Production of extra quarks decaying to Dark Matter at the LHC beyond the Narrow Width Approximation

Hugo Prager
S. Moretti, D. O'Brien, L. Panizzi

arxiv:1705.07675

Planck, Warsaw
May, 2017

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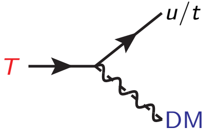

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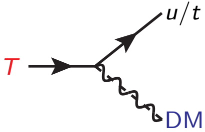

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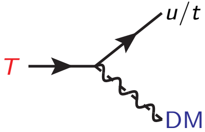

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⇒ **Goal:** From a model-independent analysis, we want to evaluate the **effects of large width** in the determination of the cross-section and in the reinterpretation of bounds from experimental searches

Lagrangian for singlet DM

Interaction terms between *singlet* DM and the new quarks (coupling to first generation):

$$\mathcal{L}_1^S = \left[\lambda_{11}^u \bar{T} P_R\, u + \lambda_{11}^d \bar{B} P_R\, d + \lambda_{21}\, \overline{\Psi}_{1/6} P_L \begin{pmatrix} u \\ d \end{pmatrix}\right] S_{DM}^0 + h.c.$$

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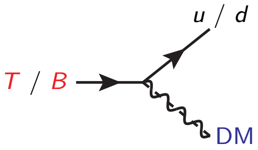

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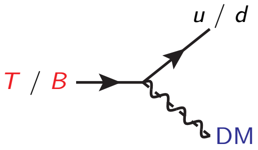

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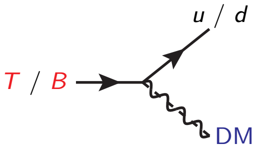

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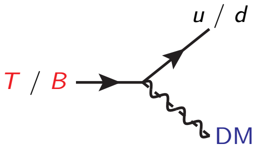

$\Rightarrow$ **Here we will only focus on a VLQ T part of a doublet.**

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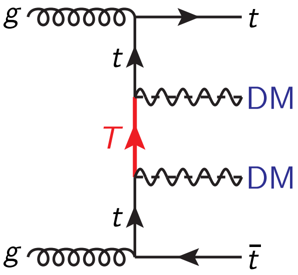
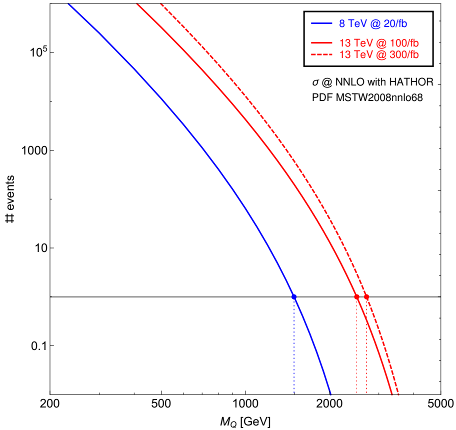


$\Rightarrow$ $(\sigma_S - \sigma_X)/\sigma_X$ measures how much the full signal differs from the NWA one.

Final states and range of validity

Focus on XQs coupling to 1st and 3rd generation, final states considered:
$T\,\bar{T} \to \{S^0_{DM}\ S^0_{DM}\ u\ \bar{u},\ S^0_{DM}\ S^0_{DM}\ t\ \bar{t},\ V^0_{DM}\ V^0_{DM}\ u\ \bar{u},\ V^0_{DM}\ V^0_{DM}\ t\ \bar{t}\}.$



Analysis only interesting for mass values for which the number of final events is larger than 1 $\to$ ideal practical validity of our results is limited to mass values of around

- 1500 GeV for LHC@8TeV,
- 2500 GeV for LHC@13TeV with 100/fb integrated luminosity,
- 2700 GeV for LHC@13TeV with 300/fb integrated luminosity.

