BSM explanations of muon g-2

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(Nanjing Normal University)

Fifth Plenary Workshop of the Muon g-2 Theory Initiative

@ The University of Edinburgh

Aim: Understand if there are *plausible* BSM explanations of the muon g-2 deviation

Not just "ambulance chasing" → Important stress test

Existence of plausible hypotheses must impact on how seriously we take this as a new physics signal

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- Get large enough corrections while evading collider limits?
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- Simultaneously explain other evidence/hints for new physics?

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* I think most people here are familiar with the broad answers
* But I will discuss these in a fresh way

Outline

- Overview of simple 1 or 2 field extension of the SM
- Special cases: dark photons, axions
- Heavy new physics: Leptoquarks , Vector-like leptons, 2HDM
- Heavy new physics that also explain dark matter
- Well motivated supersymmetric solutions

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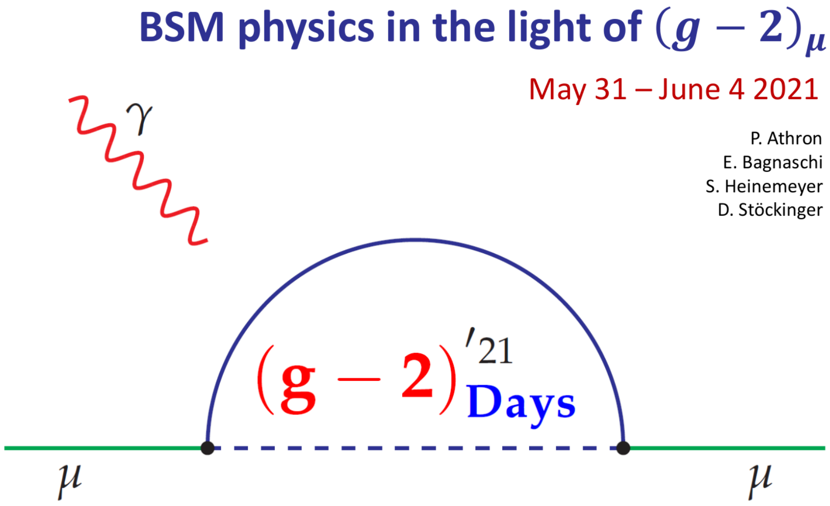
- Well motivated supersymmetric solutions

Will draw mostly from:

JHEP 09 (2021) 080,
[PA, C.Balázs, D.H.J. Jacob, W. Kotlarski,
D. Stöckinger, H. Stöckinger-Kim]

+ Recent literature, see also talks from:



http://pheno.csic.es/g-2Days21/

Minimal models for muon g-2: 1 field extensions

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\text{BNL}}$, Δa_μ^{2021}
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Excluded: $\Delta a_\mu < 0$
2 (2HDM)	0	$(\mathbf{1}, \mathbf{1}, 2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -1/2)$	Updated in Sec. 3.2
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated Sec. 3.3.
6	0	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	Excluded: LHC searches
7	0	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated Sec. 3.3.
9	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Excluded: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1}, \mathbf{1}, -1)$	Excluded: Δa_μ too small
12	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$	Excluded: LEP lepton mixing
13 (Dark photon)	1/2	$(\mathbf{1}, \mathbf{2}, -3/2)$	Excluded: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
16	1	$(\mathbf{1}, \mathbf{1}, 0)$	Special cases viable
17	1	$(\mathbf{1}, \mathbf{2}, -3/2)$	UV completion problems
18	1	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: LHC searches
19	1	$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	UV completion problems
20	1	$(\overline{\mathbf{3}}, \mathbf{1}, -5/3)$	Excluded: LHC searches
21	1	$(\overline{\mathbf{3}}, \mathbf{2}, -5/6)$	UV completion problems
22	1	$(\overline{\mathbf{3}}, \mathbf{2}, 1/6)$	Excluded: $\Delta a_\mu < 0$
23	1	$(\overline{\mathbf{3}}, \mathbf{3}, -2/3)$	Excluded: proton decay

Scalar leptoquarks: models 5–9

EXCLUDED

From:
JHEP 09 (2021) 080,
[PA, C.Balázs, D.H.J. Jacob, W. Kotlarski, D. Stöckinger, H. Stöckinger-Kim]

Builds on:
- JHEP 05 (2014) 145 [A. Freitas, J. Lykken, S. Kell & S. Westhoff],
- Phys. Rev. D 89 (2014) 095024 [F. S. Queiroz & W. Shepherd]
- JHEP 10 (2016) 002 [C. Biggio, M. Bordone, L. Di Luzio & G. Ridolfi],
- JHEP 10 (2016) 002 [C. Biggio & M. Bordone],
- JHEP 09 (2017) 112 [K. Kowalska & E. M. Sessolo]

Minimal models for muon g-2: 2 fields, different spin

$(SU(3)_C \times SU(2)_L \times U(1)_Y)_{\text{spin}}$	$+\mathbb{Z}_2$	Result for $\Delta a_\mu^{\text{BNL}}$, Δa_μ^{2021}
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Projected LHC 14 TeV exclusion, not confirmed
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	No	Excluded: LHC searches
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: LEP search
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{3},0)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{3},-1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
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$(\mathbf{1},\mathbf{3},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
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$(\mathbf{1},\mathbf{3},-1)_0 - (\mathbf{1},\mathbf{3},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},-1)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
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Why so difficult?

Many extensions ruled out by: I) wrong sign: corrections only decrease muon g-2
II) Tension with collider experiments

$$\Delta a_\mu^{2021} = (25.1 \pm 5.9) \times 10^{-10}$$

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$$\Delta a_\mu^{\mathrm{BSM}} \approx C_{\mathrm{BSM}} \frac{m_\mu^2}{M_{\mathrm{BSM}}^2} \qquad \Delta a_\mu^{2021} = (25.1 \pm 5.9) \times 10^{-10}$$

$$\text{Typically } C_{\mathrm{BSM}} \to \text{loop suppresion} \times \mathcal{O}(1) \text{ function of mass ratios.}$$

e.g. scalar leptoquark with

$$L_{LQ} = -\lambda Q_3 \cdot L_2 S_1 + \mathrm{h.c.}$$

$$\mathrm{C_{SLQ}} = \frac{\lambda^2}{64\Pi^2} E\left(\frac{m_t^2}{m_{S_1}^2}\right)$$

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For $\lambda = 3, E = 1$

$\Rightarrow M_{\text{BSM}} \approx 250\ \text{GeV}$

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$\Rightarrow M_{\rm BSM} \approx 250$ GeV

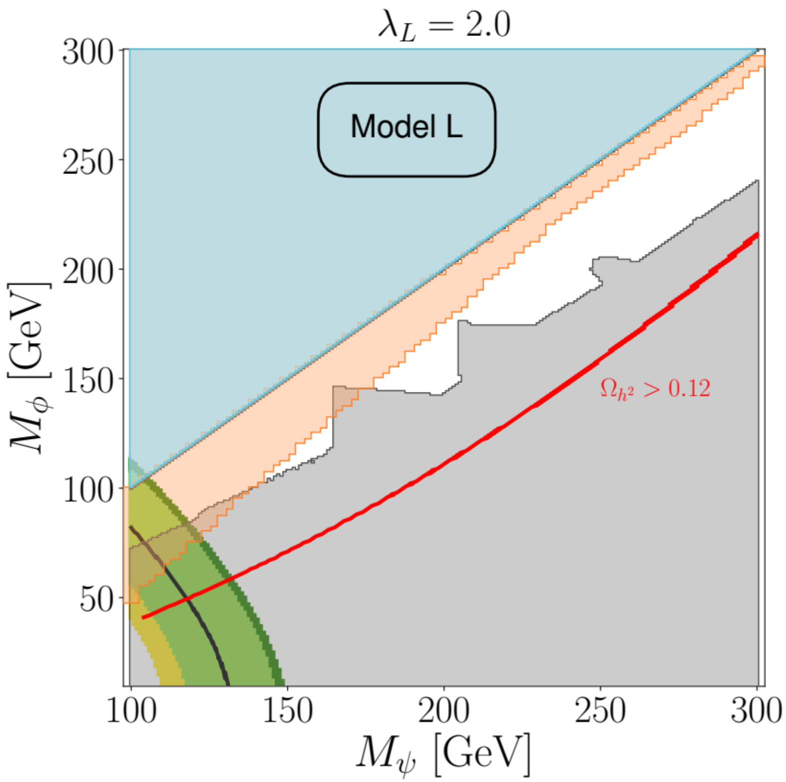
→ Generic scale of BSM physics explaining muon g-2 already probed by LHC, etc

Naive solutions have big tension between muon g-2 and collider limits

Try to evade limits with compressed spectra

Simple extension with scalar singlet and charged fermion doublet

$$\mathcal{L}_{\rm L} = (\lambda_L L \cdot \psi_d \phi - M_\psi \psi_d^c \psi_d + h.c.) - \frac{M_\phi^2}{2}|\phi|^2, \qquad C_{\rm BSM} = \frac{\lambda^2}{3\times 64\Pi^2} E(\frac{m_\psi^2}{m_\phi^2})$$



Fitting
2021 Muon g-2

Now Ruled Out

Still viable

Now viable

FlexibleSUSY 2.5.0 for muon g-2

For $\lambda_L = 2, E = 1$

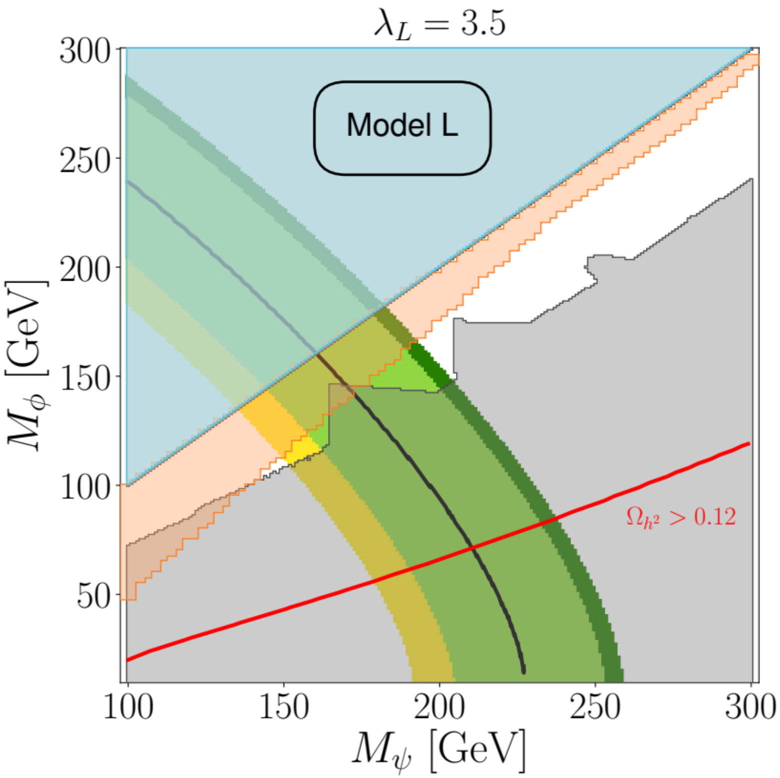
$\Rightarrow M_{\rm BSM} \approx 100$ GeV

Excluded by compressed spectra searches

Try to evade limits with compressed spectra

Simple extension with scalar singlet and charged fermion doublet

$$\mathcal{L}_{\mathrm{L}} = (\lambda_L L \cdot \psi_d \phi - M_\psi \psi_d^c \psi_d + h.c.) - \frac{M_\phi^2}{2}|\phi|^2, \qquad C_{\mathrm{BSM}} = \frac{\lambda^2}{3 \times 64\Pi^2} E(\frac{m_\psi^2}{m_\phi^2})$$



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FlexibleSUSY 2.5.0 for muon g-2

For $\lambda_L = 3.5, E = 1$

$\Rightarrow M_{\mathrm{BSM}} \approx 170$ GeV

Just finds gaps in exclusion for compressed spectra?

