$W-$mass and lepton $g-2$ in extended inert 2HDM

Based on JHEP 11 (2021) 056 and ongoing study

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Introduction

Anomaly in lepton magnetic dipole moment

- Muon anomalous magnetic moment

$$
\begin{aligned}
a_\mu^{\rm SM} &= 116591810(43)\times 10^{-11} \text{ [Aoyama et. al., 2020]}\\
a_\mu^{\rm BNL} &= 116592089(63)\times 10^{-11} \text{ [PRD 73 (2006) 072003]}\\
a_\mu^{\rm FNAL} &= 116592040(54)\times 10^{-11} \text{ [PRL. 126 (2021) 141801]}\\
a_\mu^{\rm FNAL} &= 116592055(24)\times 10^{-11} \text{ [PRL 131 (2023) no.16, 161802]}\\
\text{New world average: } a_\mu^{\rm exp.} &= 116592059(22)\times 10^{-11}
\end{aligned}
$$

- Discrepancy in MDM

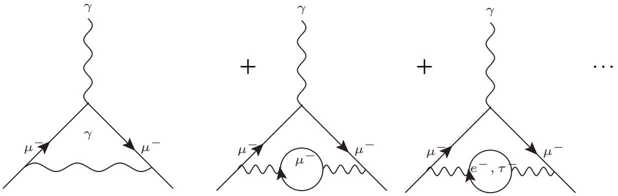
$$
\begin{aligned}
\Delta a_\mu &= a_\mu^{\rm exp.} - a_\mu^{\rm SM} = (249\pm 48)\times 10^{-11}\\
\Delta a_e &= a_e^{\rm exp.} - a_e^{\rm SM} = (-88\pm 28\pm 23\pm 2)\times 10^{-14} \text{ [Science 360 (2018) 191]}
\end{aligned}
$$

1. Muon $g-2$ (SM)

a_μ in SM

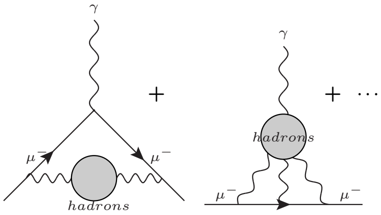
$$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED\ leptonic}) + a_\mu(\mathrm{QED\ hadronic}) + a_\mu(\mathrm{EW})$$

1. QED Contributions (leptonic)



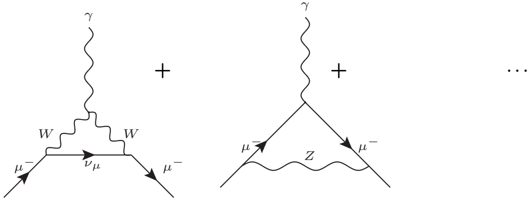
1. Muon $g-2$ (SM)

QED Hadronic contributions

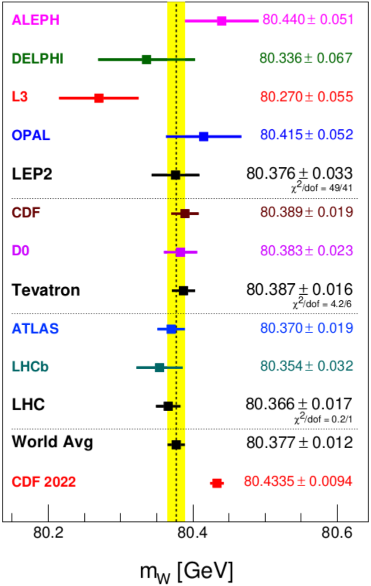


Hadronic vacuum polarization (HVP)   Hadronic light-by-light scattering (HLbyL)

Electroweak contributions



W mass problem



- The pre-2022 CDF result of $W-$ mass [PTEP 2022, 083C01 (2022) (PDG)]

$$m_W^{\rm SM} = 80.377 \pm 0.006 \; GeV$$

- CDF-2022 result [Science 376, 170 (2022)]

$$m_W^{\rm CDF} = 80.4335 \pm 0.0094 \; GeV$$

Model

- **SM augmented by 2HDM + complex scalar singlet + vector-like lepton**

$$\mathscr{L} \supset \mathscr{L}_{\rm scalar} + \mathscr{L}_Y + \mathscr{L}_{\rm VL}$$

$$\Phi_1 = \begin{bmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_{\rm SM} + \phi_1^0 + i\,\eta_1^0\right) \end{bmatrix}; \qquad \Phi_2 = \begin{bmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(\phi_2^0 + i\,\eta_2^0\right) \end{bmatrix}$$

$$\Phi_3 = \frac{1}{\sqrt{2}}\left(v_s + \phi_3^0 + i\,\eta_3^0\right); \qquad \chi^\pm$$

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- Quantum numbers

Fields	Q_l	l_L	u_R	d_R	e_R	Φ_1	Φ_2	Φ_3	χ_L	χ_R	V^μ
$SU(3)_c$	3	1	3	3	1	1	1	1	1	1	G^μ
$SU(2)_L$	2	2	1	1	1	2	2	1	1	1	W_i^μ
$U(1)_Y$	$\frac{1}{6}$	$-\frac{1}{2}$	$\frac{2}{3}$	$-\frac{1}{3}$	-1	$\frac{1}{2}$	$\frac{1}{2}$	0	-1	-1	B^μ
Z_2	+	+	+	+	+	+	−	−	−	+	+

