Past, Present and Future of the Muon (g-2)

Leah Welty-Rieger, Northwestern University

Les Rencontres de Physique de La Vallée d’Aoste
La Thuile Feb 24 - Mar 2

Outline

- Motivation to look at the muon g-2
  - What is it?
  - Current theoretical and experimental results
  - Why do we care about it?
- The experiment
  - How do you make the measurement
  - Current status of the muon g-2 experiment at Fermilab
- Conclusions

What is g?

- The magnetic moment of any elementary particle is related to its intrinsic spin by the "g-factor":

$$\vec{\mu}_S = g\frac{q}{2m}\vec{S}$$

- In the 1920s, the electron was found to have $g_e=2$:
  - Experimentally measured in spectroscopy experiments
  - Mathematically explained by Dirac in 1928.

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  - We have to look at the empty space!
    - It's not really empty → Radiative corrections!

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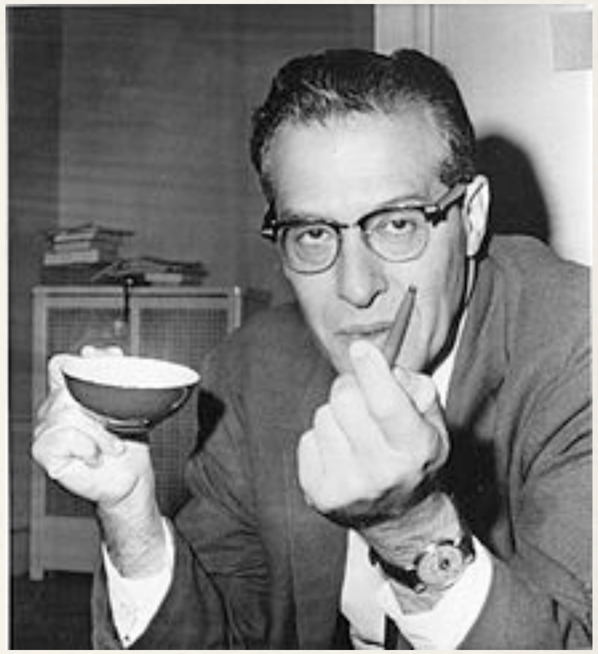

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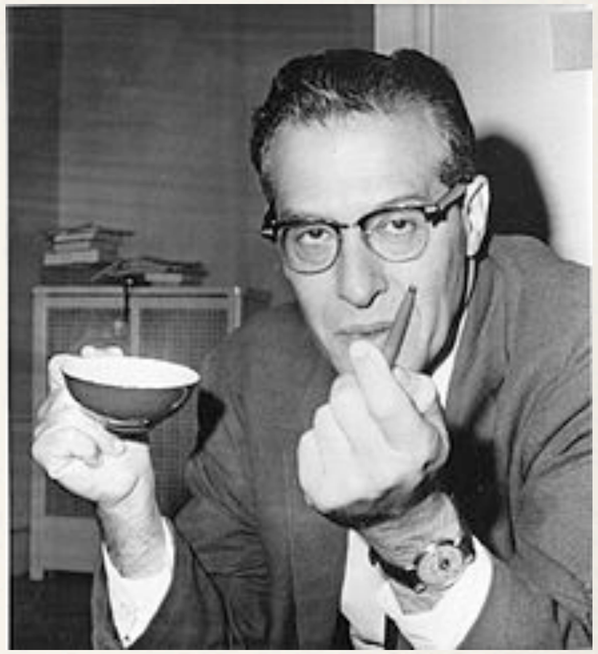

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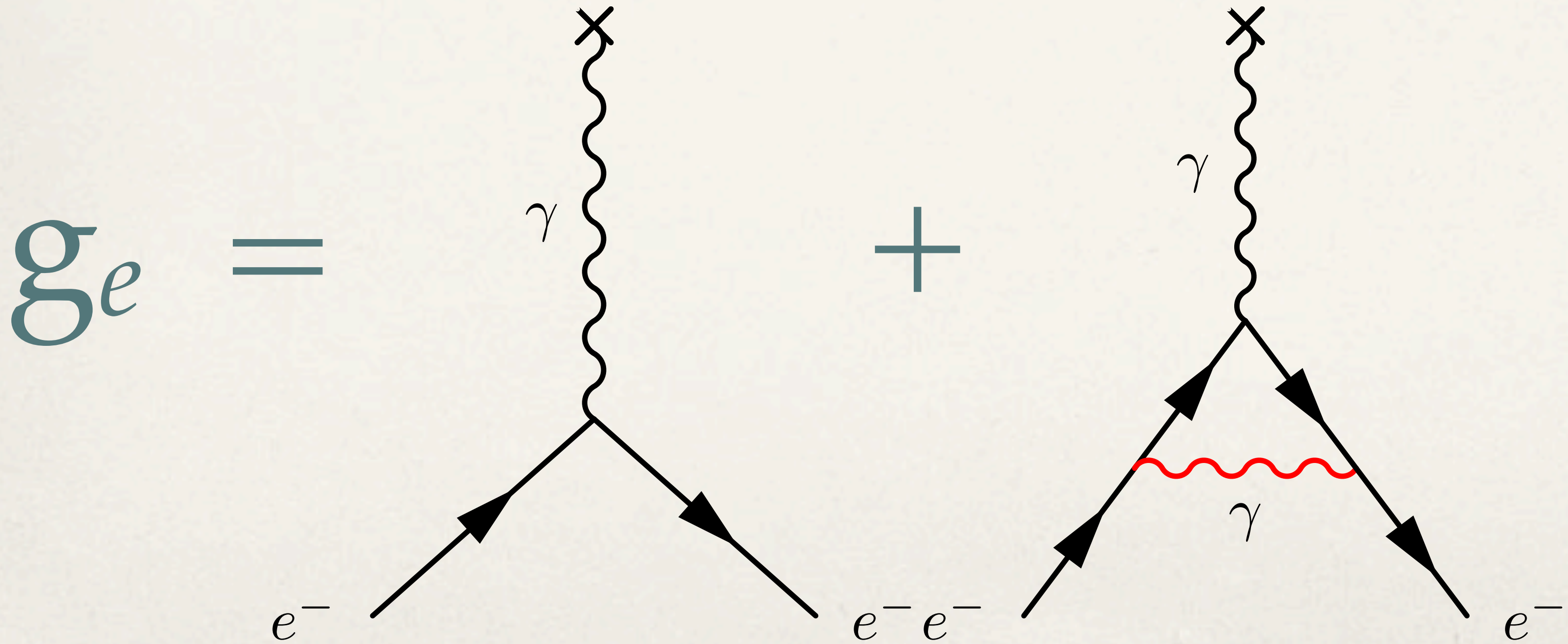

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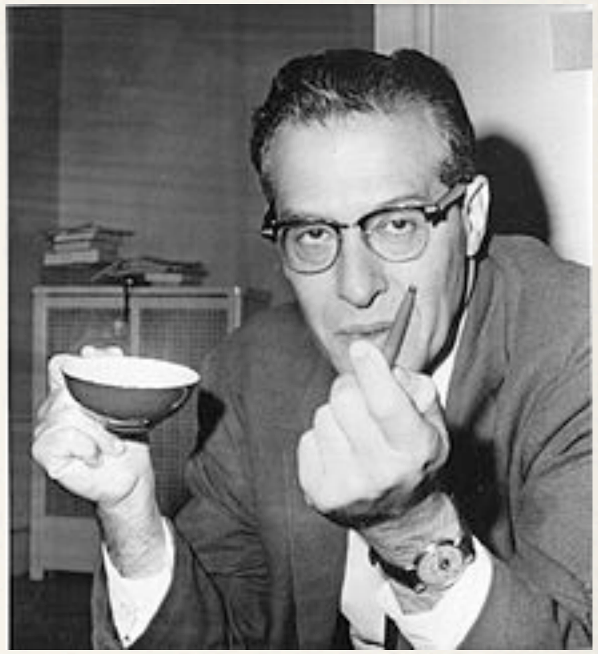

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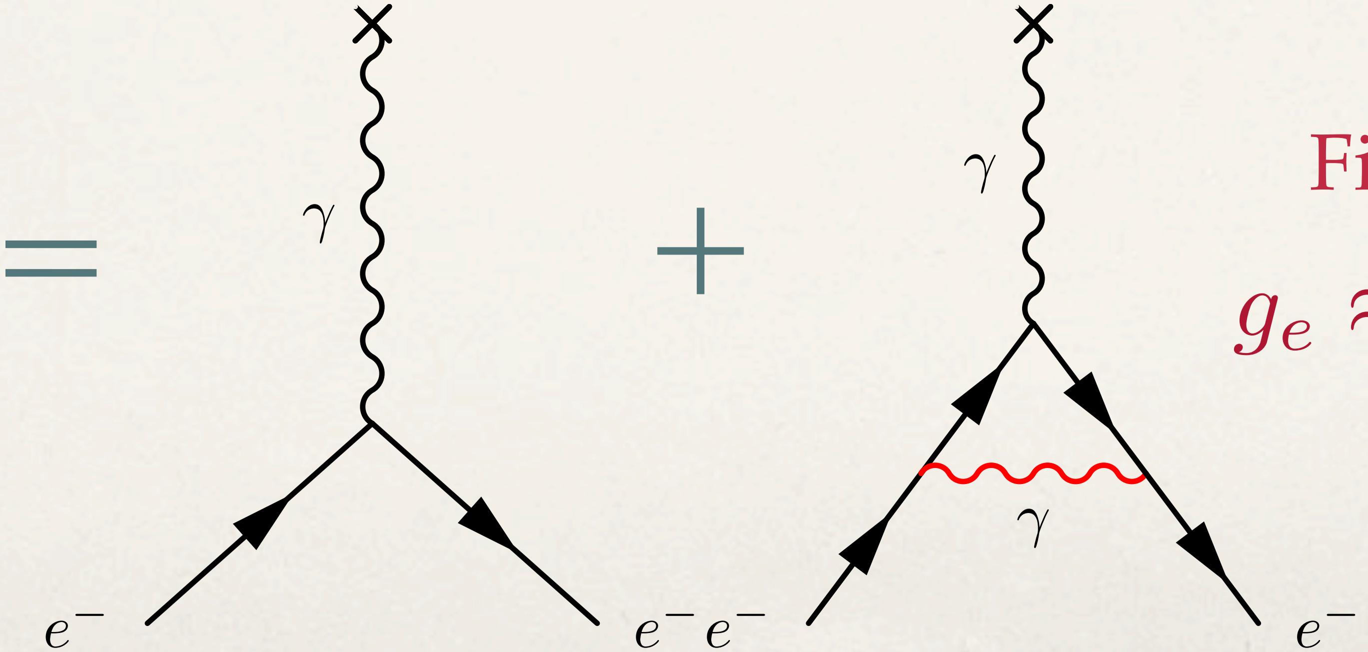
$g_e =$



First order QED corrections

$$g_e \approx 2\left(1+\frac{\alpha}{2\pi}\right) \approx 2.00232$$

Current a_e results. End of Story?

$$a_e^{exp} = 1\ 159\ 652\ 180.73(28) \times 10^{-12}$$ [PRL 100, 120801 (2008)]

$$a_e^{theory} = 1\ 159\ 652\ 181.78(77) \times 10^{-12}$$ [PRL 109, 111807 (2012)]

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- Agreement to the SM to ppt levels
- What else can we look at?
- Muons
  - Loop sensitivity depends on the mass

$$\left(\frac{m_\mu}{m_e}\right)^2 \approx 40,000$$

  - Long (2.2μs) lifetime, so able to use to make a measurement.

What to expect from the Muon?

You have to add up *everything* in the vacuum.

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$$a_\mu^{SM} =$$

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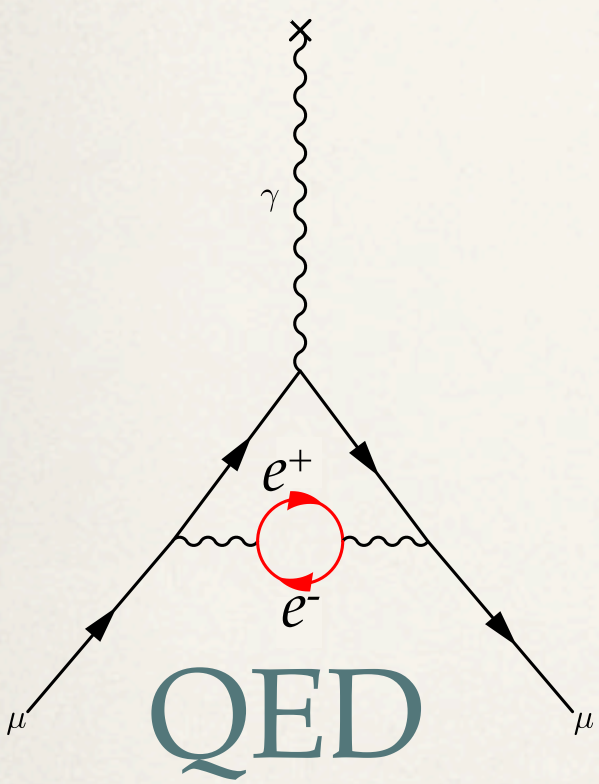
$$a_\mu^{SM} = a_\mu^{QED} +$$

a_μ ~0.1%



What to expect from the Muon?

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$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} +$$

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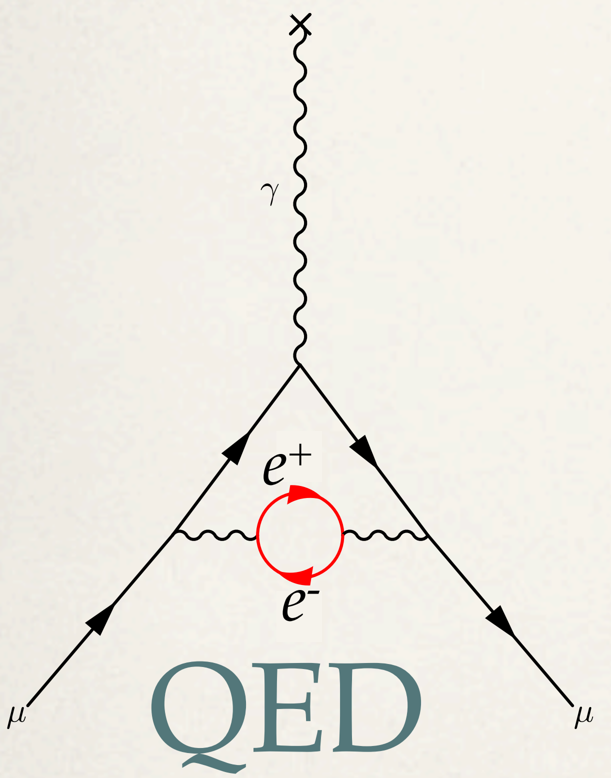
~0.00001%



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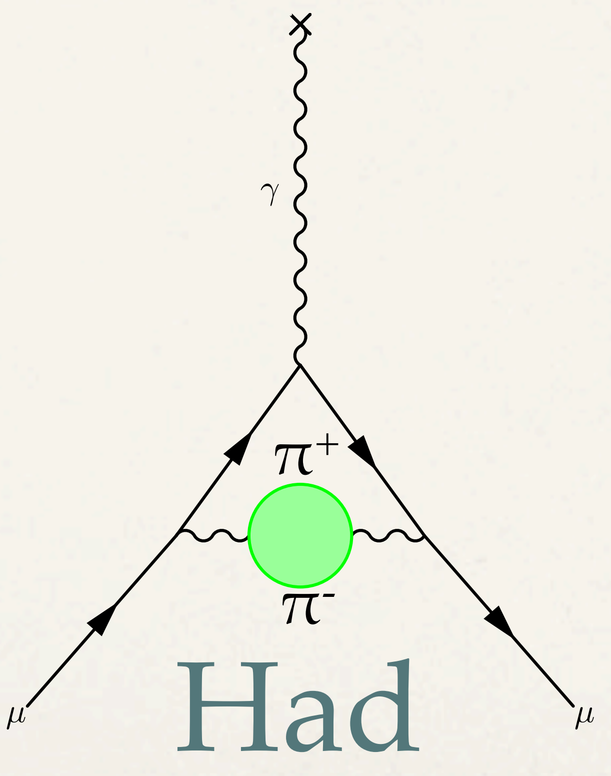

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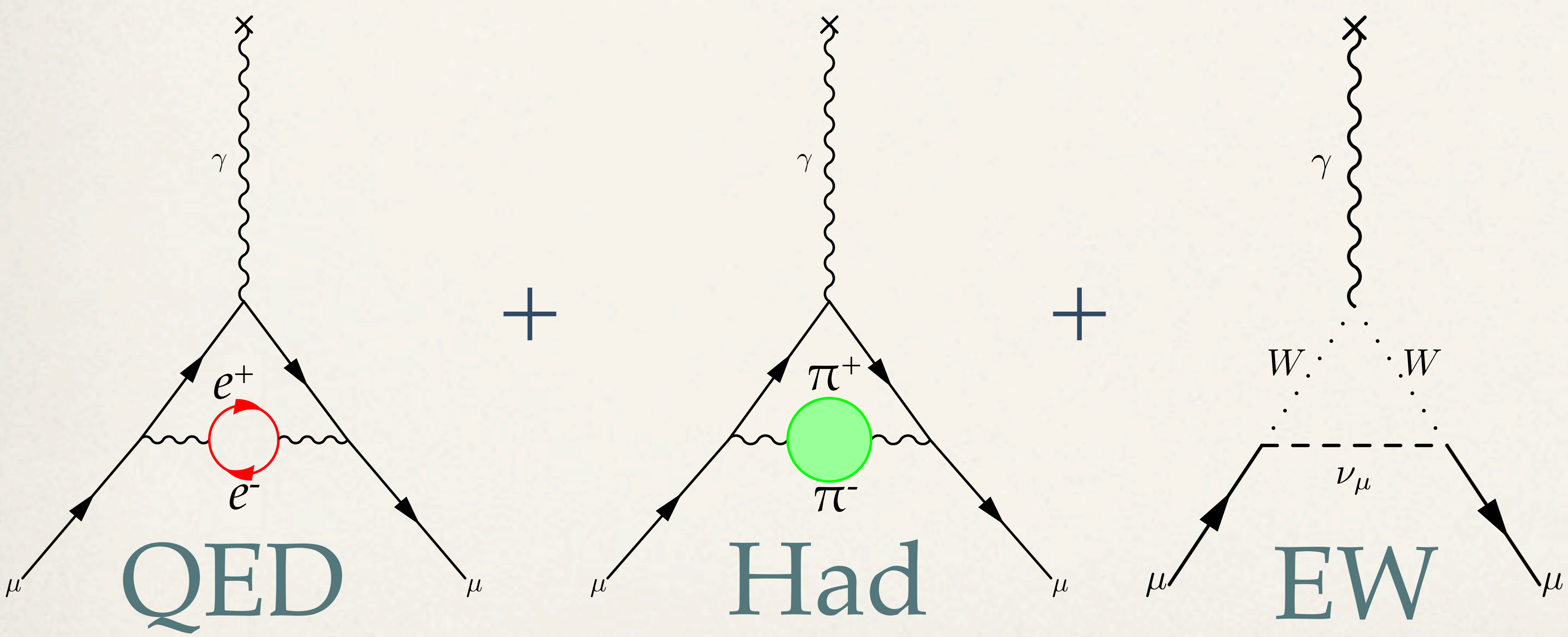


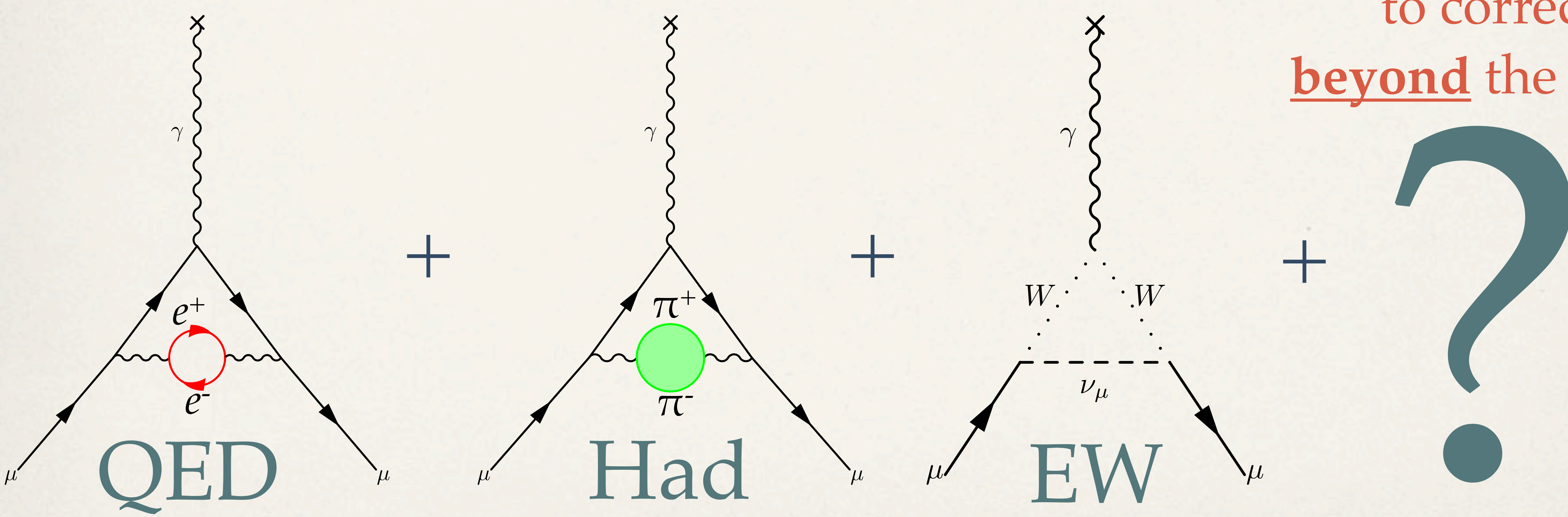
What to expect from the Muon?

You have to add up *everything* in the vacuum.

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{EW} + a_\mu^{NP}$$

A ppm measurement will be sensitive to corrections **beyond** the weak scale

a_μ ~0.1% ~0.00001% ~0.0000001%



Current $(g\text{-}2)_\mu$ status

From the Brookhaven E821 Experiment in 2001

$$a_\mu^{exp} = 116\ 592\ 089\ (63) \times 10^{-11}$$

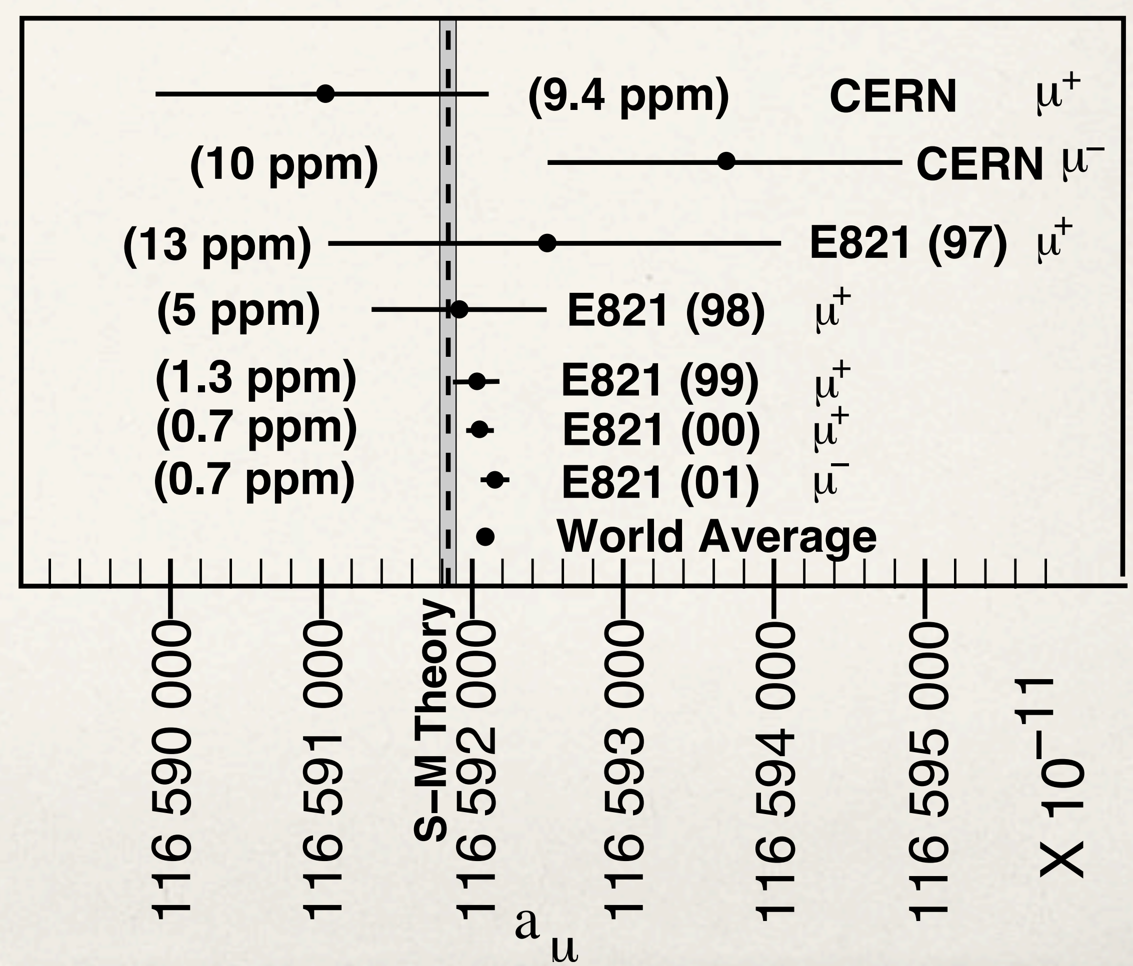
$$a_\mu^{SM} = 116\ 591\ 802\ (49) \times 10^{-11}$$

This difference is larger than 3σ!

