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## New physics explanations of $a_\mu$ 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**

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

**Deviation:**

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**Deviation:**

**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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**Deviation:**

**Fermilab Value**

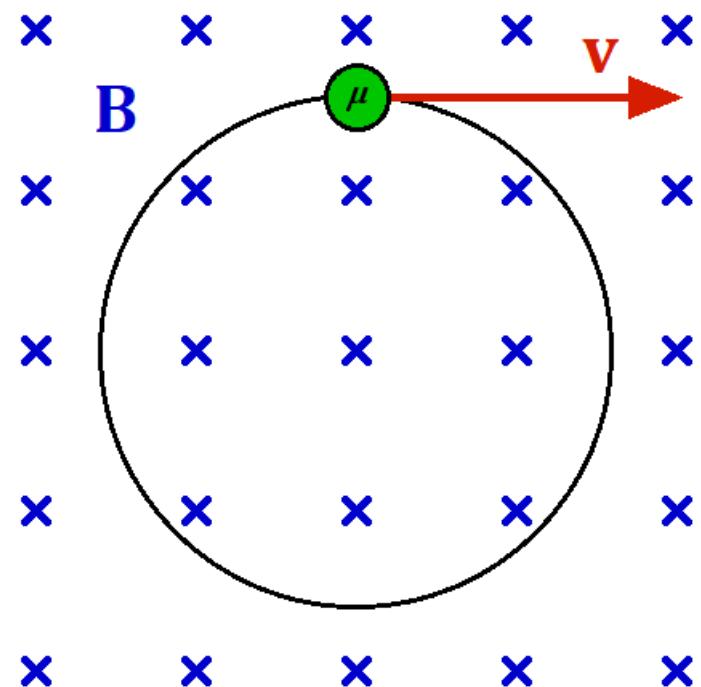
$$a_\mu^{FNAL} = 116592040(54)_{exp} \times 10^{-11} \quad \Delta a_\mu^{FNAL} = 230 \pm 69 \times 10^{-11} \quad 3.3\sigma$$

**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?

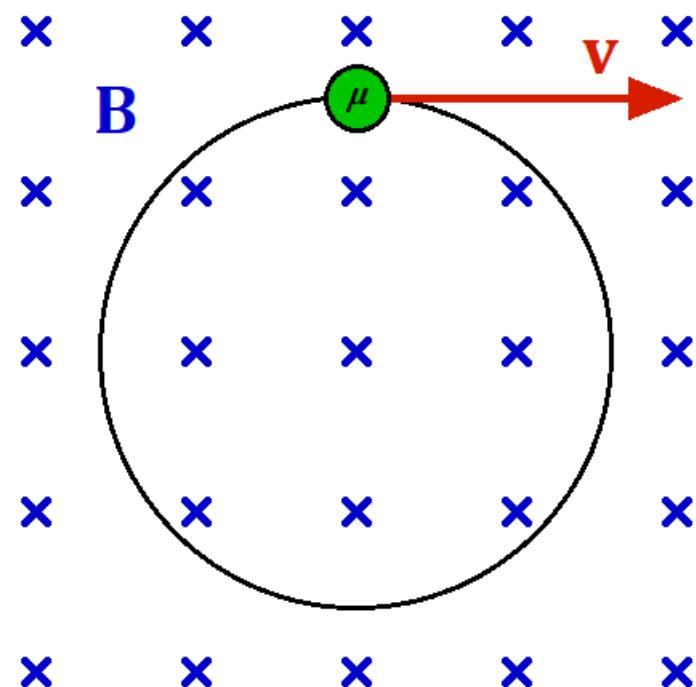
## Quantum Mechanics



# What is the Muon g-2?

## Quantum Mechanics

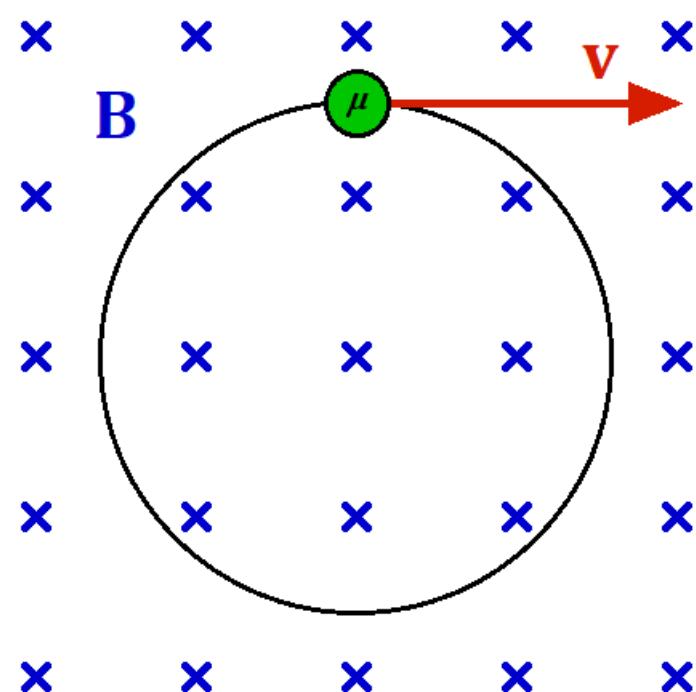
Magnetic Moment:  $\vec{M} = g \frac{q}{2m} \vec{L}$



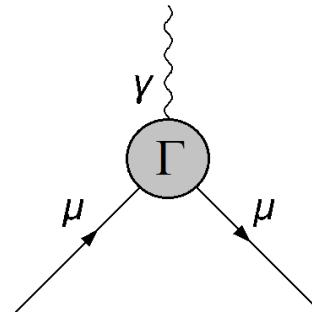
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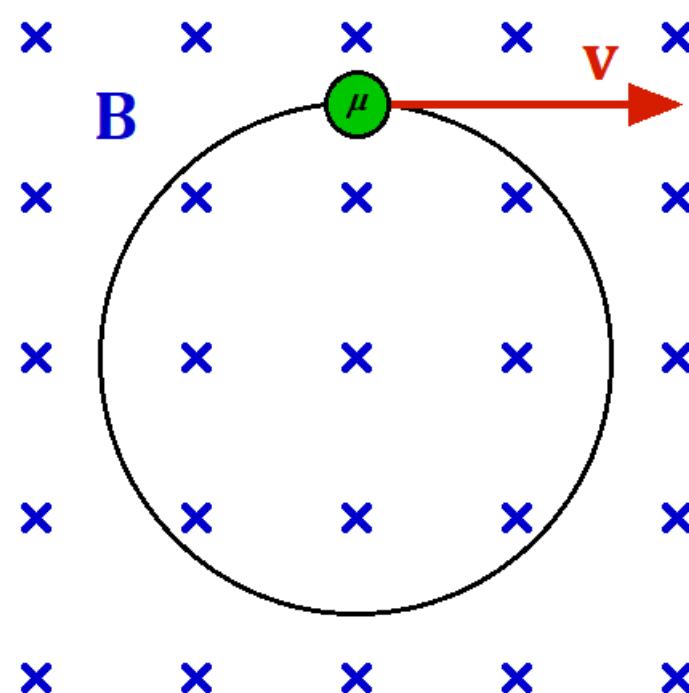
## Quantum Field Theory



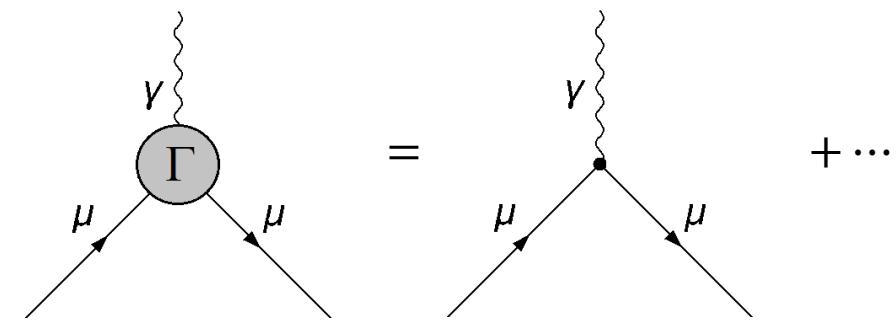
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Magnetic Moment:  $\vec{M} = g \frac{q}{2m} \vec{L}$



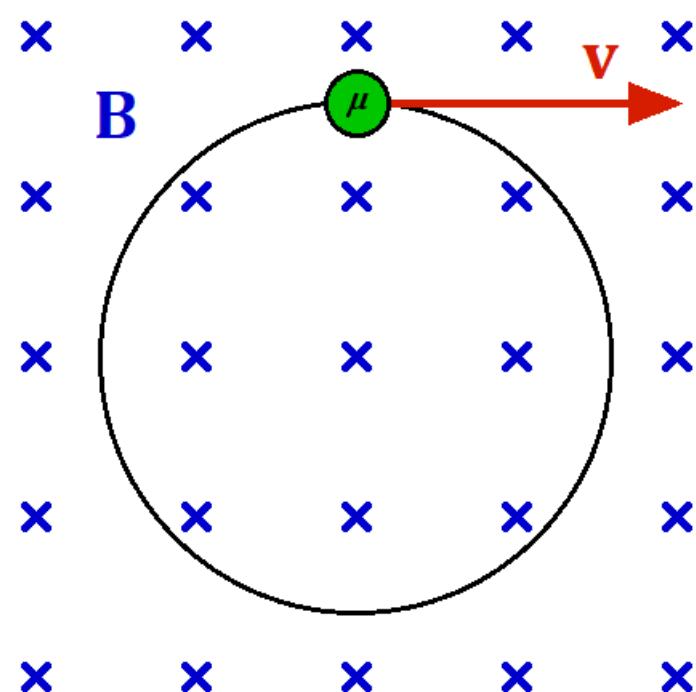
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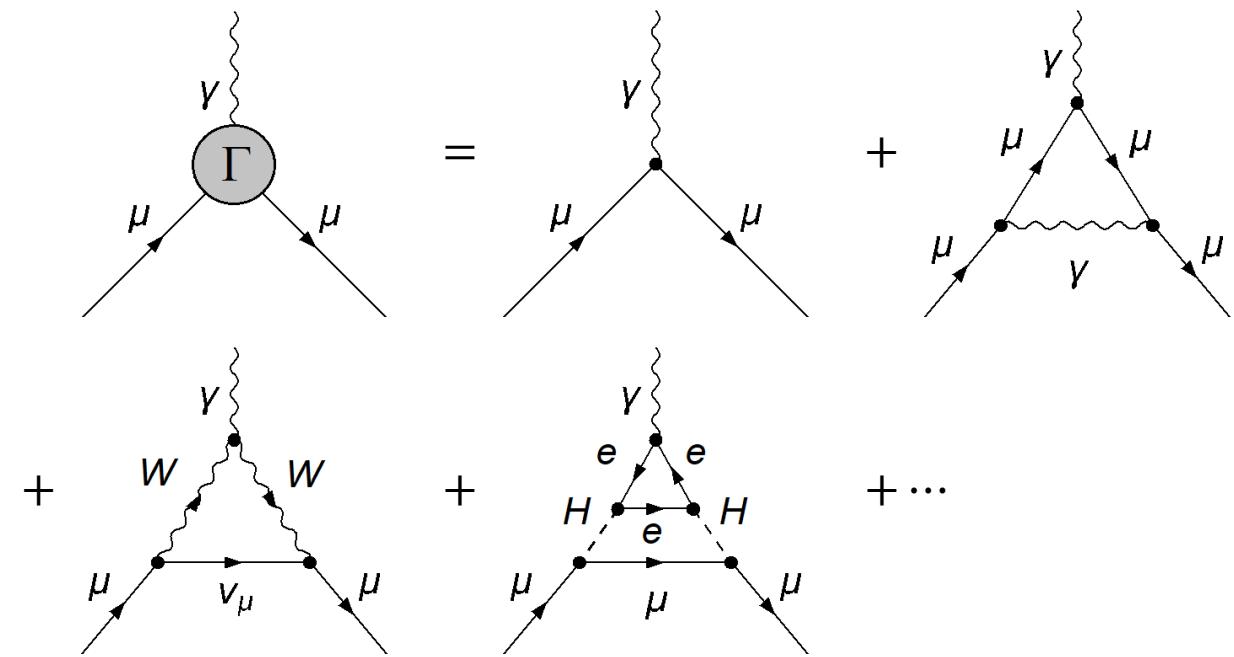
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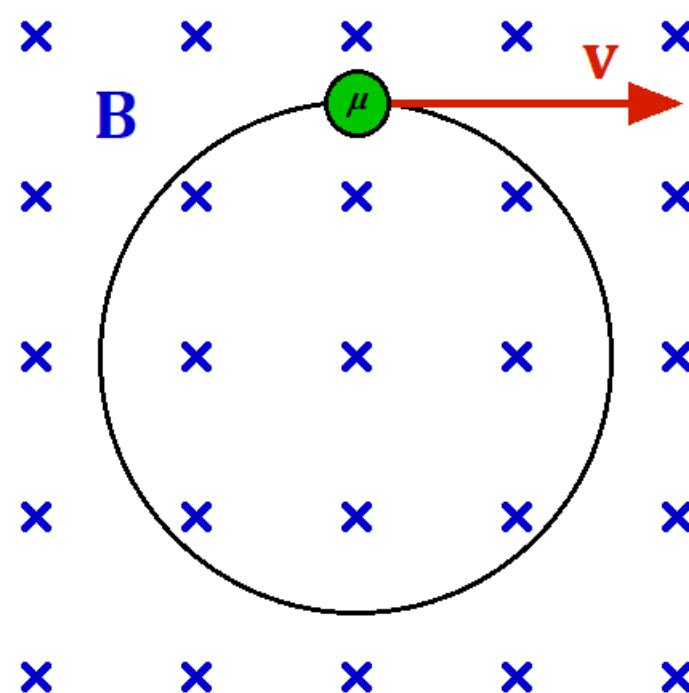
## Quantum Field Theory



