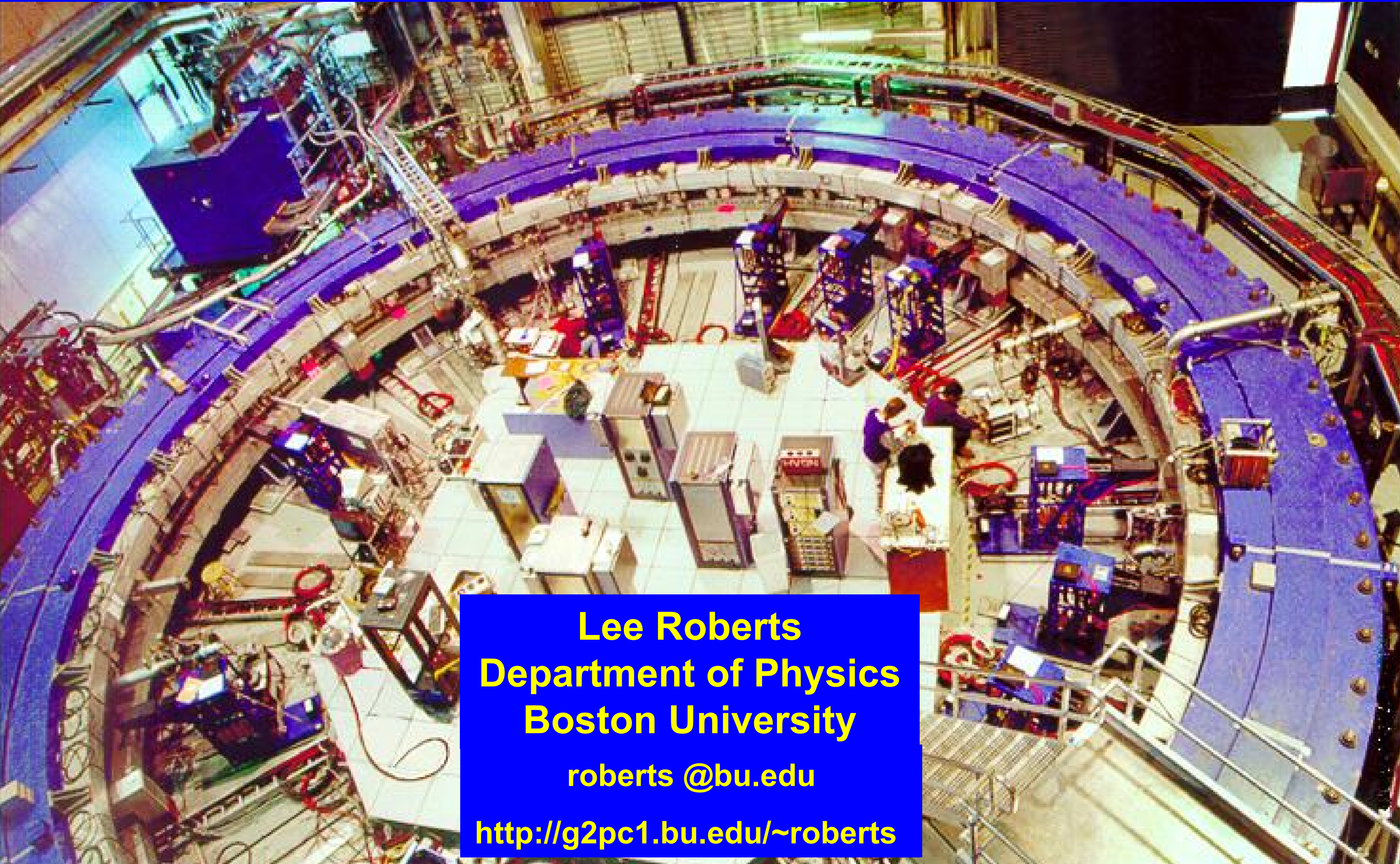
Muon (g-2): Status, and Future Possibilities at J-PARC



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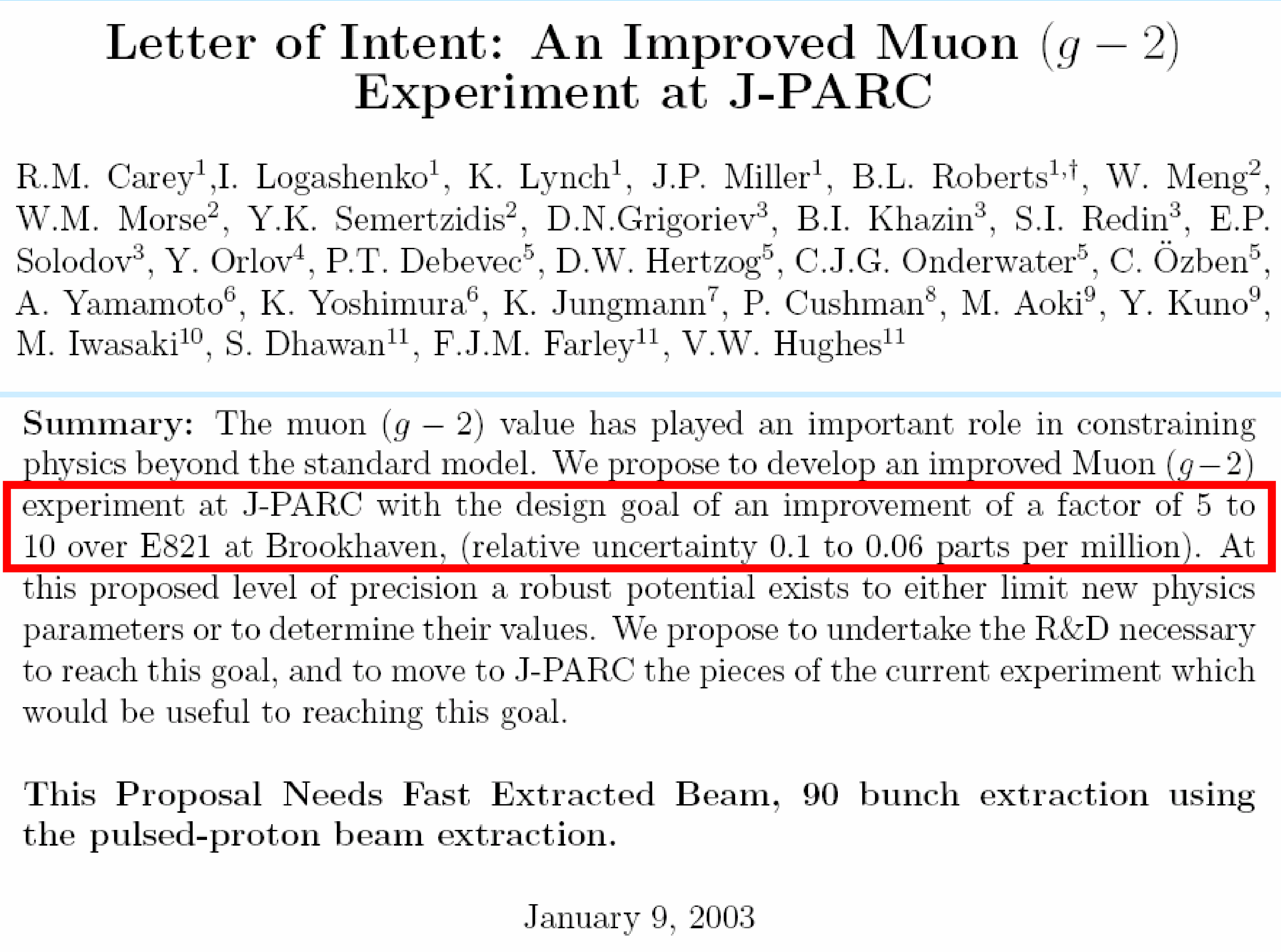
Outline

