A brief selection of BSM frameworks
(still open after LHC results)

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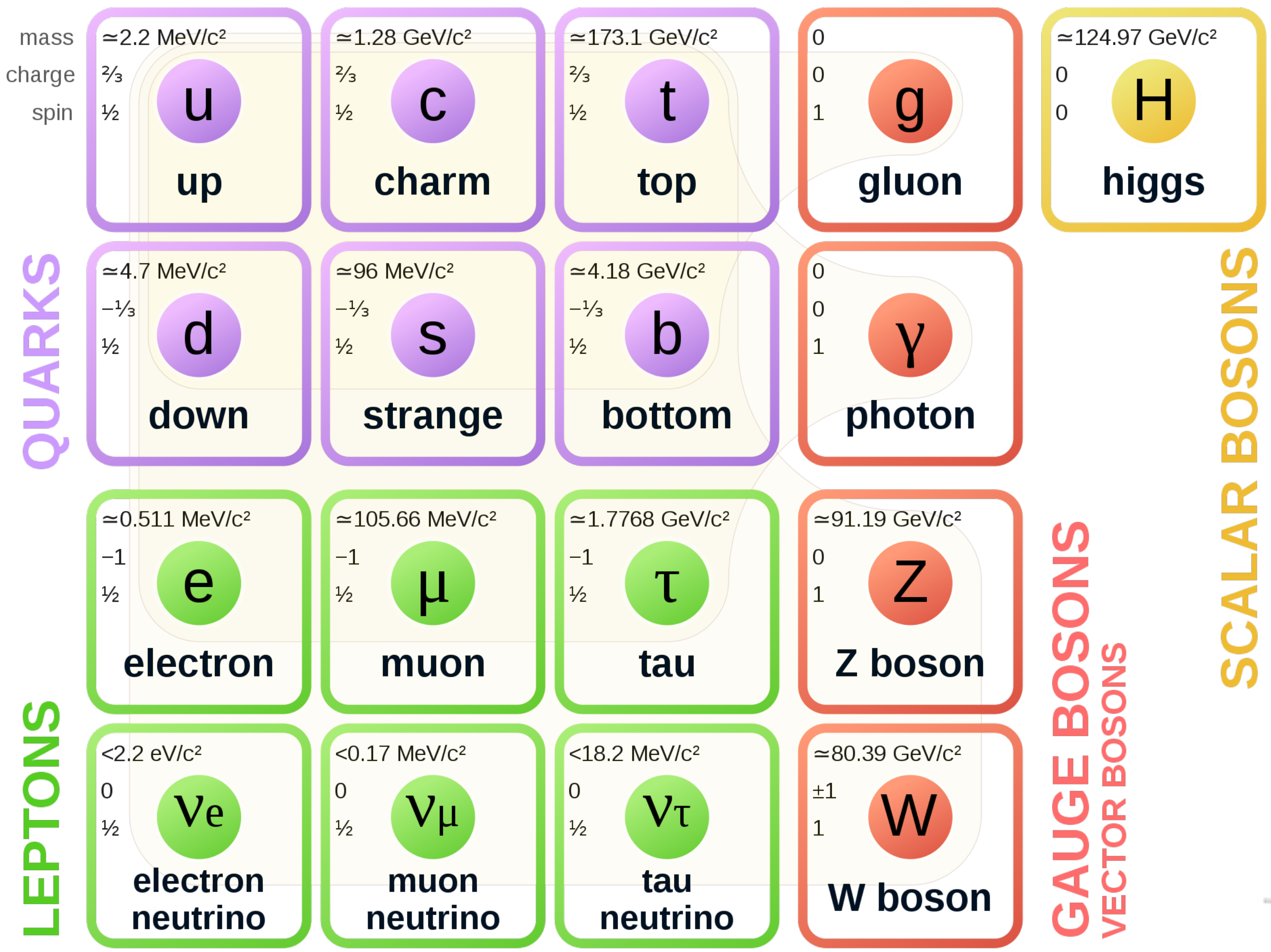
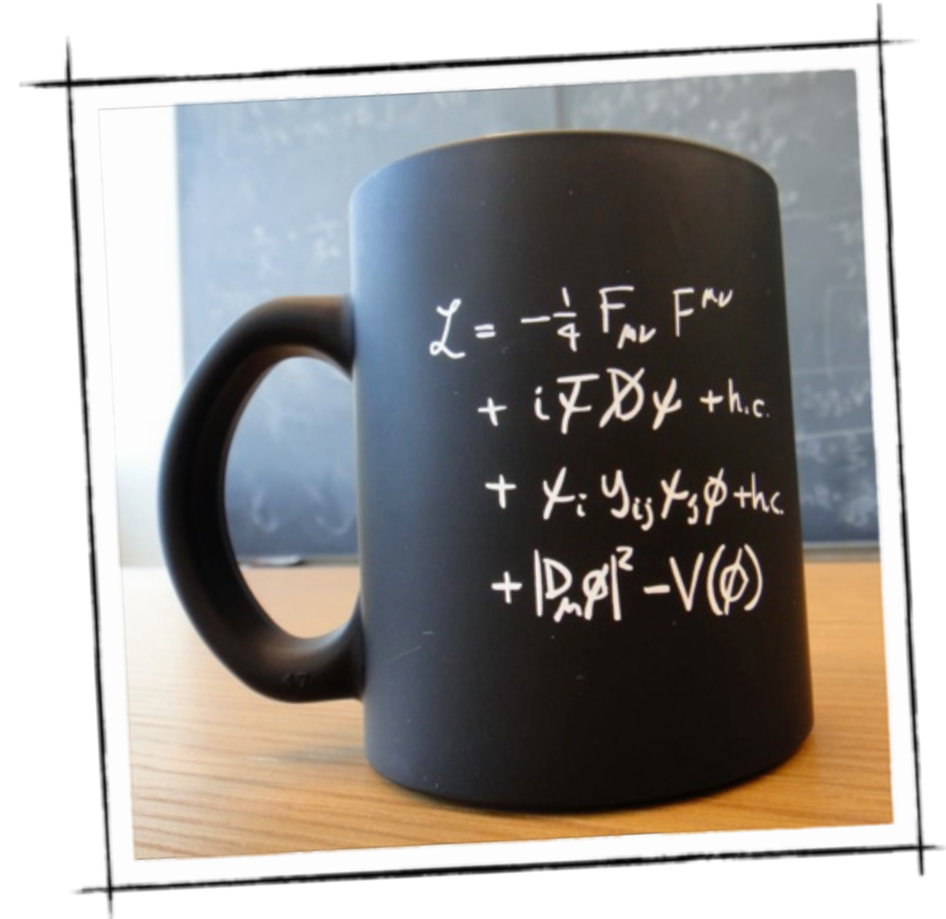
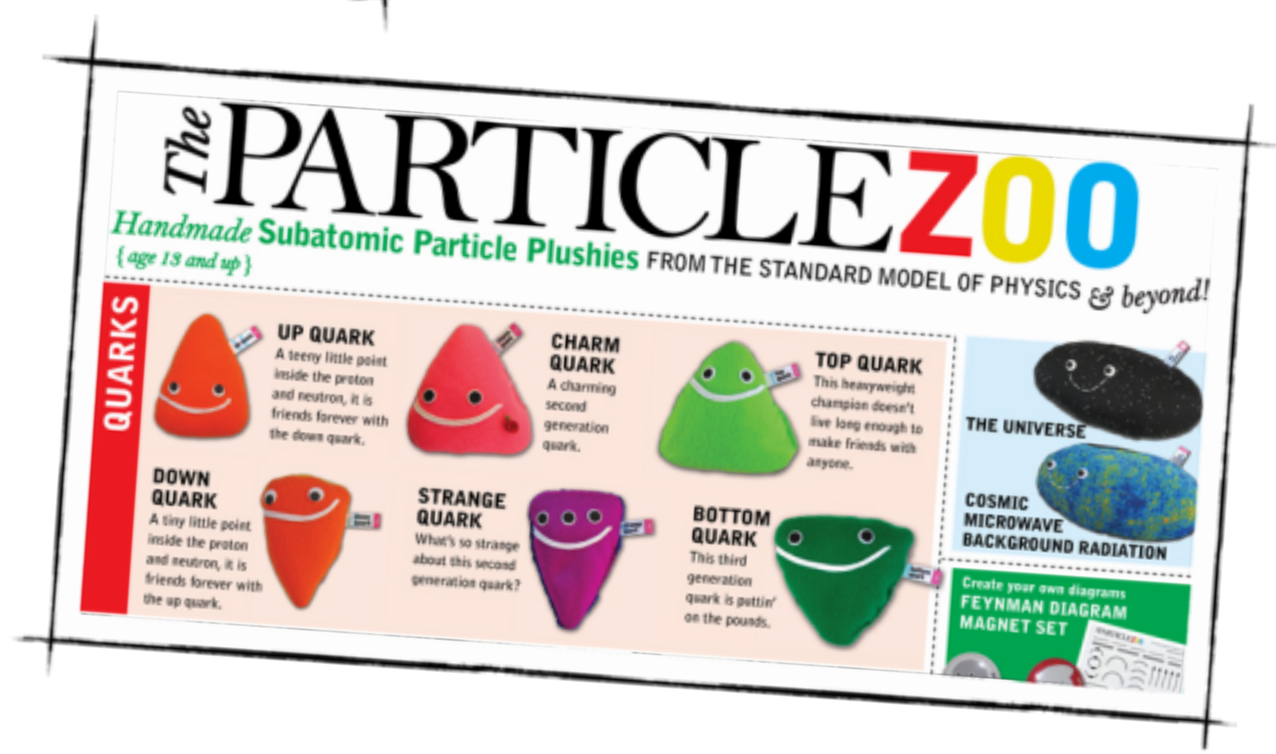
The Standard Model...

