CRC FlavCC workshop
November 2021

Simplified models with flavour violation

Michael Krämer (RWTH Aachen University)

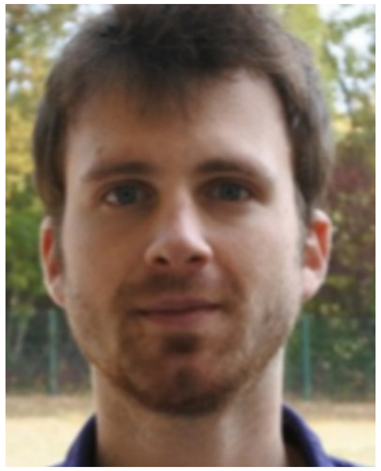
C3a: New sources of flavour and CP violation at high transverse momenta

Monika Blanke

Michael Krämer

Margarete Mühlleitner

Harun Acaroğlu



Jordan Bernigaud

Jan Heisig

Lena Rathmann

Motivation

Why BSM flavour physics?

- flavour and CP are not good symmetries of nature, already violated in the SM (Yukawa couplings, CKM matrix)
- concrete BSM models typically introduce new sources of flavour and CP violation
- B meson anomalies provide the most promising experimental hints for breakdown of SM at the TeV scale

Questions addressed in C3a

➢ What is the impact of a non-trivial flavour structure on direct LHC searches for new particles?

➢ Can high-p_T physics provide a complementary probe of the BSM flavour and CP structure?

Simplified models

PHYSICAL REVIEW D **79,** 075020 (2009)

Simplified models for a first characterization of new physics at the LHC

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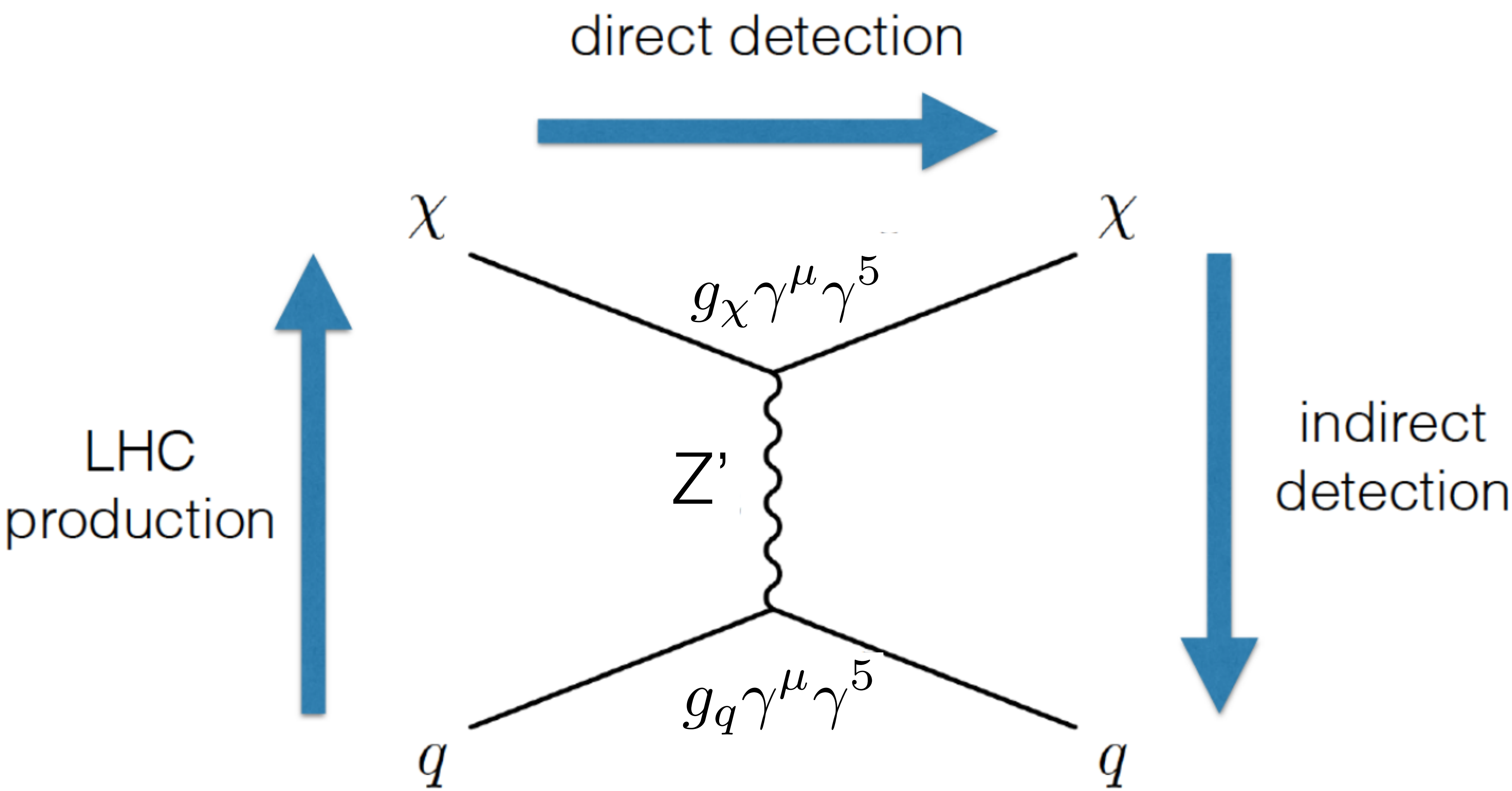
(Received 28 October 2008; published 24 April 2009)

Low-energy supersymmetry (SUSY) and several other theories that address the hierarchy problem predict pair-production at the LHC of particles with standard model quantum numbers that decay to jets, missing energy, and possibly leptons. If an excess of such events is seen in LHC data, a theoretical framework in which to describe it will be essential to constraining the structure of the new physics. We propose a basis of four deliberately simplified models, each specified by only 2–3 masses and 4–5 branching ratios, for use in a first characterization of data. Fits of these simplified models to the data furnish a quantitative presentation of the jet structure, electroweak decays, and heavy-flavor content of the data, independent of detector effects. These fits, together with plots comparing their predictions to distributions in data, can be used as targets for describing the data within any full theoretical model.

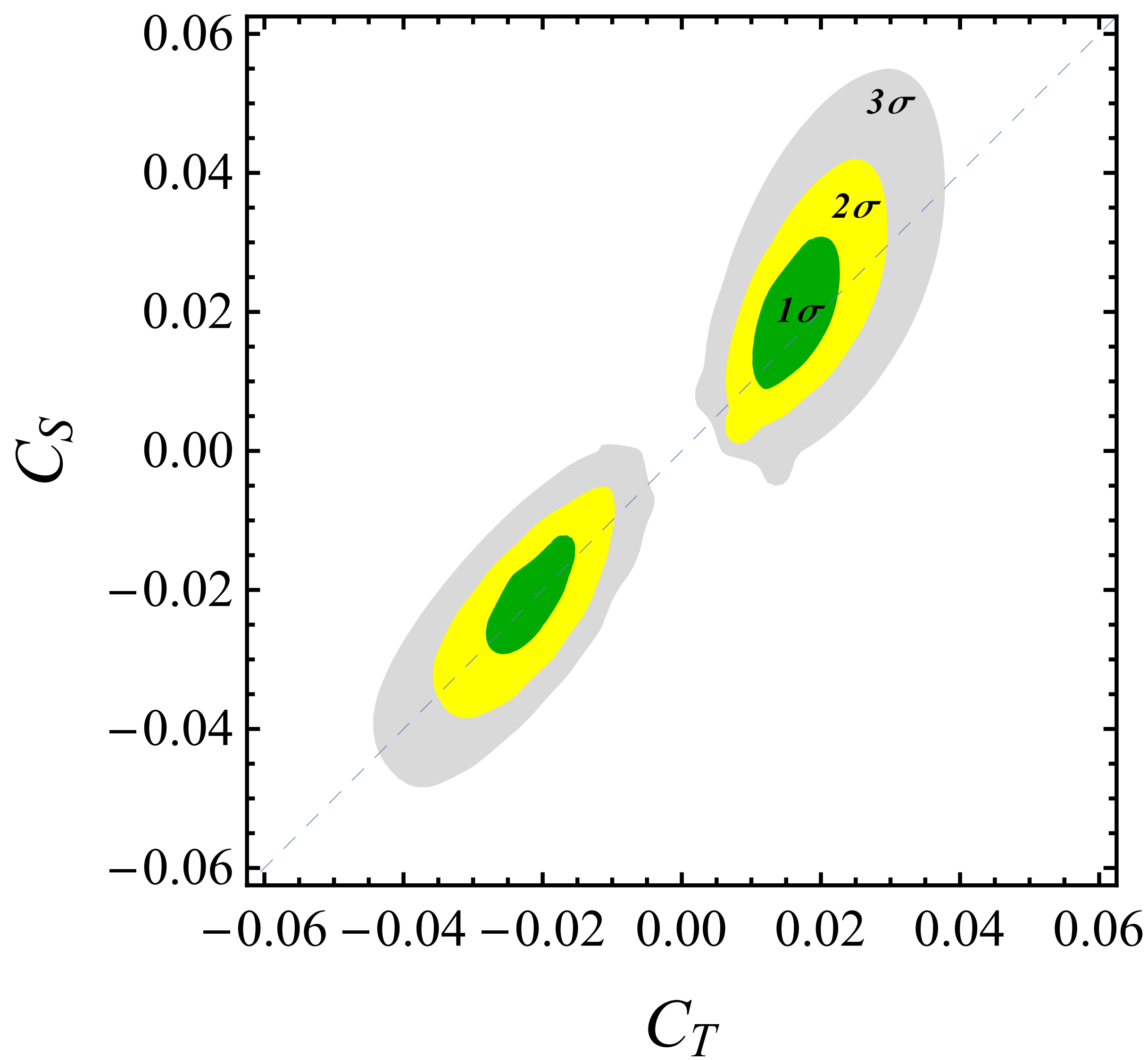
Simplified models



B physics anomalies

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

arXiv:1706.07808 [hep-ph]