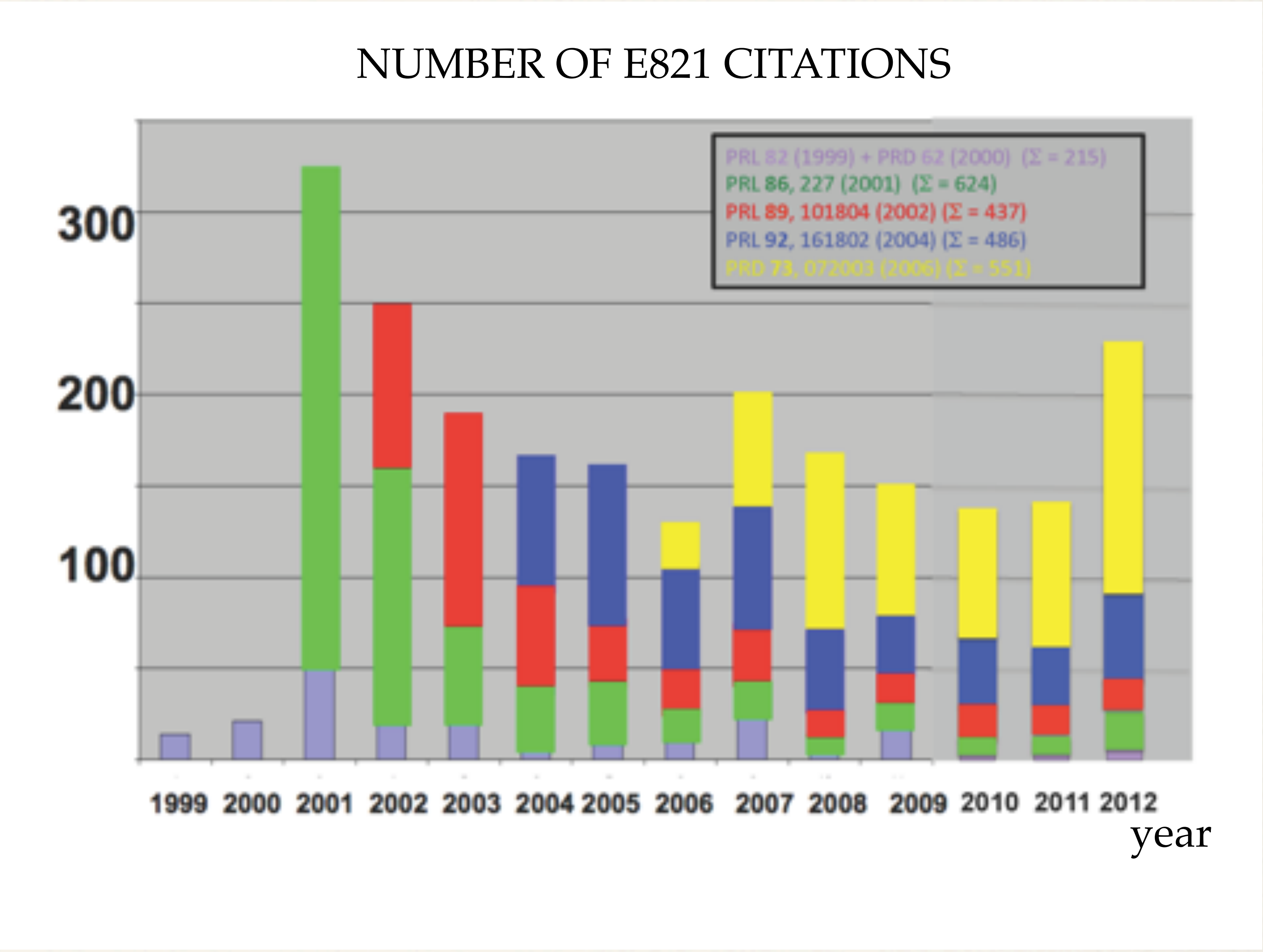
It is also larger than the EW contribution

$$a_\mu^{exp} - a_\mu^{SM} = 287\ (80) \times 10^{-11}$$

- Have we found new physics?
- More investigation is required.
  - From both theory and experiment!

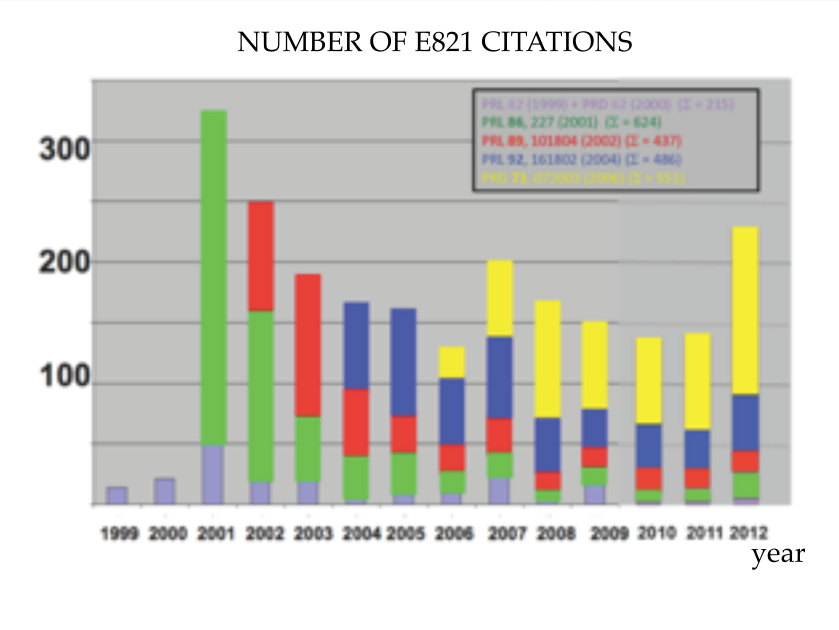


Why do we care about $(g\text{-}2)_\mu$?



Why do we care about $(g-2)_\mu$?

- If new physics discovered $(g-2)_\mu$ has important role in interpreting results



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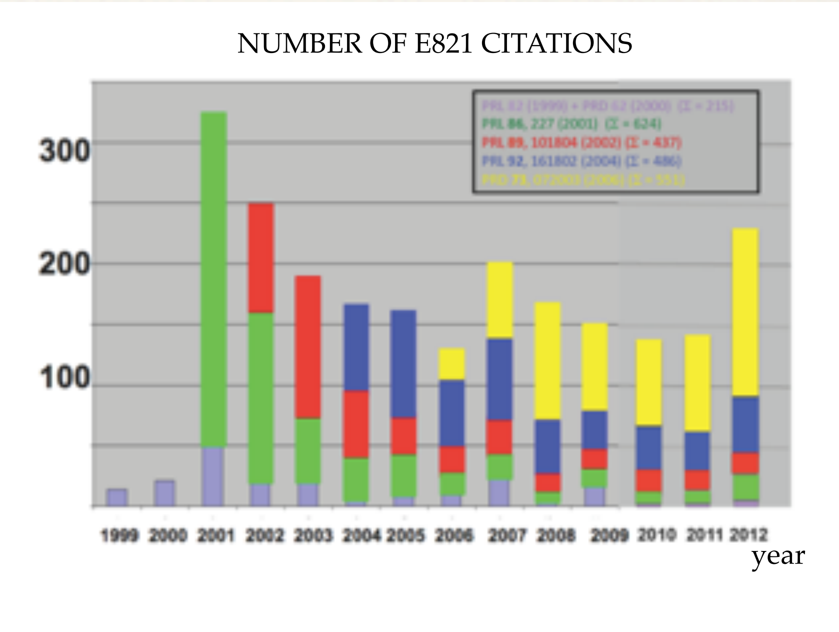
- If new physics discovered $(g\text{-}2)_\mu$ has important role in interpreting results
- If the discrepancy between the theory and the experimental result can be believed it can point to new physics



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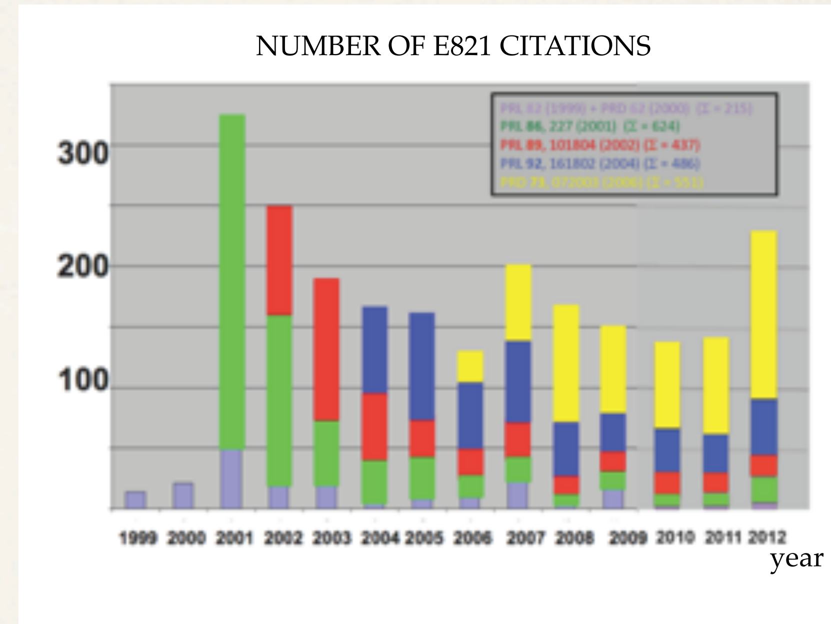
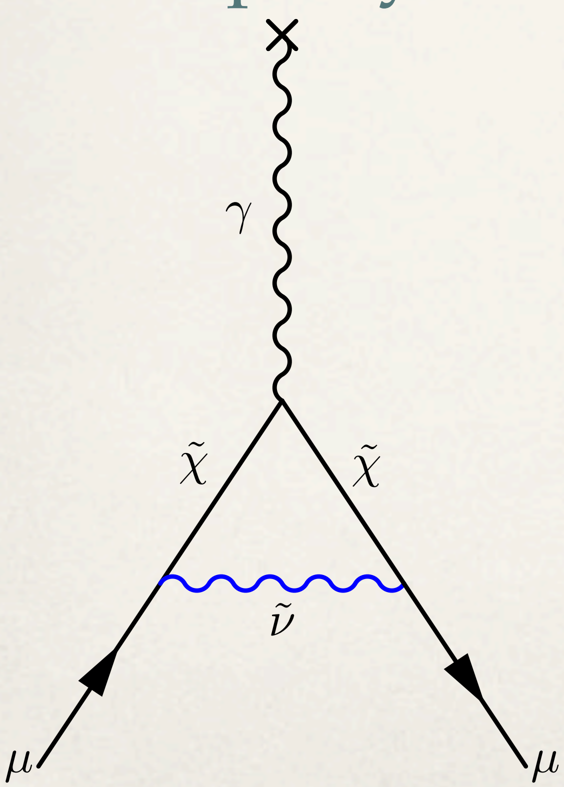
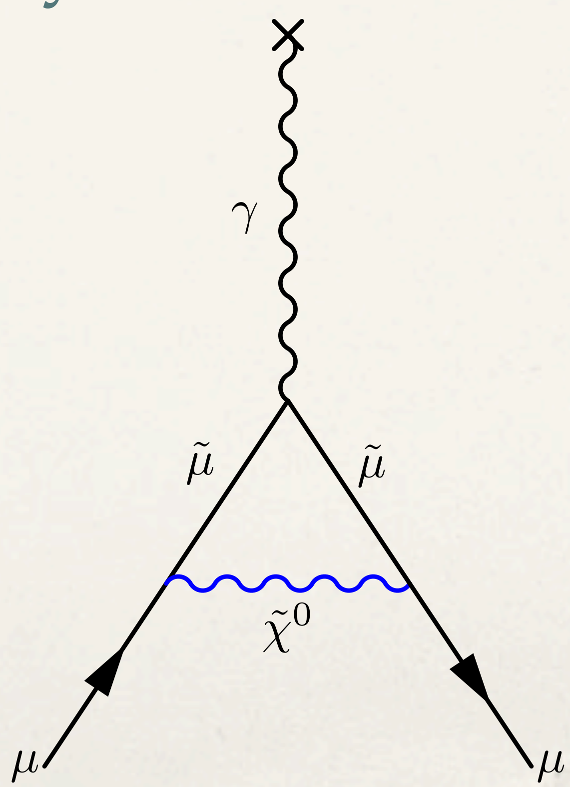
  - Supersymmetry?







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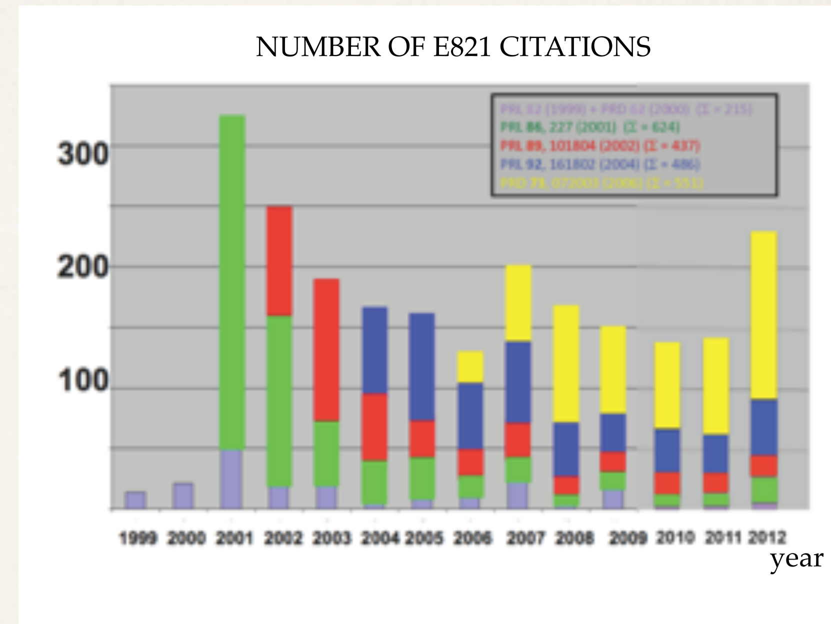
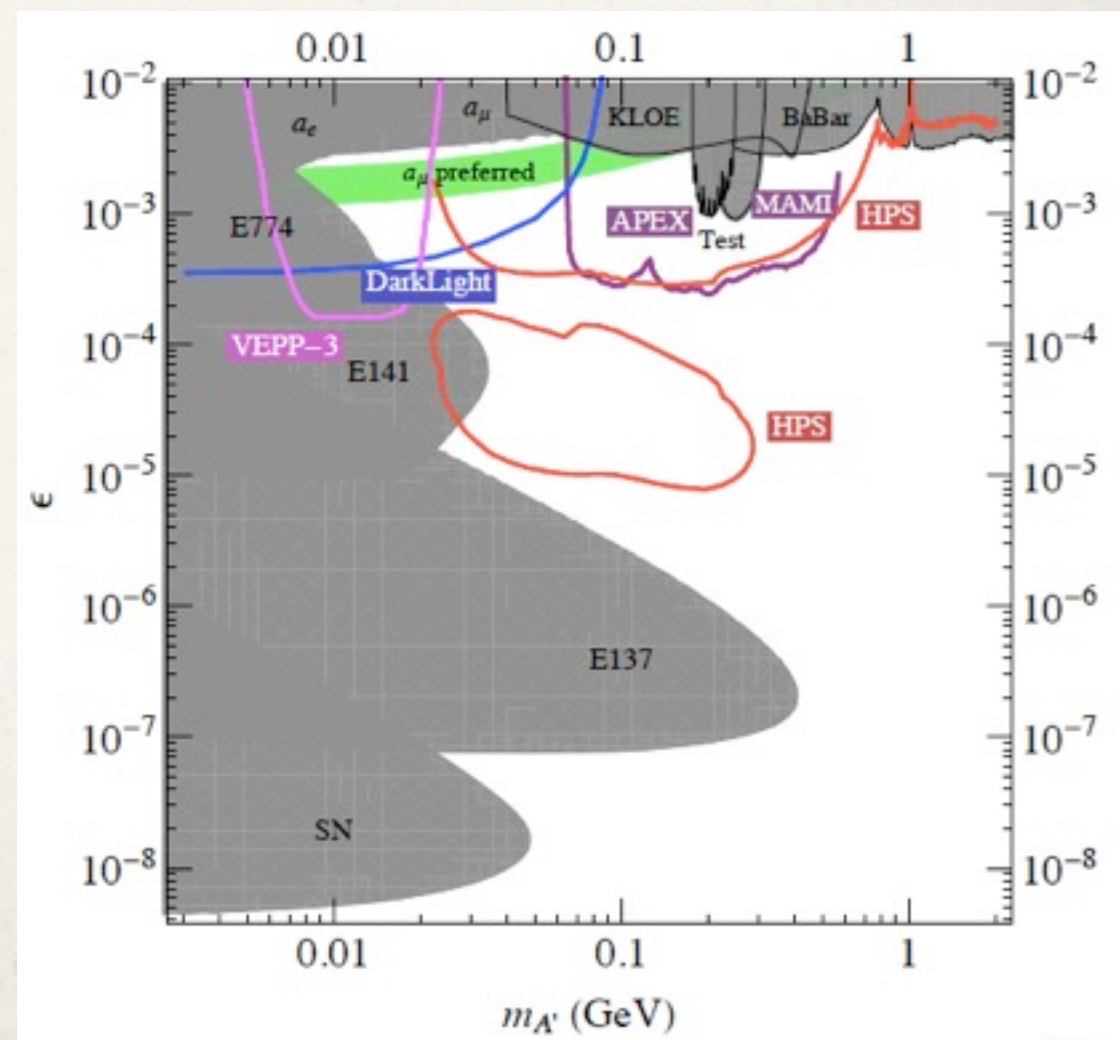
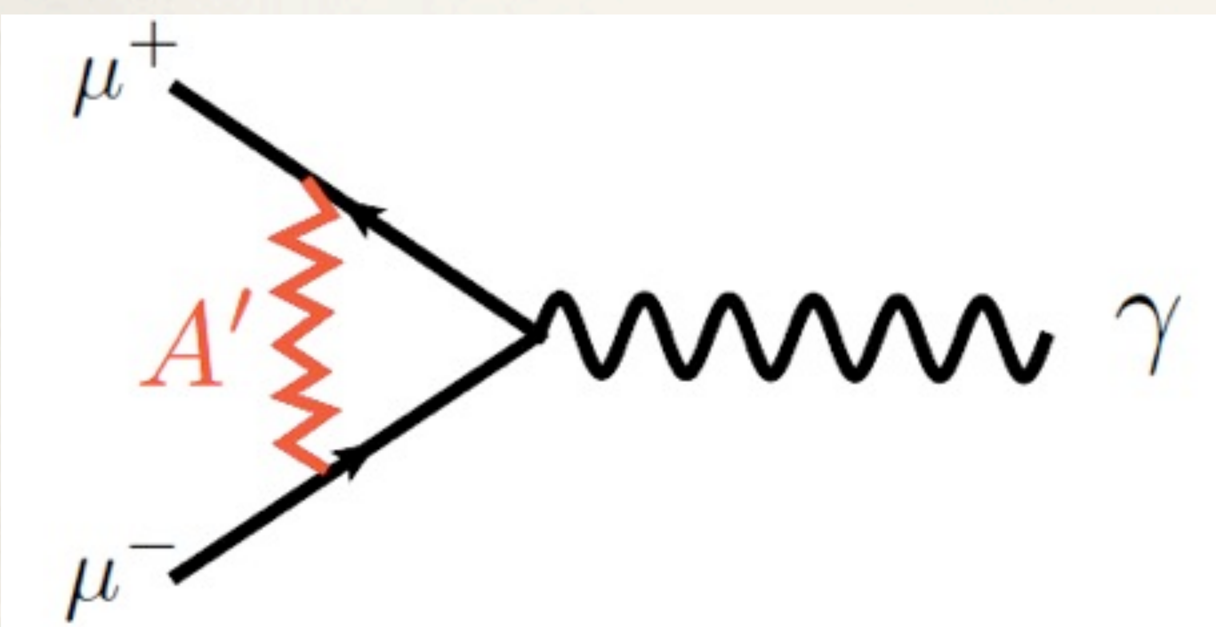
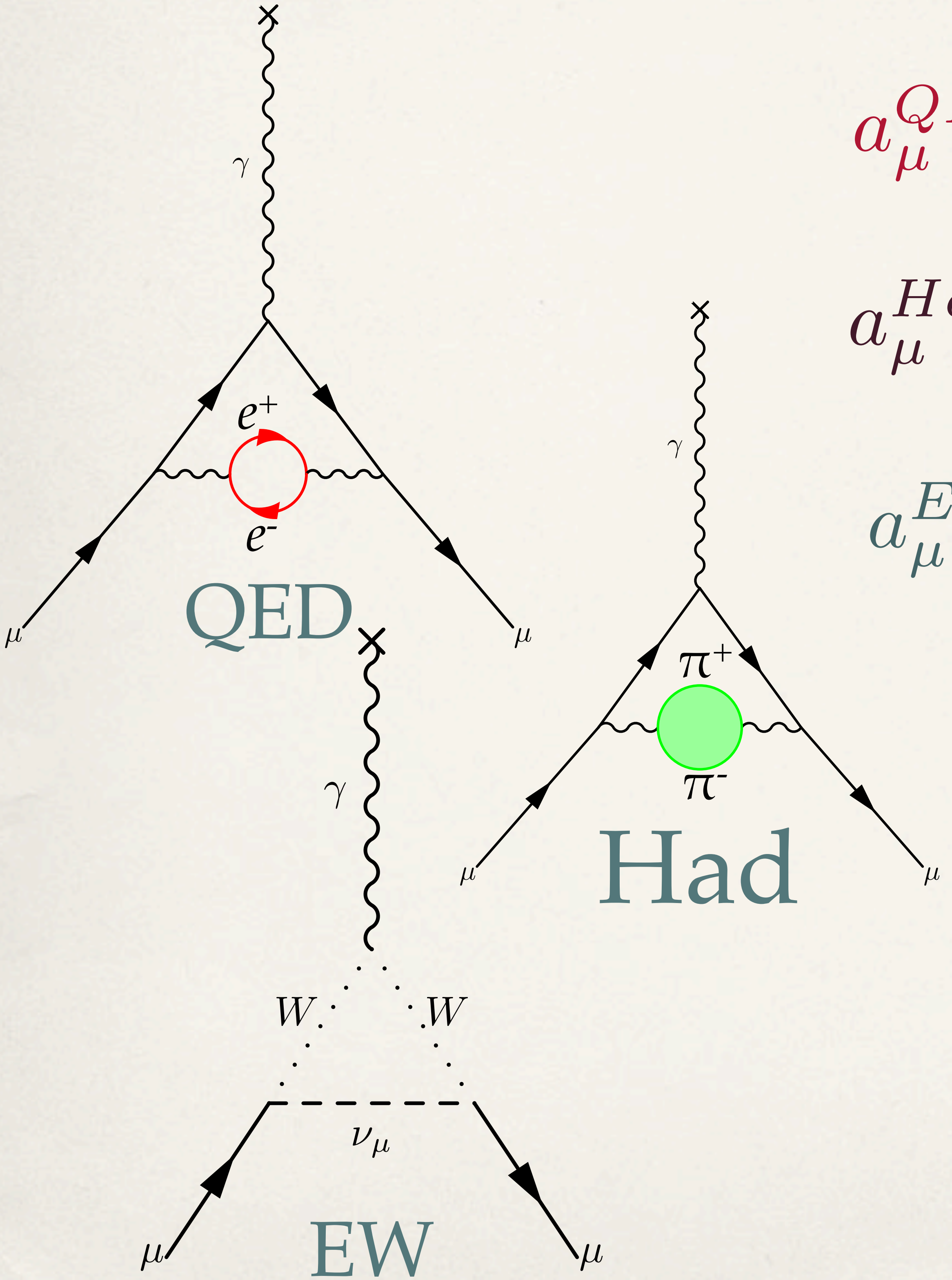
  - Supersymmetry?
  - Dark Photons?







