The anomalous magnetic moment of the muon: a crack in the Standard Model?

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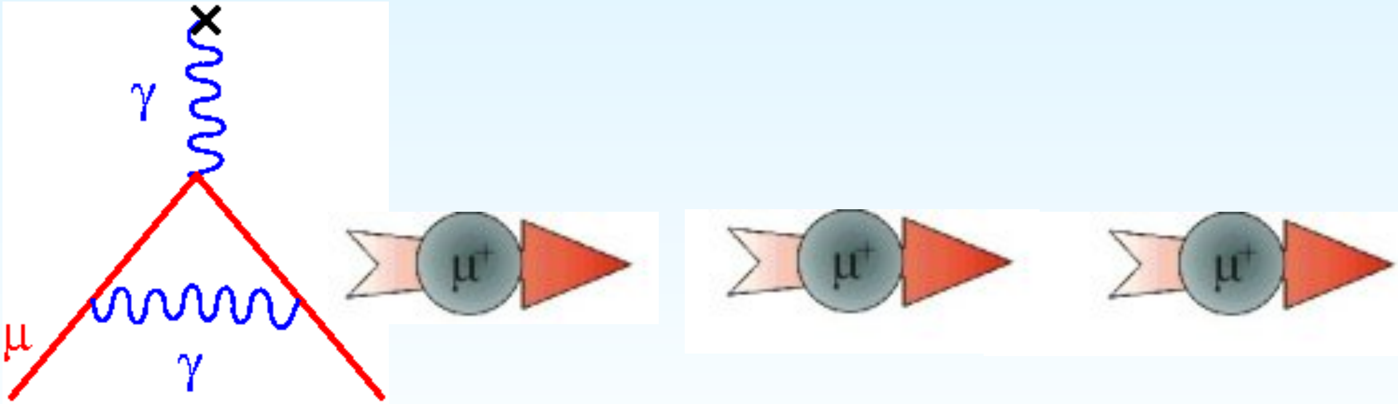


Seminar at IPN, Orsay, 7 Ottobre 2013

Outlook

- The anomalous magnetic moment of the muon : $a_\mu = (g-2)_\mu/2$
- Measurement of a_μ
- The Standard Model calculation of a_μ
  - The hadronic contribution and measurement of the hadronic cross sections at low energy
- Future measurement of a_μ at FNAL
- Conclusions

Muon anomaly

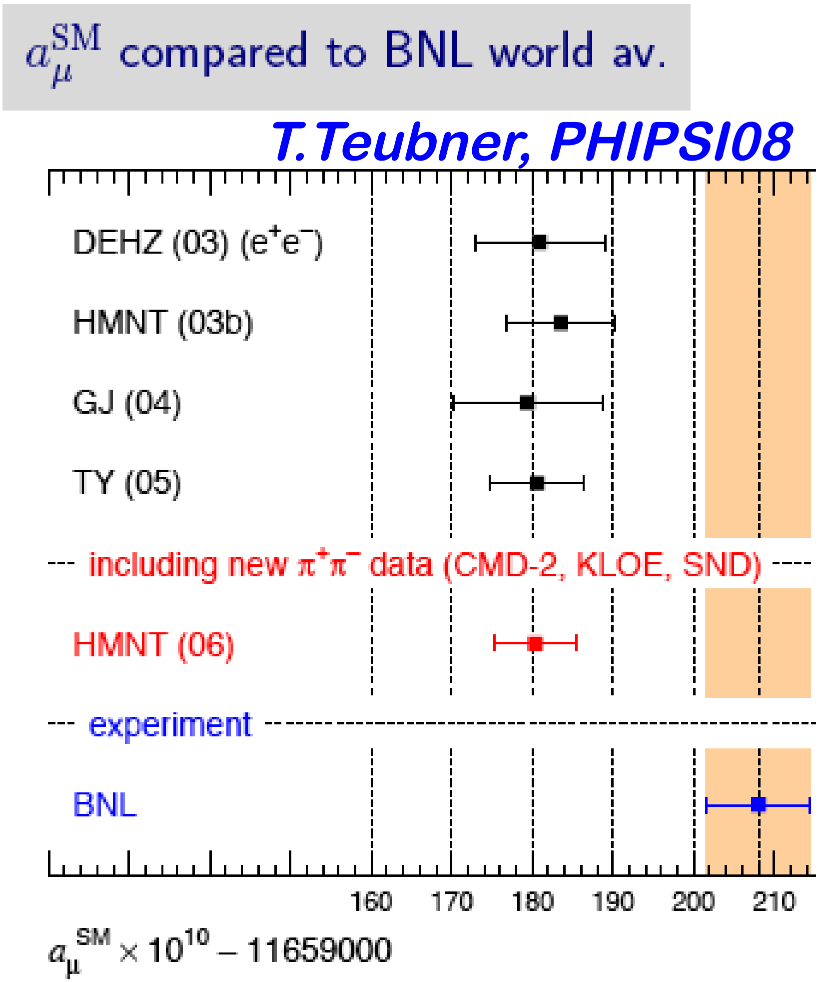
$$a_\mu = \frac{(g_\mu - 2)}{2}$$

- Measured and computed with fabulous precision (~0.5ppm)
- Long established discrepancy (>3σ) between SM prediction and BNL E821 exp.
- Theoretical error δa_μ^{SM} (~5×10^{-10}) slightly smaller than experimental one. Dominated by hadronic corrections (HLO-VP and HLBL)
- **Twofold** improvement on δa_μ^{SM} from 2001 (thanks to new e^+e^- measurements)!

In 2001 $a_\mu^{EXP}-a_\mu^{TH}=(23 \pm 16) \cdot 10^{-10}$

In 2013: $a_\mu^{EXP}-a_\mu^{TH}=(28 \pm 8) \cdot 10^{-10}$

- New g-2 experiment(s) at FNAL and J-PARC to reduce the experimental uncertainty of a factor four ($1.5 \; 10^{-10}$)



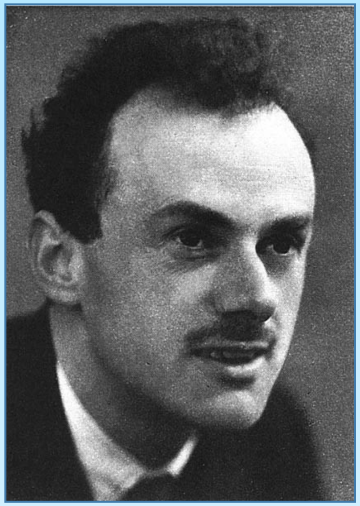
a_μ^{SM} compared to BNL world av.

T.Teubner, PHIPSI08

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

…but where all of that did start from?

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

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

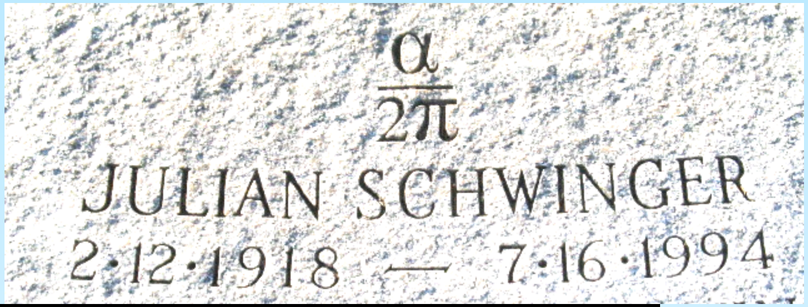
(only from loops)

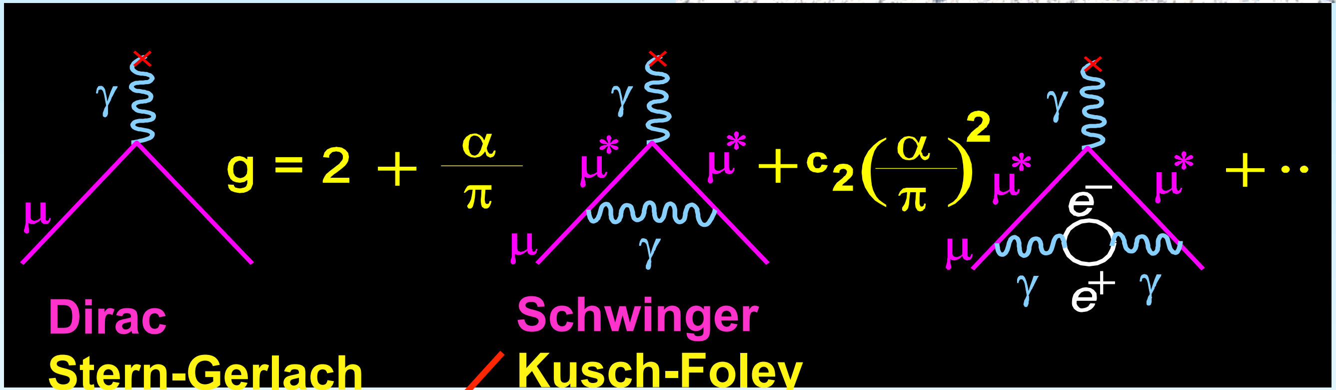
where a is the anomaly,

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

In the QED, a becomes an expansion in (α/π) from loops

$$a = \sum_{j=1} C_j \left(\frac{\alpha}{\pi}\right)^j$$





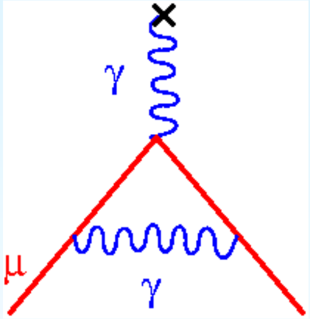
$$g = 2 + \frac{\alpha}{\pi} + c_2\left(\frac{\alpha}{\pi}\right)^2 + \cdots$$

Dirac
Stern-Gerlach

Schwinger
Kusch-Foley

$a=\alpha/2\pi$

$$\mu_e^{\mathrm{th}} = \frac{e\hbar}{2mc}\left(1+\frac{\alpha}{2\pi}\right) = \frac{e\hbar}{2mc} \times 1.00116$$



Kusch and Foley 1948:

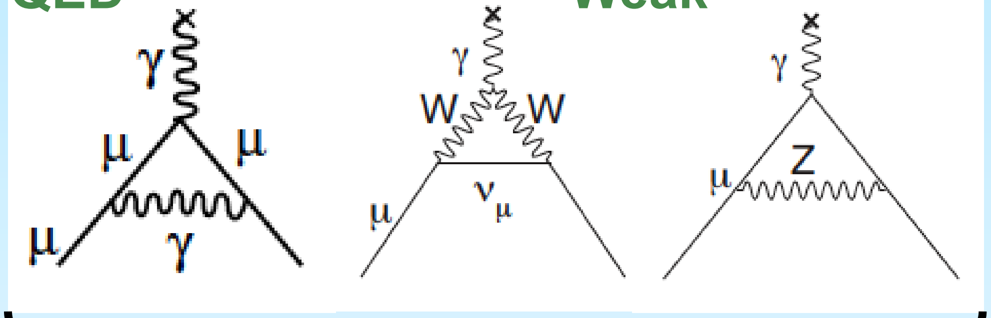
$$\mu_e^{\mathrm{exp}} = \frac{e\hbar}{2mc}\,(1.00119 \pm 0.00005)$$

triumph of QED!

Empty space is not empty… there are also other (important) contributions… (SM)

Standard Model contribution to (g-2)

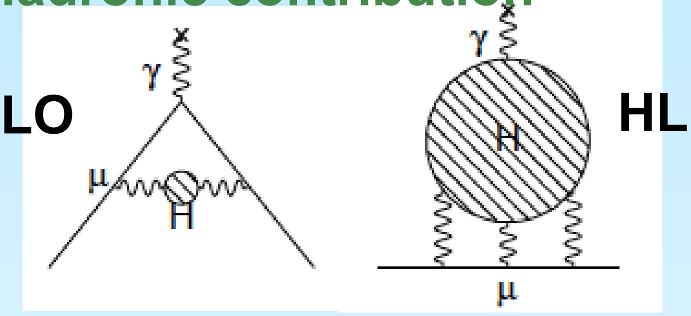
QED **Weak**



Precisely known

Hadronic contribution

HLO



HLbL

Large uncertainty

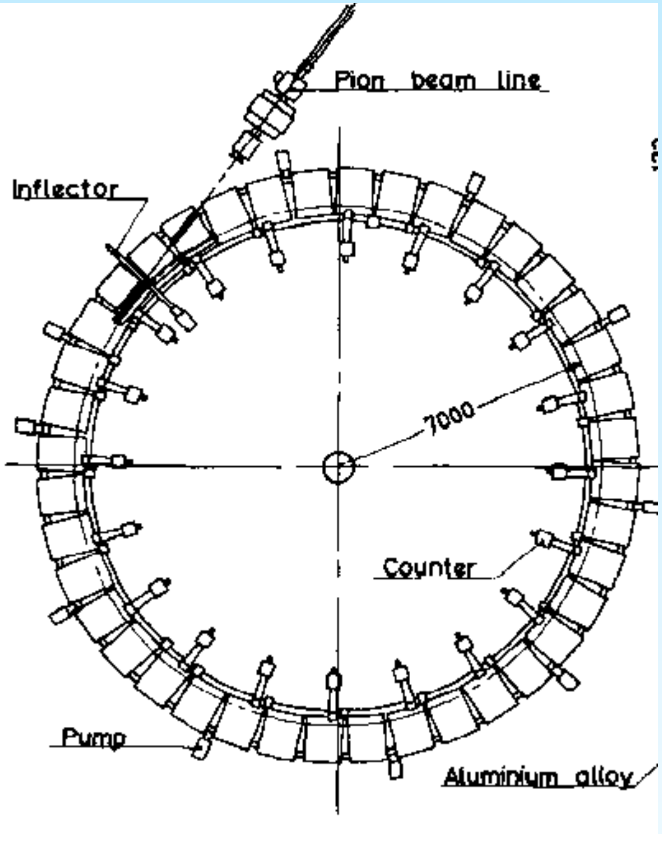
(significant work going on)

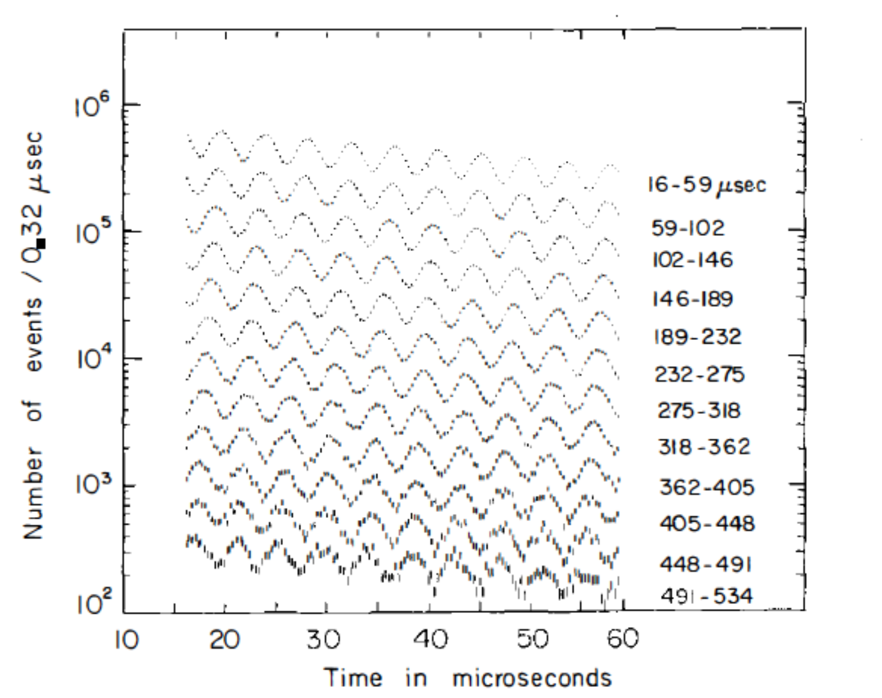
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$

a_μ^{QED} ~a/2π~ O(10^{-3}) a_μ^{HAD} ~ O(10^{-8}) a_μ^{Weak} ~ O(10^{-9})

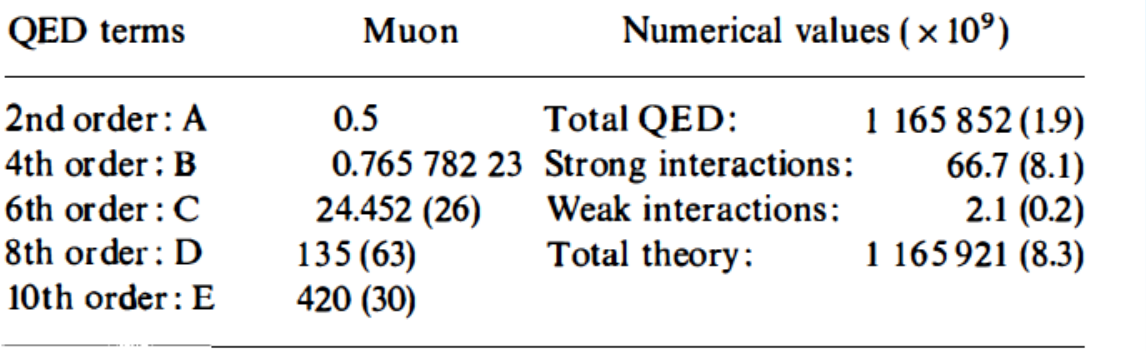
In the ’70 at CERN a_μ was measured with an uncertainty of $8x10^{-9}$ (7ppm), of the same order of a_μ^{SM} (sensitive to hadronic contribution)

Cern experiment in ‘70: a triumph for the QED





$$a_\mu \overset{\text{EXP}}{\simeq} 1\,165\,924\,(8.5) \times 10^{-9}\ (7\ \text{ppm}).$$



QED terms	Muon	Numerical values ($\times 10^9$)	
2nd order: A	0.5	Total QED:	1 165 852 (1.9)
4th order: B	0.765 782 23	Strong interactions:	66.7 (8.1)
6th order: C	24.452 (26)	Weak interactions:	2.1 (0.2)
8th order: D	135 (63)	Total theory:	1 165 921 (8.3)
10th order: E	420 (30)		

But how was possible to measure g-2 to such an accuracy?

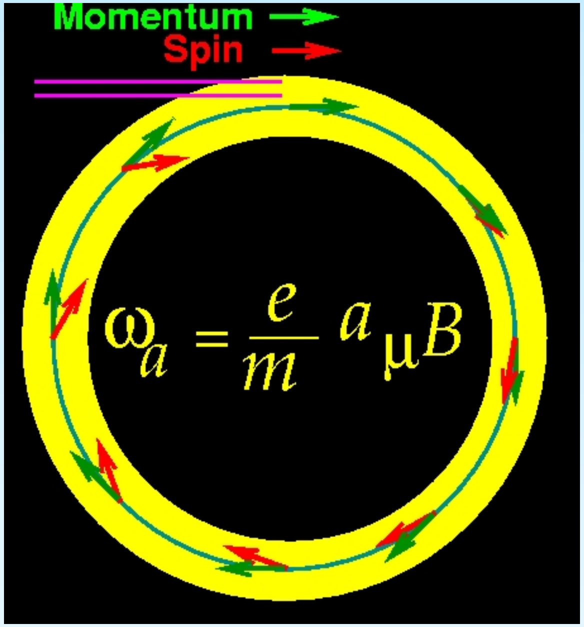
The a_μ Experiments:

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

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

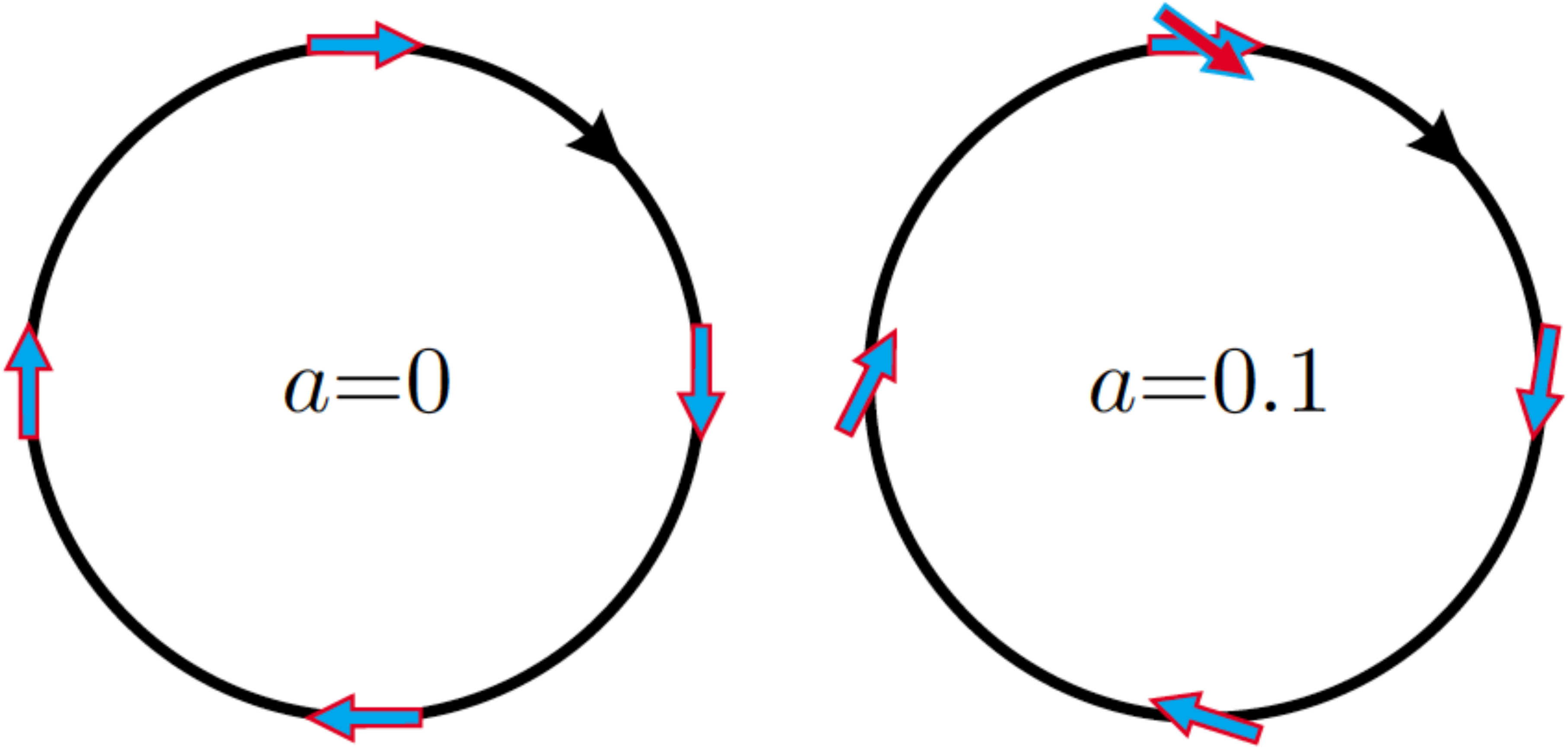
  - cyclotron frequency

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



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

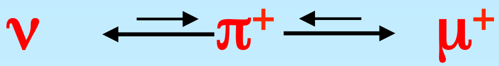
Since g > 2, the spin gets ahead of the momentum



For $a = 1$ (γ=1), spin rotates wrt momentum by 1/10 turn per turn.

