

Unification with vector-like fermions

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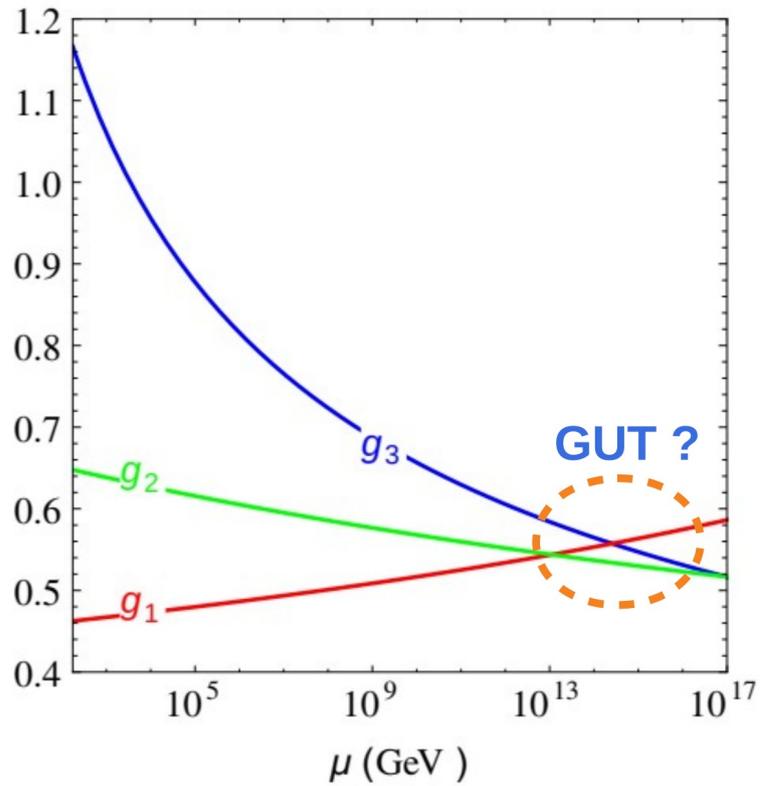
in collaboration with
D. Kumar, D. Rizzo, E. M. Sessolo

