[A. Alvarez & al., 2301.08485]

Probing a class of scotogenic models via Z and Higgs boson decays

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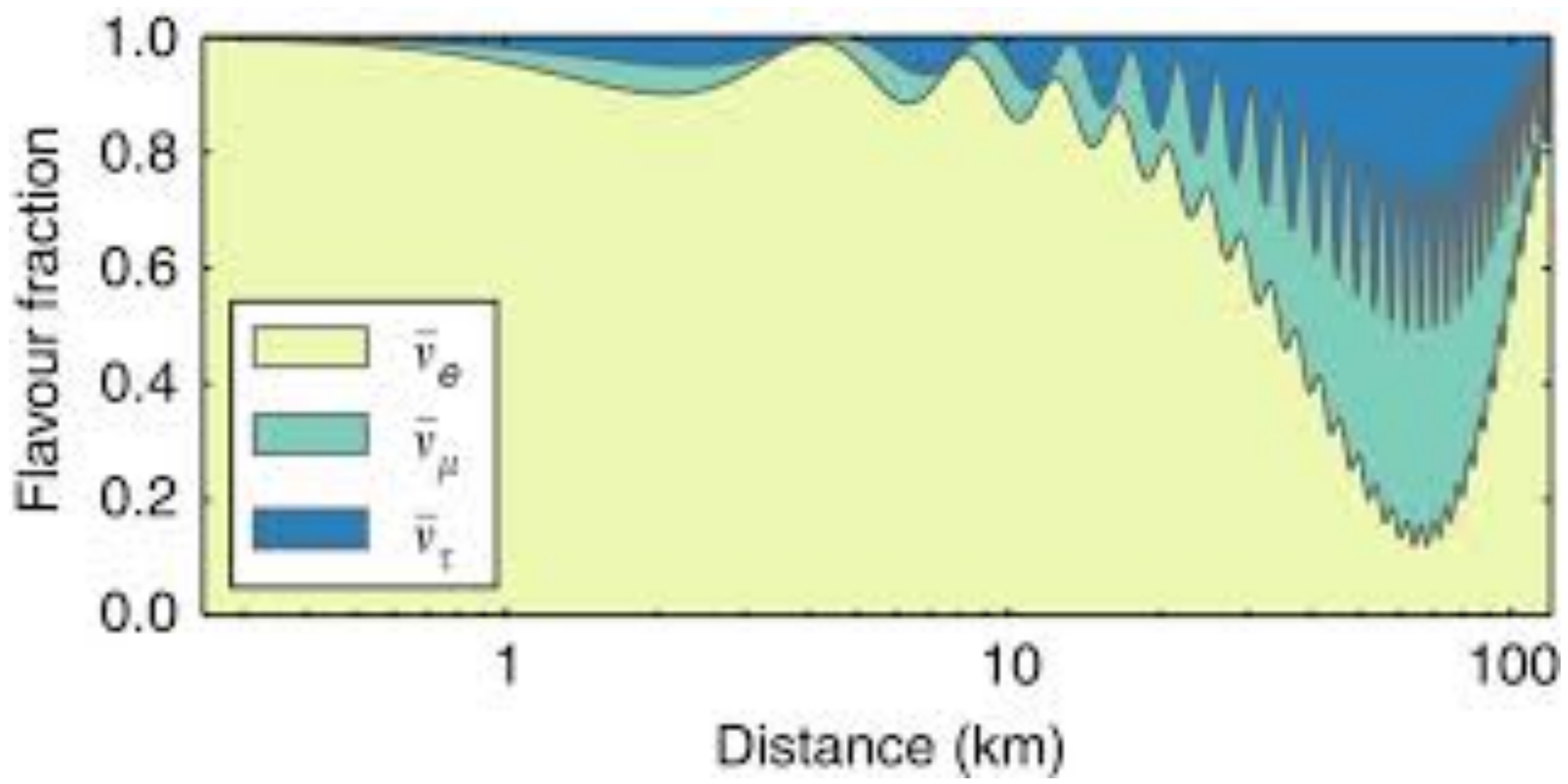
Based in work to appear soon

[Darricau, Lee, Orloff, Teixeira, 2505.xxxxx]

Standard Model: an incomplete picture

Despite its many successes, experimental evidence of the **incompleteness** of the SM:
→ Neutrino oscillations
→ Dark Matter (DM)
→ Baryon Asymmetry of the Universe (BAU)



Also some **theoretical issues**…

Standard Model: an incomplete picture

Also some **theoretical issues** such as:
→ Fundamental scales gap
→ Hierarchy problem
→ Flavour puzzle

$$\Delta M_H^2|_{1-loop}^{SM} = \frac{3\Lambda_{UV}^2}{8\pi^2 v^2}[M_H^2 + 2M_W^2 + M_Z^2 - 4m_t^2 + ...]$$

If NP at Planck scale, 30 order cancellation with bare mass!

→ How to **overcome these experimental caveats**?
→ Can we also **improve these theoretical issues**?

Scotogenic models: motivation

Extension at the **Tera** eV **Scale**

A lot of mechanisms to explain
ν mass generation!

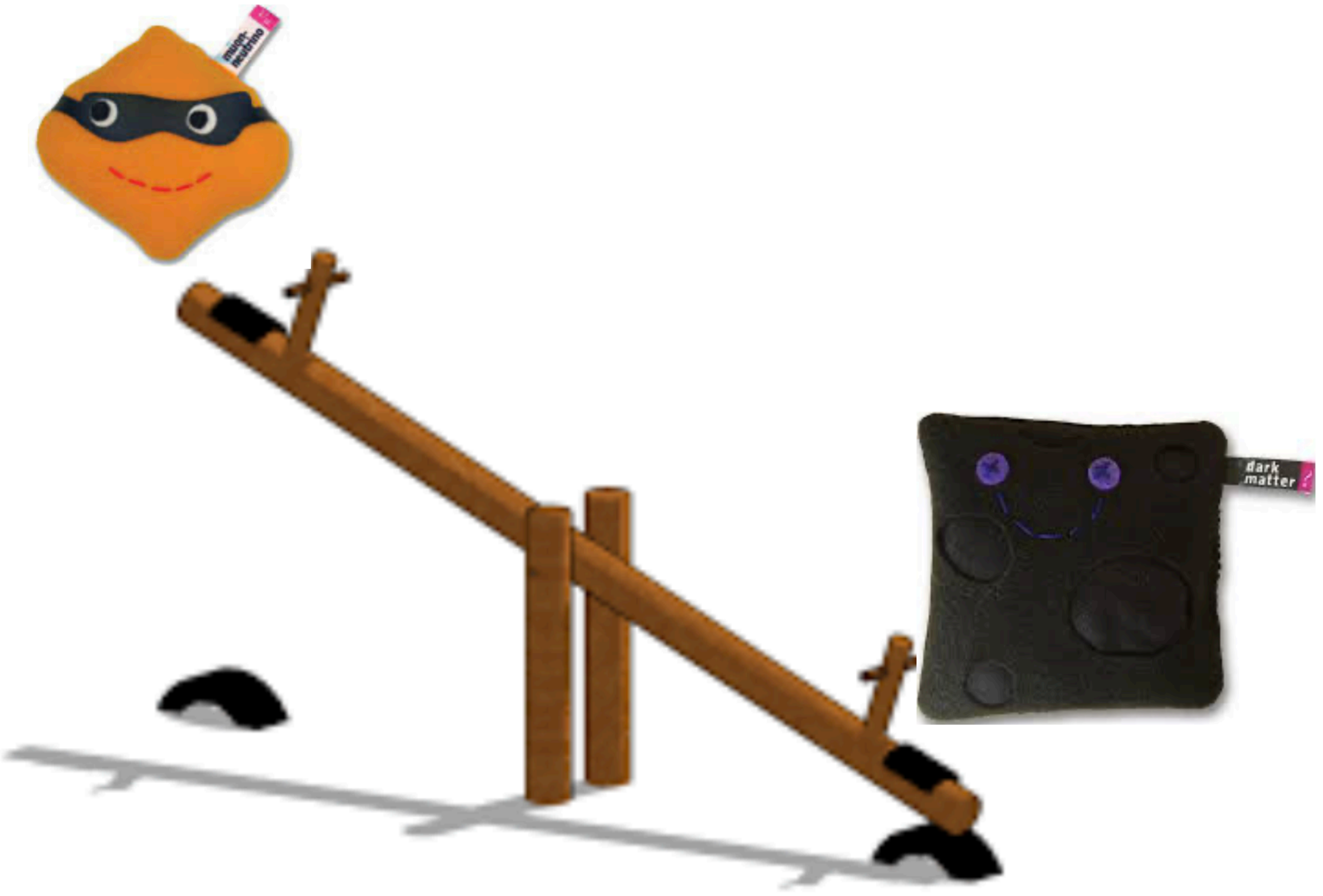
→ **Seesaw realisation, radiative mechanisms**…

A plethora of models putting forward DM candidates!

→ **WIMPs**, FIMPs…

Can both be related?

Yes !
A "Dark generation" of ν mass:
"Scotogenic"

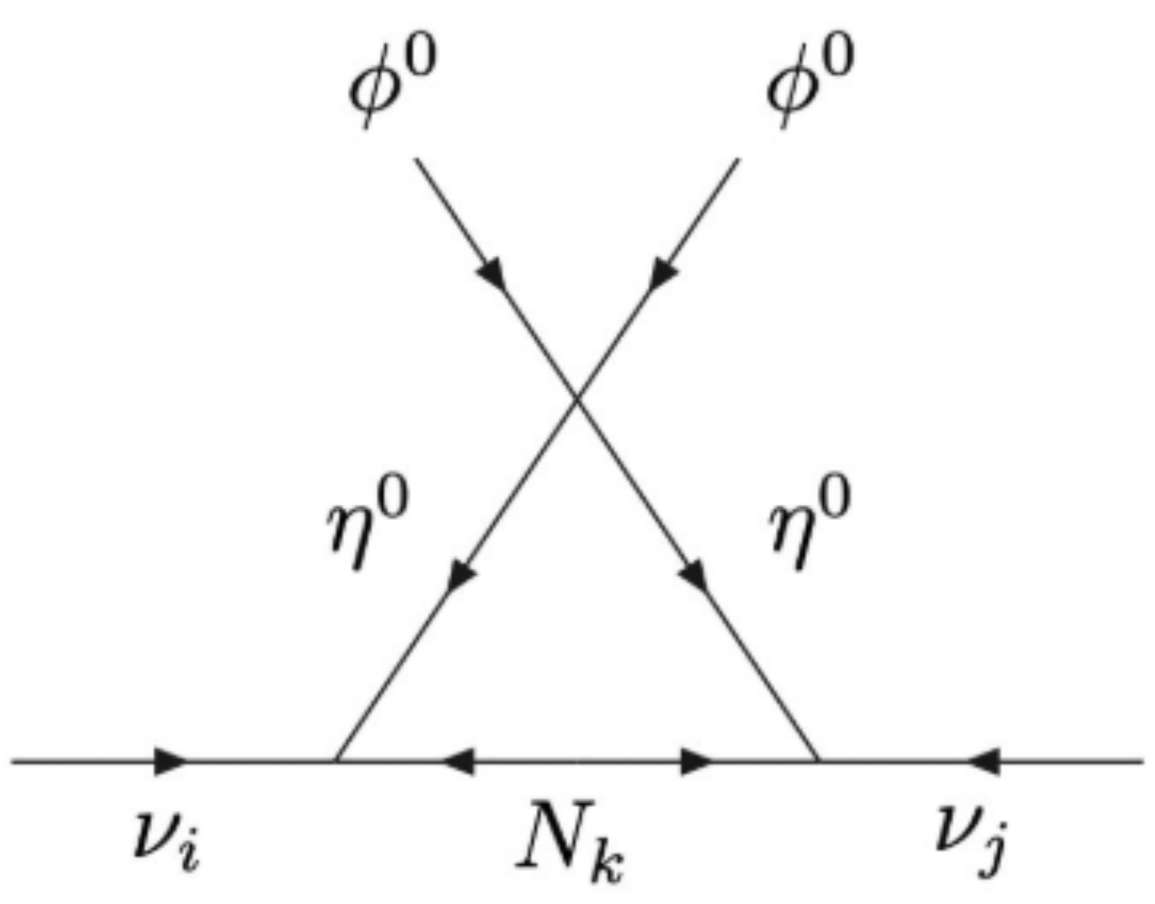


Scotogenic models: motivation

A simple **radiative seesaw ν mass generation** !

→ A global $\mathbb{Z}_2$ symmetry to **stabilise** DM candidates

→ Neutrino mass generation mechanism constrained by the global $\mathbb{Z}_2$ symmetry, **exclusion of tree level neutrino masses**



E. Ma, 0601225, 2006

vev-less Higgs-like → η; Sterile fermions → N_i

Field	η	N_i
$SU(2)_L$	**2**	**1**
$U(1)_Y$	1	0
$\mathbb{Z}_2$	1	1

Many interesting realisations of the scotogenic paradigm

T1-1-A, **T1-2-A**...

[D. Restrepo, 1308.3655]

Description of the T1-2-A setup

→ **T1-2-A setup**: adds 2 $SU(2)_L$ doublets and 2 singlets (1 fermionic, 1 scalar) charged under $\mathbb{Z}_2$

→ Extended: addition of fermion singlet and doublet

Field	η	S	F_1	F_2	Ψ_1	Ψ_2
$\mathrm{SU}(2)_L$	**2**	**1**	**1**	**1**	**2**	**2**
$\mathrm{U}(1)_Y$	1	0	0	0	-1	1

$$\mathcal{V}_{\text{scalar}} = \frac{1}{2}M_S^2\, S^2 + \frac{1}{2}\lambda_{4S}\, S^4 + M_\eta^2\, |\eta|^2 + \lambda_{4\eta}\, |\eta|^4 + \frac{1}{2}\lambda_S\, S^2|\Phi|^2 + \frac{1}{2}\lambda_{S\eta}\, S^2|\eta|^2$$
$$+ \lambda_\eta\, |\eta|^2\, |\Phi|^2 + \lambda'_\eta\, |\eta\Phi^\dagger|^2 + \frac{1}{2}\lambda''_\eta \left[\left(\Phi\eta^\dagger\right)^2 + \text{H.c.}\right] + \alpha\, S\left[\Phi\eta^\dagger + \text{H.c.}\right]$$

Trilinear coupling

Which **states** after **EWSB** ?

Vector-Like — Majorana — Dirac

$$\mathcal{V}_{\text{fermion}} = M_\nu^{\alpha\beta}\, \overline{\nu_\alpha^c}\, \nu_\beta - M_\psi\, \overline{\psi_1}\, \widetilde{\psi_2} + \frac{1}{2} M_{F\,ii}\, \overline{F_i{}^c}\, F_i - y_{1i}^*\, \overline{F_i}\, \Phi^\dagger\, \widetilde{\psi_1} - y_{2i}^*\, \overline{F_i}\, \Phi\, {\psi_2}^c$$
$$+ g_\psi^\alpha\, \overline{\psi_2}\, L_L^\alpha S + g_{F_i}^\alpha\, \overline{\widetilde{L_L^\alpha}}\, \eta F_i + g_R^\alpha \overline{e_R^\alpha}\, \eta^\dagger\, \psi_1 + \text{H.c.}$$

Yukawa-like cLFV couplings

Description of the T1-2-A setup

→ **T1-2-A setup**: adds 2 $SU(2)_L$ doublets and 2 singlets (1 fermionic, 1 scalar) charged under $\mathbb{Z}_2$

→ Extended: addition of fermion singlet and doublet

Field	η	S	F_1	F_2	Ψ_1	Ψ_2
$\mathrm{SU}(2)_L$	**2**	**1**	**1**	**1**	**2**	**2**
$\mathrm{U}(1)_Y$	1	0	0	0	-1	1

After EWSB:

→ Scalars: 2 CP even ($\phi_{1/2}$),1 CP odd (A^0) neutral states and charged $\eta^{\pm}$ state

→ Fermions: 4 Majorana states (χ_i) and 1 charged vector-like $\psi^{\pm}$

In short: → 3 potential **DM candidate** : ϕ_1, χ_1 and A^0

→ **4** Majorana states (χ_i) needed for **3** massive neutrinos (and leptogenesis)

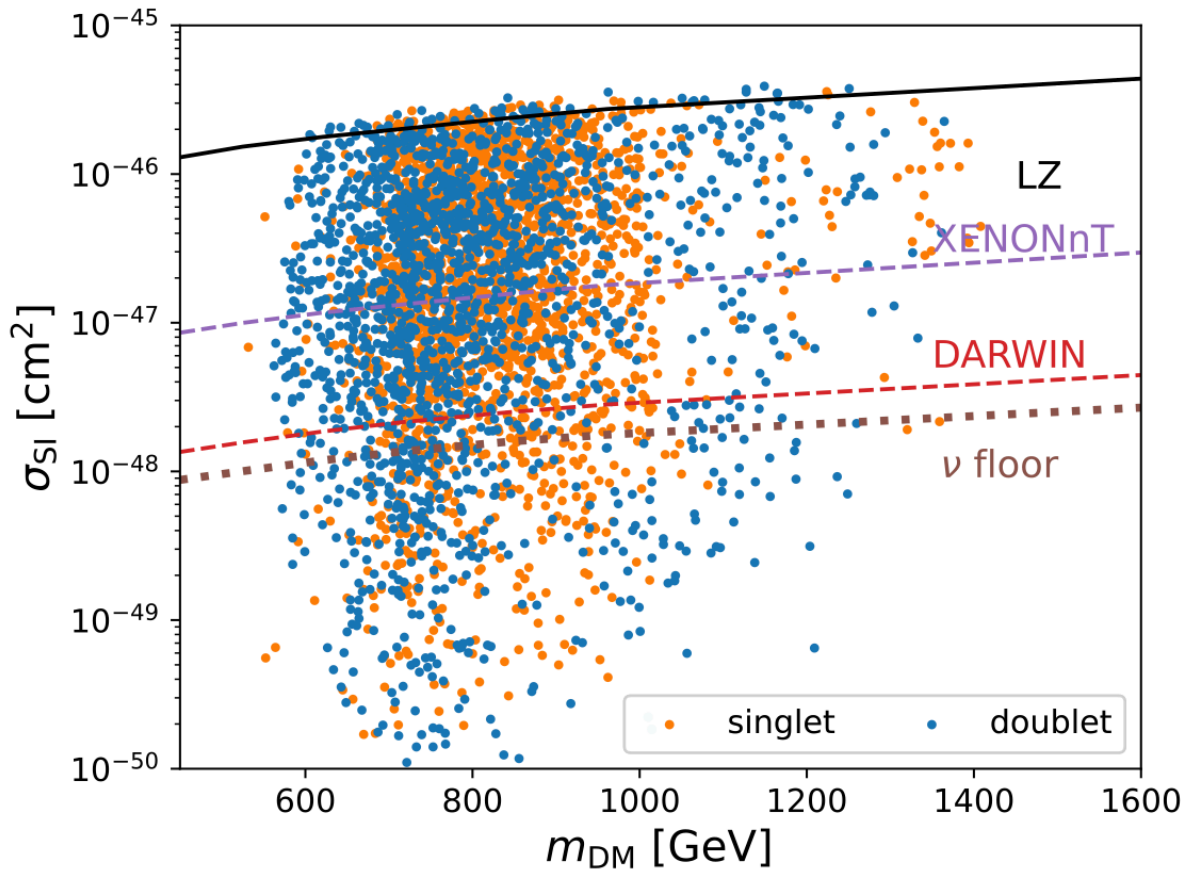
→ No mixing between CP even and odd state in scalar sector

Description of the T1-2-A setup

What has been done ?

