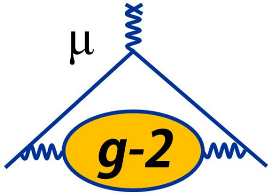
Review of g-2: theory

UNIVERSITY OF LIVERPOOL

Thomas Teubner

LIVERPOOL THEORETICAL PHYSICS



- Introduction
- QED and weak contributions
- a_μ^{had} : HLbL and VP status, work in progress
- BSM?!
- Outlook

Introduction: Lepton Dipole Moments

- **Dirac** equation (1928) combines non-relativistic Schroedinger Eq. with rel. Klein-Gordon Eq. and describes spin-1/2 particles and interaction with EM field $A_\mu(x)$:

$$(i\partial_\mu + eA_\mu(x))\,\gamma^\mu\psi(x) \;=\; m\,\psi(x)$$

with gamma matrices $\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu}I$ and 4-spinors $\psi(x)$.

- Great success: **Prediction** of anti-particles and magnetic moment $\vec{\mu} = g\frac{Qe}{2m}\vec{s}$ with g = 2 (and not 1) in agreement with experiment.

- Dirac already discussed **electric dipole moment** together with MDM: $\vec{\mu}\cdot\vec{H} + i\rho_1\vec{\mu}\cdot\vec{E}$ but discarded it because imaginary.

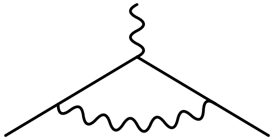
- 1947: small deviations from predictions in hydrogen and deuterium hyperfine structure; Kusch & Foley propose explanation with $g_s = 2.00229 \pm 0.00008$.

Introduction: Lepton Dipole Moments

- 1948: Schwinger calculates the famous radiative correction:

  that g = 2 (1+a), with

  a = (g-2)/2 = α/(2π) = 0.001161



`` If you can't join 'em, beat 'em "

  This explained the discrepancy and was a crucial step in the development of perturbative QFT and QED

- The anomaly a (Anomalous Magnetic Moment) is from the Pauli term:

$$\delta\mathcal{L}_{\rm eff}^{\rm AMM} = -\frac{Qe}{4m} a\bar{\psi}(x)\sigma^{\mu\nu}\psi(x)F_{\mu\nu}(x)$$

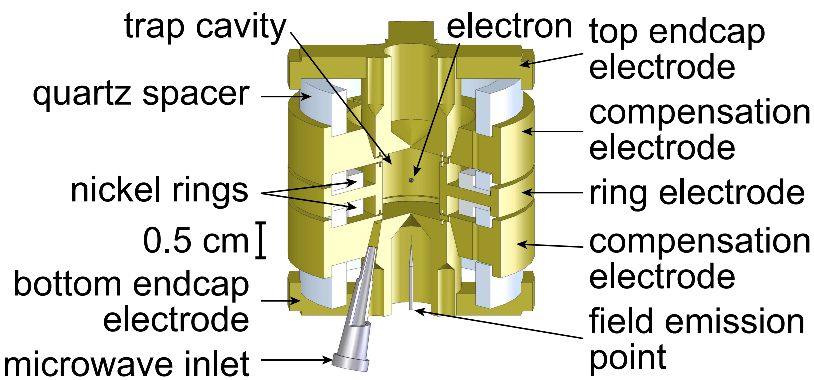
  This is a dimension 5 operator, non-renormalisable and hence not part of the fundamental (QED) Lagrangian. But it occurs through radiative corrections and is calculable in perturbation theory.

- Similarly, an EDM can come from a term $\delta\mathcal{L}_{\rm eff}^{\rm EDM} = -\frac{d}{2}\bar{\psi}(x)\, i\, \sigma^{\mu\nu}\gamma_5\psi(x)F_{\mu\nu}(x)$

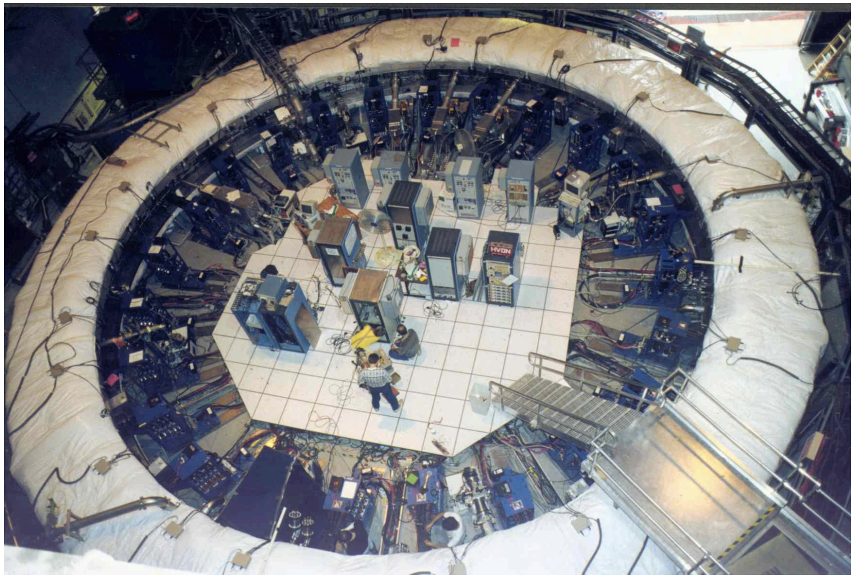
Magnetic Moments: a_e vs. a_μ

a_e= 1 159 652 180.73 (0.28) 10^{-12} [0.24ppb]
Hanneke, Fogwell, Gabrielse, PRL 100(2008)120801