- Magnetic (a_μ) dipole moments
  - E821 at BNL
- Future improvements in a_μ?
  - Possibilities at J-PARC
- Summary

Japanese Contributions to E821

- Supported magnet design engineering in 1999, before DOE funding began
- The superconducting Inflector Magnet
- The high quality magnet steel used in the storage-ring pole pieces
- The superconductor for the storage ring coils
- The concept of winding the coils on the inside of the mandrel
- The scintillating fiber beam monitors
- **We are delighted that there is interest in hosting the next generation $(g-2)_\mu$ experiment at J-PARC.**



Letter of Intent: An Improved Muon $(g-2)$ Experiment at J-PARC

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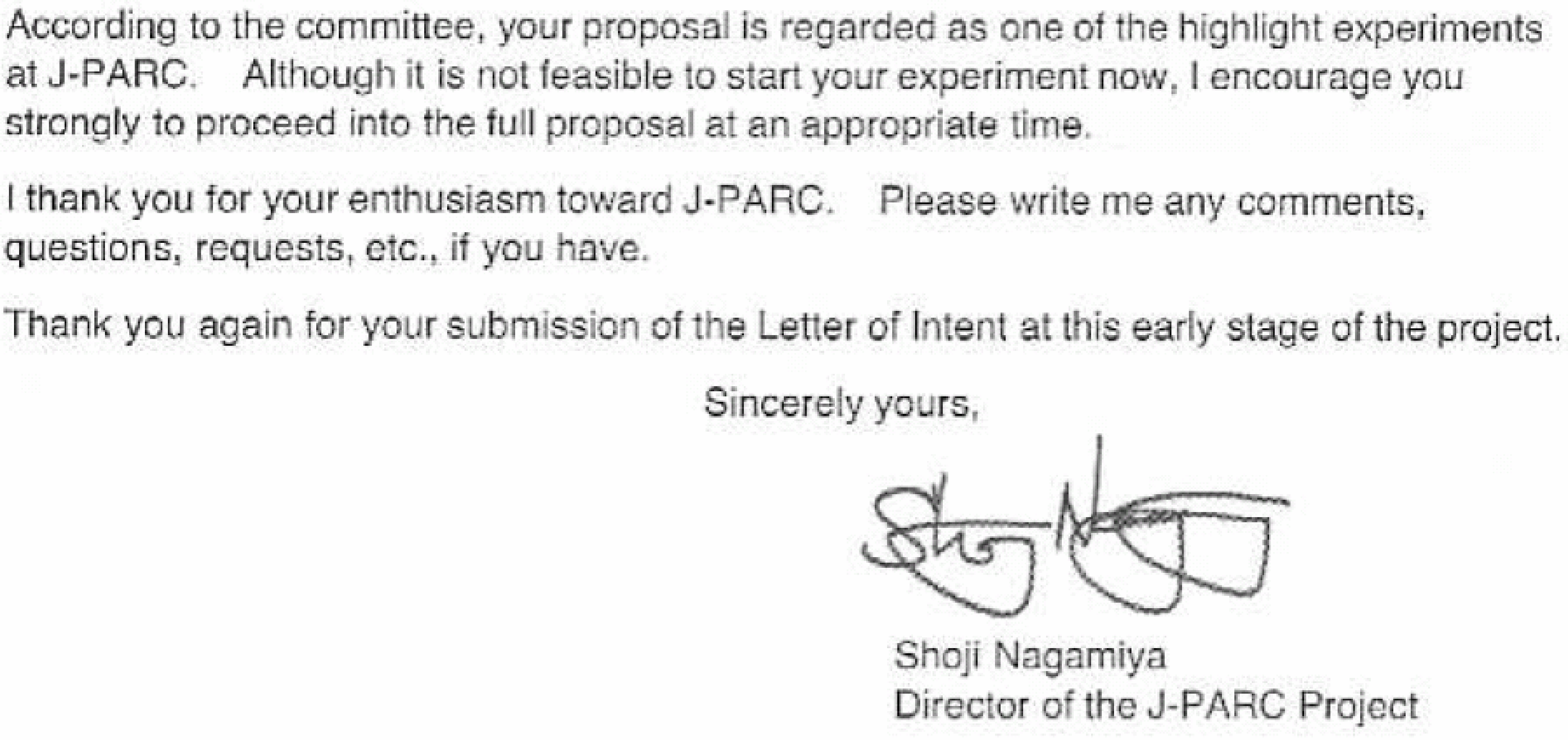
Summary: The muon $(g-2)$ value has played an important role in constraining physics beyond the standard model. We propose to develop an improved Muon $(g-2)$ experiment at J-PARC with the design goal of an improvement of a factor of 5 to 10 over E821 at Brookhaven, (relative uncertainty 0.1 to 0.06 parts per million). At this proposed level of precision a robust potential exists to either limit new physics parameters or to determine their values. We propose to undertake the R&D necessary to reach this goal, and to move to J-PARC the pieces of the current experiment which would be useful to reaching this goal.

This Proposal Needs Fast Extracted Beam, 90 bunch extraction using the pulsed-proton beam extraction.

January 9, 2003

Response to LOI



According to the committee, your proposal is regarded as one of the highlight experiments at J-PARC. Although it is not feasible to start your experiment now, I encourage you strongly to proceed into the full proposal at an appropriate time.

I thank you for your enthusiasm toward J-PARC. Please write me any comments, questions, requests, etc., if you have.

Thank you again for your submission of the Letter of Intent at this early stage of the project.

Sincerely yours,

Shoji Nagamiya
Director of the J-PARC Project

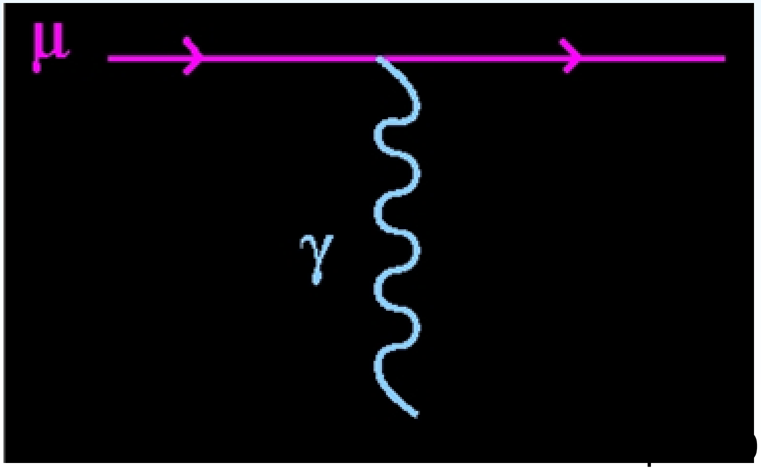
Electric and Magnetic Dipole Moments:

a_μ chiral changing

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

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

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



Spin turns relative to the momentum with the difference frequency: $\omega_a = \omega_S - \omega_C$

