Comments on the $\pi\pi$ contribution to HVP

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FOR FUNDAMENTAL PHYSICS

MuONE meeting, MITP Mainz, June 4, 2024

Outline

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

Hadronic Vacuum Polarization contribution
- Data-driven approach
- Dispersive approach for the $\pi\pi$ contribution
- Lattice vs data-driven: intermediate window

Conclusions and Outlook

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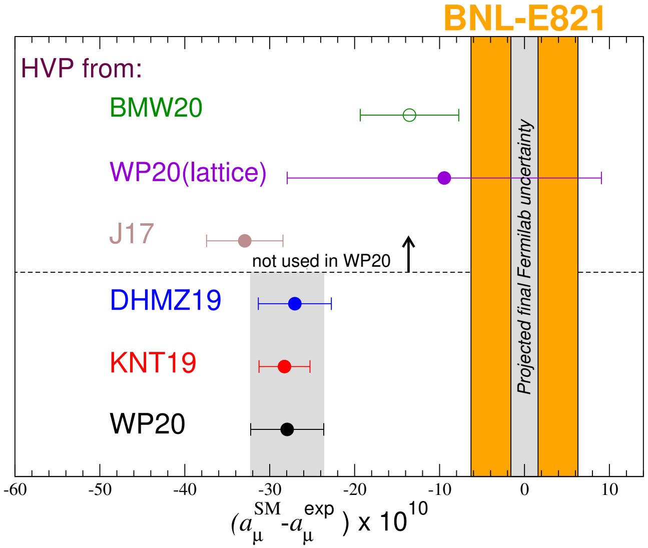
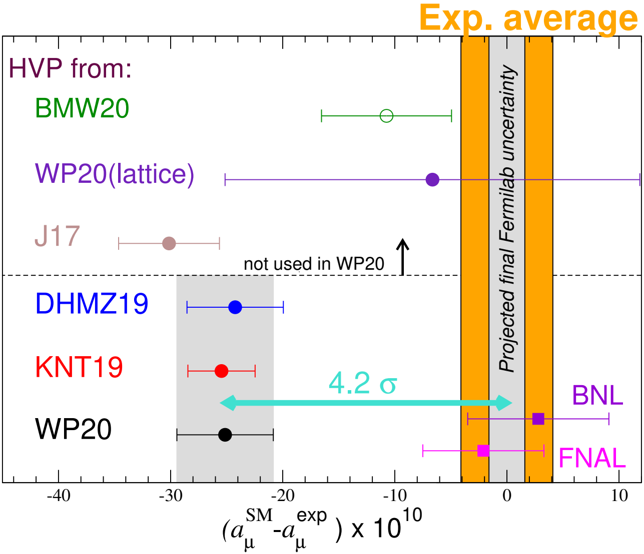
Present status of $(g-2)_\mu$: experiment vs SM

Before



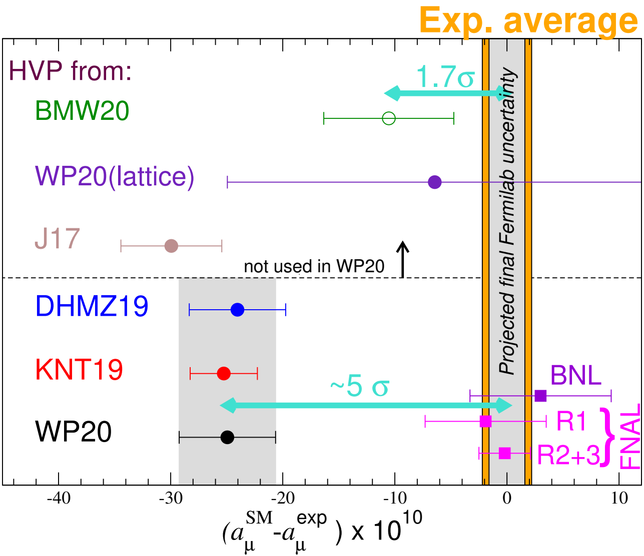
Present status of $(g-2)_\mu$: experiment vs SM

After the 2021 Fermilab result



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

After the 2023 Fermilab result



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 BMW(20), *udsc*)	7075(55)
HLbL (phenomenology)	92(19)
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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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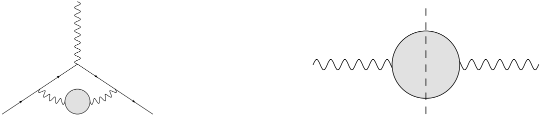
Muon $g-2$ Theory Initiative
Plenary Workshops:

