Higgs characterisation

spin and CP properties

Kentarou Mawatari

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

Dark matter characterisation
at the LHC

Kentarou Mawatari

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

First open meeting of the LHC Dark Matter WG

by M. Mangano

CERN, Dec 10-11 2015

The WG activity builds on the experience of the previous ATLAS-CMS Dark Matter Forum, whose findings are documented in http://arxiv.org/abs/1507.00966

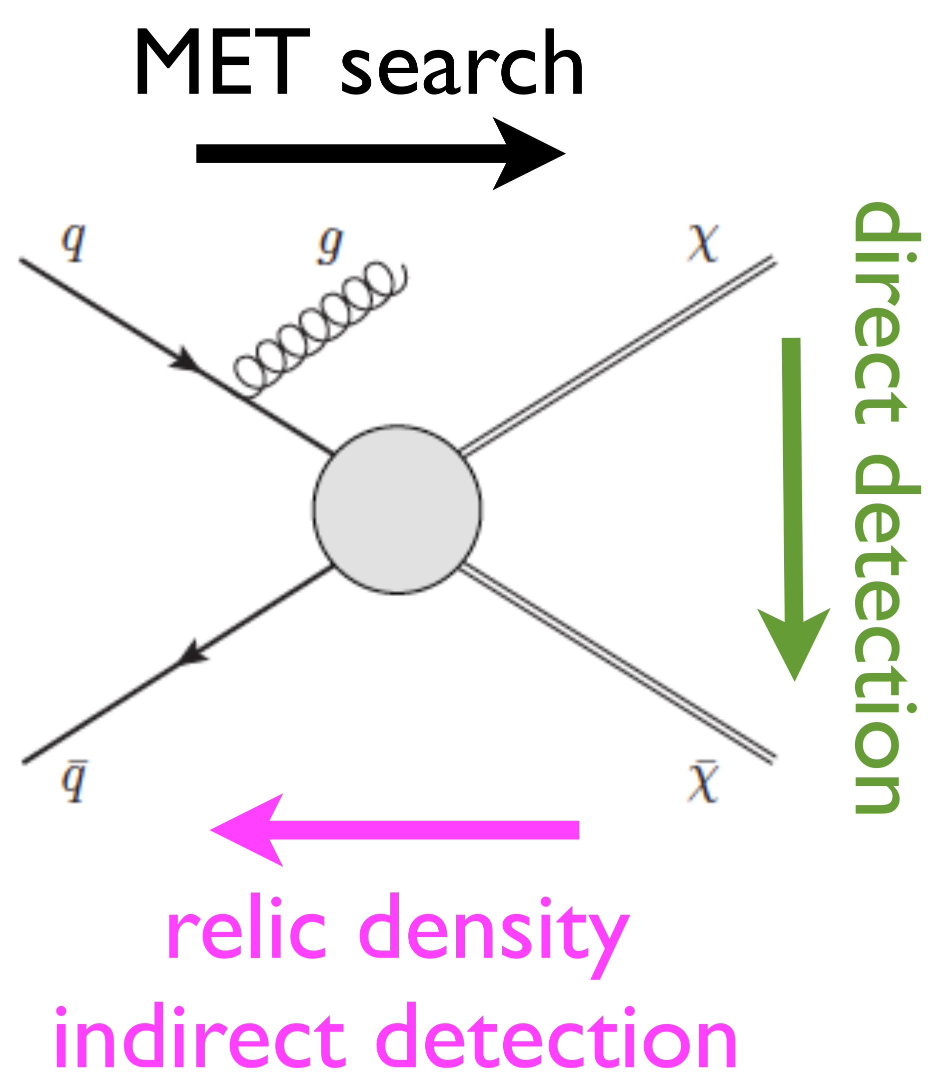
The WG

- brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC.
- develops and promotes well-defined signal models, specifying the assumptions behind them and describing the conditions under which they should be used.
- works to improve the set of tools available to the experiments, such as higher-precision calculations of the backgrounds.
- assists theorists with understanding and making use of LHC results.
- develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order to help verify and constrain particle physics models of astrophysical excesses, to understand how collider searches and non-collider experiments complement one another, and to help build a comprehensive understanding of viable dark matter models.

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; $M_\star \leqq$ (LHC accessible energy)



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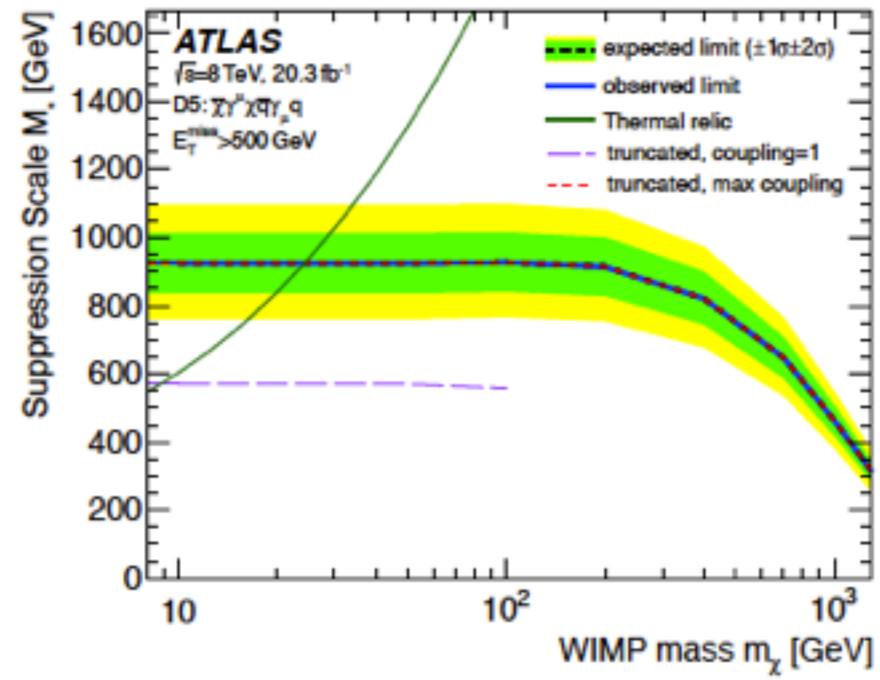
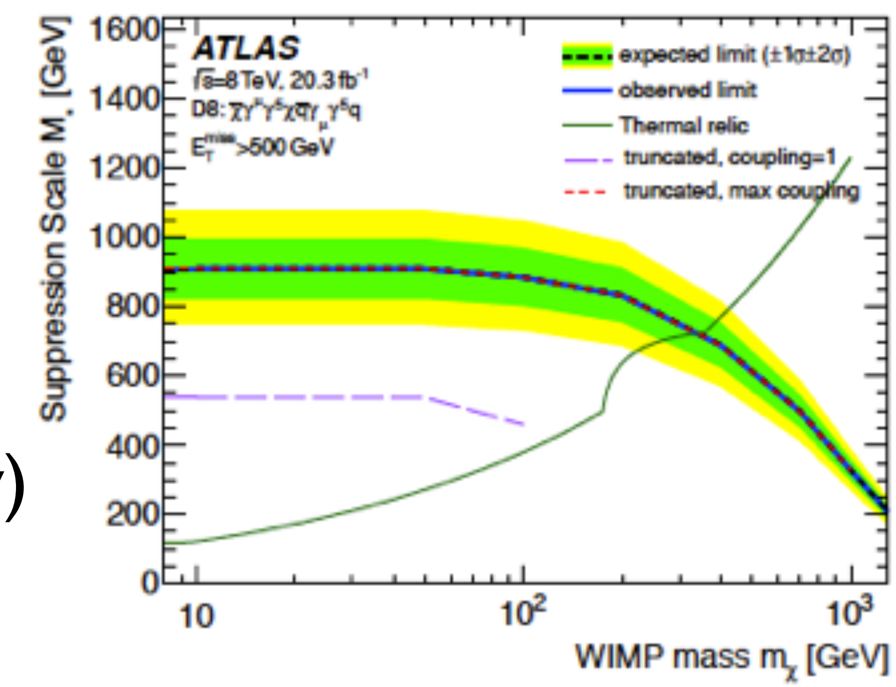
ATLAS 1502.01518

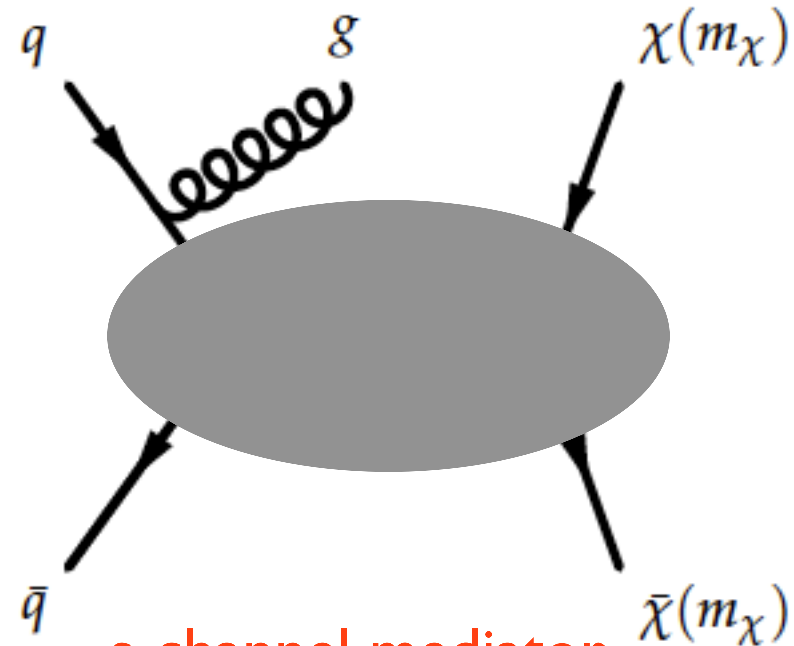




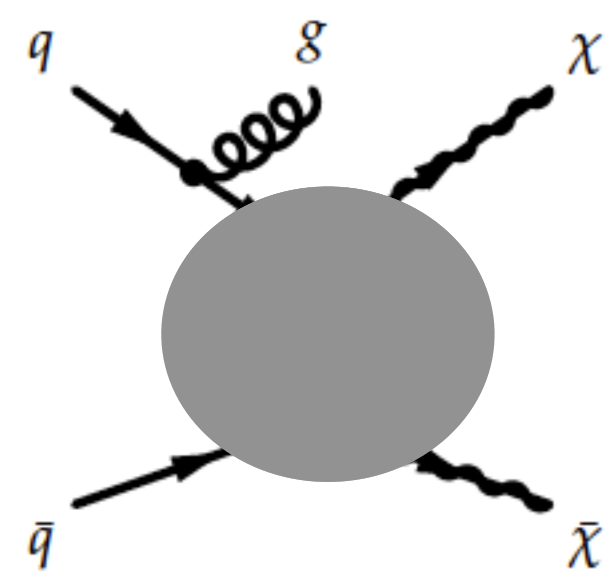
DM searches at LHC Run-II

- is employing simplified DM models.
- $$\mathcal{L}_{\text{vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_{\mu}\bar{q}\gamma^{\mu}q + g_{\chi}Z'_{\mu}\bar{\chi}\gamma^{\mu}\chi$$
  $$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_{\mu}\bar{q}\gamma^{\mu}\gamma^{5}q + g_{\chi}Z'_{\mu}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi$$
- 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.

