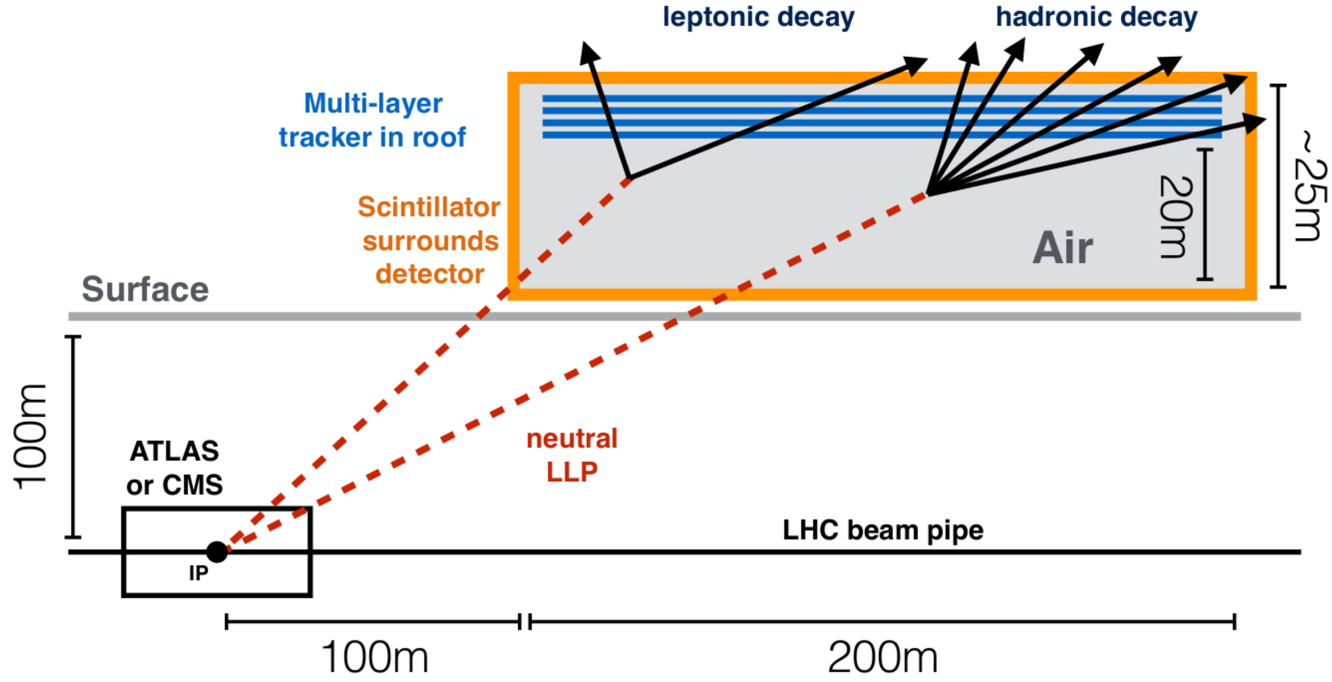
New physics with beam dump experiments

Mikael Chala (IPPP)

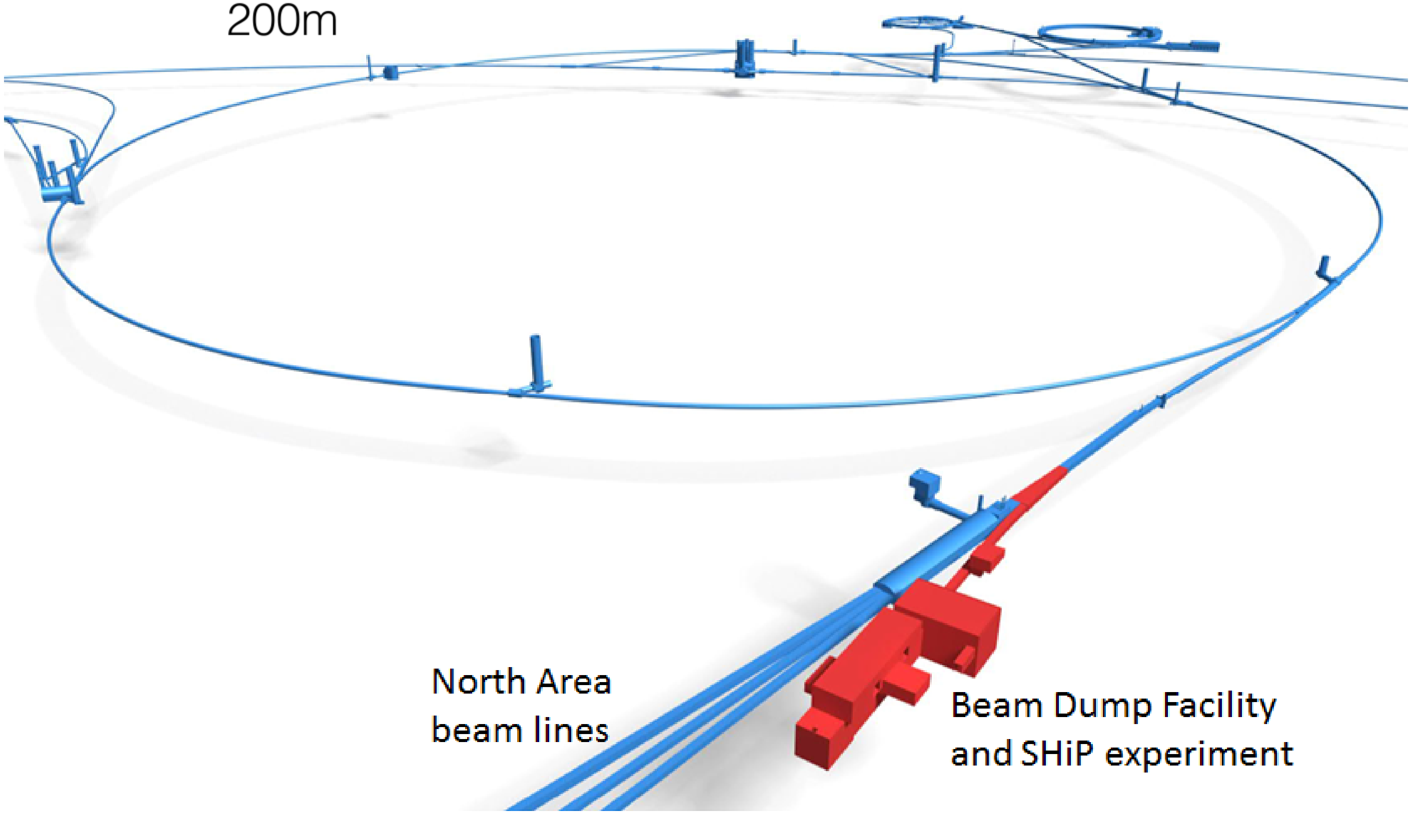
Based mainly on The SHiP physics case, *1504.04855*;

The MATHUSLA Physics Case, *1806.07396*.



MATHUSLA

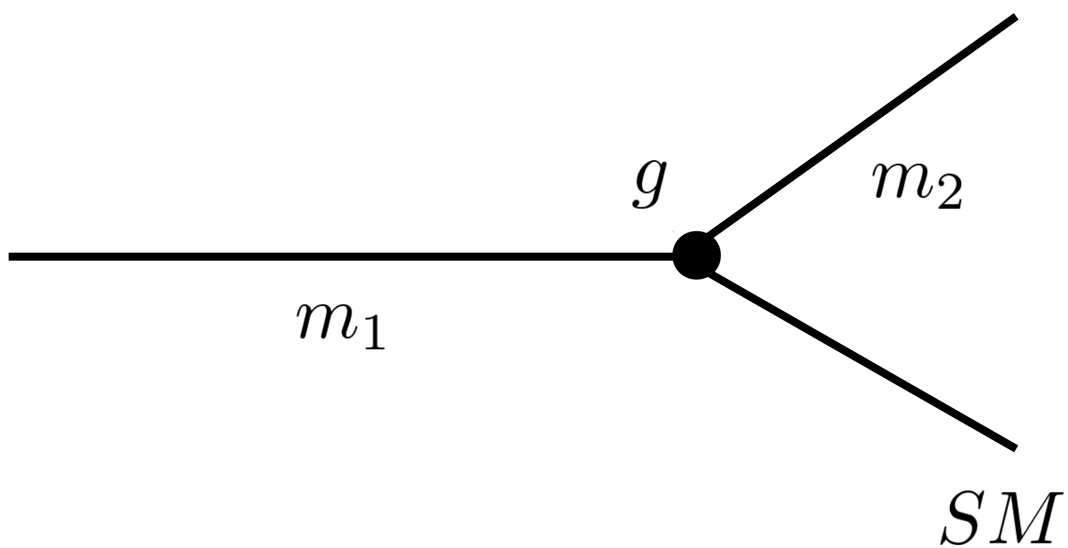
SHiP



Disclaimer

- LLPs (proper lifetime of order meter) everywhere, provided small coupling (from **effective operators, violating accidental symmetry**, etc.) and/or similar mass (**same multiplet of some *G***). As usual as in the SM (e.g. neutron)

