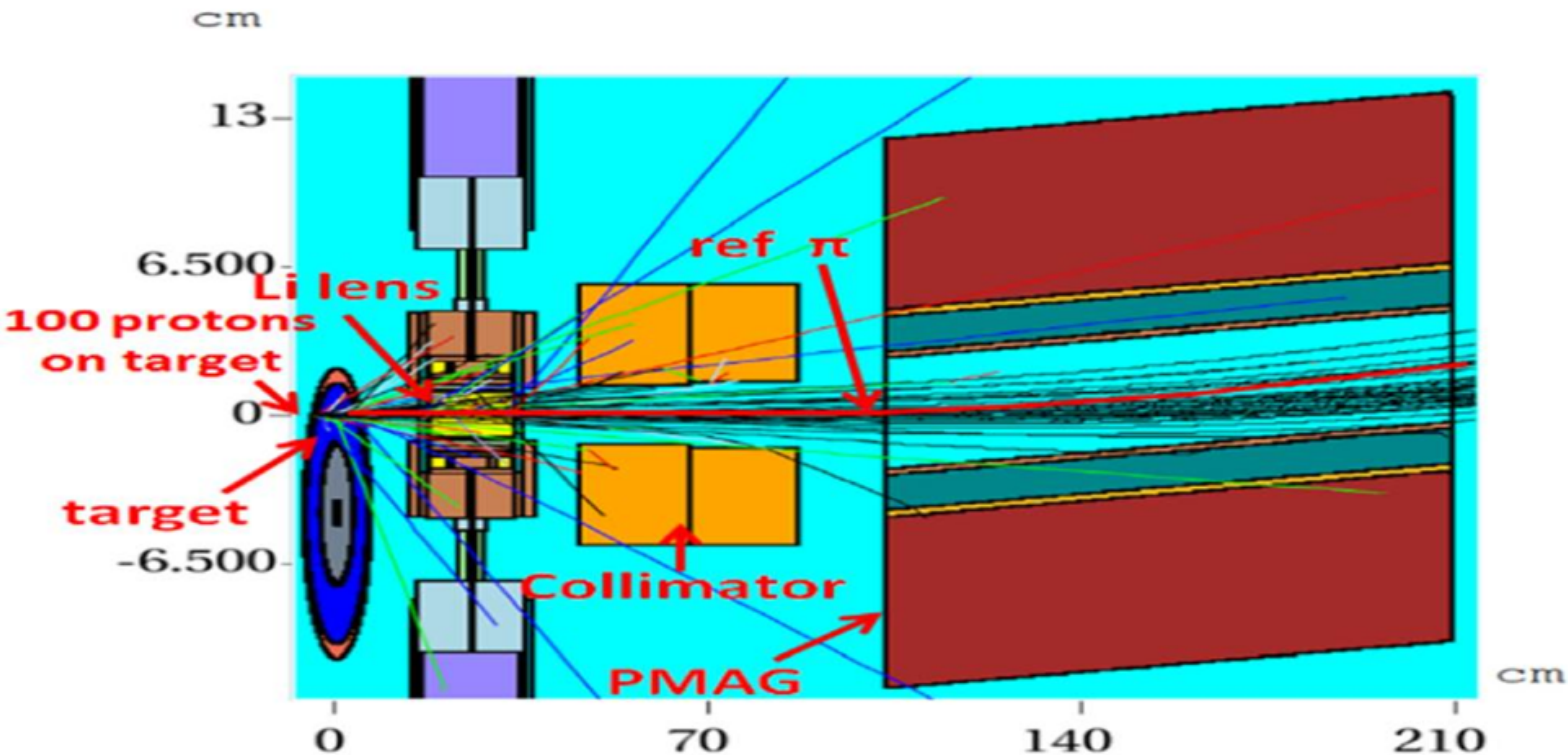
4 reflecting spheres mounted on alternate trolley, laser system tracks their passage through each rail system

- For *in situ* measurements, in special runs we will introduce known transverse gradients, compare trolley measurements to expectation