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



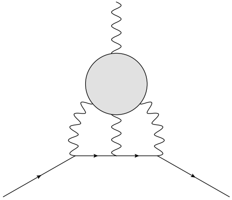
  - unitarity and analyticity ⇒ dispersive approach
  - ⇒ direct relation to experiment: $\sigma_{\rm tot}(e^+e^- \to \text{hadrons})$
  - e^+e^- Exps: BaBar, Belle, BESIII, CMD2/3, KLOE2, SND
  - alternative approach: lattice, becoming competitive

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

→ talk by D. Giusti

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

→ talk by M. Hoferichter

- lattice QCD is competitive

(Mainz, RBC/UKQCD)

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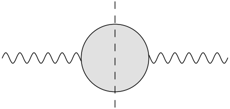
HVP contribution: Master Formula

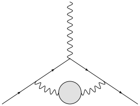
Unitarity relation: simple, same for all intermediate states



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

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

Comparison between DHMZ19 and KNT19

	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(0.83)(3.23)(0.55)	504.23(1.90)	3.62
$\pi^+\pi^-\pi^0$	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
K^+K^-	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
K_SK_L	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)(3.48)(1.47)	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 $a_\mu^{\text{HVP, LO}}$	$694.0(1.0)(3.5)(1.6)(0.1)_\psi(0.7)_{\mathrm{DV+QCD}}$	692.8(2.4)	1.2

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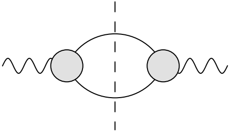
For the dominant $\pi\pi$ channel more theory input can be used

The 2π contribution

For HVP the unitarity relation is simple and looks the same for all possible intermediate states, like 2π



$$\mathrm{Im}\Pi(q^2) \propto \sigma(e^+e^- \to \pi^+\pi^-)$$

which implies

$$\bar{\Pi}_{2\pi}(q^2) == \frac{q^2}{\pi}\int_{4M_\pi^2}^{\infty} dt \frac{\alpha\sigma_\pi(t)^3|F_V^\pi(t)|^2}{12t(t-q^2)}$$

de Trocóniz, Ynduráin (01,04), Leutwyler, GC (02,03), Anthanarayan et al. (13,16)

The pion vector form factor $F_V^\pi(t)$ also satisfies a dispersion relation

Analytic properties of pion form factors

Mathematical problem:

1. $F(t)$: analytic function except for a cut for $4M_\pi^2 \leq t < \infty$
2. $e^{-i\delta(t)}F(t) \in \mathbb{R}$ for $\mathrm{Im}(t) \to 0^+$, with $\delta(t)$ a known function

Exact solution: Omnès (58)

$$F(t) = P(t)\Omega(t) = P(t)\exp\left\{\frac{t}{\pi}\int_{4M_\pi^2}^{\infty}\frac{dt'}{t'}\frac{\delta(t')}{t'-t}\right\} \quad ,$$

$P(t)$ a polynomial ⇔ behaviour of $F(t)$ for $t \to \infty$
or presence of zeros

$\Omega(t)$ is called the Omnès function

Vector form factor of the pion

Pion vector form factor

$$\langle \pi^i(p')|V_\mu^k(0)|\pi^l(p)\rangle = i\epsilon^{ikl}(p'+p)_\mu F_V^\pi(s) \qquad s=(p'-p)^2$$

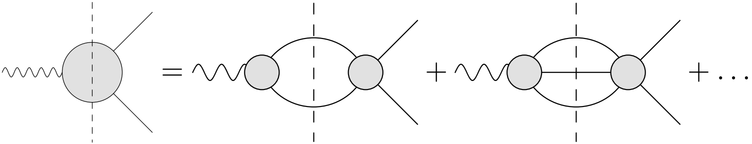
- normalization fixed by gauge invariance:

$$F_V^\pi(0)=1 \qquad \overset{\text{no zeros}}{\Longrightarrow} \qquad P(t)=1$$

→ talk by P. Stoffer

- $e^+e^- \to \pi^+\pi^-$ data $\Rightarrow$ free parameters in $\Omega(t)$

Omnès representation including isospin breaking



Omnès representation including isospin breaking

- Omnès representation

$$F_V^\pi(s) = \exp\left[\frac{s}{\pi}\int_{4M_\pi^2}^{\infty} ds' \frac{\delta(s')}{s'(s'-s)}\right] \equiv \Omega(s)$$

