The New Muon g-2 experiment at Fermilab (E989)

G. Venanzoni

LNF/INFN

Dark forces at Accelerators, LNF 17 October 2012

Fermilab *Today*

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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*

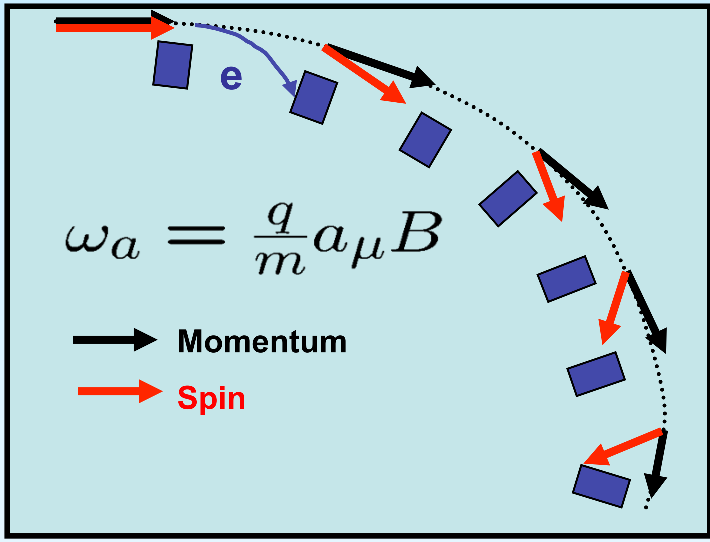
Fermilab's plans for creating a Muon Campus with top-notch Intensity Frontier experiments have received a big boost. The Department of Energy has granted Mission Need approval to the Muon g-2 project, one of two experiments proposed for the new Muon Campus. The other proposed experiment, Mu2e, is a step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

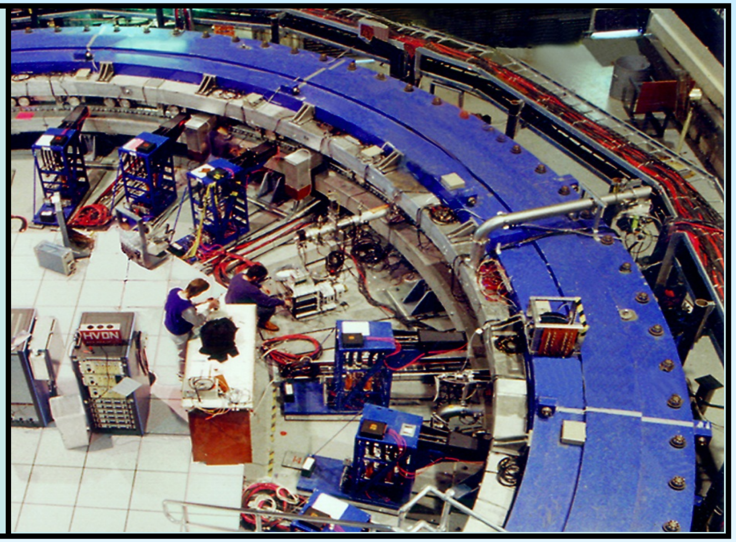
"We now are officially on DOE's roadmap," said Lee Roberts, professor at Boston University and co-spokesperson for the roughly 100 scientists collaborating on the Muon g-2 (pronounced gee minus two) experiment. "This should make it easier to increase the size of our collaboration and foster international 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 China, Germany, Italy, Japan, the Netherlands and Russia as well as 16 institutions in the United States. Physicists from several institutions in the United Kingdom are in the process of joining the collaboration.

CD0 received one month ago!

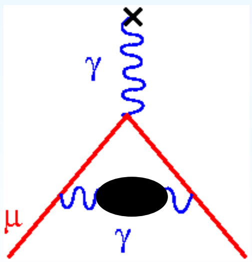
A Case for Challenging the Standard Model: Muon g-2





$$a_\mu\left(\text{Expt.}\right)=116592089\left(63\right)\pm10^{-11} \qquad \left(0.54\text{ ppm}\right)$$

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)$$



$$g = 2(1+a)\,;\; a = \frac{(g-2)}{2}$$

a is the muon anomaly, due to VP effects (g=2, according to Dirac eq.)

Muon anomaly as precision test of the SM

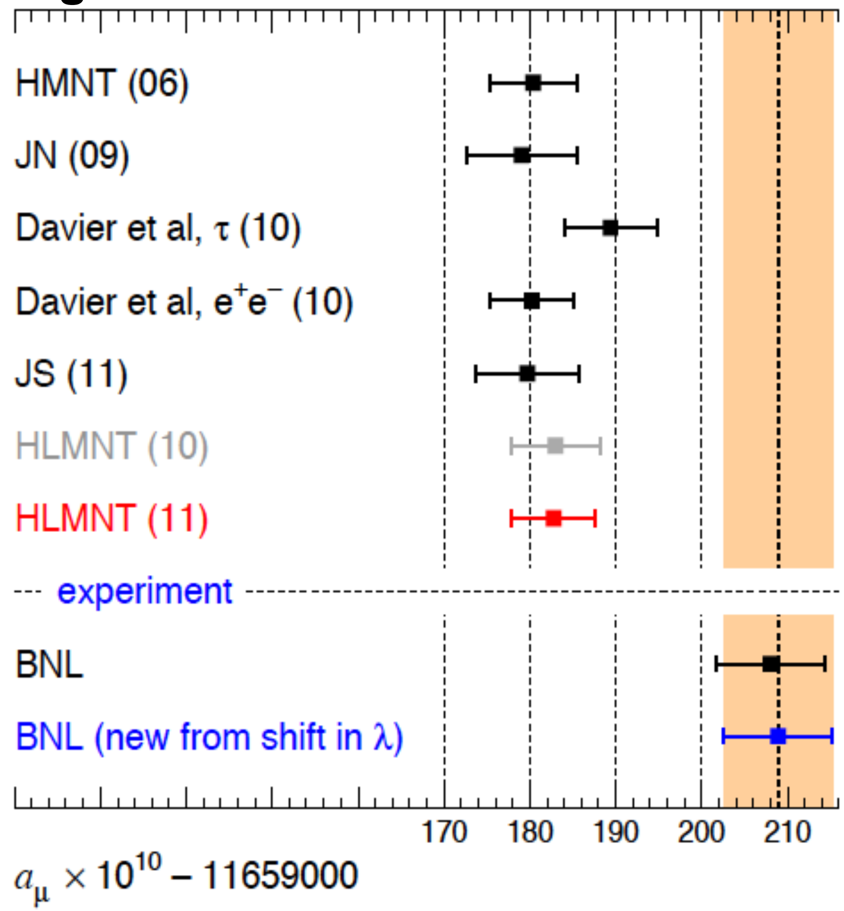
$$a_\mu = \frac{(g_\mu - 2)}{2}$$

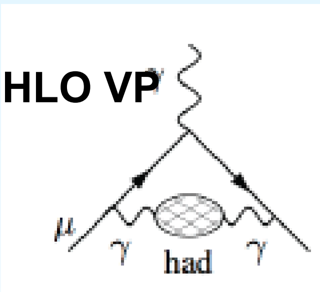
- Long established discrepancy (>3σ) between SM prediction and BNL E821 exp.
- A twofold improvement on $\delta a_\mu^{\text{TH-EXP}}$ from 2001 (thanks to BNL and new e^+e^- measurements)!

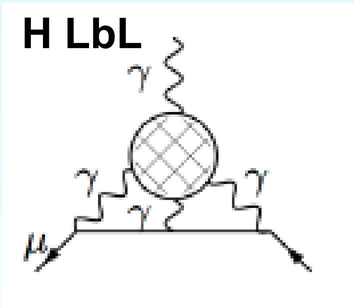
In 2001 $a_\mu^{EXP}-a_\mu^{TH}=(23\pm16)\cdot10^{-10}$

- Theoretical error δa_μ^{SM} ($5\div6\text{x}10^{-10}$) dominated by HLO VP ($4\div5\text{x}10^{-10}$) and HLbL ($2.5\div4\text{x}10^{-10}$).
- Experimental error $\delta a_\mu^{EXP}=6.3\ \text{x}10^{-10}$ (0.54 ppm), E821. Plan to reduce it to 1.6 10^{-10} (0.14 ppm) by the new g-2 experiments at FNAL (E989) and J-PARC.

Hagiwara et al. arxiv:1105.3149







$a_\mu^{HLO} = (690.9\pm4.4)10^{-10}$

[S.Eidelman, TAU08]

δa_μ^{HLO} ~0.6%

$a_\mu^{HLbL} = (10.5\pm2.6)10^{-10}$ [P. dR&V. 08]

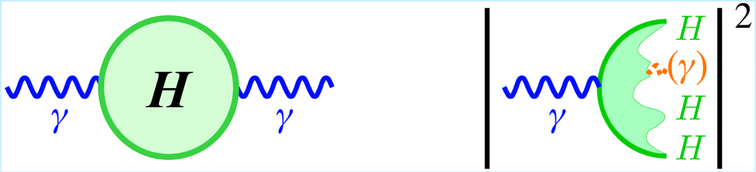
$(11\pm4)10^{-10}$ [J.N.]

δa_μ^{HLbL} ~25-40%

$$a_\mu^{\rm EXP} - a_\mu^{\rm TH} = (27.6 \pm 8.1)\cdot 10^{-10}, \ \sim 3.4\sigma$$

a_μ^{HLO}:

L.O. Hadronic contribution to a_μ can be estimated by means of a dispersion integral



1 / s² makes low energy contributions

$$a_\mu^{had} = \left(\frac{\alpha\ m\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)\,\hat{K}(s)}{s^2}$$

$e^+e^- \to \pi^+\pi^-$

especially important:

in the range < 1 GeV

contributes to 70% !

$$R(s) = \frac{\sigma_{tot}(e^+e^- \to \gamma^* \to q\,\bar{q} \to hadrons)}{\sigma_{tot}(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

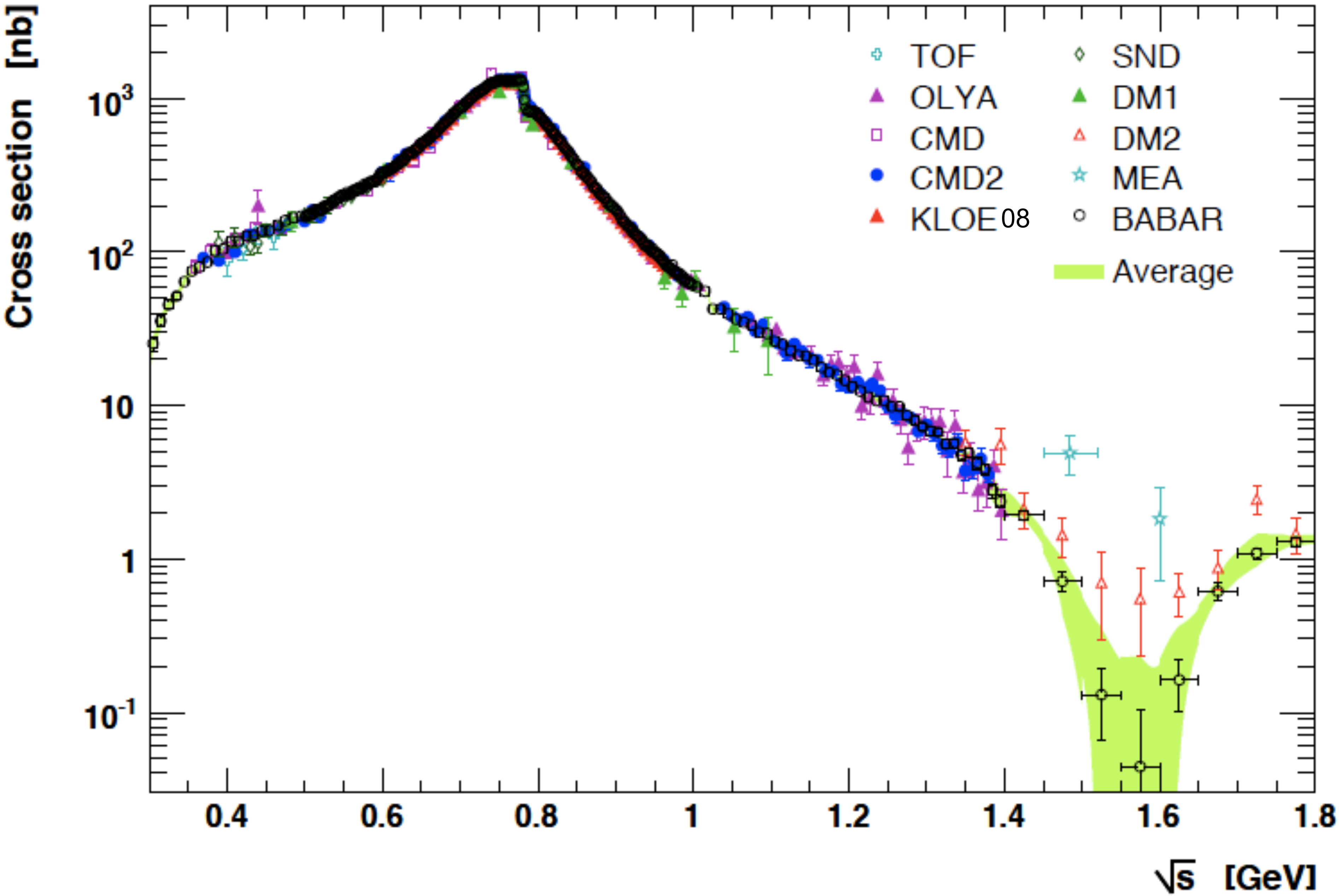
- K(s) = analytic kernel-function
- above sufficiently high energy value, typically 2…5 GeV, use *pQCD*

Input:

a) hadronic electron-positron cross section data (G.dR 69, E.J.95, A.D.H.'97,….)

b) hadronic τ- decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections) (A., D., H. '97)

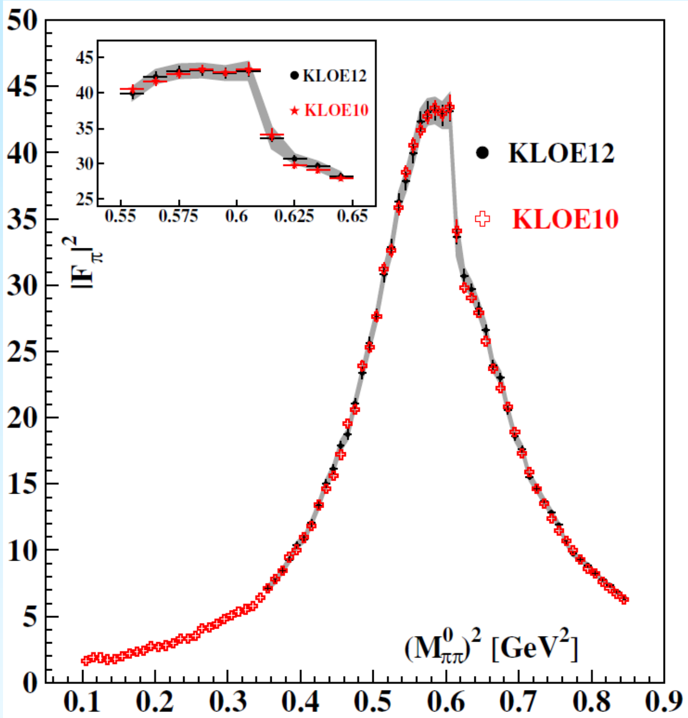
Measured Cross section for $e^+e^- \rightarrow \pi^+\pi^-$



New!!! KLOE result on $e^+e^- \rightarrow \pi^+\pi^-$ by $\pi\pi\gamma/\mu\mu\gamma$ ratio (ISR)

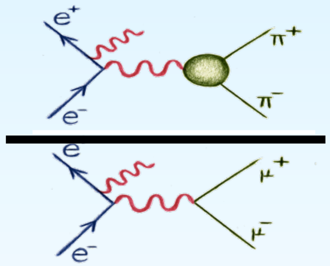
An alternative way to obtain $|F_\pi|^2$ is the bin-by-bin ratio of pion over muon yields (as done by BaBar).

$$|F_\pi(s')|^2 \approx \frac{4\left(1+2m_\mu^2/s'\right)\beta_\mu}{\beta_\pi^3} \underbrace{\frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}}_{\text{meas. quantities}}$$

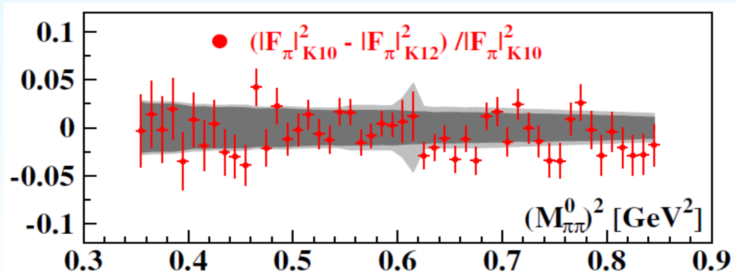


Many radiative corrections drop out:

- *radiator function*
- *int. luminosity from Bhabhas*
- *Vacuum polarization*



Analysis	$a_\mu^{\pi\pi}(0.35 - 0.85\ \text{GeV}^2) \times 10^{10}$
KLOE12	$377.4 \pm 1.1_{\text{stat}} \pm 4.5_{\text{sys+theo}}$
KLOE10	$376.6 \pm 0.9_{\text{stat}} \pm 3.3_{\text{sys+theo}}$



Result to be submitted for publication very soon

Good agreement with previousKLOE measurement!

