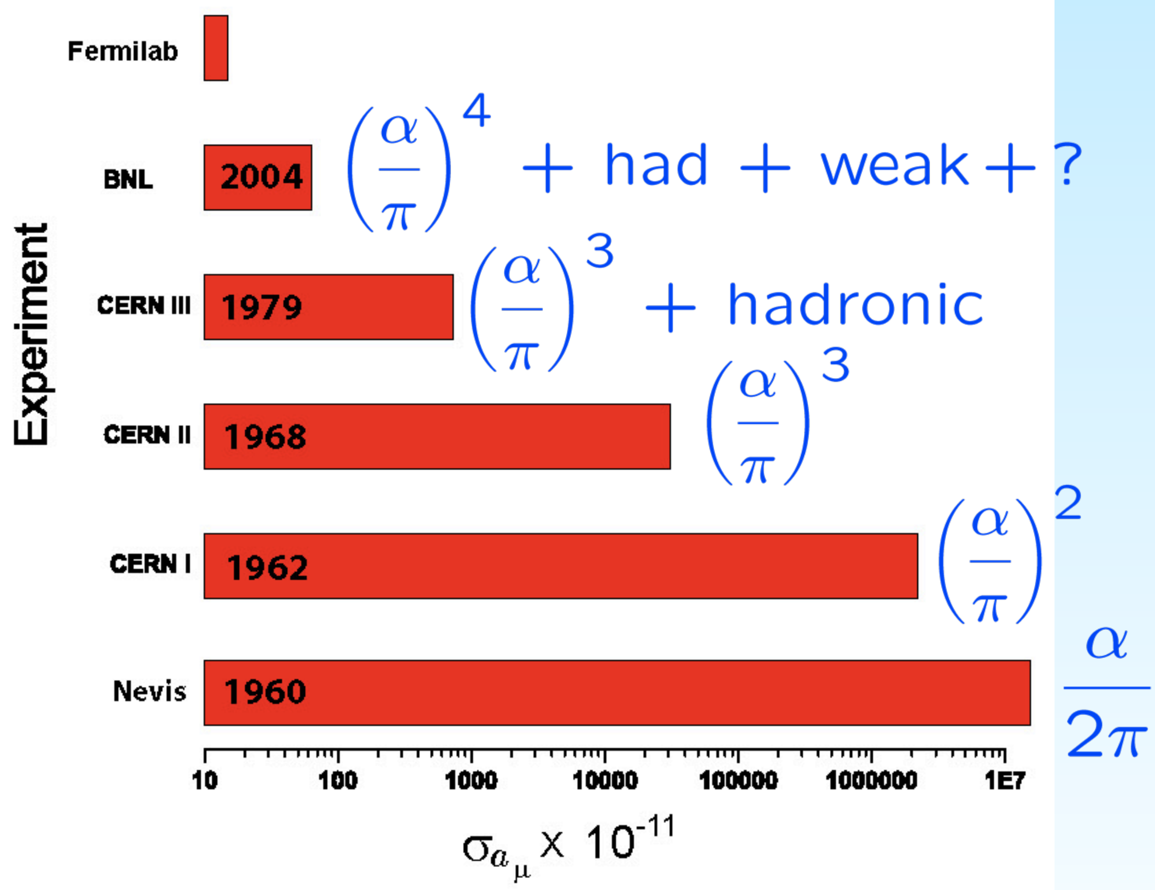
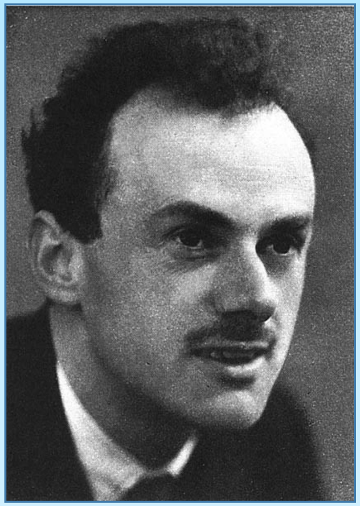
The Fermilab Muon (g-2) Experiment



Lee Roberts
for the

New Muon (g-2) Collaboration – E989

In the beginning there was Dirac



$$\boxed{i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)}$$

predicted electron magnetic moment

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}, \quad e > 0$$

$$g \equiv 2$$

However, experimentally *g* > 2; need to add a Pauli term

dimension 5 operator

$$\frac{Qe}{4m}a\bar{\psi}(x)F_{\mu\nu}(x)\sigma^{\mu\nu}\psi(x)$$

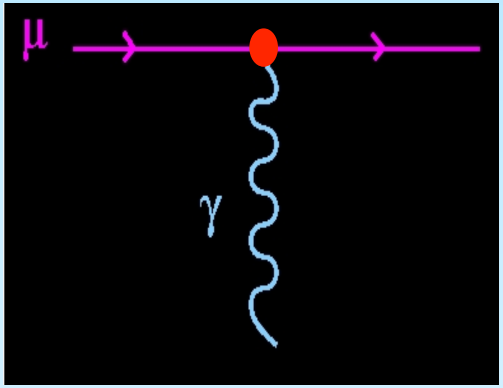
(only from loops)

where a is the anomaly,

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

Magnetic and Electric Dipole Interactions

$$\Gamma_\beta = eF_1\bar{\psi}_R\gamma_\beta\psi_R + \frac{ie}{2m}F_2\bar{\psi}_R\sigma_{\beta\delta}q^\delta\psi_L + HC$$



- Muon Magnetic Dipole Momoment a_μ chiral changing

$$\bar{u}_\mu[eF_1(q^2)\gamma_\beta + \boxed{\frac{ie}{2m_\mu}F_2(q^2)\sigma_{\beta\delta}q^\delta]u_\mu}$$

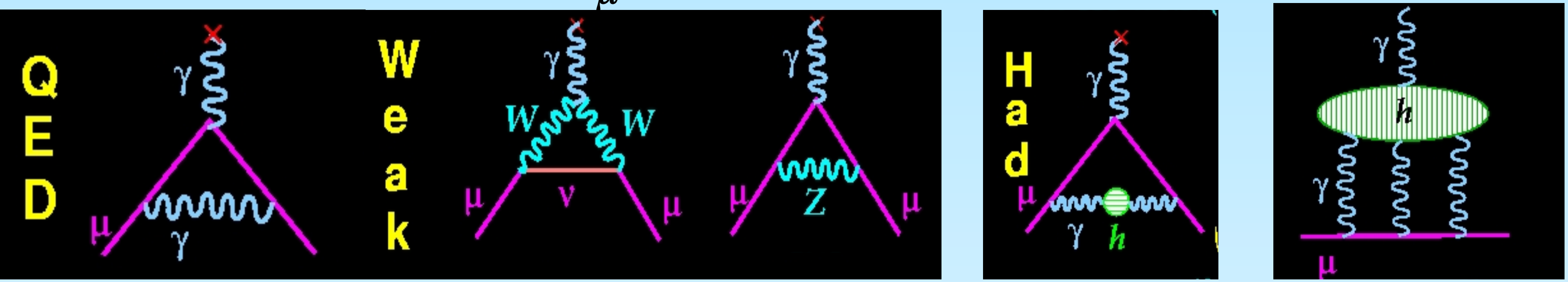
$$F_1(0) = 1 \qquad F_2(0) = a_\mu$$

- Muon EDM

$$\bar{u}_\mu\left[\frac{ie}{2m_\mu}F_2(q^2) - F_3(q^2)\gamma_5\right]\sigma_{\beta\delta}q^\delta u_\mu$$

$$F_2(0) = a_\mu \qquad F_3(0) = d_\mu;\ \text{EDM}$$

The SM Value for a_μ



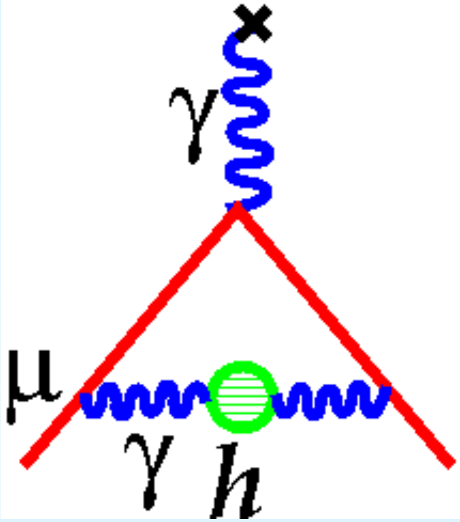
$$\frac{\alpha}{2\pi}+\cdots$$

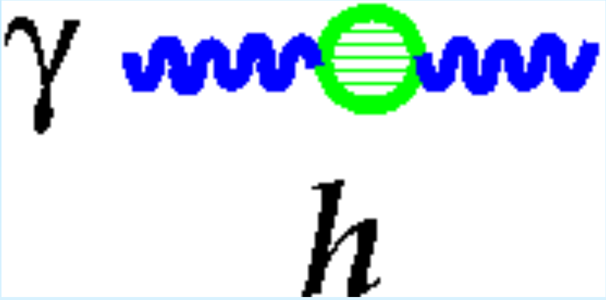
well known

significant work ongoing

- QED calculated to α^5
- Weak calculated through 2 loops
  - 2-loop contribution reduced the contribution by 20%
  - 3-loop leading logs estimated to be small

The Lowest-order Hadronic Contribution $\Pi^{\mu\nu}$ Photon self-energy diagram

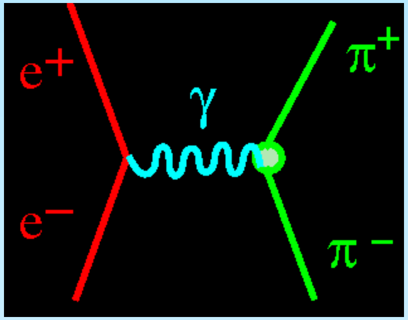


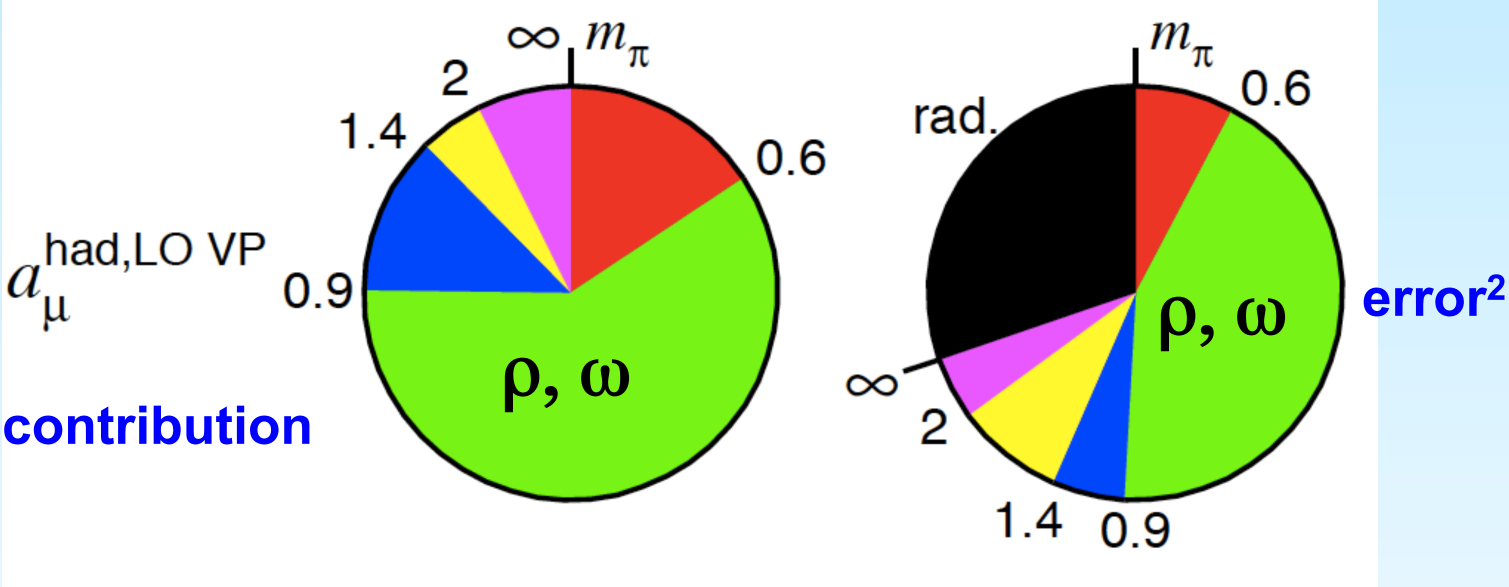


- Options
  - – Use experimental data and dispersion relations
  - – Use low energy effective Lagrangians:
    - hadronic models that contain the features of QCD
  - – non-pertubative calculations in lattice QCD

a_μ^{had}(LO) Analyticity + Optical Theorem

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

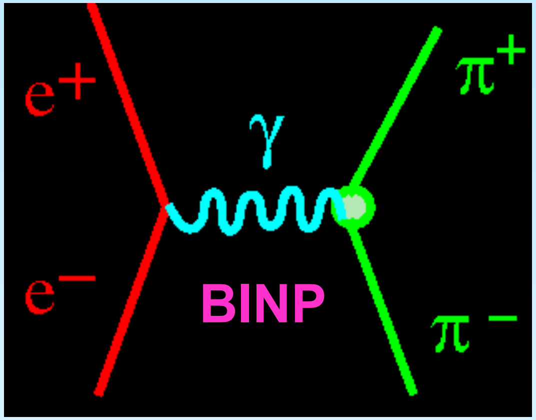




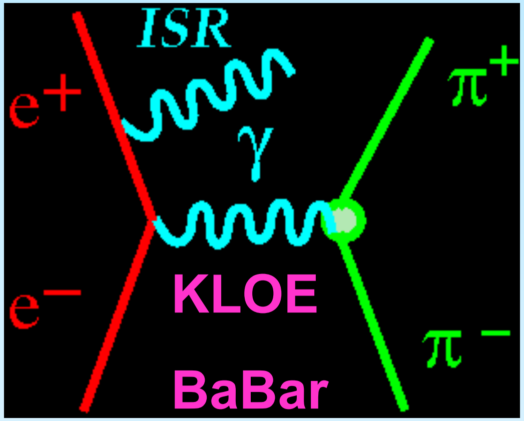
(from Hagawara et al, arXiv:1105.3149v2[hep-ph])

