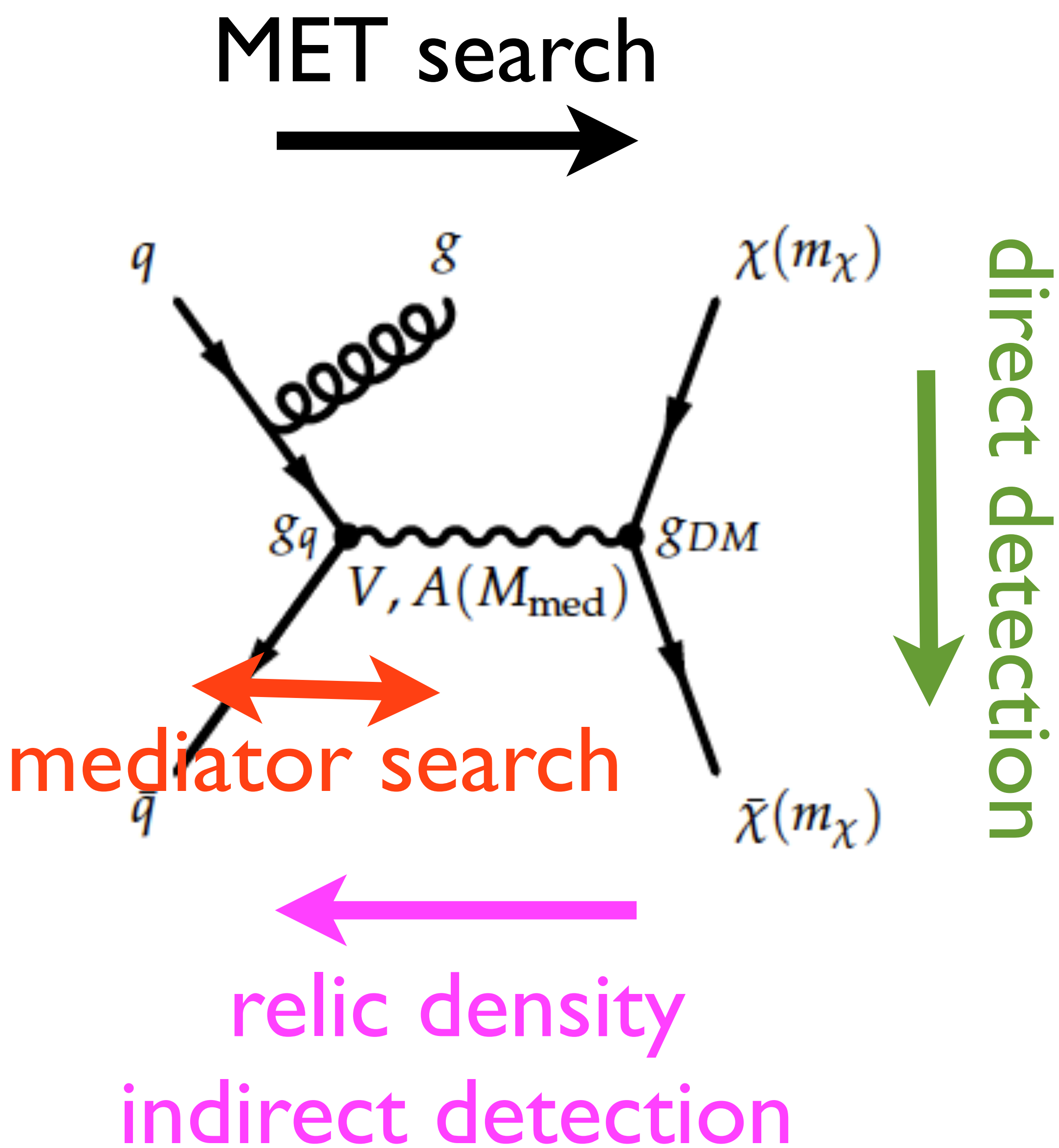
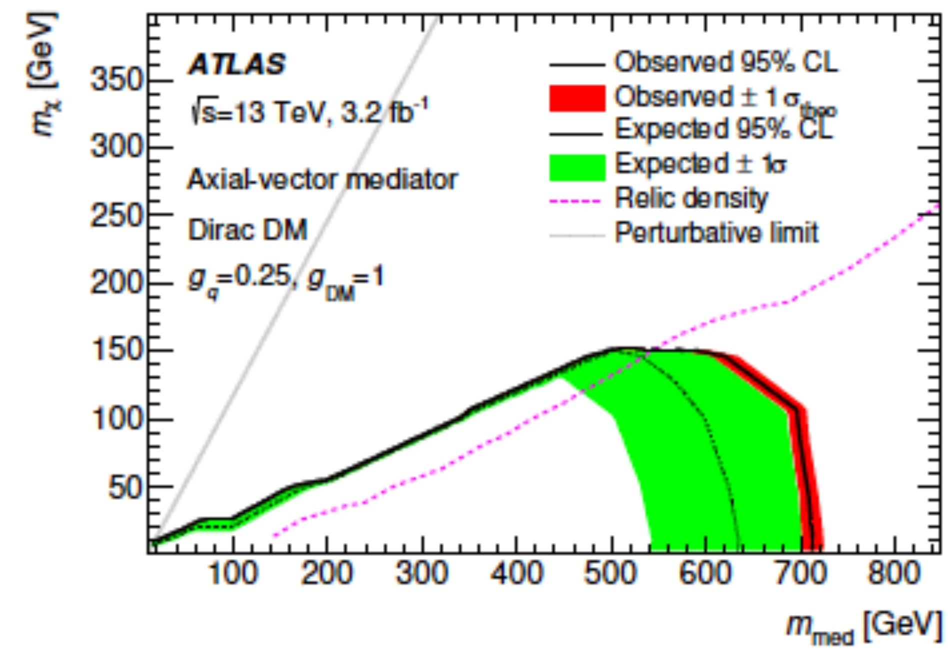
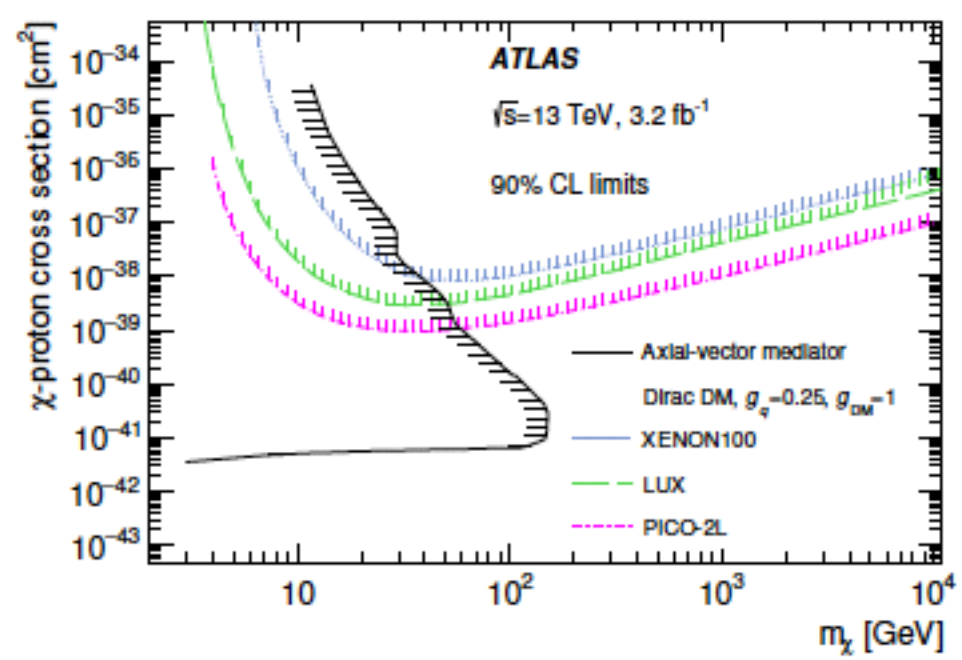
ATLAS 13TeV search for simplified DM models

LHC DM WG [1507.00966, 1603.04156]

[1604.01306]



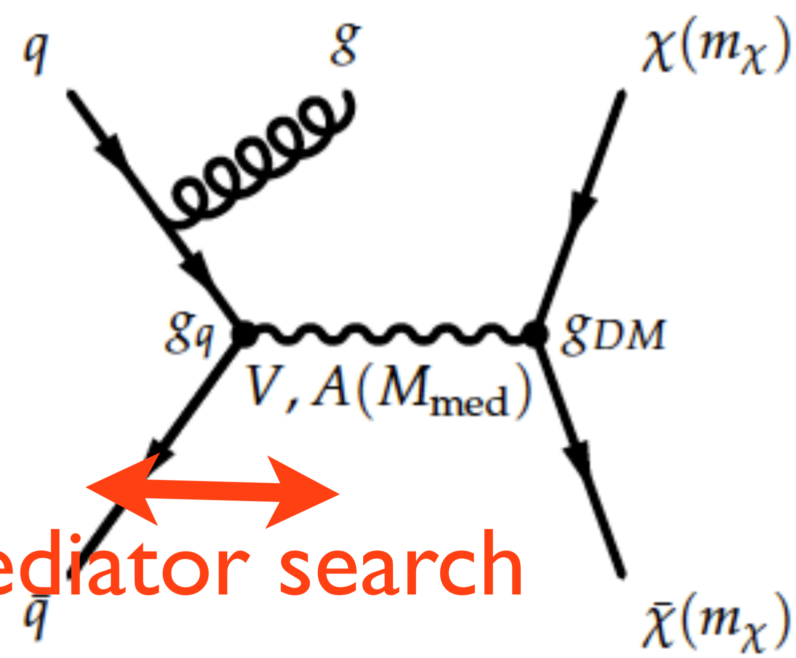




ATLAS 13TeV search for simplified DM models

LHC DM WG [1507.00966, 1603.04156]

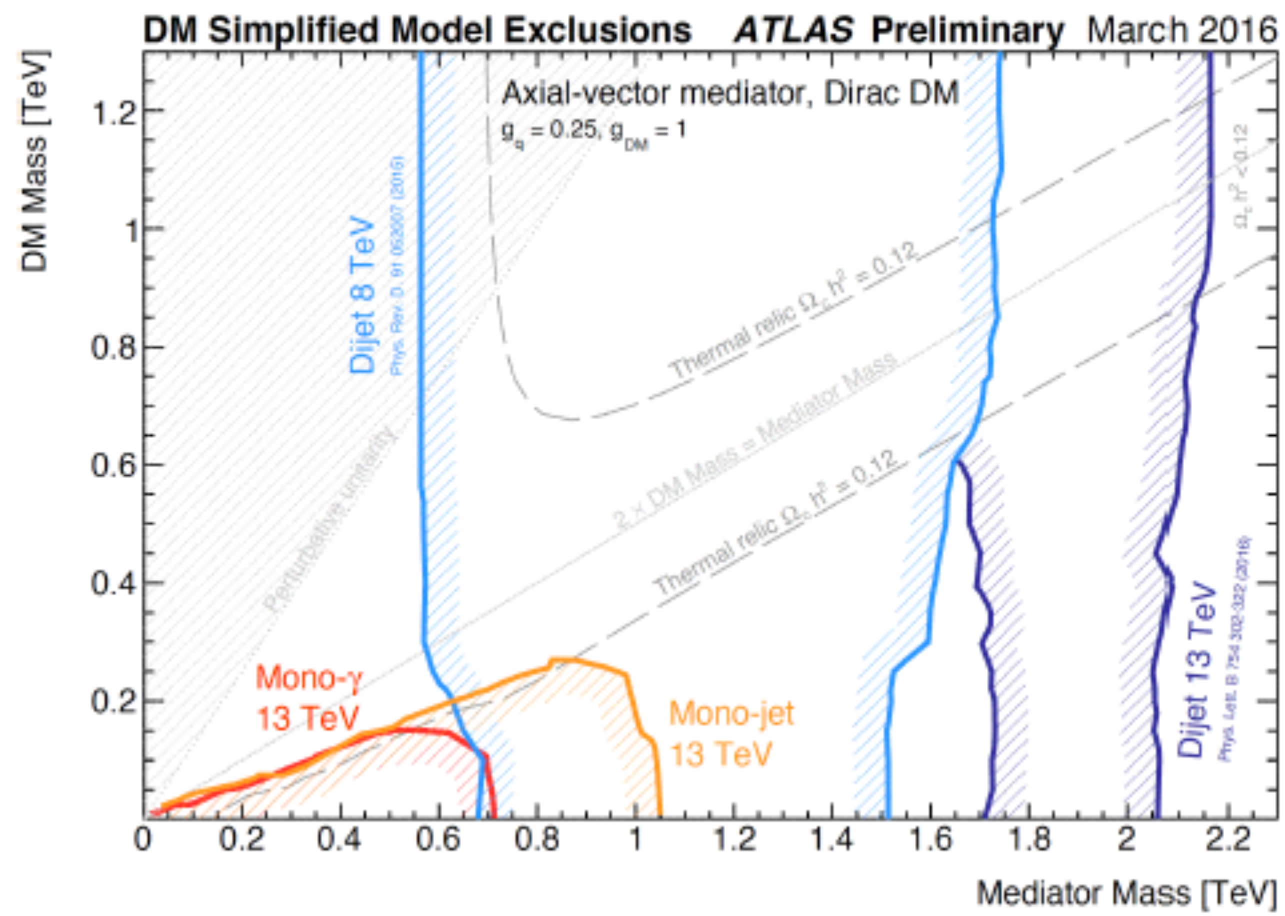
MET search →



direct detection ↓

↔ mediator search

← relic density, indirect detection



see also F. Kahlhoefer's talk

DM searches at LHC Run-2

LHC DM WG [1507.00966, 1603.04156]