No simultaneous solution with DM

~~God of~~ muon g-2 of the gaps

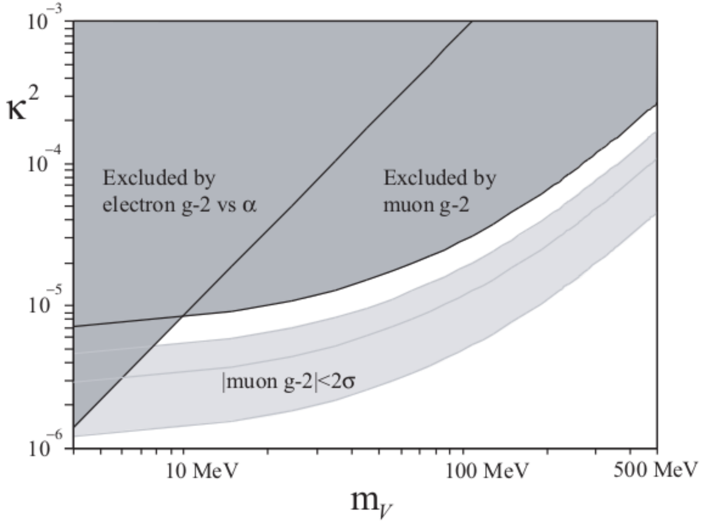
Dark Photon

Original idea: Dark $U(1)_d$ [PRD 80 (2009) 095002]

Kinetic mixing between $U(1)_d$, $U(1)_Y$: $\frac{1}{2}\kappa\tilde{F}^{\mu\nu}F_{\mu\nu}$

Diagonalise $A_\mu \to A_\mu + \kappa Z_{d\,\mu}$

→ Induced SM couplings -e$\kappa J^\mu_{\mathrm{e.m.}} Z_{d\,\mu}$



[PRD 80(2009) 095002, M. Pospelov,

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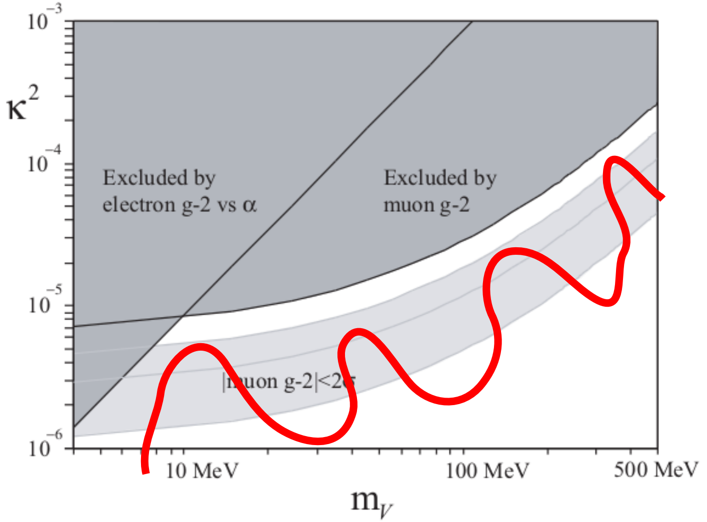

[PRD 80(2009) 095002, M. Pospelov, + My indicative red overlay]

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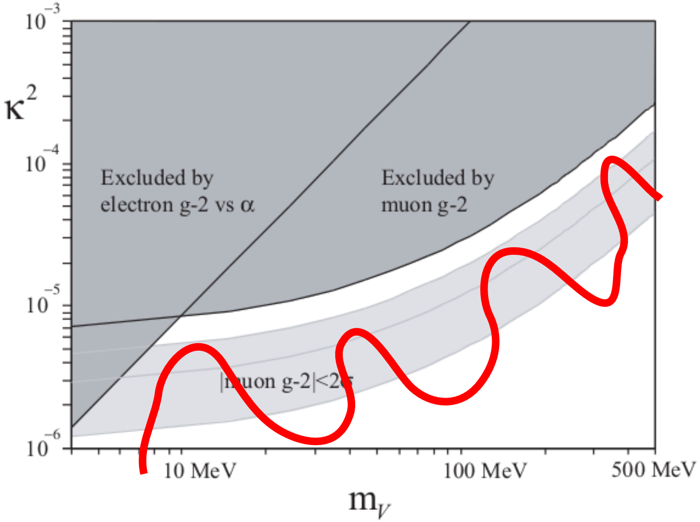

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Extensions of this still viable, e.g.

Dark Z: Include Z–Z_d mixing through EWSB if the Higgs is also charged under $U(1)_d$

[PRL 109(2012) 031802, PRD 86(2012) 095009 Davoudiasl et al, PRD 104(2021) 1, 011701 Cadeddu et al]

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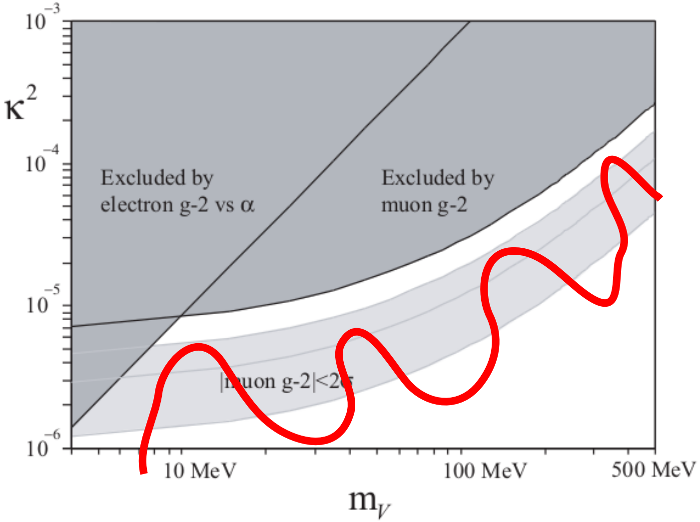

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Semi-visible decays: Dark photon/Z decays into invisible dark sector states + visible SM states
[PRD 99 (2019) 115001, G. Mohlabeng]

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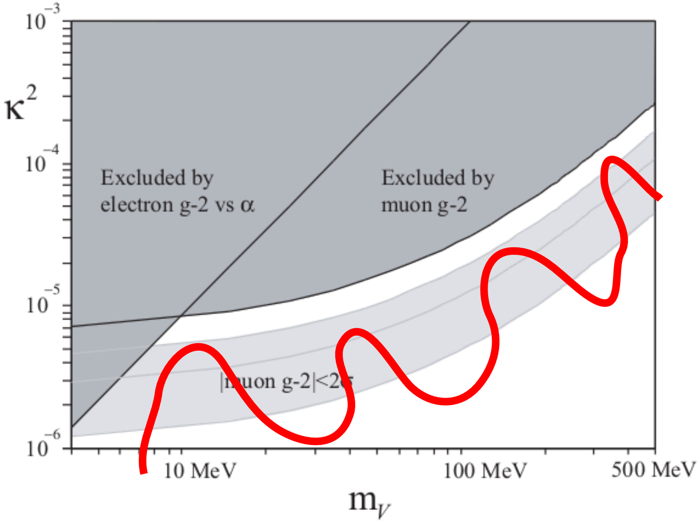

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[PRD 99 (2019) 115001, G. Mohlabeng]

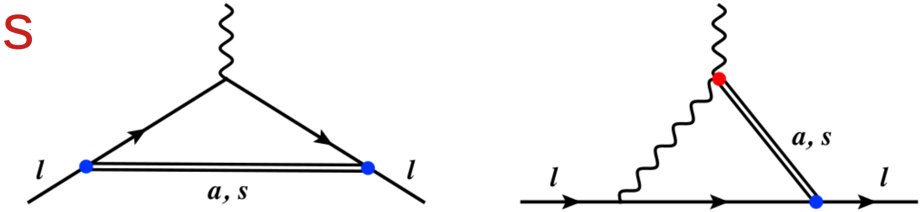
Z' / Gauged $U_{(L_\mu - L_\tau)}$ It could have direct couplings to visible states
[e.g. PRD 84 (2011) 075007, PRL 113 (2014) 091801, PLB 762 (2016) 389, PRD 103 (2021) 9, 095005]

Axions

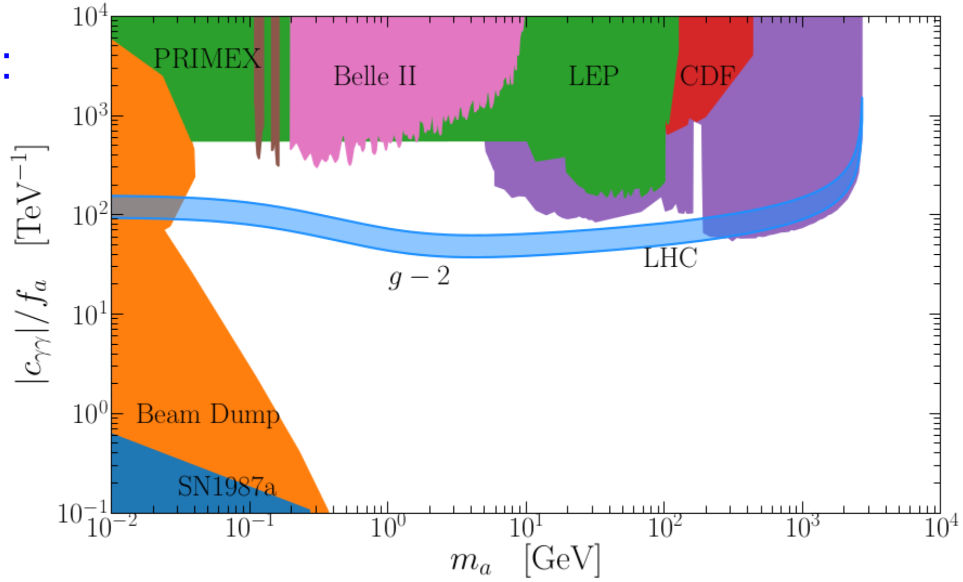
Axion Like Particles (ALPs) appear from the breaking of the approximate U(1) PQ symmetry

Axions solve the strong CP problem, but ALPs are more general

Naively the EFT ALP picture looks very promising:



[Phys.Rev.D 94 (2016) 11, 115033, W.J. Marciano, A. Masiero, P. Paradisi & M. Passera]



[JHEP 09 (2021) 101, M.A. Buen-Abad, J. Fan, M. Reece & C. Sun]

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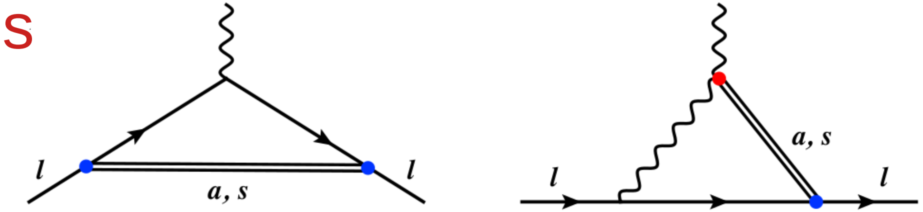

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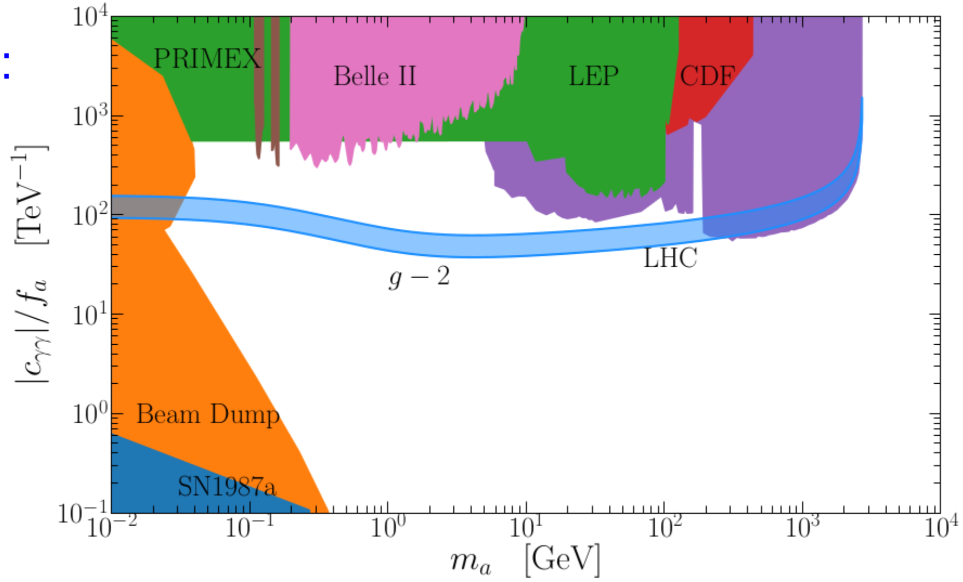
But need very large couplings