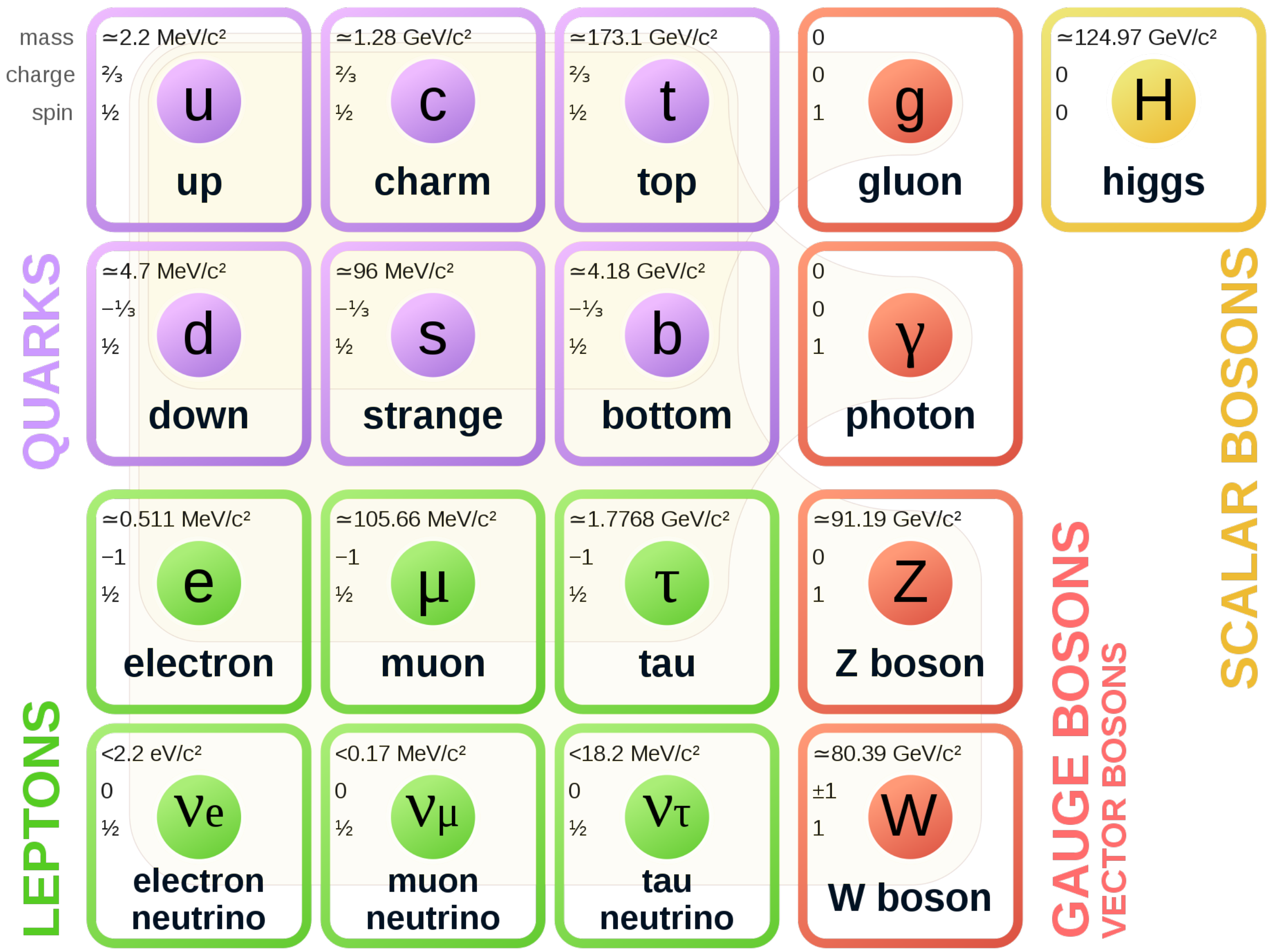


en.wikipedia.org/wiki/Standard_Model





The Standard Model... and its shortcomings



Flavour problem...?

Hierarchy problem...?

Other scalars...?

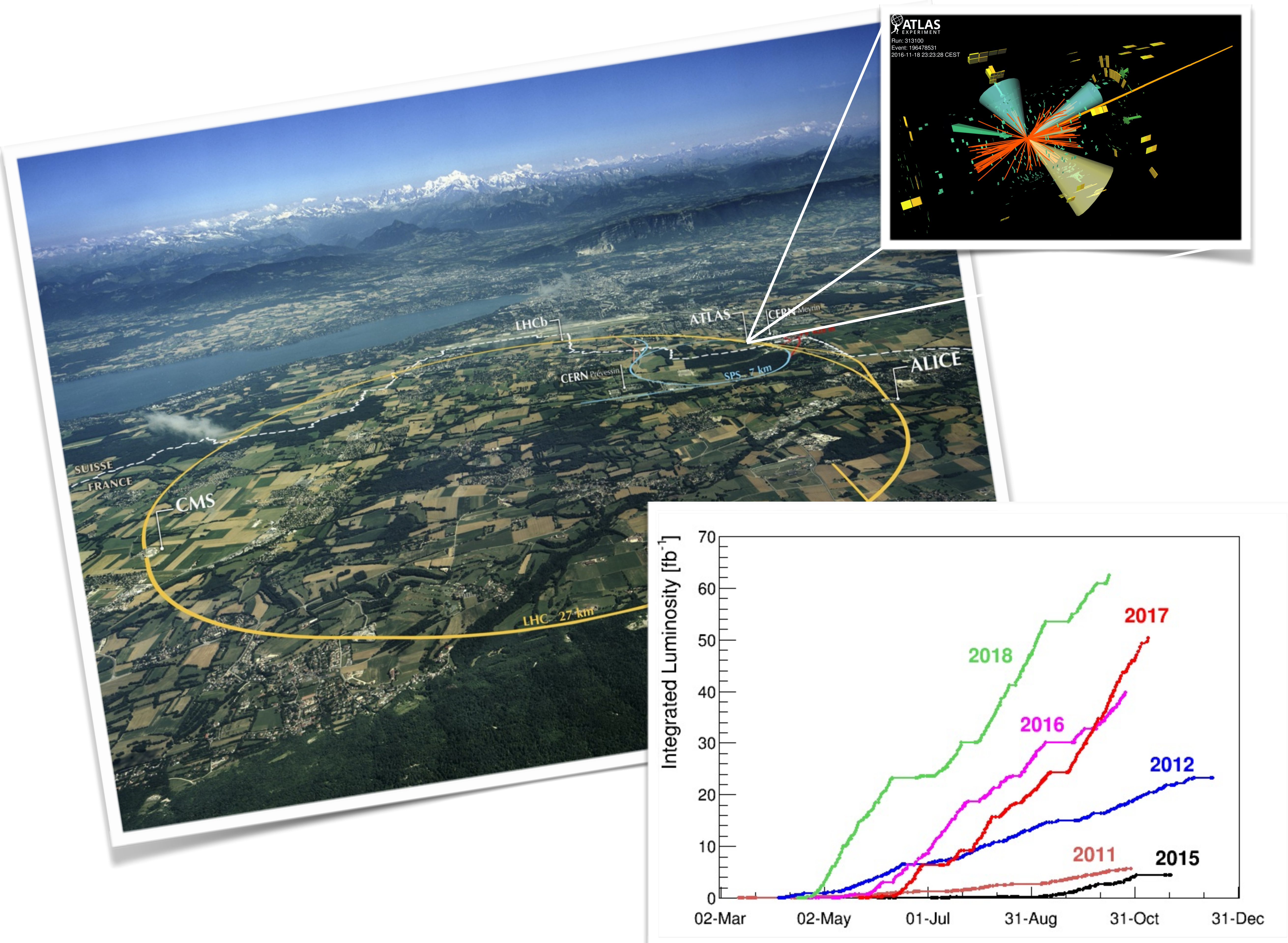
Gauge coupling unification...?

Gravity...?

Neutrino masses...?

Dark matter in the Universe...?

Lepton-flavour non-universality...?


ATLAS
EXPERIMENT
Run: 313100
Event: 196478531
2016-11-18 23:23:28 CEST
LHCb
ATLAS
CERN Meyrin
ALICE
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
LHC 27 km
Integrated Luminosity [fb^{-1}]
0
10
20
30
40
50
60
70
02-Mar
02-May
01-Jul
31-Aug
31-Oct
31-Dec
2018
2017
2016
2012
2011
2015

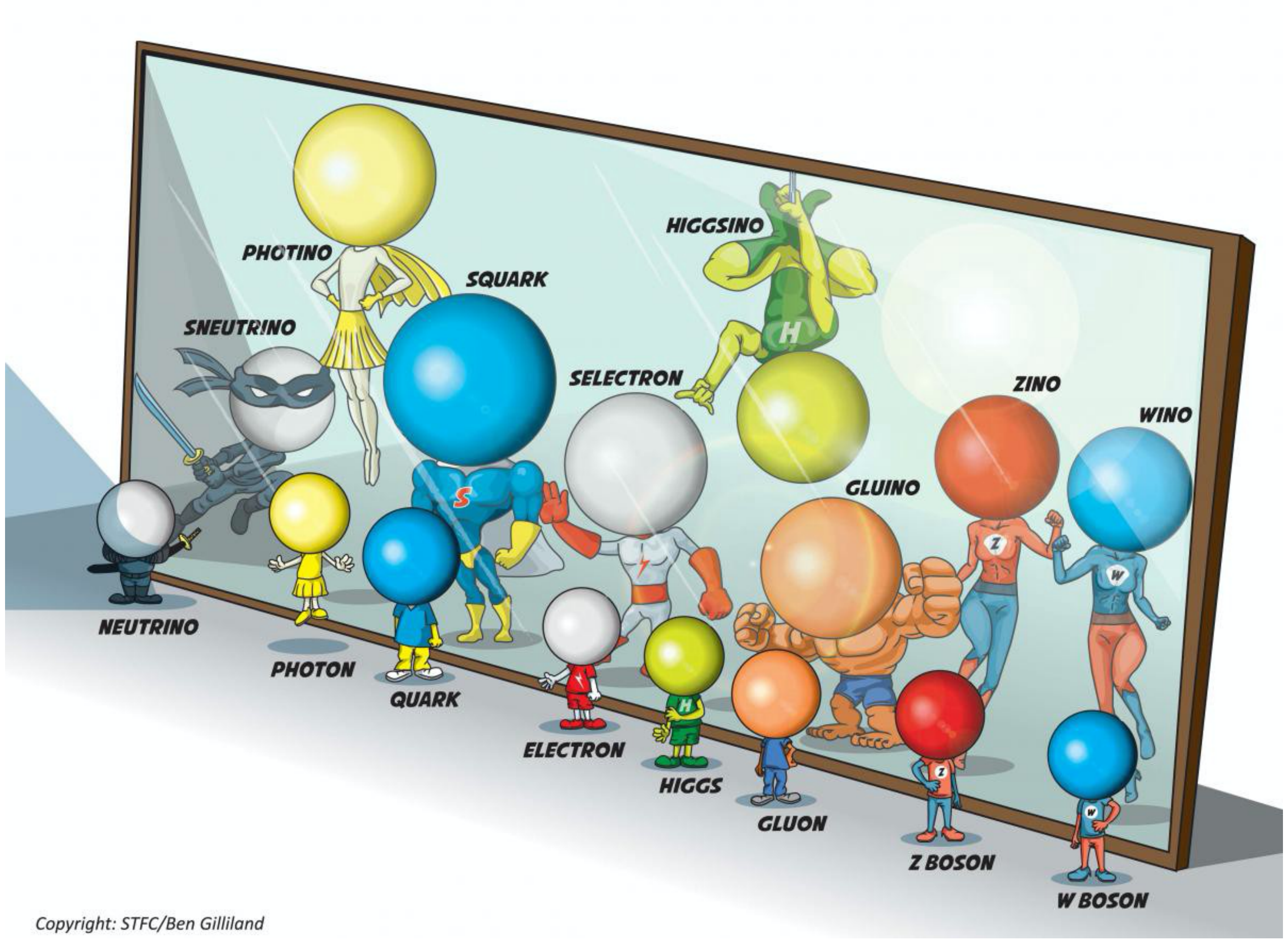
The following is a very personal selection of beyond Standard Model frameworks