LHC DM WG 1507.00966



s-channel mediator

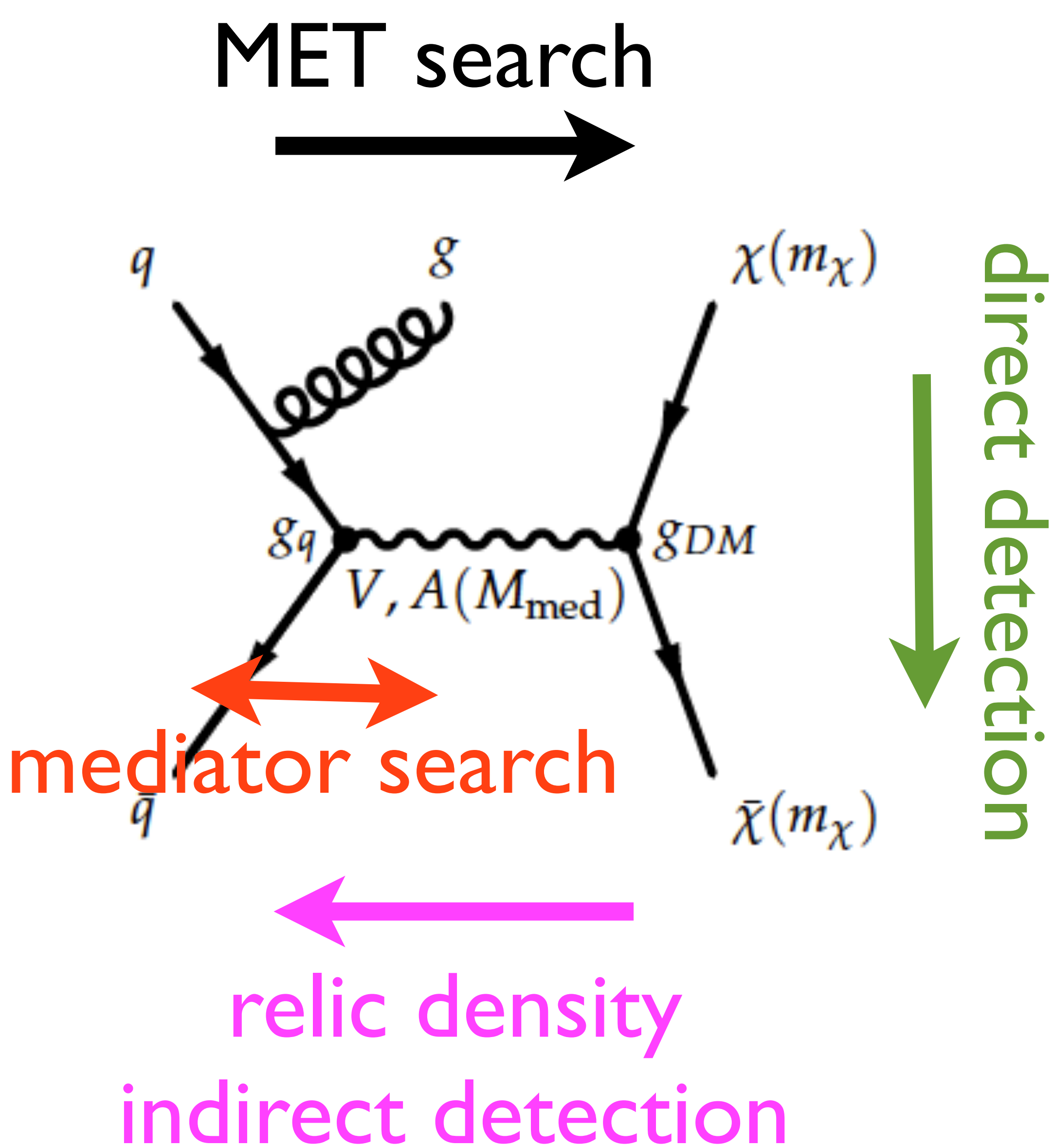


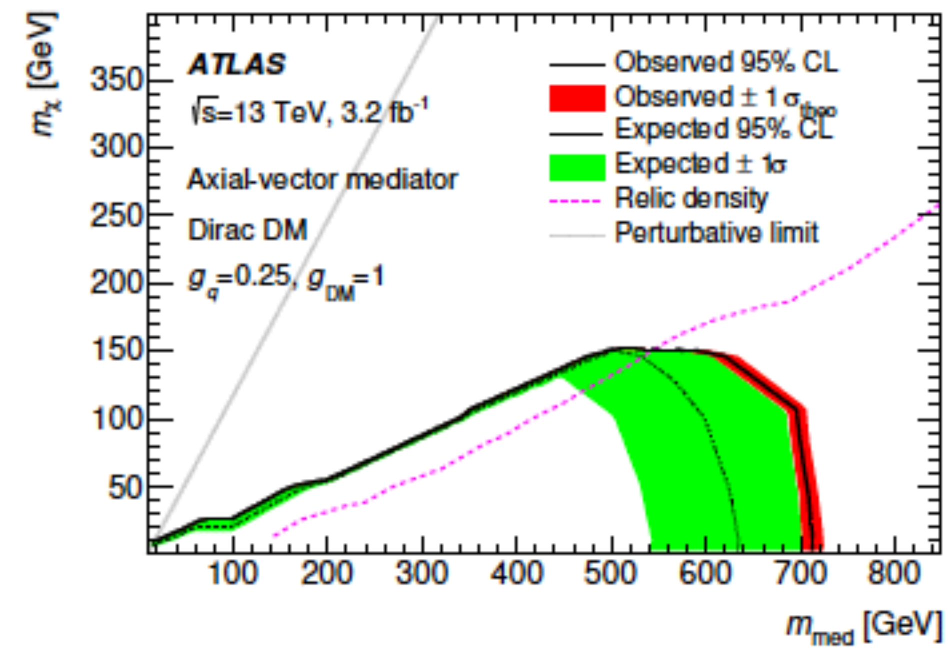
t-channel mediator

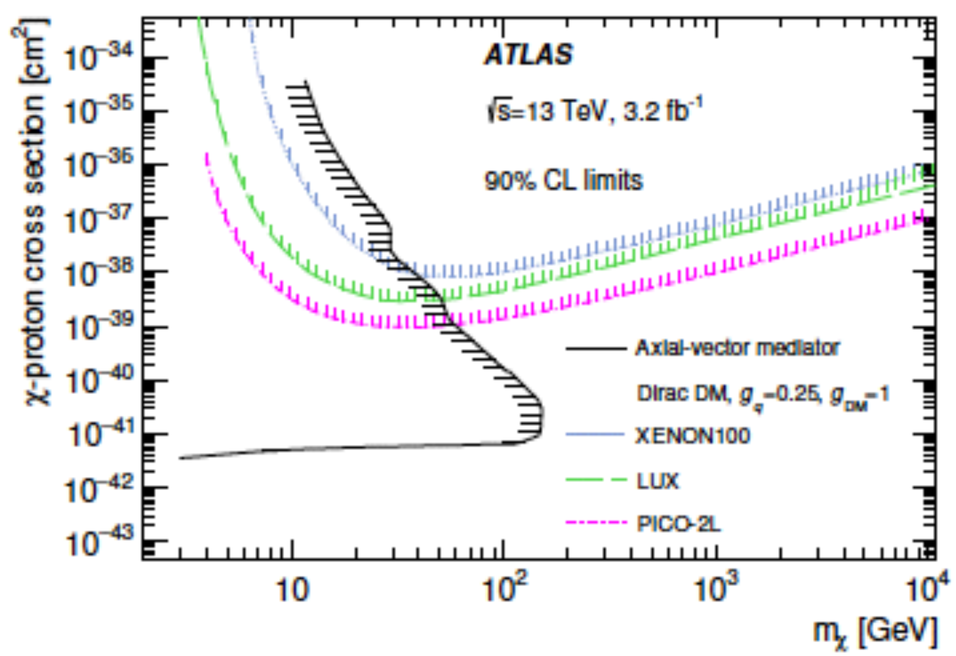
Signatures of simplified DM models

LHC DM WG [1507.00966, 1603.04156]

[ATLAS 1604.01306]