Sober analysis of possibile UV completions in JHEP 09 (2021) 101

Usually need light new degrees of freedom with mases $\mathcal{O}(10\text{–}100)\ \text{GeV}$

Less room in specific models but needs more study



[JHEP 09 (2021) 101, M.A. Buen-Abad, J. Fan, M. Reece & C. Sun]

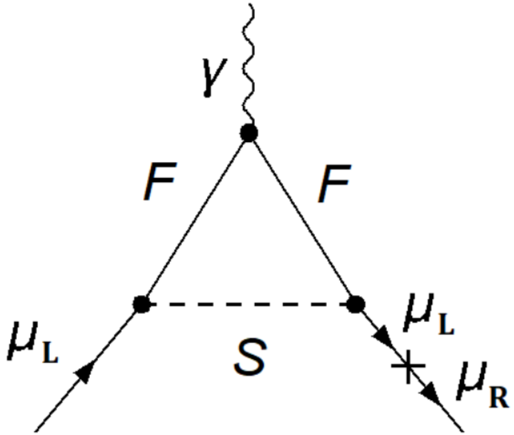
Chirality flipping enhancements

Muon g-2 is a chirality flipping operator

$$\Delta a_\mu^{\mathrm{BSM}} \approx C_{\mathrm{BSM}} \frac{m_\mu^2}{M_{\mathrm{BSM}}^2}$$

One factor of muon mass for chirality flip on outgoing muon

e.g.



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→ chirality flip *inside* the BSM loop can replace the muon mass with some BSM parameter

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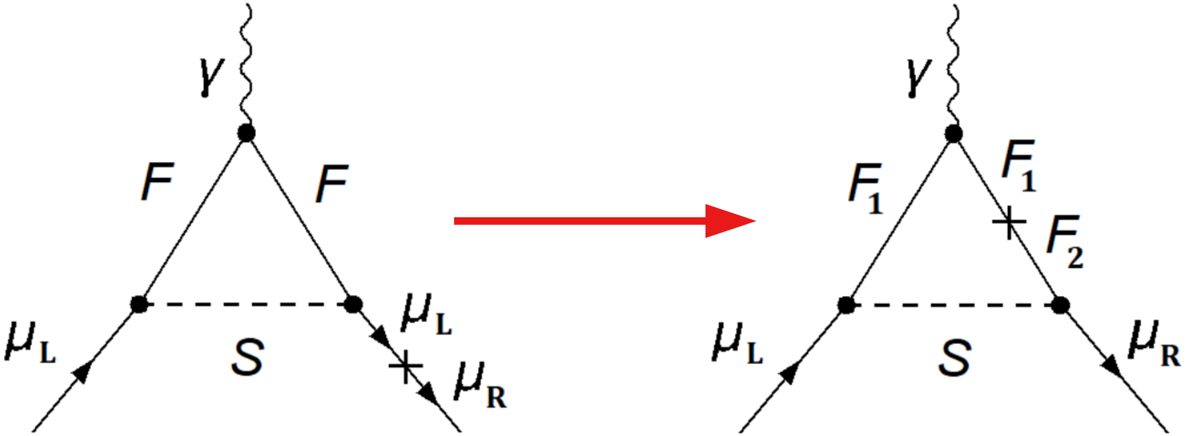

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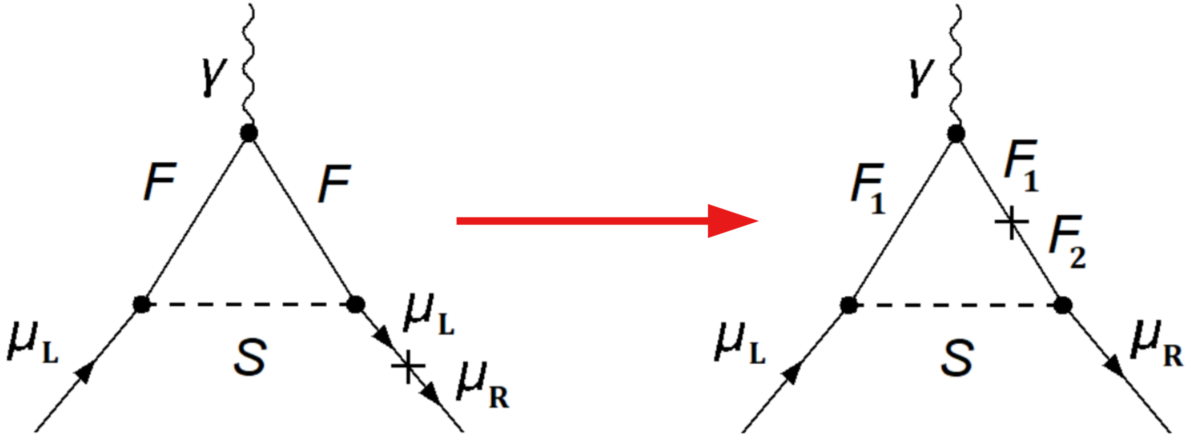
→ Enhancement to BSM corrections from am internal chirality flip $C_{\rm BSM} \propto \frac{M_{CF}}{m_\mu}$

e.g.



$m_\mu \to M_{CF}$

Chirality flipping enhancements

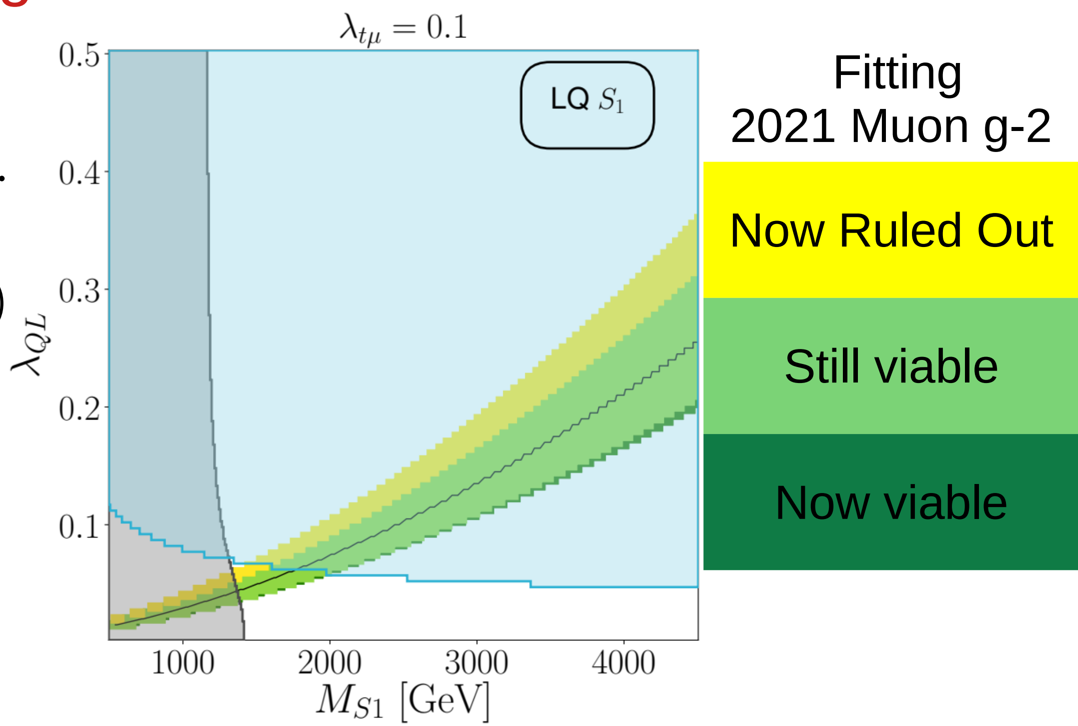
Scalar leptoquark with left and right couplings

$$\mathcal{L}_{SLQ-S_1} = -\lambda_{QL} Q_3 \cdot L_2 S_1 - \lambda_{t\mu} t \mu S_1^* + h.c.$$

$$\longrightarrow \quad C_{\rm BSM} \approx Q_t \lambda_L \lambda_R m_t/(8\pi^2 m_\mu)$$

$$m_t/m_\mu \approx 1600$$

Huge chirality flipping enhancement:
easy to explain muon g-2 with large masses



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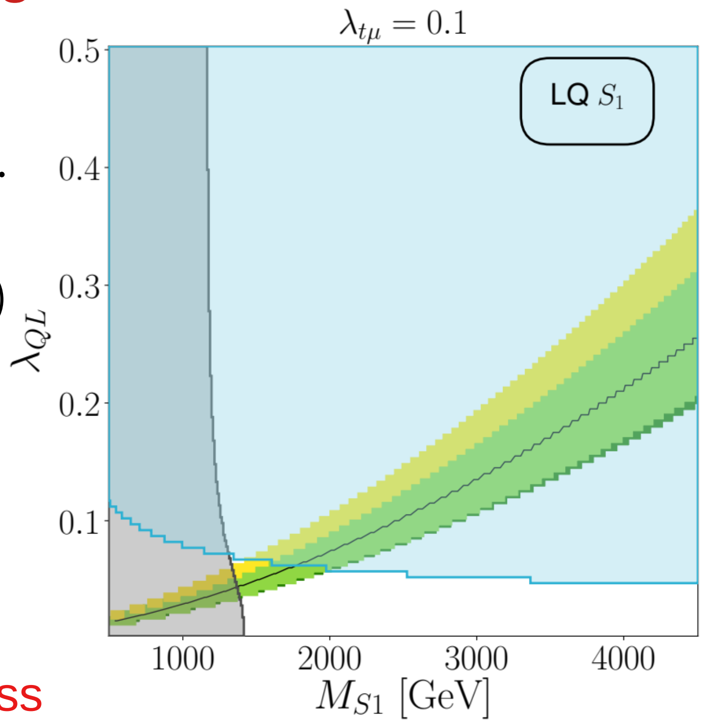
$$m_t / m_\mu \approx 1600$$



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2021 Muon g-2

Now Ruled Out

Still viable

Now viable

Huge chirality flipping enhancement:
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But hard to avoid fine tuning in the muon mass

Enhancement in muon mass corrections too

Typically $\Delta a_\mu^{\mathrm{BSM}} \approx \mathcal{O}(\Delta m_\mu / m_\mu) \frac{m_\mu^2}{M_{\mathrm{BSM}}^2}$

FlexibleSUSY 2.5.0 for muon g-2

May be testable with $BR(h \to \mu^+ \mu^-)$

[Phys.Rev.Lett. 127 (2021) 2, 021801, A. Crivellin, Dario Mueller, Francesco Saturnino]

Chirality flipping enhancements

Scalar leptoquark with left and right couplings, e.g. → $C_{\rm BSM} \approx Q_t \lambda_L \lambda_R m_t/(8\pi^2 m_\mu)$

$$\mathcal{L}_{SLQ-S_1} = -\lambda_{QL} Q_3 \cdot L_2 S_1 - \lambda_{t\mu} t \mu S_1^* + h.c.$$

$$m_t/m_\mu \approx 1600$$

Vector-like Leptons that mix, e.g. → $C_{\rm BSM} \approx \frac{M_{LR}}{m_\mu}$

$$\mathcal{L} \supset -Y_{\psi^\pm} \overline{L}_L H \psi_R^- - Y_{\psi_D} \overline{\psi}_{D,L} H \ell_R - Y_{LR} \overline{\psi}_{D,L} H \psi_R^- - Y_{RL} \overline{\psi_L^-} H^\dagger \psi_{D,R} + \text{h.c.}$$

[JHEP 02 (2012) 106, K. Kannike, M. Raidal, D.M. Straub & A. Strumia,
Phys.Rev.D 88 (2013) 013017, R. Dermíšek, A. Raval,
Phys.Rev.D 104 (2021) 5, 053008, P.M. Ferreira, B.L. Gonçalves, F.R. Joaquim, & M. Sher]

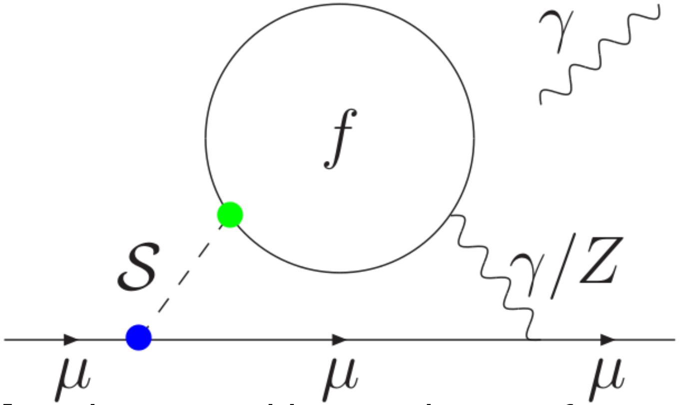
Similar to scalar leptoquark case

Solutions with heavy masses well beyond LHC

But may have issues with muon mass fine tuning.

