Correlating W-boson Mass Shift with Muon (g-2) Anomaly in the 2HDM

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In collaboration with K.S. Babu, and Sudip Jana

[arXiv:2204.05303 [hep-ph]]

Oklahoma State University

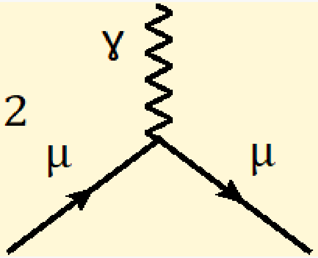
Muon Magnetic Moment: Overview

- Magnetic moment of Leptons:

$$\vec{\mu}_B = g_\mu \frac{e}{2m_\mu} \vec{S}$$

- Lande' g- factor:

$$g_\mu = 2$$



- Due to Quantum corrections, $(g-2)_\mu \neq 0$.

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$$a_\mu = \frac{(g-2)_\mu}{2}$$

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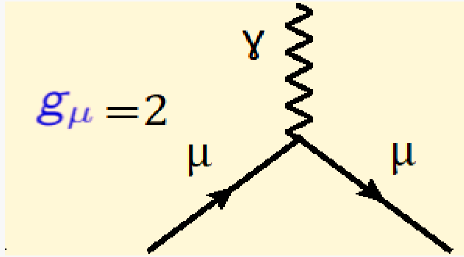

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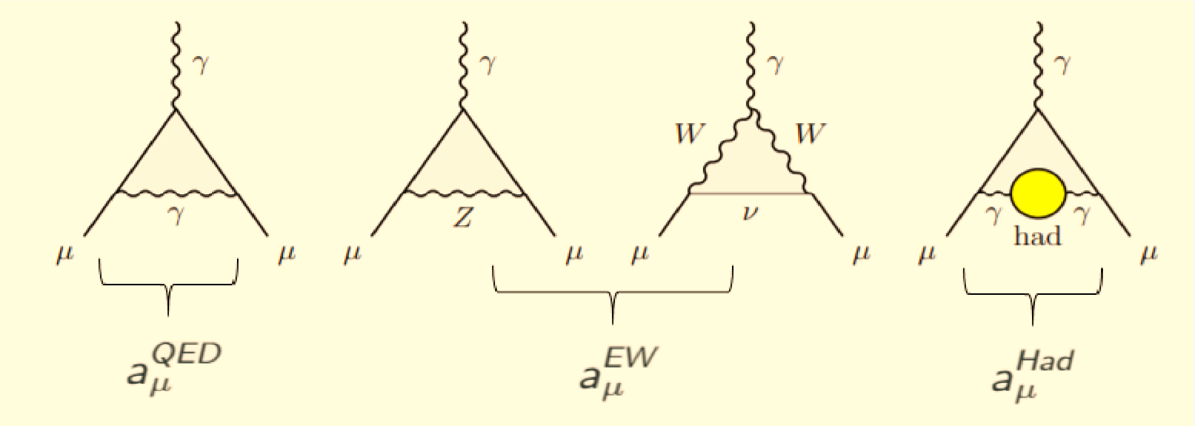
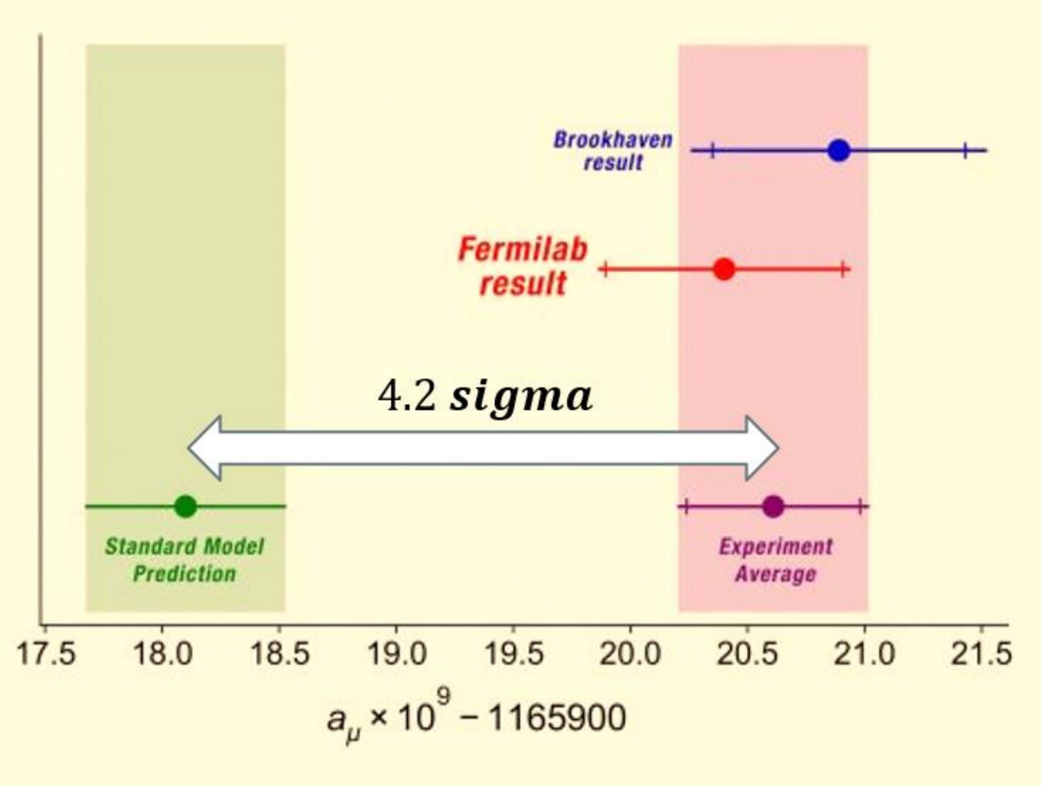
- Contributions in the SM:



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

Current Status of Muon (g-2)

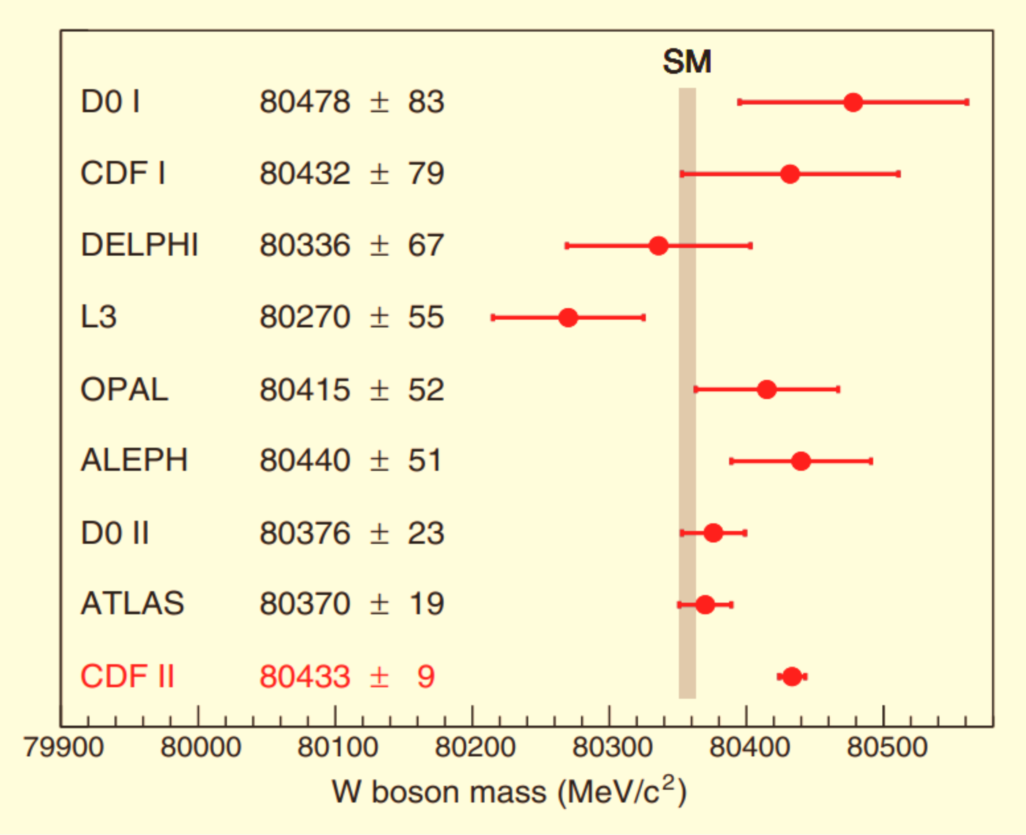


Fermilab Muon g-2 Collaboration, B. Abi *et al.* (2021)

$$10^{11} \boldsymbol{a_\mu} = \begin{cases} 116591810(43) \ \textbf{SM} \\ 116592040(54) \ \textbf{Exp} \end{cases}$$

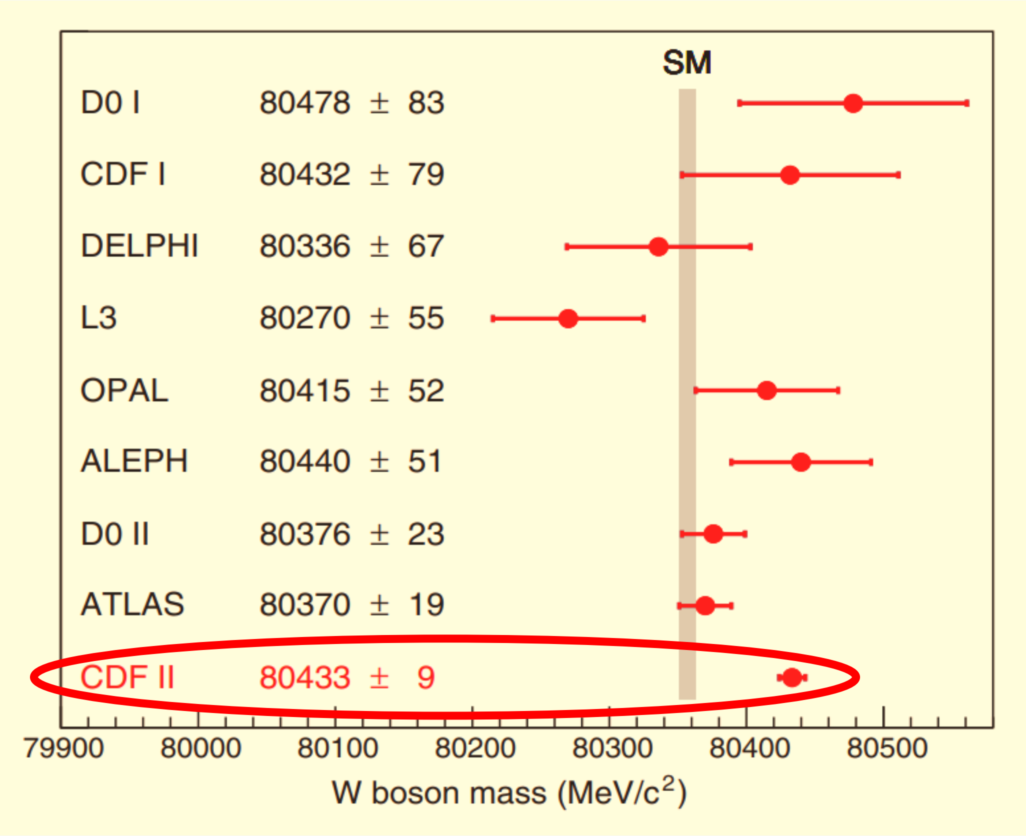
$$\Delta \boldsymbol{a_\mu} = \boldsymbol{a_\mu}^{\boldsymbol{exp}} - \boldsymbol{a_\mu}^{\boldsymbol{SM}} = 251(59) \times 10^{-11}$$