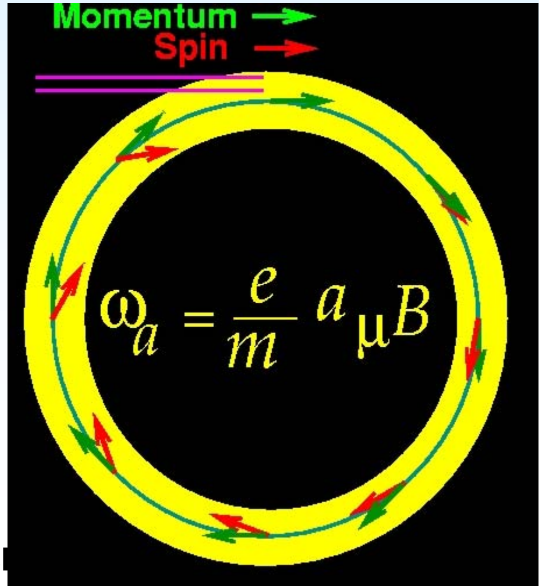
With an electric quadrupole field for vertical focusing

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

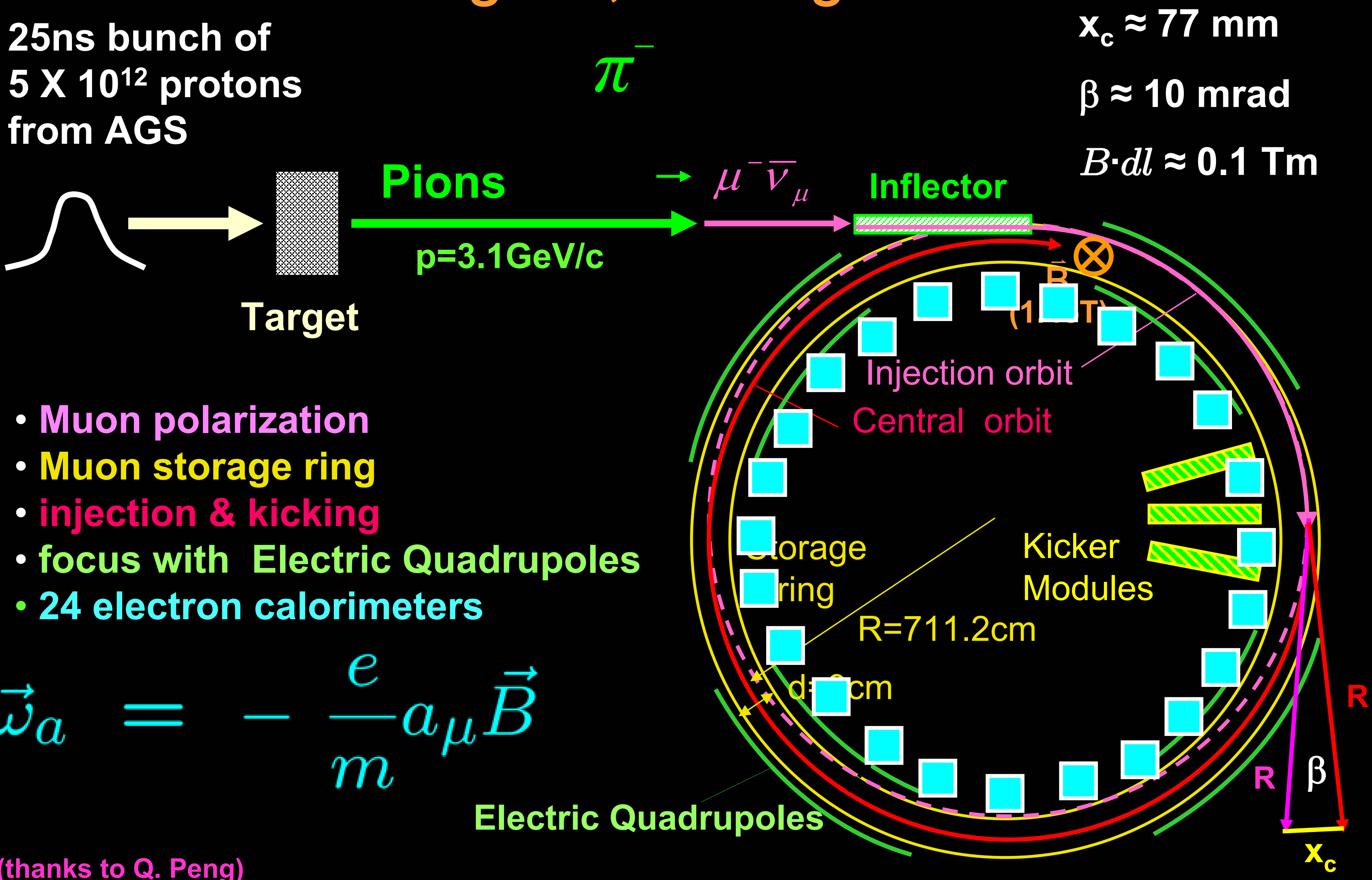
$$B \Rightarrow \langle B \rangle_{\mu-\mathrm{dist}}$$

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

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



Experimental Technique: fill ring, count until all muons are gone; do it again

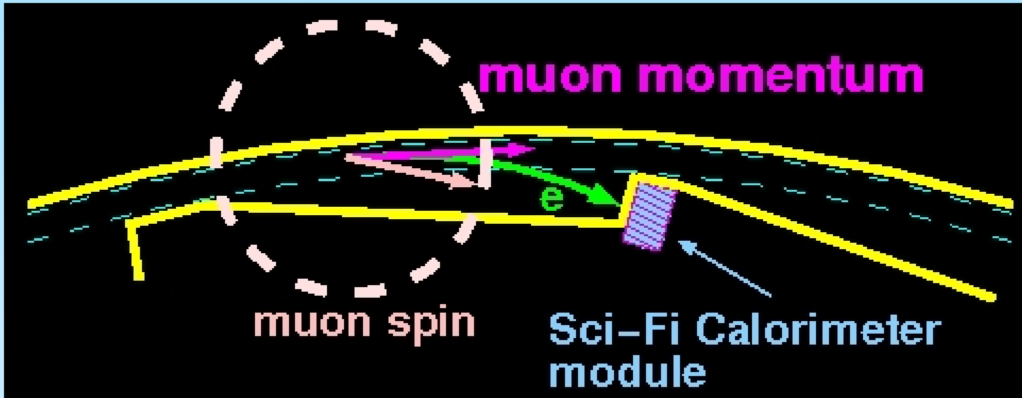


- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

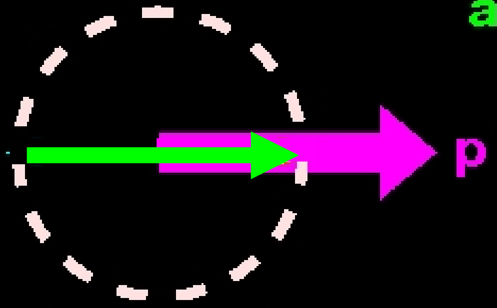
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

(thanks to Q. Peng)

To measure ω_a, we used Pb-scintillating fiber calorimeters.

