The Muon $(g-2)$ in the Standard Model

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FOR FUNDAMENTAL PHYSICS

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Outline

Introduction: $(g-2)_\mu$ in the Standard Model

Hadronic Vacuum Polarization contribution
- White Paper: data-driven approach
- Lattice: the BMW result
- Lattice vs data-driven: the window quantity
- The new CMD3 measurement of $e^+e^- \to \pi^+\pi^-$

Hadronic light-by-light

Conclusions and Outlook

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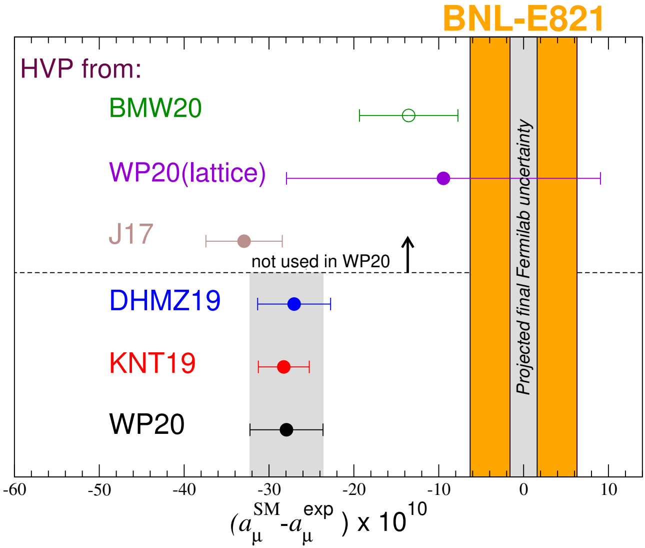
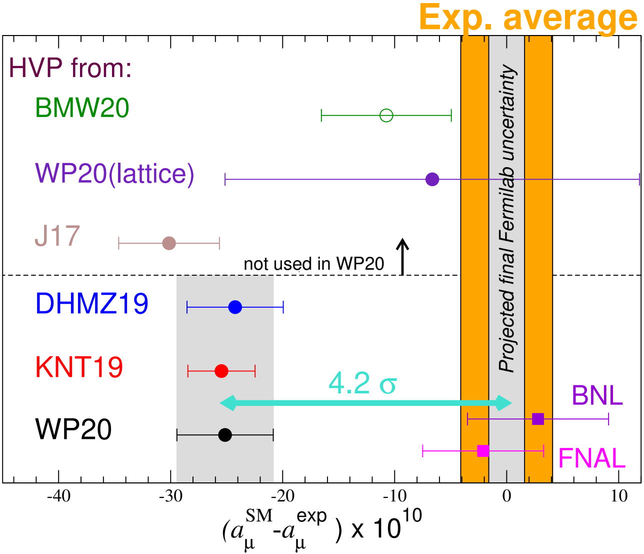
Present status of $(g-2)_\mu$: experiment vs SM

Before



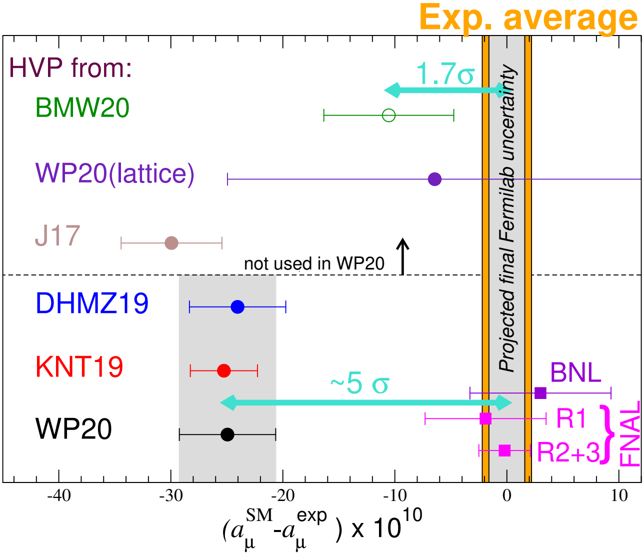
Present status of $(g-2)_\mu$: experiment vs SM

After the 2021 Fermilab result



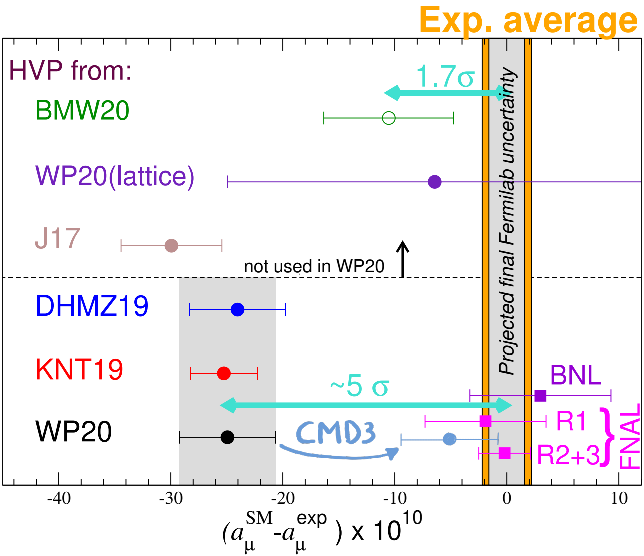
Present status of $(g-2)_\mu$: experiment vs SM

After the 2023 Fermilab result



Present status of $(g-2)_\mu$: experiment vs SM

After the 2023 Fermilab result and $\sigma(e^+e^- \to \pi^+\pi^-)$ from CMD3



White Paper (2020): $(g-2)_\mu$, experiment vs SM

Contribution	Value $\times 10^{11}$
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	$-98.3(7)$
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice, *udsc*)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, *uds*)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Experiment	116 592 059(22)
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	249(48)