Counts from a single calorimeter

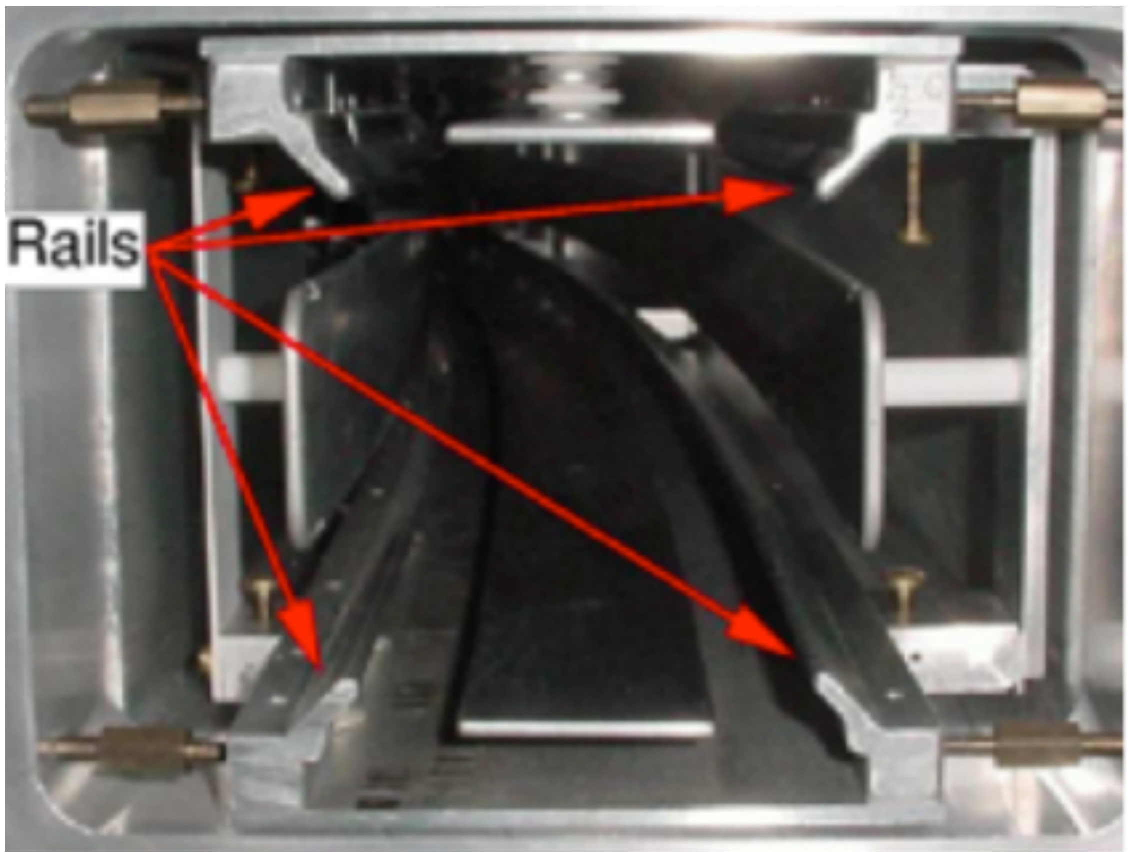


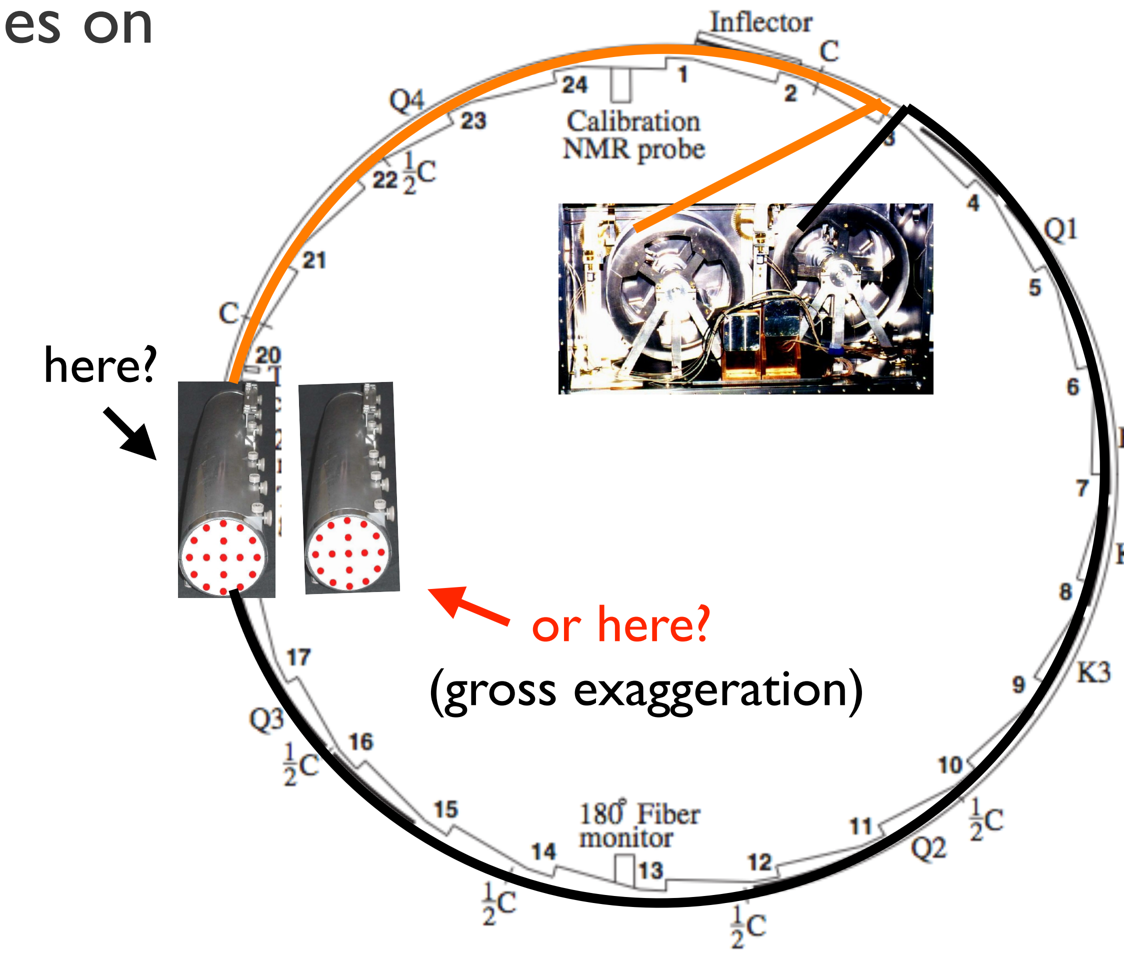
Production target



Trolley position uncertainty: transverse

- Transverse position defined by rails the trolley rides on





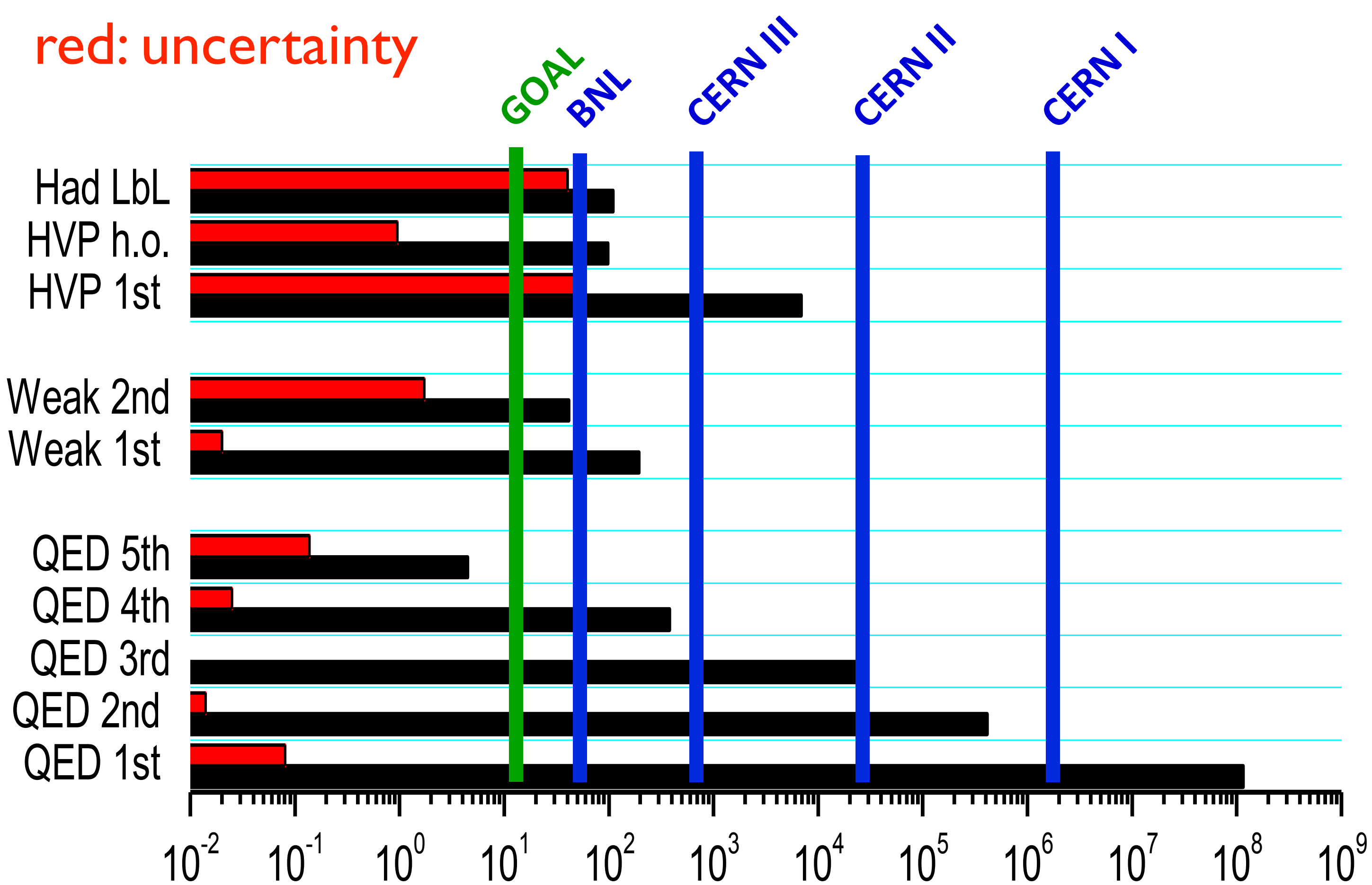
- Rail "swimming" back and forth can combine with transverse gradients such that the trolley measures the "wrong field"

- Solution for FNAL: better field homogeneity and measure rail "swimming" with laser system

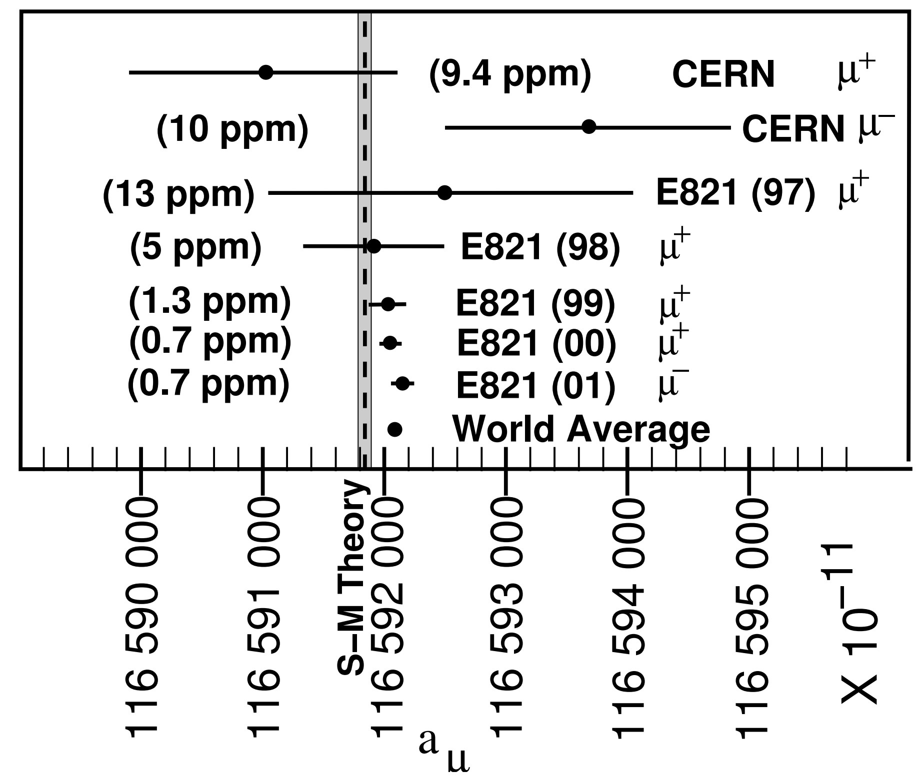
History of experimental value

- In last 60 years, technology advancements has afforded enormous progress in experimentally accessing these interactions
- Each measurement gained sensitivity to additional interaction types

black: contribution
red: uncertainty



a_μ in units of $10^{-11} \equiv \frac{g-2}{2}$

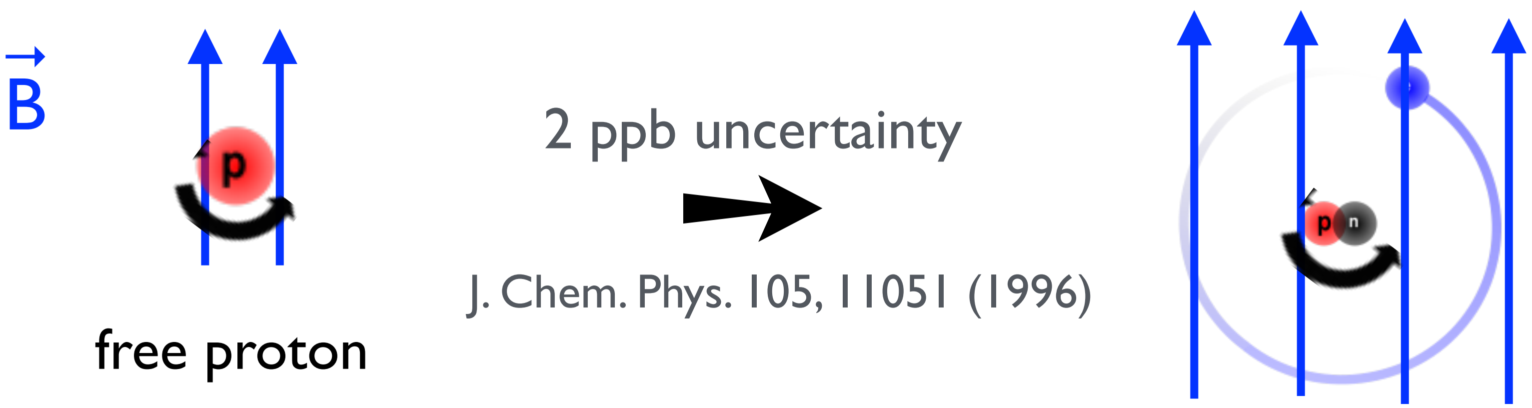


Brookhaven '04 measurement first to find robust discrepancy with SM value of ~3.6σ

$\sigma(H_20)$ (diamagnetic shift, “electron screening”)

- Bootstrap semi-empirical quantum calculation of $\sigma(H_2)$ to measure $\sigma(H_20)$

