The W boson Mass and Muon g-2 : Hadronic Uncertainties or New Physics ?

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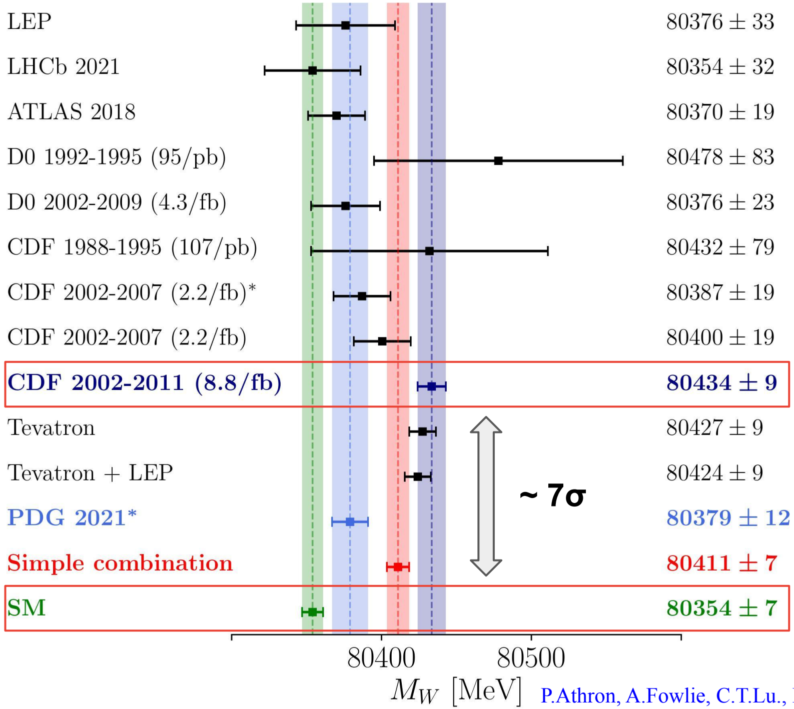
The W boson mass and width measurements



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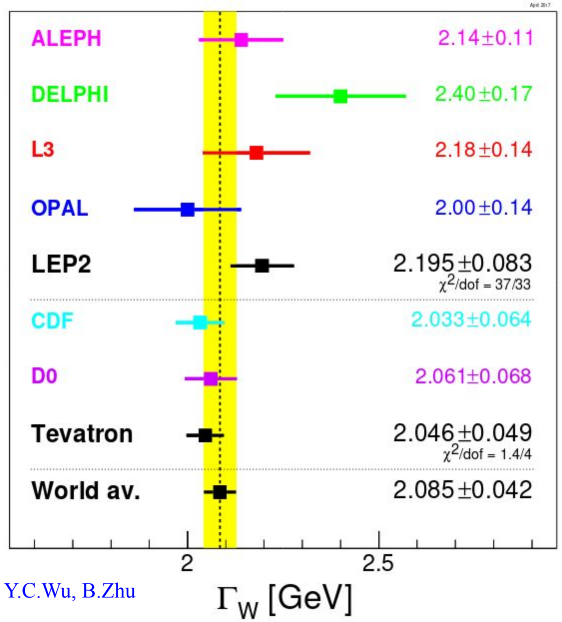
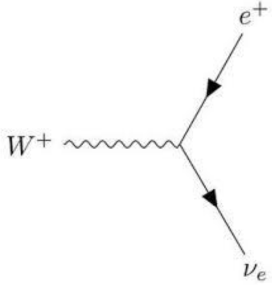
* Does not include 13.5 MeV shift in CDF 2002-2007 (2.2/fb)

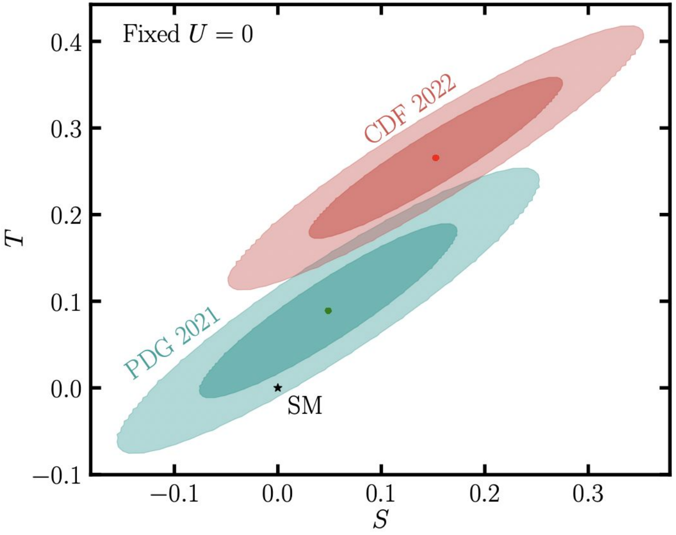
Full width $\Gamma = 2.085 \pm 0.042$ GeV