JHEP 1912 (2019) 094 (arXiv: 1910.00847)
and work in progress

Rencontres de Moriond
26.03.2025

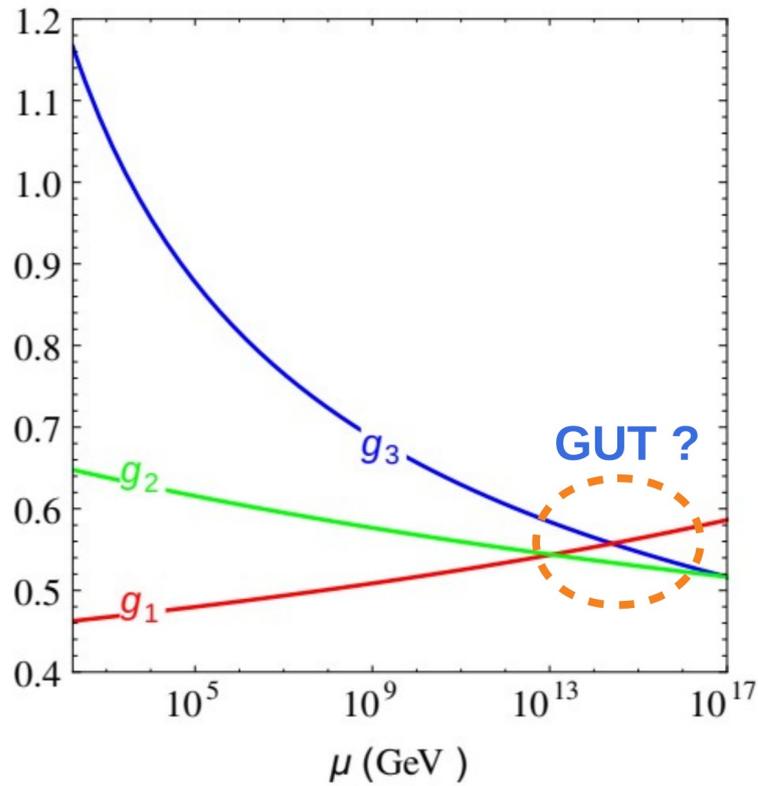
The new old story

Standard Model



The new old story

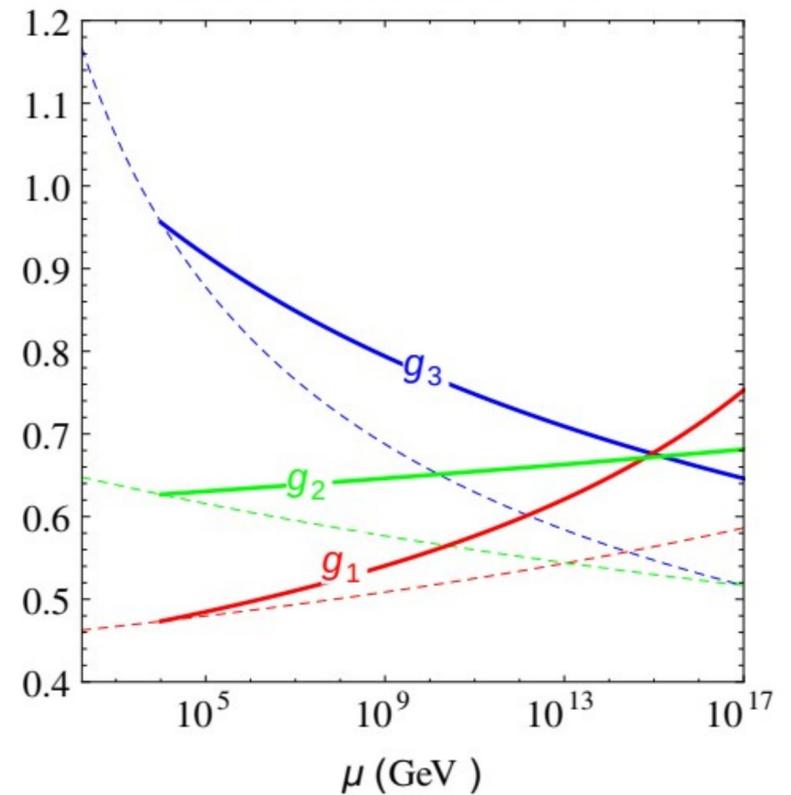
Standard Model



NP needed

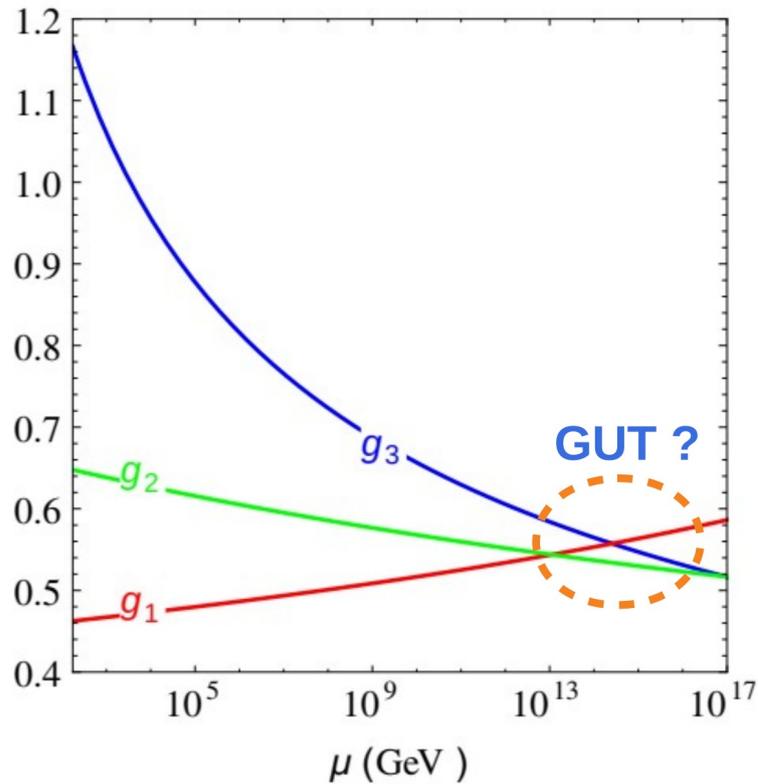


Standard Model + NP



The new old story

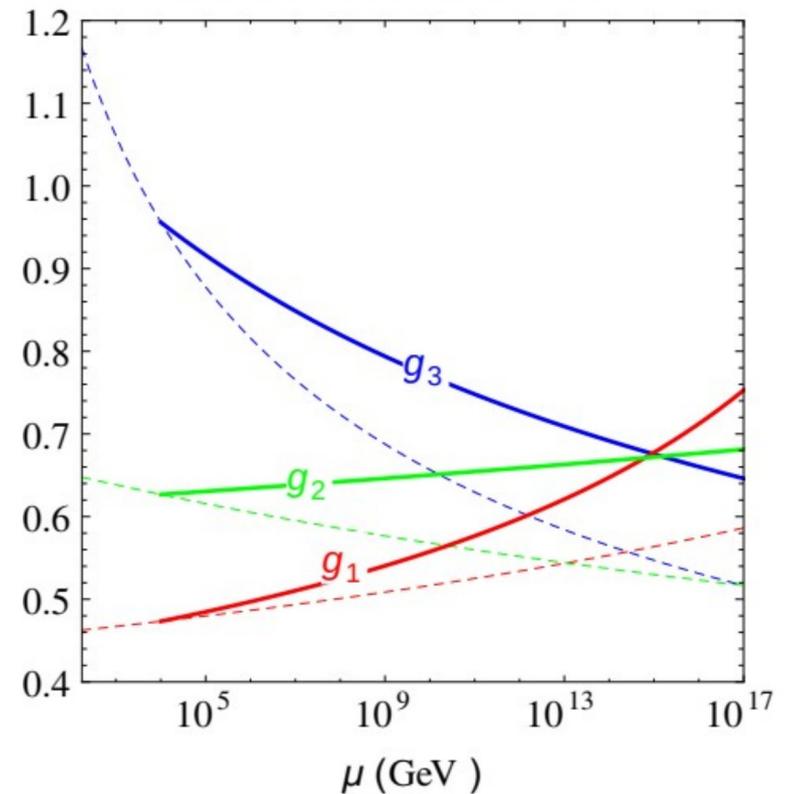
Standard Model



NP needed



Standard Model + NP



Our goal: classification of the BSM extensions with VL fermions and gauge unification

KK, D.Kumar, arXiv: 1910.00847
JHEP 12 (2019) 094

Analysis strategy

KK, D.Kumar, arXiv: 1910.00847

Some previous work:

T. G. Rizzo, Phys. Rev. D45 (1992) 3903–3905

B. Bhattacharjee, P. Byakti, A. Kushwaha, S. K. Vempati, JHEP 05 (2018) 090

Initial assumptions:

- NP = vector-like fermions (mass < 10 TeV)
- unification scale in the range 10^{15} - 10^{18} GeV
- $SU(5)$ -like GUT gauge symmetry
- perturbativity at the GUT scale

