UNIVERSITY OF LIVERPOOL

MIAPbP Workshop Precision Lepton Physics

$(g-2)_\mu$ theory overview

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(he/him)

University of Liverpool

27 April 2026

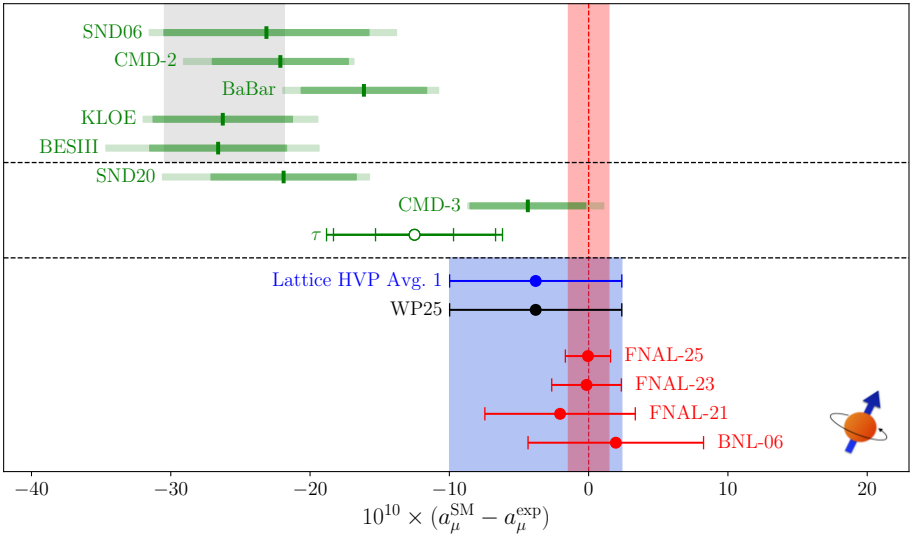
slides: talks.yannickulrich.com/26-04-27-miapbp.pdf

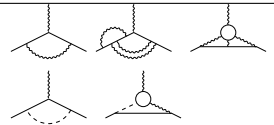
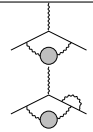
- Antonio has said much already
- I'll focus on some things he skipped
- my area of interest: Monte Carlos for HVP data extractions
- not a lattice expert
- for more information than I could ever cover $\Rightarrow$ see [WP25]

I'm not speaking for TI!

overview plot

Figure 83



		value$\times 10^{10}$	example diagrams	
QED		$11\,658\,471.88(2)$		(7.27)
EW		$15.44(4)$		(8.12)
HLbL LO	pheno:	$10.3(9)$		(5.69)
	lattice:	$12.2(9)$		(6.34)
HLbL NLO	pheno	$0.26(6)$		(5.70)
HVP LO	lattice:	$713.2(6.1)$		(3.37)
	pheno:	tbc.		
HVP (N)NLO	pheno:	$-8.72(13)$		(2.47)
total		$11\,659\,203.3(6.2)$		(9.4)

QED [Aoyama, Hayakawa, Nio, Volkov, WP25.7]

- no significant changes since WP20
- five loop cross-checked by Volkov and bug found
- six-loop contribution $\sim$ uncertainty due to parametric uncertainty of α, m_ℓ
- different values for α (Cs, Rb, a_e) differ by 2.4σ to 5.6σ
- error chosen to envelope all choices for α

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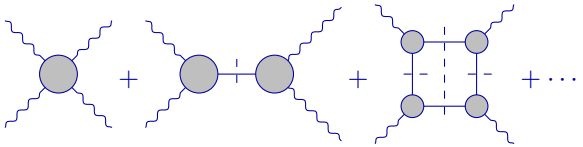
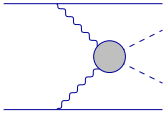
EW [Stöckinger, Stöckinger-Kim, WP25.8]

- LO $\sim g^2/(16\pi^2)m_\mu^2/m_W^2 \sim 10^{-9}$
- calculated exactly at two-loop
- leading logarithm $G_F\alpha^2\log^2(M_Z^2/m_f^2)$ estimated
- leading uncertainty: EW HVP

HLbL data driven

[Bijnens, Cappiello, Eichmann, Fischer, Gonzàlez-Solís, Hermansson-Truedsson, Hoferichter, Hoid, Holz, Kubis, Kupść, Masjuan, Procura, Rebhan, Redmer, Rodríguez-Sánchez, Roig, Sánchez-Puertas, Stoffer, Zillinger, WP25.5]