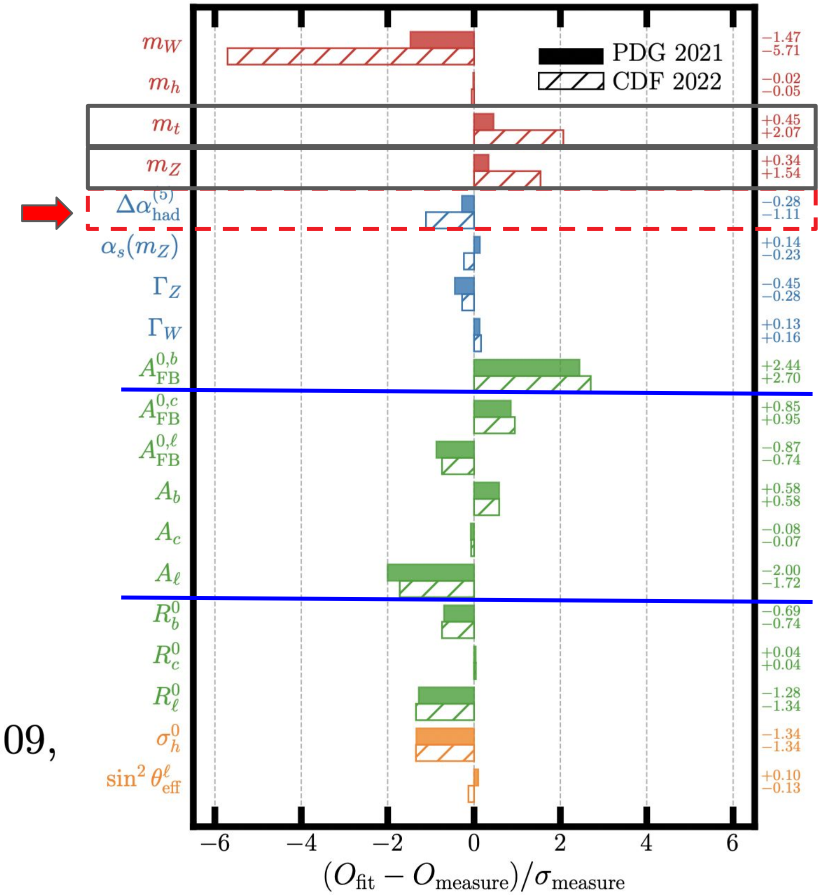


How does the W mass from CDF-II affect other electrowek precision observables ?

The updatedc EW fits after the CDF-II W mass measurement



$$S = 0.06 \pm 0.10,\ T = 0.11 \pm 0.12,\ U = 0.13 \pm 0.09,$$
$$S = 0.14 \pm 0.08,\ T = 0.26 \pm 0.06 \text{ with } U = 0$$



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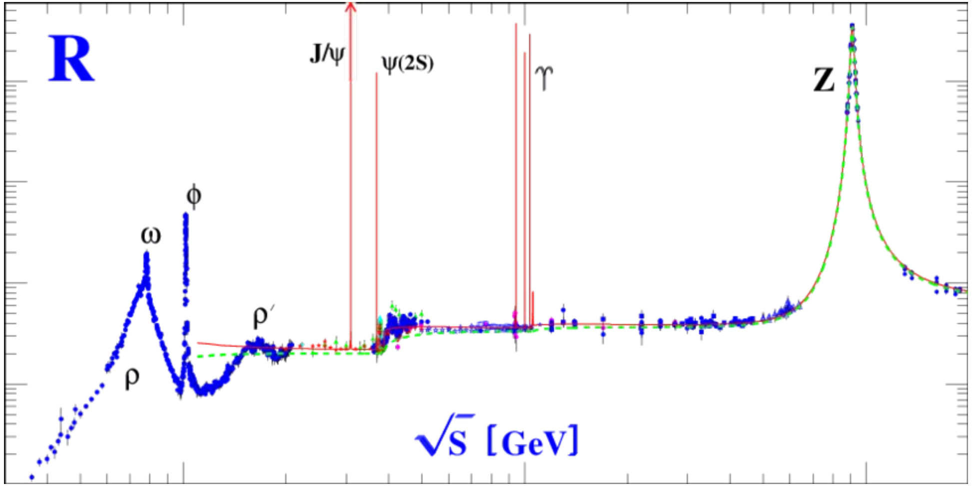
$$\alpha^{-1}(M_Z^2) = \alpha^{-1}\Big[1 - \Delta\alpha_{\rm lep}(M_Z^2) - \Delta\alpha^{(5)}_{\rm had}(M_Z^2) - \Delta\alpha_{\rm top}(M_Z^2)\Big]$$

