Dark matter study from Lagrangian to data

in the FeynRules/MadGraph5_aMC@NLO framework

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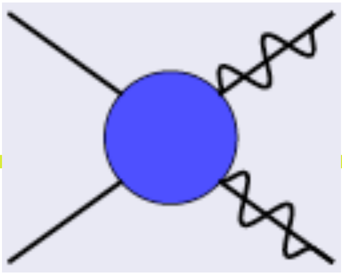
Laboratoire de Physique Subatomique et de Cosmologie



Contents

Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen [1508.05327] by M. Mangano

First open meeting of the LHC Dark Matter WG

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

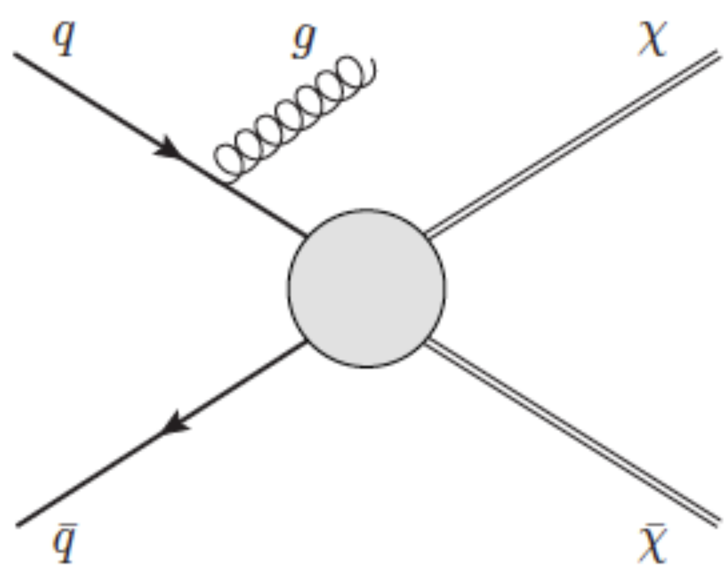
- brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC.
- develops and promotes well-defined signal models, specifying the assumptions 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.

Mono-X 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)



Mono-X DM searches at LHC Run-I

ATLAS 1502.01518

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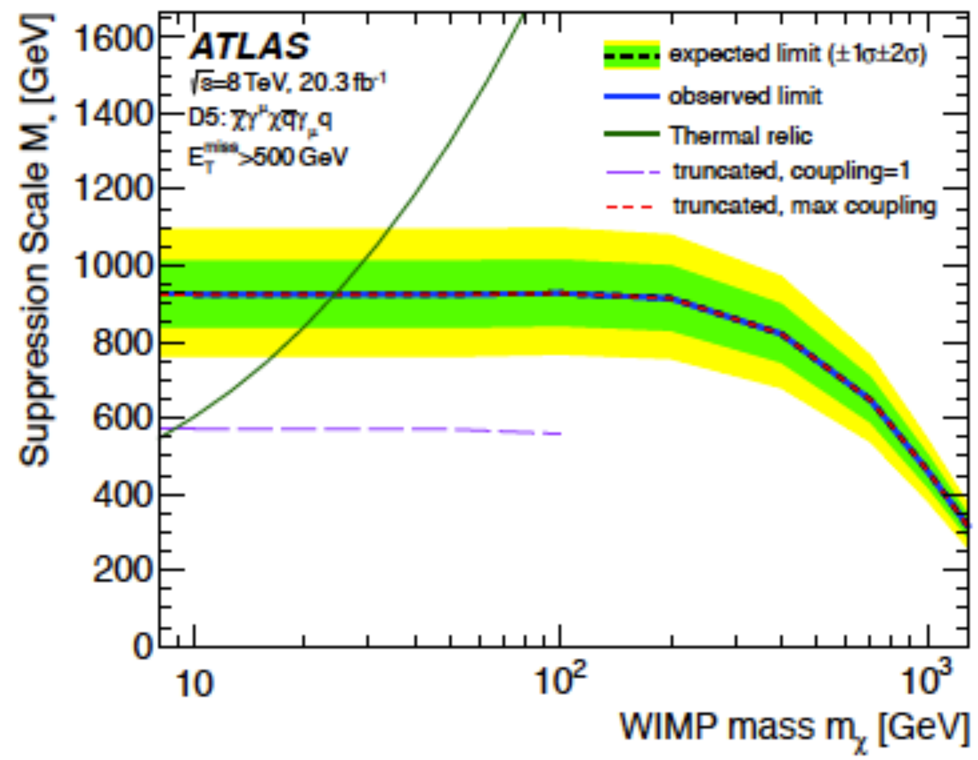
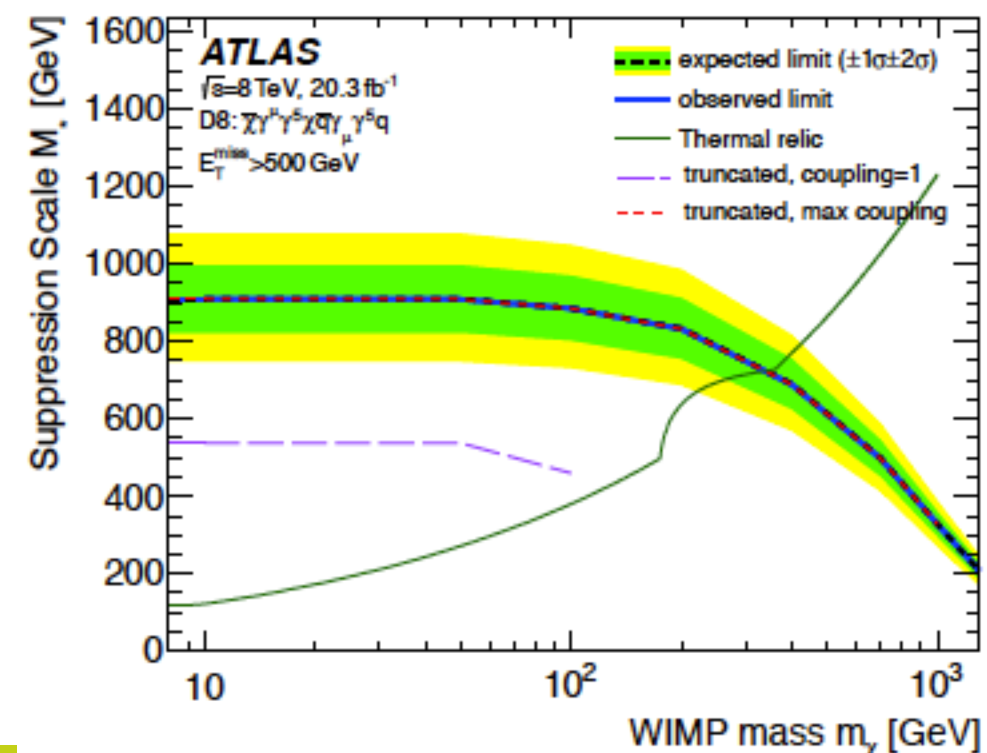
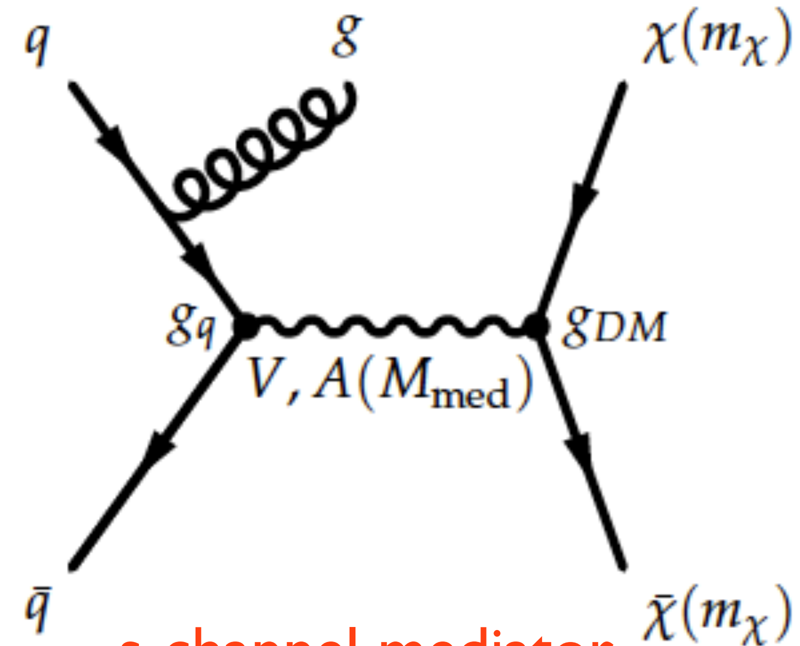