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

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

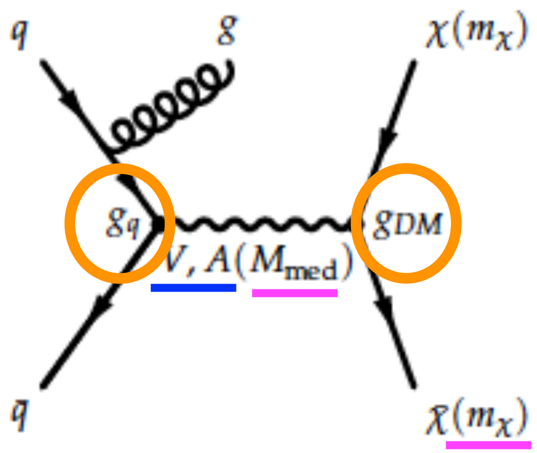
$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q\,.$$

  - spin-0 mediator

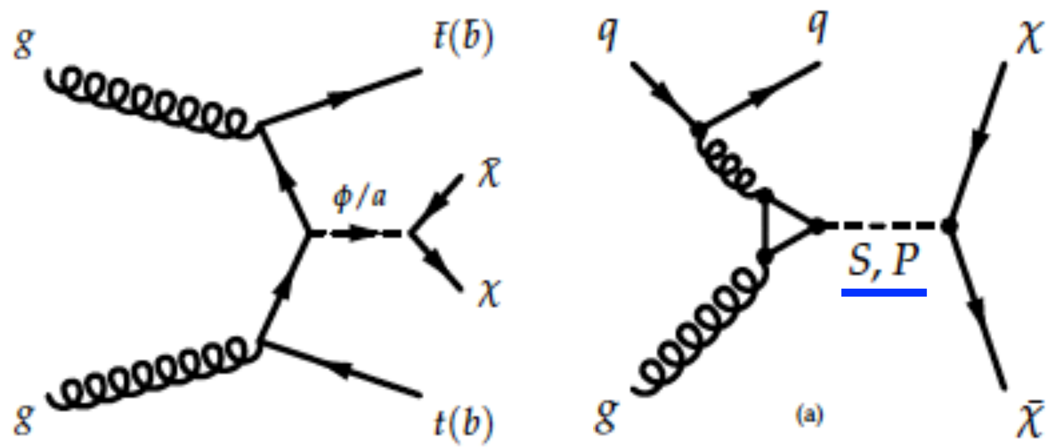
$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q\,,$$

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

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



spin-1 mediator



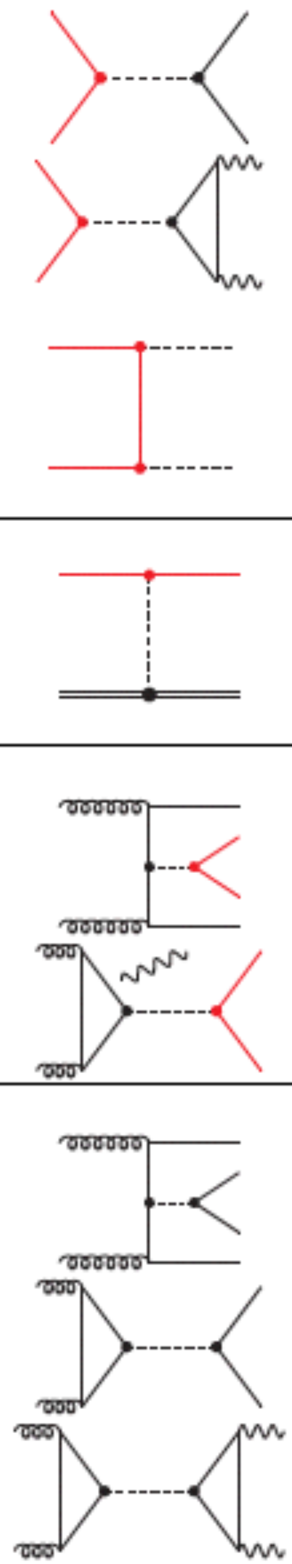
spin-0 mediator

👉 Top-philic DM models

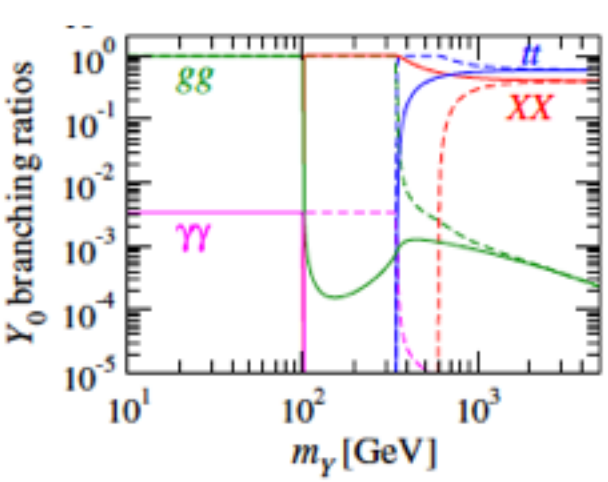
A comprehensive approach to DM studies: simplified top-philic models

X=DM
Y=mediator

[1605.09242]
51 pages, 23 figs, 8 tables



Cosmology	relic indirect	$m_X > m_t$	Planck, FermiLAT
		$m_X < m_t$	
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

MC tools for Run-2 DM searches

LHC DM WG [1507.00966]

	Benchmark models for ATLAS and CMS Run-2 DM searches	
	vector/axial vector mediator, *s*-channel (Sec. 2.1)	
Signature	State of the art calculation and tools	Implementation
jet + $\not{E}_T$	**NLO+PS (powheg, SVN r3059)**	[Forl; Foro]
	NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0)	[New]
	NLO (MCFM v7.0)	Upon request
$W/Z/\gamma + \not{E}_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Fora]
	NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0)	[New]
	scalar/pseudoscalar mediator, *s*-channel (Sec. 2.2)	
Signature	State of the art calculation and tools	Implementation
jet + $\not{E}_T$	**LO+PS, top loop (powheg, r3059)**	[Forn; Form]
	LO+PS, top loop (*DMsimp* UFO + MadGraph5_aMC@NLO v.2.3.0)	[New]
	LO, top loop (MCFM v7.0)	Upon request
$W/Z/\gamma + \not{E}_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	
$t\bar{t}, b\bar{b} + \not{E}_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Ford]
	NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0)	[New]

BSM models in the FeynRules model database

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

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 were 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 DM model files

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

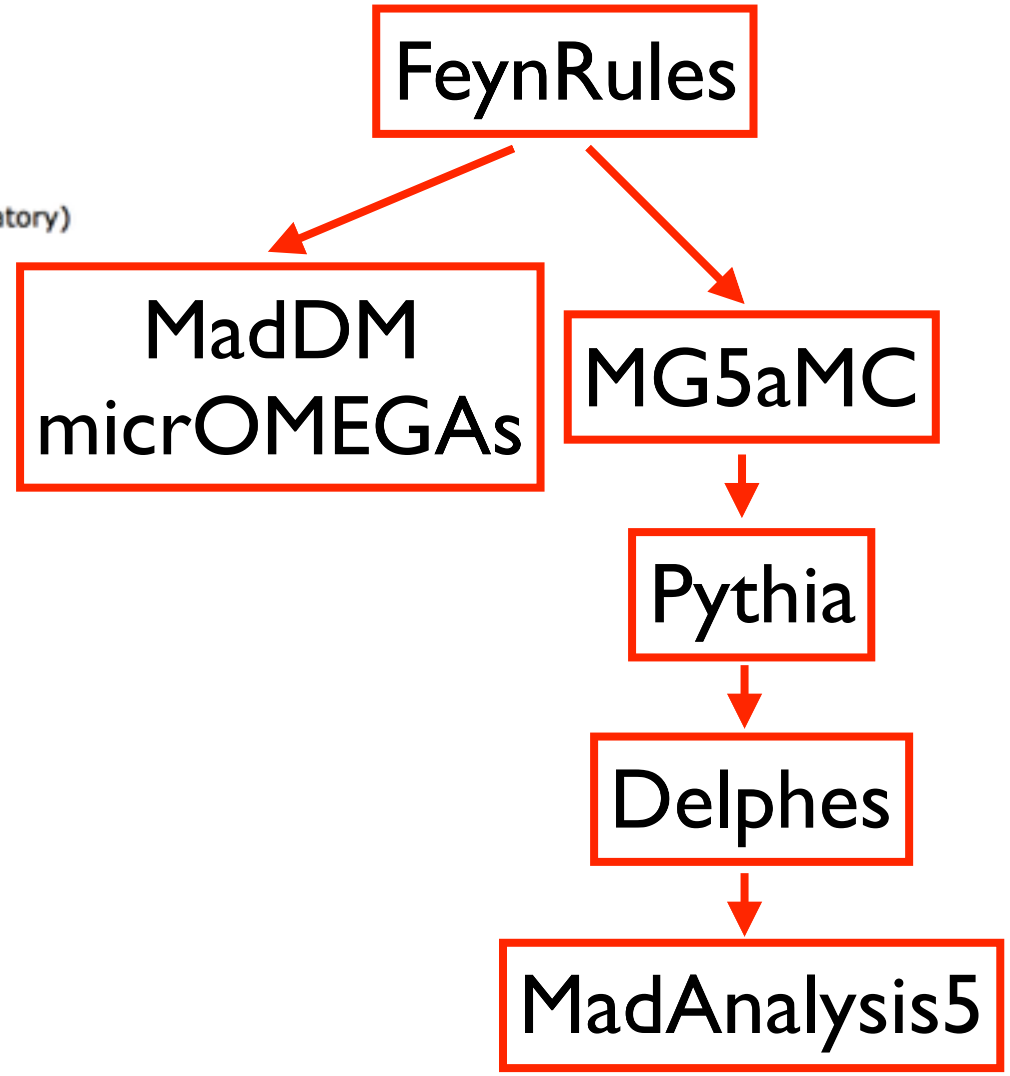
wiki: DMsimp

Start Page | Index | History

Last modified 3 weeks ago

Simplified dark matter models

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



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.)
- ...

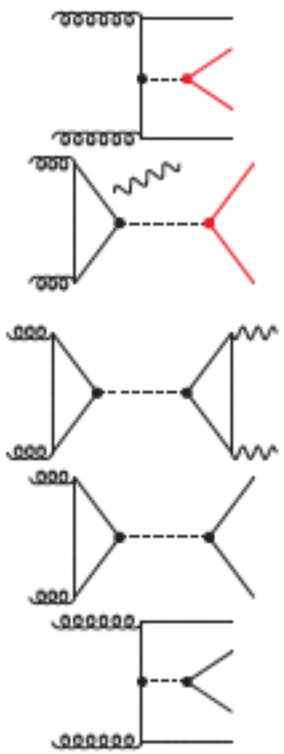
and different types of mediators:

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

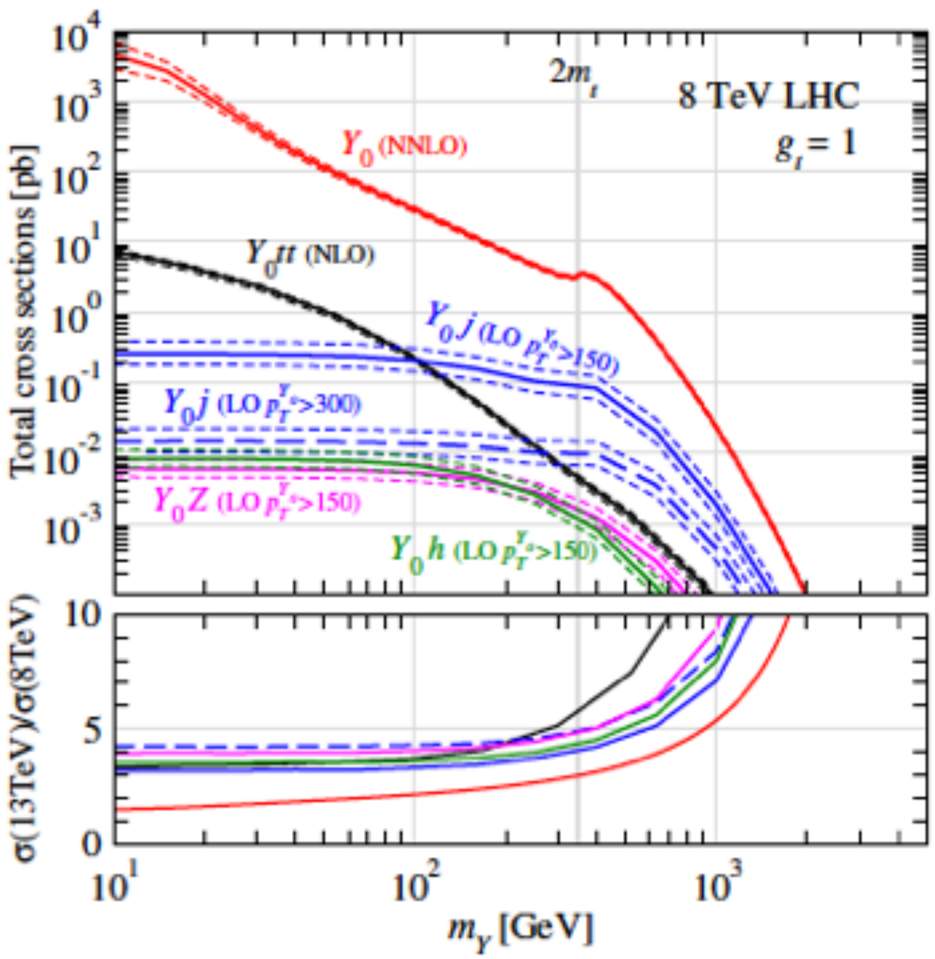
One can find the model lagrangian in the note. See more details in

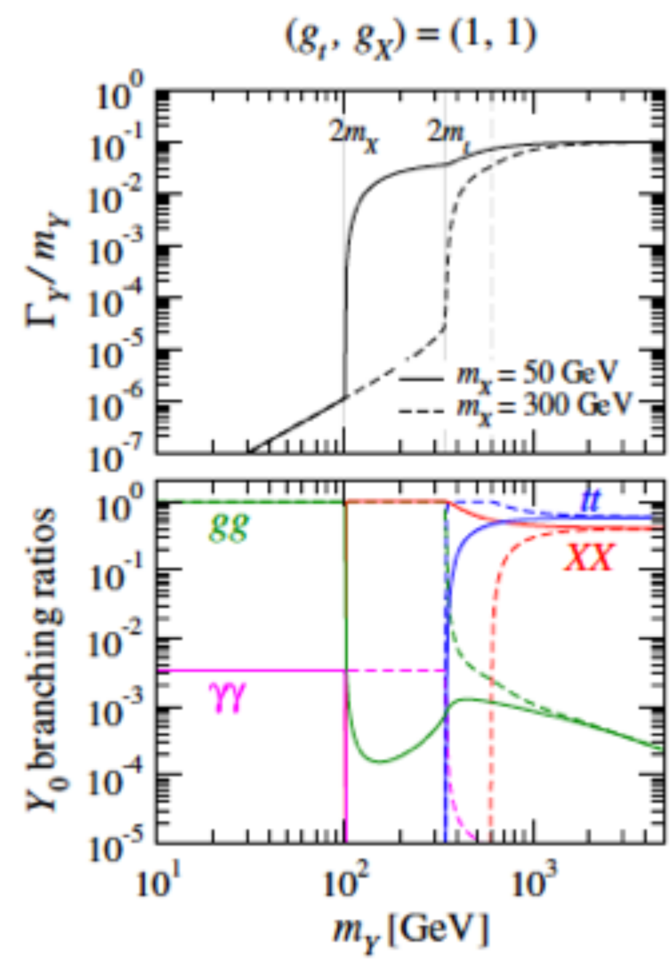
- 1508.00564 : O. Mattelaer, E. Vryonidou, "Dark matter production through loop-induced processes at the LHC: the s-channel mediator case".
- 1508.05327 : M. Backovic, M. Kramer, F. Maltoni, A. Martini, K. Mawatari, M. Pellen, "Higher-order QCD predictions for dark matter production at the LHC in simplified 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".