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HVP LO (lattice, *udsc*) → BMW(20)	7075(55)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
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White Paper (2020): $(g-2)_\mu$, experiment vs SM

White Paper:
T. Aoyama et al. Phys. Rep. 887 (2020) = WP(20)

Muon $g-2$ Theory Initiative
Steering Committee:
GC
Michel Davier (vice-chair)
Aida El-Khadra (chair)
Martin Hoferichter
Laurent Lellouch
Christoph Lehner (vice-chair)
Tsutomu Mibe (J-PARC E34 experiment)
Lee Roberts (Fermilab E989 experiment)
Thomas Teubner
Hartmut Wittig

White Paper (2020): $(g-2)_\mu$, experiment vs SM

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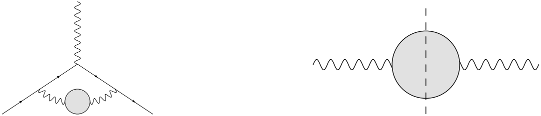
Muon $g-2$ **Theory Initiative**
Plenary Workshops:

- 1st, Q-Center (Fermilab), 3-6 June 2017
- 2nd, Mainz, 18-22 June 2018
- 3rd, Seattle, 9-13 September 2019
- 4th, KEK (virtual), 28 June-02 July 2021
- 5th, Higgs Center Edinburgh, 5-9 Sept. 2022
- 6th, Bern, 4-8 Sept. 2023
- 7th, KEK, 9-13 Sept. 2024

Theory uncertainty comes from hadronic physics

- Hadronic contributions responsible for most of the theory uncertainty
- Hadronic vacuum polarization (HVP) is $\mathcal{O}(\alpha^2)$, dominates the total uncertainty, despite being known to $< 1\%$

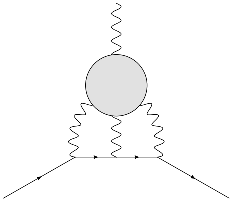


  - unitarity and analyticity ⇒ dispersive approach
  - ⇒ direct relation to experiment: $\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons})$
  - e^+e^- Exps: BaBar, Belle, BESIII, CMD2/3, KLOE2, SND
  - alternative approach: lattice, becoming competitive

(BMW, ETMC, Fermilab, HPQCD, Mainz, MILC, RBC/UKQCD)

Theory uncertainty comes from hadronic physics

- Hadronic contributions responsible for most of the theory uncertainty
- Hadronic vacuum polarization (HVP) is $\mathcal{O}(\alpha^2)$, dominates the total uncertainty, despite being known to $< 1\%$
- Hadronic light-by-light (HLbL) is $\mathcal{O}(\alpha^3)$, known to $\sim 20\%$, second largest uncertainty (now subdominant)



- earlier: model-based—uncertainties difficult to quantify
- recently: dispersive approach $\Rightarrow$ data-driven, systematic treatment
- lattice QCD is competitive

(Mainz, RBC/UKQCD)

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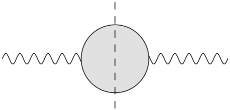
Conclusions and Outlook

HVP contribution: Master Formula

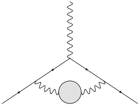
Unitarity relation: simple, same for all intermediate states



$$\mathrm{Im}\bar{\Pi}(q^2) \propto \sigma(e^+e^- \to \mathrm{hadrons}) = \sigma(e^+e^- \to \mu^+\mu^-)R(q^2)$$

Analyticity $\left[\bar{\Pi}(q^2) = \frac{q^2}{\pi}\int ds \frac{\mathrm{Im}\bar{\Pi}(s)}{s(s-q^2)}\right]$ $\Rightarrow$ Master formula for HVP

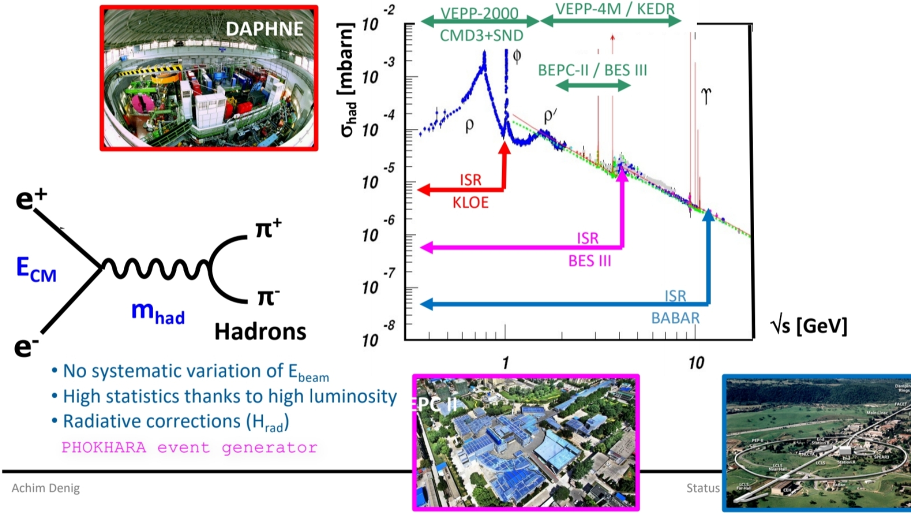
Bouchiat, Michel (61)



$$\Leftrightarrow \qquad a_\mu^{\mathrm{hvp}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{ds}{s}K(s)R(s)$$