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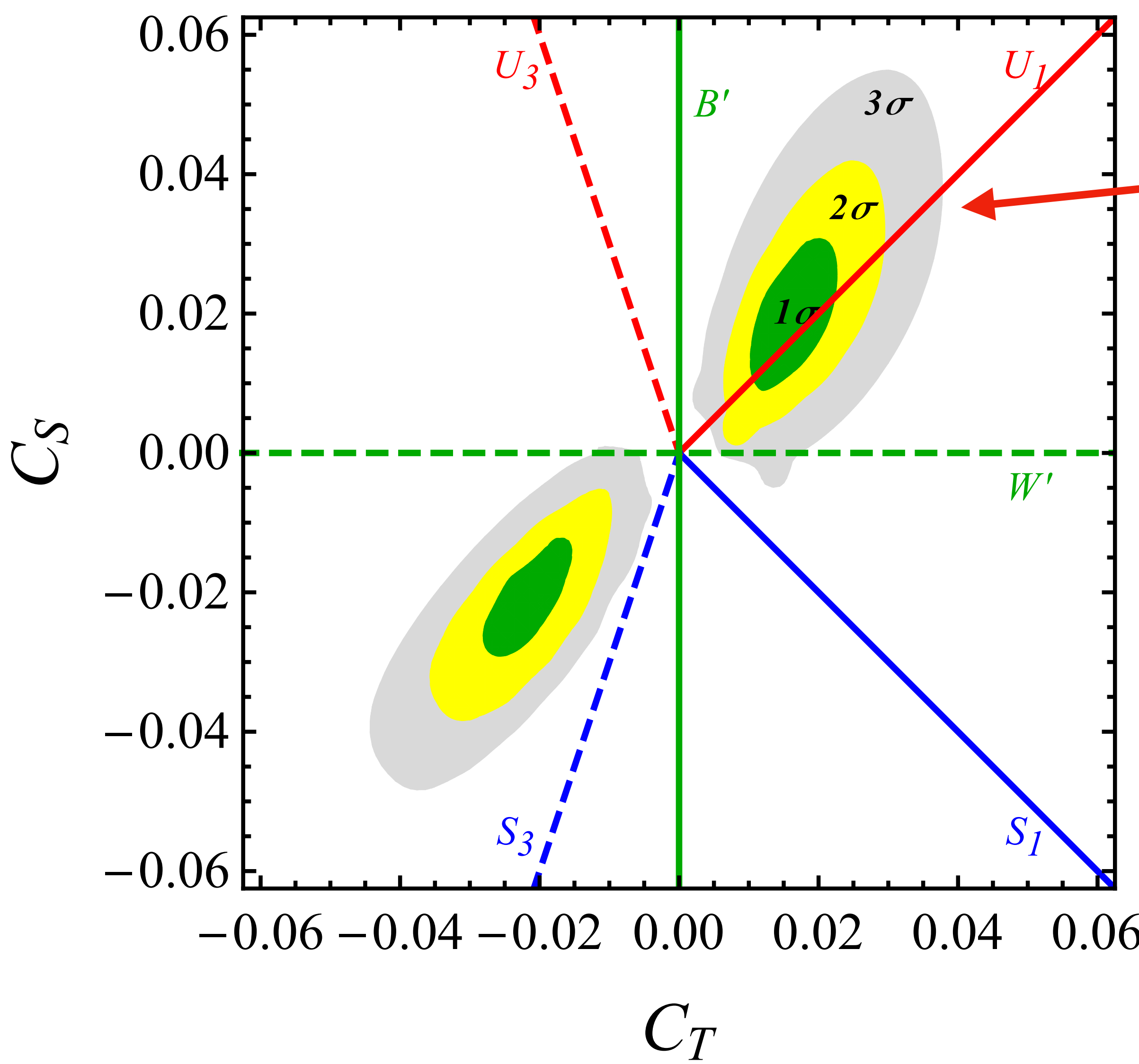

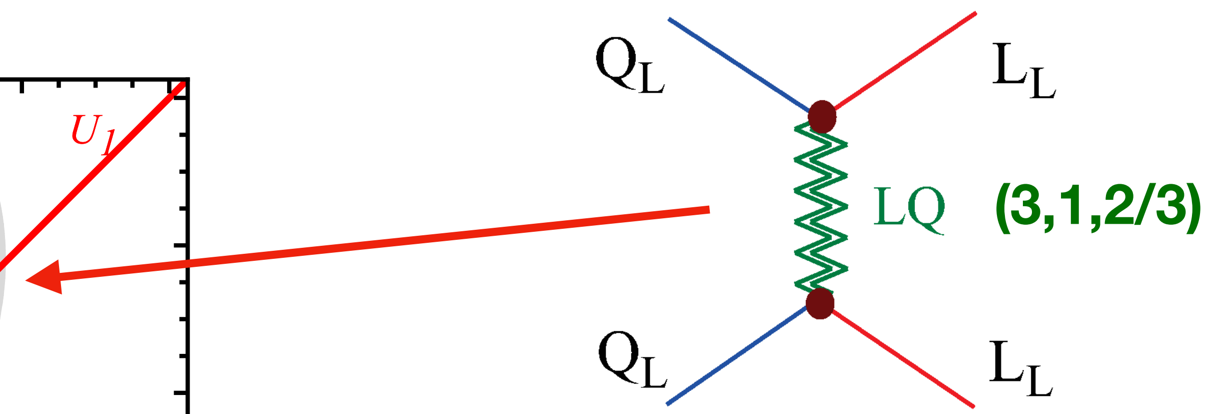

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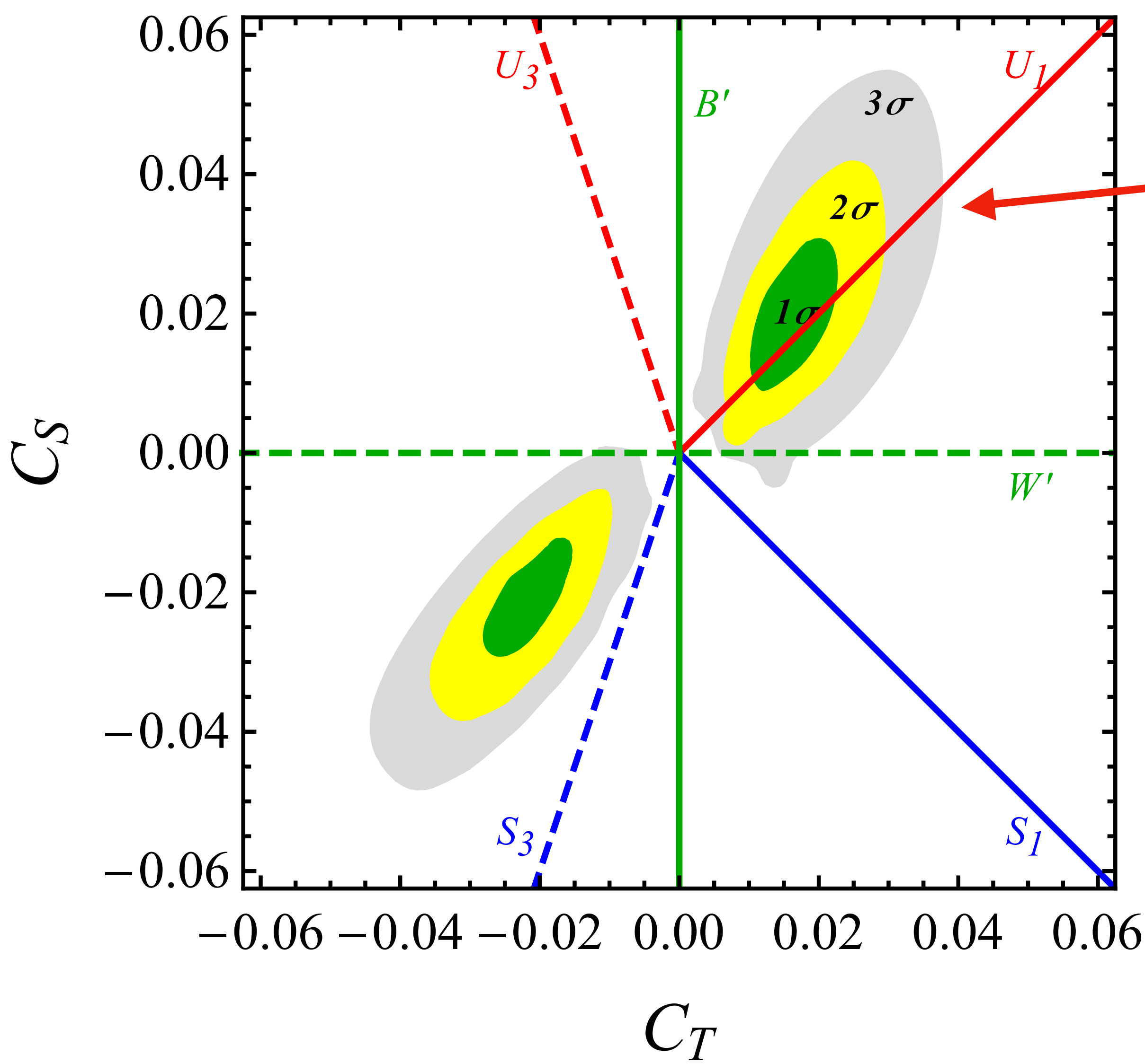
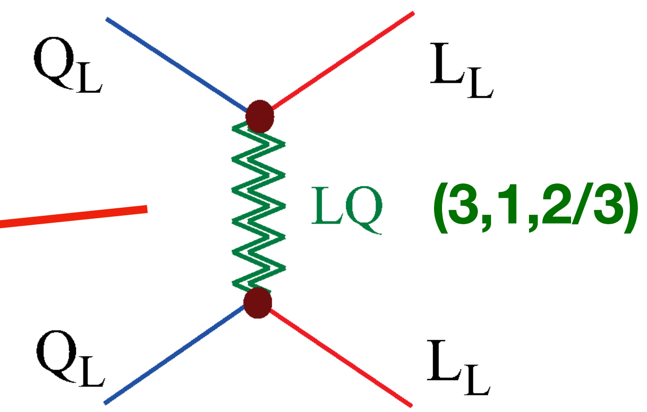