- decompose $a_\mu^{\mathrm{HLbL}} \sim \int \langle 0|j_{\mathrm{em}}^{\mu}(x) j_{\mathrm{em}}^{\nu}(y) j_{\mathrm{em}}^{\rho}(z) j_{\mathrm{em}}^{\sigma}(0)|0\rangle$
- multiple approaches: dispersive, holographic, ...
- dispersive: model hadrons in the blob
- $a_\mu^{\mathrm{HLbL}} \sim$ 
- needs data to be correct beyond pion pole
- e.g. $ee \to ee\pi\pi$ and other resonances 

[Feng, Gérardin, Jin, Lin, Meyer, WP25.6]

- use same decomposition, split by contributions (light quark, strange, charm, rest)
- additionally: relate to phenomenological calculations

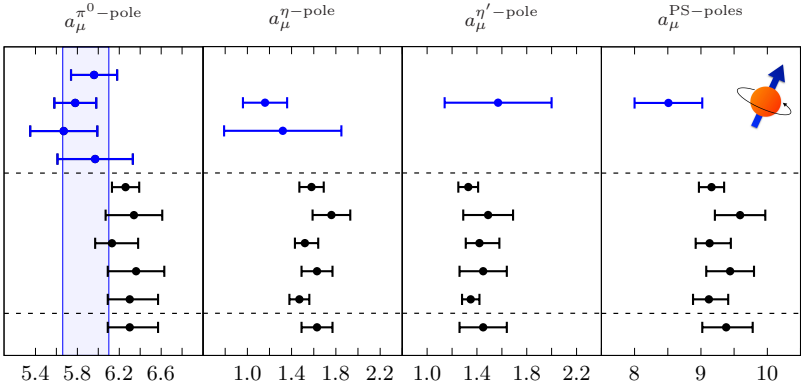
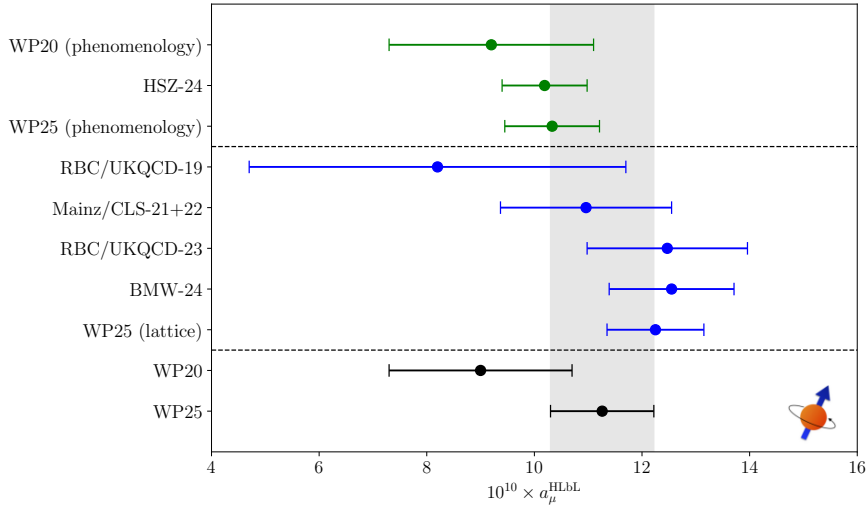


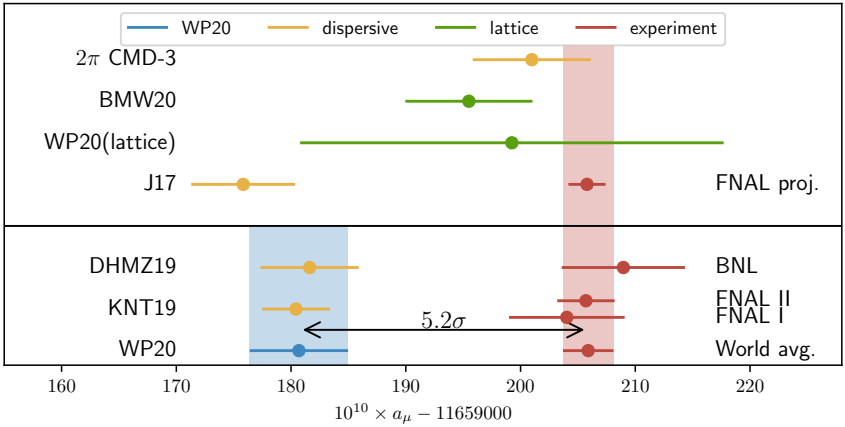
Figure 76

good agreement & consistency Figure 82



this is where all the trouble is..