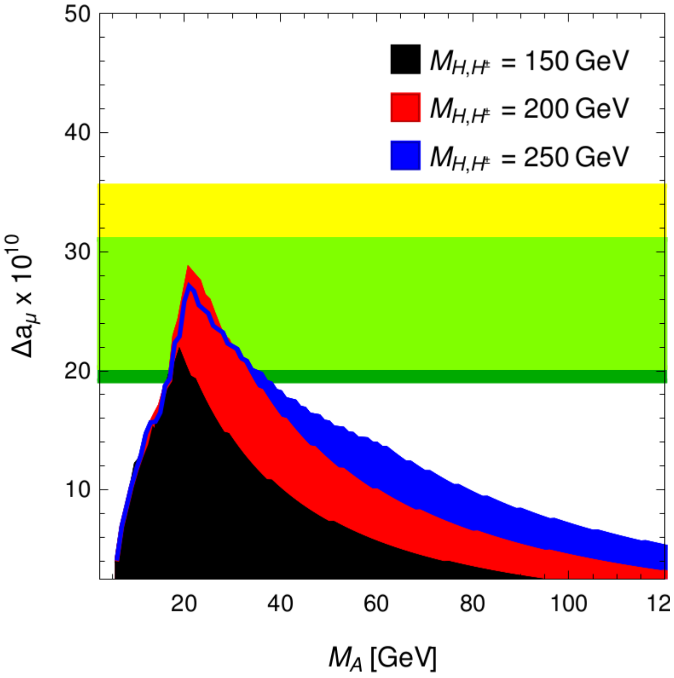
2HDM

- Light pseudoscalar can explain muon g-2 in 2HDM
- Internal chirlaity flipping via Yukawa coupling
- Two-loop Barr-Zee diagrams are essential, e.g.

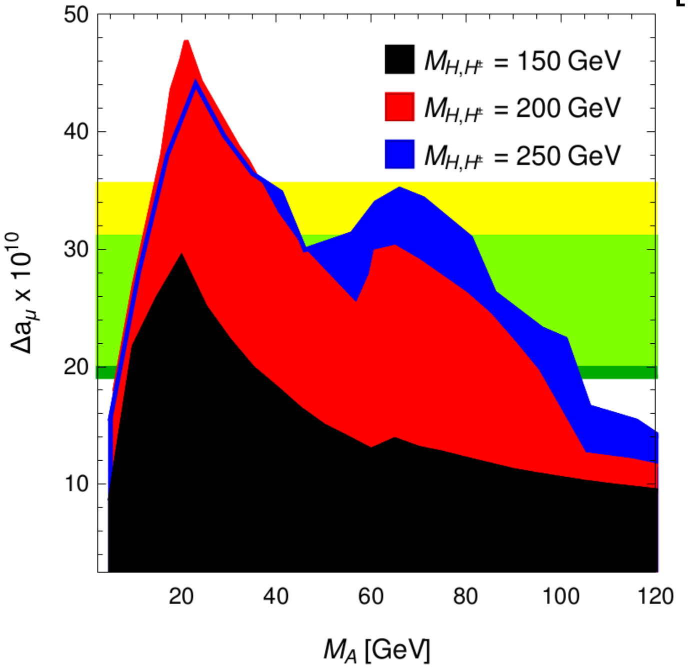


[Hyejung Stöckinger-Kim, Corfu2022]

Type X 2HDM



Flavour aligned 2HDM

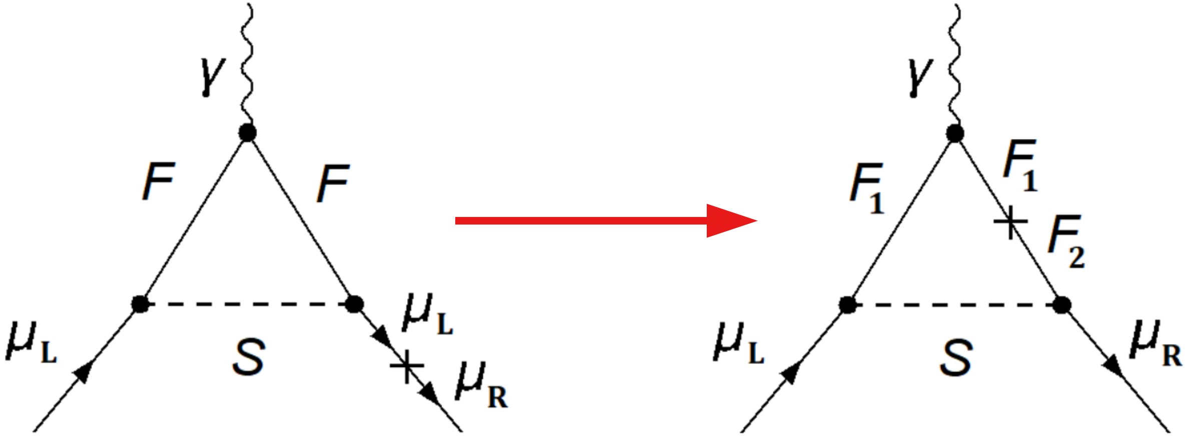


Small regions in Type X still viable

More scenrios possible in flavour aligned 2HDM

Chirality flipping enhancements

To explain DM and have a chirality flipping enhancement,
need 3 BSM fields



$$m_\mu \to M_{CF}$$

2 fields of opposite sign
(no internal chirality flip)

Add third field
(internal chirality flip)

Heavy new physics for DM and muon g-2

Example:

Scalar doublet

Scalar singlet

Charged fermion singlet

$$\mathcal{L}_{\rm 2S1F} = (a_H H\cdot\phi_d\phi_s^0 + \lambda_L \phi_d\cdot L\psi_s + \lambda_R \phi_s^0 \mu\psi_s^c - M_\psi \psi_s^c\psi_s + h.c.) - M_{\phi_d}^2|\phi_d|^2 - \frac{M_{\phi_s}^2}{2}|\phi_s^0|^2.$$

Mass Mixing between scalars

Left and right couplings to muons

Mass eigenstate coupling to left muon and right muon

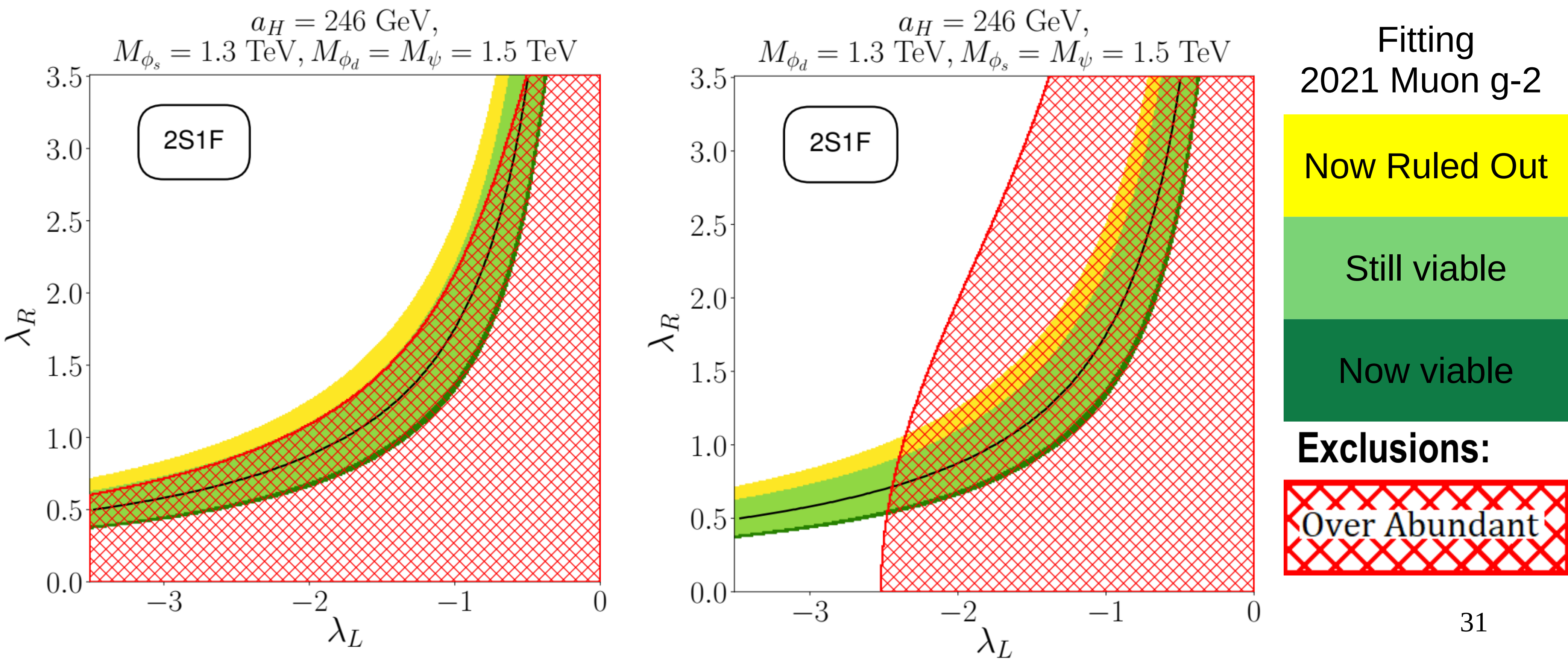
$\Rightarrow$ Non-zero $a_H + \lambda_L + \lambda_R$

Chirality flip enhancement $\dfrac{\lambda_L\lambda_R v}{m_\mu}\dfrac{a_H}{M_\psi}$

Heavy new physics for DM and muon g-2

FlexibleSUSY 2.5.0 for muon g-2

Many params influence relic density (and muon g-2)
→ many situations are possible

