Large SU(2) multiplet scalars providing sizable muon g-2 and its phenomenology

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Based on TN, H.Okada, arXiv: 2208.08704

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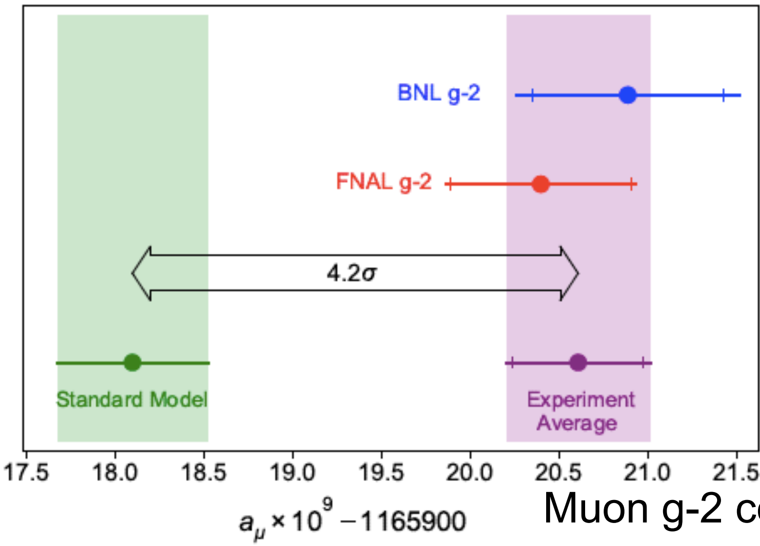
1. Introduction

Muon anomalous dipole magnetic moment (muon g-2)



$$a_\mu^{BNL} = (11659208.9 \pm 5.4 \pm 3.3) \times 10^{-10}$$

$$a_\mu^{FNAL} = (11659204.0 \pm 5.1 \pm 1.9) \times 10^{-10}$$

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{SM} = (25.1 \pm 5.9) \times 10^{-10}$$

Combined result (4.2σ deviation)

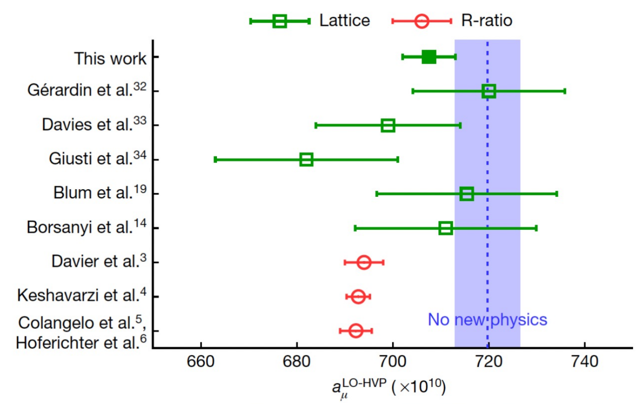
Muon g-2 collaboration, PRL126 (2021)

In fact, it is controversial

Estimation of HVP by Lattice groups: (e.g. BMWc)

Recent e+ e- → π+π- measurement :

(CMD3- Collaboration 2302.08834)



Borsanyi et al (BMWc), Nature 2021

⇨ They make SM prediction closer to experimental values (~1.5σ)

In any case the muon g-2 is good hint/test of new physics

A simple extension of the SM

⇨ Adding $SU(2)_L$ multiplet scalar/vector-like fermion(VLF)

- Extending field contents

- Simple extension but rich possibilities in phenomenology

  - Generating neutrino masses
  - New scalar with VEV → Higgs physics, electroweak precision test
  - Explaining experimental anomalies: **muon g-2** etc.
  - Collider physics
  - Etc.