8TeV constraints for top-philic DM



Final state	Imposed constraint	Reference	Comments
$\not{E}_T + t\bar{t}$	MadAnalysis5 PAD (new)	CMS [1504.03198]	Semileptonic top-antitop decay
$\not{E}_T + j$	MadAnalysis5 PAD (new)	CMS [1408.3583]	
$\not{E}_T + Z$	$\sigma(\not{E}_T > 150\ \text{GeV}) < 0.85\,\text{fb}$	CMS [1511.09375]	Leptonic Z-boson decay
$\not{E}_T + h$	$\sigma(\not{E}_T > 150\ \text{GeV}) < 3.6\,\text{fb}$	ATLAS [1510.06218]	$h \to b\bar{b}$ 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





inspirehep.net/record/1456179/

iNSPIRE HEP

Welcome to INSPIRE, the High Energy Physics information system. Please direct questions, comments or concerns to feedback@inspirehep.net.

HEP :: HEPNAMES :: INSTITUTIONS :: CONFERENCES :: JOBS :: EXPERIMENTS :: JOURNALS :: HELP

Information | Citations (1) | Files

MadAnalysis5 implementation of the CMS search for dark matter production with top quark pairs in the single lepton channel (CMS-B2G-14-004)

Fuks, Benjamin; Martini, Antony

Description: This is the MadAnalysis5 implementation of the CMS search for dark matter in a channel where a pair of dark matter particles is produced in association with a top-antitop system. This search targets events featuring a single lepton originating from the top decays and a large amount of missing transverse energy.

Information how to use this code and a detailed validation summary are available at http://madanalysis.irmp.ucl.ac.be/wiki/PhysicsAnalysisDatabase. The CMS analysis is documented at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G14004.

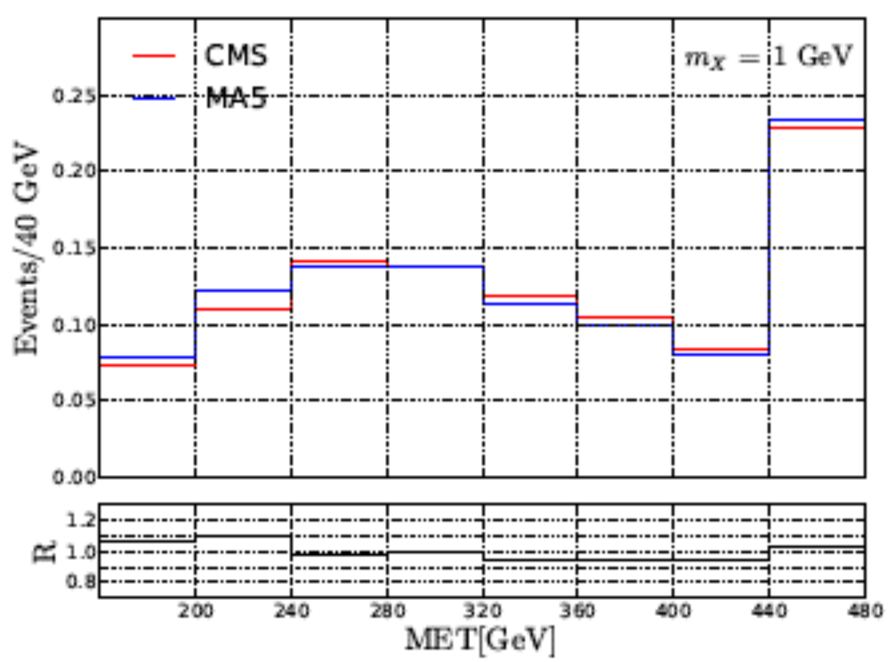
Cite as: Fuks, B., Martiny, A. (2016). MadAnalysis5 implementation of the CMS search for dark matter production with top quark pairs in the single lepton channel (CMS-B2G-14-004). doi: 10.7484/INSPIREHEP.DATA.MIHA.JR4G

Record added 2016-05-09, last modified 2016-05-09

MadAnalysis5 implementation of the CMS search for dark matter production with top quark pairs in the single lepton channel (CMS-B2G-14-004)

Fuks, Benjamin; Martini, Antony

	Selection step	CMS	$\epsilon_i^{\rm CMS}$	MA5	$\epsilon_i^{\rm MA5}$	$\delta_i^{\rm rel}$
0	Nominal	224510		224510		
1	Preselection			15468.5	0.069	
2	$\not{E}_T > 320$ GeV	4220.8		4579.8	0.296	
3	$M_T > 160$ GeV	3390.1	0.803	3648.2	0.797	0.75%
4	$\Delta\Phi(j_{1,2}, \not{E}_T) > 1.2$	2963.5	0.874	3124.3	0.856	2.06%
5	$M_{T2}^W > 200$ GeV	2267.6	0.765	2403	0.769	-0.52%



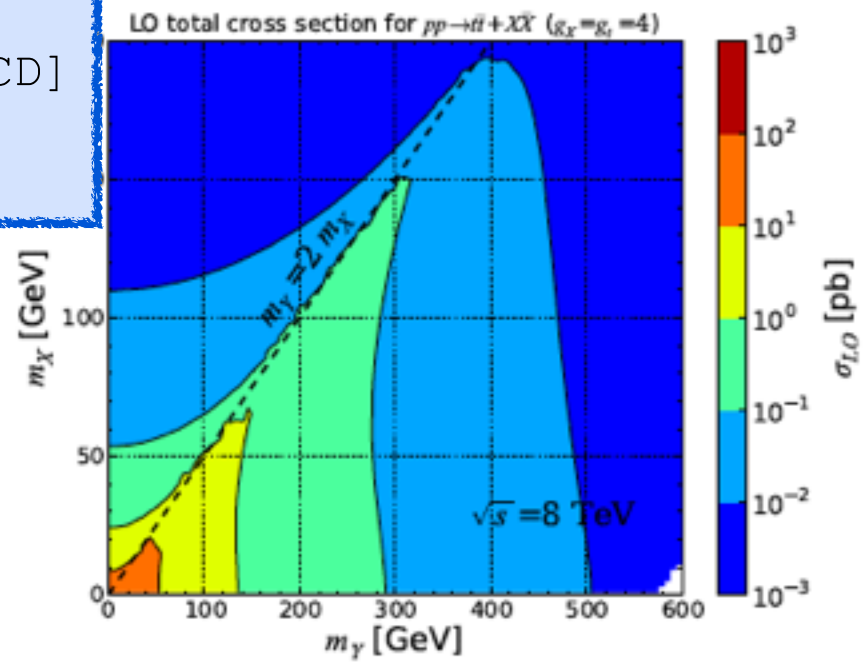
★27-email exchanges (03/12/2015-19/02/2016)

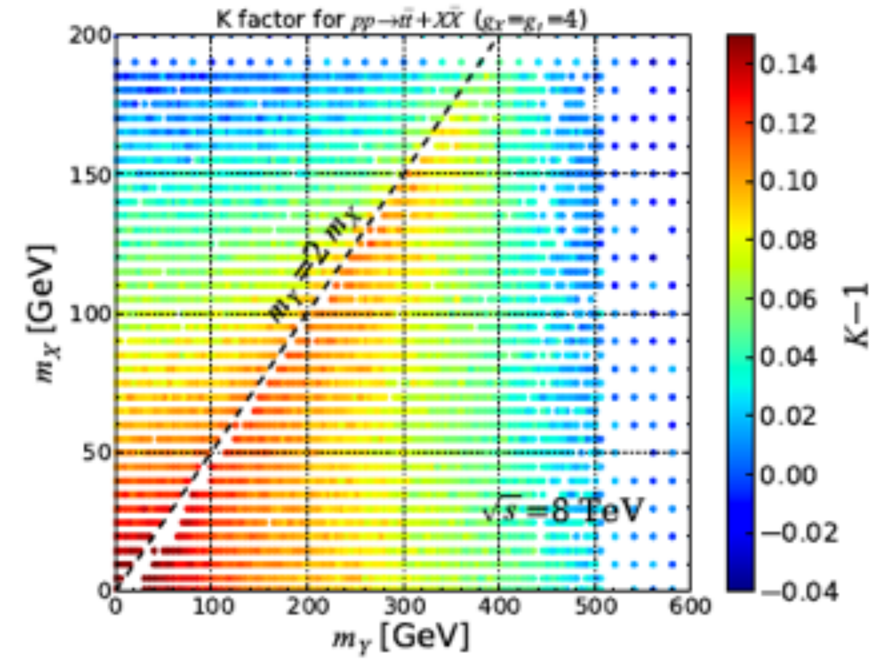
- UFO model file
- custom MG5 with proc/param/run_cards
- pythia tuning
- Root files for distributions
- Cutflow for the signal benchmark

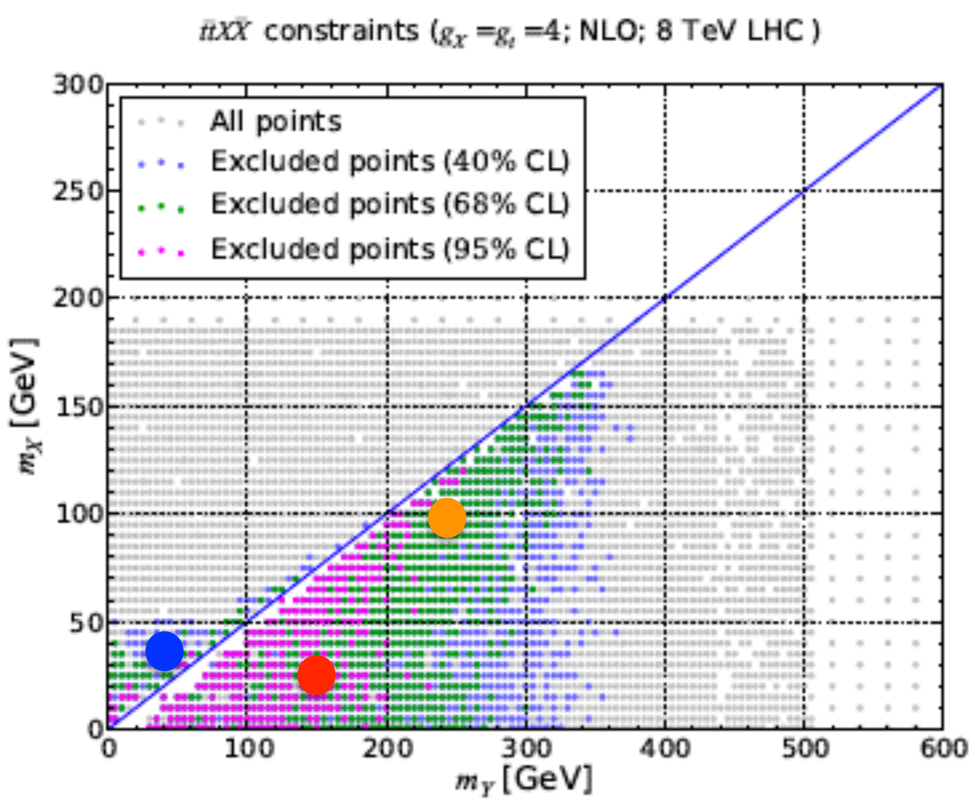
MET + a top-quark pair (NLO)

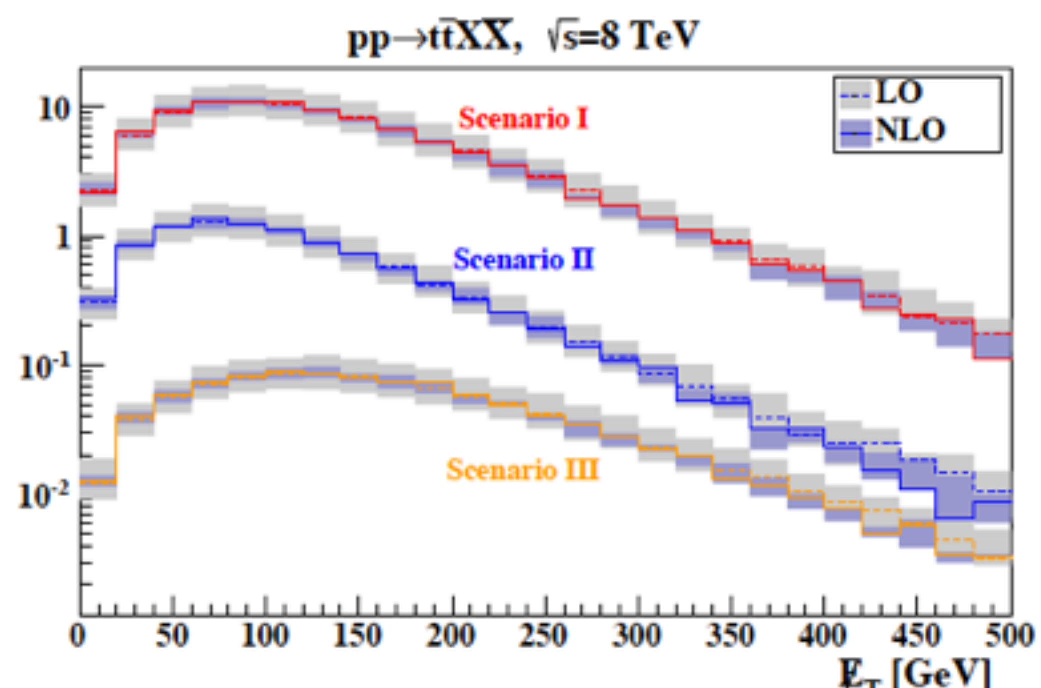
```
./bin/mg5_aMC
>import model DMsimp_s_spin0
>generate p p > t t~ xd xd~ [QCD]
>output
>launch
```

(m_Y, m_X)	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [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.

inspirehep.net/record/1413153

INSPIRE HEP

Welcome to INSPIRE, the High Energy Physics information system. Please direct questions, comments or concerns to feedback@inspirehep.net.

