Dark Matter searches at the LHC

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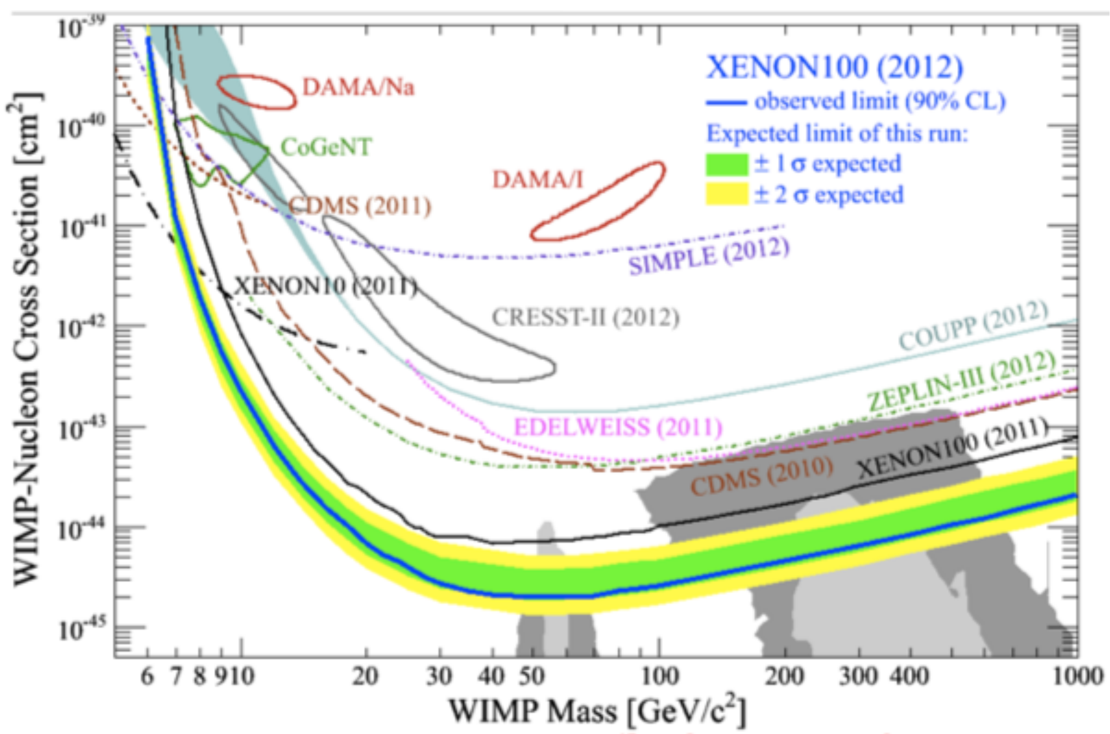
- Outline, discussion of EFT vs Full theory
- Simplified models, kinematics and widths
- Implementation in MCFM.
- Discussion of extended model with BSM loop contributions.

Some refs :

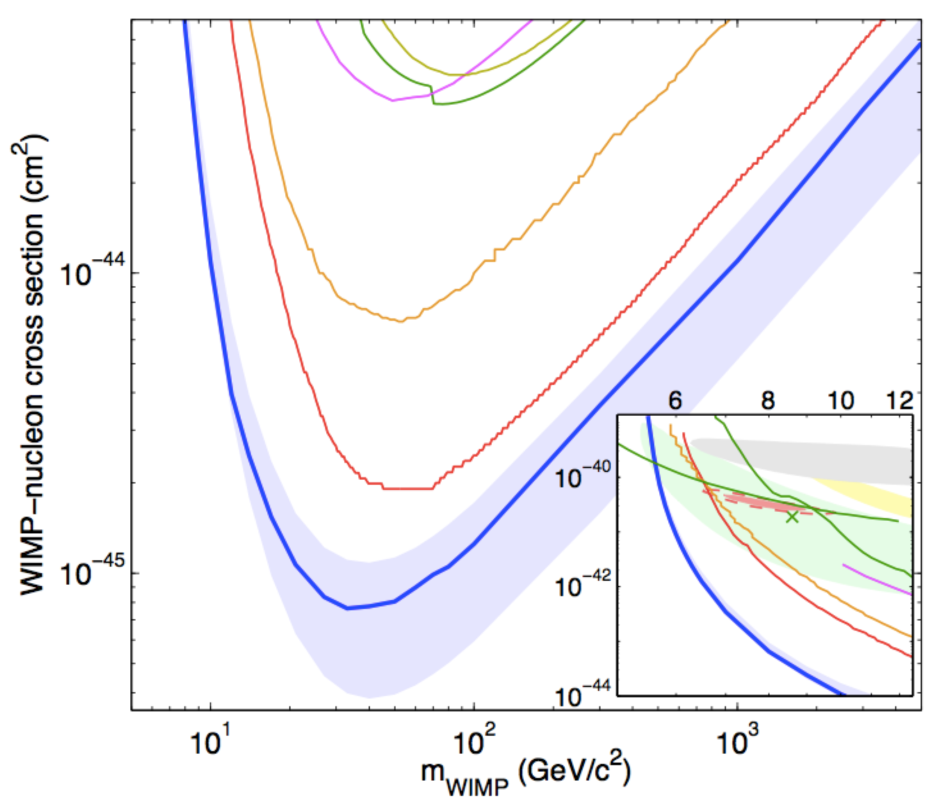
Extensive literature on related topics, for this talk the following (and refs therin) are particularly relevant

- Malik, McCabe et al 1409.4075
- Buckley, Feld, Goncalves 1410.6497
- Harris, Khoze, Spannowsky, CW 1411.0535
- CMS monojets 1408.3583
- Fox, CW 1211.6390

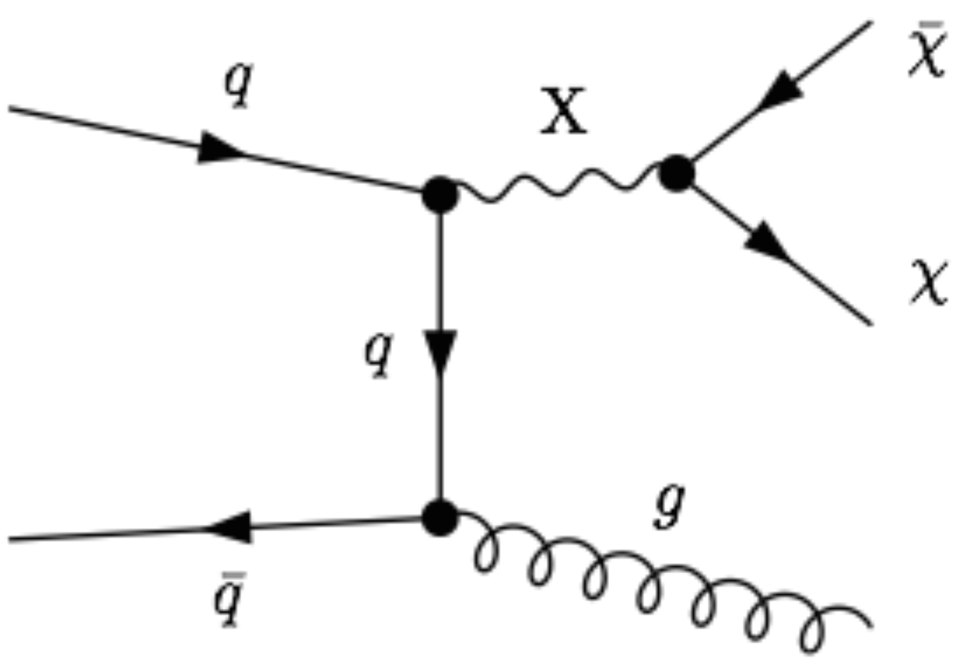
Search for DM interacting non-gravitationally is one of the most exciting in modern physics.



