t-channel dark matter at the LHC

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[See: Arina, Fuks & Mantani - 2001.05024 [hep-ph] (EPJC`20)]

LHC DM WG hands-on session

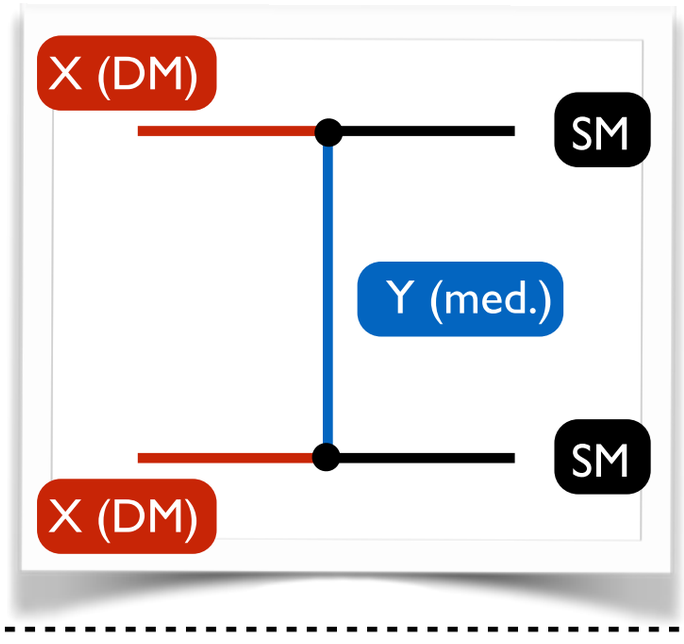
CERN, 28 April 2020

Outline

1. A short overview of the model
2. The tutorial example: the S3D model
3. Summary

A generic implementation for *t*-channel DM

✦ A generic *t*-channel DM modelling



- ✤ 2 spins: J_X, J_Y
- ✤ 13 masses:
  - ★ 1 DM mass: m_X
  - ★ 12 mediator masses (SM = Q_L, u_R, d_R)
- ✤ 9 couplings
  - ★ 3 vectors in flavour space
  - ★ SM = Q_L, u_R, d_R

Many free parameters / spin combination

✦ Spin options

X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{S}$	0	yes	ψ_Q, ψ_u, ψ_d	1/2
S	0	no		
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0
χ	1/2	no		
$\tilde{V}_\mu$	1	yes	ψ_Q, ψ_u, ψ_d	1/2
V_μ	1	no		

- ✤ Dark matter
  - ★ Spin 0, 1/2 and 1
  - ★ Majorana or not
- ✤ Mediators
  - ★ Spin 0 or 1/2 (no spin 1)
  - ★ Independent couplings to all gauge eigenstates

Model restrictions

✦ 18 restrictions with 3 parameters each

Name	DM	Mediators	Parameters
S3M_uni	$\tilde{\chi}$	φ_{Q_f}, φ_{u_f}, φ_{d_f}	M_φ, M_χ, λ_φ
S3D_uni	χ		
S3M_3rd	$\tilde{\chi}$	φ_{Q_3}, φ_{u_3}, φ_{d_3}	
S3D_3rd	χ		
S3M_uR	$\tilde{\chi}$	φ_{u_1}	
S3D_uR	χ		
F3S_uni	$\tilde{S}$	ψ_{Q_f}, ψ_{u_f}, ψ_{d_f}	M_S, M_ψ, $\hat{\lambda}_\psi$
F3C_uni	S		
F3S_3rd	$\tilde{S}$	ψ_{Q_3}, ψ_{u_3}, ψ_{d_3}	
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	ψ_{Q_f}, ψ_{u_f}, ψ_{d_f}	M_V, M_ψ, $\hat{\lambda}_\psi$
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	ψ_{Q_3}, ψ_{u_3}, ψ_{d_3}	
F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
F3W_uR	V_μ		

New restrictions trivial to implement

✤ Universal models (uni):

★ 1 dark matter particle

★ 12 mass-degenerate mediators

★ 1 flavour-conserving coupling

$$\mathcal{L}_{\texttt{X\_uni}}(X) = \sum_{F=Q,u,d} \sum_{f=1}^{3} \left[\lambda_\varphi \bar{X} F_f \varphi^\dagger_{F_f} + \text{h.c.}\right]$$

✤ 3rd generation models (3rd):

★ 1 dark matter particle

★ 4 mass-degenerate mediators

★ 1 flavour-conserving coupling

$$\mathcal{L}_{\texttt{X\_3rd}}(X) = \sum_{F=Q,u,d} \left[\lambda_\varphi \bar{X} F_3 \varphi^\dagger_{F_3} + \text{h.c.}\right]$$

✤ uR models (uR):