I will **not** cover models featuring **axions** or **leptoquarks**
(while I believe they are interesting extensions of the SM)

I will cover (non-minimal) **supersymmetric extensions**
(but only TeV-scale aspects) and **scotogenic models**

Supersymmetric frameworks

$$\mathcal{Q}\,|\text{boson}\rangle \;\rightarrow\; |\text{fermion}\rangle$$
$$\mathcal{Q}\,|\text{fermion}\rangle \;\rightarrow\; |\text{boson}\rangle$$



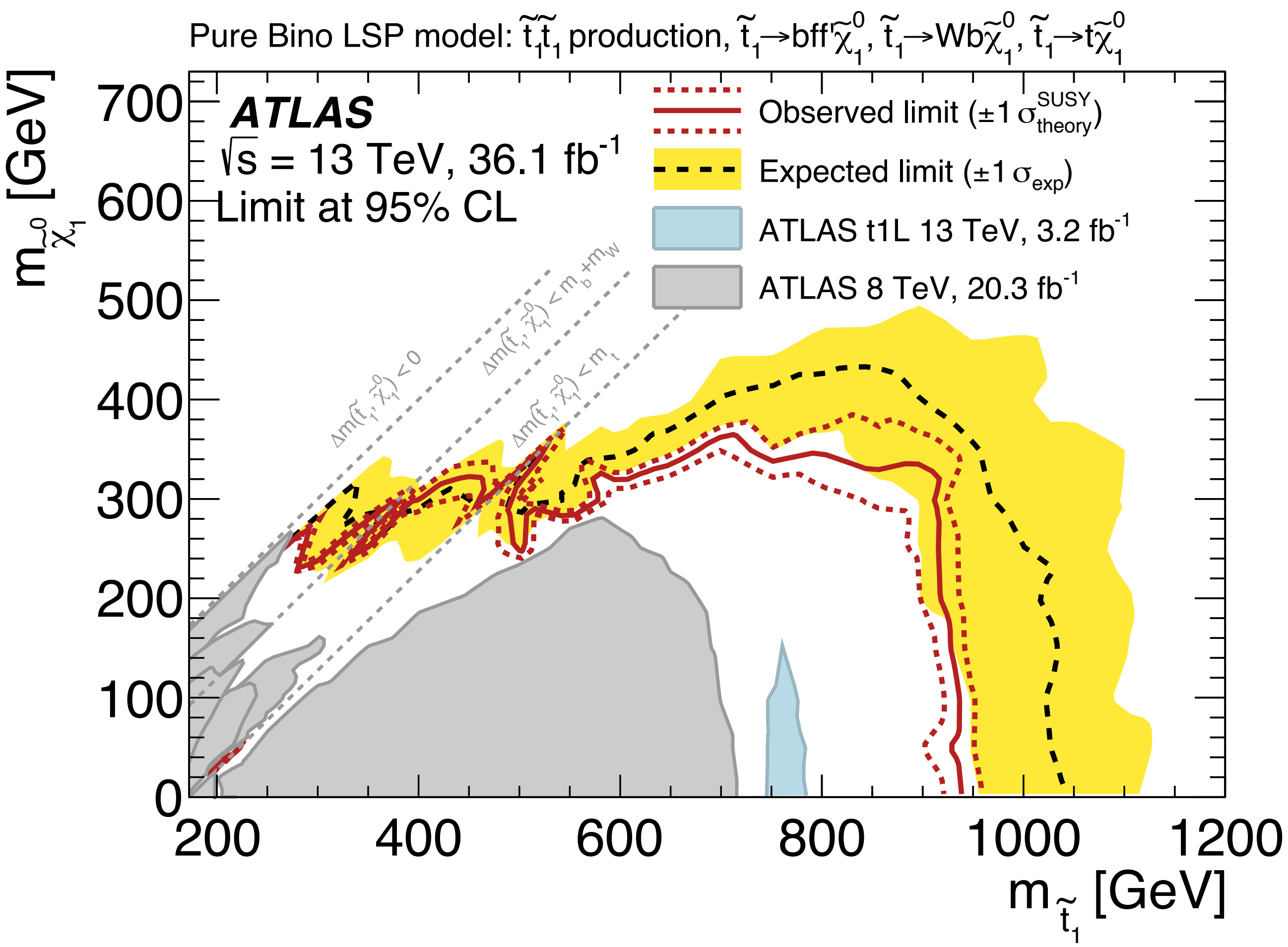
Minimal Supersymmetric Standard Model

SM Particles		Spin		Spin		Superpartners
Quarks	$(u_L \;\; d_L)$	$1/2$	Q	0	$(\tilde{u}_L \;\; \tilde{d}_L)$	Squarks
	$u_R^\dagger$	$1/2$	$\bar{u}$	0	$\tilde{u}_R^*$	
	$d_R^\dagger$	$1/2$	$\bar{d}$	0	$\tilde{d}_R^*$	
Leptons	$(\nu \;\; e_L)$	$1/2$	L	0	$(\tilde{\nu} \;\; \tilde{e}_L)$	Sleptons
	$e_R^\dagger$	$1/2$	$\bar{e}$	0	$\tilde{e}_R^*$	
Higgs	$(H_u^+ \;\; H_u^0)$	0	H_u	$1/2$	$\tilde{\chi}^0_{1,2,3,4}$	Neutralinos
	$(H_d^0 \;\; H_d^-)$	0	H_d			
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{\chi}^\pm_{1,2}$	Charginos
B boson	B^0	1				
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino

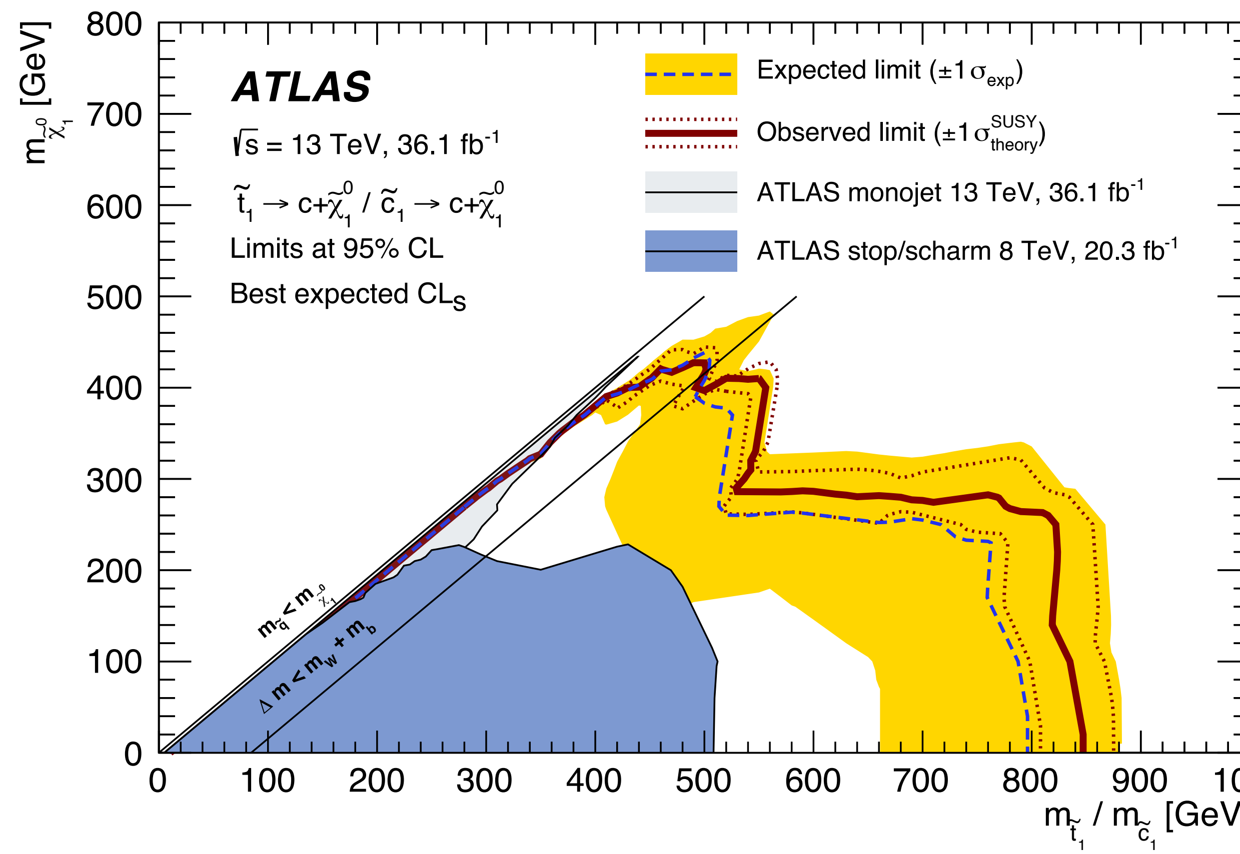
Supersymmetry broken at the TeV scale — introduce soft-breaking terms into the Lagrangian

Minimal Supersymmetric Standard Model probably best-studied BSM framework…

Reminder — Squark mass limits from ATLAS/CMS



ATLAS coll. — JHEP 1806 (2018) 108 — arXiv: 1711.11530



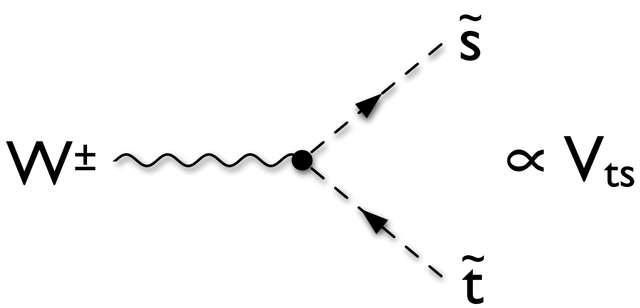
ATLAS coll. — *JHEP* 09 (2018) 050 — arXiv: 1805.01649

