# Accurate, Realistic, and Automatic Predictions for Dark Matter Production at the LHC

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based on arXiv:1509.05785 (mono-Z @ NLO)
in collaboration with M. Neubert and J. Wang

Tools available at
http://feynrules.irmp.ucl.ac.be/wiki/DMsimp ,
in collaboration with the authors of
(mono-j & ttbar) arXiv:1508.05327 (Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen)
(loop-induced mono-j/Z/H) arXiv:1508.00564 (O. Mattelaer, E. Vryonidou)

# Summary

[1509.05785 Neubert, Wang and CZ]

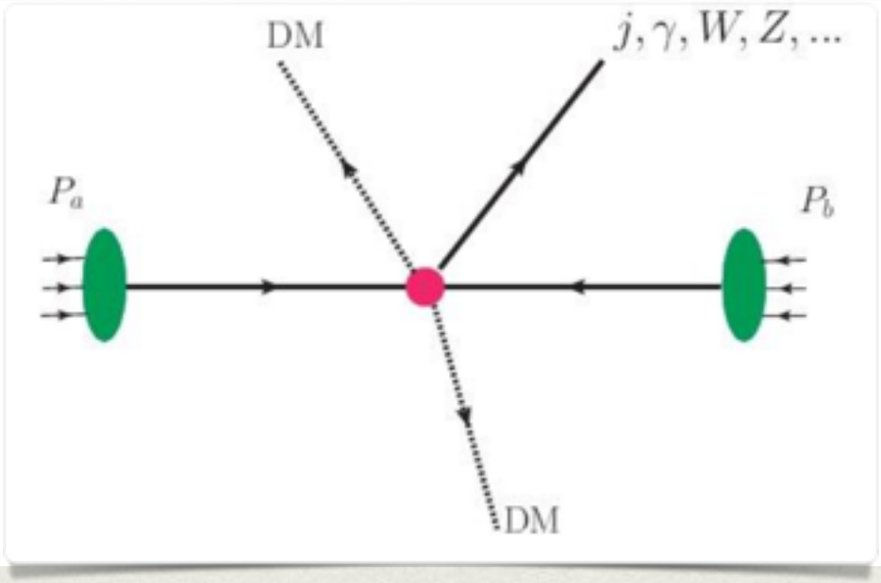
- We provide MC tool for DM production at the LHC. s-channel simplified models are implemented.
- It is based on the FeynRules/MadGraph5_aMC@NLO framework, and thus
  - Accurate: **next-to-leading** order in QCD.
  - Realistic: always matched to **parton shower.**
  - Automatic: events generated by a few command lines.
  - ...and in principle **any mono-X** signature, including loop-induced ones (but at LO).
- For illustration purpose we use it to study mono-Z production.

# Outline

- DM simplified model
- NLO implementation
- Example 1: mono-Z
- Example 2: mono-jet

# DM at the LHC

DM production at the LHC can be searched in X+missing $E_T$ final state

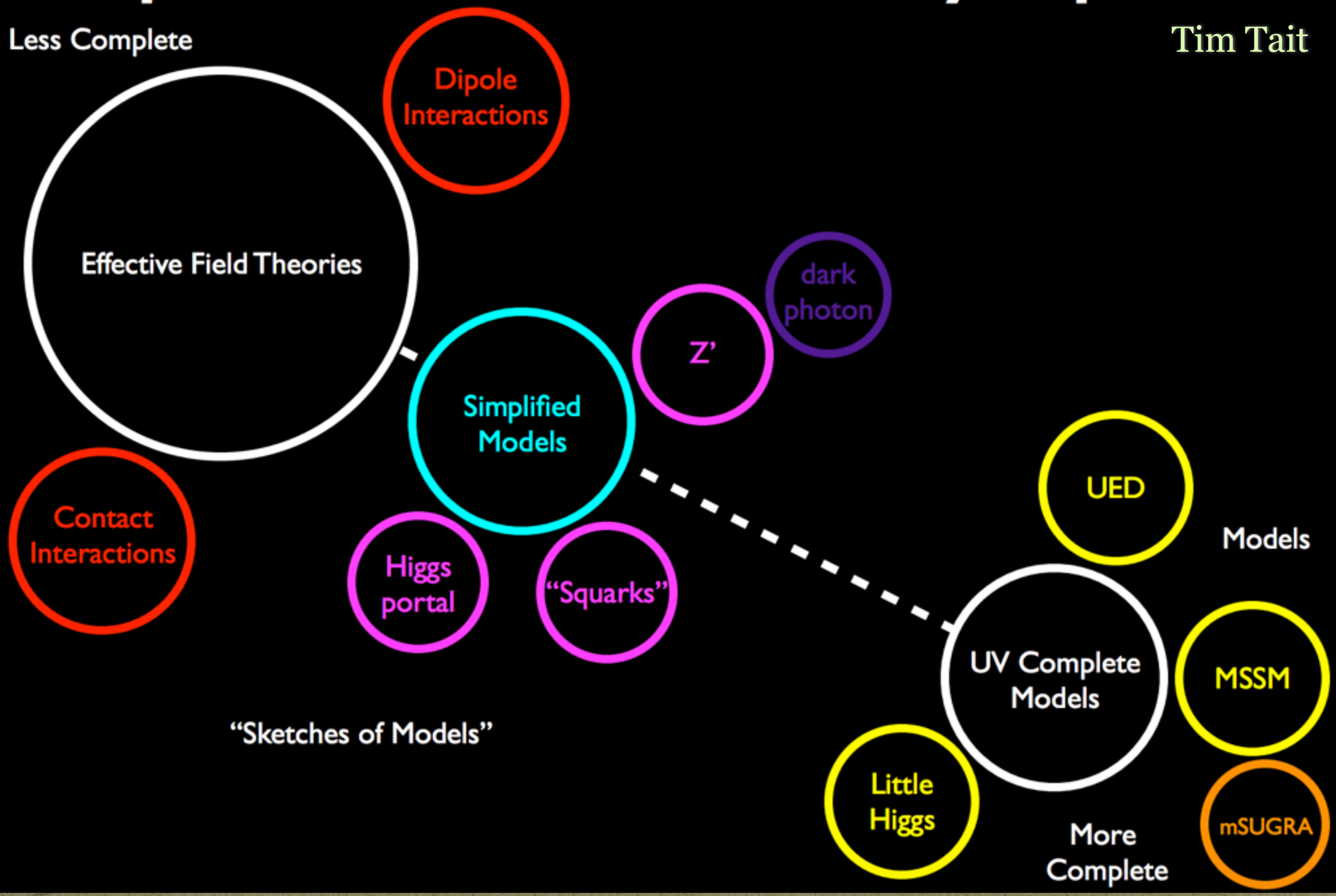



Mono-“X”

But, we **need a theory** to understand the signal and to set limits. (and to compare with other searches, i.e. direct/indirect detections.)

# Spectrum of Theory Space

Tim Tait



# Simplified Model

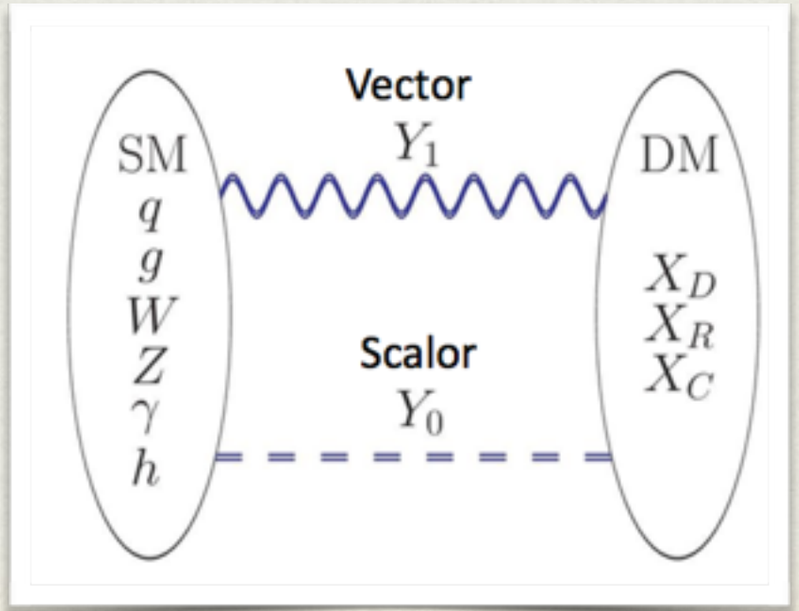
- Simplified model contains the **dark matter** as well as the most important **mediator particles.** [1409.2893 Abdallah et al.]
- Incorporate the most relevant degrees of freedom of an underlying UV model, while keeping some simplicity of EFT.
- The ATLAS/CMS DM forum has given **benchmark models/scenarios for RUN II** [1507.00966 Daniel Abercrombie et al.]
- As a first step, we consider s-channel simplified model.

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

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

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

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



# Simplified Model

LHC will rely on **precise predictions** to analyze signal and set the most stringent bounds.

- However, predictions are (were) available only at the leading order except for mono-j.
- QCD NLO calculations (and MC tools) are available for mono-W/photon, but **only in EFT.**
- Complete NLO results are difficult to obtain because there are many possibilities:
  - **Processes**: mono-j/W/Z/photon/Higgs/t/ttbar etc.
  - **Mediators**: scalar/vector/tensor, s/t-channel
  - **Dark matter**: dirac/majorana/real and complex scalar
  - **Interactions**: S/P/V/A...

# Automation with MG5_aMC

Instead of calculating all possibilities, we aim at providing a **generic tool** that is capable of all above

- The FeynRules MadGraph5_aMC@NLO (MG5) framework is ideal, as it supports **automatic NLO** predictions for custom **renormalizable models**.

[1310.1921 A. Alloul et al.]

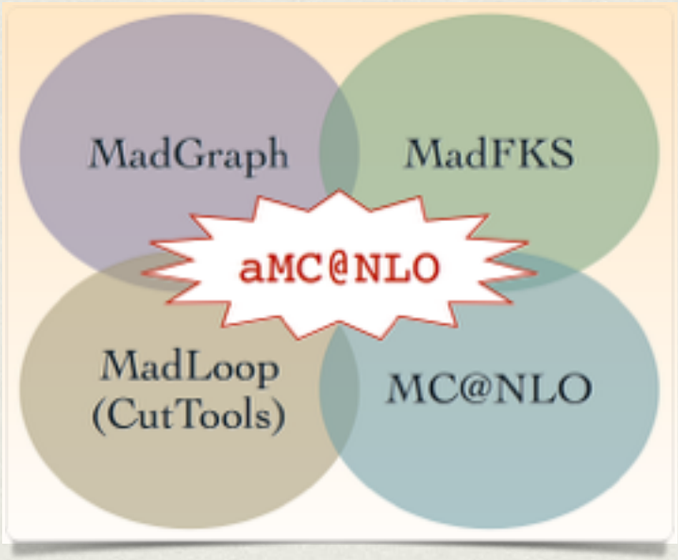
[J. Alwall et al. 2014]

- We need to provide the model file (for MG5, in **UFO** format), which contains all relevant information.

[1108.2040 C. Degrande et al.]

- In particular, including UV/R2 counterterms required at **NLO**.

[1406.3030 C. Degrande]




Automatic NLO: Loop+Real+PS

# Model files

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

## Simplified dark matter models

### Authors

- s-channel
  - Antony Martini (Université catholique de Louvain) & Kentarou Mawatari (Vrije Universiteit Brussel)
    - Emails: kentarou.mawatari @ vub.ac.be
- 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.)
- ...

# Model files

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

**Simplified dark matter models**

**Authors**

- s-ch
- s-ch

**Descrip**

This is sim

- Xr (
- Xc (
- Xd (
- Xm
- ...