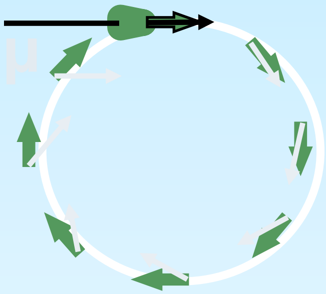
4 Key elements of modern storage-ring g-2 measurements

(1) Polarized muons



~97% polarized for forward decays

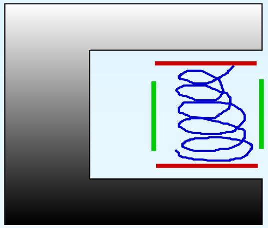
(2) Precession proportional to (g-2)



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

(3) P_μ magic momentum = 3.094 GeV/c

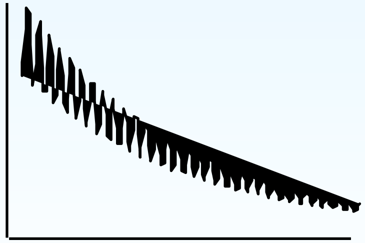
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}}\right]$$



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

of high energy electrons vs time:

ω_a

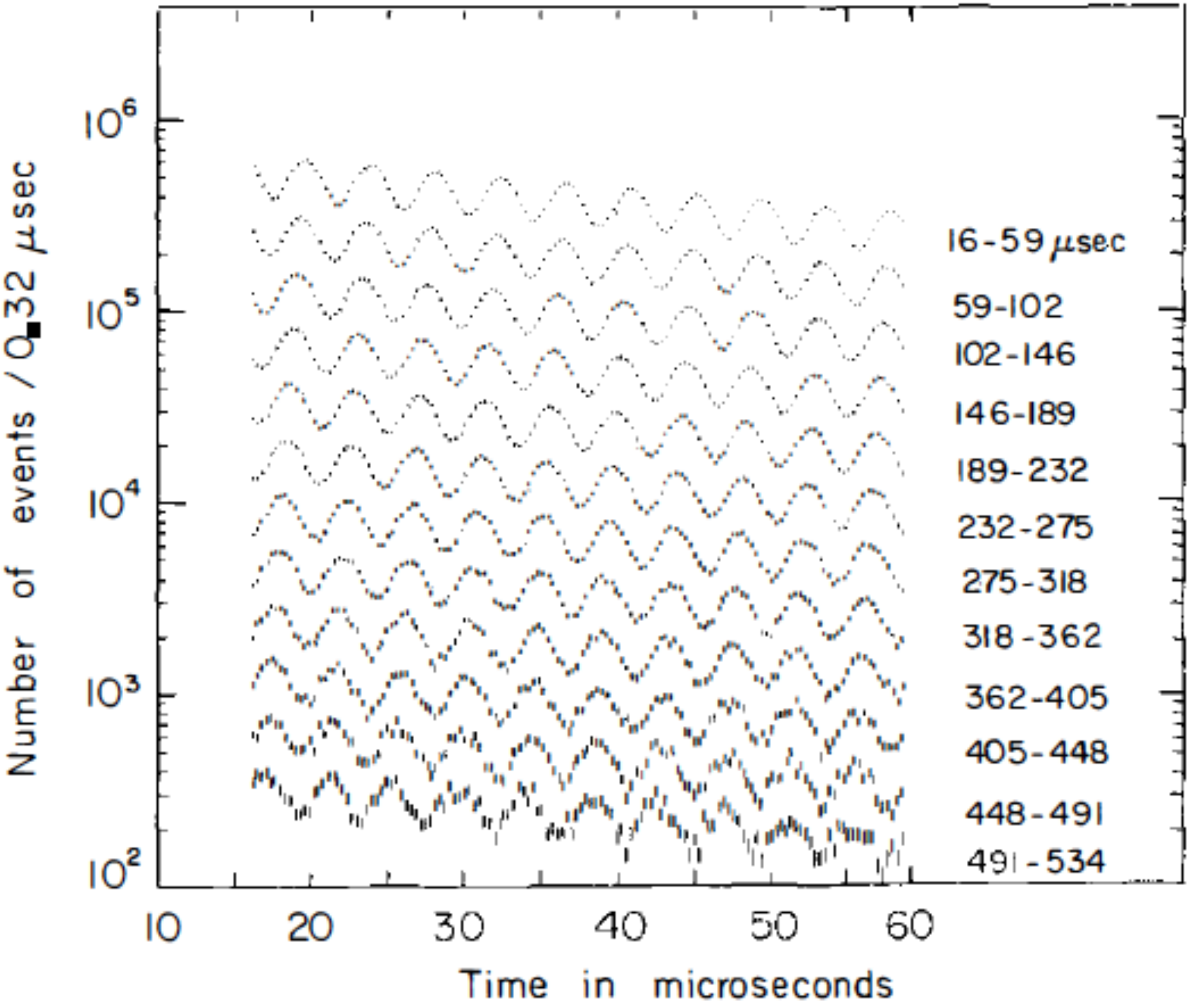
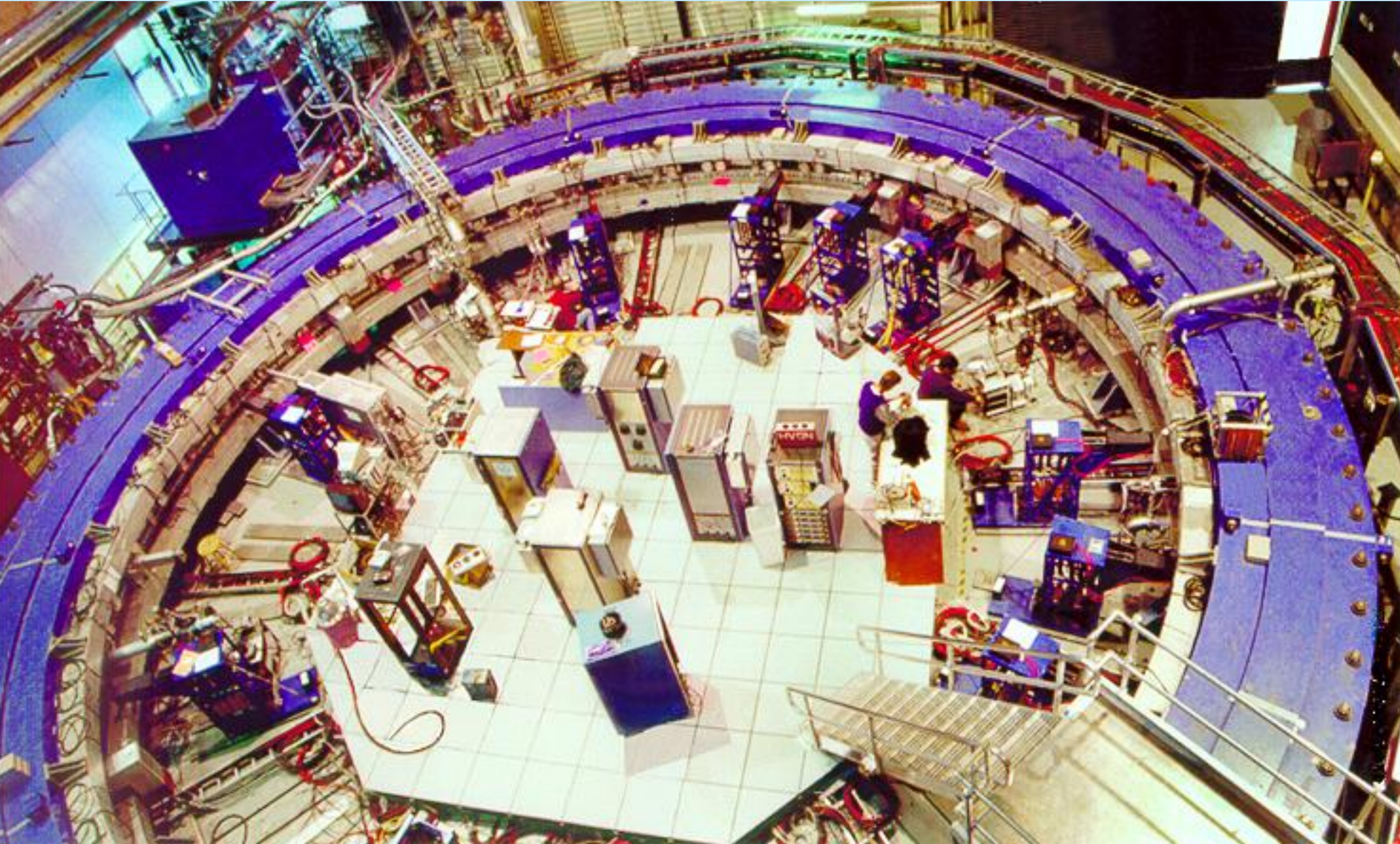


Figure 13 Muon Storage Ring II: decay electron counts versus time (in microseconds) after injection. Range of time for each line is shown on the right (in microseconds).

$$a_\mu = 1\,165\,924\,(8.5) \times 10^{-9} \text{ (7 ppm).}$$

This was the results of CERN exp ('70). Since that many advances in Experiment and Theory

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



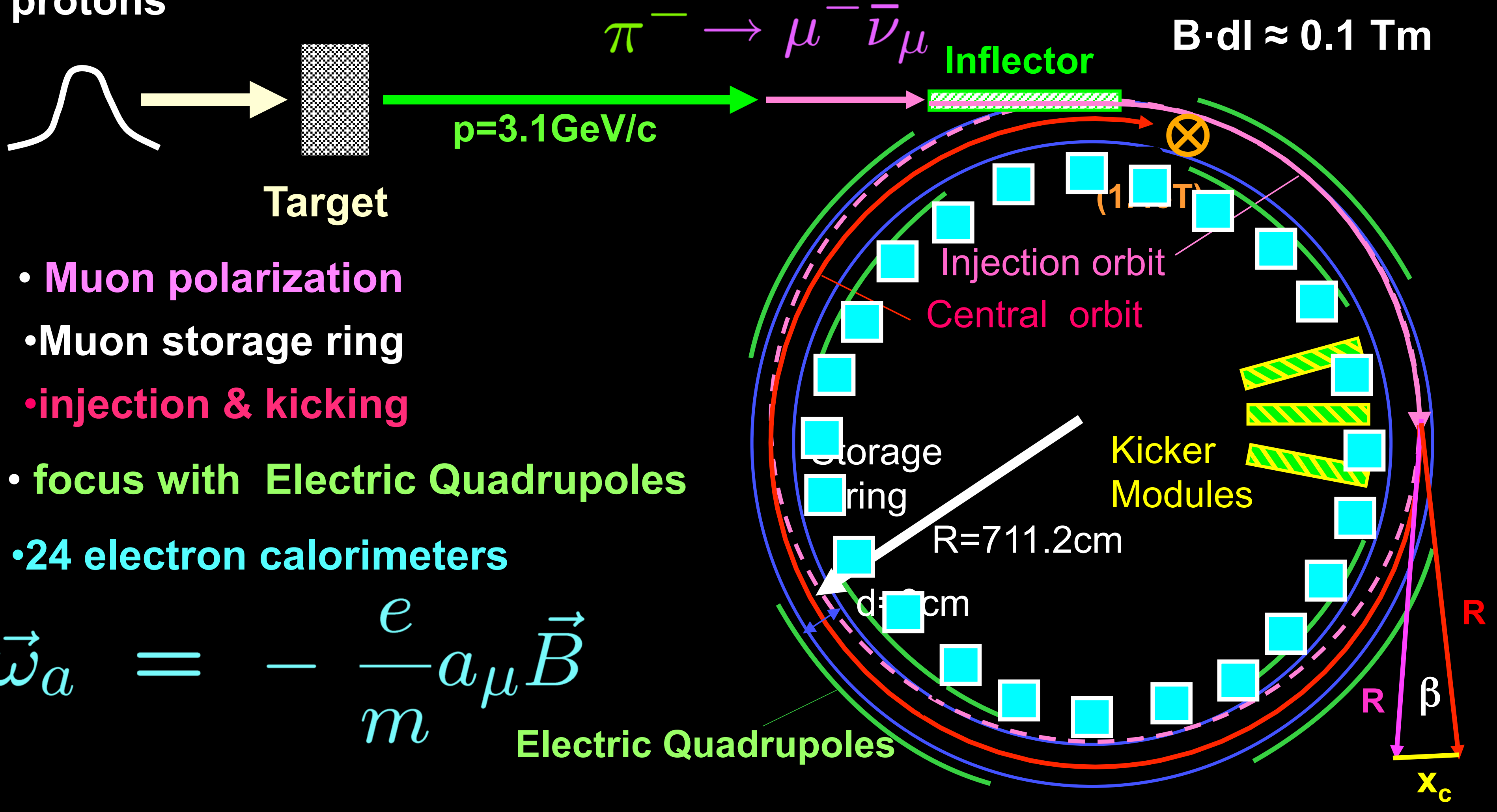
Experimental Technique

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

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

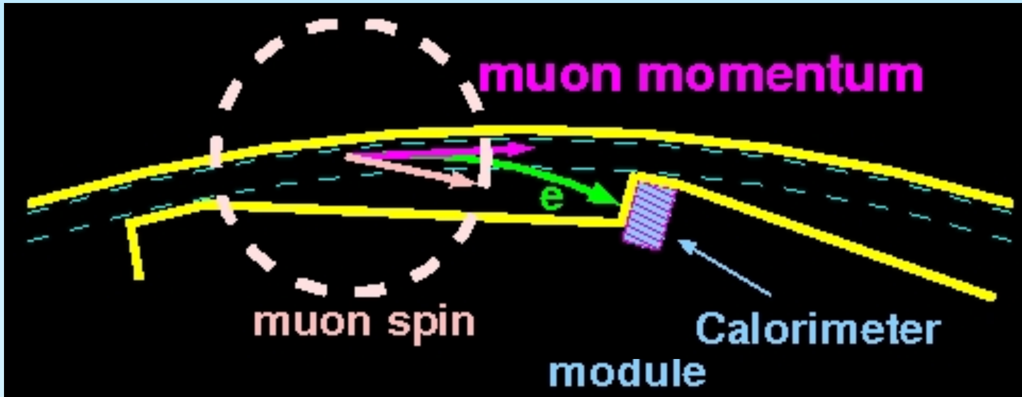
B·dl ≈ 0.1 Tm



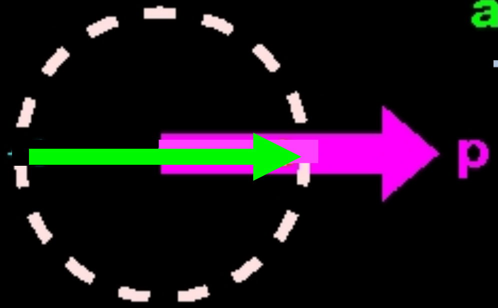
- **Muon polarization**
- **Muon storage ring**
- **injection & kicking**
- **focus with Electric Quadrupoles**
- **24 electron calorimeters**

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

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

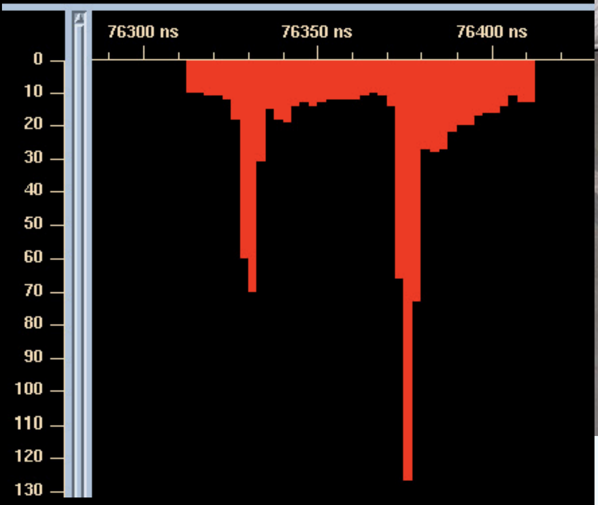


Measures Energy and time

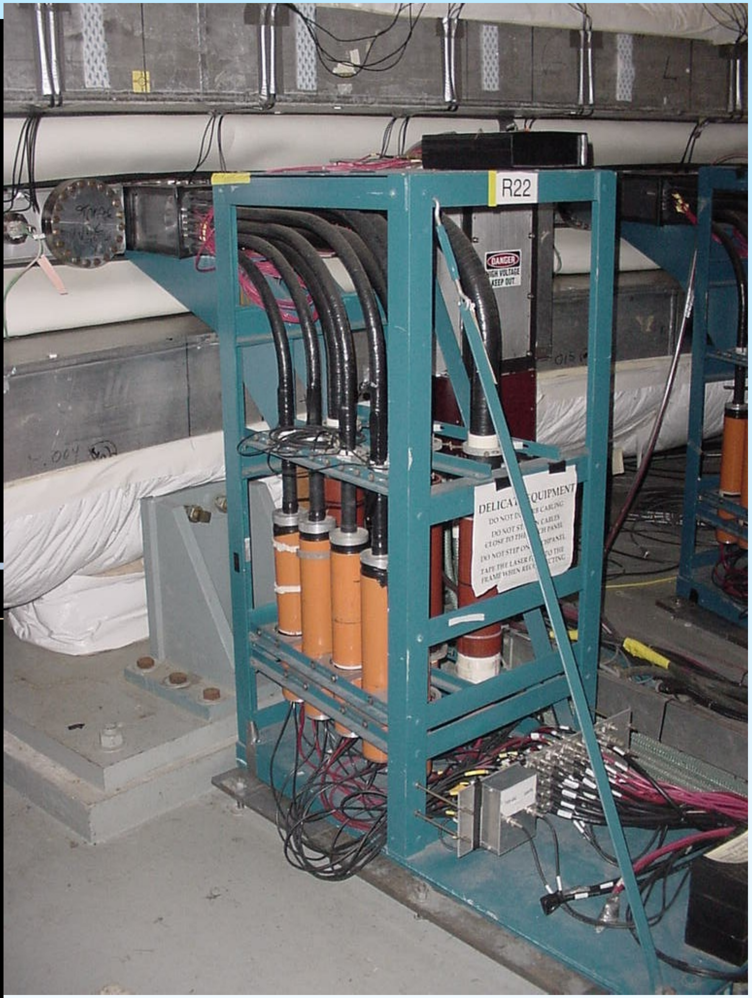


spin forward, more high energy e

spin backward, less high energy e



Waveform digitizer gives t, E



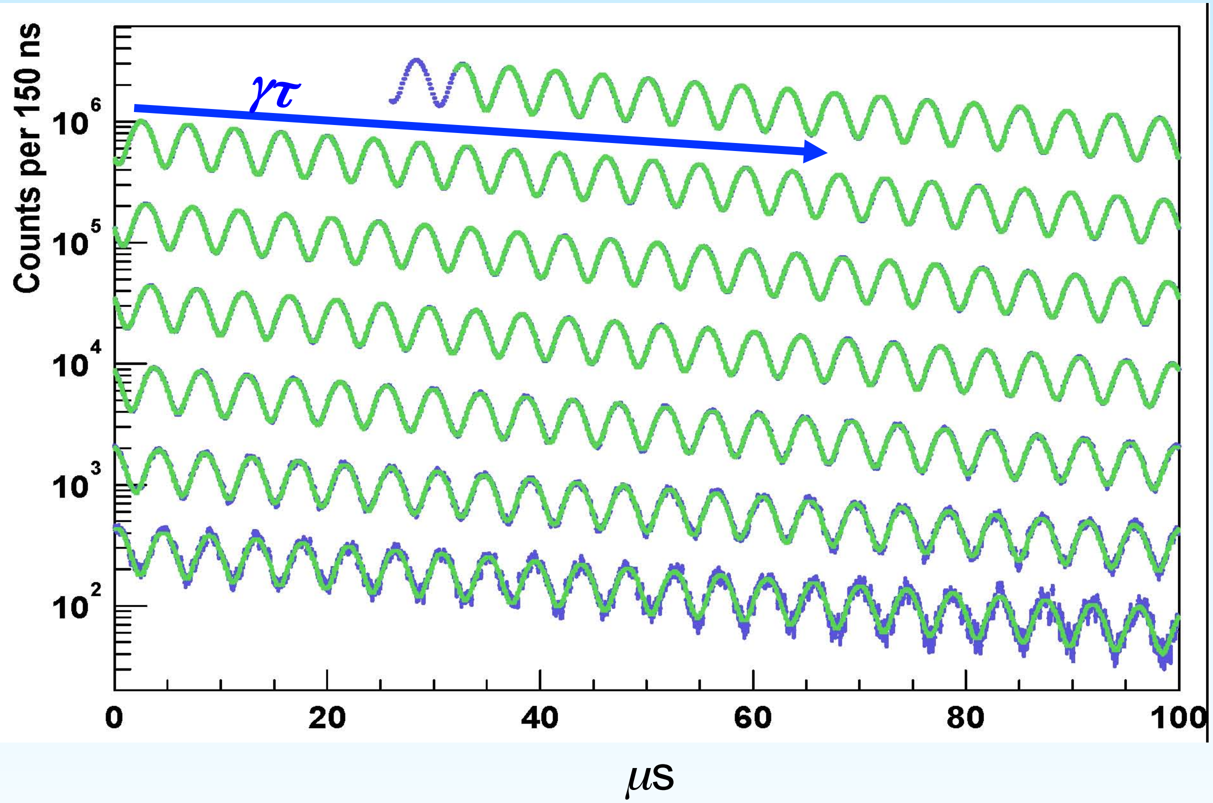
Picture of a Lead-Scifi Calorimeter from E821

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



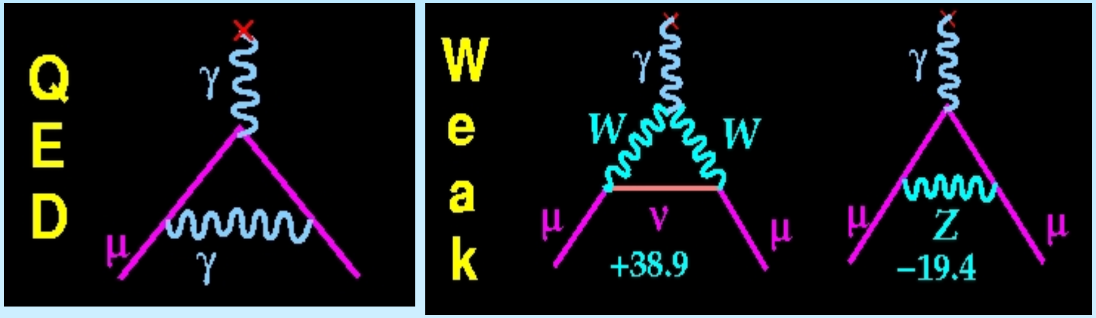
$\gamma\tau_\mu$ = 64.4 μs;
(g-2): τ_a = 4.37 μs;
Cyclotron: t_C = 149 ns

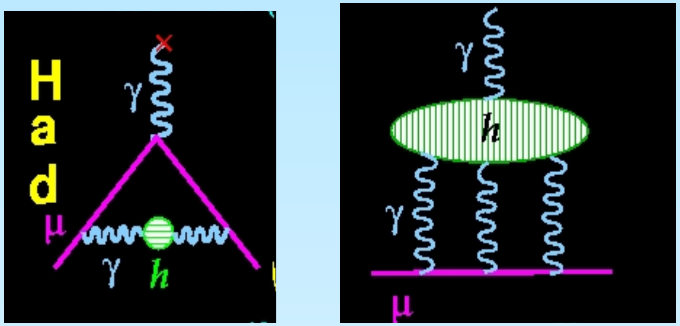
Result:

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

How does it compare with the SM?

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)

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

a_μ^{SM}: the QED contribution

$a_\mu^{QED} = (1/2)(\alpha/\pi)$ Schwinger 1948

$+ \; 0.765857408\,(27)\,(\alpha/\pi)^2$

Sommerfield; Petermann; Suura & Wichmann '57; Elend '66; MP '04

$+ \; 24.05050959\,(42)\,(\alpha/\pi)^3$

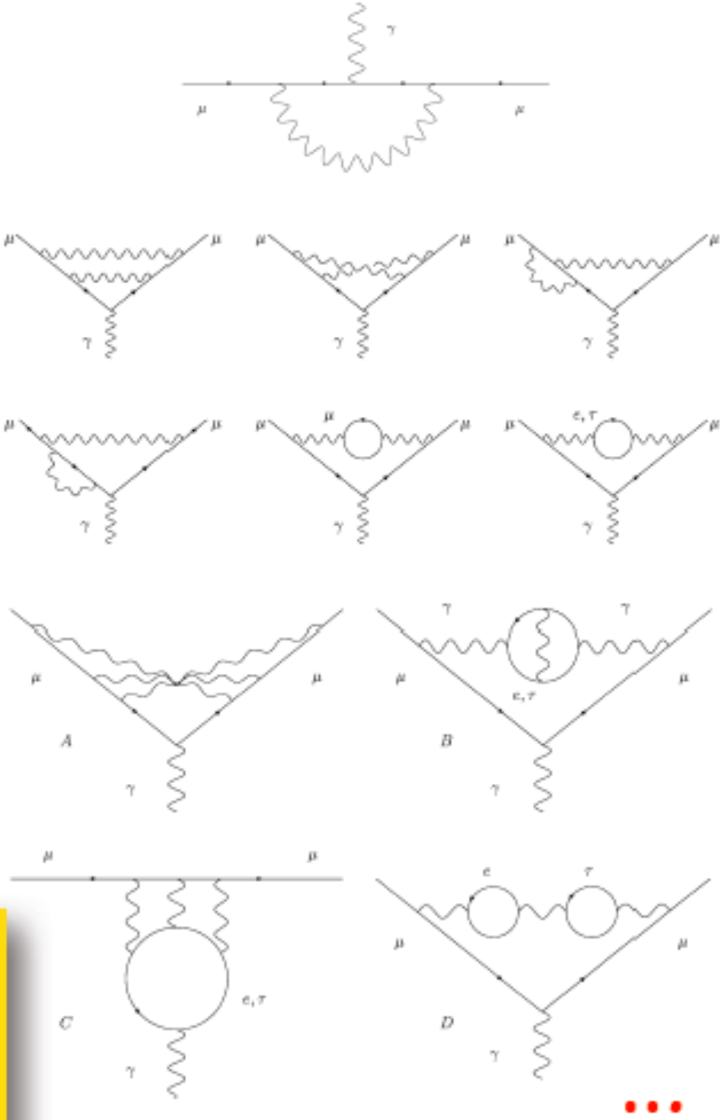
Remiddi, Laporta, Barbieri … ; Czarnecki, Skrzypek; MP '04;
Friot, Greynat & de Rafael '05, Mohr,Taylor & Newell '08

$+ \; 130.805\,(8)\,(\alpha/\pi)^4$

Kinoshita & Lindquist '81, … , Kinoshita & Nio '04, '05;
Aoyama, Hayakawa, Kinoshita & Nio, June & Dec 2007

$+ \; 663\,(20)\,(\alpha/\pi)^5$ In progress...