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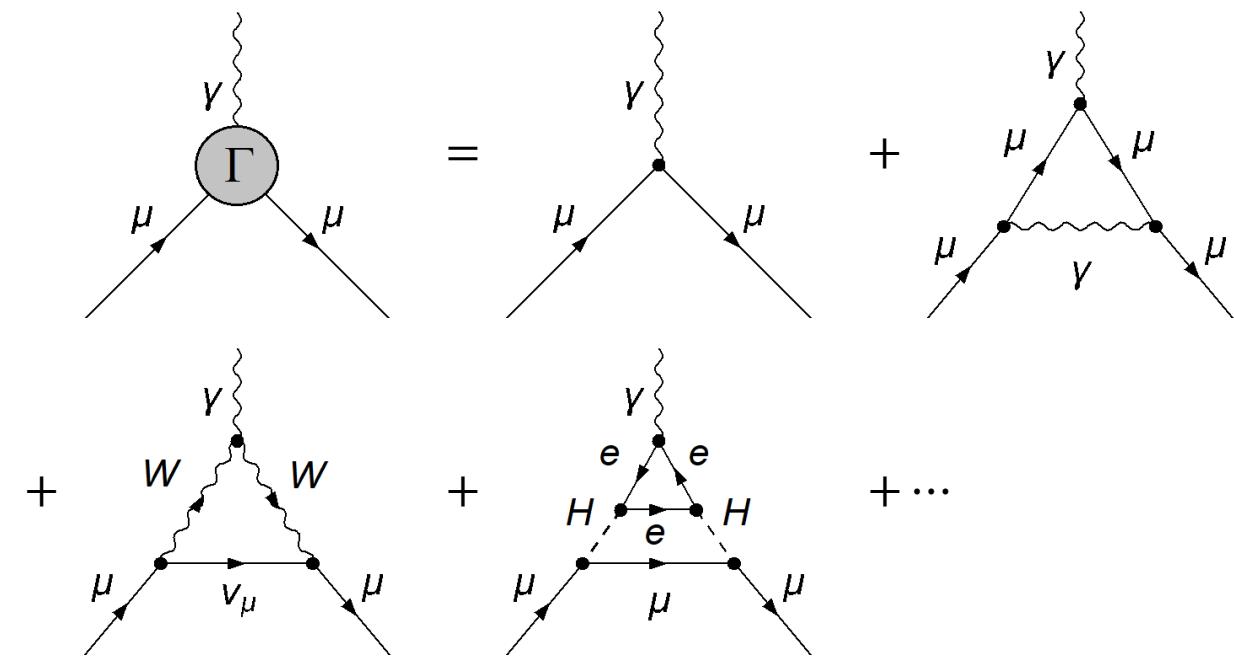
## Quantum Mechanics

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



## 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

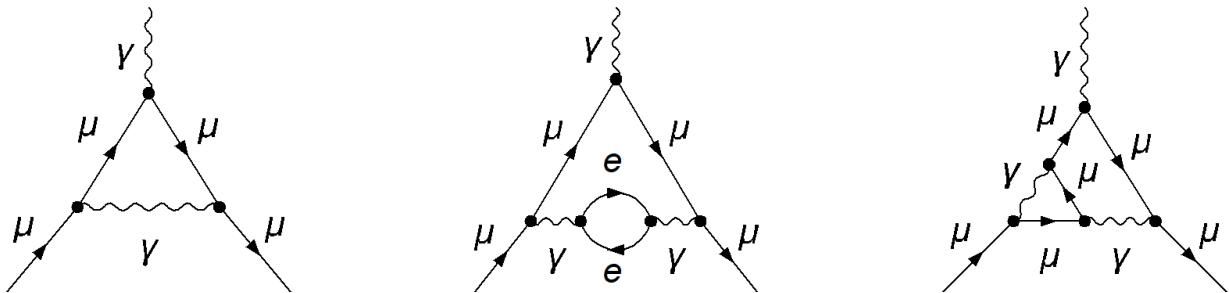
Hadronic Contributions

# 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**

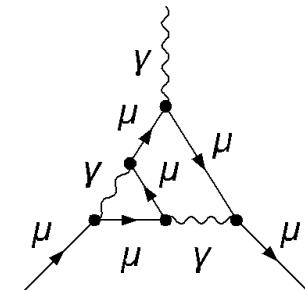
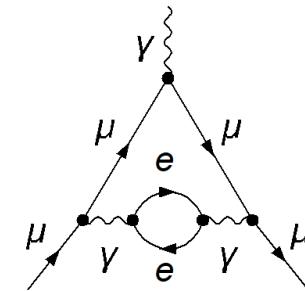
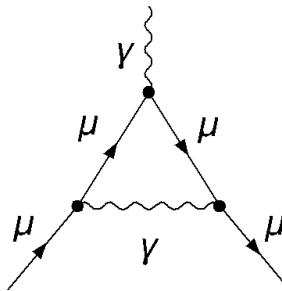
**Hadronic Contributions**

# Contributions to Muon g-2

Standard Model Contributions to Muon g-2

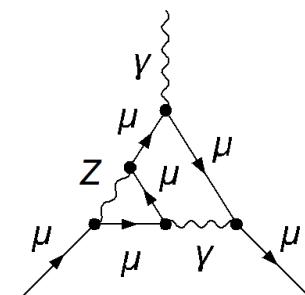
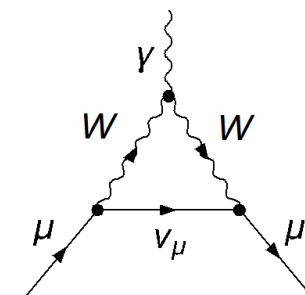
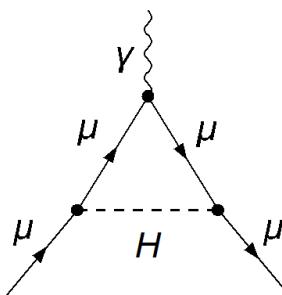
**Quantum Electrodynamics Contributions**

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



**Electroweak Contributions**

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



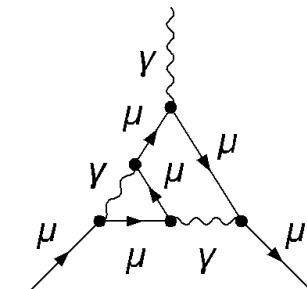
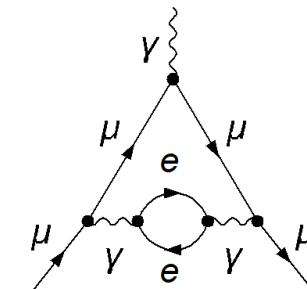
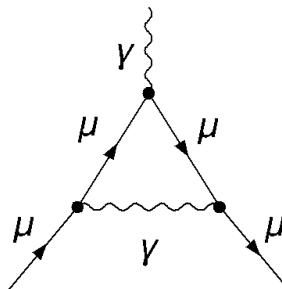
**Hadronic Contributions**

# Contributions to Muon g-2

## Standard Model Contributions to Muon g-2

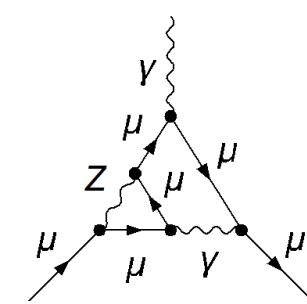
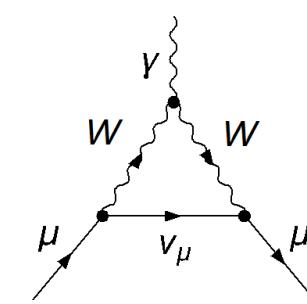
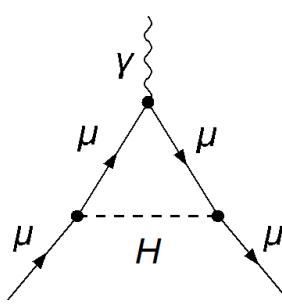
### Quantum Electrodynamics Contributions

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### Electroweak Contributions

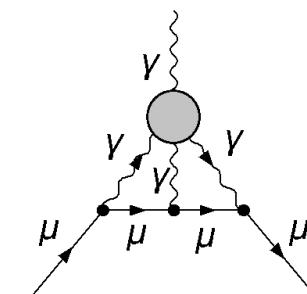
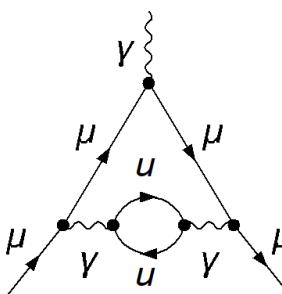
$$a_\mu^{EW} \times 10^{11} = 153.6(1.0)$$



### Hadronic Contributions

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

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



# Contributions to Muon g-2

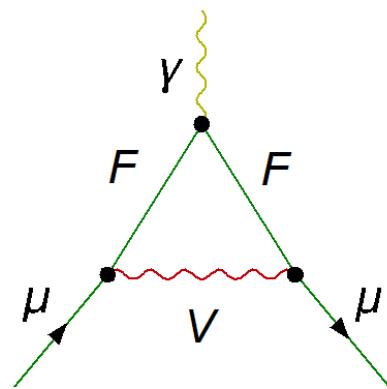
## General Contributions to Muon g-2

All possible contributions to muon g-2 from 1-loop diagrams must be of these forms.

