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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

DIS, Birmingham
April, 2017

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Introduction

- Existence of new eXtra-Quarks (XQs) besides the Standard Model (SM) ones? → some predicted by BSM models.
- Dark Matter (DM) missing in the SM → different candidates predicted by BSM models.
- Consider a simplified model where DM is scalar or vector produced through the decay of an extra charged quark (XQ). New particles odd under a $\mathbb{Z}_2$ symmetry. Representative of UED models amongst others.
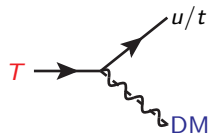
- Same signatures with MET than SUSY → possible to interpret SUSY results in the Narrow-Width Approximation (NWA) in terms of limits on XQs (arXiv:1607.0205)
- ⇒ **Goal:** From a model-independent analysis, we want to evaluate the **effects of large width** in the determination of the cross-section and in the reinterpretation of bounds from experimental searches

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   - Lagrangian
   - Observables and conventions
   - Monte Carlo analysis tools

2. Final states with third generation SM quarks
   - Large width effects at parton level
   - Large width effects at detector level

3. Final states with first generation SM quarks
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4. Conclusions

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Lagrangian for singlet DM

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

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

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

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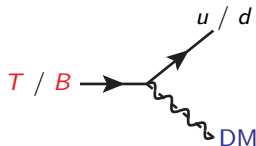**Southampton**
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where

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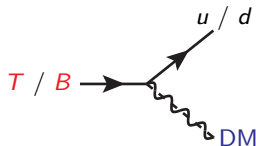**Southampton** UNIVERSITY OF

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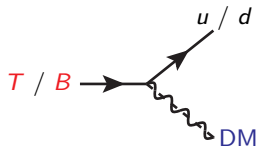
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$u \, / \, d$

$T \, / \, B \longrightarrow$

DM

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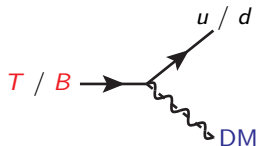**Southampton** UNIVERSITY OF

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$\Rightarrow$ **Here we will only focus on VLQ singlet T.**

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Observables and conventions

Consider two different processes leading to the same final state
DM DM q q̄:

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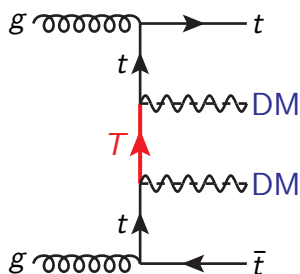Observables and conventions
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Observables and conventions

Consider two different processes leading to the same final state
$DM\ DM\ q\ \bar{q}$:

- **QCD pair production and decay of on-shell XQs** (considered in experimental searches):
  $\sigma_X(M_Q) \equiv \sigma_{2\to2}^{QCD}\ BR(Q)\ BR(\bar{Q})$

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Observables and conventions

Consider two different processes leading to the same final state $DM\ DM\ q\ \bar{q}$:

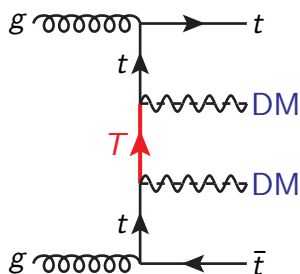- **QCD pair production and decay of on-shell XQs** (considered in experimental searches):
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- **Full signal**: $\sigma_S(M_Q, \Gamma_Q)$ where all the topologies which contain at least one XQ are taken into account, including some which are missing in the NWA.

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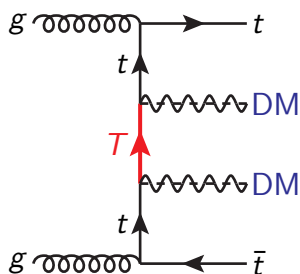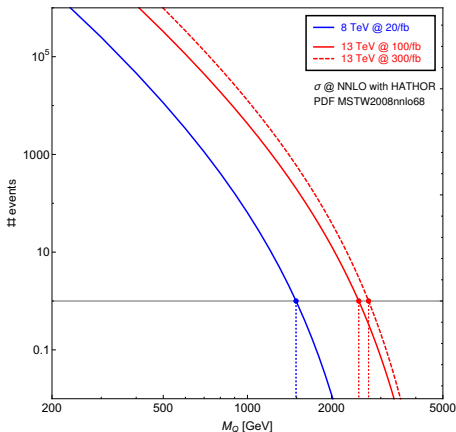

$\Rightarrow (\sigma_S - \sigma_X)/\sigma_X$ measures how much the full signal differs from the NWA one.