Fine-structure constant

$$\Delta\alpha^{(5)}_{\rm had}\big|_{e^+e^-} = 276.1(1.1) \times 10^{-4}.$$

$e^+e^- \rightarrow$ hadrons



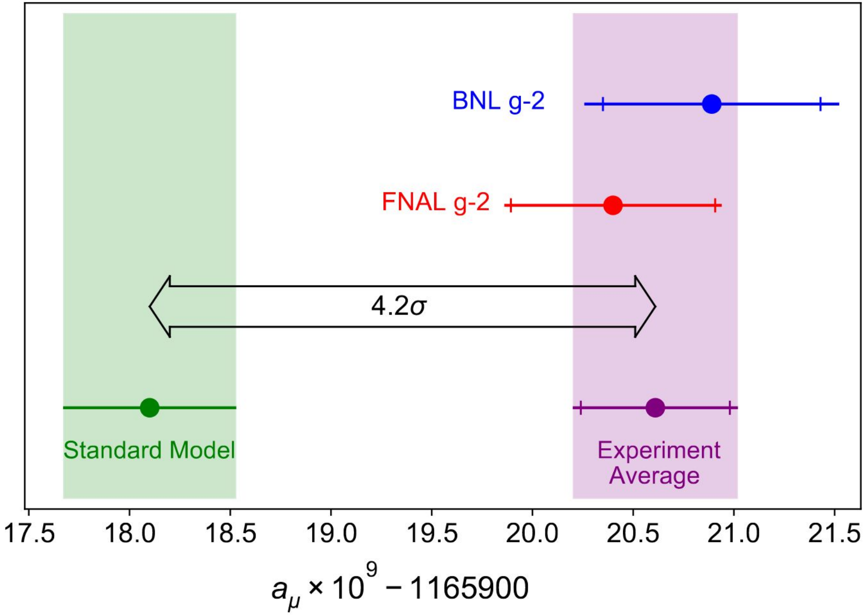
$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = \frac{\alpha M_Z^2}{3\pi} P \int_{s_{\rm thr}}^{\infty} ds \frac{R_{\rm had}(s)}{s(M_Z^2 - s)}$$

$$R_{\rm had}(s) = \frac{3s}{4\pi\alpha^2}\sigma(e^+e^- \rightarrow \text{hadrons})$$

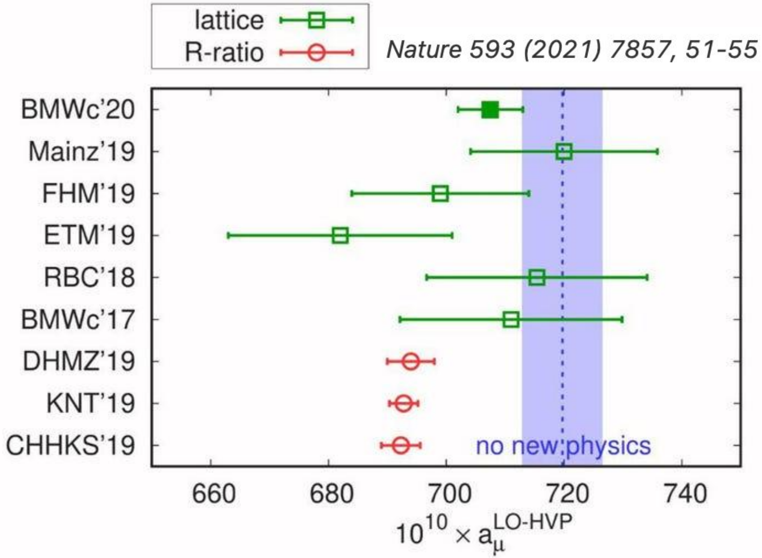
where $s_{\rm thr} = m^2_{\pi^0}$

Muon g-2 excess from BNL and FNAL

Phys.Rev.Lett. 126 (2021) 14, 141801



Are lattice calculations consistent with the SM value ?



The SM contributions to muon g-2

Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
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)
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	279(76)

Time-like :

$$a_\mu^{\text{HVP}} = \frac{m_\mu^2}{12\pi^3} \int_{m_{\pi^0}^2}^{\infty} \frac{\mathrm{d}s}{s} K(s)\, \sigma_{\text{had}}(\sqrt{s}),$$

where m_μ and m_{π^0} are the muon and neutral pion masses, respectively, and $K(s)$ is the kernel function

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What is common for W mass and muon g-2 ?