- Future efforts should reduce errors
  - CMD3 at VEPP2000, up to 2.0 GeV (next 5 years), Mainz, BES and perhaps Belle

Energy Scan (Novosibirsk); ISR KLOE and BaBar



scan e^+e^- beam energy



use ISR to lower collision energy

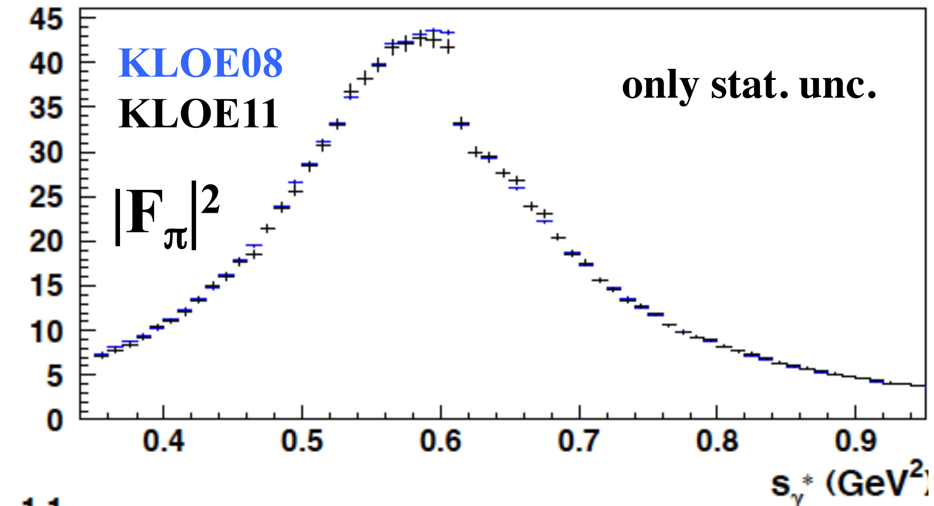
- KLOE: on or near ϕ
  - the γ is soft
    - goes down the beam pipe, (2008)
    - at large angle and is detected (2010); normalize to Bhabha, use theory to calculate $\sigma_{\mu\mu}$
  - measure $R(s)$ directly (2008 data), presented 2011 .

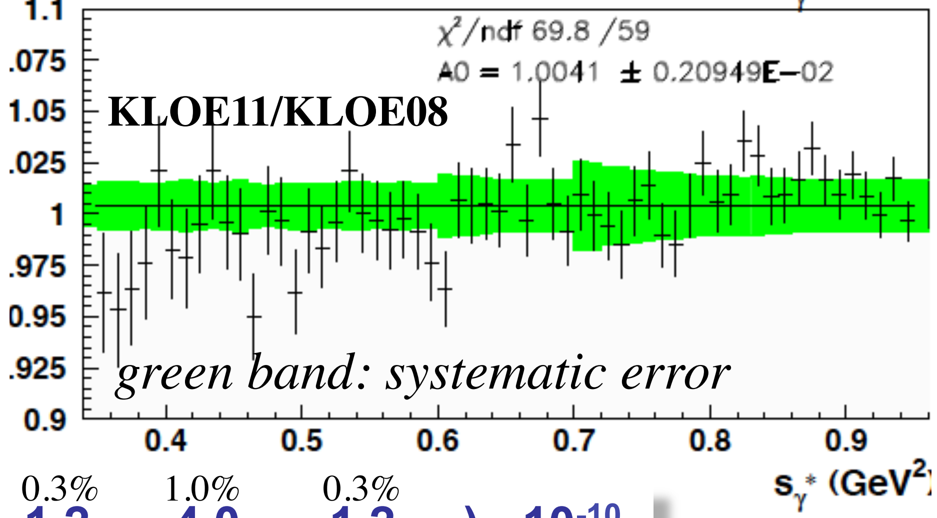
- BaBar: on the Υ 4s
  - the γ is hard, and is detected
  - excellent particle ID with μ–π separation
  - measures $R(s)$ directly

KLOE11 result on $|F_\pi|^2$ and comp. with KLOE08

Syst. errors (%)	KLOE08 $\Delta^{\pi\pi}a_\mu$ abs	KLOE11 $\Delta^{\pi\pi}a_\mu$ ratio
Reconstruction Filter	negligible	negligible
Background subtraction	0.3	0.8 $(0.3_{\pi\pi\gamma} \oplus 0.7_{\mu\mu\gamma})$
Trackmass	0.2	0.4 $(0.2_{\pi\pi\gamma} \oplus 0.4_{\mu\mu\gamma})$
Particle ID	negligible	negligible
Tracking	0.3	0.6 $(0.3_{\pi\pi\gamma} \oplus 0.5_{\mu\mu\gamma})$
Trigger	0.1	0.1 $(0.1_{\pi\pi\gamma})$
Unfolding	negligible	negligible
Acceptance $(\theta_{\pi\pi})$	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	0.1	0.1 $(0.1_{\pi\pi\gamma} \oplus 0.1_{\mu\mu\gamma})$
Luminosity	0.3 $(0.1_{th} \oplus 0.3_{exp})$	-
$\sqrt{s}$ dep. of H	0.2	-
Total exp systematics	0.6	1.0
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.3
Rad. function H	0.5	-
Total theory systematics	0.6	0.3
Total systematic error	0.9	1.1

preliminary





green band: systematic error

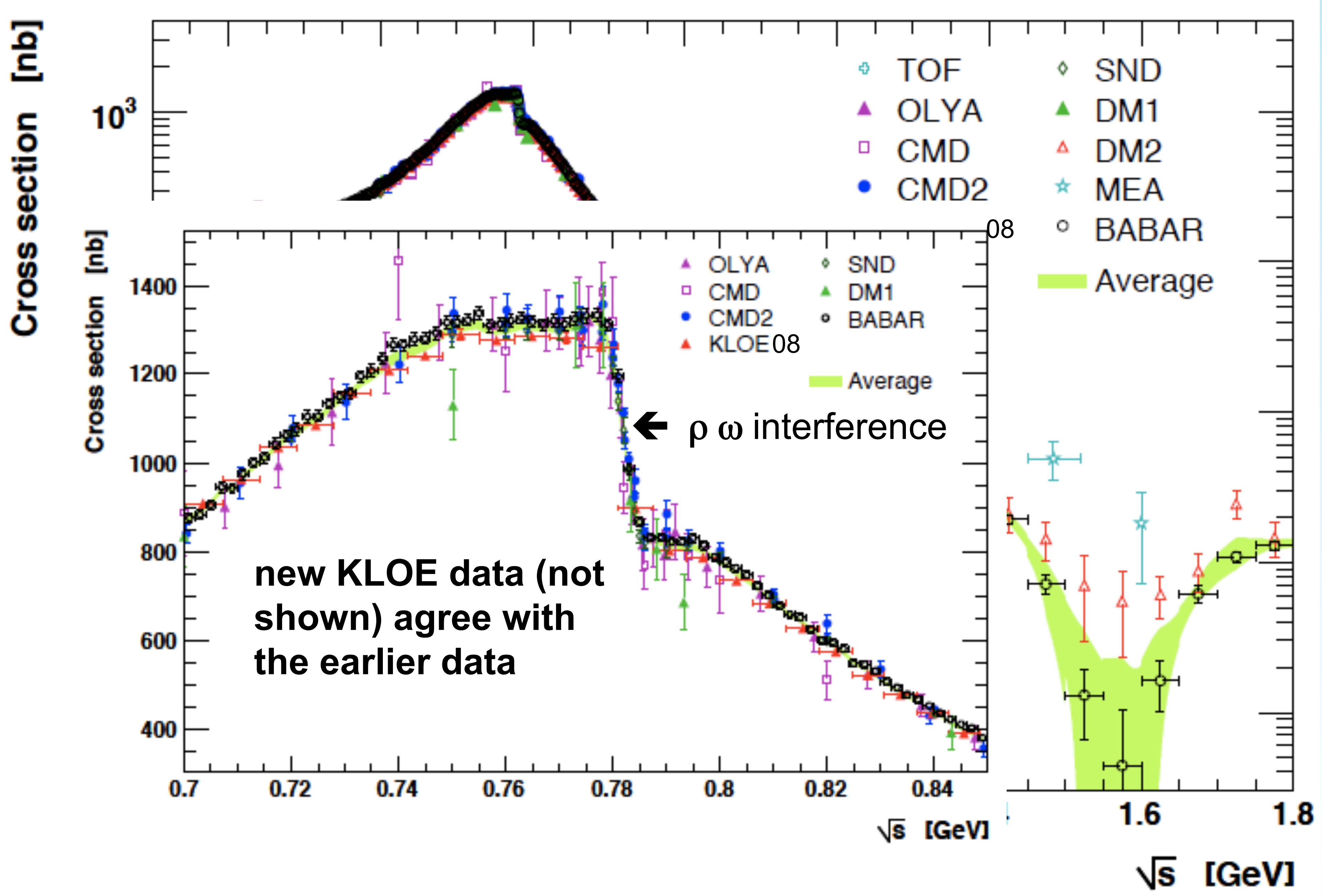
KLOE11 halves the theoretical error

0.3% 1.0% 0.3%

KLOE11: $a_\mu^{\pi\pi}$(0.35-0.95GeV²) = (384.1 ± 1.2_{stat}±4.0_{sys} ±1.2_{theo}) · 10^{-10}

KLOE08: $a_\mu^{\pi\pi}$(0.35-0.95GeV²) = (387.2 ± 0.5_{stat}±2.4_{sys} ±2.3_{theo}) · 10^{-10}

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

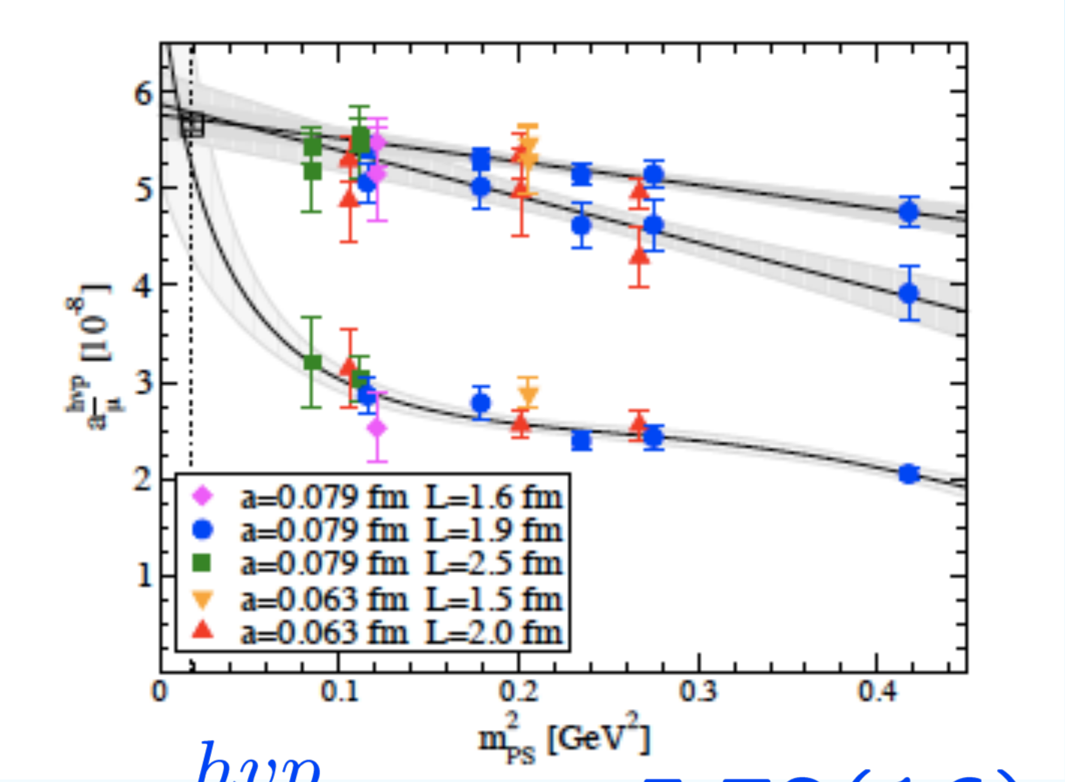


🡐 ρ ω interference

new KLOE data (not shown) agree with the earlier data

What about the lattice?

