

# New Physics Solutions to Lepton Anomalous Magnetic Moments

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Phys.Rev. D101 (2020) no.11, 115037 (S. Jana, P.K. Vishnu, Saad)

Phys.Rev. D102 (2020) no.7, 075007 (I. Doršner, S. Fajfer, Saad)

Phys.Rev. D102 (2020) no.7, 075003 (S. Jana, P.K. Vishnu, W. Rodejohann, Saad)

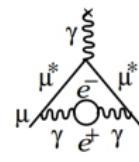
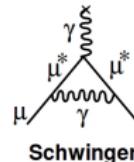
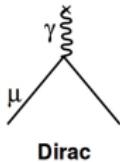
# Outline

- Anomalies in the lepton anomalous magnetic moments
- New physics solutions:
  - ✓ Light Scalar :  $M_{NP} < \mu_{EW}$
  - ✓ Scalar Leptoquark :  $M_{NP} > \mu_{EW}$
  - ✓ Vectorlike Fermion :  $M_{NP} > \mu_{EW}$

# Anomalies in Lepton AMMs

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

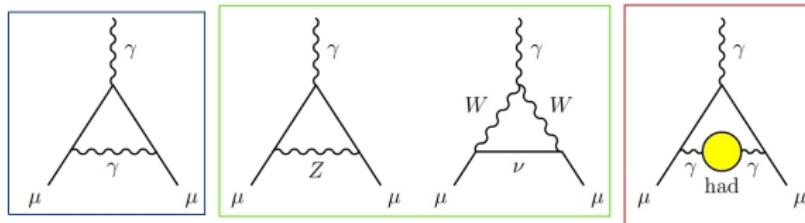
- Quantum loop corrections:  $g_\mu \neq 2$



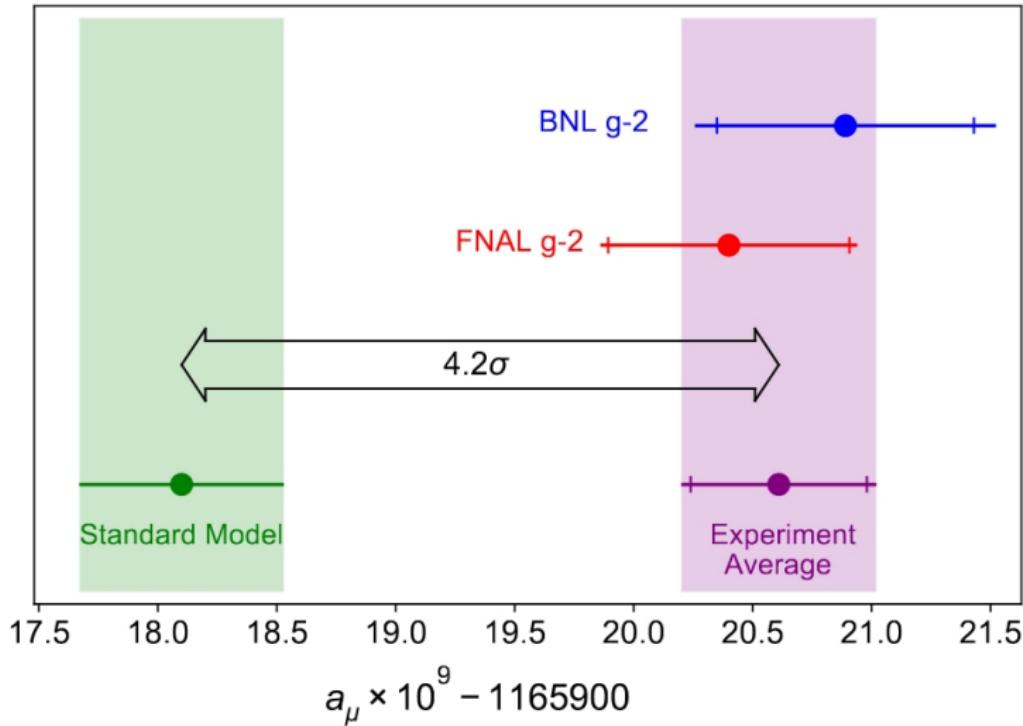
Bethe (1947) [non-relativistic framework], Schwinger (1948)