- in WP20: combinations of e^+e^- data DHMZ & KNT in agreement, no good lattice
- shortly after WP20: good lattice (BMW), new 2π data (CMD-3)



HVP lattice (in 2025)

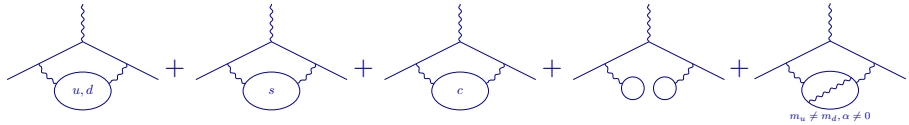
[Blum, Bruno, Cè, Clarke, Della Morte, DeTar, El-Khadra, Frezzotti, Gagliardi, Gérardin, Giusti, Gottlieb, Gülpers, Kuberski, Lahert, Lehner, Lellouch, Marinković, Meyer, Neil, Parrino, Portelli, Sitison, Tsang, Van de Water, Wang, Wittig, WP25.3]

- calculation similar to HLbL: $a_\mu^{\mathrm{HVP}} \sim \int \langle 0|j_{\mathrm{em}}^\mu(x) j_{\mathrm{em}}^\nu(0)|0\rangle$
- significant improvements since WP20: finite volume corrections, lattice scale uncertainty, full inclusion of IB, many more lattice actions are implemented
- 17 papers by 8 lattice collaborations, incl. 3 almost complete [BMW, RBC/UKQCD, Mainz]
- everything is thoroughly checked!
- introduction of window observables really helped!

HVP lattice contributions

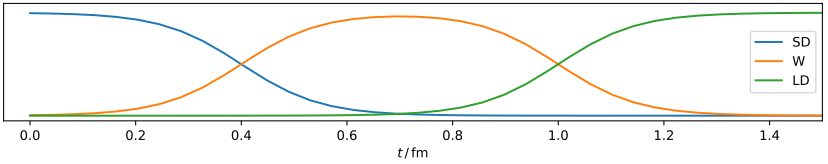
Section 3.6.1

$$a_\mu^{\mathrm{HVP}} = \underbrace{\quad}_{\sum_f a_\mu^{\mathrm{HVP}}(f,\mathrm{iso})}$$



$$= \sum_f a_\mu^{\mathrm{SD}}(f,\mathrm{iso}) + \sum_f a_\mu^{\mathrm{W}}(f,\mathrm{iso}) + \sum_f a_\mu^{\mathrm{LD}}(f,\mathrm{iso}) + \sum_f \delta a_\mu(\mathrm{IB})$$

- split by contribution and short-distance, intermediate, long-distance window



HVP lattice contributions

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$$a_\mu^{\mathrm{HVP}} = \underbrace{\quad + \quad + \quad + \quad}_{\sum_f a_\mu^{\mathrm{HVP}}(f,\mathrm{iso})} + \quad (m_u \neq m_d, \alpha \neq 0)$$

$$= \sum_f \left\langle a_\mu^{\mathrm{SD}}(f,\mathrm{iso}) \right\rangle + \sum_f \left\langle a_\mu^{\mathrm{W}}(f,\mathrm{iso}) \right\rangle + \sum_f \left\langle a_\mu^{\mathrm{LD}}(f,\mathrm{iso}) \right\rangle + \left\langle \sum_f \delta a_\mu(\mathrm{IB}) \right\rangle$$

- average all isospin-symmetric results for each window and add
- $a_\mu^{\mathrm{LD}}(\mathrm{iso})$ is tricky and was only computed by a few groups
- IB effects first added then averaged

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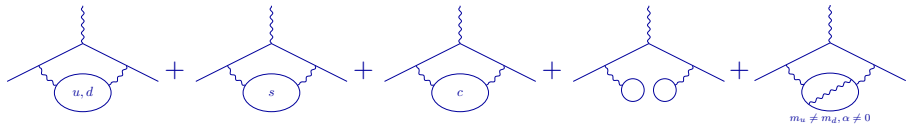

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$$= \underbrace{69.06(22)}_{(3.21)} + \underbrace{236.16(42)}_{(3.24)} + \underbrace{407.9(5.0)}_{(3.28)} + \underbrace{0.1(3.4)}_{(3.30)}$$

- average all isospin-symmetric results for each window and add
- $a_\mu^{\mathrm{LD}}(\mathrm{iso})$ is tricky and was only computed by a few groups
- IB effects first added then averaged
- value and error dominated by LD, light quark channel