- I will focus only on classes of models solving the SM main problems

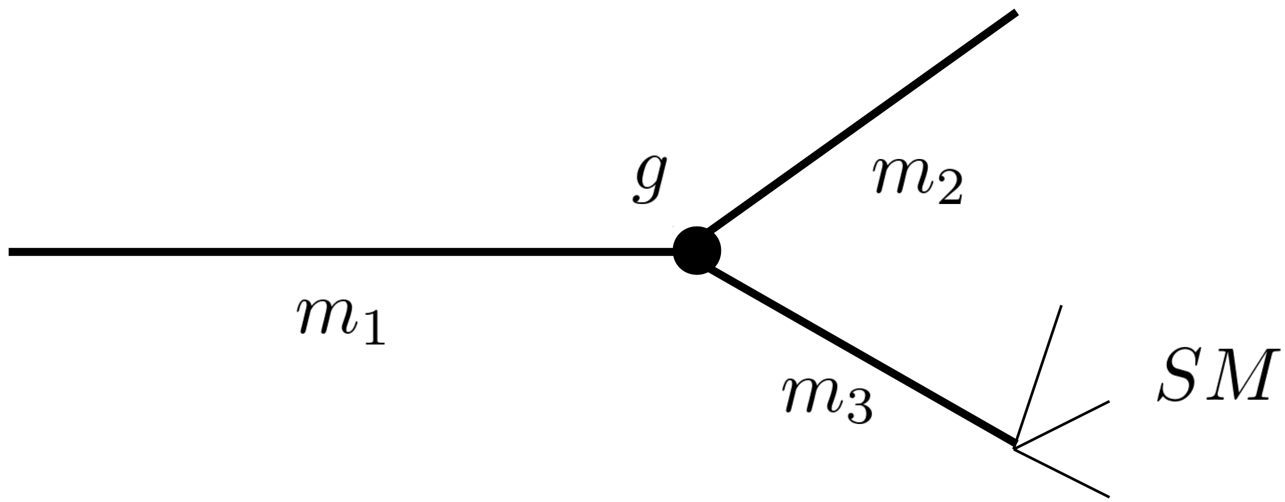


$$\Gamma \sim g^2 m_1 \sqrt{1 - \frac{m_2^2}{m_1^2}}$$

Disclaimer

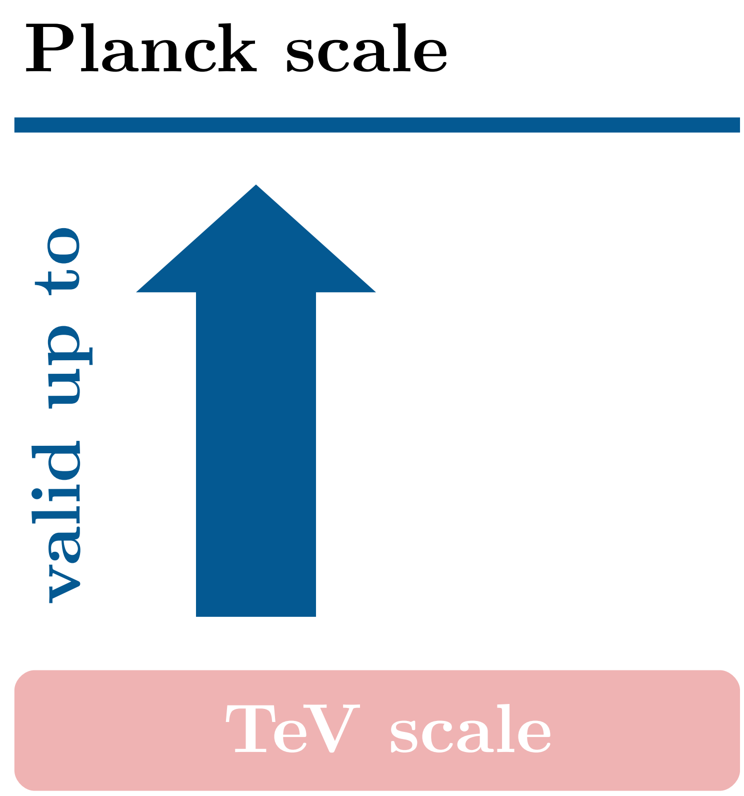
- LLPs (proper lifetime of order meter) everywhere, provided small coupling (from **effective operators, violating accidental symmetry**, etc.) and/or similar mass (**same multiplet of some *G***). As usual as in the SM (e.g. neutron)

- I will focus only on classes of models solving the SM main problems



$$\Gamma \sim g^2 \frac{\Delta m_{12}^5}{m_3^4}$$

The Standard Model is very strong, but it cannot explain all observations



Guideline for models predicting LLPs

- Hierarchy problem (SUSY and composite Higgs models)

- Neutrino masses

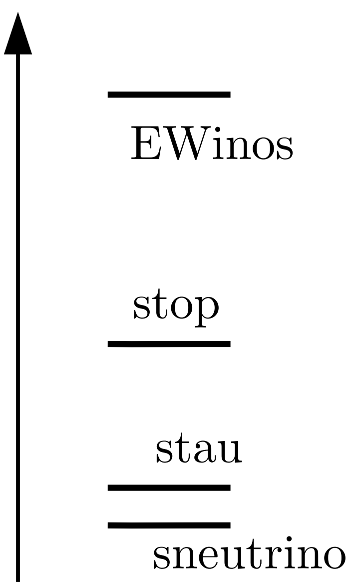
- Dark matter

- The Standard Model itself (as an effective field theory)

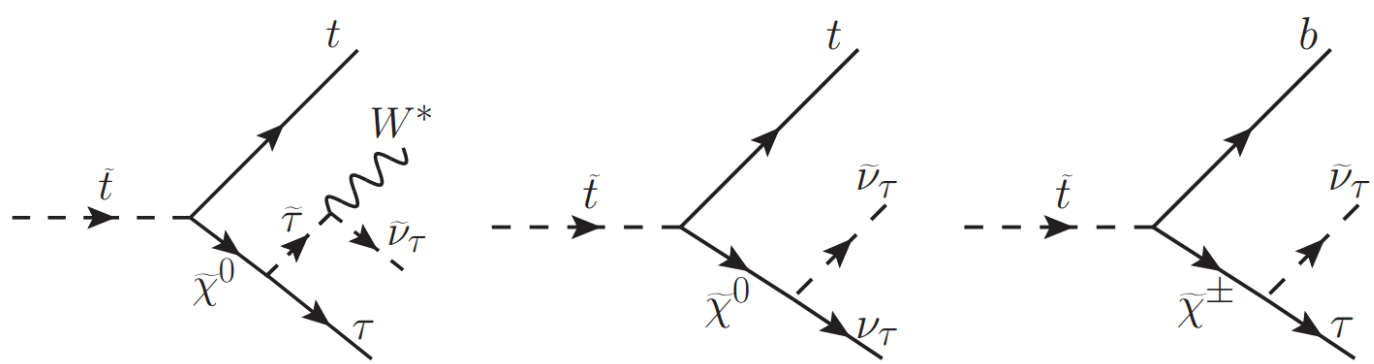
Supersymmetry

- We do not how SUSY is broken. Gauge-mediated SUSY breaking predicts a **spectrum very different** from the one assumed in most LHC searches

- **Limits** on stop mass (fine-tuning) can be **very weak**



$$m_{1/2}^2/m_0^2 \sim N f(F/M^2)$$



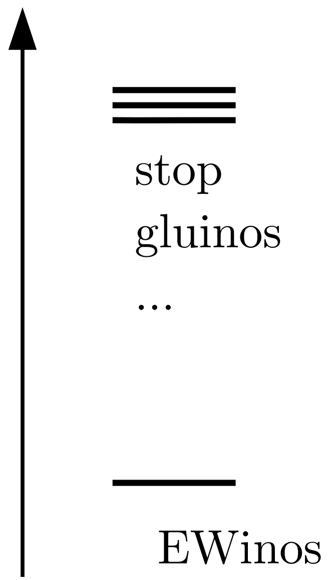
$$m_{\tilde{t}} > 350 \text{ GeV}$$

[**MC**, Delgado, Nardini, Quirós, 1702.07359]

Supersymmetry

- We do not how SUSY is broken. Gauge-mediated SUSY breaking predicts a **spectrum very different** from the one assumed in most LHC searches

- **Limits** on stop mass (fine-tuning) can be **very weak**



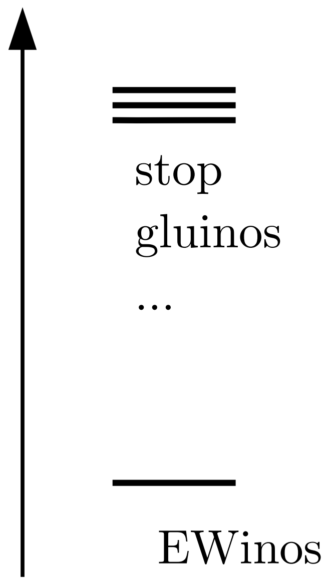
$$m^2_{1/2}/m^2_0 \sim N f(F/M^2)$$

It resembles split SUSY, LHC bounds not larger than 1 TeV

Supersymmetry

- We do not how SUSY is broken. Gauge-mediated SUSY breaking predicts a **spectrum very different** from the one assumed in most LHC searches