★ 1 dark matter particle

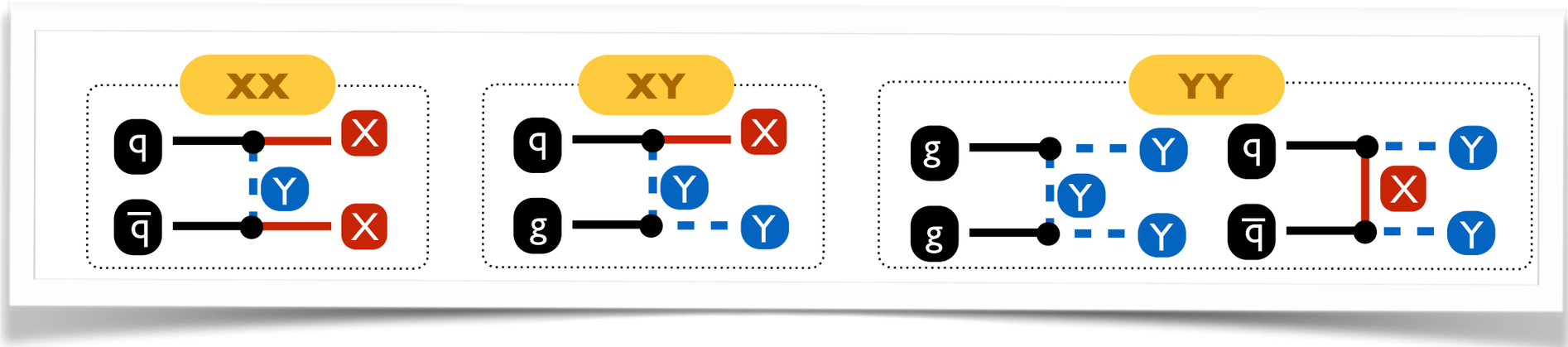
★ 1 mediator

★ Coupling to the right-handed up-quark

$$\mathcal{L}_{\texttt{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\right]$$

DM production at colliders: generalities

✦ Three classes of processes ⇝ jets generated from ISR or mediator decays



✤ The signal is less naive than from considering XX production only

★ DM pair production

★ DM/mediator associated production (+ mediator decays into DM+jet)

★ Mediator pair production (+ mediator decays into DM+jet)

✤ Mediator pair-production: *t*-channel and QCD contributions

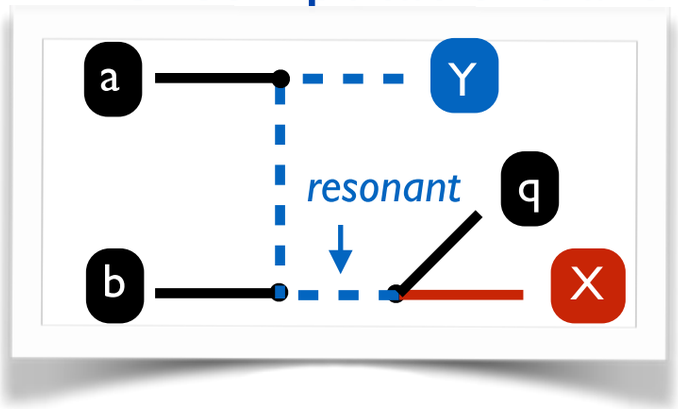
★ Model-dependent relative dominance ⇝ couplings, masses

★ Mixed order situation ⇝ to be simulated separately

★ Problem of the interference ⇝ re-weighted LO simulations

Resonance subtraction: generalities

✦ NLO computations are not trivial



✤ Overlap
- ★ YY @ LO ⊗ Y → Xq decay
- ★ YX @ NLO (real emission)

✤ Possible (huge) enhancement w.r.t. LO (if YY dominates over XY)
- ★ Spoiling the perturbative expansion for the original process

✤ All three subprocesses need to be considered separately to avoid double counting
- ★ Resonances must be subtracted

Diagram removal

✦ The full matrix element: one resonant and one non-resonant piece

$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\text{non-res.})}\right|^2 + 2\Re\left(\mathcal{A}^{(\text{non-res.})}\mathcal{A}^{(\text{res.})\dagger}\right) + \left|\mathcal{A}^{(\text{res.})}\right|^2$$

- ✤ The contribution of the last term to be minimised
- ✤ Diagram removal procedure: we drop diagrams

✦ Diagram removal

$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\text{non-res.})}\right|^2 + 2\Re\left(\mathcal{A}^{(\text{non-res.})}\mathcal{A}^{(\text{res.})\dagger}\right) + \left|\mathcal{A}^{(\text{res.})}\right|^2$$

- ✤ Any occurence of the resonant diagrams is removed

DR

✦ Diagram removal+interference

$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\text{non-res.})}\right|^2 + 2\Re\left(\mathcal{A}^{(\text{non-res.})}\mathcal{A}^{(\text{res.})\dagger}\right) + \left|\mathcal{A}^{(\text{res.})}\right|^2$$

- ✤ We only drop the squared piece
- ✤ The interference is kept

DR+I

Diagram subtraction (I)

✦ The full matrix element: one resonant and one non-resonant piece

$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\text{non-res.})}\right|^2 + 2\Re\left(\mathcal{A}^{(\text{non-res.})}\mathcal{A}^{(\text{res.})\dagger}\right) + \left|\mathcal{A}^{(\text{res.})}\right|^2$$