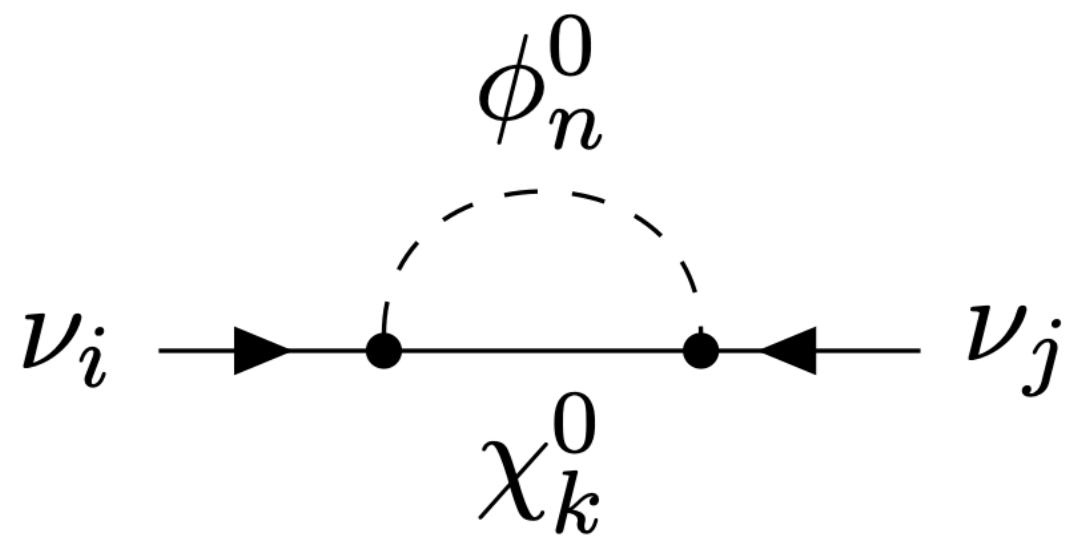
- ✔ ν **mass** mechanism, **lepton decays** and muon magnetic dipole moment ($\boldsymbol{\Delta a_\mu \sim 4\sigma}$)
- ✔ Found **2 viable DM** candidates (ϕ_1, χ_1)
- ✔ Extensive study of BAU via leptogenesis

Viable DM candidates (ϕ_1, χ_1)



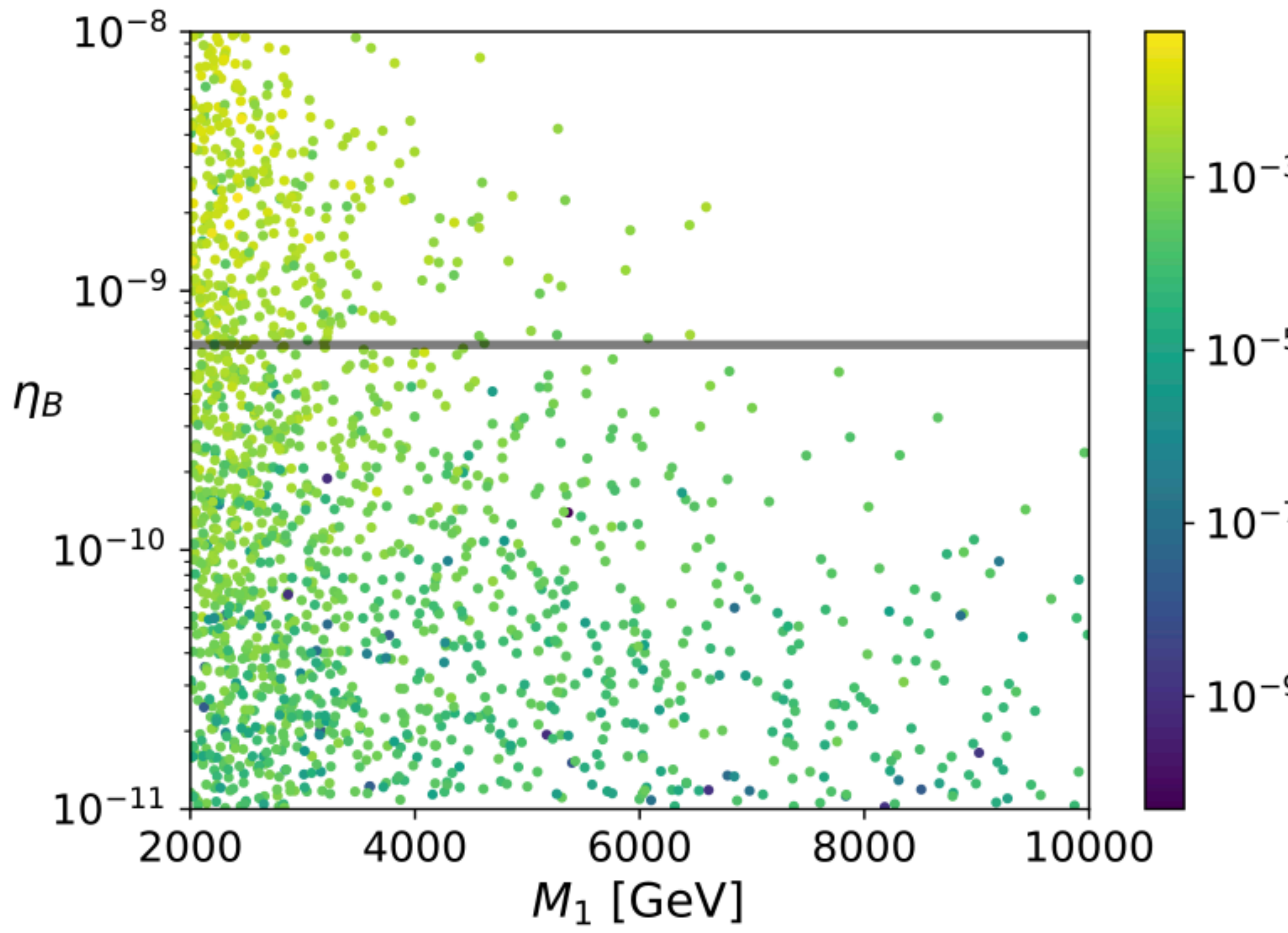
[A. Alvarez & al., 2301.08485]

ν masses



[A. Alvarez & al., 2301.08485]

BAU via leptognesis



[A. Alvarez & al., 2301.08485]

The scotogenic T1-2-A setup: revisited

Our goals ?

A flavour physics approach → **keep points** with unviable DM candidate

Relax certain (driving) **assumptions** → generic Δa_μ - from **SM-like to NP** (at ~ 4.2σ); no BAU

Thorough exploration of **flavoured** and **ElectroWeak Precision Observables** (EWPO)!

→ **cLFV decays**: leptonic (radiative, 3 body, conversion in Nuclei), $Z/H \to \ell_\alpha \ell_\beta$

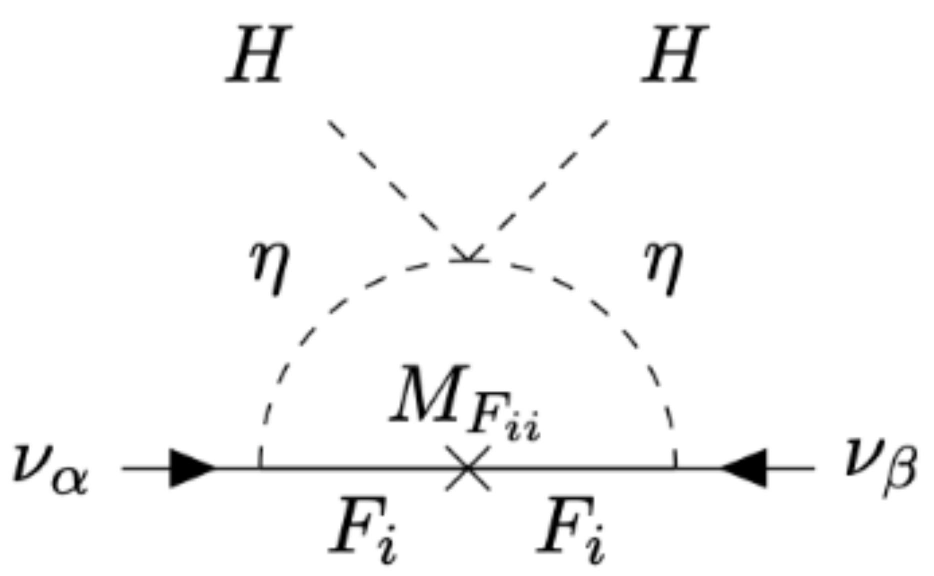
→ **EWPO**: sensitive probes of new interactions (scalar, vector, fermion…)

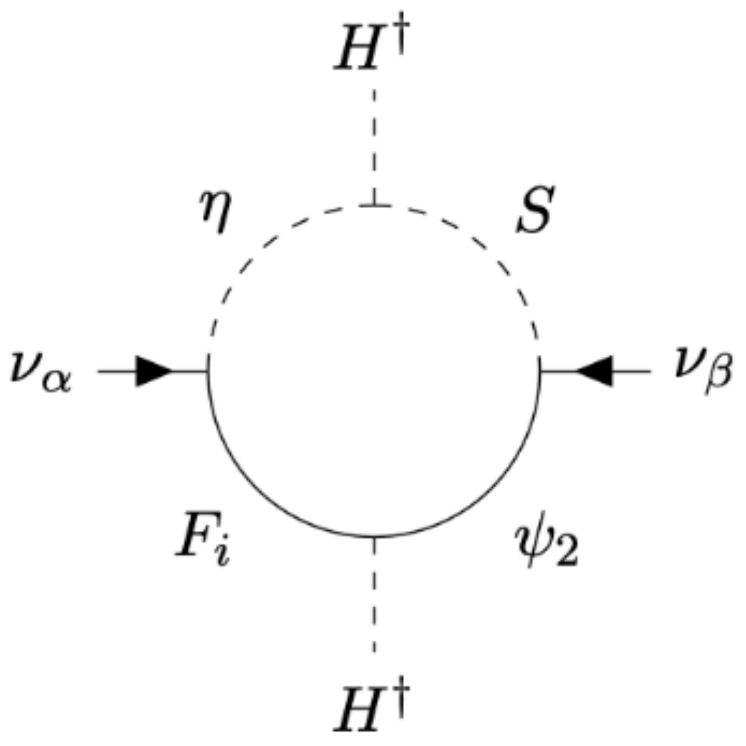
Oblique parameters (S,T,U), $Z/H \to inv$, $Z/H \to \ell_\alpha \ell_\alpha$

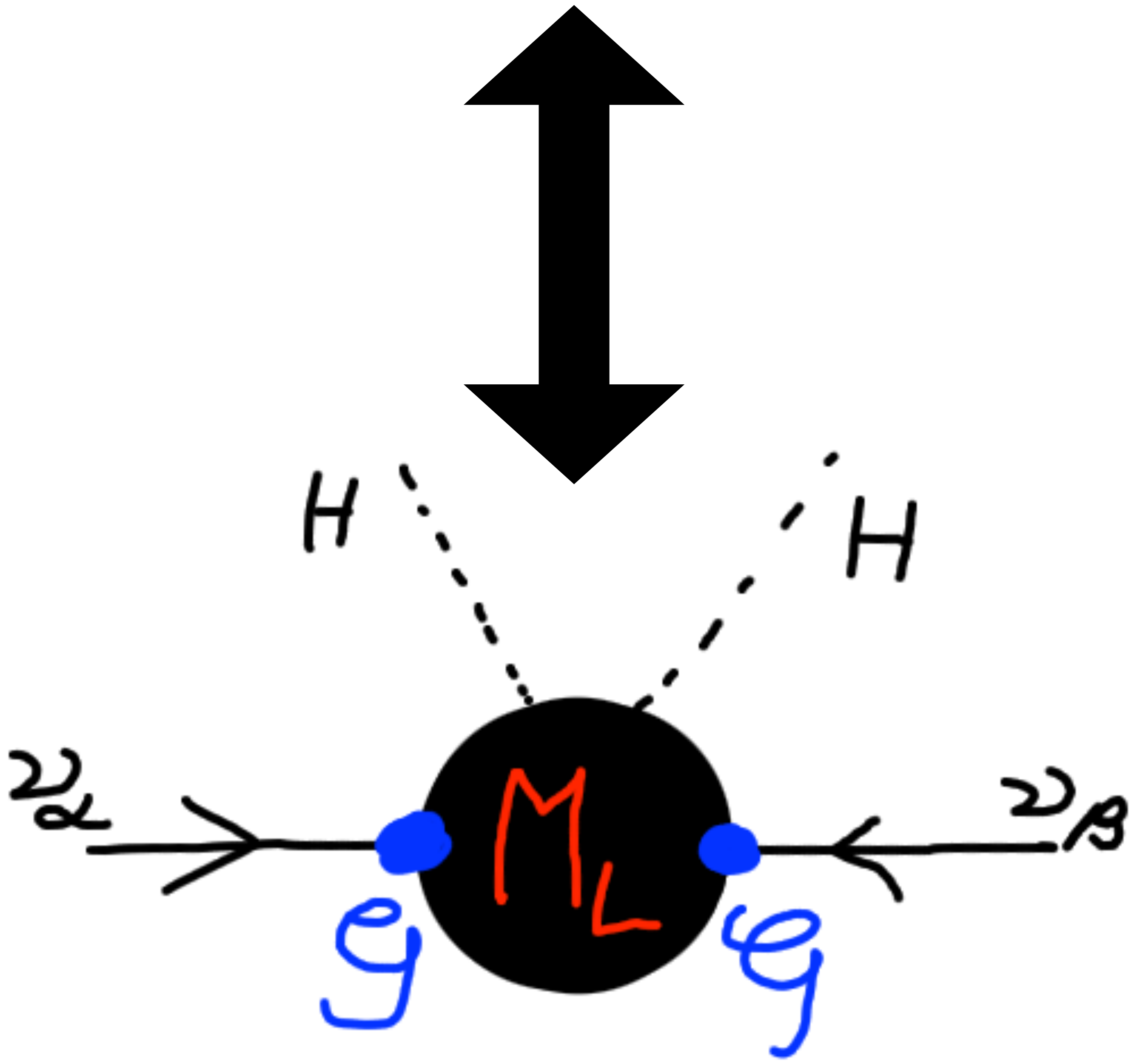
→ **Lepton Flavour Universality Violation** (LFUV)

→ In short: **revisit** a well studied model from a **flavour perspective** with **updated** $\boldsymbol{\Delta a_\mu}$

ν mass generation (at 1 loop)







ν mass generation

→ A “**seesaw” mechanism** but at 1 loop !

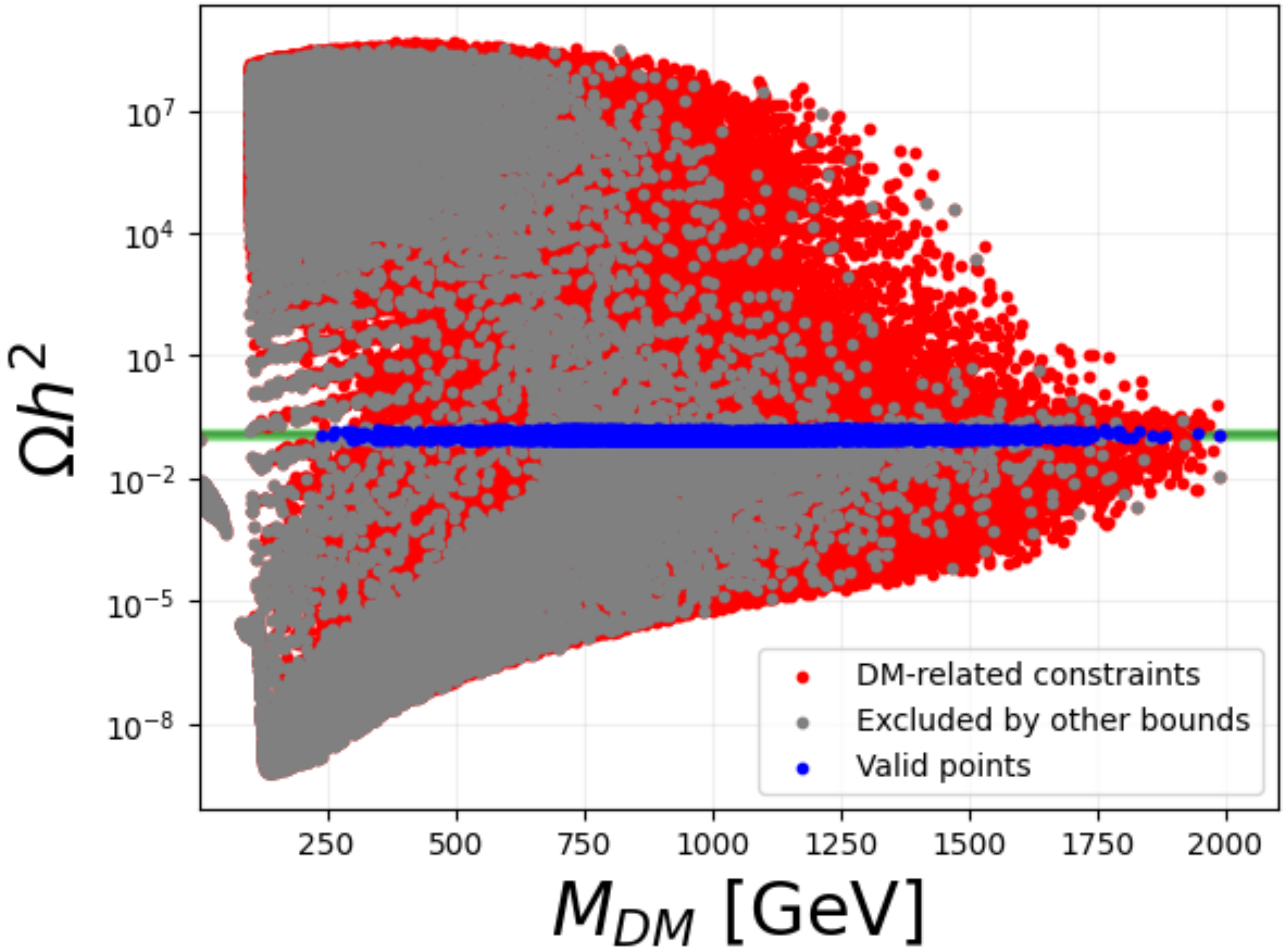
→ **Flavour violating** coupling $\mathcal{G}$ giving neutrino masses

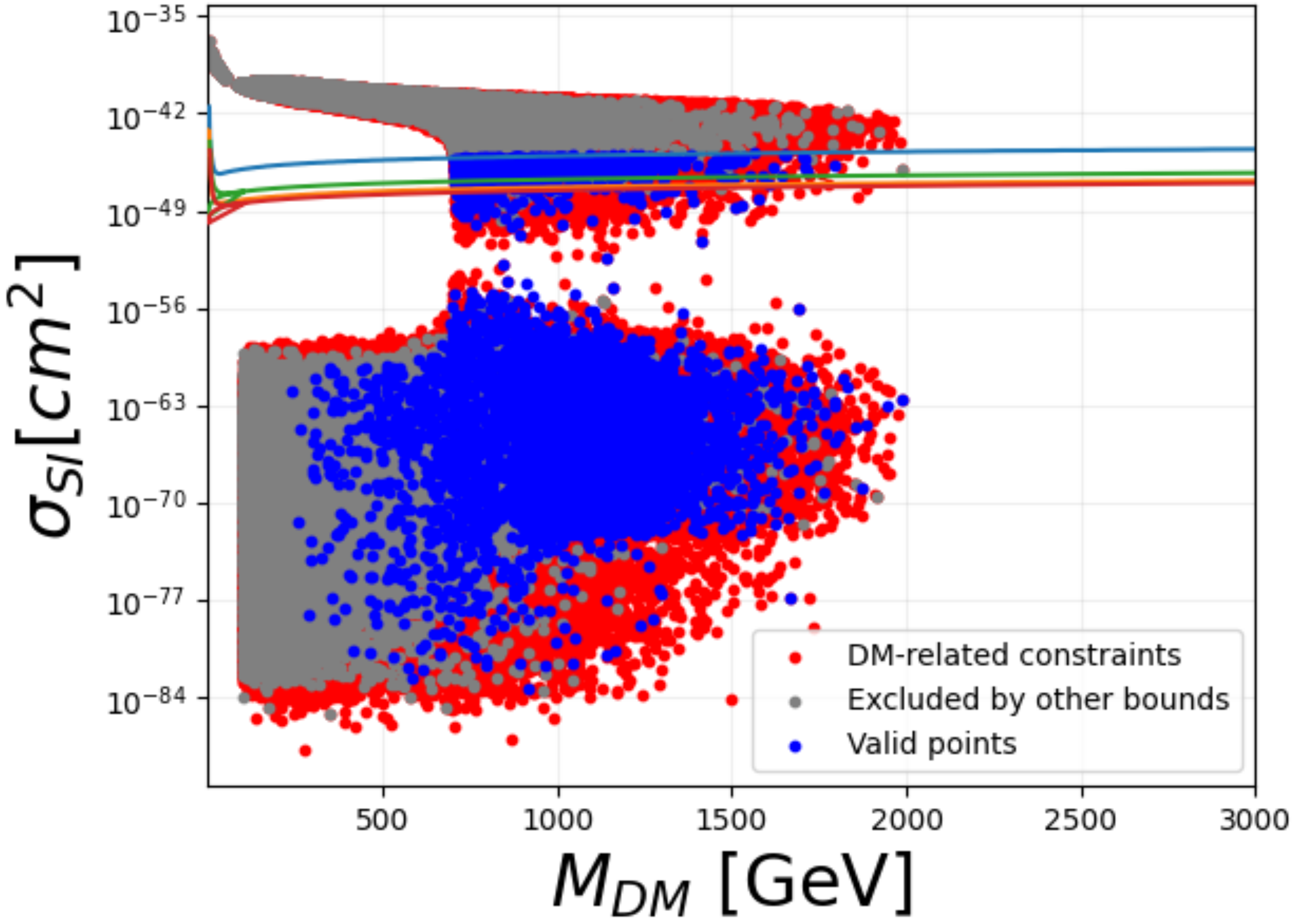
$$\mathscr{L}_{\text{fermion}} \supset -g_\psi^\alpha \widetilde{\overline{\psi_2}} L_L^\alpha S - g_{F_i}^\alpha \widetilde{\overline{L_L^\alpha}} \eta F_i$$

$$M_\nu = \mathcal{G}^T M_L \mathcal{G}$$

Naturally suppressed by a loop prefactor !