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24 distinct representations of $SU(3) \times SU(2) \times U(1)$

color singlets : $(\mathbf{1}, \mathbf{1}, 1), (\mathbf{1}, \mathbf{1}, -2), (\mathbf{1}, \mathbf{2}, \frac{1}{2}), (\mathbf{1}, \mathbf{2}, -\frac{3}{2}), (\mathbf{1}, \mathbf{3}, 0), (\mathbf{1}, \mathbf{3}, 1),$
 $(\mathbf{1}, \mathbf{4}, \frac{1}{2}), (\mathbf{1}, \mathbf{4}, -\frac{3}{2}),$

color triplets : $(\mathbf{3}, \mathbf{1}, -\frac{1}{3}), (\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}), (\bar{\mathbf{3}}, \mathbf{1}, \frac{4}{3}), (\bar{\mathbf{3}}, \mathbf{1}, -\frac{5}{3}), (\mathbf{3}, \mathbf{2}, \frac{1}{6}), (\bar{\mathbf{3}}, \mathbf{2}, \frac{5}{6}),$
 $(\bar{\mathbf{3}}, \mathbf{2}, -\frac{7}{6}), (\mathbf{3}, \mathbf{3}, -\frac{1}{3}), (\bar{\mathbf{3}}, \mathbf{3}, -\frac{2}{3}),$

color sextets : $(\bar{\mathbf{6}}, \mathbf{1}, -\frac{1}{3}), (\mathbf{6}, \mathbf{1}, -\frac{2}{3}), (\bar{\mathbf{6}}, \mathbf{2}, \frac{1}{6}), (\mathbf{6}, \mathbf{2}, \frac{5}{6}),$

color octets : $(\mathbf{8}, \mathbf{1}, 0), (\mathbf{8}, \mathbf{1}, 1), (\mathbf{8}, \mathbf{2}, \frac{1}{2}).$

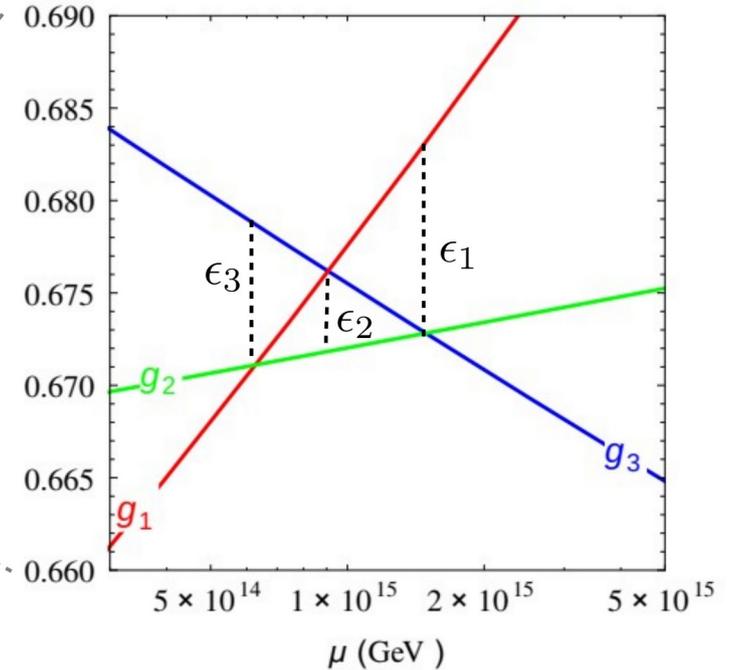
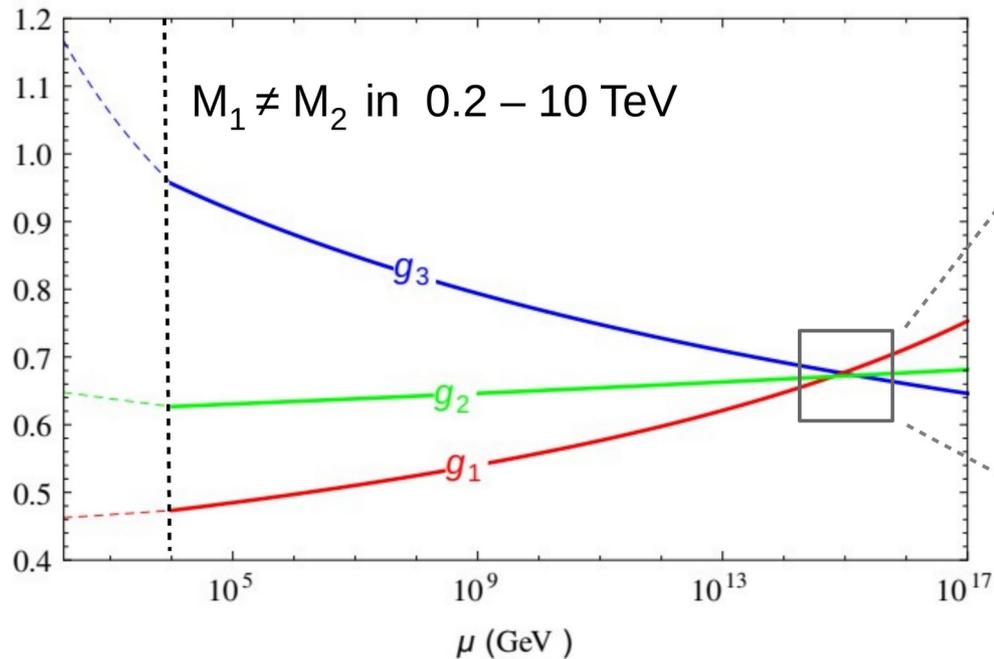
**our fundamental
building blocks**

Analysis strategy

note: no unification with 1 VL rep. (see, ex. Bhattacharjee et al. *JHEP 05 (2018) 90*)

2 VL rep: $SM + N_1 \times VL(R_1) + N_2 \times VL(R_2)$

KK, D.Kumar, arXiv: 1910.00847



precise gauge unification (PGU)

SM: $\epsilon=7\%$
MSSM: $\epsilon=1\%$

$$\epsilon \leq 1\%$$

$$\epsilon_k = \frac{g_k^2(M_{\text{GUT}}^{ij}) - g_{ij}^2}{g_{ij}^2}$$

$$\epsilon = \min(\epsilon_1, \epsilon_2, \epsilon_3)$$

goodness of unification

Summary of the results

Scenario	R_{F_1}	R_{F_2}	N_1	N_2
F1	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	12	2
F2	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	20	4
F3	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	22	4
F4	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, 0)$	8	1
F5	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, 0)$	12	2
F6	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, 0)$	14	2
F7	$(\mathbf{1}, \mathbf{3}, 0)$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	2	8
F8	$(\mathbf{1}, \mathbf{3}, 0)$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	3	12
F9	$(\mathbf{1}, \mathbf{3}, 0)$	$(\mathbf{6}, \mathbf{1}, -\frac{2}{3})$	3	2
F10	$(\mathbf{1}, \mathbf{4}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, -\frac{2}{3})$	2	4
F11	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	2	2
F12	$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	4	4
F13	$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	6	6