✦ We project the kinematics onto a resonant configuration

$$\left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi \quad \Rightarrow \quad \left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi - f(m^2)\ \mathbb{P}\left(\left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi\right)$$

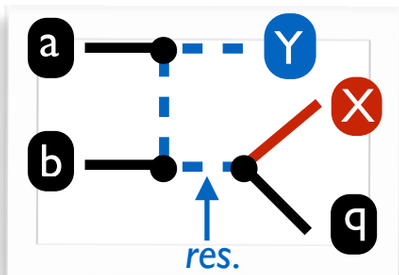
★ *t*-channel example: $m = m_{Xq} \sim m_Y$

✤ The projector operator ℙ

★ From an *n*-body kinematics to an $(n\text{-}1) \otimes (1 \to 2)$ kinematics

★ *t*-channel example:

$$\left|\mathcal{A}^{(\text{res.})}(ab \to XYq)\right|^2 = \left|\mathcal{A}(ab \to YY)\right|^2 \otimes \left|\mathcal{A}(Y \to Xq)\right|^2$$



✤ The pre-factor *f* is arbitrary (tends to 1 in the resonant limit)

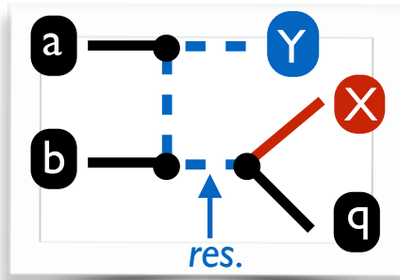
✦ Choices for the projector and pre-factor ⇝ different ways to subtract

Diagram subtraction (2)

Diagram subtraction

$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\text{non-res.})}\right|^2 + 2\Re\left(\mathcal{A}^{(\text{non-res.})}\mathcal{A}^{(\text{res.})\dagger}\right) + \left|\mathcal{A}^{(\text{res.})}\right|^2$$

$$\left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi \quad \Rightarrow \quad \left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi - f(m^2)\ \mathbb{P}\left(\left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi\right)$$



Initial-state reshuffling

- Projector: the final state momenta are unchanged
- Pre-factor: ratios of Breit-Wigner's

$$f(m^2) = \frac{\left[x\Gamma_{\text{res.}}\right]^2}{\left[m^2 - m_{\text{res.}}^2\right]^2 + \left[x\Gamma_{\text{res.}}\right]^2}$$

★ Option 1: $x = m_{\text{res.}}$ → t-ch.: $x = m_Y$ DS-1

★ Option 2: $x = m$ → t-ch.: $x = m_{Xq}$ DS-2

Final-state reshuffling

- Projector: the initial state momenta are unchanged
- Pre-factor: ratios of Breit-Wigner's (as above)

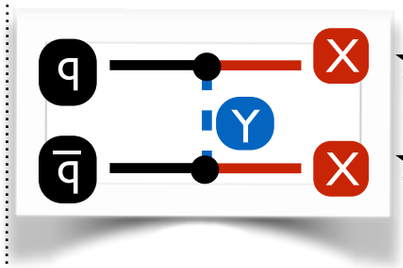
$$f(m^2) = \frac{\left[x\Gamma_{\text{res.}}\right]^2}{\left[m^2 - m_{\text{res.}}^2\right]^2 + \left[x\Gamma_{\text{res.}}\right]^2}$$

★ Option 1: $x = m_{\text{res.}}$ → t-ch.: $x = m_Y$ DS-3

★ Option 2: $x = m$ → t-ch.: $x = m_{Xq}$ DS-4

Summary - five processes to generate

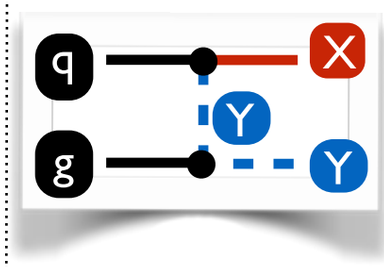
XX @ NLO



★ Jet activity → QCD radiation

★ Resonance: XY prod. + decay

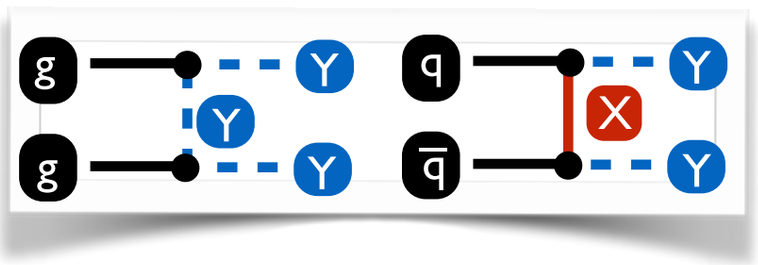
XY @ NLO



★ Jet activity → QCD radiation → mediator decay

★ Resonances: YY/XX prod. + decay (benchmark dependent)

YY @ NLO



★ Jet activity → QCD radiation and mediator decay

★ Resonance: YX production + (off-shell) decay

★ 2 interfering channels (from qqbar initials states)