Kinoshita et al. '90, Yelkhovsky, Milstein, Starshenko, Laporta,
Karshenboim,…, Kataev, Kinoshita & Nio '06, Kinoshita et al. 2011



Adding up, we get:

$a_\mu^{QED} = 116584718.08\,(14)(04) \times 10^{-11}$

from coeffs, mainly from 5-loop unc ↲ ↳ from δα('08)

with $\alpha = 1/137.035999084(51)$ [0.37 ppb]

$\delta a_\mu^{QED} = 0.001\text{ppm}$

Impressive calculation…hundreds of diagrams

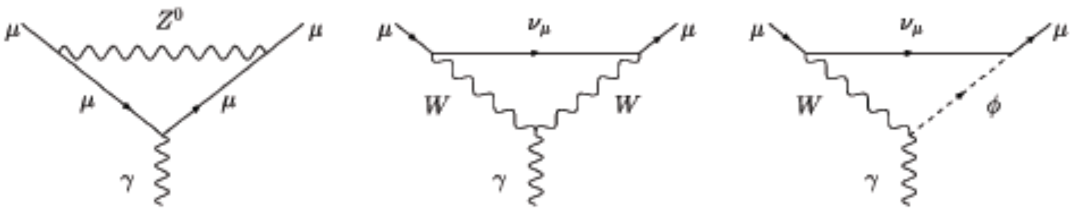
Note on 3–loop contribution (Remiddi et al., Remiddi, Laporta 1996 [after 27 years]):

Result turned out to be surprisingly compact

$$A_{1\,\mathrm{uni}}^{(6)} = \frac{28259}{5184} + \frac{17101}{810}\pi^2 - \frac{298}{9}\pi^2\ln 2 + \frac{139}{18}\zeta(3) + \frac{100}{3}\left\{\mathrm{Li}_4(\tfrac{1}{2}) + \frac{1}{24}\ln^4 2 - \frac{1}{24}\pi^2\ln^2 2\right\}$$
$$-\frac{239}{2160}\pi^4 + \frac{83}{72}\pi^2\zeta(3) - \frac{215}{24}\zeta(5) = 1.181\,241\,456\,587\ldots$$

a_μ^{SM}: the Electroweak contribution

- **One-loop term:**



$$a_\mu^{\text{EW}}(\text{1-loop}) = \frac{5G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2+O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195\times 10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;

Studenikin et al. '80s

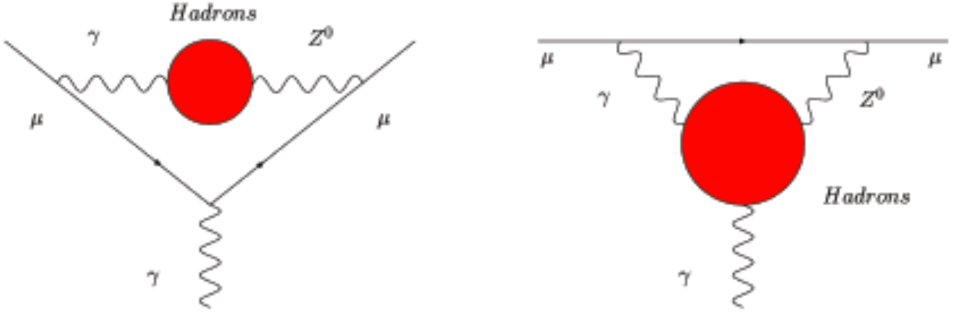
- **One-loop plus higher-order terms:**

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

Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano, Vainshtein '02; Degrassi, Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk, Czarnecki '05; Vainshtein '03.

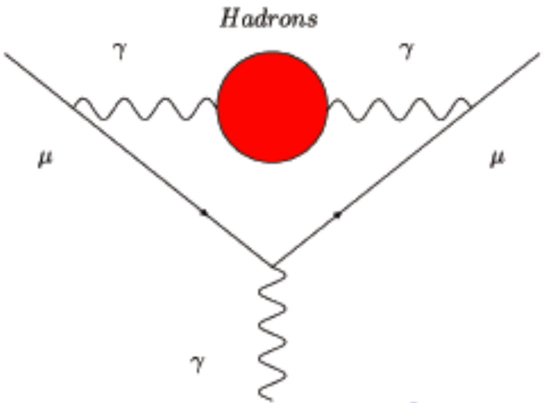
Higgs mass variation, M_{top} error, 3-loop nonleading logs

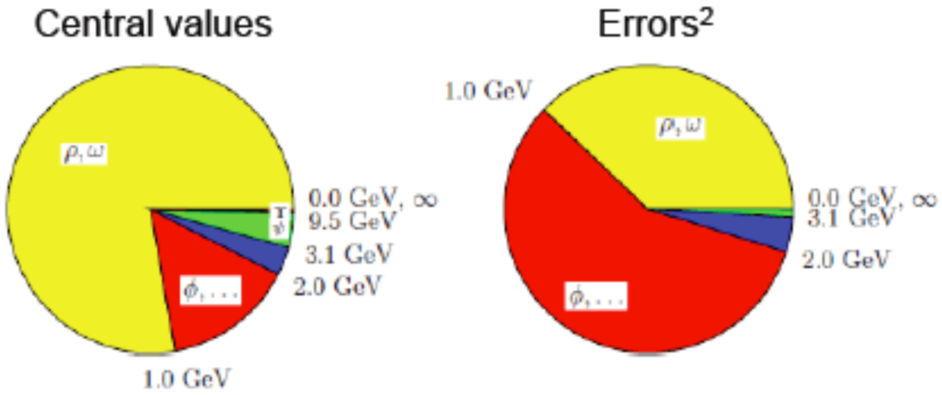
Hadronic loop uncertainties:



$\delta a_\mu^{\text{Weak}}$ =0.02 ppm

a_μ^{SM}: the hadronic leading-order (HLO) contribution




Central values

Errors²

F. Jegerlehner and A. Nyffeler, Phys. Rept. 477 (2009) 1

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)s/m_\mu^2}$$

$$a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^{(0)}(s) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s)\, R(s)$$

$a_\mu^{HLO} = 6903\ (53)_{tot} \times 10^{-11}$ F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 (2009) 1

$= 6923\ (42)_{tot} \times 10^{-11}$ Davier et al, arXiv:1010.4180 (incl. BaBar & KLOE10 2π)

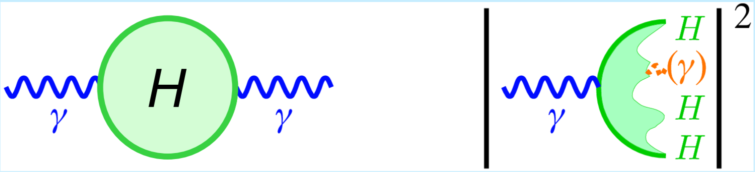
$= 6949\ (37)_{exp}\ (21)_{rad} \times 10^{-11}$ Hagiwara et al. (HLMNT11), arXiv:1105.3149

δa_μ^{HLO} =0.4 ppm

Radiative Corrections are crucial! S.Actis et al, Eur. Phys. J. C66 (2010) 585

a_μ^{HLO}:

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



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

$1\,/\,s^2$ makes low energy contributions

$e^+e^- \longrightarrow \pi^+\pi^-$ ortant:

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:

(G.dR 69, E.J.95, A.D.H.'97,….)

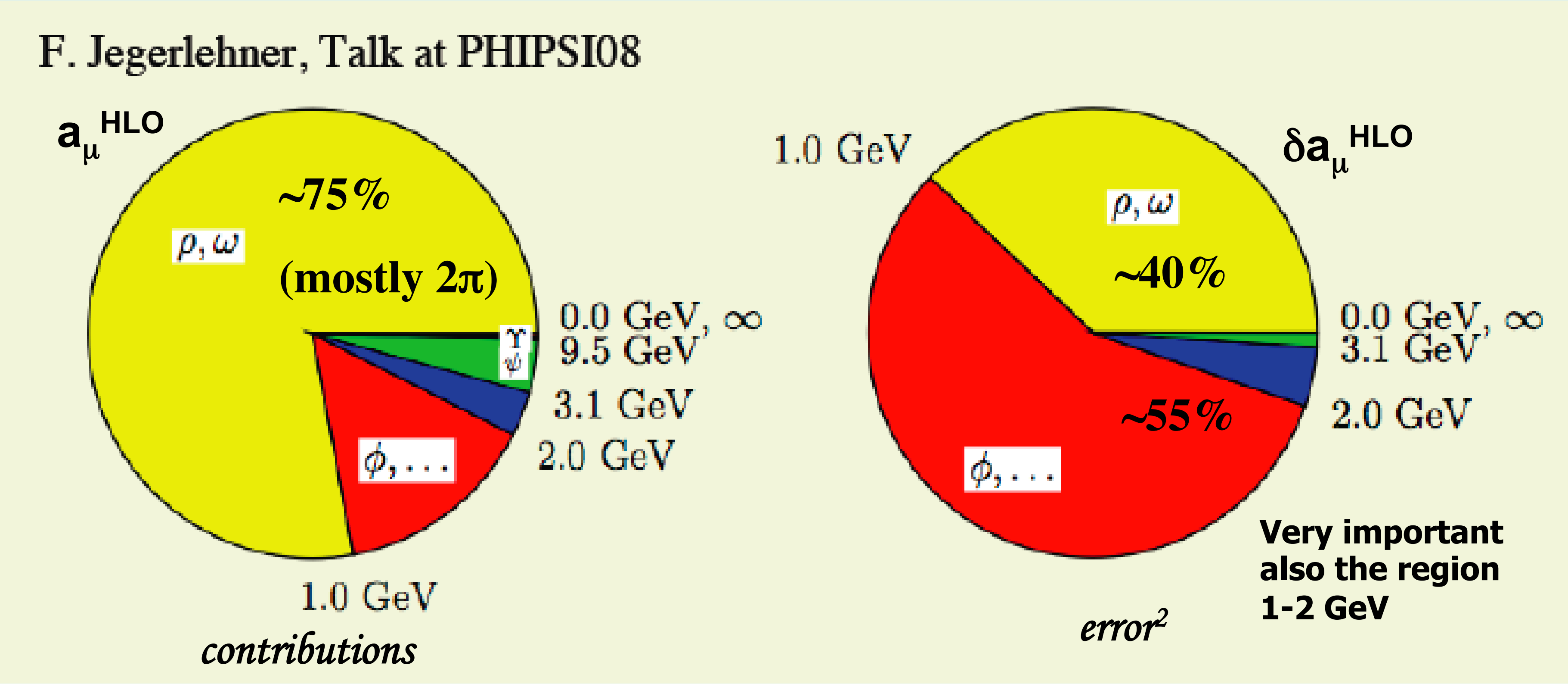
a) hadronic electron-positron cross section data

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)

Dispersion Integral:

K(s)~1/s

Contribution of different energy regions to the dispersion integral and the error to a_μ^{HLO}



F. Jegerlehner, Talk at PHIPSI08

Very important also the region 1-2 GeV

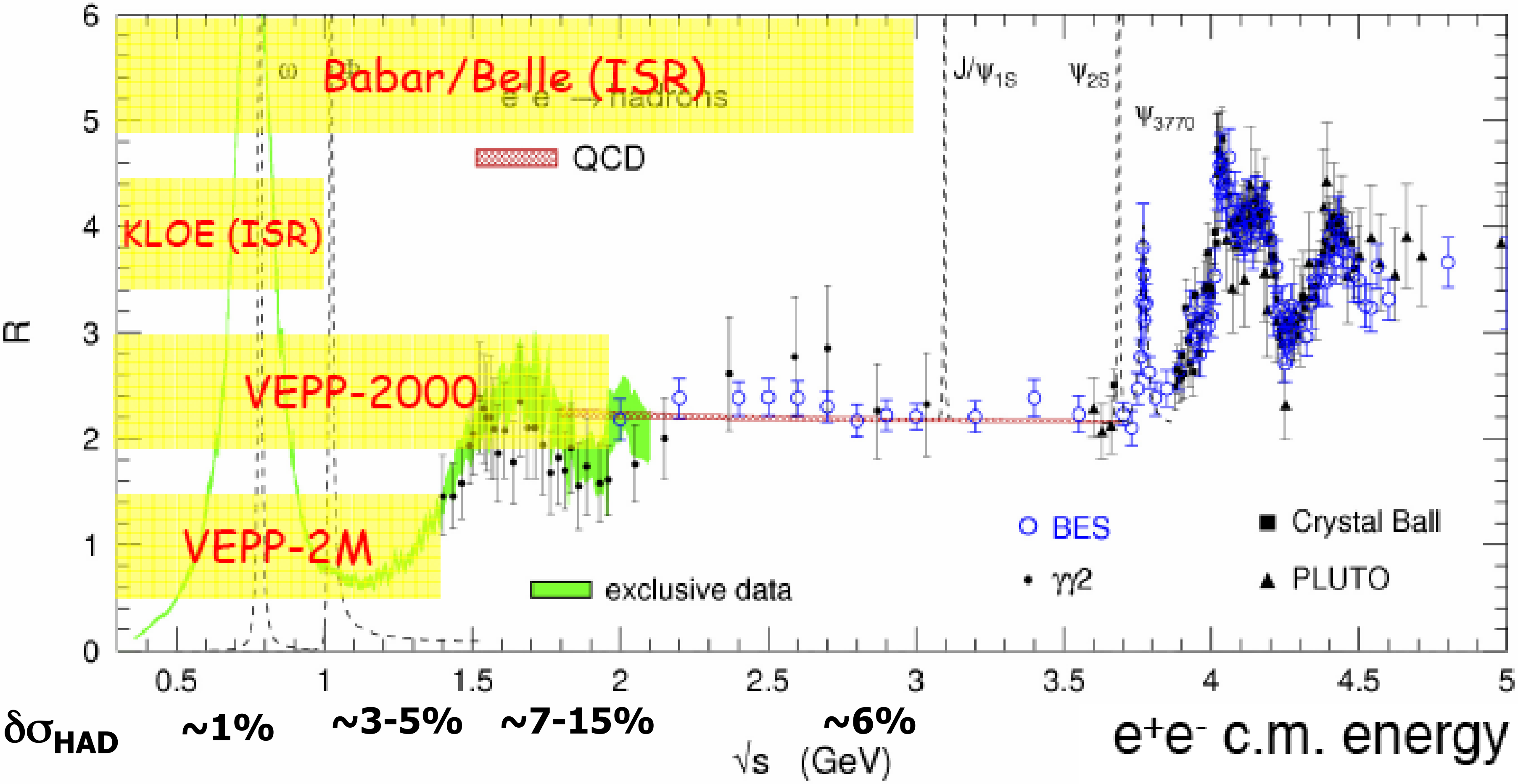
Experimental errors on σ^{had} translate into theoretical uncertainty of a_μ^{had}!

→ Needs precision measurements!

$\delta a_\mu^{exp} \rightarrow 1.5\ 10^{-10} = 0.2\%$ on a_μ^{HLO}

New g-2 exp.

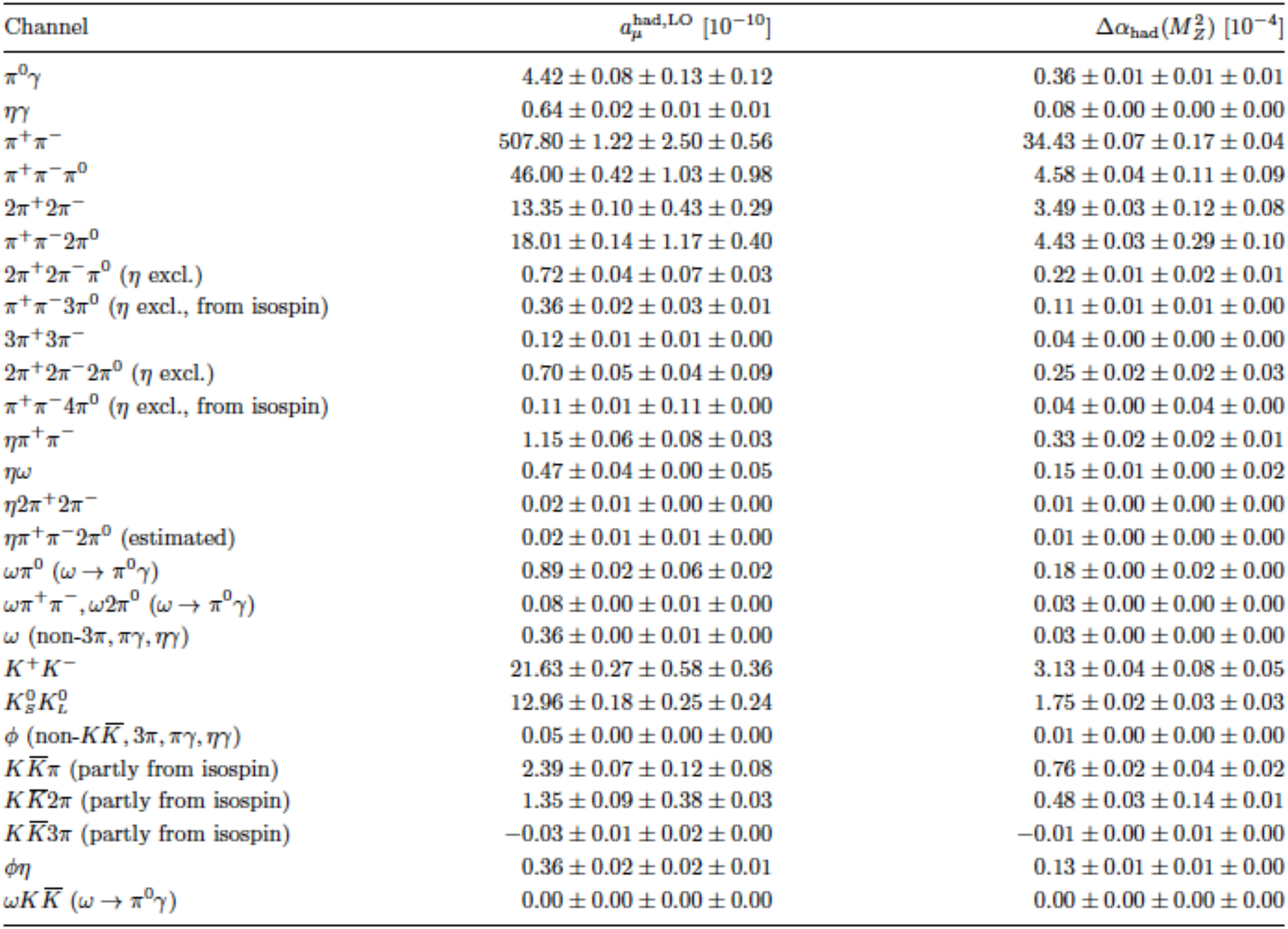
e^+e^- data: a worldwide efforts



$\delta\sigma_{HAD}$ ~1% ~3-5% ~7-15% ~6%

e^+e^- c.m. energy

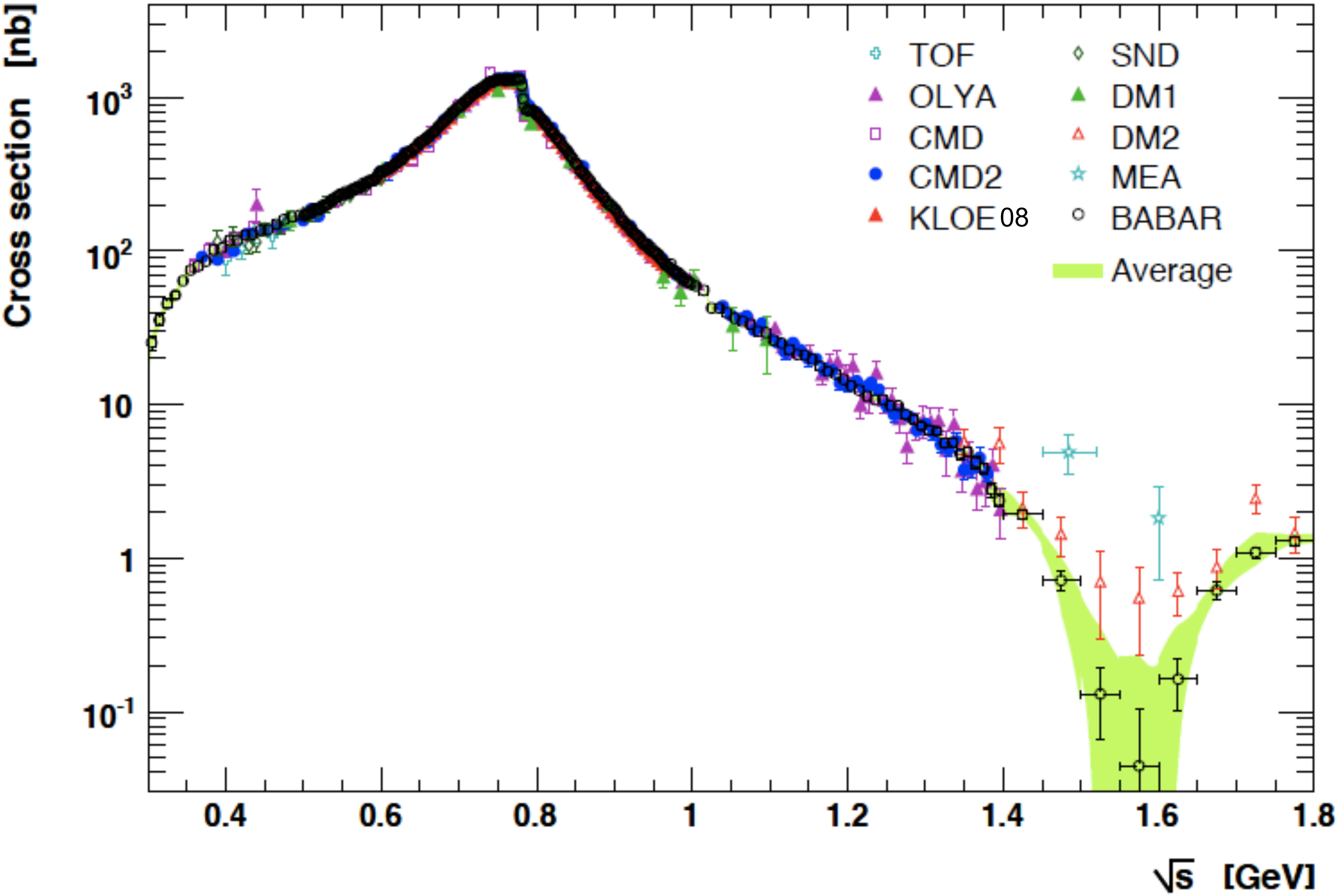
Main contributions to a_μ^{HLO} and $\Delta\alpha(M_Z)$



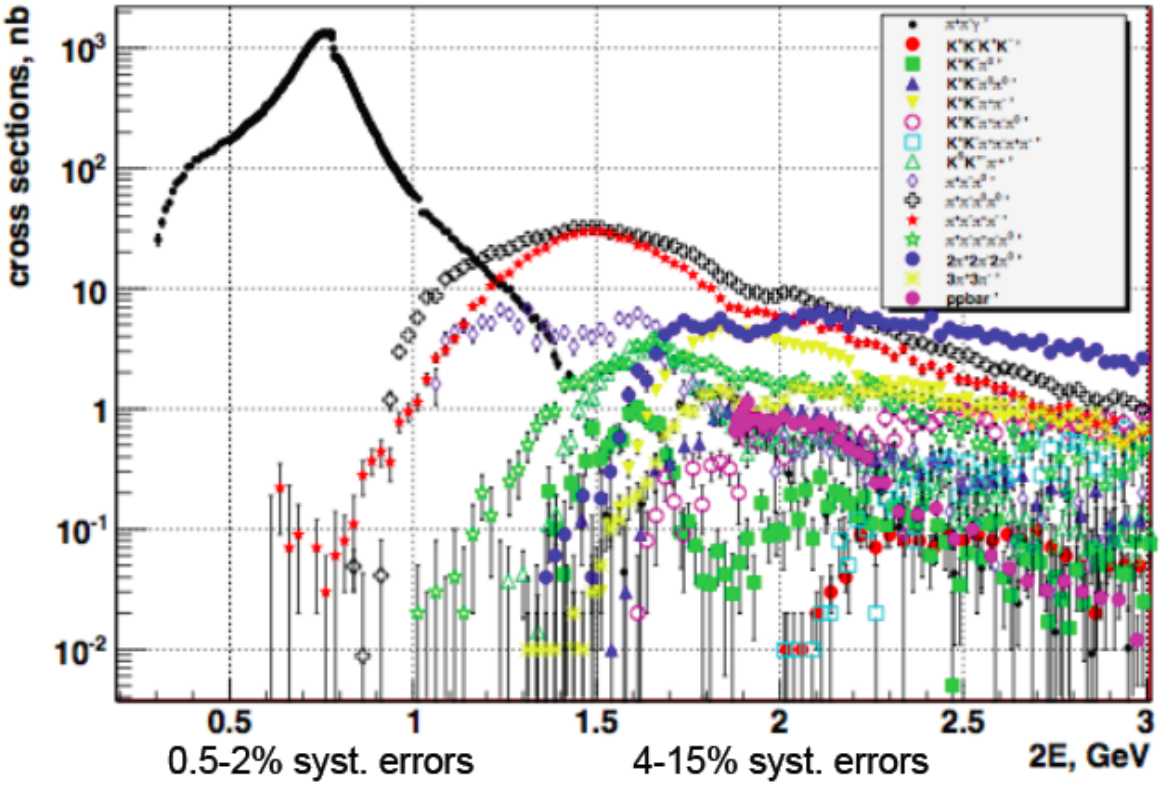
Channel	$a_\mu^{\mathrm{had,LO}}$ $[10^{-10}]$	$\Delta\alpha_{\mathrm{had}}(M_Z^2)$ $[10^{-4}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$	$0.36 \pm 0.01 \pm 0.01 \pm 0.01$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$	$0.08 \pm 0.00 \pm 0.00 \pm 0.00$
$\pi^+\pi^-$	$507.80 \pm 1.22 \pm 2.50 \pm 0.56$	$34.43 \pm 0.07 \pm 0.17 \pm 0.04$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$	$4.58 \pm 0.04 \pm 0.11 \pm 0.09$
$2\pi^+2\pi^-$	$13.35 \pm 0.10 \pm 0.43 \pm 0.29$	$3.49 \pm 0.03 \pm 0.12 \pm 0.08$
$\pi^+\pi^-2\pi^0$	$18.01 \pm 0.14 \pm 1.17 \pm 0.40$	$4.43 \pm 0.03 \pm 0.29 \pm 0.10$
$2\pi^+2\pi^-\pi^0$ (η excl.)	$0.72 \pm 0.04 \pm 0.07 \pm 0.03$	$0.22 \pm 0.01 \pm 0.02 \pm 0.01$
$\pi^+\pi^-3\pi^0$ (η excl., from isospin)	$0.36 \pm 0.02 \pm 0.03 \pm 0.01$	$0.11 \pm 0.01 \pm 0.01 \pm 0.00$
$3\pi^+3\pi^-$	$0.12 \pm 0.01 \pm 0.01 \pm 0.00$	$0.04 \pm 0.00 \pm 0.00 \pm 0.00$
$2\pi^+2\pi^-2\pi^0$ (η excl.)	$0.70 \pm 0.05 \pm 0.04 \pm 0.09$	$0.25 \pm 0.02 \pm 0.02 \pm 0.03$
$\pi^+\pi^-4\pi^0$ (η excl., from isospin)	$0.11 \pm 0.01 \pm 0.11 \pm 0.00$	$0.04 \pm 0.00 \pm 0.04 \pm 0.00$
$\eta\pi^+\pi^-$	$1.15 \pm 0.06 \pm 0.08 \pm 0.03$	$0.33 \pm 0.02 \pm 0.02 \pm 0.01$
$\eta\omega$	$0.47 \pm 0.04 \pm 0.00 \pm 0.05$	$0.15 \pm 0.01 \pm 0.00 \pm 0.02$
$\eta 2\pi^+2\pi^-$	$0.02 \pm 0.01 \pm 0.00 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$\eta\pi^+\pi^-2\pi^0$ (estimated)	$0.02 \pm 0.01 \pm 0.01 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$\omega\pi^0$ ($\omega \to \pi^0\gamma$)	$0.89 \pm 0.02 \pm 0.06 \pm 0.02$	$0.18 \pm 0.00 \pm 0.02 \pm 0.00$
$\omega\pi^+\pi^-, \omega 2\pi^0$ ($\omega \to \pi^0\gamma$)	$0.08 \pm 0.00 \pm 0.01 \pm 0.00$	$0.03 \pm 0.00 \pm 0.00 \pm 0.00$
ω (non-$3\pi, \pi\gamma, \eta\gamma$)	$0.36 \pm 0.00 \pm 0.01 \pm 0.00$	$0.03 \pm 0.00 \pm 0.00 \pm 0.00$
K^+K^-	$21.63 \pm 0.27 \pm 0.58 \pm 0.36$	$3.13 \pm 0.04 \pm 0.08 \pm 0.05$
$K_S^0 K_L^0$	$12.96 \pm 0.18 \pm 0.25 \pm 0.24$	$1.75 \pm 0.02 \pm 0.03 \pm 0.03$
ϕ (non-$K\overline{K}, 3\pi, \pi\gamma, \eta\gamma$)	$0.05 \pm 0.00 \pm 0.00 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$K\overline{K}\pi$ (partly from isospin)	$2.39 \pm 0.07 \pm 0.12 \pm 0.08$	$0.76 \pm 0.02 \pm 0.04 \pm 0.02$
$K\overline{K}2\pi$ (partly from isospin)	$1.35 \pm 0.09 \pm 0.38 \pm 0.03$	$0.48 \pm 0.03 \pm 0.14 \pm 0.01$
$K\overline{K}3\pi$ (partly from isospin)	$-0.03 \pm 0.01 \pm 0.02 \pm 0.00$	$-0.01 \pm 0.00 \pm 0.01 \pm 0.00$
$\phi\eta$	$0.36 \pm 0.02 \pm 0.02 \pm 0.01$	$0.13 \pm 0.01 \pm 0.01 \pm 0.00$
$\omega K\overline{K}$ ($\omega \to \pi^0\gamma$)	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$