Model

- Scalar Lagrangian

$$
\begin{aligned}
\mathscr{L}_{\text{scalar}} &= \left(D_\mu\Phi_1\right)^\dagger \left(D^\mu\Phi_1\right) + \left(D_\mu\Phi_2\right)^\dagger \left(D_\mu\Phi_2\right) + \left(D_\mu\Phi_3\right)^* \left(D_\mu\Phi_3\right) - V_{\text{scalar}} \\
V_{\text{scalar}} &= -\frac{1}{2}m_{11}^2\left(\Phi_1^\dagger\Phi_1\right) - \frac{1}{2}m_{22}^2\left(\Phi_2^\dagger\Phi_2\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\
&+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\left[\lambda_5\ \left(\Phi_1^\dagger\Phi_2\right)^2 + \ h.c.\right] \\
&-\frac{1}{2}m_{33}^2\ \Phi_3^*\Phi_3 + \frac{\lambda_8}{2}\left(\Phi_3^*\Phi_3\right)^2 + \lambda_{11}\left|\Phi_1\right|^2\Phi_3^*\Phi_3 + \lambda_{13}\left|\Phi_2\right|^2\Phi_3^*\Phi_3 \\
&-i\,\kappa\left[\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)\left(\Phi_3 - \Phi_3^\star\right)\right]
\end{aligned}
$$

Model

- Scalar Lagrangian

$$\mathscr{L}_{\rm scalar} = (D_\mu\Phi_1)^\dagger\,(D^\mu\Phi_1) + (D_\mu\Phi_2)^\dagger\,(D_\mu\Phi_2) + (D_\mu\Phi_3)^*\,(D_\mu\Phi_3) - V_{\rm scalar}$$

$$V_{\rm scalar} = -\frac{1}{2}m_{11}^2\left(\Phi_1^\dagger\Phi_1\right) - \frac{1}{2}m_{22}^2\left(\Phi_2^\dagger\Phi_2\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\left[\lambda_5\,\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right]$$
$$-\frac{1}{2}m_{33}^2\,\Phi_3^*\Phi_3 + \frac{\lambda_8}{2}(\Phi_3^*\Phi_3)^2 + \lambda_{11}|\Phi_1|^2\Phi_3^*\Phi_3 + \lambda_{13}|\Phi_2|^2\Phi_3^*\Phi_3$$
$$-i\kappa\left[\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)(\Phi_3 - \Phi_3^\star)\right]$$

- Yukawa terms

$$\mathscr{L}_{\rm Y} = -y_u\,\overline{Q_L}\,\widetilde{\Phi_1}\,u_R - y_d\,\overline{Q_L}\,\Phi_1\,d_R - y_l\,\overline{l_L}\,\Phi_1\,e_R - y_1\,\overline{l_L}\,\Phi_2\,e_R + \text{h.c.}$$

$$\mathscr{L}_{\rm VL} = \overline{\chi}\,i\left(\partial\!\!\!/ - ig'\frac{Y}{2}\,B\!\!\!/\right)\chi - m_\chi\,\overline{\chi}\,\chi - y_2\,\overline{\chi_L}\,\chi_R\,\Phi_3 - y_3\,\overline{\chi_L}\,e_R\,\Phi_3$$

Model

Scalar mass eigen states

- $\Phi_1 - \Phi_3$ mixing $\rightarrow$ CP even states

$$M^2_{\phi_1^0\,\phi_3^0} = \frac{1}{2}\begin{pmatrix}\phi_1^0 & \phi_3^0\end{pmatrix}\begin{pmatrix} 1\ v_{\rm SM}^2 & 11\ v_{\rm SM}\ v_s \\ 11\ v_{\rm SM}\ v_s & 8\ v_s^2 \end{pmatrix}\begin{pmatrix}\phi_1^0 \\ \phi_3^0\end{pmatrix}$$

$$m^2_{h_1} = \cos^2\theta_{13}\,\lambda_1\,v_{\rm SM}^2 + \sin(2\theta_{13})\,v_s\,\lambda_{11}\,v_{\rm SM} + \sin^2\theta_{13}\,v_s^2\,\lambda_8$$

$$m^2_{h_3} = \sin^2\theta_{13}\,\lambda_1\,v_{\rm SM}^2 - \sin(2\theta_{13})\,v_s\,\lambda_{11}\,v_{\rm SM} + \cos^2\theta_{13}\,v_s^2\,\lambda_8$$