Current Theory $(g\text{-}2)_\mu$ Status



	Contribution	Result in 10^{-11} units
a_μ^{QED}	QED (leptons)	116 584 718.09 ± 0.15
a_μ^{Had}	HVP(lo)[e+e-]	6 923 ± 42
	HVP(ho)	-98.4 ± 0.7
	HLbyL	105 ± 26
a_μ^{EW}	EW	153 ± 1
	Total	**116 591 801 ± 49**

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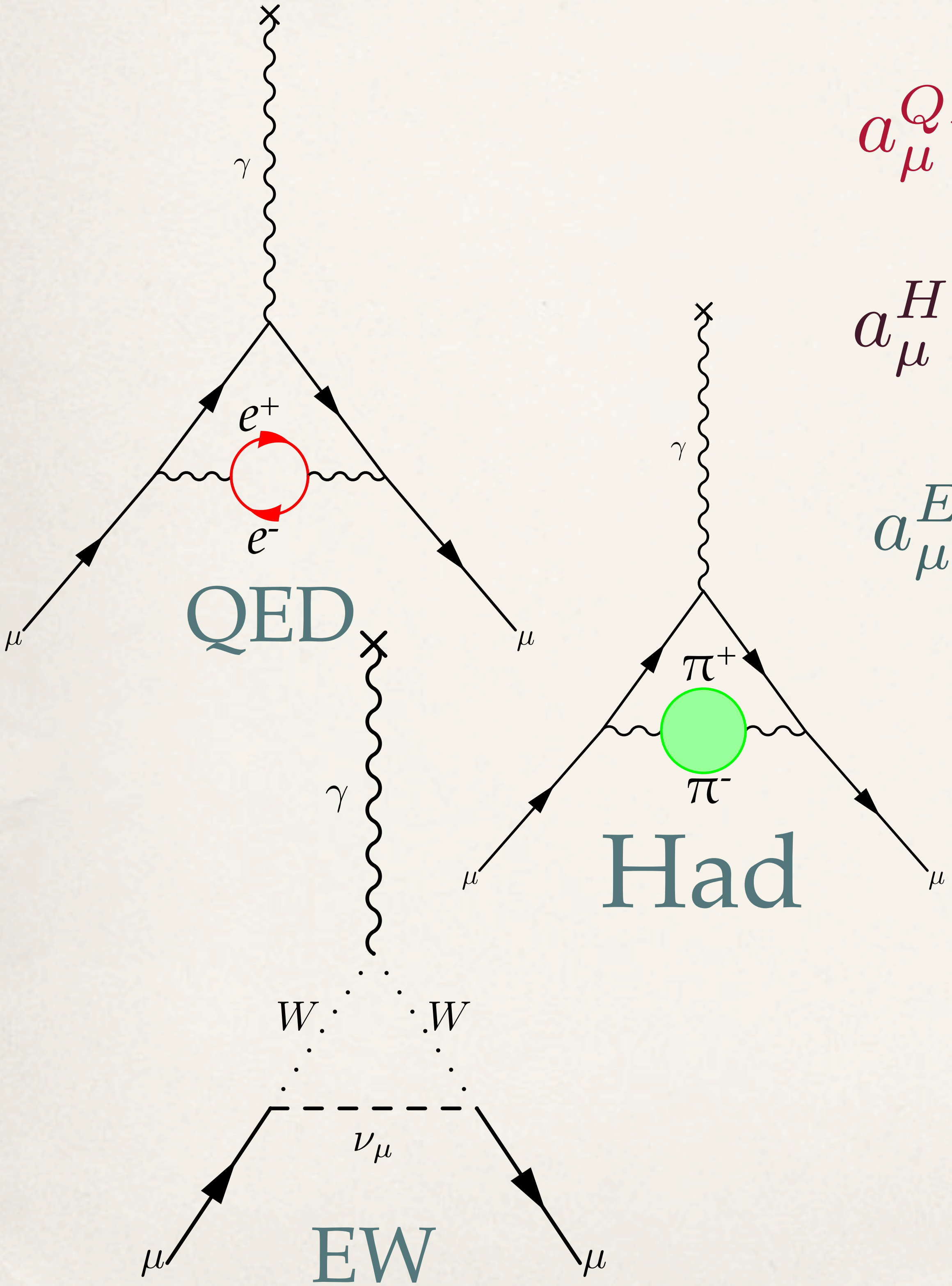

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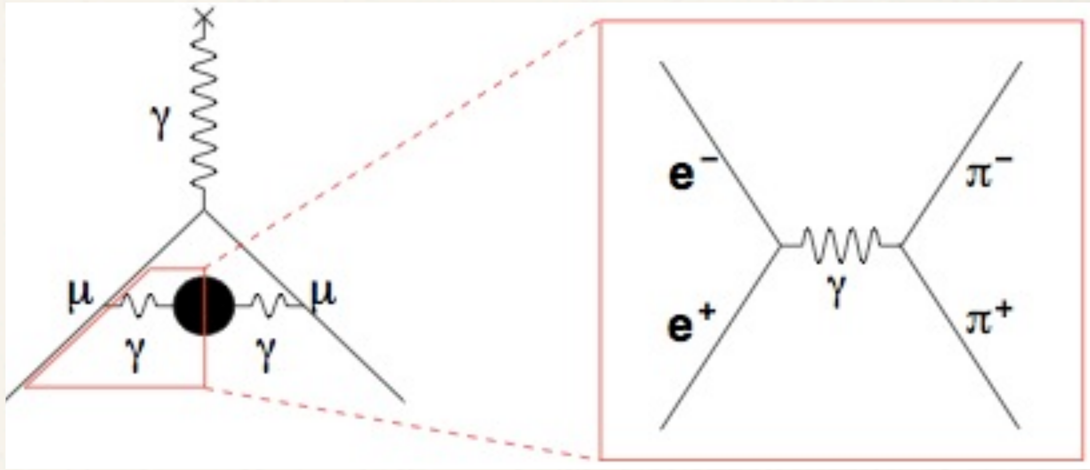
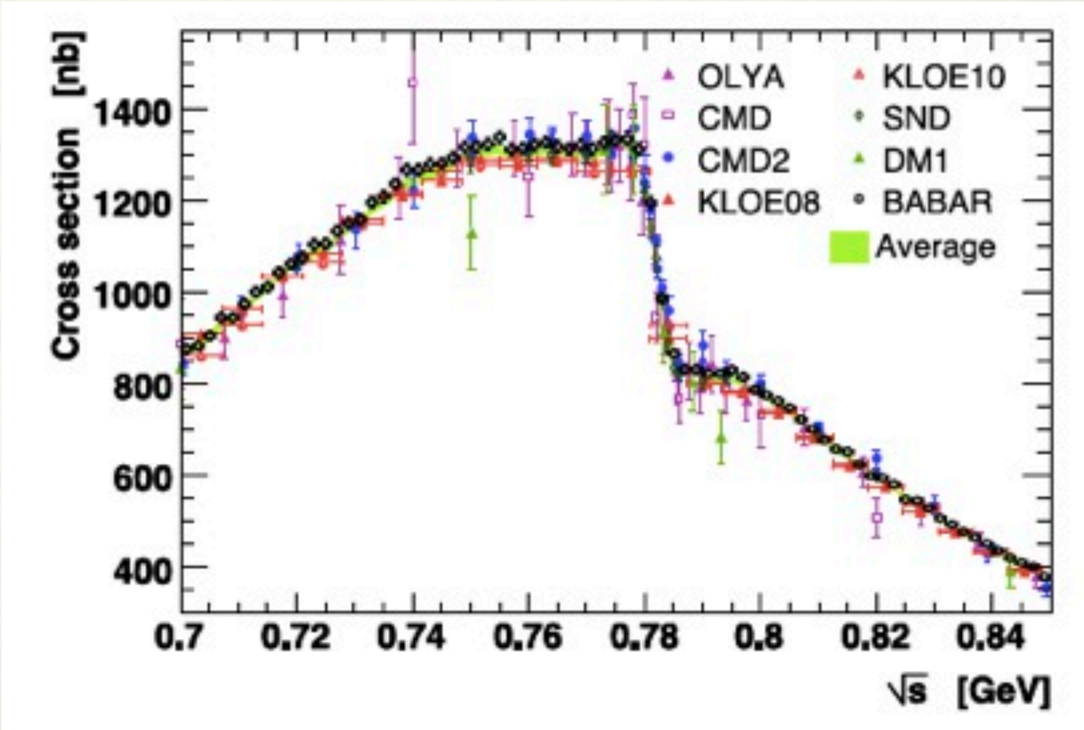
- One of the most important improvements to the error on the SM value is to improve the hadronic component (Leading Order and Light By Light)

a_μ Hadronic Leading Order

- The hadronic vacuum polarization can be related to the cross section for hadron production
- Requires a precise measurement of $e^+e^- \rightarrow$ *hadrons*
  - Determined by multiple experiments
    - CMD2, SND, KLOE, BaBar
  - Error is about 0.5%
  - 15 year effort ending with an error reduction of a factor of 4
- Prospects for even more improvements are good
  - VEPP-2000, CMD3 and SND2000 detectors
- LatticeQCD is getting involved as an independent check of this method.
  - Few-percent error in next 5 years

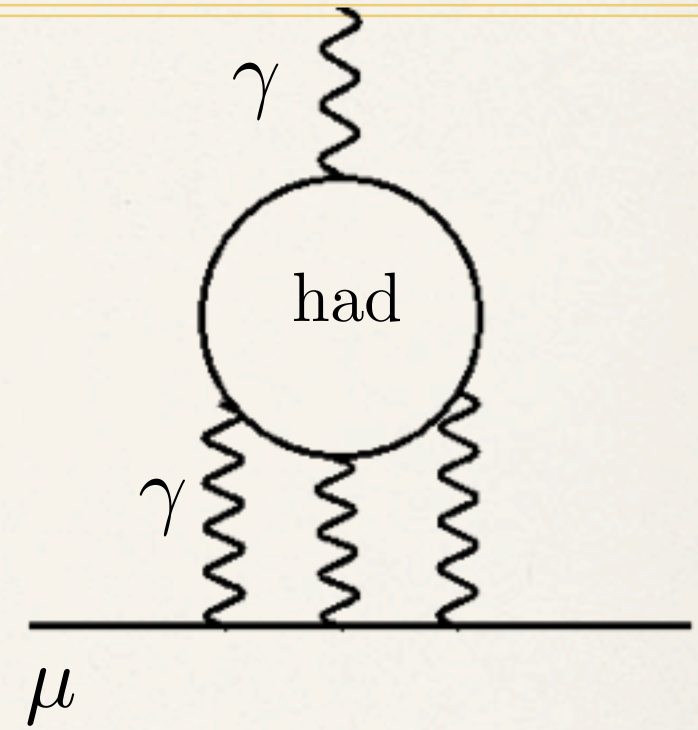


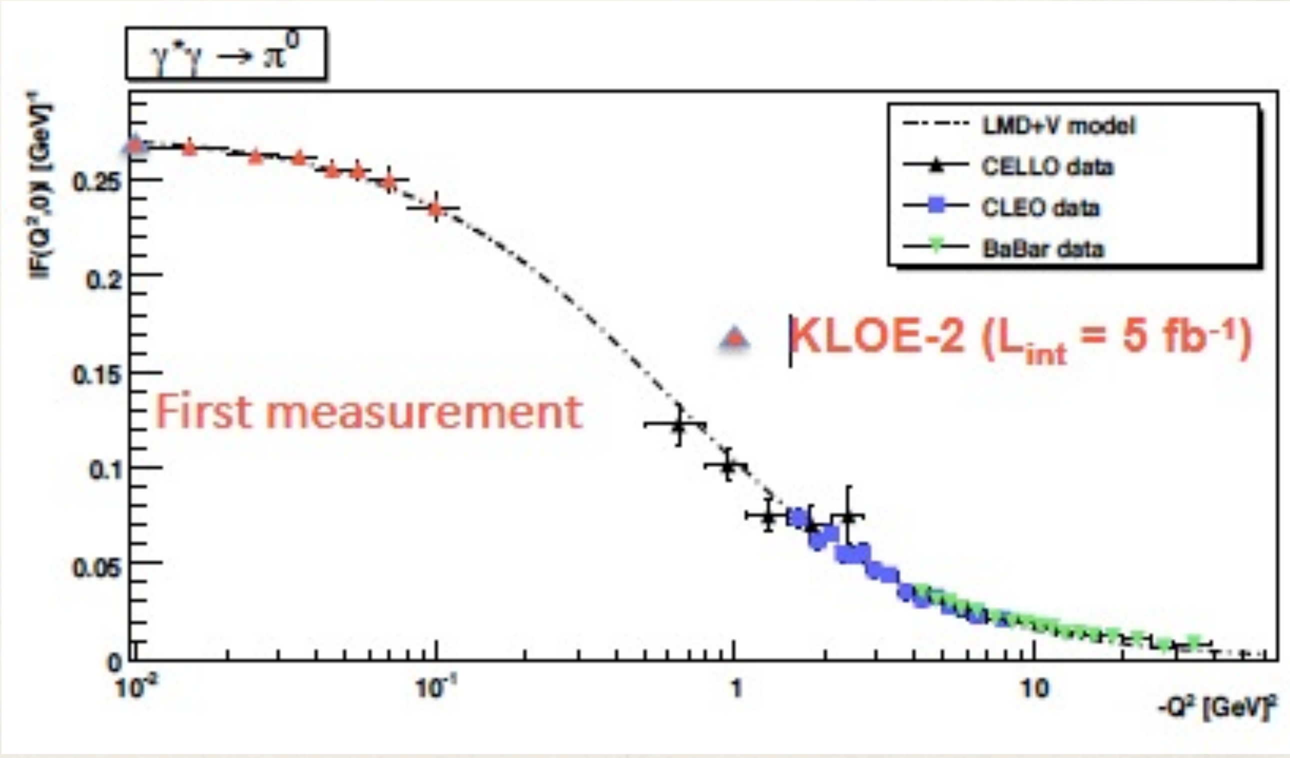
$\pi\pi$ cross section at ρ resonance



a_μ Hadronic Light By Light

- Current uncertainty is about 25%
- KLOE2 is planning a two-photon physics program which will provide experimental input.
  - A coincidence between the scattered electrons and a $\pi 0$ would provide information on $\gamma^*\gamma^* \rightarrow \pi 0$
  - Near $q^2 = 0$ for the first time
  - See previous talk from S. Miscetti for more details
- The Lattice is also starting to become involved in the HLBL component
  - 10-15% uncertainty possible but not guaranteed
  - More computing power will be necessary

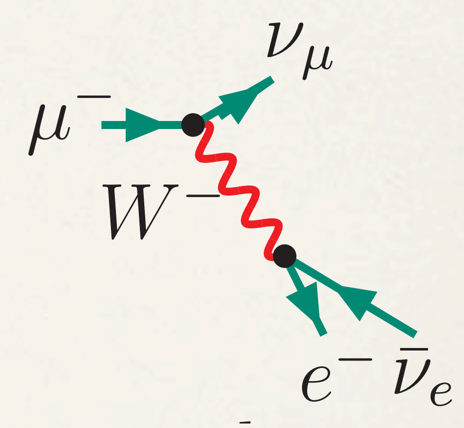




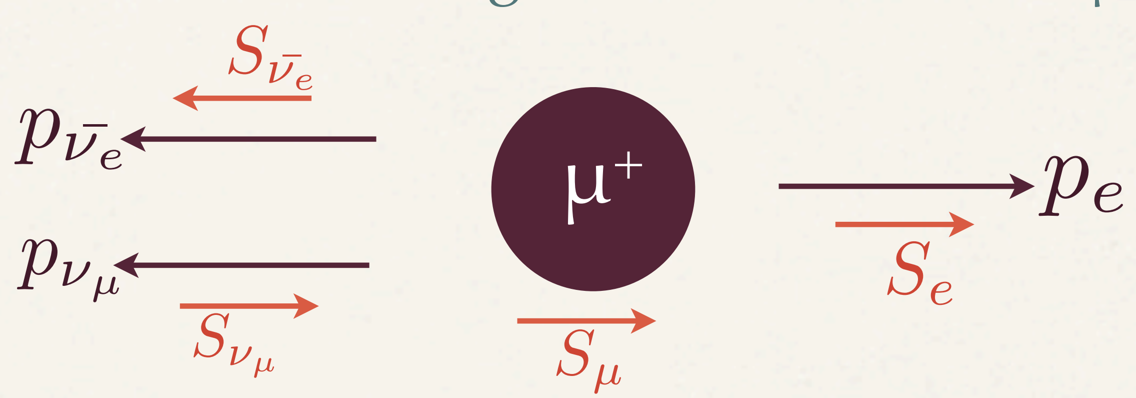
$(g\text{-}2)_\mu$ Experimentally

A Few Lucky Breaks from Nature

- Parity violation!
  - High momentum muons from pion decays
    - Longitudinally polarized
  - Muon decays are "self-analyzing"
    - The electrons emitted along the direction of the μ^+ spin

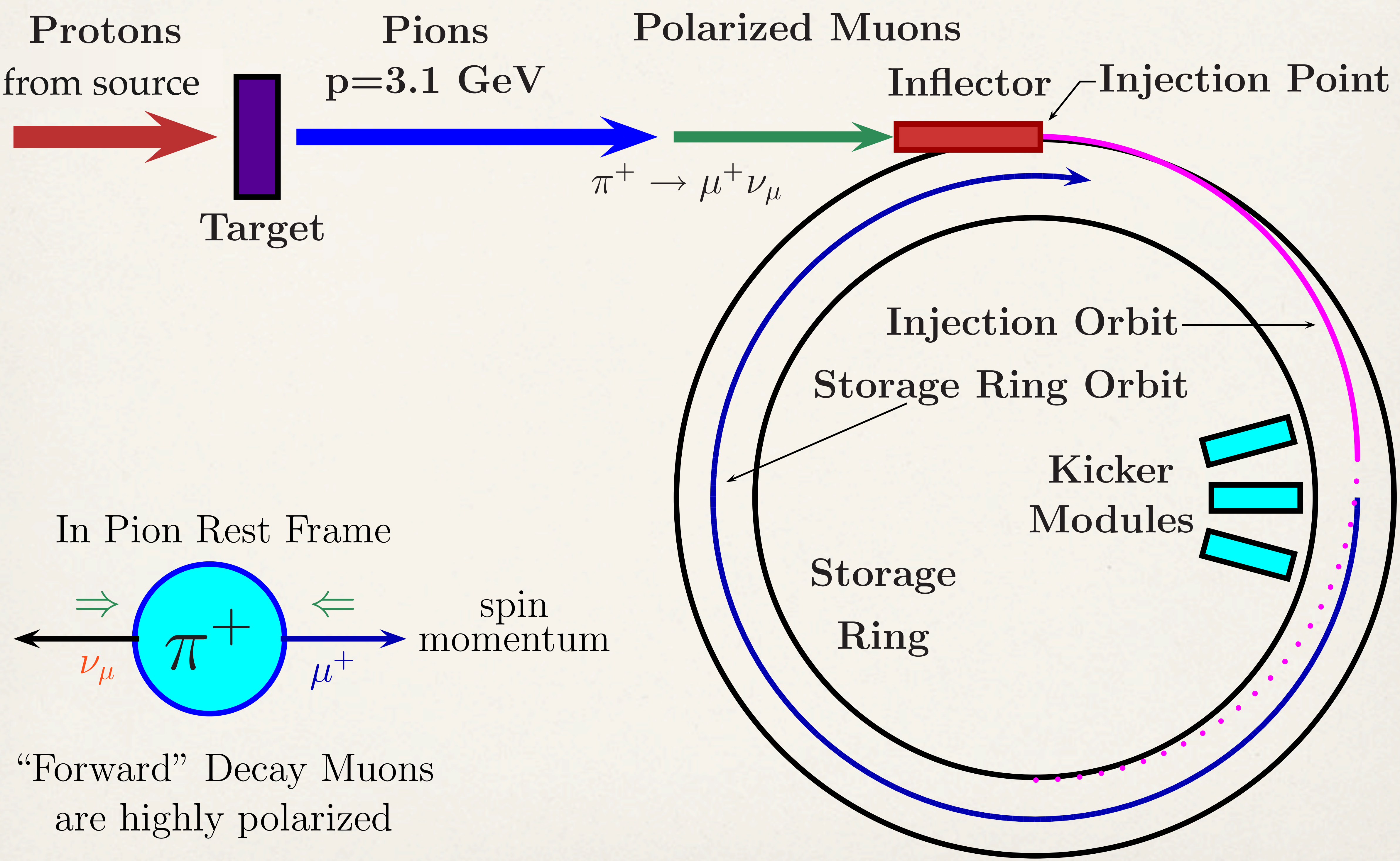


Can get the spin direction of the muon by looking at the direction the electrons are emitted.



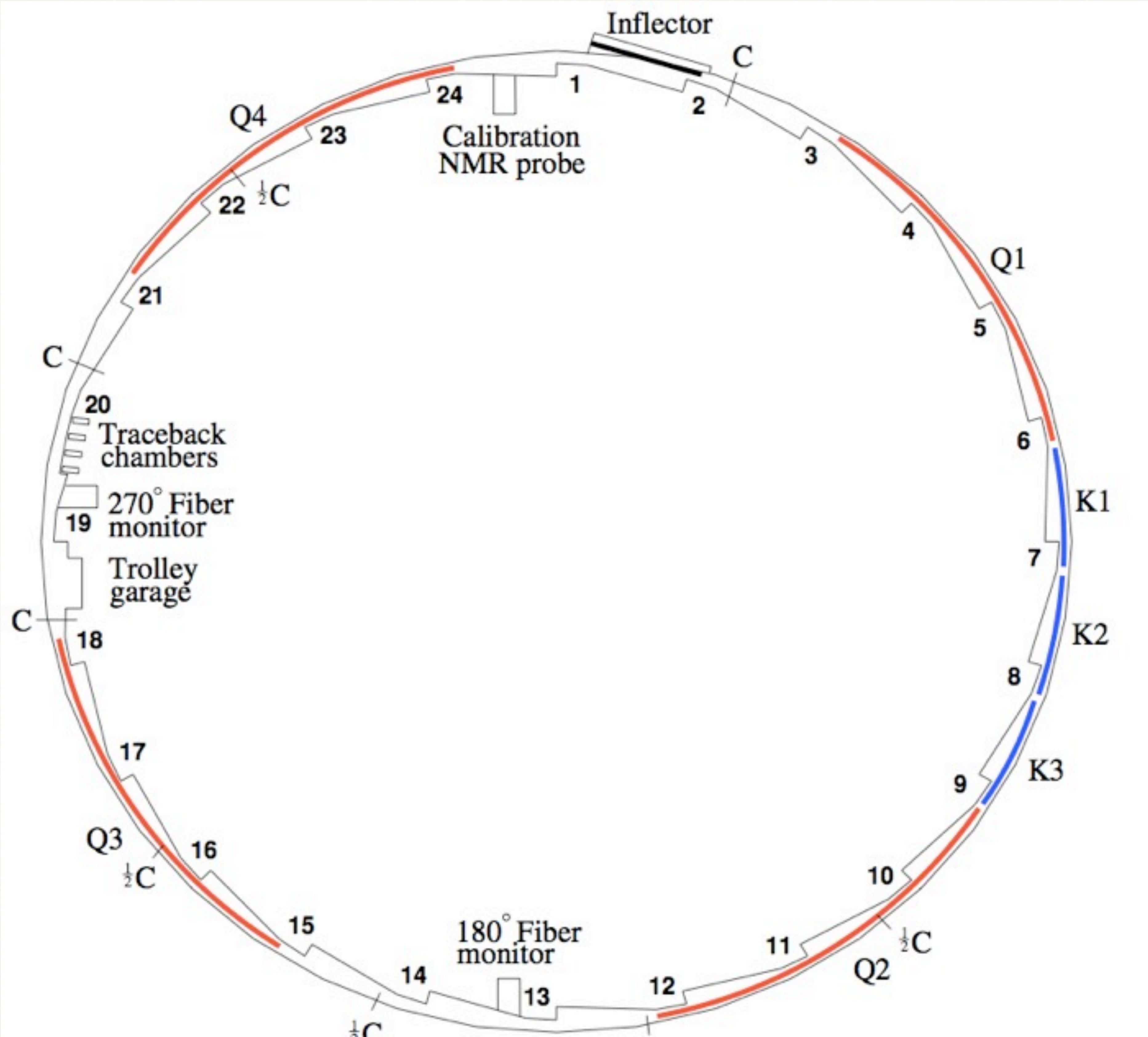
- Long lifetime of the muon (2.2μs) allows precision measurements
- Mass of the muon (~200 times the mass of the electron) gives sensitivity at the TeV scale

The Experiment



"Forward" Decay Muons
are highly polarized

The Ring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Calibration
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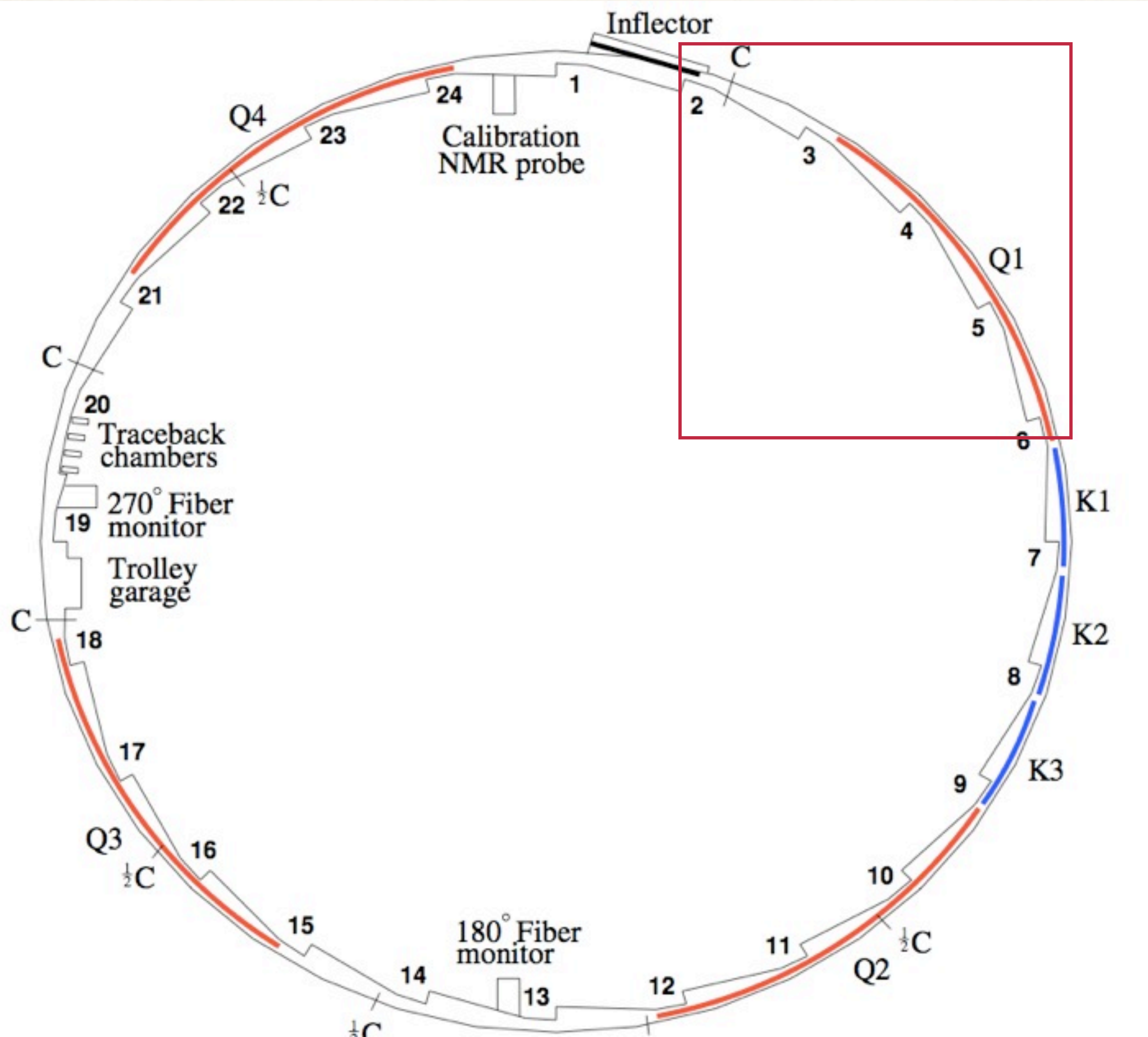