a_μ= 116 592 089(63) 10^{-11} [0.54ppm]
Bennet et al., PRD 73(2006)072003



one electron quantum cyclotron

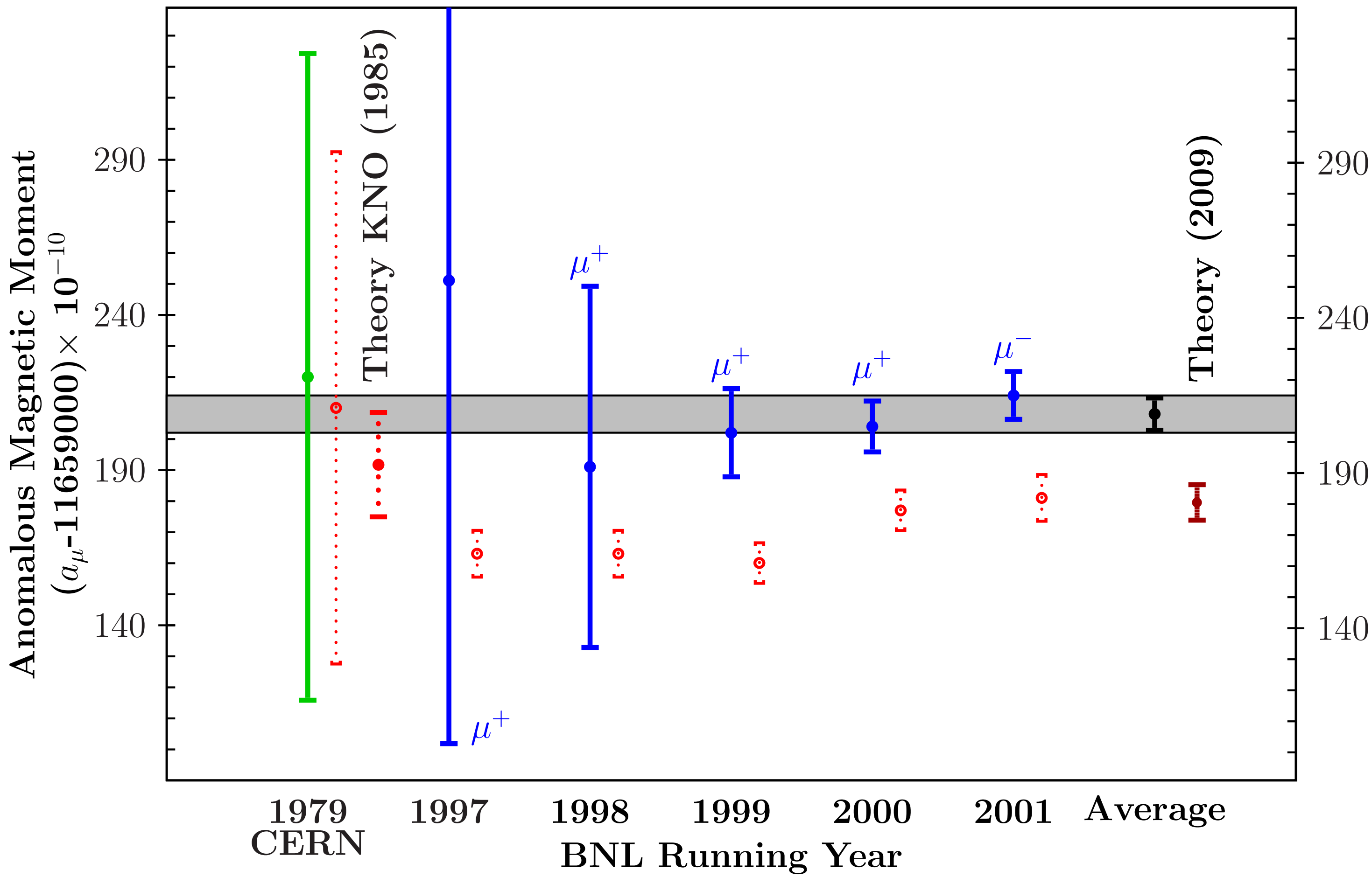


- a_e^{EXP} more than 2000 times more precise than a_μ^{EXP}, but for e^- loop contributions come from very small photon virtualities, whereas muon \`tests' higher scales
- dimensional analysis: sensitivity to NP (at high scale Λ_{NP}): $a_\ell^{\rm NP} \sim \mathcal{C}\, m_\ell^2/\Lambda_{\rm NP}^2$

→ μ wins by $m_\mu^2/m_e^2 \sim 43000$ for NP, but a_e provides best determination of α

Magnetic Moments: a_μ history

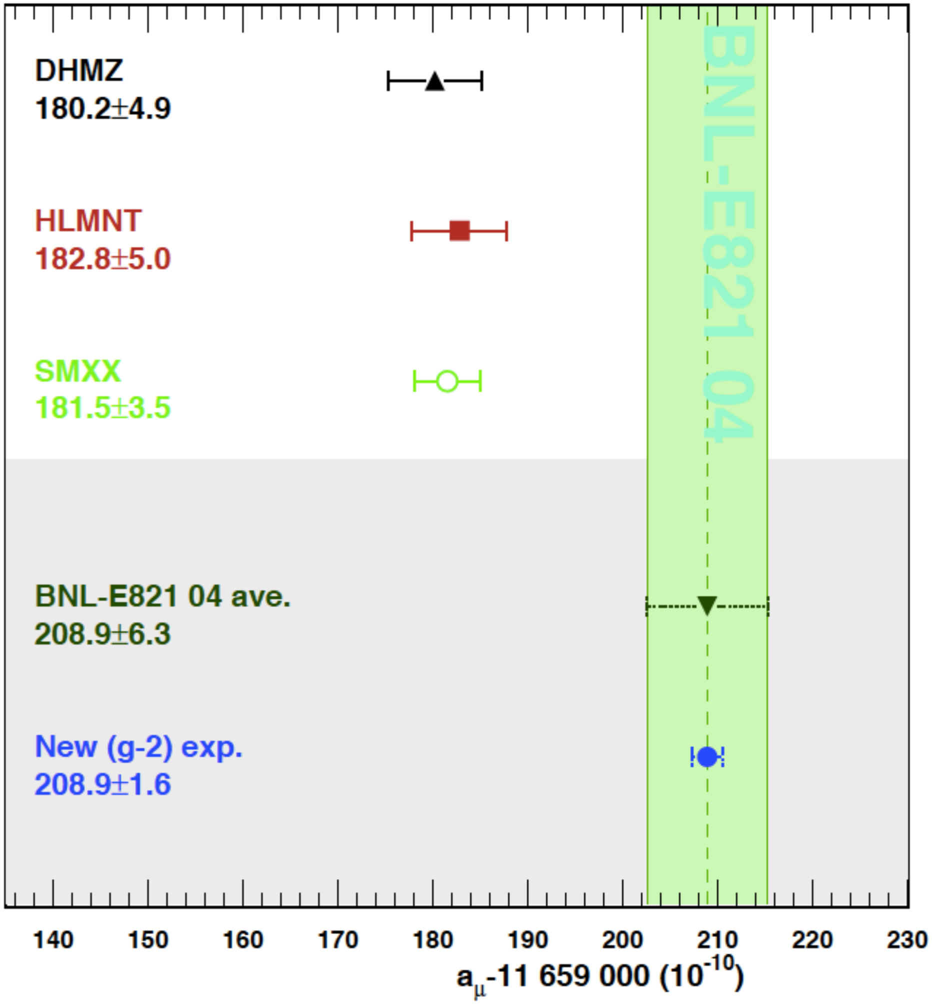
g-2 history plot and
book motto from Fred Jegerlehner: `The closer you look the more there is to see'



a_μ: Status and future projection → charge for TH

Future picture:

- if mean values stay and with no a_μ^{SM} improvement:
  5σ discrepancy
- if also EXP+TH can improve a_μ^{SM} \`as expected' (consolidation of L-by-L on level of Glasgow consensus, about factor 2 for HVP): NP at 7-8σ
- or, if mean values get closer, very strong exclusion limits on many NP models (extra dims, new dark sector, xxxSSSM)...