M. Davier et al. Eur.Phys.J. C71 (2011) 1515

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



BaBar measurements summary



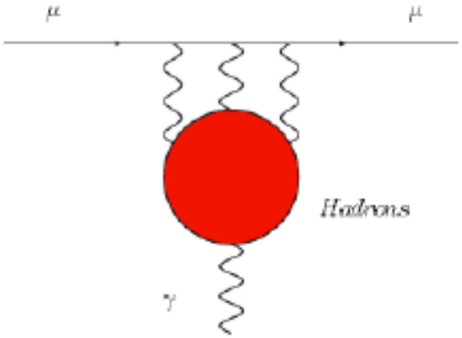
0.5-2% syst. errors

4-15% syst. errors

To calculate R in the energy range 1-2 GeV the processes $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, K_SK_L, $K_SK_L\pi\pi$, $K_SK^+\pi^-\pi^0$ are under study.
The $\pi^+\pi^-2\pi^0$ is still preliminary. Work is in progress.

a_μ^{SM}: the hadronic higher-order (HHO) contributions - LBL

HHO: Light-by-light contribution



- Unlike the HLO term, for the hadronic l-b-l term we must rely on theoretical approaches.
- This term had a troubled life! Recent values:

$a_\mu^{HHO}(lbl)$ = + 80 (40) × 10^{-11} Knecht & Nyffeler '02

$a_\mu^{HHO}(lbl)$ = +136 (25) × 10^{-11} Melnikov & Vainshtein '03

$a_\mu^{HHO}(lbl)$ = +105 (26) × 10^{-11} Prades, de Rafael, Vainshtein '09

$a_\mu^{HHO}(lbl)$ = +116 (39) × 10^{-11} Jegerlehner & Nyffeler '09

Results based also on Hayakawa, Kinoshita '98 & '02; Bijnens, Pallante, Prades '96 & '02

- "Bound" $a_\mu^{HHO}(lbl) < \sim 160 \times 10^{-11}$ Erler&Sanchez '06, Pivovarov '02 (Boughezal&Melnikov'11)
- Recent large result: 217 (91) × 10^{-11} Fischer, Goecke, Williams, PRD83 (2011) 094006
- Had lbl is likely to become the ultimate limitation of the SM prediction
- Lattice? Very hard, but in progress!

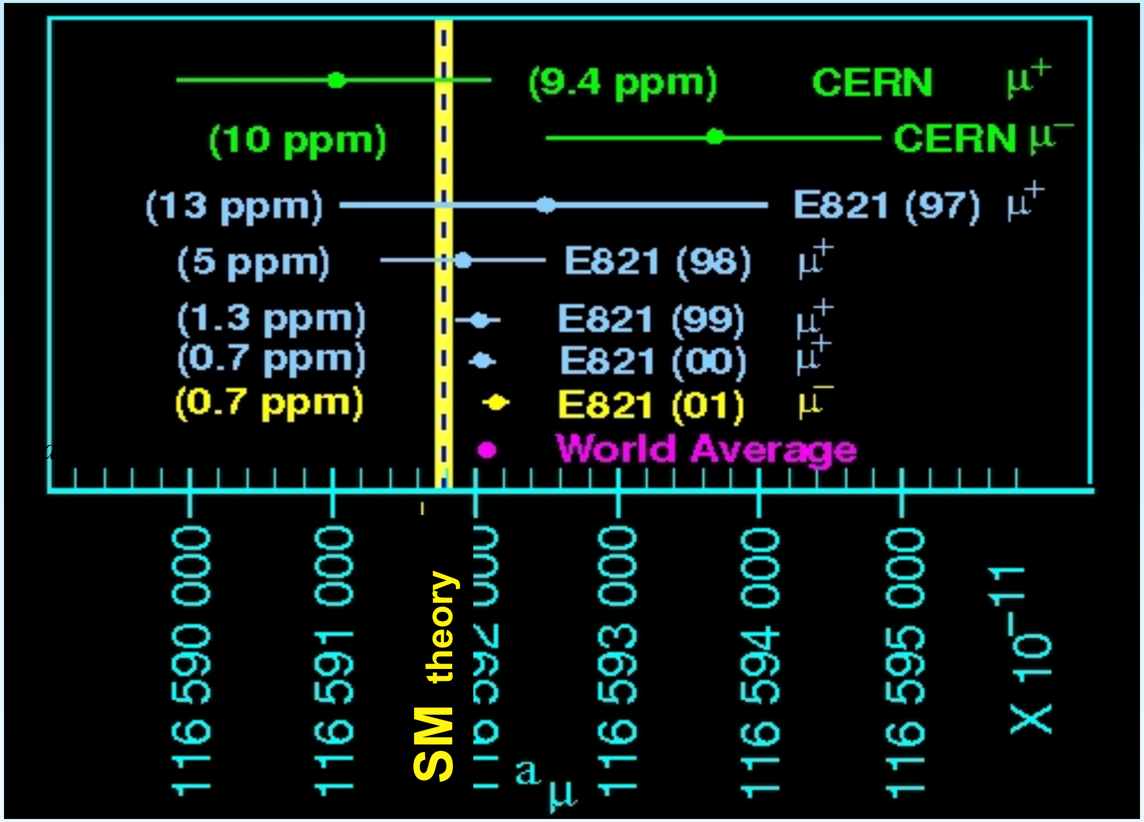
See Jansen's and Moricciani's talks

δa_μ^{HLO} =0.3 ppm

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

(0.54 ppm!)

A factor 15 improvement in accuracy respect to CERN!



~3.5 "standard deviations" with SM

Error dominated by experimental uncertainty!

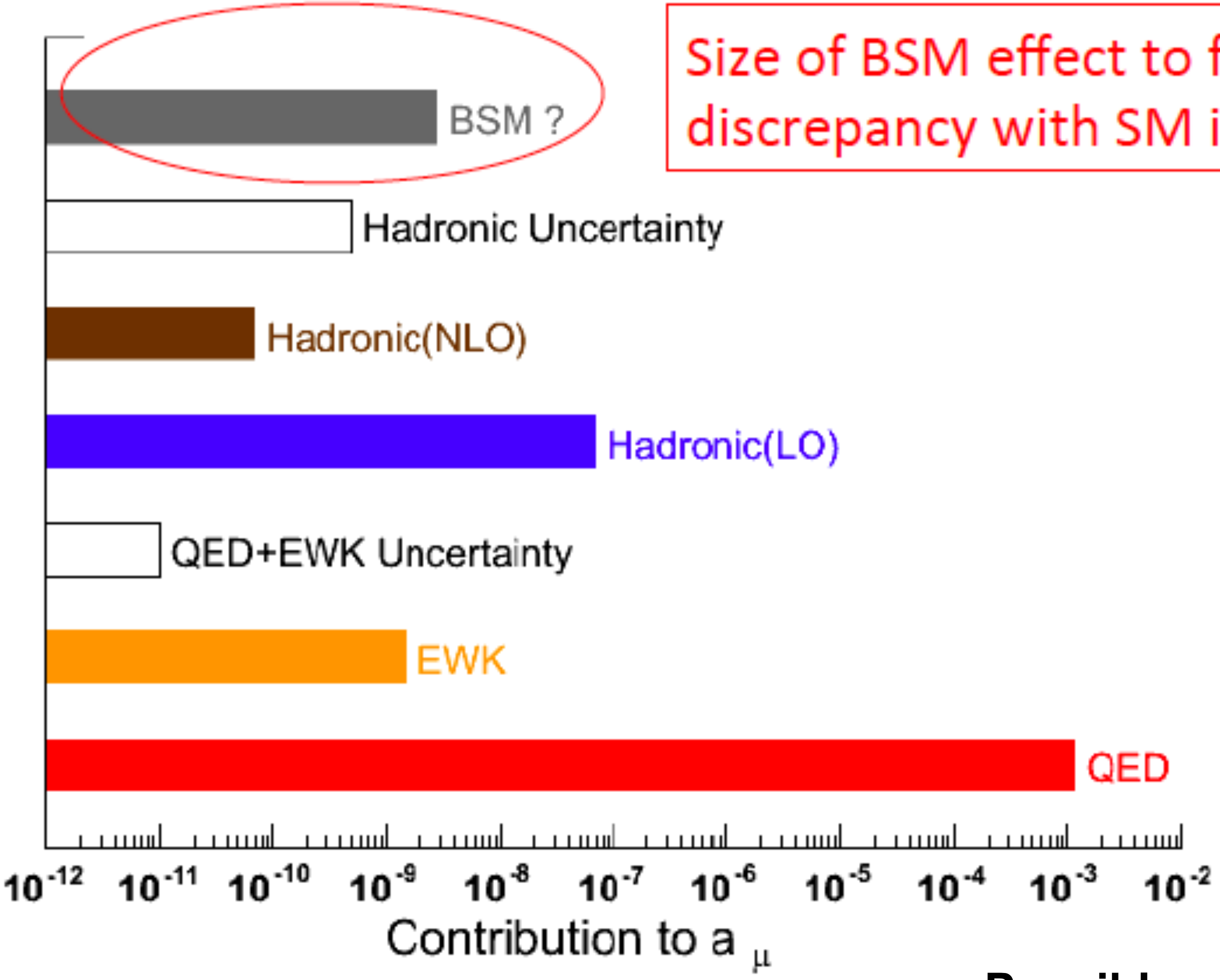
$$a_\mu^{SM} = 116\,591\,802 \pm 49 \times 10^{-11}$$

M. Davier et al. 2011

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

Hint of new physics?

What are we missing (theory or exp)?

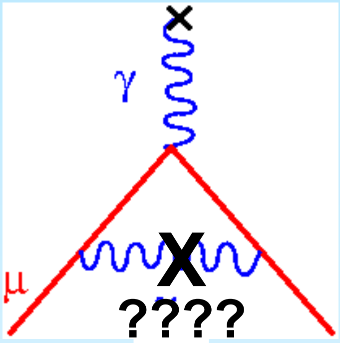


Size of BSM effect to fix current discrepancy with SM is large

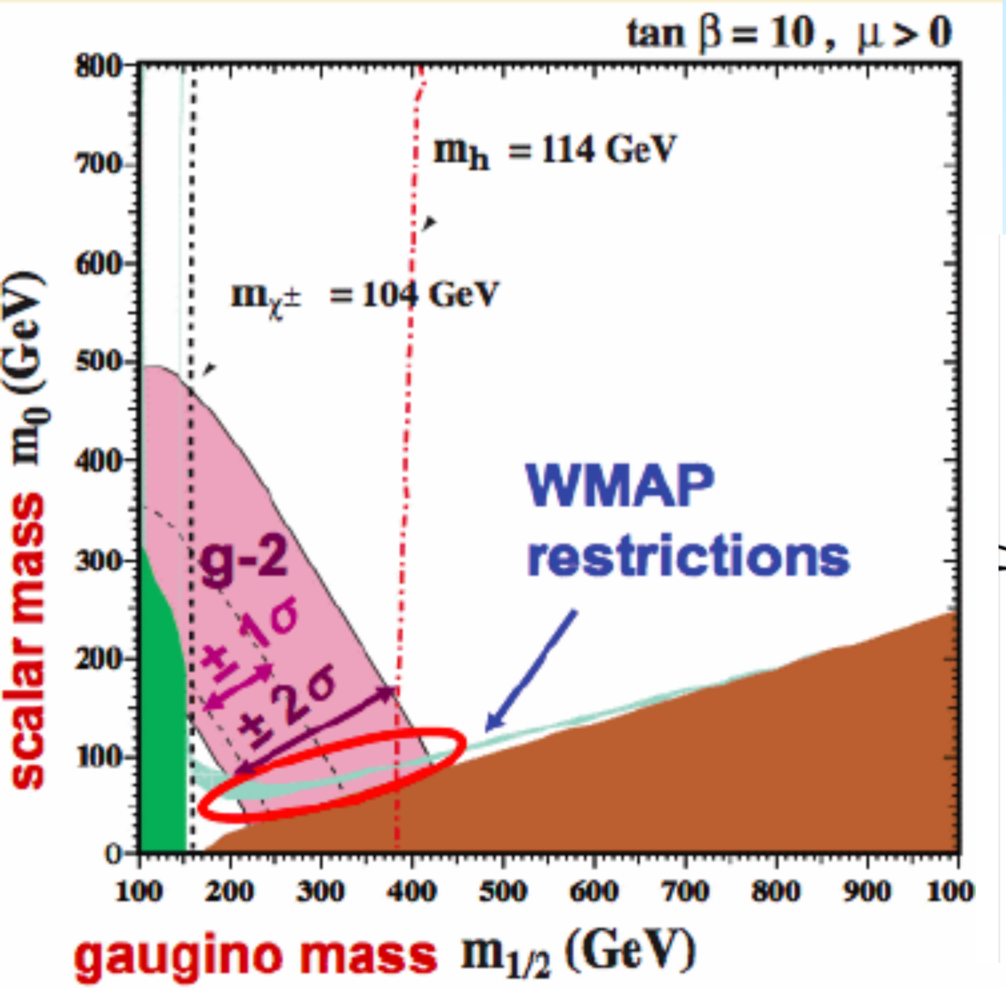
Possible explanations?

New Physics?

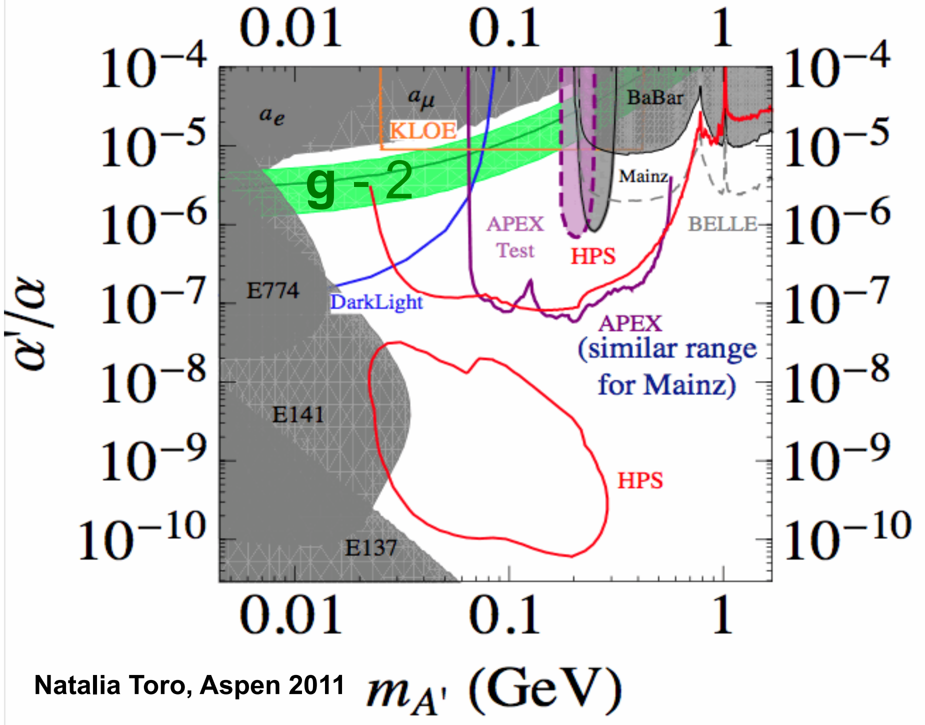
$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} + a_\mu^{???}$$



SUSY?



Dark Photons?

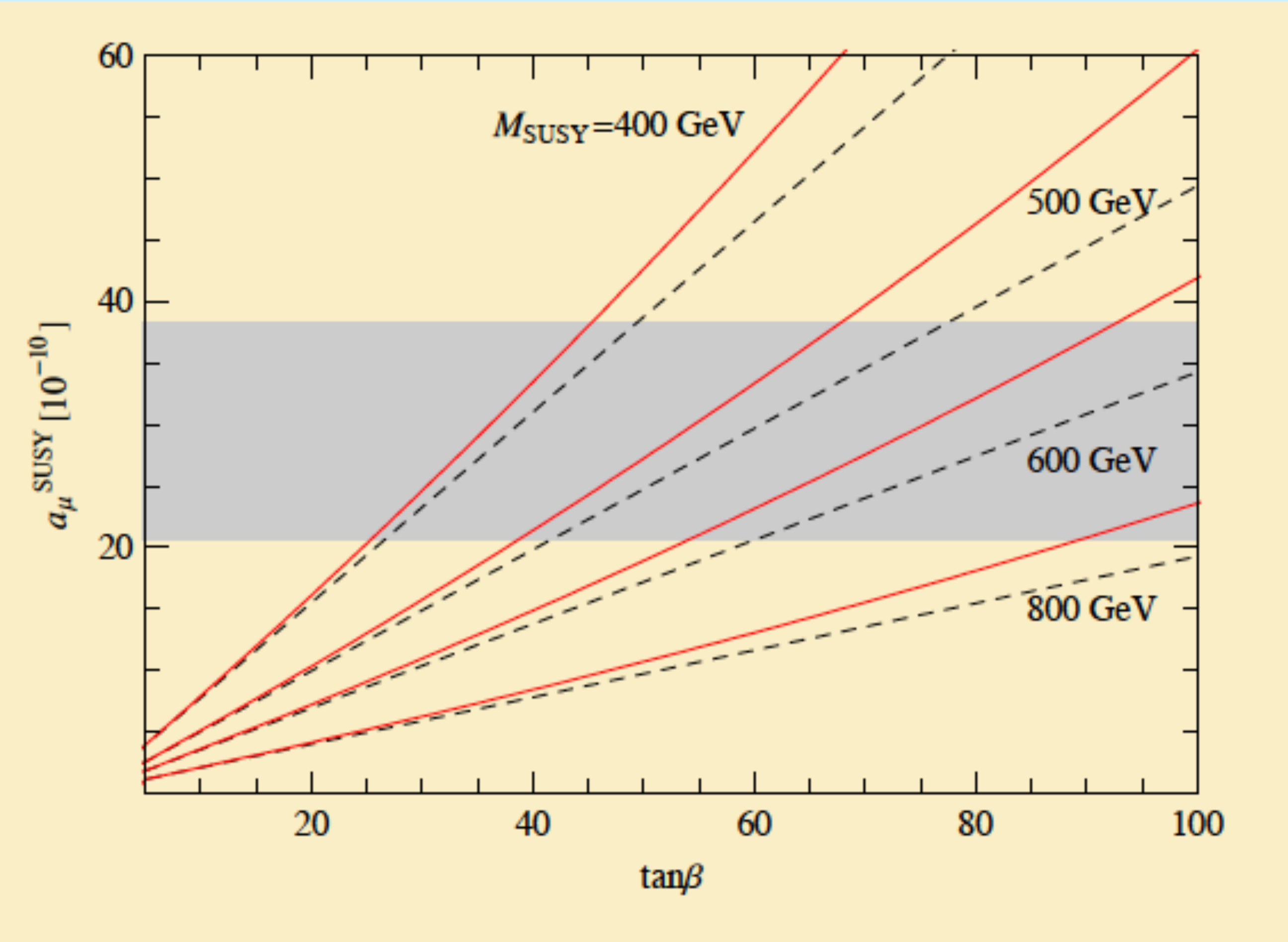


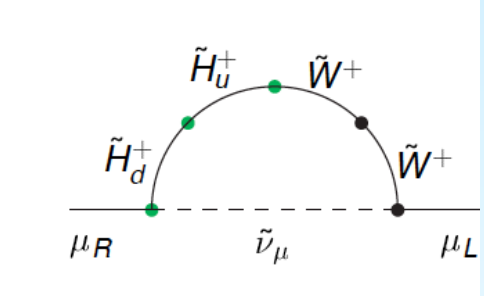
Natalia Toro, Aspen 2011

SUSY?

