Probing Muon $(g-2)_\mu$ Anomaly at a Muon Collider - Reloaded

Sixth Muon Collider Physics Potential Meeting

26/Mar/2021

Rodolfo Capdevilla
University of Toronto and
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__RC__, David Curtin, Yonatan Kahn, Gordan Krnjaic, arXiv:2006.16277, arXiv:2101.10334

Outline

1. Muon Anomalous Magnetic Moment

2. Implications for BSM Physics

    - Singlet Scenarios

    - Electroweak Scenarios

3. Summary

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1. Muon Anomalous Magnetic Moment

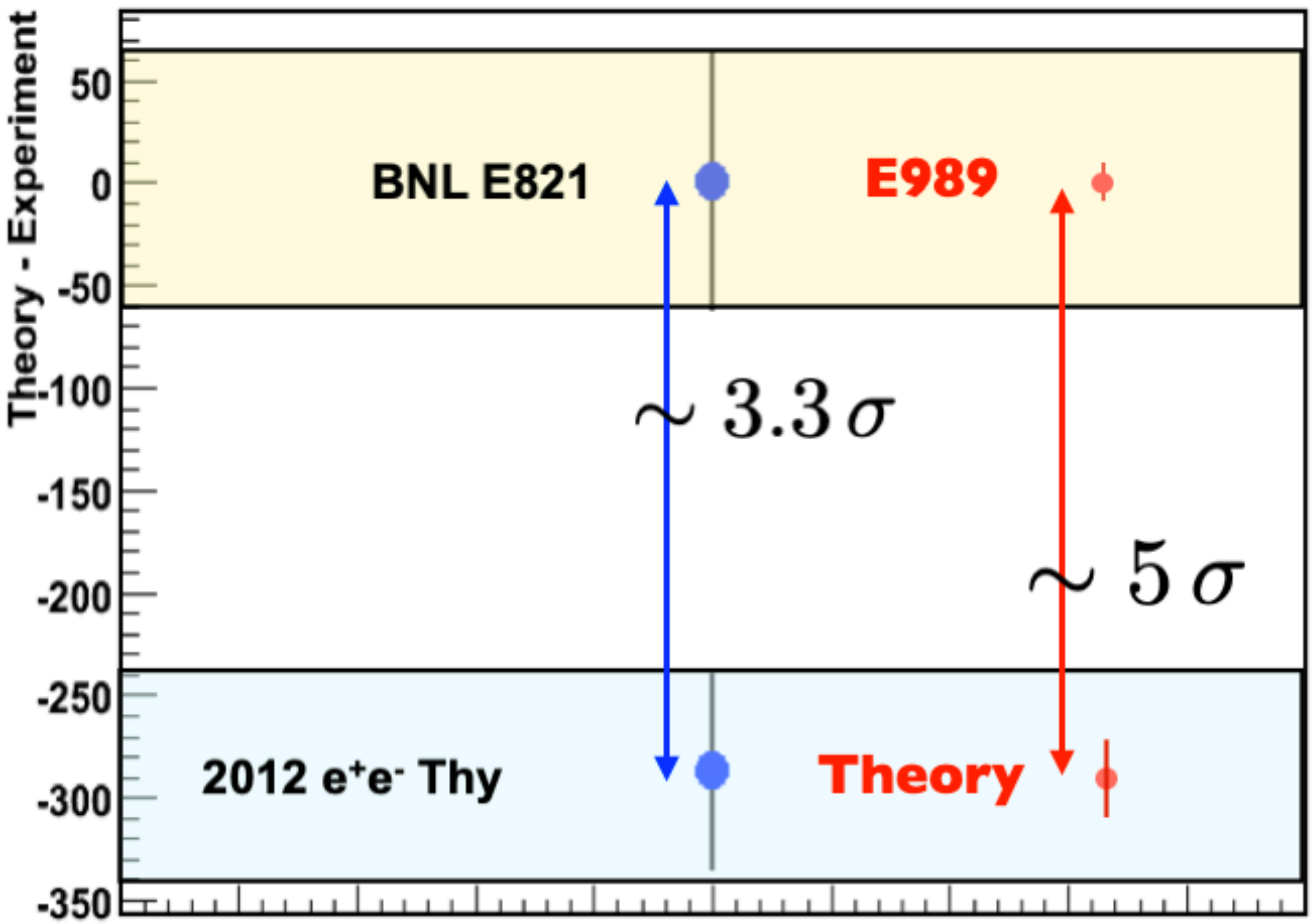
T. Aoyama et al., Phys. Rept. 887 (2020) 1-166

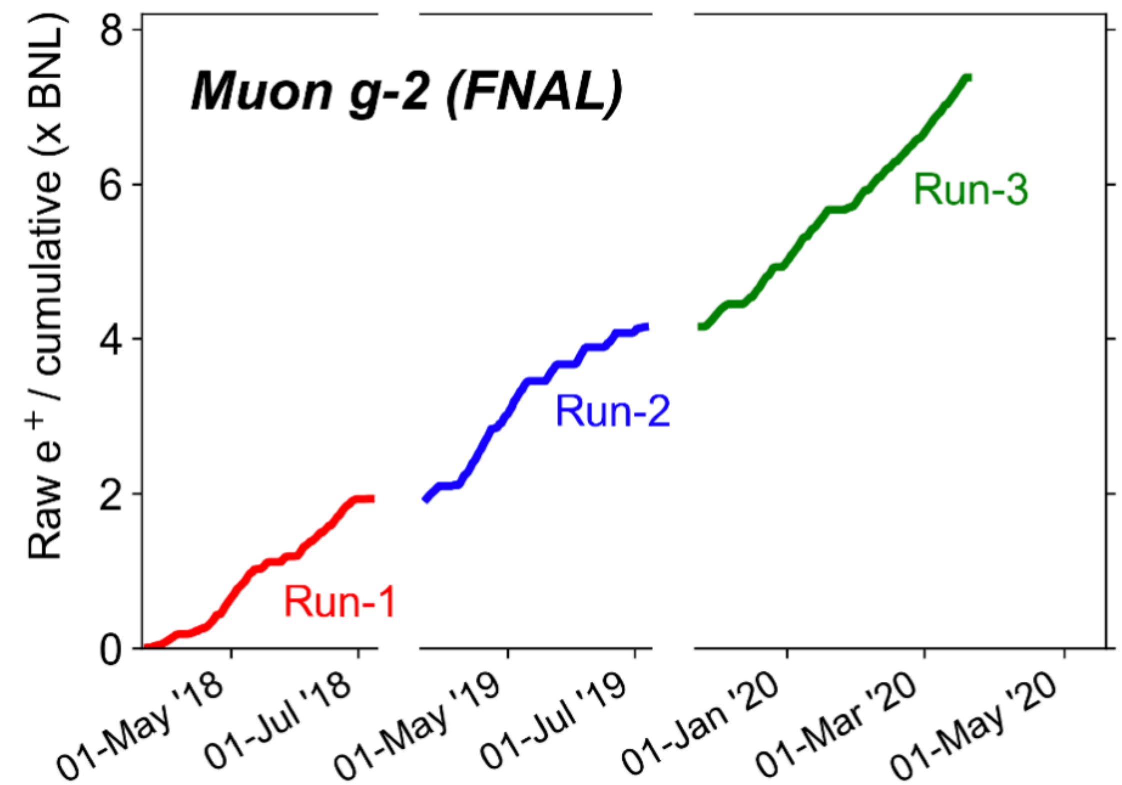
Muon g − 2 Theory Initiative

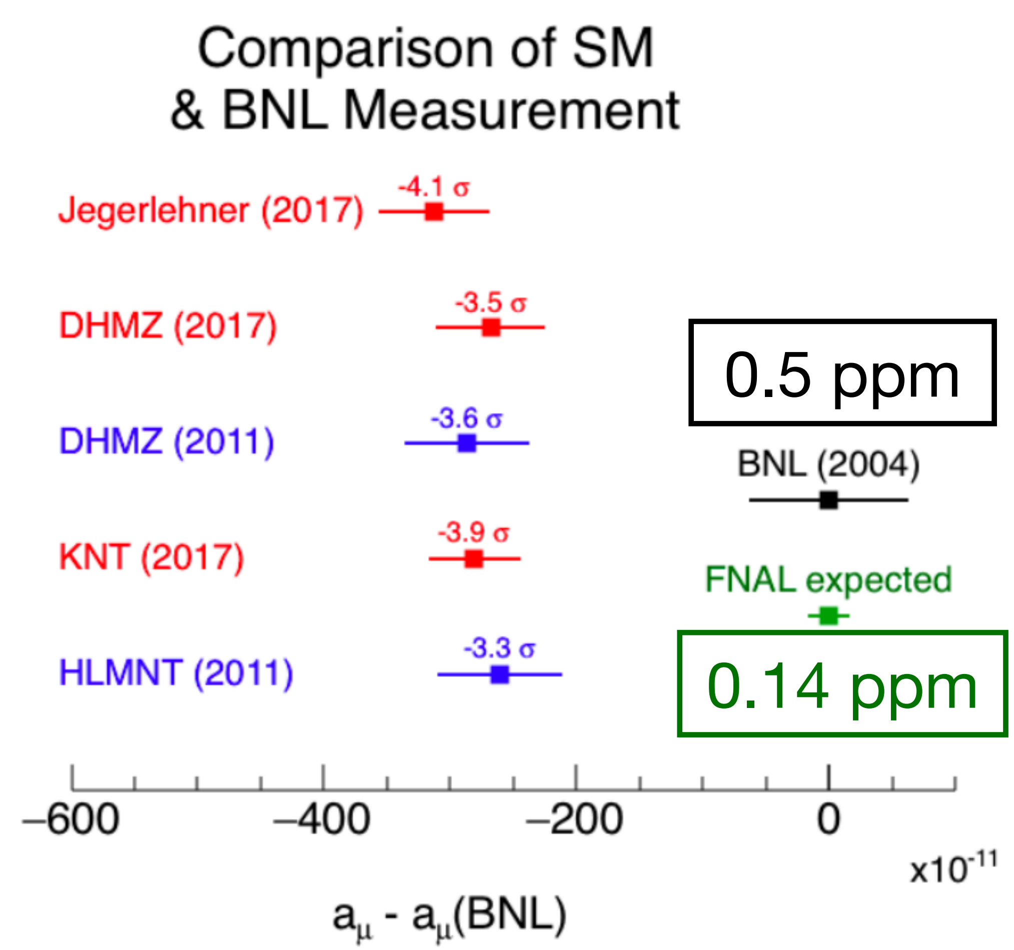
Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	−98.3(7)
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice, $udsc$)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, uds)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	279(76)

$$\Delta a_\mu \sim 3.7\,\sigma$$

1. Muon Anomalous Magnetic Moment







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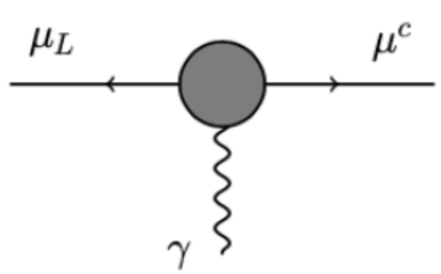
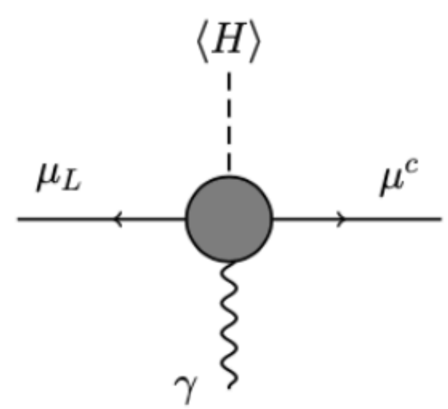
1. Muon Anomalous Magnetic Moment
2. **Implications for BSM Physics**
    - Singlet Scenarios
    - Electroweak Scenarios
3. Summary

2. Implications for BSM Physics

- How could we discover all possible BSM solutions to the (g–2)μ anomaly?