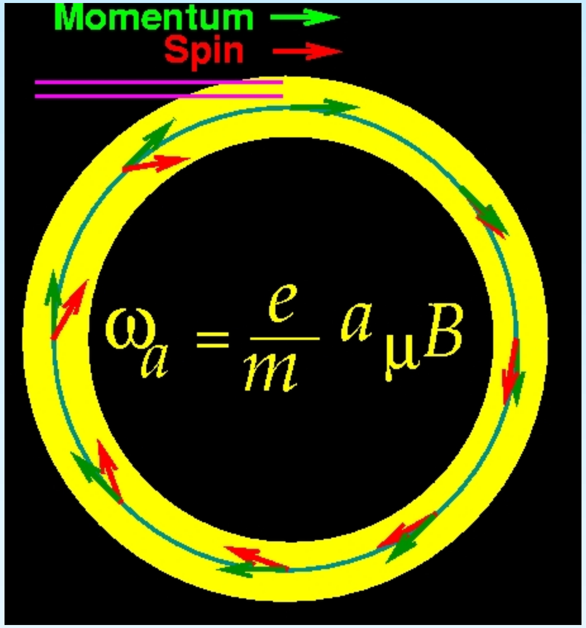
The a_μ Experiment:

- Place polarized muons in a B field
  - spin precession frequency (q = ± e)

$$\vec{\omega}_S = -g\frac{q\vec{B}}{2m} - \frac{q\vec{B}}{\gamma m}(1-\gamma)$$

  - cyclotron frequency

$$\vec{\omega}_C = -\frac{q\vec{B}}{m\gamma}$$



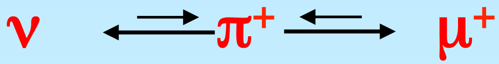
$$\vec{\omega}_a = \omega_S - \omega_C = -\frac{e}{m}a_\mu\vec{B}$$

Since g > 2, the spin gets ahead of the momentum

Measuring ω_a and B → aμ

4 Key elements of modern storage-ring g-2 measurements

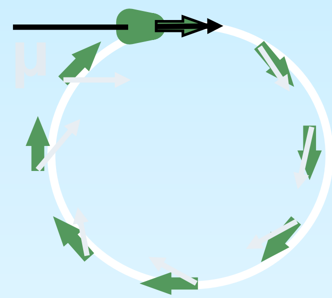
(1) Polarized muons



~97% polarized for forward decays

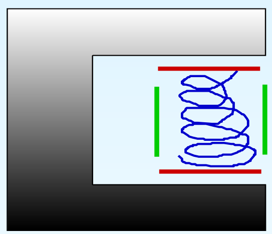
(2) Precession proportional to (g-2)

$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$



(3) P_μ magic momentum = 3.094 GeV/c

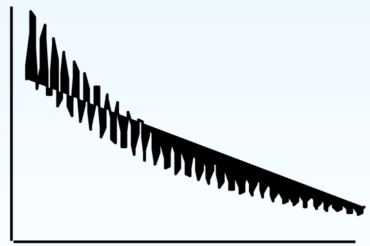
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right]$$



E field* doesn't affect muon spin when γ = 29.3

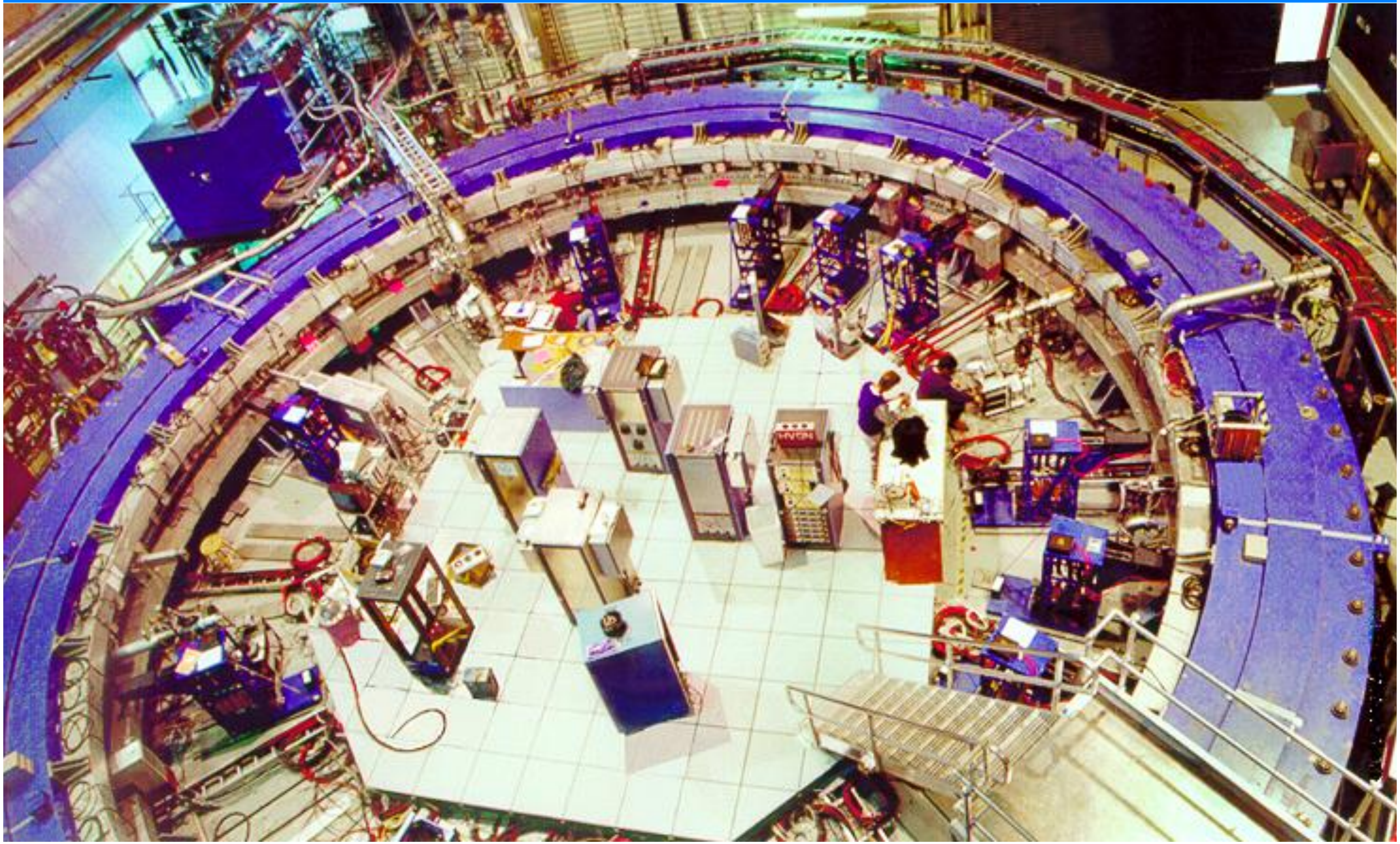
(4) Parity violation in the decay gives average spin direction

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



*Note: this carries a tiny systematic error of < 0.05 ppm in past experiment

E821 exp at BNL: Muon (g-2) storage ring



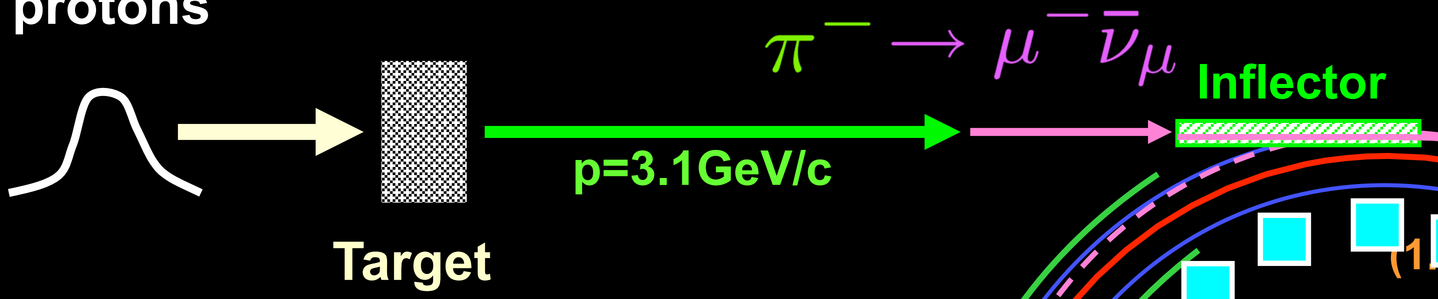
Experimental Technique

25ns bunch of $\geqslant$ 1 X 10^{12} protons

$x_c \approx 77$ mm

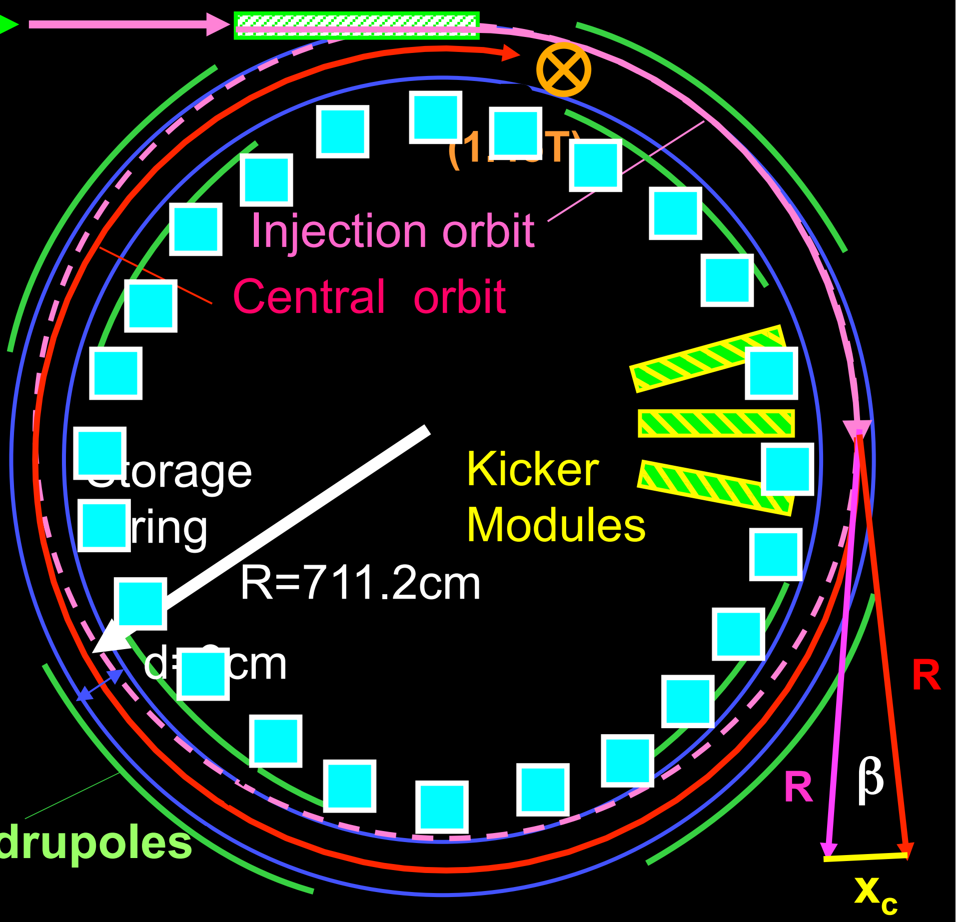
$\beta \approx 10$ mrad

B·dl ≈ 0.1 Tm

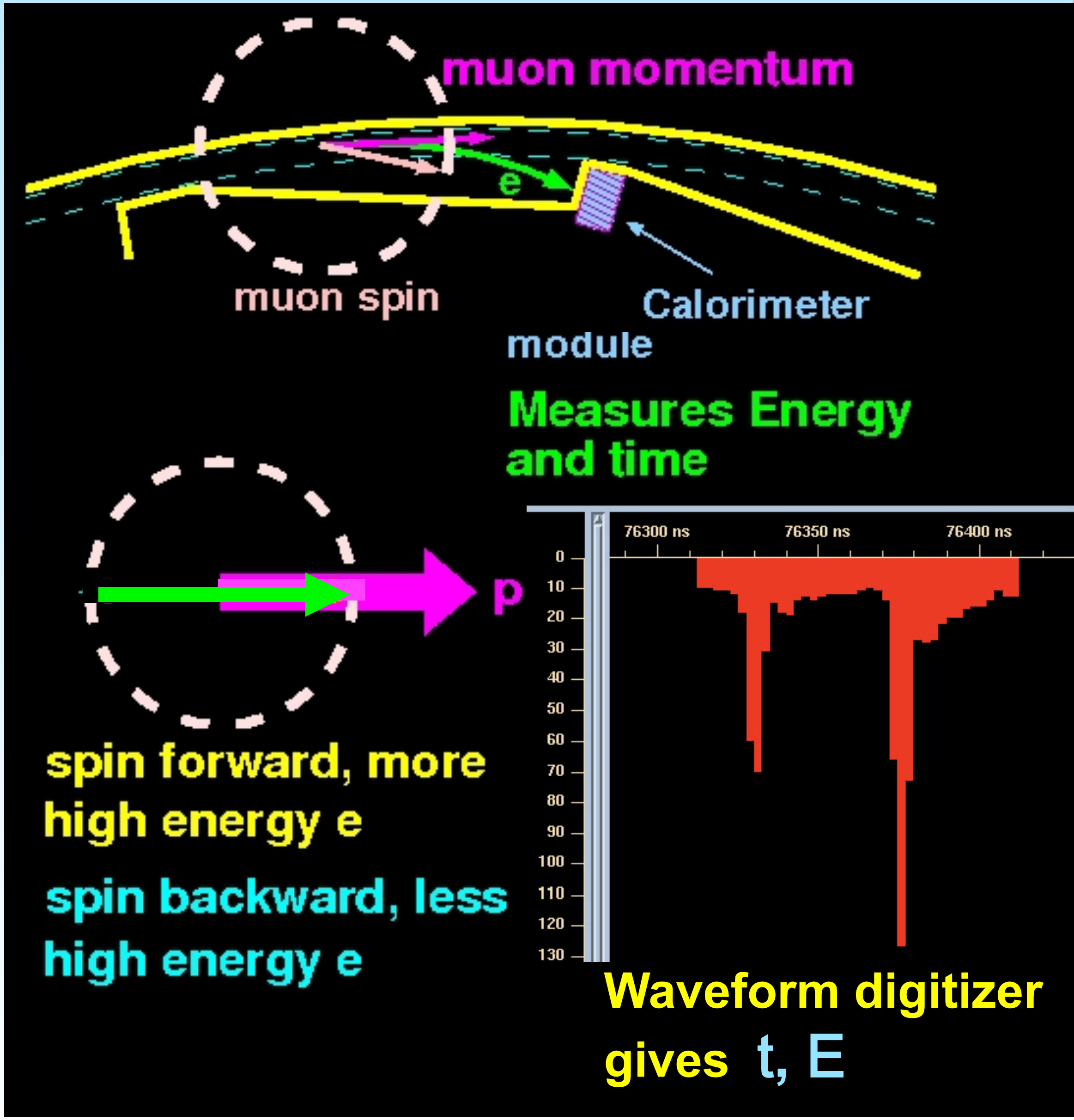


- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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



$e^{\pm}$ from $\mu^{\pm} \rightarrow e^{\pm}\nu\bar{\nu}$ are detected



Picture of a Lead-Scifi Calorimeter from E821

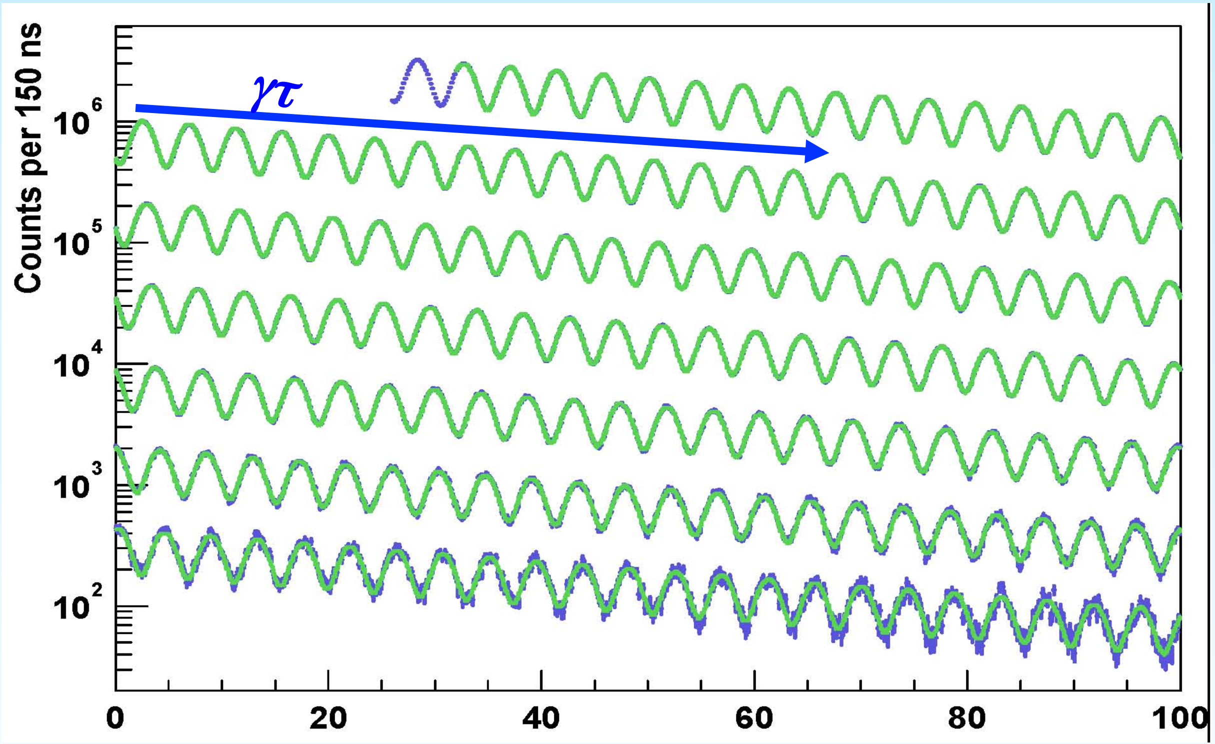
The arrival time spectrum of high-energy e^- ω_a