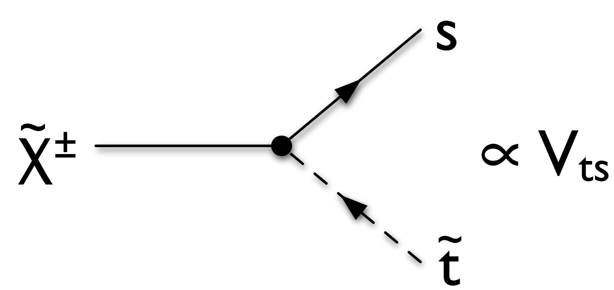
The obtained mass limits are based on (over-)simplifying assumptions (mass hierarchy, squark and gaugino composition, decay pattern, …)

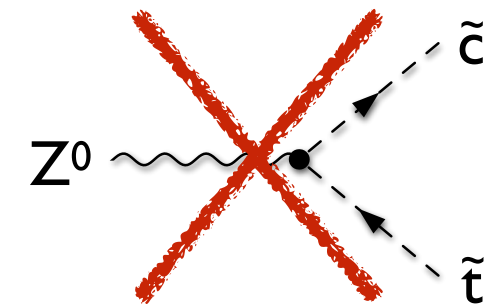
In the following: **Consider flavour structure beyond Minimal Flavour Violation…**

Squark flavour structure — MFV and beyond

Assume **same flavour structure** as in Standard Model: flavour-changing currents are related to CKM-matrix — minimal flavour violation (MFV)

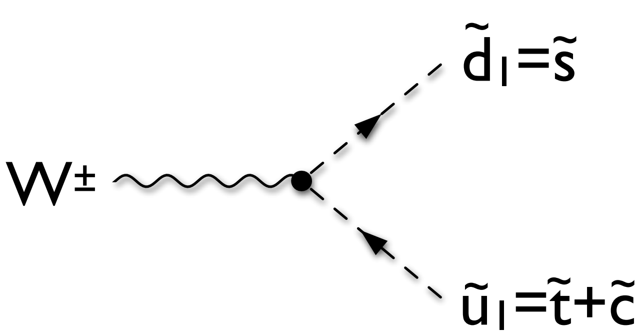


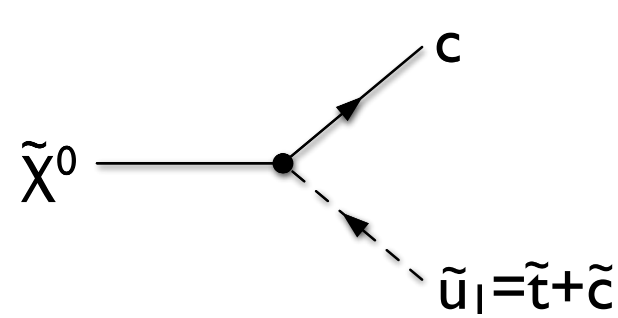


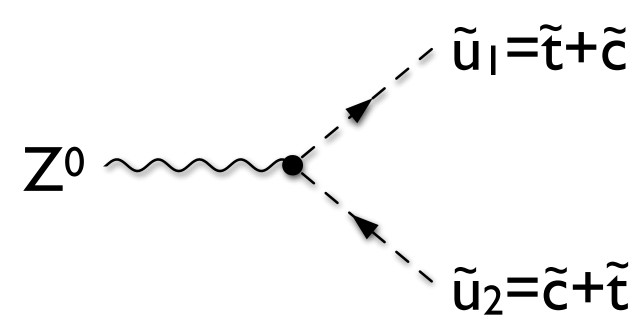


MFV vs. NMFV at LHC…?

Allow for **new sources** of flavour violation: corresponding interactions not related to CKM-matrix any more (no suppression!) — non-minimal flavour violation (NMFV)





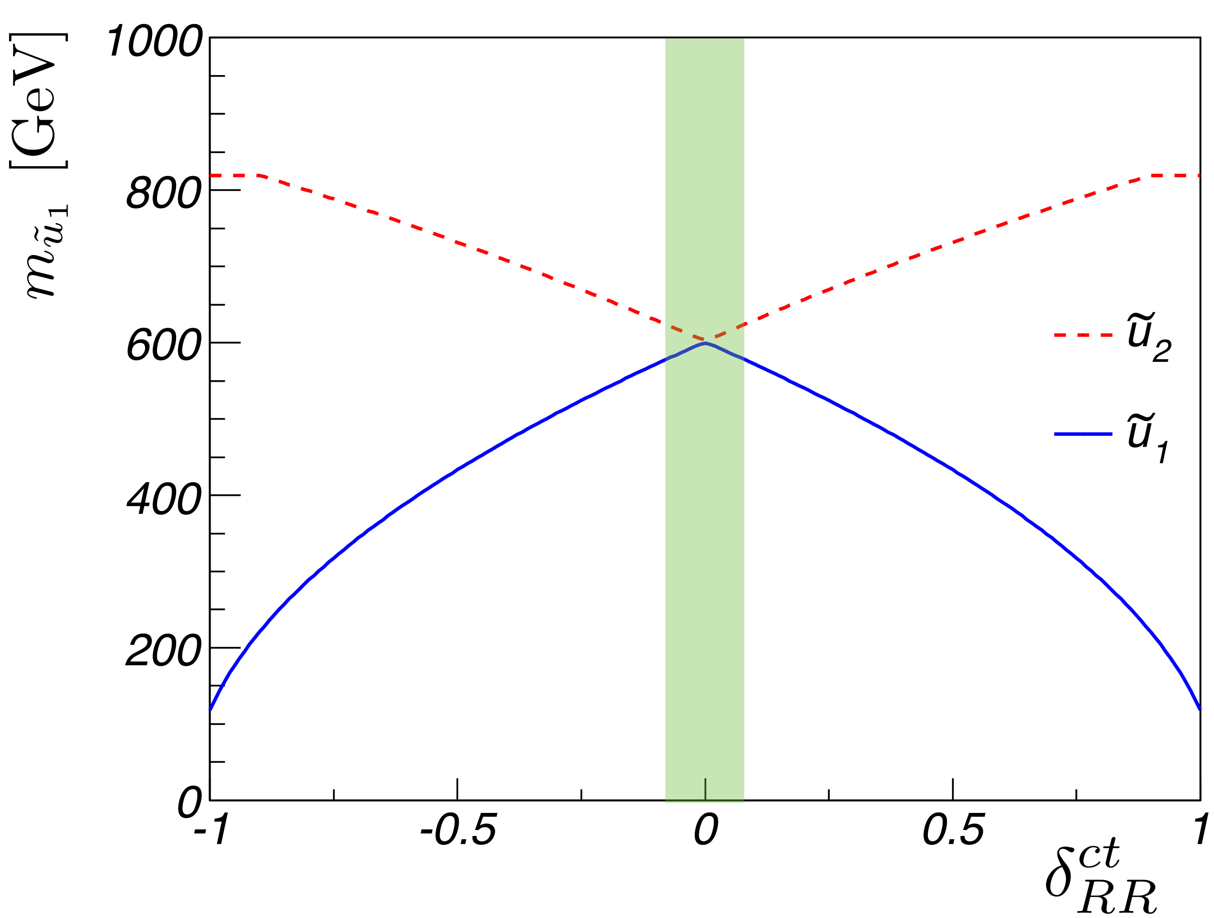


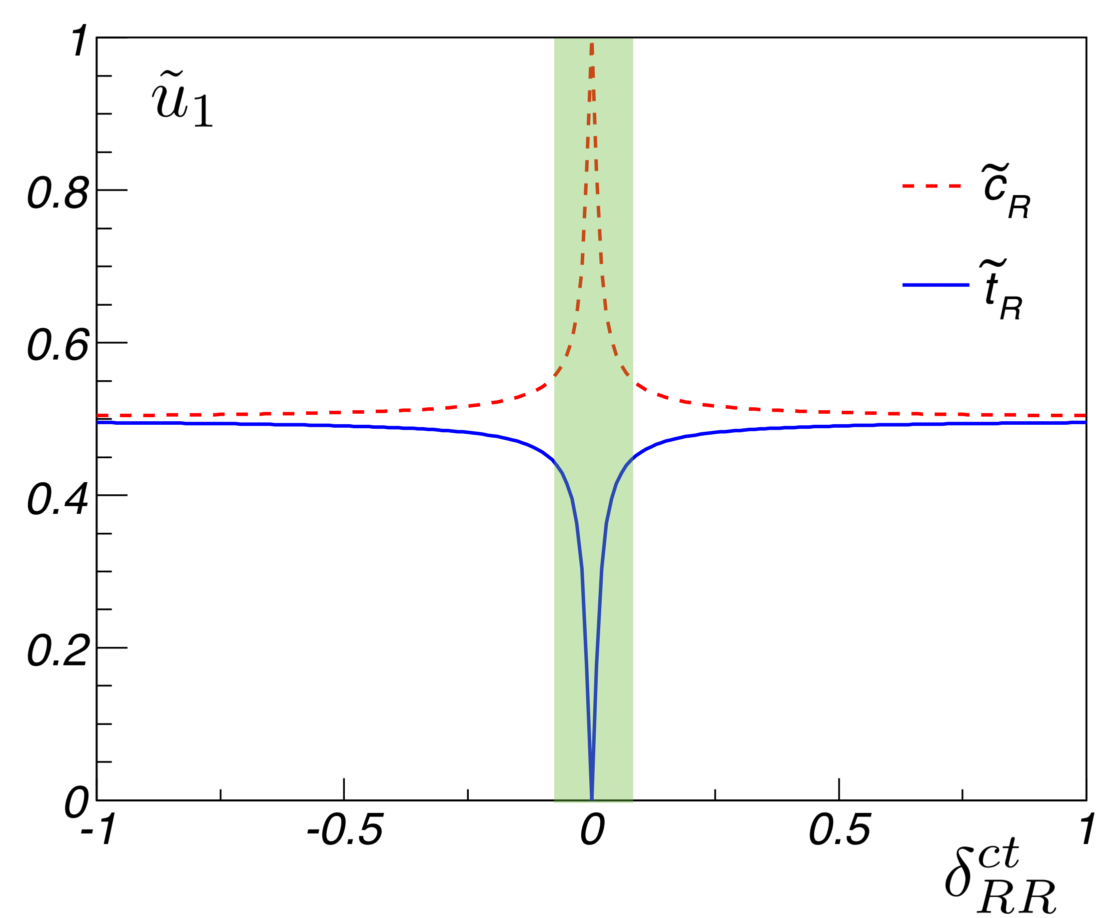
Simplified parameter setup featuring NMFV

Two active squark flavours — **bino-like neutralino** — all other states decoupled