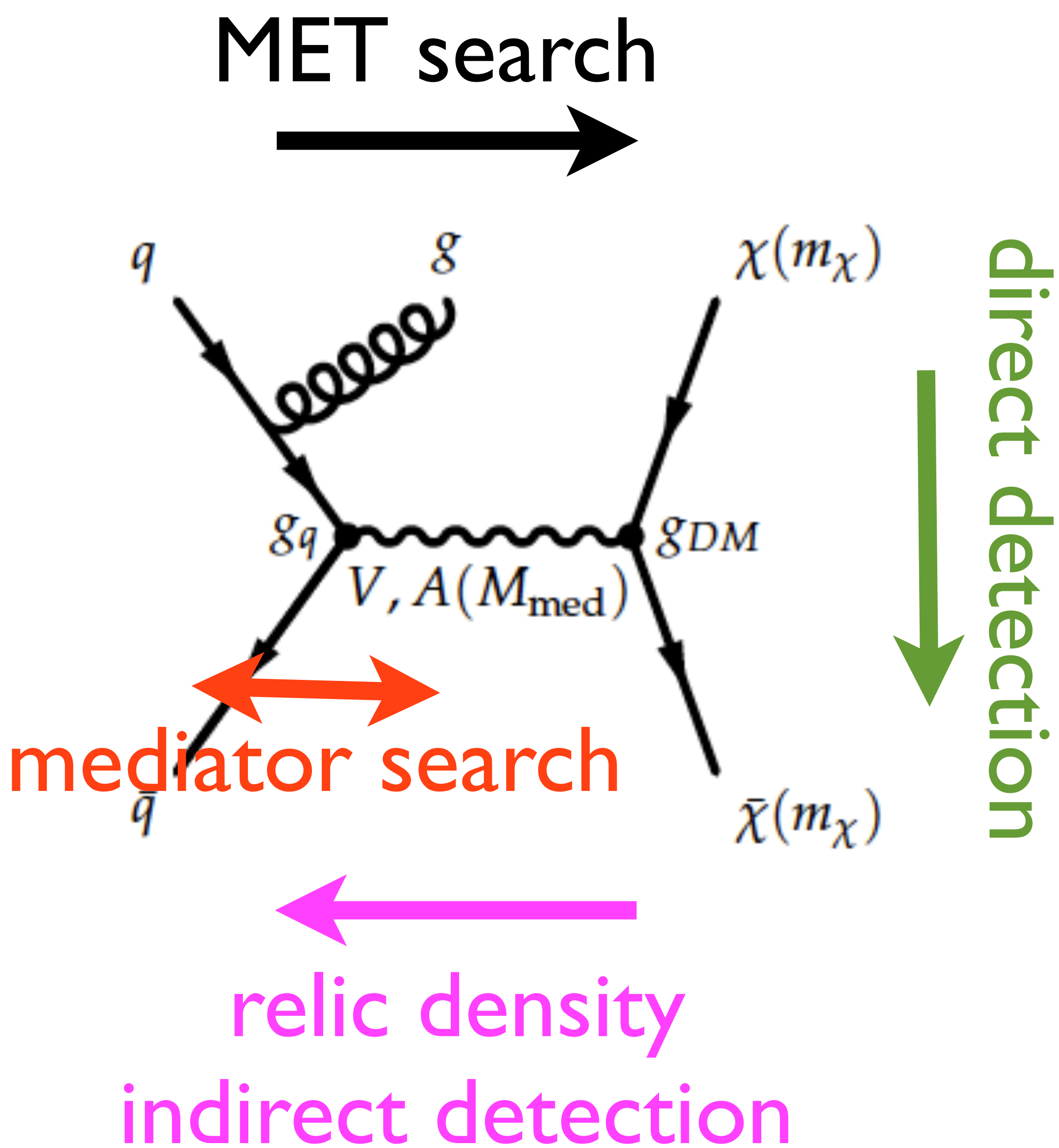


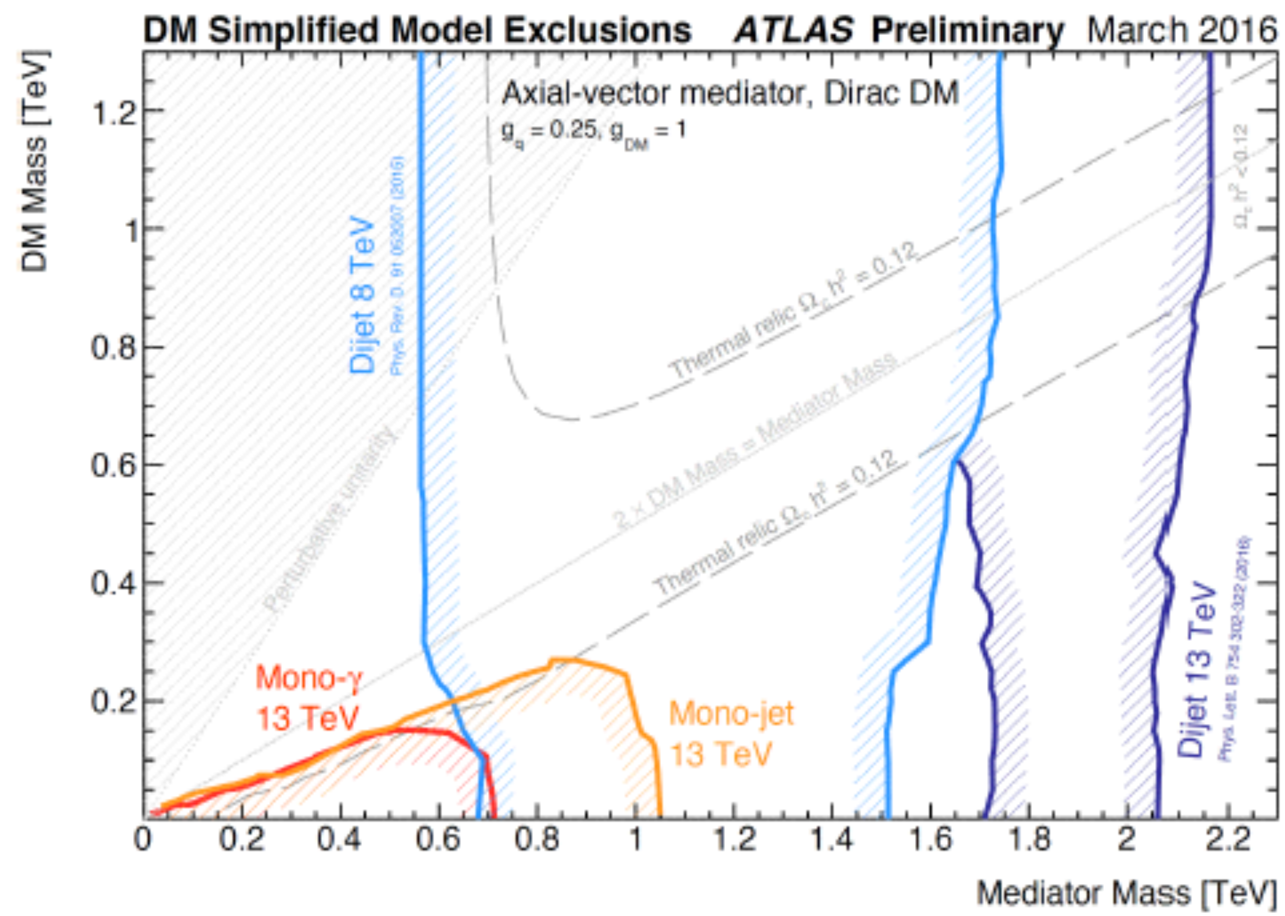




Signatures of simplified DM models

LHC DM WG [1507.00966, 1603.04156]





s-channel simplified DM models

LHC DM WG [1507.00966, 1603.04156]

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

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

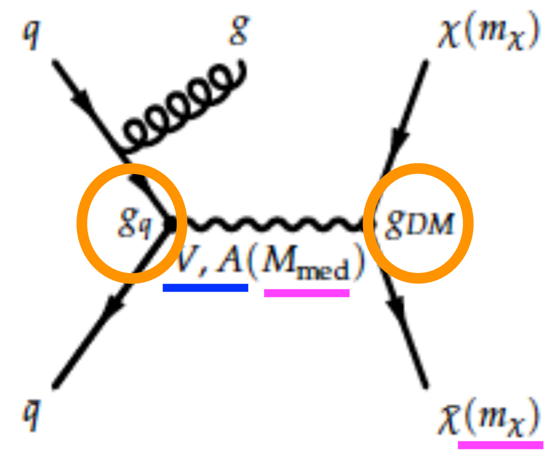
$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q\,.$$

  - spin-0 mediator

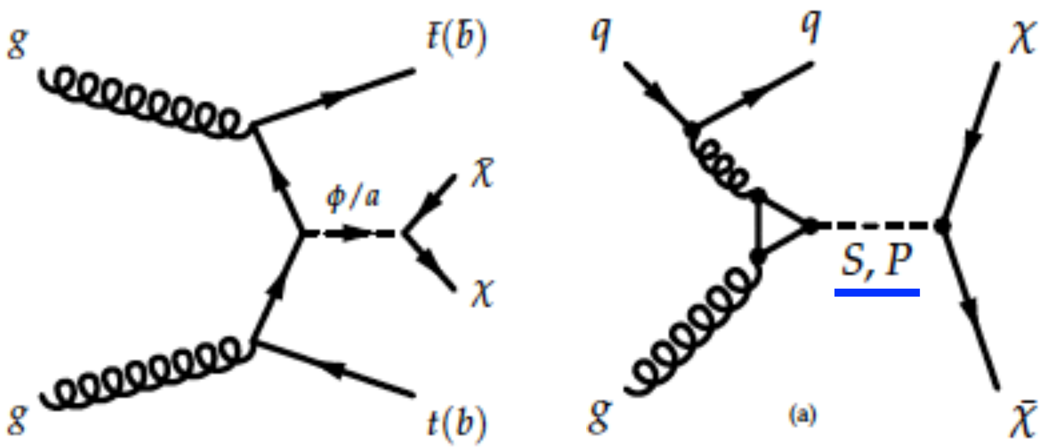
$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q\,,$$

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

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



spin-1 mediator



spin-0 mediator

DMsimp: Simplified DM model files

feynrules.irmp.ucl.ac.be/wiki/DMsimp

wiki: DMsimp

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Last modified 3 weeks ago

Simplified dark matter models

$$\mathcal{L}_{X_D}^{Y_1} = \bar{X}_D \gamma_\mu (g^V_{X_D} + g^A_{X_D}\gamma_5) X_D Y_1^\mu$$

Authors

- s-channel
  - Antony Martini (Université catholique de Louvain) & Kentarou Mawatari (LPSC Grenoble)
    - Emails: kentarou.mawatari @ lpsc.in2p3.fr
- s-channel (electroweak)
  - Jian Wang (Johnnas Gutenberg University of Mainz) & Cen Zhang (Brookhaven National Laboratory)
    - Emails: cenzhang @ bnl.gov

Description of the model

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

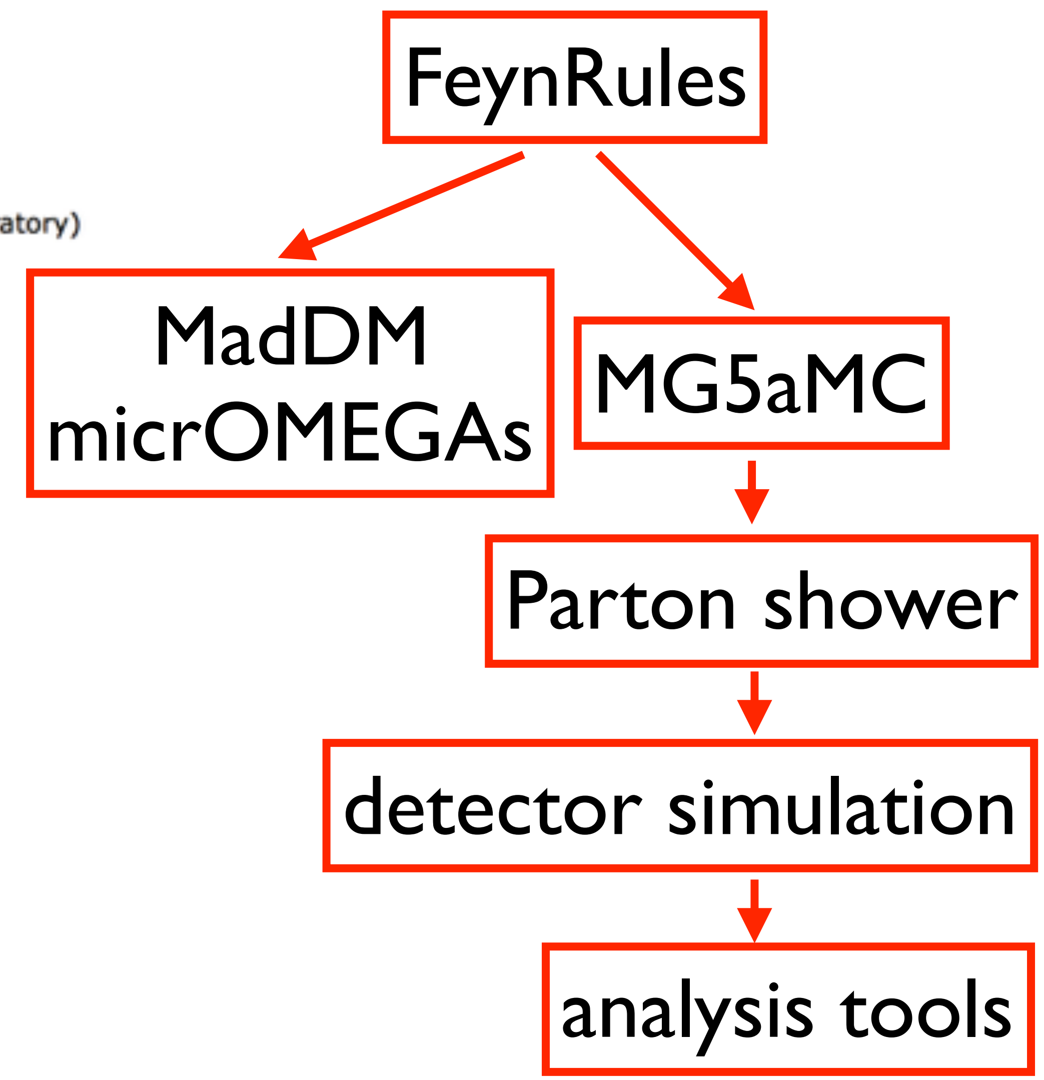
- Xr (real scalar DM)
- Xc (complex scalar DM)
- Xd (Dirac spinor DM)
- Xm (Majorana spinor DM) (to be done.)
- ...

and different types of mediators:

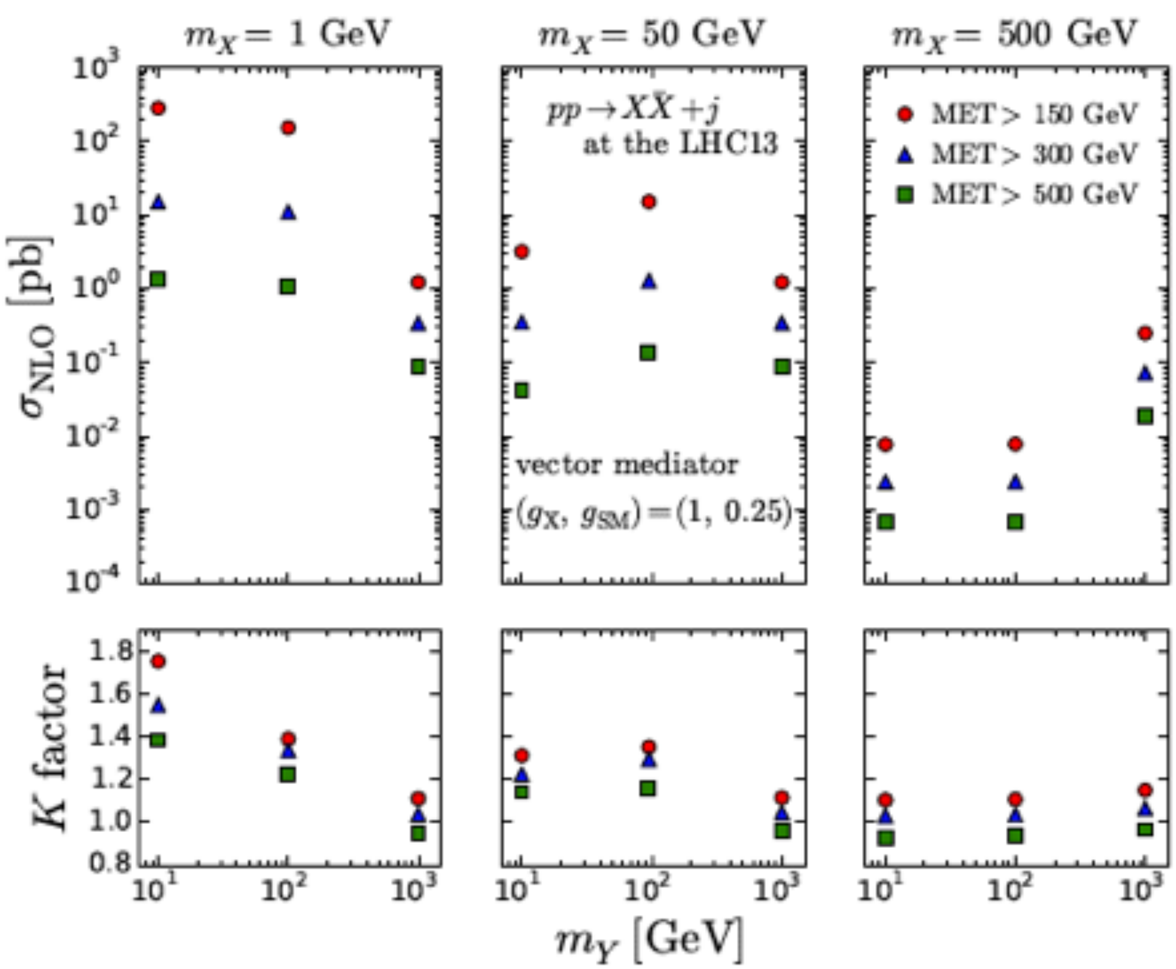
- s-channel
  - Y0 (spin-0)
  - Y1 (spin-1)
  - Y2 (spin-2) [to be done.]
  - ...
- t-channel [to be done.]

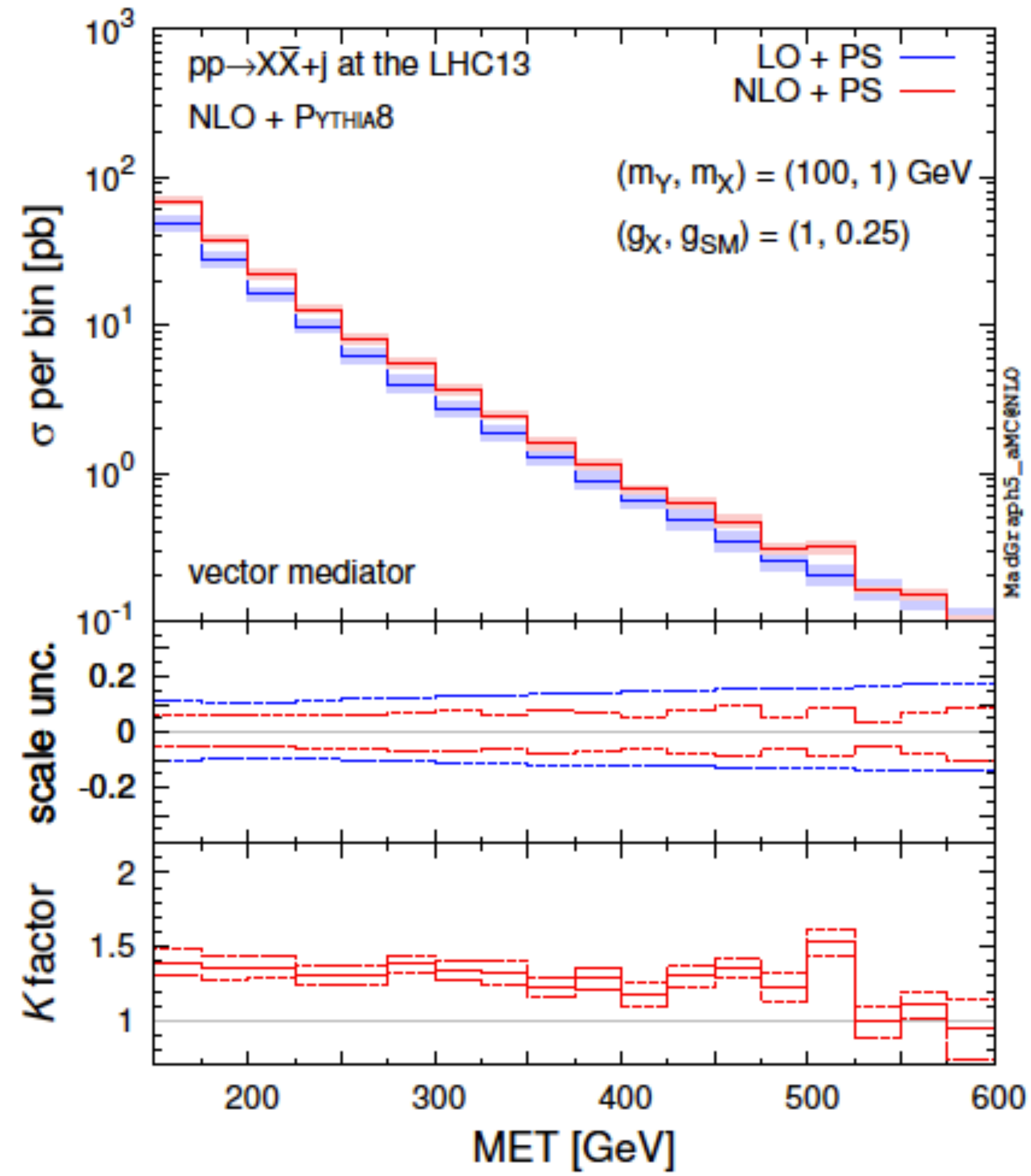
One can find the model lagrangian in the note. See more details in

- 1508.00564 : O. Mattelaer, E. Vryonidou, "Dark matter production through loop-induced processes at the LHC: the s-channel mediator case".
- 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".
- 1509.05785 : M. Neubert, J. Wang, C. Zhang, "Higher-order QCD predictions for dark matter production in mono-Z searches at the LHC".



DM production at NLO-QCD+PS

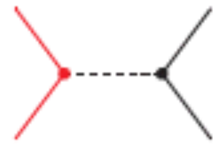
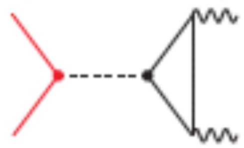
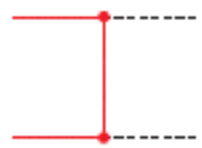
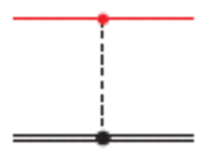
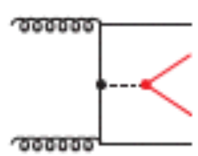
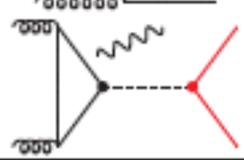
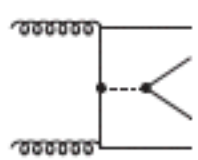
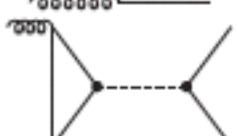
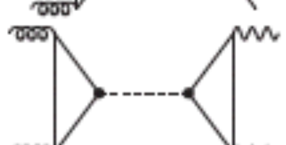




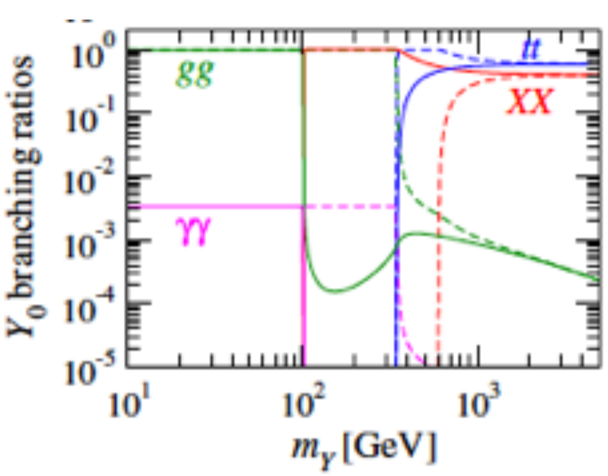
A comprehensive approach to DM studies: simplified top-philic models

X=DM
Y=mediator

[1605.09242, JHEP]
52 pages, 23 figs, 8 tables

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🔔
Backovic🔔
Heisig🇩🇪
Kraemer🇩🇪
Maltoni🔔
Conte, Fuks, Guo🇫🇷
Martini, Vryonidou🔔
Mawatari🇫🇷
Hespel🔔
Pellen🇩🇪



Relic vs. Direct detection vs. LHC

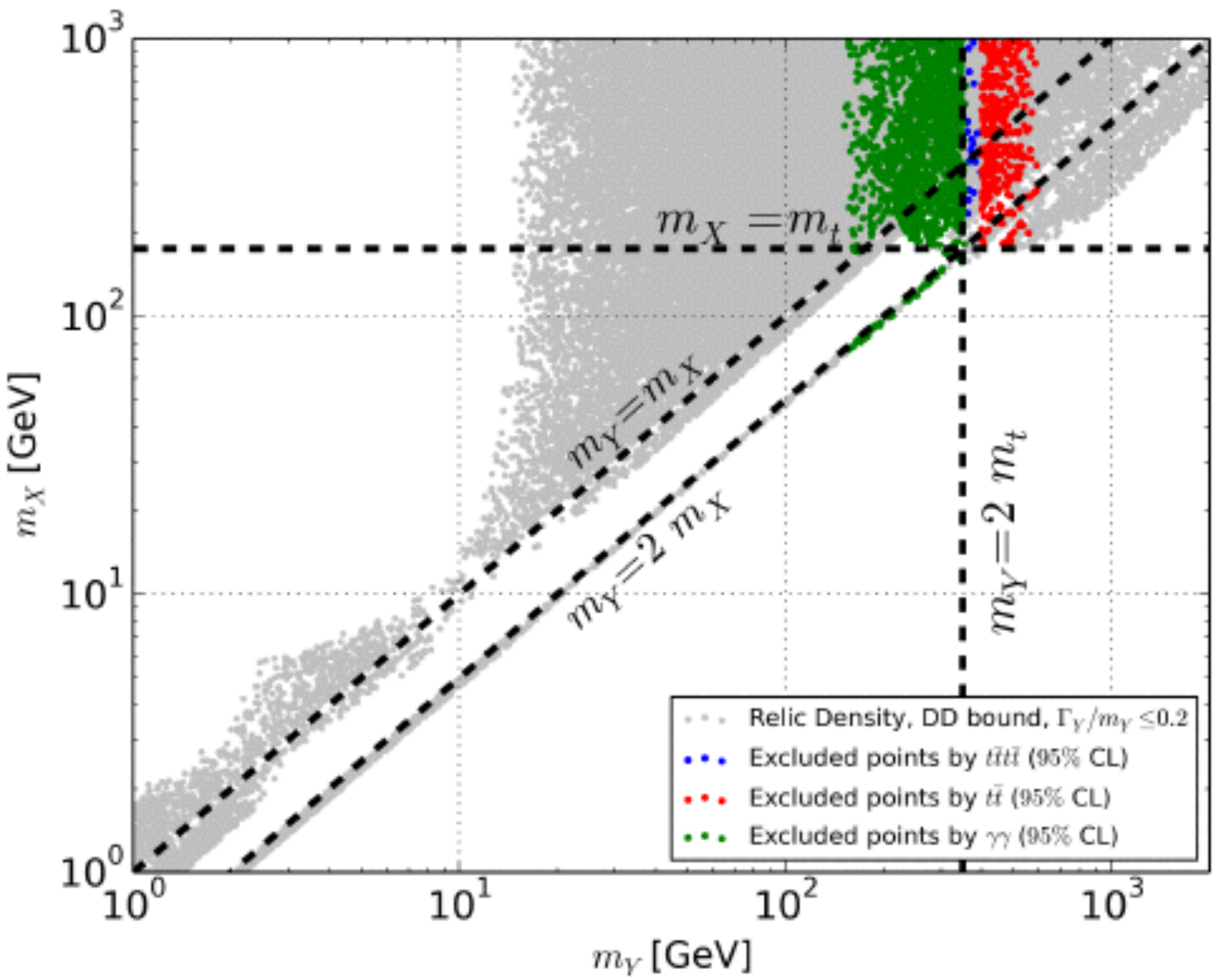


Figure 14. Results of our four-dimensional parameter scan projected onto the (m_Y, m_X) plane once constraints set from the LHC results are imposed. The points excluded by the diphoton, the $t\bar{t}$ and the four-top considered searches all satisfy the relic density, narrow width and direct detection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

What is next ?

