A no-lose theorem for discovering the new physics of $(g-2)_\mu$

Brookhaven Forum (Virtual)
4 Nov 2021

David Curtin
University of Toronto

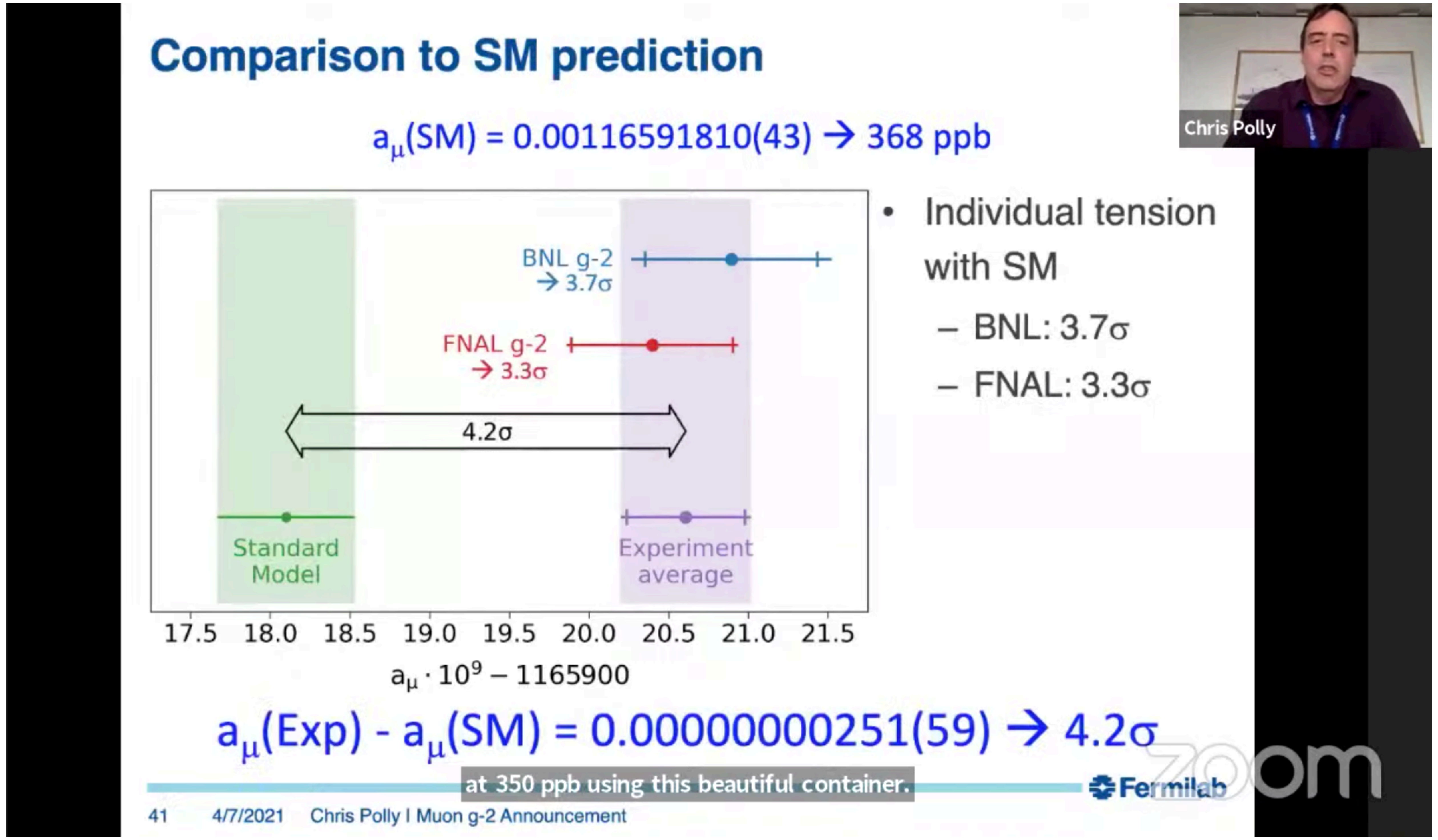
based on 2006.16277, 2101.10334 with
Rodolfo Capdevilla, Yonatan Kahn, Gordan Krnjaic

UNIVERSITY OF TORONTO



Exciting!

7 April 2021:



Upshot:

BNL + Fermilab say

$$\Delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$$

which is disagreeing with SM prediction at 4.2σ level.

If real:

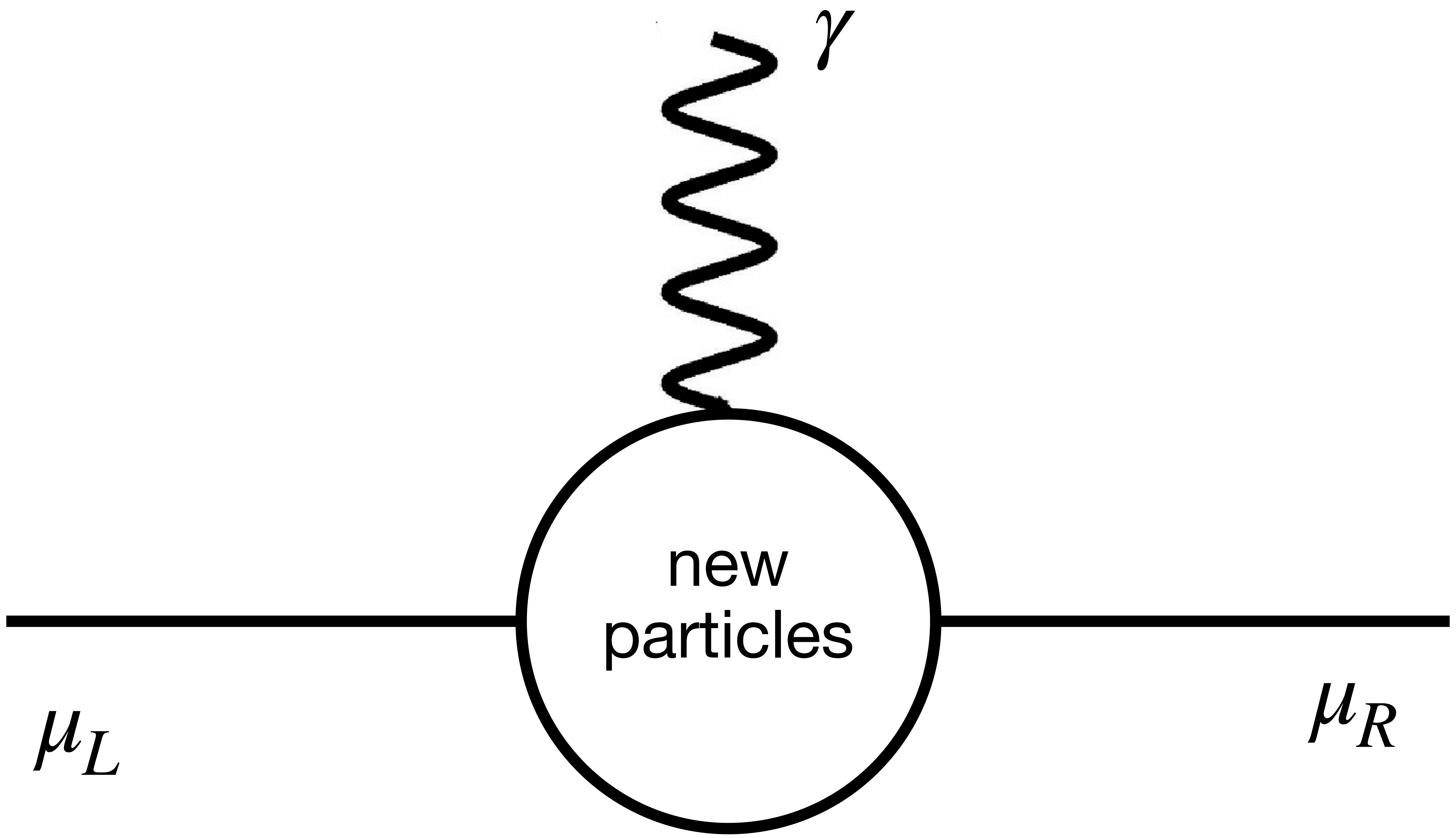
BSM physics talks to the muon!

→ Muon physics program from ~ GeV - 10 TeV will find new physics!

2006.16277, 2101.10334

BSM Physics in $(g-2)_\mu$

Very simple:



$\gtrsim O(10^3)$ papers over past decades

Could be almost anything, as long as it couples to muons

Could be connected to dark matter, SUSY, axions, …. any other new physics motivation…

This is such a general new physics contribution that it could be embedded within almost any BSM theory.

Ask a simpler question…

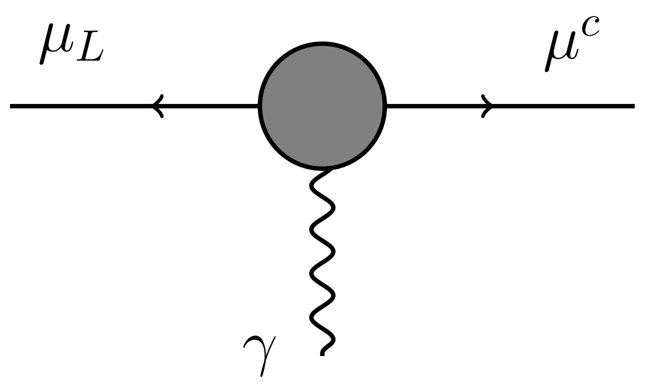
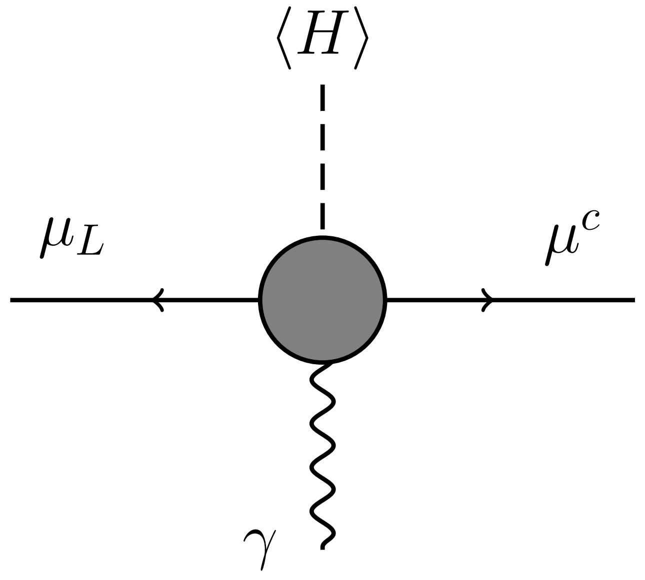
What would it take to *guarantee* we discover this new physics, *regardless* of the complete theory?

Model Exhaustive Approach

2006.16277, 2101.10334

Rodolfo Capdevilla, DC, Yonatan Kahn, Gordan Krnjaic

General BSM analysis of $(g-2)_\mu$

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

EFT analysis suggests $M \lesssim 250$ TeV…. Really?

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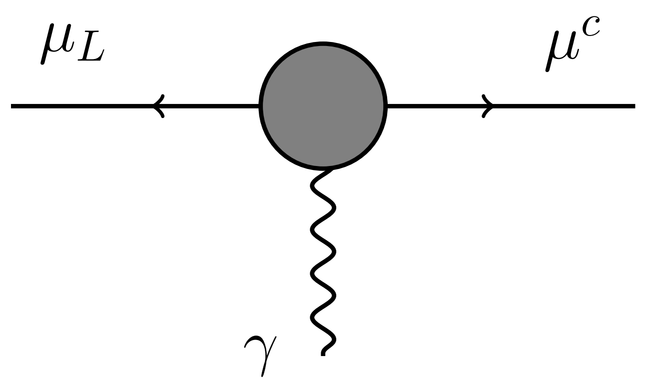
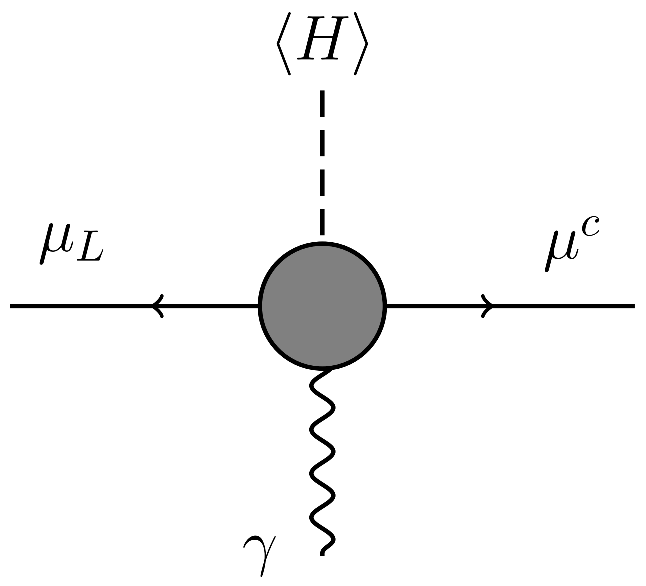
$(g-2)_\mu$ diagram		
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Model-Independent

We would love to discover this new physics DIRECTLY.

Where the new particles at??