Viable Dark Matter candidate



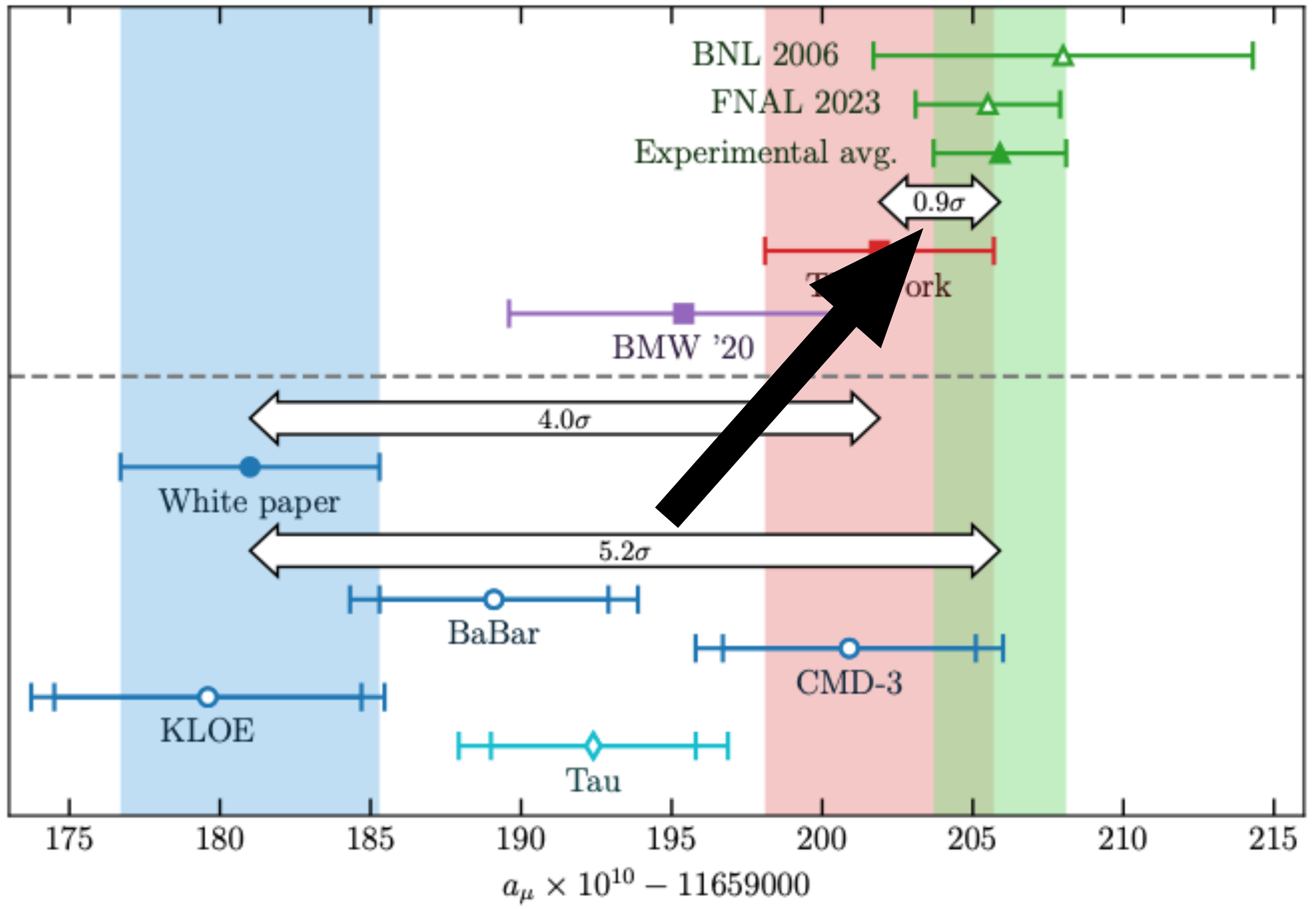


→ **MicrOmegas** to generate relic density and direct detection observables

→ CP even ϕ_1, Majorana fermion χ_1 and **new viable candidate** CP odd A^0!

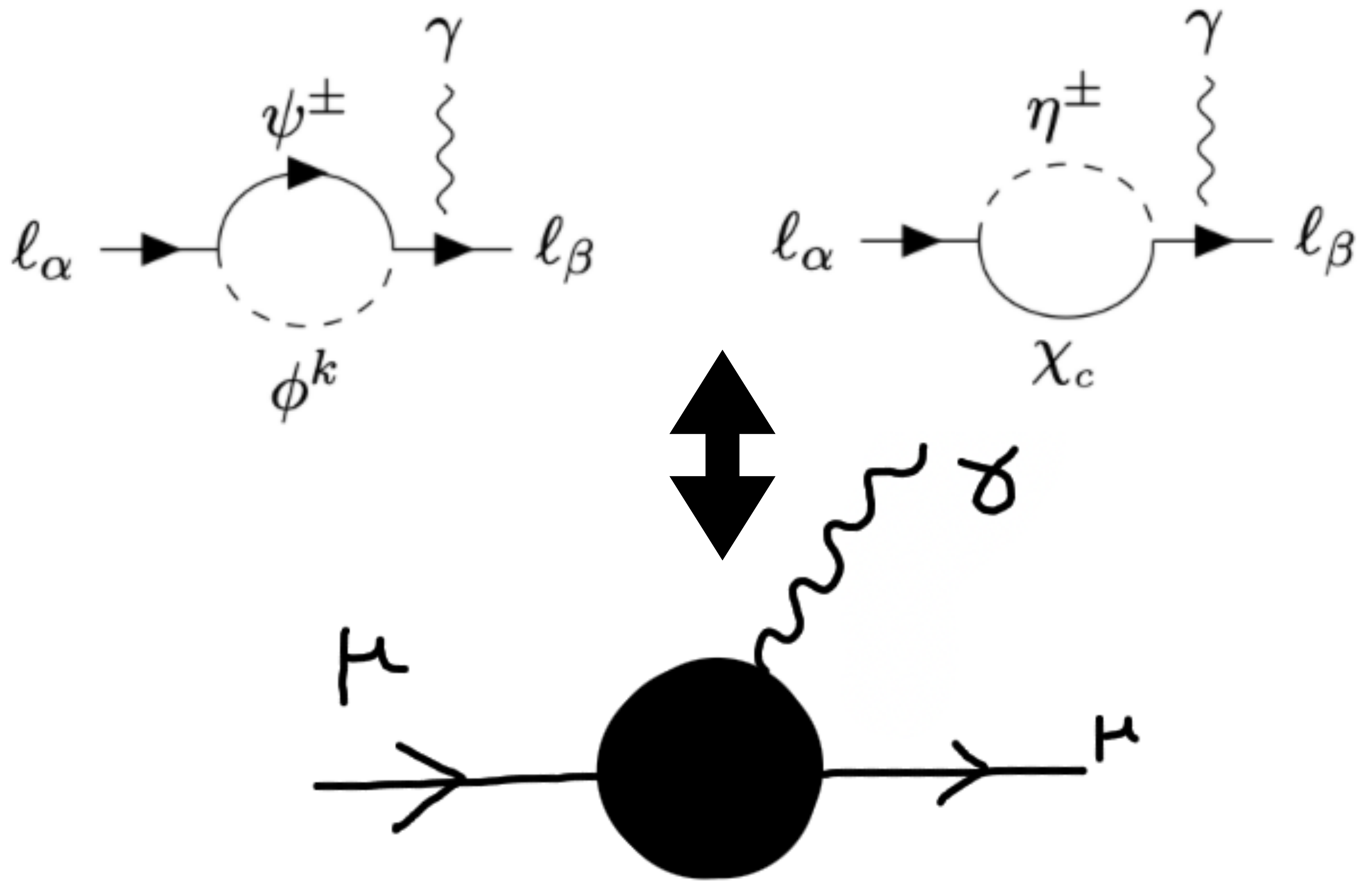
→ Most points excluded by DM-related constraints…

Muon dipole moment



[A. Boccaletti & al. 2407.10913]

Lattice QCD results **appeases tension** with experiments



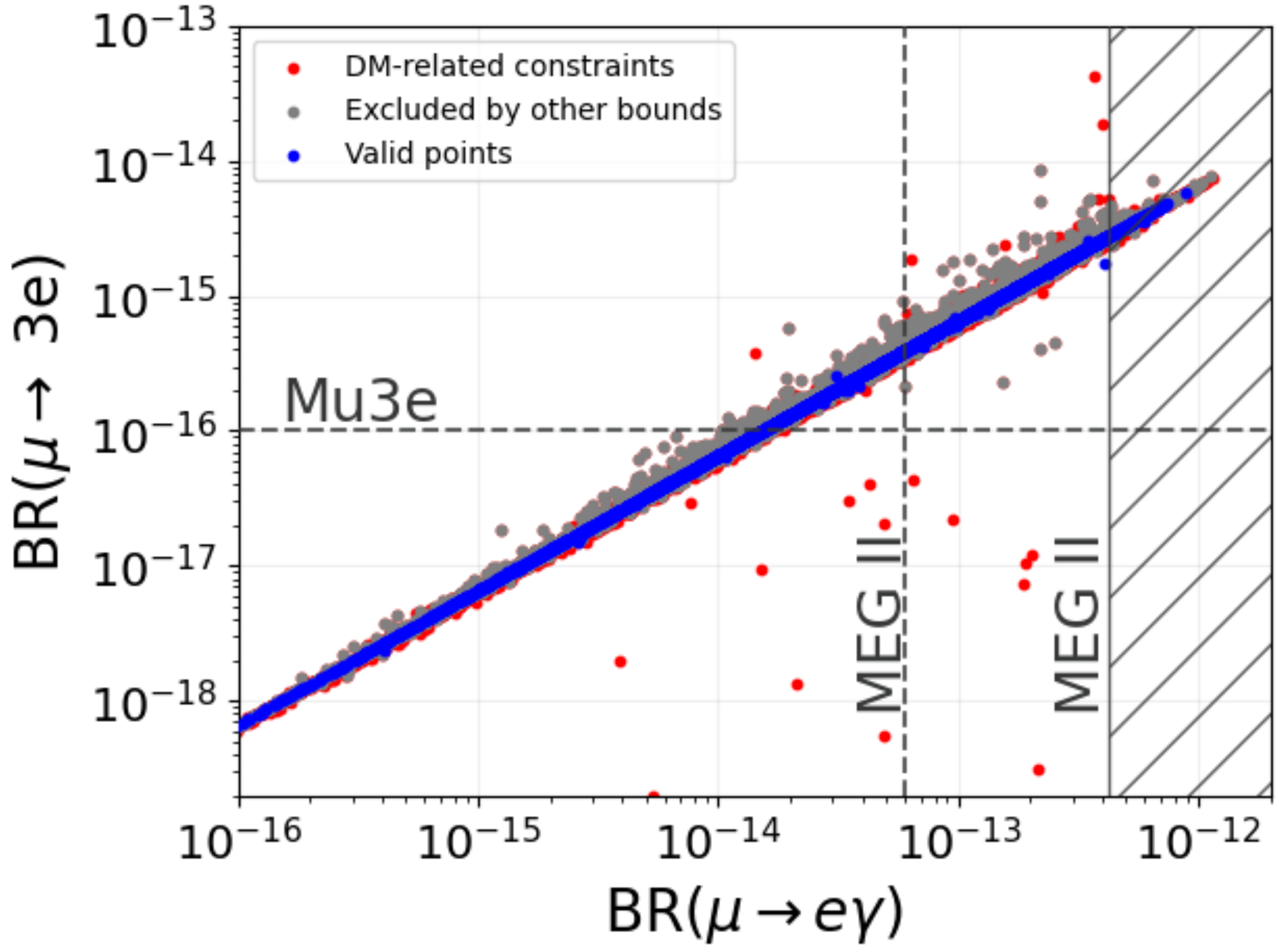
→ If large Δa_μ (4.2σ) → boosts dipole operator

→ If small Δa_μ (SM-like) → constraints on NP

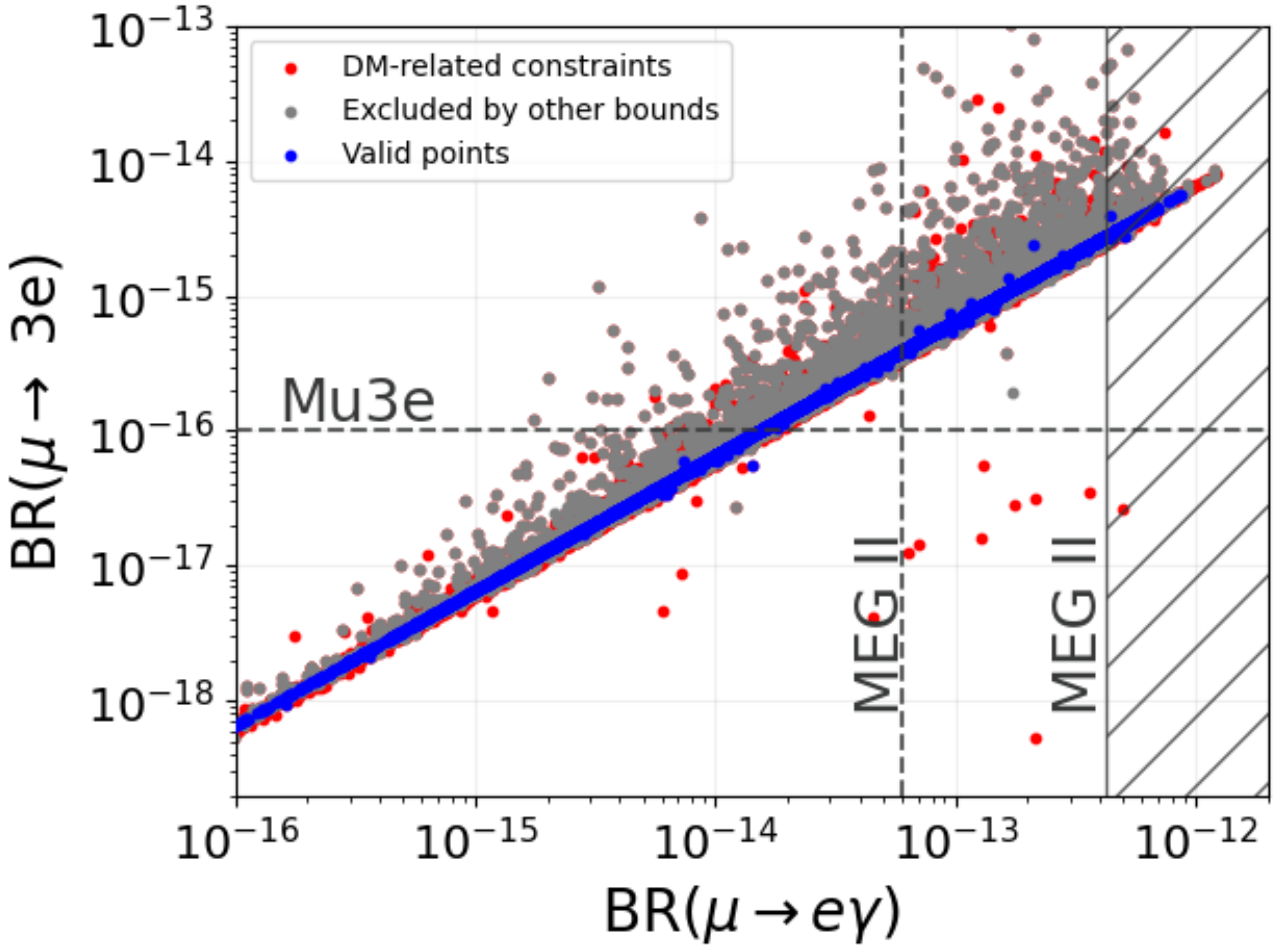
What is the impact of a more suppressed Δa_μ?

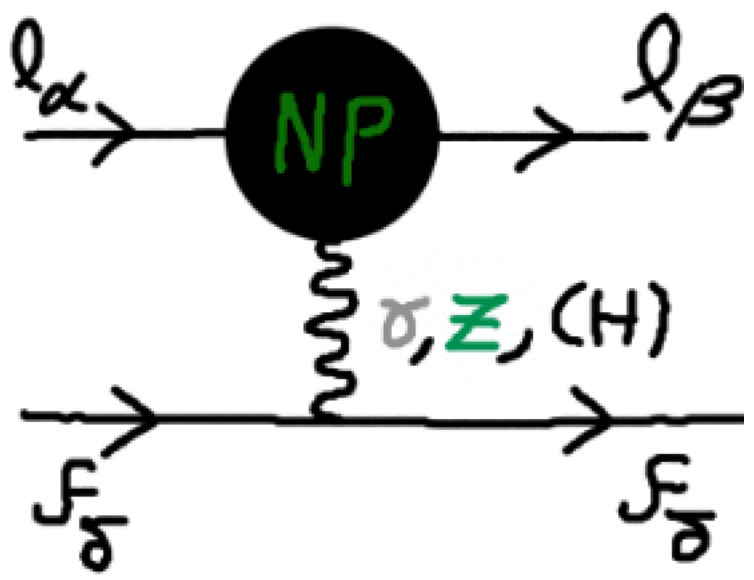
cLFV lepton processes

$\mu \to e\gamma, \mu \to 3e$; effect of NP vs SM-like Δa_μ



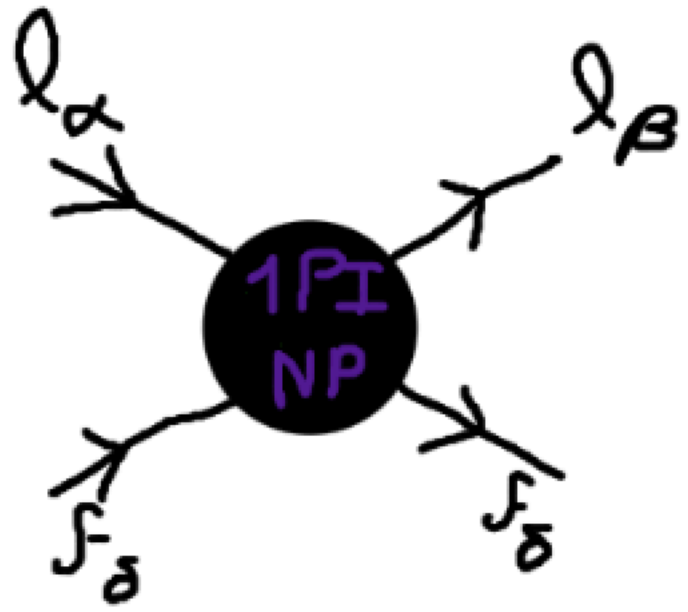
$\Delta a_\mu \sim 4\sigma \to \Delta a_\mu \sim 1\sigma$