Tutorial:
Event generation for 5 different processes

Outline

1. A short overview of the model

2. **The tutorial example: the S3D model**

3. Summary

Setup

MG5_aMC installation

✦ Event generator

- ✤ MG5_aMC version 2.6.x or 2.7.X (no 3.X)
  - ★ Necessary for the MADSTR plugin
- ✤ Installation of PYTHIA 8, NINJA and LHAPDF 6

```
install lhapdf6
install hepmc
install pythia8
install ninja
```

If PYTHIA8 installation fails (see GitHub folder):
install pythia8 --pythia8_tarball=<path-to-tarball>

✦ Parton densities

- ✤ Download the NNPDF3.0_nlo_as_0118 set from HepForge (or GitHub)
  - ★ To be put in *HEPTools/lhapdf6/share/LHAPDF*
- ✤ Update the environment variables (with absolute paths)
  - ★ Include the *<mg5-path>/HEPTools/lhapdf6/bin* folder in *$PYTHONPATH*
  - ★ Include the *<mg5-path>/HEPTools/lhapdf6/lib* folder in *$LD_LIBRARY_PATH*

✦ Model: DMSIMP-t

- ✤ Web: https://feynrules.irmp.ucl.ac.be/wiki/DMsimpt
  - ⇝ dmsimpt_v1.3.ufo.tgz (to be unpacked in the MG5 models directory)

⚠ The v1.3 of the UFO is required

MadSTR and MadAnalysis 5 installation

✦ MadSTR has to be downloaded from LaunchPad

- ✤ https://code.launchpad.net/~maddevelopers/mg5amcnlo/MadSTRPlugin
- ✤ Also available from GitHub (to be unpacked in the PLUGIN folder of MG5_aMC)

✦ Special way to start MG5_aMC: *./bin/mg5 --mode=MadSTR*

✦ Event reconstruction and analysis

- ✤ MadAnalysis 5 version 1.8.44
  - ★ Installed as a standalone package
    - ⇝ download from https://launchpad.net/madanalysis5
    - ⇝ unpack then *./bin/ma5*
- ✤ Including FastJet (event reconstruction through the anti-k_T algorithm)

install fastjet

Starting MG5_aMC with MadSTR

✦ Specific MG5 command to run the code

```
MG5_aMC>MG5_aMC>^D[fuks@LeMouth ~/Work/tools/madgraph/2.6.8$] ./bin/mg5_aMC --mode=MadSTR
Running MG5 in debug mode
Plugin PLUGIN.MadSTR has marked as NOT being validated with this version.
It has been validated for the last time with version: 2.5.0
************************************************************
*                                                          *
*                    W E L C O M E to                      *
*              M A D G R A P H 5 _ a M C @ N L O           *
*                                                          *
*                                                          *
*                  *                   *                   *
*                    *       * *       *                   *
*                      * * * * 5 * * * *                   *
*                    *       * *       *                   *
*                  *                   *                   *
*                                                          *
*         VERSION 2.6.7              2019-10-16            *
*         BZR 2.6.8                         290            *
*                                                          *
```

- ✤ Check of the MG5 version (not 3.X)
- ✤ Need of the --mode-MadSTR

Example: the S3D_uR case

✦ The S3D_uR model: Dirac DM couplings to the right-handed up quark

X (DM)	Spin	Self-conj.	Y (med.)	Spin
χ	1/2	no	φ_{u_1}	0

$$\mathcal{L}_{\text{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi_{u_1}^\dagger + \text{h.c.}\right]$$

- Benchmark: m_X = 150 GeV, m_Y = 500 GeV, λ=1
- Large DM-mediator coupling

✦ Importing the model in MG5

```
MadSTR > import model DMSimp_t-
DMSimp_t-F3C_3rd  DMSimp_t-F3S_3rd  DMSimp_t-F3V_3rd  DMSimp_t-F3W_3rd  DMSimp_t-S3D_3rd  DMSimp_t-S3M_3rd
DMSimp_t-F3C_uni  DMSimp_t-F3S_uni  DMSimp_t-F3V_uni  DMSimp_t-F3W_uni  DMSimp_t-S3D_uni  DMSimp_t-S3M_uni
DMSimp_t-F3C_uR   DMSimp_t-F3S_uR   DMSimp_t-F3V_uR   DMSimp_t-F3W_uR   DMSimp_t-S3D_uR   DMSimp_t-S3M_uR
MadSTR > import model DMSimp_t-S3D_uR --modelname
INFO: Restrict model DMSimp_t with file models/DMSimp_t/restrict_S3D_uR.dat .
```

- Tab completion can be used to check all available restrictions
- Extra restrictions can be created: models/DMSimp_t/restrict_XYZ.dat
  (XYZ being the new restriction name)
  - → Restrictions are special parameter cards (zero-parameters permanently removed)
  - → New restrictions implemented from standard parameter cards

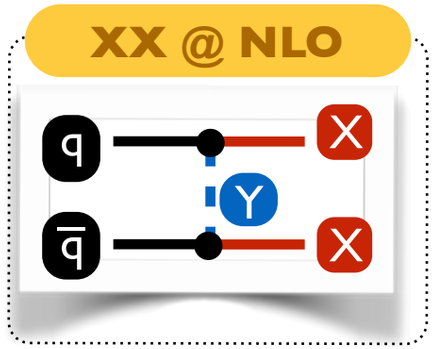
Ready to generate events!