HEP :: HEPNAMES :: INSTITUTIONS :: CONFERENCES :: JOBS :: EXPERIMENTS :: JOURNALS :: HELP

Information | Citations (1) | Files

MadAnalysis5 implementation of the CMS monojet search (EXO-12-048)

Guo,Jun; Conte, Eric; Fuks, Benjamin

Description: This is the MadAnalysis5 implementation of the CMS search for monojet systems. This search targets events featuring a single hard jet produced in association with missing energy.

Note: Information on how to use this code as well as a detailed validation summary are available at http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase. The CMS analysis is documented at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048.

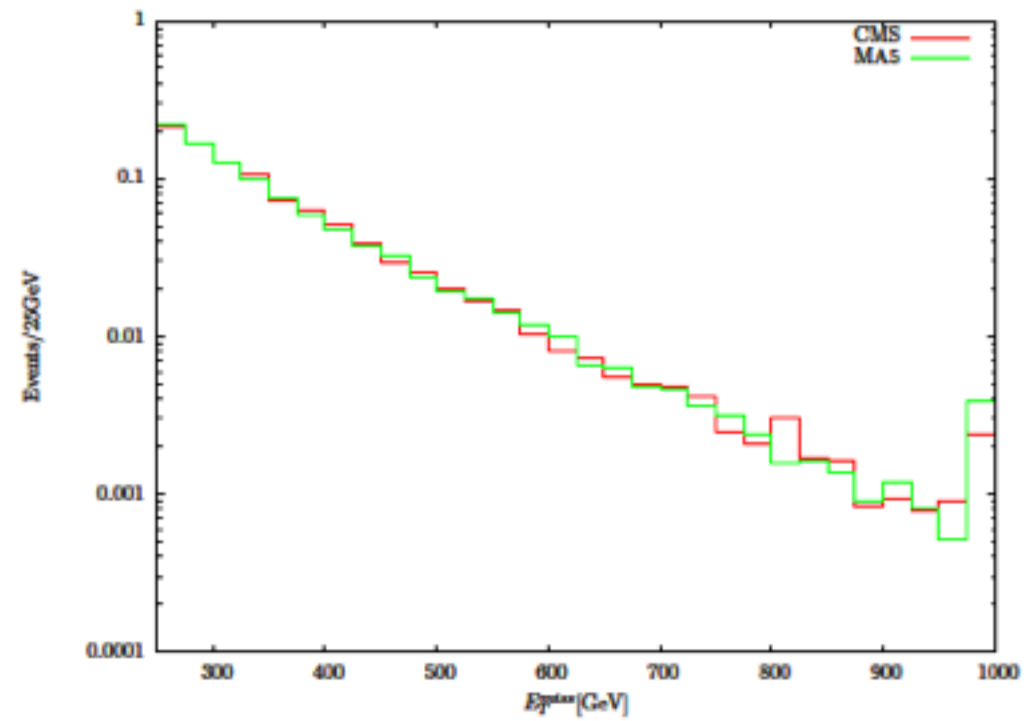
Cite as: Guo, J., Conte, E., Fuks, B. (2016). MadAnalysis5 implementation of the CMS monojet search (EXO-12-048). doi: 10.7484/INSPIREHEP.DATA.JAN2.UNDA

Record added 2016-01-06, last modified 2016-05-13

MadAnalysis5 implementation of the CMS monojet search (EXO-12-048)

Guo,Jun; Conte, Eric; Fuks, Benjamin

	Selection step	CMS	$\epsilon_i^{\rm CMS}$	MA5	$\epsilon_i^{\rm MA5}$	$\delta_i^{\rm rel}$
0	Nominal	84653.7		84653.7		
1	One hard jet	50817.2	0.6	53431.28	0.631	5.2%
2	At most two jets	36061	0.7096	38547.75	0.721	1.61%
3	Requirements if two jets	31878.1	0.884	34436.35	0.893	1.02%
4	Muon veto	31878.1	1	34436.35	1.000	0
5	Electron veto	31865.1	1	34436.35	1.000	0
6	Tau veto	31695.1	0.995	34397.54	0.998	0.3%
	$\not{E}_T > 250$ GeV	8687.22	0.274	7563.04	0.219	20.00%
	$\not{E}_T > 300$ GeV	5400.51	0.621	4477.67	0.592	4.66%
	$\not{E}_T > 350$ GeV	3394.09	0.628	2813.70	0.628	0.00%
	$\not{E}_T > 400$ GeV	2224.15	0.6553	1753.71	0.623	4.93%
	$\not{E}_T > 450$ GeV	1456.02	0.654	1110.92	0.633	3.21%
	$\not{E}_T > 500$ GeV	989.806	0.679	722.83	0.650	4.27%
	$\not{E}_T > 550$ GeV	671.442	0.678	487.54	0.674	0.59%

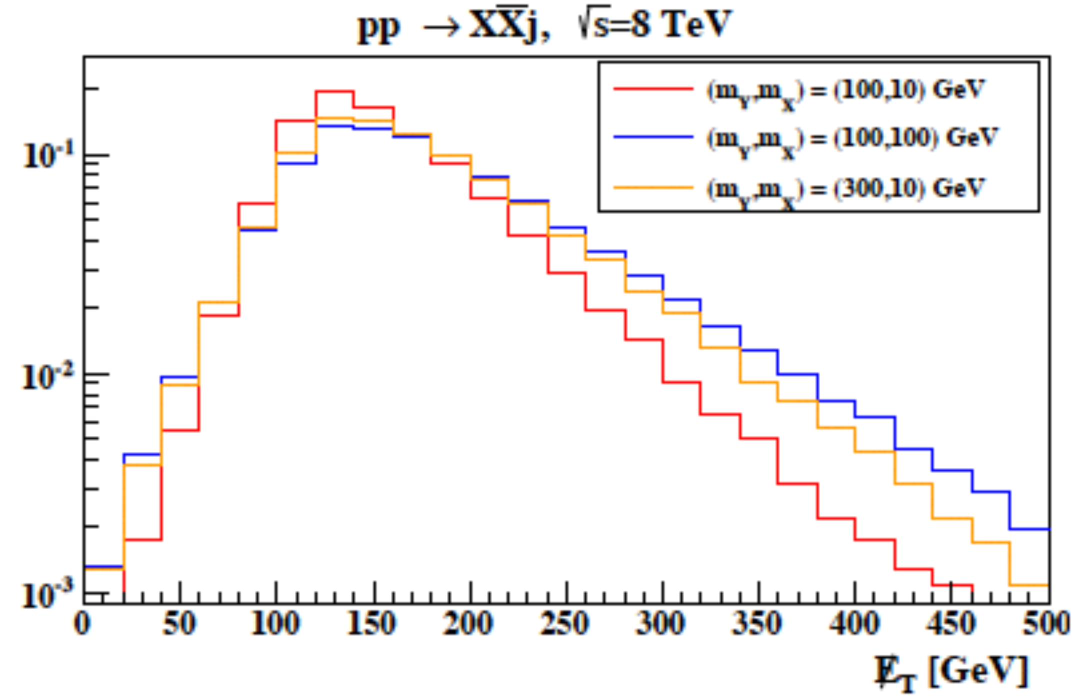


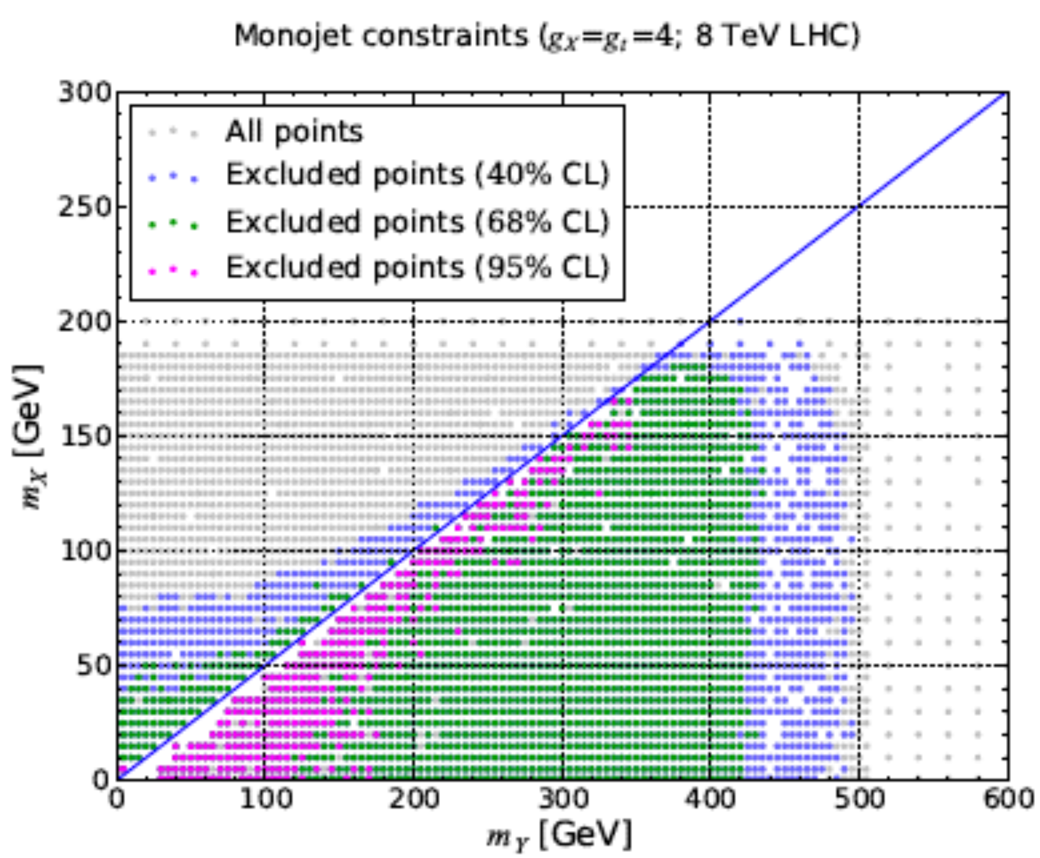
★51-email exchanges (Jul-Nov/2015)

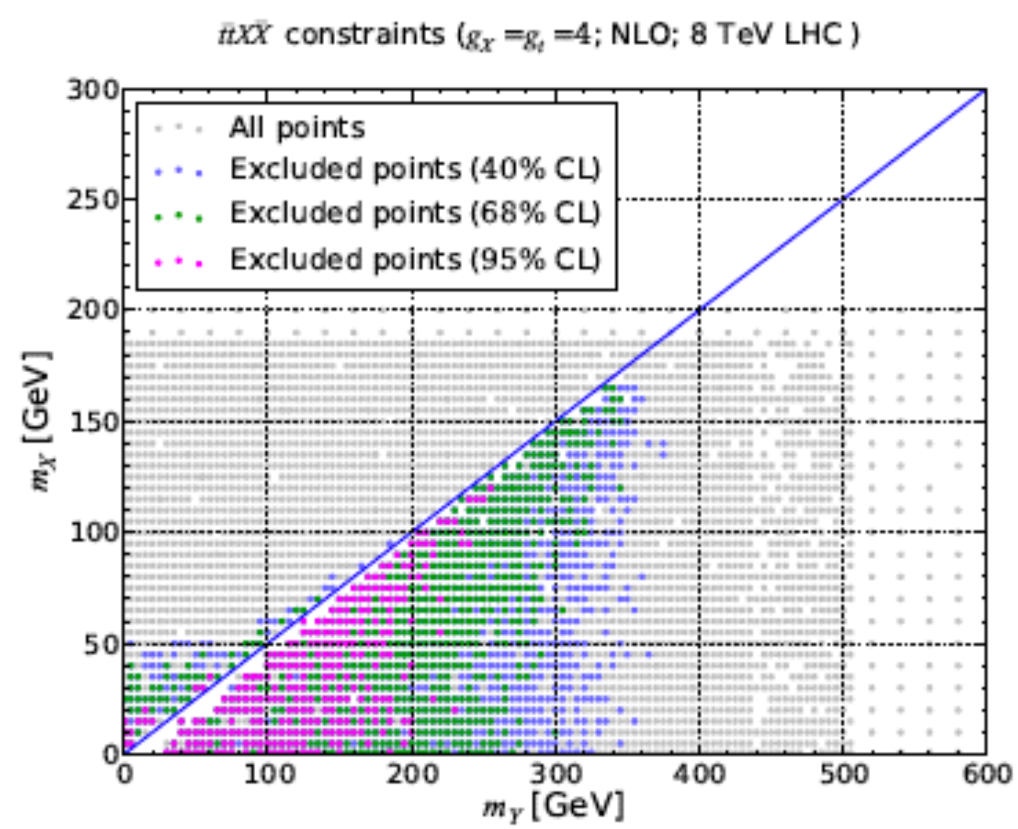
Mono-jet (LO loop-induced)