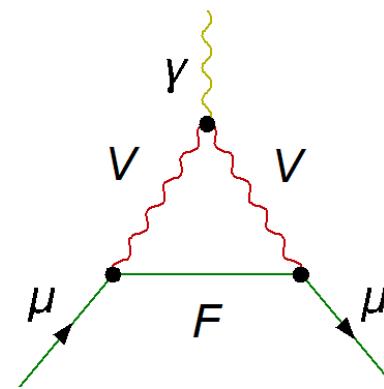
Coupling of muon to fermions and scalars/vectors:

$$\mathcal{L}_\mu = \bar{f} \gamma_\nu V^\nu (VF_L P_L + VF_R P_R) \mu + \bar{f} \phi (SF_L P_L + SF_R P_R) \mu$$

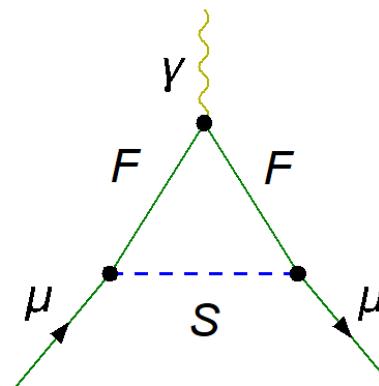
**FFV Diagram**



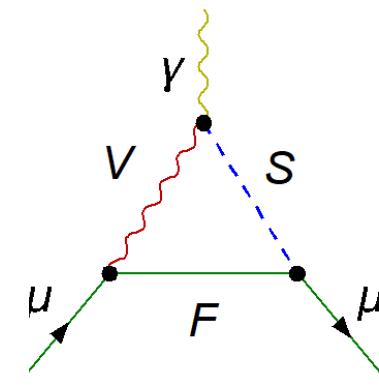
**VVF Diagram**



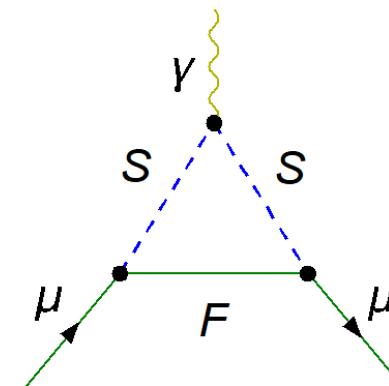
**FFS Diagram**



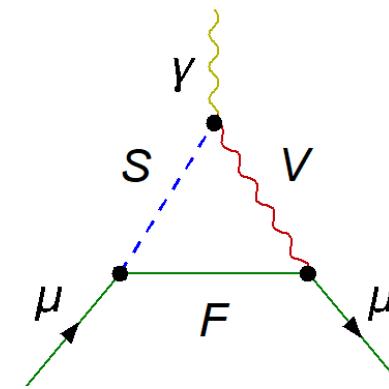
**VSF Diagram**



**SSF Diagram**



**SVF Diagram**



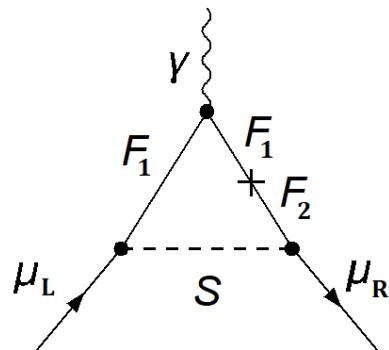
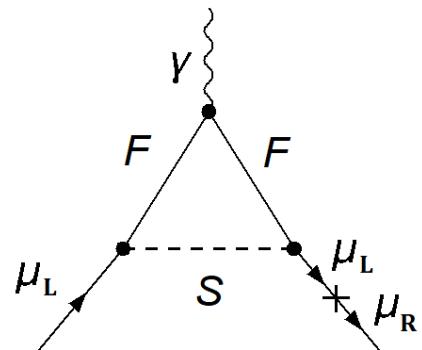
# Single Field Extensions

## Simple Explanations of Muon g-2

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

# BSM Models

## Chirality Flip



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

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

# 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

$S_1$

Interacts with the standard model through:

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

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

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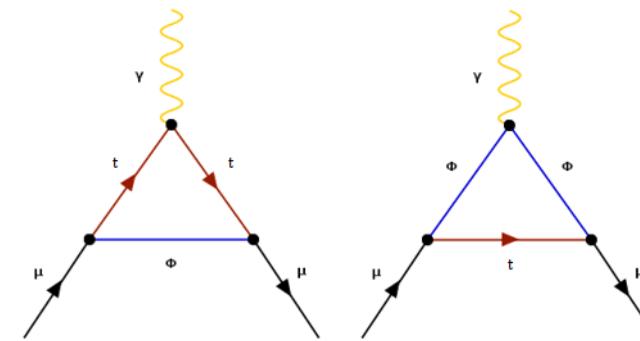
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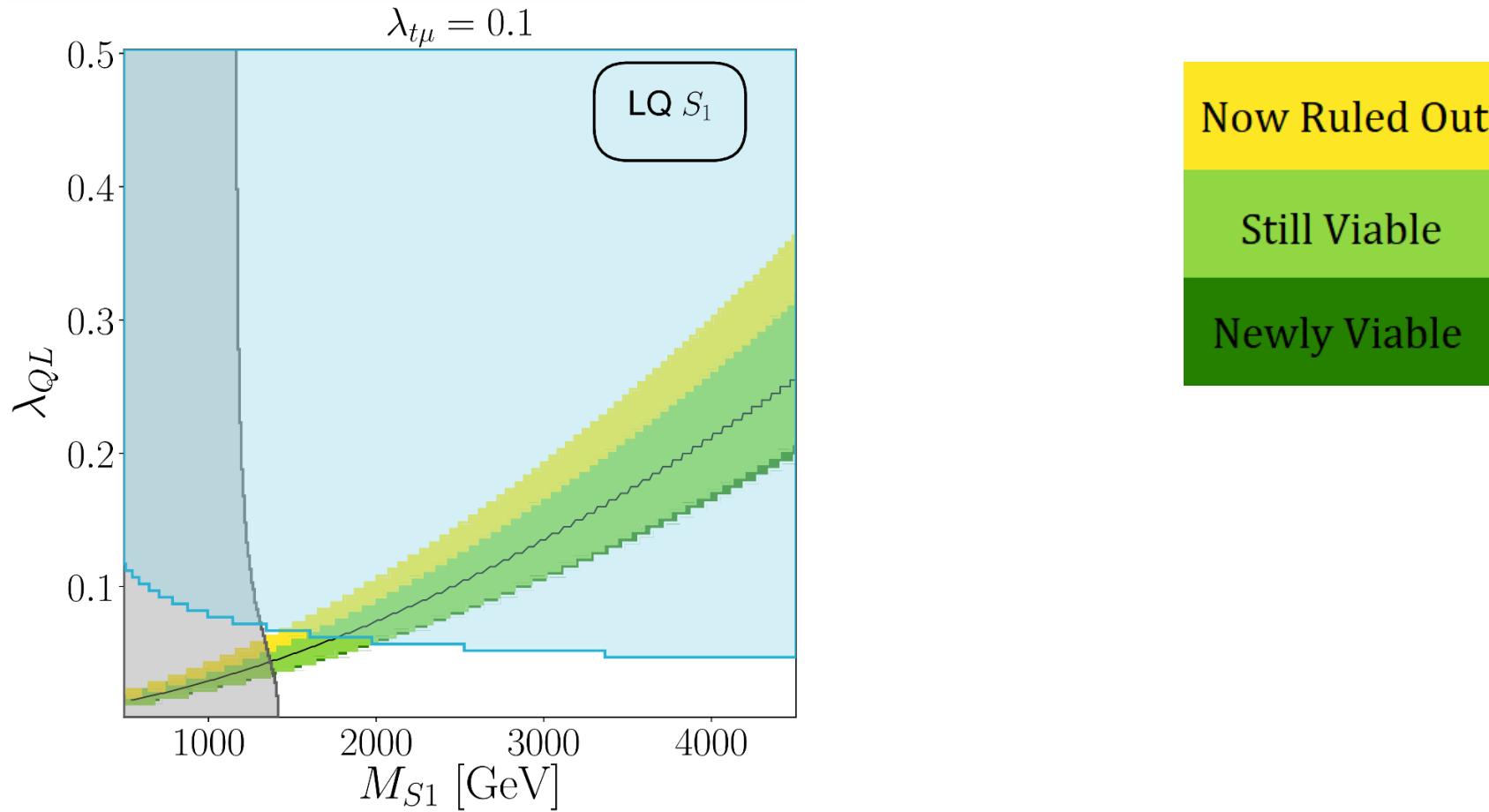
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Contributes to muon g-2



