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

Fermilab Physics Colloquium
14 April 2021

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University of Toronto

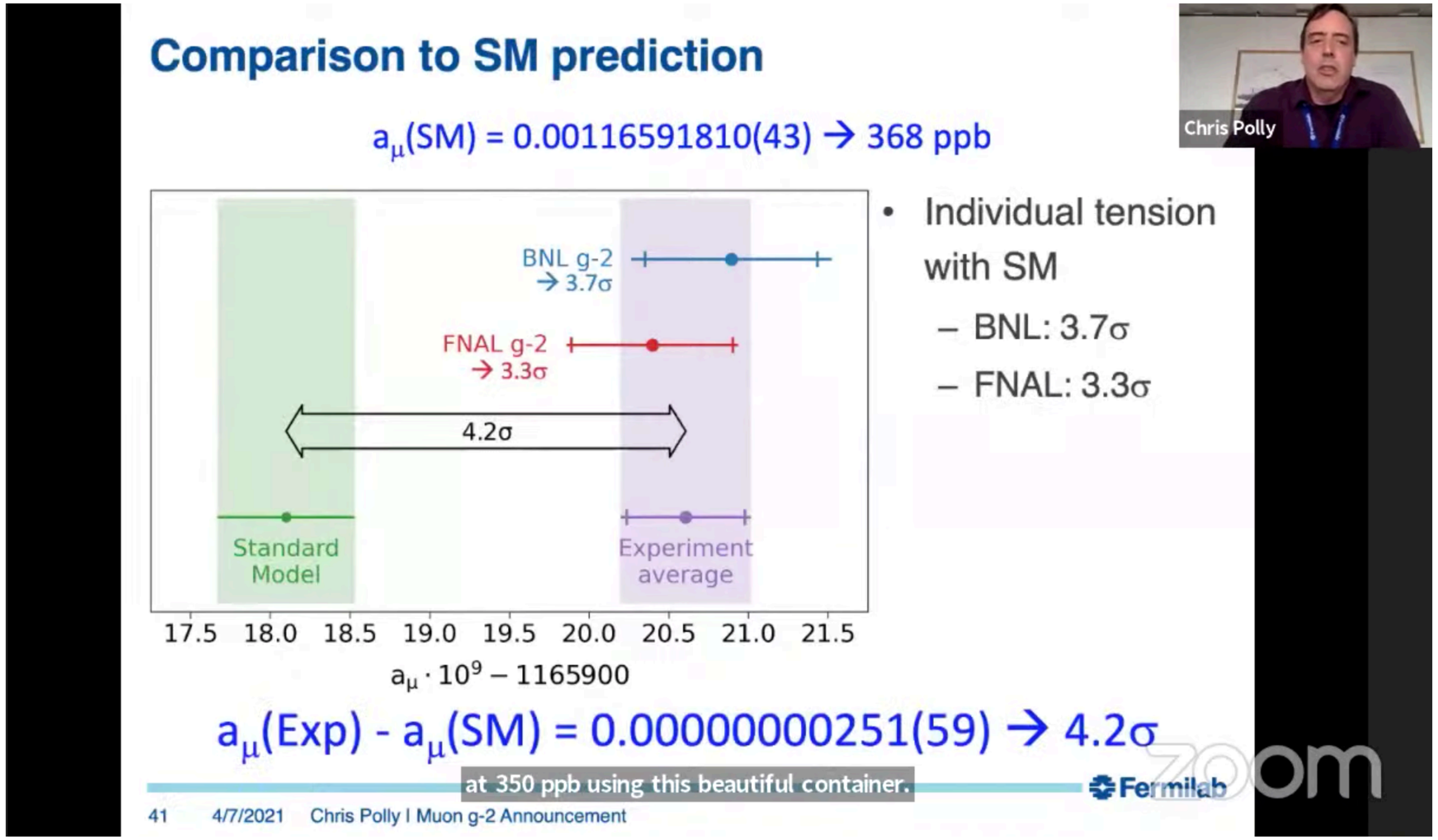
based on 2006.16277, 2101.10334 with
Rodolfo Capdevilla, Yonatan Kahn, Gordan Krnjaic

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!

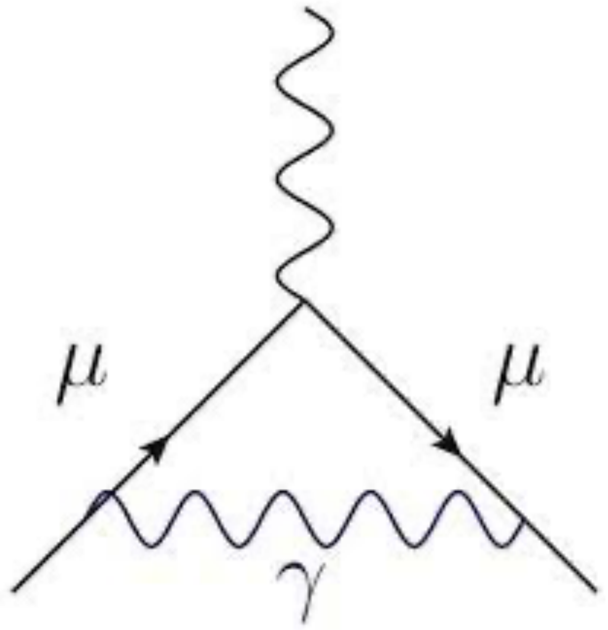
2006.16277, 2101.10334

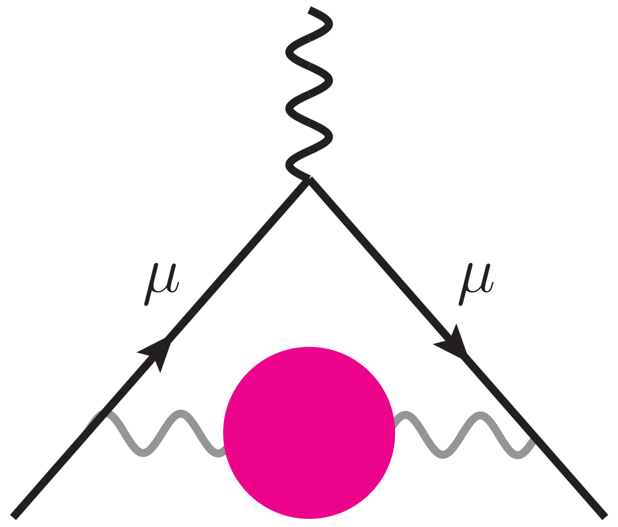
Outline

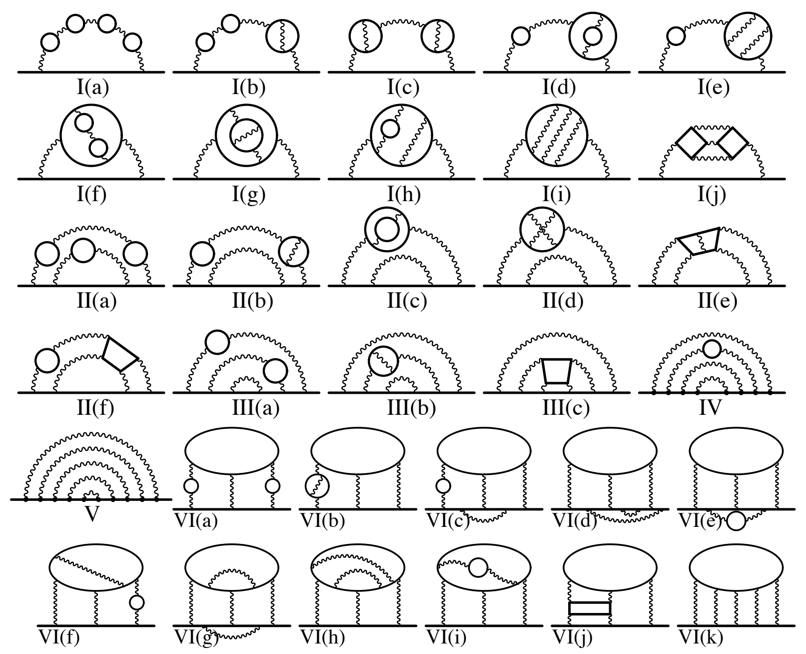
1. $(g-2)_\mu$ Overview
2. BSM physics in $(g-2)_\mu$
3. Model Exhaustive Approach
4. Experimental Target for discovering BSM Physics
5. Low Energy Experiments
6. Muon Colliders
7. A no-lose theorem for discovering the new physics of $(g-2)_\mu$

$(g-2)_\mu$ Overview

$(g-2)_\mu$ Overview







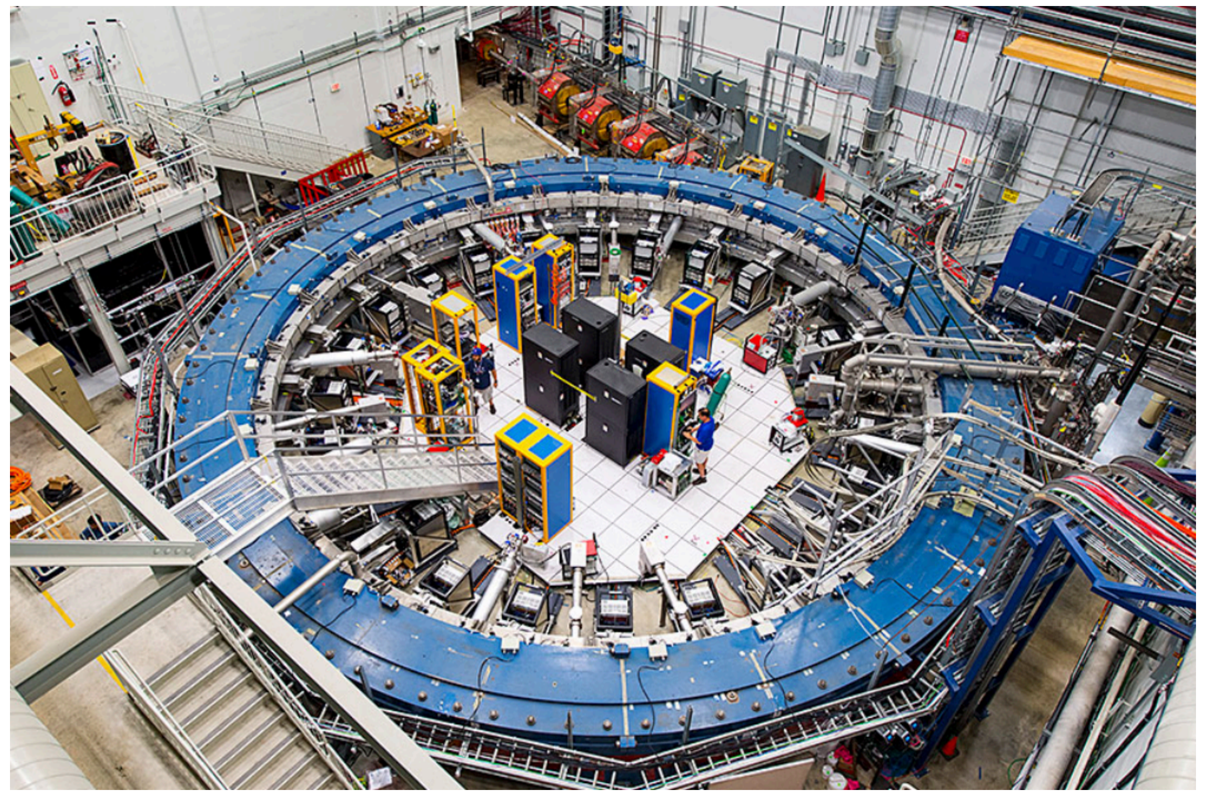
$+\ldots$

Current theoretical state-of-the-art:

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP, LO}} + a_\mu^{\text{HVP, NLO}} + a_\mu^{\text{HVP, NNLO}} + a_\mu^{\text{HLbL}} + a_\mu^{\text{HLbL, NLO}}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

2006.04822 g-2 Theory Initiative whitepaper

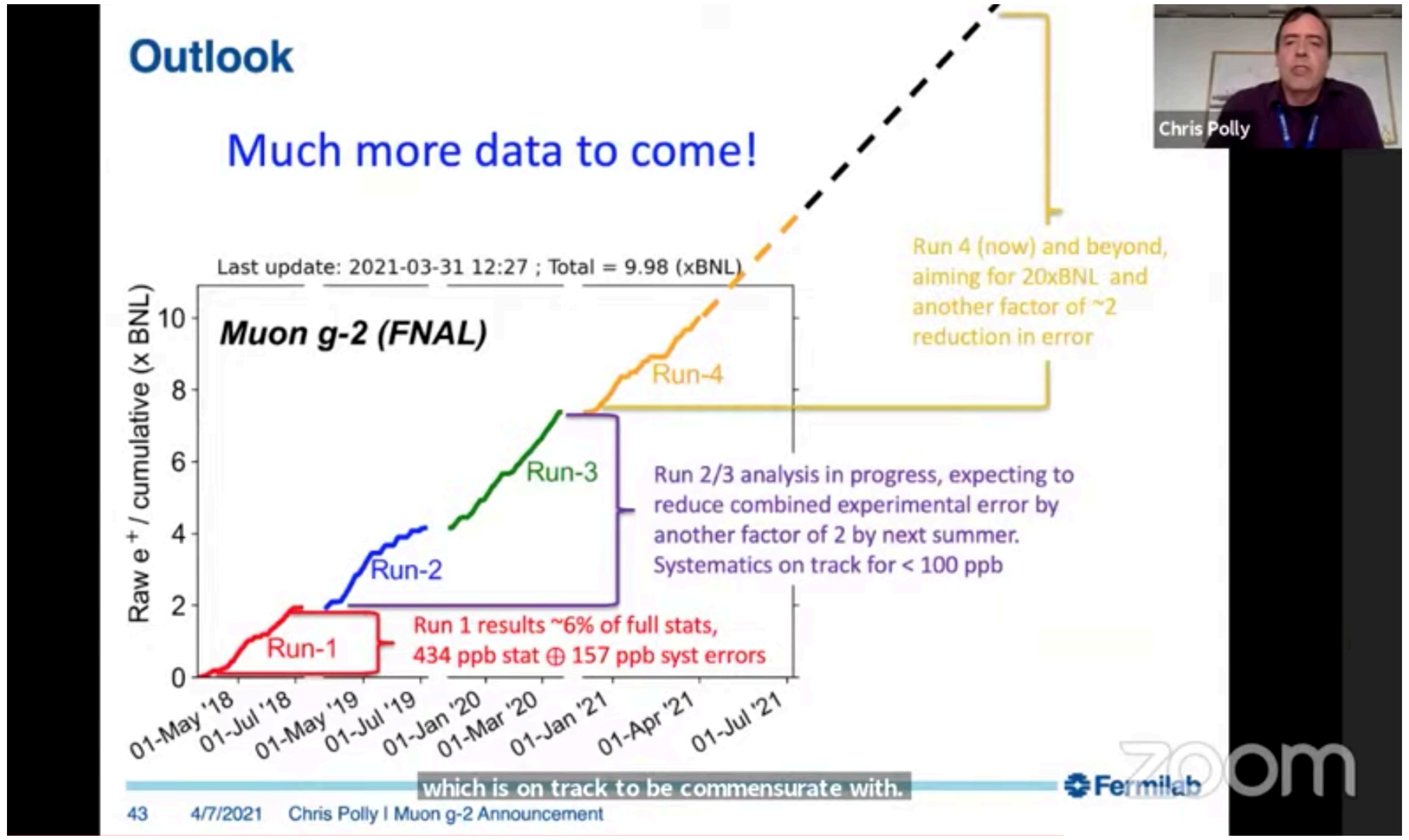
$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$$

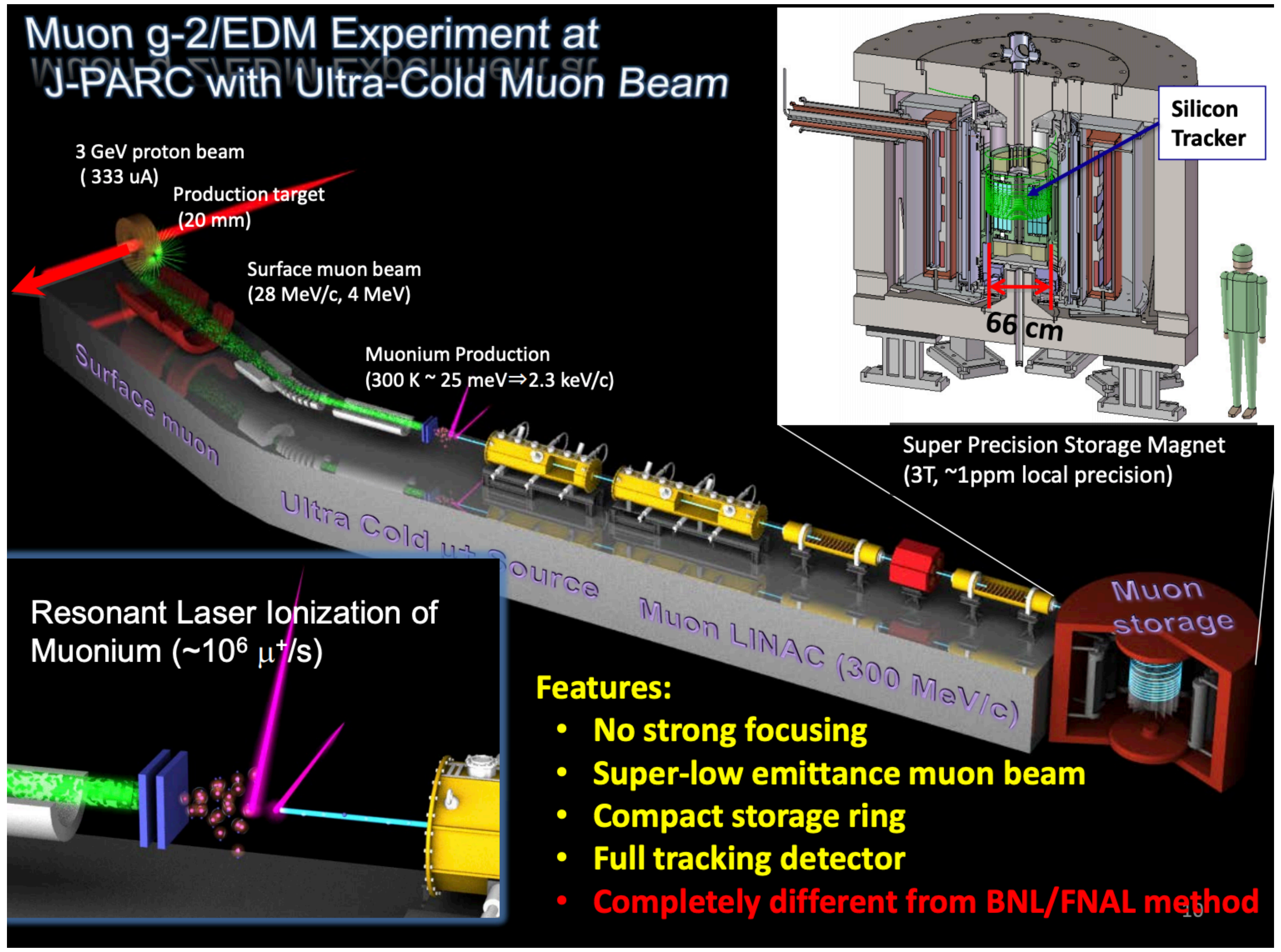


E821 @ BNL (2004):	g-2 @ Fermilab (2021)
$a_\mu^{\text{exp}} = 116\,592\,089(63) \times 10^{-11}$	$a_\mu^{\text{exp}} = 116\,592\,040\,(54) \times 10^{-11}$
$\Delta a_\mu = (2.79 \pm 0.76) \times 10^{-9}$	$\Delta a_\mu = (2.30 \pm 0.69) \times 10^{-9}$
3.7σ	3.3σ

Combined: $\Delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$ **(**4.2σ**)**

Future progress: experiment





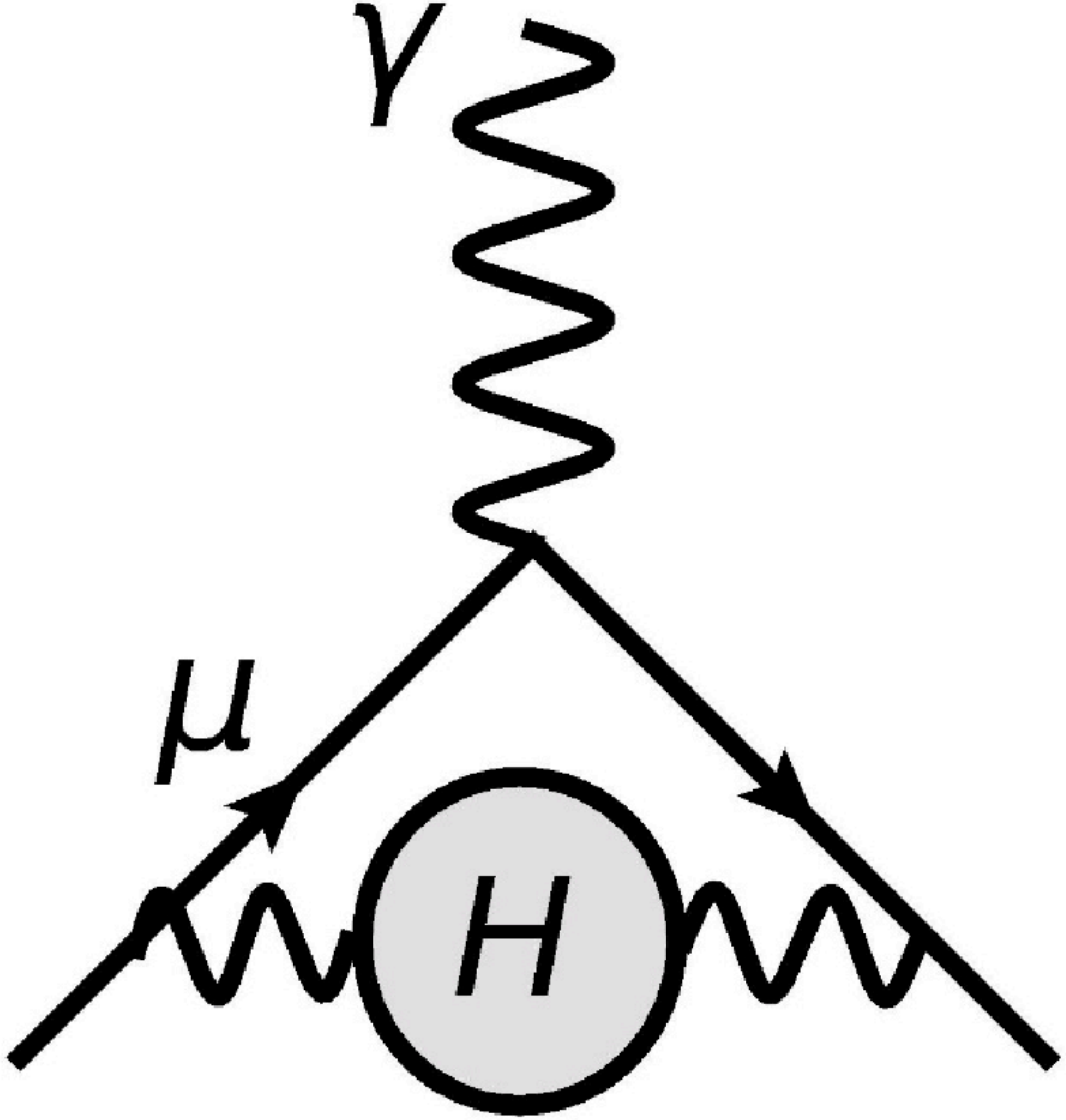
Fermilab: uncertainty reduced by factor of 2 next summer, eventually by factor of 4

J-PARC: totally independent measurement with different method & similar precision, plans to take data 2024-26