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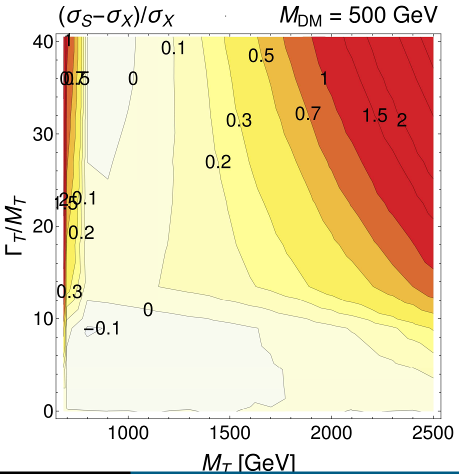
  - *ATLAS-CONF-2016-050*, a search for the stop in final states with one isolated electron or muon, jets, and missing p_T.

Parton-level results for 3rd generation

Final state $t\bar{t} + DM\ DM$, *i.e.* $t\bar{t} + \not{E}_T$.
$(\sigma_S - \sigma_X)/\sigma_X$ plotted for 13 TeV (results at 8 TeV are analogous).



Scalar DM

- $\sigma_X \sim \sigma_S$ in the NWA,
- $\sigma_X \lesssim \sigma_S$ when Γ_T increases, especially when $M_T \simeq M_{DM} + m_t$ (*threshold effect*),
- $M_T \simeq 1000$ GeV: cancellation of effects which makes $\sigma_X \sim \sigma_S$ even for large values of Γ_T.

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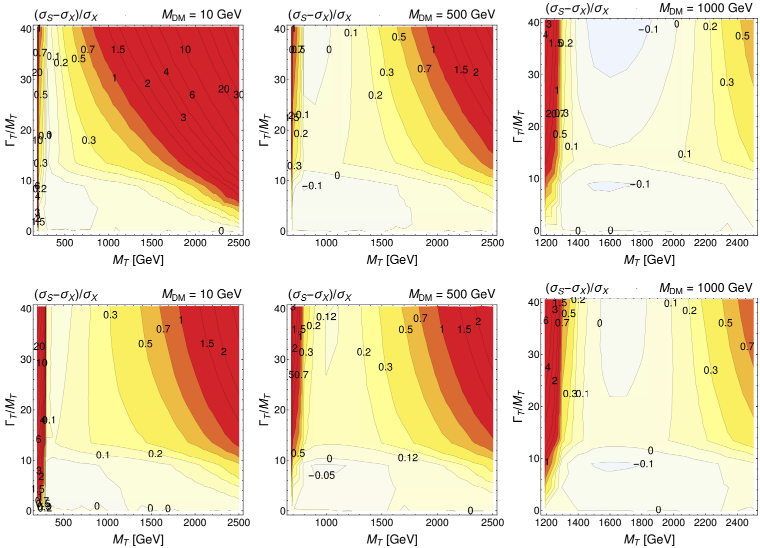

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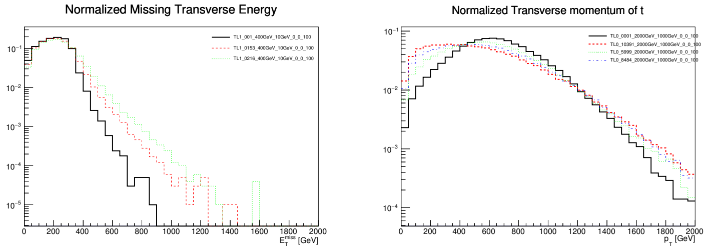
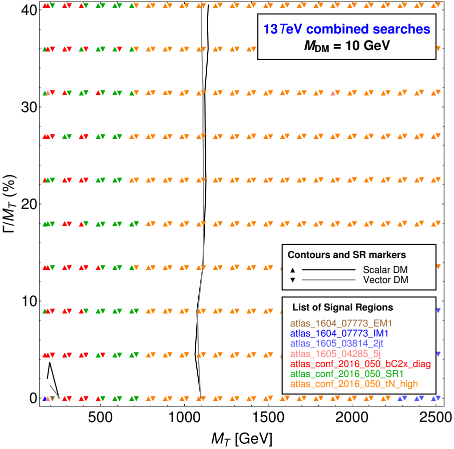


Differential distributions along the cancellation line for a scalar (vector) DM, $M_{DM} = 1000$ GeV (10 GeV) and $M_T = 2000$ GeV (400 GeV) on the left (right), for different values of Γ_T/M_T.