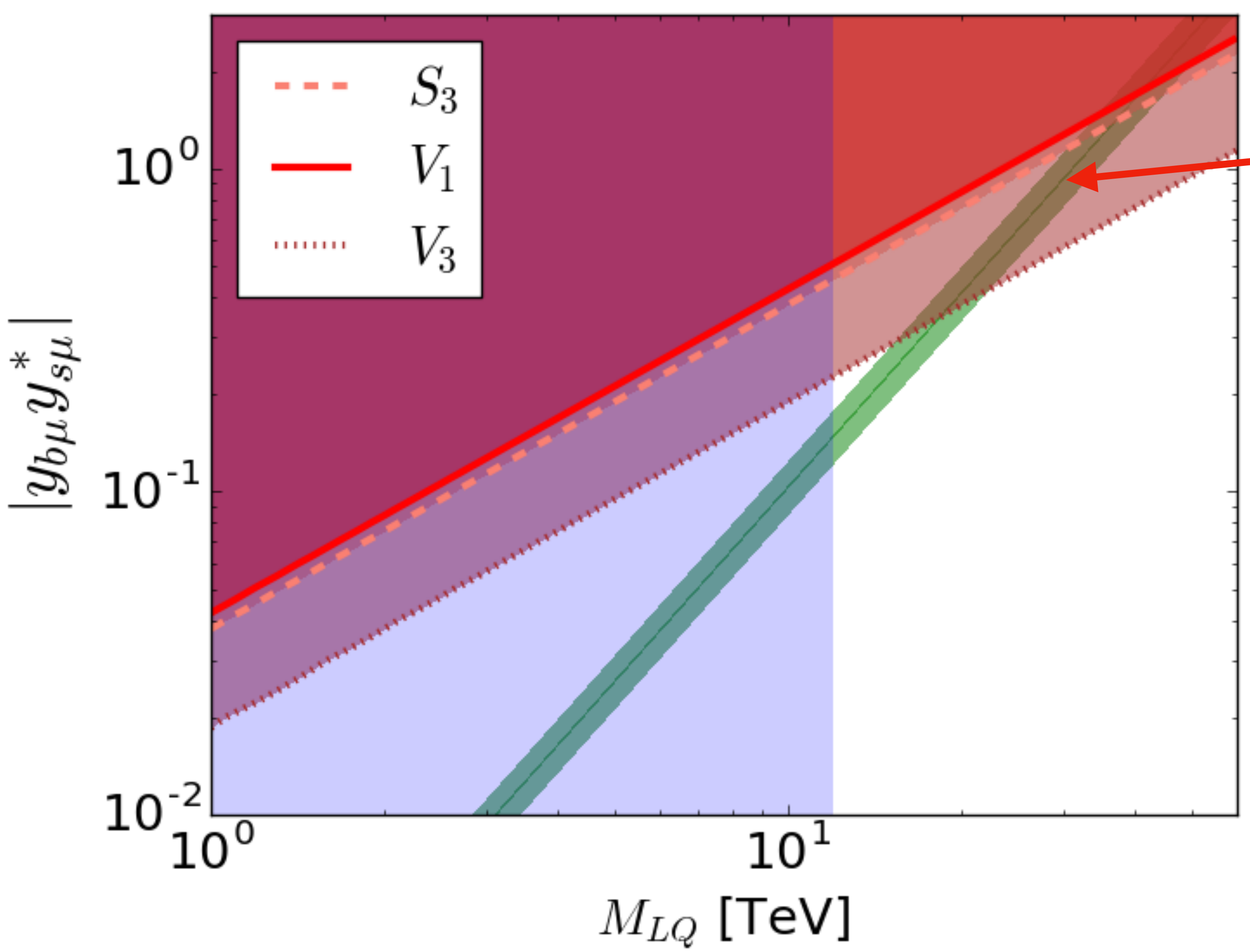
Simplified Models

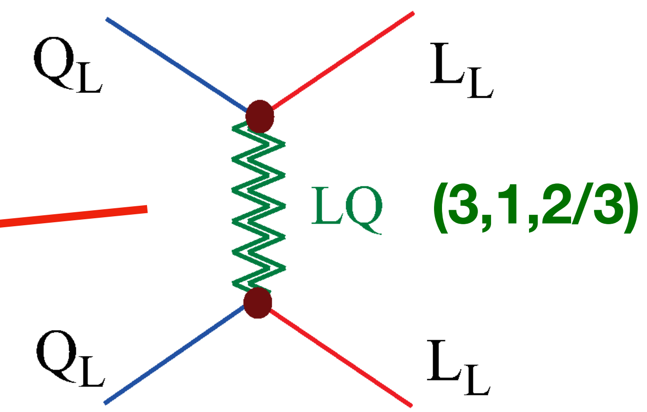
- provide a reliable framework for LHC analyses;
- allow to connect flavour physics with other (dark matter) searches.

B physics anomalies

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

arXiv:1710.06363 [hep-ph]





B physics anomalies

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

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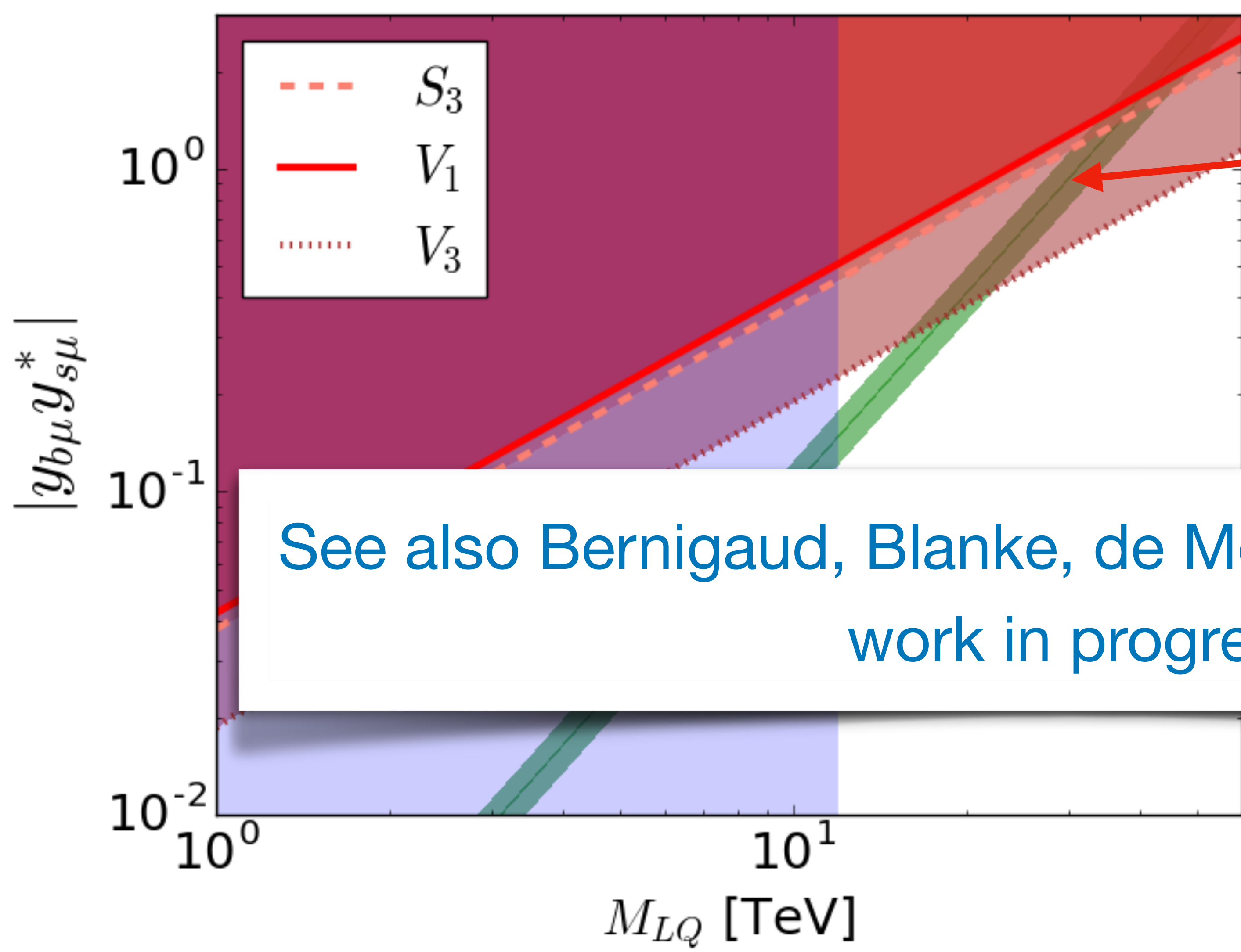

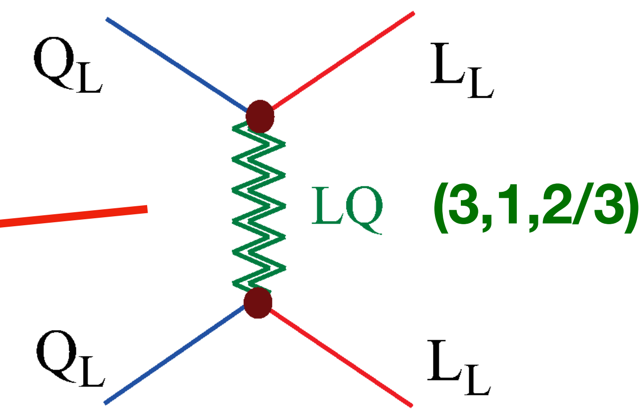

See also Bernigaud, Blanke, de Medeiros, Talbert, Zurita, work in progress

B physics anomalies

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

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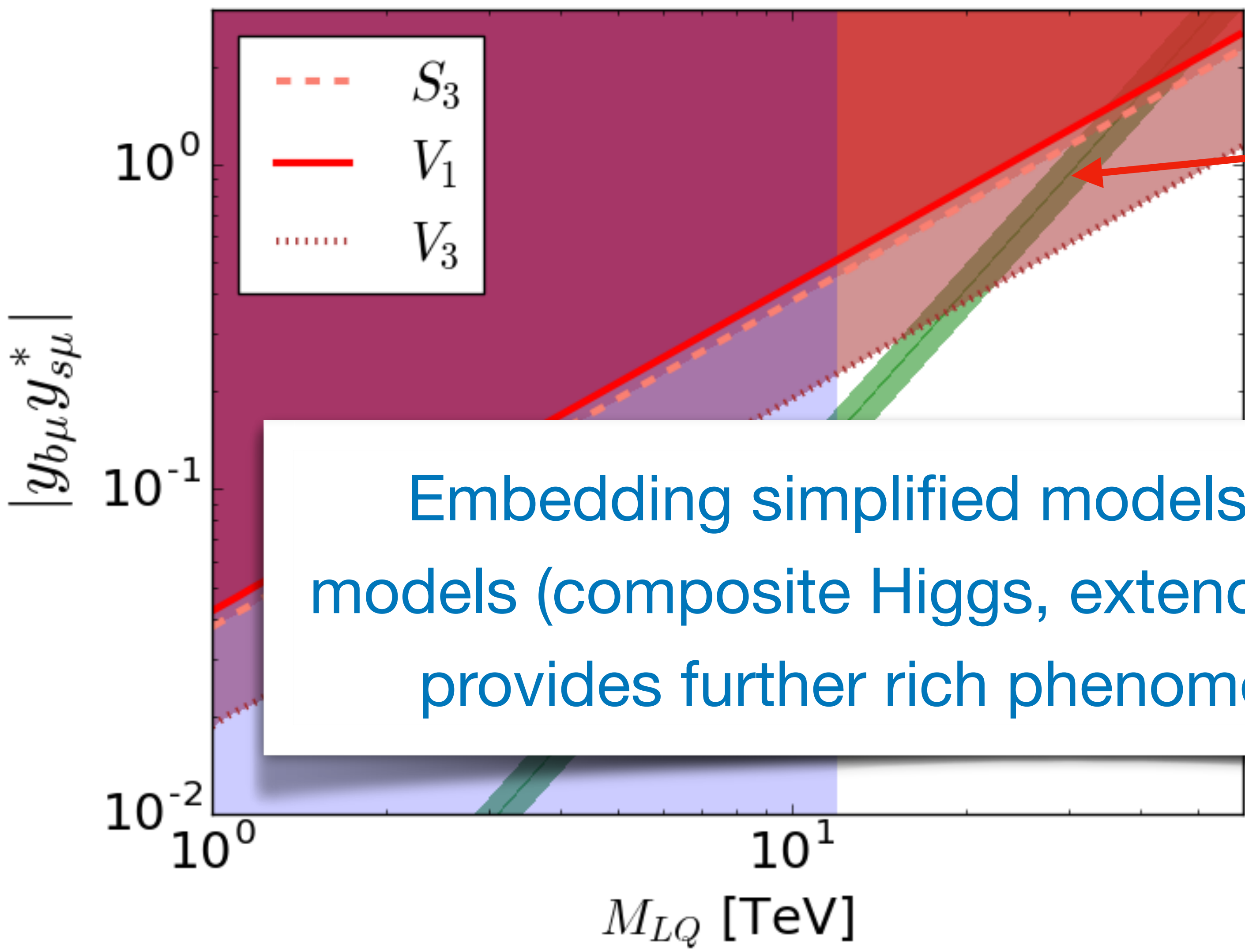
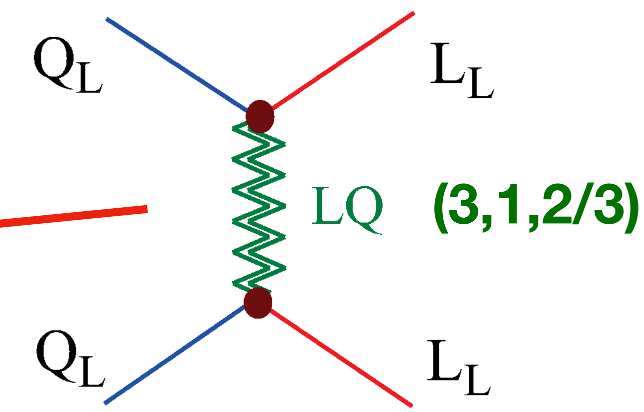