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

$3.6 \times 10^9\ e^-$

$E_e \geq 1.8$ GeV

$\gamma\tau_\mu$ = 64.4 μs;
(g-2): τ_a = 4.37 μs;
Cyclotron: t_C = 149 ns

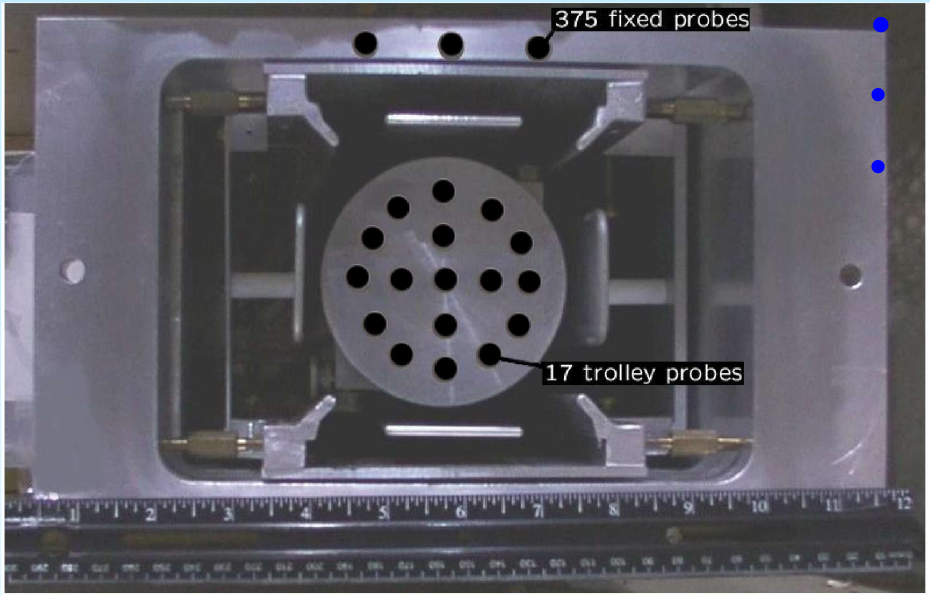


μs

Systematic uncertainty on ω_a expected to be reduced by 1/3 at E989 (compared to E821) thanks to **reduced** pion contamination,the **segmented** detectors, and an **improved** storage ring kick of the muons onto orbit.

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

ω_p

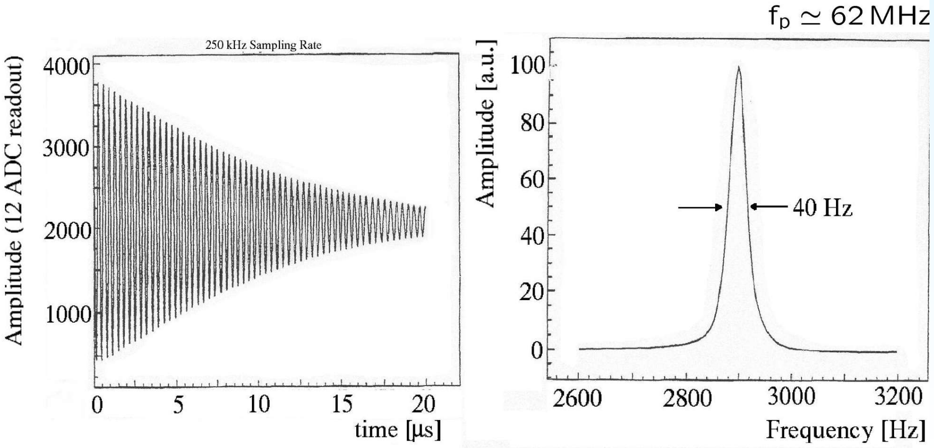


- ω_p = Larmor frequency of the <u>free</u> p
- We measure ω_a and ω_p independently
- Use $\lambda = \mu_\mu / \mu_p$ as the "fundamental constant"

Blind analysis

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

Free induction decay signals:

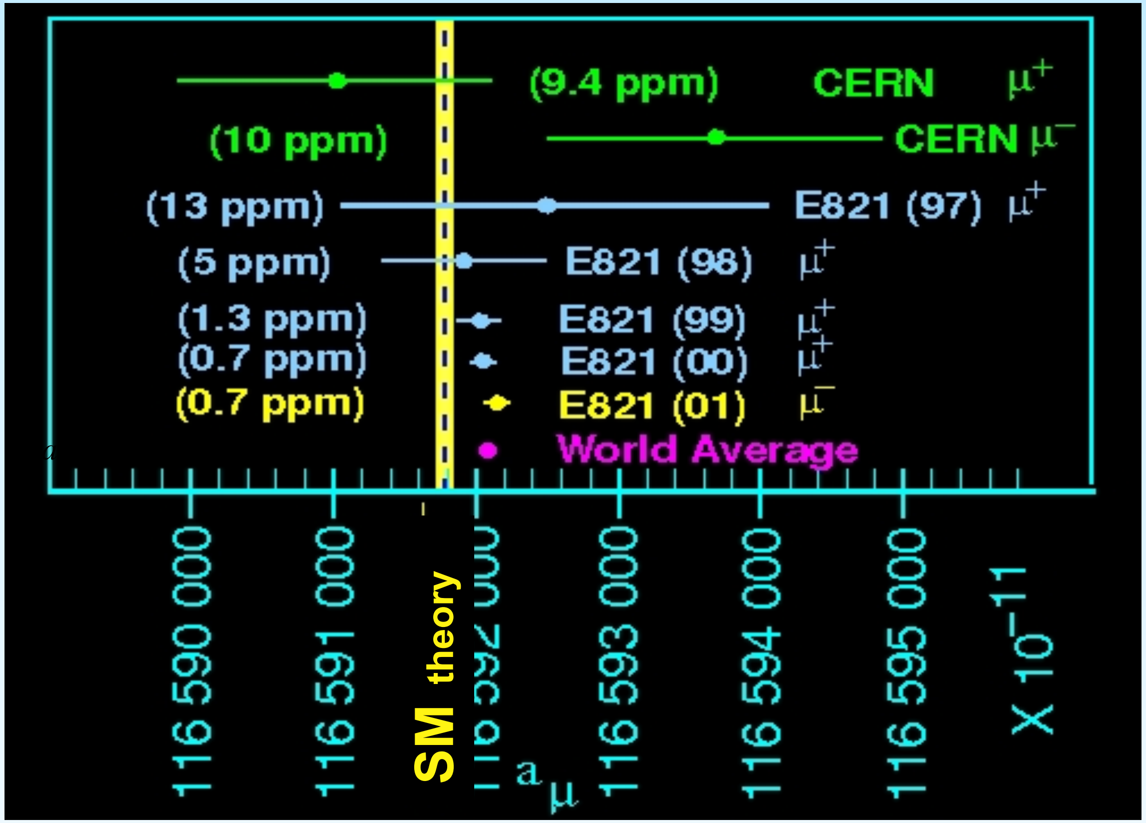


Systematic uncertainty on ω_p expected to be reduced by a factor 2 at E989 thanks to **better** shimming (uniformity of B), **relocations** of critical NMR probes, and **other** incremental changes

$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{sys}(63)_{tot} \times 10^{-11}$$

(0.54 ppm!)

A factor 15 improvement in accuracy respect to CERN!



~3.5 "standard deviations" with SM

Error dominated by experimental uncertainty!

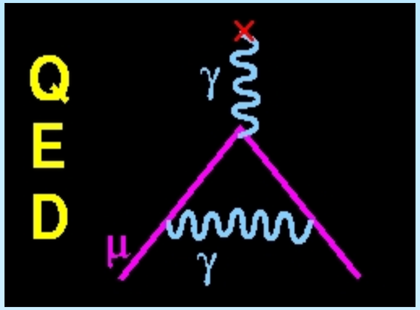
$$a_\mu^{SM} = 116\,591\,802 \pm 49 \times 10^{-11}$$

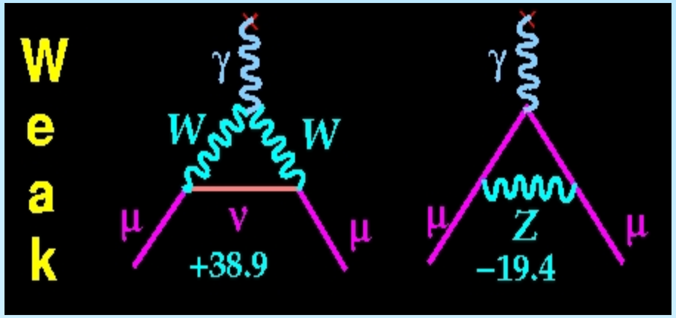
M. Davier et al. 2011

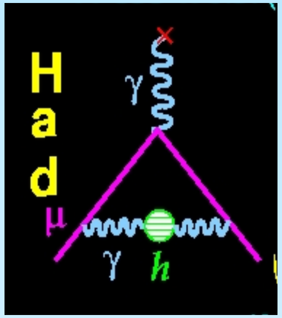
$$a_\mu^{E821} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11} \; (3.6\,\sigma)$$

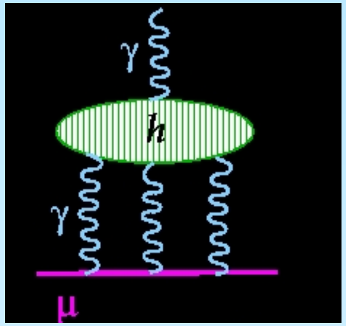
Hint of new physics?

The SM Value for a_μ









well known | **significant work ongoing**

CONTRIBUTION	RESULT ($\times 10^{-11}$) UNITS
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 923 \pm 42$
HVP(ho)	-97.9 ± 0.9
HLxL	105 ± 26
EW	$154 \pm 2_{Higgs} \pm 1_{had}$
Total SM	$116\ 591\ 802 \pm 42 \pm 26 \pm 2 (49_{tot})$

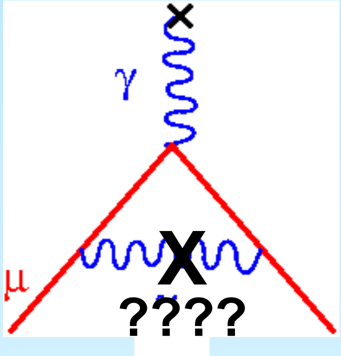
We have reached a 0.6 ppm accuracy!

(E821 @ BNL)

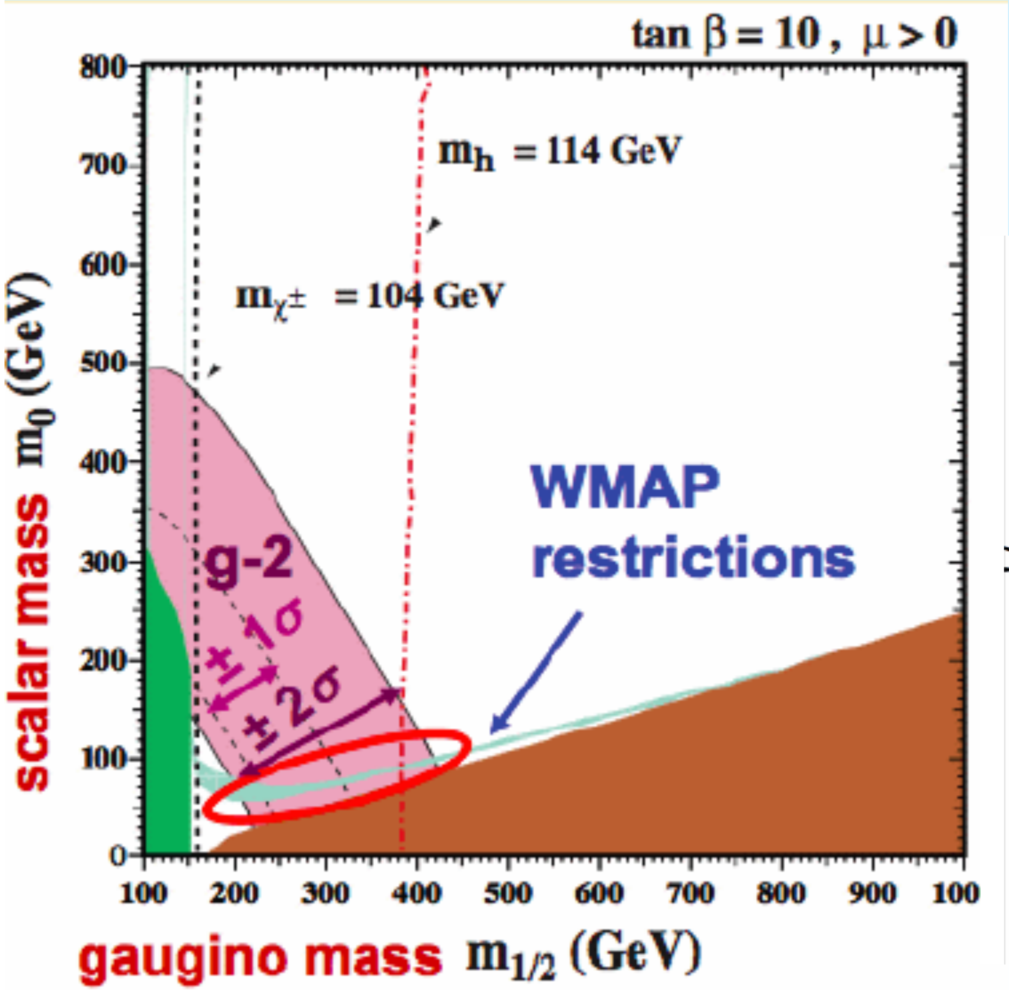
$$\sigma_{\exp} = \pm 63$$

New Physics?

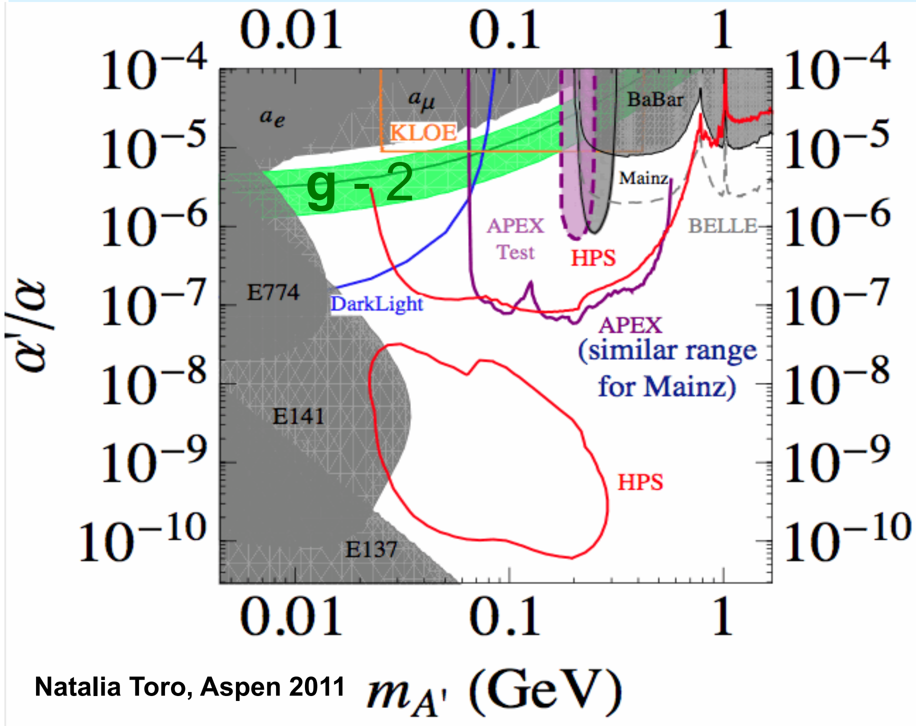
$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} + a_\mu^{???}$$



SUSY?



Dark Photons?