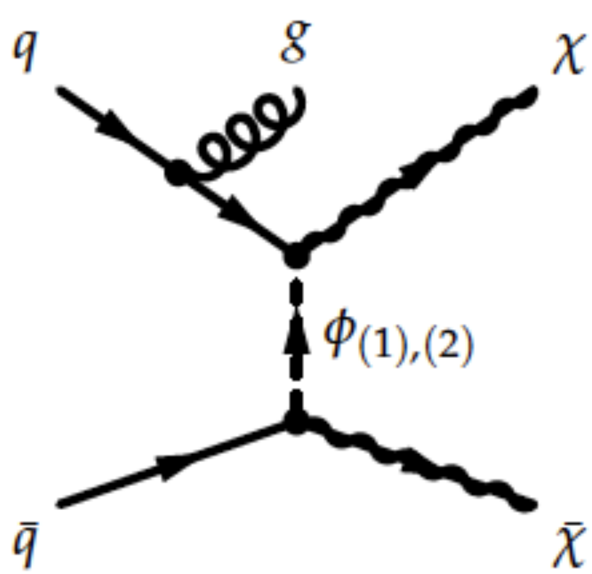
Mono-X DM searches at LHC Run-II

LHC DM WG 1507.00966

- 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.



s-channel mediator



t-channel mediator

Mono-X DM searches at LHC Run-II

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- $$\mathcal{L}_{\text{vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$
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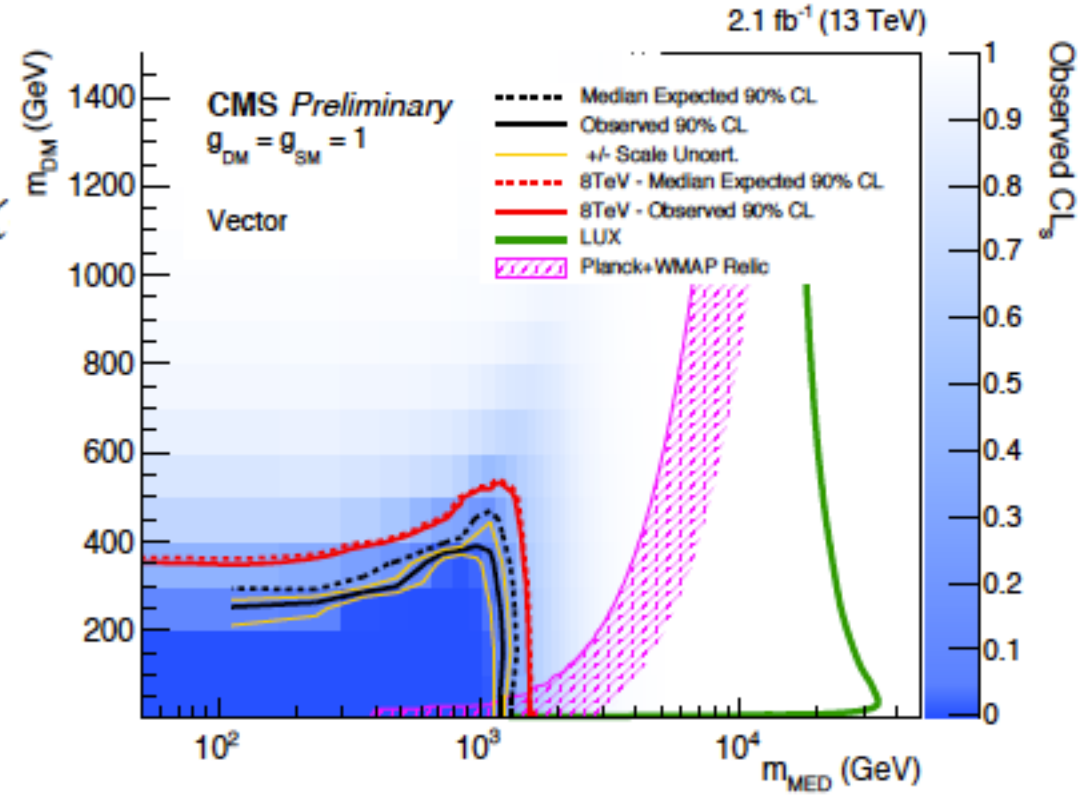
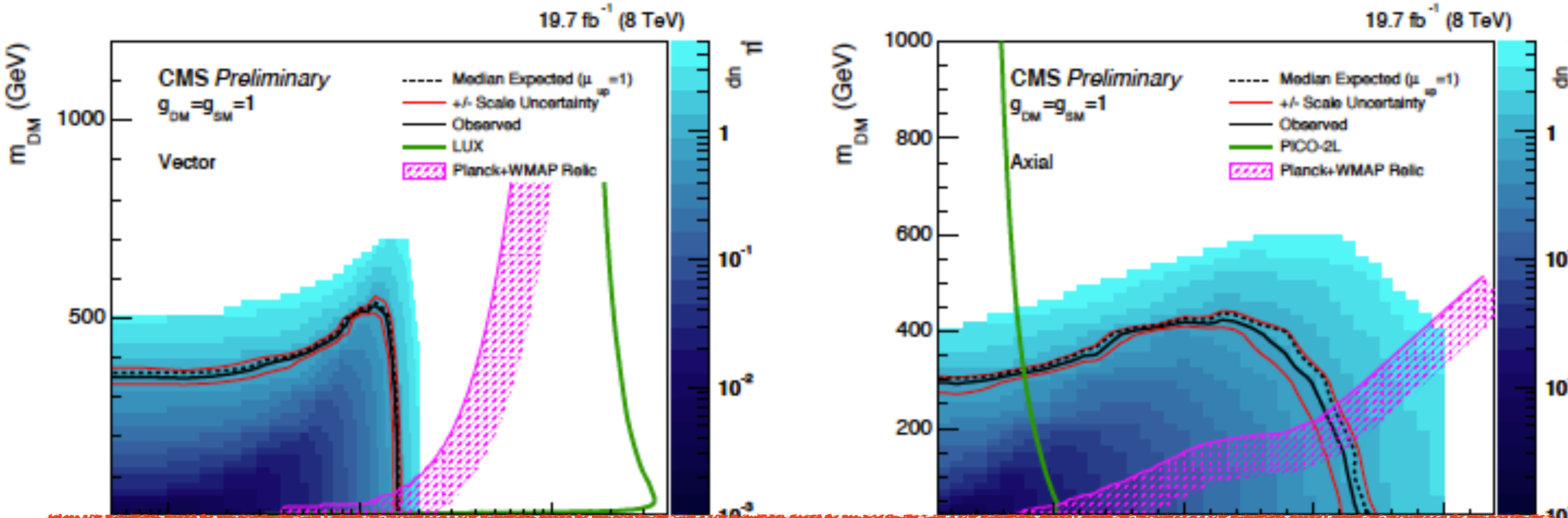
CMS PAS EXO-15-003