- Anomalous magnetic moment:  $a_\mu = \frac{g_\mu - 2}{2}$

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

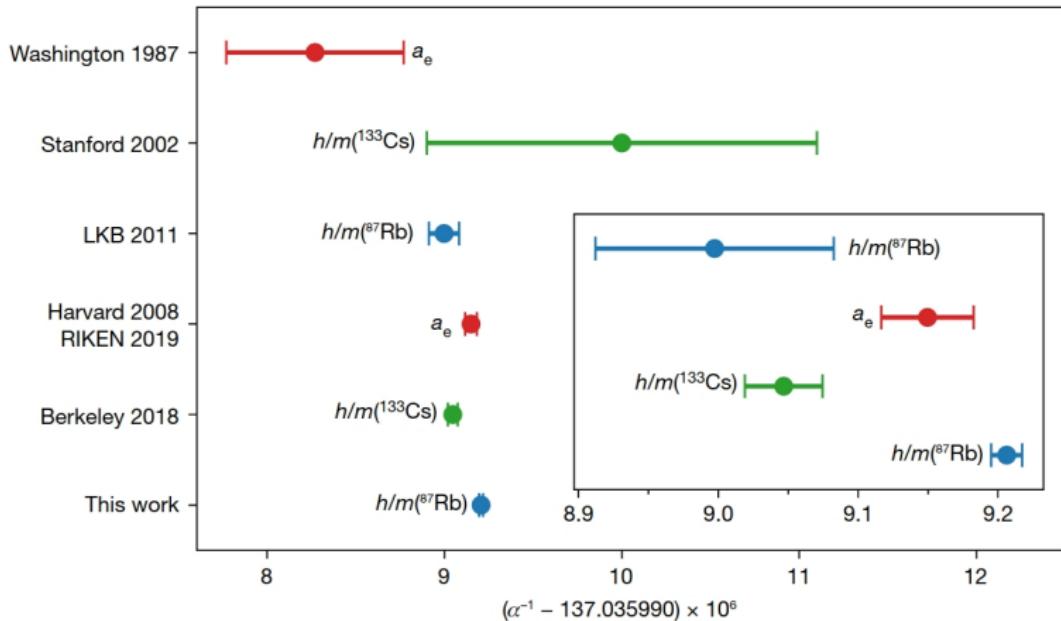


# Anomaly in $a_\mu$



Phys. Rev. Lett. 126, 141801

# Anomaly in $a_e$



$\sim 5.4\sigma$  discrepancy between recent two measurements

Nature 588 (2020) no.7836, 61-65

# Anomalies in $(g - 2)_{\mu,e}$ : Summary

- BNL (2006)+ FNAL (2021):

$$a_{\mu}^{exp} - a_{\mu}^{SM} \equiv \Delta a_{\mu} = +(251 \pm 59) \times 10^{-11} \quad \sim +4.2\sigma$$

- Berkeley (2018):

$$a_e^{exp} - a_e^{SM} \equiv \Delta a_e = -(87 \pm 36) \times 10^{-14} \quad \sim -2.5\sigma$$

- ◇ Purpose of this talk: simultaneous explanation of  $(g - 2)_{\mu,e}$  puzzles

# Model Building

- Model building challenges:
  - ◊ simultaneously providing large corrections to  $\Delta a_{\mu,e}$
  - light new physics
  - heavy new physics: chiral enhancement
  - ◊ incorporating opposite signs for  $\Delta a_\mu$  and  $\Delta a_e$
  - ◊ suppressing flavor violating processes ( $\mu \rightarrow e\gamma, \dots$ )

# Light Scalar solution

# Light Scalar solution

- 2HDM: second Higgs doublet added to SM

- ✓  $M_{NP} \ll \mu_{EW}$
- ✓ single particle solution
- ✓ most minimal possibility
- ✓ predictive and testable

# Physical Higgs

- Scalar potential:

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

- States:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v + H_1^0 + iG^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{H_2^0 + iA^0}{\sqrt{2}} \end{pmatrix}.$$

- Alignment limit:  $H_1^0 \approx h$  and  $H_2^0 \approx H$

# Mass spectrum

- our proposal:

$$m_H^2 \ll m_{H^+}^2, m_A^2$$

- ⇒ LEP constraint:

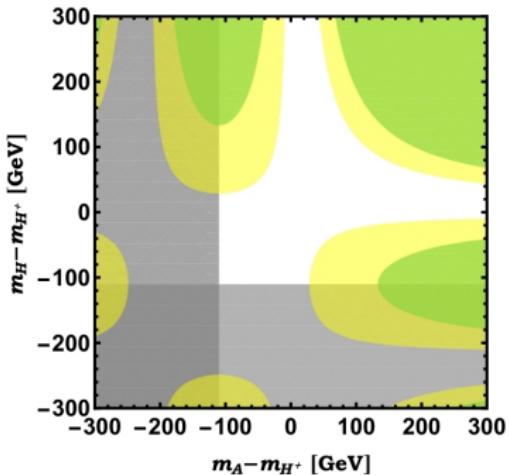
$$m_{H^+} \geq 110 \text{ GeV}$$

- ⇒ EW precision data:

$$m_{H^\pm} \approx m_{A^0}$$

- ⇒ Perturbatively:

$$m_H \sim 0 \ll m_{H^+} = m_A \lesssim 350 \text{ GeV}$$



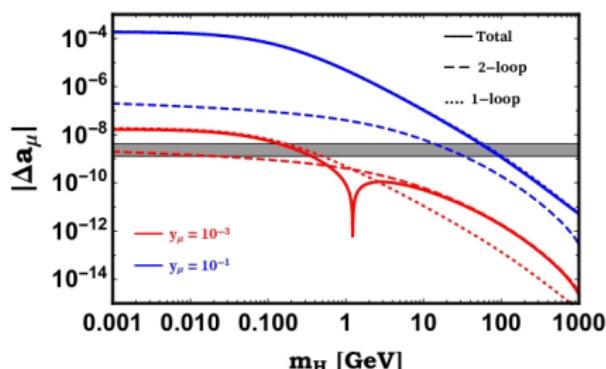
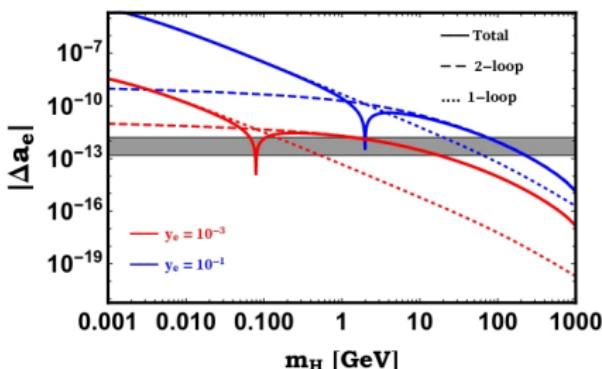
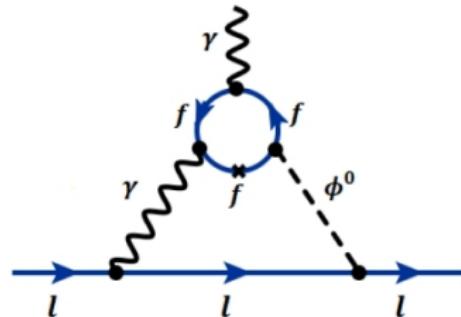
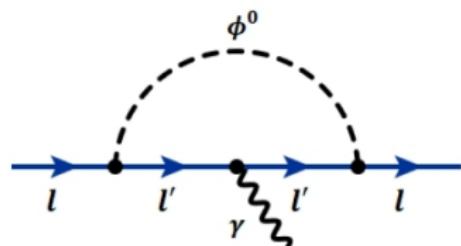
# Yukawa sector