- At the INT Workshop on the Hadronic Light-by-Light contribution in February, Karl Jansen presented a new 2-3% lattice result for the lowest-order hadronic

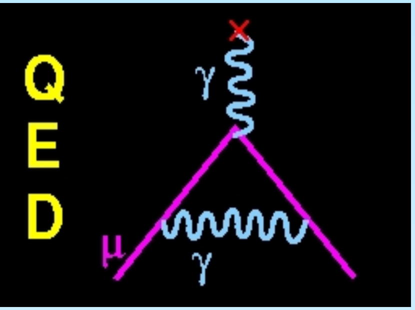


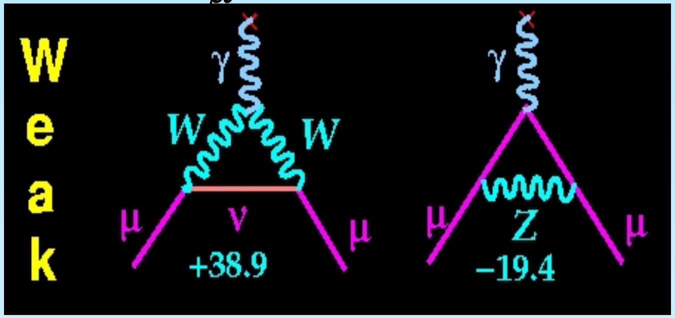
We can look forward to results from the other lattice groups!

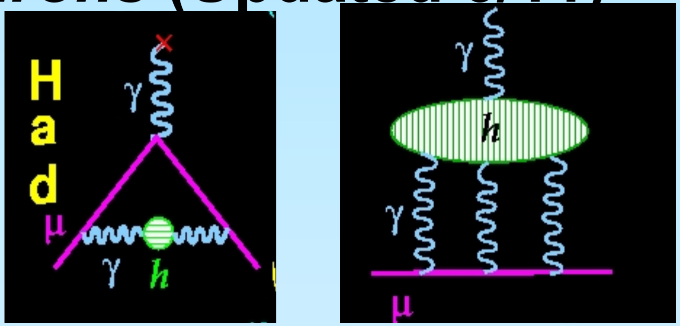
$$a_{\mu,N_f=2}^{hvp} = 5.72(16) \times 10^{-8}$$

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

The SM Value for a_μ from $e^+e^- \rightarrow$ *hadrons* (Updated 6/11)







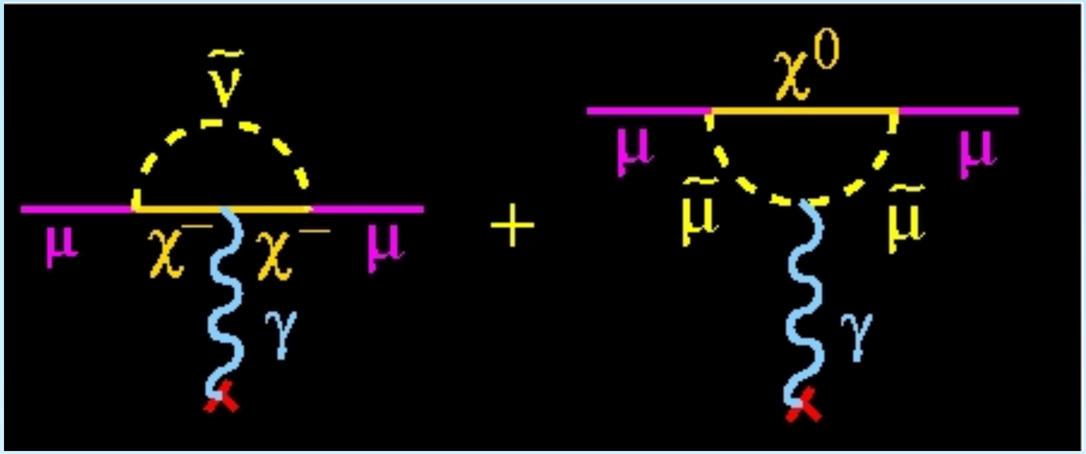
well known **significant work ongoing**

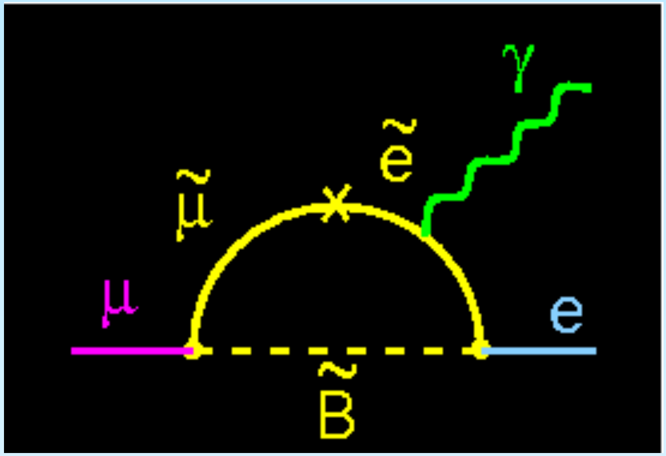
Contribution	Result ($\times 10^{-11}$) units
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 923 \pm 42$
HVP(ho)	-97.9 ± 0.9
HLxL	105 ± 26
EW	$154 \pm 2_{Higgs} \pm 1_{had}$
Total SM	$116\ 591\ 802 \pm 42 \pm 26 \pm 2\ (49_{tot})$

M. Davier, et al., Eur. Phys. J. C (2011) 71: 1515

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

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





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

difficult to measure at LHC

Related processes in SUSY

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

Spin Motion: Use Electric Field for Vertical Focusing

$$\vec{\omega}_a = \omega_S - \omega_C$$

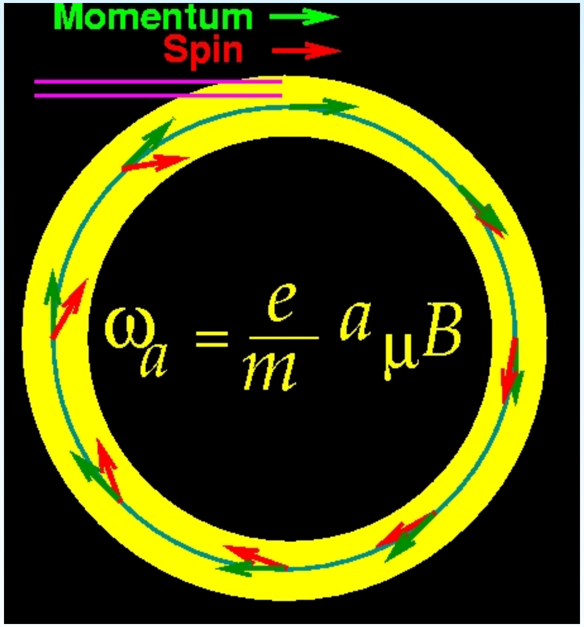
$$= -\frac{q}{m}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

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

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

Electrostatic quadrupoles cover 43% of ring

Small (< 1ppm) correction for muons not at the magic γ.



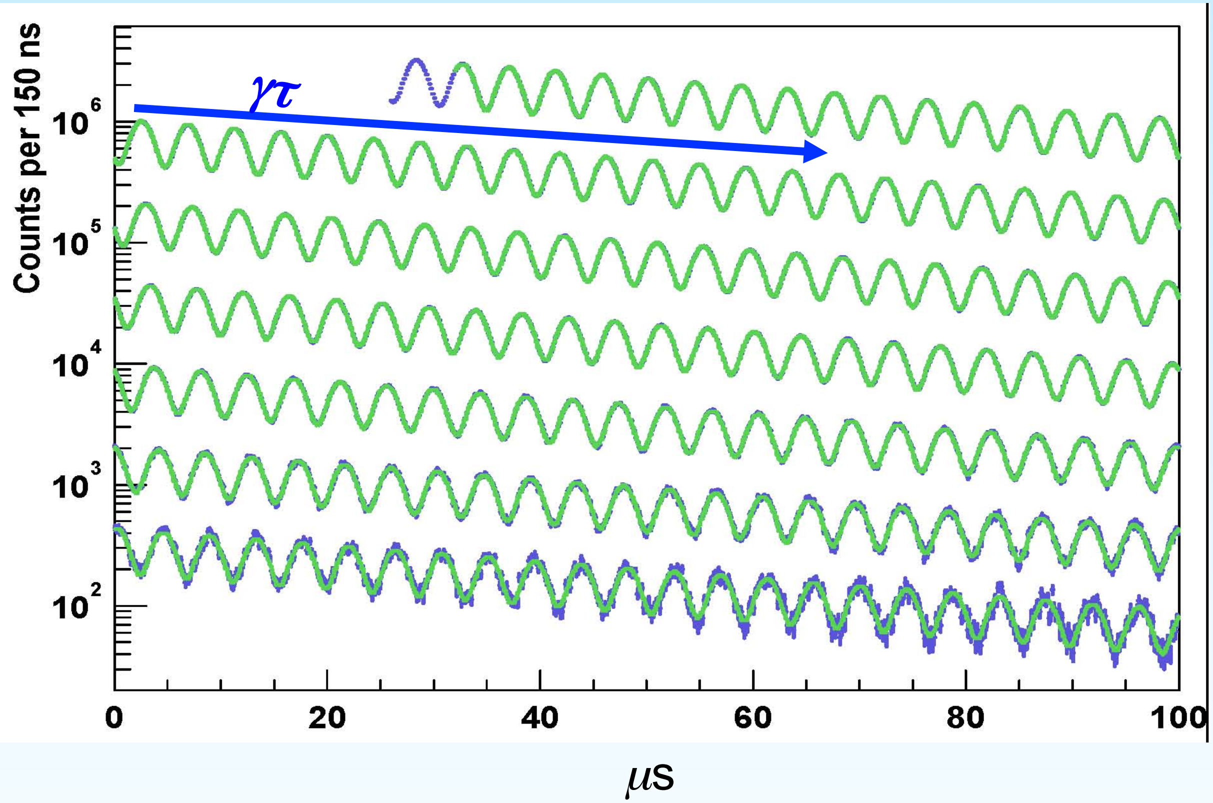
The arrival time spectrum of high-energy e^- ω_a

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

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

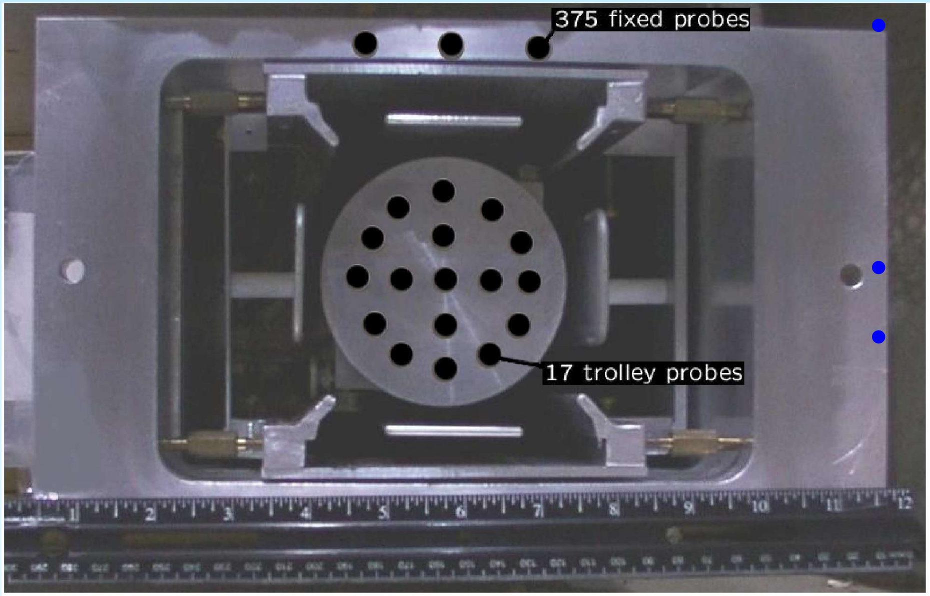
$E_e \geq 1.8$ GeV

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



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

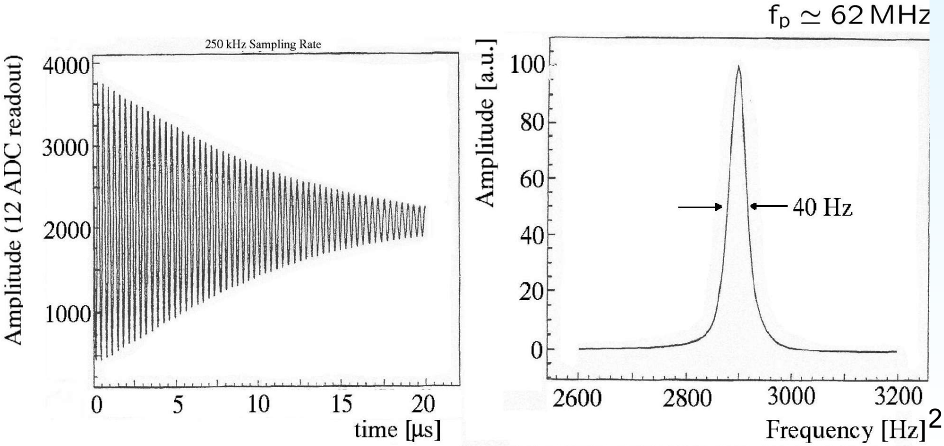
ω_a



- **Calibration to a spherical water sample that ties the field to the Larmor frequency of the free proton ω_p.**
- **We measure ω_a and ω_p independently**
- **Use $\lambda = \mu_\mu / \mu_p$ as the "fundamental constant"**