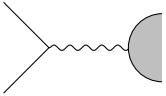
[Aliberti, Benton, Boito, Bruno, Carloni Calame, Cirigliano, Colangelo, Cotrozzi, Cottini, Davier, Denig, Druzhinin, Golterman, Hoecker, Hoferichter, Hoid, Holz, Ignatov, Keshavarzi, Kubis, Kupich, Laporta, Leplumey, Liu, Logashenko, López Castro, Lutz, Malaescu, Maltman, Miranda, Müller, Nesterenko, Nomura, Passera, Peris, Piccinini, Pilato, Polat, Roig, Ruiz de Elvira, Signer, Stoffer, Teubner, Toledo, Ulrich, Venanzoni, Wright, Zaid, Zhang, WP25.2]

basic idea: relate HVP to data

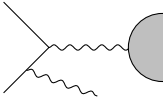
- $a_\mu^{\rm HVP} =$ $\sim \int \frac{{\rm d}^4 q}{(2\pi)^4}$
- dispersion relation $= \frac{1}{\pi} \int \frac{{\rm d}s}{s - q^2} \Im \Big($ $\Big)$
- optical theorem $2\Im \Big($ $\Big) = \sum_{\rm had} \int {\rm d}\Phi \Big|$ $\Big|^2$
- measure either in $e^+e^- \to \gamma^* \to$ hadrons or $\tau \to \nu_\tau + W(\to$ hadrons$)$ (+ flavour corrections)

HVP from e^+e^- data

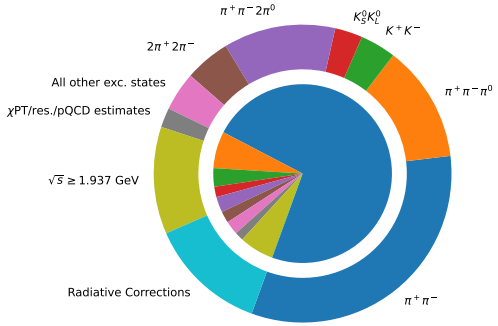
- need to measure all hadronic final states as a function of s_h
- kernel function favours low s_h contribution, $> 70\%$ from $\pi^+\pi^-$
- two ways of measuring:
  - scan [SND, CMD]



  - radiative return [KLOE, BES, BaBar]



- three fitting groups: [KNTW, DHMZ, CHKLS]



inner: a_μ, outer: δa_μ^2, KNTW data

KNTW

- data dynamically lustered to prevent over-fitting
- utilises full given covariance matrices/assumes full systematic correlation
- fit to avoid incurred d'Agostini bias
- full covariance matrices propagated to final result

DHMZ

- measurements quadratic spline interpolated and averaged on a fixed binning
- central value derived using uncertainties and local correlations
- uncertainties on channels generated from 'pseudo-experiments'

CHKLS

- select channels' spectra constrained by analyticity and unitarity

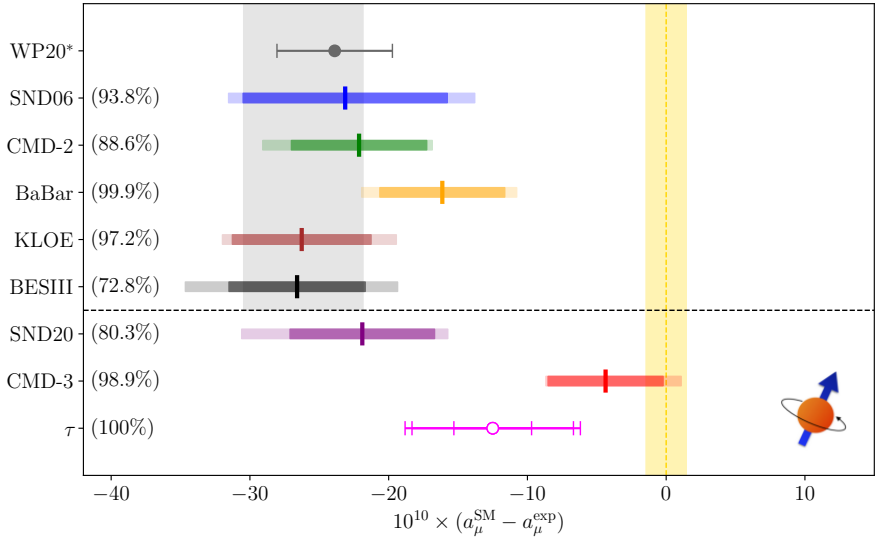
$\Rightarrow$ fit functions

- consistent w. DHMZ, KNTW despite method differing significantly

courtesy Aidan Wright, MPP2025

values for $\pi\pi$ channel

old tensions between BaBar & KLOE, new tension between CMD-3 and everything else Figure 27



