

Top-philic dark matter

Kentarou Mawatari



1. EFT to simplified model approach
2. Constraints from 8TeV LHC +Relic+DD+ID
3. 13TeV LHC?
4. Summary and outlook

The top window for dark matter [1009.0618, JHEP]

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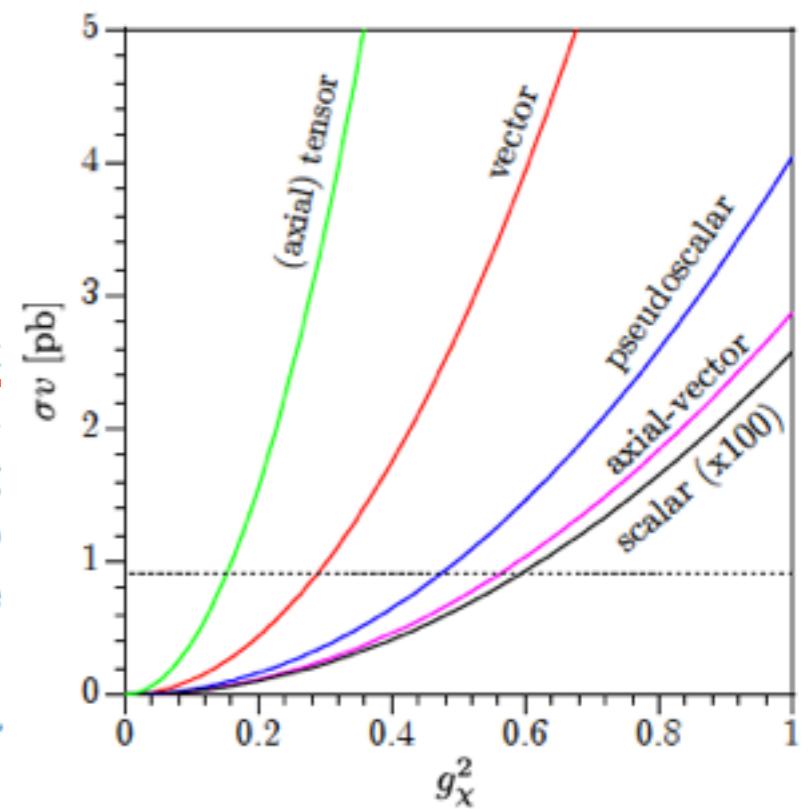
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ABSTRACT: We investigate a scenario that the top quark is the only window to the dark matter particle. We use the effective Lagrangian approach to write down the interaction between the top quark and the dark matter particle. Requiring the dark matter satisfying the relic density we obtain the size of the effective interaction. We show that the scenario can be made consistent with the direct and indirect detection experiments by adjusting the size of the effective coupling. Finally, we calculate the production cross section for $t\bar{t} + \chi\bar{\chi}$ at the Large Hadron Collider (LHC), which will give rise to an interesting signature of a top-pair plus large missing energy.

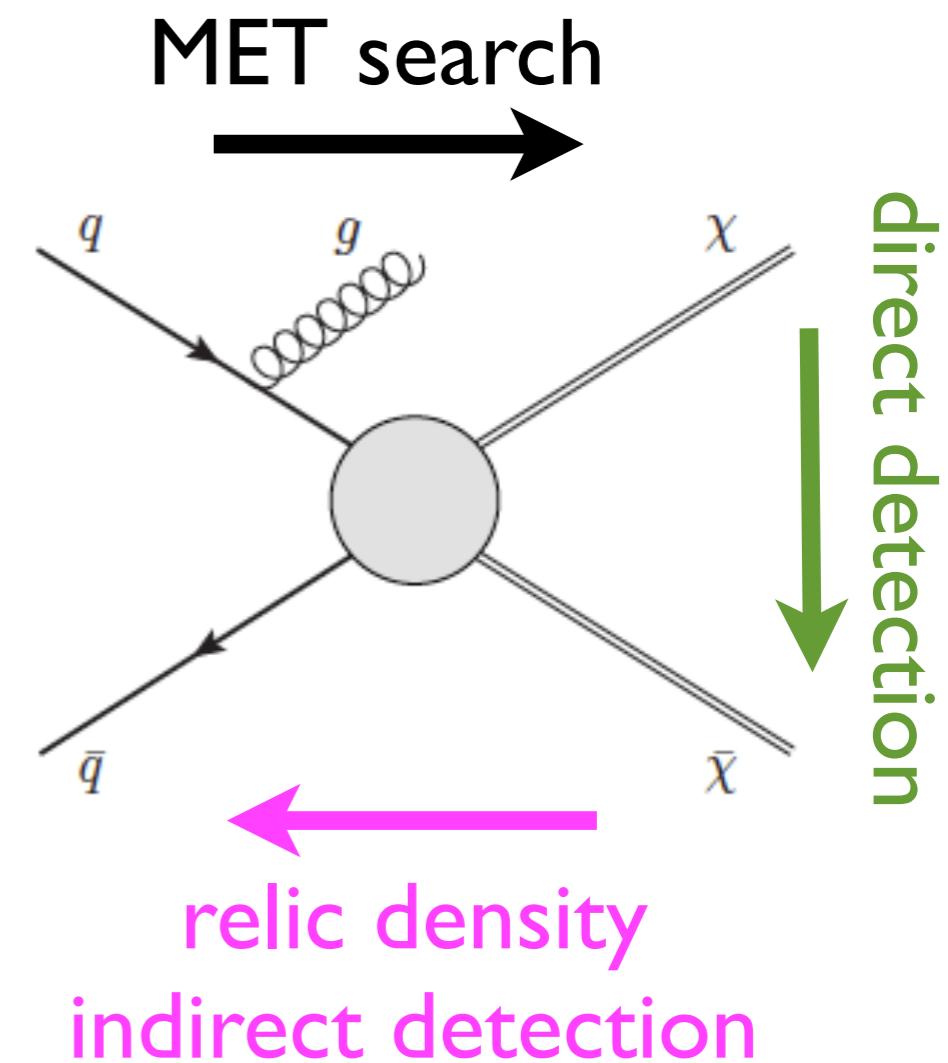
$$M_{\text{top}} \sim v_{\text{EW}} \sim M_{\text{WIMP}}$$

$$\mathcal{L} = \frac{g_\chi^2}{\Lambda^2} (\bar{\chi}\Gamma\chi) (t\bar{t}\Gamma t)$$



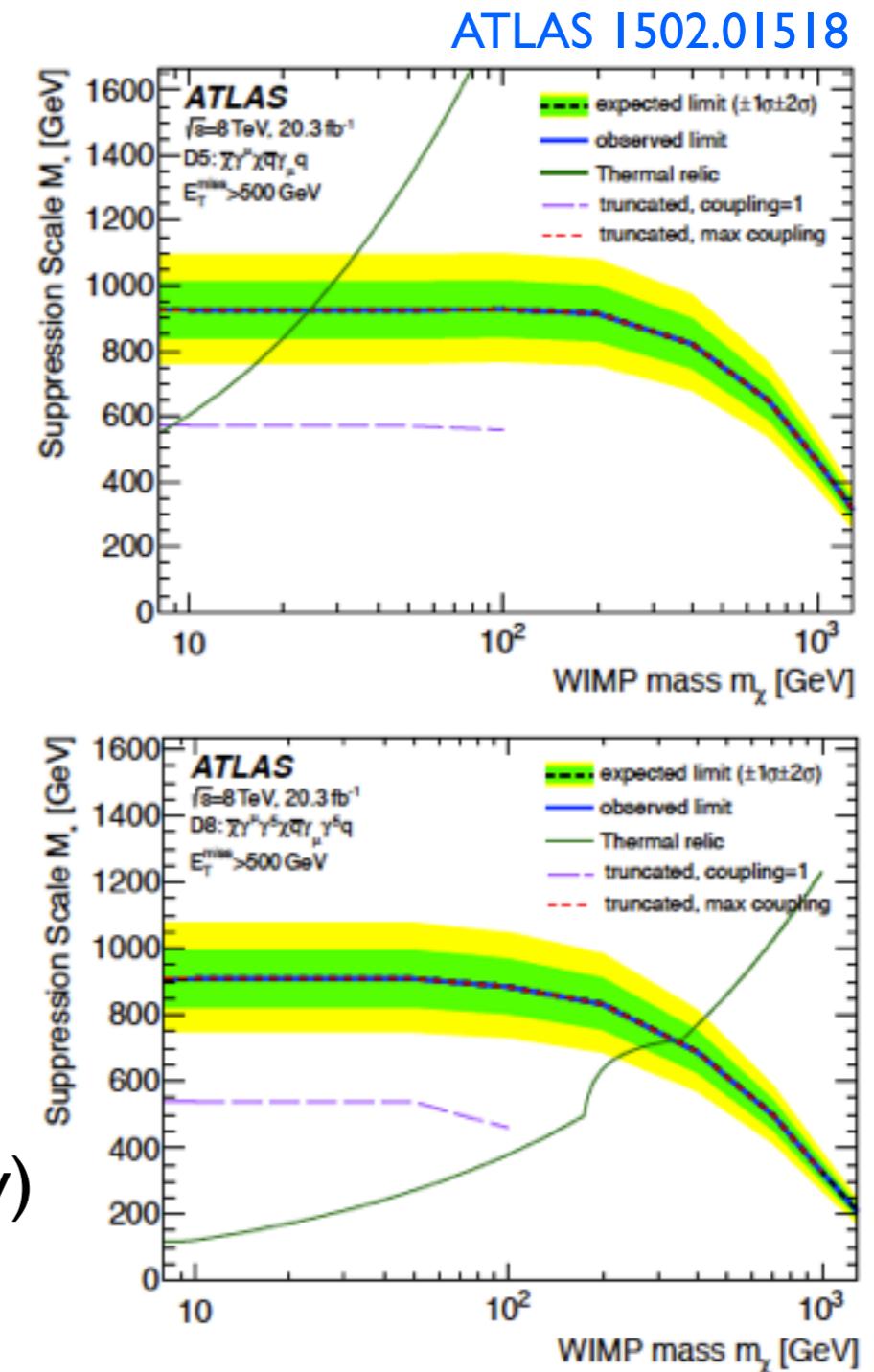
DM searches at LHC Run-I

- employed contact interaction operators in EFTs (effective field theories).
vector $\frac{1}{M_\star^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$
axial-vector $\frac{1}{M_\star^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$
- The signal is determined by the Lorentz structure, the DM mass, and the overall coupling (or the cutoff scale).
- easy interpretation to non-collider DM searches
- EFT validation; $M_\star \leq$ (LHC accessible energy)



