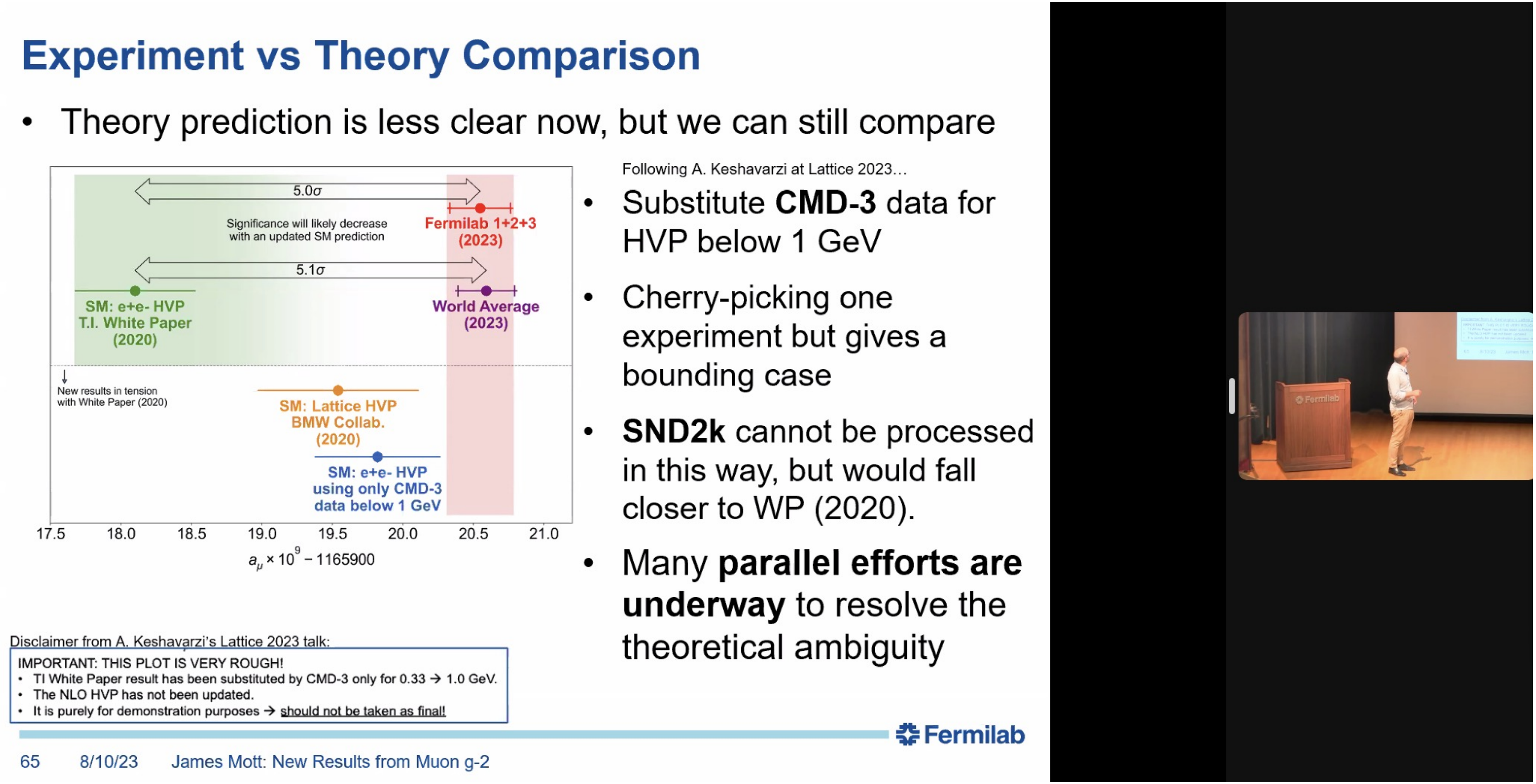
NNU · 南京师范大学
NANJING NORMAL UNIVERSITY

# Muon g-2
# SUSY vs non-SUSY explanations

Peter Athron
(Nanjing Normal University)

# As you heard earlier today there is now an updated muon g-2 measurement...



## Experiment vs Theory Comparison

- Theory prediction is less clear now, but we can still compare

Following A. Keshavarzi at Lattice 2023…

- Substitute **CMD-3** data for HVP below 1 GeV
- Cherry-picking one experiment but gives a bounding case
- **SND2k** cannot be processed in this way, but would fall closer to WP (2020).
- Many **parallel efforts are underway** to resolve the theoretical ambiguity

Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

65 8/10/23 James Mott: New Results from Muon g-2

Old world average $a_\mu^{2021} = (116592061 \pm 41) \times 10^{-11}$

New world average $a_\mu^{2023} = (116592059 \pm 22) \times 10^{-11}$

Deviation to SM estimates

$$\Delta a_\mu^{2021} = (25.1 \pm 5.9) \times 10^{-10} \quad \Rightarrow 4.2\sigma \text{ deviation}$$

$$\Delta a_\mu^{2023-\mathrm{WP}} = (24.9 \pm 4.8) \times 10^{-10} \quad \Rightarrow 5.1\sigma \text{ deviation}$$

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central value didn’t change much, so results would just become sharper

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I can’t help much here, but...

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But everything I say has an inverted interpretation where its a major constraint!

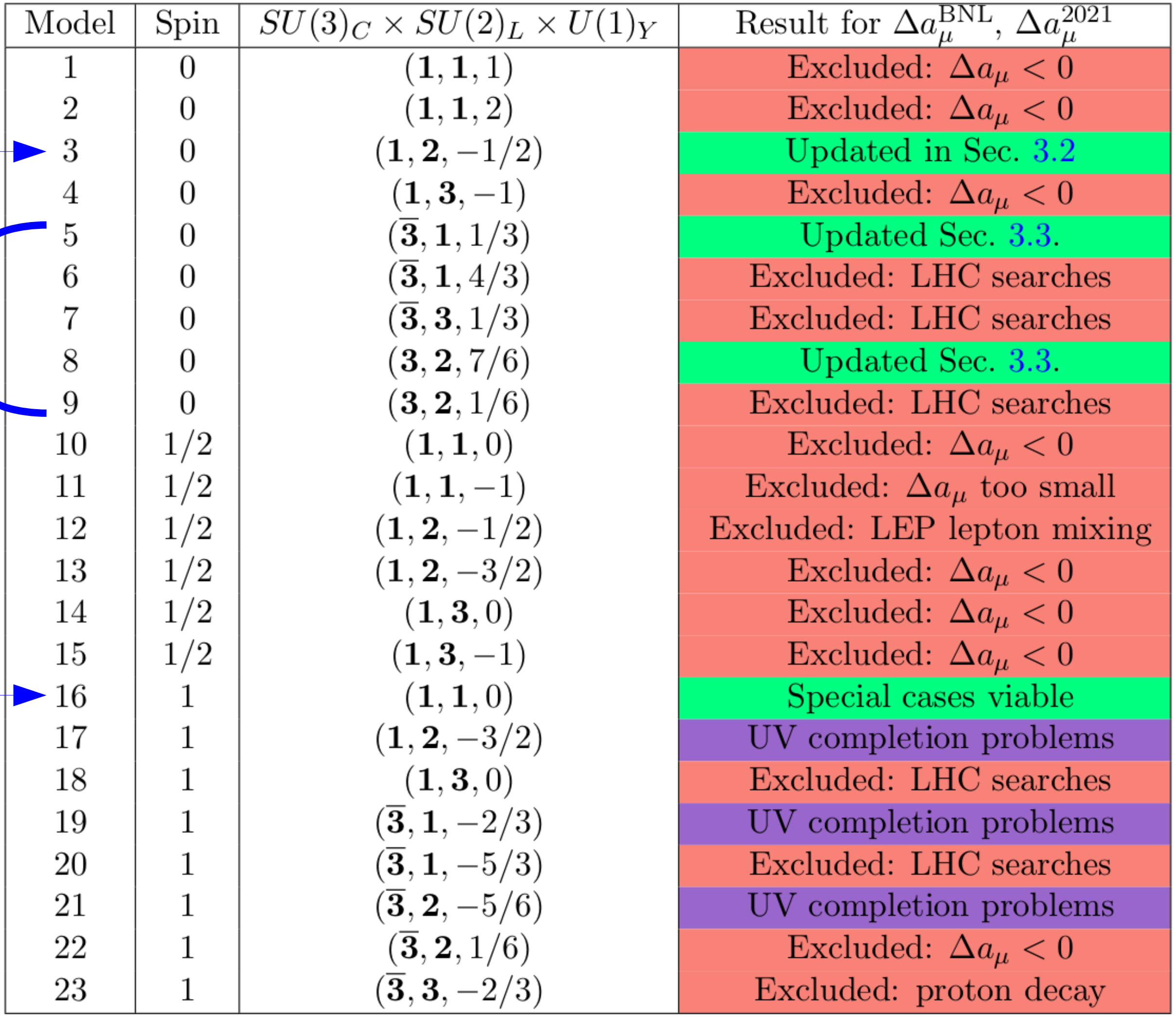
Scenarios where we explain muon g-2 would be precisely those that are ruled out only by muon g-2 if the lattice results agree with the measurement.

# Minimal models for muon g-2: 1 field extensions

2HDM

Scalar leptoquarks

Dark photon



| Model | Spin | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | Result for $\Delta a_\mu^{\mathrm{BNL}}$, $\Delta a_\mu^{2021}$ |
|---|---|---|---|
| 1 | 0 | $(\mathbf{1},\mathbf{1},1)$ | Excluded: $\Delta a_\mu < 0$ |
| 2 | 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 | $(\bar{\mathbf{3}},\mathbf{1},1/3)$ | Updated Sec. 3.3. |
| 6 | 0 | $(\bar{\mathbf{3}},\mathbf{1},4/3)$ | Excluded: LHC searches |
| 7 | 0 | $(\bar{\mathbf{3}},\mathbf{3},1/3)$ | 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: $\Delta a_\mu$ too small |
| 12 | 1/2 | $(\mathbf{1},\mathbf{2},-1/2)$ | Excluded: LEP lepton mixing |
| 13 | 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 | $(\bar{\mathbf{3}},\mathbf{1},-2/3)$ | UV completion problems |
| 20 | 1 | $(\bar{\mathbf{3}},\mathbf{1},-5/3)$ | Excluded: LHC searches |
| 21 | 1 | $(\bar{\mathbf{3}},\mathbf{2},-5/6)$ | UV completion problems |
| 22 | 1 | $(\bar{\mathbf{3}},\mathbf{2},1/6)$ | Excluded: $\Delta a_\mu < 0$ |
| 23 | 1 | $(\bar{\mathbf{3}},\mathbf{3},-2/3)$ | Excluded: proton decay |

EXCLUDED

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

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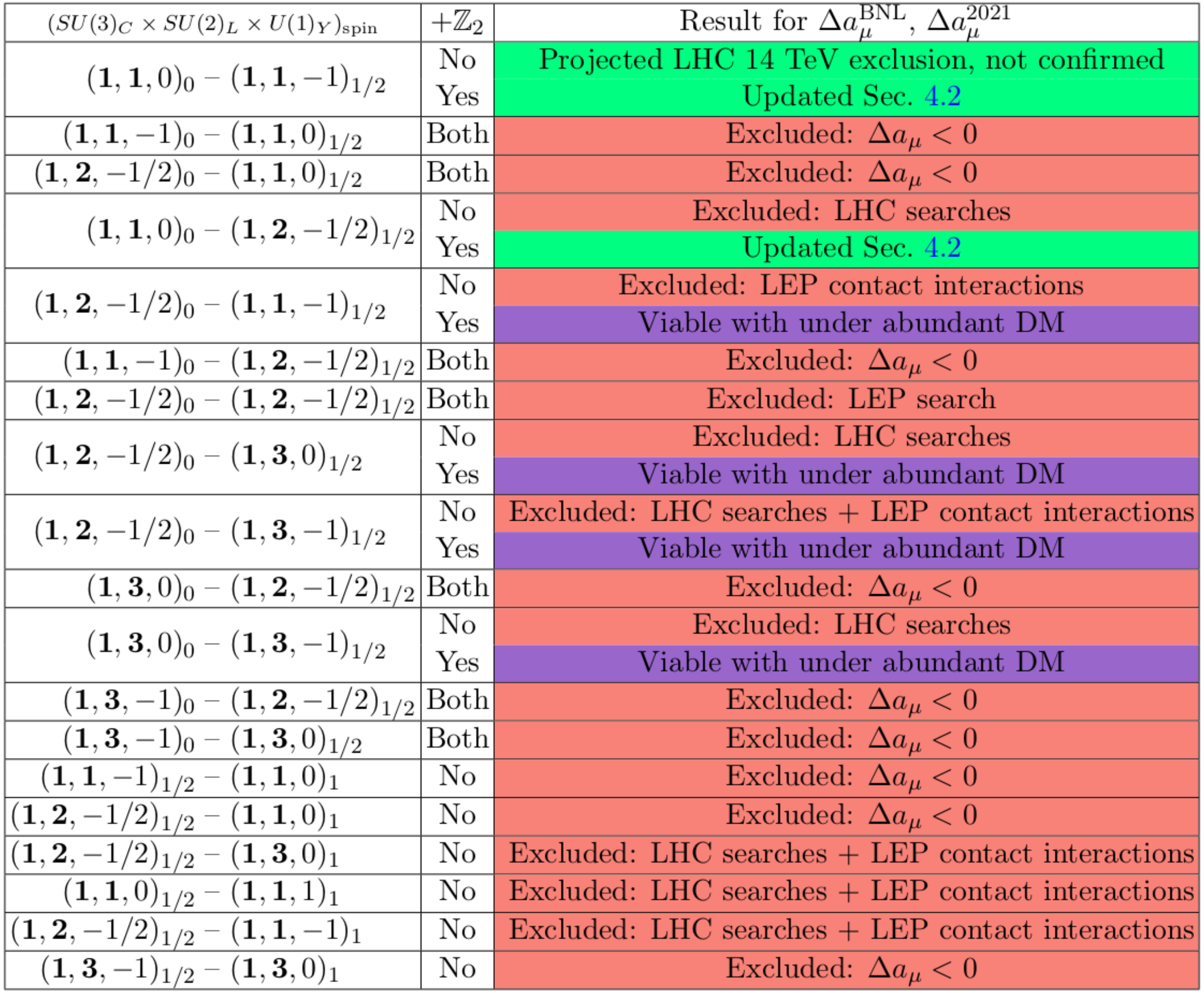
# Minimal models for muon g-2: 2 fields, different spin



| $(SU(3)_C \times SU(2)_L \times U(1)_Y)_{\text{spin}}$ | $+\mathbb{Z}_2$ | Result for $\Delta a_\mu^{\text{BNL}}$, $\Delta a_\mu^{2021}$ |
|---|---|---|
| $(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$ | No | Projected LHC 14 TeV exclusion, not confirmed |
|  | Yes | Updated 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 |
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| $(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{3},-1)_{1/2}$ | No | Excluded: LHC searches + LEP contact interactions |
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# Why so difficult?

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

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e.g. scalar leptoquark with

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

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

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For $\lambda = 3, E = 1$

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

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→ 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

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

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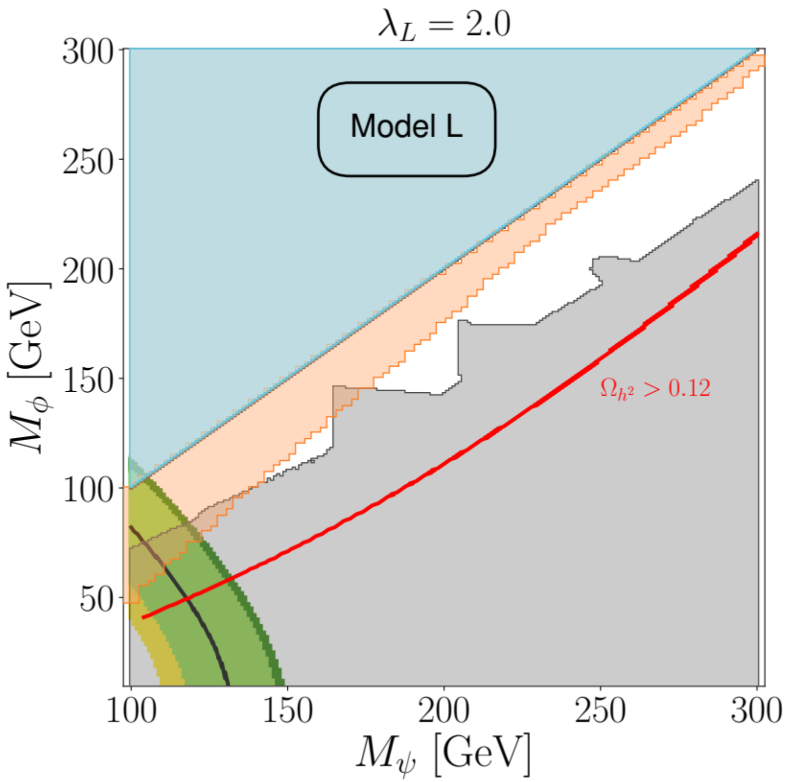

Fitting
2021 Muon g-2

🟨 Now Ruled Out

🟩 Still viable

🟩 Now viable

**FlexibleSUSY 2.5.0 for muon g-2**

$$\text{For } \lambda_L = 2, E = 1$$

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

Excluded by compressed spectra searches

# Try to evade limits with compressed spectra

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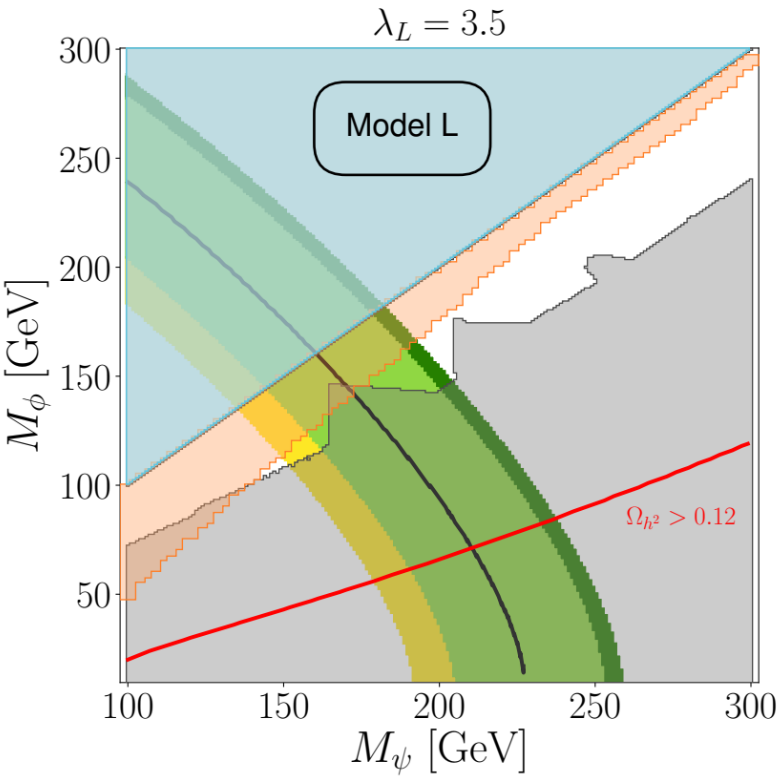