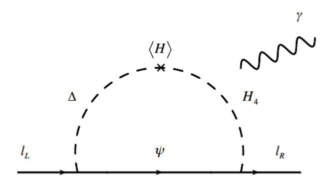
2. A model

Structure of the model (TN, H.Okada, arXiv: 2208.08704)

	L_{L_i}	e_{R_i}	ψ	H	Δ	H_4
$SU(2)_L$	**2**	**1**	**4**	**2**	**3**	**4**
$U(1)_Y$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{3}{2}$

New vector-like fermion(VLF) **New scalars**

- Introduction of Higgs triplet Δ : neutrino mass from type-II seesaw
- Quartet VLF ψ and scalar H_4 to get muon g-2 with Δ



⇨ Without chiral suppression

Muon g-2 is also enhanced by multiply charged scalars/fermions contributions

- General 2HDM is simple to get large muon g-2 but FCNC in quark sector
- Extra doublet for ψ also work but we have unwanted term $\bar{L}_L \psi_L^c$

Phenomenological consequences: LFV, collider physics

2. A model

New Lagrangian of the model

$$-\mathcal{L}_\ell = y_{\ell_{ii}} \bar{L}_{L_i} H e_{R_i} + y_{\nu_{ij}} \bar{L}_{L_i} \Delta^\dagger L^c_{L_j} + y_{D_i} [\bar{L}_{L_i} \Delta^\dagger \psi_R] + f_i [\bar{\psi}_L H_4 e_{R_i}]$$
$$+ g_L [\bar{\psi}^c_L \Delta^\dagger \psi_L] + g_R [\bar{\psi}^c_R \Delta^\dagger \psi_R] + M_\psi \bar{\psi}_L \psi_R + \text{h.c.},$$

$$V = -\mu_H^2 H^\dagger H + \mu_\Delta^2 \text{Tr}[\Delta^\dagger \Delta] + \mu_{H_4}^2 H_4^\dagger H_4 + \lambda_H (H^\dagger H)^2$$
$$+ (\text{trivial quartet terms including } \Delta \text{ and } H_4) + V_{\text{non-trivial}},$$

$$V_{\text{non-trivial}} = \mu_1 [H^\dagger \Delta^\dagger H_4 + \text{h.c.}] + \mu_2 [H^T \Delta^\dagger H] + \sum \lambda^i_{H_4 H} [H_4^\dagger H H H]_i + \text{h.c.},$$

Fields by components

$$H = (h^+, \tilde{h}^0) \qquad H_4 = (\phi_4^{+++}, \phi_4^{++}, \phi_4^+, \phi_4^0)^T,$$

$$\Delta = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix} \qquad \psi_{L(R)} = (\psi^{++}, \psi^+, \psi^0, \psi^-)^T_{L(R)},$$

Neutral components will develop VEVs $\langle H_4 \rangle = v_4/\sqrt{2}$ $\langle \Delta \rangle = v_\Delta/\sqrt{2}$

⇨ Constraints from ρ-parameter : $\rho = \frac{v_h^2 + 2v_\Delta^2 + 6v_4^2}{v_h^2 + 4v_\Delta^2 + 9v_4^2}$ $\quad v_X \lesssim 1.55 \text{ GeV}$ $\quad v_x \equiv v_\Delta = v_4$

Masses of new scalar particles

Mass eigenstates (in approximation):

$$\begin{pmatrix}\delta^{\pm}\\ \phi_4^{\pm}\end{pmatrix}=\begin{pmatrix}c_\alpha & s_\alpha\\ -s_\alpha & c_\alpha\end{pmatrix}\begin{pmatrix}H_1^{\pm}\\ H_2^{\pm}\end{pmatrix},$$

Singly charged

$$\begin{pmatrix}\delta^{\pm\pm}\\ \phi_4^{\pm\pm}\end{pmatrix}=\begin{pmatrix}c_\beta & s_\beta\\ -s_\beta & c_\beta\end{pmatrix}\begin{pmatrix}H_1^{\pm\pm}\\ H_2^{\pm\pm}\end{pmatrix},$$