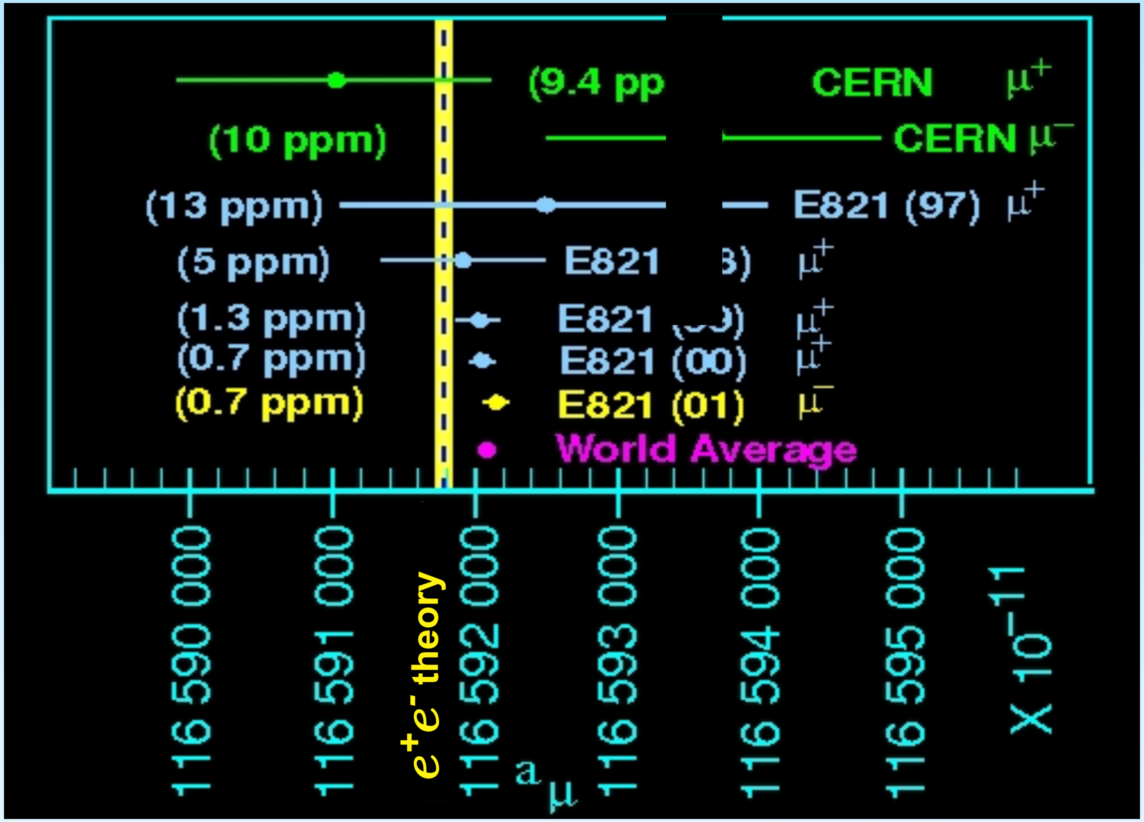
$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

Free induction decay signals:



Blind analysis

E821 achieved 0.54 ppm; e^+e^- based theory 0.49 ppm Hint is 3.2 – 3.6 σ



Theory: Davier, et al.,
Eur. Phys. J. C (2011)
71: 1515

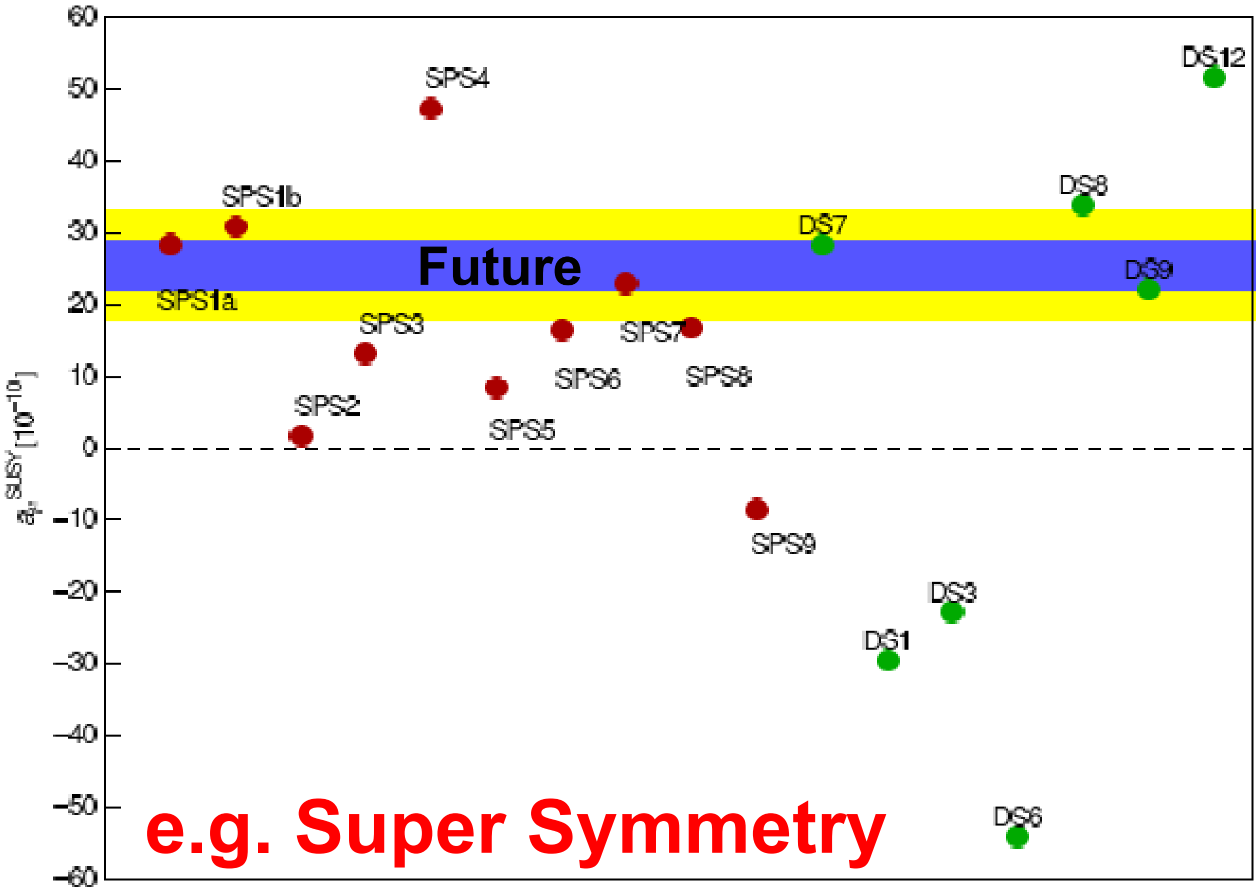
$$a_\mu^{SM} = 116\,591\,802 \pm 49 \;\; (0.42\,\text{ppm})$$

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

$$\Delta a_\mu^{(\text{today})} = (287 \pm 80) \times 10^{-11}$$

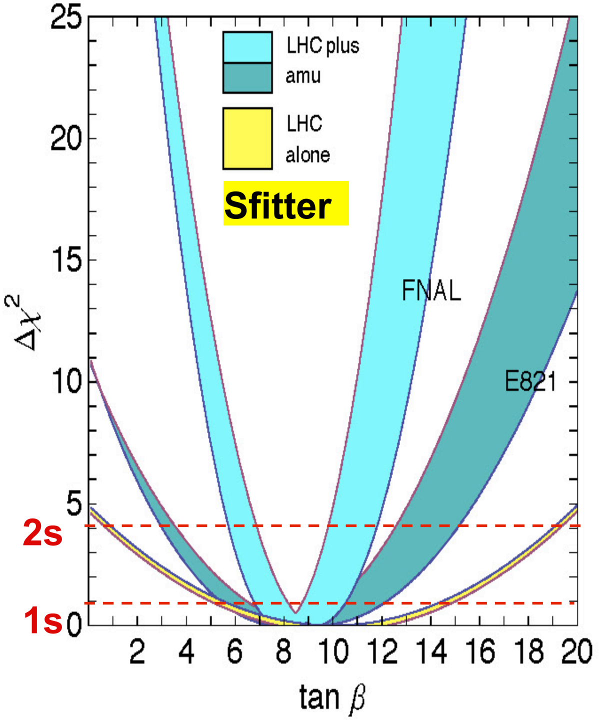
$$a_\mu^{EW} = 154(1)(2) \times 10^{-11}$$

Muon g-2 is a powerful discriminator between models; chiral-changing, flavor and CP conserving interaction.



e.g. Super Symmetry

tan *b* sensitivity



SPS1a; LHC 100 fb-1 at 14 TeV

Snowmass points and slopes (SUSY)

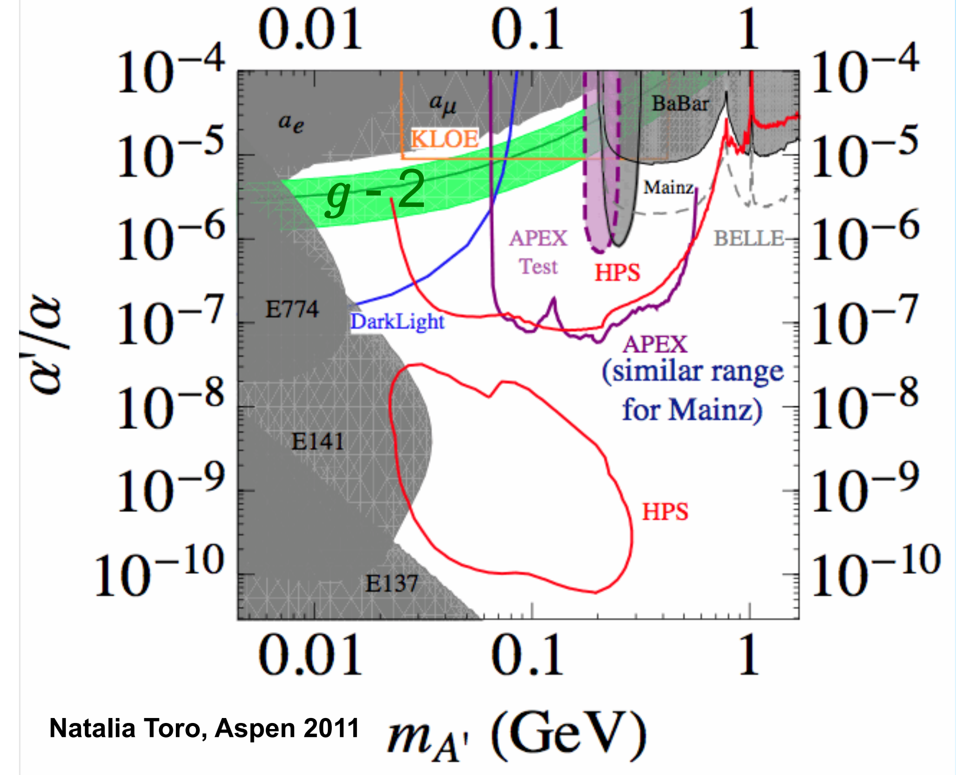
from D. Stöckinger

LHC Inverse Problem (300fb^{-1})

can't be distinguished at LHC [Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]

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

Fermilab a_μ Experiment:

- E821 at Brookhaven
  - superferric storage ring, magic γ, $<B>_\theta$ ± 1 ppm

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

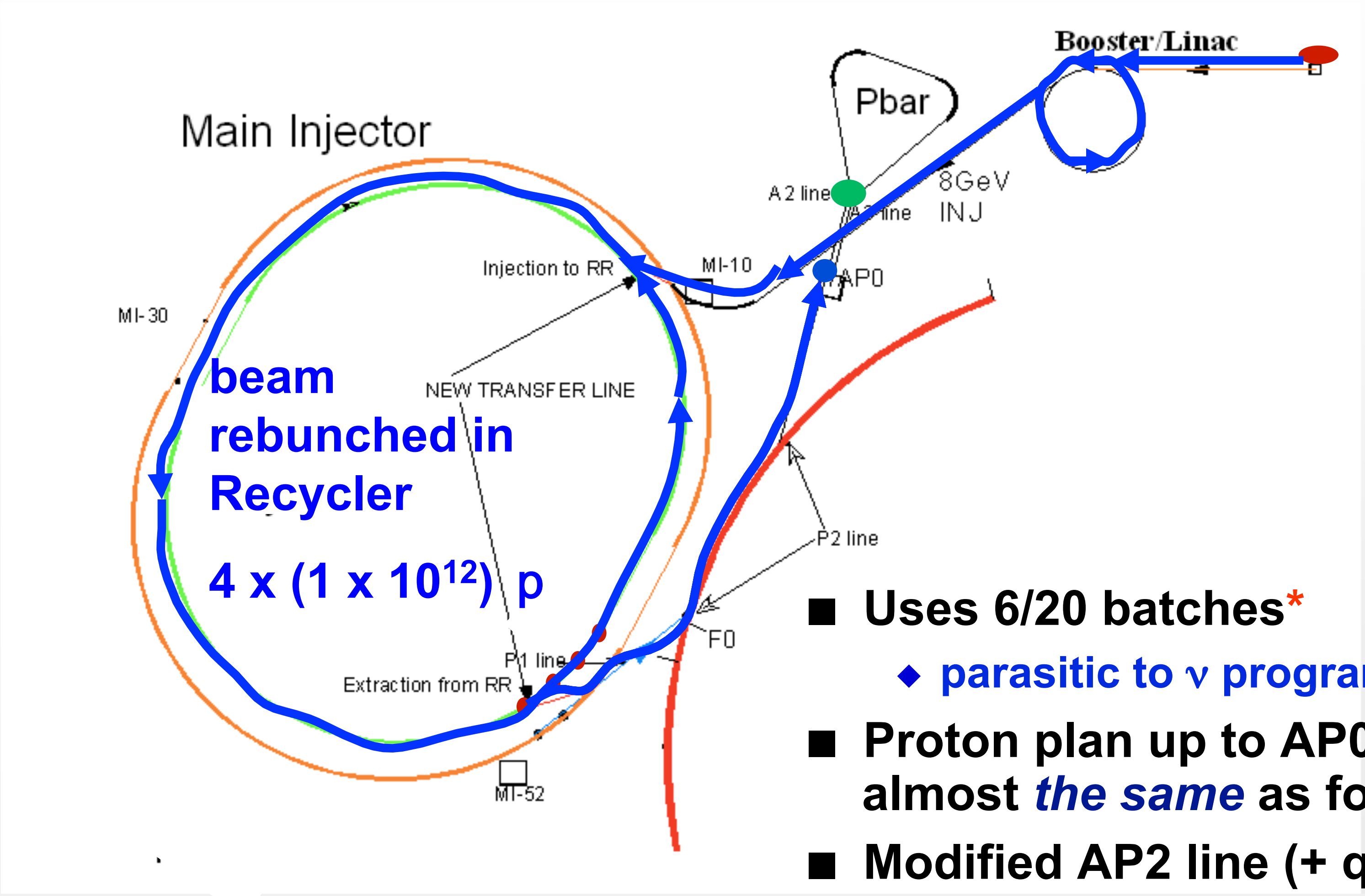
- **E989 at Fermilab**
  - move the storage ring to Fermilab, improved shimming, new detectors, electronics, DAQ,
  - new beam structure that takes advantage of the multiple rings available at Fermilab, more muons per hour, less per fill of the ring

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

Why Fermilab?

- The existence of many storage rings that are interlinked permits us to make the “ideal” beam structure.
  - proton bunch structure:
    - BNL ~5 X 10^{12} p/fill: effective rate 4.4 Hz
    - FNAL 10^{12} p/fill: effective rate 18 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

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



beam rebunched in Recycler

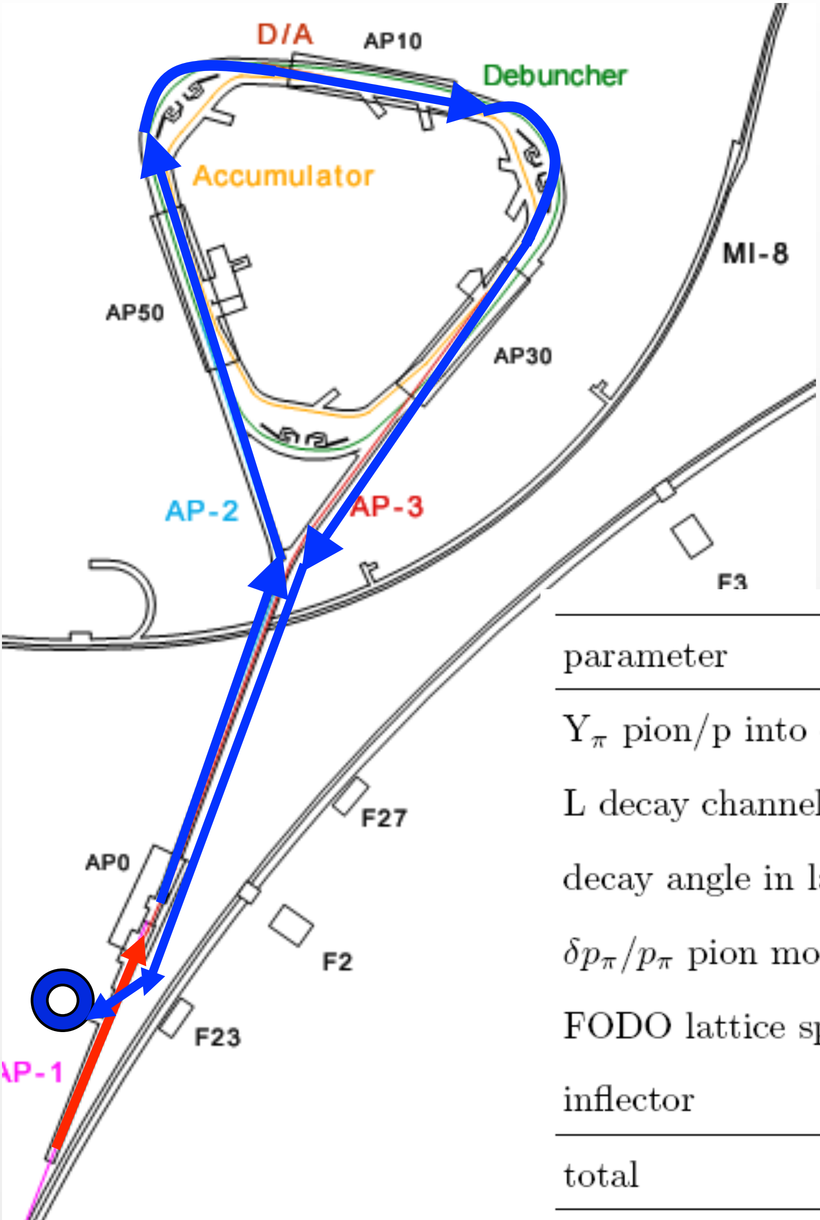
$4 \times (1 \times 10^{12})$ p

- **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**

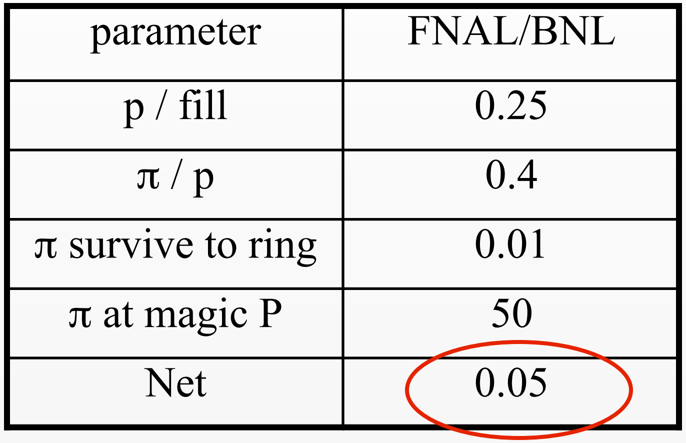
***Can use all 20 if MI program is off**

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



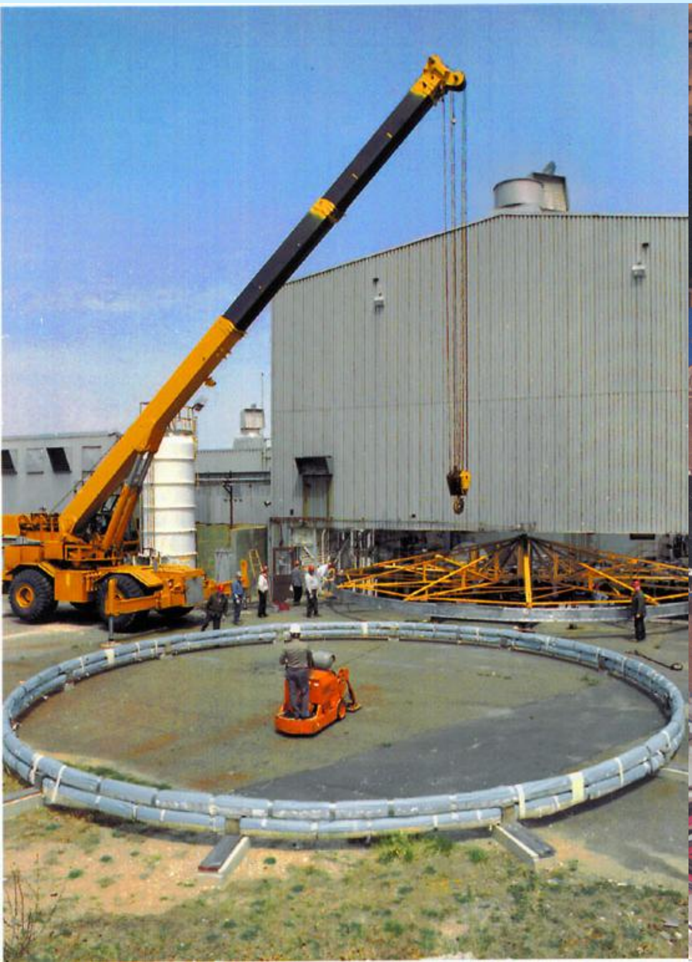
parameter	FNAL/BNL
p / fill	0.25
π / p	0.4
π survive to ring	0.01
π at magic P	50
Net	0.05

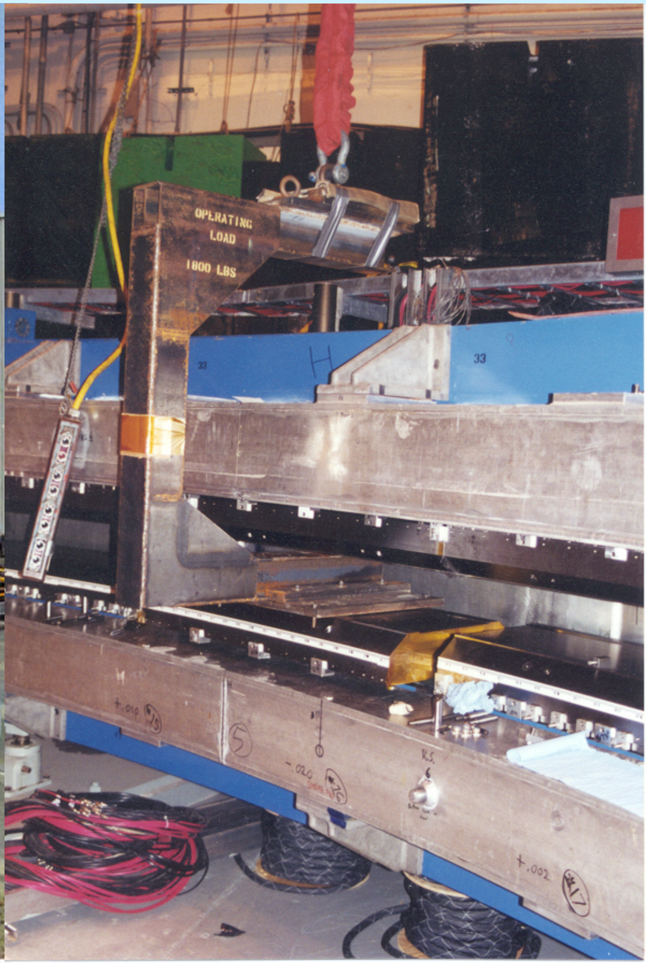
Stored Muons / POT

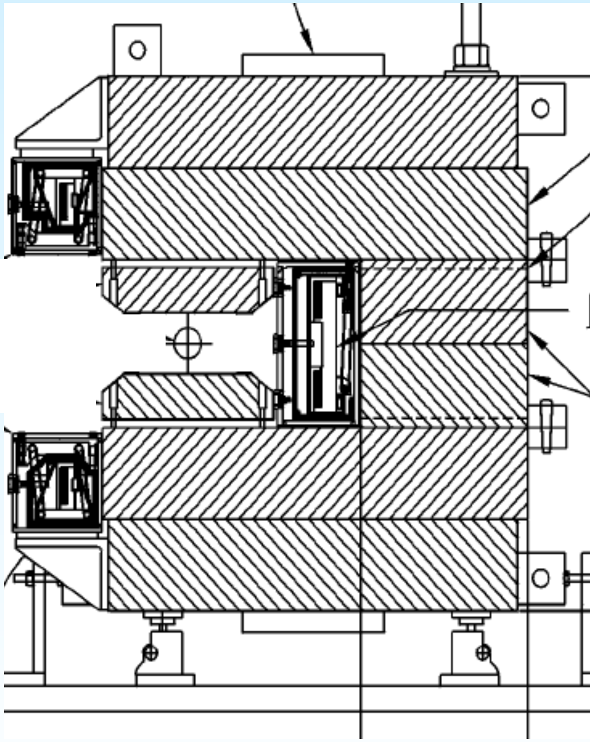
parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	≈ 2.7E-5	≈ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	±0.5%	±2%	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open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