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- $\Phi_2 - \Phi_3$ mixing $\rightarrow$ CP odd states

$$\frac{1}{2}\begin{pmatrix}\eta_2^0 & \eta_3^0\end{pmatrix}\begin{pmatrix} -\frac{1}{2}m_{22}^2 + \frac{1}{2}345\,v_{\rm SM}^2 + \frac{1}{2}v_s^2 13 & -\sqrt{2}\kappa v_{\rm SM} \\ -\sqrt{2}\kappa v_{\rm SM} & 0\end{pmatrix}\begin{pmatrix}\eta_2^0 \\ \eta_3^0\end{pmatrix}$$

$$m^2_{A^0} = \frac{1}{2}\left(\overline{\lambda}_{345}\,v_{\rm SM}^2 - m_{22}^2 + 13\,v_s^2\right)\cos^2\theta_{23} - \sqrt{2}\kappa v_{\rm SM}\sin 2\theta_{23}$$

$$m^2_{P^0} = \frac{1}{2}\left(\overline{\lambda}_{345}\,v_{\rm SM}^2 - m_{22}^2 + 13\,v_s^2\right)\sin^2\theta_{23} + \sqrt{2}\kappa v_{\rm SM}\sin 2\theta_{23}$$

Model

Scalar mass eigen states

$$\phi_2^0 \quad \rightarrow \quad h_2$$
$$\eta_1^0 \quad \rightarrow \quad G^0 \text{ (massless Nambu-Goldstone Boson)}$$
$$\phi_1^{\pm} \quad \rightarrow \quad G^{\pm} \text{ (massless Nambu-Goldstone Boson)}$$
$$\phi_2^{\pm} \quad \rightarrow \quad H^{\pm}$$

$$m_{h_2}^2 = \frac{1}{2}\left[-m_{22}^2 + (\lambda_3 + \lambda_4 + \lambda_5)\ v_{\rm SM}^2 + {}_{13}\, v_s^2\right]$$
$$m_{H^\pm}^2 = -m_{22}^2 + \lambda_3\ v_{\rm SM}^2 + {}_{13}\, v_s^2$$

Model parameters: $m_{11}^2,\ m_{22}^2,\ m_{33}^2,\ \lambda_{i=1,\dots 5},\ \lambda_8,\ \lambda_{11},\ \lambda_{13}$ and κ

$$\Downarrow$$

Physical parameters: $v_{\rm SM}, v_s, m_{h_1}^2, m_{h_1}^2, m_{h_2}^2, m_{H^\pm}^2,\ m_{A^0}^2, m_{P^0}^2, \theta_{13}, \theta_{23}$ and m_{22}^2

Model (Positivity and minimisation Conditions)

- Positivity Conditions

$$\mathscr{H} = \begin{vmatrix} \lambda_1 & \lambda_3+\lambda_4-|\lambda_5| & \lambda_{11} \\ \lambda_3+\lambda_4-|\lambda_5| & \lambda_2 & \lambda_{13} \\ \lambda_{11} & \lambda_{13} & \lambda_8 \end{vmatrix} > 0$$

along with $\lambda_1, \lambda_2 \,\text{and}\, \lambda_8 > 0$. This leads to the following co-positivity conditions:

$$\lambda_1, \lambda_2, \lambda_8 > 0,$$

$$\bar{\lambda}_{12} \equiv \lambda_3 + \Theta\left[|\lambda_5| - \lambda_4\right]\ (\lambda_4 - |\lambda_5|) + \sqrt{\lambda_1\lambda_2} > 0,$$

$$\bar{\lambda}_{13} \equiv \lambda_{11} + \sqrt{\lambda_1\lambda_8} > 0,\ \bar{\lambda}_{23} \equiv \lambda_{13} + \sqrt{\lambda_2\lambda_8} > 0 \text{ and}$$

$$\sqrt{\lambda_1\lambda_2\lambda_8} + [\lambda_3 + \Theta[|\lambda_5| - \lambda_4](\lambda_4 - |\lambda_5|)]\sqrt{\lambda_8} + \lambda_{11}\sqrt{\lambda_2} + \sqrt{2\ \bar{\lambda}_{12}\bar{\lambda}_{13}\bar{\lambda}_{23}} > 0$$

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$$\sqrt{\lambda_1\lambda_2\lambda_8} + [\lambda_3 + \Theta[|\lambda_5| - \lambda_4](\lambda_4 - |\lambda_5|)]\sqrt{\lambda_8} + \lambda_{11}\sqrt{\lambda_2} + \sqrt{2\ \bar{\lambda}_{12}\bar{\lambda}_{13}\bar{\lambda}_{23}} > 0$$

- Minimisation Conditions

$$m_{11}^2 = \lambda_1\ v_{\rm SM}^2 + \lambda_{11}\ v_s^2$$

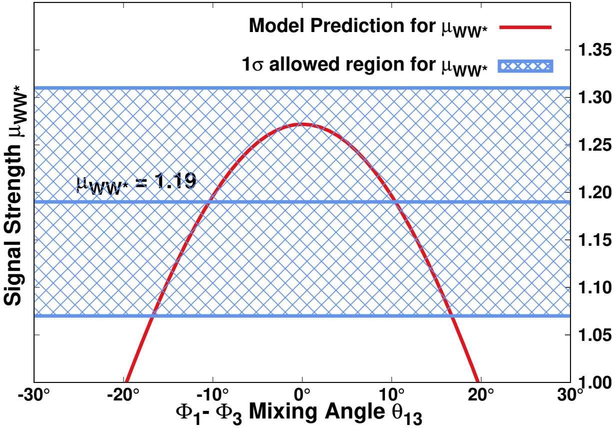
$$m_{33}^2 = \lambda_8\ v_s^2 + \lambda_{11}\ v_{\rm SM}^2$$

The m_{22}^2 parameter remains unconstrained by the extremum condition.