Doubly charged

$$\begin{pmatrix}\delta^{0}\\ \phi_4^{0}\end{pmatrix}=\begin{pmatrix}c_\gamma & s_\gamma\\ -s_\gamma & c_\gamma\end{pmatrix}\begin{pmatrix}H_1^{0}\\ H_2^{0}\end{pmatrix},$$

Neutral

$H^{\pm\pm\pm}$ Triply charged

$$\tan(2\{\alpha,\beta,\gamma\})=\frac{2\Delta M^2_{\{+,++,0\}}}{\mu_\Delta^2-\mu_{H_4}^2}$$

H-H_4 and H-Δ mixing is negligibly small due to small VEVs of H_4 and Δ

Masses:

$$m^2_{\{H_1^+,H_1^{++},H_1^0\}}=\frac{1}{2}(\mu_{H_4}^2+\mu_\Delta^2)-\frac{1}{2}\sqrt{(\mu_{H_4}^2-\mu_\Delta^2)^2+4\Delta M^4_{\{+,++,0\}}},$$

$$m^2_{\{H_2^+,H_2^{++},H_2^0\}}=\frac{1}{2}(\mu_{H_4}^2+\mu_\Delta^2)+\frac{1}{2}\sqrt{(\mu_{H_4}^2-\mu_\Delta^2)^2+4\Delta M^4_{\{+,++,0\}}},$$

$$\Delta M^2_{\{+,++,0\}}=\left\{\frac{\sqrt{3}\mu_1 v_h}{3},\frac{\sqrt{6}\mu_1 v_h}{3},\mu_1 v_h\right\}$$

$$m_{H^{+++}}=\mu_{H_4}$$

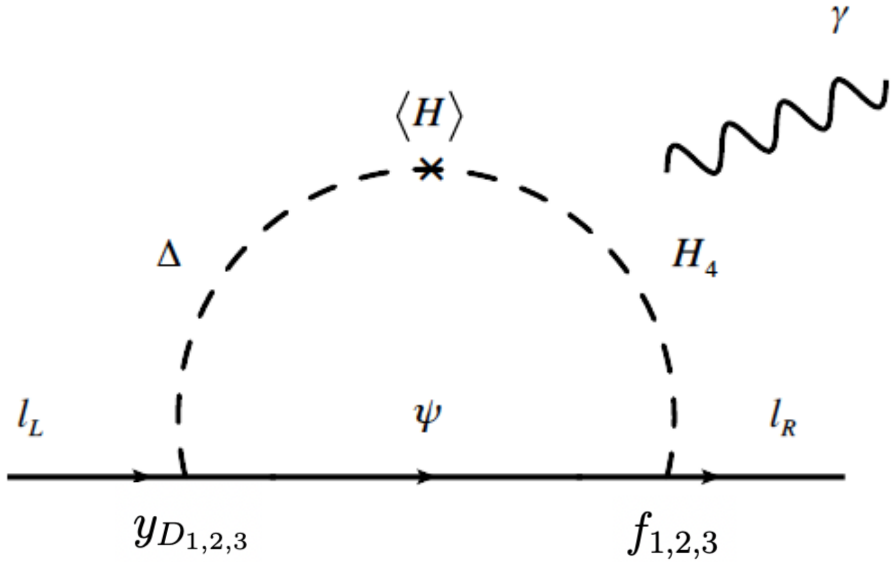
3. Phenomenology of the model

Muon g-2 and LFV processes

Relevant Lagrangian

$$
\begin{aligned}
&f_i[\overline{\psi_L} H_4 e_{R_i}] + y_{D_i}[\overline{L_{L_i}}\Delta^\dagger \psi_R] + h.c. \\
&= f_i[\overline{\psi^0_L}\phi_4^+ + \overline{\psi_L^{++}}\phi_4^{+++} + \overline{\psi_L^+}\phi_4^{++} + \overline{\psi_L^-}\phi_4^0]e_{R_i} \\
&+ \frac{y_{D_i}}{3}[\overline{e_{L_i}}(\sqrt{3}\delta^{0*}\psi_R^- + 3\delta^{--}\psi_R^+ + \sqrt{6}\delta^-\psi_R^0) + \overline{\nu_{L_i}}(\sqrt{3}\delta^{0*}\psi_R^0 + 3\delta^{--}\psi_R^{++} + \sqrt{6}\delta^-\psi_R^+)].
\end{aligned}
$$