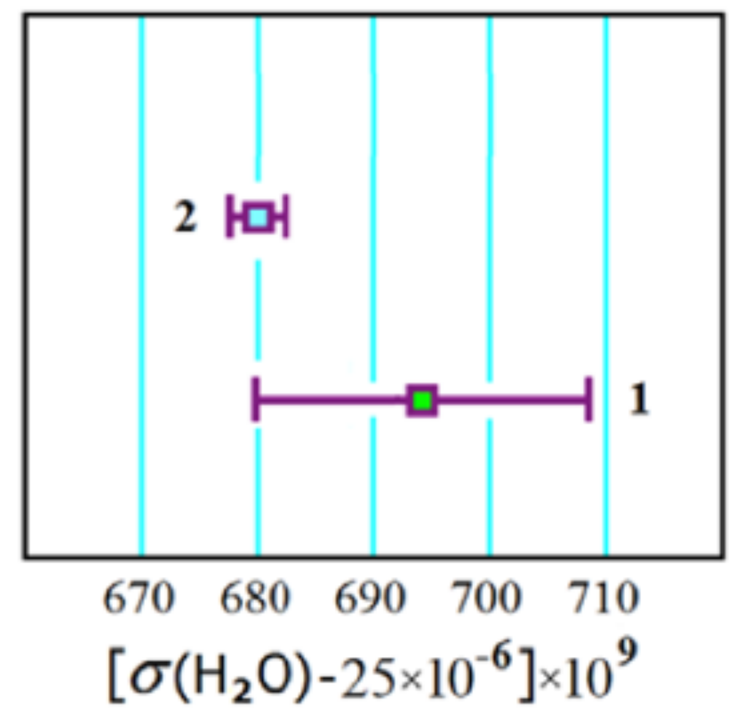
calculation



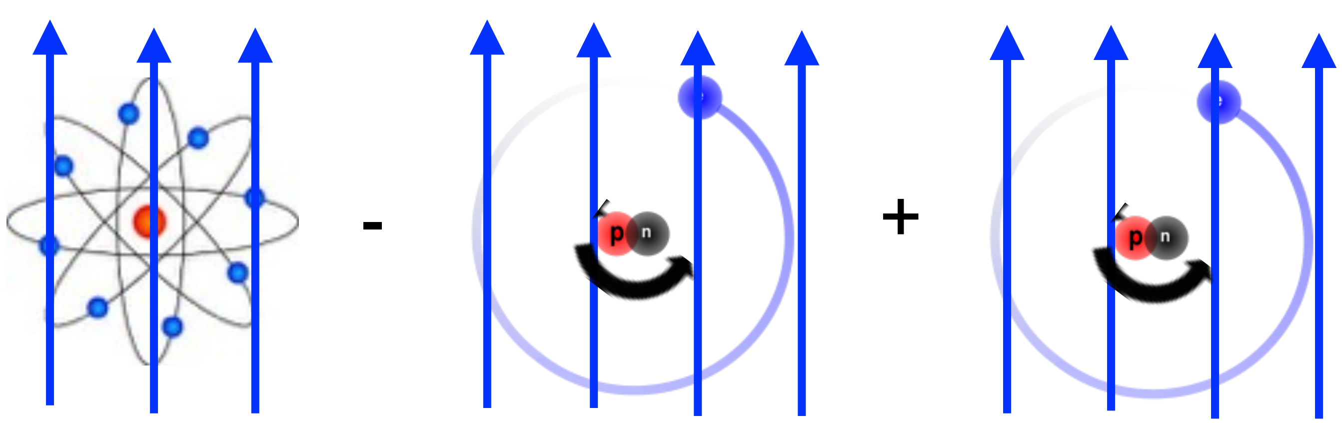
free proton
ω_p

deuterium
$\omega_p\,[1-\sigma(H_2)]$

Metrologia **51** (2014) 54–60



difference measurement | **calculation**



water
$\omega_p[1-\sigma(H_20)]$

deuterium
$\omega_p\,[1-\sigma(H_2)]$

deuterium
$\omega_p\,[1-\sigma(H_2)]$

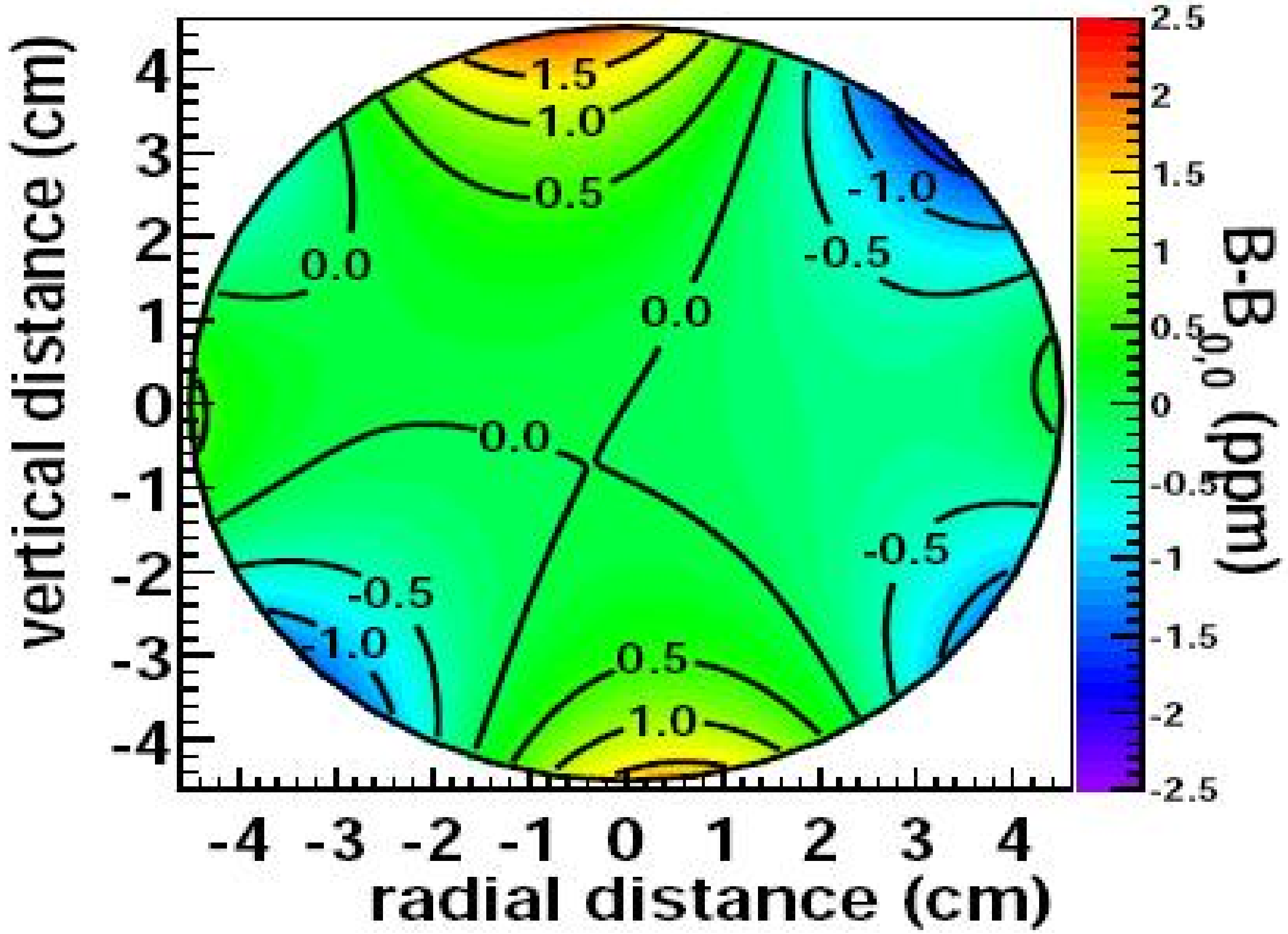
Metrologia **51** (2014) 54–60

→ $\sigma(H_20)$ = 25.6 ppm ± 2.5 ppb

Previous measurement:
different approach, agrees

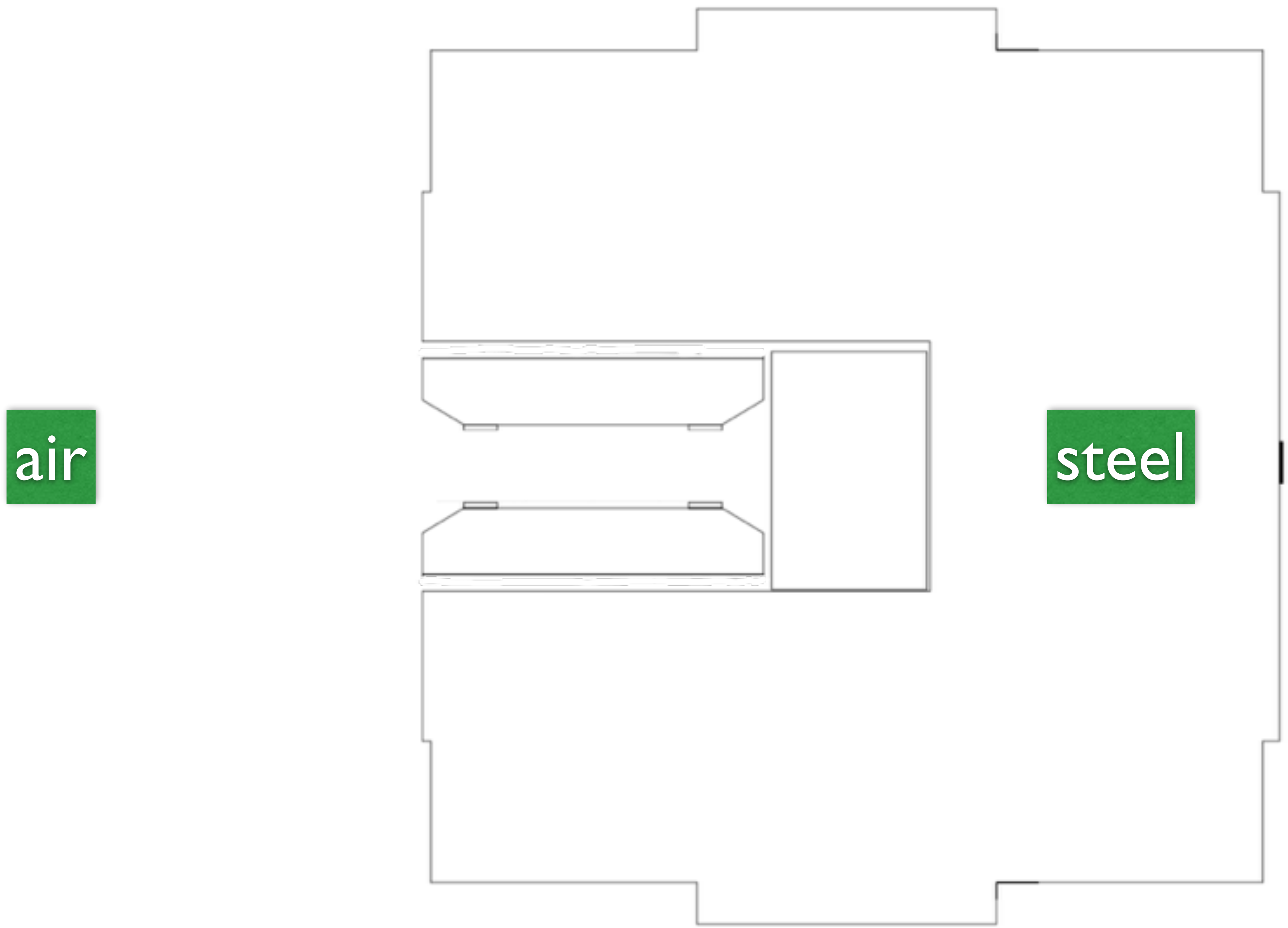
Magnetic field

- Challenge is to measure field *experienced by the muons* to 70 ppb. Enormously challenging. Many many systematic effects enter. Our best tool to reduce their effect is to make the field as homogeneous as possible.

