EW and Flavour Physics @ CEPC

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Minimal models for the muon g−2 and Dark Matter

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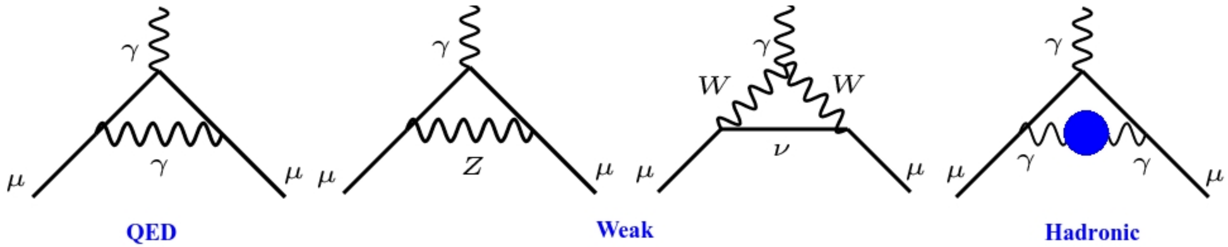
ITP-CAS, Beijing

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:

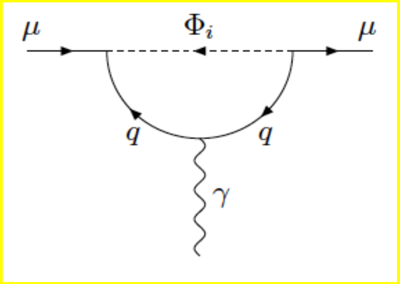
- Building the simplest extensions of the SM that, *at the same time*, (i) explain the muon g-2 anomaly, (ii) and provide a stable DM candidate
- Studying phenomenological consequences and testability of such minimal models

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 → 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,
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Coluccio Leskow 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

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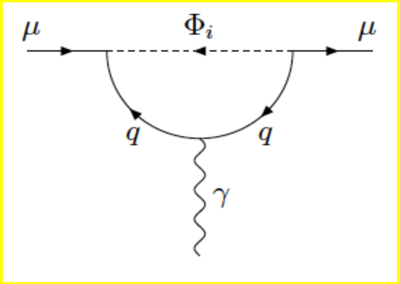

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We assume that only new particles run in the loop

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→ straightforward to introduce Z_2 for DM stability

Similar idea in Kowalska Sessolo '17 only for scalar singlet and inert doublet DM

Generic setup

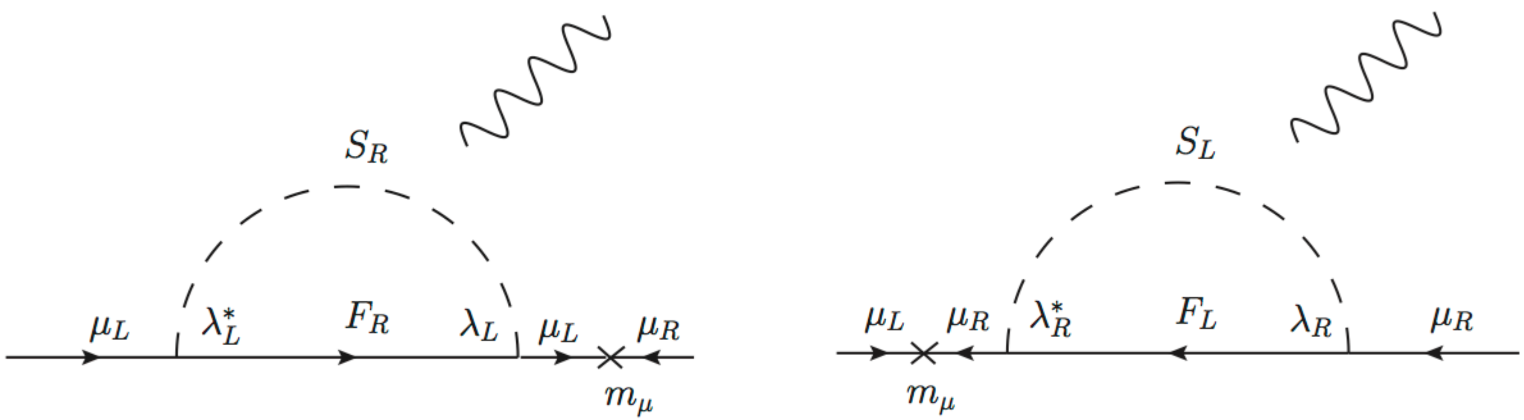
The goal is generating the usual dipole operator:

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

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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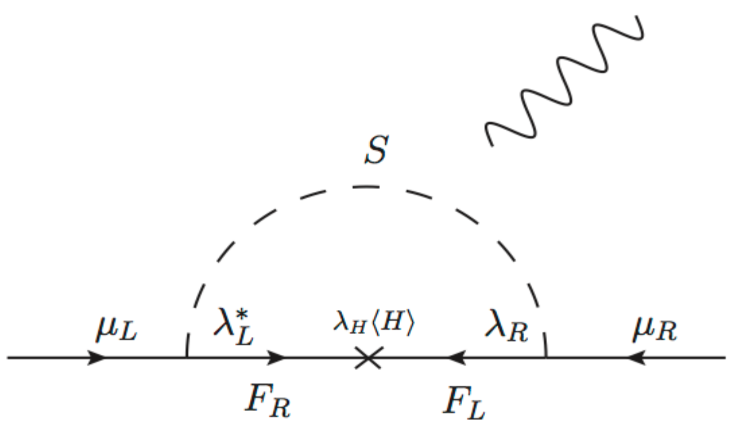
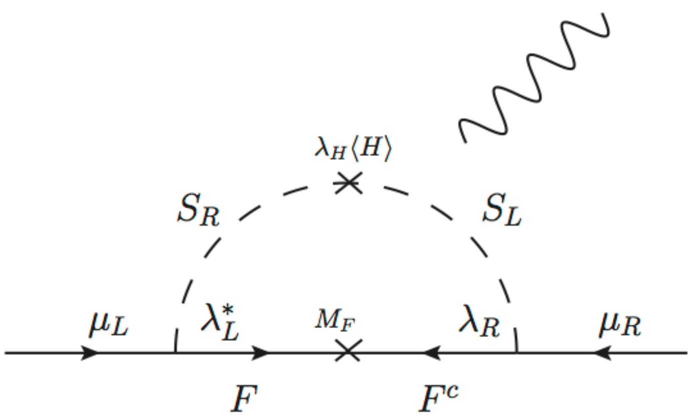
(II) Higgs insertion inside the loop:

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





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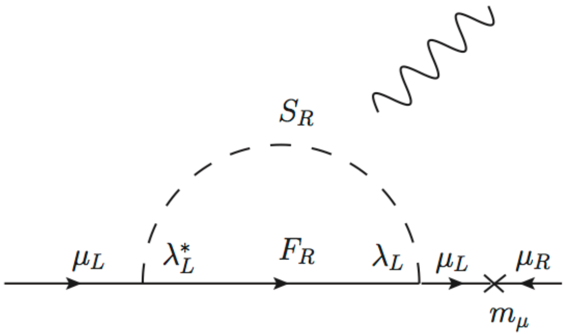
EW vev from a Higgs insertion to provide gauge invariant chirality flip

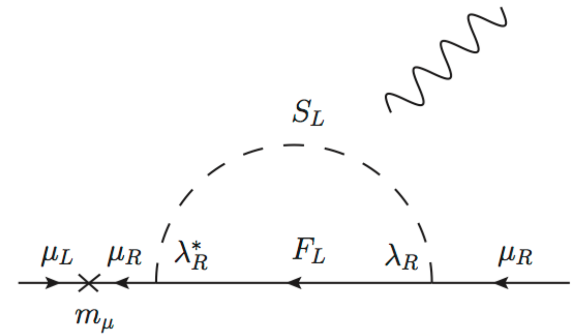
Unbroken Z_2:

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

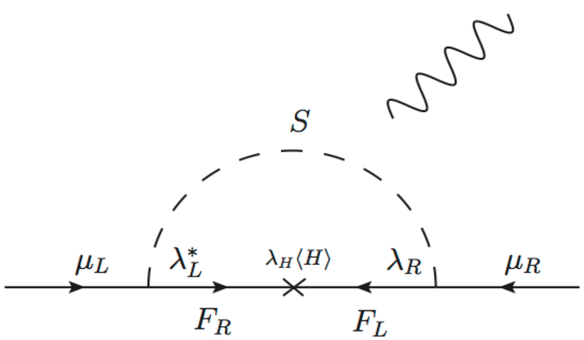
Contributions to the muon g-2

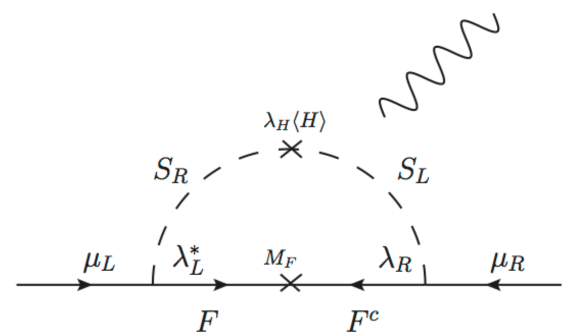
We aim at: $\Delta a_\mu = a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = 2.90\,(90) \times 10^{-9}$





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





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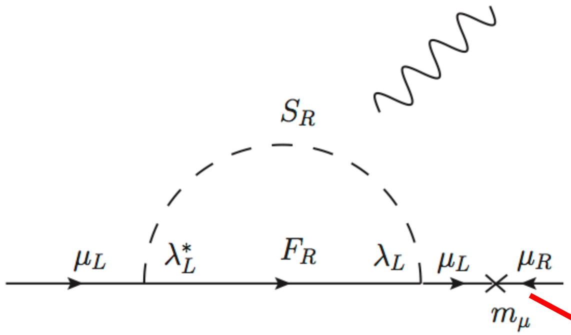

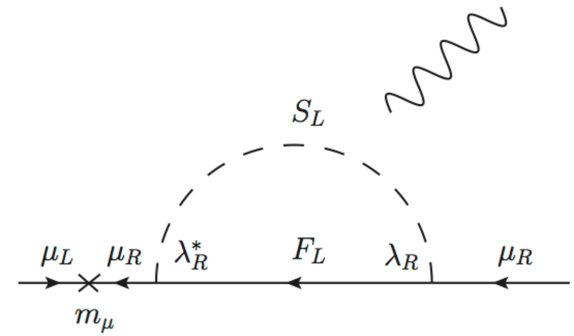

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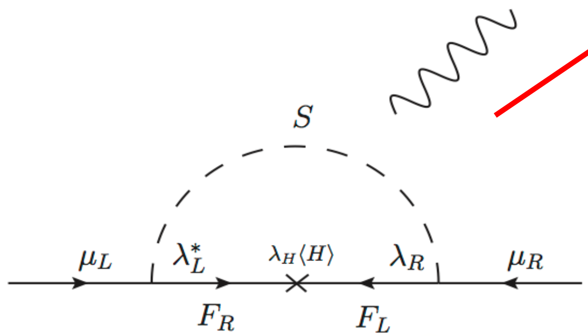

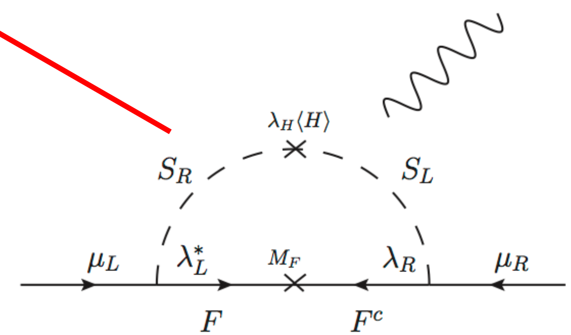

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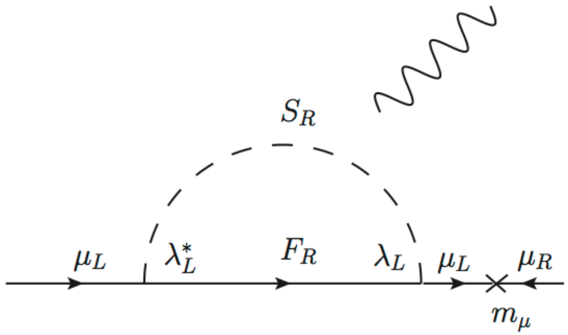

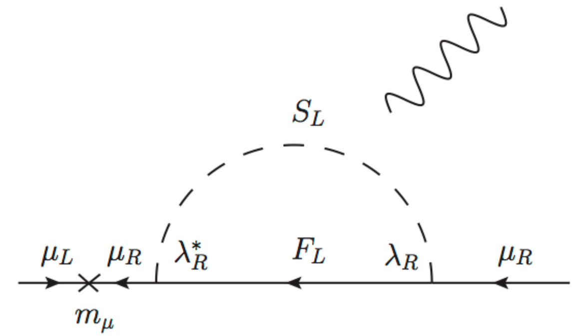

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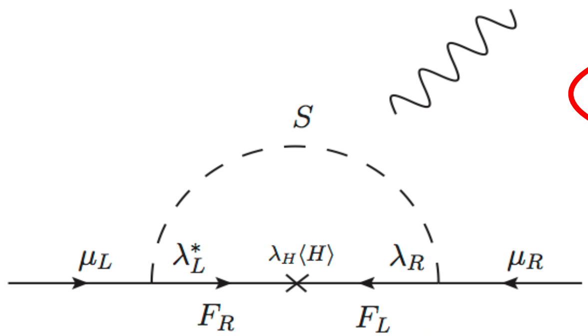
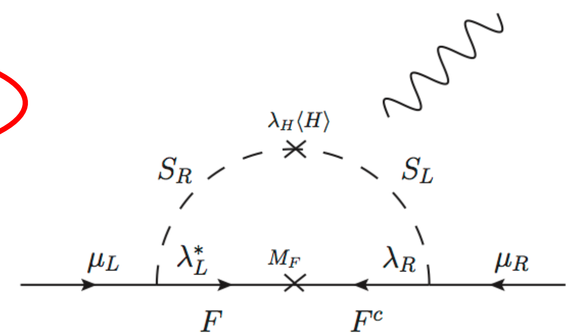
$$\left(f_{LL}^{F,S}(x) > 0, \quad f_{LR}^{F,S}(x) > 0\right)$$





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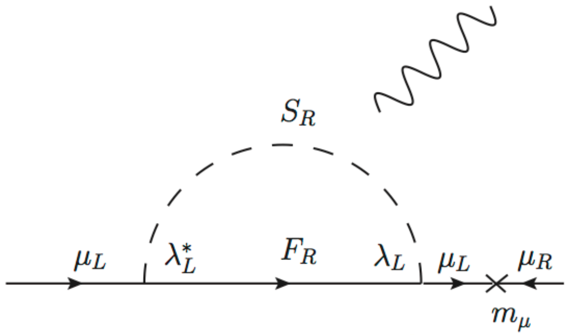

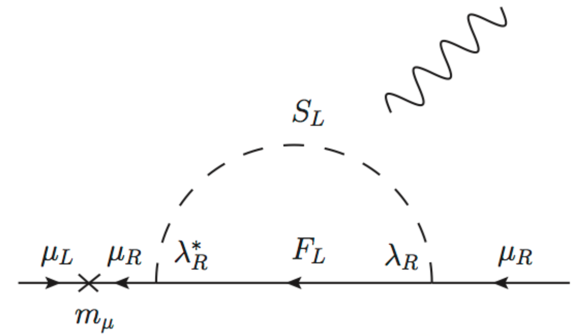

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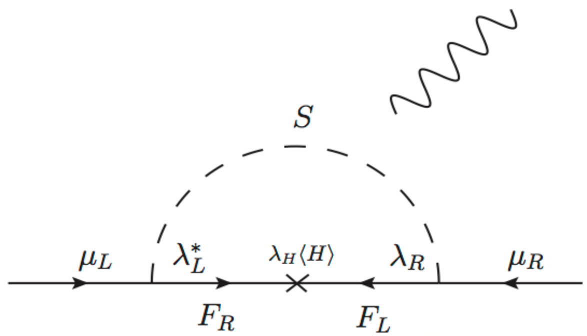
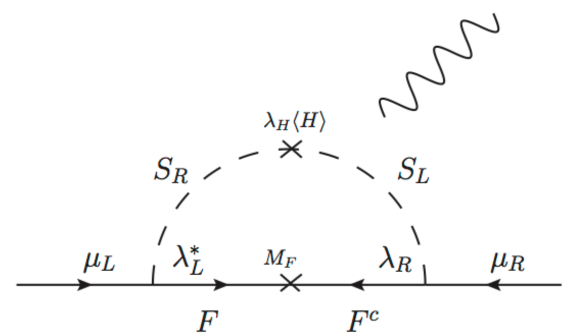


M_F/m_μ "enhancement"

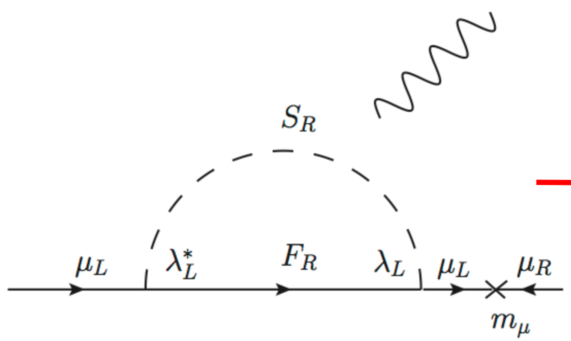


Class I models: external chirality flip

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

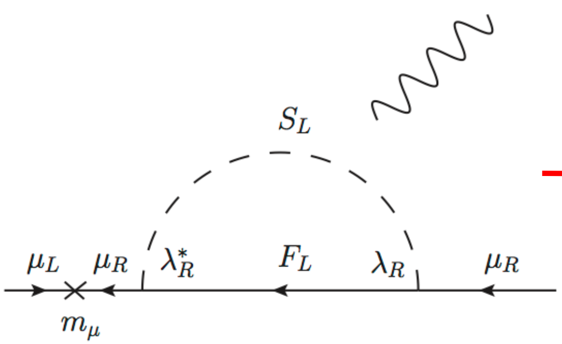
S and F must be colour singlet and contain at least one state with Q=0

$SU(2)_L \times U(1)_Y$ 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.



$\mu_R \sim 1_1$									
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.

$\star \rightarrow$ contain a neutral state

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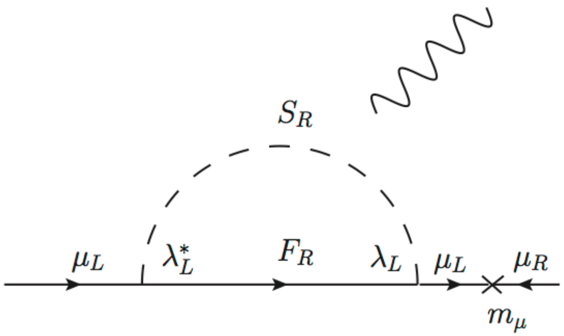
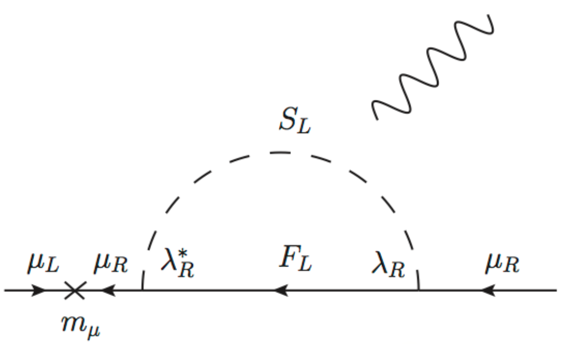


$$\Delta a_\mu^{LL,n_F=n_S\pm1} = -\frac{n\,m_\mu^2}{16\pi^2 M_S^2}|\lambda_L|^2\left[f_{LL}^S + \left(Y_S - \frac{\pm n+5}{6}\right)\left(f_{LL}^S + f_{LL}^F\right)\right]$$



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

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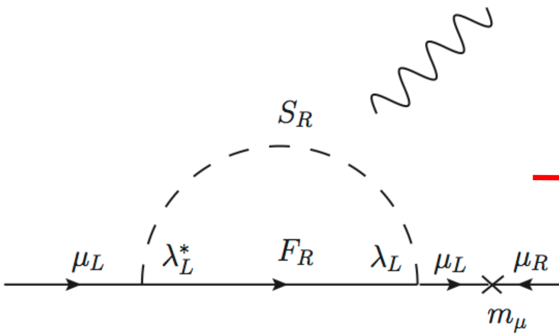

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Table I: Models with couplings to LH muons.

$\Delta a_\mu > 0$

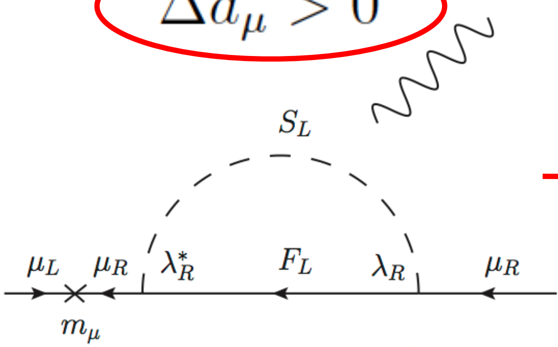

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Table II: Models with couplings to RH muons.

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

$\star \to$ contain a neutral state

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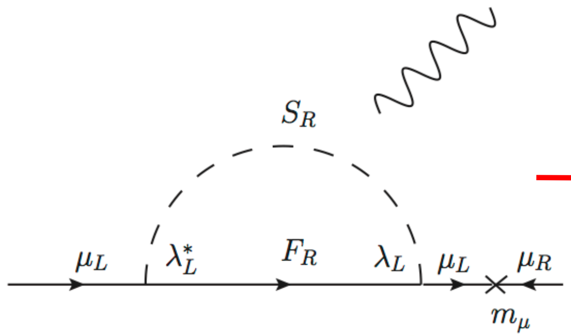

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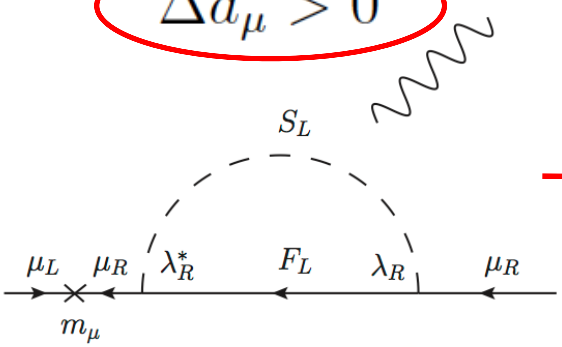

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(e.g. excludes ~ Bino-LH/RH smuon)

$\star \rightarrow$ contain a neutral state

Class I models: the two simplest examples

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

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

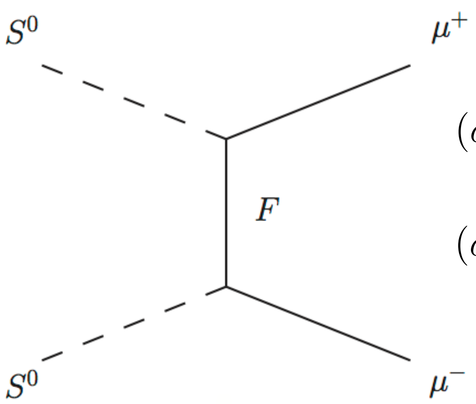
$$\mathcal{L}_{\rm RR1} = \lambda_i^R \overline{e}_{Ri} F_- S + \lambda_i^{R*} \overline{F}_- e_{Ri} S - M_F \overline{F}_- F_- - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm scalar}$$

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

Singlet scalar S

DM candidate

DM annihilation:



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

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

$$r = M_S/M_F$$

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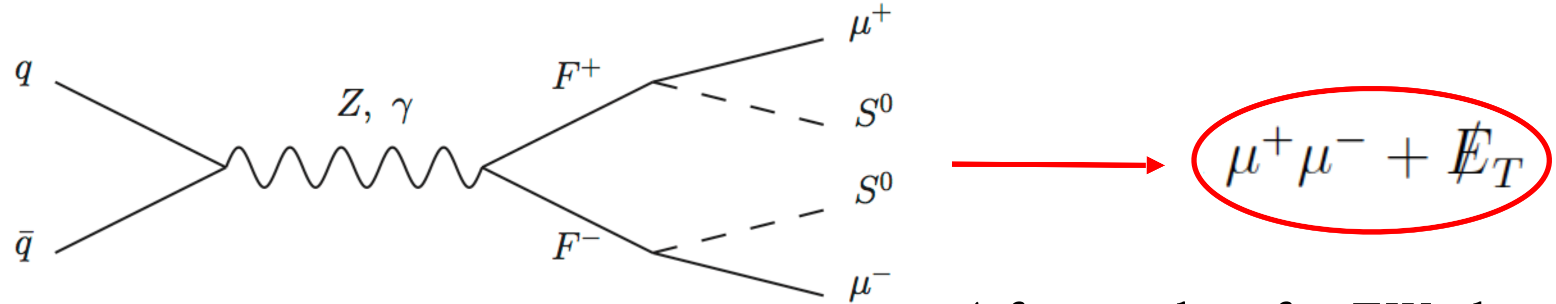
Singlet scalar S
DM candidate

LHC production and decay:

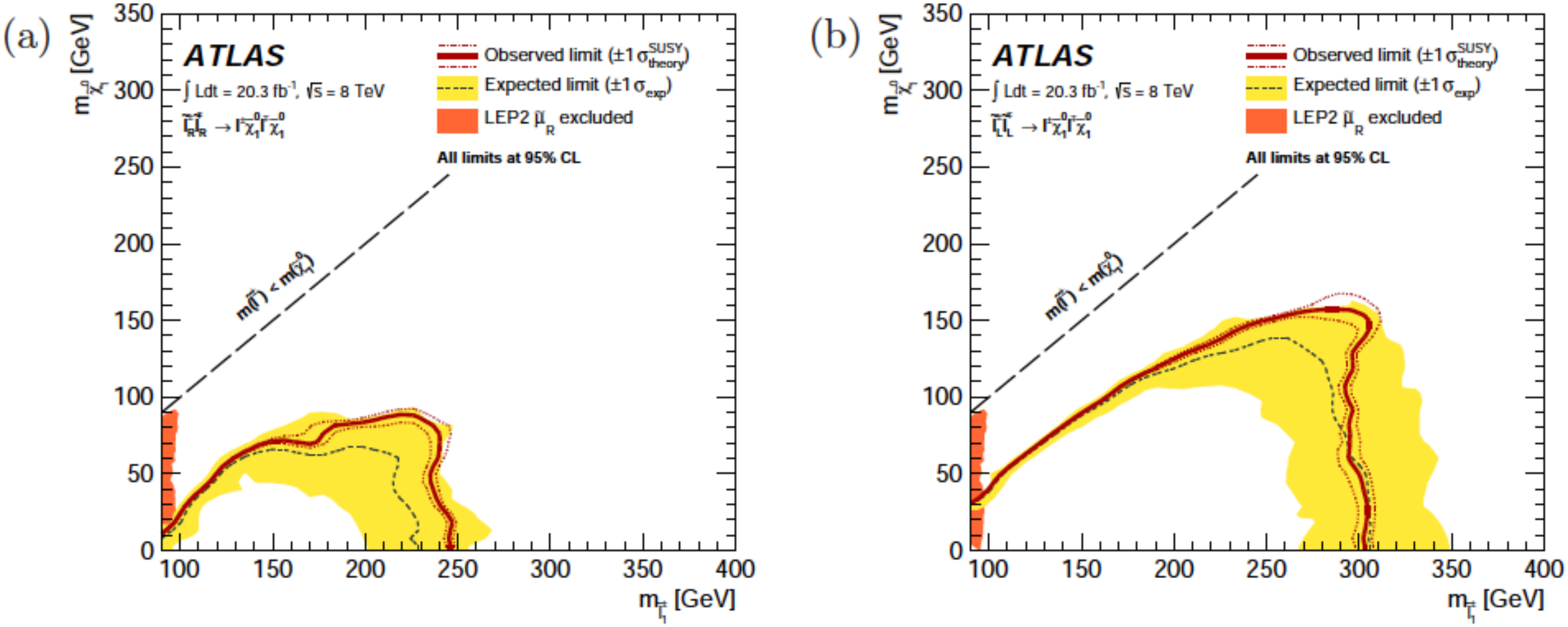


(cf. searches for EW slepton production at the LHC)

Direct slepton searches at the LHC

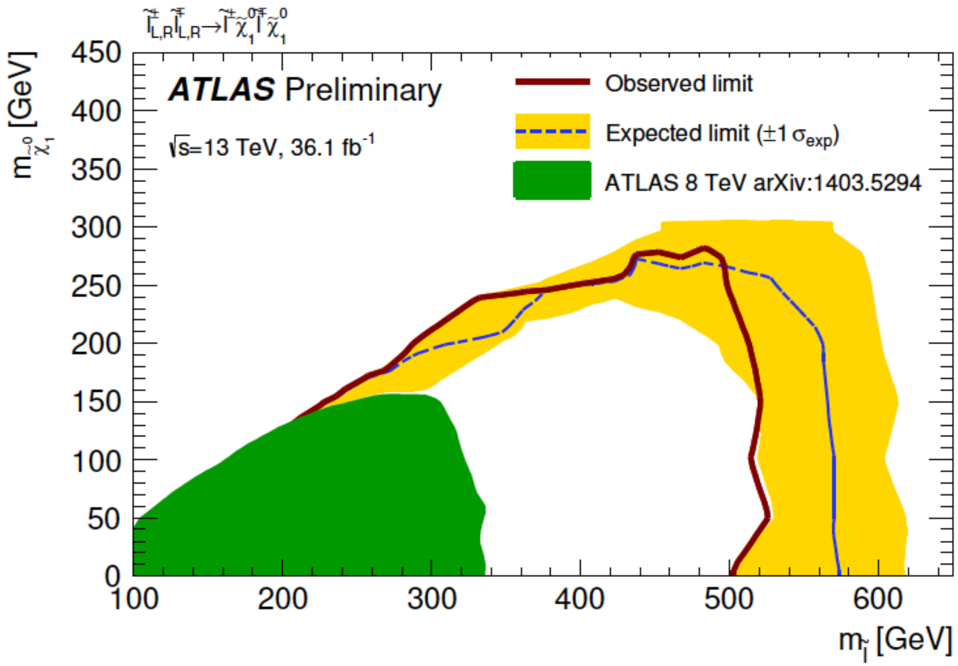
ATLAS: arXiv:1403.5294
CMS: arXiv:1405.7570

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



ATLAS-CONF-2017-039

Search for electroweak production of supersymmetric particles in the two and three lepton final state at $\sqrt{s}$ = 13 TeV with the ATLAS detector



(b) Direct $\tilde{\ell}$ pair production (combined left-handed, $\tilde{\ell}_L$, and right-handed sleptons, $\tilde{\ell}_R$)

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” : $F_L = 1_{-1}, F_L^c = 1_1, S_L = 1_0^*$

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

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

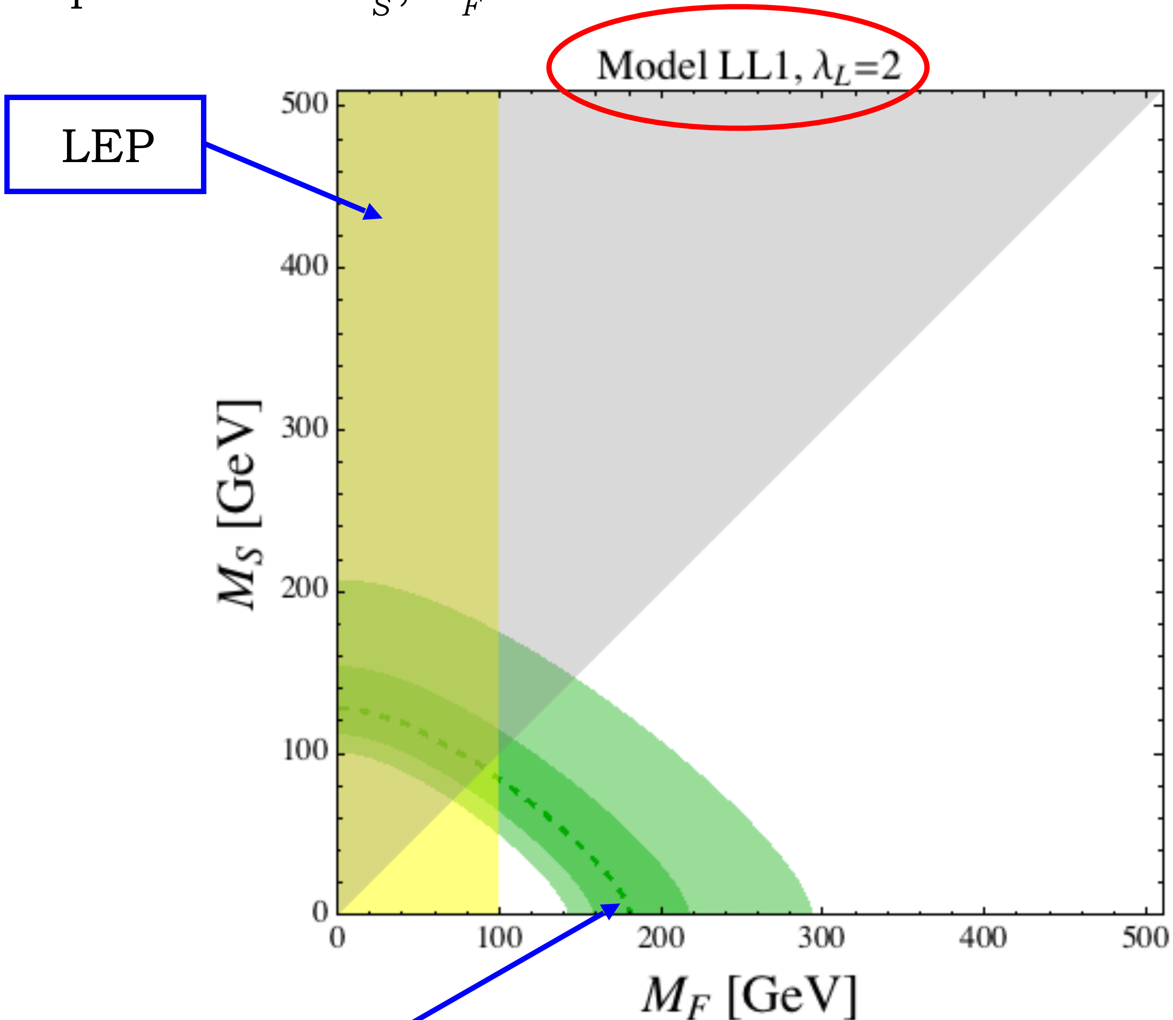
$$\Delta a_\mu^{\rm LL1,RR1} = \frac{m_\mu^2}{8\pi^2 M_S^2} |\lambda|^2 f_{LL}^F \left(\frac{M_F^2}{M_S^2} \right)$$

Singlet scalar S
DM candidate

Additional constraints:

- LFV processes (e.g. $\mu \to e\,\gamma$): small couplings to e (~10^{-5}) and τ (~10^{-2}) *or* three F generations + alignment (flavour symmetry?)
- EDMs do not arise at one loop (phase of coupling cancels in the penguin)

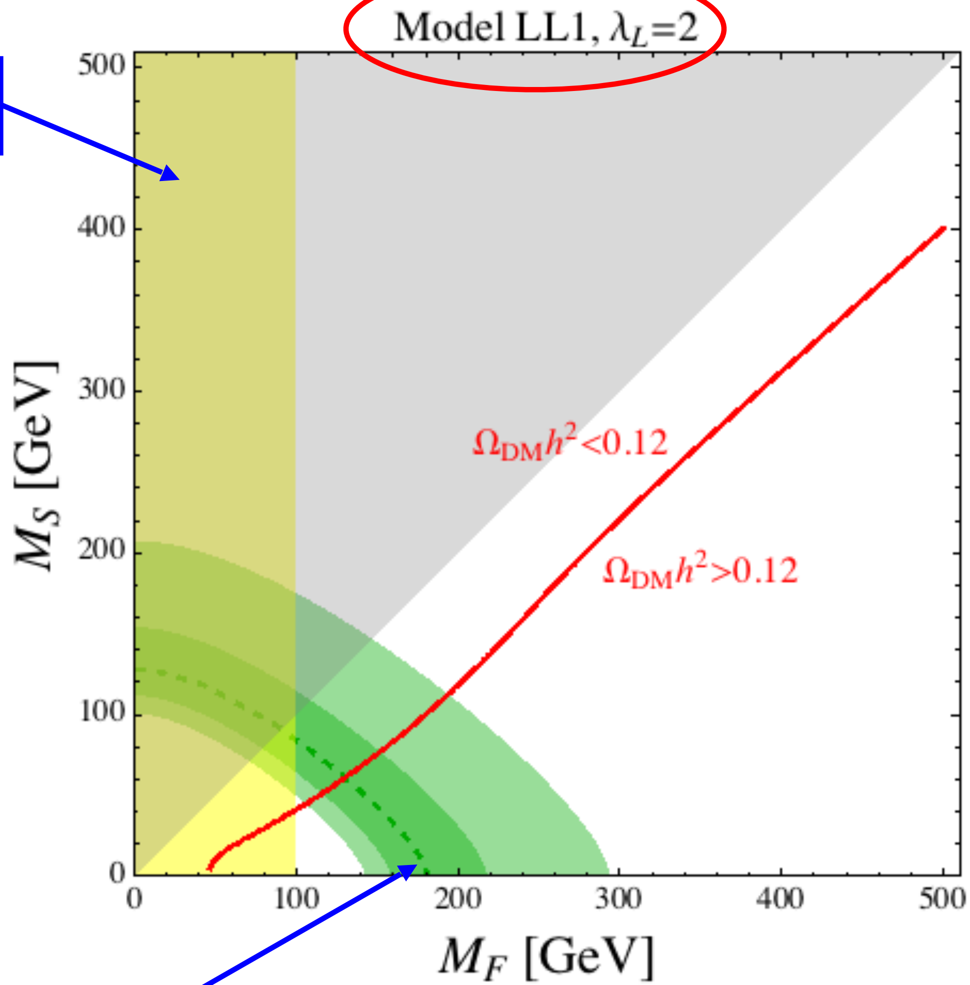
Only three parameters: M_S, M_F and λ :

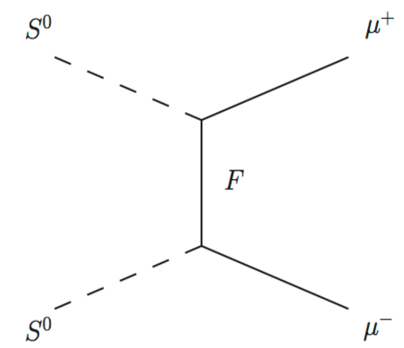


$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 2.90\,(90) \times 10^{-9}$$

Only three parameters: M_S, M_F and λ :

LEP



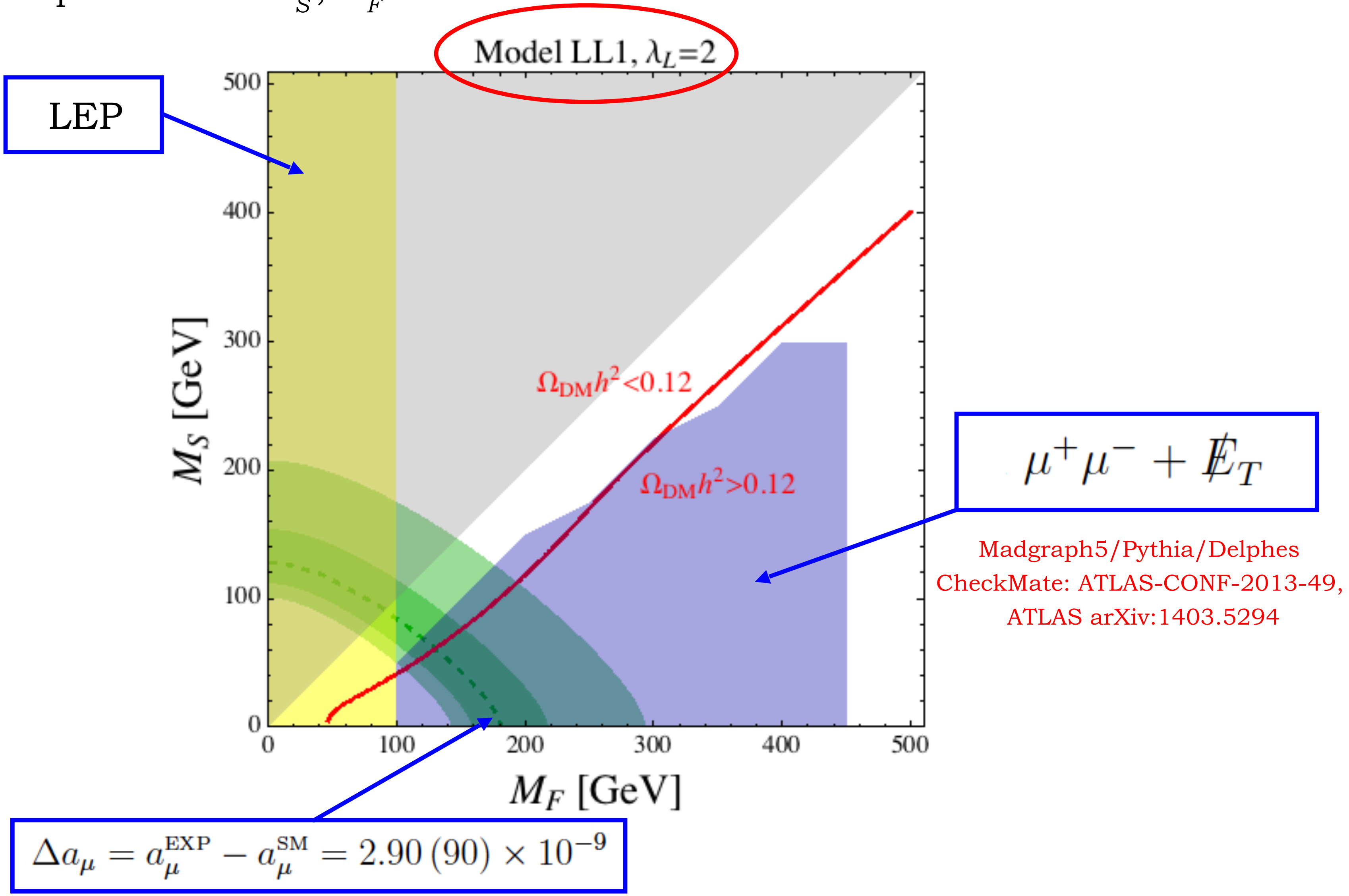


micrOMEGAs

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

The simplest LL model

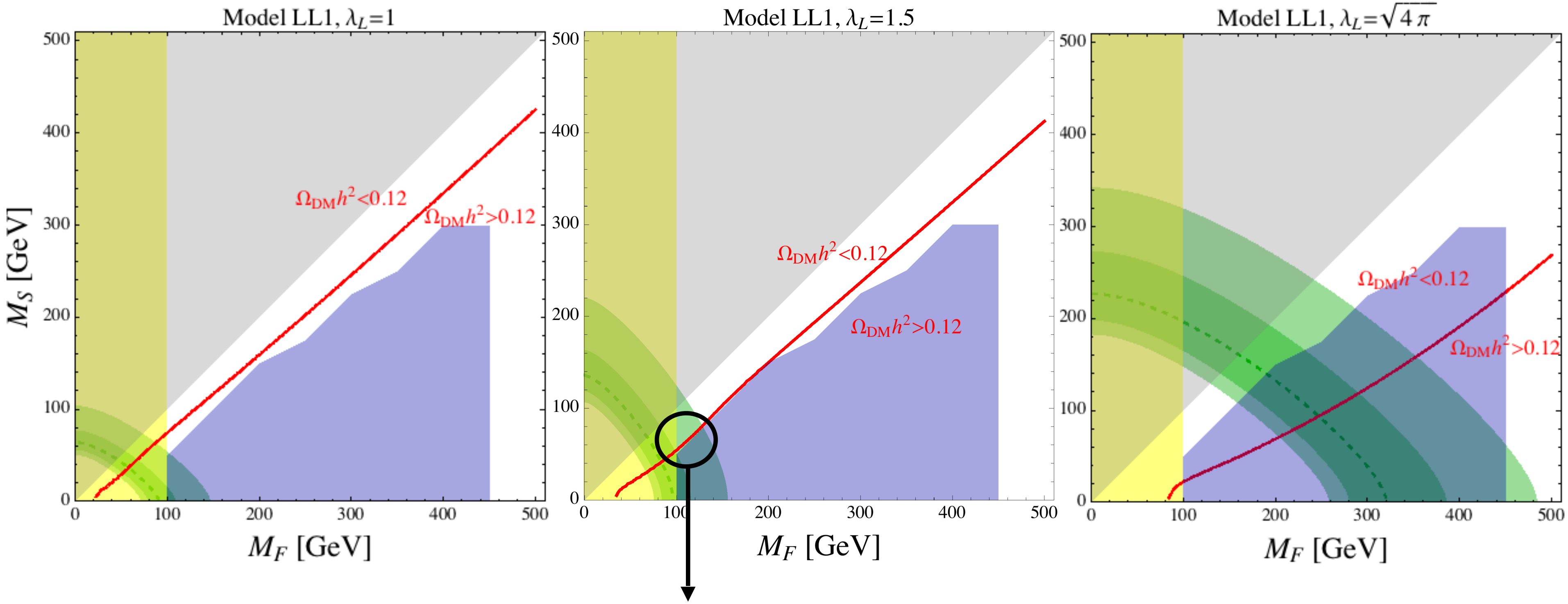
Only three parameters: M_S, M_F and λ :



The simplest LL model

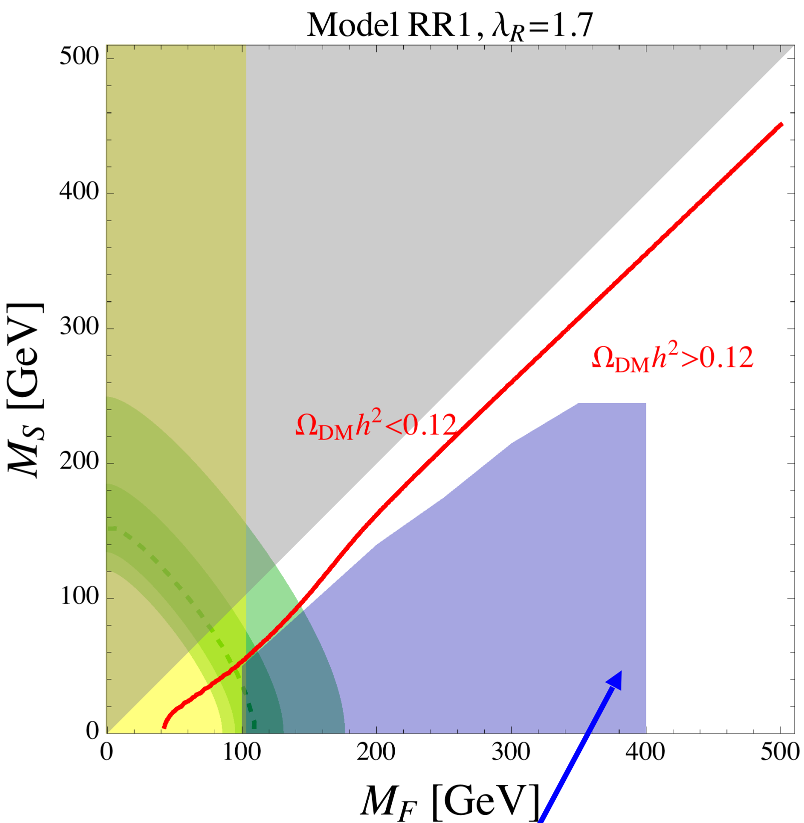
Varying λ:

$\lambda = 1$ $\lambda = 1.5$ $\lambda = \sqrt{4\pi}$



A corner of the parameter space in the compressed mass region difficult to test at the LHC (even with soft leptons searches) but it's easily accessible at CEPC

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.

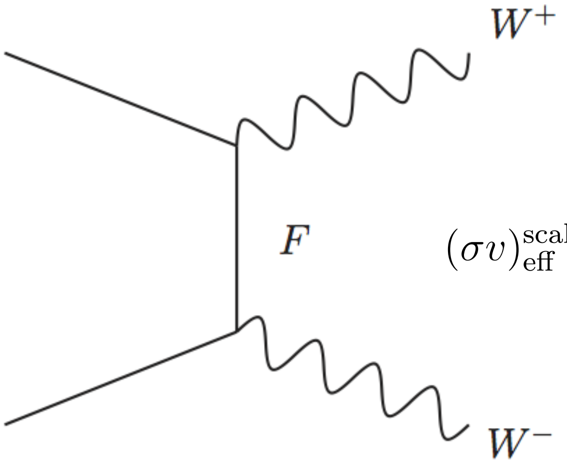
$\mu_R \sim 1_1$									
F_L	$1^\star_0$	1_{-1}	$2^\star_{-\frac{1}{2}}$	$2^\star_{\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$3^\star_{-1}$	$3^\star_0$	$3^\star_1$	3_{-2}
S_L	1_{-1}	$1^\star_0$	$2^\star_{-\frac{1}{2}}$	$2_{-\frac{3}{2}}$	$2^\star_{\frac{1}{2}}$	$3^\star_0$	$3^\star_{-1}$	3_{-2}	$3^\star_1$

Table II: Models with couplings to RH muons.

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

Other class I models

What about modes with DM in n>1, *e.g.* triplets? Is there a ‘cutoff’ on n ?



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

[for Y=0]

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

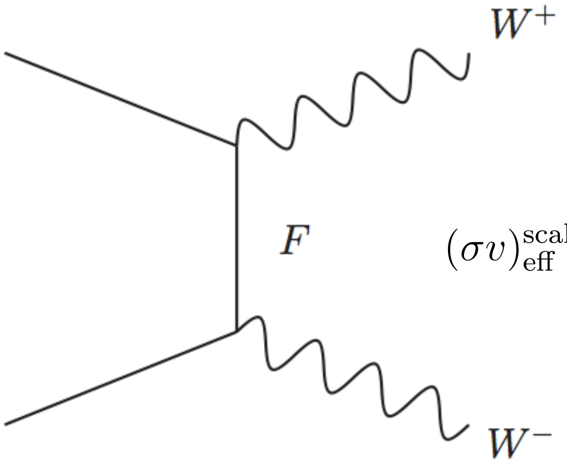
Maximizing the contribution to the g-2:

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

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

Other class I models

What about modes with DM in n>1, *e.g.* triplets? Is there a 'cutoff' on n ?



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

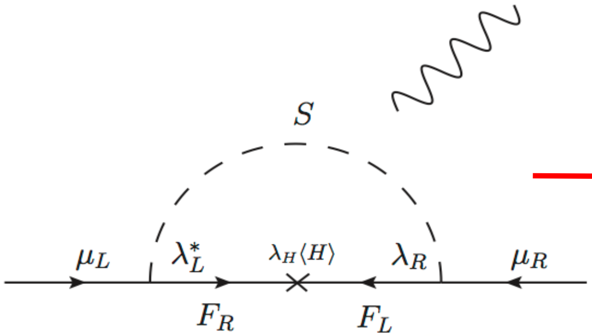
[for Y=0]

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

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

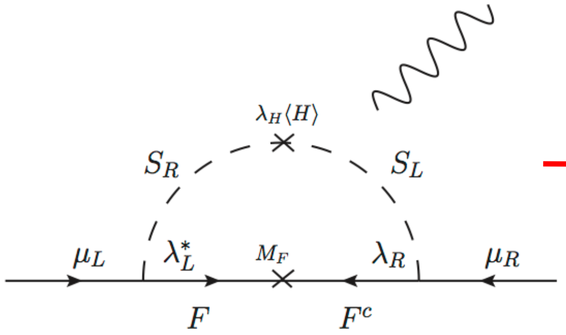
→ we have to consider additional fields allowing mixing with the Higgs inside the loop

Class II models: chirality flip inside the loop



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

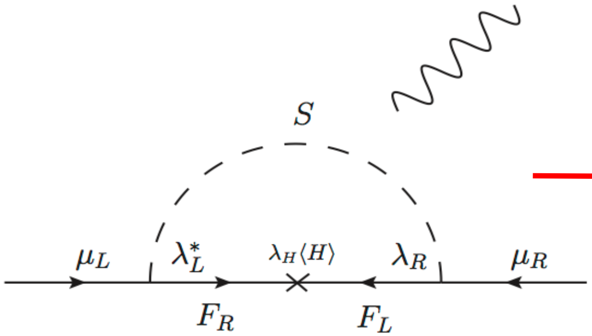
Table III: Models with fermion-Higgs couplings.



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

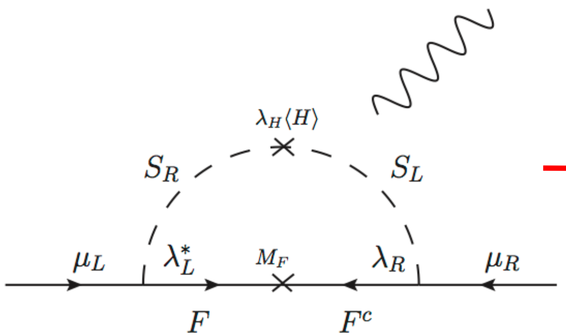
Table IV: Models with scalar-Higgs couplings.

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

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, ...

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

$$\mathcal{L}_{\text{gauge}} = \frac{g}{c_W} Z_\mu \left[\frac{1}{2}\left(V_{2i}^* V_{2j} - V_{3i}^* V_{3j}\right) \overline{F}_{0i} \gamma^\mu P_L F_{0j} + \frac{1}{2}\left(V_{2i} V_{2j}^* - V_{3i} V_{3j}^*\right) \overline{F}_{0i} \gamma^\mu P_R F_{0j}\right]$$
$$+ \frac{g}{c_W} Z_\mu \left[\left(-\frac{1}{2} + s_W^2\right) \overline{F}_- \gamma^\mu F_- + \text{h.c.}\right] + |e| A_\mu \overline{F}_- \gamma^\mu F_-$$
$$+ \frac{g}{\sqrt{2}} \left[W_\mu^+ \left(V_{2i}^* \overline{F}_{0i} \gamma^\mu P_L F_- + V_{3i} \overline{F}_{0i} \gamma^\mu P_R F_-\right) + \text{h.c.}\right]\,,$$

$$\mathcal{L}_h = -\frac{h}{\sqrt{2}} \left(\lambda_1^H V_{2i} V_{1j} + \lambda_2^H V_{3i} V_{1j}\right) \overline{F}_{0i} P_L F_{0j} + \text{h.c.}\,,$$

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

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

Class II models: a working example

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

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

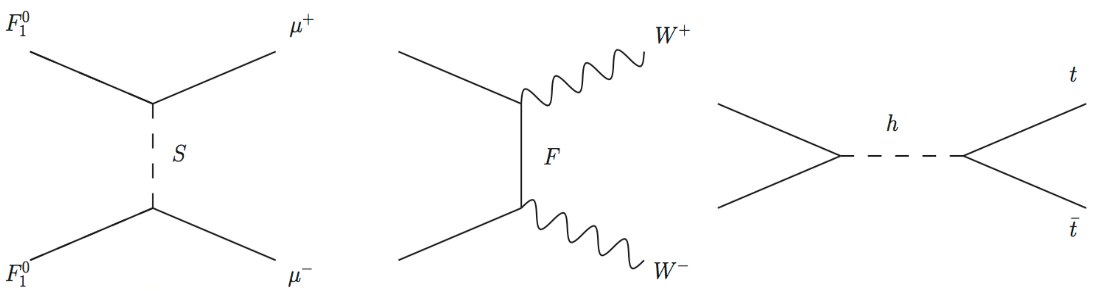
DM pheno similar to the Singlet-Doublet DM model

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

g-2:

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

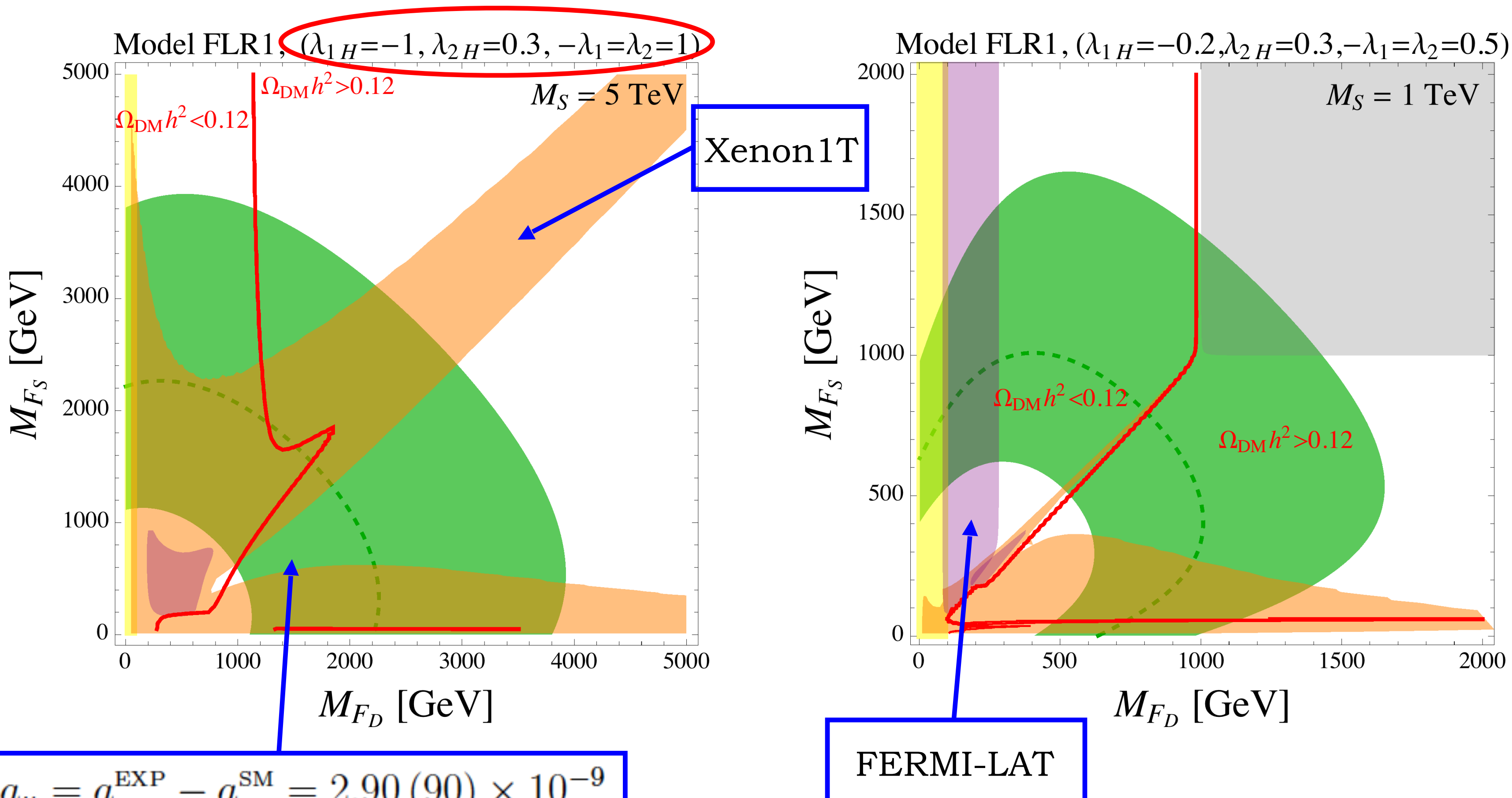
DM annihilation:



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

Class II models: a working example

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



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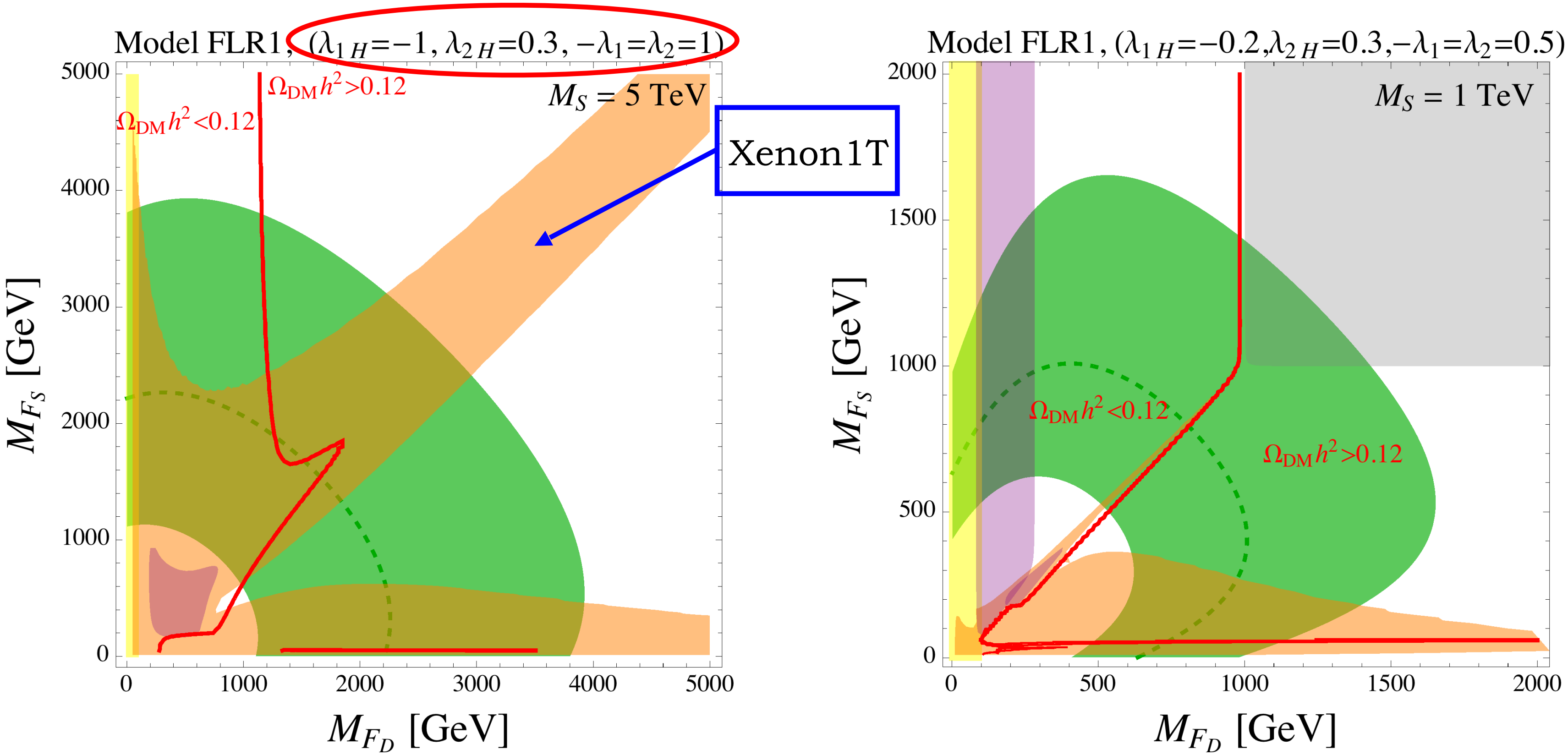


Common DM/g-2 explanation possible for masses unaccessible at colliders
However large chirality and lepton flavour universality breaking, possibly testable by precision obs., e.g. Z-mu-mu

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 simultaneously fit DM and g-2 only for fine-tuned choice of the parameters, 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 collider/DM constraints

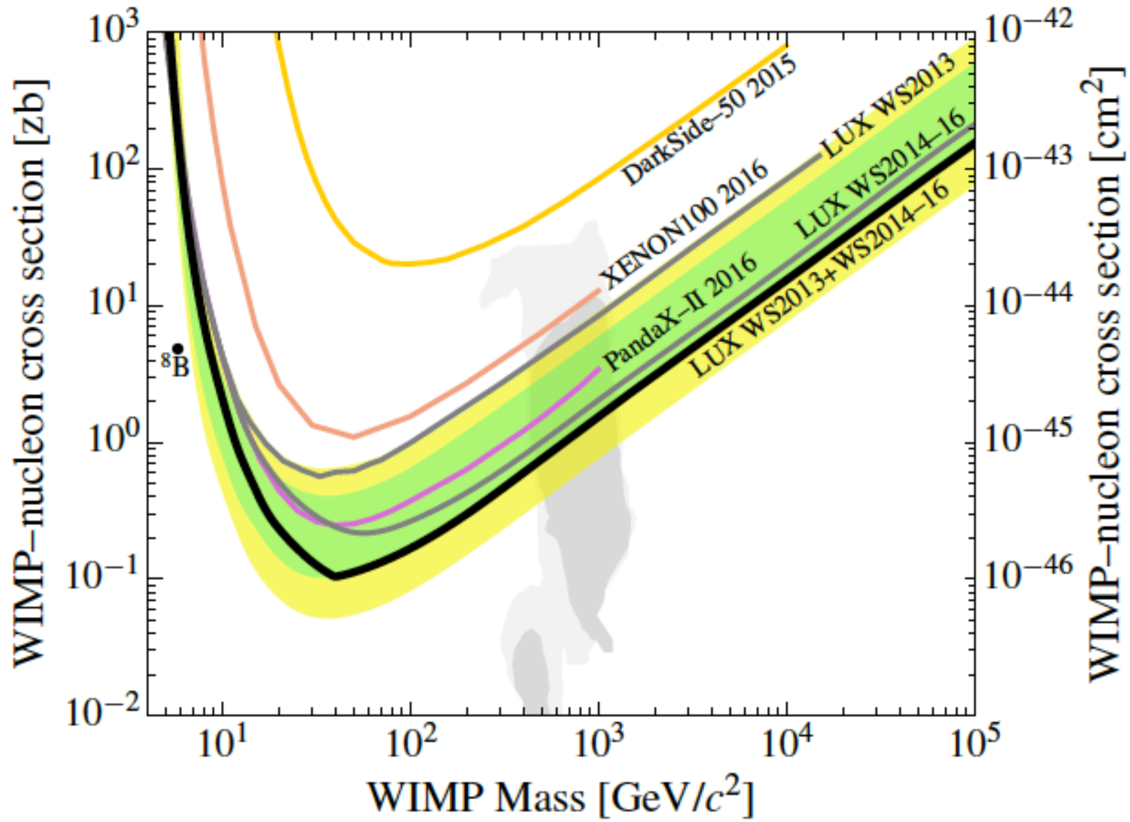
谢 谢

Additional Slides

Direct detection would exclude *minimal* hypercharged DM

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

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



Class I models: the two simplest examples

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

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

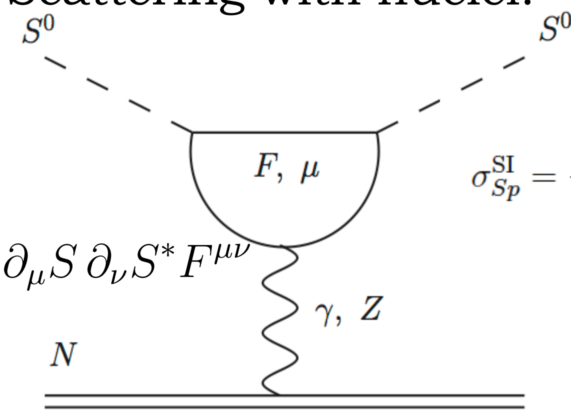
$$\mathcal{L}_{\text{RR1}} = \lambda_i^R \overline{e}_{Ri} F_- S + \lambda_i^{R*} \overline{F}_- e_{Ri} S - M_F \overline{F}_- F_- - \frac{1}{2} M_S^2 S^2 + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{scalar}}$$

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

Singlet scalar S

DM candidate

Scattering with nuclei:

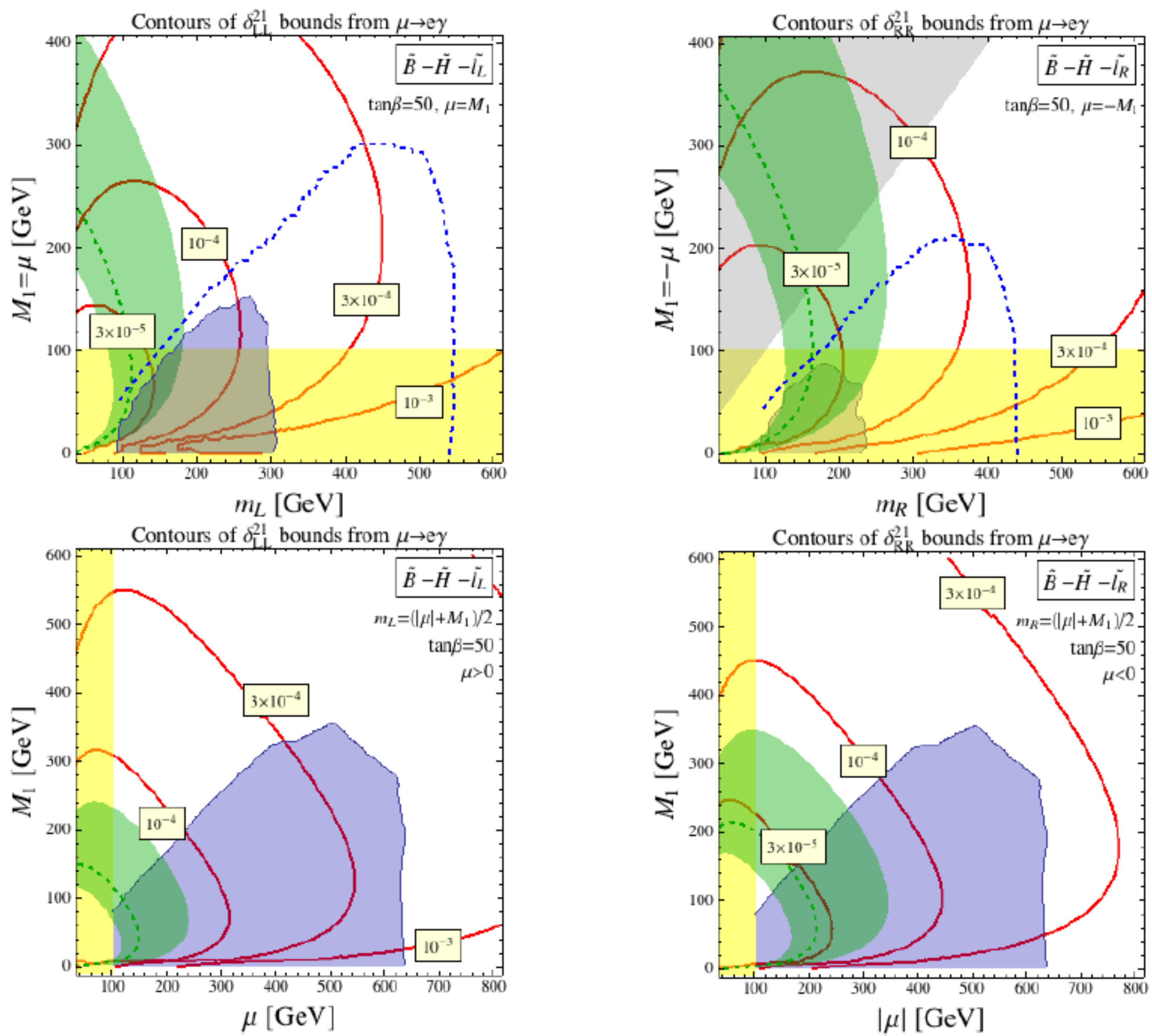


$$\sigma_{Sp}^{\text{SI}} = \frac{\alpha^2 Q_e^2}{4\pi^3} \frac{Z^2}{A^2} \frac{m_N^2 \mu_{Sp}^2}{m_S^2} \tilde{A}_{\text{tot}}^2 = 1.7 \cdot 10^{-42} \text{cm}^2 \frac{Q_e^2 Z^2}{A^2} \frac{m_N^2}{m_S^2} \left(\frac{\mu_{Sp}}{\text{GeV}} \right)^2 \left(\frac{\tilde{A}_{\text{tot}}}{1/(100\,\text{GeV})^2}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