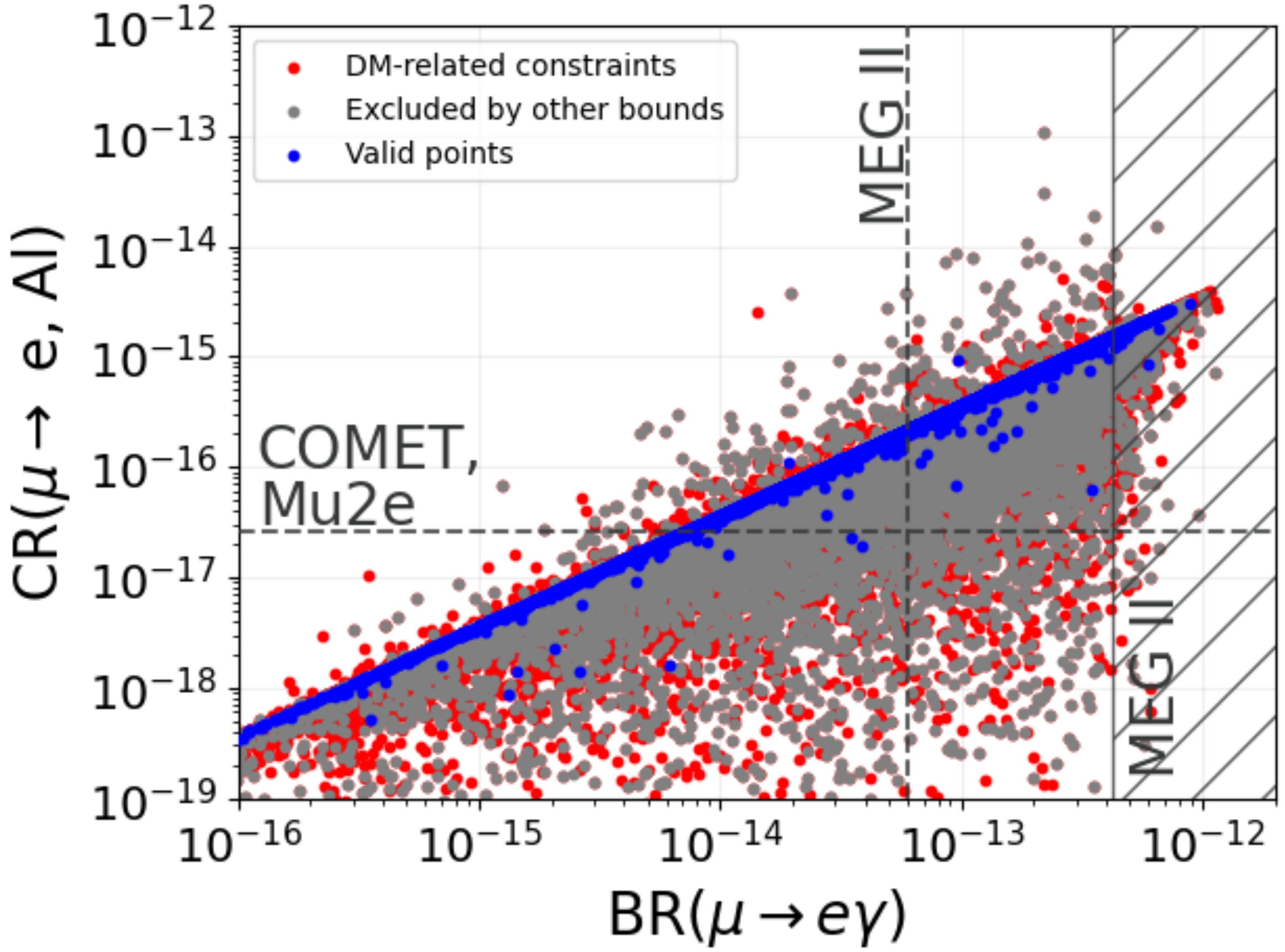


→ **Spreading from purely dipole dominated**

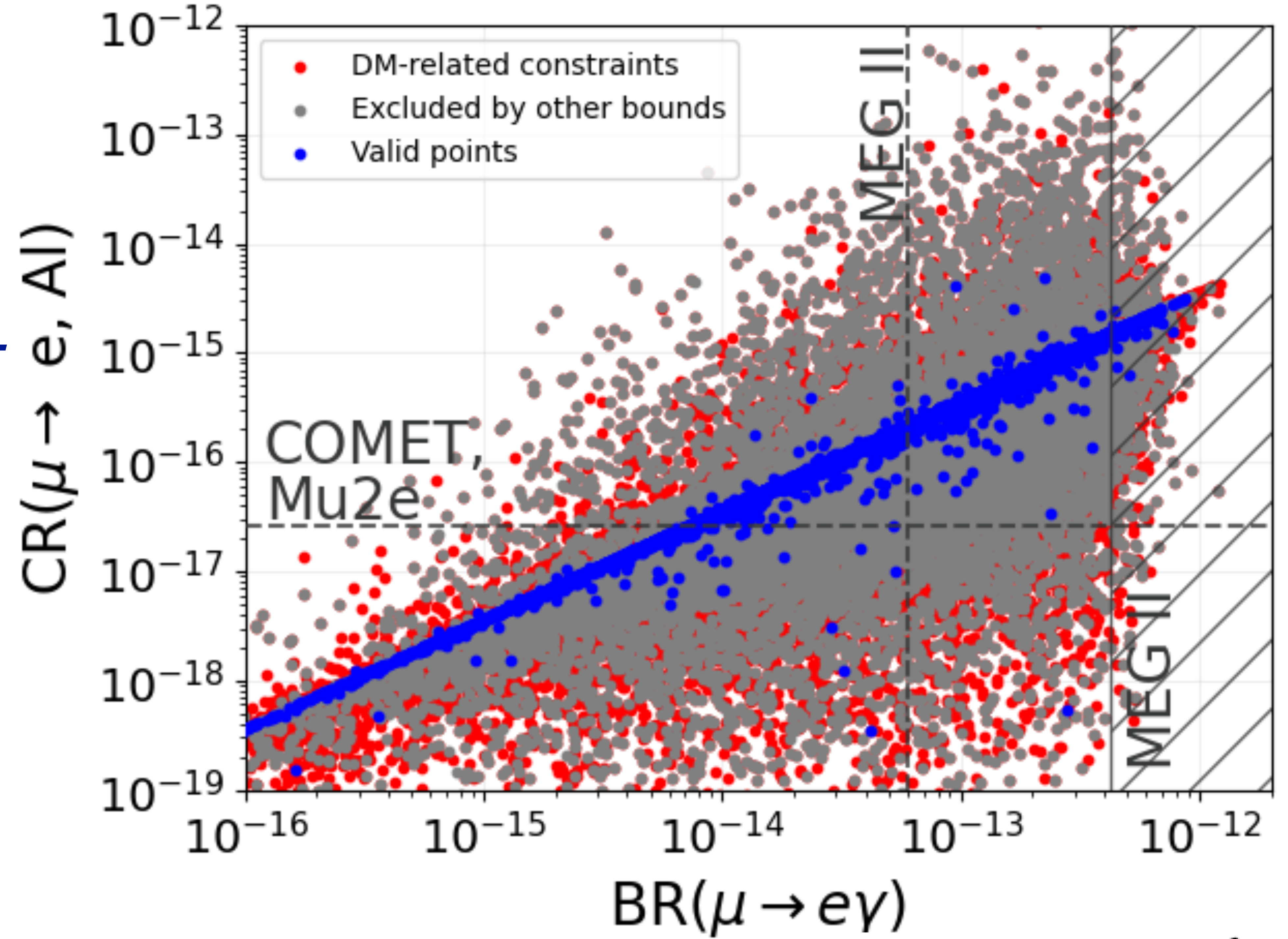
→ Box diagrams? **Z-Penguins**? Anapole?



Neutrino less **Mu-e conversion** in the **Nuclei**



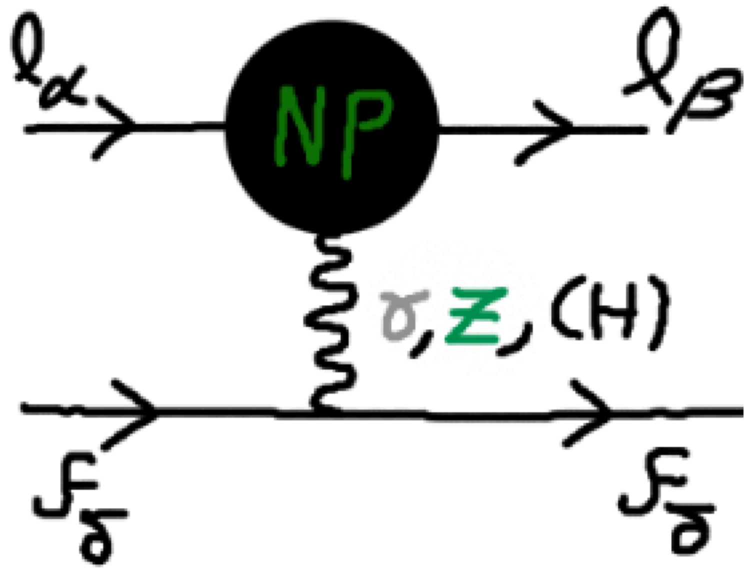
$\Delta a_\mu \sim 4\sigma \rightarrow \Delta a_\mu \sim 1\sigma$



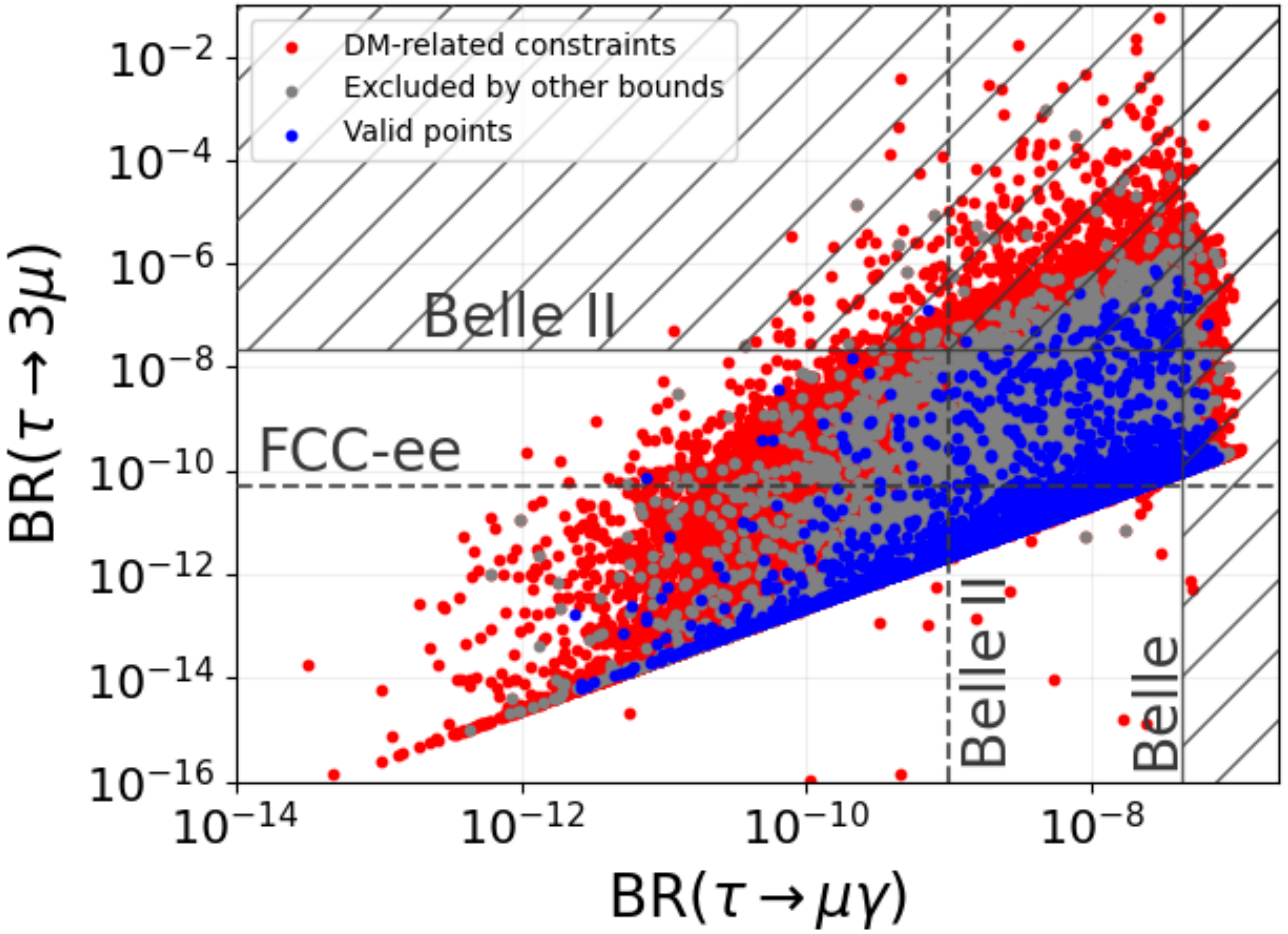
→ **No interaction** between **NP particles** and **quarks** at tree level

No box diagrams here, only anapole and **Z-Penguin**!

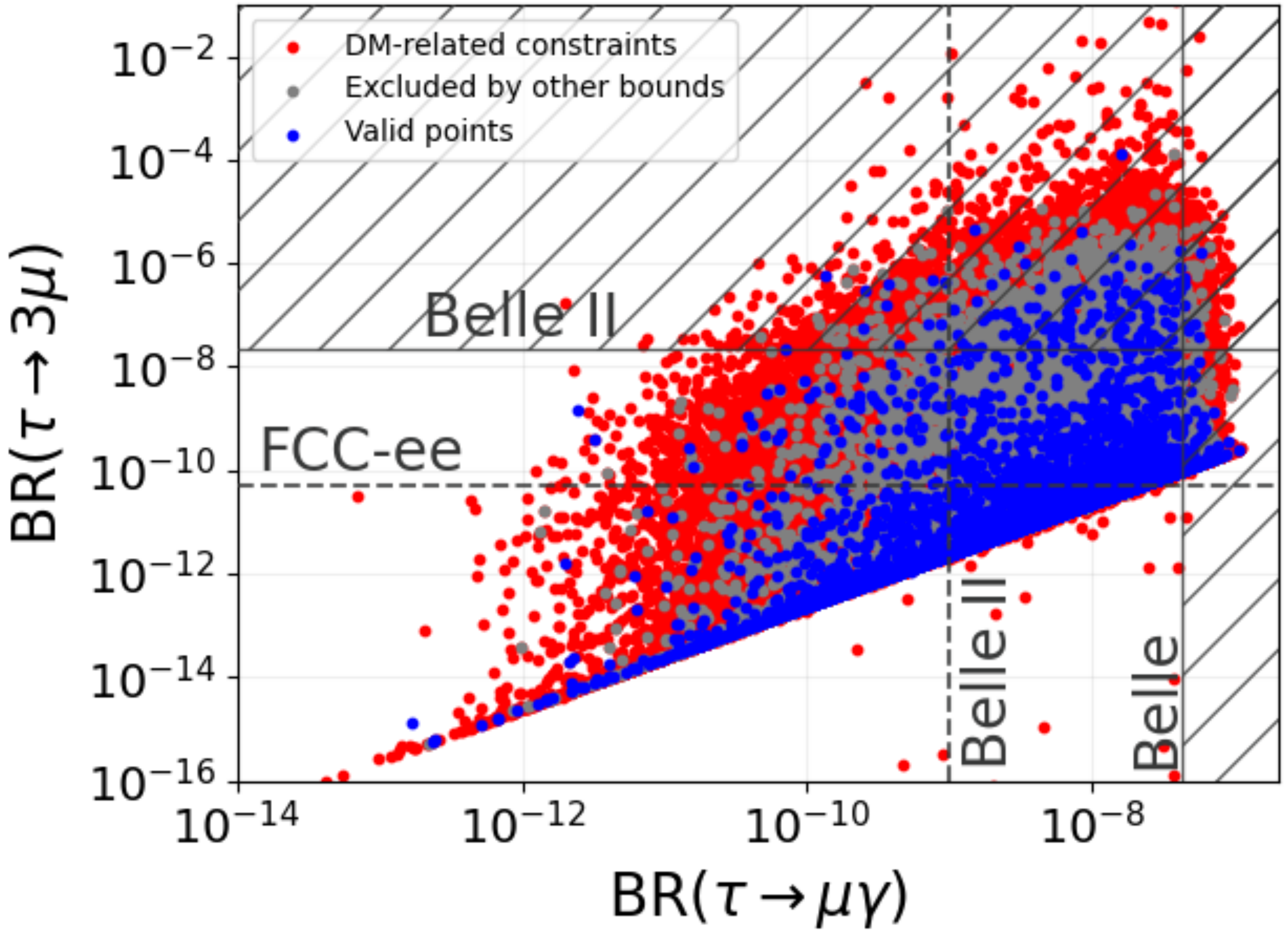
from only destructive interferences to also **Z-Penguin dominated**

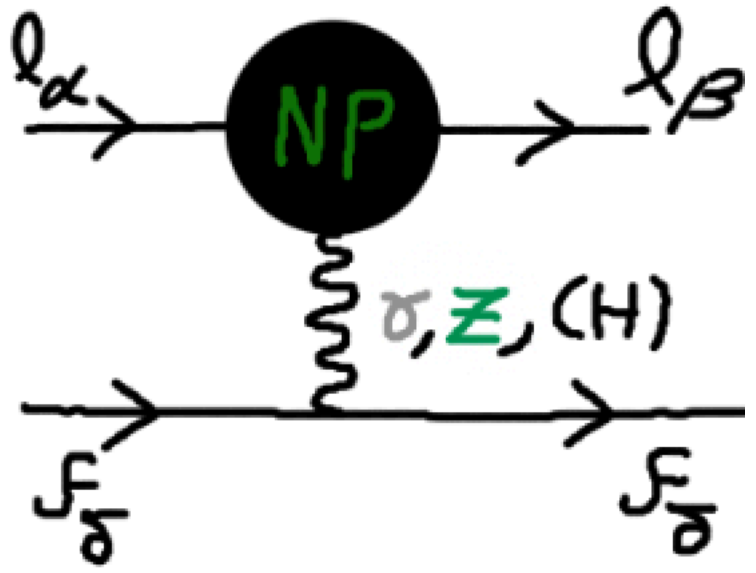


Leptonic **tau decays**



$\Delta a_\mu \sim 4\sigma \rightarrow \Delta a_\mu \sim 1\sigma$

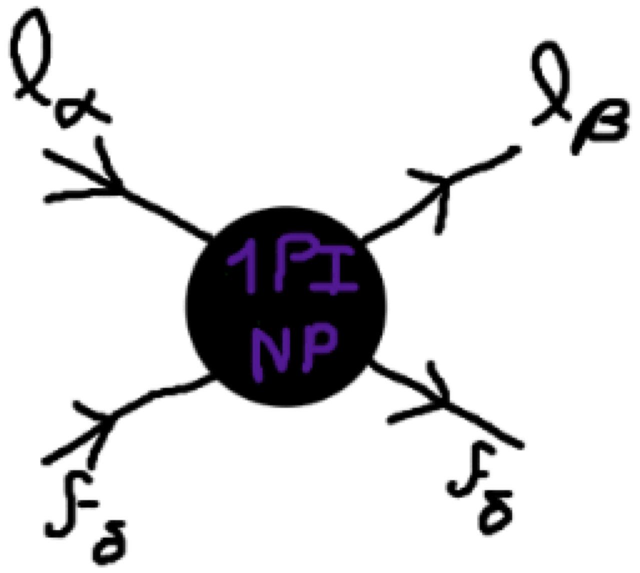




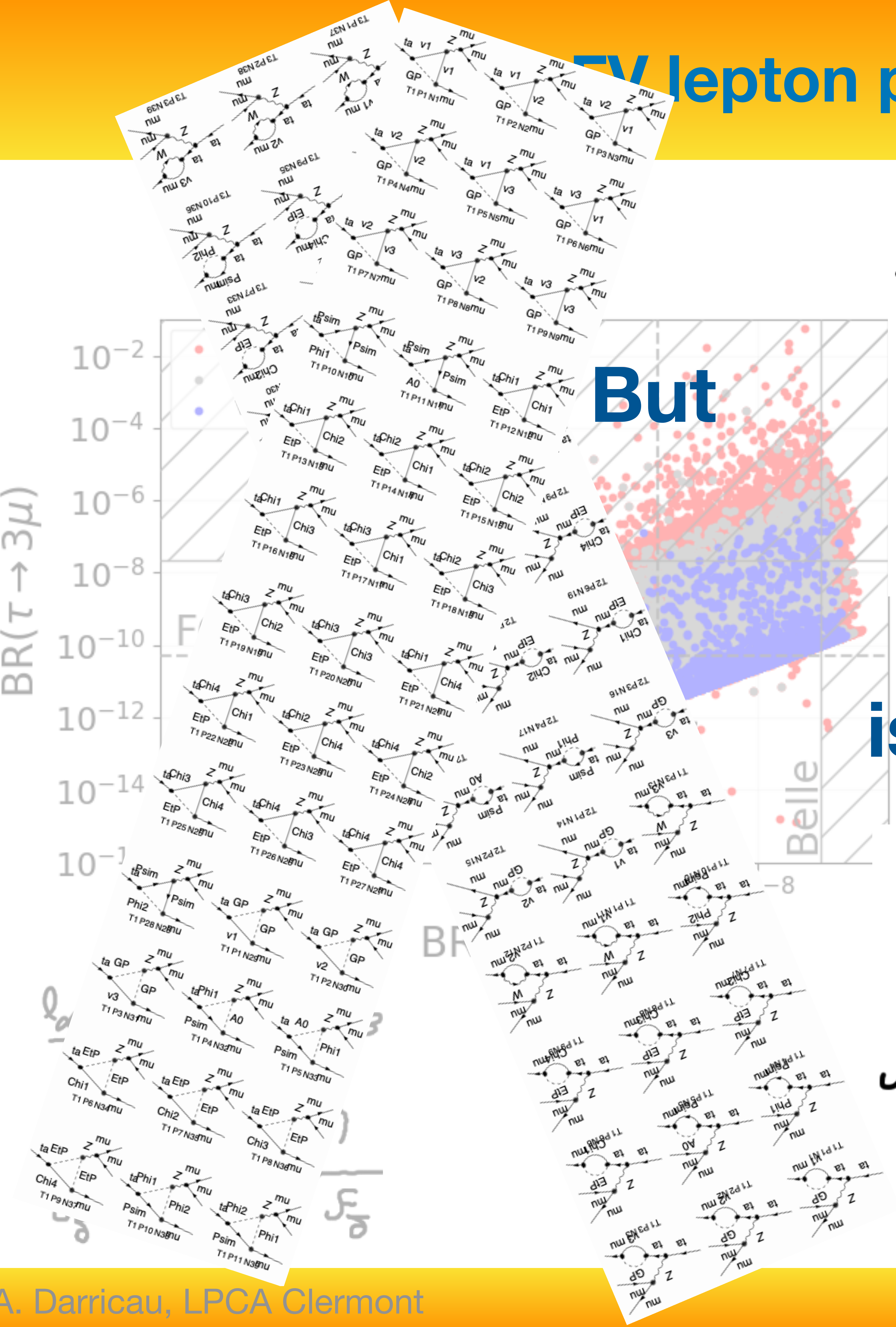
→ Sizeable **Z-penguin** contributions !