- Split elastic ($\leftrightarrow \pi\pi$ phase shift, δ_1^1) from inelastic phase

$$\delta = \delta_1^1 + \delta_{\rm in} \quad \Rightarrow \quad F_V^\pi(s) = \Omega_1^1(s)\Omega_{\rm in}(s)$$

Eidelman-Lukaszuk: unitarity bound on $\delta_{\rm in}$

$$\sin^2\delta_{\rm in} \le \frac{1}{2}\left(1 - \sqrt{1-r^2}\right), \; r = \frac{\sigma^{I=1}_{e^+e^-\to\neq 2\pi}}{\sigma_{e^+e^-\to 2\pi}} \Rightarrow s_{\rm in} = (M_\pi + M_\omega)^2$$

- $\rho-\omega$–mixing $\qquad F_V(s) = \Omega_{\pi\pi}(s)\cdot\Omega_{\rm in}(s)\cdot G_\omega(s)$

$$G_\omega(s) = 1 + \epsilon \frac{s}{s_\omega - s} \qquad \text{where} \qquad s_\omega = (M_\omega - i\Gamma_\omega/2)^2$$

Free parameters

$$\Omega_1^1(s) \quad \Rightarrow \quad \begin{cases} \phi_0 = \delta_{\pi\pi}((0.8\ \mathrm{GeV})^2) \\ \phi_1 = \delta_{\pi\pi}(68 M_\pi^2) \end{cases}$$

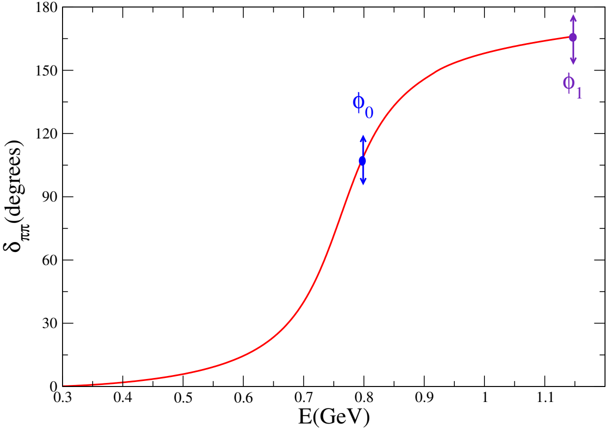
$$G_\omega(s) \quad \Rightarrow \quad \begin{cases} \epsilon & \quad \omega - \rho \text{ mixing} \\ M_\omega \end{cases}$$

$$\Omega_{\mathrm{in}}(s) \quad \Rightarrow \quad \begin{cases} c_1 \\ \vdots \\ c_P \end{cases} \qquad \mathrm{Im}\Omega_{\mathrm{in}}(s) = 0 \quad s \leq s_{\mathrm{in}}$$

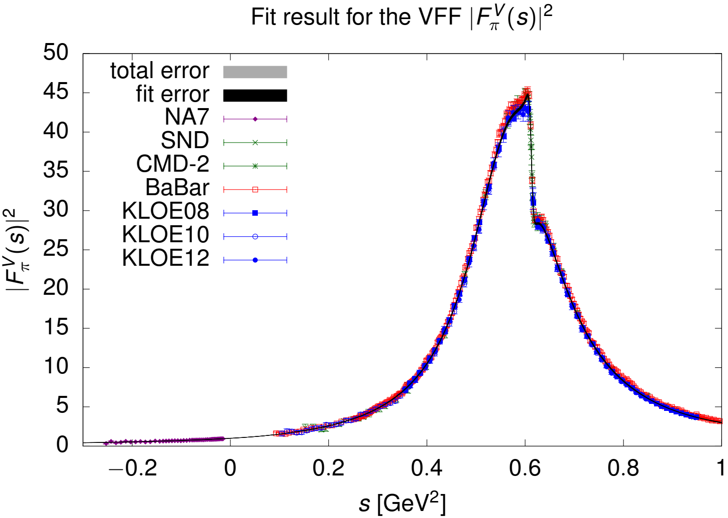
$$G_\omega(s) = 1 + \epsilon \frac{s}{s_\omega - s} \qquad \text{where} \qquad s_\omega = (M_\omega - i\Gamma_\omega/2)^2$$

$$\Omega_{\mathrm{in}}(s) = 1 + \sum_{k=1}^{N} c_k (z(s)^k - z(0)^k) \qquad z = \frac{\sqrt{s_{\pi\omega} - s_1} - \sqrt{s_{\pi\omega} - s}}{\sqrt{s_{\pi\omega} - s_1} + \sqrt{s_{\pi\omega} - s}}$$