CheckMATE results for 3rd generation

Bounds obtained with CheckMATE using all the 13 TeV searches available



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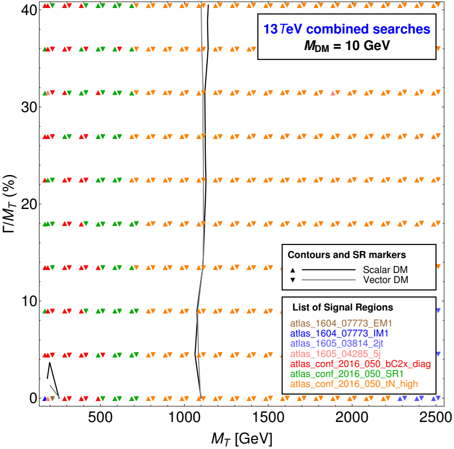

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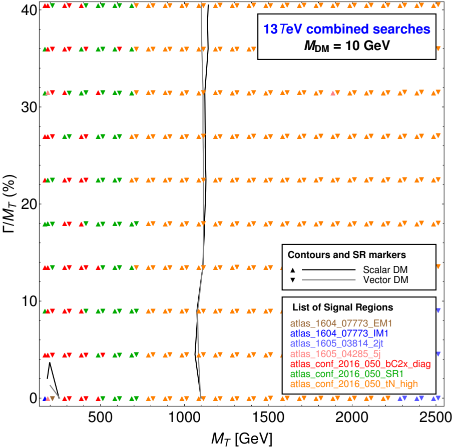

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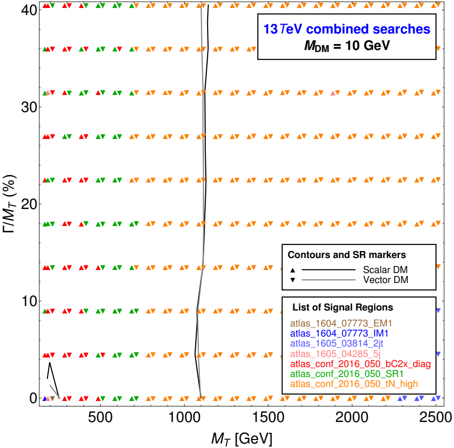