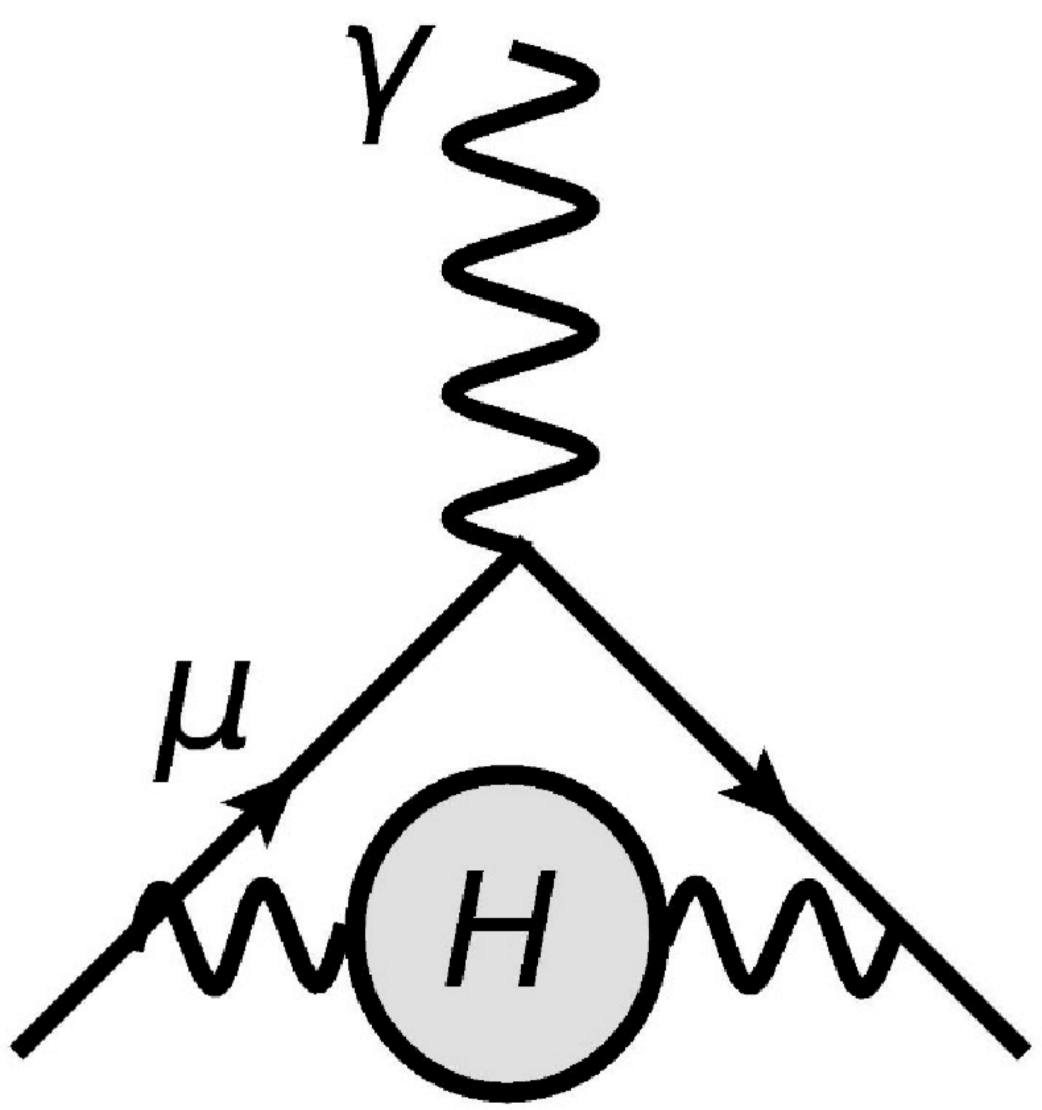
slide by K. Ishida, 19 Sep 2019

Future progress: Theory

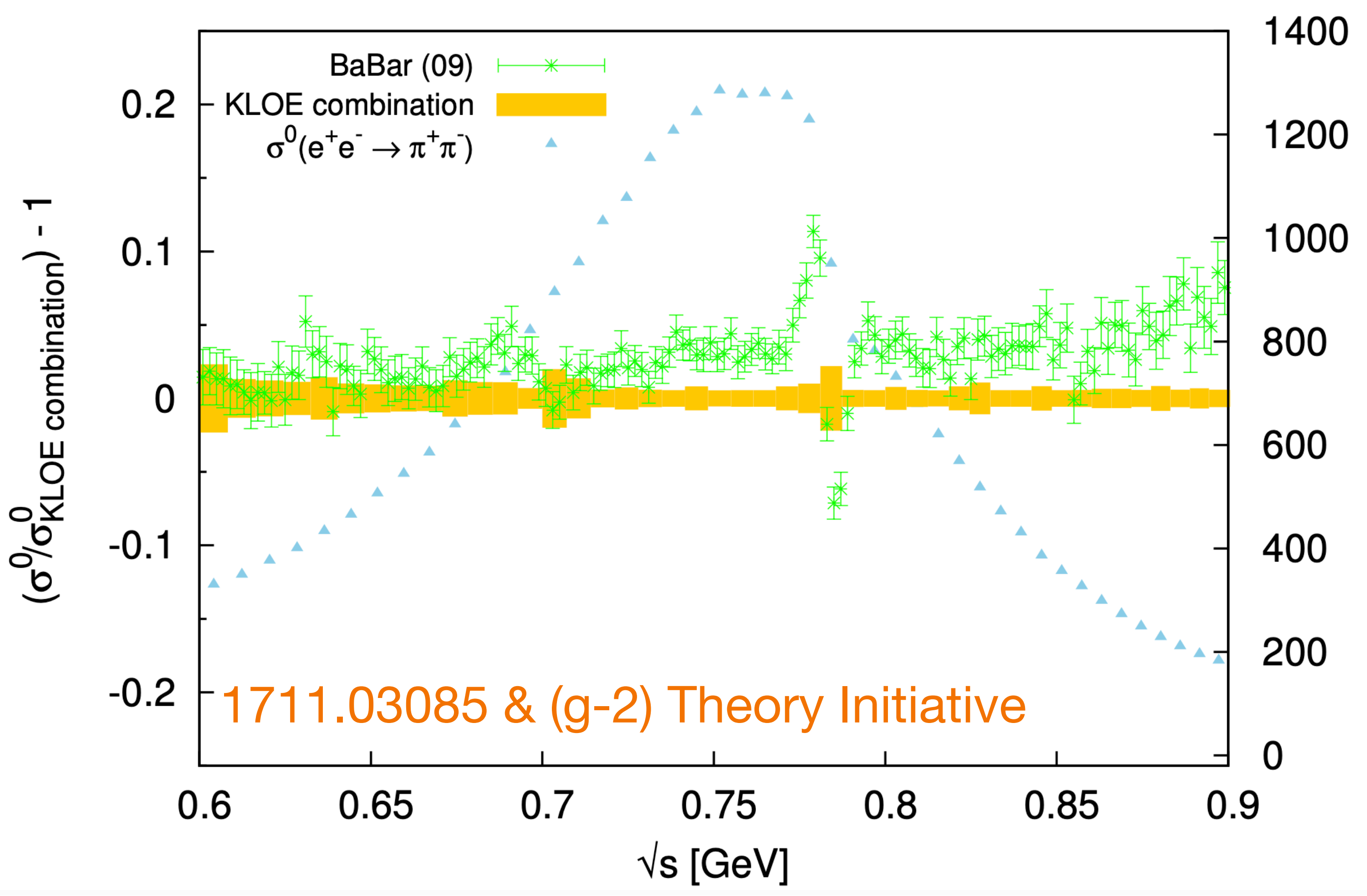
Future progress: Theory

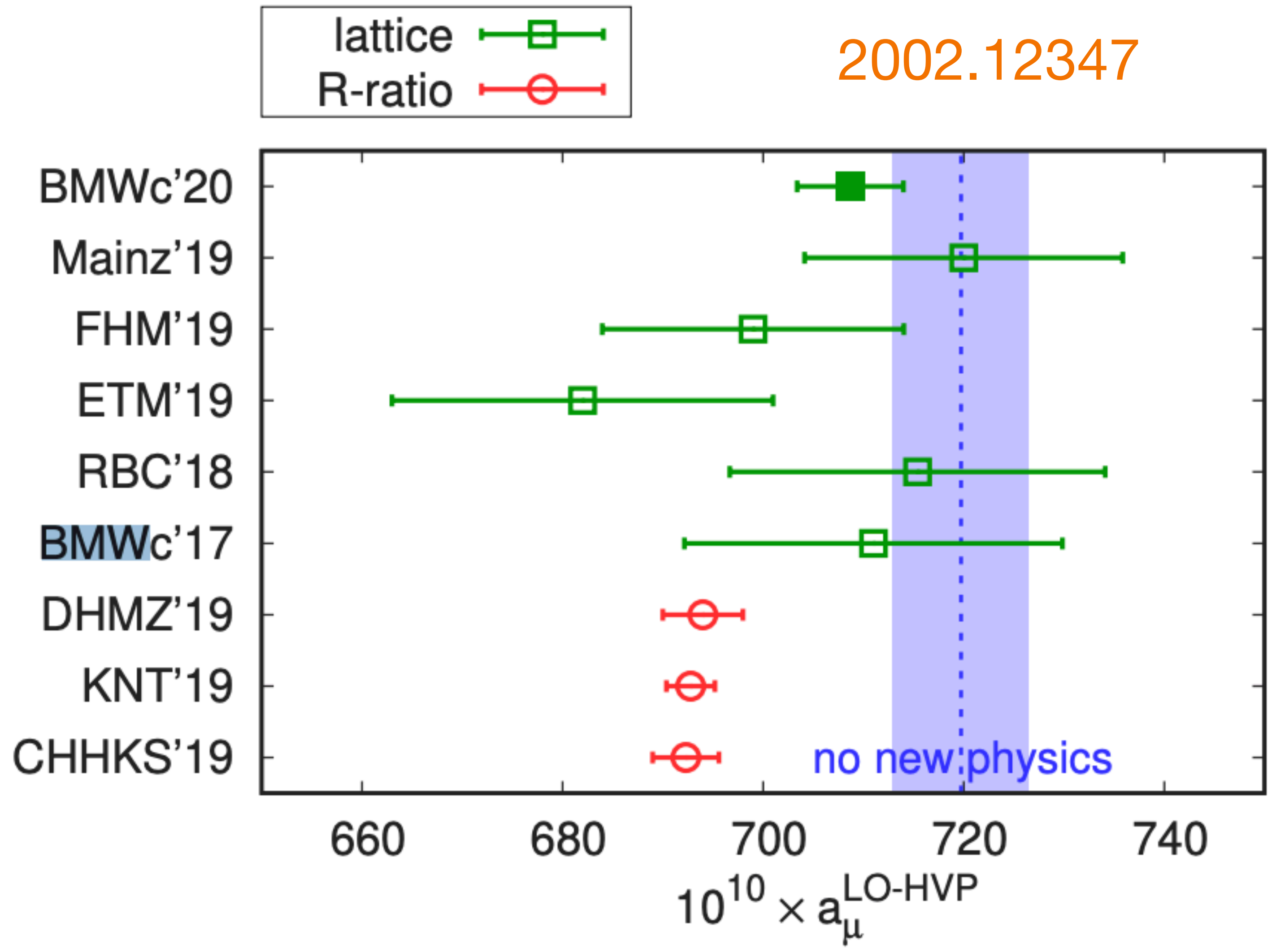


Future progress: HVP



Most “controversial” part of SM prediction:
Hadronic Vacuum Polarization (HVP)



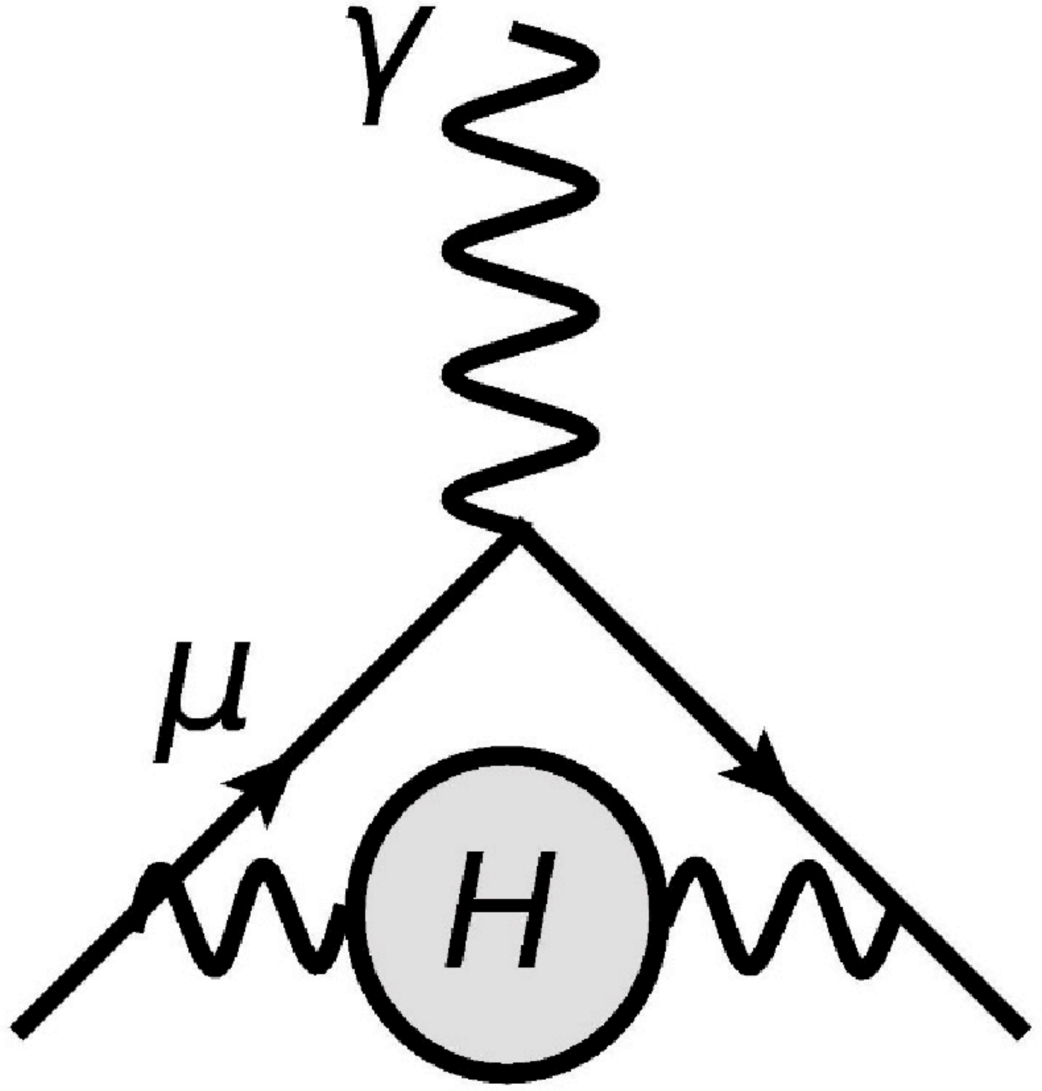


A conservative data-driven approach using R-ratio measurement, and electroweak precision, favour anomaly. 2006.04822 g-2 Theory Initiative whitepaper 2003.04886

QCD Lattice calculations not yet converged, but BMWc’20 claims SM consistency.

2002.12347

Future progress: HVP



Current status: if BMW is correct, then Electroweak precision fits would be made only slightly worse (2.4 σ) while reducing tension with (g-2) data (~1.5 σ), but introducing additional > 2.xx σ tension with < GeV hadron data.

Demonstrates non-gaussianity of theory errors in $a_\mu^{\rm SM}$!

New BMW lattice uncertainty is systematics dominated (continuum limit extrapolation). Vital for other lattice calculations to corroborate and check consistency.

Hopefully lattice updates within ~ a year.

New **experimental data** would help as well, e.g. **Belle-2** (soon?) or **MUonE** experiment at CERN (space-like HVP from μe scattering by ~2025) to **resolve BaBar-KLOE tension?**

CERN-SPSC-2019-026

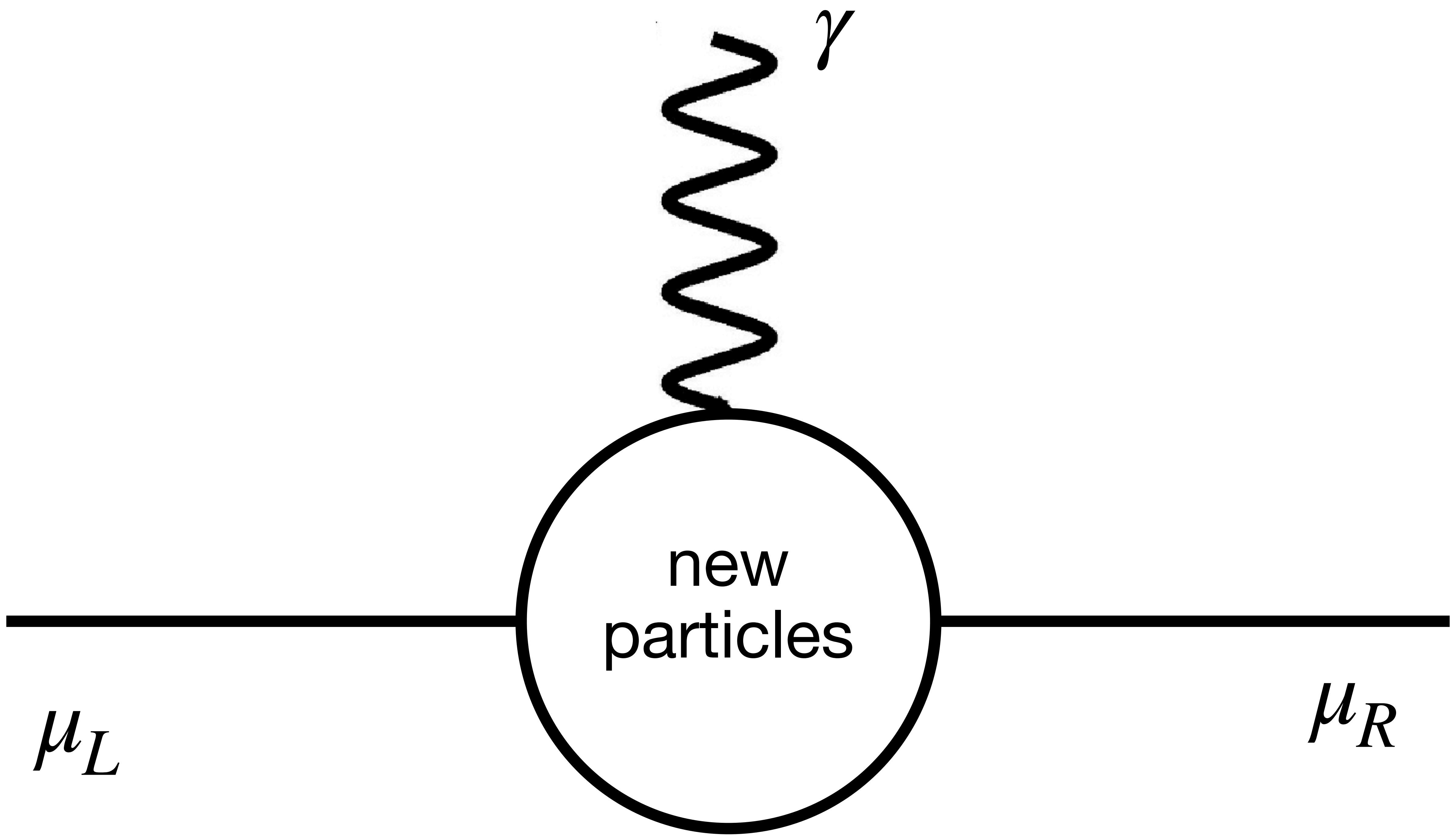
If the $(g-2)_\mu$ anomaly is real….

… what does this mean for BSM physics?

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

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

Very simple:



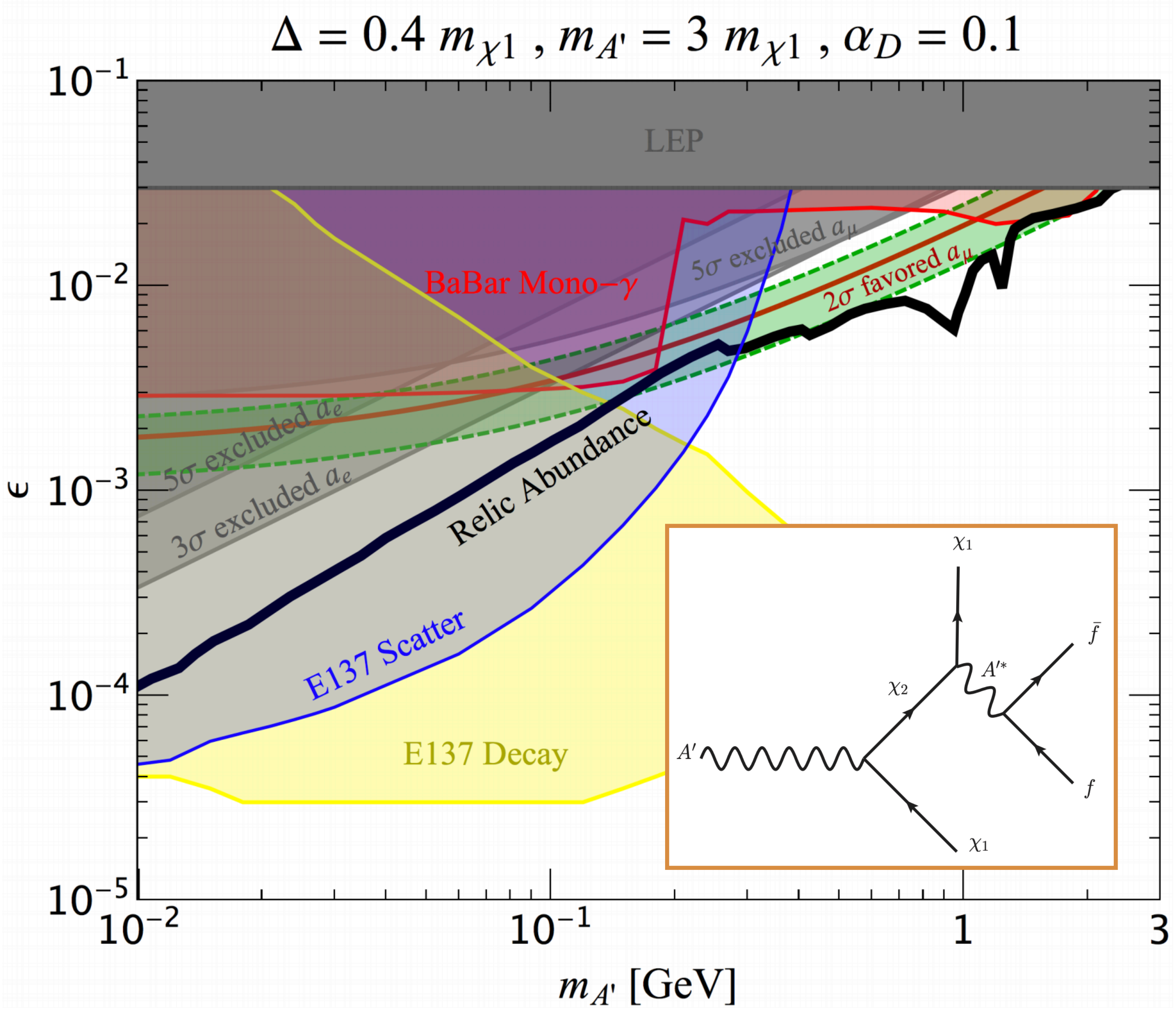
$\gtrsim O(10^3)$ papers over past decades

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

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

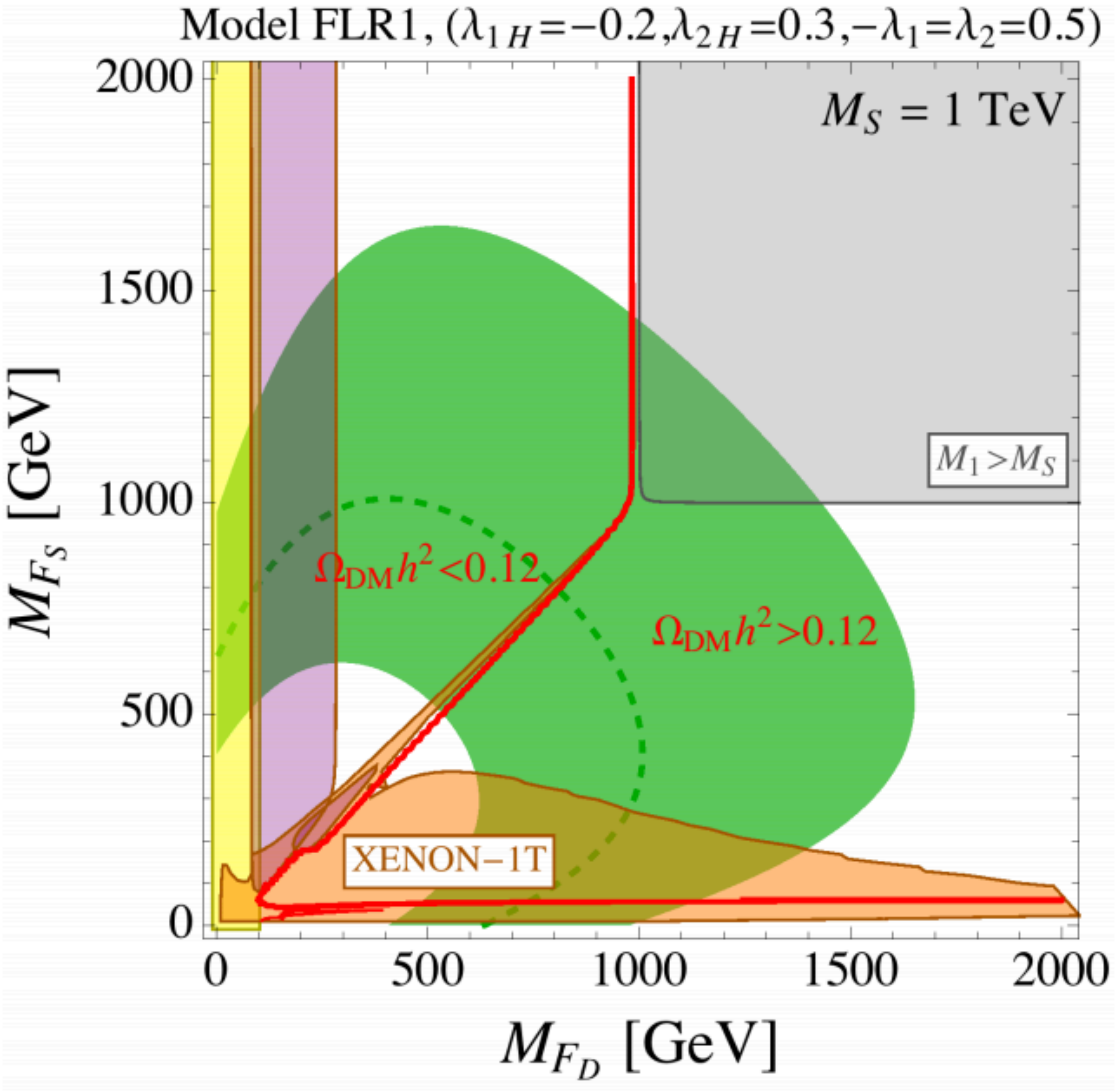
Below a GeV or above a TeV

Semi-visibly decaying dark photon



1902.05075 Mohlabeng

New electroweak scalars and fermions, including dark matter



1804.00009 Calibbi, Ziegler, Zupan

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

Ask a simpler question…

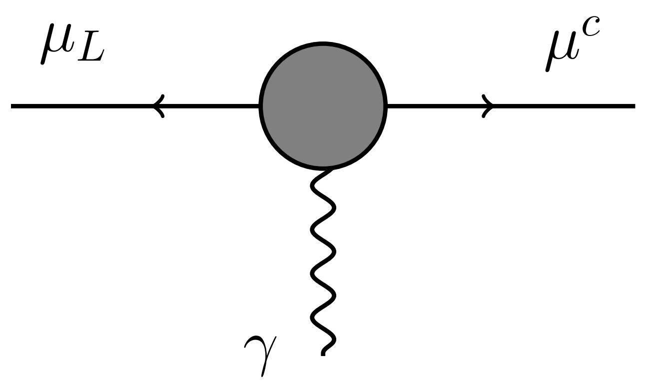
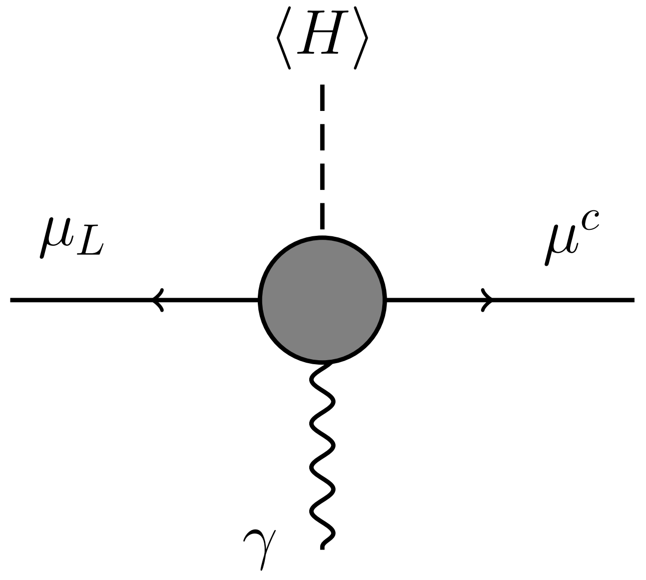
What would it take to *guarantee* we discover this new physics, *regardless* of the complete theory?

