IFT, Madrid
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Minimal models for the muon g–2 and Dark Matter

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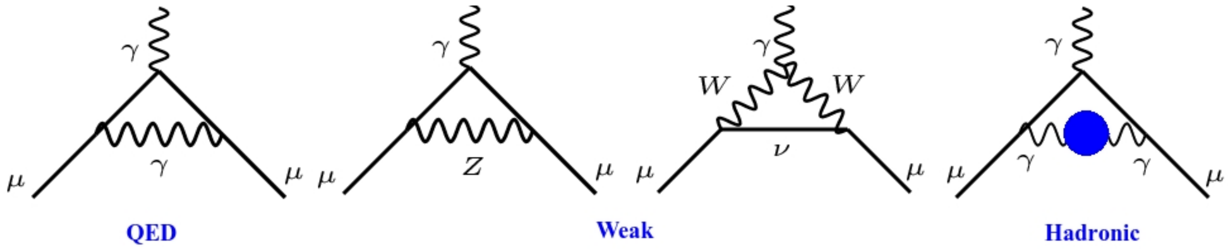
ITP-CAS, Beijing

Mainly based on work in progress with R. Ziegler and J. Zupan

Anomalous magnetic moment of the muon:

$$a_\mu = (g_\mu - 2)/2$$



$$a_\mu^{SM} = 116591802(2)(42)(26) \times 10^{-11}$$

Blum et al. ‘13

$$a_\mu^{exp} = (116592089 \pm 63) \times 10^{-11}$$

BNL E821 ‘06

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11} \; (3.6\sigma)$$

Introduction

Assumptions:

- Theory-experiment discrepancy of muon g-2 hint of new physics (NP)
- DM is a stable particle that is a thermal relic with ~ EW scale mass

Goal:

- Building the simplest extensions of the SM that, *at the same time*, (i) explain the muon g-2 anomaly, (ii) and provide a stable DM candidate
- Studying phenomenological consequences and testability of such minimal models

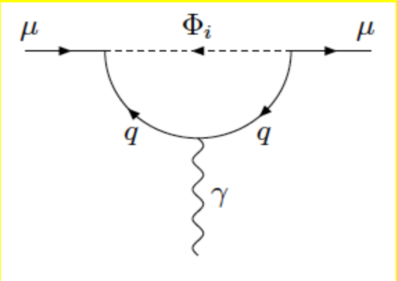
What is a “minimal” model?

- Minimal field content
- Minimal spin, weak isospin, and hypercharge quantum numbers

Single field extensions to address muon g-2:

- Few successful examples, fulfilling all constraints:
  certain scalar leptoquarks, 2HDMs, vector bosons, light ALPs

- Basic coupling SM-SM'-NP → heavy new particles decay to SM, no DM candidate



Chakraverty et al. '01, Cheung '01
Freitas et al. '14, Queiroz Sheperd '14,
Broggio et al. '14, Biggio Bordone '14,
EJ Chun et al '15, Cherchiglia et al. '16,
Biggio et al. '16, Marciano et al. '16
...

We assume that only new particles run in the loop

We need to introduce at least *two* new fields with couplings: SM-NP-NP'

→ straightforward to introduce Z_2 for DM stability

Generic setup

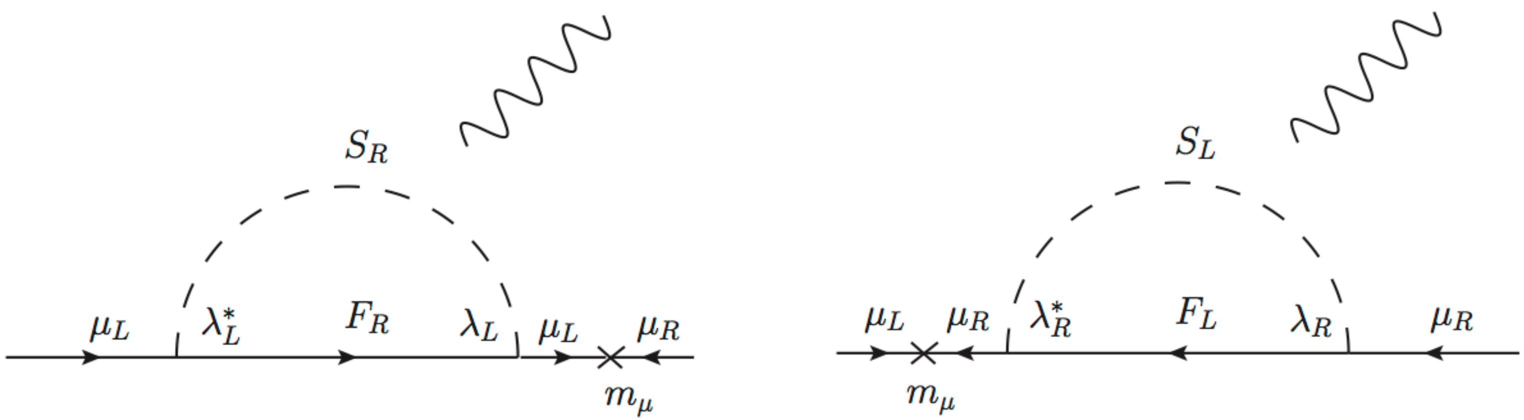
The goal is generating the usual dipole operator:

$$\frac{v}{\Lambda^2}\,\bar{\mu}_L \sigma^{\mu\nu} \mu_R\, F_{\mu\nu}$$

EW vev from a Higgs insertion to provide gauge invariant chirality flip

(I) Higgs insertion on the external line:

- Only two extra fields: a scalar and a vectorlike fermion
- Suppression from muon Yukawa coupling



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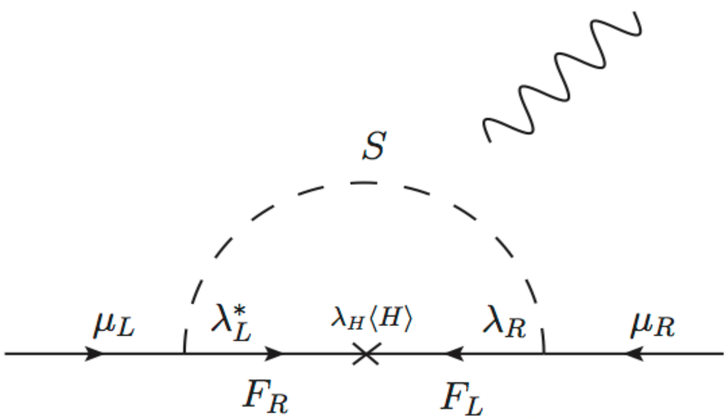
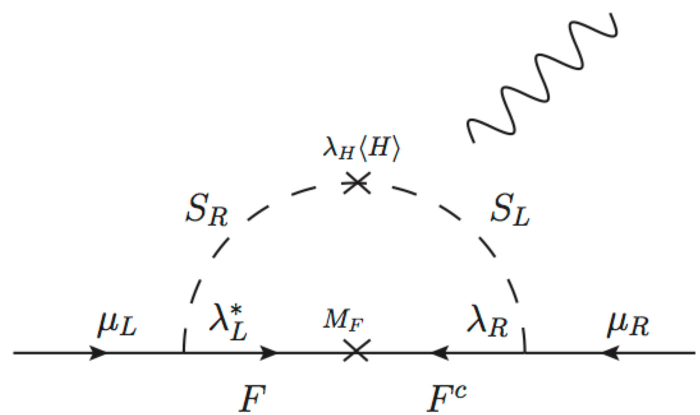
(II) Higgs insertion inside the loop:

- Three extra fields: Higgs couples either with scalars or fermions
- No suppression from light Yukawas





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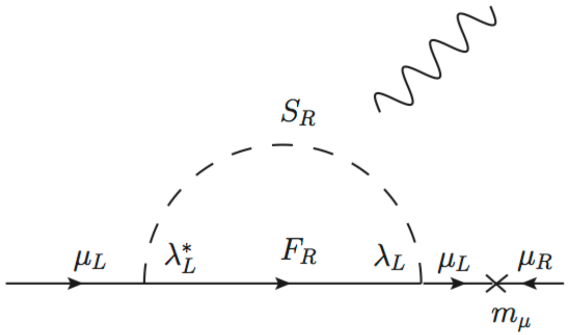
EW vev from a Higgs insertion to provide gauge invariant chirality flip

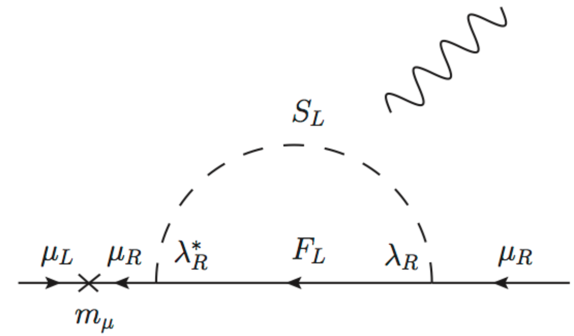
Unbroken Z_2:

- New fields (Z_2 odd) do not mix with SM fields (Z_2 even)
- Lightest new state stable, DM candidate if neutral

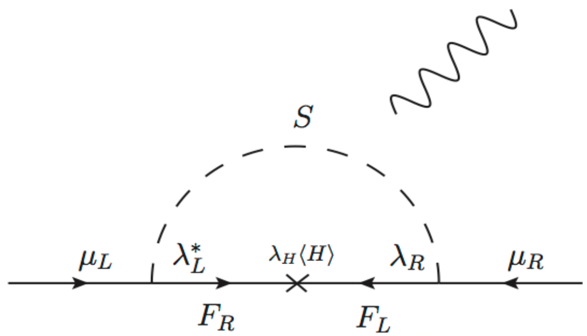
Contributions to the muon g-2

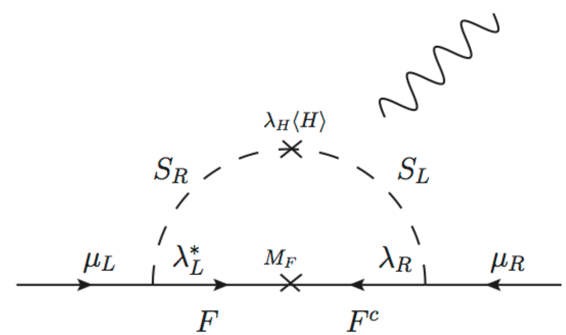
We aim at: $$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 2.90\,(90) \times 10^{-9}$$





$$\Delta a_\mu = -\frac{m_\mu^2}{8\pi^2 M_S^2} \sum_{F,S} \left(|\lambda_L|^2 + |\lambda_R|^2\right) \left[Q_F f_{LL}^F(x) + Q_S f_{LL}^S(x)\right]$$
$$- \frac{m_\mu M_F}{8\pi^2 M_S^2} \sum_{F,S} \mathrm{Re}\left(\lambda_R^* \lambda_L\right) \left[Q_F f_{LR}^F(x) + Q_S f_{LR}^S(x)\right]$$





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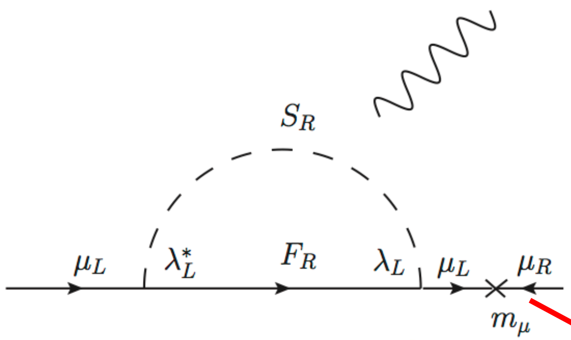

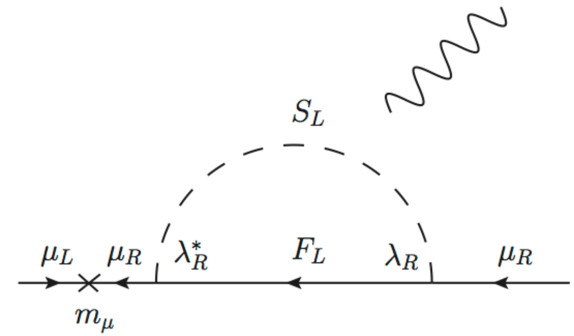

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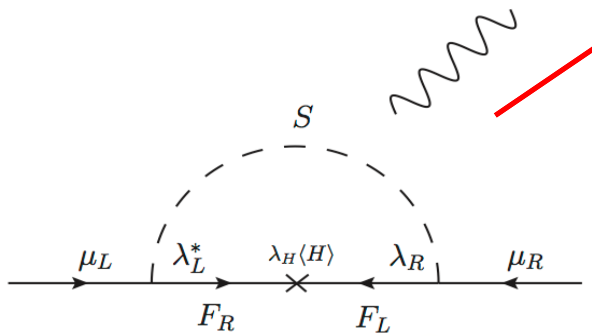

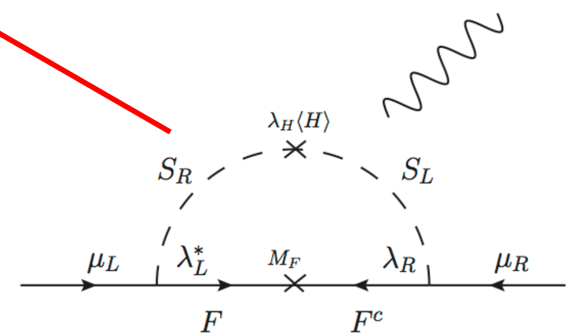

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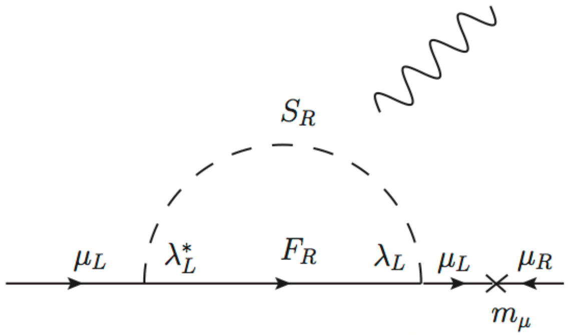

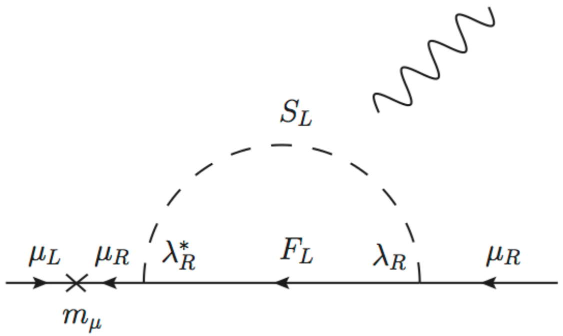

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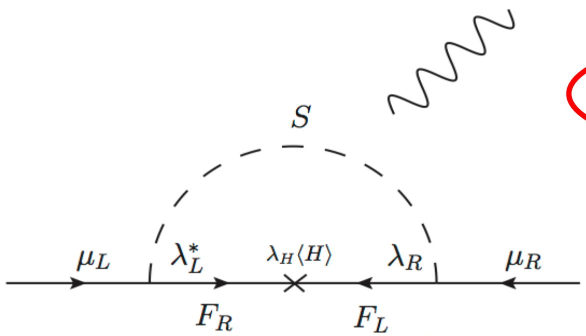
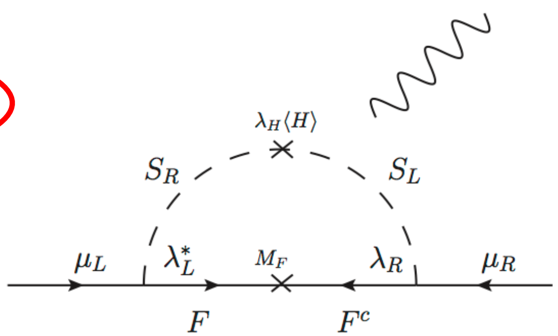
$$\left(f_{LL}^{F,S}(x) > 0, \quad f_{LR}^{F,S}(x) > 0\right)$$





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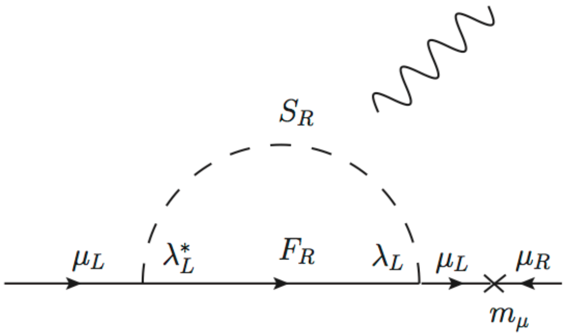

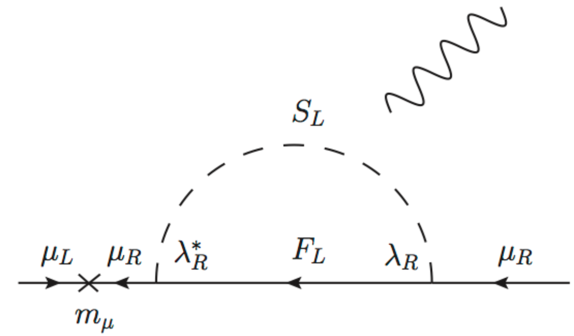

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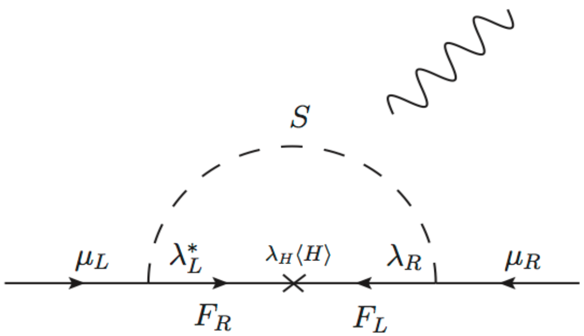
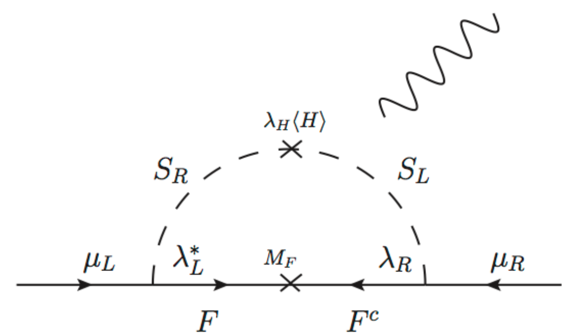
M_F/m_μ "enhancement"



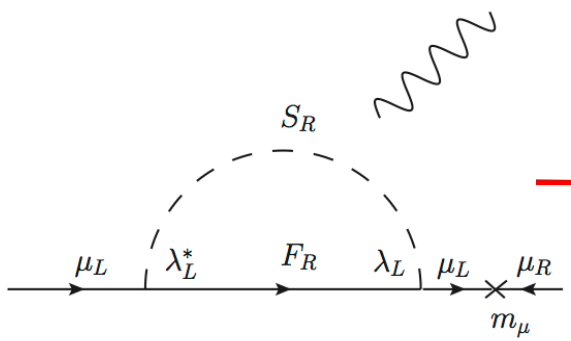


Class I models: external chirality flip

Gauge quantum numbers constrained by our requirement of a DM candidate:

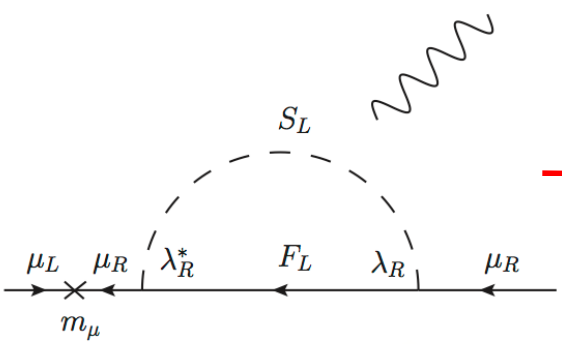
S and F must be colour singlet and contain at least one state with Q=0

$SU(2)_L \times U(1)_Y$ quantum numbers: $\mu_L \sim 2_{-1/2}\,,\quad \mu_R \sim 1_1\,,\quad F \sim (n_F)_{Y_F}\,,\quad S \sim (n_S)_{Y_S}$



$\mu_L \sim 2_{-\frac{1}{2}}$										
F_R	$1_0^\star$	1_1	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$
S_R	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	1_1	$3^\star_1$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	$2_{\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$

Table I: Models with couplings to LH muons.



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F_L	$1^\star_0$	1_{-1}	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$	3_{-2}
S_L	1_{-1}	$1^\star_0$	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$3^\star_0$	$3^\star_{-1}$	3_{-2}	$3^\star_1$

Table II: Models with couplings to RH muons.

$\star \to$ contain a neutral state

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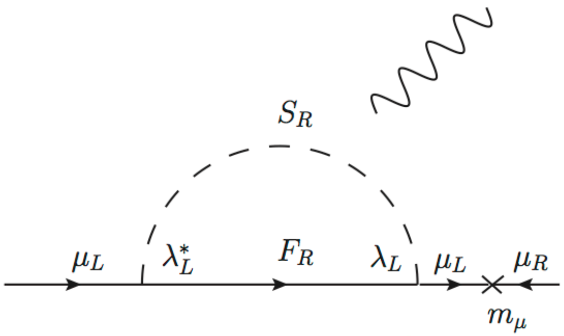
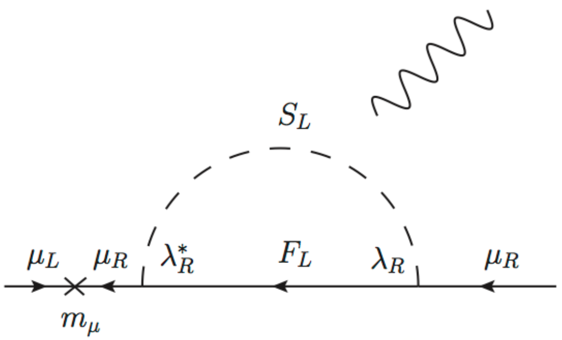


$$\Delta a_\mu^{LL, n_F = n_S \pm 1} = -\frac{n\, m_\mu^2}{16\pi^2 M_S^2} |\lambda_L|^2 \left[f_{LL}^S + \left(Y_S - \frac{\pm n + 5}{6} \right) \left(f_{LL}^S + f_{LL}^F \right) \right]$$



$$\Delta a_\mu^{RR} = -\frac{n\, m_\mu^2}{8\pi^2 M_S^2} |\lambda_R|^2 \left[f_{LL}^S + Y_{F_L} \left(f_{LL}^S + f_{LL}^F \right) \right]$$

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Constraints:

$\mu_L \sim 2_{-\frac{1}{2}}$										
F_R	$1^\star_0$	1_1	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$
S_R	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	1_1	$3^\star_1$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	$2_{\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$

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Table II: Models with couplings to RH muons.

$\star \to$ contain a neutral state

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Constraints:

- $\Delta a_\mu > 0$

(e.g. excludes ~ Bino-LH/RH smuon)

-

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F_R	~~$1^\star_0$~~	1_1	~~$2^\star_{-\frac{1}{2}}$~~	~~$2^\star_{-\frac{1}{2}}$~~	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	~~$3^\star_{-1}$~~	$3^\star_0$	$3^\star_1$
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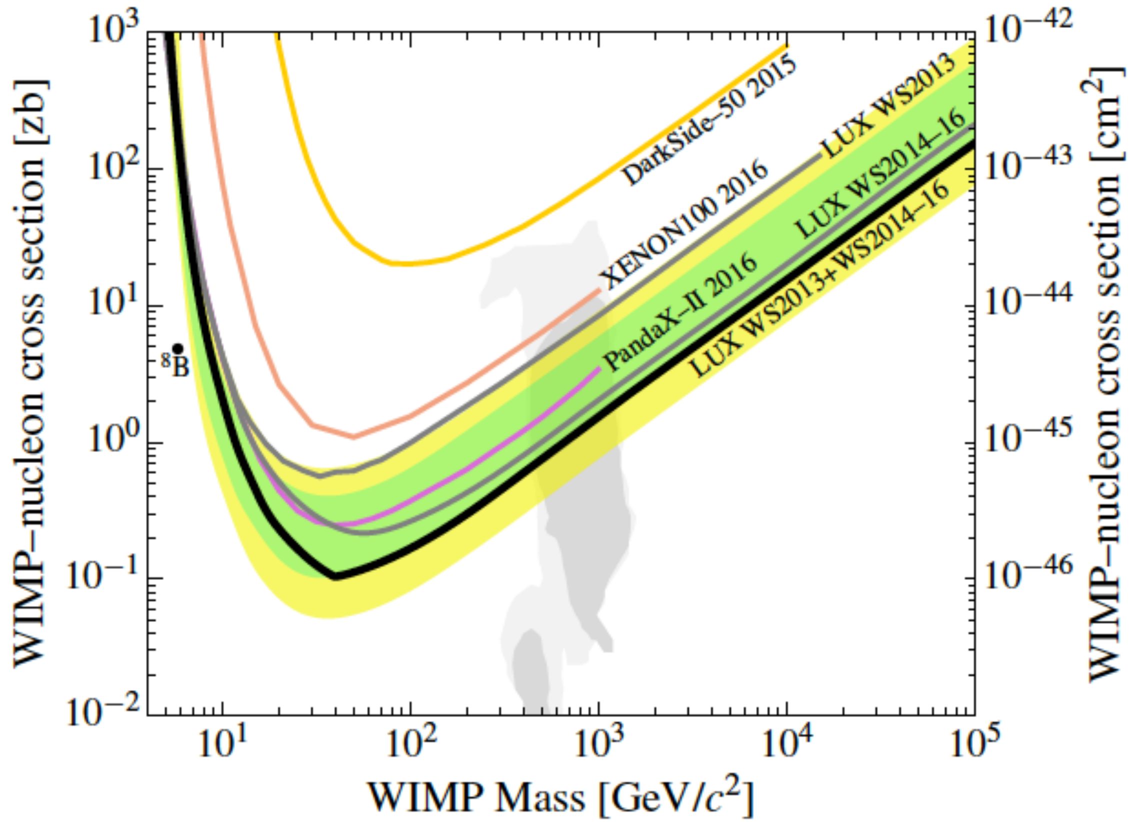
Direct detection excludes hypercharged DM

Vector coupling to Z → huge tree-level DM-nuclei cross section:

$$\sigma^{\rm SI}_{\chi-p} = \frac{2G_F^2\mu_{\chi p}^2}{\pi} Y^2 \left[\frac{N - Z\left(1-4s_W^2\right)}{A}\right]^2 \approx 3.4\cdot 10^{-38}{\rm cm}^2 \left(\frac{\mu_{\chi p}}{\rm GeV}\right)^2 Y^2 \left(\frac{N}{A}\right)^2$$



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- A (vector) coupling DM-DM-Z:

$$\sigma^{\rm SI}_{\chi p} \approx 10^{-38}\ {\rm cm}^2$$

direct detection exps bound:

$$\sigma^{\rm SI}_{\chi p} < 10^{-(45\div 46)}\ {\rm cm}^2$$

$$\Rightarrow Y_{F,S} = 0$$

$\mu_L \sim 2_{-\frac{1}{2}}$										
F_R	$1^\star_0$	1_1	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$
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Class I models: the two simplest examples

"LL1" : $F_R = 2_{\frac{1}{2}}, F_R^c = 2_{-\frac{1}{2}}, S_R = 1_0^*$, "RR1" : $F_L = 1_{-1}, F_L^c = 1_1, S_L = 1_0^*$

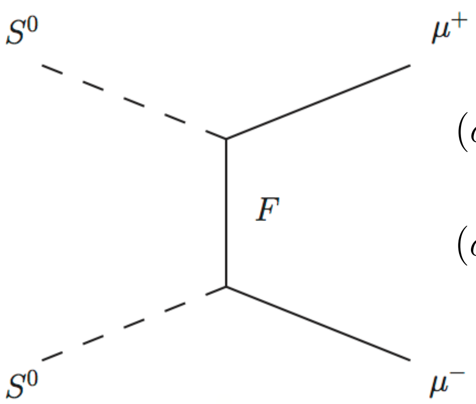
$$\mathcal{L}_{\rm LL1} = \lambda_i^L \overline{F} L_i S + \lambda_i^{L*} \overline{L_i} F S - M_F \overline{F} F - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm scalar}$$

$$\mathcal{L}_{\rm RR1} = \lambda_i^R \overline{e}_{Ri} F_- S + \lambda_i^{R*} \overline{F}_- e_{Ri} S - M_F \overline{F}_- F_- - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm scalar}$$

$$\Delta a_\mu^{\rm LL1,RR1} = \frac{m_\mu^2}{8\pi^2 M_S^2} |\lambda|^2 f_{LL}^F \left(\frac{M_F^2}{M_S^2} \right)$$

Singlet scalar S
DM candidate

DM annihilation:



$$(\sigma v)^{\rm C-scalar} = \frac{1}{4\pi M_F^2} \frac{1}{(1+r^2)^2} \left[\lambda_L^2 \lambda_R^2 + \frac{\lambda_L^4 + \lambda_R^4}{4} \left(\frac{m_\mu^2}{M_F^2} + \frac{v^2 r^2}{3} \right) \right],$$

$$(\sigma v)^{\rm R-scalar} = \frac{1}{\pi M_F^2} \frac{1}{(1+r^2)^2} \left[\lambda_L^2 \lambda_R^2 + \frac{\lambda_L^4 + \lambda_R^4}{4} \left(\frac{m_\mu^2}{M_F^2} + \frac{v^4 r^6}{15(1+r^2)^2} \right) \right]$$

$$r = M_S / M_F$$

Class I models: the two simplest examples

$$\text{“LL1”}: F_R = 2_{\frac{1}{2}},\, F_R^c = 2_{-\frac{1}{2}},\, S_R = 1_0^*, \qquad \text{“RR1”}: F_L = 1_{-1},\, F_L^c = 1_1,\, S_L = 1_0^*$$

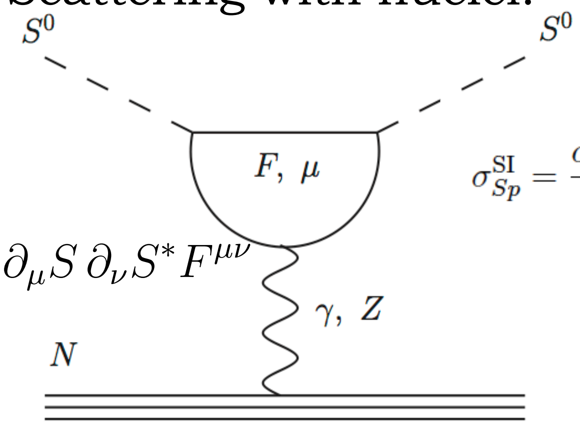
$$\mathcal{L}_{\rm LL1} = \lambda_i^L \overline{F} L_i S + \lambda_i^{L*} \overline{L_i} F S - M_F \overline{F} F - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm scalar}$$

$$\mathcal{L}_{\rm RR1} = \lambda_i^R \overline{e}_{Ri} F_- S + \lambda_i^{R*} \overline{F}_- e_{Ri} S - M_F \overline{F}_- F_- - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm scalar}$$

$$\Delta a_\mu^{\rm LL1,RR1} = \frac{m_\mu^2}{8\pi^2 M_S^2} |\lambda|^2 f_{LL}^F\left(\frac{M_F^2}{M_S^2}\right)$$

Singlet scalar S
DM candidate

Scattering with nuclei:



$$\sigma_{Sp}^{\rm SI} = \frac{\alpha^2 Q_e^2}{4\pi^3} \frac{Z^2}{A^2} \frac{m_N^2 \mu_{Sp}^2}{m_S^2} \tilde{A}_{\rm tot}^2 = 1.7 \cdot 10^{-42} {\rm cm}^2 \frac{Q_e^2 Z^2}{A^2} \frac{m_N^2}{m_S^2} \left(\frac{\mu_{Sp}}{\rm GeV}\right)^2 \left(\frac{\tilde{A}_{\rm tot}}{1/(100\,{\rm GeV})^2}\right)^2$$

$$A_{\rm tot} = q^2 \tilde{A}_{\rm tot} = \sum_{i,j} \frac{q^2}{M_i^2} \left(\lambda_{ij}^{LL} + \lambda_{ij}^{RR}\right) \left[f\left(\frac{M_S^2}{M_i^2}\right) + f_{\rm log}\left(\frac{M_S^2}{M_i^2}, \frac{m_j^2}{M_i^2}, \frac{-q^2}{M_i^2}\right)\right]$$

→ S must be *real*

Class I models: the two simplest examples

$$\text{"LL1"} : F_R = 2_{\frac{1}{2}}, F_R^c = 2_{-\frac{1}{2}}, S_R = 1_0^*, \qquad \text{"RR1"} : F_L = 1_{-1}, F_L^c = 1_1, S_L = 1_0^*$$

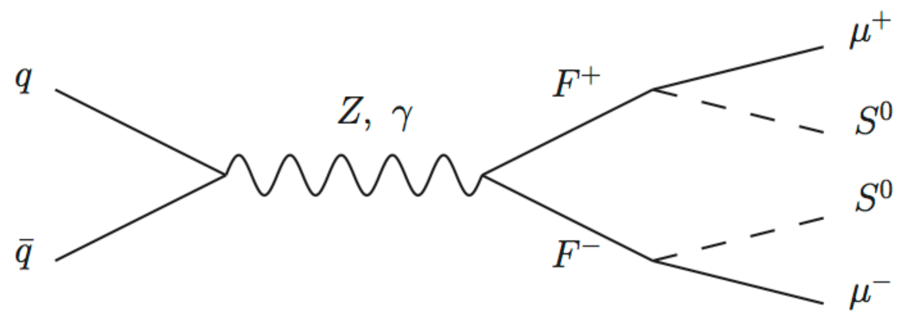
$$\mathcal{L}_{\rm LL1} = \lambda_i^L \overline{F} L_i S + \lambda_i^{L*} \overline{L_i} F S - M_F \overline{F} F - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm scalar}$$

$$\mathcal{L}_{\rm RR1} = \lambda_i^R \overline{e}_{Ri} F_- S + \lambda_i^{R*} \overline{F}_- e_{Ri} S - M_F \overline{F}_- F_- - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm scalar}$$

$$\Delta a_\mu^{\rm LL1,RR1} = \frac{m_\mu^2}{8\pi^2 M_S^2} |\lambda|^2 f_{LL}^F \left(\frac{M_F^2}{M_S^2} \right)$$

Singlet scalar S
DM candidate

LHC production and decay:

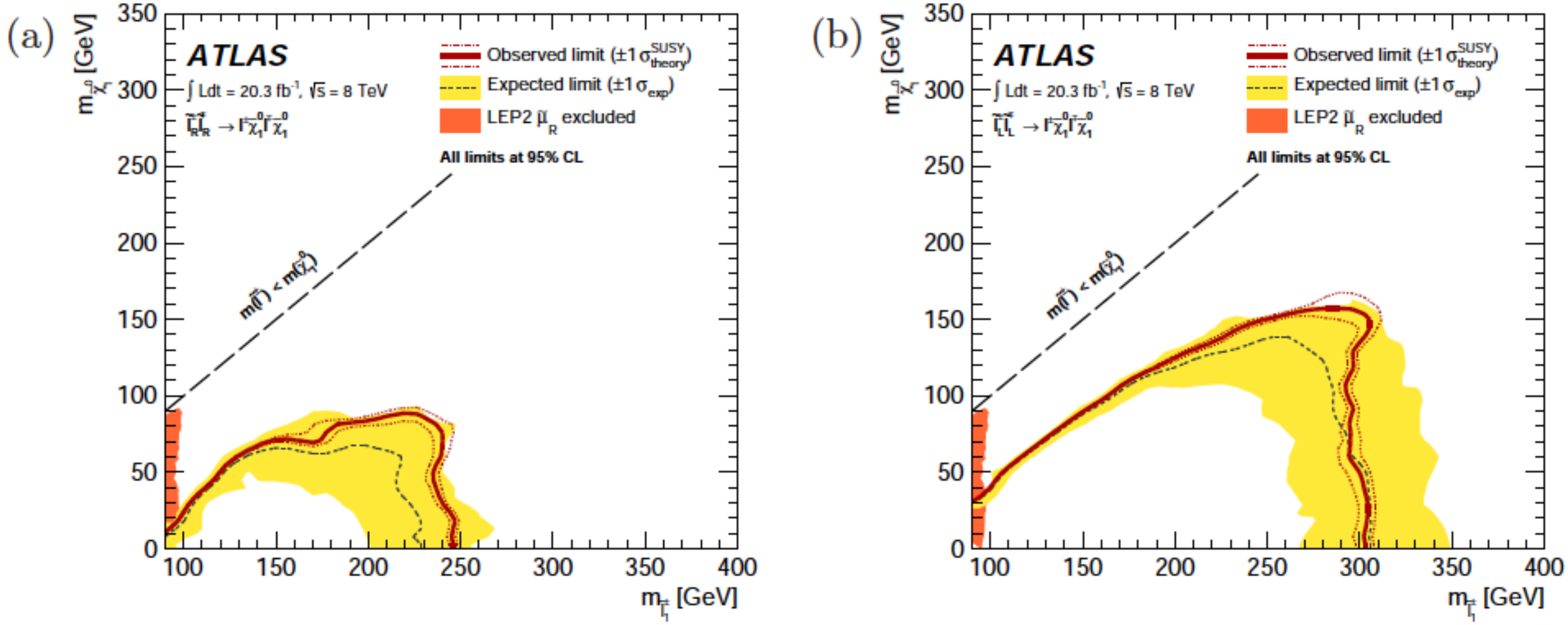


$\longrightarrow$ $\mu^+ \mu^- + \not{E}_T$

(cf. searches for EW slepton production at the LHC)

ATLAS: arXiv:1403.5294
CMS: arXiv:1405.7570

Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector



Class I models: the two simplest examples

$$\text{"LL1"} : F_R = 2_{\frac{1}{2}}, F_R^c = 2_{-\frac{1}{2}}, S_R = 1_0^*, \qquad \text{"RR1"} : F_L = 1_{-1}, F_L^c = 1_1, S_L = 1_0^*$$

$$\mathcal{L}_{\text{LL1}} = \lambda_i^L \overline{F} L_i S + \lambda_i^{L*} \overline{L_i} F S - M_F \overline{F} F - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{scalar}}$$

$$\mathcal{L}_{\text{RR1}} = \lambda_i^R \overline{e}_{Ri} F_- S + \lambda_i^{R*} \overline{F}_- e_{Ri} S - M_F \overline{F}_- F_- - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{scalar}}$$

$$\Delta a_\mu^{\text{LL1,RR1}} = \frac{m_\mu^2}{8\pi^2 M_S^2} |\lambda|^2 f_{LL}^F \left(\frac{M_F^2}{M_S^2} \right)$$

Singlet scalar S

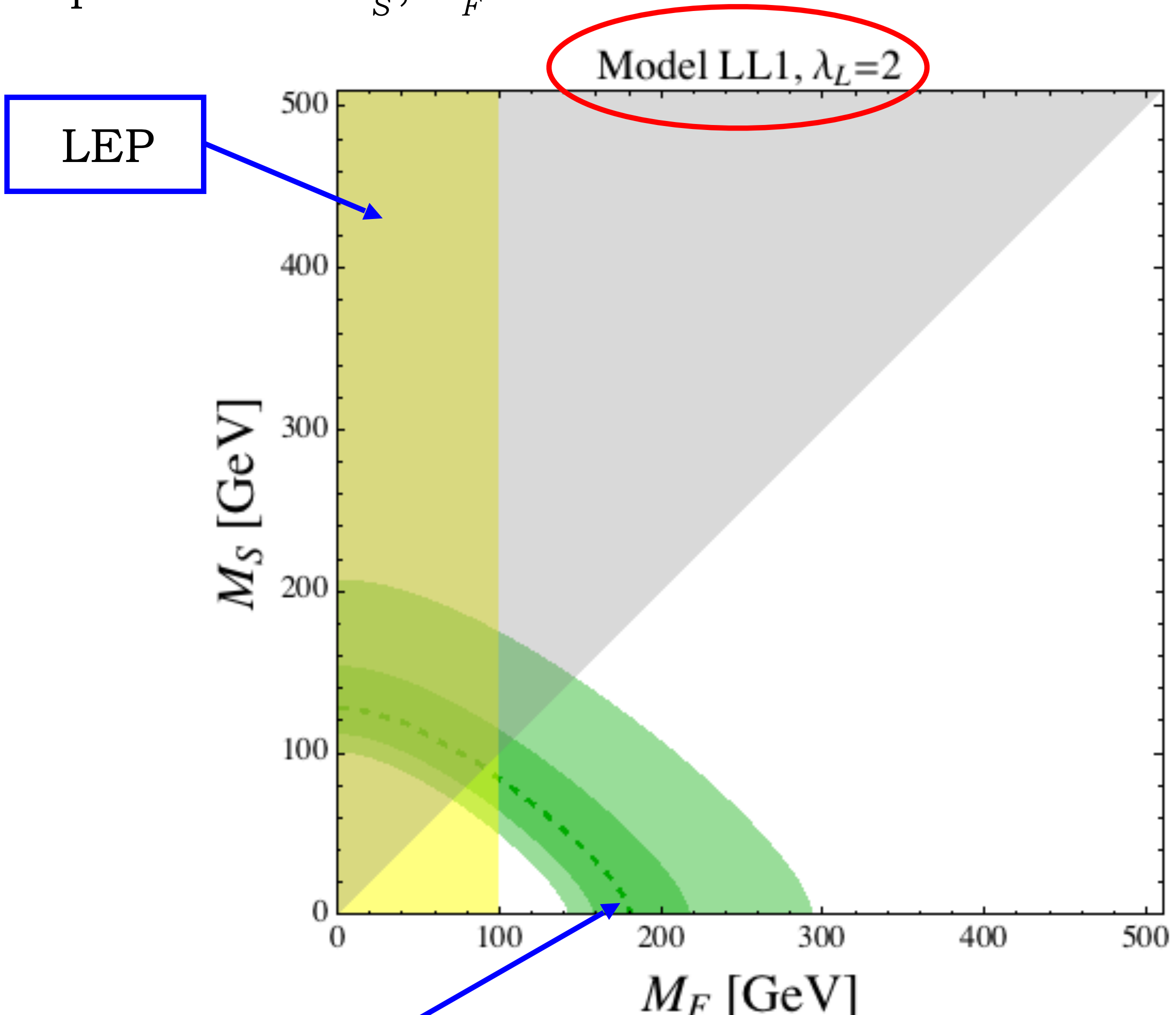
DM candidate

Additional constraints:

- LFV processes (e.g. $\mu \to e\,\gamma$): couplings to e and τ <<1
  or three F generations + alignment (flavour symmetry?)

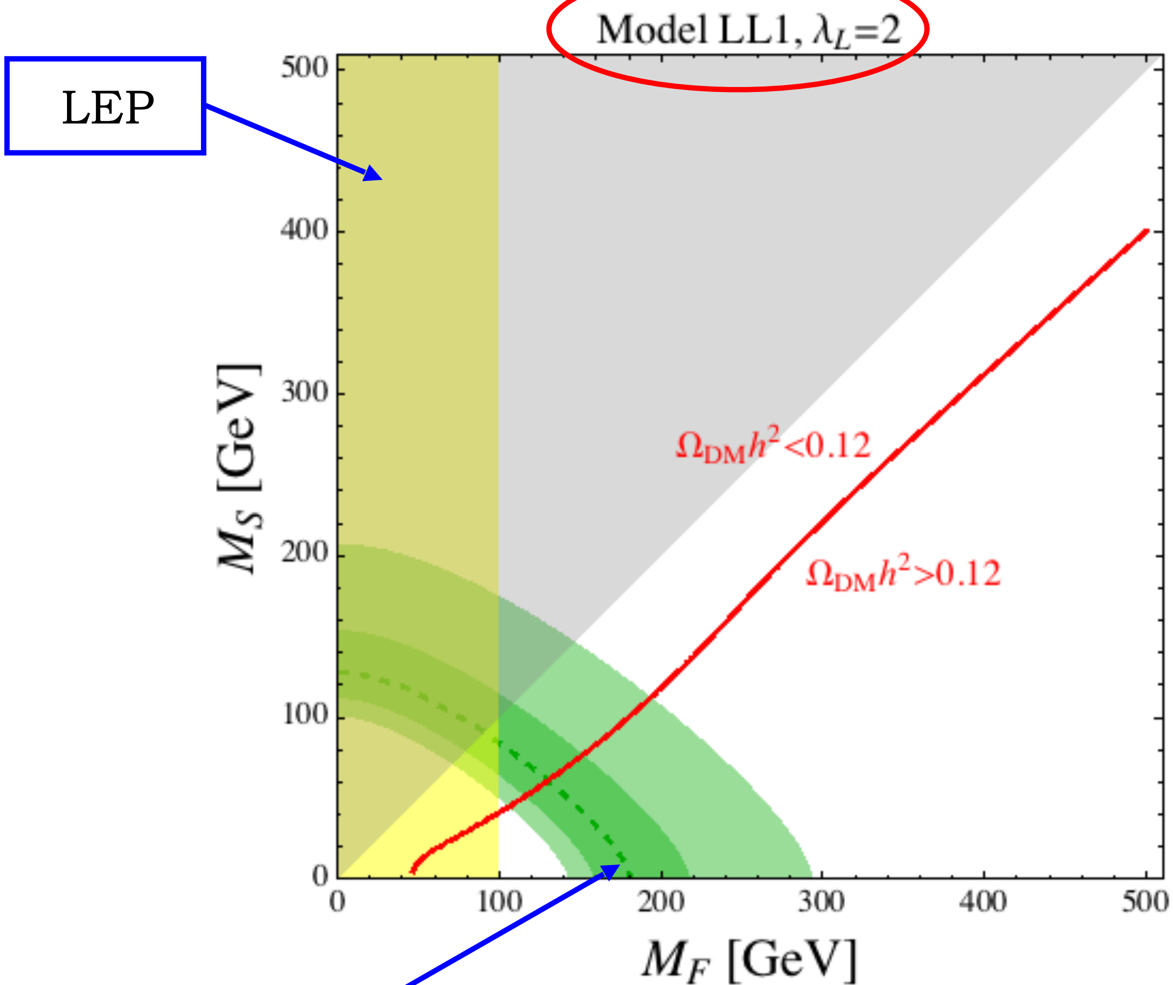
- EDMs do not arise at one loop (phase of coupling cancels in the penguin)

Only three parameters: M_S, M_F and λ :

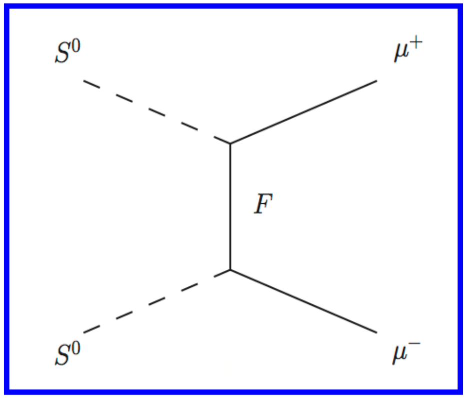


$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 2.90\,(90) \times 10^{-9}$$

Only three parameters: M_S, M_F and λ :

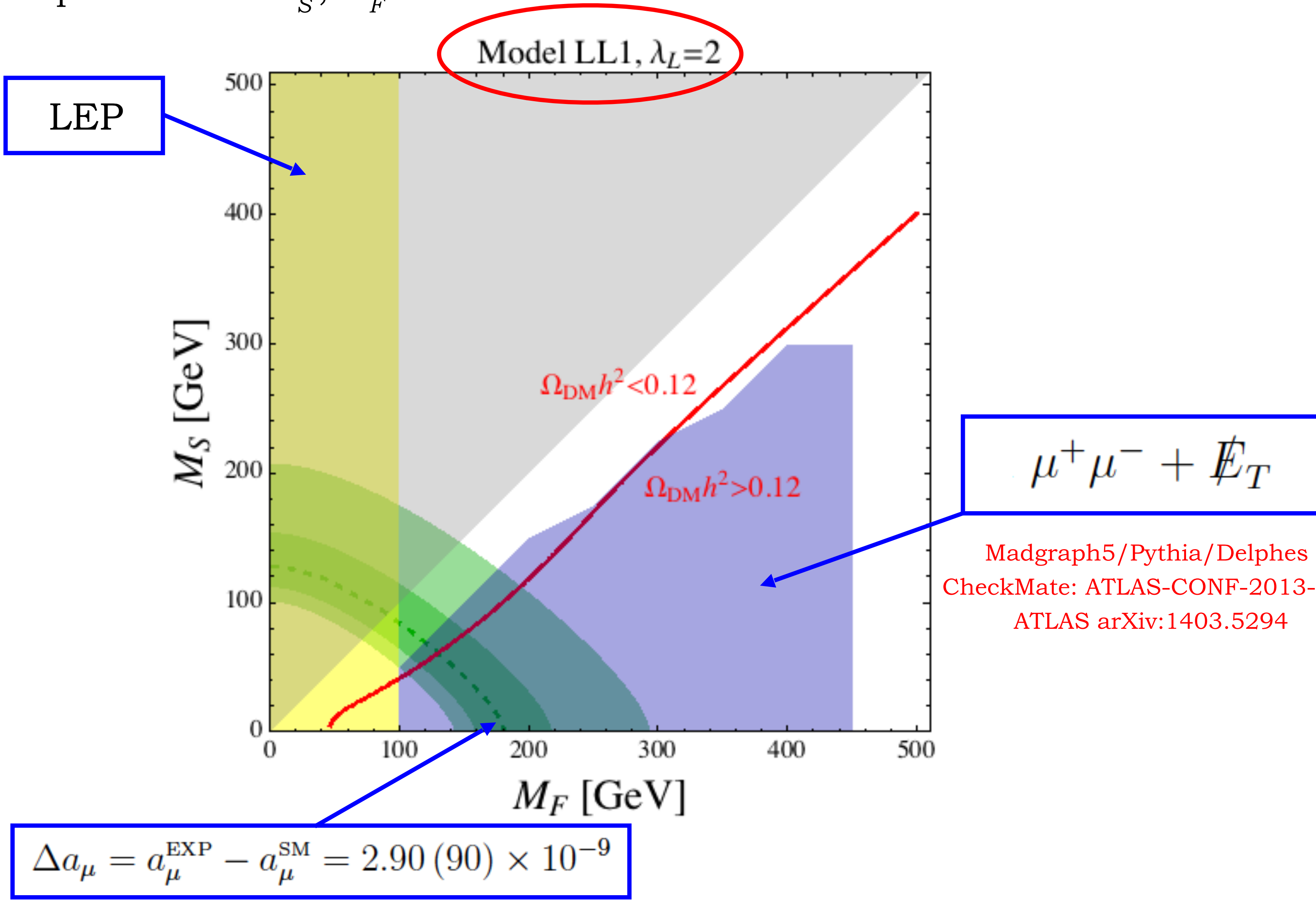


$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 2.90\,(90) \times 10^{-9}$$



micrOMEGAs

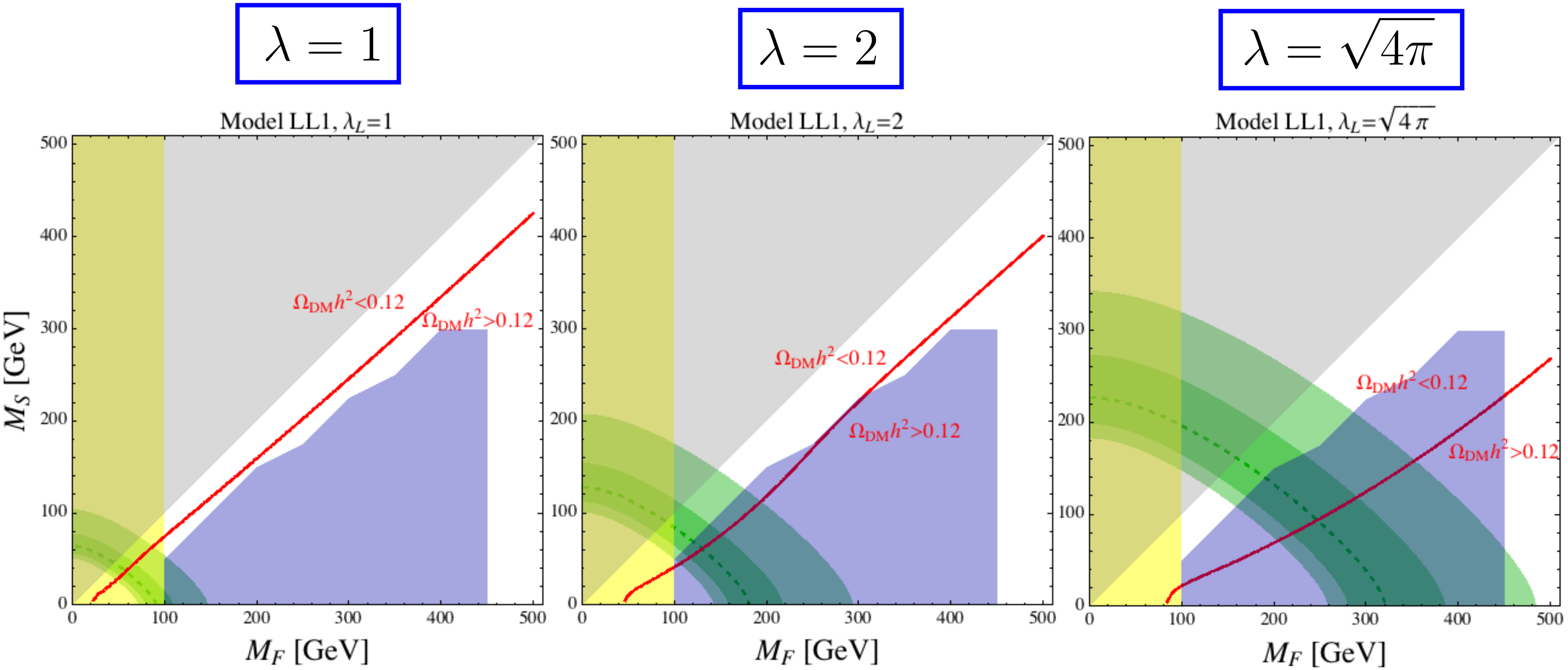
Only three parameters: M_S, M_F and λ :



Madgraph5/Pythia/Delphes
CheckMate: ATLAS-CONF-2013-49,
ATLAS arXiv:1403.5294

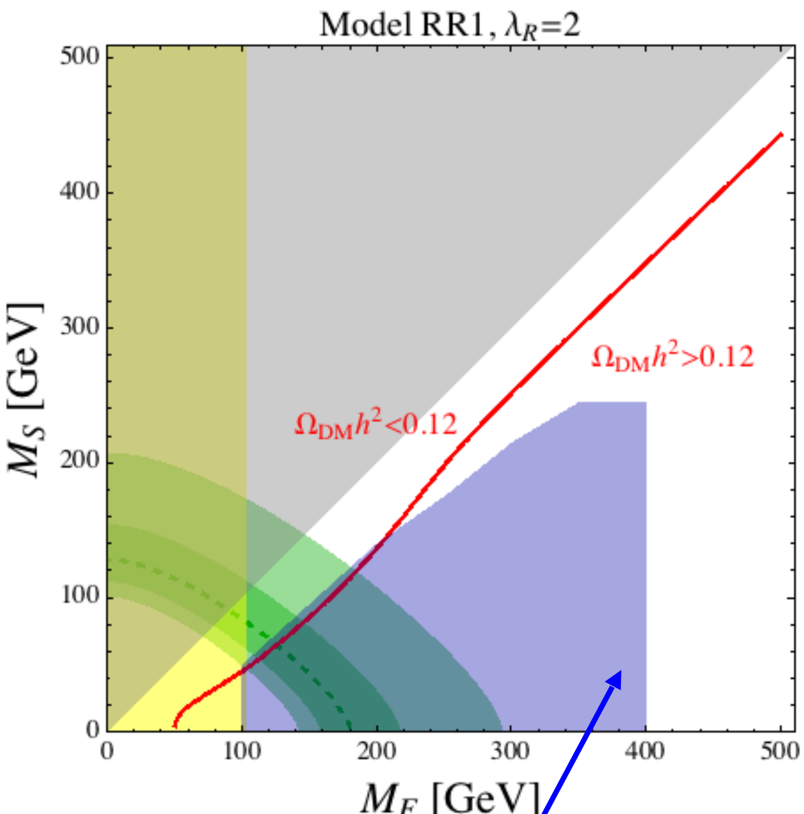
The simplest LL model

Varying λ:



Other class I models

What about the other models?



Weaker LHC bound (DY production larger for SU(2) doublet)

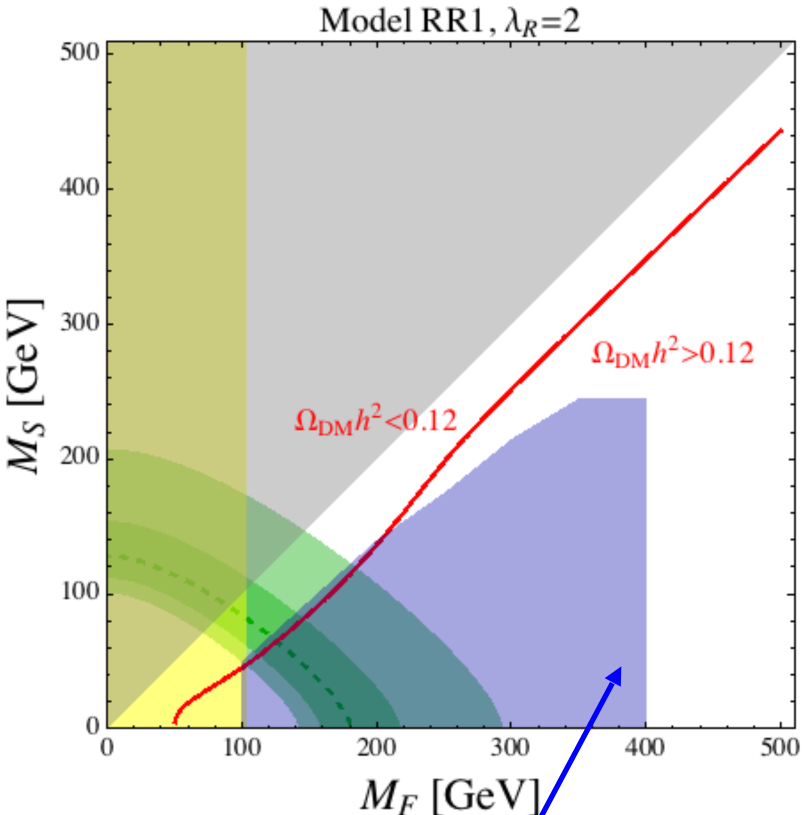
$\mu_L \sim 2_{-\frac{1}{2}}$										
F_R	$1^\star_0$	1_1	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$
S_R	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	1_1	$3^\star_1$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	$2_{\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$

Table I: Models with couplings to LH muons.

$\mu_R \sim 1_1$									
F_L	$1^\star_0$	1_{-1}	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$	3_{-2}
S_L	1_{-1}	$1^\star_0$	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$3^\star_0$	$3^\star_{-1}$	3_{-2}	$3^\star_1$

Table II: Models with couplings to RH muons.

What about the other models?



Weaker LHC bound (DY production larger for SU(2) doublet)

$\mu_L \sim 2_{-\frac{1}{2}}$										
F_R	$1^\star_0$	1_1	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$
S_R	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	1_1	$3^\star_1$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	$2_{\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$

Table I: Models with couplings to LH muons.

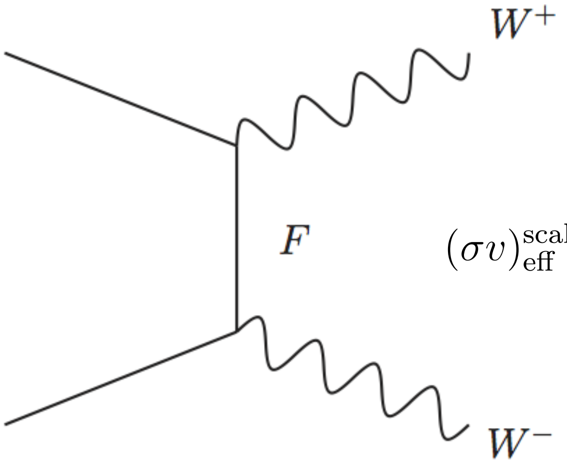
$\mu_R \sim 1_1$									
F_L	$1^\star_0$	1_{-1}	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$	3_{-2}
S_L	1_{-1}	$1^\star_0$	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$3^\star_0$	$3^\star_{-1}$	3_{-2}	$3^\star_1$

Table II: Models with couplings to RH muons.

Simplest models excluded by LHC because too light states are required to overcome the chirality flip suppression

Other class I models

What about modes with triplet? Is there a 'cutoff' on n ?



$$(\sigma v)^{\text{scalar}}_{\text{eff}} = \frac{g_2^4\,(3-4n^2+n^4)}{64\pi m_\chi^2 g_X}\,, \qquad (\sigma v)^{\text{fermion}}_{\text{eff}} = \frac{g_2^4\,(-19+17n^2+2n^4)}{128\pi m_\chi^2 g_X}$$

Efficient annihilation, lower bound on DM mass to avoid under-production
(cf. Higgsino or Wino DM in SUSY)

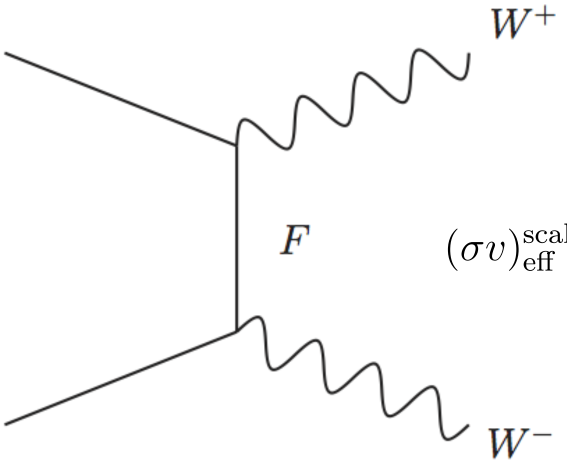
Maximizing the contribution to the g-2:

$$\Delta a_\mu^{RR} = -\frac{n\, m_\mu^2}{8\pi^2 M_S^2}|\lambda_R|^2\left[f_{LL}^S + Y_{F_L}\left(f_{LL}^S + f_{LL}^F\right)\right] \qquad \lambda_R = \sqrt{4\pi} \quad \Rightarrow \quad m_{\text{DM}} \lesssim 250\sqrt{n}\ \text{GeV}$$

$$\Omega h^2 \lesssim 0.04\frac{n^2}{3-4n^2+n^4}, \quad n=3 \ \Rightarrow \Omega h^2 \lesssim 0.007$$

Other class I models

What about modes with triplet? Is there a 'cutoff' on n ?

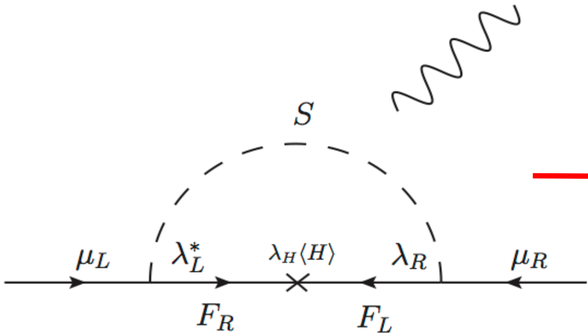


$$(\sigma v)^{\text{scalar}}_{\text{eff}} = \frac{g_2^4\left(3-4n^2+n^4\right)}{64\pi m_\chi^2 g_X}\,, \qquad (\sigma v)^{\text{fermion}}_{\text{eff}} = \frac{g_2^4\left(-19+17n^2+2n^4\right)}{128\pi m_\chi^2 g_X}$$

Efficient annihilation, lower bound on DM mass to avoid under-production
(cf. Higgsino or Wino DM in SUSY)

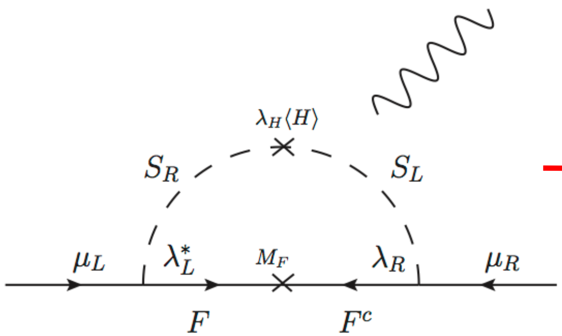
→ no models with external chirality flip can accommodate DM and muon g-2 at the same time

→ we have to consider additional fields allowing mixing with the Higgs inside the loop



$H F_L F_R$										
F_R	$1^\star_0$	1_1	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$
F_L	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$1^\star_0$	$3^\star_0$	1_{-1}	$3^\star_{-1}$	3_{-2}	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$
S_R	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	1_1	$3^\star_1$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	$2_{\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$

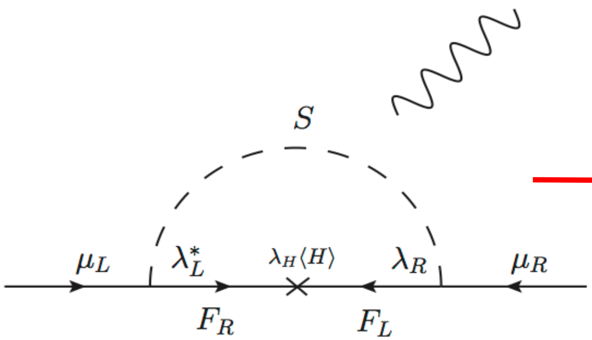
Table III: Models with fermion-Higgs couplings.



$H S_L S_R$										
S_L	$1^\star_0$	1_{-1}	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$2_{-\frac{3}{2}}$	$3^\star_0$	$3^\star_{-1}$	3_{-2}
S_R	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	1_1	$3^\star_1$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$
F_R	1_1	$1^\star_0$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$3^\star_1$	$3^\star_0$	$3^\star_{-1}$

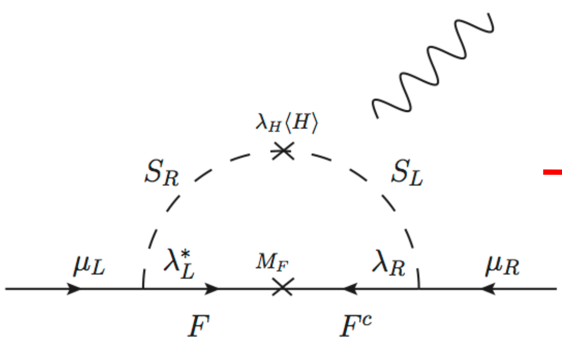
Table IV: Models with scalar-Higgs couplings.

Class II models: chirality flip inside the loop



HF_LF_R										
F_R	$1_0^\star$	1_1	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$
F_L	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$1^\star_0$	$3^\star_0$	1_{-1}	$3^\star_{-1}$	3_{-2}	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$
S_R	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	1_1	$3^\star_1$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	$2_{\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$

Table III: Models with fermion-Higgs couplings.



HS_LS_R										
S_L	$1^\star_0$	1_{-1}	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$2_{-\frac{3}{2}}$	$3^\star_0$	$3^\star_{-1}$	3_{-2}
S_R	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$1^\star_0$	$3^\star_0$	$3^\star_{-1}$	1_1	$3^\star_1$	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$
F_R	1_1	$1^\star_0$	$2^\star_{\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{\frac{3}{2}}$	$2^\star_{-\frac{1}{2}}$	$2^\star_{-\frac{1}{2}}$	$3^\star_1$	$3^\star_0$	$3^\star_{-1}$

Table IV: Models with scalar-Higgs couplings.

Class II models: a working example

Model FLR1: $F_R = 1^*_0,\ F_L = 2^*_{-\frac{1}{2}},\ F^c_L = \overline{2}^*_{\frac{1}{2}},\ S_R = 2_{\frac{1}{2}}$

Generalization of the Bino-Higgsino-Slepton(LH) system of the MSSM

DM pheno similar to the Singlet-Doublet DM model

Mahbubani Senatore '05, Enberg et al. '07, Cohen et al. '11, Cheung Sanford '13, LC Mariotti Tziveloglou '15, ...

$$\mathcal{L}_S = \lambda^S_{1i} V_{1j} \overline{F}_{0j} \left(S_0 P_L \nu_i - S_+ P_L e_i\right) + \lambda^S_{2i} S_0^* \overline{e}_i P_L F_- + \lambda^S_{2i} V_{2j} S_+^* \overline{e}_i P_L F_{0j} + \text{h.c.}\,,$$

$$\mathcal{L}_{\text{gauge}} = \frac{g}{c_W} Z_\mu \left[\frac{1}{2}\left(V^*_{2i}V_{2j} - V^*_{3i}V_{3j}\right)\overline{F}_{0i}\gamma^\mu P_L F_{0j} + \frac{1}{2}\left(V_{2i}V^*_{2j} - V_{3i}V^*_{3j}\right)\overline{F}_{0i}\gamma^\mu P_R F_{0j}\right]$$

$$+ \frac{g}{c_W} Z_\mu \left[\left(-\frac{1}{2} + s_W^2\right)\overline{F}_-\gamma^\mu F_- + \text{h.c.}\right] + |e| A_\mu \overline{F}_-\gamma^\mu F_-$$

$$+ \frac{g}{\sqrt{2}}\left[W^+_\mu \left(V^*_{2i}\overline{F}_{0i}\gamma^\mu P_L F_- + V_{3i}\overline{F}_{0i}\gamma^\mu P_R F_-\right) + \text{h.c.}\right]\,,$$

$$\mathcal{L}_h = -\frac{h}{\sqrt{2}}\left(\lambda^H_1 V_{2i}V_{1j} + \lambda^H_2 V_{3i}V_{1j}\right)\overline{F}_{0i}P_L F_{0j} + \text{h.c.}\,,$$

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} M_i \overline{F}_{0i} F_{0i} - M_L \overline{F}_- F_- - M_S^2\left(|S_+|^2 + |S_0|^2\right)\,.$$

$$F_{0i}:\quad \begin{pmatrix} M_R & \frac{\lambda^H_1 v}{\sqrt{2}} & \frac{\lambda^H_2 v}{\sqrt{2}} \\ \frac{\lambda^H_1 v}{\sqrt{2}} & 0 & M_L \\ \frac{\lambda^H_2 v}{\sqrt{2}} & M_L & 0 \end{pmatrix}$$

Class II models: a working example

Model FLR1: $F_R = 1^*_0,\, F_L = 2^*_{-\frac{1}{2}},\, F_L^c = \overline{2}^*_{\frac{1}{2}},\, S_R = 2_{\frac{1}{2}}$

Generalization of the Bino-Higgsino-Slepton(LH) system of the MSSM

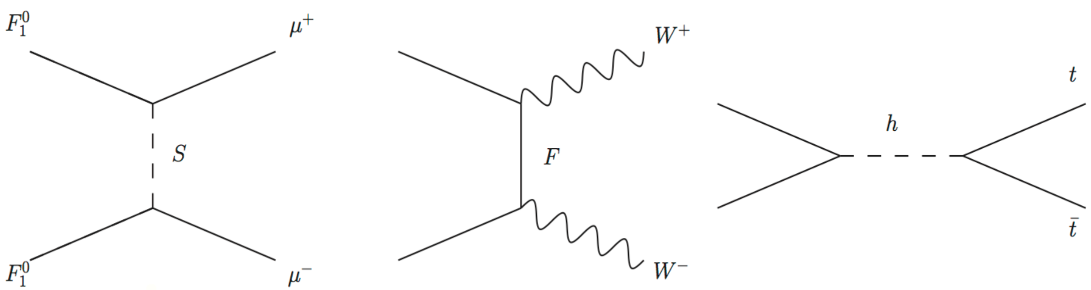
DM pheno similar to the Singlet-Doublet DM model

Mahbubani Senatore '05, Enberg et al. '07, Cohen et al. '11, Cheung Sanford '13, LC Mariotti Tziveloglou '15, ...

g-2:

$$\Delta a_\mu = \frac{m_\mu^2}{8\pi^2 M_S^2}|\lambda^S_{22}|^2 f^F_{LL}\left(\frac{M_L^2}{M_S^2}\right) + \frac{m_\mu}{8\pi^2 M_S^2}\sum_{A=1,2,3} M_A \mathrm{Re}\left(\lambda^S_{12}\lambda^S_{22}V_{1A}V_{2A}\right) f^S_{LR}\left(\frac{M_A^2}{M_S^2}\right)$$
$$- \frac{m_\mu^2}{8\pi^2 M_S^2}\sum_{A=1,2,3}\left(|\lambda^S_{22}|^2|V_{2A}|^2 + |\lambda^S_{12}|^2|V_{1A}|^2\right) f^S_{LL}\left(\frac{M_A^2}{M_S^2}\right).$$

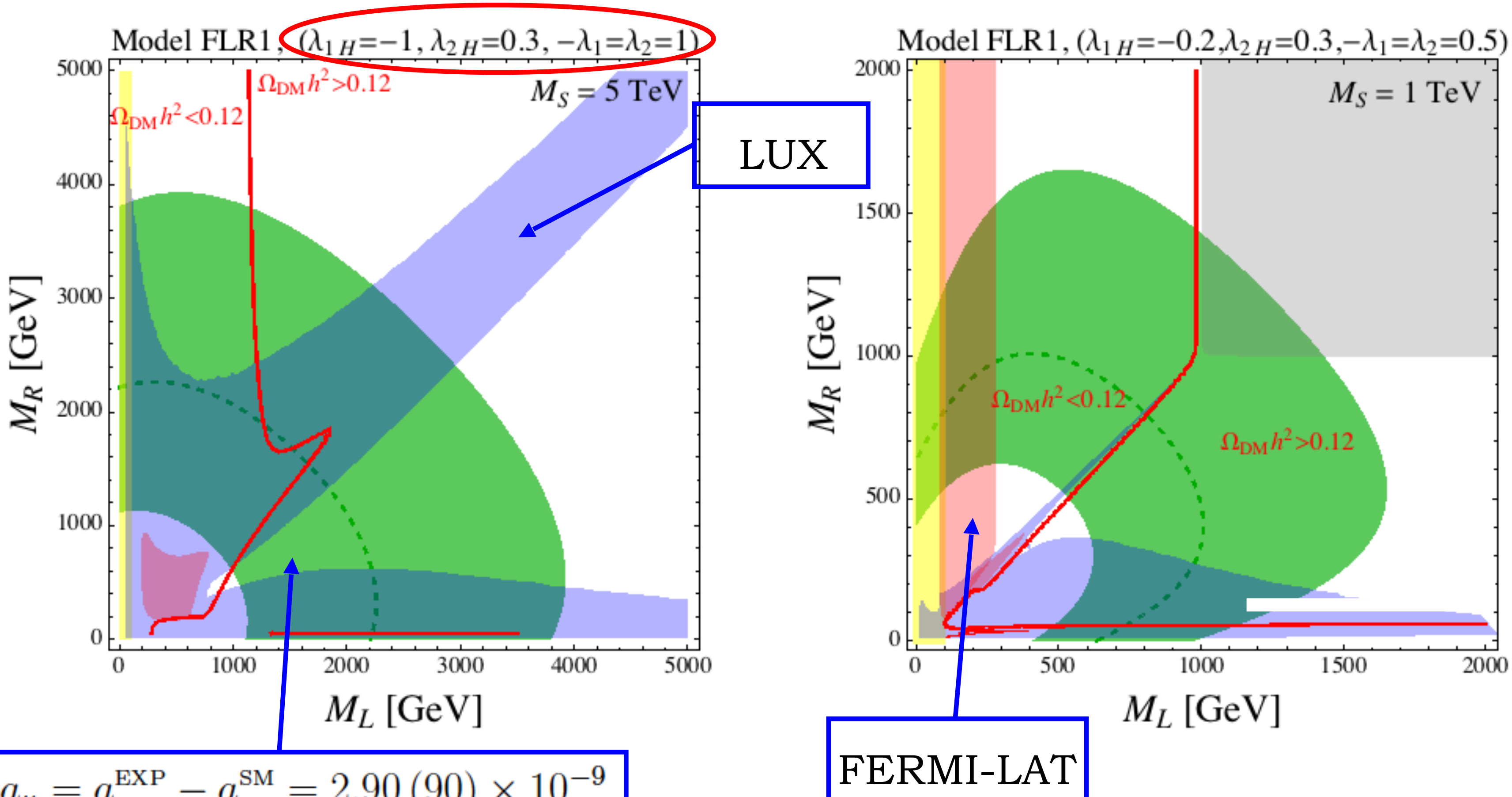
DM annihilation:



$$F_{0i}: \begin{pmatrix} M_R & \frac{\lambda_1^H v}{\sqrt{2}} & \frac{\lambda_2^H v}{\sqrt{2}} \\ \frac{\lambda_1^H v}{\sqrt{2}} & 0 & M_L \\ \frac{\lambda_2^H v}{\sqrt{2}} & M_L & 0 \end{pmatrix}$$

Class II models: a working example

Model FLR1: $F_R = 1^*_0, F_L = 2^*_{-\frac{1}{2}}, F^c_L = \overline{2}^*_{\frac{1}{2}}, S_R = 2_{\frac{1}{2}}$



$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 2.90\,(90) \times 10^{-9}$$

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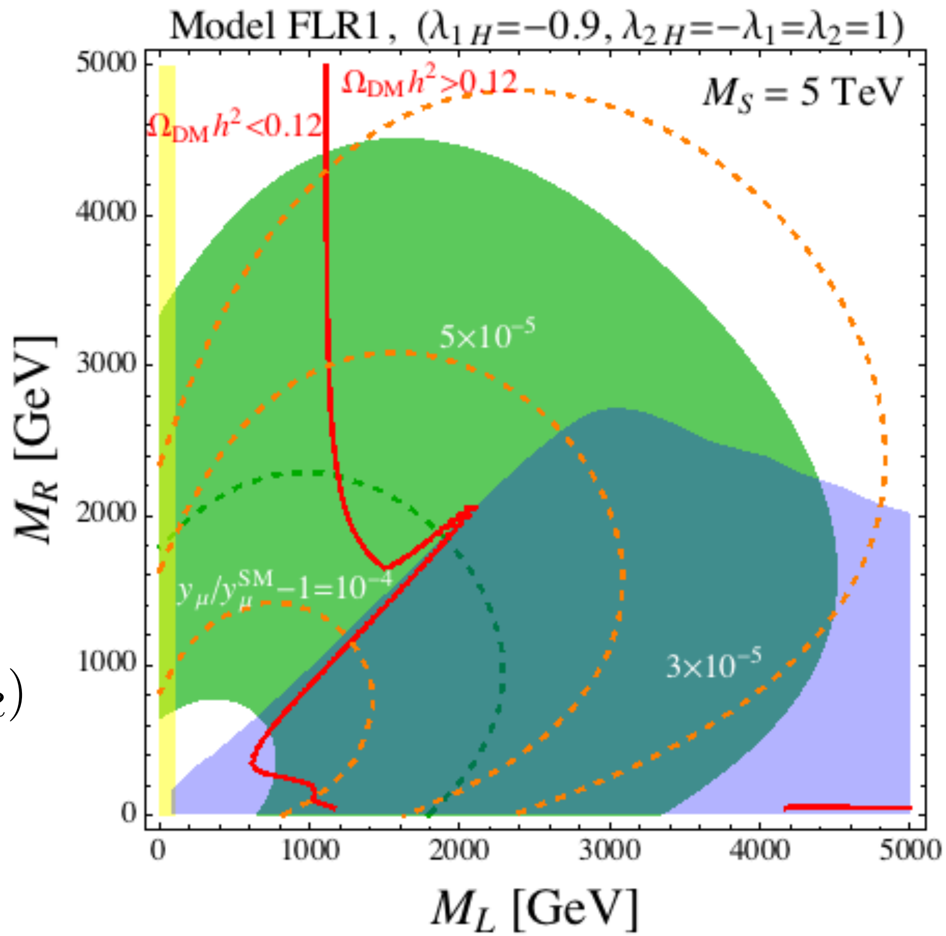
What about Higgs decays?

$$\mathcal{L} = \frac{c_{HHH}}{\Lambda^2}\overline{\mu}_L \mu_R H^\dagger H H + \text{h.c.}$$

$$\frac{y_\mu}{y_\mu^{\rm SM}} = 1 + \frac{3}{2\sqrt{2}}\frac{v^2}{\Lambda^2}c_{HHH}$$

$$\frac{c_{HHH}}{\Lambda^2} \approx -\frac{\lambda_\mu \lambda_{\mu^c}}{32\pi^2} f(y_F, \tilde{y}_F, M_S, M_L, M_R)$$

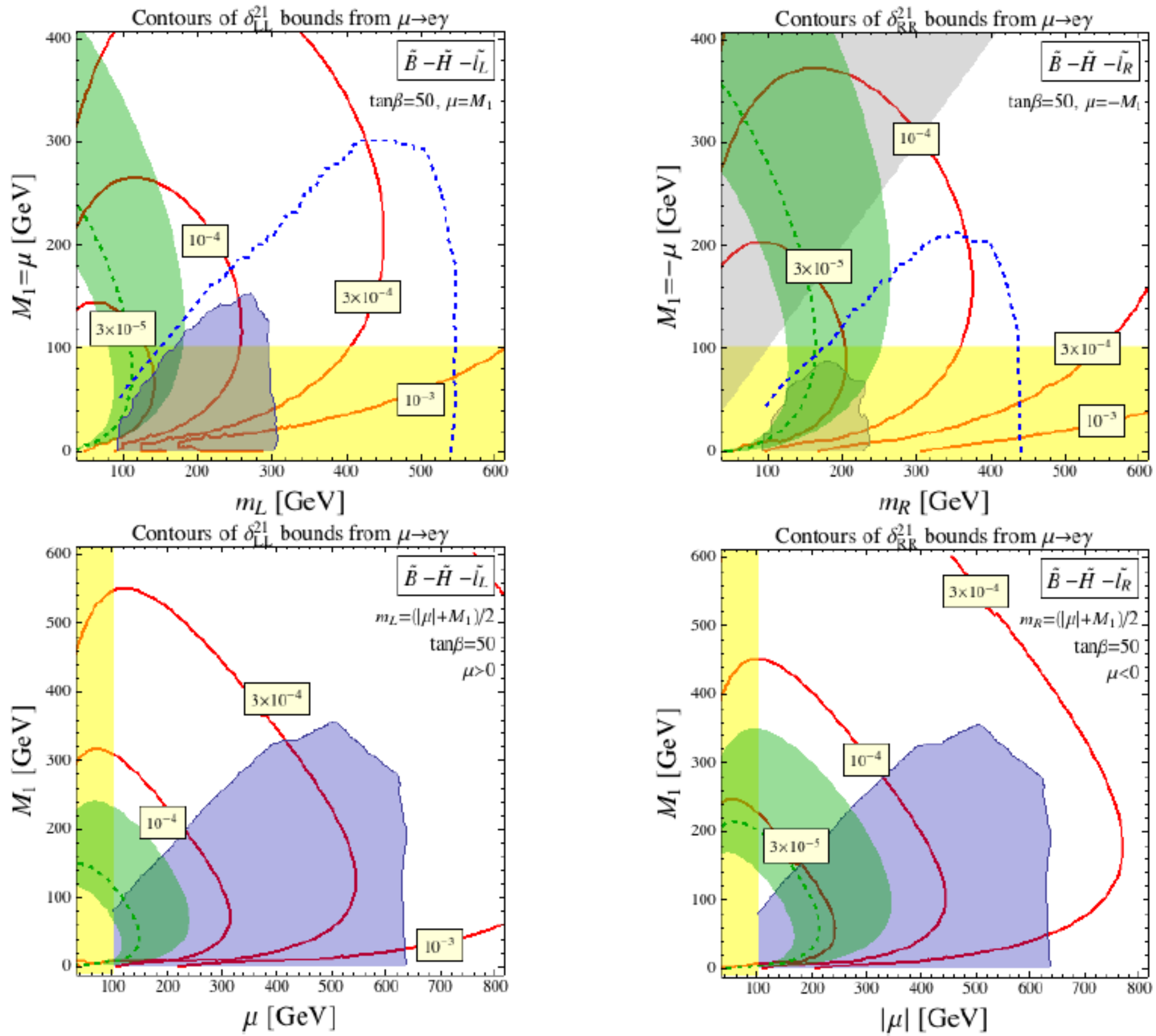


Conclusions

- We systematically built minimal models addressing the muon g-2 discrepancy and DM at the same time
- Our approach covered several known (simplified) scenarios (e.g. SUSY, vectorlike letpons)
- The simplest models, involving two new fields only, can not simultaneously fit DM and g-2, mainly due to recent LHC searches for new physics
- Large enhancement to the contribution to the muon g-2 is possible in models in which the new scalars or fermions couple to the SM Higgs
- In this class of models we can account for both DM and g-2 with multi-TeV new particles, easily evading all existing constraints

Additional Slides

Bino-Higgsino-Slepton system in SUSY



LC Galon Masiero Paradisi Shadmi '15

Singlet-Doublet DM at the LHC

ATLAS: arXiv:1402.7029
CMS: arXiv:1405.7570