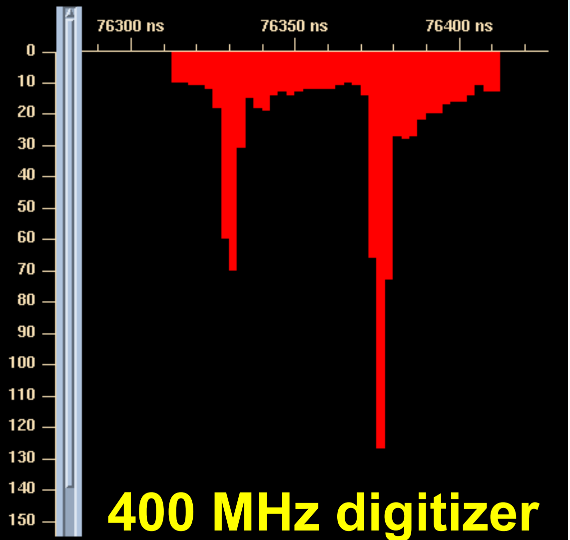


Measures Energy and time



spin forward, more high energy e

spin backward, less high energy e



400 MHz digitizer gives t, E

$\gamma\tau_\mu$ = 64.4 μs

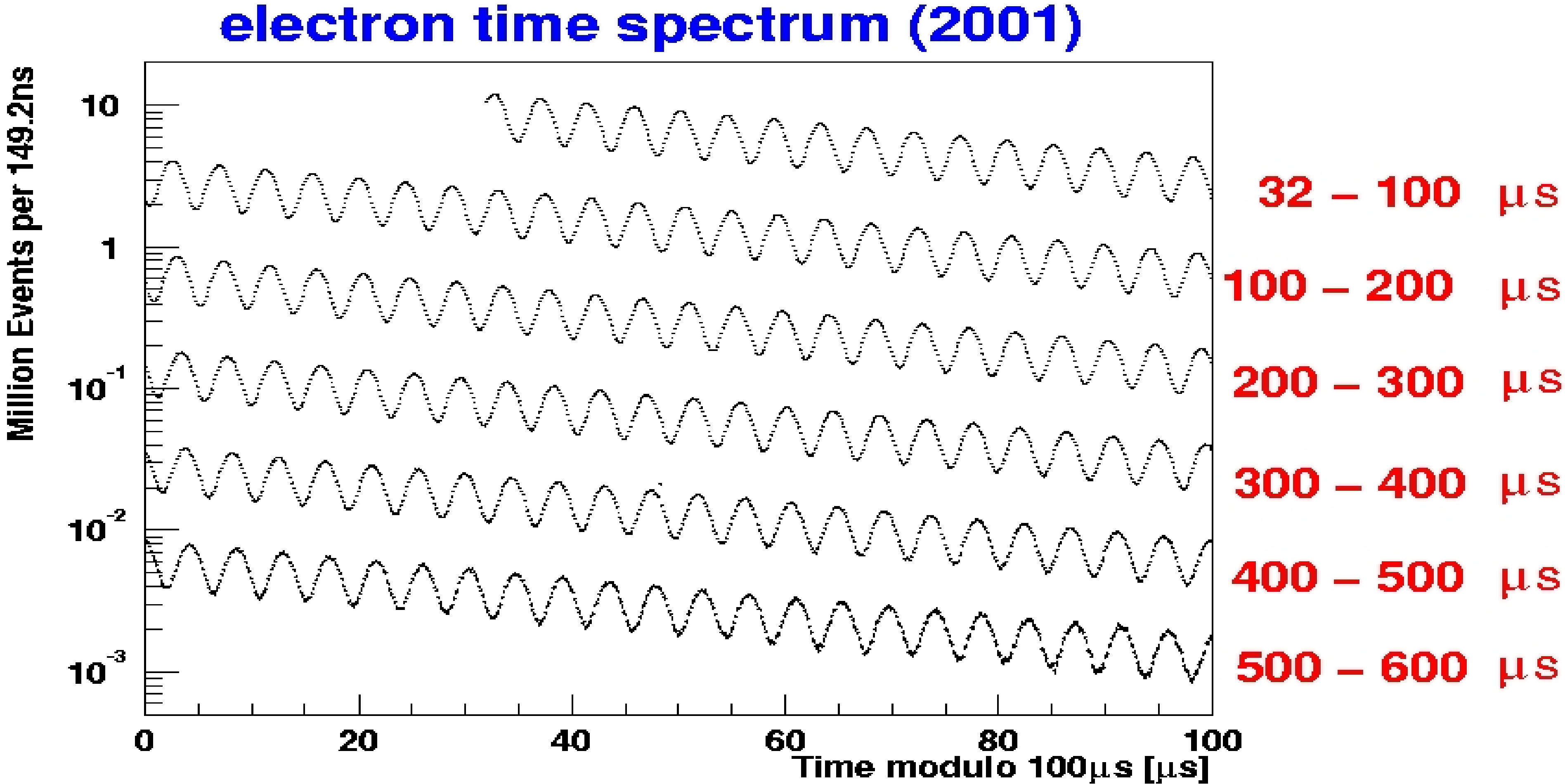
T_a = 4.37 μs

T_C = 149 ns

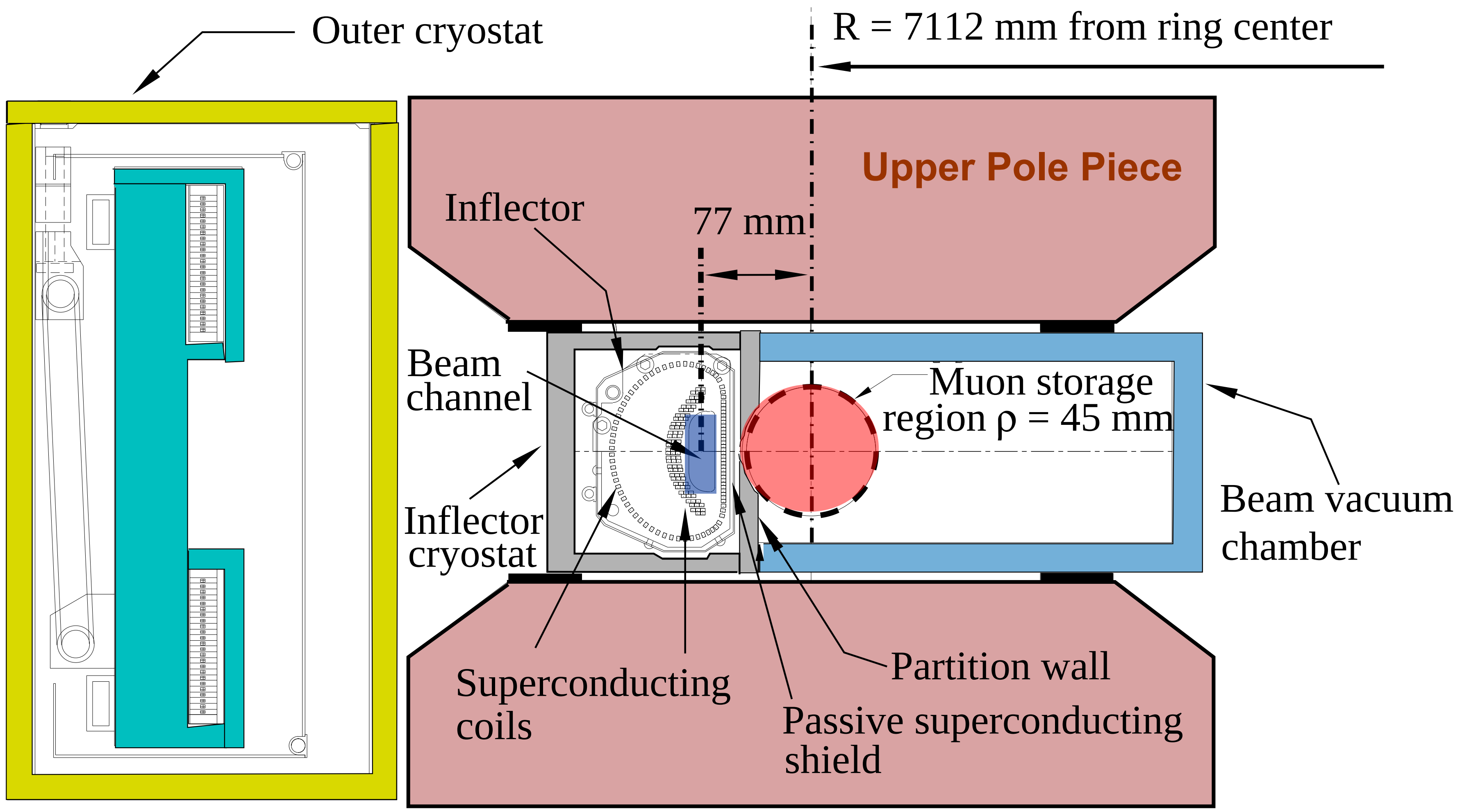
Count number of e^- with $E_e \geq 1.8$ GeV high-energy electrons as a function of time.