W mass :

$$M_W^2 = M_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2}G_\mu M_Z^2}(1+\Delta r)} \right\}$$

$$\Delta\alpha_{\mathrm{had}} = \frac{M_Z^2}{4\pi^2\alpha}\int_{m_{\pi^0}^2}^{\infty} \frac{\mathrm{d}s}{M_Z^2 - s}\,\sigma_{\mathrm{had}}(\sqrt{s}),$$

Muon g-2 :

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}}$$

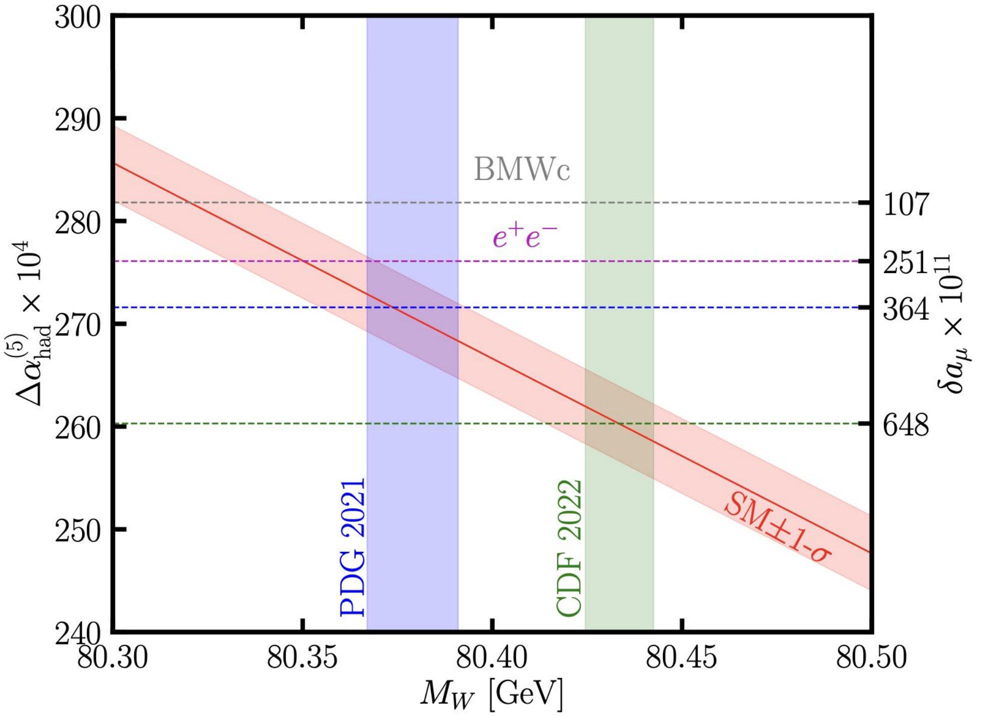
$$a_\mu^{\mathrm{HVP}} = \frac{m_\mu^2}{12\pi^3}\int_{m_{\pi^0}^2}^{\infty} \frac{\mathrm{d}s}{s} K(s)\,\sigma_{\mathrm{had}}(\sqrt{s}),$$

How many ways to determine $\Delta\alpha_{\mathrm{had}}$ and a_μ^{HVP} ?

	$e^+e^- \to \mathrm{hadrons}$	Lattice QCD	Electroweak fits
$\Delta\alpha_{\mathrm{had}}$	Yes	Partial (only the results from low energy regions are reported from BMWc !)	Yes
a_μ^{HVP}	Yes	Yes	No (the assumption of transformation is needed !)