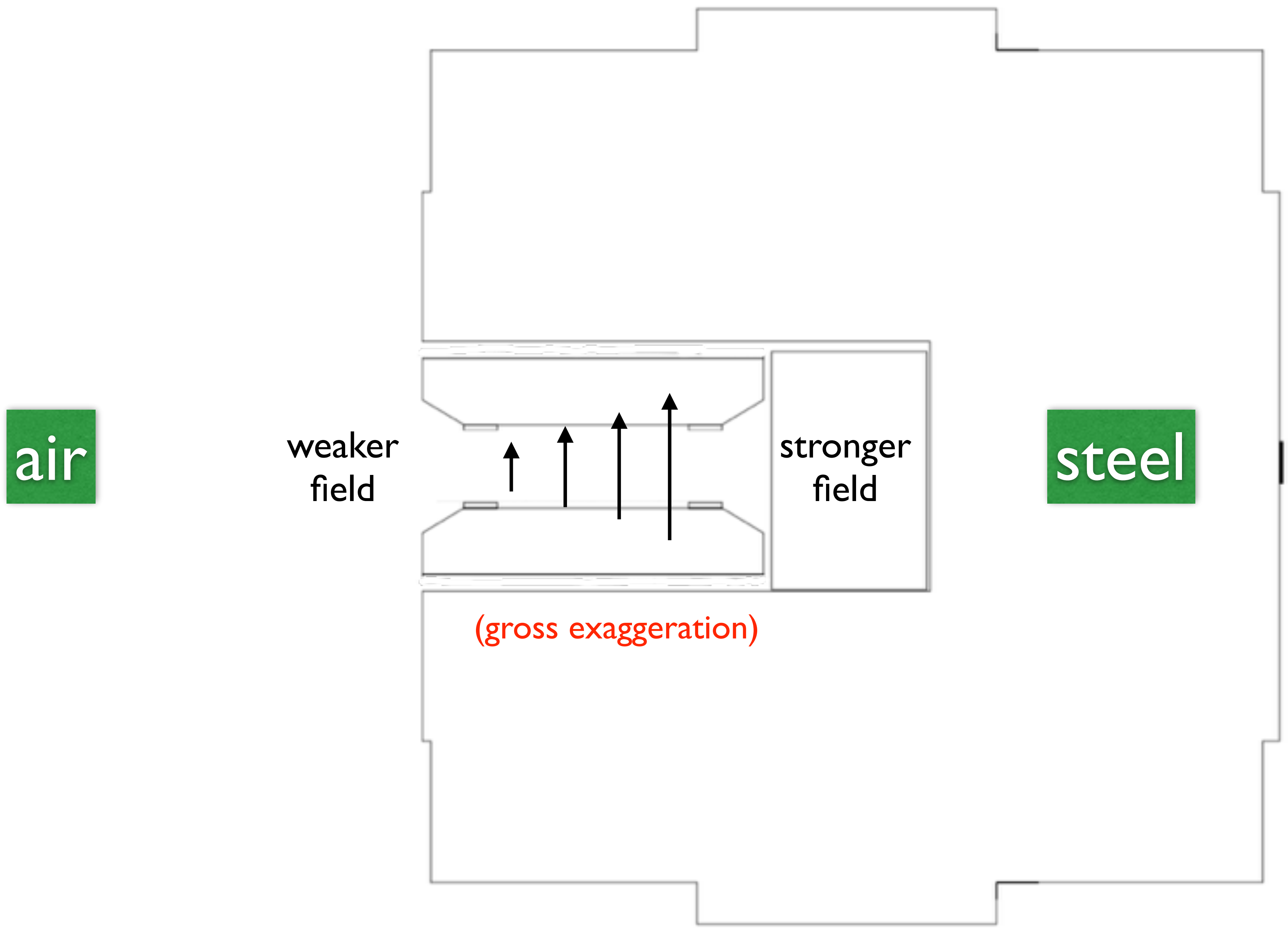


Azimuthally-averaged magnetic field achieved in BNL g-2

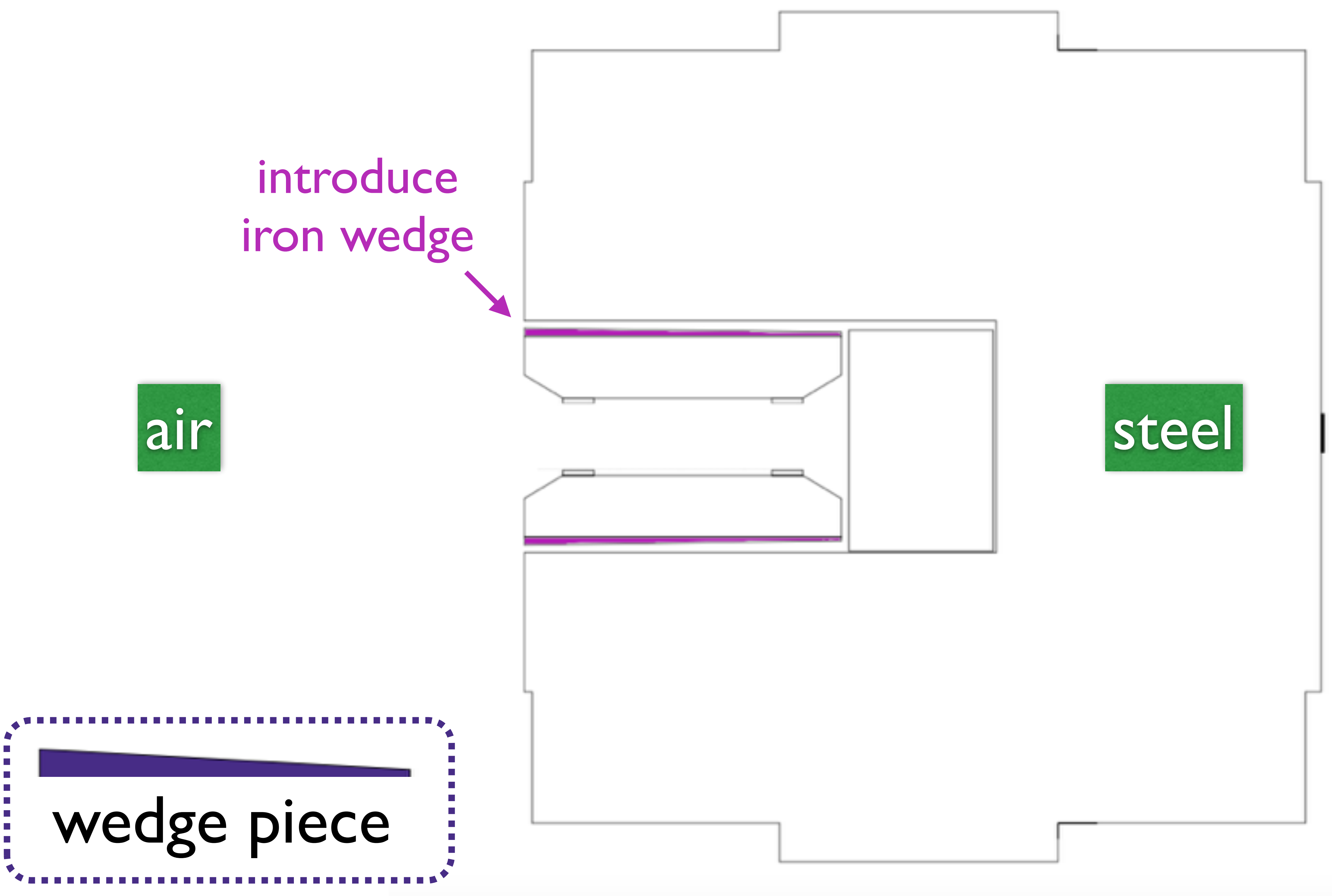
Passive shimming



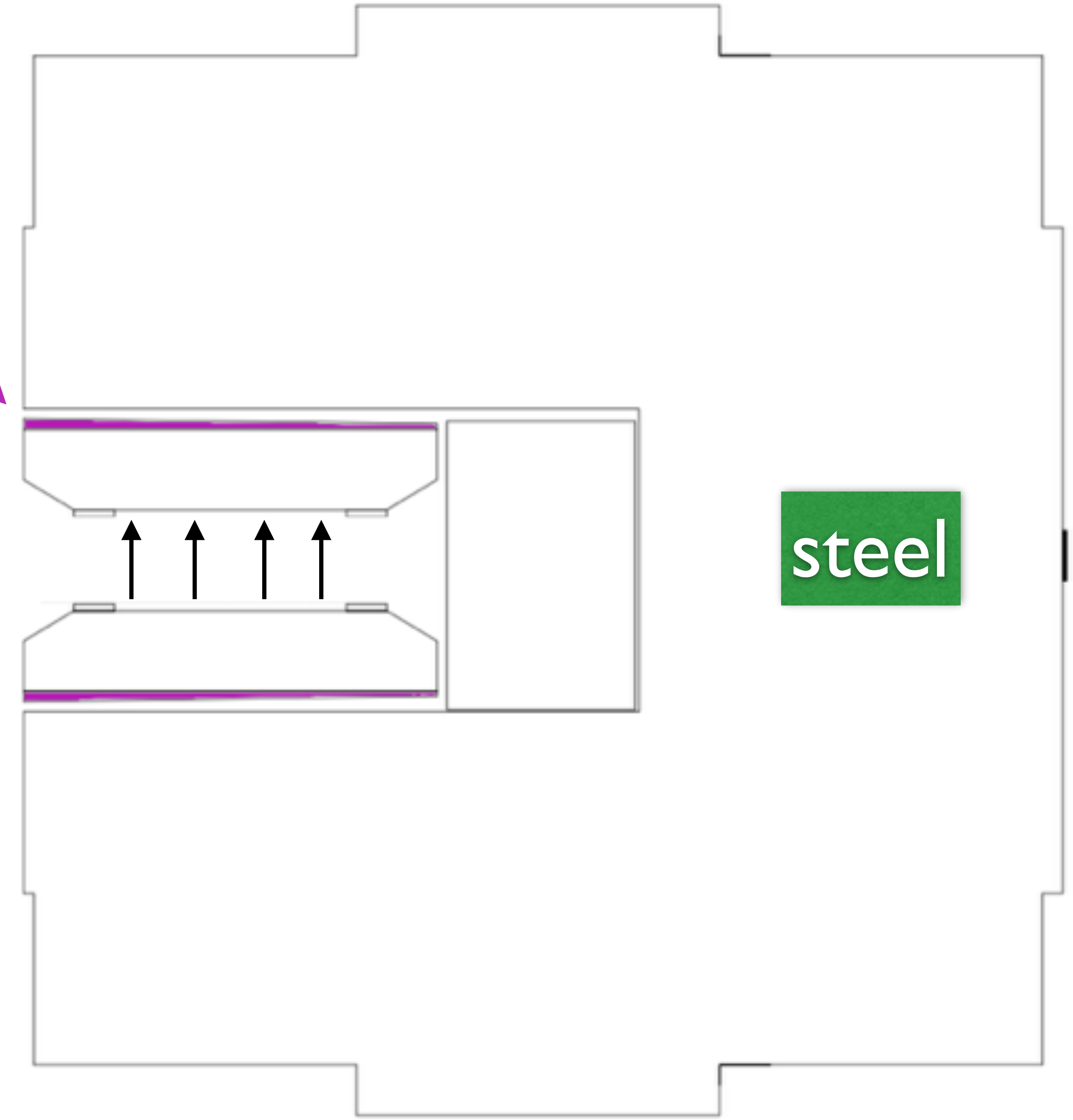
Passive shimming



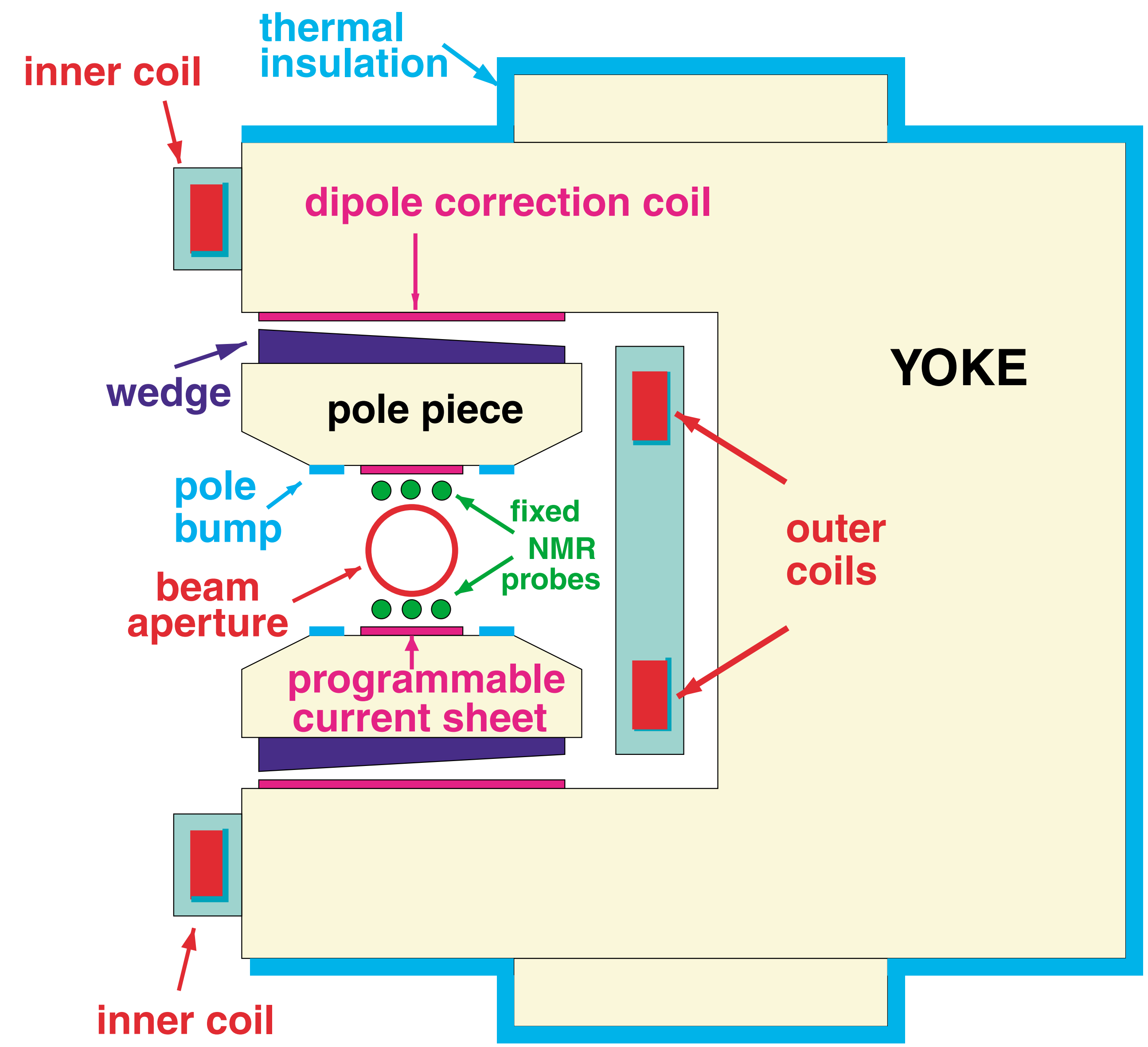
Passive shimming



Passive shimming



Magnetic field

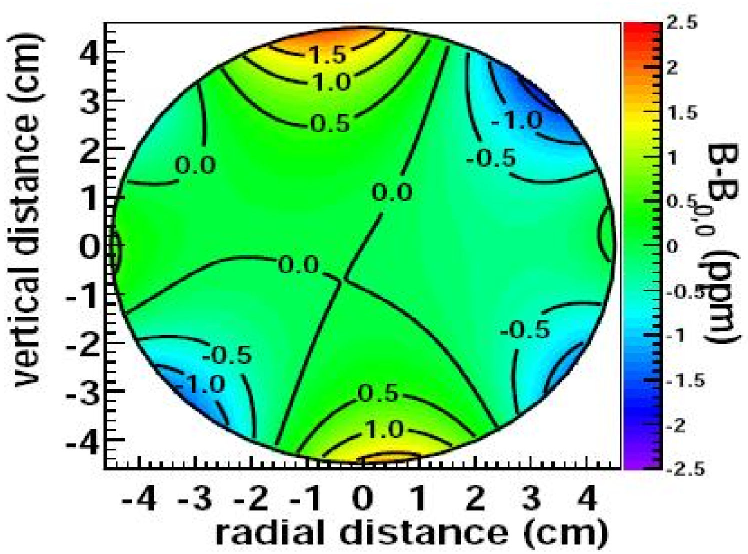