- Yukawa sector:

$$-\mathcal{L}_Y \supset \left[ Y_{\ell,ij}^{H^0} H^0 + i Y_{\ell,ij}^{A^0} A^0 \right] \bar{\ell}_{Li} \ell_{Rj} + Y_{\ell,ij}^{H^+} \bar{\nu}_{Li} \ell_{Rj} H^+ \sqrt{2} + h.c.,$$

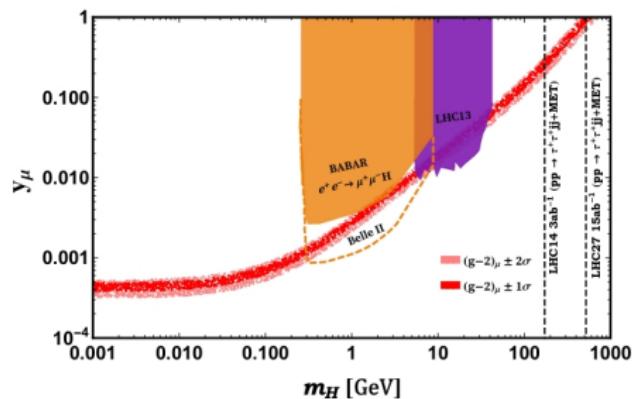
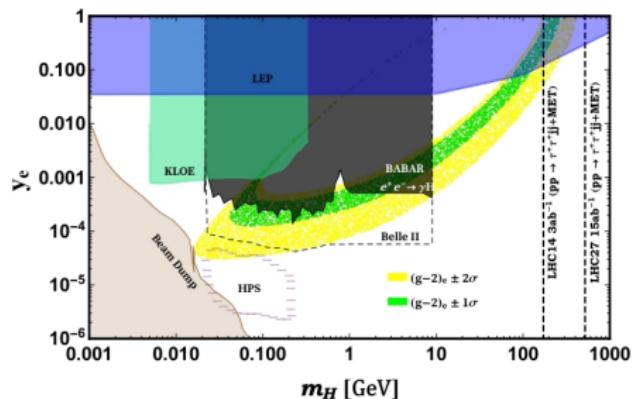
- $Y_\ell^{H^0} = Y_\ell^{A^0} = Y_\ell^{H^+} = Y_\ell$
- $Y_\ell = \text{diag}(y_e, y_\mu, y_\tau)$  (free parameters)
- $\overline{Y}_{u,ij}, \overline{Y}_{d,ij} \ll 1$

# Corrections to $(g - 2)_{\mu,e}$



$$|\gamma_\tau = 0.1|, \quad \phi^0 = H$$

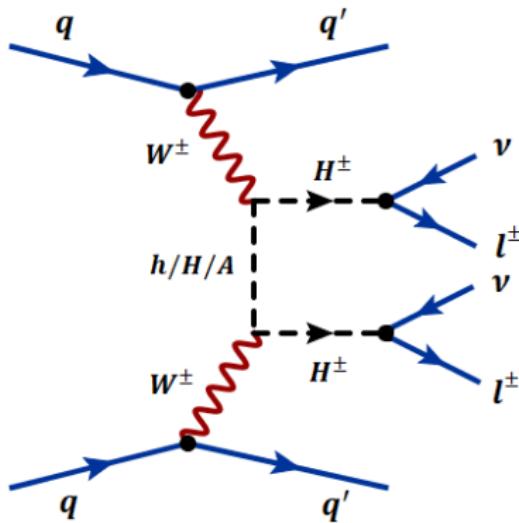
# Light Scalar solution



- $m_H \sim 40\text{-MeV to } 2\text{-GeV}$

$$|y_\tau = 0.1|$$

# Testable at LHC (Future)



- novel process:  $pp \rightarrow H^\pm H^\pm jj \rightarrow \tau^\pm \tau^\pm jj + \cancel{E}_T$
- amplitude  $\propto (m_H^2 - m_A^2)/v^2$

M. Aiko, S. Kanemura, K. Mawatari 2019

# Scalar Leptoquark solution

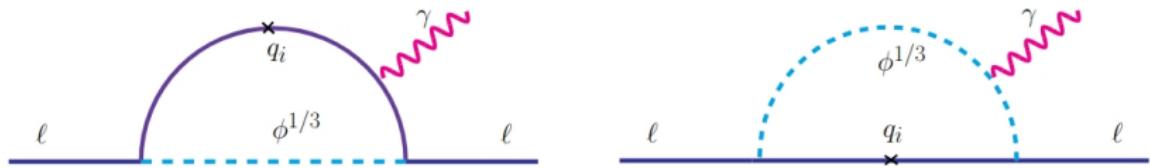
# Leptoquark solution

- LHC bound:  $M_{NP} \gtrsim \text{TeV}$  : chiral enhancement
- Single Leptoquark solution:
  - ◊  $S_1(\bar{3}, 1, 1/3)$
  - ◊  $R_2(3, 2, 7/6)$
- Mixed Leptoquark scenario:
  - ◊  $S_1(\bar{3}, 1, 1/3)$  &  $S_3(\bar{3}, 3, 1/3)$
  - ◊  $R_2(3, 2, 7/6)$  &  $\tilde{R}_2(3, 2, 1/6)$
- $\mu \rightarrow e\gamma$  constraint plays important role in this selection