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$\Rightarrow$ for WP25, data-driven HVP was only used HVP-(N)NLO

- theory Monte Carlos, esp. for $ee \to \pi\pi\gamma$ seem a bit sus..
- all rad. ret. measurements use PHOKHARA
- [DHMZ 23]: impact for KLOE & BES larger than for BaBar, refuted by [KLOE 24, BES 24]

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- RadioMonteCarLow2 Collaboration was founded to investigate this

SciPost Phys. Comm. Rep. 9 (2025)

Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions

Riccardo Aliberti[1], Paolo Beltrame[2], Ettore Budassi[3,4], Carlo M. Carloni Calame[4], Gilberto Colangelo[5], Lorenzo Cotrozzi[2], Achim Denig[1], Anna Driutti[6,7], Tim Engel[8], Lois Flower[2,9], Andrea Gurgone[3,6,7], Martin Hoferichter[5], Fedor Ignatov[2], Sophie Kollatzsch[10,11], Bastian Kubis[12], Andrzej Kupść[13,14]•, Fabian Lange[10,11], Alberto Lusiani[7,15], Stefan E. Müller[16], Jérémy Paltrinieri[2], Pau Petit Rosàs[2], Fulvio Piccinini[4], Alan Price[17], Lorenzo Punzi[7,15], Marco Rocco[10,18], Olga Shekhovtsova[19,20], Andrzej Siódmok[17], Adrian Signer[10,11]•, Giovanni Stagnitto[21], Peter Stoffer[10,11], Thomas Teubner[2], William J. Torres Bobadilla[2], Francesco P. Ucci[3,4], Yannick Ulrich[2,5]• and Graziano Venanzoni[2,7]•
(RadioMonteCarLow 2 working group)

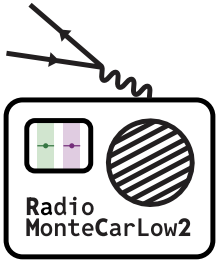
Abstract

We present the results of Phase I of an ongoing review of Monte Carlo tools relevant for low-energy hadronic cross sections. This includes a detailed comparison of Monte Carlo codes for electron–positron scattering into a muon pair, pion pair, and electron pair, for scan and radiative-return experiments. After discussing the various approaches that are used and effects that are included, we show differential cross sections obtained with AfkQed, BabaYaga@NLO, KKMC, MCGPJ, McMule, Phokhara, and Sherpa, for scenarios that are inspired by experiments providing input for the dispersive evaluation of the hadronic vacuum polarisation.

[RMCL2 23, WP25.2.4]

Phase 1 radiomontecarlow2.gitlab.io

- seven codes: AfkQed, BabaYaga@NLO, KKMC, MCGPJ, McMule, Phokhara, Sherpa
- calculate $ee \to XX(\gamma)$ with $X \in \{e, \mu, \pi\}$
- five scenarios: CMD-like, KLOE-like SA, KLOE-like LA, BES-like, B-like
- all calculate different things, compare to see what matters
  fixed order vs. YFS vs. collinear resummation vs. parton shower, ...



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- keep vital Monte Carlo software alive & accessible
- support development by pooling resources
- focus on low energy
- get people to stop calling it ISR

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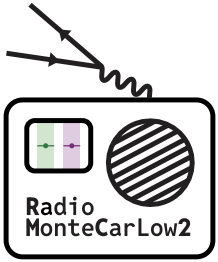

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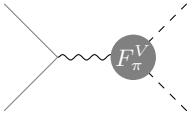

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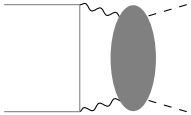

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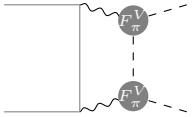

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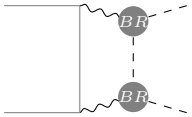

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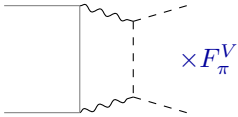

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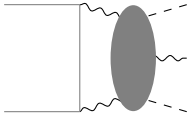

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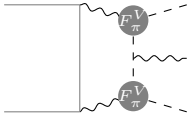

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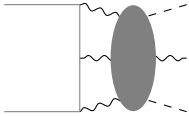


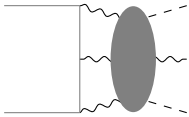
$n = 3$ FsQED approach is being tested ('Pisa consensus')

