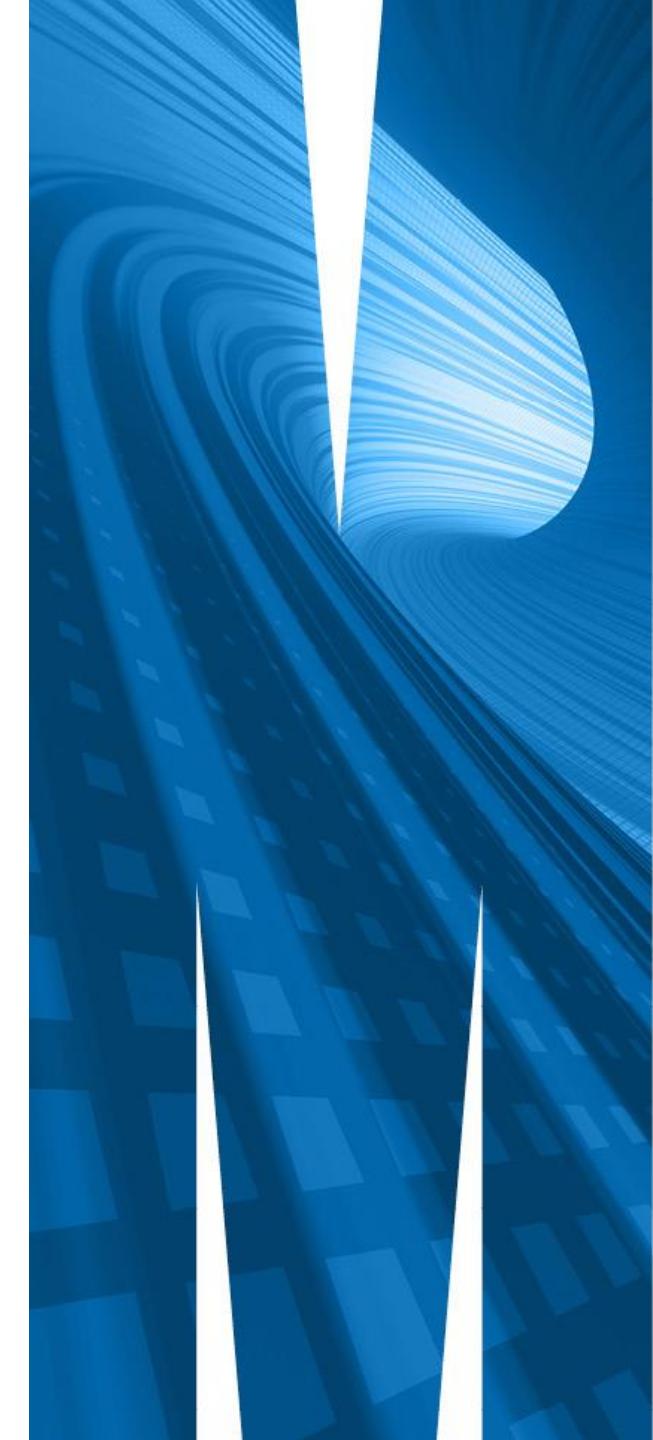


Simplified BSM explanation of the Muon $g-2$ Anomaly

Douglas HJ Jacob

- Supervisors: Csaba Balazs, Peter Athron
- Date: 27th June
- Location: G59/G60 (Old Main Building), UNSW



Outline

The anomalous magnetic moment of the muon, Muon g-2

Muon G-2

- Experimental Measurement
- Theoretical Prediction
- Current Discrepancy
- Phenomenological Description
- Contributions to Muon g-2

Results

- Dark matter from 2 New Particles
- Dark matter from 3 New Particles
- Leptoquarks
- Two Higgs Doublet Model
- Conclusions

Muon g-2 Discrepancy

Current Status of Muon g-2

New Experimental World Average

$$a_\mu^{2021} = 116592061(41)_{exp} \times 10^{-11}$$

Standard Model Theoretical Prediction

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

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$$\Delta a_\mu^{2021} = 251 \pm 59 \times 10^{-11}$$

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4.2 σ deviation!

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4. 2σ deviation!

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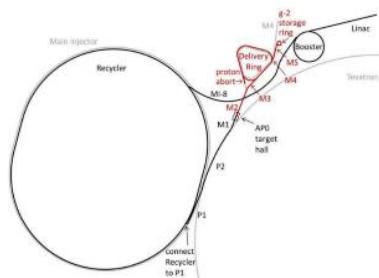
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Fermilab



Run-4 now completed. Runs-5 & 6 planned.

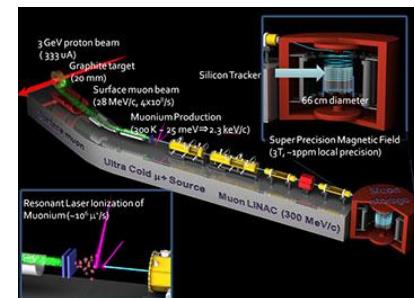
Run-4 experimental precision: 0.14ppm

Standard Model Theoretical Prediction

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4.2 σ deviation!

J-PARC

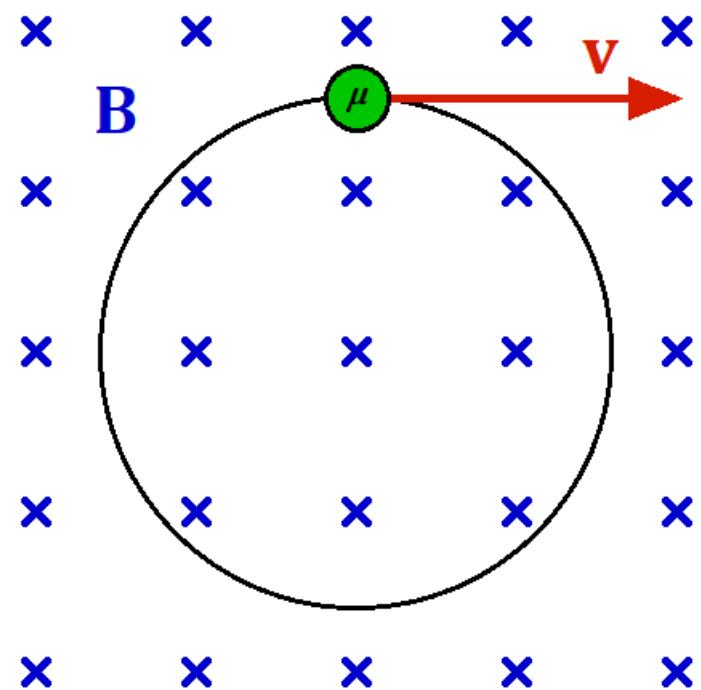


Upcoming.

Final experimental precision: 0.1ppm

What is the Muon g-2?

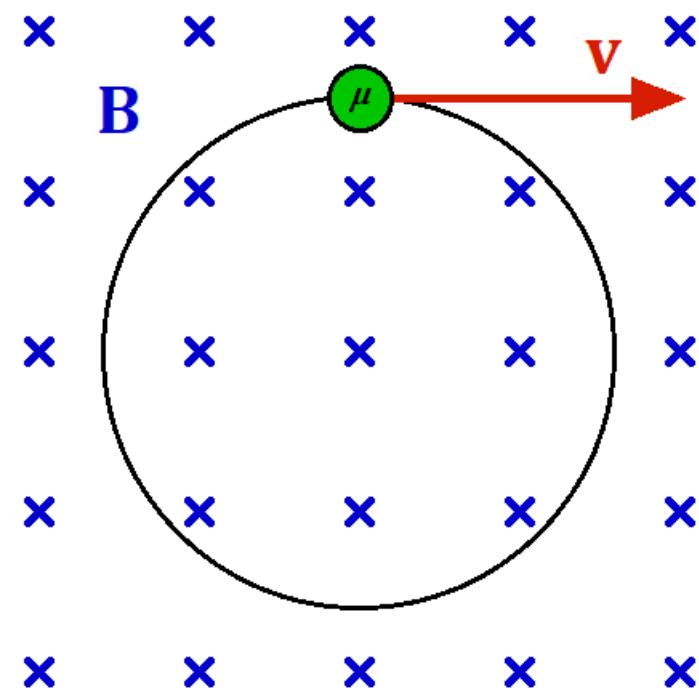
Quantum Mechanics



What is the Muon g-2?

Quantum Mechanics

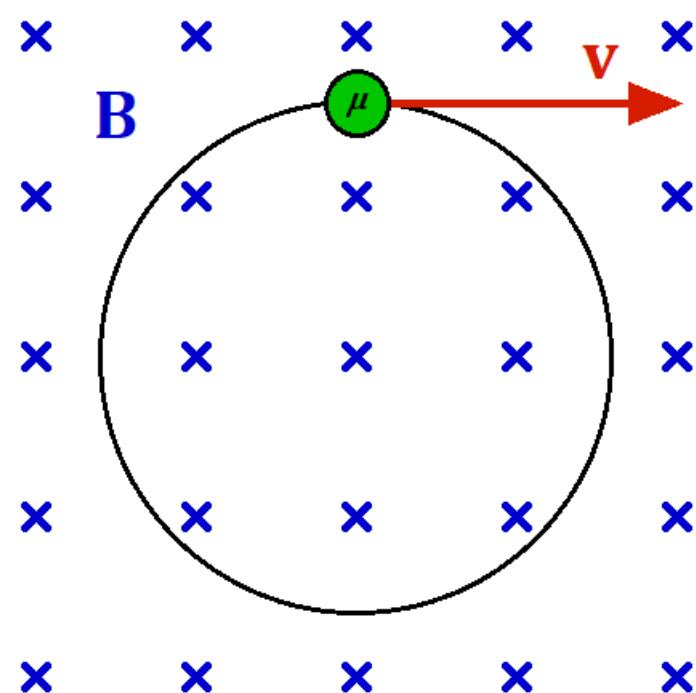
Magnetic Moment: $\vec{M} = g \frac{q}{2m} \vec{S}$



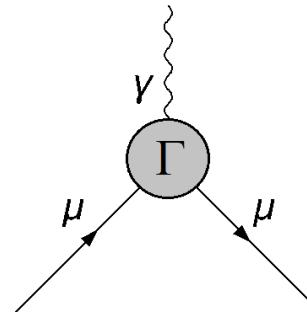
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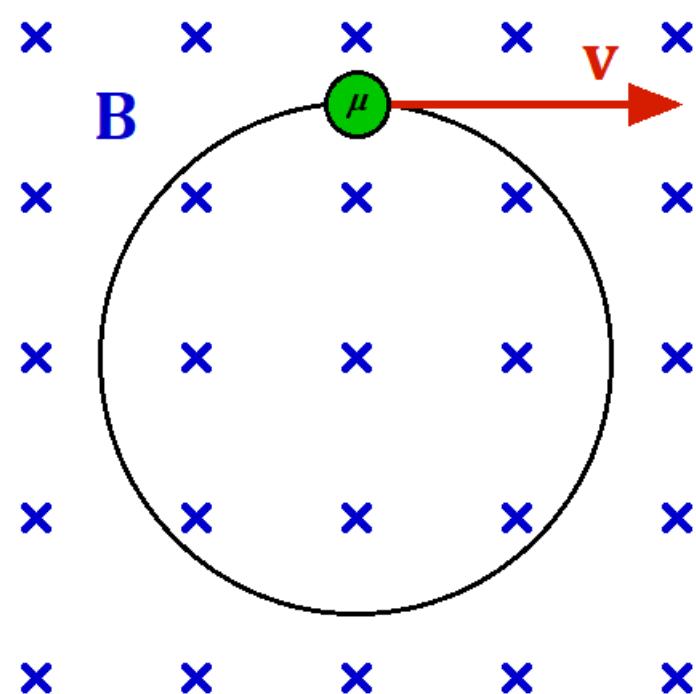
Quantum Field Theory



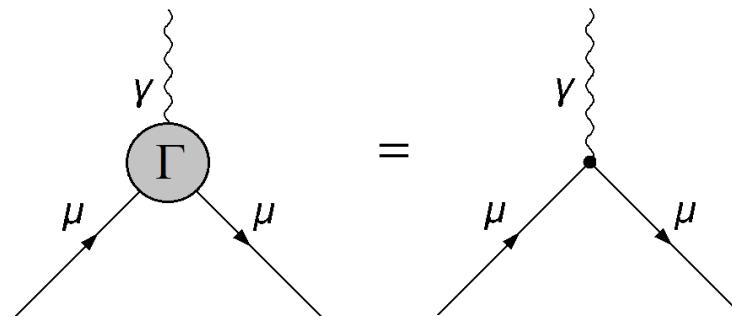
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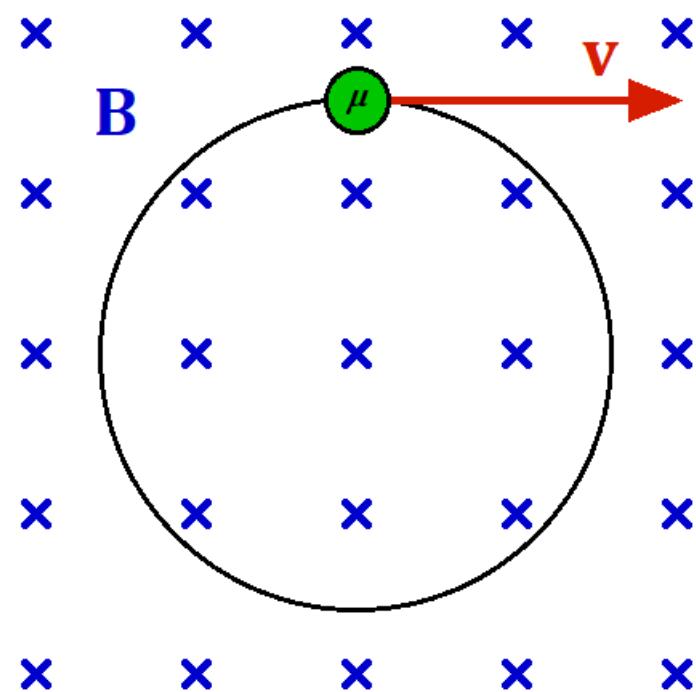
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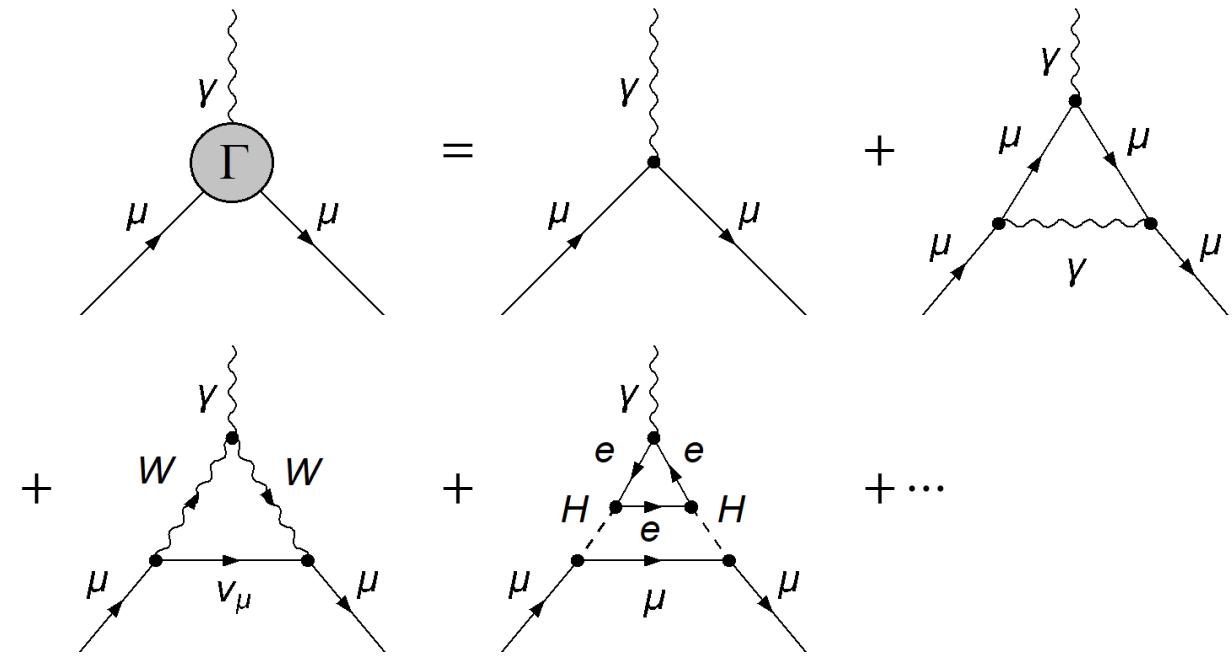
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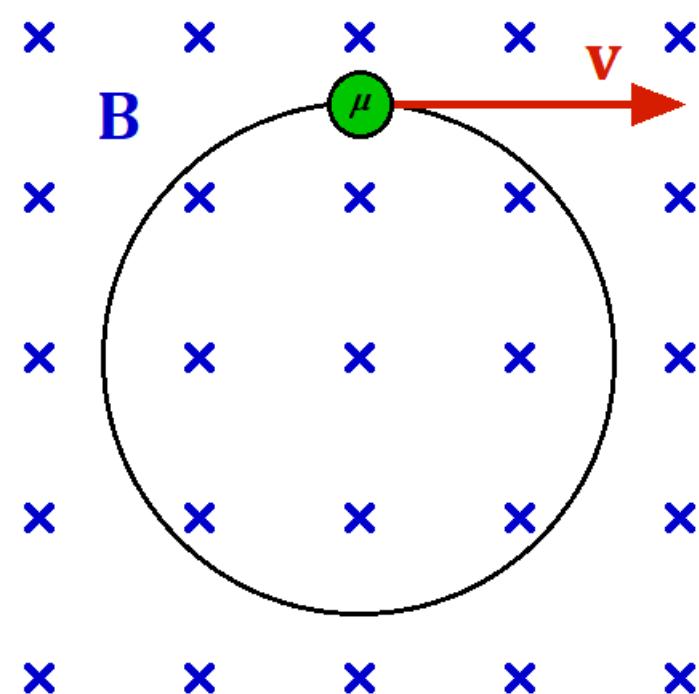
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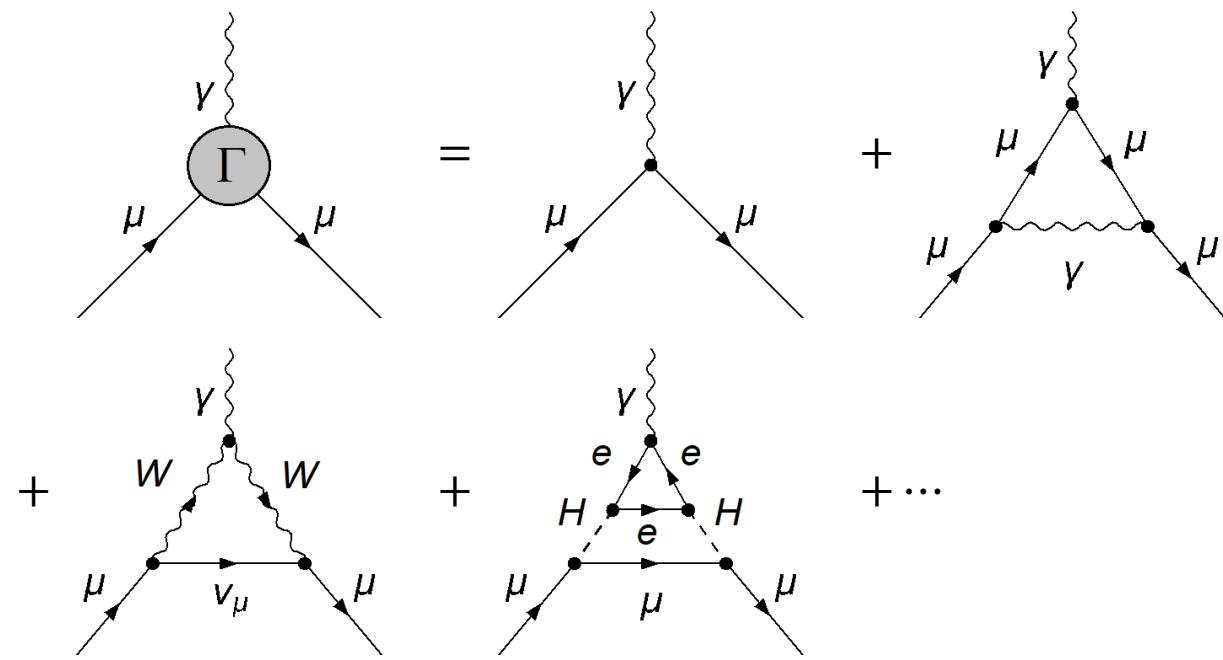
Quantum Mechanics