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

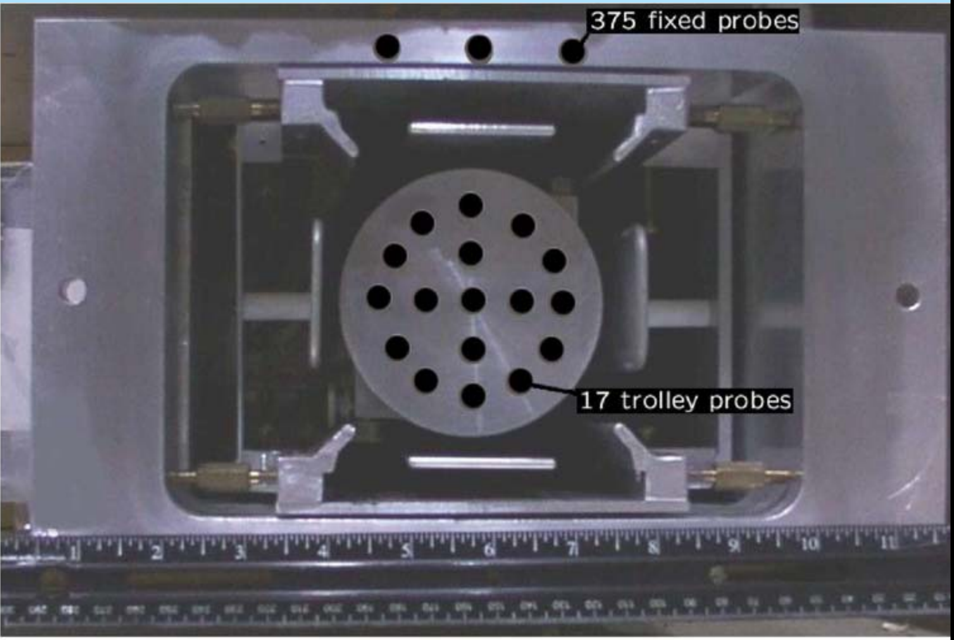
$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$

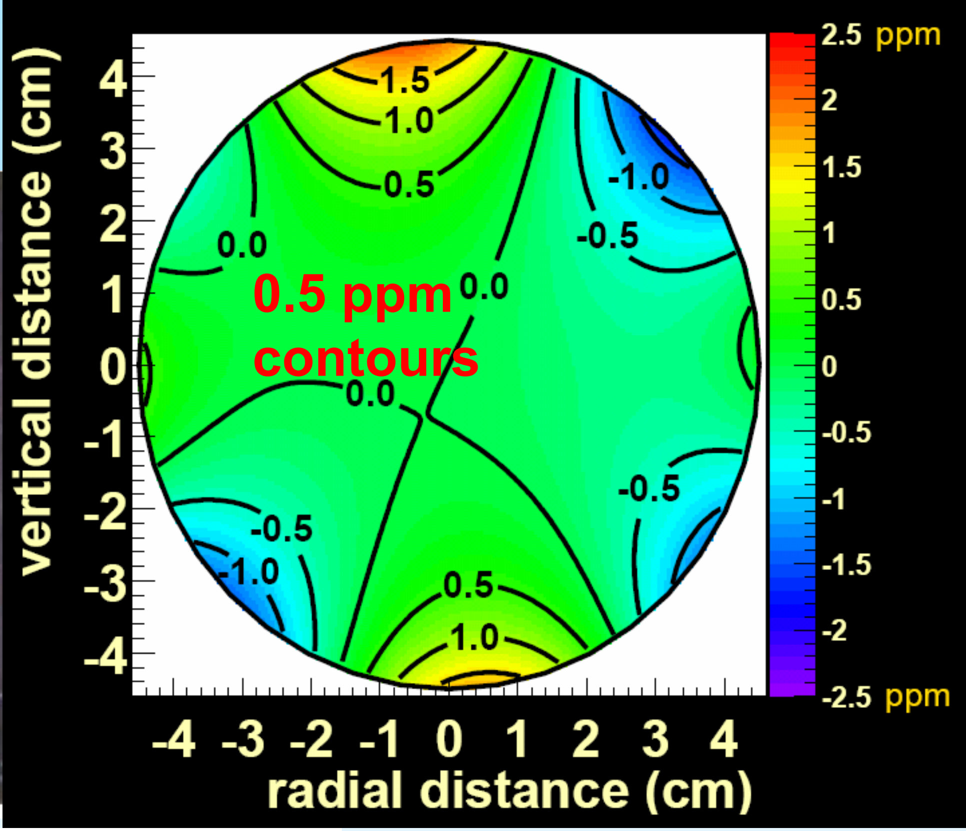


Injection Geometry: Space limitations prevent matching the inflector exit to the storage aperture