$K(s)$ known, depends on m_μ and $K(s) \sim \frac{1}{s}$ for large s

HVP contribution: Master Formula



- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Radiative corrections (H_{rad})

PHOKHARA event generator

Achim Denig

Status

Slide by Achim Denig, MUonE Workshop, June 2024

Comparison between DHMZ19 and KNT19

	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(3.38)	504.23(1.90)	3.62
$\pi^+\pi^-\pi^0$	46.21(1.45)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.30)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.55)	18.15(74)	−0.12
K^+K^-	23.08(0.44)	23.00(22)	0.08
$K_S K_L$	12.82(0.24)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.10)	4.58(10)	−0.17
Sum of the above	626.08(3.90)	623.62(2.27)	2.46
$[1.8, 3.7]\,\mathrm{GeV}$ (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
J/ψ, $\psi(2S)$	7.76(12)	7.84(19)	−0.08
$[3.7, \infty)\,\mathrm{GeV}$	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\text{HVP, LO}}$	694.0(4.0)	692.8(2.4)	1.2

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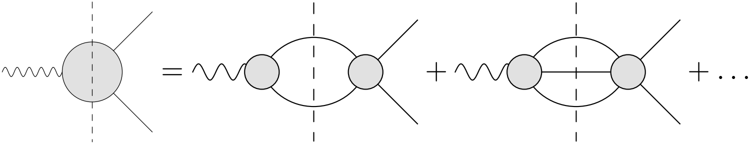
For the dominant $\pi\pi$ channel more theory input can be used

Omnès representation including isospin breaking



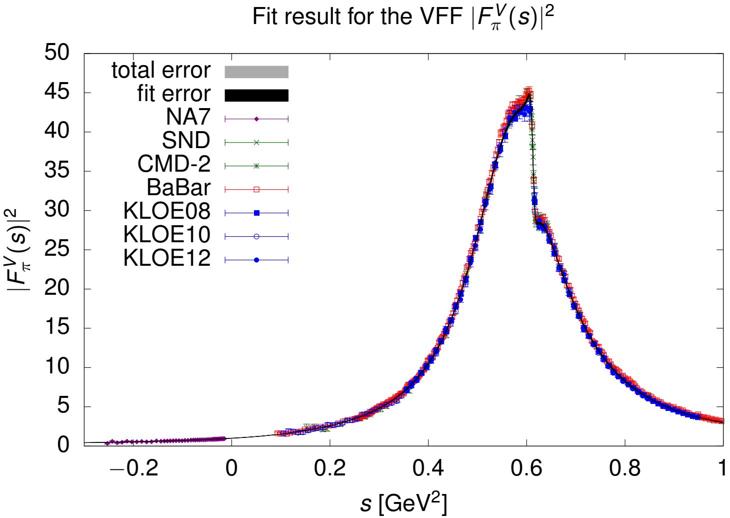
$$F_V(s) = \Omega_{\pi\pi}(s) \cdot G_\omega(s) \cdot \Omega_{\text{in}}(s)$$

main contribution $\Omega_{\pi\pi}(s)$: 2 parameters

GC, Hoferichter, Stoffer (18)

Fit results

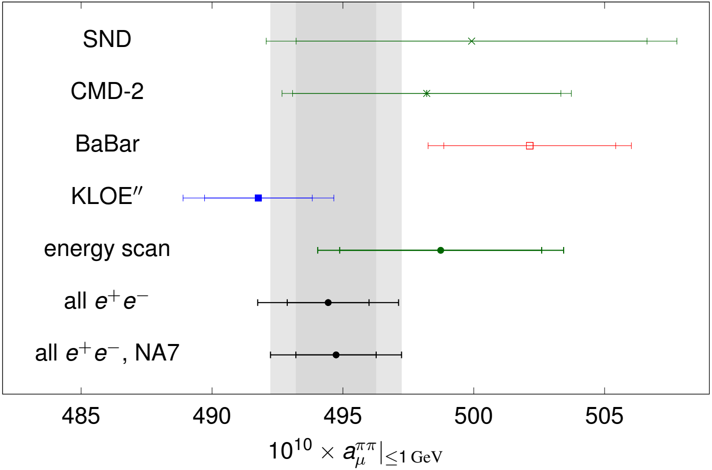
GC, Hoferichter, Stoffer (18)



Fit results

GC, Hoferichter, Stoffer (18)

Result for $a_\mu^{\pi\pi}|_{\leq 1\,\mathrm{GeV}}$ from the VFF fits to single experiments and combinations



2π: comparison with the dispersive approach

2π channel described dispersively $\Rightarrow$ more theory constraints

Ananthanarayan, Caprini, Das (19), GC, Hoferichter, Stoffer (18) WP(20)

Energy range	CHS18	DHMZ19	KNT19
$\leq 0.6\,\mathrm{GeV}$	110.1(9)	110.4(4)(5)	108.7(9)
$\leq 0.7\,\mathrm{GeV}$	214.8(1.7)	214.7(0.8)(1.1)	213.1(1.2)
$\leq 0.8\,\mathrm{GeV}$	413.2(2.3)	414.4(1.5)(2.3)	412.0(1.7)
$\leq 0.9\,\mathrm{GeV}$	479.8(2.6)	481.9(1.8)(2.9)	478.5(1.8)
$\leq 1.0\,\mathrm{GeV}$	495.0(2.6)	497.4(1.8)(3.1)	493.8(1.9)
$[0.6, 0.7]\,\mathrm{GeV}$	104.7(7)	104.2(5)(5)	104.4(5)
$[0.7, 0.8]\,\mathrm{GeV}$	198.3(9)	199.8(0.9)(1.2)	198.9(7)
$[0.8, 0.9]\,\mathrm{GeV}$	66.6(4)	67.5(4)(6)	66.6(3)
$[0.9, 1.0]\,\mathrm{GeV}$	15.3(1)	15.5(1)(2)	15.3(1)
$\leq 0.63\,\mathrm{GeV}$	132.8(1.1)	132.9(5)(6)	131.2(1.0)
$[0.6, 0.9]\,\mathrm{GeV}$	369.6(1.7)	371.5(1.5)(2.3)	369.8(1.3)
$\left[\sqrt{0.1}, \sqrt{0.95}\,\right]\,\mathrm{GeV}$	490.7(2.6)	493.1(1.8)(3.1)	489.5(1.9)