$n > 3$ nothing is known

$n = 1$ pion vector form factor $F_\pi^V(q^2)$

$n = 2$ pion Compton tensor

- full model: decomposition known, not used anywhere
- FsQED: approximate pion-pole but full form factor in loop
  used in new McMule & BabaYaga
- GVMD: approximate form factor through Breit Wigner
  used in new Phokhara, MCGPJ & BabaYaga
- F×sQED: calculate in sQED and multiply with form factor
  used in old Phokhara



$n = 3$ FsQED approach is being tested ('Pisa consensus')

$n > 3$ nothing is known

- F×sQEDis known to be insufficient, at least for $ee \to \pi\pi$ [Colangelo, Hoferichter, Monnard, de Elvira 22, Ignatov, Lee 22]
- effect for $ee \to \pi\pi\gamma$ maybe not as bad as feared [Petit Rosàs, Shekhovtsova, Torres Bobadilla 26]

terminology for RadioMonteCarLow2

- fixed-order: calculate all diagrams exactly* at LO/NLO/NNLO/... in α
  (some approximations like $m_e^2 \ll m_\mu^2, s, \ldots$ may be necessary)
- note that $2 \to 3$ (N)NLO $\subset$ $2 \to 2$ (N)NNLO
- resummation: approximate higher-order corrections rather than calculate
- YFS / CEEX / Photos: capture soft photons, potentially with interference
- PS / CS: capture collinear photons numerically or semi-analytically
- ISC / FSC: corrections only from initial state or final state, for $ee \to \pi\pi(\gamma)$ this means only $n = 1$
- event generator vs. integrator

in Phase I for Scan or Rad. return

AfkQed R: LO+ISC with CS, FSC with Photos, $X \in \{\mu, \pi\}$

BabaYaga S: NLO+PS, R: LO+PS; F×sQED

KKMC S: CEEX, R: CEEX for $X = \mu$

MCGPJ S: NLO+CS, R: LO+CS for $X \in \{e, \mu\}$; GVMD

McMule S: NNLO, R: NLO; for $X = \pi$ only ISC

Phokhara R: NLO for $X \in \{\mu, \pi\}$, F×sQED

Sherpa S: NLO+YFS for $X \in \{e, \mu\}$, YFS sQED for $X = \pi$

in Phase I for Scan or Rad. return
$\Rightarrow$ Phase II (might be out of date!)

AfkQed R: LO+ISC with CS, FSC with Photos, $X \in \{\mu, \pi\}$

BabaYaga S: NLO+PS, R: LO+PS; F×sQED
$\Rightarrow$ FsQED/GVMD, R: NLO+PS

KKMC S: CEEX, R: CEEX for $X = \mu$

MCGPJ S: NLO+CS, R: LO+CS for $X \in \{e, \mu\}$; GVMD

McMule S: NNLO, R: NLO; for $X = \pi$ only ISC
$\Rightarrow$ S: FsQED, R: partial NNLO, Pisa consesus WIP

Phokhara R: NLO for $X \in \{\mu, \pi\}$, F×sQED
$\Rightarrow$ GVMD done, NNLO & CEEX WIP

Sherpa S: NLO+YFS for $X \in \{e, \mu\}$, YFS sQED for $X = \pi$
$\Rightarrow$ GVMD & NNLO

- τ data: measure $\tau \to \nu_\tau + W(\to \pi^0\pi)$ [WP25.2.7]
  - in isospin-symmetric theory: W couples to hadrons like a photon
  - isospin breaking corrections need to be calculated

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  - use data where it's (relatively) consistent ($\geq 2.8\text{fm}$) but lattice error is large
  - results in very good error (3.8×10^{-10} vs. WP25 6.2×10^{-10})
  - however highly contentious and NOT included in WP25
    - does not address tension
    - highly dependent on switchover
    - KNTW vs. CMD-3 is still 2.8σ

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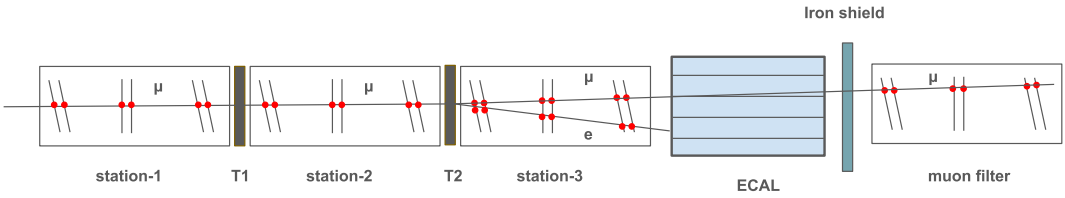
    - highly dependent on switchover
    - KNTW vs. CMD-3 is still 2.8σ
- MUonE: measure HVP in μ-e scattering (cf. Antonio's discussion, [WP25.2.10])