Constraints from Higgs decay

Signal strength:

$$\mu_{XY} \quad = \quad \frac{\sigma(pp \to h_1 \to XY)}{\sigma(pp \to h \to XY)^{\rm SM}} = \frac{\Gamma\left(h_1 \to g\,g\right)}{\Gamma\left(h^{SM} \to g\,g\right)}\,\frac{{\rm BR}\left(h_1 \to X\,Y\right)}{{\rm BR}\left(h^{\rm SM} \to X\,Y\right)} = \cos^4\theta_{13}\,\frac{\Gamma\left(h^{\rm SM} \to {\rm all}\right)}{\Gamma\left(h_1 \to {\rm all}\right)}$$



[JHEP 11 (2021) 056]

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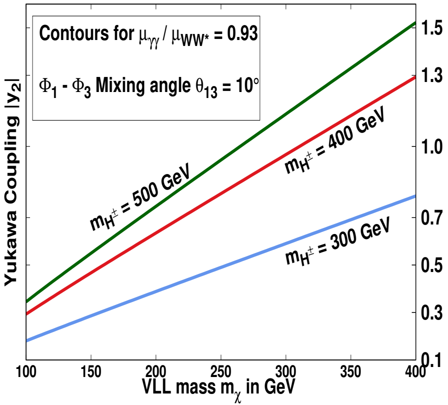

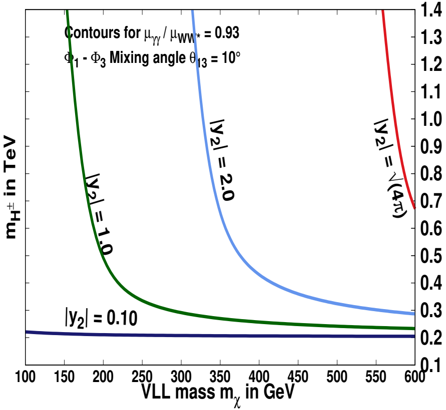

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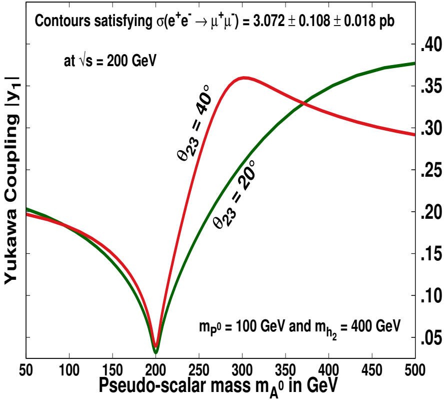
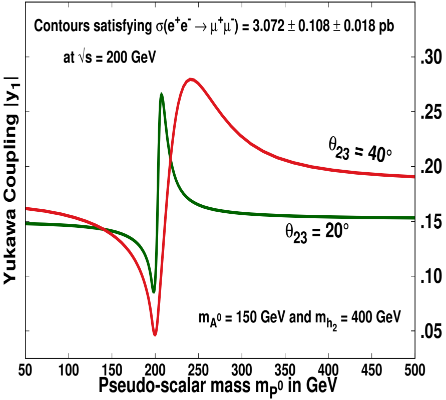
Constraints from LEP II

$\sigma(e^+ \ e^- \to \mu^+ \ \mu^-) = 3.072 \pm 0.108 \pm 0.018$ pb at $\sqrt{s} = 200\ GeV$ [Phys. Rept. 532 (2013) 119]

$$\sigma^{\rm NP}_{\mu^+\mu^-} \simeq \frac{s}{64\pi}\sqrt{\frac{1-4\frac{m_\mu^2}{s}}{1-4\frac{m_e^2}{s}}}\, y_1^4 \left[\left\{\frac{\cos^2\theta_{23}}{s-m^2_{A^0}} + \frac{\sin^2\theta_{23}}{s-m^2_{P^0}}\right\}^2 + \frac{1}{\left(s-m^2_{h_2}\right)^2}\right]$$





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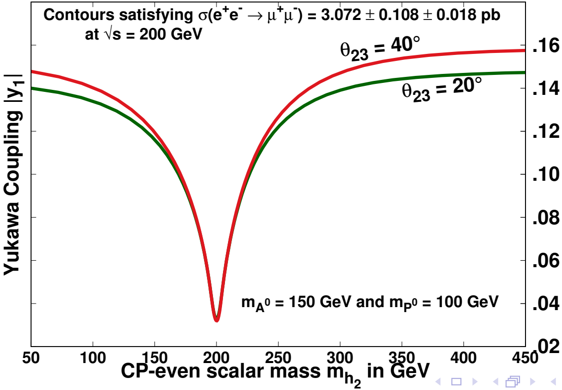
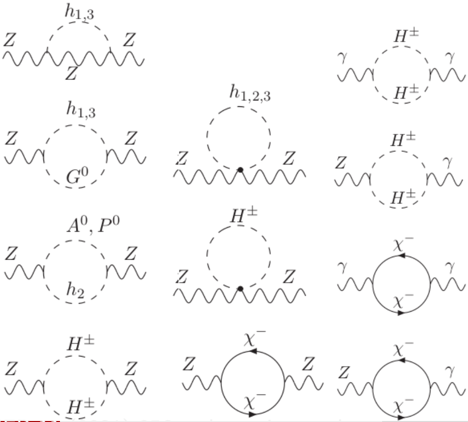


