Theory of Muon $g - 2$

Joaquim Prades
CAFPE and Universidad de Granada

Workshop on Low Energy Constraints

on Extensions of the Standard Model,

24 July 2009 Kazimierz

Plan

- Introduction: Electron $g-2$

Plan

- Introduction: Electron $g-2$
- Main Contribution to $g-2$: QED

Plan

- Introduction: Electron $g-2$
- Main Contribution to $g-2$: QED
- Electroweak Contribution to Muon $g-2$

Plan

- Introduction: Electron $g-2$
- Main Contribution to $g-2$: QED
- Electroweak Contribution to Muon $g-2$
- Hadronic Contributions to Muon $g-2$

Plan

- Introduction: Electron $g-2$
- Main Contribution to $g-2$: QED
- Electroweak Contribution to Muon $g-2$
- Hadronic Contributions to Muon $g-2$
- Conclusions and Prospects

Introduction

Fermion–External EM Field $A^\mu(q = p - p')$ Vertex

$$\bar{u}(p')\Gamma_\mu u(p) = \bar{u}(p')\left[\gamma_\mu F_1(q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2m_l}F_2(q^2) + \cdots\right]u(p)$$

Magnetic Dipole Moment for Charged Fermion ($l = e, \mu, \tau, \cdots$)

$$\vec{\mu} = g_l \frac{e}{2m_l}\vec{s} \quad \text{with} \quad g_l \equiv 2\left(F_1(0) + F_2(0)\right)$$

Dirac Vertex Prediction

Tree-Level: $F_1(0) = 1$ and $F_2(0) = 0$

Quantum Loops: $F_1(0) = 1$ and $a_l \equiv F_2(0) \neq 0$

The Electron Anomaly

Very Recent Measurement of a_e:

2006-2008 Harvard group: $a_e^{\rm exp} = (11\,596\,521\,807.3 \pm 2.8)\,10^{-13}$

1987 Univ. of Washington group:

$a_e^{\rm exp} = (11\,596\,521\,883 \pm 42)\,10^{-13}$ Factor 15 of improvement !!

α_{QED}: one order of magnitude more precise !

$\alpha^{-1} = 137.035\,999\,084(33)(39) = 137.035\,999\,084(51)$

than previous determinations

Cs atom (2002): $\alpha^{-1} = 137.036\,000\,000(1100)$

Rb atom (2006): $\alpha^{-1} = 137.035\,998\,780(910)$

Wrong: Based on a_e 2007

PDG 2008 (CODATA 2006): $\alpha^{-1} = 137.035\,999\,679(94)$

Main Contribution: QED

$$a_e^{\text{QED}} = \sum_{n=1} C_{2n} \left(\frac{\alpha}{\pi}\right)^n$$

$C_2 = 1/2$: Schwinger •

C_4: Analytical including lepton mass corrections •
Sommerfield; Petermann; Suura, Wichmann; Elend; Passera

C_6: Analytical including lepton mass corrections •
Kinoshita, Barbieri, Laporta, Remiddi, $\cdots$

C_8: Numerical (Revised value in 2007) •
Kinoshita, Nio, Aoyama, Hayakawa

$C_{10} = (0.0 \pm 4.6)$: Estimate (Calculation in progress 12672 diagrams) •
Kinoshita, Nio, Aoyama, Hayakawa

★ Aguilar, Greynat, de Rafael (specific class of eight and tenth order analytically)

Hadronic and EW Contributions

Hadronic Contribution

$a_e^{\mathrm{LO\,Hadronic}} = (16.71 \pm 0.19)\, 10^{-13}$; $a_e^{\mathrm{HLbL}} = (0.35 \pm 0.10)\, 10^{-13}$

Davier, Höcker; Krause; Knecht — J.P., de Rafael, Vainshtein

First Time a_e^{exp} Sensitive to Hadronic Contribution 6 σ !

One-loop electroweak contribution not yet needed •

$a_e^{\mathrm{EW}} = (0.297 \pm 0.005) \times 10^{-13}$

At present:

a_e together with α from Rb and Cs checks QED at 3-loops •

If comparable uncertainty in α:

Checks QED to 4-loops and electron substructure •

The Muon Anomaly: QED

Impressive achievement BNL Muon (g-2) Collaboration:

$a_\mu^{\rm exp} = (11\,659\,208.0 \pm 5.4 \pm 3.3)\,10^{-10} = (11\,659\,208.0 \pm 6.3)\,10^{-10}$

Standard Model Prediction: QED

$$a_\mu^{\rm QED} = \sum_{n=1} C_{2n} \left(\frac{\alpha}{\pi}\right)^n$$

$C_2 = 1/2$: Schwinger •

C_4: Analytical including lepton mass corrections •
Sommerfield; Petermann; Suura, Wichmann; Elend; Passera