Embedding simplified models into UV complete models (composite Higgs, extended gauge sectors,…) provides further rich phenomenology and tests

B physics anomalies

Speculations on UV completions

Second observation: we can "protect" the light families charging under SU(4) only the 3rd gen. or, more generally, "separating" the universal SU(3) component

PS group: $SU(4) \times SU(2)_L \times SU(2)_R$

- *flavor universality*

4321 models: $SU(4) \times SU(3) \times G_{EW} = \begin{cases} SU(2)_L \times SU(2)_R \\ SU(2)_L \times U(1)_Y \end{cases}$

$SU(4) \times SU(3)$

- *Non-universality via mixing*

$SU(4)_3 \times SU(3)_{1,2}$

- *Accidental* $U(2)^5$ *flavor symm. in the gauge sect.*

UV completions

$SU(3) \times G_{EW} \times G_{HC}$
Barbieri, '17

$SU(4) \times SU(3) \times G_{EW}$
Di Luzio, Greljo, Nardecchia, '17

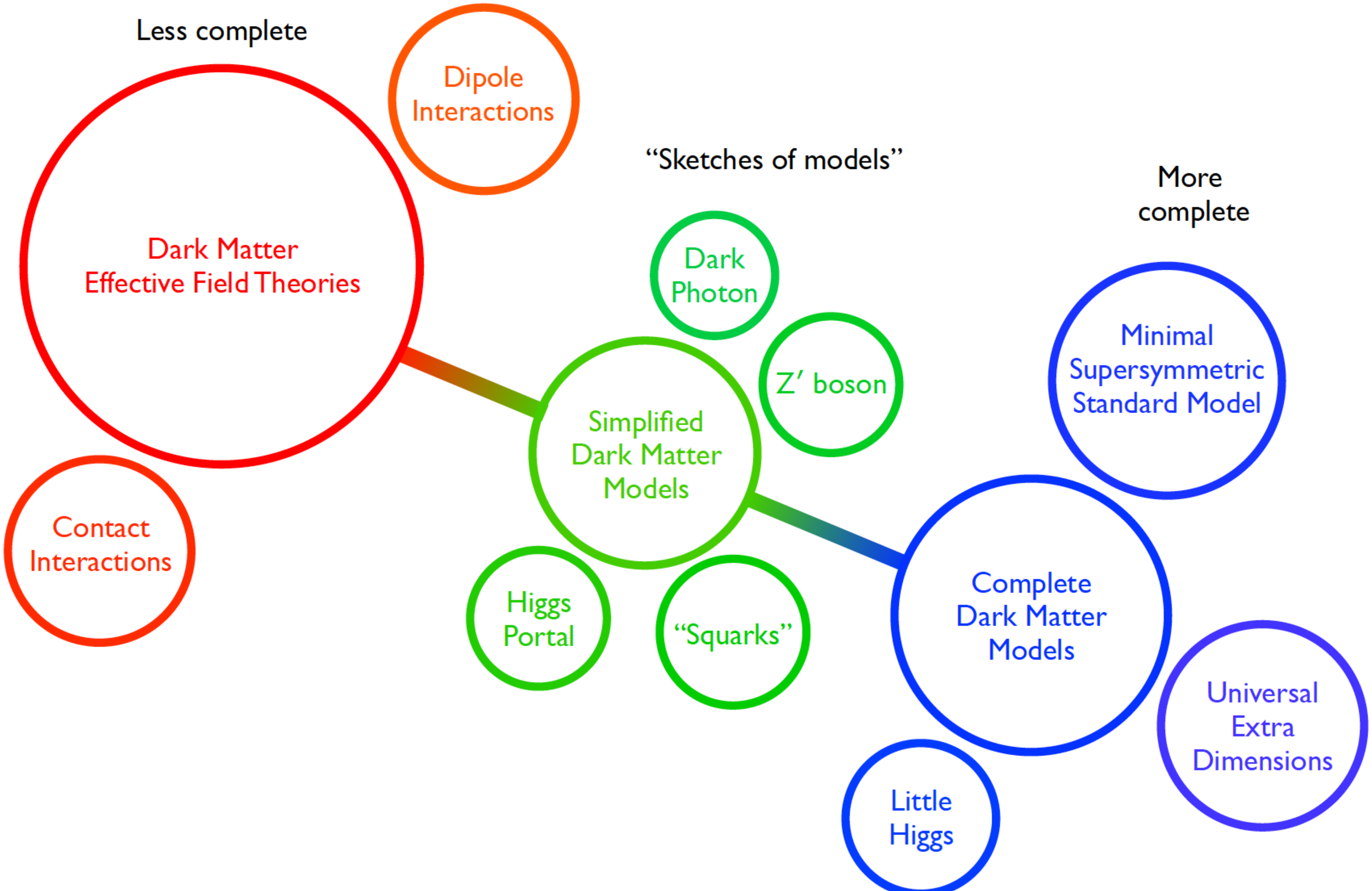
$SU(4)_h \times SU(4)_l \times G_{EW} \times G_{HC}$
Fuentes-Martin & Stangl '20

$[PS]^3 = [SU(4) \times G_{EW}]^3$
Bordone *et al.* '17

$[\ PS\ ]_{\text{warped-5d, 3-branes}}$

Fuentes-Martin *et al.* '20 + *work in prog.*

The landscape of models



arXiv:1506.03116 [hep-ph]

From full theories to EFT and back

SUSY
UED
little Higgs

Pre-LHC

LHC

Effective field theory (EFT)

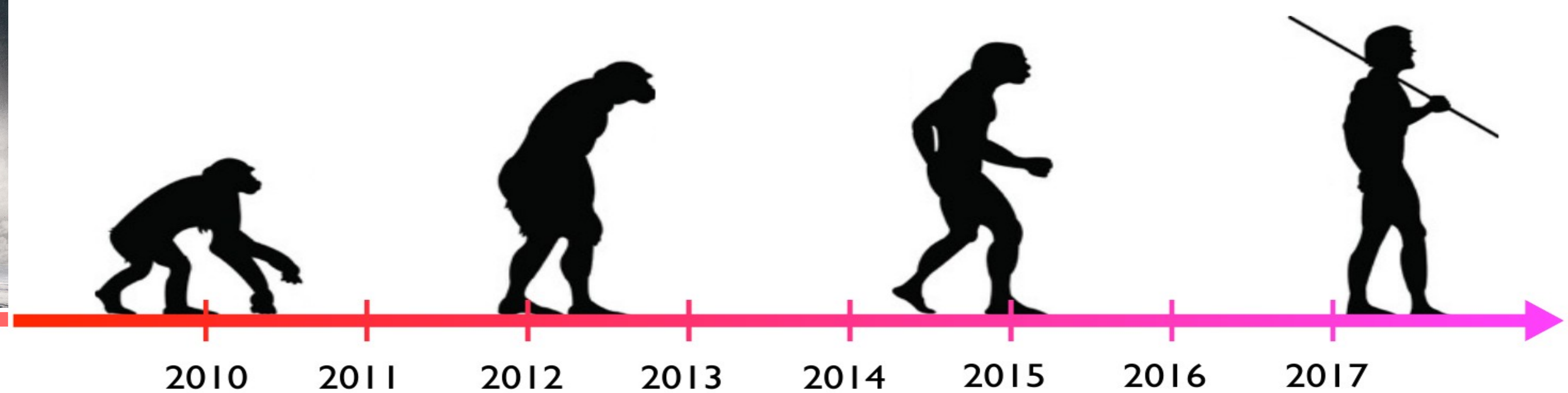
$$\frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\bar{q}q$$

Simplified models

$$g_\chi\bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$$

Consistent simplified models

$$g_\chi\bar{\chi}\chi s + Y_q\,\bar{q}Hq + \mu s|H|^2$$



(Extended from a slide by U- Haisch)

G. Polesello, Dark Matter @ LHC 2018

Simplified models

- mediate between theory and data
- allow to explore the space of theories and signatures
- allow to interpret data in a more model-independent way
- connect different kinds of searches for new physics

How do we choose the right simplified models?