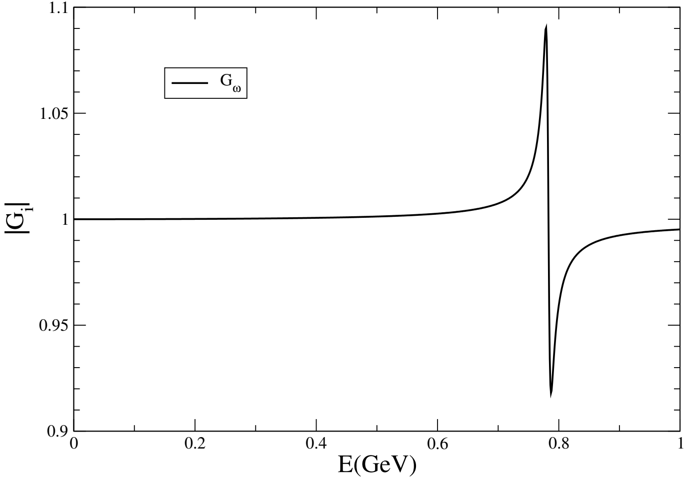
Free parameters



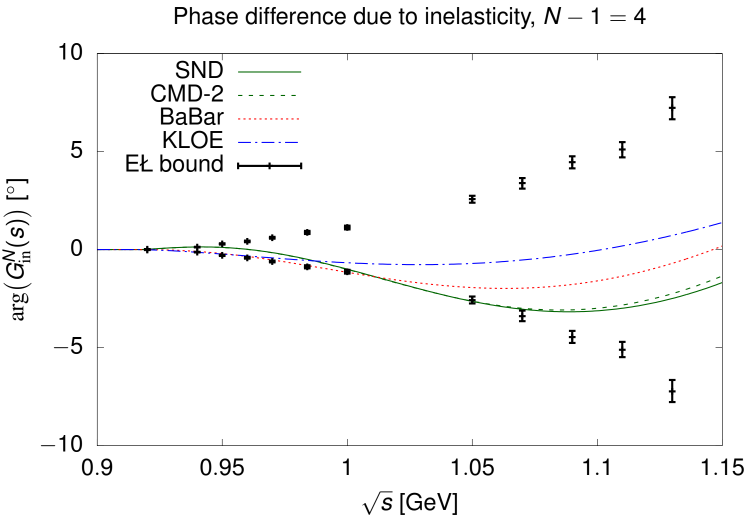
Fit results


Fit result for the VFF $|F_\pi^V(s)|^2$
$|F_\pi^V(s)|^2$
s [GeV^2]
0
5
10
15
20
25
30
35
40
45
50
−0.2
0
0.2
0.4
0.6
0.8
1
total error
fit error
NA7
SND
CMD-2
BaBar
KLOE08
KLOE10
KLOE12