C_6: Analytical including lepton mass corrections •
Kinoshita, Barbieri, Laporta, Remiddi, $\cdots$

The Muon Anomaly: QED

C_8: Numerical value (revised in 2007) •
Kinoshita, Nio, Aoyama, Hayakawa

$C_{10} = (663 \pm 20)$: Estimate
(Calculation in progress 12672 diagrams) •
Kinoshita, Nio, Aoyama, Hayakawa

Using α from a_e ➪ $a_\mu^{\rm QED} = (11\,658\,471.810 \pm 0.015) \times 10^{-10}$

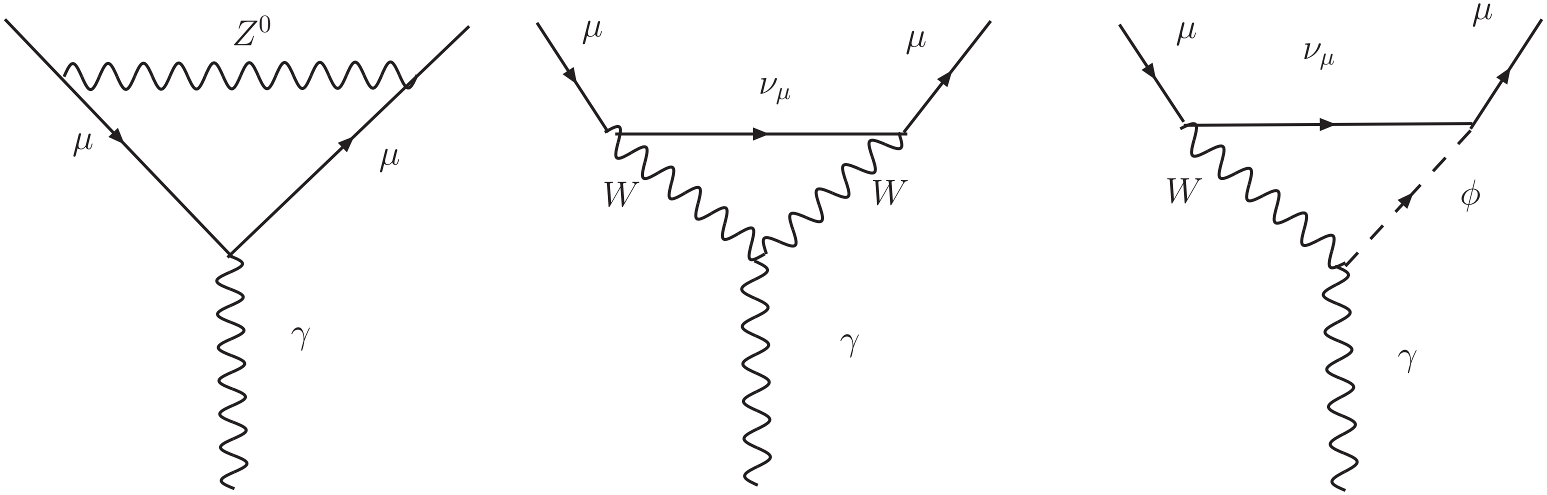
Uncertainty dominated by C_{10} •

$\Delta^{\rm exp}_{\rm Not\,QED} = (736.2 \pm 6.3) \times 10^{-10}$

Sensitive to hadronic contribution since 1975 and to electroweak contribution since 2001 •

Electroweak Contribution

At one-loop,

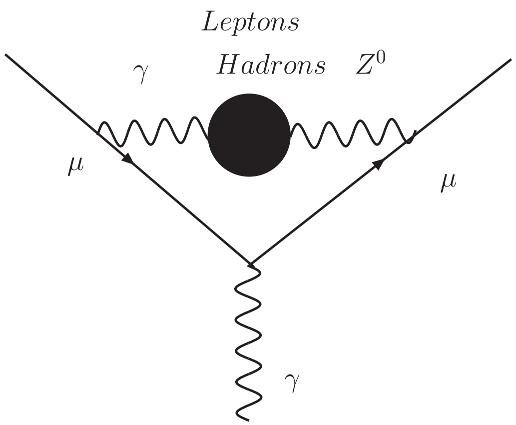


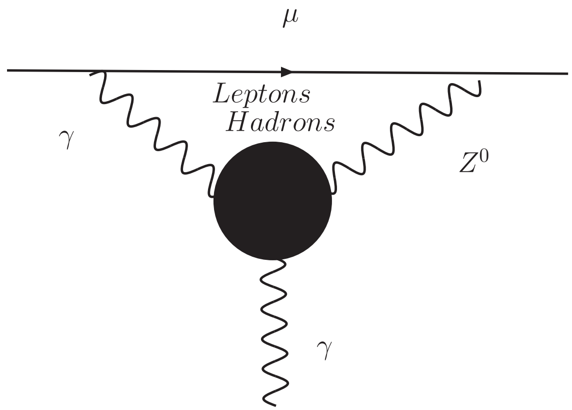
$$a_\mu^{\rm EW} = \frac{5 G_\mu m^2}{24\sqrt{2}\pi^2}\left[1 + \frac{1}{5}\left(1 - 4\sin^2(\theta_W)\right)^2 + \mathcal{O}\left(m/M_{Z,W,H}\right)^2\right]$$