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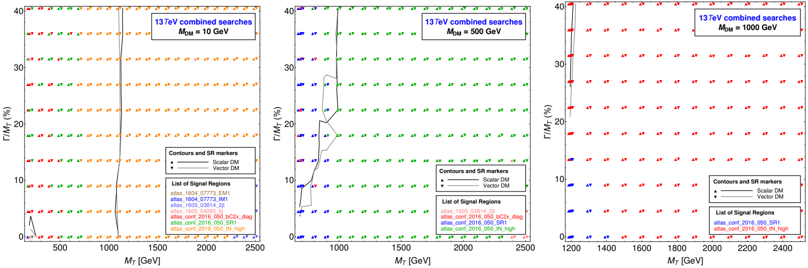
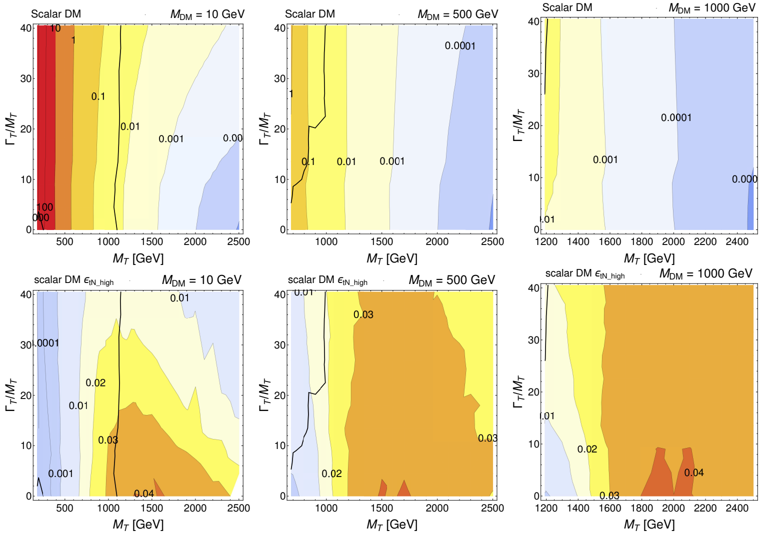
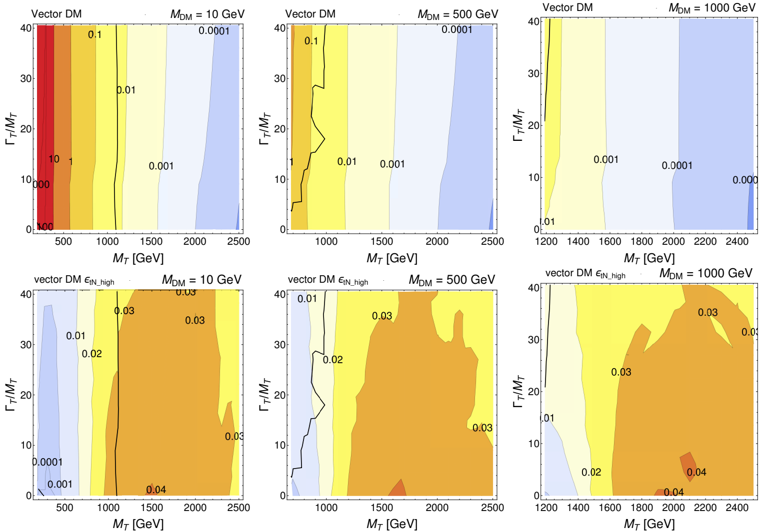


Combined plots (scalar DM)



Combined plots (vector DM)



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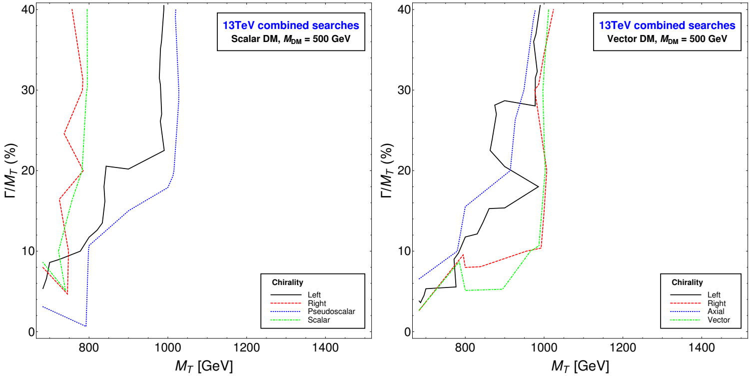
⇒ **Hypothesis made for experimental searches are conservative** because the signal CS generally increases when the VLQ width becomes larger which makes the bounds stronger. Yet this CS increase is sometimes suppressed by the analysis cuts → possibility to have stronger bounds on XQs with large width?

Dependence on the chirality of the couplings



No significant differences between chiralities for vector DM, onlys some visible differences for scalar DM (but quite large uncertainty due to the use of a recasting tool).