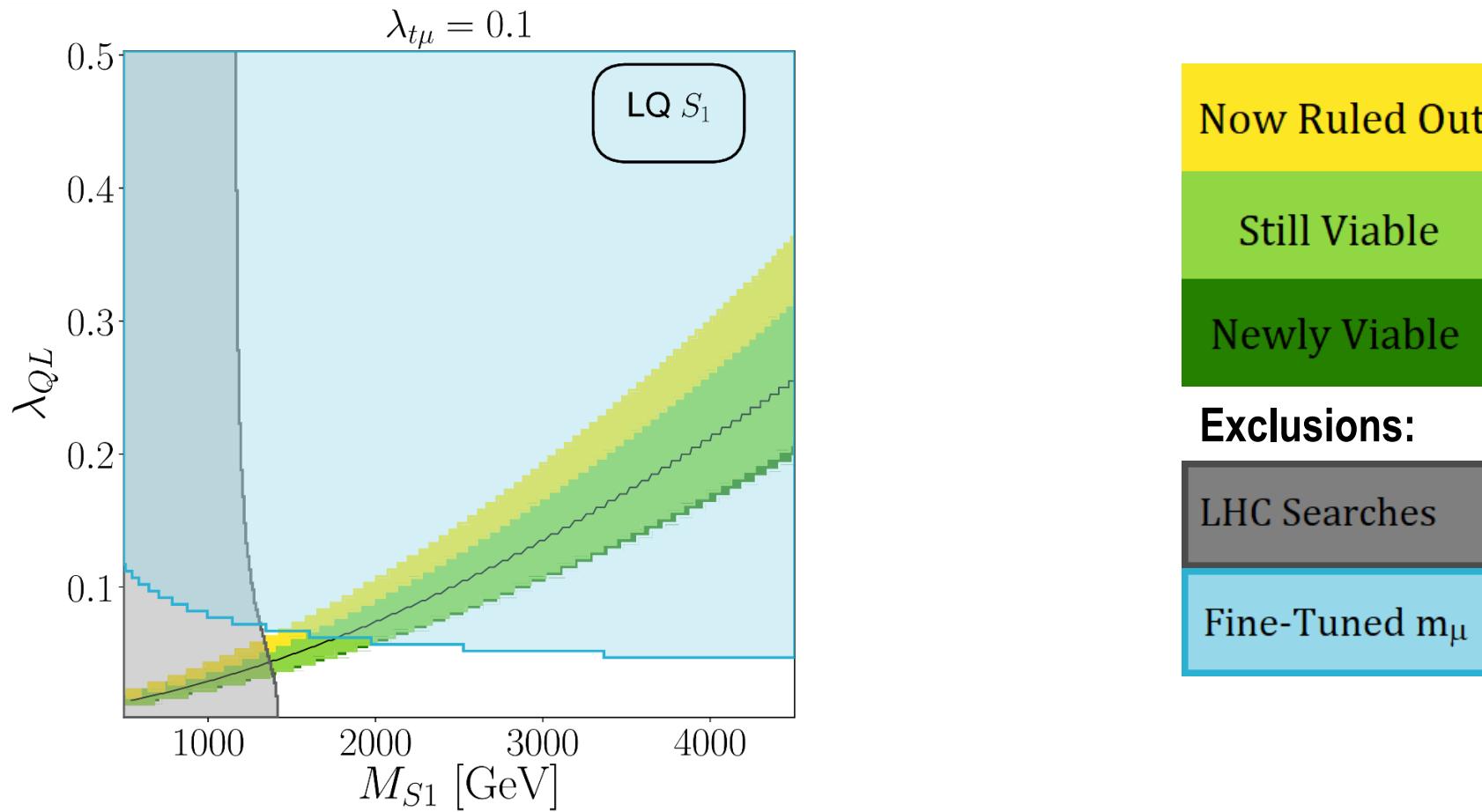
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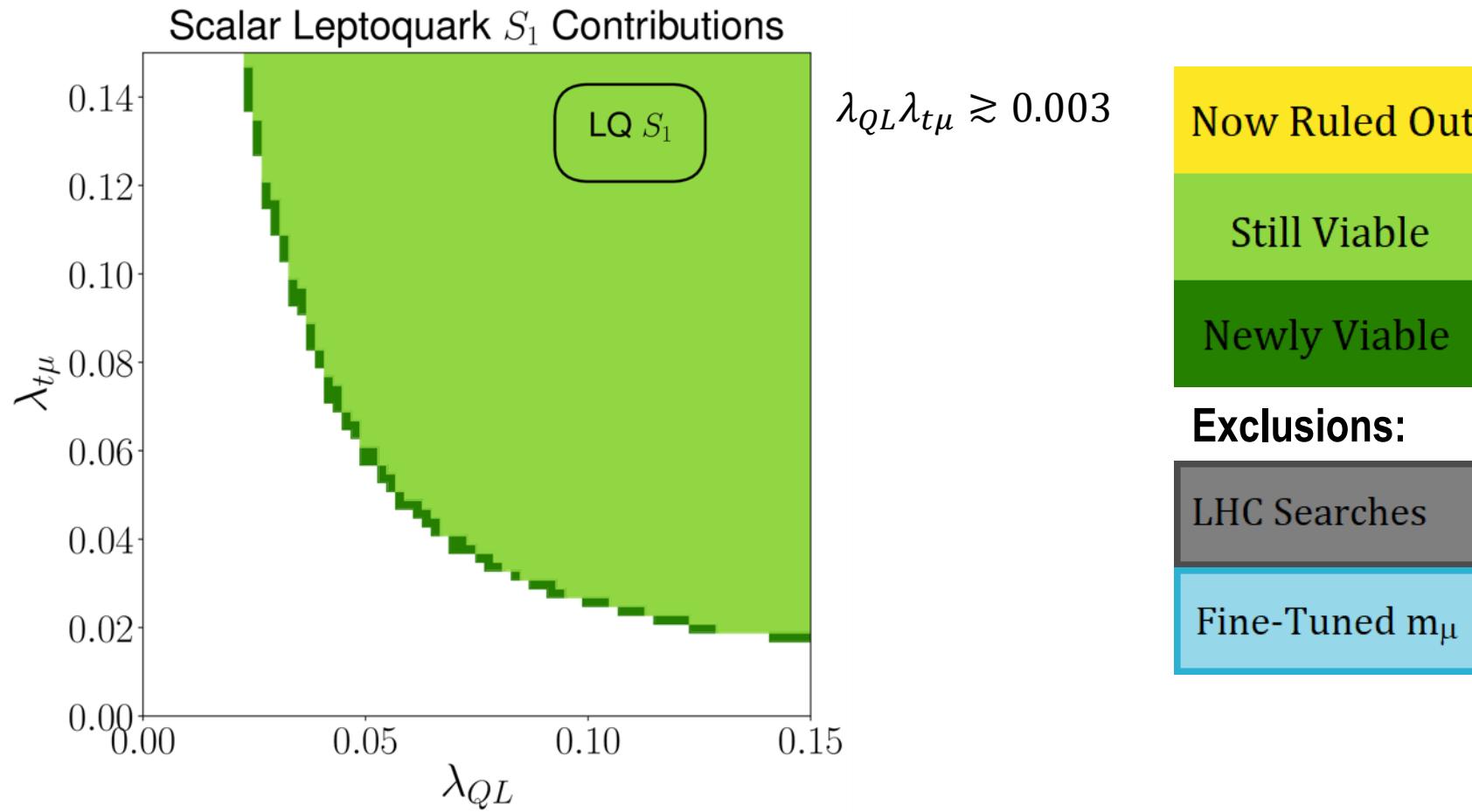
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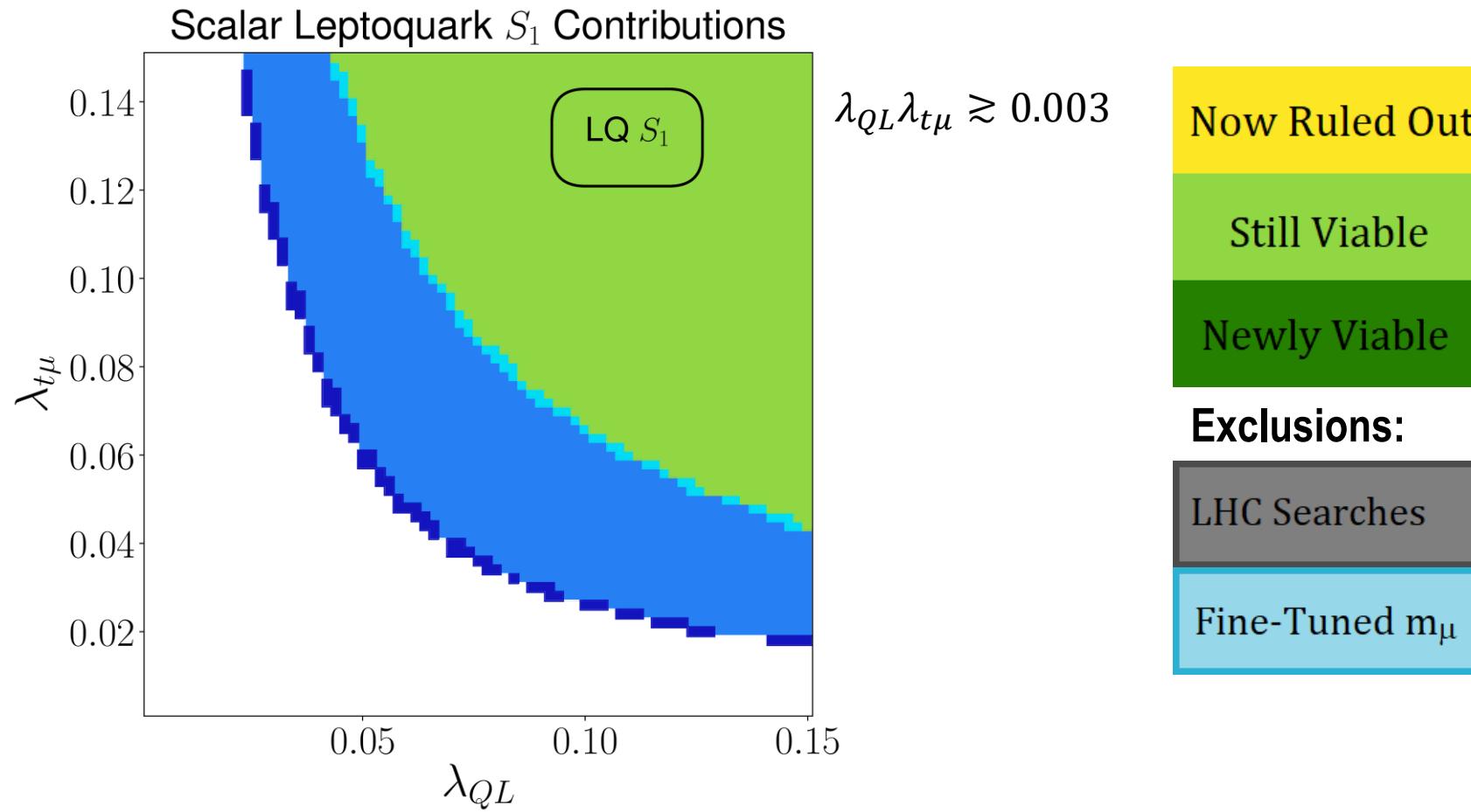
# Single Scalar Leptoquark

## Scalar Leptoquark Singlet



# Single Scalar Leptoquark

## Scalar Leptoquark Singlet



# Single Field Extensions

## Second Higgs Doublet Model (2HDM)

New Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Electric Charge
$H_2$	(1, 2, 1/2)	+1,0

$H_2$

$$\Phi_1 = \begin{pmatrix} \varphi_1^\pm \\ \frac{\nu_1 + \varphi_1 + i\sigma_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \varphi_2^\pm \\ \frac{\nu_2 + \varphi_2 + i\sigma_2}{\sqrt{2}} \end{pmatrix}$$

Interacts with the standard model through:

$$\mathcal{L}_{Yuk} = \frac{1}{v} \sum_{\varphi=h,H,A} \sum_f (Y_f^\varphi m_f \varphi \bar{f} P_R f + h.c.)$$

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$$\Phi_\nu = \begin{pmatrix} G^\pm \\ \frac{\nu + H_1 + iG^0}{\sqrt{2}} \end{pmatrix}, \Phi_\perp = \begin{pmatrix} H^\pm \\ \frac{H_2 + iA}{\sqrt{2}} \end{pmatrix}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos(\beta - \alpha) & -\sin(\beta - \alpha) \\ \sin(\beta - \alpha) & \cos(\beta - \alpha) \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

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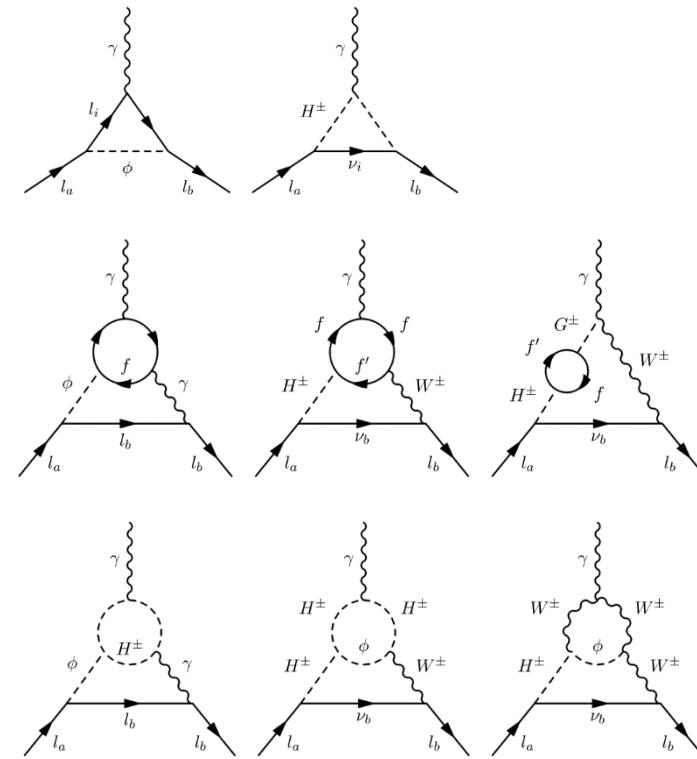
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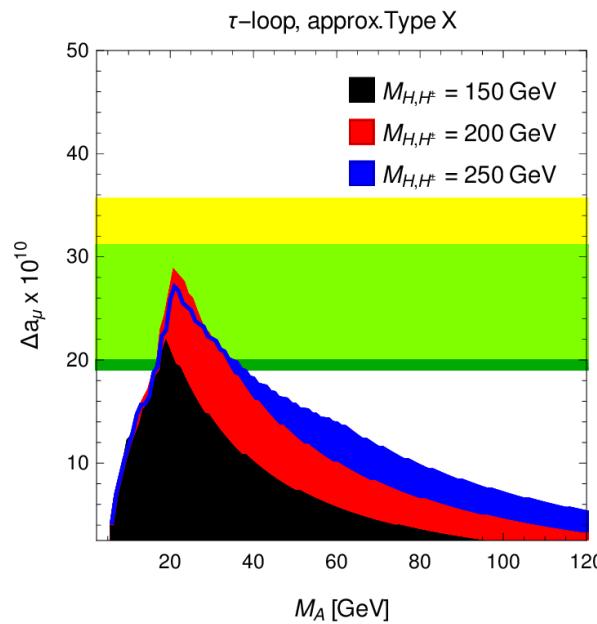