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

Electroweak Contribution

Including Two-Loops Electroweak: 1992-2004





Kukhto et al.; Czarnecki, Krause, Marciano, Vainshtein; Knecht, Peris, Perrottet, def Rafael; Degrassi, Giudice; Heinemeyer, Stöckinger, Weiglein

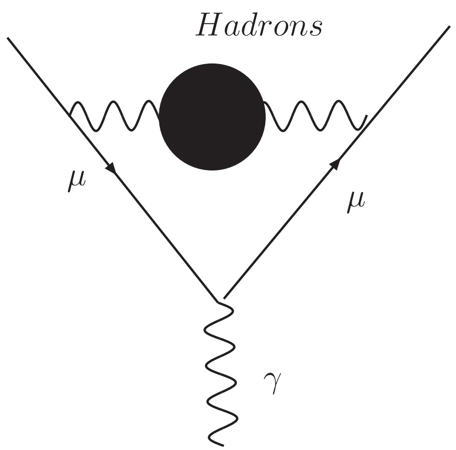
- Need full Standard Model anomaly cancellation
- Vainshtein 2003 New renormalization theorem hadronic <VVA>

$$a_\mu^{\rm EW} = [(19.5 \pm 0.2) - (4.1 \pm 0.1)]\ 10^{-10} = (15.4 \pm 0.2)\ 10^{-10}$$

Hadronic Vacuum Polarization

$\Delta^{\exp}_{\text{Not QED+EW}} = (720.8 \pm 6.3) \times 10^{-10}$ ⇨

- Need hadronic contribution with accuracy smaller than 1 %



$$a_\mu^{\text{LO Hadronic}} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} \mathrm{d}s \, K(s) \; \sigma^{(0)}(s)$$

$$K(s) = \int_0^1 \mathrm{d}x \, \frac{x^2(1-x)}{x^2 + \frac{s}{m^2}(1-x)}$$

- $\sigma^{(0)}(s)$ is the one-photon $e^+e^- \to \gamma^* \to \text{hadrons}$ cross-section

Bouchiat, Michel; Gourdin, de Rafael

Hadronic Vacuum Polarization

$\sigma^{(0)}(s)$ is (almost) experimentally obtained •

Radiative corrections:

Include final state photons but exclude $\alpha(q^2)$ running (double counting) in σ^0 •

Use QCD: At high energy ($\geq$ 13 GeV) and in between $\bar{c}c$ and $\bar{b}b$ thresholds ✔

$K(s)$ goes as m^2/s ➪ low energy (ρ-region) dominates •

$\pi^+\pi^-$ channel below 1 GeV gives 72 % of the total ✔

Hadronic Vacuum Polarization

Very precise e^+e^-data:

CMD-2 and SND at VEPP-2M (Novosibirsk) and KLOE at DAΦNE (Frascati) ✔

CMD-2 and SND in agreement ✔

KLOE: same level of accuracy and reasonable overall agreement between 0.630 and 0.958 GeV with CMD-2 and SND though lies somewhat lower ✔

Also BaBar has released first exclusive e^+e^- data ✔

Belle larger statistics, soon

Hadronic Vacuum Polarization

Authors	Contribution $\times 10^{10}$
Davier et al., τ data (2003)	$711.0 \pm 5.0_{\rm exp} \pm 0.8_{\rm rad} \pm 2.4_{\rm IB}$
de Tróconiz, Ynduráin, τ data (2004)	$702.7 \pm 4.7_{\rm exp} \pm 1.0_{\rm rad}$
Davier et al., τ data (2009)	$704.4 \pm 3.5_{\rm exp} \pm 0.7_{\rm rad} \pm 1.9_{\rm IB}$
Davier et al. e^+e^- (2006)	$690.8 \pm 3.0_{\rm exp} \pm 1.9_{\rm rad} \pm 0.7_{\rm QCD}$
Hagiwara et al. e^+e^- (2006)	$689.4 \pm 4.2_{\rm exp} \pm 1.8_{\rm rad}$
Jegerlehner e^+e^- (2006)(without KLOE)	692.1 ± 5.6
Jegerlehner e^+e^- (2008)	690.3 ± 5.3
Davier et al. e^+e^- (2009)	$689.1 \pm 3.8_{\rm exp} \pm 1.9_{\rm rad} \pm 0.7_{\rm QCD}$
Davier et al. e^+e^- (2009) (without KLOE)	$690.1 \pm 4.6_{\rm exp} \pm 1.9_{\rm rad} \pm 0.7_{\rm QCD}$