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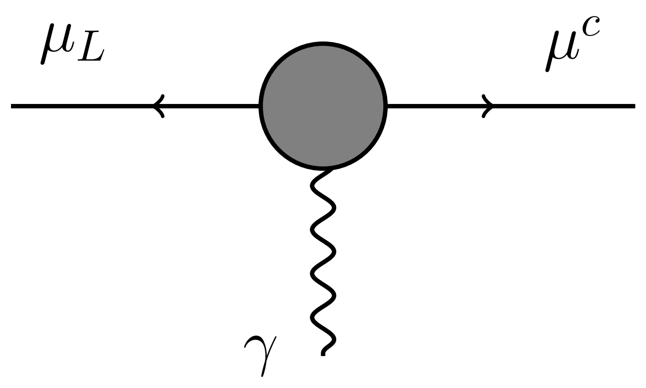
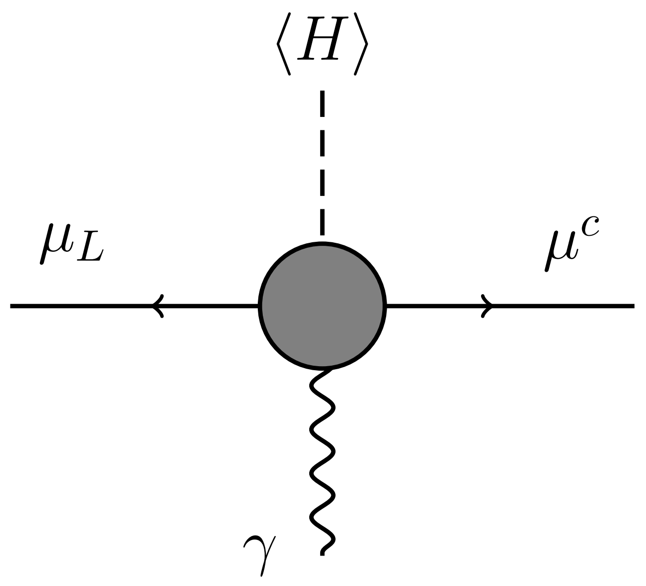
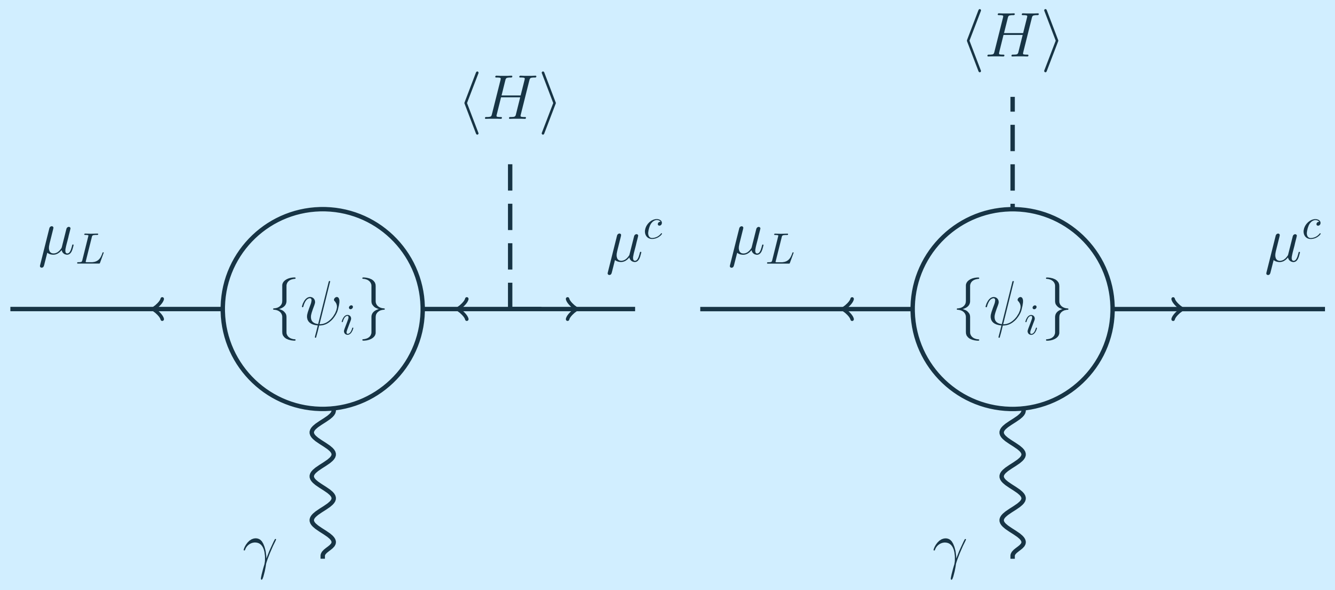
$(g-2)_\mu$ diagram			
How to predict new signatures	$\frac{1}{M}(\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$	$\frac{1}{M^2} H^\dagger (L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$	Specific choices of BSM particles and their SM quantum numbers in loop
	Model-Independent		"Model-Exhaustive"

If we assume perturbative unitarity, we can look inside the 4-point function!

Can we do this in full generality?

Model-Exhaustive Analysis

*pushing couplings right up to unitarity limit should capture parametrics of non-perturbative solutions, they still have to obey gauge invariance.

** higher loop contributions require lower BSM mass scales, should be discoverable with the experiments we consider

*** Spin 0, 1/2 and 1. Higher spin g-2 contributions highly suppressed, 2104.03231.

Assume new physics obeys perturbative unitarity.*

Assume new $(g-2)_\mu$ contribution arises at one-loop.**

Then consider:

- all possible $SU(2)_L \otimes U(1)_Y$ gauge representations for the new particles
- all possible Lorentz group representations*** for the new particles
- arbitrary multiplicity N_{BSM} of new particles
- all possible masses & couplings that generate Δa_μ^{exp}

Then ask: what are some irreducible experimental signatures?

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Divide BSM Theory Space into two classes

Singlet Scenarios:

new physics in $(g-2)_\mu$ is **SM singlets only**

simple theory space, more complicated phenomenology

Electroweak Scenarios:

everything else: i.e. new particles with non-trivial EW representations in loop

complicated theory space, simple phenomenology (new charged particles!)

Model Exhaustive Approach

Singlet Scenarios

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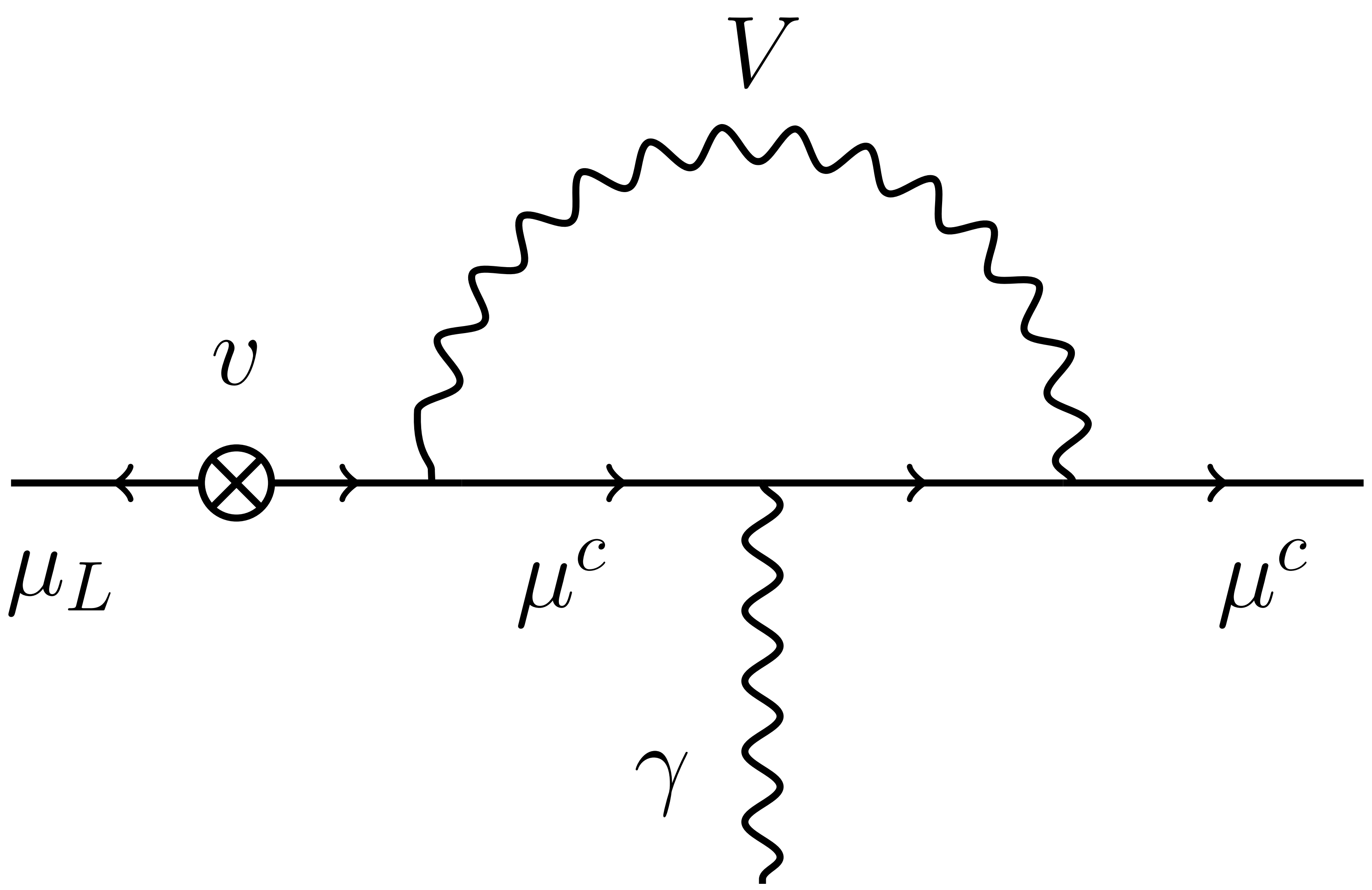
Singlet Scenarios

Vector

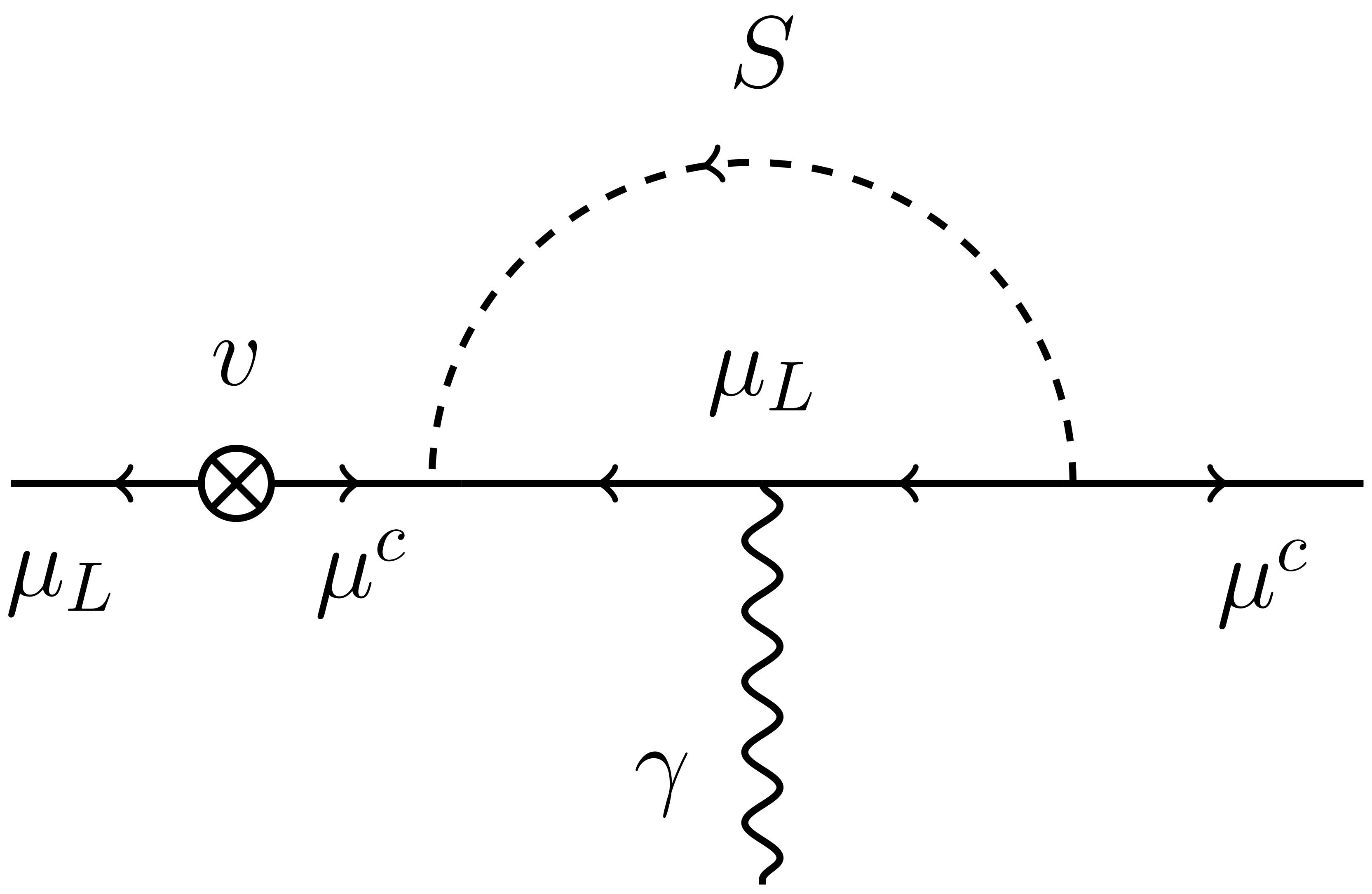
$$\mathcal{L}_{\rm V} \supset g_V V_\alpha(\mu_L^\dagger \bar{\sigma}^\alpha \mu_L + \mu^{c\,\dagger}\bar{\sigma}^\alpha \mu^c) + \frac{m_V^2}{2} V_\alpha V^\alpha$$



$$\Delta a_\mu^V / \Delta a_\mu \approx N_{\rm BSM} g_V^2 \left(\frac{200\ \rm GeV}{m_V}\right)^2$$

Scalar

$$\mathcal{L}_{\rm S} \supset -(g_S S \mu_L \mu^c + \text{h.c.}) - \frac{1}{2} m_S^2 S^2$$