# $S_1$ Leptoquark

- Yukawa interaction:

$$\mathcal{L} \supset y_{ij}^L \overline{Q^c}_i i\sigma_2 S_1 L_j + y_{ij}^R \overline{u_R^c}_i S_1 \ell_{Rj} + \text{h.c.},$$



- $(g - 2)_\mu$  requires large correction: **top-quark**
  - $(g - 2)_e$ :  $\mu \rightarrow e\gamma$  restricts
- X** top-quark
- ✓** charm-quark
- same conclusion for  $R_2$  LQ

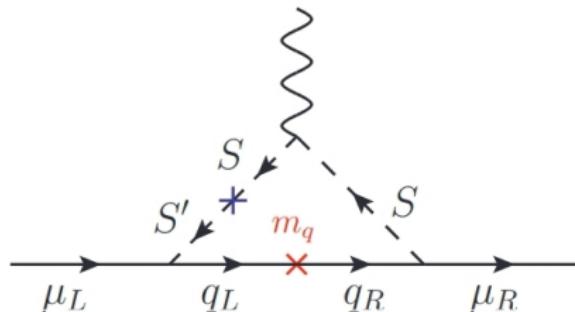
# Mixed $S_1 \& S_3$ Leptoquark

- Interaction:

$$\mathcal{L} \supset y_{ij}^R \overline{u_R^c} S_1 \ell_{Rj} + y_{ij}^S \overline{Q^c} L_i i\sigma_2 (\sigma_a S_3^a) L_{Lj} + \lambda H^\dagger (\sigma_a S_3^a) H S_1^* + \text{h.c.}$$

- Mixing: EW symmetry breaking

$$\begin{pmatrix} S_- \\ S_+ \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} S_3^{1/3} \\ S_1 \end{pmatrix}, \quad (1)$$



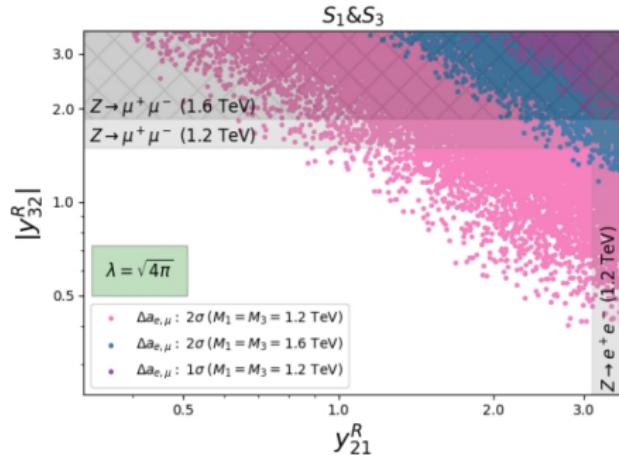
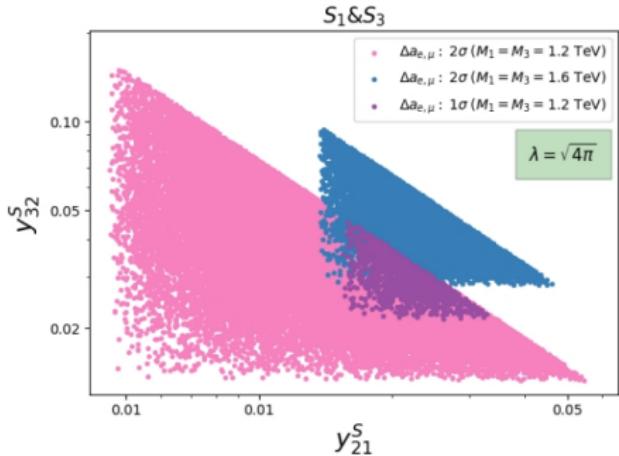
# Leptoquark solutions

- $\mu \rightarrow e\gamma$  selection

SCENARIO	$(g - 2)_e$	$(g - 2)_\mu$	$(Br(\mu \rightarrow e\gamma))^{\min}$
$S_1 : (q, Q)$	$(t, 1/3)$	$(t, 1/3)$	$\frac{\tau_\mu \alpha m_\mu^3}{8} \frac{ \Delta a_e \Delta a_\mu }{m_e m_\mu}$
$S_1 : (q, Q)$	$(c, 1/3)$	$(t, 1/3)$	0
$R_2 : (q, Q)$	$(t, 5/3)$	$(t, 5/3)$	$\frac{\tau_\mu \alpha m_\mu^3}{8} \frac{ \Delta a_e \Delta a_\mu }{m_e m_\mu}$
$R_2 : (q, Q)$	$(c, 5/3)$	$(t, 5/3)$	0
$S_1 \& S_3 : (q, Q)$	$(t, 1/3)$	$(t, 1/3)$	$\frac{\tau_\mu \alpha m_\mu^3}{8} \frac{ \Delta a_e \Delta a_\mu }{m_e m_\mu}$
$S_1 \& S_3 : (q, Q)$	$(c, 1/3)$	$(t, 1/3)$	0
$R_2 \& \tilde{R}_2 : (q, Q)$	$(b, 2/3)$	$(t, 5/3)$	$\frac{\tau_\mu \alpha m_\mu^3 \pi^2}{m_e^2 m_\mu^2 m_t^2} \frac{ V_{tb} ^2}{ V_{cb} ^2} \frac{ \Delta a_e \Delta a_\mu ^2}{(1+4 \ln x_t)^2} M^4$