Combination method and final result

Complete analyses DHMZ19 and KNT19, as well as CHS19 (2π) and HHK19 (3π), have been so combined:

- central values are obtained by simple averages (for each channel and mass range)
- the largest experimental and systematic uncertainty of DHMZ and KNT is taken
- $1/2$ difference DHMZ$-$KNT (or BABAR$-$KLOE in the 2π channel, if larger) is added to the uncertainty

Final result:

$$\begin{aligned} a_\mu^{\text{HVP, LO}} &= 693.1(2.8)_{\text{exp}}(2.8)_{\text{sys}}(0.7)_{\text{DV+QCD}} \times 10^{-10} \\ &= 693.1(4.0) \times 10^{-10} \end{aligned}$$

WP(20)

The BMW result

Borsanyi et al. Nature 2021

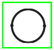
State-of-the-art lattice calculation of $a_\mu^{\text{HVP, LO}}$ based on

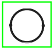
- current-current correlator, summed over all distances, integrated in time with appropriate kernel function (TMR)
- using staggered fermions on an $L \sim 6$ fm lattice ($L \sim 11$fm used for finite volume corrections)
- at (and around) physical quark masses
- including isospin-breaking effects

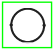
The BMW result

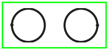
Borsanyi et al. Nature 2021

Isospin-symmetric

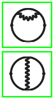

Connected light
$633.7(2.1)_{stat}(4.2)_{syst}$

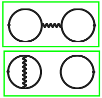

Connected strange
$53.393(89)_{stat}(68)_{syst}$


Connected charm
$14.6(0)_{stat}(1)_{syst}$

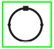

Disconnected
$-13.36(1.18)_{stat}(1.36)_{syst}$

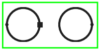
QED isospin breaking: valence


Connected $-1.23(40)_{stat}(31)_{syst}$

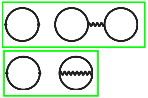

Disconnected $-0.55(15)_{stat}(10)_{syst}$

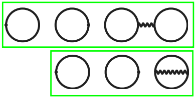
Strong–isospin breaking


Connected
$6.60(63)_{stat}(53)_{syst}$


Disconnected
$-4.67(54)_{stat}(69)_{syst}$

QED isospin breaking: sea


Connected $0.37(21)_{stat}(24)_{syst}$

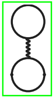

Disconnected $-0.040(33)_{stat}(21)_{syst}$

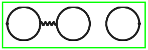
Other

Bottom; higher-order; perturbative

$0.11(4)_{tot}$

QED isospin breaking: mixed


Connected $-0.0093(86)_{stat}(95)_{syst}$


Disconnected $0.011(24)_{stat}(14)_{syst}$

Finite-size effects

Isospin-symmetric

$18.7(2.5)_{tot}$

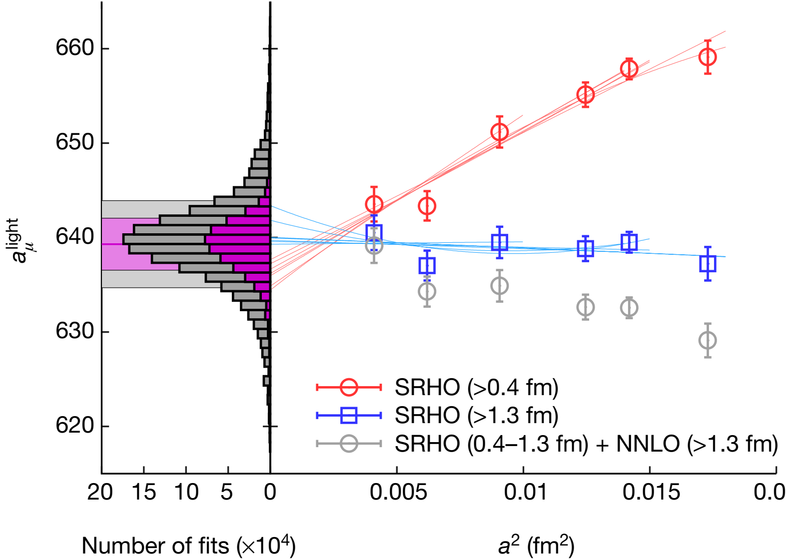
Isospin-breaking

$0.0(0.1)_{tot}$

$$a_\mu^{\text{LO-HVP}}\,(\times 10^{10}) = 707.5(2.3)_{stat}(5.0)_{syst}(5.5)_{tot}$$