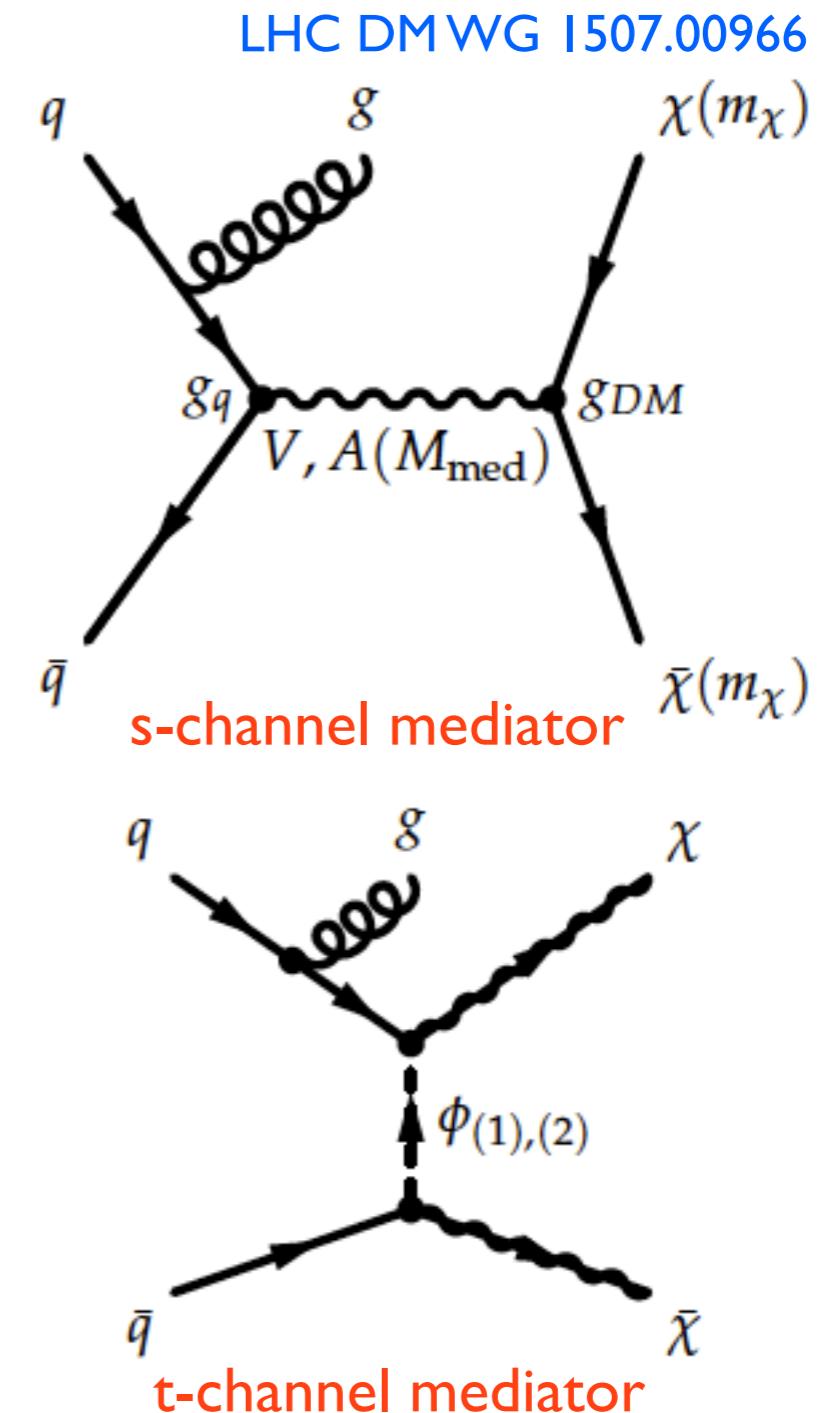
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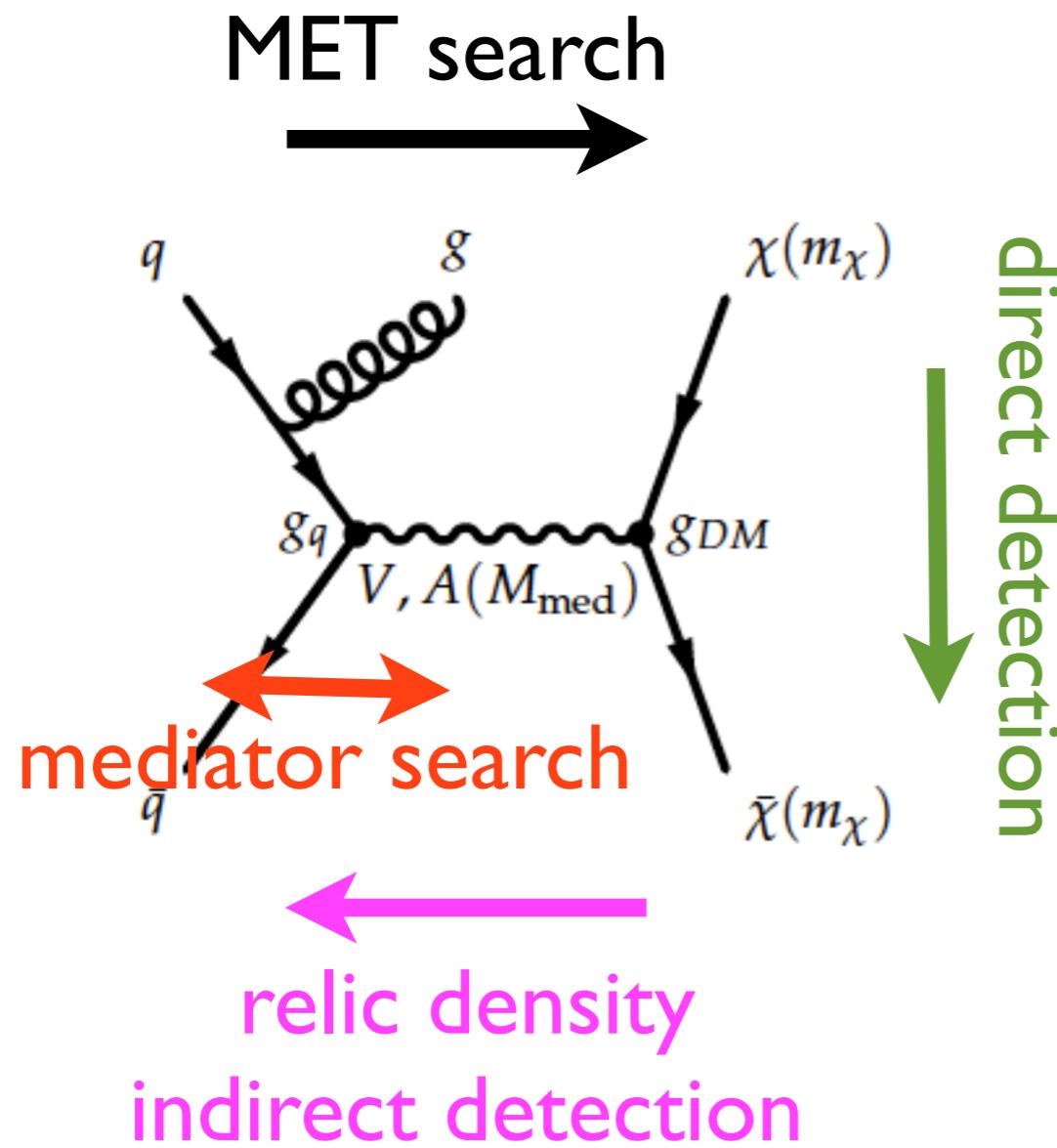
DM searches at LHC Run-II

- is employing simplified DM models.
- $\mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi$
- $\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$
- The signal is determined by the mediator type, the DM and mediator masses, and the two couplings.
- Richer phenomenology
- Interpretations to non-collider DM searches are complicated.

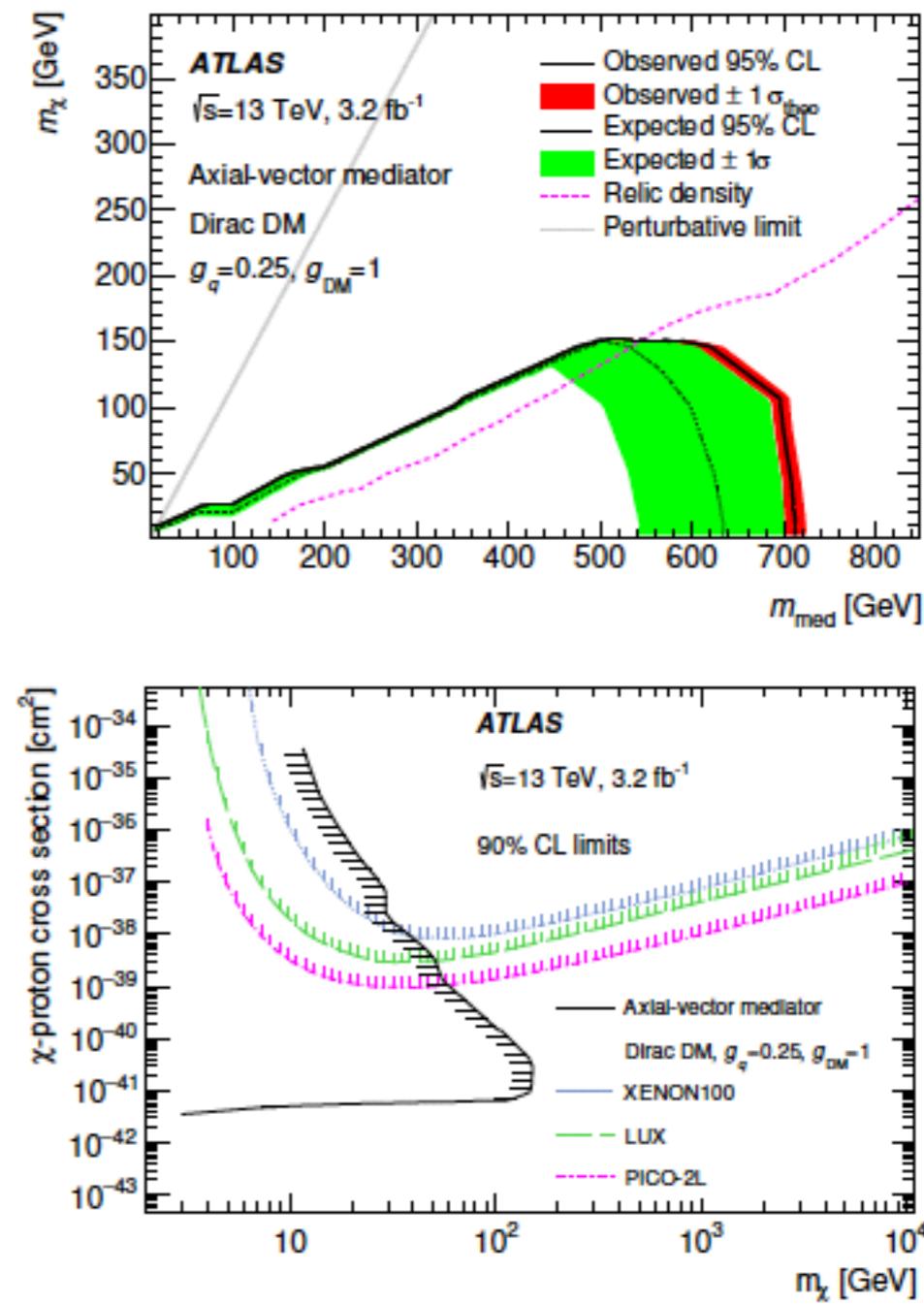


Signatures of simplified DM models

LHC DM WG [1507.00966, 1603.04156]

