The next muon g-2 experiment to 0.25 ppm

Yannis K. Semertzidis

Brookhaven National Laboratory

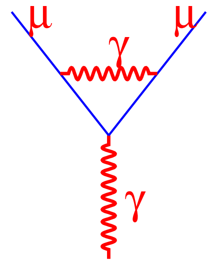
- **We made a presentation at P5 (27 March 2006) and expect a report from P5 ~summer 2006**

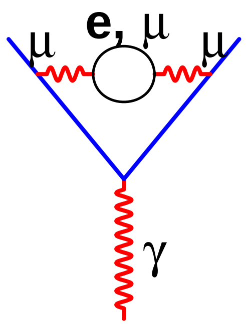
- **Physics case made (W. Marciano @ P5)**
- **E969 goal of 0.25 ppm achievable (L. Roberts @ P5)**

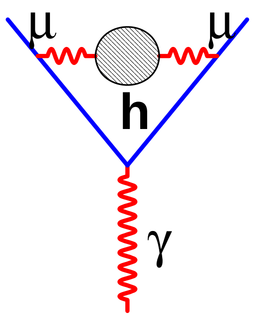
The Muon Storage Ring:
$B \approx 1.45T$, $P_\mu \approx 3$ GeV/c

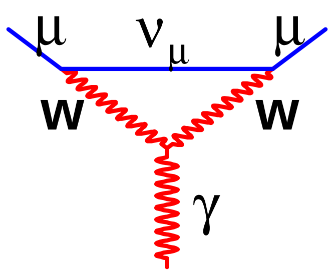
g - 2 for the muon

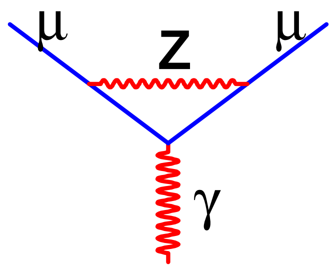
$$a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$$











Status and goal

(W. Marciano, P5)

$$a_\mu = \frac{g_\mu - 2}{2} = \frac{\alpha}{2\pi} + \cdots$$

$$\text{E821} \rightarrow a_\mu^{exp} = 116\,592\,080\,(63) \times 10^{-11}$$

$$\text{Standard Model} \rightarrow a_\mu^{SM} = 116\,591\,812\,(59)_{VP}(35)_{LBL}(2)_{EW} \times 10^{-11}$$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = \underline{268}\,\underbrace{\underbrace{(59)_{VP}(35)_{LBL}(2)_{EW}}_{(69)}(63)_{exp}}_{(93)} \times 10^{-11}$$

2.9 sigma Discrepency !

Future goal > 5 sigma

Theory

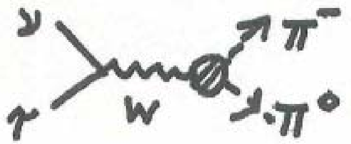
(W. Marciano, P5)

Use $e^+e^- \to$ Hadrons Cross Section + Dispersion Relation

$e^+e^- \to \pi^+\pi^-(\gamma)$ Dominates ~72% (ρ dominated)

Alternatives:

$\Gamma(\tau \to \pi^-\pi^0)$ + Isospin Corrections



or Pure Lattice Calculation (T. Blum)

For LBL: Pion Pole + Short-Distance

or

Lattice (Some Day)

$$a_\mu^{LBL} = +120(35) \times 10^{-11}$$ Conservative Error

Interesting History

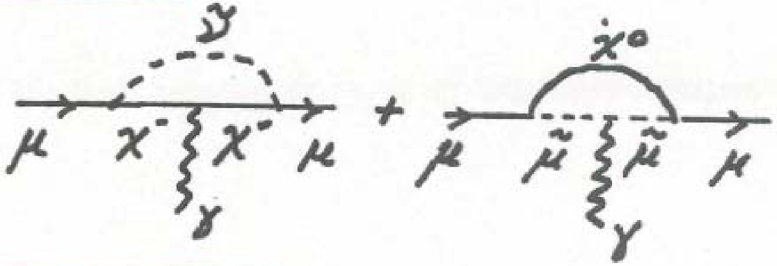
Now Stable

New Physics Implications

(W. Marciano, P5)

2) New Physics Implications:

i) SUSY Loops:



$$a_\mu^{SUSY} \simeq (\text{sign}\,\mu = +/-) \times 130 \times 10^{-11}\, \tan\beta \left(\frac{100\,\text{GeV}}{\bar{m}_{SUSY}}\right)^2$$

$$\Delta a_\mu = 268(93) \times 10^{-11}$$

Natural Explanation!

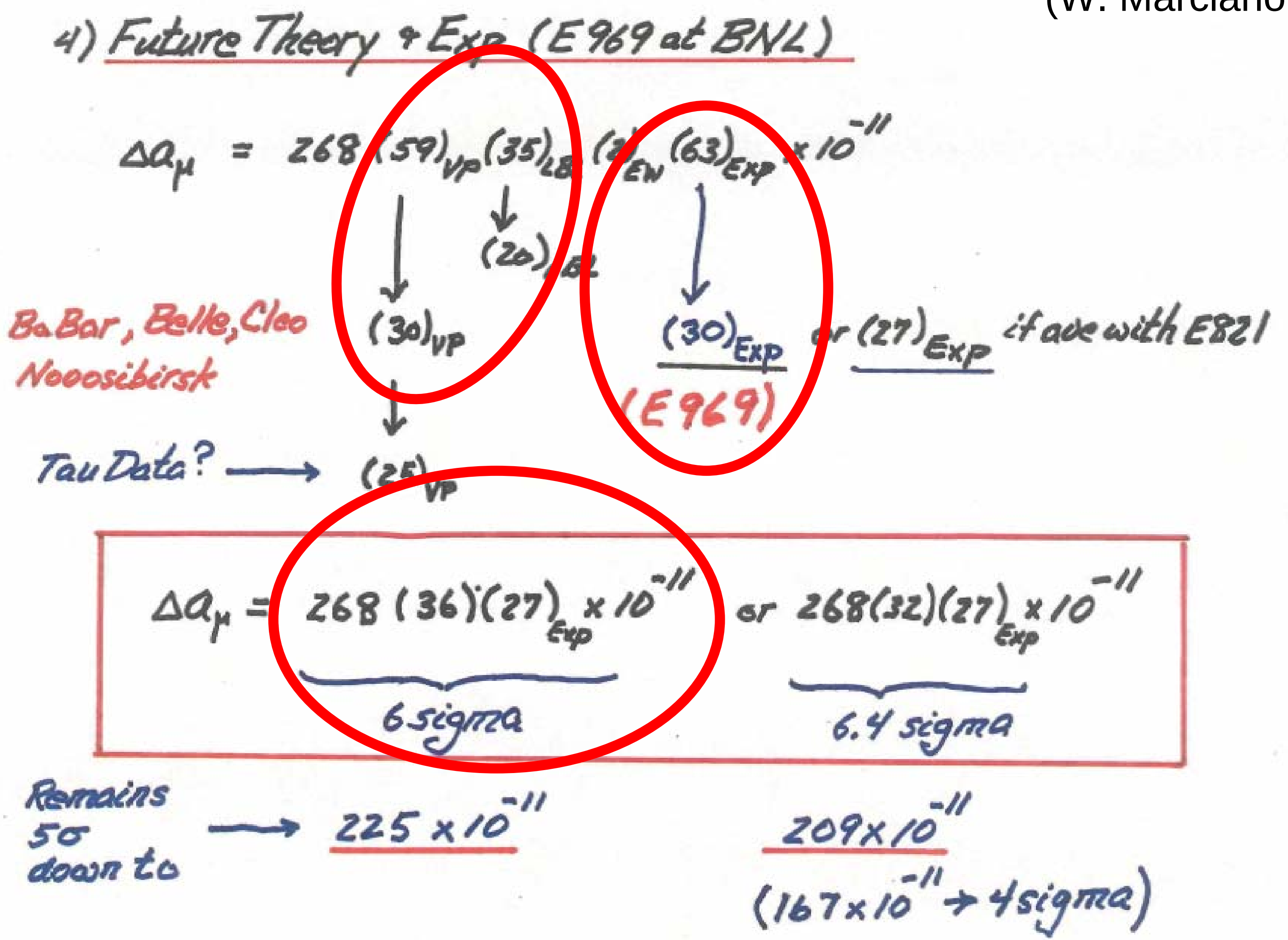
sign $\mu = +$ (Eliminates $\sim \frac{1}{2}$ Models)

