QCD tool tutorial
- in the context of DM searches -

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켄타로 마와타리

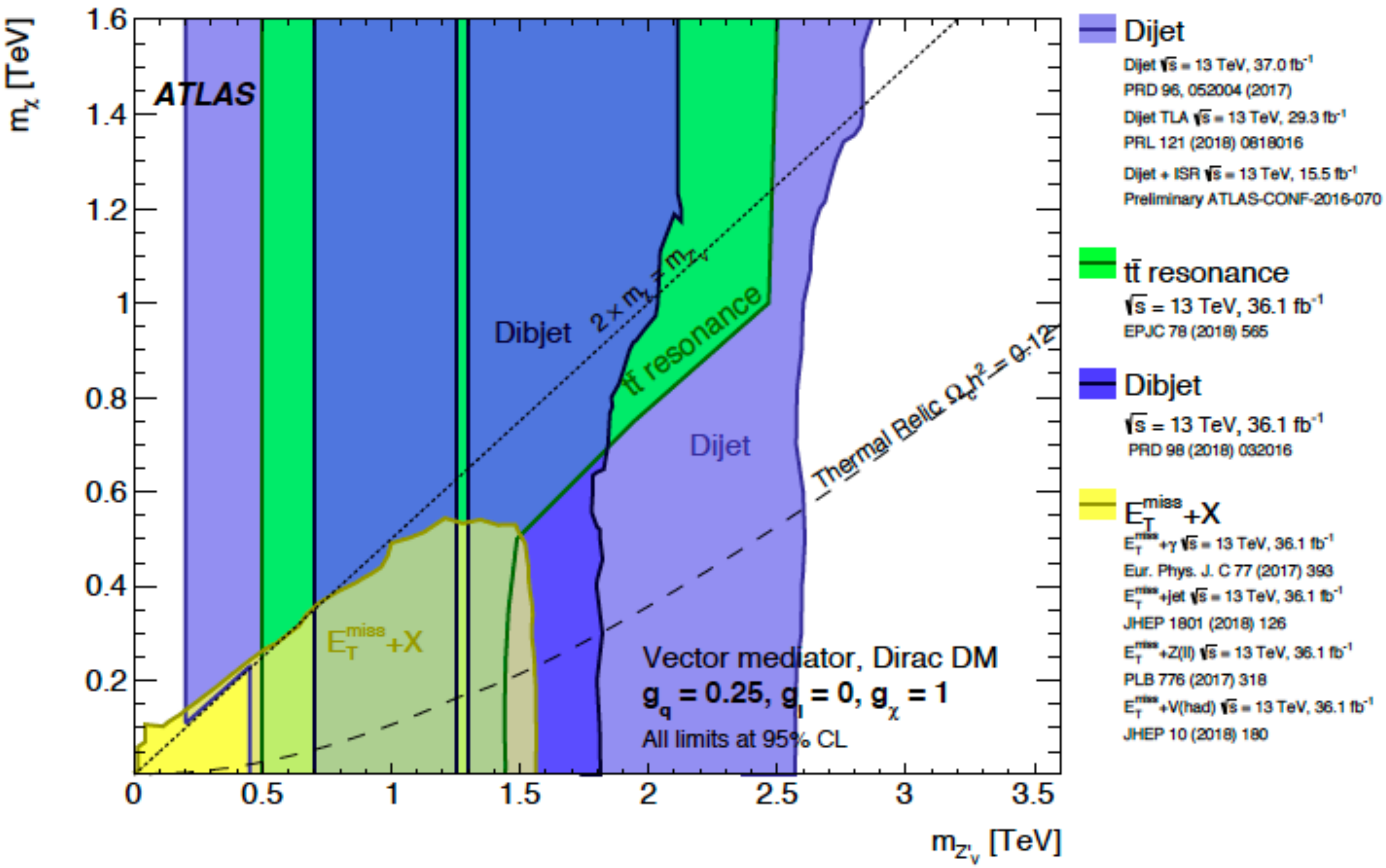
大阪大学
OSAKA UNIVERSITY

<u>disclaimer (Who am I?)</u>

- I'm not a real QCD person, but a (BSM) pheno person…
- I'm a heavy user of MG5aMC, but not a real developer…

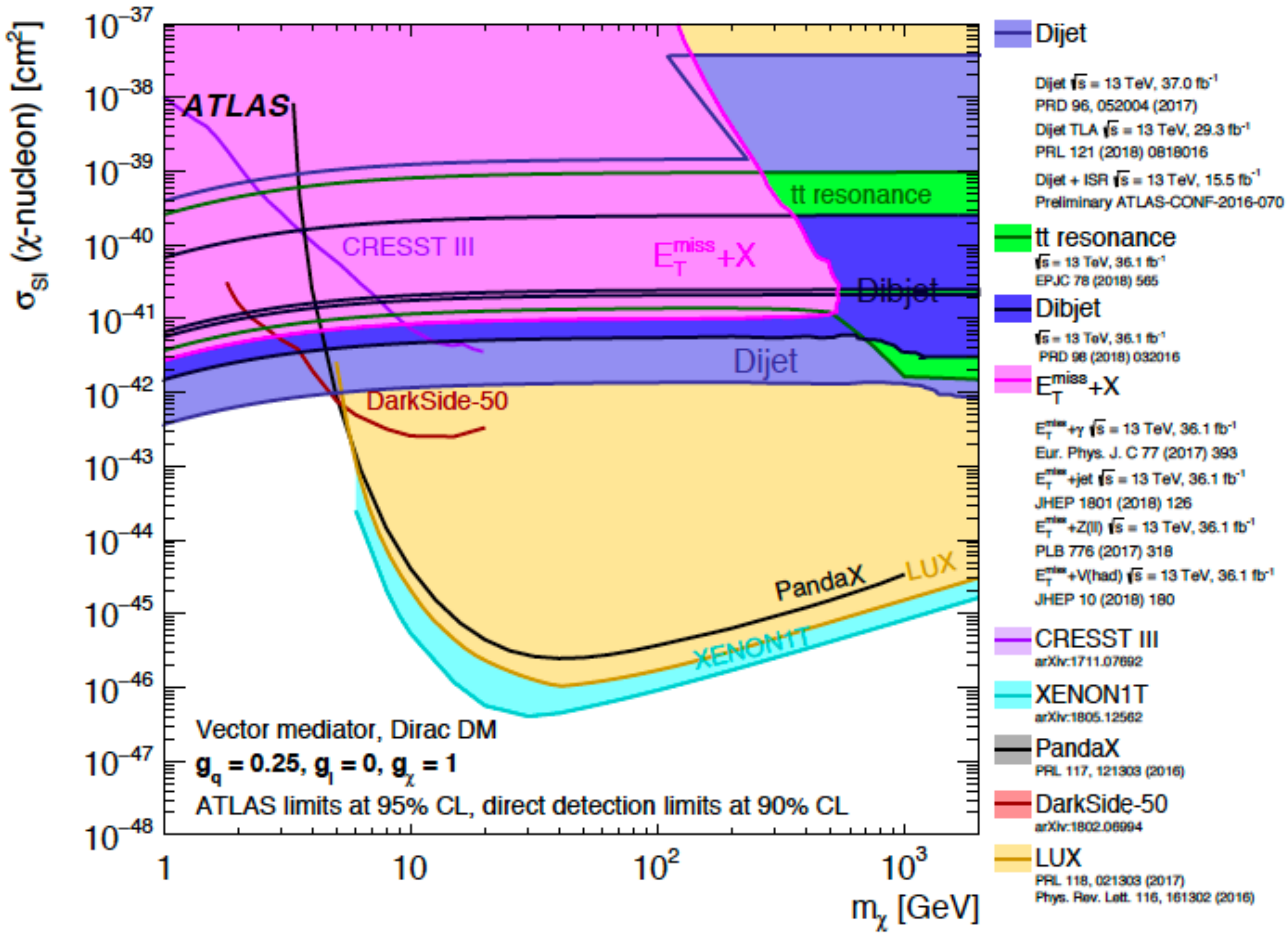
[1903.01400]