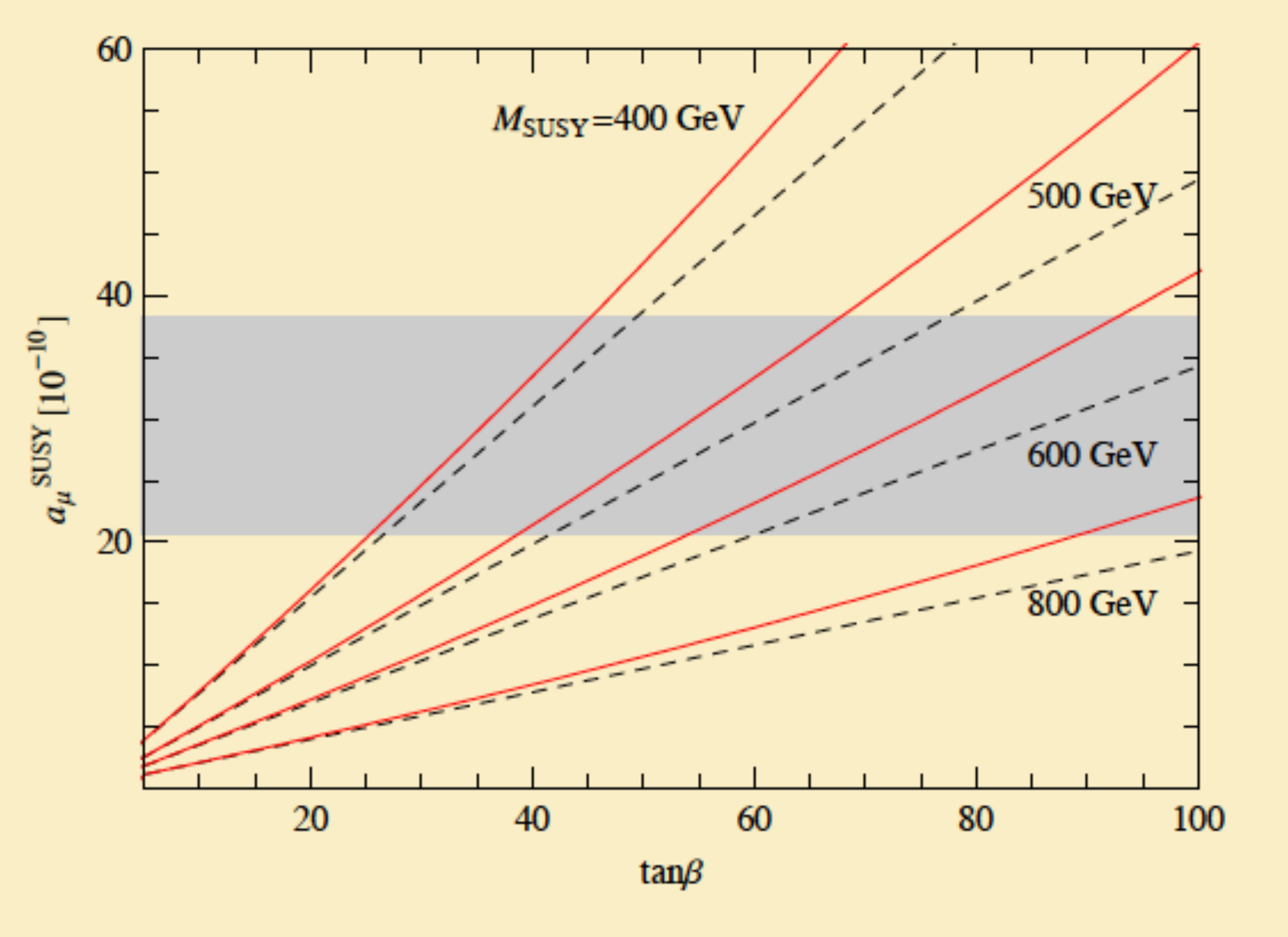


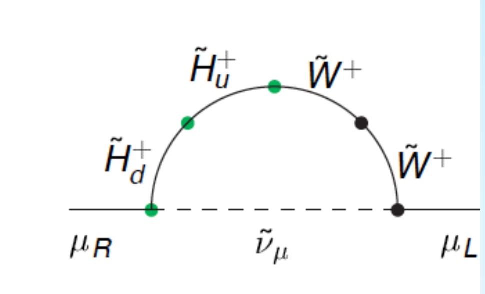
Natalia Toro, Aspen 2011

SUSY?

SUSY with mass scale of several 100 GeV is consistent with discrepancy

$$\Delta a_\mu^{SUSY} \approx 13\cdot 10^{-10}\,(\mathrm{sgn}\,\mu)\tan\beta\left(\frac{100\ GeV}{M_{SUSY}}\right)^2$$





Large tanβ, μ>0 prefer.

strong limit on M_{SUSY}

Important constraint for interpretation of BSM physics searches at LHC

Dark Photons?

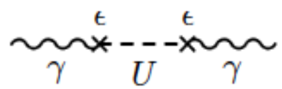
15 May 2012 **arXiv:1205.2709v1**

The Muon Anomaly and Dark Parity Violation

Hooman Davoudiasl*, Hye-Sung Lee†, and William J. Marciano‡
Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA
(Dated: May 2012)

The muon anomalous magnetic moment exhibits a 3.6σ discrepancy between experiment and theory. One explanation requires the existence of a light vector boson, Z_d (the dark Z), with mass $10 - 500$ MeV that couples weakly to the electromagnetic current through kinetic mixing. Support for such a solution also comes from astrophysics conjectures regarding the utility of a $U(1)_d$ gauge symmetry in the dark matter sector. In that scenario, we show that mass mixing between the Z_d and ordinary Z boson introduces a new source of "dark" parity violation which is potentially observable in atomic and polarized electron scattering experiments. Restrictive bounds on the mixing $(m_{Z_d}/m_Z)\delta$ are found from existing atomic parity violation results, $\delta^2 < 2 \times 10^{-5}$. Combined with future planned and proposed polarized electron scattering experiments, a sensitivity of $\delta^2 \sim 10^{-6}$ is expected to be reached, thereby complementing direct searches for the Z_d boson.

$$\mathscr{L}_{\text{mix}} = -\frac{\epsilon}{2} F^{\text{em}}_{\mu\nu} F^{\mu\nu}_{\text{DM}} \qquad (\epsilon \ll 1)\ .$$



Searches for dark photons are currently underway at e^+e^- colliders (B-,tau/charm-, ϕ-factories)and fixed target experiments (JLAB, MAMI, etc…)

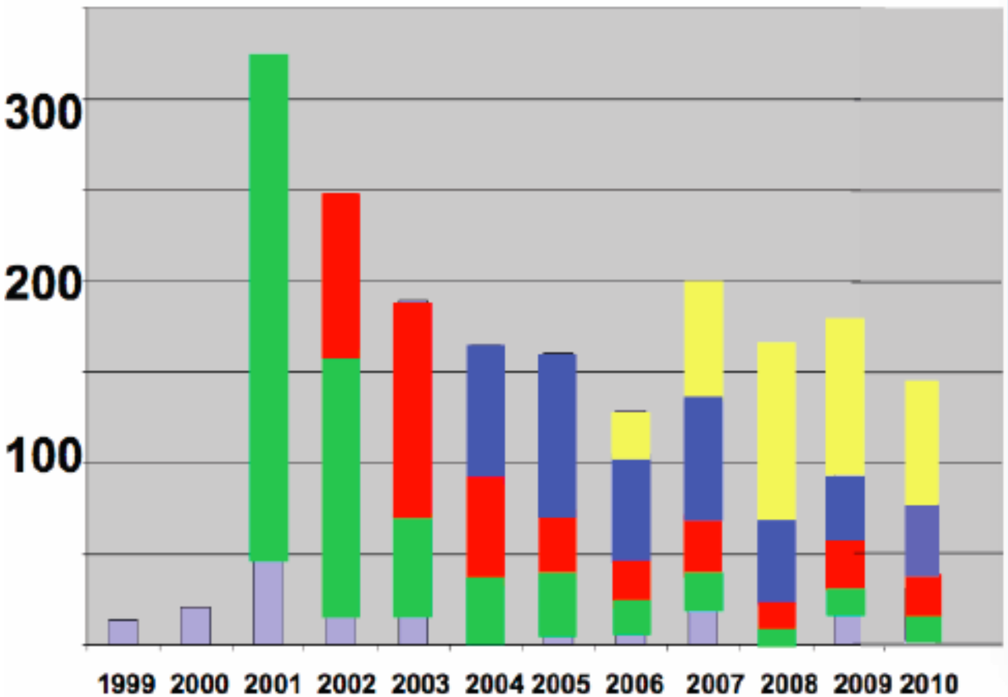
Summary of present status

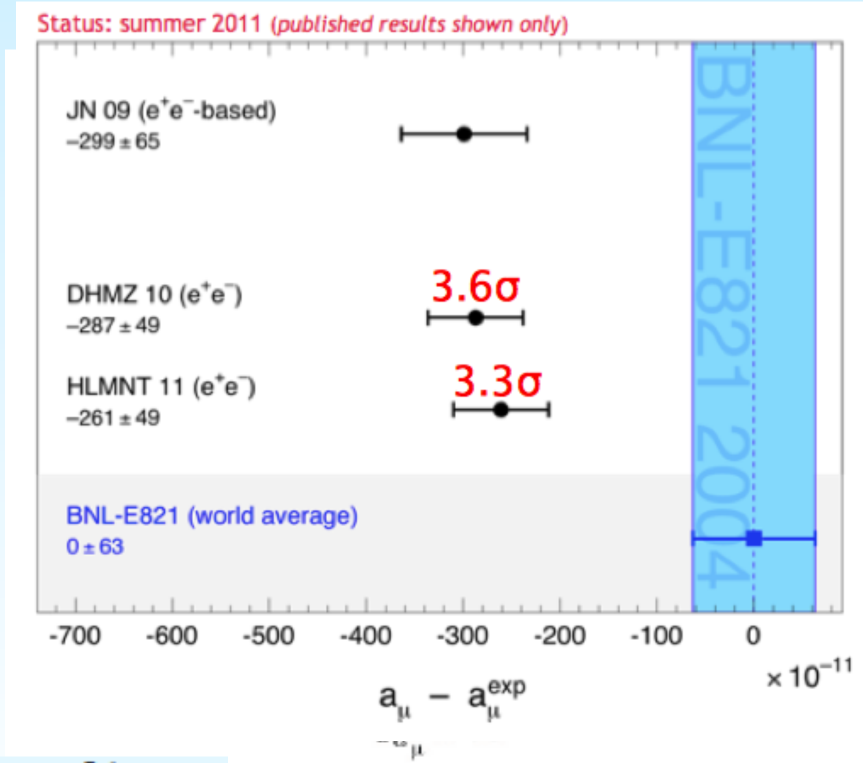
E821 experiment at BNL has generated enormous interest

Tantalizing deviation with SM (although persistent since 10 years) is ~3σ

Current discrepancy limited by experimental uncertainty (BNL)

BNL E821 citations **Present**



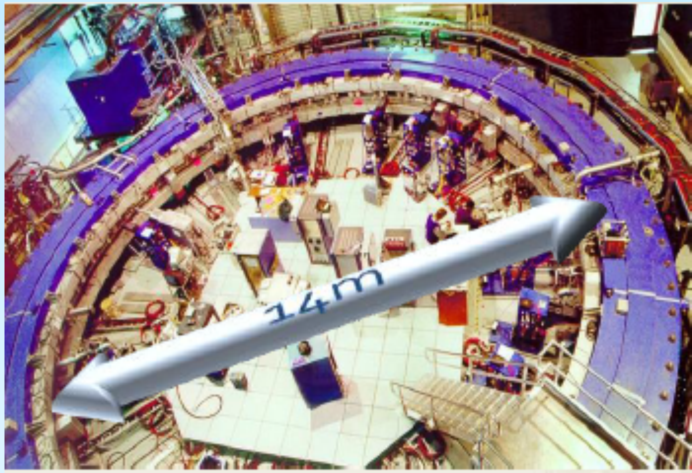


>1850 total citations to our results

We need a new experiment!

New experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x** μ w.r.t. E821. Relocate the BNL storage ring to FNAL.



- **E821 at Brookhaven**

$$\left.\begin{array}{l}\sigma_{\mathrm{stat}} = \pm 0.46\ \mathrm{ppm} \\ \sigma_{\mathrm{syst}} = \pm 0.28\ \mathrm{ppm}\end{array}\right\} \quad \sigma = \pm 0.54\ \mathrm{ppm}$$

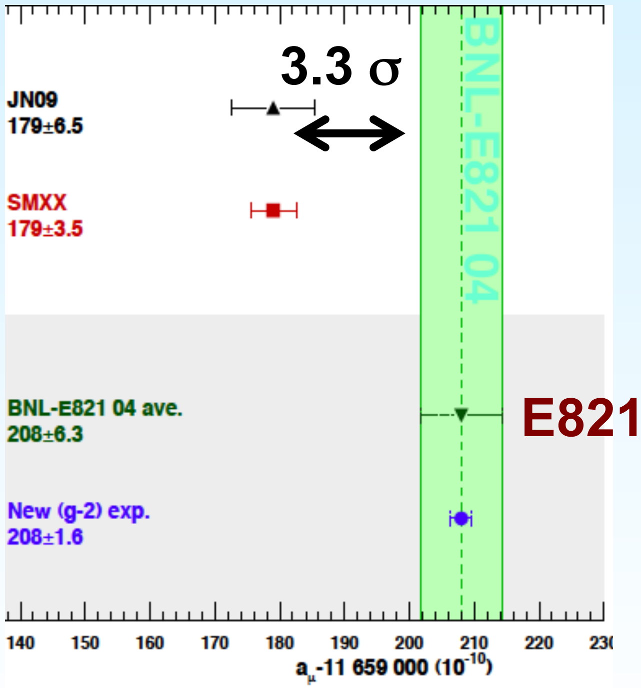
- **E989 at Fermilab**

$$\left.\begin{array}{l}\sigma_{\mathrm{stat}} = \pm 0.1\ \mathrm{ppm} \\ \sigma_{\mathrm{syst}} = \pm 0.1\ \mathrm{ppm}\end{array}\right\} \quad \sigma = \pm 0.14\ \mathrm{ppm}$$

New experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x** μ w.r.t. E821. Relocate the BNL storage ring to FNAL.

Precision target ~ 16×10^{-11} (0.14 ppm) . If the central value remains the same $\Rightarrow$ 5-8σ from SM* (enough to claim discovery of New Physics!)



***Depending on the progress on Theory**

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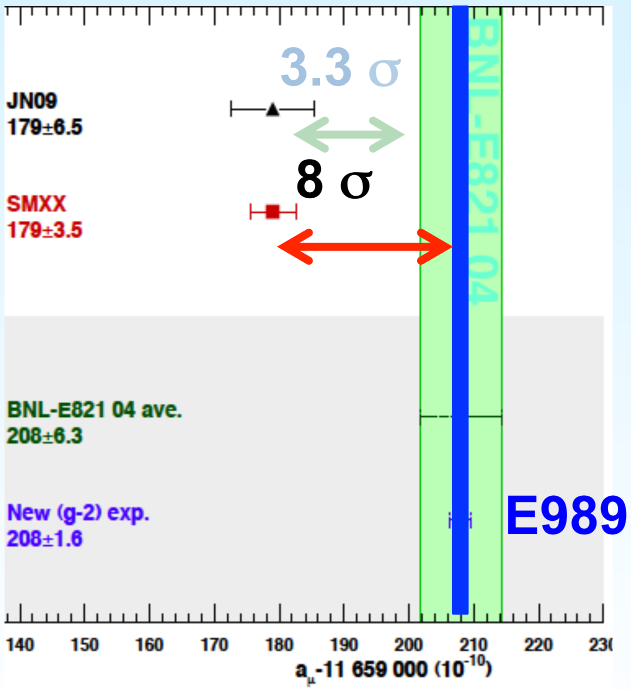


***Depending on the progress on Theory**

Fermilab E989 Experiment (July 12):

Argonne
Boston University
Brookhaven
CUNY Queens
Cornell
Fermilab
Illinois
James Madison
Kentucky
Massachusetts
Michigan
Muons Inc.
Northwestern
NIU?
Regis
Virginia
Washington

Shanghai

Dresden

KVI

Frascati
Rome

KEK
Osaka

Dubna
Novosibirsk
PNPI

UK Consortium?

