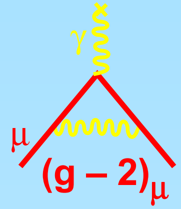
Muon (g-2) to 0.25 ppm

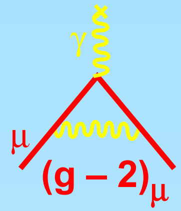


James Miller
(For the new Muon (g-2) Collaboration, E969)
Department of Physics
Boston University

miller @ bu.edu

Outline

- Brief theoretical motivation
- Comparison between theoretical prediction and experimental value from previous experiment: Case for x2 better experimental measurement
- Description of the proposed experiment: upgrades of the previous experiment



$$\vec{\mu}_s = g_s \left(\frac{e}{2m}\right) \vec{s}$$

For spin ½ particles:

$$\mu = (1 + a)\,\frac{e\hbar}{2m}$$

Dirac + Pauli moment

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

$$a = \frac{\alpha}{2\pi} = 0.00116$$

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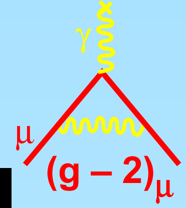
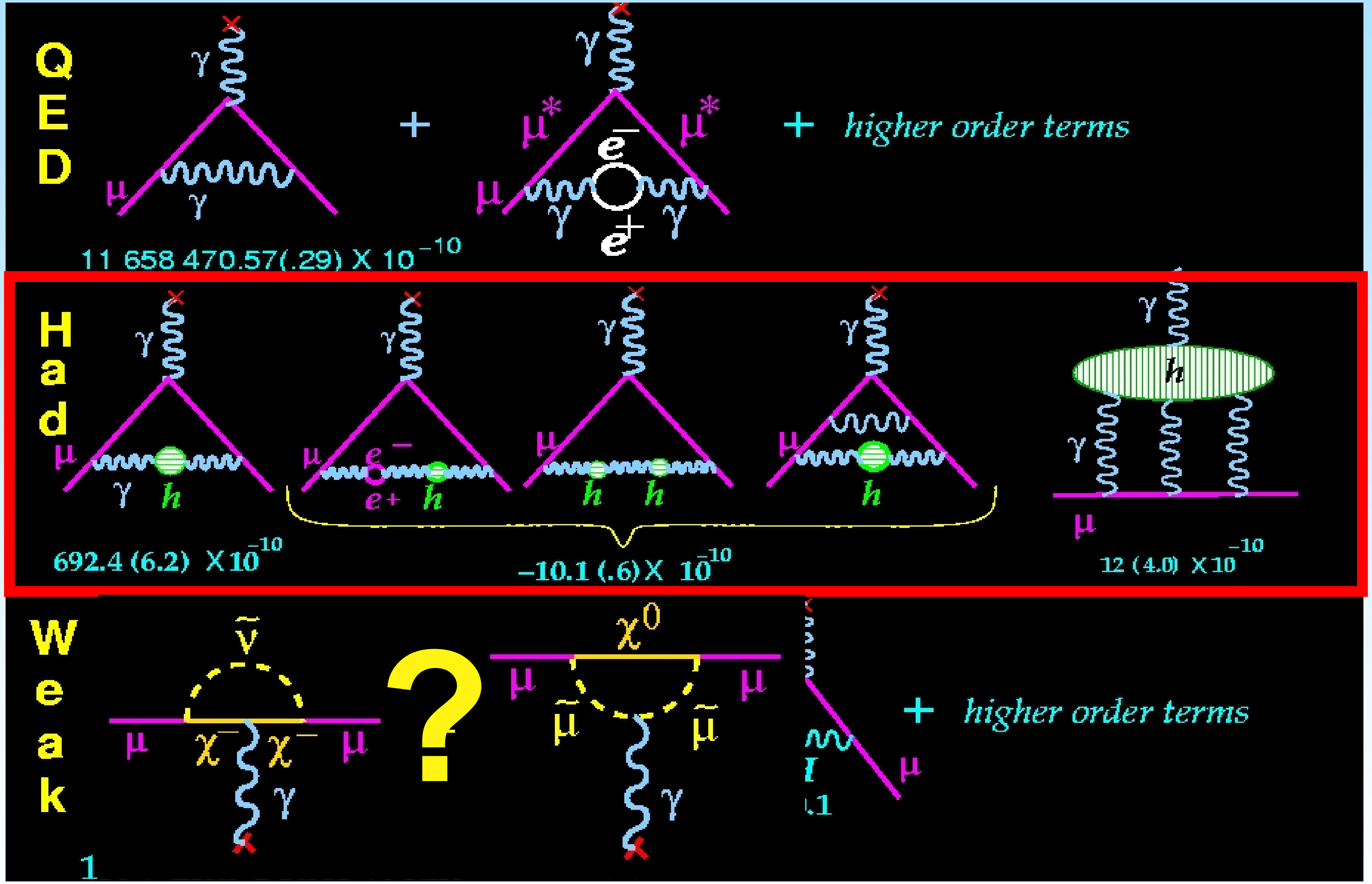
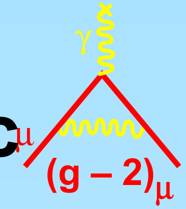
Standard Model Value for the Muon Anomaly

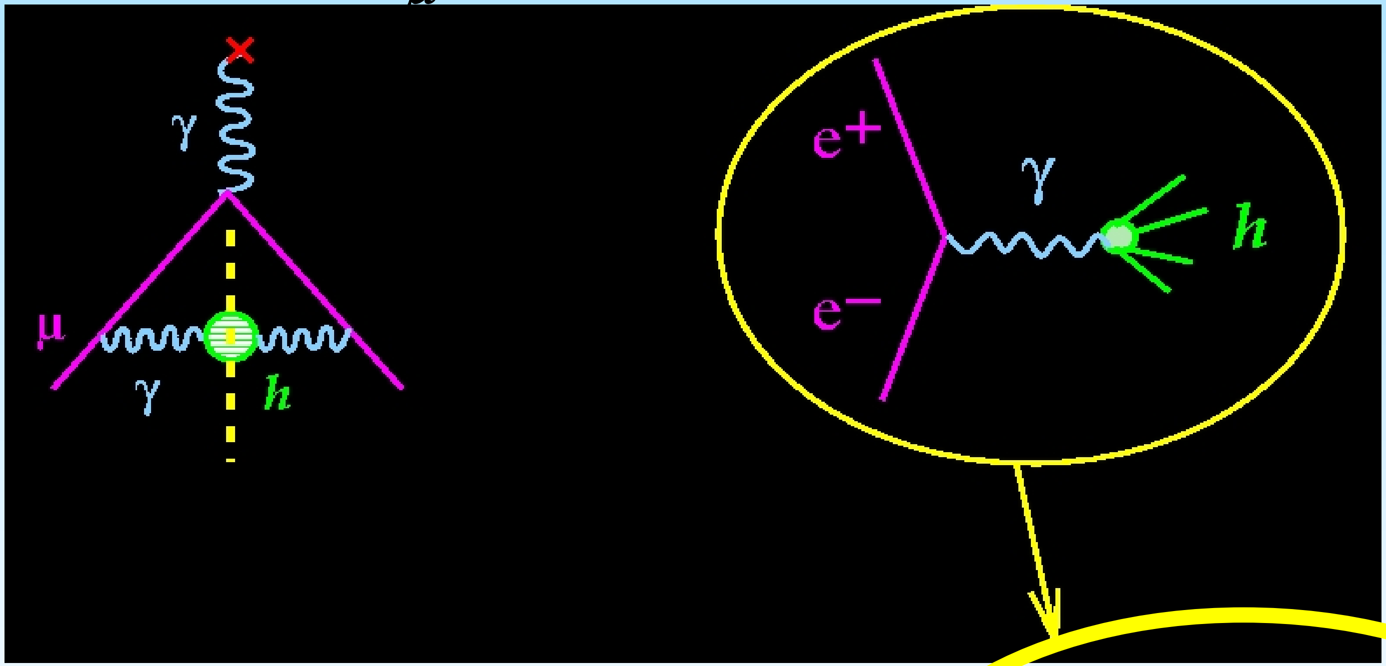




e vs. μ : relative contribution of heavier things $\left(\frac{m_\mu}{m_e}\right)^2 \simeq 40,000$

There is a relationship between e^+e^- annihilation data and the lowest-order hadronic contribution to a_μ





$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$

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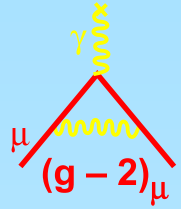
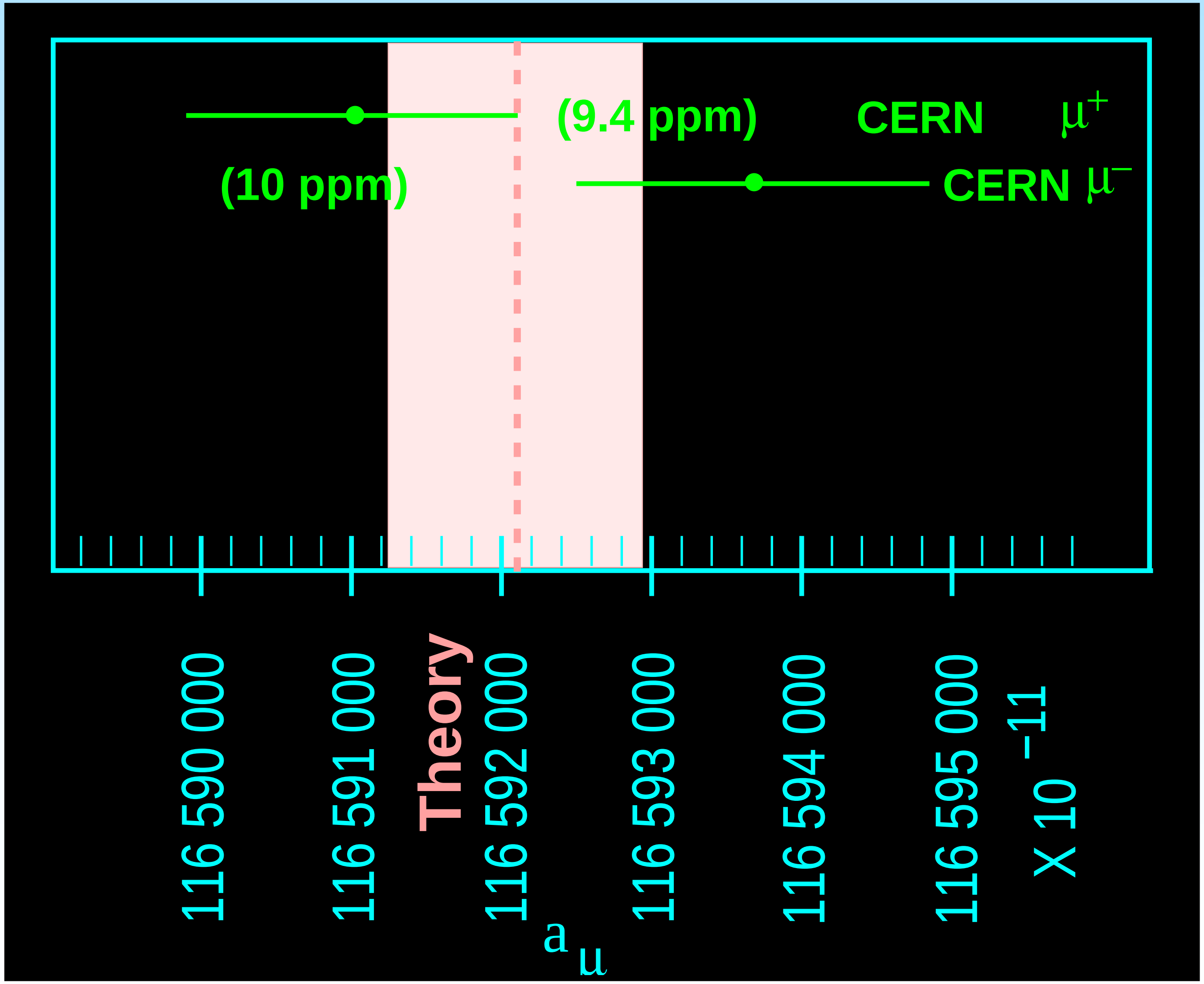
When we started in 1984, theory and experiment were known to about 10 ppm.