Hadronic Vacuum Polarization

New IB analysis including Belle data (Davier et al (2009)):

τ data vs e^+e^- smallller data discrepancy:

previous 4.5 σ ➪ (1.6 $\sim$ 2.7) σ in $(B_\tau - B_{\mathrm{CVC}})_{\pi^+\pi^0}$ ✔

New accurate e^+e^- data agree reasonably within them ✔

SU(2)-isospin effects could be larger than expected:

Much less theory involved in e^+e^- data •

Most recent evaluations include SND, CMD-2,

(before 2008) BaBar and KLOE data: 0.6 % accuracy !

$$a_\mu^{\mathrm{LO\,Hadronic}} = (689.1 \pm 4.3) \times 10^{-10}$$

Upcoming VEPP-2000 and DAΦNE-2 (normalized to $\mu^+\mu^-$) ✔

Hadronic Vacuum Polarization

That was the situation before Tau 2008 at Novosibirsk

➪ Preliminary BaBar $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ cross section between (0.5, 3.0) GeV presented (M. Davier) •

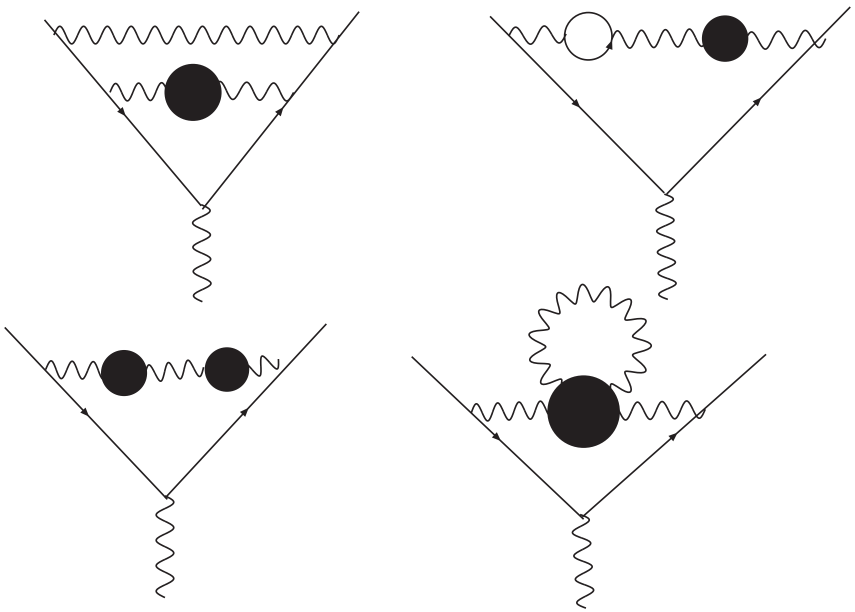
★ Disagreement with CMD-II and SND below the ρ and most notably with 2008 KLOE analysis between (0.5, 1.0) GeV ??

★ Agree better with tau data, especially with Belle and CLEO but still some disagreement with ALEPH •

★ If BaBar is the only used in (0.5,1.8) GeV the result is 3 σ away the previous e^+e^- "world average" !

★★ Caution Preliminary: Wait to final results (in two weeks !) !
no higher multi-hadronic modes included •

Higher Order Hadronic



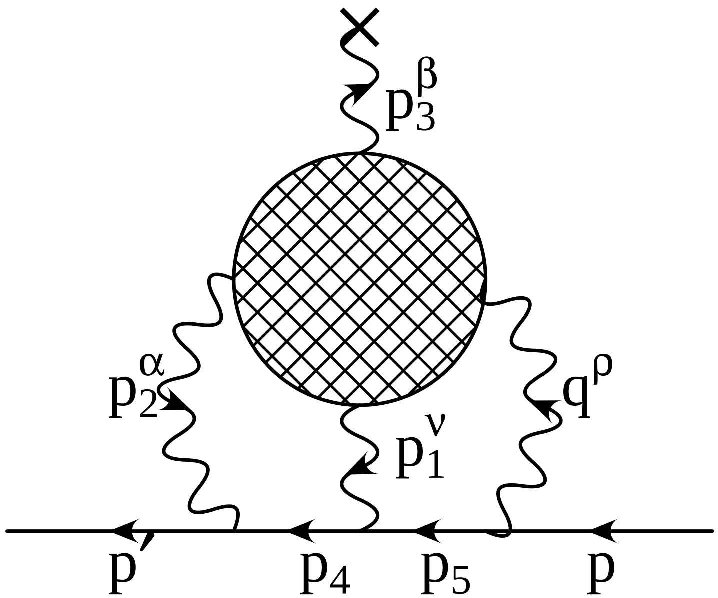
At order α^3: using same e^+e^- data as for LO •