**Model files**

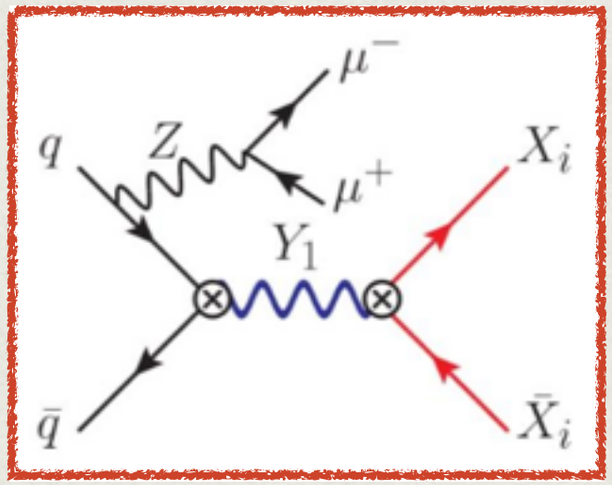
- FR files (for spin-1)
  - dm_s_spin1.fr : the main model file for spin1 mediators.
  - dm_s_spin1_ew.fr : the add-on model file for spin1 mediators for EW.
  - Cabibbo.rst, Massless_5f.rst : the restriction files.
  - DMsimp_s_spin1.nb : this is an example Mathematica notebook that loads format.
- FR files (for spin-0)
  - dm_s_spin0.fr : the main model file for spin0 mediators.
  - dm_s_spin0_ew.fr : the add-on model file for spin0 mediators for EW.
  - Cabibbo.rst, Massless_5f.rst : the restriction files.
  - DMsimp_s_spin0.nb : this is an example Mathematica notebook that loads format.
- UFO files (for, e.g. MadGraph5_aMC@NLO)
  - DMsimp_s_spin1.zip : The model files for spin1 mediators.
  - DMsimp_s_spin0.zip : The model files for spin0 mediators.

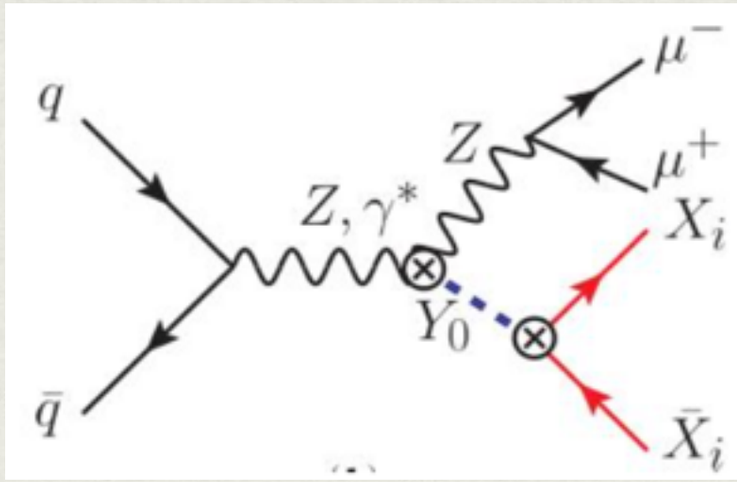
# Current status

- **s-channel** simplified model with **scalar** and **vector** mediators.
  *[C. Degrande (Durham), K. Mawatari (VU Brussels), A. Martini (UC Louvain), J. Wang (Mainz), CZ]*
  - **Validated** against similar SM processes.
  - Include couplings: X-X-Y (DM to med.), q-q-Y (quark to med.), and V-V-Y/H-H-Y (EW gauge/Higgs bosons to med.)
- Applications in several channels
  - Mono-j with vector mediator
    *[F. Maltoni, M. Backovic, A. Martini (UC Louvain), K.~Mawatari (VU Brussels)]*
  - Mono-ttbar with scalar mediator
    *[M. Kraemer, M. Pellen (Aachen)]*
  - Mono-Z with vector/scalar mediator
    *[M. Neubert, J. Wang (Mainz), CZ]*
  - **Loop-induced** mono-j/Z/H
    *[O. Mattelaer, E. Vryonidou (UC Louvain)]*
- **t-channel simplified model** (on going)
  *[B. Fuks et al. (Strasbourg)]*

# Example 1: mono-Z

Suppose we want to generate mono-Z




$$\mathcal{L}_{\rm SM}^{Y_1} = \sum_{i,j} \left[ \bar{d}_i \gamma_\mu \left( g_{d_{ij}}^V + g_{d_{ij}}^A \gamma_5 \right) d_j + \bar{u}_i \gamma_\mu \left( g_{u_{ij}}^V + g_{u_{ij}}^A \gamma_5 \right) u_j \right] Y_1^\mu$$

$$\mathcal{L}_{\rm DM}^{Y_1} = \frac{i}{2} g_{X_C}^V \left[ X_C^* (\partial_\mu X_C) - (\partial_\mu X_C^*) X_C \right] Y_1^\mu + \overline{X}_D \gamma_\mu \left( g_{X_D}^V + g_{X_D}^A \gamma_5 \right) X_D Y_1^\mu$$

To generate process:

```
>import model DMsimp_s_spin1_EW_UFO
>define p = p b b~
>define j = p
>generate p p > z xd xd~ [QCD]
>output some_DIR
```

To generate process:

```
>import model DMsimp_s_spin1_EW_UFO
>define p = p b b~
>define j = p
>generate p p > z xd xd~ [QCD]
>output some_DIR
```

some_DIR/index.html

## SubProcesses and Feynman diagrams

| Directory | Type | # Diagrams | # Subprocesses | FEYNMAN DIAGRAMS | SUBPROCESS |
|---|---|---|---|---|---|
| P0_ccx_zxdxdx | born | 2 | 1 | postscript | c c~ > z xd xd~ WEIGHTED=6 DMV=2 [ QCD ] |
| | virt | 8 | 1 | postscript | c c~ > z xd xd~ WEIGHTED=6 QED=1 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | c c~ > z xd xd~ g WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | g c~ > z xd xd~ c~ WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | c g > z xd xd~ c WEIGHTED=7 DMV=2 [ QCD ] |
| P0_cxc_zxdxdx | born | 2 | 1 | postscript | c~ c > z xd xd~ WEIGHTED=6 DMV=2 [ QCD ] |
| | virt | 8 | 1 | postscript | c~ c > z xd xd~ WEIGHTED=6 QED=1 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | c~ c > z xd xd~ g WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | g c > z xd xd~ c WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | c~ g > z xd xd~ c~ WEIGHTED=7 DMV=2 [ QCD ] |
| P0_ddx_zxdxdx | born | 2 | 1 | postscript | d d~ > z xd xd~ WEIGHTED=6 DMV=2 [ QCD ] |
| | virt | 8 | 1 | postscript | d d~ > z xd xd~ WEIGHTED=6 QED=1 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | d d~ > z xd xd~ g WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | g d~ > z xd xd~ d~ WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | d g > z xd xd~ d WEIGHTED=7 DMV=2 [ QCD ] |

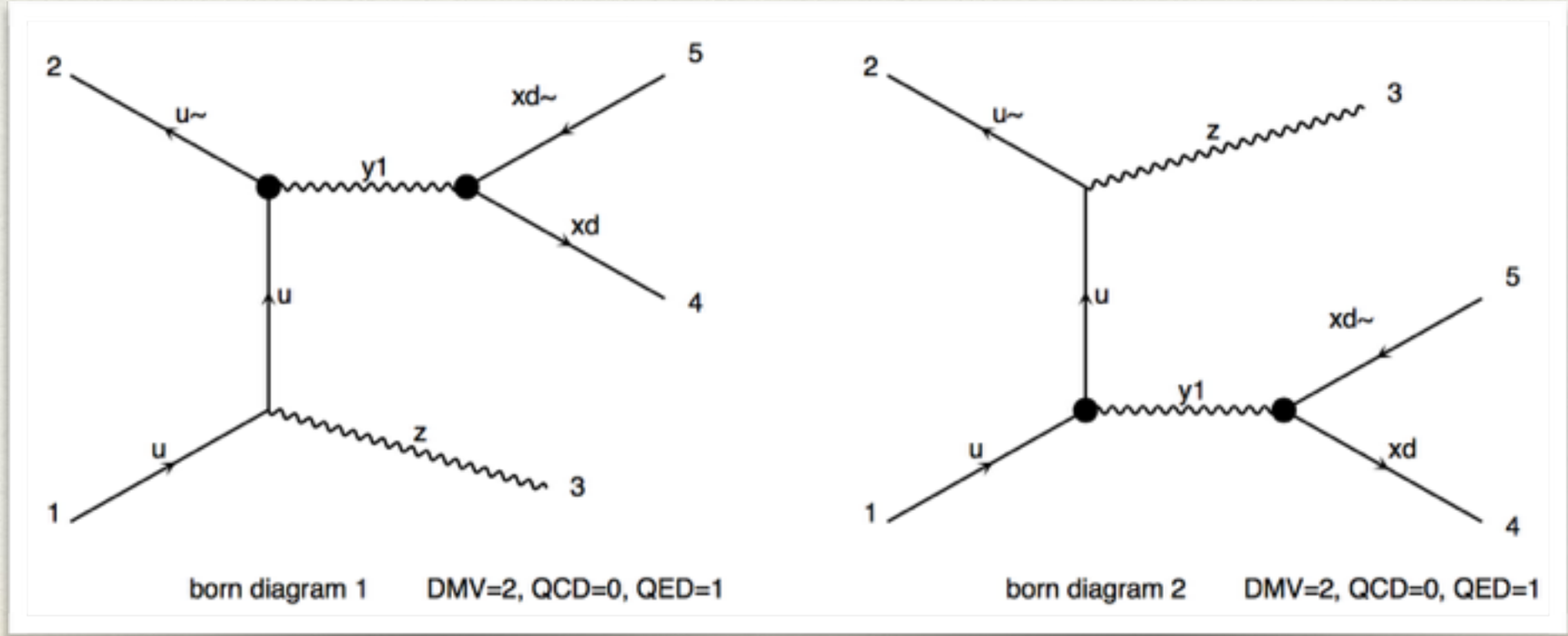
To generate process:

```
>import model DMsimp_s_spin1_EW_UFO
>define p = p b b~
>define j = p
>generate p p > z xd xd~ [QCD]
>output some_DIR
```

some_DIR/index.html

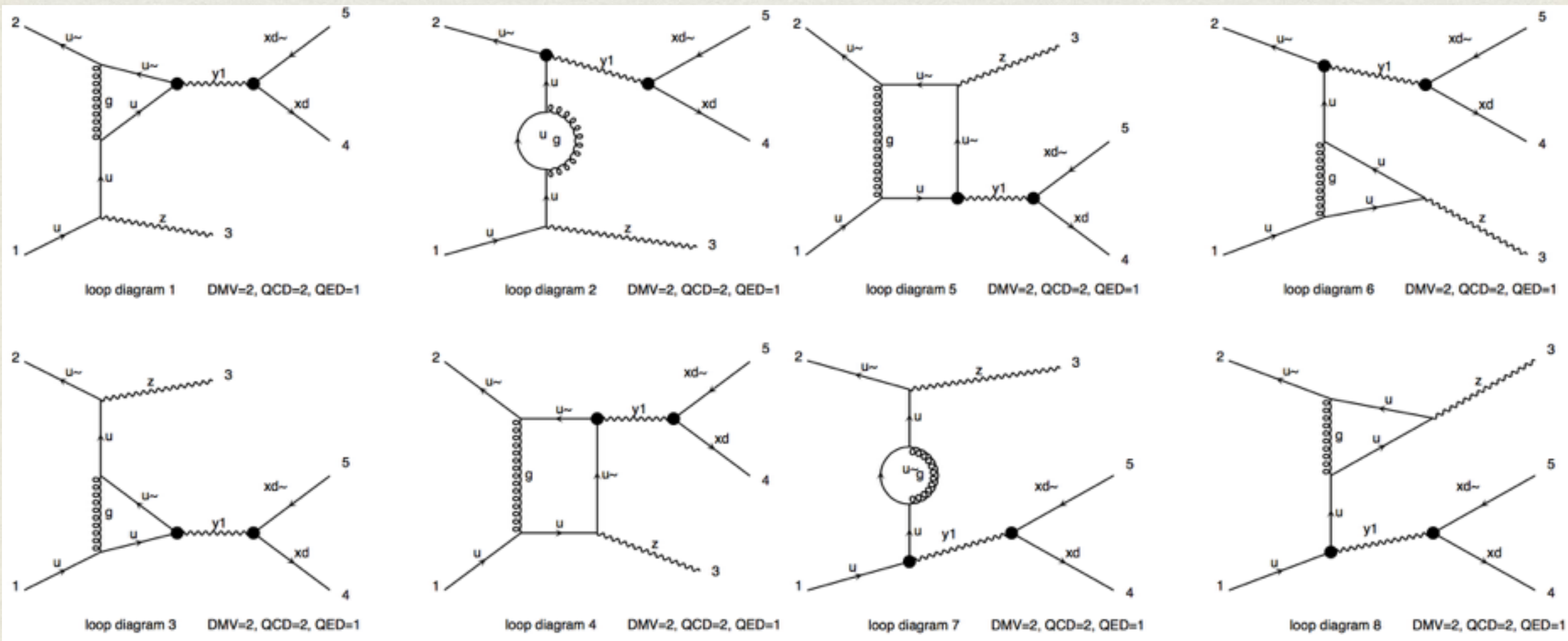
## SubProcesses and Feynman diagrams

| Directory | Type | # Diagrams | # Subprocesses | FEYNMAN DIAGRAMS | SUBPROCESS |
|---|---|---|---|---|---|
| P0_ccx_zxdxdx | born | 2 | 1 | postscript | c c~ > z xd xd~ WEIGHTED=6 DMV=2 [ QCD ] |
| | virt | 8 | 1 | postscript | c c~ > z xd xd~ WEIGHTED=6 QED=1 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | c c~ > z xd xd~ g WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | g c~ > z xd xd~ c~ WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | c g > z xd xd~ c WEIGHTED=7 DMV=2 [ QCD ] |