Constraints on mediator-based dark matter and scalar dark energy models using $\sqrt{s}$ = 13 TeV pp collision data collected by the ATLAS detector



[1903.01400]

Constraints on mediator-based dark matter and scalar dark energy models using $\sqrt{s}$ = 13 TeV pp collision data collected by the ATLAS detector

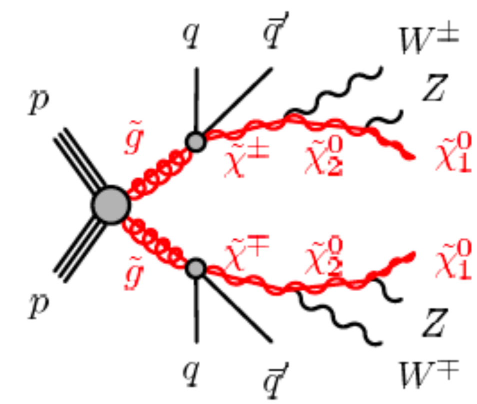


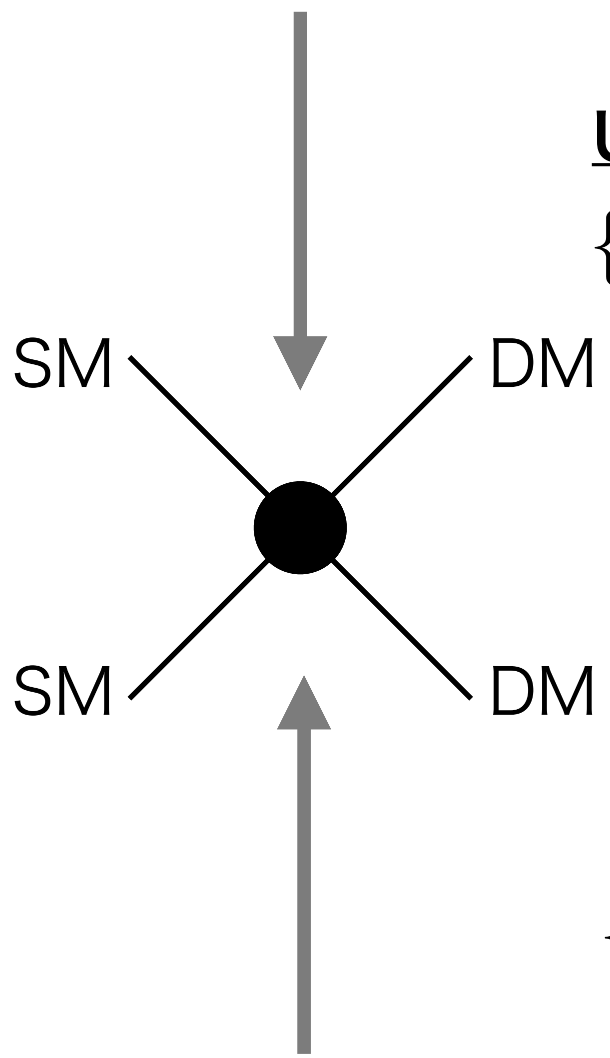
DM (or MET) searches at LHC Run-I

Top-down approach

UV model : SUSY, ExtraDim, ⋯

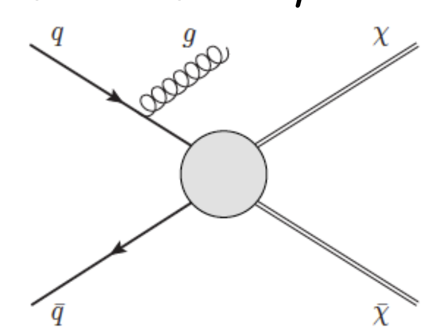
$\{\mathcal{L}; m_{\rm DM}, m_1, m_2, \cdots, g_1, g_2, \cdots\}$





EFT : SM + DM particles

$\{\mathcal{L}; m_{\rm DM}, M_*\}$ $\quad \mathcal{L} = \frac{1}{M_*^2}\bar{\chi}\Gamma^\mu\chi\,\bar{q}\Gamma_\mu q$

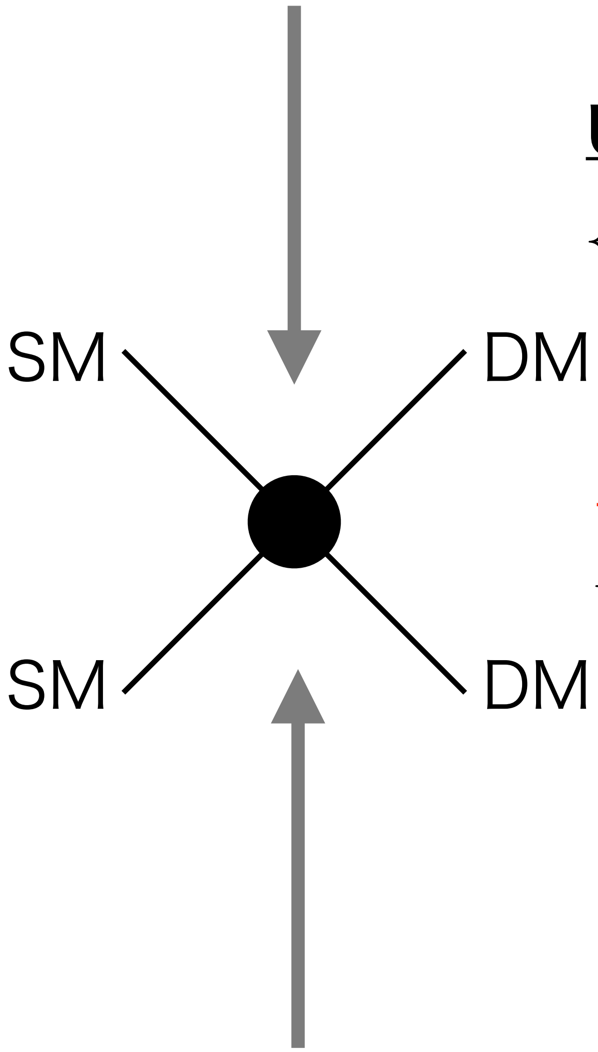


Bottom-up approach

LHC DMWG [1603.04156, 1703.05703]

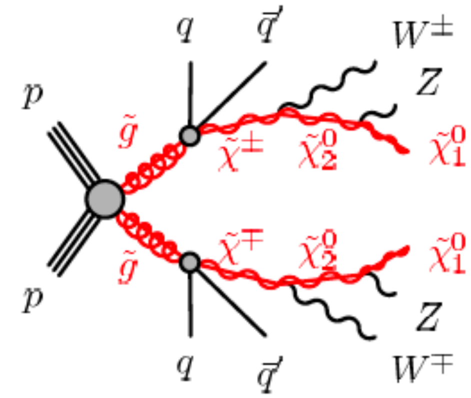
DM (or MET) searches at LHC Run-II

Top-down approach



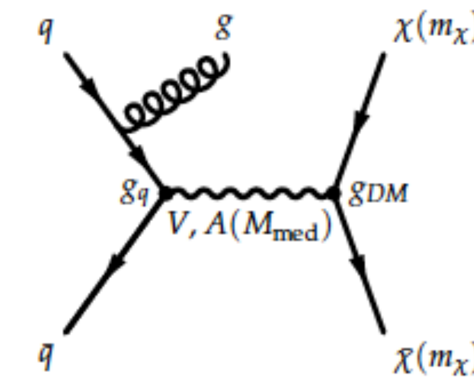
UV model : SUSY, ExtraDim, $\cdots$

$$\{\mathcal{L}; m_{\rm DM}, m_1, m_2, \cdots, g_1, g_2, \cdots\}$$



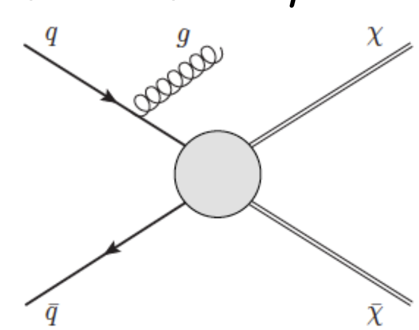
Simplified model : SM + DM + Mediator particles

$$\{\mathcal{L}; m_{\rm DM}, m_{\rm med}, g_{\rm DM}, g_q\} \quad \mathcal{L} = g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu \chi + g_q Z'_\mu \bar{q}\gamma^\mu q$$