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Final states and range of validity

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

Analysis only interesting for mass values for which the number of final events is larger than $1 \rightarrow$ 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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  - $0 < \Gamma_T/M_T < 40\%$ (extreme value).

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  - *ATLAS 1604.07773*, a search for new phenomena in final states with an energetic jet and large missing p_T,

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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.

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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).
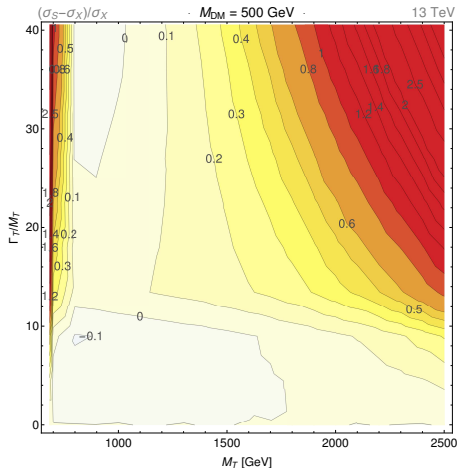
Scalar DM

- $\sigma_X \sim \sigma_S$ 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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Main conclusions:

- Off-shell contributions **negligible** in the NWA.

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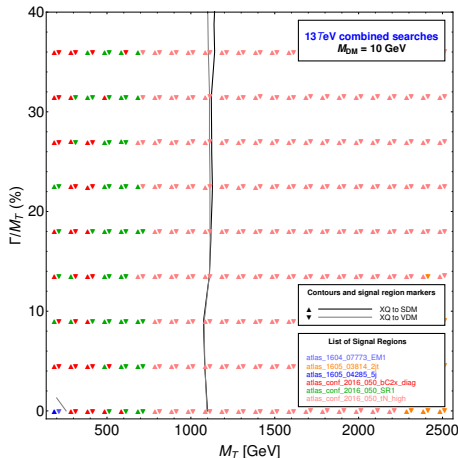
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Main conclusions:

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- **Cancellation** which makes σ_X similar to σ_S even for large values of the width.

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- **Cancellation** which makes σ_X similar to σ_S even for large values of the width.

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.

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CheckMATE results for 3rd generation

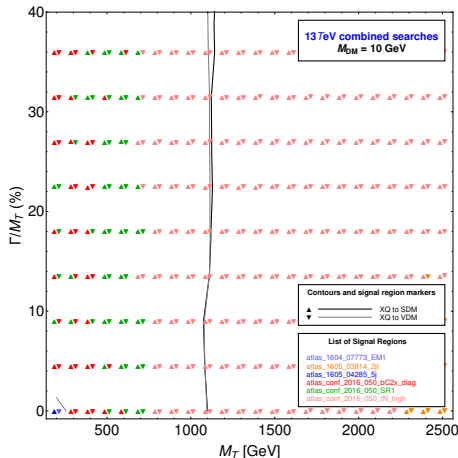Bounds obtained with CheckMATE using all the 13 TeV searches available

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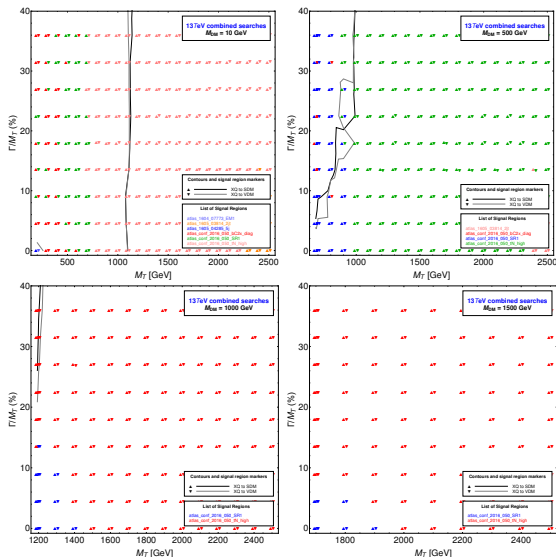
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CheckMATE results for 3rd generation