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



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

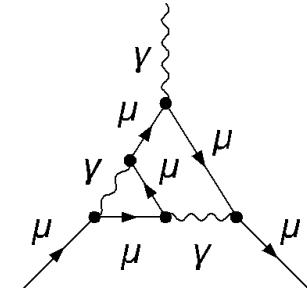
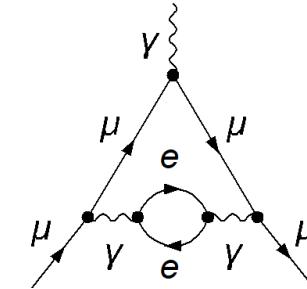
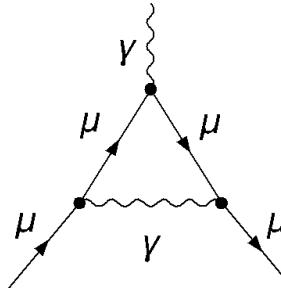
Electroweak Contributions

Hadronic Contributions

Contributions to Muon g-2

Standard Model Contributions to Muon g-2

Quantum Electrodynamics Contributions



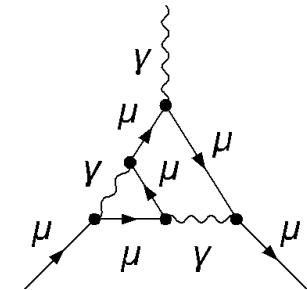
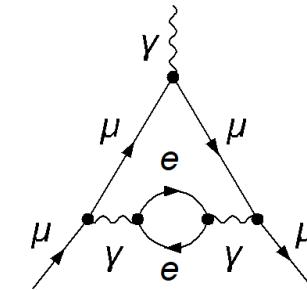
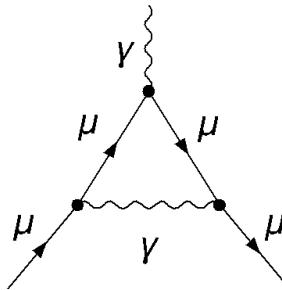
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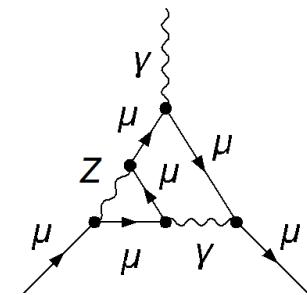
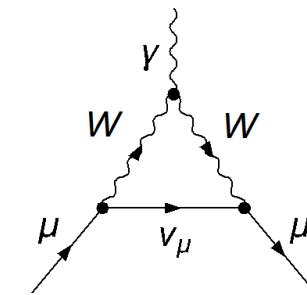
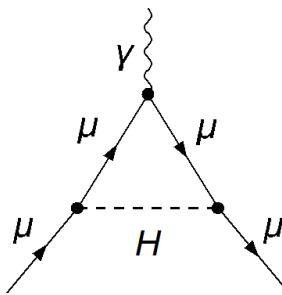
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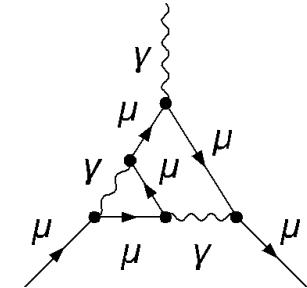
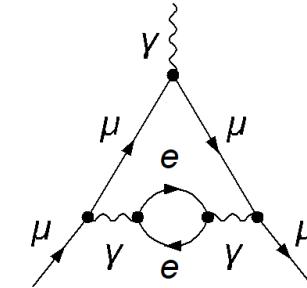
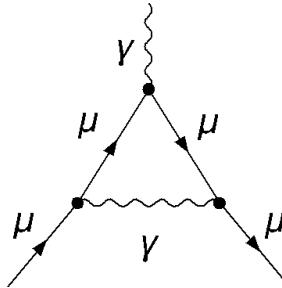


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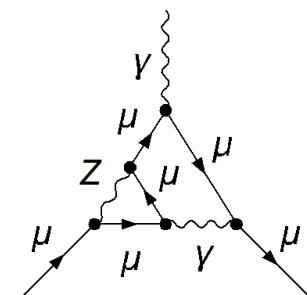
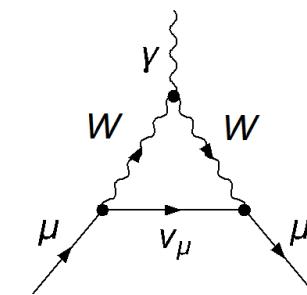
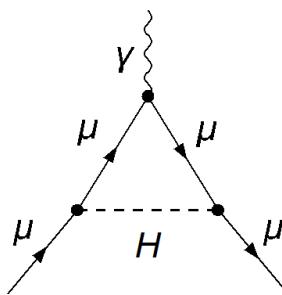
Contributions to Muon g-2

Standard Model Contributions to Muon g-2

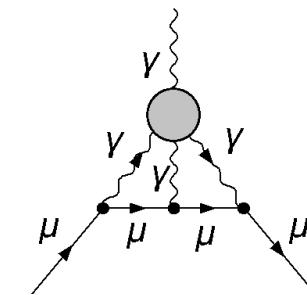
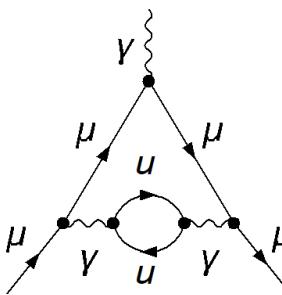
Quantum Electrodynamics Contributions



Electroweak Contributions



Hadronic Contributions



Contributions to Muon g-2

General Contributions to Muon g-2

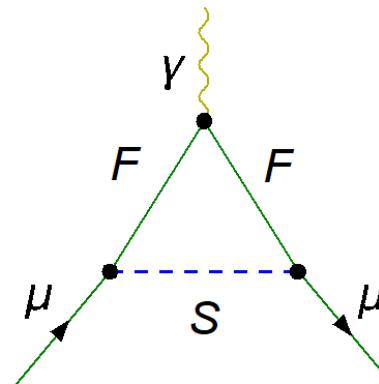
All possible contributions to muon g-2 from 1-loop diagrams must be of these forms.

Contributions to Muon g-2

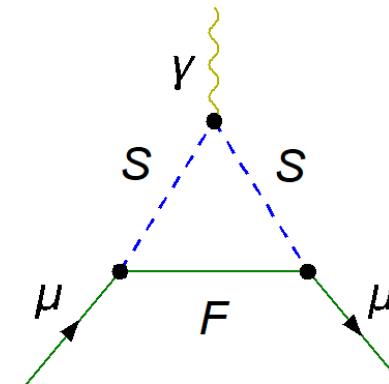
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FFS Diagram



SSF Diagram

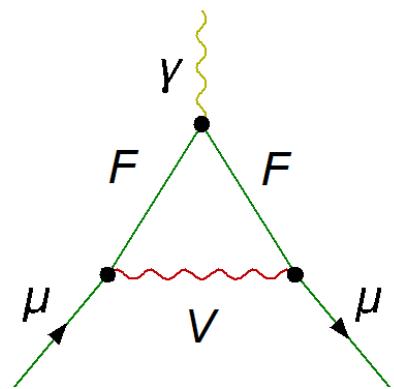


Contributions to Muon g-2

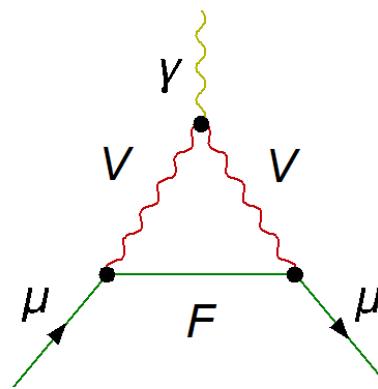
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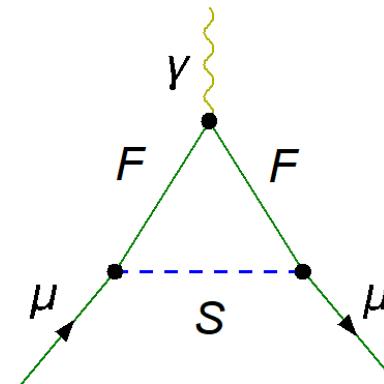
FFV Diagram



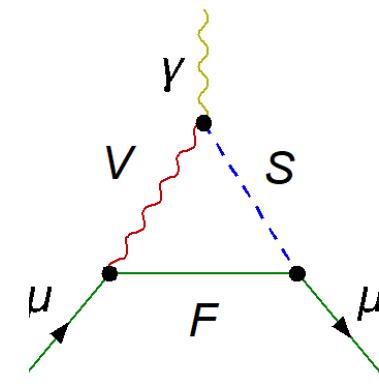
VVF Diagram



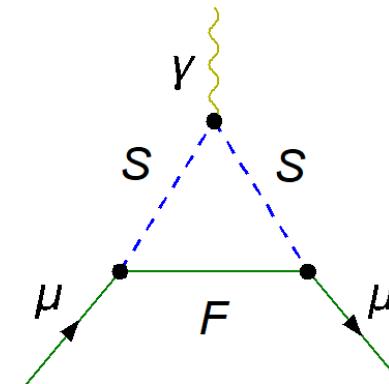
FFS Diagram



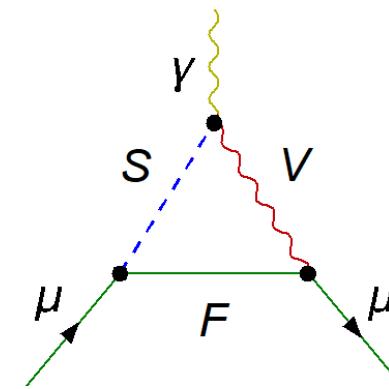
VSF Diagram



SSF Diagram



SVF Diagram



Beyond the Standard Model

Simple and SUSY Explanations of Muon g-2

My work has focused on providing explanations of the muon g-2 anomaly using simple beyond the standard model physics.

Working with collaborators, produced three papers that were focused on explaining the muon g-2 anomaly after the Fermilab result.

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Two Field Extensions

- Fermion paired with Scalar or Vector
- Mixed Vector-like Fermion Pair

Three Field Extensions

Minimal Supersymmetric Standard Model

Single Field Extensions

- New Scalars
 - 2HDM
 - Scalar Leptoquarks

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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: $\Delta a_\mu < 0$ |
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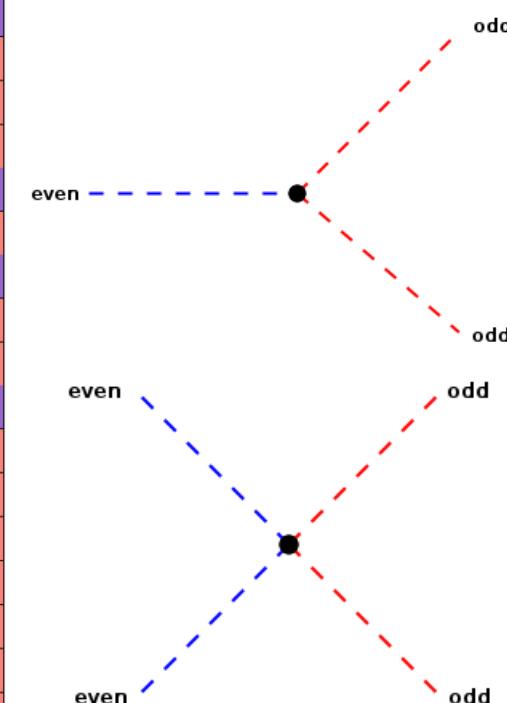
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Z2 Symmetry

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 |
| ϕ | (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

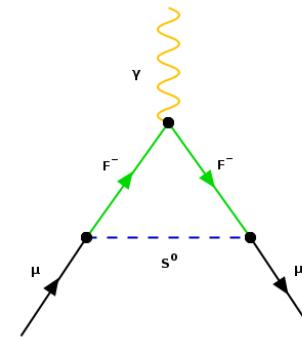
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Contributes to muon g-2