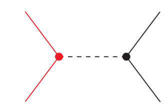
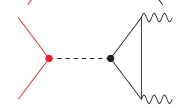
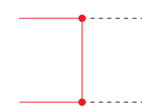
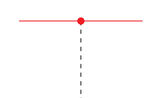
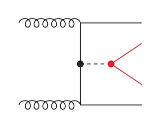
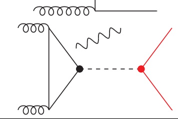
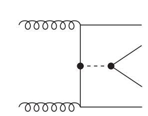
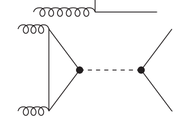
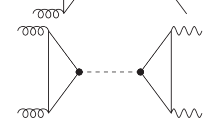
- top-down: consider limits of complete theories
- bottom-up: consider minimal extensions of the Standard Model

A good simplified model should

- connect to a wide range of complete theories
- imply novel experimental signatures
- be theoretically consistent (e.g. respect unitary)

A simplified top-philic dark matter model

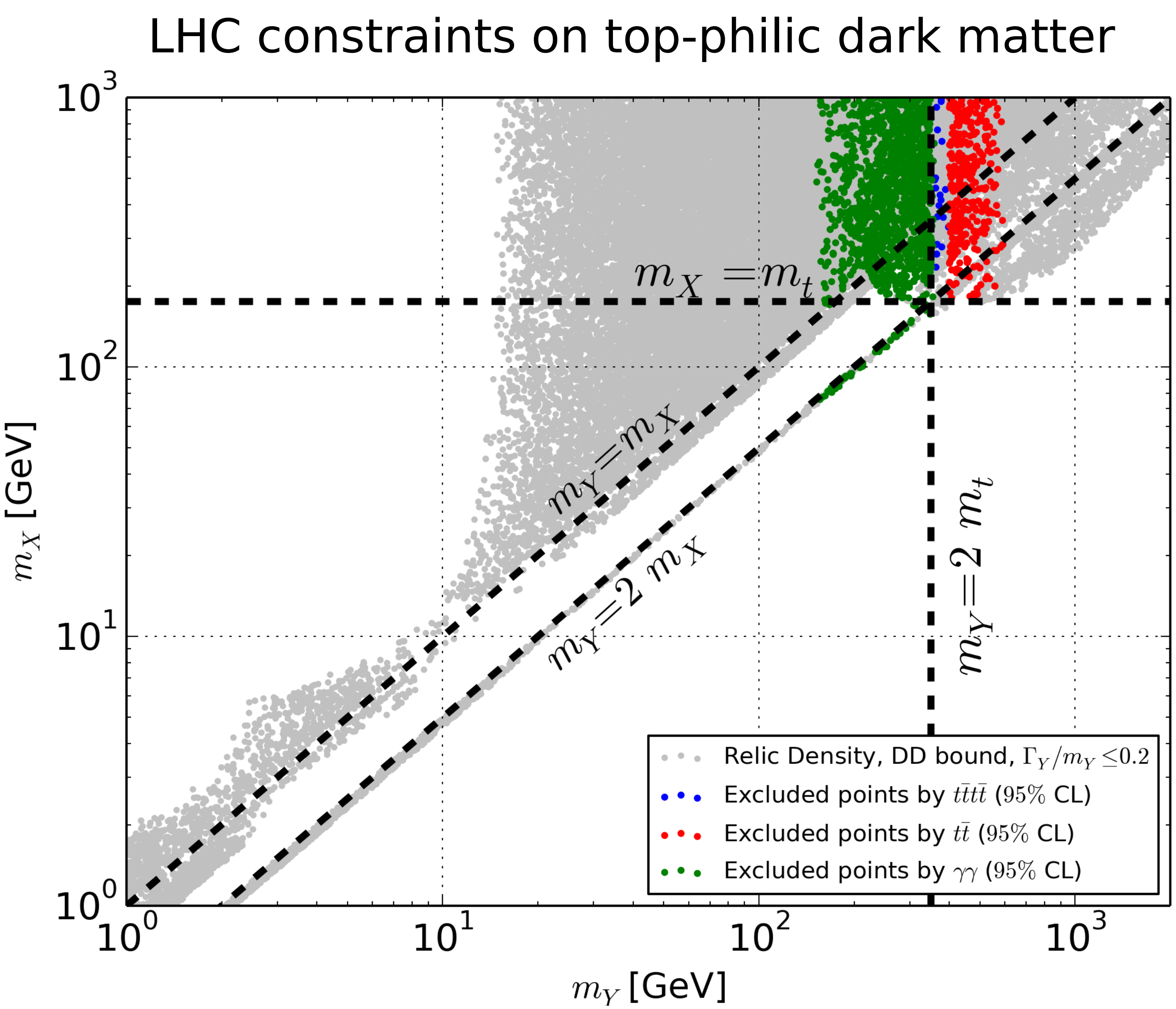
Add a fermionic DM candidate X and a scalar mediator Y to the SM

Cosmology	relic		$m_X > m_t$	
	indirect		$m_X < m_t$	Planck, FermiLAT
Astrophysics			$m_X > m_Y$	
	direct		$m_X > 1$ GeV	LUX, CDMSLite
Colliders	$\not{E}_T$		$m_Y > 2m_X$	$+t\bar{t}$
			$m_Y > 2m_X$	$+j,\ +Z,\ +h$
	no $\not{E}_T$		$m_Y > 2m_t$	$4t$
			$m_Y > 2m_t$	$t\bar{t}$
			$m_Y < 2m_X, 2m_t$	$jj,\ \gamma\gamma$

Arina,…,MK,…JHEP 1611 (2016) 111

A simplified top-philic dark matter model

Add a fermionic DM candidate X and a scalar mediator Y to the SM



Arina,...,MK,...JHEP 1611 (2016) 111

A simplified model of top-flavoured dark matter

Flavoured Dirac-fermionic DM χ_j and couples to right-handed up-type quarks via a coloured scalar mediator MB, Kast (2017)

$$\mathcal{L}_{\rm NP} = i\bar\chi \partial\!\!\!/ \chi - m_\chi \bar\chi\chi + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - \lambda^{ij}\bar{u}_{Ri}\chi_j\phi$$
$$+\lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\,\phi^\dagger\phi\,\phi^\dagger\phi$$

Assumptions:

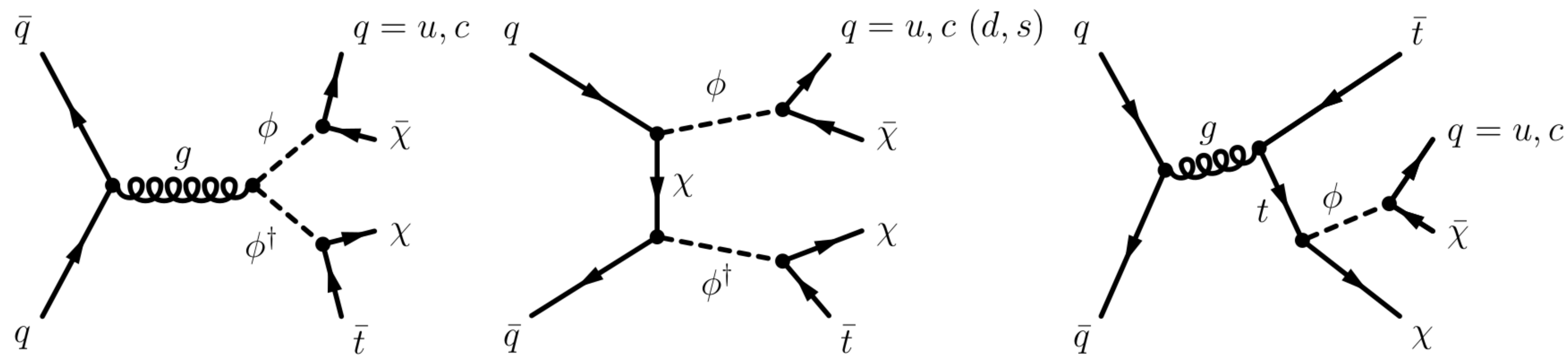
- λ constitutes the *only* new source of flavour violation
- DM is top-flavoured:[2] $m_{\chi_t} < m_{\chi_u}, m_{\chi_c}$

[2] see Jubb, Kirk, Lenz (2017) for charm-flavoured dark matter

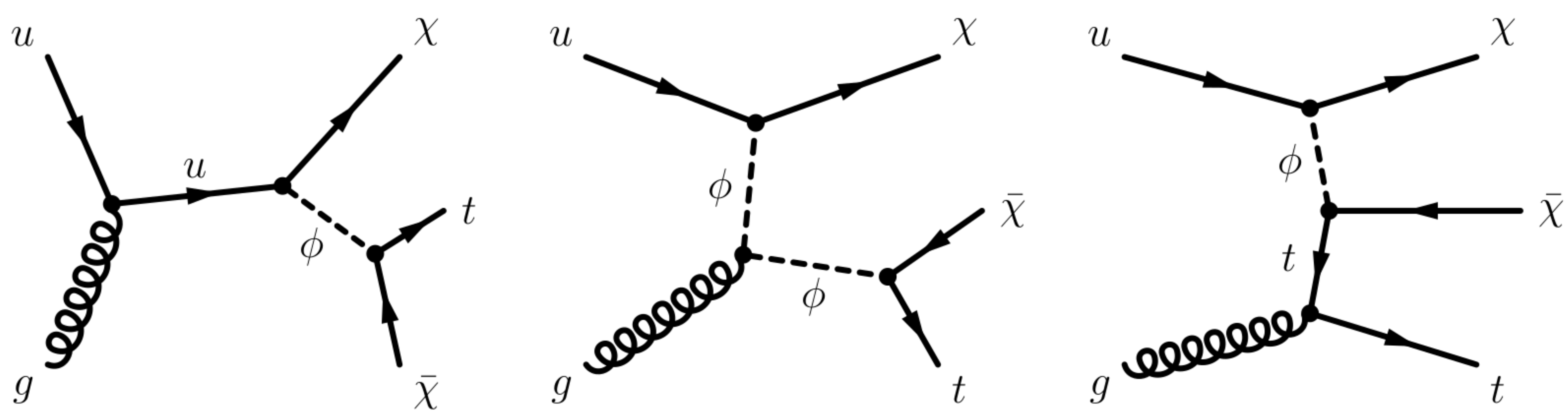
Single-top signatures of top-flavoured dark matter

Top-flavoured DM also induces **flavour-violating final states**:

- $t + j + \not{E}_T$ (dominated by mediator pair-production)