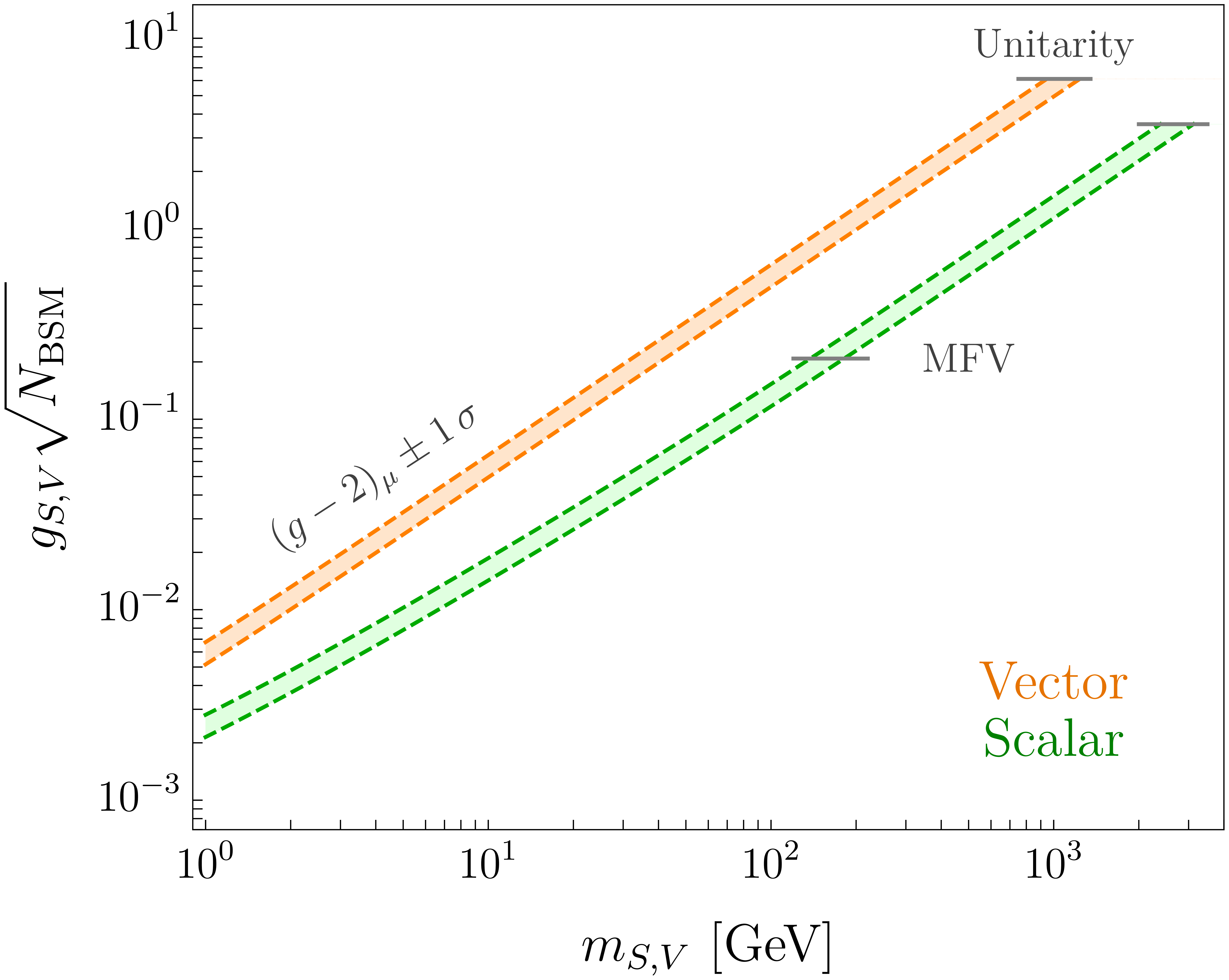


$$\Delta a_\mu^S / \Delta a_\mu \approx N_{\rm BSM} g_S^2 \left(\frac{700\ \rm GeV}{m_S}\right)^2$$

$(g-2)_\mu$ contributions from RHN-type singlet fermion is suppressed by m_ν and too small.

Interesting edge case: $aF_{\mu\nu}\tilde{F}_D^{\mu\nu}$ axion-dark-photon contribution (2104.03276), but is also discoverable.

Singlet Scenarios



Requires singlet below 3 TeV

couples to muon $g_S \propto m_S$

Model Exhaustive Approach

Electroweak Scenarios

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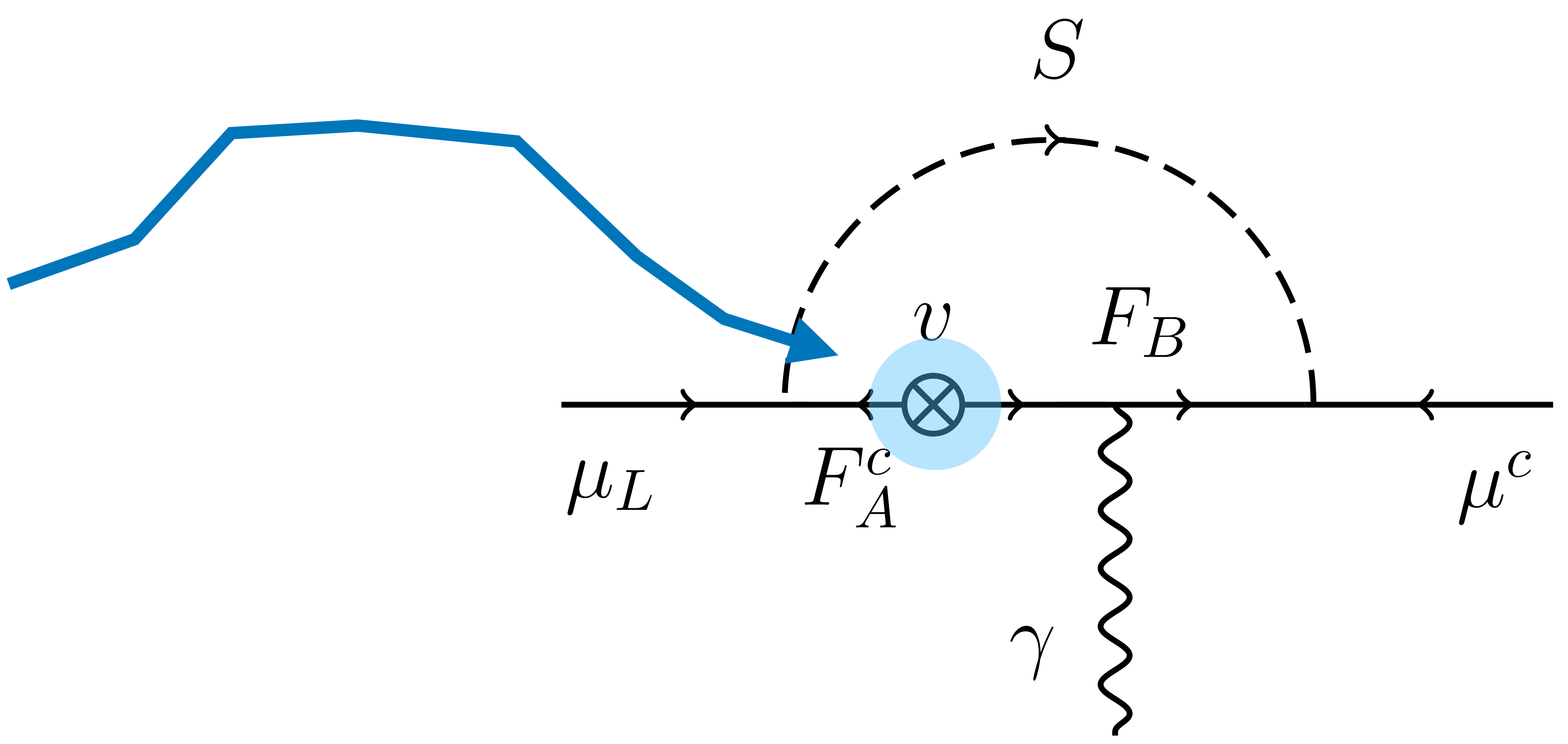
Electroweak Scenarios

In general a complicated model space: all non-singlet one-loop possibilities!

Can generate $(g-2)_\mu$ for much higher BSM masses due to **large Higgs vev / chirality flip**

$$\Delta a_\mu \propto \frac{m_\mu v g_{BSM}^3}{m_{BSM}^2}$$



But perhaps the experimental signatures are simpler: **new charged particles!**

New Charged Particles

Those are the "easiest to discover":

- guaranteed Drell-Yan Production
- have to leave some visible signal in your detector

Main question: how much collider energy $\sqrt{s}$ do I need to produce at least the **lightest** BSM charged state?

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Main question: how much collider energy $\sqrt{s}$ do I need to produce at least the **lightest** BSM charged state?

$$M^{\max}_{\mathrm{BSM,charged}} \equiv \max_{\substack{\mathrm{BSM\ \ theory\ \ space} \\ \Delta a_\mu = \Delta a_\mu^{\mathrm{obs}}}} \left\{ \min_{i \,\in\, \mathrm{BSM\ spectrum}} \left(m^{(i)}_{\mathrm{charged}} \right) \right\}$$

We can brute-force min-max across all the models' parameter space to find **the highest possible mass the lightest BSM charged state can have to be consistent with g-2.**

Electroweak Simplified Models

Model-exhaustive analyses are not a new idea, but this theory space maximization to find the largest possible BSM charged mass is non-trivial.

We will define some **simplified models** which are engineered to produce **the heaviest possible BSM charged masses** while explaining (g-2)!

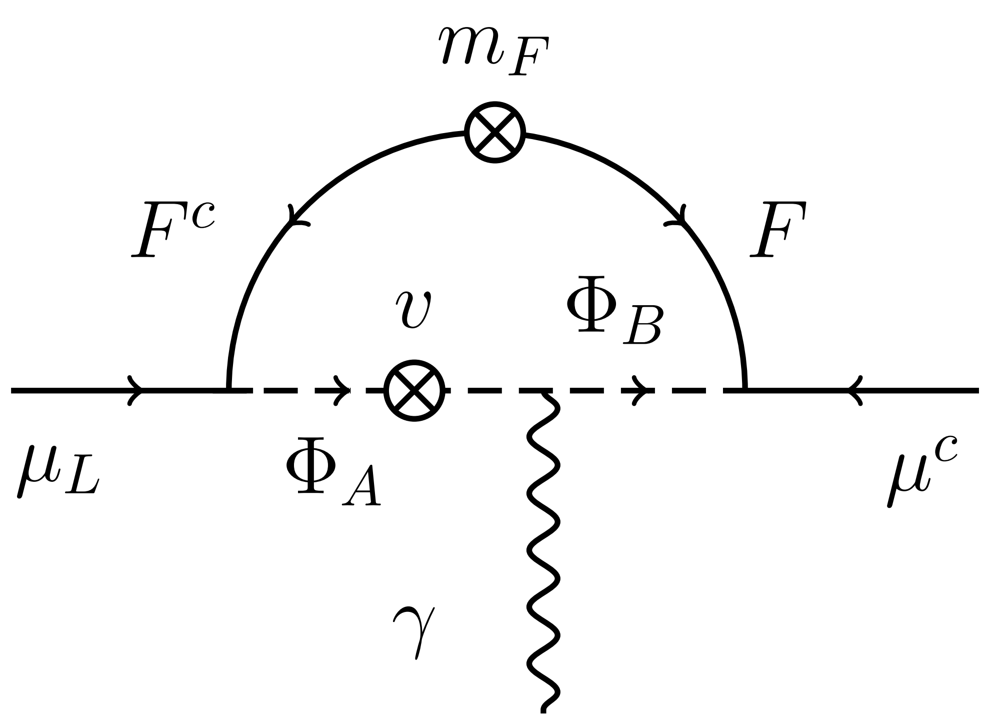
Maximizing over the space of those simplified models will give us our answer!

Engineering specs:

- need BSM (i.e. large) **chiral flip insertion**
- need BSM (i.e. large) **Higgs vev insertion**
- **need three new fields** (boson, fermion, and two of something)
- **no new sources of EWSB** (those have their own lower-mass signatures)

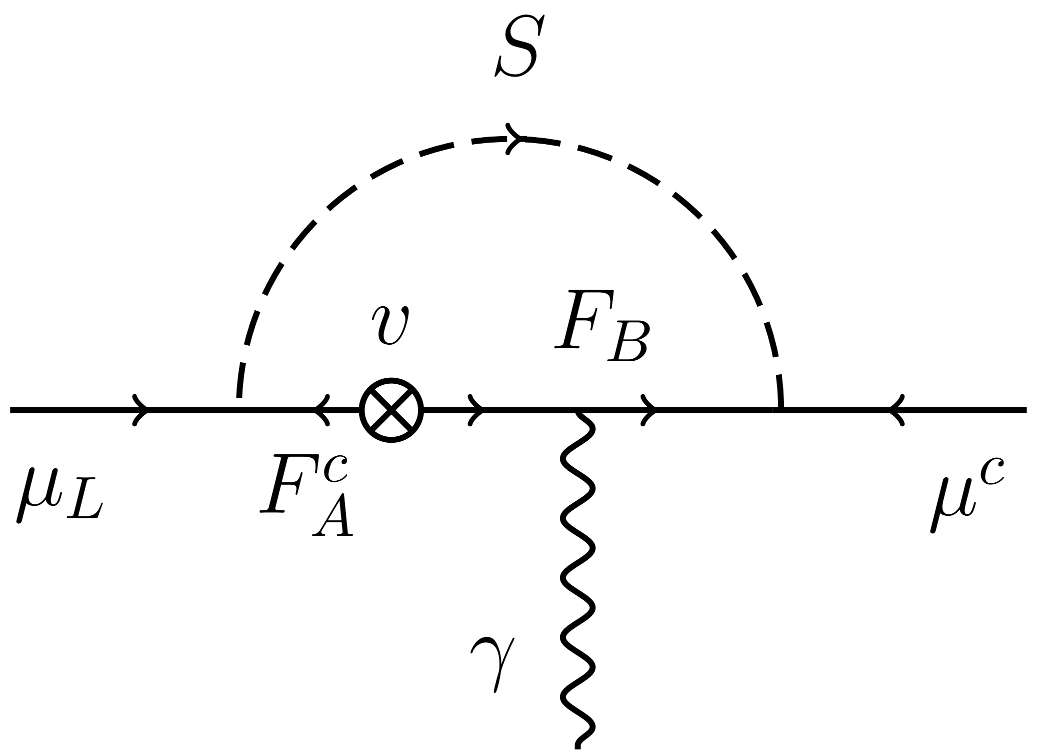
Electroweak Simplified Models

SSF



$$\mathcal{L}_{\rm SSF} \supset -y_1 F^c L_{(\mu)} \Phi_A^* - y_2 F \mu^c \Phi_B - \kappa H \Phi_A^* \Phi_B$$
$$-m_A^2 |\Phi_A|^2 - m_B^2 |\Phi_B|^2 - m_F F F^c + \text{h.c.}$$

FFS



$$\mathcal{L}_{\rm FFS} \supset -y_1 F_A^c L_{(\mu)} \Phi^* - y_2 F_B \mu^c \Phi - y_{12} H F_A^c F_B - y_{12}' H^\dagger F_A F_B^c$$
$$-m_A F_A F_A^c - m_B F_B F_B^c - m_S^2 |\Phi|^2 + \text{h.c.}$$

New complex scalars and vector-like fermions that acquire some mixing after EWSB.