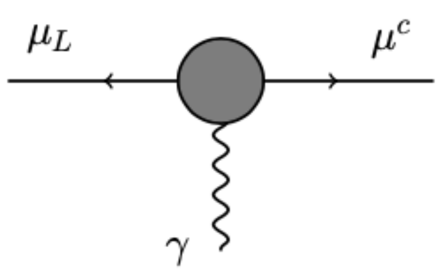
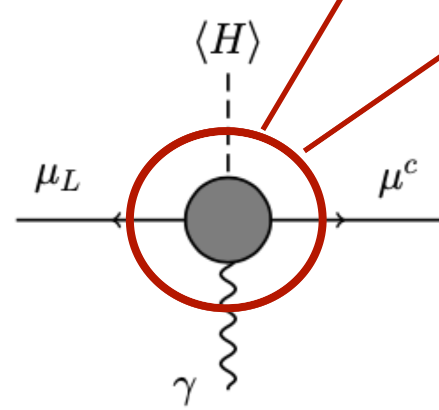
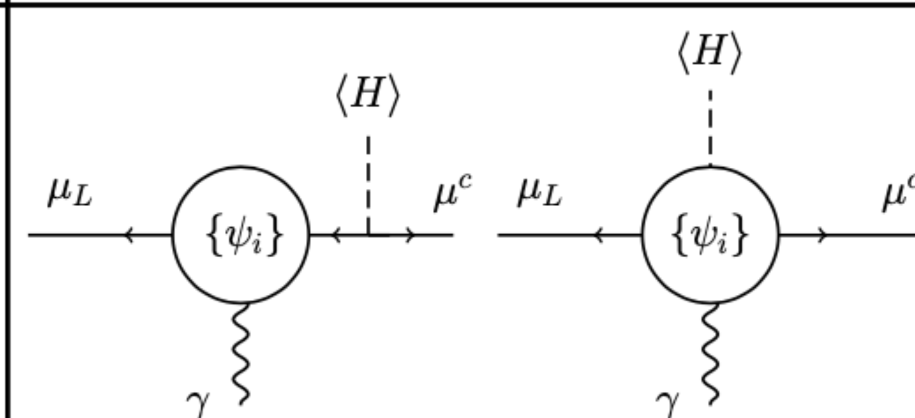
Assumptions	$\Delta a_\mu = a_\mu^{\text{obs}}$ $U(1)_{em}$ gauge invariance	$\Delta a_\mu = a_\mu^{\text{obs}}$ SM gauge invariance
$(g-2)_\mu$ diagram		
How to predict new signatures	$\frac{1}{M}(\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$	$\frac{1}{M^2} H^\dagger (L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$

Model-Independent

D. Buttazzo, P. Paradisi, e-Print: 2012.02769 [hep-ph]
W. Yin, M. Yamaguchi, e-Print: 2012.03928 [hep-ph]

Focused on indirect signatures!

2. Implications for BSM Physics

Assumptions	$\Delta a_\mu = a_\mu^{\text{obs}}$ $U(1)_{em}$ gauge invariance	$\Delta a_\mu = a_\mu^{\text{obs}}$ SM gauge invariance	$\Delta a_\mu = a_\mu^{\text{obs}}$ SM gauge invariance Perturbativity
$(g-2)_\mu$ diagram			
How to predict new signatures	$\frac{1}{M}(\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$	$\frac{1}{M^2} H^\dagger (L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$	Specific choices of BSM particles and their SM quantum numbers in loop

Model-Independent

"Model-Exhaustive"

R. Capdevilla et al., e-Print: 2101.10334
R. Capdevilla et al., e-Print: 2006.16277

2. Implications for BSM Physics

How could we discover all possible BSM solutions to the (g−2)μ anomaly?

Restrict ourselves to:

- 1-loop

2-loops point at a lower mass scale*

- Only one source of EWSB

Extra sources make the models more discoverable*

Divide the theory space into:

- Theories w/ SM singlets only

Singlet Scenarios

- Theories w/ new charged states

Electroweak Scenarios

2. Implications for BSM Physics

How could we discover all possible BSM solutions to the $(g-2)_\mu$ anomaly?

Restrict ourselves to:

- 1-loop
- Only one source of EWSB

2-loops point at a lower mass scale*

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Divide the theory space into:

- Singlet Scenarios
- Electroweak Scenarios

Simple models
Pheno ~ new couplings ← Directly produce the singlets

Complicated models
Simple pheno ← Focus on producing lightest charged state!

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2. Implications for BSM Physics

How could we discover all possible BSM solutions to the $(g-2)_\mu$ anomaly?

Particularly relevant for a Muon Collider:

- For singlet models, can couple to singlet via same coupling that makes g-2
- For EW models, can reach high energies and discover "all" charged particles with masses < Ecm/2

Divide the theory space into:

- Singlet Scenarios
- Electroweak Scenarios

Simple models
Pheno ~ new couplings ← Directly produce the singlets

Complicated models
Simple pheno ← Focus on producing lightest charged state!

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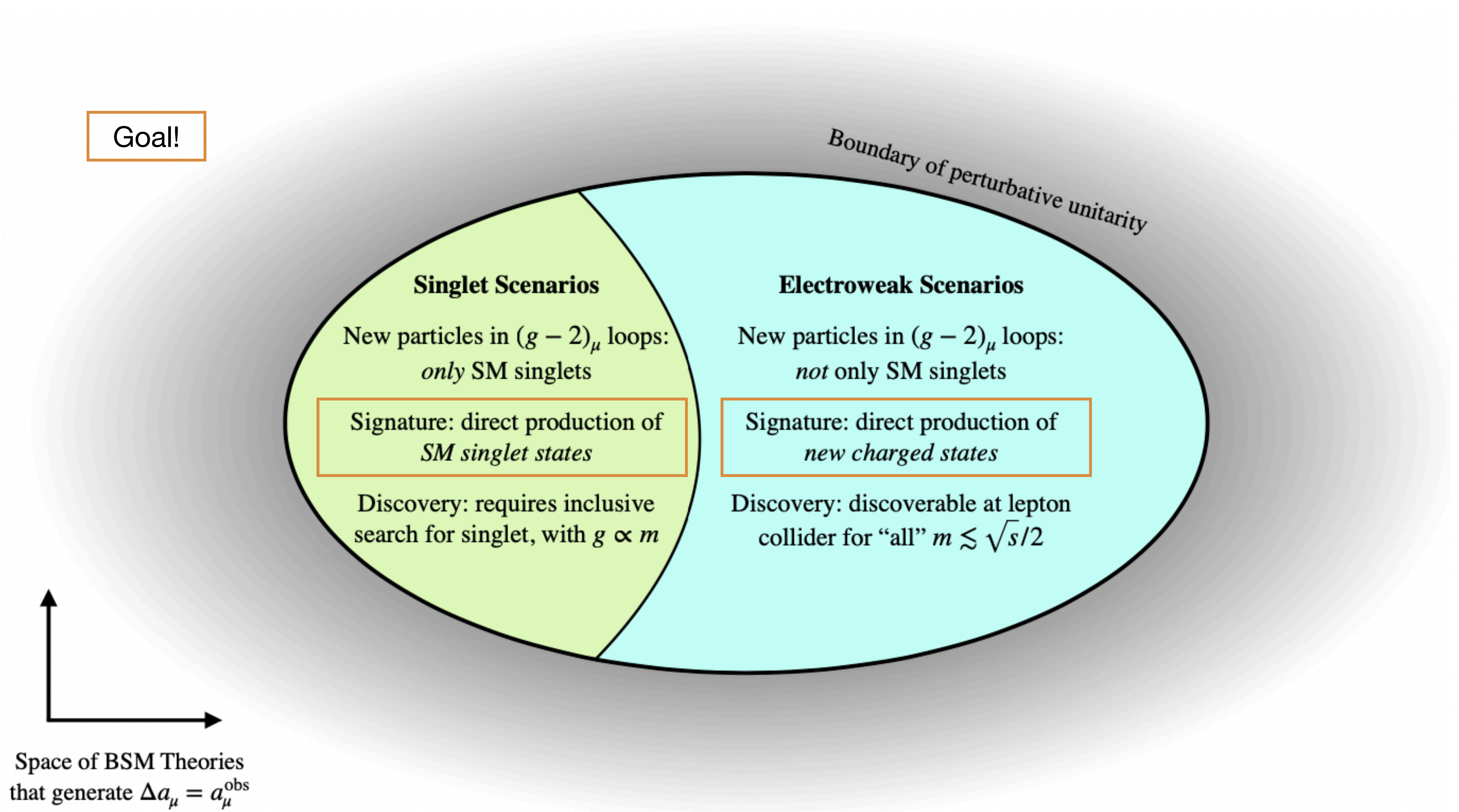
2. Implications for BSM Physics



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1. Muon Anomalous Magnetic Moment