- **Limits** on stop mass (fine-tuning) can be **very weak**

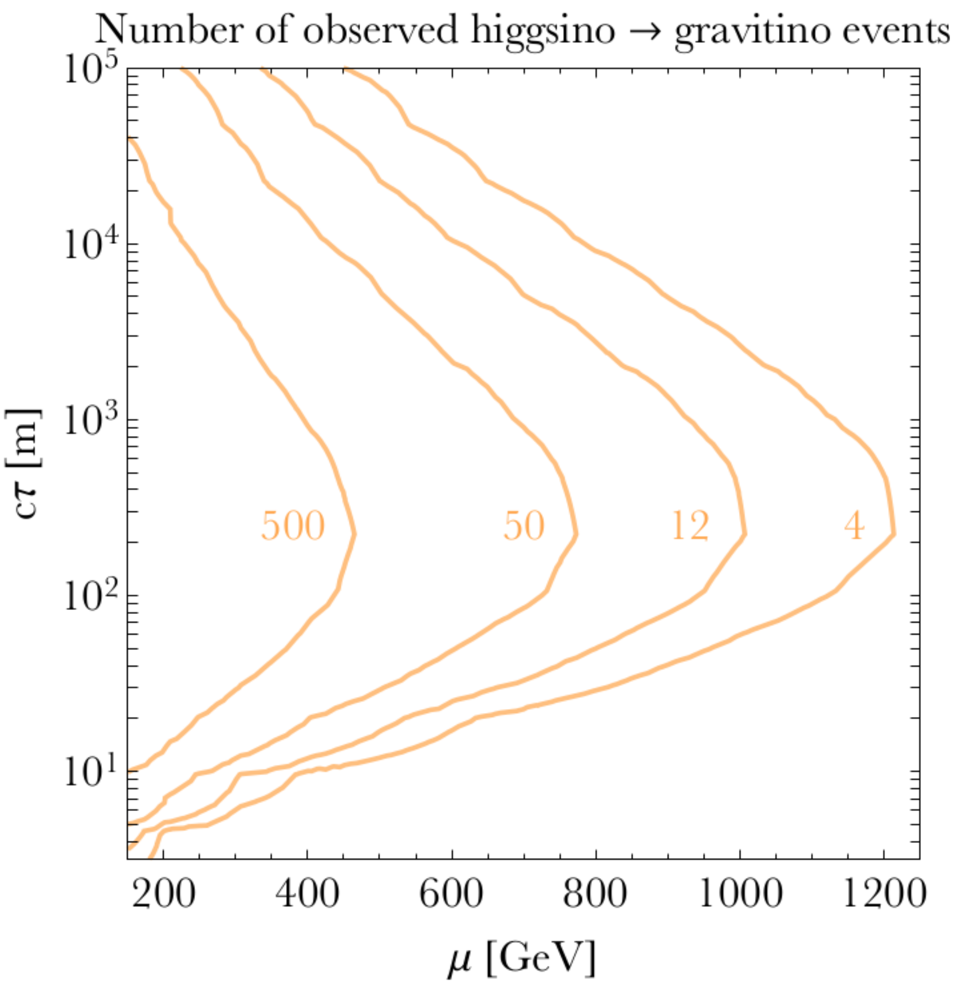


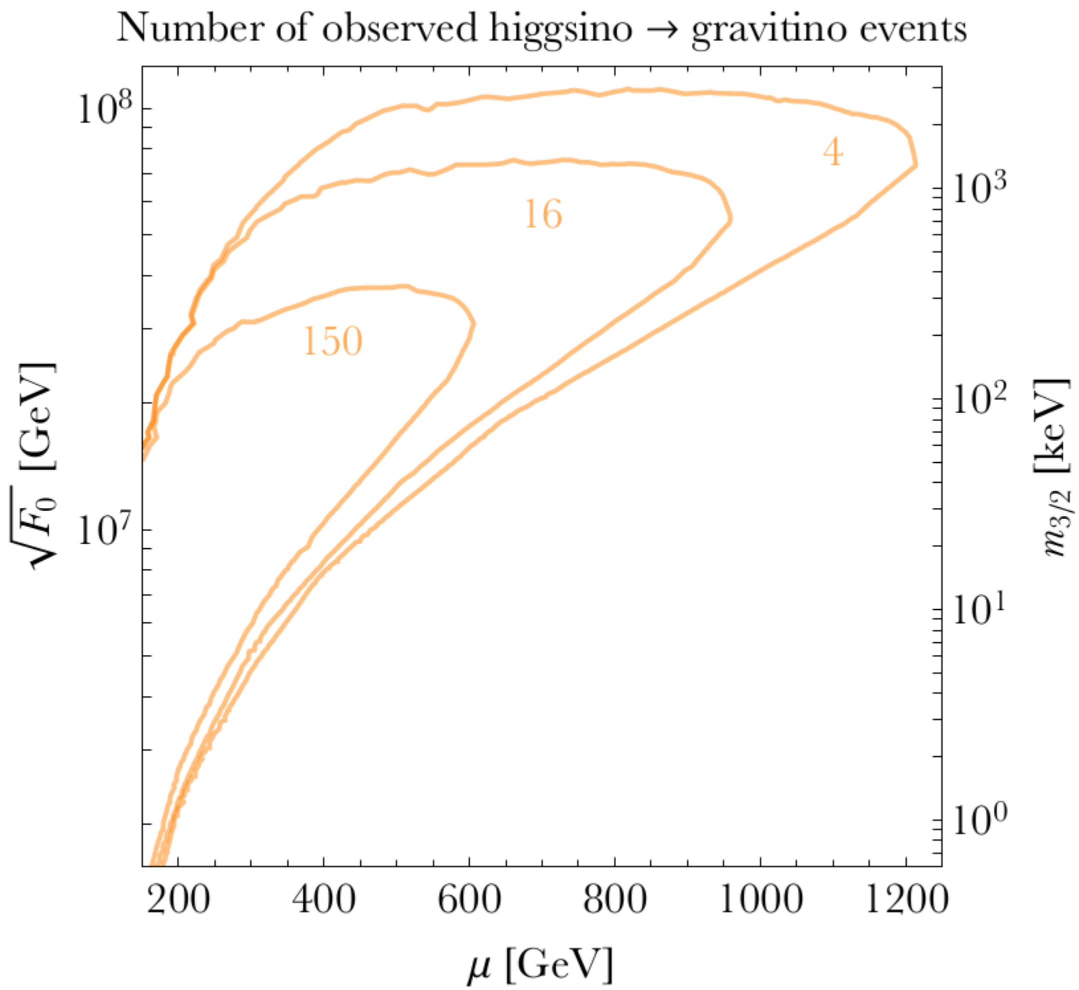
$$m^2_{1/2}/m^2_0 \sim N f(F/M^2)$$

It resembles split SUSY, LHC bounds not larger than 1 TeV

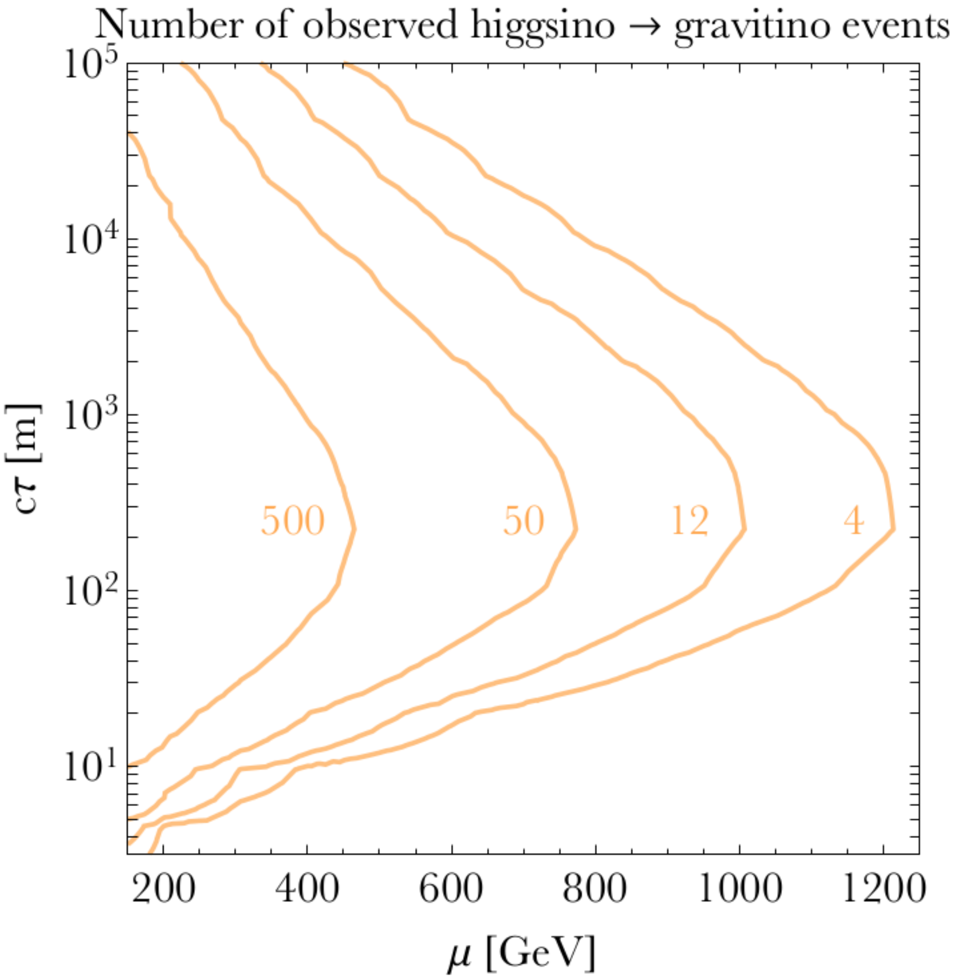
$$c\tau(\widetilde{\chi}^0_1 \to \widetilde{G} + \mathrm{SM}) = \frac{16\pi F_0^2}{m_\chi^5}$$