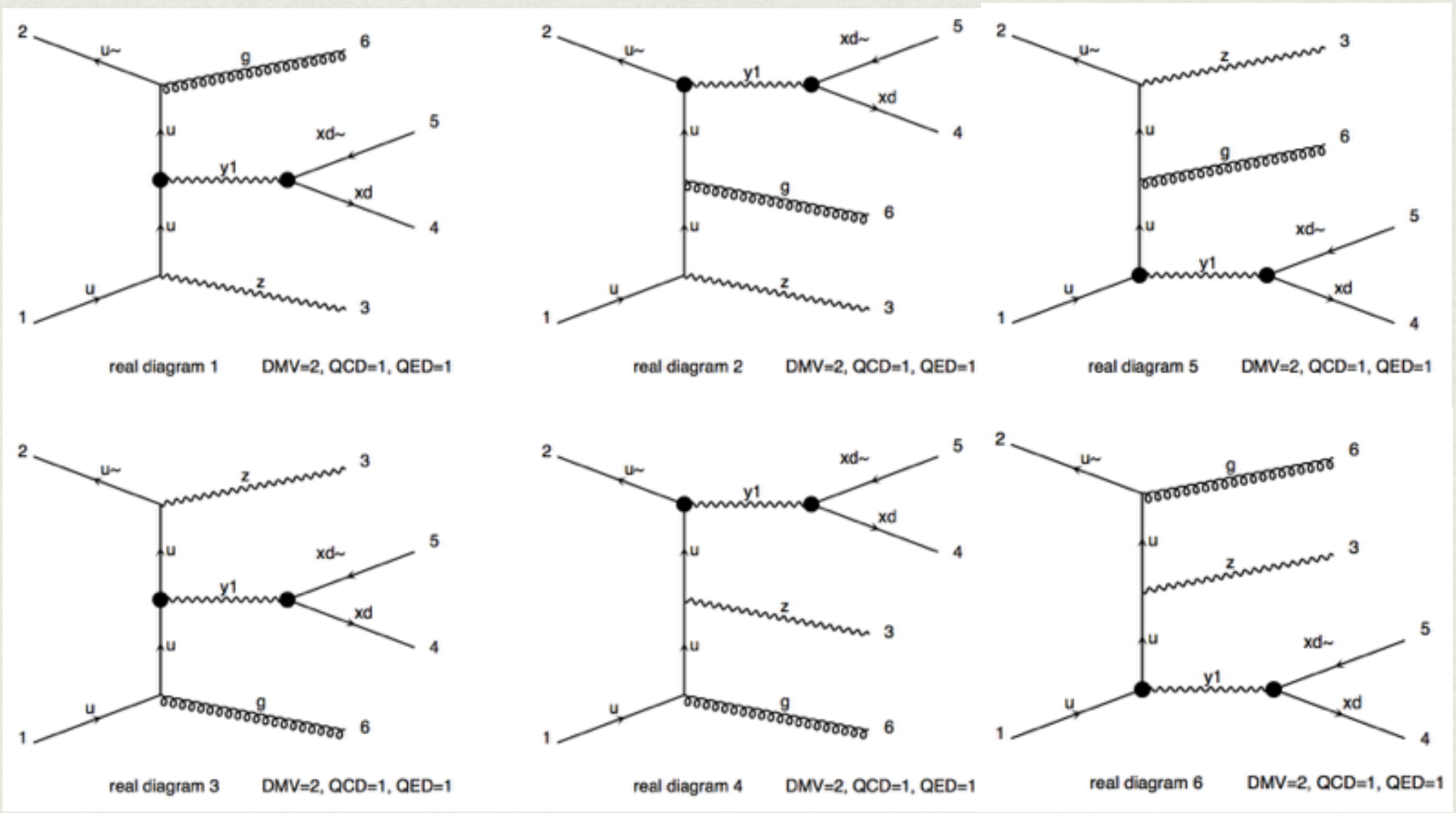
| | | | | | |
|---|---|---|---|---|---|
| P0_uux_zxdxdx | born | 2 | 1 | postscript | u u~ > z xd xd~ WEIGHTED=6 DMV=2 [ QCD ] |
| | virt | 8 | 1 | postscript | u u~ > z xd xd~ WEIGHTED=6 QED=1 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | u u~ > z xd xd~ g WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | g u~ > z xd xd~ u~ WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | u g > z xd xd~ u WEIGHTED=7 DMV=2 [ QCD ] |

# QCD corrections: virtual



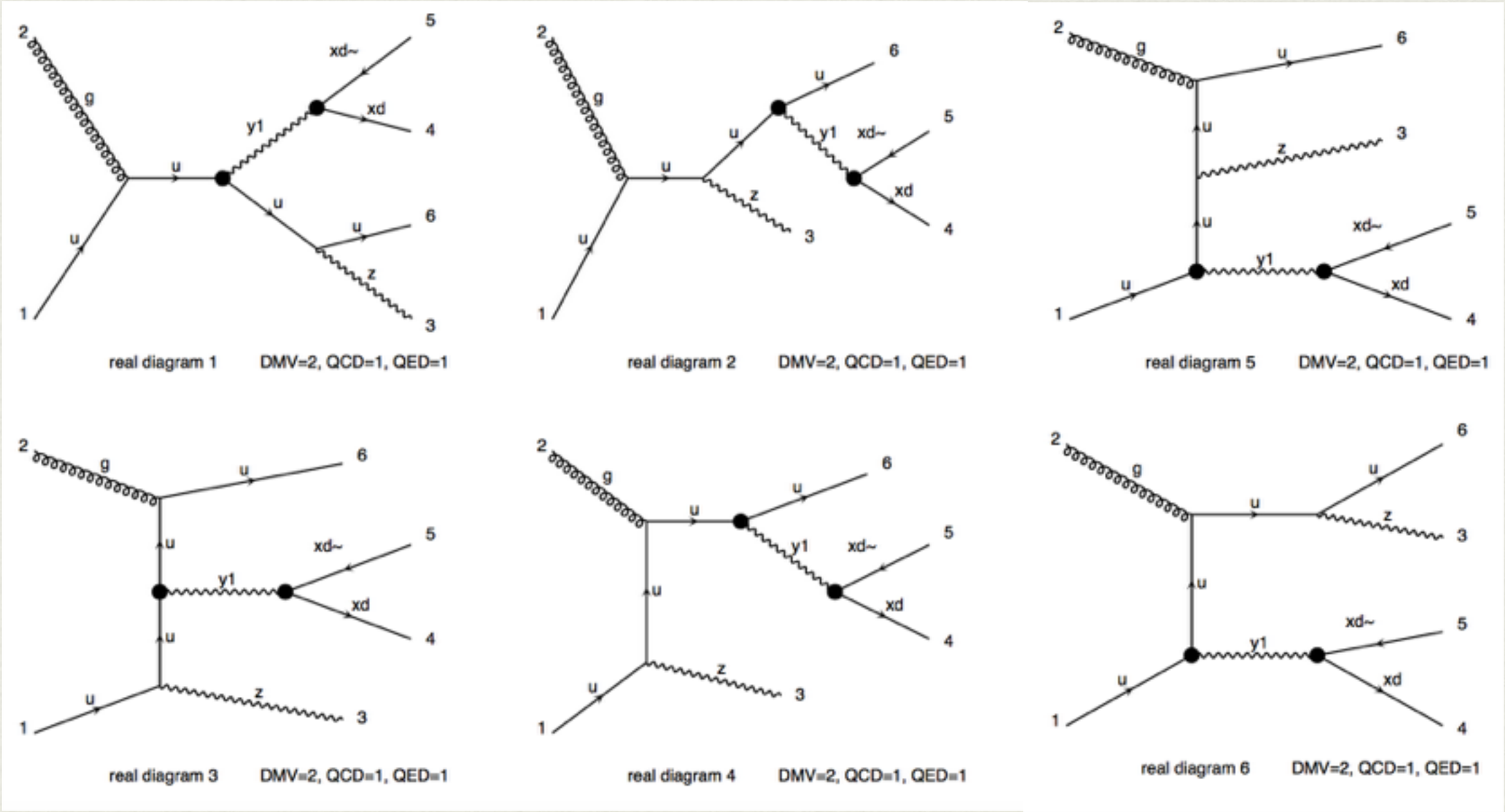
| | | | | | |
|---|---|---|---|---|---|
| P0_uux_zxdxdx | born | 2 | 1 | postscript | u u~ > z xd xd~ WEIGHTED=6 DMV=2 [ QCD ] |
| | virt | 8 | 1 | postscript | u u~ > z xd xd~ WEIGHTED=6 QED=1 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | u u~ > z xd xd~ g WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | g u~ > z xd xd~ u~ WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | u g > z xd xd~ u WEIGHTED=7 DMV=2 [ QCD ] |

# QCD corrections: real (qq channel)



| | | | | | |
|---|---|---|---|---|---|
| P0_uux_zxdxdx | born | 2 | 1 | postscript | u u~ > z xd xd~ WEIGHTED=6 DMV=2 [ QCD ] |
| | virt | 8 | 1 | postscript | u u~ > z xd xd~ WEIGHTED=6 QED=1 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | u u~ > z xd xd~ g WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | g u~ > z xd xd~ u~ WEIGHTED=7 DMV=2 [ QCD ] |
| | real | 6 | 1 | postscript | u g > z xd xd~ u WEIGHTED=7 DMV=2 [ QCD ] |

# QCD corrections: real (qg channel)



To run process:

```
>import model DMsimp_s_spin1_EW_UFO
>define p = p b b~
>define j = p
>generate p p > z xd xd~ [QCD]
>output monoz
>launch
```

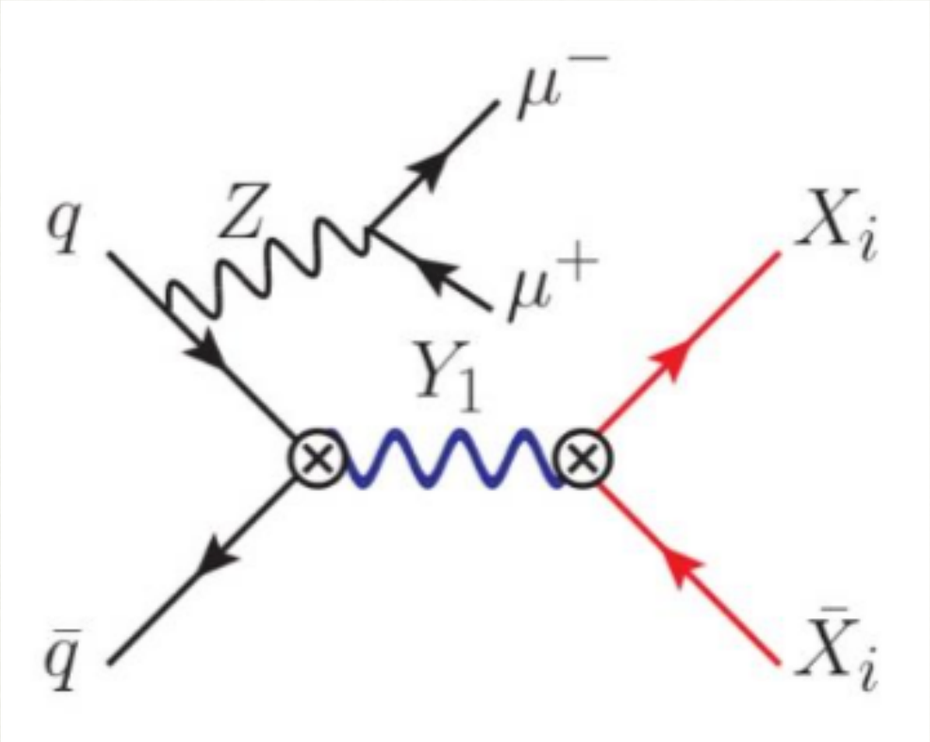
Run mode:

```
The following switches determine which operations are executed:
 1 Perturbative order of the calculation:                          order=NLO
 2 Fixed order (no event generation and no MC@[N]LO matching):   fixed_order=OFF
 3 Shower the generated events:                                     shower=ON
 4 Decay particles with the MadSpin module:                        madspin=OFF
  Either type the switch number (1 to 4) to change its default setting,
  or set any switch explicitly (e.g. type 'order=LO' at the prompt)
  Type '0', 'auto', 'done' or just press enter when you are done.
 [0, 1, 2, 3, 4, auto, done, order=LO, order=NLO, ... ][60s to answer]
>
```