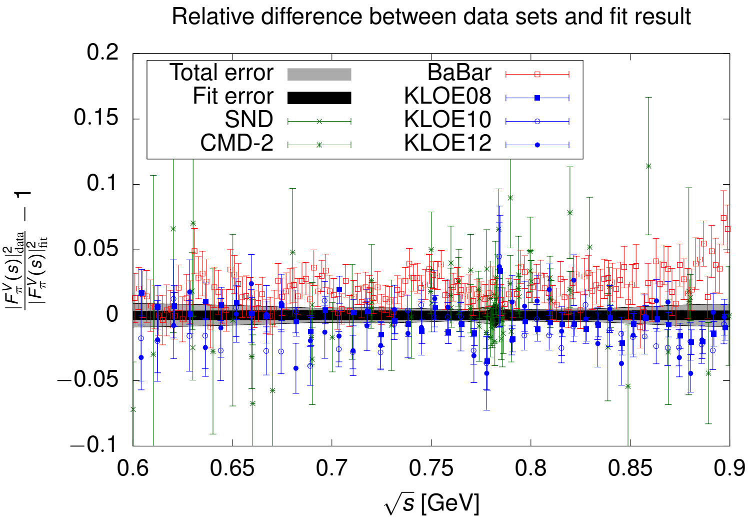
Fit results



Fit results

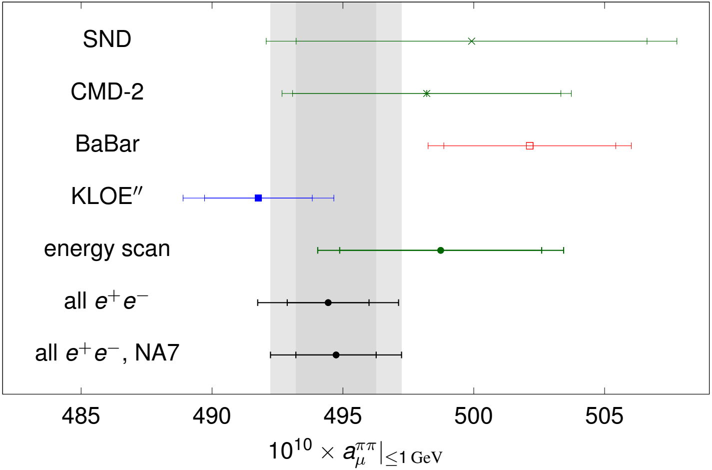

Phase difference due to inelasticity, $N-1=4$
SND
CMD-2
BaBar
KLOE
EŁ bound
$\arg\left(G_{\rm in}^{N}(s)\right)$ [°]
10
5
0
−5
−10
0.9
0.95
1
1.05
1.1
1.15
$\sqrt{s}$ [GeV]

Fit results


Relative difference between data sets and fit result
Total error
Fit error
SND
CMD-2
BaBar
KLOE08
KLOE10
KLOE12
$\frac{|F_\pi^V(s)|^2_{\text{data}}}{|F_\pi^V(s)|^2_{\text{fit}}} - 1$
0.2
0.15
0.1
0.05
0
−0.05
−0.1
0.6
0.65
0.7
0.75
0.8
0.85
0.9
$\sqrt{s}$ [GeV]

Results for $(g-2)_\mu$

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

The 2π channel can itself be described dispersively $\Rightarrow$ more constrained theoretically

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

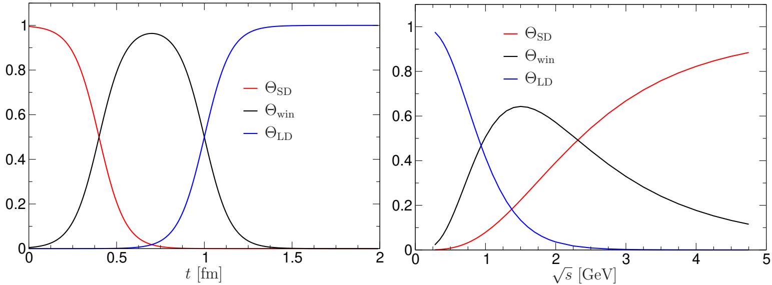
Energy range	ACD18	CHS18	DHMZ19	KNT19
$\leq 0.6\,\mathrm{GeV}$		110.1(9)	110.4(4)(5)	108.7(9)
$\leq 0.7\,\mathrm{GeV}$		214.8(1.7)	214.7(0.8)(1.1)	213.1(1.2)
$\leq 0.8\,\mathrm{GeV}$		413.2(2.3)	414.4(1.5)(2.3)	412.0(1.7)
$\leq 0.9\,\mathrm{GeV}$		479.8(2.6)	481.9(1.8)(2.9)	478.5(1.8)
$\leq 1.0\,\mathrm{GeV}$		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)
$\leq 0.63\,\mathrm{GeV}$	132.9(8)	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)

WP(20)