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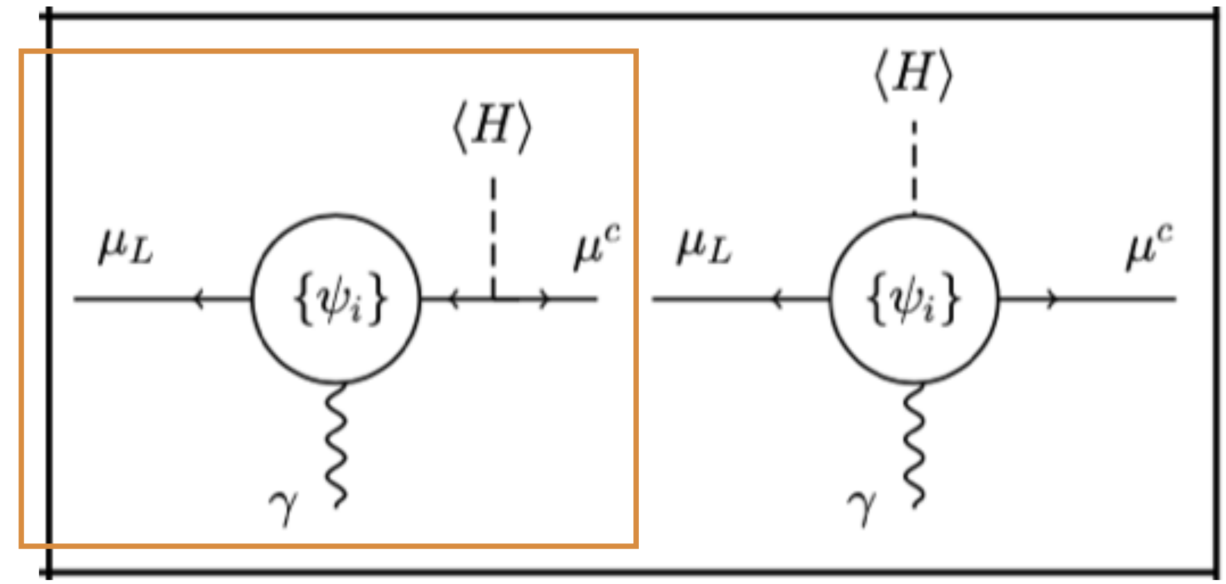
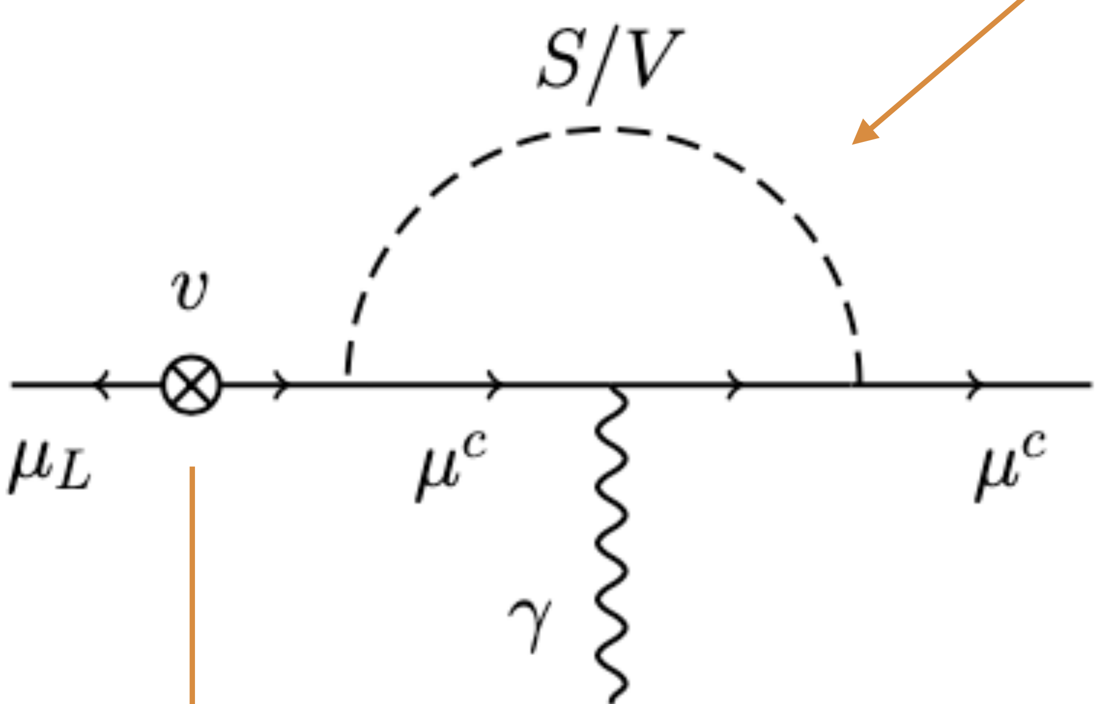
2. Implications for BSM Physics: Singlet Scenarios

- Singlet Scenarios



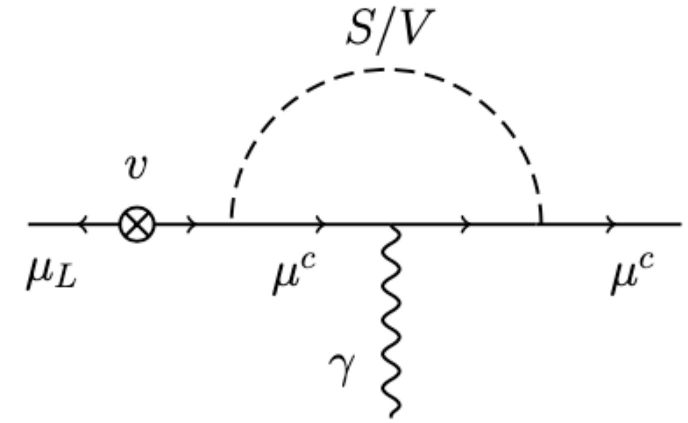


Suppressed chirality flip and EWSB insertion

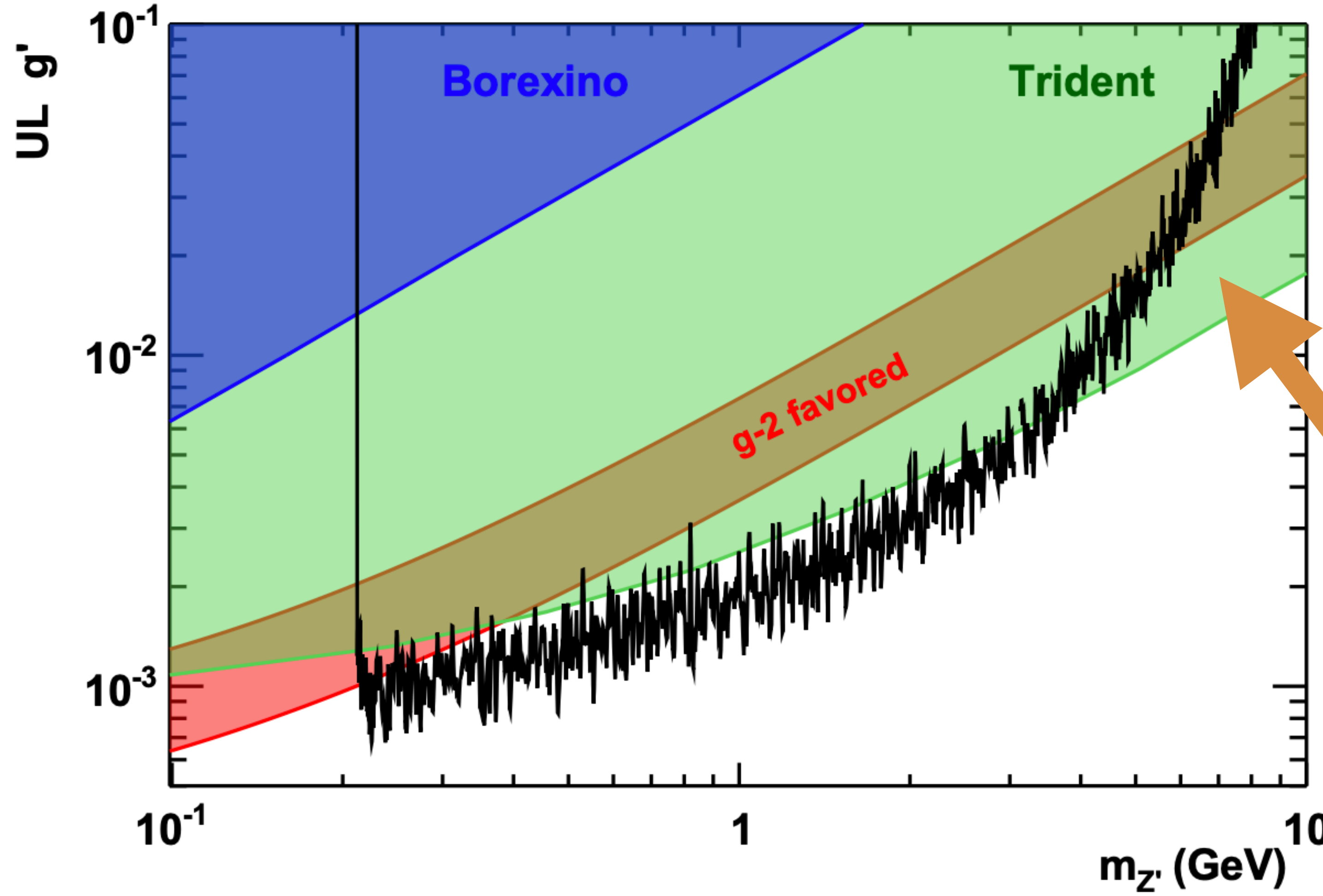
$$\Delta a_\mu \sim N_{BSM} \frac{g^2}{4\pi^2} \frac{m_\mu^2}{M^2} C_{\text{loop}}$$

Number of BSM particles in the loop

2. Implications for BSM Physics: Singlet Scenarios



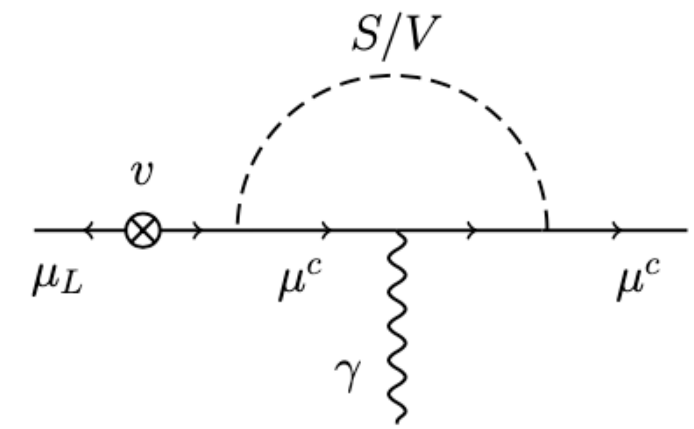
BaBar Collaboration, e-Print: 1606.03501