Magnetic field

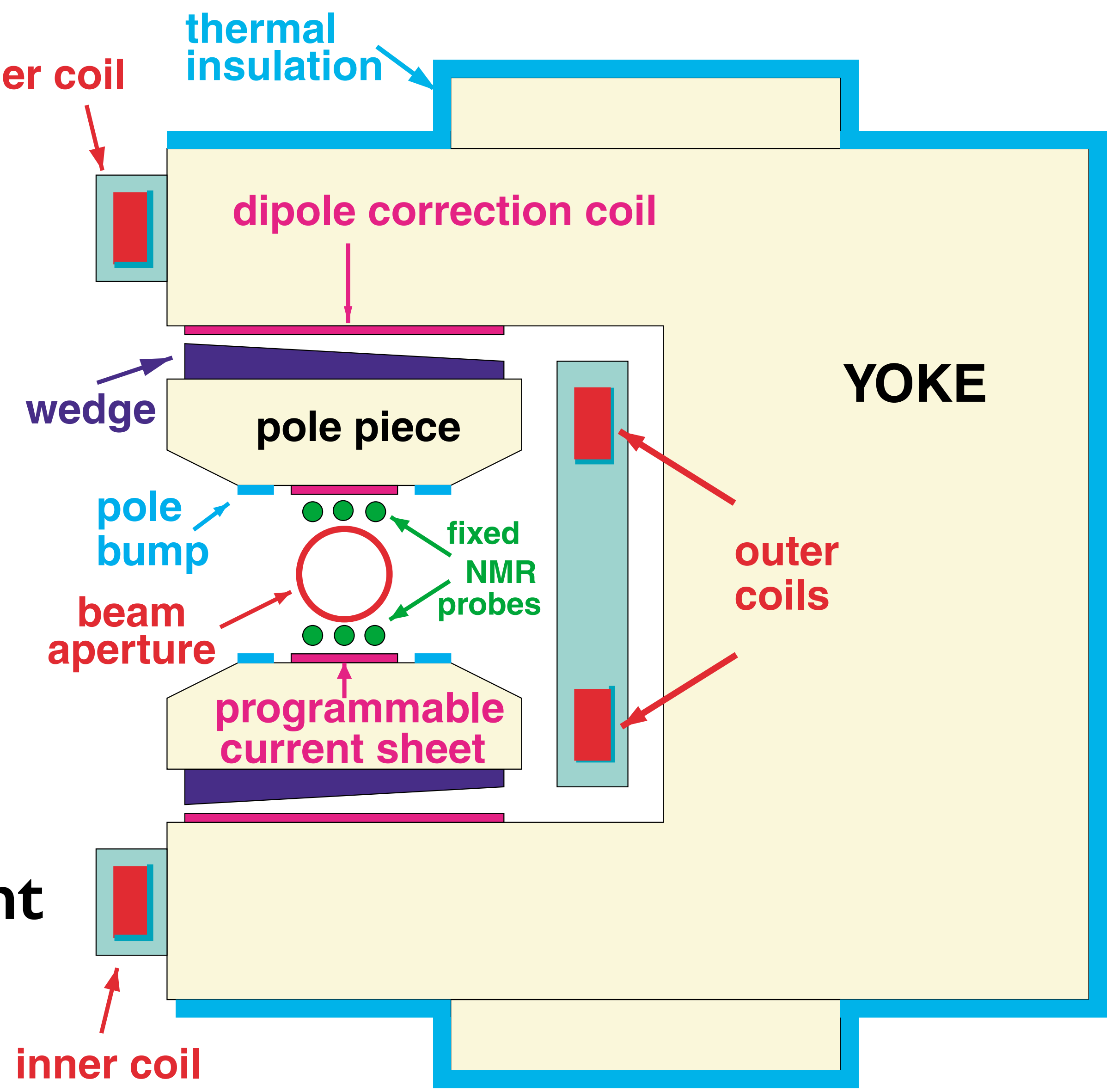
- Many more passive and active tools that control strength of various multipoles

Passive shims
- Iron wedges
- Pole tilt
- Iron pole bumps
- Thermal insulation

Active shims
- Dipole correction coils
- Surface correction coils



FNAL g-2 goal is x2 improvement in homogeneity



Why study *muon* g-2?