$$a_\mu^{\mathrm{HO\,Hadronic}} = -(9.79 \pm 0.10) \times 10^{-10}$$

Uncertainty includes unaccounted radiative corrections •

Hadronic Light-by-Light Scattering

Hadronic light-by-light contribution to muon $g-2$



$$\mathcal{M} = |e|^7 \beta \int \frac{d^4 p_1}{(2\pi)^4} \int \frac{d^4 p_2}{(2\pi)^4} \frac{1}{q^2\, p_1^2\, p_2^2 (p_4^2 - m^2)\,(p_5^2 - m^2)}$$
$$\times \underline{\Pi^{\rho\nu\alpha\beta}(p_1, p_2, p_3)}\, \bar{u}(p')\gamma_\alpha(\not{p}_4 + m)\gamma_\nu(\not{p}_5 + m)\gamma_\rho u(p)$$

Introduction

Need

$$\Pi^{\rho\nu\alpha\beta}(p_1,p_2,p_3) = i^3 \int d^4x \int d^4y \int d^4z \, \exp^{i(p_1\cdot x + p_2\cdot y + p_3\cdot z)} \times$$
$$\times \langle 0|T[V^\rho(0)V^\nu(x)V^\alpha(y)V^\beta(z)]|0\rangle$$

with $V^\mu(x) = [\overline{q}\,\widehat{Q}\gamma^\mu q](x)$ and $\widehat{Q} = \frac{1}{3}\mathrm{diag}(2,-1,-1)$

full four-point function with $p_3 \to 0$ •

Using current conservation

$$\Pi^{\rho\nu\alpha\lambda}(p_1,p_2,p_3) = -p_{3\beta}\frac{\delta\Pi^{\rho\nu\alpha\beta}(p_1,p_2,p_3)}{\delta p_{3\lambda}}$$

one just needs derivatives at $p_3 = 0$ •

Introduction

★ Many scales involved: Impose low energy and several OPE limits ➪ Not full first principle calculation at present •

(Two lattice groups just starting: Not clear final uncertainty) •

Large N_c and CHPT counting:
Organizes different degrees of freedom contributions •
E. de Rafael

- Goldstone boson exchange: $\mathcal{O}(N_c)$ and $\mathcal{O}(p^6)$ •
- One-meson irreducible vertex and non-Goldstone boson exchange: $\mathcal{O}(N_c)$ and $\mathcal{O}(p^8)$ •
- Goldstone bosons Loop: $\mathcal{O}(1)$ in $1/N_c$ and $\mathcal{O}(p^4)$ •
- Non-Goldstone bosons Loop: $\mathcal{O}(1)$ in $1/N_c$ and $\mathcal{O}(p^8)$ •

Introduction

Based on this counting:

- Two full calculations
  J. Bijnens, E. Pallante, J.P. (BPP)
  M. Hayakawa, T. Kinoshita, A. Sanda (HKS)

- Dominant pseudo-scalar exchange: Extensive analytic analysis •
  M. Knecht, A. Nyffeler (KN)

  Found sign mistake ✔
  M. Knecht, A. Nyffeler, M. Perrottet, E. de Rafael

Introduction

★ New four-point form factor short-distance constraint:

K. Melnikov, A. Vainshtein

(see also M. Knecht, S. Peris, M. Perrottet, E. de Rafael)

Model:

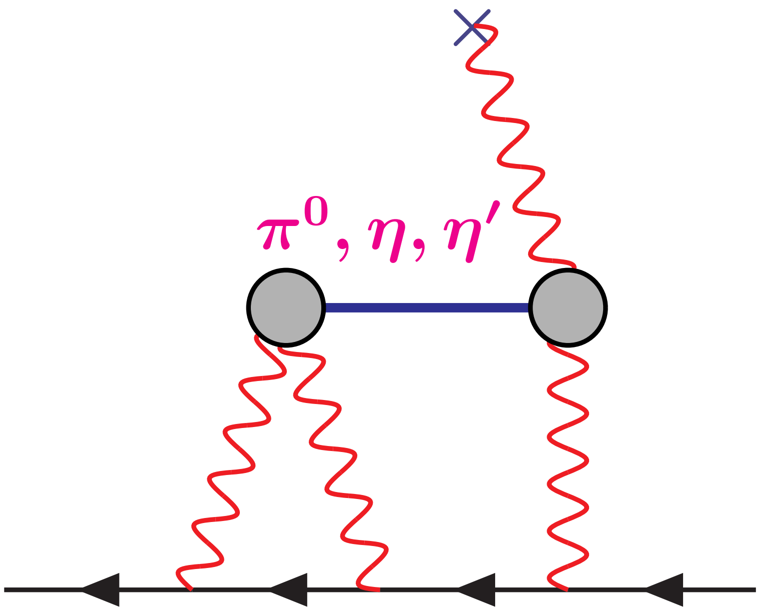
Full light-by-light saturated by pseudo-scalar and pseudo-vector pole exchanges •