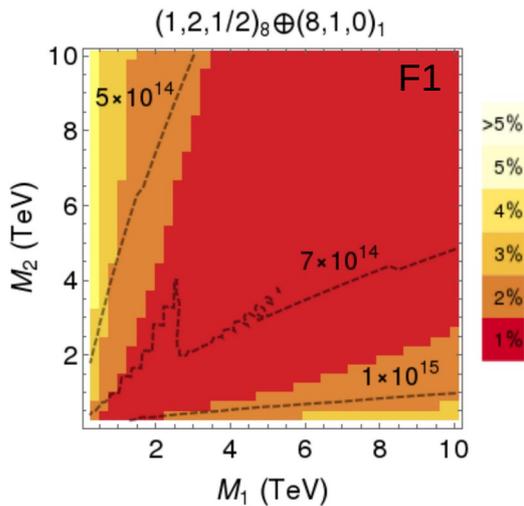
276 initial models



7 PGU models

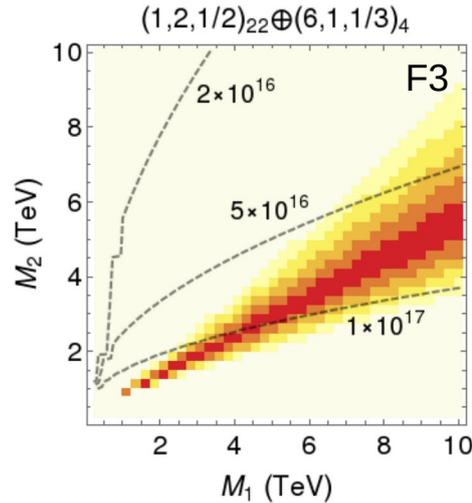
Probing the PGU models

GUT scale → Proton decay



low

$$M_{\text{GUT}} \simeq 10^{15} \text{ GeV}$$



moderate/high

$$M_{\text{GUT}} \sim 10^{16} - 10^{17} \text{ GeV}$$

Scenario	\mathbf{R}_{F_1}	\mathbf{R}_{F_2}	N_1	N_2
F1	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	12	2
F2	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	20	4
F3	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	22	4
F4	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, \mathbf{0})$	8	1
F5	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, \mathbf{0})$	12	2
F6	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, \mathbf{0})$	14	2
F7	$(\mathbf{1}, \mathbf{3}, \mathbf{0})$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	2	8
F8	$(\mathbf{1}, \mathbf{3}, \mathbf{0})$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	3	12
F9	$(\mathbf{1}, \mathbf{3}, \mathbf{0})$	$(\mathbf{6}, \mathbf{1}, \frac{2}{3})$	3	2
F10	$(\mathbf{1}, \mathbf{4}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, -\frac{2}{3})$	2	4
F11	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	2	2
F12	$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	4	4
F13	$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	6	6

SK

HK

EXCLUDED

- unification possible for a wide range of masses
- excluded or to be excluded by the **proton decay** measurements at SK/HK

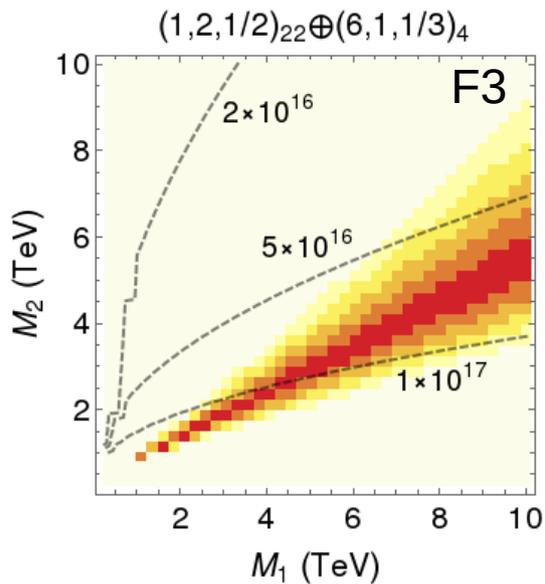
$$\tau_p^{\text{SK}} > 1.6 \times 10^{34} \text{ years}$$

- compressed / hierarchical spectrum

$$\tau_p^{\text{HK}} > 2 \times 10^{35} \text{ years}$$

Probing the PGU models

GUT scale → Proton decay



unification scale decreases
when VL mass increases



$$\tau_p = \left(\frac{4\pi}{g_{\text{GUT}}^2} \right)^2 \left(\frac{M_{\text{GUT}}}{\text{GeV}} \right)^4 \times 2.0 \times 10^{-32}$$

for $g_{\text{GUT}}=0.7$

$$M_{\text{GUT}} = 10^{15} \text{ GeV} \rightarrow \tau_p = 1.3 \times 10^{31} \text{ years}$$

$$M_{\text{GUT}} = 10^{16} \text{ GeV} \rightarrow \tau_p = 1.3 \times 10^{35} \text{ years}$$