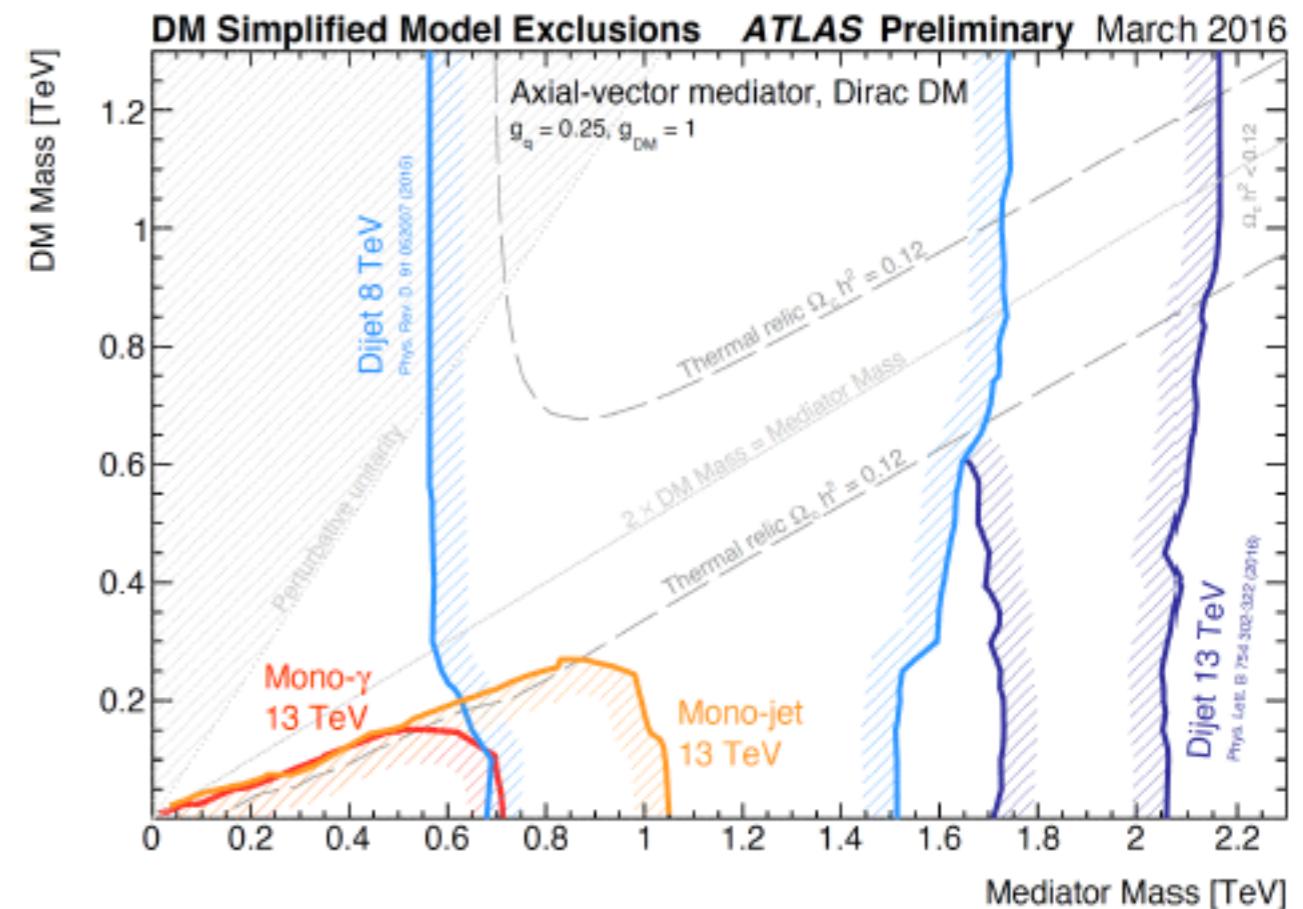
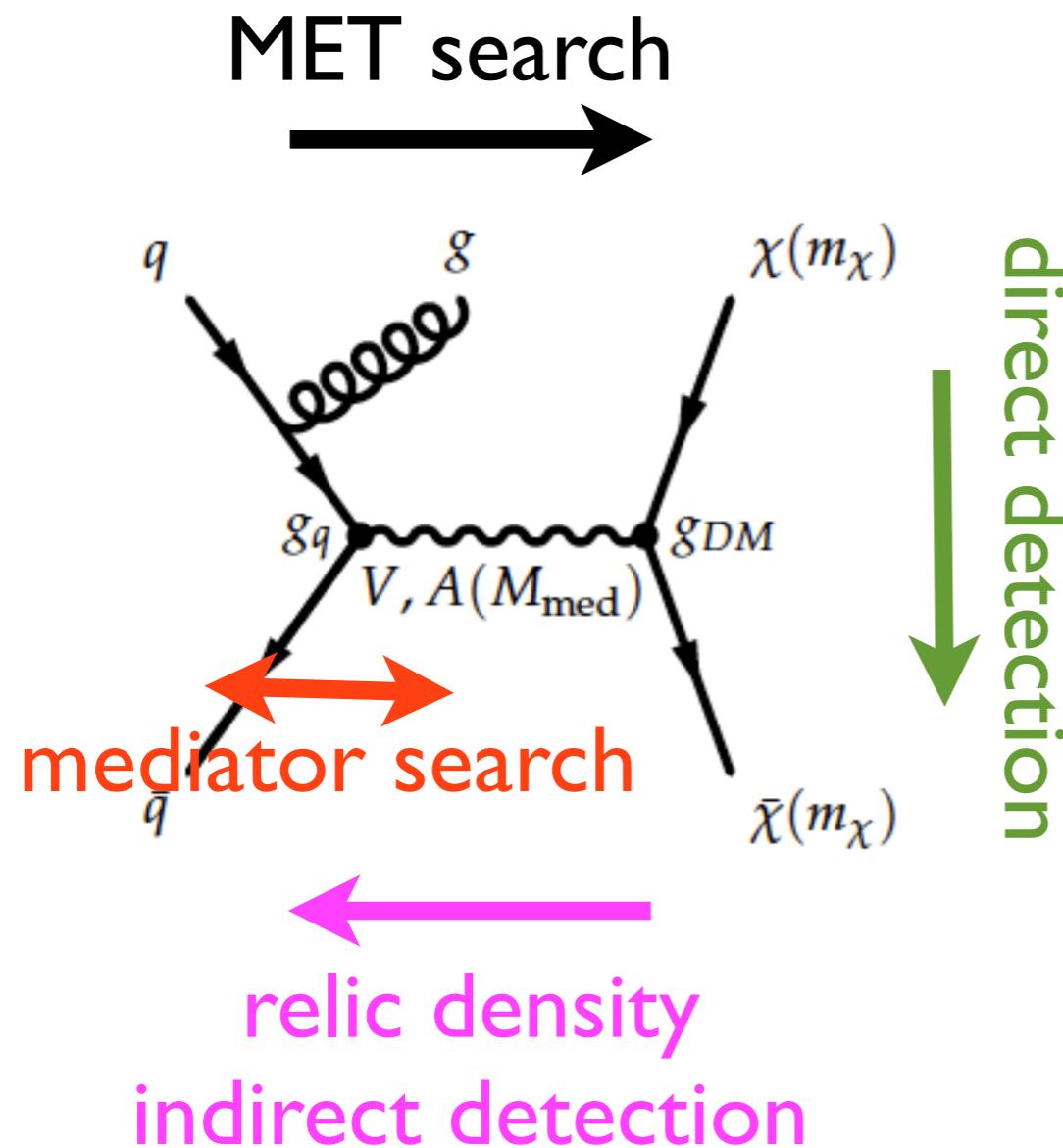


[ATLAS 1604.01306]



Signatures of simplified DM models

LHC DM WG [I507.00966, I603.04156]



s-channel simplified DM models

LHC DM WG [1507.00966, 1603.04156]

- Simplified DM models (s-channel):
 - spin-1 mediator

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q ,$$

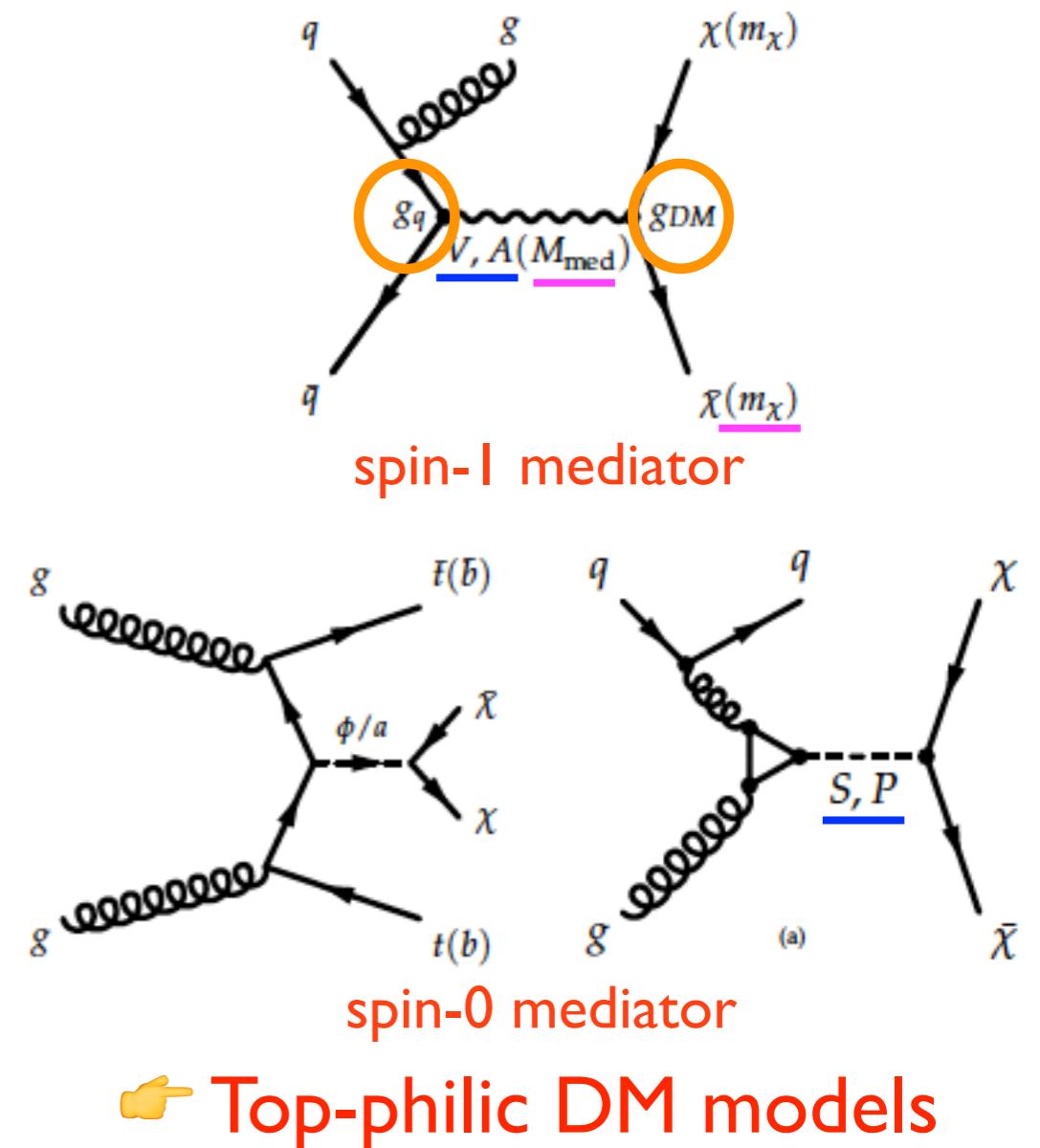
$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma_5 q .$$

- spin-0 mediator

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi} \chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -ig_{\text{DM}} \phi \bar{\chi} \gamma_5 \chi - ig_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} \gamma_5 q ,$$

- The signal is determined by
 - the mediator type (V, A, S, P)
 - the DM and mediator masses
 - the two couplings



Simplified dark matter models with a spin-2 mediator at the LHC

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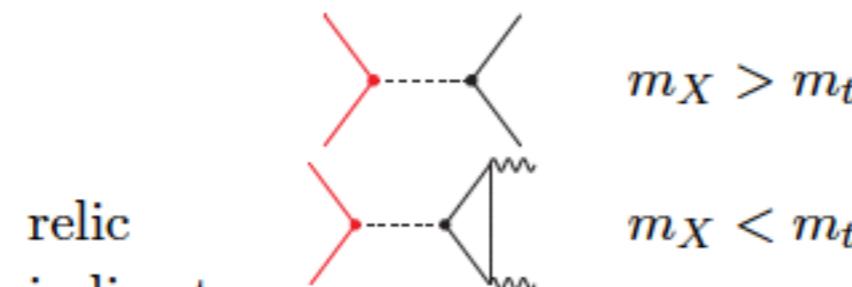
Abstract. We consider simplified dark matter models where a dark matter candidate couples to the standard model (SM) particles via an *s*-channel spin-2 mediator, and study constraints on the model parameter space from the current LHC data. Our focus lies on the complementarity among different searches, in particular monojet and multijet plus missing energy searches and resonance searches. For universal couplings of the mediator to SM particles, missing-energy searches can give stronger constraints than WW , ZZ , dijet, dihiggs $t\bar{t}$, $b\bar{b}$ resonance searches in the low-mass region and/or when the coupling of the mediator to dark matter is much larger than its couplings to SM particles. The strongest constraints however come from diphoton and dilepton resonance searches. Only if these modes are suppressed, missing-energy searches can be competitive in constraining dark matter models with a spin-2 mediator.