EFT : SM + DM particles

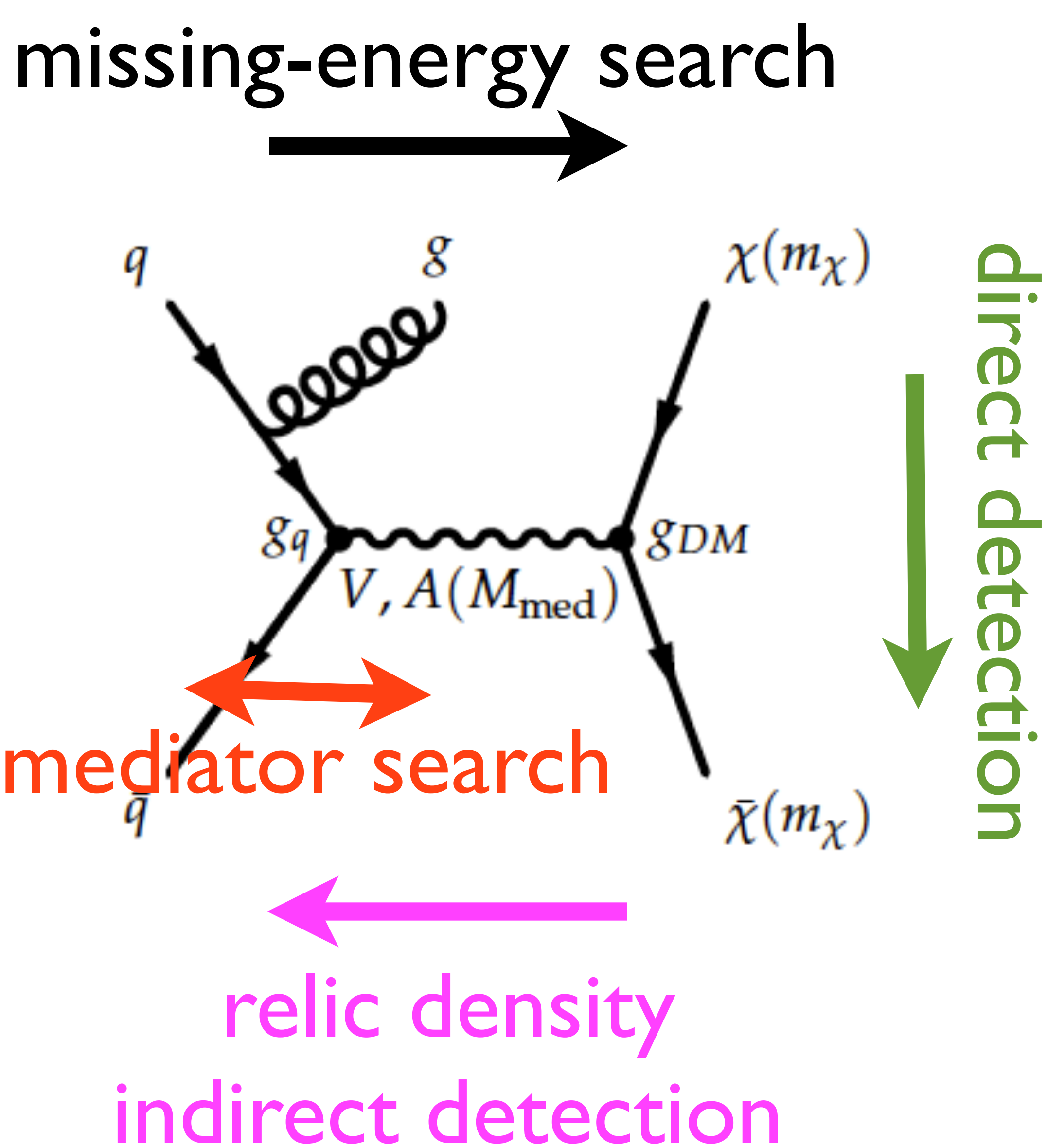
$$\{\mathcal{L}; m_{\rm DM}, M_*\} \quad \mathcal{L} = \frac{1}{M_*^2} \bar{\chi}\Gamma^\mu \chi\, \bar{q}\Gamma_\mu q$$

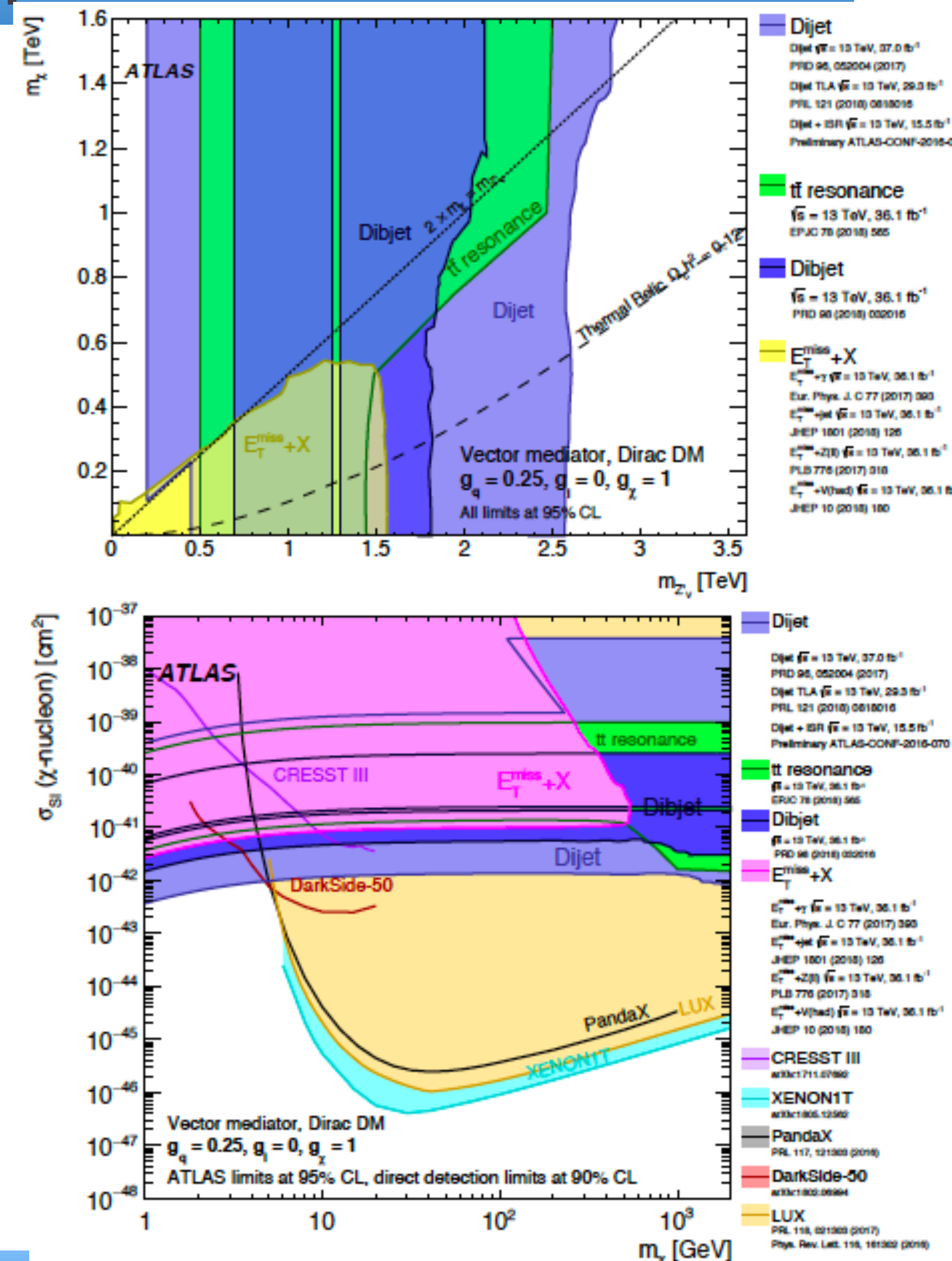


Bottom-up approach

Signatures of simplified DM models

LHC DMWG [1603.04156, 1703.05703]