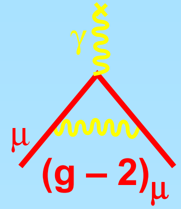


Theory uncertainty was ~ 9 ppm

Experimental uncertainty was 7.3 ppm (from the CERN g-2 measurement of the 1970's)



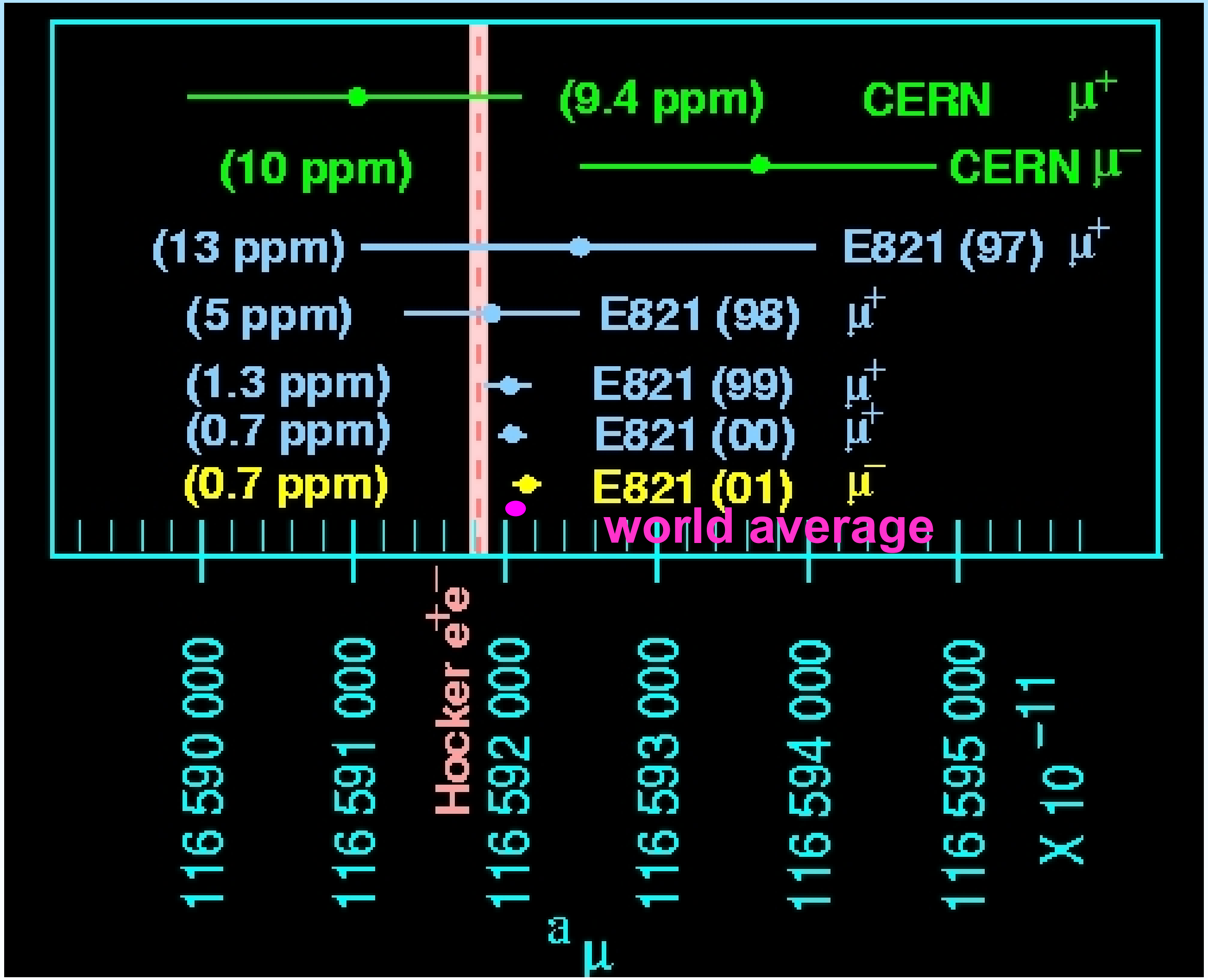
E821 achieved 0.5 ppm and the e^+e^- based theory is also at the 0.5 ppm level. Both can be improved.



All E821 results were obtained with a "<u>blind</u>" analysis.

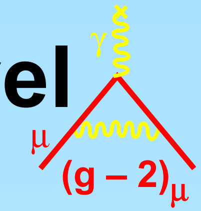
$\sigma_{stat} = \pm 0.46$ ppm

$\sigma_{syst} = \pm 0.28$ ppm



$$a_\mu = 11\,659\,208(6) \times 10^{-10} \quad (0.54 \text{ ppm})$$

With an apparent discrepancy at the level of 3.3 σ . . .

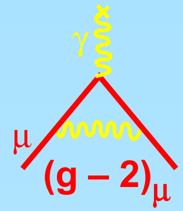


Have to work harder to improve the measurement <u>and</u> the theory value ….

Better e+-e- scattering data

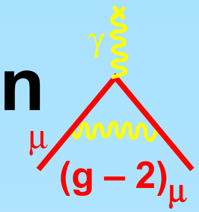
Better (g-2) data

A (g-2)$_\mu$ Experiment to ± 0.25 ppm Precision –BNL E969 Collaboration



R.M. Carey, I. Logashenko, K.R. Lynch, J.P. Miller B.L. Roberts- Boston University; G. Bunce, W. Meng, W. Morse, P. Pile, Y.K. Semertzidis -Brookhaven; D. Grigoriev, B.I. Khazin, S.I. Redin, Yuri M. Shatunov, E. Solodov – Budker Institute; F.E. Gray, B. Lauss, E.P. Sichtermann – UC Berkeley and LBL; Y. Orlov – Cornell University; J. Crnkovic, P. Debevec, D.W. Hertzog, P. Kammel, S. Knaack, R. McNabb – University of Illinois UC; K.L. Giovanetti – James Madison University; K.P. Jungmann, C.J.G. Onderwater – KVI Groningen; T.P. Gorringe, W. Korsch – U. Kentucky, P. Cushman – Minnesota; Y. Arimoto, Y. Kuno, A. Sato, K. Yamada – Osaka University; S. Dhawan, F.J.M. Farley – Yale University

We measure the difference frequency between the spin and momentum precession, and B



$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$

$$\langle \omega_a \rangle_\mu, \langle B \rangle_\mu$$

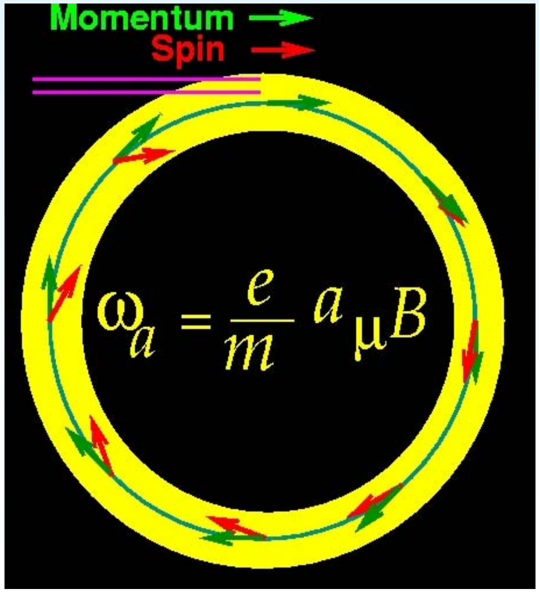
With an electric quadrupole field for vertical focusing