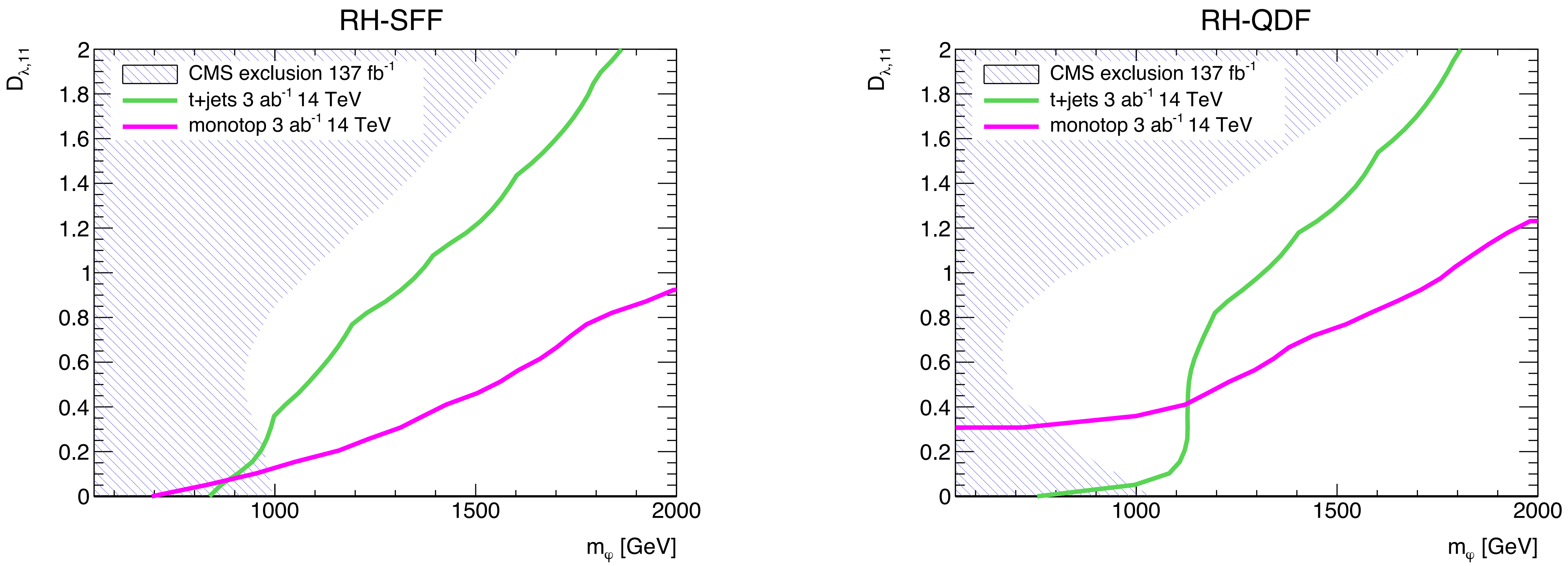
- "monotop" $t + \not{E}_T$



Blanke, Pani, Polesello, Rovedi JHEP 01 (2021) 194

(HL-)LHC reach for single-top final states

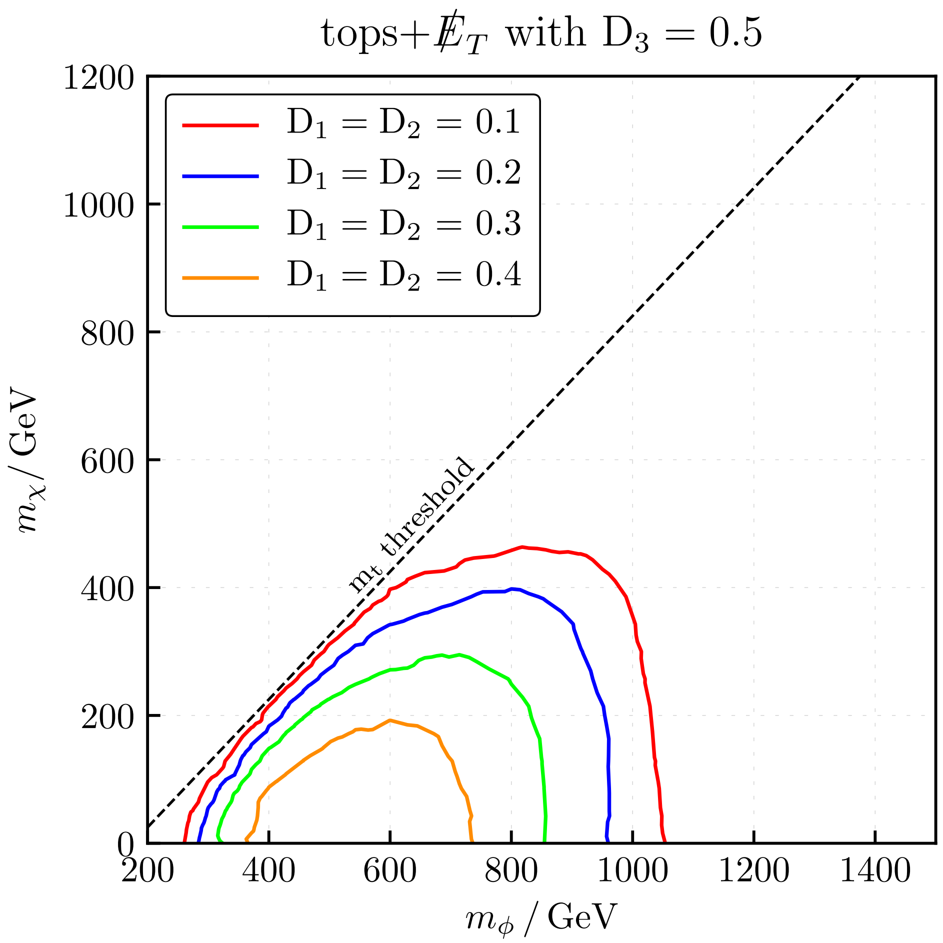
Blanke, Pani, Polesello, Rovedi JHEP 01 (2021) 194



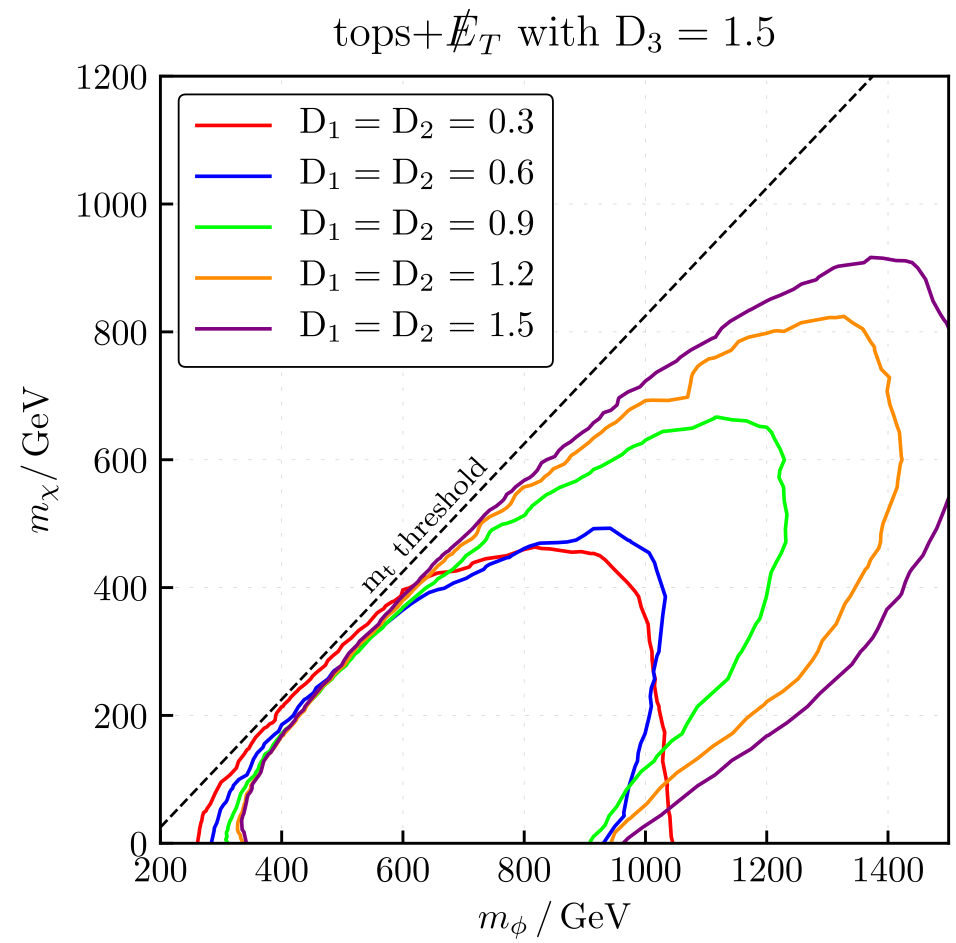
dedicated single-top searches

- cover additional parameter space
- have significant discovery reach at the HL-LHC

Testing flavoured Majorana dark matter



(a) $D_3 = 0.5$ and varying $D_1 = D_2$

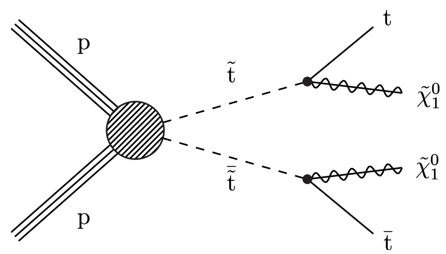


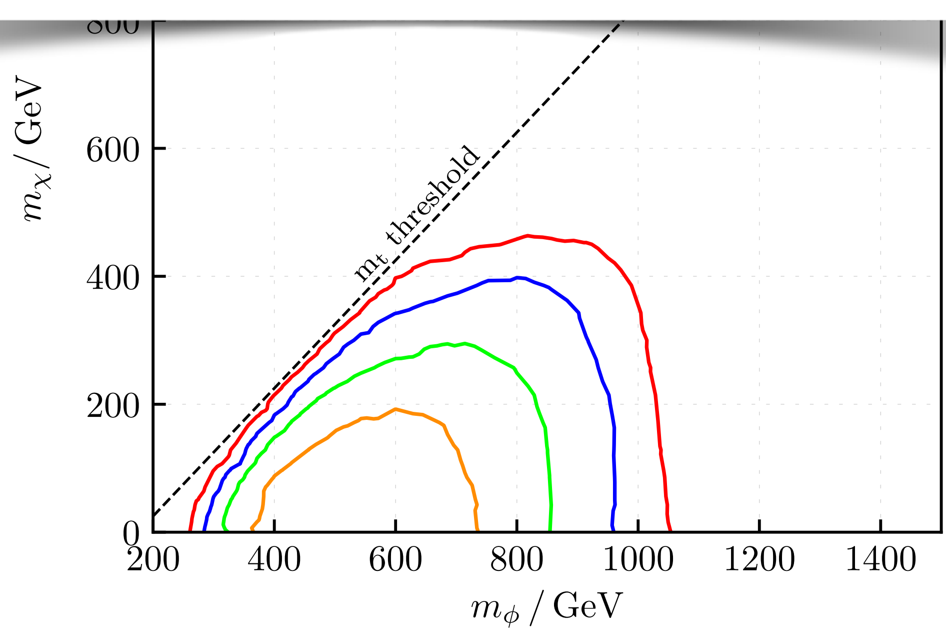
(b) $D_3 = 1.5$ and varying $D_1 = D_2$

Acaroglu, Blanke, e-Print: 2109.10357 [hep-ph]