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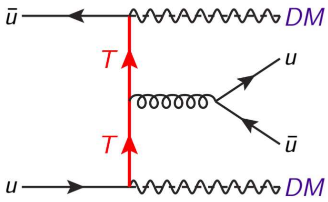
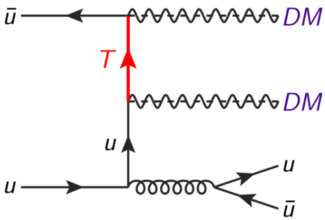
New topologies in the case of mixing with 1st generation





Important additionnal topologies

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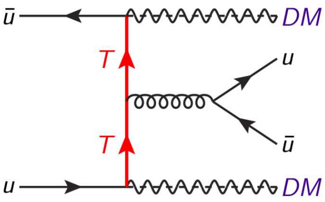
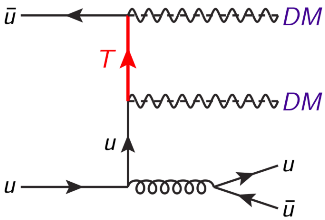
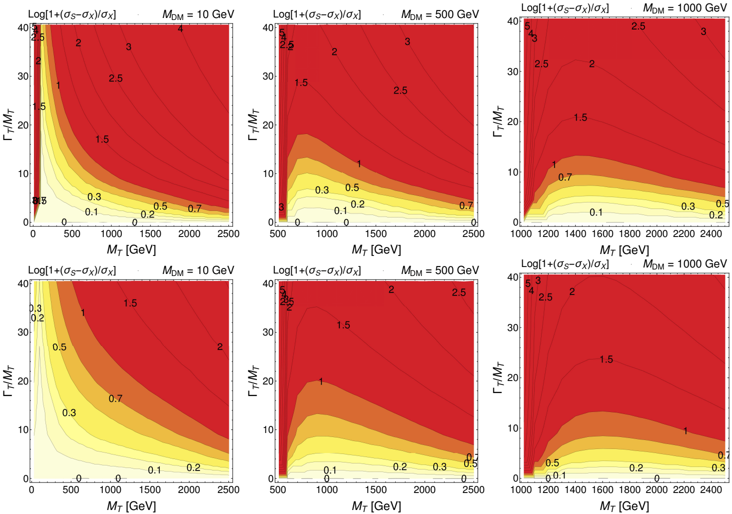




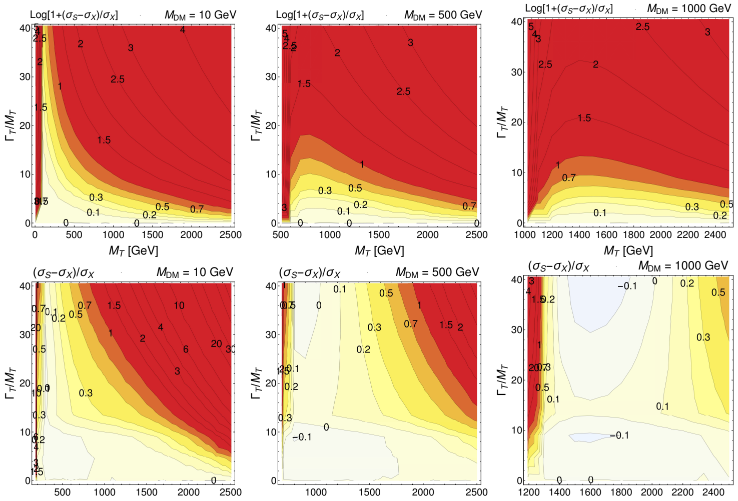
These topologies contribute to the signal and cannot be removed: σ_S affected, but not σ_X. Moreover these topologies contain collinear divergences due to the gluon splitting $\rightarrow$ large increase of $(\sigma_S - \sigma_X)/\sigma_X$ $\rightarrow$ use of log plots

Parton-level results for 1st generation

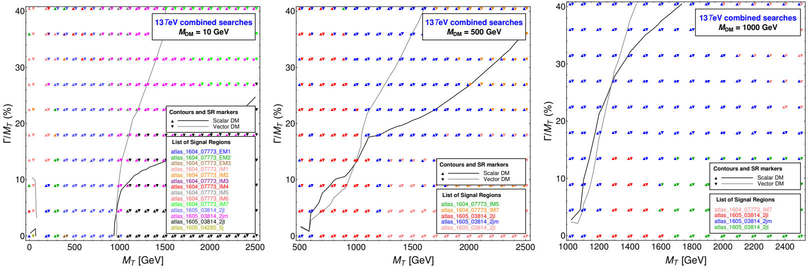
$\mathrm{Log}[1 + (\sigma_S - \sigma_X)/\sigma_X]$ plotted for an LHC energy of 13 TeV