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

0

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09 \text{ GeV/c}$$



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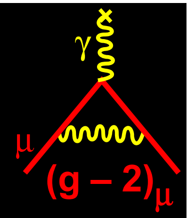
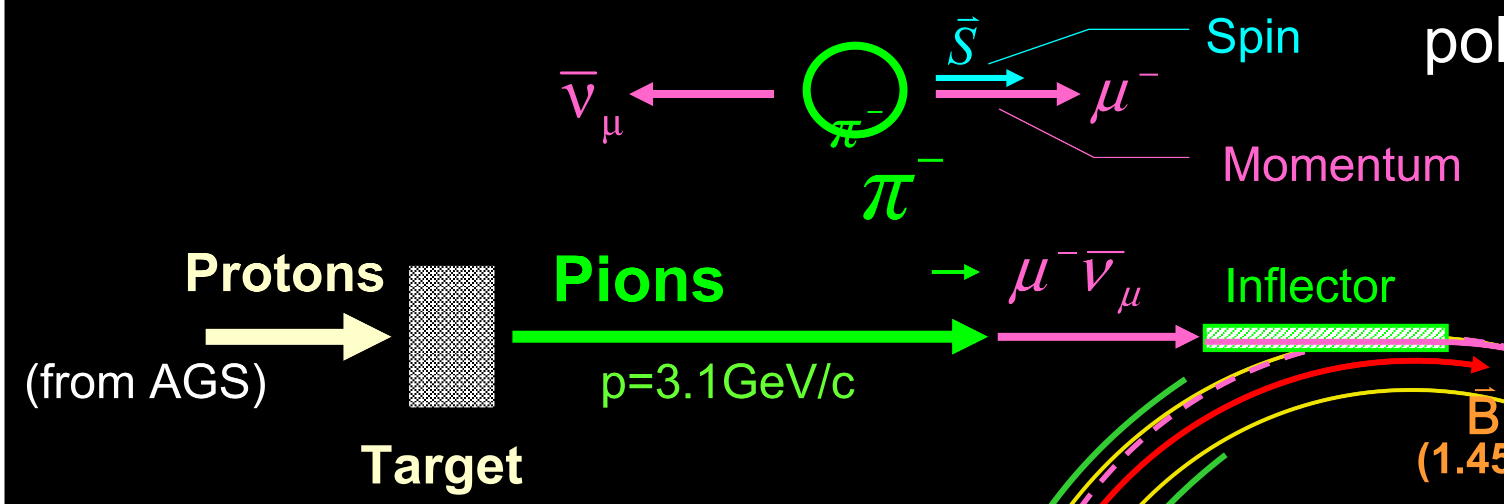
Experimental Technique

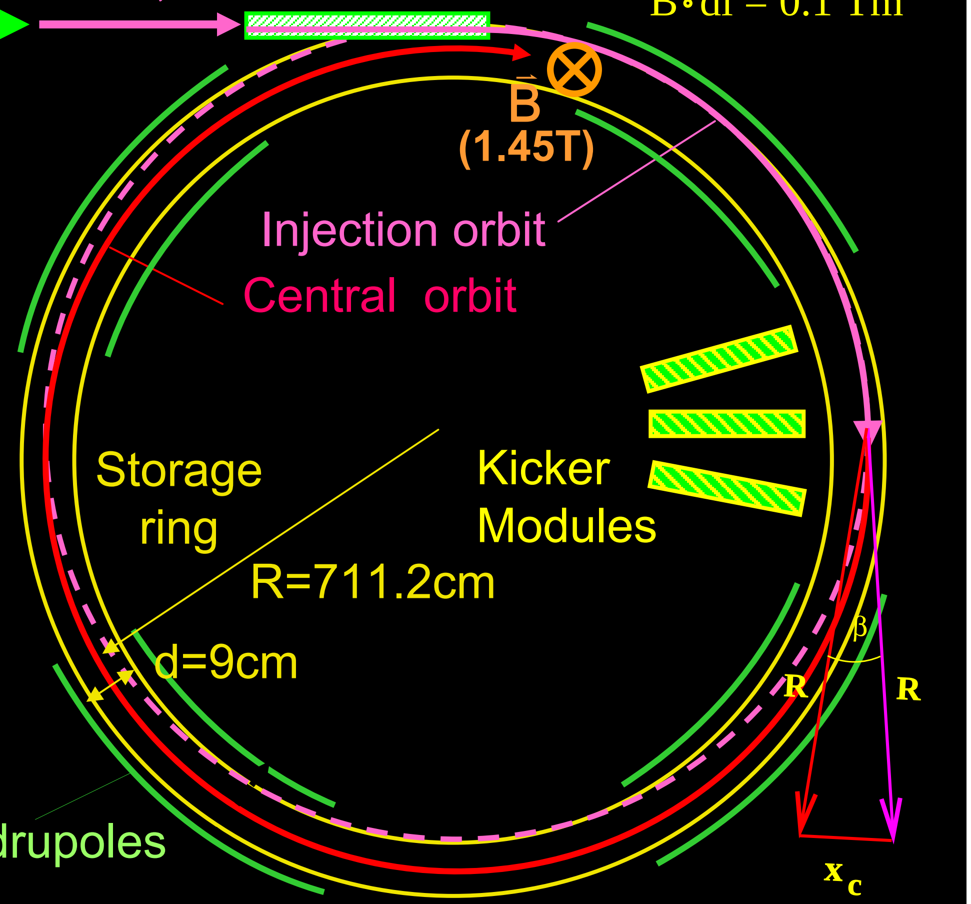




$x_c \cong 77$ mm

$\beta \cong 10$ mrad

$B \cdot dl \cong 0.1$ Tm



- Muon polarization
- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

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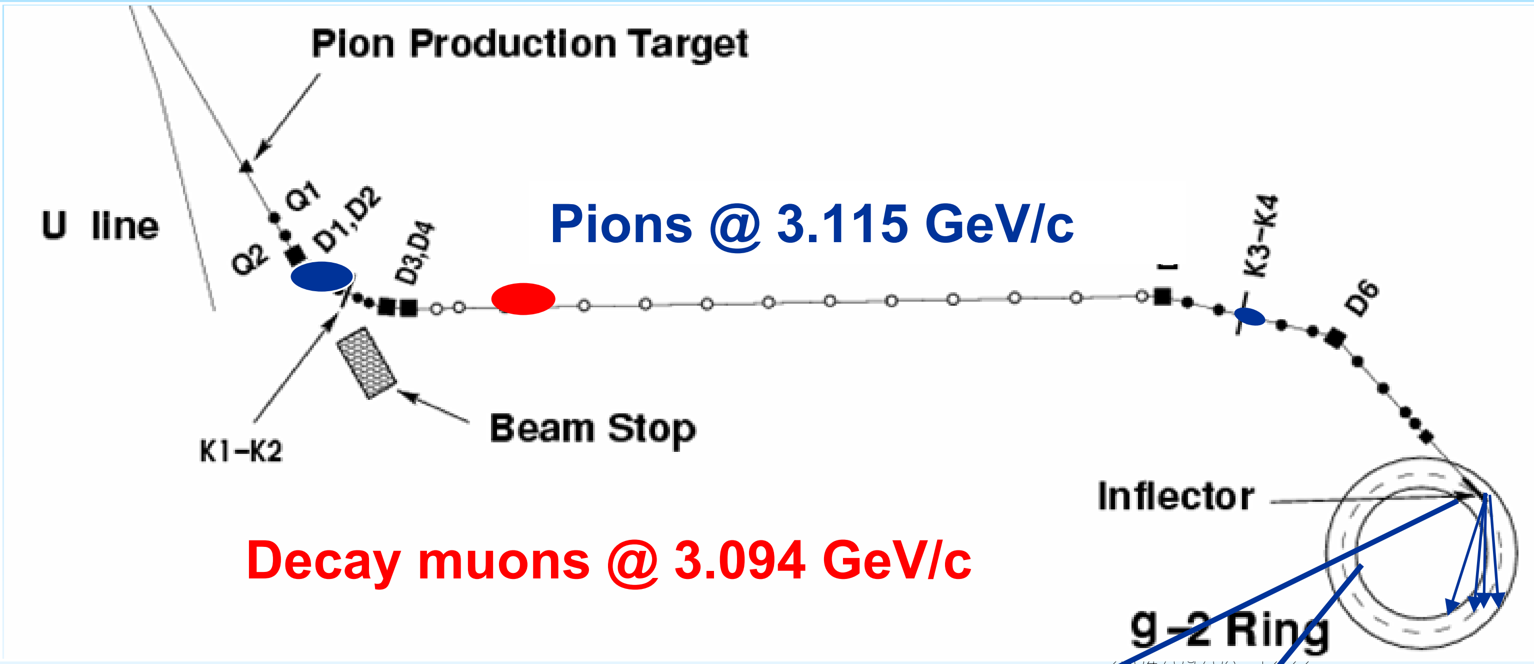
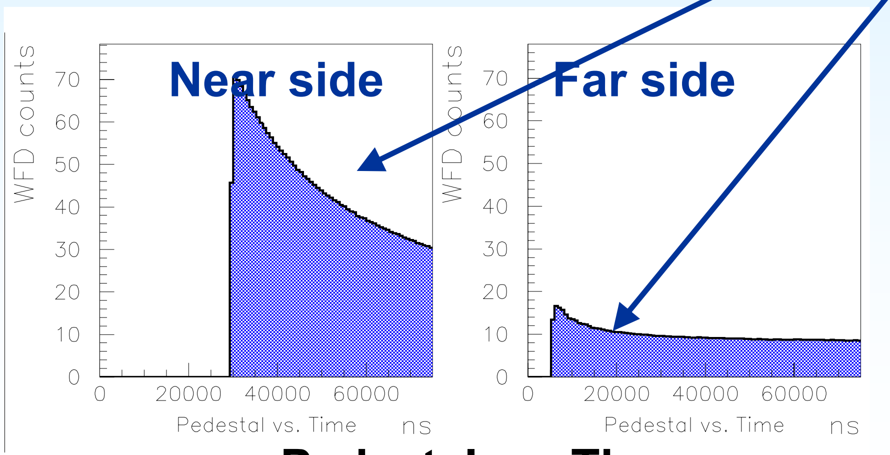
E821: used a “forward” decay beam