Constraints from electroweak precision observables

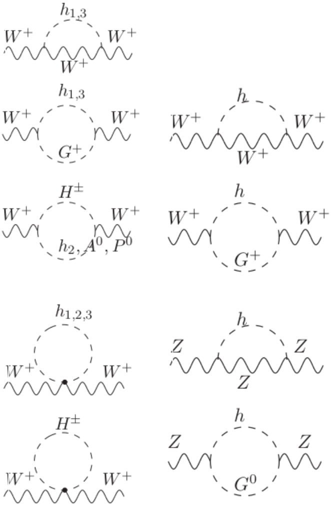
- The deviation in the theoretical predictions from the electroweak precision measurements [PTEP 2022, 083C01 (2022) (PDG)]

$$\Delta S = S_{\text{expt.}} - S_{\text{SM}} = 0.01 \pm 0.10$$

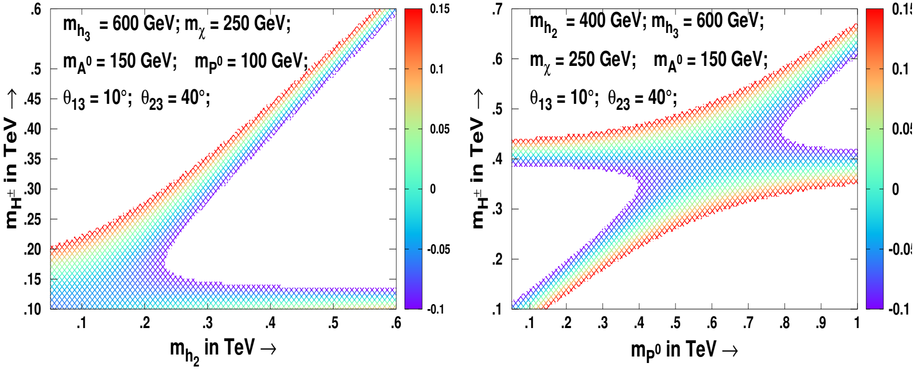
$$\Delta T = T_{\text{expt.}} - T_{\text{SM}} = 0.03 \pm 0.12$$



Constraints from electroweak precision observables



Constraints from electroweak precision observables



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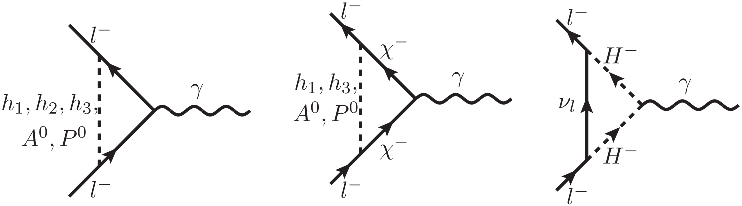
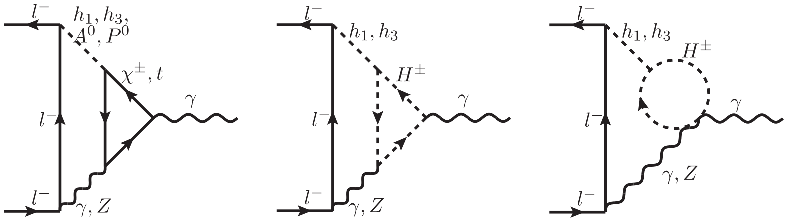
Anomalous Magnetic dipole moment of leptons (1-loop)



$$\Delta a_l^{1-\mathrm{loop}} = \frac{1}{16\pi^2}\Bigg[2\,\frac{m_l^4}{v_{\mathrm{SM}}^2}\left(\frac{\cos^2\theta_{13}}{m_{h_1}^2}+\frac{\sin^2\theta_{13}}{m_{h_3}^2}-\frac{1}{m_{h^{\mathrm{SM}}}^2}\right)\mathrm{I}_1 + m_l^2\left(\frac{\cos^2\theta_{23}}{m_{A^0}^2}+\frac{\sin^2\theta_{23}}{m_{P^0}^2}\right)y_1^2\;\mathrm{I}_2$$