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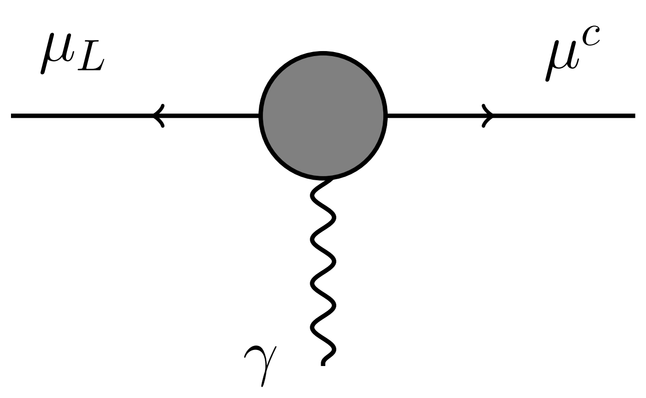
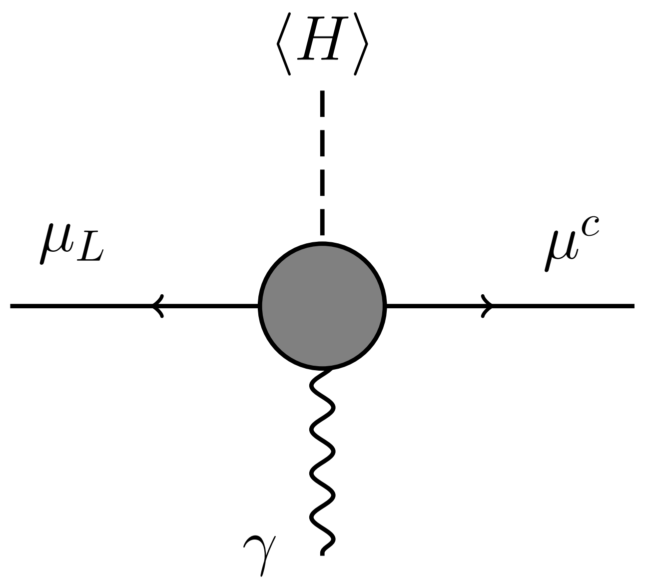
$(g-2)_\mu$ diagram		
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Model-Independent

We would love to discover this new physics DIRECTLY.

Where the new particles at??

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

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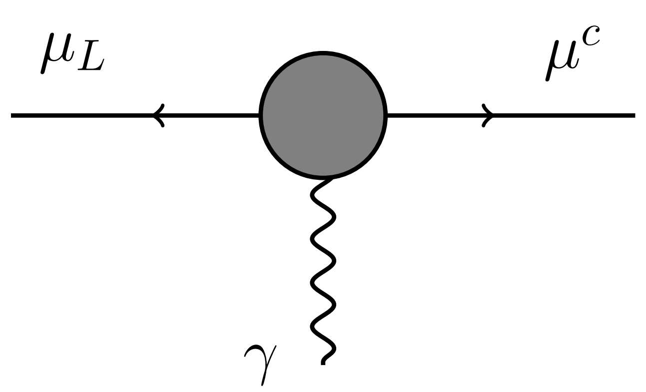
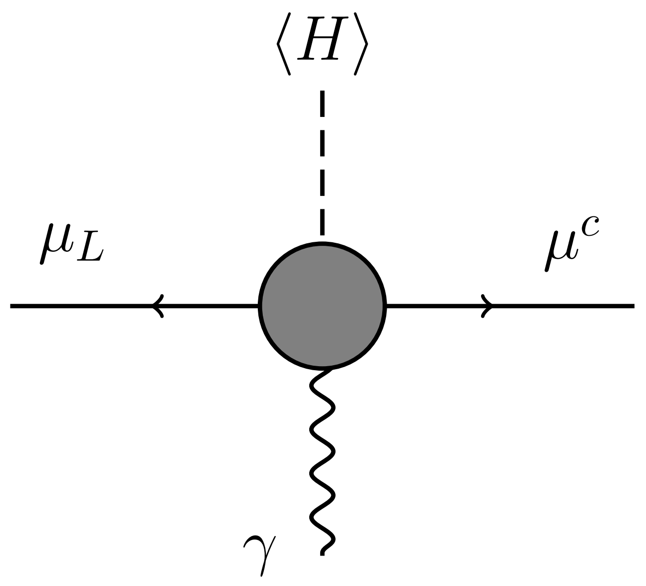
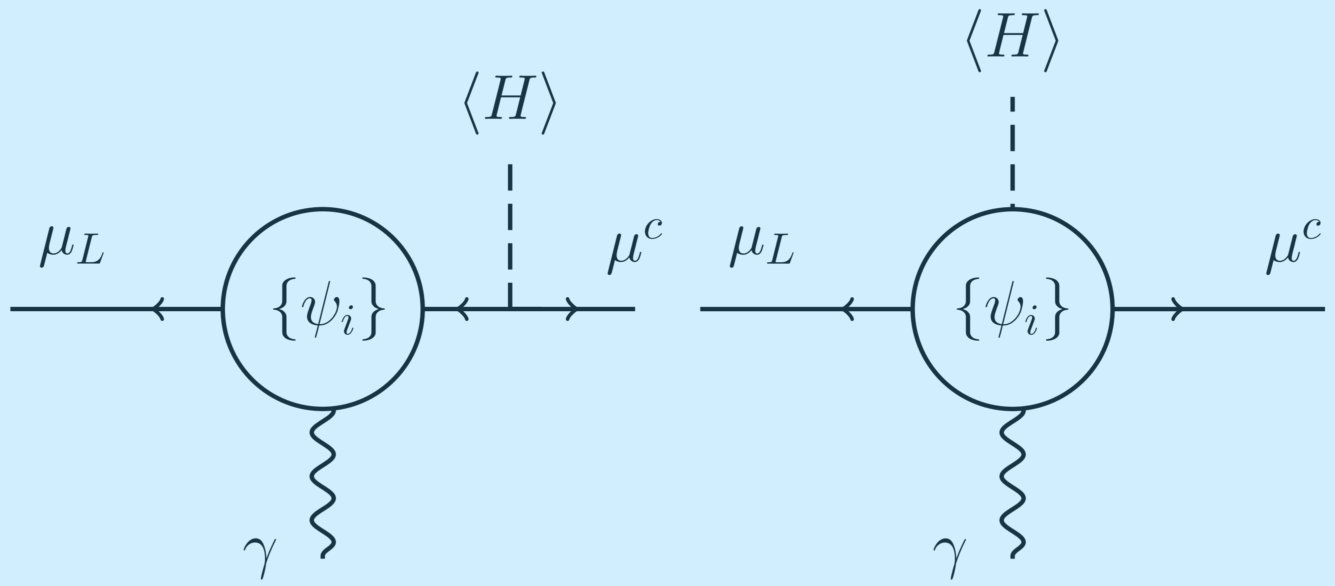
Assumptions	$\Delta a_\mu = a_\mu^{\text{obs}}$ $U(1)_{em}$ gauge invariance	$\Delta a_\mu = a_\mu^{\text{obs}}$ SM gauge invariance	$\Delta a_\mu = a_\mu^{\text{obs}}$ SM gauge invariance Perturbativity
$(g-2)_\mu$ diagram			
How to predict new signatures	$\frac{1}{M}(\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$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

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?

Model-Exhaustive Analysis

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Then ask: what are some irreducible experimental signatures?

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!)


Boundary of perturbative unitarity
Singlets in muon annihilation and scattering
Singlet Scenarios
New particles in $(g-2)_\mu$ loops: *only* SM singlets
Signature: direct production of *SM singlet states*
Discovery: requires inclusive search for singlet, with $g \propto m$
Electroweak Scenarios
New particles in $(g-2)_\mu$ loops: *not* only SM singlets
Signature: direct production of *new charged states*
Discovery: discoverable at lepton collider for "all" $m \lesssim \sqrt{s}/2$
new charged particles!
Indirect Signatures?
Space of BSM Theories that generate $\Delta a_\mu = a_\mu^{\text{obs}}$
2012.02769 Buttazzo, Paradisi
2012.03928 Yin, Yamaguchi

Model Exhaustive Approach

Singlet Scenarios

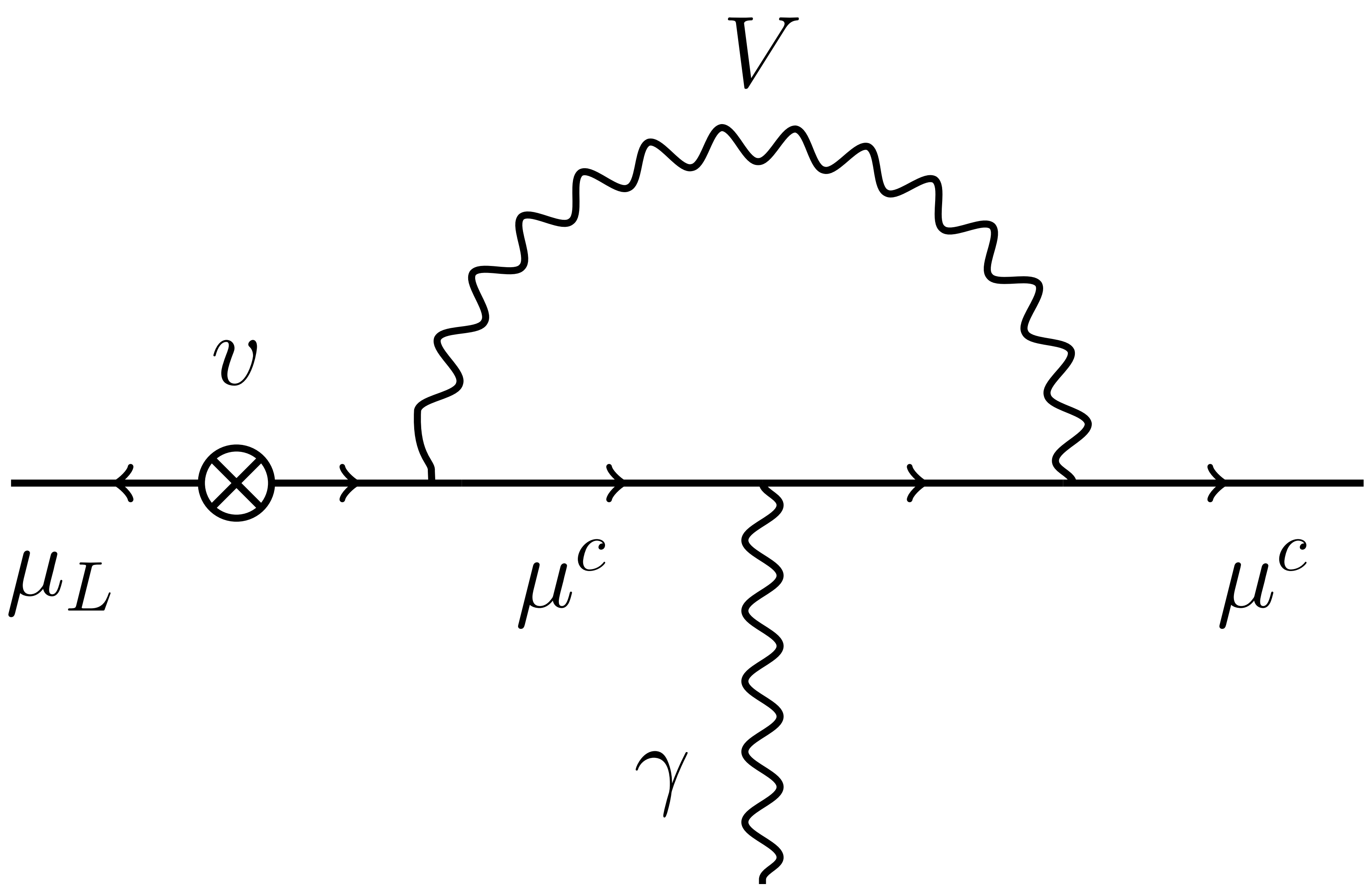
2006.16277, 2101.10334

Rodolfo Capdevilla, DC, Yonatan Kahn, Gordan Krnjaic

Singlet Scenarios

Vector

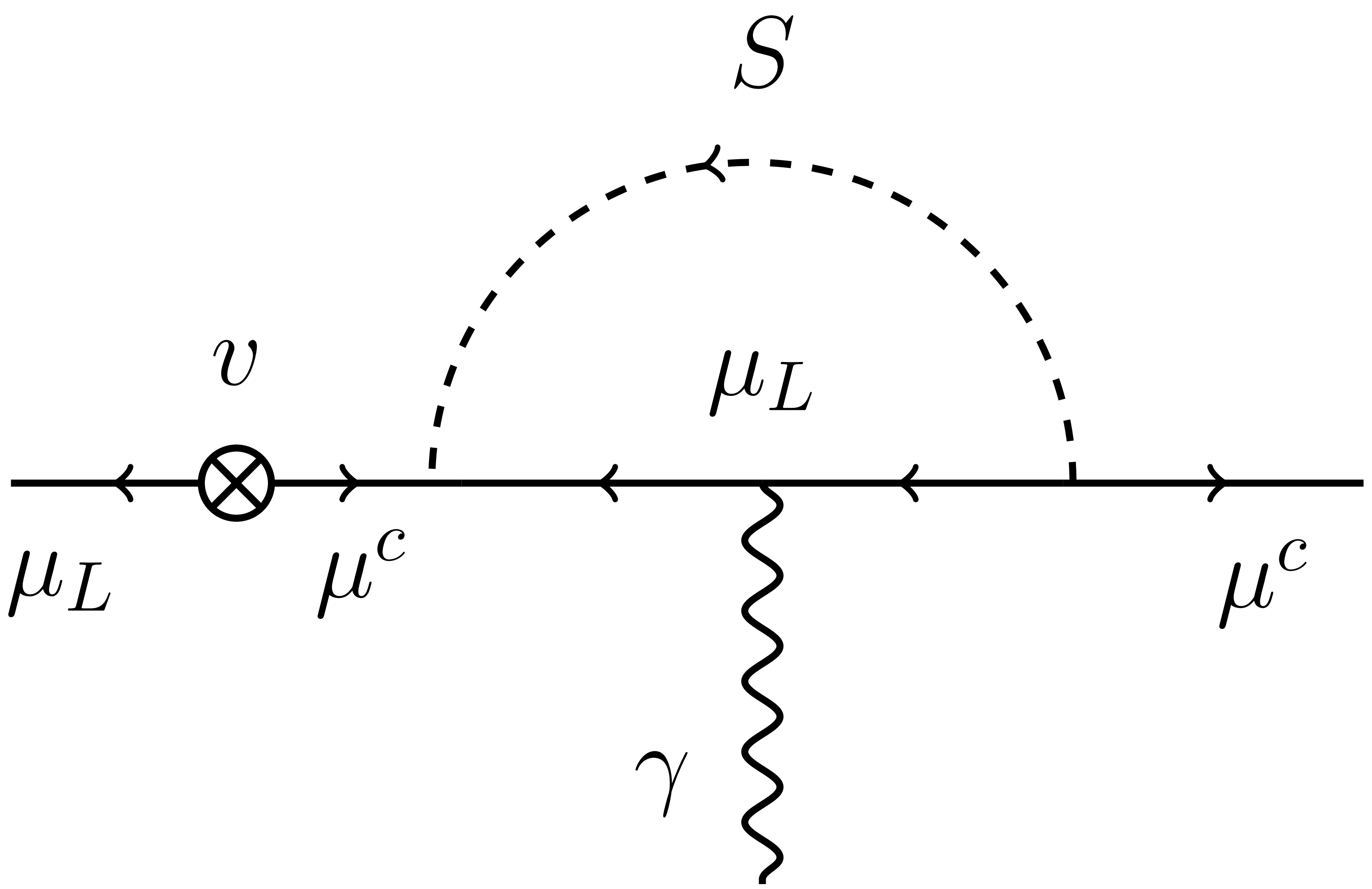
$$\mathcal{L}_{\rm V} \supset g_V V_\alpha (\mu_L^\dagger \bar{\sigma}^\alpha \mu_L + \mu^{c\,\dagger} \bar{\sigma}^\alpha \mu^c) + \frac{m_V^2}{2} V_\alpha V^\alpha$$



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

Scalar

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

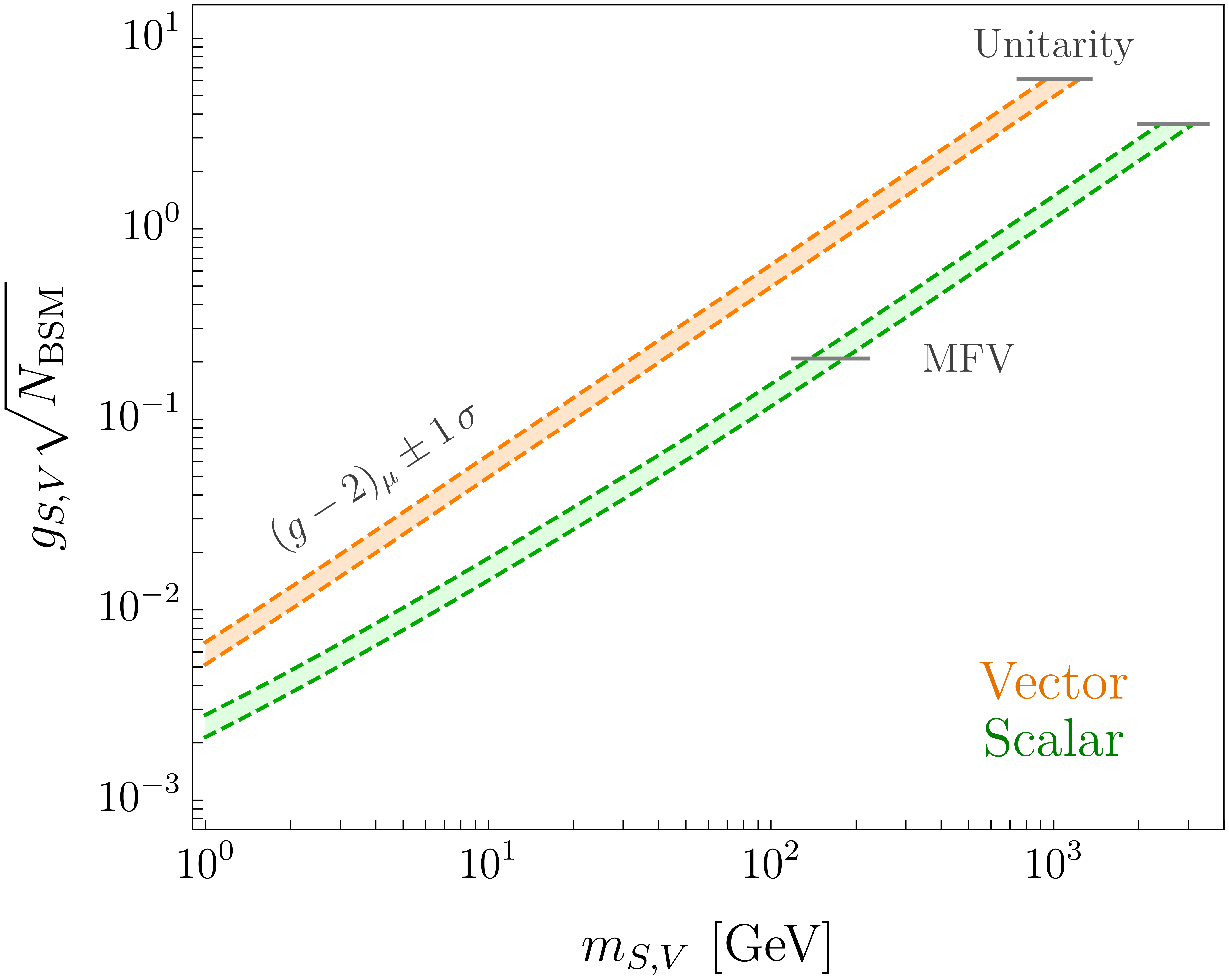


$$\Delta a_\mu^S / \Delta a_\mu \approx N_{\rm BSM} g_S^2 \left(\frac{700 \text{ GeV}}{m_S} \right)^2$$

$(g-2)_\mu$ 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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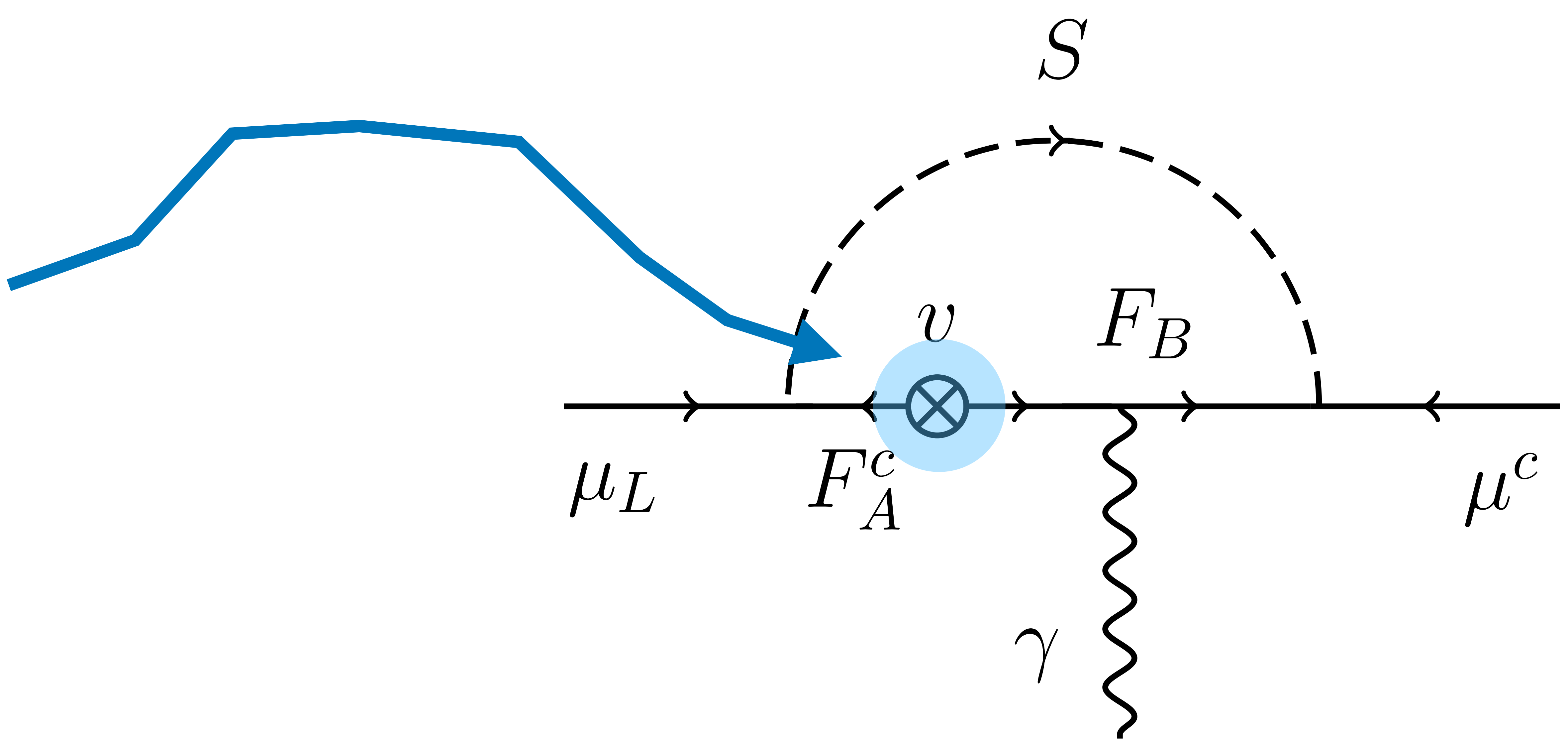
Electroweak Scenarios

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

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Consider all EW scenarios, for all possible masses and couplings that explain (g-2)...