Direct detection experiments cover a substantial part of the phase space, but interpretation of the results can lead to conflicts.



The LHC provides a complementary tool, since the underlying interactions of the signal may be identical, but the search strategy/machine strengths are very different.



The LHC directly produces the DM, and does not suffer from low mass threshold effects.

However collider backgrounds are large, and set a lower bound for the rate.

$$\mathcal{O}_V = \frac{(\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)}{\Lambda^2} ,$$

$$\mathcal{O}_A = \frac{(\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)}{\Lambda^2} ,$$

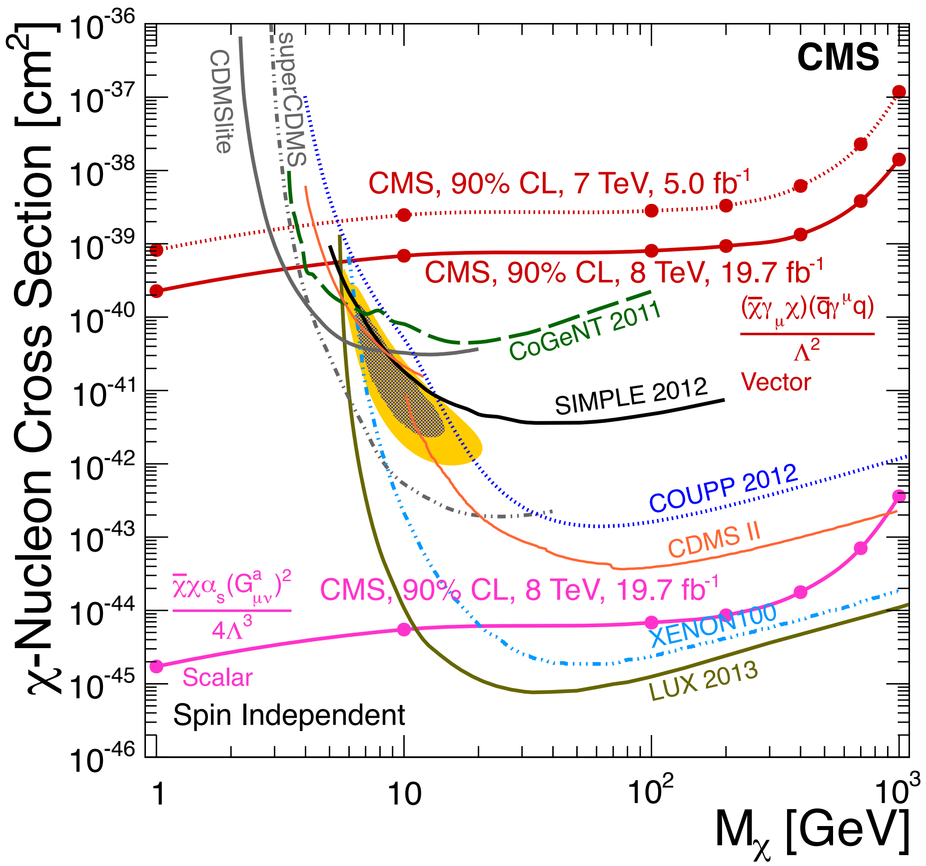
$$\mathcal{O}_g = \alpha_s \frac{(\chi\overline{\chi})(G_a^{\mu\nu}G_{a,\mu\nu})}{\Lambda^3} ,$$

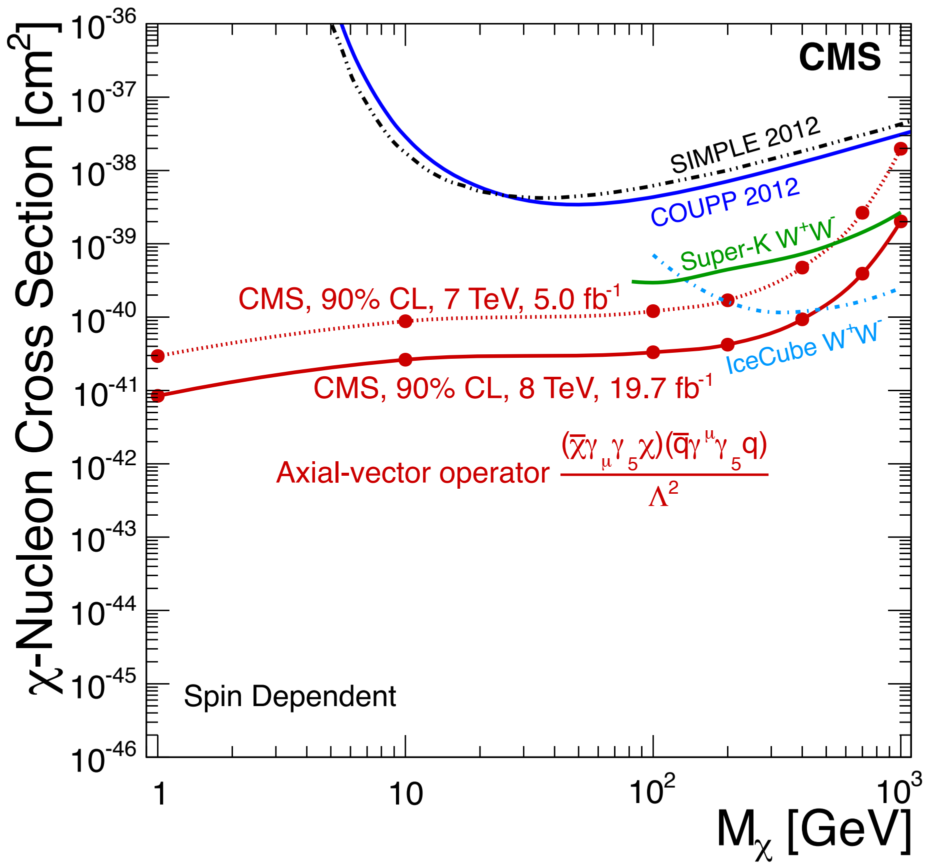
$$\mathcal{O}_S = \frac{m_q(\overline{\chi}\chi)(\overline{q}q)}{\Lambda^3} ,$$