Very recently, A. Nyffeler used a $\pi^0\gamma^*\gamma^*$ off-shell form factor •

First step, one needs more work to have the full light-by-light •

“Old” Calculations: Pseudo-Scalar Exchange

Dominant contribution ⇨ pseudo-scalar exchange •



Nambu-Goldstone π^0 makes special enhacement •

$$a(\pi^0) = \left(\frac{\alpha}{\pi}\right)^3 N_c \frac{m^2 N_c}{48\pi^2 f_\pi^2} \left[\ln^2 \frac{M_\rho}{m_\pi} + \mathcal{O}(\ln \frac{M_\rho}{m_\pi}) + \mathcal{O}(1)\right]$$

M. Knecht, A. Nyffeler, M. Perrottet, E. de Rafael

“Old” Calculations: Pseudo-Scalar Exchange

Here, I discuss work in J. Bijnens, E. Pallante, J.P. •
We used a variety of $\pi^0\gamma^*\gamma^*$ form factors

$$\mathcal{F}^{\mu\nu}(p_1,p_2) = \frac{N_c}{6\pi}\frac{\alpha}{f_\pi}\, i\varepsilon^{\mu\nu\alpha\beta}\, p_{1\alpha}p_{2\beta}\, \underline{\mathcal{F}(p_1^2,p_2^2)}$$

fulfilling as many as possible QCD constraints •
(Short-distance, data, U$_A$(1) normalization and slope at the origin). In particular,

$$\mathcal{F}(Q^2,Q^2) \rightarrow \frac{A}{Q^2}$$
$$\mathcal{F}(Q^2,0) \rightarrow \frac{B}{Q^2}$$

for Q^2 Euclidean and very large

"Old" Calculations: Pseudo-Scalar Exchange

All form factors we used converge for $\mu \sim (2-4)$ GeV and the numerical difference between them is small ✔

Somewhat different $\pi^0\gamma^*\gamma^*$ form factors used in M. Hayakawa, T. Kinoshita, A. Sanda and M. Knecht, A. Nyffeler •

Results agree very well (after correcting a mistake in the sign of the phase space) •

Adding π^0, η and η' contributions

	$10^{10} \times a_\mu$
BPP	(8.5 ± 1.3)
HKS	(8.3 ± 0.6)
KN	(8.3 ± 1.2)

“Old” Calculations: Pseudo-Vector Exchange

Need $f_1\gamma\gamma^*$ and $f_1\gamma^*\gamma^*$ form factors •

➪ related to $\pi^0\gamma\gamma^*$ and $\pi^0\gamma^*\gamma^*$ by anomalous Ward identities ✔

Pseudo-vector exchange

	$10^{10} \times a_\mu$
BPP	(0.25 ± 0.10)
HKS	(0.17 ± 0.10)

"Old" Calculations: Scalar Exchange

Need $S^0\gamma\gamma^*$ and $S^0\gamma^*\gamma^*$ form factors •

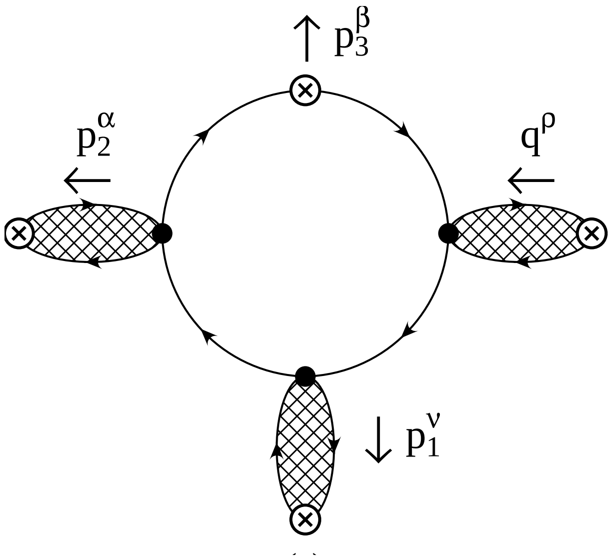
They are constrained by CHPT at $\mathcal{O}(p^4)$: L_i's reproduced ✔