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

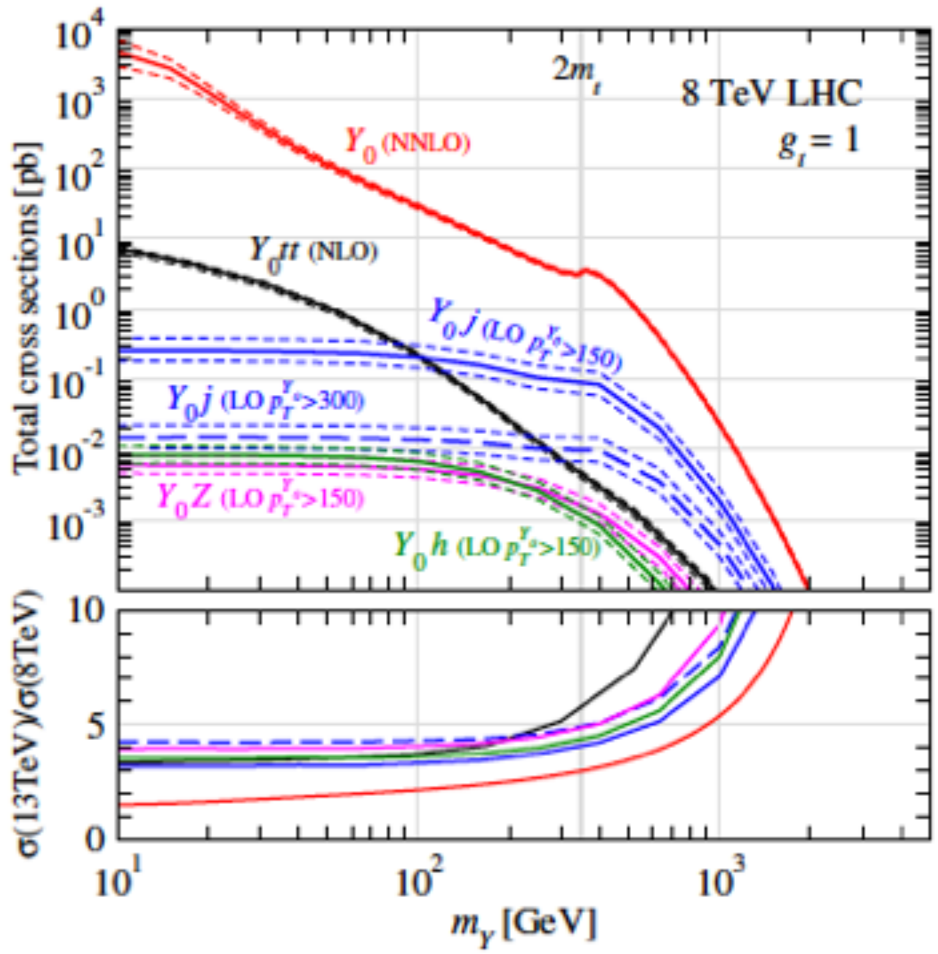
Complementarity between the different searches.

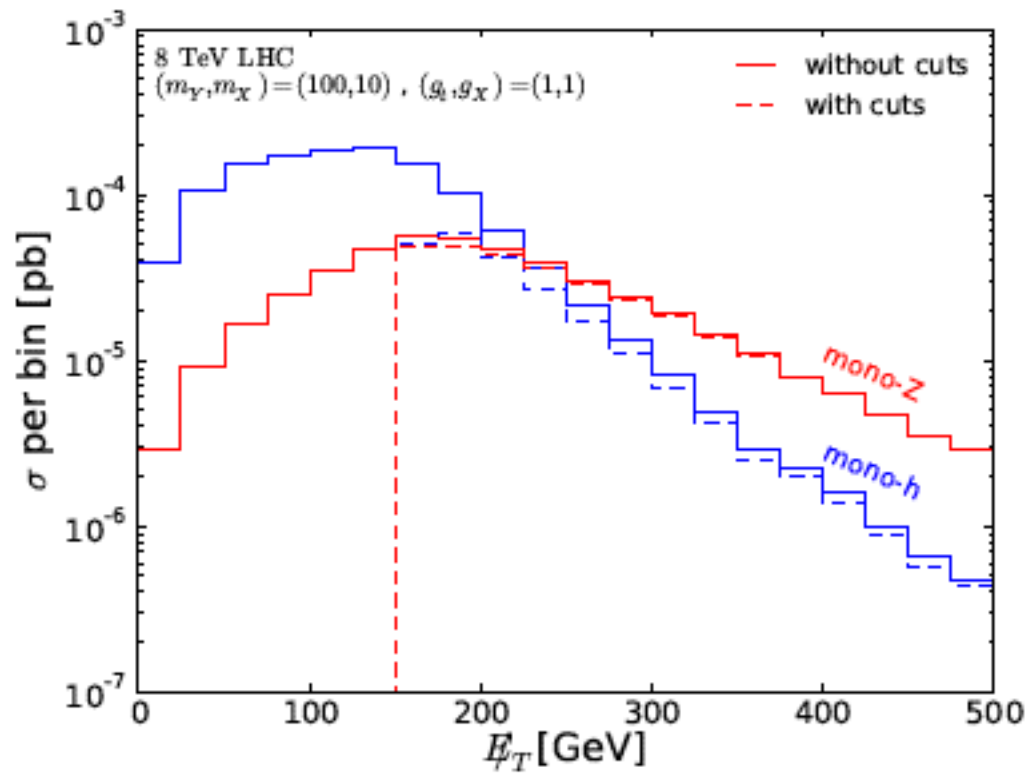






Mono-Z/h (LO loop-induced)



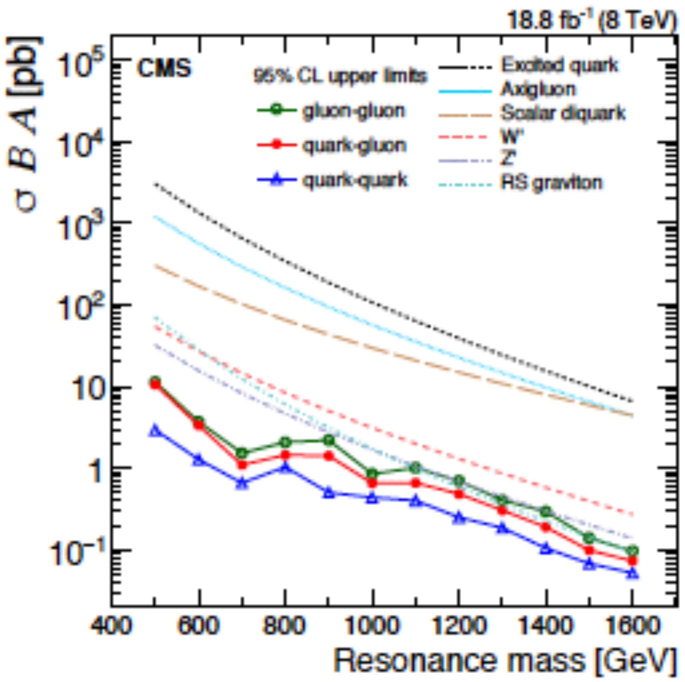


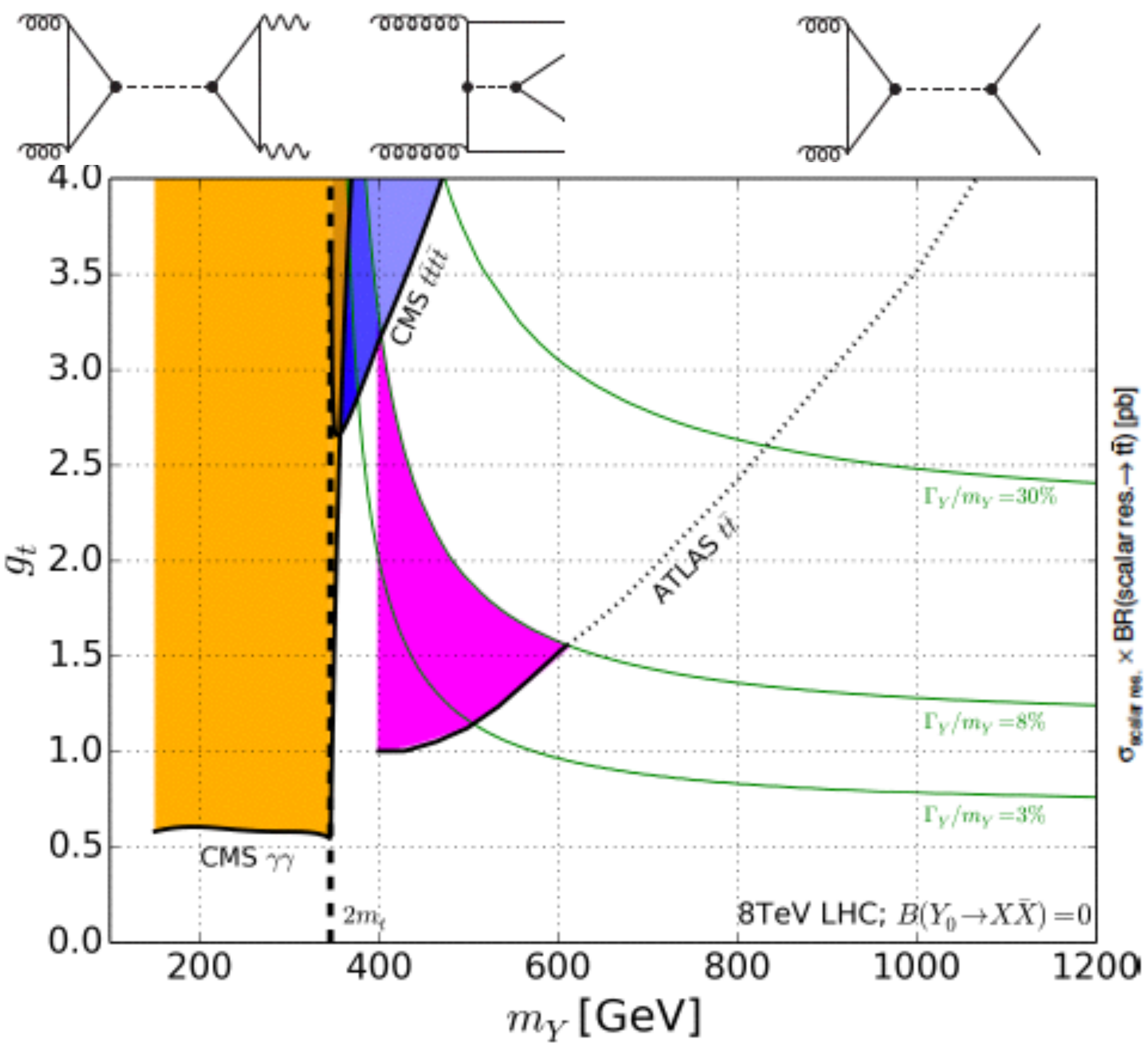
$\not{E}_T + Z$	$\sigma(\not{E}_T > 150\ \mathrm{GeV}) < 0.85\,\mathrm{fb}$
$\not{E}_T + h$	$\sigma(\not{E}_T > 150\ \mathrm{GeV}) < 3.6\,\mathrm{fb}$

$\Longrightarrow$ $g_t<2$ for $m_Y<200$GeV

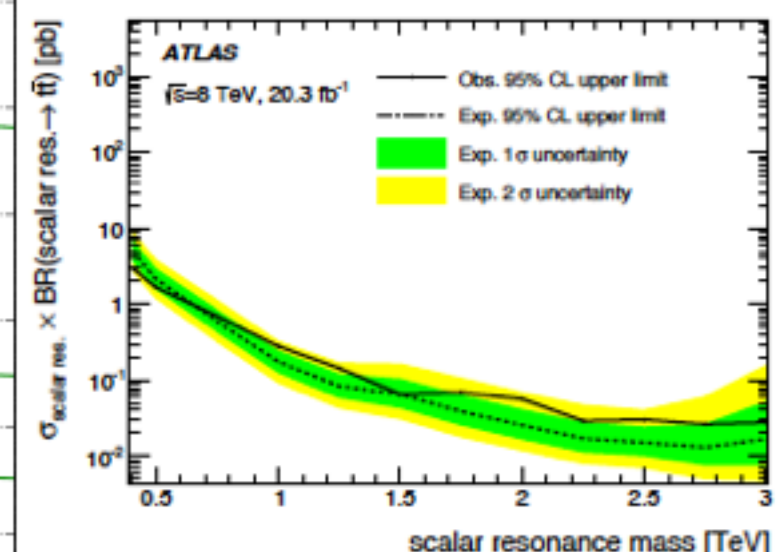
The dedicated recasting is needed.