Contributes to muon g-2



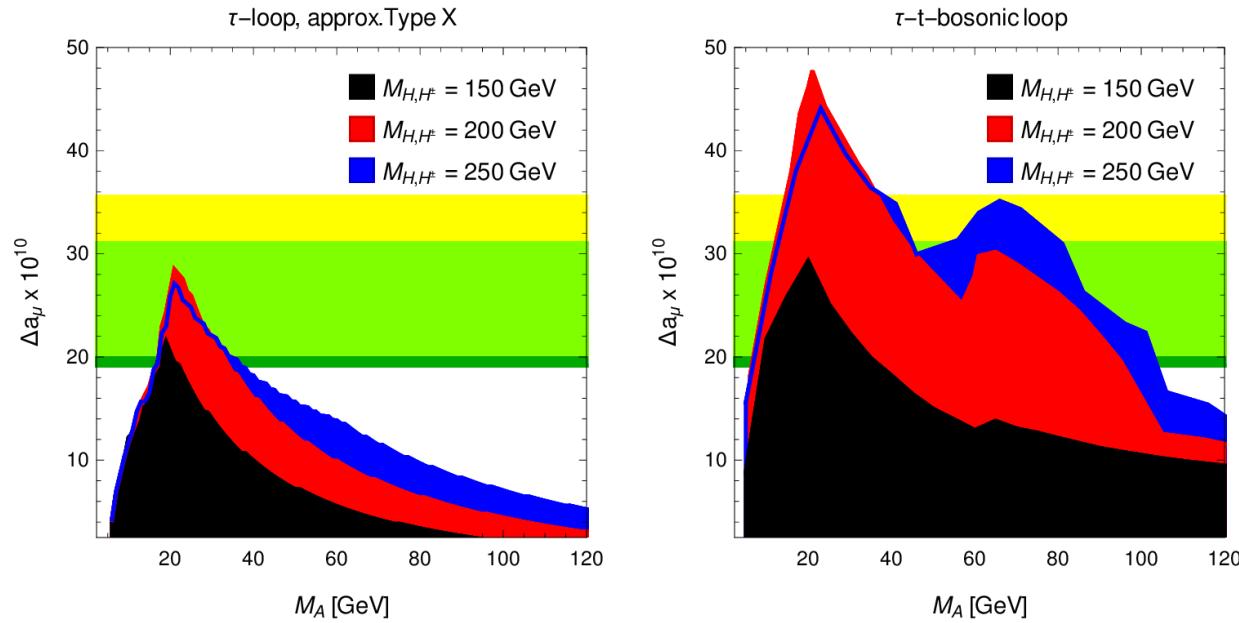
# Single Field Extensions

## Second Higgs Doublet Model (2HDM)



# Single Field Extensions

## Second Higgs Doublet Model (2HDM)



# 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 $\Delta a_\mu^{\text{BNL}}, \Delta a_\mu^{2021}$
$(\mathbf{1}, \mathbf{1}, 0)_0 - (\mathbf{1}, \mathbf{1}, -1)_{1/2}$	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
$(\mathbf{1}, \mathbf{2}, -1/2)_0 - (\mathbf{1}, \mathbf{1}, -1)_{1/2}$	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
$(\mathbf{1}, \mathbf{2}, -1/2)_0 - (\mathbf{1}, \mathbf{3}, 0)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1}, \mathbf{2}, -1/2)_0 - (\mathbf{1}, \mathbf{3}, -1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
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$(\mathbf{1}, \mathbf{3}, -1)_0 - (\mathbf{1}, \mathbf{3}, 0)_{1/2}$	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

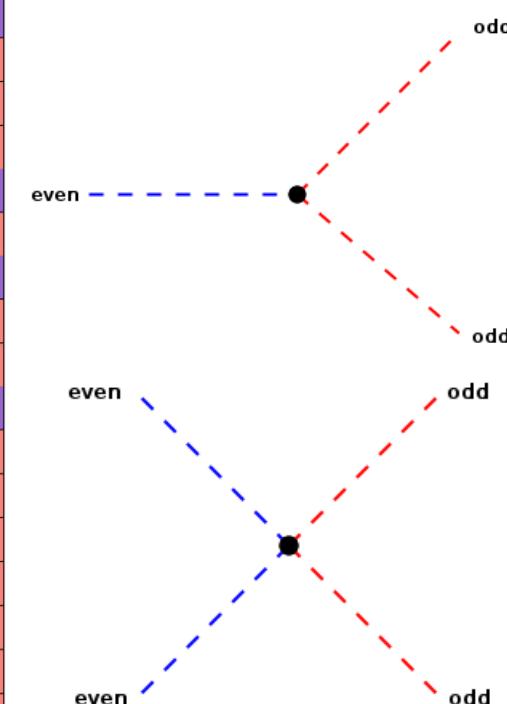
## Simple Explanations of Muon g-2

$(SU(3)_C \times SU(2)_L \times U(1)_Y)_{\text{spin}}$	$+ \mathbb{Z}_2$	Result for $\Delta a_\mu^{\text{BNL}}, \Delta a_\mu^{2021}$
$(\mathbf{1}, \mathbf{1}, 0)_0 - (\mathbf{1}, \mathbf{1}, -1)_{1/2}$	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
$(\mathbf{1}, \mathbf{2}, -1/2)_0 - (\mathbf{1}, \mathbf{1}, -1)_{1/2}$	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
$(\mathbf{1}, \mathbf{2}, -1/2)_0 - (\mathbf{1}, \mathbf{3}, 0)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1}, \mathbf{2}, -1/2)_0 - (\mathbf{1}, \mathbf{3}, -1)_{1/2}$	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: $\Delta a_\mu < 0$
$(\mathbf{1}, \mathbf{3}, 0)_0 - (\mathbf{1}, \mathbf{3}, -1)_{1/2}$	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: $\Delta a_\mu < 0$

## Z2 Symmetry

Z2-odd fields interact only in pairs:

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



# 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
$\psi_d = (\psi_d^+, \psi_d^0)$	(1, 2, 1/2)	1,0
$\phi$	(1, 1, 0)	0



Interacts with the standard model through:

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

Source: 1804.00009

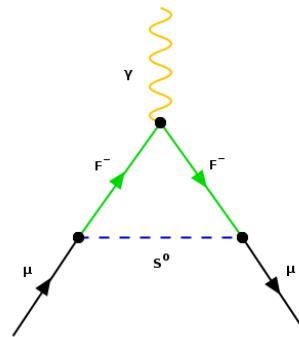
# Two Fields with Dark Matter

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



Contributes to muon g-2



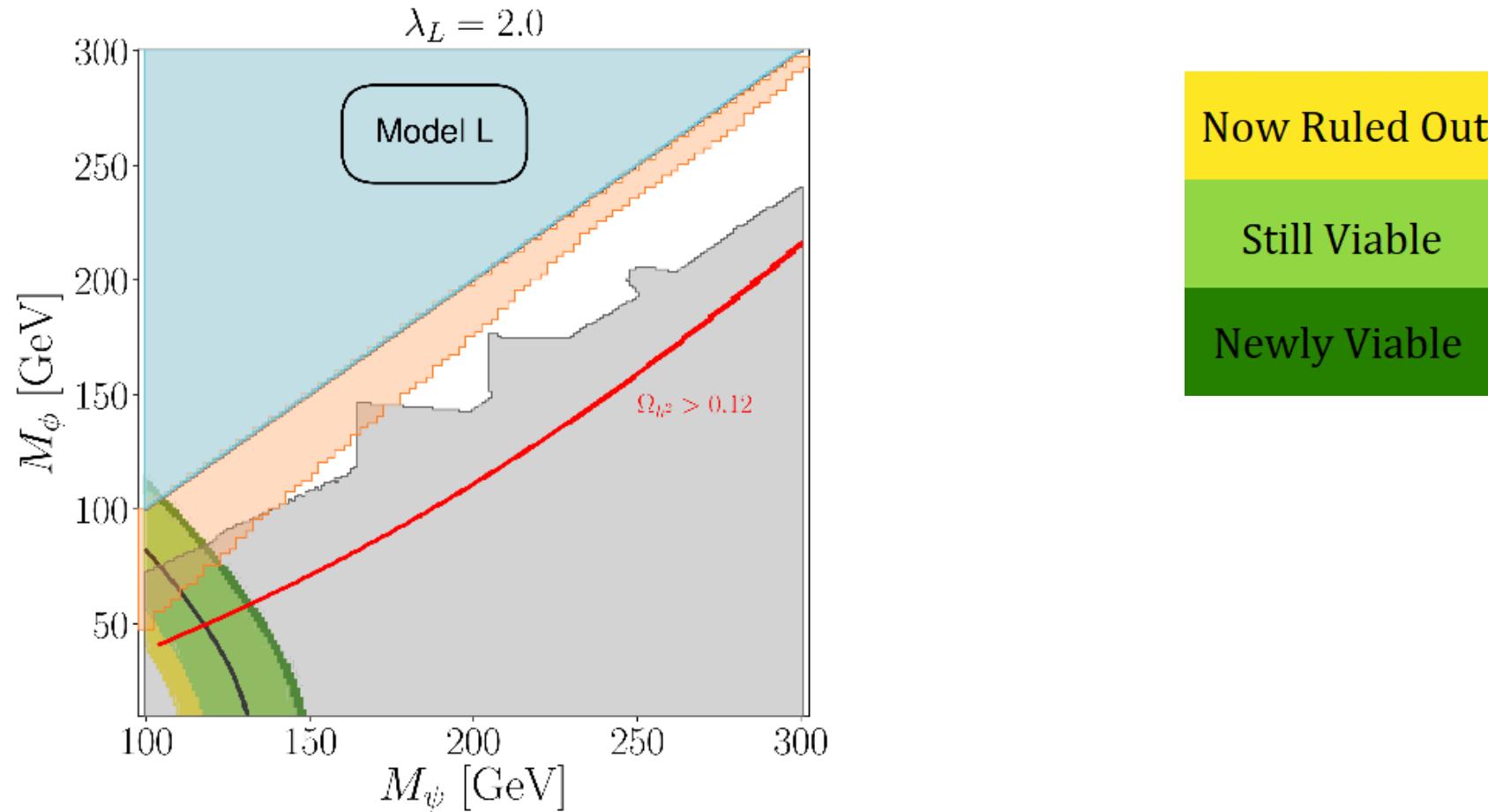
Interacts with the standard model through:

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

Source: 1804.00009

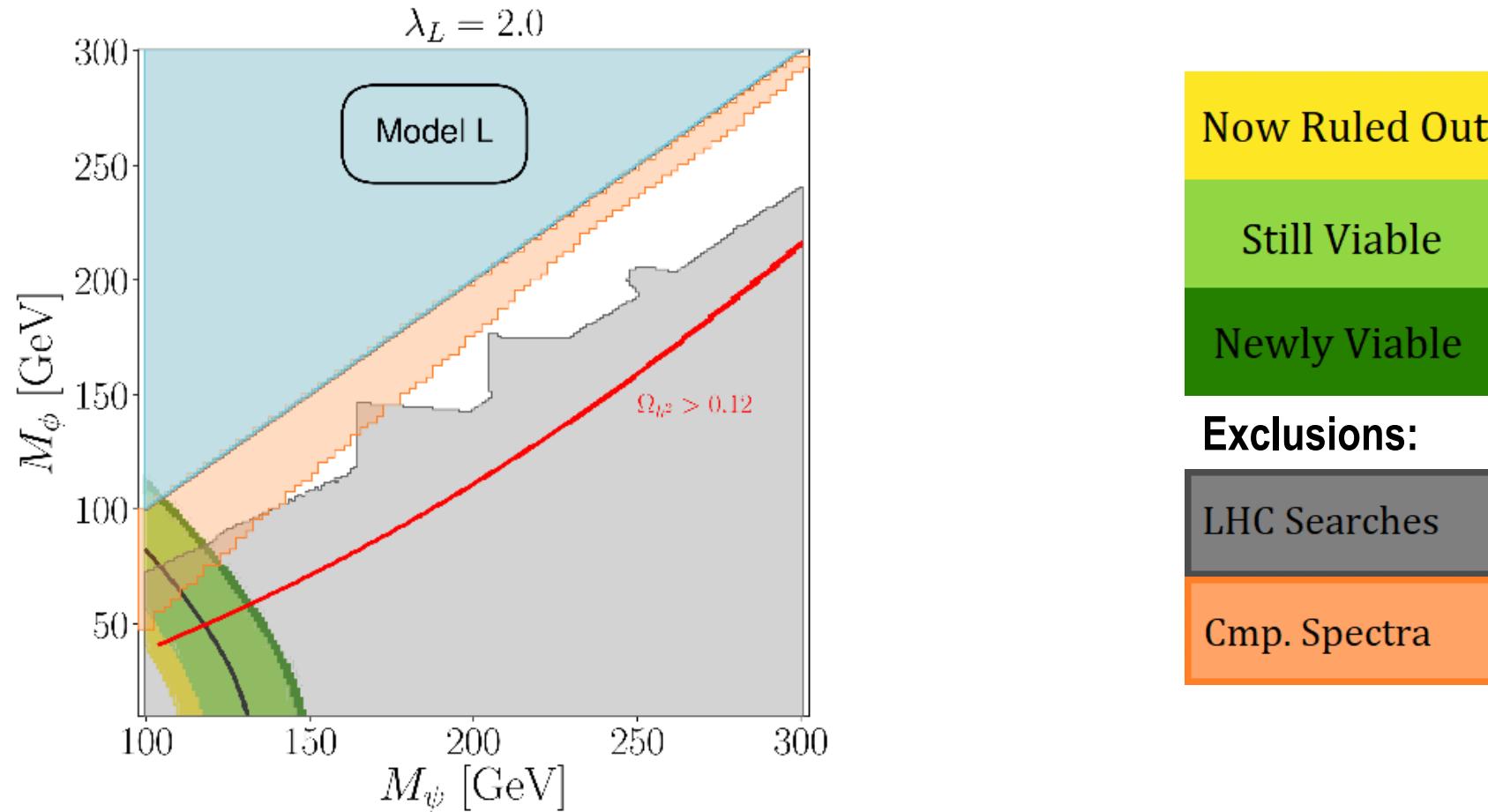
# Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon



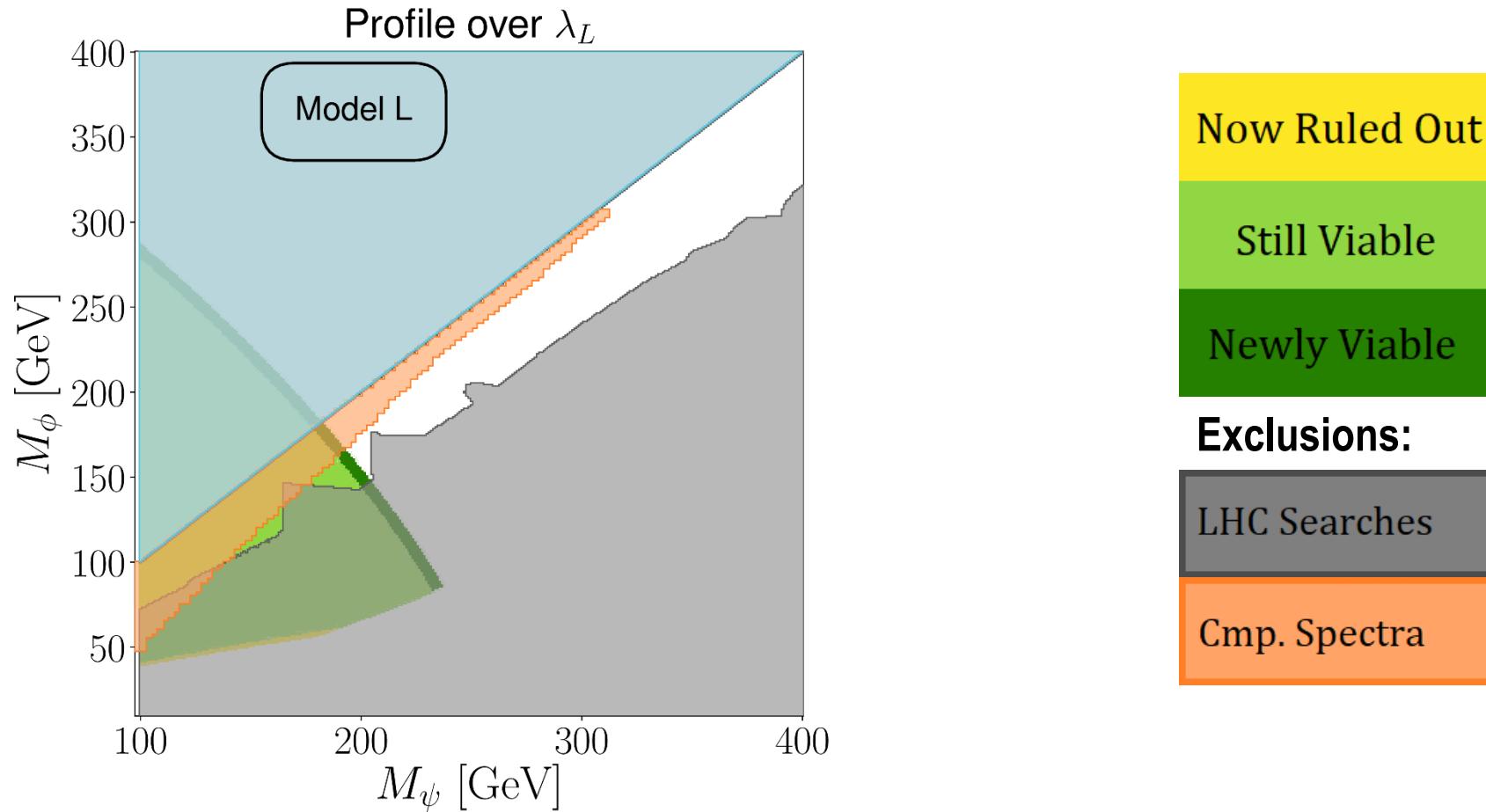
# Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon



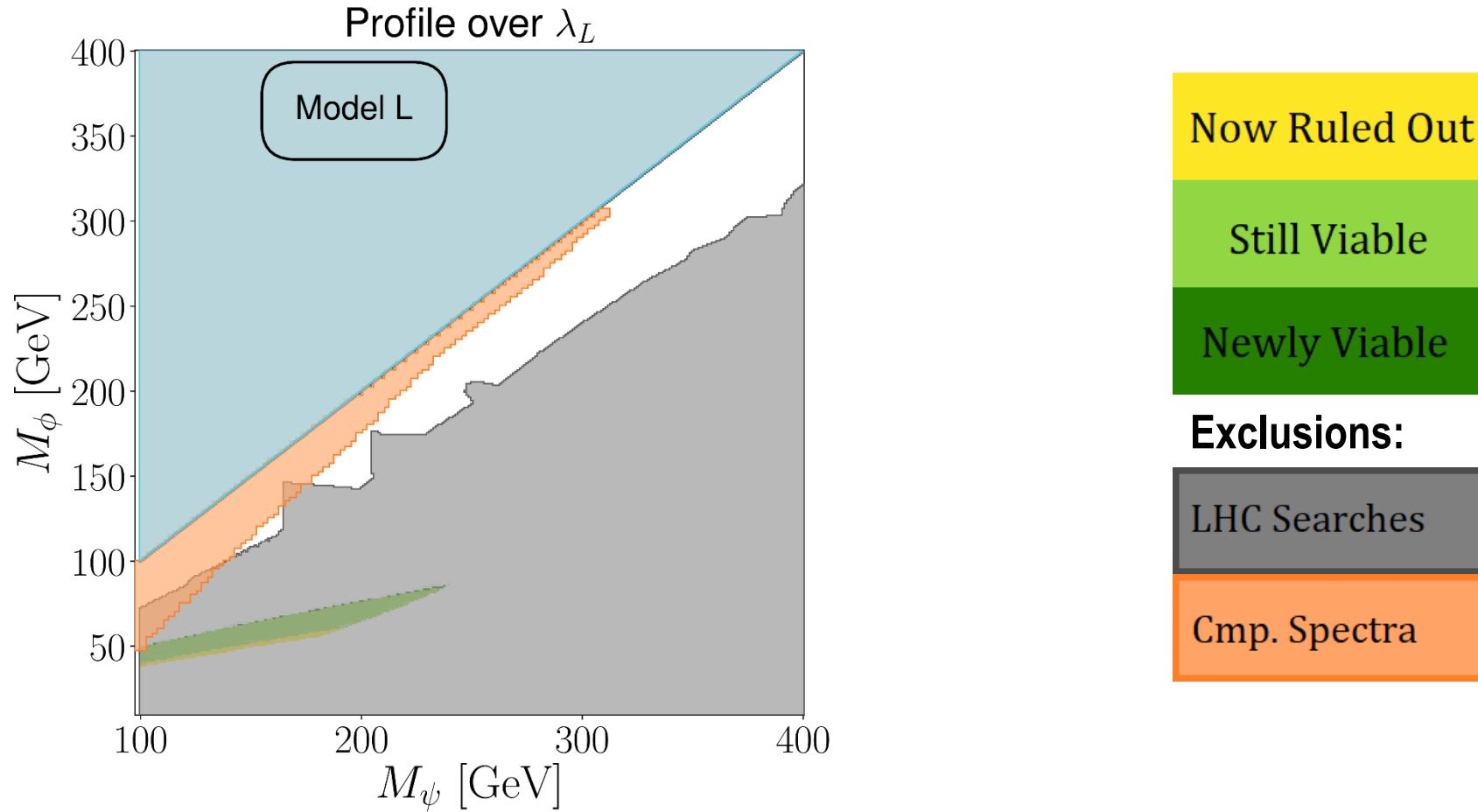
# Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon



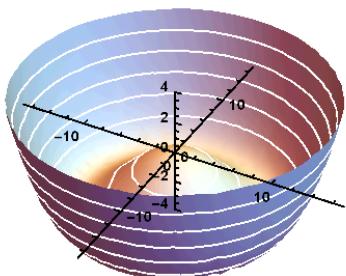
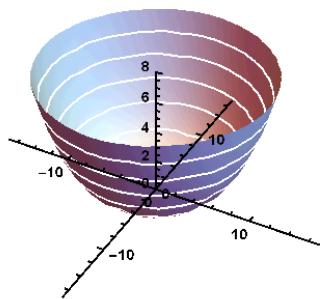
# Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon



# BSM Models

## Mixing Fermions and Scalars



After EWSB, mixed fields with identical electric charges mix:

$$\begin{aligned}\psi_s^0, \psi_d^0 &\rightarrow \psi_1^0, \psi_2^0 \\ \psi_s^-, \psi_d^- &\rightarrow \psi_1^-, \psi_2^-\end{aligned}$$

# Three Fields with Dark Matter

Pair of New Scalars + Fermion

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



Interacts with the standard model through:

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

# Three Fields with Dark Matter

Pair of New Scalars + Fermion

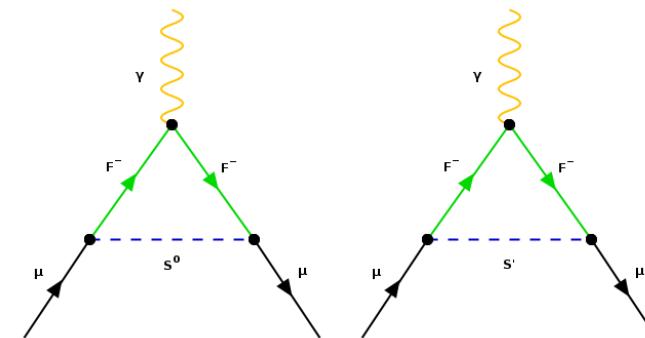
New Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Electric Charge
$\psi_s = \psi_s^{-\dagger}$	(1, 1, 1)	1
$\phi_s = \phi_s^0$	(1, 1, 0)	0
$\phi_d = (\phi_d^0, \phi_d^-)$	(1, 2, -1/2)	0, -1

Interacts with the standard model through:

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

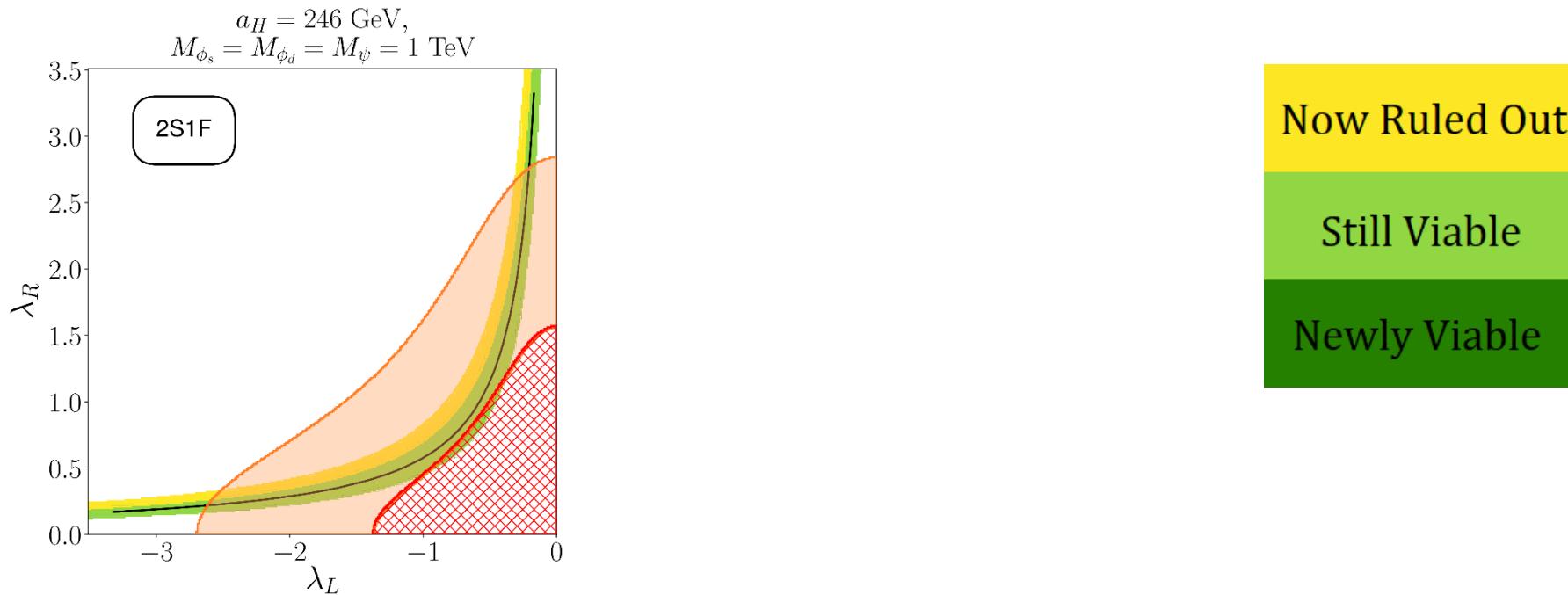


Contributes to muon g-2



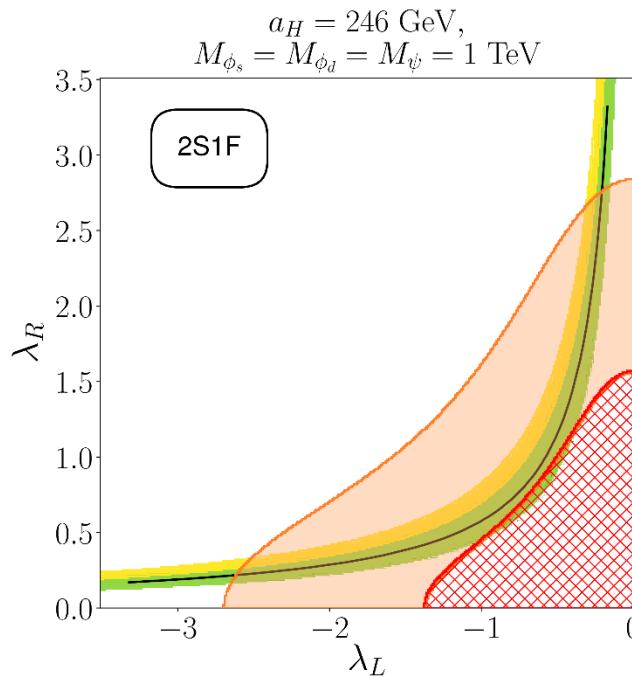
# Three Fields with Dark Matter

Pair of New Fermions + Scalar

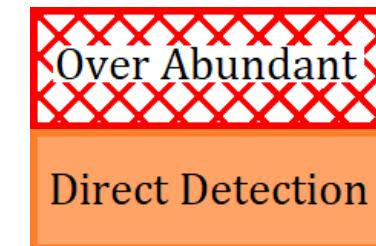


# Three Fields with Dark Matter

Pair of New Fermions + Scalar

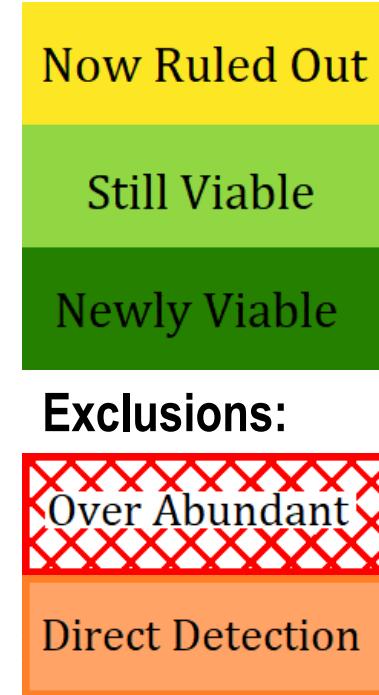
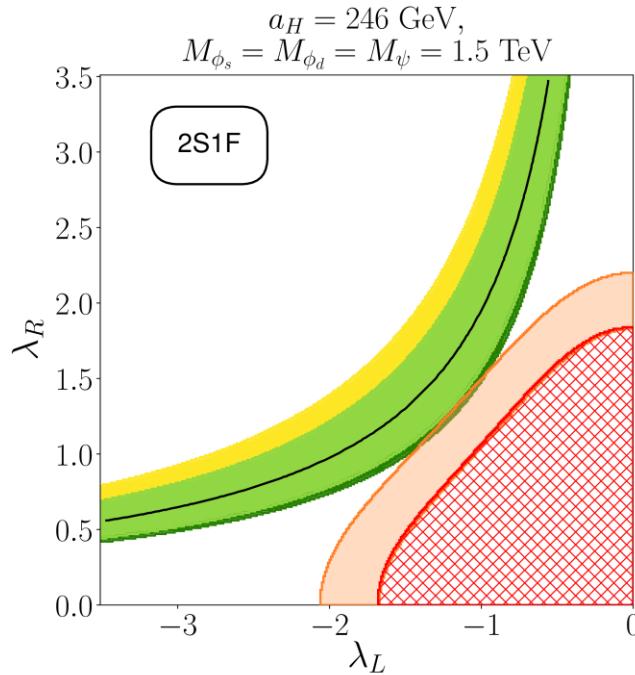


**Exclusions:**



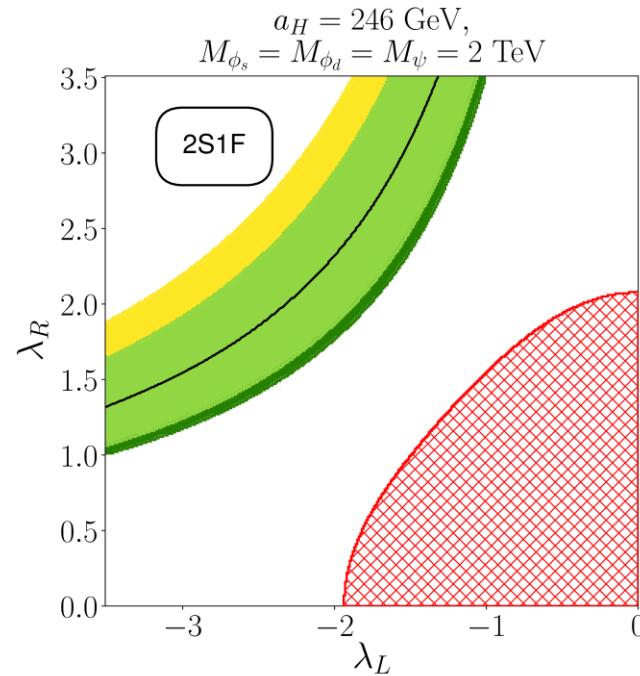
# Three Fields with Dark Matter

Pair of New Fermions + Scalar



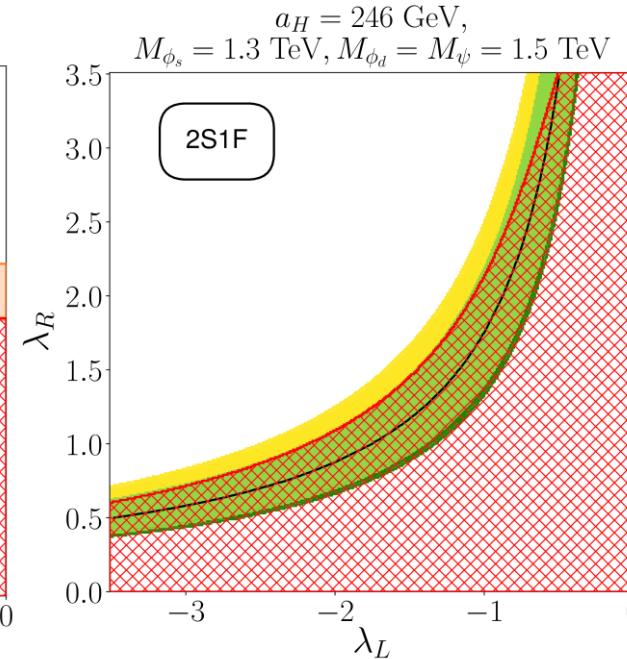
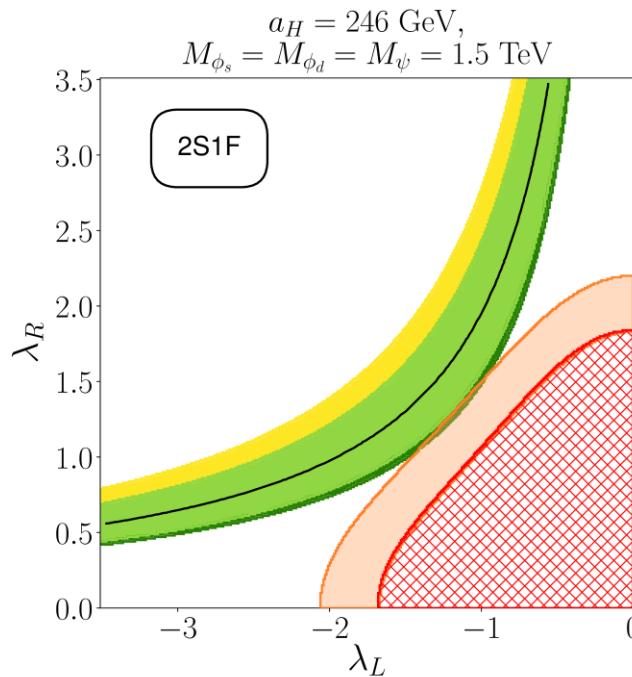
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Pair of New Fermions + Scalar