A comprehensive approach to DM studies: simplified topophilic models

X=DM

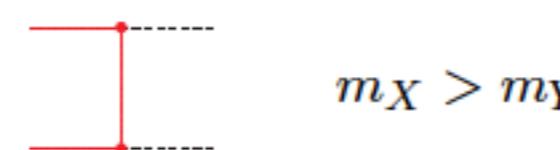
Y=mediator

Cosmology



$$m_X > m_t$$

Astrophysics



$$m_X > m_Y$$

Kraemer

Maltoni



$$m_X > 1 \text{ GeV}$$

Planck, FermiLAT

[1605.09242, JHEP]

52 pages, 23 figs, 8 tables

Arina



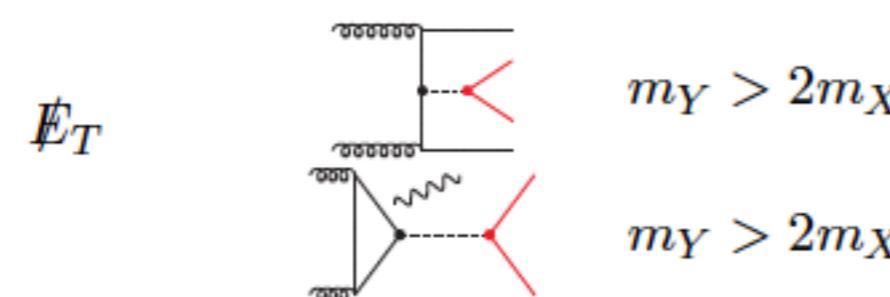
Backovic



Heisig



Colliders



$$m_Y > 2m_X$$

$$+t\bar{t}$$

Conte, Fuks, Guo



Martini, Vryonidou



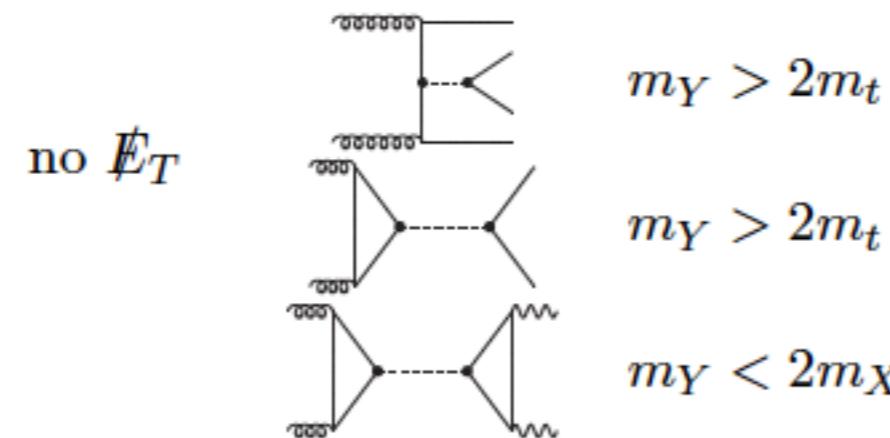
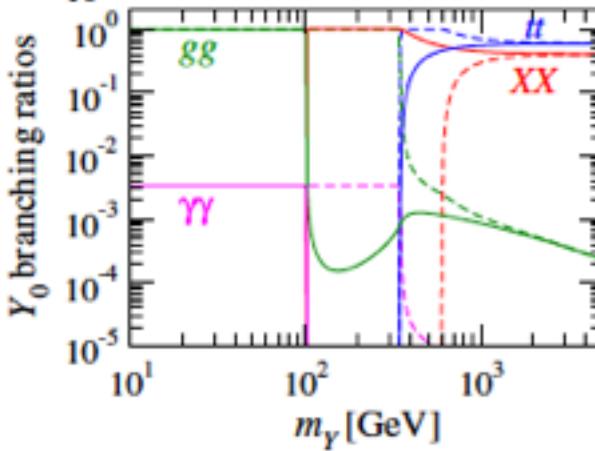
Mawatari



Hespel

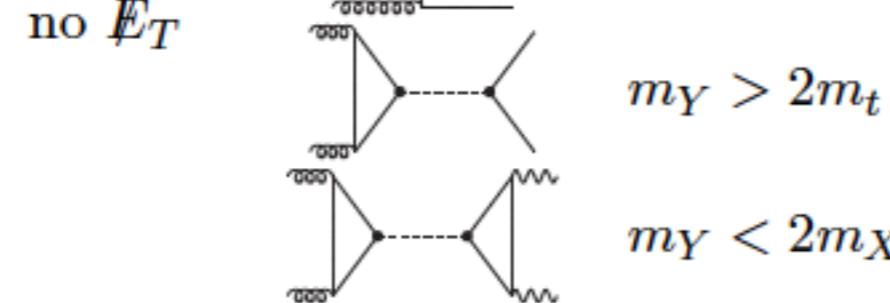


Pellen



$$m_Y > 2m_t$$

$$4t$$



$$m_Y < 2m_X, 2m_t$$

$$t\bar{t}$$

$$jj, \gamma\gamma$$

BSM models in the FeynRules model database

The screenshot shows a web browser window with the URL feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage. The page content is as follows:

FeynRules model database

This page contains a collection of models that are already implemented in FeynRules. For each model, a complete model-file is available, containing all the information that is needed, as well as the Lagrangian, as well as the references to the papers where this Lagrangian was taken from. All model-files can be freely downloaded and changed, serving like this as the starting point for building new models. A TeX-file for each model containing a summary of the Feynman Rules produced by FeynRules is also available.

The Standard model model-file is already included in the distribution of the FeynRules, but it can also be downloaded independently from the corresponding link below.

We encourage model builders writing a FeynRules implementation of their model to make their model file(s) public in the FeynRules model database, in order to make them useful to a community as wide as possible. For further information on how to make your model implementation public via the FeynRules model database, please send an email to

- neil@...
- celine.degrande@...
- claude.duhr@...
- benjamin.fuks@...

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous	
NLO	Models ready for NLO computations

Simplified dark matter models

Authors

- s-channel (spin-0 and spin-1)
 - Antony Martini (Université catholique de Louvain) & Kentarou Mawatari (LPSC Grenoble)
 - Emails: kentarou.mawatari @ ipsc.in2p3.fr
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- s-channel (spin-2)
 - Goutam Das (Saha Inst.), Celine Degrande (CERN) & Kentarou Mawatari (LPSC Grenoble)
 - Emails: goutam.das @ saha.ac.in, celine.degrande @ cern.ch, kentarou.mawatari @ ipsc.in2p3.fr

Description of the model

This is simplified dark matter models for NLO. Our lagrangian consists of different types of DM:

- X_r (real scalar DM)
- X_c (complex scalar DM)
- X_d (Dirac spinor DM)
- X_m (Majorana spinor DM) [to be done.]
- X_v (vector DM)
- ...

and different types of mediators:

- s-channel
 - Y_0 (spin-0)
 - Y_1 (spin-1)
 - Y_2 (spin-2)
 - ...
- t-channel [to be done.]

See more details in

- [1508.00564](#) : O. Mattelaer, E. Vryonidou, "Dark matter production through loop-induced processes at the LHC: the s-channel mediator case" (EPJC75(2015)436).
- [1508.05327](#) : M. Backovic, M. Kramer, F. Maltoni, A. Martini, K. Mawatari, M. Pellen, "Higher-order QCD predictions for dark matter production at the LHC in simplified models with s-channel mediators" (EPJC75(2015)482).
- [1509.05785](#) : M. Neubert, J. Wang, C. Zhang, "Higher-order QCD predictions for dark matter production in mono-Z searches at the LHC" (JHEP1602(2016)082).
- [1605.09359](#) : G. Das, C. Degrande, V. Hirschi, F. Maltoni, H. Shao, "NLO predictions for the production of a spin-two particle at the LHC"
- [1701.07008](#) : S. Kraml, U. Laa, K. Mawatari, K. Yamashita, "Simplified dark matter models with a spin-2 mediator at the LHC".

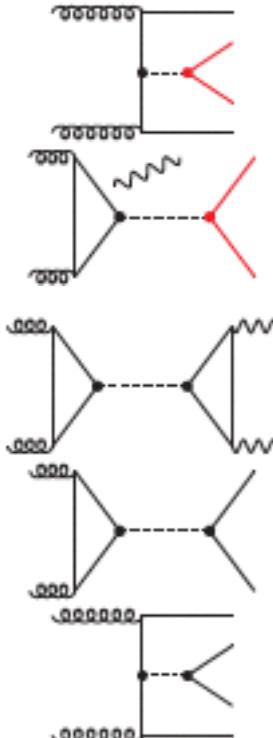
$$\mathcal{L}_{t,X}^{Y_0} = - \left(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X \right) Y_0$$