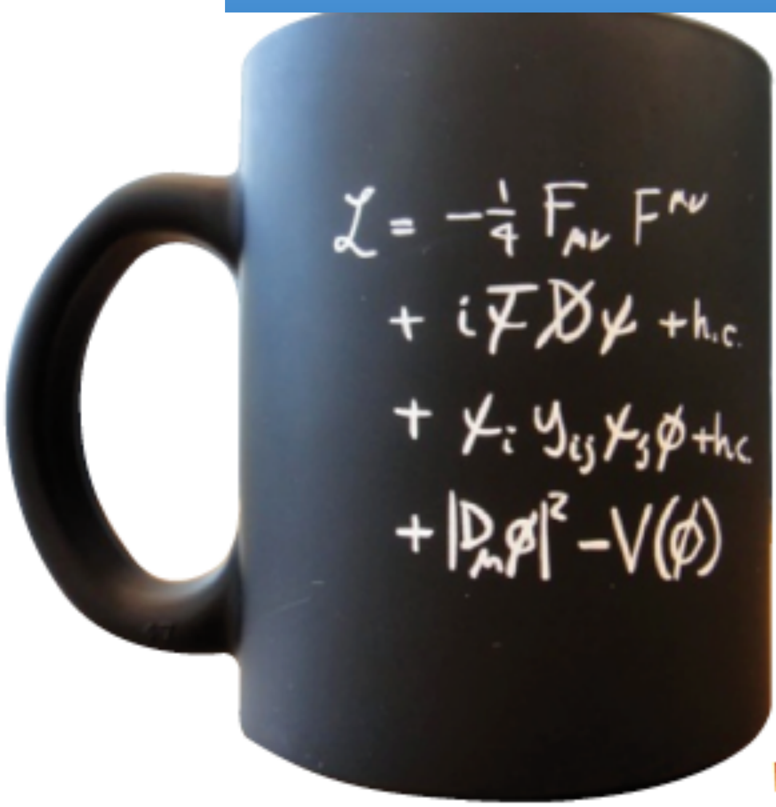


Event generations

Table 2: Details of the generation setup and Universal FeynRules Output (UFO) model used for the spin-1 mediator simplified models, for each signature considered in this paper.

Model and Final State	UFO	Generator and Parton Shower	Cross-section	Additional details
$Z'(\chi\bar{\chi}) + j$	DMV [26, 170]	POWHEG-BOX v2 [171] + PYTHIA 8.205 [172]	NLO	Particle-level rescaling of leptophobic Z'_A scenario of Ref. [26] (see Appendix A.1)
$Z'(\chi\bar{\chi}) + \gamma$	DMSimp [113, 173]	MG5_AMC@NLO 2.4.3 (NLO) [174] + PYTHIA 8.212	NLO	Leptophobic Z'_A scenario simulated, other scenarios obtained by cross-section rescaling (see Appendix A.1)
$Z'(\chi\bar{\chi}) + V$	DMSimp	MG5_AMC@NLO 2.5.3 (NLO) + PYTHIA 8.212	NLO	Particle-level rescaling of LO samples of Ref. [20] to each of the four NLO scenarios (see Appendix A.1)
$Z'(qq)$ or $Z'(qq)$+ISR	DMSimp	MG5_AMC@NLO 2.2.3 (NLO) + PYTHIA 8.210	NLO	Leptophobic Z'_A scenario simulated, other scenario obtained by Gaussian resonance limits and cross-section rescaling [175]
$Z'(b\bar{b})$	DMSimp	MG5_AMC@NLO 2.2.3 (NLO) + PYTHIA 8.210	NLO	Leptophobic Z'_A scenario simulated, other scenario obtained by Gaussian resonance limits and cross-section rescaling [175]
$Z'(\ell\ell)$	DMSimp	MG5_AMC@NLO 2.2.3 (NLO)	NLO	Gaussian resonance limits and cross-section rescaling [175]
$Z'(t\bar{t})$	DMSimp	MG5_AMC@NLO 2.4.3 (LO) + PYTHIA 8.186	LO	Particle-level rescaling of the topcolour-assisted technicolour samples of Ref. [176] (see Appendix A.1)

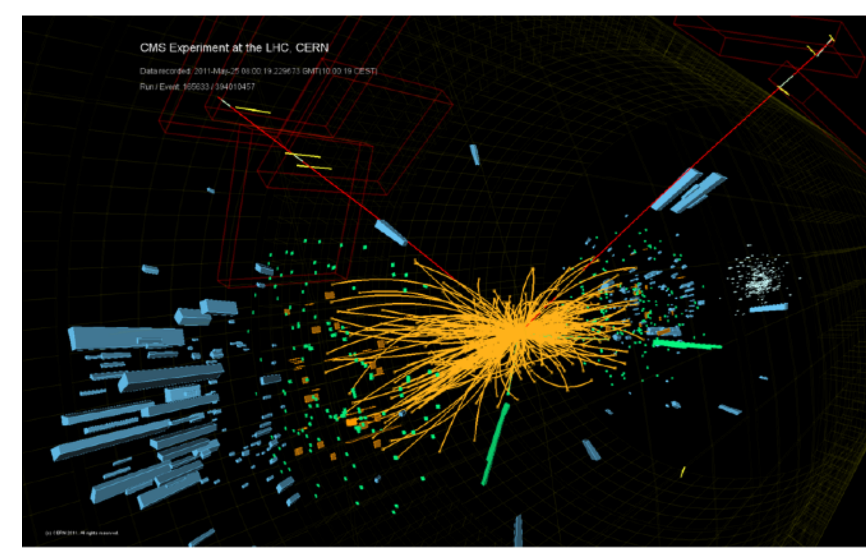
Lagrangian (TH) ⇔ Data (EXP)