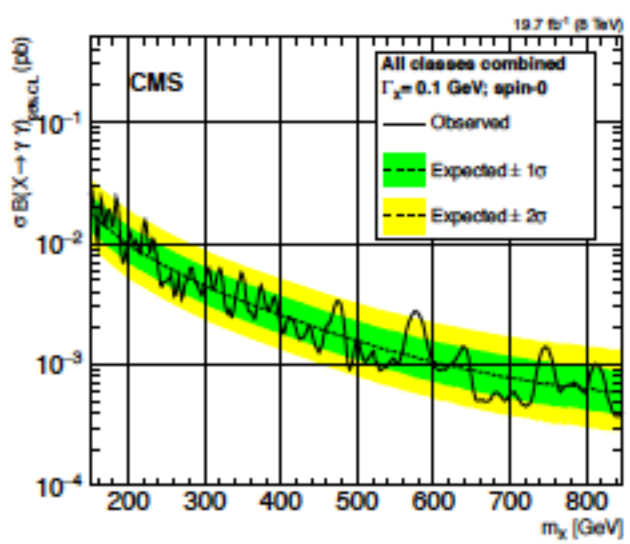
Resonance search constraints





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 $m_Y > 400\,\text{GeV}$
$t\bar{t}t\bar{t}$	$\sigma < 32\,\text{fb}$	CMS [1409.7339]	Upper limit on the SM cross section

Relic vs. DD vs. LHC

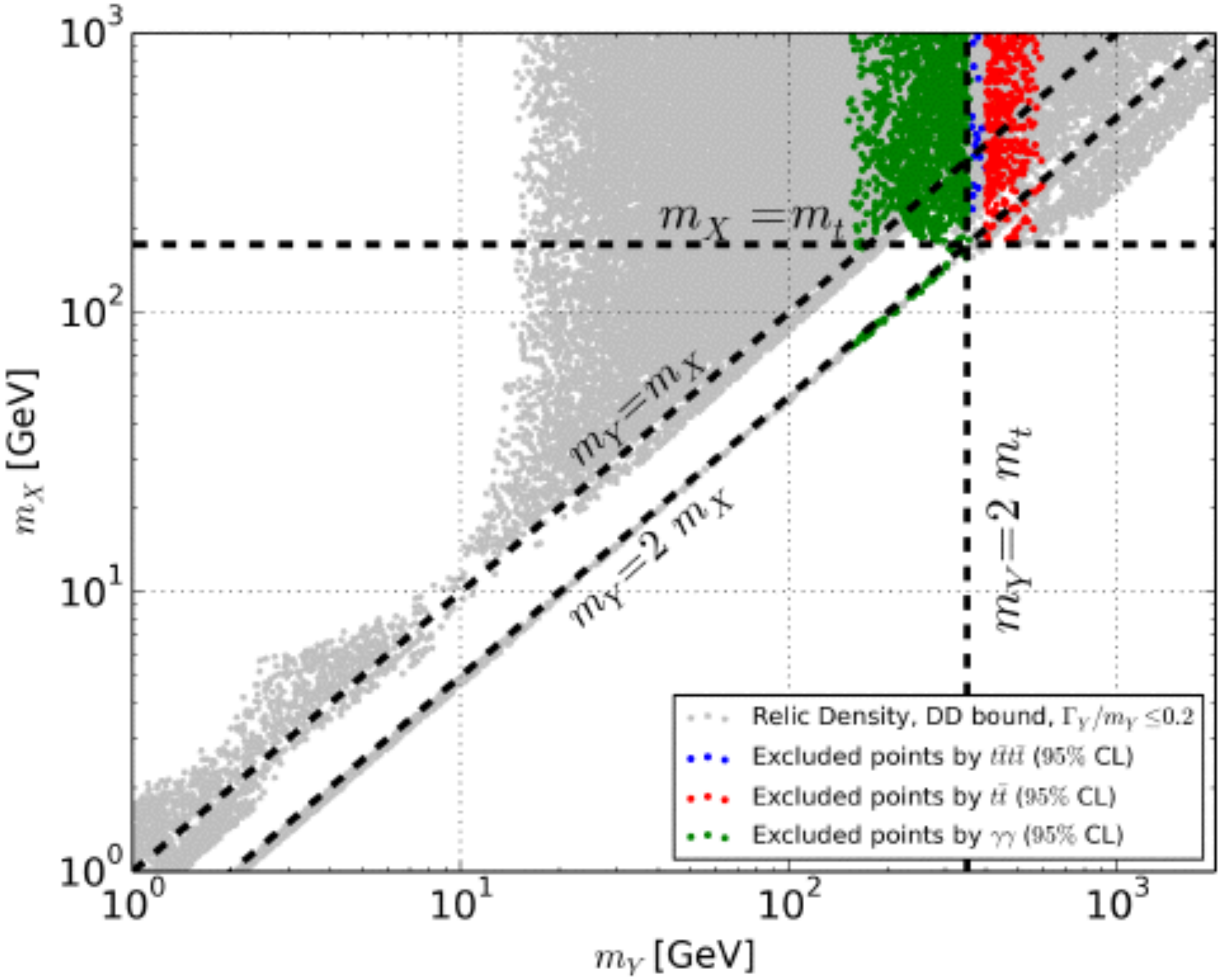


Figure 14. Results of our four-dimensional parameter scan projected onto the (m_Y, m_X) plane once constraints set from the LHC results are imposed. The points excluded by the diphoton, the $t\bar{t}$ and the four-top considered searches all satisfy the relic density, narrow width and direct detection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

Lessons from 1605.09242

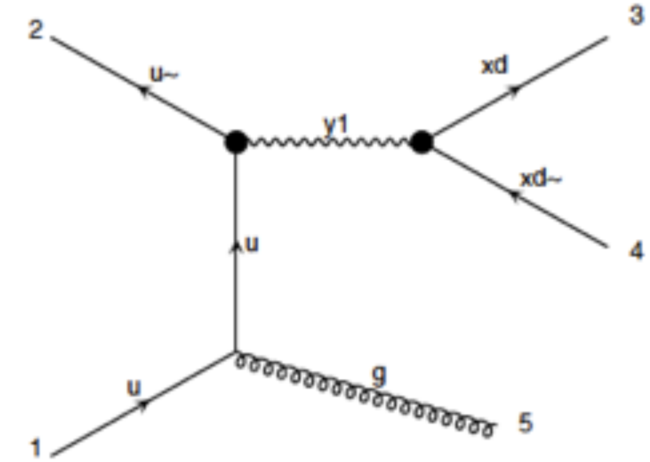
- The systematic simulation framework have been developed not only for LHC but also for non-collider experiments.
- Proper recasting still takes time.
- NLO predictions not only provide reliable rate but also reduce the theoretical uncertainty.
- In the DM context, not only mono-j but also mono-γ/Z/h are important.
- A single model can be constrained by many different LHC searches (and also by non-collider searches).
- Management of a 'big' collaboration is very difficult…

backup

Simplified s-channel models of DM

Dark matter (X):
- real scalar
- complex scalar
- Dirac spinor

Mediator (Y):
- spin-0
- spin-1
- spin-2 (to be done)



spin-0 mediator

$$\mathcal{L}_{X_D}^{Y_0} = \bar{X}_D(g^S_{X_D} + i g^P_{X_D}\gamma_5)X_D\, Y_0$$

$$\mathcal{L}_{\rm SM}^{Y_0} = \sum_{i,j}\Big[\bar{d}_i \frac{y^d_{ij}}{\sqrt{2}}(g^S_{d_{ij}} + i g^P_{d_{ij}}\gamma_5)d_j + \bar{u}_i \frac{y^u_{ij}}{\sqrt{2}}(g^S_{u_{ij}} + i g^P_{u_{ij}}\gamma_5)u_j\Big] Y_0$$

spin-1 mediator

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

$$\mathcal{L}_{\rm SM}^{Y_1} = \sum_{i,j}\Big[\bar{d}_i\gamma_\mu(g^V_{d_{ij}} + g^A_{d_{ij}}\gamma_5)d_j + \bar{u}_i\gamma_\mu(g^V_{u_{ij}} + g^A_{u_{ij}}\gamma_5)u_j\Big] Y_1^\mu$$

- "DM production through loop-induced processes at the LHC"
  Mattelaer, Vryonidou [1508.00564]
- "Higher-order QCD predictions for DM production at the LHC in simplified models"
  Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen [1508.05327]
- "Higher-order QCD predictions for DM production in mono-Z searches at the LHC"
  Neubert, Wang, Zhang [1509.05785]

3-min MadGraph5_aMC@NLO tutorial

```
./bin/mg5_aMC
>import model DMsimp_s_spin1
>generate p p > xd xd~ j [QCD]
>output
>launch
```

- Start the MG5aMC shell
- Import the model
- Generate the process at NLO
- Write the code (including html)
- Generate the LO/NLO events

param_card.dat

```
###############################
## INFORMATION FOR DMINPUTS
###############################
Block dminputs
    1 0.000000e+00 # gVXc
    2 1.000000e+00 # gVXd
    3 0.000000e+00 # gAXd
    4 2.500000e-01 # gVd11
    5 2.500000e-01 # gVu11
    6 2.500000e-01 # gVd22
    7 2.500000e-01 # gVu22
    8 2.500000e-01 # gVd33
    9 2.500000e-01 # gVu33
   10 0.000000e+00 # gAd11
   11 0.000000e+00 # gAu11
   12 0.000000e+00 # gAd22
   13 0.000000e+00 # gAu22
   14 0.000000e+00 # gAd33
   15 0.000000e+00 # gAu33
```

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

$$\mathcal{L}_{\rm SM}^{Y_1} = \sum_{i,j}\left[\bar{q}_i\gamma_\mu(g^V_{q_{ij}} + g^A_{q_{ij}}\gamma_5)q_j\right] Y_1^\mu$$

```
###############################
## INFORMATION FOR MASS
###############################
Block mass
    6 1.720000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118760e+01 # MZ
   25 1.250000e+02 # MH
   51 1.000000e+01 # MXc
   52 1.000000e+01 # MXd
   55 1.000000e+03 # MY1
 5000001 1.000000e+01 # MXr
```

run_card.dat

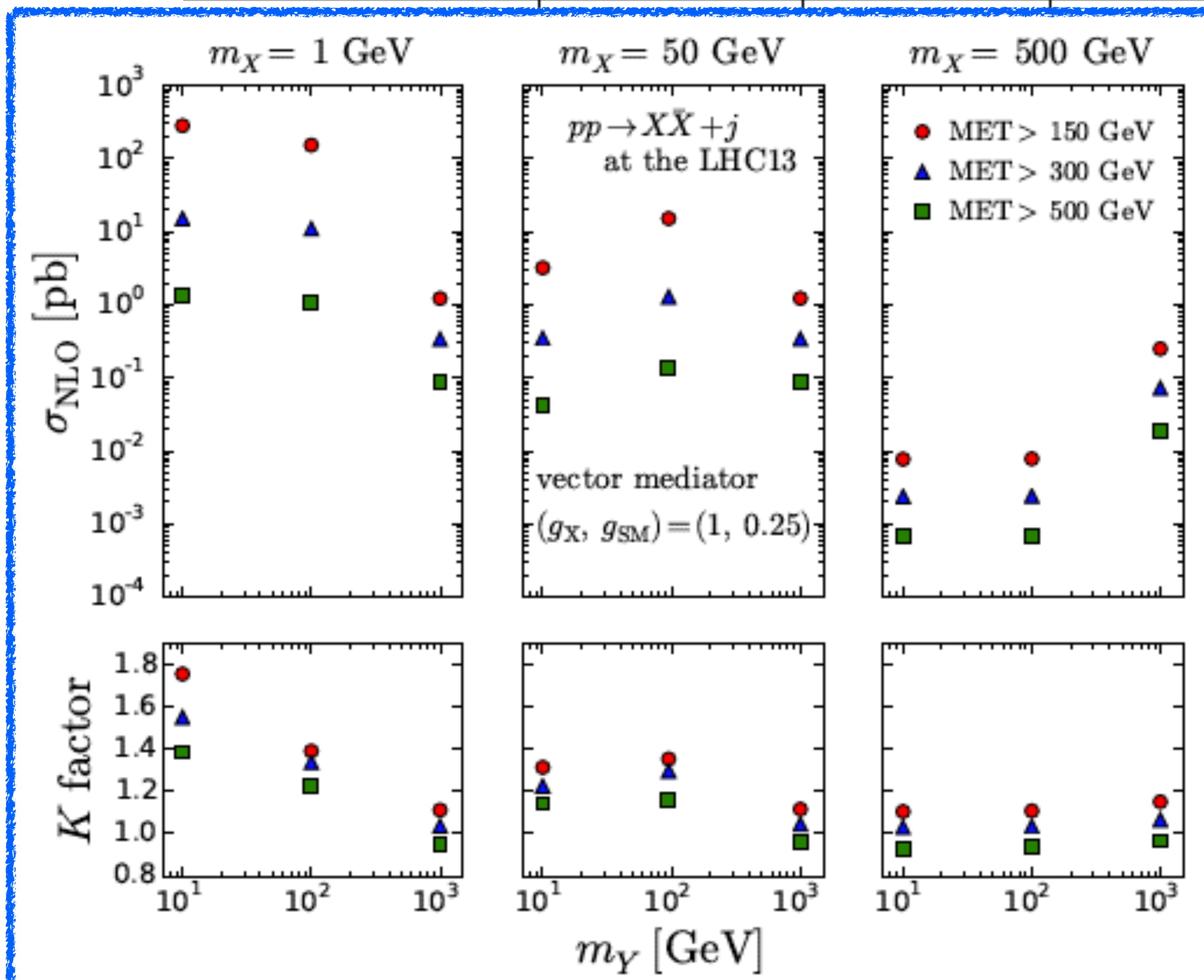
```
#*********************************************************************
# Collider type and energy
#*********************************************************************
   1   = lpp1    ! beam 1 type (0 = no PDF)
   1   = lpp2    ! beam 2 type (0 = no PDF)
 6500  = ebeam1  ! beam 1 energy in GeV
 6500  = ebeam2  ! beam 2 energy in GeV
#*********************************************************************
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.
#*********************************************************************
 nn23nlo   = pdlabel   ! PDF set
 230000    = lhaid     ! if pdlabel=lhapdf, this is the lhapdf number
#*********************************************************************
# Include the NLO Monte Carlo subtr. terms for the following parton
# shower (HERWIG6 | HERWIGPP | PYTHIA6Q | PYTHIA6PT | PYTHIA8)
# WARNING: PYTHIA6PT works only for processes without FSR!!!!
#*********************************************************************
  HERWIG6    = parton_shower
```

Total cross sections for mono-j at LHC13

(m_Y, m_X) [GeV]			MET > 150 GeV	MET > 300 GeV
$(100, 1)$	$m_Y > 2m_X$	$\sigma_{\rm LO}$ [pb] $\sigma_{\rm NLO}$ [pb] K factor	$1.100 \times 10^2\,^{+10.6}_{-9.3} \pm 1.5\,\%$ $1.530 \times 10^2\,^{+6.5}_{-5.7} \pm 0.5\,\%$ 1.39	$0.822 \times 10^1\,^{+14.4}_{-12.0} \pm 1.1\,\%$ $1.100 \times 10^1\,^{+7.4}_{-7.2} \pm 0.6\,\%$ 1.34
			$10^1\,^{+11.0}_{-9.6} \pm 1.5\,\%$ $10^1\,^{+6.0}_{-5.5} \pm 0.5\,\%$	$0.988 \times 10^0\,^{+14.7}_{-12.2} \pm 1.1\,\%$ $1.281 \times 10^0\,^{+6.8}_{-6.8} \pm 0.6\,\%$ 1.30
			$10^{-3}\,^{+17.4}_{-14.0} \pm 4.3\,\%$ $10^{-3}\,^{+5.3}_{-6.4} \pm 2.2\,\%$	$2.329 \times 10^{-3}\,^{+18.9}_{-15.0} \pm 4.6\,\%$ $2.411 \times 10^{-3}\,^{+5.5}_{-6.8} \pm 2.3\,\%$ 1.04