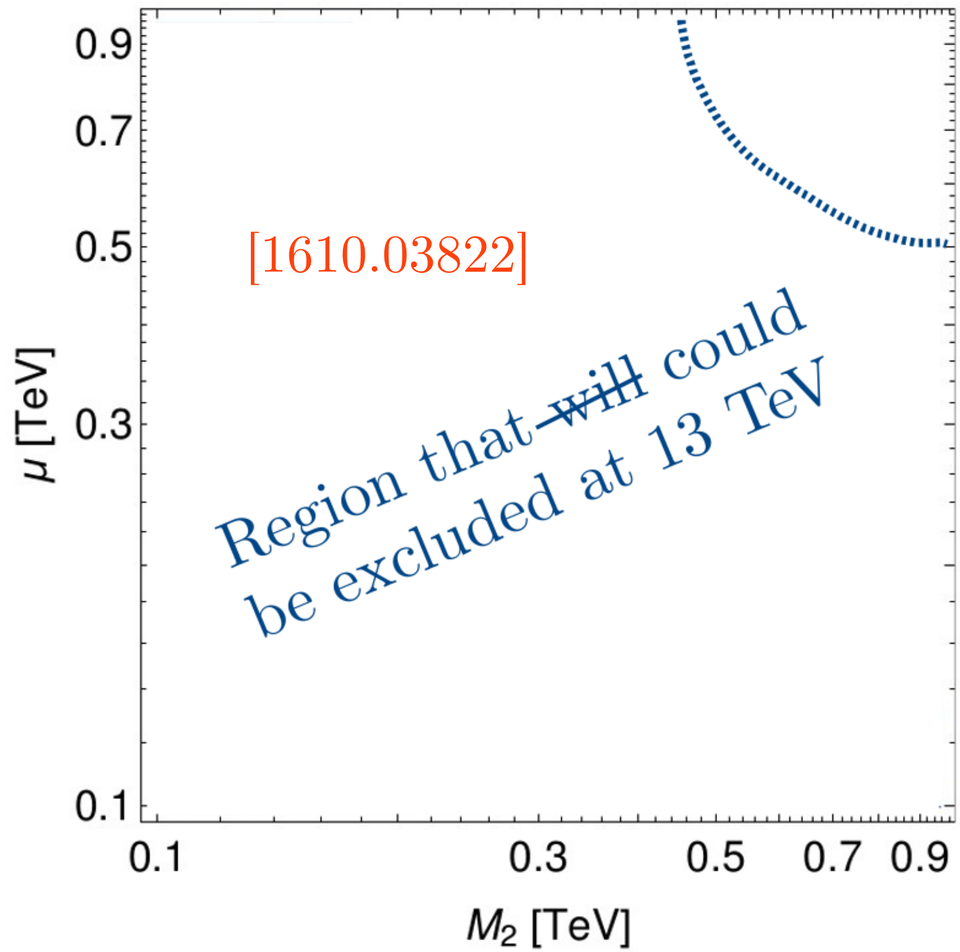
Reach at future beam dump experiments



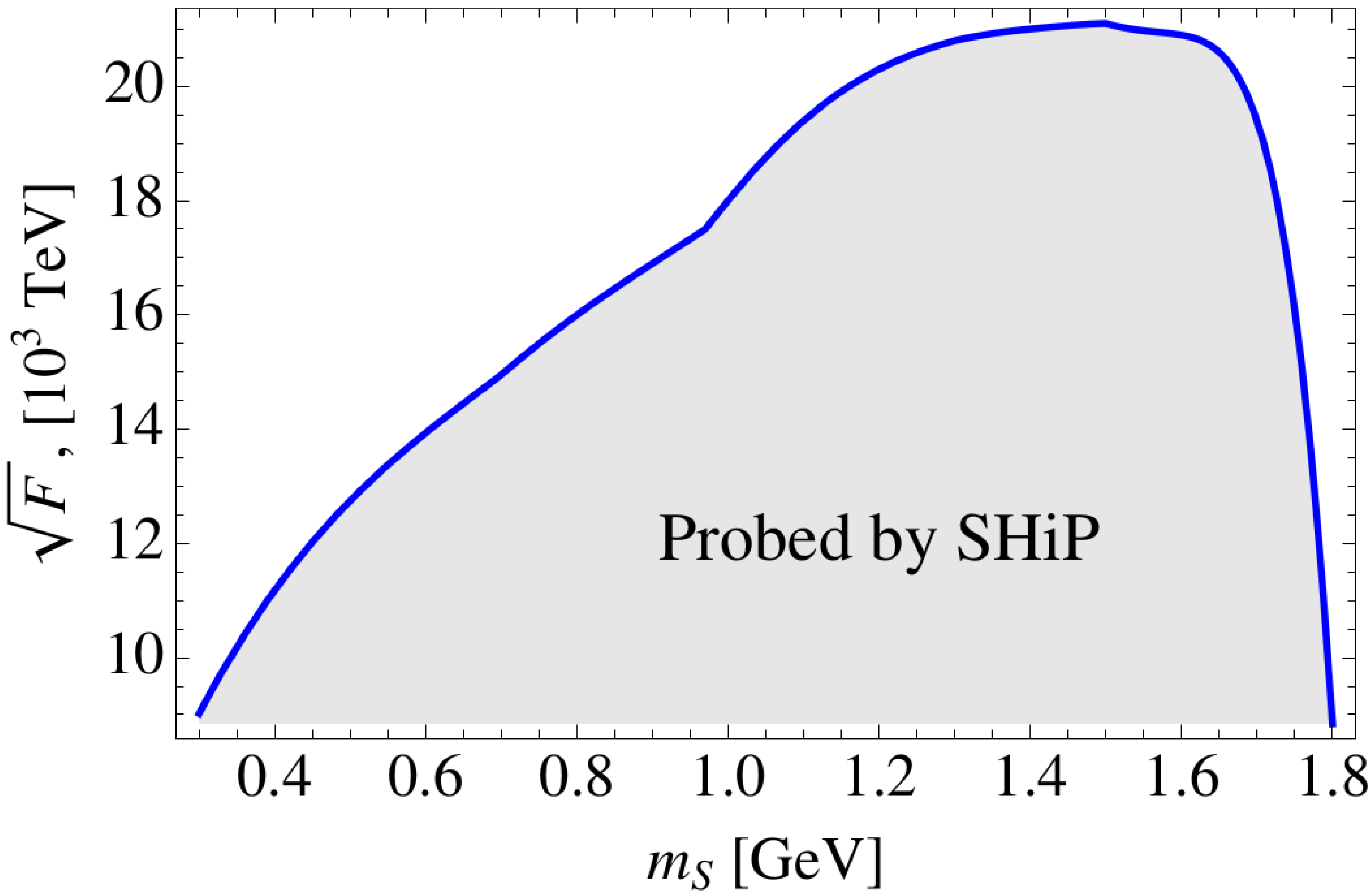


Reach at future beam dump experiments





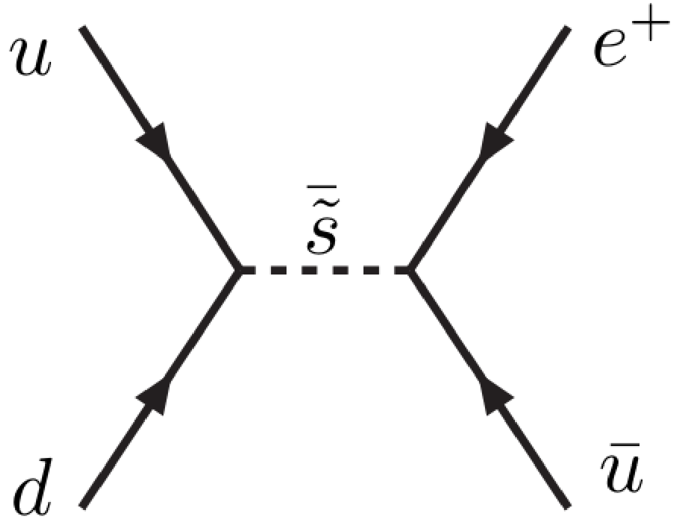
Reach at future beam dump experiments



Supersymmetry

- **R-parity is not fundamental**. Other ways of avoiding proton decay include baryon parity, lepton parity, etc; see *Dreiner 9707435*. None of them preferred by GUT or string theory

- **LHC limits on RPV** stop masses **are** as **weak** as 300 GeV; see *[1710.07171]*



Explain neutrino masses, constrained by neutrinoless double beta decay

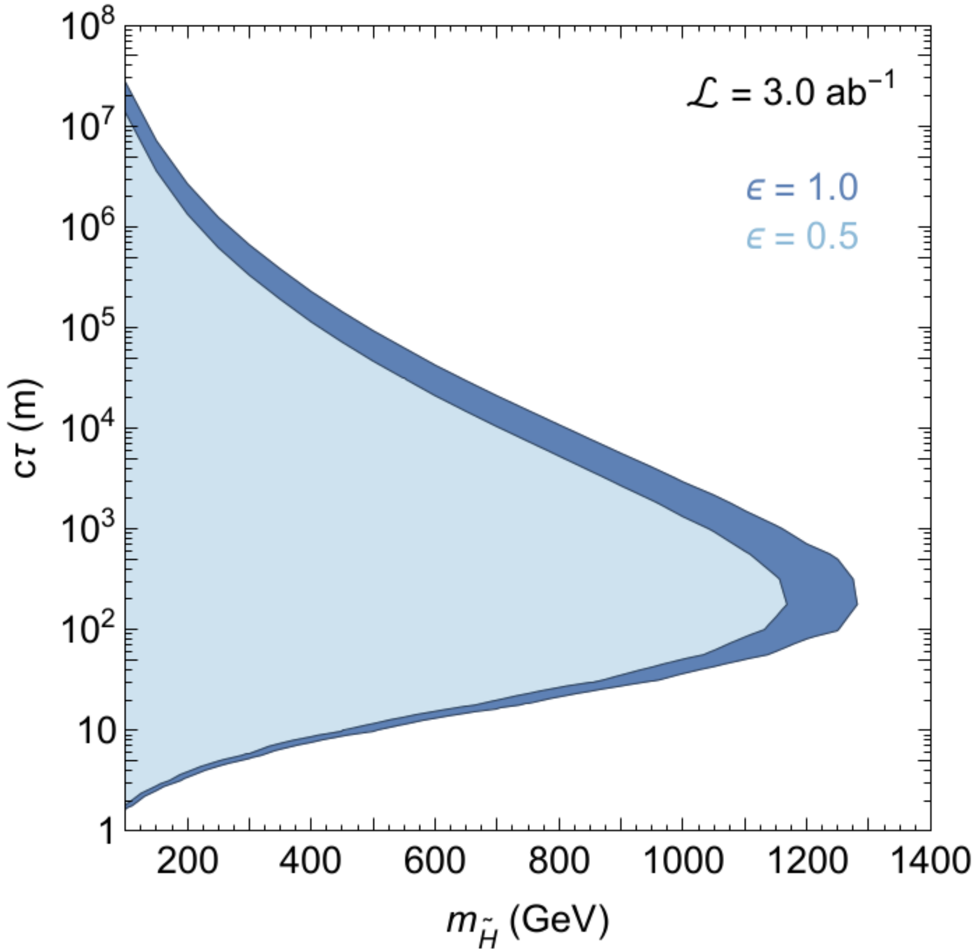
$$W_{RPV} = \lambda_{ijk} l_i l_j \overline{e_k} + \lambda'_{ijk} l_i q_j \overline{d_k}$$

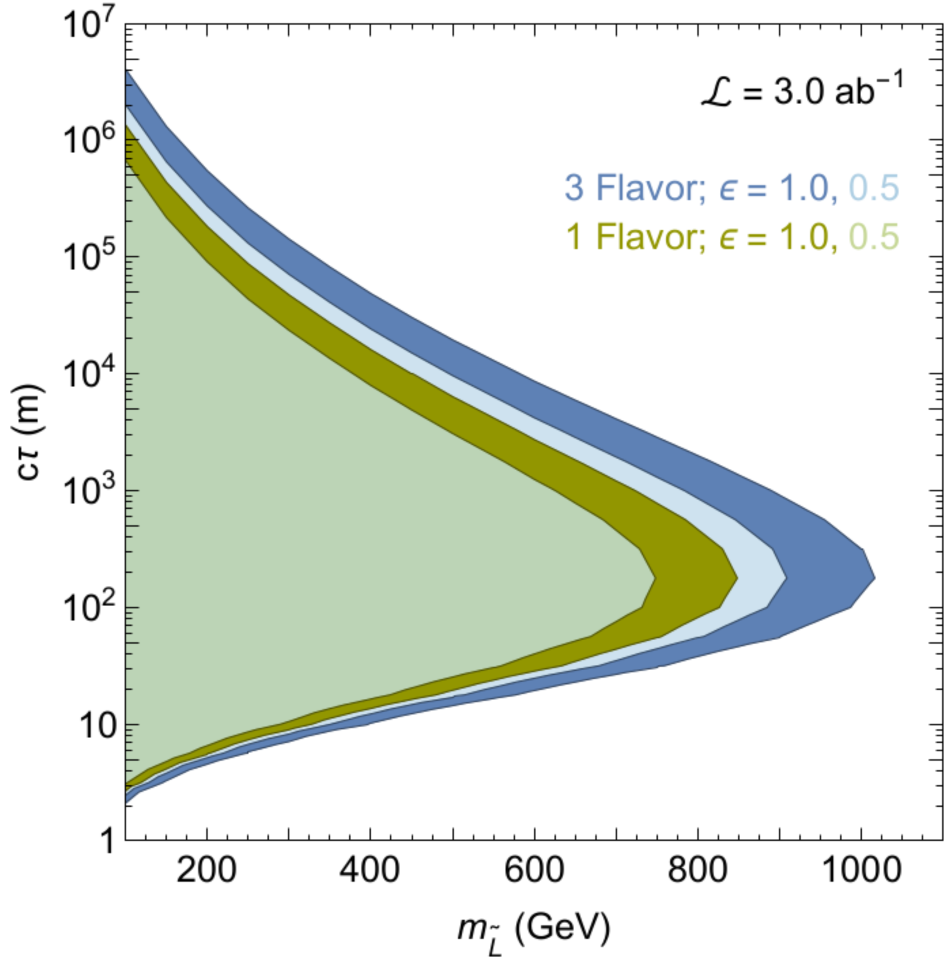
$$+\lambda''_{ijk} \overline{u_i}\, \overline{d_j}\, \overline{d_k}$$

Violates baryon number

Reach at future beam dump experiments

Competitive/complementary to LHC





Composite Higgs models

- In CHMs the hierarchy problem is solved because the Higgs is composite

- In short, they are a **high-energy copy of QCD**

UV

GeV scale

IR

$$L \sim m_q \, \overline{q_L} q_R + SU(2)_L \times SU(2)_R$$

quark condensate

$$p, n, \Delta, \Sigma, \cdots$$

$$\pi^0, \pi^\pm \qquad SU(2)_V$$

Composite Higgs models

- In CHMs the hierarchy problem is solved because the Higgs is composite

- In short, they are a **high-energy copy of QCD**

UV

$$L \sim \lambda[\Lambda_{UV}]\overline{q_i}\mathcal{O}_F^{d_i} + \text{new global}\,\mathcal{G}$$

TeV scale

parton condensate

$$L \sim \lambda[\text{TeV}]\overline{q_i}Q^i$$

IR

$$h, S, \cdots \qquad\qquad \mathcal{H} \supset \mathcal{G}_{SM}$$

Composite Higgs models

- Most choices of G/H (even if H contains the SM gauge group), do not produce pNGBs with the Higgs quantum numbers

- With the exception of SO(5)/SO(4) (which cannot be UV completed), **most models include extra scalars (in particular singlets)**

$$\frac{SO(6)}{SO(5)}$$
0902.1483, 1204.2808

$$\frac{SO(7)}{SO(6)}$$
1605.08663, 1707.07685

$$\frac{SU(7)}{SU(6)\times U(1)}$$
1409.7391

$$\frac{SO(7)}{SO(5)}$$

$$\frac{SO(7)}{G_2}$$
1210.6208, 1704.07388

$$\frac{SU(5)}{SO(5)}$$
1304.4579

$$\frac{SO(5)\times U(1)}{SO(4)}$$
1605.09647

$$\frac{SO(6)}{SO(4)}$$

$$\frac{SO(6)}{SO(4)\times U(1)}$$
1105.5403

Composite Higgs models

- SU(7)/SU(6)xU(1) is the smallest coset containing SU(5) (for gauge coupling unification) as well as the Higgs and S (dark matter); f > 10 TeV

- It gives 12 pNGBS, (T, H, S) forming a 5 of SU(5). T is the lightest colour state. Due to residual symmetries, it can only decay through dimension 6 ops.