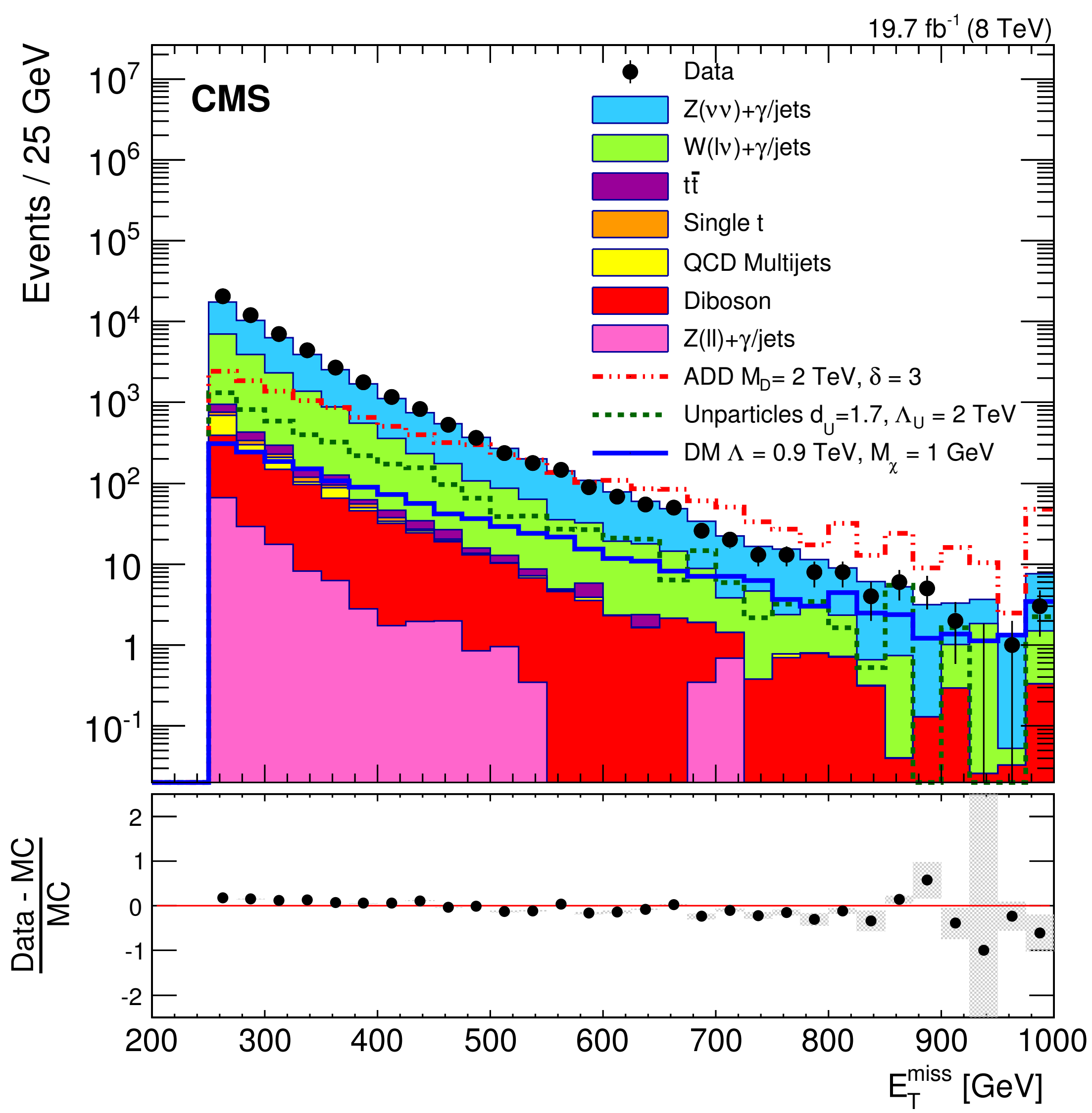
$$\mathcal{O}_{PS} = \frac{m_q(\overline{\chi}\gamma_5\chi)(\overline{q}\gamma_5 q)}{\Lambda^3} .$$

Initial searches at the Tevatron and LHC naturally worked in a regime with maximal simplicity (i.e. few parameters and good theoretical predictivity).

This was achieved by working in an Effective field theory (EFT), in which the mediator is assumed to be heavy.