The BMW result

Borsanyi et al. Nature 2021



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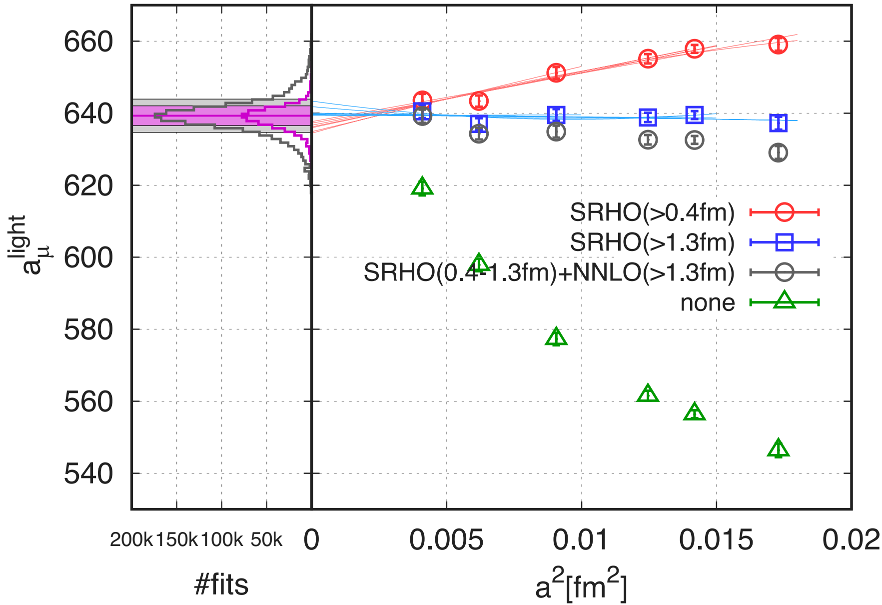
Borsanyi et al. Nature 2021



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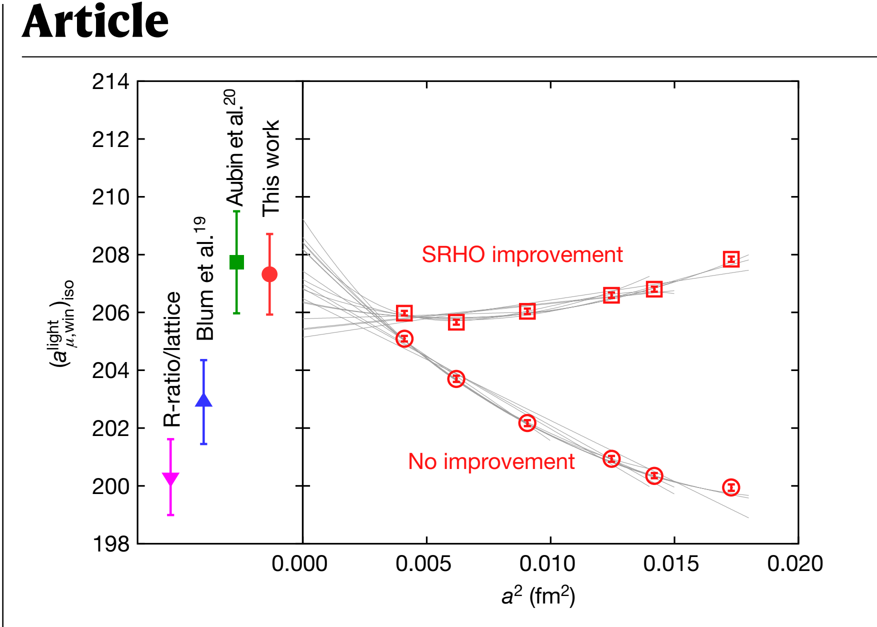
Borsanyi et al. Nature 2021

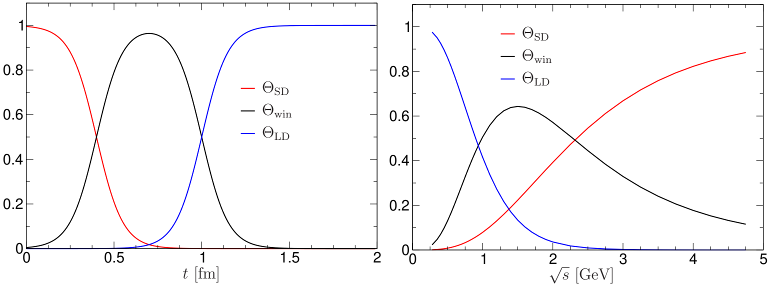


The BMW result

Borsanyi et al. Nature 2021

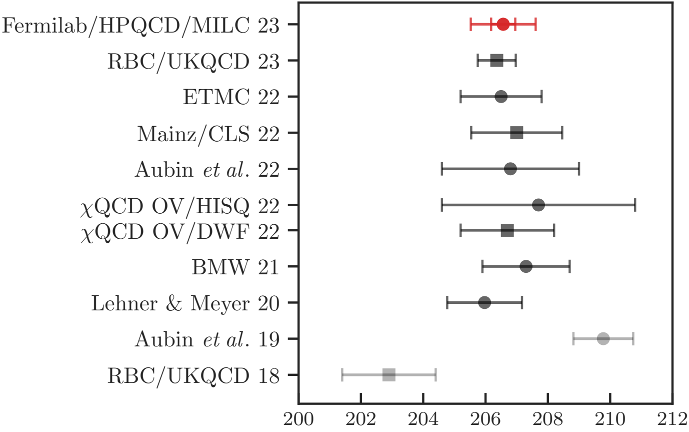
Weight functions for window quantities

RBC/UKQCD (18)



Present status of the window quantities

Several lattice calculations have confirmed BMW's result



`arXiv:2301.08274`, Fermilab Lattice-HPQCD-MILC (23)