→ Even when boxes dominate, **still non-negligible effect**

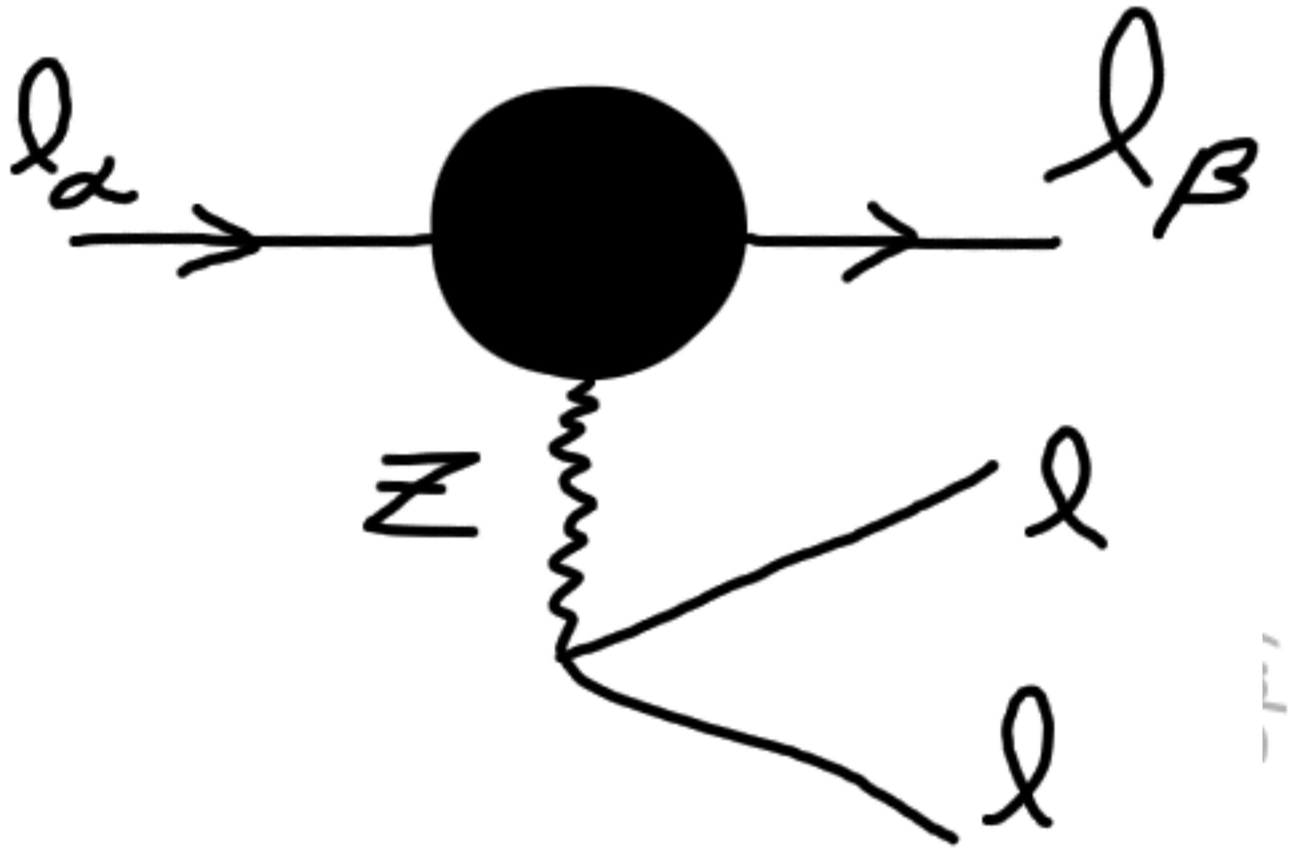
→ Even more points testable in the future!



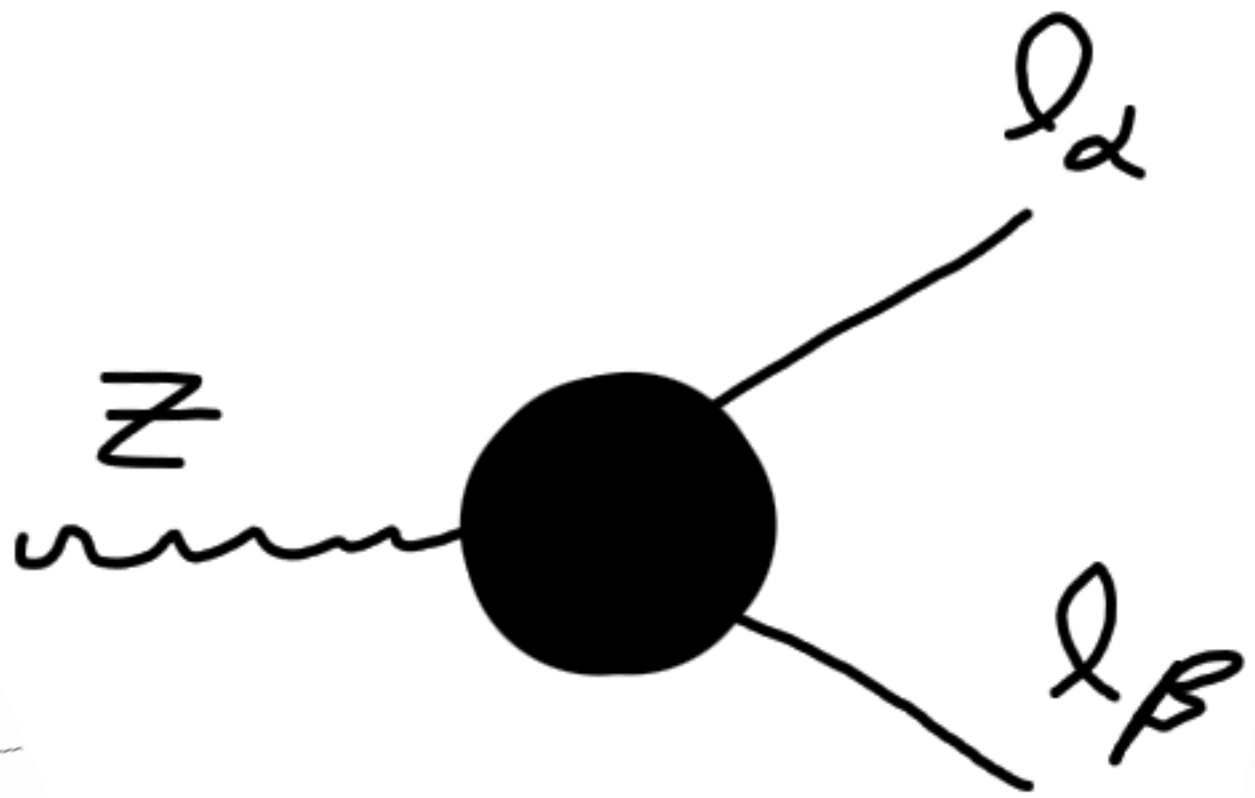
FV lepton processes

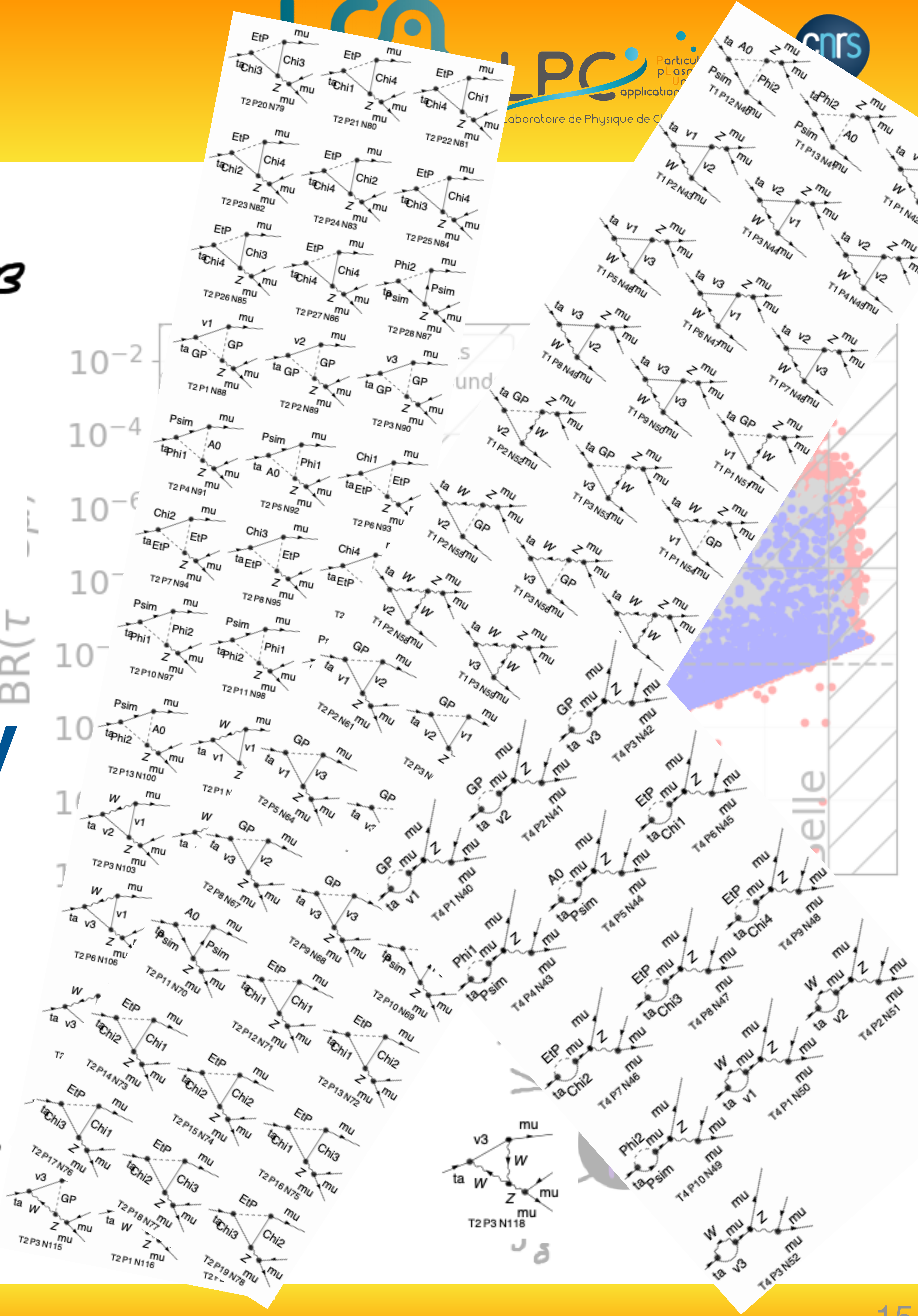


But

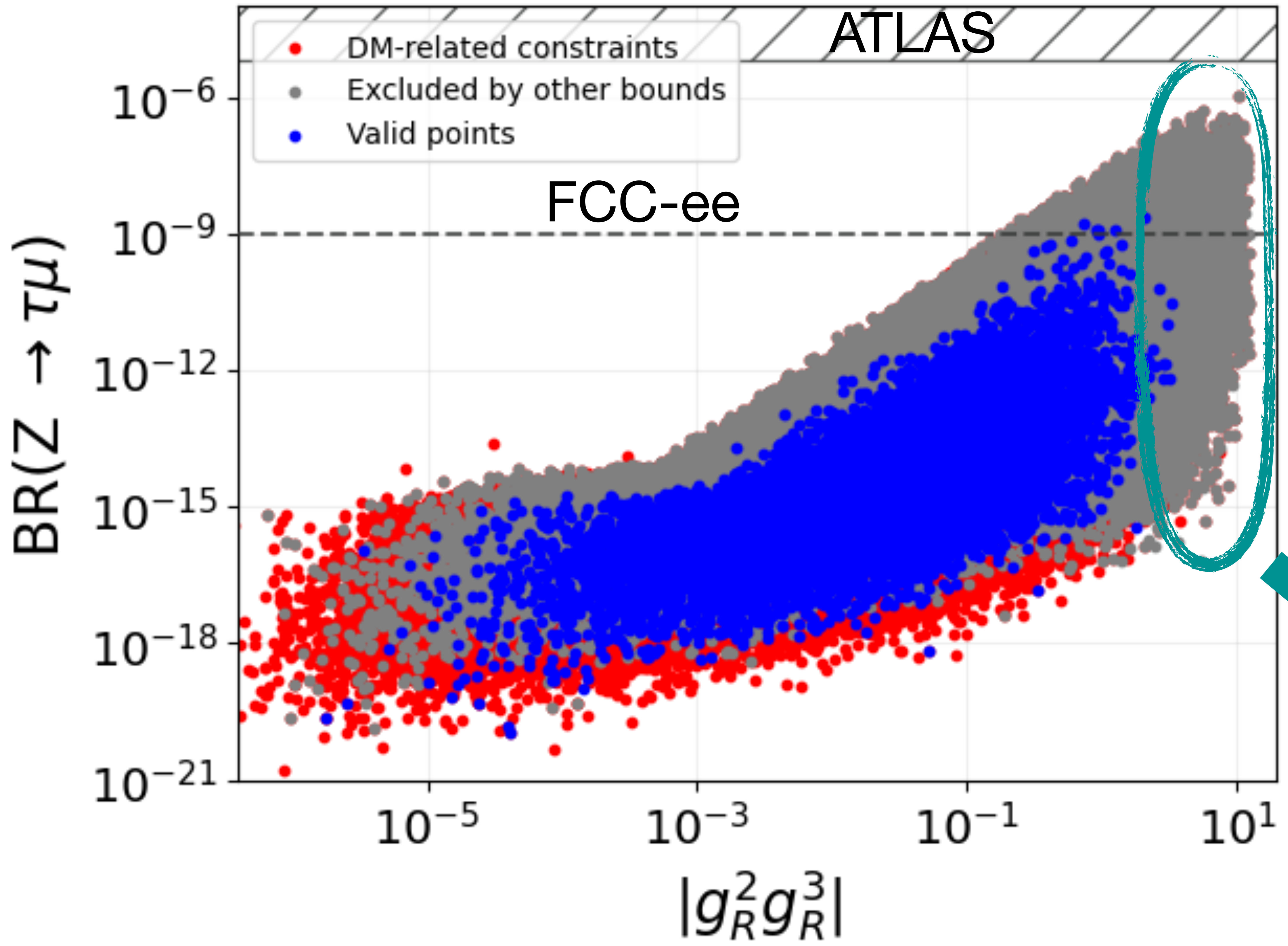


is fundamentally





Z cLFV decays



→ **Representative** of the other Z cLFV decays

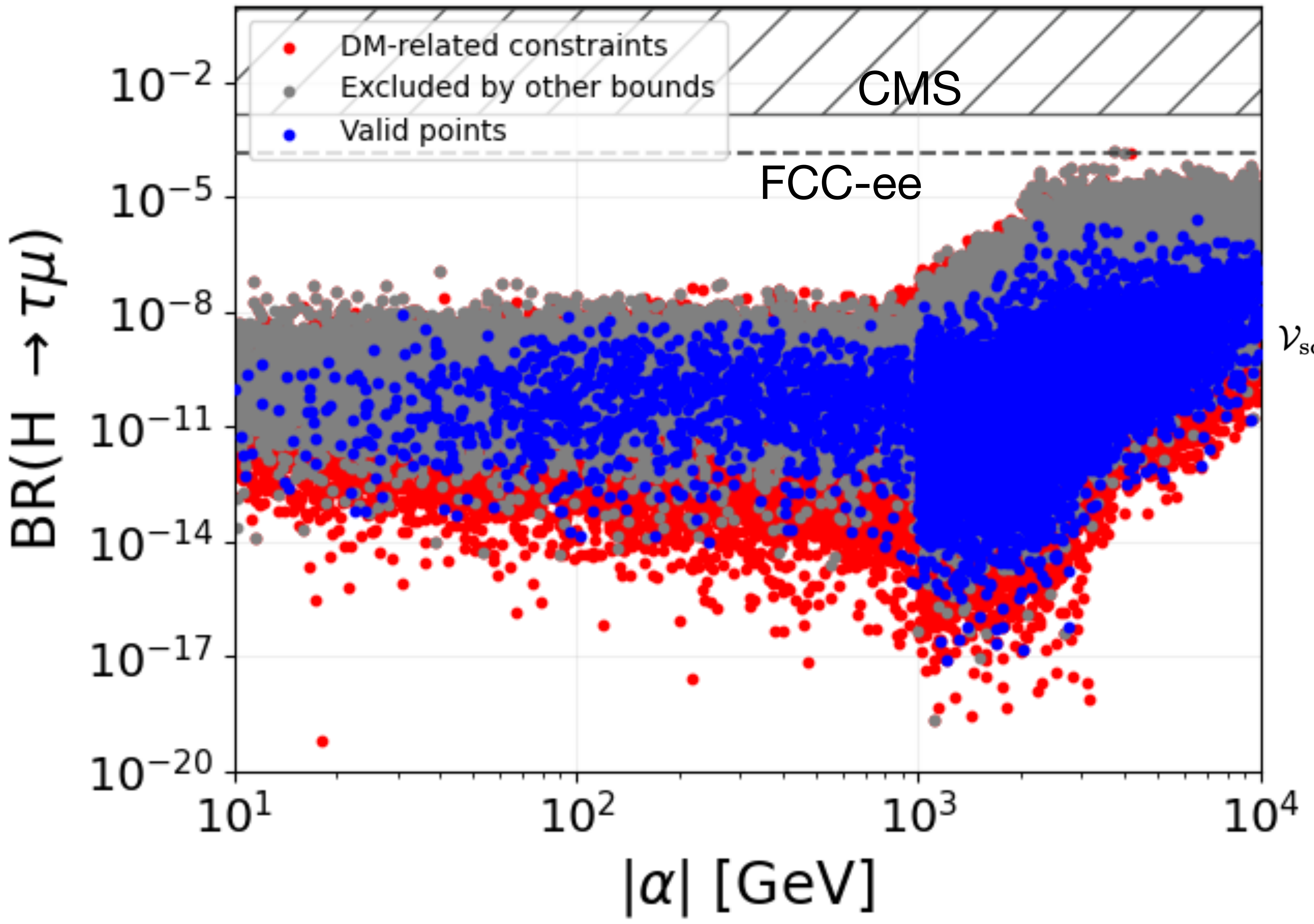
→ Driven by the NP coupling to right-handed leptons g_R^α

$$\mathcal{V}_{\text{fermion}} = M_\nu^{\alpha\beta}\,\overline{\nu_\alpha^c}\,\nu_\beta - M_\psi\,\overline{\psi_1}\,\widetilde{\psi_2} + \frac{1}{2}\,M_{F\,ii}\,\overline{F_i}^c\,F_i - y_{1i}^*\,\overline{F_i}\,\Phi^\dagger\,\widetilde{\psi_1} - y_{2i}^*\,\overline{F_i}\,\Phi\,\psi_2{}^c$$
$$+\, g_\psi^\alpha\,\overline{\widetilde{\psi_2}}\,L_L^\alpha S + g_{F_i}^\alpha\,\overline{\widetilde{L_L^\alpha}}\,\eta F_i + g_R^\alpha \overline{e_R^\alpha}\,\eta^\dagger\,\psi_1 + \text{H.c.}$$

Beyond future sensitivity ($\tau \to 3\mu$)

Not as important as expected…

Higgs cLFV decays



→ **Representative** of the other H cLFV

→ Driven by the NP trilinear coupling α when large

$$\mathcal{V}_{\rm scalar} = \frac{1}{2}M_S^2\, S^2 + \frac{1}{2}\lambda_{4S}\, S^4 + M_\eta^2\, |\eta|^2 + \lambda_{4\eta}\, |\eta|^4 + \frac{1}{2}\lambda_S\, S^2|\Phi|^2 + \frac{1}{2}\lambda_{S\eta}\, S^2|\eta|^2$$
$$+ \lambda_\eta\, |\eta|^2\, |\Phi|^2 + \lambda'_\eta\, |\eta\Phi^\dagger|^2 + \frac{1}{2}\lambda''_\eta \left[\left(\Phi\eta^\dagger\right)^2 + \text{H.c.}\right] + \alpha\, S\left[\Phi\eta^\dagger + \text{H.c.}\right]$$

Again, beyond future sensitivity…

Maybe EWPO ? LFUV ?

ElectroWeak Precision Observables (EWPO)

→ **EWPO**: sensitive probes of new interactions (scalar, vector, fermion…)

Oblique parameters (S,T,U), $Z/H \rightarrow inv$, $Z/H \rightarrow \ell_\alpha \ell_\alpha$ and their sensitive ratios

Why important? → Towards **high precision tests of the SM** (FCC-ee…)

→ $Z/H \rightarrow inv$

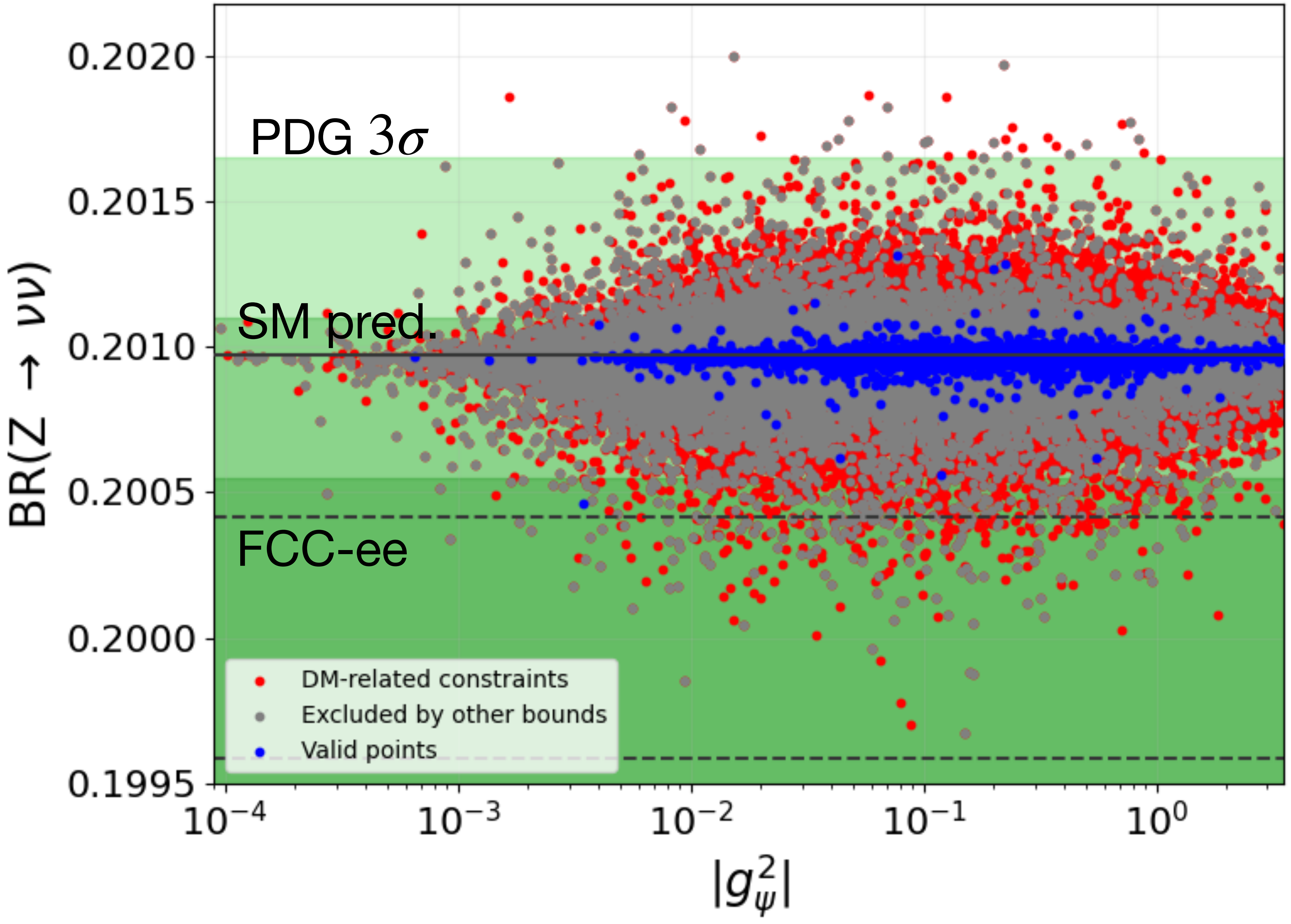
→ Oblique parameters

→ $Z/H \rightarrow \ell_\alpha \ell_\alpha$ + LFUV

ElectroWeak Precisi... ...ervables (E...