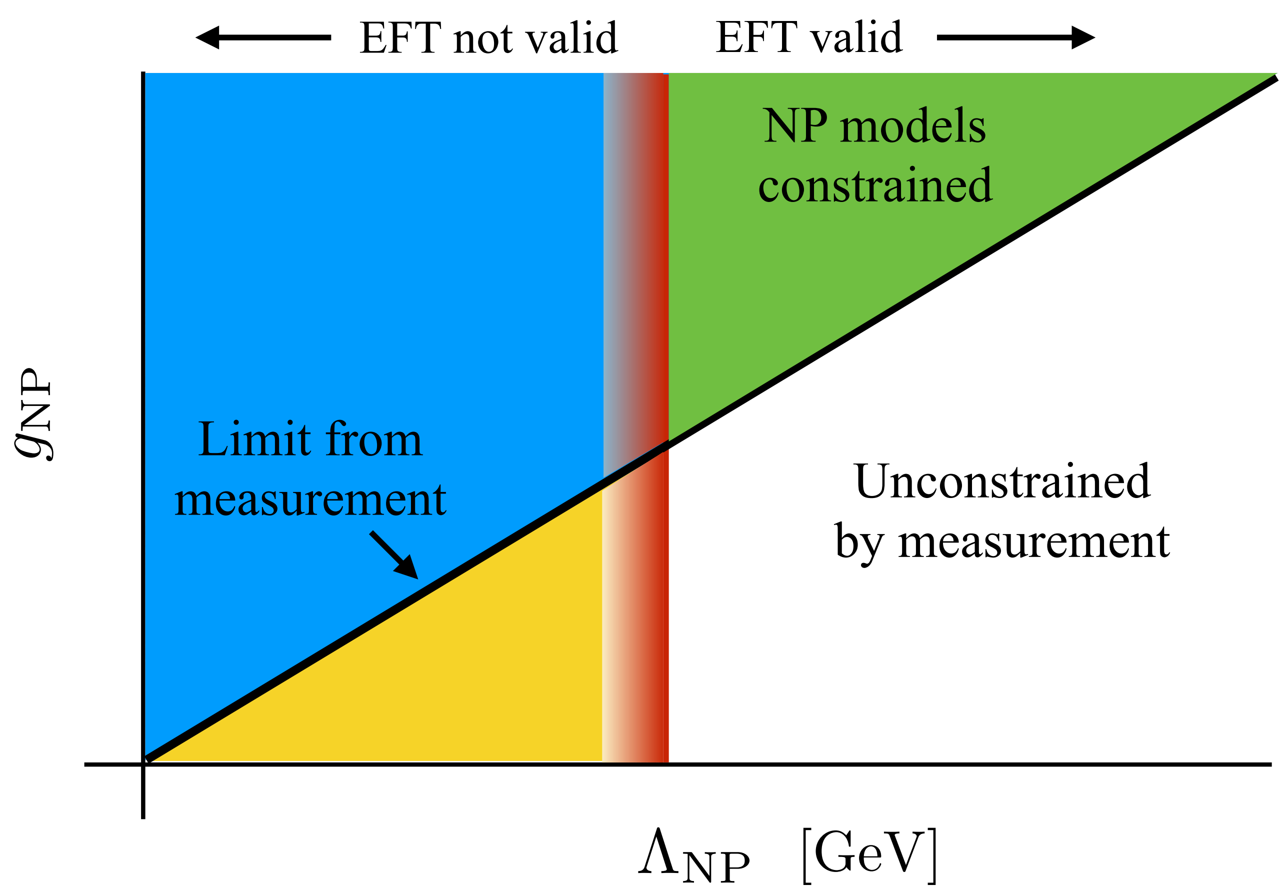






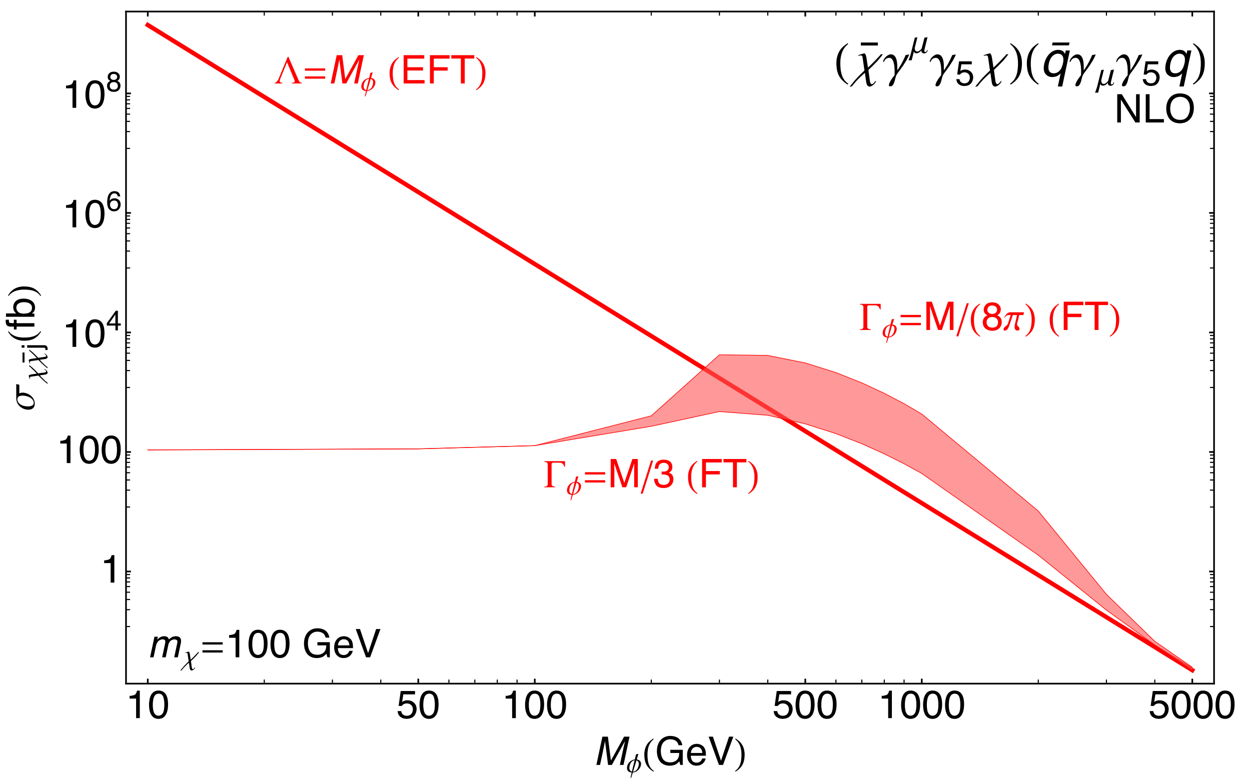
For example CMS mono-jet analysis sets bounds on EFT operators.

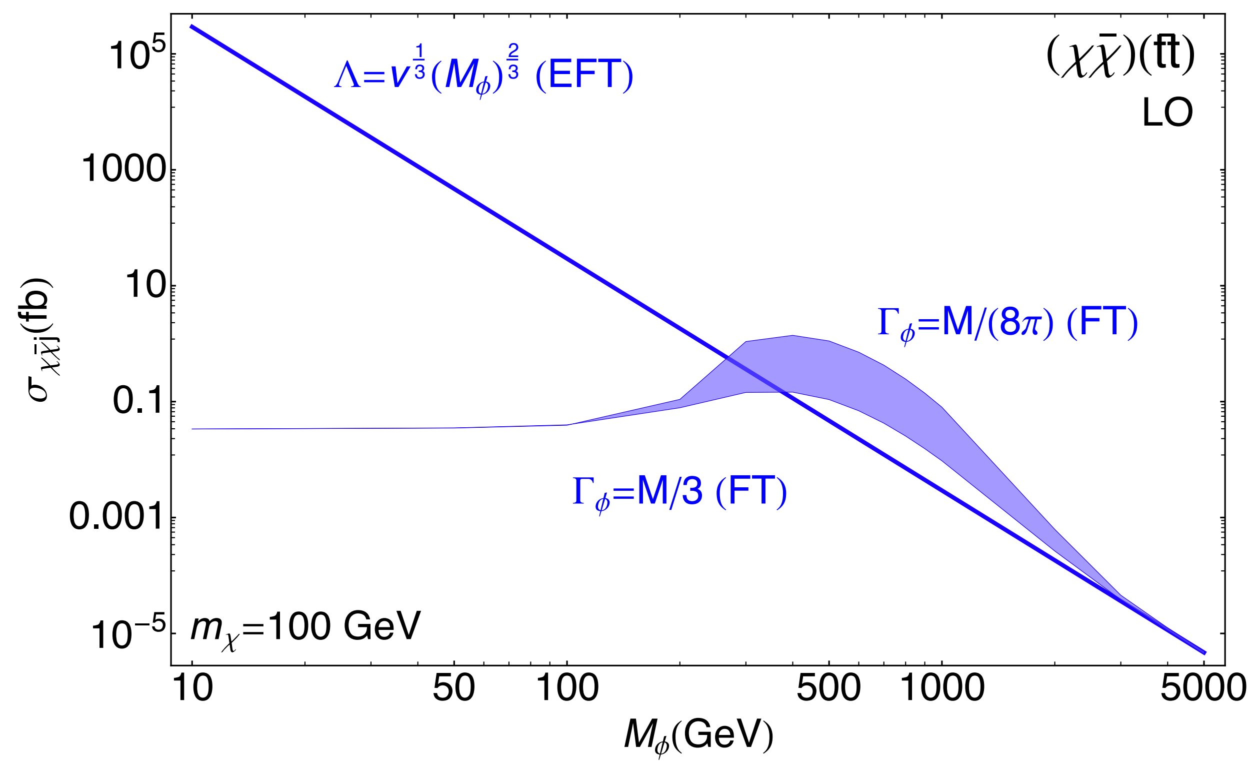
Perils of the EFT approach



Whilst useful, and a very sensible first strategy, EFT’s run into trouble if the scales at which the theory is probed break the UV scale of the EFT.

Perils of the EFT approach II





Producing mediators in the experiment can lead to dramatic breakdowns of the EFT, in which the limit is either conservative, or completely useless.

This is inherently linked to the properties of the propagating resonance, and whether it is included in the fiducial cuts.

Going beyond the EFT : Simplified Models

Experimental analysis are mature enough now to extend the models to include the effect of propagating mediators.

Such models require more parameters to be specified by the theory, and are thus less predictive, and harder to set limits on.

We begin by considering the non-exhaustive list.

$$\mathcal{L}_{\mathrm{scalar}} \supset -\frac{1}{2} m_{\mathrm{MED}}^2 S^2 - g_{\mathrm{DM}} S\, \bar{\chi}\chi - g_{SM}^t S\, \bar{t}t - g_{SM}^b S\, \bar{b}b\,,$$

$$\mathcal{L}_{\mathrm{pseudo-scalar}} \supset -\frac{1}{2} m_{\mathrm{MED}}^2 P^2 - g_{\mathrm{DM}} P\, \bar{\chi}\gamma^5\chi - g_{SM}^t P\, \bar{t}\gamma^5 t - g_{SM}^b P\, \bar{b}\gamma^5 b\,,$$

$$\mathcal{L}_{\mathrm{vector}} \supset \frac{1}{2} m_{\mathrm{MED}}^2 Z'_\mu Z'^\mu - g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum_q g_{SM}^q Z'_\mu \bar{q}\gamma^\mu q\,,$$

$$\mathcal{L}_{\mathrm{axial}} \supset \frac{1}{2} m_{\mathrm{MED}}^2 Z''_\mu Z''^\mu - g_{\mathrm{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu \bar{q}\gamma^\mu\gamma^5 q\,.$$

An example, a simple Higgs portal model.