B averaged over azimuth





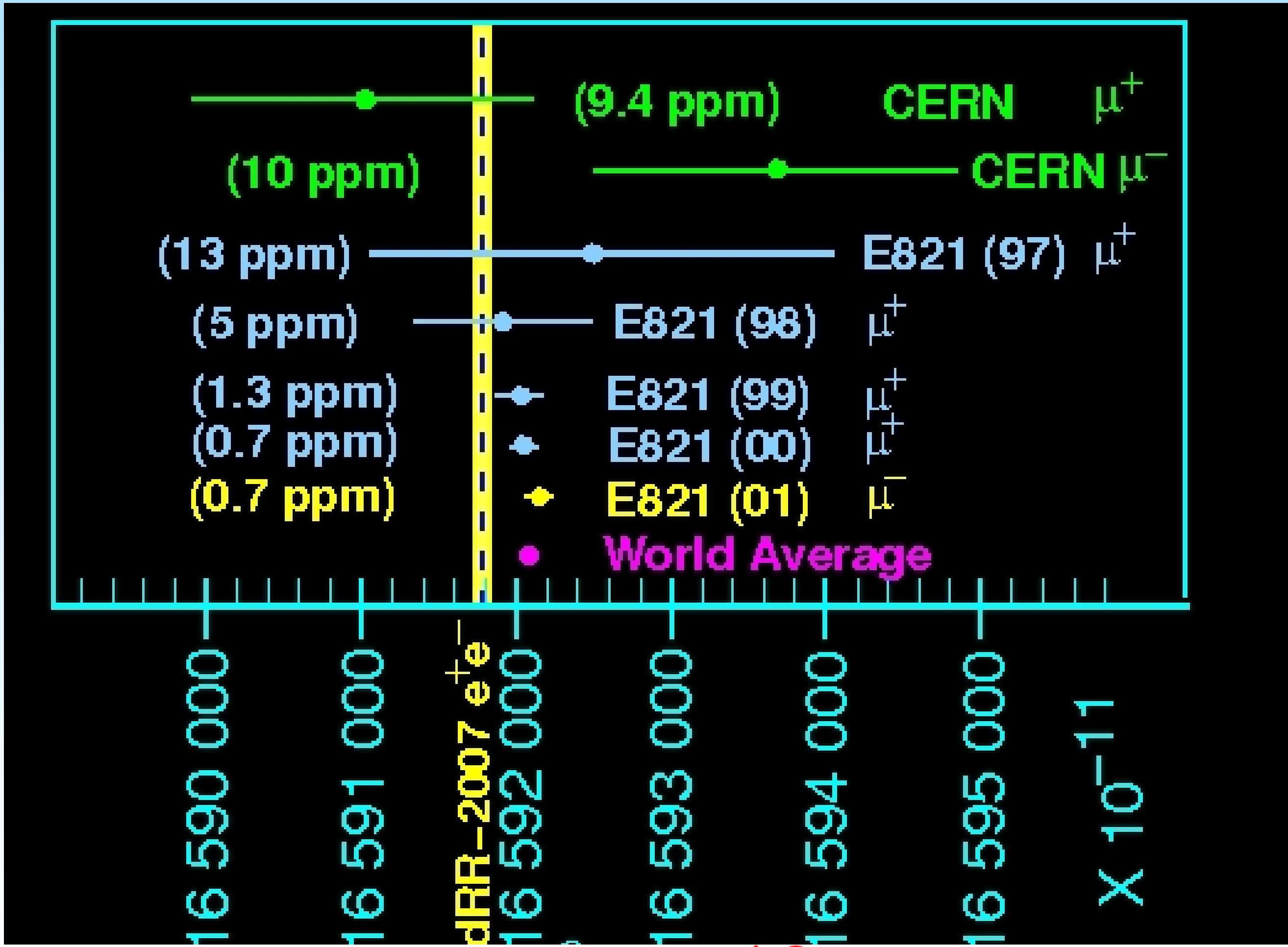
0.5 ppm contours

$$\sigma_{\text{syst}} \text{ on } \langle B \rangle_{\mu-\text{dist}} = \pm 0.03 \text{ ppm}$$

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

ω_p – free proton larmor frequency

E821 achieved 0.5 ppm and the e^+e^- based theory is also at the 0.6 ppm level. Difference is 3.4σ

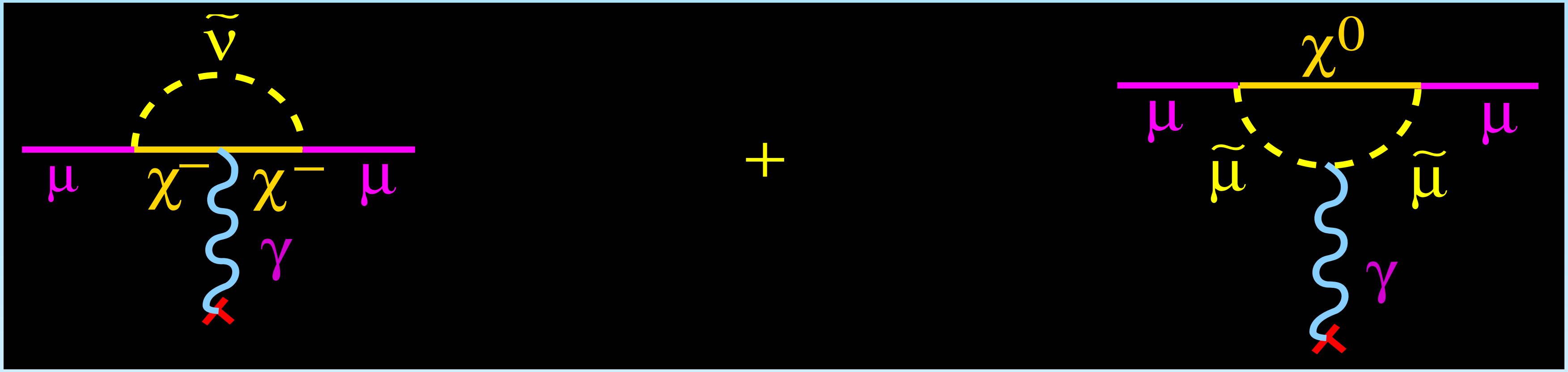


MdRR=Miller, de Rafael, Roberts, Rep. Prog. Phys. **70** (2007) 795

$$a_\mu^{E821} = 11\,659\,208.0(6.3) \times 10^{-10} \quad (0.54\,\text{ppm})$$

$$\Delta a_\mu^{(\text{today})} = (29.5 \pm 8.8) \times 10^{-10}$$

a_μ represents a sum over all physics that couples to the muon, e.g. SUSY



$$a_\mu(\mathrm{SUSY}) \simeq \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \left(1 - \frac{4\alpha}{\pi} \ln \frac{\tilde{m}}{m_\mu}\right)$$

$$\simeq (\mathrm{sgn}\mu)\ 13 \times 10^{-10} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

and many other things (extra dimensions, etc.)

Snowmass Points and Slopes: some “reasonable SUSY benchmarks

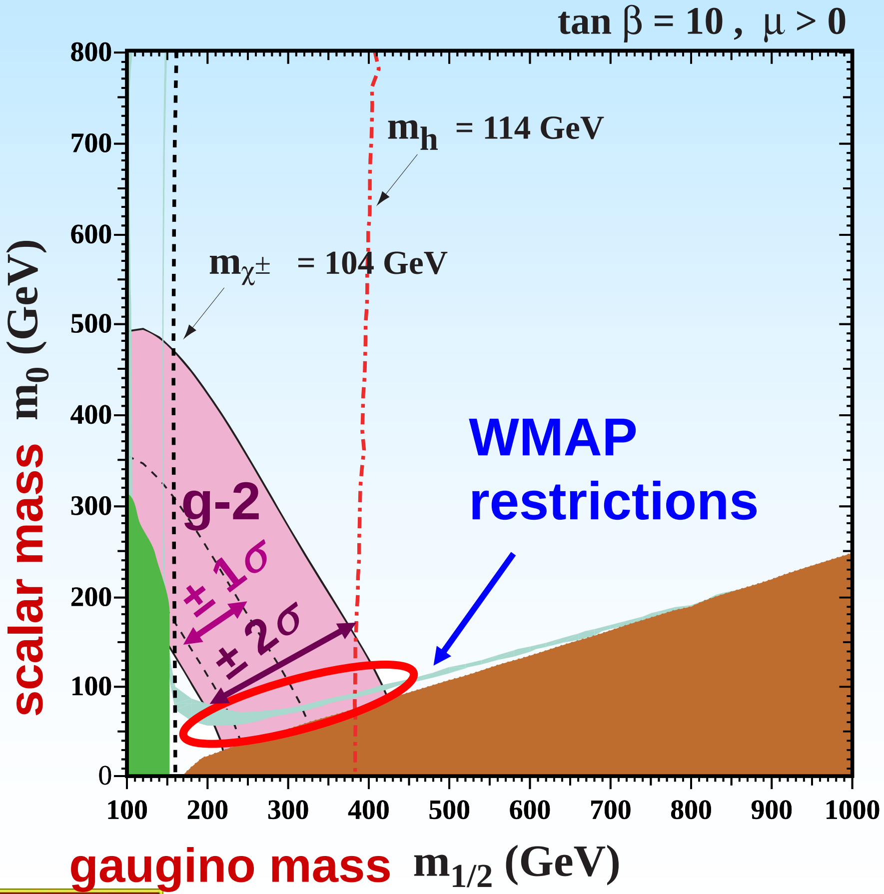
SPS Point	$a_\mu^{\text{SUSY,1L}}$ x10^{11}
SPS 1a	293
SPS 1b	318
SPS 2	16.5
SPS 3	135
SPS 4	490
SPS 5	86
SPS 6	169
SPS 7	237
SPS 8	173
SPS 9	-90

$$\Delta a_\mu^{(\text{today})} = (295 \pm 88) \times 10^{-11}$$

$$¿\Delta a_\mu^{(\text{future})} = (295 \pm 39) \times 10^{-11} \ ?$$

a_μ helps constrain new physics

In a constrained minimal supersymmetric model, $(g-2)_\mu$ provides an independent constraint on the SUSY LSP (lightest supersymmetric partner) being the dark matter candidate.