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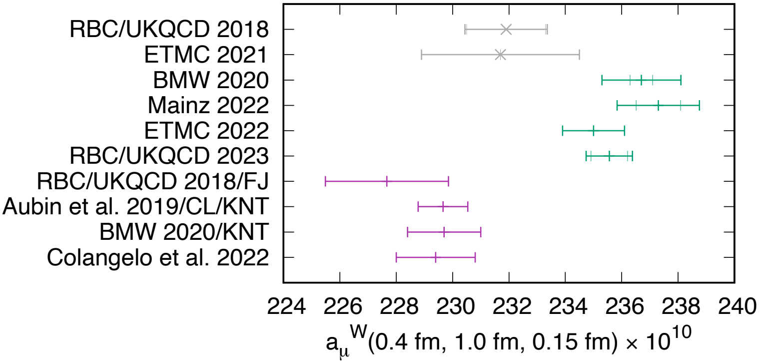


`arXiv:2301.08696` RBC/UKQCD (23)

Individual-channel contributions to a_μ^{win}

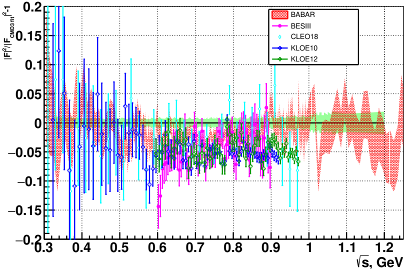
Channel	total	window
$\pi^+\pi^-$	504.23(1.90)	144.08(49)
$\pi^+\pi^-\pi^0$	46.63(94)	18.63(35)
$\pi^+\pi^-\pi^+\pi^-$	13.99(19)	8.88(12)
$\pi^+\pi^-\pi^0\pi^0$	18.15(74)	11.20(46)
K^+K^-	23.00(22)	12.29(12)
K_SK_L	13.04(19)	6.81(10)
$\pi^0\gamma$	4.58(10)	1.58(4)
Sum of the above	623.62(2.27)	203.47(78)
$[1.8, 3.7]$ GeV (without $c\bar{c}$)	34.45(56)	15.93(26)
J/ψ, $\psi(2S)$	7.84(19)	2.27(6)
$[3.7, \infty)$ GeV	16.95(19)	1.56(2)
WP(20) / GC, El-Khadra *et al.* (22)	693.1(4.0)	229.4(1.4)
BMWc	707.5(5.5)	236.7(1.4)
Mainz/CLS		237.3(1.5)
ETMc		235.0(1.1)
RBC/UKQCD		235.6(0.8)

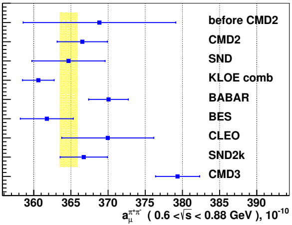
Numbers for the channels refer to KNT19 — thanks to Alex Keshavarzi for providing them

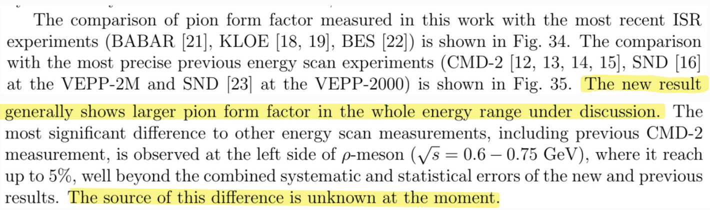
$$\Delta a_\mu^{\text{HVP, LO}} = 14.4(6.8)\,(2.1\sigma), \qquad \Delta a_\mu^{\mathrm{win}} \sim 6.5(1.5)\,(\sim 4.3\sigma)$$

CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$

F. Ignatov et al., CMD-3, `arXiv:2302.08834`



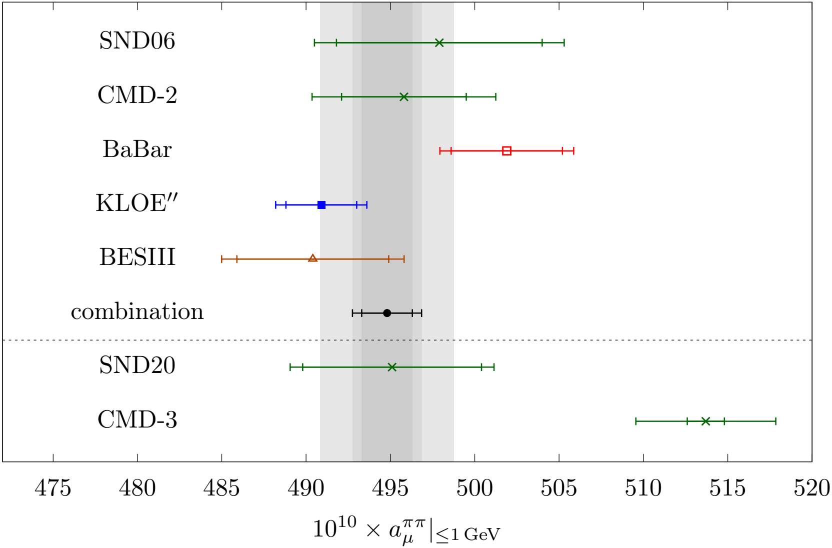




The comparison of pion form factor measured in this work with the most recent ISR experiments (BABAR [21], KLOE [18, 19], BES [22]) is shown in Fig. 34. The comparison with the most precise previous energy scan experiments (CMD-2 [12, 13, 14, 15], SND [16] at the VEPP-2M and SND [23] at the VEPP-2000) is shown in Fig. 35. The new result generally shows larger pion form factor in the whole energy range under discussion. The most significant difference to other energy scan measurements, including previous CMD-2 measurement, is observed at the left side of ρ-meson ($\sqrt{s} = 0.6 - 0.75$ GeV), where it reach up to 5%, well beyond the combined systematic and statistical errors of the new and previous results. The source of this difference is unknown at the moment.