One-loop diagram inducing muon g-2 and LFVs $l \to l'\gamma$



Dominant contribution

Muon g-2 and LFV processes

Analytic formula

Muong g-2 : $$\Delta a_\mu \approx -\frac{m_\mu}{(4\pi)^2}[a_{L_{22}} + a_{R_{22}}]$$

LFV decay : $$\mathrm{BR}(\ell_i \to \ell_j \gamma) = \frac{48\pi^3 \alpha_{\rm em} C_{ij}}{(4\pi)^4 \mathrm{G_F^2} m_{\ell_i}^2}\left(|a_{R_{ij}}|^2 + |a_{L_{ij}}|^2\right)$$

Amplitudes:

$$a_{R_{ji}} = -y_{D_j} f_i (-1)^{k-1}\left[\frac{\sqrt{6} s_\alpha c_\alpha}{3} D_a F(m_{c_k}, D_a) + M_\psi \left(s_\beta c_\beta \left(F(m_{d_k}, M_\psi) - G(m_{d_k}, M_\psi)\right) + \frac{s_\gamma c_\gamma}{\sqrt{3}} G(m_{h_k}, M_\psi)\right)\right],$$

$$a_{L_{ji}} = -f_j^\dagger y_{D_i}^\dagger (-1)^{k-1}\left[\frac{\sqrt{6} s_\alpha c_\alpha}{3} D_a F(m_{c_k}, D_a) + M_\psi \left(s_\beta c_\beta \left(F(m_{d_k}, M_\psi) - G(m_{d_k}, M_\psi)\right) + \frac{s_\gamma c_\gamma}{\sqrt{3}} G(m_{h_k}, M_\psi)\right)\right],$$

$$F(m_a, m_b) \approx \frac{m_a^4 - m_b^4 + 2m_a^2 m_b^2 \ln\left(\frac{m_b^2}{m_a^2}\right)}{2(m_a^2 - m_b^2)^3},$$

$$G(m_a, m_b) \approx -\frac{3m_a^4 + m_b^4 - 4m_a^2 m_b^2 + 2m_a^4 \ln\left(\frac{m_b^2}{m_a^2}\right)}{2(m_a^2 - m_b^2)^3}$$

Neutrino mass generation

We have type-II seesaw and inverse seesaw contributions

$$M_N = \begin{bmatrix} m_\nu^{(II)} & m_D & 0 \\ m_D^T & m_R & M_\psi \\ 0 & M_\psi & m_L \end{bmatrix}$$

Basis is $(\nu_L^c, \psi_R, \psi_L^c)^T$

$$-\mathcal{L}_\ell = y_{\ell_{ii}} \bar{L}_{L_i} H e_{R_i} + y_{\nu_{ij}} \bar{L}_{L_i} \Delta^\dagger L_{L_j}^c + y_{D_i} [\bar{L}_{L_i} \Delta^\dagger \psi_R] + f_i [\bar{\psi}_L H_4 e_{R_i}] + g_L [\bar{\psi}_L^c \Delta^\dagger \psi_L] + g_R [\bar{\psi}_R^c \Delta^\dagger \psi_R] + M_\psi \bar{\psi}_L \psi_R + \text{h.c.},$$

$$m_\nu^{(II)} \equiv y_\nu v_\Delta,\ m_D \equiv y_D v_\Delta/\sqrt{3},\ m_R \equiv 2 g_R v_\Delta/3, \text{ and } m_L \equiv 2 g_L v_\Delta/3$$