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**FlexibleSUSY 2.5.0 for muon g-2**

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

Only solutions hide in the gaps

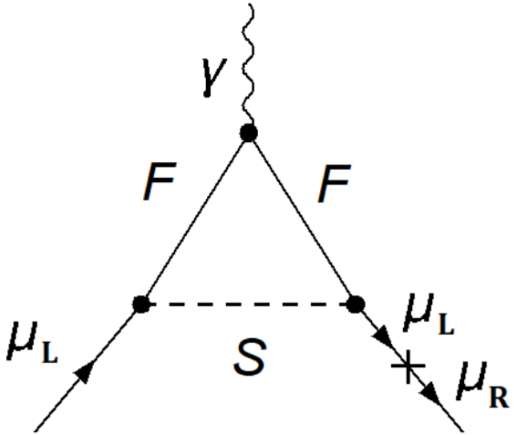
# Chirality flipping enhancements

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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← One factor of muon mass for chirality flip on outgoing muon

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

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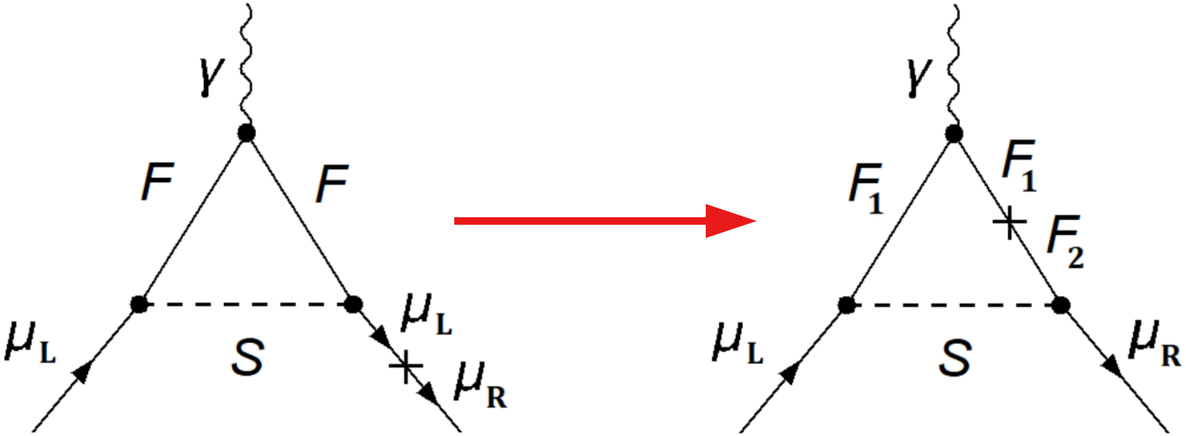

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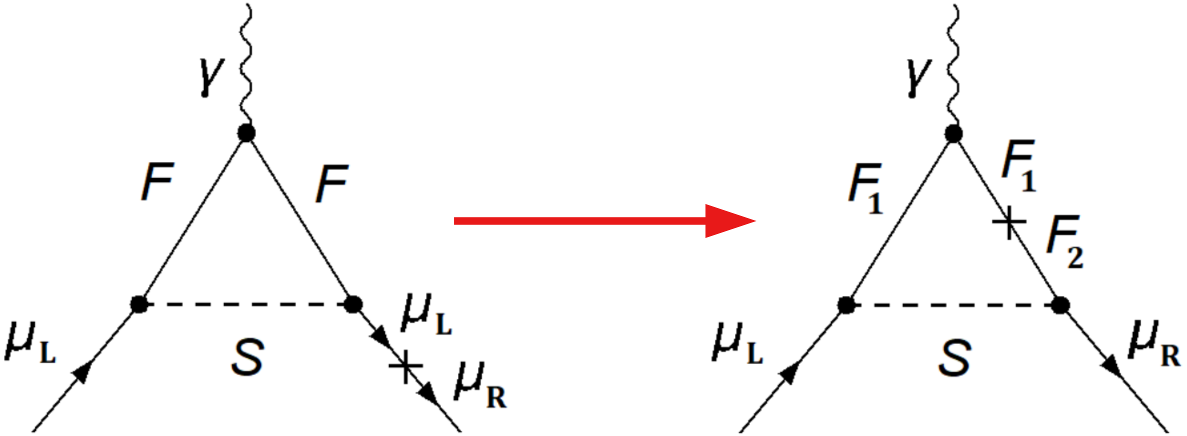
Enhancement to BSM corrections from am internal chirality flip $C_{\mathrm{BSM}} \propto \frac{M_{CF}}{m_\mu}$

e.g.



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

# Chirality flipping enhancements

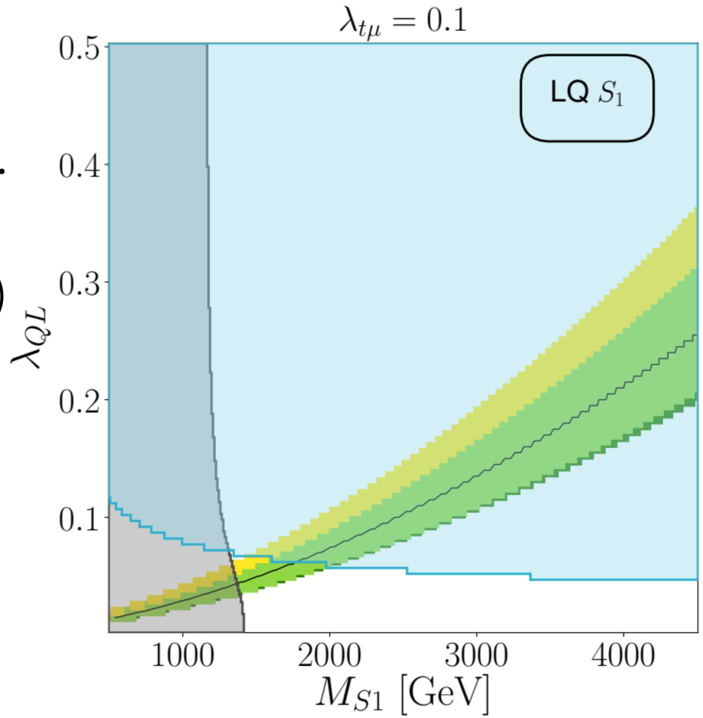
Scalar leptoquark with left and right couplings

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

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

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

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



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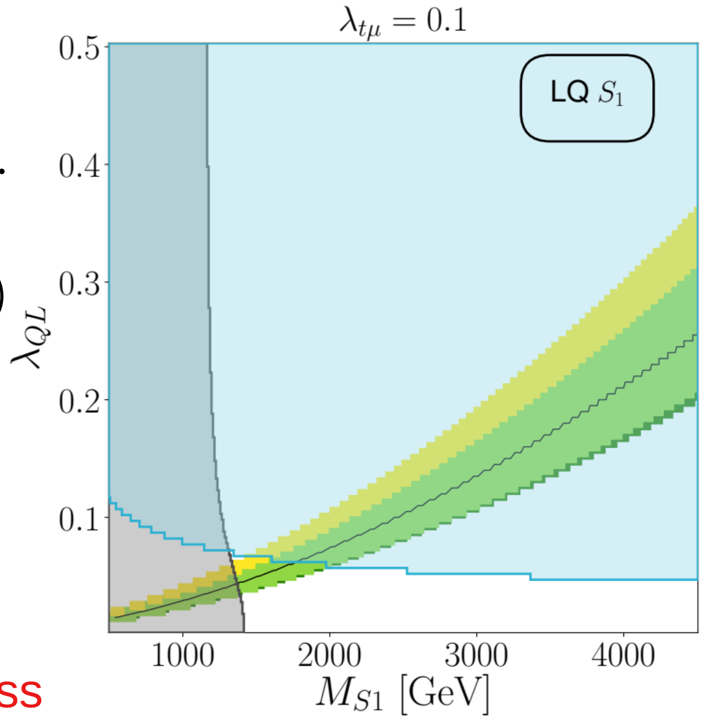

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2021 Muon g-2

🟨 Now Ruled Out

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But hard to avoid fine tuning in the muon mass

Enhancement in muon mass corrections too

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

**FlexibleSUSY 2.5.0 for muon g-2**

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Huge chirality flipping enhancement:
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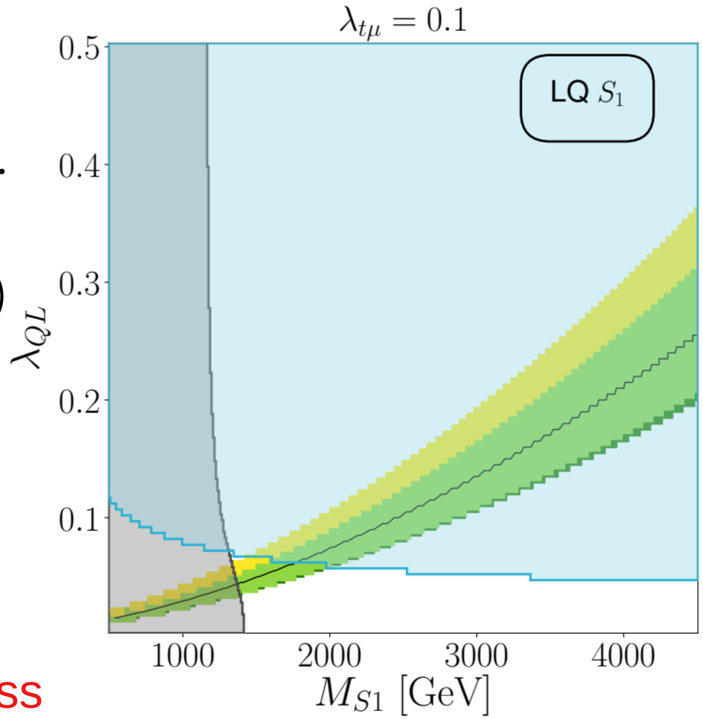


Fitting
2021 Muon g-2

🟨 Now Ruled Out

🟩 Still viable

🟩 Now viable

But hard to avoid fine tuning in the muon mass

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

Enhancement in muon mass corrections too

Testable with $BR(h \to \mu^+ \mu^-)$ at the CEPC

**FlexibleSUSY 2.5.0
for muon g-2**

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

# Muon g-2 and CDF MW?

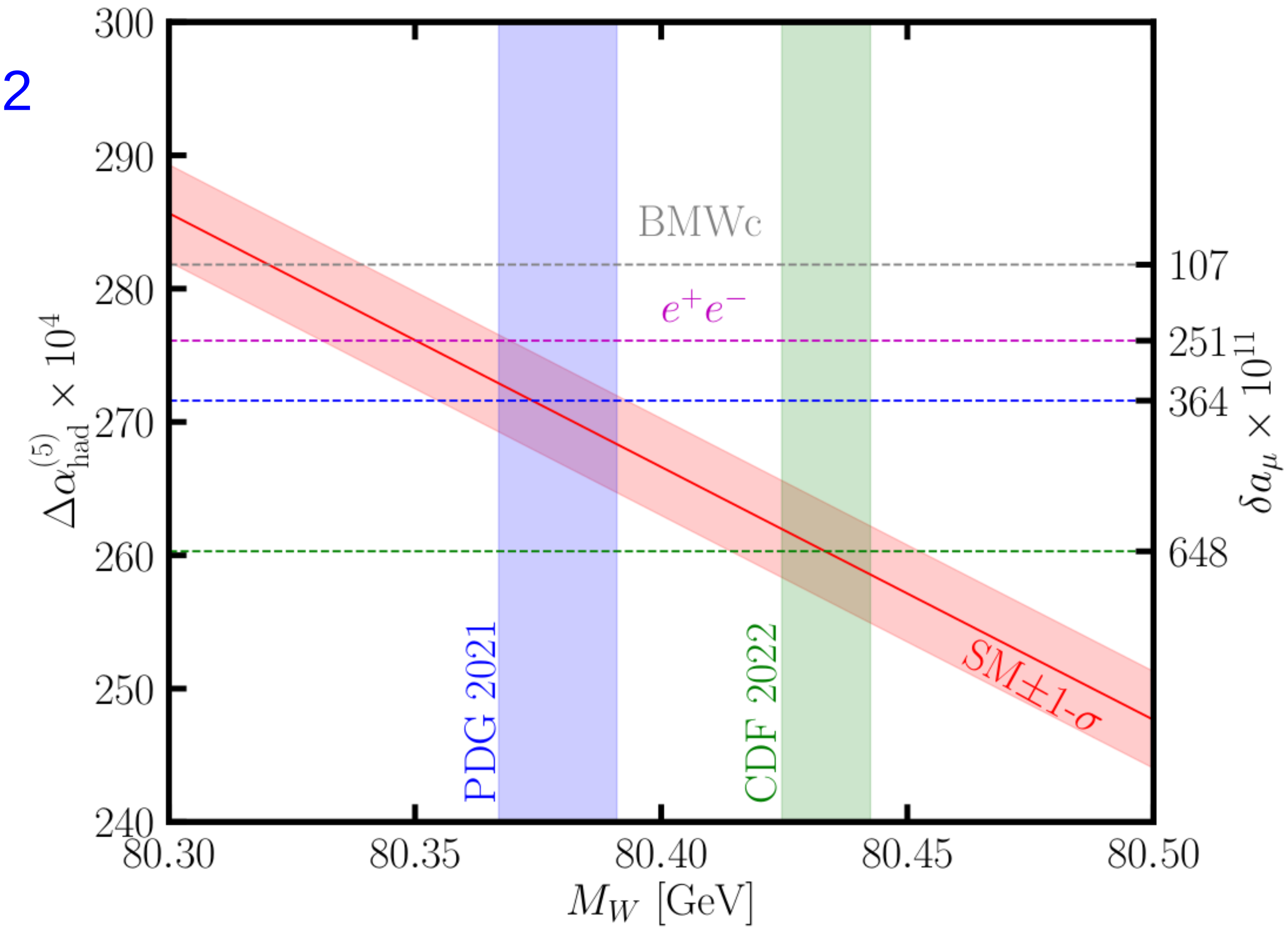
# Global EW fit Tension

[Nature Commun. 14 (2023) 659, PA, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, B. Zhu]

The W mass and muon g-2 pull in opposite directions

Red EW fit band cannot agree with both muon g-2 and CDF MW

Very hard for a change in the hadronic cross section to explain both



# Simultaneous BSM explanation of MW and muon g-2

[arXiv:2204.03996,PA, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, B. Zhu]

## Two scalar leptoquarks that mix together (proof of principle)

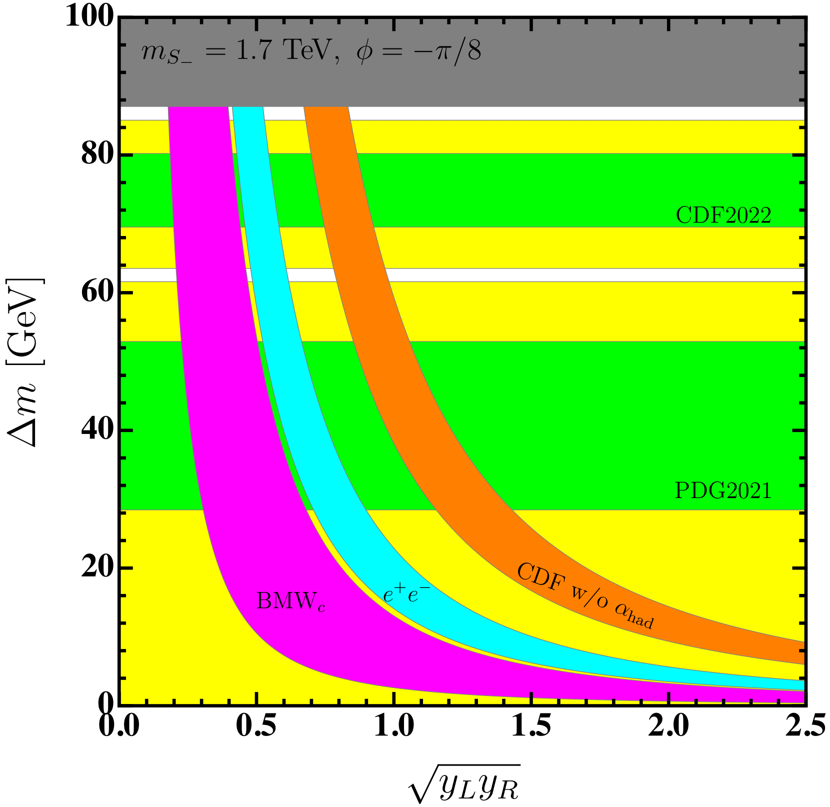
$$S_1 \ (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$$

$$\mathrm{S}_3 \ (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$\mathcal{L}_{S_1 \& S_3} = \mathcal{L}_{\mathrm{mix}} + \mathcal{L}_{\mathrm{LQ}},$$

$$\mathcal{L}_{\mathrm{mix}} = \lambda H^\dagger \left(\vec{\tau} \cdot \overrightarrow{S_3}\right) H S_1^* + \ \mathrm{h.c.}$$

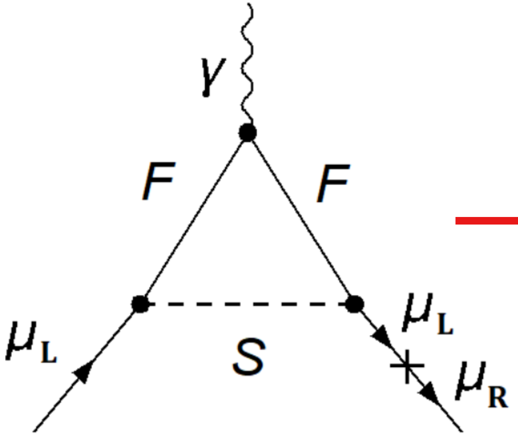
$$\mathcal{L}_{\mathrm{LQ}} = y_R^{ij} \bar{u}_{Ri}^C e_{Rj} S_1 + y_L^{ij} \bar{Q}_i^C i\tau_2 \left(\vec{\tau} \cdot \vec{S}_3\right) L_j + \mathrm{h.c.}$$



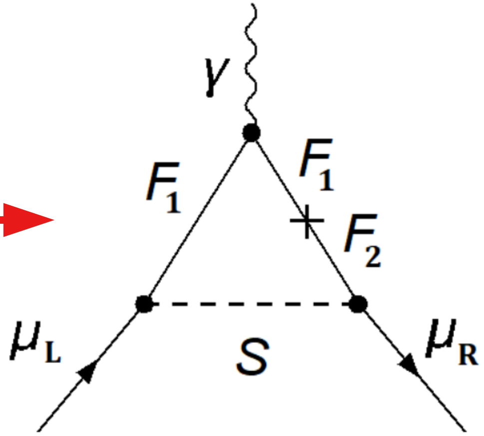
# Muon g-2 and Dark Matter?