W- boson mass



CDF collaboration, T. Aaltonen *et.al* (2022)

W- boson mass



CDF collaboration, T. Aaltonen *et.al* (2022)

$$M_W = \begin{cases} 80357(6)\ \text{MeV}\ \ (\textbf{SM}) \\ 80433(9)\ \text{MeV}\ (\textbf{CDF II}) \end{cases}$$

- Discrepancy at the $\sim 7\sigma$ level!
- Tantalizing evidence for New Physics?

Calculation of *W*- boson mass

- W-boson mass can be calculated in terms of G_F, α_{em}, M_Z, and Δr

$$M_W^2 = \frac{M_Z^2}{2}\left[1 + \sqrt{1 - \frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_F M_Z^2}(1+\Delta r)}\right] .$$

loop corrections

- Oblique corrections can modify the Δr

$$\Delta r' = \frac{\alpha}{s_w^2}\left(-\frac{1}{2}S + c_w^2 T + \frac{c_w^2 - s_w^2}{4s_w^2}U\right)$$

Calculation of *W*- boson mass

- One of the minimal model which could resolve the W-boson mass anomaly is the two Higgs doublet model.

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \end{pmatrix} \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2^0 + iA) \end{pmatrix}$$

- In order to generate large contributions to the oblique parameters, one need to consider large mass splitting for the scalar states.

- However, in general 2HDM, there is no particular reason to have such large mass splitting.

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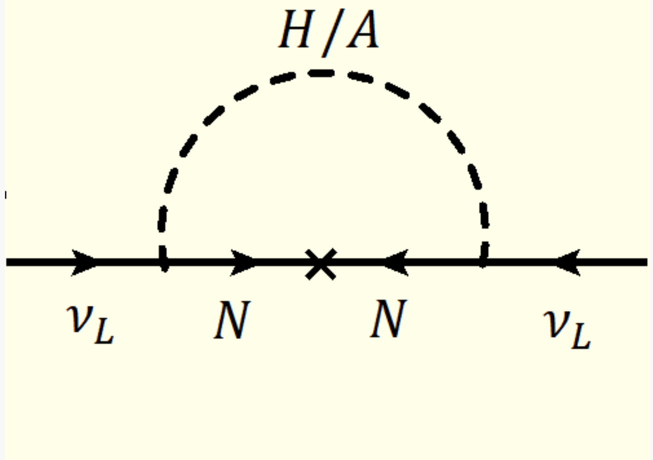
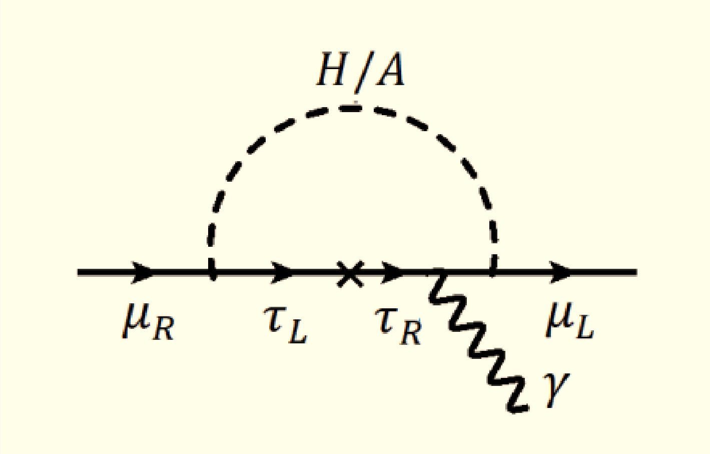
- However, in general, there is no particular reason to have such large mass splitting.

- Exceptions:
  - Scotogenic model



R. Dcruz, A. Thapa (2022)
A. Batra *et.al* (2022)

- Muon (g-2)



Two Higgs Doublet Model

- **Scalar potential:**

$$V = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - \{m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\}$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2)$$
$$+ \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \text{h.c.}\right\}$$
$$+ \left\{\left[\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \text{h.c.}\right\}.$$

- **Alignment limit:** the SM-like Higgs $\phi_1^0 \approx h$ decouples from the new CP- even Higgs $\phi_2^0 \approx H$.