$$\{g_t, g_X, m_X, m_Y\}$$

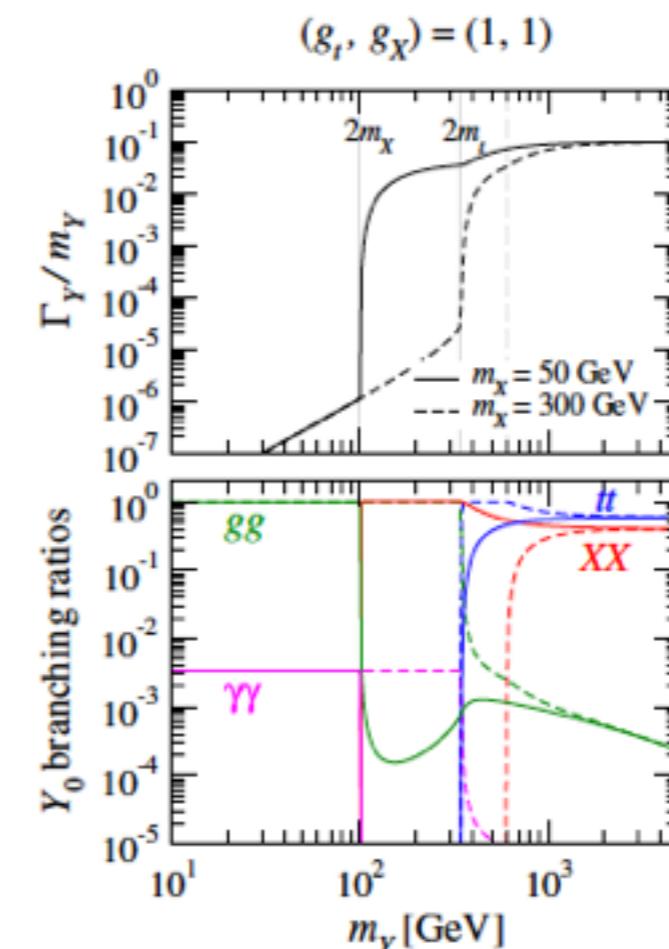
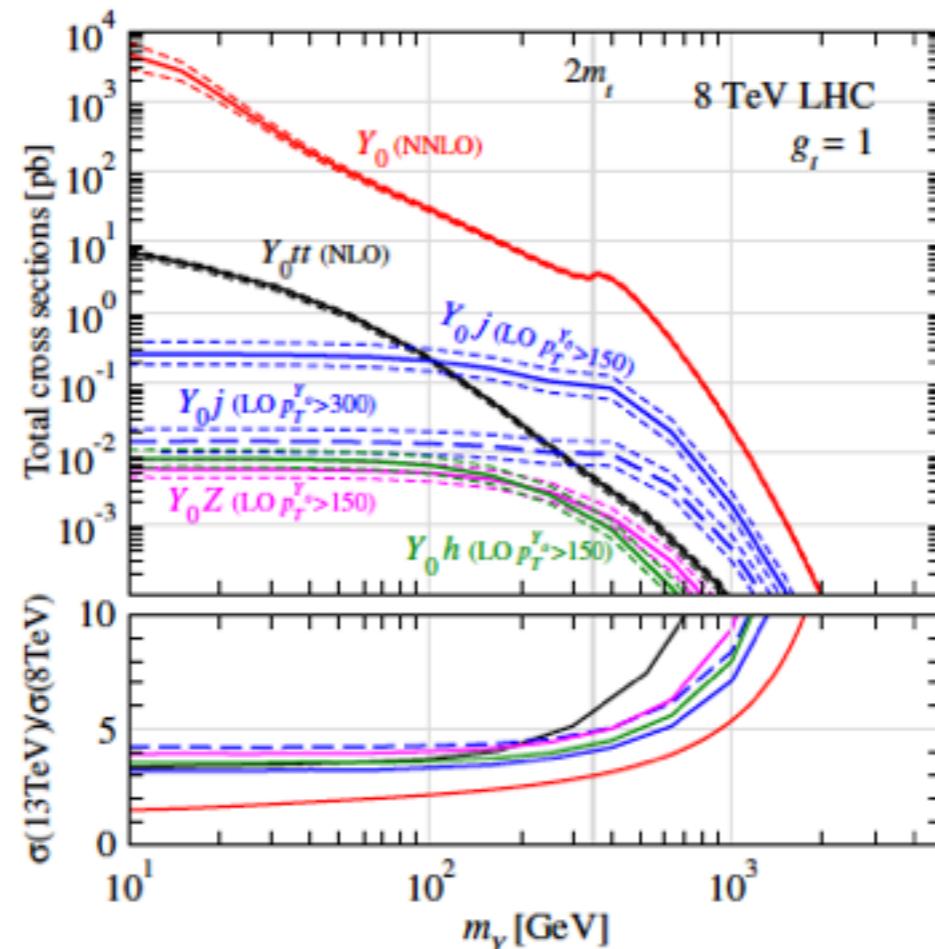
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graph TD
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micrOMEGAs]
    FR --> MG[MG5aMC]
    MG --> Py[Pythia]
    Py --> Del[Delphes]
    Del --> MA[MadAnalysis5]
  
```

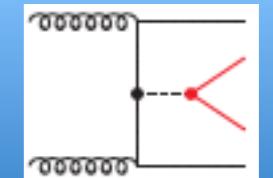
8TeV constraints for top-philic DM



Final state	Imposed constraint	Reference	Comments
$E_T + t\bar{t}$	MADANALYSIS5 PAD (new)	CMS [1504.03198]	Semileptonic top-antitop decay
$E_T + j$	MADANALYSIS5 PAD (new)	CMS [1408.3583]	
$E_T + Z$	$\sigma(E_T > 150 \text{ GeV}) < 0.85 \text{ fb}$	CMS [1511.09375]	Leptonic Z-boson decay
$E_T + h$	$\sigma(E_T > 150 \text{ GeV}) < 3.6 \text{ fb}$	ATLAS [1510.06218]	$h \rightarrow b\bar{b}$ decay
jj	$\sigma(m_Y = 500 \text{ GeV}) < 10 \text{ pb}$	CMS [1604.08907]	Only when $m_Y > 500 \text{ GeV}$
$\gamma\gamma$	$\sigma(m_Y = 150 \text{ GeV}) < 30 \text{ fb}$	CMS [1506.02301]	Only when $m_Y > 150 \text{ GeV}$
$t\bar{t}$	$\sigma(m_Y = 400 \text{ GeV}) < 3 \text{ pb}$	ATLAS [1505.07018]	Only when $m_Y > 400 \text{ GeV}$
$t\bar{t}t\bar{t}$	$\sigma < 32 \text{ fb}$	CMS [1409.7339]	Upper limit on the SM cross section

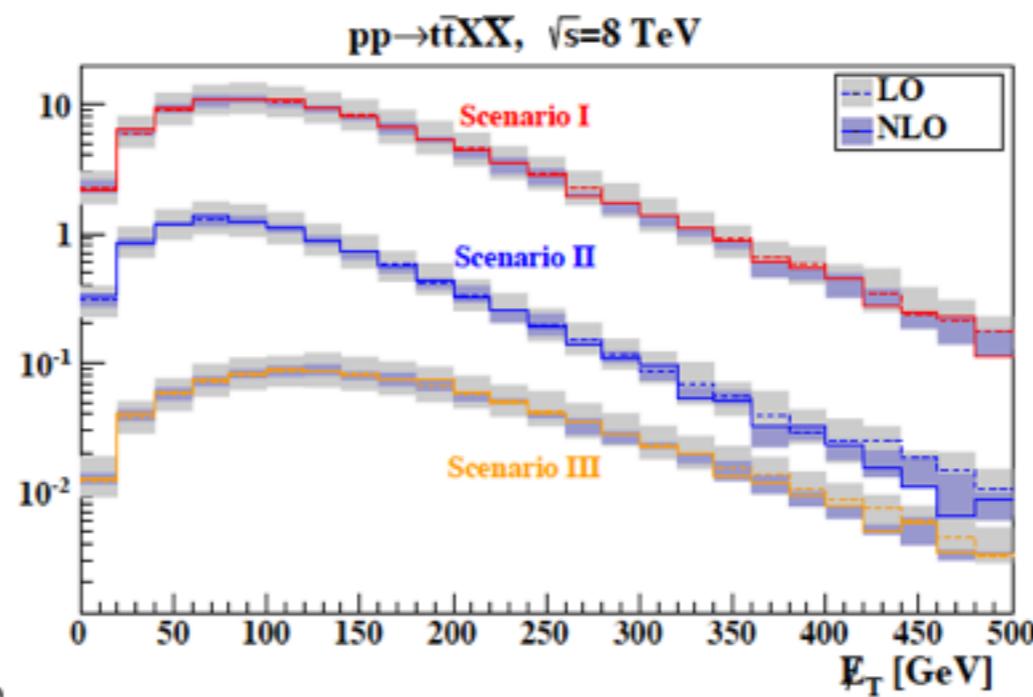
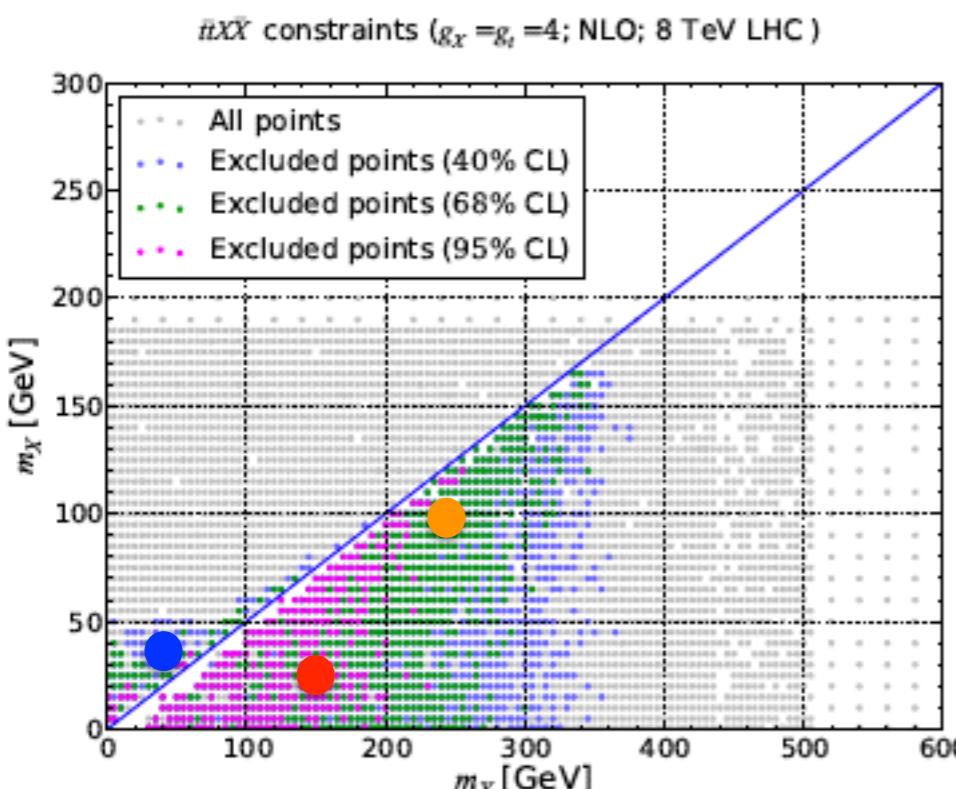
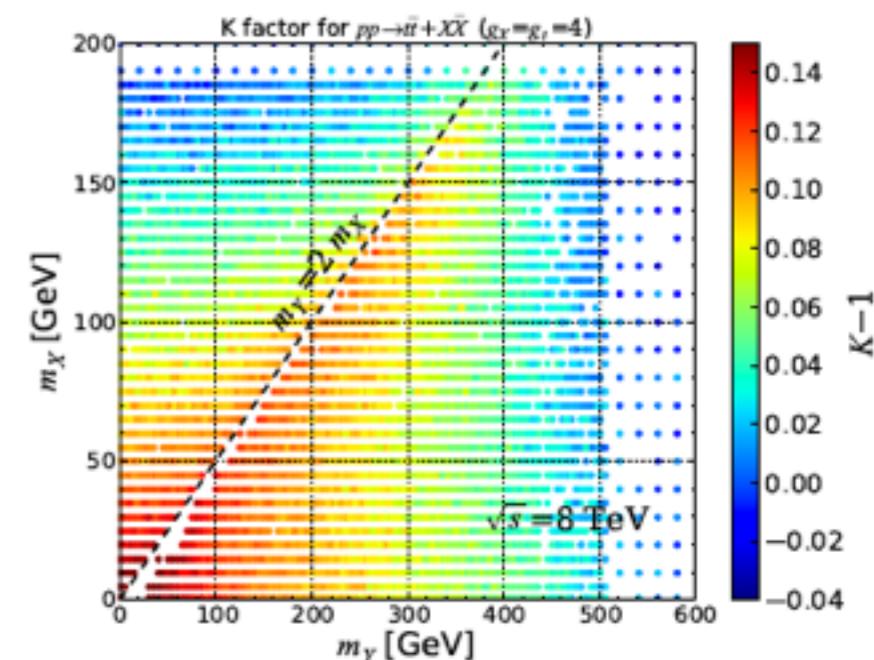
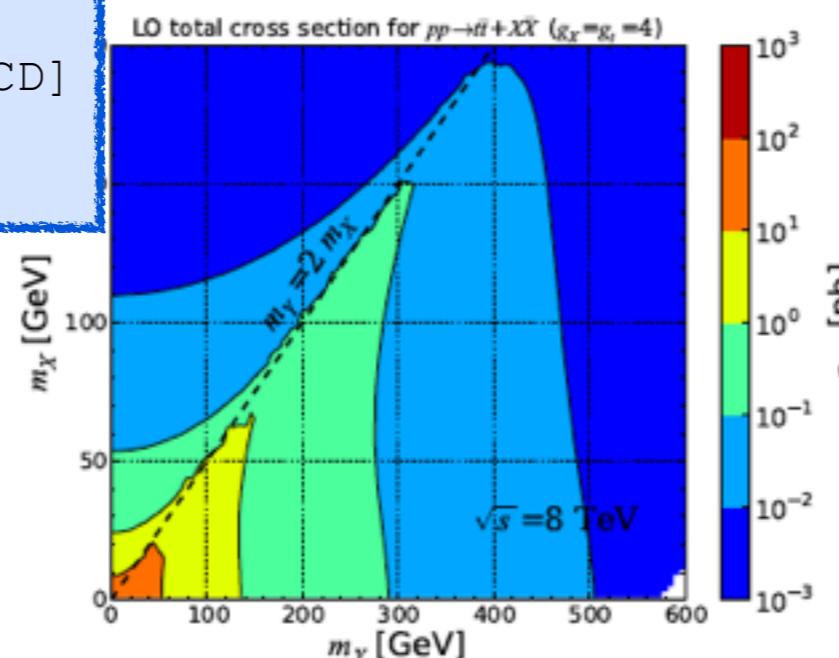


MET + a top-quark pair (NLO)



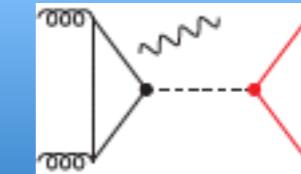
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>import model DMsimp_s_spin0
>generate p p > t t~ xd xd~ [QCD]
>output
>launch
```