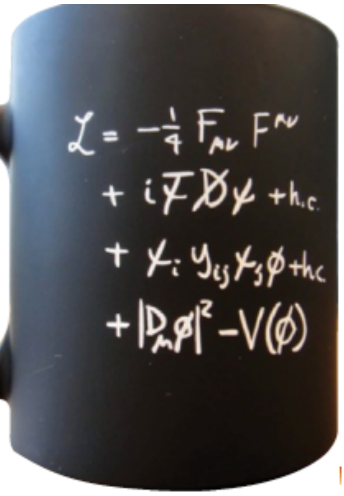
simulation tools

prediction

interpretation

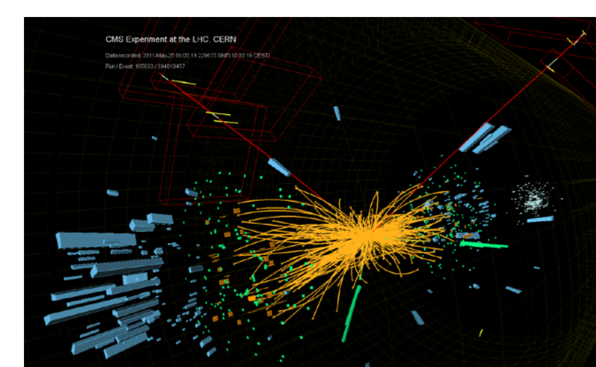


Beyond-Standard-Model workflow in the LHC era



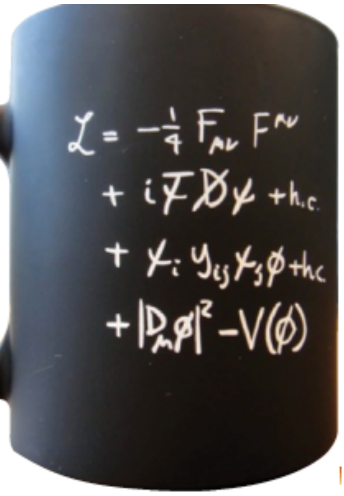
- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules — Model providers
    - draw Feynman diagrams for any interesting processes
      - compute the amplitude (squared) — Matrix-element generators
        - generate events
    - parton-shower/hadronisation — Shower MC
    - detector simulation — Detector simulation tools
    - analysis — Analysis tools

DM physics tool
- DM annihilation (relic, indirect detection)
- DM-N cross section (direct detection)



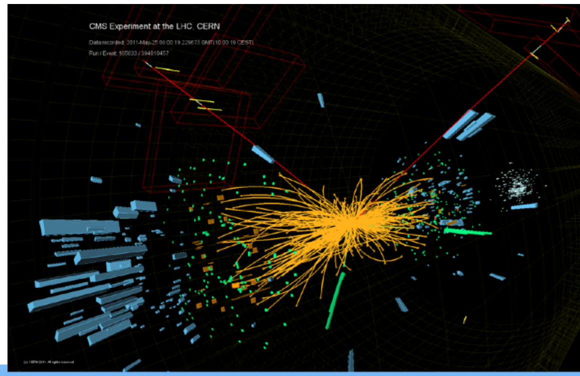
Beyond-Standard-Model workflow in the LHC era

at NLO



- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules — FeynRules +NLOCT
    - draw Feynman diagrams for any interesting processes
      - compute the amplitude (squared) — MadGraph5_aMC@NLO
        - generate events
          - parton-shower/hadronisation — Pythia8
            - detector simulation — Delphes
              - analysis — MadAnalsysi5

MadDM



DMsimp: Simplified DM model files

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

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

DMsimp: Simplified dark matter models

Authors

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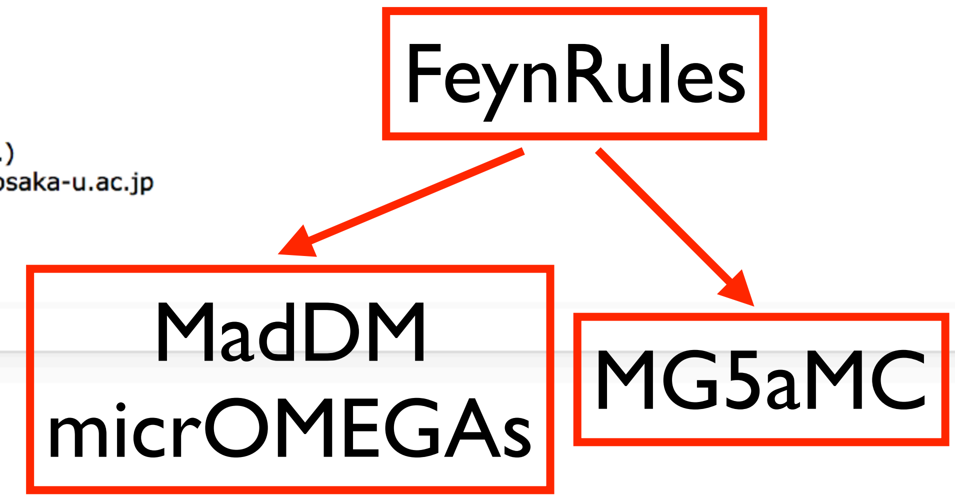


Description of the model

This is simplified dark matter models for NLO.

The mixed spin-0 mediator model is a LO model for MadDM with the inclusion of effective ggY and aaY couplings.

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.]
- Xv (vector DM)
- ...

and different types of mediators:

- s-channel
  - Y0 (spin-0)
  - Y1 (spin-1)
  - Y2 (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" (PLB770(2017)507).
- 1701.07008 : S. Kraml, U. Laa, K. Mawatari, K. Yamashita, "Simplified dark matter models with a spin-2 mediator at the LHC" (EPJC77(2017)326).
- 1703.08087 : C. Arina, M. Backovic, J. Heisig, M. Lucente, "Solar gamma rays as a complementary probe of dark matter" (PRD96(2017)063010).
- 1811.08002 : Y. Afik, F. Maltoni, K. Mawatari, P. Pani, G. Polesello, Y. Rozen, M. Zaro, "DM+bb simulations with DMSimp: an update".