# Chirality flipping enhancements

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



2 fields of opposite sign
(no internal chirality flip)



$m_\mu \to M_{CF}$

Add third field
(internal chirality flip)

# Heavy new physics for DM and muon g-2

Scalar doublet

Scalar singlet

Charged fermion singlet

Example:

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

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Mass Mixing between scalars

Left and right couplings to muons

Mass eigenstate coupling to left muon and right muon

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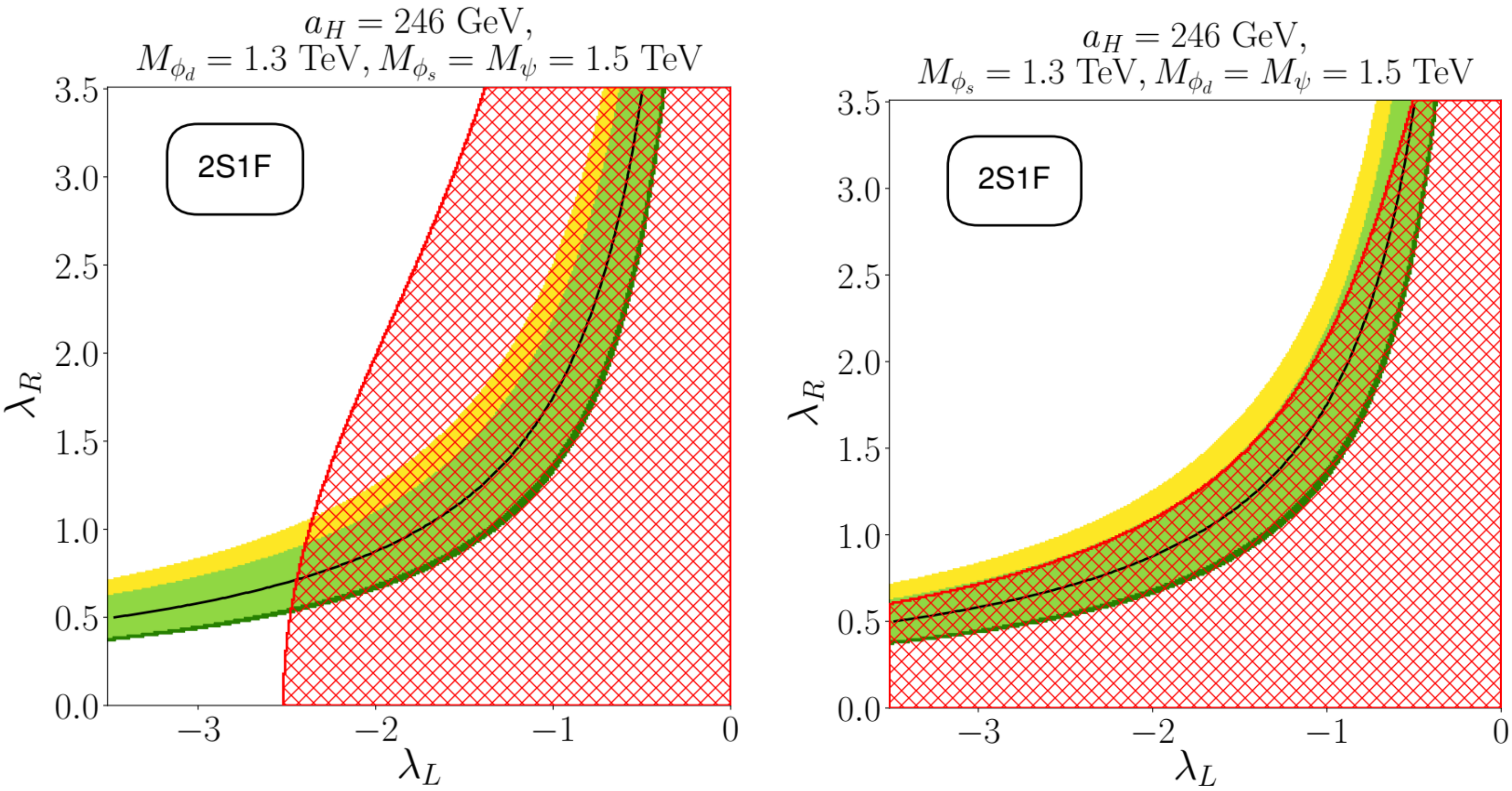
$\Rightarrow$ Non-zero $a_H + \lambda_L + \lambda_R$

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

# 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 e.g.



Fitting 2021 Muon g-2

🟨 Now Ruled Out

🟩 Still viable

🟩 Now viable

**Exclusions:**

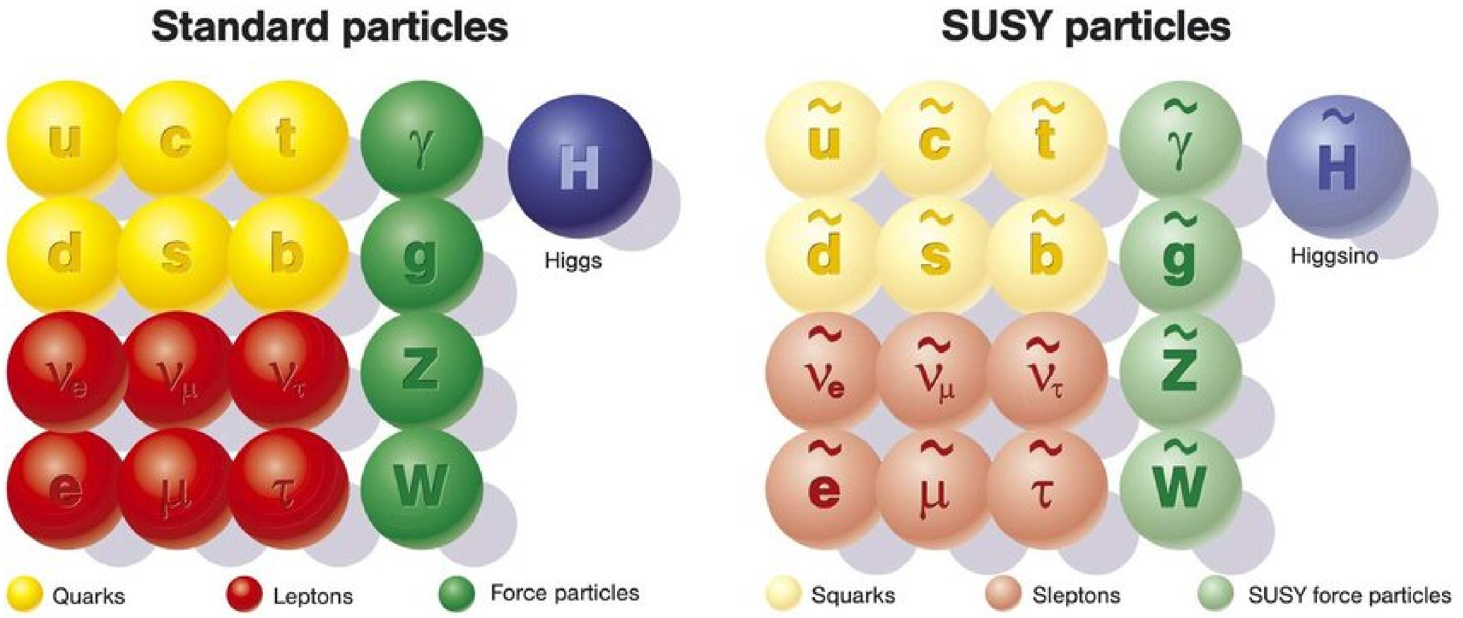
▨ Over Abundant

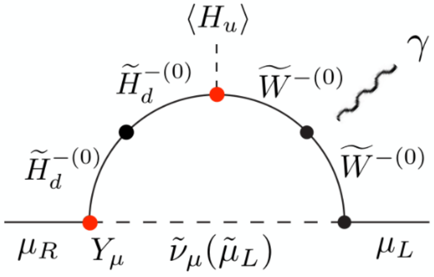
# Minimal SUSY (MSSM) solutions

Interest:

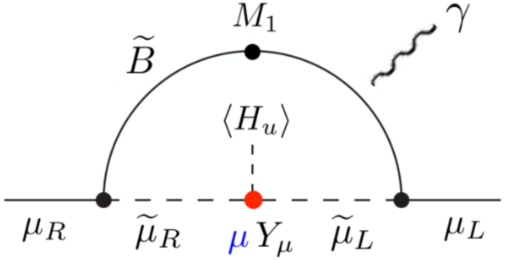
- Well motivated
- Solves Hierarchy Problem
- Has chirality flipping enhancement via $\tan\beta = v_u/v_d$

One-loop contributions from EWinos, smuons and smuon neutrinos

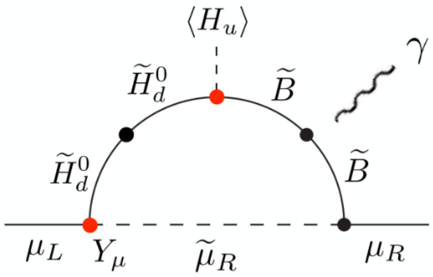




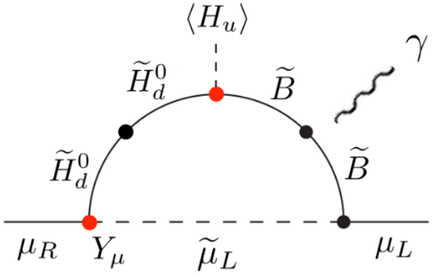
WHL



BLR



**BHR**



**BHL**

Four main diagrams with internal chirality flip

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

All are linear in tan beta

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

BLR is also linear in mu

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

WHL and BLR most important for phenomenology

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

[ 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) ]

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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

➔ Large $\tan\beta \gtrsim 70$ leads to non-perturbative Yukawas

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

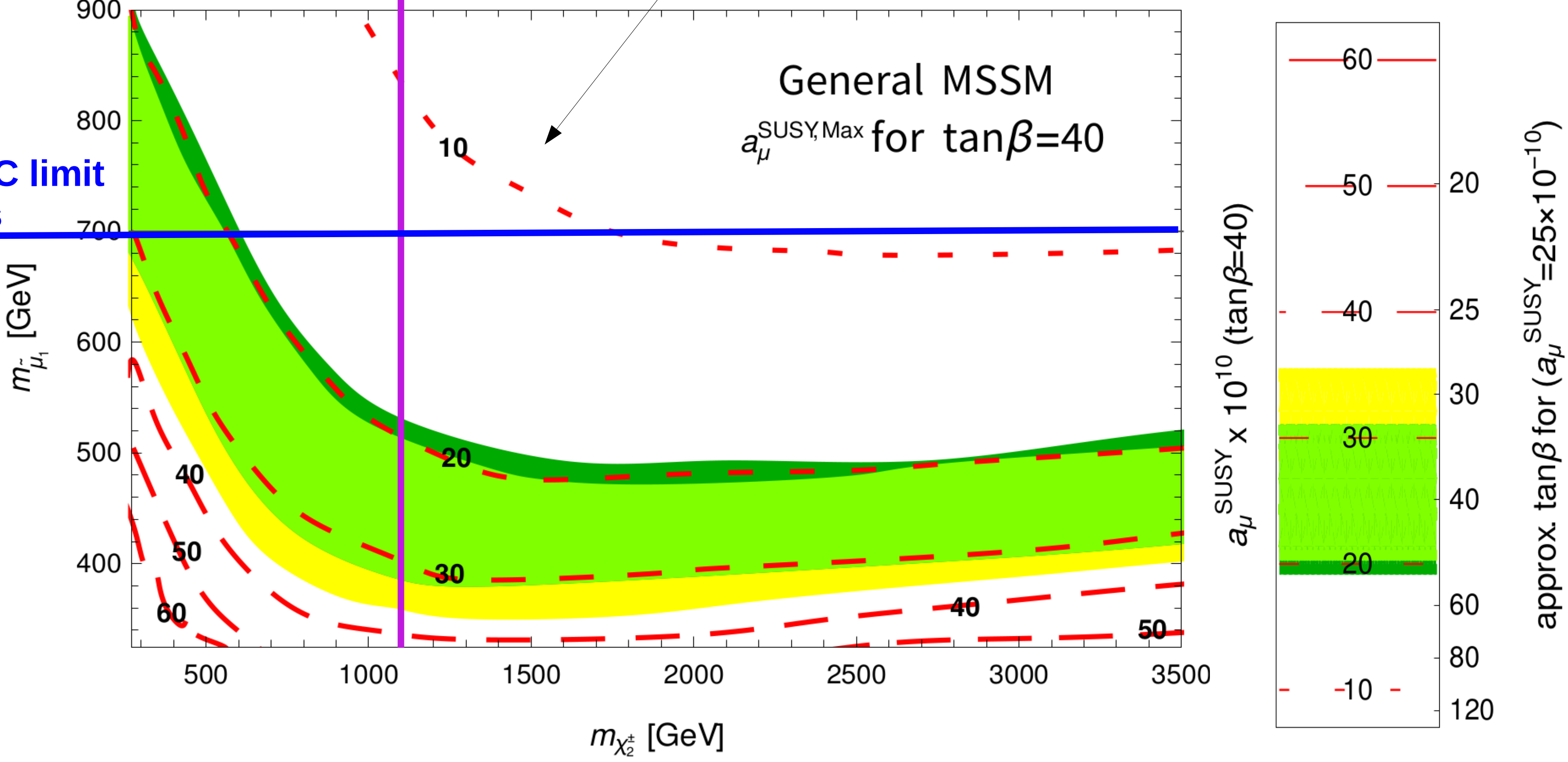
**Maximum LHC limit**
**Chargino mass < 1.1 TeV**

“Obviously allowed” region has either:

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

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)

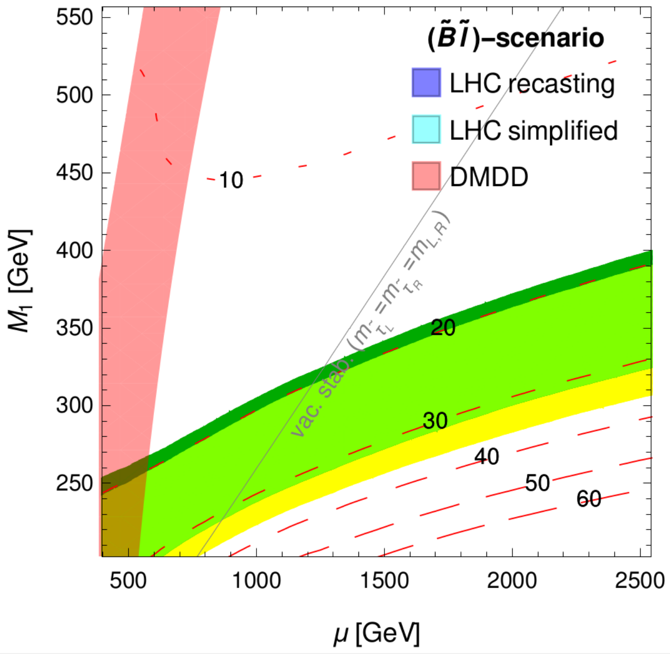
→ Plenty of viable parameter space:

DM also explained

No DM explanation

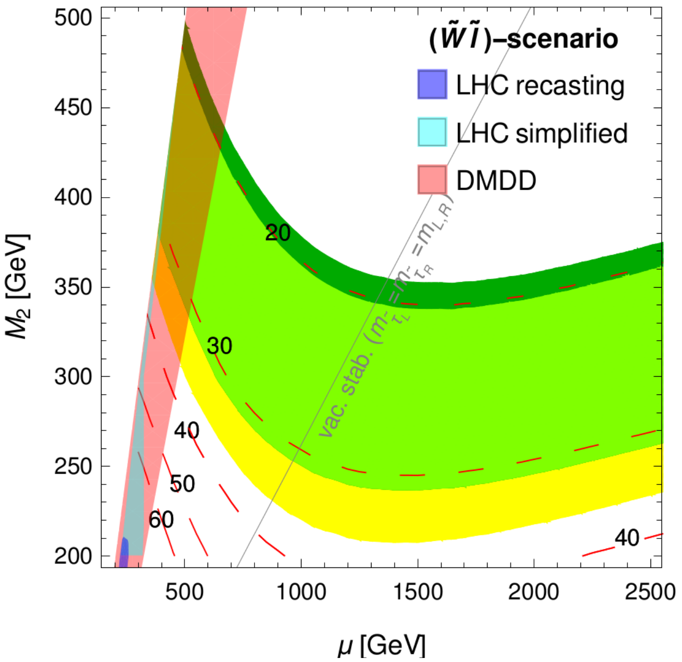
## Bino LSP

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



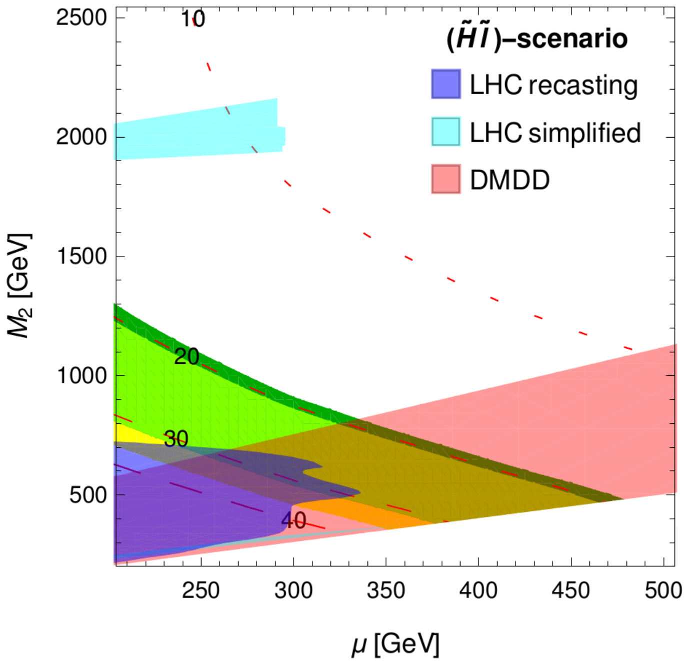
## Wino LSP

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



## Higgsino LSP

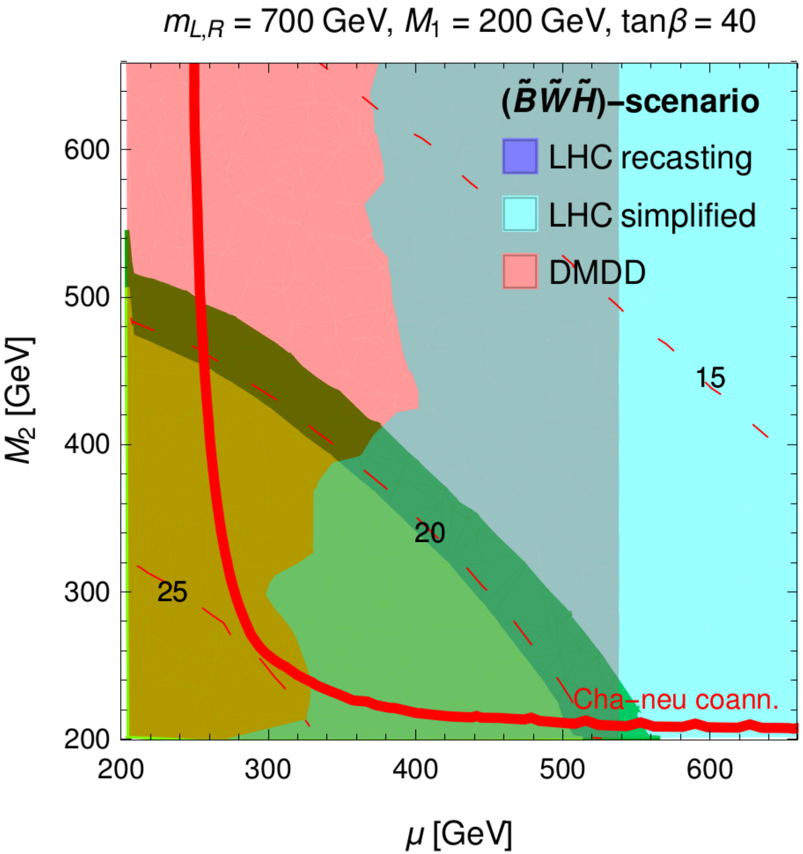
$m_{L,R} = \mu$+50 GeV, $M_1$ = 2000 GeV, tan$\beta$ = 40