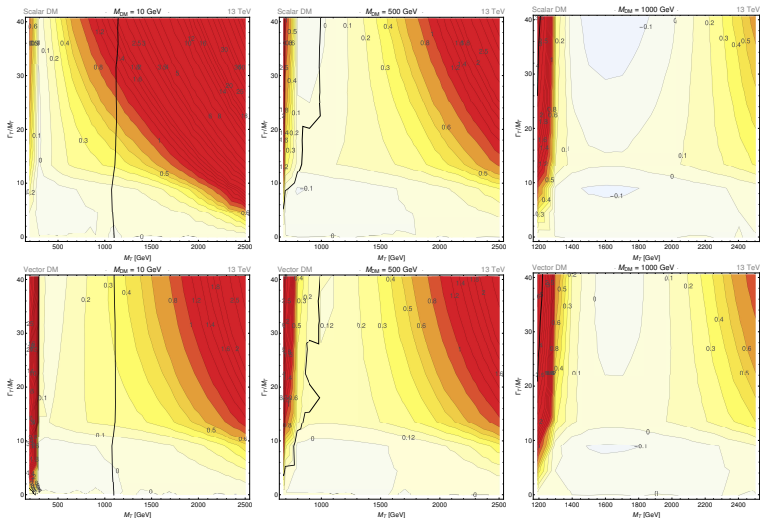Bounds obtained with CheckMATE using all the 13 TeV searches available

- Bounds for scalar and vector **very similar**,

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CheckMATE results for 3rd generation

Bounds obtained with CheckMATE using all the 13 TeV searches available

- Bounds for scalar and vector **very similar**,
- Bounds **independent on the width**,

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CheckMATE results for 3rd generation

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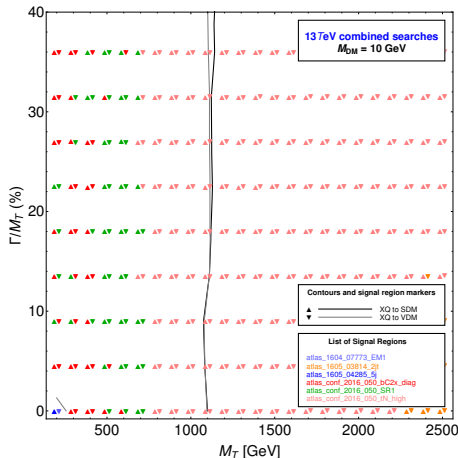
- Bounds for scalar and vector **very similar**,
- Bounds **independent on the width**,
- Point in the bottom left corner not excluded, with $r_{max} \sim 0 \rightarrow$ influence of the **top background**.

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Combined plots

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Analysis and conclusions for 3rd generation

- Bounds for scalar and vector very similar $\rightarrow$ **no spin effect**.

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Analysis and conclusions for 3rd generation

- Bounds for scalar and vector very similar → **no spin effect**.
  - $M_{DM} = 10$ GeV, **no width dependence** even if the CS ratio becomes much larger when the width increase → seems to be due to a combination of different cuts (work in progress),

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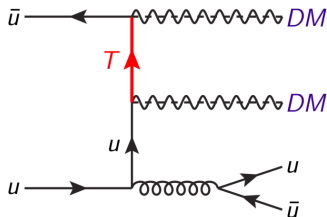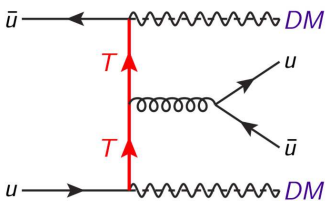Southampton UNIVERSITY OF

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  - $M_{DM} = 1500$ GeV, nothing is excluded.
- ⇒ **Hypothesis made for experimental searches are conservative** because the signal cross section 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?