- **Mass spectrum:**

$$m_h^2 = \lambda_1 v^2,\ m_H^2 = m_{22}^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5),$$
$$m_A^2 = m_H^2 - v^2 \lambda_5,\ m_{H\pm}^2 = m_H^2 - \frac{v^2}{2}(\lambda_4 + \lambda_5).$$

Two Higgs Doublet Model

- **Yukawa Coupling:**

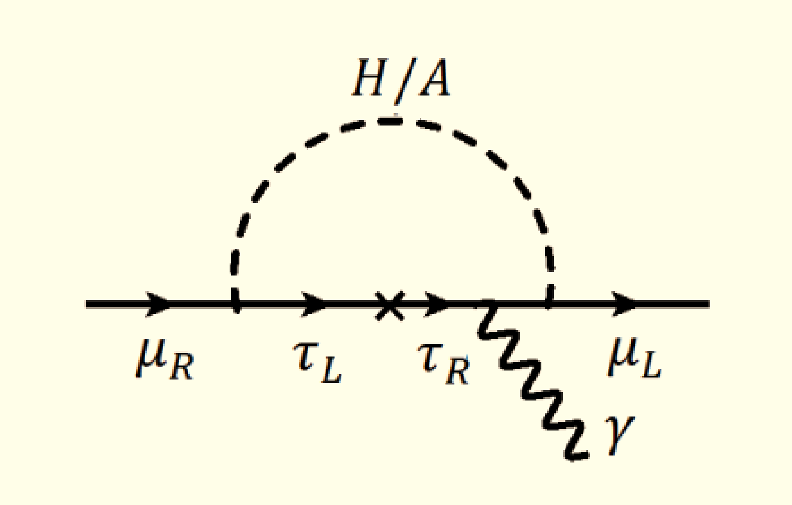
$$-\mathcal{L}_{\rm Yuk} \supset Y \bar{\ell}_L H_1 \ell_R + \widetilde{Y} \bar{\ell}_L H_2 \ell_R + h.c.$$

- Assuming

$$\tilde{Y}_{\mu\tau} \neq 0, \;\; \tilde{Y}_{\tau\mu} \neq 0, \;\; \tilde{Y}_{ij} = 0 \text{ for all other } i, j \;.$$

  - ✓ Muon (g-2) contributions is helicity enhancement proportional to m_τ / m_μ.
  - ✓ Lepton flavor violation constraints are automatically satisfied.
  - ✓ Ansatz can be embedded in Z_4 symmetry setup.

NP Contribution to Muon (g-2) and *W*-boson Mass



$$\Delta a_\mu = \frac{\widetilde{Y}_{\mu\tau}\widetilde{Y}_{\tau\mu}}{16\pi^2}\left(\frac{m_\tau}{m_\mu}\right)\left[G\left(\frac{m_\tau^2}{m_\mu^2},\frac{m_H^2}{m_\mu^2}\right) - G\left(\frac{m_\tau^2}{m_\mu^2},\frac{m_A^2}{m_\mu^2}\right)\right]$$

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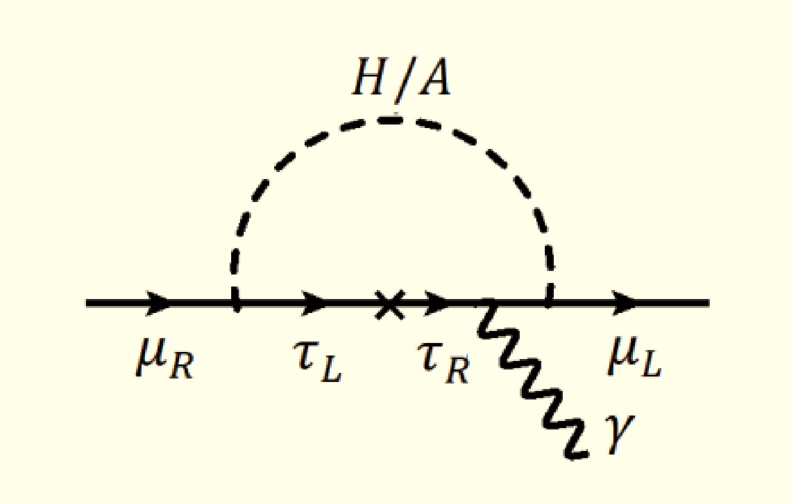

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- W-boson mass can be calculated in terms of G_F, α_{em}, M_Z, and Δr

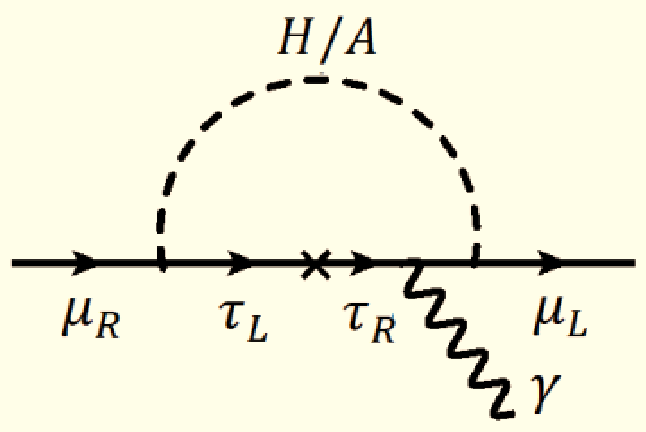
$$M_W^2 = \frac{M_Z^2}{2}\left[1 + \sqrt{1 - \frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_F M_Z^2}(1+\Delta r)}\right] .$$

loop corrections

- In our setup, the NP contributions to Δr arises as oblique corrections dominated by T-parameter.

$$T = \frac{1}{16\pi^2\alpha_{\rm em}(M_Z)v^2}\{\mathcal{F}(m_{H^+}^2, m_H^2) + \mathcal{F}(m_{H^+}^2, m_A^2) - \mathcal{F}(m_H^2, m_A^2)\}$$

NP Contribution to Muon (g-2) and W-boson Mass



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Non-zero contribution to muon (g-2) requires a mass splitting between m_H and m_A.