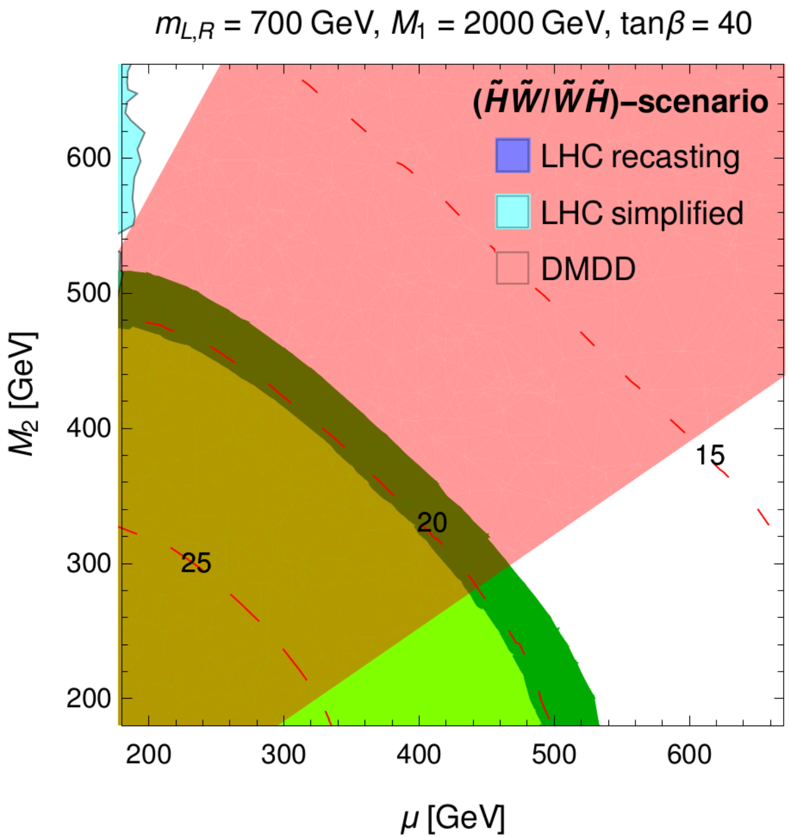


# Evading broad limits on sleptons and charginos

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 $2\sigma$ region with large $\tan\beta$ close to 50.
- Very large $\tan\beta \gg 50$
- Tune slepton masses so $m_{\tilde{l}} < m_{\mathrm{LSP}} + \Delta m_{\mathrm{LHC\text{-}gap}}$
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Some issues that can reduce plausibility though

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Still room for new ideas!

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  - There is a large tuning in the muon mass and significant corrections to $h \to \mu\mu$ that may be targetted with precision Higgs measurements
- Many reasonable models can fit muon g-2, but there is still room for new ideas

# Back Up Slides

# Other Possibilities

There are many other possibilities not covered here.

e.g.

- Axion Like Particles
- Dark $Z$
- Gauged $U_{(L_\mu - L_\tau)}$
- Vector like leptons (similar to leptoquark solution)
- Next-to-Minimal Supersymmetric Standard Model (NMSSM,
- Flavourful Supersymmetric Standard Model (larger chirality flipping enhancement)
- ….

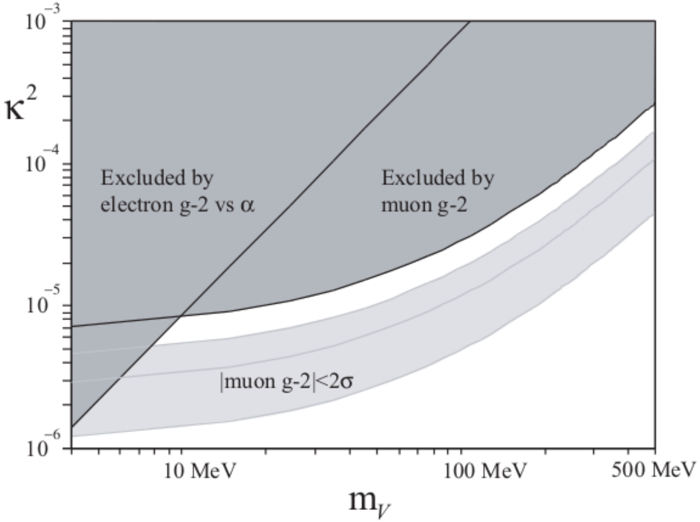
# Dark Photon

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 $A_\mu \rightarrow A_\mu + \kappa Z_{d\,\mu}$

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



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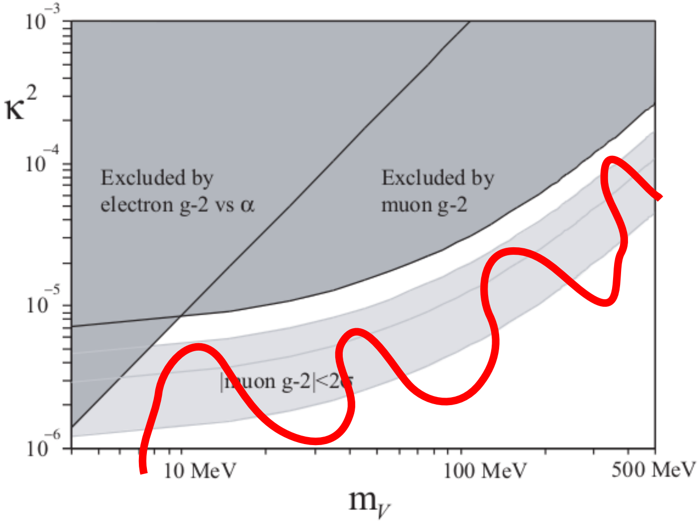

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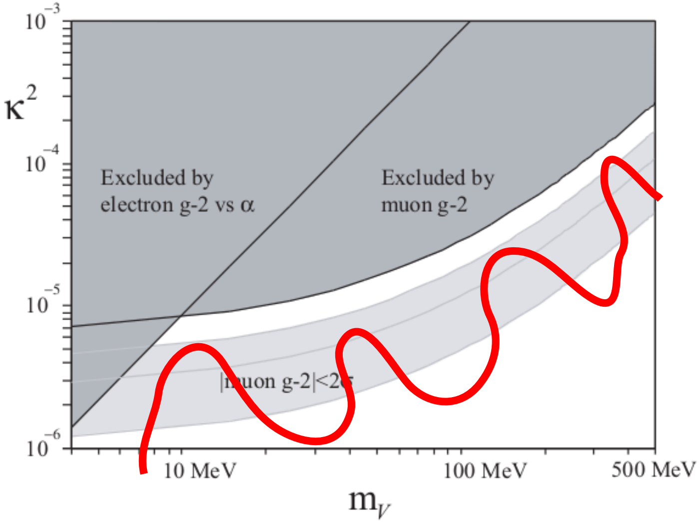

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Extensions of this still viable, e.g.

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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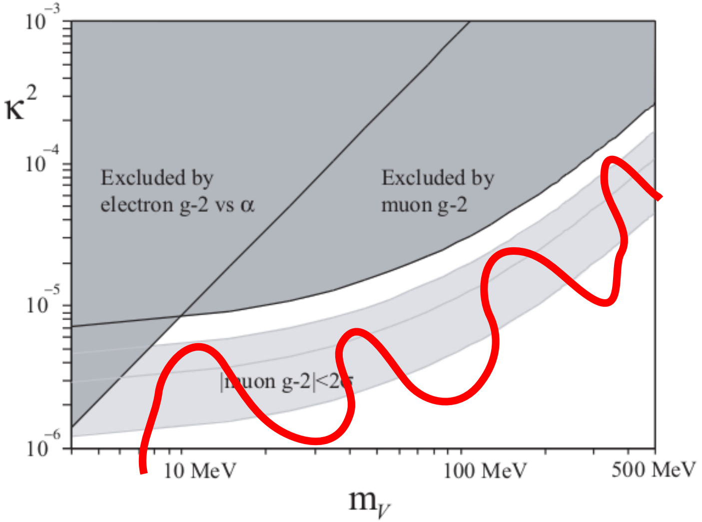

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Semi-visible decays: Dark photon/Z decays into invisible dark sector states + visible SM states

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

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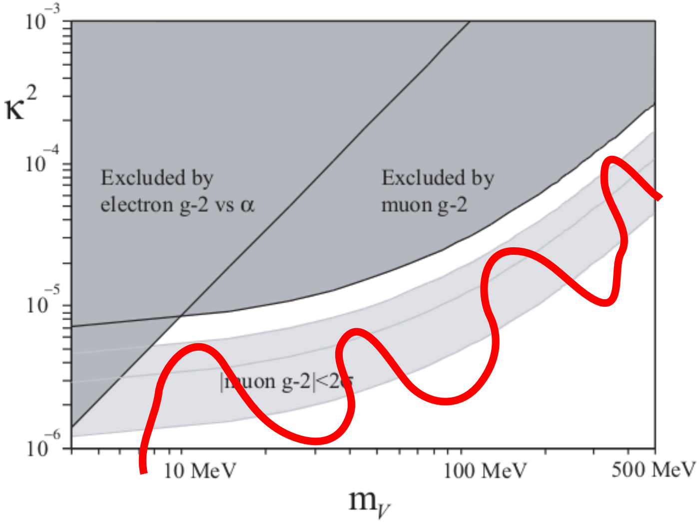

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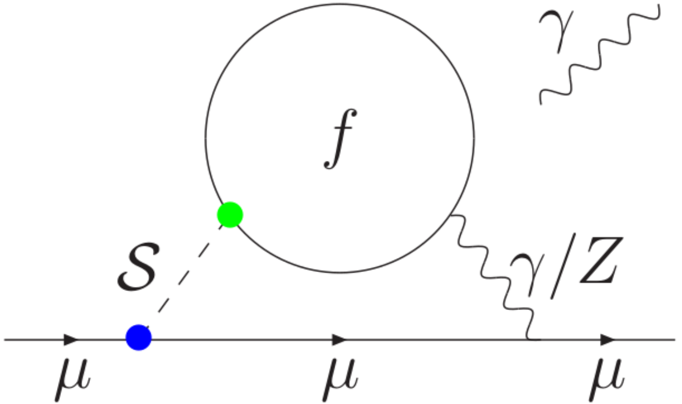
Semi-visible decays: Dark photon/Z decays into invisible dark sector states + visible SM states
[PRD 99 (2019) 115001, G. Mohlabeng]

$Z'$ / 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]

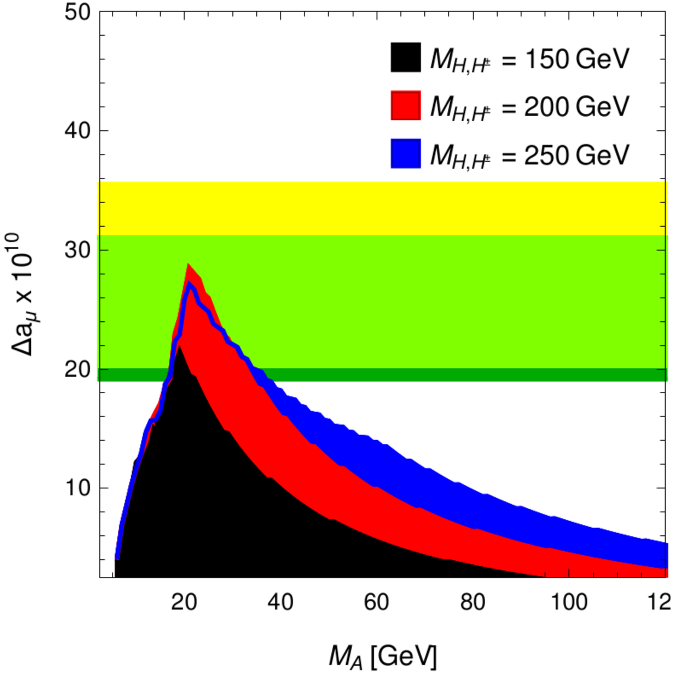
# 2HDM

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

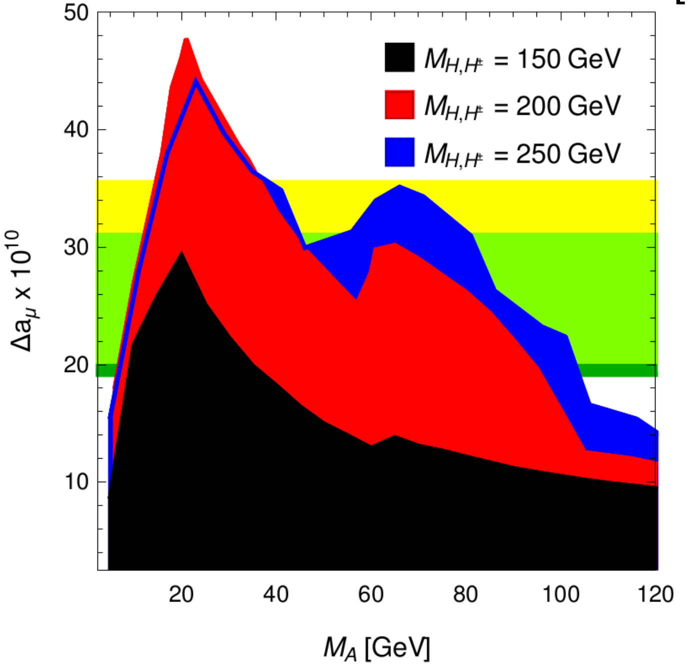


[Hyejung Stöckinger-Kim, Corfu2022]

Type X 2HDM



Flavour aligned 2HDM



Small regions in Type X still viable

More scenrios possible in flavour aligned  2HDM

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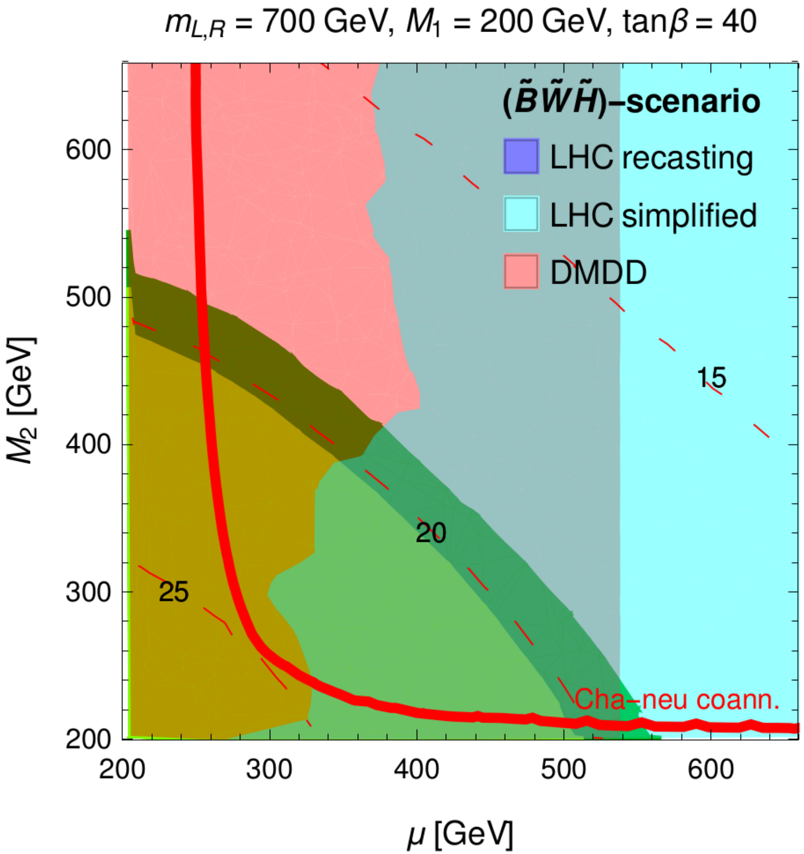


Since the overlapping colors make this hard to read...