$$T \to t^c b^c S S$$

[1409.7391]

$$c\tau = 100\ \mathrm{m} \left(\frac{1}{c_3^T}\right)^2 \left(\frac{8}{g_\rho}\right)^3 \left(\frac{3\ \mathrm{TeV}}{m_T}\right)^5 \left(\frac{f}{200\ \mathrm{TeV}}\right)^4 \frac{1}{J(m_t, m_S)}$$

Composite Higgs models

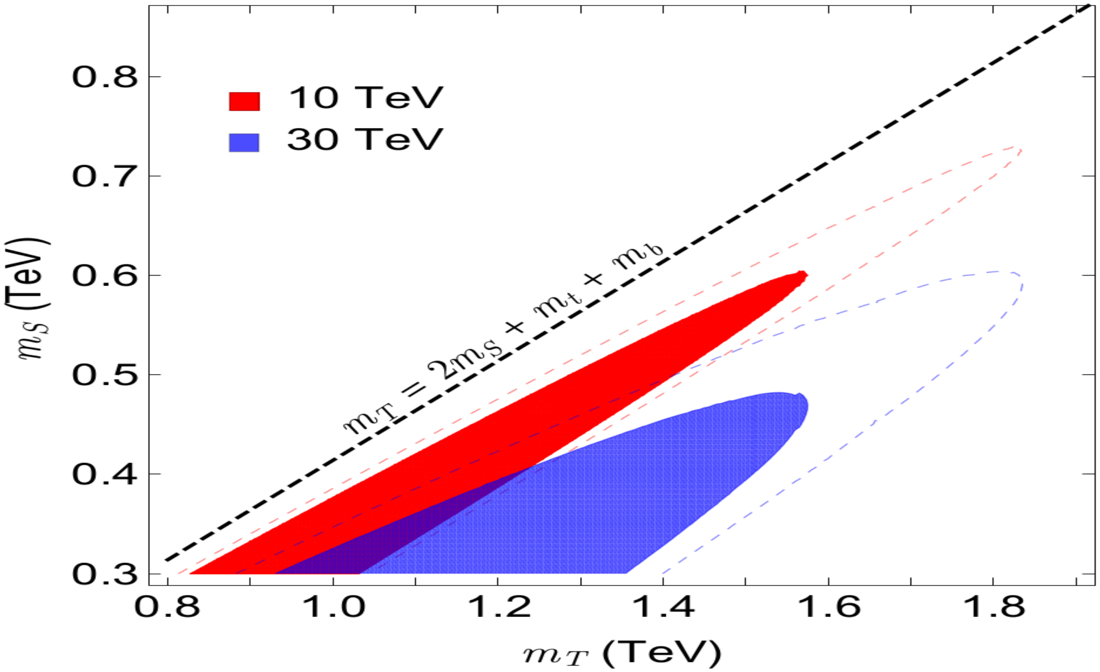
- SU(7)/SU(6)xU(1) is the smallest coset containing SU(5) (for gauge coupling unification) as well as the Higgs and S (dark matter); f > 10 TeV

- It gives 12 pNGBS, (T, H, S) forming a 5 of SU(5). T is the lightest colour state. Due to residual symmetries, it can only decay through dimension 6 ops.

$$T \to t^c b^c S S$$

[1409.7391]

$$c\tau = 100\ \mathrm{m} \left(\frac{1}{c_3^T}\right)^2 \left(\frac{8}{g_\rho}\right)^3$$



Composite Higgs models

- The minimal CHM that can be UV completed in four dimensions is *SO(6)/SO(5)*. The scalar sector it provides is H+S (pseudoscalar). **S is therefore an ALP**

- If lifetime too large, S decays would flood the neutron-proton bath with SM particles, modifying n/p

It triggers the decay of S. It is equivalent to a mixing angle of $\gamma v/f (\lesssim 10^{-6})$

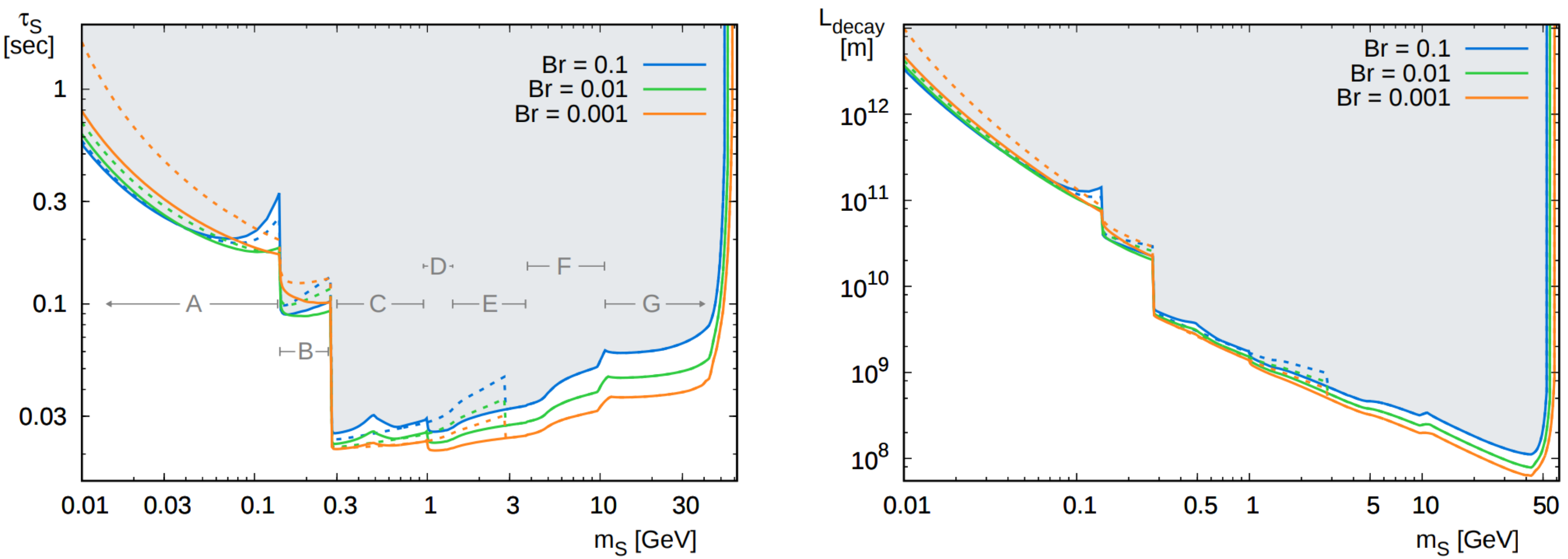
It keeps S in equilibrium in the early universe

$$L_{H,S} \sim \frac{i y_\psi \gamma}{f} S \overline{\phi_L} H \psi_R - \frac{\lambda_{HS}}{2} S^2 |H|^2$$

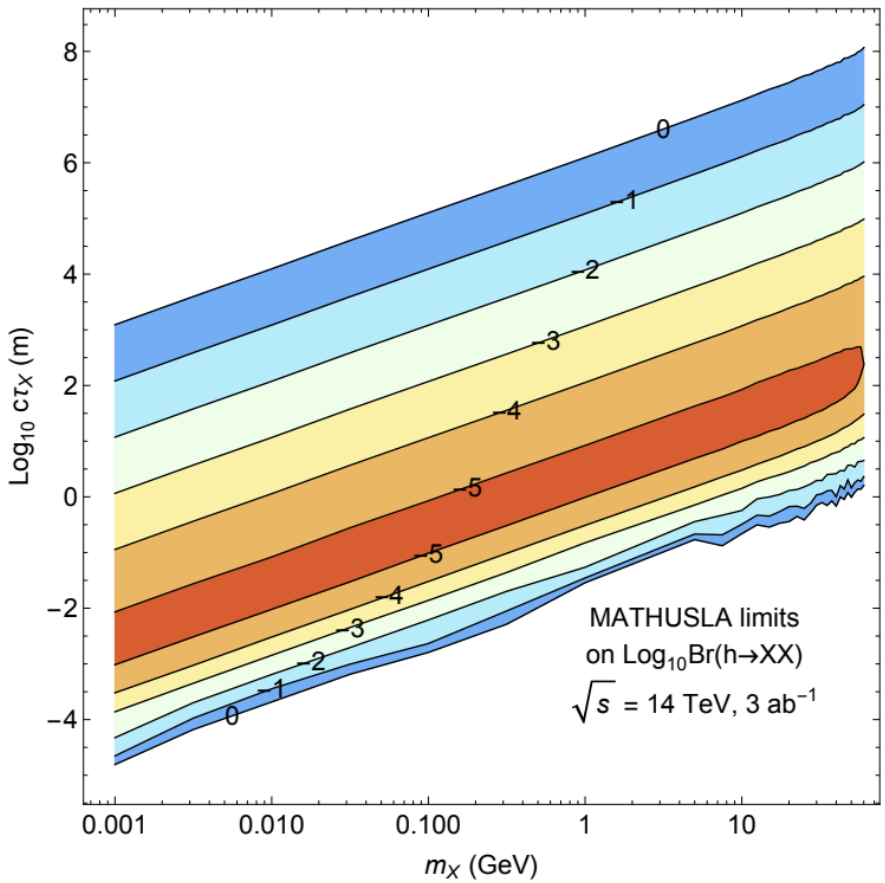
Composite Higgs models

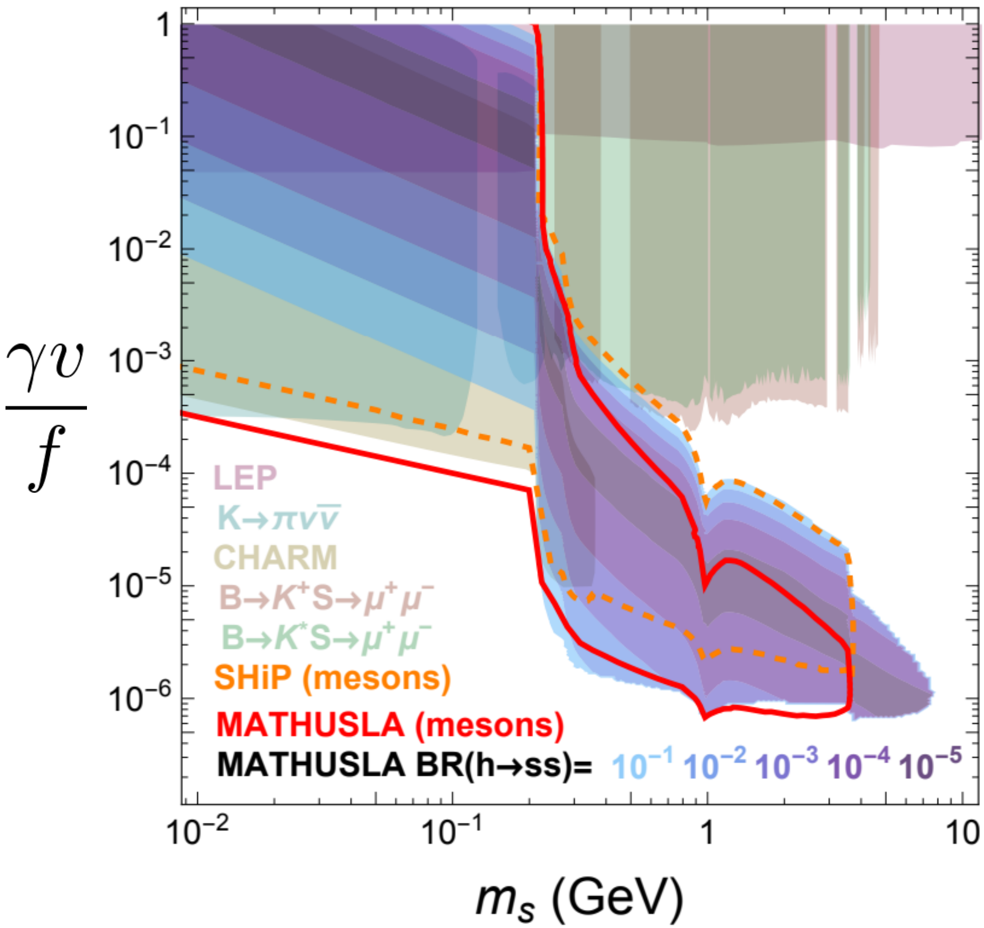
- The minimal CHM that can be UV completed in four dimensions is $SO(6)/SO(5)$. The scalar sector it provides is $H+S$