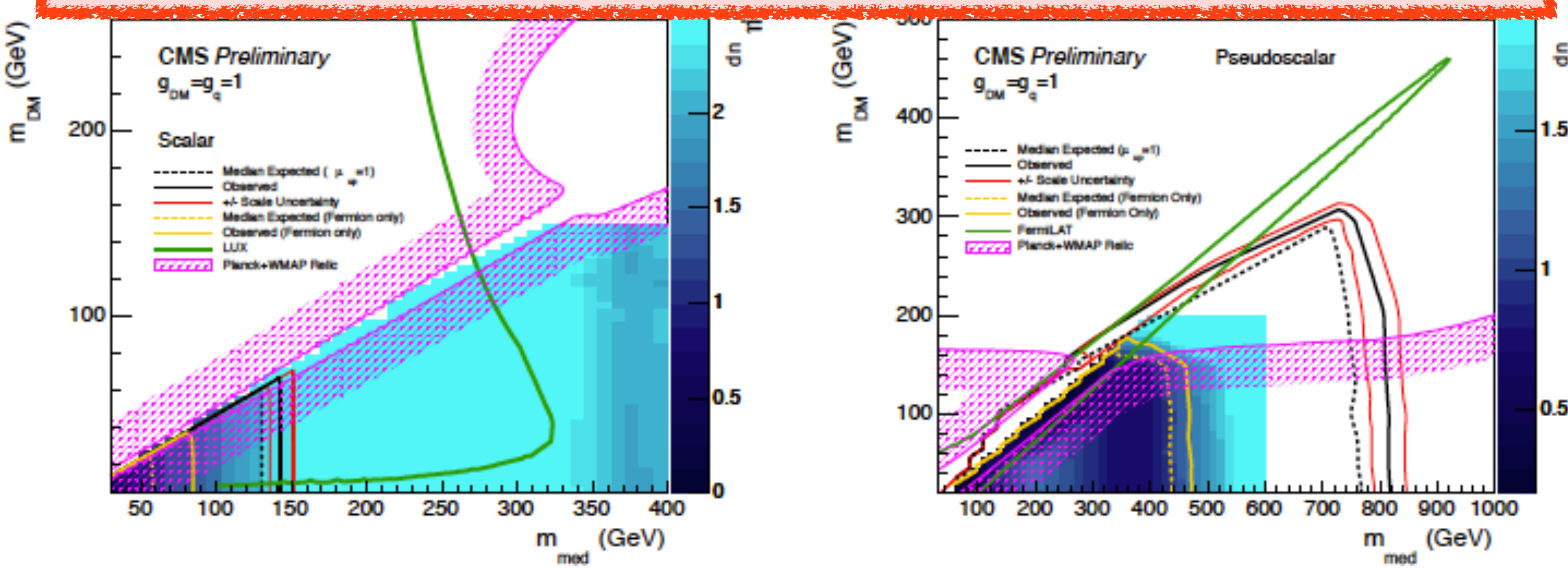


DM searches at the LHC and (in)direct experiments

CMS PAS EXO-12-055



How can we test our own DM models?

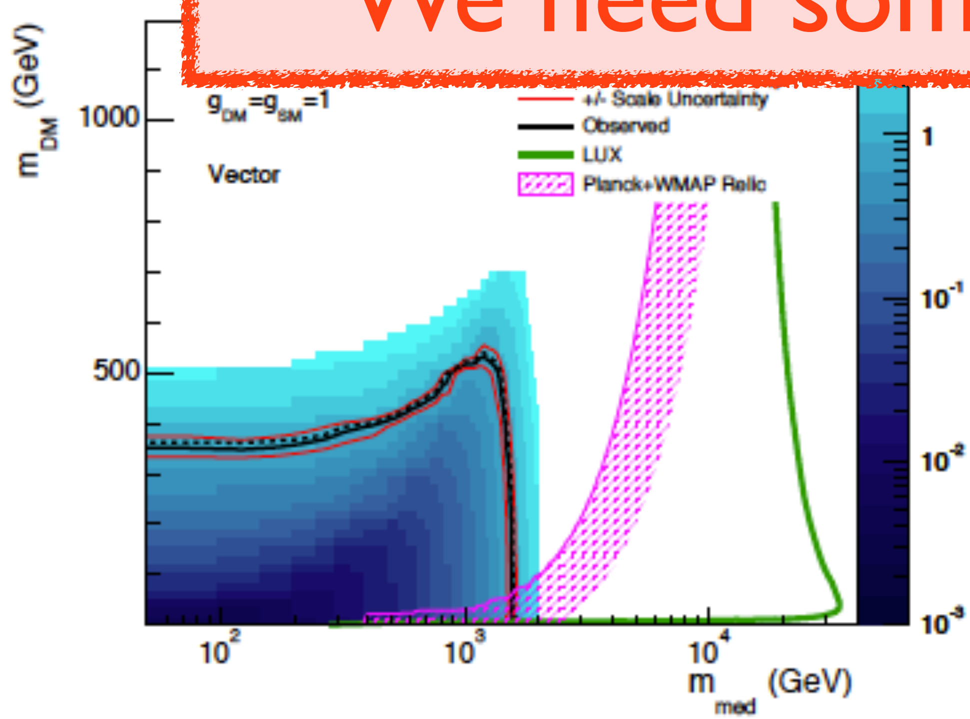


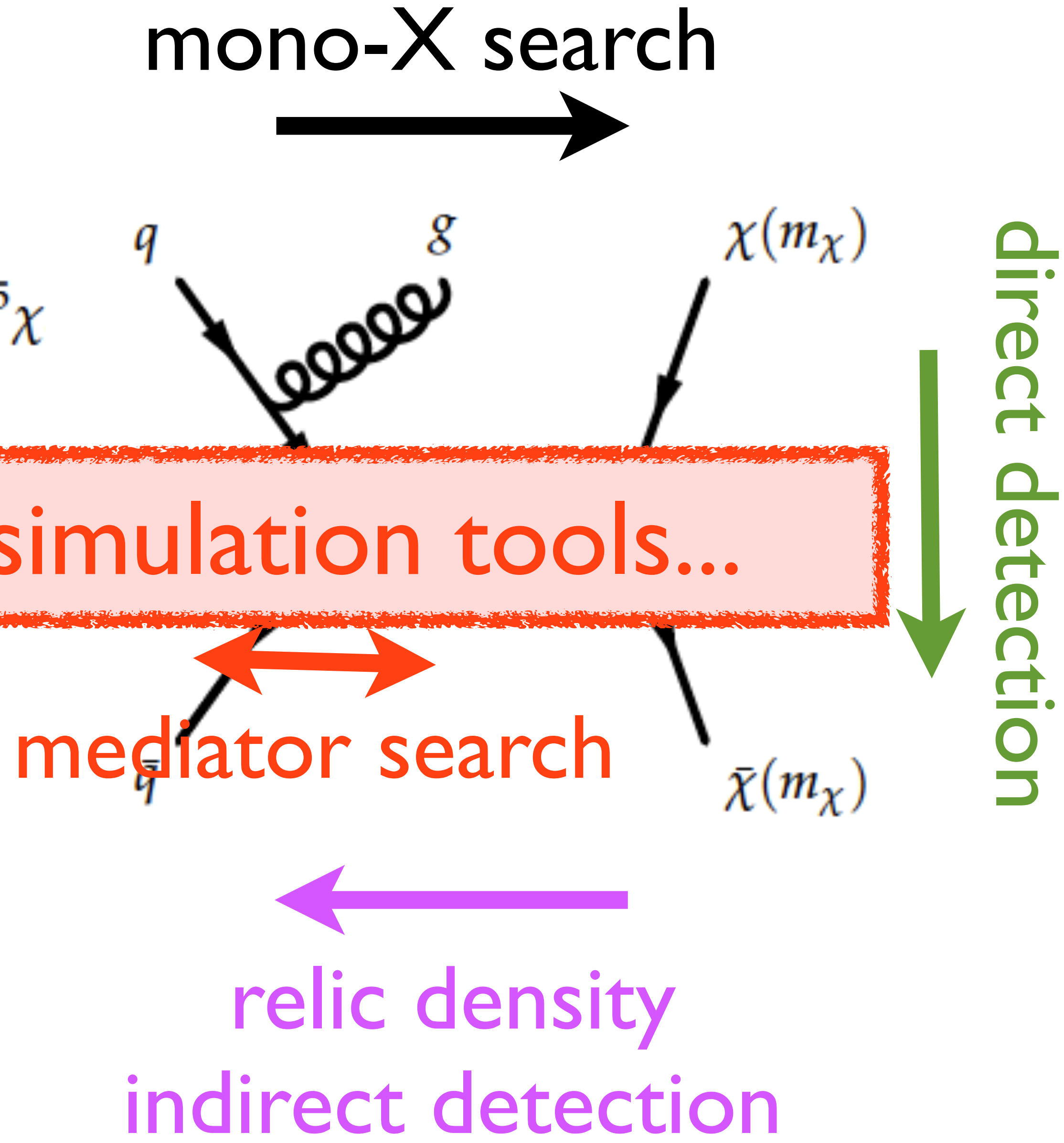
How can we test our own DM models?