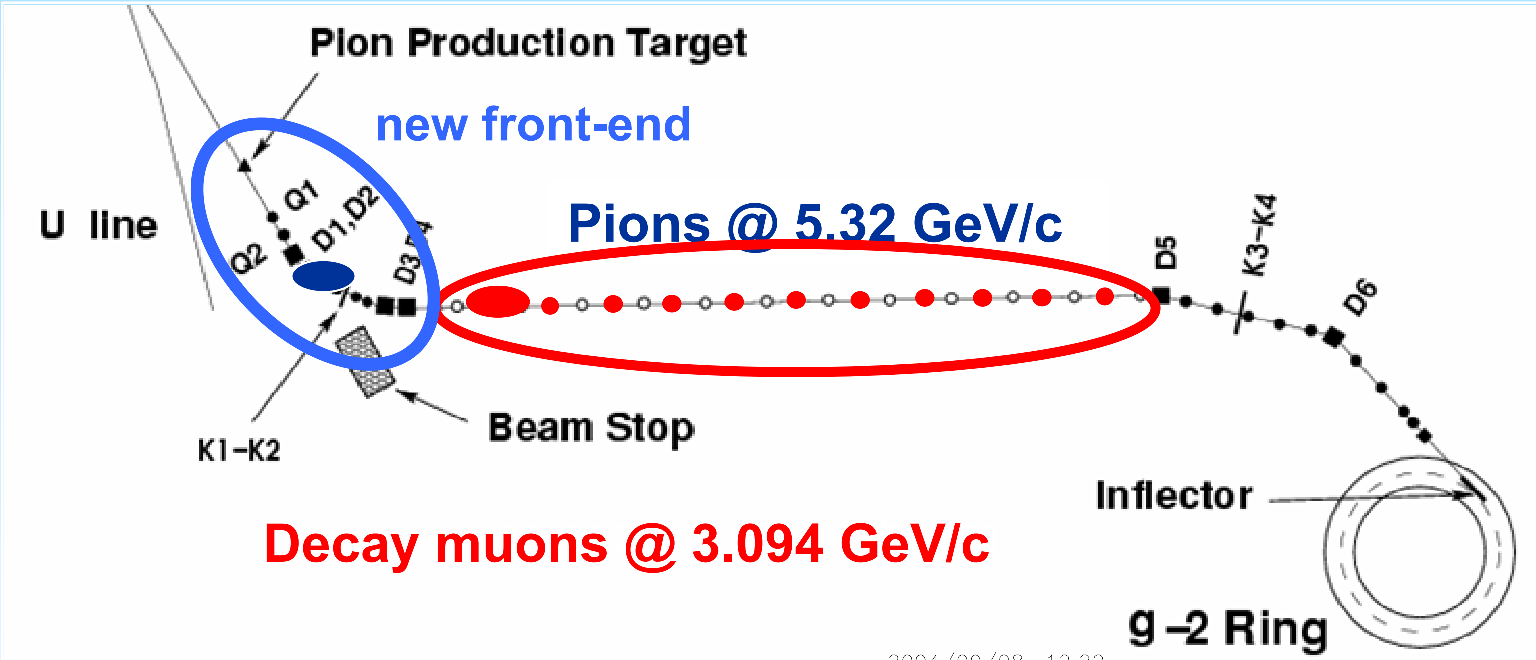


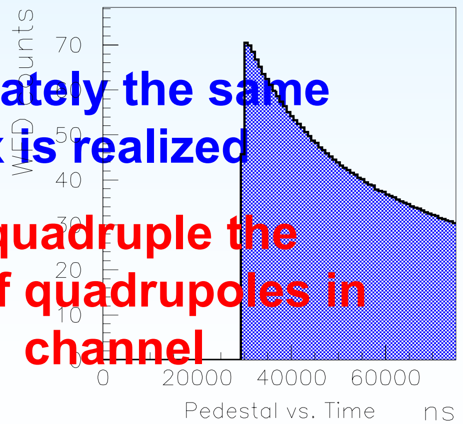
This baseline limits how early we can fit data



Pedestal vs. Time

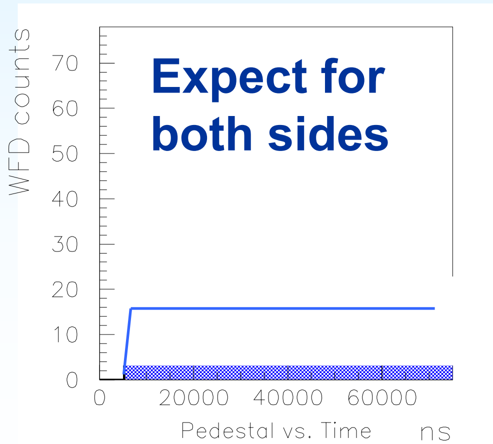
E969: may use a "backward" decay beam





Approximately the same muon flux is realized

Then we quadruple the number of quadrupoles in the decay channel



Expect for both sides

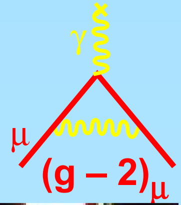
No hadron-induced prompt flash

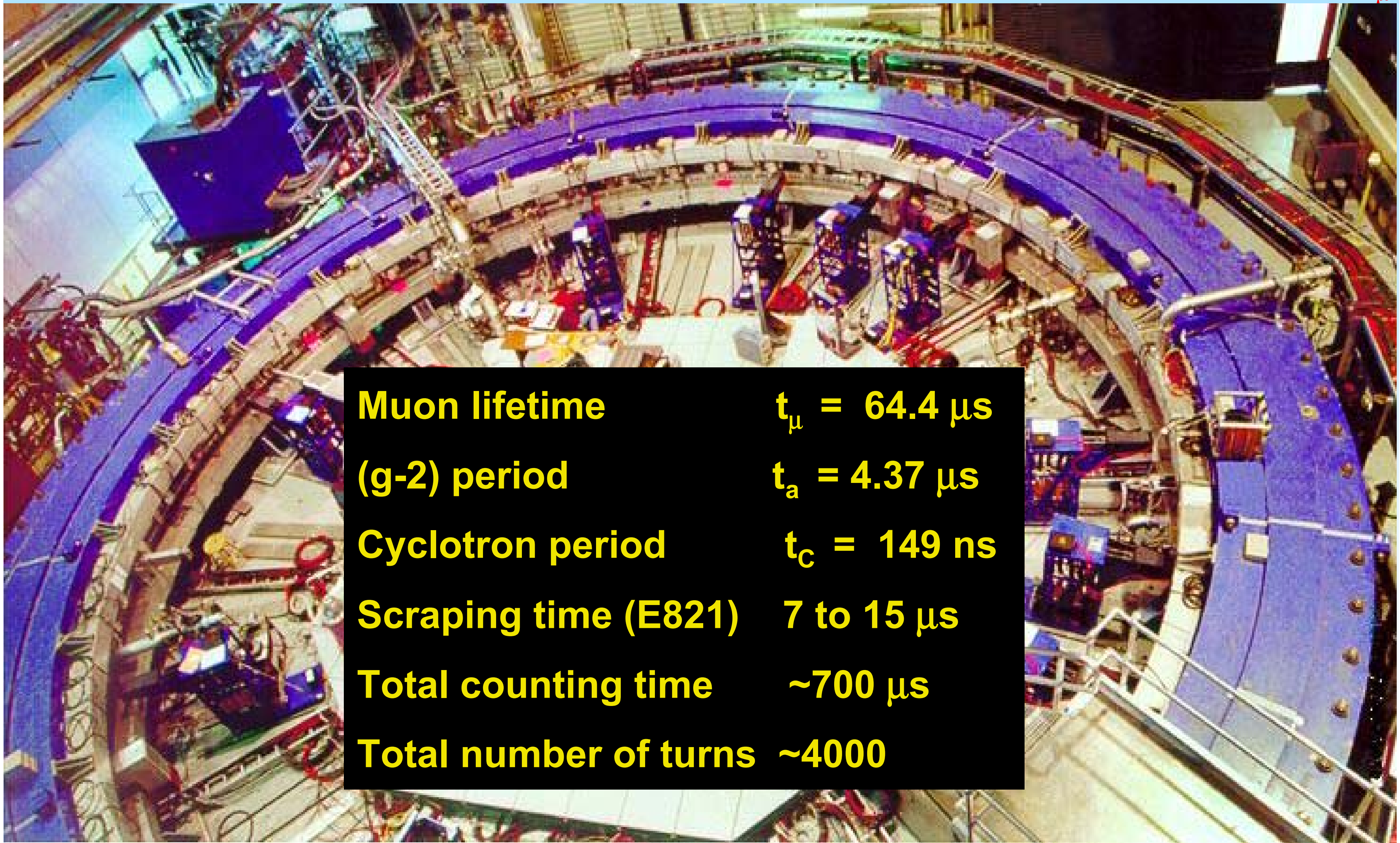
x 1 more muons

> x 2.5

The 700 ton $(g\text{-}2)_\mu$ precision storage ring

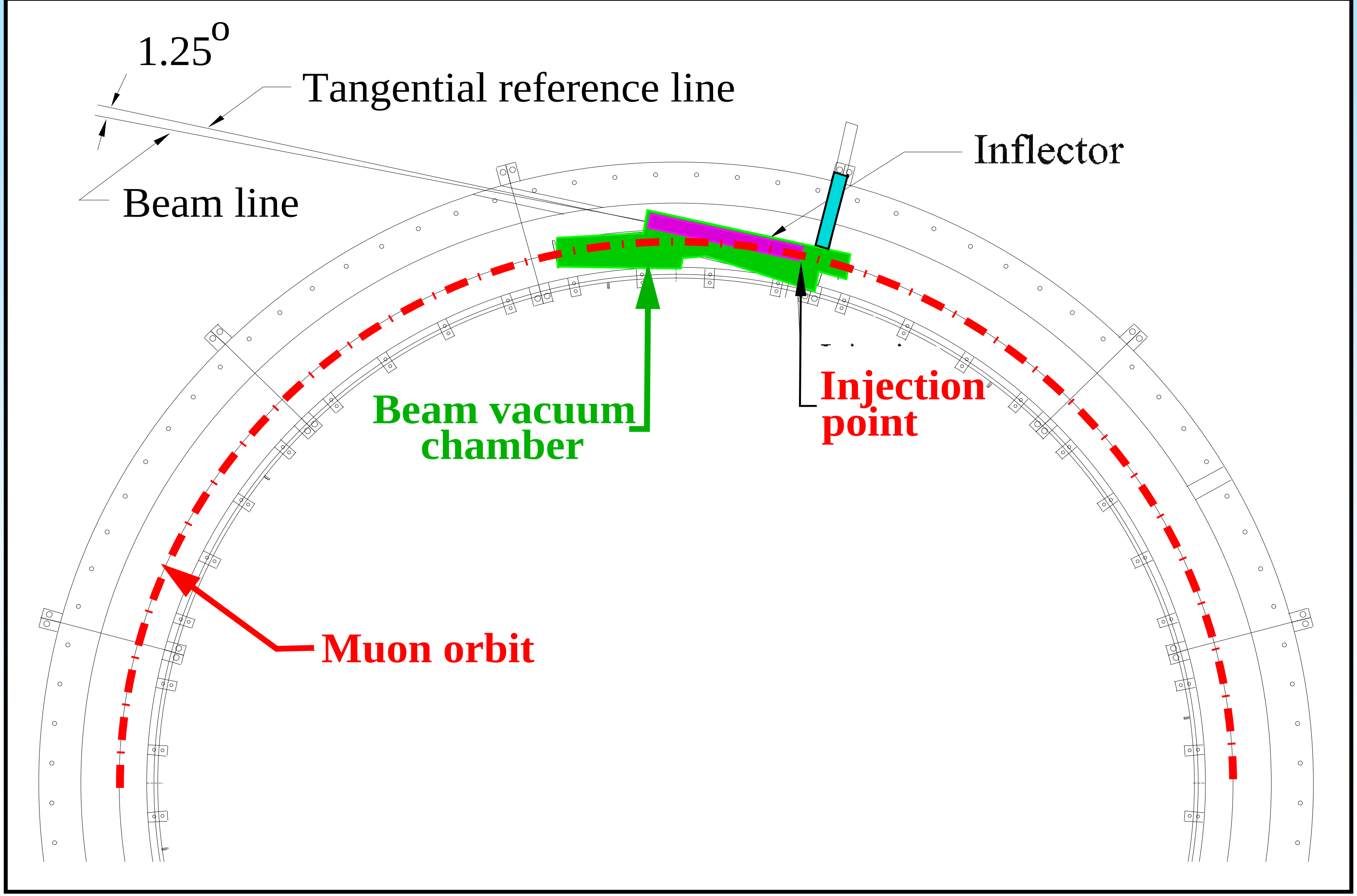
(B=1.45 T, R=7.1 m)