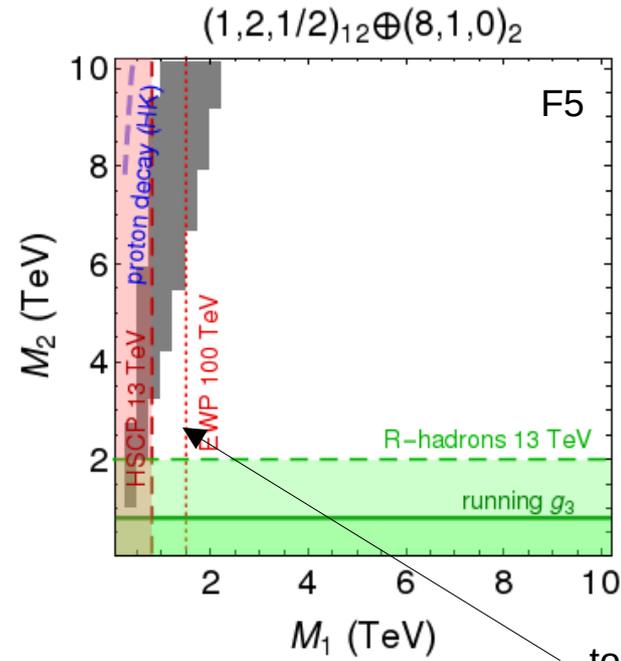
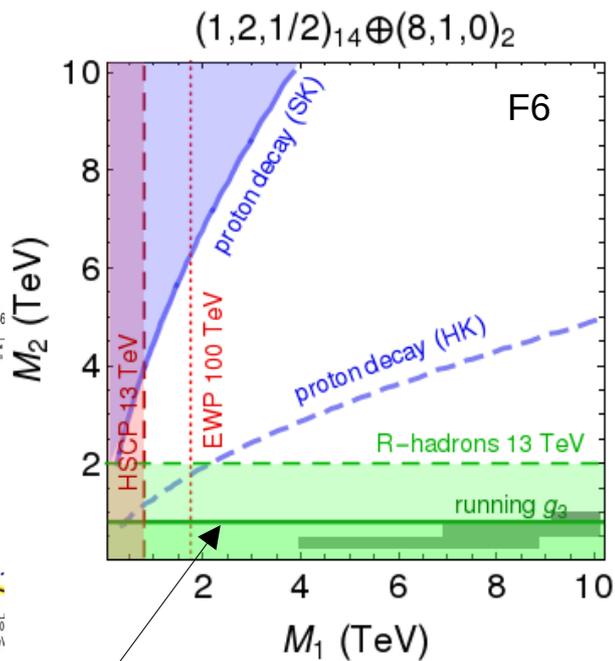
Model	Proton decay	
	M_1^{max}	M_2^{max}
F1	Excluded	
F2	25	180
F3	350	200
F4	Excluded	
F5	10	50
F6	500	50
F7	20	100
F8	2×10^5	5×10^5
F9	Excluded HK	
F10	250	1000
F11	600	200
F12	6×10^4	400
F13	-	2×10^6

masses
in TeV

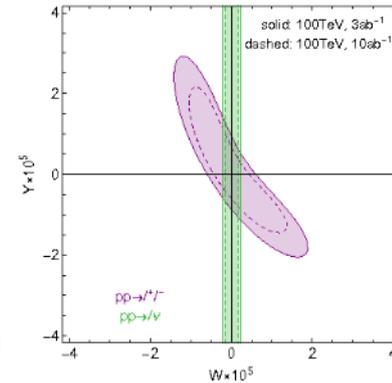
upper bounds on VL mass

Probing the PGU models

Mass hierarchy → running couplings, EW precision



See M. Farina, G. Panico, D. Pappadopulo, J. T. Ruderman, R. Torre, A. Wulzer, PLB '17 for the FCC limits



to be probed by the EWP tests

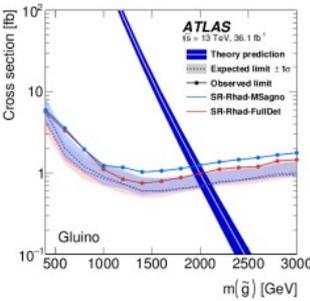
almost excluded by running g_3

Does not depend on Yukawa/scalar sectors

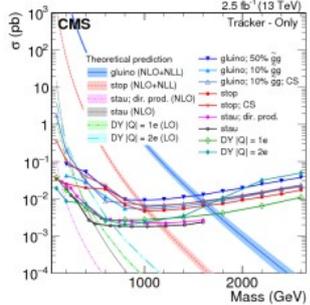
Probing the PGU models

Mass hierarchy → R hadrons, HSCP searches

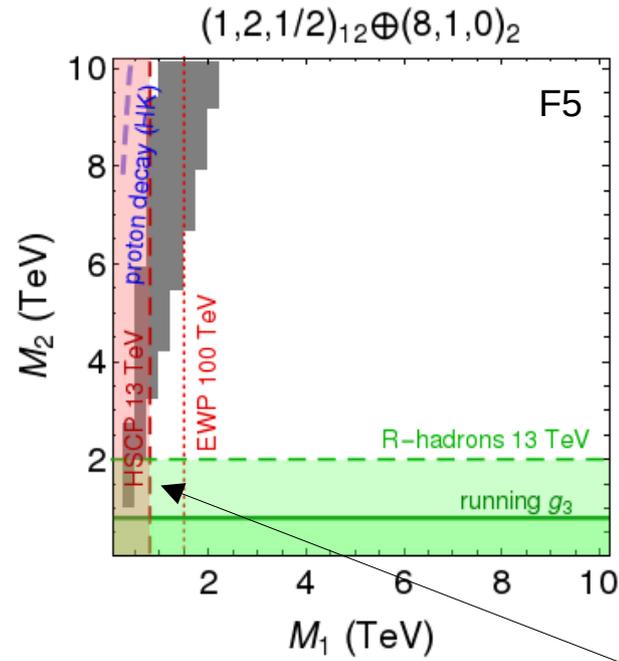
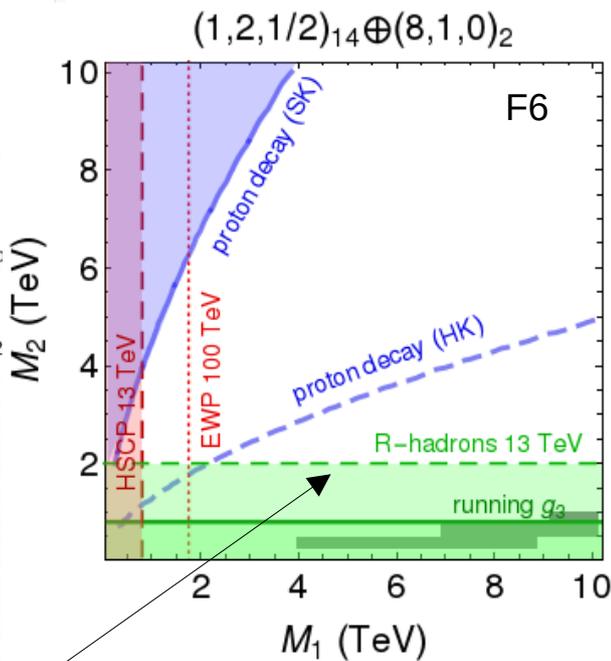
ATLAS
Phys. Rev. D99 no. 9, (2019) 092007