(m_Y, m_X)	σ_{LO} [pb]	σ_{NLO} [pb]
(150, 25) GeV	$0.658^{+34.9\%}_{-24.0\%}$	$0.773^{+6.1\%}_{-10.1\%}$
(40, 30) GeV	$0.776^{+34.2\%}_{-24.1\%}$	$0.926^{+5.7\%}_{-10.4\%}$
(240, 100) GeV	$0.187^{+37.1\%}_{-24.4\%}$	$0.216^{+6.7\%}_{-11.4\%}$



NLO predictions reduce the theoretical uncertainty.

Mono-jet (LO loop-induced)

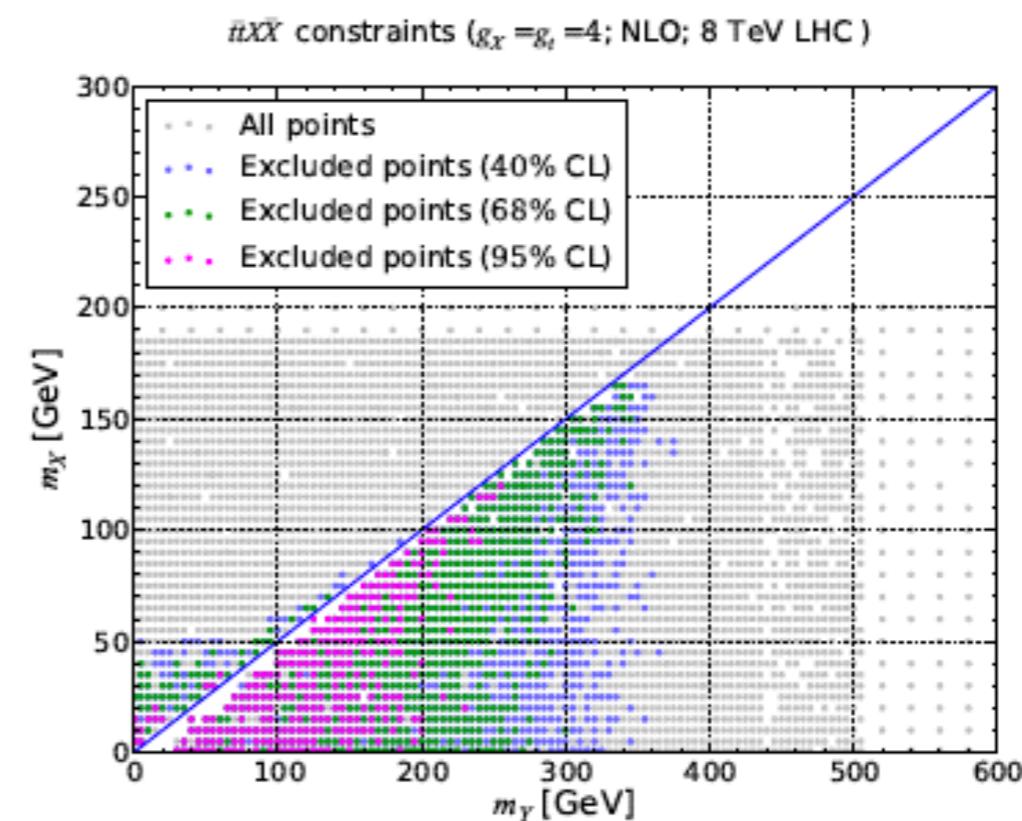
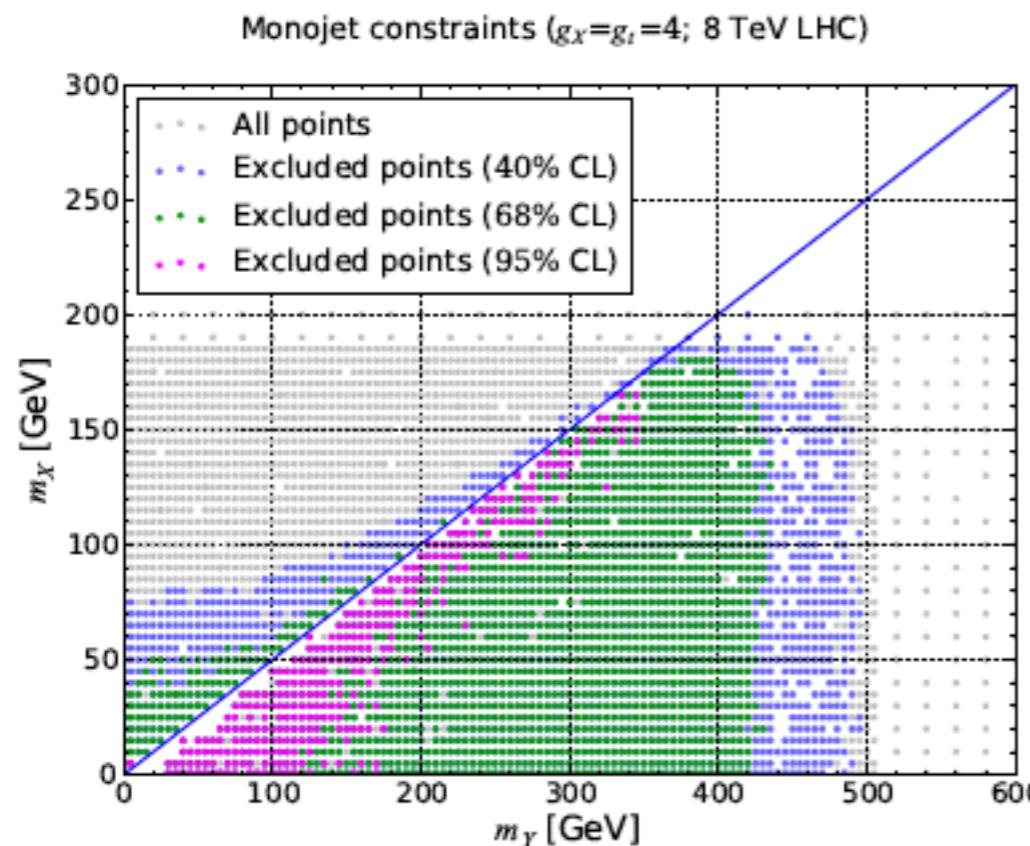
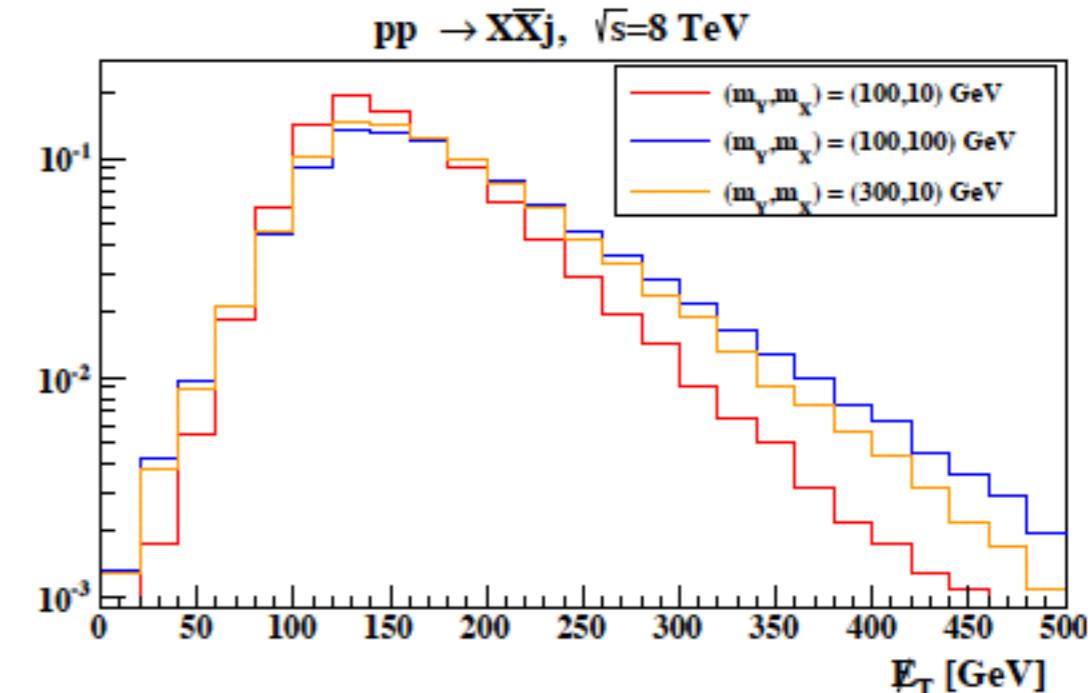