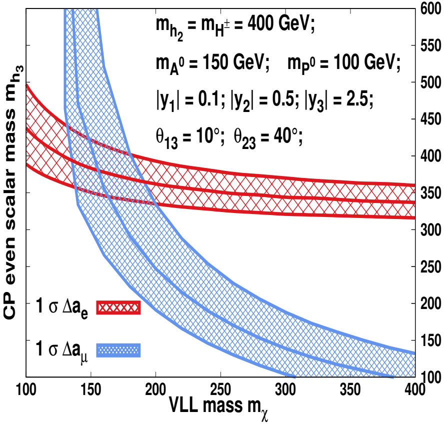
$$+\frac{m_l^2}{m_{h_2}^2}\,y_1^2\;\mathrm{I}_1 + \sum_{s_i=h_1,h_3,A^0,P^0}\left|y_{l\chi s_i}\right|^2\frac{m_l^2}{m_{s_i}^2}\,\mathrm{I}_3 + |y_1|^2\,\frac{m_l^2}{m_{H^\pm}^2}\,\mathrm{I}_4\Bigg]$$

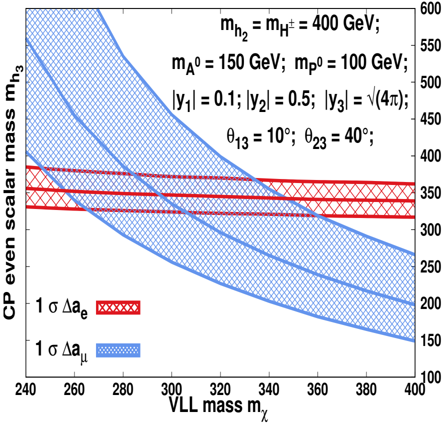
Anomalous Magnetic dipole moment of leptons (2-loop)



$$
\begin{aligned}
\Delta a_l{}^{2-loop} \quad = \quad & \frac{\alpha_{em}}{4\ \pi^3} \left[\frac{m_l}{v_{\mathrm{SM}}} \frac{y_2}{\sqrt{2}}\ \sin\theta_{13}\ \cos\theta_{13} \left\{ f\left(\frac{m_\chi^2}{m_{h_3}^2}\right) - f\left(\frac{m_\chi^2}{m_{h_1}^2}\right) \right\} \right. \\
& + \frac{m_l}{v_{\mathrm{SM}}} \frac{m_t}{v_{\mathrm{SM}}} \left\{ \sin^2\theta_{13}\ f\left(\frac{m_t^2}{m_{h_3}^2}\right) - \cos^2\theta_{13}\ f\left(\frac{m_t^2}{m_{h_1}^2}\right) + f\left(\frac{m_t^2}{m_{h^{\mathrm{SM}}}^2}\right) \right\} \\
& + \frac{y_1\ y_2}{2} \frac{m_l}{m_\chi} \sin\theta_{23}\ \cos\theta_{23} \left\{ g\left(\frac{m_\chi^2}{m_{A^0}^2}\right) - g\left(\frac{m_\chi^2}{m_{P^0}^2}\right) \right\} \\
& \left. - \frac{m_l^2}{4} \frac{m_l}{v_{\mathrm{SM}}^2} \left\{ \frac{\cos\theta_{13}}{m_{h_1}^2}\ g_{h_1 H^+ H^-}\ \tilde{f}\left(\frac{m_{H^\pm}^2}{m_{h_1}^2}\right) - \frac{\sin\theta_{13}}{m_{h_3}^2}\ g_{h_3 H^+ H^-}\ \tilde{f}\left(\frac{m_{H^\pm}^2}{m_{h_3}^2}\right) \right\} \right]
\end{aligned}
$$

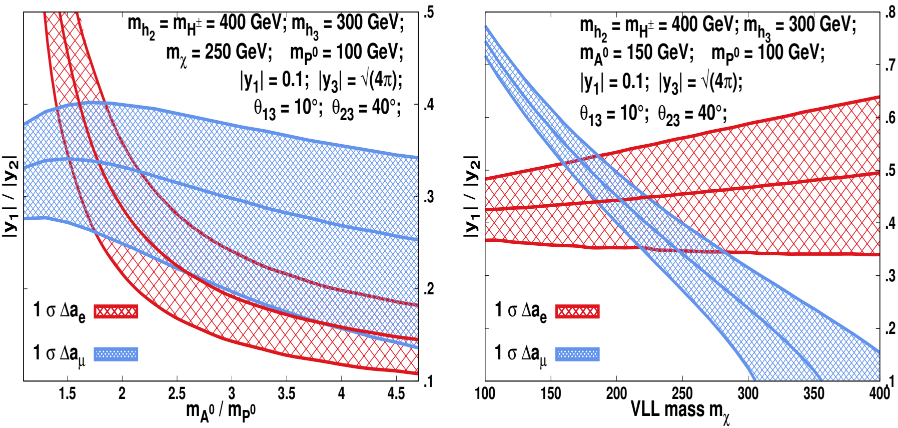
Parameter scan for Δa_μ and Δa_e





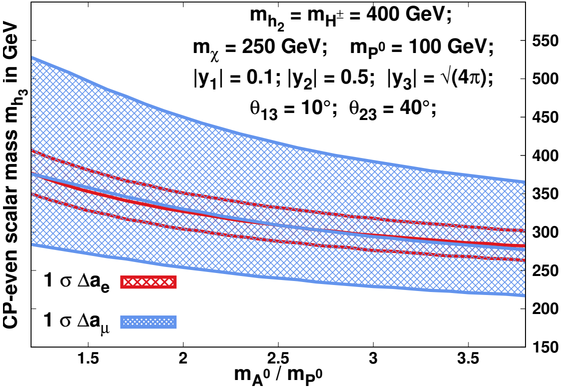
[JHEP 11 (2021) 056]