- $[Br(\mu \rightarrow e\gamma)]^{\min} = 0$  permitted by choice of Yukawa textures

# Additional constraint



- $K_L^0 \rightarrow e^\pm \mu^\mp$  and  $Z \rightarrow \ell^+ \ell^-$

**X**  $S_1 \& S_3$

# Leptoquark solutions

SCENARIO	$(g - 2)_e$	$(g - 2)_\mu$	$(Br(\mu \rightarrow e\gamma))^{\min}$
✗ $S_1 : (q, Q)$	$(t, 1/3)$	$(t, 1/3)$	$\frac{\tau_\mu \alpha m_\mu^3}{8} \frac{ \Delta a_e \Delta a_\mu }{m_e m_\mu}$
✓ $S_1 : (q, Q)$	$(c, 1/3)$	$(t, 1/3)$	0
✗ $R_2 : (q, Q)$	$(t, 5/3)$	$(t, 5/3)$	$\frac{\tau_\mu \alpha m_\mu^3}{8} \frac{ \Delta a_e \Delta a_\mu }{m_e m_\mu}$
✓ $R_2 : (q, Q)$	$(c, 5/3)$	$(t, 5/3)$	0
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✗ $S_1 \& S_3 : (q, Q)$	$(c, 1/3)$	$(t, 1/3)$	0
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I. Doršner, S. Fajfer, Saad 2020

- LHC and Flavor constraints are satisfied for  $1.5 \lesssim M_{LQ} \lesssim 60$  TeV I. Bigaran, R. R. Volkas 2020
- Rich phenomenology: vast literature

# Vectorlike Fermion solution

# Vectorlike Fermion solution

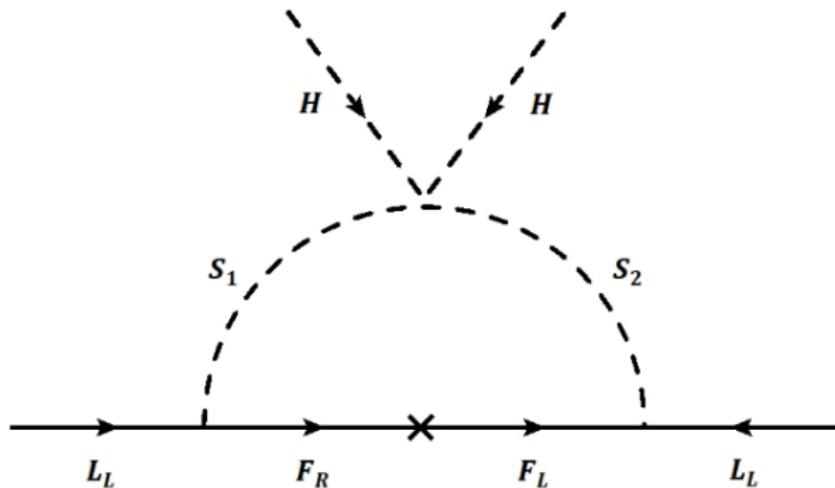
- ◊ chiral enhancement from Vectorlike fermions (VLF)
- approximate bounds  $M_{NP} \gtrsim \text{TeV}$

- Unified framework:

- ✓ Neutrino mass
- ✓ Dark Matter
- ✓ Testable in colliders

# Model Framework

- VLF:  $Y \neq 0$  ( $\Rightarrow S_1 \neq S_2$ )
- BSM states:  $\mathcal{Z}_2$  odd
- Neutrino mass  $\sim$  scotogenic



# Ma's Scotogenic Model

- $N_R: Y = 0 \quad (\Rightarrow S_1 = S_2)$

- Neutrino mass:

$$\mathcal{M}_\nu \sim \frac{\lambda \langle H \rangle^2}{32\pi^2} \frac{y^2}{M_N} \sim 0.05 \left( \frac{\text{TeV}}{M_N} \right) \left( \frac{y}{2.3 \times 10^{-5}} \right)^2 \text{ eV},$$

- ✗ Large Yukawa requirement:

$$-\Delta a_\mu \sim m_\mu^2 \frac{|y|^2}{32\pi^2 M_S^2} \sim 10^{-21} \left( \frac{M_S}{\text{TeV}} \right)^{-2} \left( \frac{y}{10^{-5}} \right)^2.$$

- ✗ sign of  $\Delta a_\mu$

- ✗ Large flavor violation:

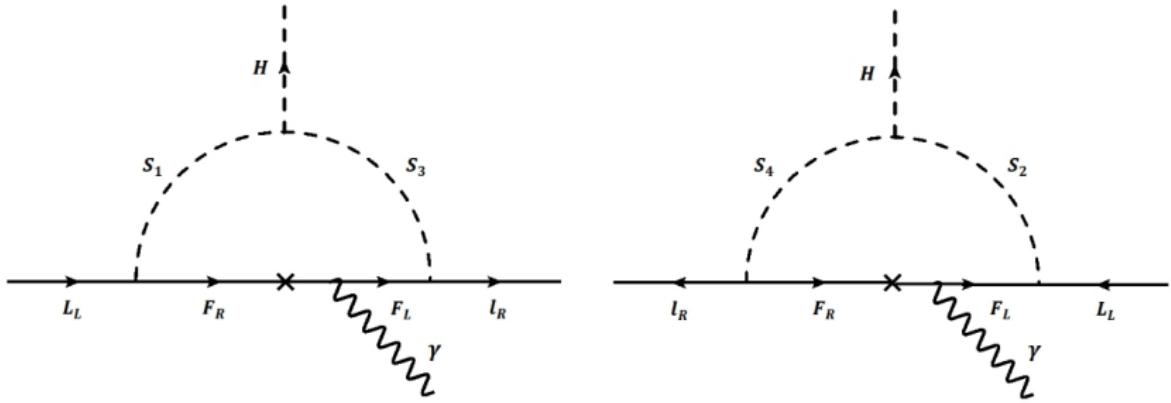
$$\text{BR}(\mu \rightarrow e\gamma) \sim \frac{3\alpha y^4}{32\pi G_F^2 M_S^4} \sim 10^{-26} \left( \frac{M_S}{\text{TeV}} \right)^{-4} \left( \frac{y}{10^{-5}} \right)^4,$$