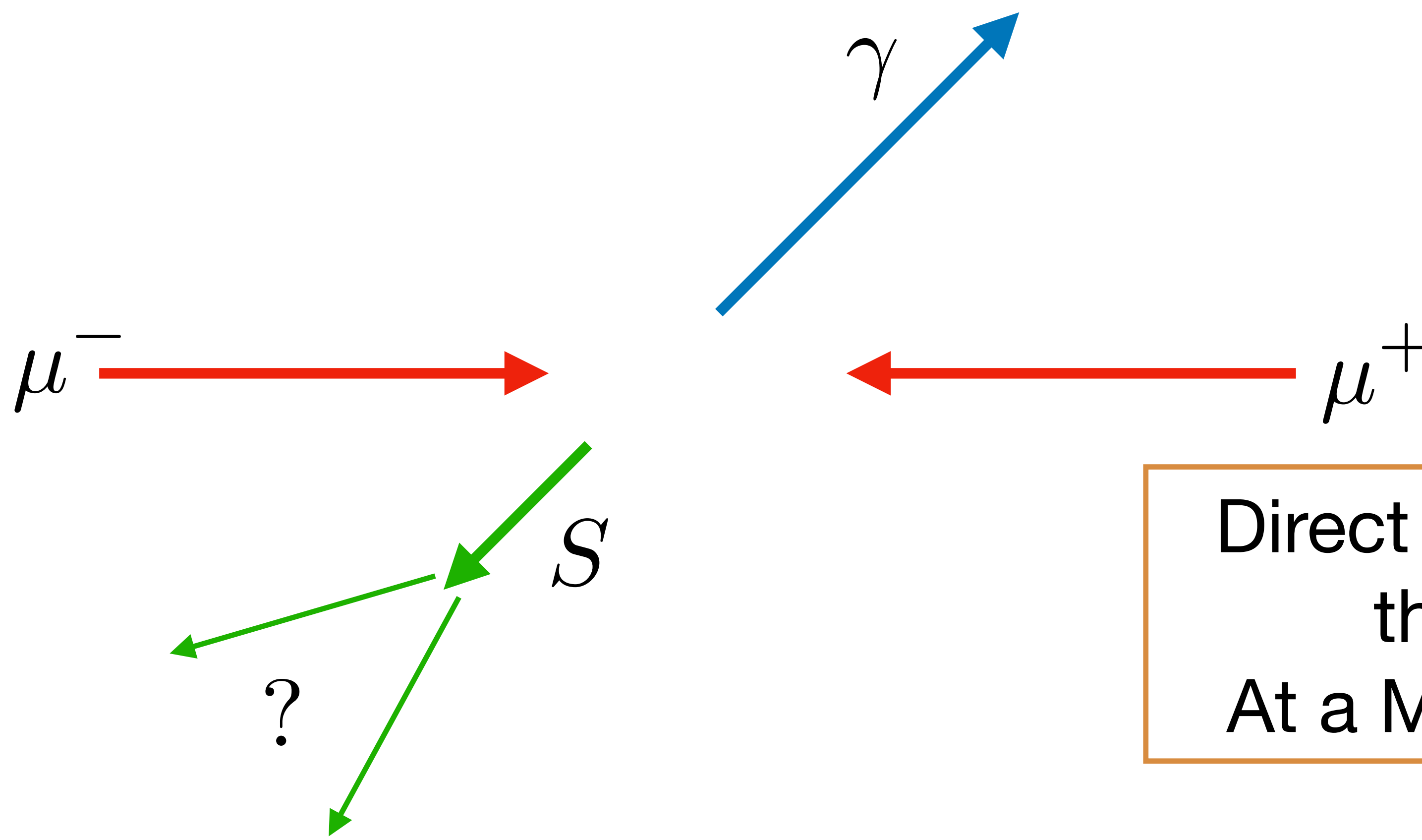


Low energy experiments constrain parameter space from below

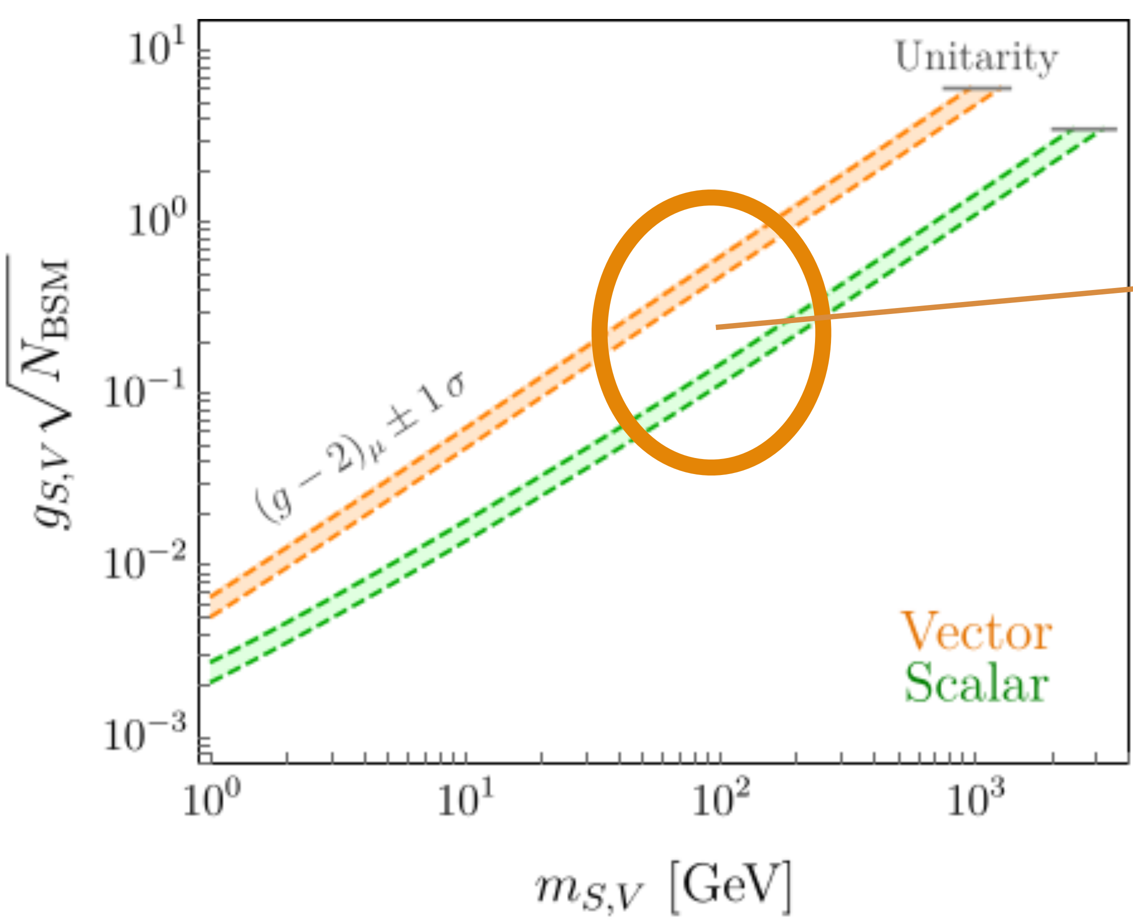
$$\Delta a_\mu \sim N_{BSM} \frac{g^2}{4\pi^2} \frac{m_\mu^2}{M^2} C_{\text{loop}}$$

2. Implications for BSM Physics: Singlet Scenarios





Direct production of the singlet At a Muon Collider!



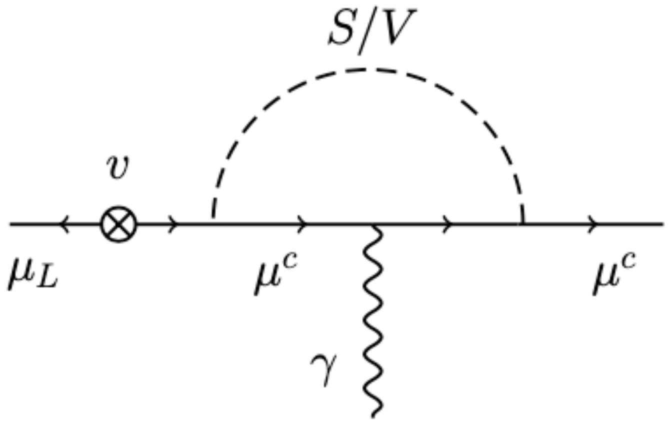
$$m_S \gtrsim 100\,\mathrm{GeV}$$
$$g \gtrsim 0.1$$

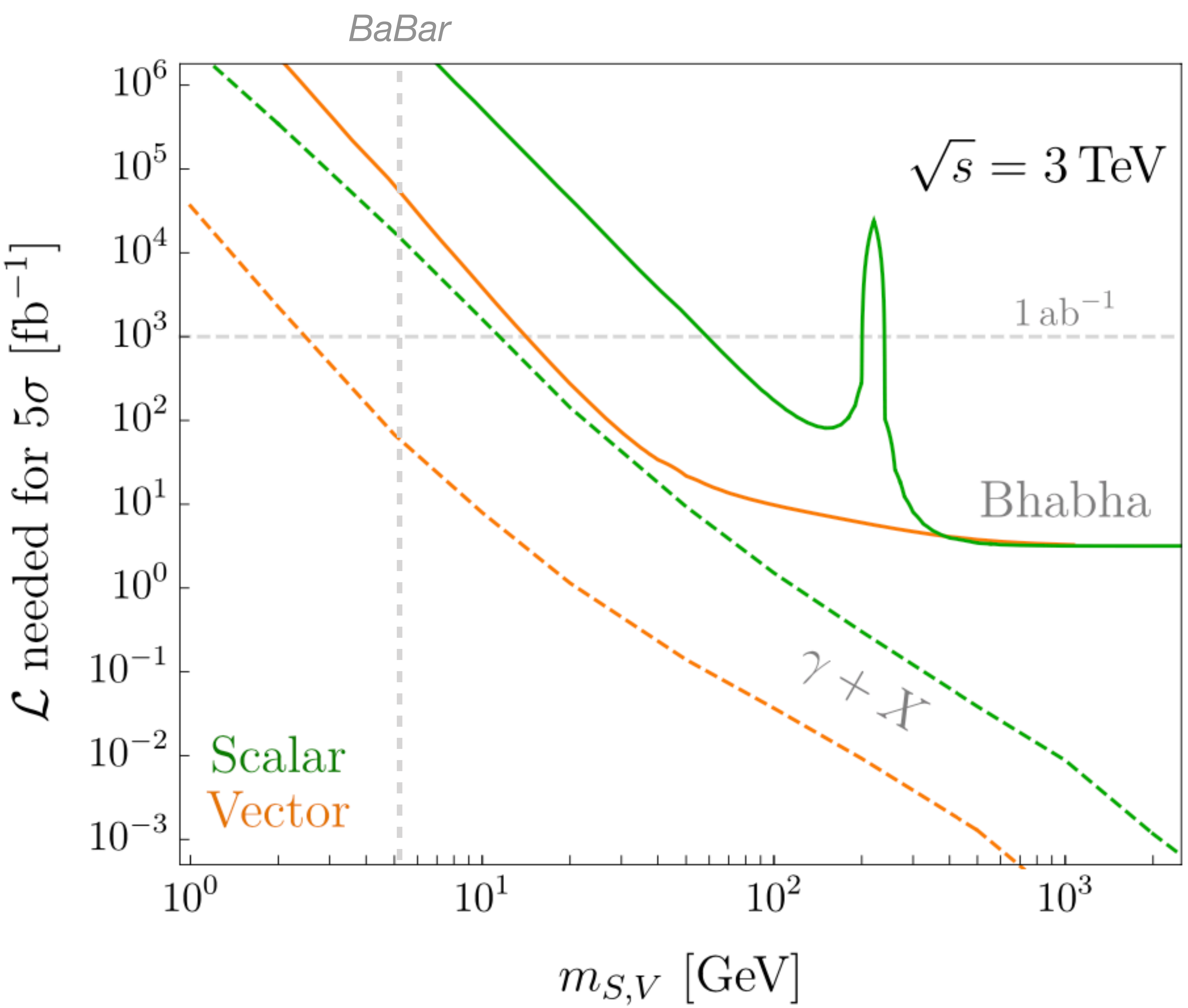
Reasonable to assume

$$S \to \mu^+\mu^-$$

Dominant decay mode

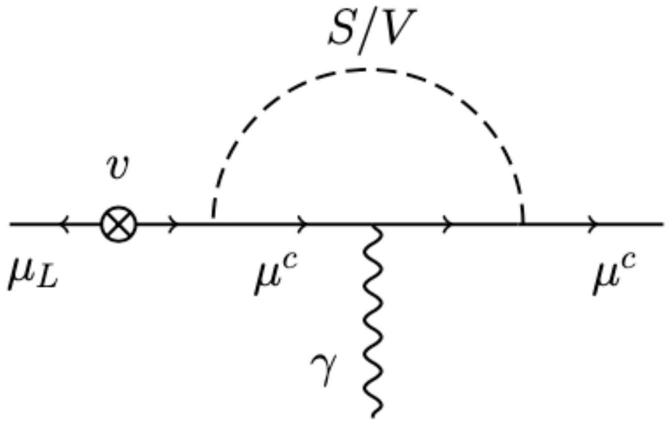
2. Implications for BSM Physics: Singlet Scenarios