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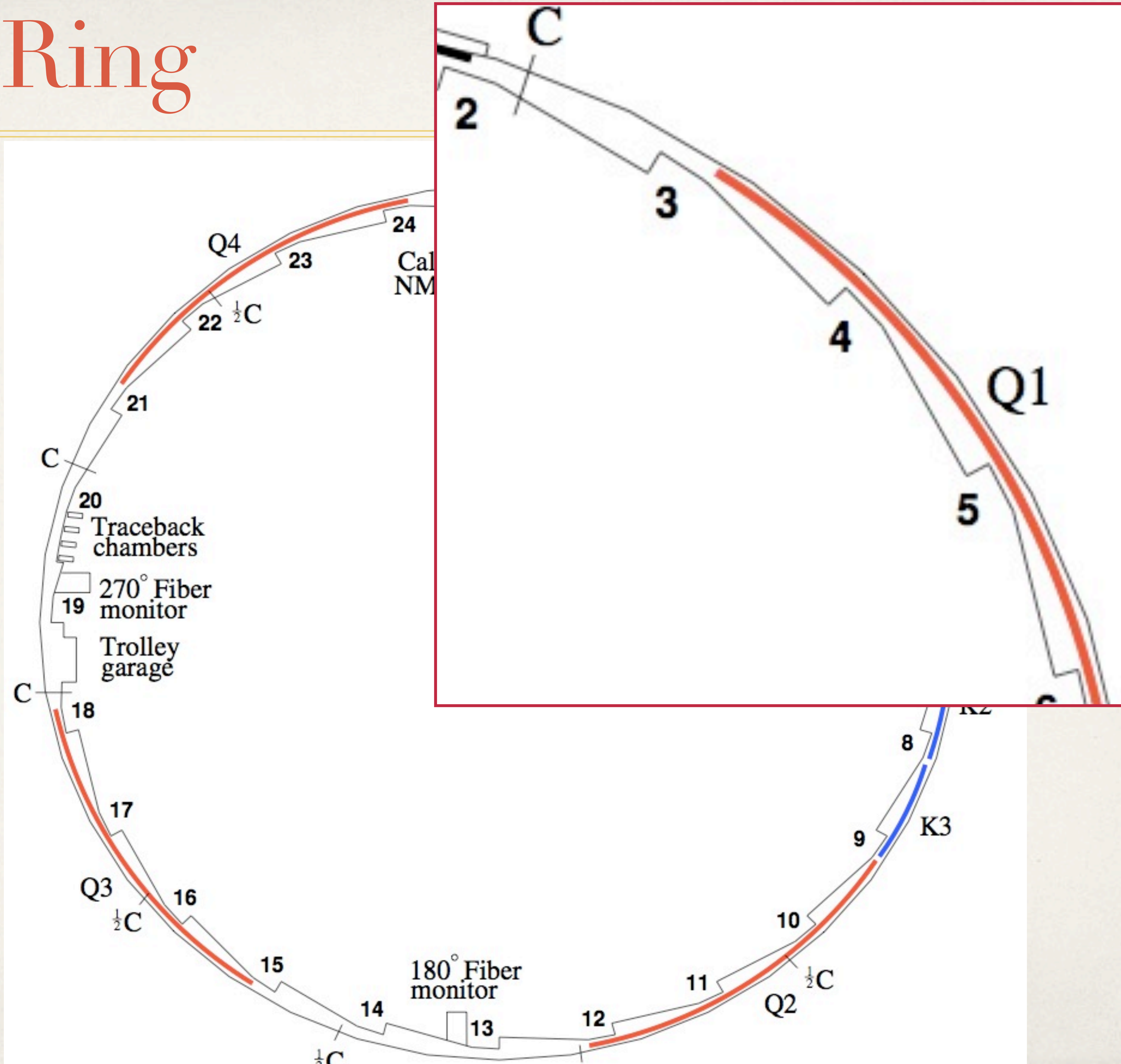
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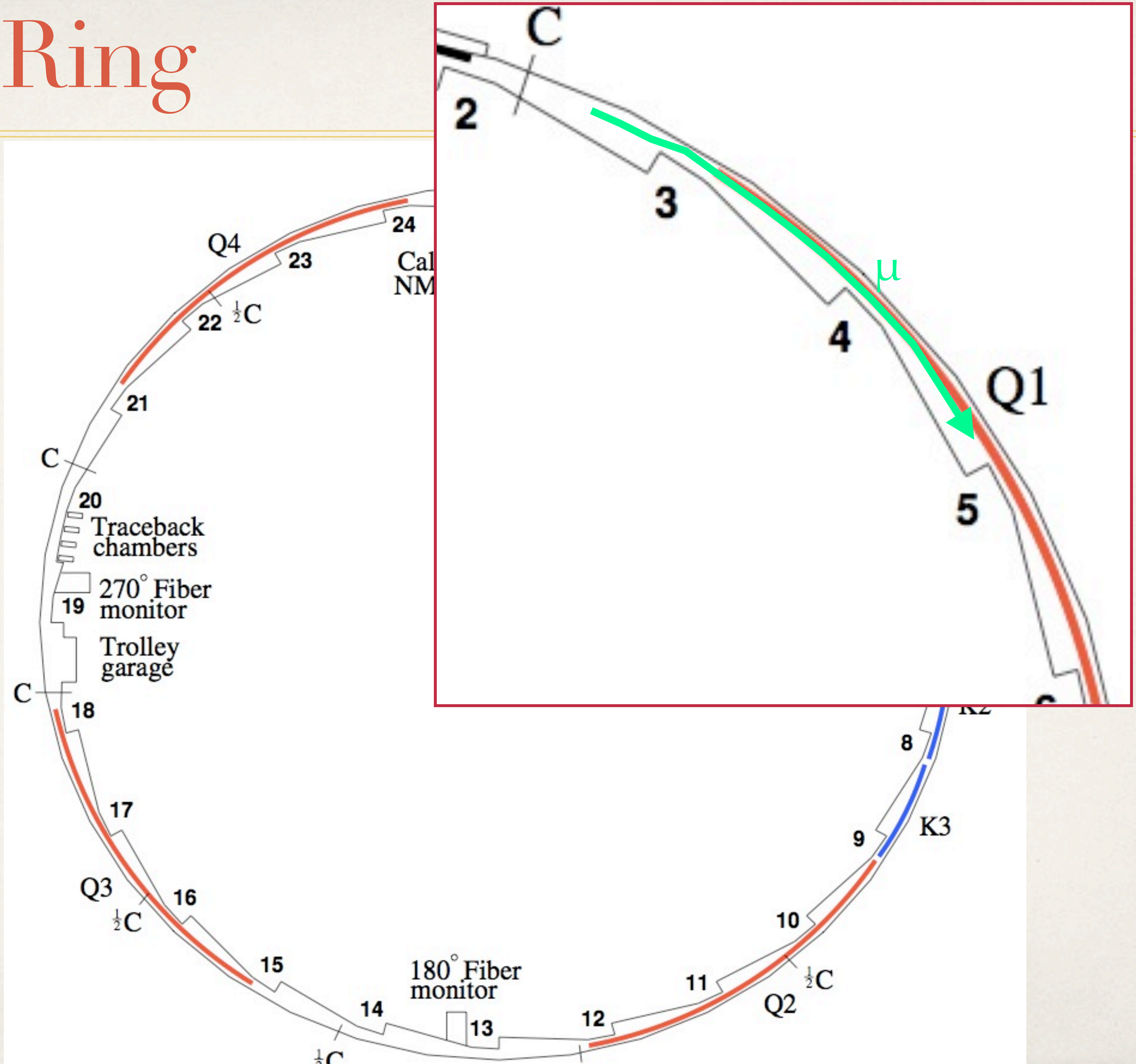
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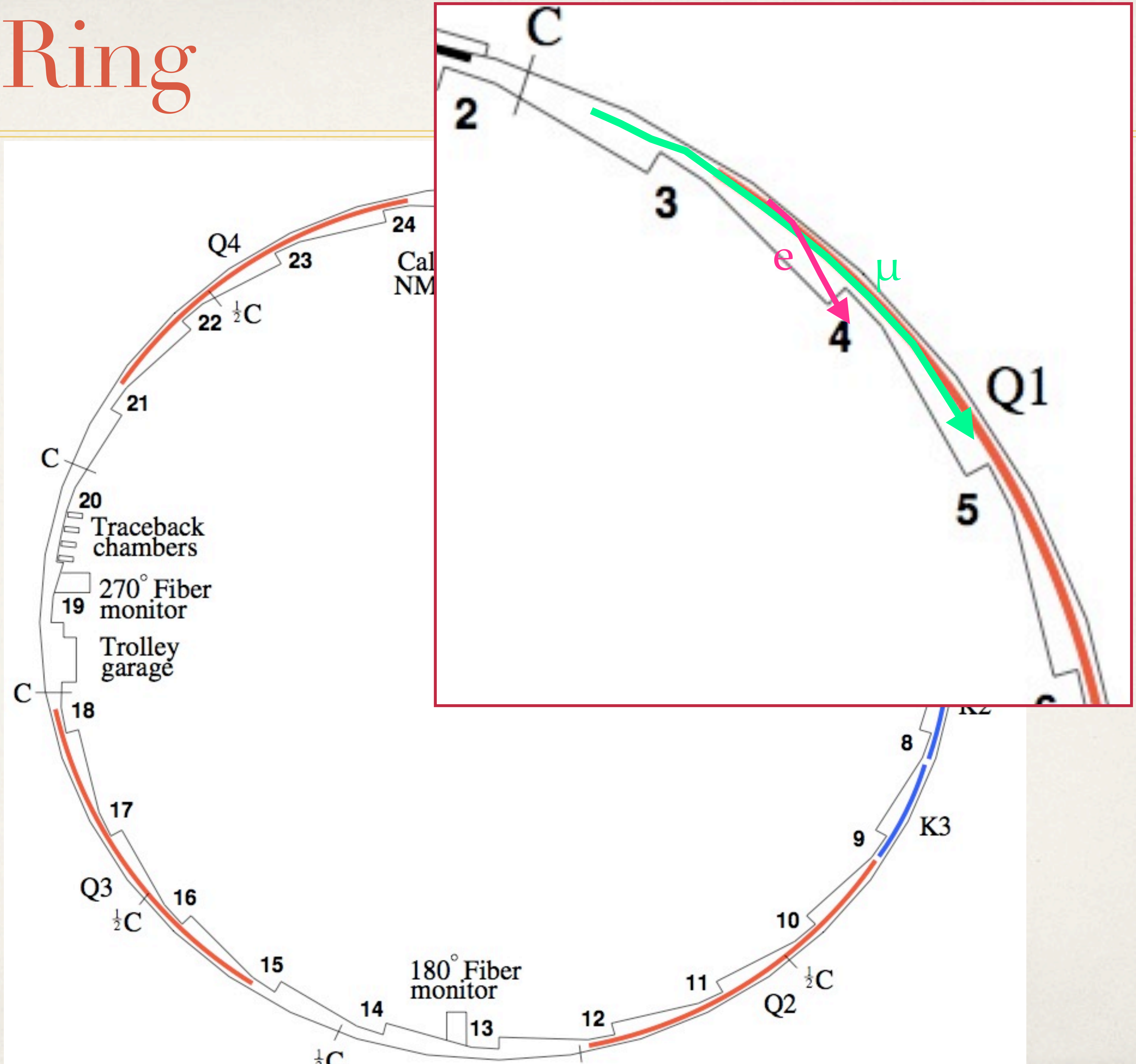
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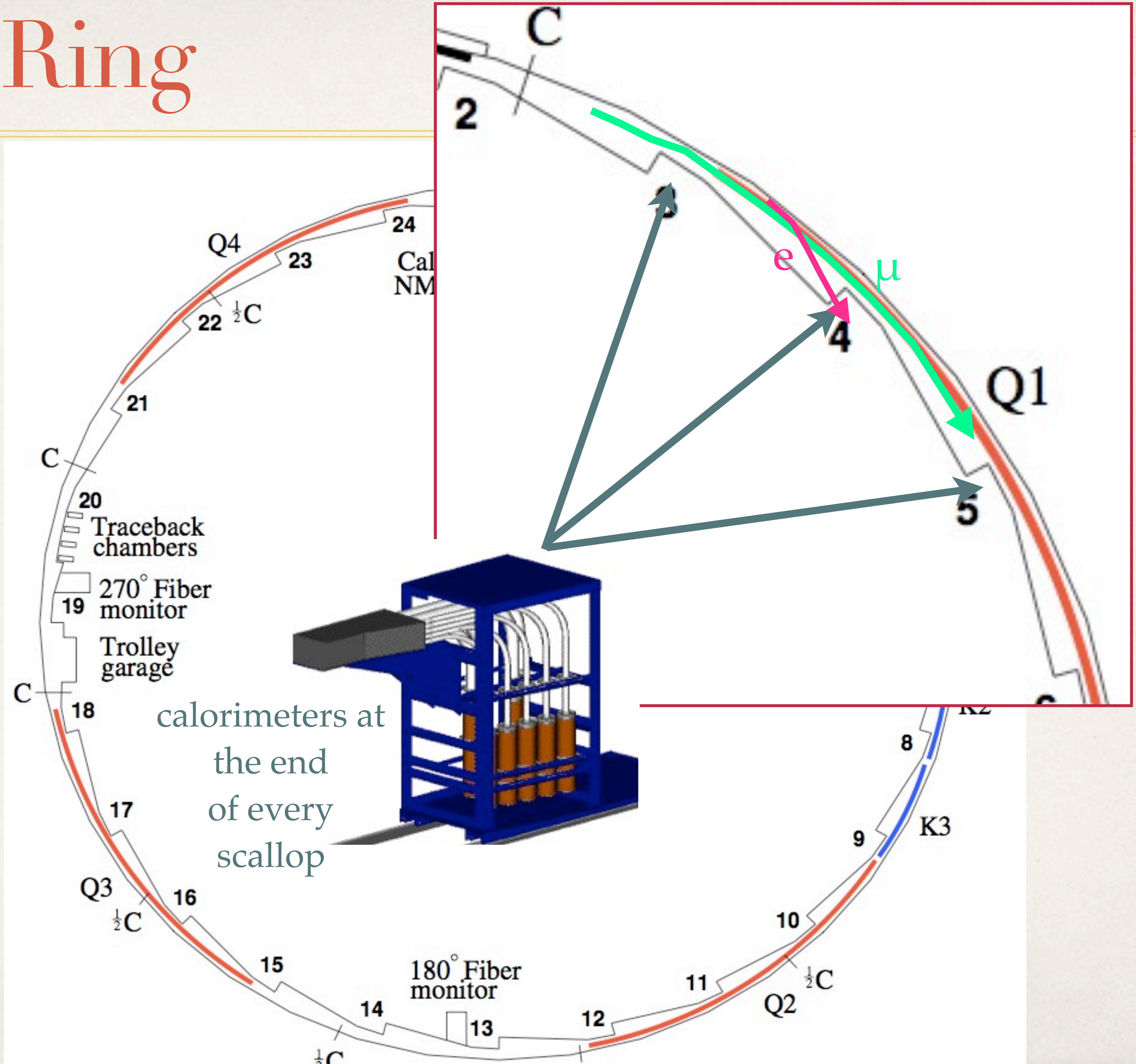

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calorimeters at the end of every scallop

Spin Precession in a Cyclotron

- Put polarized muons into a storage ring
- The Key! Take the difference of the cyclotron and Larmor frequencies:

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

angular momentum precesses about the external B field…think spinning top

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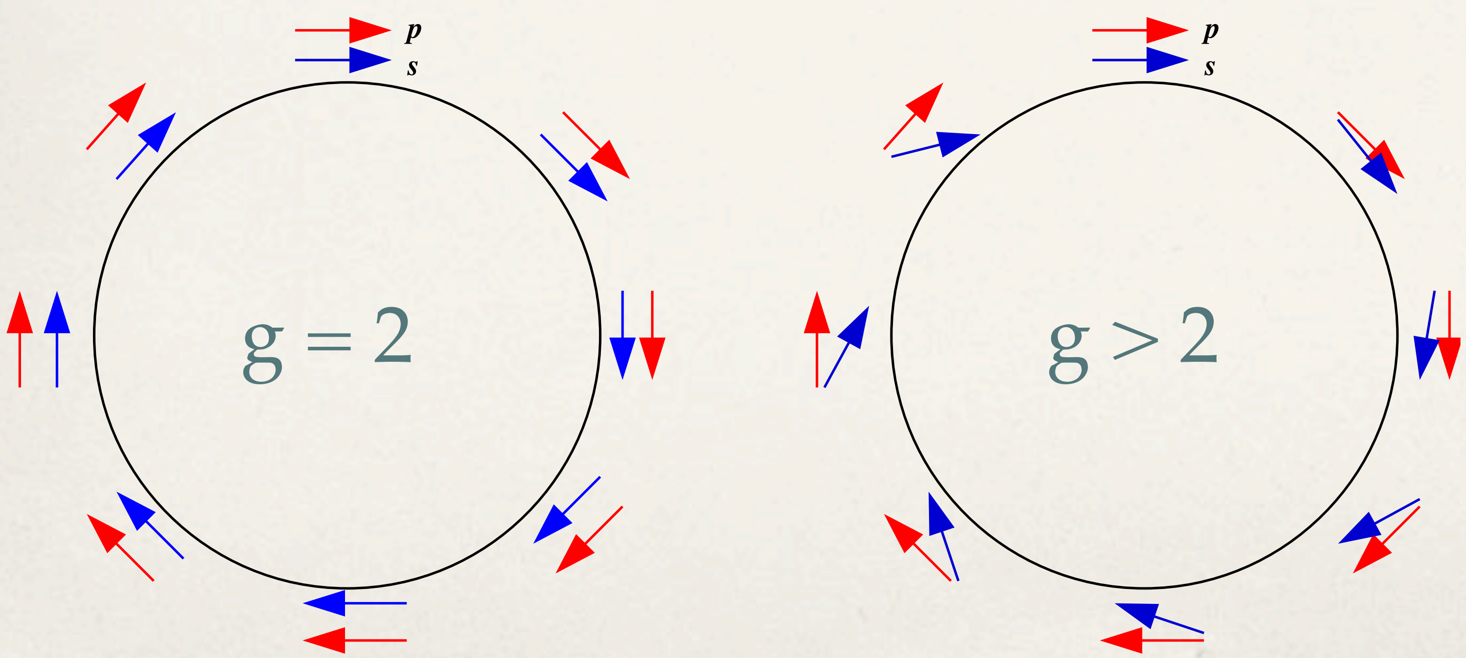

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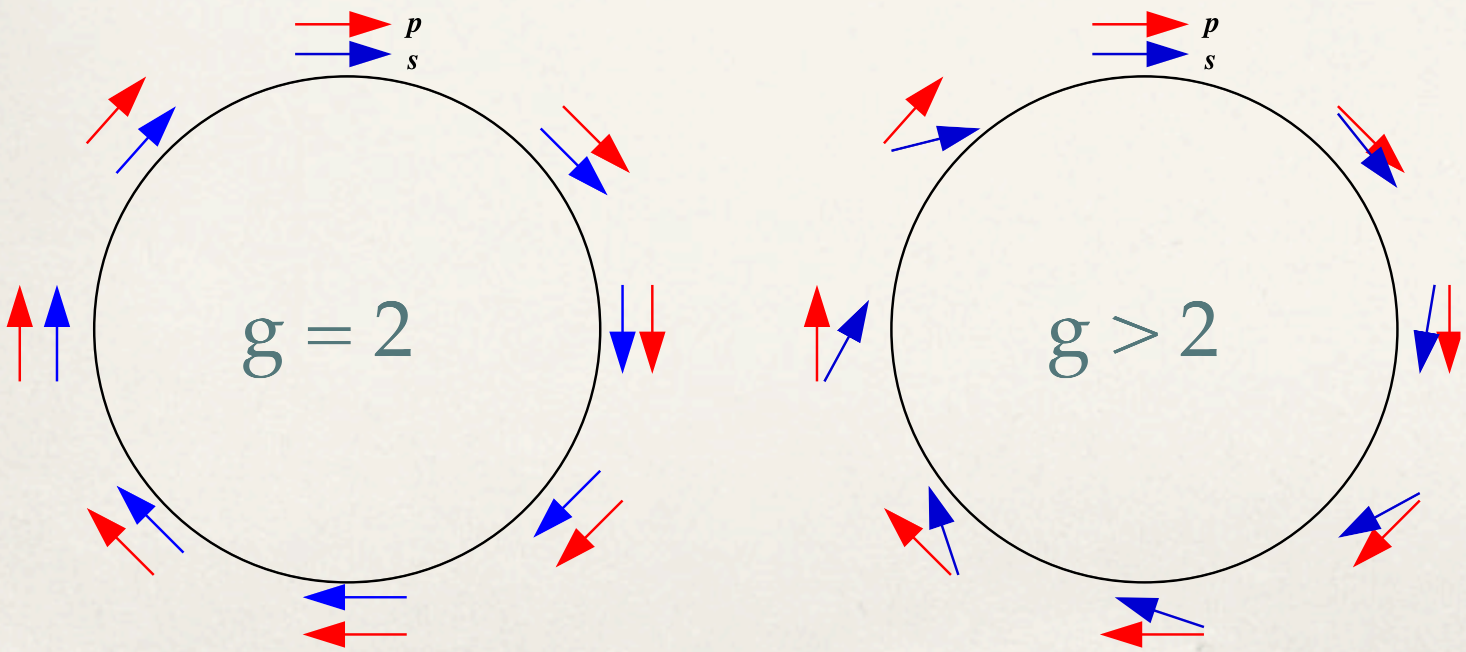
$$\omega_c = \frac{eB}{mc}$$

$$\omega_s = g\frac{eB}{2mc}$$

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



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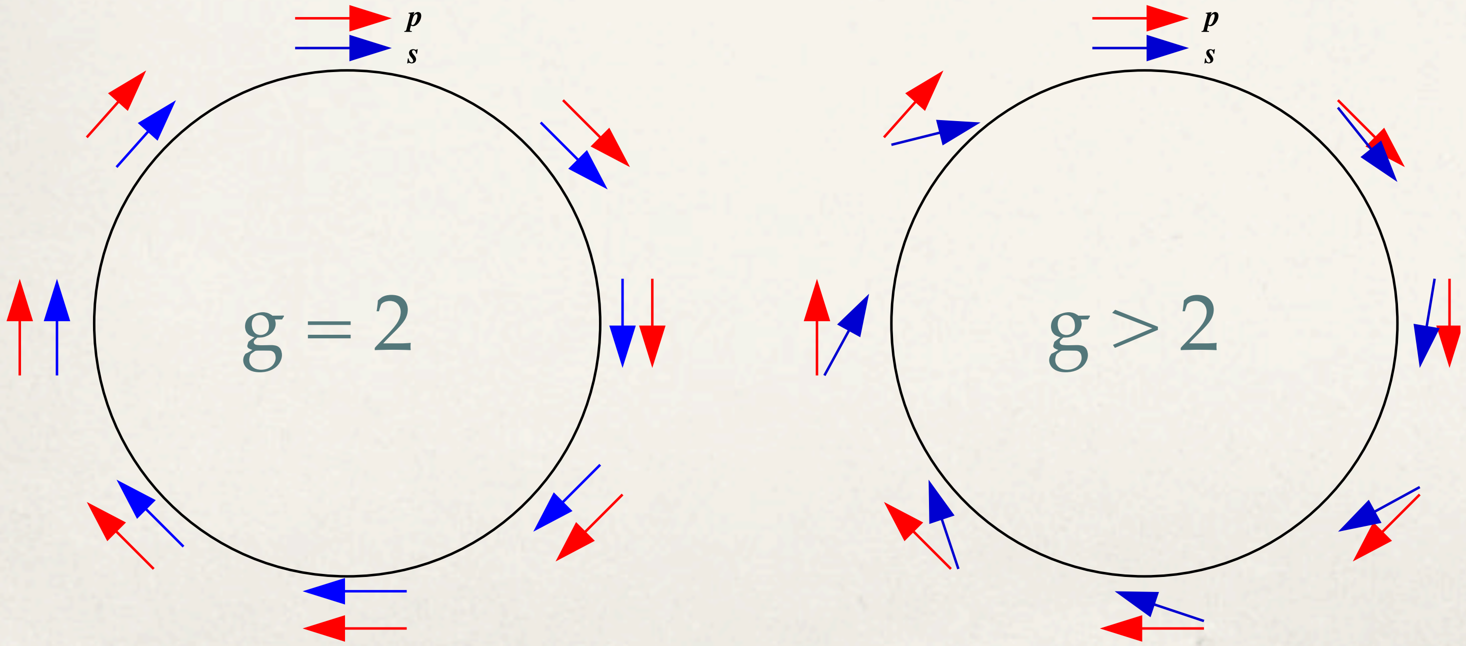

We can measure the anomaly directly by measuring the B field and the precession frequency!

Magic Gamma

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

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  - $p_{magic} = 3.09$ GeV

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  - $\gamma_{magic} = 29.3$
  - $p_{magic} = 3.09$ GeV
- Nature again is kind!
  - If a_μ had been 100 times smaller would need $p_\mu \approx 30$ GeV!