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{tc} & \sin\theta_{tc} \\ -\sin\theta_{tc} & \cos\theta_{tc} \end{pmatrix} \begin{pmatrix} \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} \qquad m_{\tilde{\chi}_1^0} < m_{\tilde{u}_1} < m_{\tilde{u}_2}$$

This four-parameter setup captures the essential features of non-minimal flavour mixing

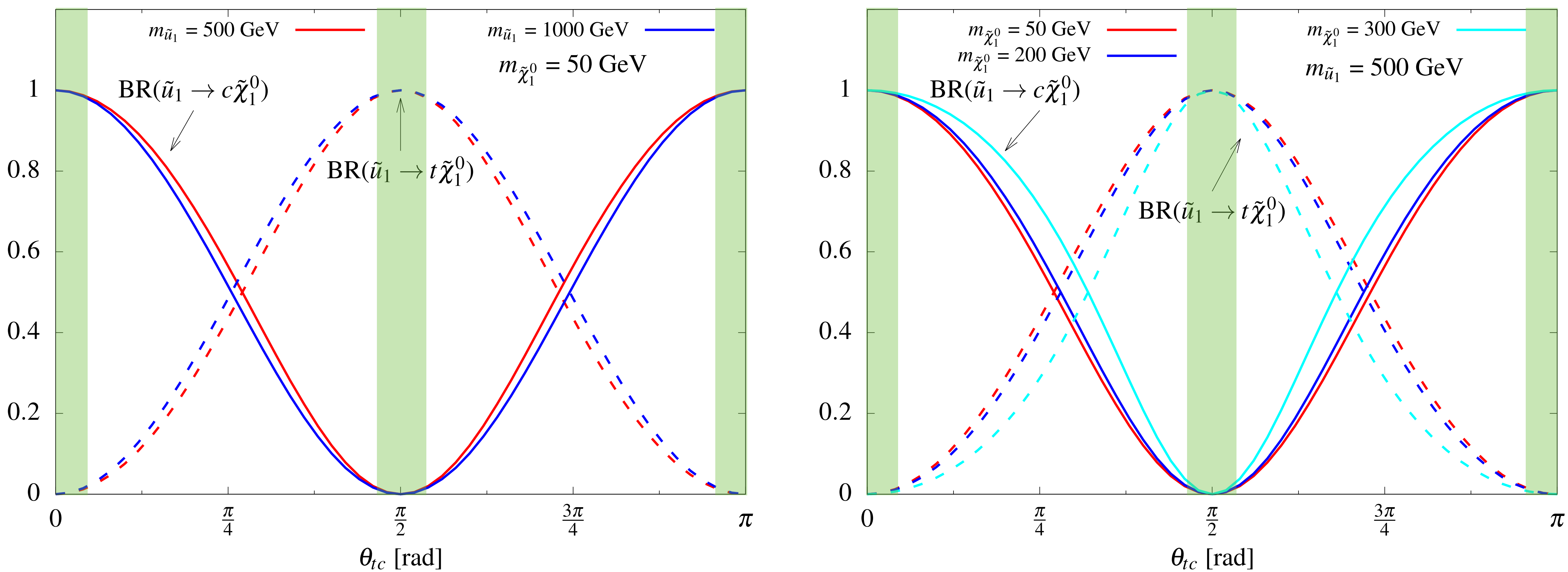




Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — *Eur.Phys.J.C* 78 (2018) 10, 844 — arXiv:1808.07488 [hep-ph]

Squark production and decay in the NMFV-MSSM

The flavour-violating elements influence squark masses, flavour decomposition, production cross-sections and open new decay channels — **characteristic NMFV signatures at LHC**

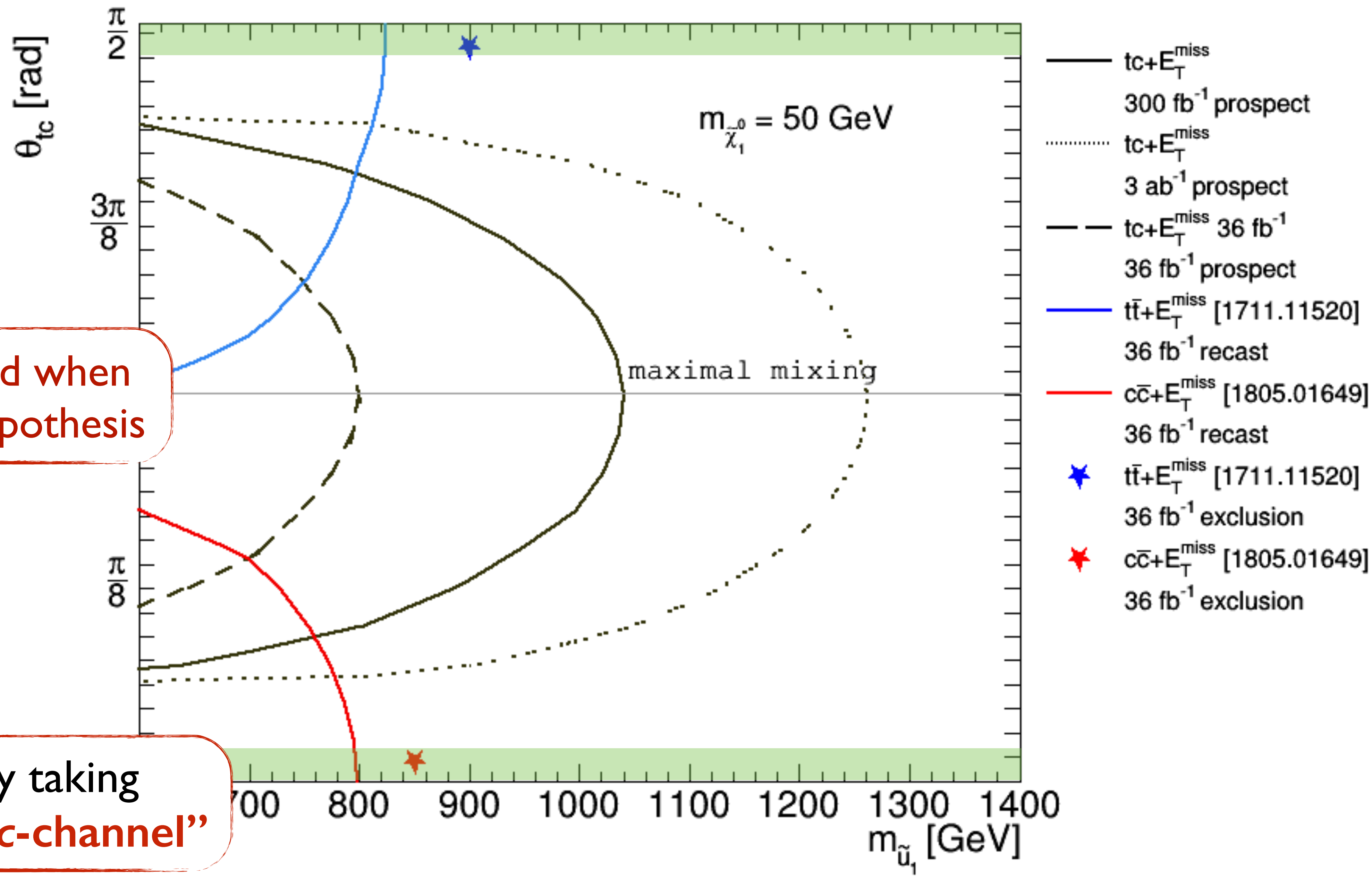


Both decay modes of a mixed squark can be equally important — **expect weaker limits!**

Impact of mass configuration on the branching ratio less important than flavour content…

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — *Eur.Phys.J.C* 78 (2018) 10, 844 — arXiv:1808.07488 [hep-ph]

Modified limits and complementary analysis



Limits are weakened when relaxing the MFV hypothesis

Gap may be filled by taking into account the **"*tc*-channel"**

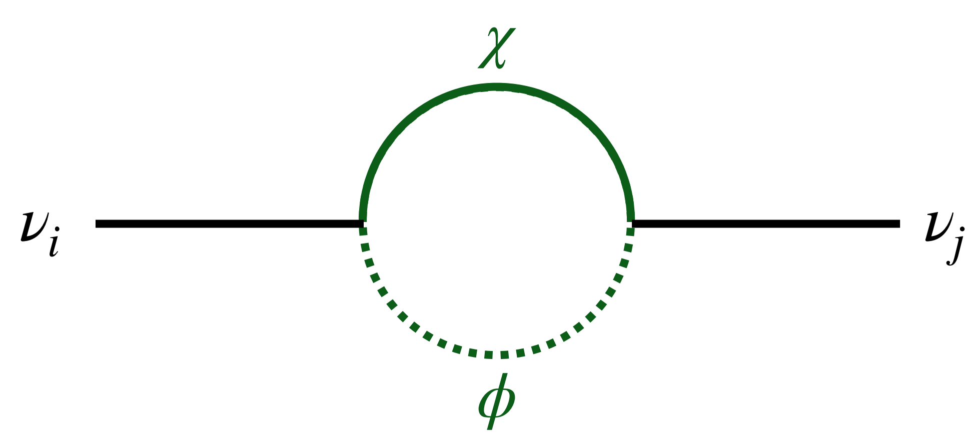
$$pp \;\to\; \tilde{u}_1\, \tilde{u}_1^* \;\to\; t\, c\, \tilde{\chi}_1^0\, \tilde{\chi}_1^0 \;\to\; \ell\, b\, c\, E_T^{\rm miss}$$

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — *Eur.Phys.J.C* 78 (2018) 10, 844 — arXiv:1808.07488 [hep-ph]

Scotogenic frameworks

"σκότος" — "darkness"

"γεννώ" — "generate"



Radiative generation of neutrino masses involving particles from the dark sector…

A singlet-doublet scotogenic framework

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left[v + h^0 + iG^0\right] \end{pmatrix} \quad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left[\phi^0 + iA^0\right] \end{pmatrix} \quad S \qquad \Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix} \quad \Psi_2 = \begin{pmatrix} -\left(\Psi_2^-\right)^\dagger \\ \left(\Psi_2^0\right)^\dagger \end{pmatrix} \quad F$$

Standard Model + $\phi_1^0,\ \phi_2^0,\ A^0,\ \phi^\pm$ + $\chi_1^0, \chi_2^0, \chi_3^0,\ \chi^\pm$