Contents

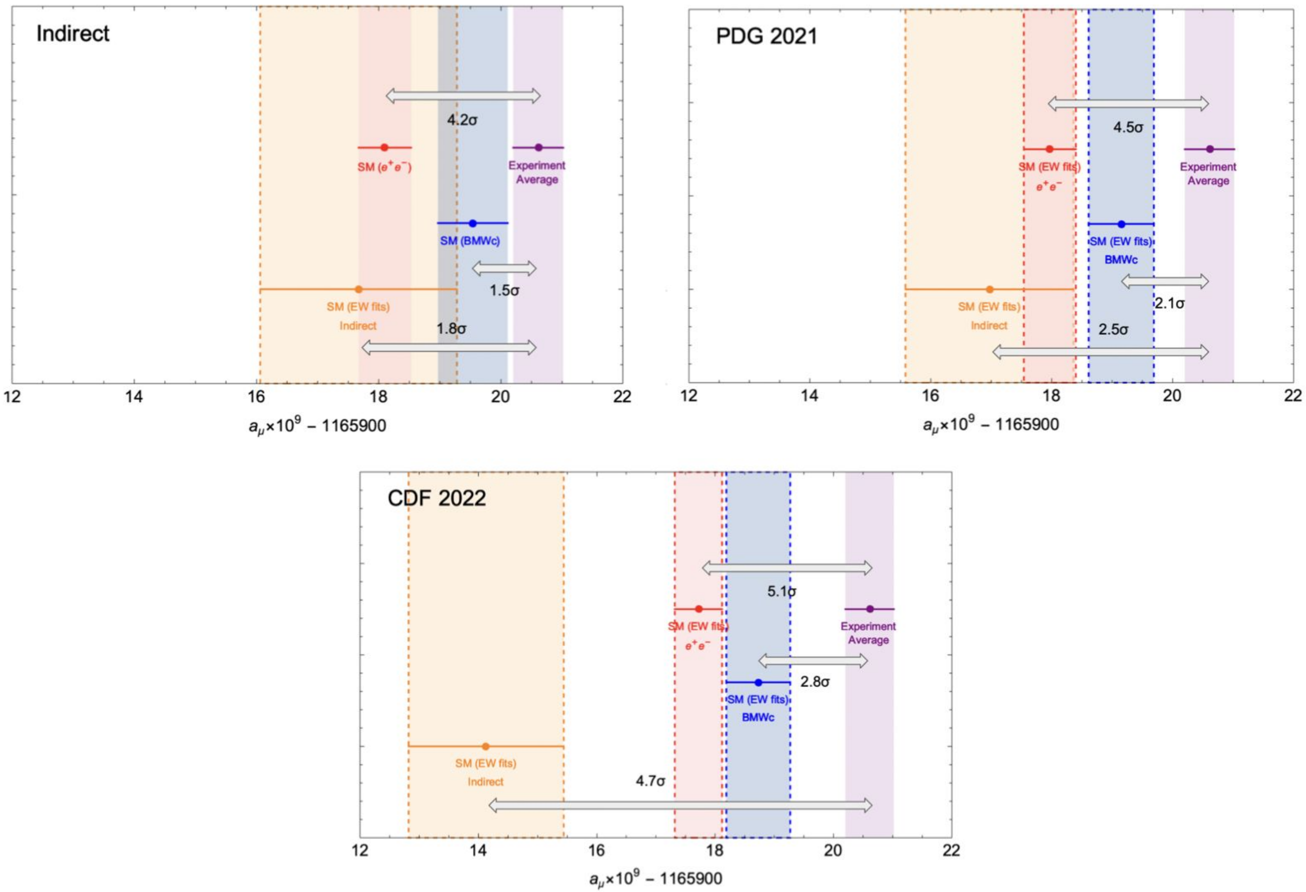
The relation between $\Delta\alpha_{\mathrm{had}}$ (δa_μ) and M_W



EW fits table of the W mass and muon g-2

	M_W	Indirect			PDG 2021			CDF 2022		
	$\Delta\alpha_{\text{had}}$	BMWc	e^+e^-	Indirect	BMWc	e^+e^-	Indirect	BMWc	e^+e^-	Indirect
Input	M_W [GeV]	-	-	-	80.379(12)	80.379(12)	80.379(12)	80.4335(94)	80.4335(94)	80.4335(94)
	$\Delta\alpha_{\text{had}} \times 10^4$	281.8(1.5)	276.1(1.1)	-	281.8(1.5)	276.1(1.1)	-	281.8(1.5)	276.1(1.1)	-
Fitted	χ^2/dof	18.32/15	16.01/15	15.89/14	23.41/16	18.74/16	17.59/15	74.51/16	62.58/16	47.19/15
	M_W [GeV]	80.348(6)	80.357(6)	80.359(9)	80.355(6)	80.361(6)	80.367(7)	80.375(5)	80.380(5)	80.396(7)
	$\Delta\alpha_{\text{had}} \times 10^4$	280.9(1.4)	275.9(1.1)	274.4(4.4)	280.3(1.4)	275.6(1.1)	271.7(3.8)	278.6(1.4)	274.7(1.0)	260.9(3.6)
	$\delta a_\mu \times 10^{11}$	-	-	294(166)	146(68)	264(59)	364(145)	188(68)	289(57)	648(137)
	Tension	-	-	1.8σ	2.1σ	4.5σ	2.5σ	2.8σ	5.1σ	4.7σ
	δM_W [MeV]	86(11)	77(11)	75(13)	79(11)	73(11)	67(12)	59(11)	54(11)	38(12)
	Tension	7.8σ	7.0σ	5.8σ	7.2σ	6.6σ	5.6σ	5.4σ	4.9σ	3.2σ

$$\delta M_W \equiv M_W^{\text{CDF}} - M_W$$


Indirect
4.2σ
SM (e^+e^-)
Experiment Average
SM (BMWc)
1.5σ
SM (EW fits) Indirect
1.8σ
12 14 16 18 20 22
$a_\mu \times 10^9$ − 1165900
PDG 2021
4.5σ
SM (EW fits) e^+e^-
Experiment Average
SM (EW fits) BMWc
2.1σ
SM (EW fits) Indirect
2.5σ
12 14 16 18 20 22
$a_\mu \times 10^9$ − 1165900
CDF 2022
5.1σ
SM (EW fits) e^+e^-
Experiment Average
2.8σ
SM (EW fits) BMWc
SM (EW fits) Indirect
4.7σ
12 14 16 18 20 22
$a_\mu \times 10^9$ − 1165900

The key observation

We demonstrate that the two anomalies pull the hadronic contributions in **opposite directions** by performing electroweak fits in which the hadronic contribution was allowed to float.