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

Sabine Kraml[1], Ursula Laa[1,2], Kentarou Mawatari[1,3], Kimiko Yamashita[4]

[1] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 53 Avenue des Martyrs, F-38026 Grenoble, France
[2] LAPTh, Université Savoie Mont Blanc, CNRS, B.P.110 Annecy-le-Vieux, F-74941 Annecy Cedex, France
[3] Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, and International Solvay Institutes, Pleinlaan 2, B-1050 Brussels, Belgium
[4] Department of Physics, Graduate School of Humanities and Sciences, and Program for Leading Graduate Schools, Ochanomizu University, Tokyo 112-8610, Japan

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 13 TeV LHC data. We show 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, dilepton (and diphoton) resonance searches provide the strongest constraints for mediator masses above 200 (500) GeV. Missing energy searches are competitive only in the low-mass region. They can, however, be more important in non-universal coupling scenarios and/or when the coupling of the mediator to dark matter is much larger than its couplings to SM particles.

Model

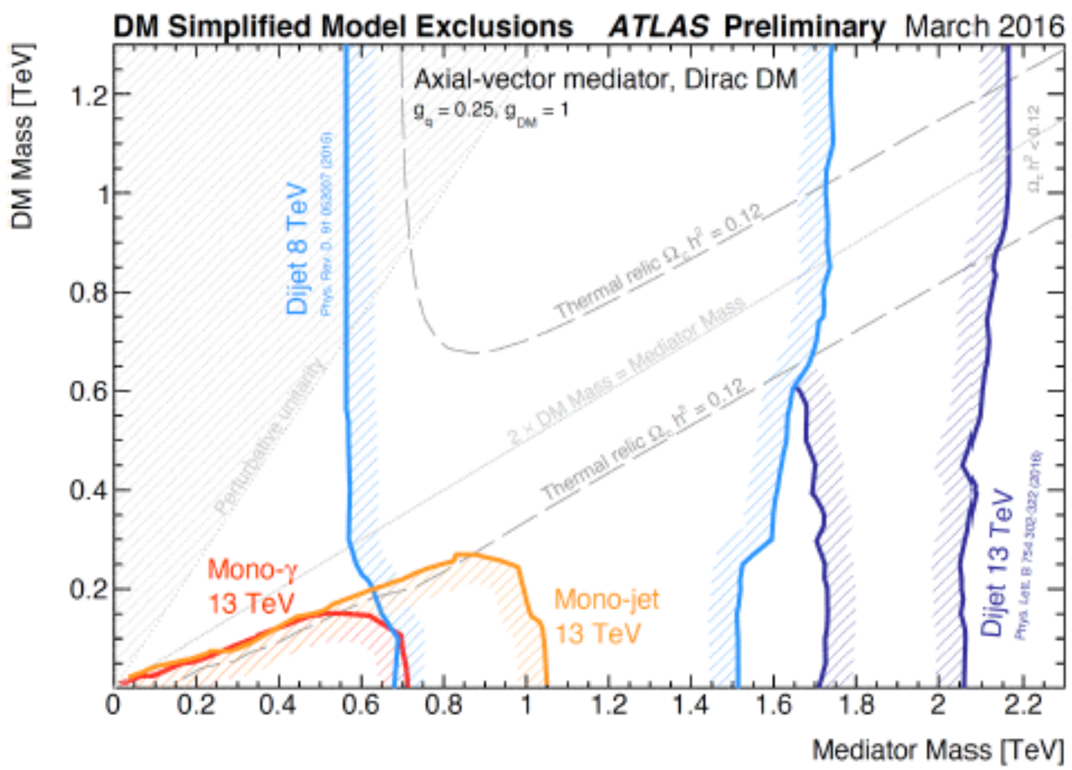
Gravity-mediated DM: Lee, Park, Sanz [1306.4107, 1401.5301]

$$\mathcal{L}_X^{Y_2} = -\frac{1}{\Lambda} g_X^T \, T_{\mu\nu}^X Y_2^{\mu\nu} \qquad \mathcal{L}_{\rm SM}^{Y_2} = -\frac{1}{\Lambda} \sum_i g_i^T \, T_{\mu\nu}^i Y_2^{\mu\nu}$$

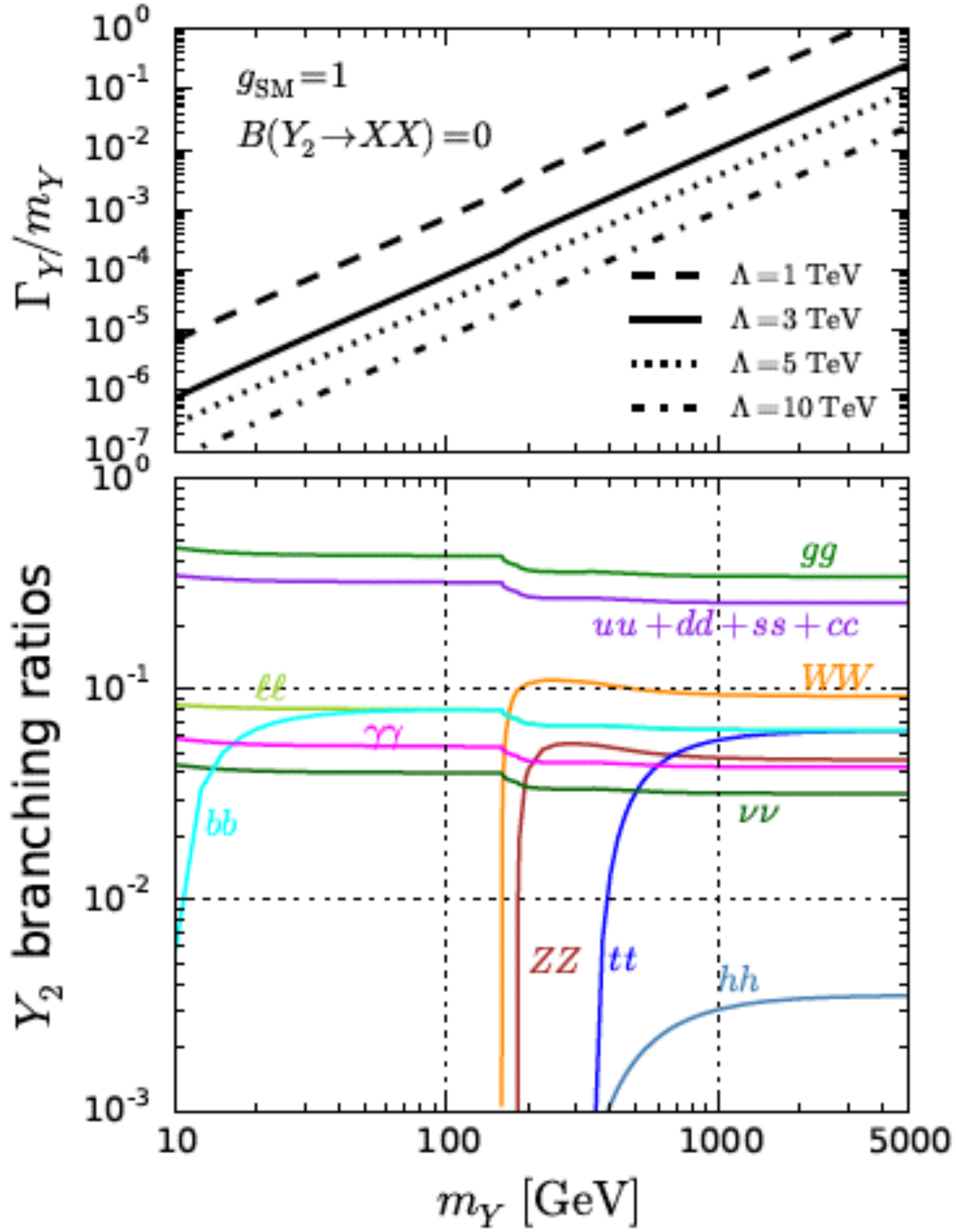
$$g_{\rm SM} \equiv g_H^T = g_q^T = g_\ell^T = g_g^T = g_W^T = g_B^T$$

$$\{m_X,\, m_Y,\, g_X/\Lambda,\, g_{\rm SM}/\Lambda\}$$

- Which analyses can constrain the model at the LHC ?
- Which analyses can provide the best constraint ?
- Can we find some interesting parameter space ?



Y_2 decay (w/o DM)



$$\Gamma_S = \frac{g_S^2 m_Y^3}{960\pi\Lambda^2}\,\beta_S^5\,,$$

$$\Gamma_F = \frac{g_F^2 N_\nu N_C^F m_Y^3}{160\pi\Lambda^2}\,\beta_F^3\left(1+\frac{8}{3}r_F\right),$$

$$\Gamma_V = \frac{g_V^2 N_s N_C^V m_Y^3}{40\pi\Lambda^2}\,\beta_V\, f(r_V)\,,$$

where $\beta_i = \sqrt{1-4r_i}$ with $r_i = m_i^2/m_Y^2$

m_Y [GeV]	branching ratios [%]							
	jj	WW	tt	ZZ	$\gamma\gamma$	$\nu\nu$	ee	hh
100	86.5	0	0	0	5.3	4.0	2.7	0
500	79.1	9.9	3.3	5.0	4.4	3.3	2.2	0.2
1000	78.5	9.4	5.7	4.7	4.3	3.2	2.1	0.3