Within ENJL: Ward identities impose relations between Quark loop and Scalar exchange •

$$a_\mu(\text{Scalar}) = -(0.7 \pm 0.2) \times 10^{-10}$$

Not included by M. Hayakawa, T. Kinoshita and A. Sanda nor by K. Melnikov and A. Vainshtein •

“Old” Calculations: Non-Meson Exchange “Quark-Loop”



Λ [GeV]	$10^{10} \times a_\mu$
0.7	2.2
1.0	2.0
2.0	1.9
4.0	2.0

- Low Energy (0 to Λ): ENJL model •
- High Energy (Λ to ∞): Short-distance QCD bare quark loop •
- Numerical matching ✔

“Old” Calculations: Pion- and Kaon-Loop

Leading contribution in chiral counting, suppressed by $1/N_c$

No $\gamma^*\gamma^* \to \pi\pi$ data available: Models needed !

Model for $\pi\pi\gamma^*(\gamma^*)$	$10^{10} \times a_\mu$
BPP (Full VMD)	-1.8
HKS (HGS)	-0.4
No Photon Form Factor	-4.6

Kaon loop is much smaller: -0.05×10^{-10} •

New Short Distance Constraints

K. Melnikov and A. Vainshtein

New short-distance constraint on four-point function form factor

$$\langle 0|T[V^\nu(p_1)V^\alpha(p_2)V^\rho(-(p_1+p_2+p_3))]|\gamma(p_3\to 0)\rangle$$

using OPE with $-p_1^2 \simeq -p_2^2 >> -(p_1+p_2)^2$ Euclidean and large,

$$T[V^\nu(p_1)V^\alpha(p_2)] \sim \frac{1}{\widehat{p}^2}\,\varepsilon^{\nu\alpha\mu\beta}\,\widehat{p}_\mu\,[\overline{q}\,\widehat{Q}^2\gamma_\beta\gamma_5 q](p_1+p_2)$$

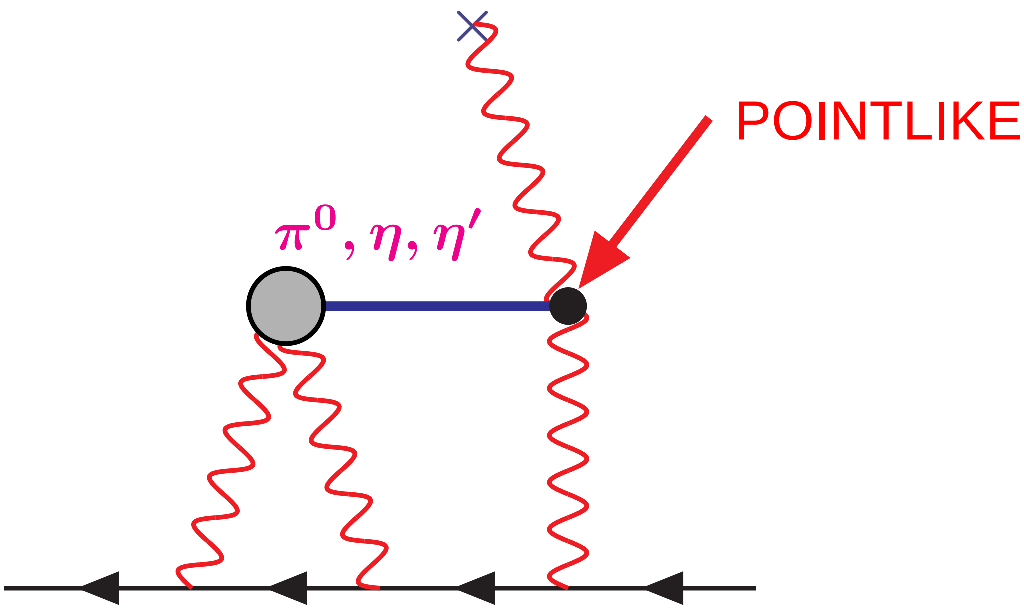
with $\widehat{p} = (p_1-p_2)/2 \simeq p_1 \simeq -p_2$

New OPE Constraint: Pseudo-scalar exchange

New OPE constraint saturated by pseudo-scalar exchange

➾ Model uses a point-like vertex when $p_3 \to 0$ •

Not all OPE constraints satisfied: Negligible numerically •



New OPE Constraint: Axial-Vector exchange

Axial-Vector exchange depends very much on the resonance mass mixing •

K. Melnikov and A. Vainsthein:
Ideal mixing for $f_1(1285)$ and $f_1(1420)$ •

Mass mixing	$10^{10} \times a_\mu$
No New OPE (Nonet symmetry)	0.3 $\pm$ 0.1
M=1.3 GeV (Nonet symmetry)	0.7
M=M$_\rho$ (Nonet symmetry)	2.8
Ideal mixing	2.2 $\pm$ 0.5