M. Lindner, M. Platscher, F. S. Queiroz 2016

- straightforwardly generalized to other iso-non-singlets with  $Y = 0$

# Dark Matter assisted $(g - 2)_{\mu,e}$

- Either of the two contributions to  $(g - 2)_\ell$



- DM in the loop

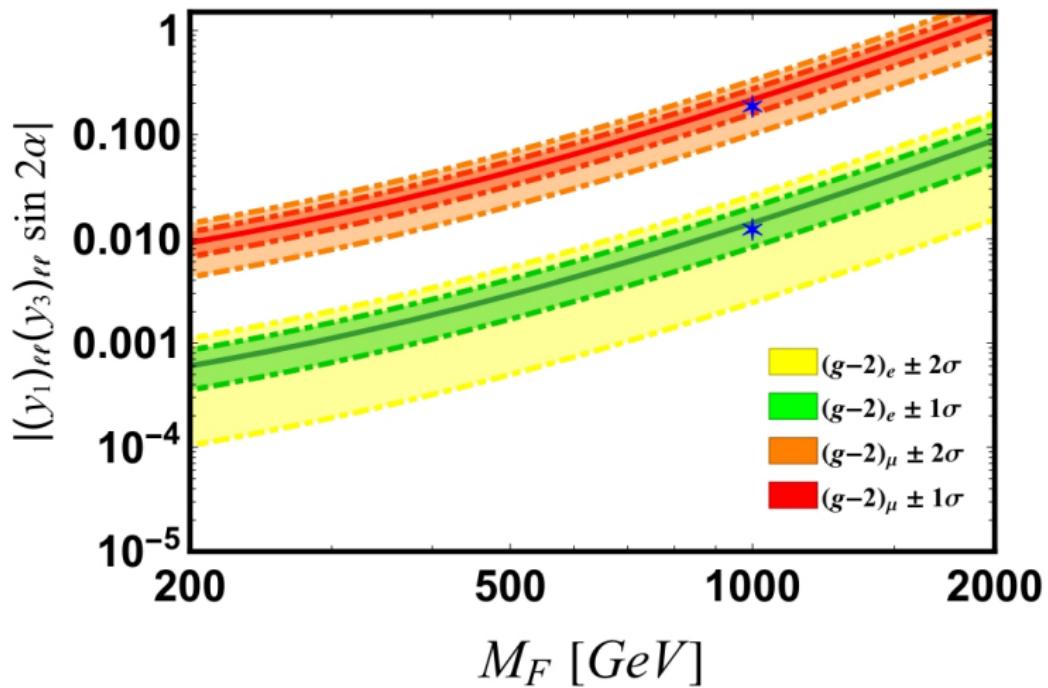
# Class of Models

Multiplets	Model-I	Model-II	Model-III	Model-IV	Model-V	Model-VI	Model-VII
$F_{L,R}$	(1,1,-1)	(1,1,-1)	(1,2,-1/2)	(1,2,-1/2)	(1,2,-3/2)	(1,3,1)	(1,3,1)
$S_1$	(1,2,1/2)	(1,2,1/2)	(1,1,0)	(1,1,0)	(1,1,1)	(1,2,3/2)	(1,2,3/2)
$S_2$	(1,2,3/2)	(1,2,3/2)	(1,3,1)	(1,3,1)	(1,3,-2)	(1,2,1/2)	(1,2,1/2)
$S_3$	(1,1,0)	-	(1,2,1/2)	-	(1,2,1/2)	(1,3,2)	-
$S_4$	-	(1,1,2)	-	(1,2,3/2)	-	-	(1,3,0)