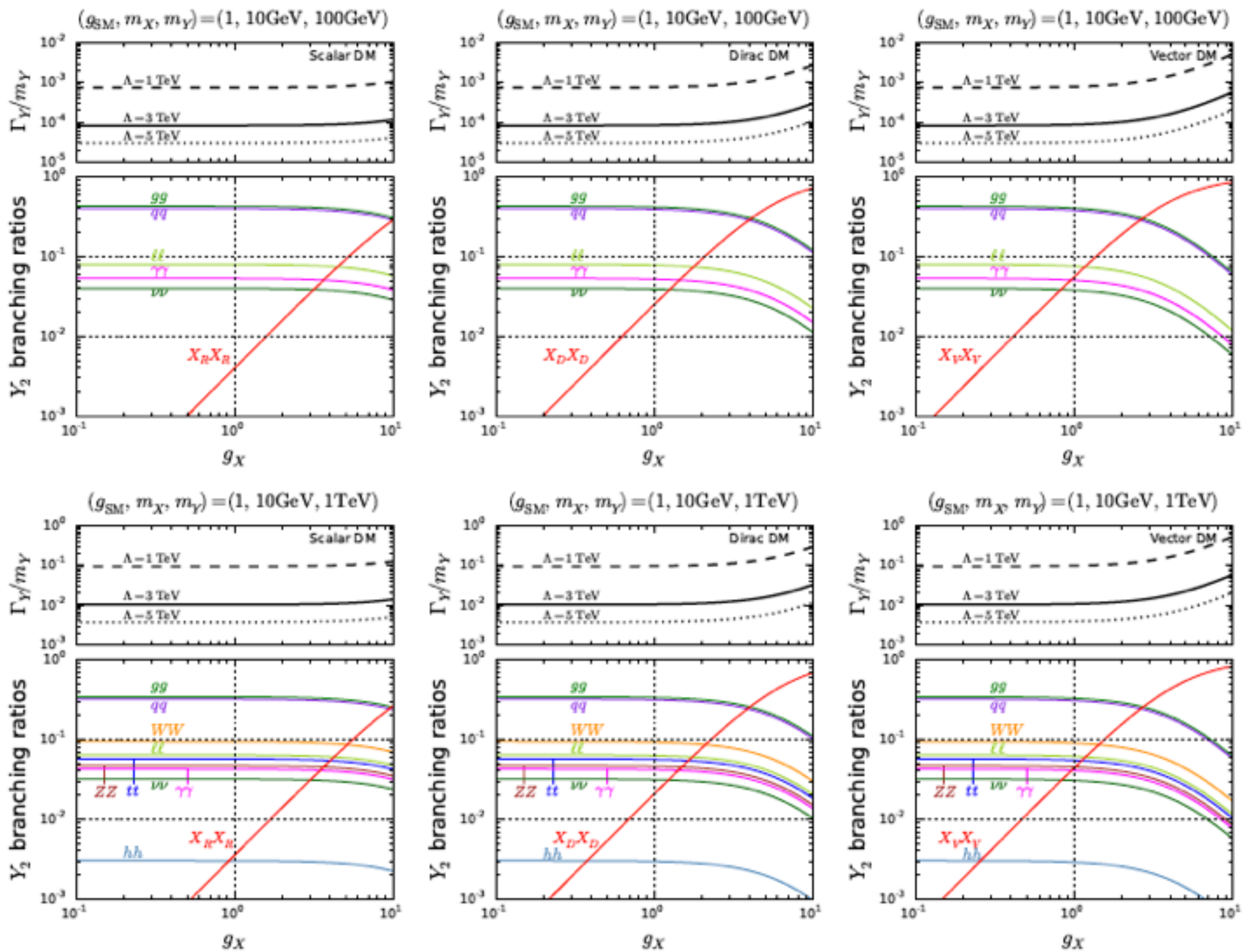
Table 1. Branching ratios of the spin-2 mediator for $g_{SM}=1$ and $B(Y_2 \to XX)=0$; jj includes gluons and five flavours of quarks, and $\nu\nu$ includes three flavours of neutrinos.

Y_2 decay (w/ DM)

$$\Gamma_S = \frac{g_S^2 m_Y^3}{960\pi\Lambda^2}\,\beta_S^5\,,$$

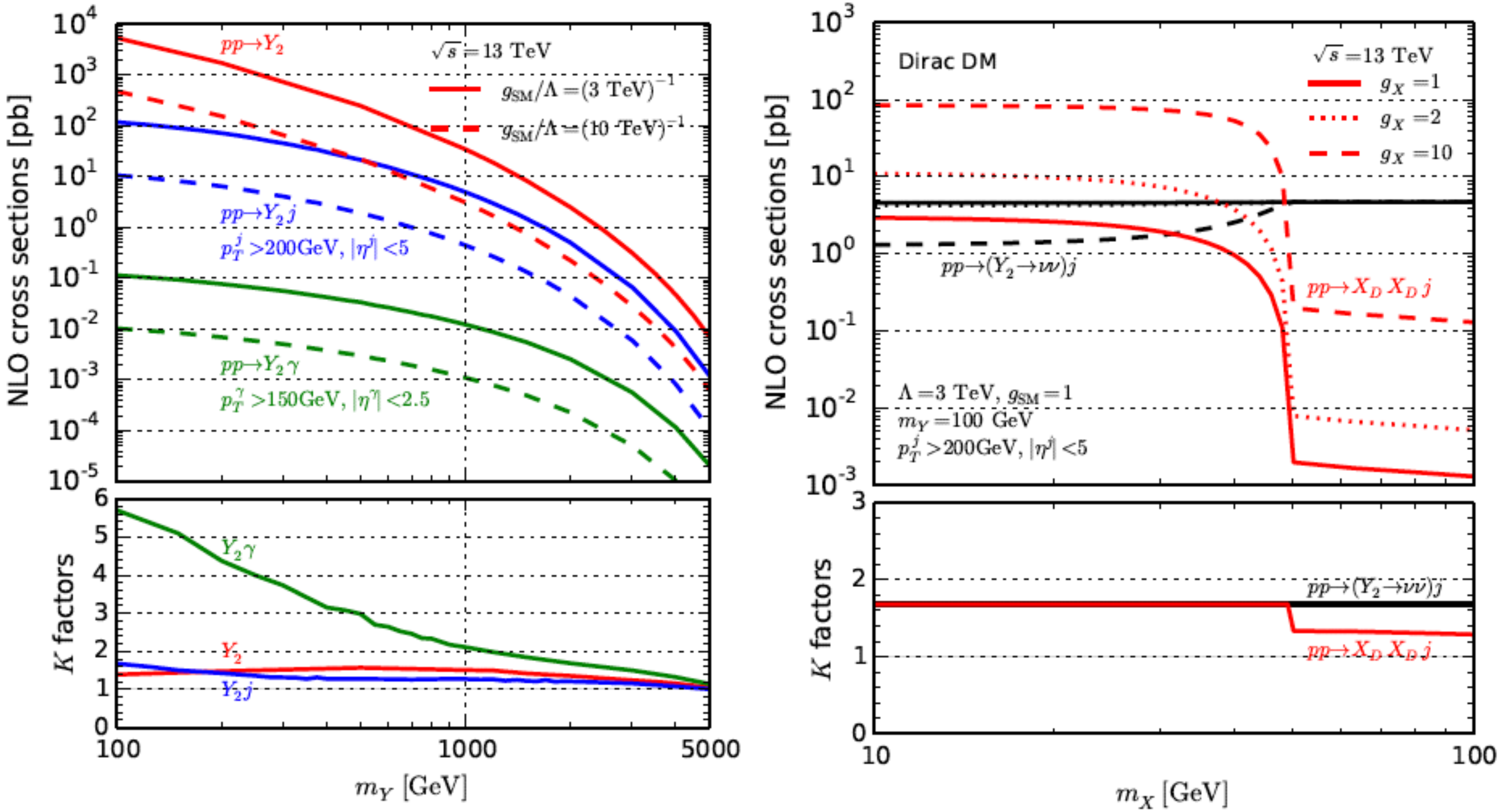
$$\Gamma_F = \frac{g_F^2 N_\nu N_C^F m_Y^3}{160\pi\Lambda^2}\,\beta_F^3\,(1+\frac{8}{3}r_F)\,,$$

$$\Gamma_V = \frac{g_V^2 N_s N_C^V m_Y^3}{40\pi\Lambda^2}\,\beta_V\,f(r_V)\,,$$

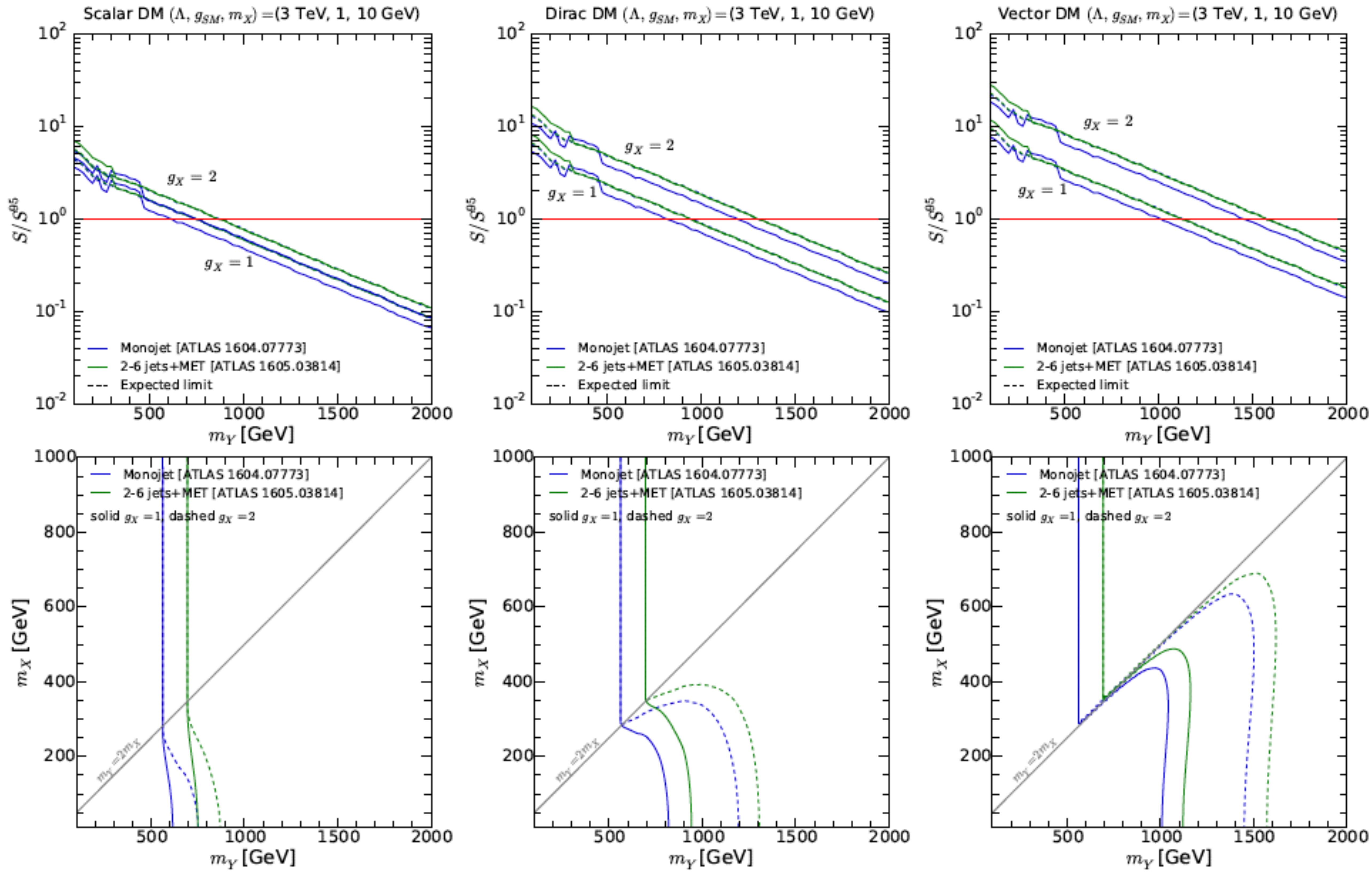


by Das, Degrande, Hirschi, Maltoni, Shao [1605.09359]