- If lifetime too large, S decays would flood the neutron-proton bath with SM particles, modifying n/p



Reach at future beam dump experiments





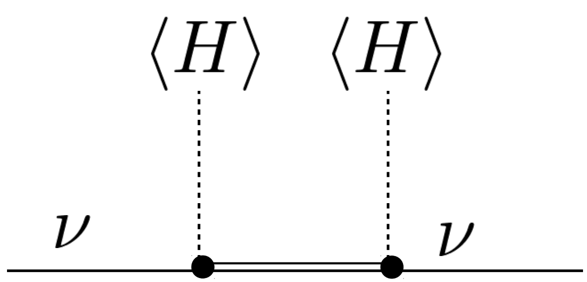
Neutrino masses

- The non-vanishing neutrino masses constitute the only experimental signature of new particle physics. Accommodated by the Weinberg operator,

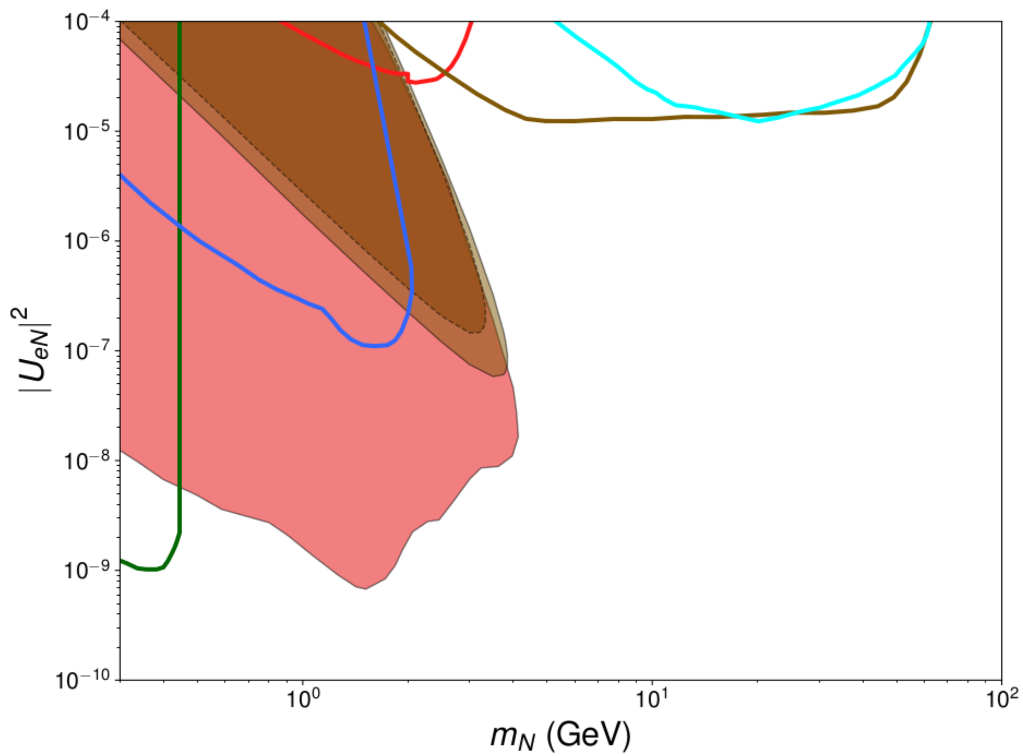
$$\frac{\overline{l_L} H^2 l_L}{\Lambda}$$

- CP-violating interactions of the mediator can trigger lepton asymmetry, that can eventually be transformed into baryon asymmetry via sphalerons

[1606.00017]



$$m_\nu \sim \frac{y^2 v^2}{M} \sim \frac{U^2}{M}$$



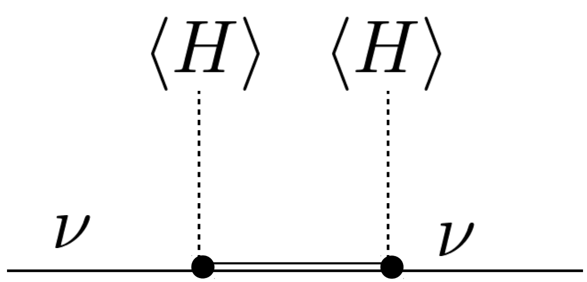
Neutrino masses

- The non-vanishing neutrino masses constitute the only experimental signature of new particle physics. Accommodated by the Weinberg operator,

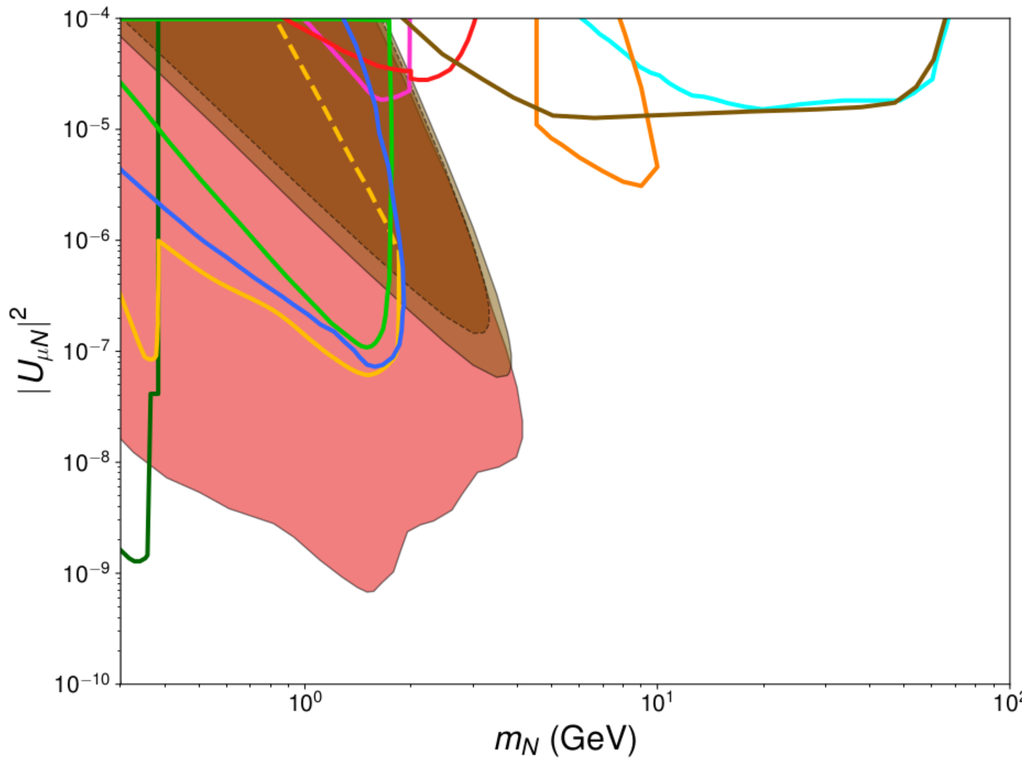
$$\frac{\overline{l_L} H^2 l_L}{\Lambda}$$

- CP-violating interactions of the mediator can trigger lepton asymmetry, that can eventually be transformed into baryon asymmetry via sphalerons

[1606.00017]



$$m_\nu \sim \frac{y^2 v^2}{M} \sim \frac{U^2}{M}$$



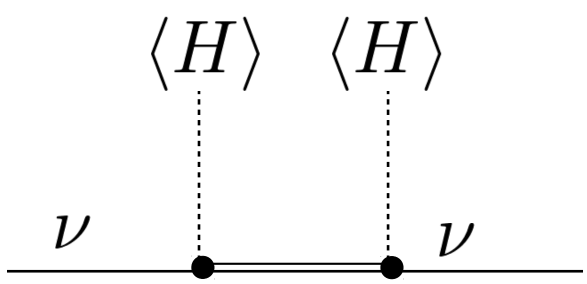
Neutrino masses

- The non-vanishing neutrino masses constitute the only experimental signature of new particle physics. Accommodated by the Weinberg operator,

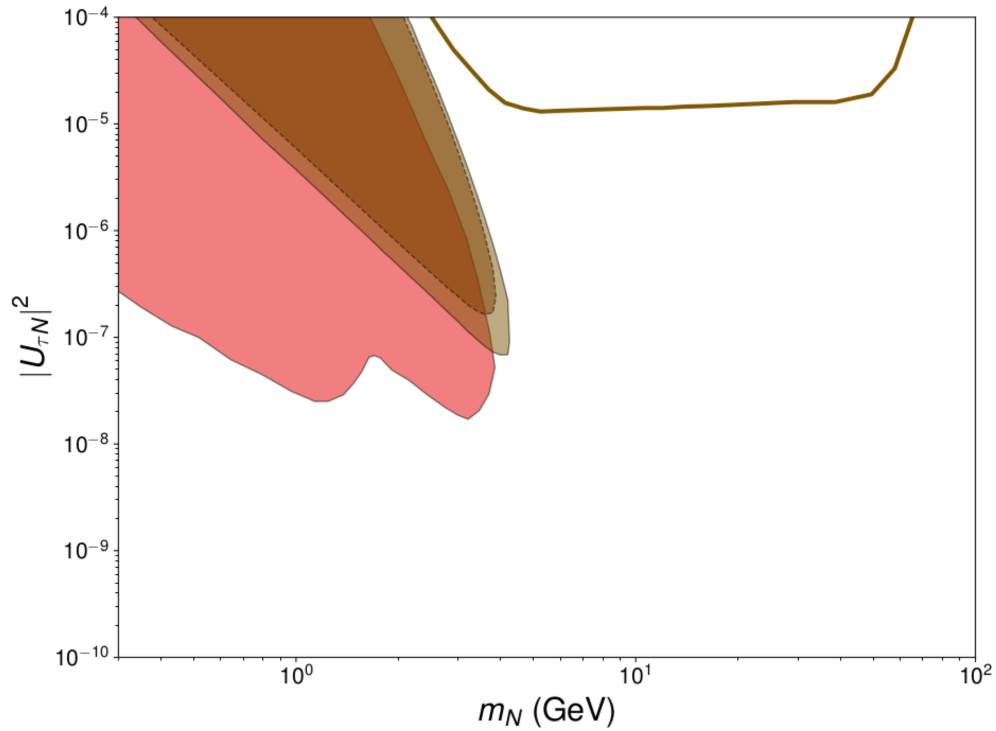
$$\frac{\overline{l_L} H^2 l_L}{\Lambda}$$