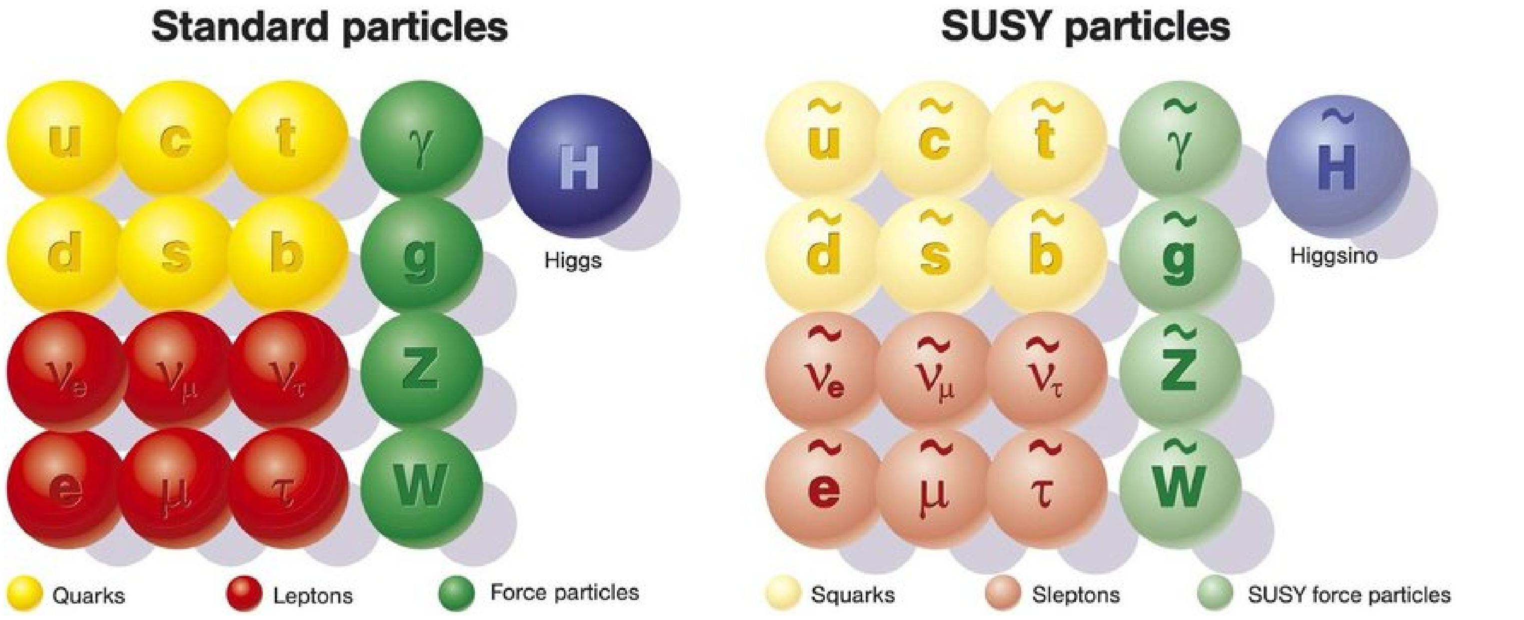


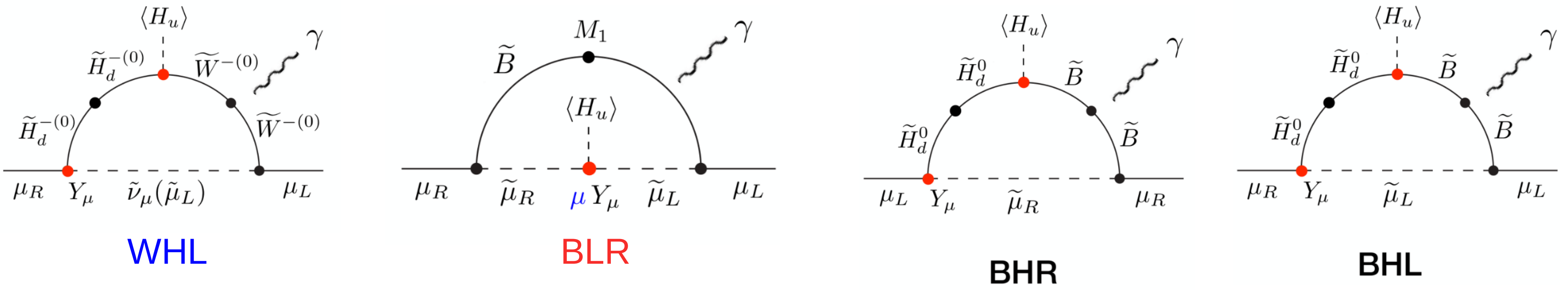
Minimal SUSY (MSSM) solutions

Interest:

- Well motivated
- Solves Hierarchy Problem
- Has chirality flipping enhancement via $\tan\beta = v_u/v_d$

One-loop contributions from EWinos, smuons and smuon neutrinos





Four main diagrams with internal chirality flip

All are linear in tan beta

BLR is also linear in mu

WHL and BLR most important for phenomenology

$$a_\mu^{\rm WHL} \approx 21 \times 10^{-10} {\rm sign}(\mu M_2) \left(\frac{500\ {\rm GeV}}{M_{\rm SUSY}}\right)^2 \frac{\tan\beta}{40},$$

$$a_\mu^{\rm BLR} \approx 2.4 \times 10^{-10} {\rm sign}(\mu M_1) \left(\frac{500\ {\rm GeV}}{M_{\rm SUSY}}\right)^2 \frac{\tan\beta}{40} \frac{\mu}{500\ {\rm GeV}},$$

$$a_\mu^{\rm BHR} \approx -2.4 \times 10^{-10} {\rm sign}(\mu M_1) \left(\frac{500\ {\rm GeV}}{M_{\rm SUSY}}\right)^2 \frac{\tan\beta}{40}$$

$$a_\mu^{\rm BHL} \approx 1.2 \times 10^{-10} {\rm sign}(\mu M_1) \left(\frac{500\ {\rm GeV}}{M_{\rm SUSY}}\right)^2 \frac{\tan\beta}{40},$$

[Diagrams from M.Chakraborti, S.Iwamoto, J.S.Kim, R.Maselek, K.Sakura, arxiv:2202.12928,
Fit formulae from PA, C.Balázs, D.H.J.Jacob, W.Kotlarski, D.Stöckinger, H.Stöckinger-Kim JHEP 09 (2021) 080)]

MSSM solutions

Interest:

- Well motivated
- Solves Hierarchy Problem
- Has chirality flipping enhancement via $\tan\beta = v_u/v_d$

One-loop contributions from EWinos, charginos, smuons and smuon neutrinos

The main four diagrams could map to three field EFTs similar to previous model but...

Challenge: Much less freedom than a generic three field model for DM:

➔ Interactions fixed to gauge couplings

➔ Can't just make the coupling 1 or larger

Use GM2Calc for all MSSM results State-of-the-art 2-loop corrections

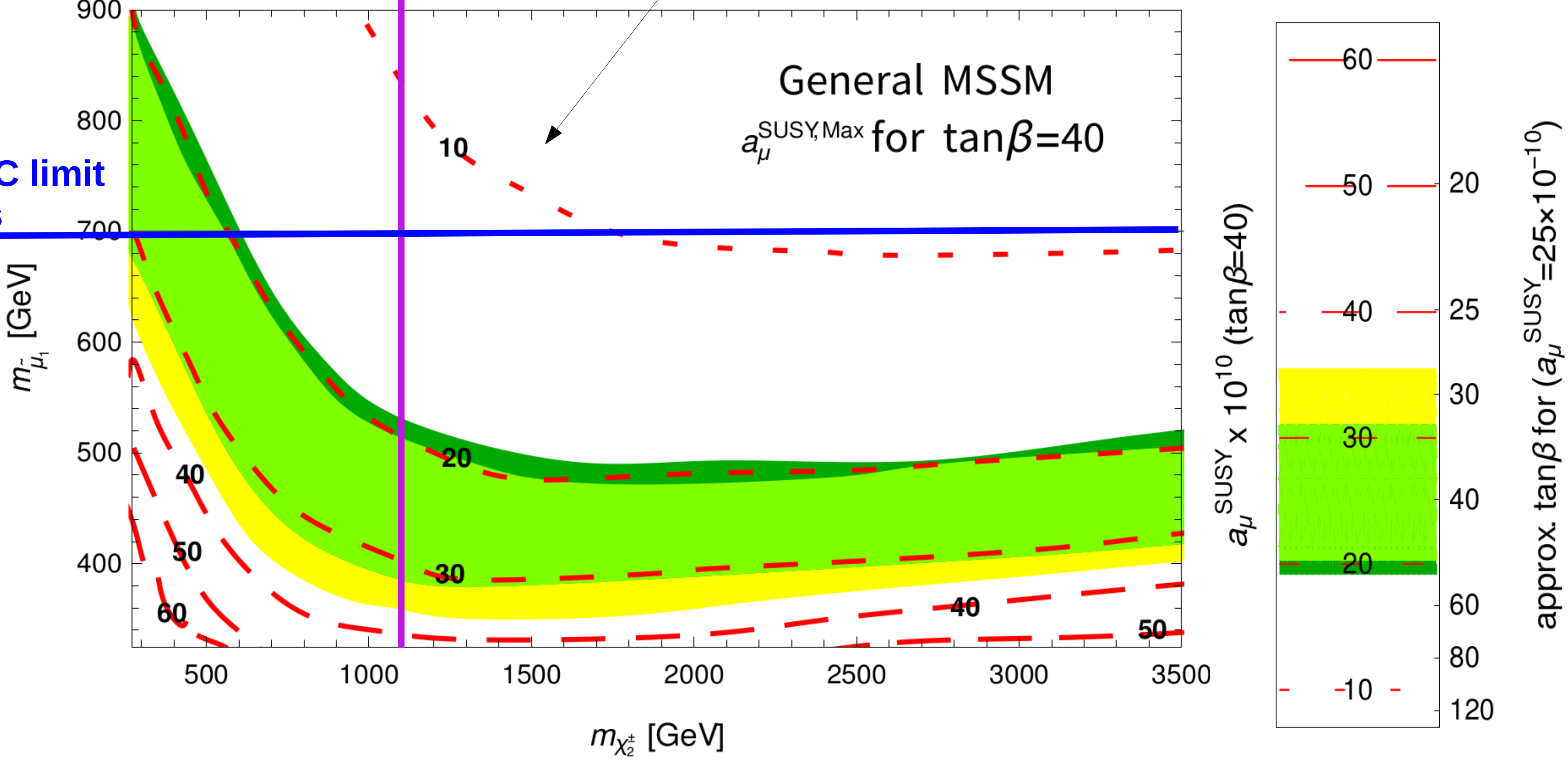
Maximum LHC limit Chargino mass < 1.1 TeV

“Obviously allowed” region has either:

Too low $\Delta a_\mu^{\rm BSM}$

Or very large $\tan\beta \gg 40$

Maximum LHC limit Slepton mass < 700 GeV



Evading limits on sleptons and charginos

Idea 1: Make sleptons light but close in mass to LSP (compressed spectra again)

If you accept this tuning to evade collider limits (and deplete DM relic density)

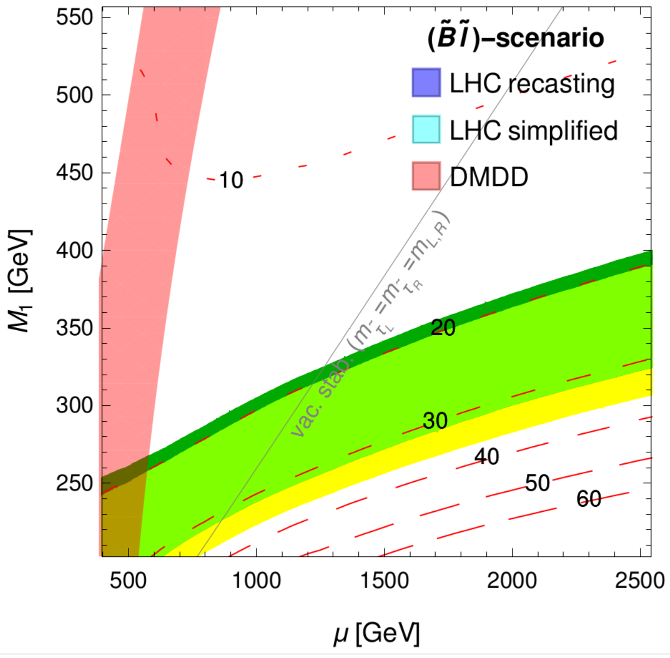
→ Plenty of viable parameter space:

DM also explained

No DM explanation

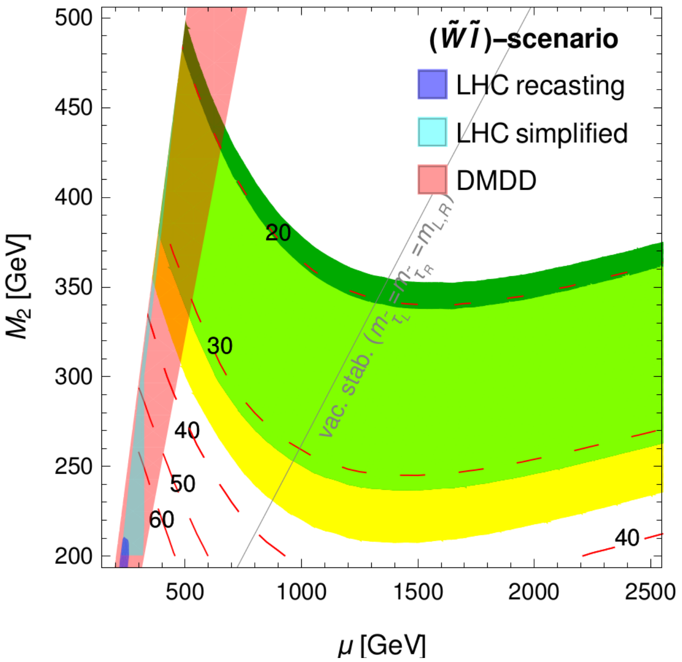
Bino LSP

$m_{L,R} = M_1 + 50$ GeV, $M_2 = 1200$ GeV, $\tan\beta = 40$



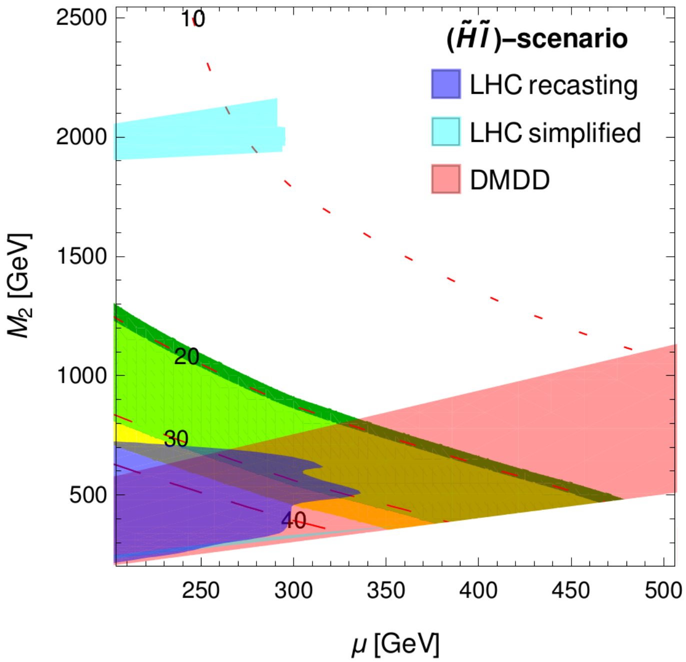
Wino LSP

$m_{L,R} = M_2 + 50$ GeV, $M_1 = 600$ GeV, $\tan\beta = 40$



Higgsino LSP

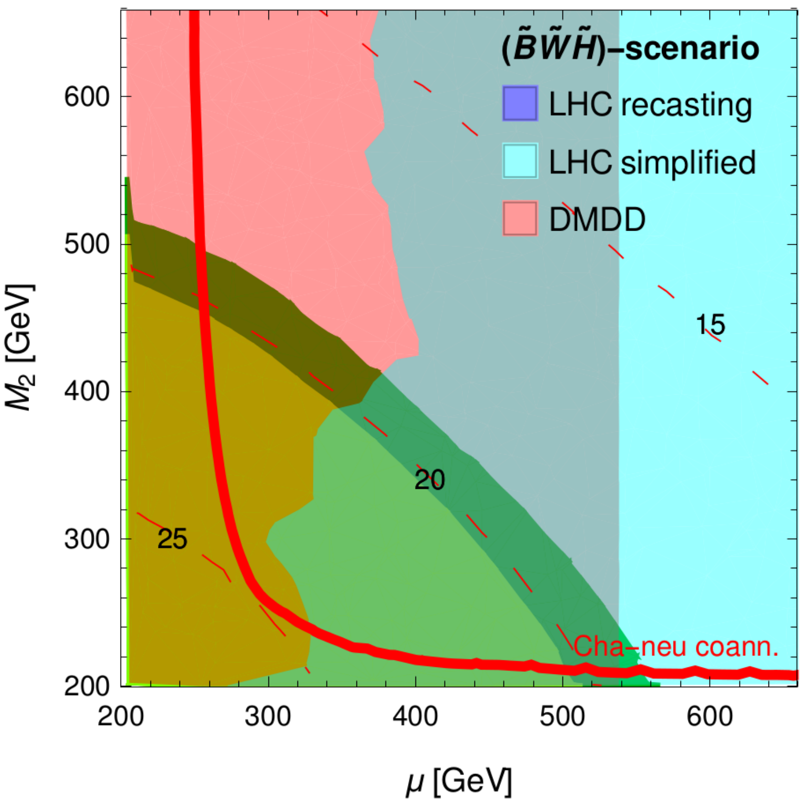
$m_{L,R} = \mu + 50$ GeV, $M_1 = 2000$ GeV, $\tan\beta = 40$

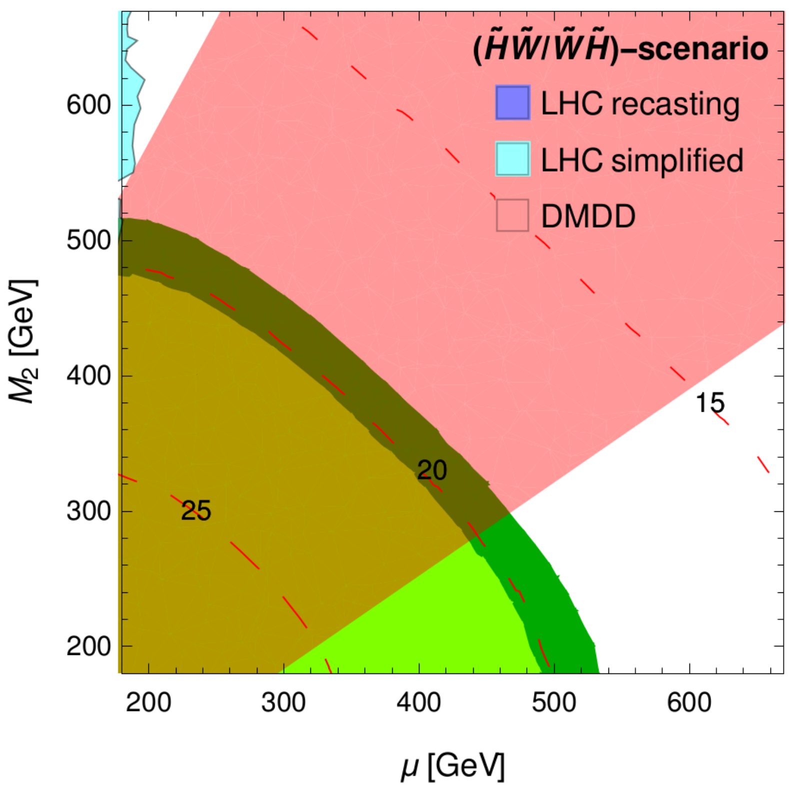


Evading broad limits on sleptons and charginos

Idea 2: Make charginos lighter than sleptons

Does not assume tuning, but the parameter space is quite constrained





Although restrictive there are many ways to explain a large muon g-2 deviation

MSSM muon g-2 solutions

- Scrape into 2σ region with large $\tan\beta$ close to 50.
- Very large $\tan\beta \gg 50$ — Special case
- Tune slepton masses so $m_{\tilde{l}} < m_{\text{LSP}} + \Delta m_{\text{LHC-gap}}$ — Muon g-2 of the gaps
- Choose $m_{\chi^{\pm}_{1,2}} < m_{\tilde{l}}$ — Limited viable space

Non-SUSY solutions

- Chirality flip enhancement e.g. leptoquarks, — muon mass fine tuning
- Hide from LHC with compressed spectra — Muon g-2 of the gaps
- DM can be comfortable explained with 3 or more fields — Unmotivated without restrictions

Some issues that can reduce plausibility though

My Conclusions and Outlook

- The muon g-2 deviation is a powerful discriminator amongst BSM theroies and scenarios
- Many reasonable models can fit muon g-2, many ways to combine with DM
- No solution in survey is perfect, hard to explain without some tuning, hiding in some corner of parameter space, or going to special cases
- Motivates proper Bayesian studies checking the plausibility of explanations, accounting for naturalness questions
- Still room for new ideas, more natural/plausible explanations

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Back Up Slides

Heavy new physics for DM and muon g-2

Example:

Scalar doublet

Scalar singlet

Charged fermion singlet

$$\mathcal{L}_{2\mathrm{S1F}} = (a_H H\cdot\phi_d\phi_s^0 + \lambda_L \phi_d\cdot L\psi_s + \lambda_R \phi_s^0 \mu\psi_s^c - M_\psi \psi_s^c\psi_s + h.c.) - M_{\phi_d}^2|\phi_d|^2 - \frac{M_{\phi_s}^2}{2}|\phi_s^0|^2.$$

Mass Mixing between scalars

Left and right couplings to muons

Scalar doublet mass

Scalar singlet mass

Scalar DM:

Relic density (co)annihilations mech.

- scalar singlet DM → via Higgs portal, λ_R t-channel exchange ψ_s
- inert doublet scalar DM → SU(2) co-ann, λ_L t-channel exchange of ψ_s
- Mixed singlet-doublet scalar DM → All of the above + a_H driven singlet-doublet co-ann

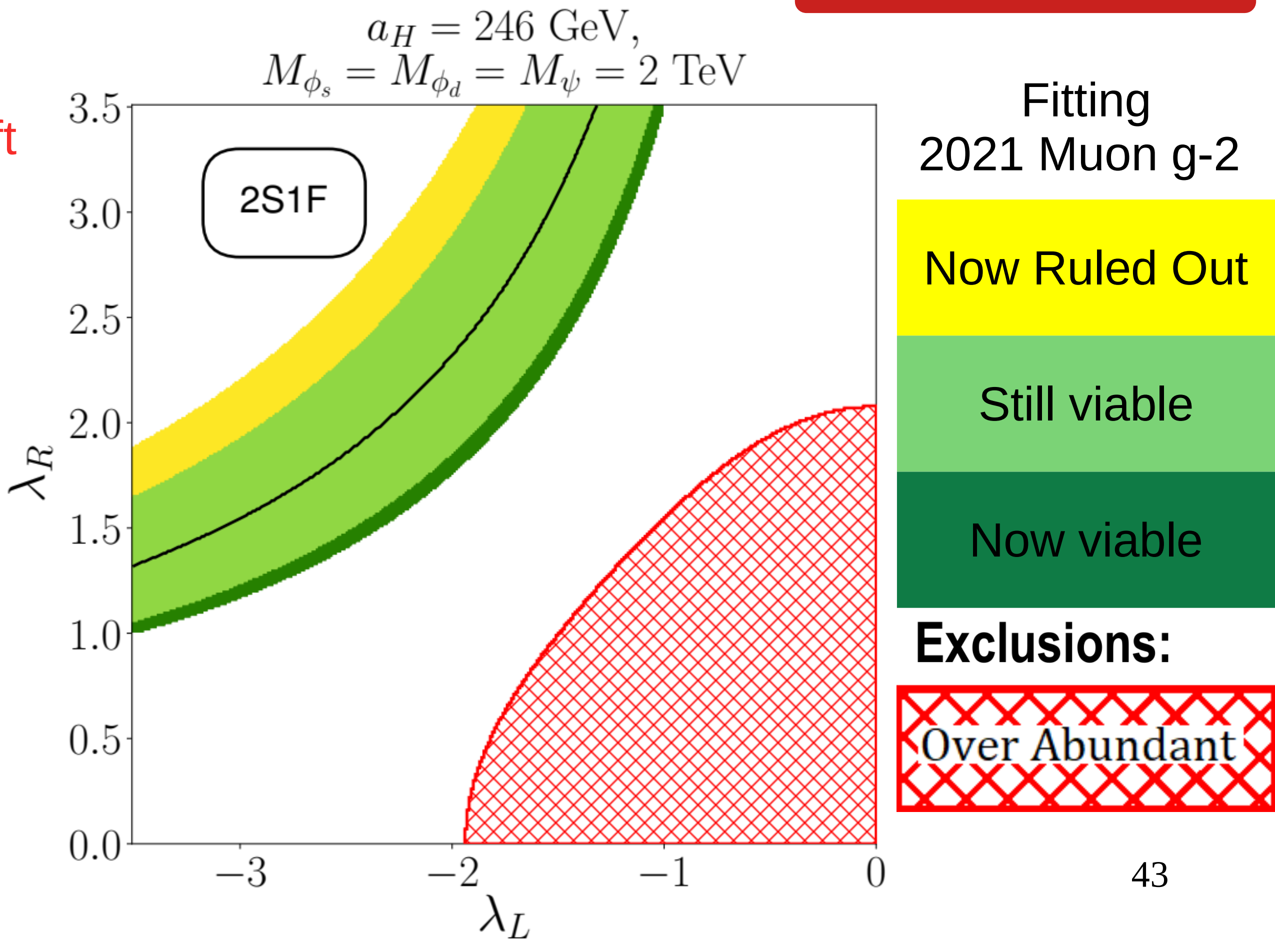
Direct detection of dark matter via a_H

Heavy new physics for DM and muon g-2

Use FlexibleSUSY 2.5.0 for muon g-2

Many params influence relic density (and muon g-2)
→ many situations are possible