Dark matter pair-production

Dark matter particle pair production

✦ NLO cross section calculation (no event generation yet)

- ✤ Generic model → exclusion of any irrelevant particle
- ✤ Addition of a jet p_T cut (targeting monojets)
- ✤ Reminder: m_X = 150 GeV, m_Y = 500 GeV, λ=1
  - ★ Treatment of the mediator width (not a free parameter)



✦ Definition of a label for all irrelevant particles.

- ✤ No decoupled particles appearing at the one-loop level
  - → all non 'xd' dark matter candidates (xs, xc, xm, xv, xw)
  - → all non 'ys3u1' mediator (fermionic, LH and 2nd/3rd generation RH scalar mediators)
  - → no EW channels (photon and *Z*): expected to be sub-leading

```
MG5_aMC> define excluded =  a z yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 \
                            yf3d2 yf3d3 ys3qu1 ys3qu2 ys3qu3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 \
                            ys3d2 ys3d3 xs xc xm xv xw
```

✦ Working directory generation (with MADSTR)

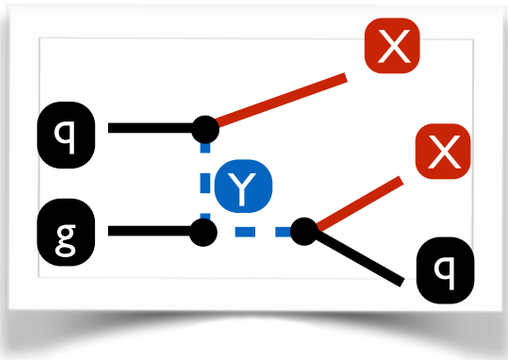
- ✤ Standard generate/output commands
- ✤ QCD tag to be added (NLO QCD calculations)

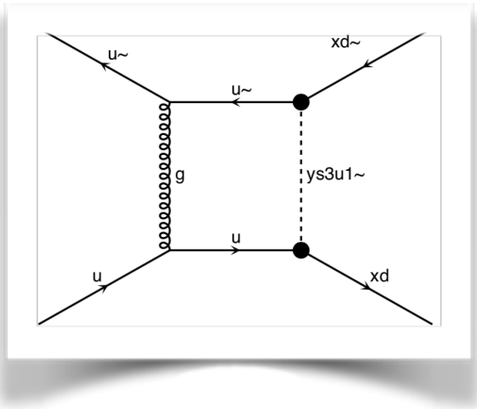
```
MG5_aMC>define dm = xd xd~
Defined multiparticle dm = xd xd~
MG5_aMC>generate p p > dm dm / excluded [QCD]; output s3d_xx;
```

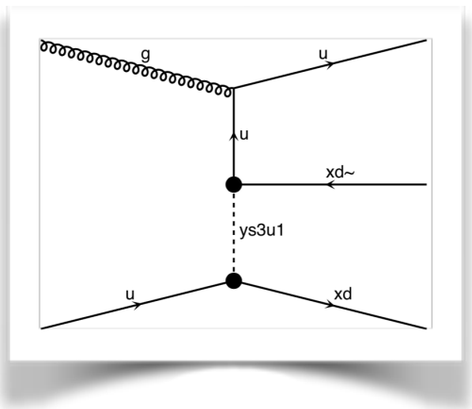
Working directory generation

✦ Automated detection of the real emission resonant configurations

```
INFO: Generating FKS-subtracted matrix elements for born process: u u~ > xd xd~ DMT<=2 [ all = QCD ] / a ys3qu1 ys3qu2 ys3q
u3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3
d2 yf3d3 z xs xc xv xw xm (1 / 2)
INFO: Generating FKS-subtracted matrix elements for born process: u~ u > xd xd~ DMT<=2 [ all = QCD ] / a ys3qu1 ys3qu2 ys3q
u3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3
d2 yf3d3 z xs xc xv xw xm (2 / 2)
INFO: Generating virtual matrix elements using MadLoop:
INFO: Generating virtual matrix element with MadLoop for process: u u~ > xd xd~ DMT<=2 [ all = QCD ] / a ys3qu1 ys3qu2 ys3q
u3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3
d2 yf3d3 z xs xc xv xw xm (1 / 2)
INFO: Generating virtual matrix elements using MadLoop:
INFO: Generating virtual matrix element with MadLoop for process: u~ u > xd xd~ DMT<=2 [ all = QCD ] / a ys3qu1 ys3qu2 ys3q
u3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3
d2 yf3d3 z xs xc xv xw xm (2 / 2)
INFO: Generated 2 subprocesses with 18 real emission diagrams, 2 born diagrams and 8 virtual diagrams
MadSTR_plugin.Interface: Looking for on-shell singularities in the real emissions...
MadSTR_plugin.madstr_fks: Process g u~ > ys3u1~ xd~ WEIGHTED=3, ys3u1~ > xd u~ has been generated for on-shell subtraction
MadSTR_plugin.madstr_fks: Process u g > xd ys3u1 WEIGHTED=3, ys3u1 > xd~ u has been generated for on-shell subtraction
MadSTR_plugin.madstr_fks: Process g u > xd ys3u1 WEIGHTED=3, ys3u1 > xd~ u has been generated for on-shell subtraction
MadSTR_plugin.madstr_fks: Process u~ g > ys3u1~ xd~ WEIGHTED=3, ys3u1~ > xd u~ has been generated for on-shell subtraction
MadSTR_plugin.Interface: Found 4 on-shell contributions
```