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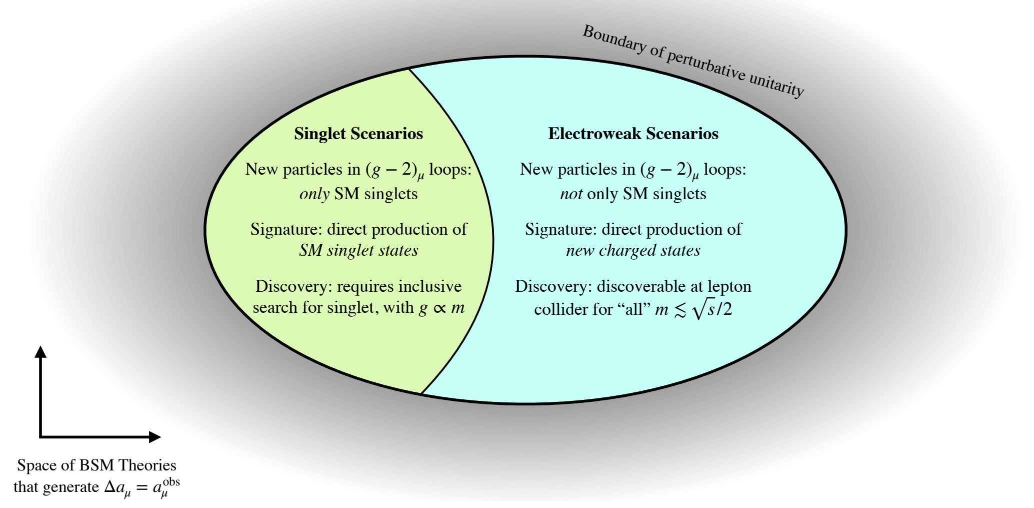

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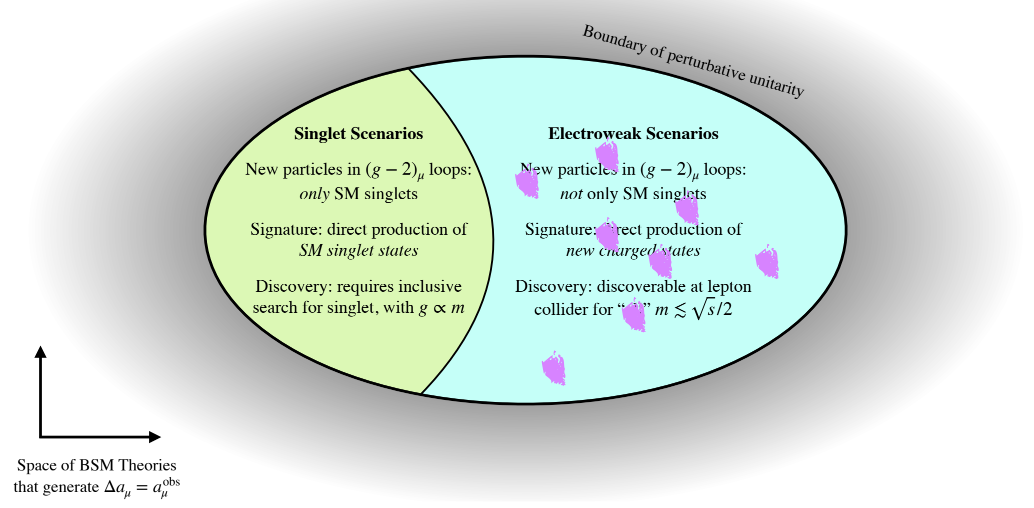

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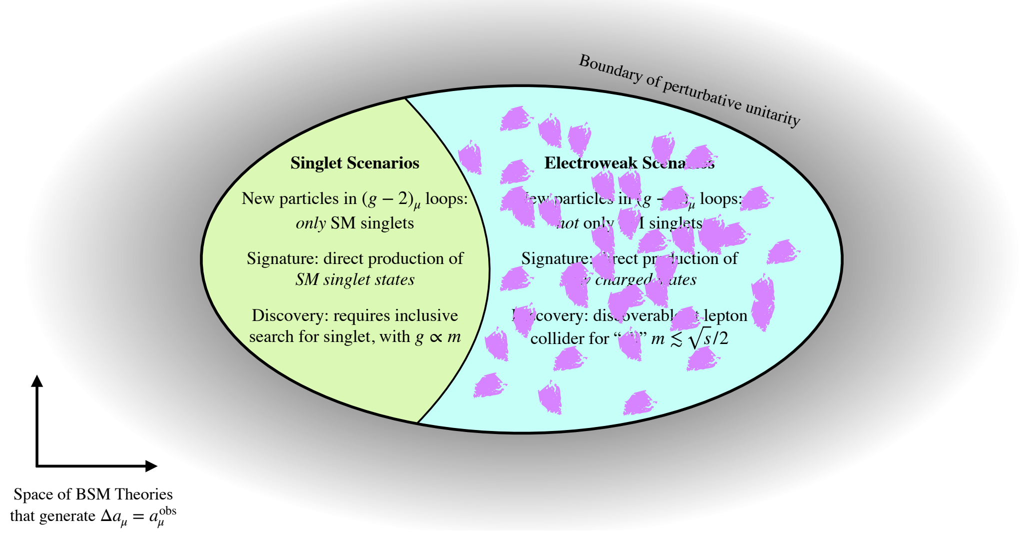

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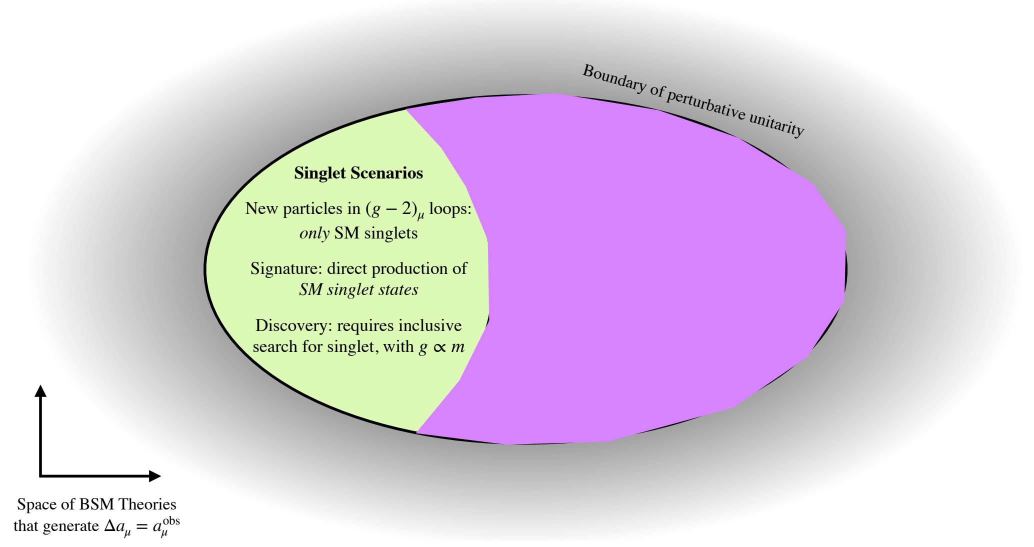

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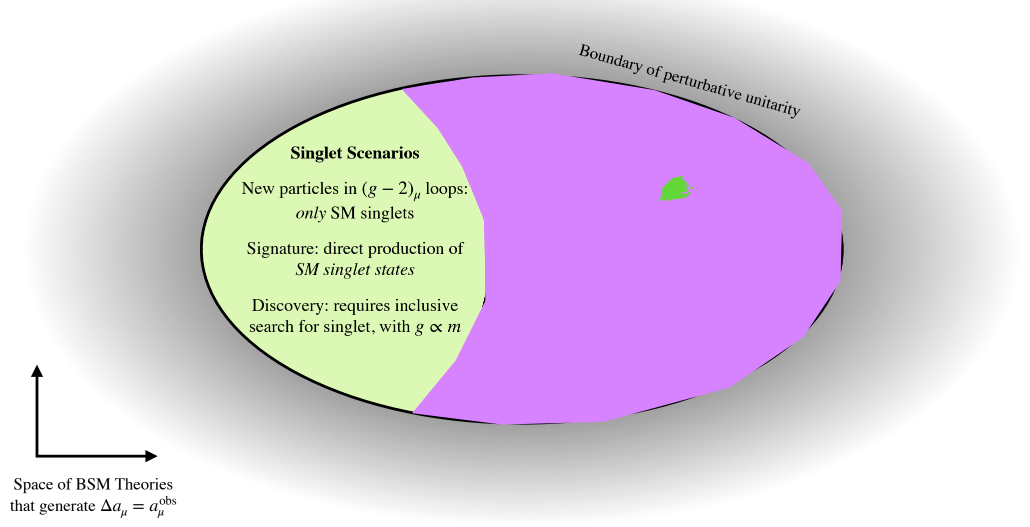

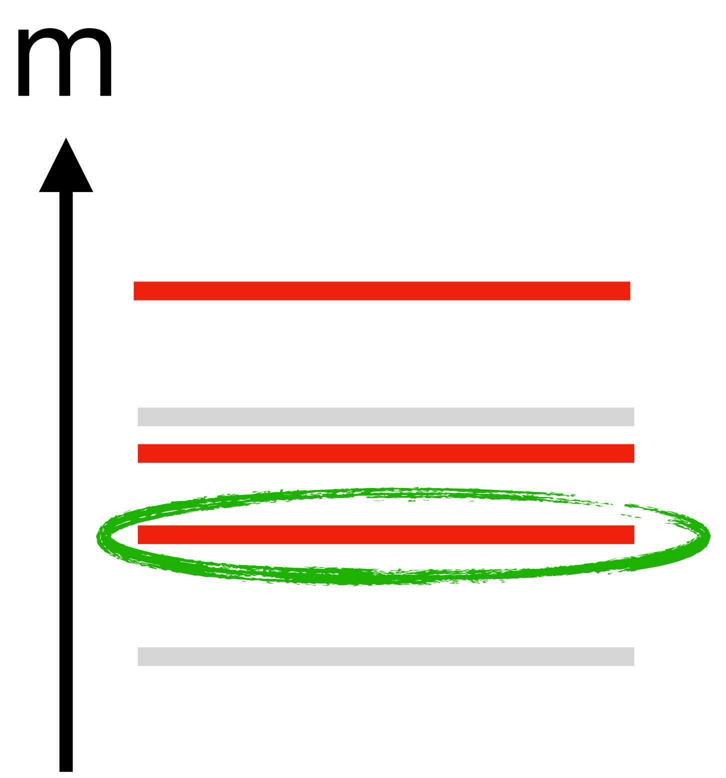

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Consider all EW Scenarios, for all possible masses and couplings that explain (g-2)...

... for each such scenario, find the mass of the LIGHTEST BSM charged state...

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?

... what is the HEAVIEST that this lowest-lying new charged state could be?

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Consider all EW scenarios, for all possible masses and couplings that explain (g-2)...

... for each such scenario, find the mass of the LIGHTEST BSM charged state...

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)!

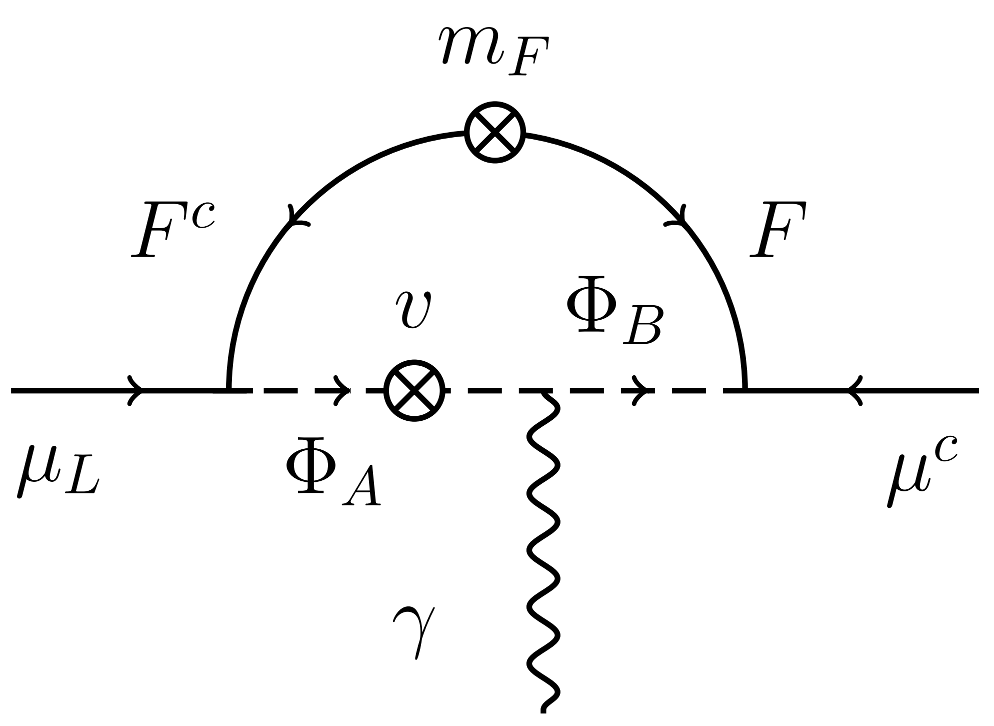
Maximizing over the space of those simplified models will give us our answer!

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)

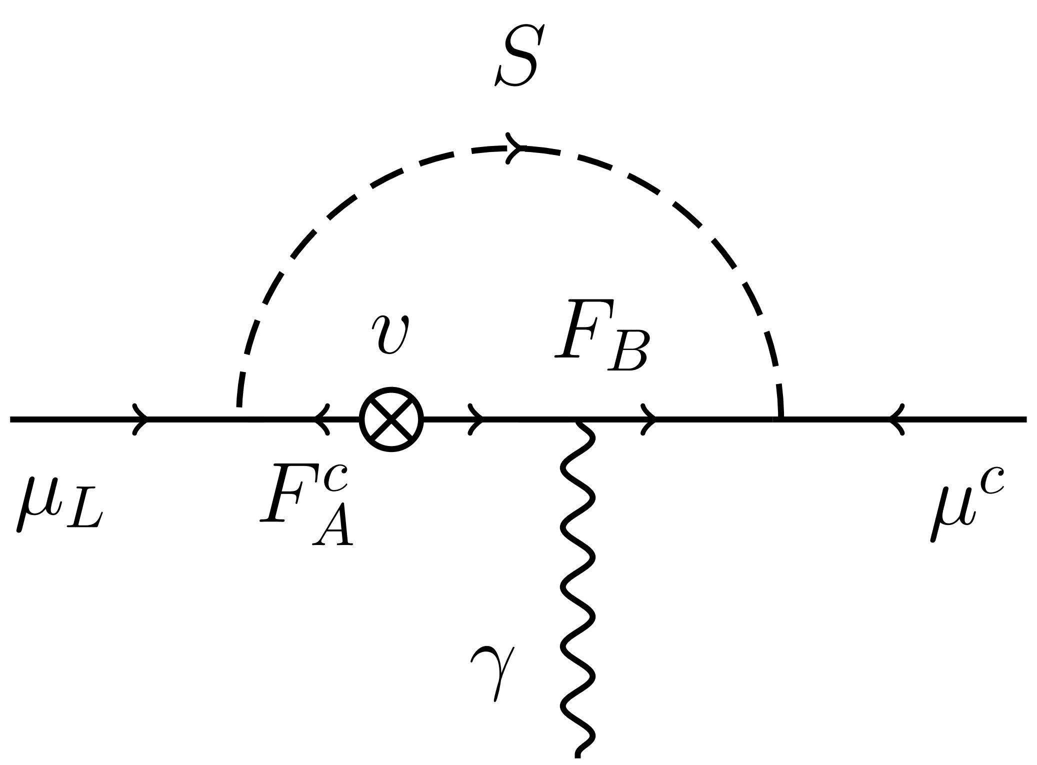
Electroweak Simplified Models

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.

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

Turn the crank: all possible EW representations

Model	R	R_A	R_B
SSF	1_{-1}	$2_{1/2}$	1_0
	1_{-2}	$2_{3/2}$	1_1
	1_0	$2_{-1/2}$	1_{-1}
	1_1	$2_{-3/2}$	1_{-2}
	$2_{-1/2}$	3_0	$2_{-1/2}$
	$2_{-3/2}$	3_1	$2_{1/2}$
	$2_{1/2}$	3_{-1}	$2_{-3/2}$
	$2_{-1/2}$	1_0	$2_{-1/2}$
	$2_{-3/2}$	1_1	$2_{1/2}$
	$2_{1/2}$	1_{-1}	$2_{-3/2}$
	3_{-1}	$2_{1/2}$	3_0
	3_0	$2_{-1/2}$	3_{-1}

Model	R	R_A	R_B
FFS	1_{-1}	$2_{1/2}$	1_0
	1_{-2}	$2_{3/2}$	1_1
	1_0	$2_{-1/2}$	1_{-1}
	1_1	$2_{-3/2}$	1_{-2}
	$2_{-1/2}$	3_0	$2_{-1/2}$
	$2_{-3/2}$	3_1	$2_{1/2}$
	$2_{1/2}$	3_{-1}	$2_{-3/2}$
	$2_{-1/2}$	1_0	$2_{-1/2}$
	$2_{-3/2}$	1_1	$2_{1/2}$
	$2_{1/2}$	1_{-1}	$2_{-3/2}$
	3_{-1}	$2_{1/2}$	3_0
	3_0	$2_{-1/2}$	3_{-1}

Consider SU(2) representations up to triplets and electric charges $|Q| \leq 2$

Arbitrary N_{BSM} but $\lesssim 10$ motivated by… reasonableness…

All of the above is also motivated by avoiding Electroweak Landau Poles.

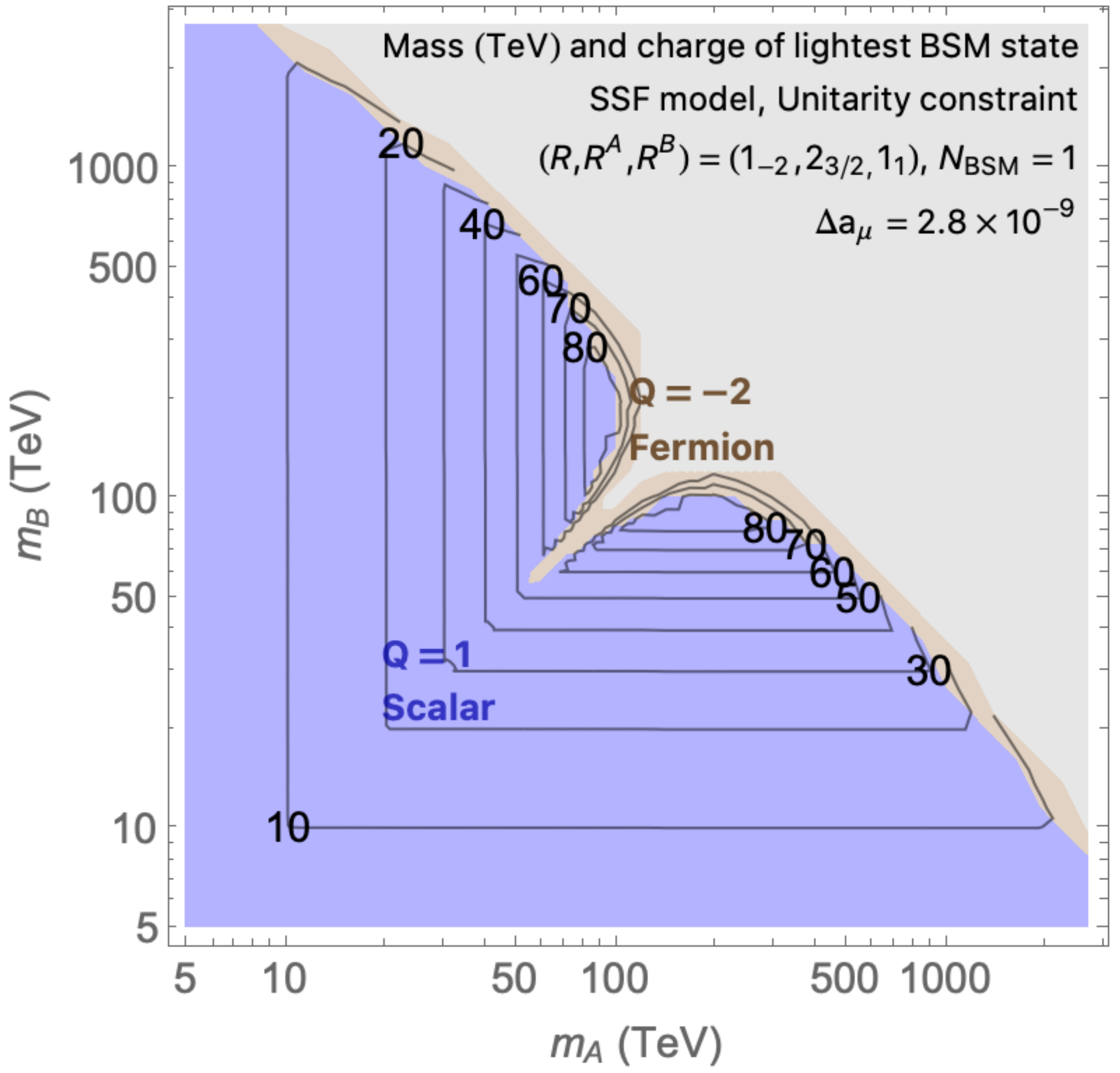
What's the result?