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
```

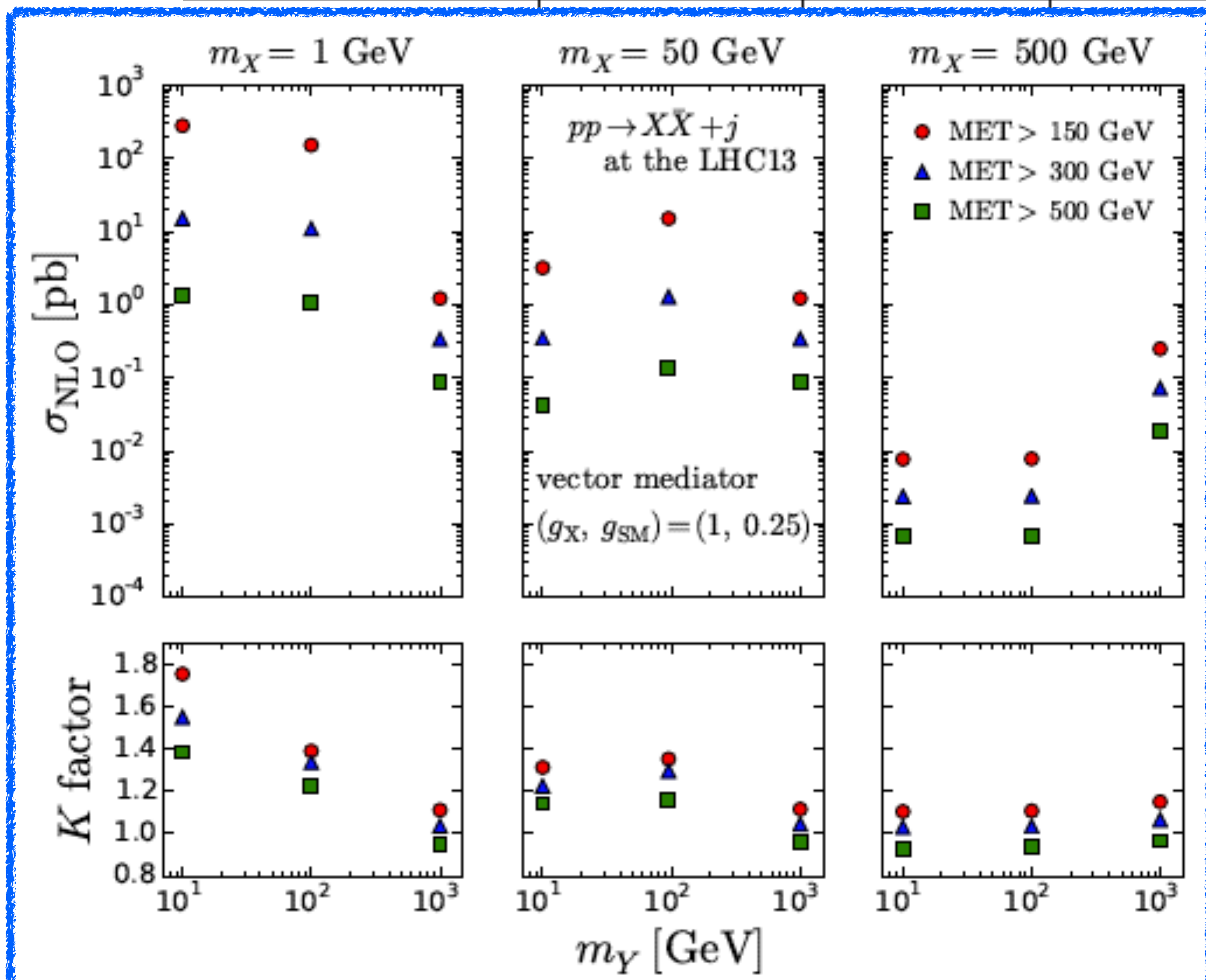
DMsimp(spin-0,1): Backovic, Kramer, Maltoni, Martini, KM, Pellen [1508.05327, EPJC]

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

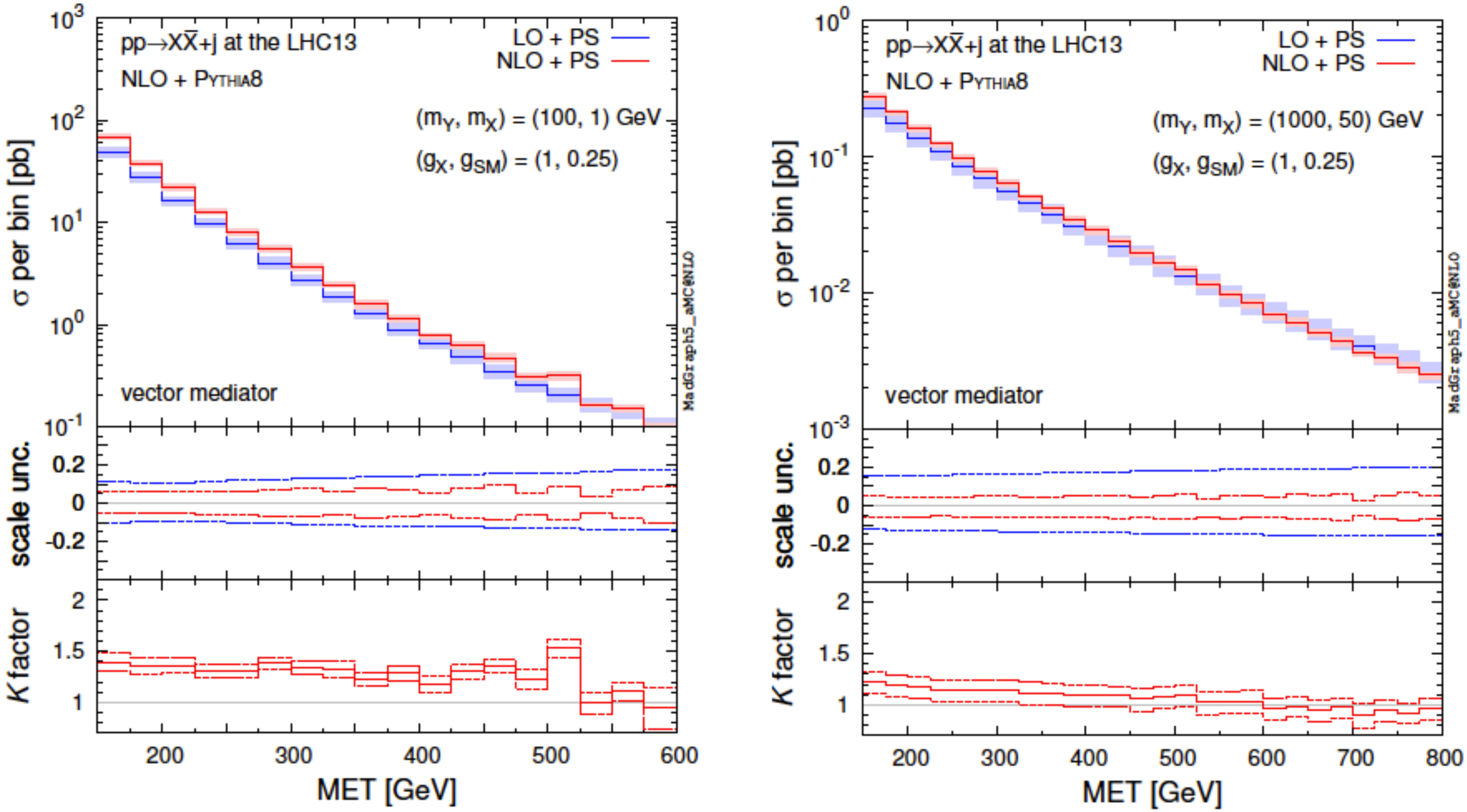


NLO corrections

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

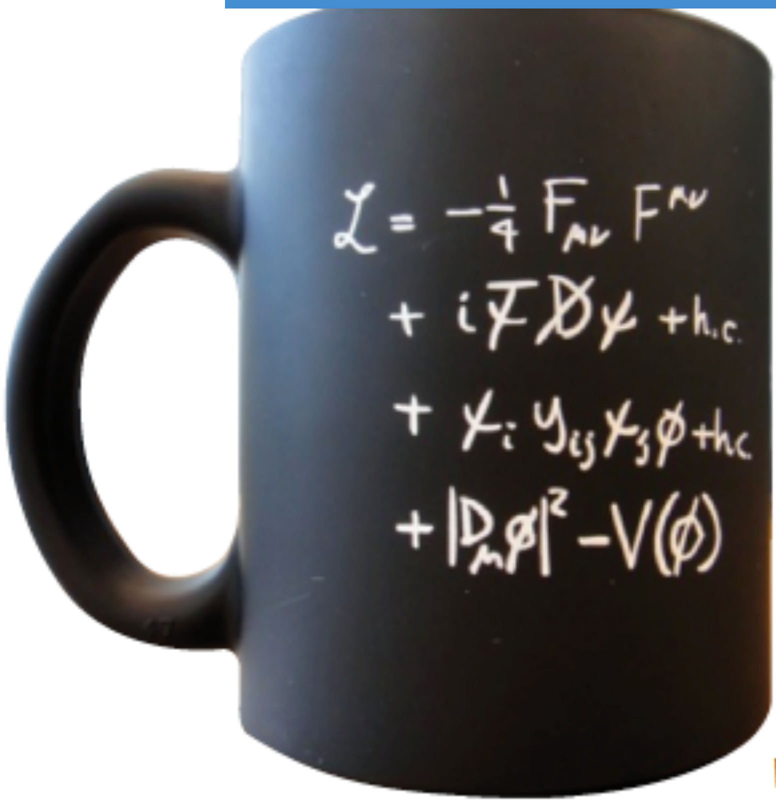
DMsimp(spin-0,1): Backovic, Kramer, Maltoni, Martini, KM, Pellen [1508.05327, EPJC]

DM production at NLO+PS



NLO corrections affect not only the total rate, but also the shape of the distributions.
➡ should go beyond the simple scaling by a constant K factor.

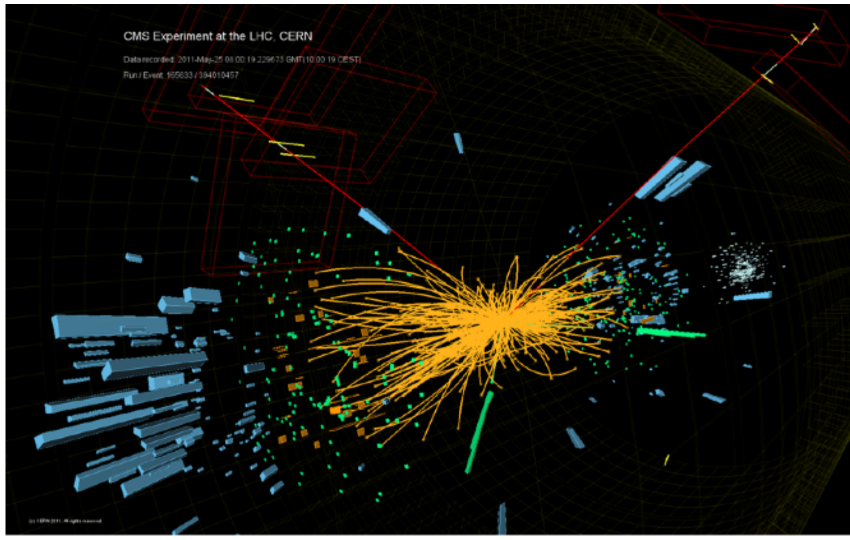
Lagrangian (TH) ⇔ Data (EXP)



simulation tools

prediction

interpretation



so easy, so powerful!

= so dangerous...

Let's learn its proper usage!

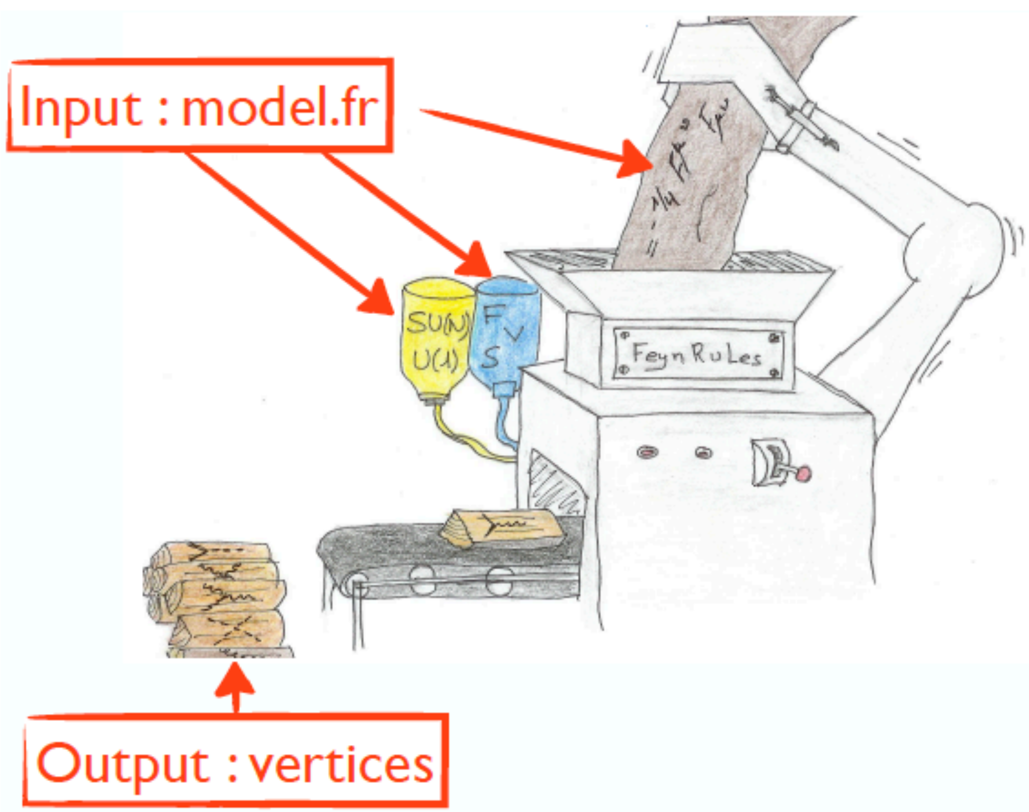
Back-up

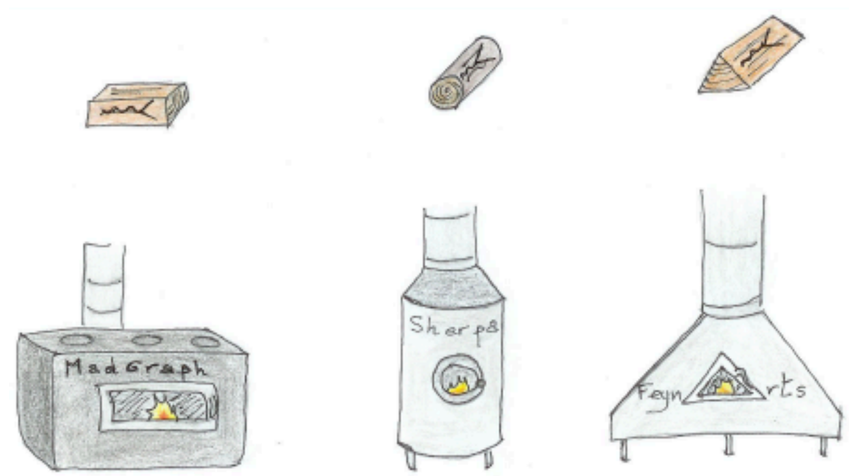
https://feynrules.irmp.ucl.ac.be

FeynRules in a nutshell

Alloul, Christensen, Degrande, Duhr, Fuks [1310.1921, CPC]
Degrande [1406.3030, CPC]

- a mathematica package that allows to
  - calculate Feynman rules for any QFT models, i.e. Lagrangians
  - output them to various event generators (CalcHEP, FeynArts, MG5aMC, Sherpa, Whizard)





FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

C. Degrande

* Universal FeynRules Output
Degrande et al. [1108.2040, CPC]

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

https://launchpad.net/mg5amcnlo

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MADGRAPH

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, an the NLO accuracy in the case of models that support this kind of calculations -- prominent among these are QCD and EW 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]. In addition to that, computations in mixed-coupling expansions and/or of NLO corrections in theories other than QCD (eg NLO EW) require the citation of: R. Frederix et al, "The automation of next-to-leading order electroweak calculations", arXiv:1804.10017 [hep-ph]. A more complete

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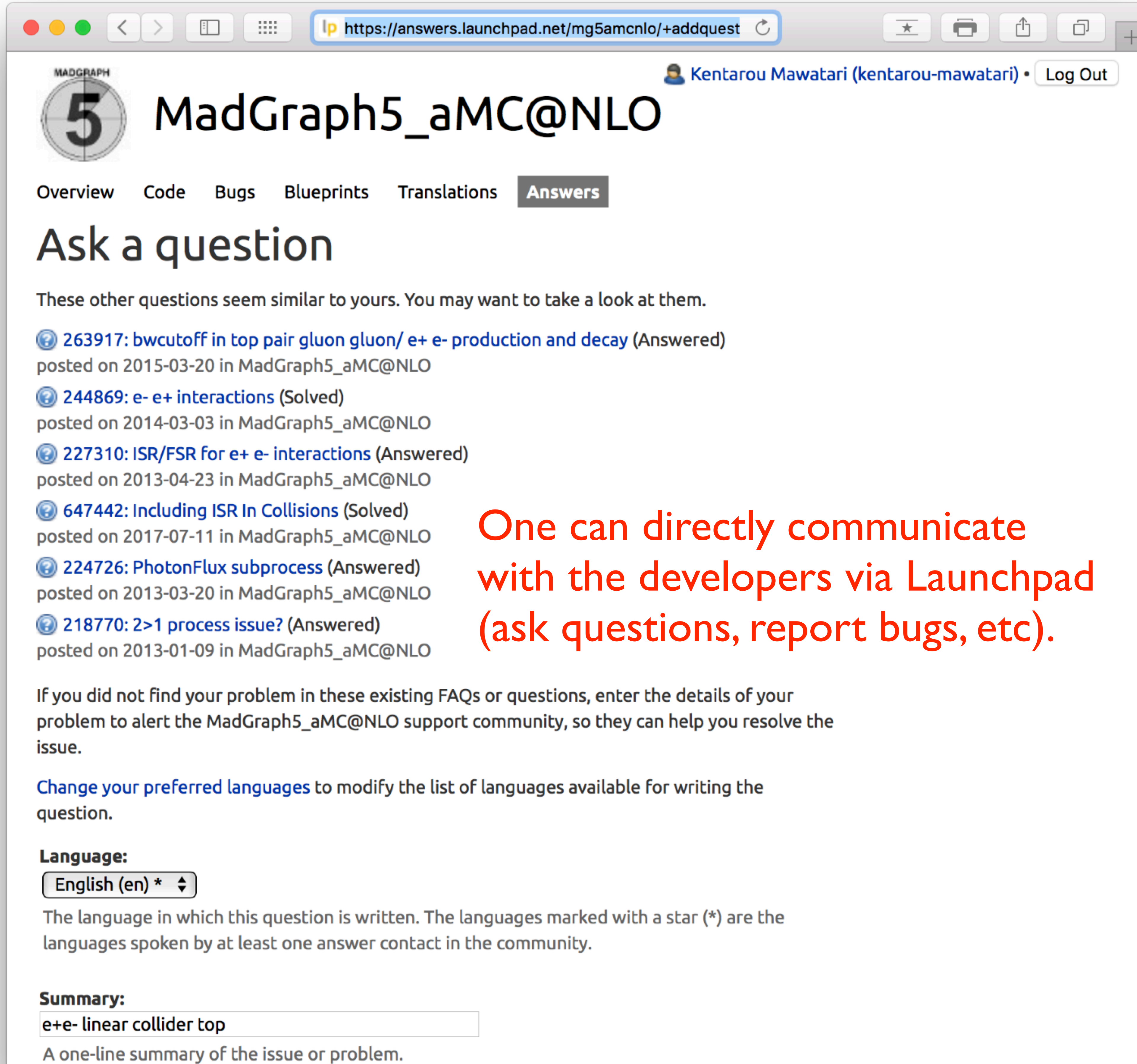
Latest version is 2.6.x

MG5_aMC_v2.6.2.tar.gz

MG5_aMC_v3....beta.tar.gz

released on 2017-08-15

All downloads


https://answers.launchpad.net/mg5amcnlo/+addquest

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MADGRAPH 5

MadGraph5_aMC@NLO

Overview Code Bugs Blueprints Translations **Answers**

Ask a question

These other questions seem similar to yours. You may want to take a look at them.

263917: bwcutoff in top pair gluon gluon/ e+ e- production and decay (Answered)
posted on 2015-03-20 in MadGraph5_aMC@NLO