Consider all possible choices of $SU(2)_L \otimes U(1)_Y$ representations $R \leq \mathbf{3}, Q \leq 2$.

Arbitrary number of BSM degrees of freedom (copies) N_{BSM}.

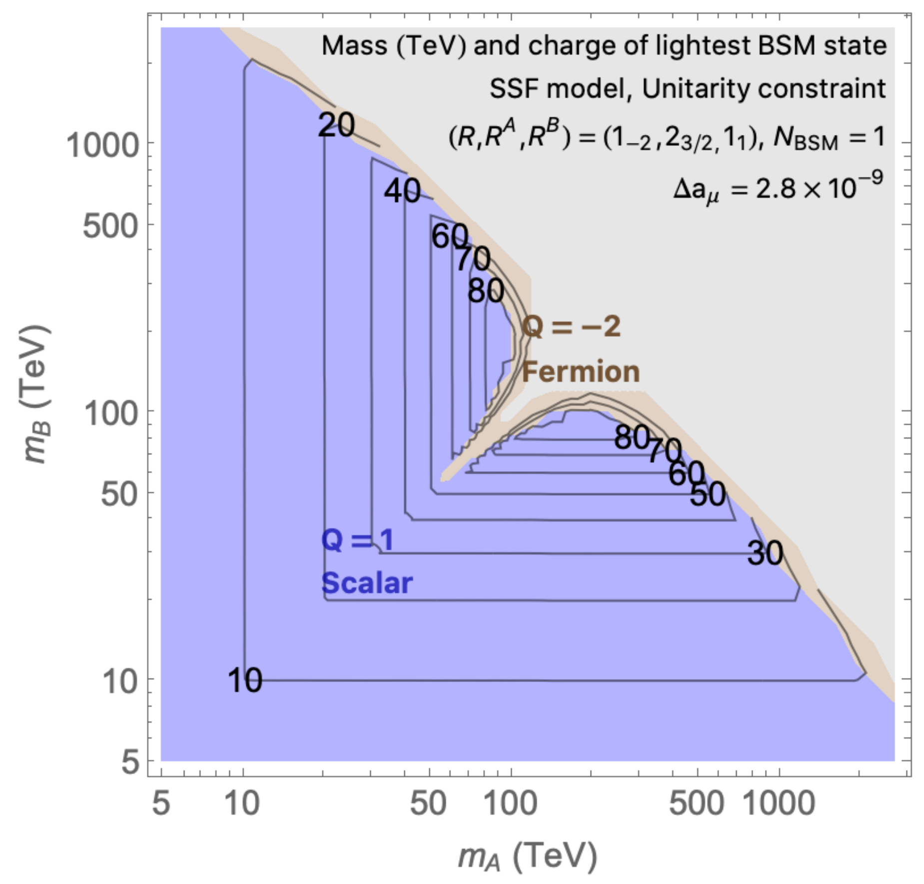
We have checked that other simplified models with fewer BSM fields, or involving Majorana fermions, new vectors, etc give smaller Δa_μ → lower masses for new charged states → do not affect theory space maximization

What's the result?

$$M^{\rm max}_{\rm BSM,charged} \equiv \max_{\substack{\text{BSM theory space} \\ \Delta a_\mu = \Delta a_\mu^{\rm obs}}} \left\{ \min_{i \in \text{BSM spectrum}} \left(m^{(i)}_{\rm charged} \right) \right\}$$

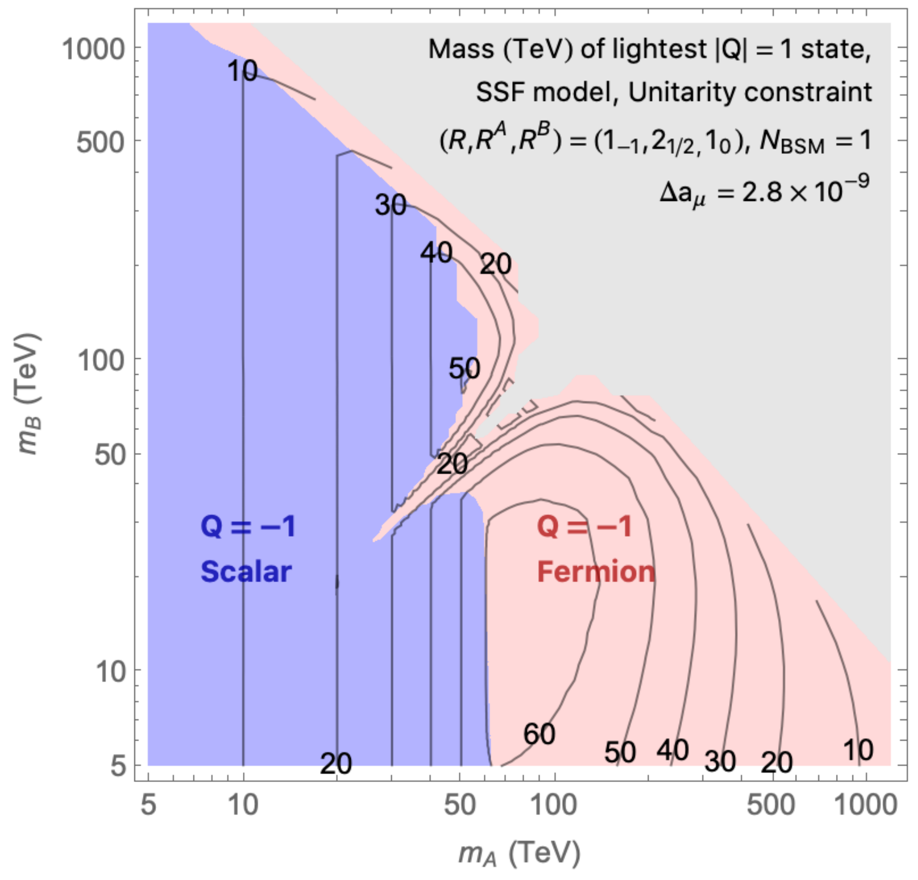
Example of parameter space plot for two EW models, showing lightest BSM charged particle mass with unitarity constraints only

SSF, all BSM fields charged



$M^{\rm max,unitarity}_{\rm BSM,charged} = 86$ TeV

SSF, charged and neutral fields



$M^{\rm max,unitarity}_{\rm BSM,charged} = 65$ TeV

EW Model Results

$$M_{\mathrm{BSM,charged}}^{\mathrm{max,X}} \approx \left(\frac{2.8\times 10^{-9}}{\Delta a_\mu^{\mathrm{obs}}}\right)^{\frac{1}{2}} \times \begin{cases} (100\,\mathrm{TeV})\ N_{\mathrm{BSM}}^{1/2} & \text{for} \quad X = (\text{unitarity*}), \\ (20\,\mathrm{TeV})\ N_{\mathrm{BSM}}^{1/2} & \text{for} \quad X = (\text{unitarity+MFV}), \\ (20\,\mathrm{TeV})\ N_{\mathrm{BSM}}^{1/6} & \text{for} \quad X = (\text{unitarity+naturalness*}), \\ (9\,\mathrm{TeV})\ N_{\mathrm{BSM}}^{1/6} & \text{for} \quad X = (\text{unitarity+naturalness+MFV}). \end{cases}$$

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Imposing only unitarity constraints on all couplings.

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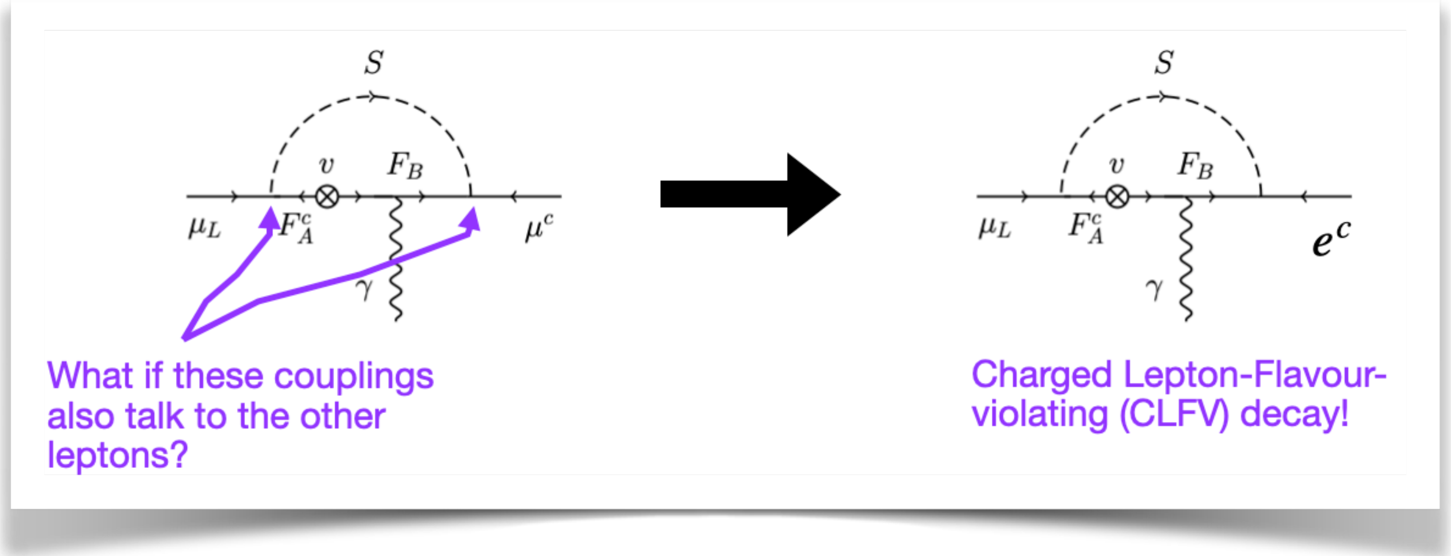

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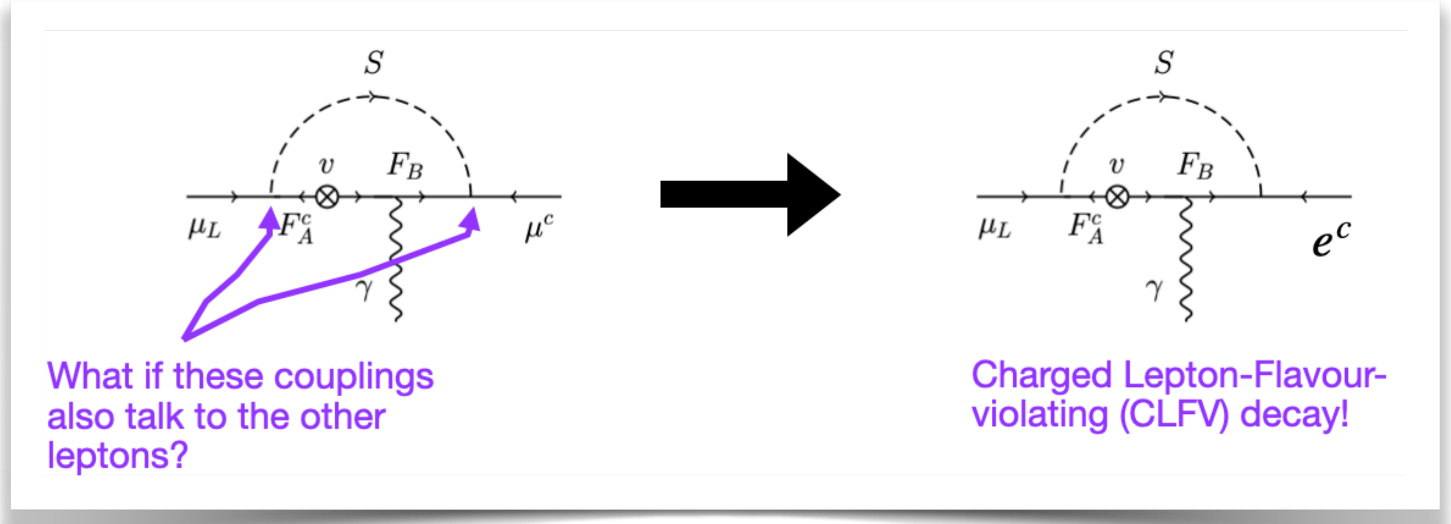
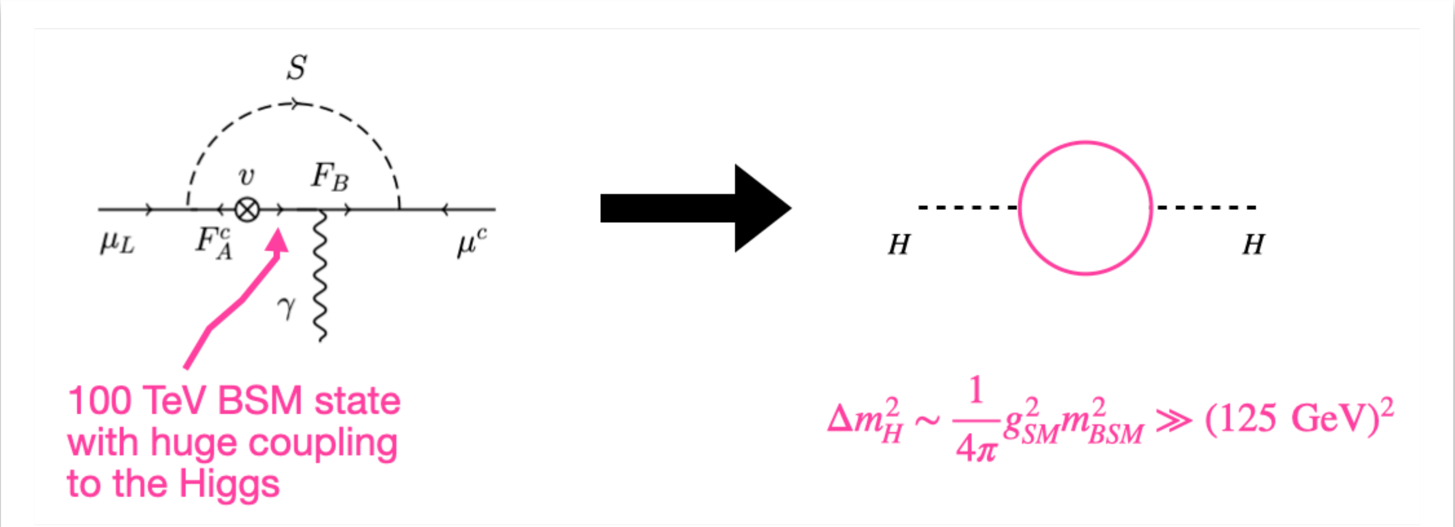


Imposing $\Delta < 100$ Naturalness constraint, since BSM particles generate **calculable and large** corrections to Higgs & μ mass.