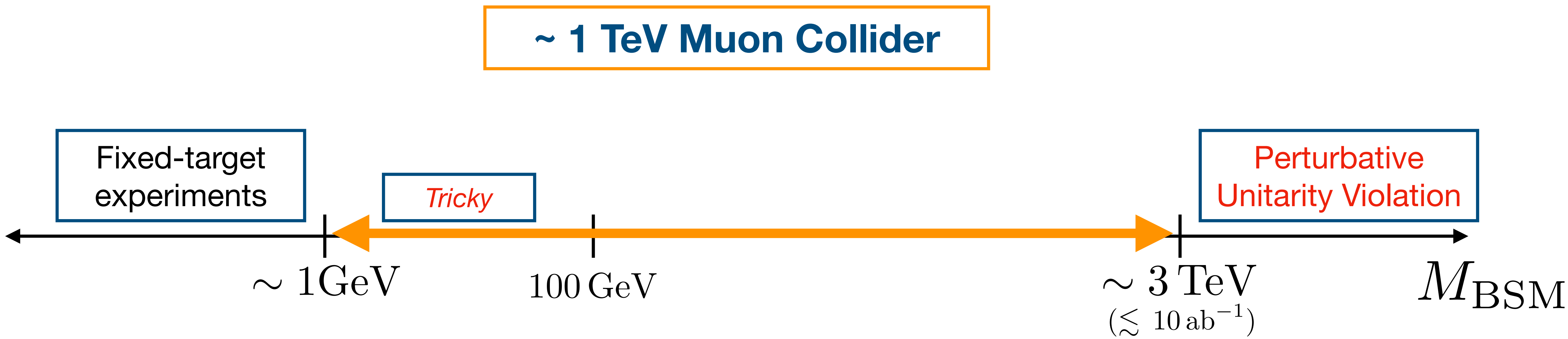




A 3 TeV Muon Collider can probe all Singlet explanations for g-2

2. Implications for BSM Physics: Singlet Scenarios





R. Capdevilla et al., e-Print: 2101.10334
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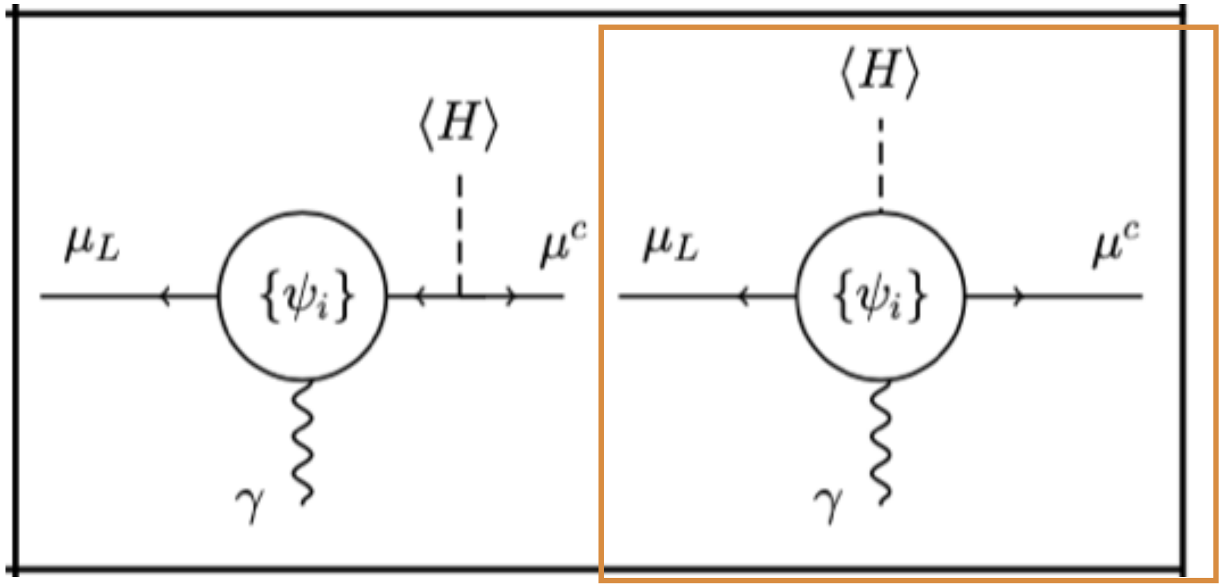
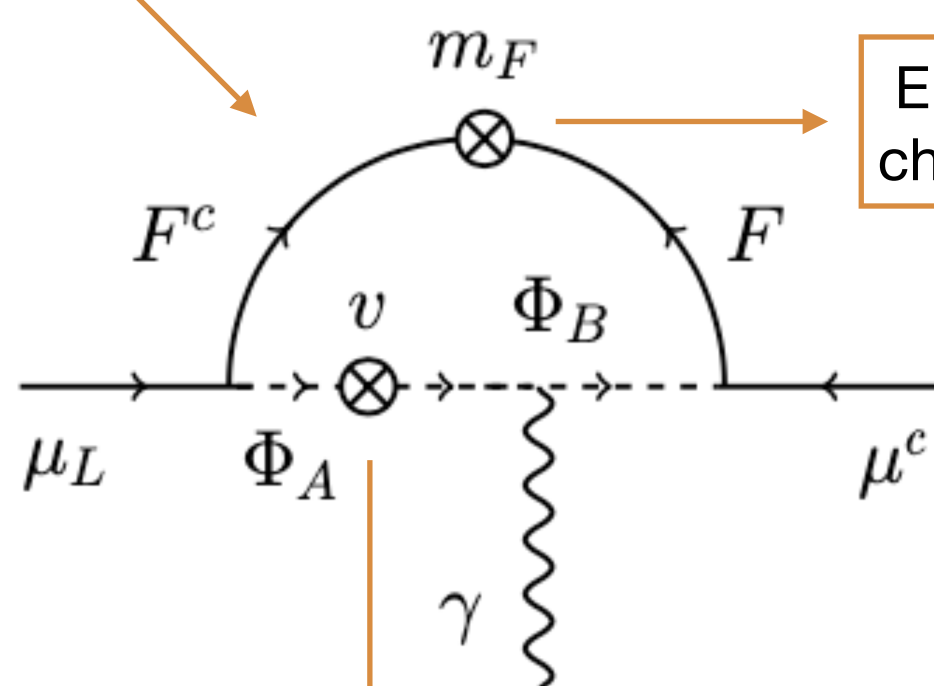
2. Implications for BSM Physics: EW Scenarios



- EW Models

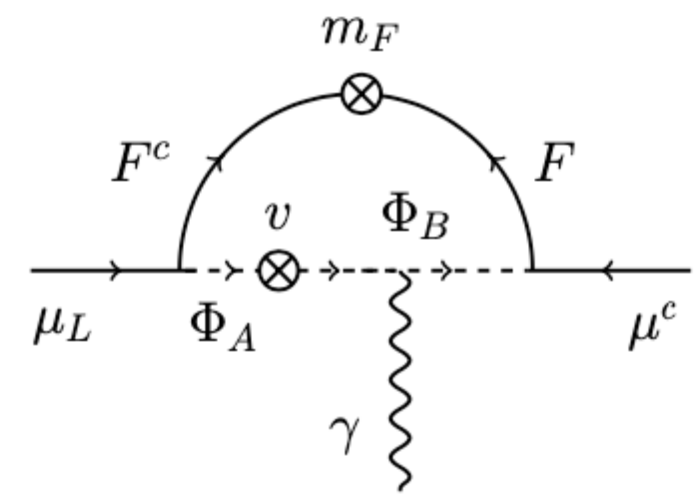


Enhanced chirality flip

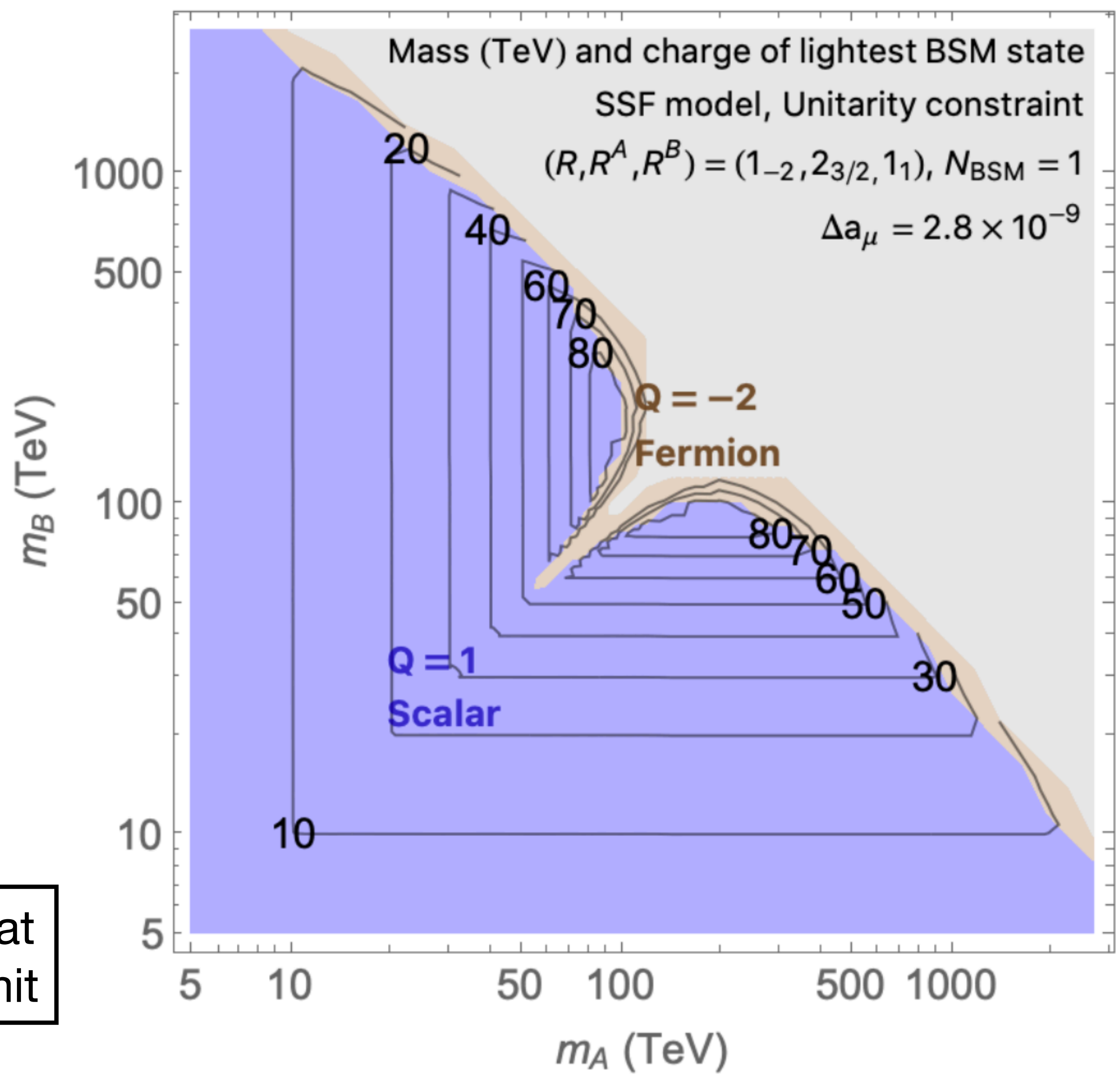
Enhanced EWSB insertion

$$\Delta a_\mu \propto \frac{m_\mu m_F}{\Lambda^2}$$

2. Implications for BSM Physics: EW Scenarios



Unitarity only



- EW representations up to **3**
- Models with charged scalars up to Q = 2
- BSM number of flavours up to 10