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

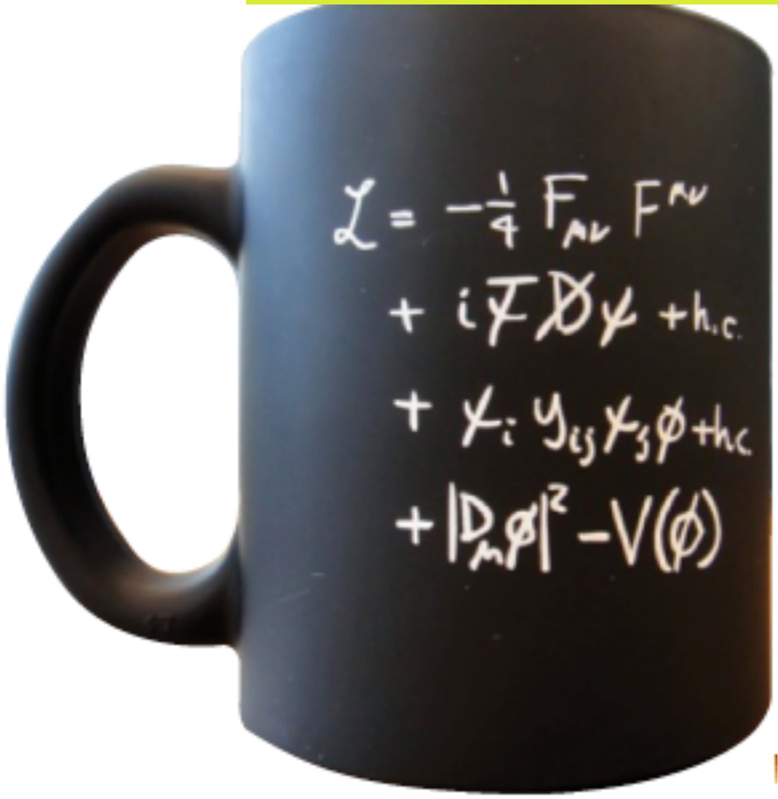
$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

We need some simulation tools...





Simulation chain: from Lagrangian to data



model provider
(FeynRules/...)

model files

DM tools
(MadDM/micrOMEGAs/...)

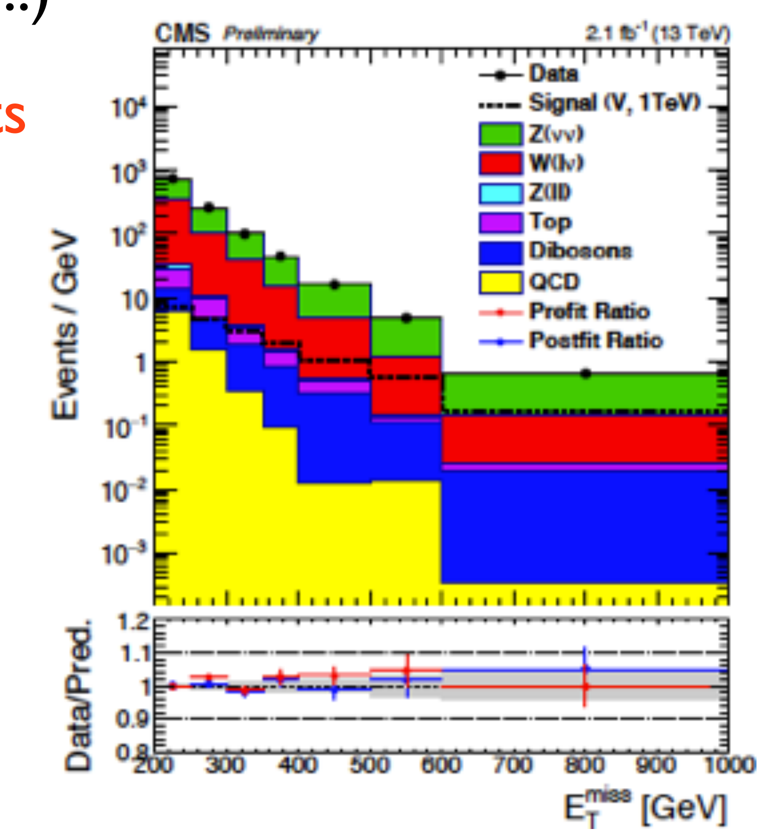
event generator
(MadGraph5_aMC@NLO/Pythia/Herwig/...)

hadron-level events

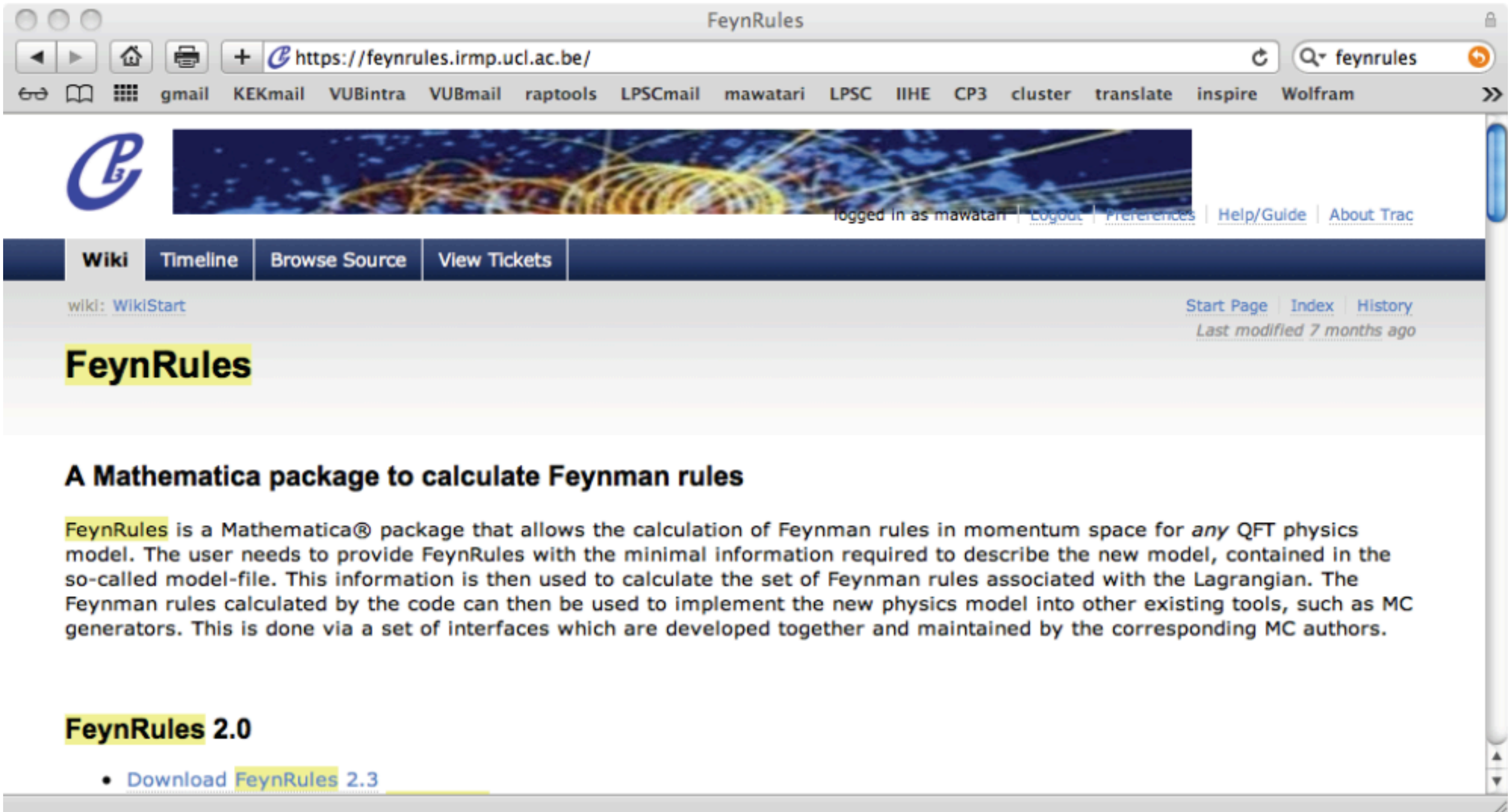
detector simulation
(Delphes/...)

reco-level events

analysis
(MadAnalysis5/CheckMate/...)