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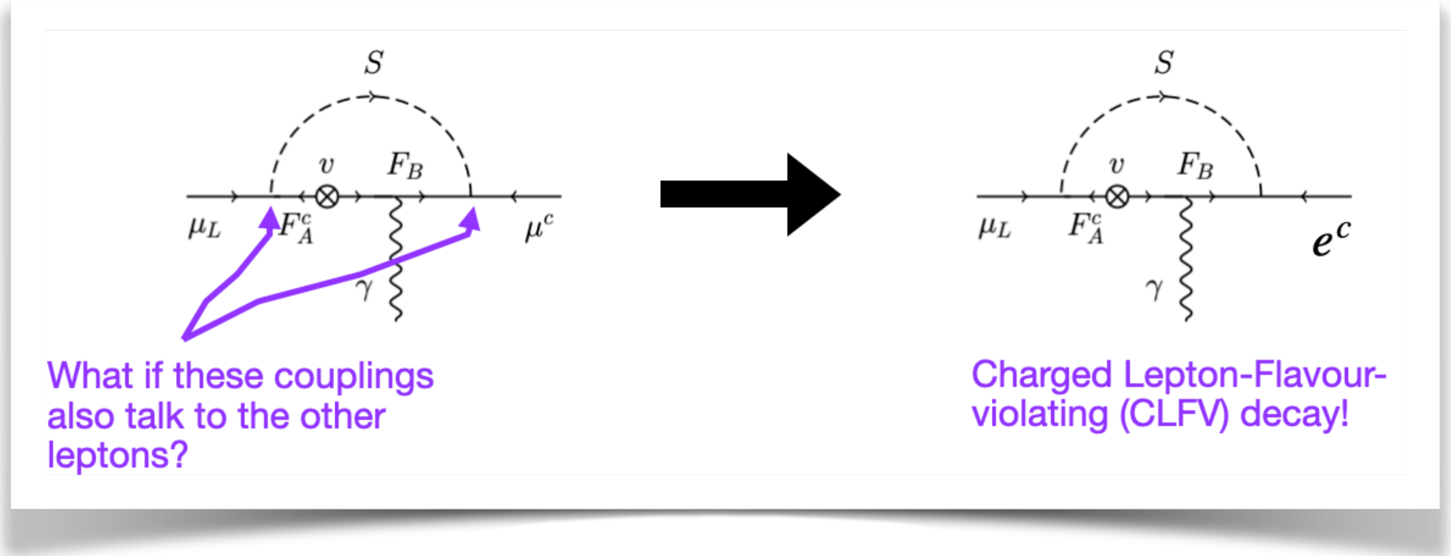

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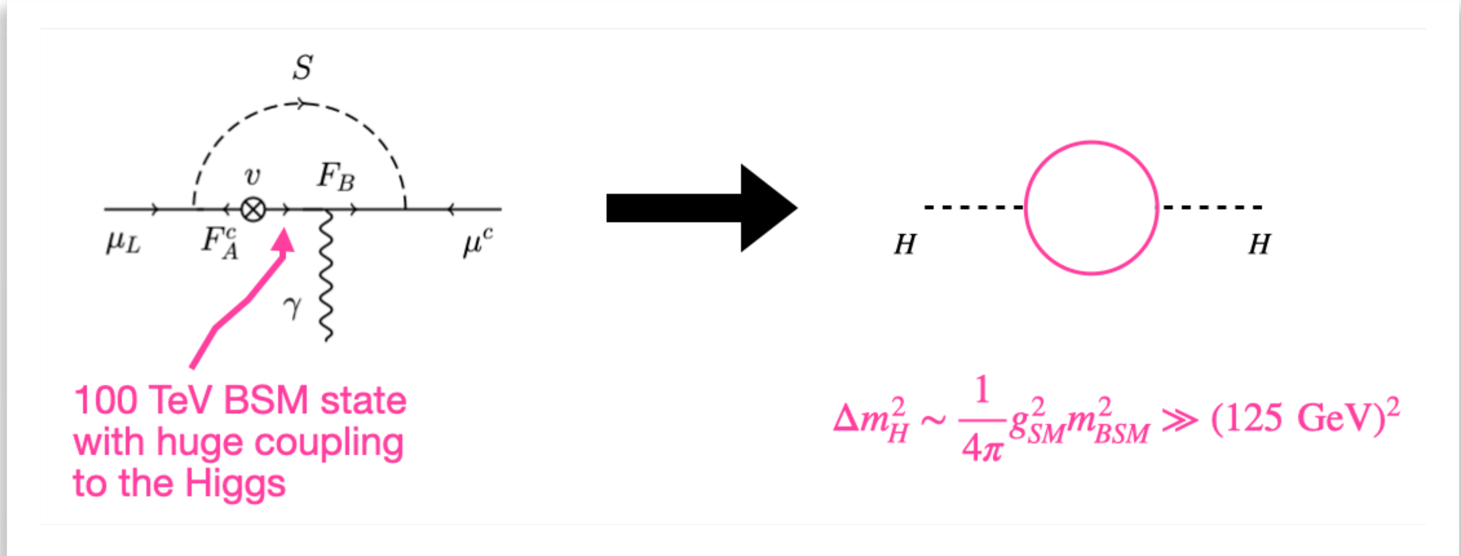

MFV + naturalness: the most "reasonable" upper bound!

Experimental Target for discovering BSM

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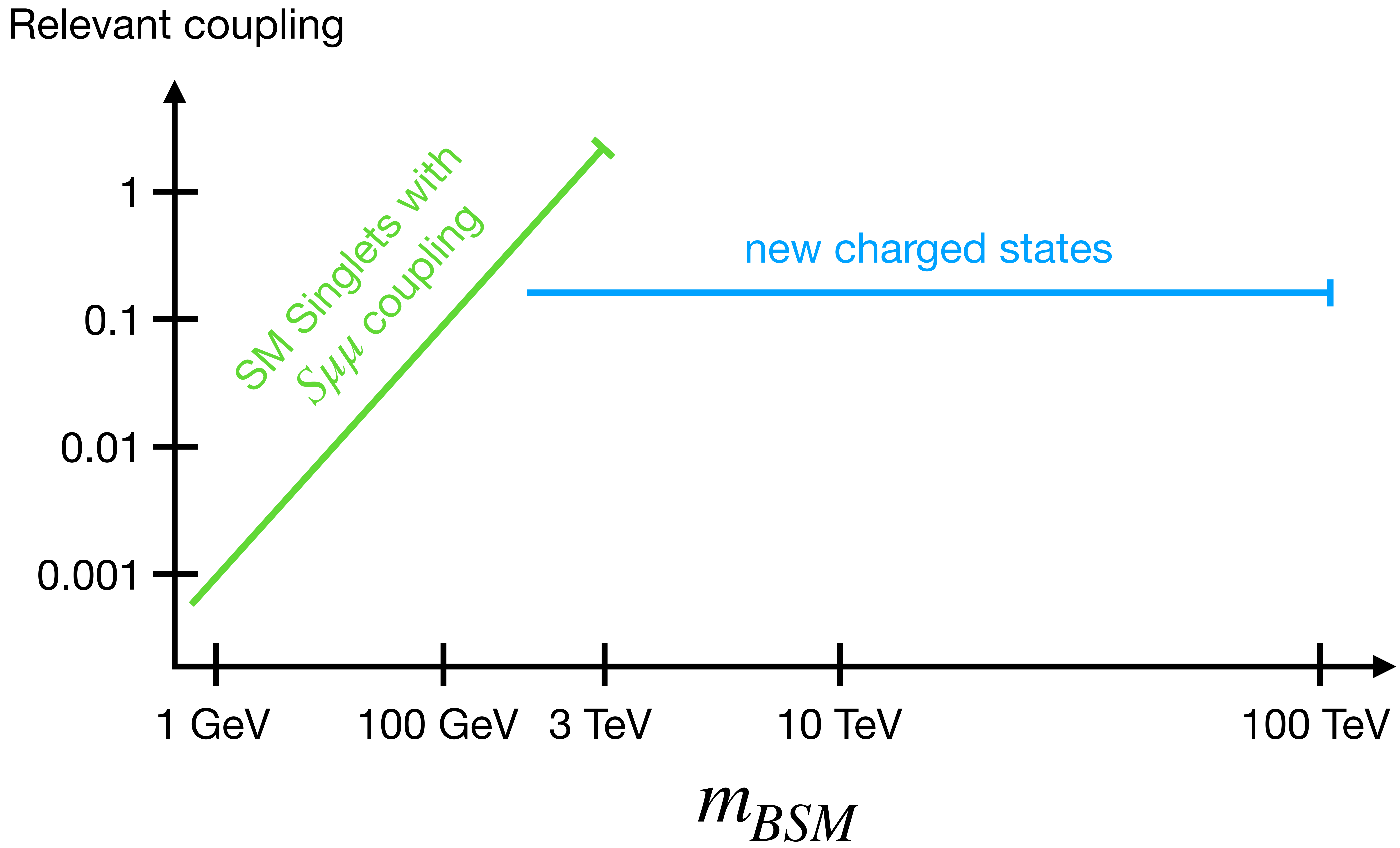
Irreducible Signatures of $(g-2)_\mu$ Solutions



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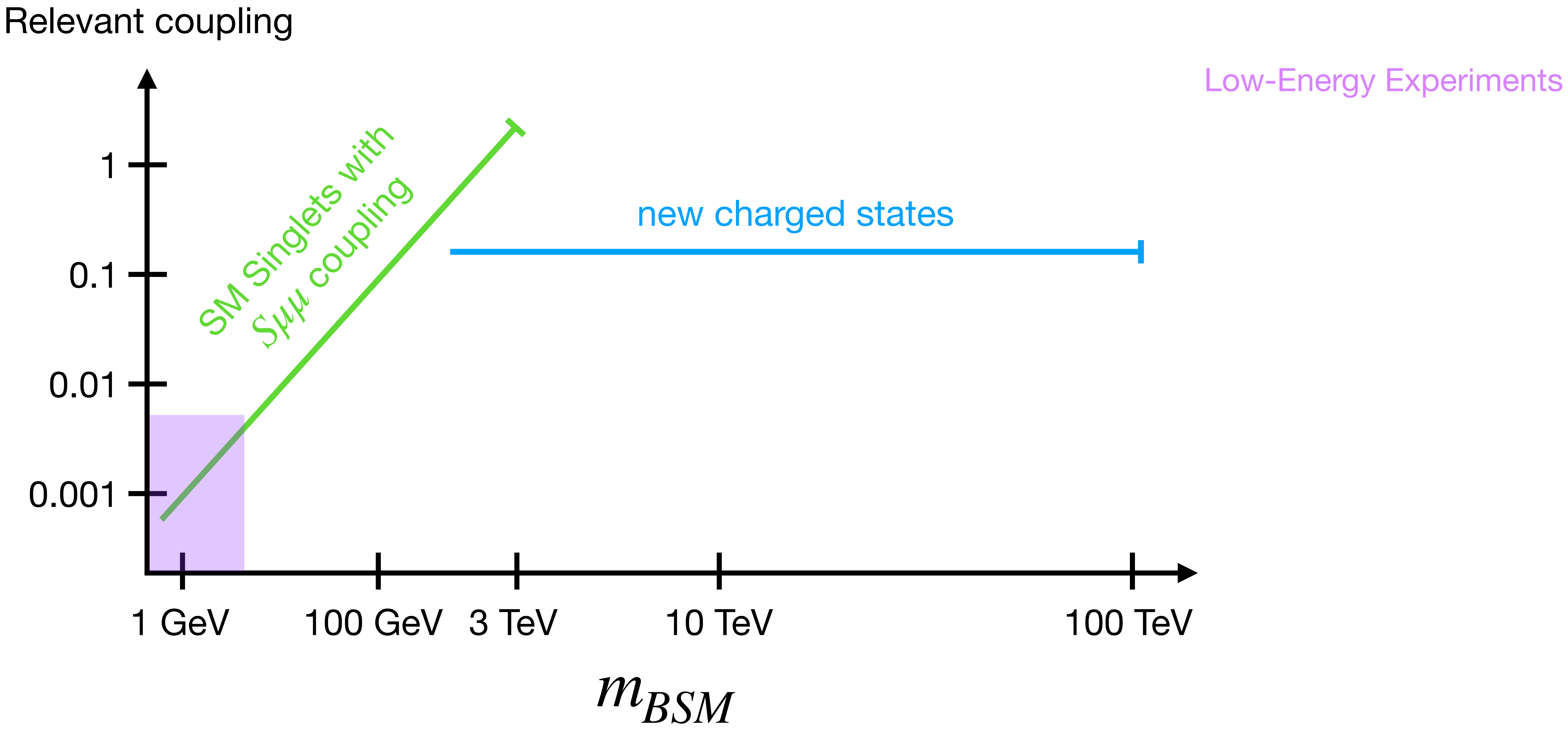