a_μ^{SM}: status of the SM prediction

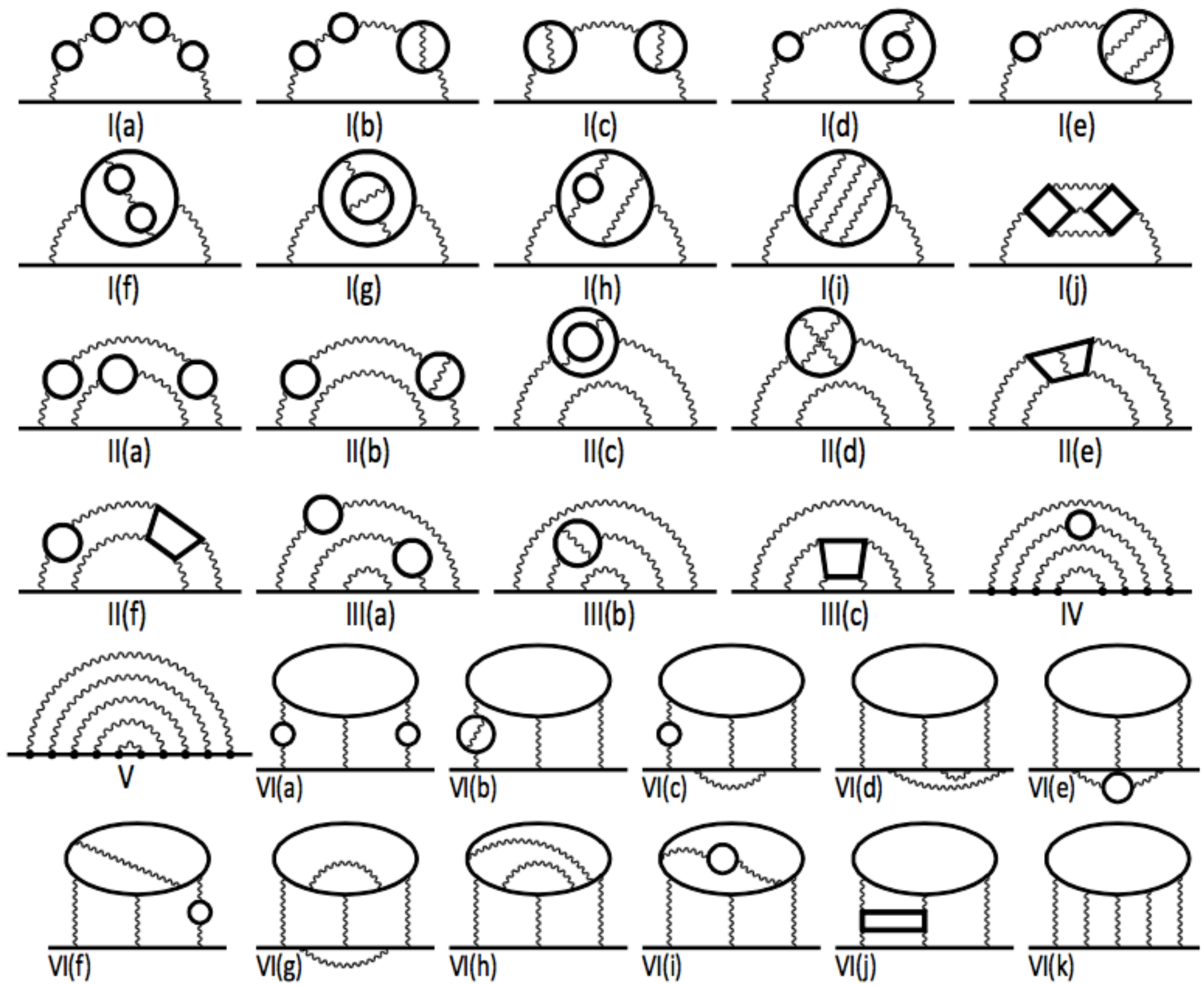
$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{hadronic}} + a_\mu^{\mathrm{NP?}}$$

a_μ^{QED} Kinoshita et al.: g-2 at 5-loop order

T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRLs, 2012)

A triumph for perturbative QFT and computing!

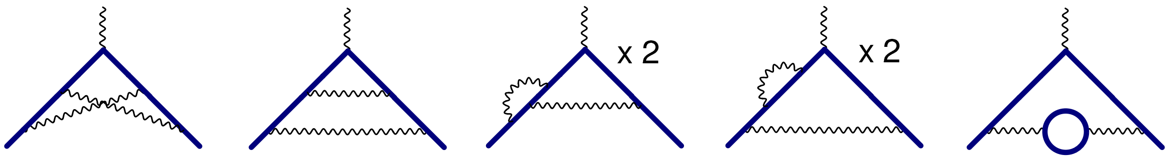
10th
12672
diagrams



- code-generating code, including
- renormalisation
- multi-dim. numerical integrations

a_μ^{QED}

- Schwinger 1948: 1-loop a = (g-2)/2 = α/(2π) = 116 140 970 × 10^{-11}
- 2-loop graphs:



- 72 3-loop and 891 4-loop diagrams …
- Kinoshita et al. 2012: 5-loop completed numerically (12672 diagrams):

a_μ^{QED} = 116 584 718.951 (0.009) (0.019) (0.007) (0.077) × 10^{-11}

errors from: lepton masses, 4-loop, 5-loop, α from ^{87}Rb

- QED extremely accurate, and the series is stable: $$a_\mu^{\rm QED} = C_\mu^{2n} \sum_n \left(\frac{\alpha}{\pi}\right)^n$$

$$C_\mu^{2,4,6,8,10} = 0.5,\ 0.765857425(17),\ 24.05050996(32),\ 130.8796(63),\ 753.29(1.04)$$

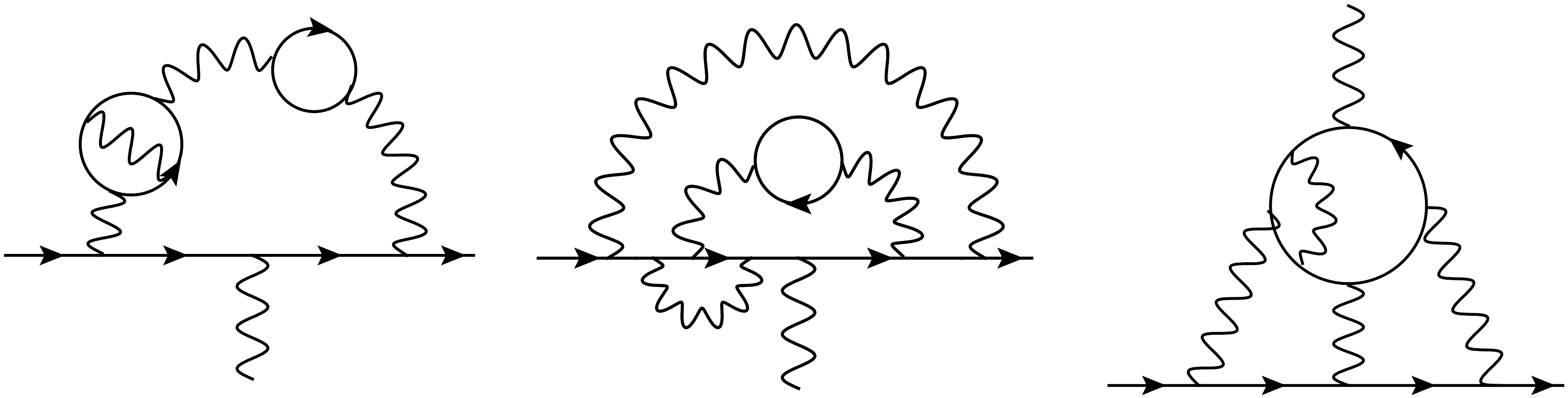
- Could a_μ^{QED} still be wrong?
  Some classes of graphs known analytically (Laporta; Aguilar, Greynat, deRafael),

a_μ^{QED}

- … but 4-loop and 5-loop rely heavily on numerical integrations

- Recently several independent checks of 4-loop and 5-loop diagrams:
  Baikov, Maier, Marquard [NPB 877 (2013) 647], Kurz, Liu, Marquard, Smirnov AV+VA, Steinhauser [NPB 879 (2014) 1, PRD 92 (2015) 073019, 93 (2016) 053017]:

- all 4-loop graphs with internal lepton loops now calculated independently, e.g.