$\bar{m}_{SUSY} \simeq 70\sqrt{\tan\beta}$ GeV $\simeq$ 100 ~ 500 GeV

Someday $\tan\beta \simeq 2\,(\bar{m}_{SUSY}/100\,\text{GeV})^2$ * Best Determination

Future Theory and Experiment

(W. Marciano, P5)



Motivation

(W. Marciano, P5)

Conclusions: E969 Goal $\pm 30\times10^{-11}$ Well Motivated

$>5\sigma$ Discovery Potential

(Even if τ data moves Δa_μ down somewhat)

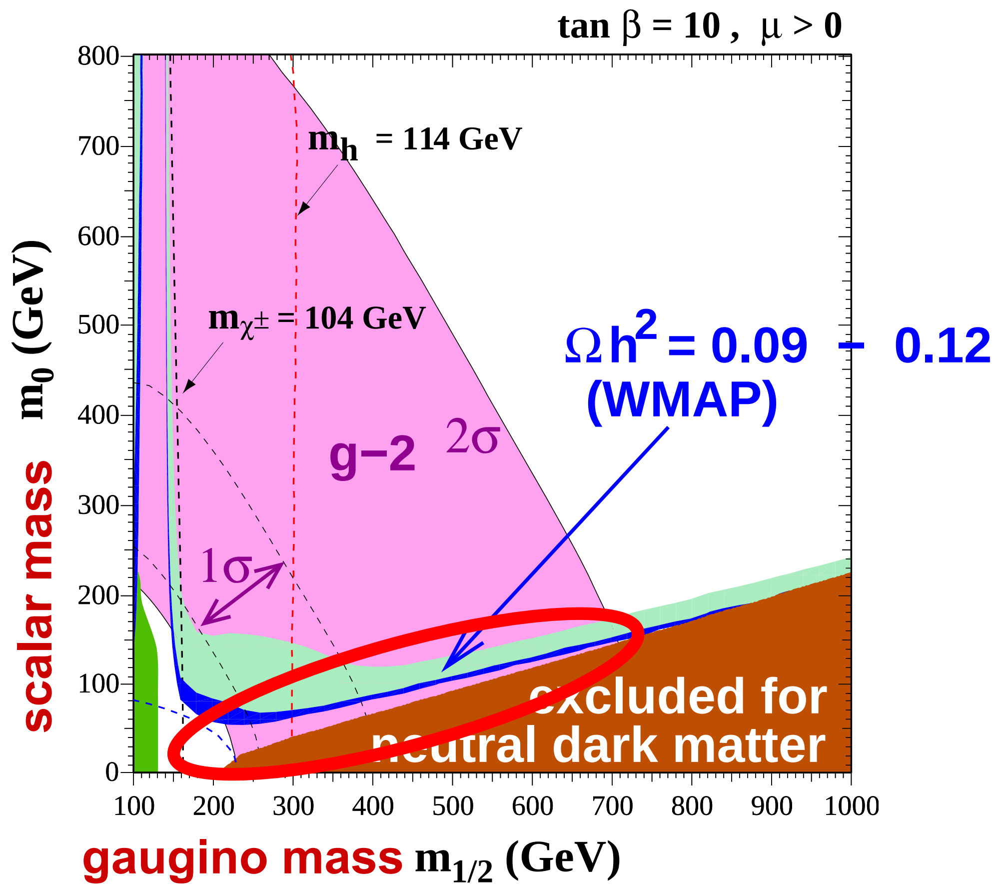
Complements LHC Discoveries eg $\tan\beta_{SUSY}$

Exp. & Theory Unc. Well Matched
Over Next Few Years

E969 - Must Do Experiment

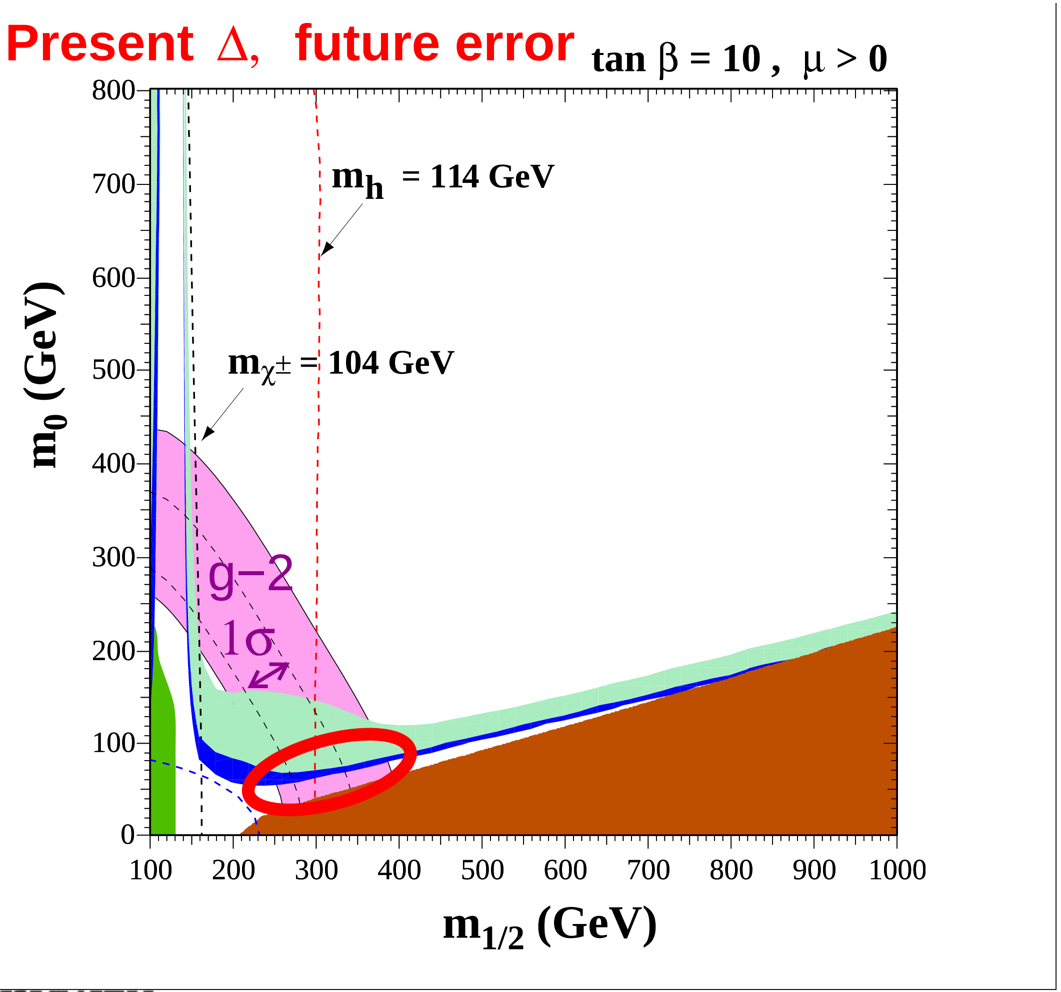
The (g-2) discrepancy is consistent with other constraints on the SUSY LSP being the dark matter candidate.