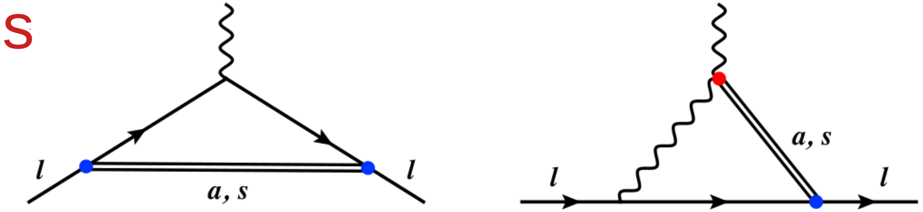
- The shaded red DMDD region is all $\mu < 550$ GeV
- Cyan is everywhere with $\mu \gtrsim 350$ GeV and gives the jagged vertical line roughly around this value of $\mu$.
- the cyan exclusion only applies whenever stau co-annihilation is needed to deplete the relic density,
- However that is everywhere 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

# Axions

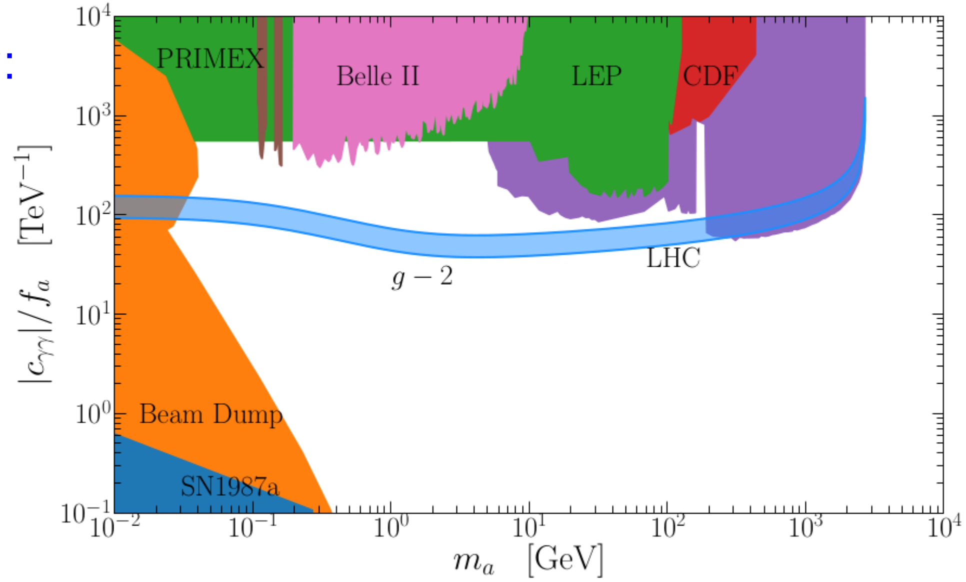
Axion Like Particles (ALPs) appear from the breaking of the approximate U(1) PQ symmetry

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

Naively the EFT ALP picture looks very promising:



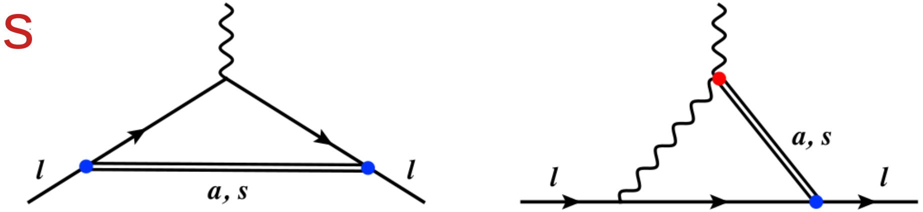
[Phys.Rev.D 94 (2016) 11, 115033,
W.J. Marciano, A. Masiero, P. Paradisi & M. Passera]



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

# Axions

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



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

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

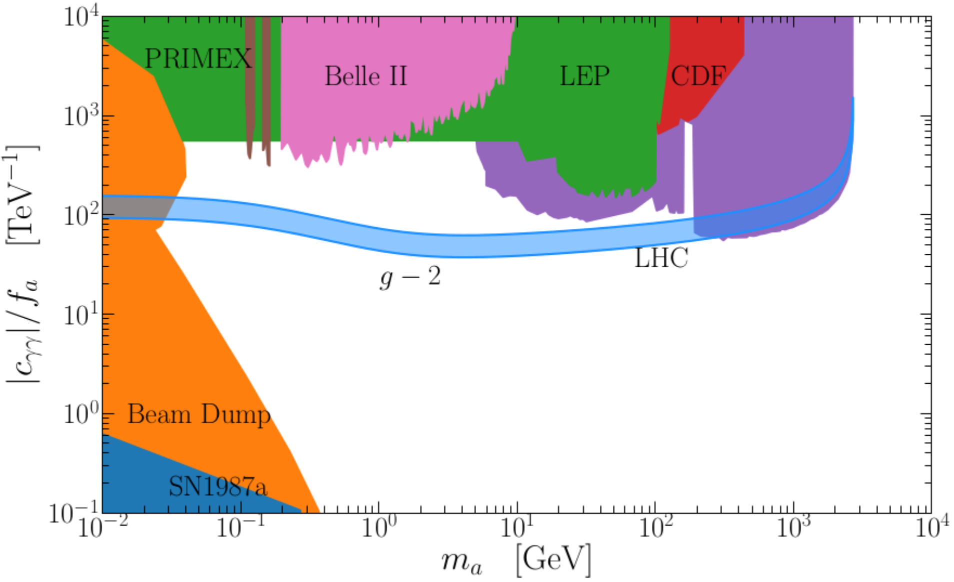
Naively the EFT ALP picture looks very promising:

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 $\mathcal{O}(10\text{–}100)\ \mathrm{GeV}$

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

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

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

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

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

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

[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]

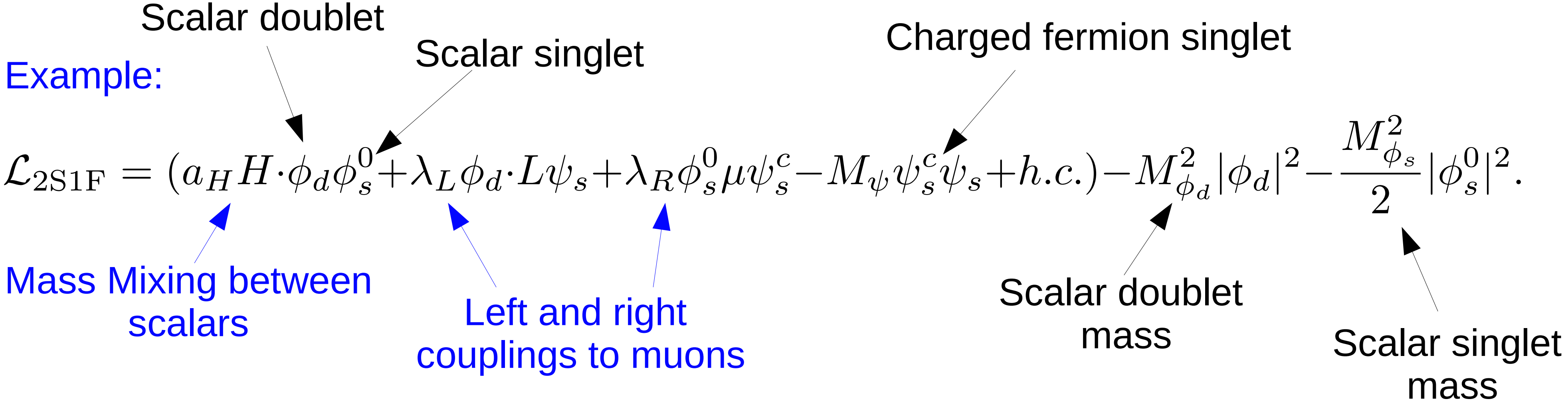
Similar to scalar leptoquark case

Solutions with heavy masses well beyond LHC

But may have issues with muon mass fine tuning.

# 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

Scalar doublet mass

Scalar singlet mass

Scalar DM:

Relic density (co)annihilations mech.

- scalar singlet DM → via Higgs portal, $\lambda_R$ t-channel exchange $\psi_s$
- inert doublet scalar DM → SU(2) co-ann, $\lambda_L$ t-channel exchange of $\psi_s$
- Mixed singlet-doublet scalar DM → All of the above + $a_H$ driven singlet-doublet co-ann

Direct detection of dark matter via $a_H$

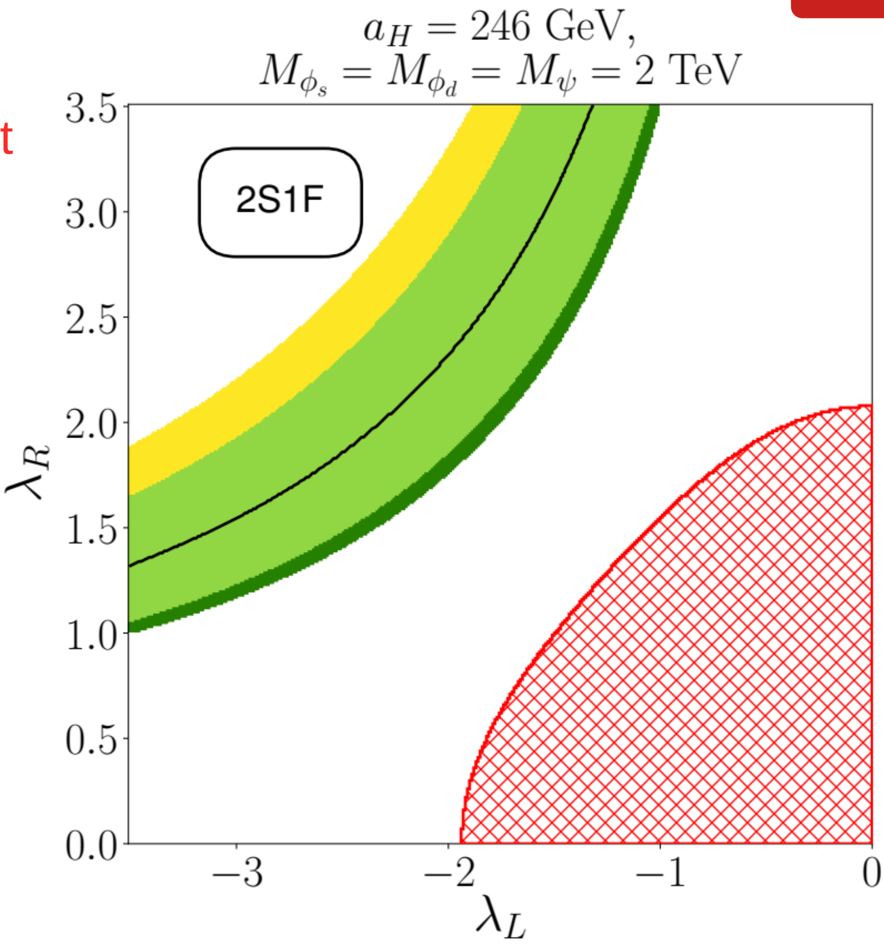
# Heavy new physics for DM and muon g-2

**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

$a_H = 246$ GeV,
$M_{\phi_s} = M_{\phi_d} = M_\psi = 2$ TeV



Fitting
2021 Muon g-2

🟨 Now Ruled Out

🟩 Still viable

🟩 Now viable

**Exclusions:**

▨ Over Abundant

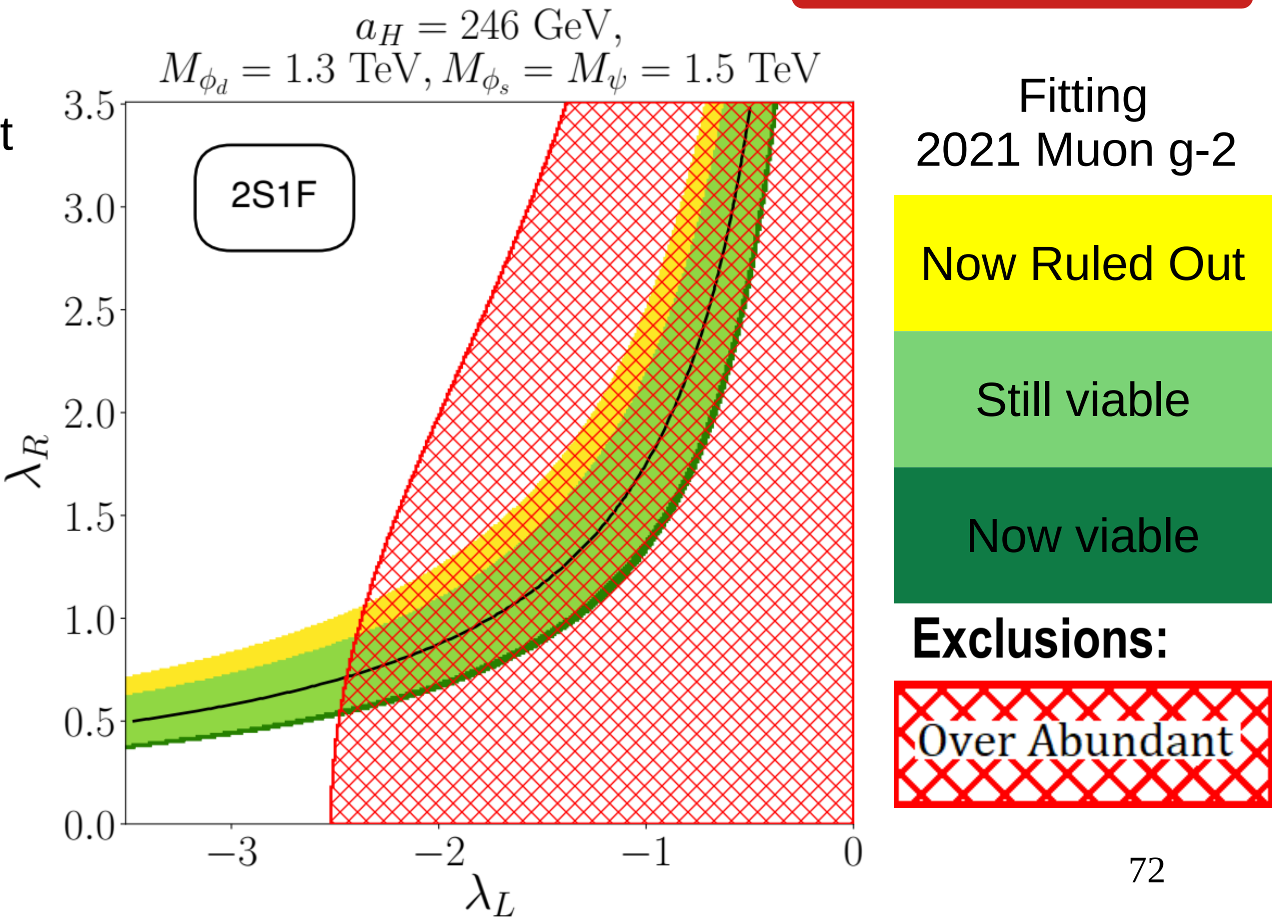
# Heavy new physics for DM and muon g-2

**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 $\lambda_L$
  → point where g-2 and RD explained simultaneously

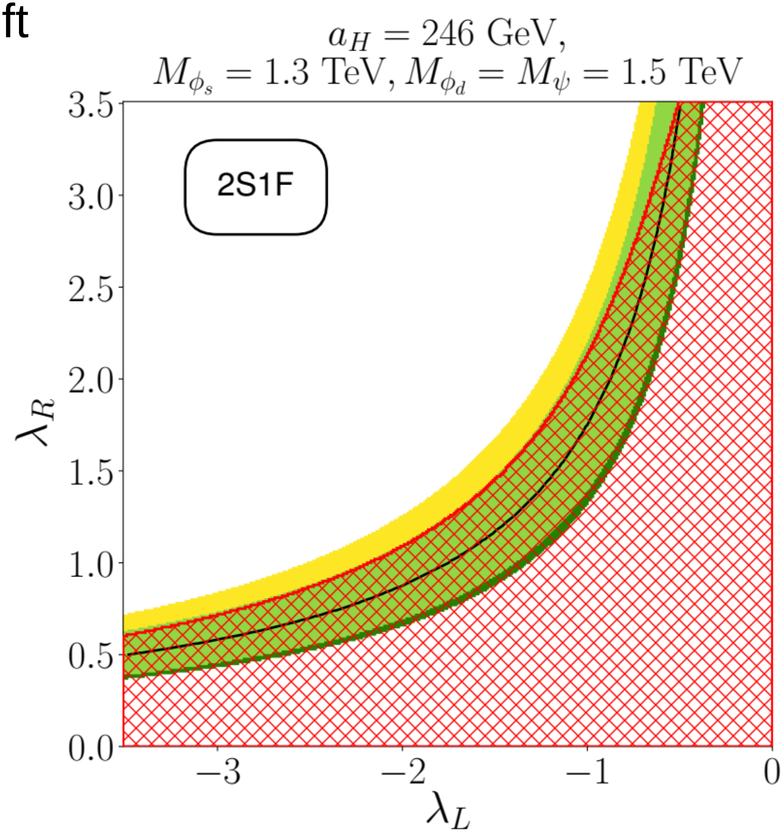


# Heavy new physics for DM and muon g-2

**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 $\lambda_L$
  → 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

🟨 Now Ruled Out

🟩 Still viable

🟩 Now viable

**Exclusions:**

▨ Over Abundant

# The W mass

# A very Surprising New Result..

New experimental result

$$M_W^{\mathrm{CDF}} = 80.4335 \pm 0.0094 \ \mathrm{GeV}$$

Previous world average

$$M_W^{2021} = 80.379 \pm 0.012 \ \mathrm{GeV}$$

Theory predictions

$$\left.\begin{aligned} M_W^{\mathrm{SM,OS}} &= 80.355 \pm 0.006 \ \mathrm{GeV} \\ M_W^{\mathrm{SM,\overline{MS}}} &= 80.351 \pm 0.006 \ \mathrm{GeV} \\ M_W^{\mathrm{SM,\ EW\ fit}} &= 80.3591 \pm 0.0052 \ \mathrm{GeV} \end{aligned}\right\} \quad \text{Good agreement}$$

$$\Rightarrow \approx 7\sigma \ \text{deviation!}$$

But in significant tension with previous measurements…

# Naive Combination

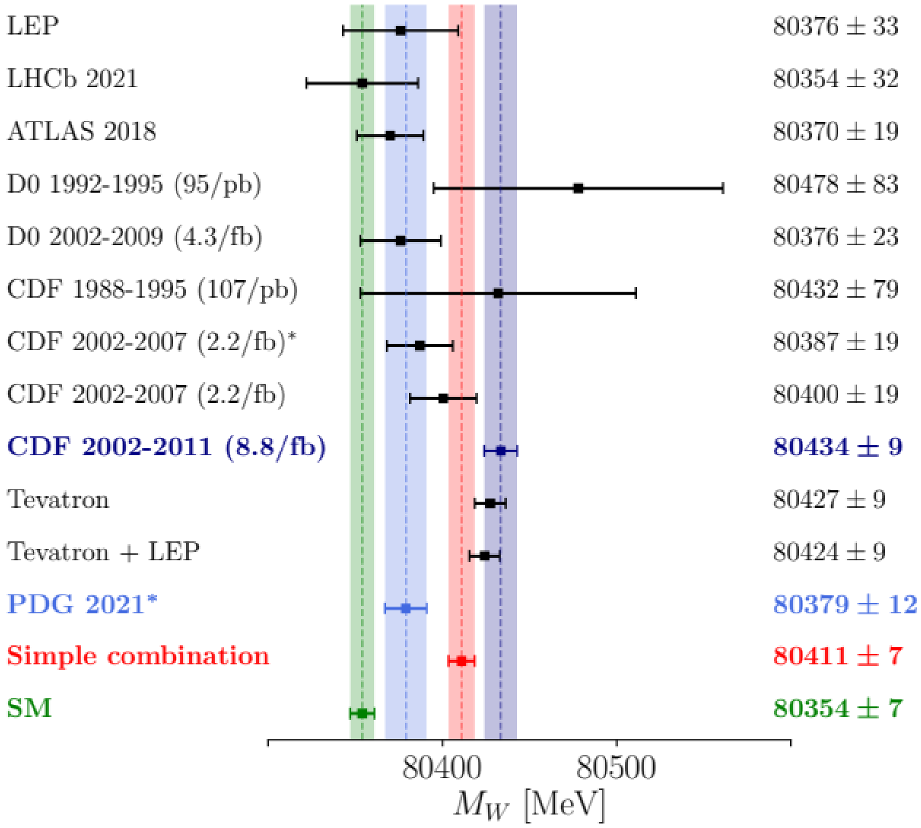
[arXiv:2204.03996,PA, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, B. Zhu]