Parameters:

```
Do you want to edit a card (press enter to bypass editing)?
  1 / param      : param_card.dat
  2 / run        : run_card.dat
  3 / shower     : shower_card.dat
 you can also
   - enter the path to a valid card or banner.
   - use the 'set' command to modify a parameter directly.
     The set option works only for param_card and run_card.
     Type 'help set' for more information on this command.
   - call an external program (ASperGE/MadWidth/...).
     Type 'help' for the list of available command
 [0, done, 1, param, 2, run, 3, shower, enter path]
>
```

```
##################################
## INFORMATION FOR DMINPUTS
##################################
Block dminputs
     1 1.000000e+04 # Lambda
     2 0.000000e+00 # gVXc
     3 1.000000e+00 # gVXd
     4 0.000000e+00 # gAXd
     5 2.500000e-01 # gVd11
     6 2.500000e-01 # gVu11
     7 2.500000e-01 # gVd22
     8 2.500000e-01 # gVu22
     9 2.500000e-01 # gVd33
    10 2.500000e-01 # gVu33
    11 0.000000e+00 # gAd11
    12 0.000000e+00 # gAu11
    13 0.000000e+00 # gAd22
    14 0.000000e+00 # gAu22
    15 0.000000e+00 # gAd33
    16 0.000000e+00 # gAu33
    17 0.000000e+00 # gVh
```




$$\mathcal{L}_{\rm SM}^{Y_1} = \sum_{i,j} \left[ \bar{d}_i \gamma_\mu \left( g_{d_{ij}}^V + g_{d_{ij}}^A \gamma_5 \right) d_j + \bar{u}_i \gamma_\mu \left( g_{u_{ij}}^V + g_{u_{ij}}^A \gamma_5 \right) u_j \right] Y_1^\mu$$

$$\mathcal{L}_{\rm DM}^{Y_1} = \frac{i}{2} g_{X_C}^V \left[ X_C^* (\partial_\mu X_C) - (\partial_\mu X_C^*) X_C \right] Y_1^\mu + \overline{X}_D \gamma_\mu \left( g_{X_D}^V + g_{X_D}^A \gamma_5 \right) X_D Y_1^\mu$$

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     1 1.000000e+04 # Lambda
     2 0.000000e+00 # gVXc
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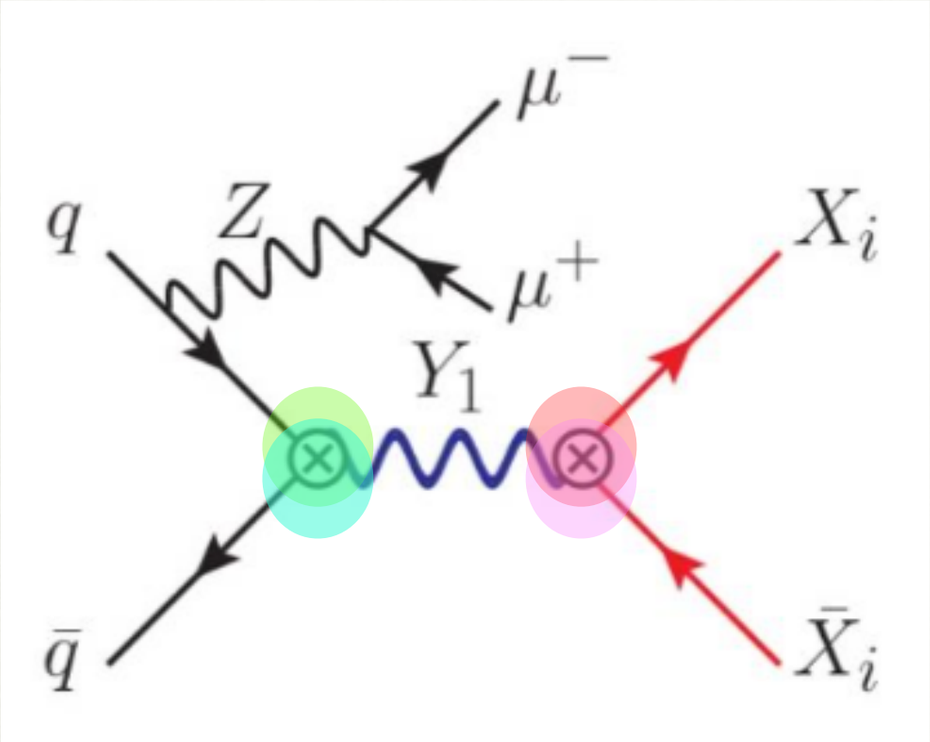
     4 0.000000e+00 # gAXd
     5 2.500000e-01 # gVd11
     6 2.500000e-01 # gVu11
     7 2.500000e-01 # gVd22
     8 2.500000e-01 # gVu22
     9 2.500000e-01 # gVd33
    10 2.500000e-01 # gVu33
    11 0.000000e+00 # gAd11
    12 0.000000e+00 # gAu11
    13 0.000000e+00 # gAd22
    14 0.000000e+00 # gAu22
    15 0.000000e+00 # gAd33
    16 0.000000e+00 # gAu33
    17 0.000000e+00 # gVh
```



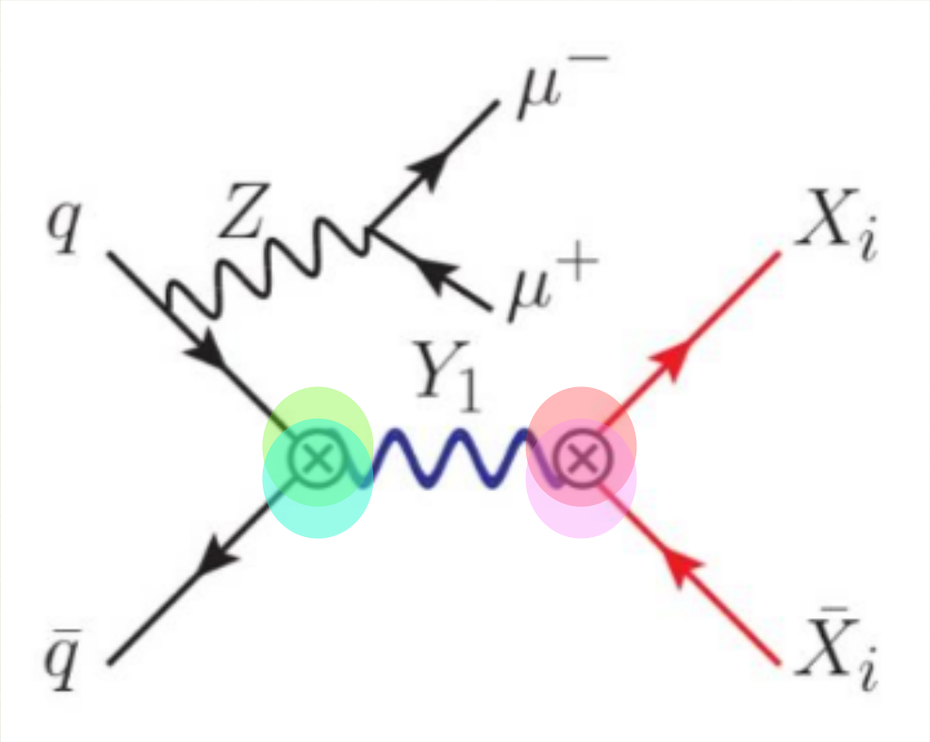

CP-even/CP-odd SM-Y1

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

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

CP-even/CP-odd DM-Y1

```
##################################
## INFORMATION FOR DMINPUTS
##################################
Block dminputs
     1 1.000000e+04 # Lambda
     2 0.000000e+00 # gVXc
     3 1.000000e+00 # gVXd
     4 0.000000e+00 # gAXd
     5 2.500000e-01 # gVd11
     6 2.500000e-01 # gVu11
     7 2.500000e-01 # gVd22
     8 2.500000e-01 # gVu22
     9 2.500000e-01 # gVd33
    10 2.500000e-01 # gVu33
    11 0.000000e+00 # gAd11
    12 0.000000e+00 # gAu11
    13 0.000000e+00 # gAd22
    14 0.000000e+00 # gAu22
    15 0.000000e+00 # gAd33
    16 0.000000e+00 # gAu33
    17 0.000000e+00 # gVh
```




CP-even/CP-odd SM-Y1

$$\mathcal{L}_{\rm SM}^{Y_1} = \sum_{i,j} \left[ \bar{d}_i \gamma_\mu \left( g_{d_{ij}}^V + g_{d_{ij}}^A \gamma_5 \right) d_j + \bar{u}_i \gamma_\mu \left( g_{u_{ij}}^V + g_{u_{ij}}^A \gamma_5 \right) u_j \right] Y_1^\mu$$

$$\mathcal{L}_{\rm DM}^{Y_1} = \frac{i}{2} g_{X_C}^V \left[ X_C^* (\partial_\mu X_C) - (\partial_\mu X_C^*) X_C \right] Y_1^\mu + \overline{X}_D \gamma_\mu \left( g_{X_D}^V + g_{X_D}^A \gamma_5 \right) X_D Y_1^\mu$$

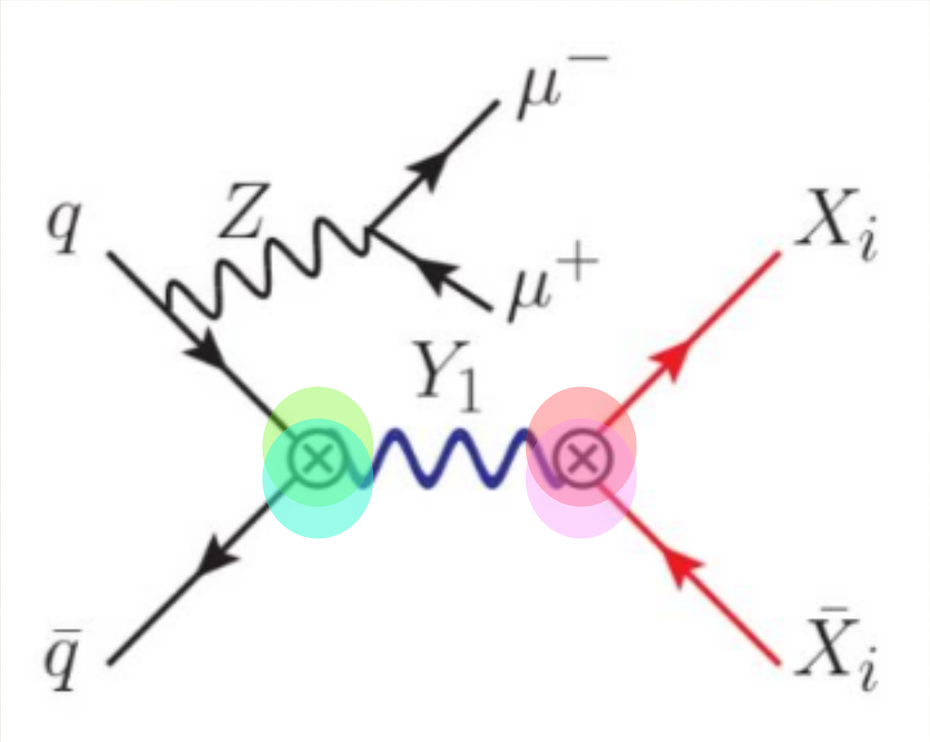
CP-even/CP-odd DM-Y1

Mass & width