Alloul, Christensen, Degrande, Duhr, Fuks [1310.1921]



NLOModels – FeynRules

https://feynrules.irmp.ucl.ac.be/wiki/NLOModels

gmail KEKmail VUBintra VUBmail raptools LPSCmail mawatari LPSC IIHE CP3 cluster translate inspire Wolfram

FeynRules models to be used for NLO calculations with aMC@NLO

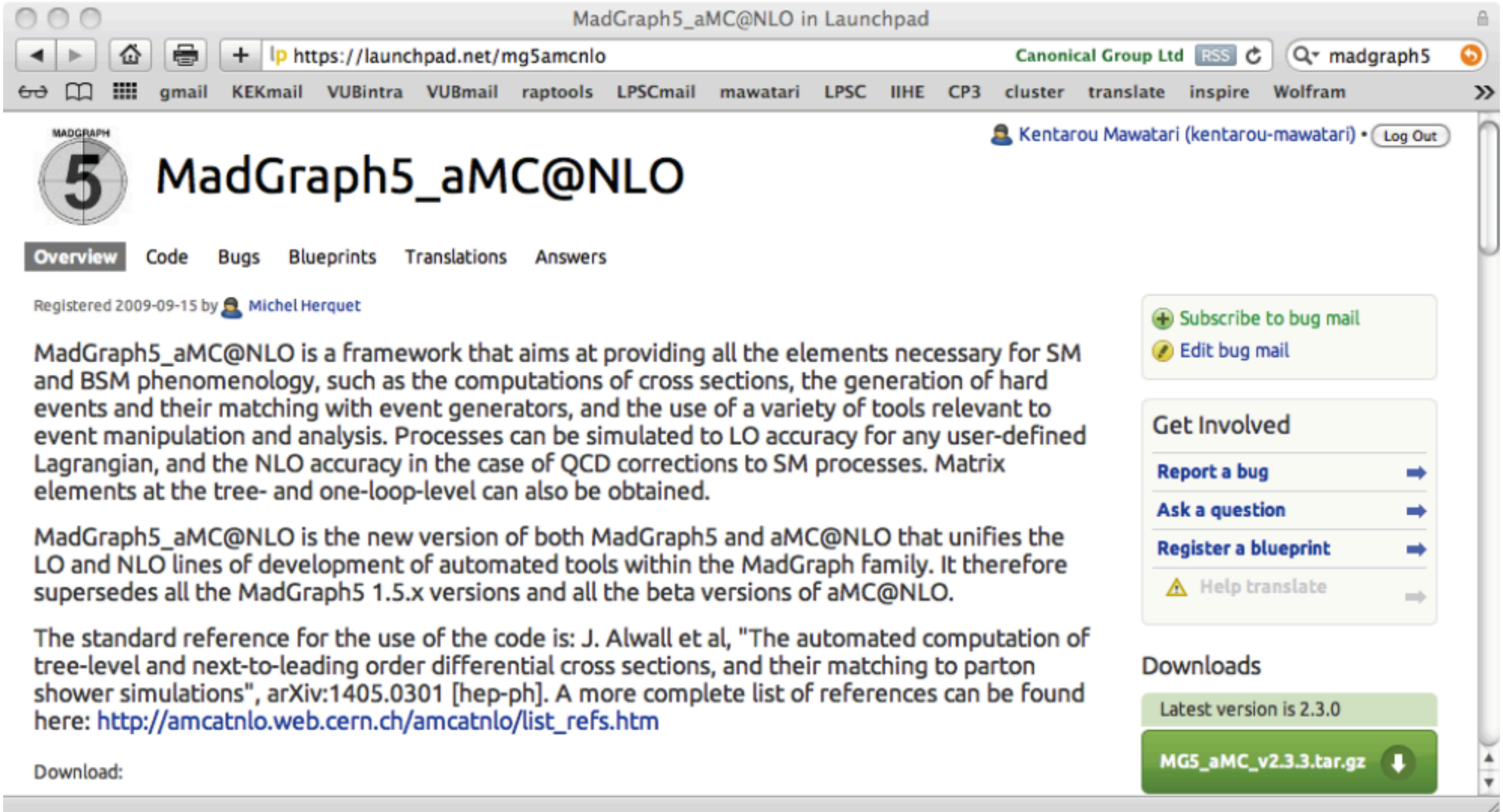
This page contains a collection of models that have been implemented in FeynRules in the context of NLO calculations in the framework of aMC@NLO. It contains up to now simplified models inspired by the current searches undertaken by ATLAS and CMS, as well as a model developed to characterise the properties of the recently discovered Higgs boson. For each model:

- we include a brief description of the relevant signature,
- we provide the FeynRules model files as well as the UFO library to be used with MadGraph5_aMC@NLO,
- we indicate reference paper with the documentation on the model, together with the name of the contact person,
- validation figures generated in the framework of each model are provided, so that any user could try to reproduce them to verify their setup.

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089 , arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro [1405.0301]



MadGraph5_aMC@NLO in Launchpad

https://launchpad.net/mg5amcnlo

Canonical Group Ltd RSS

madgraph5

gmail KEKmail VUBintra VUBmail raptools LPSCmail mawatari LPSC IIHE CP3 cluster translate inspire Wolfram

Kentarou Mawatari (kentarou-mawatari) • Log Out

MADGRAPH 5

MadGraph5_aMC@NLO

Overview Code Bugs Blueprints Translations Answers

Registered 2009-09-15 by Michel Herquet

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

MadGraph5_aMC@NLO is the new version of both MadGraph5 and aMC@NLO that unifies the LO and NLO lines of development of automated tools within the MadGraph family. It therefore supersedes all the MadGraph5 1.5.x versions and all the beta versions of aMC@NLO.

The standard reference for the use of the code is: J. Alwall et al, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", arXiv:1405.0301 [hep-ph]. A more complete list of references can be found here: http://amcatnlo.web.cern.ch/amcatnlo/list_refs.htm

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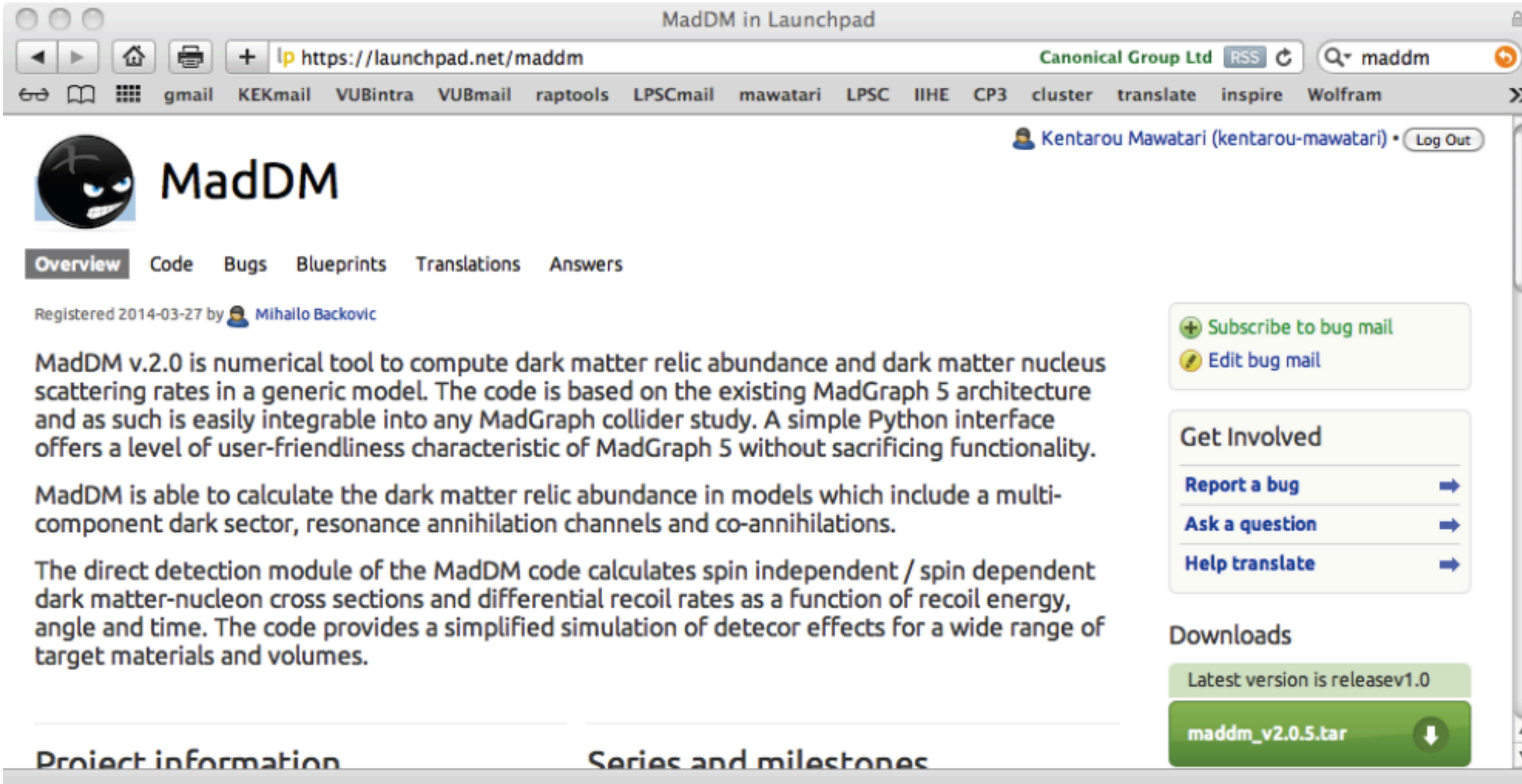
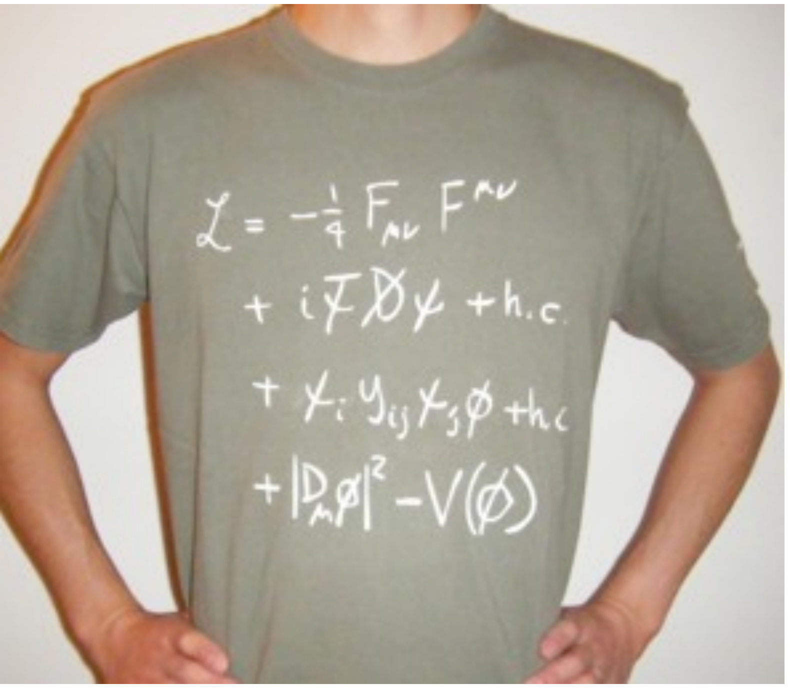
Latest version is 2.3.0