Naively combine all measurements,
avoiding double counting
of old CDF results

$$\bar{x} \pm \Delta x = \frac{\sum_{i=1}^{N} w_i x_i}{\sum_{i=1}^{N} w_i} \pm \left( \sum_{i=1}^{N} w_i \right)^{-1/2}$$

$$\Rightarrow M_W^{\text{simple comb.}} = 80.411 \pm 0.007 \text{ GeV}$$

With tension: $2.5\sigma$



# Predicting MW

Electroweak sector $\{M_W, M_Z, G_F, \sin\theta_W, \alpha_e\} \xrightarrow{\text{Choose}} \{M_Z, G_F, \alpha_e\}^{\text{EW inputs}}$

Redundancy amongst these quantities

$$\left.\begin{aligned} &M_W^2 = \frac{1}{4}g^2v^2 \quad M_Z^2 = \frac{1}{4}\sqrt{(g^2+g'^2)}v^2 \quad \sin^2\theta_W = \frac{g'^2}{g^2+g'^2} \\ &\alpha_e = \frac{e^2}{4\pi} \quad e = \frac{gg'}{g^2+g'^2} = g'\sin\theta_W = g\cos\theta_W \\ &G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2\sin^2\theta_W} \end{aligned}\right\}$$

The Fermi constant is very precisely measured

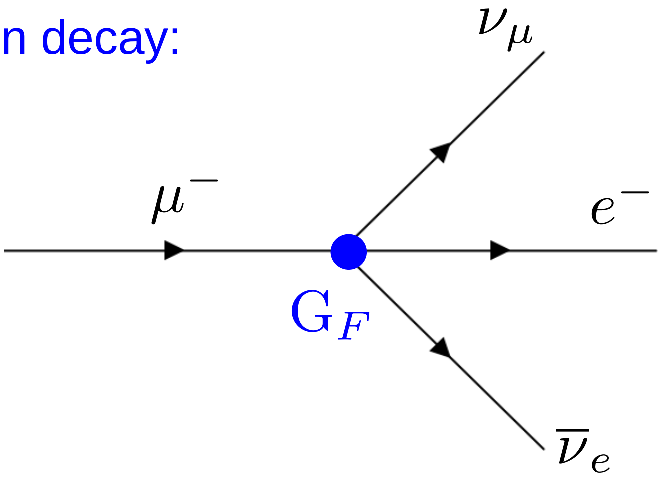
Tree-level EW relations in SM

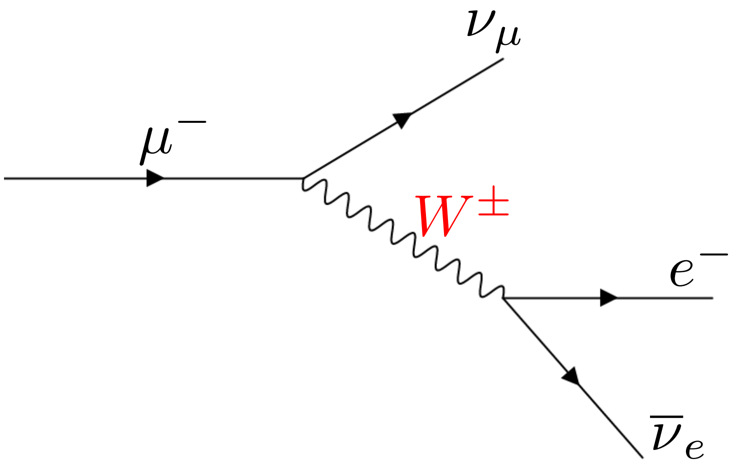
$\Rightarrow$ **Predict $M_W$ from $G_F$**

# Predicting MW from muon decay

Just calculate corrections from W self energy? $M_W^2 = M_W^{2\,\text{tree}} + \Pi_{WW}(M_W^2)$ ✗

Predict through muon decay:





Muon lifetime:

$$\tau_\mu^{-1} = G_F \frac{m_\mu^5}{192\pi^3}(1 + \ldots)$$

$$G_F^{\text{tree}} = \frac{\pi\alpha}{\sqrt{2} M_W^2 \sin^2\theta_W}$$

# OS calculation of MW

Calculate from muon decay:

$$G_F = \frac{\pi\alpha}{\sqrt{2} M_W^{2\,\mathrm{OS}} \sin^2\theta_W}\left(1 + \Delta r\right)$$

$$M_W^{2\,\mathrm{OS}} = M_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2} G_F M_Z^2}\left(1 + \Delta r\right)} \right\}$$

At one loop: $\Delta r^{(\alpha)} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r^{\mathrm{remainder}}$

Charge renormalisation

$$\begin{aligned}\Delta\alpha &:= \Pi_{AA}^{\mathrm{light}}(0) - \Pi_{AA}^{\mathrm{light}}(M_Z^2) \\ &= \Delta\alpha^{\mathrm{had}} + \Delta\alpha^{\mathrm{lep}}\end{aligned}$$

Correction to the $\rho$ parameter

$$\rho = \frac{M_W^2}{M_Z^2 c_W^2}$$

# OS calculation of MW

Calculate from muon decay:

$$G_F = \frac{\pi\alpha}{\sqrt{2} M_W^{2\,\mathrm{OS}} \sin^2\theta_W}\left(1+\Delta r\right)$$

$$M_W^{2\,\mathrm{OS}} = M_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2} G_F M_Z^2}\left(1+\Delta r\right)} \right\} \longleftarrow$$

Assumes no tree-level correction to $\rho$ parameter

At one loop: $\Delta r^{(\alpha)} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r^{\mathrm{remainder}}$

Charge renormalisation

$$\Delta\alpha := \Pi_{AA}^{\mathrm{light}}(0) - \Pi_{AA}^{\mathrm{light}}(M_Z^2)$$
$$= \Delta\alpha^{\mathrm{had}} + \Delta\alpha^{\mathrm{lep}}$$

Correction to the $\rho$ parameter

$$\rho = \frac{M_W^2}{M_Z^2 c_W^2}$$

# $\overline{\text{MS}}$ calculation of MW

Calculate from muon decay:

$$G_F = \frac{\pi\hat{\alpha}(M_Z)}{\sqrt{2}M_W^2\hat{s}_{\theta W}}\left(1+\Delta\hat{r}_W\right)$$

$$M_W^2 = M_Z^2\hat{\rho}\left\{\frac{1}{2}+\sqrt{\frac{1}{4}-\frac{\pi\hat{\alpha}(M_Z)}{\sqrt{2}G_F M_Z^2\hat{\rho}}\left(1+\Delta r_W\right)}\right\}$$

$$\hat{\alpha}(M_Z) = \frac{\alpha}{1-\Delta\hat{\alpha}(M_Z)}$$

Also Includes $\Delta\alpha^{\mathrm{had}} + \Delta\alpha^{\mathrm{lep}}$

You may see other fomulations,
many subtleties.

Again hadronic contributions
to charge renormalisation
play a role

# Hadronic uncertainties in muon g-2

Skepticism exists because:

- Extraordinairy claims require extraordinairy evidence
- $a_\mu^{\rm HVP}\,(\text{and}\,\Delta\alpha^{\rm had})$ are hard to calculate
- The new BMW Lattice result does not agree

  (and some parts agreement in 2206.06582, arXiv:2206.15084)

Early lattice results (at this precsion)
→ need for caution, but increases concerns

Muon g-2 situation already motivated comparsion to EW fits with $\Delta\alpha^{\rm had}$

If BMW result is correct → tension in EW fits

[A. Crivellin, M. Hoferichter, C. A. Manzari, and M. Montull, PRL 125, 091801 (2020)]

But what about the new W mass measurement?

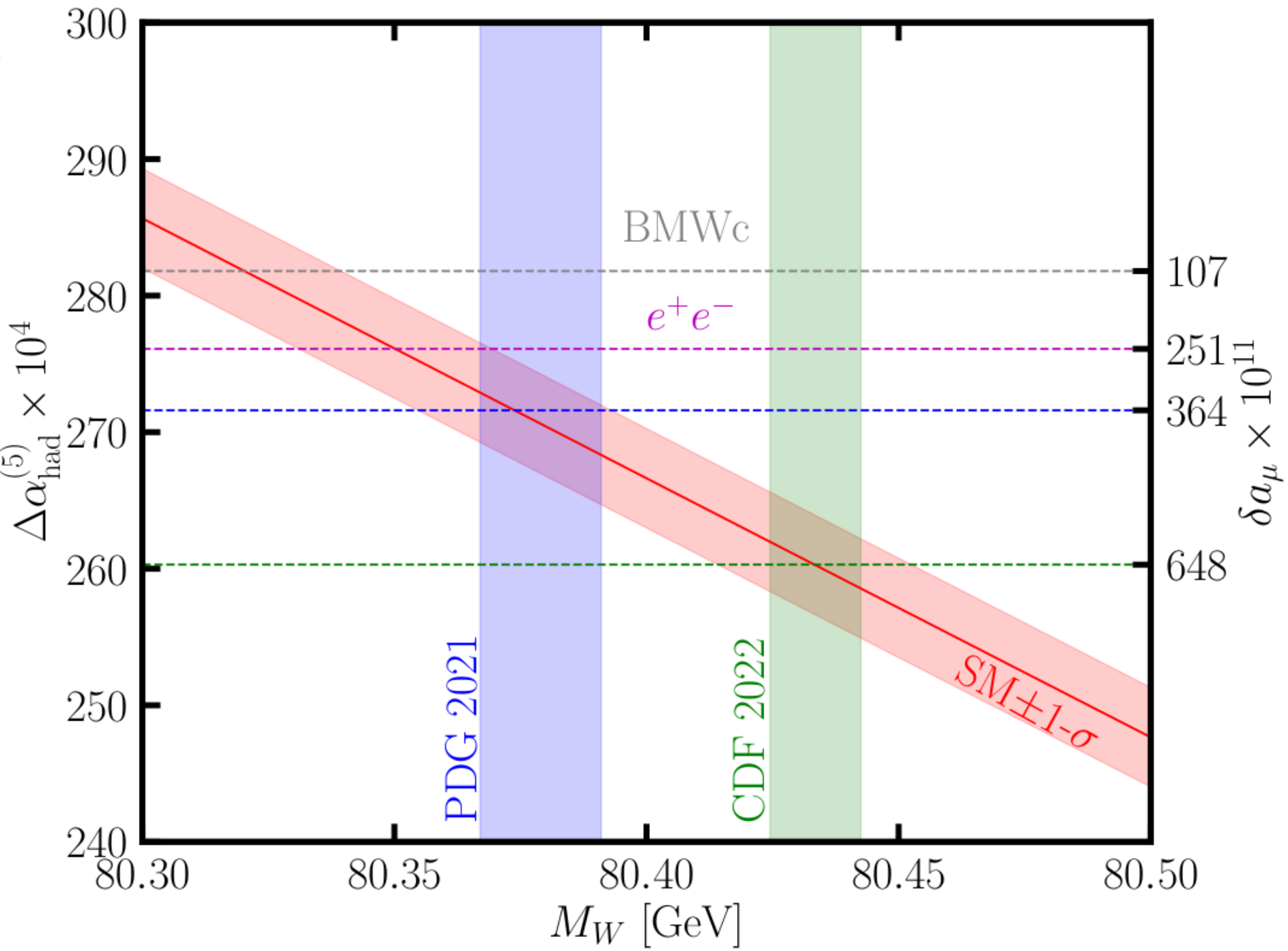
# Global EW fit Tension

[arXiv:2204.03996,PA, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, B. Zhu]

The W mass and muon g-2 pull in opposite directions

Red EW fit band cannot agree with both muon g-2 and CDF MW

Very hard for a change in the hadronic cross section to explain both



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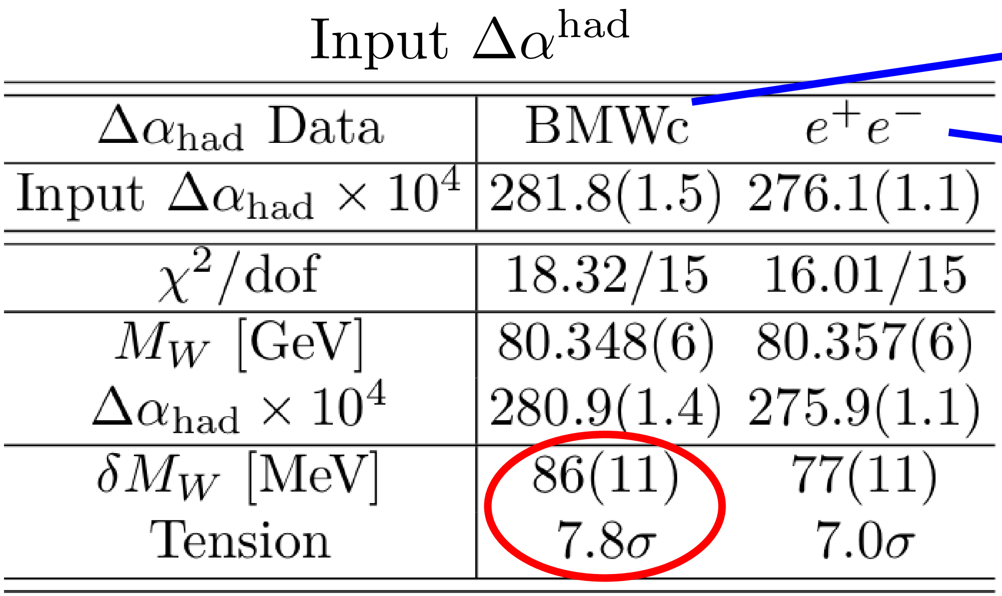


Input $\Delta\alpha^{\text{had}}$

| $\Delta\alpha_{\text{had}}$ Data | BMWc | $e^+e^-$ |
|---|---|---|
| Input $\Delta\alpha_{\text{had}} \times 10^4$ | 281.8(1.5) | 276.1(1.1) |
| $\chi^2/\text{dof}$ | 18.32/15 | 16.01/15 |
| $M_W$ [GeV] | 80.348(6) | 80.357(6) |
| $\Delta\alpha_{\text{had}} \times 10^4$ | 280.9(1.4) | 275.9(1.1) |
| $\delta M_W$ [MeV] | 86(11) | 77(11) |
| Tension | $7.8\sigma$ | $7.0\sigma$ |

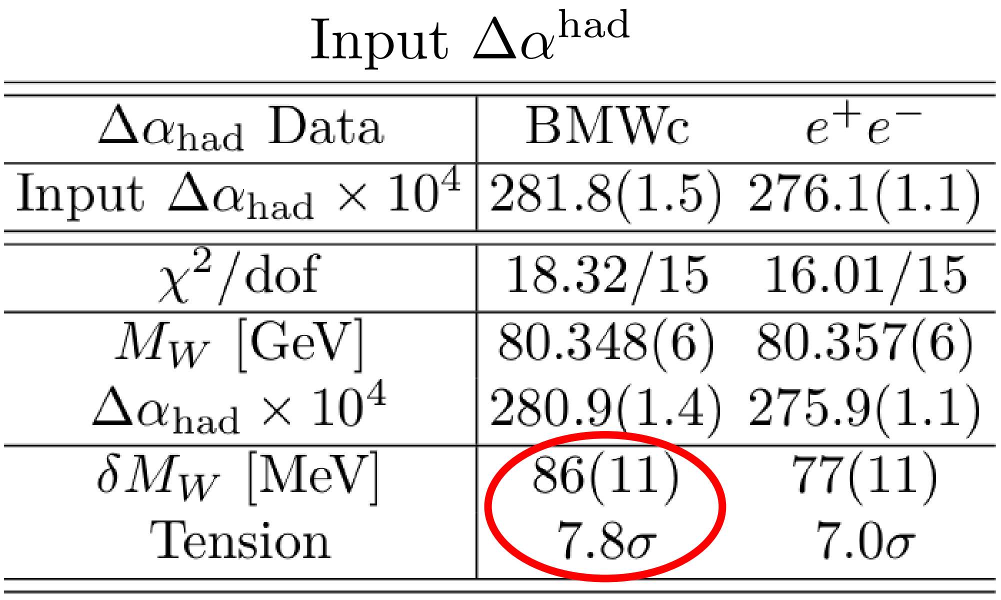
$a_\mu$ deviation $1.7\sigma$

$a_\mu$ deviation $4.2\sigma$

Inputting BMW data increases tension with CDF W mass measurement

# Global EW fit Tension

[arXiv:2204.03996,PA, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, B. Zhu]



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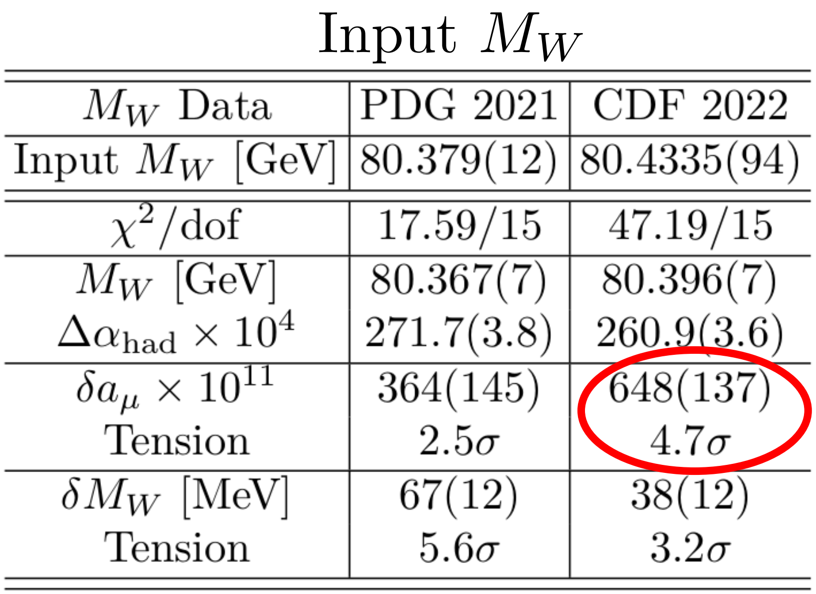


Input $M_W$

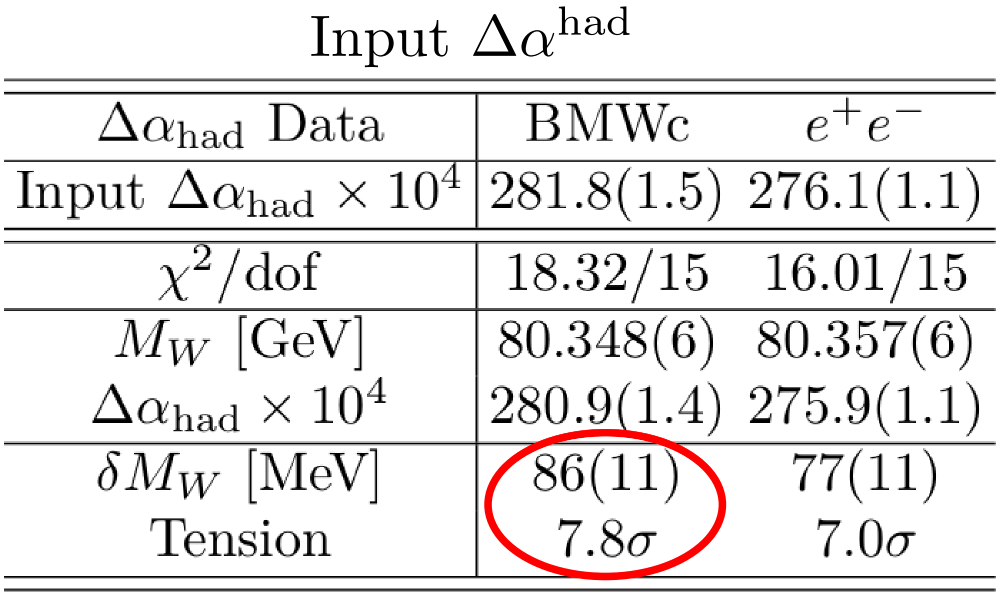
| $M_W$ Data | PDG 2021 | CDF 2022 |
|---|---|---|
| Input $M_W$ [GeV] | 80.379(12) | 80.4335(94) |
| $\chi^2$/dof | 17.59/15 | 47.19/15 |
| $M_W$ [GeV] | 80.367(7) | 80.396(7) |
| $\Delta\alpha_{\mathrm{had}} \times 10^4$ | 271.7(3.8) | 260.9(3.6) |
| $\delta a_\mu \times 10^{11}$ | 364(145) | 648(137) |
| Tension | $2.5\sigma$ | $4.7\sigma$ |
| $\delta M_W$ [MeV] | 67(12) | 38(12) |
| Tension | $5.6\sigma$ | $3.2\sigma$ |