244869: e- e+ interactions (Solved)
posted on 2014-03-03 in MadGraph5_aMC@NLO

227310: ISR/FSR for e+ e- interactions (Answered)
posted on 2013-04-23 in MadGraph5_aMC@NLO

647442: Including ISR In Collisions (Solved)
posted on 2017-07-11 in MadGraph5_aMC@NLO

224726: PhotonFlux subprocess (Answered)
posted on 2013-03-20 in MadGraph5_aMC@NLO

218770: 2>1 process issue? (Answered)
posted on 2013-01-09 in MadGraph5_aMC@NLO

If you did not find your problem in these existing FAQs or questions, enter the details of your problem to alert the MadGraph5_aMC@NLO support community, so they can help you resolve the issue.

Change your preferred languages to modify the list of languages available for writing the question.

Language:

English (en) *

The language in which this question is written. The languages marked with a star (*) are the languages spoken by at least one answer contact in the community.

Summary:

e+e- linear collider top

A one-line summary of the issue or problem.

One can directly communicate with the developers via Launchpad (ask questions, report bugs, etc).

Conte, Fuks, Serret [1206.1599]
Conte, Dumont, Fuks, Wymant [1405.3982]
Dumont, Fuks, Kraml, Bein, Chalons, Conte, Kulkarni, Sengupta, Wymant [1407.3278]

Canonical Group Ltd launchpad.net/madanalysis5

Kentarou Mawatari (kentarou-mawatari) • Log Out

MadAnalysis 5

Overview Code Bugs Blueprints Translations Answers

Registered 2013-04-13 by Eric Conte

MadAnalysis 5 is a new framework for phenomenological investigations at particle colliders. Based on a C++ kernel, this program allows to efficiently perform, in a straightforward and user-friendly fashion, sophisticated physics analyses of event files such as those generated by a large class of Monte Carlo event generators.

MadAnalysis 5 has been recently extended to allow for the recasting of existing LHC analyses. These features are available from version 1.1.12 onwards (currently available as beta version). For documentation on the MA5 PAD (public analysis database) and on instructions to implement new analyses, see http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase

The latest stable version of the MadAnalysis 5 package can be obtained in two ways:
- directly from the Bazaar versioning system by typing in a shell:
  bzr branch lp:madanalysis5
- as a tar-ball (to be downloaded from the right of this page).

More information on the program can be found on the wiki http://madanalysis.irmp.ucl.ac.be

If you use MadAnalysis 5, please cite
1. E. Conte, B. Fuks and G. Serret,
   Comput. Phys. Commun. 184 (2013) 222
   http://arxiv.org/abs/1206.1599

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Latest version is v1.3
MadAnalysis5_v1.3.tar.gz