MG5_aMC_v2.3.3.tar.gz

Backovic, Kong, McCaskey, Martini, Mattelaer, Mohlabeng [1308.4955, 1505.04190]



Simulation chain: from Lagrangian to data



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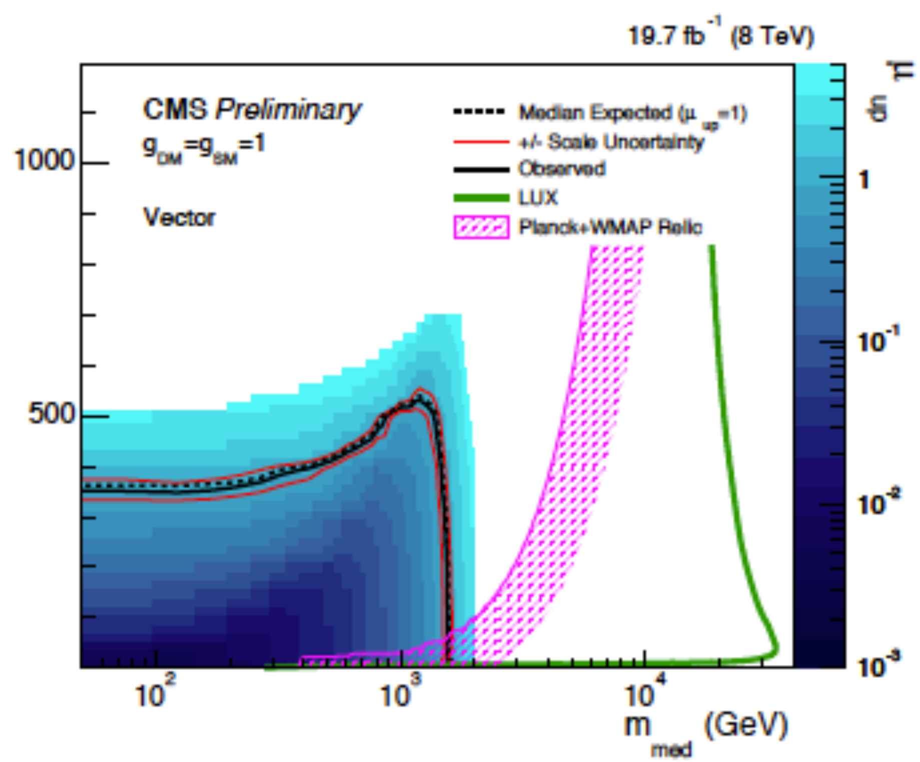
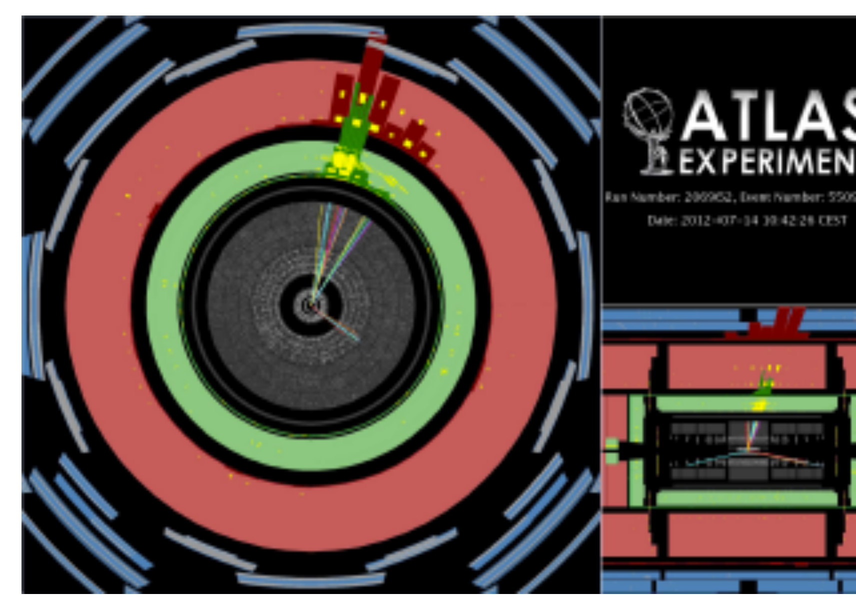




DMsimp collaboration

FeynRules/NLOCT - MG5aMC/MadDM - MadAnalysis

DM simplified model
C. Degrande (Durham)
K. Mawatari (VU Brussel/LPSC Grenoble), C. Zhang (BNL)

j+MET: spin-1 mediator
F. Maltoni, A. Martini (UC Louvain)

tt+MET: spin-0 mediator
M. Kraemer, M. Pellen (Aachen)

W/Z/H+MET
M. Neubert, J. Wang (Mainz)

loop-induced
O. Mattelaer (Durham), E. Vryonidou (UC Louvain)