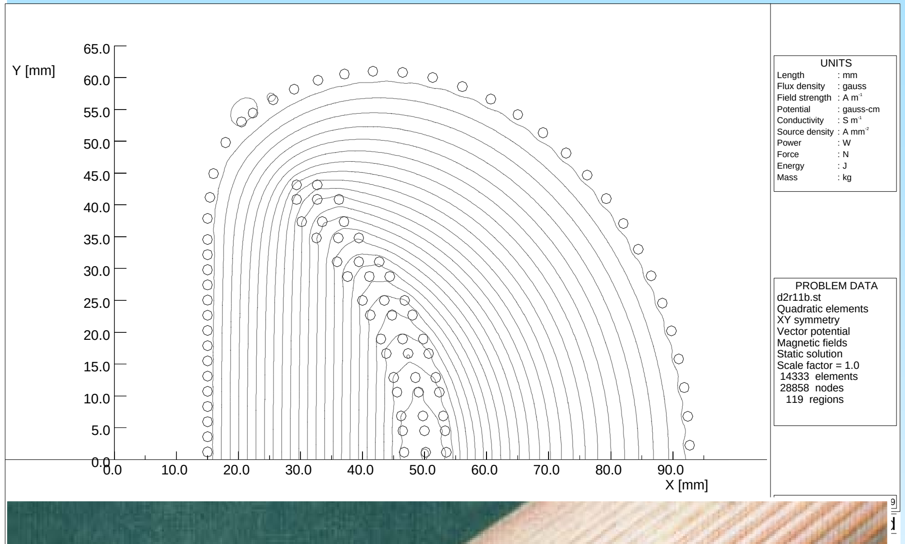


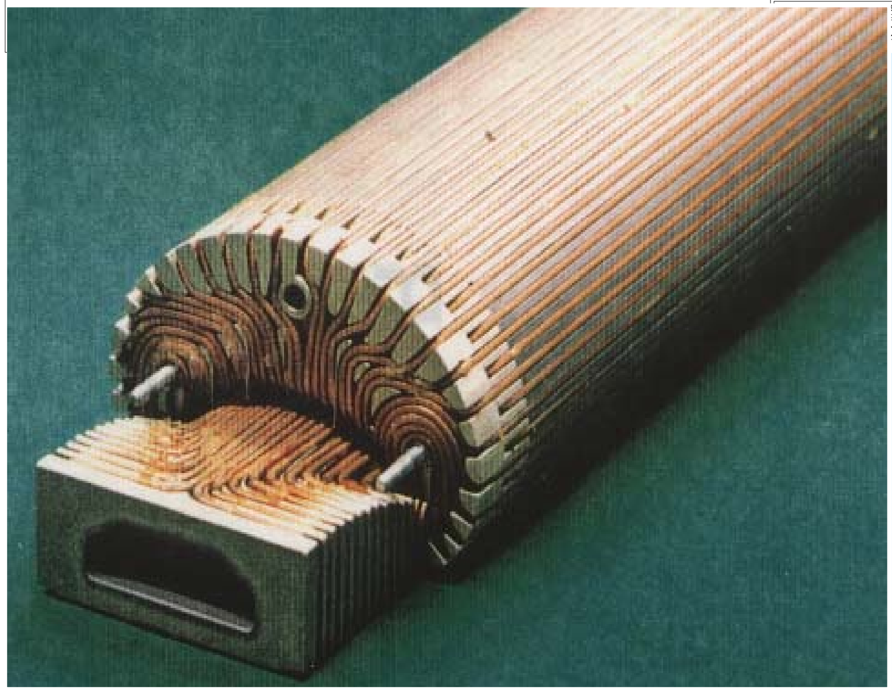
Muon lifetime	t_μ = 64.4 μs
(g-2) period	t_a = 4.37 μs
Cyclotron period	t_C = 149 ns
Scraping time (E821)	7 to 15 μs
Total counting time	~700 μs
Total number of turns	~4000

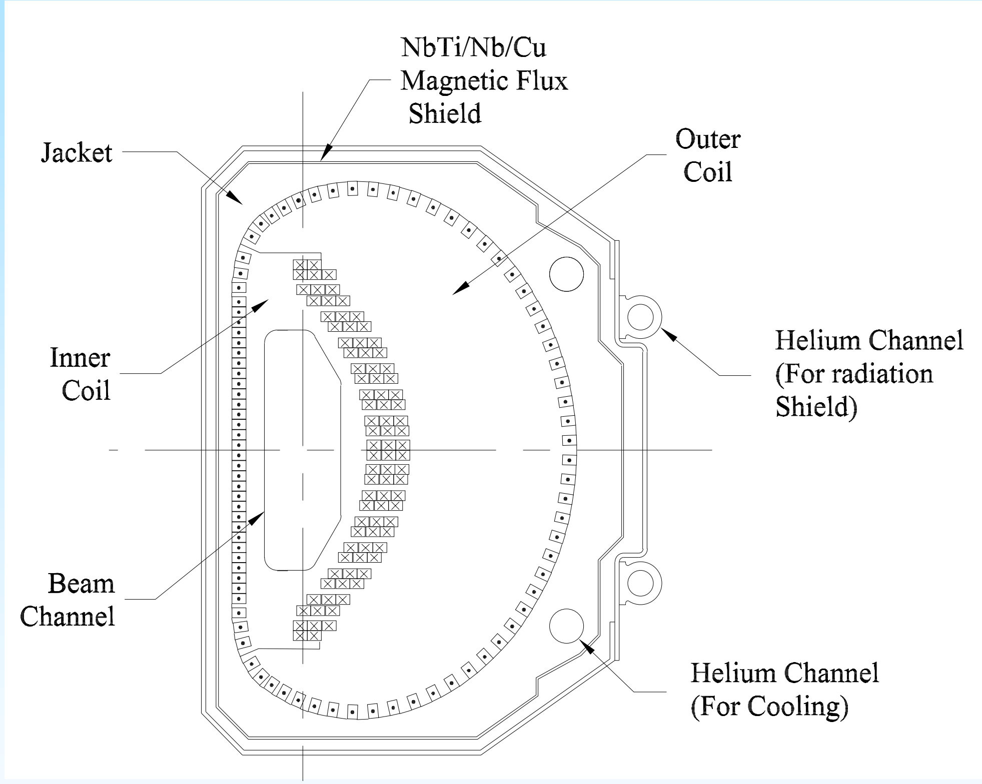
The incident beam must enter through the magnet yoke and through an inflector magnet



The E821 inflector magnet had closed ends which lost half the beam.