Inputting BMW data increases tension with CDF W mass measurement

Inputting CDF W mass increases tension with muon g-2

# Global EW fit Tension

[arXiv:2204.03996,PA, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, B. Zhu]



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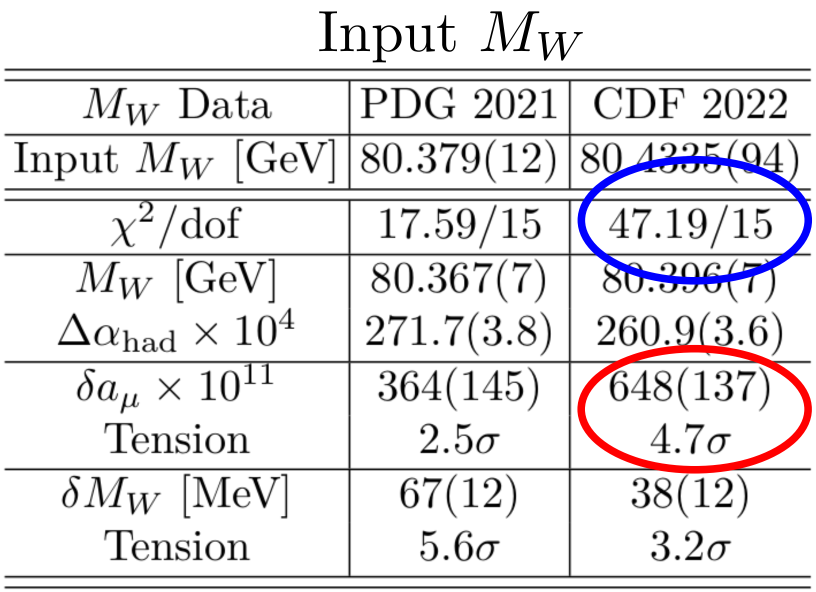

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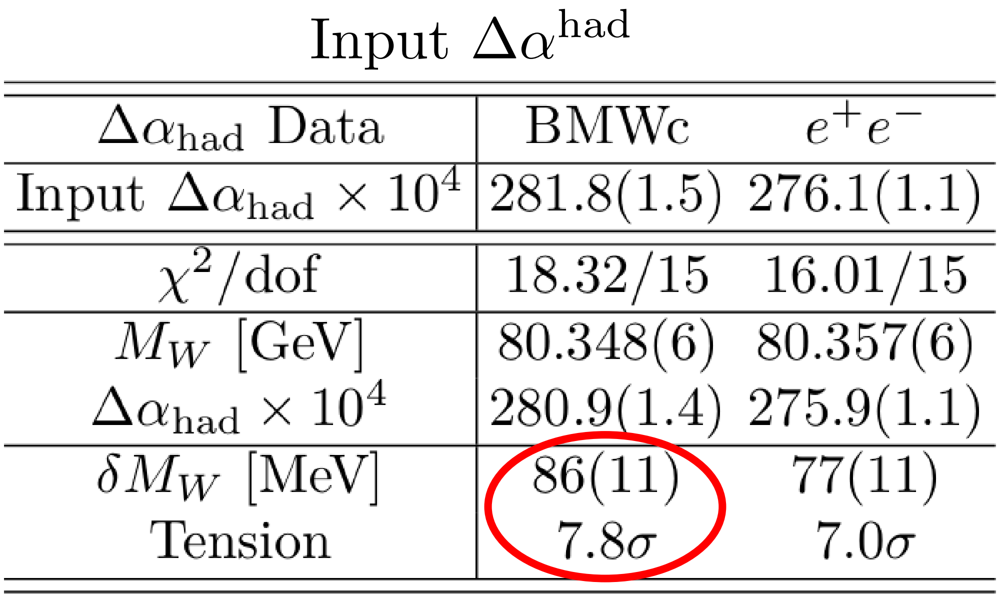
Inputting BMW data increases tension with CDF W mass measurement

Inputting CDF W mass increases tension with muon g-2

And we have a bad EW fit

# Global EW fit Tension

[arXiv:2204.03996,PA, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, B. Zhu]



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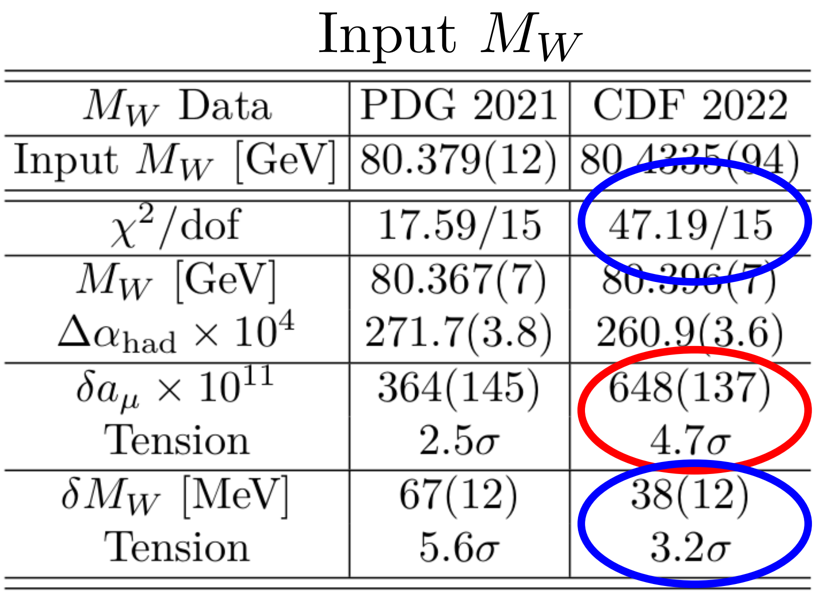

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| Tension | $5.6\sigma$ | $3.2\sigma$ |

Inputting BMW data increases tension with CDF W mass measurement

Inputting CDF W mass increases tension with muon g-2

And there is still a tension in the W mass

## In general:

For *any* choice to constrain $\Delta\alpha^{\mathrm{had}}$ via
CDF-MW, 2021 PDG-MW, e+e- or BMW lattice data

Reducing the $\Delta M_W^{\mathrm{CDF}}$ anomally increases $\Delta a_\mu$ anomally
and vice versa
… and every choice has: $\sqrt{(\Delta M_W^{\mathrm{CDF}})^2 + (\Delta a_\mu)^2} > 5\sigma$

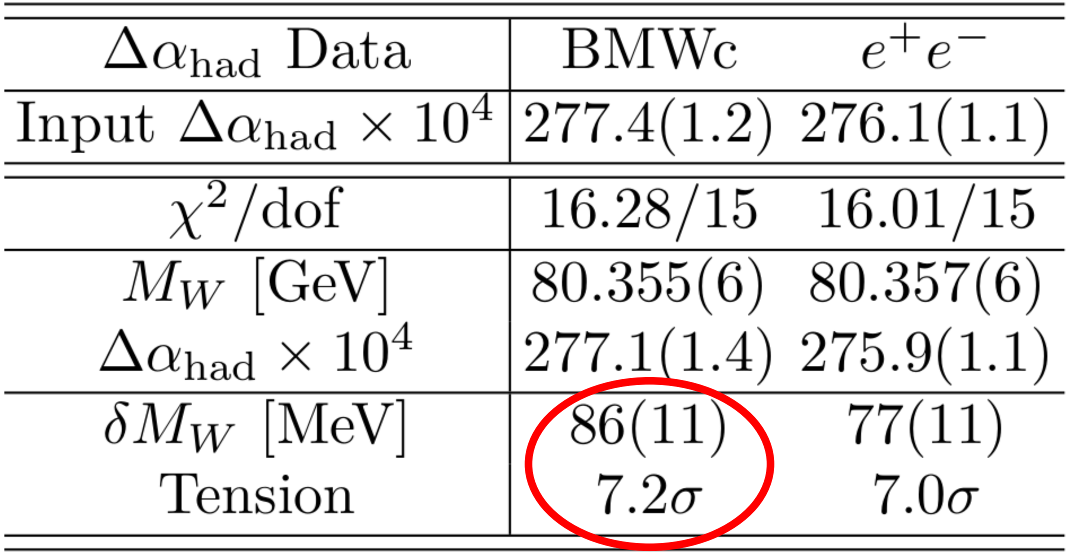
Big Caveat: this all depends on our assumptions about
energy dependence of the hadronic cross-section

(we applied universal scaling over the full integration range)

## Alternative hypothesis:

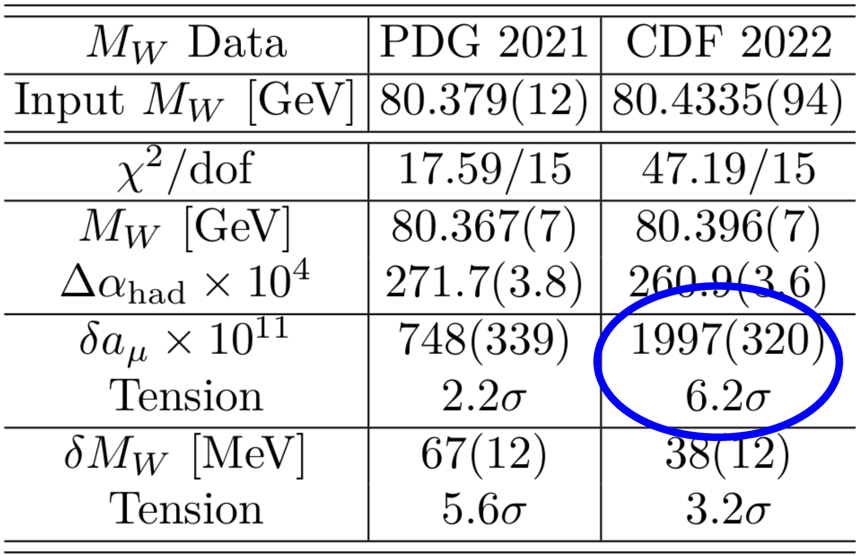
cross section only changes at low energies $m_{\pi_0} \leq \sqrt{s} \leq 1.937\ \mathrm{GeV}$,

Input $\Delta\alpha^{\mathrm{had}}$



| $\Delta\alpha_{\mathrm{had}}$ Data | BMWc | $e^+e^-$ |
|---|---|---|
| Input $\Delta\alpha_{\mathrm{had}} \times 10^4$ | 277.4(1.2) | 276.1(1.1) |
| $\chi^2/\mathrm{dof}$ | 16.28/15 | 16.01/15 |
| $M_W$ [GeV] | 80.355(6) | 80.357(6) |
| $\Delta\alpha_{\mathrm{had}} \times 10^4$ | 277.1(1.4) | 275.9(1.1) |
| $\delta M_W$ [MeV] | 86(11) | 77(11) |
| Tension | $7.2\sigma$ | $7.0\sigma$ |

Input $M_W$



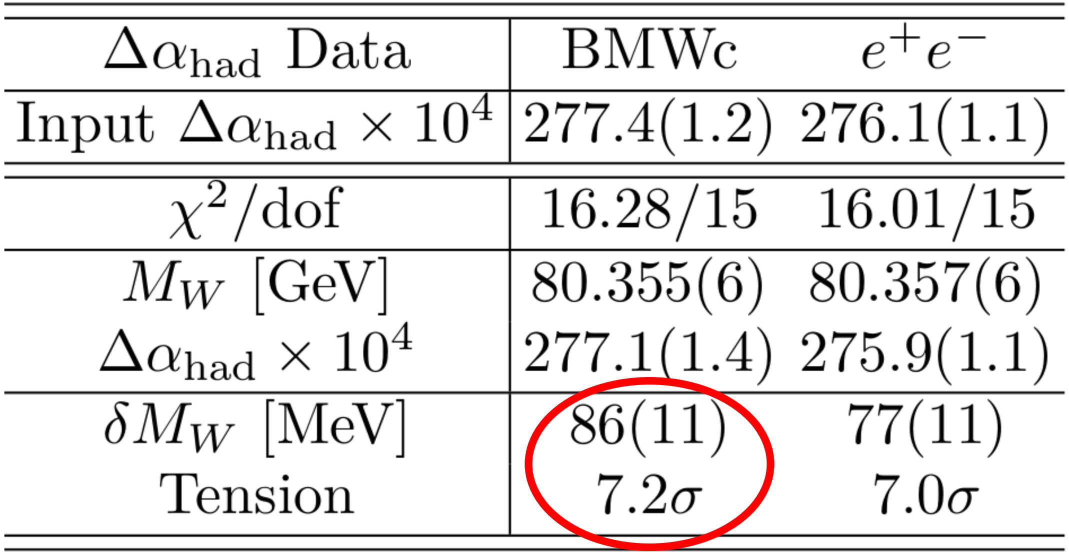
| $M_W$ Data | PDG 2021 | CDF 2022 |
|---|---|---|
| Input $M_W$ [GeV] | 80.379(12) | 80.4335(94) |
| $\chi^2/\mathrm{dof}$ | 17.59/15 | 47.19/15 |
| $M_W$ [GeV] | 80.367(7) | 80.396(7) |
| $\Delta\alpha_{\mathrm{had}} \times 10^4$ | 271.7(3.8) | 260.9(3.6) |
| $\delta a_\mu \times 10^{11}$ | 748(339) | 1997(320) |
| Tension | $2.2\sigma$ | $6.2\sigma$ |
| $\delta M_W$ [MeV] | 67(12) | 38(12) |
| Tension | $5.6\sigma$ | $3.2\sigma$ |

BMW doesn’t increase tension
with MW as much

CDF data makes muon
g-2 anomally even worse

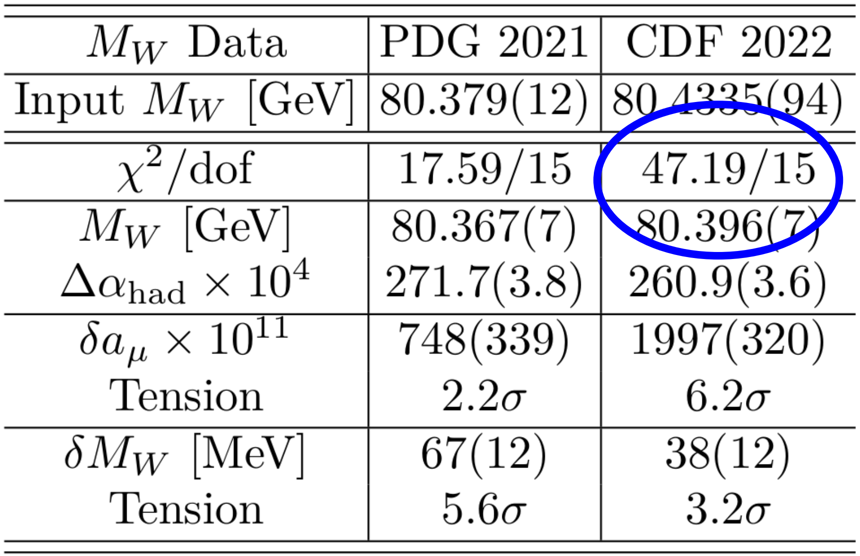
## Alternative hypothesis:
## cross section only changes at low energies $m_{\pi_0} \leq \sqrt{s} \leq 1.937\ \mathrm{GeV},$

Input $\Delta\alpha^{\mathrm{had}}$



| $\Delta\alpha_{\mathrm{had}}$ Data | BMWc | $e^+e^-$ |
|---|---|---|
| Input $\Delta\alpha_{\mathrm{had}} \times 10^4$ | 277.4(1.2) | 276.1(1.1) |
| $\chi^2/\mathrm{dof}$ | 16.28/15 | 16.01/15 |
| $M_W$ [GeV] | 80.355(6) | 80.357(6) |
| $\Delta\alpha_{\mathrm{had}} \times 10^4$ | 277.1(1.4) | 275.9(1.1) |
| $\delta M_W$ [MeV] | 86(11) | 77(11) |
| Tension | $7.2\sigma$ | $7.0\sigma$ |

Input $M_W$



| $M_W$ Data | PDG 2021 | CDF 2022 |
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| Input $M_W$ [GeV] | 80.379(12) | 80.4335(94) |
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BMW doesn't increase tension
with MW as much

And the EW fit is still
bad!