Testing flavoured Majorana dark matter

Recast simplified SUSY model searches





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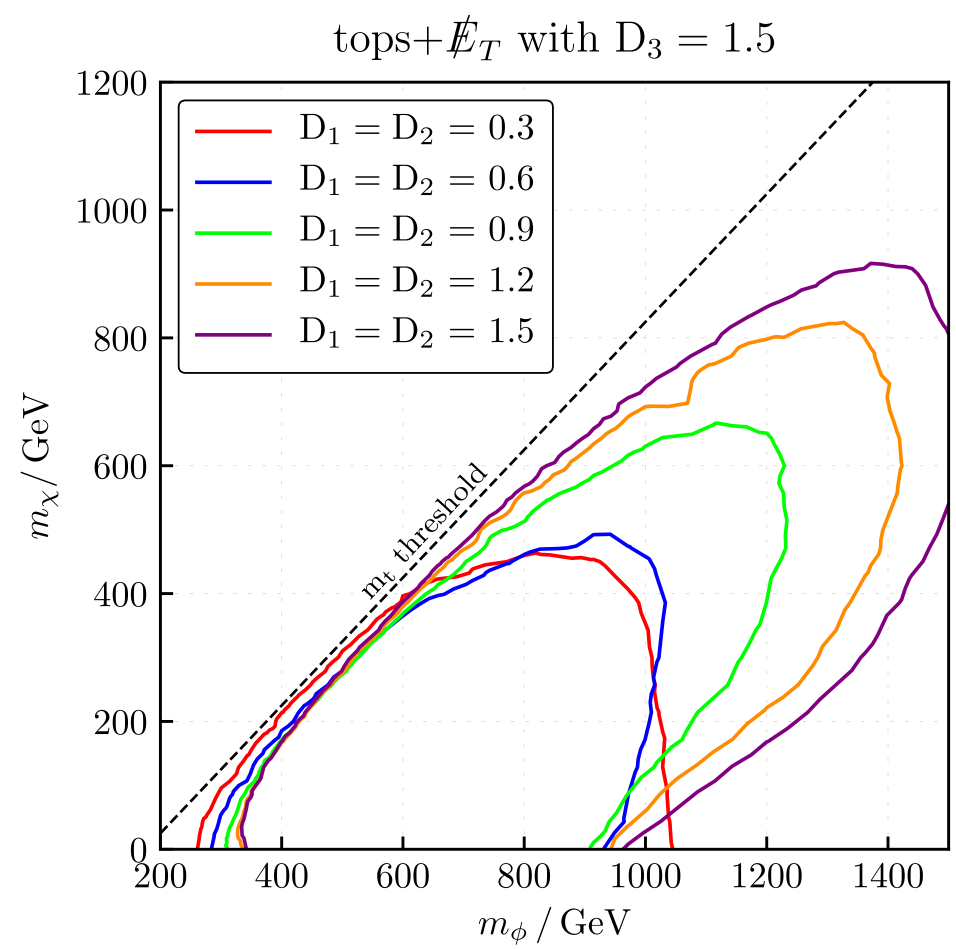
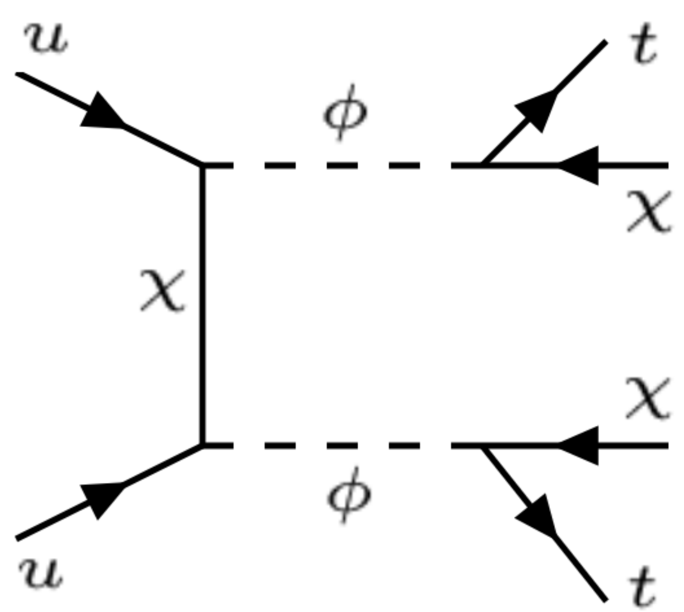


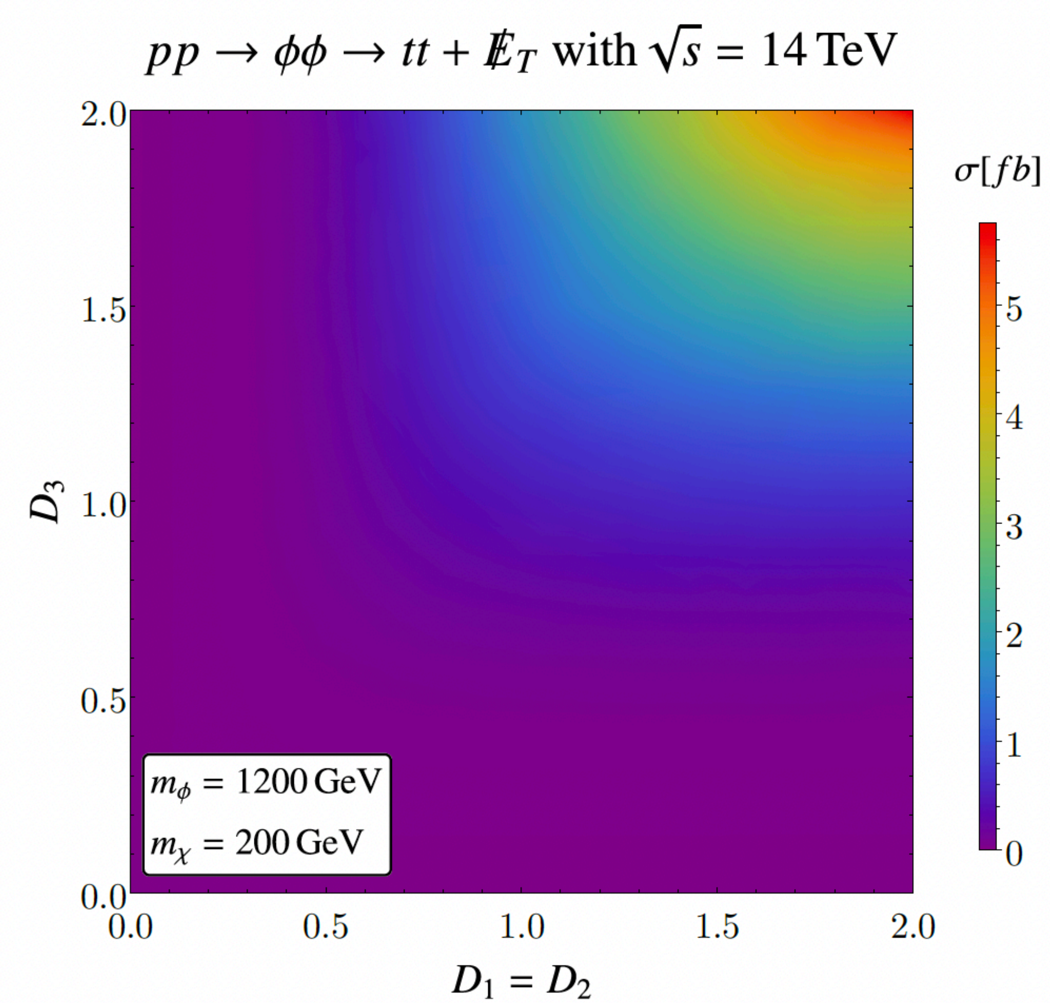
(b) $D_3 = 1.5$ and varying $D_1 = D_2$

Acaroglu, Blanke, e-Print: 2109.10357 [hep-ph]

Testing flavoured Majorana dark matter

Interesting new signature: same-sign di-tops + MET





Acaroglu, Blanke, e-Print: 2109.10357 [hep-ph]

Testing flavoured Majorana dark matter: work in progress

- Refine dark matter relic density calculations and indirect detection limits.
- Explore different LHC signatures and search limits, using tools such as SModelS, Contur, CheckMATE, MadAnalysis.
- Recast existing LHC searches to probe novel DFV signatures.
- Focus in particular on long-lived particle searches.
- Devise strategies to distinguish Dirac and Majorana dark matter.
- Improve theory prediction by higher-order effects.

Flavour anomalies at future colliders

Switch to the management area of this event

Future Collider Forum: 1st Workshop

6-8 October 2021
Europe/Berlin timezone

- Overview
- Scientific Programme
- Call for Abstracts
- Timetable
- Contribution List
- Registration
- Participant List

This is the first workshop of the German Future Collider Forum. Due to the circumstances, it is unfortunately online-only, held on three consecutive days in the mornings.

Connection is via Zoom:

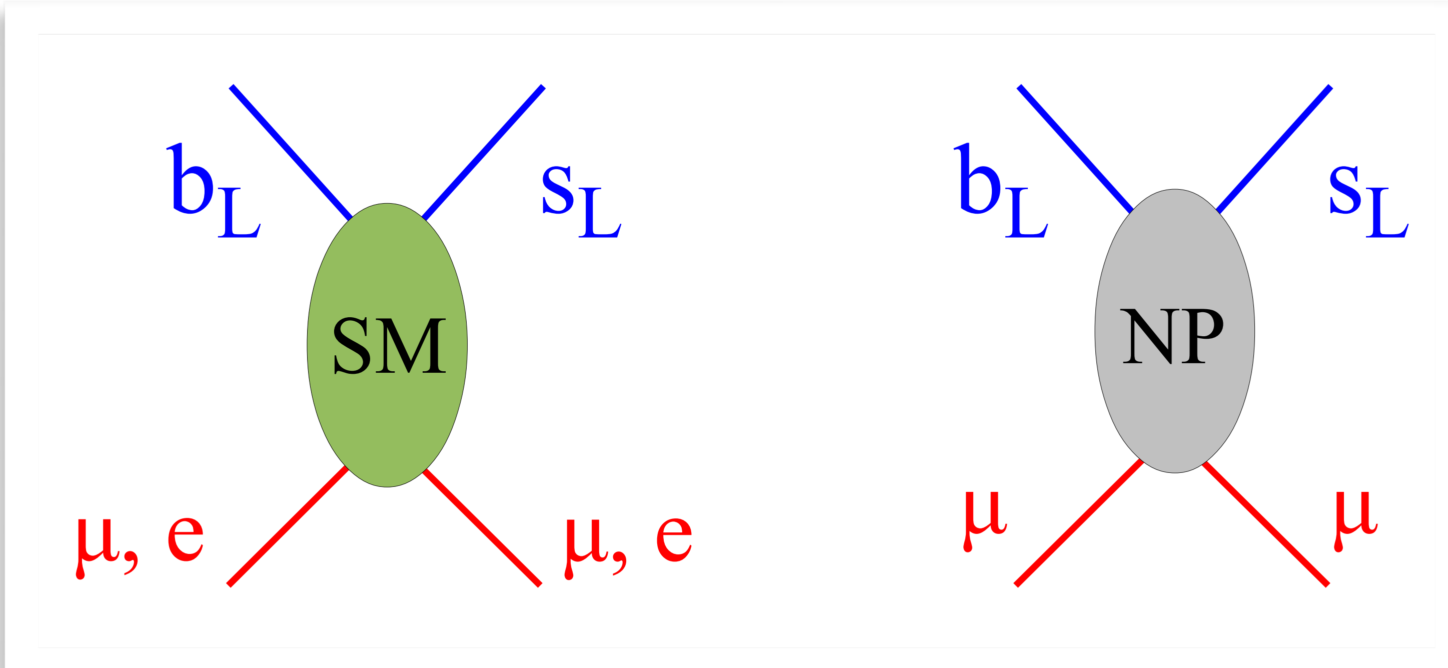
https://cern.zoom.us/j/65920623195?pwd=bnZYWVNndUVxNEtlaFp5SmhMSTJNQT09