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

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





Large tanβ, μ>0 prefer

strong limit on M_{SUSY}

Important constraint for interpretation of BSM physics searches at LHC

Correlation btw g-2 and LHC result on H->γγ

Correlation between the Higgs Decay Rate to Two Photons and the Muon $g-2$

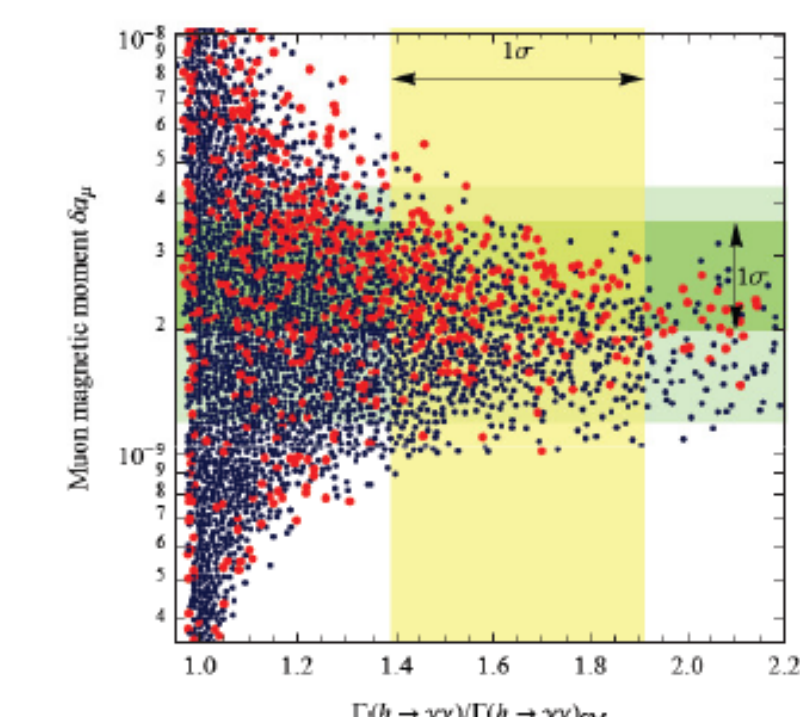
Gian F. Giudice[a], Paride Paradisi[a] and Alessandro Strumia[a,b]

arXiv:1207.6393v1

Post Higgs paper

26 Jul 2012

- Observations:
  - **production rate is too high by ~40-50%**
  - **Higgs rates in ZZ* and WW* are consistent with the SM**
  - **Muon anomaly differs from SM by ~ +280 x 10^{-11}**
- Theoretical SUSY model that fits observations
  - **light stau with large left-right mixing**
  - **light Bino**
  - **heavy higgsinos**
- Other consequences
  - ✓ **Predicts Muon Anomaly exactly**
  - ✓ **Compatible with thermal dark matter**
  - ✓ **Predicts small deviations in h → γZ and h → ττ**
  - ✓ **Predicts measureable violations of Lepton Non-Universality in τ−μ and τ-e**
  - ✓ **Predicts NO violation in the μ-e sector**



Large corrections to $\Gamma(h\to\gamma\gamma)$ arise from large mixing of the L-R s-leptons

Correlation btw g-2 and μ->eγ

N.B.: in SUSY (an in most NP modes) there is a natural link between $\mu \to e\gamma$ and non-SM contributions to $(g-2)_\mu$

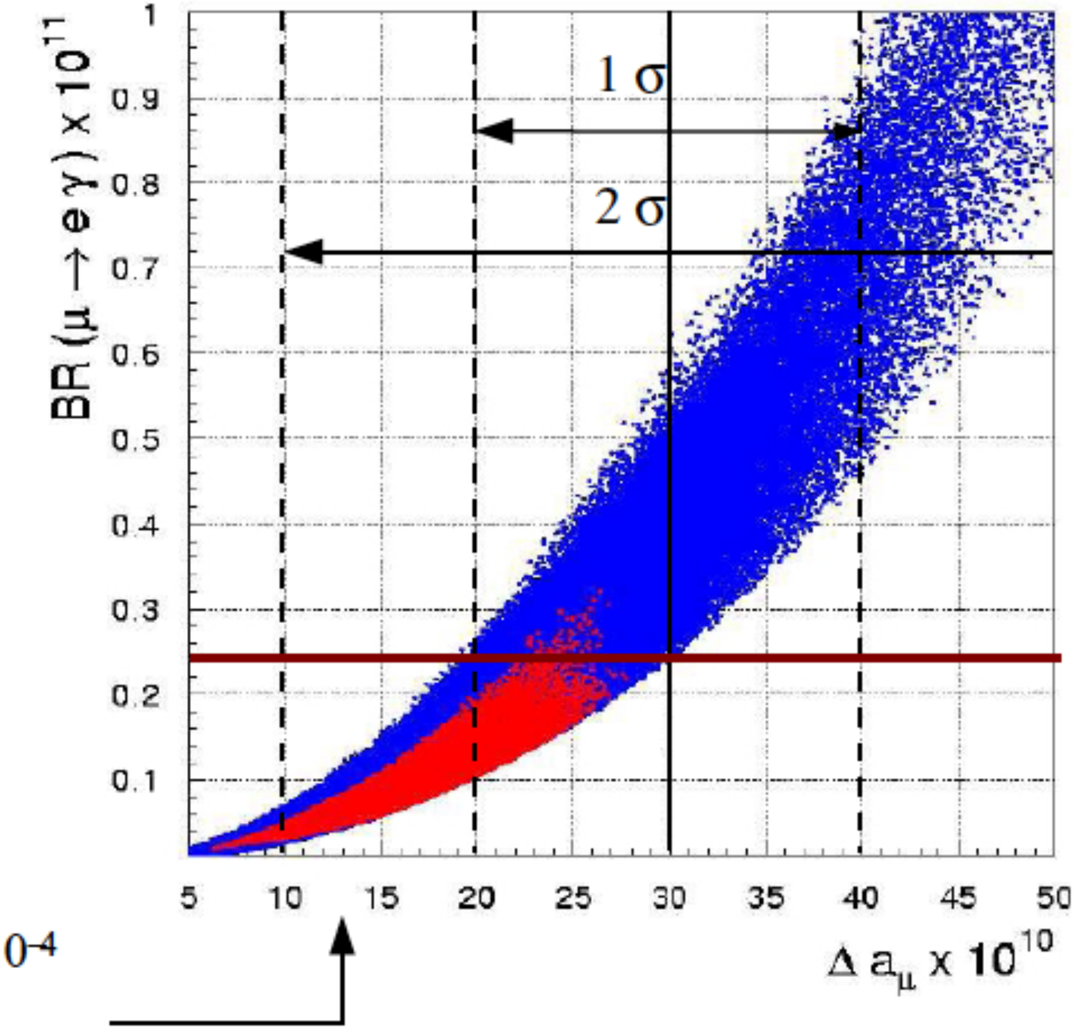
$$L_L^i \sigma^{\mu\nu} E_R^j \phi F_{\mu\nu}$$

Within SUSY:

- same tanβ enhancement,
- same dep. on slepton masses
- only the flavor structure distinguish the two effects

E.g.: $M_R \sim 10^{12}$ GeV $\rightarrow (\delta_{LL})_{12} \sim 10^{-4}$

- No constraints from B physics
- With B physics constraints

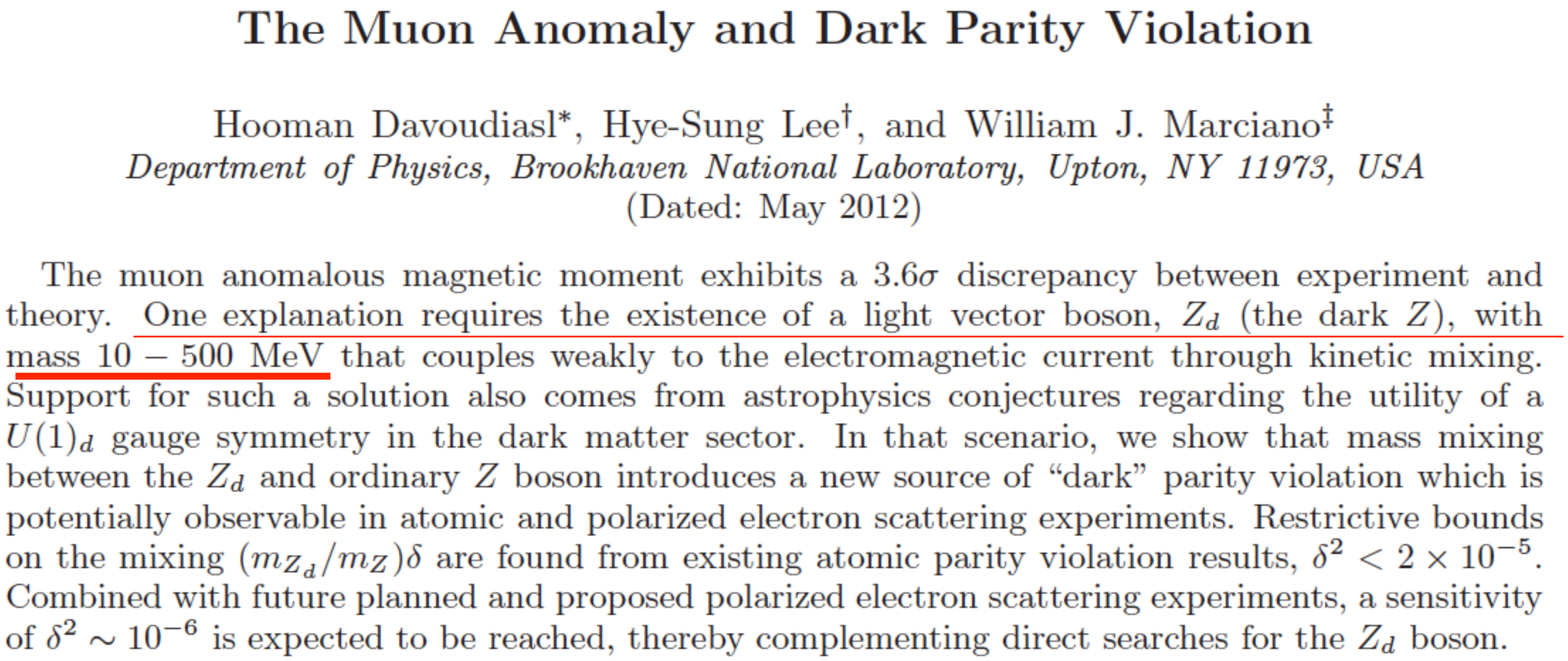


G.I., Mescia, Paradisi, Temes, '07

Dark Photons?

15 May 2012

arXiv:1205.2709v1



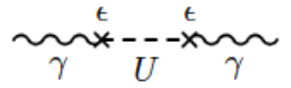
The Muon Anomaly and Dark Parity Violation

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 (KLOE)and fixed target experiments

Summary of present status

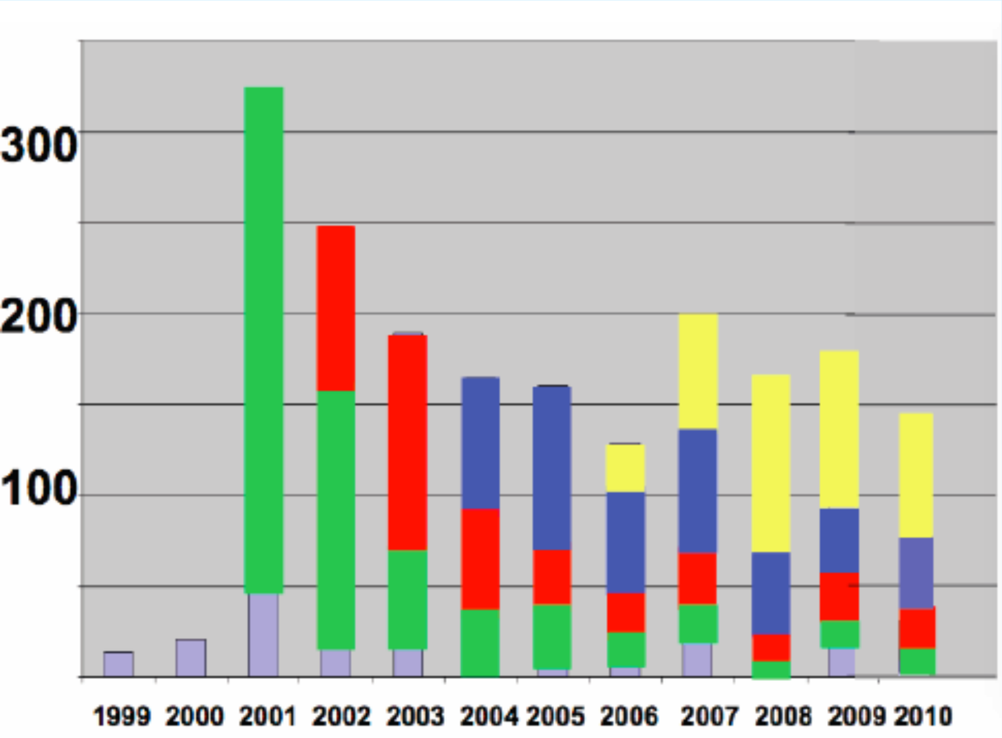
E821 experiment at BNL has generated enormous interest

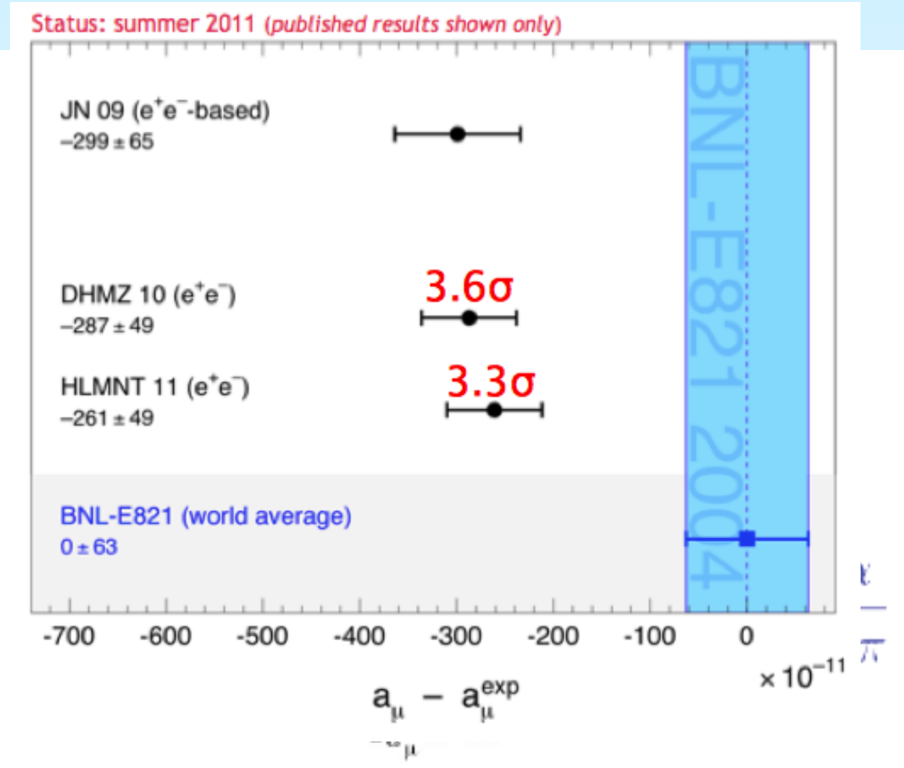
Tantalizing deviation with SM (although persistent since 10 years) is ~3σ

Current discrepancy limited by experimental uncertainty (BNL)

BNL E821 citations

Present



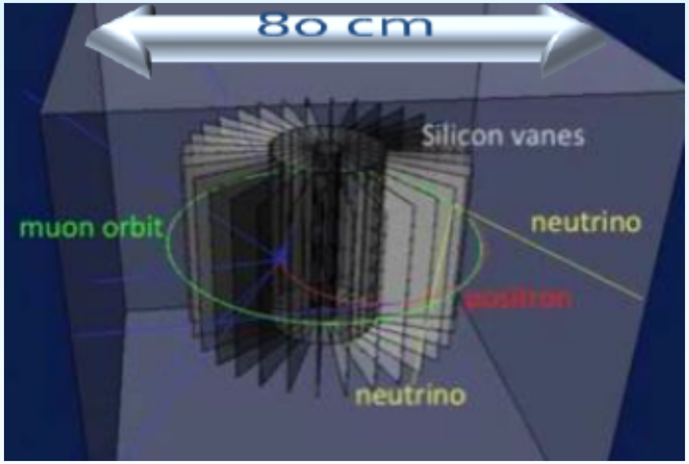


We need a new (possible more) (g-2) experiment(s)!

We need a new (possibly more) $(g\text{-}2)_\mu$ experiment(s)!

Current discrepancy limited by experimental uncertainty. Two proposals to improve it x4:

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20** x μ w.r.t. E821. Relocate the BNL storage ring to FNAL. Has got a Stage-1 approval!

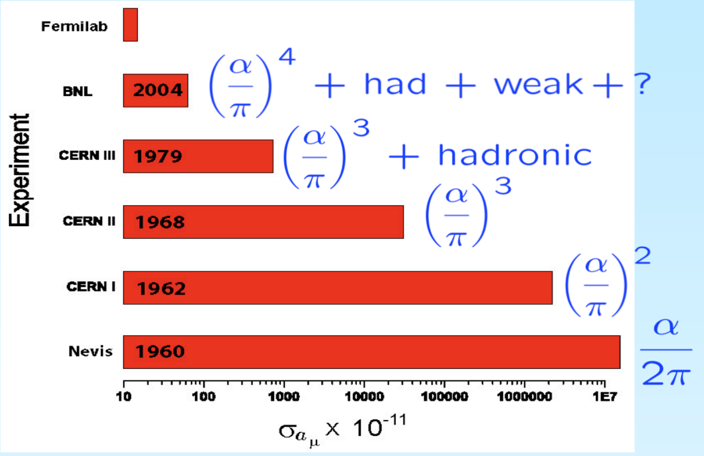


- Alternative proposal at J-PARC w/ out magic momentum and no E field, requiring ultra-slow muons generated from laser-ionised muonium atoms (see talk of Saito)

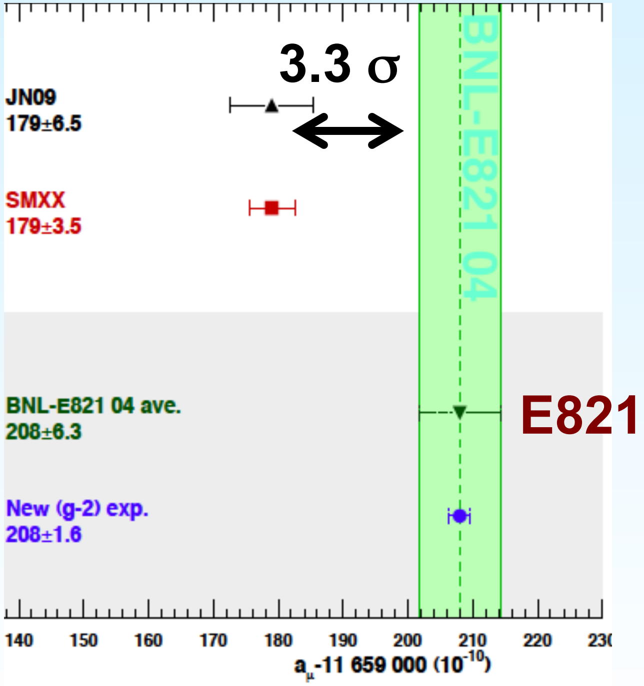
Precision target (E989): 16×10^{-11} (0.14 ppm) . If the central value remains the same ⇒ >7σ from SM!

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 ⇒ 5-8σ from SM* (enough to claim discovery of New Physics!)



***Depending on the progress on Theory**

New experiment at FNAL (E989)

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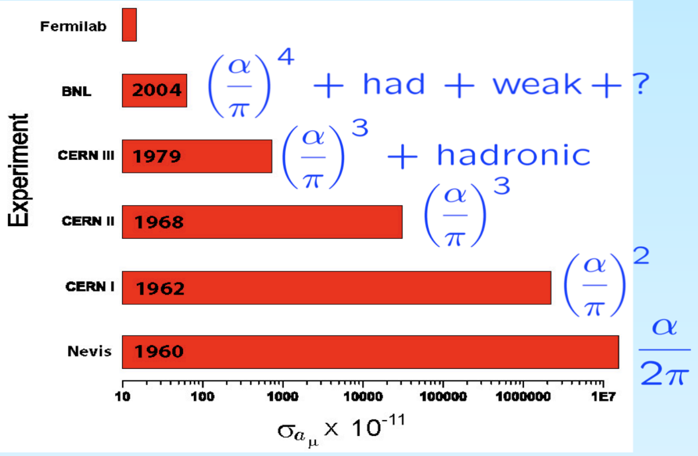

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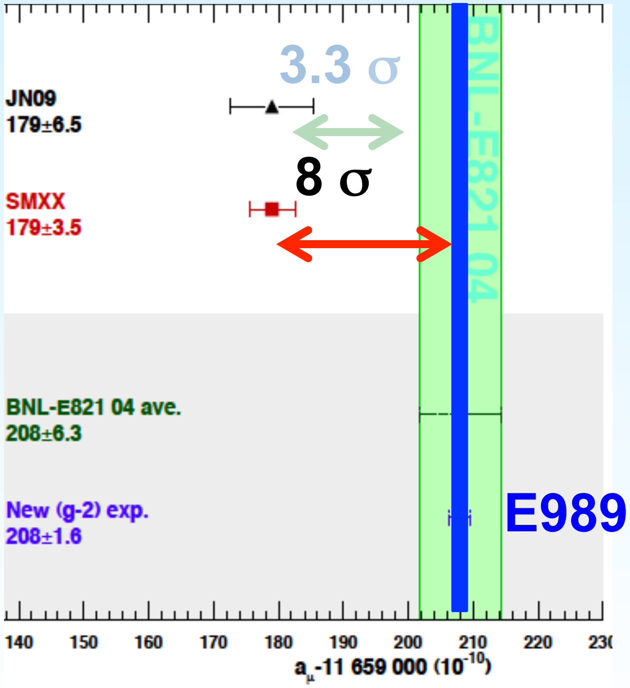


***Depending on the progress on Theory**

Fermilab (g-2) Experiment:

- **E821 at Brookhaven**

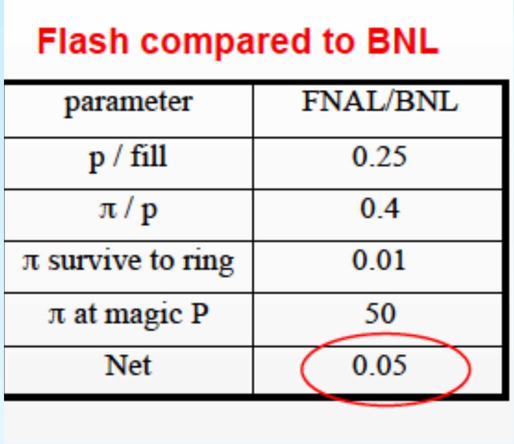
$$\left.\begin{aligned}\sigma_{\text{stat}} &= \pm 0.46\ \text{ppm} \\ \sigma_{\text{syst}} &= \pm 0.28\ \text{ppm}\end{aligned}\right\}\ \sigma = \pm 0.54\ \text{ppm}$$

- **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**

$$\left.\begin{aligned}\sigma_{\text{stat}} &= \pm 0.1\ \text{ppm} \\ \sigma_{\text{syst}} &= \pm 0.1\ \text{ppm}\end{aligned}\right\}\ \sigma = \pm 0.14\ \text{ppm}$$

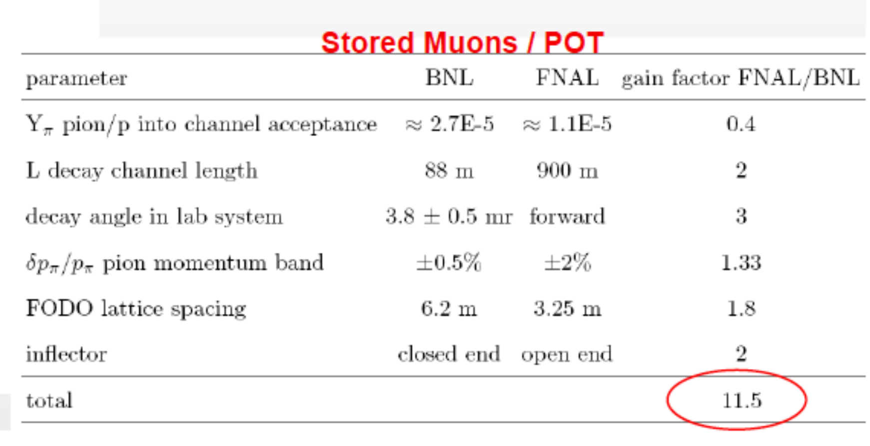
Why Fermilab?