Preliminary analysis of the CMD-3 measurement

GC, Hoferichter and Stoffer, `arXiv:2308.04217` (thanks for providing the plot)



Preliminary analysis of the CMD-3 measurement

GC, Hoferichter and Stoffer, `arXiv:2308.04217`

$10^{10}\times$	$a_\mu^{\pi\pi}\vert_{\leq 1\mathrm{GeV}}$	$a_\mu^{\pi\pi,\mathrm{win}}\vert_{\leq 1\mathrm{GeV}}$	χ^2/dof
SND06	497.9(6.1)(4.2)	139.6(1.8)(1.0)	1.09
CMD-2	495.8(3.7)(4.0)	139.4(1.0)(0.8)	1.01
BaBar	501.9(3.3)(2.2)	140.6(1.0)(0.7)	1.17
KLOE”	490.9(2.1)(1.7)	137.1(0.6)(0.4)	1.13
BESIII	490.4(4.5)(3.0)	137.8(1.3)(0.4)	1.01
SND20	495.1(5.3)(2.9)	139.2(1.5)(0.4)	1.88
CMD-3	513.7(1.1)(4.0)	144.0(0.3)(1.1)	1.09
Combination	494.8(1.5)(1.4)(3.4)	138.3(0.4)(0.3)(1.1)	1.21

Combination: NA7 + all data sets other than SND20 and CMD-3

$$\Delta a_\mu^{\text{HVP, LO}}(\text{CMD-3-Comb.}) = 18.9(5.1)\,, \qquad \Delta a_\mu^{\mathrm{win}}(\text{CMD-3-Comb.}) = 5.7(1.5)$$

$$\Delta a_\mu^{\text{HVP, LO}}(\text{BMW-WP20}) = 14.4(6.8), \qquad \Delta a_\mu^{\mathrm{win}}(\text{Lattice-WP20}) \sim 6.5(1.5)$$

Preliminary analysis of the CMD-3 measurement

GC, Hoferichter and Stoffer, `arXiv:2308.04217`

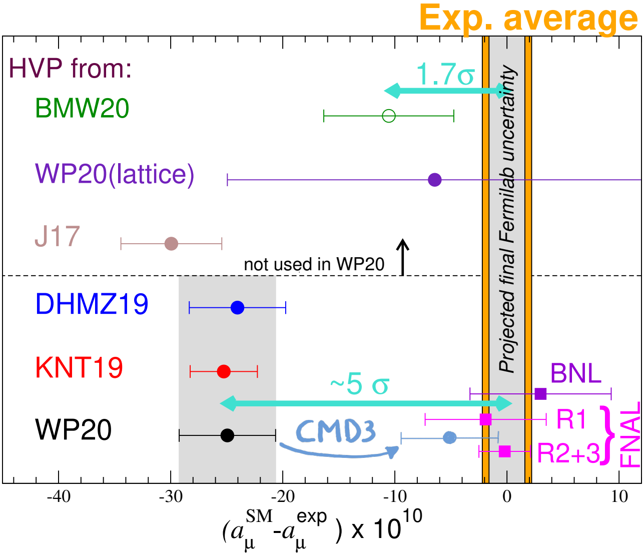
Discrepancy	$a_\mu^{\pi\pi}\big\vert_{[0.60,0.88]\,\text{GeV}}$	$a_\mu^{\pi\pi}\big\vert_{\leq 1\,\text{GeV}}$	int window
SND06	1.8σ	1.7σ	1.7σ
CMD-2	2.3σ	2.0σ	2.1σ
BaBar	3.3σ	2.9σ	3.1σ
KLOE″	5.6σ	4.8σ	5.4σ
BESIII	3.0σ	2.8σ	3.1σ
SND20	2.2σ	2.1σ	2.2σ
Combination	4.2σ [6.1σ]	3.7σ [5.0σ]	3.8σ [5.7σ]

Combination: NA7 + all data sets other than SND20 and CMD-3

$$\Delta a_\mu^{\text{HVP, LO}}(\text{CMD-3-Comb.}) = 18.9(5.1)\,, \qquad \Delta a_\mu^{\text{win}}(\text{CMD-3-Comb.}) = 5.7(1.5)$$

$$\Delta a_\mu^{\text{HVP, LO}}(\text{BMW-WP20}) = 14.4(6.8), \qquad \Delta a_\mu^{\text{win}}(\text{Lattice-WP20}) \sim 6.5(1.5)$$

Present status of $(g-2)_\mu$: experiment vs SM



Outline

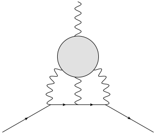
Introduction: $(g-2)_\mu$ in the Standard Model

Hadronic Vacuum Polarization contribution
- White Paper: data-driven approach
- Lattice: the BMW result
- Lattice vs data-driven: the window quantity
- The new CMD3 measurement of $e^+e^- \to \pi^+\pi^-$

Hadronic light-by-light

Conclusions and Outlook

HLbL contribution: Master Formula



$$a_\mu^{\text{HLbL}} = \frac{2\alpha^3}{48\pi^2}\int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau \sqrt{1-\tau^2}\sum_{i=1}^{12} T_i(Q_1,Q_2,\tau)\bar{\Pi}_i(Q_1,Q_2,\tau)$$

Q_i^μ are the Wick-rotated four-momenta and τ the four-dimensional angle between Euclidean momenta: $Q_1 \cdot Q_2 = |Q_1||Q_2|\tau$
The integration variables $Q_1 := |Q_1|$, $Q_2 := |Q_2|$.