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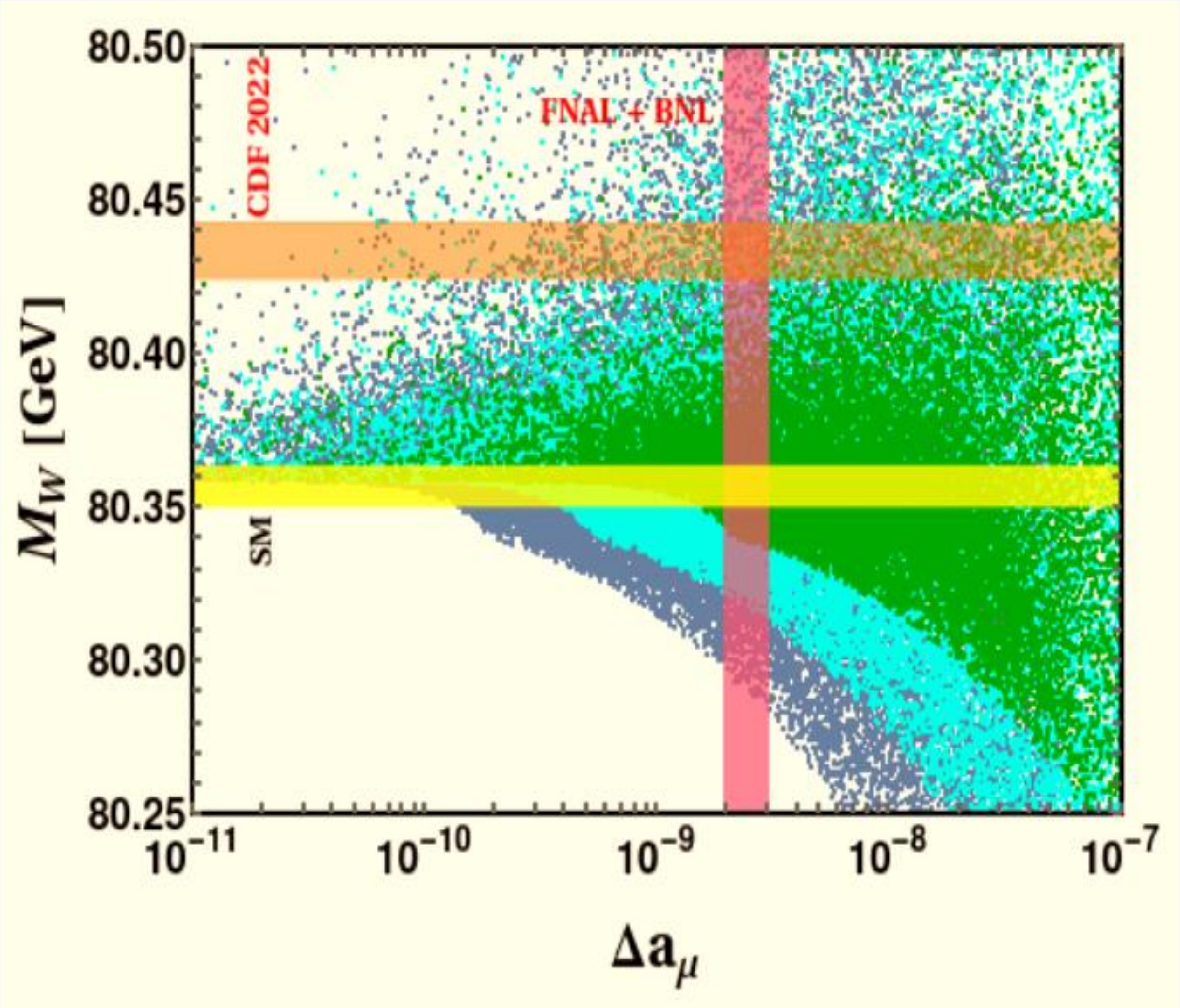