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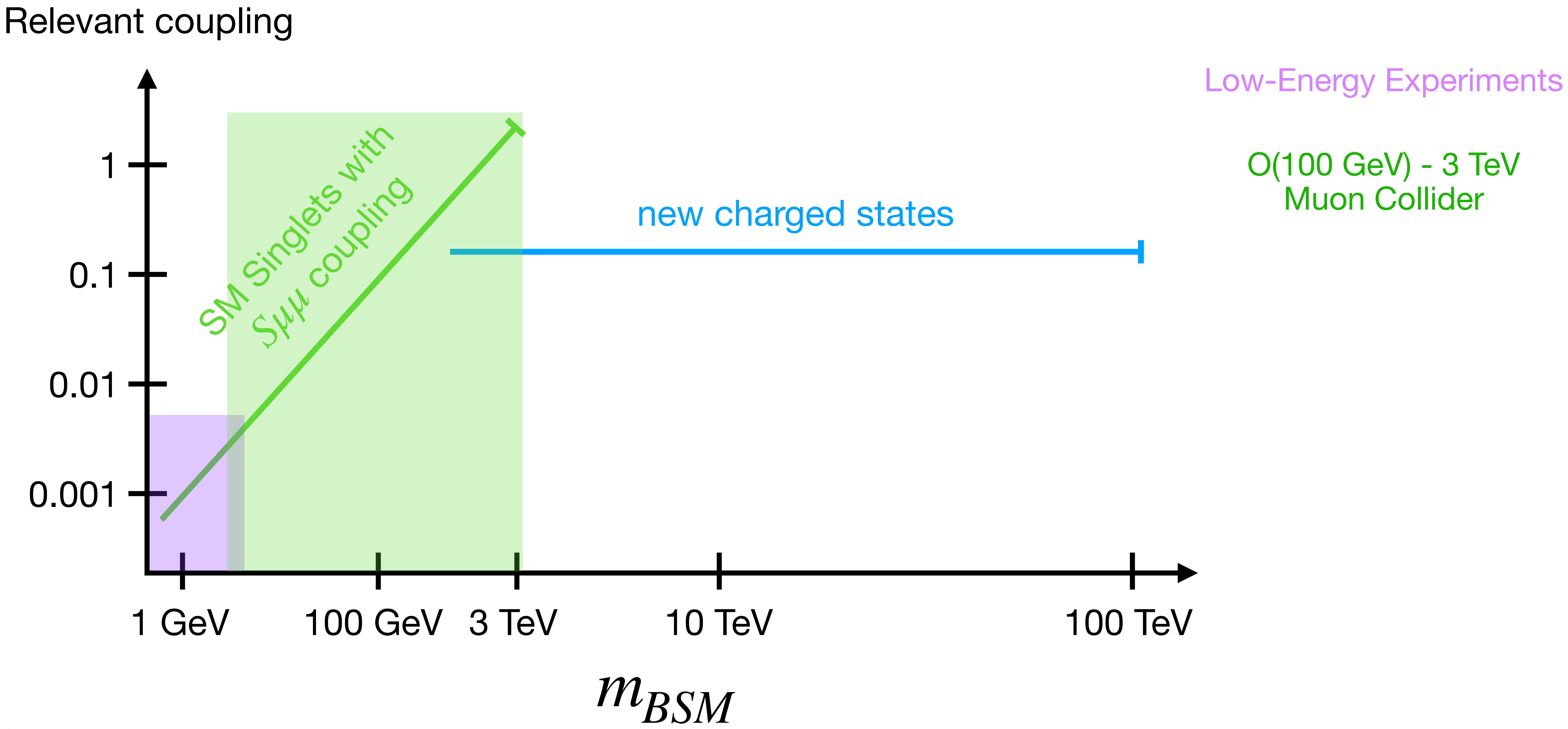

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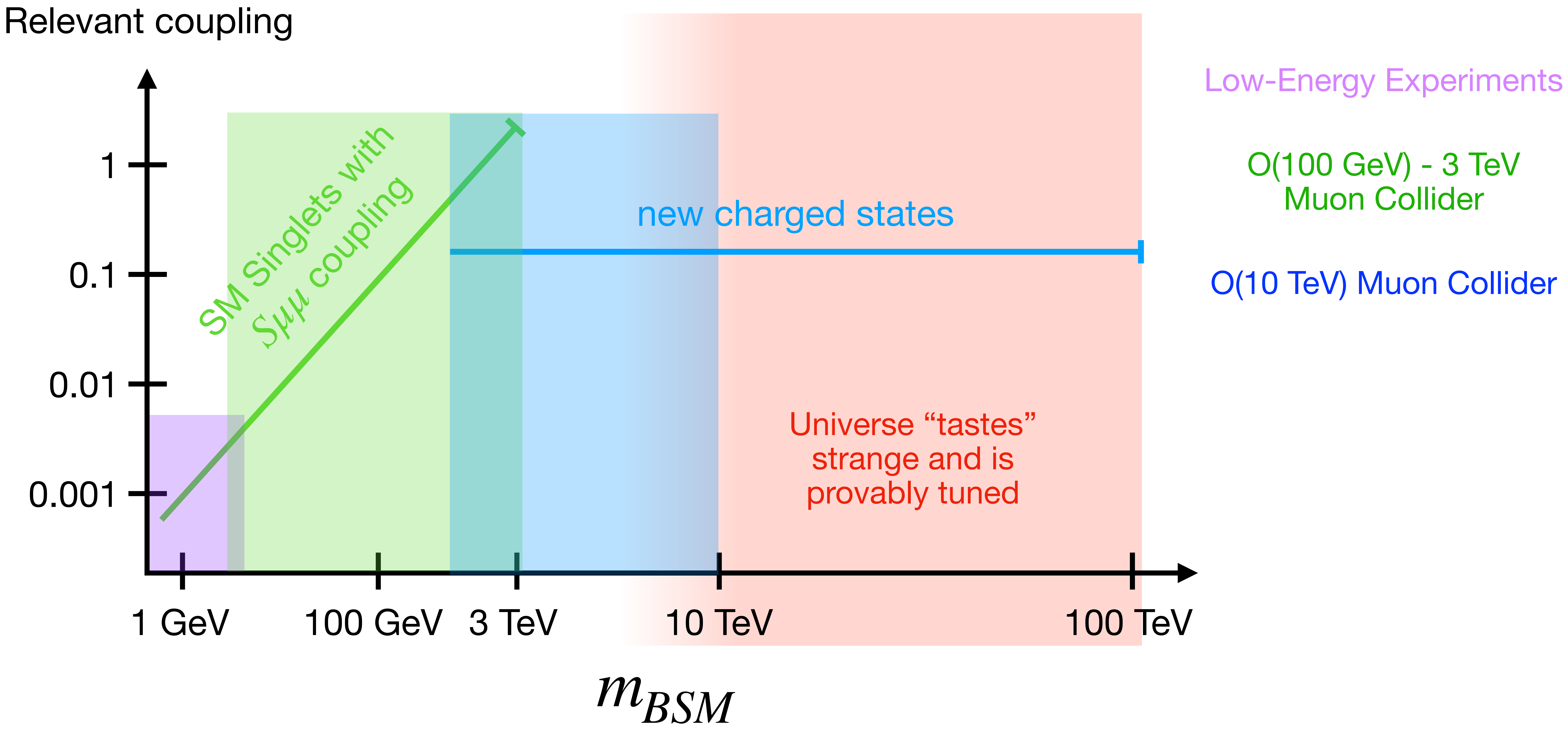

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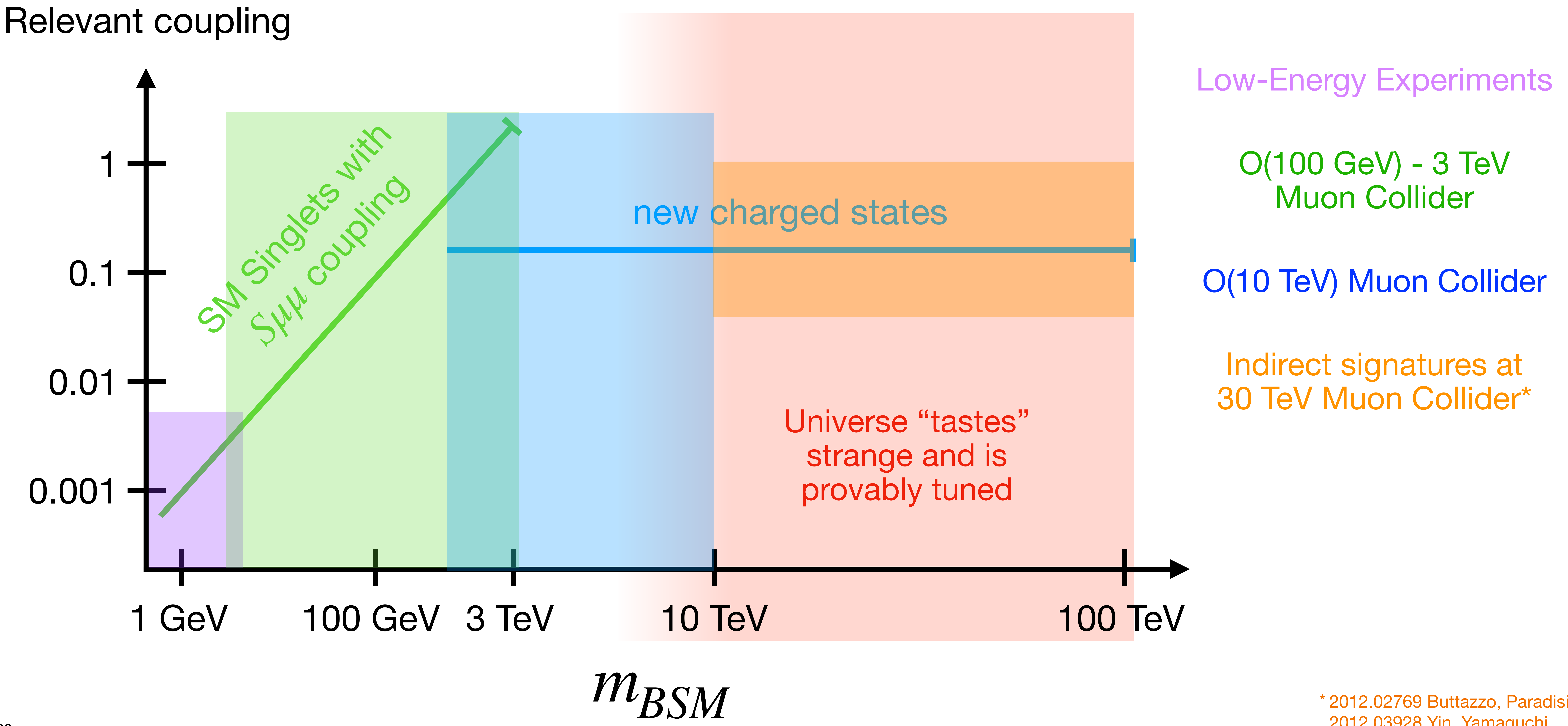


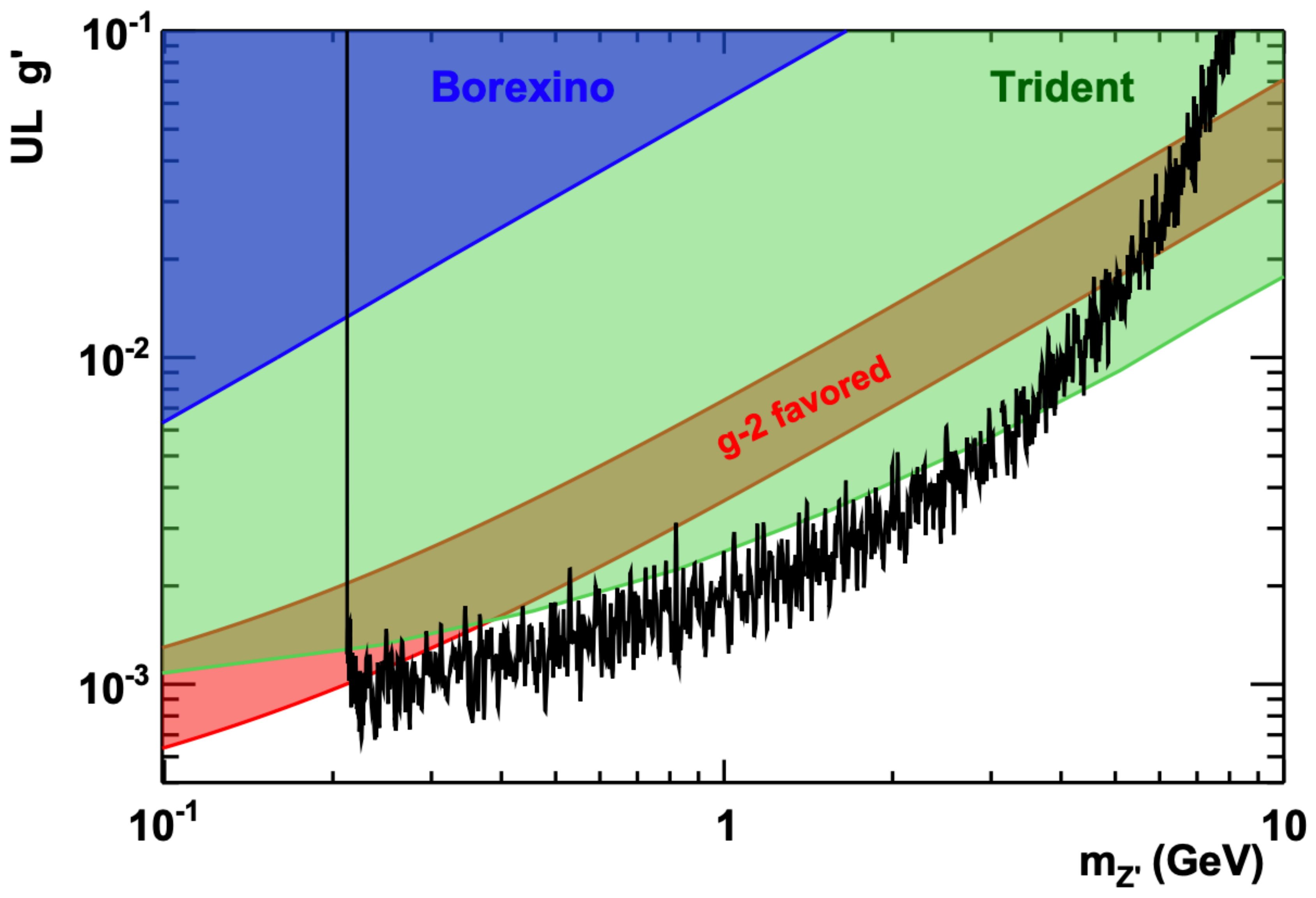
* 2012.02769 Buttazzo, Paradisi
2012.03928 Yin, Yamaguchi

Low Energy Experiments

Intensity Frontier Experiments

A lot of Singlet Scenario parameter space is already excluded below a few GeV.