Ring relocation to Fermilab

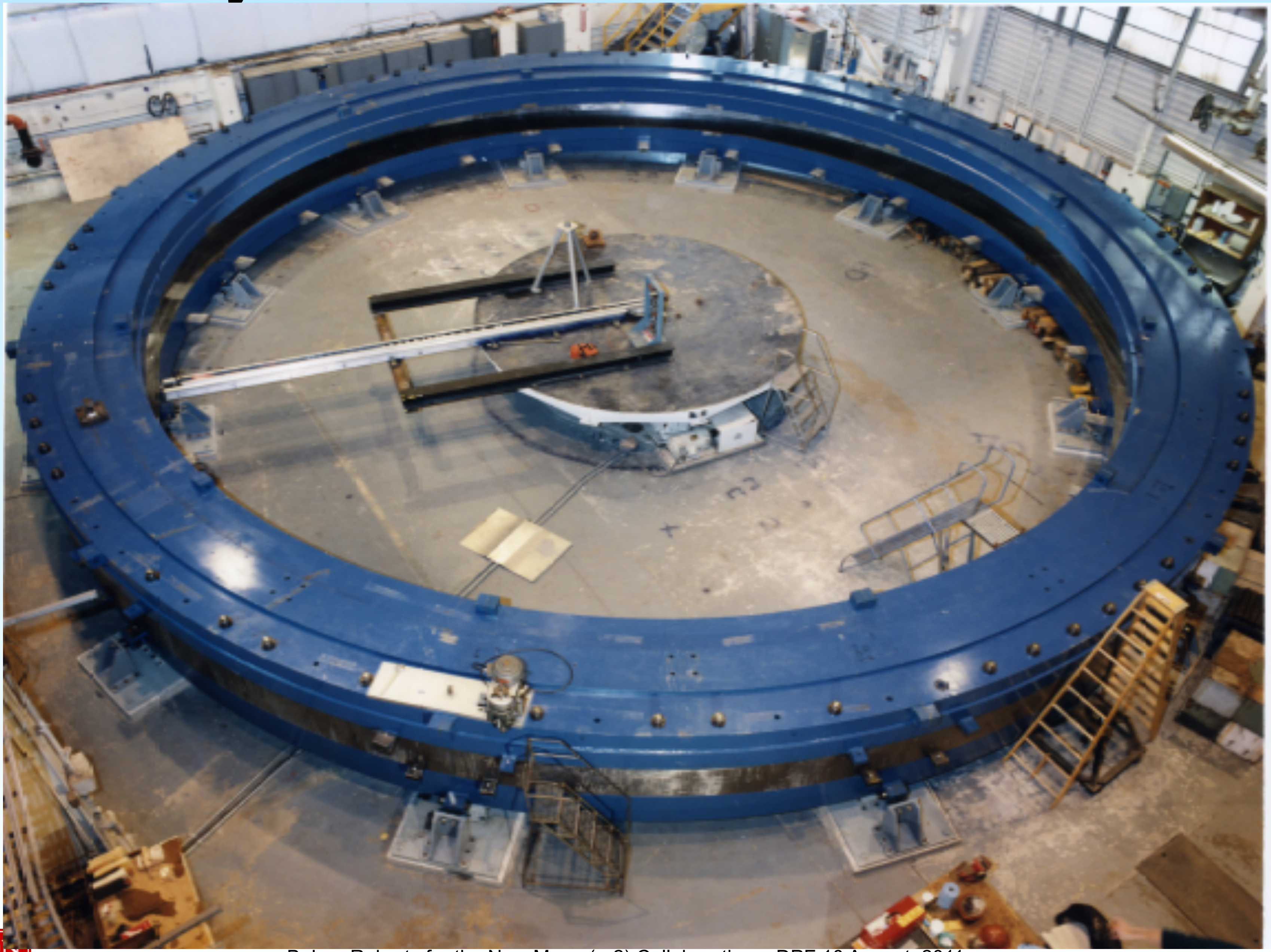
- Heavy-lift helicopters bring coils to a barge
- Rest of magnet is a “kit” that can be trucked to and from the barge







Yoke fully assembled



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.

Goal is to be ready for data in 2015 - 2016
Subject to funding availability

- Total project cost ~$4XM
  - CD0 expected this fall
  - Conceptual Design Report being prepared
- FY2011 Funding began this June
- FY12 and beyond is being discussed between DOE and Fermilab

Summary:

- The measurements of $e^{\pm}$ and $\mu^{\pm}$ magnetic dipole moments have been important benchmarks for the development of QED and the Standard Model.
- At present there appears to be a > 3 σ difference between a_μ and the SM prediction.
  - – if confirmed it would fit well with SUSY expectations, but LHC data will play a role in the interpretation.
- A worldwide effort continues to improve the SM value.
- The Fermilab experiment, E989, will improve the error on a_μ by a factor of ≥4.
- The muon EDM limit could be improved by $\approx 10^2$
- First results could be available around 2017

Thank you!

THE END

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 – ω_p	0.5	0.4	0.24	0.17		0.07
Anomalous precession – ω_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

Systematic errors on ω_a (ppm)

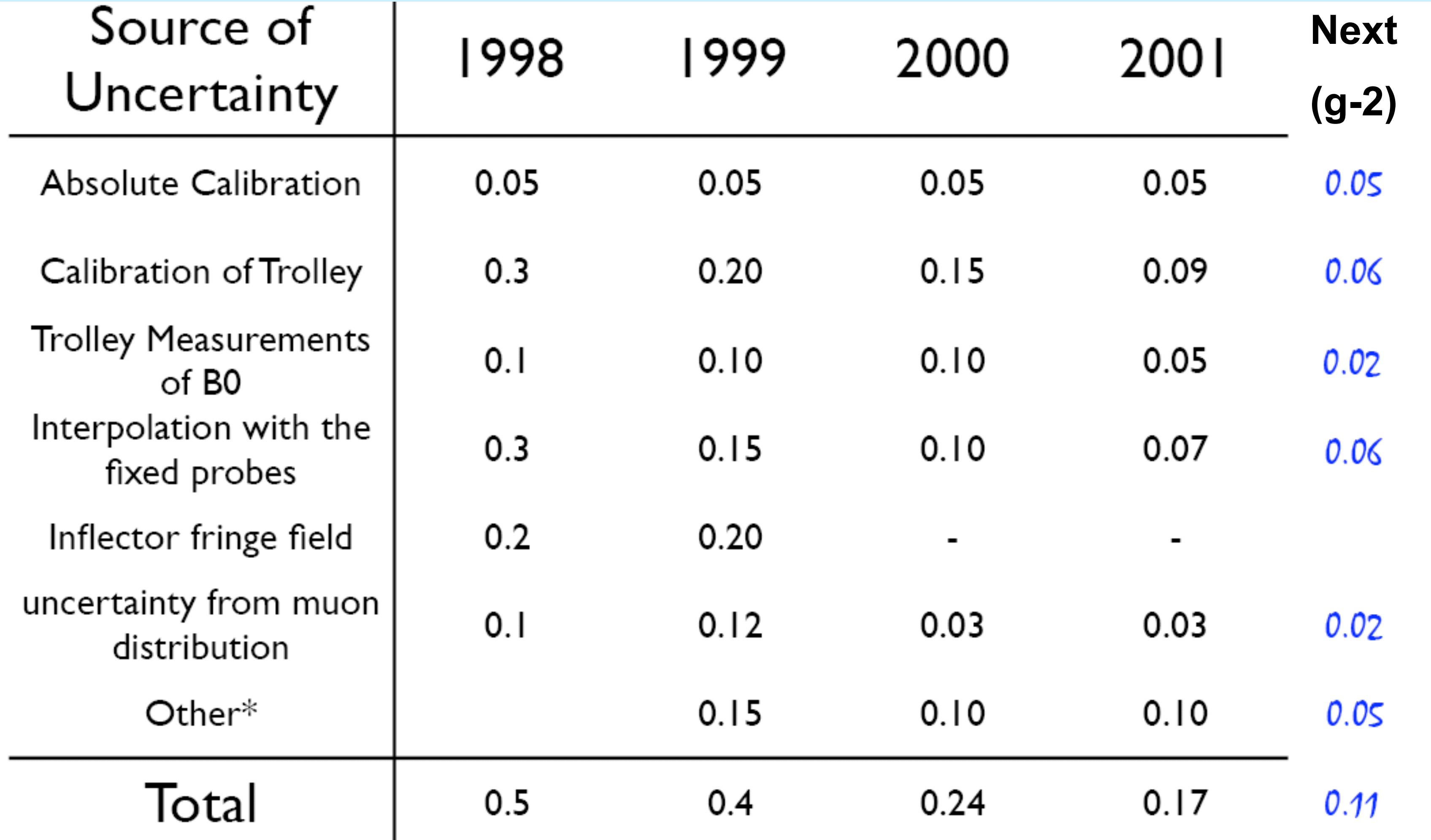
$\sigma_{\text{systematic}}$	1999	2000	2001	Future
Pile-up	0.13	0.13	0.08	0.04
AGS Background	0.10	0.10	0.015*	
Lost Muons	0.10	0.10	0.09	0.02
Timing Shifts	0.10	0.02	0.02	
E-Field, Pitch	0.08	0.03	0.06*	0.03
Fitting/Binning	0.07	0.06	0.06*	
CBO	0.05	0.21	0.07	0.04
Beam Debunching	0.04	0.04	0.04*	
Gain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

⭕ **better with Fermilab beam structure and improved detectors/electronics**

Σ* = 0.11

The Precision Field: Systematic errors

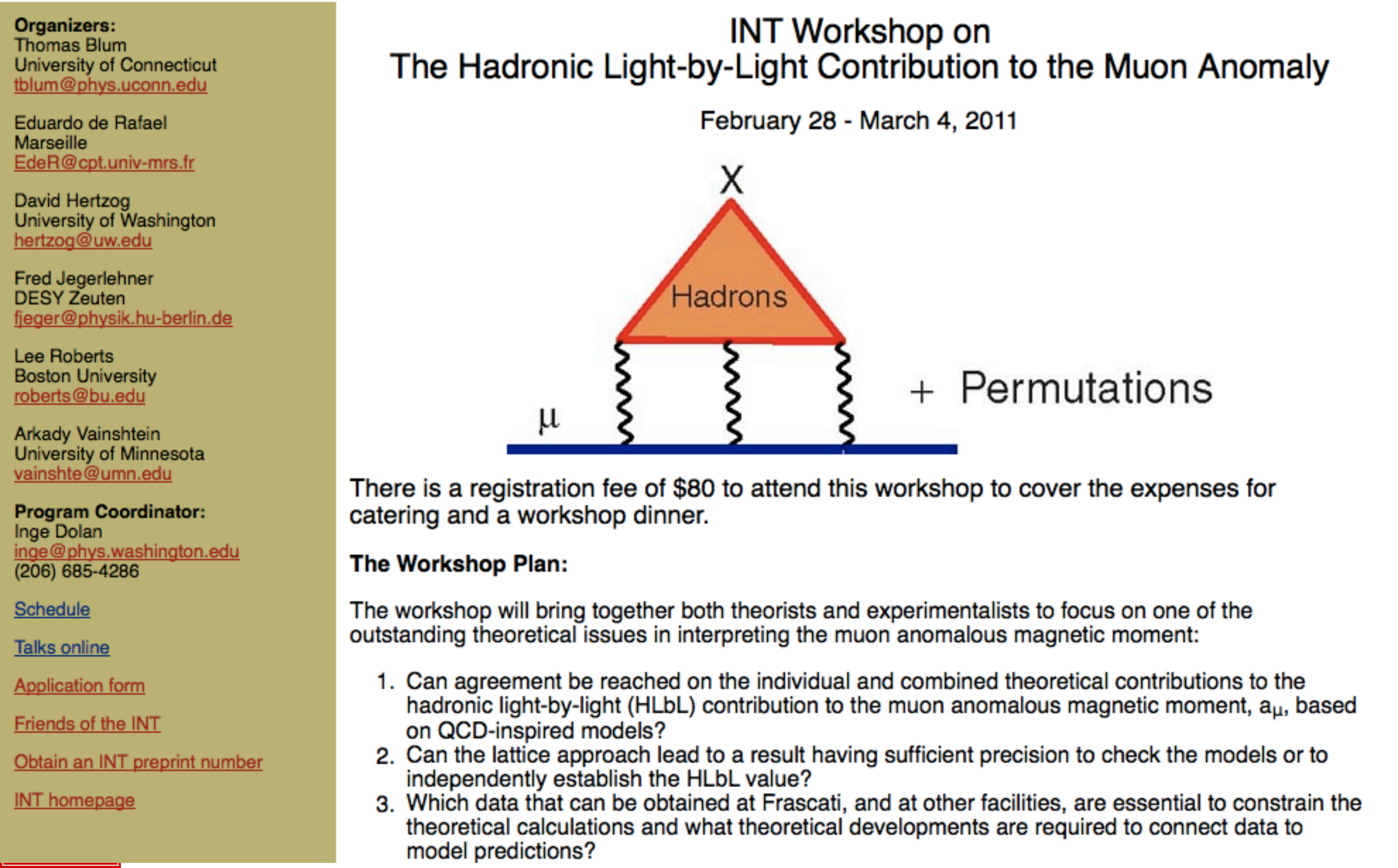
- Why is the error 0.11 ppm?
  - That's with *existing* knowledge and experience
    - with R&D defined in proposal, it will get better