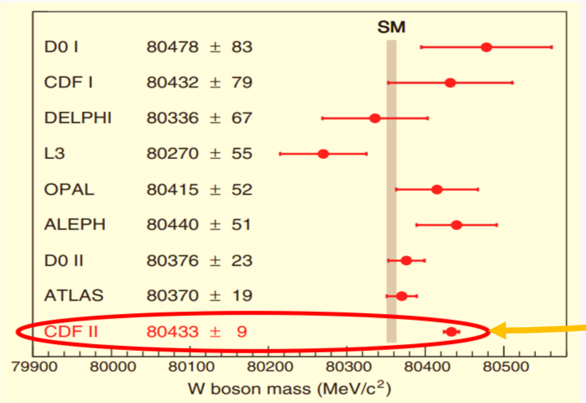
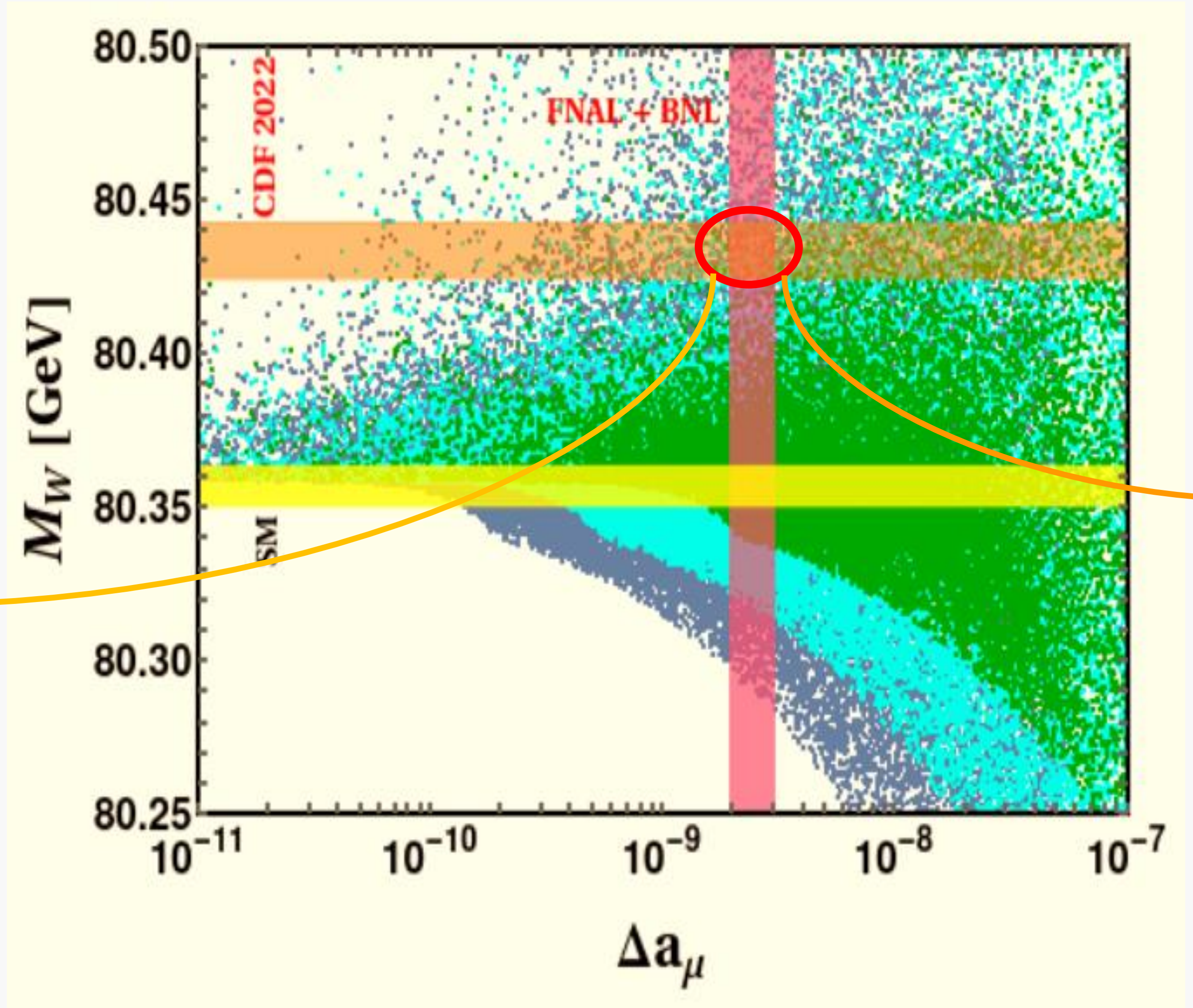
Induce corrections to W-boson mass.