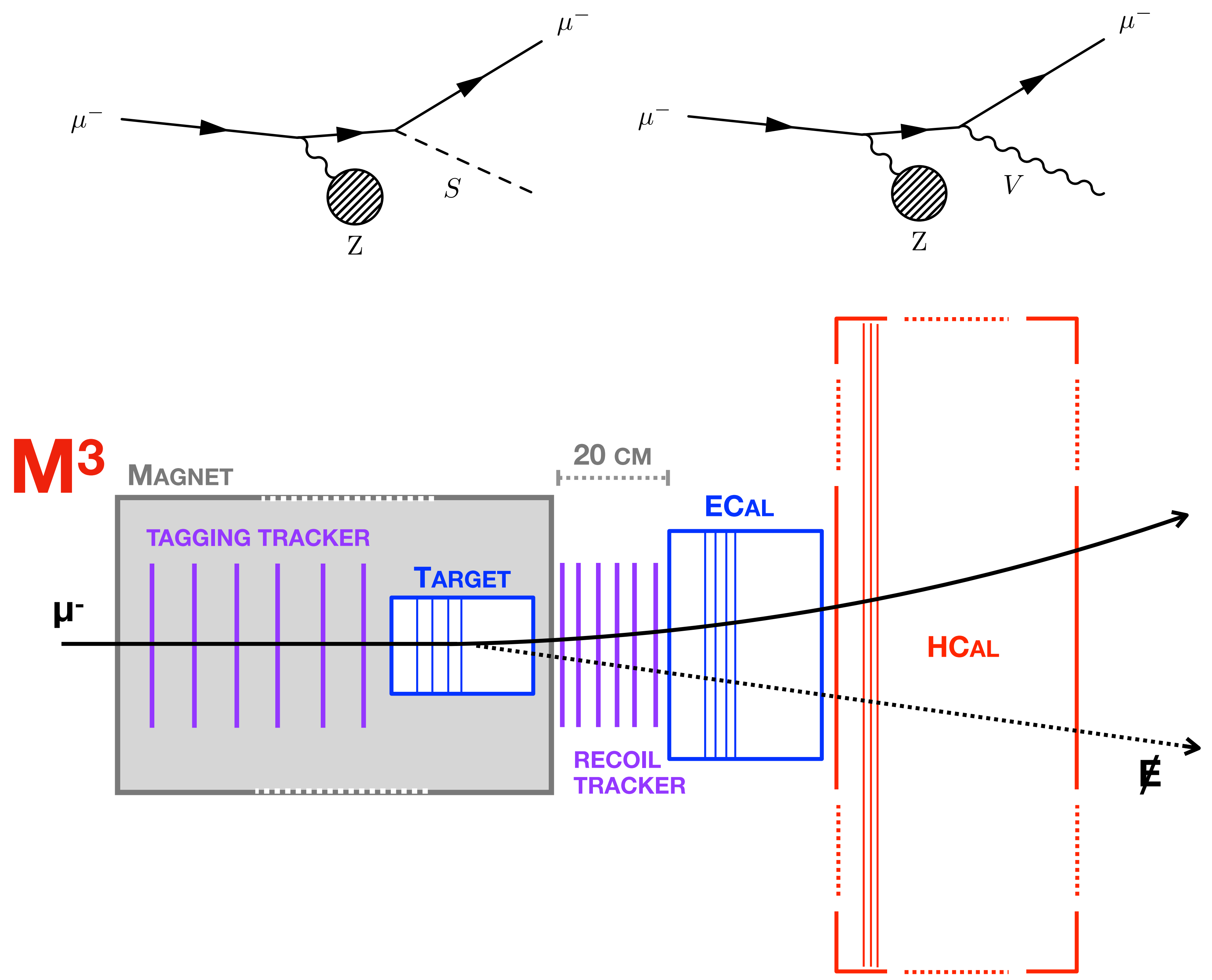
BaBar Collaboration 1606.03501



See also e.g.:
Mohlabeng 1809.07768
Dark Sector Community Report 1707.04591
SHiP physics case 1504.04855
Krnjaic 1512.04119
Batell, Freitas, Ismail, McKeen 1712.10022
Chen, Pospelov, Zhong, 1701.07437
Bauer, Foldenauer, Jaeckel, 1803.05466

Remaining space can be fully covered by **Muon Fixed Target experiments:**

M^3 proposal at Fermilab / NA64μ at CERN



S.N. Gninenko, N.V. Krasnikov, M.M. Kirsanov, D.V. Kirpichnikov 1604.08432
Kahn, Krnjaic, Tran, Whitbeck, 1804.03144

A muon fixed-target experiment would allow *fully inclusive* coverage for $\lesssim \mathrm{GeV}$ solutions of the $(g-2)_\mu$ anomaly.

Very important near-term experimental opportunity!

Muon Colliders

Muon colliders an incredibly attractive path to explore high energy physics.

Muon Colliders 1901.06150

The Muon Collider Working Group
Jean Pierre Delahaye[1], Marcella Diemoz[2], Ken Long[3], Bruno Mansoulié[4], Nadia Pastrone[5] (chair), Lenny Rivkin[6], Daniel Schulte[1], Alexander Skrinsky[7], Andrea Wulzer[1,8]

The Muon Smasher's Guide 2103.14043

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dario Buttazzo[3], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid Ekhterachian[5], JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9], Seth Koren[10], Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Alberto Mariotti[13], Amara McCune[1], Patrick Meade[7], Isobel Ojalvo[14], Umut Oktem[1], Diego Redigolo[15,16], Matthew Reece[9], Filippo Sala[17], Raman Sundrum[5], Dave Sutherland[18], Andrea Tesi[16,19], Timothy Trott[1], Chris Tully[14], Lian-Tao Wang[10], and Menghang Wang[1]

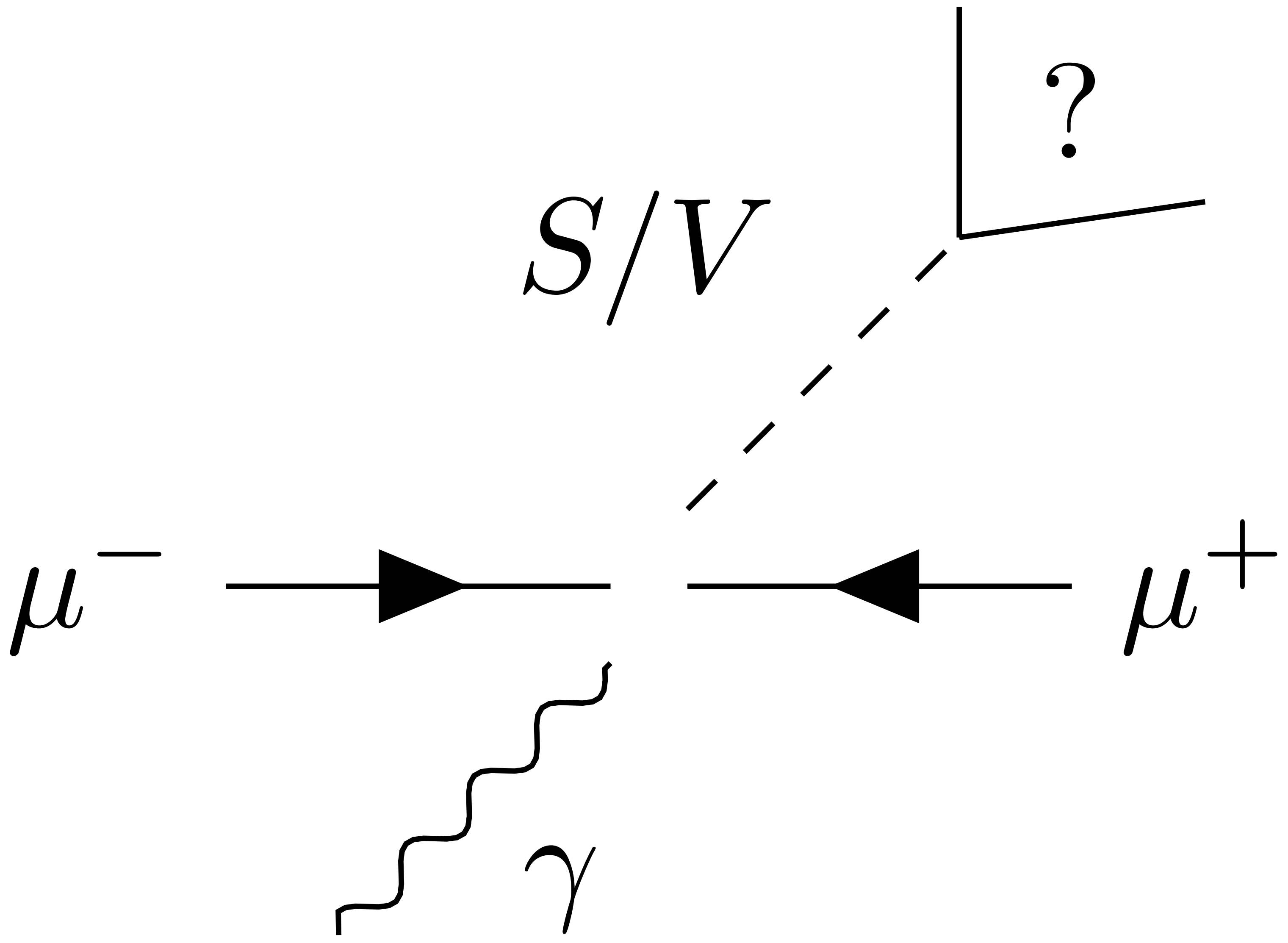
2005.10289 Constantini, De Lillo, Maltoni, Mantani, Mattelaer, Ruiz, Zhao

Bonus:

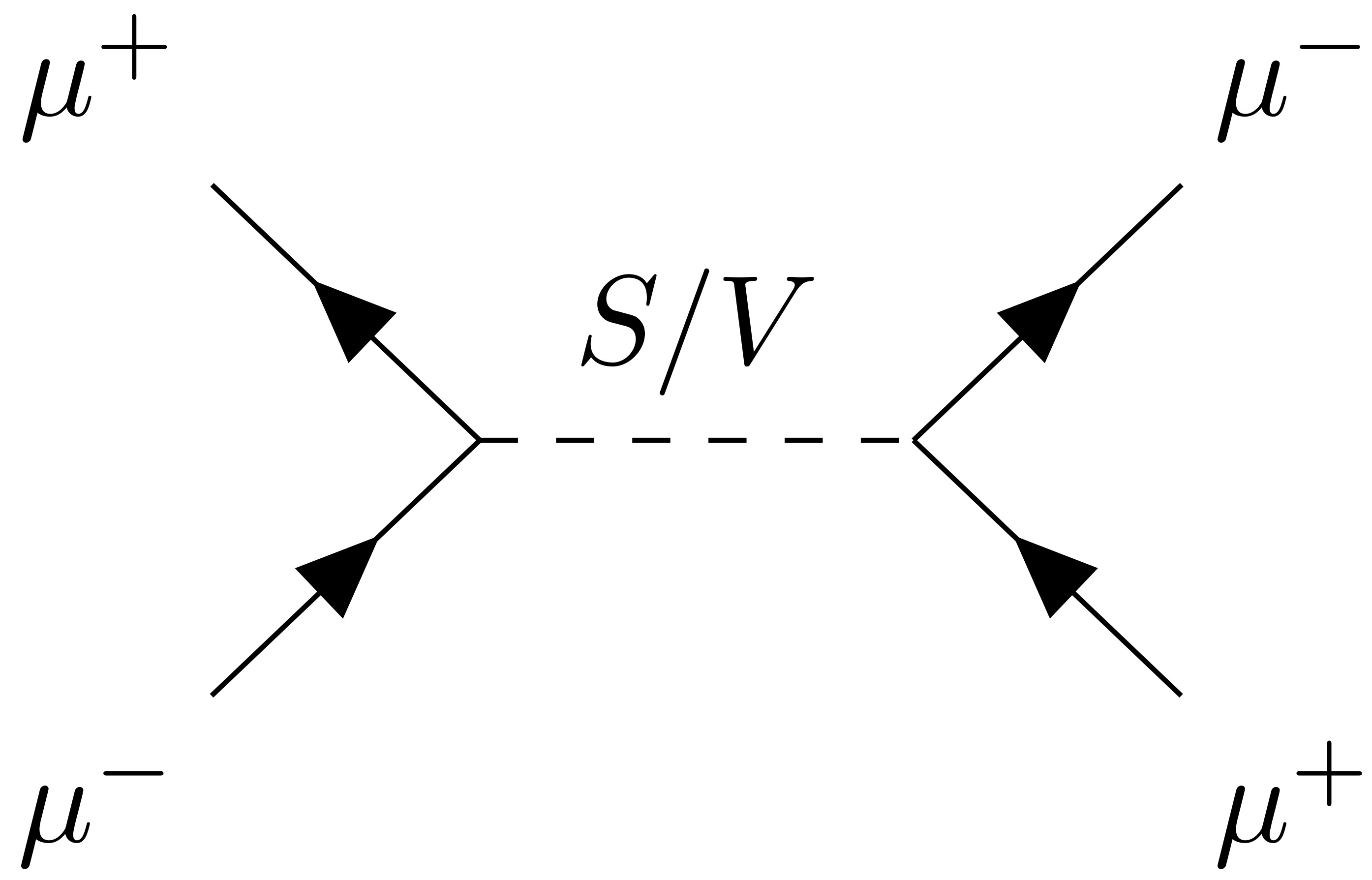
They are also "guaranteed" to discover the new physics of $(g-2)_\mu$