```
    52 1.000000e+01 # MXd
    55 1.000000e+03 # MY1
```

```
DECAY  55 Auto          # WY1
```

```
##################################
## INFORMATION FOR DMINPUTS
##################################
Block dminputs
     1 1.000000e+04 # Lambda
     2 0.000000e+00 # gVXc
     3 1.000000e+00 # gVXd
     4 0.000000e+00 # gAXd
     5 2.500000e-01 # gVd11
     6 2.500000e-01 # gVu11
     7 2.500000e-01 # gVd22
     8 2.500000e-01 # gVu22
     9 2.500000e-01 # gVd33
    10 2.500000e-01 # gVu33
    11 0.000000e+00 # gAd11
    12 0.000000e+00 # gAu11
    13 0.000000e+00 # gAd22
    14 0.000000e+00 # gAu22
    15 0.000000e+00 # gAd33
    16 0.000000e+00 # gAu33
    17 0.000000e+00 # gVh
```




CP-even/CP-odd SM-Y1

$$\mathcal{L}_{\rm SM}^{Y_1} = \sum_{i,j} \left[ \bar{d}_i \gamma_\mu \left( g_{d_{ij}}^V + g_{d_{ij}}^A \gamma_5 \right) d_j + \bar{u}_i \gamma_\mu \left( g_{u_{ij}}^V + g_{u_{ij}}^A \gamma_5 \right) u_j \right] Y_1^\mu$$

$$\mathcal{L}_{\rm DM}^{Y_1} = \frac{i}{2} g_{X_C}^V \left[ X_C^* (\partial_\mu X_C) - (\partial_\mu X_C^*) X_C \right] Y_1^\mu + \overline{X}_D \gamma_\mu \left( g_{X_D}^V + g_{X_D}^A \gamma_5 \right) X_D Y_1^\mu$$

CP-even/CP-odd DM-Y1

Mass & width

```
    52 1.000000e+01 # MXd
    55 1.000000e+03 # MY1
```

```
DECAY  55 Auto          # WY1
```

Find results at some_DIR/crossx.html

| Run | Collider | Banner | Cross section (pb) | Events | Data | Output | Action |
|---|---|---|---|---|---|---|---|
| run_01 | p p<br>6500 x 6500 GeV | tag_1 | 0.2627 ± 0.00054 | 10000 | parton aMC@NLO | LHE | remove run |
| | | | | | shower aMC@NLO | HEP | remove run |

cross section details

showered events

Find results at some_DIR/crossx.html

| Run | Collider | Banner | Cross section (pb) | Events | Data | Output | Action |
|---|---|---|---|---|---|---|---|
| run_01 | p p<br>6500 x 6500 GeV | tag_1 | 0.2627 ± 0.00054 | 10000 | parton aMC@NLO | LHE | remove run |
| | | | | | shower aMC@NLO | HEP | remove run |

cross section details

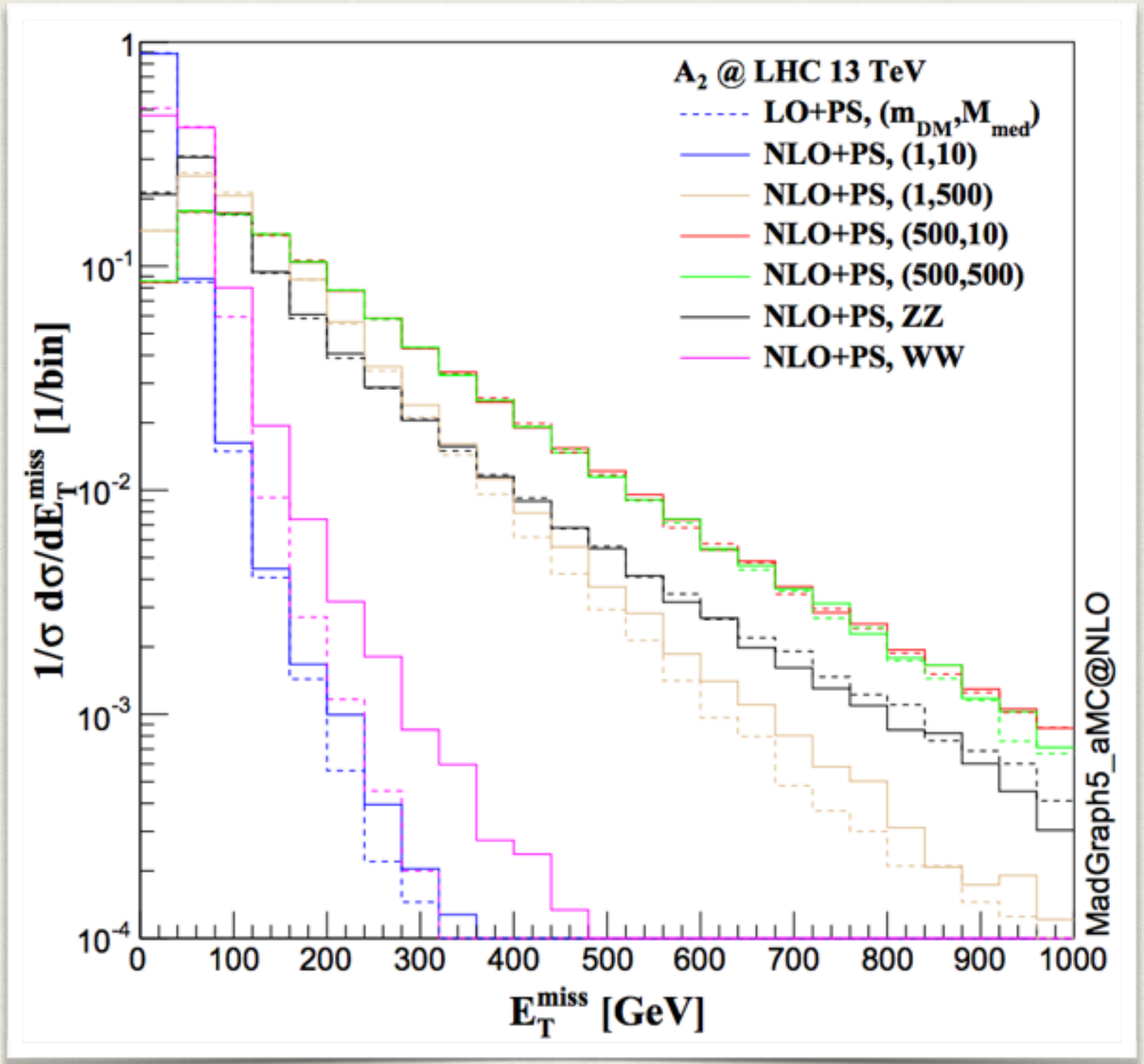
showered events

e.g. cross sections for axial coupling case, LHC13, in pb

| $m_{DM}$ [GeV] | $M_{med}$ [GeV] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 20 (15) | 50 | 100 (95) | 200 | 300 (295) | 500 | 1000 (995) | 2000 (1995) | 10000 |
| 1 | 8.5 | 3.5 | 1.0 | 0.35 | 0.10 | 4.5e-2 | 1.3e-2 | 1.7e-3 | 1.1e-4 | 1.3e-8 |
| 10 | 4.6e-2 | 5.8e-2 | 0.90 | 0.34 | | | | | | 1.3e-8 |
| 50 | 2.5e-3 | | 2.9e-3 | 6.6e-3 | 8.0e-2 | 4.1e-2 | | | | 1.2e-8 |
| 150 | 2.0e-4 | | | | 3.0e-4 | 8.5e-4 | 8.8e-3 | 1.6e-3 | | 1.0e-8 |
| 500 | 3.5e-6 | | | | | | 4.5e-6 | 2.8e-5 | 7.8e-5 | 4.1e-9 |
| 1000 | 1e-7 | | | | | | | 1.4e-7 | 1.3e-6 | 9.4e-10 |
| $m_{DM}$ [GeV] | $K$-factor | | | | | | | | | |
| 1 | 1.57 | 1.46 | 1.49 | 1.48 | 1.42 | 1.39 | 1.38 | 1.35 | 1.29 | 1.29 |
| 10 | 1.49 | 1.50 | 1.48 | 1.47 | | | | | | 1.29 |
| 50 | 1.41 | | 1.42 | 1.43 | 1.42 | 1.41 | | | | 1.29 |
| 150 | 1.38 | | | | 1.38 | 1.39 | 1.40 | 1.36 | | 1.29 |
| 500 | 1.33 | | | | | | 1.34 | 1.36 | 1.29 | 1.23 |
| 1000 | 1.21 | | | | | | | 1.22 | 1.27 | 1.09 |

Benchmark points are chosen according to DM forum
[1507.00966 Daniel Abercrombie et al.]

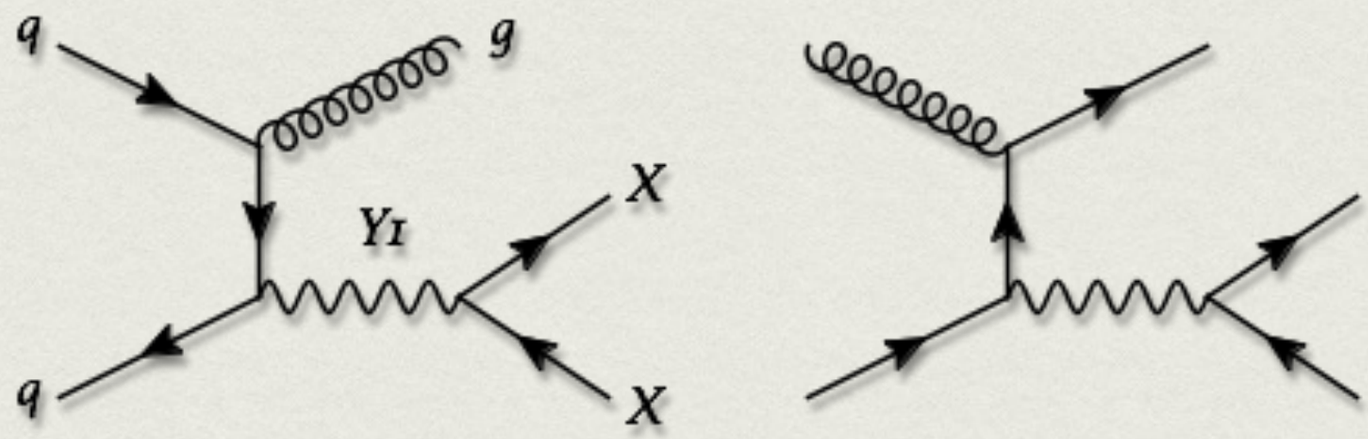
# Distributions (with parton shower)




More details in

[1509.05785 Neubert, Wang and CZ]

# Example 2: mono-jet

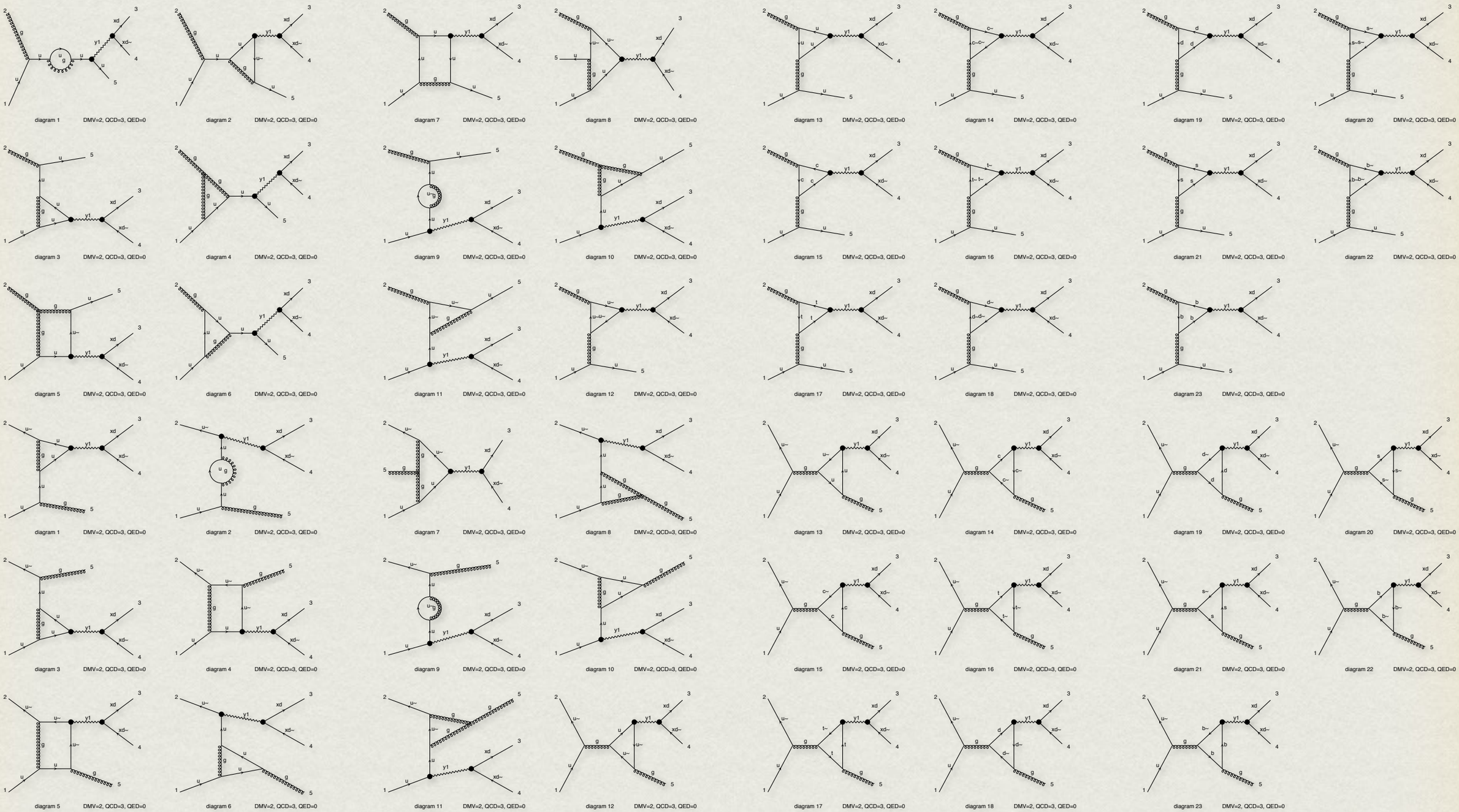