⇩

$$m_\nu \approx m_\nu^{(II)} + \frac{m_D m_D^T m_L}{M_\psi^2}$$

Numerical analysis

Scanning free parameters

$$M_\psi \supset [10^3, 10^5]\ \text{GeV}, \quad m \supset [0.01, 10]\ \text{GeV}, \quad \mu_{H_4} = 1.2 M_\psi, \quad \mu_\Delta = 0.8 M_\psi,$$

$$\mu_1 \supset [100, \mu_{H_4}]\ \text{GeV}, \quad \{|f_2|, |y_{D_2}|\} \supset [0.1, 2.0], \quad \{|f_{1,3}|, |y_{D_{1,3}}|\} \supset [10^{-5}, 0.1],$$

Searching solution to explain muon g-2

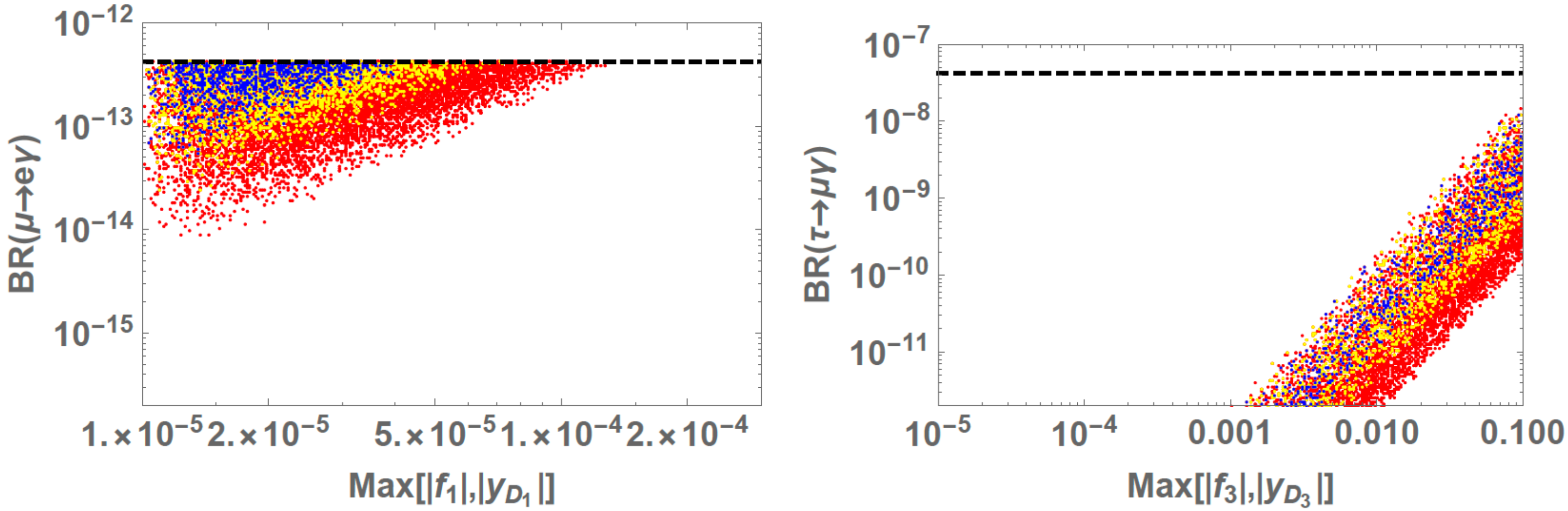
Constraints:

$$\text{BR}(\mu \to e\gamma) \le 4.2 \times 10^{-13}, \quad \text{BR}(\tau \to \mu\gamma) \le 4.4 \times 10^{-8}, \quad \text{BR}(\tau \to e\gamma) \le 3.3 \times 10^{-8}$$