>100 Collaborators,

~30 Institutions

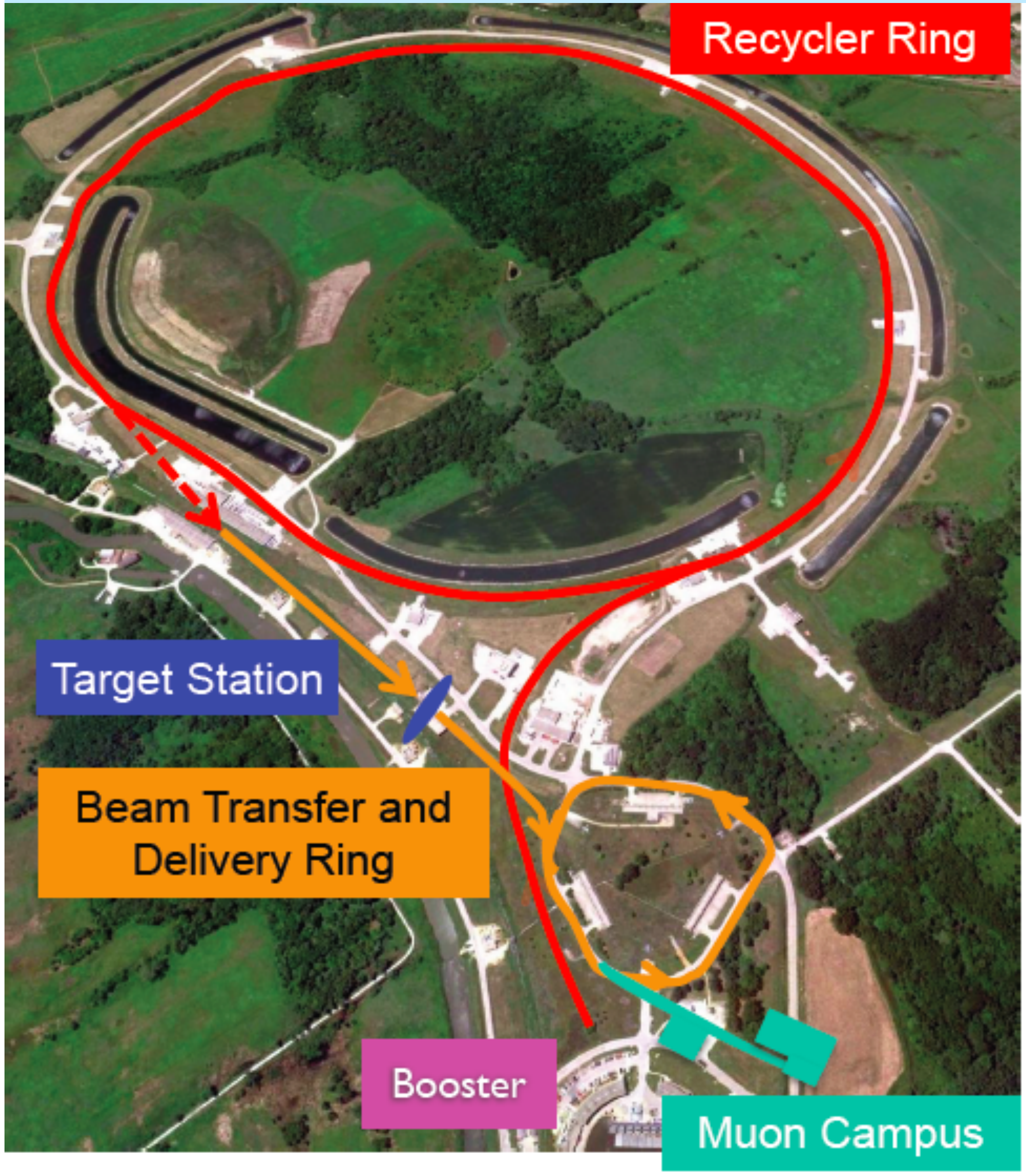
"Collaboration has attained critical mass…have to put all this expertise to good use by matching tasks onto interests and capabilities"

C. Polly, Project Manager, June 12

Why Fermilab?

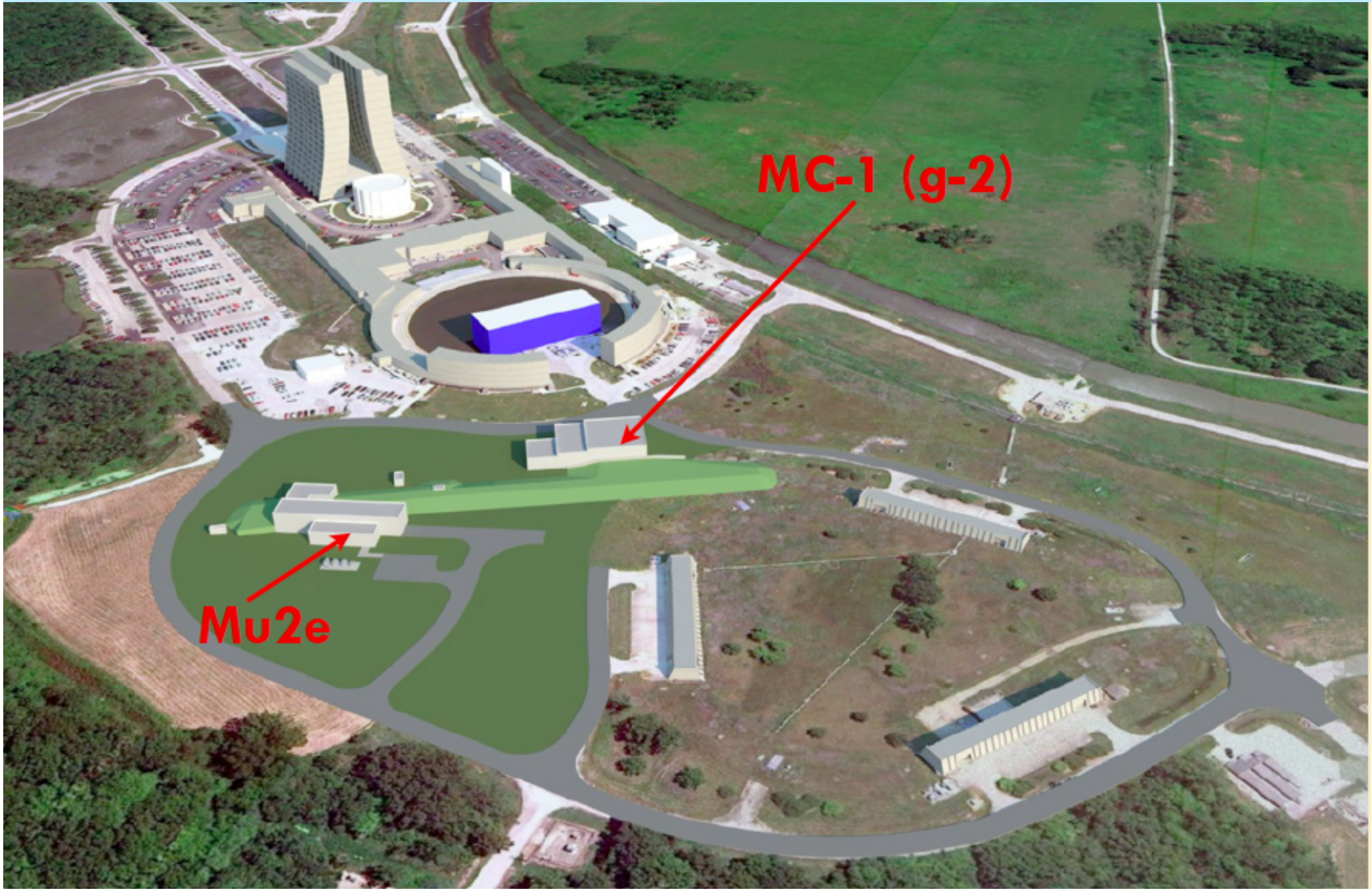
- The existence of many storage rings that are interlinked permits us to make the “ideal” beam structure.
  - proton bunch structure:
    - BNL 4 X 10^{12} p/fill: repetition rate 4.4 Hz
    - FNAL 10^{12} p/fill: repetition rate 15 Hz
  - using antiproton rings as an 900m pion decay line
    - 20 times **less** pion flash at injection than BNL
  - 0^{o} muons
    - ~5-10x increase μ/p over BNL
  - Can run parasitic to main injector experiments (e.g. to NOVA) or take all the booster cycles
- Expected data taking in 2016

Beam delivery to g-2



- 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

Fermilab Muon Campus



Total cost of Muon Program

Muon Campus

MC-1 Building GPP
MC Beamline Enclosure GPP
MC Site Prep GPP
MC Cryo Plant AIP
Recycler AIP
Delivery Ring AIP
Total cost ~$50M

Muon g-2 Project

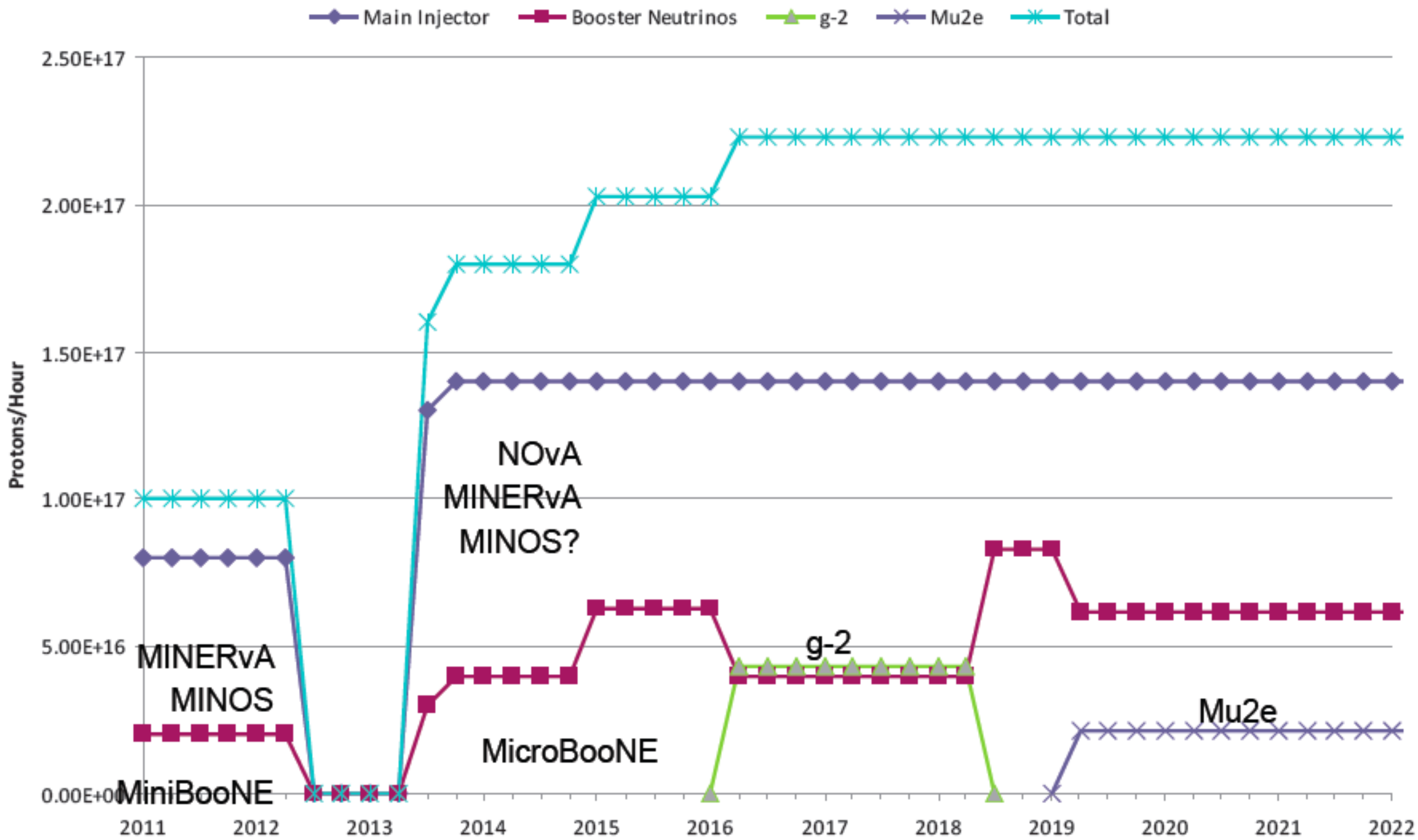
g-2 Accelerator
Ring Reassembly/Upgrades
E821 Equipment Transfer
Project Management
Total cost ~$30M

Mu2e Project

Accelerator
Civil Construction
Solenoids
Muon Channel
Tracker
Calorimeter
CRV
DAQ
Project Management
Total cost ~$230M

Total muon program $310M
spread over 2012-19

Who gets beam when?



Upgrades at Fermilab

- New segmented detectors to reduce pileup
  - PbF2 Crystals?
  - W-scifi prototype under study X_0 = 0.7 cm?
  - SiPM or PMT?
- New electronics
  - 500 MHz 12-bit WFDs, with deep memories
- Improvements in the magnetic field calibration, measurement and monitoring.

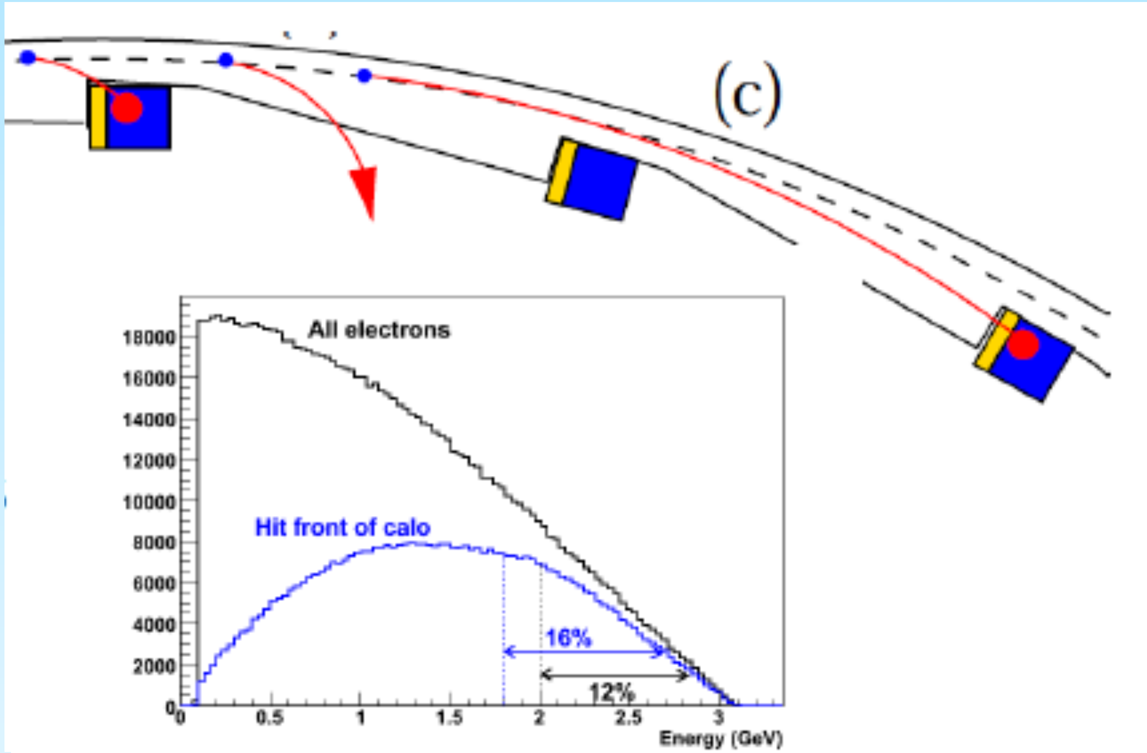
Calorimeters

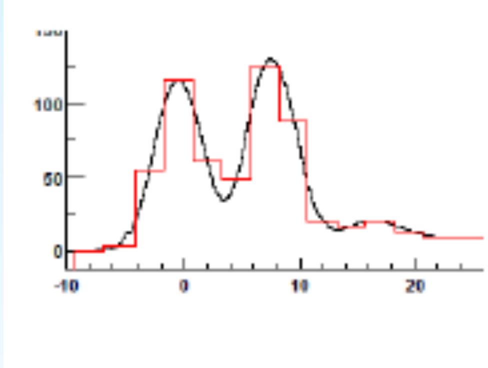
ω_a is determined from e+ arrivals with E>1.8 GeV.

Non magnetic, compact (to separate two pulse in space), fast (to separate two pulse in time) and with moderate energy resolution.

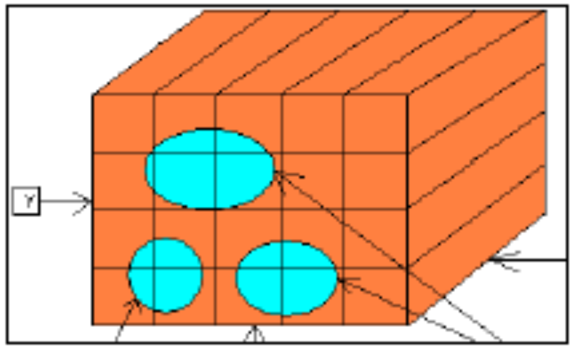
Present design:

- 24 stations
- 35 crystals (5x7 array)/ station
- 3x3x14 cm3 PbF2 crystals (Cherenkov)
- σE/E~ 3-5%/sqrt(E)
- SiPM readout with optimized pulse shape





(b) $\Delta t = 8$ ns



Muon (g-2) storage ring to be relocated to FNAL

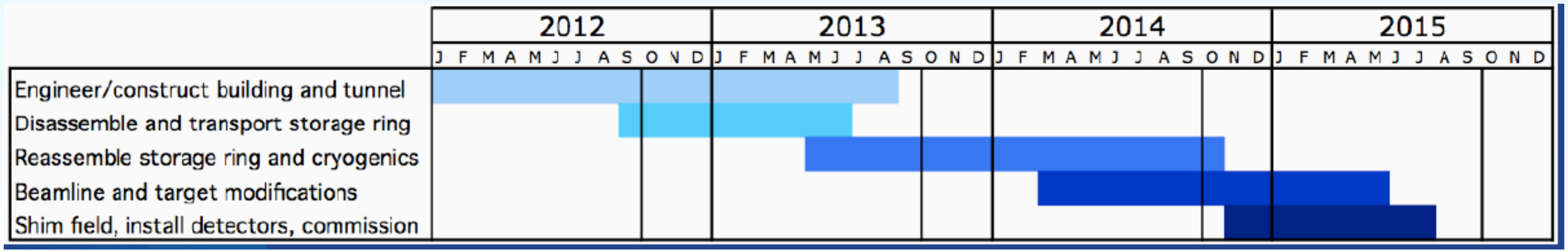
Sikorsky S64F 12.5 T hook weight (Outer coil 8T)

- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

E989 Status and Timeschedule

- Fermilab Stage 1 approval on 2011
- CD0 received on Sep 12
- Conceptual Design Report being prepared
- CD-1 expected in early 2013

Goal is to be ready for data in 2016



Conclusion

• During the last ten years the muon (g-2) provided one of the strongest tests of the SM, thanks to the impressive accuracy of BNL experiment (δa_μ^{EXP} = 0.54 ppm). Important interplay with LHC!