- CP-violating interactions of the mediator can trigger lepton asymmetry, that can eventually be transformed into baryon asymmetry via sphalerons

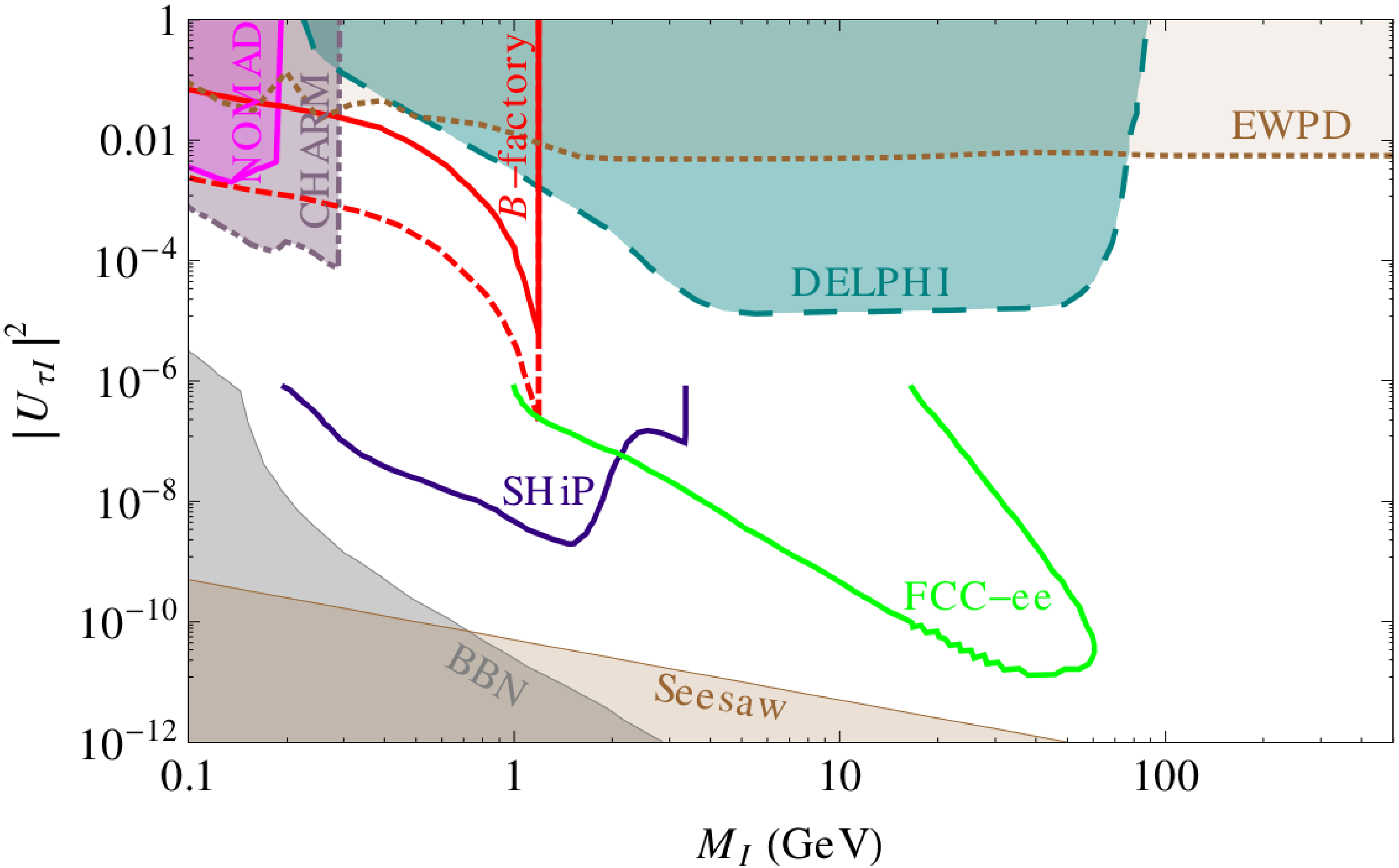
[1606.00017]



$$m_\nu \sim \frac{y^2 v^2}{M} \sim \frac{U^2}{M}$$



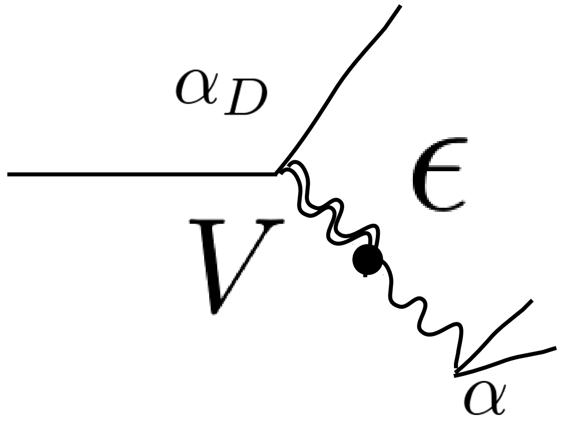
Reach at SHiP



Dark matter

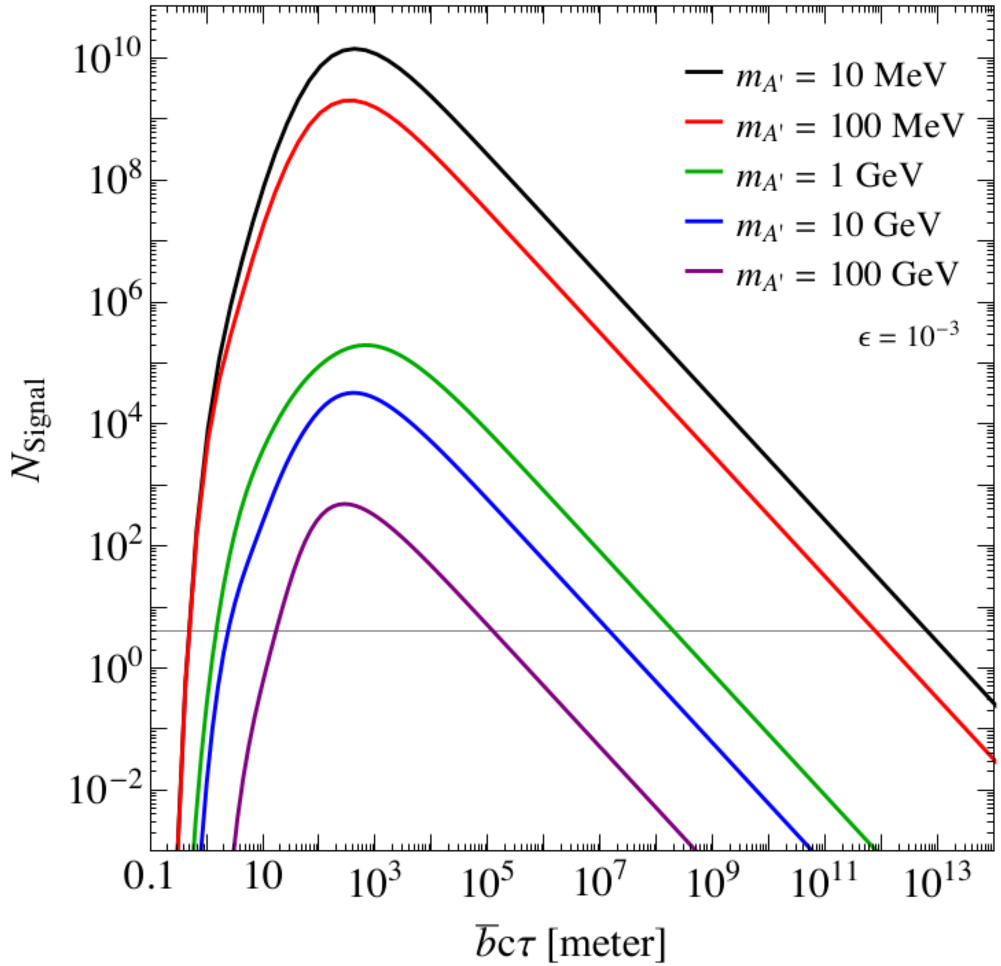
- **Composite** (strongly interacting QCD like) **dark matter can predict its stability**

- It can explain galactic structure anomalies potentially related to large dark matter self interactions. It can explain small interaction with nuclei. **It is often connected to the gauge hierarchy problem**



$$\Gamma \sim \frac{\alpha_D \alpha \epsilon^2}{18\pi} \frac{m_D^5}{m_V^4}$$

Reach at future beam dump experiments



The SM Effective Field Theory

- All relevant degrees of freedom and symmetries are known (assume SM-like)

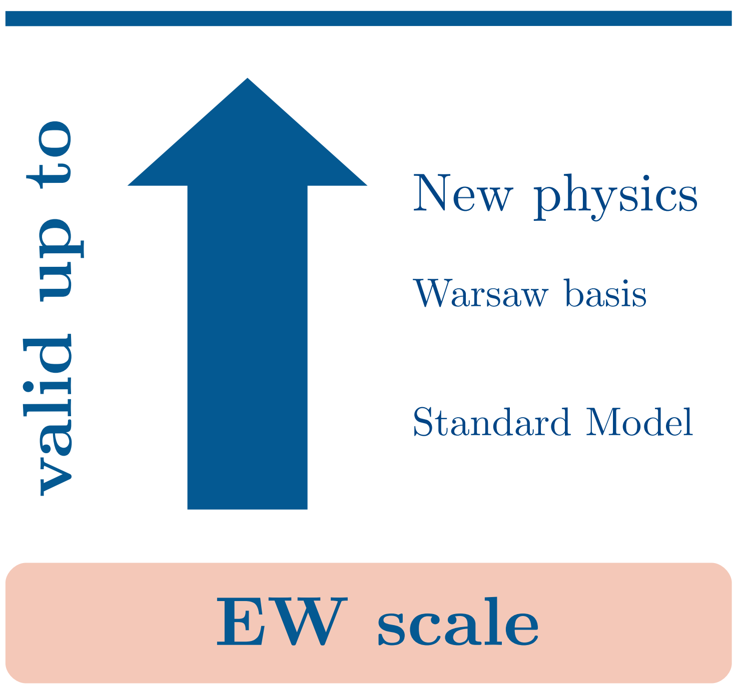
- Mass gap between EW and new physics scales

- Keep up to dimension six operators

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{\alpha_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