The fits show that including the g−2 measurement worsens the tension with the CDF measurement and conversely that adjustments that alleviate the CDF tension worsen the g−2 tension beyond 5σ.

Contents

The singlet-triplet scalar leptoquark model

1. We consider the singlet-triplet scalar leptoquark(LQ) mdoel to explain the muon g-2 and W boson mass.
2. The quantum numbers of the singlet and triplet scalar LQ are defined as

$$S_1 \ (\overline{\mathbf{3}}, \mathbf{1}, 1/3) \qquad S_3 \ (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

3. The relevant Lagrangian terms include

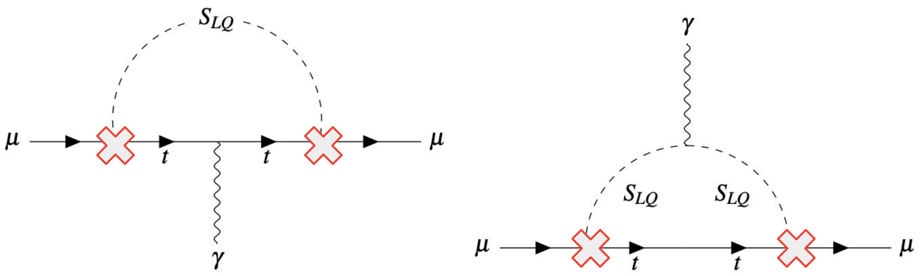
$$\boxed{\mathcal{L}_{S_1 \& S_3} = \mathcal{L}_{\text{mix}} + \mathcal{L}_{\text{LQ}},}$$

$$\mathcal{L}_{\text{mix}} = \lambda H^\dagger \left(\vec{\tau} \cdot \overrightarrow{S_3}\right) H S_1^* + \text{ h.c.}$$

$$\mathcal{L}_{\text{LQ}} = y_R^{ij} \bar{u}_{Ri}^C e_{Rj} S_1 + y_L^{ij} \bar{Q}_i^C i\tau_2 \left(\vec{\tau} \cdot \vec{S}_3\right) L_j + \text{h.c.}$$

*Although a coupling between S_1 and the LH lepton and quark fileds is allowed, we don't cosider it here.

1. We The mixing between interaction eigenstates allows the physical mass eigenstates to have both LH and RH couplings to muons and induces chirality flipping enhancements in the one-loop muon g-2 correctior



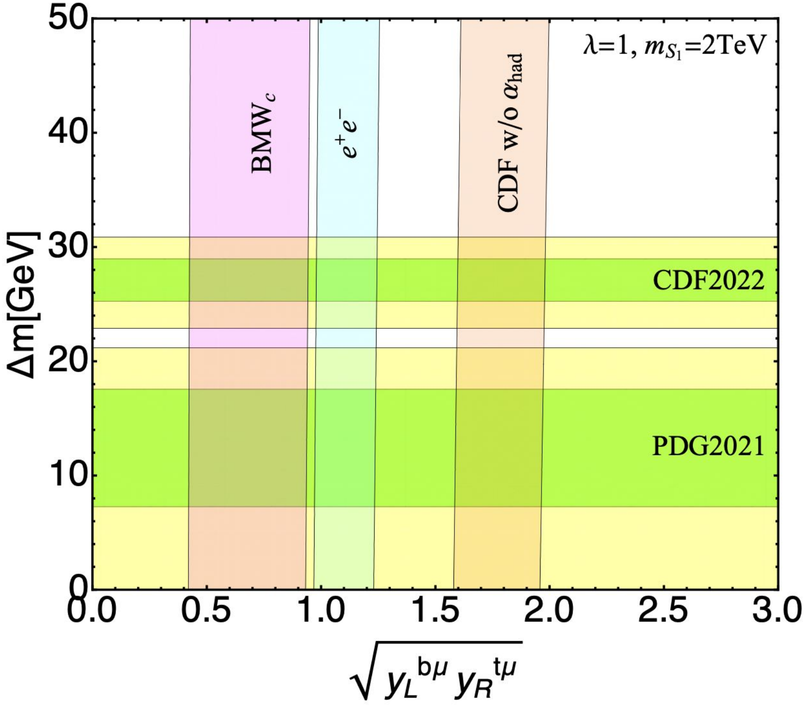
arXiv: 2204.09031

2. Two scalar LQs with Q = ⅓ can mix through the mixing interaction after EWSB

$$m_{S_\pm}^2 = \frac{m_{S_1}^2 + m_{S_3}^2}{2} \pm \frac{1}{2}\sqrt{\left(m_{S_1}^2 - m_{S_3}^2\right)^2 + 4\delta^2} \qquad \text{where } \delta \equiv \lambda v^2/2.$$

such mass splitting can generate an extra contribution to the T parameter and provide the shift in W mass from the SM predictuion.