- 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 the booster cycles



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

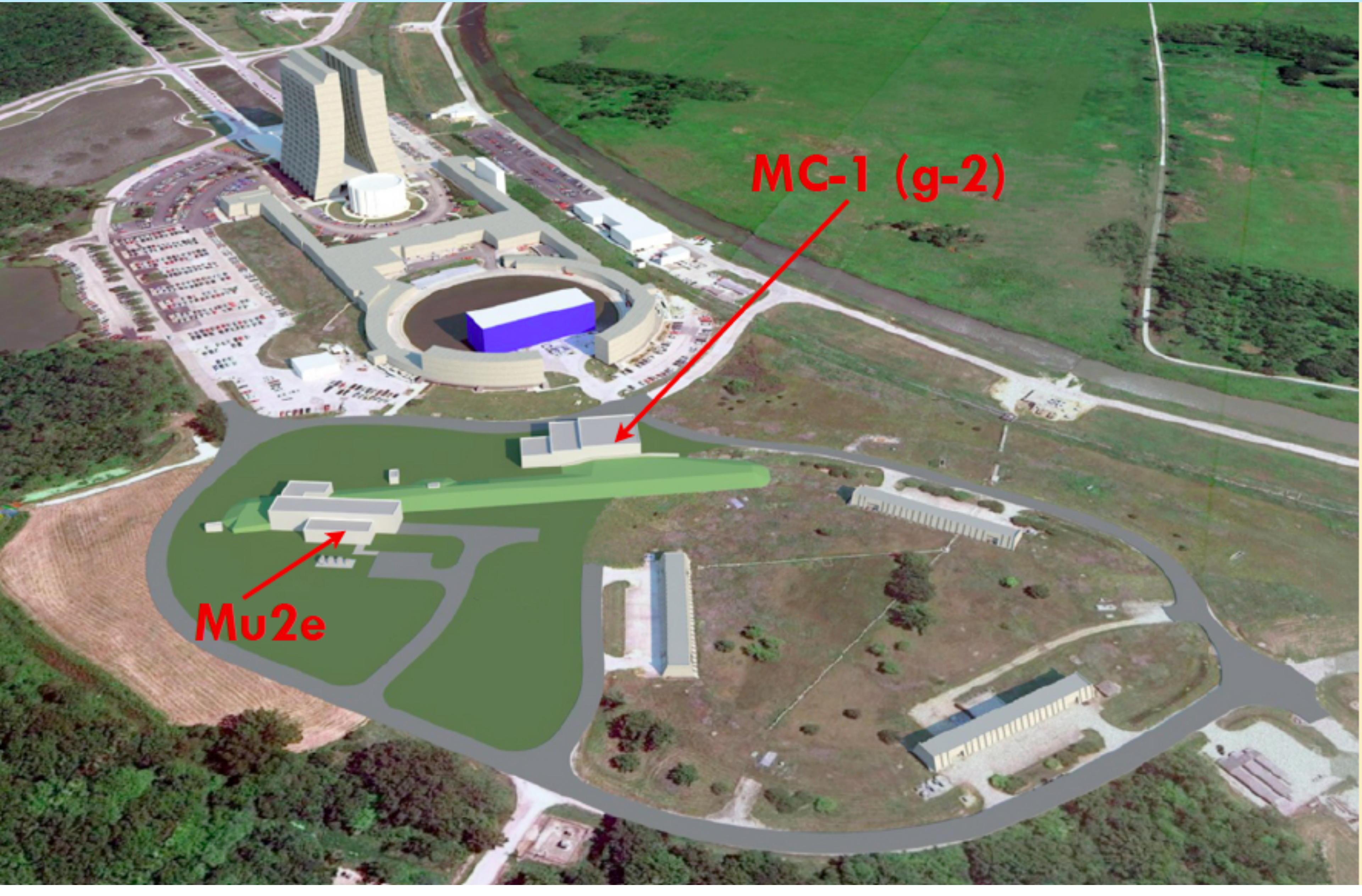
parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi/p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8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

- Expected data taking in 2016

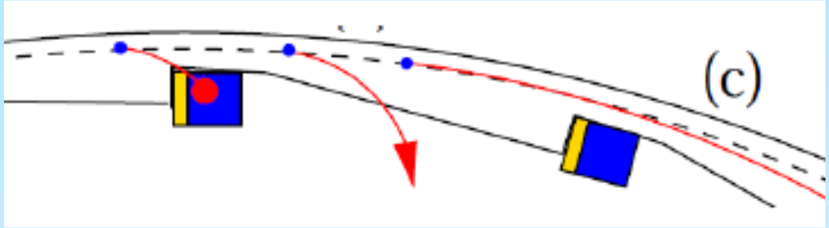
Beam delivery to g-2

- 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

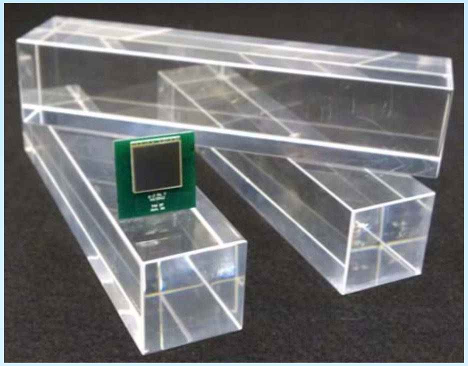
Fermilab Muon Campus



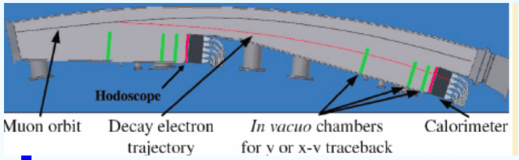
Upgrades at Fermilab



- New segmented detectors to reduce pileup
  - PbF2 Crystals with SIPM
  - $X_0 = 0.93$ cm
  - $\sigma/E \sim 3.5\% / \sqrt{E}$
  - 4 ns pulse width

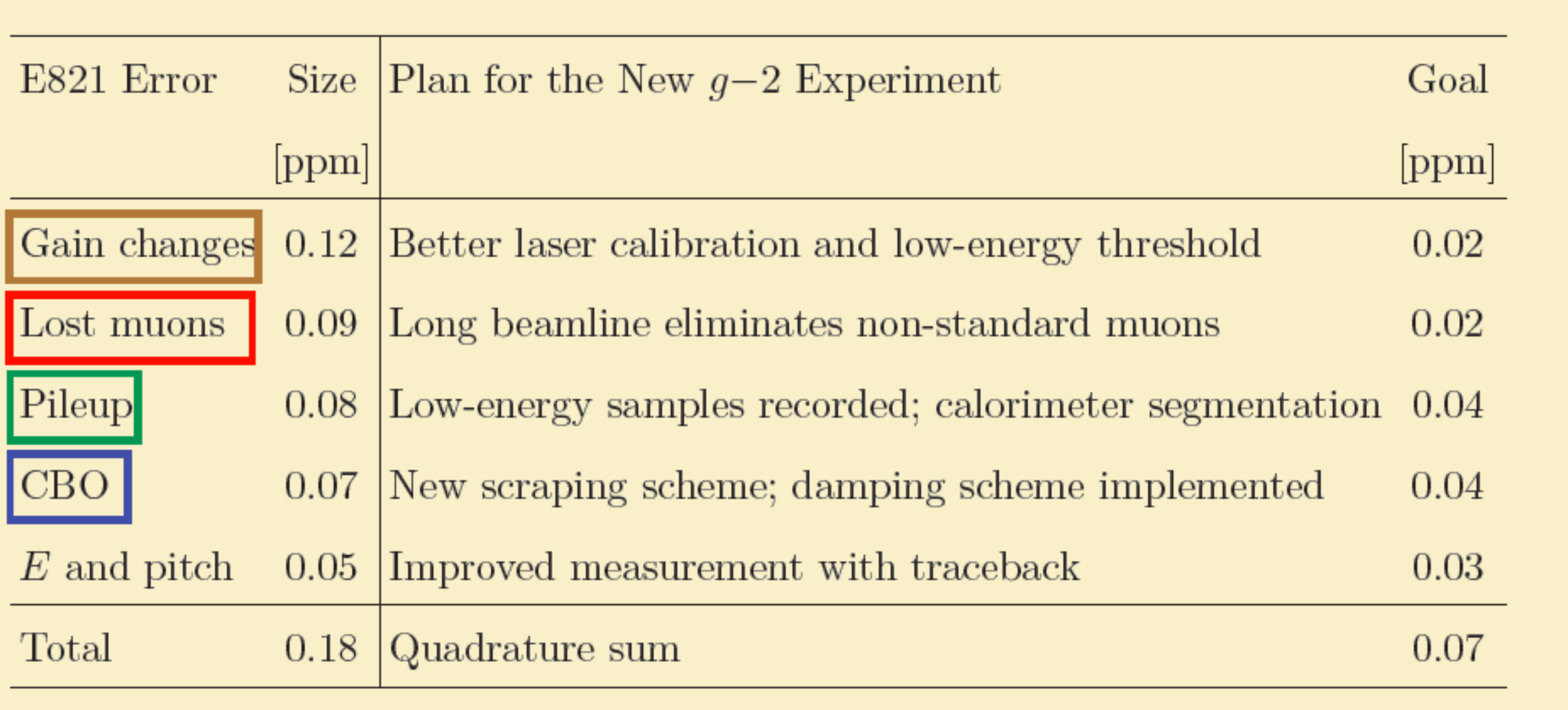


- Calorimeter stability tracked with laser pulsing system (Italian contribution)
- New electronics
  - 500 MHz 12-bit WFDs, with deep memories
- New tracking stations (in vacuum)



- Improvements in the magnetic field calibration, measurement and monitoring.

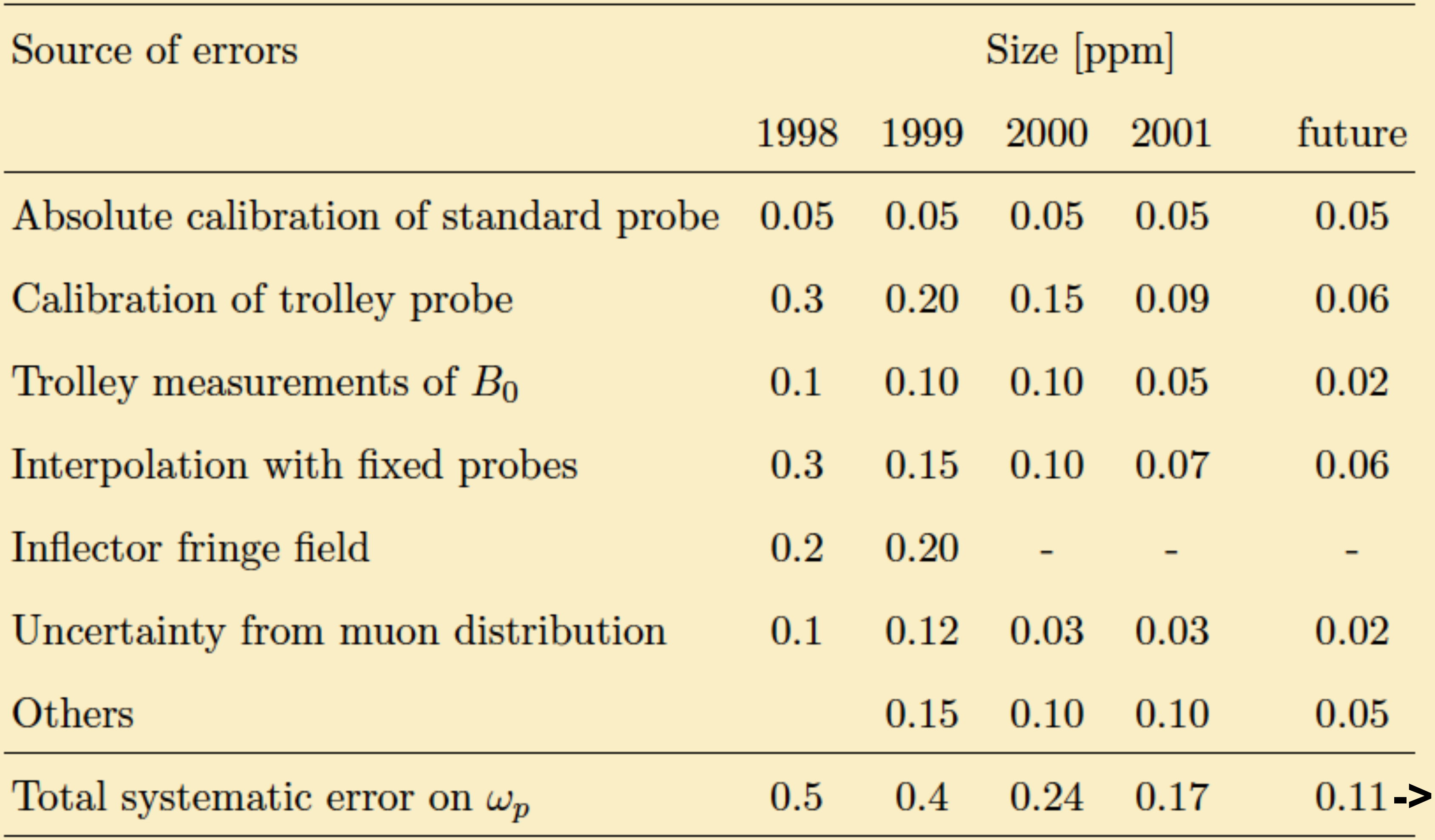
Improving ω_a



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

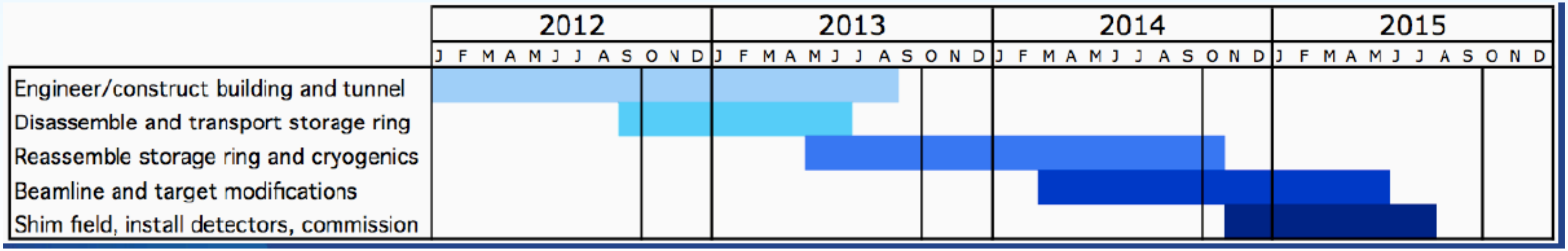


Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe 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**->0.07**

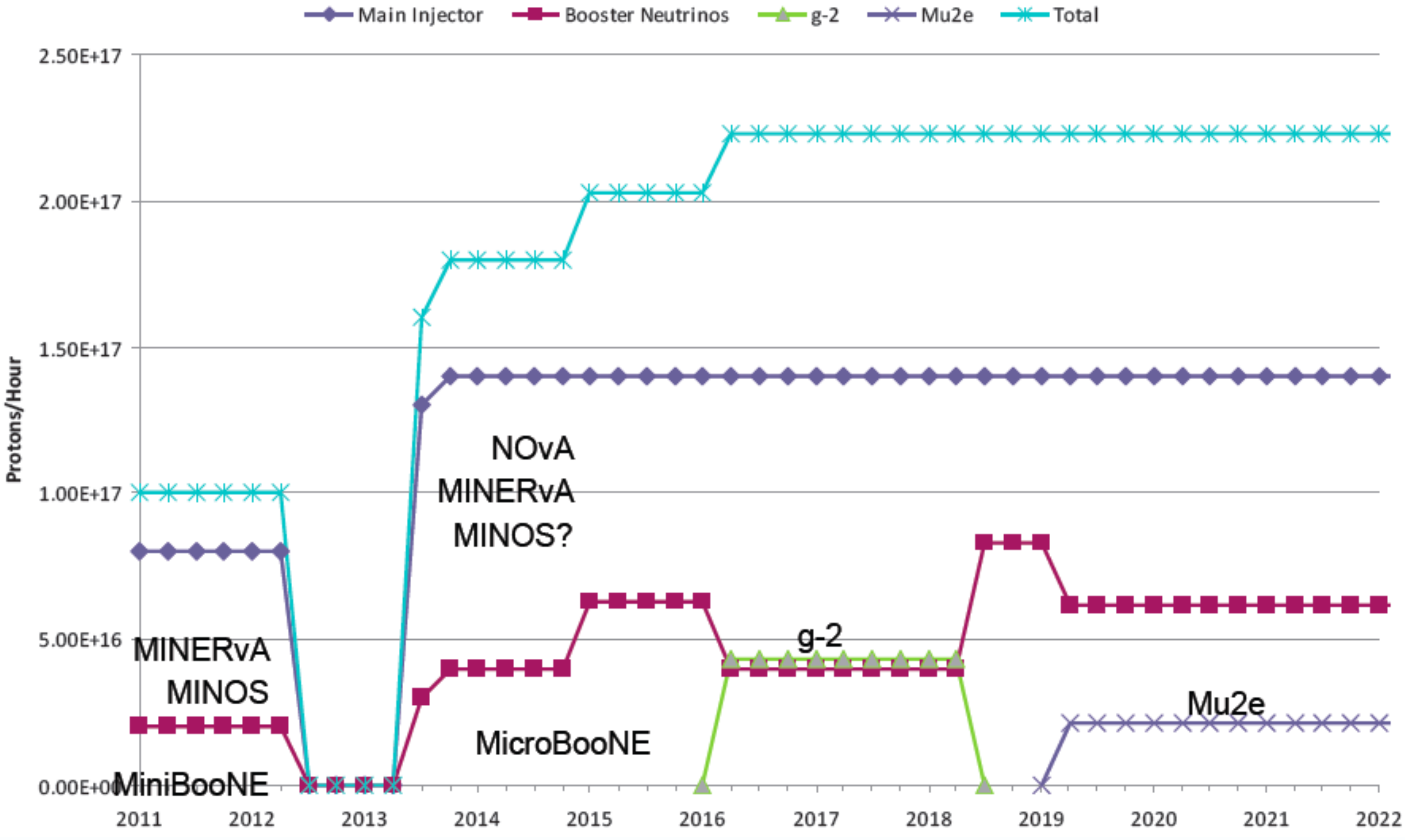
Systematic uncertainty on ω_p expected to be reduced by a factor 2 thanks to **better** shimming (uniformity of B), **relocations** of critical NMR probes, and **other** incremental changes

Time schedule of the Experiment

- Proposal submitted to FNAL, February 2009 (66 authors)
  Positive response from PAC, April 2009
- Stage-I approval January 2010
- CD0 obtained on Settembre 2012
- CD1 review on 17,18 Settembre 2013 (CDR ready (>100 auhtors)) :
- CD2/CD3 in 2014/15
- Expected beam 2016/17



Who gets beam when?



Fermilab Today

Wednesday, Sept. 19, 2012

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.

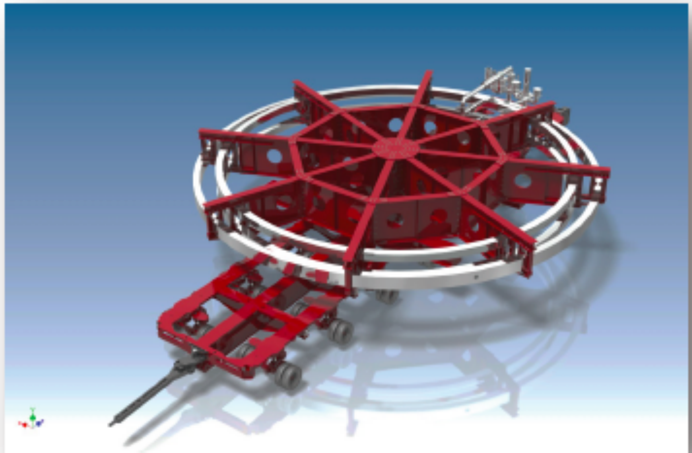
"We now are officially on DOE's roadmap," said Lee Roberts, professor at Boston University and co-spokesperson for the roughly 100 scientists collaborating on the Muon g-2 (pronounced gee minus two) experiment. "This should make it easier to increase the size of our collaboration and foster international 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.

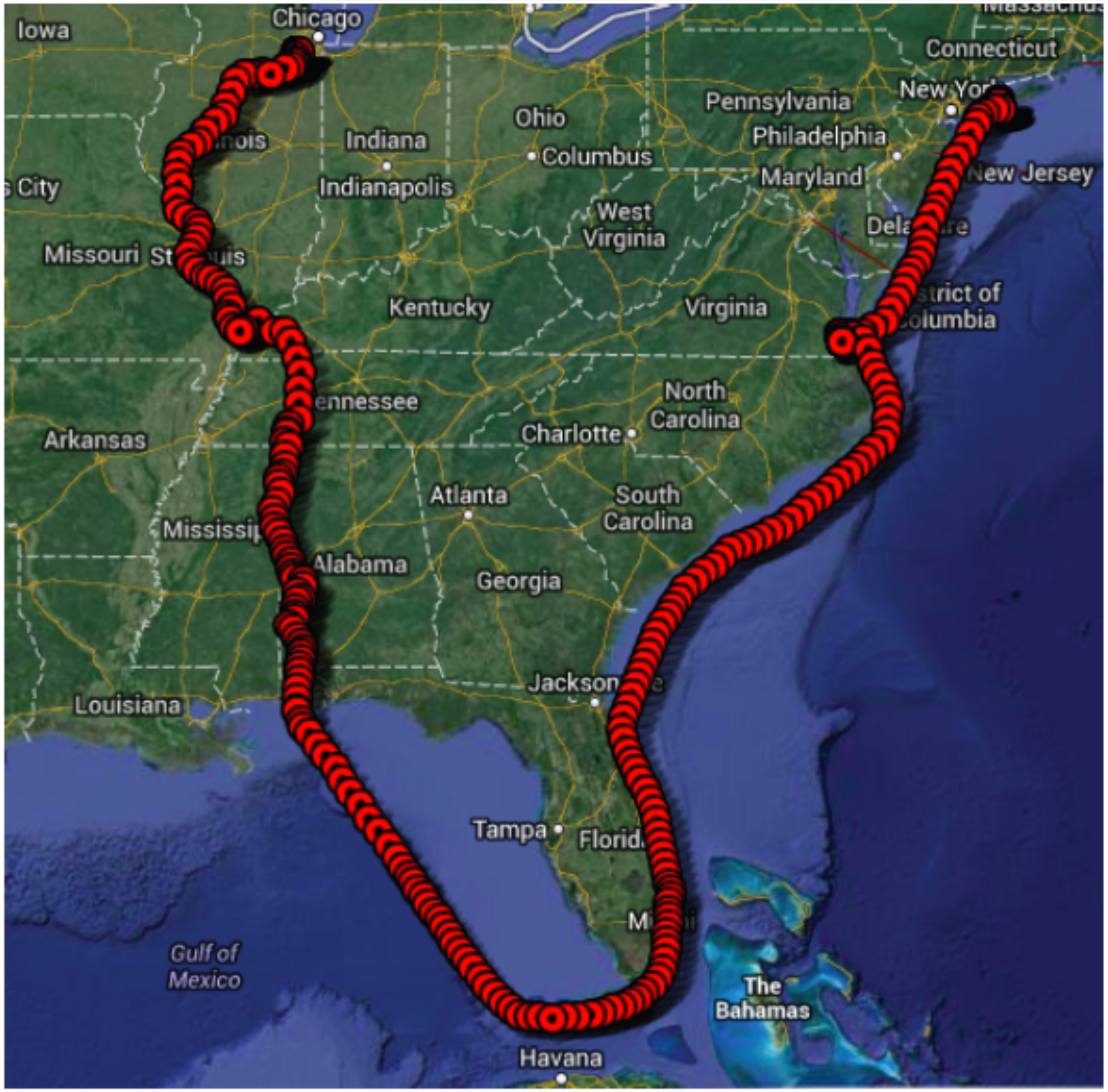
CD0 received in September!

WBS 476.5 Disassembly & Transport

- Most difficult part of transport is delivery of 50 ft diameter superconducting coils
- Emmert International contracted to transport coils
- Coils left BNL Jun 23



WBS 476.5 Disassembly & Transport



- Ended up choosing Southern route for transport
    - Longer, but…
    - Average wave height less than N. Atlantic
    - Never more than 12 hrs from safe harbor
    - $300k cheaper

- Live GPS used to follow ring and engage public
    - Website had more hits than any other special FNAL webpage
    - People came out all along the riverway to see the magnet pass by

WBS 476.5: Start of Chicago ground transport

WBS 476.5: Arrival at FNAL to 3000+ crowd

BNL ring arrived at FNAL for the new g-2 experiment

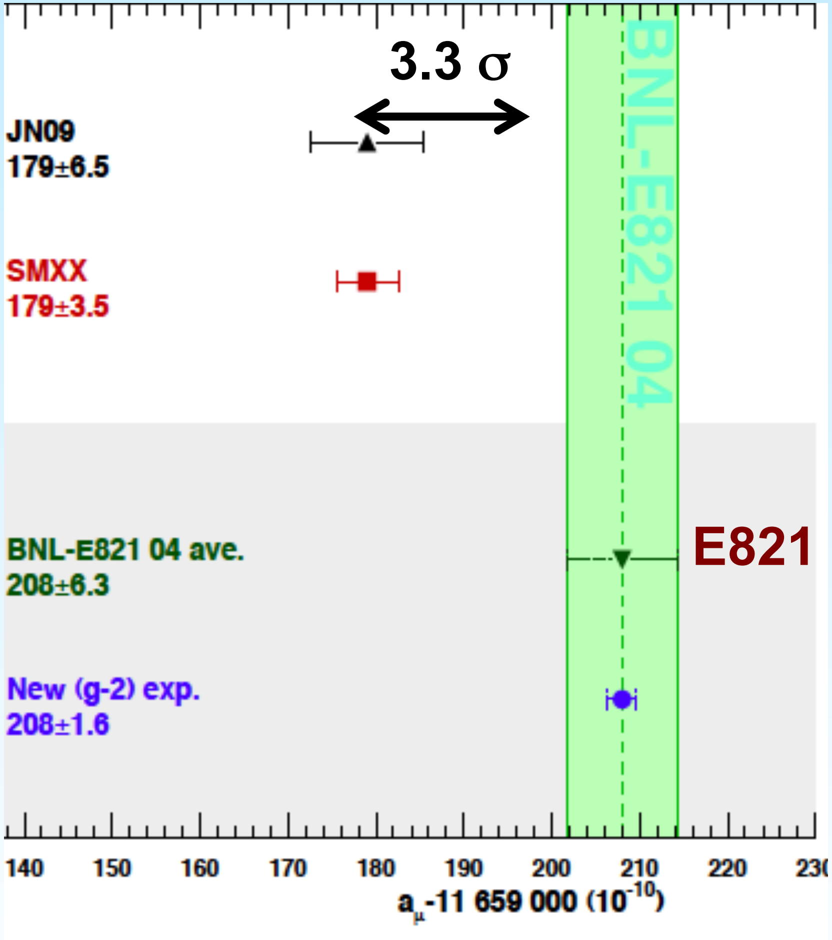

July 26 2013

Which improvements we expect from Theory?