The SM Effective Field Theory

In black, those generated at tree level by new physics in the scalar sector



	Operator	Notation	Operator	Notation
S	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}\left(\phi^\dagger\phi\right)^3$	$\mathcal{O}_{\phi}$
SVF	$(\phi^\dagger iD_\mu\phi)\,(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger\sigma_a iD_\mu\phi)\,(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
	$(\phi^\dagger iD_\mu\phi)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
	$(\phi^\dagger iD_\mu\phi)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger\sigma_a iD_\mu\phi)\,(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
	$(\phi^\dagger iD_\mu\phi)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$(\phi^\dagger iD_\mu\phi)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
	$(\phi^T i\sigma_2 iD_\mu\phi)\,(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
STF	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\tilde{\phi}\,B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\tilde{\phi}\,W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
	$(\overline{q_L}\sigma^{\mu\nu}T_A u_R)\,\tilde{\phi}\,G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}T_A d_R)\,\phi\,G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
SF	$(\phi^\dagger\phi)\,(\overline{l_L}\,\phi\,e_R)$	$\mathcal{O}_{e\phi}$		
	$(\phi^\dagger\phi)\,\left(\overline{q_L}\,\tilde{\phi}\,u_R\right)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)\,(\overline{q_L}\,\phi\,d_R)$	$\mathcal{O}_{d\phi}$
Oblique	$(\phi^\dagger D_\mu\phi)\,((D^\mu\phi)^\dagger\,\phi)$	$\mathcal{O}_{\phi D}$		
	$\phi^\dagger\phi\;B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\;\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
	$\phi^\dagger\phi\;W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\;\widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
	$\phi^\dagger\sigma_a\phi\;W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\;\widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
	$\phi^\dagger\phi\;G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\;\widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
Gauge	$\varepsilon_{abc}\,W^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_{W}$	$\varepsilon_{abc}\,\widetilde{W}^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{W}}$
	$f_{ABC}\,G^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_{G}$	$f_{ABC}\,\widetilde{G}^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{G}}$

The SM Effective Field Theory

In black, those generated at tree level by new physics in the scalar sector

valid up to

EW scale

	Operator	Notation	Operator	Notation
LLLL	$\frac{1}{2}\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\mathcal{O}_{ll}^{(1)}$		
	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu q_L\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{qq}^{(1)}$	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu T_A q_L\right)\left(\overline{q_L}\gamma^\mu T_A q_L\right)$	$\mathcal{O}_{qq}^{(8)}$
	$\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{lq}^{(1)}$	$\left(\overline{l_L}\gamma_\mu \sigma_a l_L\right)\left(\overline{q_L}\gamma^\mu \sigma_a q_L\right)$	$\mathcal{O}_{lq}^{(3)}$
RRRR	$\frac{1}{2}\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{e_R}\gamma^\mu e_R\right)$	$\mathcal{O}_{ee}$		
	$\frac{1}{2}\left(\overline{u_R}\gamma_\mu u_R\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{uu}^{(1)}$	$\frac{1}{2}\left(\overline{d_R}\gamma_\mu d_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{dd}^{(1)}$
	$\left(\overline{u_R}\gamma_\mu u_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{ud}^{(1)}$	$\left(\overline{u_R}\gamma_\mu T_A u_R\right)\left(\overline{d_R}\gamma^\mu T_A d_R\right)$	$\mathcal{O}_{ud}^{(8)}$
	$\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{eu}$	$\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{ed}$
LLRR & LRRL	$\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{e_R}\gamma^\mu e_R\right)$	$\mathcal{O}_{le}$	$\left(\overline{q_L}\gamma_\mu q_L\right)\left(\overline{e_R}\gamma^\mu e_R\right)$	$\mathcal{O}_{qe}$
	$\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{lu}$	$\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{ld}$
	$\left(\overline{q_L}\gamma_\mu q_L\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{qu}^{(1)}$	$\left(\overline{q_L}\gamma_\mu T_A q_L\right)\left(\overline{u_R}\gamma^\mu T_A u_R\right)$	$\mathcal{O}_{qu}^{(8)}$
	$\left(\overline{q_L}\gamma_\mu q_L\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{qd}^{(1)}$	$\left(\overline{q_L}\gamma_\mu T_A q_L\right)\left(\overline{d_R}\gamma^\mu T_A d_R\right)$	$\mathcal{O}_{qd}^{(8)}$
	$\left(\overline{l_L}e_R\right)\left(\overline{d_R}q_L\right)$	$\mathcal{O}_{ledq}$		
LRLR	$\left(\overline{q_L}u_R\right) i\sigma_2 \left(\overline{q_L}d_R\right)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$\left(\overline{q_L}T_A u_R\right) i\sigma_2 \left(\overline{q_L}T_A d_R\right)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
	$\left(\overline{l_L}e_R\right) i\sigma_2 \left(\overline{q_L}u_R\right)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$\left(\overline{l_L}u_R\right) i\sigma_2 \left(\overline{q_L}e_R\right)^{\mathrm{T}}$	$\mathcal{O}_{luqe}$
$\not{B}$ & $\not{L}$	$\epsilon_{ABC}(\overline{l_L} i\sigma_2 q_L^{c\,A})(\overline{d_R^B} u_R^{c\,C})$	$\mathcal{O}_{lqdu}$	$\epsilon_{ABC}(\overline{q_L^A} i\sigma_2 q_L^{c\,B})(\overline{e_R} u_R^{c\,C})$	$\mathcal{O}_{qqeu}$
	$\epsilon_{ABC}(\overline{l_L} i\sigma_2 q_L^{c\,A})(\overline{q_L^B} i\sigma_2 q_L^{c\,C})$	$\mathcal{O}_{lqqq}^{(1)}$	$\epsilon_{ABC}(\overline{u_R^A} d_R^{c\,B})(\overline{e_R} u_R^{c\,C})$	$\mathcal{O}_{udeu}$
	$\epsilon_{ABC}(\overline{l_L}\sigma_a i\sigma_2 q_L^{c\,A})(\overline{q_L^B}\sigma_a i\sigma_2 q_L^{c\,C})$	$\mathcal{O}_{lqqq}^{(3)}$		

The SM Effective Field Theory

In black, those generated at tree level by new physics in the scalar sector

valid up to

EW scale

	Operator	Notation	Operator	Notation
LLLL	$\frac{1}{2}\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	[illegible]	[illegible]	[illegible]
	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu q_L\right)$ [illegible]	[illegible]	[illegible]	[illegible]
	$\left(\overline{l_L}\gamma_\mu l_L\right)$ [illegible]	[illegible]	[illegible]	[illegible]
RRRR	$\frac{1}{2}\left(\overline{e_R}\gamma_\mu e_R\right)$ [illegible]	[illegible]	[illegible]	[illegible]
	$\frac{1}{2}\left(\overline{u_R}\right.$ [illegible]	[illegible]	[illegible]	[illegible]
	$\left(\overline{u_R}\right.$ [illegible]	[illegible]	[illegible]	[illegible]
	$\left(\overline{e_R}\right.$ [illegible]	[illegible]	[illegible]	[illegible]
LLRR & LRRL	$\left(\overline{l_L}\gamma_\mu l\right.$ [illegible]	[illegible]	[illegible]	[illegible]
	$\left(\overline{l_L}\gamma_\mu\right.$ [illegible]	[illegible]	[illegible]	[illegible]
	$\left(\overline{q_L}\gamma_\mu q\right.$ [illegible]	[illegible]	[illegible]	$\mathcal{O}_{qu}^{(8)}$
	$\left(\overline{q_L}\gamma_\mu q_L\right)$ [illegible]	[illegible]	[illegible]	$\mathcal{O}_{qd}^{(8)}$
	$\left(\overline{l_L}e_R\right)\left(\overline{d_R}q_L\right)$	[illegible]		
LRLR	$\left(\overline{q_L}u_R\right)i\sigma_2\left(\overline{q_L}d_R\right)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	[illegible] $i\sigma_2\left(\overline{q_L}T_A d_R\right)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
	$\left(\overline{l_L}e_R\right)i\sigma_2\left(\overline{q_L}u_R\right)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$\left(\overline{l_L}u_R\right)i\sigma_2\left(\overline{q_L}e_R\right)^{\mathrm{T}}$	$\mathcal{O}_{luqe}$
$\not B$ & $\not L$	$\epsilon_{ABC}(\overline{l_L}i\sigma_2 q_L^{c\,A})(\overline{d_R^B}u_R^{c\,C})$	$\mathcal{O}_{lqdu}$	$\epsilon_{ABC}(\overline{q_L^A}i\sigma_2 q_L^{c\,B})(\overline{e_R}u_R^{c\,C})$	$\mathcal{O}_{qqeu}$
	$\epsilon_{ABC}(\overline{l_L}i\sigma_2 q_L^{c\,A})(\overline{q_L^B}i\sigma_2 q_L^{c\,C})$	$\mathcal{O}_{lqqq}^{(1)}$	$\epsilon_{ABC}(\overline{u_R^A}d_R^{c\,B})(\overline{e_R}u_R^{c\,C})$	$\mathcal{O}_{udeu}$
	$\epsilon_{ABC}(\overline{l_L}\sigma_a i\sigma_2 q_L^{c\,A})(\overline{q_L^B}\sigma_a i\sigma_2 q_L^{c\,C})$	$\mathcal{O}_{lqqq}^{(3)}$		

Under RGEs, this operator Renormalizes

$$\sim F_{\mu\nu}\overline{l_L}\sigma^{\mu\nu}e_R H$$

affecting *e.g.*

$$\tau \to e(\mu)\gamma$$

The SM Effective Field Theory

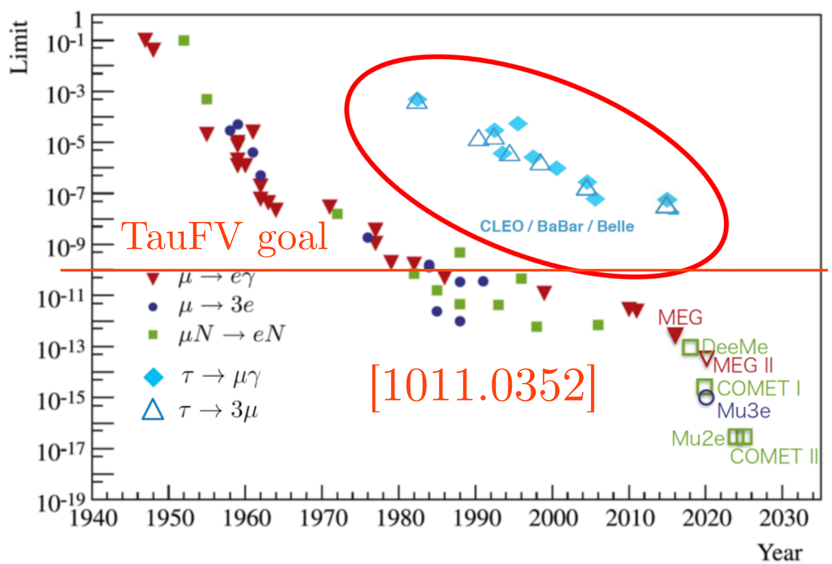
- **New physics** in leptons **more likely in the tau sector**. Sensitivity to other (*e.g.* top) operators also possible due to RGEs

- Lepton flavour violation (order 1e-10 in BR) **strongly motivated by the recent *B* anomalies**

- Enormous tau production rate in SPS beam from Ds to tau neutrino

Current limits on tau to three muons

Belle	2.1×10^{-8}	[PLB 687 (2010) 139]
BaBar	3.3×10^{-8}	[PLB 687 (2010) 139]
LHCb	4.6×10^{-8}	[PLB 687 (2010) 139]



Conclusions

- Long-lived particles appear in the best motivated new physics models, including: **SUSY, CHMs, neutrino models and models of dark matter**

- **MATHUSLA** and **ShiP** can overcome the reach of LHC searches, particularly in: GMSB and RPV (NLSP mass above TeV vs few hundred GeV); NMCHMs (f scale up to 1000 TeV vs no more than 1 TeV); see-saw mixing angle in the tau sector (totally unconstrained at the LHC)

- **TauFV** can test better the SMEFT, in particular region strongly motivated by current flavour anomalies!