PDF uncertainty

scale (renormalization and factrorization) uncertainty



NLO corrections

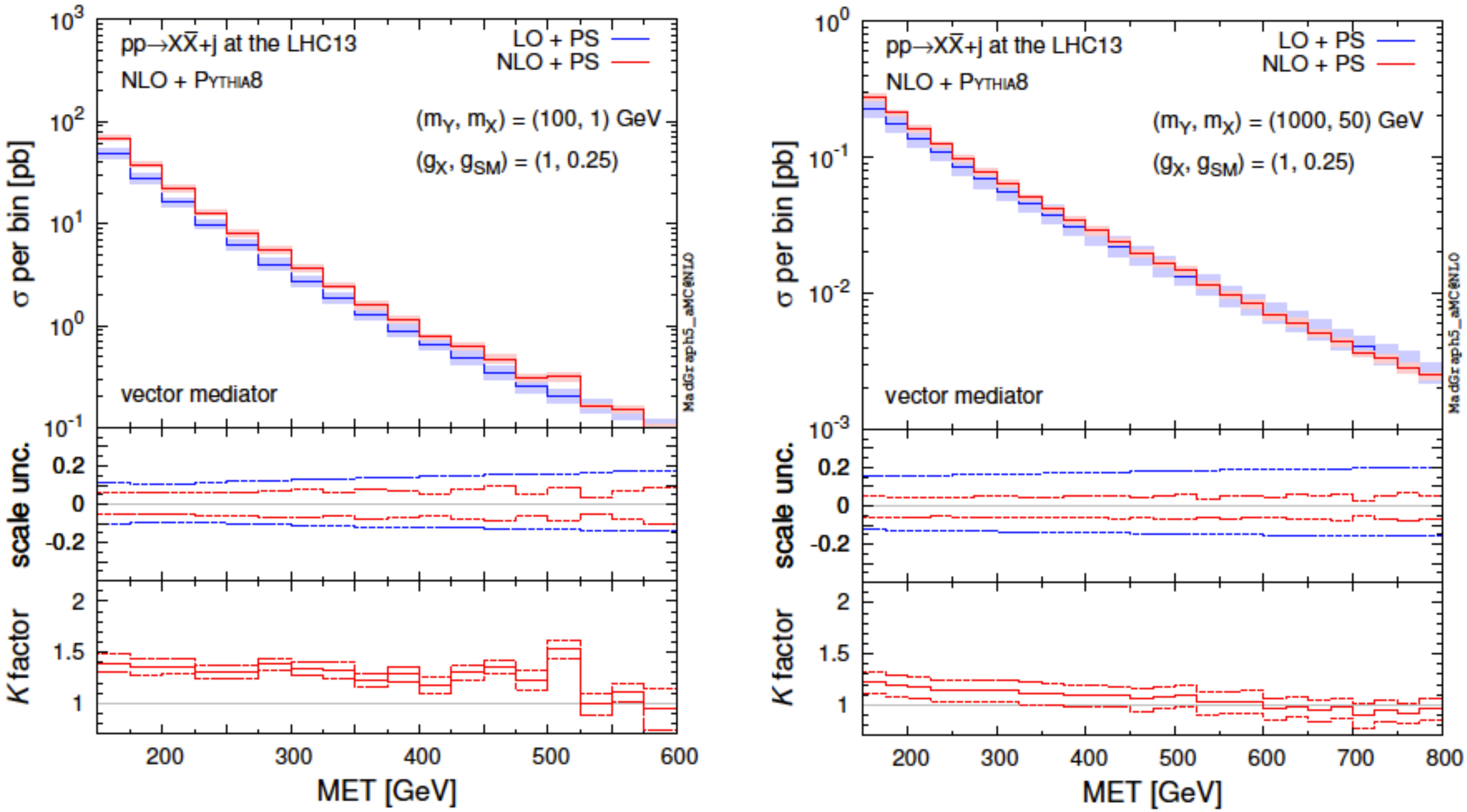
- strongly depends on the mass spectrum and the kinematical cuts.
- sizeably reduces of the scale and PDF uncertainties.

Total cross sections for mono-j at LHC13

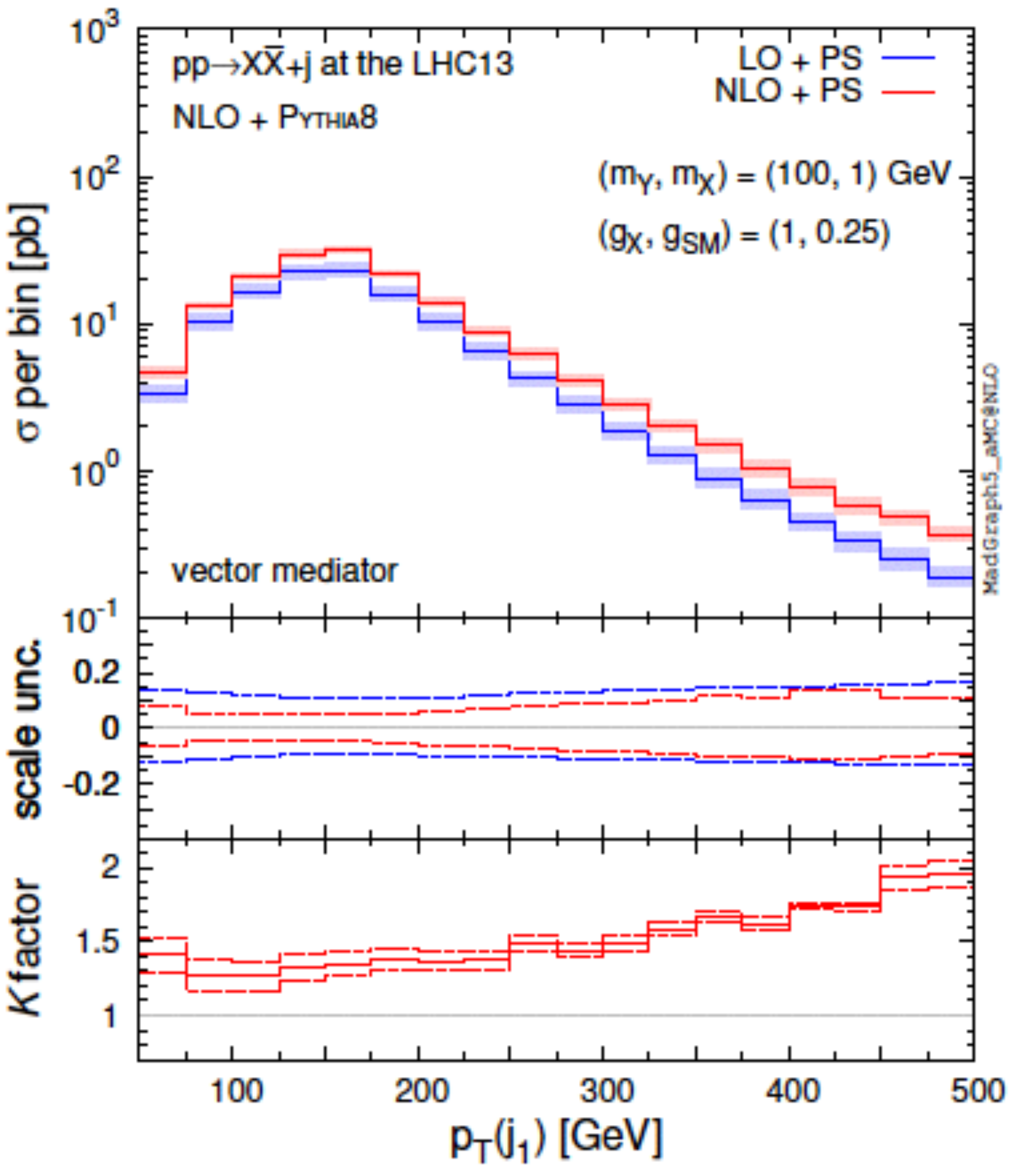
* the axial-vector mediator case

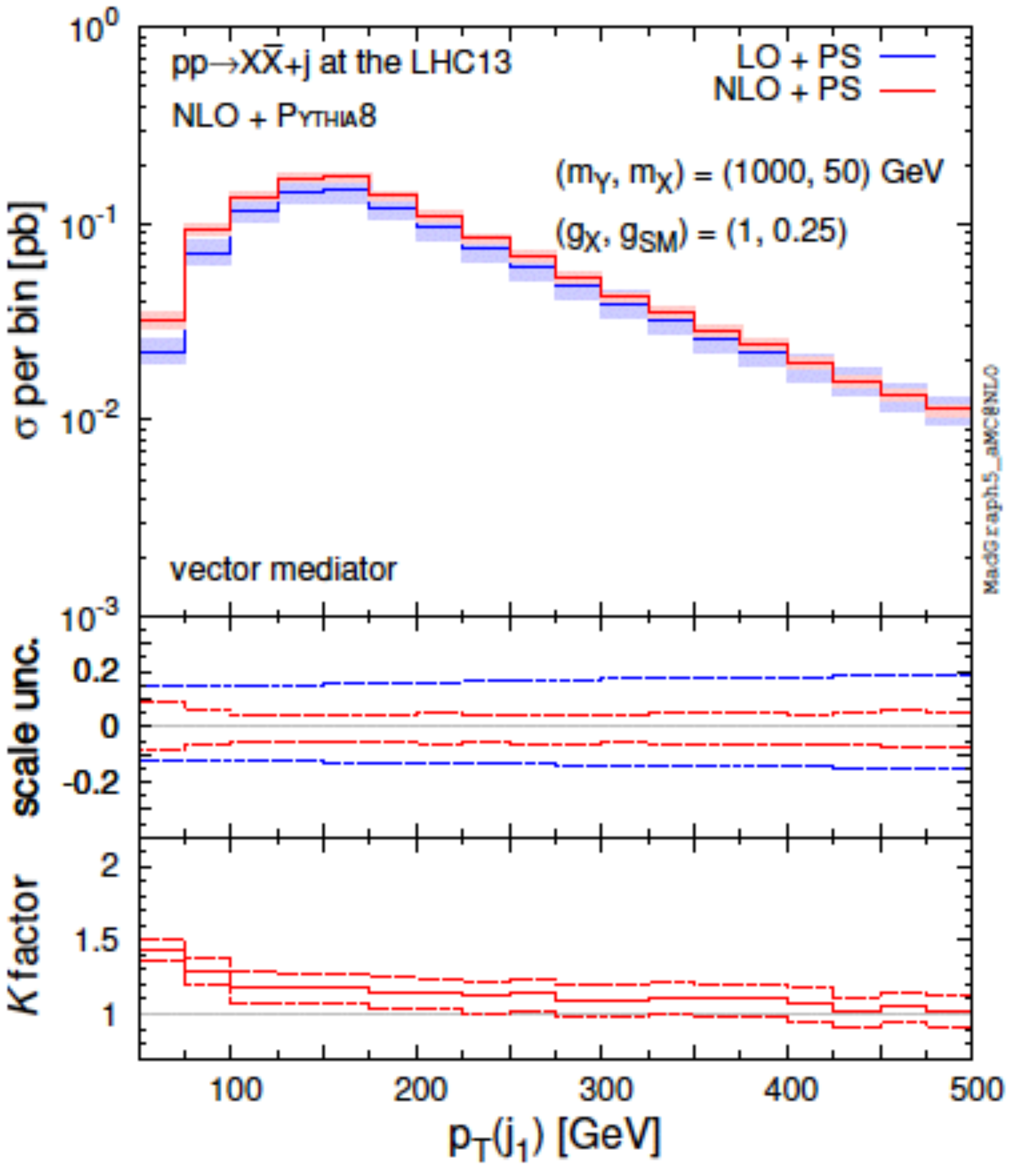
(m_Y, m_X) [GeV]			axial-vector MET > 150 GeV	axial-vector MET > 300 GeV	axial-vector MET > 500 GeV
100	undecayed	$\sigma_{\rm LO}$ [pb]	$2.130 \times 10^2\ ^{+10.6}_{-9.3}\ \pm 1.6\,\%$	$1.573 \times 10^1\ ^{+14.4}_{-12.0}\ \pm 1.1\,\%$	$1.633 \times 10^0\ ^{+17.3}_{-14.0}\ \pm 1.9\,\%$
		$\sigma_{\rm NLO}$ [pb]	$3.063 \times 10^2\ ^{+6.9}_{-6.1}\ \pm 0.5\,\%$	$2.153 \times 10^1\ ^{+7.7}_{-7.4}\ \pm 0.6\,\%$	$2.055 \times 10^0\ ^{+8.4}_{-8.3}\ \pm 1.6\,\%$
		K factor	1.44	1.37	1.26
(100, 1)	$m_Y > 2m_X$	$\sigma_{\rm LO}$ [pb]	$1.101 \times 10^2\ ^{+10.6}_{-9.3}\ \pm 1.6\,\%$	$0.825 \times 10^1\ ^{+14.4}_{-12.1}\ \pm 1.1\,\%$	$0.854 \times 10^0\ ^{+17.4}_{-14.1}\ \pm 2\,\%$
		$\sigma_{\rm NLO}$ [pb]	$1.549 \times 10^2\ ^{+6.8}_{-6.0}\ \pm 0.5\,\%$	$1.127 \times 10^1\ ^{+7.4}_{-7.2}\ \pm 0.6\,\%$	$1.063 \times 10^0\ ^{+8.2}_{-8.2}\ \pm 1.2\,\%$
		K factor	1.41	1.37	1.24
(95, 50)	$m_Y \lesssim 2m_X$	$\sigma_{\rm LO}$ [pb]	$3.070 \times 10^0\ ^{+11.6}_{-10.0}\ \pm 1.5\,\%$	$3.359 \times 10^{-1}\ ^{+14.9}_{-12.4}\ \pm 1.2\,\%$	$4.457 \times 10^{-2}\ ^{+17.7}_{-14.3}\ \pm 1.8\,\%$
		$\sigma_{\rm NLO}$ [pb]	$4.093 \times 10^0\ ^{+6.0}_{-5.7}\ \pm 0.5\,\%$	$4.302 \times 10^{-1}\ ^{+6.7}_{-6.9}\ \pm 0.7\,\%$	$5.079 \times 10^{-2}\ ^{+6.9}_{-7.4}\ \pm 1.3\,\%$
		K factor	1.33	1.28	1.14
(100, 500)	$m_Y < 2m_X$	$\sigma_{\rm LO}$ [pb]	$2.298 \times 10^{-3}\ ^{+18.1}_{-14.5}\ \pm 5\,\%$	$7.839 \times 10^{-4}\ ^{+19.5}_{-15.4}\ \pm 5.3\,\%$	$2.558 \times 10^{-4}\ ^{+21.2}_{-16.5}\ \pm 6.3\,\%$
		$\sigma_{\rm NLO}$ [pb]	$2.502 \times 10^{-3}\ ^{+5.9}_{-6.8}\ \pm 2.5\,\%$	$7.972 \times 10^{-4}\ ^{+6.2}_{-7.3}\ \pm 2.6\,\%$	$2.383 \times 10^{-4}\ ^{+6.1}_{-7.5}\ \pm 3.0\,\%$
		K factor	1.09	1.02	0.93