Comparison: Leading order in N_c

Leading order in N_c:

Quark Loop + Pseudo-Scalar + Pseudo-Vector + Scalar Exchanges •

Total at $\mathcal{O}(N_c)$	$10^{10} \times a_\mu$
BPP (Nonet symmetry)	(10.9 ± 1.9) + $-(0.7 \pm 0.1)$ = (10.2 ± 1.9)
HKS (Nonet symmetry)	$(9.4 \pm 1.6\ )$ + ??Scalar??

MV: Hadronic model saturated by pole exchanges:
Cannot compare individual contributions •

Total at $\mathcal{O}(N_c)$	$10^{10} \times a_\mu$
MV (Nonet symmetry)	(12.1 ± 1.0) + ??Scalar??
MV (Ideal mass mixing)	(13.6 ± 1.5) + ??Scalar??

Masses produce main difference in pseudo-vector exchange •

Conclusions and Prospects

At present, large N_c results agree within 1 σ ✔

$$a_\mu^{N_c,\mathrm{HLbL}} = (11.0 \pm 4.0) \times 10^{-10}$$

Based partly in this discussion: Recent new analysis of HLbL

J.P., E. de Rafael and A. Vainshtein

★ $1/N_c$ expansion works reasonably well ✔

★ Chiral enhancement factors demand more than the lightest Nambu-Golsdtone bosons •

Conclusions Prospects

Adding effects beyond leading order in $1/N_c$, in a conservative analysis, J.P., E. de Rafael and A. Vainshtein

π^0, η and η' exchanges: $(11.4 \pm 1.3) \times 10^{-10}$
(includes non-meson exchange in ENJL case)

Scalar exchange : $-(0.7 \pm 0.7) \times 10^{-10}$

Axial-vector exchange : $(1.5 \pm 1.0) \times 10^{-10}$

Pion and kaon loops: $-(1.9 \pm 1.9) \times 10^{-10}$

Charm quark loop: 0.23×10^{-10}

★ Our final result is $a_\mu^{\mathrm{HLbL}} = (10.5 \pm 2.6) \times 10^{-10}$

Standard Model Prediction of a_μ

$$\begin{aligned}
10^{10}\, a_\mu^{\mathrm{SM}} &= \overbrace{(11\,658\,471.810 \pm 0.015)}^{\text{QED}} + \overbrace{(15.4 \pm 0.2)}^{\text{EW}} + \\
&+ \underbrace{(689.1 \pm 4.3)}_{\text{LO Had}} \underbrace{-(9.79 \pm 0.10)}_{\text{HO Had}} + \underbrace{(10.5 \pm 2.6)}_{\text{HLbL}} \\
&= \underbrace{(11\,658\,487.2 \pm 0.2)}_{\text{QED + EW}} + \underbrace{(689.8 \pm 5.0)}_{\text{Hadronic}} \\
&= \underline{(11\,659\,177.0 \pm 5.0)}
\end{aligned}$$

Theory error smaller than experiment error ✔

$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (31.0 \pm 8.1) \times 10^{-10}$ ➪ 3.8 σ

$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (30.0 \pm 8.5) \times 10^{-10}$ ➪ 3.5 σ (without KLOE)

Prospects for Theory and Experiment

New e^+e^- experiments:
cross-checks and reduce final uncertainty of $a_\mu^{\mathrm{LO\,Had}}$ •

New τ data at B-factories and new tau-charm factory at Beijing:
cross-checks with actual tau data •

Recall the preliminary (and partial) BaBar result •

Need theoretical understanding isospin violation to use τ data •

A new full calculation of a_μ^{HLbL} is desirable and possible: Goal:
$\sim (1.5 - 2.0) \times 10^{-10}$ uncertainty in a_μ^{HLbL} •

Prospects for total theory uncertainty: $\sim 3.5 \times 10^{-10}$ •

Prospects for Theory and Experiment

A tantalizing discrepancy $(3.5 \sim 3.8)\,\sigma$ and expectations to reduce theory uncertainty ✔

★ New $g-2$ experiment at Fermilab approved but not funded yet
➩: reduces the E861 uncertainty from 6.3×10^{-10} to 1.6×10^{-10}
✔

★ J-PARC project (Japan) goal: reduce it even more !

➩ Very timely: Make new ($ 55 Million at FNAL) experiment to measure a_μ

May become first new physics discovery !