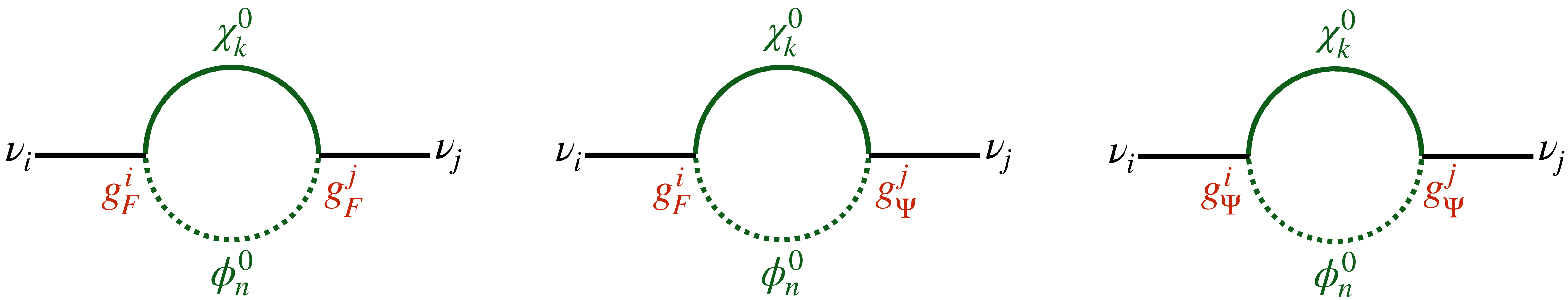
Scalars — Fermions

$$-\mathscr{L}_{\text{scalar}} = \mu_H^2\left|H\right|^2 + \lambda_H\left|H\right|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{4S}S^4 + \mu_\Phi^2\left|\Phi\right|^2 + \lambda_{4\Phi}\left|\Phi\right|^4 + \frac{1}{2}\lambda_S S^2\left|H\right|^2 + \lambda_\Phi\left|\Phi\right|^2\left|H\right|^2 + \lambda'_\Phi\left|H\Phi^\dagger\right|^2 + \frac{1}{2}\lambda''_\Phi\left\{\left(H\Phi^\dagger\right)^2 + \text{h.c.}\right\} + T\left\{SH\Phi^\dagger + \text{h.c.}\right\}$$

$$-\mathscr{L}_{\text{fermion}} = -\frac{i}{2}\left(\overline{\Psi}_1\sigma^\mu D_\mu\Psi_1 + \overline{\Psi}_2\sigma^\mu D_\mu\Psi_2\right) + \frac{1}{2}M_F F^2 + M_\Psi\Psi_1\Psi_2 + y_1\Psi_1 HF + y_2\overline{\Psi}_2 H\overline{F} + \text{h.c.}$$

$$-\mathscr{L}_{\text{int}} = g_\Psi^i\Psi_2 L_i S + g_F^i\Phi L_i F + g_R^i L_{Ri}^c\Phi^\dagger\Psi_1$$

Neutrino masses and coupling parameters

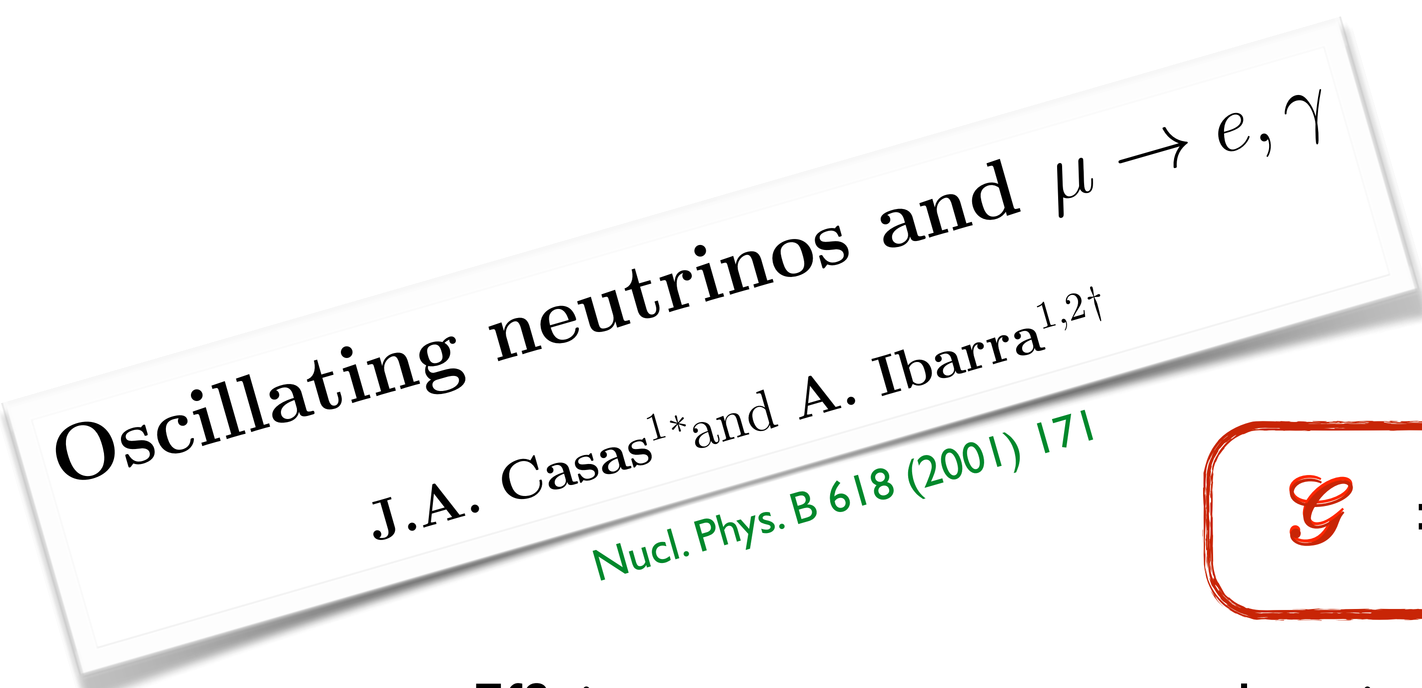


$$\sim g_F^j \frac{m_{F_k}}{16\pi^2} B_0(0; m_{\chi_k}, m_{\phi_n})\ g_F^i$$

$$\mathscr{M}_\nu = \mathscr{G}^t M_{\text{Loop}} \mathscr{G}$$

Neutrino mass matrix

$$\mathscr{G} = \begin{pmatrix} g_\Psi^1 & g_\Psi^2 & g_\Psi^3 \\ g_F^1 & g_F^2 & g_F^3 \end{pmatrix}$$


Oscillating neutrinos and $\mu \to e, \gamma$

J.A. Casas[1*] and A. Ibarra[1,2†]

Nucl. Phys. B 618 (2001) 171

Rotation matrix

Neutrino masses and mixing angles

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

Efficient parameter space exploration thanks to **Casas-Ibarra parametrization**

Parameters and constraints

Observable	Constraint
m_H	125.0 ± 3.0 GeV
$\Omega_{\rm CDM} h^2$	0.1198 ± 0.0042
$\mathrm{BR}(\mu^- \to e^- \gamma)$	$< 4.2 \cdot 10^{-13}$
$\mathrm{BR}(\tau^- \to e^- \gamma)$	$< 3.3 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \gamma)$	$< 4.4 \cdot 10^{-8}$
$\mathrm{BR}(\mu^- \to e^- e^+ e^-)$	$< 1.0 \cdot 10^{-12}$
$\mathrm{BR}(\tau^- \to e^- e^+ e^-)$	$< 2.7 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \mu^+ \mu^-)$	$< 2.1 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^+ e^- e^-)$	$< 1.5 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^-)$	$< 2.1 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^+ \mu^- \mu^-)$	$< 1.7 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^- \mu^+ \mu^-)$	$< 2.7 \cdot 10^{-8}$

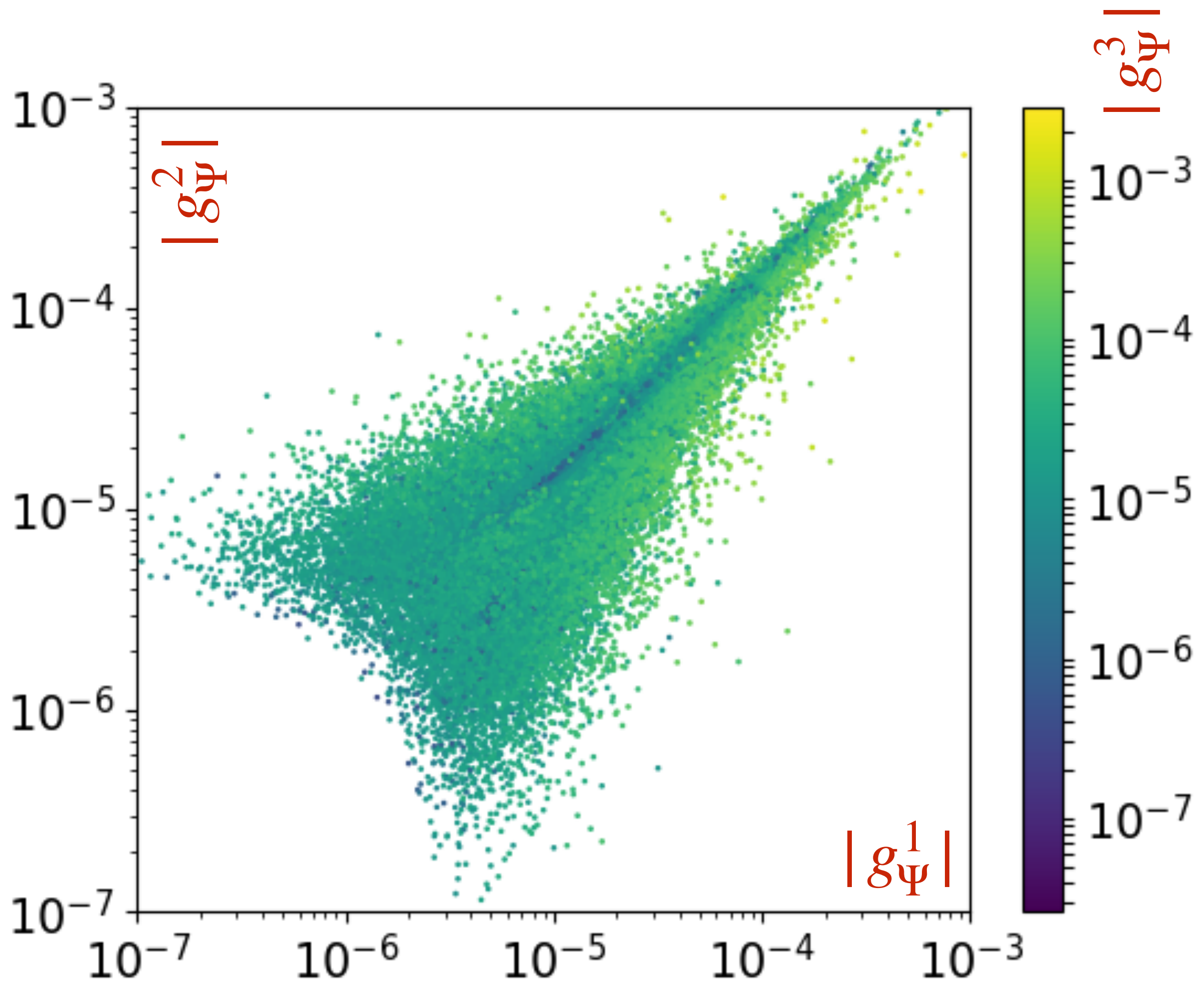
Observable	Constraint
$\mathrm{BR}(Z^0 \to e^\pm \mu^\mp)$	$< 7.5 \cdot 10^{-7}$
$\mathrm{BR}(Z^0 \to e^\pm \tau^\mp)$	$< 9.8 \cdot 10^{-6}$
$\mathrm{BR}(Z^0 \to \mu^\pm \tau^\mp)$	$< 1.2 \cdot 10^{-5}$
$\mathrm{BR}(\tau^- \to e^- \pi^0)$	$< 8.0 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \pi^0)$	$< 1.1 \cdot 10^{-7}$
$\mathrm{BR}(\tau^- \to e^- \eta)$	$< 9.3 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^- \eta')$	$< 1.6 \cdot 10^{-7}$
$\mathrm{BR}(\tau^- \to \mu^- \eta)$	$< 6.5 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \eta')$	$< 1.3 \cdot 10^{-7}$
$\mathrm{CR}_{\mu \to e}(\mathrm{Ti})$	$< 4.3 \cdot 10^{-12}$
$\mathrm{CR}_{\mu \to e}(\mathrm{Pb})$	$< 4.6 \cdot 10^{-11}$
$\mathrm{CR}_{\mu \to e}(\mathrm{Au})$	$< 7.0 \cdot 10^{-13}$