N_{BSM}

Maximal couplings at the perturbativity limit

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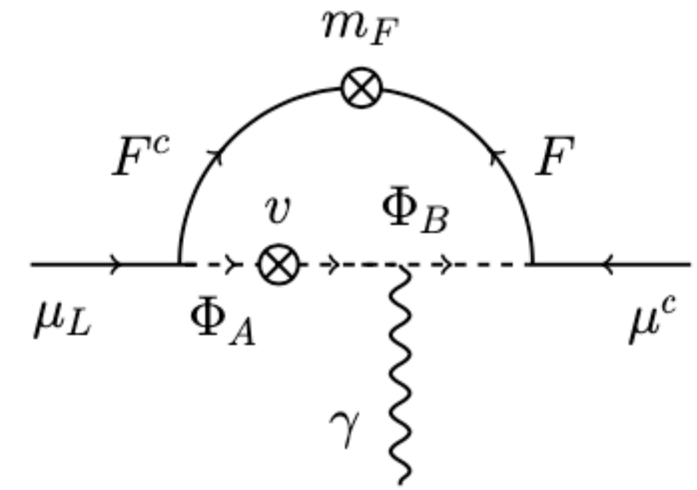
2. Implications for BSM Physics: EW Scenarios



If only perturbative unitarity

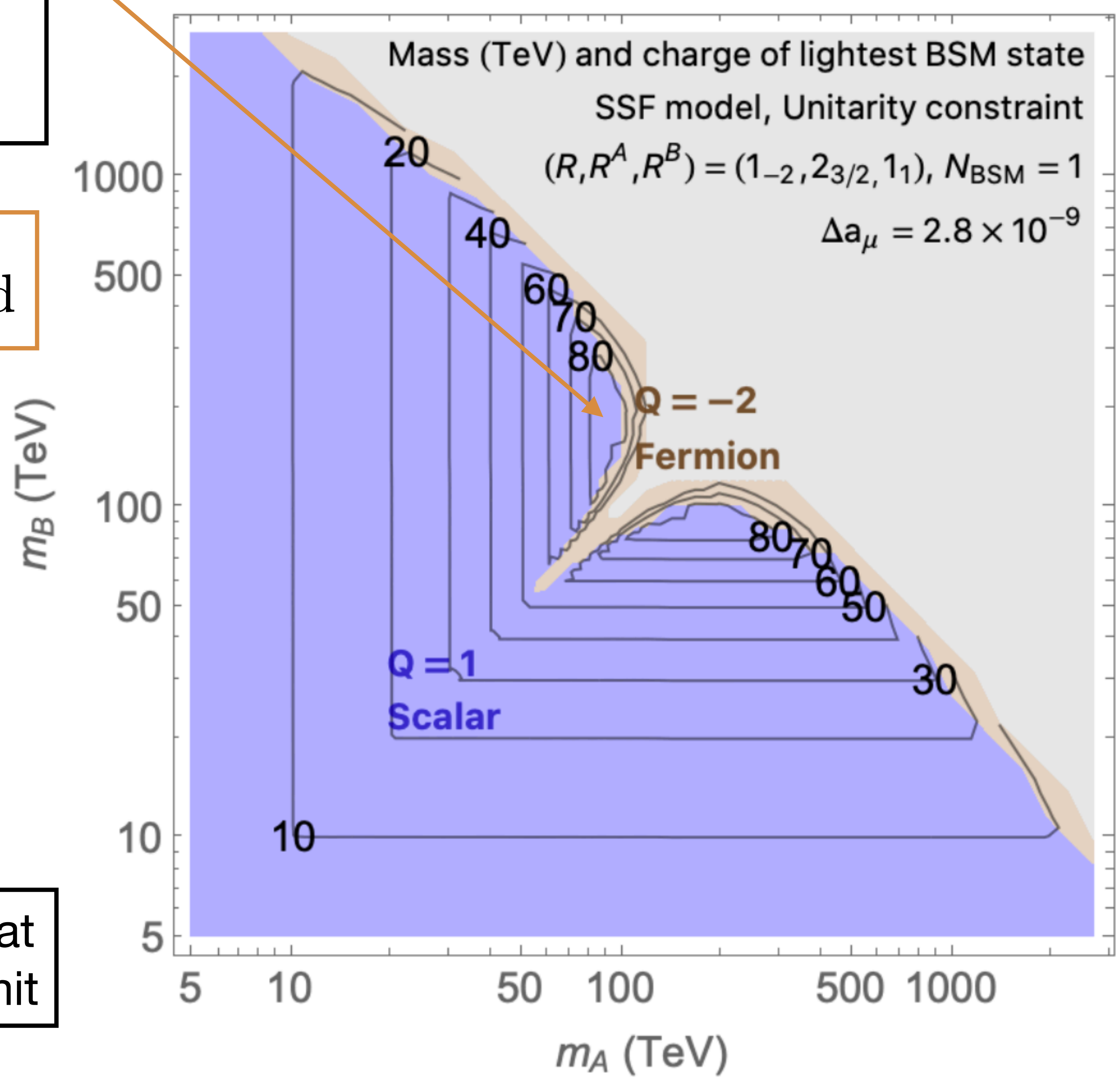
Heaviest states at

$\sim 100\,\mathrm{TeV}$

$M^{\max}_{\mathrm{BSM,charged}}$

Maximal couplings at the perturbativity limit

Unitarity only



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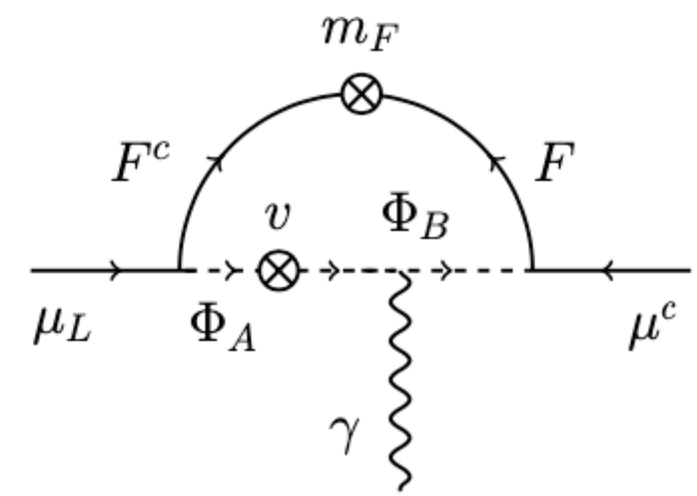


- Flavor?

$$-\mathcal{L} \supset y_1^i F^c L_i \Phi_A^* + y_2^i F \ell_i^c \Phi_B^*$$

Flavor Specific couplings?

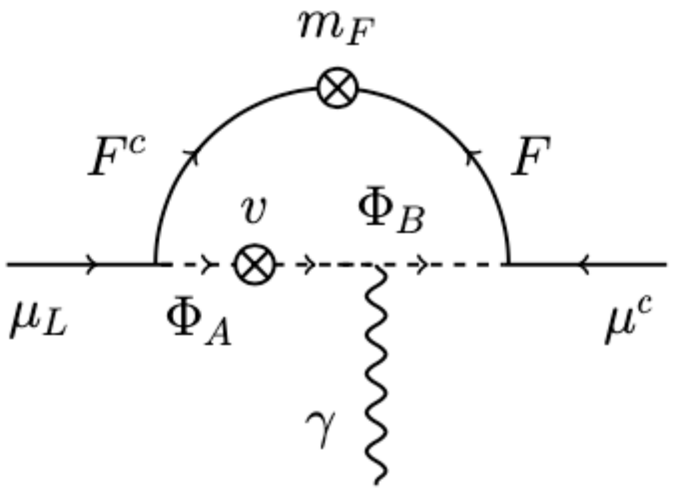
B. Batell, A. Freitas, A. Ismail, D. Mckeen, e-Print: 1712.10022

$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$
$$\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

$$\frac{y_{1,2}^e}{y_{1,2}^\mu} \lesssim 10^{-5}$$

$$\frac{y_{1,2}^\tau}{y_{1,2}^\mu} \lesssim 10^{-1}$$

2. Implications for BSM Physics: EW Scenarios



- Minimal Flavor Violation?

$$-\mathcal{L} \supset Y_1^i \left(F^c L \Phi_A^*\right)_i + Y_2^i \left(F \ell^c \Phi_B^*\right)_i$$

Proportional to SM yukawas

Can transform under the flavour group

$$L \sim (3,1)$$
$$e^c \sim (1,\bar{3})$$
$$F \sim (3,1)$$
$$F^c \sim (\bar{3},1)$$
$$S_{A,B} \sim (1,1)$$

An example

$$\rightarrow \quad y_2 \sim y_e \sim (\bar{3},3) \qquad y_1 \sim (1,1) \quad \rightarrow \quad \frac{(y_{1,2})_\tau}{(y_{1,2})_\mu} \sim \frac{(y_{SM})_\tau}{(y_{SM})_\mu}$$

- The tauonic coupling reaches the perturbativity limit before the muonic one.
- The relevant coupling for g-2 is reduced by ~ one order of magnitude!