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

Imposing Unitarity Only

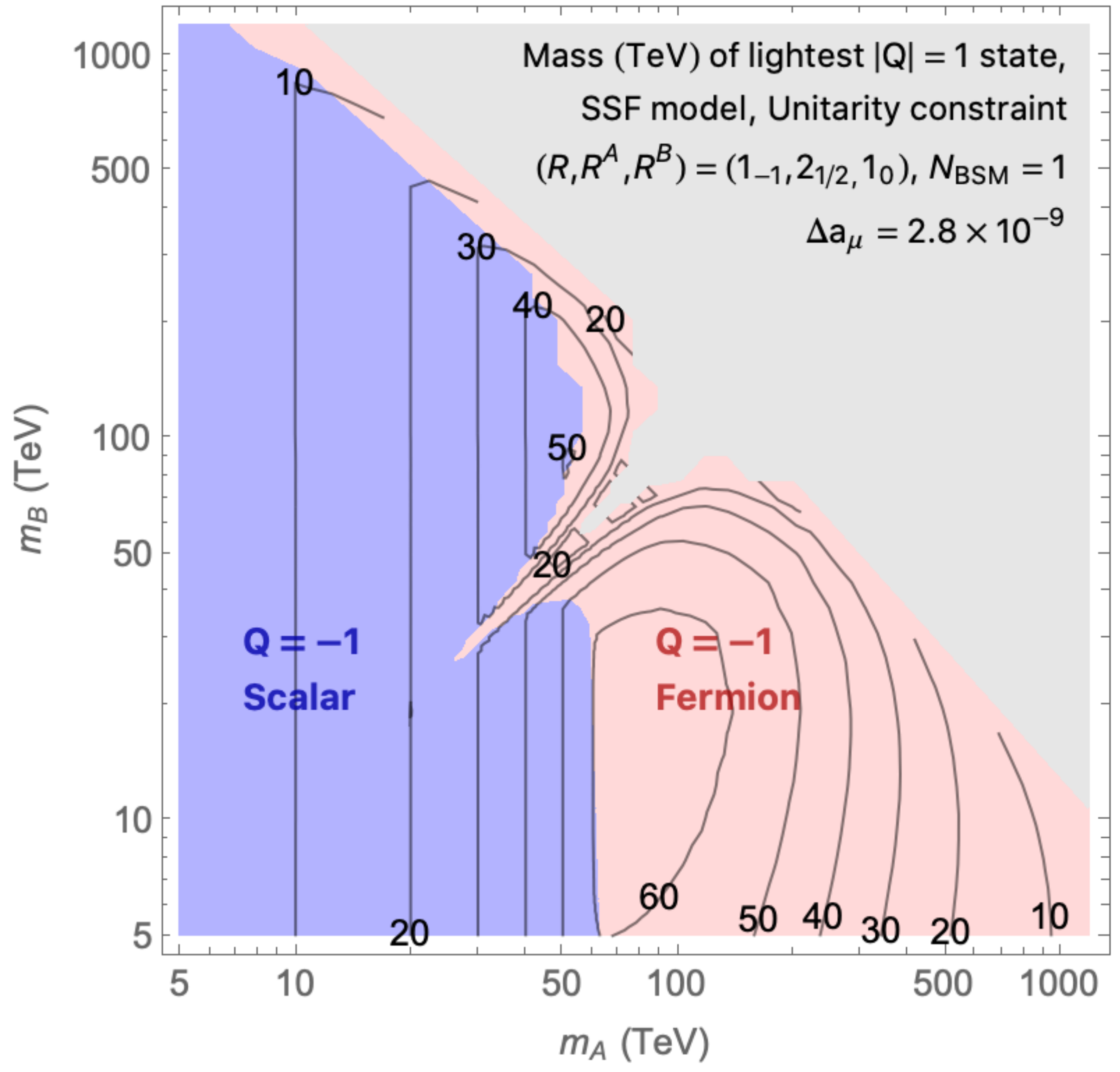
Two representative models:

SSF, all BSM fields charged



$$M_{\text{BSM,charged}}^{\text{max,unitarity}} = 86 \text{ TeV}$$

SSF, charged and neutral fields



$$M_{\text{BSM,charged}}^{\text{max,unitarity}} = 65 \text{ TeV}$$

All the models:

Model	R	R_A	R_B	Highest possible mass (TeV) of lightest charged BSM state: Unitarity only, N_{BSM}: 1	Unitarity only, N_{BSM}: 10	Unitarity + MFV, N_{BSM}: 1	Unitarity + MFV, N_{BSM}: 10	Unitarity + Naturalness, N_{BSM}: 1	Unitarity + Naturalness, N_{BSM}: 10	Unitarity + Naturalness + MFV, N_{BSM}: 1	Unitarity + Naturalness + MFV, N_{BSM}: 10
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	1_{-2}	$2_{3/2}$	1_1	85.9	321	18.1	64.8	19.2	19.2	8.41	12.3
	1_0	$2_{-1/2}$	1_{-1}	46.2	176	9.41	34.1	15.6	17.5	5.93	8.56
	1_1	$2_{-3/2}$	1_{-2}	81.8	302	17.1	63.7	19.3	19.3	8.38	12.1
	$2_{-1/2}$	3_0	$2_{-1/2}$	21.4	107	4.2	15.5	7.47	8.99	3.23	5.0
	$2_{-3/2}$	3_1	$2_{1/2}$	83.7	308	16.6	60.7	13.4	13.4	7.06	10.6
	$2_{1/2}$	3_{-1}	$2_{-3/2}$	95.5	356	18.3	67.8	15.6	15.6	7.75	11.3
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	3_0	$2_{-1/2}$	3_{-1}	39.4	144	7.82	28.6	10.8	15.1	4.14	6.08
FFS	1_{-1}	$2_{1/2}$	1_0	37.3	118	8.87	28	12.3	18.7	4.6	7.04
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	1_1	$2_{-3/2}$	1_{-2}	73.2	231	17.4	55	13.9	19.7	5.04	7.25
	$2_{-1/2}$	3_0	$2_{-1/2}$	40	126	9.38	29.7	8.0	11.5	2.88	4.34
	$2_{-3/2}$	3_1	$2_{1/2}$	56.3	178	13.6	42.9	11.8	16.2	4.26	6.1
	$2_{1/2}$	3_{-1}	$2_{-3/2}$	82.3	260	19.2	60.6	13.6	19	4.93	7.0
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	3_{-1}	$2_{1/2}$	3_0	71	225	17	53.6	13.1	18.1	4.04	6.97
	3_0	$2_{-1/2}$	3_{-1}	23.4	75	5.29	16.9	7.3	7.69	2.73	4.03
$M_{\text{BSM,charged}}^{\text{max}}$ (max in each column)				**95.5**	**359**	**19.4**	**73**	**20.1**	**30**	**8.41**	**12.3**

Consistent with parametric expectation: $\Delta a_\mu \propto \frac{m_\mu g_{\text{BSM}} v}{M_{\text{BSM}}^2}$, $M_{\text{BSM}} \simeq 20 \text{ TeV}$

$$M_{\text{BSM,charged}}^{\text{max,unitarity}} \approx (100 \text{ TeV}) \cdot N_{\text{BSM}}^{1/2}$$

From unitarity alone, $(g-2)_\mu$ could be explained by ~ 100 TeV charged states

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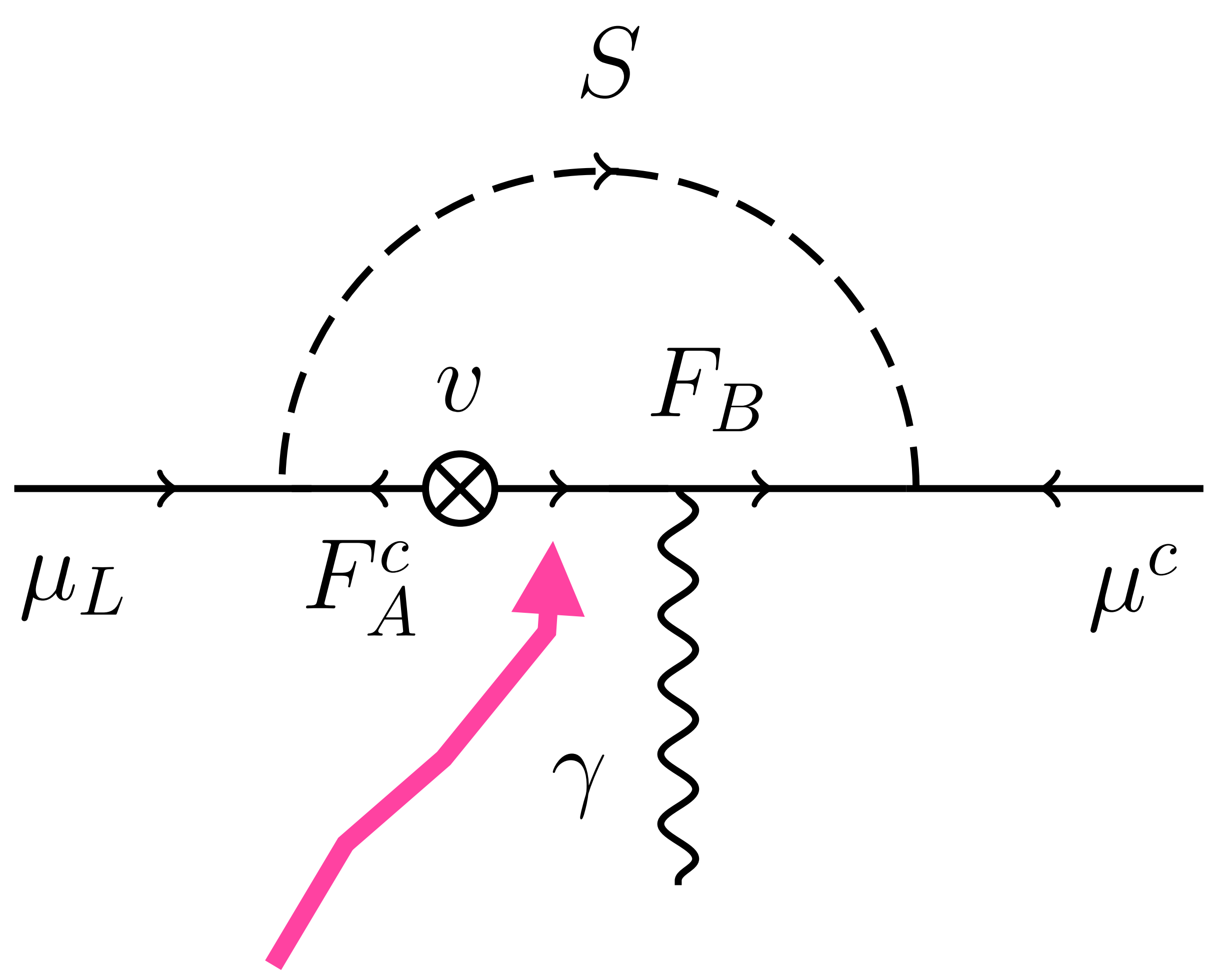
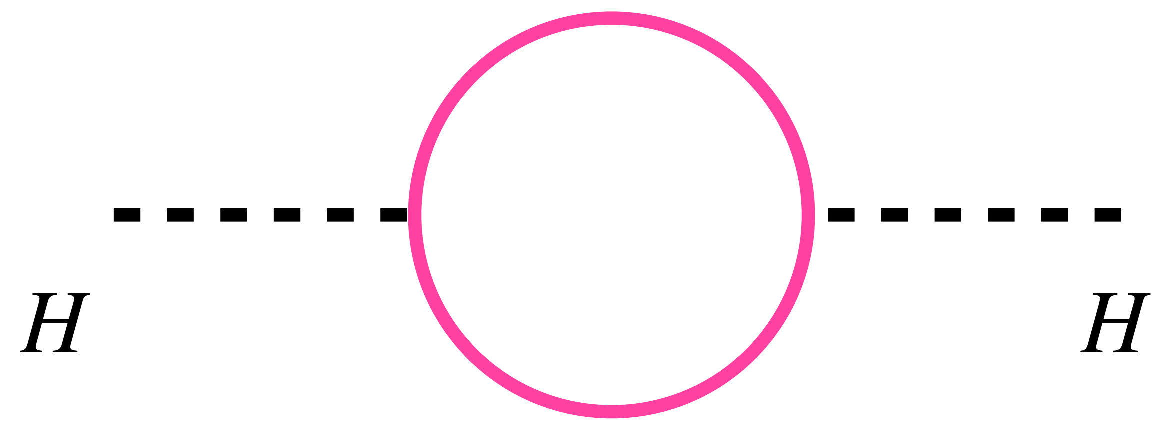
But let's put our (model-agnostic) theorist hat back on. What would this *mean* for nature/physics/the universe?

The Hierarchy Problem Made Real



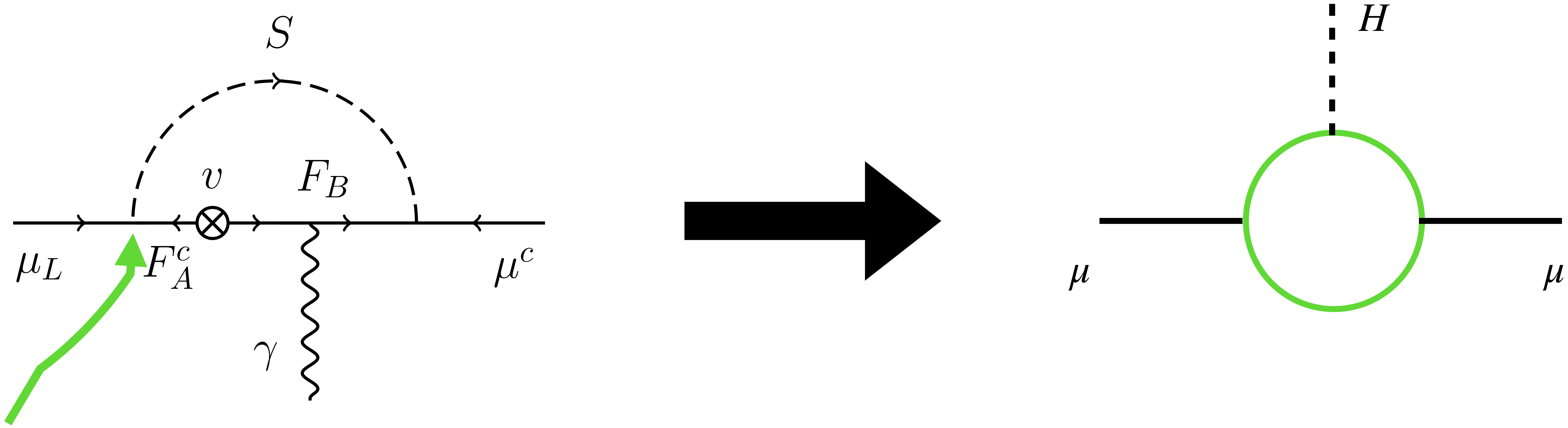
100 TeV BSM state
with huge coupling
to the Higgs



$$\Delta m_H^2 \sim \frac{1}{4\pi} g_{SM}^2 m_{BSM}^2 \gg (125 \text{ GeV})^2$$

If $(g-2)_\mu$ is explained by such crazy heavy physics, then there **have to be** calculable, finite but **large** Higgs mass corrections.

… but wait, there's more: a μ-archy Problem!



new fermions couple to
muon and share its
chiral symmetry

$$\Delta y_\mu \sim \frac{1}{4\pi^2} g_{BSM}^3$$

Calculable, finite but **large** muon Yukawa correction.

Muon mass no longer technically natural!

Discovering these super-high-scale BSM solutions to $(g-2)_\mu$ would *prove* that the universe is *calculably* fine-tuned!

So what would happen if the universe is *not* super-fine-tuned?

Impose conservative naturalness constraint

Let's "allow" both the Higgs and muon mass to be 1% tuned.

This stops couplings and masses from being super-large and lowers the charged mass upper bound.

$$M_{\mathrm{BSM,charged}}^{\mathrm{max,naturalness}} \approx (20\,\mathrm{TeV}) \cdot N_{\mathrm{BSM}}^{1/6}$$

That's more like it!

Model	R	R_A	R_B	Highest possible mass (TeV) of lightest charged BSM state: Unitarity only, N_{BSM}: 1	Unitarity only, 10	Unitarity + MFV, N_{BSM}: 1	Unitarity + MFV, 10	Unitarity + Naturalness, N_{BSM}: 1	Unitarity + Naturalness, 10	Unitarity + Naturalness + MFV, N_{BSM}: 1	Unitarity + Naturalness + MFV, 10
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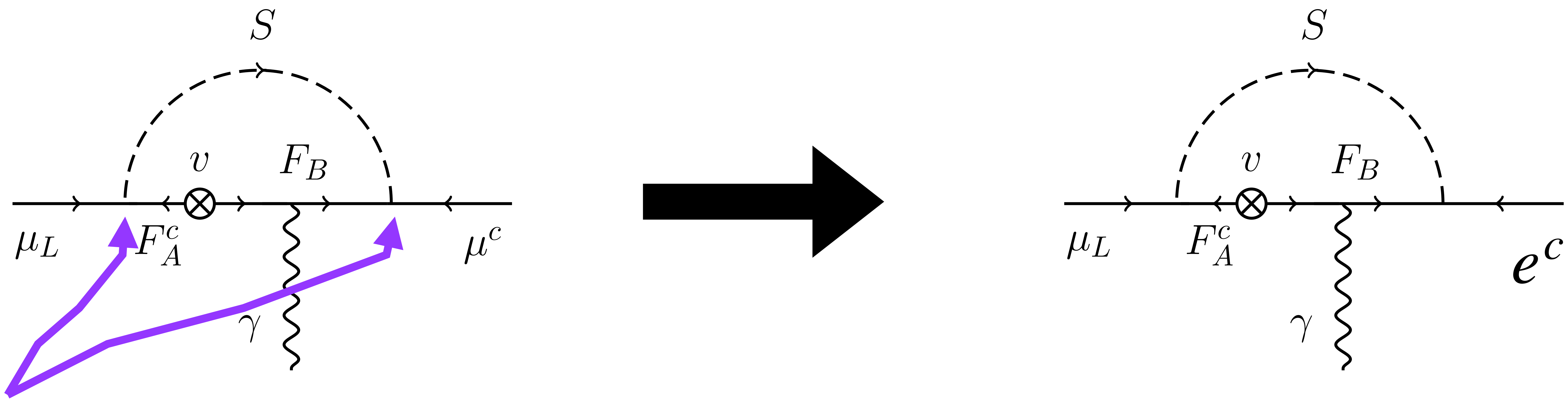
$M_{\mathrm{BSM,charged}}^{\mathrm{max}}$ (max in each column)				**95.5**	**359**	**19.4**	**73**	**20.1**	**30**	**8.41**	**12.3**

Any notion of (calculable, concrete, conservative) naturalness pushes the upper bound to the ~10 TeV scale.

...

What about Flavour?

Flavour Constraints



What if these couplings also talk to the other leptons?

Charged Lepton-Flavour-violating (CLFV) decay!

Flavour Constraints

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

$$\Rightarrow \quad \frac{y^e_{1,2}}{y^\mu_{1,2}} \lesssim 10^{-5} \quad , \quad \frac{y^\tau_{1,2}}{y^\mu_{1,2}} \lesssim 10^{-1} \quad , \quad \frac{y^\tau_{1,2}}{y^\mu_{1,2}}\frac{y^e_{1,2}}{y^\mu_{1,2}} \lesssim 10^{-1}$$

Flavour-anarchic models highly disfavoured!

There needs to be some kind of flavour structure.

Simplest ansatz for avoiding CLFVs: Minimal Flavour Violation (MFV)!

All flavour violation ~ SM Yukawas.

Impose Minimal Flavour Violation

Some Muon-type and Tau-type BSM couplings are then related by $m_\tau / m_\mu \approx 17$.

The larger Tau-type coupling has to obey the unitarity bound.

$$M_{\text{BSM,charged}}^{\text{max,MFV}} \approx (20\,\text{TeV}) \cdot N_{\text{BSM}}^{1/2} .$$

Flavour points us below 20 TeV as well!

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Flavour or Naturalness separately impose ~ 20 TeV charged mass upper bounds.

They're both pretty important. What if we impose them together?

Impose MFV + Naturalness

$$M_{\text{BSM,charged}}^{\text{max,naturalness,MFV}} \approx (9\,\text{TeV}) \cdot N_{\text{BSM}}^{1/6}$$

10 TeV scale, with little dependence on BSM multiplicity!

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	1_1	$2_{-3/2}$	1_{-2}	73.2	231	17.4	55	13.9	19.7	5.04	7.25
	$2_{-1/2}$	3_0	$2_{-1/2}$	40	126	9.38	29.7	8.0	11.5	2.88	4.34
	$2_{-3/2}$	3_1	$2_{1/2}$	56.3	178	13.6	42.9	11.8	16.2	4.26	6.1
	$2_{1/2}$	3_{-1}	$2_{-3/2}$	82.3	260	19.2	60.6	13.6	19	4.93	7.0
	$2_{-1/2}$	1_0	$2_{-1/2}$	37.3	118	8.87	28	12.3	18.7	4.6	7.04
	$2_{-3/2}$	1_1	$2_{1/2}$	67.3	213	15.8	50	13.5	18.8	4.86	6.93
	$2_{1/2}$	1_{-1}	$2_{-3/2}$	46.2	146	11.2	35.4	9.83	13.8	3.49	5.18
	3_{-1}	$2_{1/2}$	3_0	71	225	17	53.6	13.1	18.1	4.04	6.97
	3_0	$2_{-1/2}$	3_{-1}	23.4	75	5.29	16.9	7.3	7.69	2.73	4.03
$M_{\text{BSM,charged}}^{\text{max}}$ (max in each column)				**95.5**	**359**	**19.4**	**73**	**20.1**	**30**	**8.41**	**12.3**

Charged BSM Particle Mass Upper Bounds

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

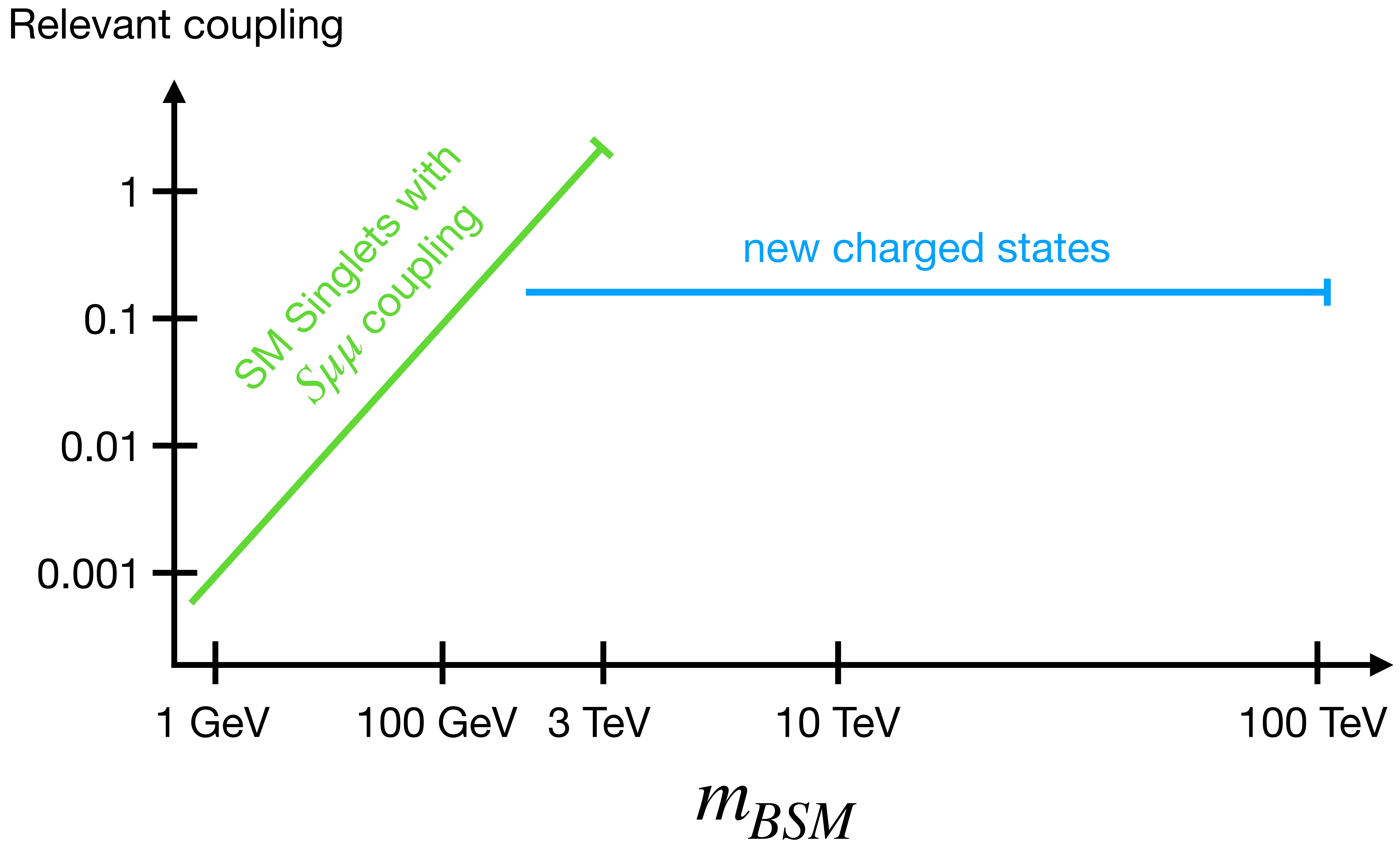
Any “reasonable” theory wants to live below 10 TeV.