```
>import model DMsimp_s_spin1_EW_UFO
>define p = p b b~
>define j = p
>generate p p > j xd xd~ [QCD]
>output some_DIR
>launch
```

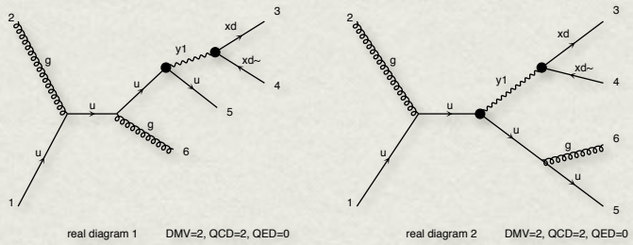
# A list of sub-channels for mono-jet

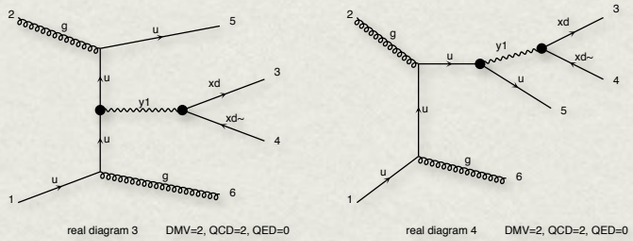
| | | | | | |
|---|---|---|---|---|---|
| P0_ug_xdxdxu | born | 2 | 1 | postscript | u g > xd xd~ u WEIGHTED=5 DMV=2 [ QCD ] |
| | virt | 23 | 1 | postscript | u g > xd xd~ u WEIGHTED=5 DMV=2 QCD=1 [ QCD ] |
| | real | 8 | 1 | postscript | u g > xd xd~ u g WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u s > xd xd~ u s WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u b~ > xd xd~ u b~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u b > xd xd~ u b WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 8 | 1 | postscript | g g > xd xd~ u u~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 8 | 1 | postscript | u u~ > xd xd~ u u~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 8 | 1 | postscript | u u > xd xd~ u u WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u c~ > xd xd~ u c~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u c > xd xd~ u c WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u d~ > xd xd~ u d~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u d > xd xd~ u d WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u s~ > xd xd~ u s~ WEIGHTED=6 DMV=2 [ QCD ] |
| P0_uux_xdxdxg | born | 2 | 1 | postscript | u u~ > xd xd~ g WEIGHTED=5 DMV=2 [ QCD ] |
| | virt | 23 | 1 | postscript | u u~ > xd xd~ g WEIGHTED=5 DMV=2 QCD=1 [ QCD ] |
| | real | 8 | 1 | postscript | u u~ > xd xd~ g g WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 8 | 1 | postscript | g u~ > xd xd~ u~ g WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 8 | 1 | postscript | u g > xd xd~ u g WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 8 | 1 | postscript | u u~ > xd xd~ u u~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u u~ > xd xd~ c c~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u u~ > xd xd~ d d~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u u~ > xd xd~ s s~ WEIGHTED=6 DMV=2 [ QCD ] |
| | real | 4 | 1 | postscript | u u~ > xd xd~ b b~ WEIGHTED=6 DMV=2 [ QCD ] |

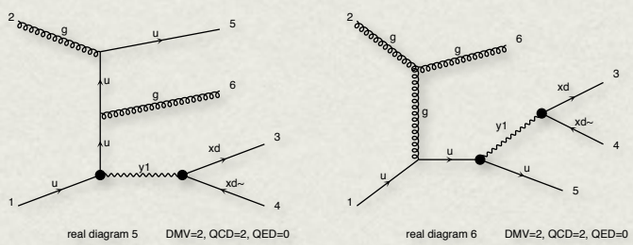
# Virtual correction (gu and uubar channel)

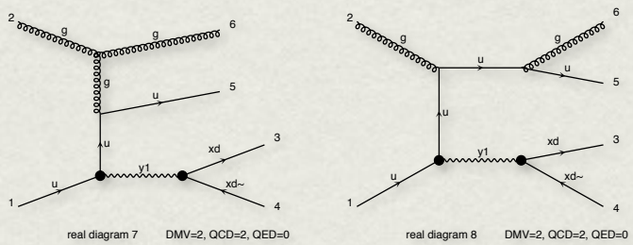


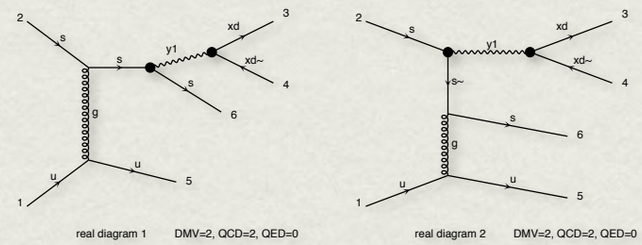
# Real correction (gu, uubar and uqbar channels)

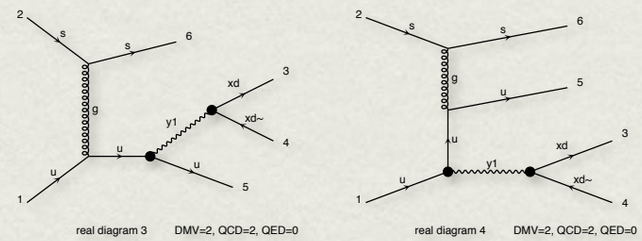


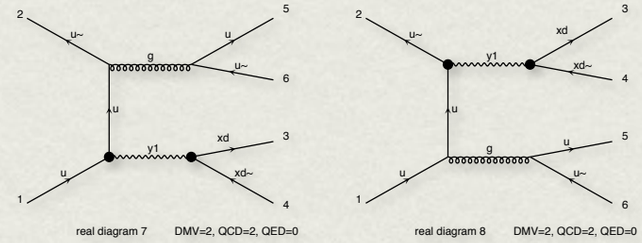



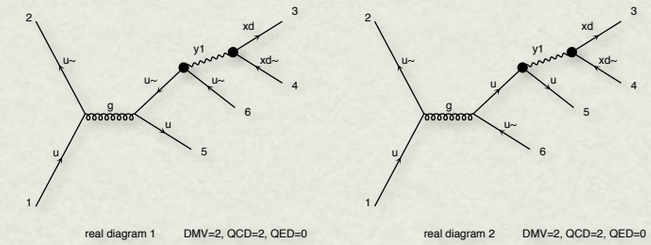



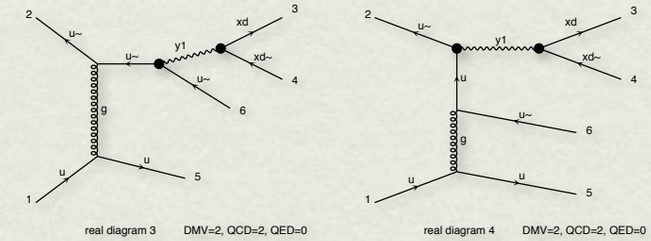



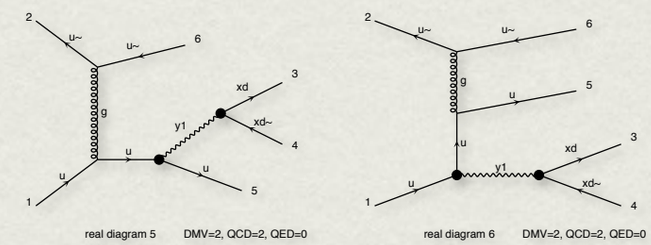




- More complicated than mono-Z.

  *...but, other than this there is no real difference than mono-Z channel*

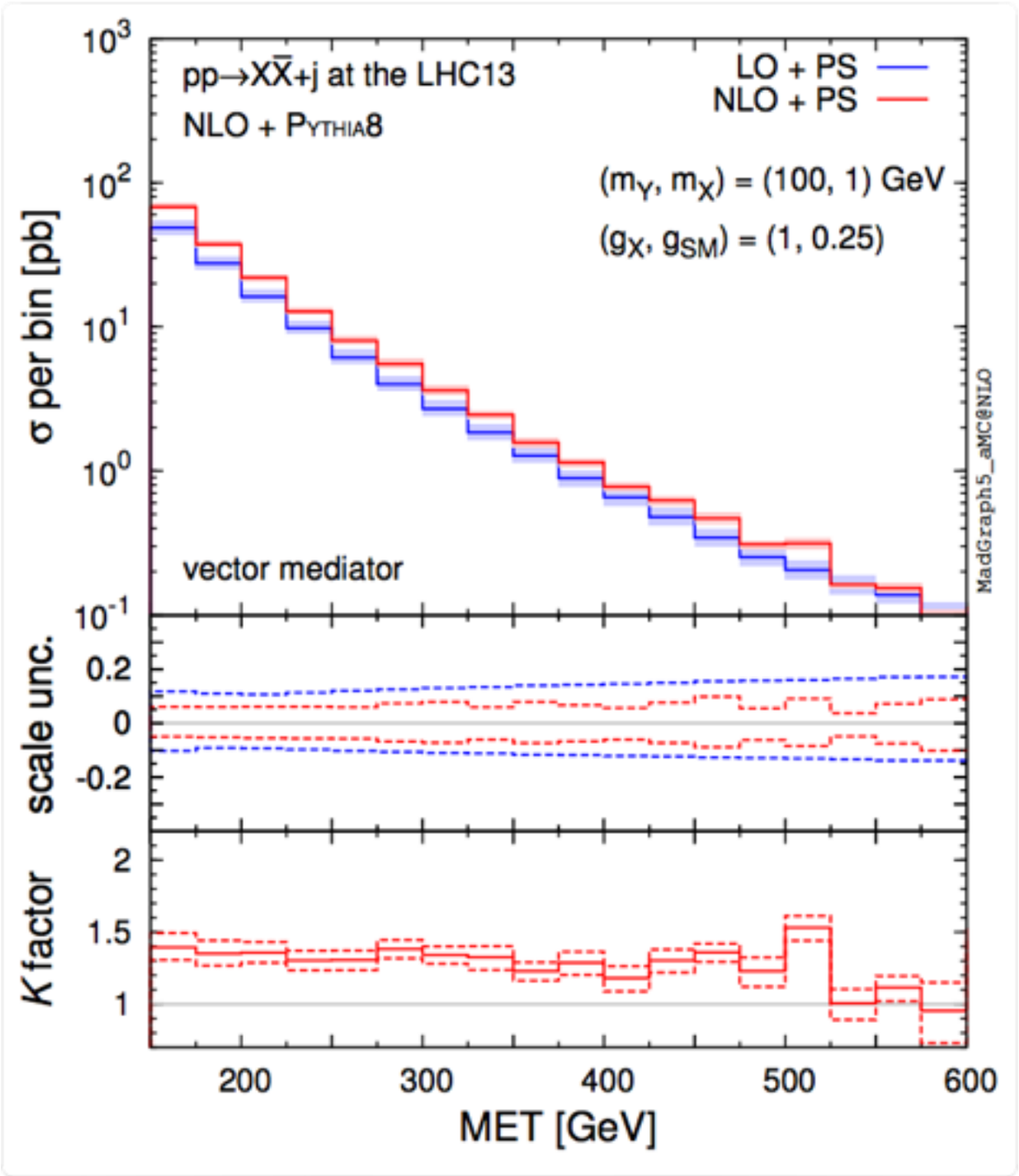
# Some results for mono-j: total cross sections at LHC13

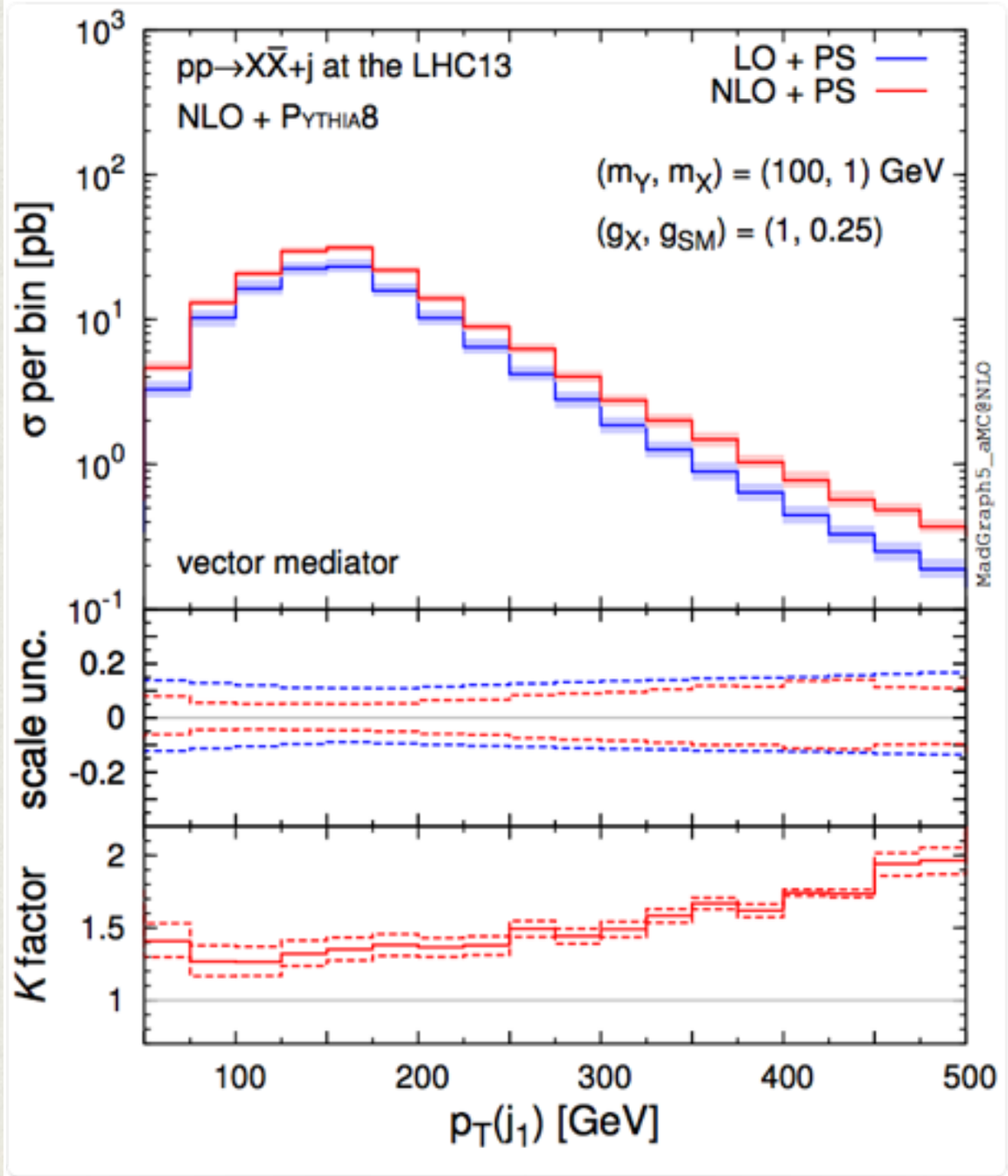
[arXiv:1508.05327 Backovic et al.]

| $(m_Y, m_X)$ [GeV] | | | vector | | |
|---|---|---|---|---|---|
| | | | MET > 150 GeV | MET > 300 GeV | MET > 500 GeV |
| 10 | undecayed | $\sigma_{\rm LO}$ [pb] | $2.923 \times 10^{2}\,^{+10.7}_{-8.9}\,\pm 1.6\,\%$ | $1.734 \times 10^{1}\,^{+14.2}_{-11.9}\,\pm 1.1\,\%$ | $1.695 \times 10^{0}\,^{+17.4}_{-14.0}\,\pm 1.8\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $5.093 \times 10^{2}\,^{+10.3}_{-8.2}\,\pm 0.5\,\%$ | $2.689 \times 10^{1}\,^{+10.4}_{-9.1}\,\pm 0.6\,\%$ | $2.433 \times 10^{0}\,^{+11.1}_{-10.0}\,\pm 1.1\,\%$ |
| | | $K$ factor | 1.74 | 1.55 | 1.44 |