## Model-I:

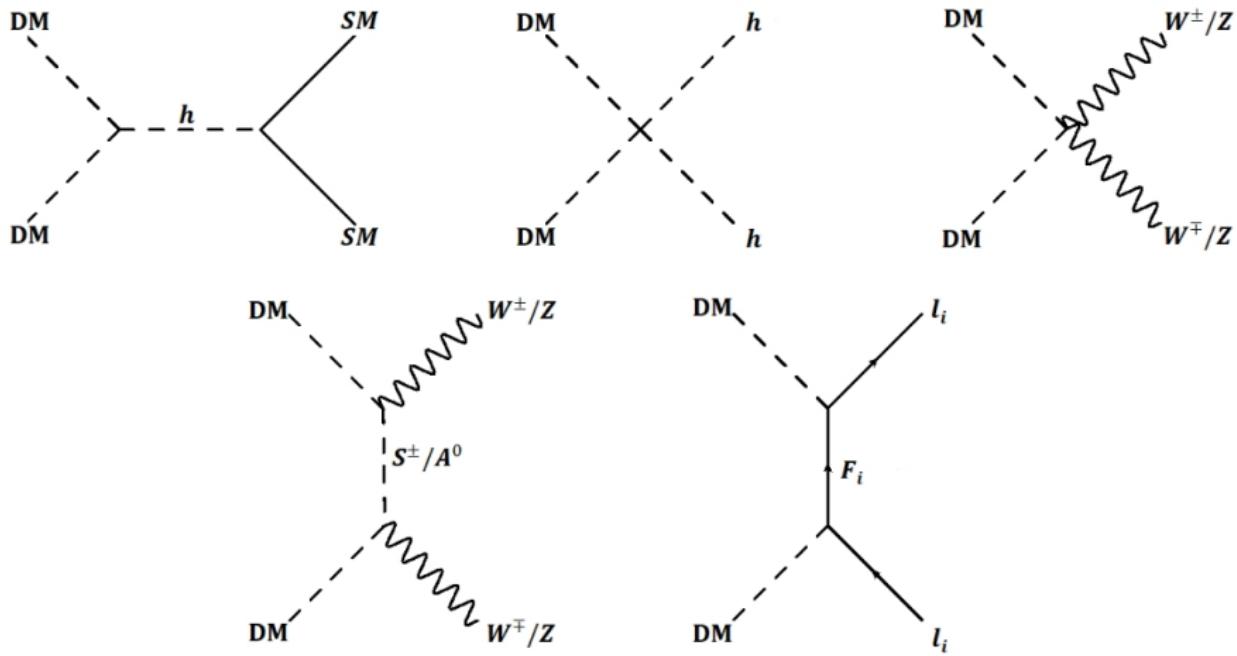
Multiplets	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$\mathcal{Z}_2$
Scalars	$\phi_1(1, 2, \frac{1}{2})$ $\phi_2(1, 2, \frac{3}{2})$ $\eta(1, 1, 0)$	— — —
Vector-like fermion	$F_{L,R}(1, 1, -1)$	—

# Dark Matter assisted $a_{\mu,e}$



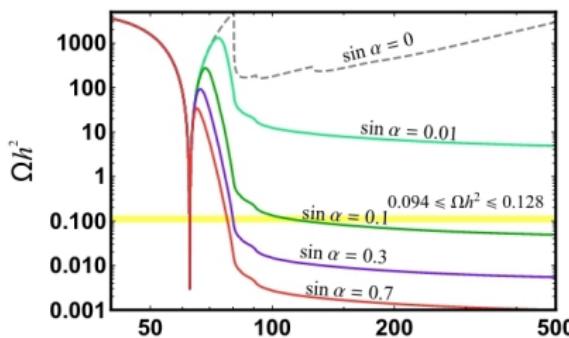
[for simplicity:  $y_{1,3}$  diagonal to avoid LFV]

# Annihilation of Dark Matter



$$\mathcal{L} = \frac{\lambda_{\text{HP}}}{2} (S_1^0)^2 H^\dagger H + \frac{\lambda_{\text{LP}}}{\sqrt{2}} S_1^0 \bar{\ell}_{L,R} F_{R,L} .$$

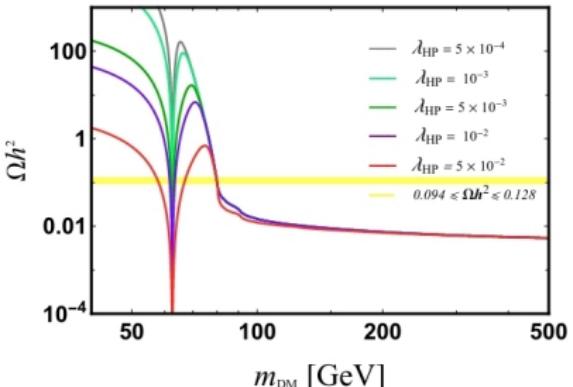
# Relic Density



$$\lambda_{\text{HP}} = 10^{-3}$$

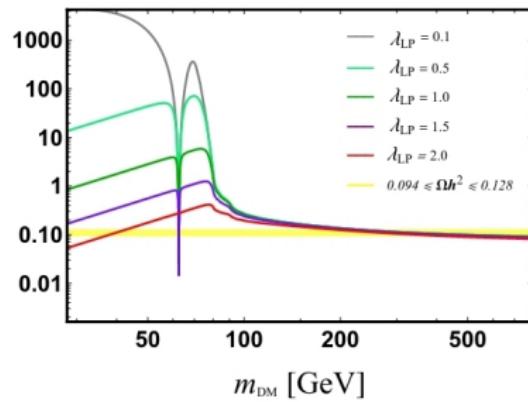
$$m_{\text{DM}} [\text{GeV}]$$

$$\lambda_{\text{LP}} = 0.1$$



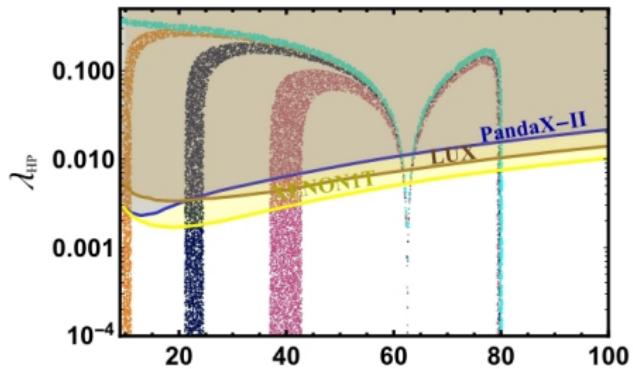
$$\begin{aligned} \sin \alpha &= 0.3 \\ \lambda_{\text{LP}} &= 0.1 \end{aligned}$$

$$\begin{aligned} \sin \alpha &= 0.07 \\ \lambda_{\text{HP}} &= 10^{-3} \end{aligned}$$