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/



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Schedule

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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:

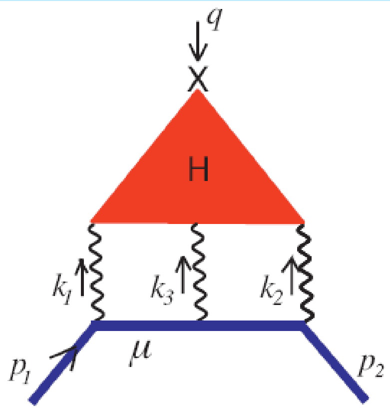
The workshop will bring together both theorists and experimentalists to focus on one of the outstanding theoretical issues in interpreting the muon anomalous magnetic moment:

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]



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

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

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

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

Dynamical models with QCD behavior

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

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 ....

The π^0 (Goldstone) contribution fixes sign of the contribution From χpt and large N_c QCD

$$a_\mu^{[\chi pt]} = \boxed{\left(\frac{\alpha}{\pi}\right)^3} \left\{ \frac{N_c^2}{48\pi^2} \frac{m_\mu^2}{F_\pi^2} \ln^2\left(\frac{\mu}{m}\right) + \mathcal{O}\left[\ln\left(\frac{\mu}{m}\right) + \kappa(\mu)\right] \right\}$$

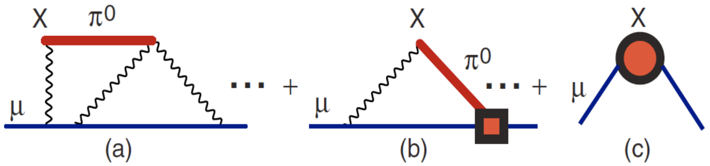
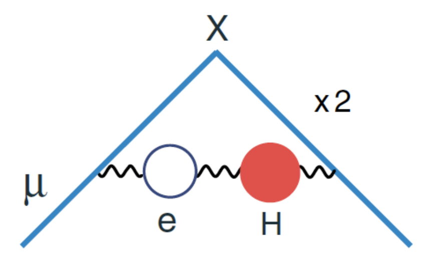
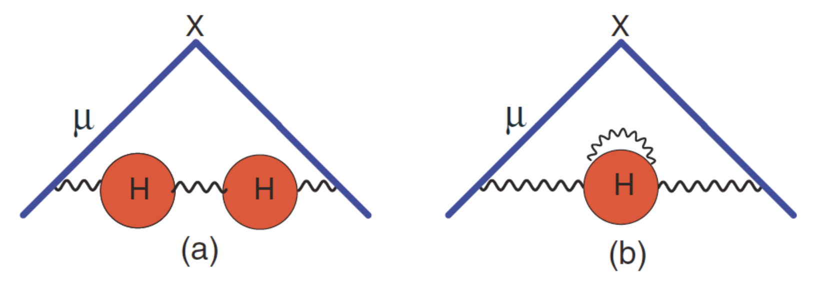


Figure 53. One Goldstone reducible diagrams in chiral perturbation theory.

Examples of other 3-loop hadronic contributions:



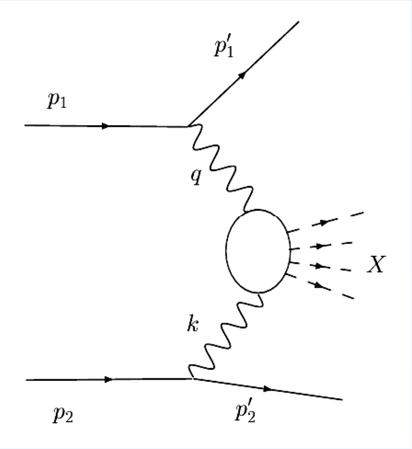


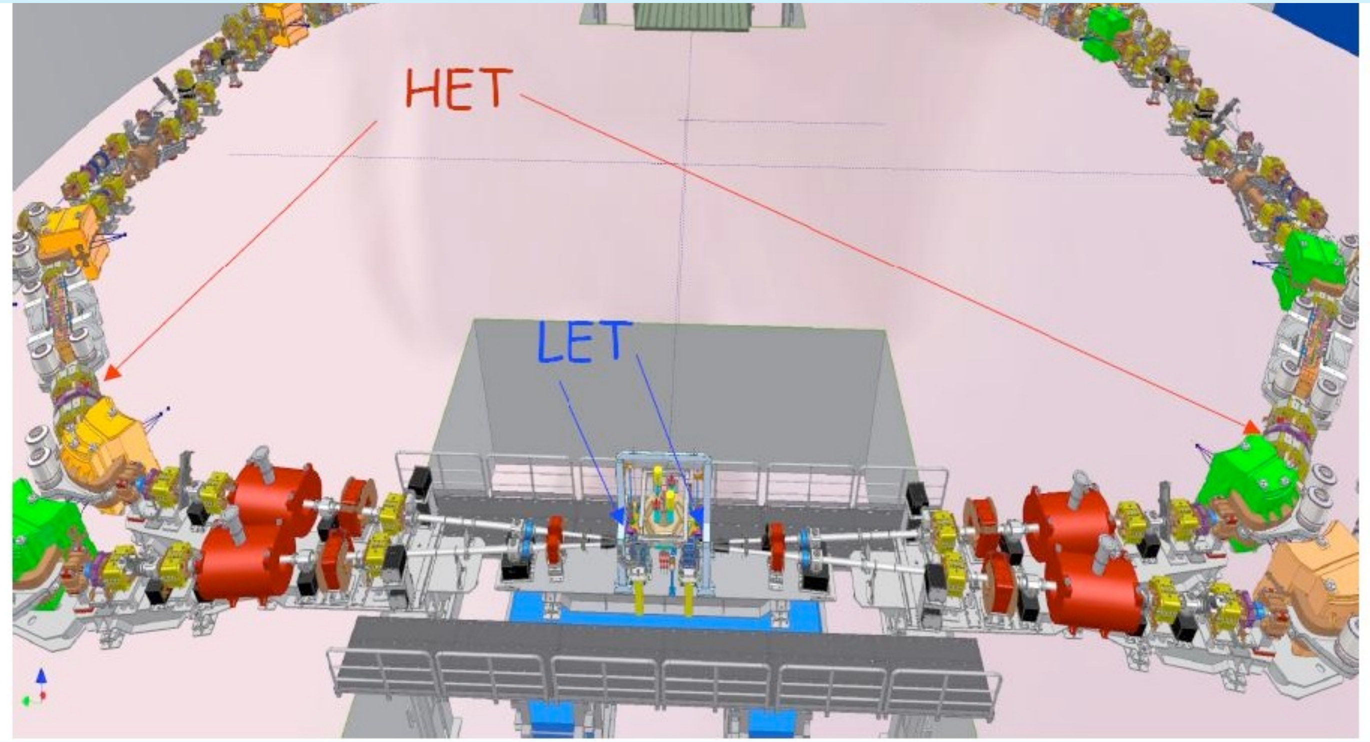
$$a_\mu^{H6} = -97.9\ (.9) \times 10^{-11}$$

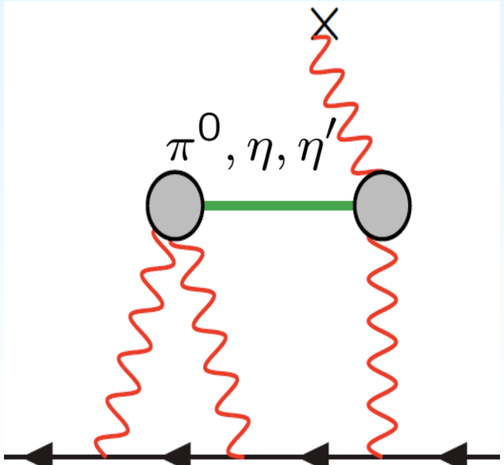
- The magnitude of the HLBL is about the same as the magnitude of the 3-loop HVP which can be calculated from the dispersion relation.
- It's hard to believe that the HLBL would be huge compared to the other 3-loop contributions.

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

- Constrain the off-shell amplitudes and remove a significant portion of the theoretical uncertainty on the HLBL

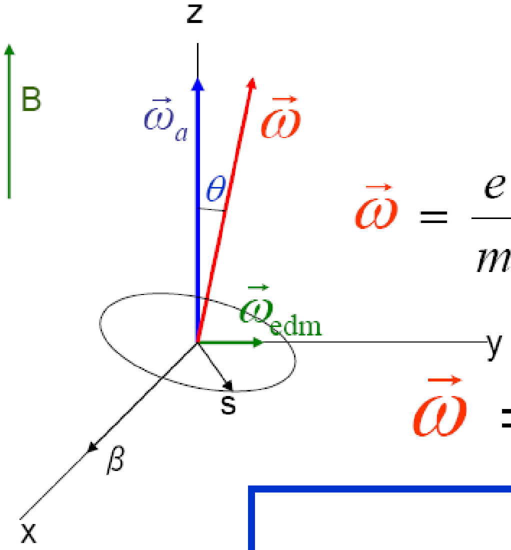






EDMs in Storage Rings: E821@ BNL

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



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

$$\vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s}$$

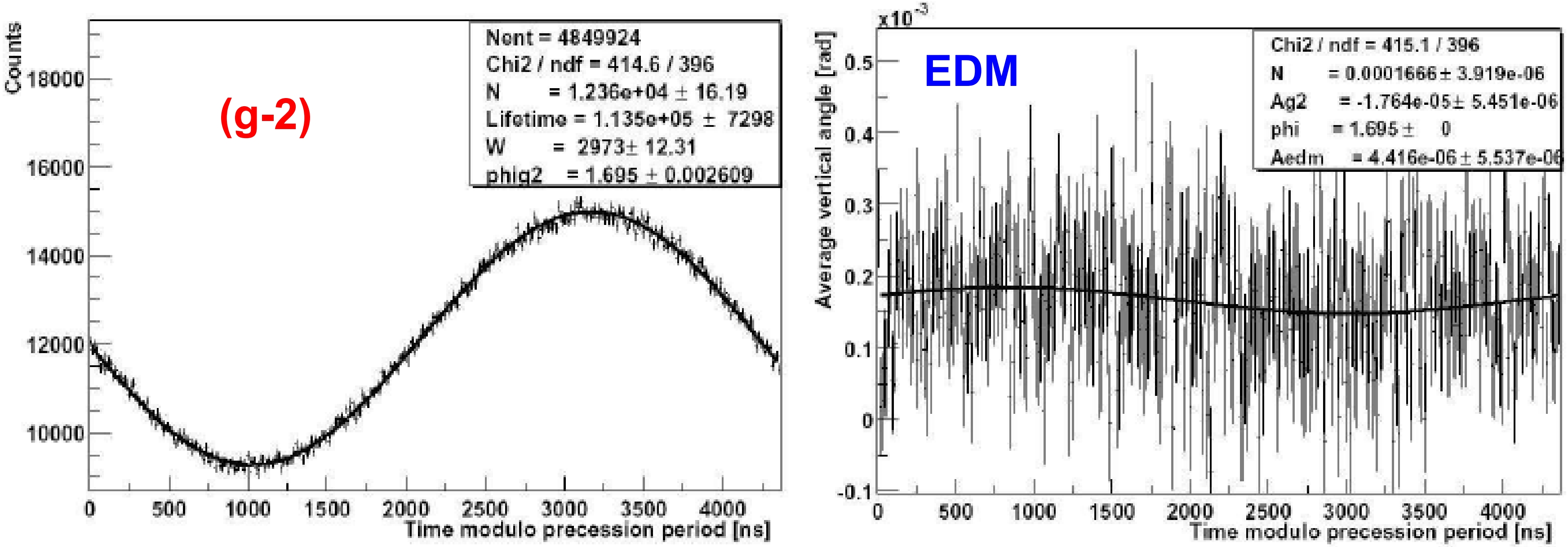
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$

$$\omega_{\mathrm{edm}} <<<<<< \omega_a$$

Muon EDM in the BNL E821 Storage Ring

E821 Data



Vertical Oscillation out of phase with ω_a

$$N^{\pm}(t) \propto 1 + A_{\mu} \cos(\omega t + \phi) \mp A_{EDM} \sin(\omega t + \phi)$$