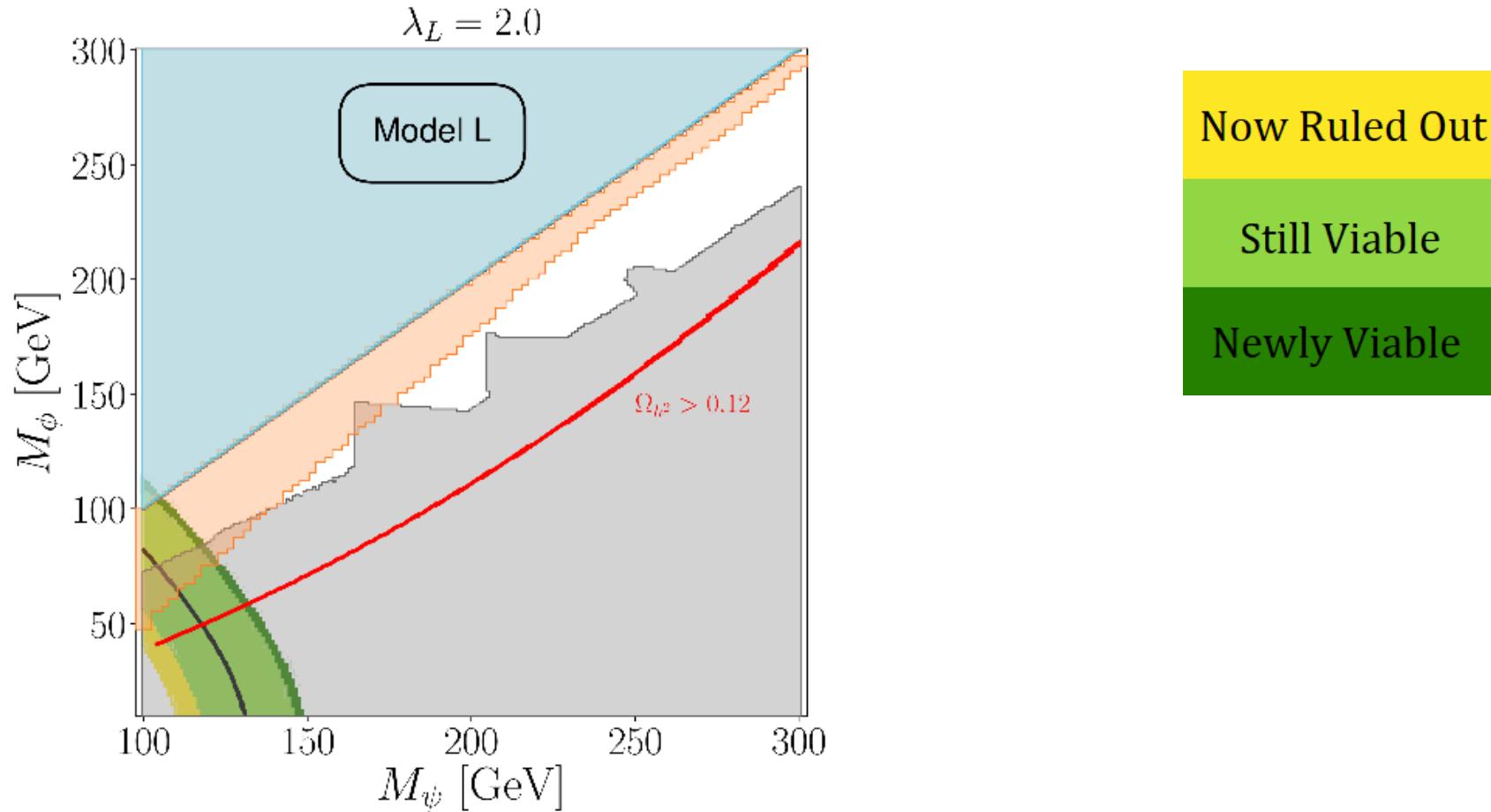
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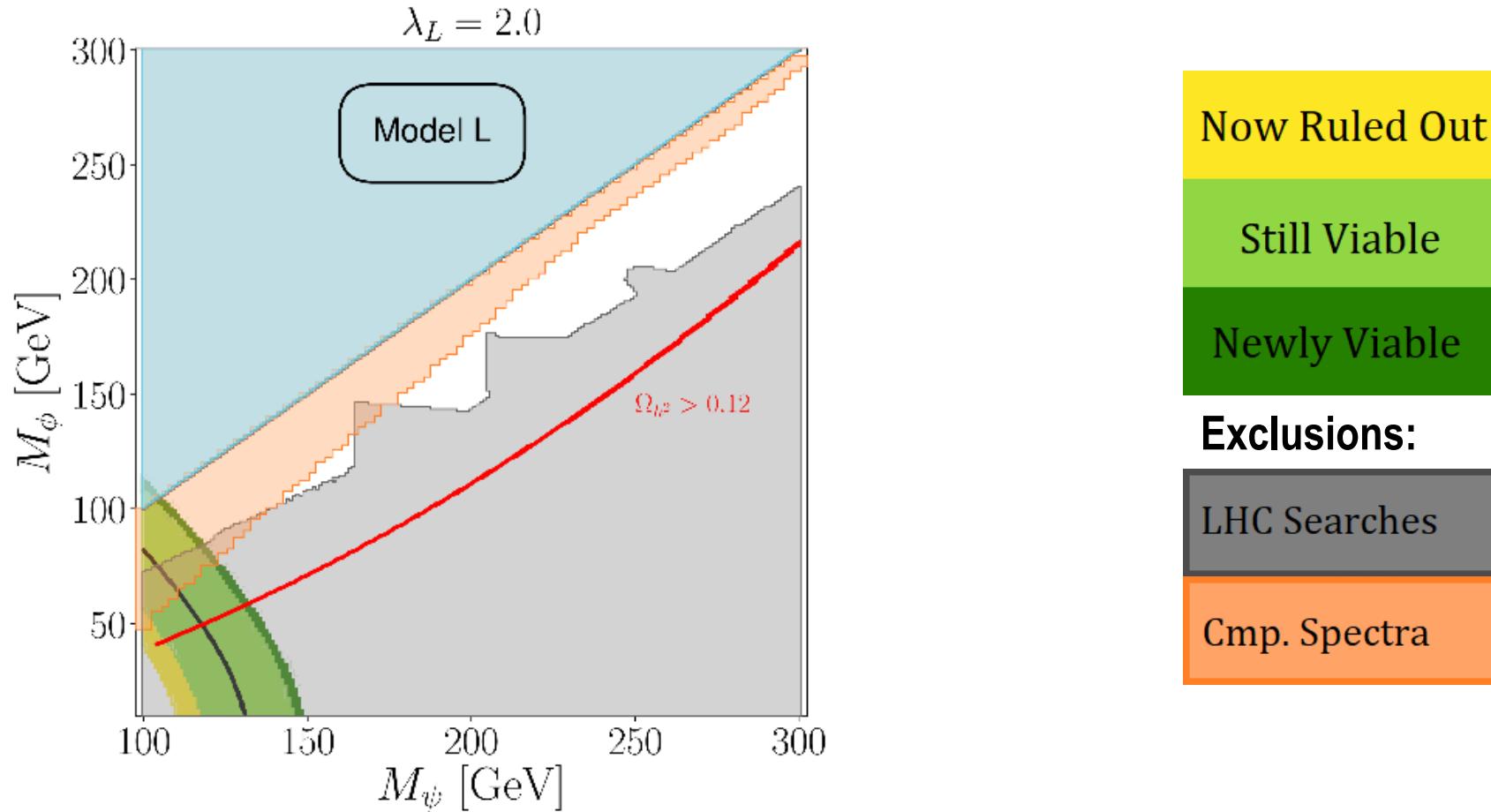
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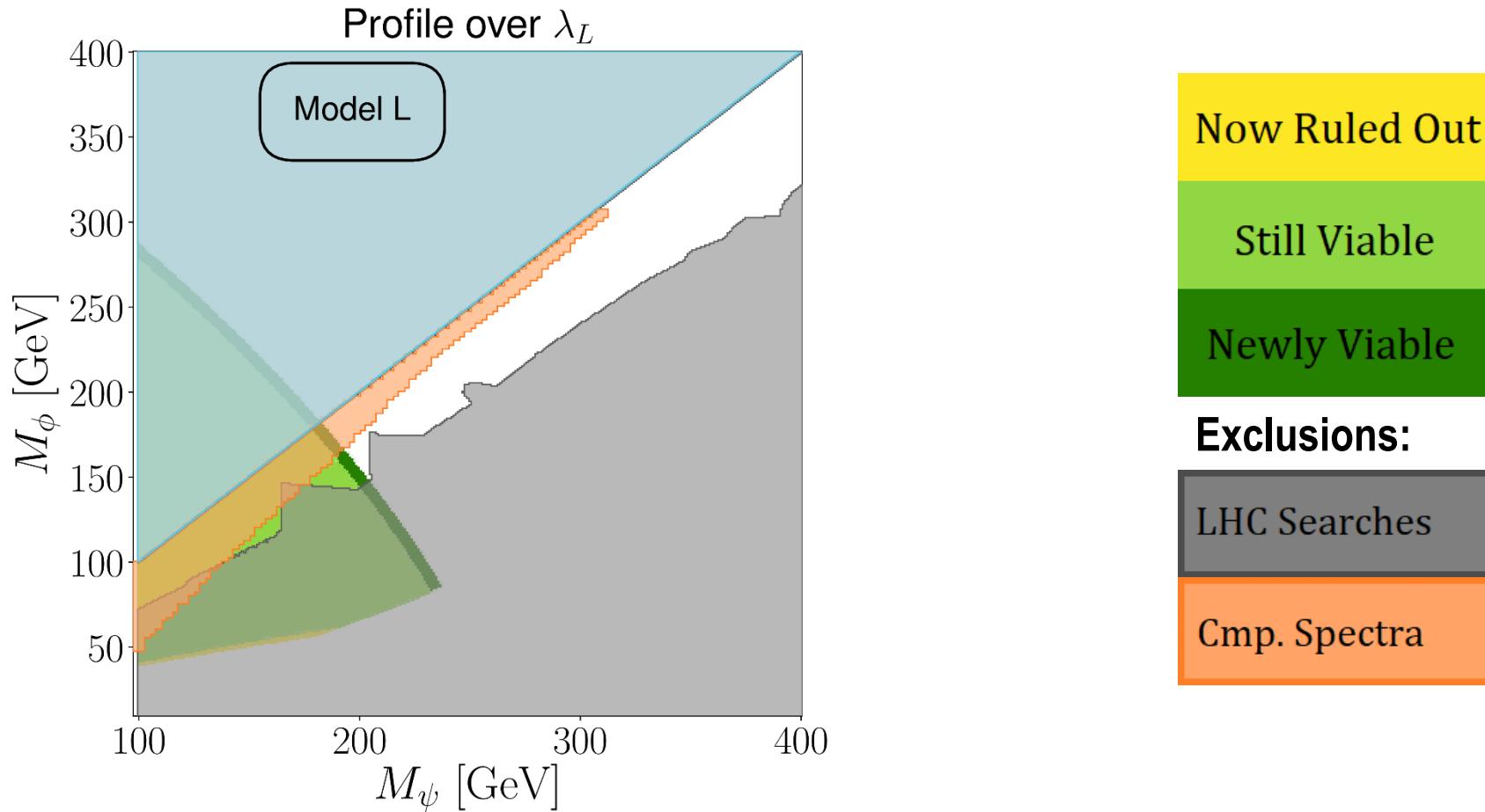
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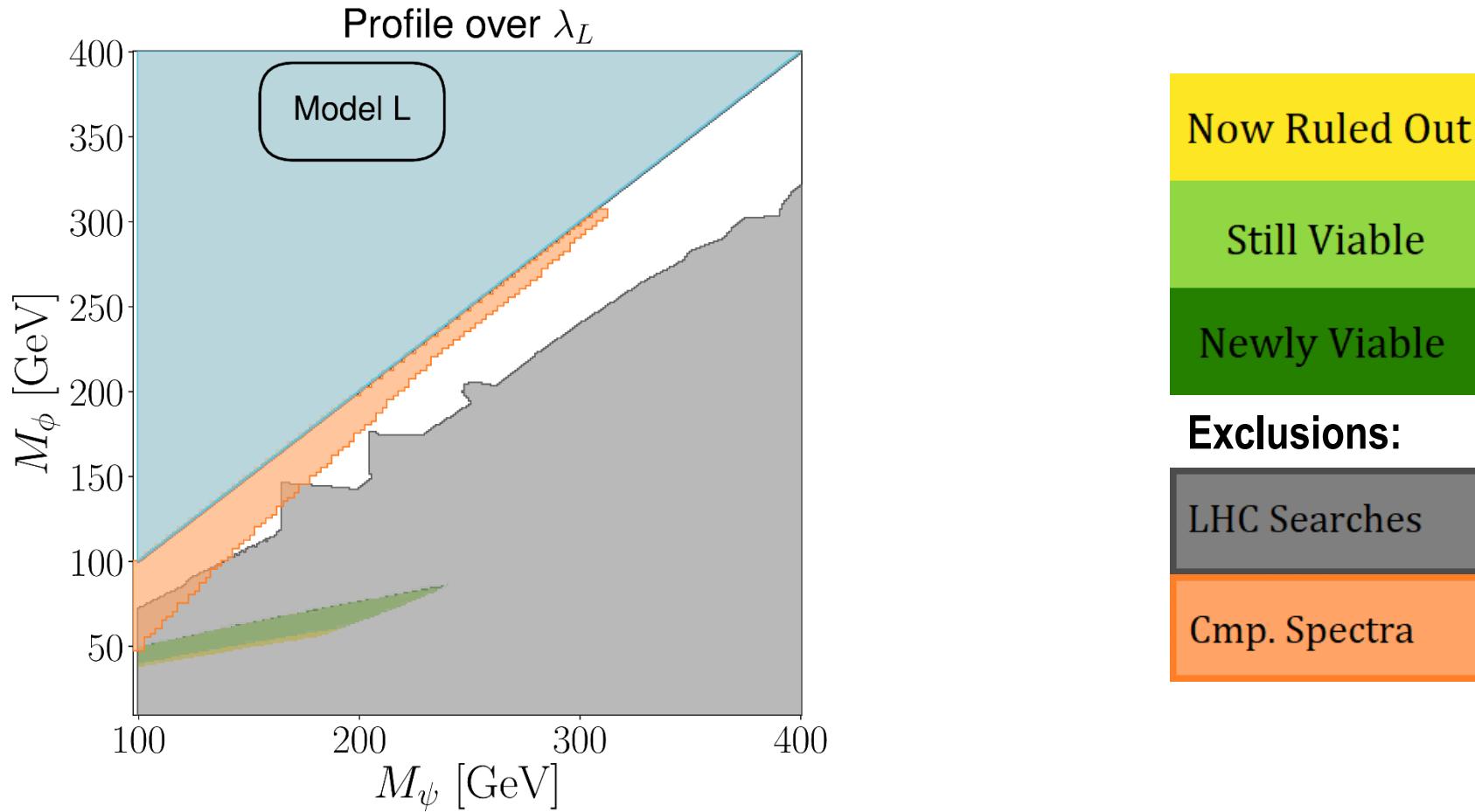
Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon



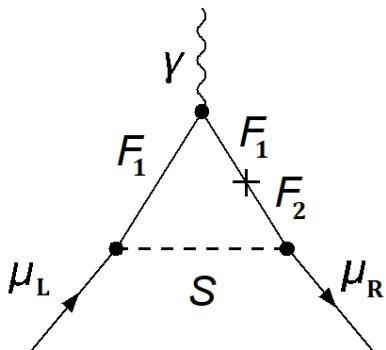
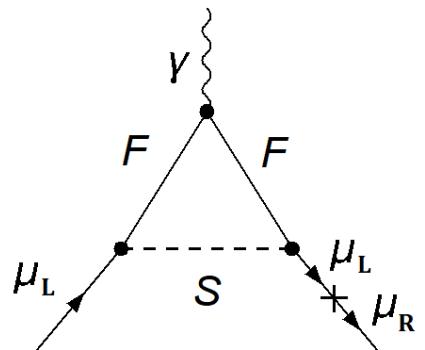
Two Fields with Dark Matter

New Fermion and Scalar Coupling to Left-Handed Muon



Contributions to Muon g-2

Chirality Flip



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

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

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

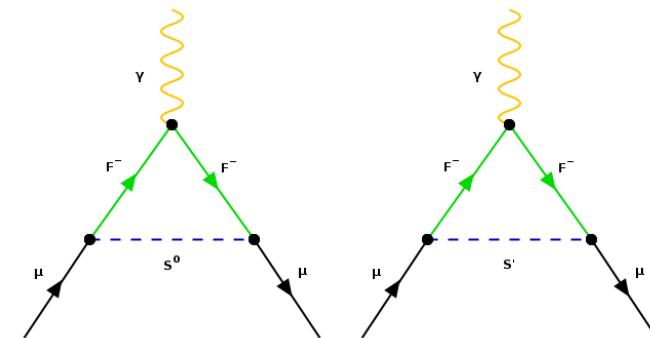
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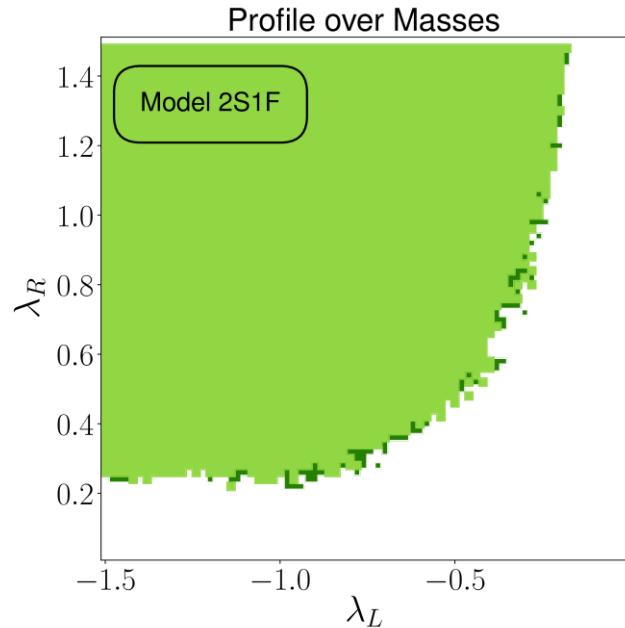


Contributes to muon g-2



Three Fields with Dark Matter

Pair of New Scalars + Fermion



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



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: Δa_μ 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 |

Leptoquarks

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:

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

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

Leptoquarks

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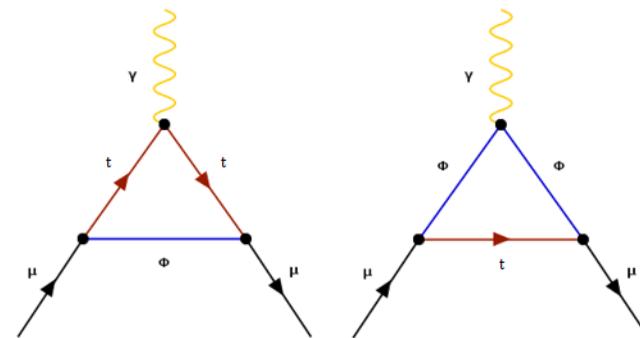
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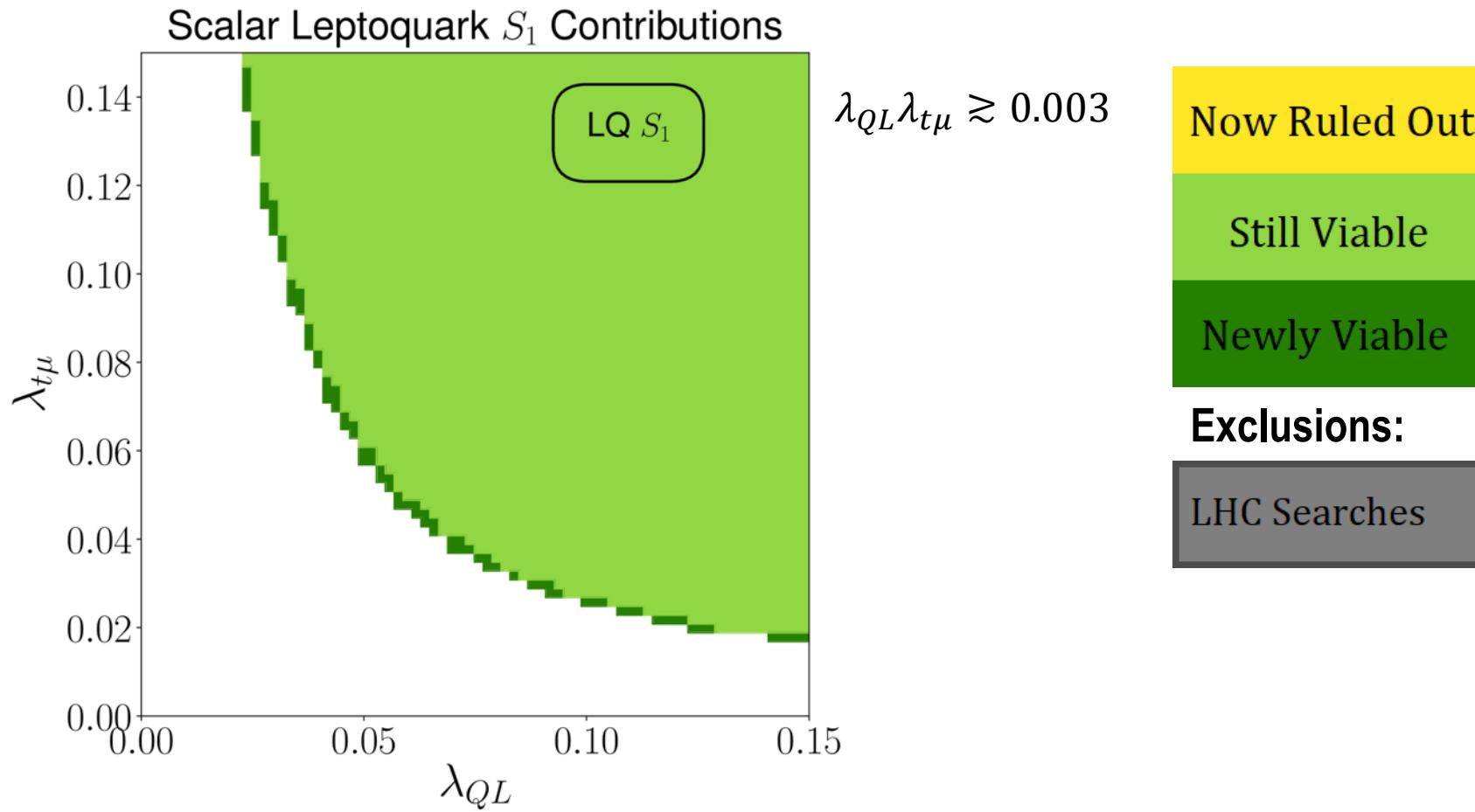
$$-M_{S1}^2 |S_1|^2 - g_{HP} |H|^2 |S_1|^2 - \frac{\lambda_\phi}{2} |S_1|^4$$

Contributes to muon g-2



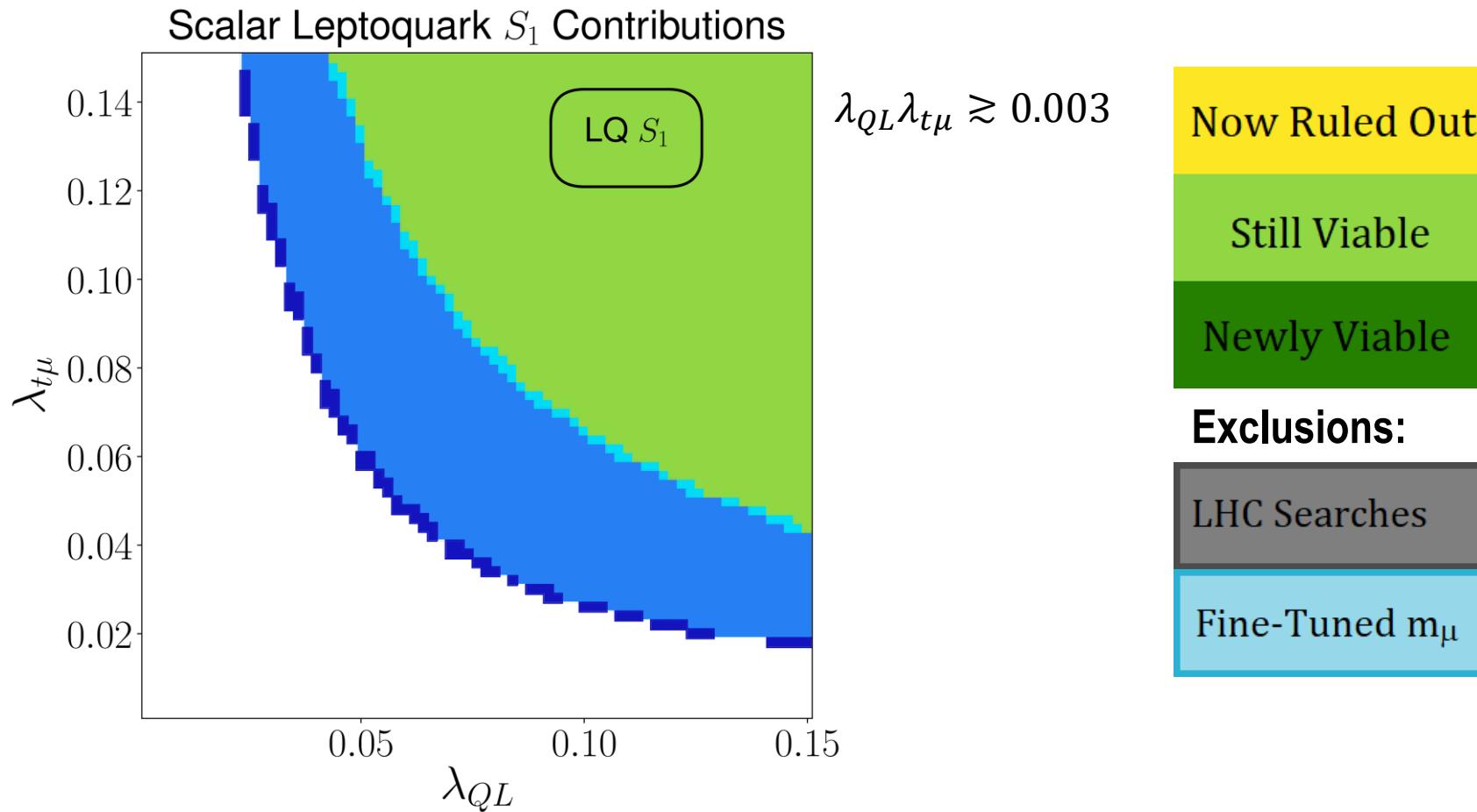
Leptoquarks

Scalar Leptoquark Singlet



Leptoquarks

Scalar Leptoquark Singlet



Two Higgs Doublet Model

Definition

Two Higgs doublets with identical properties

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

Couples the Higgs doublets to the SM

$$\mathcal{L}_{Yuk} = \sum_{i=1,2} (Y_i^u Q_L \Phi_i u_R + Y_i^d Q_L \Phi_i d_R + Y_i^e L_L \Phi_i e_R)$$

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Comes in 6 different types depending on which Higgs doublets we couple to which SM fermions.

| Type | Φ_1 | Φ_2 |
|-----------------|---|----------|
| I | None | U, D, L |
| II | U | D, L |
| X | L | U, D |
| Y | D | U, L |
| Flavour-Aligned | All with diagonal, proportional couplings | |
| General | All with off-diagonal couplings | |

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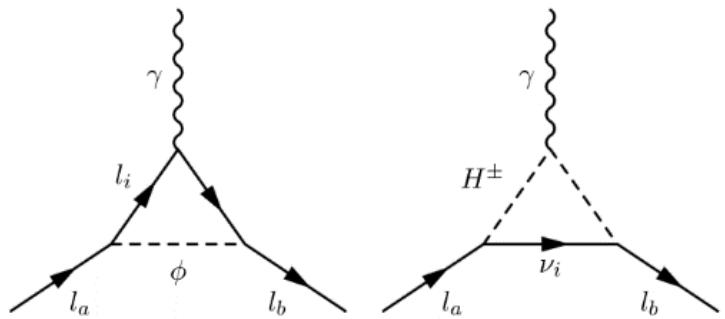
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Two Higgs Doublet Model

Muon g-2 Contributions

One-Loop Contributions

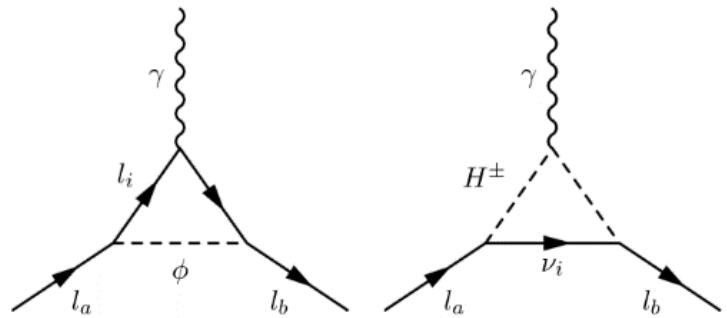


The one-loop contributions for the 2HDM are well known as easy to calculate.

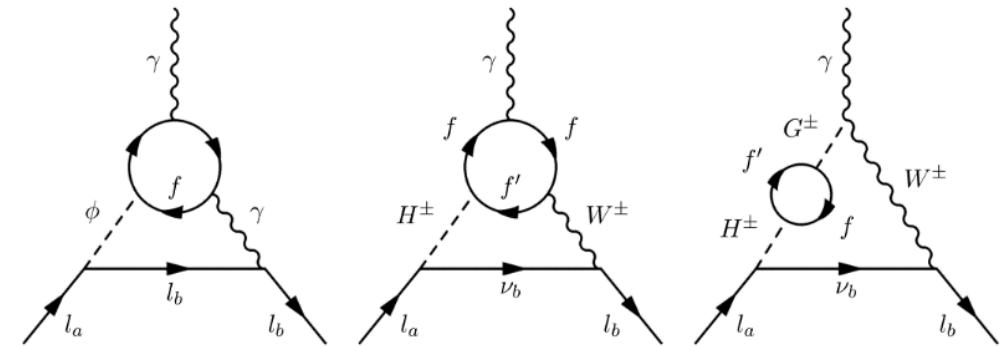
Two Higgs Doublet Model

Muon g-2 Contributions

One-Loop Contributions

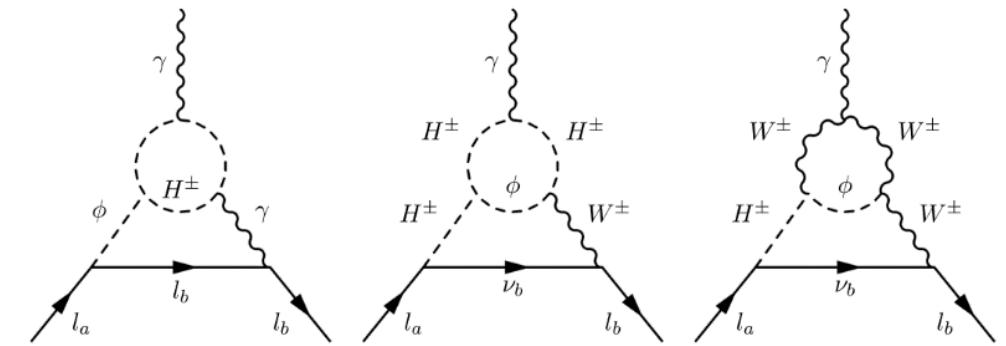


Two-Loop Contributions



The one-loop contributions for the 2HDM are well known as easy to calculate.

However it is the two-loop contributions that dominant.



GM2Calc2 - 2HDM

Muon g-2 Contributions

Features

- Contributions up to the two-loop level
- Uncertainty calculation
- Lepton Flavour Violation
- Effects from CKM mixing

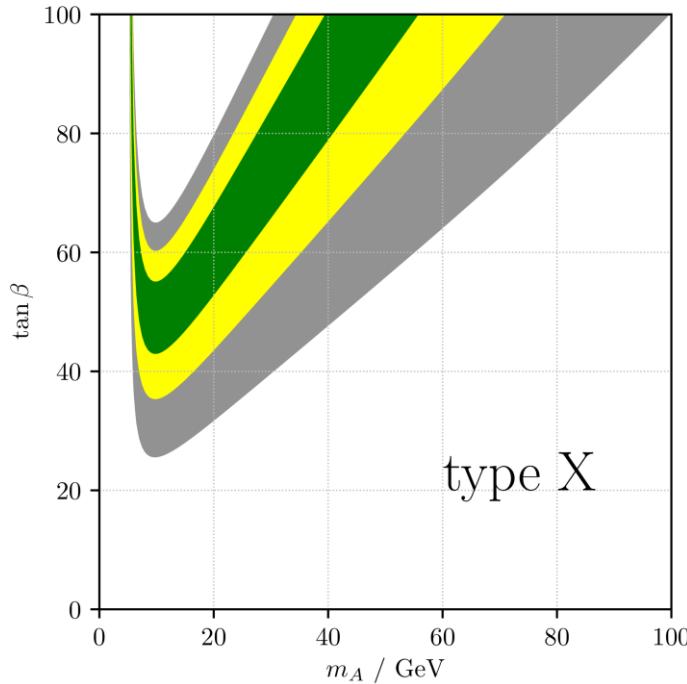
Interfaces

| | |
|---------------------------------|---------------------------|
| C | (0.05 ms) |
| C++ | (0.05 ms) |
| Mathematica | (0.5 ms) |
| Python2 or 3 loading library | (0.08 ms) + (1s) overhead |

Based a machine with an Intel(R) Core(TM) i7-5600U CPU @ 2.60GHz processor.