$\sqrt{s}$ ~ 200 GeV - 3 TeV: Discovering Singlet Scenarios

Discovering the singlet production in fully inclusive search:
mono-photon + anything



Indirect observation: corrections to
Bhabha scattering

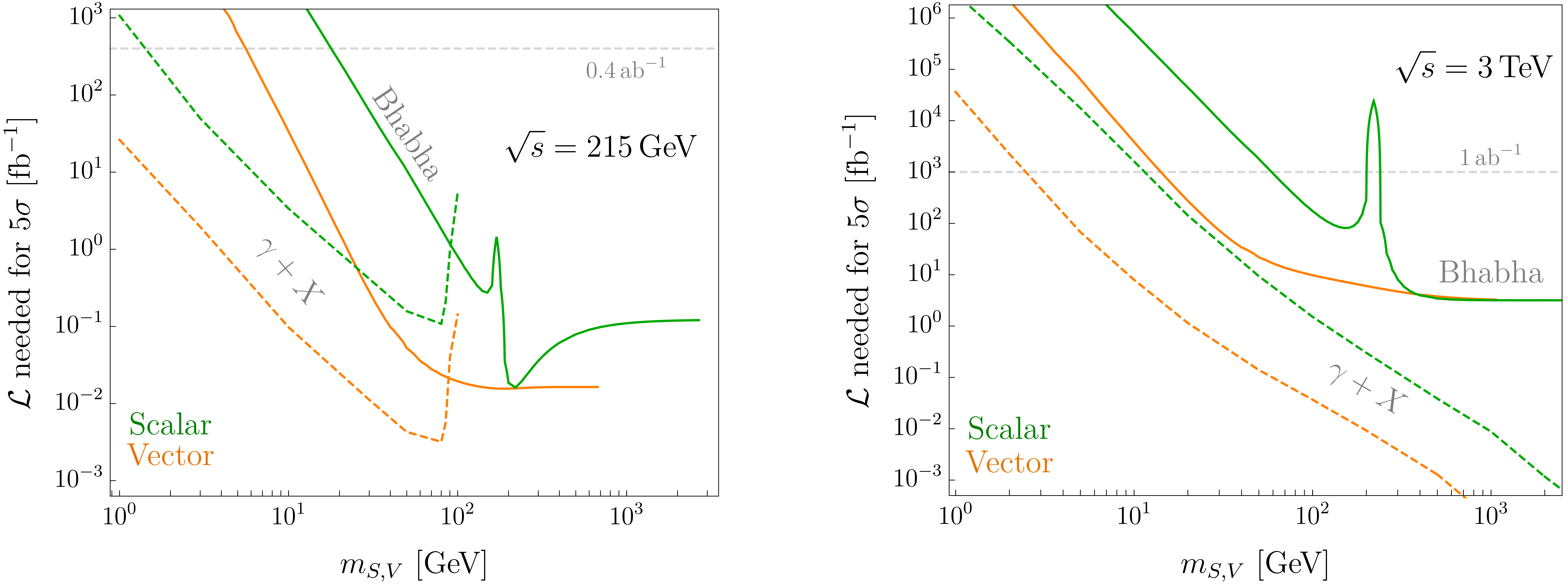


Only *guaranteed* coupling of singlet is to muons: Muon Collider is special!

2006.16277, 2101.10334 Rodolfo Capdevilla, DC, Yonatan Kahn, Gordan Krnjaic

$\sqrt{s}$ ~ 200 GeV - 3 TeV: Discovering Singlet Scenarios

Collider study including conservative detector effects shows lumi needed for discovery



2006.16277, 2101.10334 Rodolfo Capdevilla, DC, Yonatan Kahn, Gordan Krnjaic

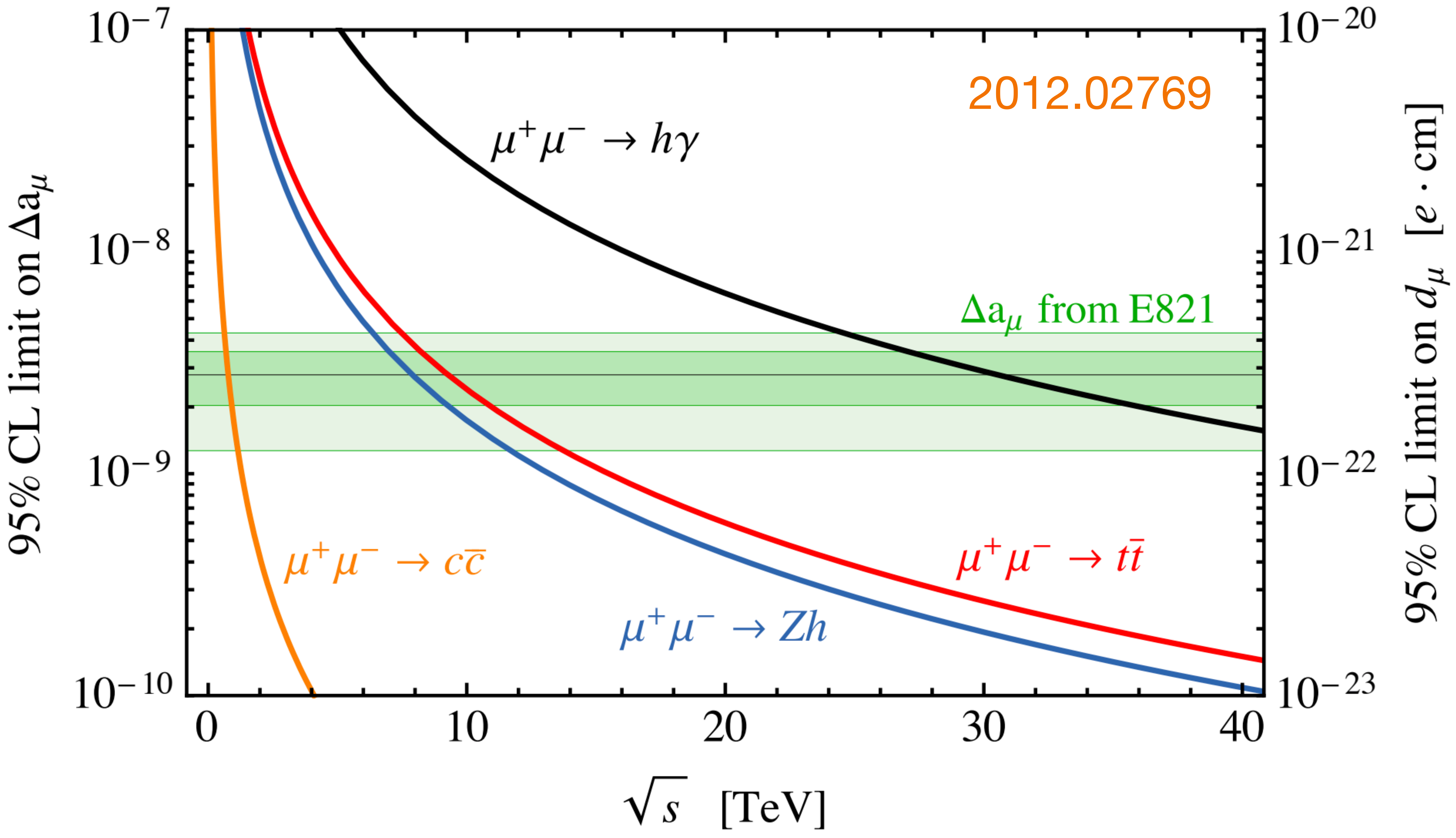
A **TeV-scale muon collider** program would discover all **Singlet solutions** to the $(g-2)_\mu$ anomaly.

A **30 TeV muon** collider will discover all “reasonable” **EW Scenarios** that account for the $(g-2)_\mu$ anomaly.

But what if you don’t see anything?

$\sqrt{s} \sim 10$ TeV: Indirect $h\gamma$ Signal

2012.02769 Buttazzo, Paradisi
2012.03928 Yin, Yamaguchi



If the new physics is heavier than 15 TeV, a 30 TeV muon collider could still see the

$$\mu\mu \to h\gamma$$

signal produced by the same operator

$$\frac{1}{M^2} H^\dagger (L\sigma^{\nu\rho}\mu^c) F_{\nu\rho}$$

A 30 TeV muon collider will see either new charged states, and/or the indirect $\mu\mu \to h\gamma$ signal!

Therefore, if you don't see new charged states, you **know** the states are there but at higher masses.

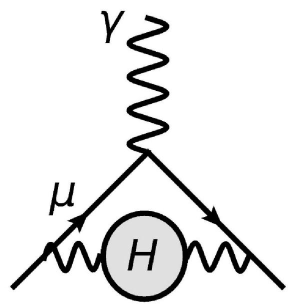
$\to$ Proof of a very weird and tuned universe!

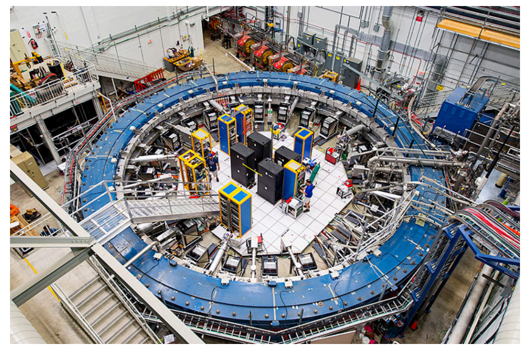
A no-lose theorem for $(g-2)_\mu$

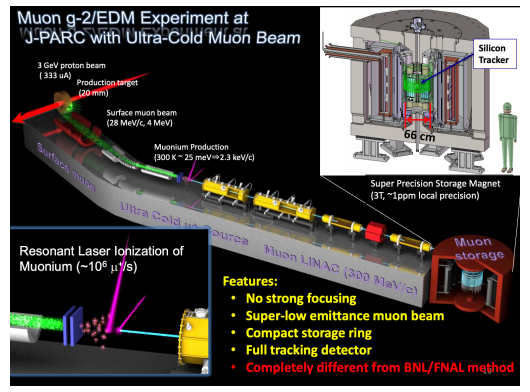
2006.16277, 2101.10334

Rodolfo Capdevilla, DC, Yonatan Kahn, Gordan Krnjaic

No-Lose Theorem for $(g-2)_\mu$

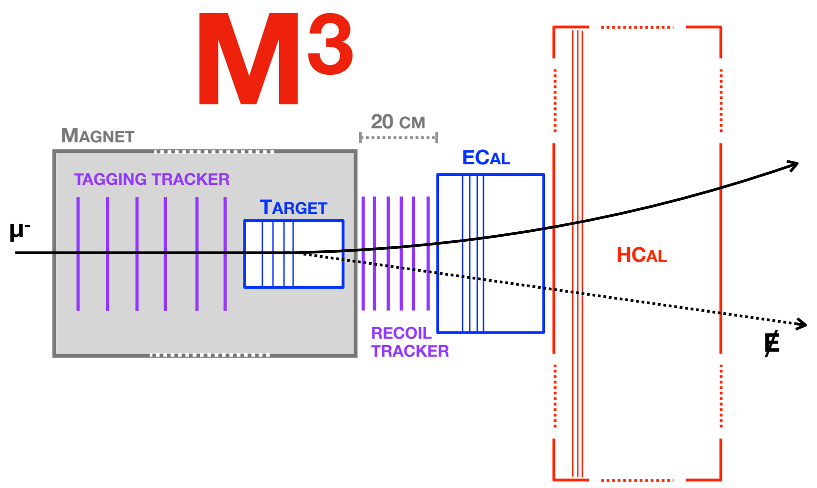






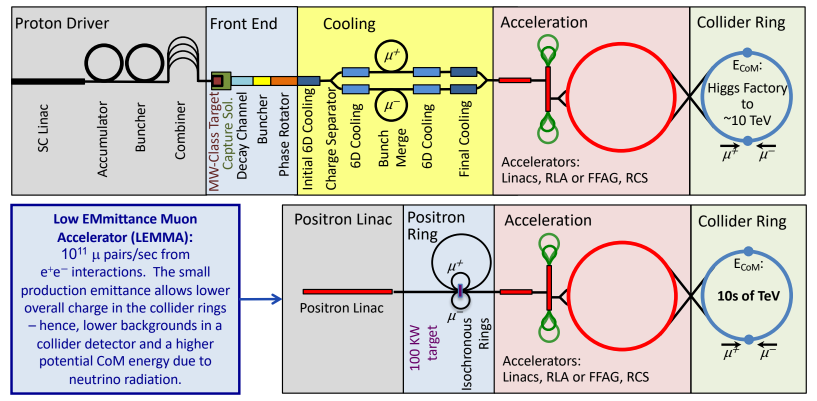
1. Confirm the $(g-2)_\mu$ anomaly is real.

2. Look for $\lesssim$ GeV Singlet Scenarios in μ fixed target experiments.



3. Build a TeV-scale muon collider. Discover **all** Singlet solutions (and probe deep into EW Scenario parameter space as well).

4. Build a 10-TeV-scale muon collider. Discover **all** "reasonable" Electroweak solutions, and/or observe $h\gamma$ signal.



5. **Either find new particles, or prove the universe is explicitly, calculably fine-tuned with weird flavour physics.**

Either way, a comprehensive muon program revolutionizes our understanding of the universe.

Thank you!