Historically muon (g-2) has played an important role in restricting models of new physics.

It provides constraints that are <u>independent and complementary</u> to high-energy experiments.

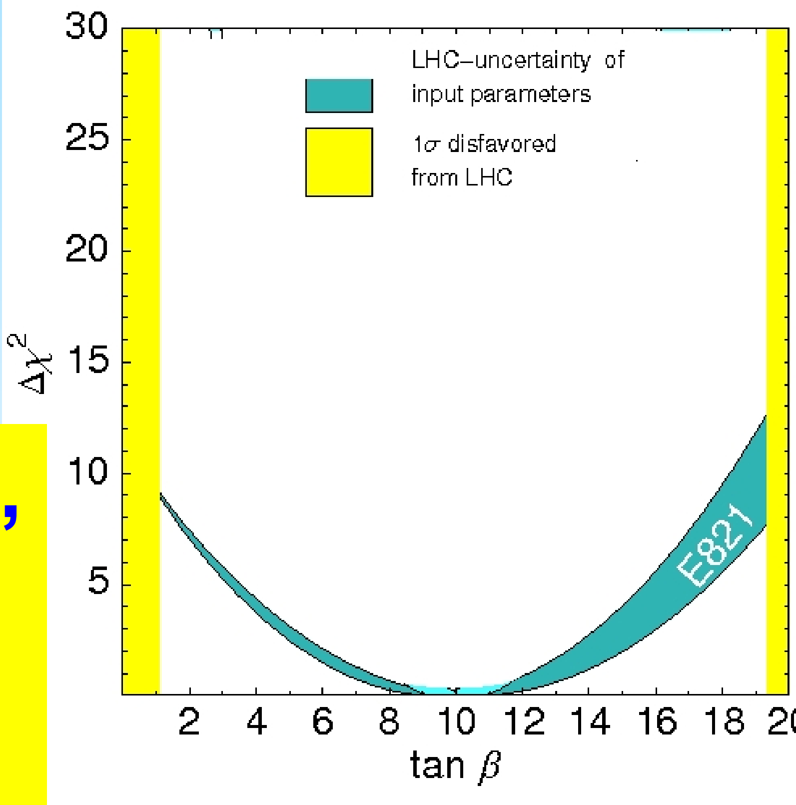
CMSSM calculation Following Ellis, Olive, Santoso, Spanos, provided by K. Olive

a_μ will help constrain the interpretation of LHC data, e.g. tan β and sgn μ parameter

MSSM reference point SPS1a

With these SUSY parameters, LHC gets tan β of 10.22 ± 9.1.

See: arXiv:0705.4617v1 [hep-ph]



Even with no improvement, a_μ will provide the best value for tan β, and show $\mu > 0$ to $> 3\ \sigma$

$$\Delta a_\mu^{(\mathrm{today})} = (29.5 \pm 8.8) \times 10^{-10}$$

Improved experiment and theory for a_μ is important

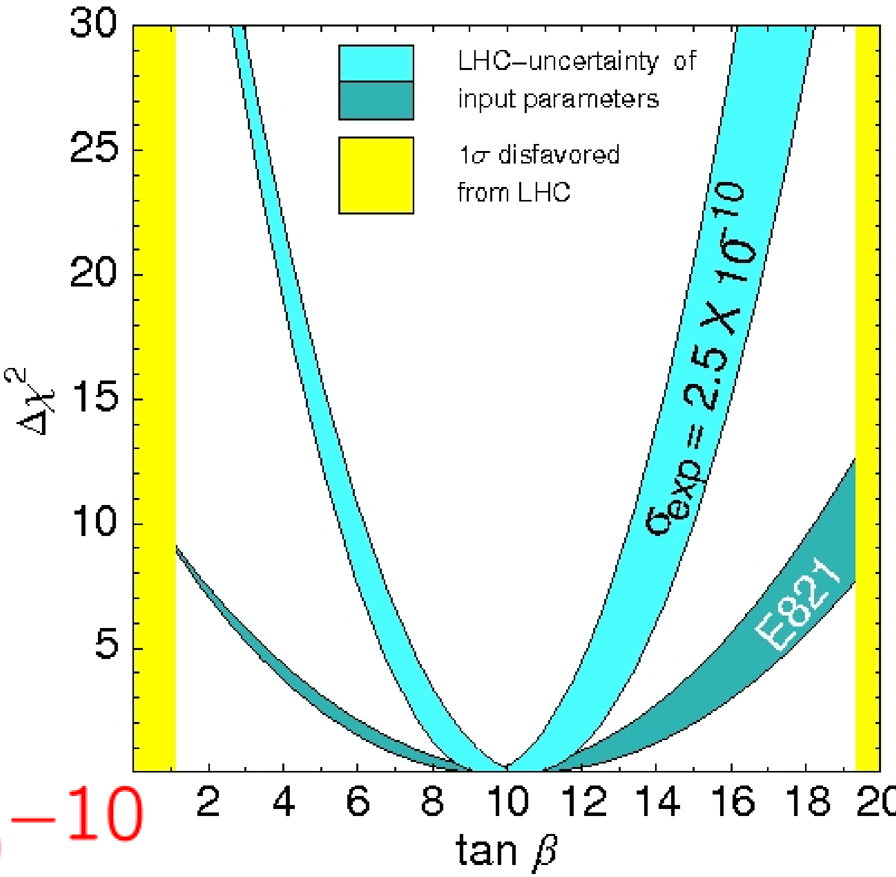
MSSM reference point SPS1a

With these SUSY parameters, LHC gets tan β of 10.22 ± 9.1.

See: arXiv:0705.4617v1 [hep-ph]

$\mu > 0$ by > 6 σ

tan β to < 20%



$$\sigma^{E821} \quad (6.3 \rightarrow 2.5) \times 10^{-10}$$

$$\sigma^{SM} \quad (6.1 \rightarrow 3.0) \times 10^{-10}$$

$$\Delta a_\mu^{(\text{future})} = (29.5 \pm 3.9) \times 10^{-10}$$

Future Improvements in a_μ?

$$\sigma^{E821}_{\text{stat}} = \pm 0.46 \text{ ppm}$$

$$\sigma^{E821}_{\text{syst}} = \pm 0.28 \text{ ppm}$$

- Theory (strong interaction part) will improve.
  - both lowest order, and light-by-light
- How well could we do in an improved experiment?
  - The systematic limit of our technique is between ~0.1 and 0.06 ppm. (Jan. 2003 LOI to J-PARC presented)
- What to improve to get and use more muons:
  - the detectors
  - the inflector
  - the muon kicker
  - the beamline

Many studies are necessary to understand improved systematic errors.

- Let's take a quick look at our BNL proposal, E969 which had a goal of 2.5 times better, from 0.54 → 0.2 ppm total error.