Checking the diagrams

✦ Postscript files with the diagrams are available

✤ Two subprocesses ($u\bar{u}$ and $\bar{u}u$)

```
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8$] cd s3d_xx/SubProcesses/
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xx/SubProcesses$] ls P0_u
P0_uux_xdxdx_1/ P0_uxu_xdxdx_2/
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xx/SubProcesses$] cd P0_uux_xdxdx_1/
```

✤ Born and real diagrams (including the resonant-subtracted ones)

```
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xx/SubProcesses$] cd P0_uux_xdxdx_1/
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xx/SubProcesses/P0_uux_xdxdx_1$] ls *ps
born.ps          matrix_1.ps      matrix_2.ps      matrix_2_os_1.ps matrix_3.ps      matrix_3_os_1.ps
```

✤ Loop diagrams

```
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xx/SubProcesses/P0_uux_xdxdx_1/V0_uux_xdxdx_0$] ls *ps
born_matrix.ps loop_matrix.ps
```

✦ Direct links also available from the generated HTML page (*open index.html*)

Initiating a cross section calculation

✦ Step1: Exit MG5_aMC!

✤ Different from a non-MADSTR run

✦ Step2: Enter the working directory and start the cross section calculation

```
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xx$ ./bin/aMCatNLO
Running MG5 in debug mode
No module named madgraph
INFO: ************************************************************
*                                                          *
*          W E L C O M E  to  M A D G R A P H 5            *
*                     a M C @ N L O                        *
*                                                          *
*                  *                       *               *
*                    *       * *       *                 *
*                      * * * * 5 * * * *                   *
*                    *       * *       *                 *
*                  *                       *               *
*                                                          *
*         VERSION 5.2.6.7               20xx-xx-xx         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*                  http://amcatnlo.cern.ch                 *
*                                                          *
*               Type 'help' for in-line help.              *
*                                                          *
************************************************************
INFO: load configuration from /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xx/Cards/amcatnlo_configuration.txt
INFO: load configuration from /Users/fuks/Work/tools/madgraph/2.6.8/input/mg5_configuration.txt
INFO: load configuration from /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xx/Cards/amcatnlo_configuration.txt
Using default text editor "vi". Set another one in ./input/mg5_configuration.txt
s3d_xx>calculate_xsect
```

Calculation setup

Specificities of a cross section calculation

- The calculation is at fixed order (NLO, not NLO+PS)
- No shower, no decay (the dark matter is stable)

```
The following switches determine which programs are run:
/============== Description ==============|============== values ==============|========== other options ==========\
| 1. Type of perturbative computation      |       order = NLO                  |   LO                               |
| 2. No MC@[N]LO matching / event generation | fixed_order = ON                 |   OFF                              |
| 3. Shower the generated events           |      shower = OFF                  |   PYTHIA6Q|PYTHIA6PT|PYTHIA8|HERWIG6 |
| 4. Decay onshell particles               |     madspin = OFF                  |   ON|onshell                       |
| 5. Add weights to events for new hypp.   |    reweight = OFF                  |   ON|NLO|NLO_TREE|LO               |
| 6. Run MadAnalysis5 on the events generated | madanalysis = Not Avail.        |   Please install module            |
\=========================================================================================================/
```

Parameter and run cards to be edited

- Parameter card: X and Y masses, couplings, Y width
- Run card: accuracy, cuts on the jets, parton densities

```
INFO: will run in mode: NLO
Do you want to edit a card (press enter to bypass editing)?
/-----------------------------------------------------------\
|  1. param      : param_card.dat                           |
|  2. run        : run_card.dat                             |
|  3. FO_analyse : FO_analyse_card.dat                      |
\-----------------------------------------------------------/
```

Benchmark

- Four values to change in the param card (param_card.dat)
  - Benchmark: m_X = 150 GeV, m_Y = 500 GeV, λ=1 & Γ_Y = Automatic

```
###################################
## INFORMATION FOR DMS3U
###################################
Block dms3u.
    1   1 1.000000e+00 # lamS3u1x1.
###################################
## INFORMATION FOR LOOP
###################################
Block loop.
    1 9.118800e+01 # MU_R.

###################################
## 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.
   52 1.000000e+09 # set of param :1*MX
*MYS3Qd3, 1*MYS3u2, 1*MYS3u3, 1*MYS3d1,
1*MYF3u1, 1*MYF3u2, 1*MYF3u3, 1*MYF3d1,
   57 1.500000e+02 # MXd.
 2000002 5.000000e+02 # MYS3u1.
```

```
###################################
## INFORMATION FOR DECAY
###################################
DECAY   6 1.470788e+00 # WT.
DECAY  23 2.415848e+00 # WZ.
DECAY  24 2.002780e+00 # WW.
DECAY  25 4.070000e-03 # WH.
DECAY  57 1.000000e-06 # WXd.
DECAY 2000002 Auto # WYS3u1.
```