Not discovering charged states below 10 TeV would then be ***proof*** *of a tuned universe with flavour weirdness*

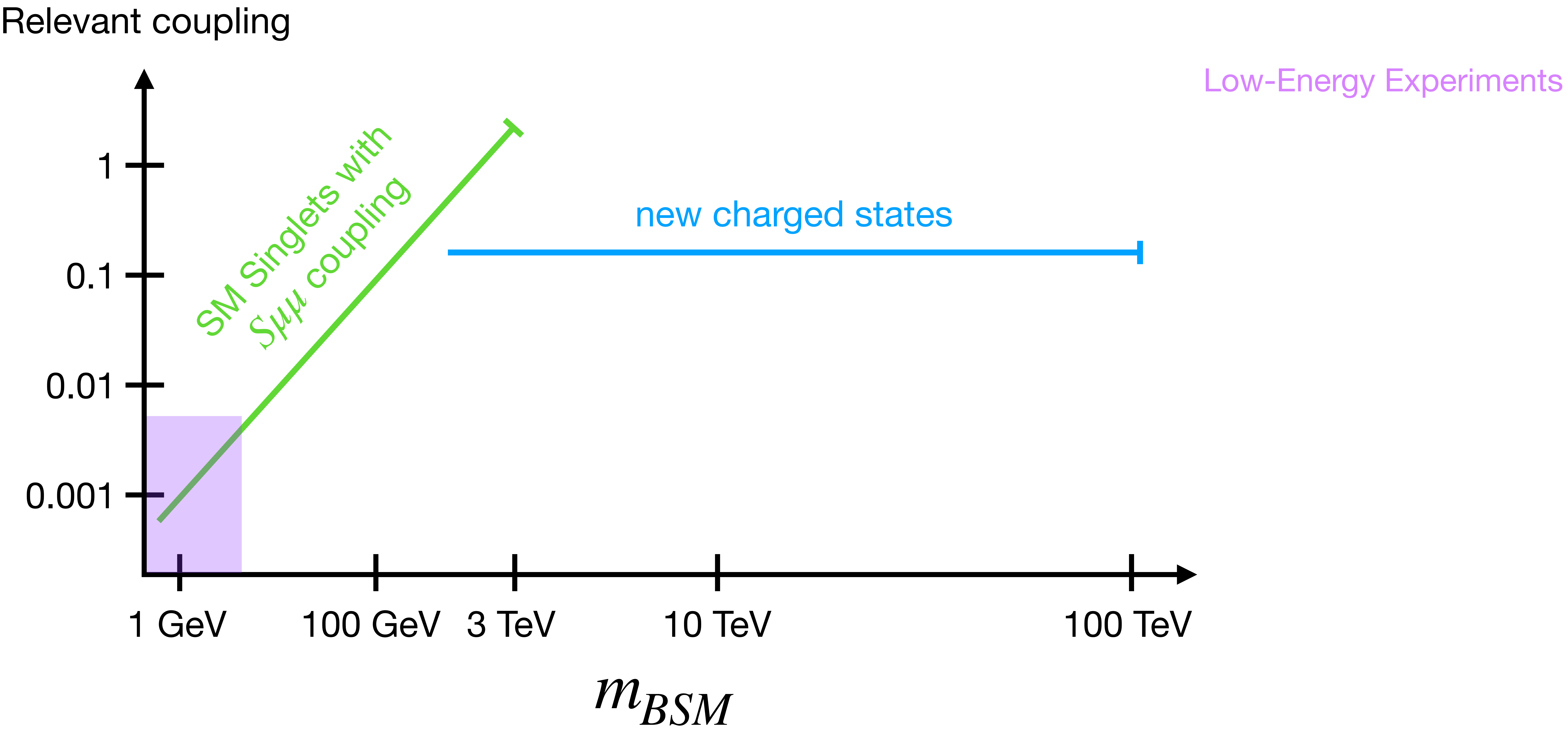
Experimental Target for discovering BSM

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

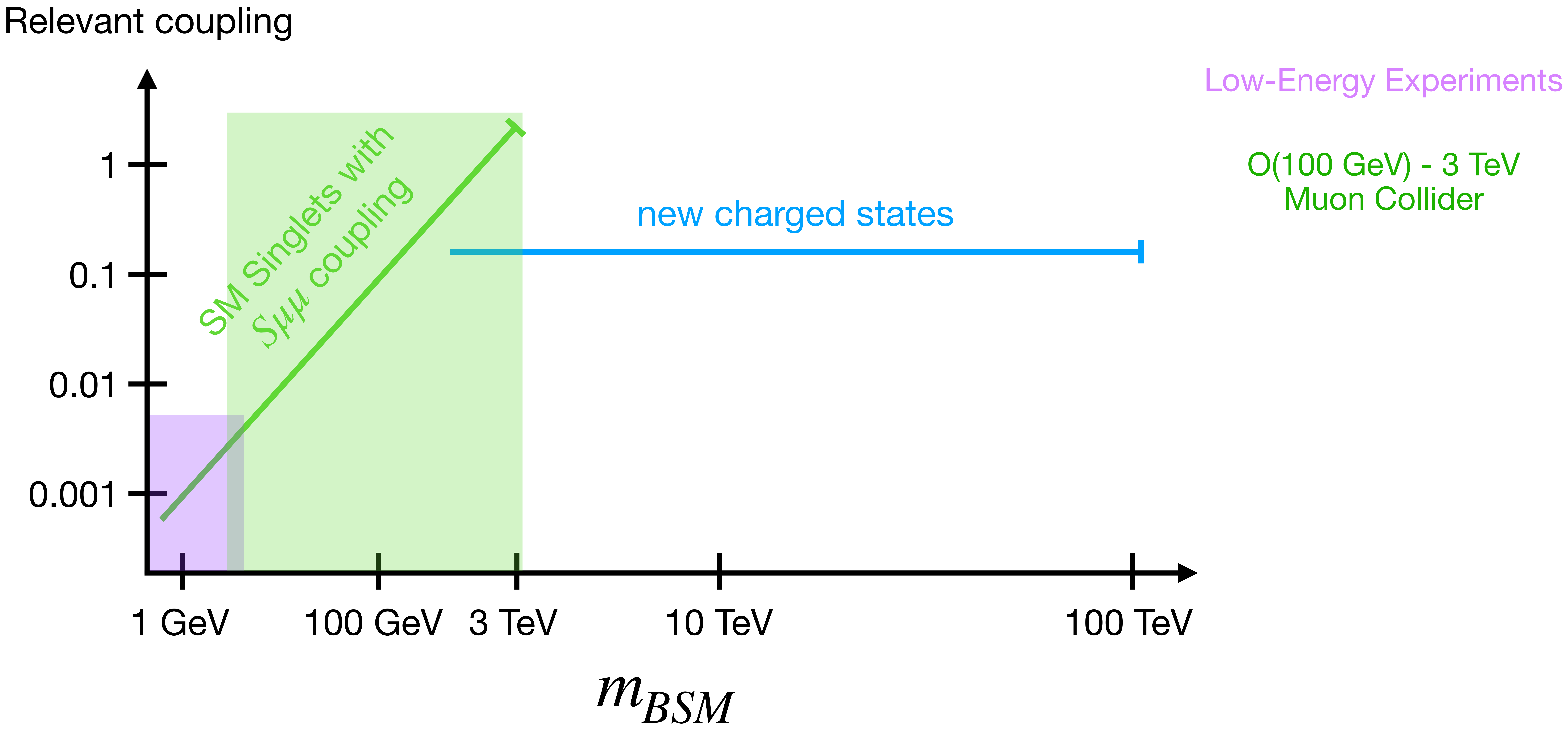
Irreducible Signatures of $(g-2)_\mu$ Solutions



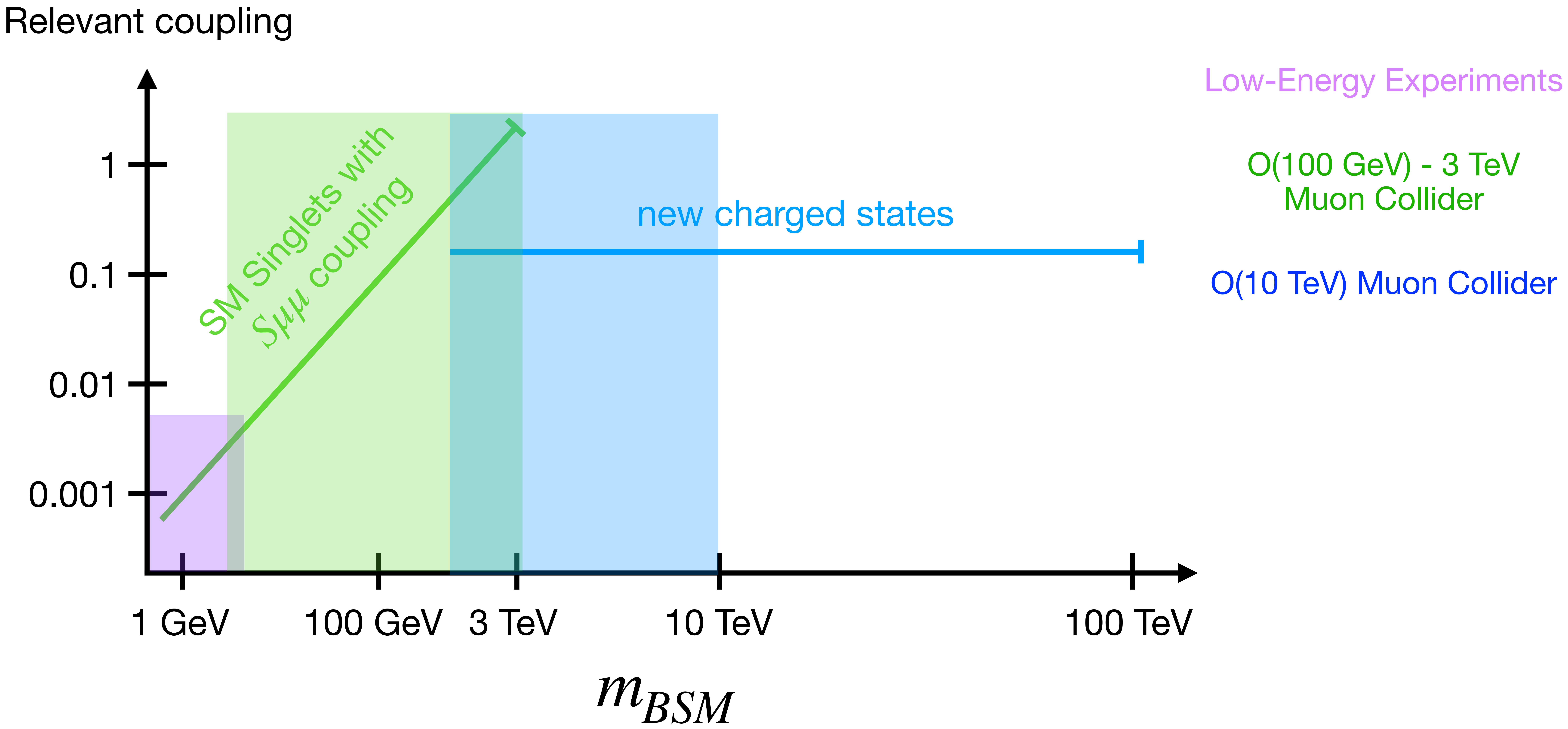
Irreducible Signatures of $(g-2)_\mu$ Solutions



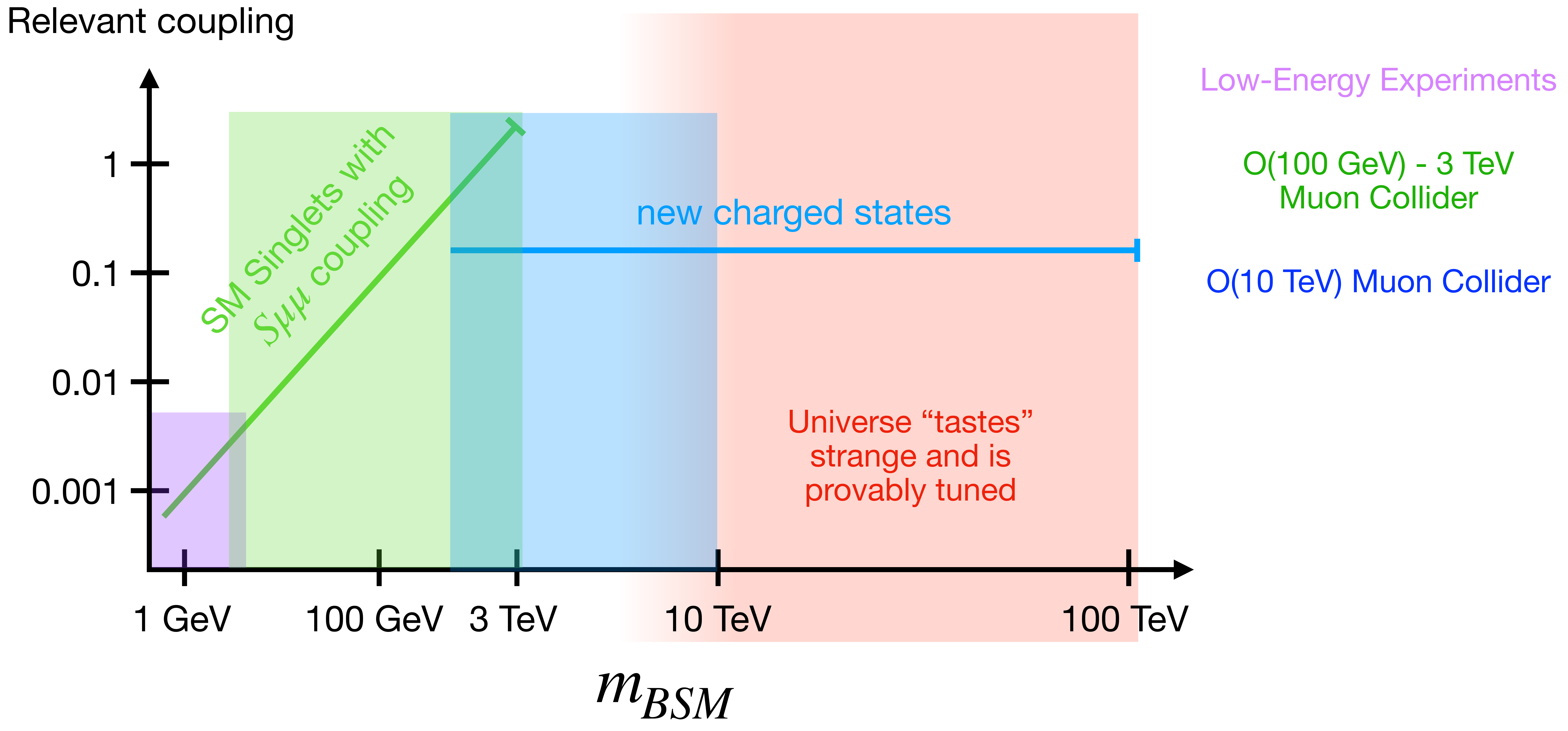
Irreducible Signatures of $(g-2)_\mu$ Solutions



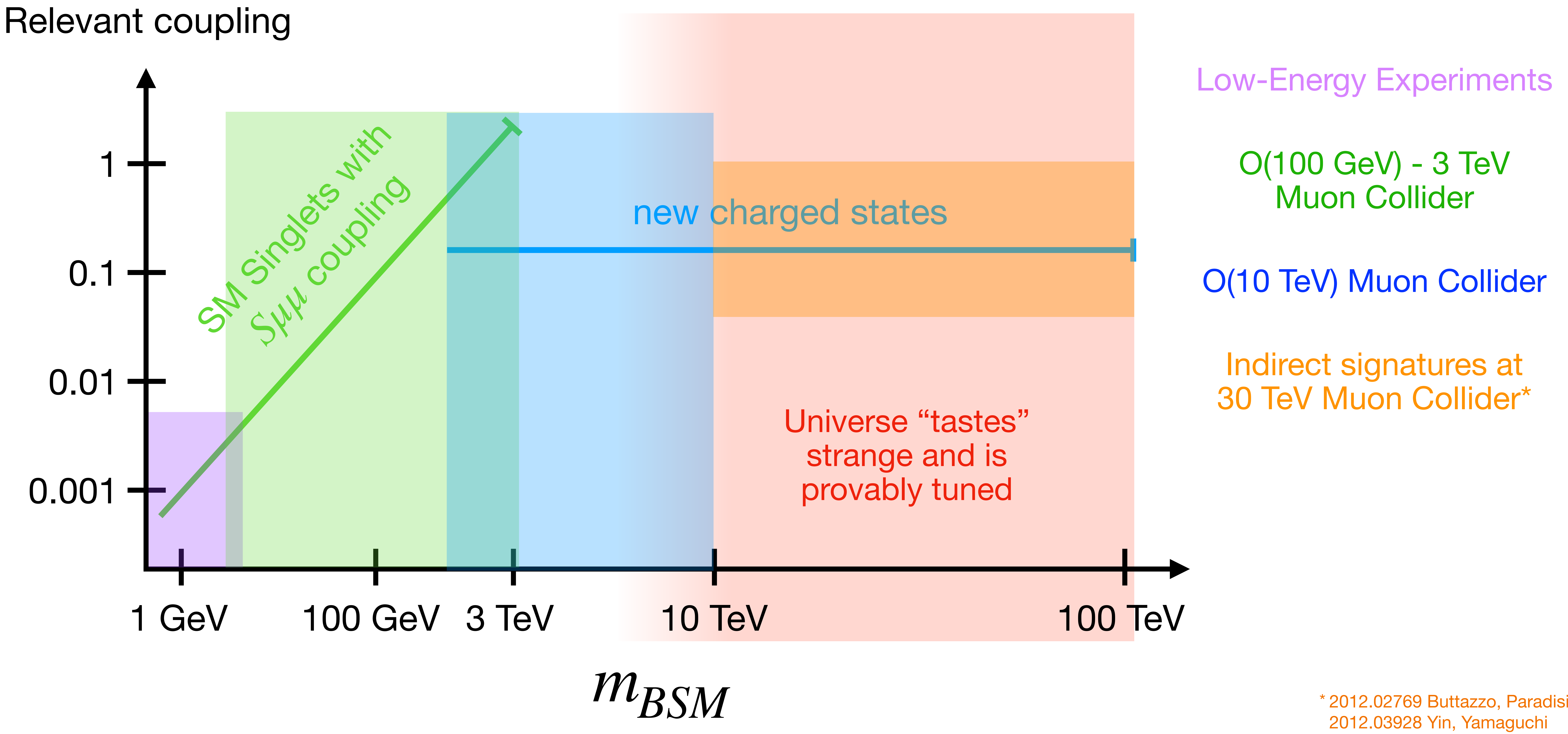
Irreducible Signatures of $(g-2)_\mu$ Solutions



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



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



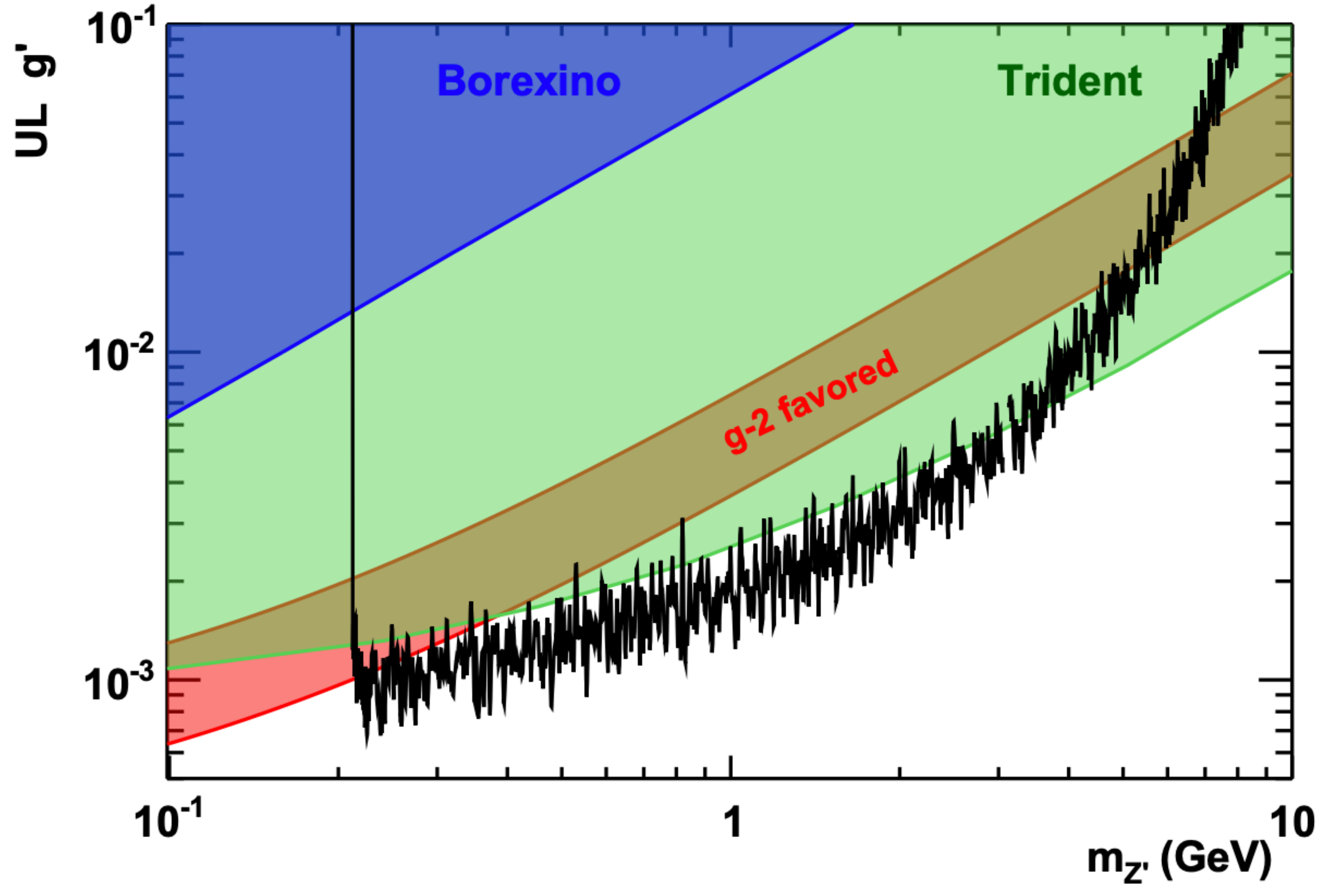
* 2012.02769 Buttazzo, Paradisi
2012.03928 Yin, Yamaguchi

Low Energy Experiments

Intensity Frontier Experiments

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

BaBar Collaboration 1606.03501



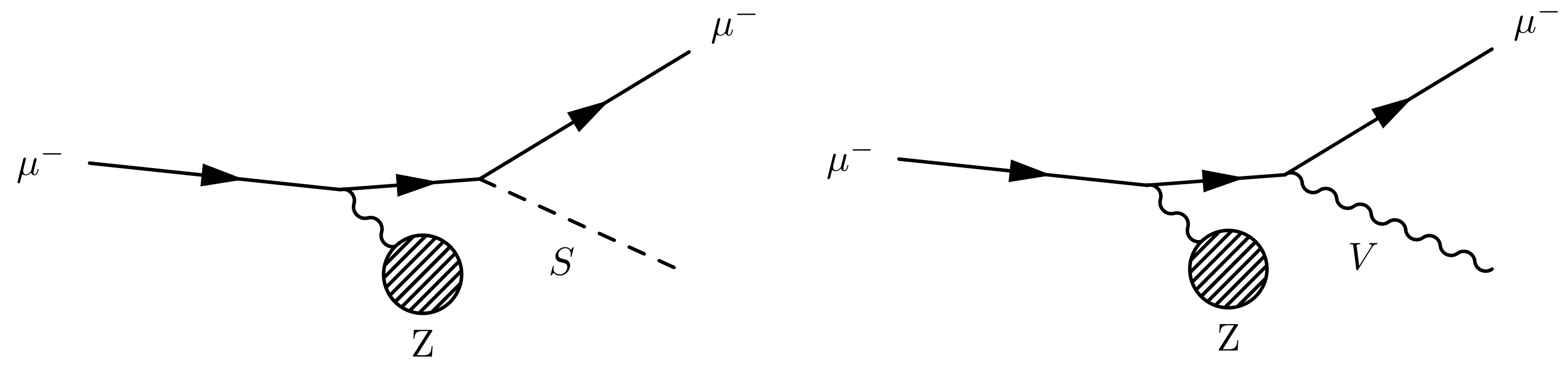
See also e.g.:

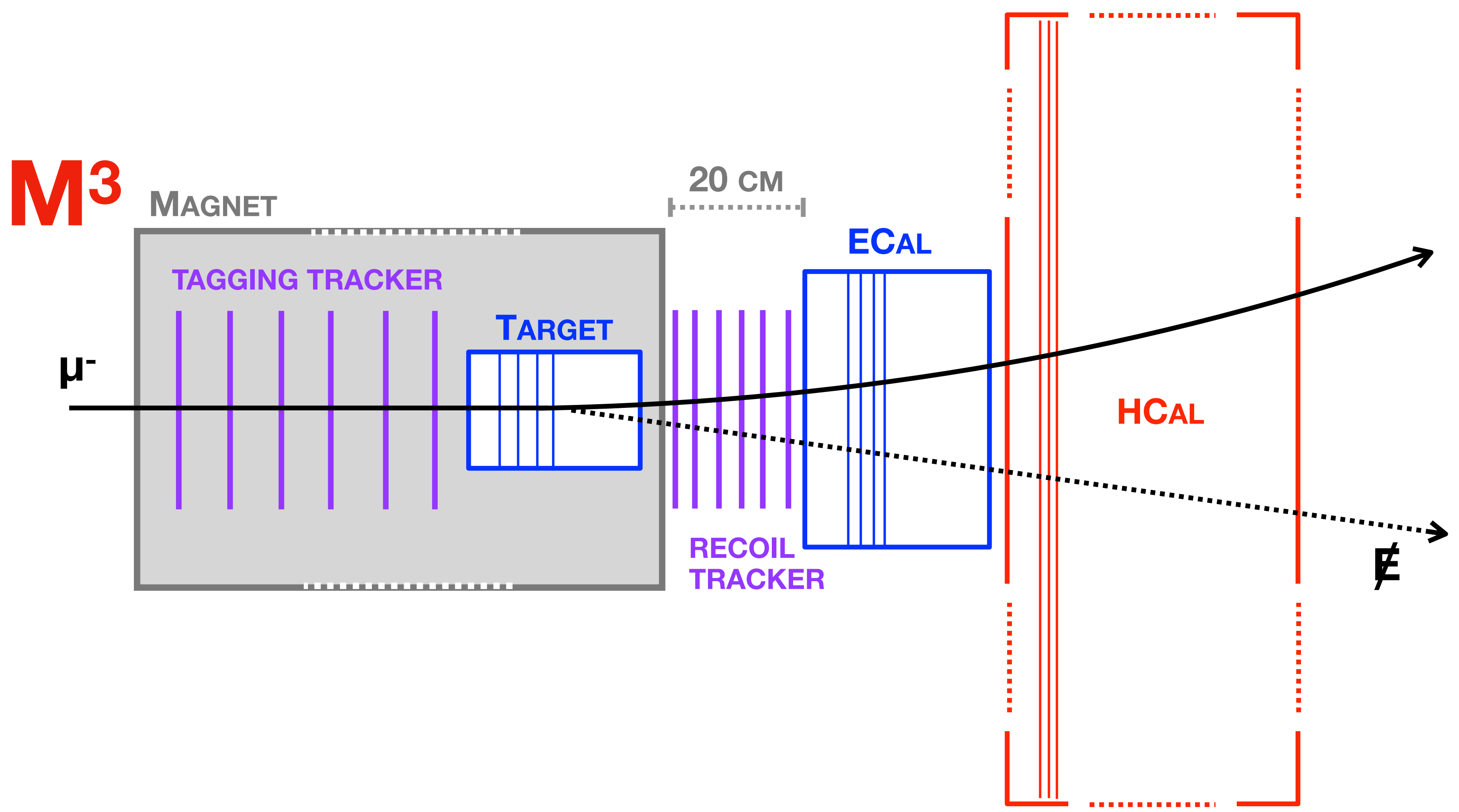
Mohlabeng 1809.07768
Dark Sector Community Report 1707.04591
SHiP physics case 1504.04855
Krnjaic 1512.04119
Batell, Freitas, Ismail, McKeen 1712.10022
Chen, Pospelov, Zhong, 1701.07437
Bauer, Foldenauer, Jaeckel, 1803.05466