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Important additionnal topologies

VLQs coupling to 1st generation SM quarks, possible final state is $DM\, u\, DM\, \bar{u}$, i.e. $2\,j + \not{E}_T$.
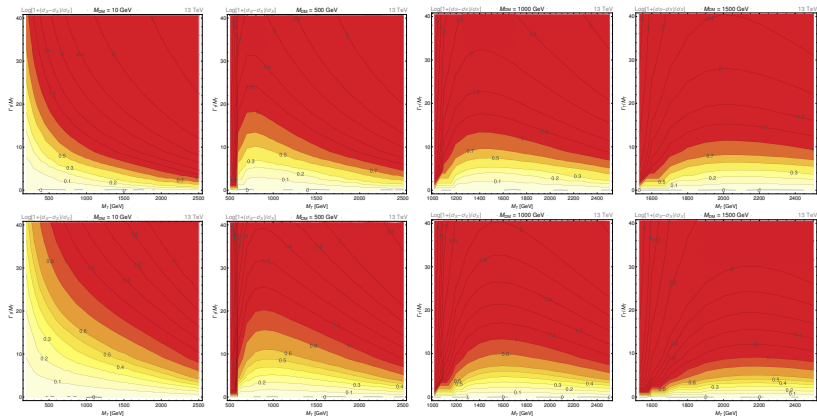
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New topologies in the case of mixing with 1st generation

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New topologies in the case of mixing with 1st generation

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

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Parton-level results for 1st generation

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

- $\sigma_X \sim \sigma_S$ in the NWA
- $\sigma_X \ll \sigma_S$ when Γ_T increases $\to$ due to the additional diagrams

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

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CheckMATE results for 1st generation

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Combined plots
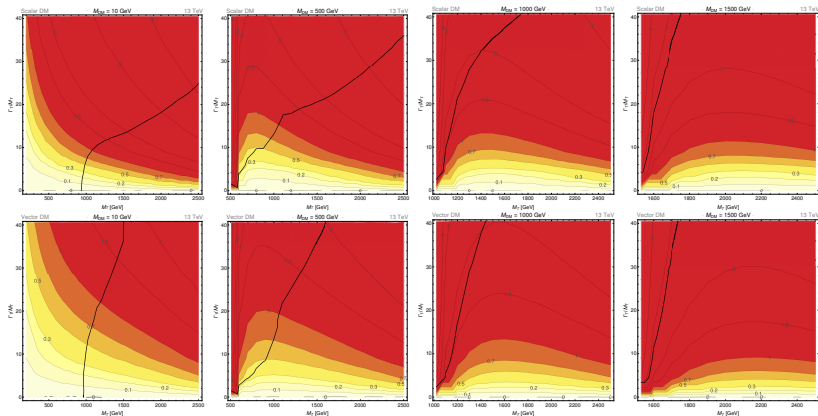
Important differences with 3rd generation: **bounds have an important
width dependence**, and they are **quite different for scalar and vector
DM**, apart from in the NWA region.

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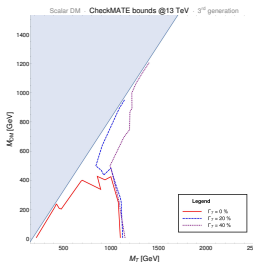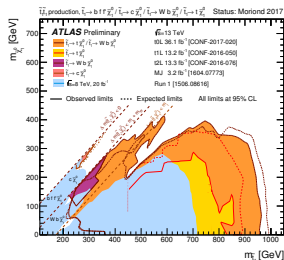Southampton
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Analysis and conclusions

- Both scalar and vector DM bounds **track the different behaviours in the scaling of the CS ratios**; these ratios scale in a different way and the bound basically follows them.

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- Both scalar and vector DM bounds **track the different behaviours in the scaling of the CS ratios**; these ratios scale in a different way and the bound basically follows them.
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- **Bounds do not depend on the spin in the NWA** because $\sigma_S(M_T, NWA) = \sigma_X(M_T, NWA) = \sigma_X(M_T)$ leading to the same excluded value.

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- **Bounds do not depend on the spin in the NWA** because $\sigma_S(M_T, NWA) = \sigma_X(M_T, NWA) = \sigma_X(M_T)$ leading to the same excluded value.