Present status of the window quantities

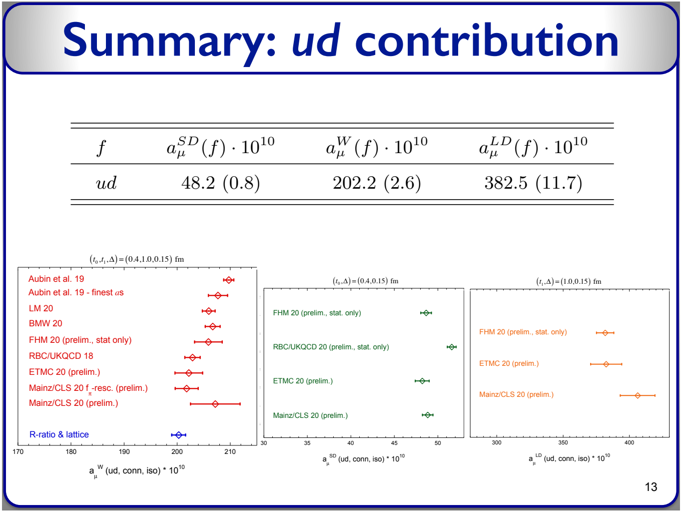
Weight functions for window quantities

RBC/UKQCD (18)



Present status of the window quantities

Lattice calculations of a_μ^{win}, circa 2021



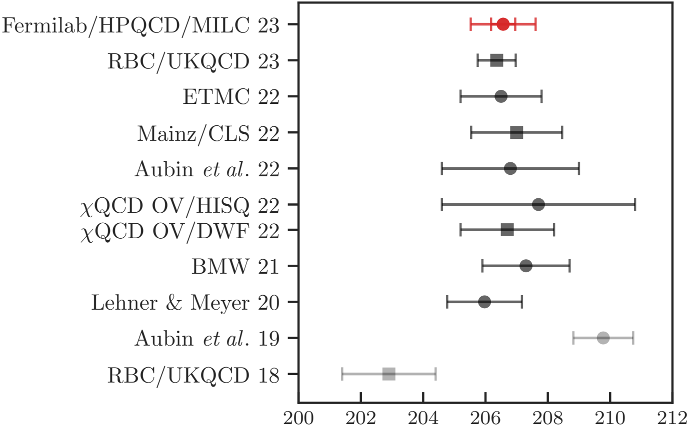
Summary: *ud* contribution

f	$a_\mu^{SD}(f)\cdot 10^{10}$	$a_\mu^{W}(f)\cdot 10^{10}$	$a_\mu^{LD}(f)\cdot 10^{10}$
ud	48.2 (0.8)	202.2 (2.6)	382.5 (11.7)

D. Giusti, talk at Lattice 2021

Present status of the window quantities

Now several lattice calculations confirm BMW's result



Fermilab Lattice-HPQCD-MILC (23)

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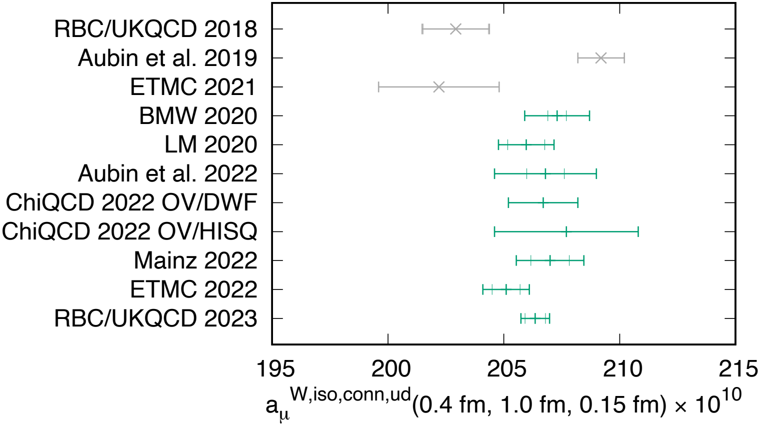

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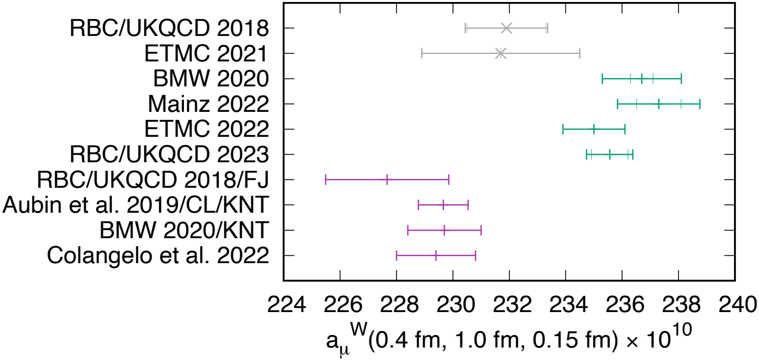