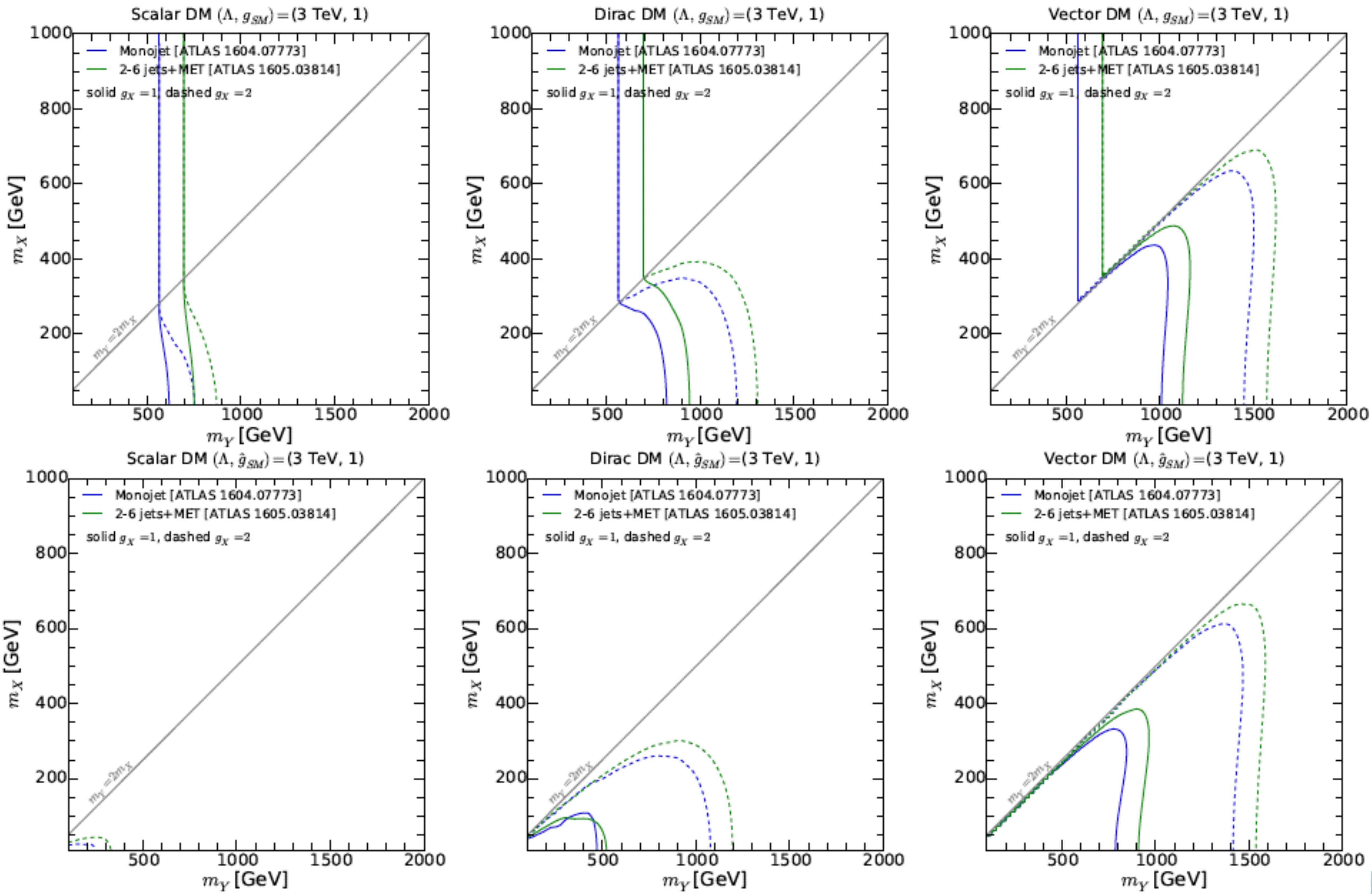
Y_2 production (at NLO-QCD)