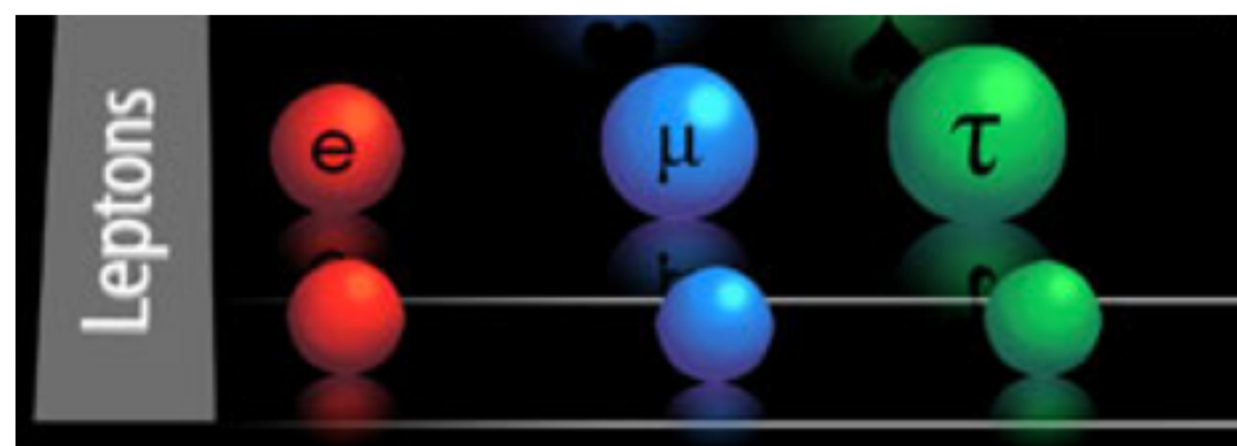
- Electron:

$$\delta(a_\mu)^{\text{expt}} = 540\,\text{pp}\underline{\text{b}};\quad \delta(a_e)^{\text{expt}} = 240\,\text{pp}\underline{\text{t}}$$

Phys. Rev. Lett. **100**, 120801 (2008)

  - relative sensitivity to heavy physics couples with the squared mass of the probe
    - $(m_\mu/m_e)^2 \sim 10^4$
  - example: EW contributes 1.3 ppm to a_μ (observable), 26 ppt to a_e (still invisible)

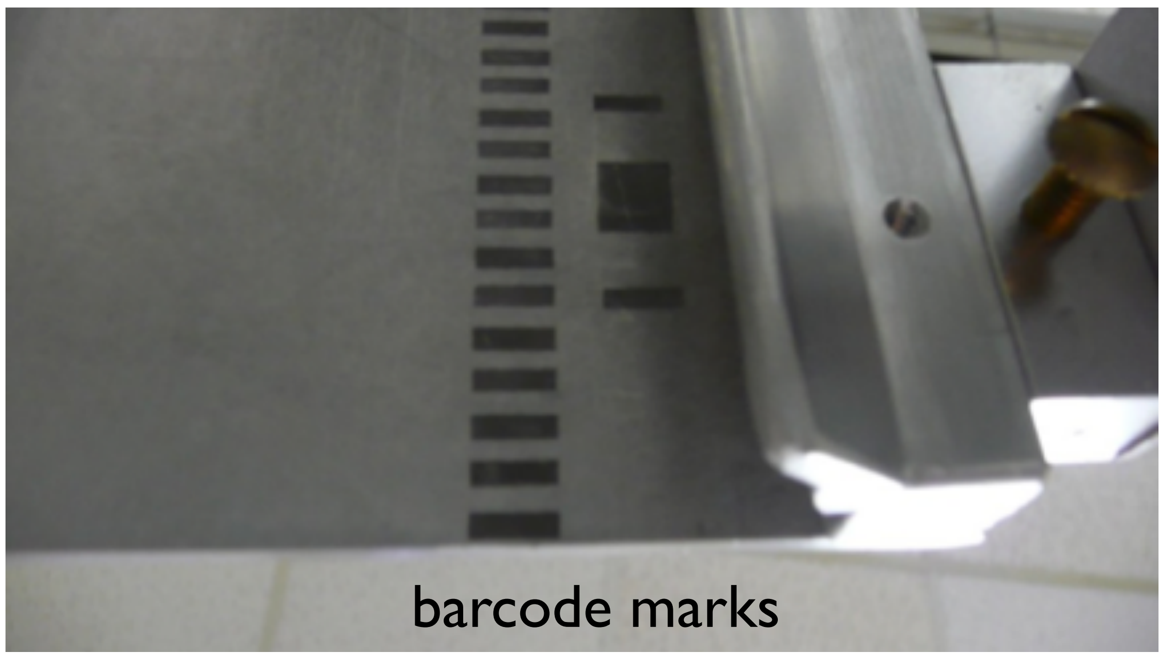
- Tau:
  - For same *g*-2 uncertainty, tau is a better probe of heavy physics
  - Experimentally untenable:
    - Low production cross section in accelerator environment
    - Rapid lifetime (10^{-13} s)
    - a_τ^{exp} still consistent with zero!



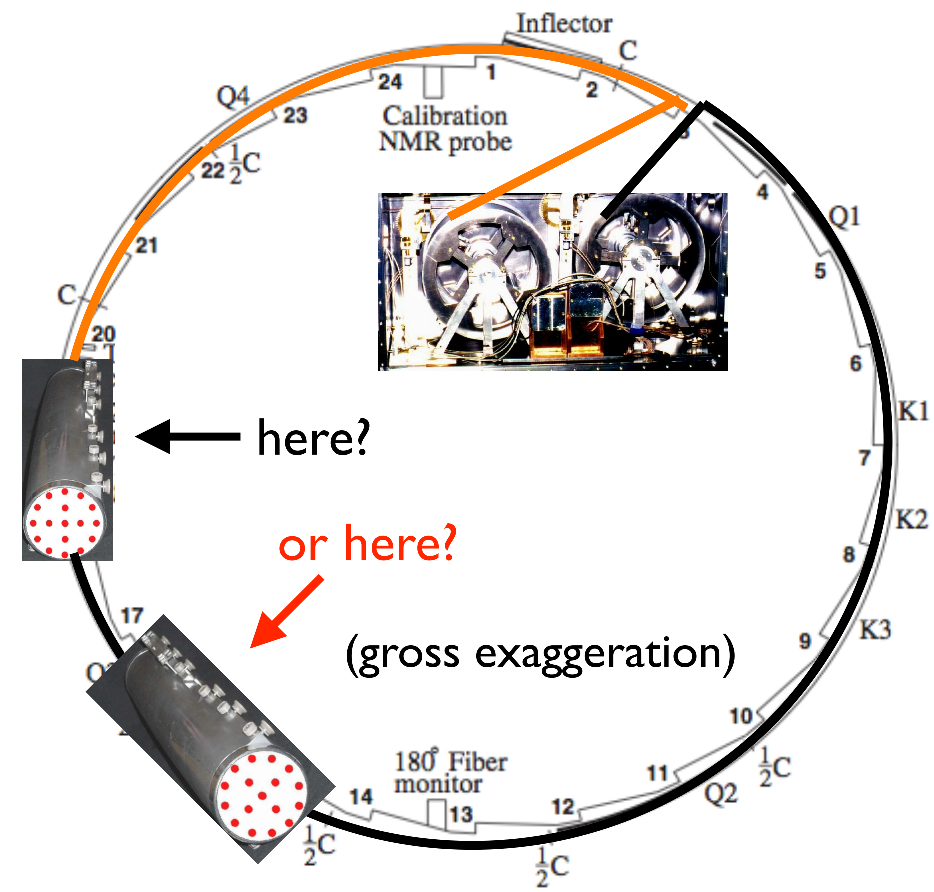
⇒ **The μ is an ideal probe**

Trolley position uncertainty

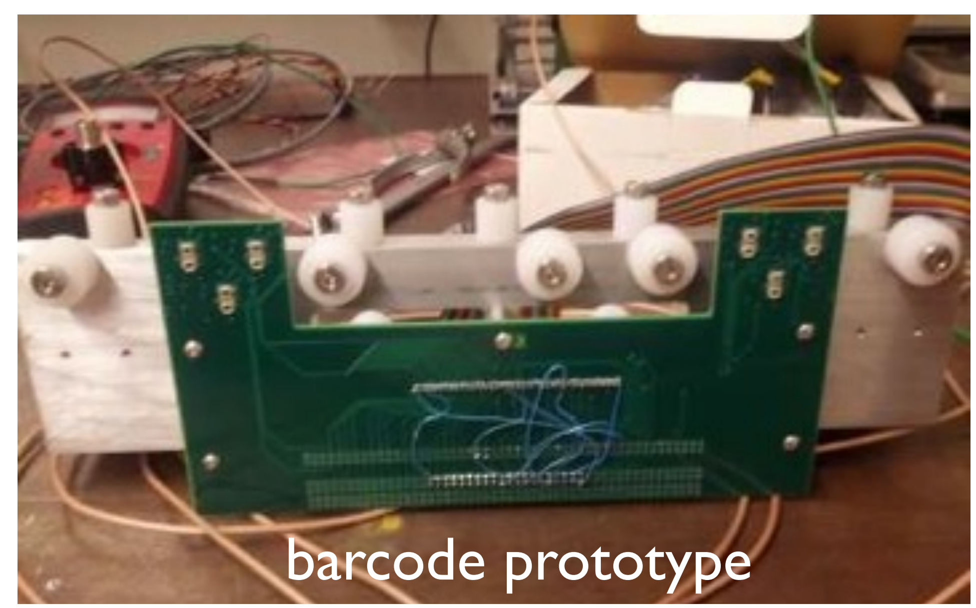
- Cable-pulling geometry resulted in non-linearites between trolley position and read-out



barcode marks



- Improvements for FNAL: better field homogeneity, realize barcode reader
  - existing marks yield ~2mm longitudinal position resolution