Run configuration [1/2]

✦ A few parameters to change in the run card (run_card.dat)

✤ The fixed-order computation accuracy: 0.1 % [reminder: no event generation]

```
#*********************************************************************
# Number of points per itegration channel (ignored for aMC@NLO runs)   *
#*********************************************************************
0.001   = req_acc_FO      ! Required accuracy (-1=ignored, and use the.
>------                  ! number of points and iter. below)
```

✤ Recent parton densities: NNPDF 3.0 NLO [default is NNPDF 2.3]

```
#*********************************************************************
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.  *
#*********************************************************************
lhapdf  = pdlabel ! PDF set
260000  = lhaid   ! If pdlabel=lhapdf, this is the lhapdf number. Only.
          ! numbers for central PDF sets are allowed. Can be a list;.
          ! PDF sets beyond the first are included via reweighting.
```

(PDF set to be downloaded)

✤ Theory error calculation

```
#*********************************************************************.
# Reweight variables for scale dependence and PDF uncertainty          *
#*********************************************************************
 1.0, 2.0, 0.5 = rw_rscale ! muR factors to be included by reweighting
 1.0, 2.0, 0.5 = rw_fscale ! muF factors to be included by reweighting
 True = reweight_scale ! Reweight to get scale variation using the.
          ! rw_rscale and rw_fscale factors. Should be a list of.
          ! booleans of equal length to dynamical_scale_choice to
          ! specify for which choice to include scale dependence.
 True  = reweight_PDF  ! Reweight to get PDF uncertainty. Should be a
          ! list booleans of equal length to lhaid to specify for
          !  which PDF set to include the uncertainties.
```

Run configuration [2/2]

✦ A few parameters to change in the run card

✤ Resonance subtraction option unchanged: istr = 2 [default]

```
#*********************************************************************
# Parameters relevant for the MasSTR plugin:                         *
# iSTR controls the strategy for the resonance treatment             *
#  istr = 1 -> DR without interferece                                *
#  istr = 2 -> DR with interferece                                   *
#  istr = 3 -> DS with reshuffling on initial state, standard BW     *
#  istr = 4 -> DS with reshuffling on initial state, running BW      *
#  istr = 5 -> DS with reshuffling on all FS particles, standard BW  *
#  istr = 6 -> DS with reshuffling on all FS particles, running BW   *
#*********************************************************************
  2 = istr ! strategy to be used to remove resonances.
           ! appearing in real emissions
 True = str_include_pdf ! compensate for PDFs when doing reshuffling
 True = str_include_flux ! compensate for flux when doing reshuffling
```

istr = 1: DR
istr = 2: DR+I
istr = 3: DS-1
istr = 4: DS-2
istr = 5: DS-3
istr = 6: DS-4
str_include_pdf: PDF reshuffling
str_include_flux: flux factor reshuffling

✤ Jet cuts (monojets are targeted): $p_T > 100$ GeV and $|\eta| < 5$

```
#*********************************************************************
# Cuts on the jets. Jet clustering is performed by FastJet.          *
#  - When matching to a parton shower, these generation cuts should be *
#    considerably softer than the analysis cuts.                      *
#  - More specific cuts can be specified in SubProcesses/cuts.f       *
#*********************************************************************
  1.0  = jetalgo   ! FastJet jet algorithm (1=kT, 0=C/A, -1=anti-kT)
  0.7  = jetradius ! The radius parameter for the jet algorithm
 100.0  = ptj      ! Min jet transverse momentum
 5.0  = etaj     ! Max jet abs(pseudo-rap) (a value .lt.0 means no cut)
```

Ready to start the calculation

The results

- The calculation takes about 20-25 minutes on a 16-core machine
  - Decrease the precision if too long (2 minutes for a 1% precision)

```
------------------------------------------------------------
   Final results and run summary:
   Process p p > dm dm / excluded [QCD]
   Run at p-p collider (6500.0 + 6500.0 GeV)
   Total cross section: 9.271e-01 +- 1.0e-03 pb
------------------------------------------------------------
   Scale variation (computed from histogram information):
       Dynamical_scale_choice -1 (envelope of 9 values):
           9.270e-01 pb  +1.7% -1.2%
   PDF variation (computed from histogram information):
       NNPDF30_nlo_as_0118 (101 members; using replicas method):
           9.270e-01 pb  +1.9% -1.9%
------------------------------------------------------------
```