Constraints from searches w/ MET

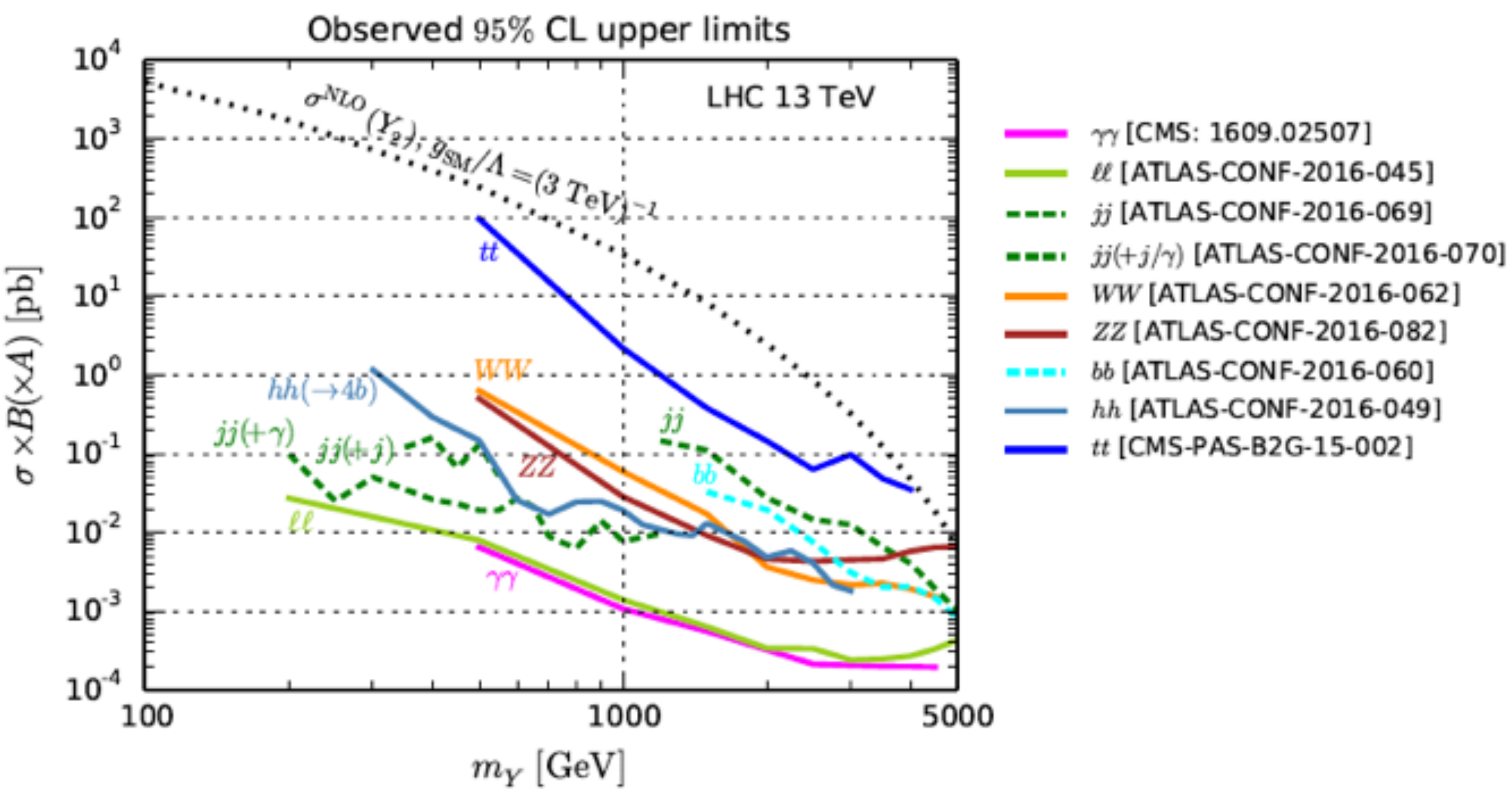


MET search: Universal vs. leptophobic

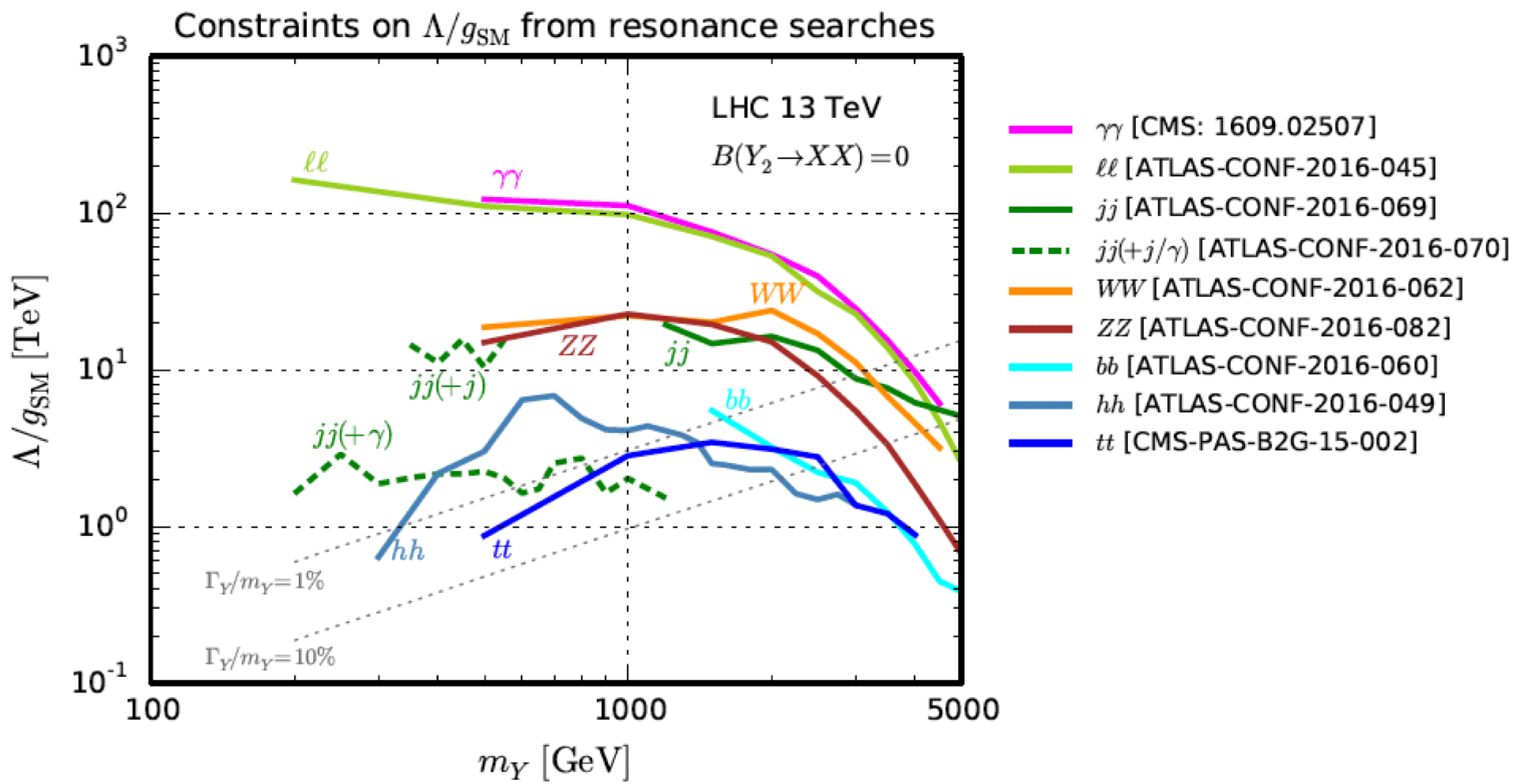


Resonance searches at Run-II

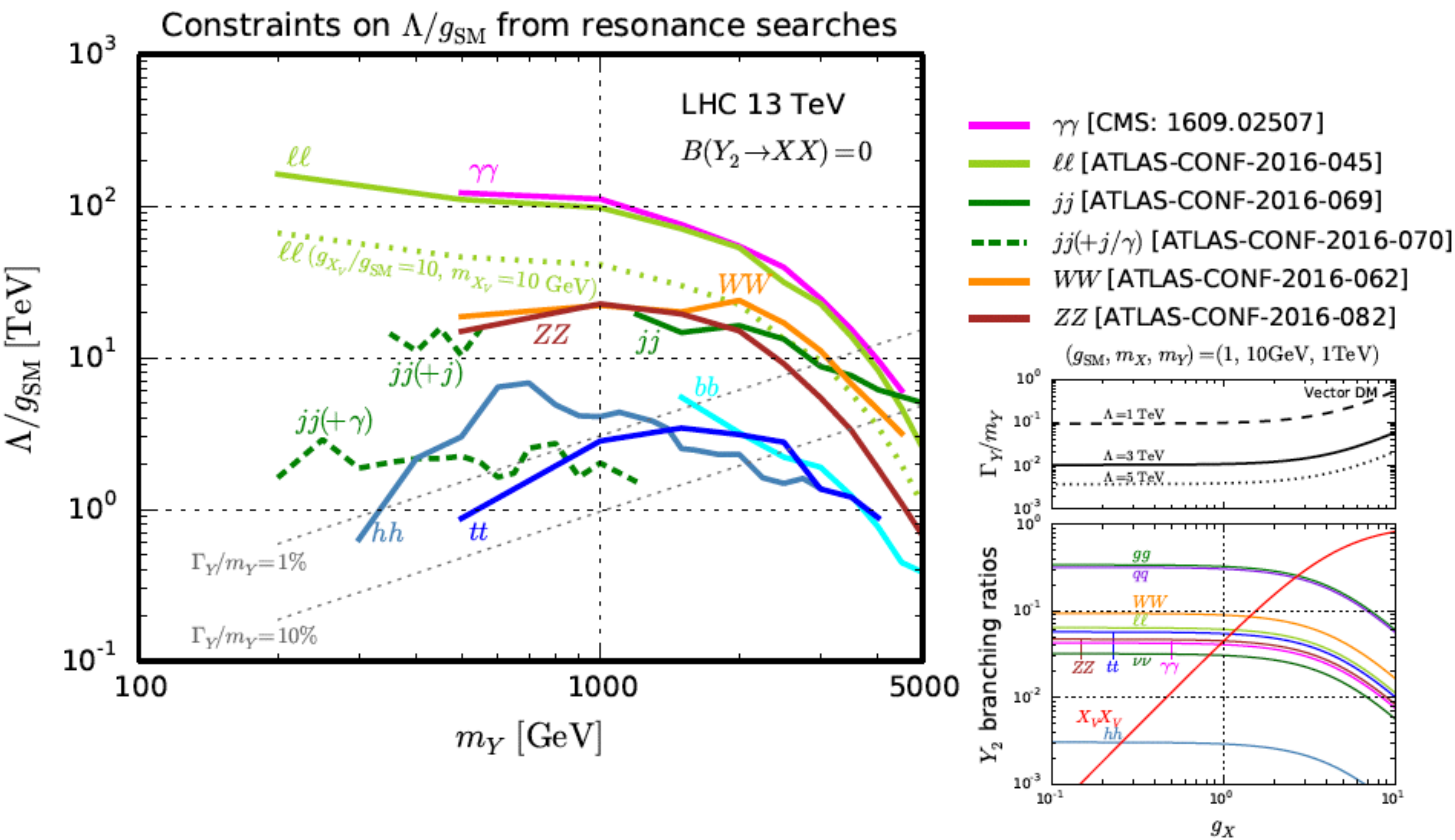
decay mode	reference	limit Tab./Fig.	limit on	$\sqrt{s}$ (TeV)	L (fb^{-1})
jj	ATLAS-CONF-2016-069 [53]	Tab. 2 (Res)	σ(Gaussian) $\times B \times A$	13	15.7
$jj(+j/\gamma)$	ATLAS-CONF-2016-070 [54]	Tab. 4/3 (Res)	σ(Gaussian) $\times B \times A$	13	15.5
WW	ATLAS-CONF-2016-062 [52]	Fig. 6	$\sigma(G_{\rm RS}) \times B$	13	13.2
bb	ATLAS-CONF-2016-060 [60]	Fig. 7(b) (Res)	σ(Gaussian) $\times B \times A \times \epsilon_{2b}$	13	13.3
tt	CMS-PAS-B2G-15-002 [61]	Tab. 4 (1%)	$\sigma(Z') \times B$	13	2.6
ZZ	ATLAS-CONF-2016-082 [55]	Fig. 10(d)	$\sigma(G_{\rm RS}) \times B$	13	13.2
$\gamma\gamma$	CMS 1609.02507 [56]	Fig. 6(middle)	$\sigma(G_{\rm RS}) \times B$	13+8	16.2+19.7
$\ell\ell$	ATLAS-CONF-2016-045 [51]	Fig. 3(c)	$\sigma(Z') \times B$	13	13.3
hh	ATLAS-CONF-2016-049 [62]	Fig. 11	$\sigma(G_{\rm RS}) \times B$	13	13.3



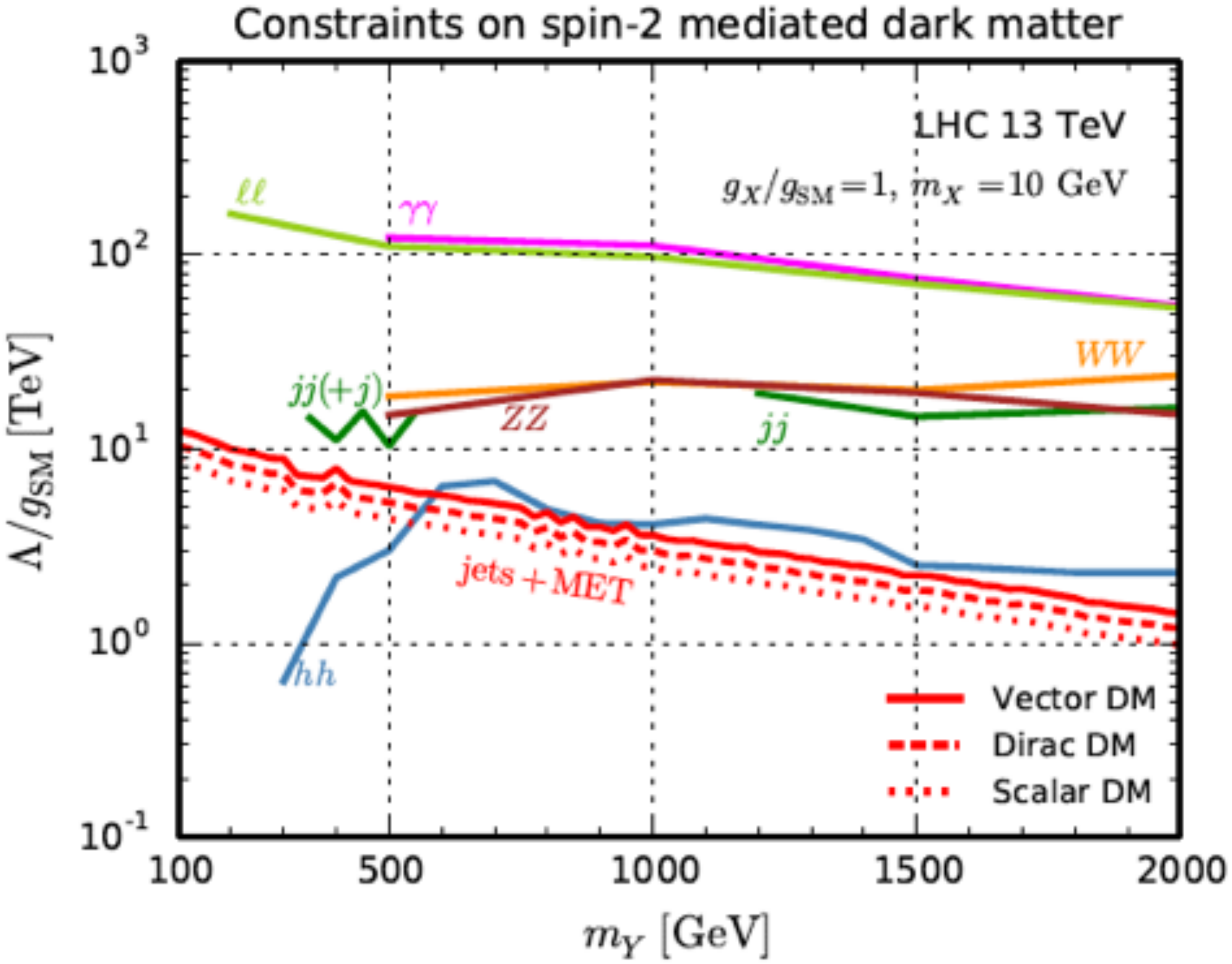
Constraints from resonance searches (w/o DM)

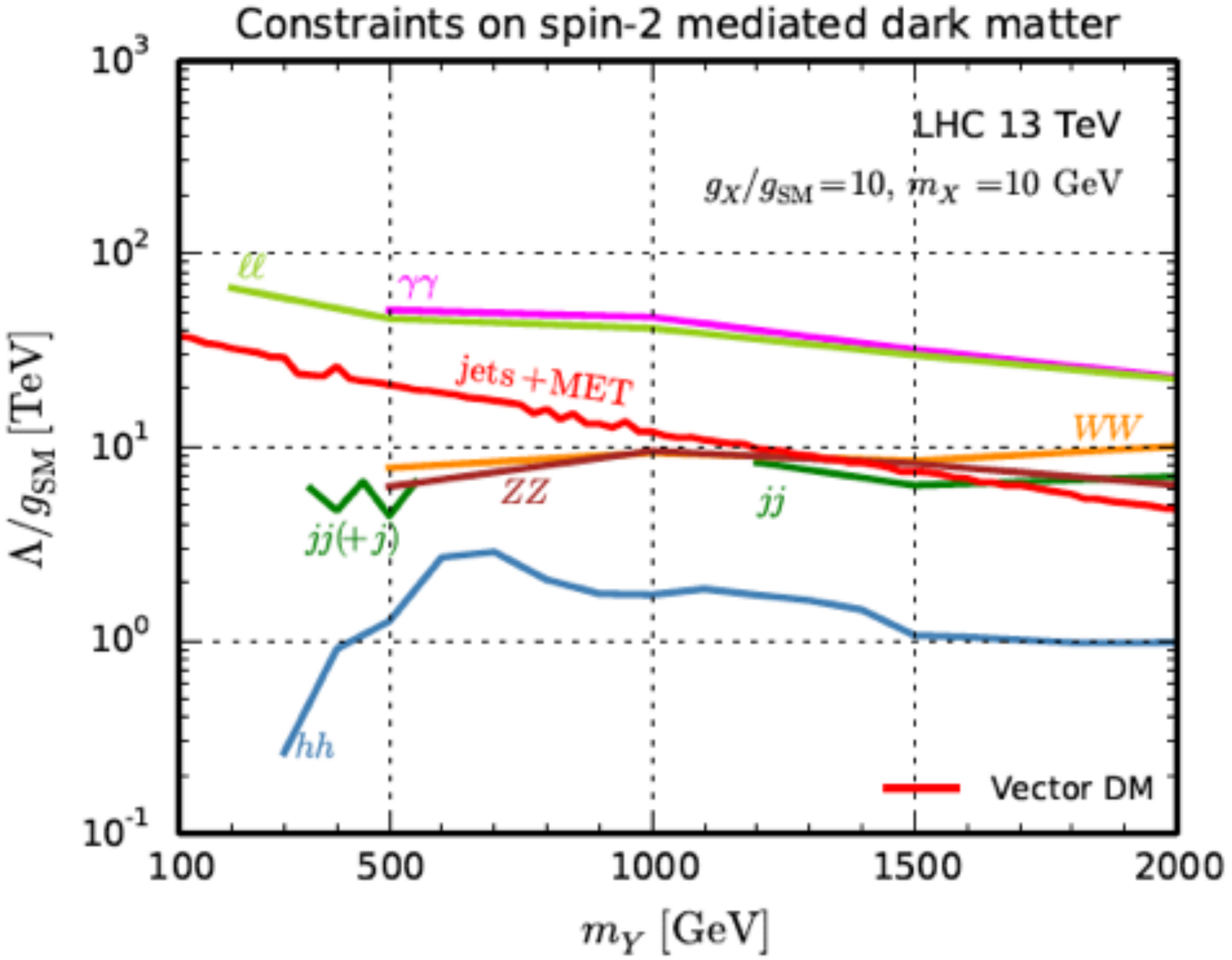


Constraints from resonance searches (w/ DM)



MET vs. resonance searches





Summary

- The systematic simulation framework for DM physics 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.
- A simple (e.g. 4 parameters) model can be constrained by many different LHC searches and also by non-collider searches.