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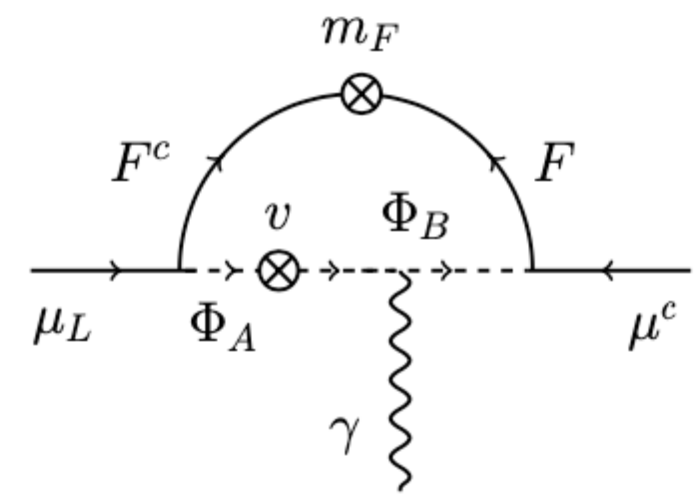
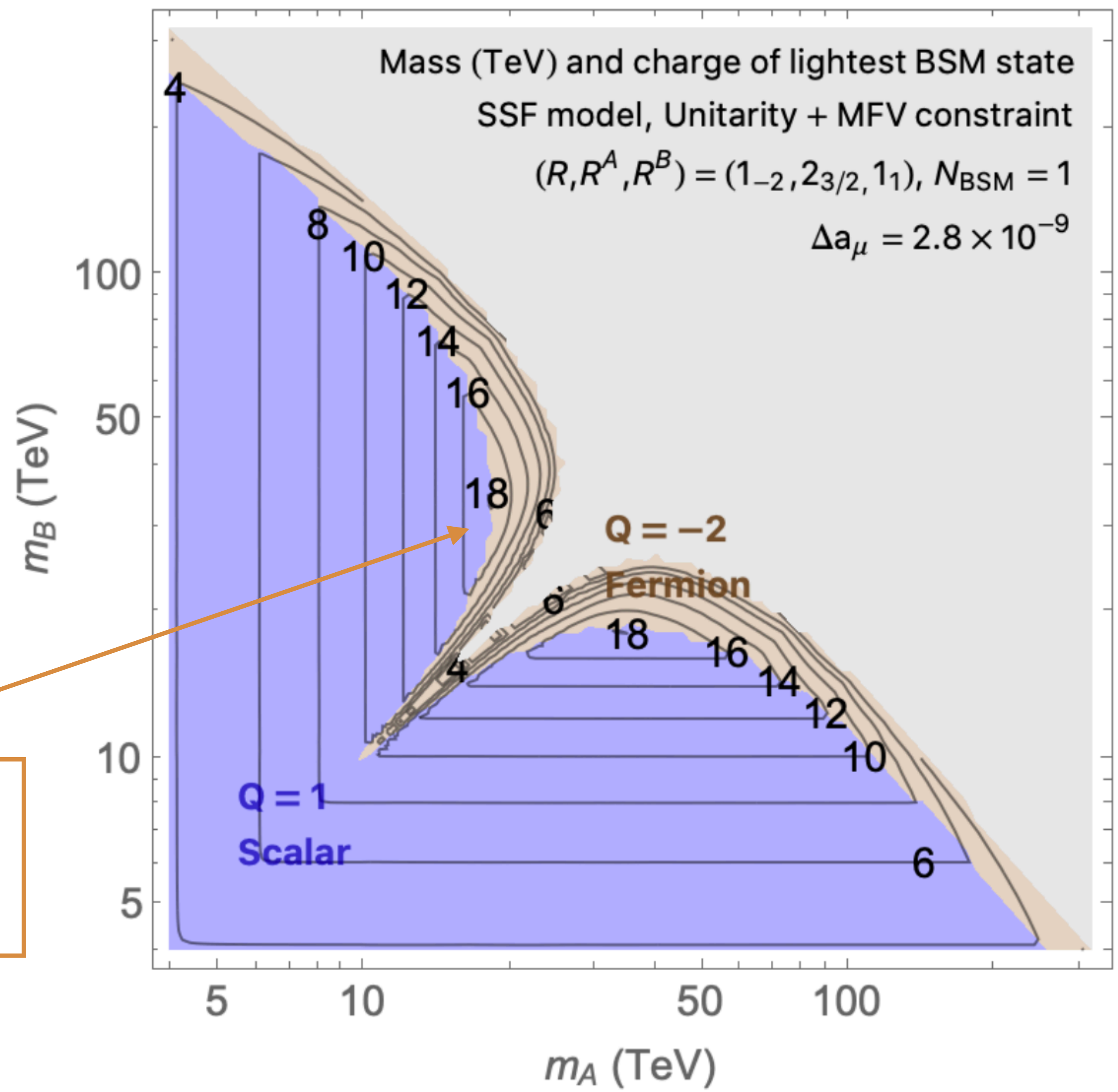
2. Implications for BSM Physics: EW Scenarios



- What about flavour?

Unitarity + MFV



Heaviest states at

$\sim 20\,\mathrm{TeV}$

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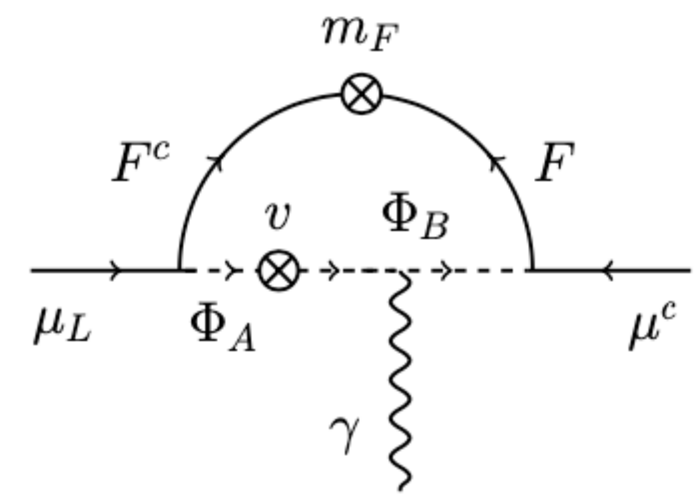
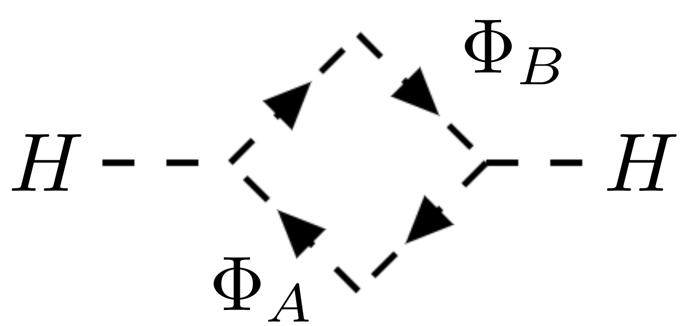
2. Implications for BSM Physics: EW Scenarios

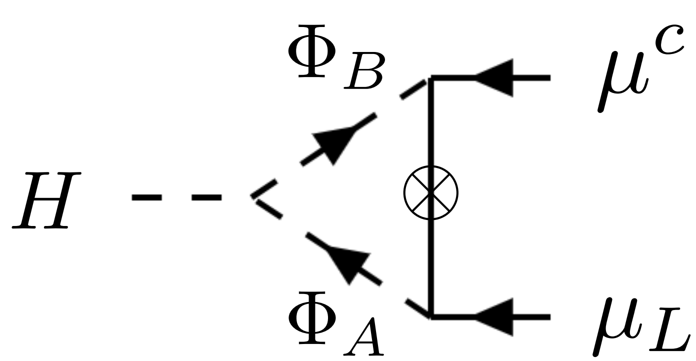


- Naturalness?

Two calculable hierarchy problem!



$$\Delta\mu_H^2 \sim \frac{\kappa^2}{16\pi^2} C'_{\text{loop}}$$



$$\Delta y_\mu \sim \frac{y_1 y_2 m_F \kappa}{16\pi^2 M_{A/B}^2} C_{\text{loop}}$$

Muon mass technically unnatural

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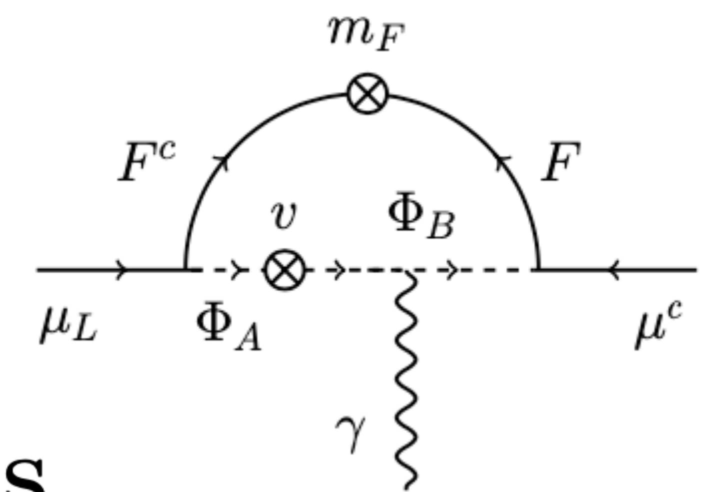
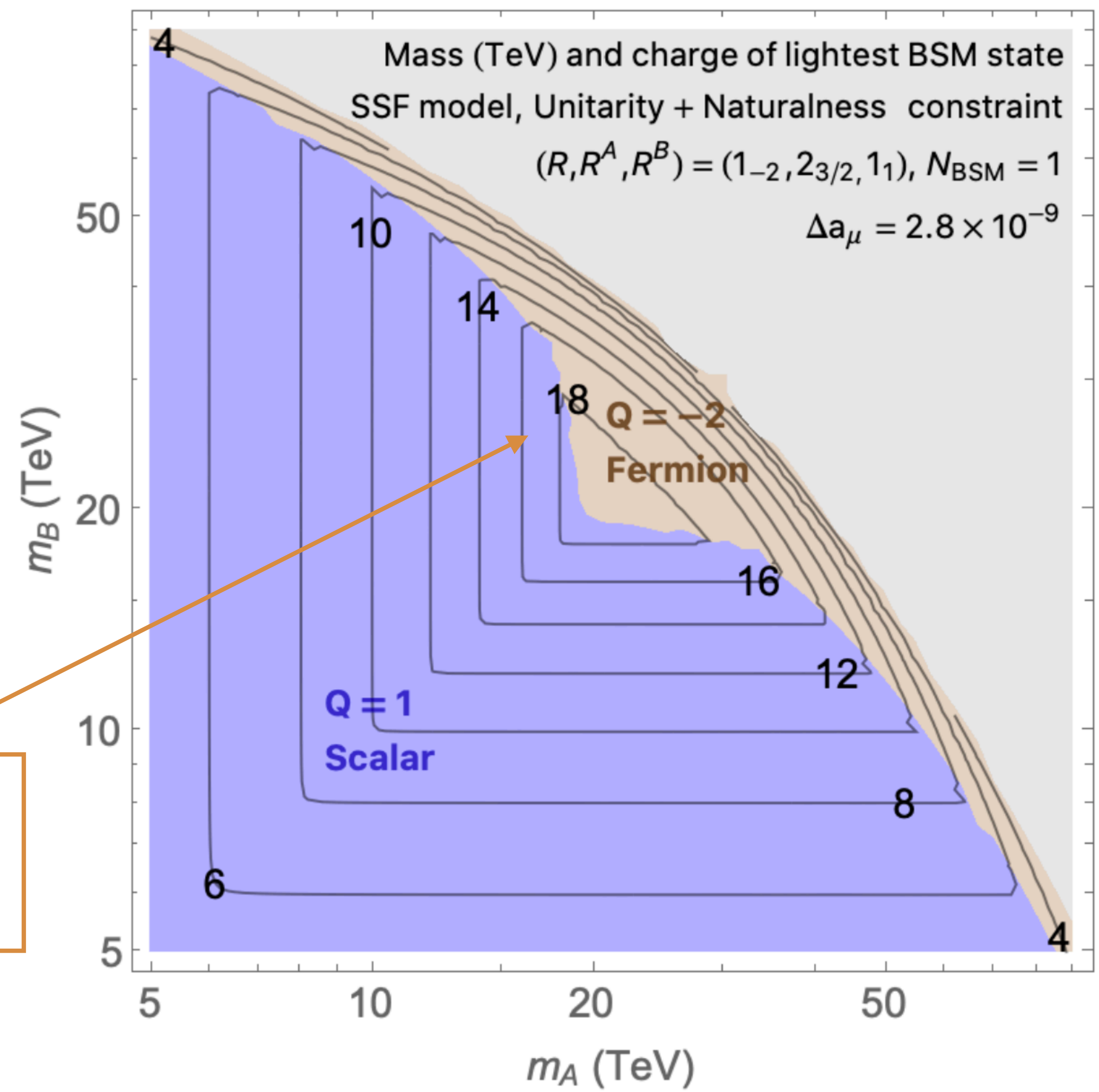
2. Implications for BSM Physics: EW Scenarios



- What about naturalness?