GM2Calc2 - 2HDM

Applications



$$m_H = m_{H^\pm} = 200 \text{ GeV}$$
$$\lambda_1 = \sqrt{4\pi}$$
$$m_{12}^2 = \frac{m_H^2}{\tan \beta} + \frac{(m_h^2 - \lambda_1 v^2)}{\tan \beta^3}$$

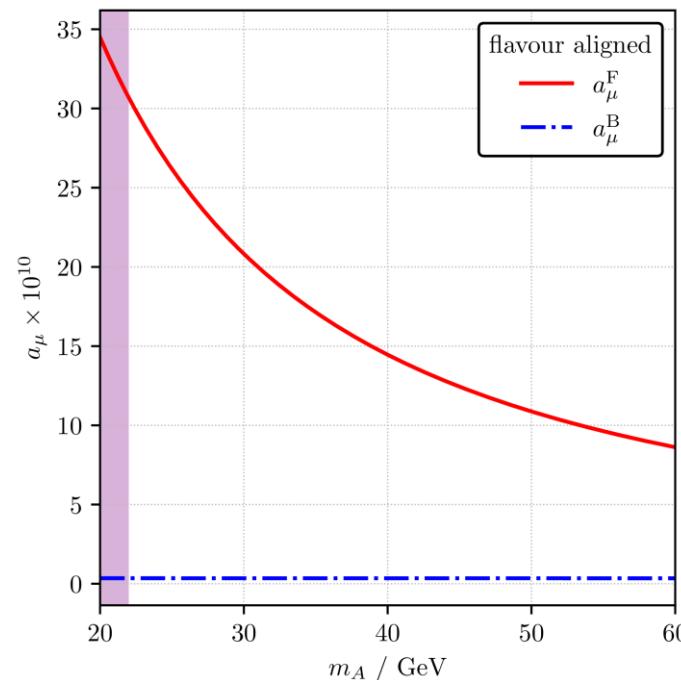
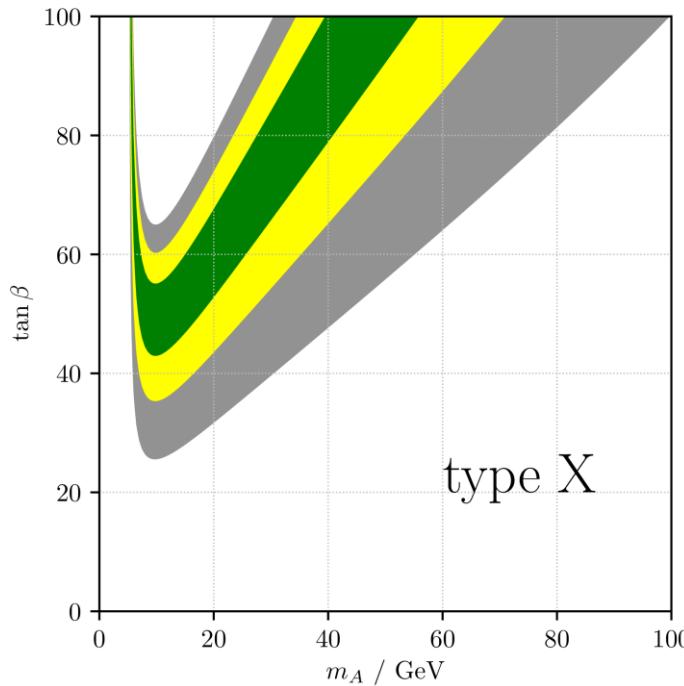
Compare to
arXiv:1409.3199

arXiv:2110.13238

19

GM2Calc2 - 2HDM

Applications



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$$\lambda_1 = \sqrt{4\pi}$$
$$m_{12}^2 = \frac{m_H^2}{\tan \beta} + \frac{(m_h^2 - \lambda_1 v^2)}{\tan \beta^3}$$

$$m_H = m_{H^\pm} = 150 \text{ GeV}$$
$$\sin(\beta - \alpha) = 0.999$$
$$\tan \beta = 2$$
$$\zeta_u = \zeta_d = -0.1$$
$$\zeta_l = 50$$
$$m_{12}^2 \text{ fixed to avoid } h \rightarrow AA \text{ decays}$$

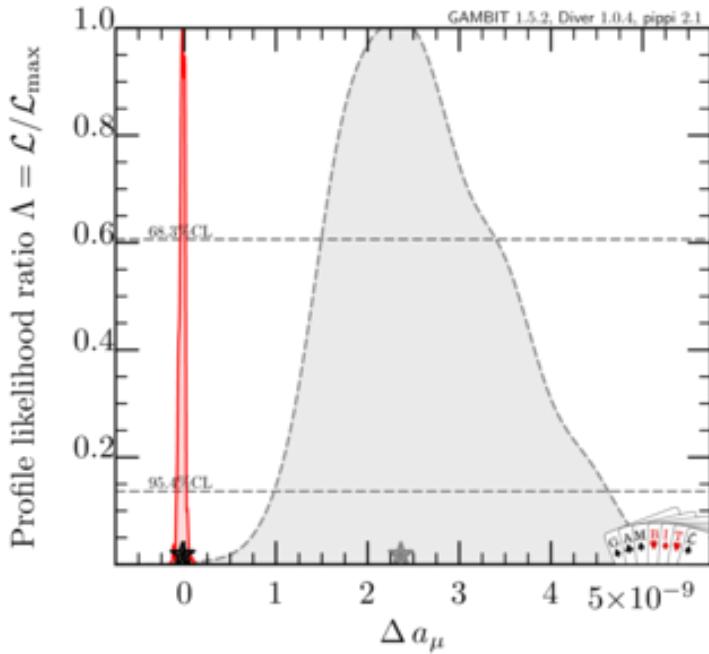
Compare to
arXiv:1409.3199

arXiv:1711.11567

arXiv:2110.13238

Two Higgs Doublet Model

General Two Higgs Doublet Model



An explanation of the muon $g-2$ anomaly in the General 2HDM is in tension with the observables $R(K^*)$ and decays of B -mesons.

However we use a simplified version of the contributions compared to those in GM2Calc2.

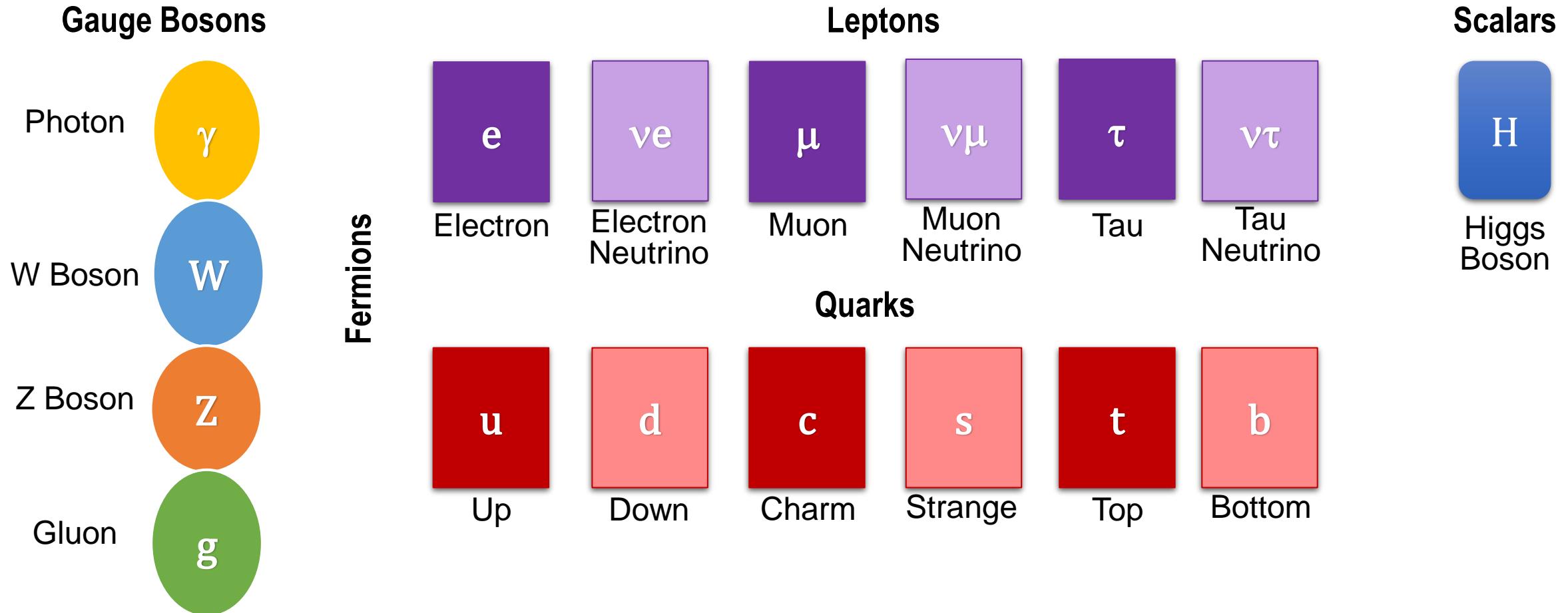
Conclusions

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.
- Can explain it with the simple extensions of a pair of new fields, a leptoquark, or second Higgs
- **Outlook**
- Upcoming muon g-2 experiments at Fermilab & J-PARC are set to further increase the precision.

Thank you for Listening!

Standard Model of Particle Physics



Backup Slides

Standard Model of Particle Physics

Limitations

- Flavour Sector anomalies e.g. $R(D^*)$, $R(K^*)$
- Complete lack of dark matter, i.e. more than 3/4s of the universe
- Not enough funds to build more supercolliders
- Gives no prediction for 18 parameters
- No source of electric dipole moment for baryogenesis
- Discrepancy in the value of Muon g-2

Backup Slides

Latest Theoretical Prediction

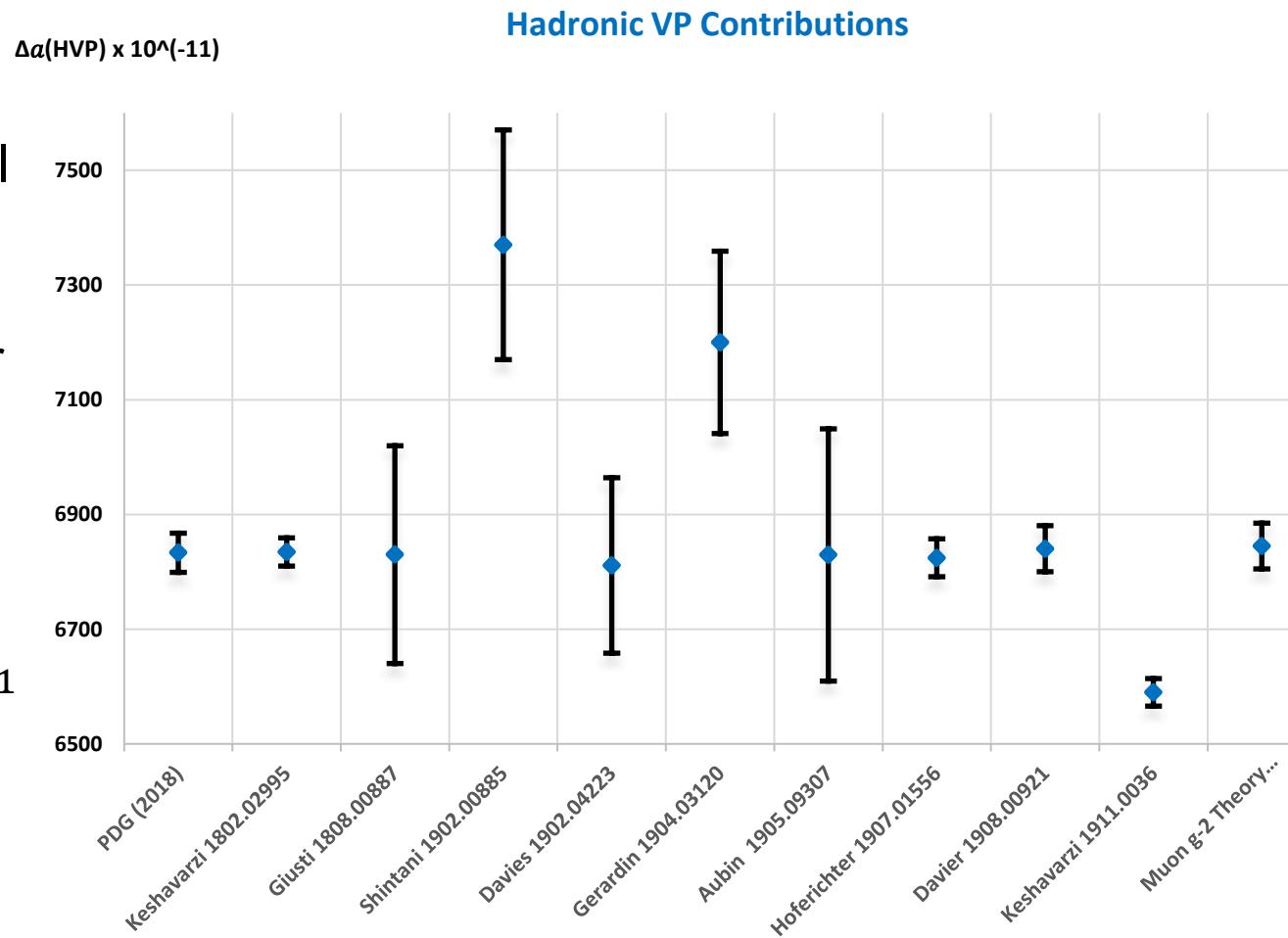
Muon g-2 Theory Initiative

Goal: Produce a single definitive standard model (SM) prediction for the value for the anomalous magnetic moment of the muon to rule them all.

Before publication, many different predictions for Hadronic contributions.

The current standard model (SM) prediction for the muon g-2 is:

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



Backup Slides

The sensitivity of g-2 to new particles

Coupling Strength of Muon to New Particles

The contribution to a mass m particle's g-2 from a diagram with a single loop of particles with mass of order M are proportional to

$$\Delta a \propto \frac{m^2}{M^2}$$

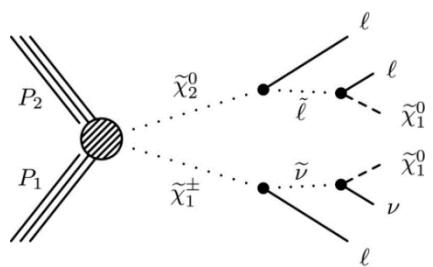
Since the muon is 207 times larger than the electron, contributions from new particles are of order $m_\mu^2/m_e^2 \approx 40000$ times larger to the muon g-2 than the electron g-2. So even though we can measure the electron g-2 more precisely, we expect to find evidence of new contribution in the muon g-2 first.

The colour confinement of quarks makes it difficult to measure their g-2. The short lifetimes of the tau particle and particles of similar mass make it difficult to measure their g-2 at a level of precision close to that of the muon and electron.

Backup Slides

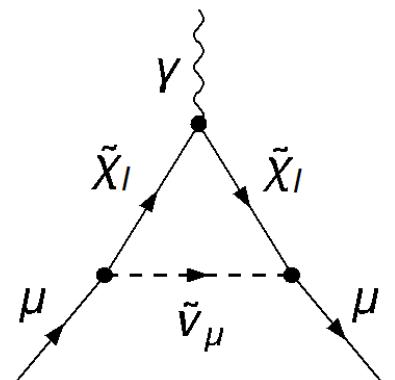
Detecting BSM Particles

Direct Observation



Direct detection of new physics through the change in momentum of some search particle, or observation through scattering.

Adjustment of Physical Observables



Discovery of new physics through contributions causing a deviation in the measured value of some physical observable compared to the standard model prediction.

Backup Slides

Goldstone Diagrams

Gauge-Fixing

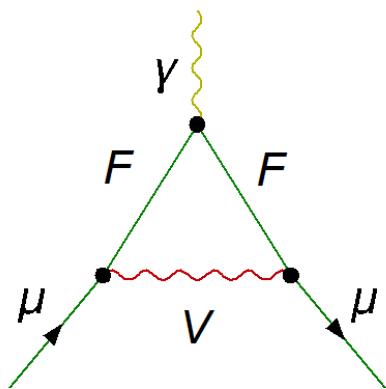
$$\begin{aligned} & \frac{1}{2} V_\nu (g^{\nu\lambda} \partial^2 - \partial^\nu \partial^\lambda) V_\lambda - e' v V^\nu \partial_\nu \phi_2 + \frac{1}{2\xi} (\partial_\nu V^\nu - \xi e' v \phi_2)^2 \\ &= \frac{1}{2} V_\nu (g^{\nu\lambda} \partial^2 - (1 - 1/\xi) \partial^\nu \partial^\lambda) V_\lambda - e' v V^\nu \partial_\nu \phi_2 + e' v V^\nu \partial_\nu \phi_2 + \xi e'^2 v^2 \phi_2^2 \\ &= \frac{1}{2} V_\nu (g^{\nu\lambda} \partial^2 - (1 - 1/\xi) \partial^\nu \partial^\lambda) V_\lambda + \xi e'^2 v^2 \phi_2^2 \end{aligned}$$

| Gauge | Vector Propagator | Goldstone Propagator |
|---------------|---|-----------------------|
| R_ξ gauge | $-i(g^{\nu\lambda} - k^\nu k^\lambda / m_V^2)/(k^2 - m_V^2) - i(k^\nu k^\lambda / m_V^2)/(k^2 - \xi m_V^2)$ | $i/(k^2 - \xi m_V^2)$ |
| Feynman gauge | $-ig^{\nu\lambda}/(k^2 - m_V^2)$ | $i/(k^2 - m_V^2)$ |
| Landau gauge | $-i(g^{\nu\lambda} - k^\nu k^\lambda / k^2)/(k^2 - m_V^2)$ | i/k^2 |
| Unitary Gauge | $-i(g^{\nu\lambda} - k^\nu k^\lambda / m_V^2)/(k^2 - m_V^2)$ | 0 |

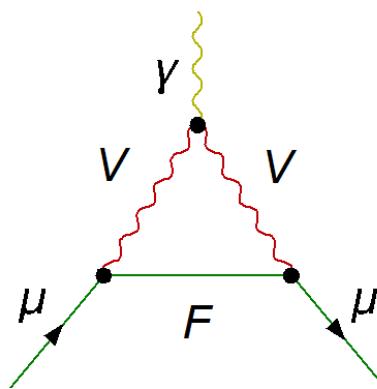
Backup Slides

General Contributions to g-2

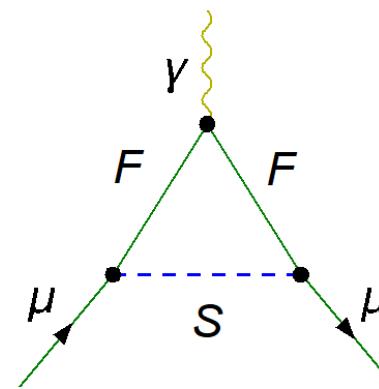
FFV Diagram



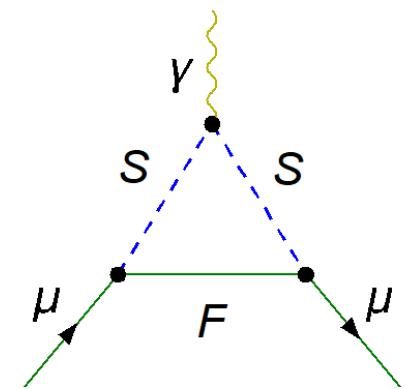
VVF Diagram



FFS Diagram



SSF Diagram



Coupling of muon to fermions/vectors:

$$\mathcal{L}_{\mu f V} = \bar{f} \gamma_\nu V^\nu (V F_L P_L + V F_R P_R) \mu + h.c$$