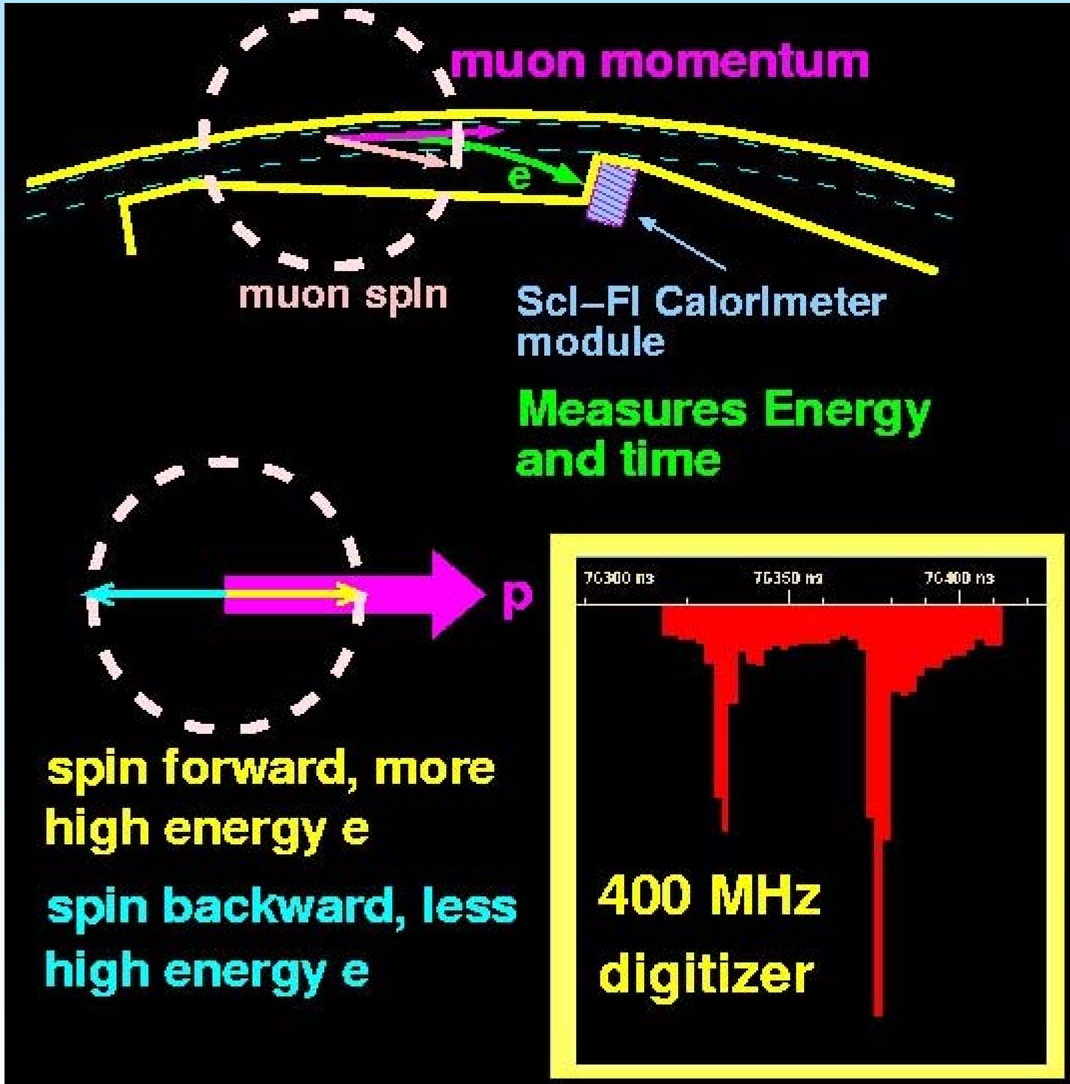
Length = 1.7 m

Central field = 1.45 T

Open end prototype, built and tested

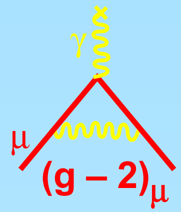
→ X2 Increase in Beam

E821 Electron Detectors were Pb-scintillating fiber calorimeters read-out by 4 PMTs: signals summed



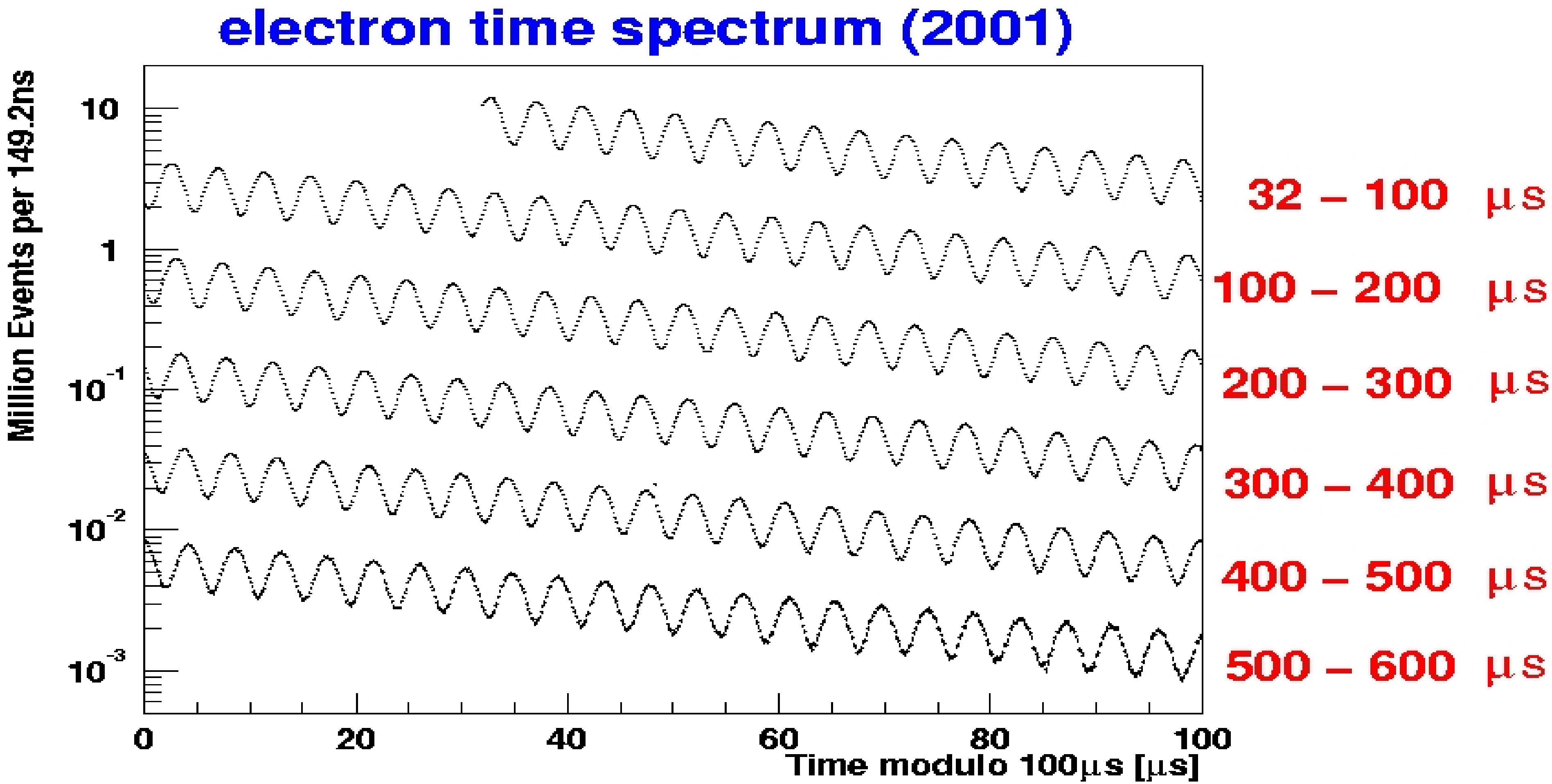
New experiment needs segmented detectors for pileup reduction.

We count high-energy e^- or e^+ from muon decays as a function of time. Shown here:

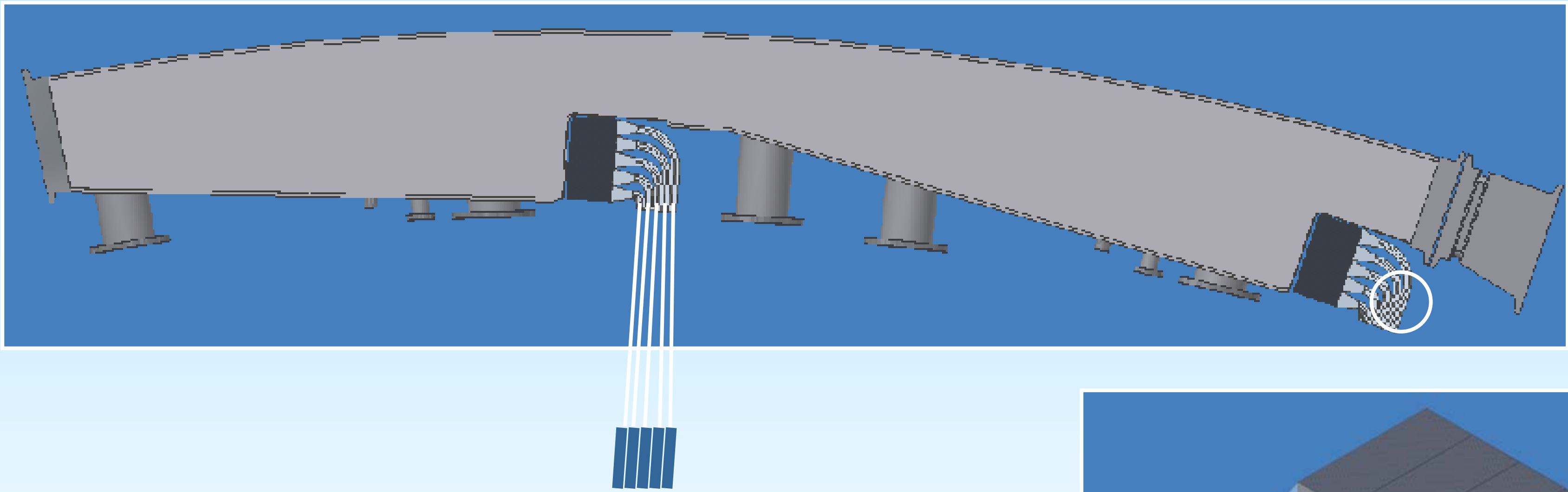


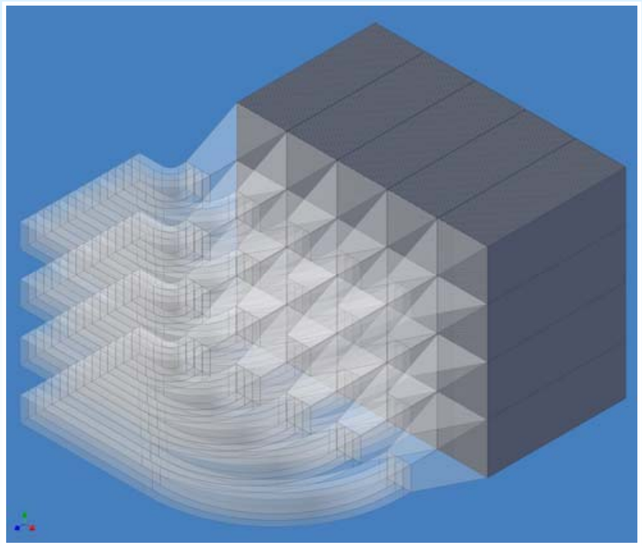
$$4 \times 10^9 \quad e^-, \; E_{e^-} \geq 1.8 \text{ GeV}$$

$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$



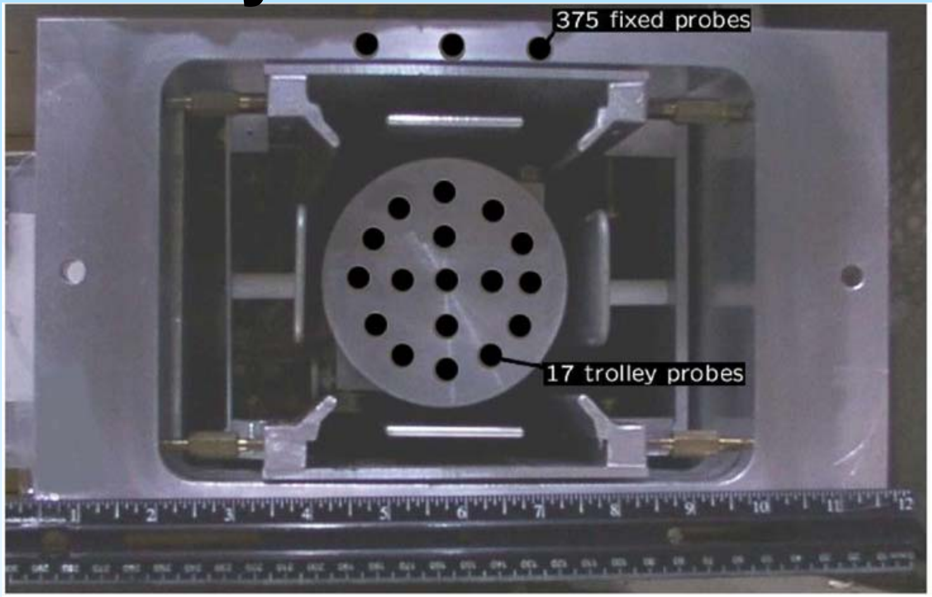
New segmented detectors of tungsten/scintillating- fiber ribbons to handle pile-up