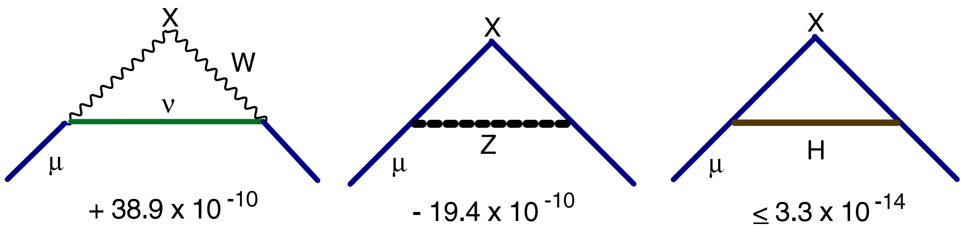


(from Steinhauser et al., arXiv:160202785)

- … and agree with Kinoshita et al.'s results
- remaining, not yet checked 4-loop universal (purely photonic) term is small, of the same order as the 5-loop contribution, and less than ¼ of the discrepancy), so
- QED on safe ground.

a_μ Electro-Weak

- Electro-Weak 1-loop diagrams:



$a_\mu^{EW(1)} = 195 \times 10^{-11}$

- known to 2-loop (1650 diagrams, the first EW 2-loop calculation):
  Czarnecki, Krause, Marciano, Vainshtein; Knecht, Peris, Perrottet, de Rafael

- agreement, a_μ^{EW} relatively small, 2-loop relevant: $a_\mu^{EW(1+2\ loop)} = (154 \pm 2) \times 10^{-11}$

- Higgs mass now known, update by Gnendiger, Stoeckinger, S-Kim,
  PRD 88 (2013) 053005

$$a_\mu^{EW(1+2\ loop)} = (153.6 \pm 1.0) \times 10^{-11}$$ ✓

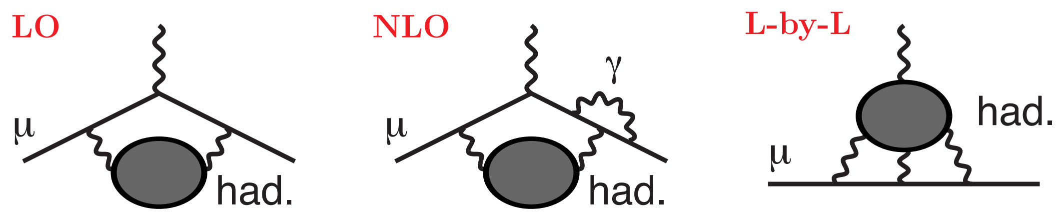
compared with $a_\mu^{QED} = 116\ 584\ 718.951\ (80) \times 10^{-11}$

a_μ hadronic

$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{hadronic}} + a_\mu^{\mathrm{NP?}}$$

- QED: Kinoshita et al. 2012: 5-loop completed (12672 diags) [some 4-l checks] ✓
- EW: 2-loop (and SM Higgs mass now known) ✓
- Hadronic: non-perturbative, the limiting factor of the SM prediction ✗

$$a_\mu^{\mathrm{had}} = a_\mu^{\mathrm{had,VP\ LO}} + a_\mu^{\mathrm{had,VP\ NLO}} + a_\mu^{\mathrm{had,Light-by-Light}}$$

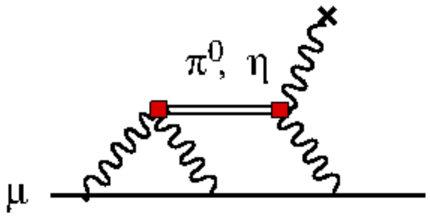


L-by-L: - so far use of model calculations, form-factor data will help improving,
- also lattice QCD, and
- new dispersive approach

→ talks by Taku Izubuchi, Fu-Guang Cao, Christoph Redmer

$a_\mu^{had, L-by-L}$: Light-by-Light (I)

- L-by-L: $\gamma \rightarrow hadrons \rightarrow \gamma^*\gamma^*\gamma^*$ non-perturbative, impossible to fully measure ✗
- so far use of model calculations, based on large N_c limit, Chiral Perturbation Theory, plus short distance constraints from OPE and pQCD
- meson exchanges and loops modified by form factor suppression, but with limited experimental information:



- in principle off-shell form-factors (π^0, η, η', $2\pi \rightarrow \gamma^* \gamma^*$) needed
- at most possible, directly experimentally: π^0, η, η', $2\pi \rightarrow \gamma\gamma^*$
- additional quark loop, pQCD matching; theory not fully satisfying conceptually ☹
- several independent evaluations, different in details, but good agreement for the leading N_c (π^0 exchange) contribution, differences in sub-leading bits
- mostly used recently:
  - \`Glasgow consensus' by Prades+deRafael+Vainshtein:

    $$a_\mu^{had,L-by-L} = (105 \pm 26) \times 10^{-11}$$

  - compatible with Nyffeler's $a_\mu^{had,L-by-L} = (116 \pm 39) \times 10^{-11}$

$a_\mu^{\text{had, L-by-L}}$: Overview from A Nyffeler @ Frascati 2016

HLbL scattering: Summary of selected results for $a_\mu^{\mathrm{HLbL}} \times 10^{11}$

Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN
π^0, η, η'	85±13	82.7±6.4	83±12	114±10	–	114±13	99 ± 16
axial vectors	2.5±1.0	1.7±1.7	–	22±5	–	15±10	22±5
scalars	−6.8±2.0	–	–	–	–	−7±7	−7±2
π, K loops	−19±13	−4.5±8.1	–	–	–	−19±19	−19±13
π,K loops +subl. N_C	–	–	–	0±10	–	–	–
quark loops	21±3	9.7±11.1	–	–	–	2.3 (c-quark)	21±3
Total	83±32	89.6±15.4	80±40	136±25	110±40	105 ± 26	116 ± 39

BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, AN '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = AN '09, JN = Jegerlehner, AN '09

- Pseudoscalar-exchanges dominate numerically. Other contributions not negligible. Cancellation between π, K-loops and quark loops !
- Note that recent reevaluations of axial vector contribution lead to much smaller estimates than in MV: $a_\mu^{\mathrm{HLbL;axial}} = (8 \pm 3) \times 10^{-11}$ (Pauk, Vanderhaeghen '14; Jegerlehner '14, '15). This would shift central values of compilations downwards: $a_\mu^{\mathrm{HLbL}} = (98 \pm 26) \times 10^{-11}$ (PdRV) and $a_\mu^{\mathrm{HLbL}} = (102 \pm 39) \times 10^{-11}$ (N, JN).
- PdRV: Analyzed results obtained by different groups with various models and suggested new estimates for some contributions (shifted central values, enlarged errors). Do not consider dressed light quark loops as separate contribution. Added all errors in quadrature !
- N, JN: New evaluation of pseudoscalar exchange contribution imposing new short-distance constraint on off-shell form factors. Took over most values from BPP, except axial vectors from MV. Added all errors linearly.

$a_\mu^{\text{had, L-by-L}}$: Light-by-Light (III): Prospects

- Transition FFs can be measured by KLOE-2 and BESIII using small angle taggers:
  $e^+e^- \to e^+e^-\gamma\gamma^* \to \pi^0,\ \eta,\ \eta',\ 2\pi$ expected to constrain leading pole contributions from π, η, η' to ~ 15% Nyffeler, arXiv:1602.03398
- or calculate on the lattice: $\pi^0 \to \gamma^* \gamma^*$ Gerardin, Meyer, Nyffeler, arXiv:1607.08174

- New dispersive approaches promising Pauk, Vanderhaeghen, PRD 90 (2014) 113012
  Colangelo et al., see e.g. EPJ Web of Conf. 118 (2016) 01030

  - dispersion relations formulated for the general HLbL tensor or for a_μ directly
  - allowing to constrain/calculate the HLbL contributions from data
  - e.g. Colangelo et al. have first results for the π-box contribution from data for $F_V^\pi(q^2)$

- Ultimately: `First principles' full prediction from lattice QCD+QED
  - several groups: USQCD, UKQCD, ETMC, … much increased effort and resources
  - within 3-5 years a 10% estimate may be possible, 30% would already be useful
  - first results encouraging, proof of principle already exists, more news later…