Coupling of muon to fermions/scalars:

$$\mathcal{L}_{\mu f \phi} = \bar{f} \phi (S F_L P_L + S F_R P_R) \mu + h.c$$

Backup Slides

Form Factors

Vertex Correction Function:

$$\Gamma^\nu = A \times \gamma^\nu + \delta\Gamma^\nu$$

$$\Gamma^\nu = A \times \gamma^\nu + B \times p^\nu + C \times p'^\nu$$

$$\Gamma^\nu = f_1(q^2) \times \gamma^\nu + f_2(q^2) \times (p^\nu + p'^\nu) + f_3(q^2) \times q^\nu$$

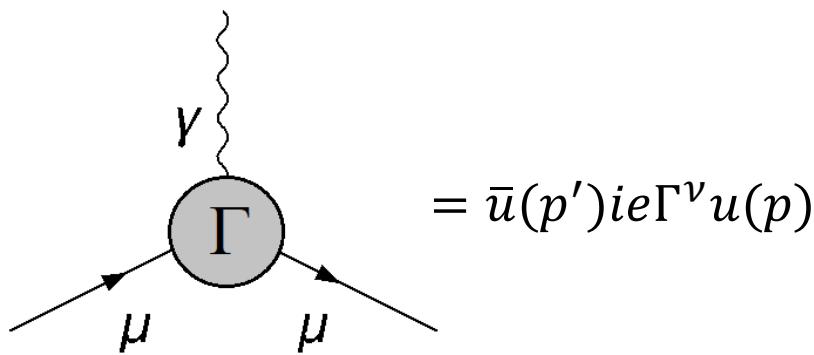
Ward Identity:
 $q_\nu \Gamma^\nu = 0$

$$\Gamma^\nu = (f_1(q^2) + 2mf_2(q^2)) \times \gamma^\nu - 2mf_2(q^2) \times i \frac{\sigma^{\nu\lambda} q_\lambda}{2m}$$

$$\Gamma^\nu = F_1 \times \gamma^\nu + F_2 \times i \frac{\sigma^{\nu\lambda} q_\lambda}{2m}$$

Gordon Identity:

$$\bar{u}(p') \frac{p^\nu + p'^\nu}{2m} u(p) = \bar{u}(p') (\gamma^\nu - i \frac{\sigma^{\nu\lambda} q_\lambda}{2m}) u(p)$$



$$= \bar{u}(p') i e \Gamma^\nu u(p)$$

Backup Slides

General Contributions

General 1-Loop Diagram Contributions to Muon g-2

Working in the Feynman ($\xi \rightarrow 1$) Gauge:

$$a_{\mu}^{FFS} = \frac{q_F m_F m_{\mu} (SF_L^2 + SF_R^2)(3 - 4x + x^2 + 2 \log x)}{16m_S^2 \pi^2 (1-x)^3} - \frac{q_F m_{\mu}^2 S F_L S F_R (2 + 3x - 6x^2 + x^3 + 6x \log x)}{24m_S^2 \pi^2 (1-x)^4}$$
$$a_{\mu}^{SSF} = \frac{q_S m_F m_{\mu} (SF_L^2 + SF_R^2)(1 - x^2 + 2x \log x)}{16m_S^2 \pi^2 (1-x)^3} - \frac{q_S m_{\mu}^2 S F_L S F_R (1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x)}{24m_S^2 \pi^2 (1-x)^4}$$
$$a_{\mu}^{FFV} = \frac{q_F m_{\mu}^2 (VF_L^2 + VF_R^2)(4 - 9x + 5x^3 + (6 - 12x) \log x)}{48m_V^2 \pi^2 (1-x)^4} - \frac{q_F m_F m_{\mu} V F_L V F_R (1 - x^2 + 2x \log x)}{4m_V^2 \pi^2 (1-x)^3}$$
$$a_{\mu}^{VVF}$$
$$= \frac{q_V m_{\mu}^2 (VF_L^2 + VF_R^2)(7 - 33x + 57x^2 - 31x^3 + 6x^2(3x - 1) \log x)}{96m_V^2 \pi^2 (1-x)^4}$$
$$+ \frac{3q_V m_F m_{\mu} V F_L V F_R (1 - 4x + 3x^2 - 2x^2 \log x)}{16m_V^2 \pi^2 (1-x)^3}$$

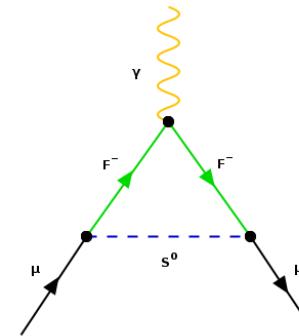
Two Fields with Dark Matter

New Fermion and Scalar Coupling to Right-Handed Muon

| New Fields | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | Electric Charge |
|---------------|--|-----------------|
| $F_S = F_S^-$ | (1, 1, -1) | -1 |
| S | (1, 1, 0) | 0 |



Contributes to muon g-2

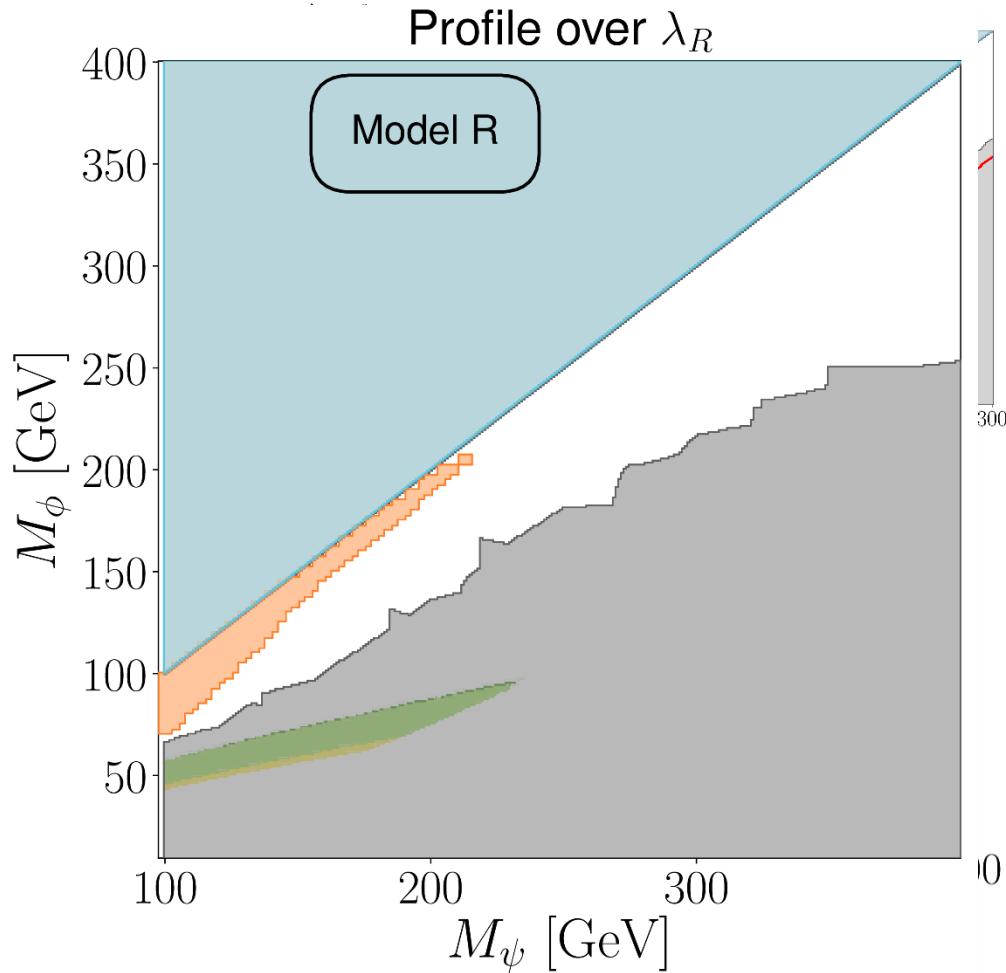


Interacts with the standard model through:

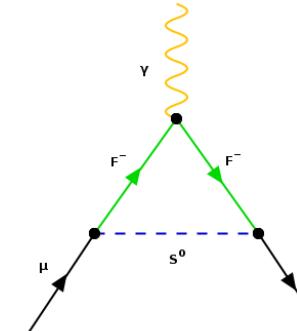
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Two Fields with Dark Matter

New Fermion and Scalar Coupling to Right-Handed Muon



Contributes to muon g-2



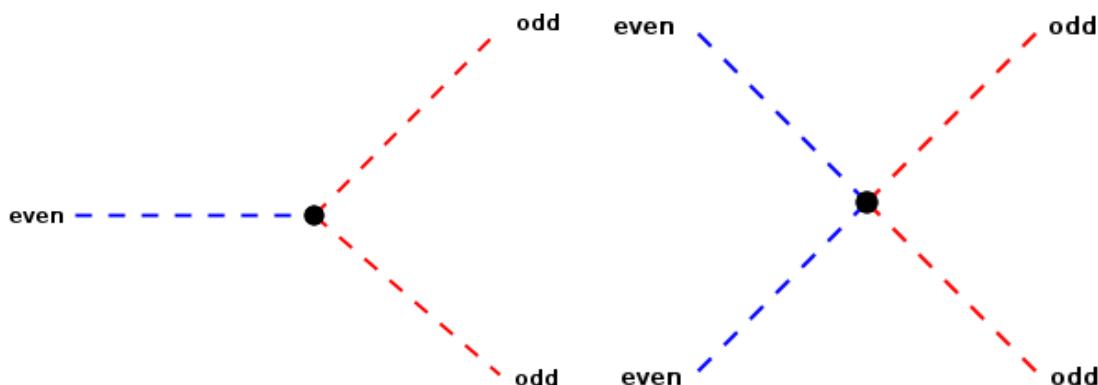
- Now Ruled Out
 - Still Viable
 - Newly Viable
- Exclusions:**
- LHC Searches
 - Cmp. Spectra

Backup Slides

Z2 Symmetry

Z2-odd fields interact
only in pairs:

$$\begin{aligned}\psi_{even} &\rightarrow \psi_{even} \\ \psi_{odd} &\rightarrow \psi_{odd} e^{i\pi}\end{aligned}$$

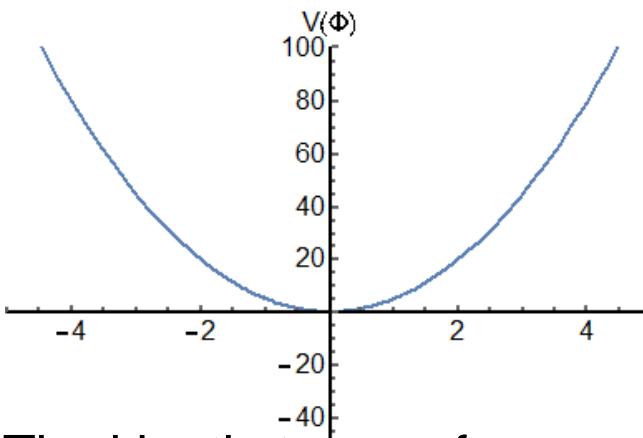


Constraints

- Muon g-2 Contributions: FlexibleSUSY
- Dark Matter Limits: MicrOmegas
- Direct Detection Limits: DDCalc
- Particle Collider Constraints: SModelS

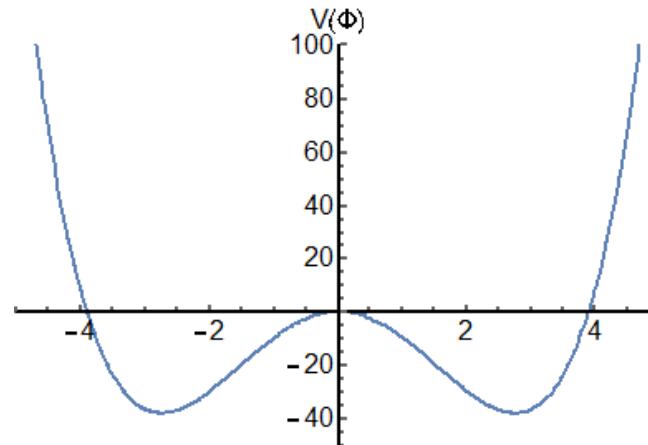
Backup Slides

Symmetry Breaking



$$\Phi \rightarrow (\phi_1 + i\phi_2)$$

VEV: $\langle \Phi \rangle = 0$



$$\Phi \rightarrow (v + \phi_1 + i\phi_2)$$

VEV: $\langle \Phi \rangle = v$

$$e'v \rightarrow m_V$$

The kinetic terms of a complex scalar singlet Φ :

$$\frac{1}{2}(|\partial_\nu \phi_2|^2 + |\partial_\nu \phi_1|^2 - e' V^\nu (\phi_1 \partial_\nu \phi_2 - \phi_2 \partial_\nu \phi_1)) + e'^2 V^\nu V_\nu (\phi_1^2 + \phi_2^2))$$

$$\frac{1}{2}(|\partial_\nu \phi_2|^2 + |\partial_\nu \phi_1|^2 - e' V^\nu (\phi_1 \partial_\nu \phi_2 - \phi_2 \partial_\nu \phi_1)) + e'^2 V^\nu V_\nu (\phi_1^2 + 2v\phi_1 + \phi_2^2) + e'^2 v^2 V^\nu V_\nu - e' v V^\nu \partial_\nu \phi_2)$$

Gauge-fixing term removes the mixing between vectors and Goldstones: $\frac{1}{2\xi}(\partial_\nu V^\nu - \xi e' v \phi_2)^2$

Backup Slides

Contributions to g-2

Symmetry Breaking

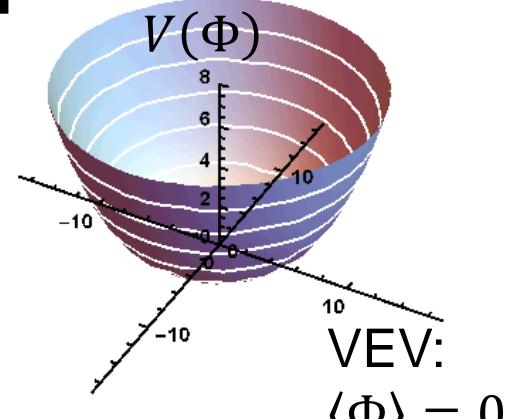
The kinetic terms of a complex scalar Φ :

$$\mathcal{L}_{D\Phi} = |D_\nu \Phi|^2 = \left| (\partial_\nu - ie' V_\nu) \frac{1}{\sqrt{2}} (\phi_1 + i\phi_2) \right|^2$$

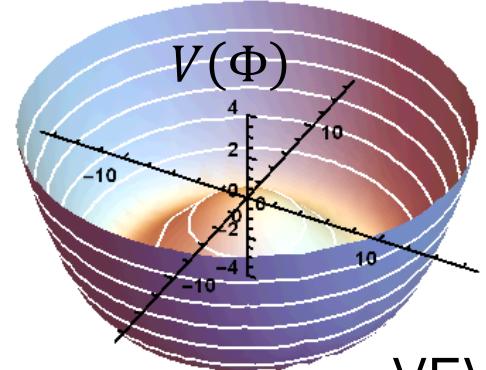
$$= \frac{1}{2} \left(|\partial_\nu \phi_2|^2 + |\partial_\nu \phi_1|^2 + e'^2 V^\nu V_\nu (\phi_1^2 + \phi_2^2) - e' V^\nu (\phi_1 \partial_\nu \phi_2 - \phi_2 \partial_\nu \phi_1) \right)$$

$$\mathcal{L}_{D\Phi} = \frac{1}{2} \left(|\partial_\nu \phi_2|^2 + |\partial_\nu \phi_1|^2 + e'^2 V^\nu V_\nu (\phi_1^2 + 2\nu \phi_1 + \phi_2^2) + e'^2 \nu^2 V^\nu V_\nu \right.$$

$$\left. - e' V^\nu (\phi_1 \partial_\nu \phi_2 - \phi_2 \partial_\nu \phi_1) - e' \nu V^\nu \partial_\nu \phi_2 \right)$$



VEV:
 $\langle \Phi \rangle = 0$



VEV:
 $\langle \Phi \rangle = \nu$

$$\Phi \rightarrow (\nu + \phi_1 + i\phi_2)$$

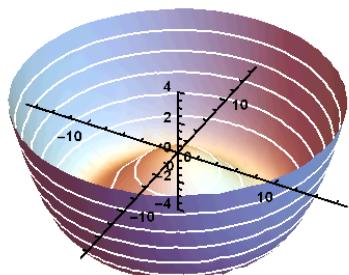
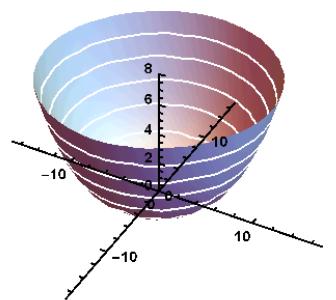
$$e' \nu \rightarrow m_V$$