The singlet-triplet scalar leptoquark model



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Conclusions

1. We show that the W mass and muon g-2 anomalies pull the hadronic contributions in opposite directions, the new CDF W mass measurement indirectly increases the deviation in muon g-2.
2. The singlet-triplet scalar leptoquark model can simultaneously explain both W mass and muon g-2 anomalies.
3. The results point to new physics that has large chirality flipping enhancements in the one-loop diagrams for muon g−2 and significant BSM contributions to the oblique T parameter that can be given through custodial symmetry violation.

Thank you
for your attention

Back up

The time-like and space-like master formulae for $\Delta\alpha_{\rm had}$ and $a_\mu^{\rm HVP}$

1. **Time-like** : Using for $e^+e^- \to \rm hadrons$ data calculations

$$a_\mu^{\rm HVP,\,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{s_{\rm thr}}^{\infty} ds\, \frac{\hat{K}(s)}{s^2} R_{\rm had}(s) \qquad R_{\rm had}(s) = \frac{3s}{4\pi\alpha^2}\sigma(e^+e^- \to \text{hadrons})$$

where $s_{\rm thr} = m_{\pi^0}^2$

$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = \frac{\alpha M_Z^2}{3\pi} P \int_{s_{\rm thr}}^{\infty} ds \frac{R_{\rm had}(s)}{s(M_Z^2 - s)}$$

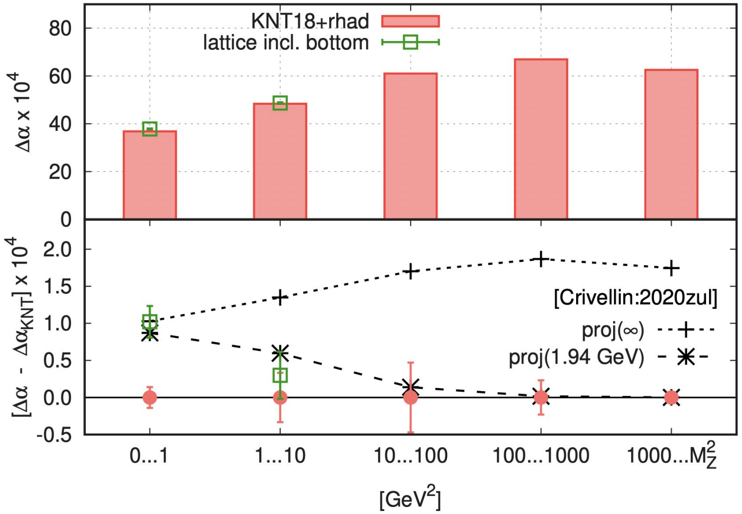
2. **Space-like** : Using for lattice QCD calculations

$$a_\mu^{\rm HVP,\,LO} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^{\infty} ds\, f(s)\hat{\Pi}(-s) \qquad \hat{\Pi}(s) = 4\pi^2\left[\Pi(s) - \Pi(0)\right]$$

$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = \frac{\alpha}{\pi}\hat{\Pi}(-M_Z^2) + \frac{\alpha}{\pi}\left(\hat{\Pi}(M_Z^2) - \hat{\Pi}(-M_Z^2)\right)$$

The problem to compare $\Delta\alpha_{\rm had}$ form data-driven and lattice QCD

1. The $\Delta\alpha_{\rm had}$ is calculated at the scale MZ for five quark flavors from data-driven method with $\Delta\alpha^{(5)}_{\rm had}|_{e^+e^-} = 276.1(1.1) \times 10^{-4}$. KNT, DHMZ
2. However, we don't have enough informaiton for $\Delta\alpha_{\rm had}$ from lattice QCD side.



For example,
using the whole energy range project [proj(∞)] :

$$a_\mu^{\rm HVP}({\rm BMWc}) = 707.5(5.5) \times 10^{-10}$$

$$\Rightarrow \Delta\alpha_{\rm had}({\rm BMWc}) = 276.1(1.1) \times 10^{-4} \times \frac{707.5}{693.1} = 281.8(1.5) \times 10^{-4}$$

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The 3rd way to extract $\Delta\alpha_{\rm had}$: Global Electrowek Fits