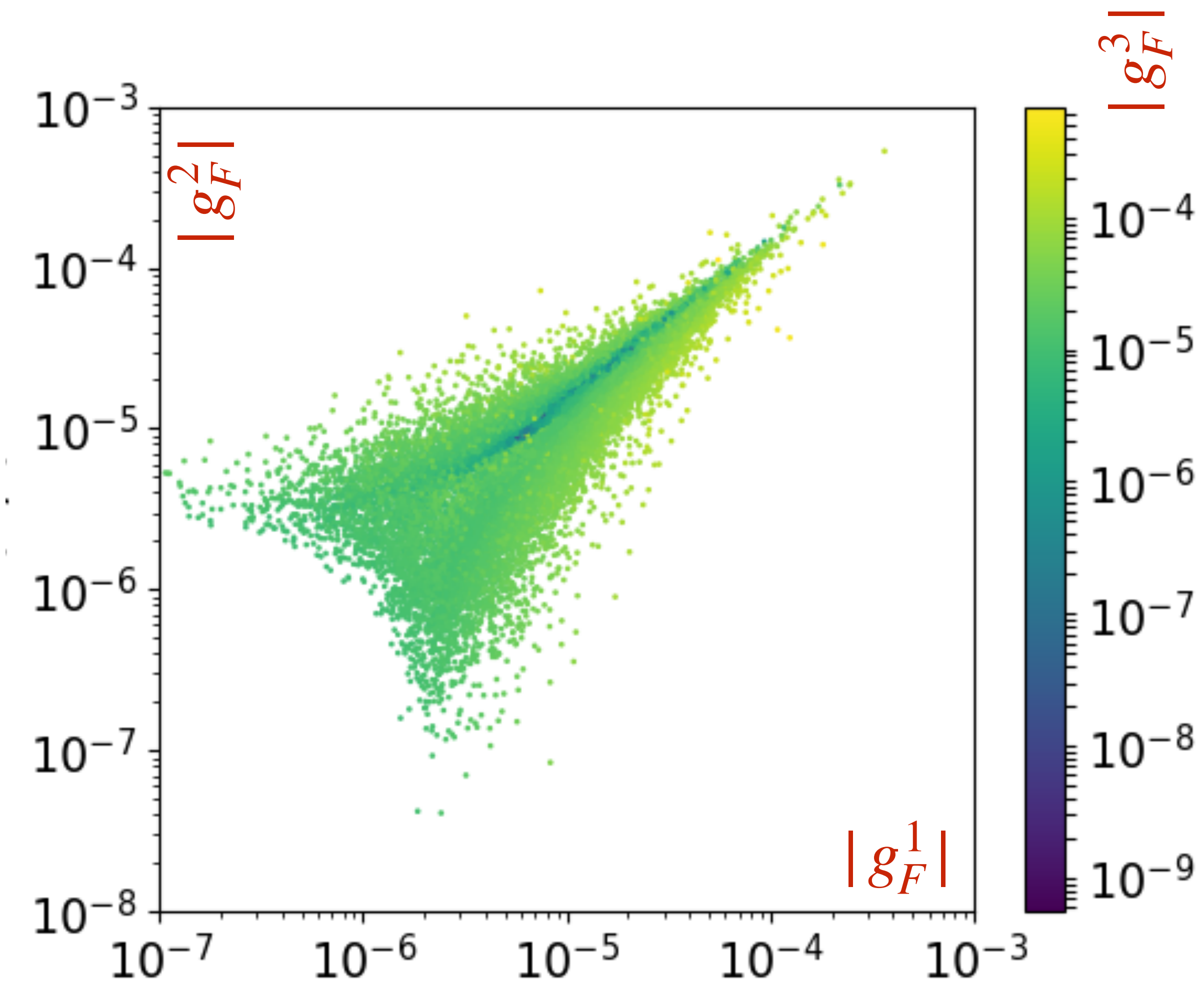
+ dark matter direct detection limits (XENON-1T)

Numerical evaluation — **SARAH** + **SPheno** Staub, Porod, Goodsell (2003-2021)

— **micrOMEGAs** Bélanger, Boudjema, Pukhov, Semenov *et al.* (2004-2021)