1 TeV

# Direct Detection Bounds

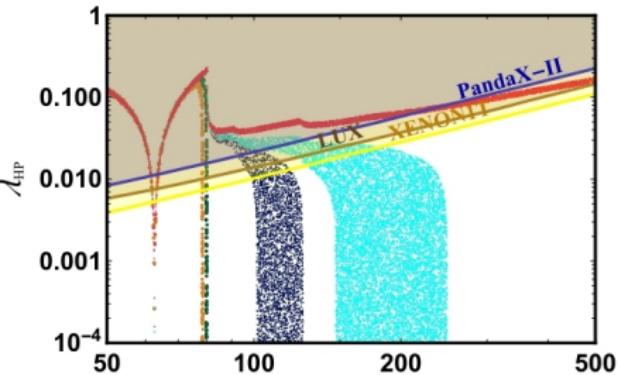


$$\sin \alpha = 0.3$$

$$m_{\text{DM}} [\text{GeV}]$$

$\lambda_{\text{LP}} = 0.5$  (cyan),  $\lambda_{\text{LP}} = 1.0$  (orange),  
 $\lambda_{\text{LP}} = 1.5$  (blue),  $\lambda_{\text{LP}} = 2.0$  (pink).

$$1 \text{ TeV.}$$

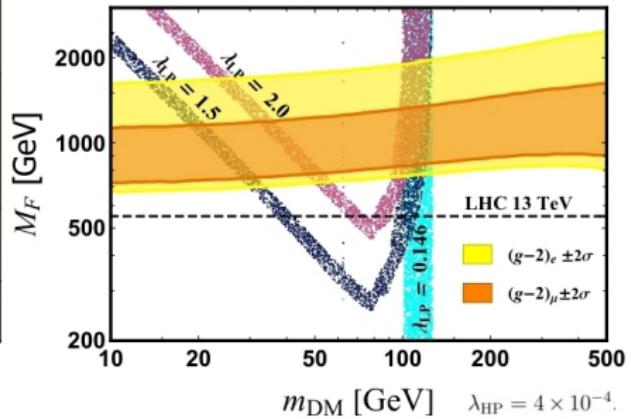
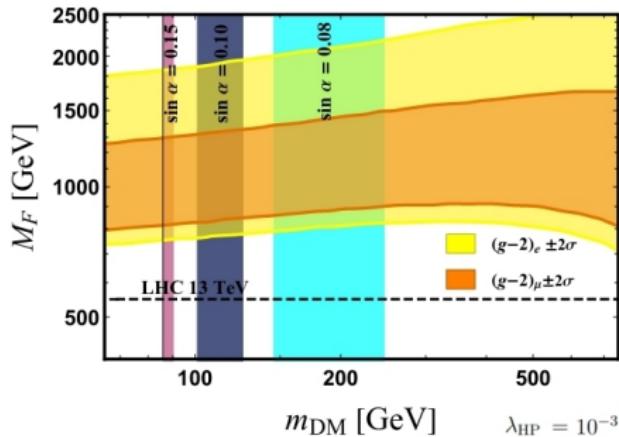


$m_{\text{DM}} [\text{GeV}]$

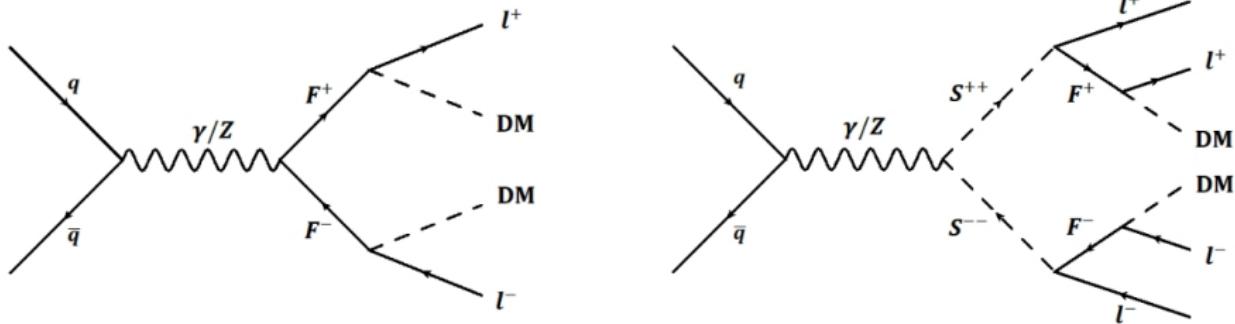
$\lambda_{\text{LP}} = 0.1$ .

$\sin \alpha = 0.01$  (red),  $\sin \alpha = 0.08$  (cyan),  
 $\sin \alpha = 0.1$  (blue),  $\sin \alpha = 0.3$  (green), and  $\sin \alpha = 0.5$  (orange).

# Correlation: $(g - 2)_\ell$ , DM, LHC



# Collider signal of DM at LHC



- unique discovery prospects
- ◊ non-standard DM signals with multi-lepton signature
- ◊ displaced vertex signature, disappearing tracks at the collide  
(current bounds  $M_F \gtrsim 550$  GeV,  $M_{S^{++}} \gtrsim 660$  GeV)

# Summary

# Summary

- Strong evidence of new physics
  - ◊ BNL+FNAL:  $\Delta a_\mu = + (2.51 \pm 0.59) \times 10^{-9}$   $\sim +4.2\sigma$
  - ◊ Berkeley:  $\Delta a_e = - (8.7 \pm 3.6) \times 10^{-13}$   $\sim -2.5\sigma$
- Exciting new physics possibilities:
  - ✓ Light Scalar  $(M_{NP} < \mu_{EW})$
  - ✓ Scalar Leptoquark  $(M_{NP} > \mu_{EW})$
  - ✓ Vectorlike Fermion  $(M_{NP} > \mu_{EW})$
  - each having its own unique experimental prospects

THANK YOU!