•The SM prediction has steadily improved thanks to precise e^+e^- data (worldwide effort): δa_μ^{SM} = 0.43 ppm

•At present a discrepancy of more than 3 "standard deviations" between SM and Experiment; uncertainty dominated by BNL experiment

• New $(g\text{-}2)_\mu$ experiment at Fermilab with a fourfold reduction δa_μ^{EXP} = 0.14 ppm . First results could be available around 2017/18

• Theoretical uncertainty will improve thanks to current and planned experimental activities (as well as theoretical ones)

Stay Tuned!

SPARES

Why Fermilab?

- The existence of many storage rings that are interlinked permits us to make the "ideal" beam structure.
  - proton bunch structure:
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    - FNAL 10^{12} p/fill: repetition rate 15 Hz
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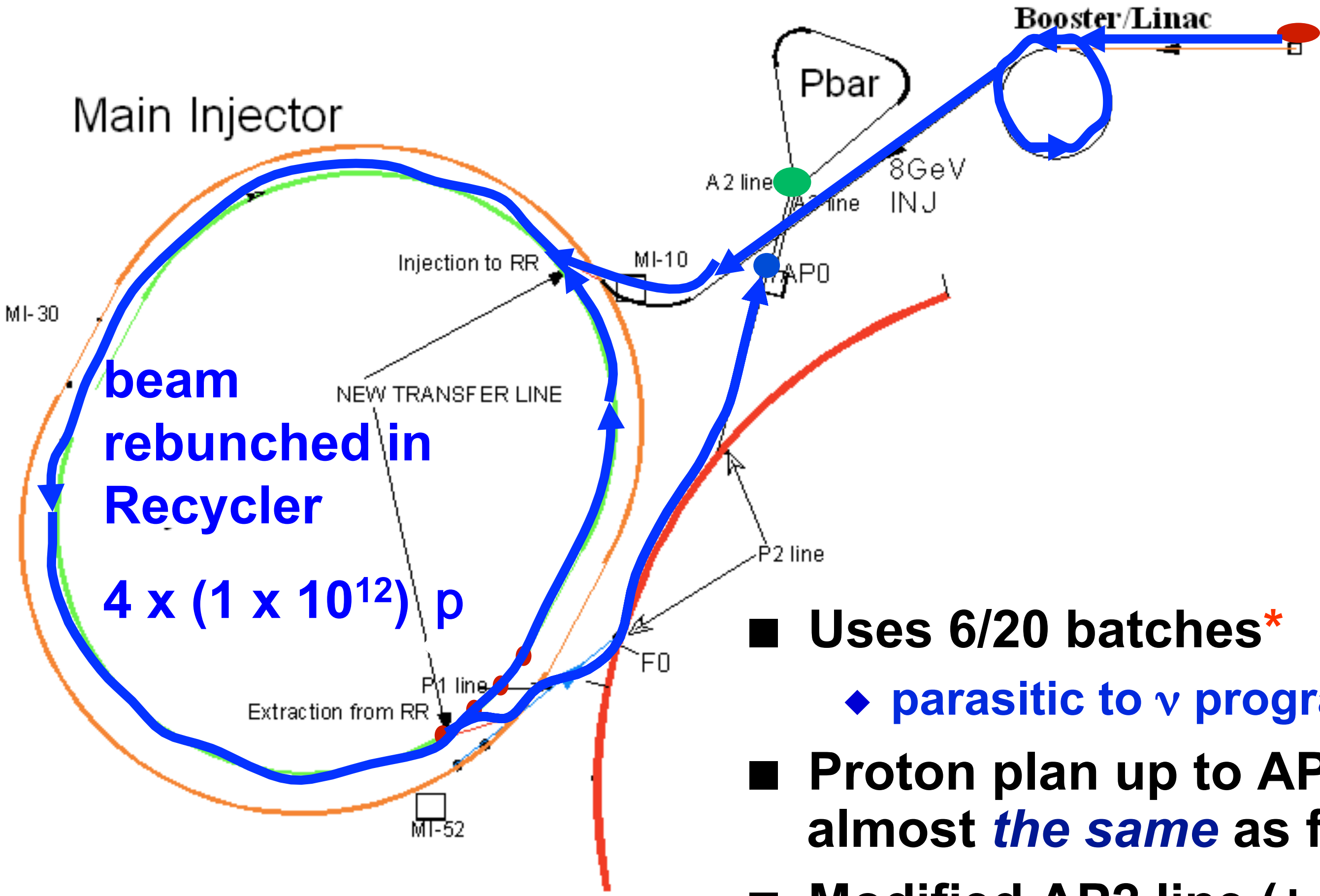
  - 0^o muons
    - ~5-10x increase μ/p over BNL
  - Can run parasitic to main injector experiments (e.g. to NOVA) or take all the booster cycles
- Expected data taking in 2016

Polarized muons delivered and stored in the ring at the magic momentum, 3.094 GeV/c

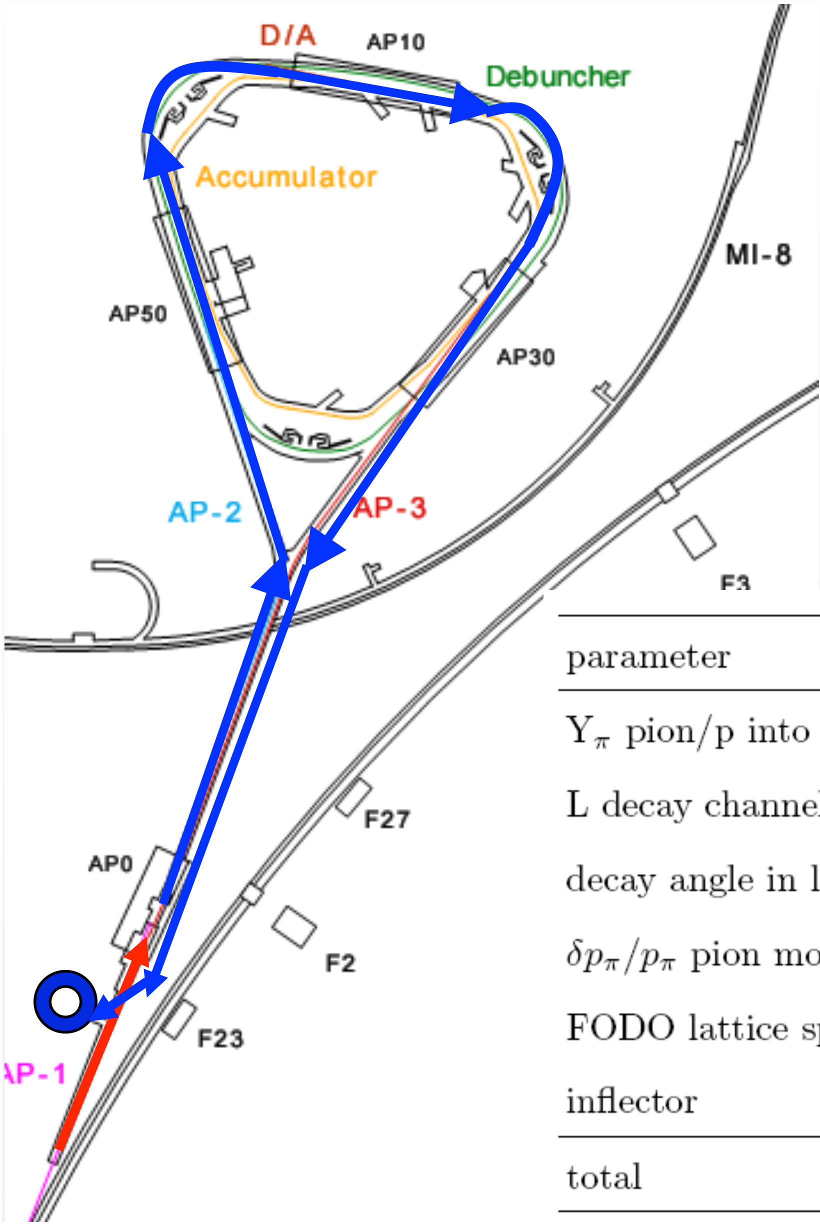


- Uses 6/20 batches*
  - parasitic to ν program
- Proton plan up to AP0 target is almost ***the same*** as for Mu2e
- Modified AP2 line (+ quads)
- New beam stub into ring

*Can use all 20 if MI program is off

The 900-m long decay beam reduces the pion "flash" by x20 and leads to 6 – 12 times more stored muons per proton

(compared to BNL)



Flash compared to BNL

parameter	FNAL/BNL
p / fill	0.25
π / p	0.4
π survive to ring	0.01
π at magic P	50
Net	0.05

Stored Muons / POT

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	≈ 2.7E-5	≈ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	±0.5%	±2%	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

Improving ω_a

E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

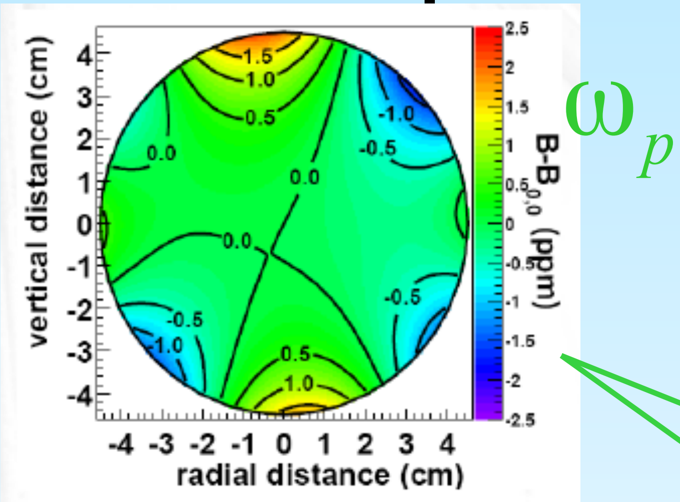
Systematic uncertainty on ω_a expected to be reduced by 1/3 at E989 (compared to E821) thanks to **reduced** pion contamination,the **segmented** detectors, and an **improved** storage ring kick of the muons onto orbit.

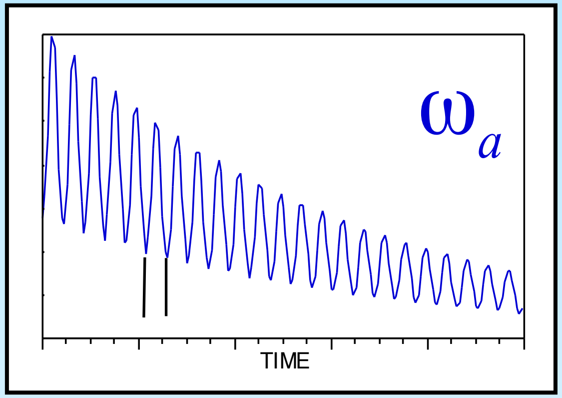
Improving ω_p

Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with 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
Others		0.15	0.10	0.10	0.05
Total systematic error on ω_p	0.5	0.4	0.24	0.17	0.11

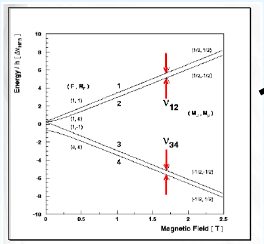
Systematic uncertainty on ω_p expected to be reduced by a factor 2 thanks to **better** shimming (uniformity of B), **relocations** of critical NMR probes, and **other** incremental changes

The anomaly is obtained from three well-measured quantities





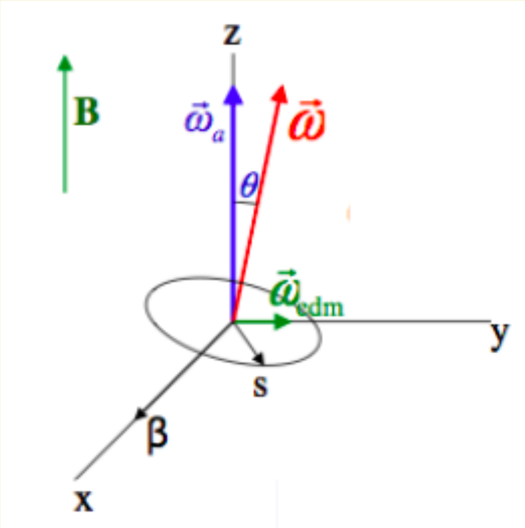
$$a_\mu = \frac{\dfrac{\omega_a}{\omega_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\omega_p}}$$

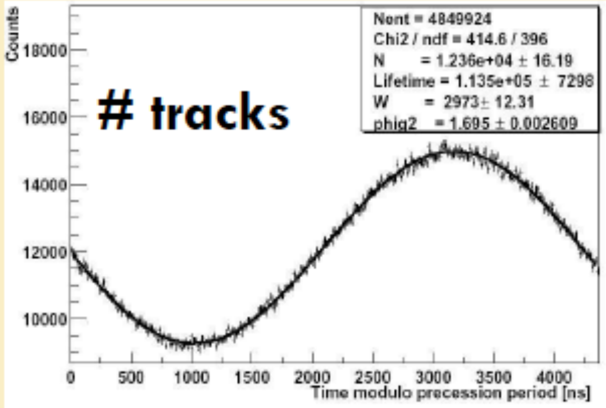


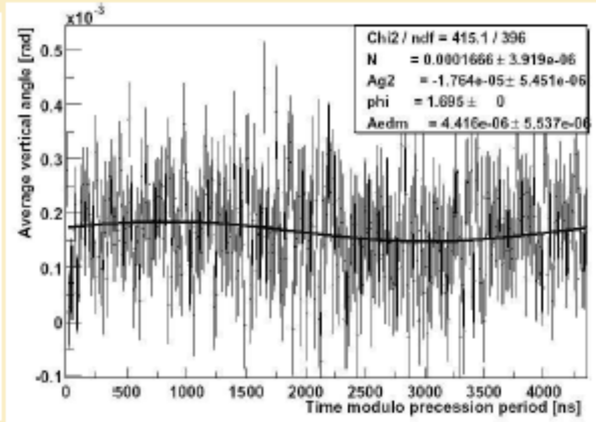
μ_μ/μ_p = 3.183 345 24(37) (120 ppb)

= *3.183 345 39(10) (31 ppb)*

Muon EDM





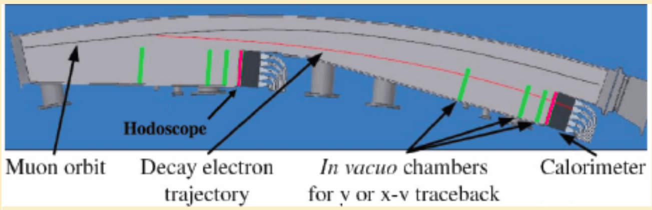


vertical angle of tracks

Precession plane tilted, vertical out of phase oscillation of ω_a

Current best limit from E821

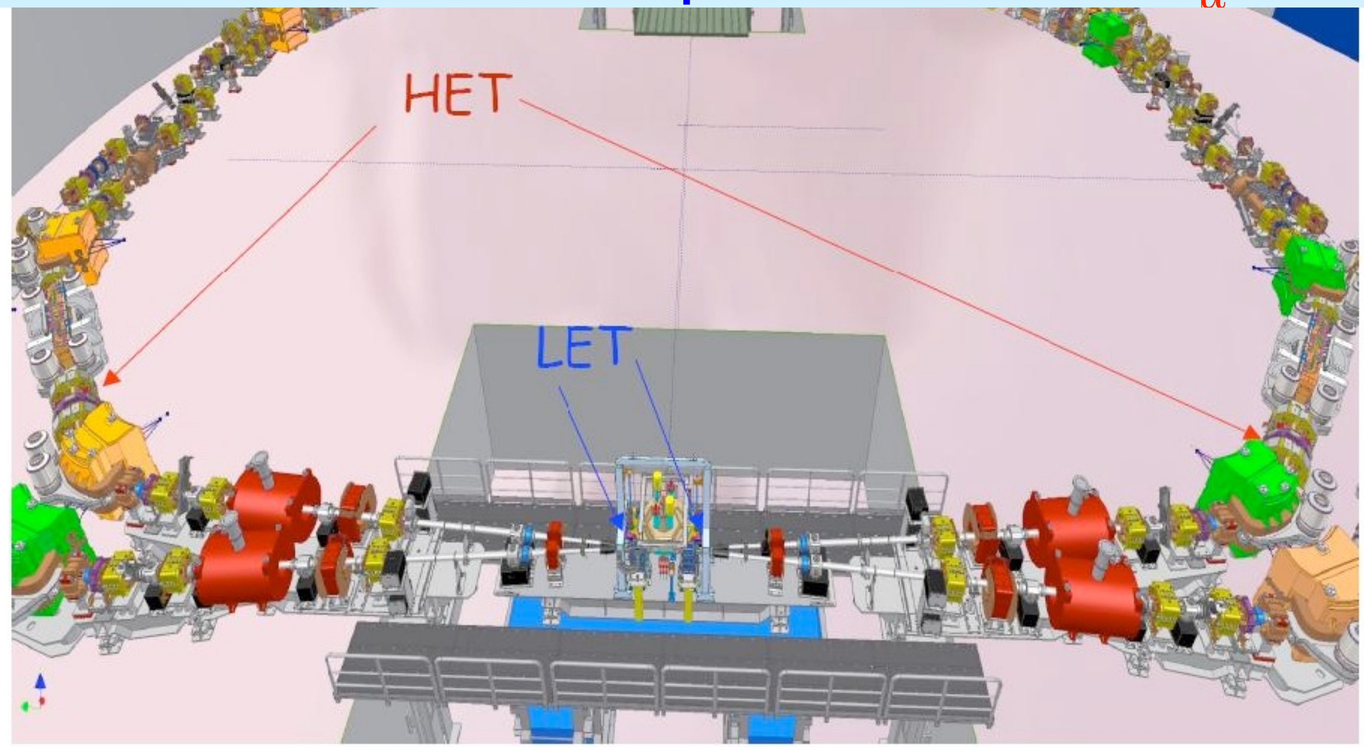
$$|d_\mu| < 1.8 \times 10^{-19}\, e \text{ cm (95\% C.L.)}$$