A rough estimate for g-2: now

$a_\mu^{exp} - a_\mu^{theo,SM} = (27.7 \pm 8.4) 10^{-10}$ (3.3σ)

$8.4 = \sim 5_{HLO} \oplus \sim 3_{HLbL} \oplus 6_{BNL}$



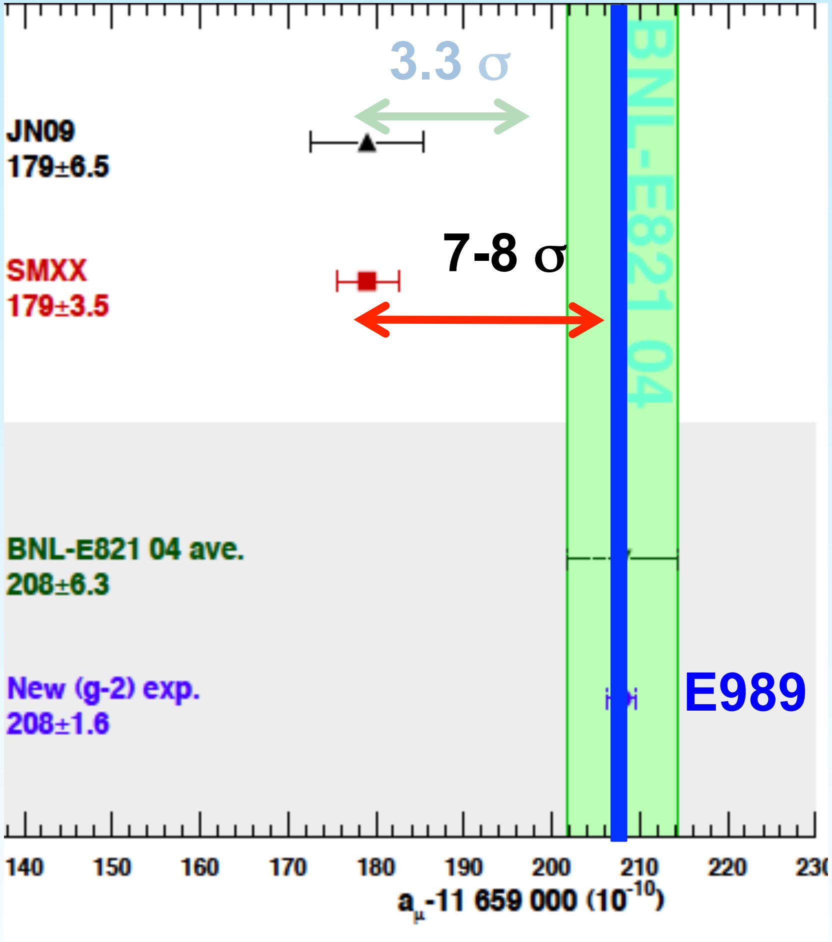
$\delta a_\mu^{HLO} = 5.3 = 3.3(\sqrt{s} < 1 GeV) \oplus 3.9(1 < \sqrt{s} < 2 GeV) \oplus 1.2(\sqrt{s} > 2 GeV)$

A rough estimate for g-2: …and (possible) future

$a_\mu^{exp} - a_\mu^{theo,SM} = (27.7 \pm 8.4)10^{-10}$ (3.3σ)

$8.4 = \sim 5_{HLO} \oplus \sim 3_{HLbL} \oplus 6_{BNL}$

4 3 3 $1.6_{\text{NEW G-2}}$



$a_\mu^{exp} - a_\mu^{theo,SM} = (XXX \pm 3.8)10^{-10}$

If central value is the same → 7-8σ

(if no progress on theory → 5 σ)

$\delta a_\mu^{HLO} \rightarrow 2.6 = 1.9\ (\sqrt{s} < 1\,\text{GeV}) \oplus 1.3\ (1 < \sqrt{s} < 2\,\text{GeV}) \oplus 1.2 (\sqrt{s} > 2\,\text{GeV})$

This is possible if:

- $\delta\sigma_{HAD}$ ~ 0.4% $\sqrt{s}<1$GeV (instead of 0.7% as now)

(Possible at KLOE2 with 1-2 fb^{-1} at 1 GeV)

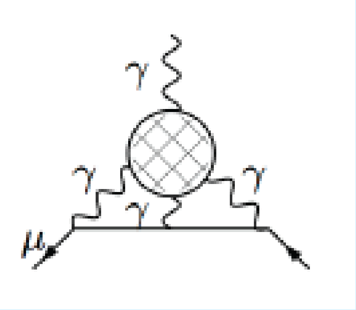
- $\delta\sigma_{HAD}$ ~ 2% $1<\sqrt{s}<2$GeV (instead of 6% as now)

(Possible with direct scan at VEP2000 and with ISR at Flavour factories)

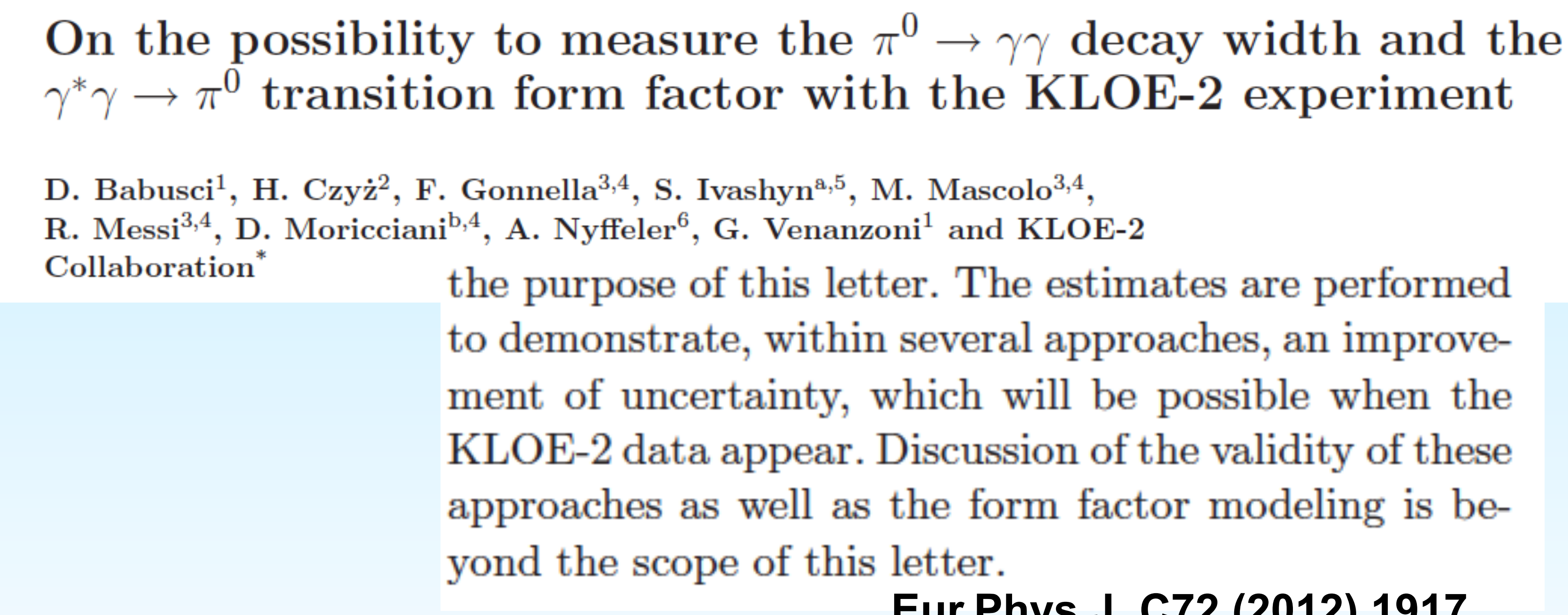
δa_{μ}^{HLO} = 2.6 (instead of ~5 as now)

Understanding of Radiative Corrections essential!!!

What about HLbL ?



- As today δa_{μ}^{LbL} =[2.5-4]10^{-10}
- How to improve? γγ physics can help? YES!



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[1], H. Czyż[2], F. Gonnella[3,4], S. Ivashyn[a,5], M. Mascolo[3,4], R. Messi[3,4], D. Moricciani[b,4], A. Nyffeler[6], G. Venanzoni[1] and KLOE-2 Collaboration*

the purpose of this letter. The estimates are performed to demonstrate, within several approaches, an improvement of uncertainty, which will be possible when the KLOE-2 data appear. Discussion of the validity of these approaches as well as the form factor modeling is beyond the scope of this letter.

Eur.Phys.J. C72 (2012) 1917

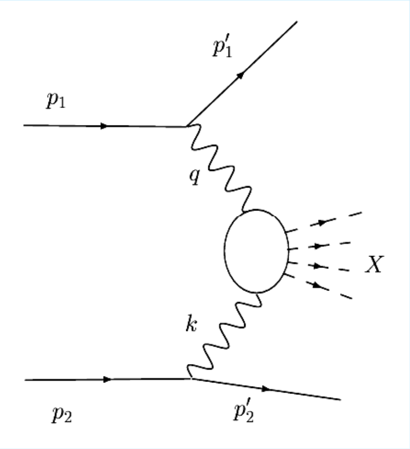
γγ physics is done at B-factories.

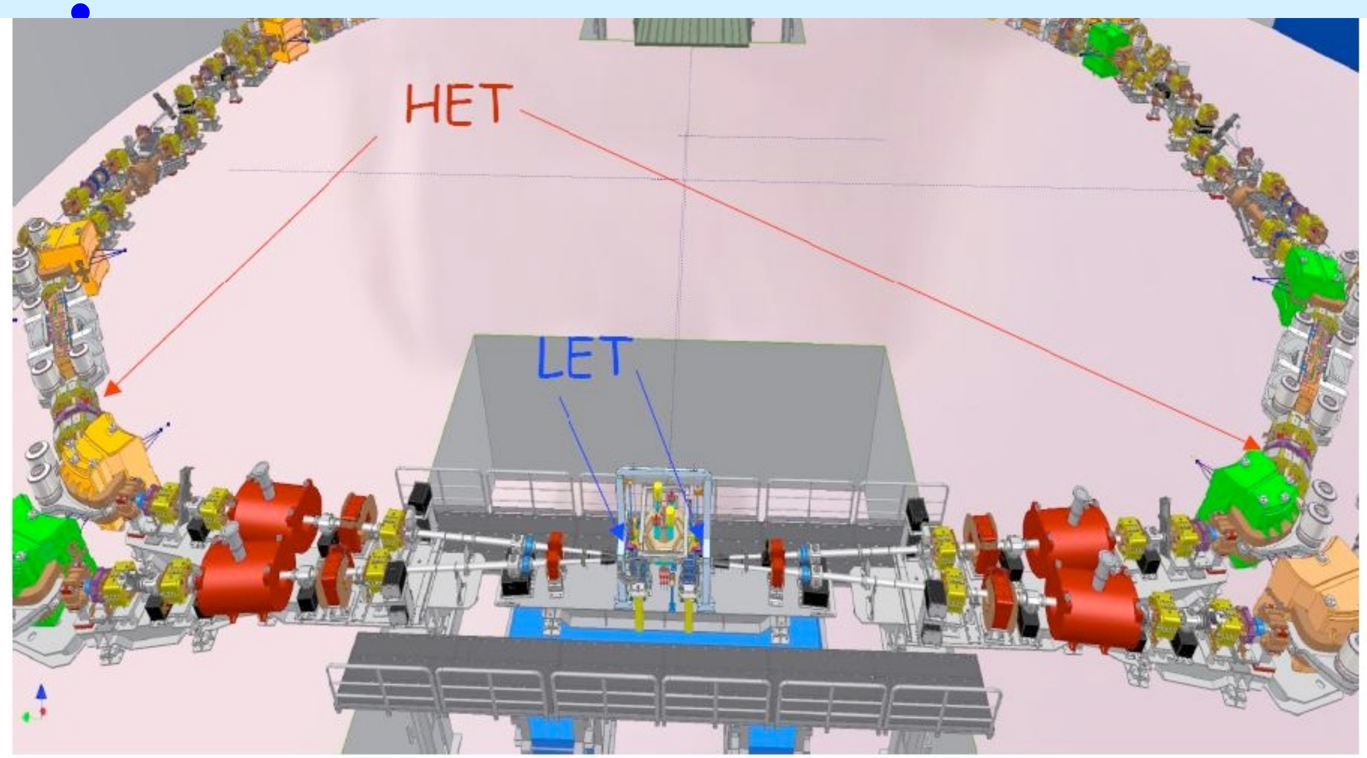
It will also be done at KEDR, KLOE-2 and BESIII with dedicated detectors, in a region where data are scarse

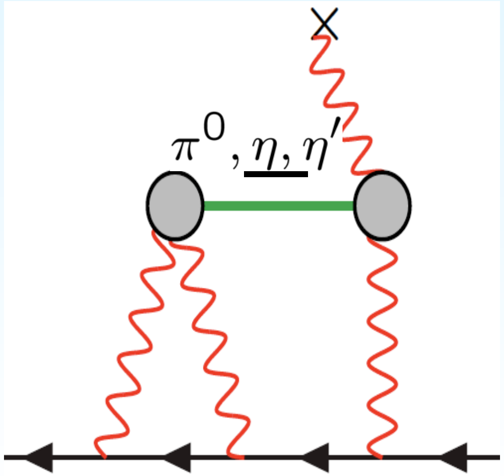
Also e+e- → PSγ can help (at KLOE2, BESIII, etc…)

KLOE-2 to measure $\gamma\gamma^* \to \pi^0,\eta$ to constrain a_μ^{HLBL}

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



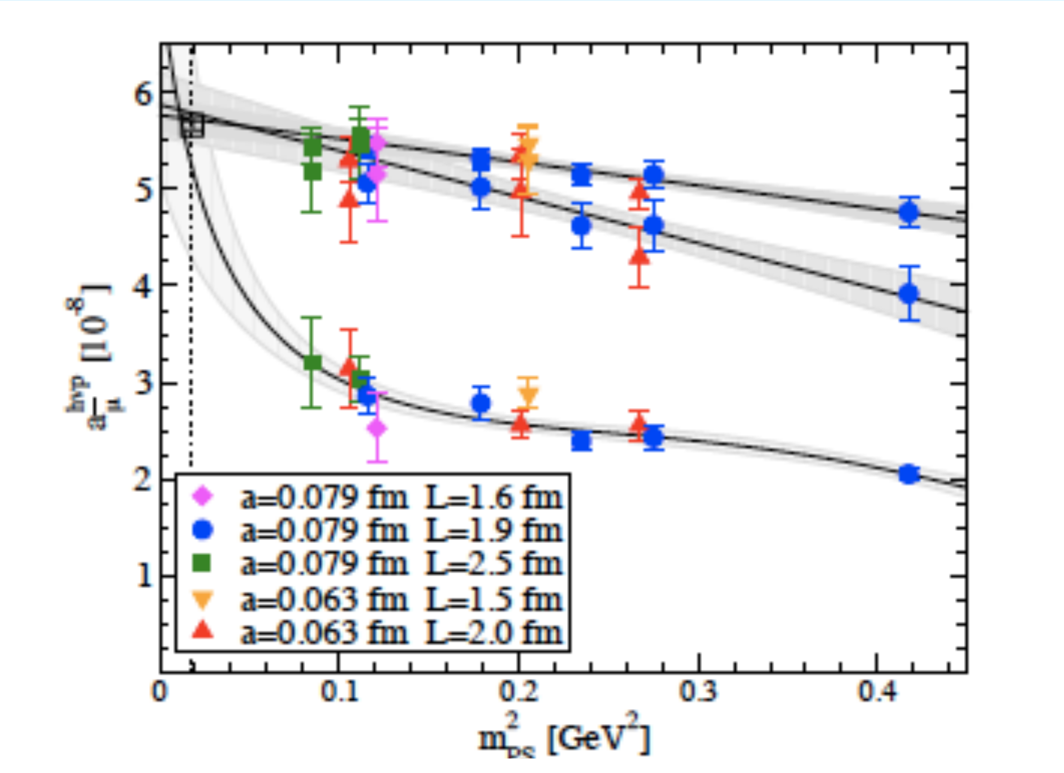




For details see: D. Babusci et al., Eur.Phys.J. C72 (2012) 1917

Of course other approaches are possible

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



Very promising results!

Prospects for HLBL?

Experimental value:

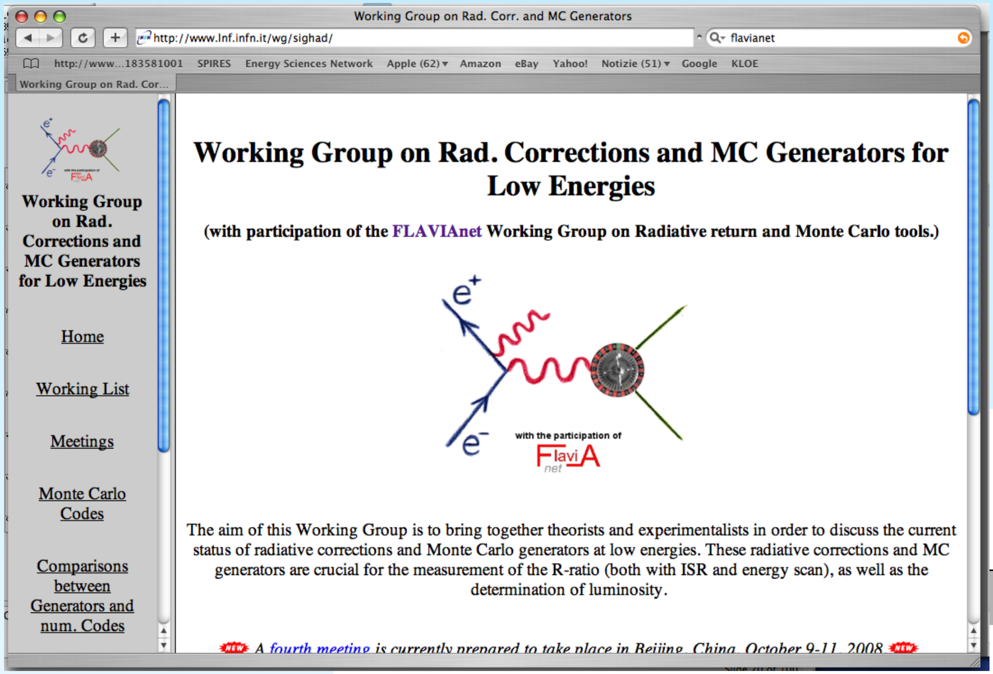
$$a_{\mu,N_f=2}^{\mathrm{hvp,exp}} = 5.66(05)10^{-8}$$

$$a_{\mu,N_f=2}^{\mathrm{hvp,new}} = 5.66(11)10^{-8}$$

← ***Excellent agreement***

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

In both cases experimental and theoretical activities are essential!



Working Group on Rad. Corrections and MC Generators for Low Energies

(with participation of the FLAVIAnet Working Group on Radiative return and Monte Carlo tools.)

The aim of this Working Group is to bring together theorists and experimentalists in order to discuss the current status of radiative corrections and Monte Carlo generators at low energies. These radiative corrections and MC generators are crucial for the measurement of the R-ratio (both with ISR and energy scan), as well as the determination of luminosity.

NEW A fourth meeting is currently prepared to take place in Beijing, China, October 9-11, 2008 NEW

Radio MonteCarLow WG

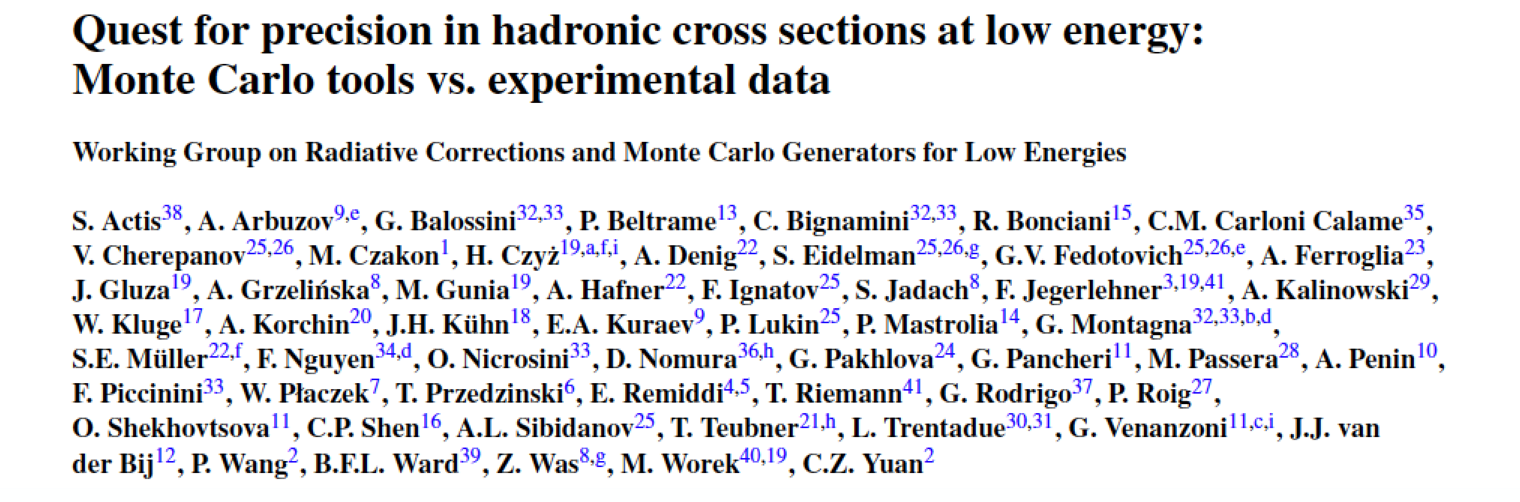
H.Czyz and G.V. conveners

60 participants, 13 countries

See www.lnf.infn.it/wg/sighad

for more information

THE EUROPEAN PHYSICAL JOURNAL C



Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies

S. Actis[38], A. Arbuzov[9,e], G. Balossini[32,33], P. Beltrame[13], C. Bignamini[32,33], R. Bonciani[15], C.M. Carloni Calame[35], V. Cherepanov[25,26], M. Czakon[1], H. Czyż[19,a,f,i], A. Denig[22], S. Eidelman[25,26,g], G.V. Fedotovich[25,26,e], A. Ferroglia[23], J. Gluza[19], A. Grzelińska[8], M. Gunia[19], A. Hafner[22], F. Ignatov[25], S. Jadach[8], F. Jegerlehner[3,19,41], A. Kalinowski[29], W. Kluge[17], A. Korchin[20], J.H. Kühn[18], E.A. Kuraev[9], P. Lukin[25], P. Mastrolia[14], G. Montagna[32,33,b,d], S.E. Müller[22,f], F. Nguyen[34,d], O. Nicrosini[33], D. Nomura[36,h], G. Pakhlova[24], G. Pancheri[11], M. Passera[28], A. Penin[10], F. Piccinini[33], W. Płaczek[7], T. Przedzinski[6], E. Remiddi[4,5], T. Riemann[41], G. Rodrigo[37], P. Roig[27], O. Shekhovtsova[11], C.P. Shen[16], A.L. Sibidanov[25], T. Teubner[21,h], L. Trentadue[30,31], G. Venanzoni[11,c,i], J.J. van der Bij[12], P. Wang[2], B.F.L. Ward[39], Z. Was[8,g], M. Worek[40,19], C.Z. Yuan[2]

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. Possible sign of New Physics?

- 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

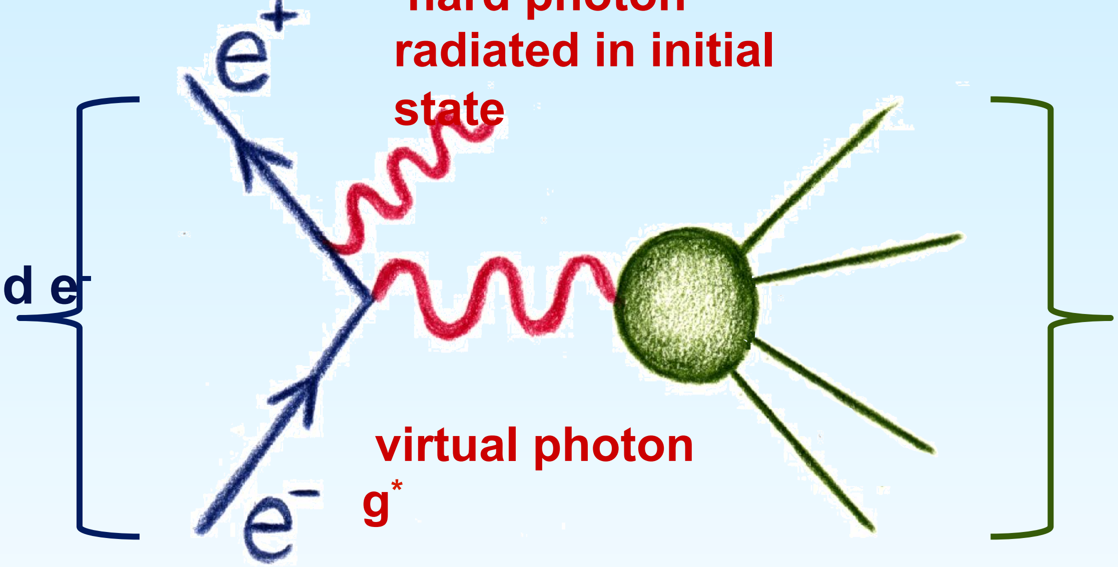
- Theoretical uncertainty will improve thanks to current and planned experimental activities (as well as theoretical ones)

Stay Tuned!