Measuring the B Field in E821

$$\omega_a = a_\mu \frac{e\textcircled{B}}{mc}$$

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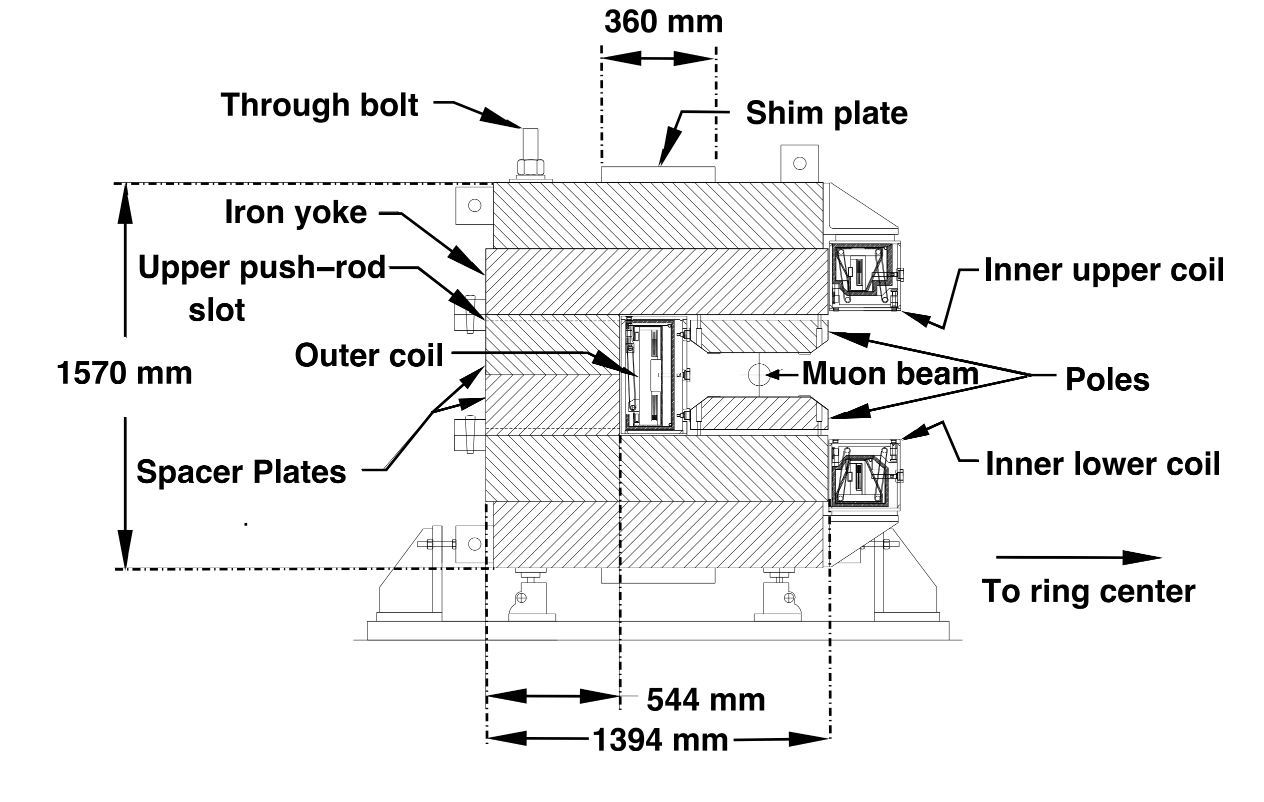
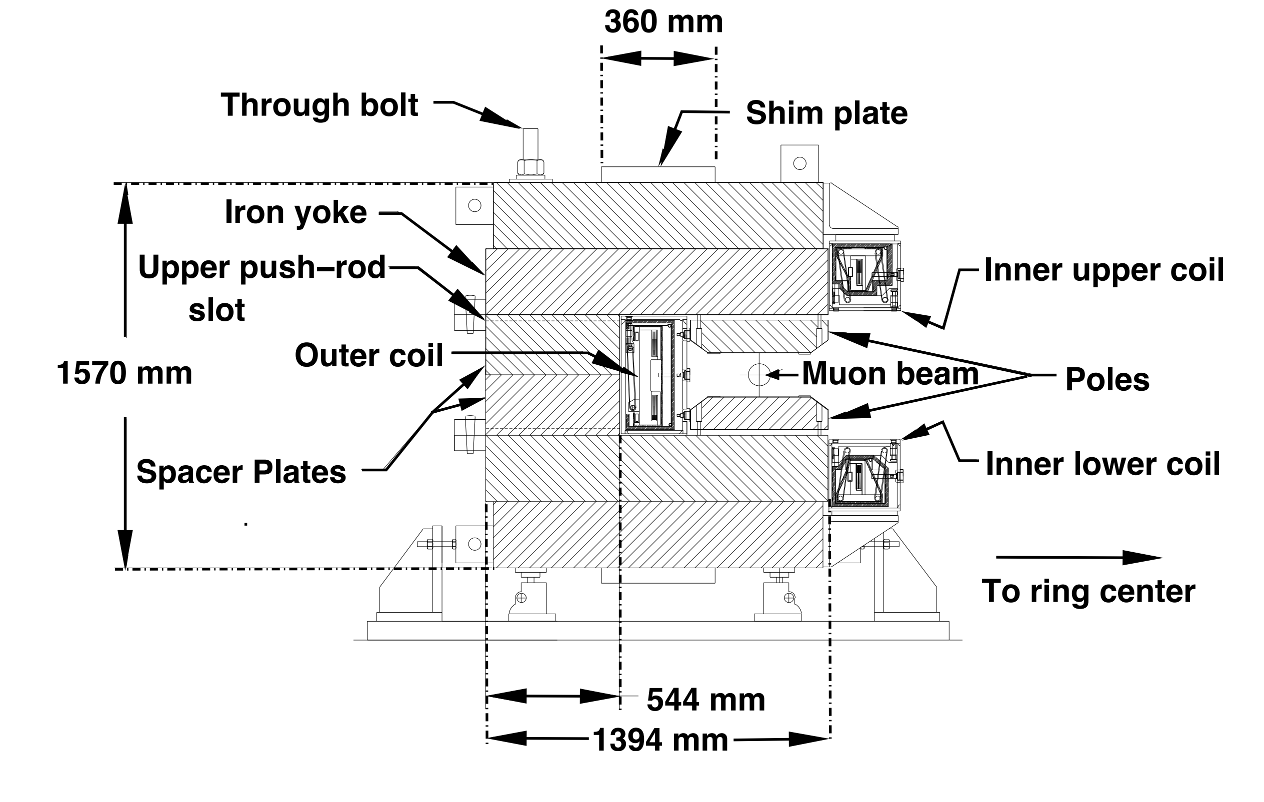
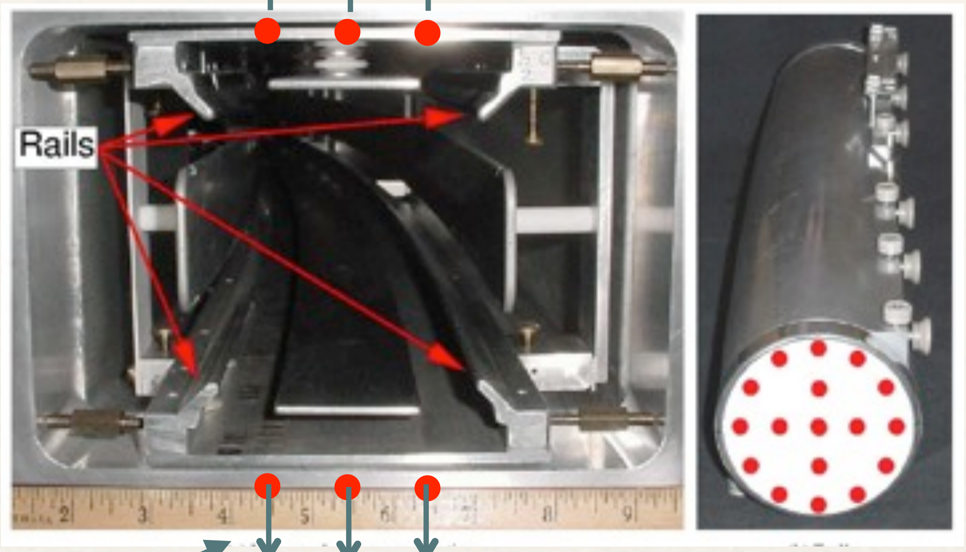


Measuring the B Field in E821

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

- Trolley and NMR probes for the measurement





360 fixed NMR probes

17 NMR probes on trolley. Map Field at 6000 azimuthal positions

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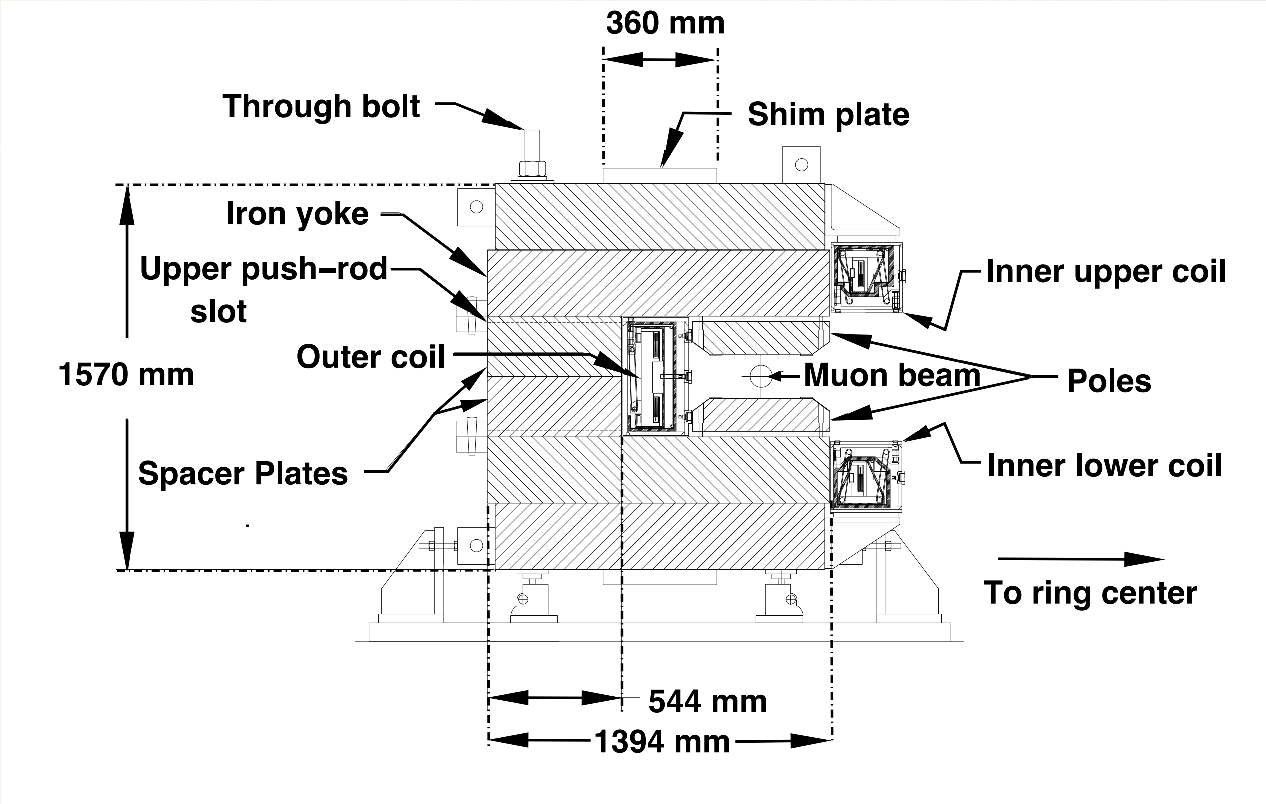

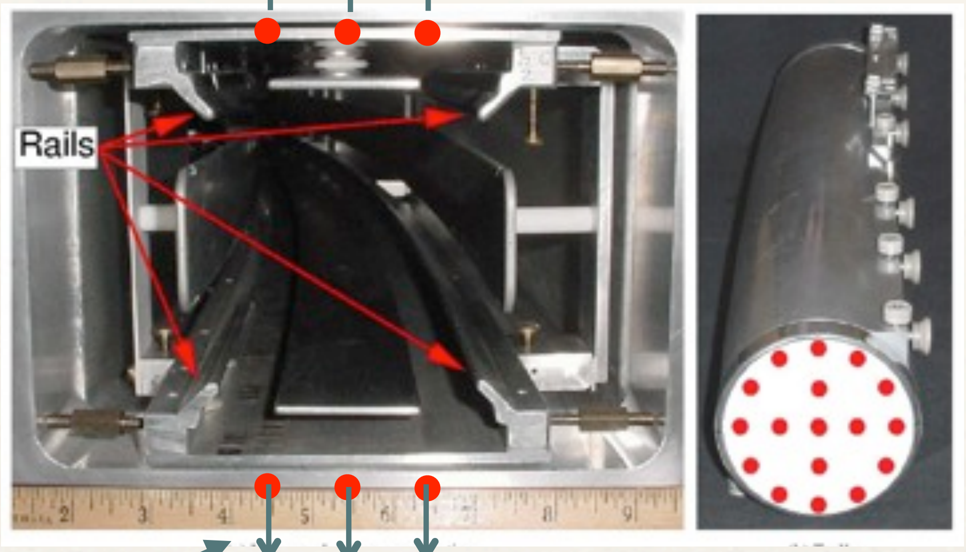

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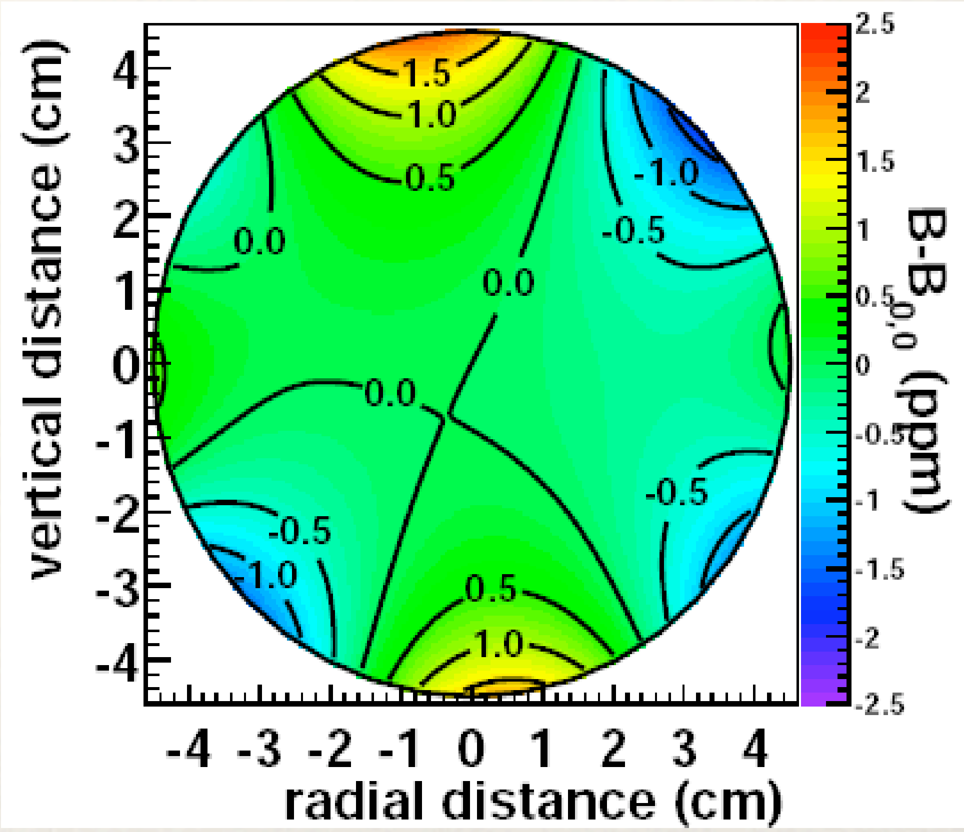


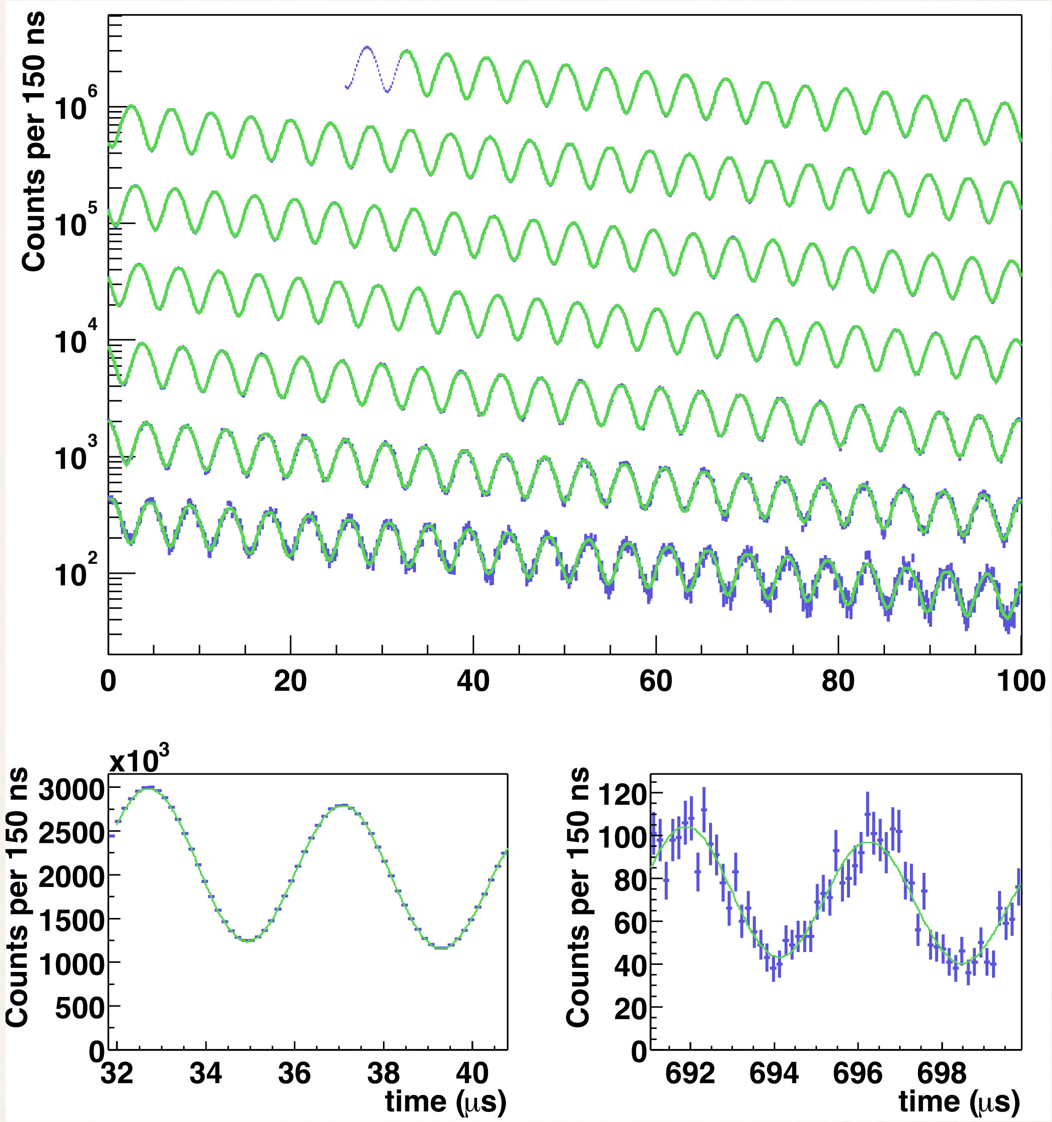
ω_a from E821

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

- Highest energy decay electrons emitted in the direction of the muon spin.
- Decay electron will measure a time distribution

$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos\left(\omega_a t + \phi\right)\right]$$

2001 data from E821



Final combined results from E821 $a_\mu^{exp} = 116\ 592\ 089\ (63) \times 10^{-11}$

Fermilab Improvements

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The statistical error alone will drop from **~0.4 ppm to ~0.1ppm**

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ω_p improvements

Source of errors	**E821 2001 (ppm)**	**E989 FNAL (ppm)**
Absolute calibration of standard probe	0.05	0.05
Calibration of trolley probe	0.09	0.06
Trolley measurements of B0	0.05	0.02
Interpolation with fixed probes	0.07	0.06
Inflector fringe field	-	-
Uncertainty from muon distribution	0.03	0.02
Others	0.10	0.05
Total systematic error	**0.17**	**0.11**

We want to drop this to 0.07 ppm.

Need more probes, better absolute and relative calibration, shimming and temperature control.

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New Tracking Detectors

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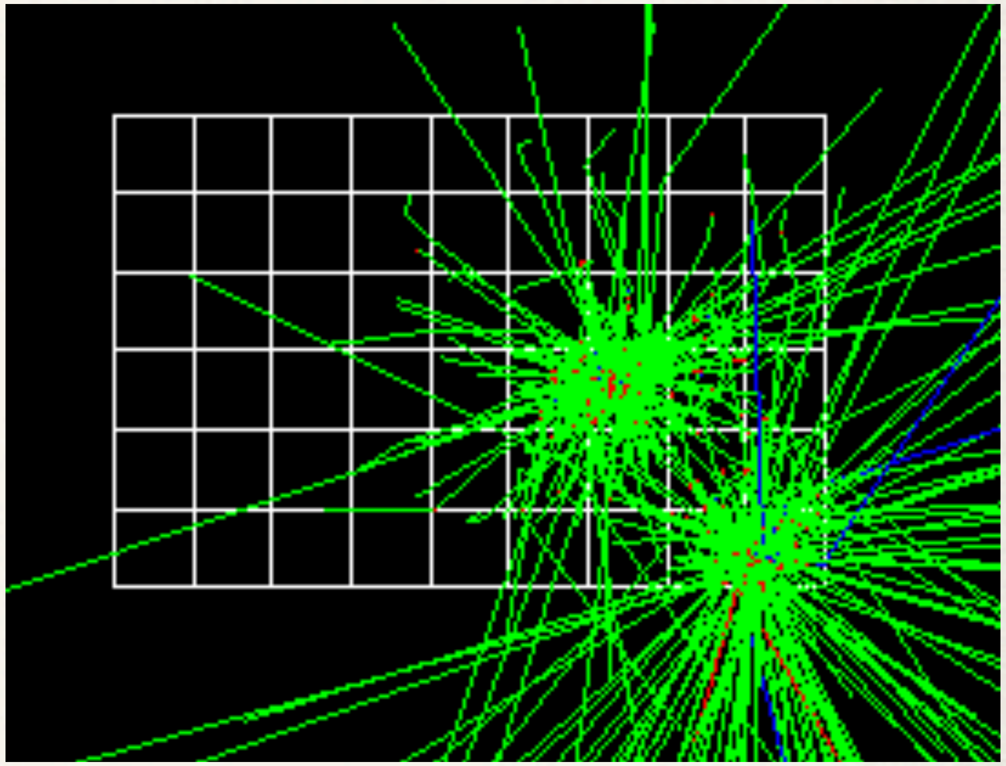
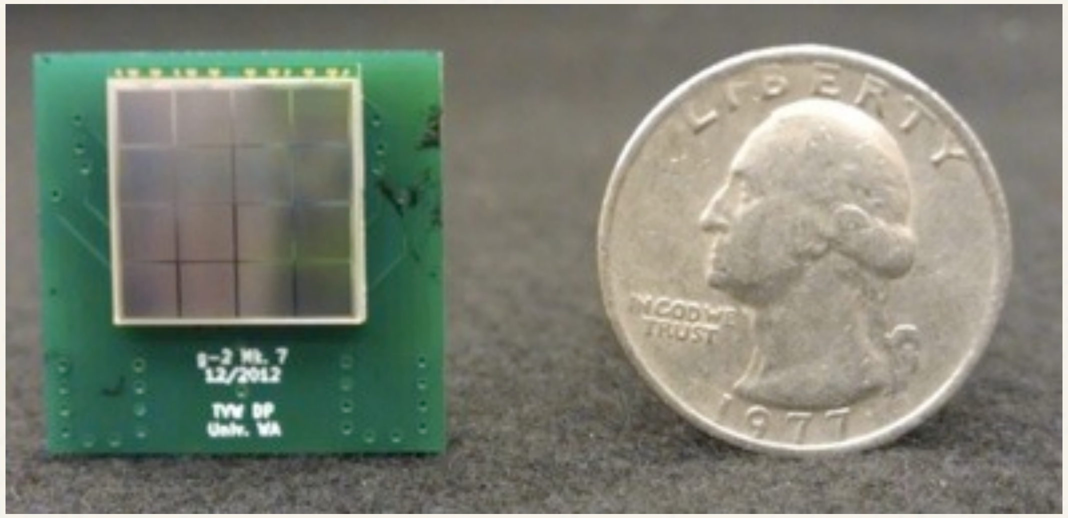
Why Fermilab? What do you Get?