A potential realization of these simplified models, is a Higgs portal model, which introduces a new scalar field, which is coupled to the dark sector (here taken to be a fermion), and to the SM through the Higgs portal

$$\mathcal{L}_{\mathrm{portal}} = \lambda_{\mathrm{hp}} |H|^2 |\Phi|^2 - g_{\mathrm{DM}} \ \bar{\chi} \Phi \chi .$$

After EWSB, the following Lagrangian is obtained,

$$\mathcal{L}_{\mathrm{portal}} \supset 2\lambda_{\mathrm{hp}} \langle \Phi \rangle \, v \ \phi h + \lambda_{\mathrm{hp}} v^2 \ \phi^2 + \lambda_{\mathrm{hp}} \langle \Phi \rangle^2 h^2 - g_{\mathrm{DM}} \ \bar{\chi} (\langle \Phi \rangle + \phi) \chi .$$

One scalar is identified with the 125 GeV Higgs boson, the other is that which we will actively search for!

Quantifying the Simplified Model.

An advantage of the EFT approach is that analysis can target individual Wilson coefficients, one at a time. i.e. there is nominally two parameters to measure per operator, (Wilson coefficient + dm mass)

A UV complete Simplified model will contain a wealth of new parameters which specify the theory.

2 x couplings : $g_{SM} \quad g_{DM}$

2 x masses : $m_\chi \quad m_{med}$

and the mediator width: Γ_{med}

The mediator width,

One can always define a minimal width, which encapsulates the known properties of the width (i.e. masses and specified couplings).

$$\Gamma^{V,A}_{\text{MED,min}} = \Gamma^{V,A}_{\chi\bar{\chi}} + \sum_{i=1}^{N_f} N_c \Gamma^{V,A}_{q_i\bar{q}_i} + N_c \Gamma^{V,A}_{t\bar{t}}$$

$$\Gamma^{S,P}_{\text{MED,min}} = \Gamma^{S,P}_{\chi\bar{\chi}} + N_c \Gamma^{S,P}_{t\bar{t}}$$

$$\Gamma^{V}_{f\bar{f}} = \frac{g_f^2 (m^2_{\text{MED}} + 2m_f^2)}{12\pi m_{\text{MED}}} \sqrt{1 - \frac{4m_f^2}{m^2_{\text{MED}}}}$$

$$\Gamma^{A}_{f\bar{f}} = \frac{g_f^2 (m^2_{\text{MED}} - 4m_f^2)}{12\pi m_{\text{MED}}} \sqrt{1 - \frac{4m_f^2}{m^2_{\text{MED}}}}$$

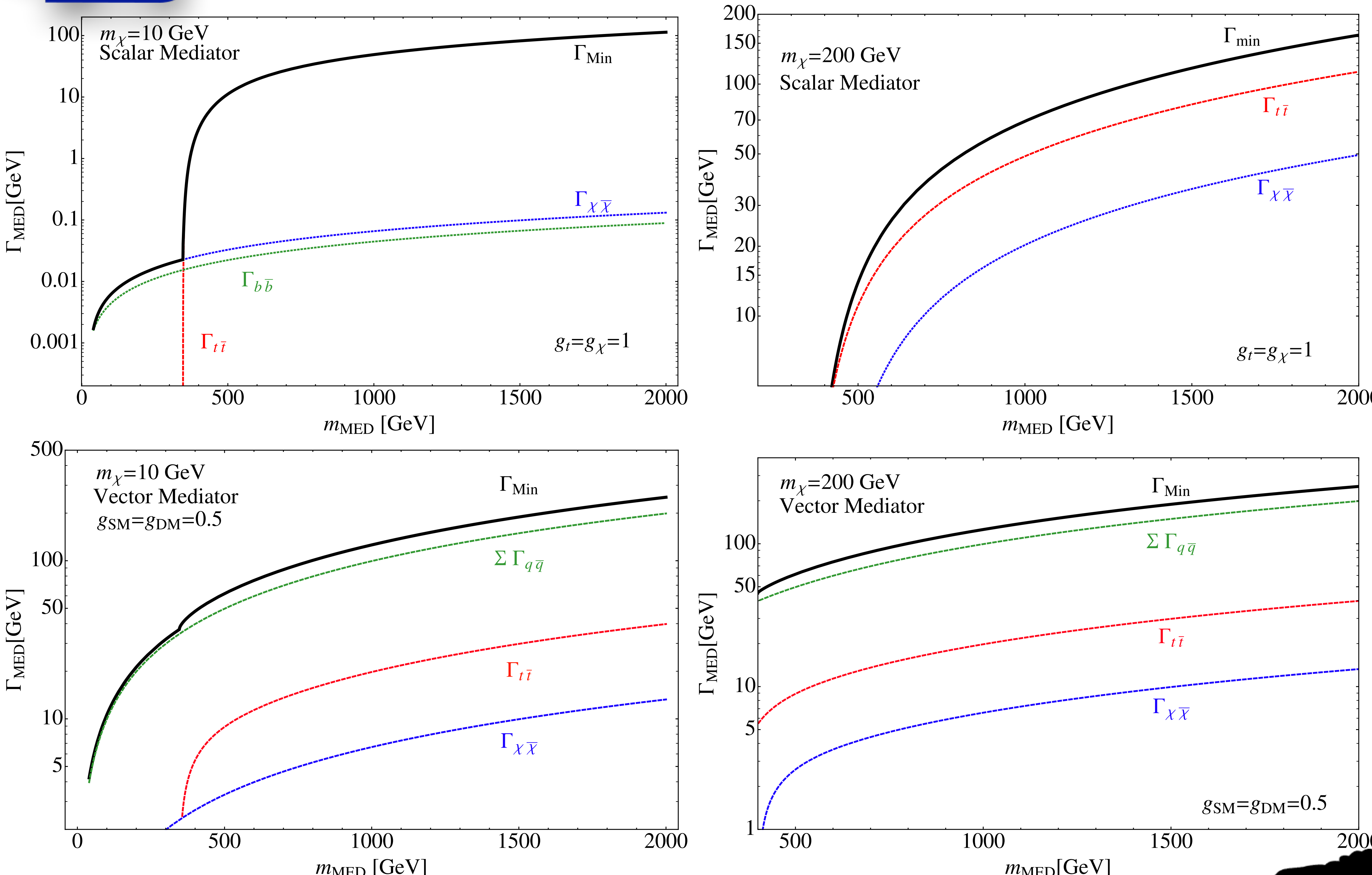
$$\Gamma^{S}_{f\bar{f}} = \frac{g_f^2 m_f^2 m_{\text{MED}}}{8\pi v^2} \left(1 - \frac{4m_f^2}{m^2_{\text{MED}}}\right)^{\frac{3}{2}}$$

$$\Gamma^{P}_{f\bar{f}} = \frac{g_f^2 m_f^2 m_{\text{MED}}}{8\pi v^2} \left(1 - \frac{4m_f^2}{m^2_{\text{MED}}}\right)^{\frac{1}{2}}$$

The width can be significantly bigger than this, e.g. by extending the dark sector, off-shell decays, or additional decays to SM gauge bosons etc.