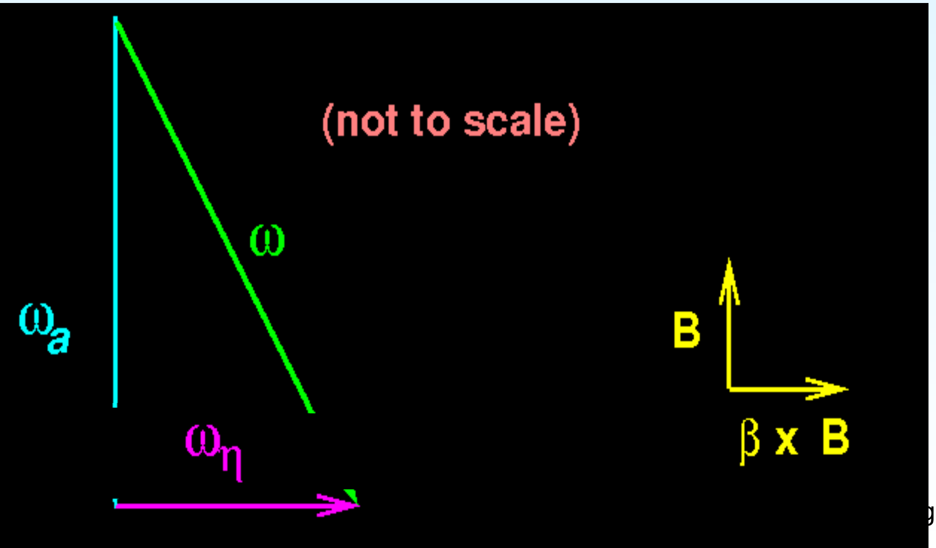
$$d_{\mu} < 1.8 \times 10^{-19} \text{ (95\% CL)}$$

How do we get rid of the (g - 2) signal?

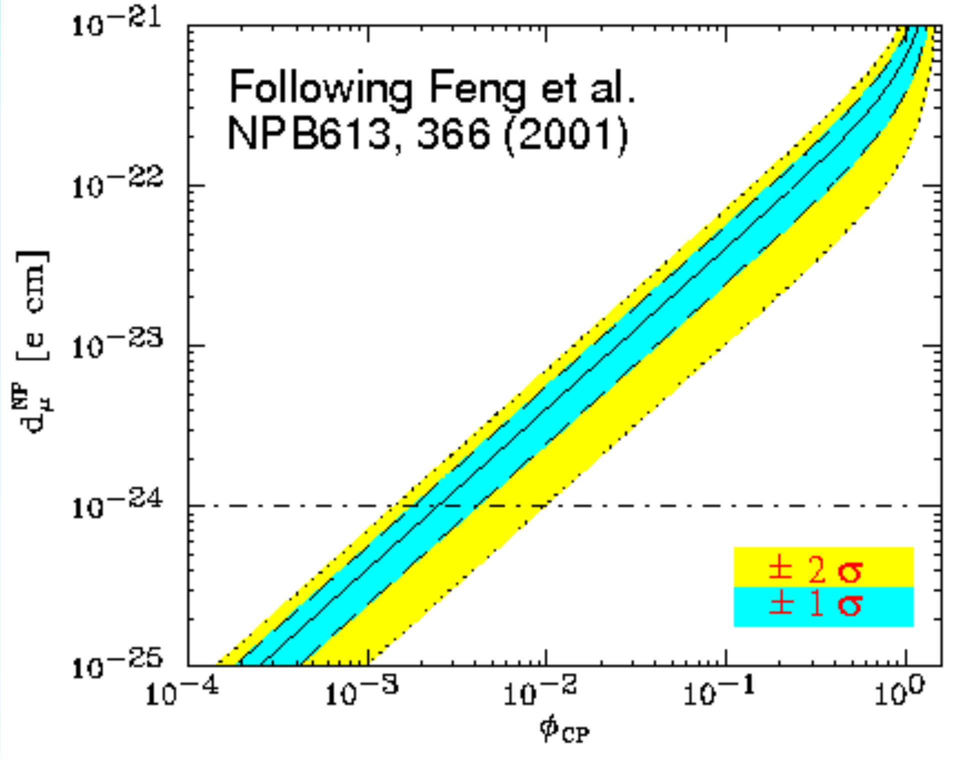
- Y. Semertzidis idea of the “frozen spin”
  - Use a radial E field to turn off the ω_a precession

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

$$+\frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right]$$



a_μ implications for the muon EDM assuming same New Physics participates (recall that (Δ^{today}=255(80) X10^{-11})



Assuming that

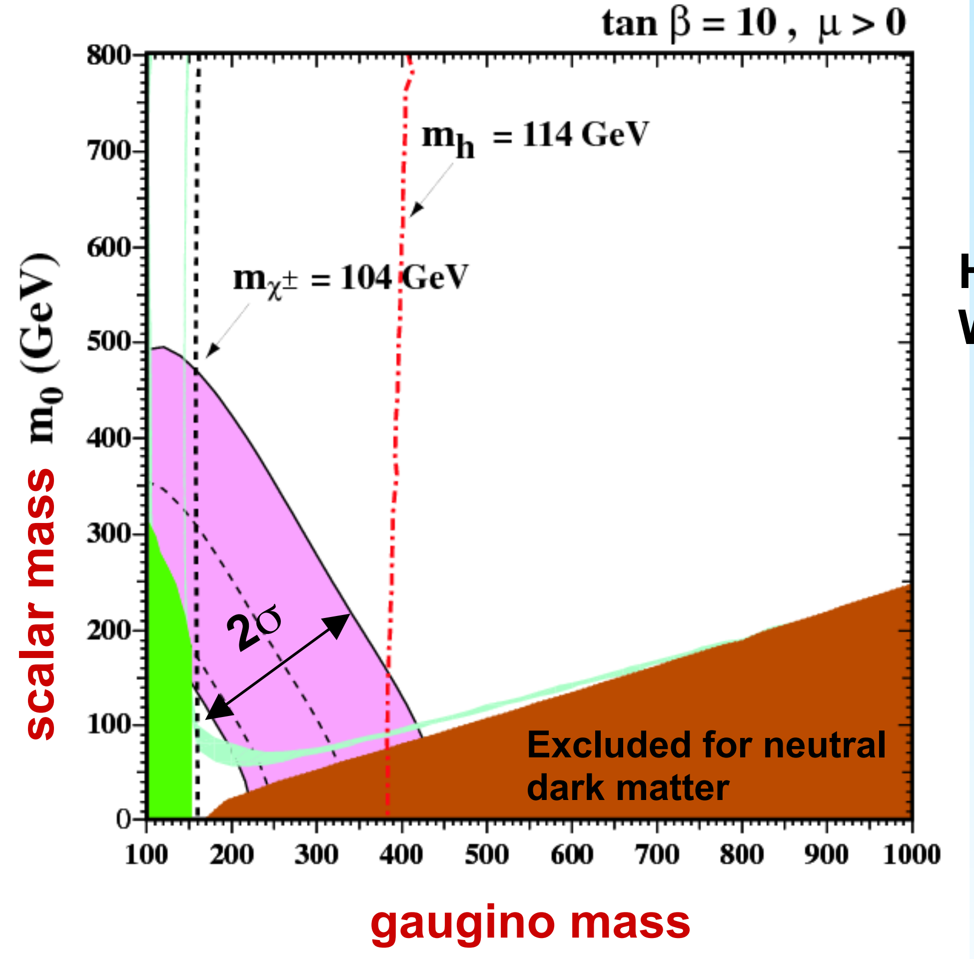
$$a_\mu^{\text{NP}} = 300(100) \times 10^{-11}$$

$$d_\mu^{\text{NP}} \simeq 3 \times 10^{-22} \left(\frac{a_\mu^{\text{NP}}}{3 \times 10^{-9}} \right) \tan \phi_{CP} \quad \text{e} \cdot \text{cm}$$

where ϕ_{CP} is a CP violating phase.

Either d_μ is **of order 10^{-22} e cm**, or the CP phase is strongly suppressed!

Typical CMSSM 2D space showing g-2 effect (note: NOT an exclusion plot)



Present:
$\Delta a_\mu = 295 \pm 88 \times 10^{-11}$

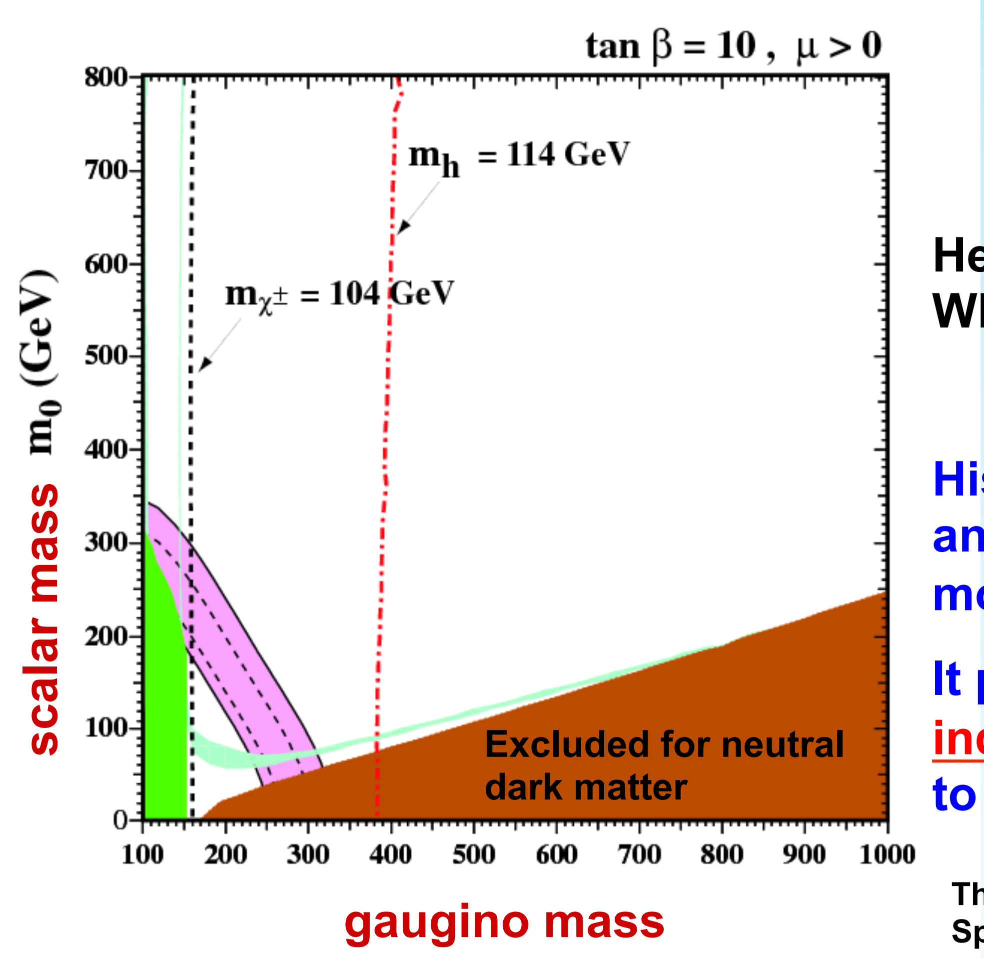
Here, neutralino accounts for the WMAP implied dark matter density

courtesy Keith Olive

This CMSSM calculation: Ellis, Olive, Santoso, Spanos. Plot update: K. Olive

Typical CMSSM 2D space showing g-2 effect (note: NOT an exclusion plot)

Back



Future
$\Delta a_\mu = 295 \pm 34 \times 10^{-11}$

Here, neutralino accounts for the WMAP implied dark matter density

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

It provides constraints that are independent and complementary to high-energy experiments.

This CMSSM calculation: Ellis, Olive, Santoso, Spanos. Plot update: K. Olive

With new experimental and theoretical precision and same Δa_μ

courtesy Keith Olive