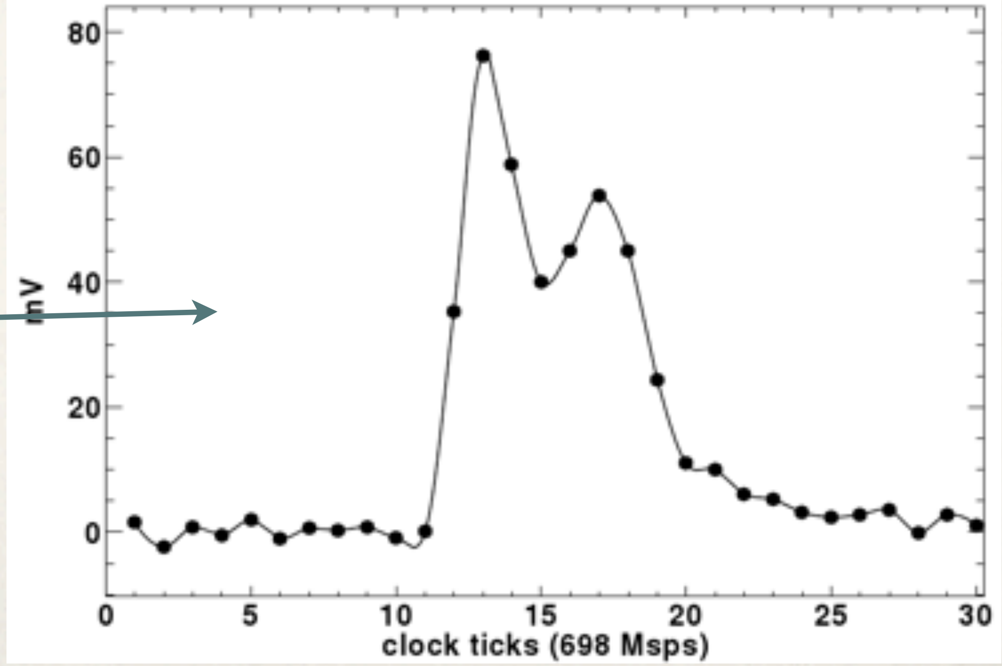
- New muon program at Fermilab is established
  - g-2 is a part of this
- Existing infrastructure in the form of beam lines and antiproton source
  - More beam. Which means more statistics.
    - 21 times more statistics than at E821
  - Longer beam line
    - 1900m decay line
      - 20x longer than BNL
      - No pion background, hadronic flash

Calorimeter Upgrades

- Segmented crystal calorimeters
  - Helps with pileup systematics
  - Change from E821
- Using Silicon PhotoMultipliers for detection on the back of each crystal

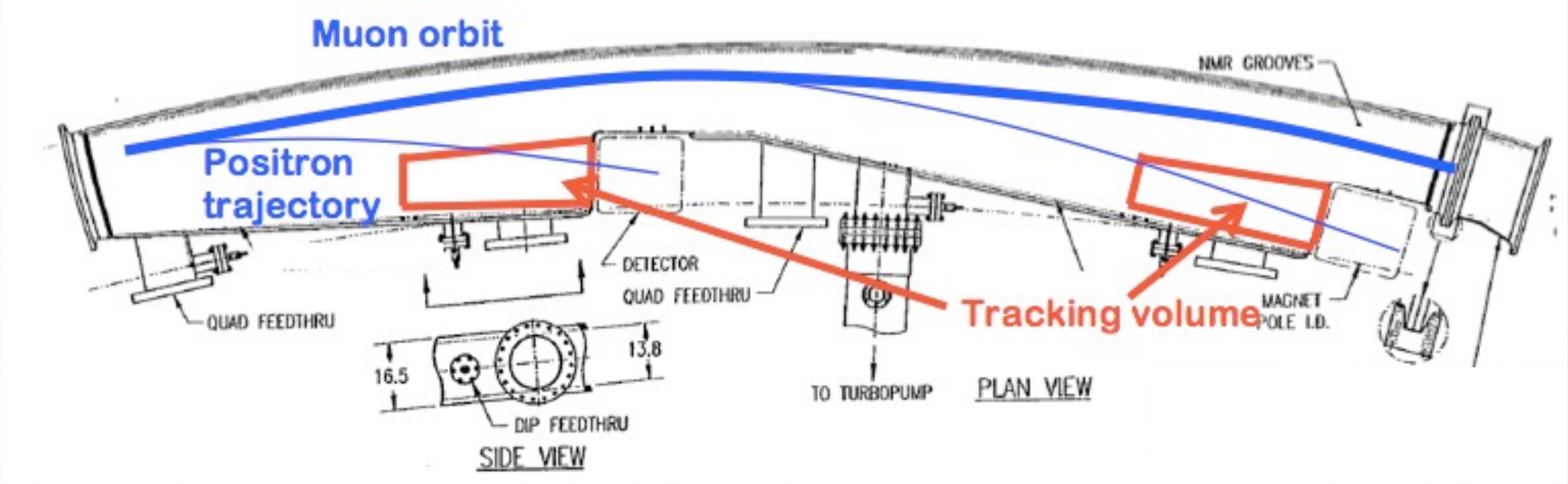






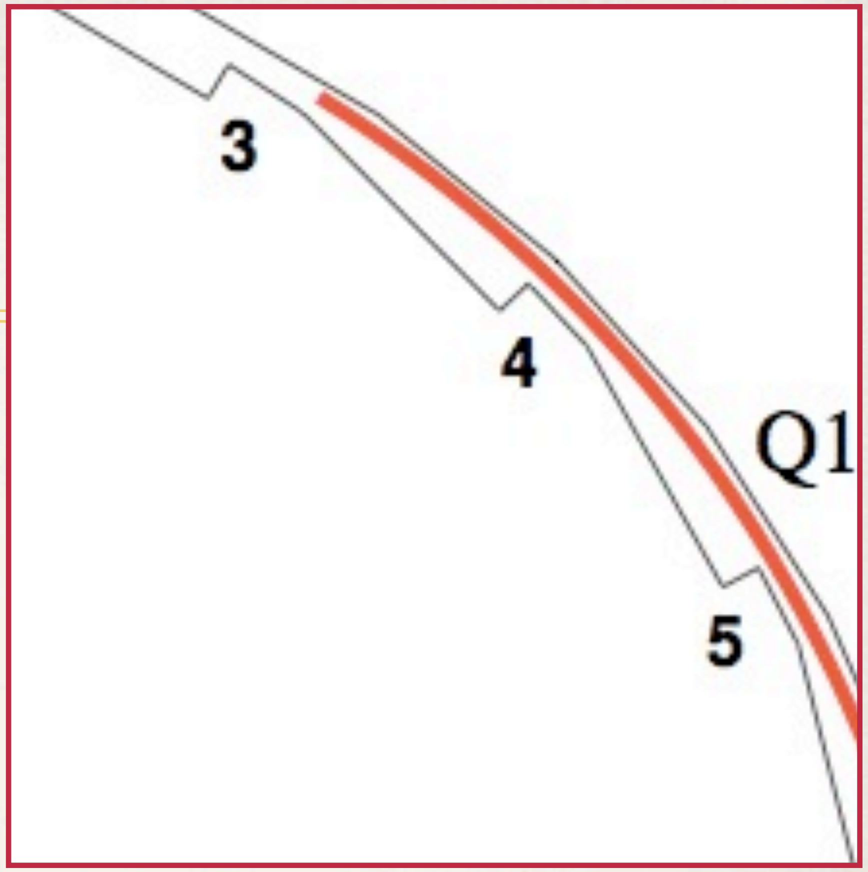
Two pulses from laser directed directly at SiPM separated by 5ns

Why Have a Tracker?



- Calibrate beam dynamics
  - Determine the momentum of the muons
    - Because they can't all be at exactly the magic momentum
  - Betatron motion of the beam leads to ppm corrections to ω_a
  - Want mm resolution of the beam profile
- Better measurement of the pileup
  - Information on multiple positrons hitting the calorimeter

Tracking detectors



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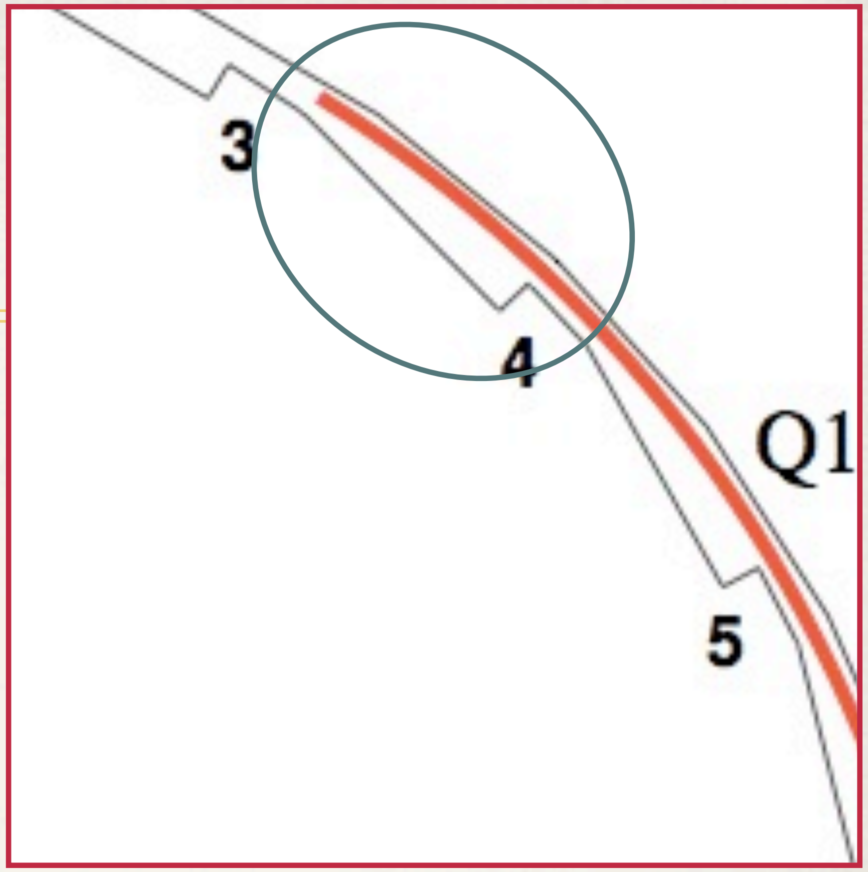

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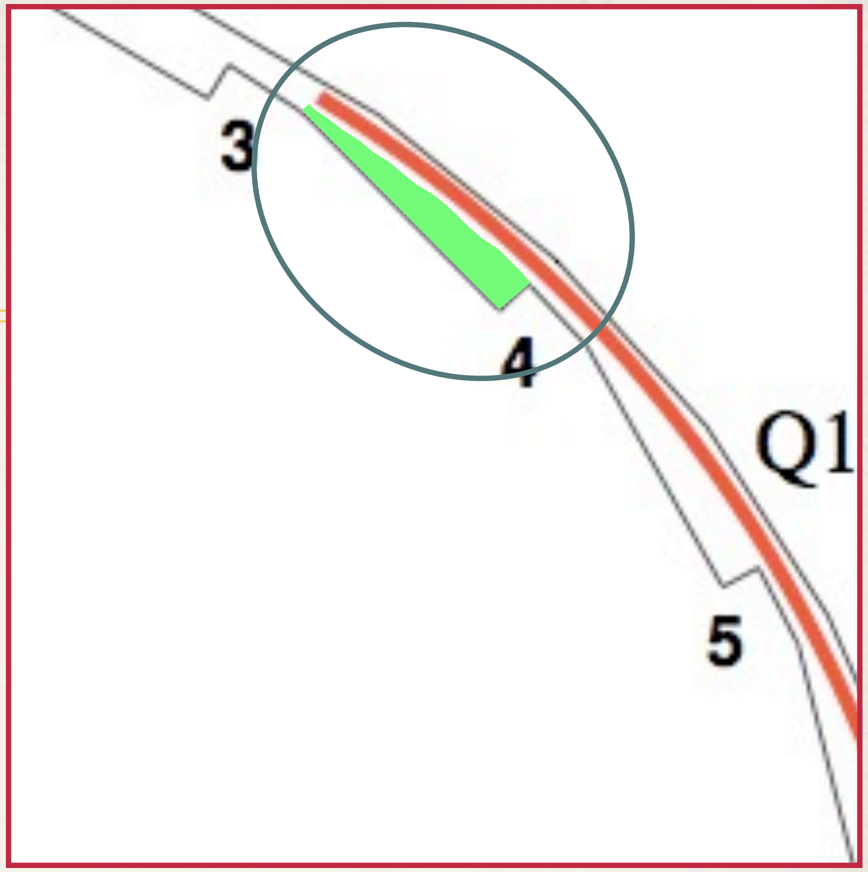

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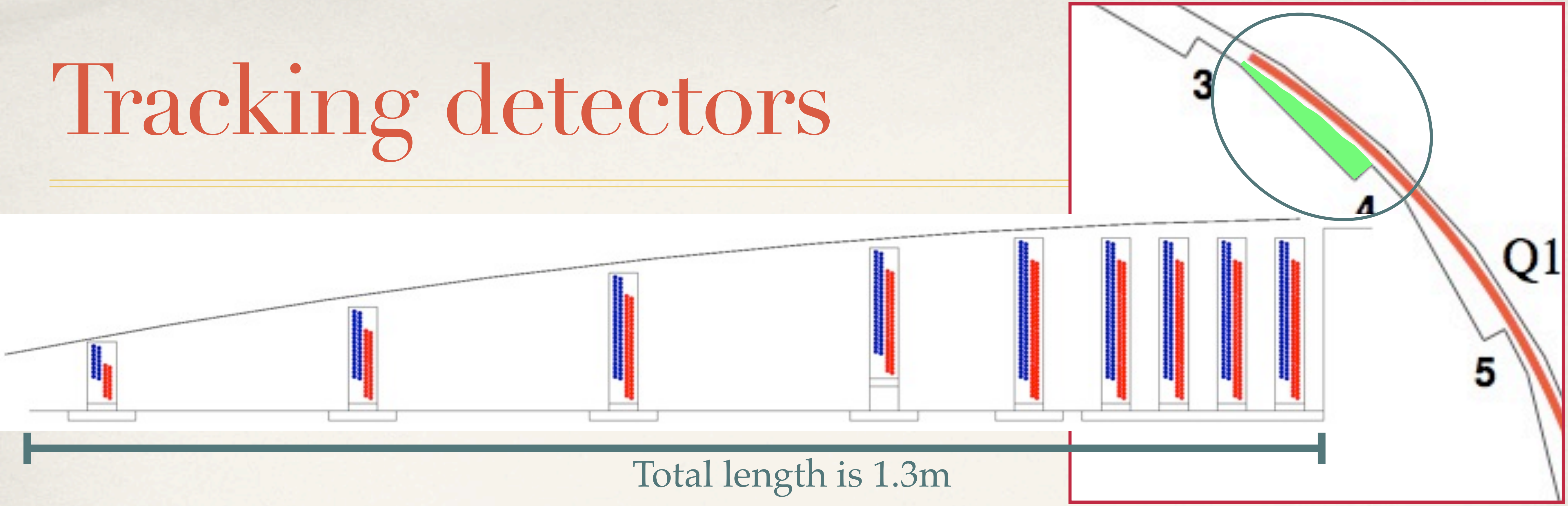
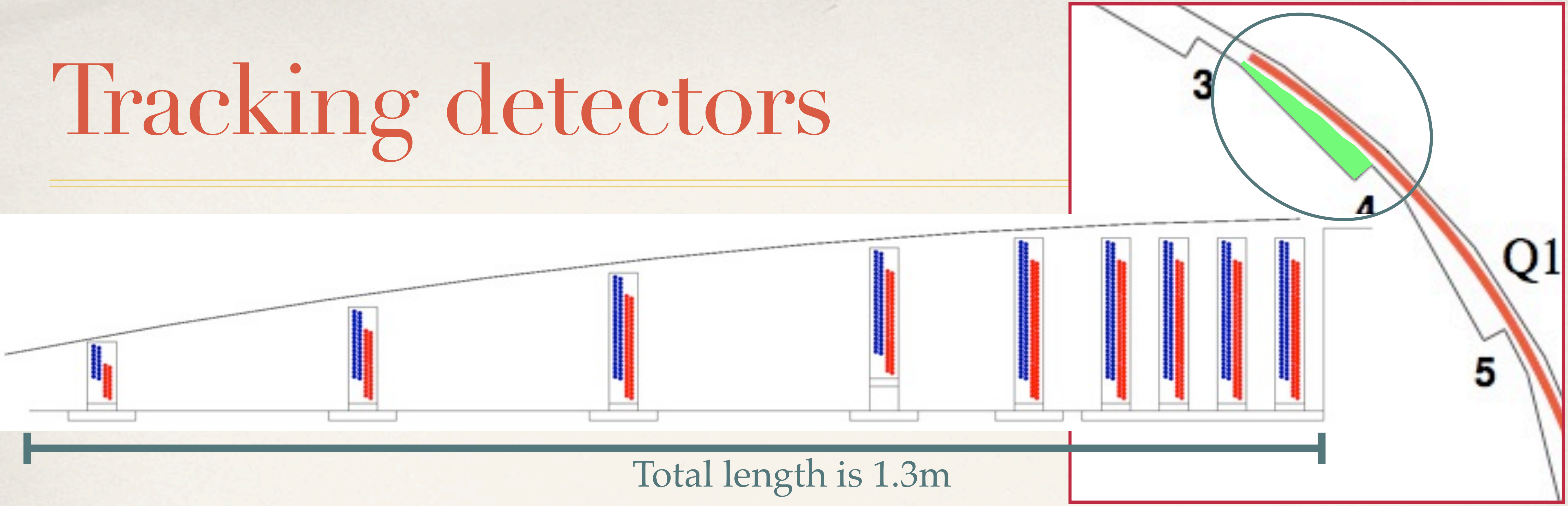
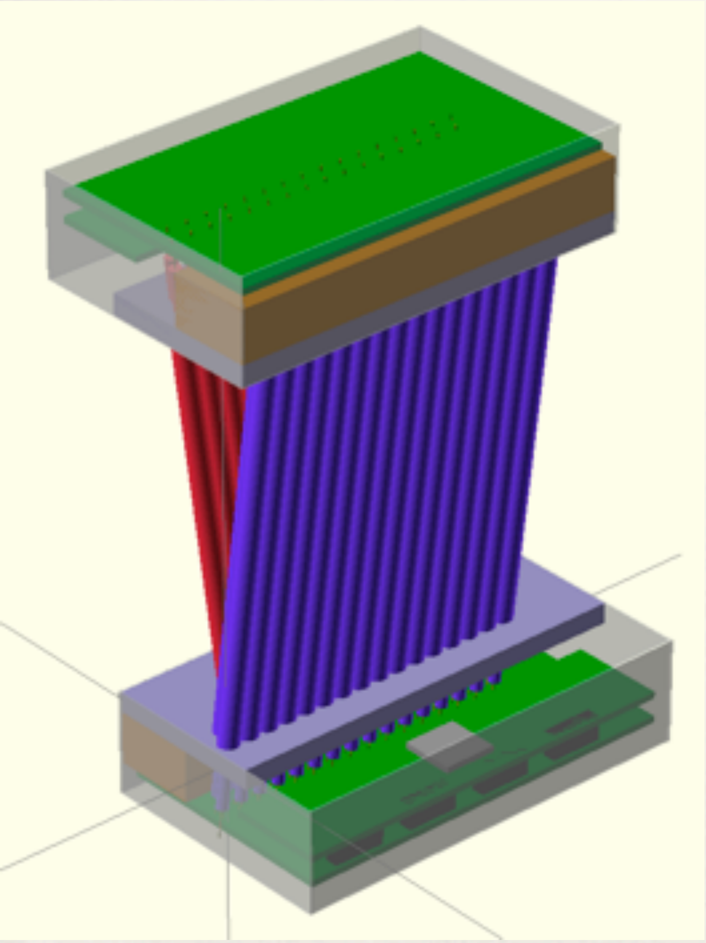


Total length is 1.3m

Tracking detectors



Each station is a doublet of UV straw chambers.



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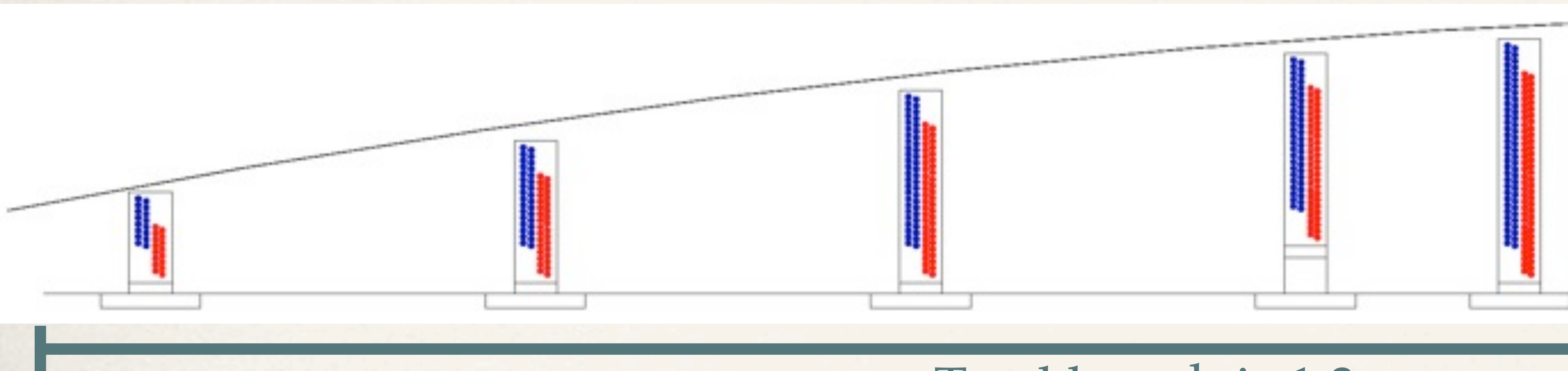

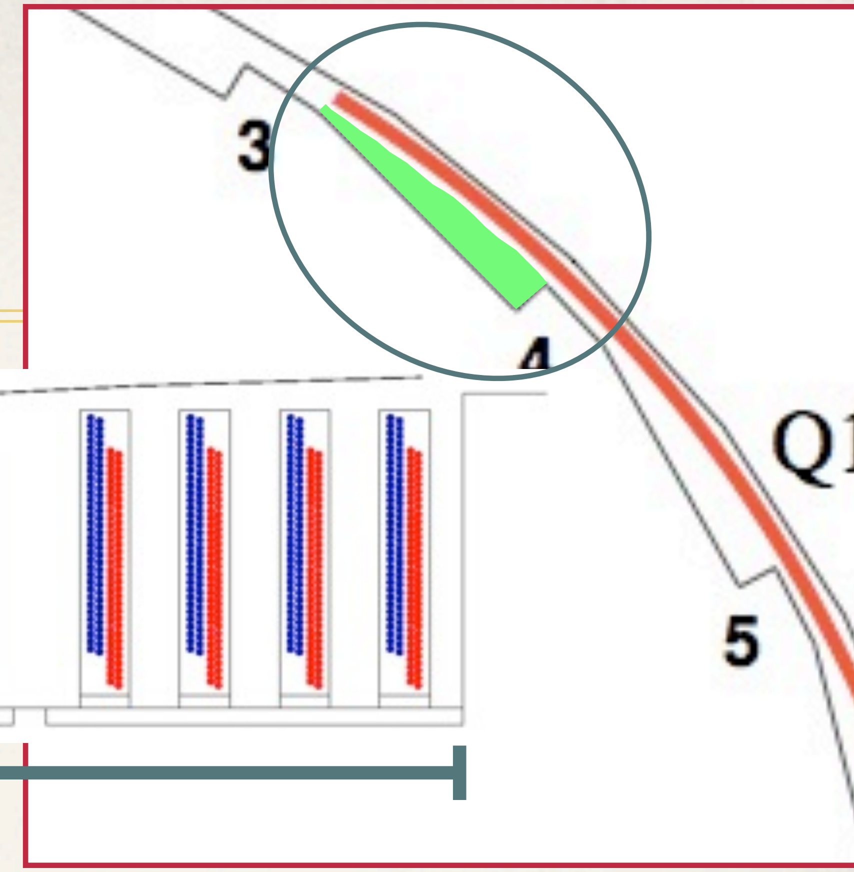

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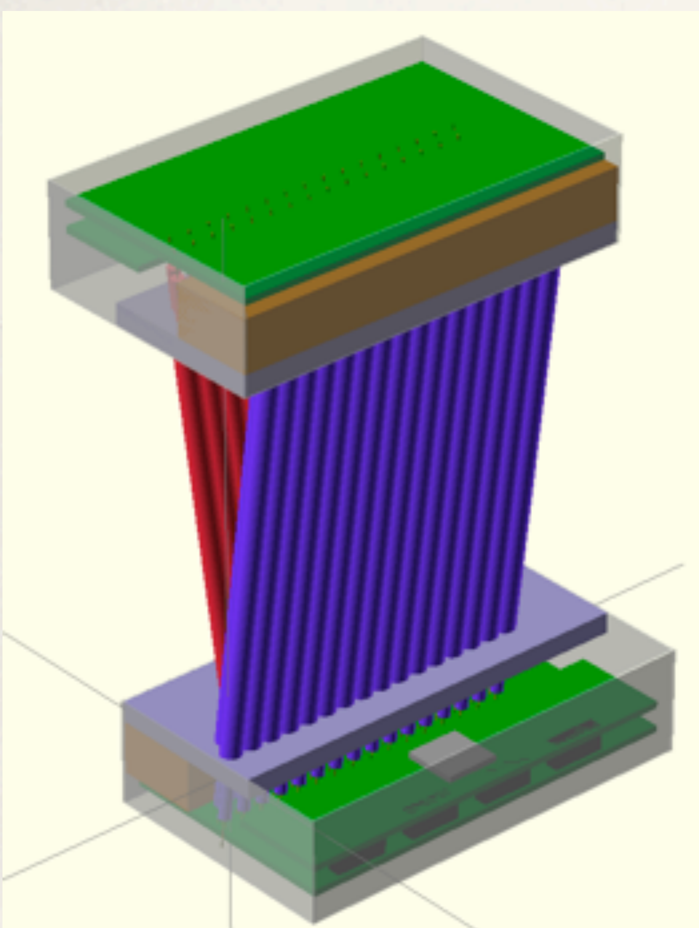