For us the minimal widths can be built from the following,

Examples



m_χ=10 GeV
Scalar Mediator
$\Gamma_{\rm Min}$
$\Gamma_{\chi\bar{\chi}}$
$\Gamma_{b\bar{b}}$
$\Gamma_{t\bar{t}}$
$g_t=g_\chi=1$
$\Gamma_{\rm MED}$[GeV]
$m_{\rm MED}$ [GeV]
m_χ=200 GeV
Scalar Mediator
$\Gamma_{\rm min}$
$\Gamma_{t\bar{t}}$
$\Gamma_{\chi\bar{\chi}}$
$g_t=g_\chi=1$
m_χ=10 GeV
Vector Mediator
$g_{\rm SM}=g_{\rm DM}$=0.5
$\Gamma_{\rm Min}$
$\Sigma\,\Gamma_{q\bar{q}}$
$\Gamma_{t\bar{t}}$
$\Gamma_{\chi\bar{\chi}}$
m_χ=200 GeV
Vector Mediator
$g_{\rm SM}=g_{\rm DM}$=0.5

Putting it all together.

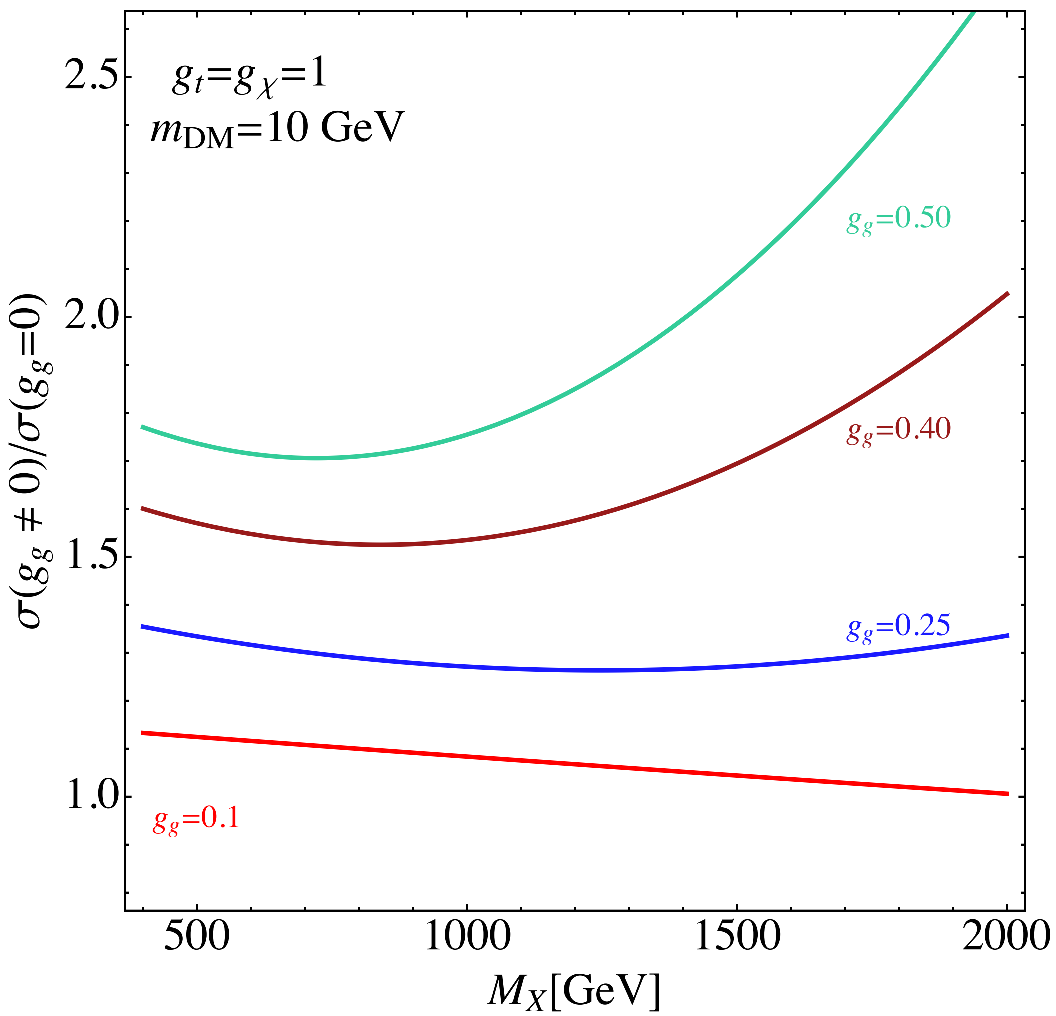
Now that we have a full simplified model we can test it against LHC data and compare it to data.

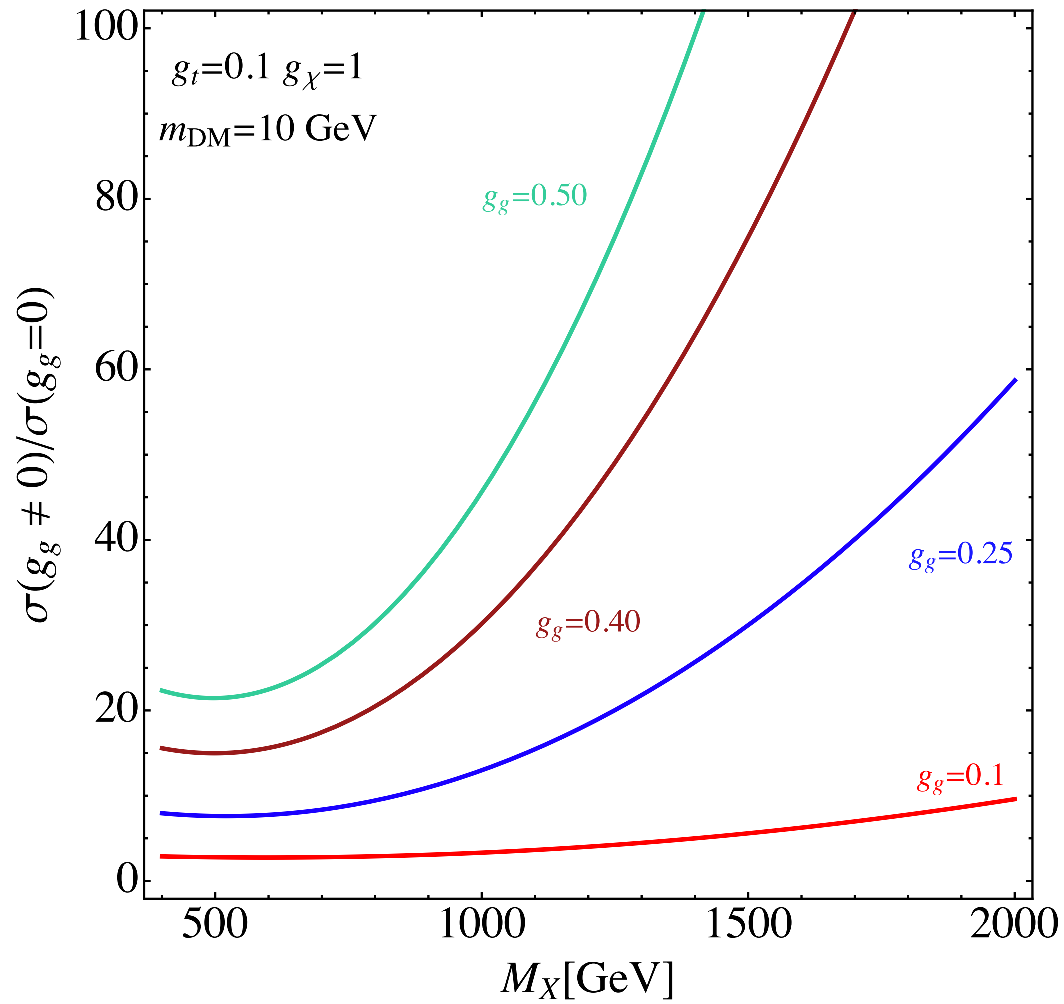
Phil gets the fun of that!