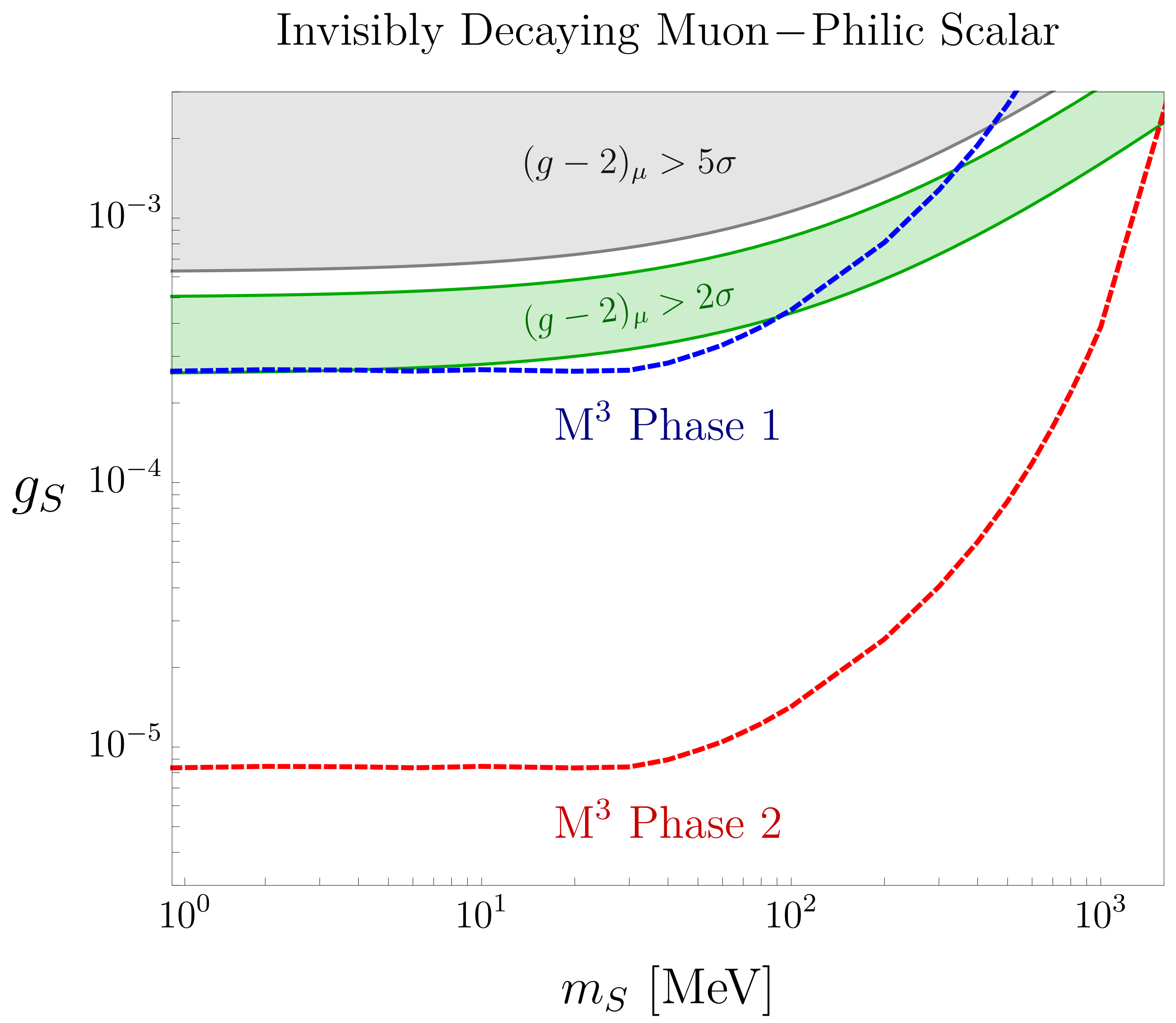
Muon Fixed Target Experiment

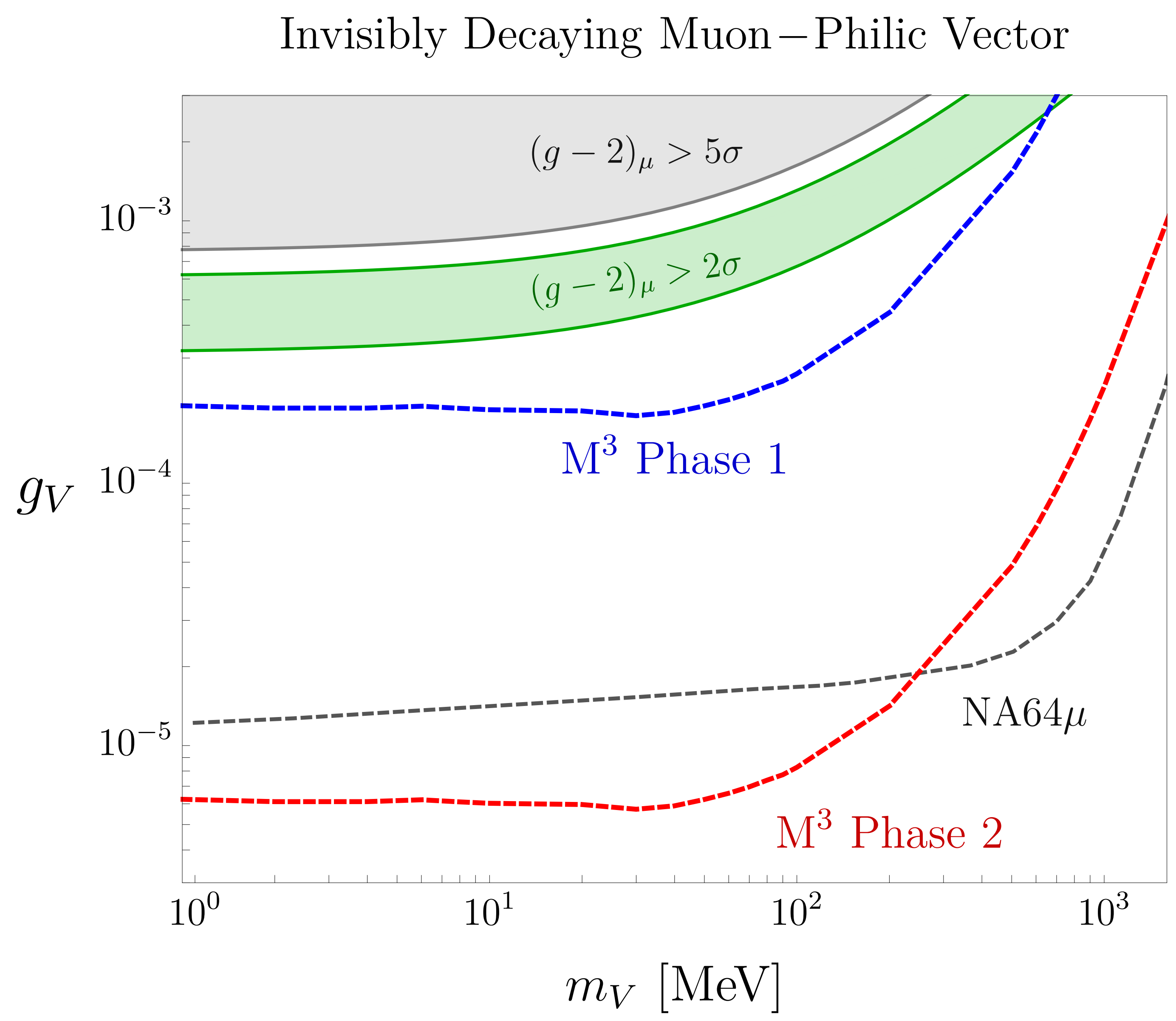
Could do fully inclusive search for $\lesssim$ few GeV singlet coupling to muon.

M³ proposal at Fermilab / NA64μ at CERN: Complete coverage for 15 / 150 GeV muon beam on target.









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: not a crazy idea

A lepton collider to reach the highest energies?

Muon Colliders 1901.06150

The Muon Collider Working Group

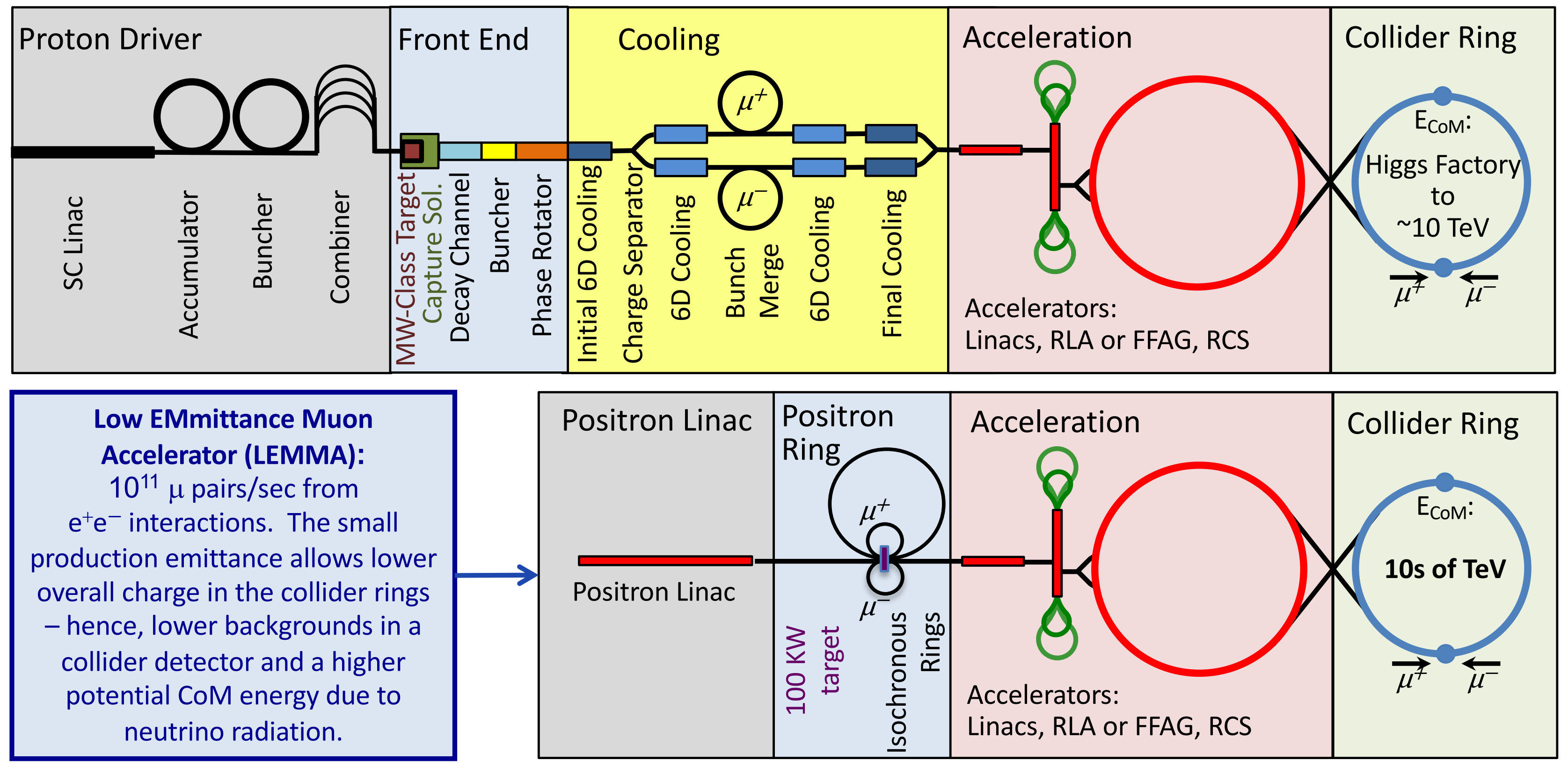
Jean Pierre Delahaye[1], Marcella Diemoz[2], Ken Long[3], Bruno Mansoulié[4], Nadia Pastrone[5] (chair), Lenny Rivkin[6], Daniel Schulte[1], Alexander Skrinsky[7], Andrea Wulzer[1,8]

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]

Significant progress on muon cooling problem:

Hot muons from pions



or cold muons from positrons

APS April Meeting 2021

Saturday–Tuesday, April 17–20, 2021; Virtual; Time Zone: Central Daylight Time, USA

Session Index

Session B08: Muon Collider Symposium I

Focus Live

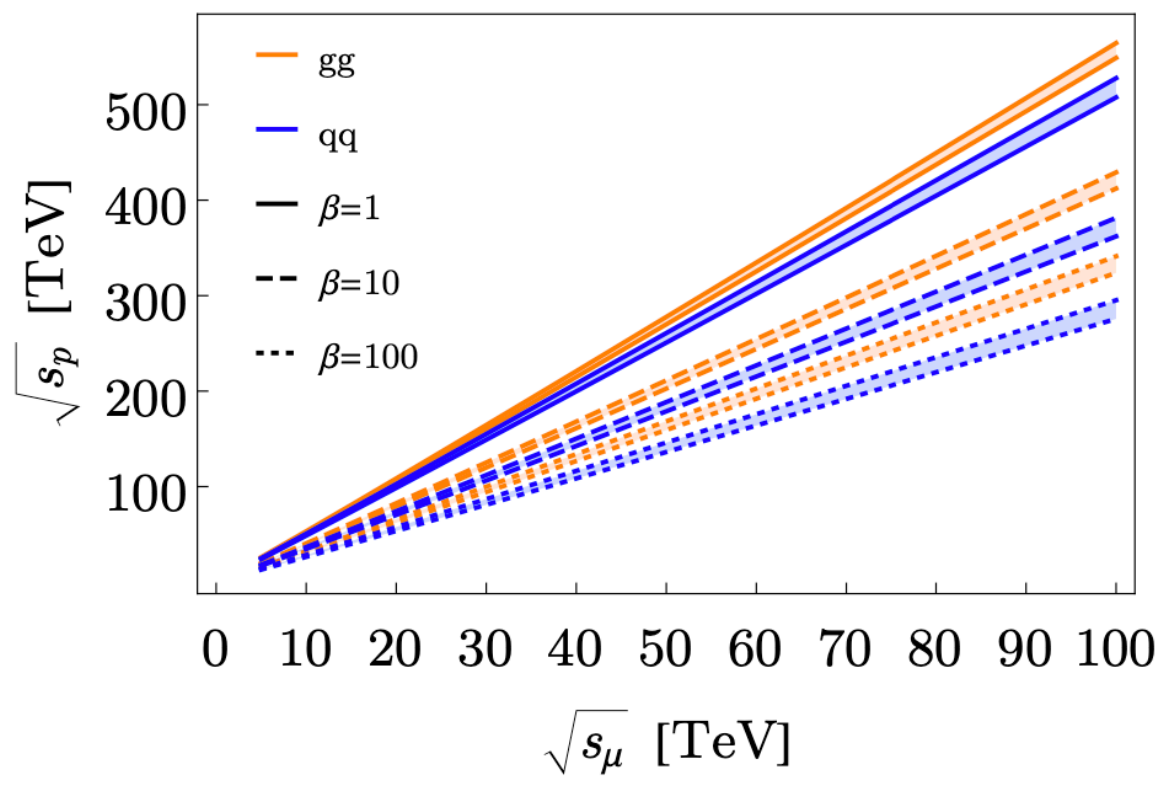
Sponsoring Units: DPB DPF
Chair: Nadia Pastrone, INFN

4 dedicated sessions at APS this year! Interest is there, g-2 is more "value added" for physics motivation

see Snowmass Muon Collider Forum for current status updates:
https://indico.fnal.gov/event/48416/

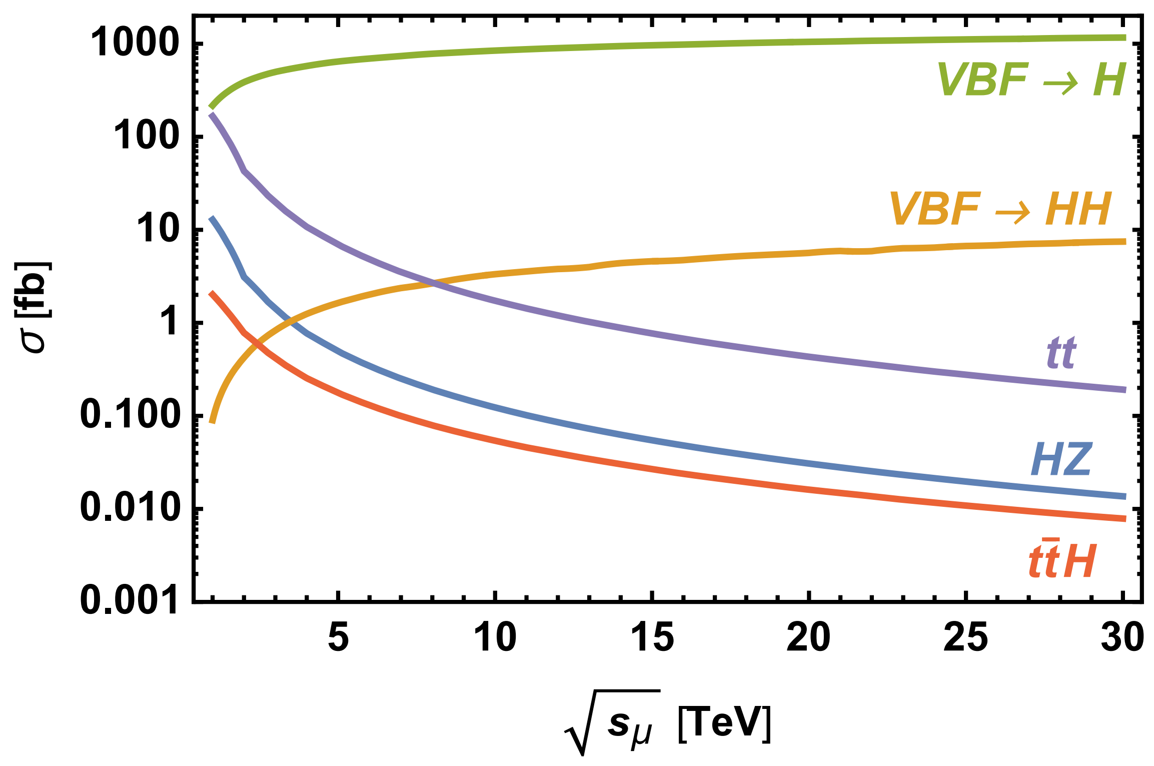
Muon Colliders: energy and precision

Colliding elementary particles allows full beam energy to go into new particle production.



Huge enhancement for VBF production of EW states with

$$m \ll \sqrt{s}$$



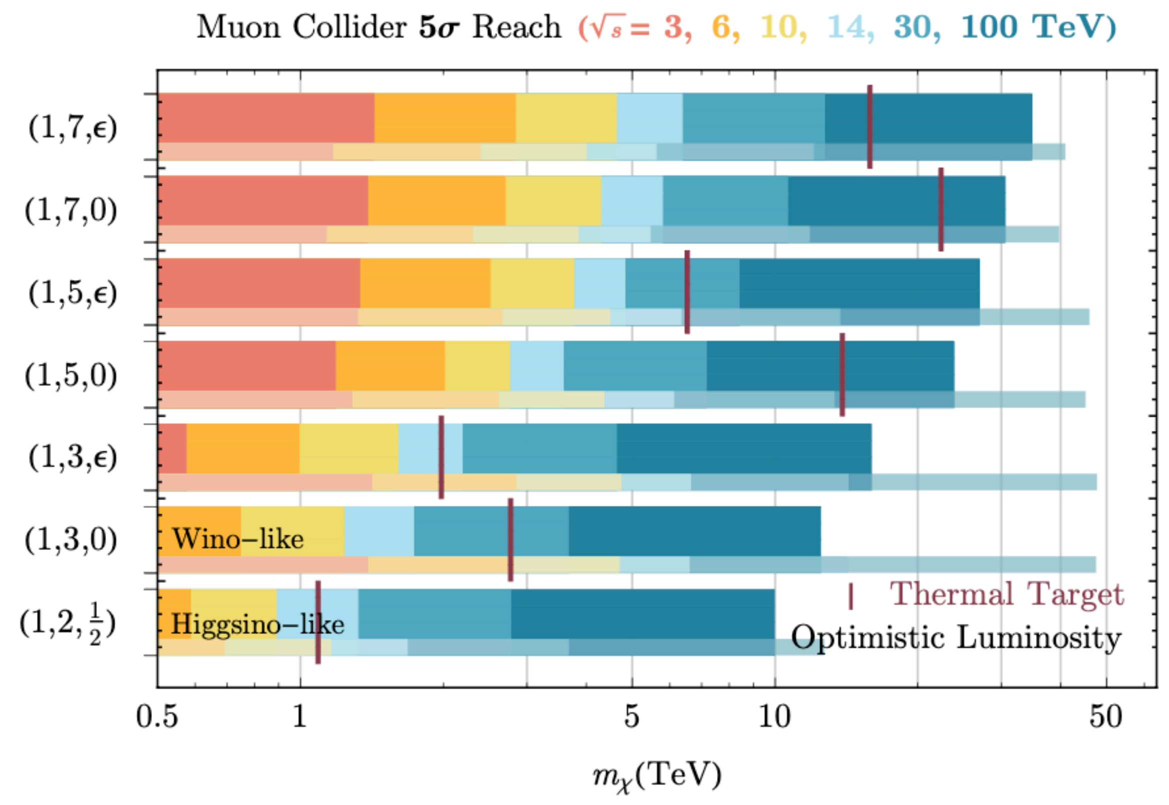
Higgs precision!

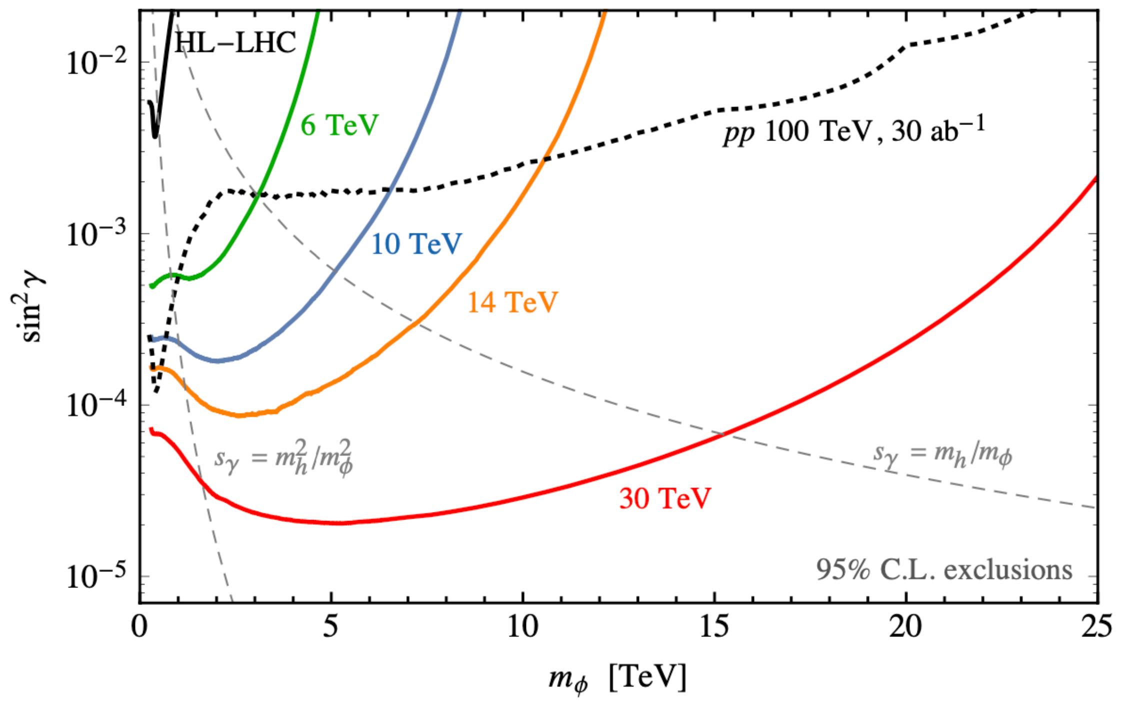
10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
W-fusion	bb	490	7.4	0.17
	cc	24	1.4	1.7
	jj	72	37	0.19
	$\tau^+\tau^-$	53	6.5	0.54
	$WW^*(jj\ell\nu)$	53	21	0.30
	$WW^*(4j)$	86	4.9	0.49
	$ZZ^*(4\ell)$	0.1	6.6	12
	$ZZ^*(jj\ell^+\ell^-)$	2.1	8.9	2.3
	$ZZ^*(4j)$	11	4.6	1.4
	$\gamma\gamma$	1.9	33	1.3
	$Z(jj)\gamma$	0.9	27	2.0
	$\mu^+\mu^-$	0.2	37	0.37
Z-fusion	bb	51	8.1	0.49
	$WW^*(4j)$	8.9	6.2	1.3
W-fusion tth	bb	0.06	12	12

High energy and high precision = 'best-of-both-worlds' BSM reach

If cooling problem can be solved, O(10 TeV) energies being considered.