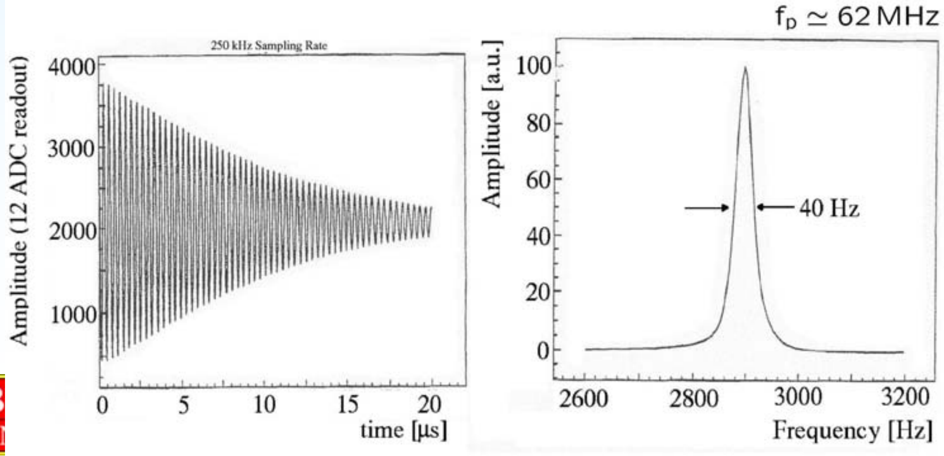


- System fits in available space
- Prototype under construction
- Again the bases will be gated.

The magnetic field is measured and controlled using pulsed NMR and the free-induction decay.



Free induction decay signals:



- Calibration to a spherical water sample that ties the field to the Larmor frequency of the free proton ω_p.
- Fixed probes, above and below storage region, monitor the field between trolley mappings.
- So we measure ω_a and ω_p

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

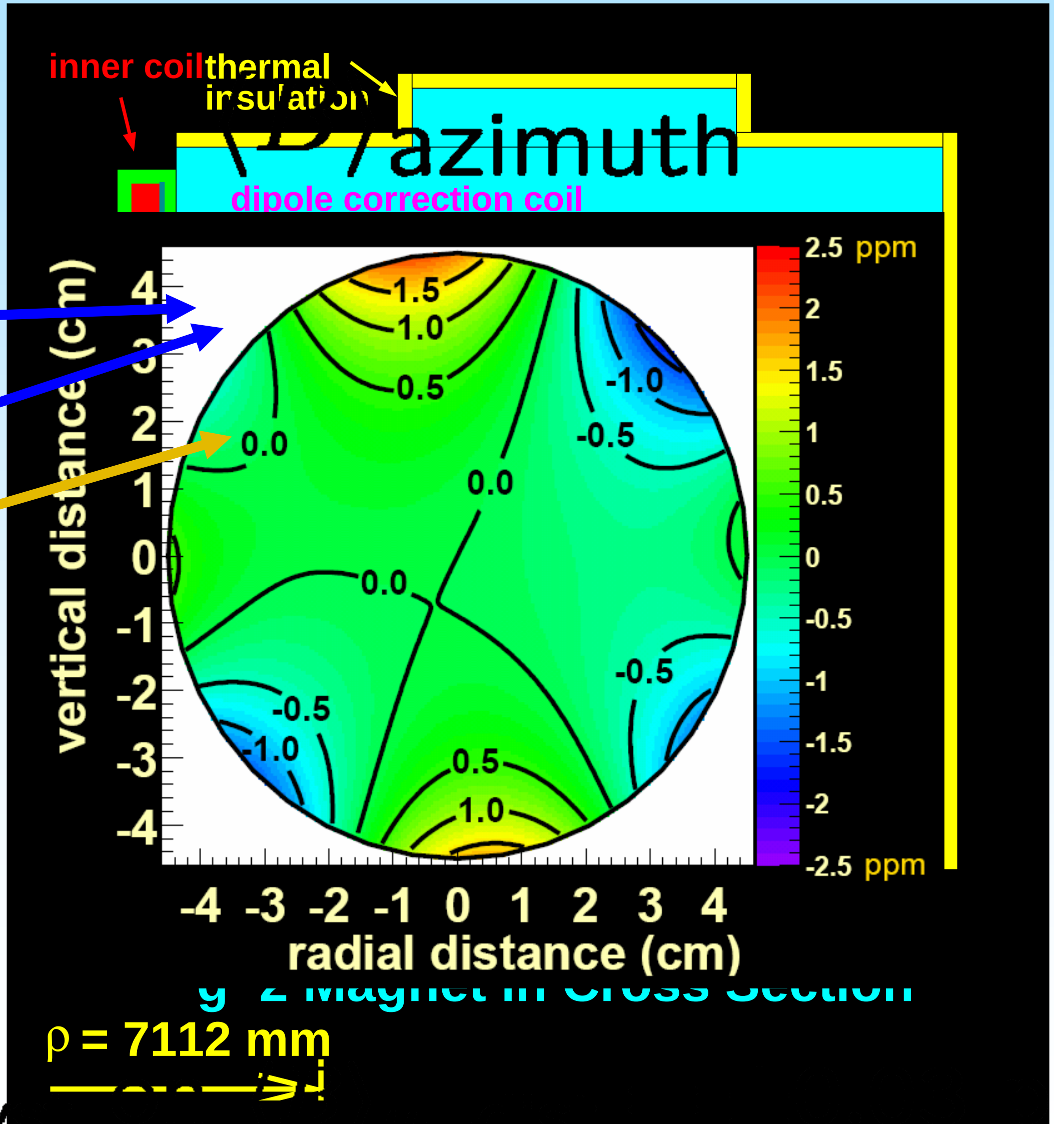
The ± 1 ppm uniformity in the average field is obtained with special shimming tools.

We can shim the

dipole,

quadrupole

sextupole



0.5 ppm contours

E969 needs 4 times more stored muons than E821.

• Open Inflector	X2
• Backward Beam ?	X1
• Quadruple the Quadrupoles	X 2.5-3
Beam increase design factor	>X 5

Forward beam: higher muon flux , but no increase in flash over E821

Backward beam: flash eliminated

Systematic errors on ω_a (ppm)

$\sigma_{systematic}$	1999	2000	2001
Pile-up	**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**	**0.02**
E-Field, Pitch	**0.08**	**0.03**	*
Fitting/Binning	**0.07**	**0.06**	*
CBO	**0.05**	**0.21**	**0.07**
Beam Debunching	**0.04**	**0.04**	*
Gain Change	**0.02**	**0.13**	**0.13**
total	**0.3**	**0.31**	**0.21**

Detector segmentation and lower energy-threshold required for pile-up rejection with higher rates

Beam manipulation

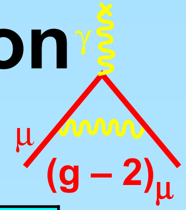
Simulation of effects of island length, wider islands

Systematic errors on ω_p (ppm)

Source of Uncertainty	1998	1999	2000	2001
Absolute Calibration	0.05	0.05	0.05	0.05
Calibration of Trolley	0.3	0.20	0.15	0.09
Trolley Measurements of B0	0.1	0.10	0.10	0.05
Interpolation with the fixed probes	0.3	0.15	0.10	0.07
Inflector fringe field	0.2	0.20	-	-
uncertainty from muon distribution	0.1	0.12	0.03	0.03
Other*		0.15	0.10	0.10
Total	0.5	0.4	0.24	0.17

*higher multipoles, trolley voltage and temperature response, kicker eddy currents

The error budget for E969 represents continuation of improvements already made during E821



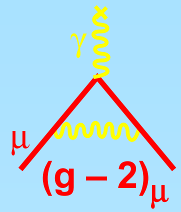
Systematic uncertainty (ppm)	1998	1999	2000	2001	E969 Goal
Magnetic field – ω_p	0.5	0.4	0.24	0.17	0.1
Anomalous precession – ω_a	0.8	0.3	0.31	0.21	0.1
Statistical uncertainty (ppm)	4.9	1.3	0.62	0.66	0.2
Total Uncertainty (ppm)	5.0	1.3	0.73	0.72	0.25

- **Field improvements:** better trolley calibrations, better tracking of the field with time, temperature stability of room, improvements in the hardware
- **Precession improvements** will involve new scraping scheme, lower thresholds, more complete digitization periods, better energy calibration, increased detector segmentation

Summary

- E821 Achieved a precision of ± 0.5 ppm
- There appears to be a discrepancy between experiment and e^+e^- based theory –> hint of new physics?
- E969 proposes to achieve a precision down to ± 0.25 ppm (factor of 2 improvement) with 4x as many muons
- Lots of continuing work worldwide on the hadronic theory piece, both experimental and theoretical.

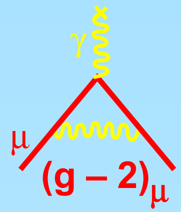
Outlook:



- E969 is being considered by the national U.S. Particle Physics Project Prioritization Panel (P5): recommendation due this week!
- We hope that our friends in the theory, e^+e^- and τ communities will continue to work on the hadronic contribution to a_μ
- If both theory and experiment can improve by a factor of 2, the stage is set for another potential confrontation between theory and experiment.