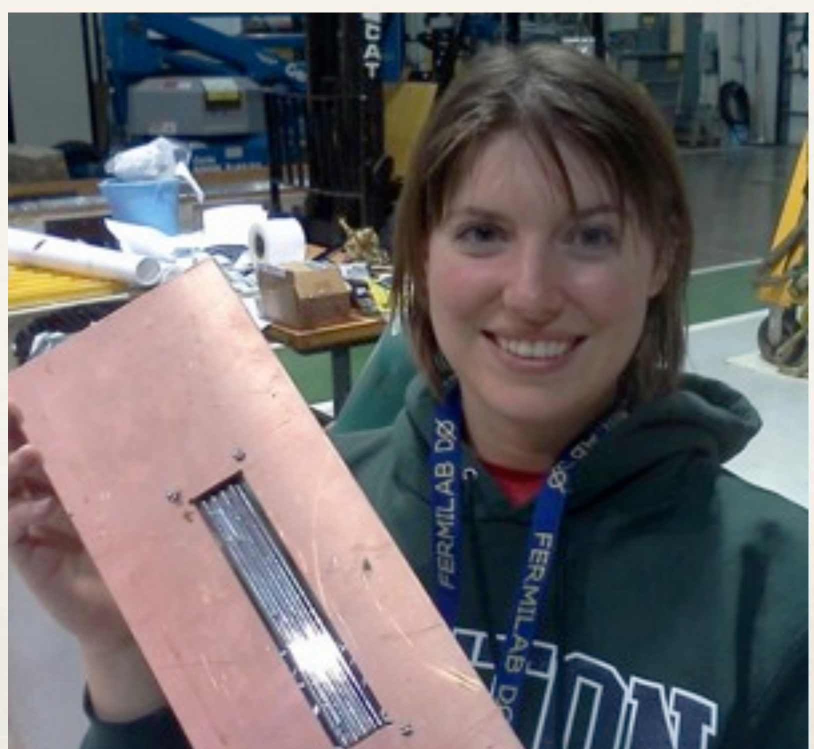

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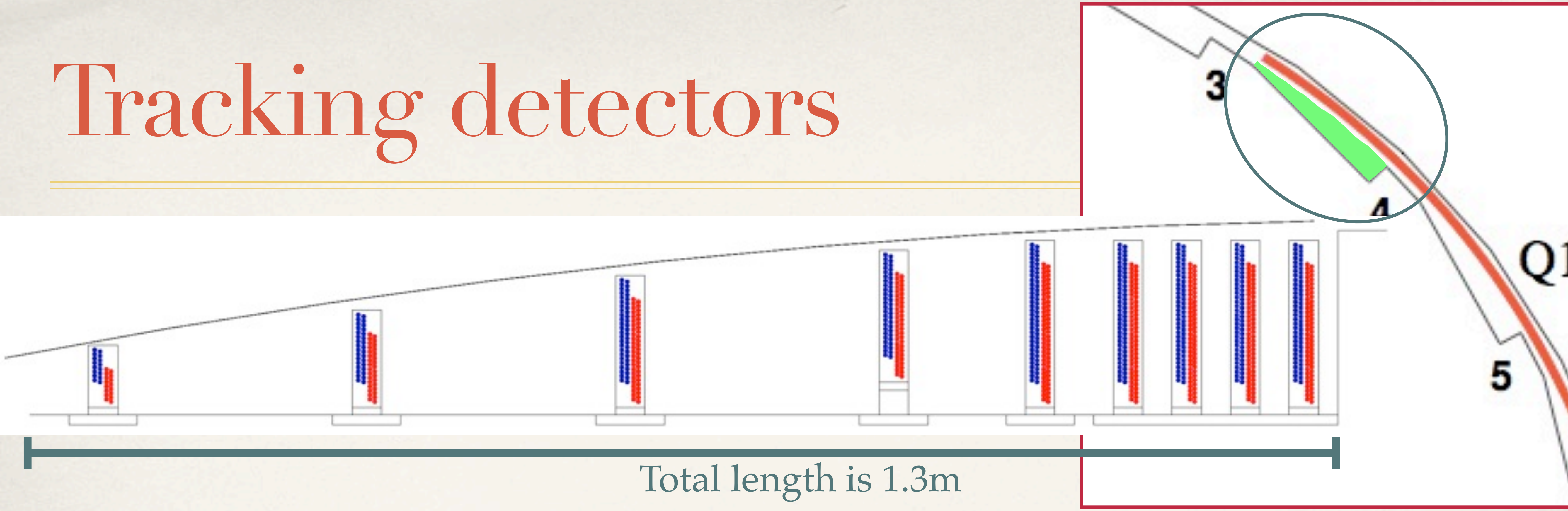

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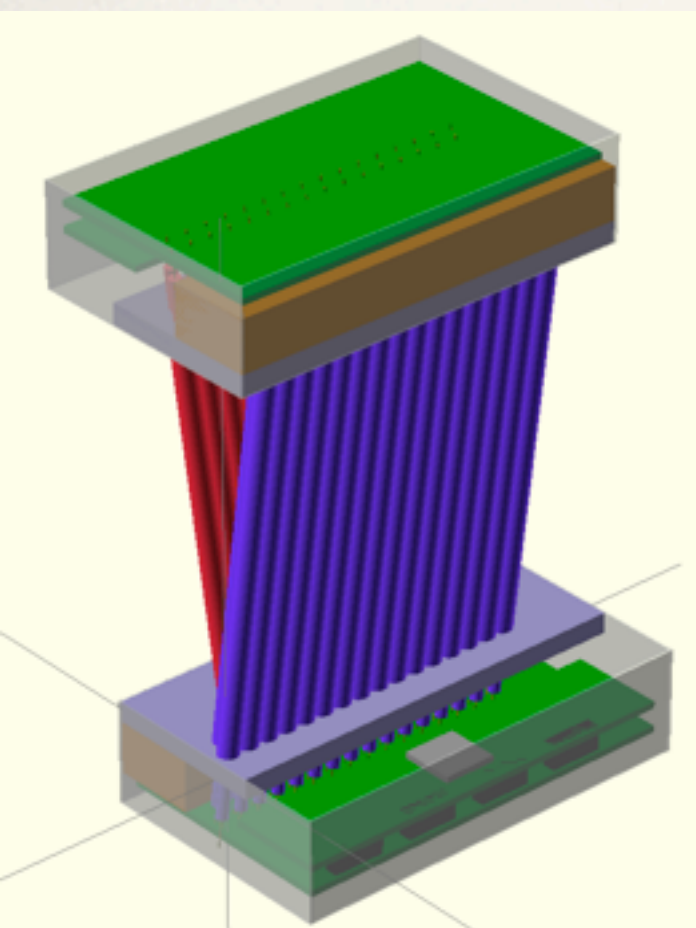
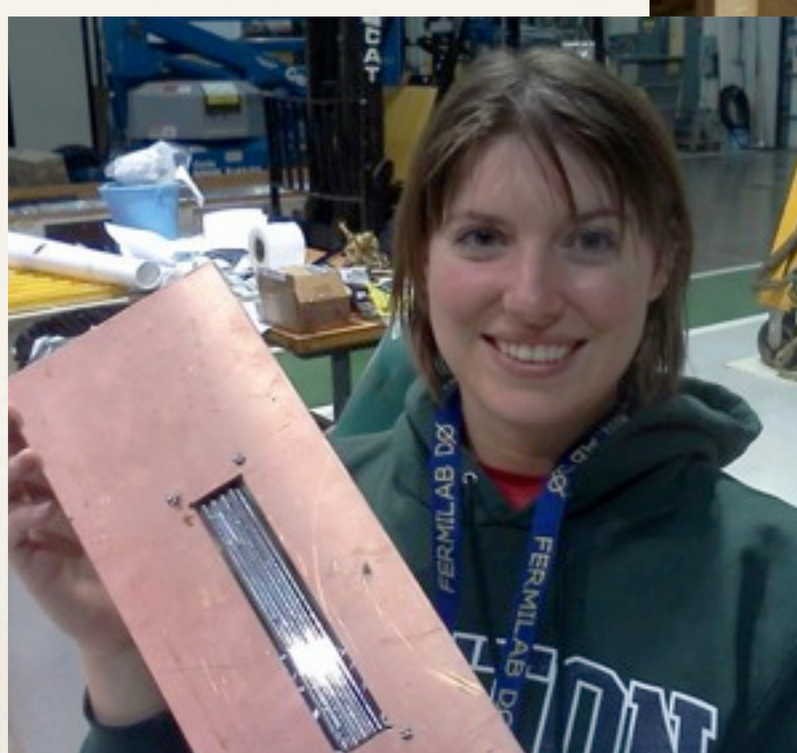
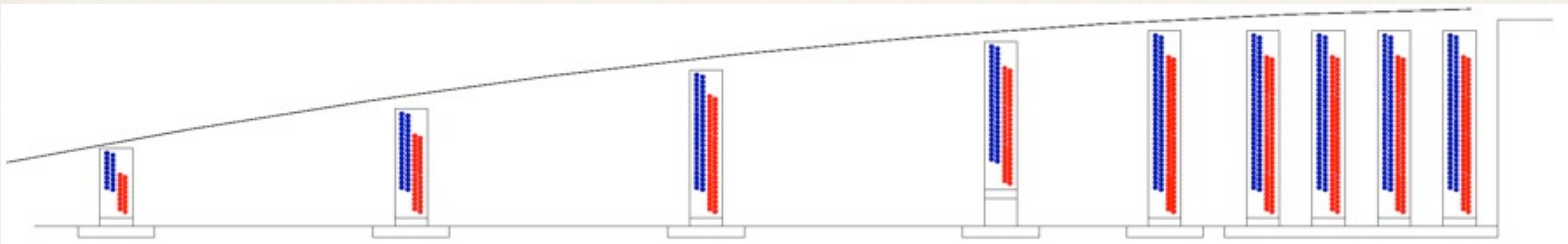
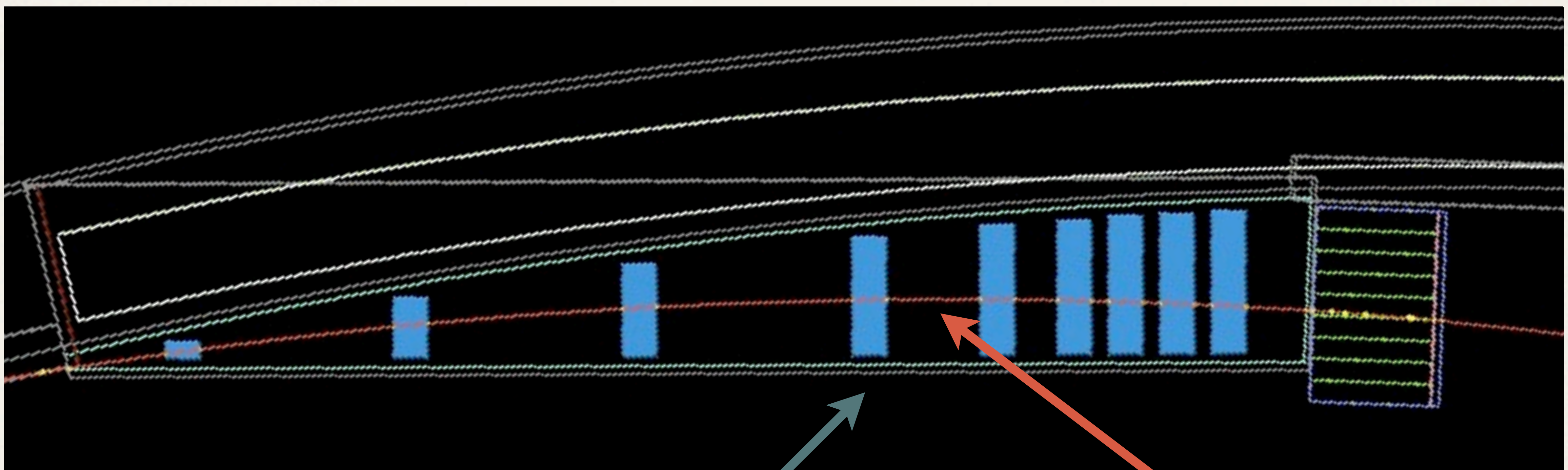




"Ship in the bottle" tests

Geant4 Traceback Detectors





Geant4 Sensitive tracking detectors in place and easy to move for testing purposes.

Track!

Updates at Fermilab

Feature

Second muon experiment receives Mission Need approval from DOE

This rendering shows the location of the proposed Muon Campus at Fermilab. The arrow points to the proposed site of the planned Muon g-2 experiment. Click to enlarge. *Image: Muon Department/FESS*

Fermilab's plans for creating a Muon Campus with top-notch Intensity Frontier experiments have received a big boost. The Department of Energy has granted Mission Need approval to the Muon g-2 project, one of two experiments proposed for the new Muon Campus. The other proposed experiment, Mu2e, is a step ahead and already received the next level of DOE approval, known as Critical Decision 1.

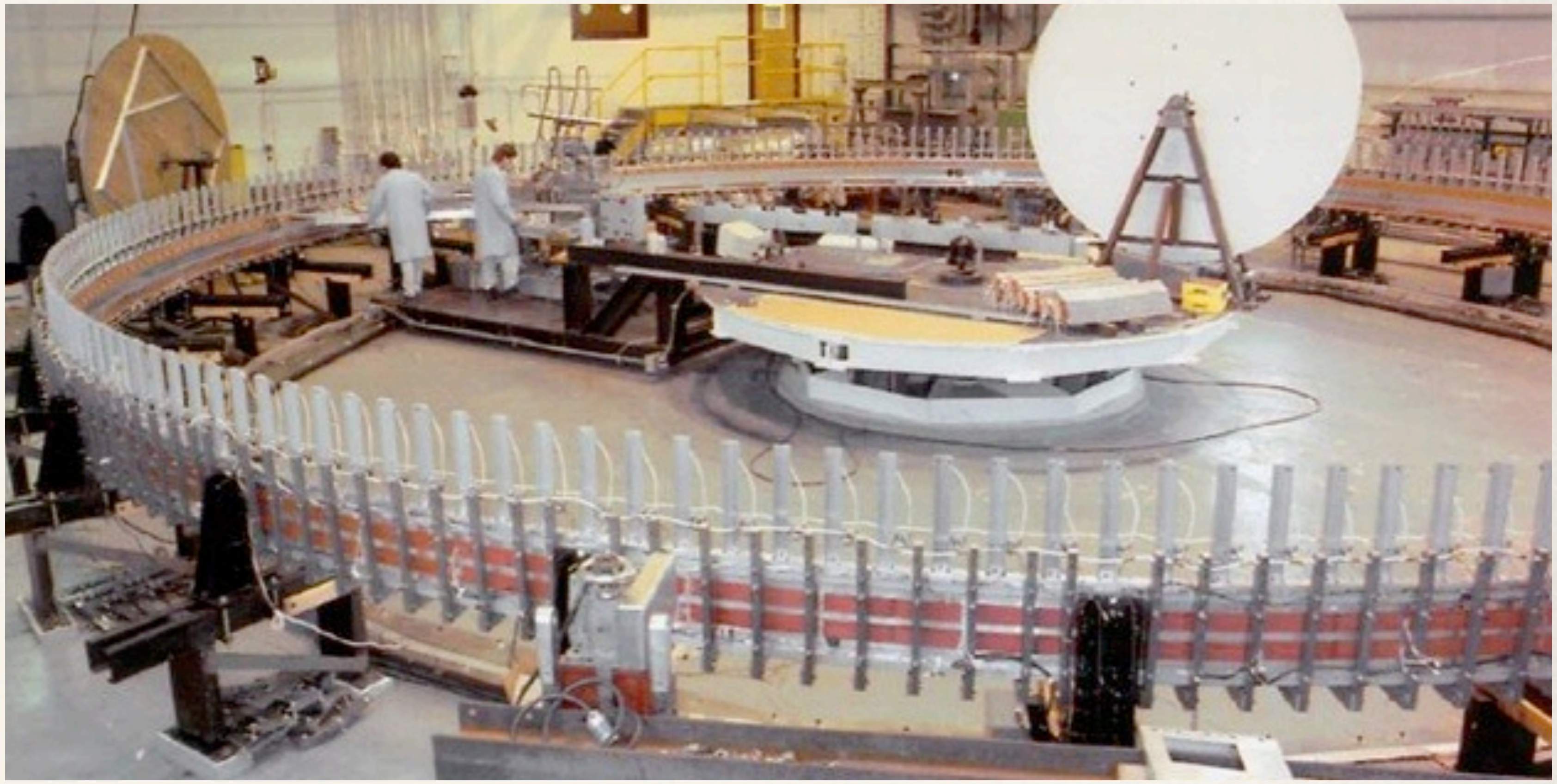
"We now are officially on DOE's roadmap," said Lee Roberts, professor at Boston University and co-spokesperson for the roughly 100 scientists collaborating on the Muon g-2 (pronounced gee minus two) experiment. "This should make it easier to increase the size of our collaboration and foster international participation. Potential collaborators supported by the National Science Foundation or foreign funding agencies will be happy to see that we now have DOE's official Mission Need approval."

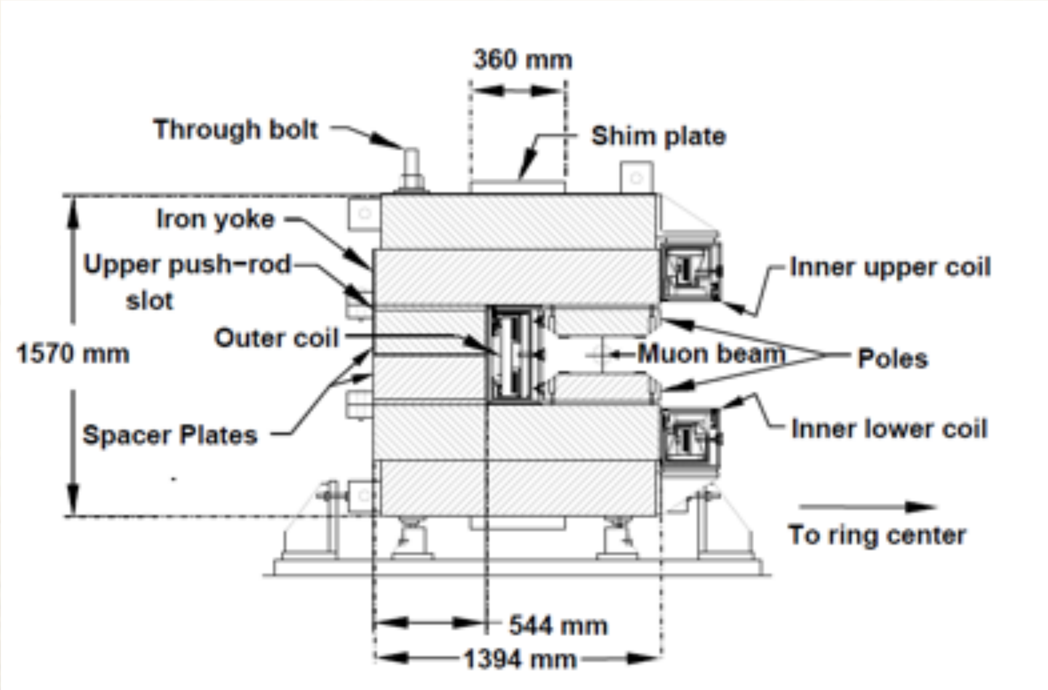
At present, the Muon g-2 collaboration includes scientists from institutions in

Current Funding = CD0!

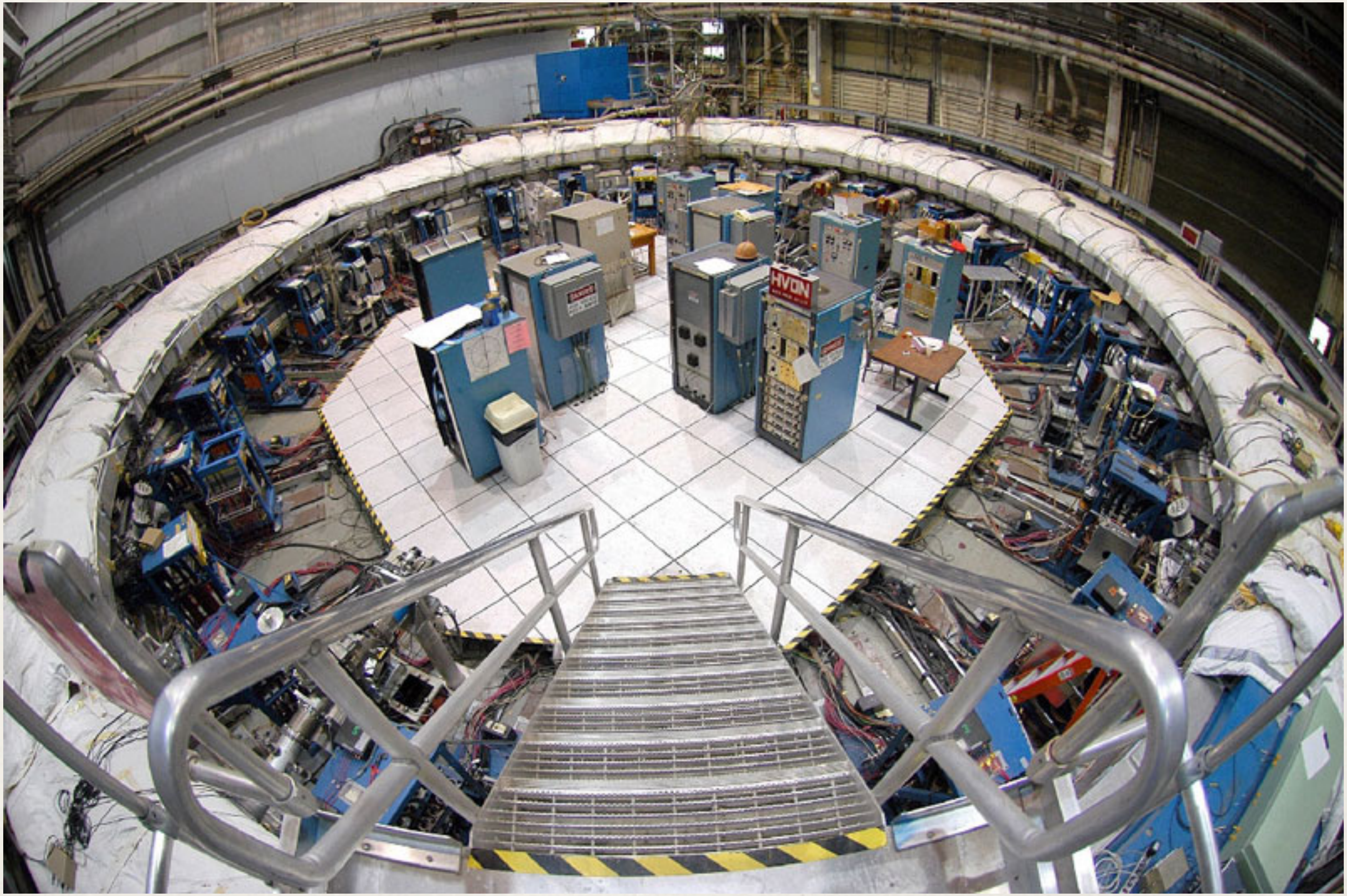
Move. That. Ring.

- The plan for the g-2 experiment at Fermilab is to reuse much of the ring from the AGS E821 experiment.
  - The storage ring.
  - The magnets
- That means disassembly. And moving.
- Why keep the old ring?
  - Money!
  - 50′ ring is continuous superconducting coils and pole pieces





End of E821



Summer 2011

Summer & Fall 2012

First yoke piece taken apart on September 28, 2012

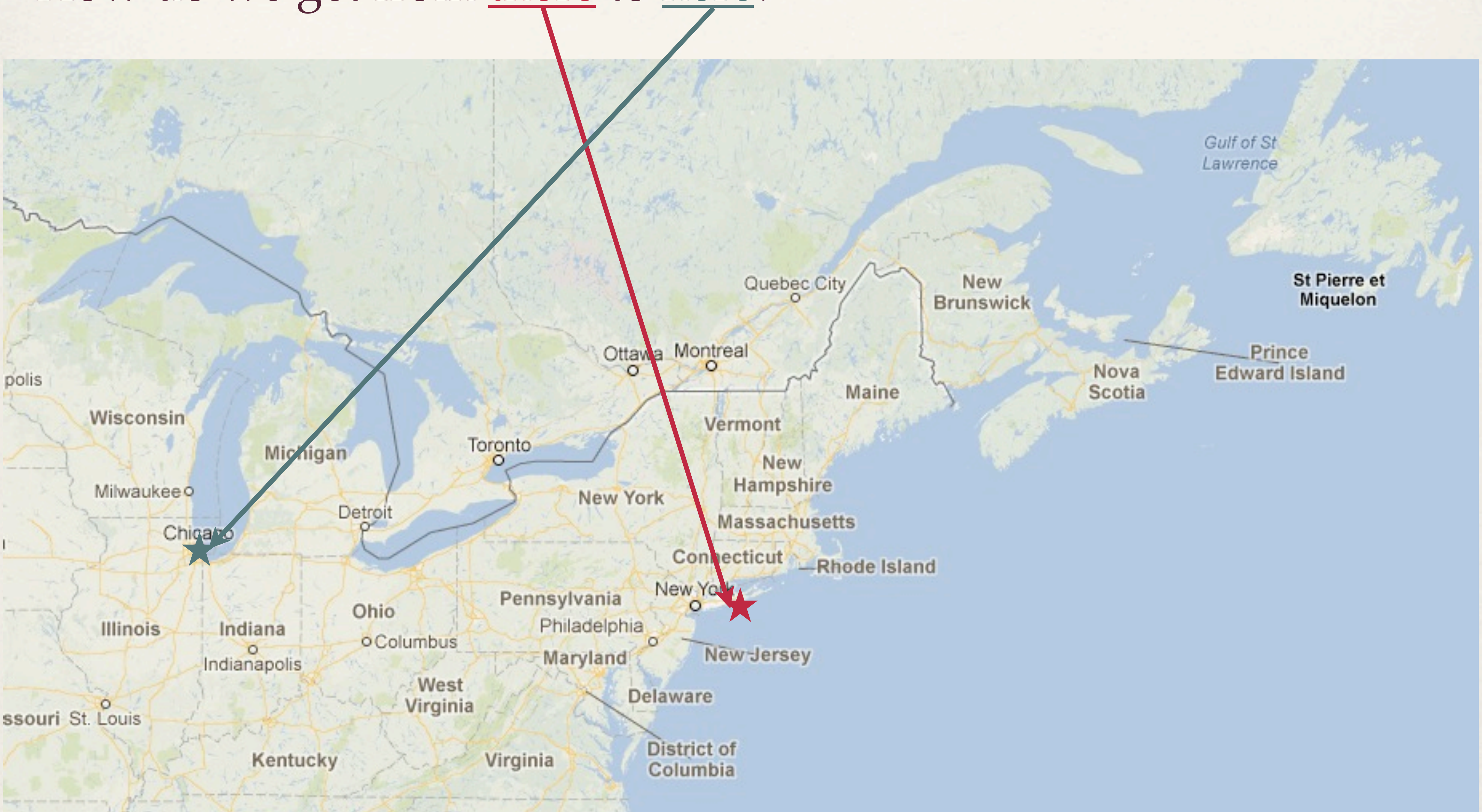
September 30, 2012

- All yokes removed. The ring is completely bare.

