New Physics Solutions to Lepton Anomalous Magnetic Moments

Shaikh Saad

University of Basel

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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:

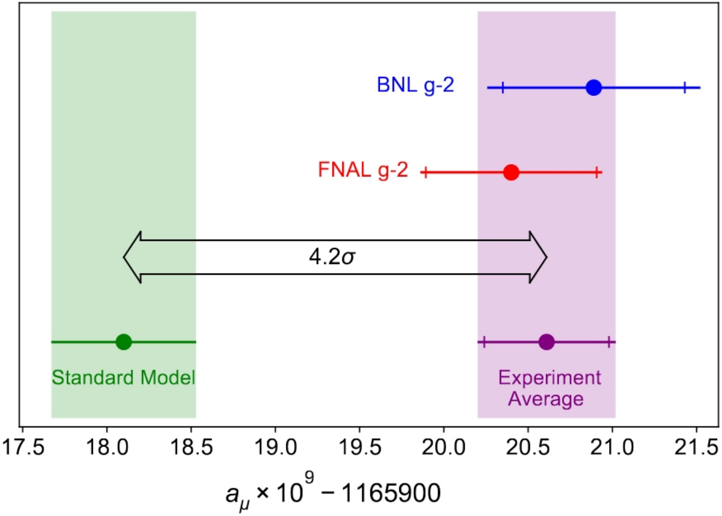
✓ Light Scalar : $M_{NP} < \mu_{EW}$ Solution-A

✓ Scalar Leptoquark : $M_{NP} > \mu_{EW}$ Solution-B

✓ Vectorlike Fermion : $M_{NP} > \mu_{EW}$ Solution-C

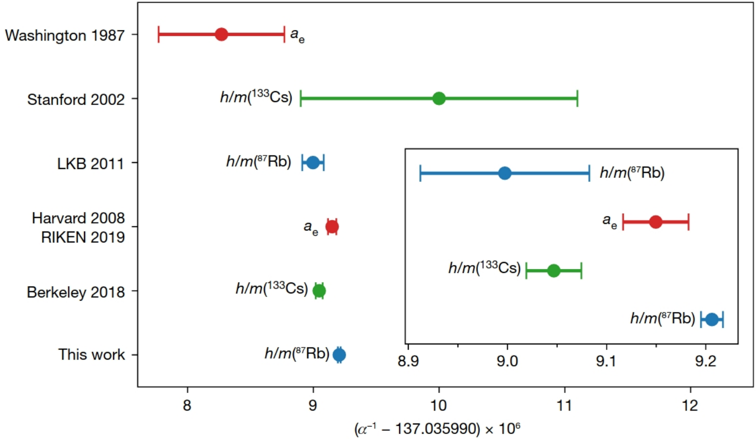
Anomalies in Lepton AMMs

Anomaly in a_μ



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

- Berkeley (2018):
  $a_e^{exp} - a_e^{SM} \equiv \Delta a_e = -(87 \pm 36) \times 10^{-14}$ $\sim -2.5\sigma$

◇ 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 Δa_μ and Δa_e

◇ suppressing flavor violating processes ($\mu \to e\gamma, ..$)

Light Scalar solution

(solution-A)

Light Scalar solution

- 2HDM: second Higgs doublet added to SM

✓ $M_{NP} \ll \mu_{EW}$

✓ single particle solution

✓ most minimal possibility

✓ predictive and testable

S. Jana, P.K. Vishnu, Saad 2020

Physical Higgs

- Scalar potential:

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

- States:

$$
H_1 = \begin{pmatrix} G^+ \\ \frac{v + H_1^0 + i G^0}{\sqrt{2}} \end{pmatrix}, \; H_2 = \begin{pmatrix} H^+ \\ \frac{H_2^0 + i A^0}{\sqrt{2}} \end{pmatrix} .
$$

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

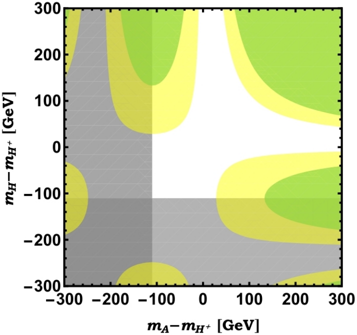
Mass spectrum

- our proposal:
  $m_H^2 \ll m_{H^+}^2, m_A^2$

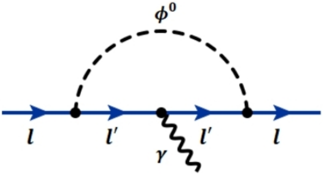
$\Rightarrow$ LEP constraint:
$m_{H^+} \geq 110$ GeV

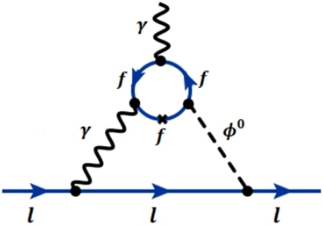
$\Rightarrow$ EW precision data:
$m_{H^\pm} \approx m_{A^0}$

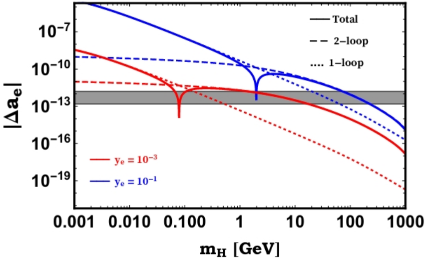
$\Rightarrow$ Perturbatively:
$m_H \sim 0 \ll m_{H^+} = m_A \lesssim 350$ GeV

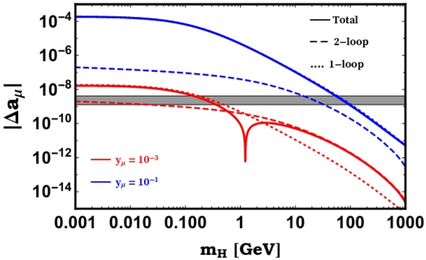


Corrections to $(g-2)_{\mu,e}$



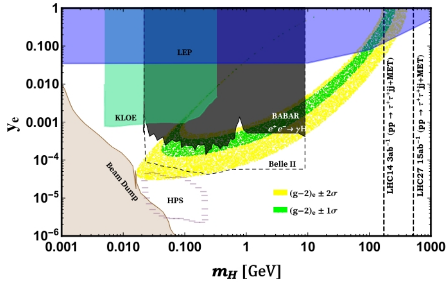


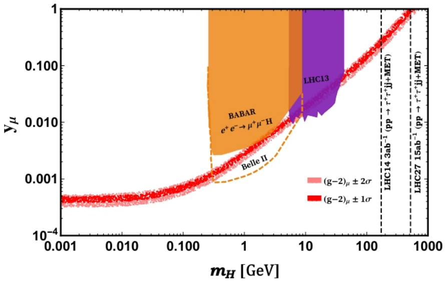




$Y_\ell = diag(y_e, y_\mu, y_\tau)$ (free parameters), $|y_\tau = 0.1|$, $\phi^0 = H$

Light Scalar solution

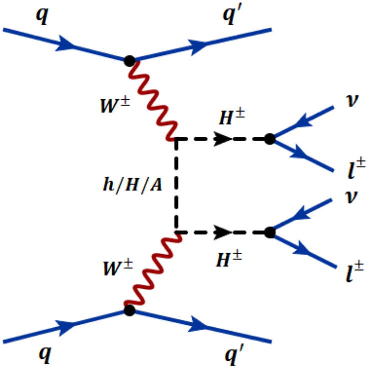




- $m_H \sim$ 40-MeV to 2-GeV

$|y_\tau = 0.1|$

Testable at LHC (Future)



- novel process: $pp \to H^{\pm}H^{\pm}jj \to \tau^{\pm}\tau^{\pm}jj + \not{E}_T$
- amplitude $\propto (m_H^2 - m_A^2)/v^2$ M. Aiko, S. Kanemura, K. Mawatari 2019

Scalar Leptoquark solution

(solution-B)

Leptoquark solution

- LHC bound: $M_{NP} \gtrsim$ TeV : chiral enhancement
- Single Leptoquark solution:

◇ $S_1(\overline{3}, 1, 1/3)$

◇ $R_2(3, 2, 7/6)$

- Mixed Leptoquark scenario:

◇ $S_1(\overline{3}, 1, 1/3)$ & $S_3(\overline{3}, 3, 1/3)$

◇ $R_2(3, 2, 7/6)$ & $\widetilde{R}_2(3, 2, 1/6)$

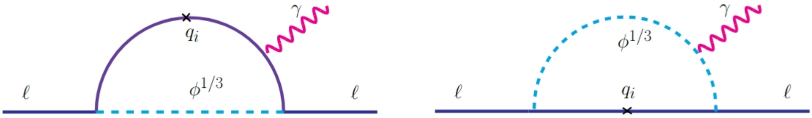
- $\mu \to e\gamma$ constraint plays important role in this selection

I. Doršner, S. Fajfer, Saad 2020

S_1 Leptoquark

- Yukawa interaction:

$$\mathcal{L} \supset y^L_{ij}\ \overline{Q^c}_i i\sigma_2 S_1 L_j + y^R_{ij}\ \overline{u^c_R}_i S_1 \ell_{Rj} + \text{h.c.},$$



- $(g-2)_\mu$ requires large correction: top-quark
- $(g-2)_e$: $\mu \to e\gamma$ restricts

✗ top-quark

✓ charm-quark

- same conclusion for R_2 LQ

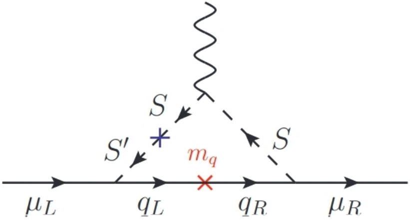
Mixed $S_1 \& S_3$ Leptoquark

- Interaction:

$$\mathcal{L} \supset y_{ij}^R \, \overline{u_{R}^c}_i S_1 \ell_{Rj} + y_{ij}^S \overline{Q^c}_{Li} i\sigma_2 (\sigma_a S_3^a) L_{Lj} + \lambda \, H^\dagger (\sigma_a S_3^a) H S_1^* + \mathrm{h.c.}$$

- Mixing: EW symmetry breaking

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



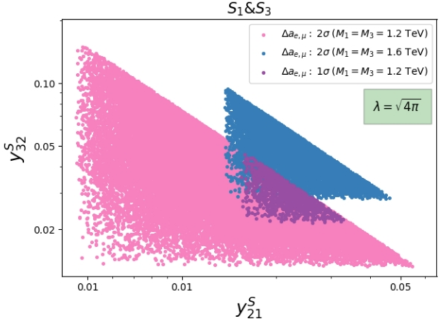
I. Doršner, S. Fajfer, O. Sumensari 2019

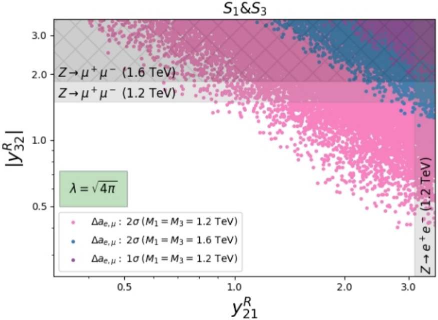
Leptoquark solutions

- $\mu \to e\gamma$ selection

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

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





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

✗ $S_1\&S_3$

Leptoquark solutions

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

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

(solution-C)

Vectorlike Fermion solution

◇ chiral enhancement from Vectorlike fermions (VLF)

→ approximate bounds $M_{NP} \gtrsim$ TeV

- Unified framework:

✓ Neutrino mass

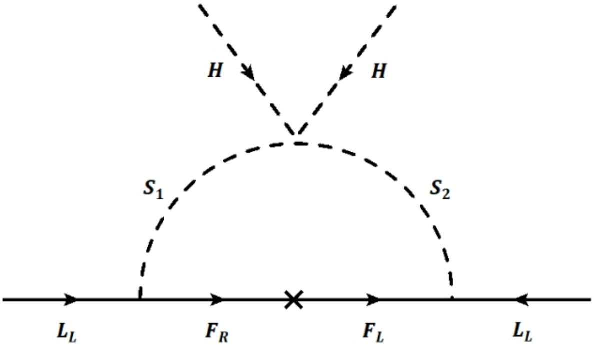
✓ Dark Matter

✓ Testable in colliders

S. Jana, P.K. Vishnu, W. Rodejohann, Saad 2020

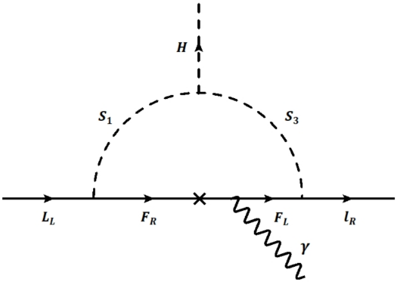
Model Framework

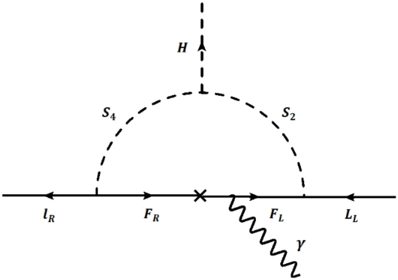
- VLF: $Y \neq 0 \quad (\Rightarrow S_1 \neq S_2)$
- BSM states: $\mathcal{Z}_2$ odd
- Neutrino mass $\sim$ scotogenic



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

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





- DM in the loop

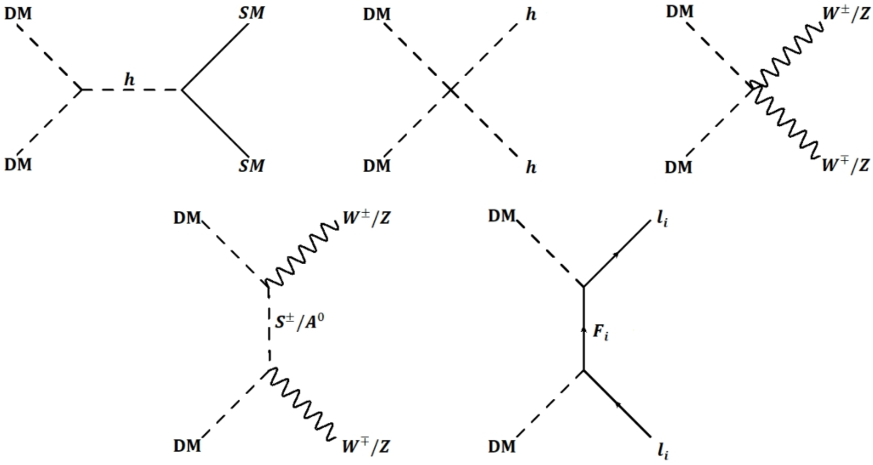
Class of Models

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:

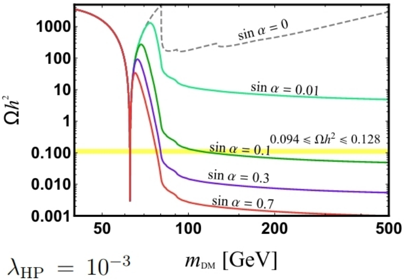
Multiplets	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$\mathcal{Z}_2$
Scalars	$\phi_1(1,2,\frac{1}{2})$	$-$
	$\phi_2(1,2,\frac{3}{2})$	$-$
	$\eta(1,1,0)$	$-$
Vector-like fermion	$F_{L,R}(1,1,-1)$	$-$

Annihilation of Dark Matter

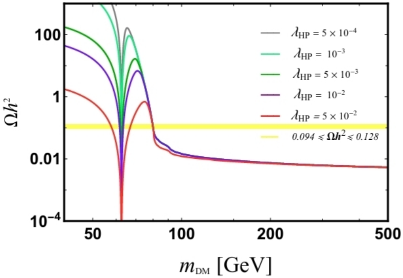


$$\mathcal{L} = \frac{\lambda_{\rm HP}}{2}\,(S_1^0)^2\, H^\dagger H + \frac{\lambda_{\rm LP}}{\sqrt{2}}\, S_1^0\, \overline{\ell}_{L,R}\, F_{R,L}\,.$$

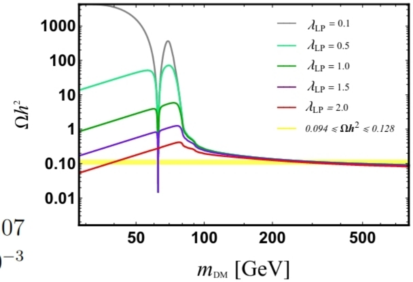
Relic Density



$\lambda_{\rm HP} = 10^{-3}$
$\lambda_{\rm LP} = 0.1$



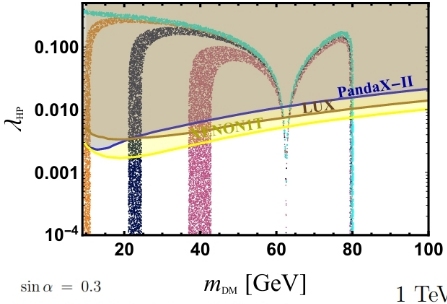
$\sin\alpha = 0.3$
$\lambda_{\rm LP} = 0.1$



$\sin\alpha = 0.07$
$\lambda_{\rm HP} = 10^{-3}$

1 TeV

Direct Detection Bounds

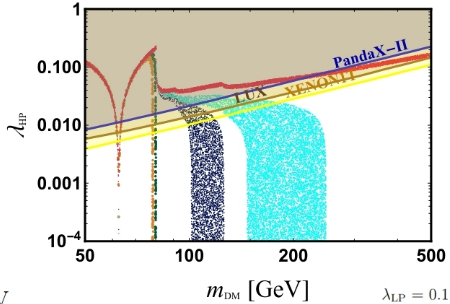


$\sin\alpha = 0.3$

$\lambda_{LP} = 0.5$ (cyan), $\lambda_{LP} = 1.0$ (orange),

$\lambda_{LP} = 1.5$ (blue), $\lambda_{LP} = 2.0$ (pink).

1 TeV.

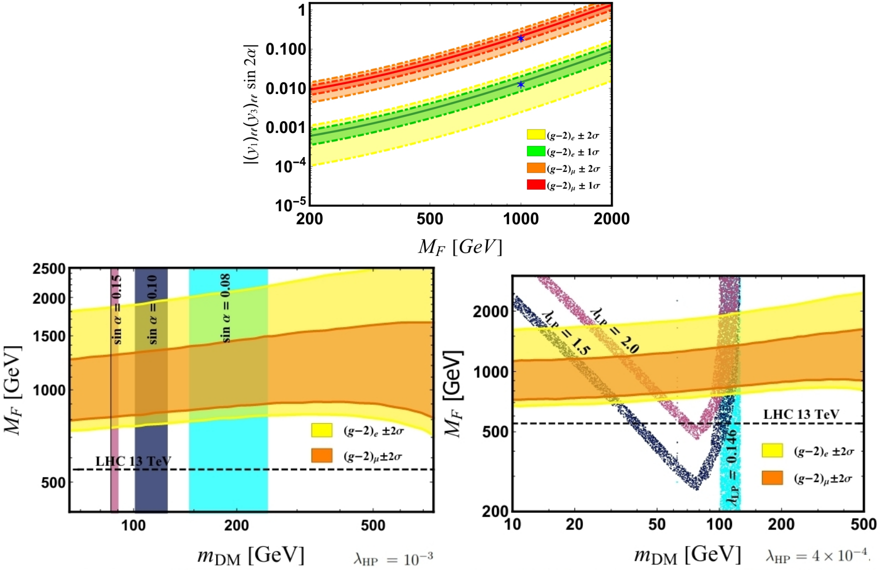


$\lambda_{LP} = 0.1$.

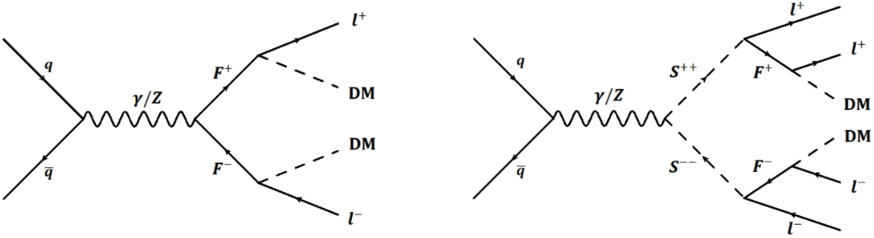
$\sin\alpha = 0.01$ (red), $\sin\alpha = 0.08$ (cyan),

$\sin\alpha = 0.1$ (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!