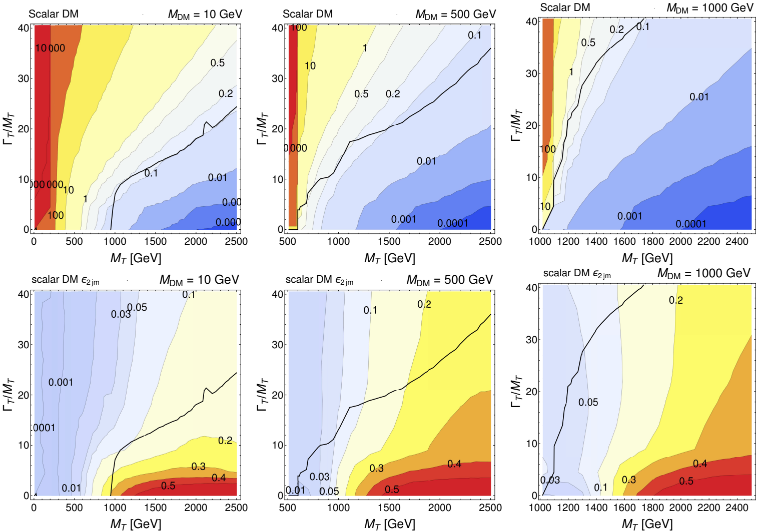
No cancellation which makes σ_S similar to σ_X for large width, only a noticeable decrease of the CS ratio in similar regions that for 3rd generation $\rightarrow$ cancellation of opposite effects + additional diagrams



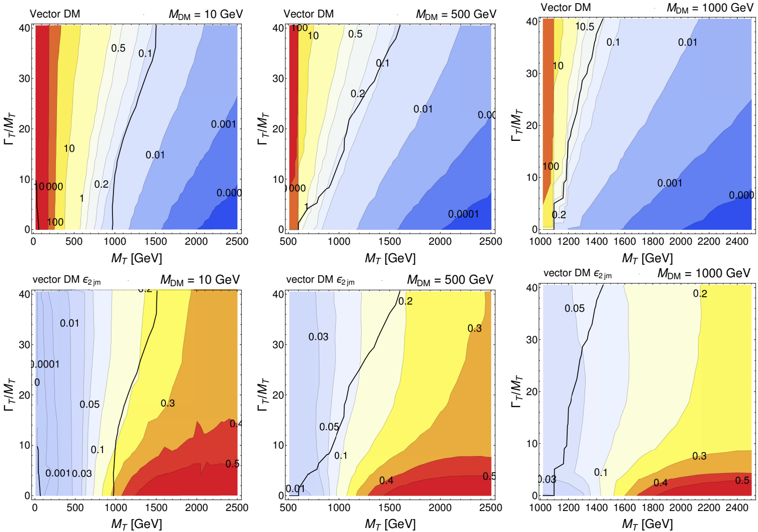
CheckMATE results for 1st generation



Combined plots (scalar DM)



Combined plots (vector DM)



Analysis and conclusions

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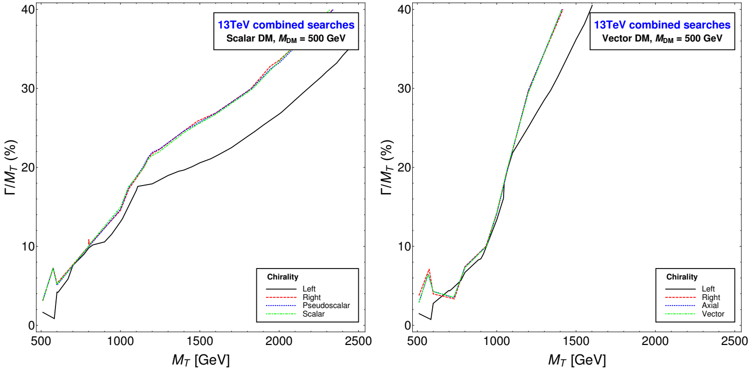
$\Rightarrow$ **Hypothesis made by experimentalist conservative** since the bounds in the NWA are always weaker than the ones for large width. But bounds could be much stronger for large width, even reaching excluded values larger than $M_T = 2.5$ TeV in some cases!