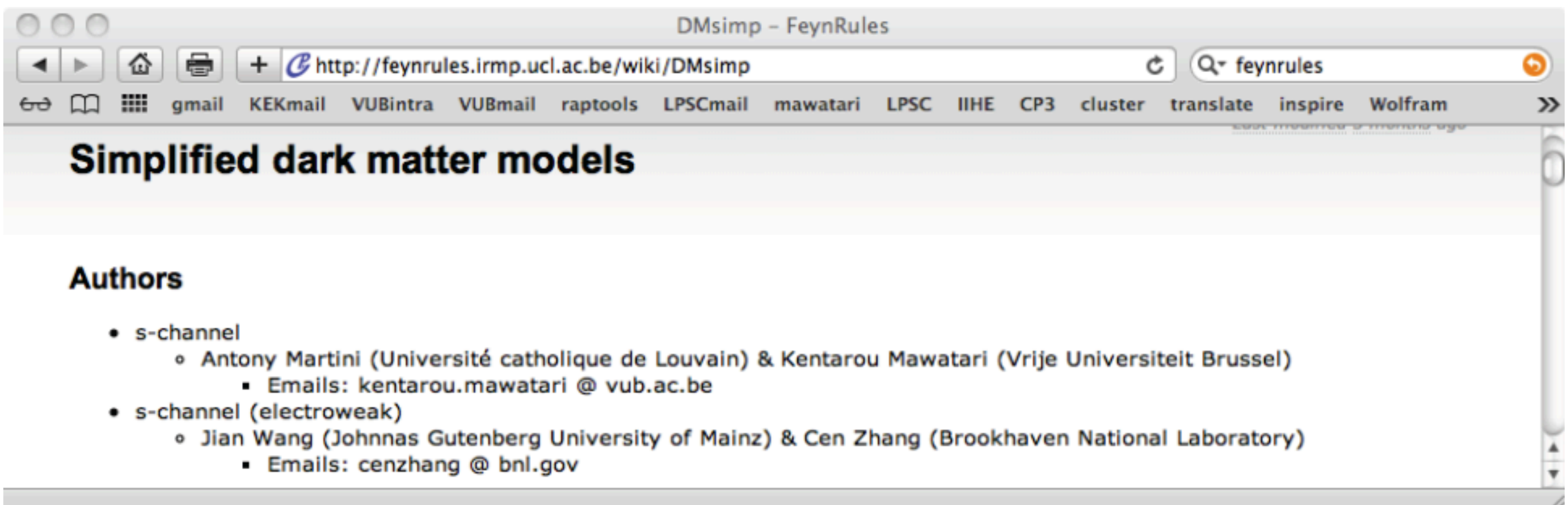
MadDM
C. Arina, M. Backovic, A. Martini (UC Louvain)

Analysis
B. Fuks (Paris)

- "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]

DM simplified models

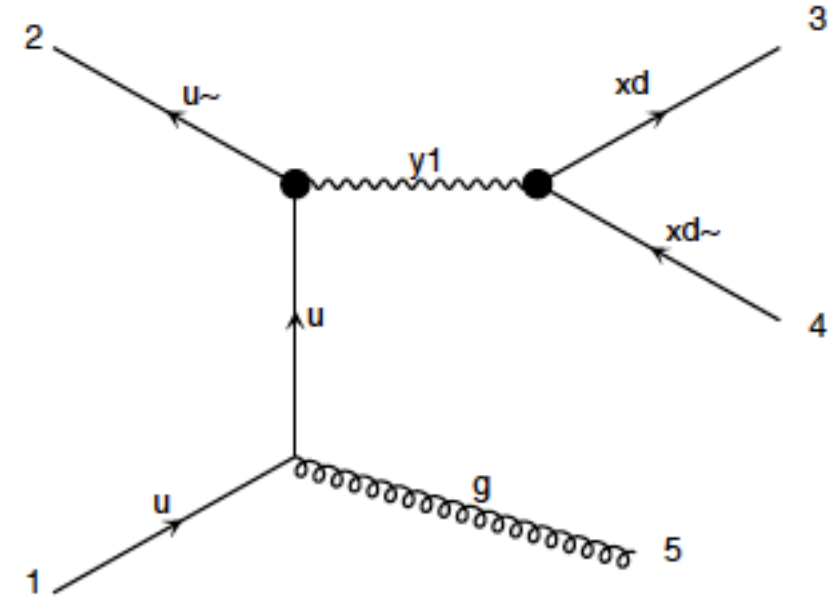
- to provide a public framework to perform AAA (Automatic, Accurate and A...) simulations for DM production (similar to Higgs Characterisation (HC)).
- equally useful for theorists (it can be systematically improved, changed easily) and experimentalists (event generation easily).



DM simplified FR models

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

Mediator (Y):
- spin-0
- spin-1
- spin-2
- ...



1.1 Spin-0 mediator

$$\mathcal{L}_{X_D}^{Y_0} = \frac{1}{2} M_{X_R}\, g^S_{X_R} X_R X_R Y_0 + M_{X_C}\, g^S_{X_C} X_C^* X_C Y_0 + \overline{X}_D (g^S_{X_D} + i g^P_{X_D} \gamma_5) X_D\, Y_0$$

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

1.2 Spin-1 mediator

$$\mathcal{L}_{X_D}^{Y_1} = \frac{i}{2} g^V_{X_C} (X_C^* (\partial_\mu X_C) - (\partial_\mu X_C^*) X_C) Y_1^\mu + \overline{X}_D \gamma_\mu (g^V_{X_D} + i g^A_{X_D} \gamma_5) X_D\, Y_1^\mu$$

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

1-min MadGraph5_aMC@NLO tutorial

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

- Start the MG5_aMC shell
- Import the model
- Generate the process
- 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