| (10, 1) | $m_Y > 2m_X$ | $\sigma_{\rm LO}$ [pb] | $1.605 \times 10^{2}\,^{+10.7}_{-8.9}\,\pm 1.6\,\%$ | $0.978 \times 10^{1}\,^{+14.3}_{-12.0}\,\pm 1.1\,\%$ | $0.970 \times 10^{0}\,^{+17.4}_{-14.1}\,\pm 2.0\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $2.818 \times 10^{2}\,^{+10.1}_{-8.1}\,\pm 0.5\,\%$ | $1.517 \times 10^{1}\,^{+10.0}_{-8.9}\,\pm 0.6\,\%$ | $1.345 \times 10^{0}\,^{+10.5}_{-9.6}\,\pm 1.1\,\%$ |
| | | $K$ factor | 1.76 | 1.55 | 1.39 |
| (10, 50) | $m_Y < 2m_X$ | $\sigma_{\rm LO}$ [pb] | $2.434 \times 10^{0}\,^{+11.8}_{-10.1}\,\pm 1.5\,\%$ | $2.843 \times 10^{-1}\,^{+15.0}_{-12.5}\,\pm 1.2\,\%$ | $3.786 \times 10^{-2}\,^{+18.0}_{-14.5}\,\pm 2.4\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $3.198 \times 10^{0}\,^{+5.6}_{-5.4}\,\pm 0.5\,\%$ | $3.485 \times 10^{-1}\,^{+5.9}_{-6.3}\,\pm 0.7\,\%$ | $4.325 \times 10^{-2}\,^{+7.3}_{-7.8}\,\pm 1.3\,\%$ |
| | | $K$ factor | 1.31 | 1.23 | 1.14 |
| (10, 500) | $m_Y < 2m_X$ | $\sigma_{\rm LO}$ [pb] | $6.968 \times 10^{-3}\,^{+17.4}_{-14.0}\,\pm 4.3\,\%$ | $2.314 \times 10^{-3}\,^{+18.9}_{-15.0}\,\pm 4.6\,\%$ | $7.317 \times 10^{-4}\,^{+20.6}_{-16.1}\,\pm 5.6\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $7.698 \times 10^{-3}\,^{+5.4}_{-6.4}\,\pm 2.2\,\%$ | $2.385 \times 10^{-3}\,^{+5.7}_{-6.9}\,\pm 2.3\,\%$ | $6.800 \times 10^{-4}\,^{+5.5}_{-7.1}\,\pm 2.6\,\%$ |
| | | $K$ factor | 1.10 | 1.03 | 0.93 |
| 1000 | undecayed | $\sigma_{\rm LO}$ [pb] | $2.248 \times 10^{0}\,^{+16.1}_{-13.2}\,\pm 3.2\,\%$ | $6.865 \times 10^{-1}\,^{+17.7}_{-14.3}\,\pm 3.3\,\%$ | $1.979 \times 10^{-1}\,^{+19.6}_{-15.5}\,\pm 4.1\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $2.601 \times 10^{0}\,^{+5.1}_{-6.0}\,\pm 1.7\,\%$ | $7.393 \times 10^{-1}\,^{+5.2}_{-6.4}\,\pm 1.8\,\%$ | $1.909 \times 10^{-1}\,^{+5.3}_{-6.8}\,\pm 2.1\,\%$ |
| | | $K$ factor | 1.16 | 1.08 | 0.96 |
| (1000, 1) | $m_Y > 2m_X$ | $\sigma_{\rm LO}$ [pb] | $1.093 \times 10^{0}\,^{+16.4}_{-13.3}\,\pm 3.1\,\%$ | $3.278 \times 10^{-1}\,^{+18.0}_{-14.4}\,\pm 3.3\,\%$ | $9.182 \times 10^{-2}\,^{+19.7}_{-15.6}\,\pm 4.1\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $1.215 \times 10^{0}\,^{+4.2}_{-5.5}\,\pm 1.7\,\%$ | $3.399 \times 10^{-1}\,^{+4.5}_{-6.0}\,\pm 1.7\,\%$ | $8.743 \times 10^{-2}\,^{+4.8}_{-6.5}\,\pm 2.0\,\%$ |
| | | $K$ factor | 1.11 | 1.04 | 0.95 |
| (1000, 50) | $m_Y > 2m_X$ | $\sigma_{\rm LO}$ [pb] | $1.094 \times 10^{0}\,^{+16.4}_{-13.3}\,\pm 3.1\,\%$ | $3.268 \times 10^{-1}\,^{+18.0}_{-14.4}\,\pm 3.3\,\%$ | $9.137 \times 10^{-2}\,^{+19.7}_{-15.6}\,\pm 4.1\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $1.221 \times 10^{0}\,^{+4.3}_{-5.6}\,\pm 1.7\,\%$ | $3.416 \times 10^{-1}\,^{+4.6}_{-6.0}\,\pm 1.7\,\%$ | $8.807 \times 10^{-2}\,^{+4.9}_{-6.6}\,\pm 2.0\,\%$ |
| | | $K$ factor | 1.12 | 1.05 | 0.96 |
| (995, 500) | $m_Y \lesssim 2m_X$ | $\sigma_{\rm LO}$ [pb] | $2.169 \times 10^{-1}\,^{+16.4}_{-13.3}\,\pm 3.4\,\%$ | $6.777 \times 10^{-2}\,^{+18.0}_{-14.4}\,\pm 3.6\,\%$ | $1.981 \times 10^{-2}\,^{+19.7}_{-15.6}\,\pm 4.4\,\%$ |
| | | $\sigma_{\rm NLO}$ [pb] | $2.497 \times 10^{-1}\,^{+5.3}_{-6.2}\,\pm 1.8\,\%$ | $7.223 \times 10^{-2}\,^{+5.5}_{-6.6}\,\pm 1.9\,\%$ | $1.914 \times 10^{-2}\,^{+5.3}_{-6.8}\,\pm 2.1\,\%$ |
| | | $K$ factor | 1.15 | 1.07 | 0.97 |

# Some results for mono-j: MET and pt jet distributions at LHC13

[arXiv:1508.05327 Backovic et al.]



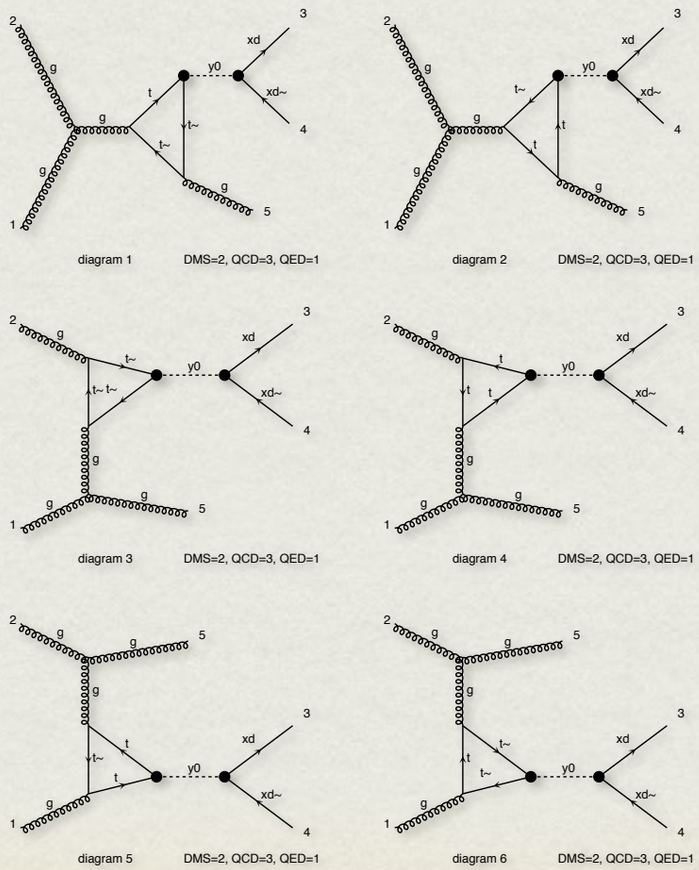



# Loop-induced

- **Loop-induced** processes are now available in MG5_aMC (version **5.2.3**).
  [V. Hirschi, O. Mattelaer 2015]
- Why is this important? It is likely that the **scalar mediator** couples proportional to quark masses, i.e. **mainly to the top**.
- Can be generated via