We add a gauge-fixing term to our Lagrangian to remove the mixing between vectors and Goldstones:

$$\frac{1}{2\xi} (\partial_\nu V^\nu - \xi e' \nu \phi_2)^2$$

BSM Models

Mixing Fermions and Scalars

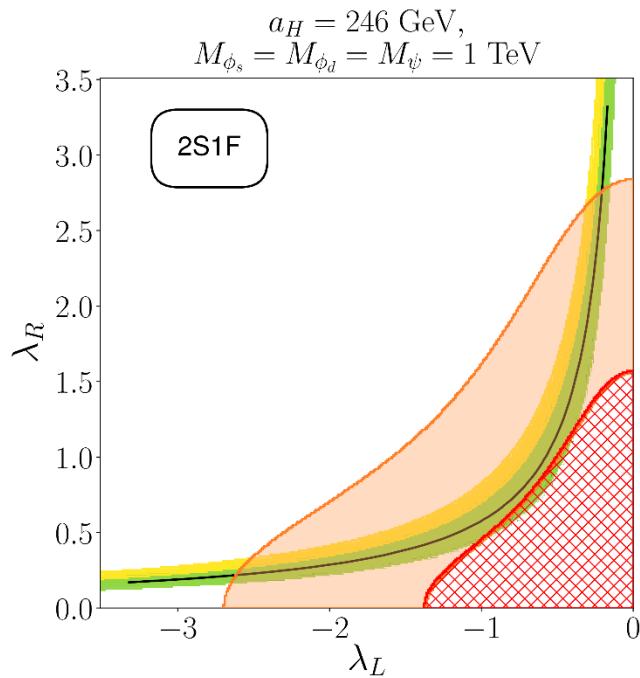


After EWSB, mixed fields with identical electric charges mix:

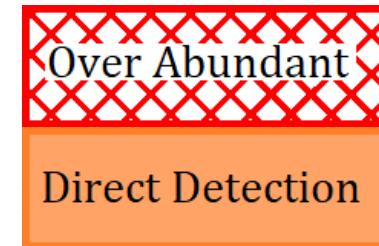
$$\begin{aligned} F_S^0, F_D^0 &\rightarrow F_1^0, F_2^0 \\ F_S^-, F_D^- &\rightarrow F_1^-, F_2^- \end{aligned}$$

Three Fields with Dark Matter

Pair of New Scalars + Fermion

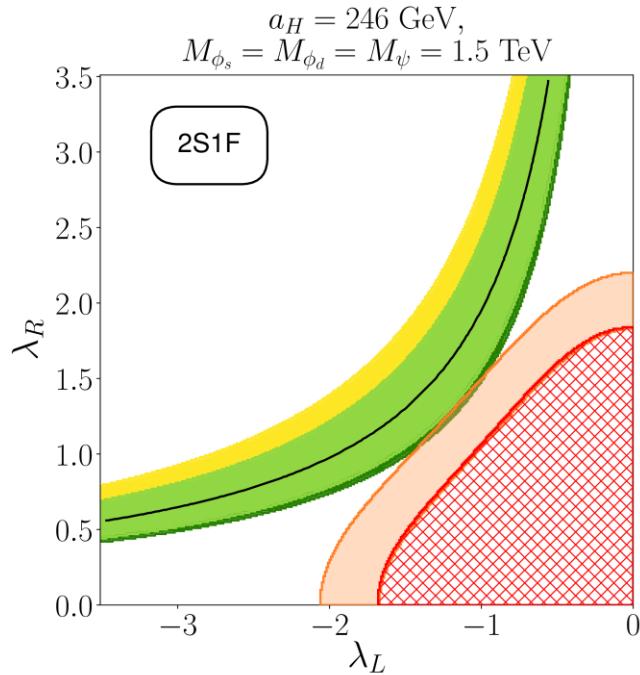


Exclusions:



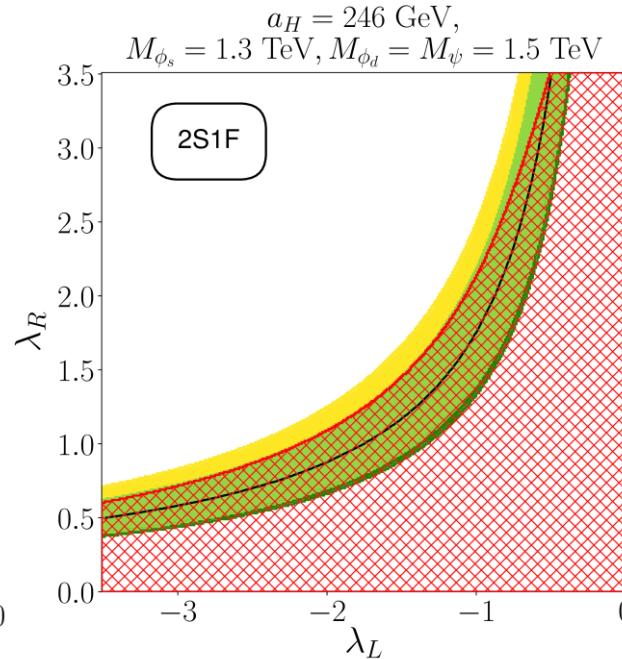
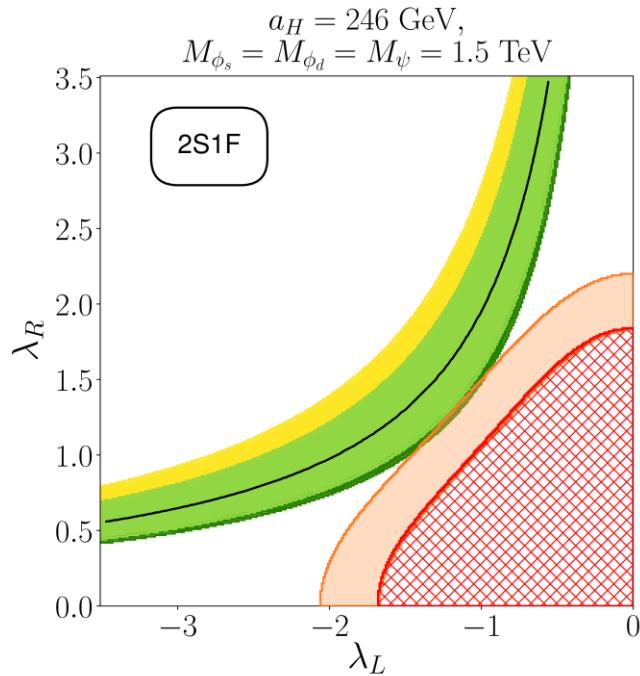
Three Fields with Dark Matter

Pair of New Scalars + Fermion



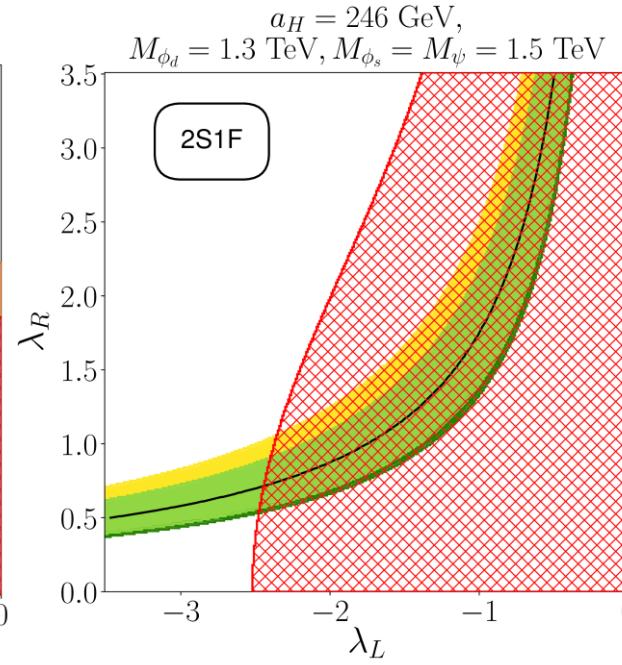
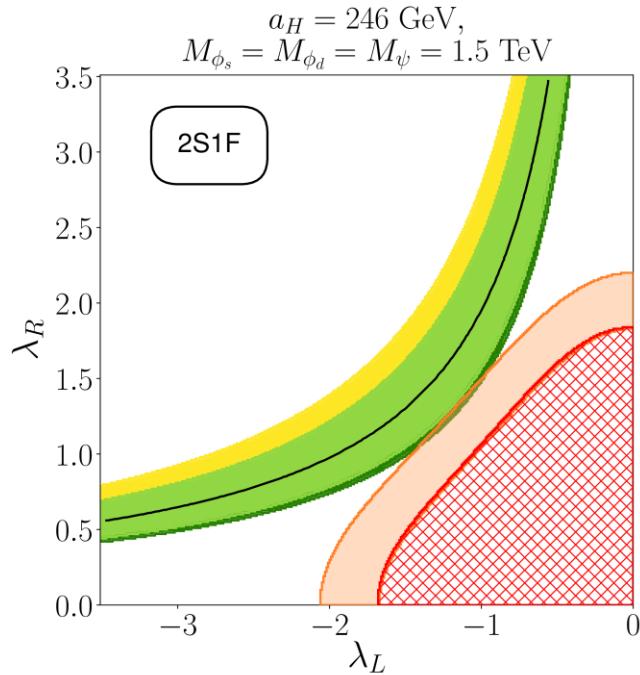
Three Fields with Dark Matter

Pair of New Scalars + Fermion

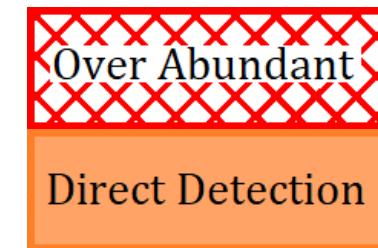


Three Fields with Dark Matter

Pair of New Scalars + Fermion

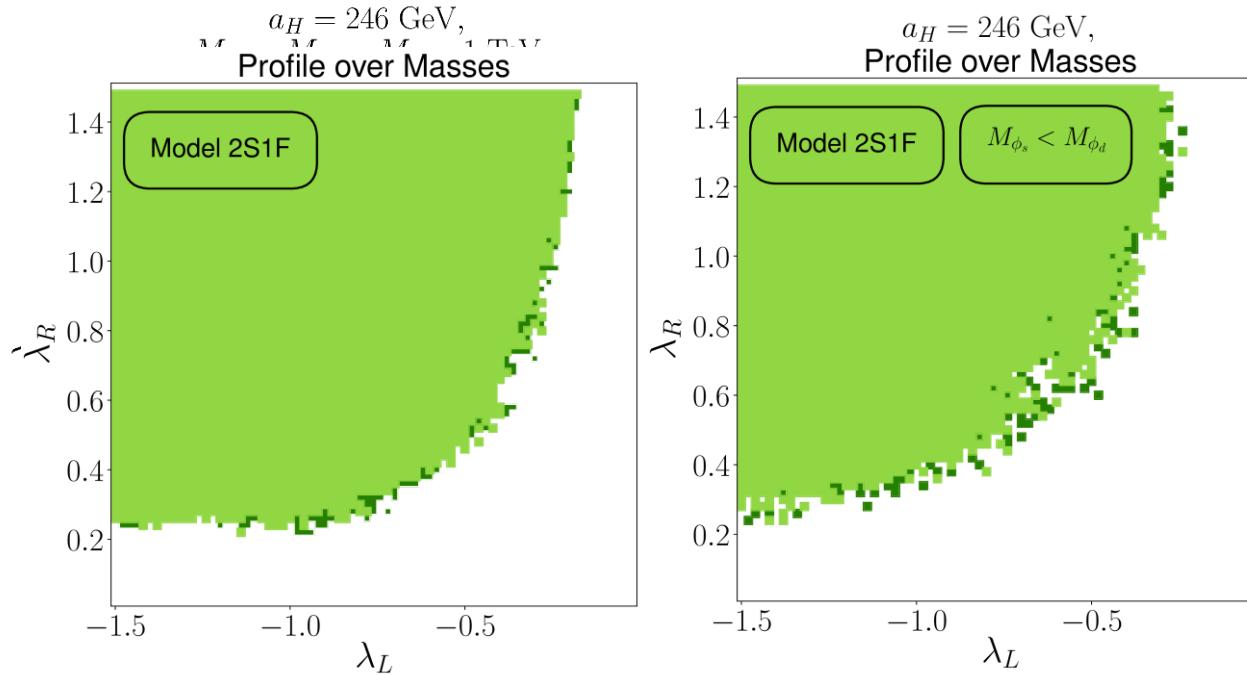


Exclusions:

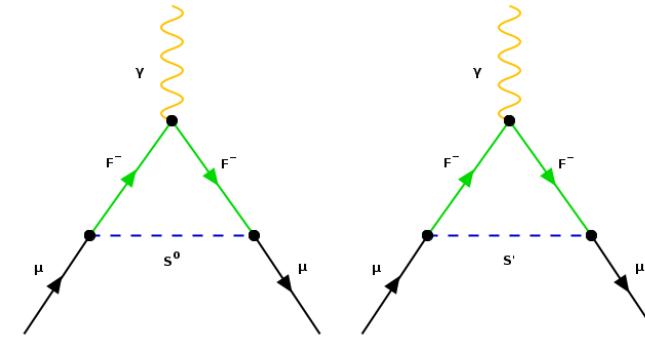


Three Fields with Dark Matter

Pair of New Fermions + Scalar



Contributes to muon g-2



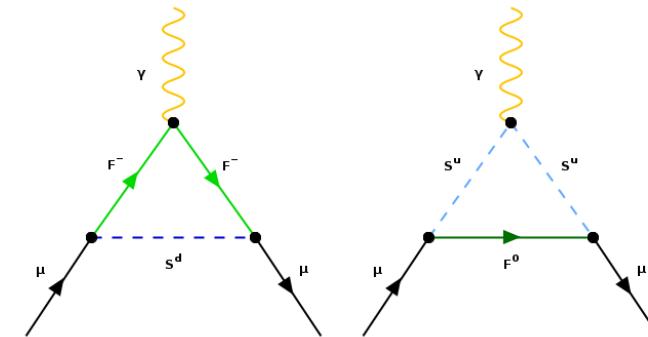
Three Fields with Dark Matter

Pair of New Fermions + Scalar

| New Fields | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | Electric Charge |
|------------------------|--|-----------------|
| $F_L = (F_L^0, F_L^-)$ | (1, 2, -1/2) | 0, -1 |
| $F_R = F_R^0$ | (1, 1, 0) | 0 |
| $S_R = (S_R^+, S_R^0)$ | (1, 2, 1/2) | 1, 0 |



Contributes to muon g-2

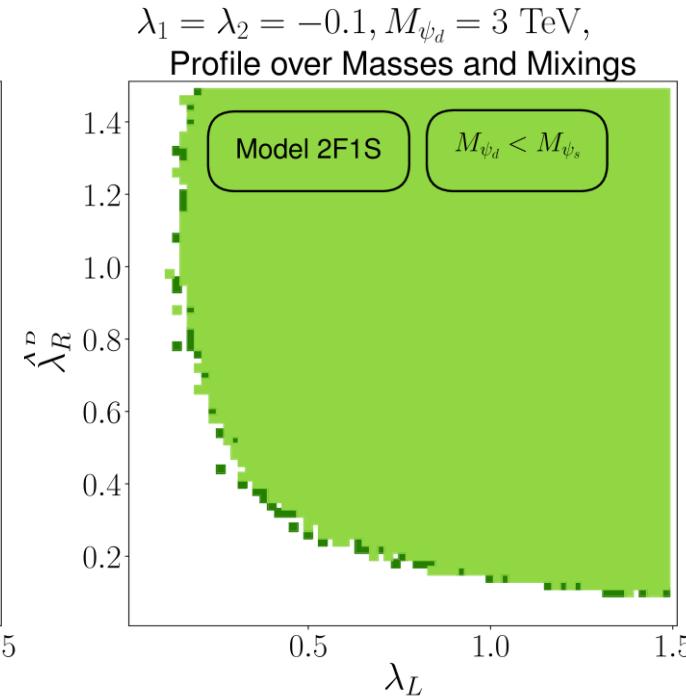
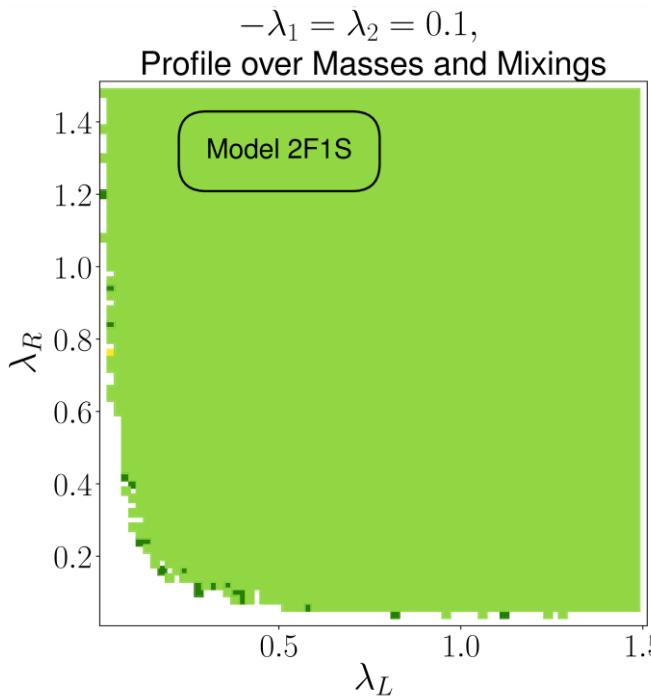