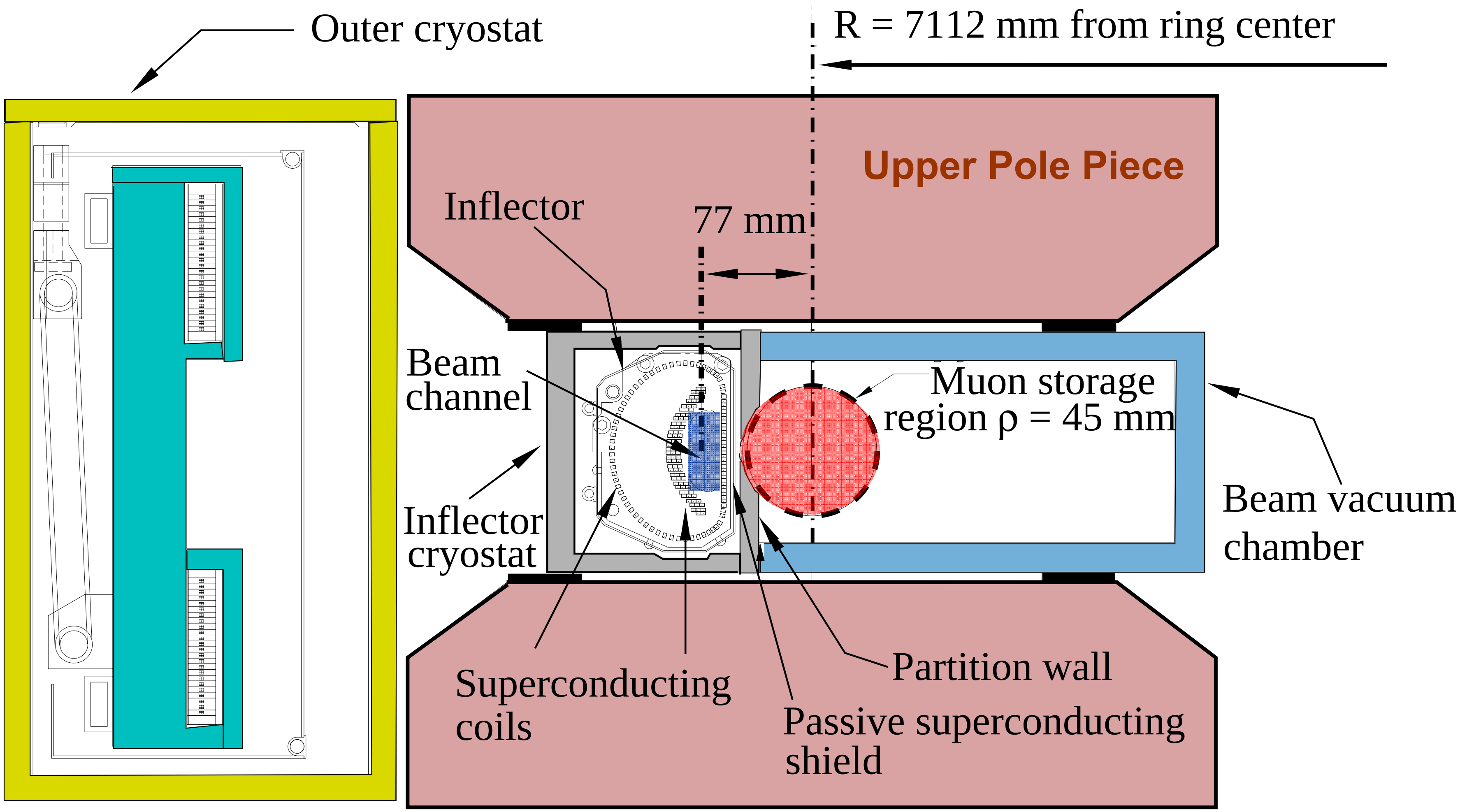
Thanks to the organizers of this excellent conference!

E969 Builds on the apparatus and Experience of E821

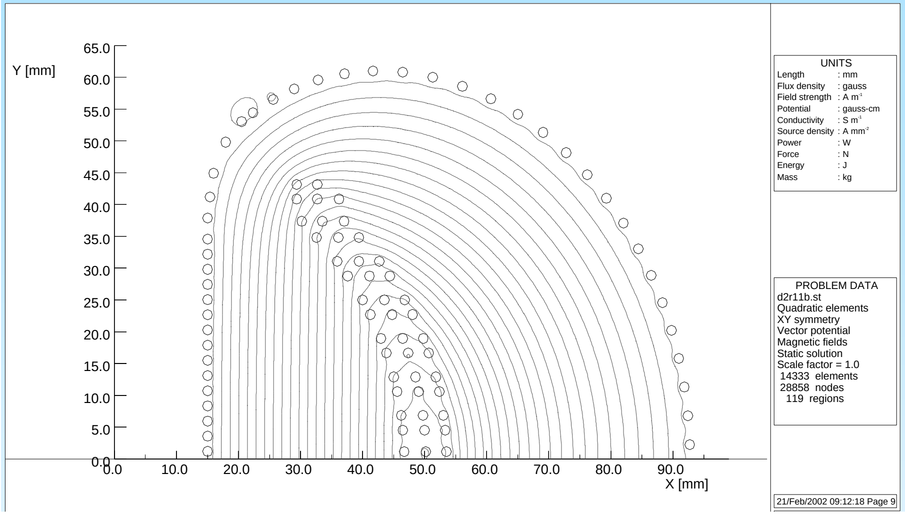


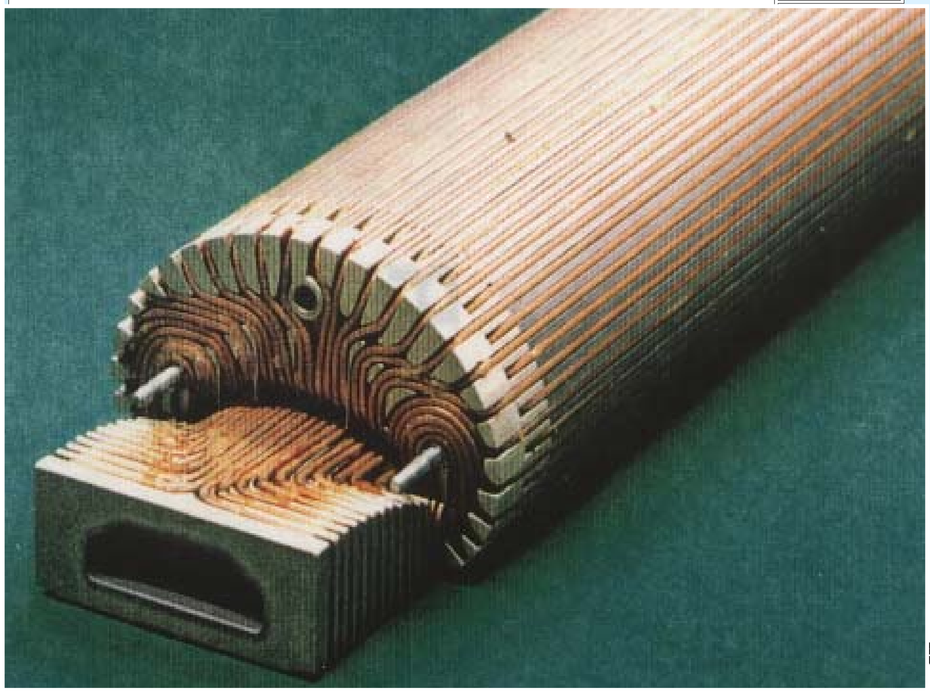
1. AGS Proton Beam 12 – bunches from the AGS 60 Tp total intensity
2. 0^o π Beam
3. π decay channel
4. μ Beam injected into the ring through a superconducting inflector
5. Fast Muon Kicker
6. Precision Magnetic Storage Ring
7. Electron calorimeters, custom high-rate electronics and wave-form digitizers

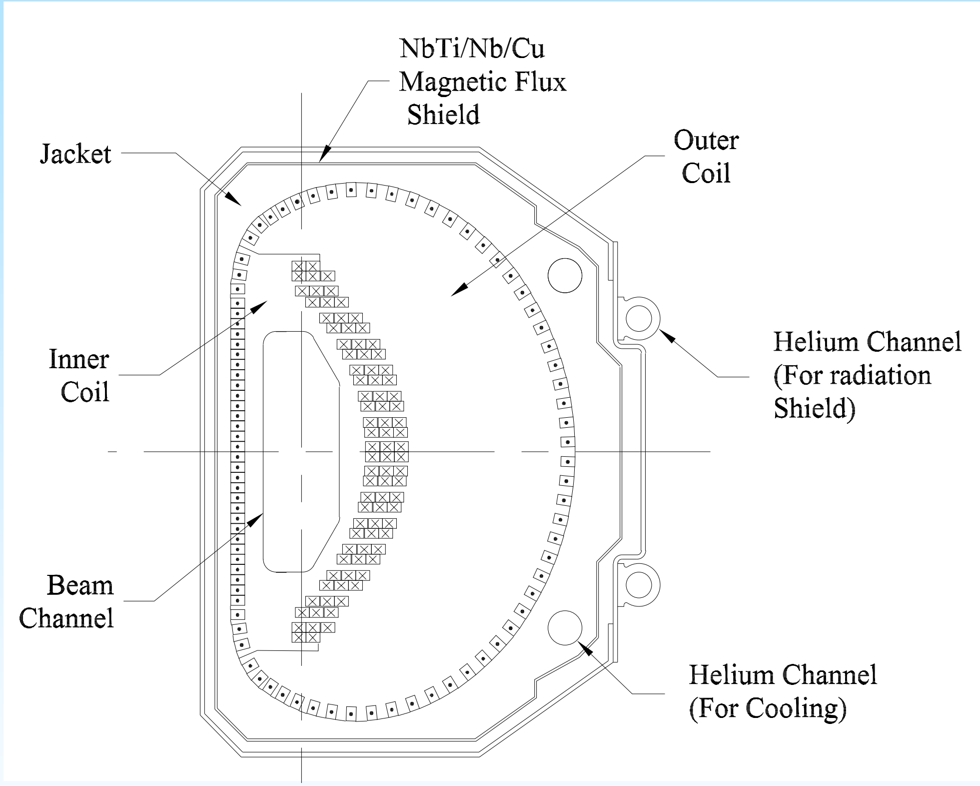
The mismatch between the inflector exit and the storage aperture + imperfect kick causes coherent beam oscillations



The E821 inflector magnet had closed ends which lost half the beam.







Length = 1.7 m

Central field = 1.45 T

Open end prototype, built and tested

→ X2 Increase in Beam

The fast kicker is the major new feature not in the CERN experiment. Kicker Modulator is an