Not the same exercise…

EWPO: $Z \to inv$



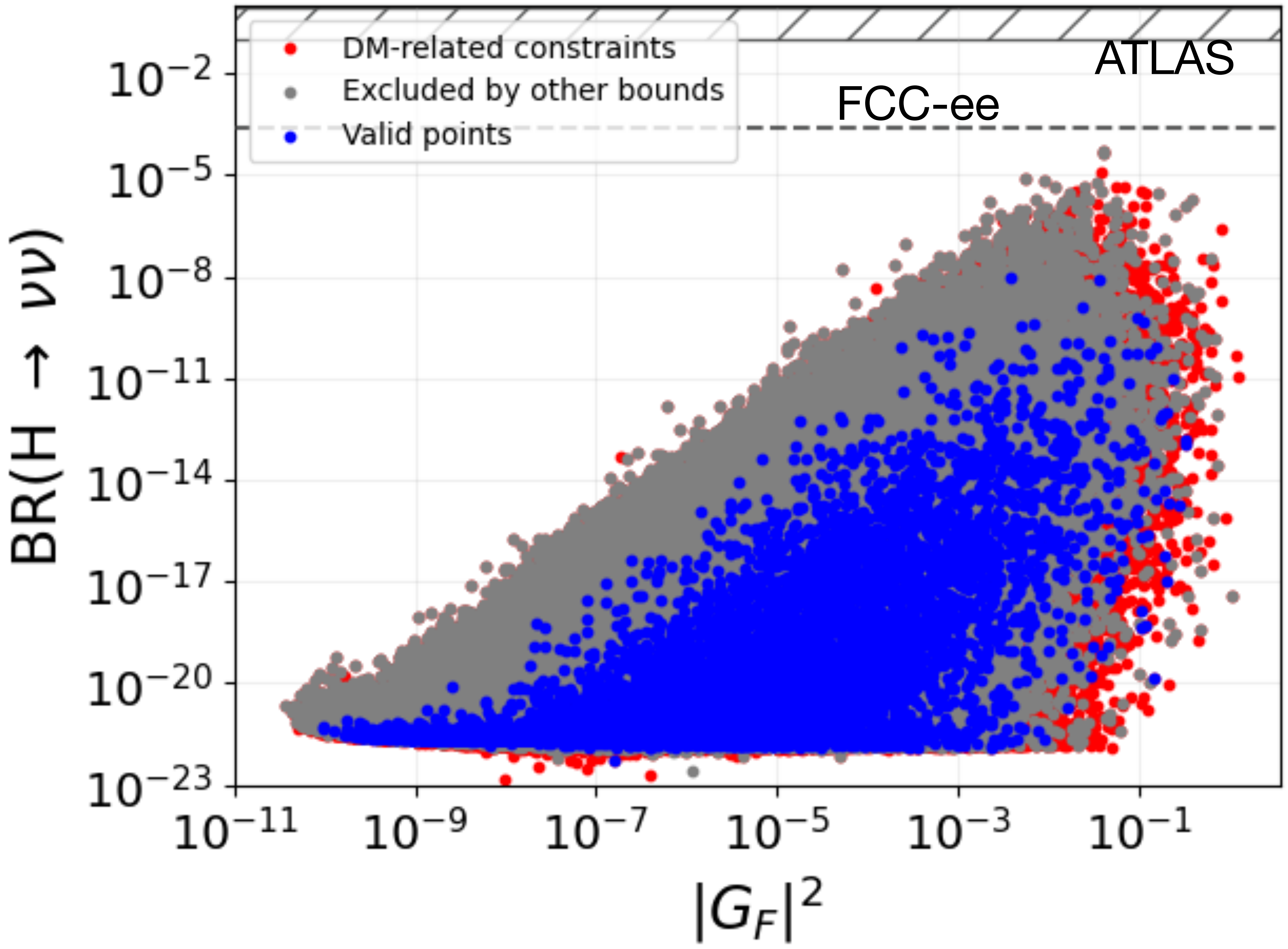
→ Strong constraint to NP and strongly **disfavours light invisible states** $M_{inv} < M_Z/2$

→ Small **tension with the SM**, points reaching toward the experimental measurements ? **Sensible by future experiments** ?

Again, beyond future sensitivity…

$$\mathcal{V}_{\text{fermion}} = M_\nu^{\alpha\beta}\, \overline{\nu_\alpha^c}\, \nu_\beta - M_\psi\, \overline{\psi_1}\, \widetilde{\psi_2} + \frac{1}{2} M_{F\,ii}\, \overline{F_i{}^c}\, F_i - y_{1i}^*\, \overline{F_i}\, \Phi^\dagger\, \widetilde{\psi_1} - y_{2i}^*\, \overline{F_i}\, \Phi\, \psi_2{}^c$$
$$+ g_\psi^\alpha\, \overline{\widetilde{\psi_2}}\, L_L^\alpha S + g_{F_i}^\alpha\, \overline{\widetilde{L_L^\alpha}}\, \eta F_i + g_R^\alpha\, \overline{e_R^\alpha}\, \eta^\dagger\, \psi_1 + \text{H.c.}$$

Invisible Higgs decays



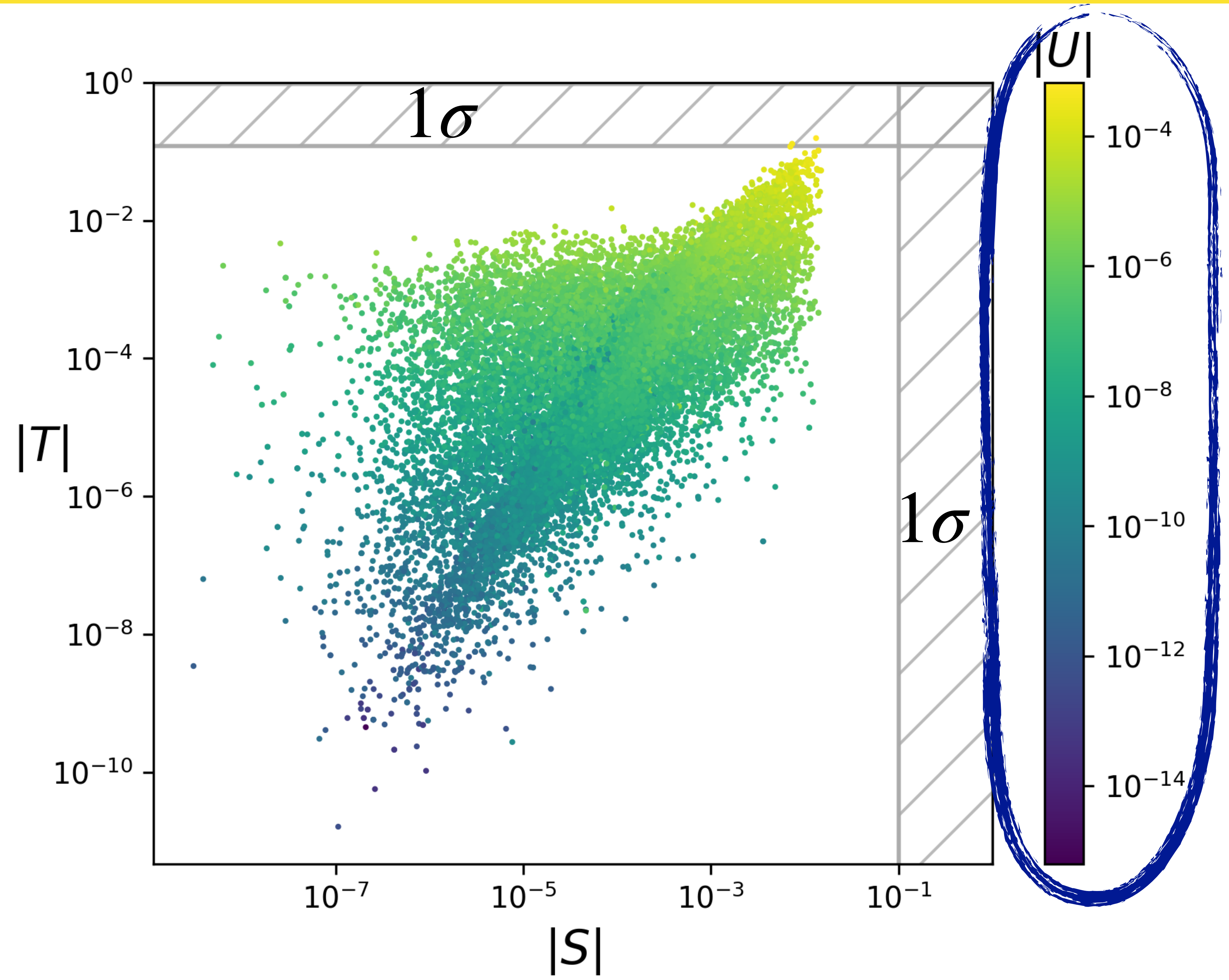
→ Strong constraint to NP and strongly **disfavours light invisible states** $M_{inv} < M_H/2$

→ A lower floor driven by m_ν

Again, beyond future sensitivity…

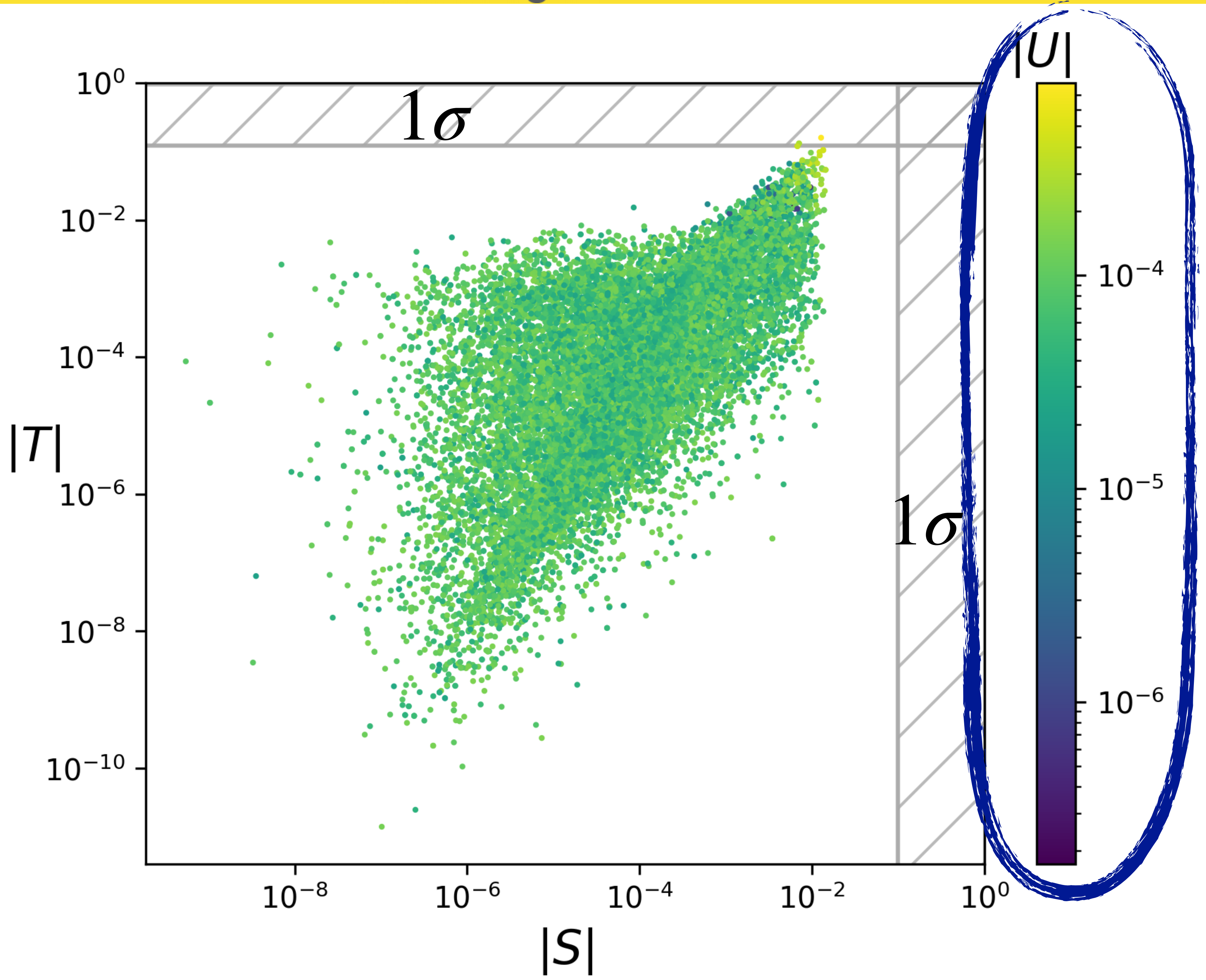
$$\mathcal{V}_{\rm fermion} = M_\nu^{\alpha\beta}\,\overline{\nu_\alpha^c}\,\nu_\beta - M_\psi\,\overline{\psi_1}\,\widetilde{\psi_2} + \frac{1}{2}\,M_{F\,ii}\,\overline{F_i{}^c}\,F_i - y_{1i}^*\,\overline{F_i}\,\Phi^\dagger\,\widetilde{\psi_1} - y_{2i}^*\,\overline{F_i}\,\Phi\,\psi_2{}^c$$
$$+\, g_\psi^\alpha\,\overline{\widetilde{\psi_2}}\,L_L^\alpha S + g_{F_i}^\alpha\,\overline{\widetilde{L_L^\alpha}}\,\eta F_i + g_R^\alpha\,\overline{e_R^\alpha}\,\eta^\dagger\,\psi_1 + {\rm H.c.}$$

Oblique parameters



Full analytical computation

Numerical rounding issues for U!



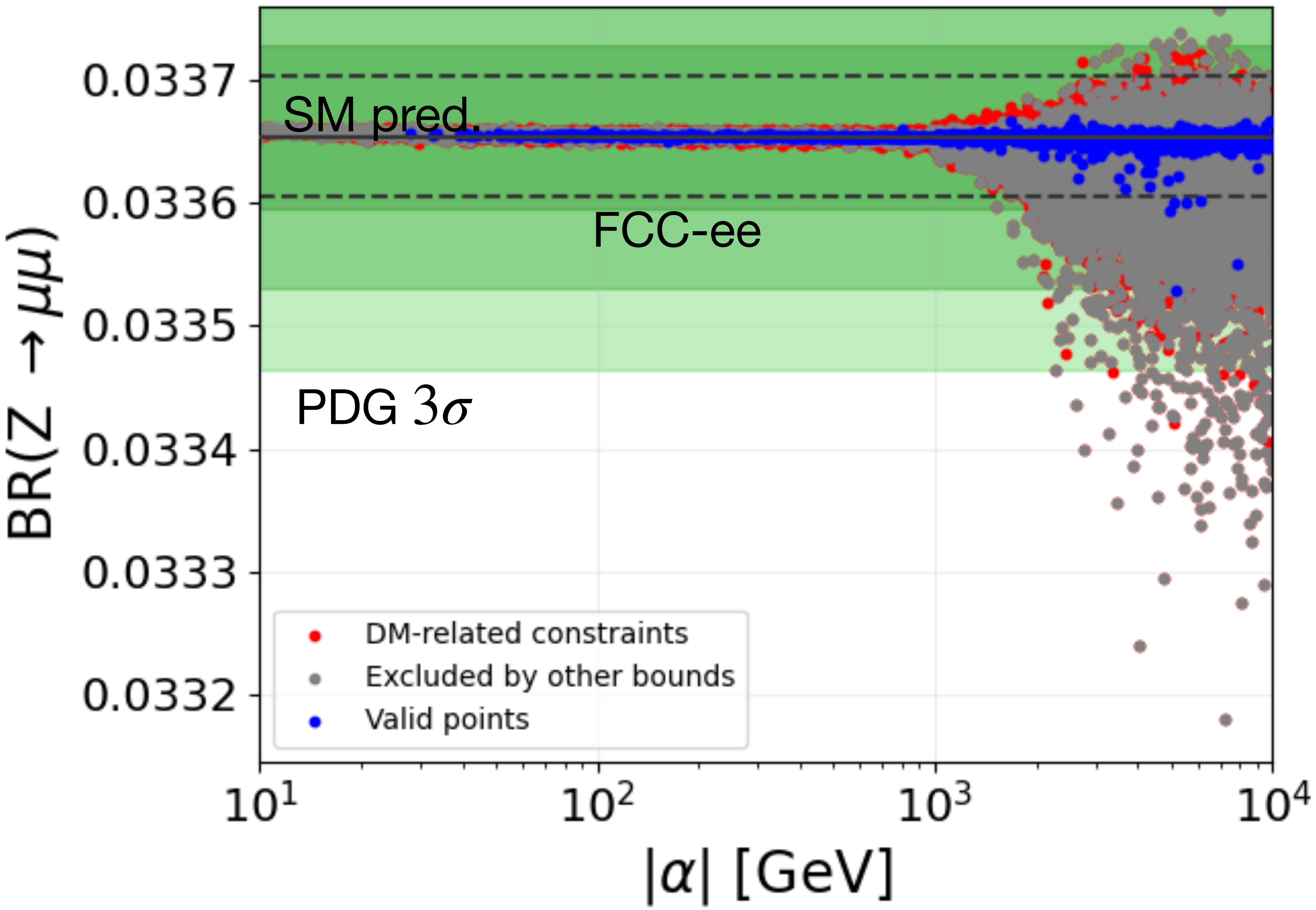
SPheno output

[W. Porod & al., 1104.1573]

→ A reminder on the **importance of analytical derivation**

→ Still not within reach…

Z flavour conserving decays



→ Representative of the other Z conserving decays

→ Large trilinear coupling α yields **sizeable contributions**!