P.Athron, A.Fowlie, C.T.Lu., L.Wu, Y.C.Wu, B.Zhu

GFitter

	M_W	Indirect			PDG 2021			CDF 2022		
	$\Delta\alpha_{\rm had}$	BMWc	e^+e^-	Indirect	BMWc	e^+e^-	Indirect	BMWc	e^+e^-	Indirect
Input	M_W [GeV]	-	-	-	80.379(12)	80.379(12)	80.379(12)	80.4335(94)	80.4335(94)	80.4335(94)
	$\Delta\alpha_{\rm had}\times 10^4$	281.8(1.5)	276.1(1.1)	-	281.8(1.5)	276.1(1.1)	-	281.8(1.5)	276.1(1.1)	-
Fitted	χ^2/dof	18.32/15	16.01/15	15.89/14	23.41/16	18.74/16	17.59/15	74.51/16	62.58/16	47.19/15
	M_W [GeV]	80.348(6)	80.357(6)	80.359(9)	80.355(6)	80.361(6)	80.367(7)	80.375(5)	80.380(5)	80.396(7)
	$\Delta\alpha_{\rm had}\times 10^4$	280.9(1.4)	275.9(1.1)	274.4(4.4)	280.3(1.4)	275.6(1.1)	271.7(3.8)	278.6(1.4)	274.7(1.0)	260.9(3.6)
	$\delta a_\mu\times 10^{11}$	-	-	294(166)	146(68)	264(59)	364(145)	188(68)	289(57)	648(137)
	Tension	-	-	1.8σ	2.1σ	4.5σ	2.5σ	2.8σ	5.1σ	4.7σ
	δM_W [MeV]	86(11)	77(11)	75(13)	79(11)	73(11)	67(12)	59(11)	54(11)	38(12)
	Tension	7.8σ	7.0σ	5.8σ	7.2σ	6.6σ	5.6σ	5.4σ	4.9σ	3.2σ

Then, how to transform the information between $\Delta\alpha_{\rm had}$ and $a_\mu^{\rm HVP}$?

Here we consider the whole energy range projection.

Three various projections between $\Delta\alpha_{\rm had}$ and $a_\mu^{\rm HVP}$

1. According to *Crivellin:2020zul*, there are three different hypotheses for the projection between $\Delta\alpha_{\rm had}$ and $a_\mu^{\rm HVP}$:

(1) Low energy for the sum of exclusive channels : $m_{\pi_0} \leq \sqrt{s} \leq 1.937\,\mathrm{GeV}$,

(2) Energy below the perturbative contributions : $m_{\pi_0} \leq \sqrt{s} \leq 11.199\,\mathrm{GeV}$ or

(3) The whole energy range : $m_{\pi_0} \leq \sqrt{s} \leq \infty$,

(**<u>Hypothesis</u>** : The part above the upper energy threshold is the same as data driven one and the uniform scaling is applied.)

2. Open questions : (1) Which projection should be preferred ?

   (The low energy projection agrees better with BMWc restuls.)

   (2) Can we go beyond the uniform scaling (energy independent) hypothesis ?

Using Global EW Fits to extract $\Delta\alpha_{\text{had}}$: Low energy projection

P.Athron, A.Fowlie, C.T.Lu., L.Wu, Y.C.Wu, B.Zhu

GFitter

	M_W	Indirect			PDG 2021			CDF 2022		
	$\Delta\alpha_{\text{had}}$	BMWc	e^+e^-	Indirect	BMWc	e^+e^-	Indirect	BMWc	e^+e^-	Indirect
Input	M_W [GeV]	-	-	-	80.379(12)	80.379(12)	80.379(12)	80.4335(94)	80.4335(94)	80.4335(94)
	$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2) \times 10^4$	277.4(1.2)	276.1(1.1)	-	277.4(1.2)	276.1(1.1)	-	277.4(1.2)	276.1(1.1)	-
Fitted	χ^2/dof	16.28/15	16.01/15	15.89/14	19.51/16	18.74/16	17.59/15	65.07/16	62.58/16	47.19/15
	M_W [GeV]	80.355(6)	80.357(6)	80.359(9)	80.360(6)	80.361(6)	80.367(7)	80.379(5)	80.380(5)	80.396(7)
	$\Delta\alpha_{\text{had}} \times 10^4$	277.1(1.2)	275.9(1.1)	274.4(4.4)	276.8(1.1)	275.6(1.1)	271.7(3.8)	275.6(1.1)	274.7(1.0)	260.9(3.6)
	$\delta a_\mu \times 10^{11}$	-	-	438(396)	173(54)	306(54)	748(339)	306(54)	416(54)	1997(320)
	Tension	-	-	1.1σ	3.2σ	5.7σ	2.2σ	5.7σ	7.7σ	6.2σ
	δM_W [MeV]	79(11)	77(11)	75(13)	74(11)	73(11)	67(12)	55(11)	54(11)	38(12)
	Tension	7.2σ	7.0σ	5.8σ	6.7σ	6.6σ	5.6σ	5.0σ	4.9σ	3.2σ

For the case of low energy projection, $\Delta\alpha_{\text{had}}$ is shrunk, but a_μ^{HVP} is enlarged after the transformation compared with the whole energy range projection.