- Annhilations so effective little DM left when muon g-2 is explained



Heavy new physics for DM and muon g-2

FlexibleSUSY 2.5.0 for muon g-2

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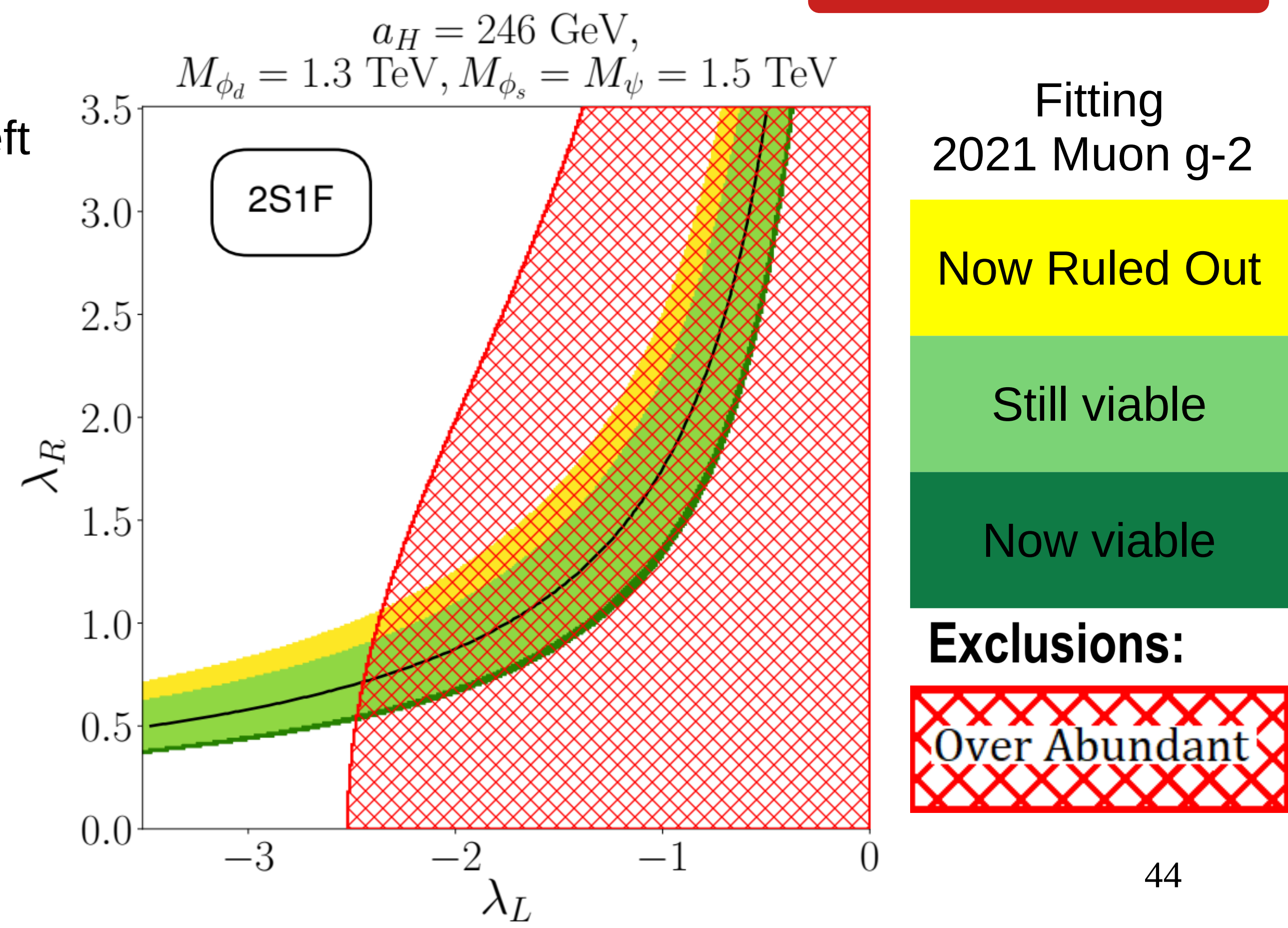
- RD depends much more on λ_L
→ point where g-2 and RD explained simultaneously



Heavy new physics for DM and muon g-2

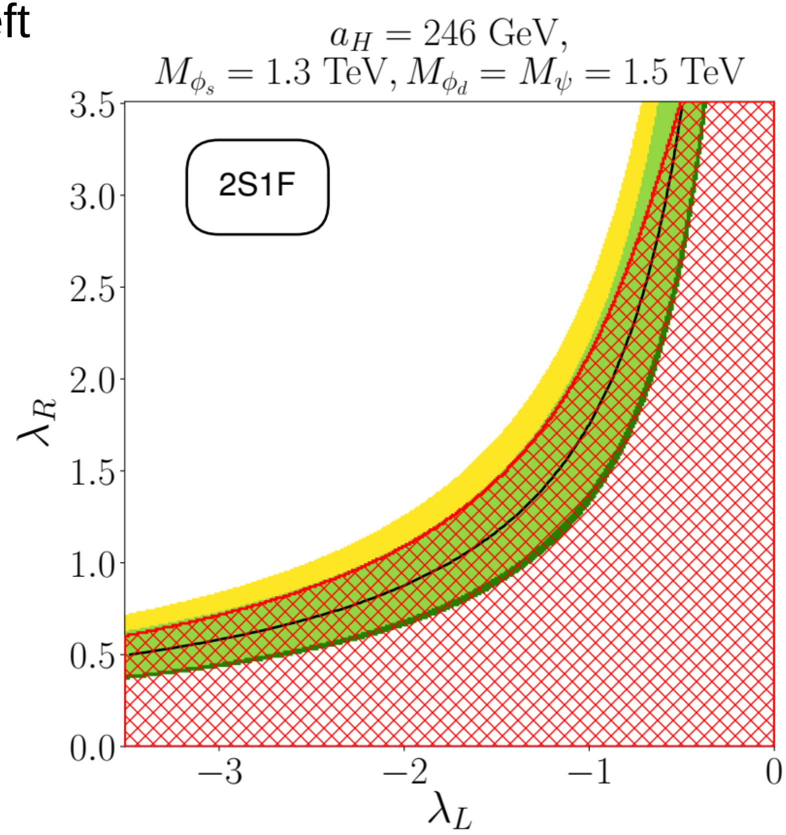
FlexibleSUSY 2.5.0 for muon g-2

Many params influence relic density (and muon g-2)
→ many situations are possible

- Annhilations so effective little DM left when muon g-2 is explained

- RD depends much more on λ_L
  → point where g-2 and RD explained simultaneously

- Dependency on muon couplings just right for simultaneous solution along the allowed curve



Fitting 2021 Muon g-2

Heavy new physics for DM and muon g-2

Example:

Scalar doublet — Scalar singlet — Charged fermion singlet

$$\mathcal{L}_{\rm 2S1F} = (a_H H\cdot\phi_d\phi_s^0 + \lambda_L\phi_d\cdot L\psi_s + \lambda_R\phi_s^0\mu\psi_s^c - M_\psi\psi_s^c\psi_s + h.c.) - M_{\phi_d}^2|\phi_d|^2 - \frac{M_{\phi_s}^2}{2}|\phi_s^0|^2.$$

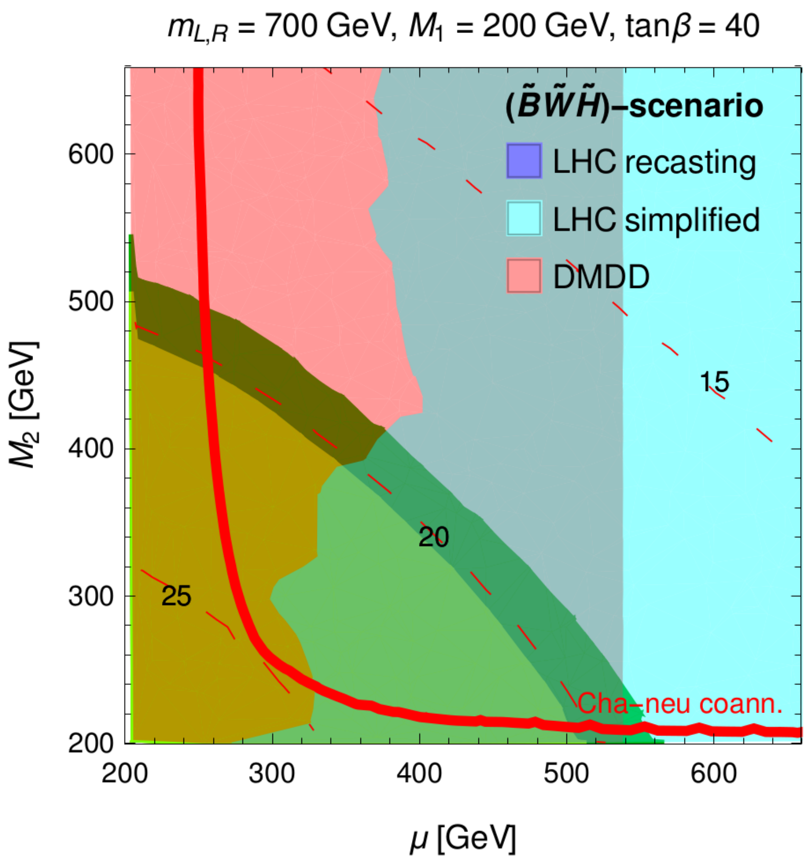
Chirality flip and DM candidate:

- Plenty of unconstrained parameter space at high masses
- No need to hide in LHC exclusion gaps
- Simultanous solutions with DM possible,
- DM solutions don’t seem very “rigged” or unnatural to me
- Muon mass fine tuning still an affliction in large mass region
- No solution to the Hierarchy problem (ignored so far)

Evading broad limits on sleptons and charginos

Idea 2: Make charginos lighter than sleptons

Does not assume tuning, but the parameter space is quite constrained



Since the overlapping colors make this hard to read...

- The shaded red DMDD region is all $\mu < 550$ GeV
- Cyan is everywhere with $\mu \gtrsim 350$ GeV and gives the jagged vertical line roughly around this value of μ.
- the cyan exclusion only applies whenever stau co-annihilation is needed to deplete the relic density,
- However that is everywhere except the red line where we get chargino co-annihilation
- So we have a tiny region of viable explanations in the botton right of the plot where the red line overlaps with the green

Naturalness in Bayesian statistics

If you have an incredibly simple theory that predicts everything with very few ingrediants you don't need to quantify the fine tuning

If you have an incredibly ugly theory with horrific fine tuning you don't need to worry about a careful statistical treatement

But if you have:

- a theory that makes powerful predictions but seems to have a few cancelations or
- only predicts it in specific regions fo the parameter space or
- has several small tunings that may or may not combine

.