- scattering $160\,\mathrm{GeV}$ muon beam on low-Z material ($_4\mathrm{Be}$)
- pure t-channel $-s \simeq Q^2 \simeq 0$

$\Rightarrow$ high $s \leftrightarrow$ measure more of the curve

- 10^{-2} measurement $\times$ 10^{-3} effect $= 10^{-5}$ precision
- NNLO calculated, effect 10^{-3} - 10^{-4}, depending on scenario [Broggio, Engel, Ferroglia, Mandal, Mastrolia, Rocco, Ronca, Signer, Torres Bobadilla, Zoller, YU 22]

$\Rightarrow$ partial N^{3}LO and resummation needed



clarification from last week

- WP25 uses lattice for HVP
- data is used but only for HVP at (N)NLO because lattice is not ready yet
- very conservative estimate: envelope of KNT and KNT+CMD3
- $\delta a_\mu \lesssim$ HVP (N)NLO so even if you don't believe the data at all, it's fine

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conclusion & opinions

- $(g-2)_\mu$ is not a solved problem
- is the explanation BSM? probably not..
- lattice works, thanks to window observables
- lattice vs. data needs to be solved!
- 'Resolving the puzzles will require new measurements, together with an improved understanding of higher-order radiative corrections and their implementation in MC generators.'

full HVP comparison

Figure 40

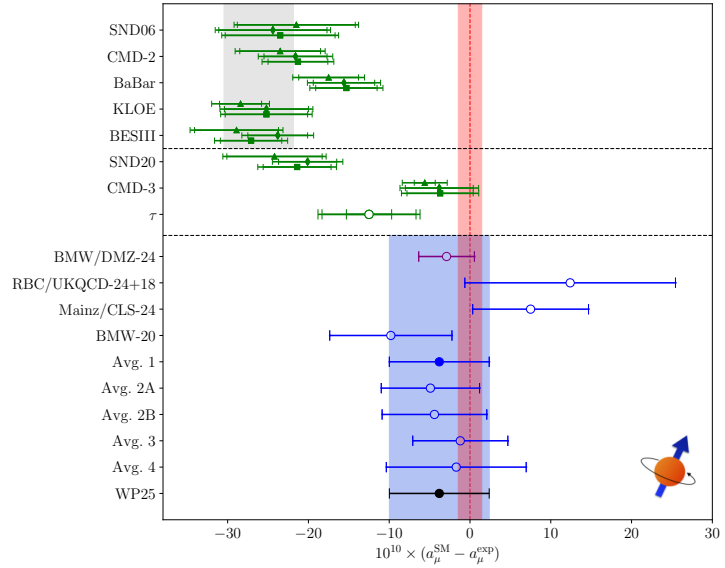


Figure 38

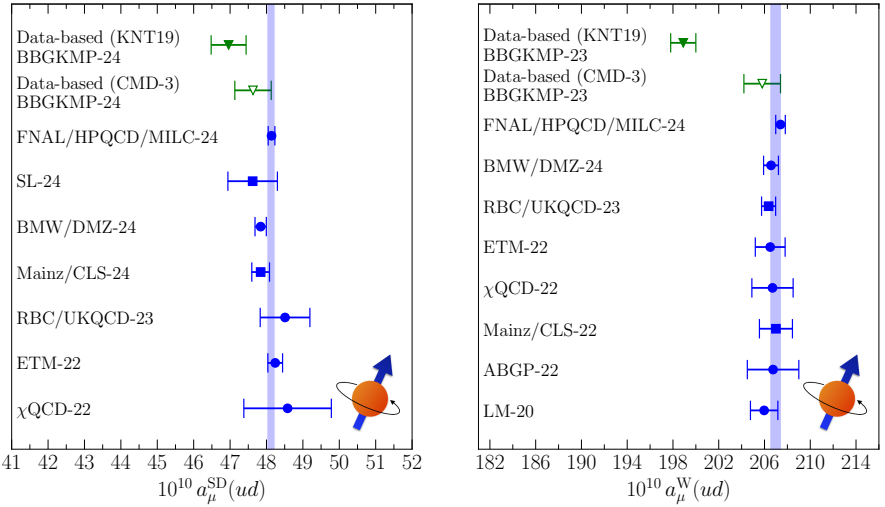
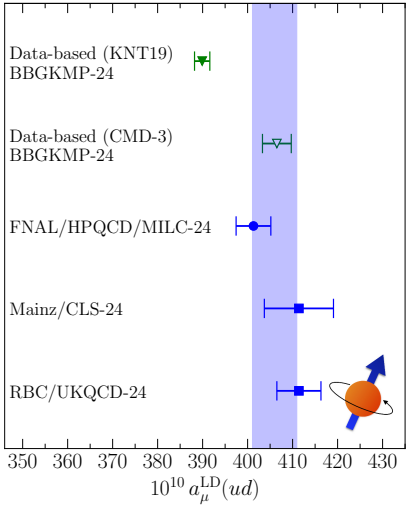