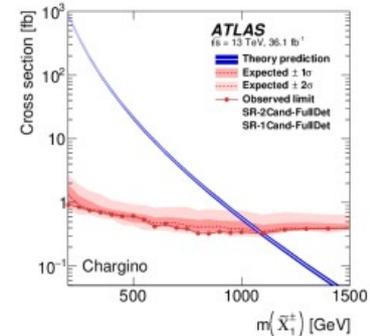
CMS
Phys. Rev. D94 no. 11, (2016) 112



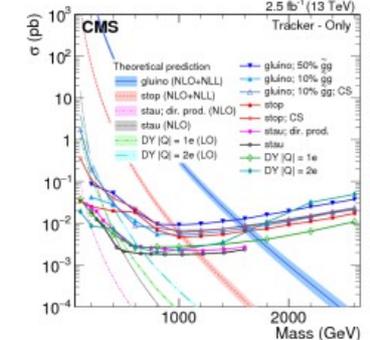
R-hadrons



ATLAS
Phys. Rev. D99 no. 9, (2019) 092007



CMS
Phys. Rev. D94 no. 11, (2016) 11200

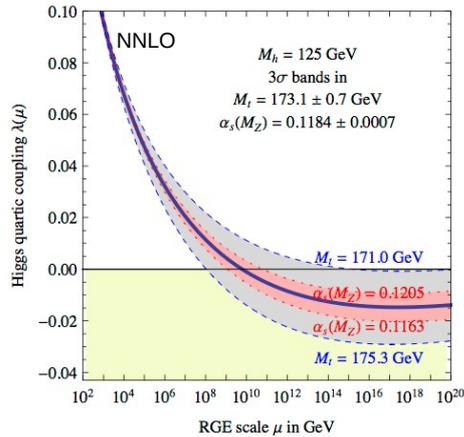


lepton-like

Assumption: no Yukawa interactions

Vacuum stability in PGUs

G. Degrandi, S. Di Vita, J. Elias-Miró, J. Espinosa, G. Giudice, G. Isidori, A. Strumia, *J. High Energ. Phys.* 2012, 98 (2012)



SM vacuum is metastable



stability can be restored in BSM

ex. with VL fermions

Gopalakrishna, Velusamy, *PRD* 99 (2019),
Arsenault et al. *PRD* 107 (2023), Hiller et al.
arXiv: 2401.08811, Adhikary et al. *ArXiv: 2406.16050*... many more

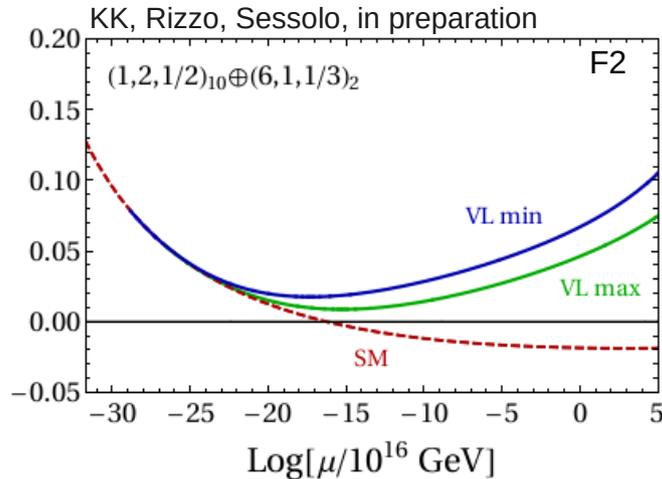
$$16\pi^2 \beta(\lambda) = 24\lambda^2 + \frac{3}{8}g_Y^4 + C\lambda y_{\text{BSM}}^2 - 6y_t^4 - B y_{\text{BSM}}^4 + f(g_Y, g_2, \lambda)$$

no BSM Yukawa interactions

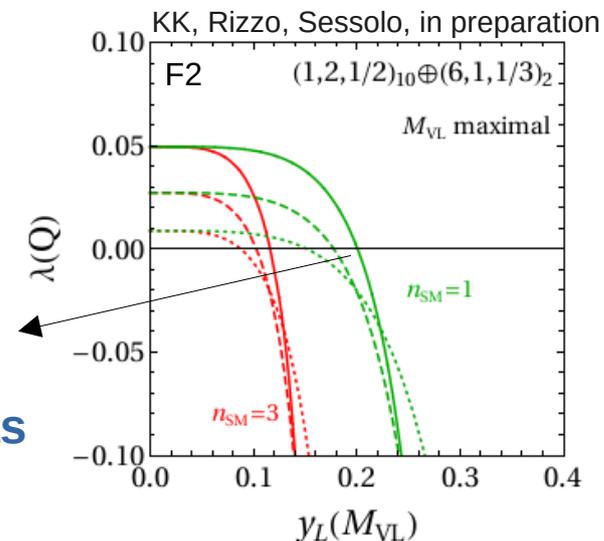
vacuum gets stabilized

with BSM Yukawa interactions

vacuum gets destabilized



**Upper bound on the BSM Yukawas
~ 0.1 - 0.3**



Other scalars?