→ **Points excluded** by other bounds… Actually from $H \to \ell_\alpha \ell_\alpha$!

$$\mathcal{V}_{\text{scalar}} = \frac{1}{2}M_S^2\, S^2 + \frac{1}{2}\lambda_{4S}\, S^4 + M_\eta^2\, |\eta|^2 + \lambda_{4\eta}\, |\eta|^4 + \frac{1}{2}\lambda_S\, S^2|\Phi|^2 + \frac{1}{2}\lambda_{S\eta}\, S^2|\eta|^2 + \lambda_\eta\, |\eta|^2\, |\Phi|^2 + \lambda'_\eta\, |\eta\Phi^\dagger|^2 + \frac{1}{2}\lambda''_\eta\left[\left(\Phi\eta^\dagger\right)^2 + \text{H.c.}\right] + \alpha\, S\left[\Phi\eta^\dagger + \text{H.c.}\right]$$

H flavour conserving decays

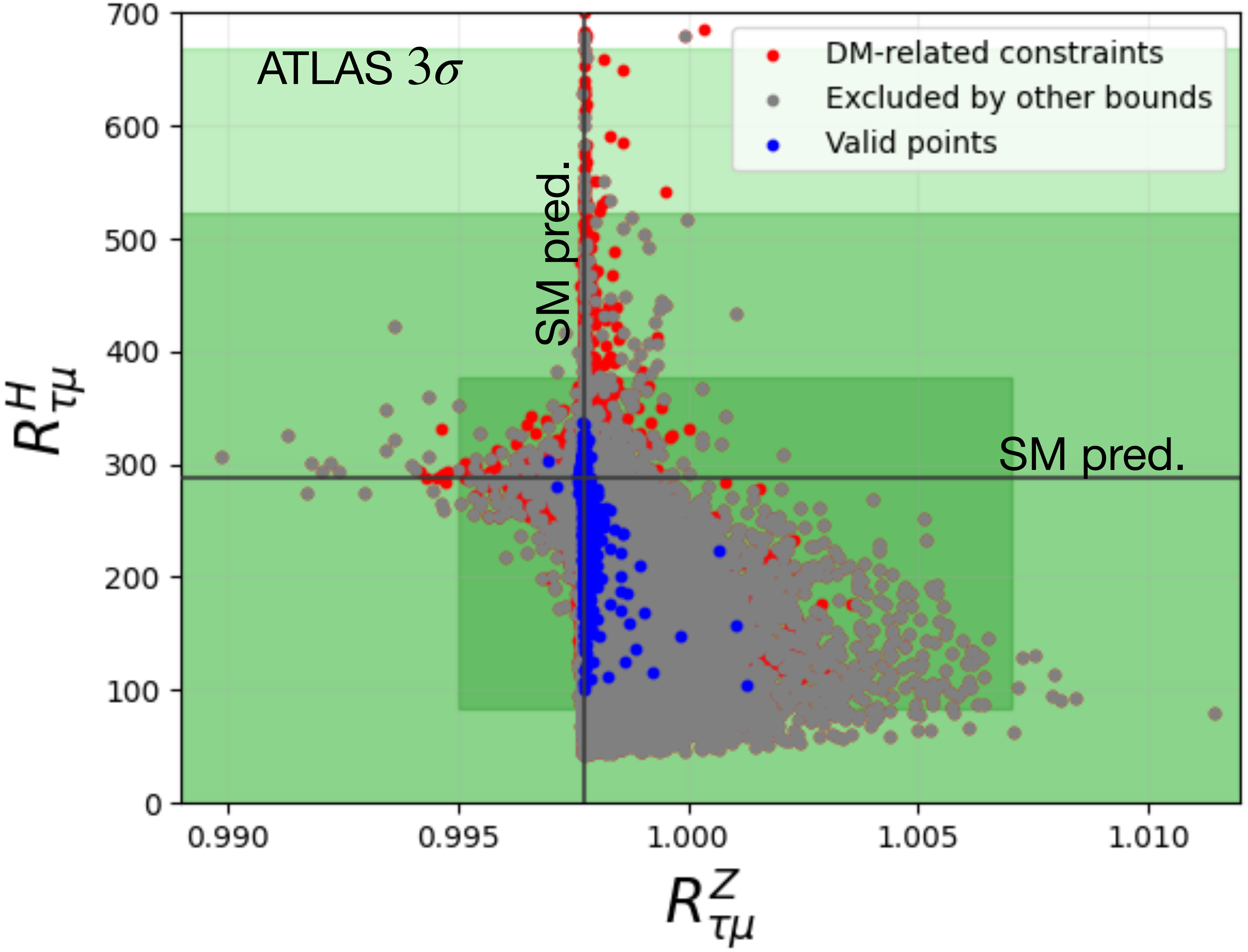
→ Representative of the other H conserving decays

→ **Light** masses for CP-Even state ϕ_1 **disfavoured**!

→ Important corrections! **Strong constraints** on the parameter space!

→ SM-Like Δa_μ **relaxes constraints**

Lepton Flavour Universality Violation



$$R^{Z/H}_{\alpha\beta} \equiv \frac{\Gamma(Z/H \to \ell_\alpha \ell_\alpha)}{\Gamma(Z/H \to \ell_\beta \ell_\beta)}$$

→ Representative of the other ratios

→ SM Predicts LFUC (other than mass effects)

→ Z LFUV corrections **fully under control**!

→ H LFUV corrections **favours small**

trilinear coupling α

$$\mathcal{V}_{\rm scalar} = \frac{1}{2}M_S^2\, S^2 + \frac{1}{2}\lambda_{4S}\, S^4 + M_\eta^2\, |\eta|^2 + \lambda_{4\eta}\, |\eta|^4 + \frac{1}{2}\lambda_S\, S^2|\Phi|^2 + \frac{1}{2}\lambda_{S\eta}\, S^2|\eta|^2$$
$$+ \lambda_\eta\, |\eta|^2\, |\Phi|^2 + \lambda'_\eta\, |\eta\Phi^\dagger|^2 + \frac{1}{2}\lambda''_\eta \left[\left(\Phi\eta^\dagger\right)^2 + {\rm H.c.}\right] + \alpha\, S\left[\Phi\eta^\dagger + {\rm H.c.}\right]$$

Conclusion

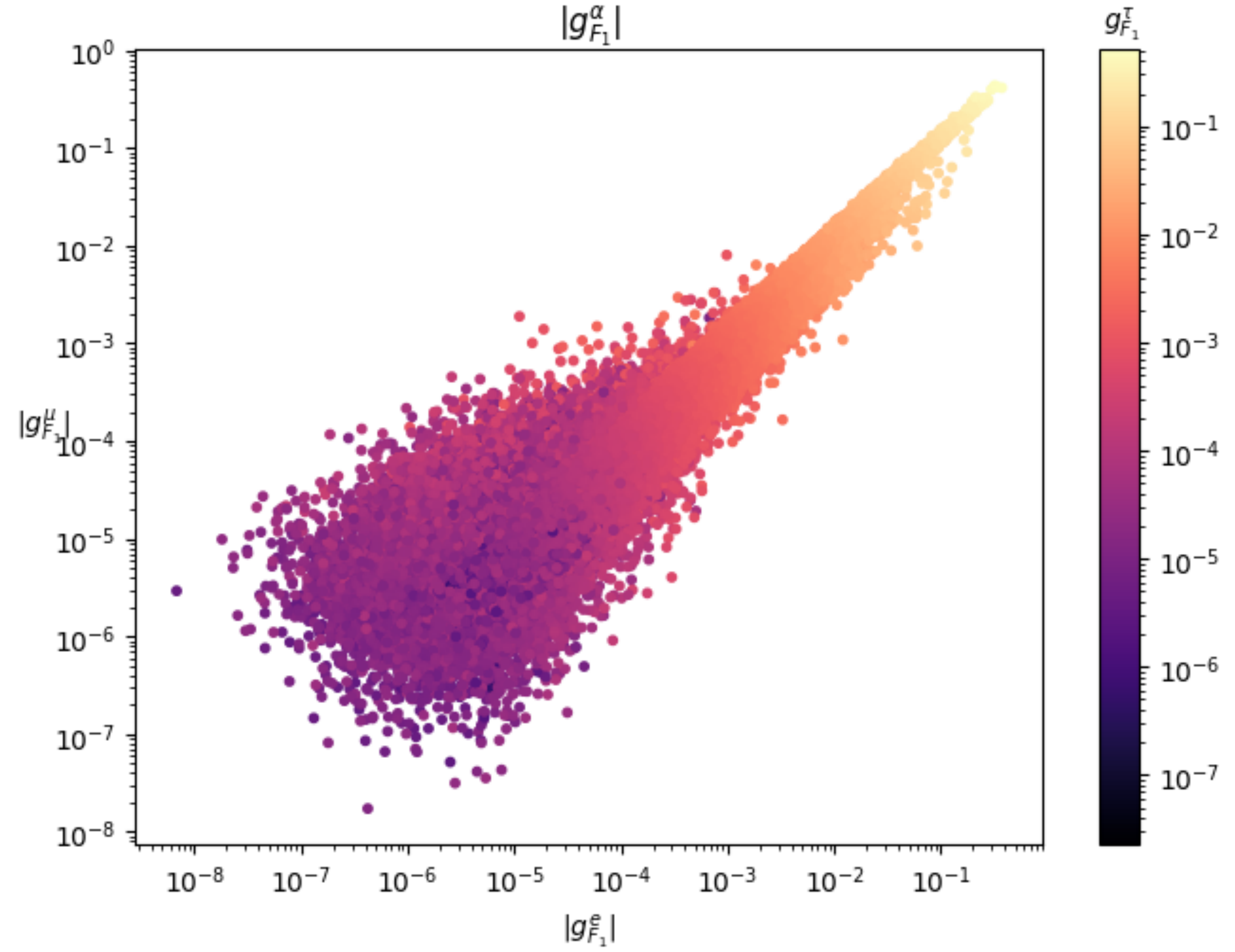
→ **Thorough analysis** on the flavour phenomenology

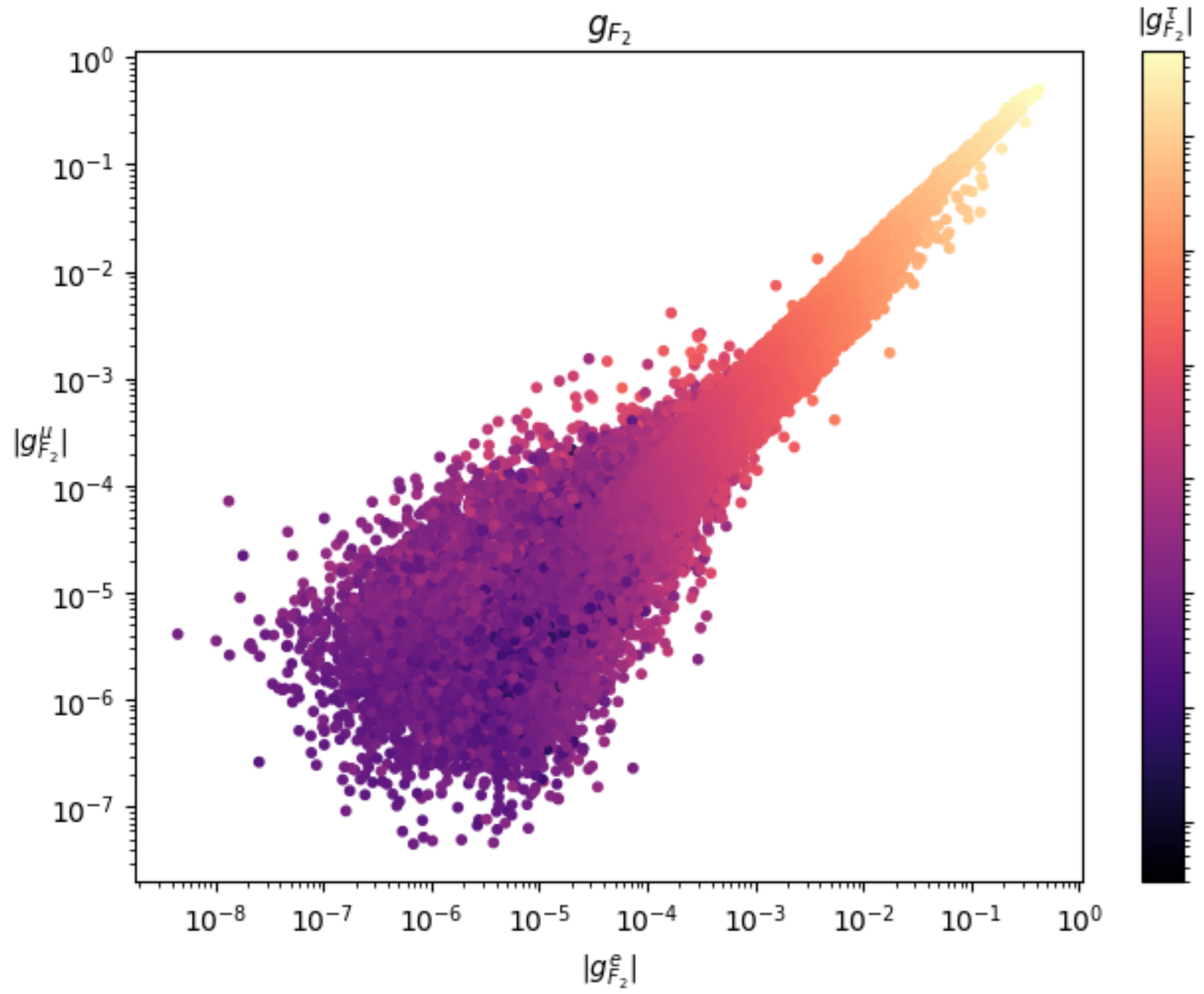
→ Found a new viable DM candidate: A^0

→ Put forward the **consequences** of relaxing Δa_μ

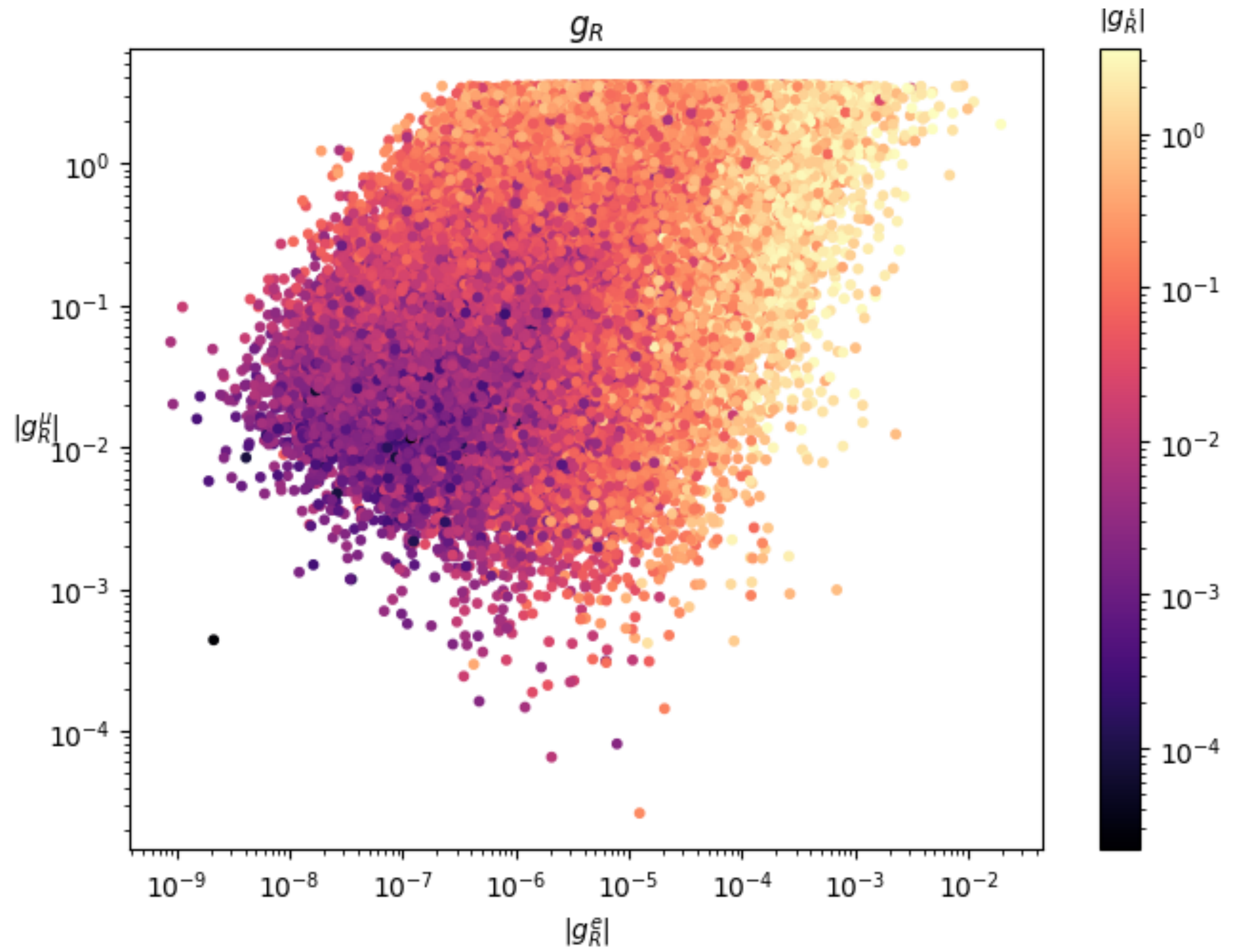
→ Parameter space favoured by leptogenesis **disfavoured by EWPO**