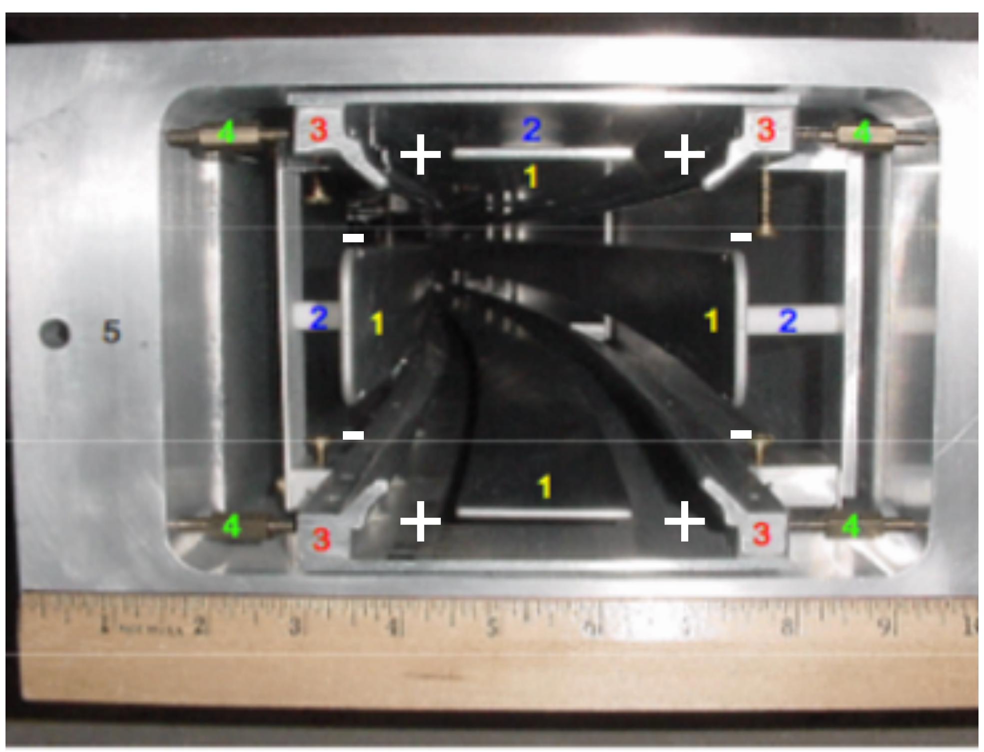
barcode prototype

Focusing quadrupoles

- Static electric field in lab frame $\Longrightarrow$ magnetic field in muon rest frame
  - high sensitivity to E-field, beam dynamics

- Fortunate trick: judicious choice of muon energy
  - pioneered by CERN III (1979)

$$\vec{\omega}_a \equiv \color{red}{\vec{\omega}_s} \color{black}{-} \color{blue}{\vec{\omega}_c} \color{black}{=} \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$



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

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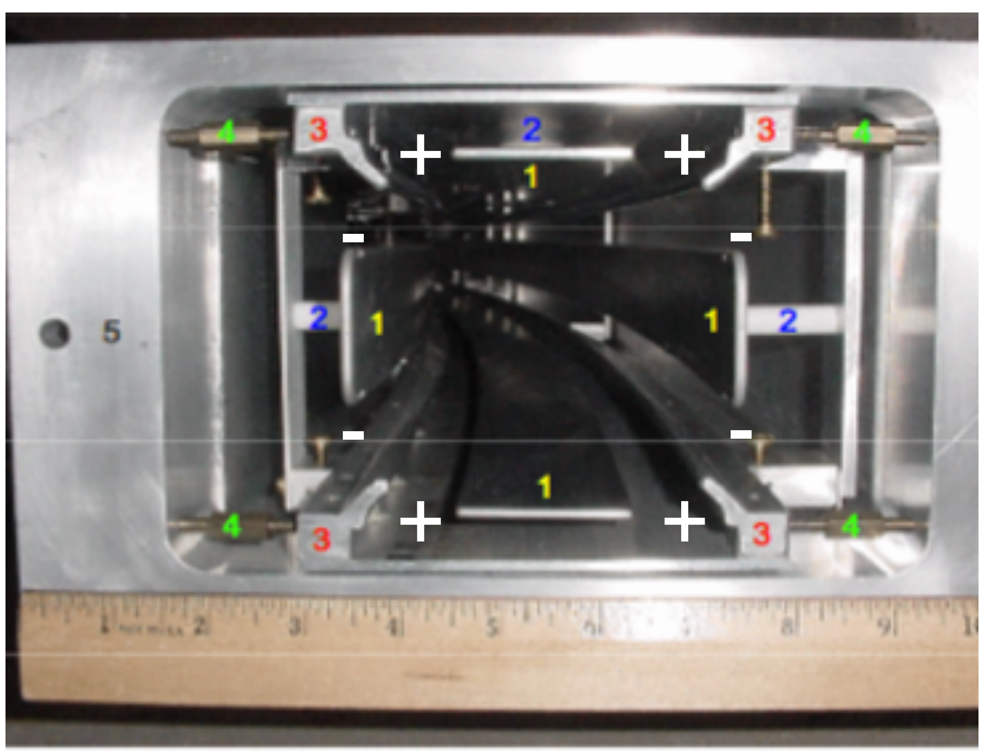
$\emptyset$

for γ = 29.3
finite γ spread
leads to small
correction



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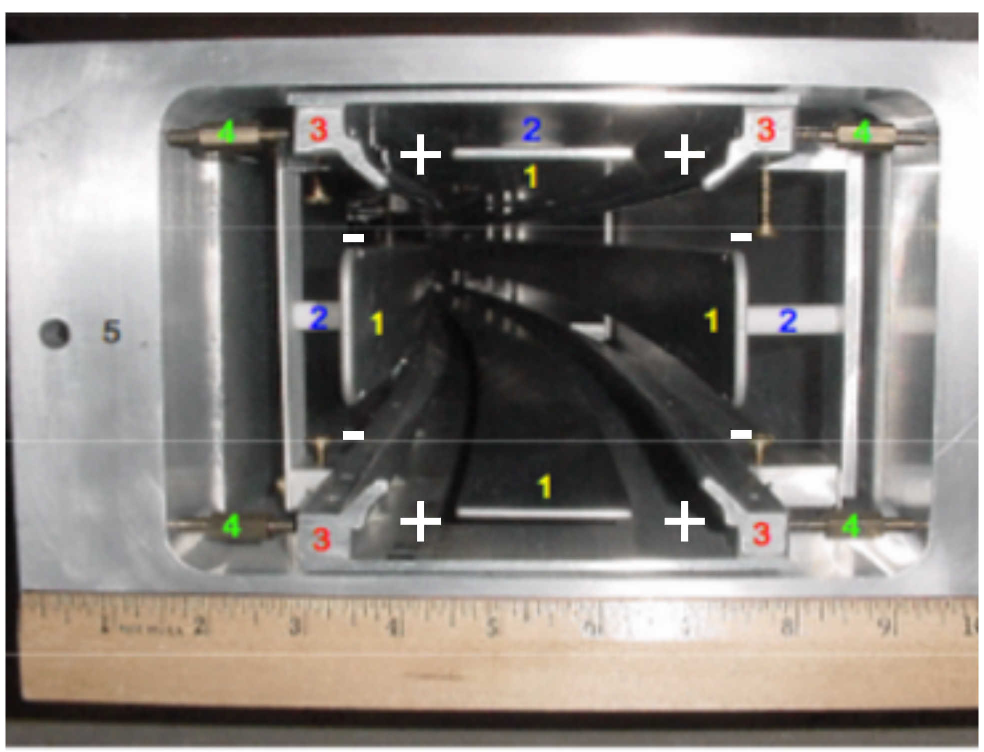
$\emptyset$ — for γ = 29.3 finite γ spread leads to small correction

$\emptyset$ — Aside: JPARC g-2 plans to use 300 MeV muons, low dispersion; no E-field req'd



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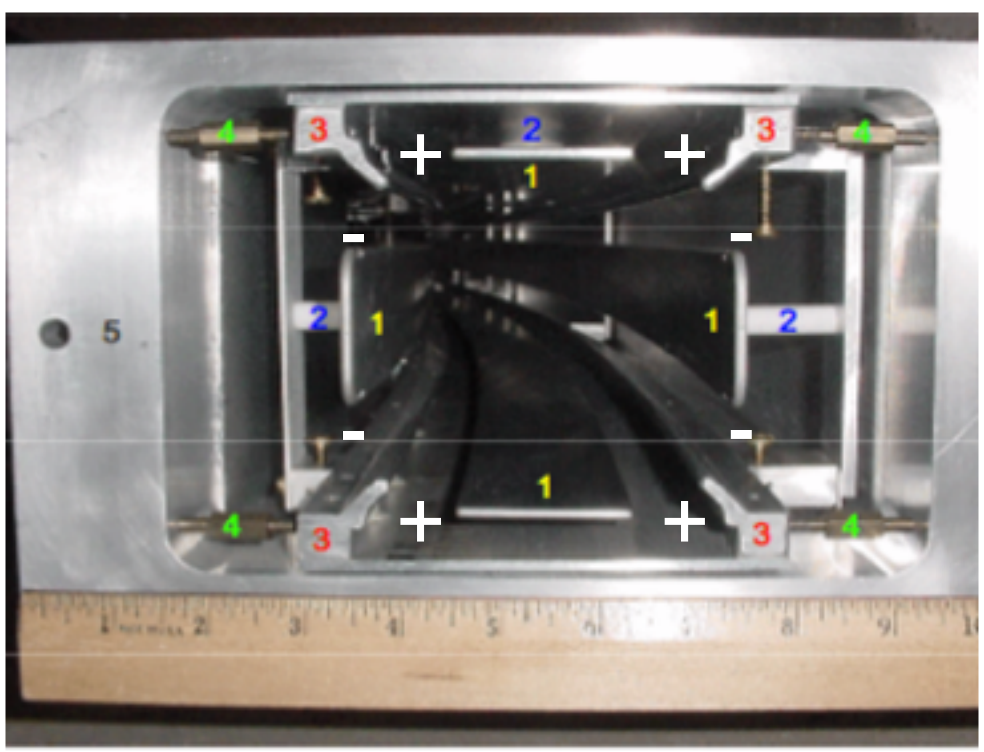