Parameter scan for Δa_μ and Δa_e



[JHEP 11 (2021) 056]

Parameter scan for Δa_μ and Δa_e



[JHEP 11 (2021) 056]

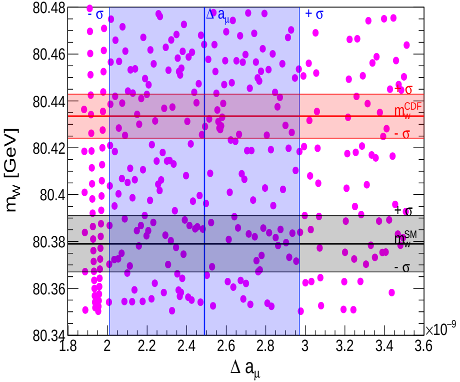
W-mass Anomaly

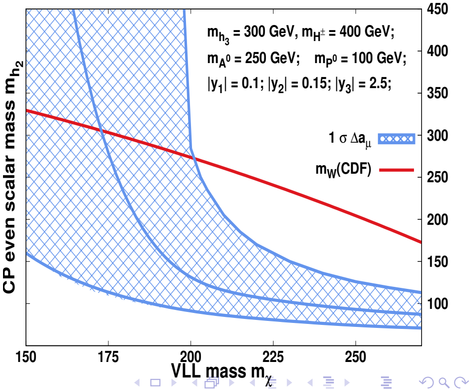
$$m_W^{\rm SM} = 80.377 \pm 0.006 \; GeV$$ [PTEP 2022, 083C01 (2022)]

$$m_W^{\rm CDF} = 80.4335 \pm 0.0094 \; GeV$$ [Science 376, 170 (2022)]

$$\frac{\Delta m_W^2}{m_W^2} = \frac{2\Delta m_W}{m_W} = \frac{\alpha_{em}}{c_W^2 - s_W^2}\left(-\frac{\Delta S}{2} + c_W^2\,\Delta T + \frac{c_W^2 - s_W^2}{4\,s_W^2}\,\Delta U\right)$$

[Chin. Phys. C **47** (2023) no.4, 043102]





Thank You

Backup slides

Yukawa Couplings

y_{ffh_1}	$\left(\sqrt{2}m_f/v_{\rm SM}\right)\cos\theta_{13}$	y_{llh_2}	y_1
y_{ffh_3}	$-\left(\sqrt{2}m_f/v_{\rm SM}\right)\sin\theta_{13}$	y_{llP^0}	$-i\ y_1\sin\theta_{23}$
$y_{\chi\chi h_1}$	$y_2\ \sin\theta_{13}$	y_{llA^0}	$i\ y_1\cos\theta_{23}$
$y_{\chi\chi h_3}$	$y_2\ \cos\theta_{13}$	$y_{l\chi h_1}$	$y_3\sin\theta_{13}$
$y_{\chi\chi P^0}$	$i\ y_2\ \cos\theta_{23}$	$y_{l\chi h_3}$	$y_3\cos\theta_{13}$
$y_{\chi\chi A^0}$	$i\ y_2\ \sin\theta_{23}$	$y_{l\chi P^0}$	$i\ y_3\cos\theta_{23}$
$y_{l\nu H^-}$	y_1	$y_{l\chi A^0}$	$i\ y_3\sin\theta_{23}$

Backup slides

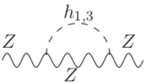
S, T, U

$$S \equiv \frac{1}{g^2}\left(16\pi\cos\theta_W^2\right)\left[F_{ZZ}(m_Z^2) - F_{\gamma\gamma}(m_Z^2) + \left(\frac{2\sin\theta_W^2 - 1}{\sin\theta_W\cos\theta_W}\right)F_{Z\gamma}(m_Z^2)\right]$$

$$T \equiv \frac{1}{\alpha_{em}}\left[\frac{A_{WW}(0)}{m_W^2} - \frac{A_{ZZ}(0)}{m_Z^2}\right]$$

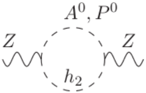
$$U \equiv \frac{1}{g^2}(16\pi)\left[F_{WW}(m_W^2) - F_{\gamma\gamma}(m_W^2) - \frac{\cos\theta_W}{\sin\theta_W}F_{Z\gamma}(m_W^2)\right] - S$$

Constraints from electroweak precision observables

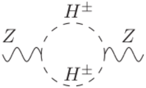


$$= -\frac{g^2 M_Z^2}{16\pi^2 c_W^2}\left[\cos^2\theta_{13} B_0(q^2; m_Z^2, m_{h_1}^2) + \sin^2\theta_{13} B_0(q^2; m_Z^2, m_{h_3}^2)\right]$$

$$= \frac{g^2}{16\pi^2 c_W^2}\left[\cos^2\theta_{13} B_{22}(q^2; m_Z^2, m_{h_1}^2) + \sin^2\theta_{13} B_{22}(q^2; m_Z^2, m_{h_3}^2)\right]$$