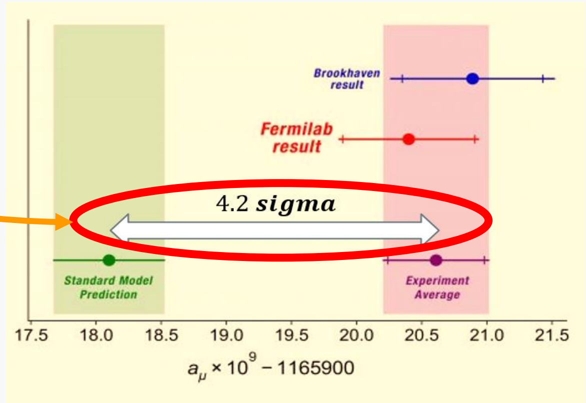
Muon (g-2) and W-boson Mass



Muon (g-2) and *W*-boson Mass





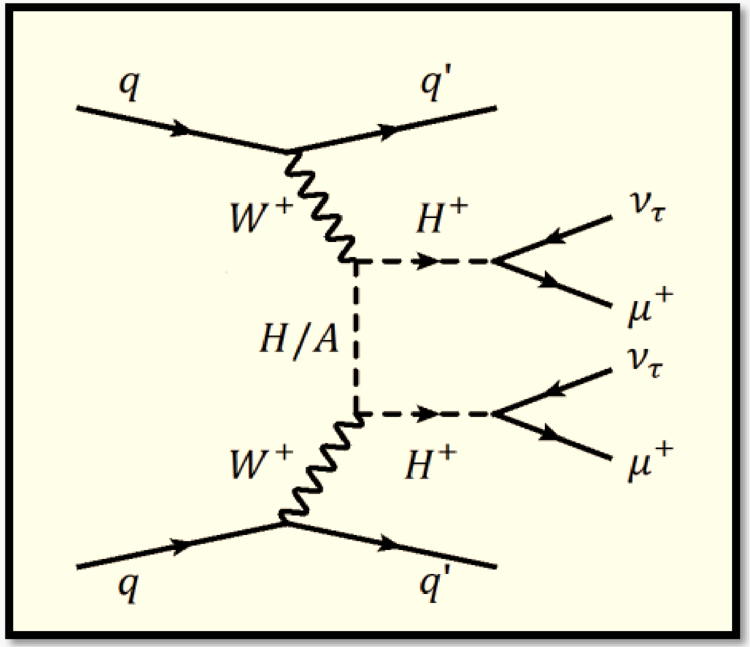


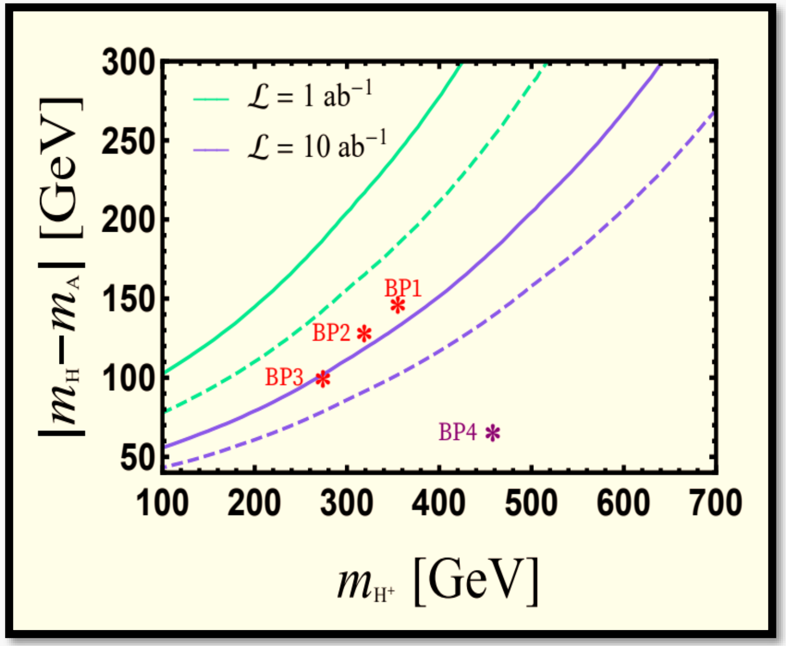
Muon (g-2) and *W*-boson Mass

$\sqrt{\lvert\tilde{Y}_{\mu\tau}\tilde{Y}_{\tau\mu}\rvert}$		m_H (GeV)	m_A (GeV)	$m_{H^\pm}$ (GeV)	M_W (GeV)	$\Delta a_\mu \times 10^9$
0.3	BP1	445.15	343.42	274.21	80.4372	3.04
	BP2	372.48	503.42	318.88	80.4241	2.95
	BP3	402.50	551.76	355.12	80.4203	2.66
0.5	BP4	593.90	526.20	457.68	80.4227	2.08
	BP5	397.48	430.29	511.94	80.4293	2.32
	BP6	128.68	126.95	233.72	80.4476	2.98
1.0	BP7	508.26	494.50	598.65	80.4292	2.28
	BP8	400.32	409.43	501.73	80.4294	2.73
	BP9	575.44	555.96	466.60	80.4257	2.31

- For a simultaneous explanations of the two anomalies, the charged and neutral scalars of the model cannot be heavier than 600 GeV.

Testable at LHC (Future)





K. S. Babu, S. Jana, **VPK** (2022)

- Novel process: $pp \to (\mu^+\mu^+ jj + \not{E}_T)$
- Amplitude, $A \propto (m_H^2 - m_A^2)/v^2$. M. Aiko, S. Kanemura, K. Mawatari (2019)

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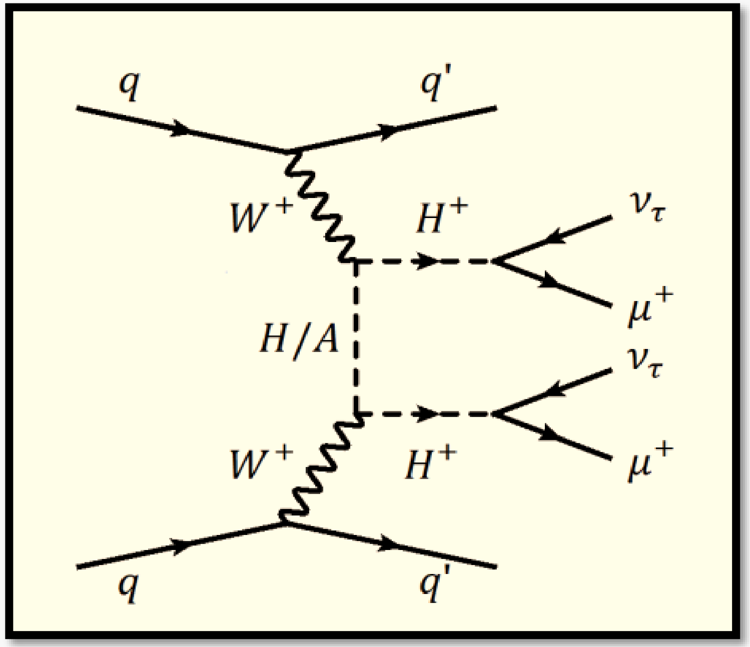