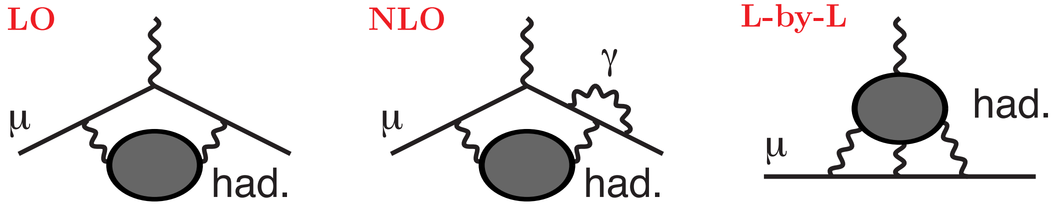
- Conservative prediction: we will at least be able to defend/confirm the error estimate of the Glasgow consensus, and possibly bring it down significantly. ✓

$a_\mu^{\text{had, VP}}$: Hadronic Vacuum Polarisation

$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{hadronic}} + a_\mu^{\text{NP?}}$$

- QED: ✓
- EW: ✓
- Hadronic: the limiting factor of the SM prediction ✗

$$a_\mu^{\text{had}} = a_\mu^{\text{had,VP LO}} + a_\mu^{\text{had,VP NLO}} + a_\mu^{\text{had,Light-by-Light}}$$



HVP: - most precise prediction by using e^+e^- hadronic cross section (+ tau) data and well known dispersion integral

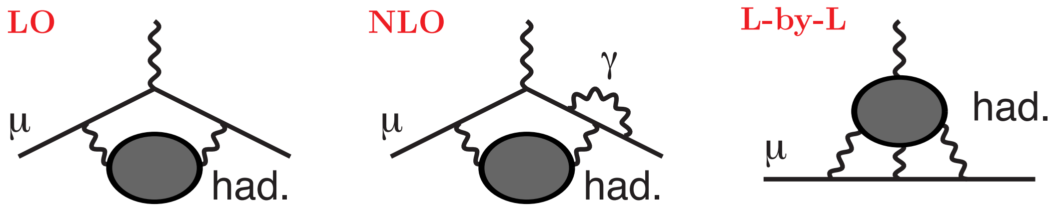
- done at LO and NLO (see graphs)
- now even at NNLO [Steinhauser et al., PLB 734 (2014) 144] ➔

- alternative: lattice QCD, but also need QED corrections; systematics <1% ?
➔ next talk, by Bipasha Chakraborty

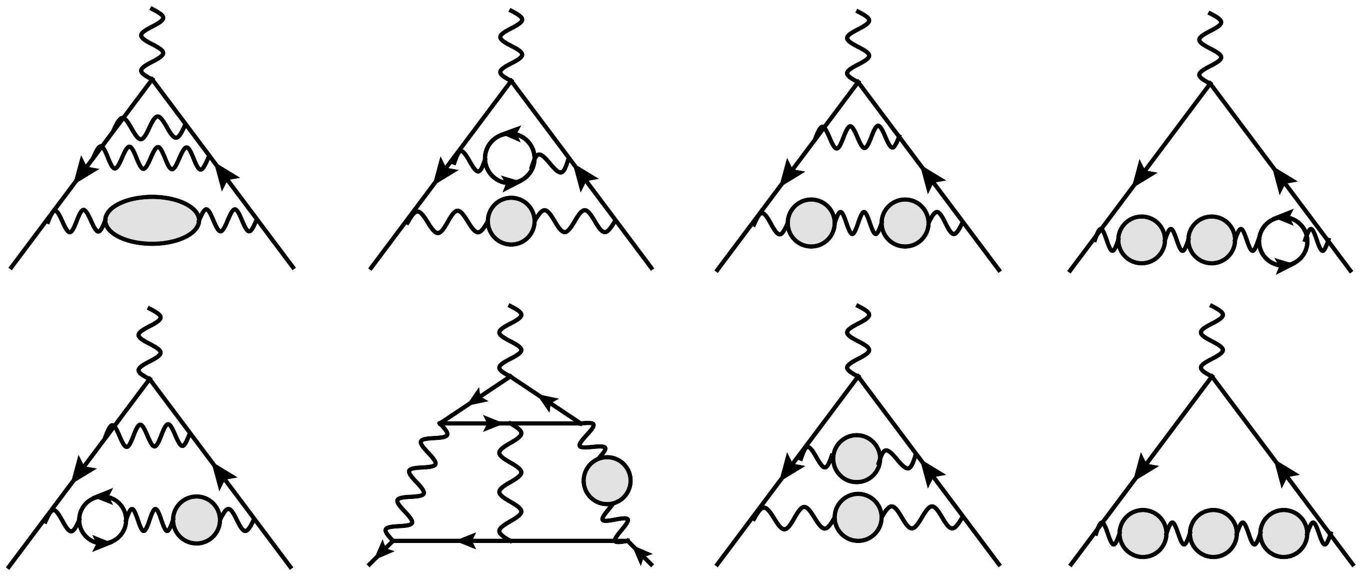
$a_\mu^{\text{had, VP}}$: Hadronic Vacuum Polarisation

- HVP: still the largest error in the SM prediction ✗

$$a_\mu^{\text{had}} = a_\mu^{\text{had,VP LO}} + a_\mu^{\text{had,VP NLO}} + a_\mu^{\text{had,Light-by-Light}}$$

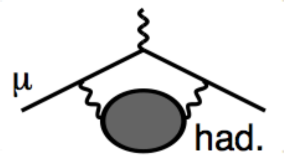


HVP at NNLO by Steinhauser et al.: $a_\mu^{\text{HVP, NNLO}} = + 1.24 \times 10^{-10}$ not so small

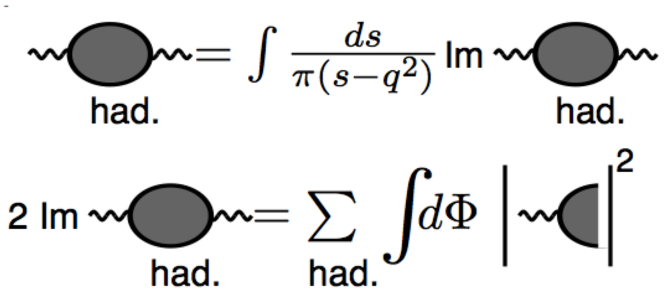


Hadronic Vacuum Polarisation, essentials:

Use of data compilation for HVP:



pQCD not useful. Use the dispersion relation and the optical theorem.



$$a_\mu^{\rm had,LO} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\rm th}}^{\infty} ds \, \frac{1}{s} \hat{K}(s) \sigma_{\rm had}(s)$$

- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s$

$\Longrightarrow$ Lower energies more important

$\Longrightarrow$ $\pi^+\pi^-$ channel: 73% of total $a_\mu^{\rm had,LO}$

How to get the most precise $\sigma^0_{\rm had}$? e^+e^- data:

- Low energies: sum ~ 25 exclusive channels, 2π, 3π, 4π, 5π, 6π, KK, KKπ, KKππ, ηπ, …, use iso-spin relations for missing channels
- Above ~1.8 GeV: can start to use pQCD (away from flavour thresholds), supplemented by narrow resonances (J/Ψ, Υ)
- Challenge of data combination (locally in √s): many experiments, different energy bins, stat+sys errors from different sources, correlations; must avoid inconsistencies/bias
- traditional \`direct scan' (tunable $e^+e^-$ beams) vs. \`Radiative Return' [+ τ spectral functions]
- $\sigma^0_{\rm had}$ means \`bare' σ, but WITH FSR: RadCorrs [HLMNT '11: $\delta a_\mu^{\rm had,\, RadCor\ VP+FSR} = 2 \times 10^{-10}$!]