Present Δ



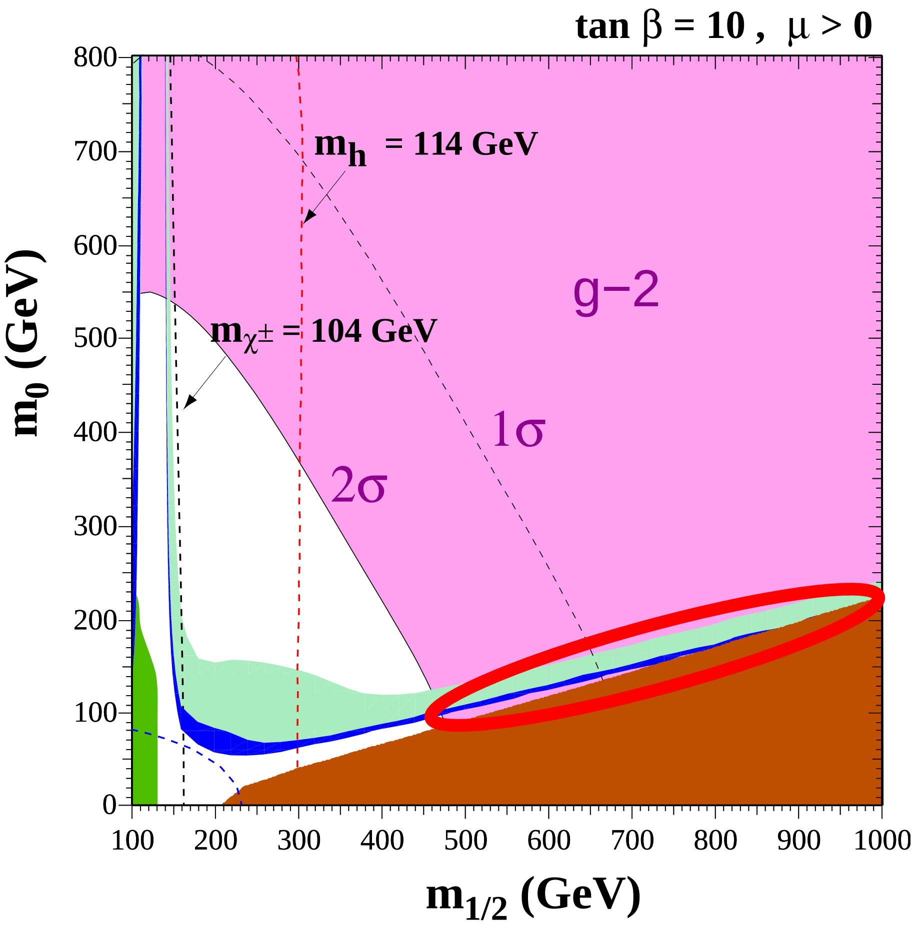
CMSSM calculation Following Ellis, Olive, Santoso, Spanos, from K. Olive

Future Comparison: $\sigma_{E969} = 0.25$ ppm; $\Delta_{E969} = \Delta_{now}$



Future Comparison:
$\sigma_{E969} = 0.25$ ppm; $\Delta_{E969} = 0$

Δ=0 **Future error**



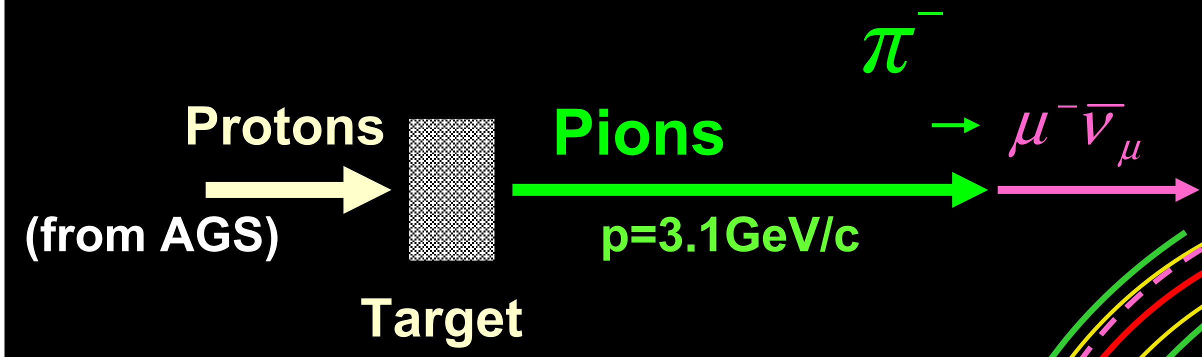
BNL E969 Collaboration

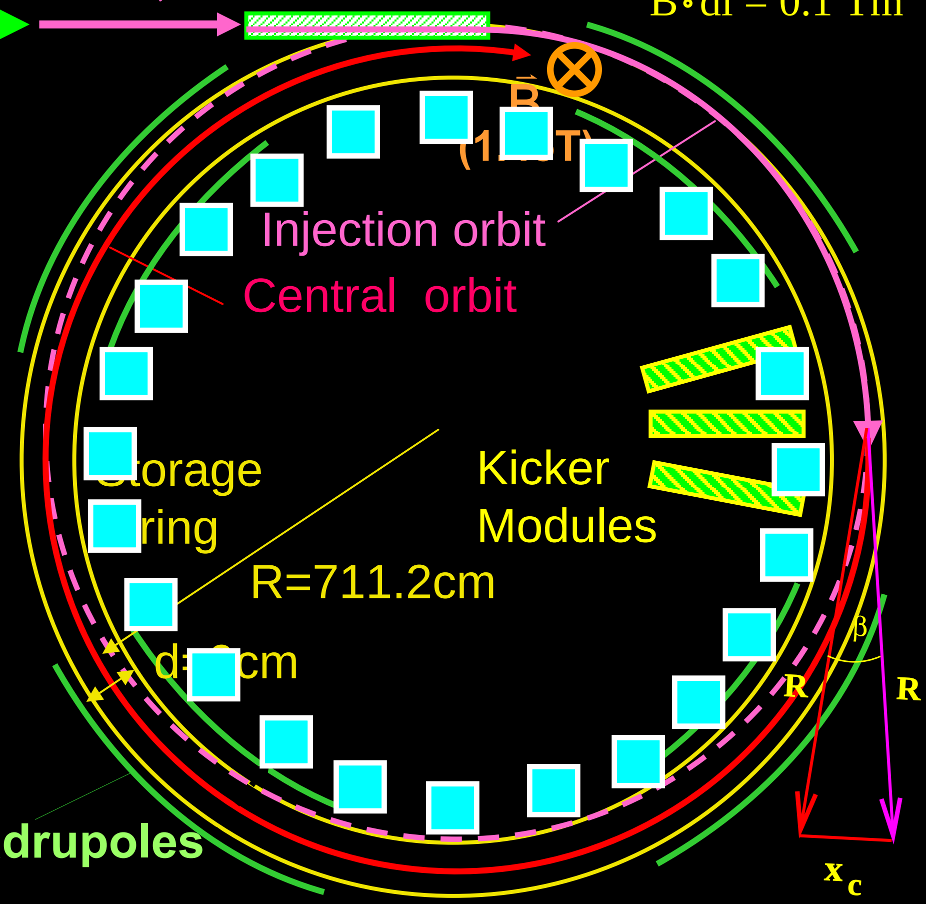
(L. Roberts, P5)