released on 2016-03-01

All downloads

MadDM1: Backovic, Kong, McCaskey [1308.4955]
MadDM2: Backovic, Kong, Martini, Mattelaer, Mohlabeng [1505.04190]
MadDM3: Ambrogi, Arina, Backovic, Heisig, Maltoni, Mantani, Mattelaer, Mohlabeng [1804.00044]

https://launchpad.net/maddm

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MadDM

Overview Code Bugs Blueprints Translations Answers

Registered 2014-03-27 by Mihailo Backovic

ATTENTION: MadDM is now a plugin for MadGraph 5. In order to install it and run it, start madgraph and type

install maddm

in the command line. Then exit and start maddm with ./maddm.py.

M5G_aMC@NLO v.2.6.2 is required to be able to run MadDM v.3.0.

MadDM v.3.0 is a numerical tool to compute dark matter relic abundance, dark matter nucleus scattering rates and dark matter indirect detection predictions in a generic model. The code is based on the existing MadGraph 5 architecture and as such is easily integrable into any MadGraph collider study. A simple Python interface offers a level of user-friendliness characteristic of MadGraph 5 without sacrificing functionality.

MadDM is able to calculate the dark matter relic abundance in models which include a multi-component dark sector, resonance annihilation channels and co-annihilations.

MadDM v1

The direct detection module of the MadDM code calculates spin independent / spin dependent dark matter-nucleon cross sections and differential recoil rates as a function of recoil energy, angle and time. The code provides a simplified simulation of detector effects for a wide range of target materials and volumes.

MadDM v2

The indirect detection module of the MadDM code computes the velocity averaged cross-section for dark matter particles annihilating into n final state particles. It further provides the energy spectra of photons, neutrinos and cosmic-rays generated by these final states after decaying, showering and hadronization. It automatically computes the flux of prompt neutrinos and gamma rays at detection while it provides a user friendly interface with the numerical DRAGON code for obtaining the flux of cosmic rays at Earth. It also provides a user friendly interface with the nested sampling PyMultiNest algorithm for efficient sampling of the model parameter space and allows as well to test the model against the Fermi-LAT dwarf spheroidal galaxy likelihood.

MadDM v3

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Latest version is maddmv3.0

MadDM_v3.0.beta.tar.gz

released on 2018-03-29

All downloads

Announcements

MadDM v.3.0 beta released on 2018-04-03
We are pleased to release the v.3.0 of the MadDM code, which is now a MG5_aMC...

Update for MadDM v.2.0 released on 2015-06-29