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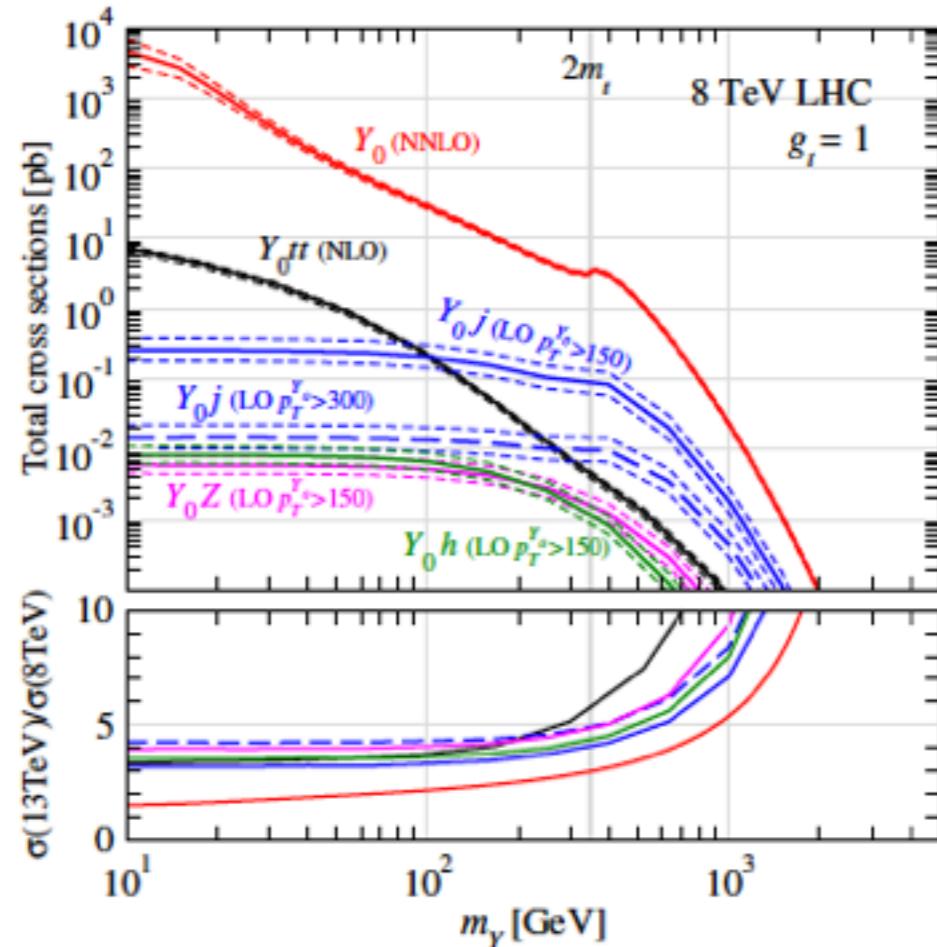
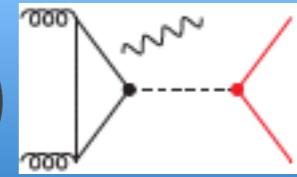
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>import model DMsimp_s_spin0
>generate p p > j xd xd~ [QCD]
>output
>launch

```

Complementarity between the different searches.

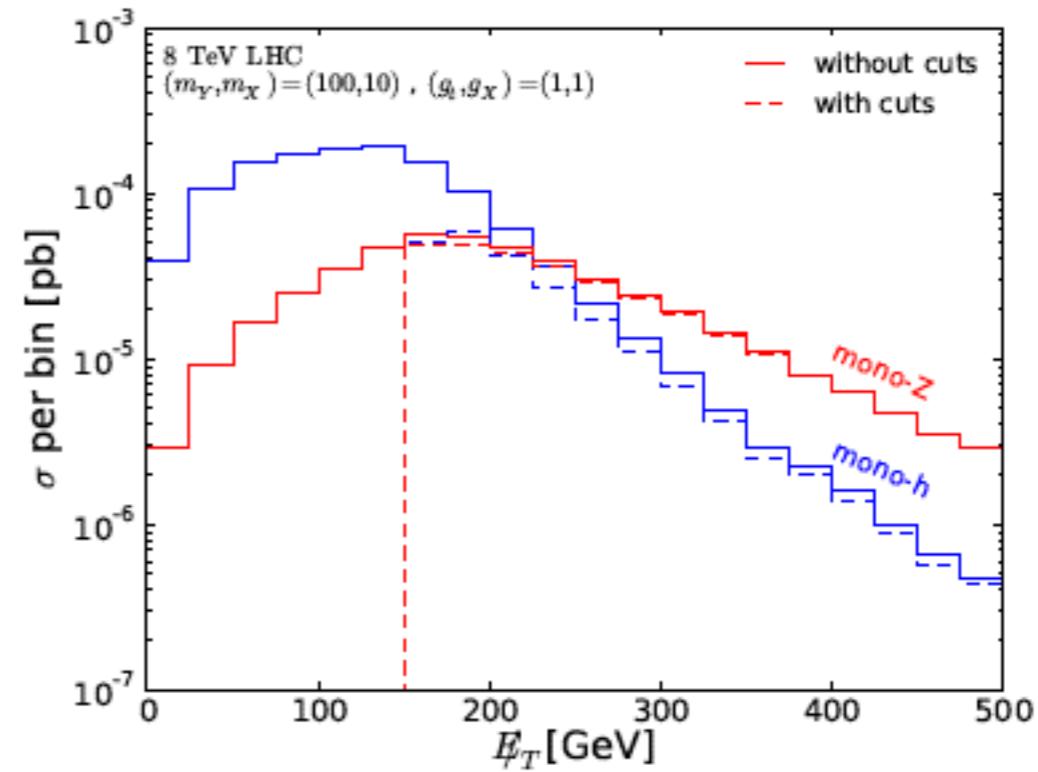


Mono-Z/h (LO loop-induced)



$$\begin{array}{ll} \not{E}_T + Z & \sigma(\not{E}_T > 150 \text{ GeV}) < 0.85 \text{ fb} \\ \not{E}_T + h & \sigma(\not{E}_T > 150 \text{ GeV}) < 3.6 \text{ fb} \end{array}$$

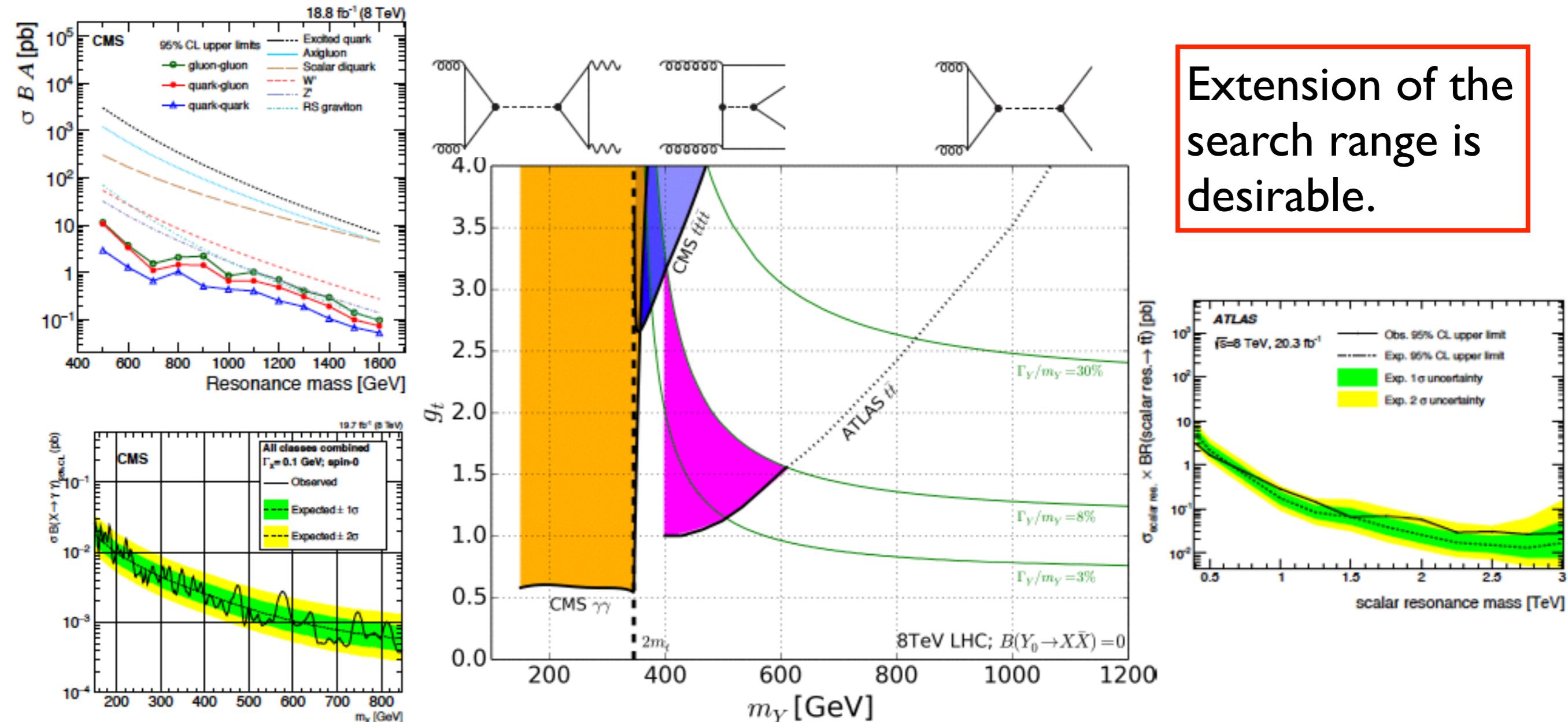
```
./bin/mg5_aMC
>import model DMsimp_s_spin0
>generate p p > z xd xd~ [QCD]
>output
>launch
```



$\rightarrow g_t < 2$ for $m_Y < 200 \text{ GeV}$

Mono-EW is also interesting.

Resonance search constraints



Extension of the search range is desirable.

jj	$\sigma(m_Y = 500 \text{ GeV}) < 10 \text{ pb}$	CMS [1604.08907]	Only when $m_Y > 500 \text{ GeV}$
$\gamma\gamma$	$\sigma(m_Y = 150 \text{ GeV}) < 30 \text{ fb}$	CMS [1506.02301]	Only when $m_Y > 150 \text{ GeV}$