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 National Laboratory
D. Grigoriev, B.I. Khazin, S.I. Redin, Y. M. Shatunov, E. Solodov
Budker Institute of Nuclear Physics
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 at Urbana-Champaign
K.L. Giovanetti – James Madison University
K.P. Jungmann, C.J.G. Onderwater – KVI Groningen
T.P. Gorringe, W. Korsch U. Kentucky
P. Cushman – University of Minnesota
M. Aoki, Y. Arimoto, Y. Kuno, A. Sato, K. Yamada
Osaka University
S. Dhawan, F.J.M. Farley – Yale University

Experimental Technique

(L. Roberts, P5)



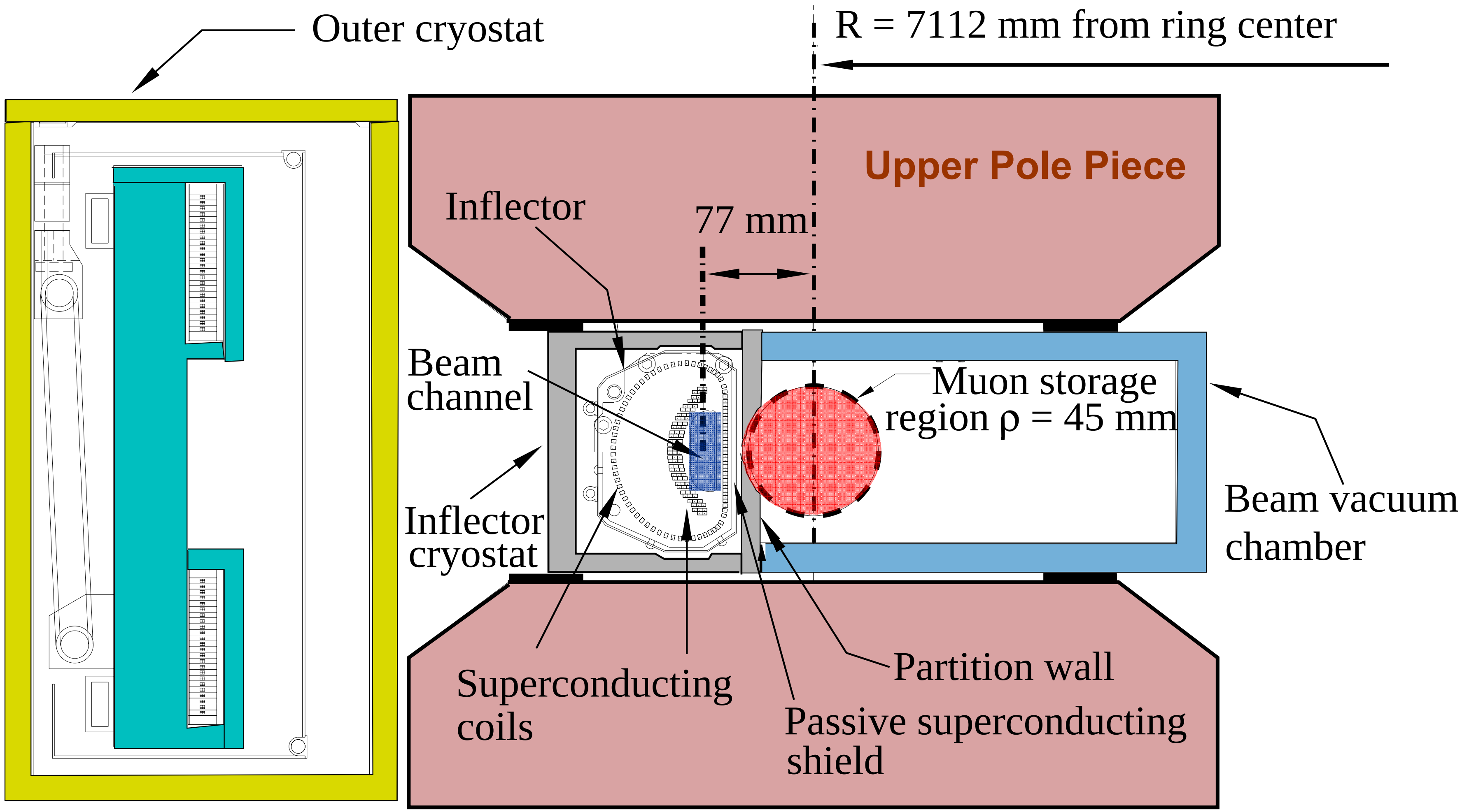


- Muon polarization
- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles
- 24 electron calorimeters

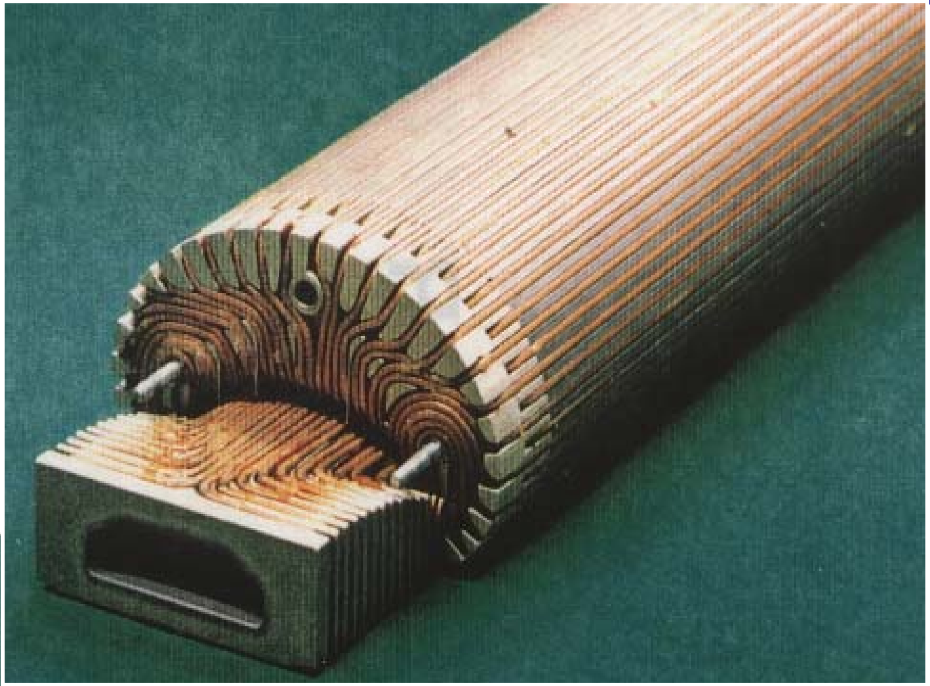
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

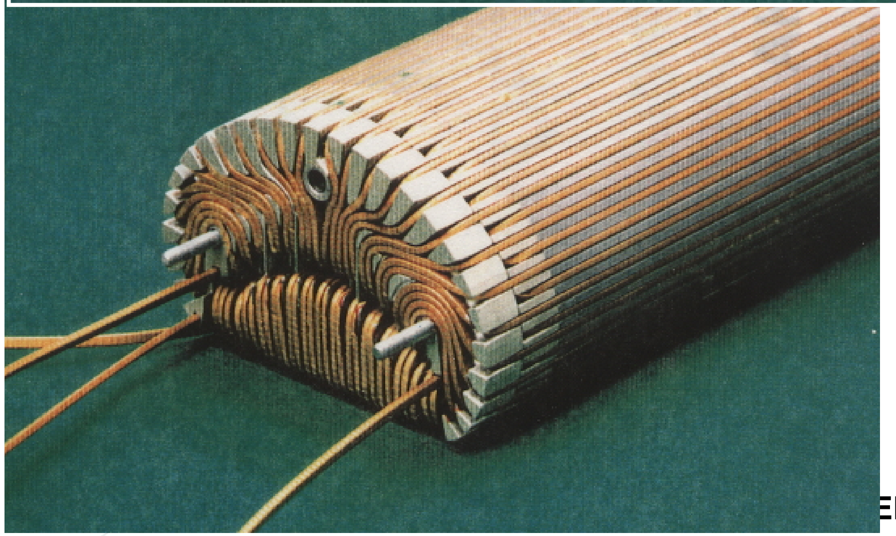
Space limitations prevent matching the inflector exit to the storage aperture