In SU(5): $\mathcal{L}_{\text{Yuk}} = Y_d \bar{\mathbf{5}} \times \mathbf{10} \times \bar{\mathbf{5}}_{\text{H}} + Y_u \mathbf{10} \times \mathbf{10} \times \mathbf{5}_{\text{H}}$ } Higgs doublet
color triplet

Scalars can emerge naturally in GUTs

- **SU(5)**

$$24, 75 \supset (1, 1)_0 \quad \longrightarrow \quad \text{singlet S}$$

- **SU(6)** (and larger)

$$\mathcal{L}_{\text{Yuk}} = Y_{15} \mathbf{15} \times \mathbf{15} \times \mathbf{15}^{H_1} + Y_6 \mathbf{15} \times \bar{\mathbf{6}} \times \bar{\mathbf{6}}^{H_2} \quad \longrightarrow \quad \text{2HDM}$$

$$SU(6) \rightarrow SU(5) \times U(1)_5$$

$$\mathbf{6} = \mathbf{1}_{-5} + \mathbf{5}_1 \quad \longrightarrow \quad \text{singlet S + U(1)'}$$

Complementary signals with scalars?

Other scalars?

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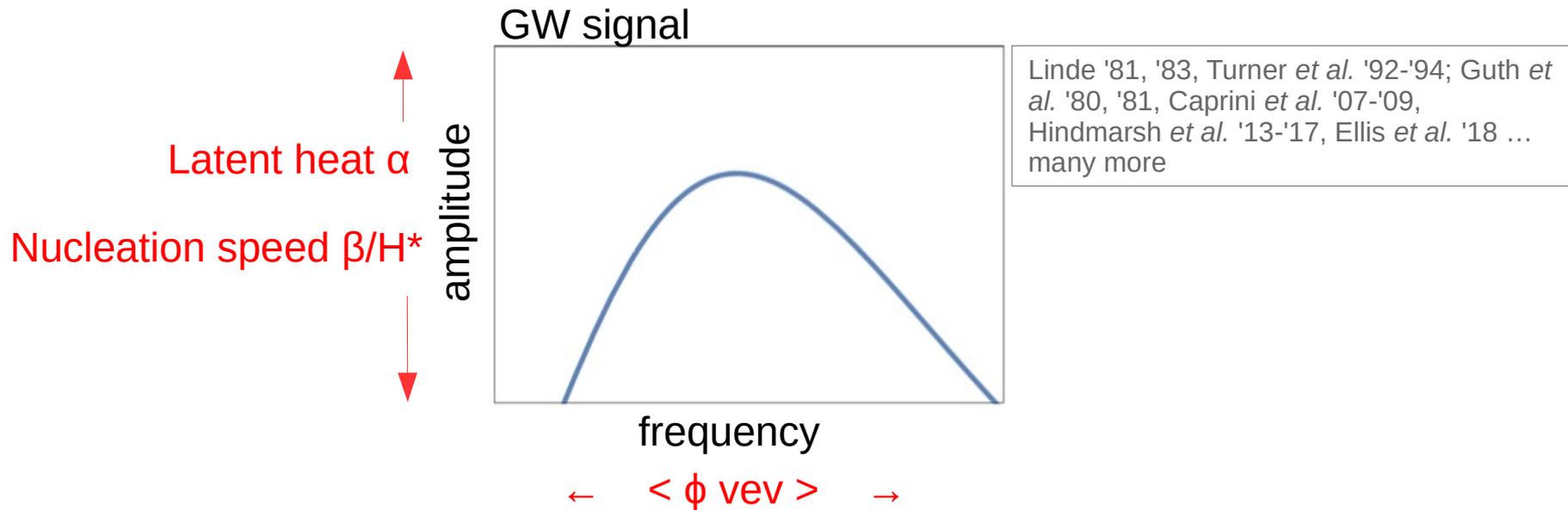
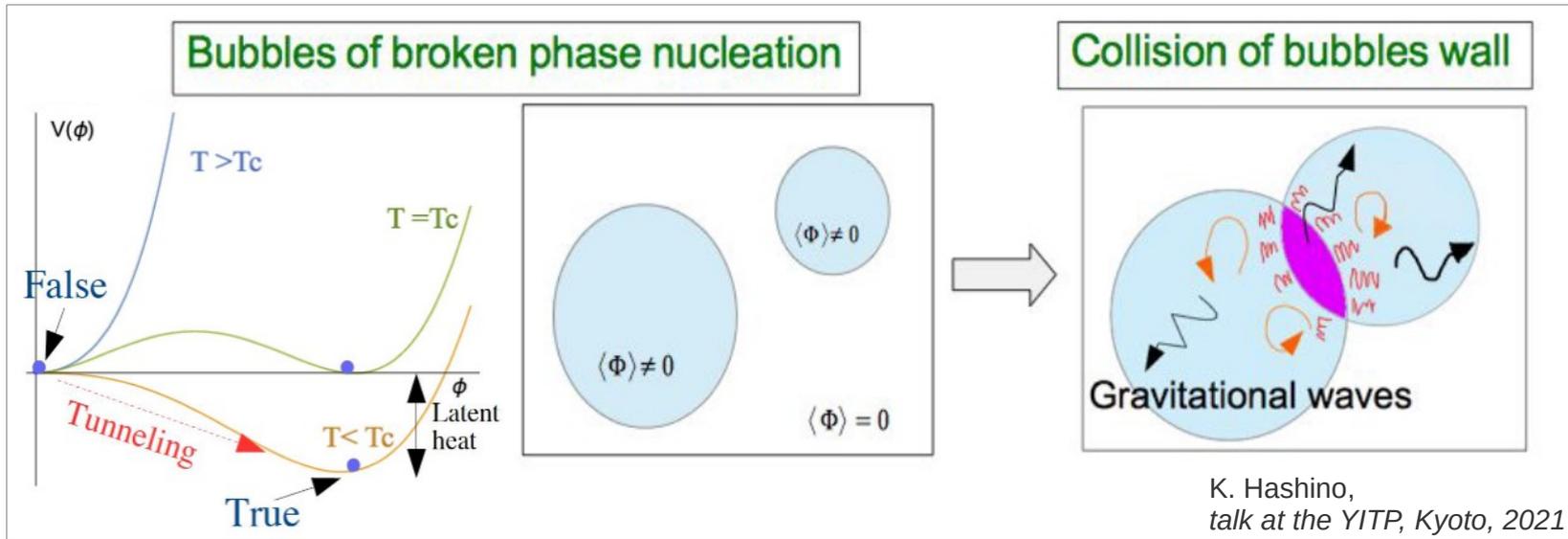
$$SU(6) \rightarrow SU(5) \times U(1)_5$$

$$\mathbf{6} = \mathbf{1}_{-5} + \mathbf{5}_1 \quad \longrightarrow \quad \text{singlet S + U(1)'}$$

Complementary signals with scalars?