GC, Hoferichter, Procura, Stoffer (15)

- T_i: known kernel functions
- $\bar{\Pi}_i$ are amenable to a dispersive treatment:
  imaginary parts are related to measurable subprocesses

Improvements obtained with the dispersive approach

Contribution	PdRV(09) *Glasgow consensus*	N/JN(09)	J(17)	WP(20)
π^0, η, η'-poles	114(13)	99(16)	95.45(12.40)	93.8(4.0)
π, K-loops/boxes	−19(19)	−19(13)	−20(5)	−16.4(2)
S-wave $\pi\pi$ rescattering	−7(7)	−7(2)	−5.98(1.20)	−8(1)
subtotal	88(24)	73(21)	69.5(13.4)	69.4(4.1)
scalars	–	–	–	− 1(3)
tensors	–	–	1.1(1)	
axial vectors	15(10)	22(5)	7.55(2.71)	6(6)
u, d, s-loops / short-distance	–	21(3)	20(4)	15(10)
c-loop	2.3	–	2.3(2)	3(1)
total	105(26)	116(39)	100.4(28.2)	92(19)

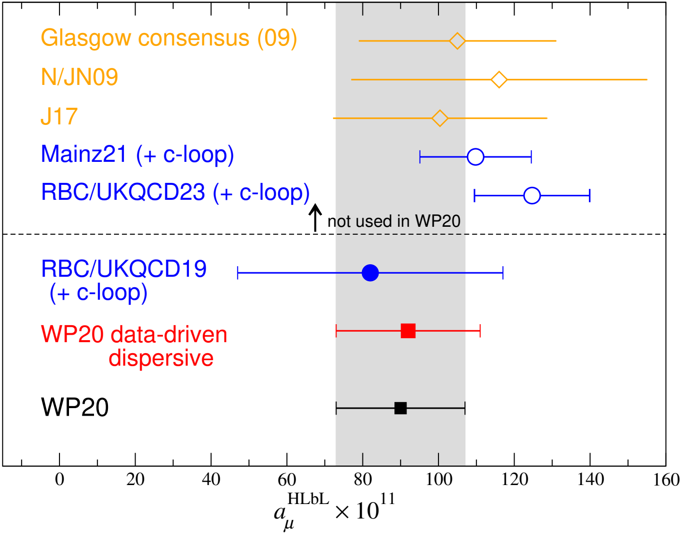
- significant reduction of uncertainties in the first three rows

  CHPS (17), Masjuan, Sánchez-Puertas (17) Hoferichter, Hoid et al. (18), Gerardin, Meyer, Nyffeler (19)

- resonances and short-distance constraints need to be improved

  Danilkin, Hoferichter, Stoffer (21), Lüdtke, Procura, Stoffer (23), Melnikov, Vainshtein (04), Nyffeler (09), Bijnens et al. (20,21), Cappiello et al. (20), Leutgeb, Rebhan (19,21)

Situation for HLbL



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Hadronic light-by-light

Conclusions and Outlook

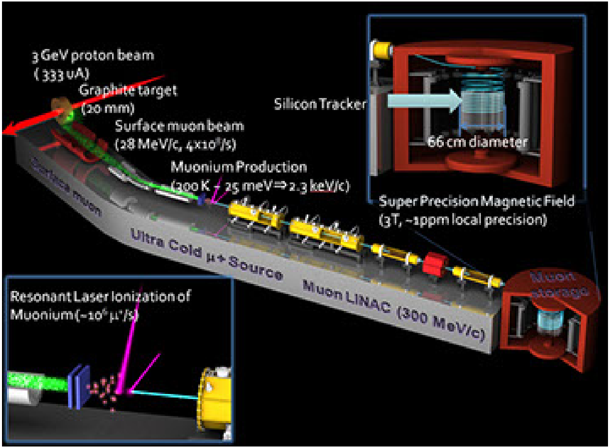
Conclusions

- Data-driven evaluation of the HVP contribution (WP20):
  0.6% error $\Rightarrow$ dominates the theory uncertainty
- Dominant contribution to HVP: $\pi\pi$ (<1 GeV). WP20 based on:
  CMD-2, SND06, BaBar, KLOE, BES-III
  New puzzle: measurement by CMD-3 significantly higher!
- Recent lattice calculation [BMW(20)] has reached a similar precision but differs from the dispersive one (=from e^+e^- data).
  If confirmed $\Rightarrow$ discrepancy with experiment $\searrow$ below 2σ
- Intermediate window of BMW has been confirmed by other lattice collaborations (Aubin et al., Mainz, ETMc, RBC/UKQCD, Fermilab-HPQCD-MILC) and disagrees with data-driven [other than CMD-3, which would agree]
- Evaluation of the HLbL contribution based on the dispersive approach: 20% accuracy. Two recent lattice calculations [RBC/UKQCD(23), Mainz(21)] agree with it

Outlook

- The Fermilab experiment aims to reduce the BNL uncertainty by a factor four ⇒ potential 7σ discrepancy
- Improvements on the SM theory/data side:
  - Situation for HVP data-driven urgently needs to be clarified:
    - New CMD-3 result—after thorough scrutiny—is a puzzle
    - Forthcoming measur./analyses: BaBar, Belle II, BESIII, KLOE,SND
    - Model-independent evaluation of RadCorr underway (but unlikely the culprit)
    - Monte Carlo codes used by experiments: what is their role?
    - MuonE will provide an alternative way to measure HVP
  - HVP lattice:
    calculations w/ precision ∼ BMW for $a_\mu^{\text{HVP, LO}}$ expected soon
  - HLbL: goal of ∼ 10% uncertainty within reach
    (both data-driven and lattice)

Future: Muon $g-2$/EDM experiment @ J-PARC



Credit: J-PARC