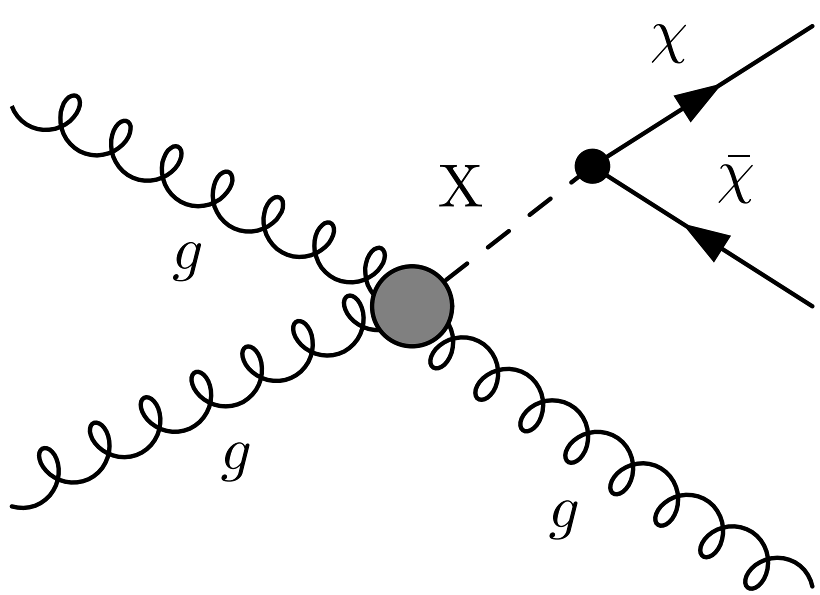
Dark matter processes in MCFM.

Mediator	LO	NLO	LHE
Vector	★	★	★
Axial	★	★	★
Scalar	★	☆	★
PS	★	☆	★

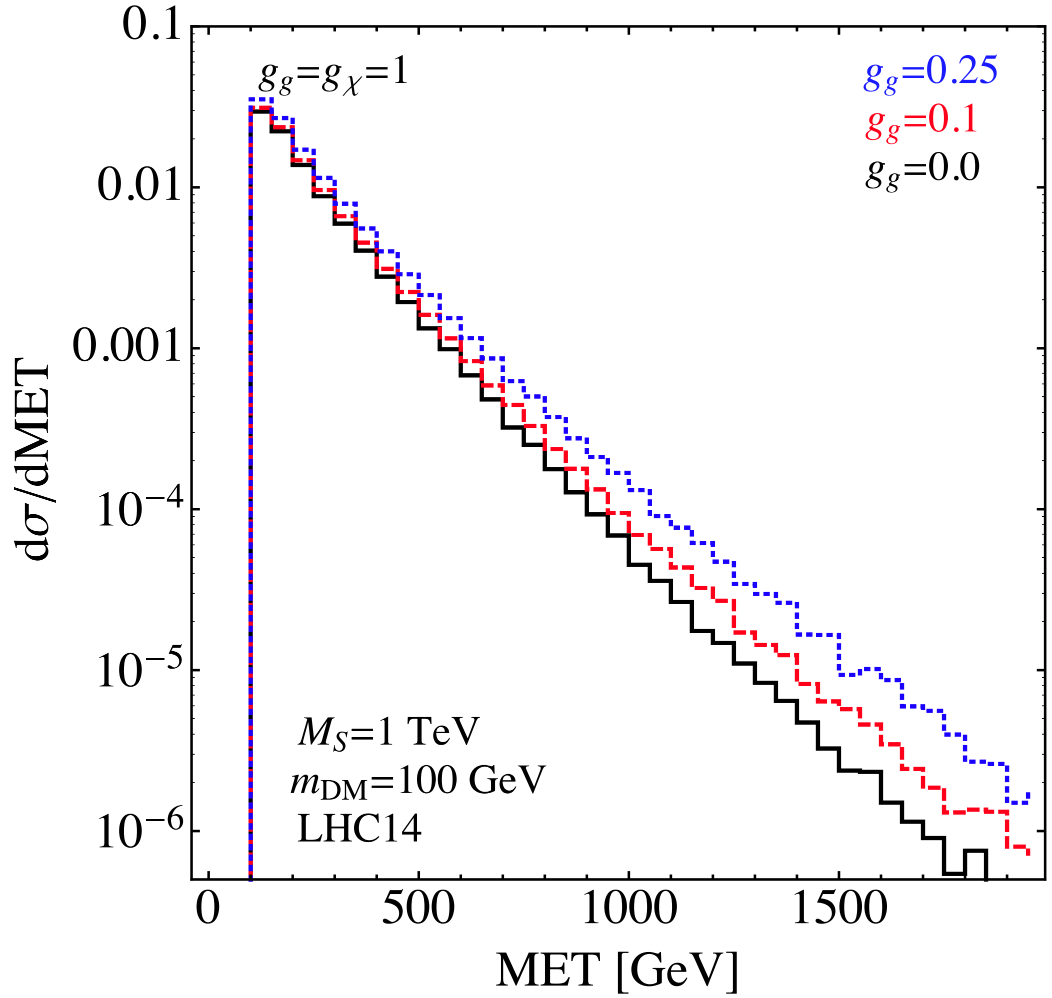
MCFM contains a variety of processes for s-channel mediators for mono-jet production. Most of which are available at NLO (NLO + PS Powheg implementation is available, Haisch, Kahlhoefer, Re 13). For the S + PS process we have NLO in the heavy top limit, and LO in the full theory.