*Even* if we remove all four of these contraints on $\Delta\alpha^{\rm had}$

(i.e extractions from MW and from e+e- data or BMW lattice data)

We find

$$\Delta M_W^{\rm CDF} = (75 \pm 13)\ {\rm MeV}, \Rightarrow 5.8\sigma\ {\rm Tension}$$

EW observables are very sensitive to $\alpha(M_Z)$

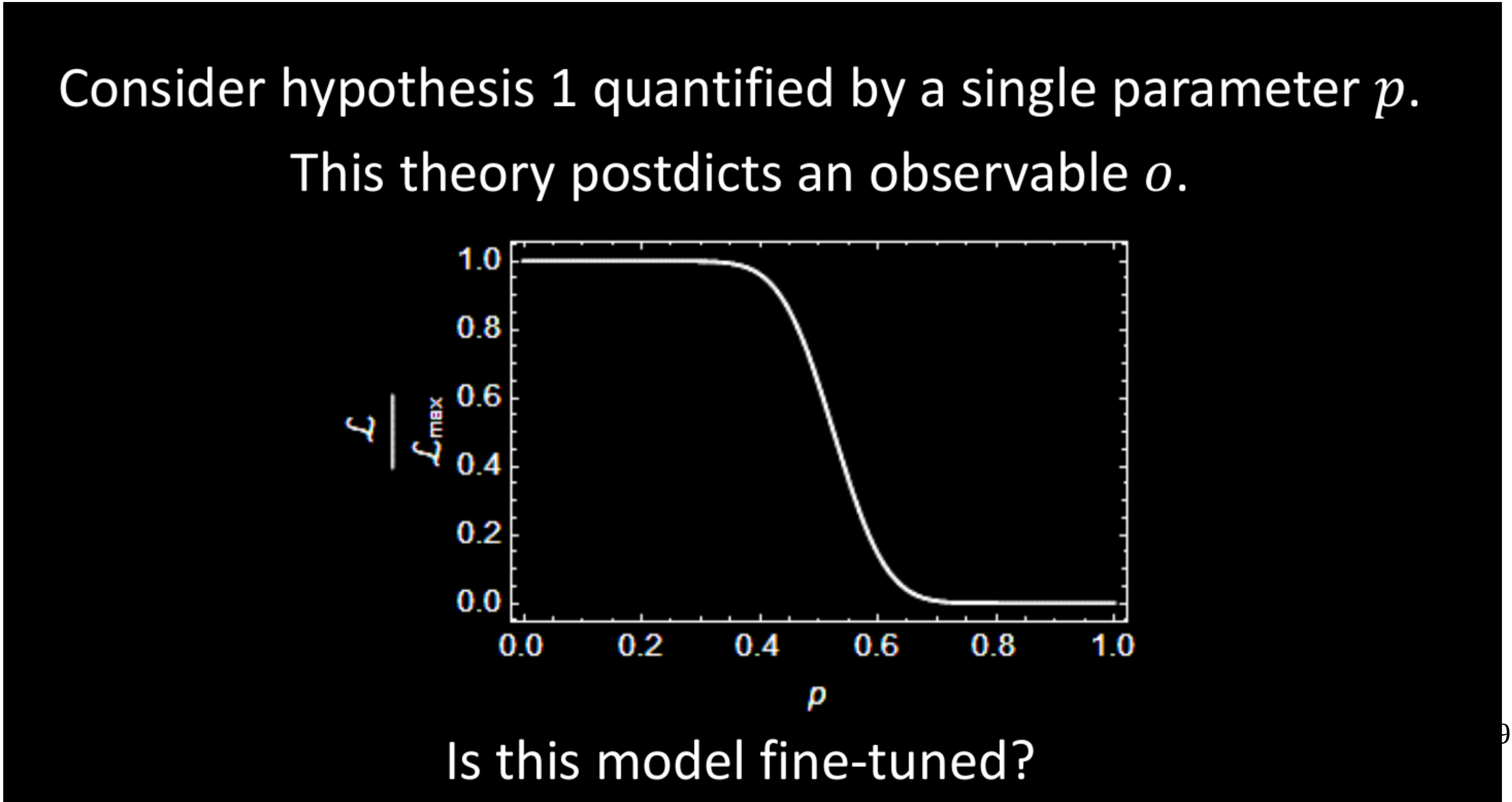
No way to explain CDF meaurement even without any data driven estimates from hadronic cross sections

Conversely $\Delta a_\mu$ does depend on the data driven estimates

But inputting a heavy MW pulls us further away from the BMW prediction and the measured value

# 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

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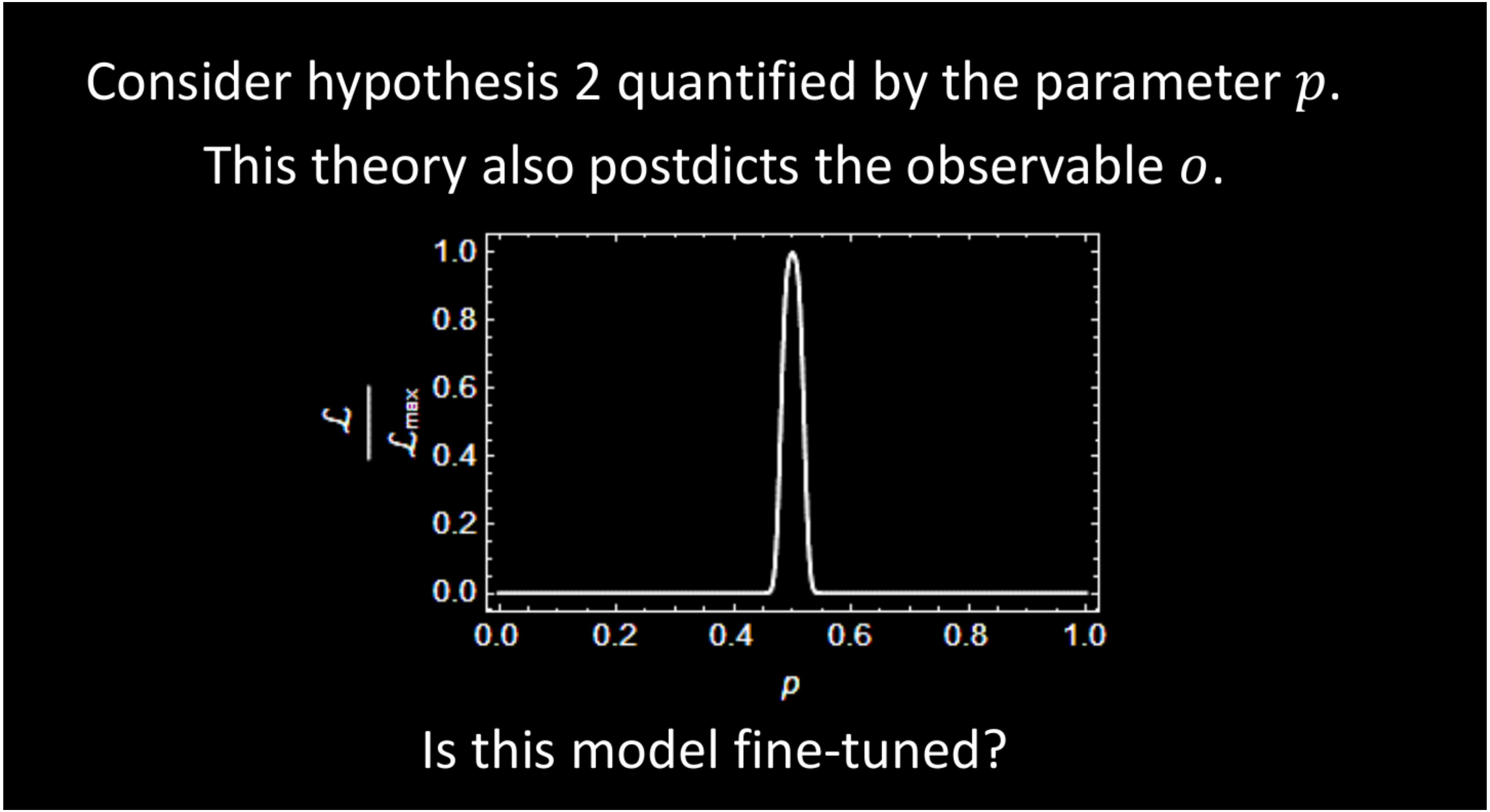


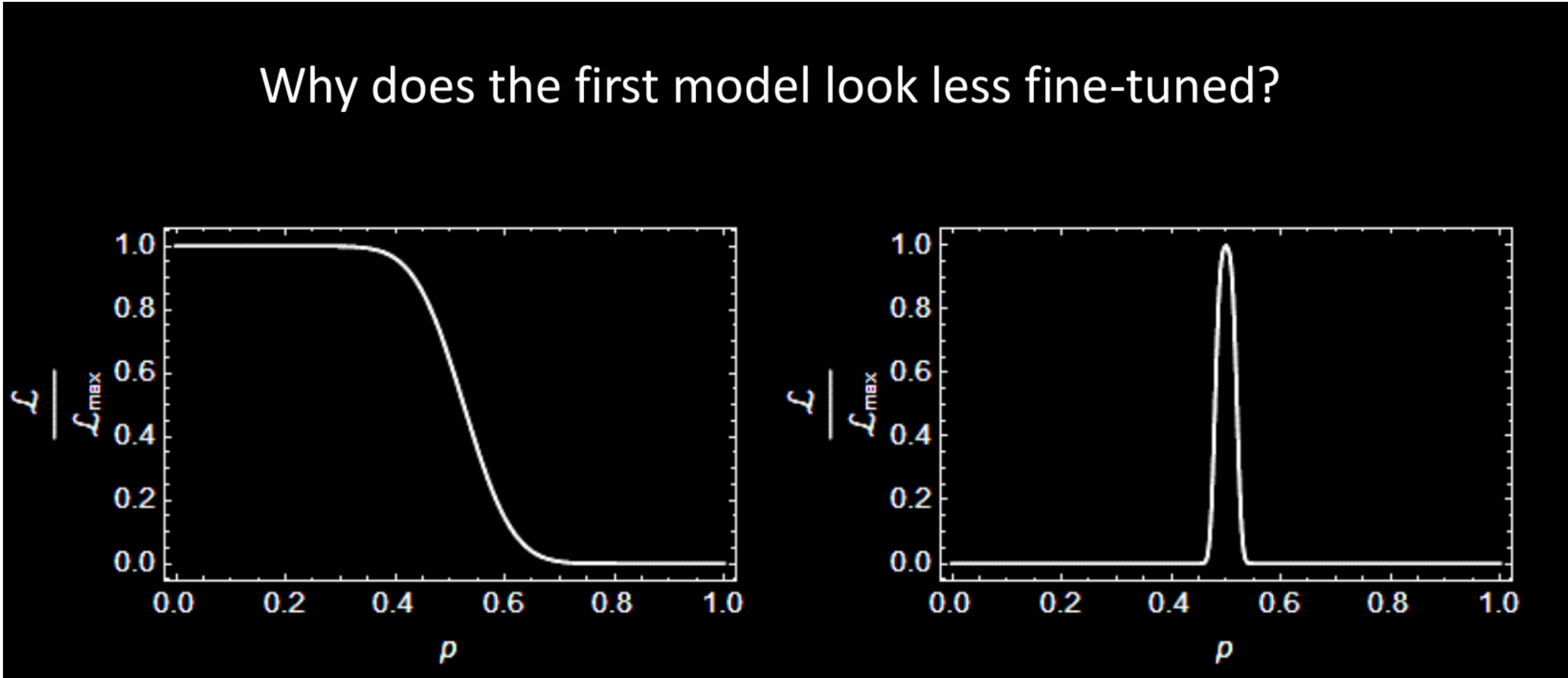
Consider hypothesis 2 quantified by the parameter $p$.

This theory also postdicts the observable $o$.

Is this model fine-tuned?

# Naturalness in Bayesian statistics

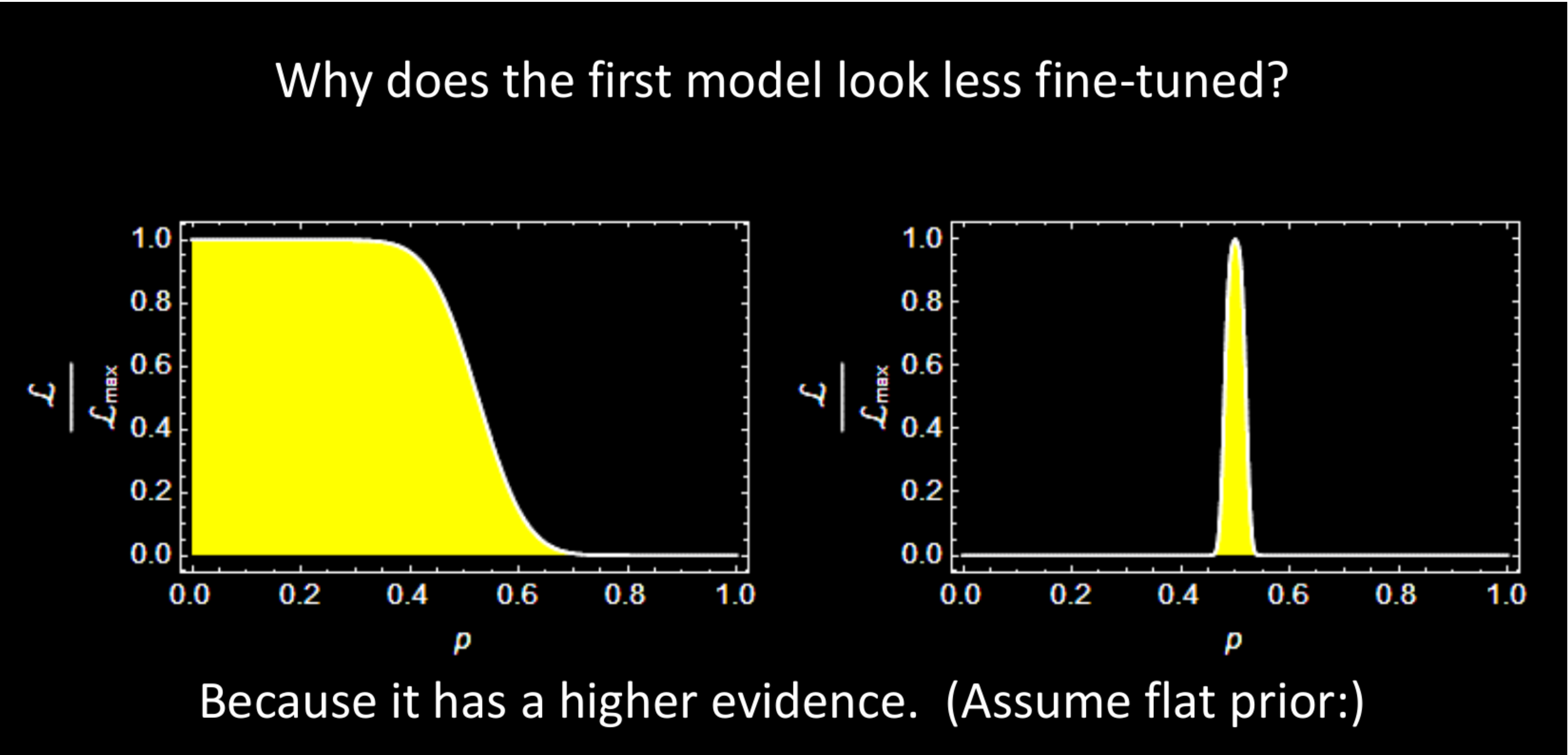
Slide nicked from Csaba Balazs



Why does the first model look less fine-tuned?

# Naturalness in Bayesian statistics

Slide nicked from Csaba Balazs

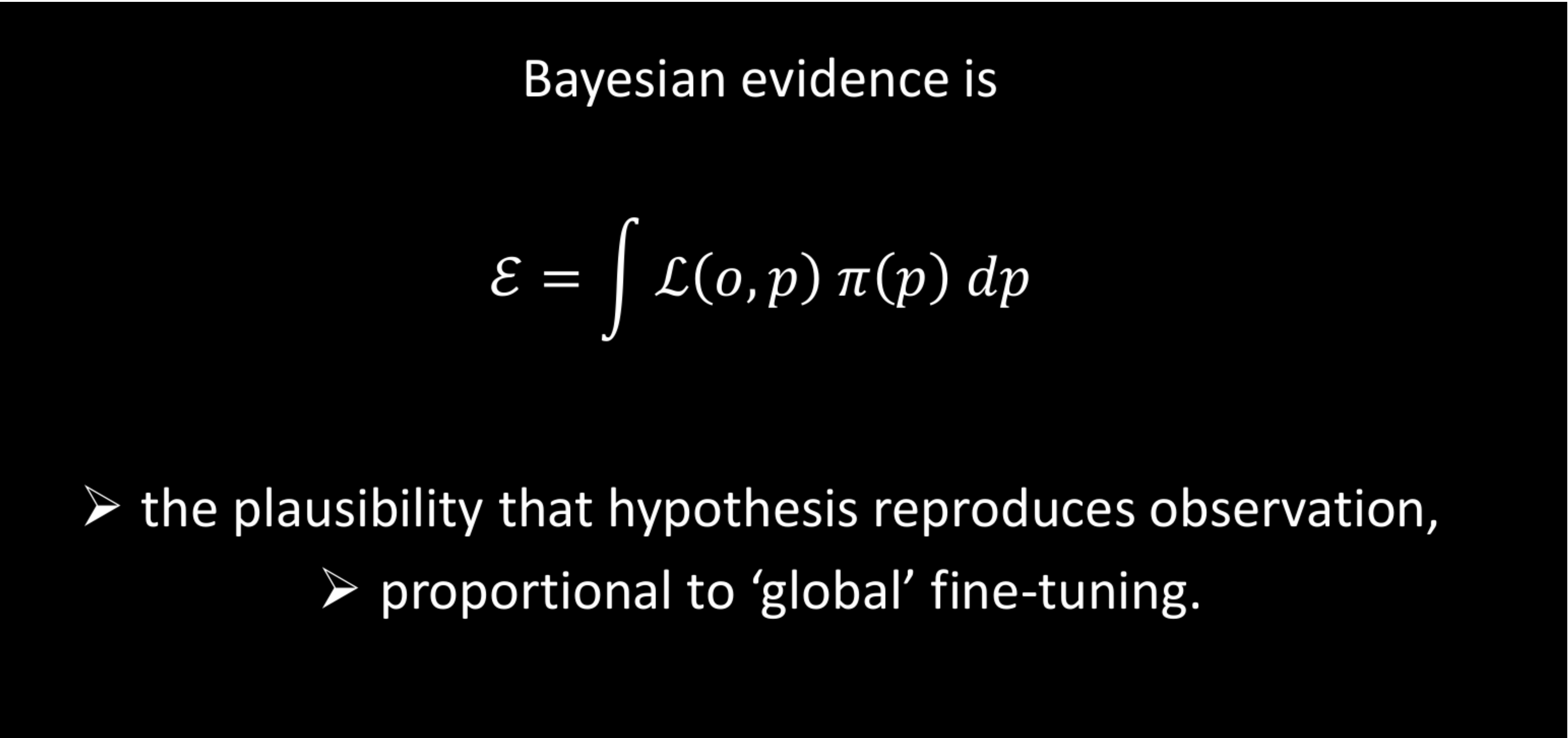


Why does the first model look less fine-tuned?

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.

# 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 obvioulsy perfect, hard to explain without some tuning, hiding in some corner of parameter space, or going to special cases
- Usually large muon g-2 corrections need ligh  solution in survey is obvioulsy 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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Give a broad overview of physics beyond the standard model
that can explain a large deviation from the SM prediction in muon g-2

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Give a broad overview of physics beyond the standard model
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Existence of plausible hypotheses must impact on how seriously
we take this as a new physics signal

By the end of this talk I hope you will understand:

- the challenges to explaining muon g-2 with BSM physics,
- the advantages and drawbacks of most obvious solutions
- what overcoming them implies for future experiments like the CEPC

## Note I will use SM prediction from the theory initiative white paper

This gives: $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$ $\Rightarrow 4.2\sigma$ deviation

But this is based on:

$a_\mu^{\mathrm{HVP,LO}} \times 10^{10} = 694.0 \pm 4$ [KNT, PRD 101 (2020) 1, 014029]

$692.78 \pm 2.42$ [BHMZ, EPJC 80 (2020) 3, 241

$693.1 \pm 4$ [White Paper, Phys.Rept. 887 (2020) 1-166]

$707.5 \pm 5.5$ [BMW Lattice, Nature 593, 51 (2021)] (not included SM Estimate above)

There seems to be a tension between data driven estimates and early lattice results.

I am not an expert on computing hadronic contributions

and I mostly won’t comment on this, but...