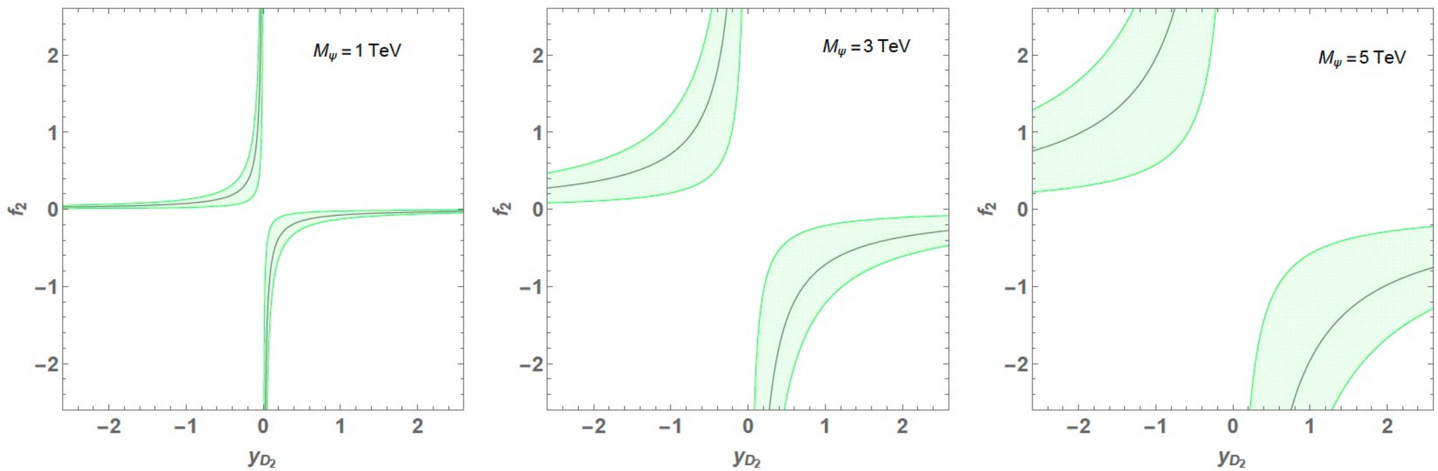
A. M. Baldini *et al.* [MEG], Eur. Phys. J. C **76** (2016) no.8, 434 doi:10.1140/epjc/s10052-016-4271-x [arXiv:1605.05081 [hep-ex]].

3. Phenomenology

Muon g-2, μ→eγ, τ→μγ, and parameters



Blue: 1σ, Yellow: 2σ, Red: 3σ for $\Delta a_\mu = a_\mu^{\exp} - a_\mu^{SM} = (25.1 \pm 5.9) \times 10^{-10}$



Region giving 3σ of muon g-2 fixing some parameters

$$\mu_1 = \mu_{H_4} = 1.2 M_\psi,\ \mu_\Delta = 0.8 M_\psi,\ m = 10\ \text{GeV and } y_{D_{1,3}} = f_{1,3} = 0$$

Multi-charged particle signature at the LHC

$$pp \to Z/\gamma \to \psi^{++}\psi^{--}, H^{+++}H^{---}$$

Width of dominant decay channel (assuming mass relation)

$$\Gamma(H^{+++} \to \ell^+ \psi^{+++}) = \frac{f_\ell^2}{16\pi} m_{H^{+++}} \left(1 - \frac{M_\psi^2}{m_{H^{+++}}^2}\right)^2$$

$$\Gamma(\psi^{++} \to \nu_\ell \delta^{++}) = \frac{y_\ell^2}{8\pi} M_\psi.$$

Decay chain at the experiments

$$\psi^{++}\overline{\psi^{++}} \to \nu\bar{\nu}\delta^{++}\delta^{--} \to \nu\bar{\nu}W^+W^+W^-W^-,$$