a_μ^{SM}: overview, numbers as of HLMNT '11

- Several groups have produced hadronic compilations over the years
- At present 3–4 σ discrepancy; HVP still dominates the SM error
- Many more precise data in the meantime and more expected for near future

➔ for details/update/comparison, see M Davier's talk tomorrow

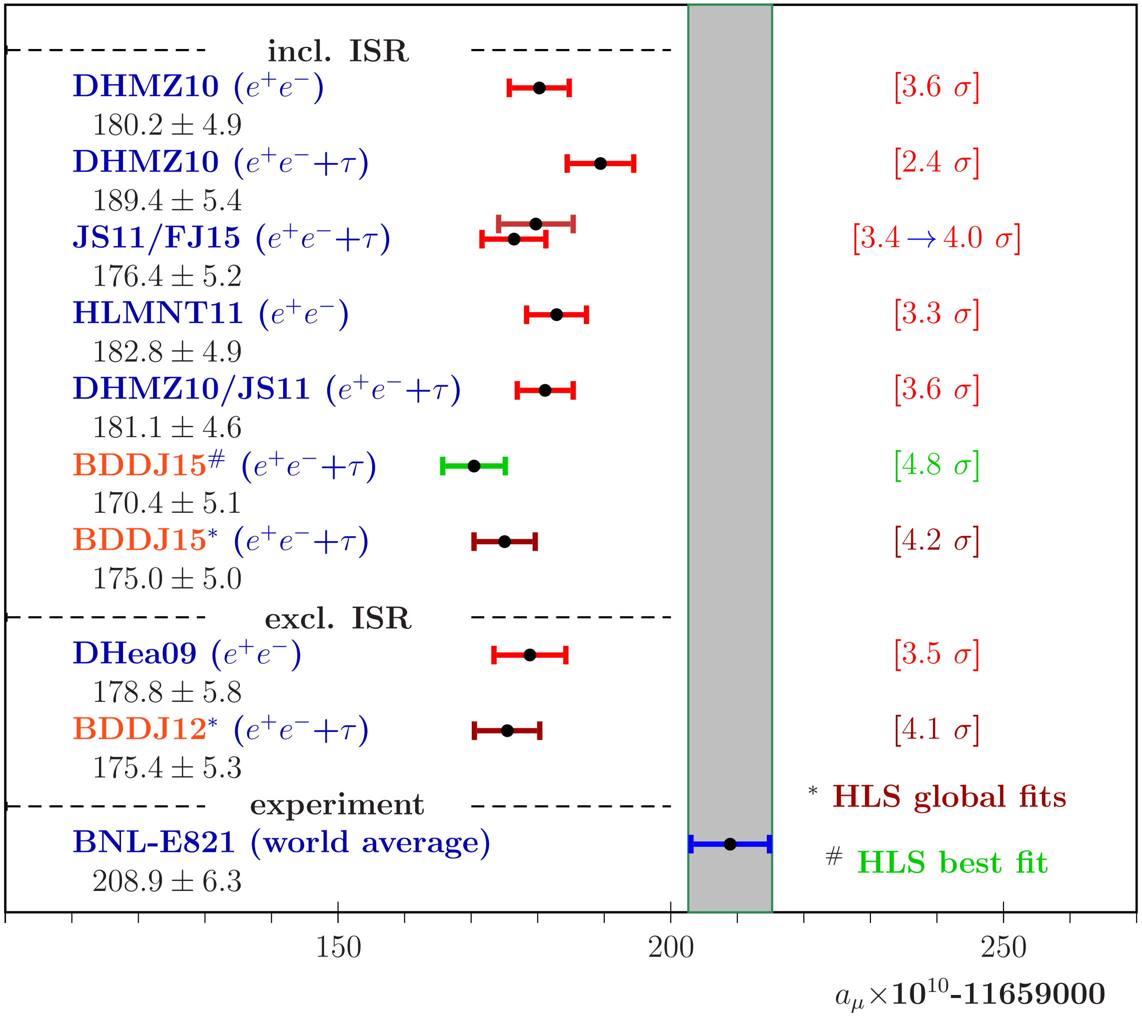
QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	−9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

a_μ^{SM}: overview, recent analyses

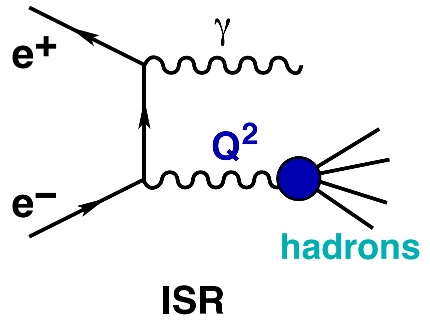
➔ for more details see M Davier's talk tomorrow

From Fred Jegerlehner's arXiv:1511.04473:

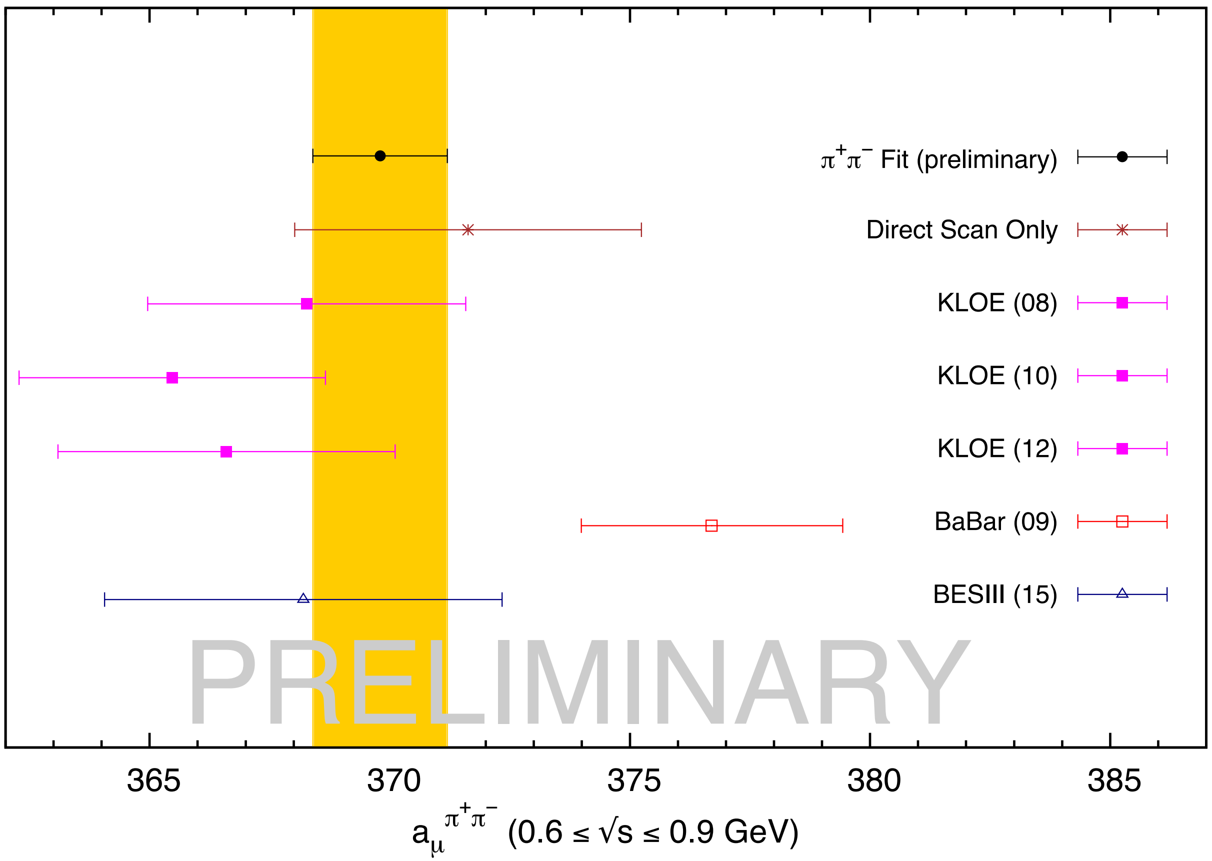


HVP: HLMNT -> HKMNT in preparation

$\pi^+\pi^-$ channel: + KLOE12, + BES III from Rad. Ret.:



Prel. HKMNT combination w. full cov.-matrices:



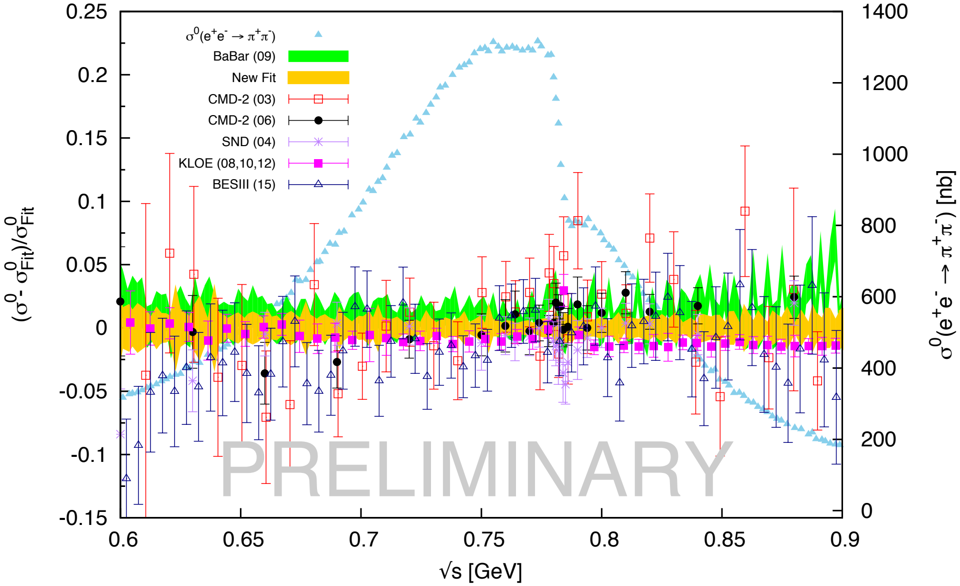
- χ^2_{min}/d.o.f. = 1.4
- further improvements expected from CMD-3, more also from BaBar?

➔ see Simon Eidelman's talk on CMD-3

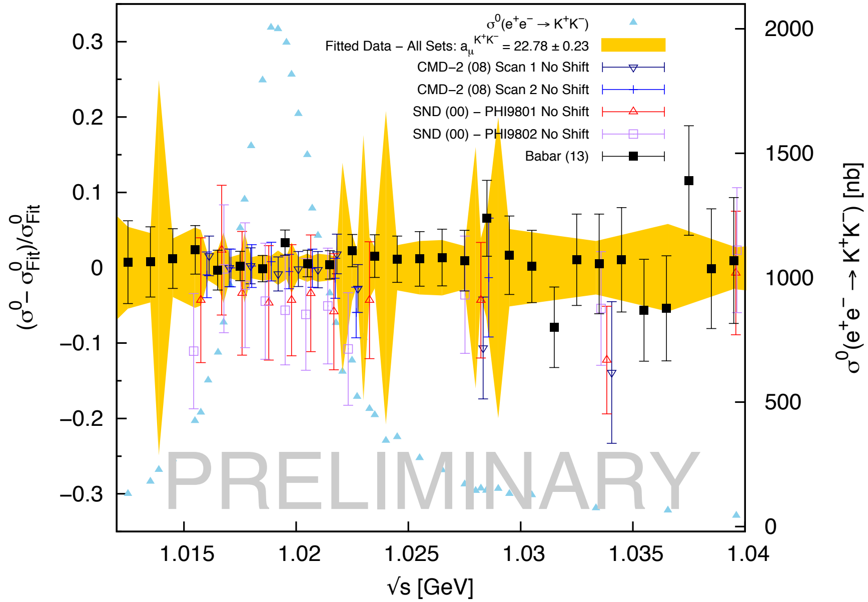
➔ Yaquian Wang's talk on BES III π FF & ISR

HVP: HLMNT -> HKMNT in preparation

$\pi^+\pi^-$ channel



K^+K^- channel with recent BaBar



- Many new data sets and an improved combination algorithm, which takes fully into account all available covariance matrices, give significantly reduced errors and a slightly smaller mean value
- Previously sizeable additional (conservative) error from uncertainty in treatment of radiative corrections (VP + FSR), mainly from older data sets, gets reduced
- More exclusive data in multi-pion and K channels reduce uncertainty from estimate based on Iso-spin correlations

Further improvements for a_μ^{HVP}:

1. Data input:

- Most important 2π:
  - more from CMD-3 and BaBar
  - if discrepancy with BaBar persists, could direct scan & ISR be done in the same experiment?
- The `subleading' 3pi (in resonance regions) and in particular $\pi^+\pi^-\pi^0\pi^0$ need more & newer/final data
- Inclusive measurements from KEDR and BES-III at higher energies are/will be important
- Lattice simulation are becoming more and more competitive

2. Analysis techniques

- Refined treatment of errors and correlations make maximum use of the data
- MC studies for impact of FSR, VP refinements
- Global fits based on Hidden Local Symmetry (M. Benayoun et al.) bring in further constraints and lead to a smaller error and larger discrepancy
- Analyses based on HLS or using ρ-γ mixing directly see no discrepancy between e^+e^- and τ spectral function data, but gain from including τ

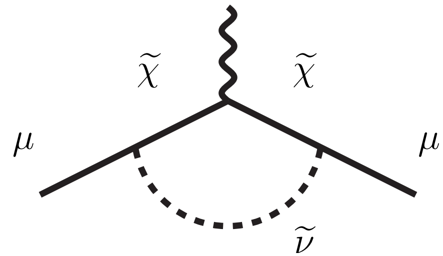
➔ I believe we can half the HVP error in time for the new g-2

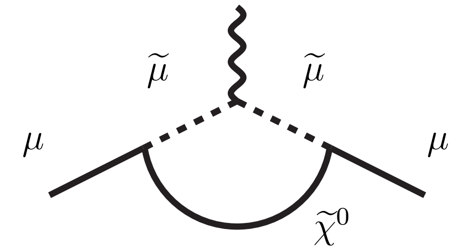
New Physics?