(L. Roberts, P5)



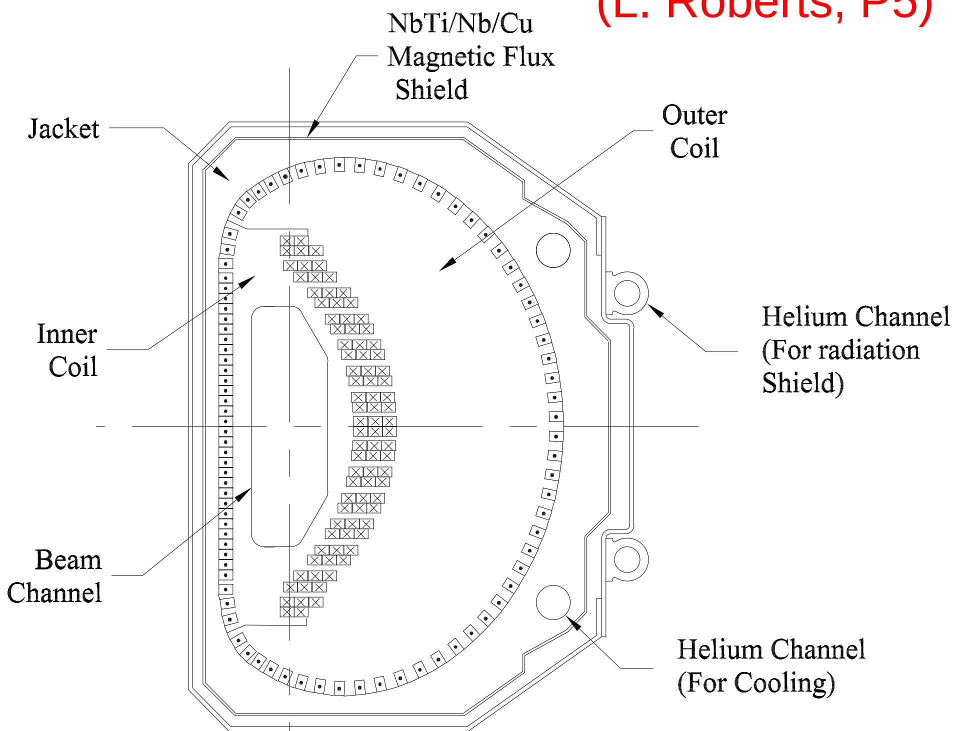
The E821 inflector magnet had closed ends which scattered away half the beam.





ERN

(L. Roberts, P5)



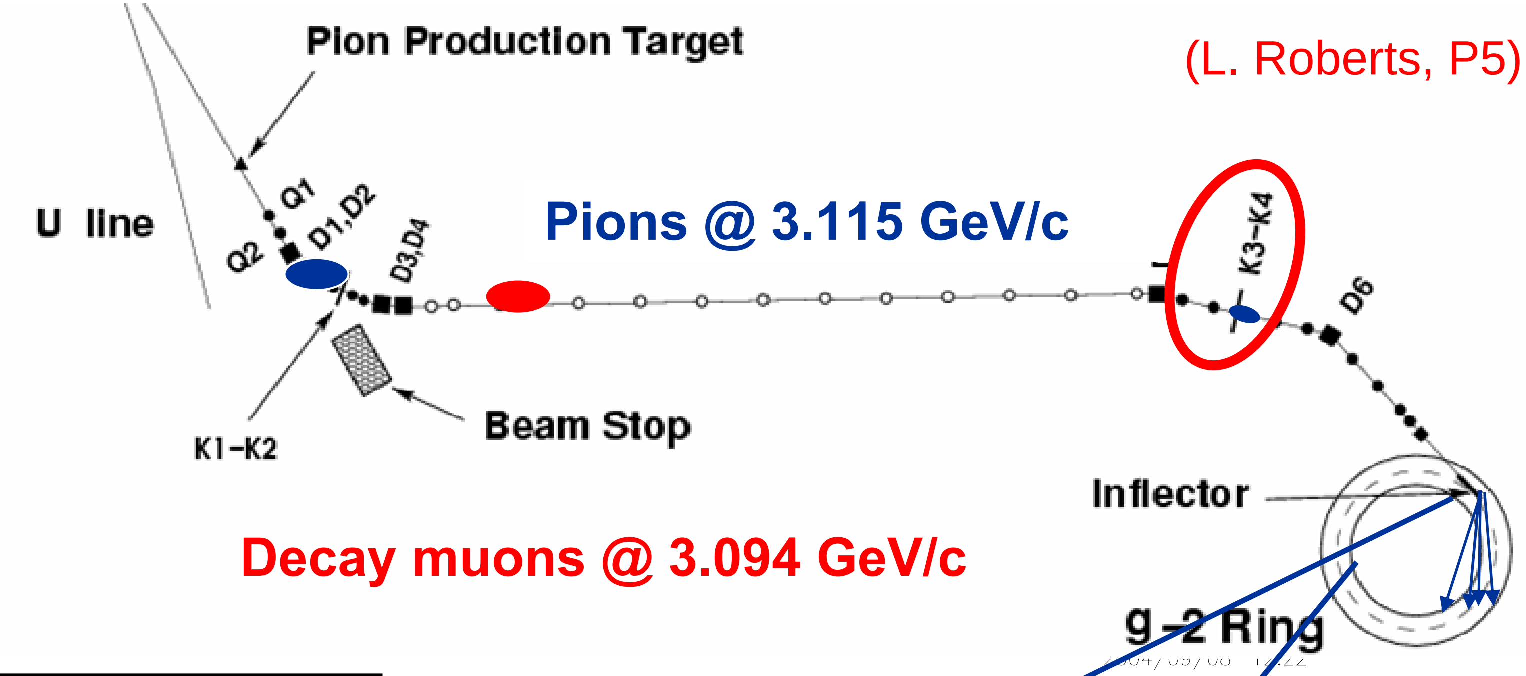
Length = 1.7 m; Central field = 1.45T

Open end prototype, built and tested

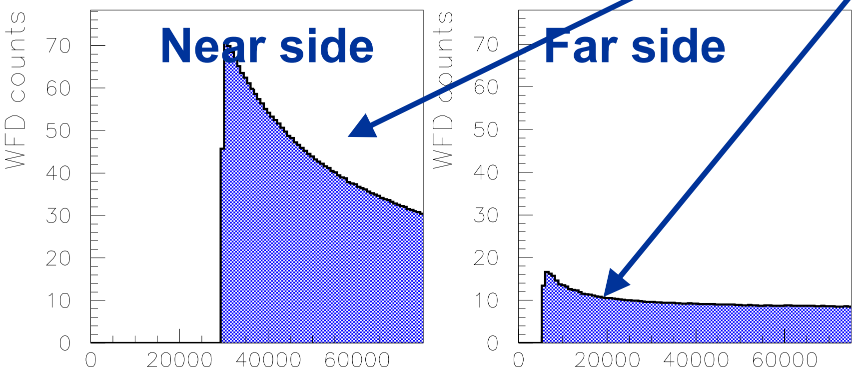
→X2 Increase in Beam

E821 used a “forward” decay beam, with p_π 1.7% above p_{magic} to provide a separation at K3/K4

(L. Roberts, P5)