First order phase transition... Gravitational waves...

Gravitational waves from FOPT



Gravitational waves in PGUs

singlet scalar + U(1)_x

scalar potential

$$V(H, S) = \lambda_1 (H^\dagger H)^2 + \lambda_2 (S^\dagger S)^2 + \lambda_3 (H^\dagger H) (S^\dagger S)$$

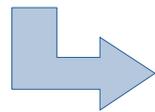
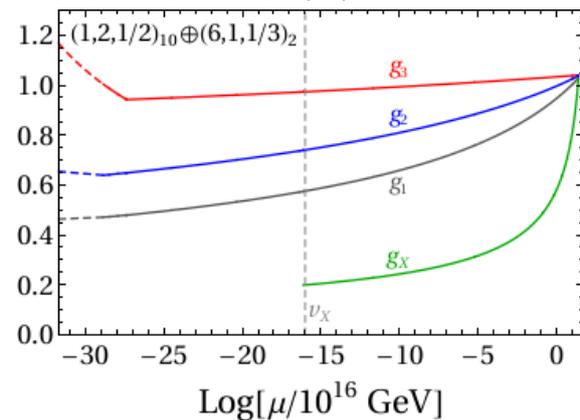
$$Q_S = 2, \quad \phi = \sqrt{2} \text{Re}(S)$$

symmetry breaking through CW:

$$V(\phi) = \frac{1}{4} \lambda_2(t) \phi^4 + \frac{1}{128 \pi^2} [20 \lambda_2^2(t) + 96 g_X^4(t)] \phi^4 \left(-\frac{25}{6} + \ln \frac{\phi^2}{\mu^2} \right)$$

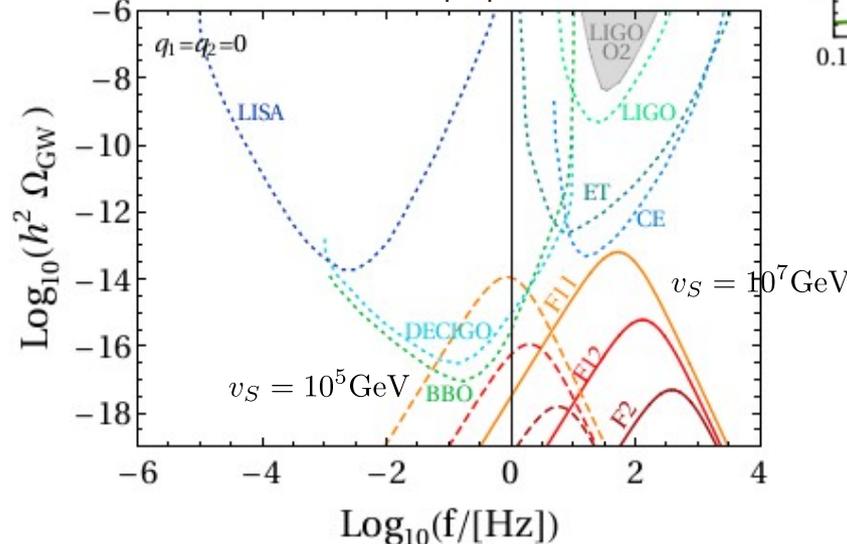
PGU: unification condition fixes g_x at every scale

KK, Rizzo, Sessolo, in preparation



VL not charged under U(1)_x

KK, Rizzo, Sessolo, in preparation

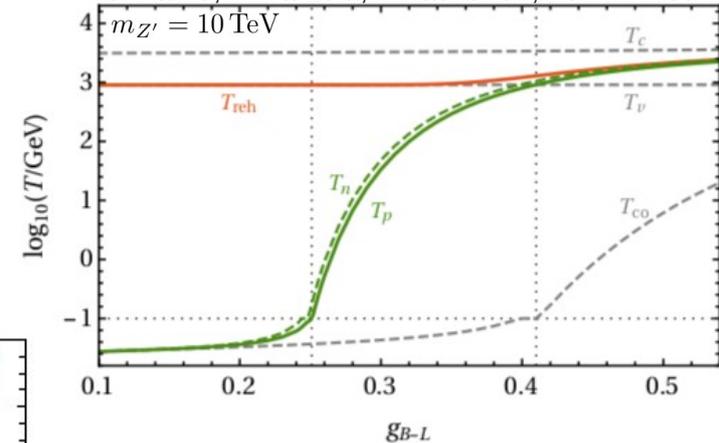


U(1)_x=U(1)_{B-L}

Ellis et al. JCAP 06 (2019), Jinno, Takimoto PRD 95 (2017), Okada, Seto PRD 98 (2018), Marzo et al. EPJC 79 (2019), Hasegawa et al. PRD 99 (2019), Haba, Yamada PRD 101 (2020)... many more

strength of the GW signal given by g_x

C.Marzo, L.Marzola, V.Vaskonen, 1811.11169



GW signal fixed for each PGU model

Conclusions

- Only a **few models** with VL fermions allow for **precise gauge coupling unification**.
- **Upper bounds** on VL masses from **proton decay**.
- **Upper bounds** on the BSM **Yukawa couplings** from the EW **vacuum stability**.
- Possible **discriminative power in gravitational waves** for scenarios with an extra gauge $U(1)_X$.