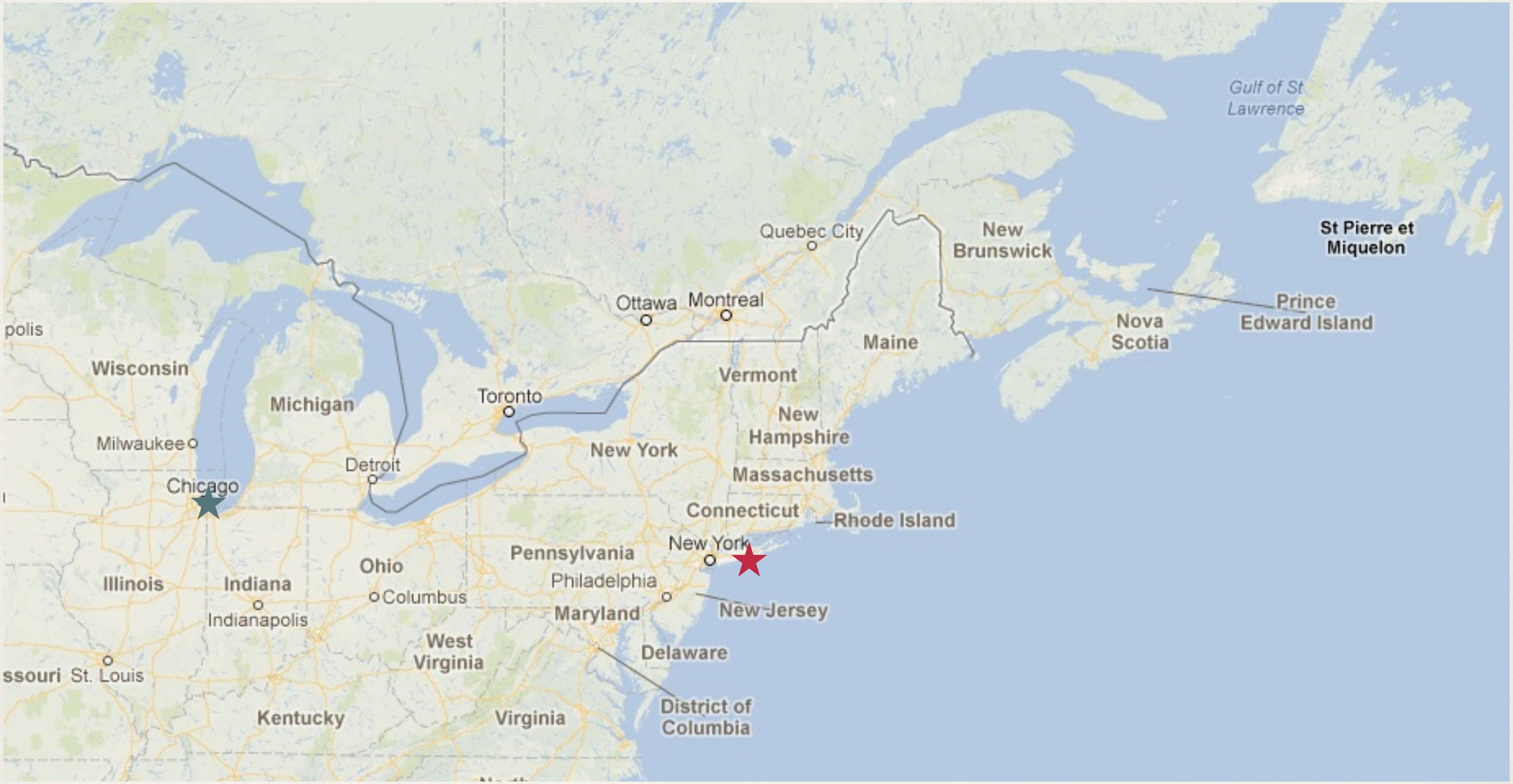
Can see this 14.5m continuous ring.
This is what is moving.

New York to Chicago

- The 50′ cryostat needs to be moved as is
- How do we get from there to here?



Transporting to Illinois



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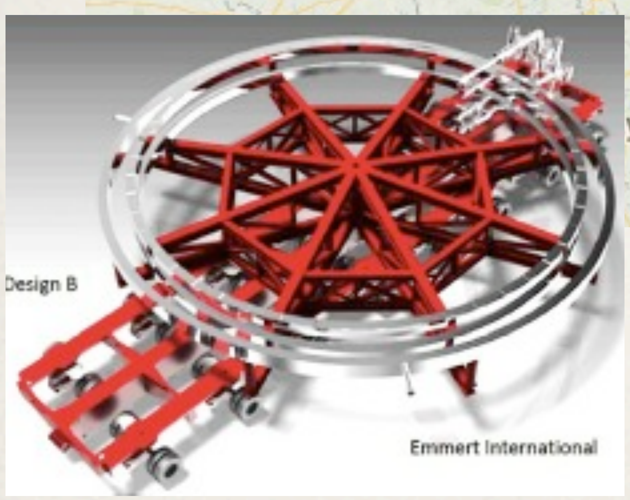


*Note there is a possibility that we will take the southern route around Florida and up the Mississippi. Either way it involves transit on a barge.

Transporting to Illinois

- We have to fit through the tolls booths!
- It's tight with only 30cm to spare.

Transporting to Illinois

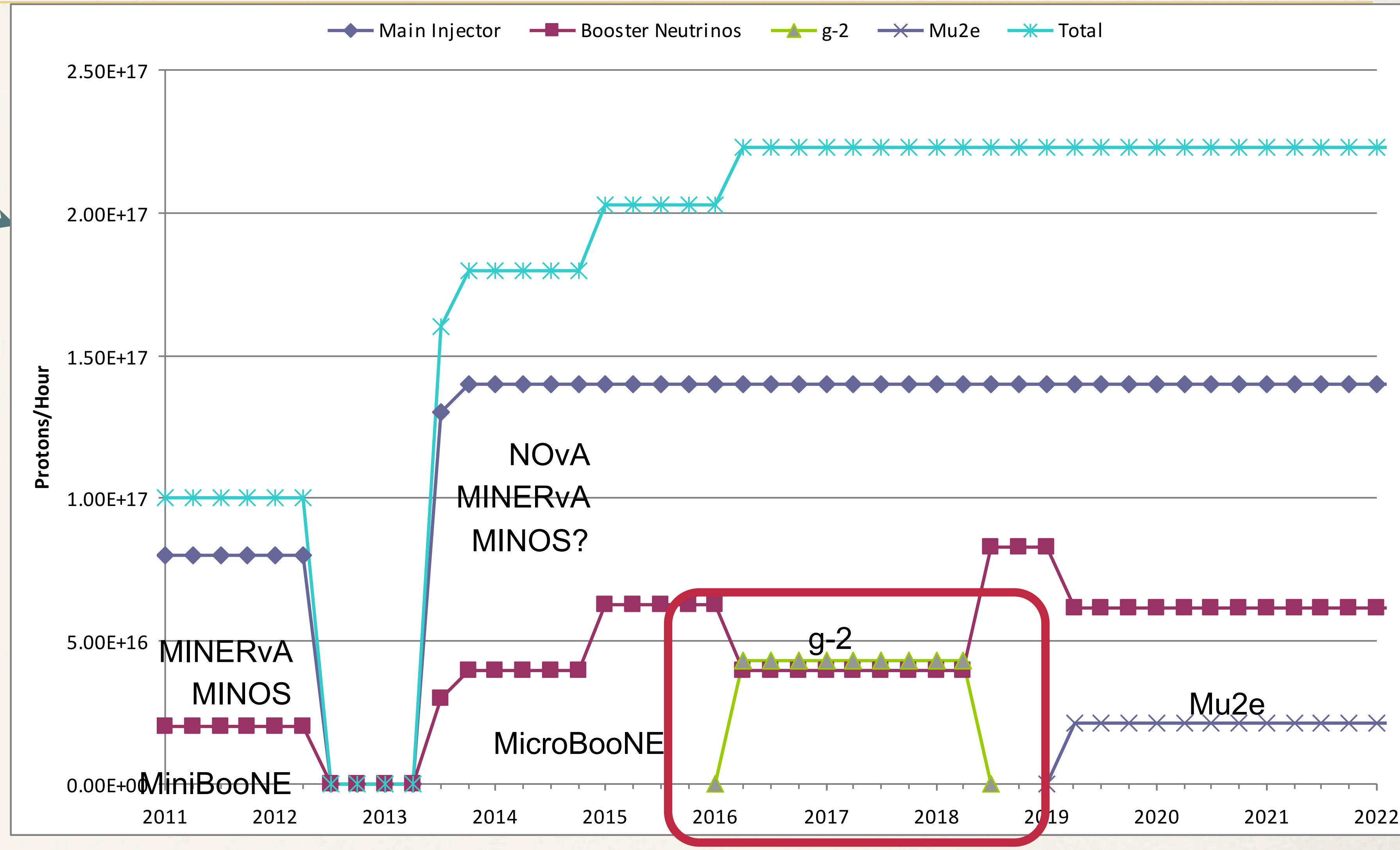
- Arrival at the new Muon campus on the Fermilab site.

Transporting to Illinois

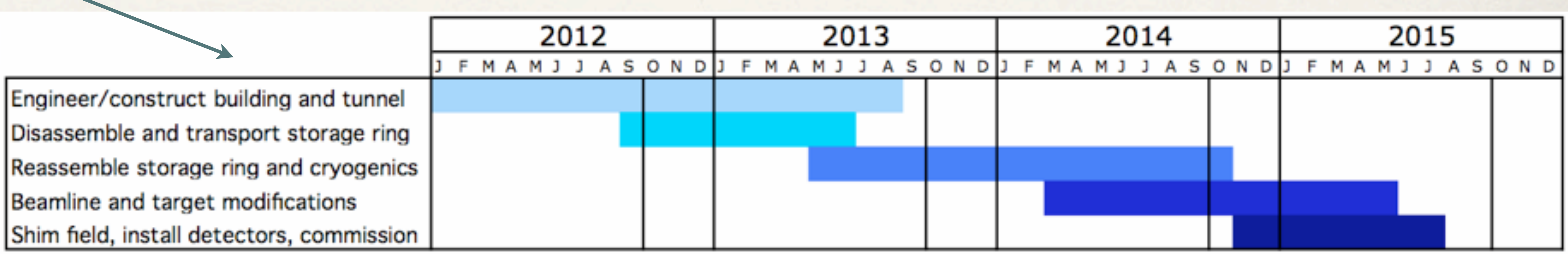
- Arrival at the new Muon campus on the Fermilab site.

Time Table

The future plan for Fermilab



Detailed breakdown of specific g-2 work happening now and in the next 3 years.



Fermilab $(g\text{-}2)_\mu$ Collaboration (E989)

28 institutions
106 collaborators

Conclusions

- Where can we be in 5 years?
  - Lower error on both experimental and theoretical measurements

$$\text{Future: } \Delta a_\mu(\text{Expt - Theory}) = \text{xx } (34) \times 10^{-11}$$

  - If the central value stays the same, this will indicate a larger than 5σ difference.
- Work being done in the theoretical community on lowering the errors on the hadronic component of a_μ
- Fermilab project underway with Mission Need approval granted
  - Work being done upgrading every facet of the experiment from simulations to hardware.
- Exciting time for this measurement!

Backup Slides

Remove Mass Dependence

- In order to removed the dependence on the mass of the muon, we rename variables

$$\omega_a = a_\mu \frac{eB}{mc} \Rightarrow a_\mu = \frac{R}{\lambda - R}; \quad \boxed{R = \frac{\omega_a}{\omega_p}}$$

ω_a: rate at which the muon spin turns relative to the momentum

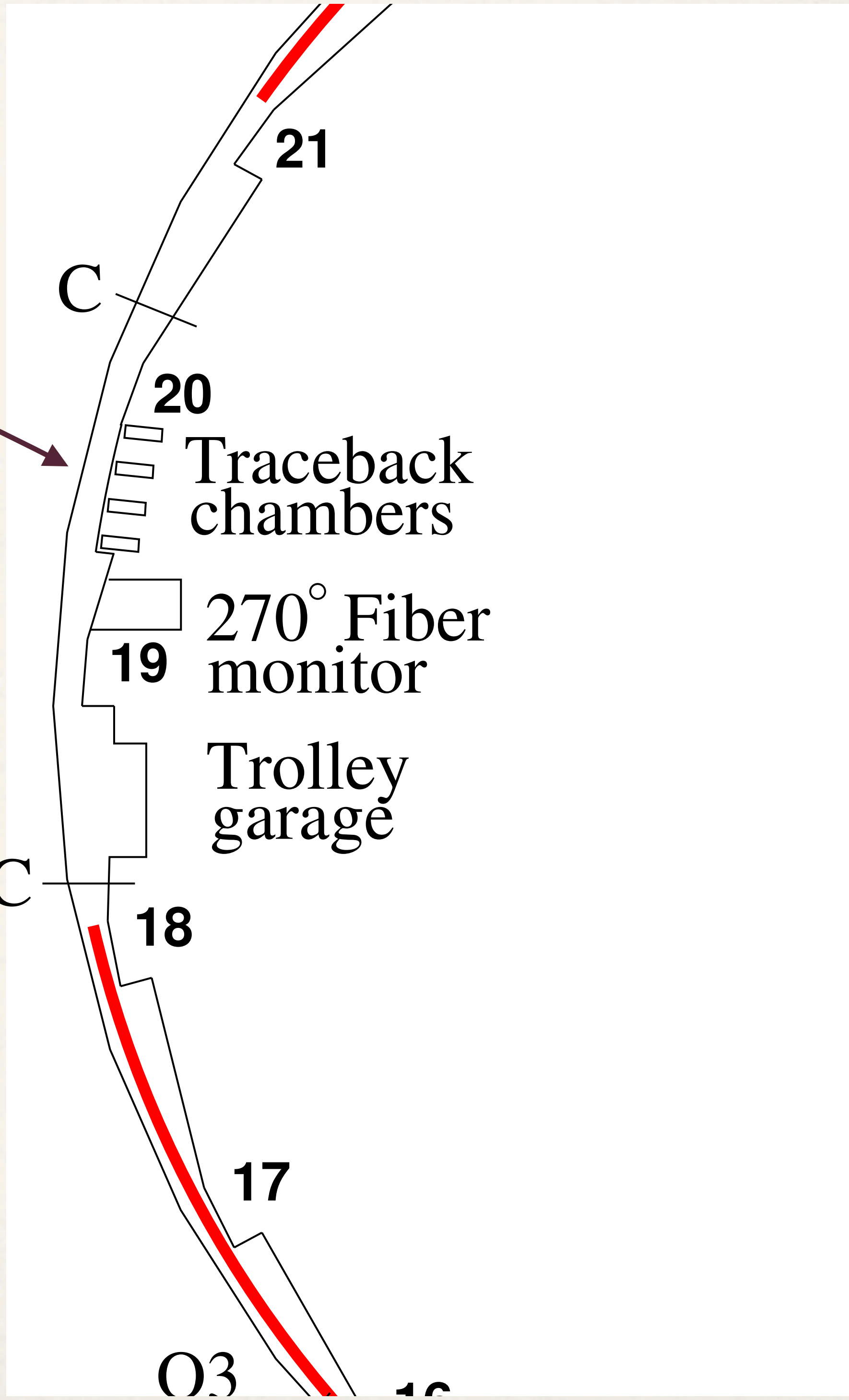
ω_p: the magnetic field in terms of the Larmor frequency of a free proton

λ: Ratio of magnetic moments for the muon to the proton.

This is what we measure in the g-2 experiment

Updating Tracking Detectors

- In E821 traceback chambers were placed in a truncated scallop
  - This rendered the calorimeter data at position 20 unusable in the final analysis
  - This scallop will be rebuilt for the new experiment.
- In the Fermilab (g-2) experiment we plan on putting these *within* the vacuum
  - Cut open the vacuum to insert straw chambers.



Why Have a Tracker?

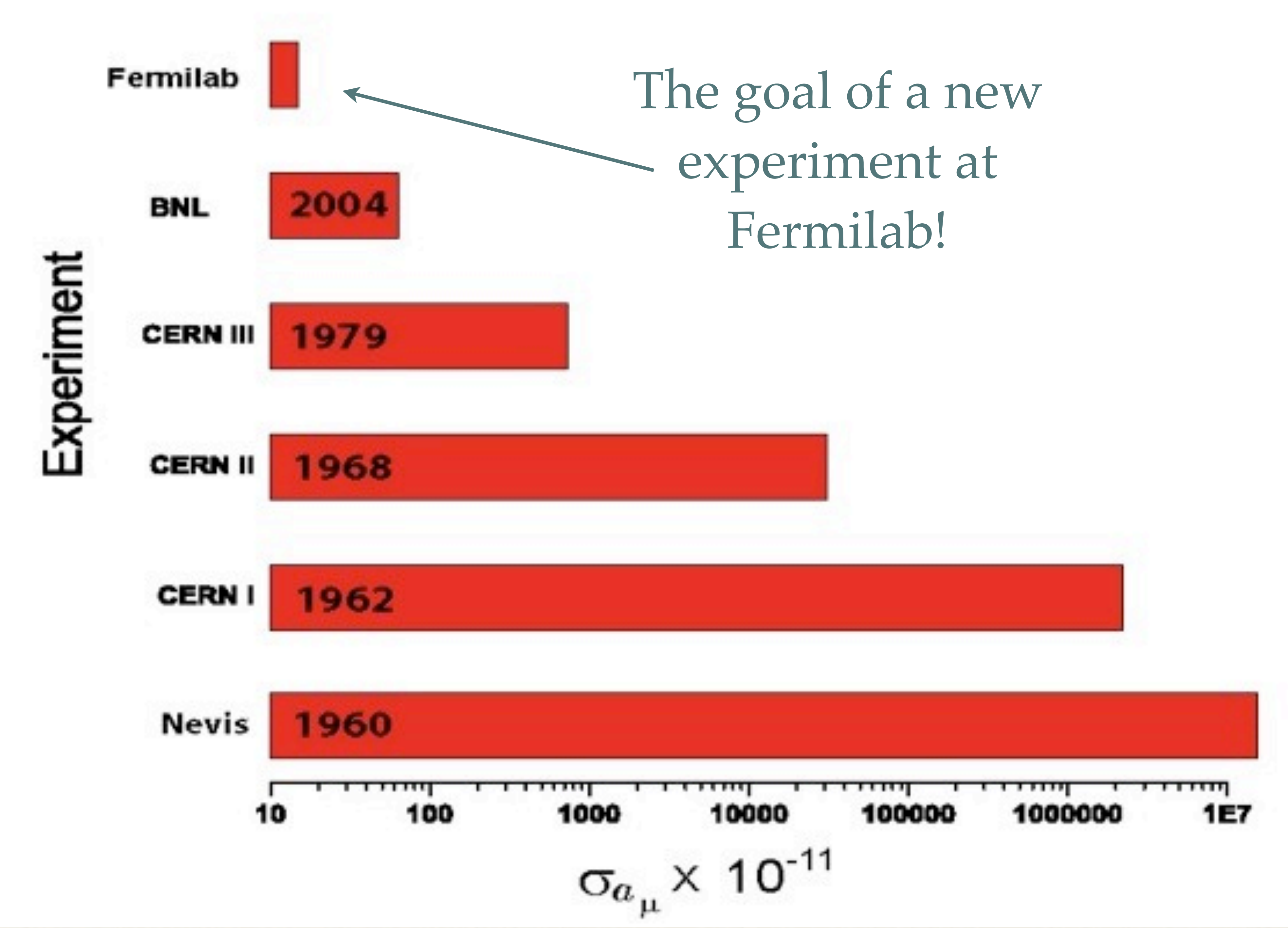
$$\vec{\omega_a} = -\frac{q}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

- Calibrate beam dynamics
  - Determine the momentum of the muons
    - Because they can't all be at exactly the magic momentum
  - Betatron motion of the beam
  - Want *mm* resolution of the beam profile
- Better measurement of the pileup
  - Information on multiple positrons hitting the calorimeter

Fermilab Objects for Reuse

- g-2 ring
- g-2 beamline
- Debuncher Ring
- Magnets, pumps, stands and other Accumulator Ring components
- AP transfer lines
- AP-0 Target Station
- AP-2 beamline magnets
- Main Injector RF ferrites
- Tevatron satellite refrigerators
- Tevatron N2 and He storage tanks
- Tevatron cryo line
- Tevatron High Temperature Superconducting leads
- Tevatron vacuum equipment
- Tevatron loss monitors
- Tevatron BPM electronics
- Tevatron electronics crates
- Tevatron control cards
- Tevatron damper system
- Misc. Tevatron Instrumentation
- Shielding steel
- Transformers

Do it again? Do it better!

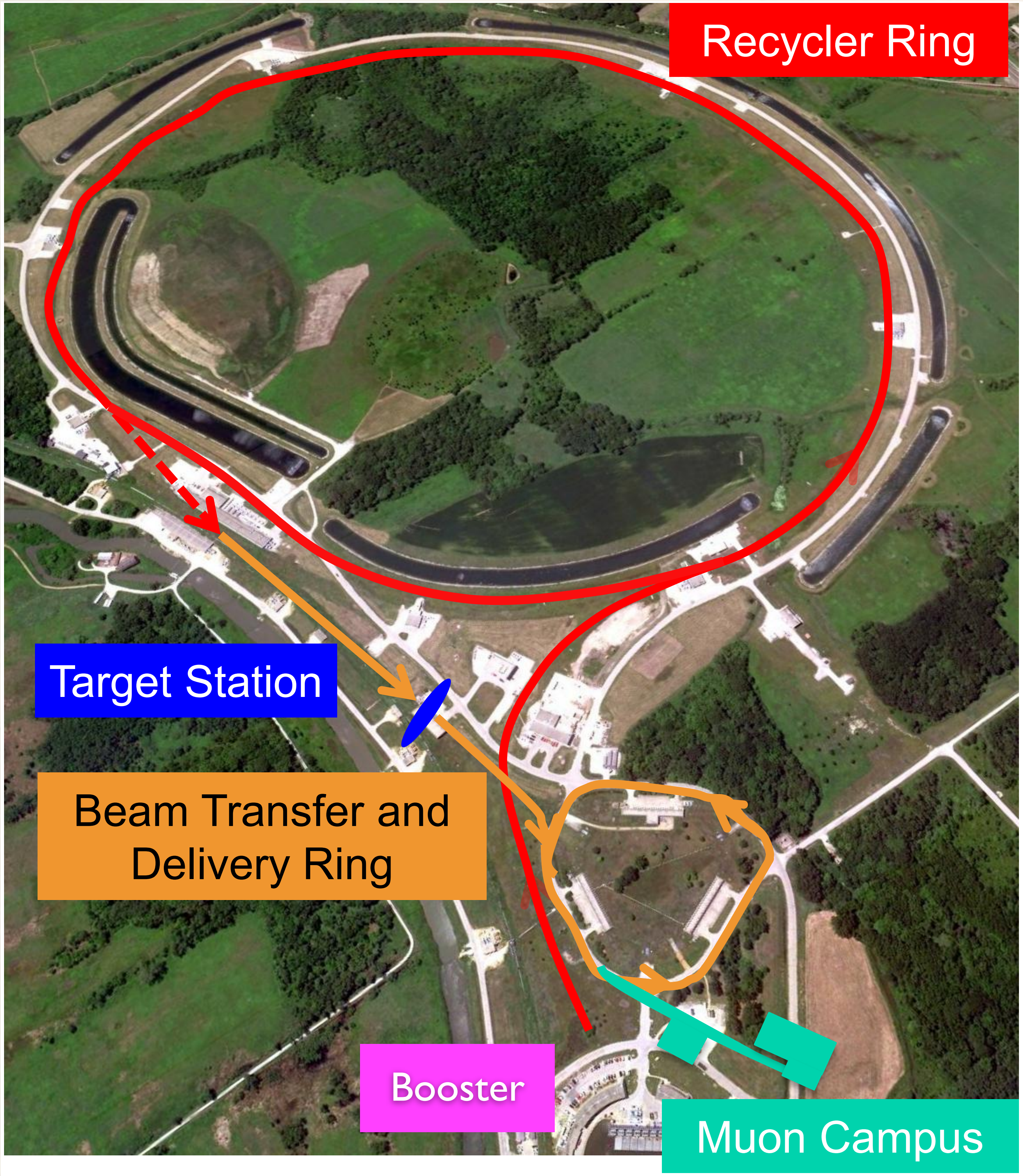


The goal of a new experiment at Fermilab!

Error Improvements

- Experimental uncertainty from 63×10^{-11} to 16×10^{-11}
- Theoretical uncertainty from 51×10^{-11} to 30×10^{-11}

Fermilab Beam Lines



- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - Target to M2 to M3 to Delivery Ring
  - Proton removal
  - Extraction line (M4) to g-2 stub to ring in MC1 building

JParc g-2 Experiment

- Stop trying to do magic momentum experiment. Use an ultra cold muon source.
- Higher rate in a smaller device

$$\sigma_\omega = \frac{\sqrt{2}}{A\,\gamma\,\tau_\mu\sqrt{N}}$$

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm