New physics explanations of a_μ in light of the FNAL muon g – 2 measurement

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Muon g-2 Discrepancy

Latest Experiment Values

SM Prediction

$$a_\mu^{SM} = 116591810(1)_{EW}(40)_{HVP}(18)_{Hlbl} \times 10^{-11}$$

Brookhaven Value

$$a_\mu^{BNL} = 116592089(54)_{stat}(33)_{sys} \times 10^{-11}$$

$$\Delta a_\mu^{BNL} = 279 \pm 76 \times 10^{-11}$$

Deviation:

3.7σ

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$a_\mu^{BNL} = 116592089(54)_{stat}(33)_{sys} \times 10^{-11}$ $\quad \Delta a_\mu^{BNL} = 279 \pm 76 \times 10^{-11}$ $\quad 3.7\sigma$

Fermilab Value

$a_\mu^{FNAL} = 116592040(54)_{exp} \times 10^{-11}$ $\quad \Delta a_\mu^{FNAL} = 230 \pm 69 \times 10^{-11}$ $\quad 3.3\sigma$

Muon g-2 Discrepancy

Latest Experiment Values

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$$a_\mu^{SM} = 116591810(1)_{EW}(40)_{HVP}(18)_{Hlbl} \times 10^{-11}$$

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Fermilab Value

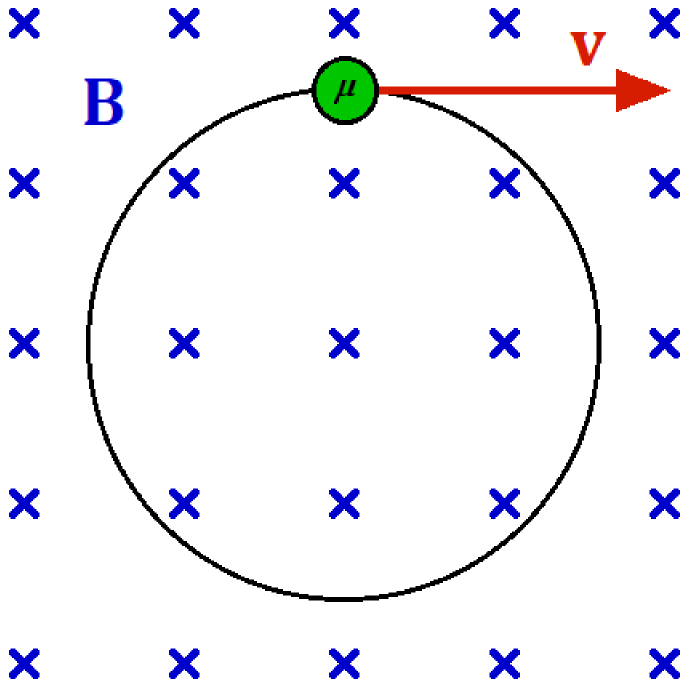
$a_\mu^{FNAL} = 116592040(54)_{exp} \times 10^{-11}$ $\quad$ $\Delta a_\mu^{FNAL} = 230 \pm 69 \times 10^{-11}$ $\quad$ 3.3σ

New World Average

$a_\mu^{2021} = 116592061(41)_{exp} \times 10^{-11}$ $\quad$ $\Delta a_\mu^{2021} = 251 \pm 59 \times 10^{-11}$ $\quad$ $4.2\sigma!$

What is the Muon g-2?

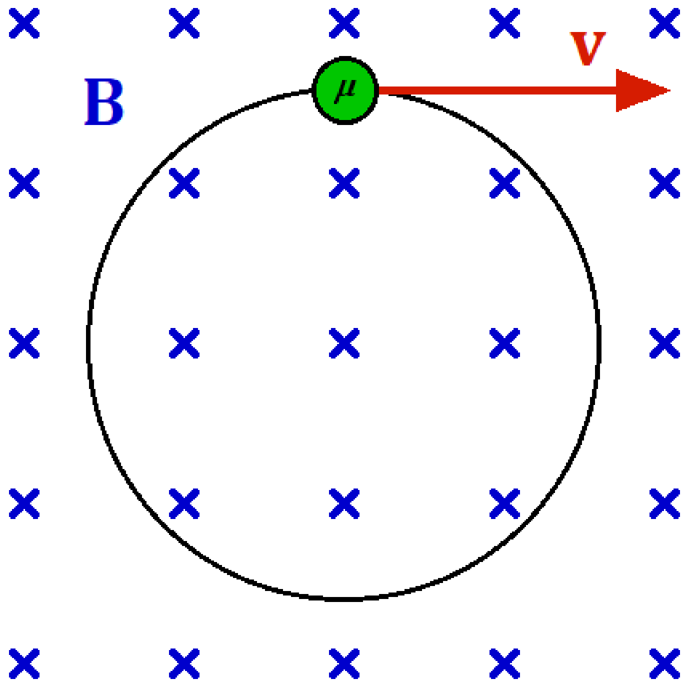
Quantum Mechanics



What is the Muon g-2?

Quantum Mechanics

Magnetic Moment: $\vec{M} = g \frac{q}{2\,m} \vec{L}$



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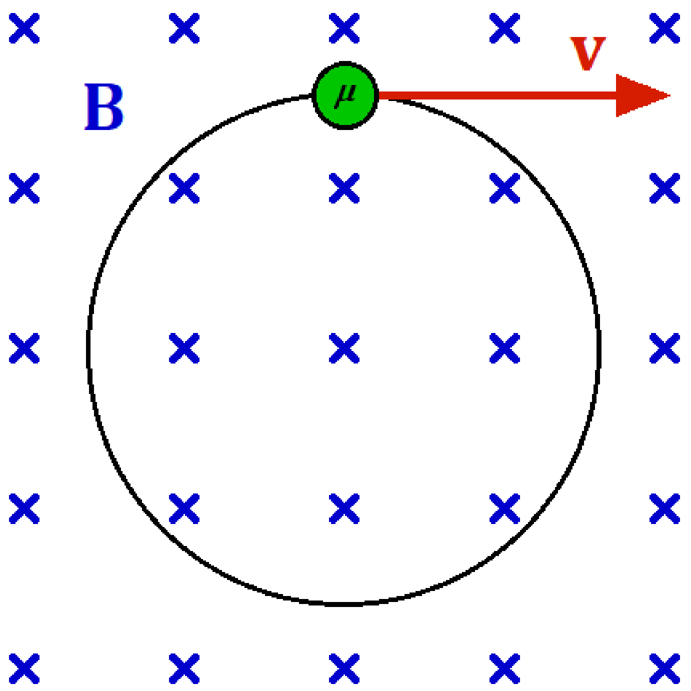
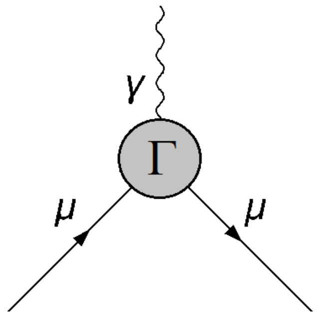


Quantum Field Theory



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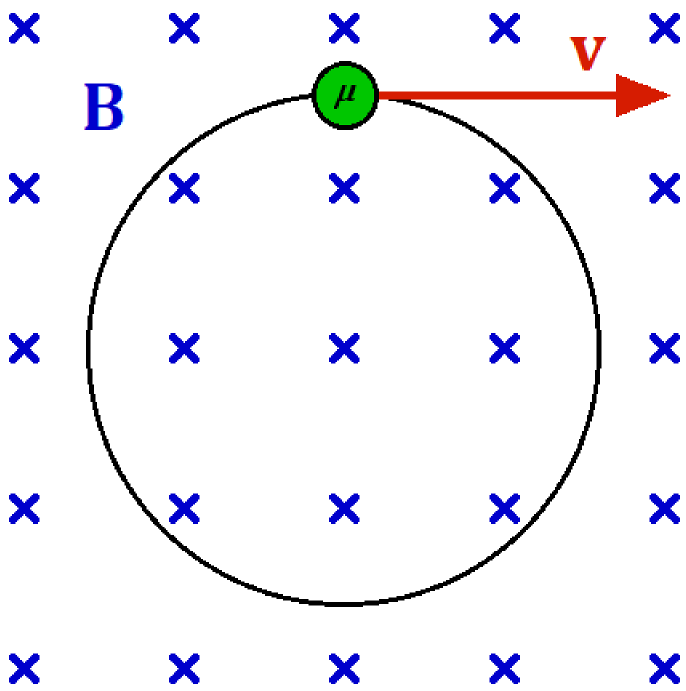

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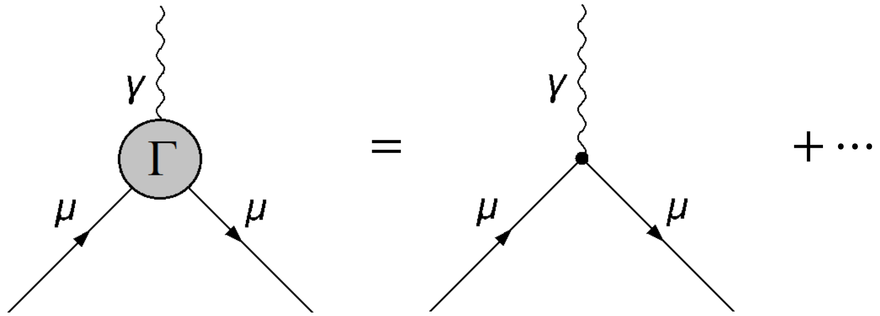

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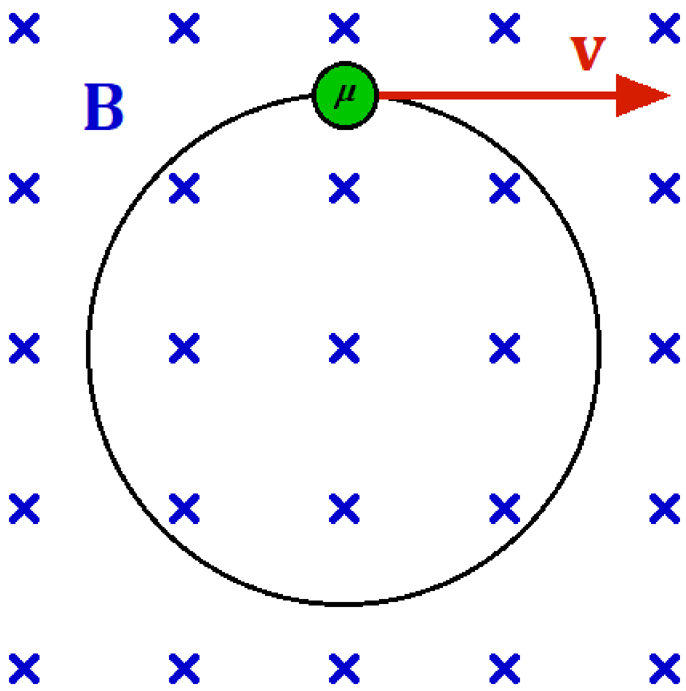

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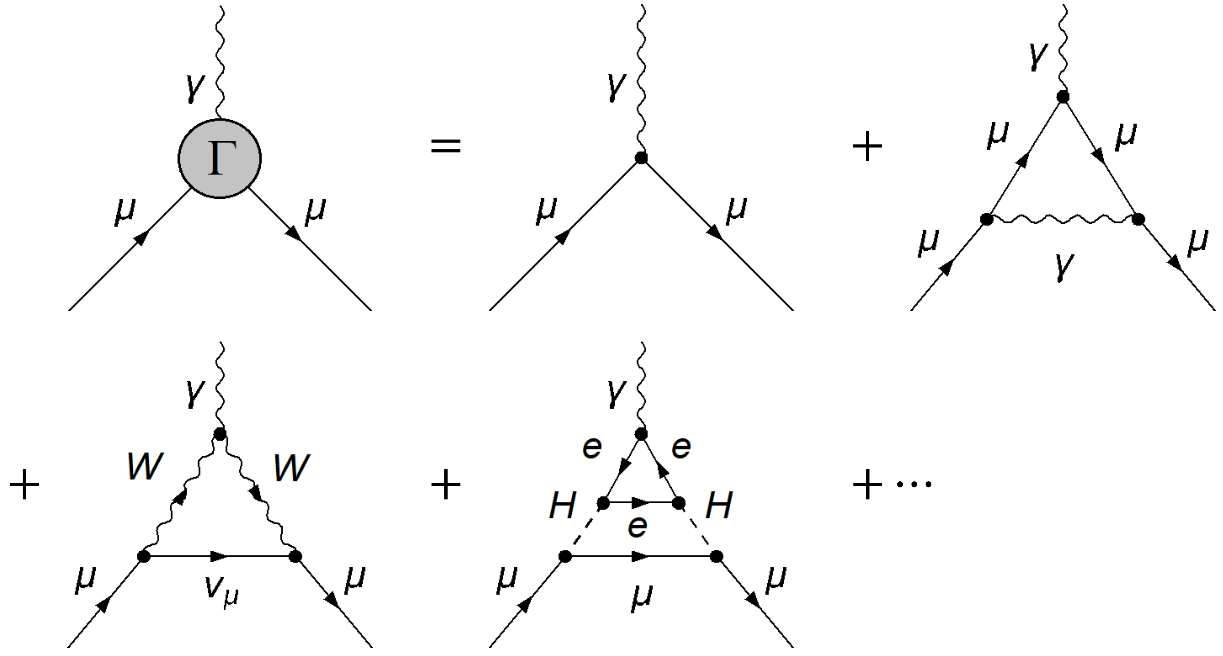

What is the Muon g-2?

Quantum Mechanics

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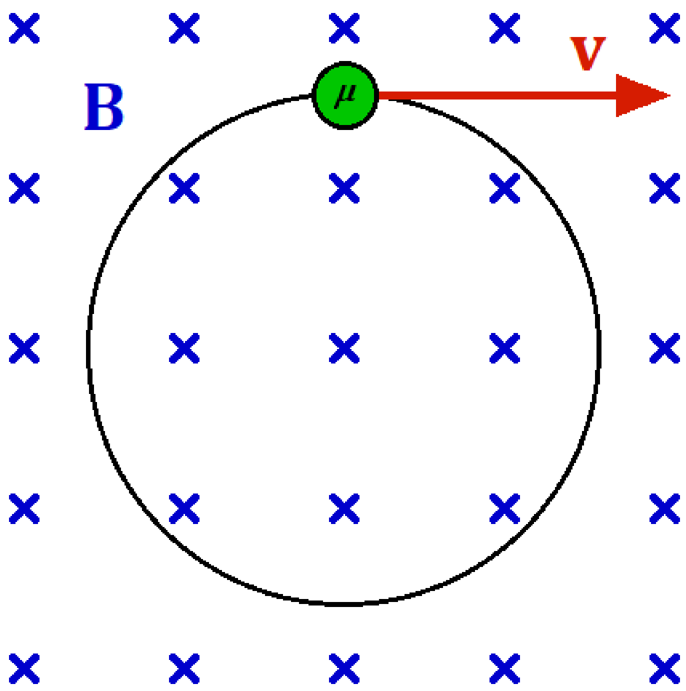
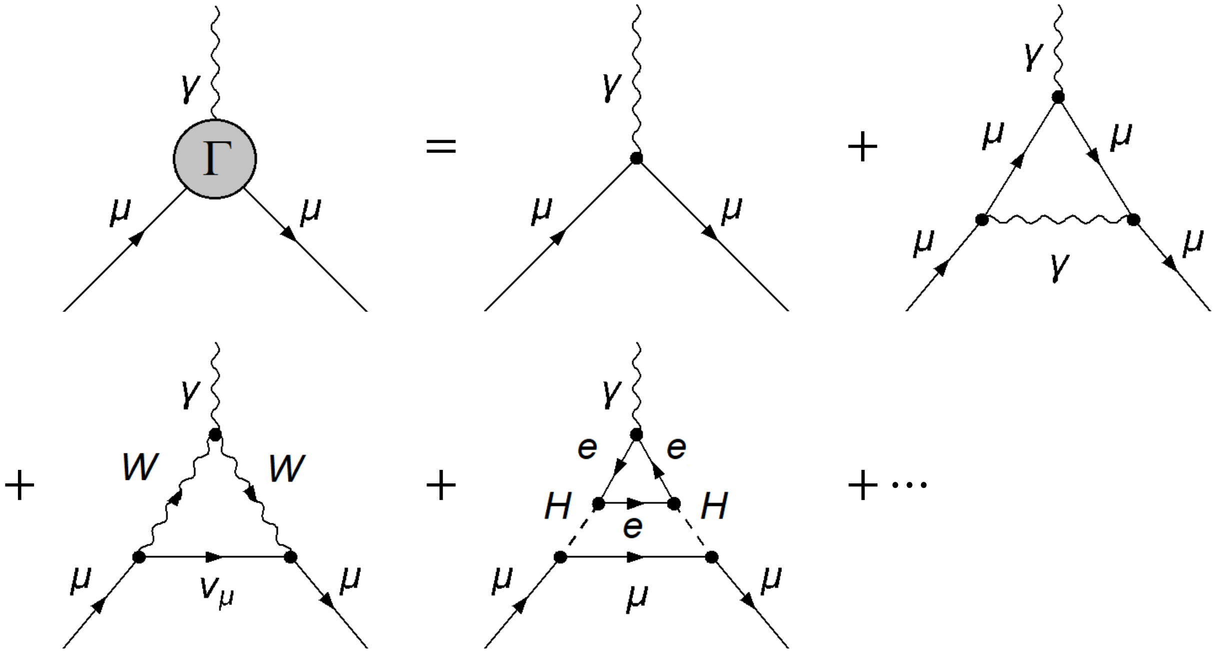


Quantum Field Theory

Anomalous Magnetic Moment: $a = (g-2)/2$



Contributions to Muon g-2

Standard Model Contributions to Muon g-2

Quantum Electrodynamics Contributions

Electroweak Contributions

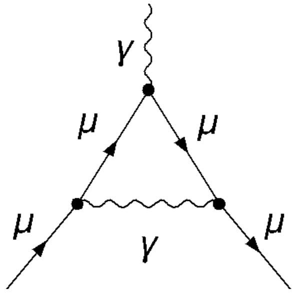
Hadronic Contributions

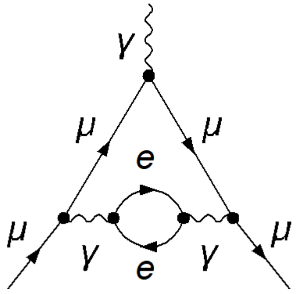
Contributions to Muon g-2

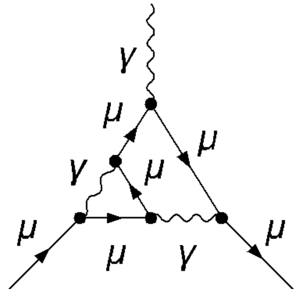
Standard Model Contributions to Muon g-2

Quantum Electrodynamics Contributions

$a_\mu^{QED} \times 10^{11} = 116\,584\,718.931(104)$







Electroweak Contributions

Hadronic Contributions

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Contributions to Muon g-2

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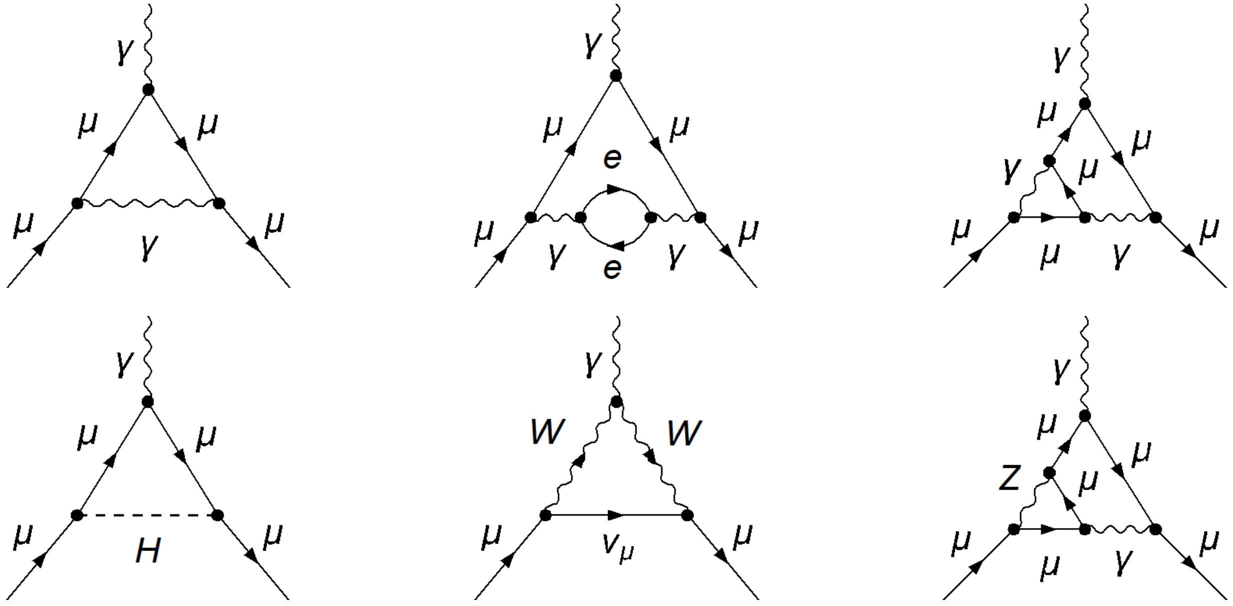
$a_\mu^{QED} \times 10^{11} = 116\,584\,718.931(104)$

Electroweak Contributions

$a_\mu^{EW} \times 10^{11} = 153.6(1.0)$

Hadronic Contributions



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Contributions to Muon g-2

Standard Model Contributions to Muon g-2

Quantum Electrodynamics Contributions

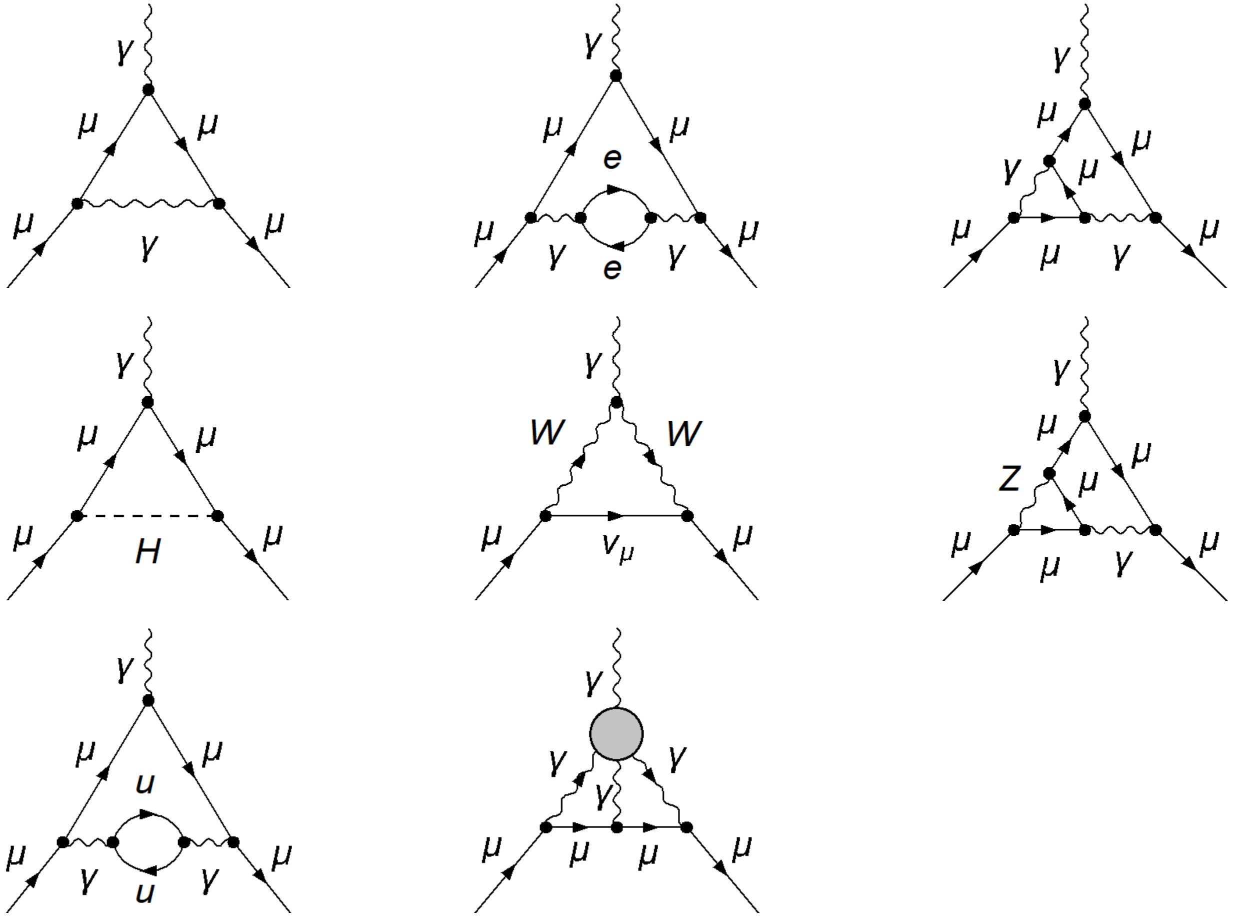
$a_\mu^{QED} \times 10^{11} = 116\,584\,718.931(104)$

Electroweak Contributions

$a_\mu^{EW} \times 10^{11} = 153.6(1.0)$

Hadronic Contributions

$a_\mu^{HVP} \times 10^{11} = 6845(40)$
$a_\mu^{Hlbl} \times 10^{11} = 92(18)$



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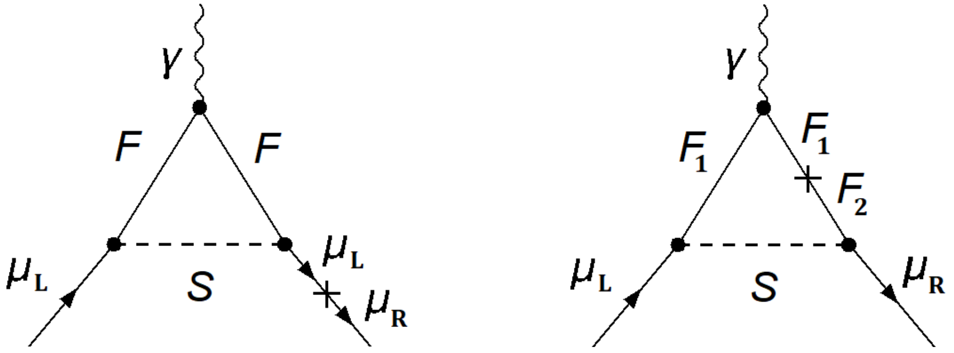
Single Field Extensions

Simple Explanations of Muon g-2

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\rm BNL}$, Δa_μ^{2021}
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Excluded: $\Delta a_\mu < 0$
2	0	$(\mathbf{1}, \mathbf{1}, 2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -1/2)$	Updated
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated
6	0	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	Excluded: LHC searches
7	0	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated
9	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Excluded: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1}, \mathbf{1}, -1)$	Excluded: Δa_μ too small
12	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$	Excluded: LEP lepton mixing
13	1/2	$(\mathbf{1}, \mathbf{2}, -3/2)$	Excluded: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
16	1	$(\mathbf{1}, \mathbf{1}, 0)$	Special cases viable
17	1	$(\mathbf{1}, \mathbf{2}, -3/2)$	UV completion problems
18	1	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: LHC searches
19	1	$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	UV completion problems
20	1	$(\overline{\mathbf{3}}, \mathbf{1}, -5/3)$	Excluded: LHC searches
21	1	$(\overline{\mathbf{3}}, \mathbf{2}, -5/6)$	UV completion problems
22	1	$(\overline{\mathbf{3}}, \mathbf{2}, 1/6)$	Excluded: $\Delta a_\mu < 0$
23	1	$(\overline{\mathbf{3}}, \mathbf{3}, -2/3)$	Excluded: proton decay

BSM Models

Chirality Flip



Contributions from diagrams with an internal chirality flip enhanced by a factor:

$$\frac{\lambda_{BSM}^2}{\lambda_\mu^2}$$

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Single Scalar Leptoquark

Scalar Leptoquark Singlet

Leptoquark	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Electric Charge
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$1/3$

Interacts with the standard model through:

$$\mathcal{L}_{BSM} = \left(\lambda_{QL} Q.L S_1 + \lambda_{t\mu} t \mu S_1^* + h.c.\right)$$

$$-M_{S1}^2 |S_1|^2 - g_{HP} |H|^2 |S_1|^2 - \frac{\lambda_\phi}{2} |S_1|^4$$

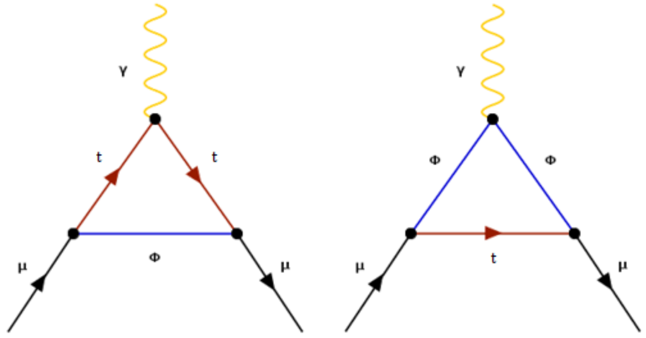
Single Scalar Leptoquark

Scalar Leptoquark Singlet

Leptoquark	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Electric Charge
S_1	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$1/3$

S_1

Contributes to muon g-2



Interacts with the standard model through:

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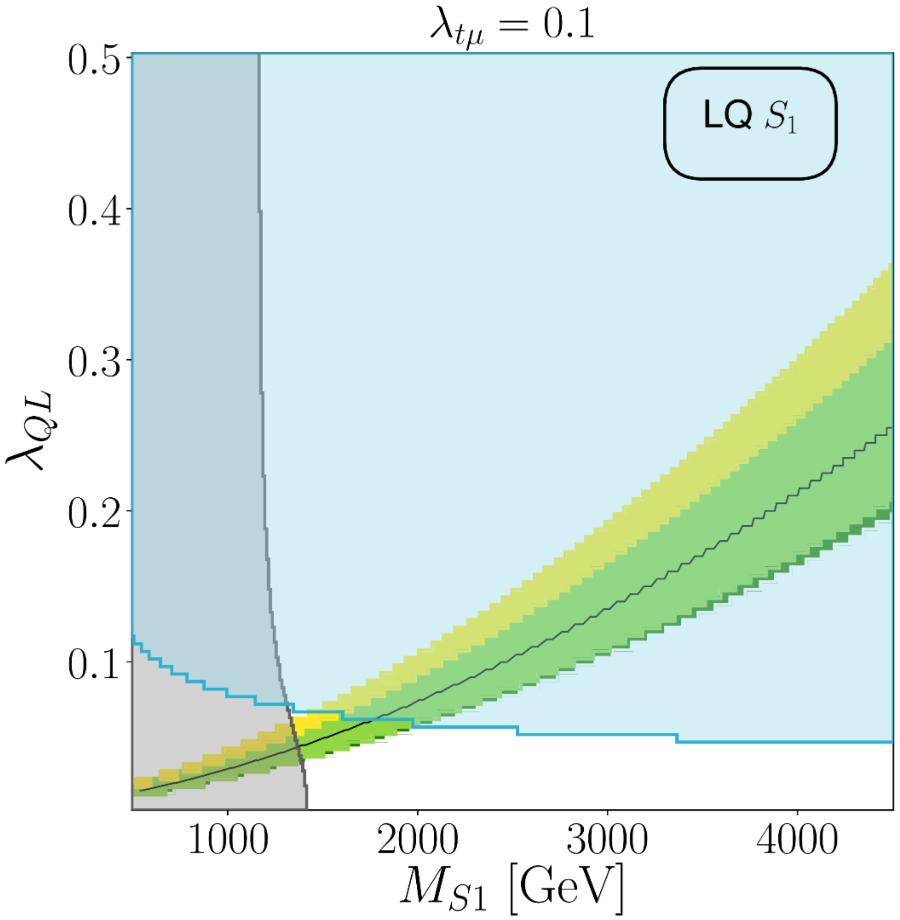


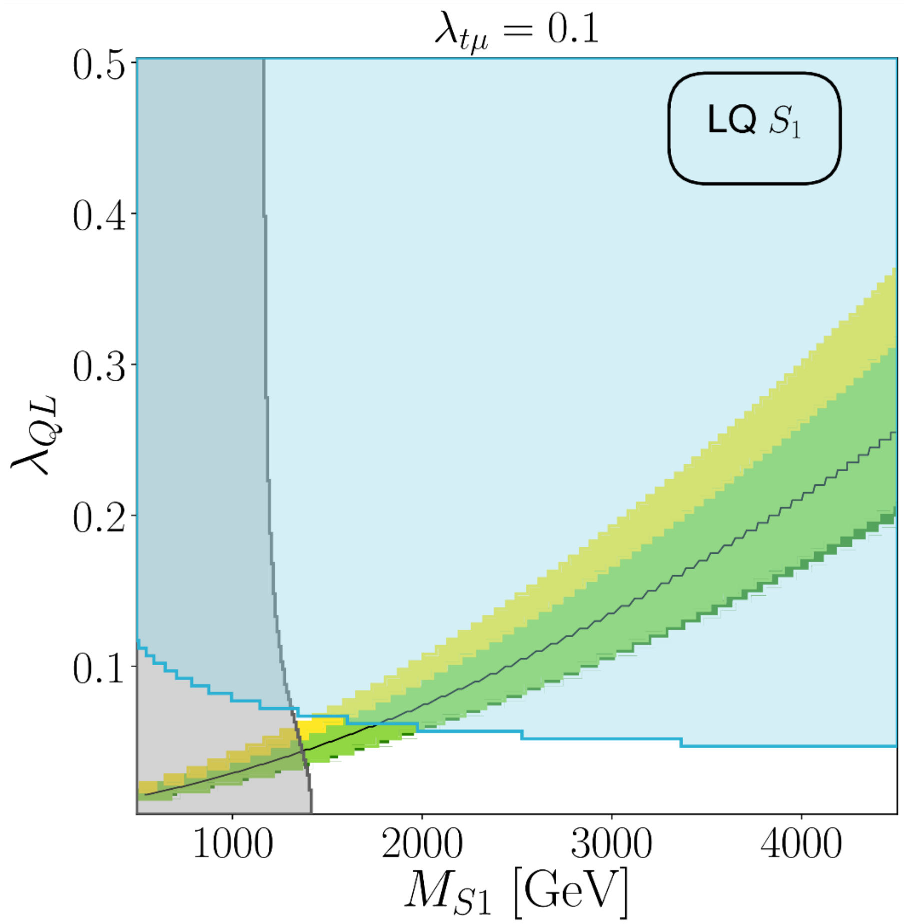
Now Ruled Out

Still Viable

Newly Viable

Single Scalar Leptoquark

Scalar Leptoquark Singlet



Now Ruled Out

Still Viable

Newly Viable

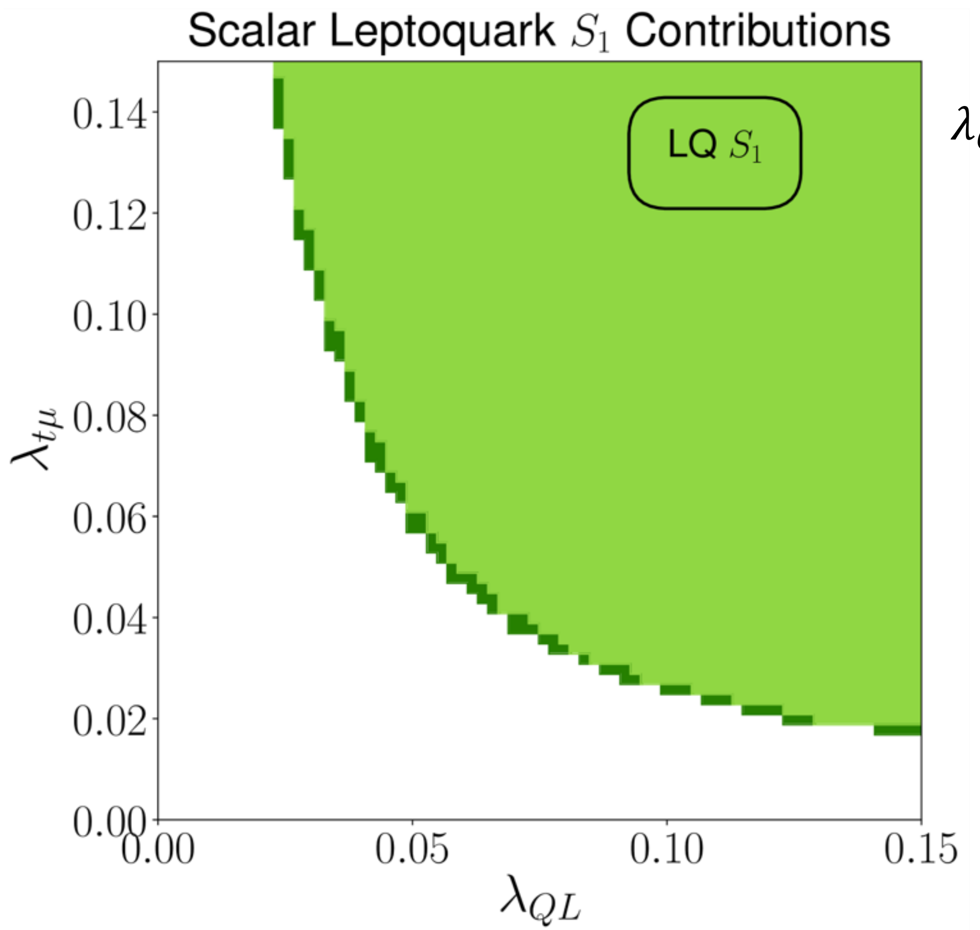
Exclusions:

LHC Searches

Fine-Tuned m_μ

Single Scalar Leptoquark

Scalar Leptoquark Singlet



$\lambda_{QL}\lambda_{t\mu} \gtrsim 0.003$

Now Ruled Out

Still Viable

Newly Viable

Exclusions:

LHC Searches

Fine-Tuned m_μ

Two Field Extensions

Simple Explanations of Muon g-2

$(SU(3)_C \times SU(2)_L \times U(1)_Y)_{\text{spin}}$	$+\mathbb{Z}_2$	Result for $\Delta a_\mu^{\text{BNL}}$, Δa_μ^{2021}
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Projected LHC 14 TeV exclusion, not confirmed
	Yes	Updated
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	No	Excluded: LHC searches
	Yes	Updated
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: LEP search
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{3},-1)_0 - (\mathbf{1},\mathbf{3},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},-1)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{1},0)_{1/2} - (\mathbf{1},\mathbf{1},1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},-1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{3},-1)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: $\Delta a_\mu < 0$

Two Field Extensions

Simple Explanations of Muon g-2

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$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	No	Excluded: LHC searches
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$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
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$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
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$(\mathbf{1},\mathbf{3},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
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$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: LHC searches + LEP contact interactions
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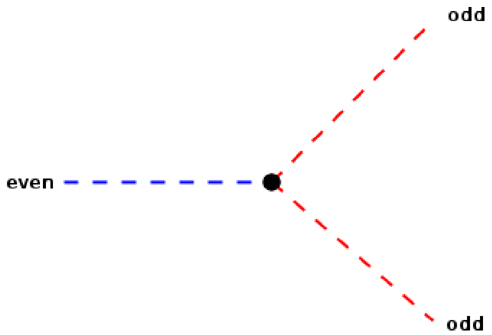
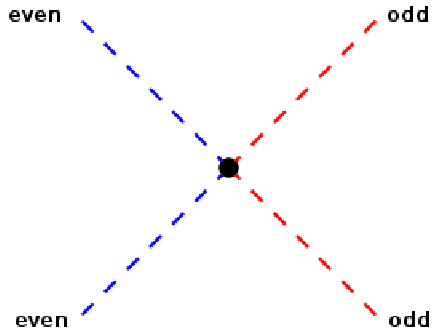
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},-1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{3},-1)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: $\Delta a_\mu < 0$

Z2 Symmetry

Z2-odd fields interact only in pairs:

$$\psi_{even} \rightarrow \psi_{even}$$
$$\psi_{odd} \rightarrow \psi_{odd} e^{i\pi}$$





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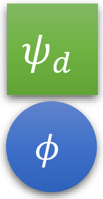
Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon

New Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Electric Charge
$\psi_d = (\psi_d^+, \psi_d^0)$	$(\mathbf{1}, \mathbf{2}, 1/2)$	1,0
ϕ	$(\mathbf{1}, \mathbf{1}, 0)$	0



Interacts with the standard model through:

$$\mathcal{L}_{BSM} = (\lambda_L L_L . \psi_d\, \phi - M_\psi \psi_d^c \psi_d + h.c.) - \frac{M_\phi^2}{2} \phi^2$$

Source: 1804.00009

Two Fields with Dark Matter

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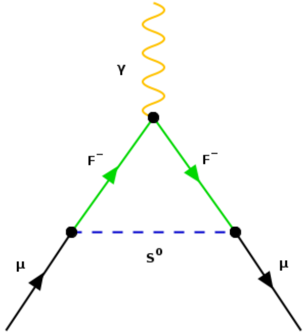
ψ_d

ϕ

Contributes to muon g-2



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Two Fields with Dark Matter

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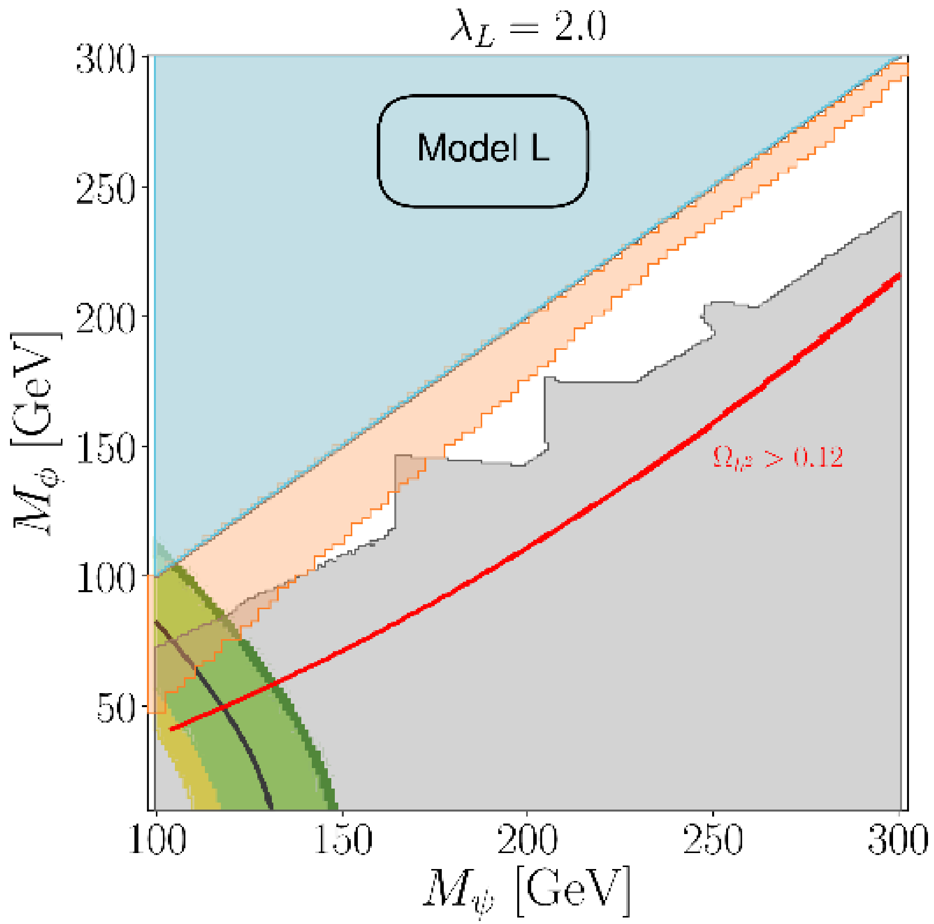

Now Ruled Out

Still Viable

Newly Viable

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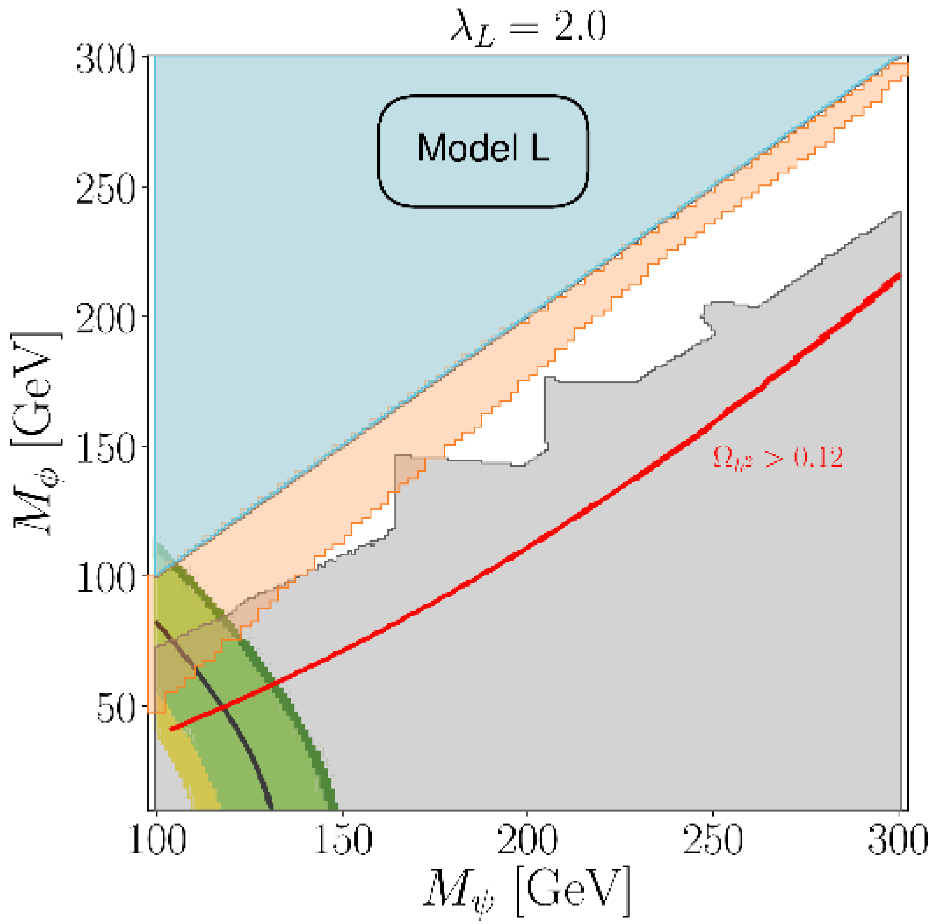
New Fermion and Scalar Coupling to Left-Handed Muon



Now Ruled Out

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Exclusions:

LHC Searches

Cmp. Spectra

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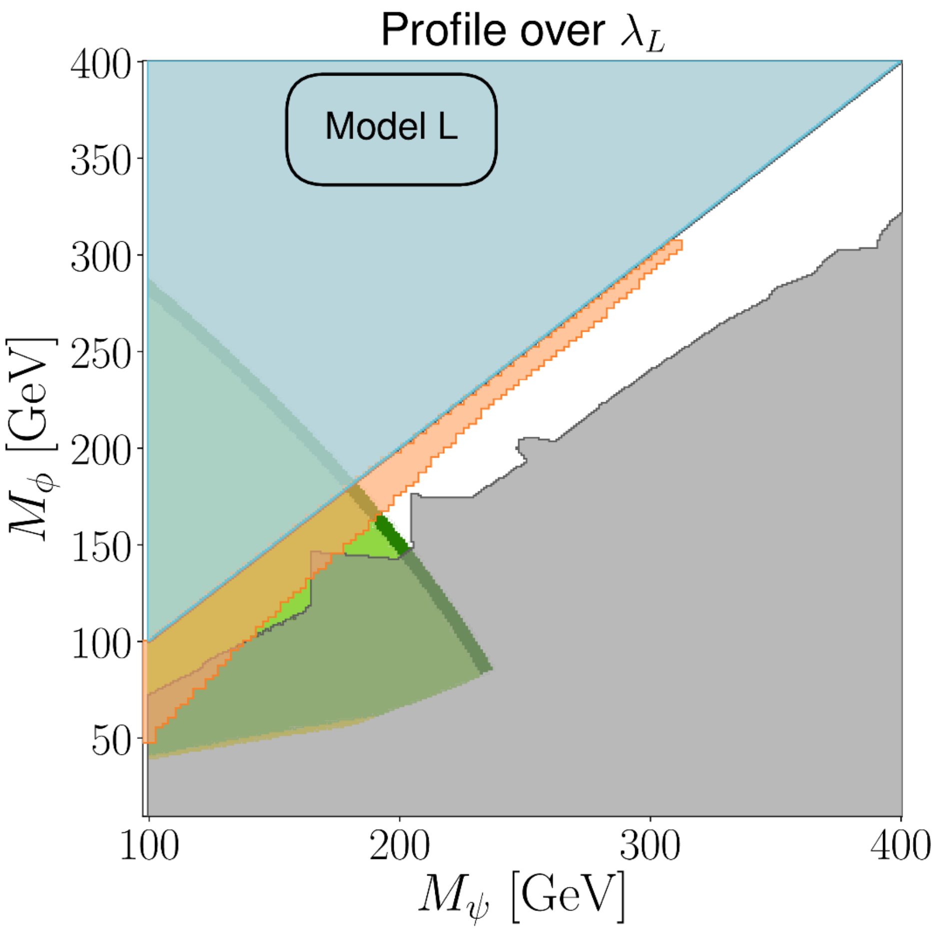

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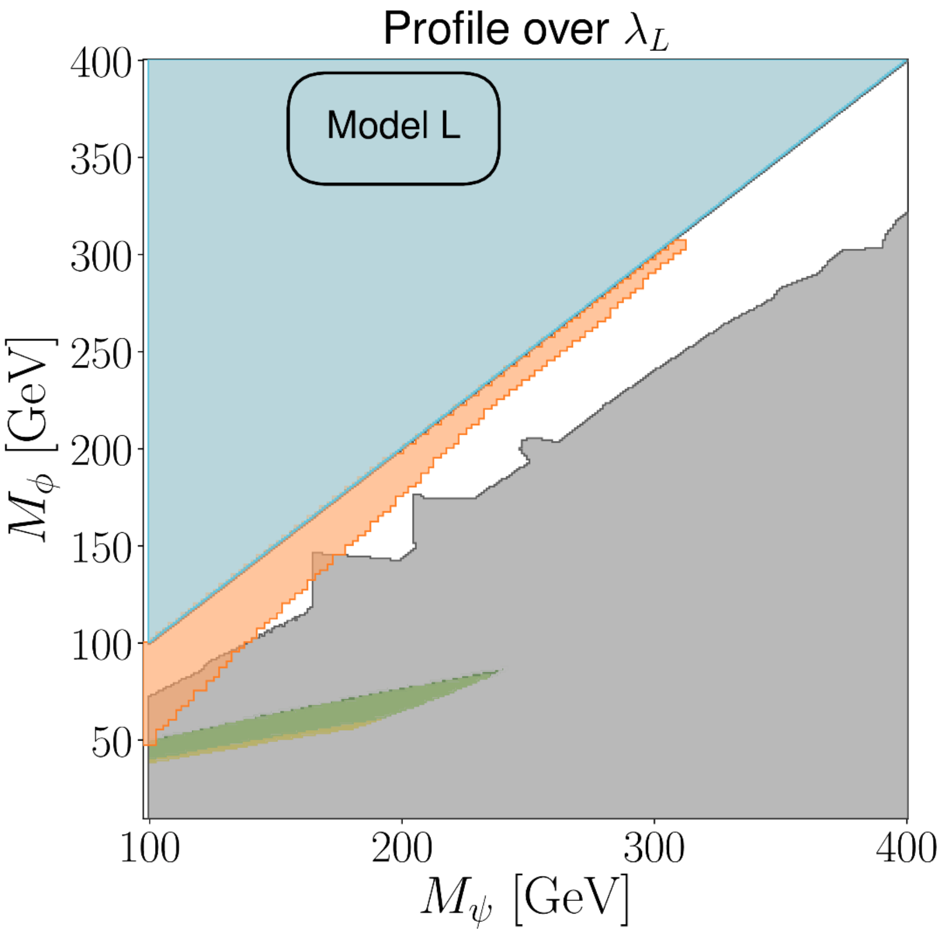
Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon



Now Ruled Out

Still Viable

Newly Viable

Exclusions:

LHC Searches

Cmp. Spectra

Three Fields with Dark Matter

TECHNISCHE UNIVERSITÄT DRESDEN

Pair of New Scalars + Fermion

New Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Electric Charge
$\psi_s = \psi_s^{-\dagger}$	$(\mathbf{1}, \mathbf{1}, 1)$	1
$\phi_s = \phi_s^0$	$(\mathbf{1}, \mathbf{1}, 0)$	0
$\phi_d = (\phi_d^0, \phi_d^-)$	$(\mathbf{1}, \mathbf{2}, -1/2)$	0,−1

ψ_s ϕ_s ϕ_d

Interacts with the standard model through:

$$\mathcal{L}_{BSM} = (a_H H.\phi_d \phi_s + \lambda_L L_L.\phi_d \psi_s + \lambda_R \phi_s \mu_R^\dagger \psi_s^c - M_\psi \psi_s^c \psi_s + h.c.) - \frac{M_{\phi d}}{2} |\phi_d|^2 - M_{\phi s}^2 |\phi_s|^2$$

arXiv:2104.03691

MONASH University

Three Fields with Dark Matter

Pair of New Scalars + Fermion

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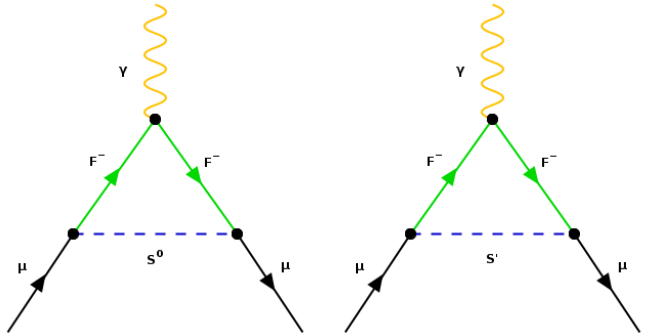
Interacts with the standard model through:

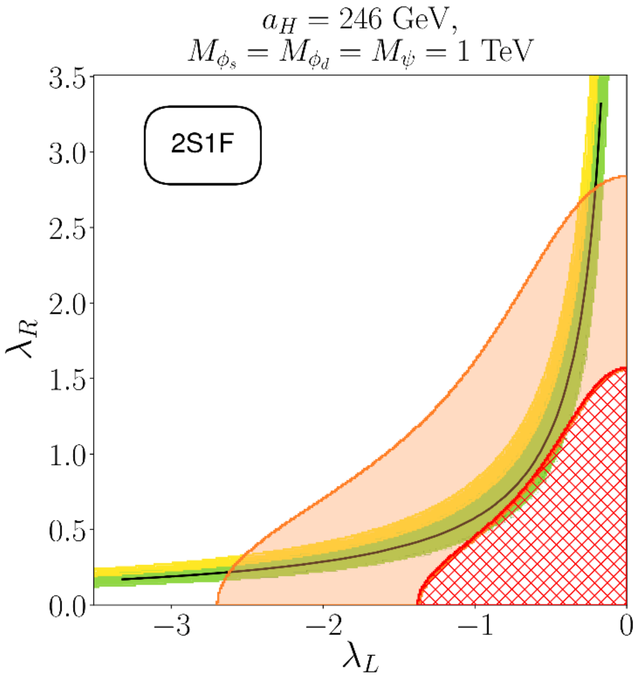
$$\mathcal{L}_{BSM} = (a_H H.\phi_d \phi_s + \lambda_L L_L.\phi_d \psi_s + \lambda_R \phi_s e_R^\dagger \psi_s^c$$
$$-M_\psi \psi_s^c \psi_s + h.c.) - \frac{M_{\phi d}}{2} |\phi_d|^2 - M_{\phi s}^2 |\phi_s|^2$$

Contributes to muon g-2



Three Fields with Dark Matter

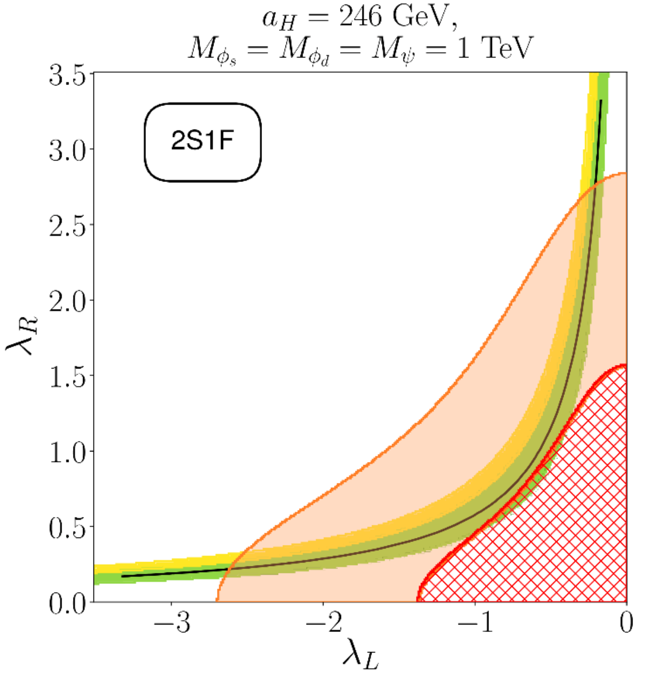
Pair of New Fermions + Scalar



Now Ruled Out
Still Viable
Newly Viable

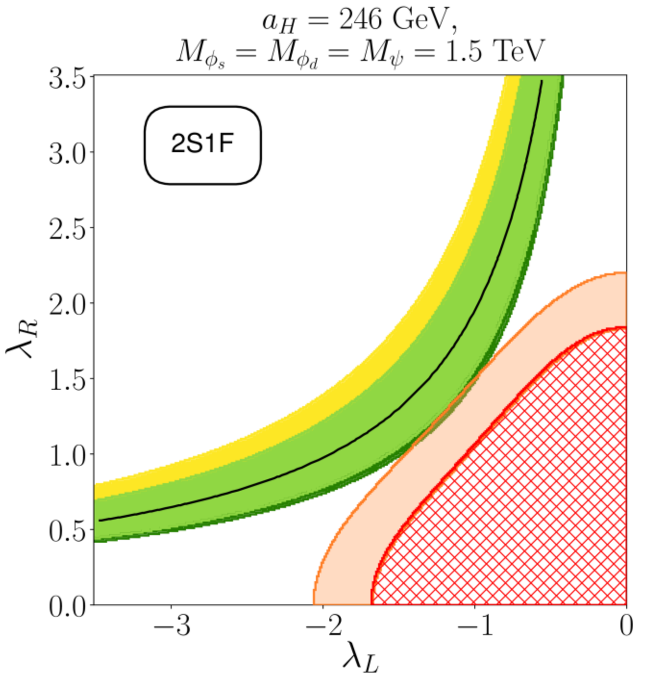
Three Fields with Dark Matter

Pair of New Fermions + Scalar



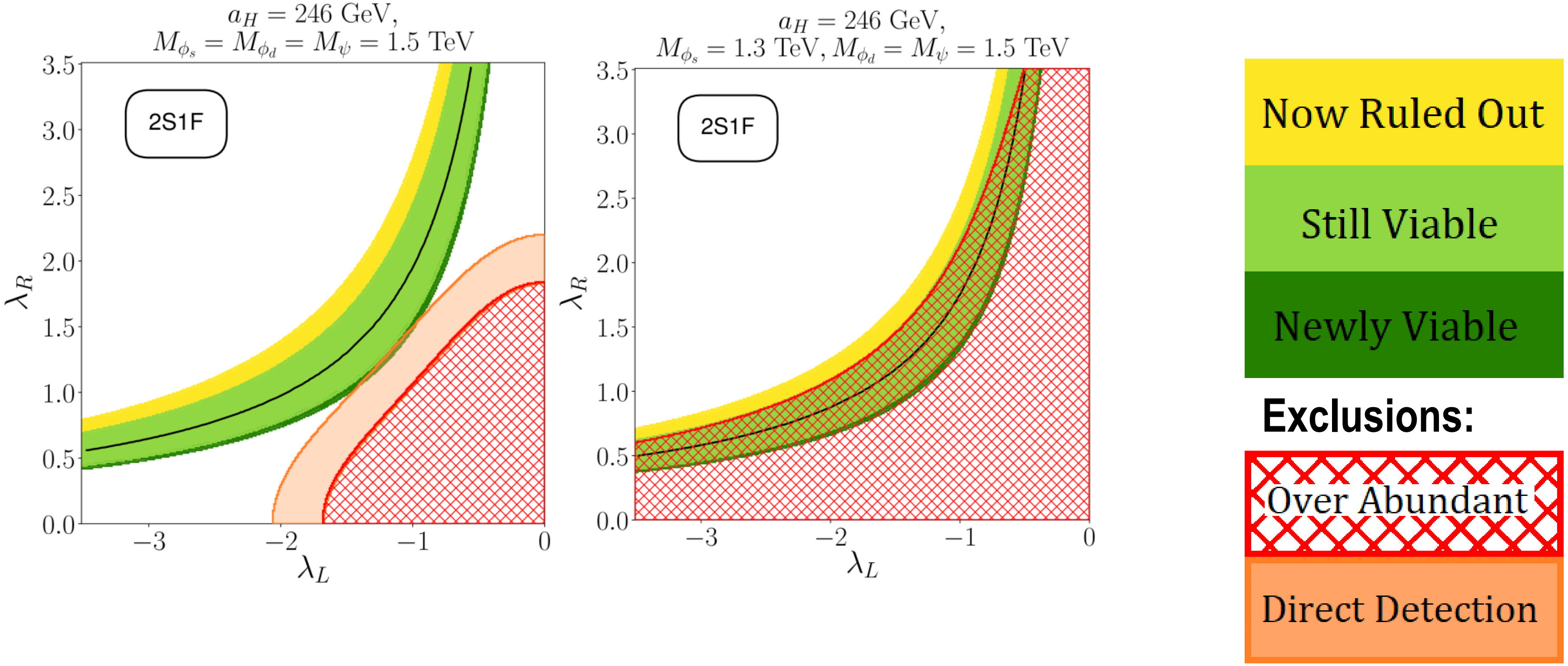
Three Fields with Dark Matter

Pair of New Fermions + Scalar



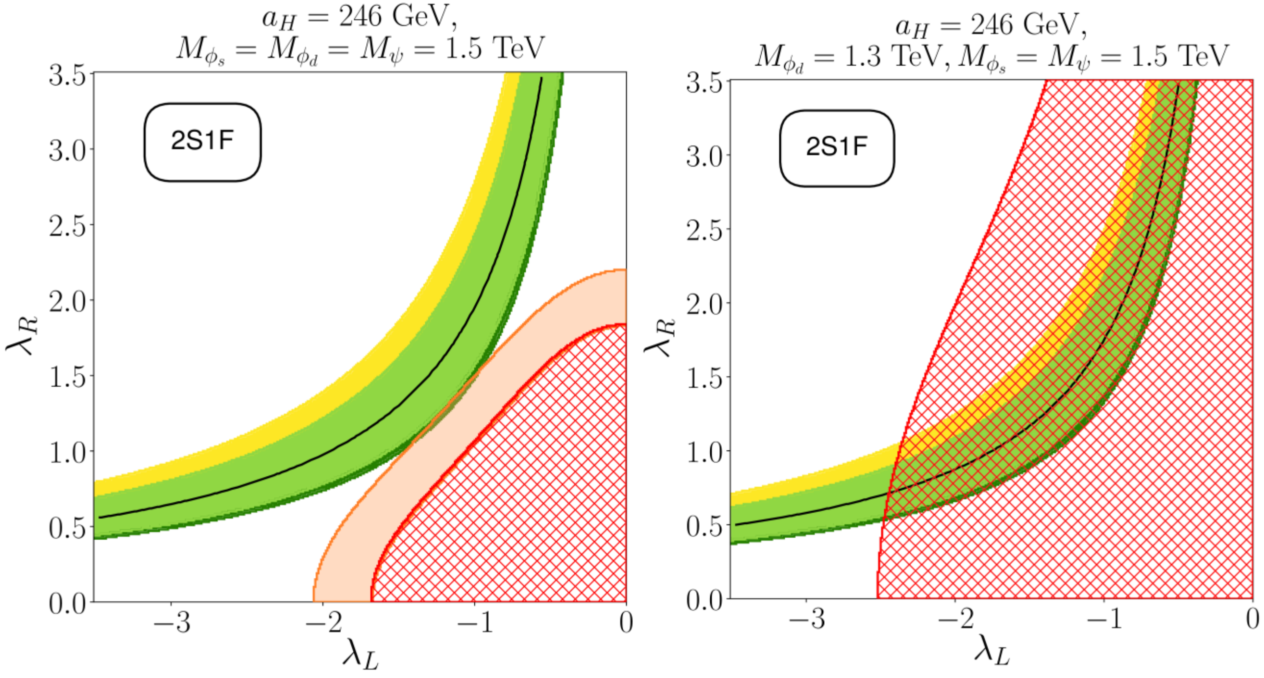
Three Fields with Dark Matter

Pair of New Fermions + Scalar



Three Fields with Dark Matter

Pair of New Fermions + Scalar



Now Ruled Out

Still Viable

Newly Viable

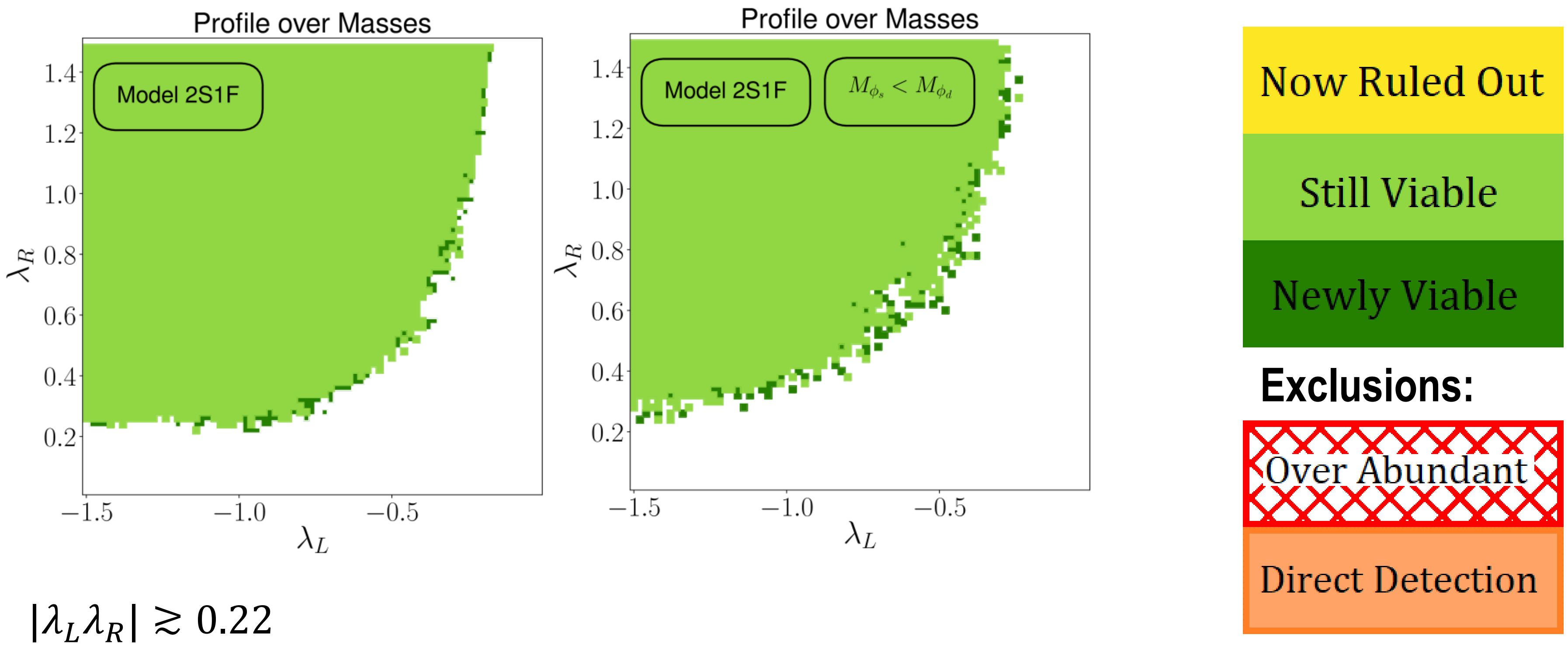
Exclusions:

Over Abundant

Direct Detection

Three Fields with Dark Matter

Pair of New Fermions + Scalar



$|\lambda_L \lambda_R| \gtrsim 0.22$

Conclusions

The anomalous muon magnetic moment, muon g-2

- **Current state of muon g-2**
- New muon g-2 value from Fermilab disagrees with SM prediction by 4.2σ.
- Many simple BSM theories cannot produce a contribution that is both positive and large.

- **Outlook**
- Upcoming muon g-2 experiments are set to further increase the precision, and if the measured value stays the same or increases, then disagreement between the SM and experiment will increase.

Thank you for Listening!

Standard Model of Particle Physics

Gauge Bosons

- Photon — γ
- W Boson — W
- Z Boson — Z
- Gluon — g

Fermions

Leptons

- e — Electron
- νe — Electron Neutrino
- μ — Muon
- νμ — Muon Neutrino
- τ — Tau
- ντ — Tau Neutrino

Quarks

- u — Up
- d — Down
- c — Charm
- s — Strange
- t — Top
- b — Bottom

Scalars

- h — Higgs Boson