Data-based (KNT19)
BBGKMP-24
Data-based (CMD-3)
BBGKMP-24
FNAL/HPQCD/MILC-24
SL-24
BMW/DMZ-24
Mainz/CLS-24
RBC/UKQCD-23
ETM-22
χQCD-22
41 42 43 44 45 46 47 48 49 50 51 52
$10^{10}\, a_\mu^{\rm SD}(ud)$
Data-based (KNT19)
BBGKMP-23
Data-based (CMD-3)
BBGKMP-23
FNAL/HPQCD/MILC-24
BMW/DMZ-24
RBC/UKQCD-23
ETM-22
χQCD-22
Mainz/CLS-22
ABGP-22
LM-20
182 186 190 194 198 202 206 210 214
$10^{10}\, a_\mu^{\rm W}(ud)$

Figure 38


Data-based (KNT19)
BBGKMP-24
Data-based (CMD-3)
BBGKMP-24
FNAL/HPQCD/MILC-24
Mainz/CLS-24
RBC/UKQCD-24
350 360 370 380 390 400 410 420 430
$10^{10}\, a_\mu^{\rm LD}(ud)$

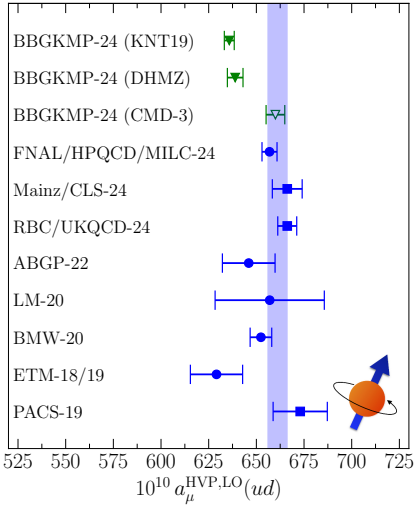
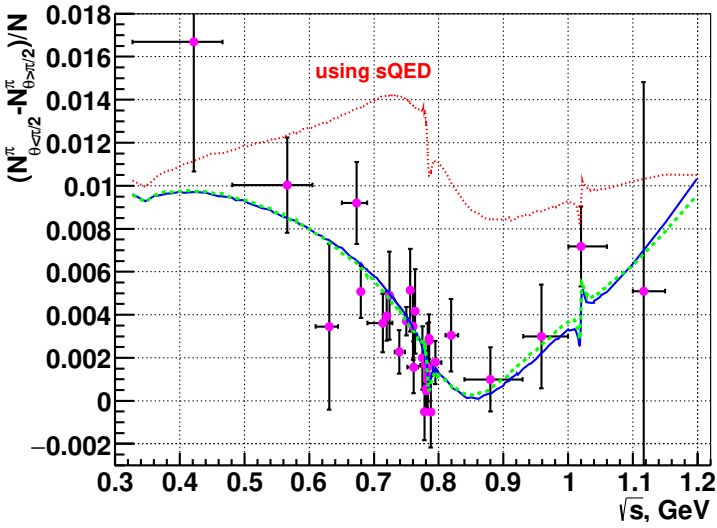

BBGKMP-24 (KNT19)
BBGKMP-24 (DHMZ)
BBGKMP-24 (CMD-3)
FNAL/HPQCD/MILC-24
Mainz/CLS-24
RBC/UKQCD-24
ABGP-22
LM-20
BMW-20
ETM-18/19
PACS-19
525 550 575 600 625 650 675 700 725
$10^{10}\, a_\mu^{\rm HVP,LO}(ud)$

Figure 2


using sQED
$(N^{\pi}_{\theta<\pi/2} - N^{\pi}_{\theta>\pi/2})/N$
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
−0.002
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
$\sqrt{s}$, GeV