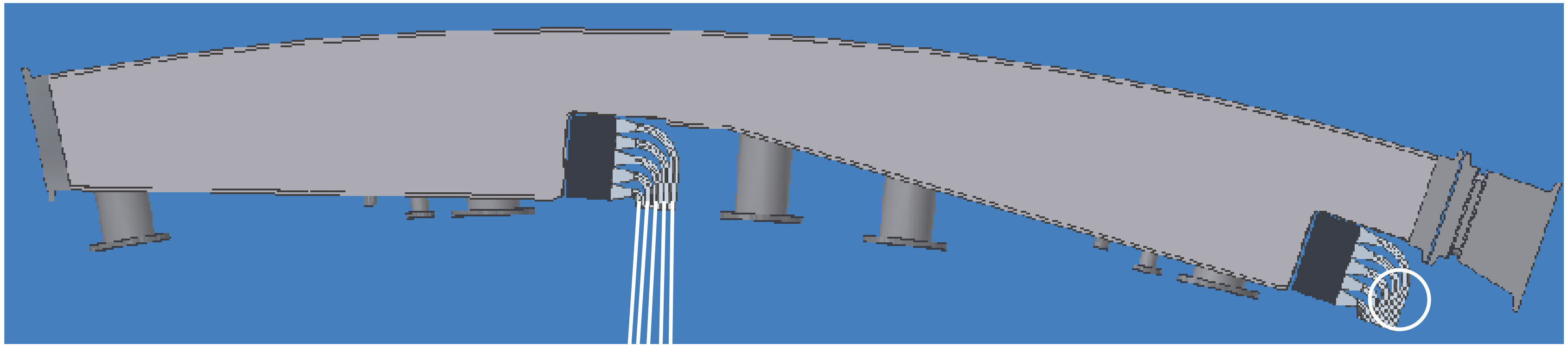


Our models show that by quadrupling the quads and going further above p_{magic} the flash is decreased and the muon flux will grow by approximately 2-3

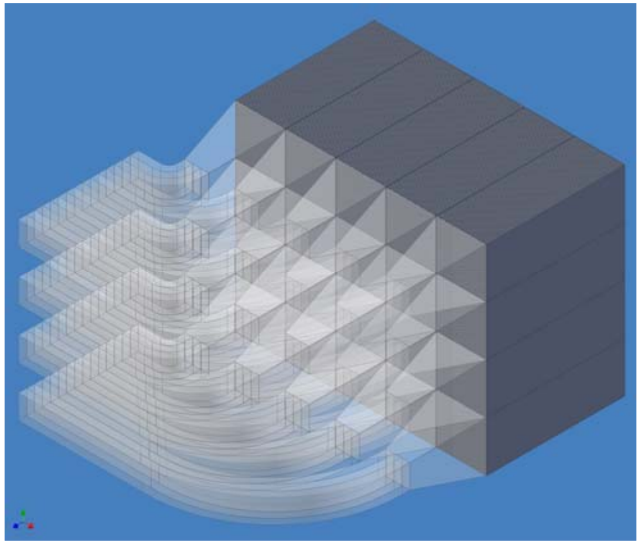


We base our request on a modified version of this proven concept.

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

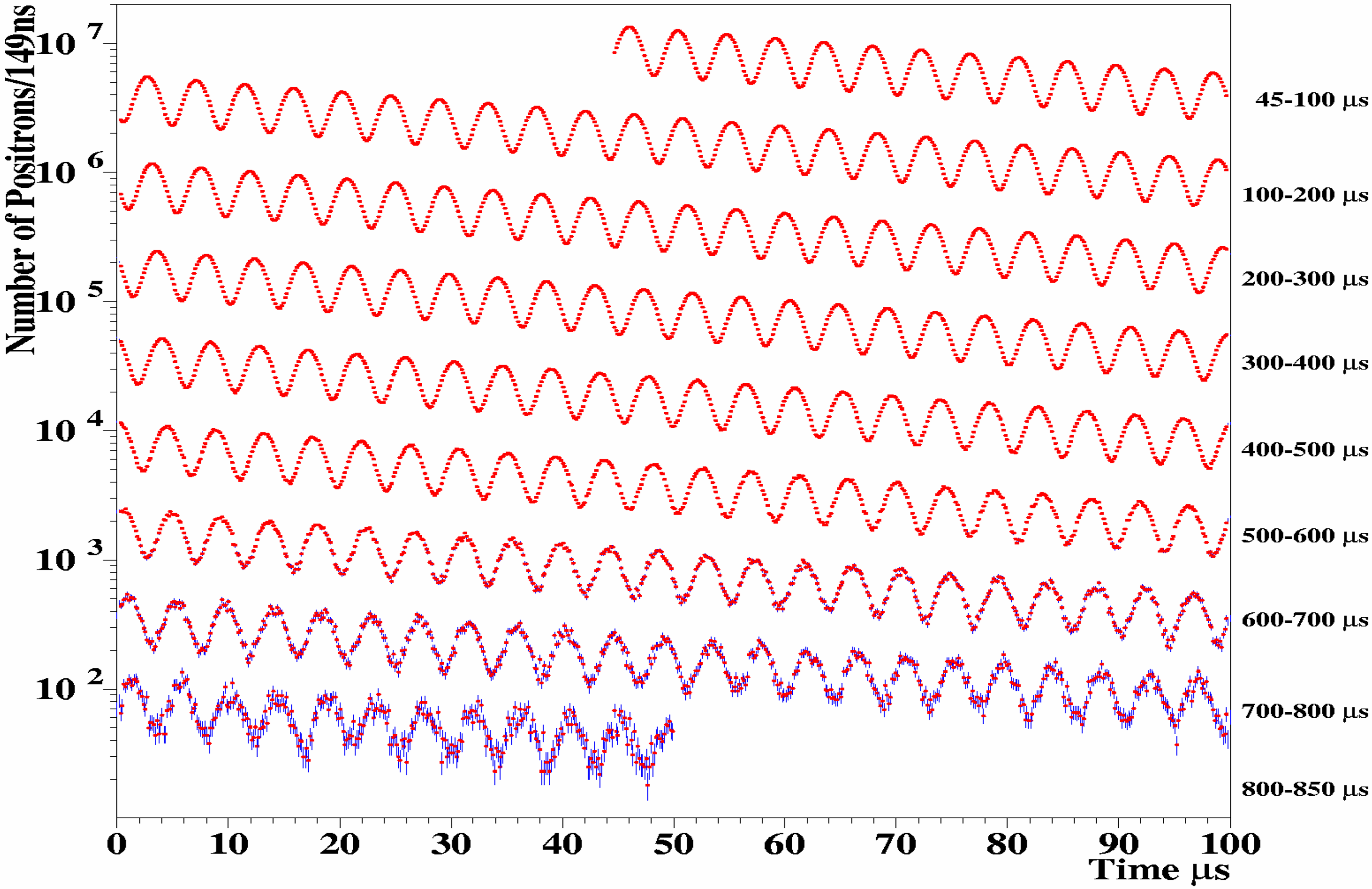


- Prototype work and simulations @ UIUC
- Calibration method reasonable
- Bases will be gated.
- New custom electronics and DAQ



4 Billion e⁺ with E>2GeV

$$dN/dt = N_0 e^{-\frac{t}{\tau}}\left[1 + A\cos(\omega_a t + \phi_a)\right]$$



(L. Roberts, P5)

E969 needs 5 times the muon flux that E821 stored.