```
>import model DMsimp_s_spin0_EW_UFO
>define p = p b b~
>define j = p
>generate p p > j xd xd~ [noborn=QCD]
>output
```

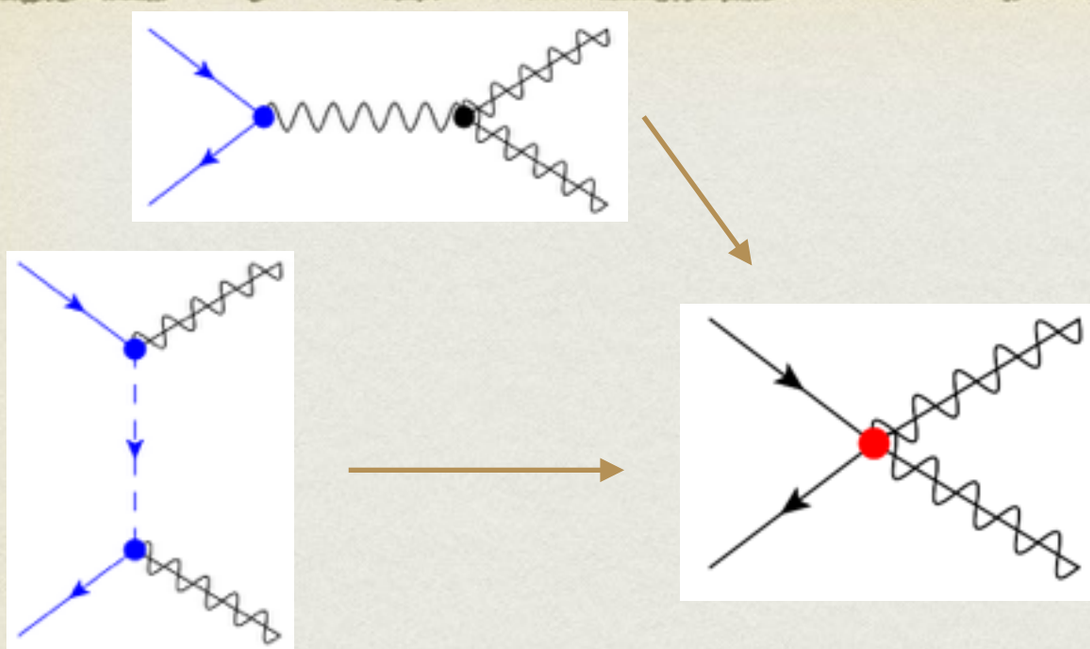
[1508.00564 O. Mattelaer, E. Vryonidou]



# Summary

- **s-channel DM simplified model** is implemented in the MG5_aMC framework.
  - It provides **automatic NLO QCD** prediction matched to **parton shower**.
  - In principle covers **any production channel**, such as mono-jet/Z/W/photon/Higgs/ttbar etc., plus loop-induced processes.
  - Available at http://feynrules.irmp.ucl.ac.be/wiki/DMsimp
- Mono-Z/jet/ttbar and some loop-induced processes have been studied with details.
- Things to do
  - Pheno studies of more channels.
  - Implementation of more models: t-channel mediator, Higgs portal, etc.

# Effective Field Theory



| Name | Type | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | 1 | 1 |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | 1 |
| M3 | $qq$ | $im_q/2M_*^3$ | 1 | $\gamma_5$ |
| M4 | $qq$ | $m_q/2M_*^3$ | $\gamma_5$ | $\gamma_5$ |
| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma^\mu$ |
| M6 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma_5\gamma^\mu$ |
| M7 | $GG$ | $\alpha_s/8M_*^3$ | 1 | - |
| M8 | $GG$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |
| M9 | $G\tilde{G}$ | $\alpha_s/8M_*^3$ | 1 | - |
| M10 | $G\tilde{G}$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |

J. Goodman et al 2010;

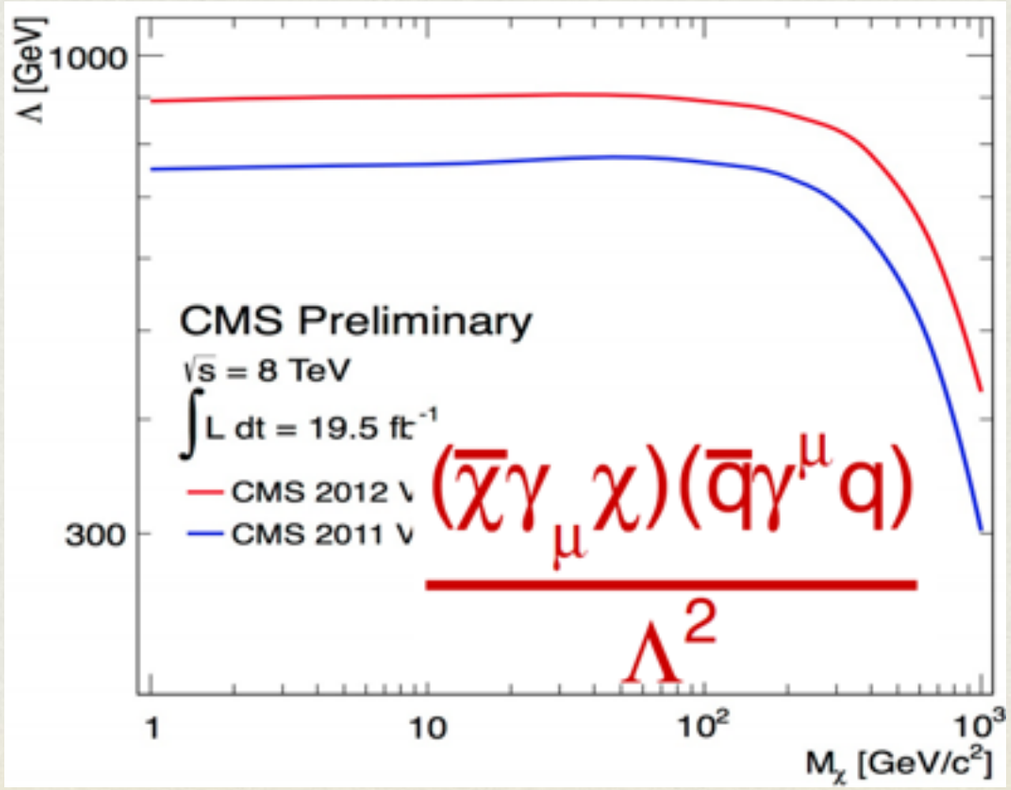
Y.Bai et al 2010;

Q.H.Cao et al 2009;

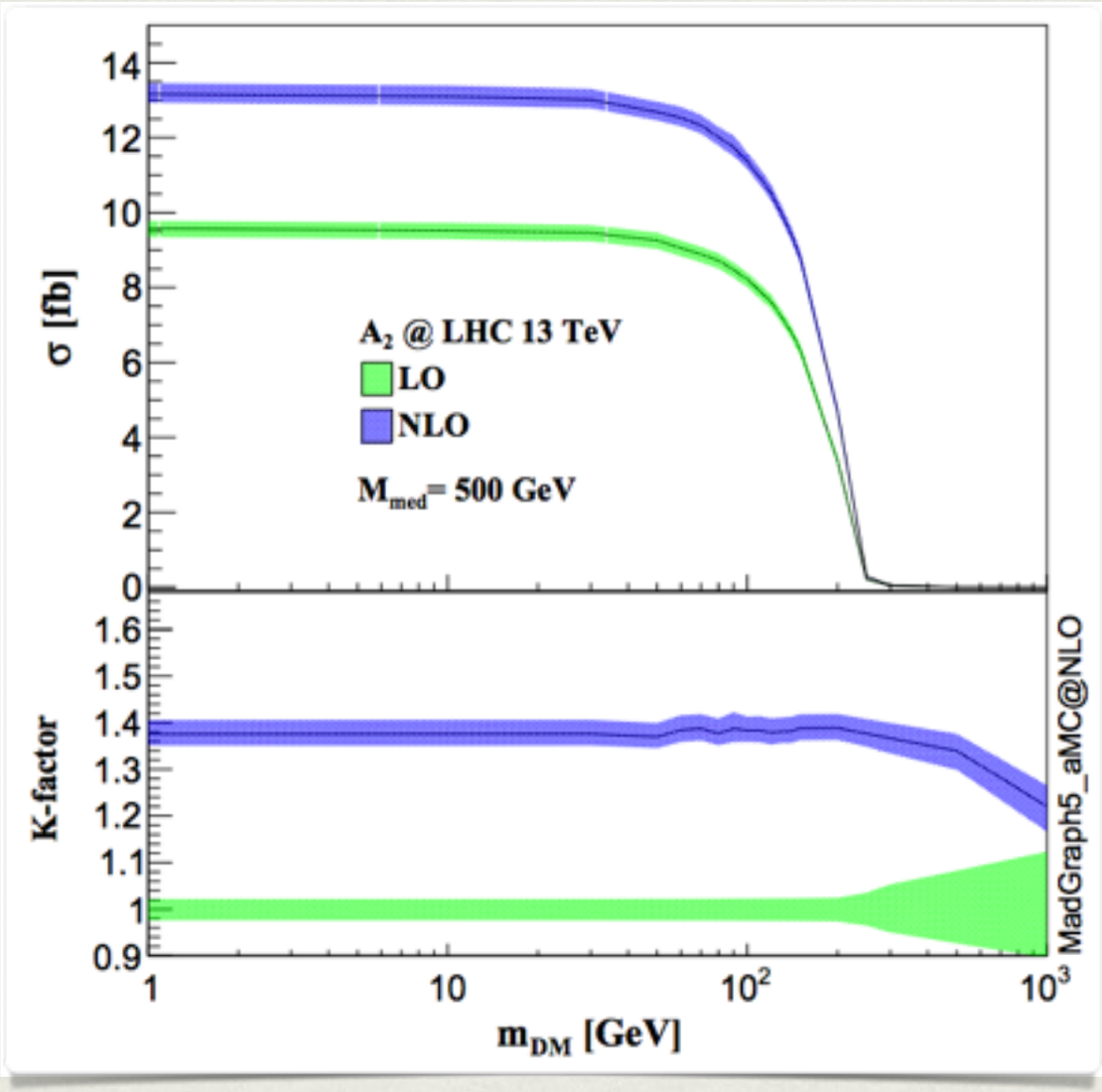
M. Beltran et al 2010;

P. J. Fox et al 2011

- **Run-I** mainly based on EFT.
- **NLO** available for mono-j and photon, in both **MCFM** and **POWHEG**.
- However, **validity** is always problem
  - bounds are at ~1 TeV but LHC can probe higher.
  - **Difficult to predict** where it breaks down: it depends on PDF and UV completion.



cross section vs. DM mass




Discovery limit LHC 13