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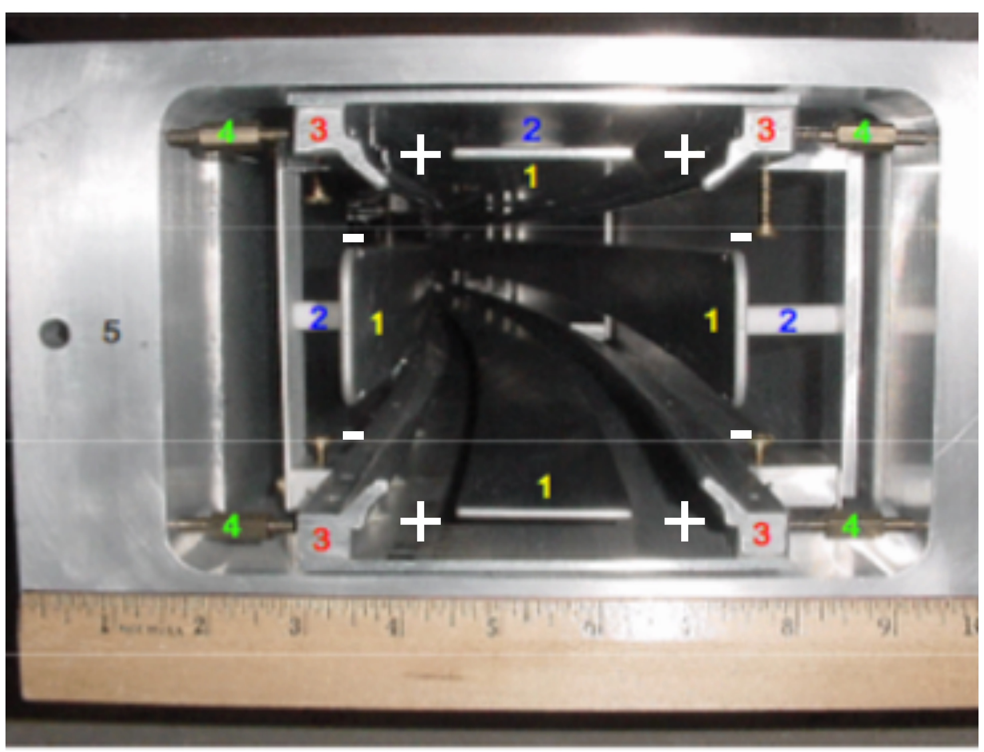
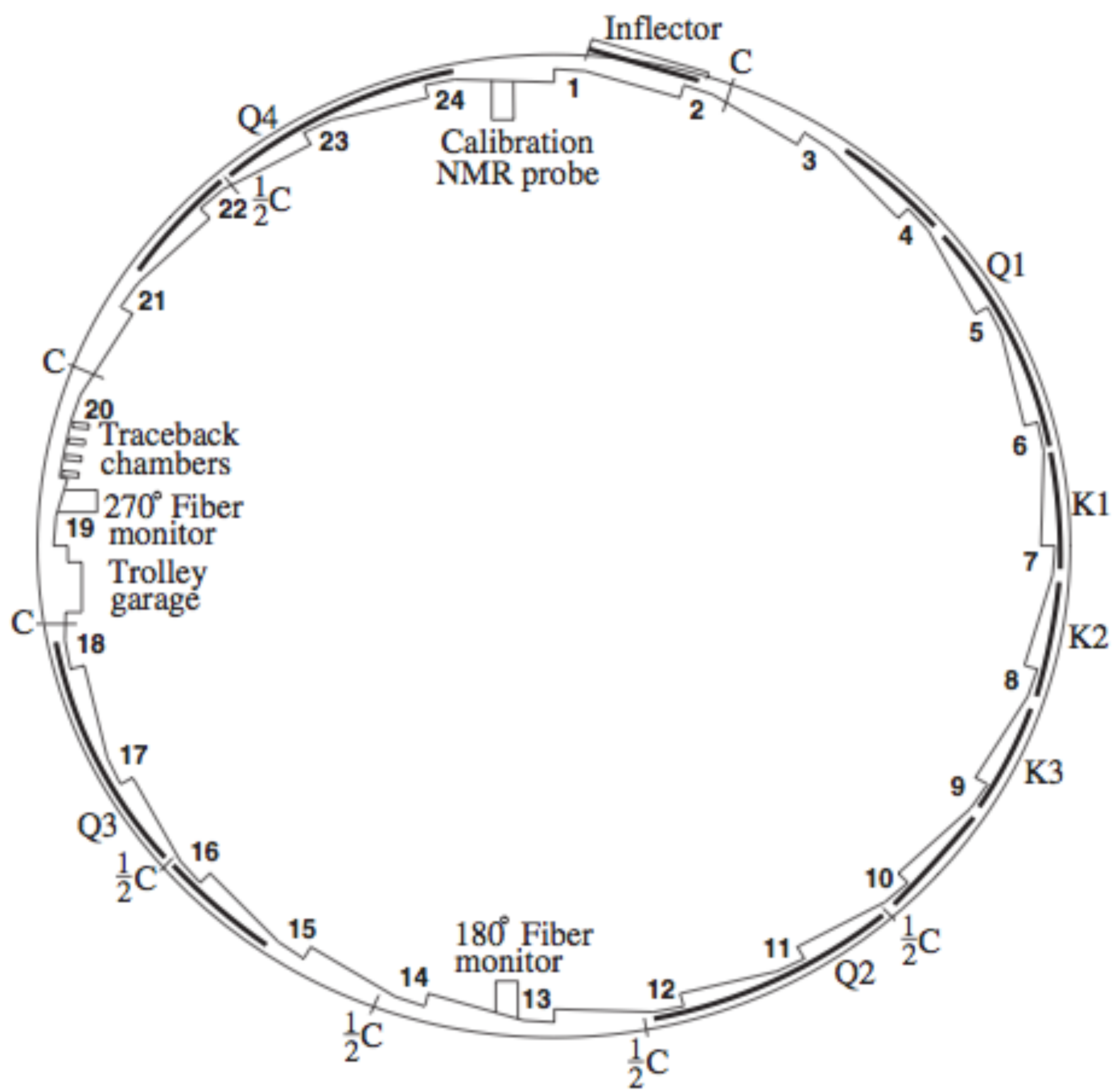
$\emptyset$



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

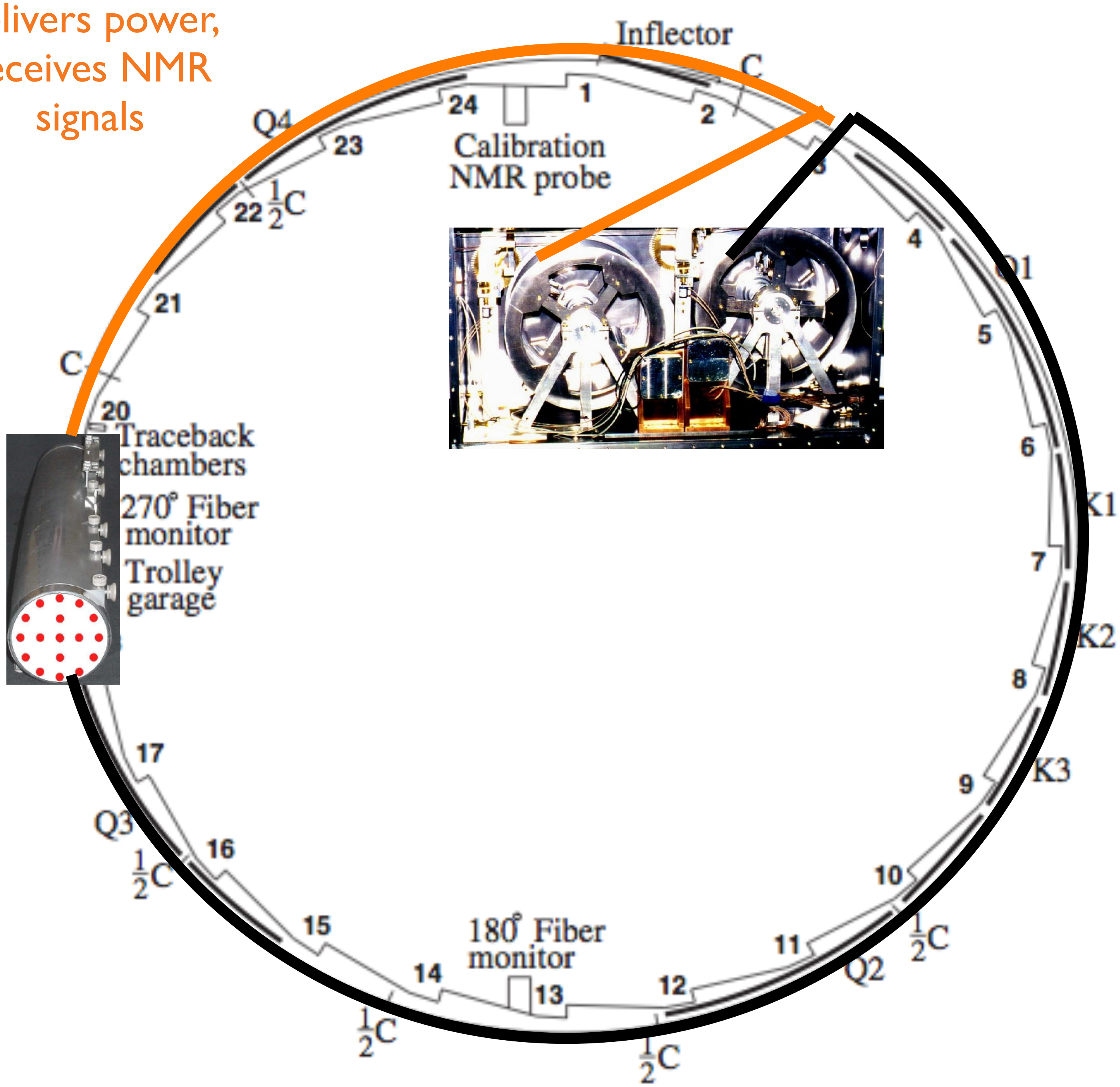
for γ = 29.3
finite γ spread
leads to small
correction

Measuring "B_μ": average field felt by muons

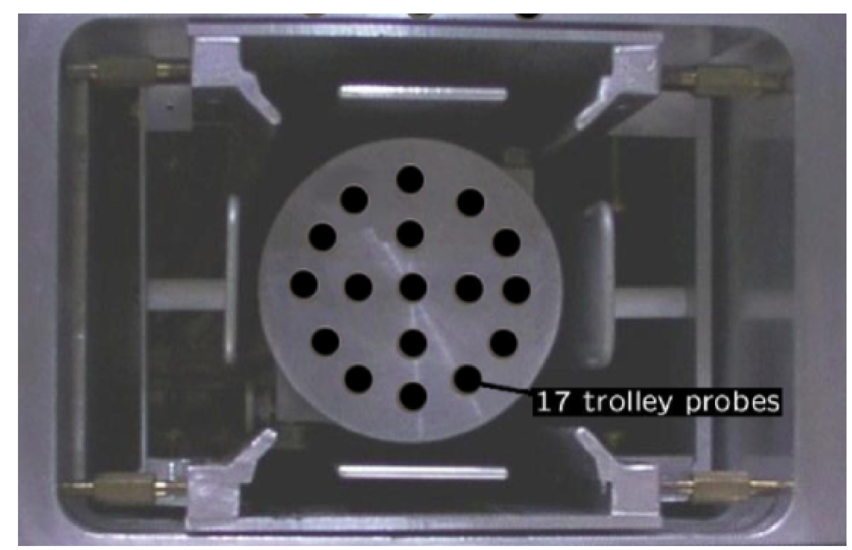


Measuring "B_μ": average field felt by muons

Coax cable delivers power, receives NMR signals



- Two motor/driver pairs wind and unwind drums to pull trolley through muon storage region
- Each of 17 probes records ~*6000* NMR readings each run
  - must know 3D position at measurement time!



critical path of NMR active volumes defined by cable pull and rail support structure