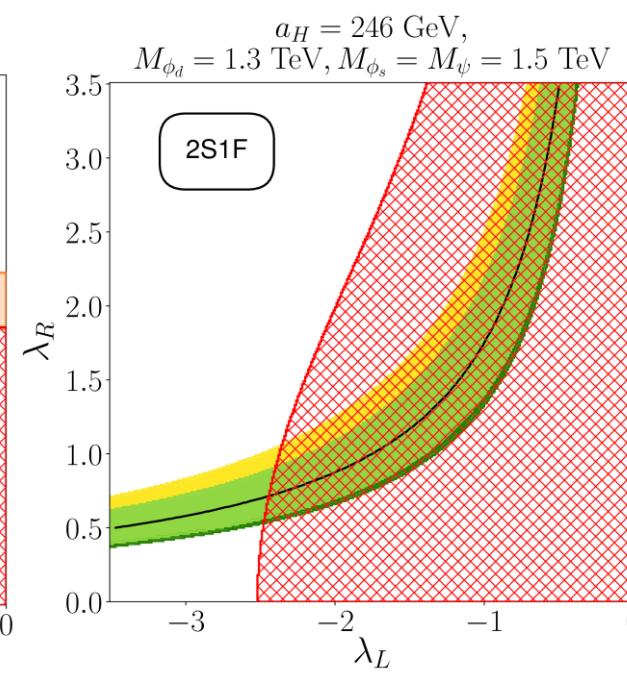
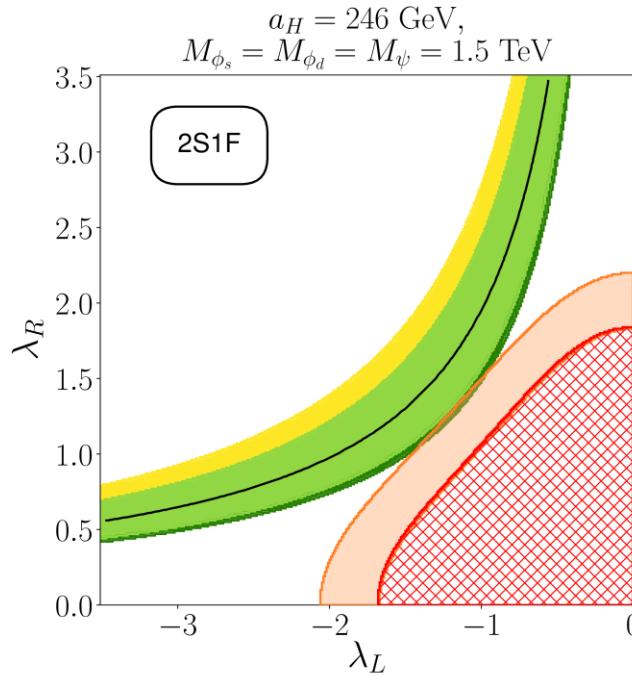
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Pair of New Fermions + Scalar



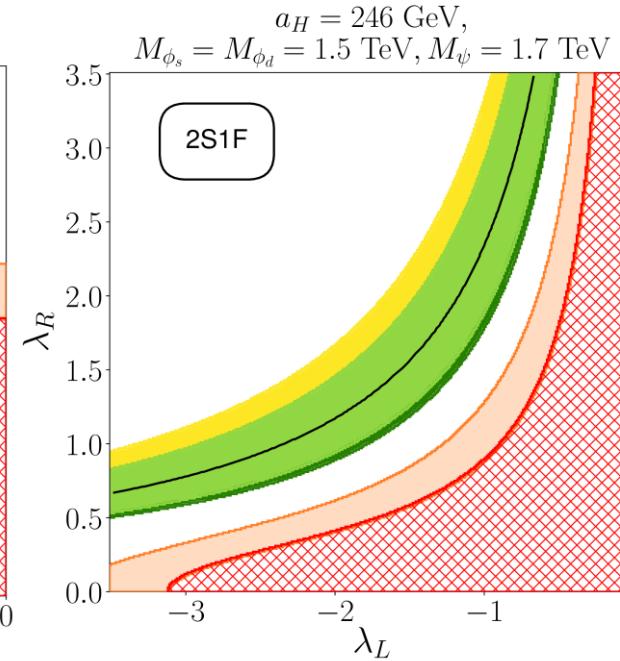
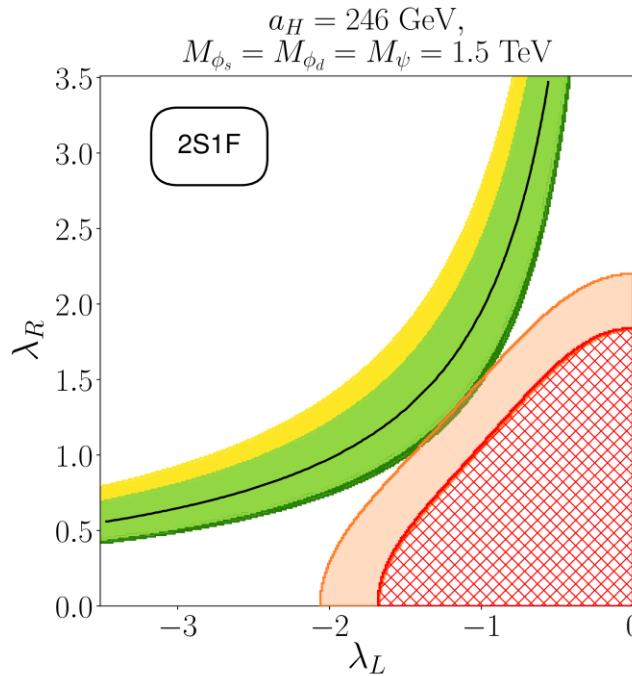
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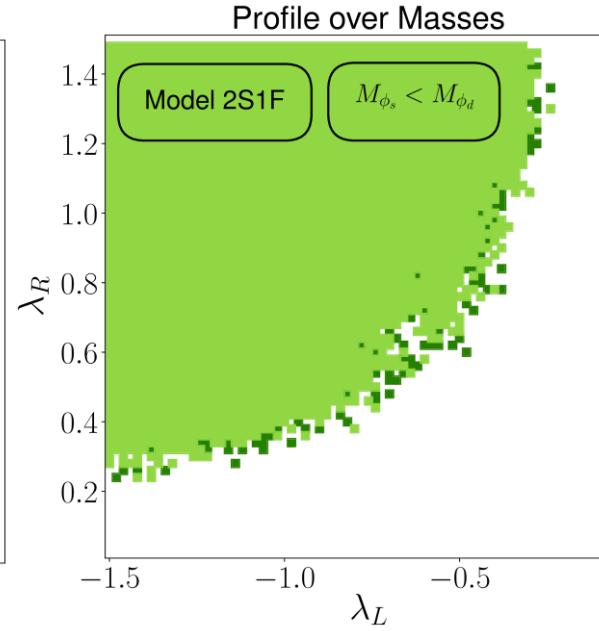
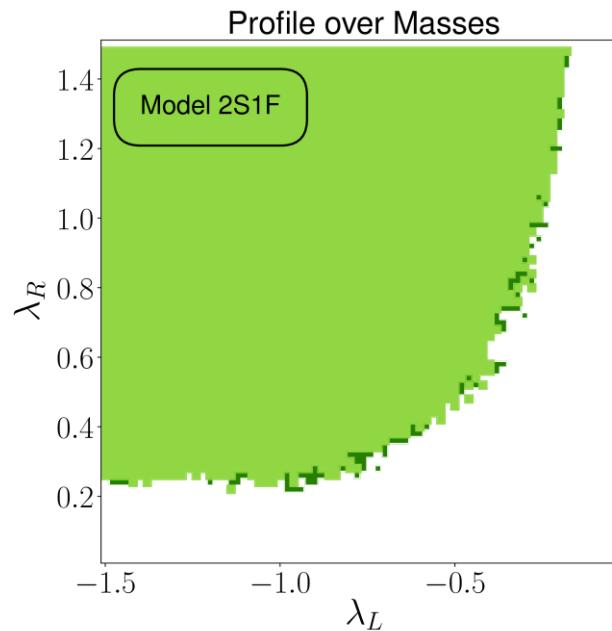
# Three Fields with Dark Matter

Pair of New Fermions + Scalar



# Three Fields with Dark Matter

Pair of New Fermions + Scalar



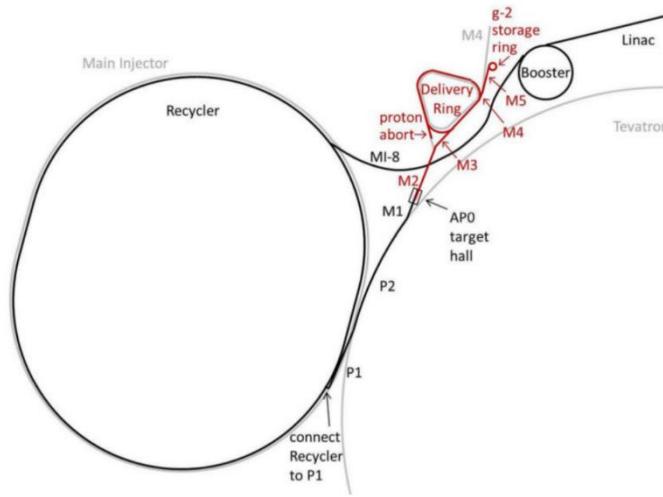
$$|\lambda_L \lambda_R| \gtrsim 0.22$$



# Future Developments

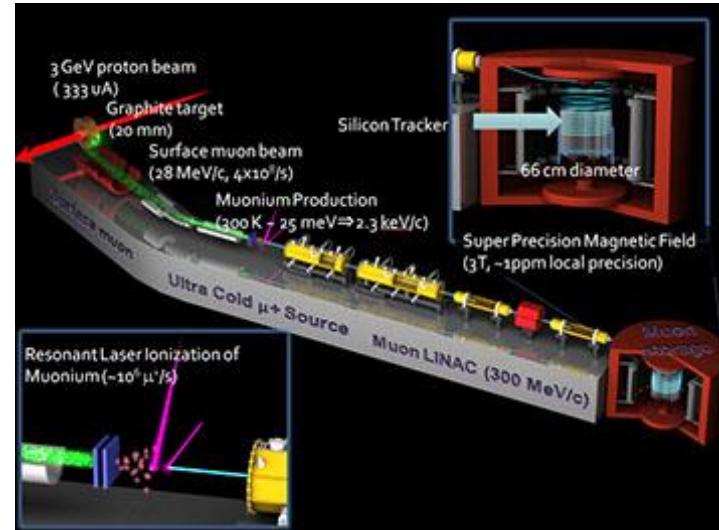
## Upcoming Experiments Measurements

### Fermilab



Run-4 now completed. Runs-5 & 6 planned.  
 Run-4 experimental precision: 0.14ppm

### J-PARC



Upcoming.  
 Final experimental precision: 0.1ppm

# 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  $4.2\sigma$ .
  - 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