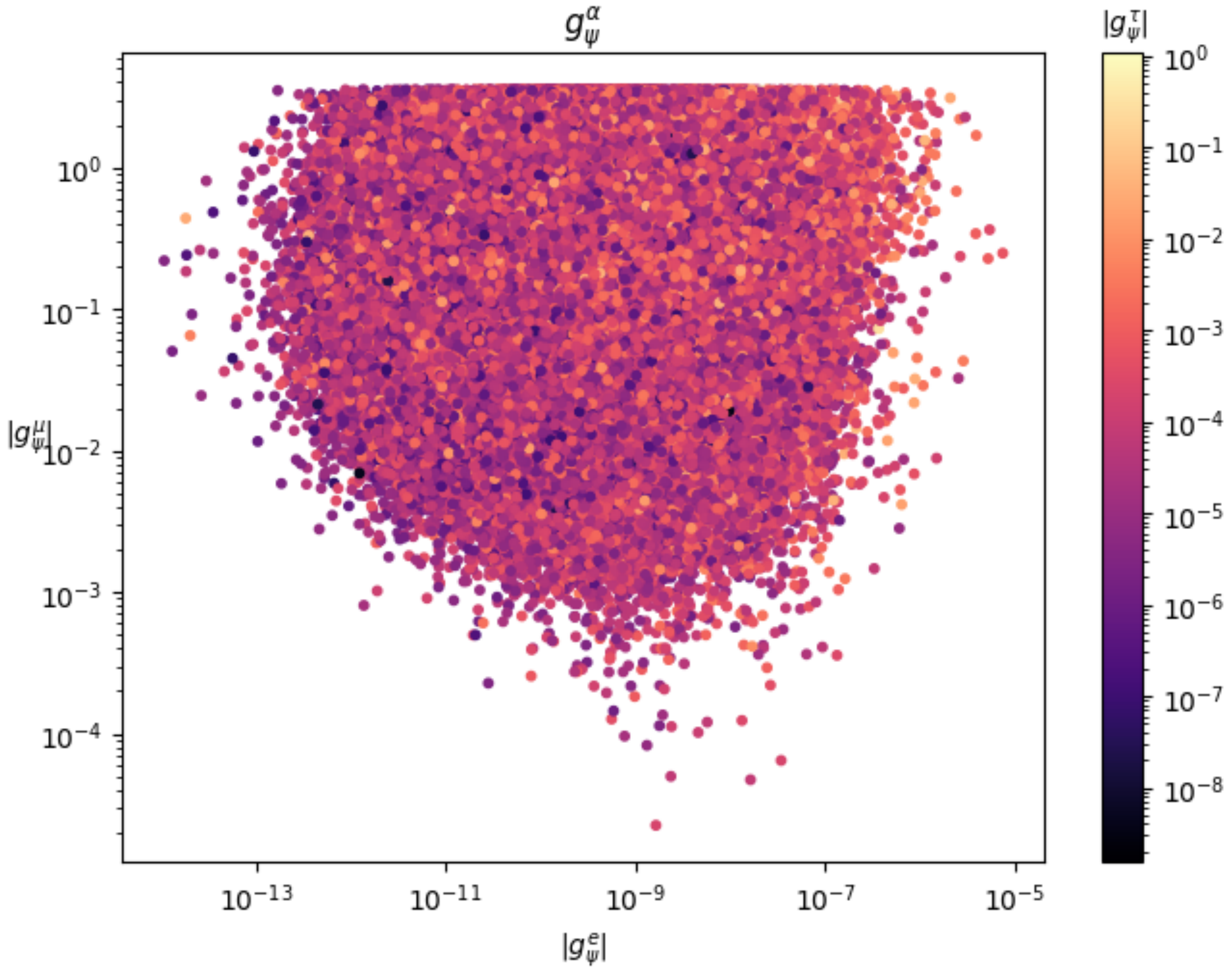
Parameter space



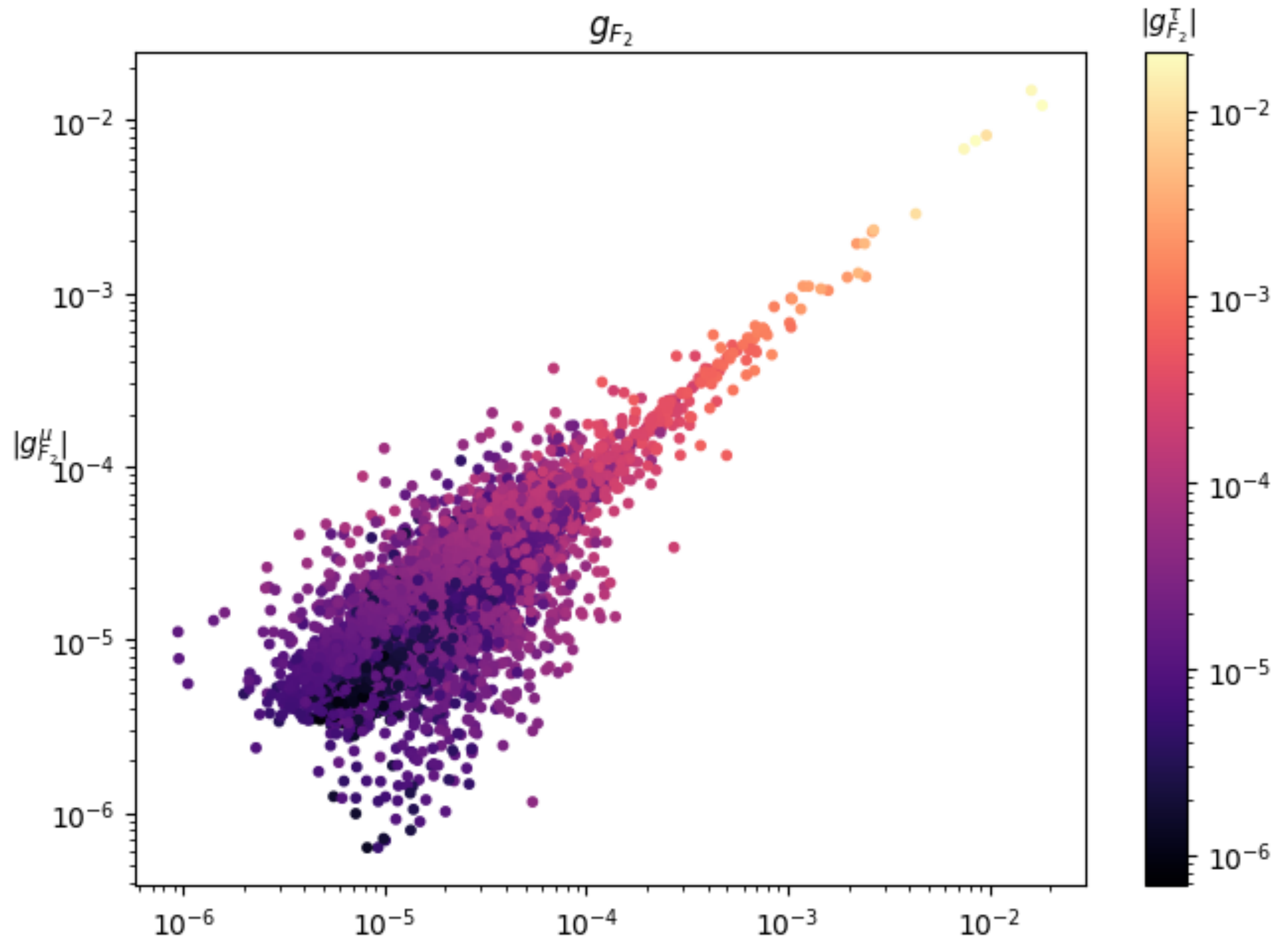


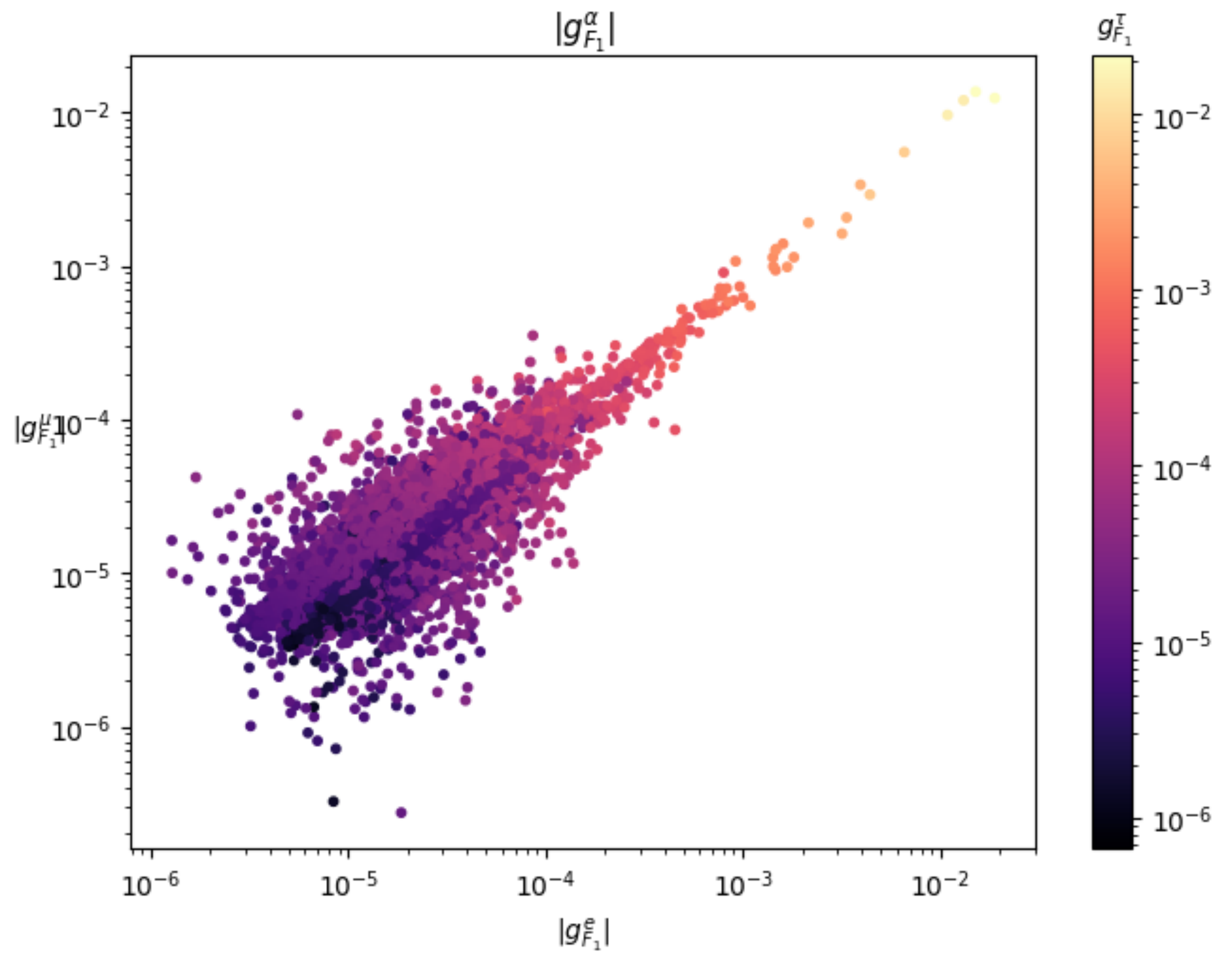
Parameter	Range	Parameter	Range
λ_H	$[0.1, 0.4]$	M_S^2, M_η^2	$[5\times10^5, 5\times10^6]$
$\lambda_{4S}, \lambda_{4\eta}$	$[10^{-7}, 1]$	M_1, M_2	$[100, 20000]$
$\lambda_{S\eta}, \lambda_S$	$\pm[10^{-3}, 1]$	M_ψ	$[700, 2000]$
$\lambda_\eta, \lambda_{\eta'}, \lambda_{\eta''}$	$\pm[10^{-3}, 1]$	$y_{11,12,21,22}$	$\pm[10^{-10}, 10^{-4}]$
α	$\pm[10, 10^4]$	m_{ν_1}	$[10^{-19}, 10^{-10}]$





Normal Ordering vs Inverse Ordering

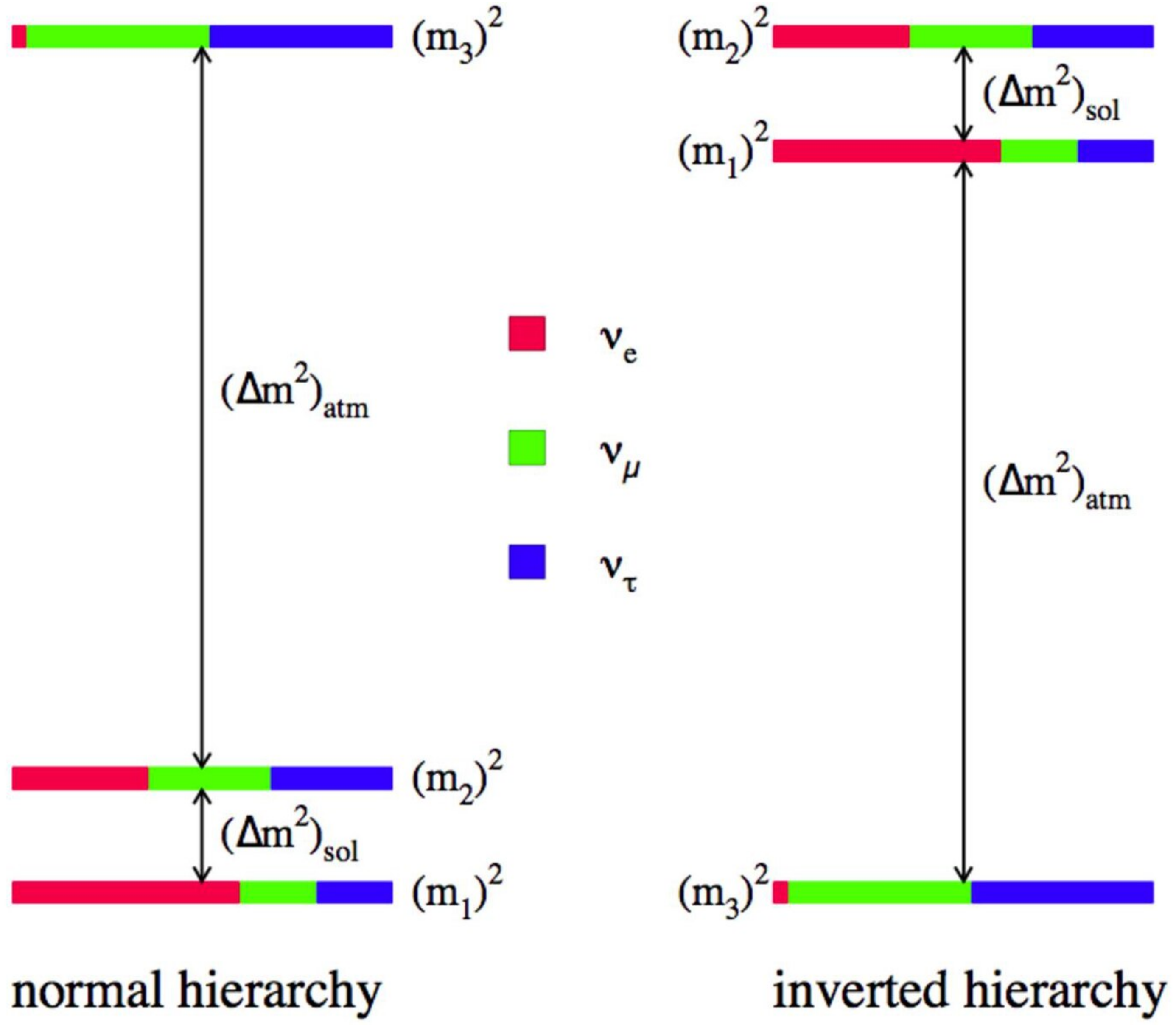




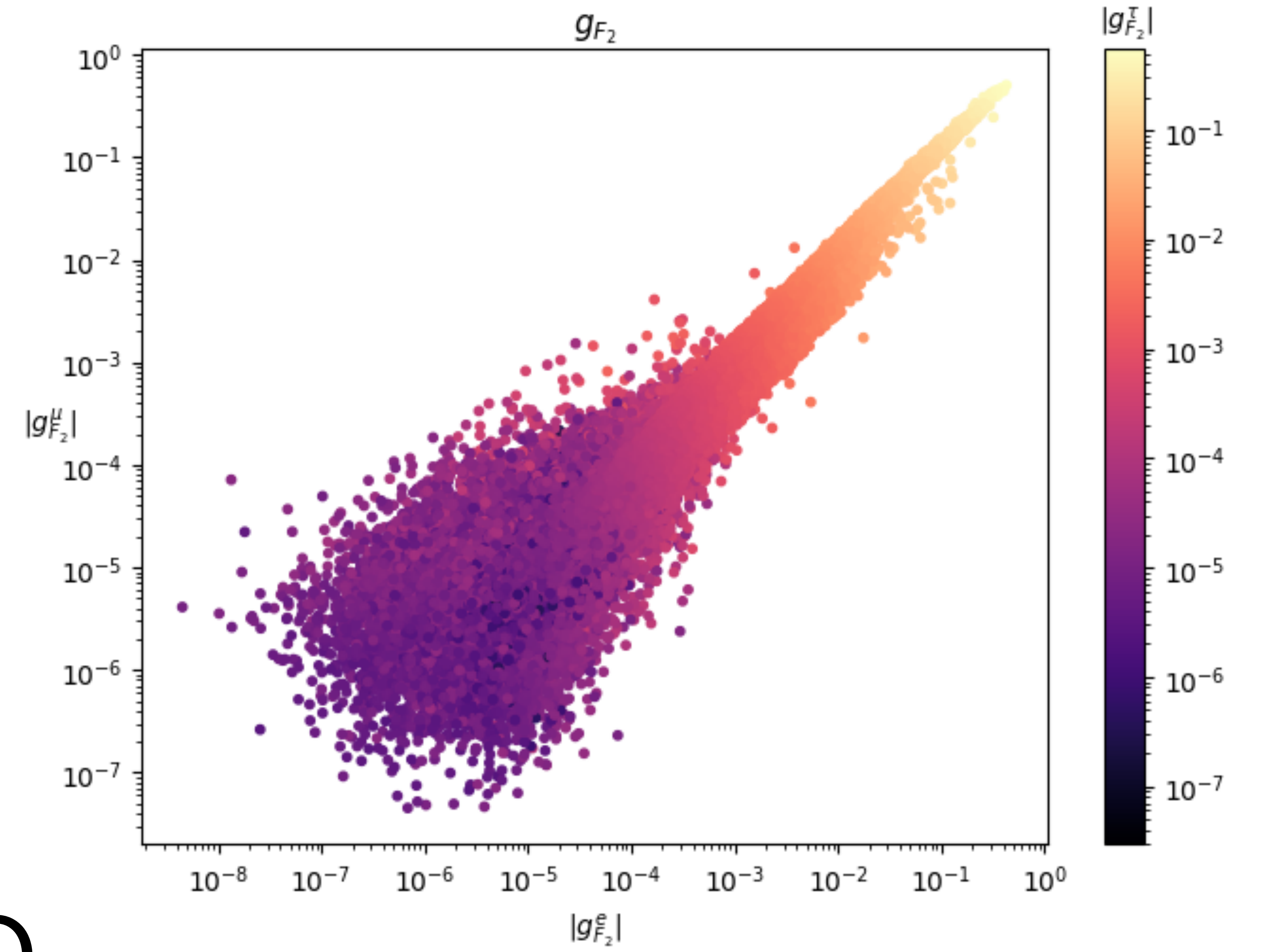
NO

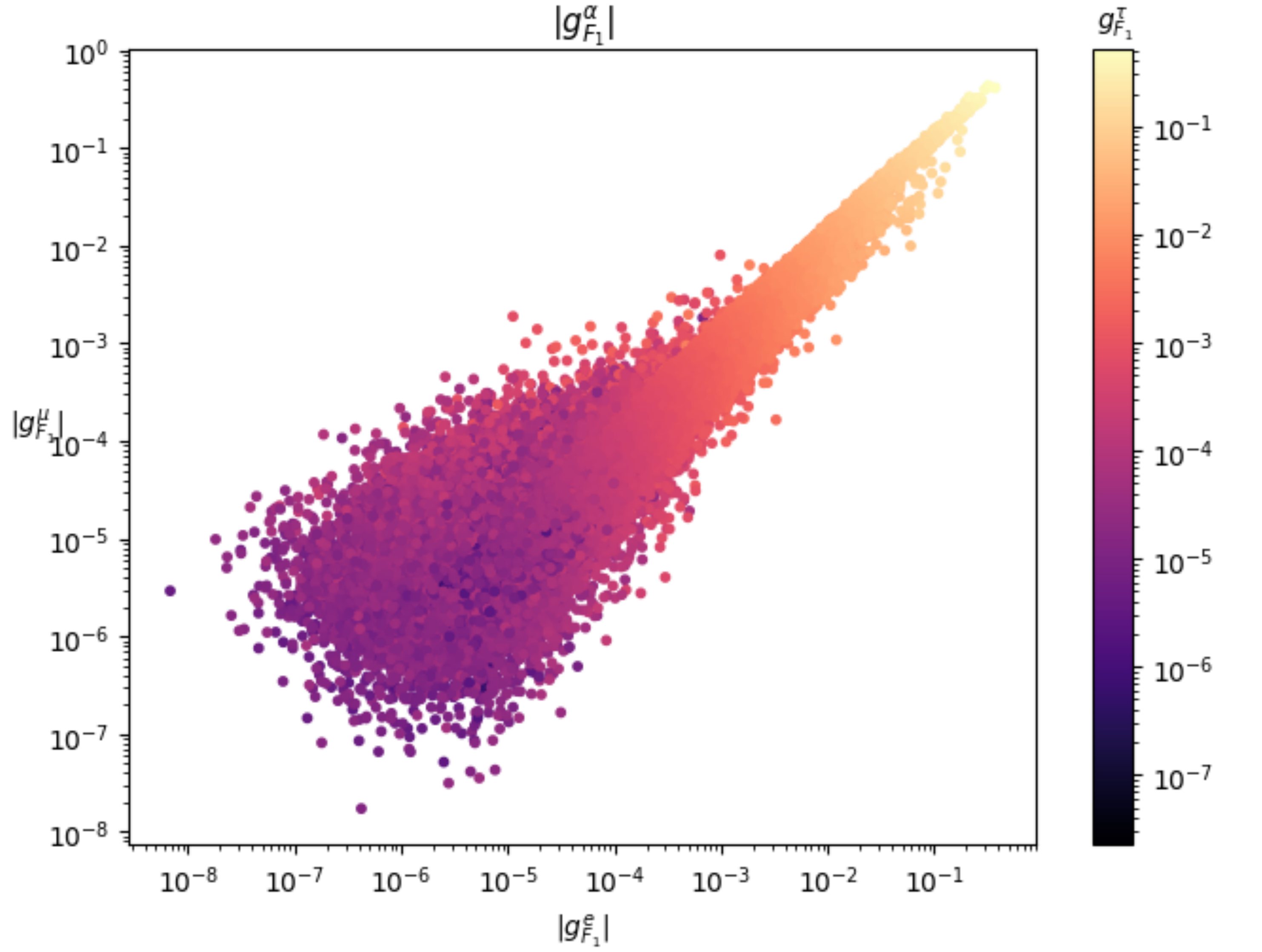
Less favoured high $\mathscr{G}_F$

Same phenomenology



IO



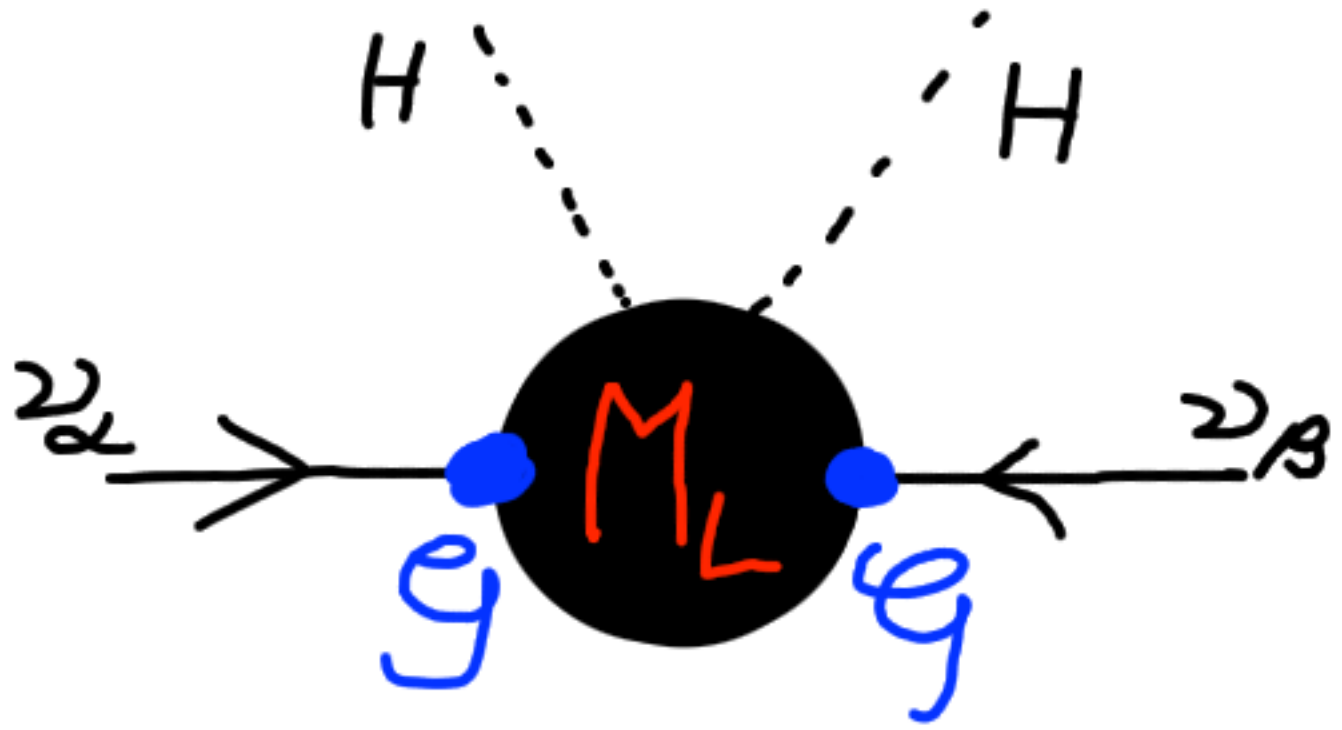


Casas-Ibara

→ **Links** $M_\nu^{\alpha\beta}$ to its experimental values through M_L , $\mathscr{G}$ and R a complex orthogonal matrix

→ **Use extra degrees of freedom** of R to **set** Δa_μ and **keep** $\ell_\alpha \to \ell_\beta \gamma$ under control

→ This **generates** a fine tuned $\mathscr{G}$ matrix and g_R^α vector as a byproduct



$$M_\nu = \mathscr{G}^T M_L \mathscr{G}$$

$$\mathscr{G} = U_L D_L^{-1/2} R D_\nu^{1/2} U^*_{\text{PMNS}}$$