RBC/UKQCD (23)

Individual-channel contributions to a_μ^{win}

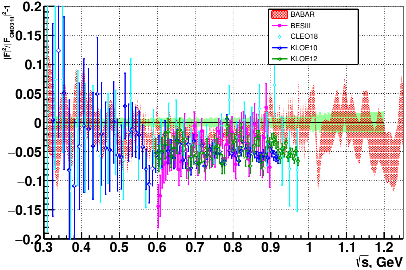
Channel	total	window
$\pi^+\pi^-$	504.23(1.90)	144.08(49)
$\pi^+\pi^-\pi^0$	46.63(94)	18.63(35)
$\pi^+\pi^-\pi^+\pi^-$	13.99(19)	8.88(12)
$\pi^+\pi^-\pi^0\pi^0$	18.15(74)	11.20(46)
K^+K^-	23.00(22)	12.29(12)
K_SK_L	13.04(19)	6.81(10)
$\pi^0\gamma$	4.58(10)	1.58(4)
Sum of the above	623.62(2.27)	203.47(78)
$[1.8, 3.7]$ 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)

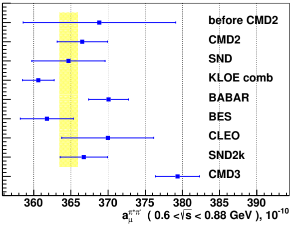
Numbers for the channels refer to KNT19 — thanks to Alex Keshavarzi for providing them

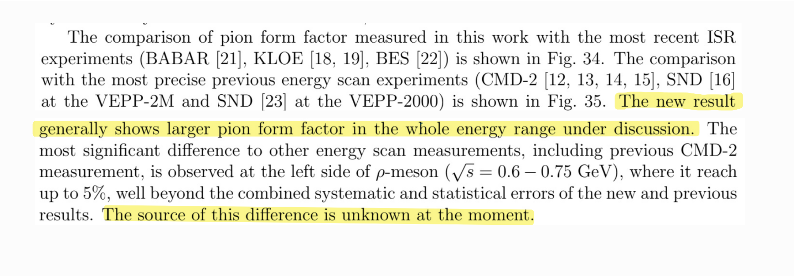
$$\Delta a_\mu^{\text{HVP, LO}} = 14.4(6.8)\,(2.1\sigma), \qquad \Delta a_\mu^{\mathrm{win}} \sim 6.5(1.5)\,(\sim 4.3\sigma)$$

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

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



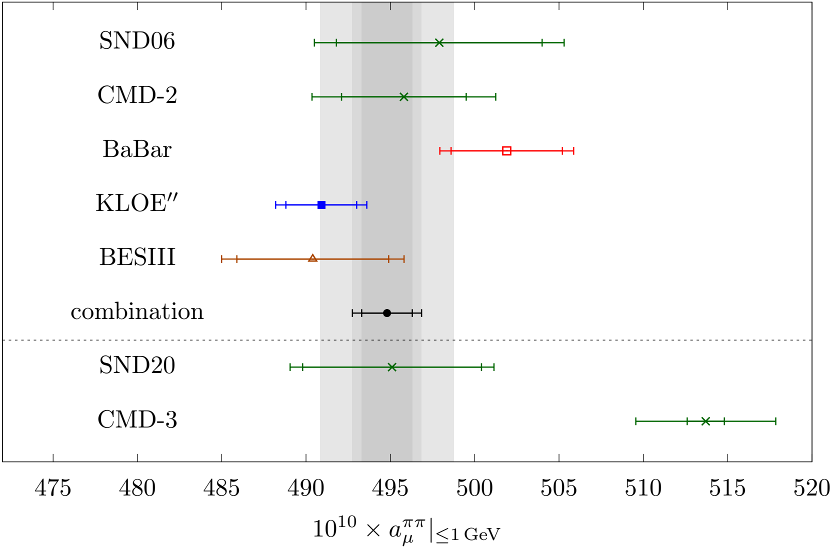




The comparison of pion form factor measured in this work with the most recent ISR experiments (BABAR [21], KLOE [18, 19], BES [22]) is shown in Fig. 34. The comparison with the most precise previous energy scan experiments (CMD-2 [12, 13, 14, 15], SND [16] at the VEPP-2M and SND [23] at the VEPP-2000) 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