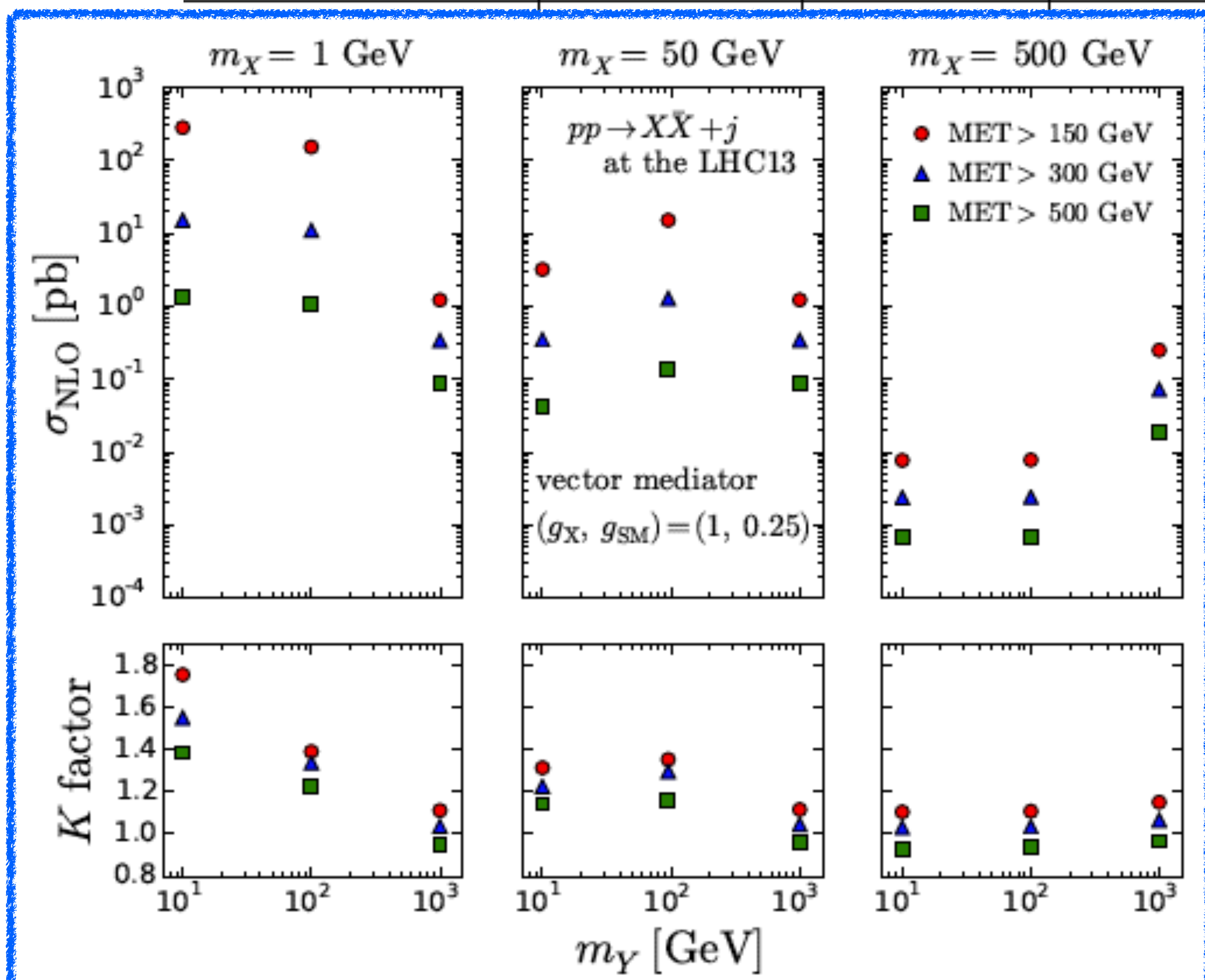
```
#*********************************************************************
# Collider type and energy                                           *
#*********************************************************************
   1   = lpp1    ! beam 1 type (0 = no PDF)
   1   = lpp2    ! beam 2 type (0 = no PDF)
 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

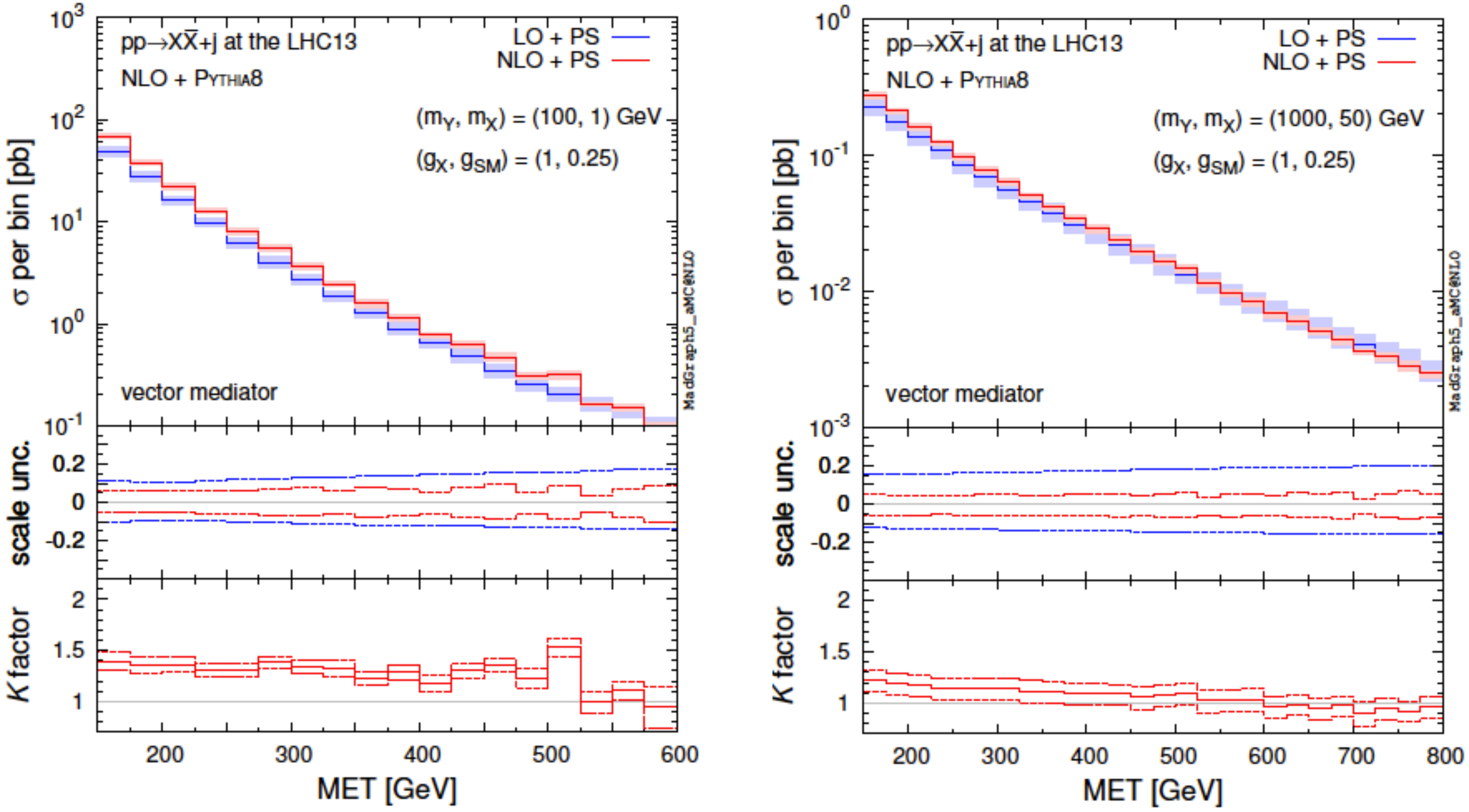
scale (renormalization and factrorization) uncertainty



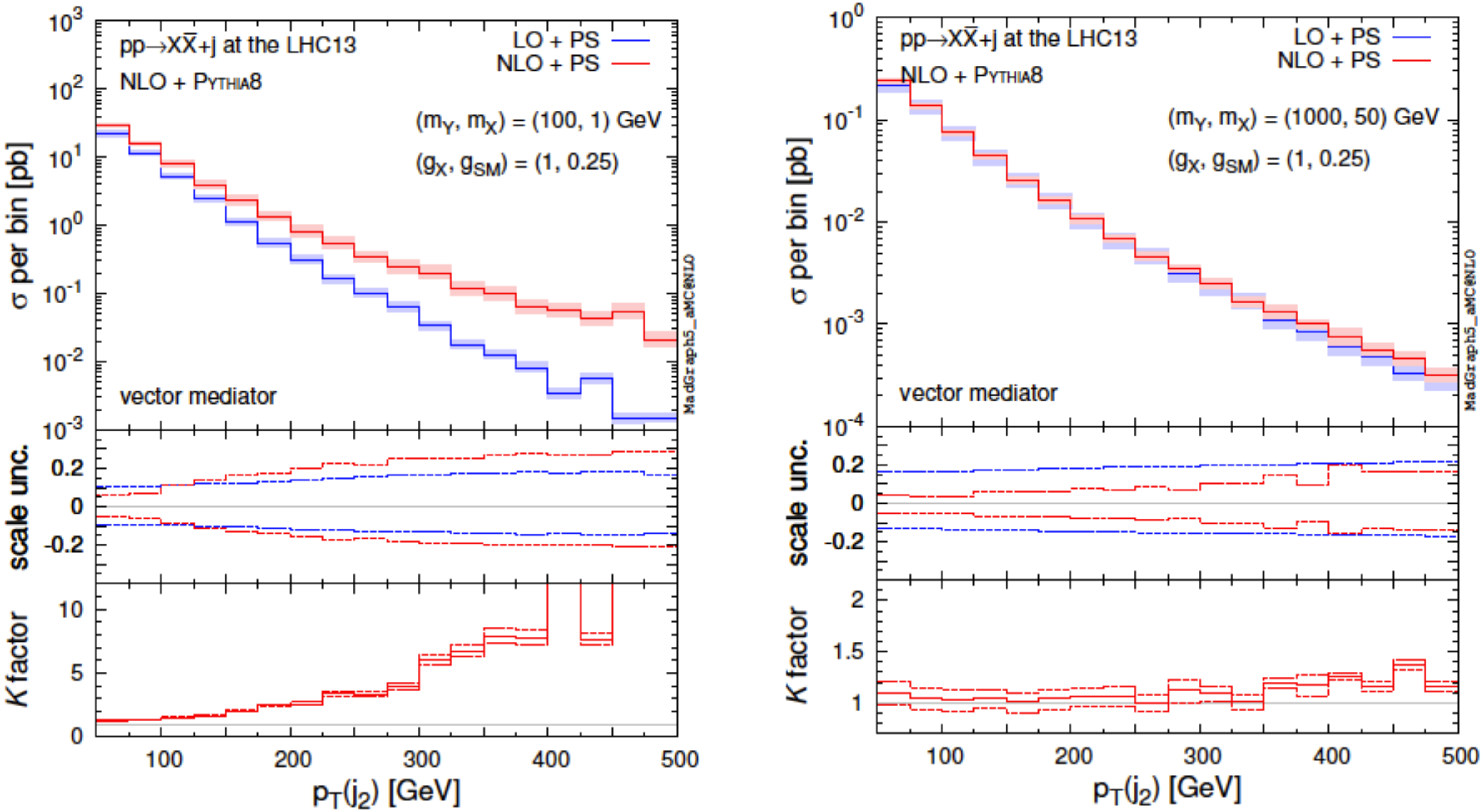
NLO corrections

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

MET distributions for mono-j at LHC13



$p_T(j_2)$ distributions for mono-j at LHC13



Summary

- In this talk we introduced
  - LHC dark matter working group
  - simulation chains from Lagrangian to data at the LHC as well as at non-collider experiments.

- We provide a public framework to perform AAA simulations for DM production in simplified models.
  - Higher-order corrections have a significant effect both on the overall production rate as well as on the shape of relevant differential distributions, with a sizable reduction of the theoretical uncertainties.