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

Muon Smasher's Guide 2103.14043

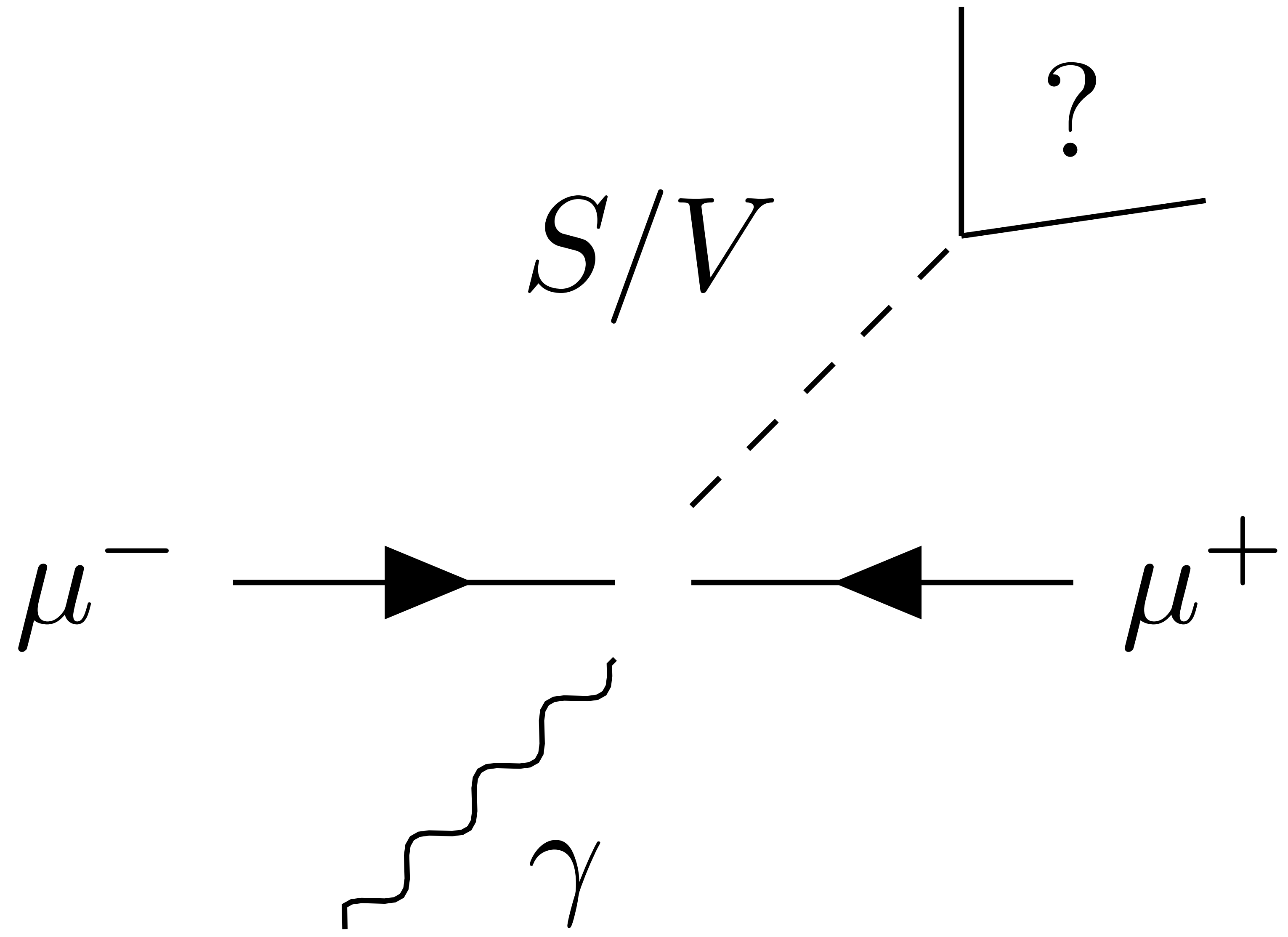
Muon colliders an incredibly attractive path to explore high energy physics.

Bonus:

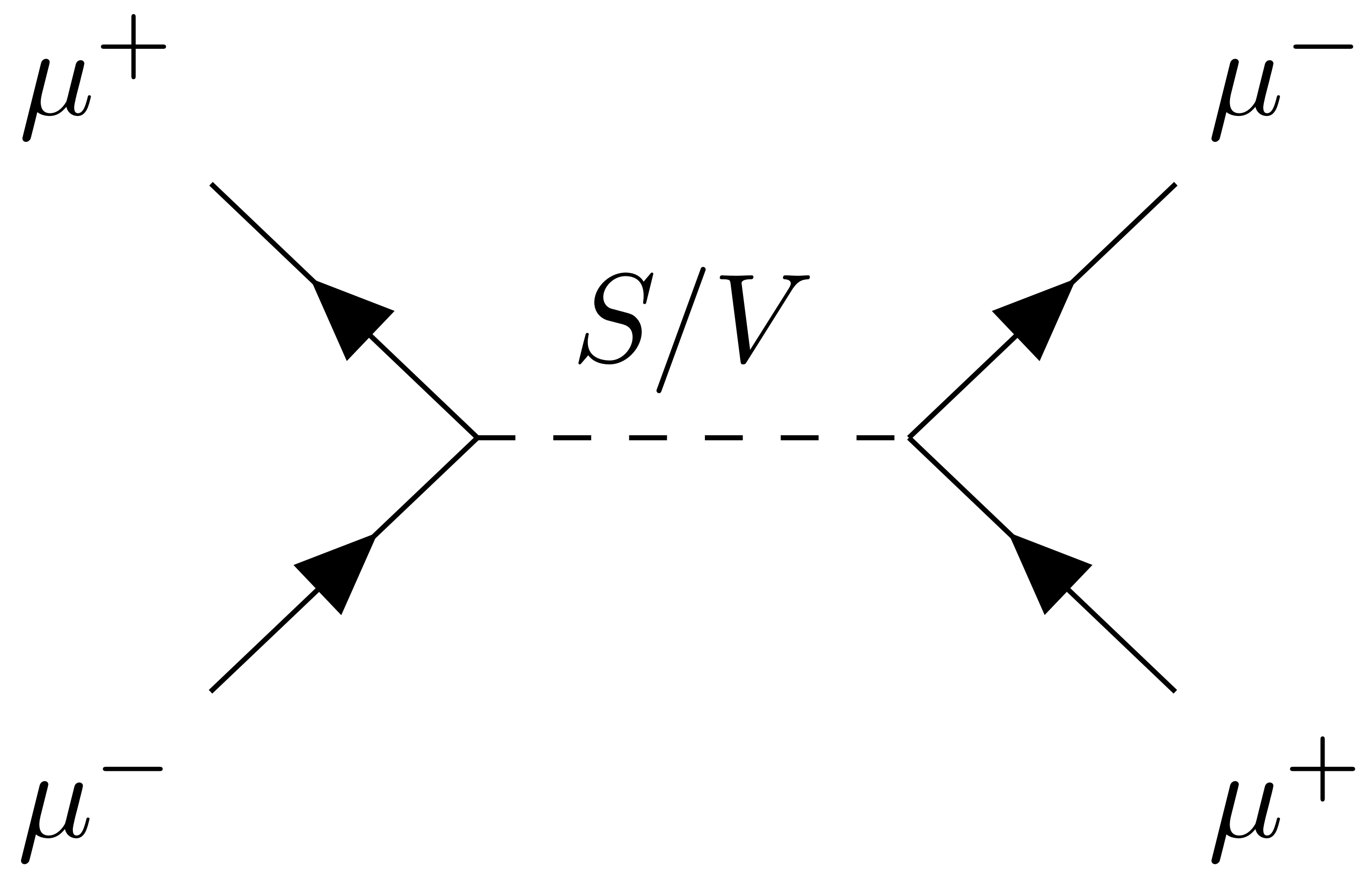
They are also “guaranteed” to discover the new physics of $(g-2)_\mu$

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

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



Indirect observation: corrections to
Bhabha scattering

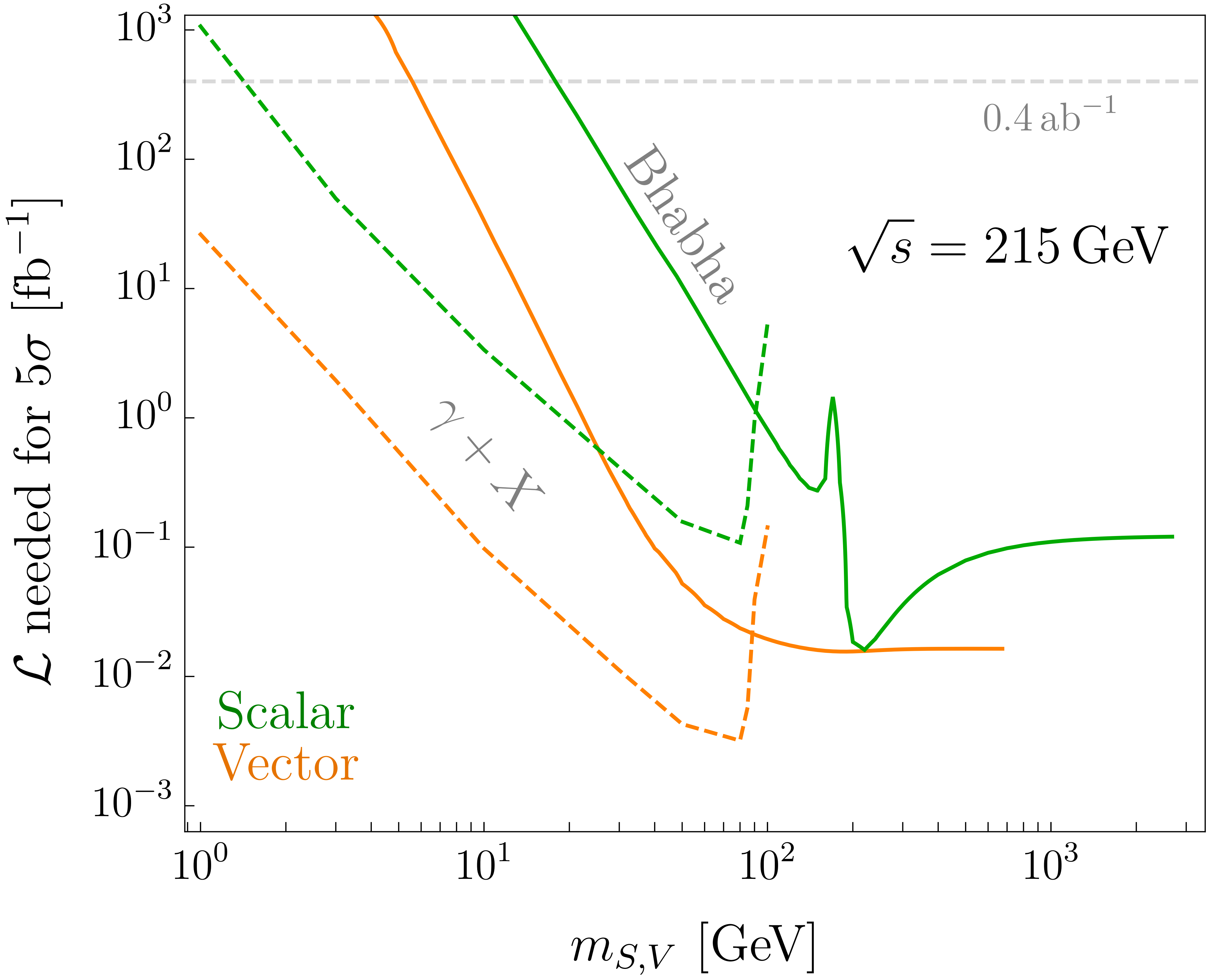


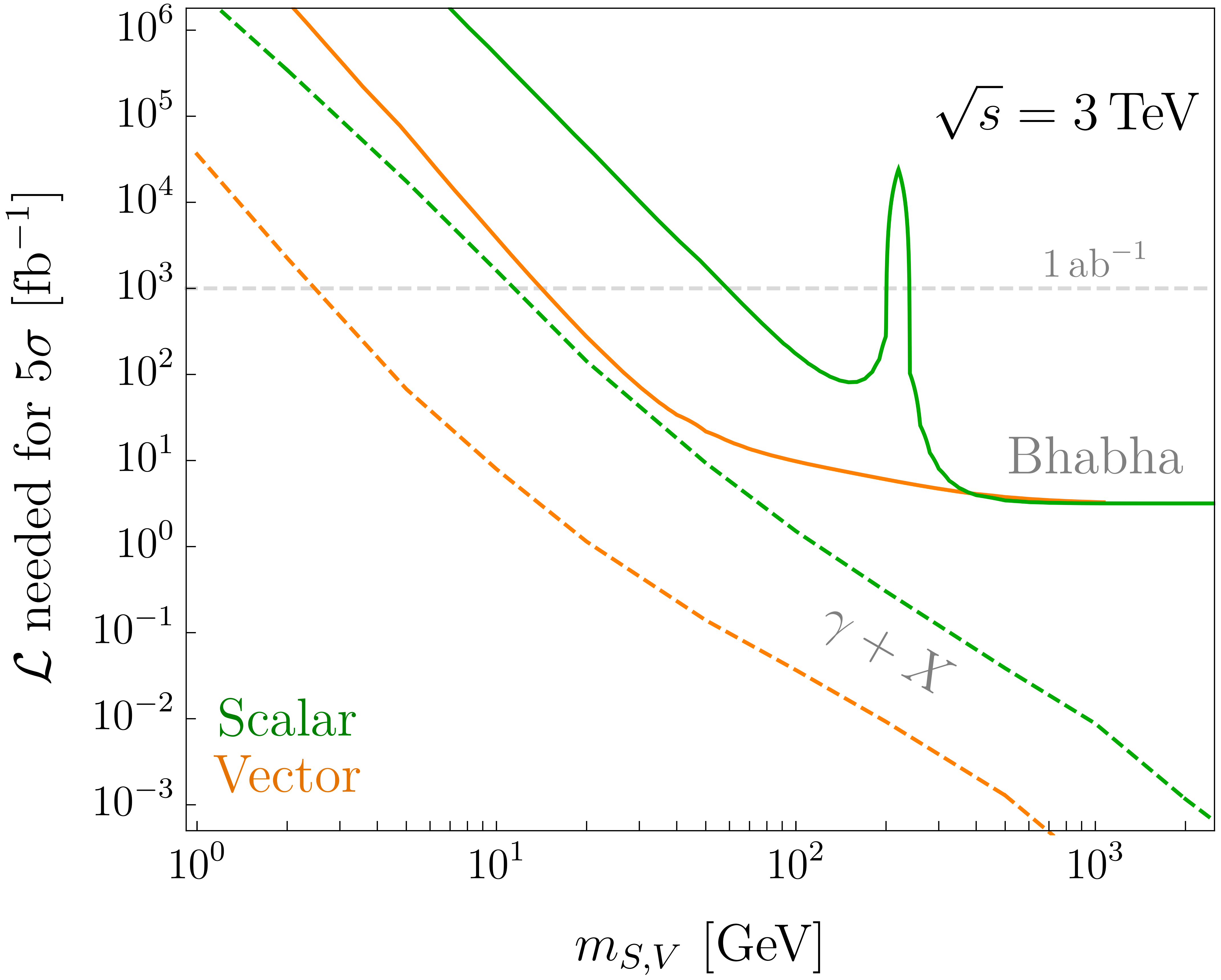
Only *guaranteed* coupling of singlet is to muons: Muon Collider is special!

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.

$\sqrt{s} \sim$ 10 TeV: Discovering EW Scenarios

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

Lepton collider: if you can make the charged state, you should be able to discover it regardless of decay mode. $\Rightarrow \sqrt{s} \gtrsim 2m_{\text{charged}}$

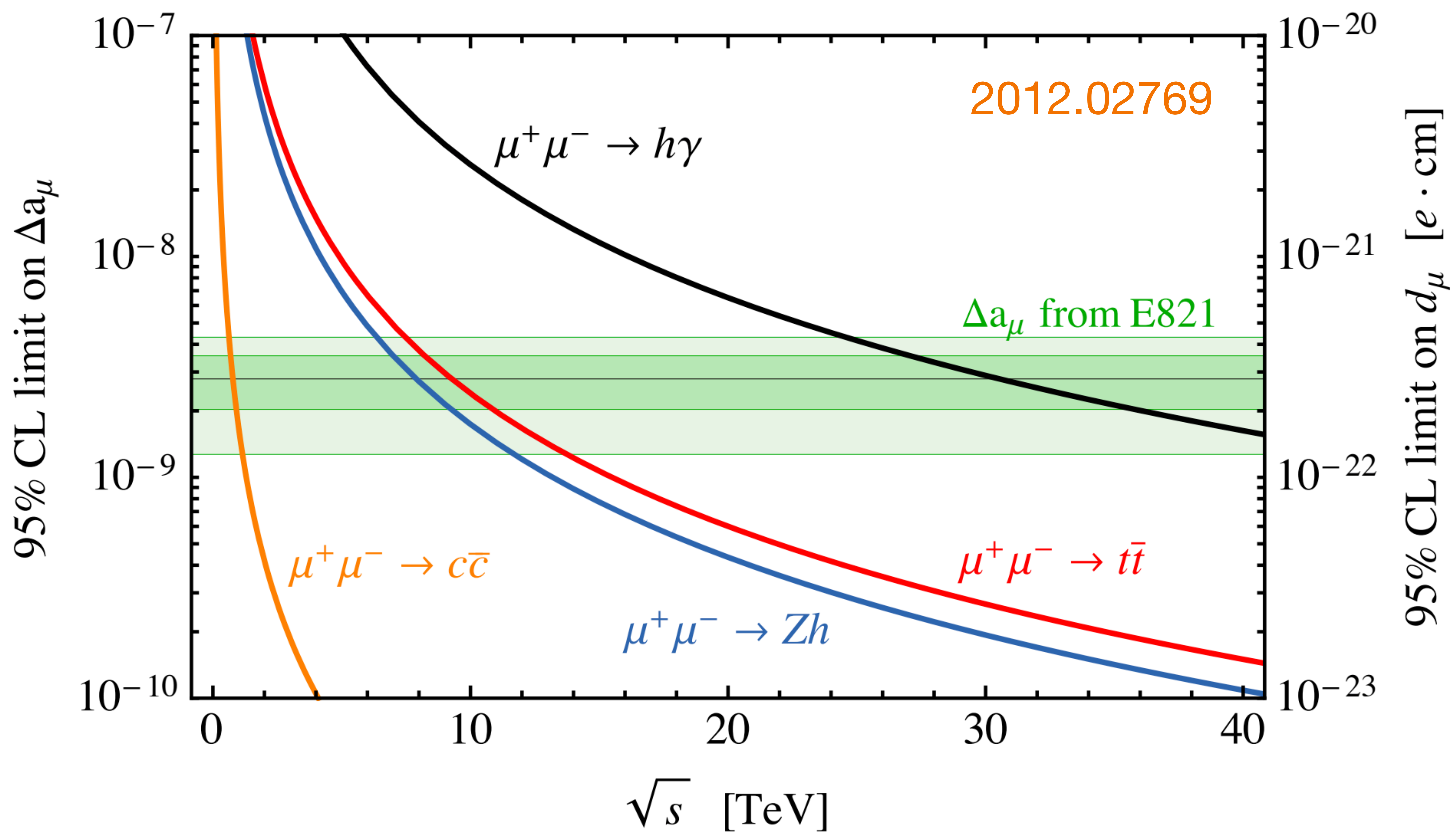
10 TeV muon collider covers by far the most motivated parameter space…
30 TeV if you "want to be sure" to catch all remotely natural possibilities.

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.**

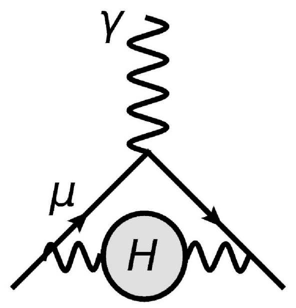
$\to$ Proof of a very weird and tuned universe!

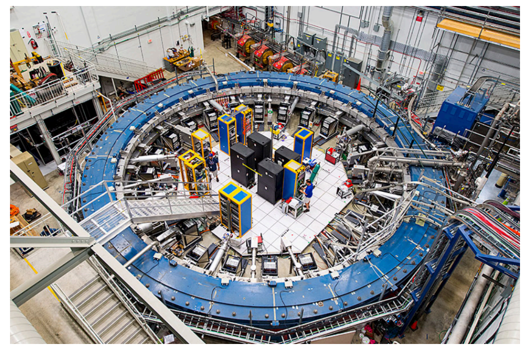
A no-lose theorem for $(g-2)_\mu$

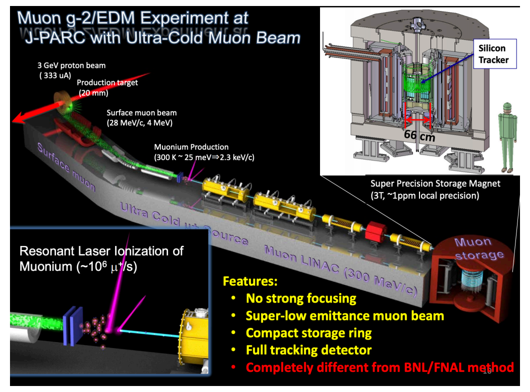
2006.16277, 2101.10334

Rodolfo Capdevilla, DC, Yonatan Kahn, Gordan Krnjaic

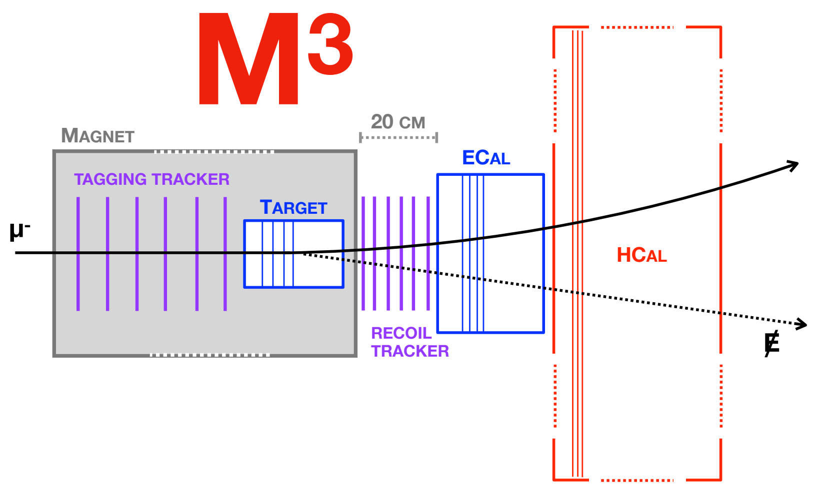
No-Lose Theorem for $(g-2)_\mu$



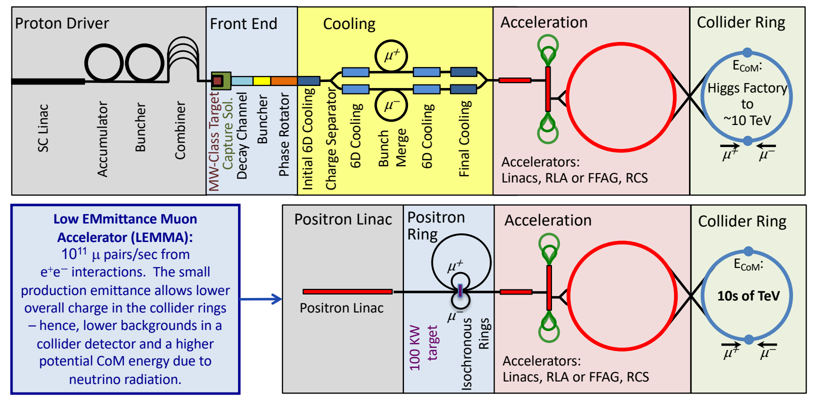




1. Confirm the $(g-2)_\mu$ anomaly is real.



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!