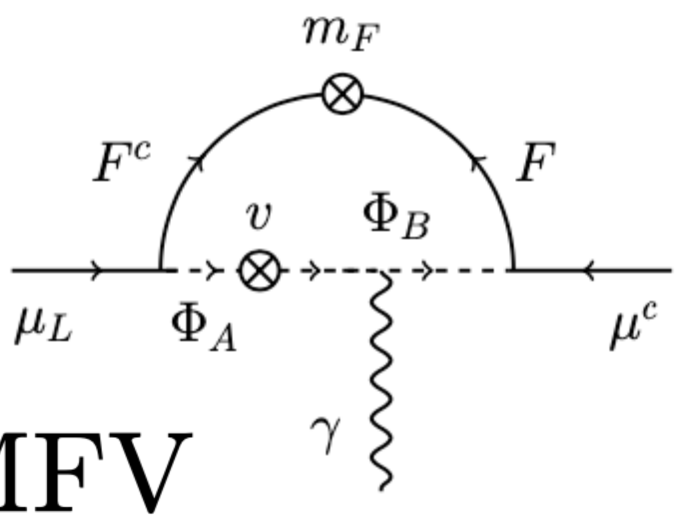
Unitarity + Naturalness



Heaviest states at

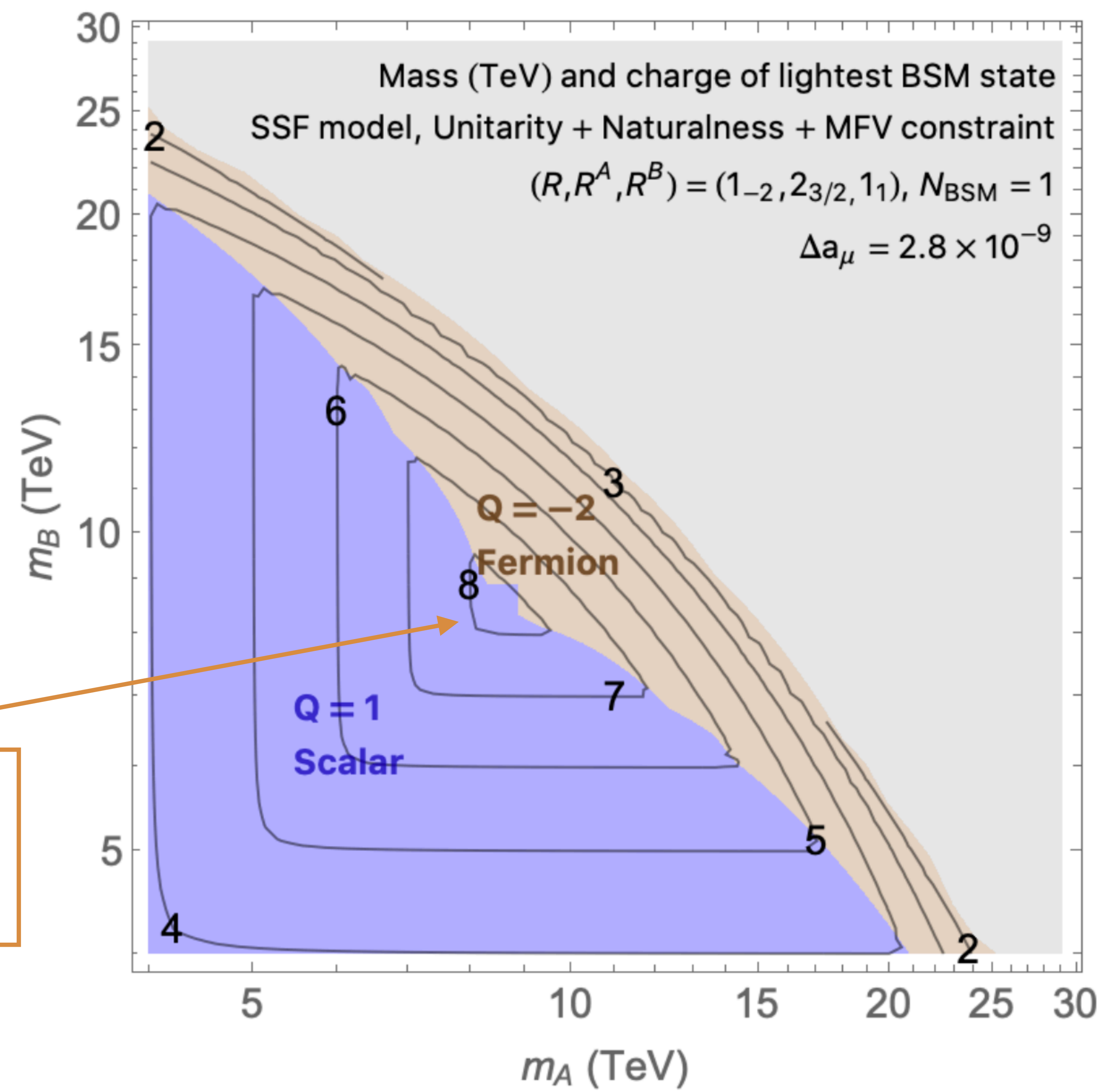
$\sim 20\,\text{TeV}$

2. Implications for BSM Physics: EW Scenarios



- What about all?

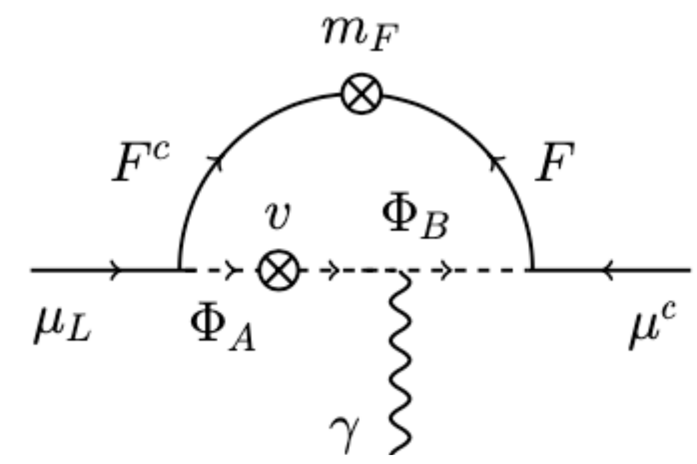
$$\text{Unitarity} + \text{Naturalness} + \text{MFV}$$



Heaviest states at

$$\sim 10\,\text{TeV}$$

2. Implications for BSM Physics: EW Scenarios



- What about all?

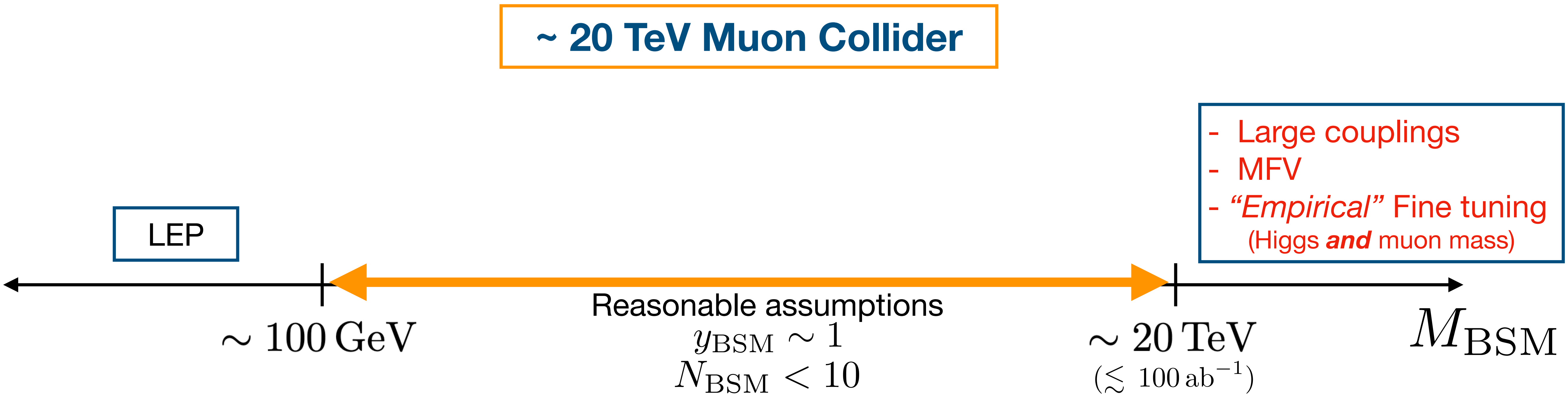
$$M_{\rm BSM,charged}^{\rm max,X} \approx \begin{cases} (100\,{\rm TeV})\ N_{\rm BSM}^{1/2} & \text{for} \quad X = (\text{unitarity}^*) \\ (20\,{\rm TeV})\ N_{\rm BSM}^{1/2} & \text{for} \quad X = (\text{unitarity} + \text{MFV}) \\ (20\,{\rm TeV})\ N_{\rm BSM}^{1/6} & \text{for} \quad X = (\text{unitarity} + \text{naturalness}^*) \\ (9\,{\rm TeV})\ N_{\rm BSM}^{1/6} & \text{for} \quad X = (\text{unitarity} + \text{naturalness} + \text{MFV}) \end{cases}$$

- At a MuC

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Muon collider collaboration

2. Implications for BSM Physics: EW Scenarios



R. Capdevilla et al., e-Print: 2101.10334
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Summary

1. Muon g-2 anomaly: **If** confirmed, what does it mean?

2. A MuC is in a privileged position: It collides the particles of the anomaly and it can reach high COM energies

3. We analyze the *theory space* that can solve the g-2 anomaly, and identify the nightmare scenarios → If a MuC can find these, it can find any scenario!

4. **This tells us what kind of MuC do we need to guarantee a discovery!**

5. We found models with new singlets and models with new EW states.

6. A ~ TeV MuC can probe all *singlet models* and a ~20 TeV MuC can probe the *EW models* under reasonable assumptions.

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Thanks!