Bayesian statistics is the rigorous answer to how plausible it is

and which of these should be prefered,

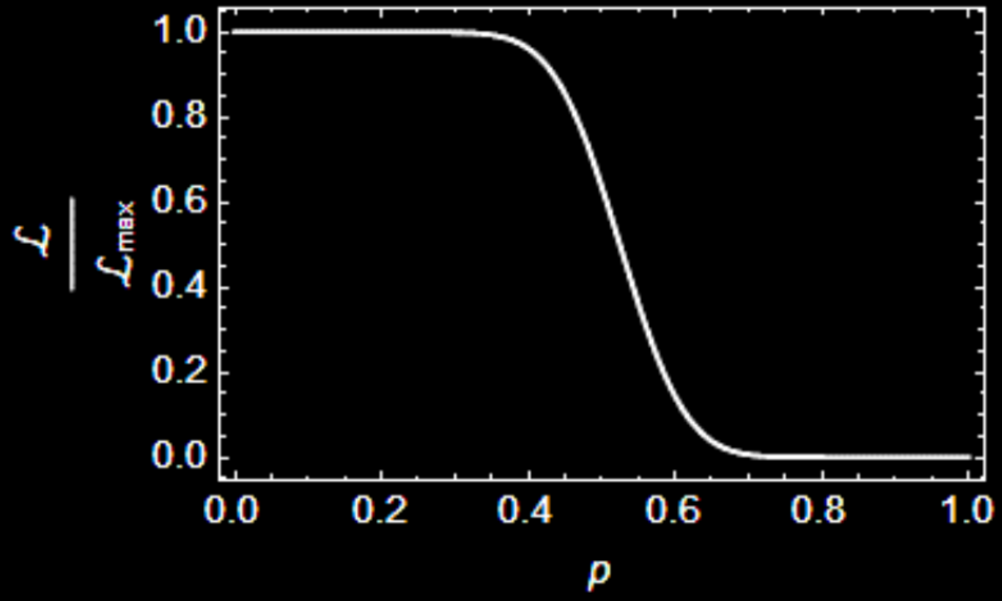
taking account of all these naturalness/plausibility issues

Naturalness in Bayesian statistics

Slide nicked from Csaba Balazs

Consider hypothesis 1 quantified by a single parameter p.

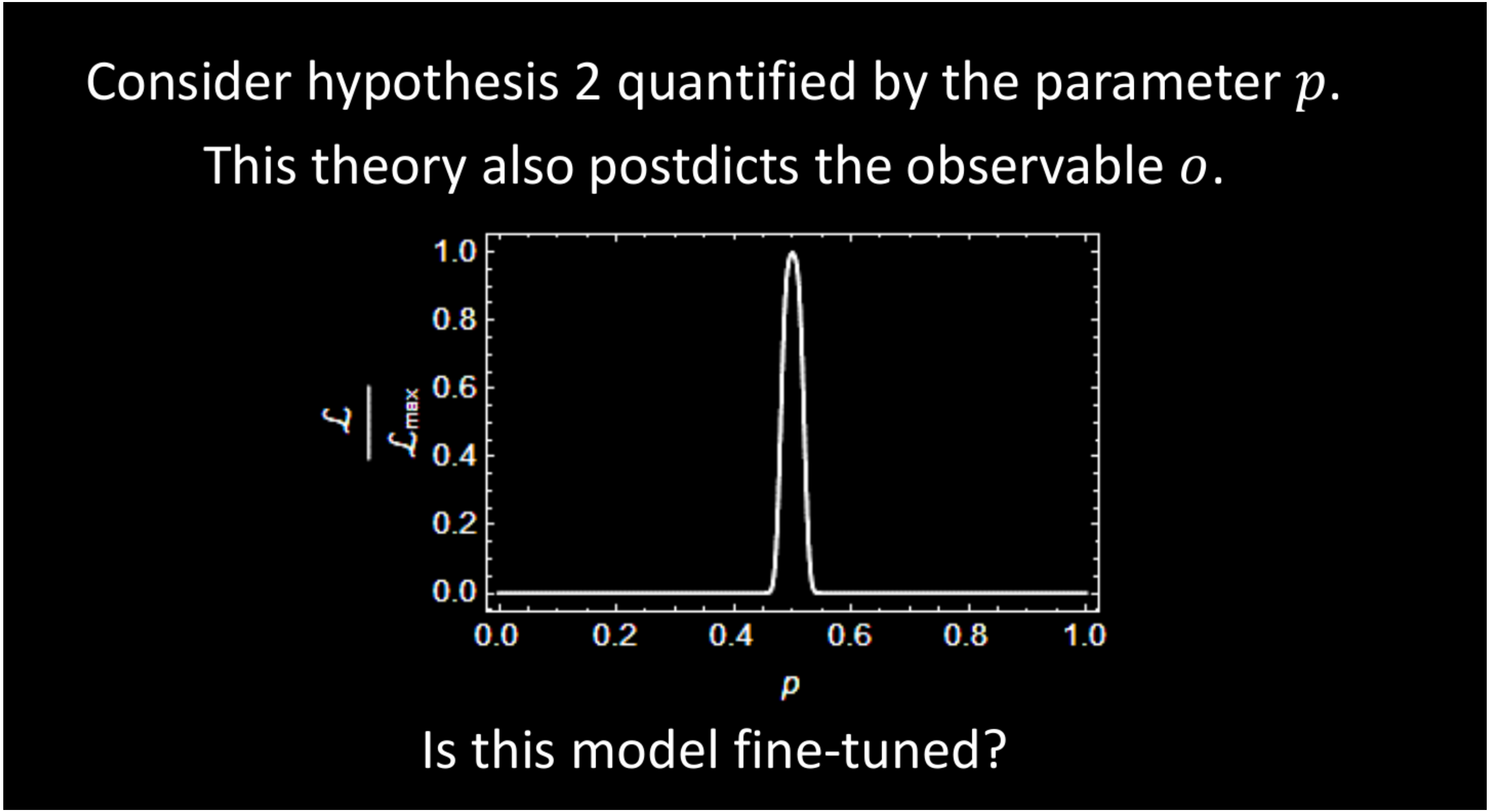
This theory postdicts an observable o.



Is this model fine-tuned?

Naturalness in Bayesian statistics

Slide nicked from Csaba Balazs



Naturalness in Bayesian statistics

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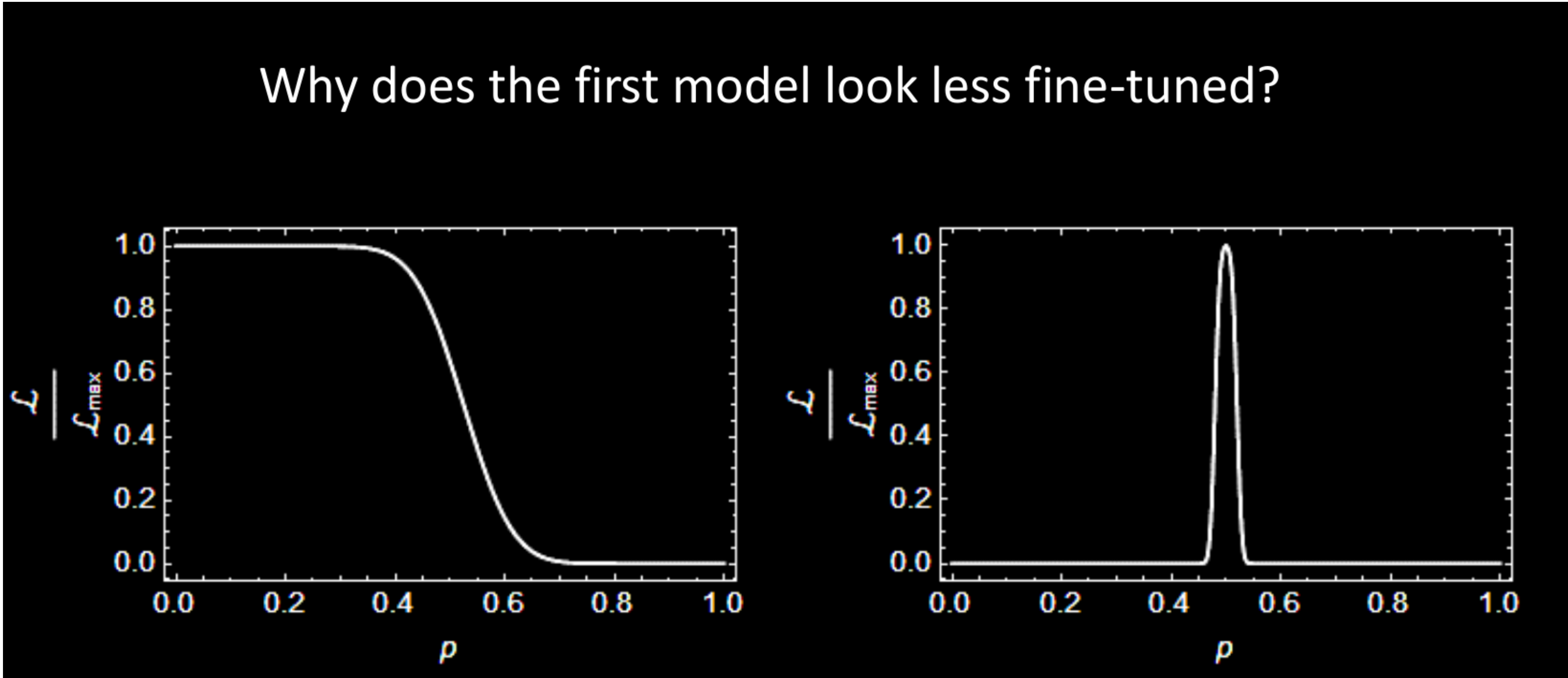
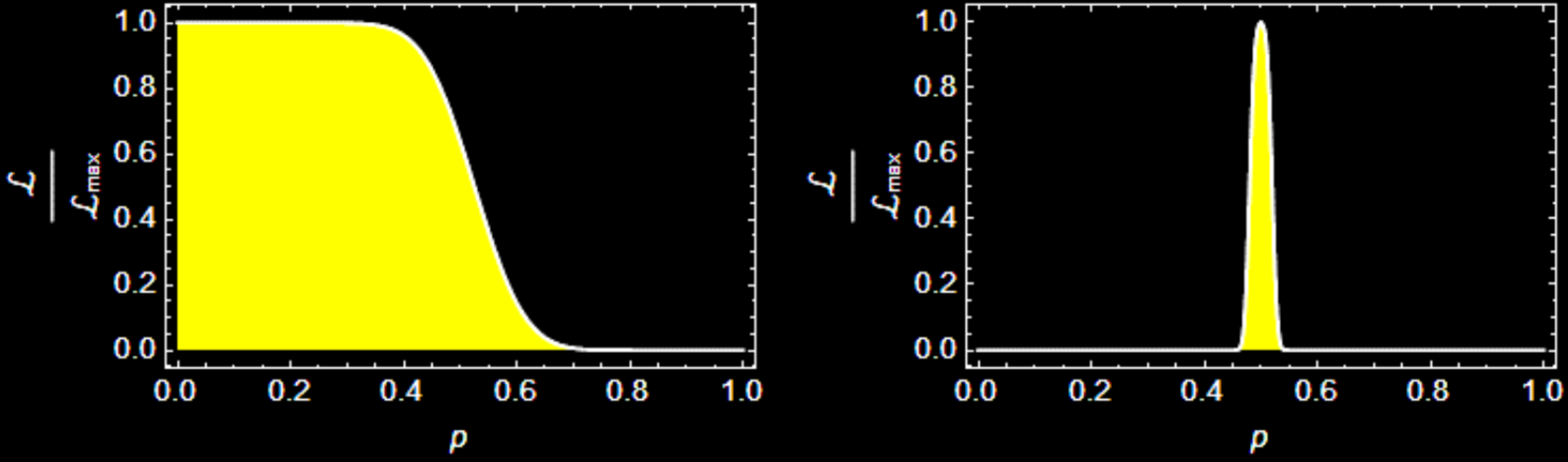


Naturalness in Bayesian statistics

Slide nicked from Csaba Balazs

Why does the first model look less fine-tuned?



Because it has a higher evidence. (Assume flat prior:)

Naturalness in Bayesian statistics

Slide nicked from Csaba Balazs

Bayesian evidence is

$$\mathcal{E} = \int \mathcal{L}(o,p)\,\pi(p)\,dp$$

- the plausibility that hypothesis reproduces observation,
- proportional to ‘global’ fine-tuning.