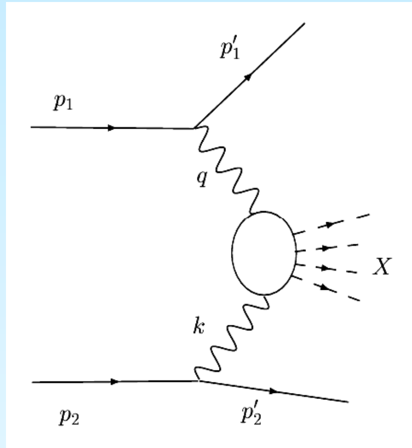


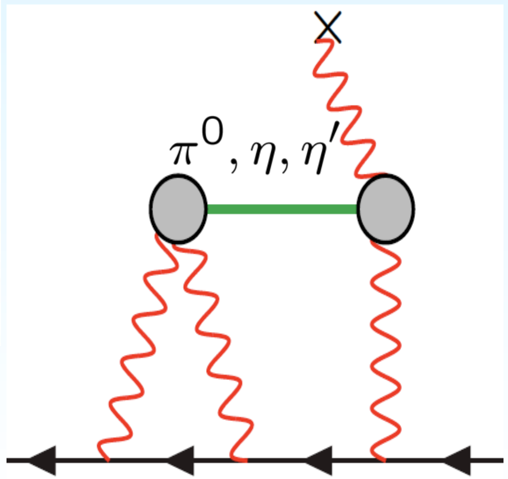
Expect 10-30x better in new experiment

KLOE-2 to measure $\gamma\gamma^* \rightarrow$ *hadrons* to constrain HLBL

- Constrain the on-shell amplitudes and remove a significant portion of the theoretical uncertainty on the HLBL
- A reasonable improvement on $a_\mu^{\pi 0}$



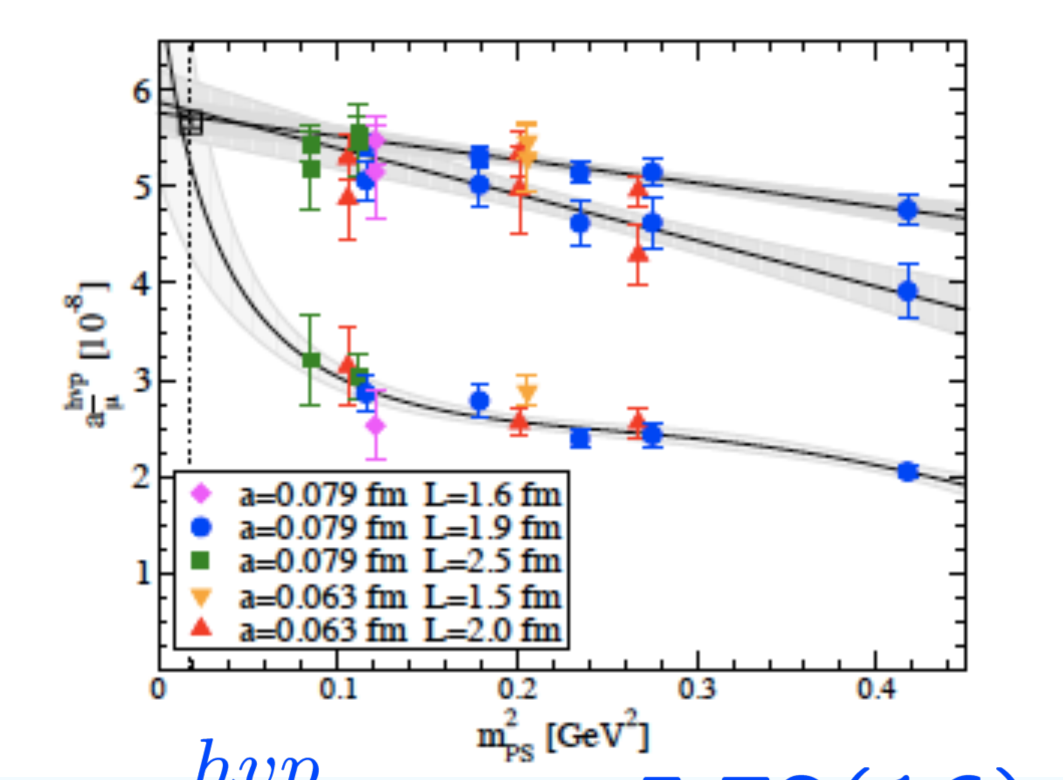




For more details see Moricciani's talk

What about the lattice?

- A new 2-3% lattice result for the lowest-order hadronic (u,d quarks only)contribution:



Very promising results!

Prospects for HLBL?

See Jansen's talk

$$a^{hvp}_{\mu,N_f=2} = 5.72(16) \times 10^{-8}$$

Feng, Jansen, Petschlies, Renner, arXiv:1103.4818v1 [hep-lat]

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

Systematic uncertainty (ppm)	1998	1999	2000	2001	E821 final	P989 Goal
Magnetic field – w_p	0.5	0.4	0.24	0.17		0.07
Anomalous precession – w_a	0.8	0.3	0.31	0.21		0.07

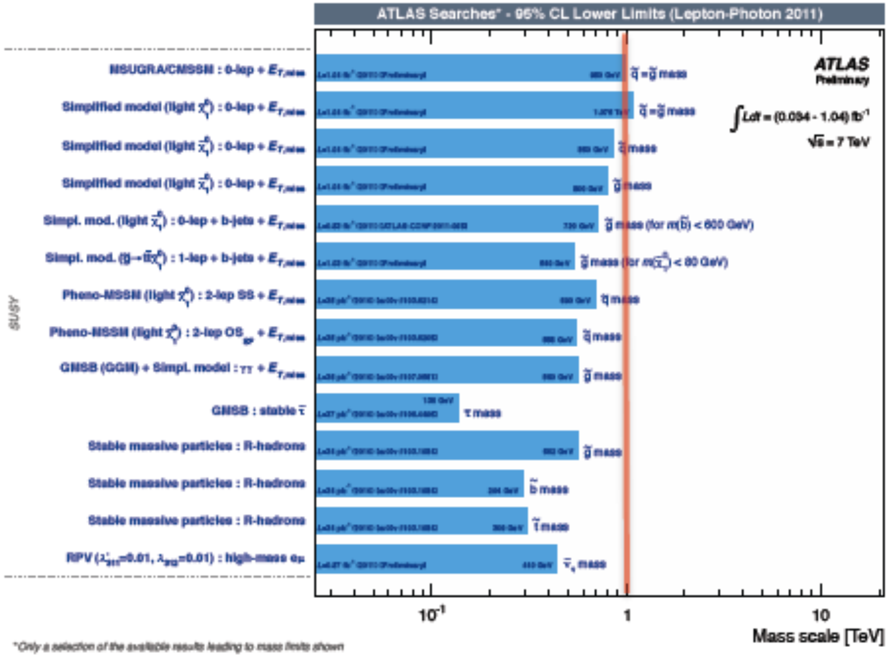
Statistical uncertainty (ppm)	4.9	1.3	0.62	0.66	0.46	0.1
Systematic uncertainty (ppm)	0.9	0.5	0.39	0.28	0.28	0.1
Total Uncertainty (ppm)	5.0	1.3	0.73	0.72	0.54	0.14

What could a $\Delta a_\mu \approx 30\times10^{-10}$ Deviation Tell Us?

Amount of discrepancy in ballpark of SUSY with mass scale of several 100 GeV

$$\Delta a_\mu^{\text{SUSY}} \approx +13\cdot10^{-10}\,\text{sgn}(\mu)\left(\frac{100\ \text{GeV}}{m_{\text{SUSY}}}\right)^2 \tan\beta$$

But strong m_{SUSY} limits from LHC require large $\tan\beta$



Alternative recent scenario involves "dark photons"

→ Light vector boson from dark matter sector coupling to SM through mixing with photon

Coupling to charged particles with strength $\varepsilon\cdot e$

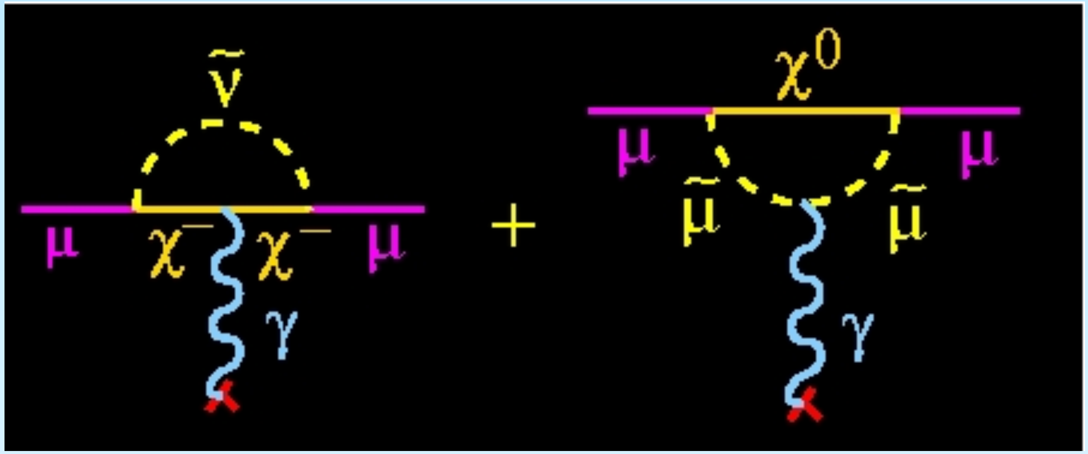
$$\Delta a_\mu^{\text{dark}\,\gamma} \approx \frac{\alpha}{2\pi}\varepsilon^2\cdot F\left(\frac{m_{\text{dark}\,\gamma}}{m_\mu}\right)$$

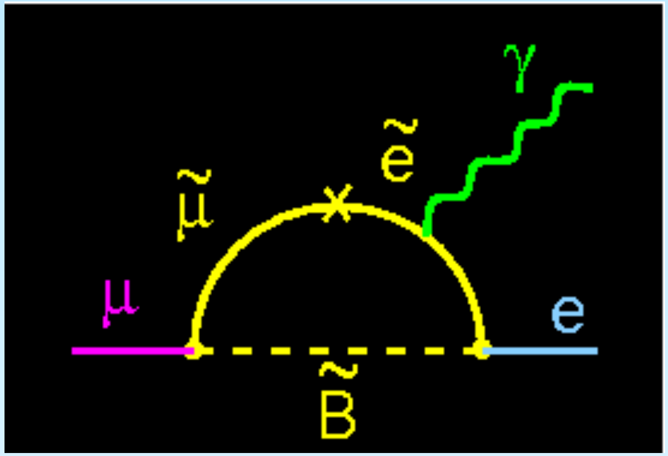
which, for $\varepsilon \approx 0.001$–$0.002$ and $m_{\text{dark}\,\gamma} \approx 10$–$100$ MeV, can provide a solution for the discrepancy

Searches for the dark photon in that mass range are currently underway at Jefferson Lab, USA, and MAMI in Mainz, Germany

Pospelov, PRD 80, 095002 (2009)
Tucker-Smith and Yavin, PRD 83, 101702 (2011)

a_μ is sensitive to a wide range of new physics, e.g.SUSY





$$a_\mu(\mathrm{SUSY}) \simeq (\mathrm{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

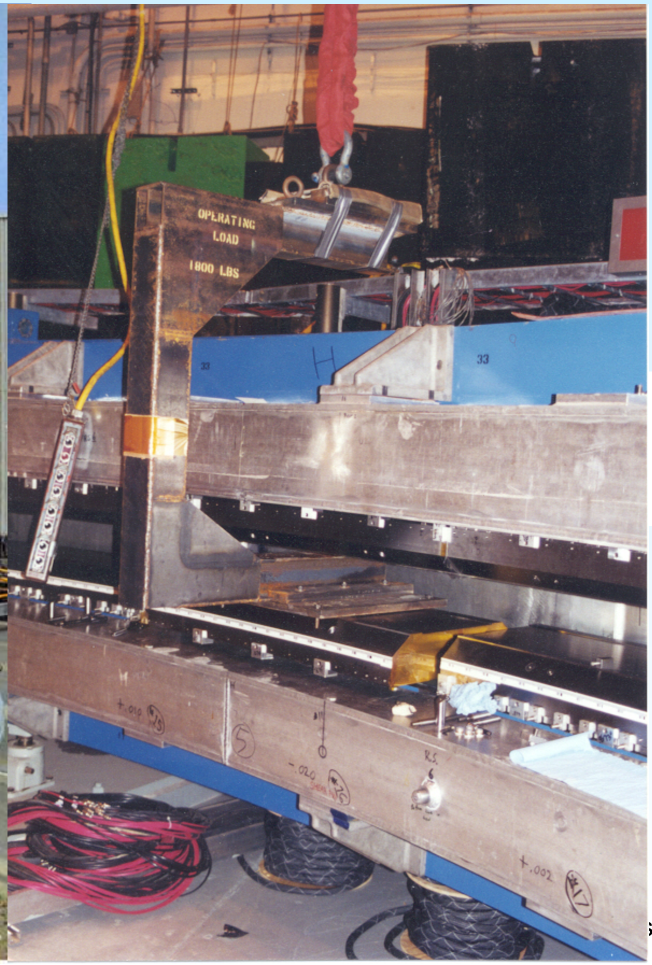
difficult to measure at LHC

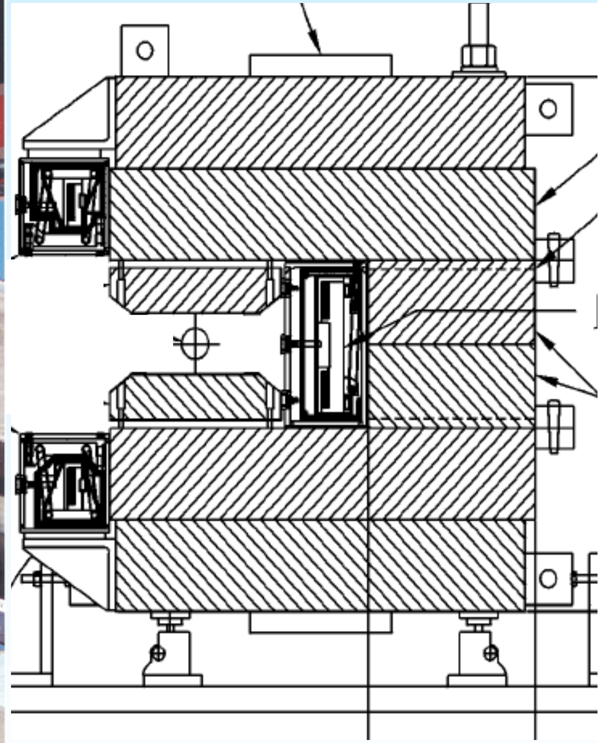
Related processes in SUSY

$$\mu^+ \to e^+\gamma;\ \ \mu^- + \mathcal{N} \to e^- + \mathcal{N}$$

Ring relocation to Fermilab

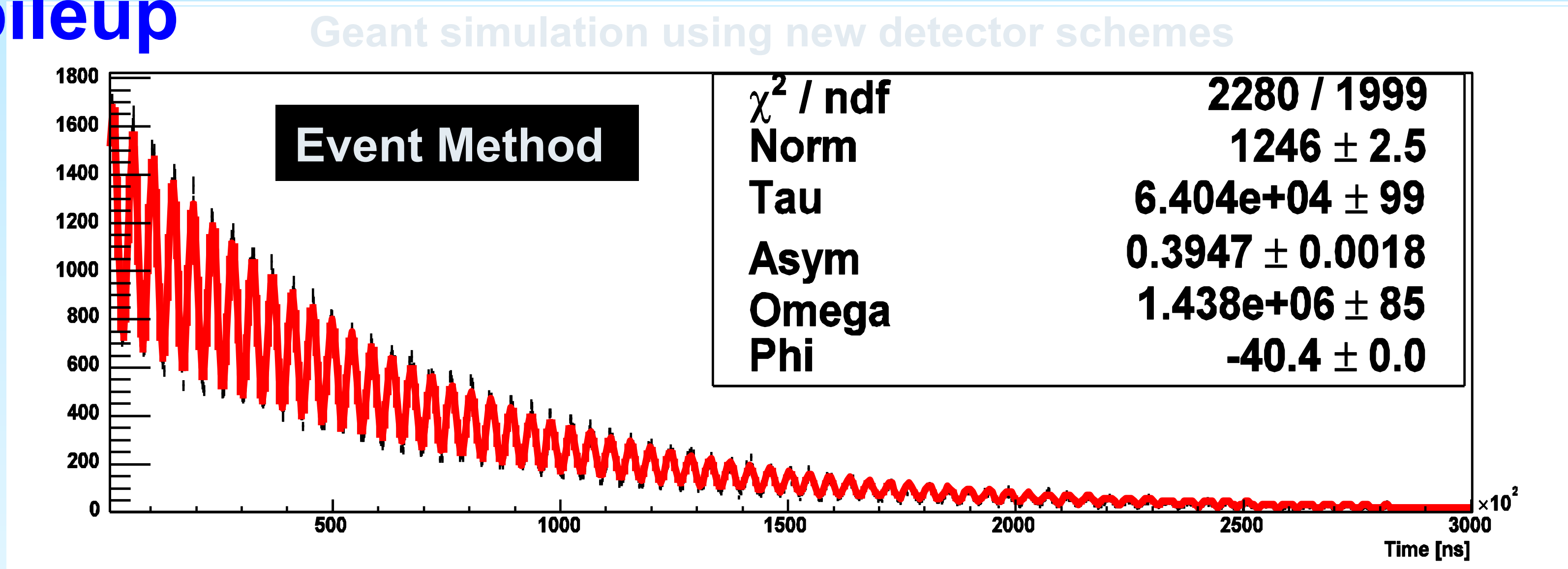
- Heavy-lift helicopters bring coils to a barge
- Rest of magnet is a “kit” that can be trucked to and from the barge