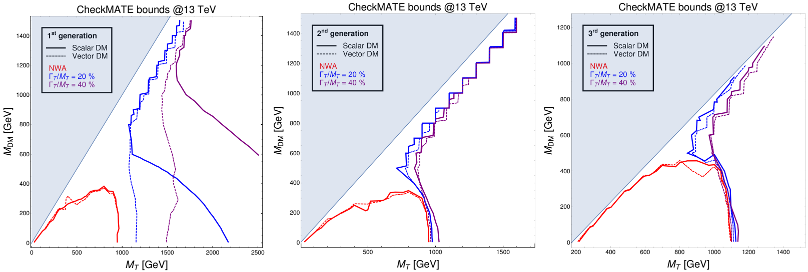
Dependence on the chirality of the couplings



Similar behaviour in all cases with a slightly stronger width dependence for L coupling (but quite large uncertainty due to the use of a recasting tool)

Exclusion limits in the $M_T - M_{DM}$ plane

Exclusion limits shown in the T - DM (similar to $\tilde{t}_1$ - $\tilde{\chi}^0_1$) mass plane for $\Gamma_T \simeq 0$, 20 and 40 % of M_T



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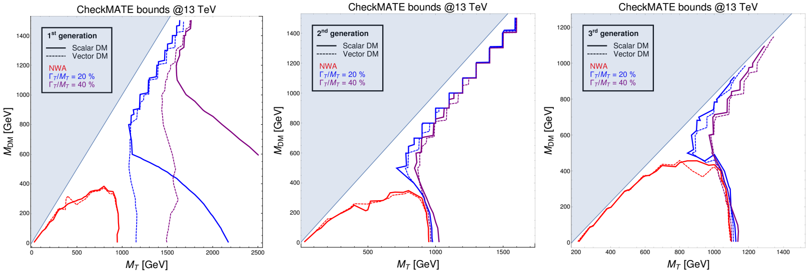

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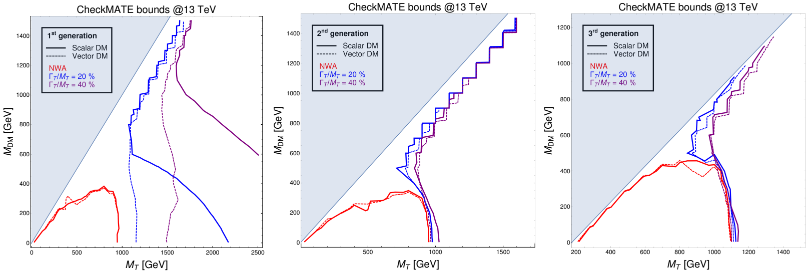

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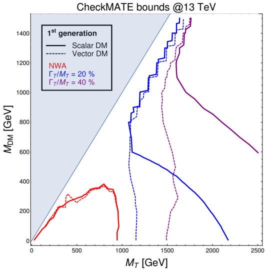

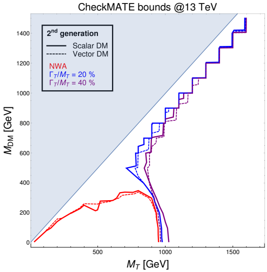

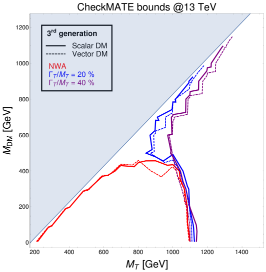

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- For large width, even the **almost degenerate region is excluded**,
- The **width dependence** is much more important for 1st generation.