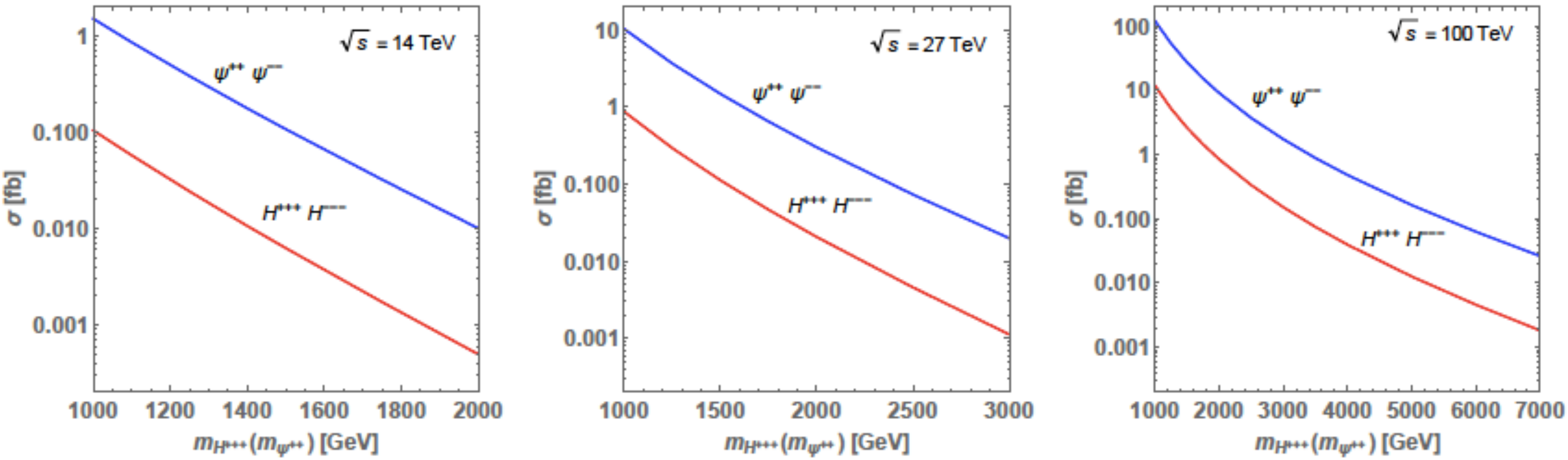
$$H^{+++}H^{---} \to \ell^+\ell^-\psi^{++}\overline{\psi^{++}} \to \ell^+\ell^-\nu\bar{\nu}\delta^{++}\delta^{--} \to \ell^+\ell^-\nu\bar{\nu}W^+W^+W^-W^-,$$

Signal events

Signal 1: $\ell^\pm\ell^\pm 4j \not{E}_T,$

Signal 2: $\ell^\pm\ell^\pm\ell^\pm\ell^\mp 4j \not{E}_T$

Signal cross sections



Backgrounds

$$pp \to \{ZZZ,\ ZW^+W^-,\ ZZW^\pm,\ ZZZZ,\ W^+W^-W^+W^-,\ ZZW^+W^-,\ ZZZW^\pm\}$$

$$\sigma(pp \to ZZZ) = 10.3\text{ fb},\ \sigma(pp \to ZW^+W^-) = 9.44\text{ fb},\ \sigma(pp \to ZZW^+) = 19.9\text{ fb}$$

$$\sigma(pp \to ZZW^-) = 10.4\text{ fb},\ \sigma(pp \to ZZZZ) = 1.95 \times 10^{-2}\text{ fb},$$

$$\sigma(pp \to W^+W^-W^+W^-) = 0.571\text{ fb},\ \sigma(pp \to ZZW^+W^-) = 0.436\text{ fb},$$

$$\sigma(pp \to ZZZW^+) = 4.21 \times 10^{-2}\text{ fb},\ \sigma(pp \to ZZZW^-) = 1.87 \times 10^{-2}\text{ fb},\quad \sqrt{s} = 14\,\text{TeV}$$