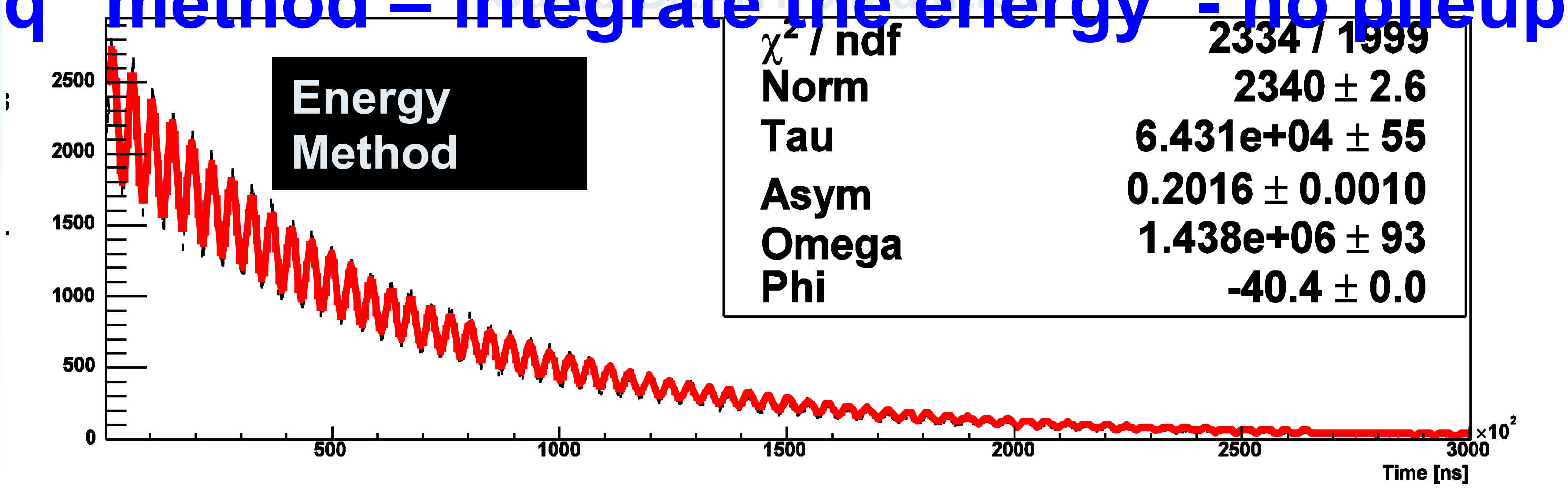


Complementary ways to collect data

- “t” method – time and energy of each event - pileup

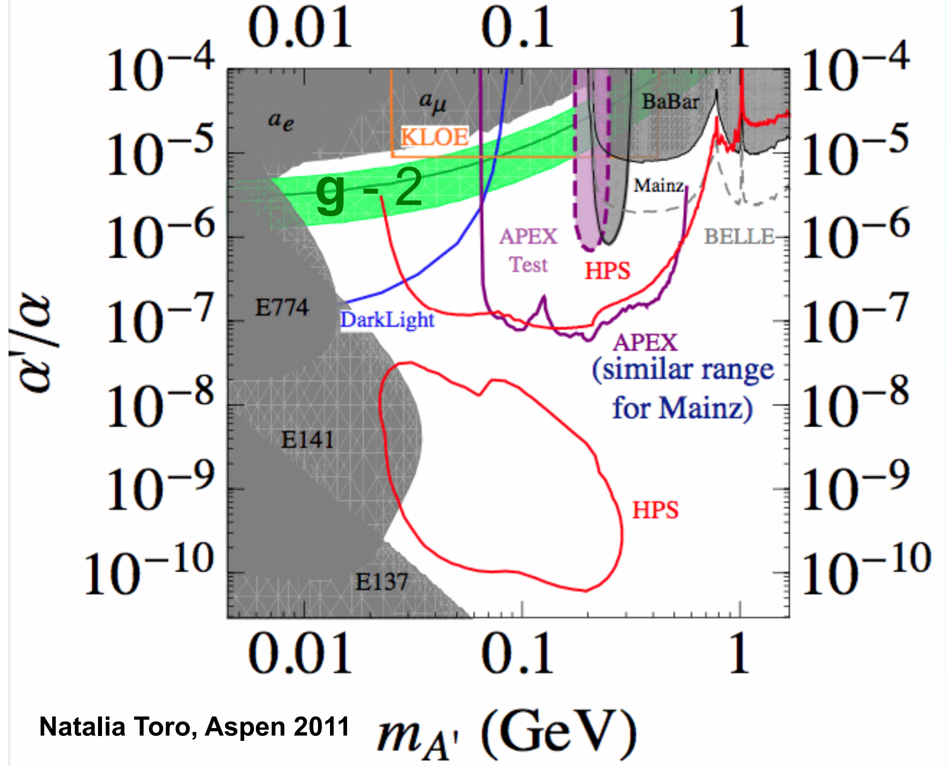


- “q” method – integrate the energy - no pileup



Other Models

- Technicolor
  - small Δa_μ
- Littlest Higgs with T-parity
  - small Δa_μ
- Universal Extra Dimensions
  - small Δa_μ
- Randall Sundrum
  - could accommodate large Δa_μ
- Two Higgs doublets, shadow Higgs
  - small Δa_μ
- Additional light bosons that can affect EM interactions (difficult to study at LHC)
  - secluded U(1),etc., could have significant Δa_μ



Natalia Toro, Aspen 2011

The Precision Field: Systematic errors

- Why is the error 0.11 ppm?
  - That's with *existing* knowledge and experience
    - with R&D defined in proposal, it will get better

Source of Uncertainty	1998	1999	2000	2001	**Next (g-2)**
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

Hadronic Light-by-Light Contribution

see: http://www.int.washington.edu/PROGRAMS/11-47w/

Organizers:
Thomas Blum
University of Connecticut
tblum@phys.uconn.edu

Eduardo de Rafael
Marseille
EdeR@cpt.univ-mrs.fr

David Hertzog
University of Washington
hertzog@uw.edu

Fred Jegerlehner
DESY Zeuten
fjeger@physik.hu-berlin.de

Lee Roberts
Boston University
roberts@bu.edu

Arkady Vainshtein
University of Minnesota
vainshte@umn.edu

Program Coordinator:
Inge Dolan
inge@phys.washington.edu
(206) 685-4286

Schedule

Talks online

Application form

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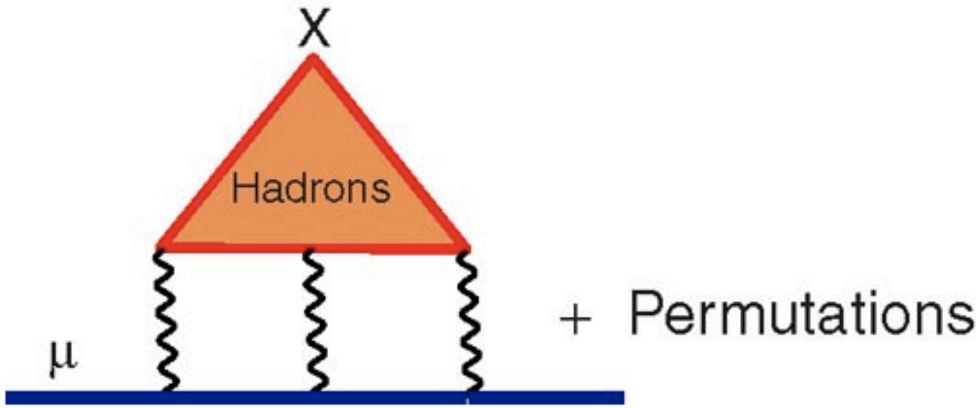
INT Workshop on
The Hadronic Light-by-Light Contribution to the Muon Anomaly

February 28 - March 4, 2011



There is a registration fee of $80 to attend this workshop to cover the expenses for catering and a workshop dinner.

The Workshop Plan:

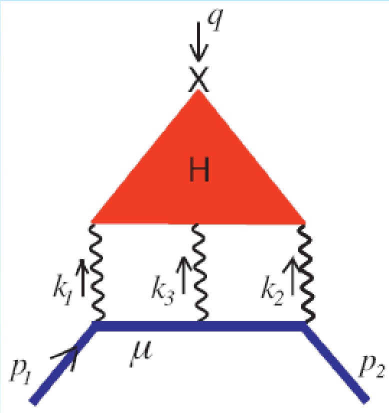
The workshop will bring together both theorists and experimentalists to focus on one of the outstanding theoretical issues in interpreting the muon anomalous magnetic moment:

1. Can agreement be reached on the individual and combined theoretical contributions to the hadronic light-by-light (HLbL) contribution to the muon anomalous magnetic moment, a_μ, based on QCD-inspired models?
2. Can the lattice approach lead to a result having sufficient precision to check the models or to independently establish the HLbL value?
3. Which data that can be obtained at Frascati, and at other facilities, are essential to constrain the theoretical calculations and what theoretical developments are required to connect data to model predictions?

Hadronic Light–by–Light Scattering Contribution to the Muon Anomalous Magnetic Moment

arXiv:0901.0306v1

Joaquim Prades[a], Eduardo de Rafael[b] and Arkady Vainshtein[c]



$$a^{\rm HLbL}(\pi\,,\eta\,,\eta') = (11.4 \pm 1.3) \times 10^{-10}$$

$$a^{\rm HLbL}({\rm scalars}) = -(0.7 \pm 0.7) \times 10^{-10}$$

$$a^{\rm HLbL}(\pi{-}{\rm dressed\ loop}) = -(1.9 \pm 1.9) \times 10^{-10}$$

$$a^{\rm HLbL}({\rm pseudovectors}) = (1.5 \pm 1) \times 10^{-10}$$

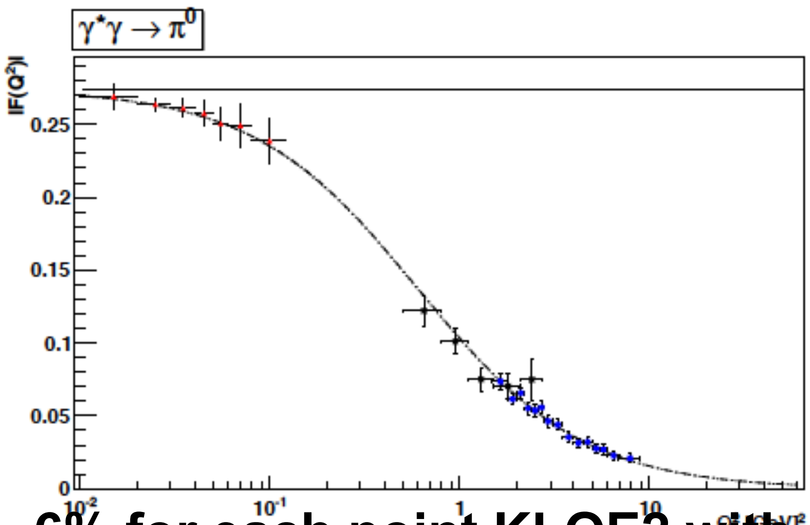
Dynamical models with QCD behavior

$$a_\mu^{\rm HLBL} = 105\ (26) \times 10^{-11}$$

Note, with $\Delta a_\mu = 295 \times 10^{-11}$ … If HLBL is the source of the difference with SM, it would need to increase by 11 σ ....

KLOE-2 contribution to $F_{\pi^0\gamma^*\gamma}(q_1^2,0)$ and $a_\mu^{LbL,\pi 0}$

By including KLOE-2→a reduction of a factor 2 in the error of $a_\mu^{\pi 0}$!



On the possibility to measure the $\pi^0 \to \gamma\gamma$ decay width
and the $\gamma^*\gamma \to \pi^0$ transition form factor
with the KLOE-2 experiment
(D. Babusci et al. to be submitted to journal)

6% for each point KLOE2 with 5 fb^{-1}

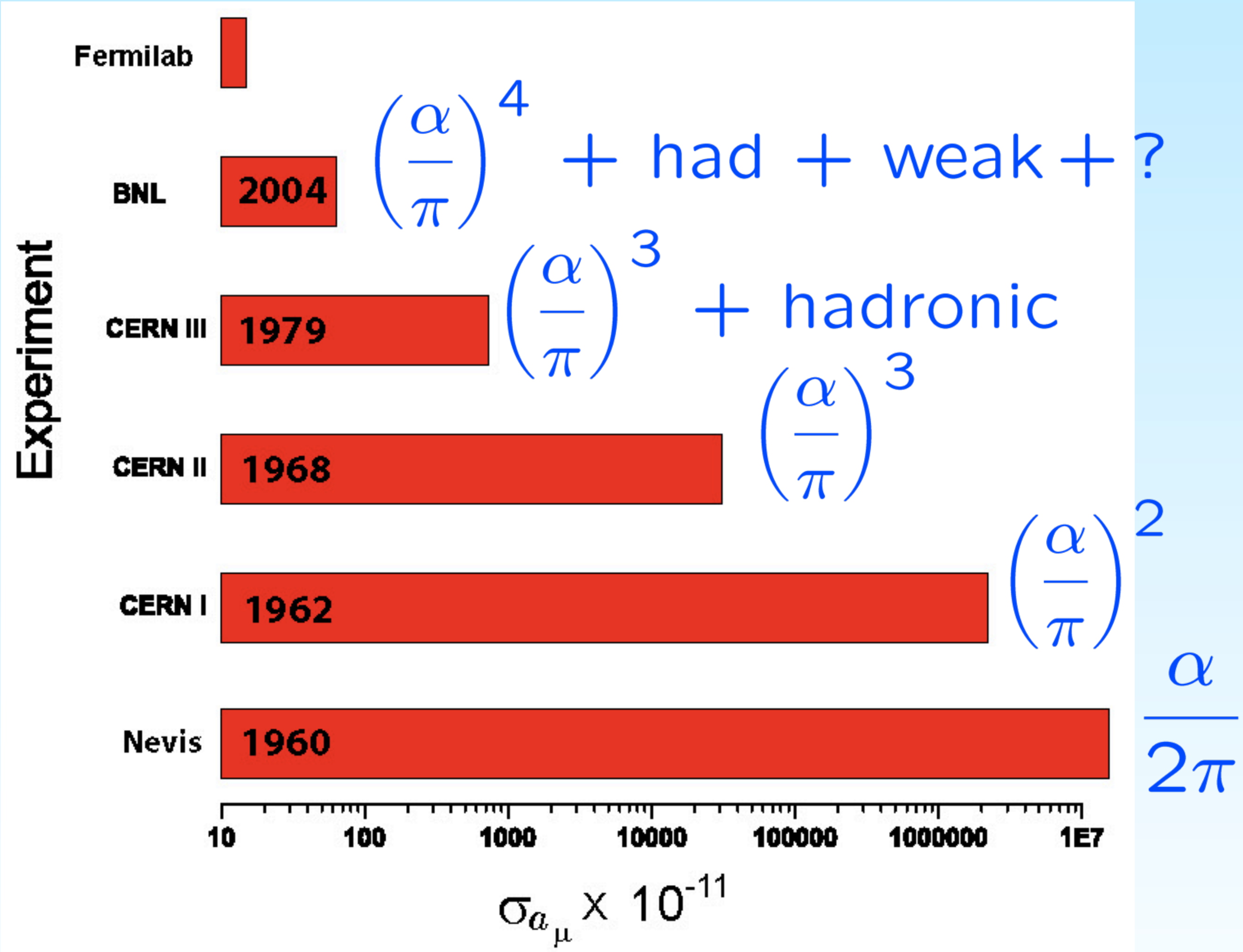
See the talk of Ivashin

Model	Data	$\chi^2/d.o.f.$	parameters		$a_\mu^{LbyL;\pi^0} \times 10^{11}$
VMD	A	6.6/19	M_V = 776(13) MeV	F_π = 0.0919(13) GeV	$(57.7 \pm 2.1)_{JN}$
VMD	B	7.5/27	M_V = 778(11) MeV	F_π = 0.0923(4) GeV	$(57.3 \pm 1.1)_{JN}$
VMD	C	78/36	M_V = 813(8) MeV	F_π = 0.0925(13) GeV	—
VMD	D	79/44	M_V = 813(5) MeV	F_π = 0.0925(4) GeV	—

A : CLEO, CELLO, PrimEx;
B : CLEO, CELLO, PrimEx, KLOE-2;
C : CLEO, CELLO, BaBar, PrimEx;
D : CLEO, CELLO, BaBar, PrimEx, KLOE-2;

In addition the measurement of $\Gamma(\pi^0\to\gamma\gamma)$ will constrain $F_{\pi 0}(q^2=0)$ (which is now obtained by WZW model $1/4\pi f_\pi$ w/o error)

Thank you for your attention!



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