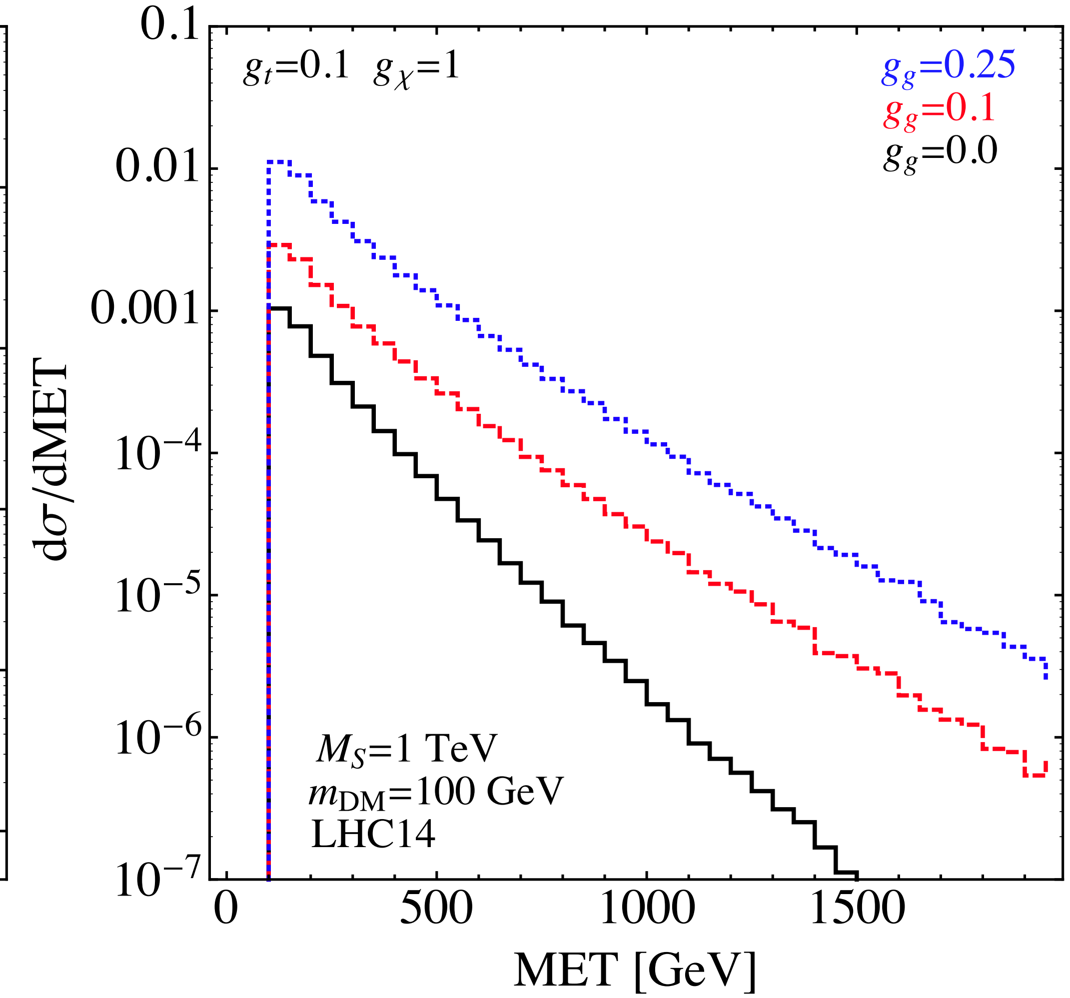






MCFM also allows the inclusion of a sixth parameter, which models the potential of heavy new physics in the loop. This can be relevant in certain models, in which the couplings to the top quark is suppressed.



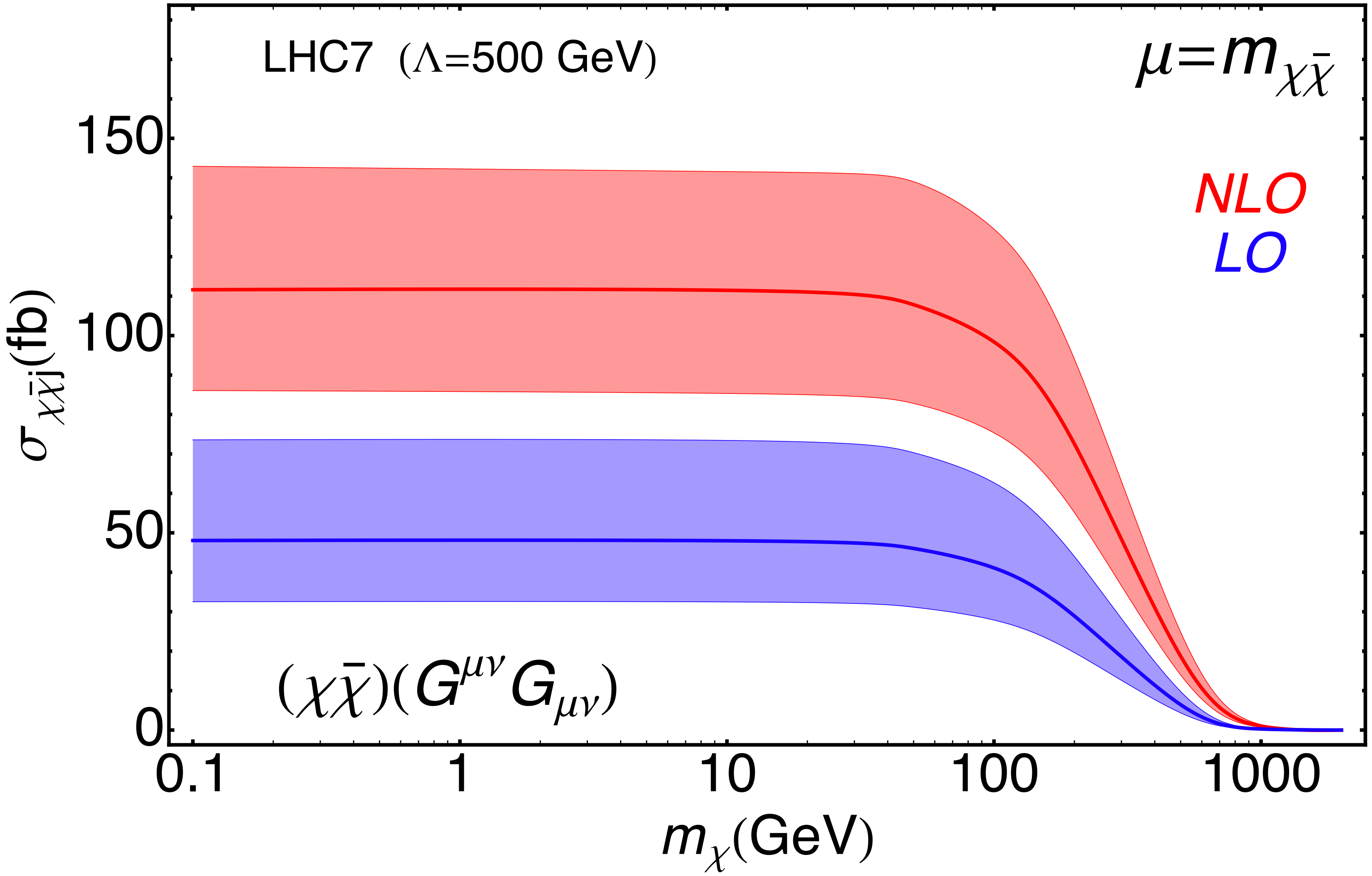


These models are valid if,

$$g_g \sim \frac{g_{NP}}{\Lambda_{NP}} \frac{v}{g_w}$$

and are worth investigating in the future (once the simplified model approach with 5 parameters is mature!).

Impact of NLO on Higgs portal models.



These models will have large NLO corrections, and can be partly estimated by computing the result in the limit of the heavy top. Order 100% corrections!

Conclusions.

- The days of the EFT are numbered (over?)
- Run II analysis will instead probe a range of simplified models. This leads to a proliferation of parameters, and increases the complexity of the analyses.
- These simplified models can be realized by general Z' models and Higgs portal models.
- MCFM provides LO and NLO predictions for a variety of s-channel processes, and allows LHE events to be generated for most (LO) processes (from v6.9 onwards)
- Stay tuned for Phils talk, which will present our results!