We generate events by MADGRAPH5 with Pythia8 and Delphes

3. Phenomenology

Numerical simulation choosing signal : $\ell^{\pm}\ell^{\pm}$ + at least 3 jets

Number of events before and after kinematical cuts for event selection of $\ell^{-}\ell^{-}$+jets

	N_{signal}	N_{ZZZ}	$N_{ZW^+W^-}$	$N_{ZZW^{\pm}}$	N_{4Z}	$N_{2W^+W^-}$	$N_{ZZW^+W^-}$	$N_{ZZZW^{\pm}}$	S
Without cuts	33.4	7.83	13.6	53.5	0.0819	10.3	3.02	0.313	3.36
With cuts	26.0	0.824	3.02	4.58	0.0164	2.27	0.820	0.0572	6.04

M_{ψ} = 1000 GeV
M_{δ} = 500 GeV

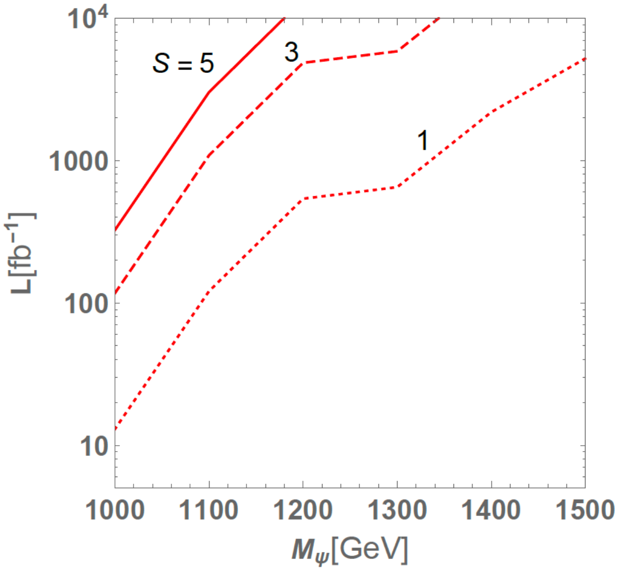
$\sqrt{s} = 14\,\text{TeV}$

$L = 1\ \text{ab}^{-1}$

Kinematical cuts : $p_T(\ell_1^{\pm}) > 100$ GeV, $\not{E}_T > 100$ GeV

Required luminosity to test the signal :

$$S = \sqrt{2\left[(N_S + N_{BG})\ln\left(1 + \frac{N_S}{N_{BG}}\right) - N_S\right]}$$



Further kinematical cuts would improve significance

Summary

Extension of the SM with extra $SU(2)_L$ multiplets

- ✓ Neutrino mass generation (mainly type-II seesaw)
- ✓ Muon g-2 without chiral suppression
- ✓ Multiply charged particles
- ✓ Small mixing between new scalar and SM Higgs
  - → Due to small VEVs of large multiplet scalars

□ Phenomenology

- ✓ Muon g-2 and LFV
- ✓ Collider physics

  possible signatures at the (HL-)LHC

  We can have signatures at future collider experiments

Appendix

VEVs of scalar fields

$$\frac{\partial V}{\partial v_h} = \frac{\partial V}{\partial v_\Delta} = \frac{\partial V}{\partial v_4} = 0.$$

⇩

$$v_h \simeq \sqrt{\frac{\mu_H^2}{\lambda_H}}, \quad v_\Delta \simeq \frac{1}{\mu_\Delta^2}\left(\frac{1}{3}\sqrt{\frac{3}{2}}\mu_1 v_4 v_h + \mu_2 v_h^2\right), \quad v_4 \simeq \frac{1}{3}\sqrt{\frac{3}{2}}\frac{\mu_1 v_\Delta v_h}{\mu_{H_4}^2}.$$

Small VEVs for triplet and quartet can be naturally achieved

Signal and BG distributions