- Open inflector x 2
- Quadruple the quadrupoles x 2 – 3

- Beam increase design factor x 4 – 6

E969 Baseline – 0.25 ppm total error

(L. Roberts, P5)

- **Systematic error goals:**
  - for ω_a: **0.1 ppm**
  - for ω_p: **0.1 ppm**

- **Statistical error goal:**
  - for ω_a: **0.2 ppm**

- **Total Error Goal:**
  - a_μ: **0.25 ppm**

(L. Roberts, P5)

Field systematic uncertainties, ordered by importance

Source	E821 (ppm)	E969 (ppm)	Comment
Calibration of trolley probe	**0.09**	**0.06**	Improved shimming in the calibration region; improved registration of trolley location in ring
Interpolation with fixed probes	**0.07**	**0.06**	Repairs and retuning of a number of probes to improve the sampling of the ring field
Absolute calibration	**0.05**	**0.05**	Could improve using a ^{3}He based probe
Trolley measurements of B0	**0.05**	**0.02**	More frequent trolley runs; mechanical maintenance of trolley drive and garage; Extensive measurements of trolley NMR probe active volumes
Muon distribution	**0.03**	**0.02**	Simulations of storage ring; improved shimming
"Other" eddy currents higher multipoles trolley temp and PS response	**0.10**	**0.05**	 *in situ* measurement of eddy currents Improved shimming Modifications to trolley and PS
Total	**0.17**	**0.11**	

(L. Roberts, P5)

Precession frequency systematic uncertainties, ordered by importance

Source	E821 (ppm)	E969 (ppm)	Comments
Gain stability	0.12	0.03	Full WFD samples recorded; stability of laser calibration with local reference detectors; single-phase WFDs
Lost muons	0.09	0.04	New scraping scheme; improved kick
Pileup: T method Q method (not applicable)	0.08	0.07	Recording all samples, no threshold, will eliminate ambiguity from low-energy pulses
CBO: coherent betatron oscillations	0.07	0.04	Improved kick; new scraping; taller calorimeters
E and pitch correction	0.05	0.05	Should be improved with better storage ring simulation, but we keep it as is for now
Timing shifts	0.02	0.01	Laser calibration; precision determined by amount of data collected
AGS background	0.01	0.01	Sweeper magnet maintained
Fit procedure and bin width	0.06	0.01	Limited by number of simulated trials performed
Vertical waist	0.03	0.01	CBO related; see above
Other small effects	< 0.03	< 0.02	These either scale with the data set size or from the simulations demonstrating "no effect"
Total	**0.21**	**0.11**	

(L. Roberts, P5)

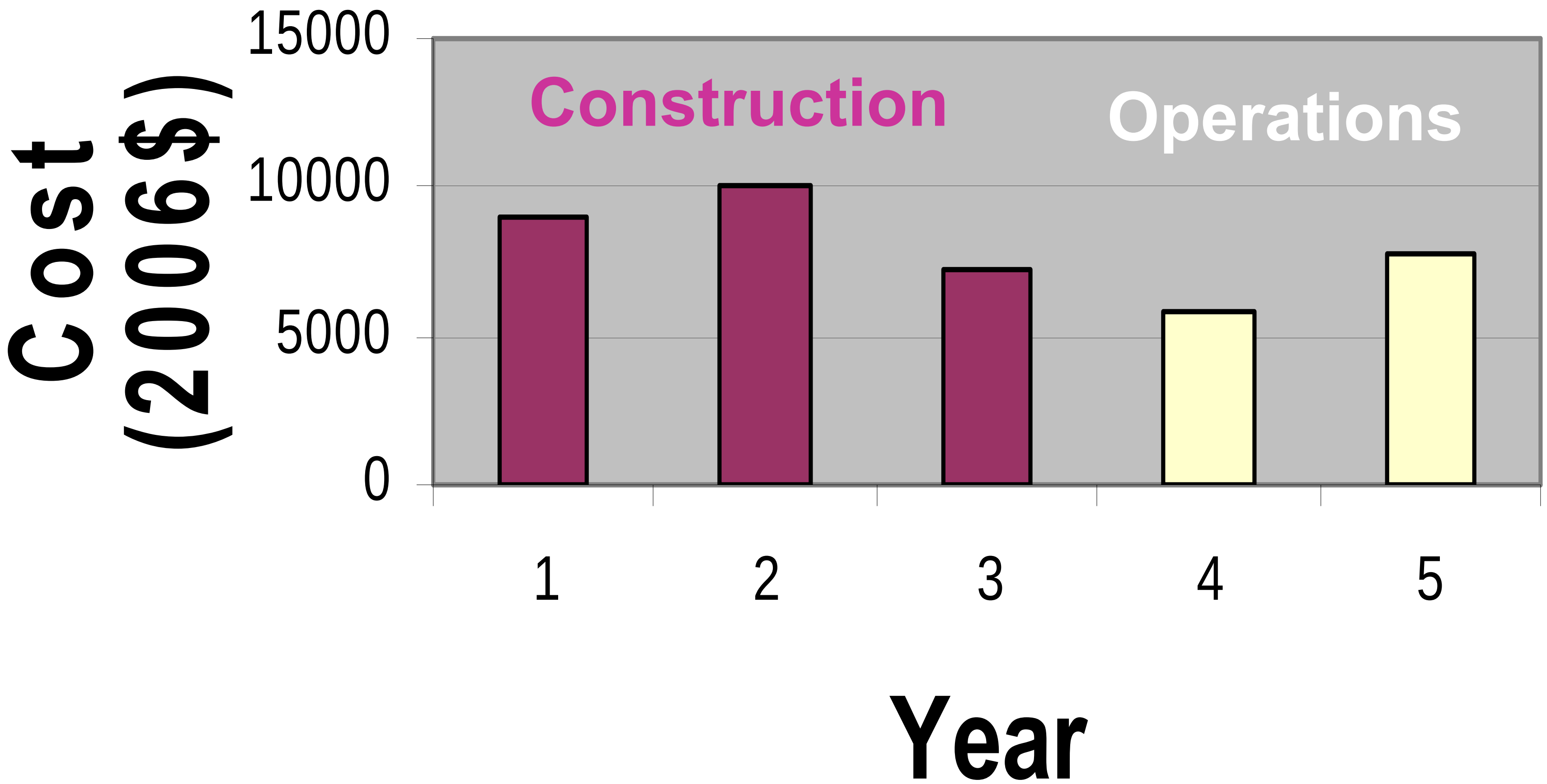
The error budget for E969 represents a continuation of improvements already made during E821

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

Funding Profile by Year

(L. Roberts, P5)



Summary

(L. Roberts, P5)

- **Historically (g-2) has placed a major hurdle in the path of new theories beyond the standard model.**
  - **(See the letters from Altarelli, Davier, Ellis, Jackiw, Jaffe, Kane, Wilczek, Winstein sent to P5)**

- **The (g-2) result must fit with other evidence into a consistent picture of new physics.**

Summary, ctd.

(L. Roberts, P5)

- Muon g-2 is unique and complementary to other information.

- It will be important to particle physics even beyond the LHC era
  - e.g., determining the value of tan β

- Theory can and will support the proposed experimental improvement.
  - (letters from Davier, De Rafael)

- E969 provides an important opportunity to capitalize on the substantial investment in E821.