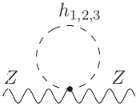


$$= \frac{g^2}{16\pi^2 c_W^2}\left[\cos^2\theta_{23} B_{22}(q^2; m_{h_2}^2, m_{A^0}^2) + \sin^2\theta_{23} B_{22}(q^2; m_{h_2}^2, m_{P^0}^2)\right]$$

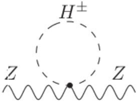


$$= \frac{g^2}{16\pi^2 c_W^2} c_{2W}^2 B_{22}(q^2; m_{H^\pm}^2, m_{H^\pm}^2)$$

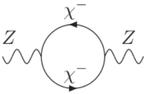
Constraints from electroweak precision observables



$$= -\frac{1}{2}\frac{g^2}{16\pi^2}\sec^2\theta_W\left[\cos^2\theta_{13}A_0(m_{h_1}^2)+\sin^2\theta_{13}A_0(m_{h_3}^2)+A_0(m_{h_2}^2)\right]$$

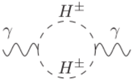


$$= -\frac{1}{2}\frac{g^2}{16\pi^2}\left[(-2s_W^2+c_W^2+s_W^2t_W^2)A_0(m_{H^\pm}^2)\right]$$

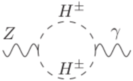


$$= \frac{-e^2}{4\pi^2}\,\frac{s_W^2}{c_W^2}\left[m_\chi^2\;B_0(q^2;m_\chi^2,m_\chi^2)\;-\;2\;B_{22}(q^2;m_\chi^2,m_\chi^2)\right]$$

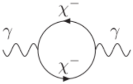
Constraints from electroweak precision observables



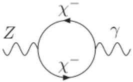
$$= 4\frac{g^2}{16\pi^2} s_W^2 B_{22}(m_Z^2; m_{H^\pm}^2, m_{H^\pm}^2)$$



$$= \frac{2g^2}{16\pi^2 c_W} s_W c_{2W} B_{22}(m_Z^2; m_{H^\pm}^2, m_{H^\pm}^2)$$

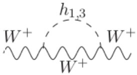


$$= \frac{-e^2}{4\pi^2} \left[m_\chi^2 \; B_0(q^2; m_\chi^2, m_\chi^2) \; - \; 2 \; B_{22}(q^2; m_\chi^2, m_\chi^2) \right]$$



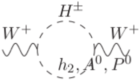
$$= \frac{e^2}{4\pi^2} \frac{s_W}{c_W} \left[m_\chi^2 \; B_0(q^2; m_\chi^2, m_\chi^2) \; - \; 2 \; B_{22}(q^2; m_\chi^2, m_\chi^2) \right]$$

Constraints from electroweak precision observables



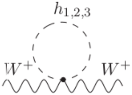
$$= -\frac{g^2 m_W^2}{16\pi^2}\left[\cos^2\theta_{13} B_0(q^2; m_W^2, m_{h_1}^2) + \sin^2\theta_{13} B_0(q^2; m_W^2, m_{h_3}^2)\right]$$

$$= \frac{g^2}{16\pi^2}\left[\cos^2\theta_{13} B_{22}(q^2; m_W^2, m_{h_1}^2) + \sin^2\theta_{13} B_{22}(q^2; m_W^2, m_{h_3}^2)\right]$$

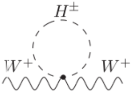


$$= \frac{g^2}{16\pi^2}\Big[B_{22}(q^2; m_{H^\pm}^2, m_{h_2}^2) + \cos^2\theta_{23} B_{22}(q^2; m_{H^\pm}^2, m_{A^0}^2)$$

$$+ \sin^2\theta_{23} B_{22}(q^2; m_{H^\pm}^2, m_{P^0}^2)\Big]$$

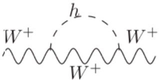


$$= -\frac{1}{2}\frac{g^2}{16\pi^2}\left[\cos^2\theta_{13} A_0(m_{h_1}^2) + \sin^2\theta_{13} A_0(m_{h_3}^2) + A_0(m_{h_2}^2)\right]$$



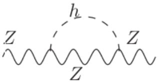
$$= -\frac{1}{2}\frac{g^2}{16\pi^2} A_0(m_{H^\pm}^2)$$

Constraints from electroweak precision observables



$$= -\frac{g^2 m_W^2}{16\pi^2} B_0(q^2; m_W^2, m_h^2)$$

$$= \frac{g^2}{16\pi^2} B_{22}(q^2; m_W^2, m_h^2)$$



$$= -\frac{g^2 m_Z^2}{16\pi^2 c_W^2} B_0(q^2; m_Z^2, m_h^2)$$

$$= \frac{g^2}{16\pi^2 c_W^2} B_{22}(q^2; m_Z^2, m_h^2)$$