Interacts with the standard model through:

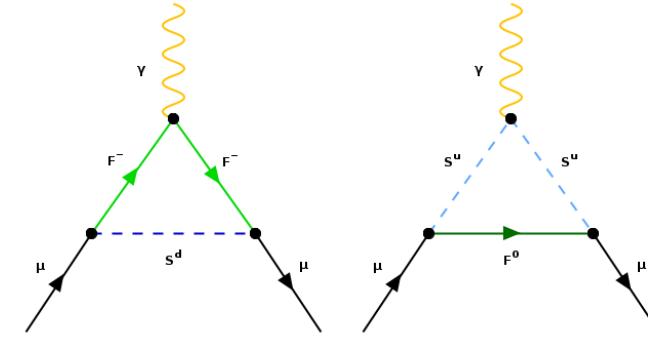
$$\begin{aligned} \mathcal{L}_{BSM} = & (\lambda_{H1} H \cdot F_L F_R + \lambda_{H2} H^\dagger \cdot F_L^c F_R + \lambda_L L_L \cdot S_R F_R \\ & + \lambda_R F_L e_R^\dagger S_R^\dagger - M_{FL} F_L^c F_L + h.c.) \\ & - \frac{M_{FR}}{2} F_R F_R - M_S^2 |S_R|^2 \end{aligned}$$

Three Fields with Dark Matter

Pair of New Fermions + Scalar

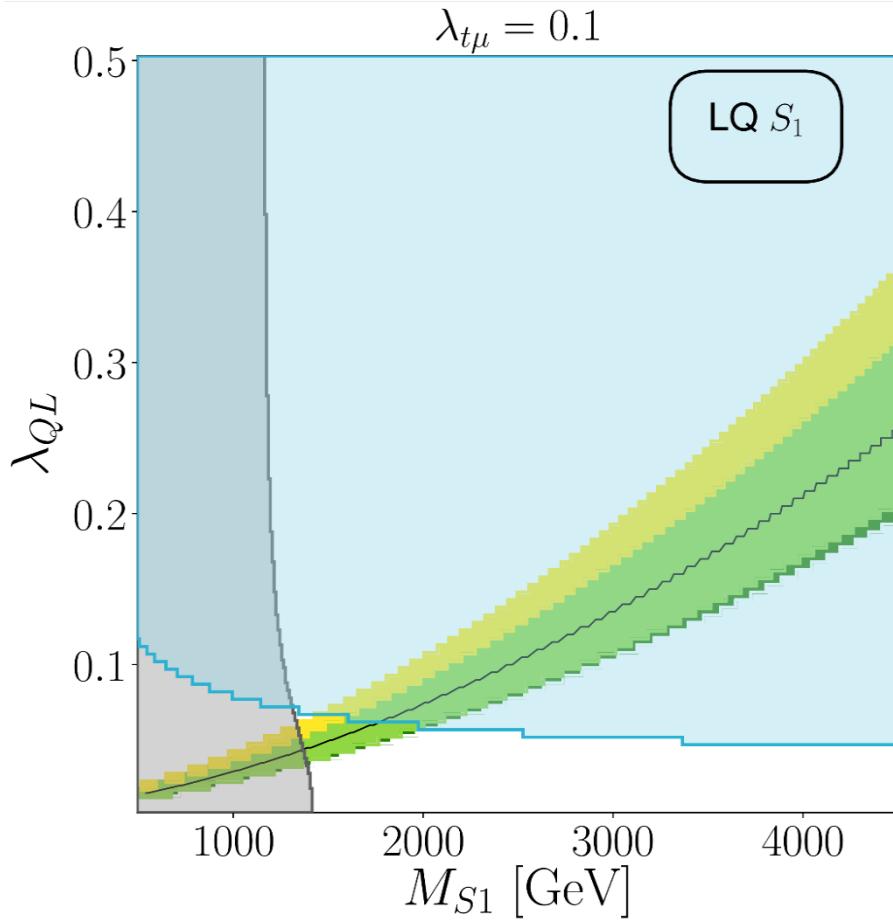


Contributes to muon g-2



Leptoquarks

Scalar Leptoquark Singlet



Now Ruled Out
Still Viable
Newly Viable

Exclusions:

LHC Searches

Fine-Tuned m_μ

Single Scalar Leptoquark

Scalar Leptoquark Doublet

| Leptoquark | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | Electric Charge |
|------------------------|--|-----------------|
| $R_2 = (R_2^u, R_2^d)$ | (3, 2, 7/6) | 5/3, 2/3 |

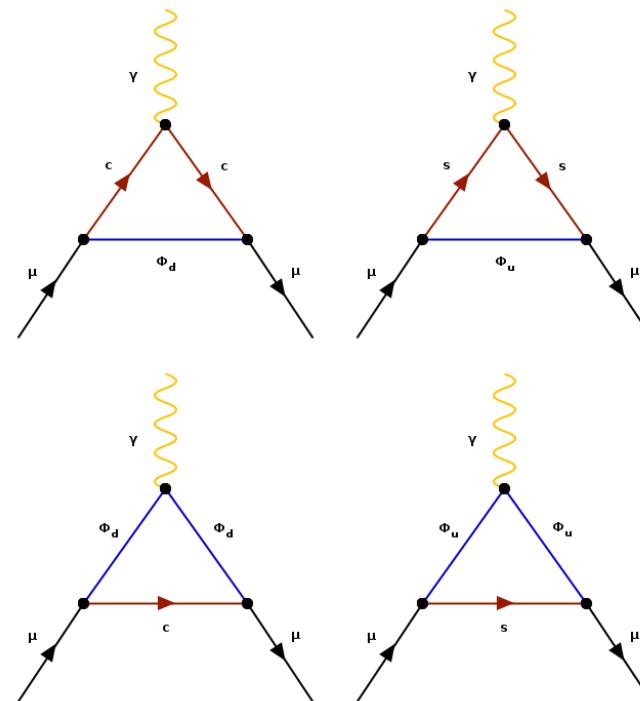
R_2

Interacts with the standard model through:

$$\mathcal{L}_{BSM} = (\lambda_{Q\mu} R_2^\dagger \mu Q + \lambda_{tL} L \cdot R_2 t + h.c.)$$

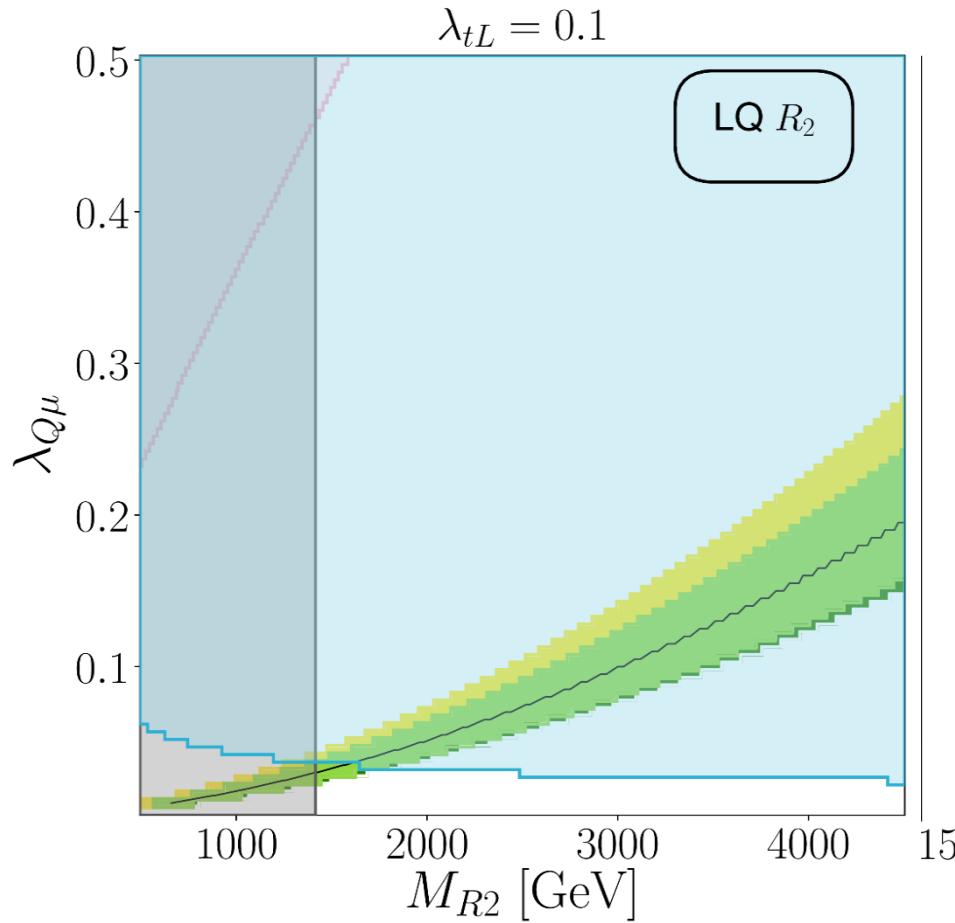
$$-M_{R2}^2 |R_2|^2 - g_{HP} |H|^2 |R_2|^2 - \frac{\lambda_\phi}{2} |R_2|^4$$

Contributes to muon g-2

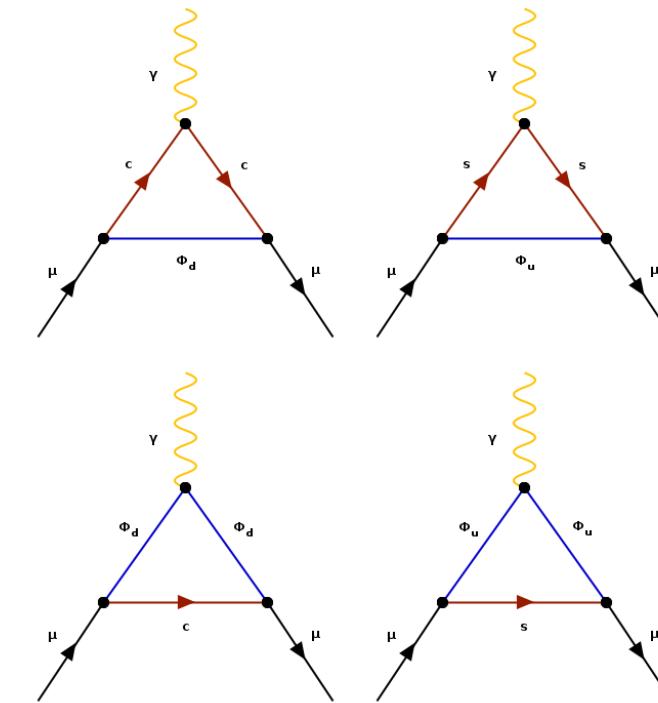


Single Scalar Leptoquark

Scalar Leptoquark Doublet



Contributes to muon g-2



Now Ruled Out

Still Viable

Newly Viable

Exclusions:

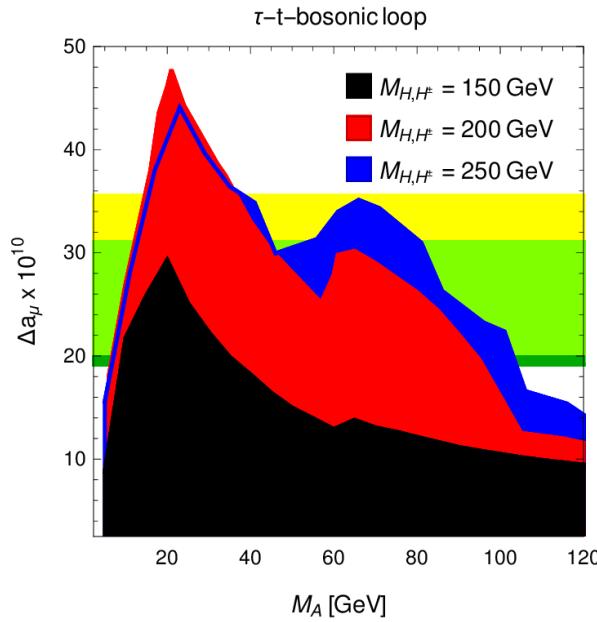
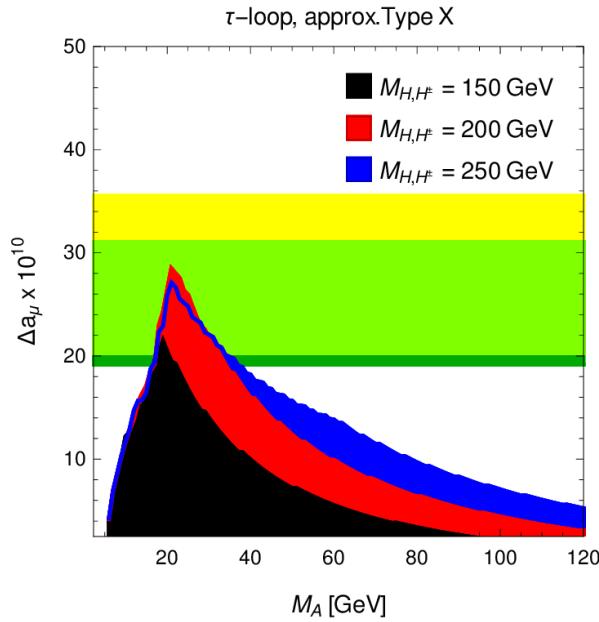
LHC Searches

Fine-Tuned m_μ

$Z \rightarrow \nu\nu$

Two Higgs Doublet Model

Type X and Flavour Aligned 2HDM



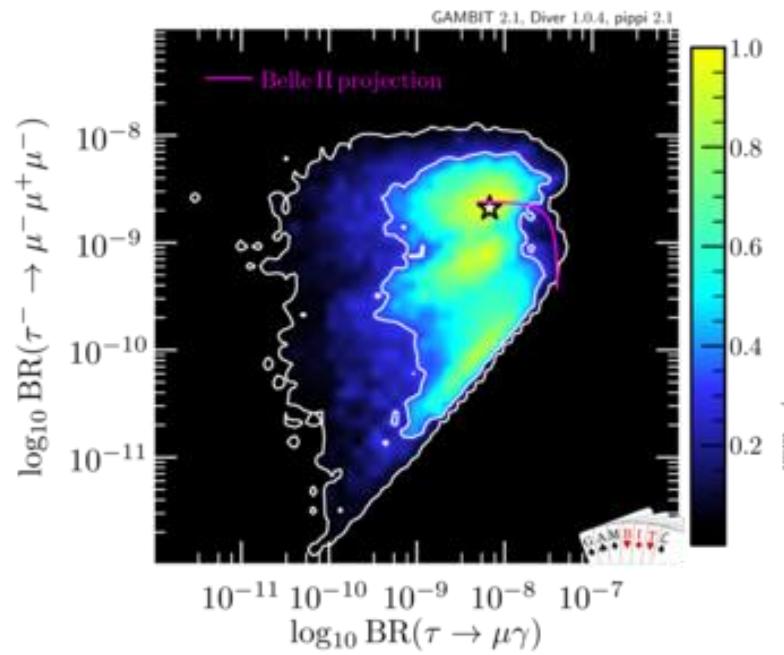
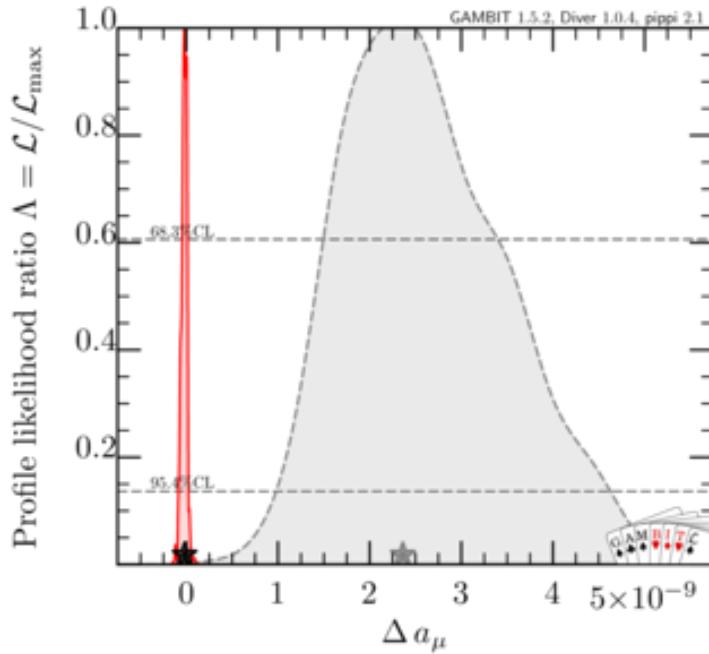
Now Ruled Out

Still Viable

Newly Viable

Two Higgs Doublet Model

General Two Higgs Doublet Model



arXiv:2111.10464

An explanation of the muon g-2 anomaly in the General 2HDM is in tension with the observables $R(K^*)$ and decays of B-mesons.

However we use a simplified version of the contributions compared to those in GM2Calc2.

Ongoing project in General 2HDM to explain muon g-2