- Many BSM studies use g-2 as constraint or even motivation

- SUSY could easily explain g-2:

  - Main 1-loop contributions:





  - Simplest case:

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

  - Needs $\mu>0$, `light' SUSY-scale Λ and/or large tan β to explain 260×10^{-11}

  - This is already excluded by LHC searches in the simplest SUSY scenarios (like CMSSM); causes large χ^2 in simultaneous SUSY-fits with LHC data and g-2

  - However note: SUSY does not have to be minimal (w.r.t. Higgs), could have large mass splittings (with lighter sleptons), or corrections (to g-2 and Higgs mass) different from simple models, or not be there at all, but don't write it off yet…

New Physics? just five of many other recent examples

- Don’t need full MSSM (like coded in GM2Calc [by Athron, ..., Stoeckinger et al., EPJC 76 (2016) 62], which includes all latest two-loop contributions), an

- extended Higgs sector could do, see, e.g. Stoeckinger et al., arXiv:160706292, `The muon magnetic moment in the 2HDM: complete two-loop result’

-- lesson: 2-loop contributions can be highly relevant in both cases; a one-loop analysis can be misleading

- 1 TeV Leptoquark Bauer + Neubert, PRL 116 (2016) 14, 141802

  - one new scalar could explain several anomalies seen by BaBar and LHC in the flavour sector (violation of lepton universality in B -> Kll, enhanced B -> Dτν) and solve g-2, while satisfying all bounds from LEP and LHC

- light Z’ can evade many searches involving electrons by non-standard couplings preferring heavy leptons (but see BaBar’s arXiv:1606.03501 direct search limits in a wide mass range), or invoke flavour off-diagonal Z’ to evade constraints [Altmannshofer et al., arXiv:1607.06832]

- `dark photon’-like fifth force particle [Feng et al., PRL 117 (2016) 7, 071803],
- or axion-like particle (ALP), contributing like π^0 in HLbL [Marciano et al., arXiv:1607.01022]

Conclusions/Outlook:

- All sectors of the Standard Model prediction of g-2 have been scrutinised a lot in recent years

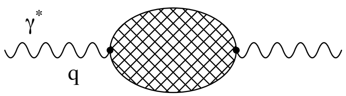
- The basic picture has not changed, but recent data, many from IRS, significantly improve the prediction for Δa_μ^{HVP} , and a
- discrepancy > 3σ is firmly consolidated

- With further anticipated hadronic data, also on FF for HLbL, and with efforts from lattice, the goal of halfing Δa_μ^{SM}, to stay competitive with the new g-2 experiments, is in reach

- Many approaches to explain the discrepancy with NP, linking g-2 with other precision observables, the flavour sector, dark matter, and many direct searches, but where is the NP?

Aside I: Hadronic VP for running $\alpha(q^2)$

- Dyson summation of Real part of one-particle irreducible blobs $\boldsymbol{\Pi}$ into the effective, real running coupling $\boldsymbol{\alpha}_{\mathbf{QED}}$:

$\Pi \; =$ 

Full photon propagator $\sim \; 1 \; + \; \Pi \; + \; \Pi \cdot \Pi \; + \; \Pi \cdot \Pi \cdot \Pi \; + \; \ldots$

$$\rightsquigarrow \qquad \alpha(q^2) \; = \; \frac{\alpha}{1 - \mathrm{Re}\Pi(q^2)} \; = \; \alpha \,/\, \left(1 - \Delta\alpha_{\mathrm{lep}}(q^2) - \Delta\alpha_{\mathrm{had}}(q^2)\right)$$

- The Real part of the VP, $\mathrm{Re}\Pi$, is obtained from the Imaginary part, which via the *Optical Theorem* is directly related to the cross section, $\mathrm{Im}\Pi \sim \sigma(e^+e^- \to hadrons)$:

$$\Delta\alpha^{(5)}_{\mathrm{had}}(q^2) \; = \; -\frac{q^2}{4\pi^2\alpha}\, \mathrm{P} \int_{m_\pi^2}^{\infty} \frac{\sigma^0_{\mathrm{had}}(s)\,\mathrm{d}s}{s - q^2}\,, \qquad \sigma_{\mathrm{had}}(s) = \frac{\sigma^0_{\mathrm{had}}(s)}{|1 - \Pi|^2}$$

[$\to \sigma^0$ requires 'undressing', e.g. via $\cdot(\alpha/\alpha(s))^2$ $\rightsquigarrow$ iteration needed]

- Observable cross sections σ_{had} contain the |full photon propagator|^2, i.e. |infinite sum|^2.
  $\to$ To include the subleading Imaginary part, use dressing factor $\frac{1}{|1-\Pi|^2}$.

Aside II: Lepton EDMs and MDMS: d_μ vs. a_μ

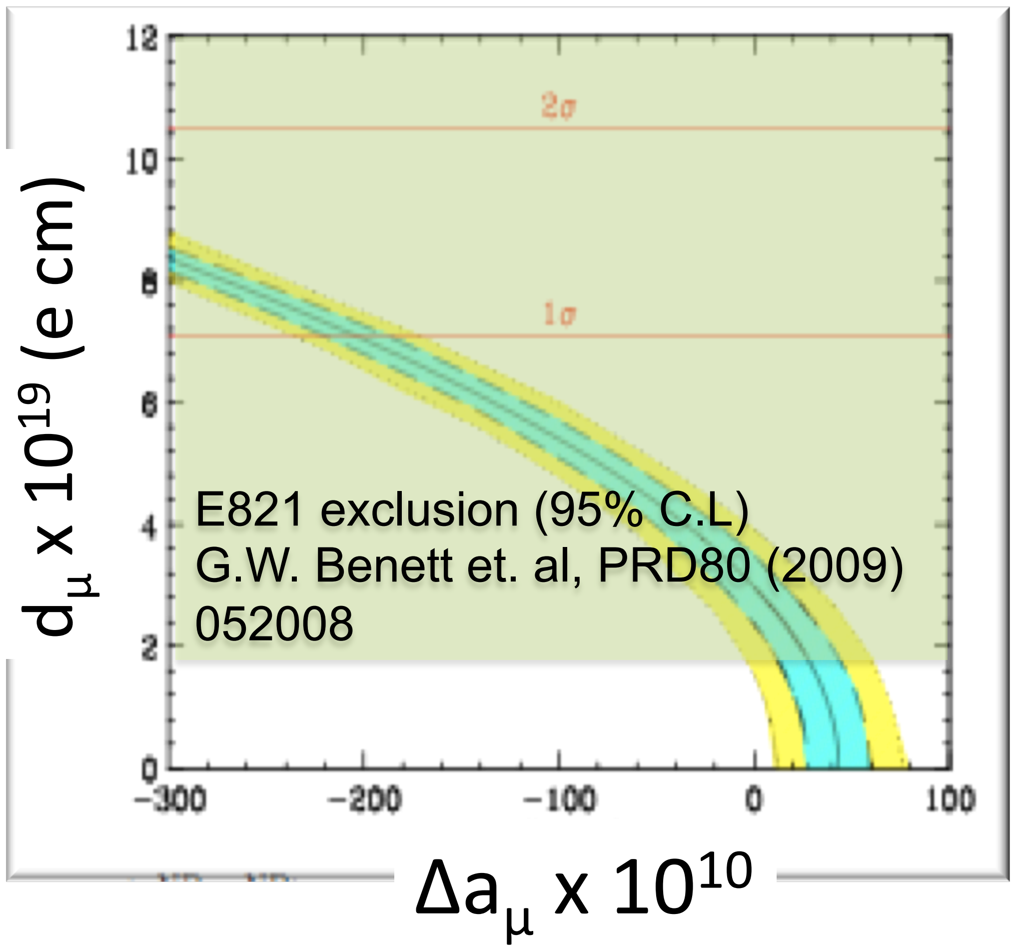
- One more reason to push for best possible muon EDM measurement:

  μEDM could in principle fake muon AMM `The g-2 anomaly isn't' (Feng et al. 2001)

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

↓

$$\omega = \sqrt{\vec{\omega}_a^2 + \vec{\omega}_\eta^2}$$



- Less room than there was before E821 improved the limit, still want to measure