Conclusion

Model with a XQ decaying to DM: What is the influence of the width effects?

- **3rd generation coupling**

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Thank you for your attention.

Backup slides

UNIVERSITY OF Southampton

Lagrangian for doublet DM

Interaction terms between *doublet* DM and the XQs coupling to first generation quarks:

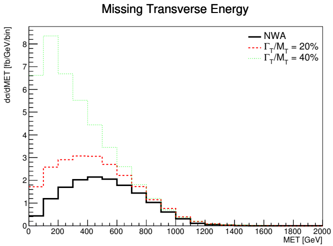
$$\begin{aligned}
\mathcal{L}_2^S &= \left[\lambda_{12}^d \bar{B} P_L \binom{u}{d} + \lambda_{22}^d \,\overline{\Psi}_{1/6} P_R\, d + (\lambda_{22}^u)' \,\overline{\Psi}_{5/6} P_R\, u\right] \Sigma_{\rm DM} \\
&+ \left[\lambda_{12}^u \bar{T} P_L \binom{u}{d} + \lambda_{22}^u \,\overline{\Psi}_{1/6} P_R\, u + (\lambda_{22}^d)' \,\overline{\Psi}_{-1/6} P_R\, d\right] \Sigma_{\rm DM}^c \\
\mathcal{L}_2^V &= \left[g_{12}^d \bar{B} \gamma_\mu P_L \binom{u}{d} + g_{22}^d \overline{\Psi}_{1/6} \gamma_\mu P_R\, d + (g_{22}^t)' \,\overline{\Psi}_{5/6} \gamma_\mu P_R\, u\right] \mathcal{V}_{\rm DM}^\mu \\
&+ \left[g_{12}^u \bar{T} \gamma_\mu P_L \binom{u}{d} + g_{22}^u \,\overline{\Psi}_{1/6} \gamma_\mu P_R\, u + (g_{22}^d)' \overline{\Psi}_{-1/6} \gamma_\mu P_R\, d\right] \mathcal{V}_{\rm DM}^{c,\mu}
\end{aligned}$$

where

- T, B and $\Psi_{1/6} = (T \;\; B)^T$ extra quarks,
- $\Psi_{7/6} = (X_{5/3} \;\; T)^T$ and $\Psi_{-5/6} = (B \;\; Y_{-4/3})^T$ new doublets
- $\Sigma_{DM} = (S^+ \;\; S^0_{DM})^T$ if scalar or as $\mathcal{V}_{DM} = (V^+ \;\; V^0_{DM})^T$.

$\Rightarrow$ **Non-minimal extension because of S^+/V^+, $X_{5/3}$ and $Y_{-4/3}$**

Distribution along the bound for 3rd generation



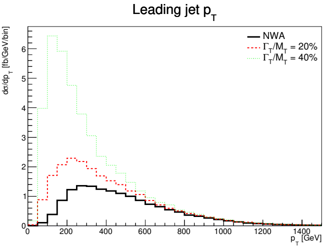
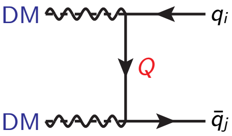


Figure: Differential distributions along the bound for a T with mass $M_T = 1100$ GeV coupling to the top quark and scalar DM with mass $M_{DM} = 10$ GeV.

Relic density

Value of the **relic density** driven by the annihilation of two DM particles (cf diagrams). Value of Ω_{DM} computed *numerically* using **MadDM** and compared to the experimental value

$$\Omega_{DM} = 0.1198 \pm 0.0026.$$



- Overabundant region *excluded* but not underabundant one if multicomponent DM.
- Only main contribution considered (cf diagram) $\rightarrow$ need to include photon Bremsstrahlung[1]?

[1] A. Ibarra et al., Sharp Gamma-ray Spectral Features from Scalar DM Annihilations
F. Giacchino et al., Bremsstrahlung and Gamma Ray Lines in 3 Scenarios of DM Annihilation
T. Toma, Internal Bremsstrahlung Signature of Real Scalar DM and Consistency with Thermal Relic Density