Work in progress, GC, Hoferichter and Stoffer (thanks for providing the plots)



Preliminary analysis of the CMD-3 measurement

Work in progress, GC, Hoferichter and Stoffer (thanks for providing the plots)

$10^{10}\times$	$a_\mu^{\pi\pi}\vert_{\leq 1\mathrm{GeV}}$	$a_\mu^{\pi\pi,\mathrm{win}}\vert_{\leq 1\mathrm{GeV}}$	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

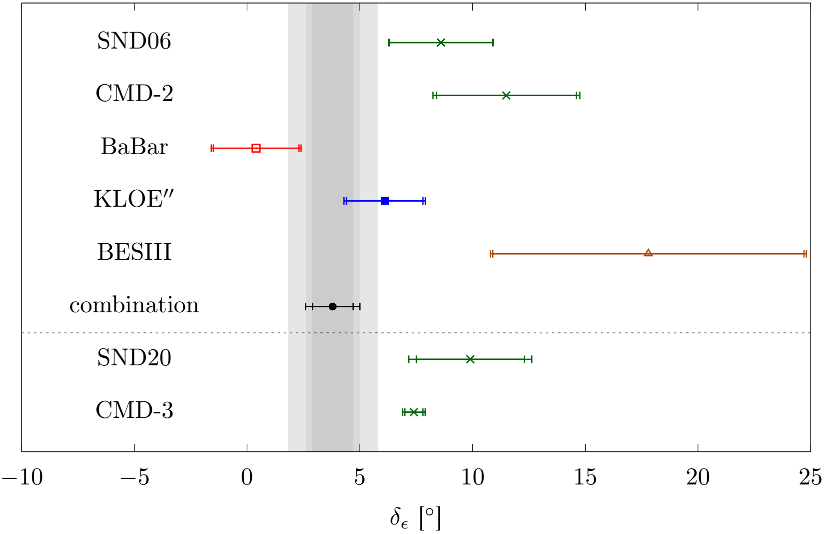
Combination: NA7 + all data sets other than SND20 and CMD-3

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

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

Preliminary analysis of the CMD-3 measurement

Work in progress, GC, Hoferichter and Stoffer



Preliminary analysis of the CMD-3 measurement

Work in progress, GC, Hoferichter and Stoffer

	M_ω(MeV)	$10^3 \cdot \mathrm{Re}\,\epsilon_\omega$	$\delta_\epsilon[^\circ]$
SND06	782.12(33)(2)	2.03(5)(2)	8.6(2.3)(0.3)
CMD-2	782.65(33)(4)	1.90(6)(3)	11.5(3.1)(1.0)
BaBar	781.89(18)(4)	2.06(4)(2)	0.4(1.9)(0.6)
KLOE"	782.45(24)(5)	1.96(4)(2)	6.1(1.7)(0.6)
BESIII	783.07(61)(2)	2.03(19)(7)	17.8(6.9)(1.2)
SND20	782.34(28)(6)	2.07(5)(2)	9.9(2.4)(1.3)
CMD-3	782.33(6)(3)	2.08(1)(2)	7.4(4)(3)
Combination	782.07(12)(5)(8)	1.99(2)(2)(0)	3.8(0.9)(0.8)(1.6)

→ talk by P. Stoffer

Outline

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

Hadronic Vacuum Polarization contribution
- Data-driven approach
- Dispersive approach for the $\pi\pi$ contribution
- Lattice vs data-driven: intermediate window

Conclusions and Outlook

Conclusions

- Data-driven evaluation of the HVP contribution (WP20):
  0.6% error ⇒ dominates the theory uncertainty
- Dominant contribution to HVP: $\pi\pi$ (<1 GeV). WP20 based on:
  CMD-2, SND06, BaBar, KLOE
  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 ⇒ discrepancy with experiment ↘ 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]

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:
    - Thorough scrutiny of the new CMD-3 result
    - Forthcoming measur./analyses: BaBar, Belle II, BESIII, KLOE,SND
    - Model-independent evaluation of RadCorr underway (but cannot be the culprit)
    - MuonE will provide an alternative way to measure HVP
  - HVP lattice:
    calculations with precision $\sim$ BMW for $a_\mu^{\text{HVP, LO}}$ are awaited