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

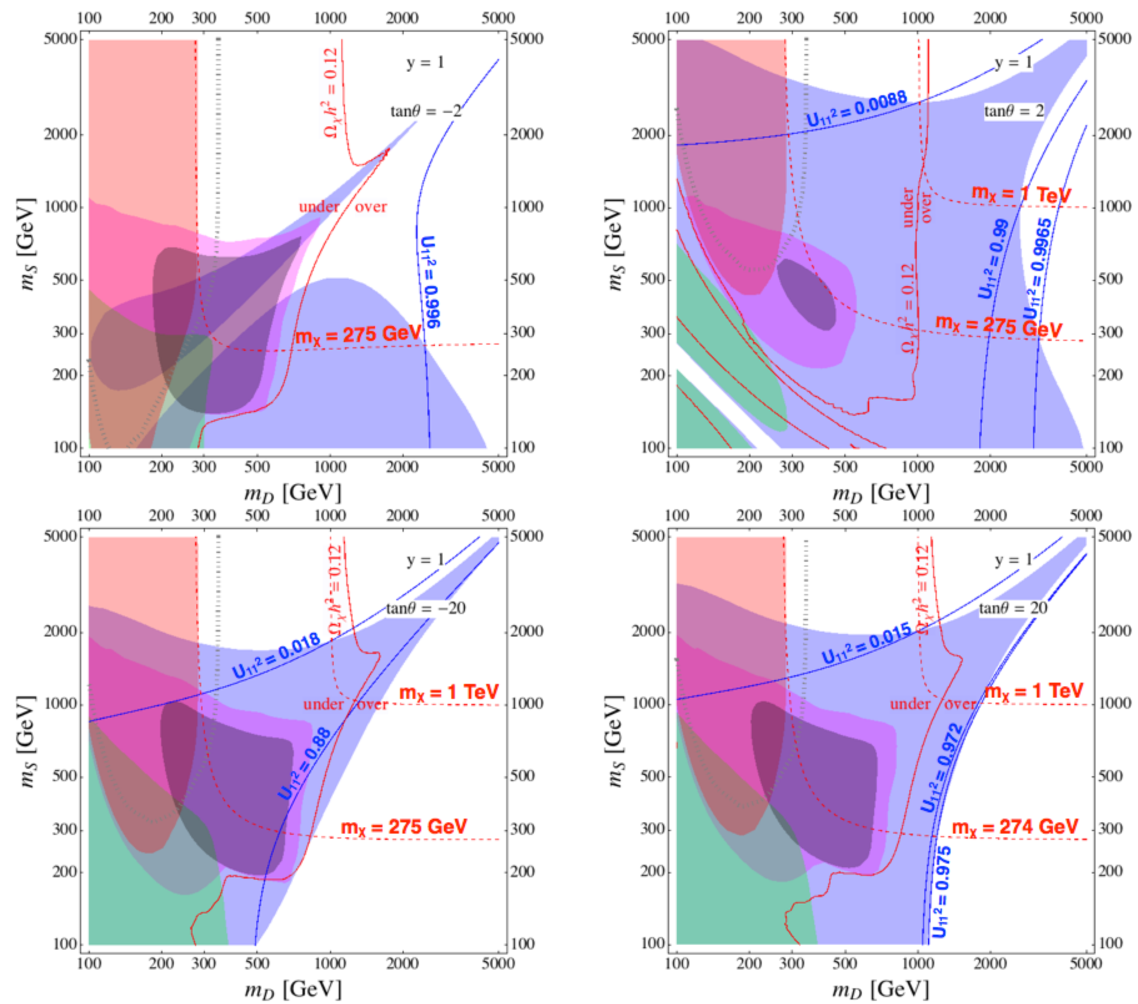
→ S must be *real* or O(100) keV real/ imaginary part splitting

Bino-Higgsino-Slepton system in SUSY



LC Galon Masiero Paradisi Shadmi '15

Singlet-Doublet DM

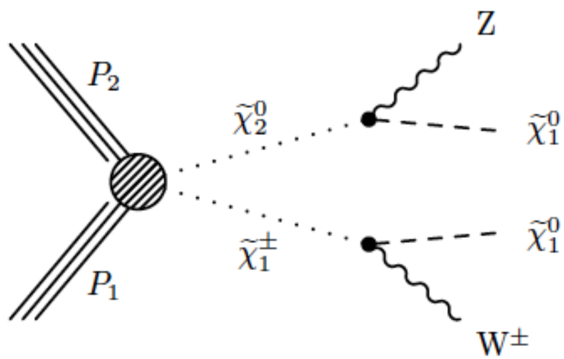


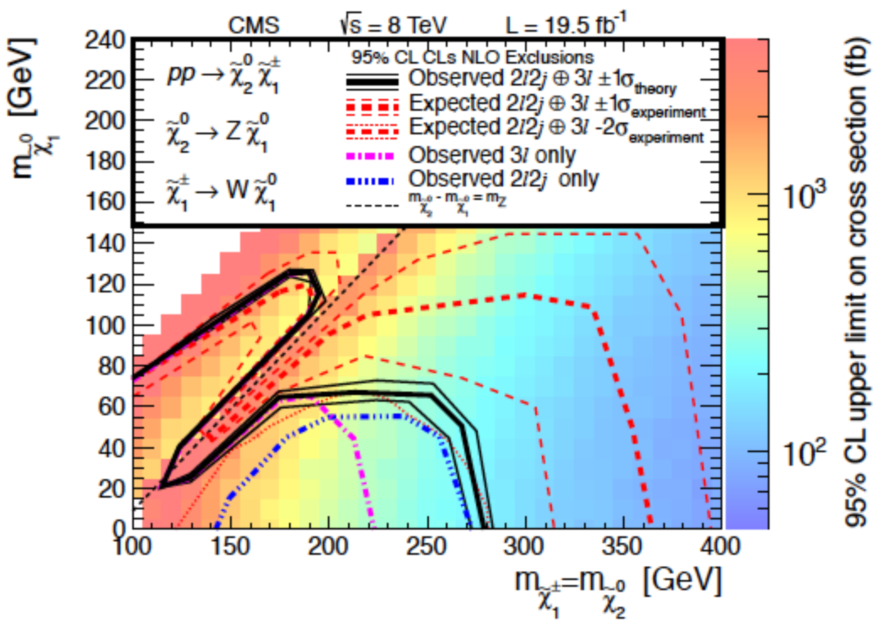
$$c_{h\chi\chi} = -\frac{(2y_1 y_2 m_{\rm D} + (y_1^2 + y_2^2) m_1) v}{m_{\rm D}^2 + (y_1^2 + y_2^2)\frac{v^2}{2} + 2 m_{\rm S}\, m_1 - 3 m_1^2}\,,$$

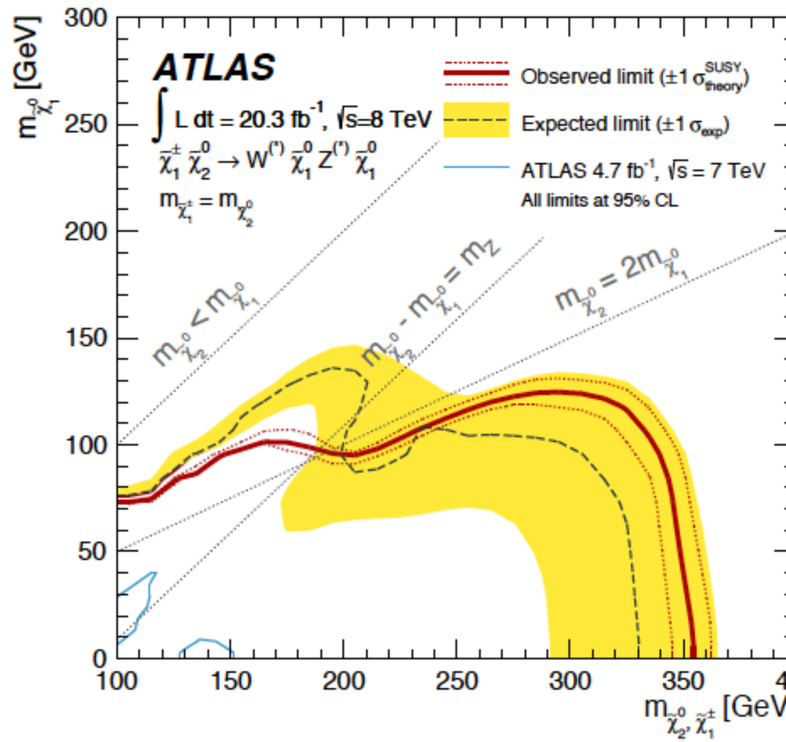
LC Mariotti Tziveloglou '15

Singlet-Doublet DM at the LHC

ATLAS: arXiv:1402.7029
CMS: arXiv:1405.7570







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

What about Higgs decays?

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

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

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