Coupling parameters

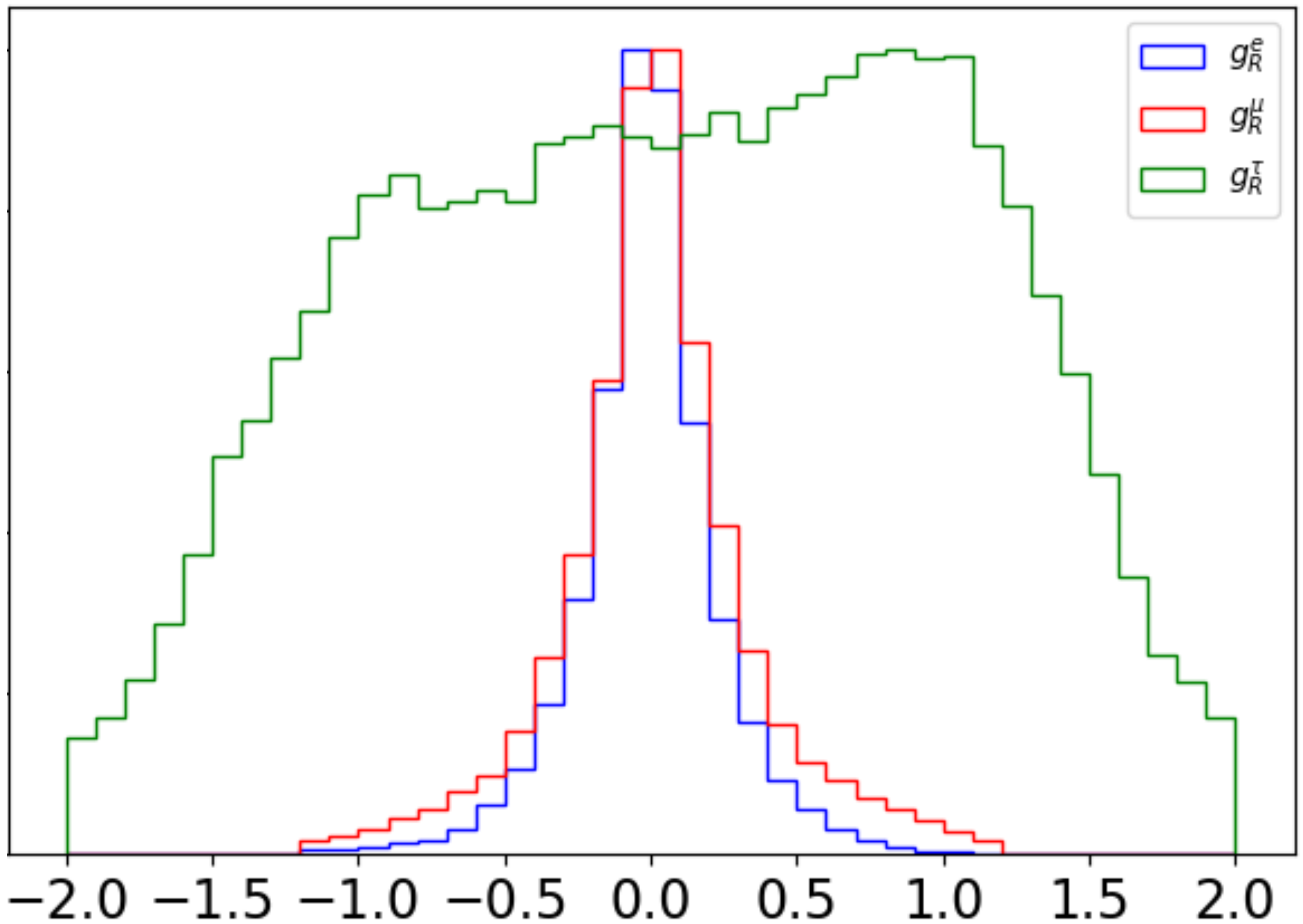


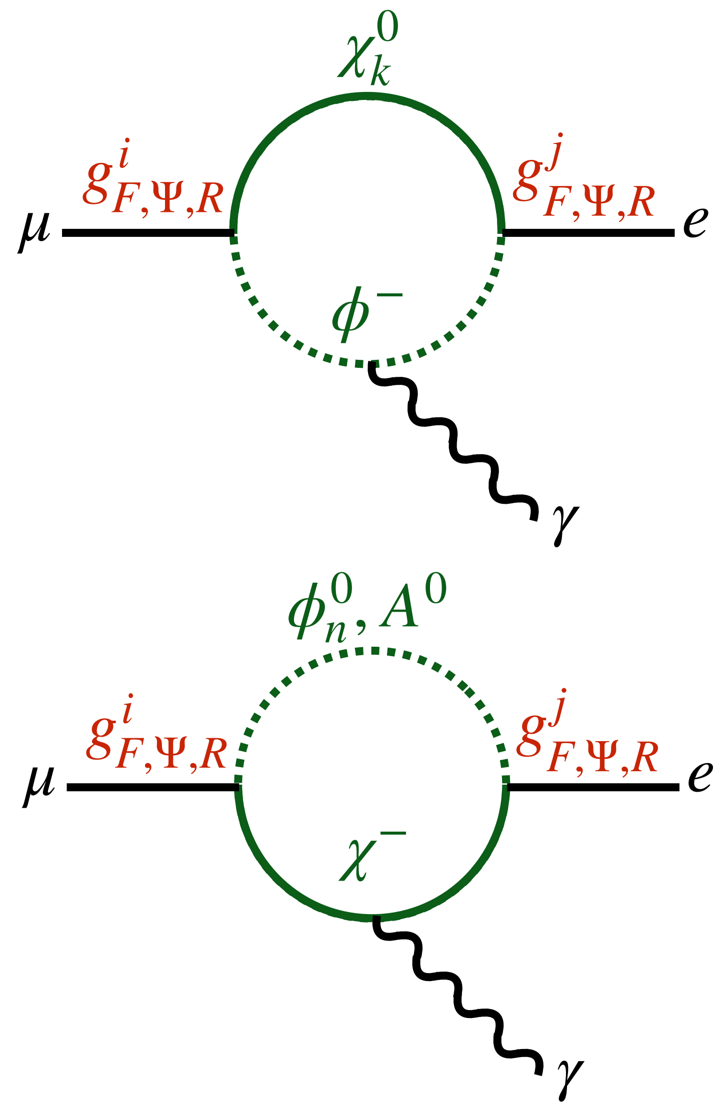


Couplings g_F and g_Ψ mainly bound by **neutrino mass constraints**
(via Casas-Ibarra parametrization)

$$\bar{\mathcal{G}} = \left(g_\Psi^1 g_\Psi^2 g_\Psi^3 g_F^1 g_F^2 g_F^3\right)^{1/6} \sim 10^{-5} - 10^{-4}$$

Coupling parameters

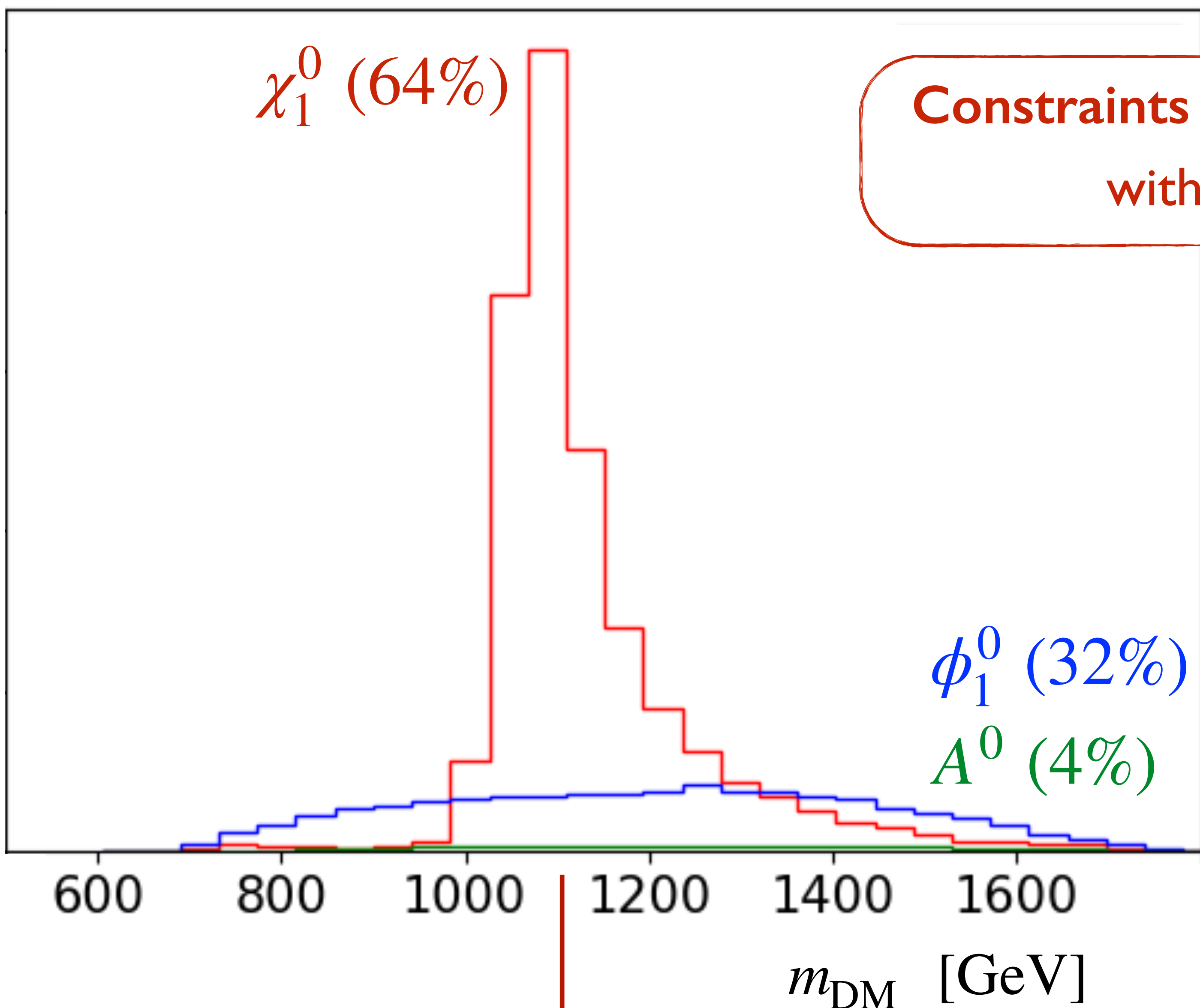




Couplings g_R constrained by **lepton-flavour violating processes**

(in particular $\mu \to e\gamma$)

Dark matter mass and nature

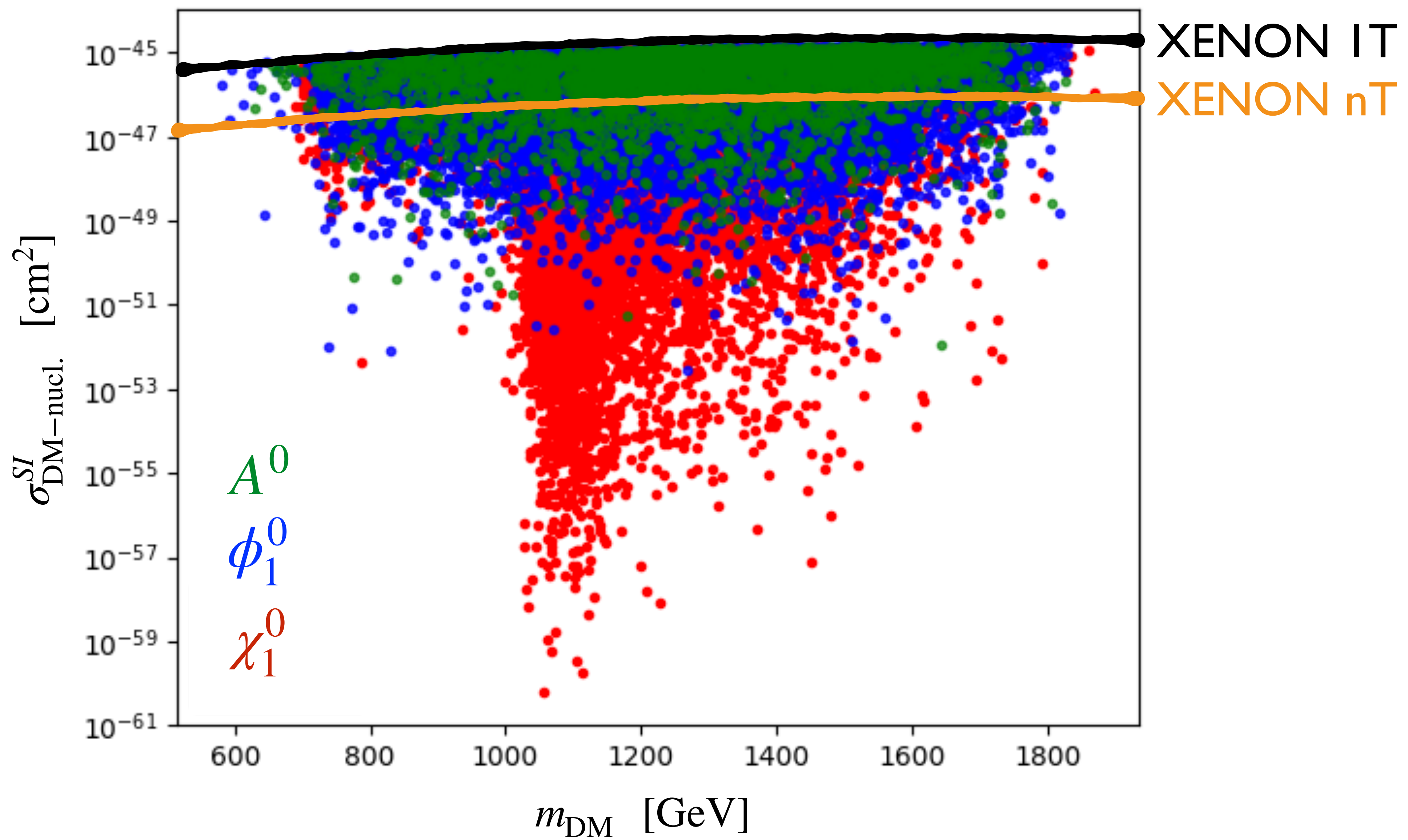


Constraints prefer fermionic dark matter
with $m_{\chi_1^0} \sim 1.0 - 1.2$ TeV

Scalar dark matter mainly singlet-like

Fermion mass prediction driven by co-annihilations
(dark matter mainly doublet-dominated)

Direct detection



Upcoming experiments will constrain mainly (doublet-like) scalar dark matter

Fermionic dark matter (especially the doublet) difficult to constrain

— efficient co-annihilation around m_{DM} $1-1.2$ TeV allows for small couplings

Summary and outlook

No direct signal for new physics so far…

New physics may be hiding in "next-to-simple" decay patterns…

Mass spectrum may be quite predictive due to various constraints…

Interesting times lay ahead of us!

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