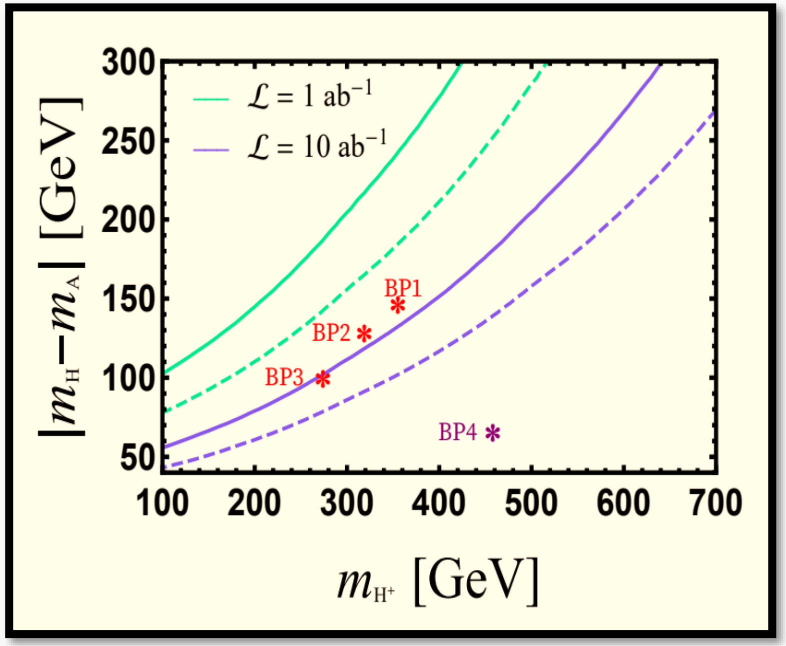

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- LHC could also look for pair production of *H* and *A* via *Z*-boson exchange. Each of these scalars would decay into $\mu^\pm\tau^\mp$
- All the benchmark points can be explored with a significance more than 3 sigma at 14 TeV LHC with $L = 1ab^{-1}$

Constraints

- **Tau- decay universality constraints**:
  - The charged scalar in the model leads to $\tau^- \to \mu^- \nu_\mu \overline{\nu}_\tau$ ⟹ $\left| \frac{\tilde{Y}_{\mu\tau} \tilde{Y}^*_{\tau\mu}}{g^2} \frac{M_W^2}{M_{H+}^2} \right| \leq 0.089$

- **LEP constraint**: $m_{H^\pm} > 110$ GeV

- **Perturbative constraints:** $|\lambda_i| \lesssim |\lambda_{\max}| = \sqrt{4\pi}$.

Few comments...

- **Corrections to Fermi-constant:**

  - New contributions affecting W- μ- ϑ_μ coupling

$$\frac{\delta G_F}{G_F} \simeq \frac{|\tilde{Y}_{\mu\tau}|^2}{32\pi^2}\left(1 - f(m_H^2, m_{H^\pm}^2) - f(m_A^2, m_{H^\pm}^2)\right)$$

Where the function f is

$$f(m_1^2, m_2^2) \equiv \frac{m_1^2 + m_2^2}{4(m_1^2 - m_2^2)} \ln \frac{m_1^2}{m_2^2}$$

  - These corrections would contribute to the W-boson mass

$$M_W^2 = \frac{M_Z^2}{2}\left[1 + \sqrt{1 - \frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_F M_Z^2}(1 + \Delta r)}\right].$$

  - Leads to shift in W-boson mass below 1 MeV.

- **S-parameter contribution:**

$$\Delta M_W \simeq -\frac{M_W \alpha(M_Z) S}{4(c_W^2 - s_W^2)}$$

- However, the S-parameter contribution is typically small in our setup, leads to shift in the W-boson mass in (5-10) MeV range.

- **Partial decay width of W and Z bosons:**

- Loop corrections to the W- μ- ϑ_μ (Z- μ-μ) coupling, as well as the oblique parameters T and S would affect the partial decay width $\Gamma(W \to \mu\overline{\vartheta_\mu})$ ($\Gamma(Z \to \mu\bar{\mu})$).

- $\Delta\Gamma(W \to \mu\overline{\vartheta_\mu}) < 0.5$ MeV and $\Delta\Gamma(Z \to \mu\bar{\mu}) < 1$ MeV.

Conclusions

- We have shown an interesting correlation between the W-boson mass shift observed by the CDF collaboration and Muon (g-2) anomaly in the context of 2HDM.

- The charged and neutral scalars of the model cannot be heavier than about 600 GeV for a simultaneous explanation of the two anomalies.

- The entire parameter space of the model can be tested at the LHC by a combination of same sign dimuon signals in $pp \to (\mu^+\mu^+jj + \not{E}_T)$ and $pp \to (\mu^+\mu^-\tau^+\tau^- + X)$ signals.

Thank You !