Extra Slides

Summary: E821 and E969 Costs

E969 Costs (2006 M$)

Baselining costs	0.4
AGS/Booster Rehab including ES&H	11.7
Construction (44% contingency)	12.2
Universities (27% contingency)	2.4
Operations (includes FTEs to support cryo and external beam operations)	13.6
Total Costs	40.2

- E821 costs (M$) (as spent $)
  - Capital 25.0 1989-1998 (L. Roberts, P5)
  - Operations 54.0 1998-2001
  - Total E821 79.0

Funds needed to baseline the costs (not included in construction cost estimate)

(L. Roberts, P5)

- 1.0 g-2 Ring/Building maintenance
  - 1 man month to engineer an air conditioning system for bldg 919
- 1.1 V/V1 Beam Lines
  - 1 man-months engineering
  - 1 man-months physicist
- 1.2 Inflector
  - A quote from the Furukawa Company for superconductor
- 1.3 E Quads
  - Nothing new, defendable
- 1.8 Kicker
  - Nothing new, defendable
- 1.11 Cryogenics (to determine scope)
  - 2 man-months engineering
  - 1 man-month tech
- 1.12 Vacuum System
  - 1 man-month engineering
- 1.14 Booster/AGS
  - 0.5 man month engineering
  - 0.5 man month physicist

- ES&H – review operation within present guidelines
  - 1 man-month physicist
  - 1 man month engineer
- Preparation of Cost Books, Resource Loaded Schedules, CD0-1 documents etc
  - 4 man-months engineering
  - 4 man--months physicist
- Summary
  - 11 man-month engineering
  - 7 man-month physicist
  - 1 man-month tech

- **Required Budget ~ $360K**
- **Calendar Time Required ~ 6-8 months**

Cost Summary: E969 Construction

(L. Roberts, P5)

	M$	Contingency
• **Experiment Construction, Direct Costs**		
– G-2 Ring and building	$ 0.56	21%
– V/V1 Beam Line modifications	$ 2.59	18%
– Inflector (open ends)	$ 0.64	19%
– E-Quad rebuild	$ 0.13	15%
– Additional muon Kicker	$ 0.41	15%
– Cryogenic plant rehab	$ 0.74	233%
– Ring Vacuum System	$ 0.16	29%
– Equipment Testing	$ 0.69	20%
– Project Office	$ 0.37	20%
• **Sub-Total, direct costs**	$ 6.3	
• **Indirects (reduced)**	$ 2.2	
• **Contingency (44%)**	$ 3.7	
• **Sub-Total, with indirects**	$ 12.2	
• **University (Detectors/DAQ)**	$ 2.4	
• **Total**	**$ 14.6**	

FY 2006 $'s

Cost Summary: AGS/Booster Restoration to High Intensity

AGS/Booster, Direct Costs	M$	Contingency
– Electrical Modifications	$ 2.11	22% (L. Roberts, P5)
– Mechanical Modifications	$ 1.25	20%
– RF System Modifications	$ 0.67	22%
– Instrumentation	$ 0.34	20%
– Project Support	$ 0.33	34%
– Controls	$ 0.16	24%
– ES&H (CAPS)	$ 2.63	28%

- Sub-Total, direct costs $ 7.5
- Indirects (reduced) $ 1.9
- Contingency (24%) $ 2.3

- **Total $ 11.7**

FY 2006 $'s

E969 Operations Cost Summary

(L. Roberts, P5)

FY 2006 $'s

Year	Wks w/RHIC	Wks Alone	Physics Wks	Cost (M$)
1st	12	0	3	$ 5.8
2nd	20	0	15	$ 7.8
Total	**34**	**0**	**18**	**$ 13.6**

If warranted to push beyond 0.25 ppm, an additional 10-15 week run with RHIC adds ~$6-7M

Milestones/Timeline (by FY) (L. Roberts, P5)

-1
- CD0 Beamline design – backward/forward decision; detector prototype; simulations of injection, scraping, CBO damping; decide on scope of cryo work; begin tube/base development

0
- +9 Months CD1; Begin electronics engineering
- CD2 - Engineering on beamline, Cryo

+1
- CD3 - Start to order long leadtime items e.g. Inflector, rad-hard front-end magnets, etc.; Refurbish storage ring; develop on-line; develop NMR tools for 0.1 ppm.

+2

Construction

+3
- Shim magnet, improve on absolute calibration
- CD4 - Finish construction, few weeks of low intensity beam

+4
- Commission experiment, engineering and short physics run

+5
- Major data collection run

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

(L. Roberts, P5)

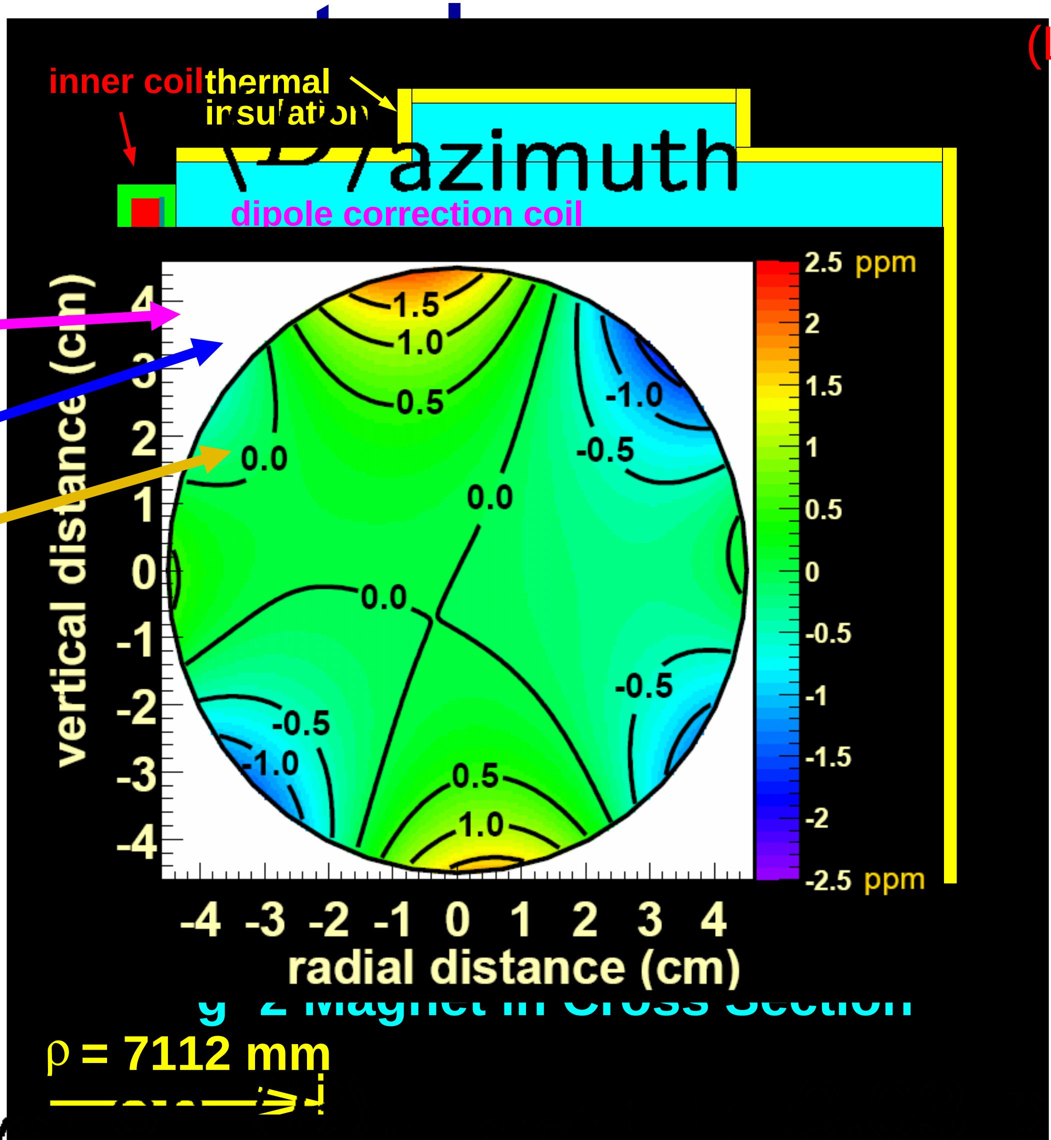
We can shim the

dipole,

quadrupole

sextupole

independently



0.5 ppm contours

E969 will require additional shimming, monitoring and calibration