- $\Rightarrow$ **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!
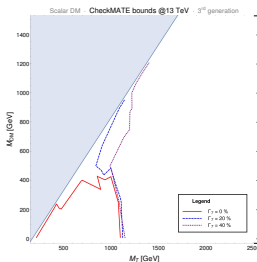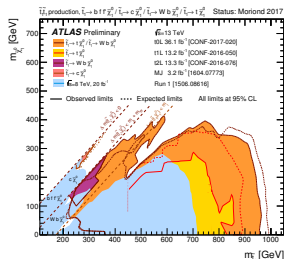
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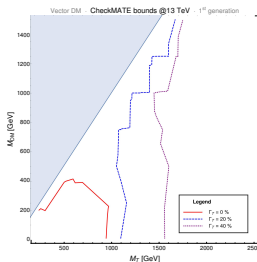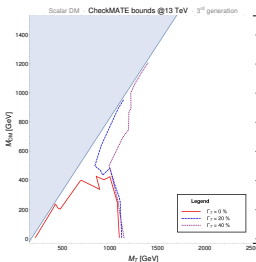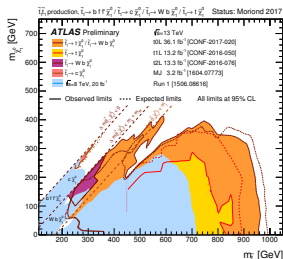Southampton

Plots in the mass plane *[preliminary results]*

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

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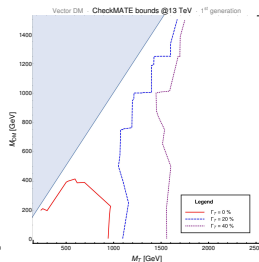# Plots in the mass plane *[preliminary results]*

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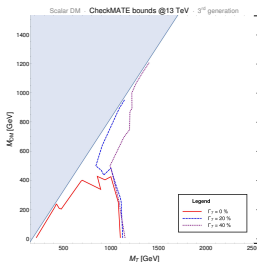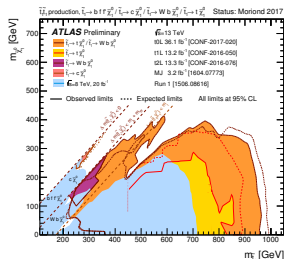
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- Exclusion lines **similar to the SUSY** ones in the NWA,
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- The **width dependence** is more important for 1st generation.

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Conclusion

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

- **3rd generation coupling**

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

- **3rd generation coupling**
  - *no spin dependence* and *small width dependence* on the exclusion

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

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  - cross section becomes larger when the width increases but this contribution is *suppressed by some cuts from the analysis*

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Further studies:

- understand the origin of the threshold effect,

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Further studies:

- understand the origin of the threshold effect,
- understand which cuts reduce the width-dependence for a coupling with 3rd generation.
- ongoing similar study with XQ decaying to SM particles instead of DM (arXiv:1603.0923).

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Thank you for your attention.

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Lagrangian for doublet DM

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

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

$$\mathcal{L}_2^V = \left[g_{12}^d \bar{B} \gamma_\mu P_L \begin{pmatrix} u \\ d \end{pmatrix} + g_{22}^d \overline{\Psi}_{1/6} \gamma_\mu P_R \, d + (g_{22}^t)' \, \overline{\Psi}_{5/6} \gamma_\mu P_R \, u \right] \mathcal{V}_{\text{DM}}^\mu$$

$$+ \left[g_{12}^u \bar{T} \gamma_\mu P_L \begin{pmatrix} u \\ d \end{pmatrix} + g_{22}^u \overline{\Psi}_{1/6} \gamma_\mu P_R \, u + (g_{22}^d)' \overline{\Psi}_{-1/6} \gamma_\mu P_R \, d \right] \mathcal{V}_{\text{DM}}^{c,\mu}$$
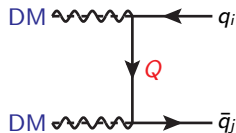
where

- 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
- $\Sigma_{DM} = (S^+\ S_{DM}^0)^T$ if scalar or as $\mathcal{V}_{DM} = (V^+\ V_{DM}^0)^T$.

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

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Relic density

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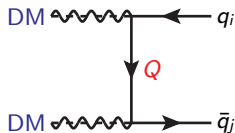**MadDM** and compared to the experimental
value

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

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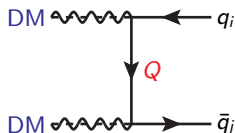
$$\Omega_{DM} = 0.1198 \pm 0.0026.$$

DM ⚬⚬⚬⚬⚬ ⟵ q_i

Q

DM ⚬⚬⚬⚬⚬ ⟶ $\bar{q}_j$

- Overabundant region *excluded* but not underabundant one if multicomponent DM.

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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. Giacchito 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