MET distributions for mono-j at LHC13



$p_T(j_1)$ distributions for mono-j at LHC13



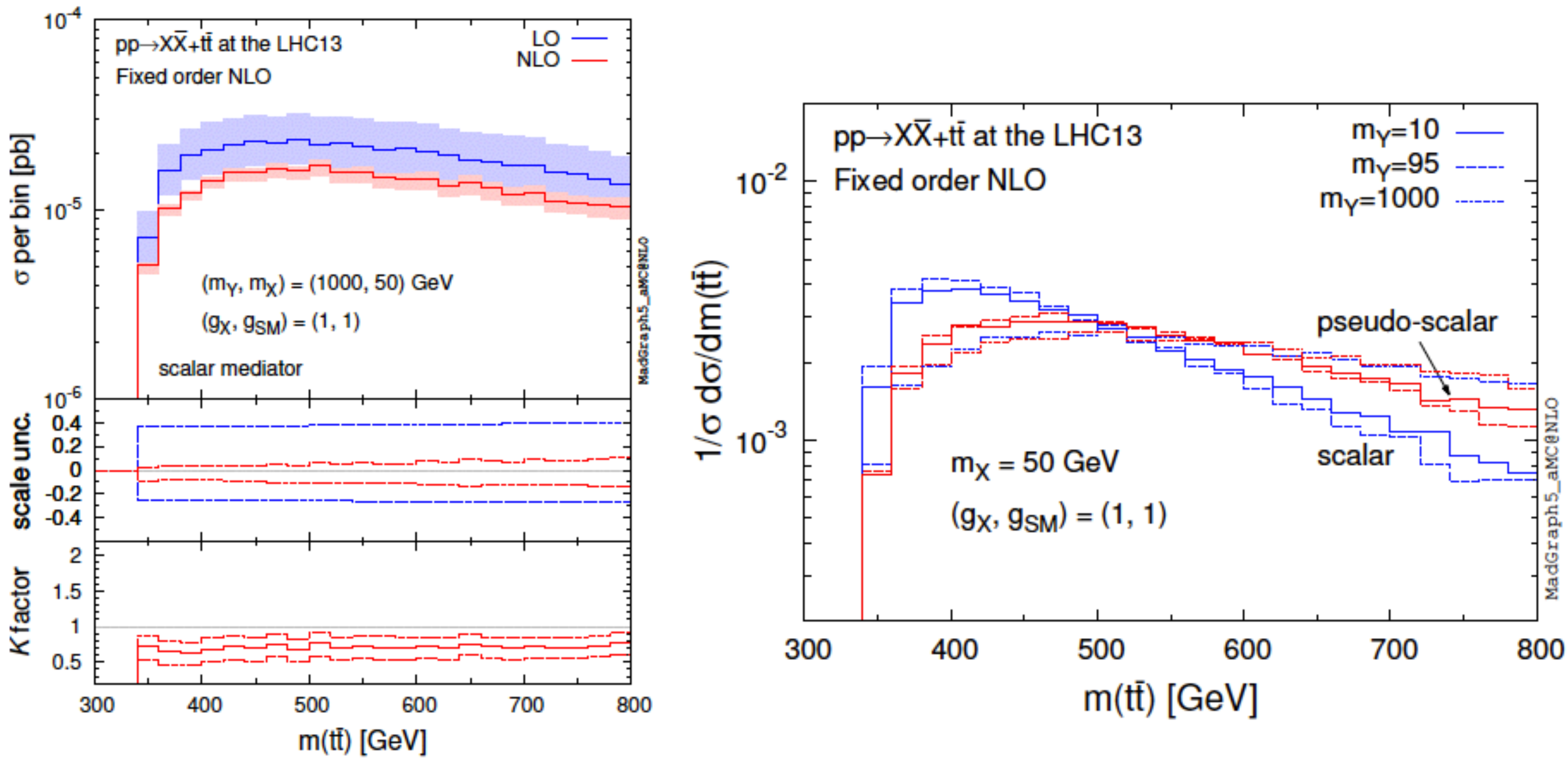


We cannot apply for a constant K factor.

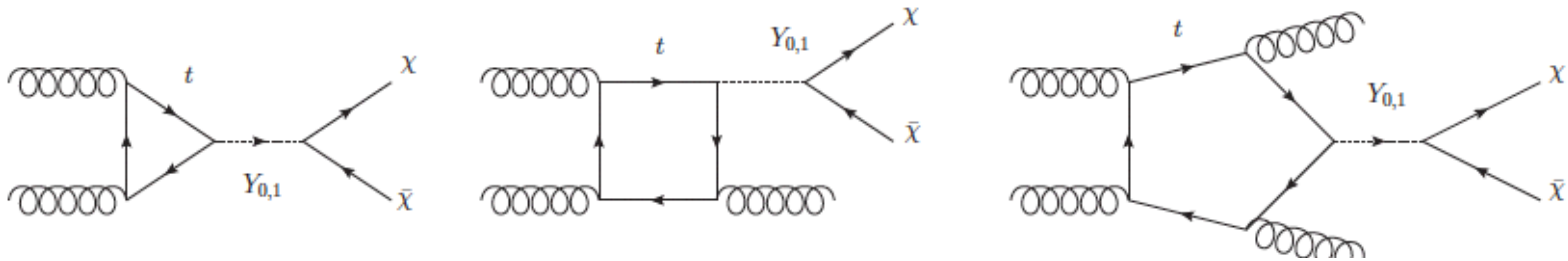
Total cross sections for tt+MET at LHC13

(m_Y, m_X) [GeV]			scalar	pseudo-scalar
10	undecayed	$\sigma_{\rm LO}$ [pb]	$2.278 \times 10^{1}\,{}^{+28.0}_{-20.4} \pm 4.2\,\%$	$5.202 \times 10^{-1}\,{}^{+30.8}_{-22.0} \pm 6.0\,\%$
		$\sigma_{\rm NLO}$ [pb]	$2.435 \times 10^{1}\,{}^{+5.4}_{-8.5} \pm 1.8\,\%$	$5.431 \times 10^{-1}\,{}^{+7.4}_{-10.2} \pm 2.6\,\%$
		K factor	1.07	1.04
(10, 1)	$m_Y > 2m_X$	$\sigma_{\rm LO}$ [pb]	$2.294 \times 10^{1}\,{}^{+28.0}_{-20.5} \pm 4.2\,\%$	$5.500 \times 10^{-1}\,{}^{+30.8}_{-22.1} \pm 6.0\,\%$
		$\sigma_{\rm NLO}$ [pb]	$2.460 \times 10^{1}\,{}^{+5.4}_{-8.5} \pm 1.8\,\%$	$5.739 \times 10^{-1}\,{}^{+7.4}_{-10.2} \pm 2.6\,\%$
		K factor	1.07	1.04
(10, 50)	$m_Y < 2m_X$	$\sigma_{\rm LO}$ [pb]	$2.415 \times 10^{-3}\,{}^{+30.5}_{-21.8} \pm 5.8\,\%$	$3.329 \times 10^{-3}\,{}^{+33.9}_{-23.8} \pm 8.7\,\%$
		$\sigma_{\rm NLO}$ [pb]	$2.340 \times 10^{-3}\,{}^{+5.8}_{-9.1} \pm 2.8\,\%$	$3.133 \times 10^{-3}\,{}^{+7.5}_{-11.0} \pm 3.9\,\%$
		K factor	0.97	0.94
100	undecayed	$\sigma_{\rm LO}$ [pb]	$8.226 \times 10^{-1}\,{}^{+28.7}_{-20.9} \pm 4.4\,\%$	$2.442 \times 10^{-1}\,{}^{+32.2}_{-22.9} \pm 7.2\,\%$
		$\sigma_{\rm NLO}$ [pb]	$8.391 \times 10^{-1}\,{}^{+5.3}_{-8.6} \pm 2.1\,\%$	$2.431 \times 10^{-1}\,{}^{+7.6}_{-10.7} \pm 3.2\,\%$
		K factor	1.02	1.00
(100, 1)	$m_Y > 2m_X$	$\sigma_{\rm LO}$ [pb]	$8.135 \times 10^{-1}\,{}^{+28.8}_{-20.9} \pm 4.4\,\%$	$2.464 \times 10^{-1}\,{}^{+32.4}_{-23.0} \pm 7.2\,\%$
		$\sigma_{\rm NLO}$ [pb]	$8.207 \times 10^{-1}\,{}^{+4.8}_{-8.3} \pm 2.1\,\%$	$2.427 \times 10^{-1}\,{}^{+7.0}_{-10.4} \pm 3.2\,\%$
		K factor	1.01	0.98
(95, 50)	$m_Y \lesssim 2m_X$	$\sigma_{\rm LO}$ [pb]	$7.986 \times 10^{-3}\,{}^{+29.5}_{-21.3} \pm 5.0\,\%$	$1.404 \times 10^{-2}\,{}^{+32.9}_{-23.3} \pm 7.8\,\%$
		$\sigma_{\rm NLO}$ [pb]	$7.897 \times 10^{-3}\,{}^{+5.5}_{-8.8} \pm 2.4\,\%$	$1.362 \times 10^{-2}\,{}^{+7.4}_{-10.8} \pm 3.5\,\%$
		K factor	0.99	0.97
1000	undecayed	$\sigma_{\rm LO}$ [pb]	$1.571 \times 10^{-3}\,{}^{+40.2}_{-27.0} \pm 17.1\,\%$	$1.827 \times 10^{-3}\,{}^{+40.4}_{-27.1} \pm 17.4\,\%$
		$\sigma_{\rm NLO}$ [pb]	$1.127 \times 10^{-3}\,{}^{+10.9}_{-13.6} \pm 8.7\,\%$	$1.297 \times 10^{-3}\,{}^{+10.8}_{-13.7} \pm 8.8\,\%$
		K factor	0.72	0.71
(1000, 1)	$m_Y > 2m_X$	$\sigma_{\rm LO}$ [pb]	$7.499 \times 10^{-4}\,{}^{+40.8}_{-27.2} \pm 16.8\,\%$	$8.174 \times 10^{-4}\,{}^{+40.9}_{-27.3} \pm 17.0\,\%$
		$\sigma_{\rm NLO}$ [pb]	$5.201 \times 10^{-4}\,{}^{+8.4}_{-12.7} \pm 8.4\,\%$	$5.675 \times 10^{-4}\,{}^{+8.6}_{-12.9} \pm 8.5\,\%$
		K factor	0.69	0.69
(1000, 50)	$m_Y > 2m_X$	$\sigma_{\rm LO}$ [pb]	$7.354 \times 10^{-4}\,{}^{+40.7}_{-27.2} \pm 16.8\,\%$	$8.137 \times 10^{-4}\,{}^{+41.0}_{-27.3} \pm 17.0\,\%$
		$\sigma_{\rm NLO}$ [pb]	$5.125 \times 10^{-4}\,{}^{+8.6}_{-12.8} \pm 8.5\,\%$	$5.595 \times 10^{-4}\,{}^{+8.3}_{-12.7} \pm 8.5\,\%$
		K factor	0.69	0.69

m(tt) distributions for tt+MET at LHC13



Loop-induced mono-j at LHC13



Benchmark	Scalar		Pseudoscalar	
Jet p_T cut in GeV	50	200	50	200
Resonant	$4.11\ ^{+49\%\ +0.8\%}_{-31\%\ -0.9\%}$	$0.244\ ^{+50\%\ +1.1\%}_{-31\%\ -1.1\%}$	$10.1\ ^{+49\%\ +0.8\%}_{-31\%\ -0.9\%}$	$0.584\ ^{+50\%\ +1.1\%}_{-31\%\ -1.1\%}$
Heavy mediator	$3.22 \cdot 10^{-2}\ ^{+55\%\ +1.7\%}_{-33\%\ -1.7\%}$	$4.92 \cdot 10^{-3}\ ^{+55\%\ +1.8\%}_{-33\%\ -1.8\%}$	$4.23 \cdot 10^{-2}\ ^{+55\%\ +1.6\%}_{-33\%\ -1.6\%}$	$6.47 \cdot 10^{-3}\ ^{+54\%\ +1.8\%}_{-33\%\ -1.8\%}$
Heavy DM	$4.33 \cdot 10^{-5}\ ^{+55\%\ +2.2\%}_{-33\%\ -2.1\%}$	$8.54 \cdot 10^{-6}\ ^{+55\%\ +2.3\%}_{-33\%\ -2.2\%}$	$1.73 \cdot 10^{-4}\ ^{+54\%\ +2.0\%}_{-33\%\ -2.0\%}$	$3.35 \cdot 10^{-5}\ ^{+54\%\ +2.1\%}_{-33\%\ -2.1\%}$