Meeting ID: 659 2062 3195
Passcode: 348687

Starts 6 Oct 2021, 09:00
Ends 8 Oct 2021, 13:00
Europe/Berlin

Online-only

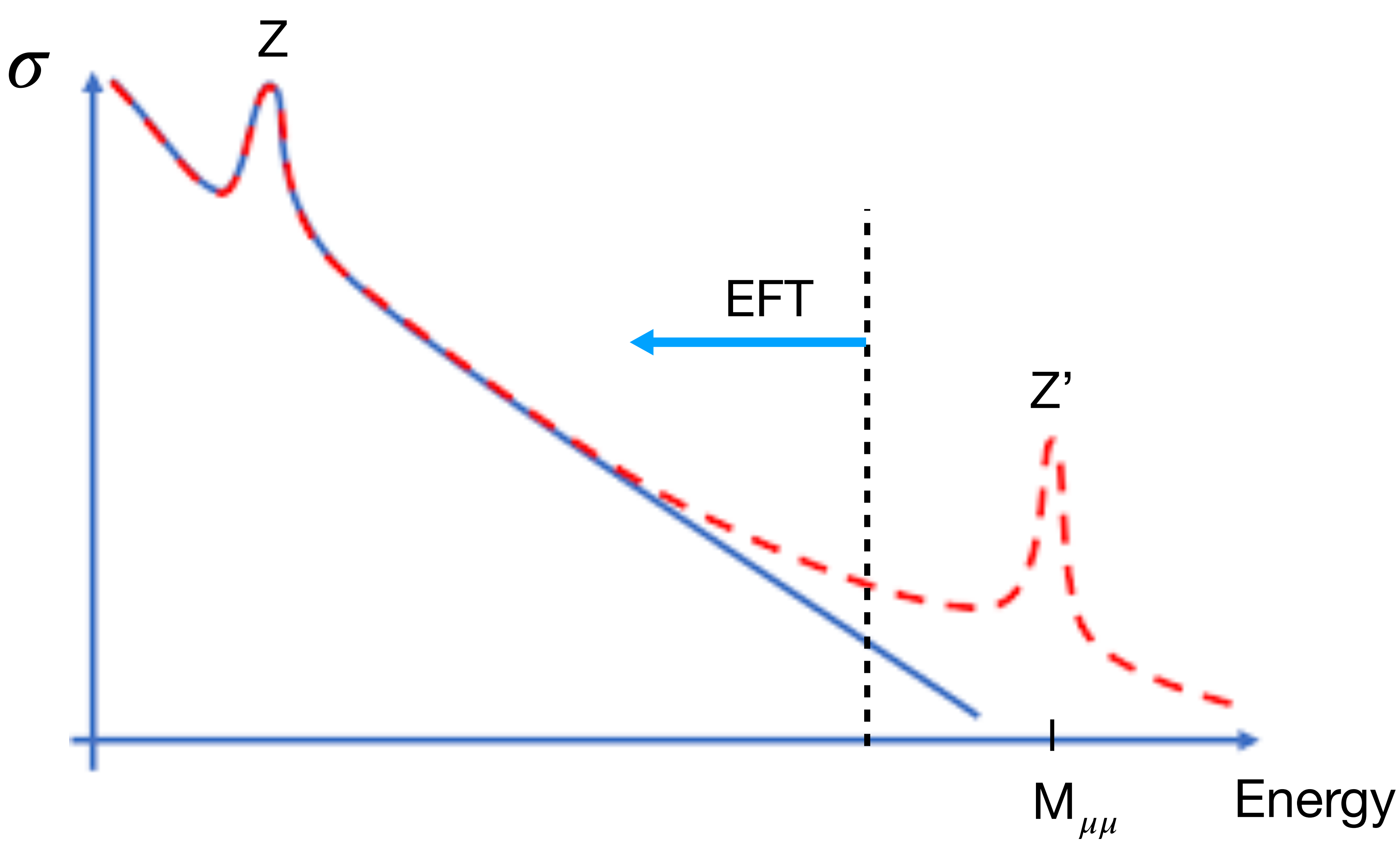
Flavour anomalies at future colliders



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{(40\,\text{TeV})^2}(\bar{s}\gamma_\mu b)(\bar{\mu}\gamma^\mu \mu)$$

Exploring physics beyond the SM with effective field theories

$$\mathcal{L}_{\mathrm{SM-EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$



See Susanne's talk

BSM searches: EFT vs full model

Vector-triplet benchmark model

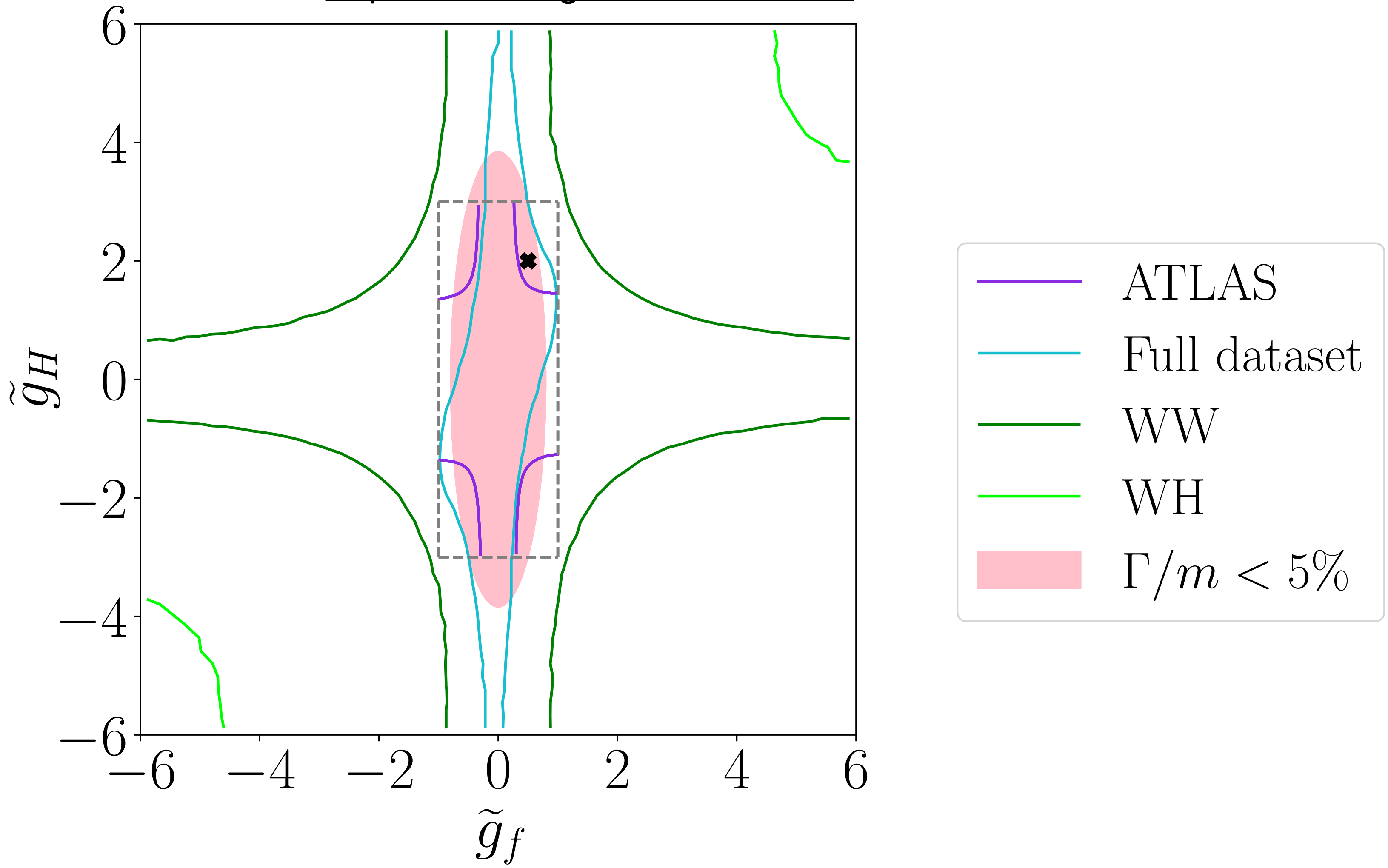
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\widetilde{V}^{\mu\nu A}\widetilde{V}^{A}_{\mu\nu} - \frac{\tilde{g}_M}{2}\,\widetilde{V}^{\mu\nu A}\widetilde{W}^{A}_{\mu\nu} + \frac{\tilde{m}_V^2}{2}\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu}$$
$$+ \sum_f \tilde{g}_f\,\widetilde{V}^{\mu A}J^{fA}_{\mu} + \tilde{g}_H\,\widetilde{V}^{\mu A}J^{HA}_{\mu} + \frac{\tilde{g}_{VH}}{2}\,|\phi|^2\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu}$$

- One-loop matching to dim-6 SMEFT Lagrangian
- Global fit to EWPO, Higgs & di-boson measurements and resonance searches
- Comparison with limits from direct searches

Brivio, Brugisser, Geoffrey, Kilian, MK, Luchmann, Plehn, Summ, arXiv:2108.01094 [hep-ph]

Exploring physics beyond the SM: EFT vs full model

https://arxiv.org/abs/2108.01094



- SMEFT sensitivity from EWPO
- Complementarity of direct and SMEFT searches

Flavour anomalies at future colliders

- Matching of various BSM models for flavour anomalies to EFT Lagrangian;
- global fit of the resulting EFT to flavour observables;
- global fit of the EFT to existing collider data and future collider projections;
- explore complementary of EFT global fits and direct searches;
- provide targets for future colliders, e.g. precision vs. energy.

Thank you!