$t\bar{t}$	$\sigma(m_Y = 400 \text{ GeV}) < 3 \text{ pb}$	ATLAS [1505.07018]	Only when $m_Y > 400 \text{ GeV}$
$t\bar{t}\bar{t}\bar{t}$	$\sigma < 32 \text{ fb}$	CMS [1409.7339]	Upper limit on the SM cross section

Relic vs. Direct detection vs. LHC

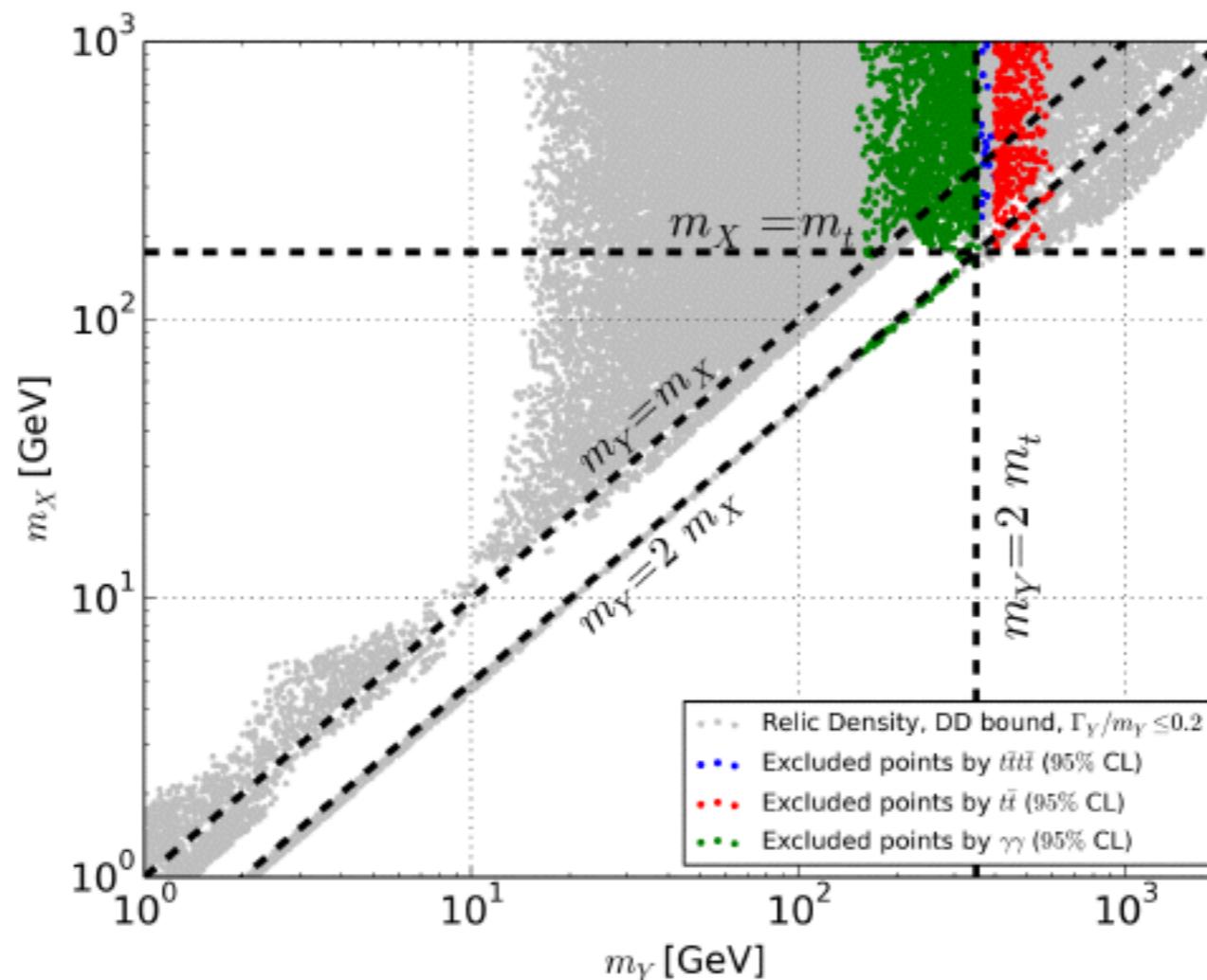
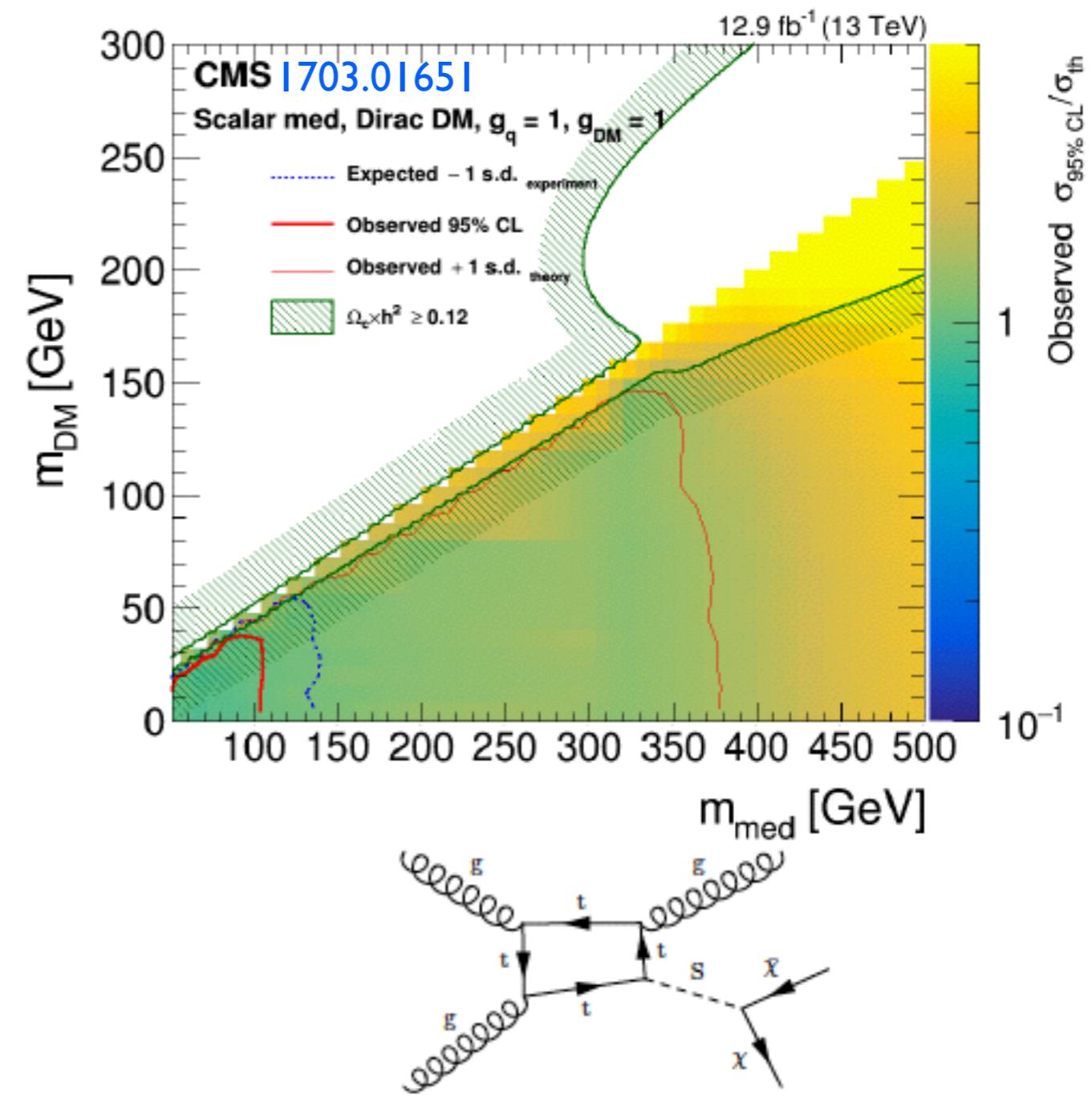
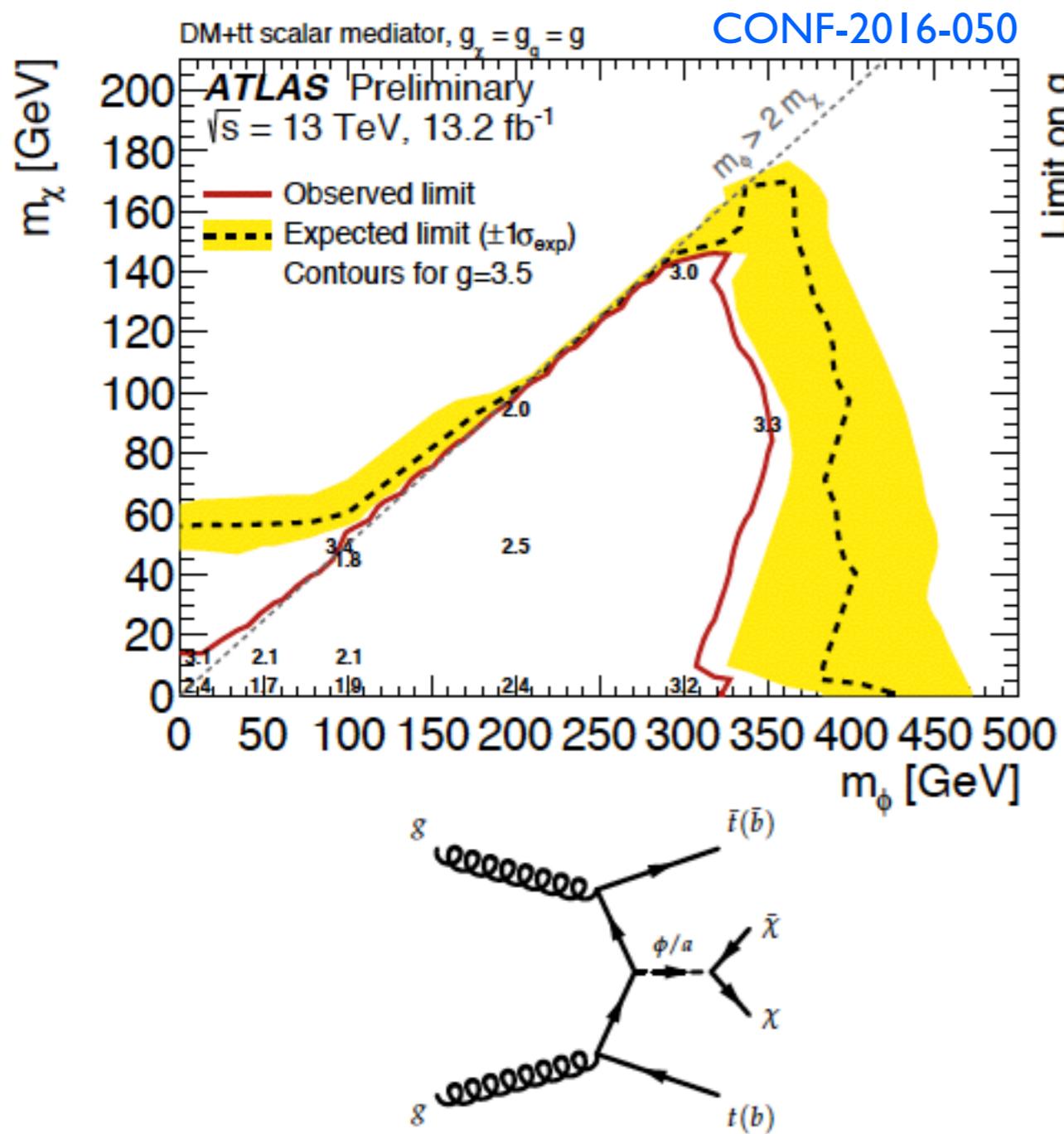


Figure 14. Results of our four-dimensional parameter scan projected onto the (m_Y, m_X) plane once constraints set from the LHC results are imposed. The points excluded by the diphoton, the $t\bar{t}$ and the four-top considered searches all satisfy the relic density, narrow width and direct detection constraints.

13TeV MET constraints



Summary and outlook

- The systematic simulation framework have been developed not only for LHC but also for non-collider experiments.
- NLO predictions not only provide reliable rate but also reduce the theoretical uncertainty.
- In the DM context, not only mono-j but also mono-EW and tt+MET are important.
- A single model can be constrained by many different LHC searches and also by non-collider searches.
- Are the simplified DM models too simple?