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

Systematic uncertainty (ppm)	1998	1999	2000	2001	Future 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	?
Total Uncertainty (ppm)	5.0	1.3	0.73	0.72	?

- 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

E821 ω_p systematic errors (ppm)

Source of Uncertainty	1998	1999	2000	2001	**Future (969)**
Absolute Calibration	0.05	0.05	0.05	0.05	0.05
Calibration of Trolley	0.3	0.20	0.15	0.09	0.06
Trolley Measurements of B0	0.1	0.10	0.10	0.05	0.02
Interpolation with the fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	
uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Other*		0.15	0.10	0.10	0.05
Total	0.5	0.4	0.24	0.17	0.11

*higher multipoles, trolley voltage and temperature response, kicker eddy currents, and time-varying stray fields.

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Systematic errors on ω_a (ppm)

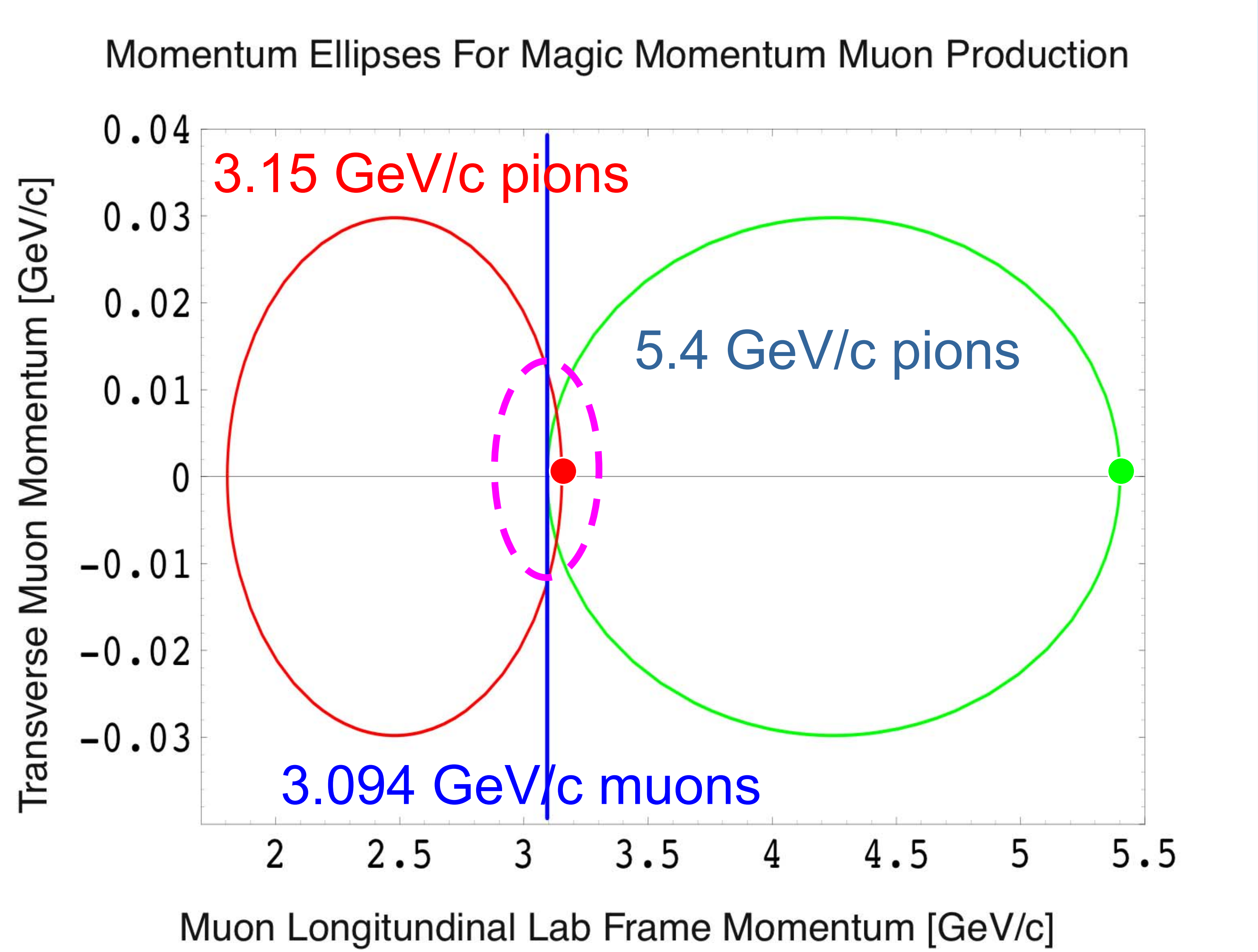
$\sigma_{systematic}$	1999	2000	2001	Future
Pile-up	0.13	0.13	0.08	0.04
AGS Background	0.10	0.10	0.015*	
Lost Muons	0.10	0.10	0.09	0.04
Timing Shifts	0.10	0.02	0.02	
E-Field, Pitch	0.08	0.03	0.06*	0.05
Fitting/Binning	0.07	0.06	0.06*	
CBO	0.05	0.21	0.07	0.04
Beam Debunching	0.04	0.04	0.04*	
Gain Change	0.02	0.13	0.13	0.03
total	0.3	0.31	0.21	~0.09

$\Sigma^* = 0.11$

To improve ω_a measurement

- Get rid of the pions!
  - E821 beam: π/μ = 1 and e:μ:π:p = 1:1:1:$^1/_3$
  - π, p interact directly and also produce delayed neutrons
  - **affects: gain, time stability; pileup extraction, start time of fits**
- Reduce instantaneous rates (pileup) and improve pile-up knowledge
  - measure pileup to lower energies
  - and/or use "Q" (charge integrating) method
  - segment detectors
  - more proton bunches per unit time, with less protons per bunch
    - E821 had:
      - **12 bunches, 6 X 10^{12} protons per bunch per 2.7s cycle time**
  - Ideal beam structure:
    - 1 proton bunch every milli-second with ~1 X 10^{12} ppb
- Reduce muon losses and coherent betatron oscillations
  - improve fast muon kicker
  - better beam scraping in the ring

For E969, we considered the idea of backward muon production … the advantages are appealing … but need longer beamline



How to go to the very forward/backward μ, and get rid of the π

- backward beam p_π = 5.3 GeV/c p_μ = 3.1 GeV/c
  - eliminates π and p in the μ beam
  - needs long beamline (~200 m ?)

- forward decay beamline (very long)
  - would eliminate π by decay, p by TOF
  - impractical since it needs ~800 m beamline

- muon accumulator ring with forward beam
  - also eliminates π by decay, and time separates p
  - requires a challenging kicker for injection/ejection

Ideal beam structure – real structure will be a compromise

- The muon lifetime in the ring is 64.4 μs, so we count for 10 lifetimes.
- Ideal time between fills of the ring

  ≈ 1 to 2 ms (probably 10 ms is a practical limit)
- Beam width at injection

  $\sigma \leq 24$ ns
- Proton intensity

  ≈ few 10^{12} protons or less
- No additional protons can hit the production target during (g-2) data collection

  need pulsed sweeper magnet in the muon beamline to remove afterpulses

Summary

- a_μ has been particularly valuable in restricting physics beyond the standard model, and will continue to do so in the LHC Era.
- The 3.4 σ difference with the SM is already very interesting.
- J-PARC could provide an excellent place for a new (g-2) experiment, and the experimental errors could be improved significantly
  - eventually to a factor of 4-6 over the present value
- Machine people and kicker engineers are studying the possibilities and the issues.
- A new experiment will further stimulate improvements in the theoretical value.

THE END