SPARES

ISR: Initial State Radiation

Particle factories (DAFNE, PEP-II, KEK-B) can measure hadronic cross sections as a function of the hadronic c.m. energy using initial state radiation (radiative return to energies below the collider energy $\sqrt{s}$).



hard photon radiated in initial state

incoming e^+ and e^-

with $M^2_{ee} = s$

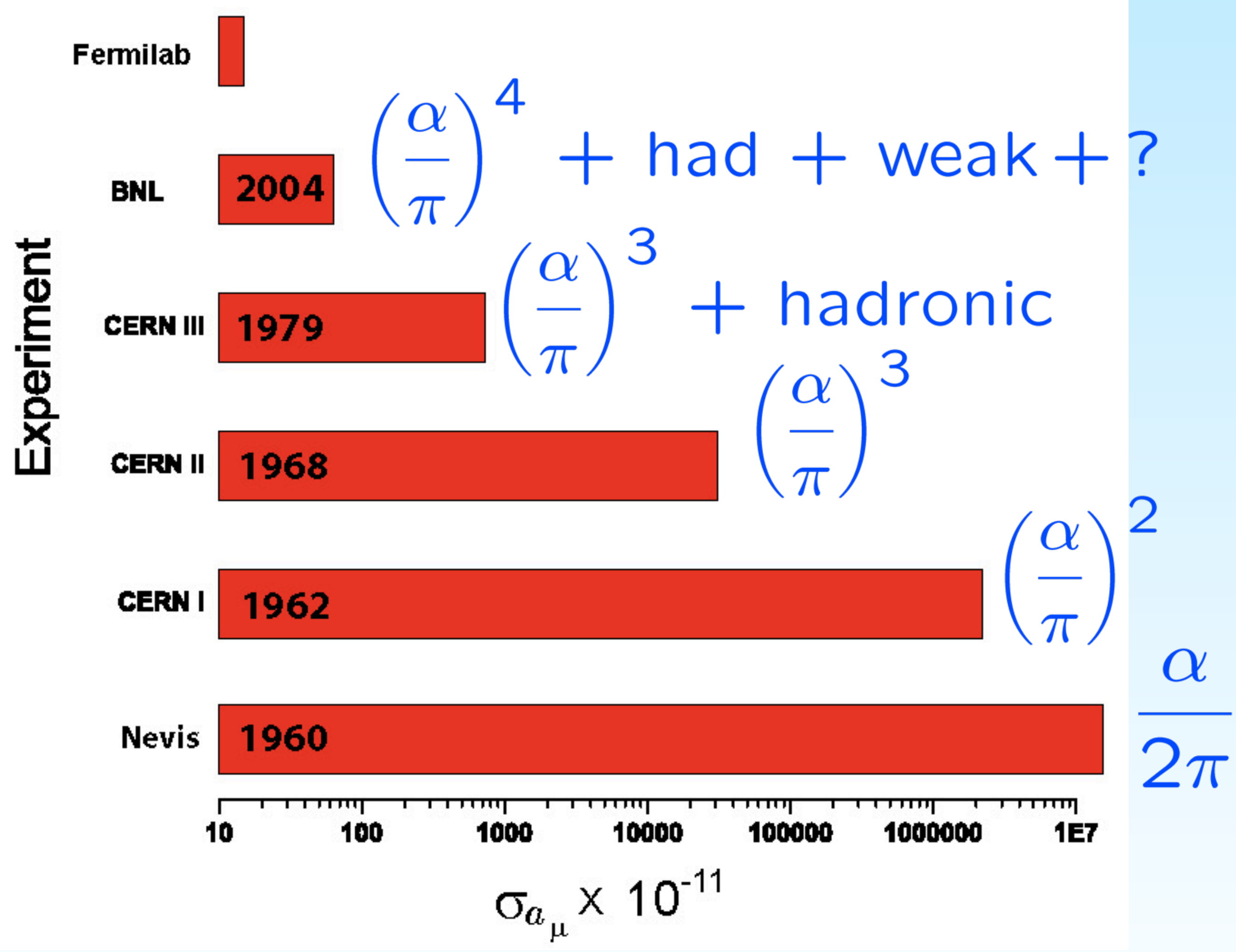
hadrons

virtual photon g^*

with $M^2_{g^*} < s$

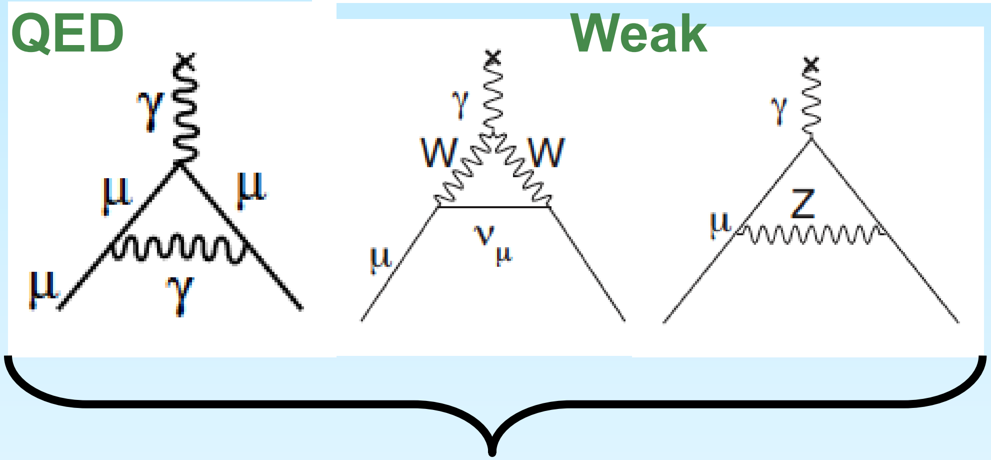
The emission of a hard g in the bremsstrahlung process in the initial state reduces the energy available to produce the hadronic system in the e^+e^- collision.

Thank you for your attention!

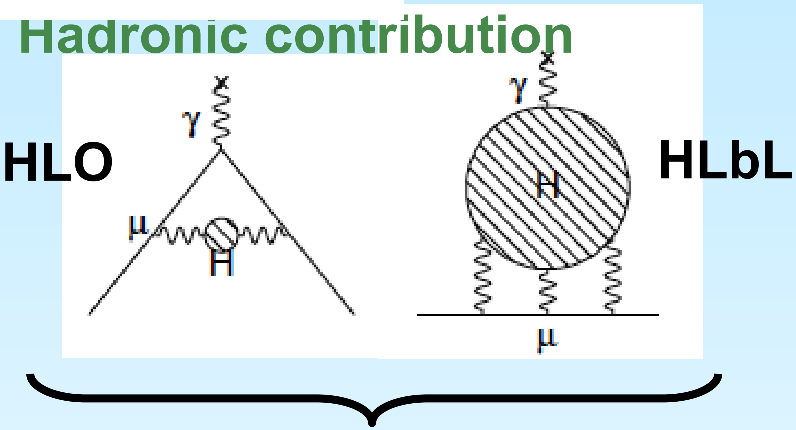


“Standard Model” contribution to (g-2)

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$



Precisely known



Large uncertainty

(significant work going on)

$a_\mu^{QED} \sim \alpha/2\pi \sim O(10^{-3})$ $a_\mu^{Weak} \sim O(10^{-9})$[2ppm] $a_\mu^{HAD} \sim 7\text{x}10^{-8}$ [60ppm]

$\delta a_\mu^{QED} \sim 0.001$ppm $\delta a_\mu^{Weak} \sim 0.02$ppm $\delta a_\mu^{HAD} \sim 0.5$ppm (dominates)

- CERN (’70): $\delta a_\mu^{exp} \sim 8\text{x}10^{-9}$ [7ppm] -> sensitive to a_μ^{HAD}
- E821 (’01): δa_μ^{exp} $6\text{x}10^{-10}$ [0.54 ppm] -> sensitive to a_μ^{WEAK} 3σ with SM!
- FNAL E989 (‘1X) -> δa_μ exp $1.6\text{x}10^{-10}$ [0.14 ppm] -> $a_\mu^{New\ Physics}$?

Need of Electric field for Vertical Focusing

$$\begin{aligned}\vec{\omega}_a &= \omega_S - \omega_C \\ &= -\frac{q}{m}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}}\right]\end{aligned}$$

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

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

If p_μ= 3.09 GeV (magic momentum) there is no effect of the electric field on the precession frequency!

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

Measure (precisely) ω_a and B and get a_μ!

But…how to measure ω_a?

Produce polarized muons and let them decay…

The Muons

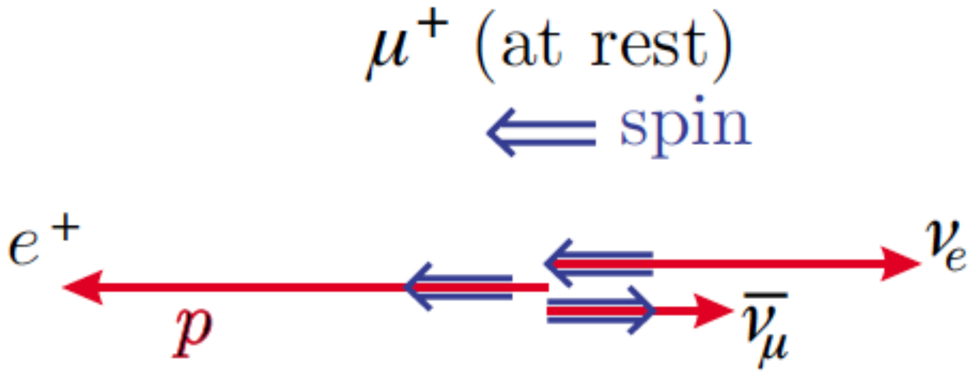
- produced polarized in “forward” direction

$$\pi^- \longrightarrow \mu^- \; \bar{\nu}_\mu$$

- decay with information on where their spin was at the time of decay

$$\mu^- \longrightarrow e^- \; \bar{\nu}_e \; \nu_\mu$$

S-p correlation fundamental to all muon anomaly experiments

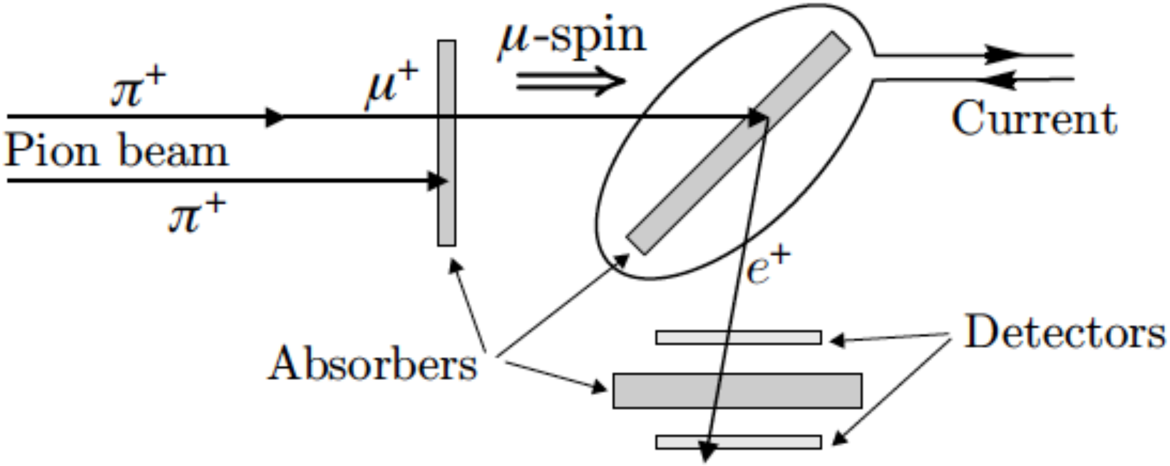


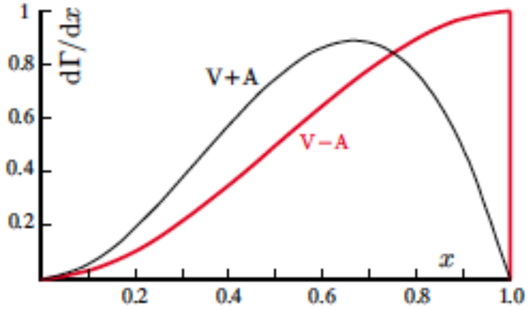
High energy positrons have momentum along the muon spin. The opposite is true for electrons from μ^-.

Detect high energy electrons. The time dependence of the signal tracks muon precession.

highest energy $e^\pm$ carry μ spin information

4. $\pi \rightarrow \mu \rightarrow e$





The rate of high energy decay electrons is time modulated with a frequency corresponding to the precession of a magnetic moment $e/m(\mu)$ or a muon with g=2. First measurement of $g(\mu)$!!

Arrival time of high energy electron:

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

Cross section data:

At low energies (< 2 GeV) only measurements of exclusive channels, two approaches:

Energy scan (CMD2, SND):

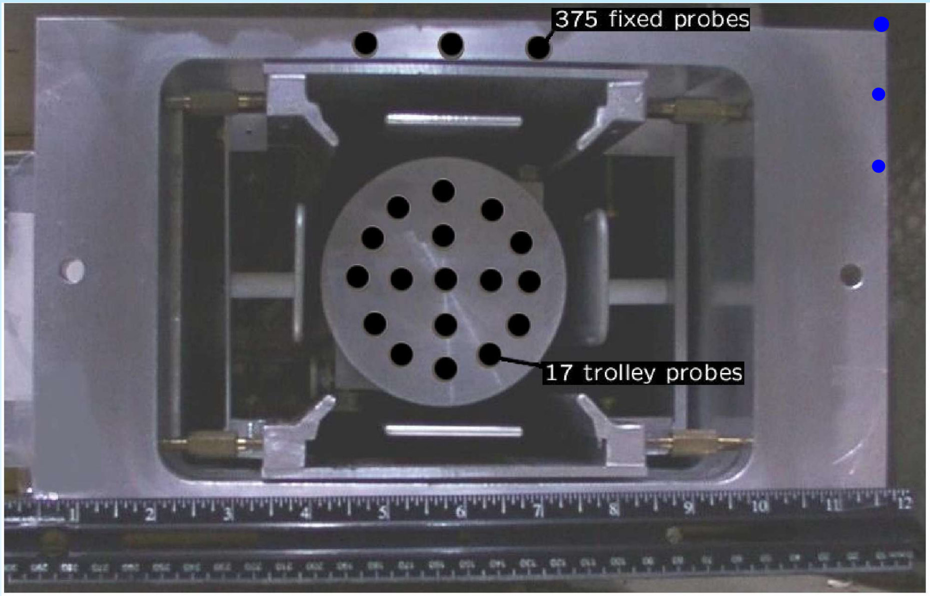
- energy of colliding beams is changed to the desired value
- "direct" measurement of cross sections
- needs dedicated accelerator/physics program
- needs to measure luminosity and beam energy for every data point

Radiative return (KLOE, BABAR, BELLE):

- runs at fixed-energy machines (meson factories)
- use initial state radiation process to access lower lying energies or resonances
- data come as by-product of standard physics program
- requires precise theoretical calculation of the radiator function
- luminosity and beam energy enter only once for all energy points

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

ω_p

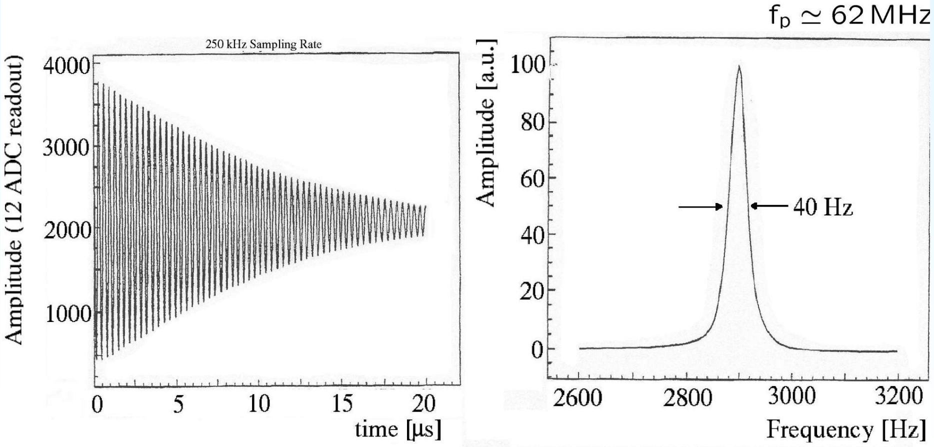


- ω_p= Larmor frequency of the free p
- We measure ω_a and ω_p independently
- Use $\lambda = \mu_\mu / \mu_p$ as the "fundamental constant"

Blind analysis

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

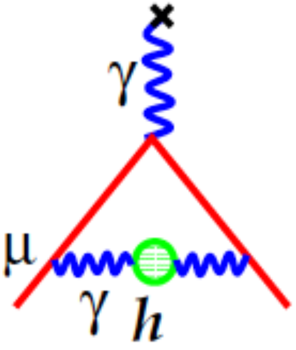
Free induction decay signals:



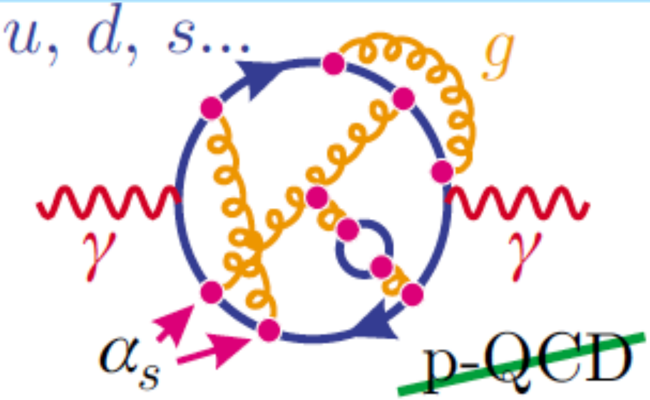
So which was the result for aμ?

Hadronic contribution to g-2 : a_μ^{HLO} failure of PQCD

Need



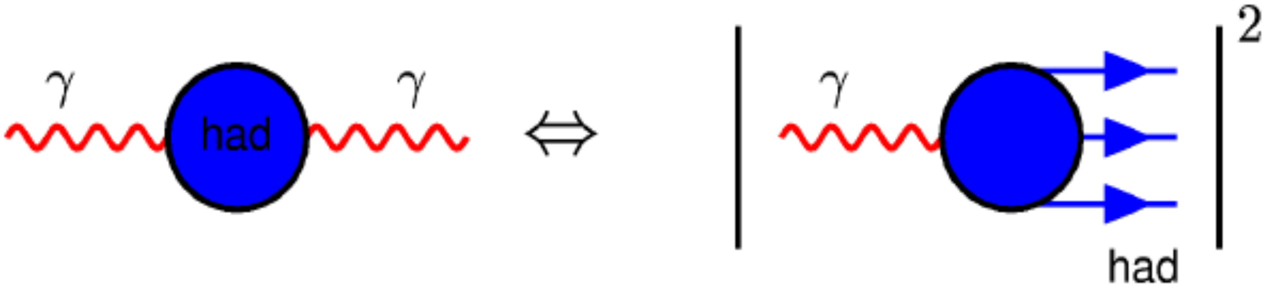
i.e.



which is not calculable at low q^2.

But. . .

Measure $\sigma(e^+e^- \to \text{hadrons})$ and use dispersion relations:



$\Pi'_\gamma(q^2)$

$\sim \sigma^{\text{had}}_{\text{tot}}(q^2)$

1 / s² makes important **low energy contributions (<2.5 GeV)**

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

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

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

hadronic electron-positron cross section data

a_μ SM vs experiment: 3.3σ

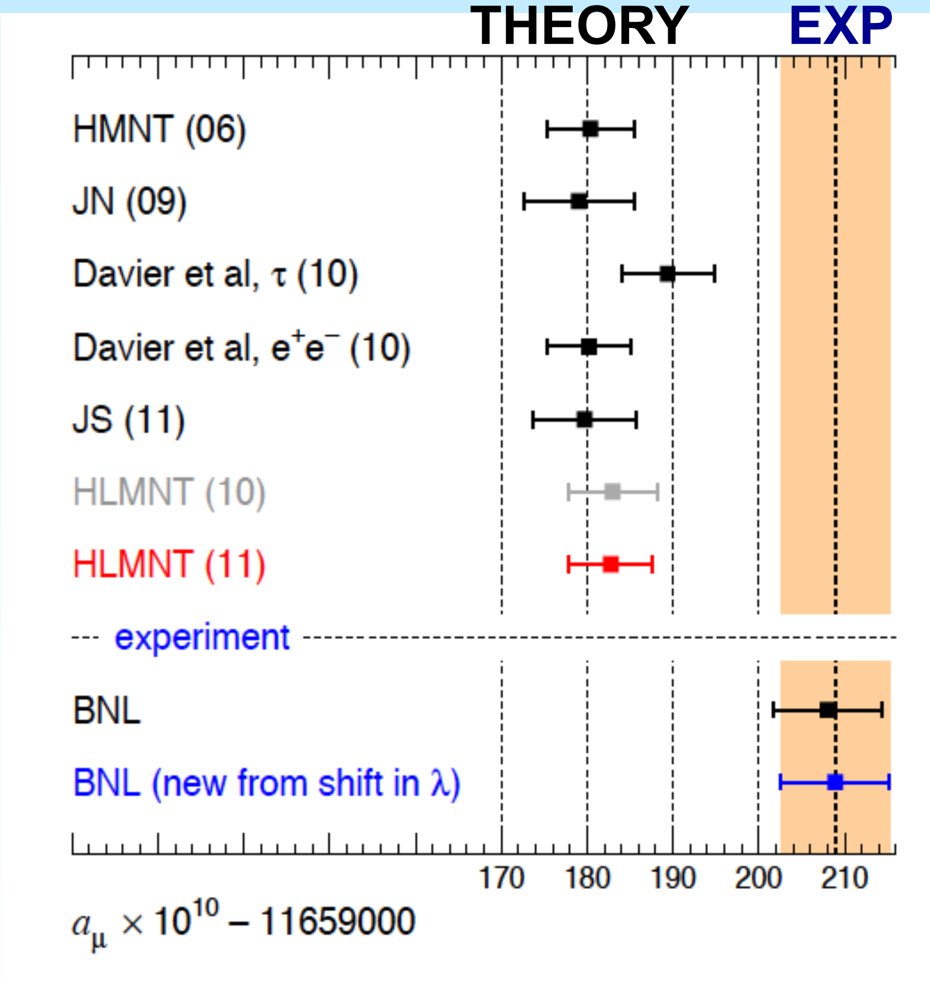
$$a_\mu = \frac{(g_\mu - 2)}{2}$$

- Long established discrepancy (>3σ) between SM prediction and BNL E821 exp.

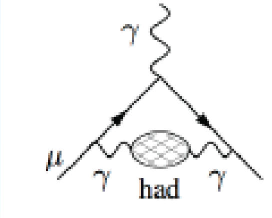
$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{TH}} = (27.6 \pm 8.1) \cdot 10^{-10}, \ \sim \mathbf{3.4\sigma}$$

- Theoretical error δa_μ^{SM} ($5 \div 6 \times 10^{-10}$) dominated by hadronic contributions (HLO and LbL)

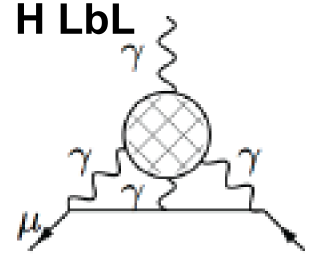
- Experimental error $\delta a_\mu^{EXP} = 6.3 \times 10^{-10}$ (0.54 ppm), E821. Plan to reduce it to $1.6\ 10^{-10}$ (0.14 ppm) at FNAL



HLO VP



H LbL



$a_\mu^{HLO} = (690.9 \pm 4.4) 10^{-10}$

[S.Eidelman, TAU08]

δa_μ^{HLO} ~0.6%

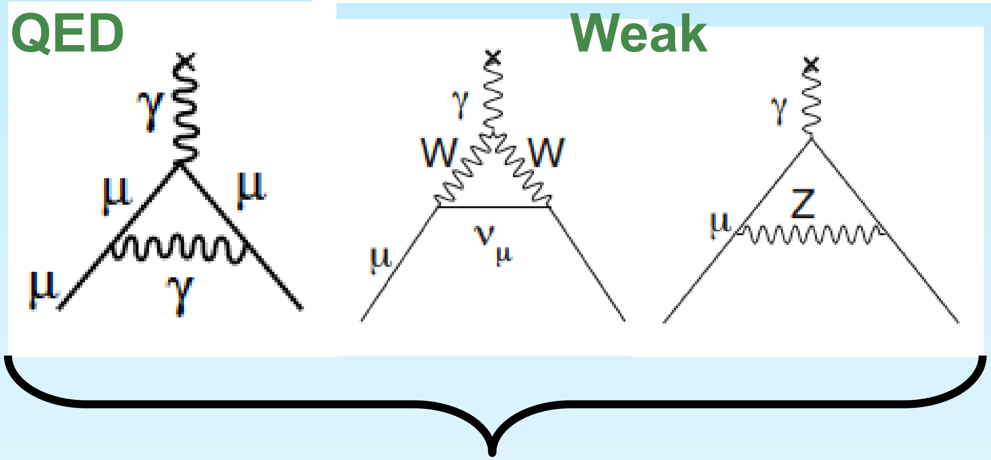
$a_\mu^{HLbL} = (10.5 \pm 2.6) 10^{-10}$ [P. dR&V. 08]

$(11 \pm 4) 10^{-10}$ (J.N.)

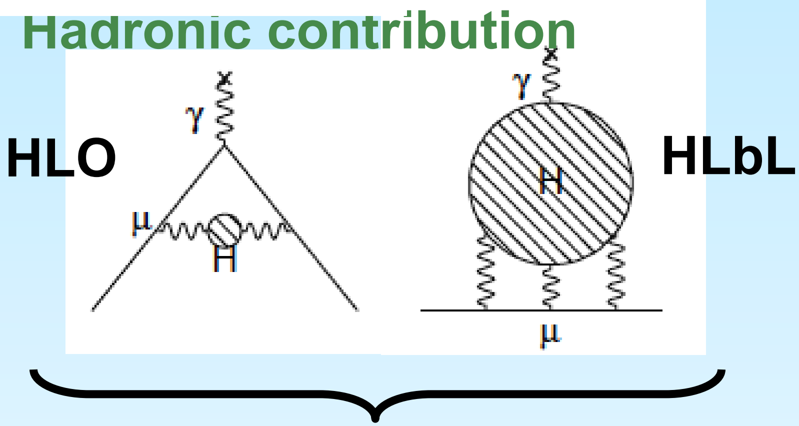
δa_μ^{HLbL} ~25-40%

"Standard Model" contribution to (g-2)

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$



Precisely known



Large uncertainty

(significant work going on)

a_μ^{QED} ~$\alpha/2\pi$~ $O(10^{-3})$ a_μ^{Weak} ~ $O(10^{-9})$[2ppm] a_μ^{HAD} ~ $7\mathrm{x}10^{-8}$ [60ppm]

δa_μ^{QED} ~ 0.001ppm δa_μ^{Weak} ~ 0.02ppm δa_μ^{HAD} ~ 0.5ppm (dominates)

- **CERN ('70): δa_μ^{exp} ~$8\mathrm{x}10^{-9}$ [7ppm] -> sensitive to a_μ^{HAD}**
- **E821 ('01): δa_μ^{exp} $6\mathrm{x}10^{-10}$ [0.54 ppm] -> sensitive to a_μ^{WEAK} 3σ with SM!**
- **FNAL E989 ('1X) -> δa_μ exp $1.6\mathrm{x}10^{-10}$ [0.14 ppm] -> $a_\mu^{New\ Physics}$?**