$$\sigma_{\mathrm{NLO}}^{(XX)} = 927^{+1.7\%}_{-1.2\%} \pm 1.9\% \text{ fb}$$

Initiating event generation

- Event generation is handled similarly (the *generate_events* command)

```
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xx$] ./bin/aMCatNLO
Running MG5 in debug mode
No module named madgraph
INFO: ************************************************************
*                                                          *
*          W E L C O M E  to  M A D G R A P H 5            *
*                     a M C @ N L O                        *
*                                                          *
*                  *                       *               *
*                    *       * *       *                 *
*                      * * * * 5 * * * *                   *
*                    *       * *       *                 *
*                  *                       *               *
*                                                          *
*         VERSION 5.2.6.7                  20xx-xx-xx      *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*                  http://amcatnlo.cern.ch                 *
*                                                          *
*                Type 'help' for in-line help.             *
*                                                          *
************************************************************
INFO: load configuration from /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xx/Cards/amcatnlo_configuration.txt
INFO: load configuration from /Users/fuks/Work/tools/madgraph/2.6.8/input/mg5_configuration.txt
INFO: load configuration from /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xx/Cards/amcatnlo_configuration.txt
Using default text editor "vi". Set another one in ./input/mg5_configuration.txt
s3d_xx>generate_events
```

Event generation: setup

✦ Specificities of the event generation process

- ✤ The calculation is at NLO+PS → PYTHIA 8 (supersedes the default choice of HW)
- ✤ No need for any decay (the dark matter is stable)

```
/============== Description ==============|============ values ============|========== other options ==========\
| 1. Type of perturbative computation      |      order = NLO               |   LO                               |
| 2. No MC@[N]LO matching / event generation | fixed_order = OFF  ⇐ ~~ON~~  |   OFF                              |
| 3. Shower the generated events           |     shower = PYTHIA8           |   HERWIG6|OFF|PYTHIA6Q|PYTHIA6PT   |
| 4. Decay onshell particles               |    madspin = OFF               |   ON|onshell                       |
| 5. Add weights to events for new hypp.   |   reweight = OFF               |   ON|NLO|NLO_TREE|LO               |
| 6. Run MadAnalysis5 on the events generated | madanalysis = Not Avail.    |   Please install module            |
\=========================================================================================================/
```

- ✤ No need to modify the cards (already done before; default = 10,000 events)
  - → Note: 10,000 events yield a less precise cross section (numerical error)

```
INFO: Preparing MCatNLO run
INFO: Using LHAPDF v6.1.6 interface for PDFs
INFO: Compiling MCatNLO for PYTHIA8...
INFO:                       ... done
INFO: Showering events...
INFO: (Running in /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xx/MCatNLO/RUN_PYTHIA8_1)
INFO:  Idle: 1,  Running: 0,  Completed: 0 [ current time: 15h01 ]
INFO:  Idle: 0,  Running: 1,  Completed: 0 [  5m 0s  ]
INFO:  Idle: 0,  Running: 0,  Completed: 1 [  7m 8s  ]
INFO:  Idle: 0,  Running: 0,  Completed: 0 [ current time: 15h08 ]
INFO: The file /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xx/Events/run_03/events_PYTHIA8_0.hepmc.gz has been generated.
It contains showered and hadronized events in the HEPMC format obtained showering the parton-level event file /Users/fuks/Work/too
ls/madgraph/2.6.8/s3d_xx/Events/run_03/events.lhe.gz with PYTHIA8
INFO: Run complete
```

Event reconstruction with MadAnalysis 5

✦ From a huge Pythia8 HepMC file to a small reco-level LHE-file

✤ Start MadAnalysis 5 in the reco mode

```
[fuks@LeMouth ~/Work/tools/madanalysis/bzr/v1.8_beta$] ./bin/ma5 -R
MA5:
MA5: ************************************************************
MA5: *                                                          *
MA5: *       W E L C O M E  to  M A D A N A L Y S I S  5         *
MA5: *                                                          *
MA5: *                                                          *
MA5: *                                                          *
MA5: *                                                          *
MA5: *                                                          *
MA5: *                                                          *
MA5: *                                                          *
MA5: *                                                          *
MA5: *   MA5 release : 1.8.44                    2020/04/17     *
```

✦ Initiating a FastJet run on the events (1-2 minutes)

```
[ma5>set main.fastsim.package = fastjet
[ma5>set main.fastsim.algorithm = antikt
[ma5>set main.outputfile = xx.reco.lhe.gz
```

✤ The new invisible states must be tagged as such

```
[ma5>define invisible = invisible 57 -57
MA5-WARNING: Particle/Multiparticle labelled 'invisible' is already defined.
MA5-WARNING: Would you like to overwrite the previous definition ? (Y/N)
[Answer: y
```

✤ Sample import & submission

```
[ma5>import /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xx/Events/run_03/events_PYTHIA8_0.hepmc.gz
MA5:    -> Storing the file 'events_PYTHIA8_0.hepmc.gz' in the dataset 'defaultset'.
[ma5>submit
```

✤ Output in *ANALYSIS_0/Output/SAF/_defaultset/lheEvents0_0*

A pair of plots

✦ Interesting distributions: MET and HT spectra

✤ Start MADANALYSIS 5 in the parton mode

```
[fuks@LeMouth ~/Work/tools/madanalysis/bzr/v1.8_beta$ ./bin/ma5
MA5:
MA5: ************************************************************
MA5: *                                                          *
MA5: *        W E L C O M E  to  M A D A N A L Y S I S  5        *
MA5: *                                                          *
```

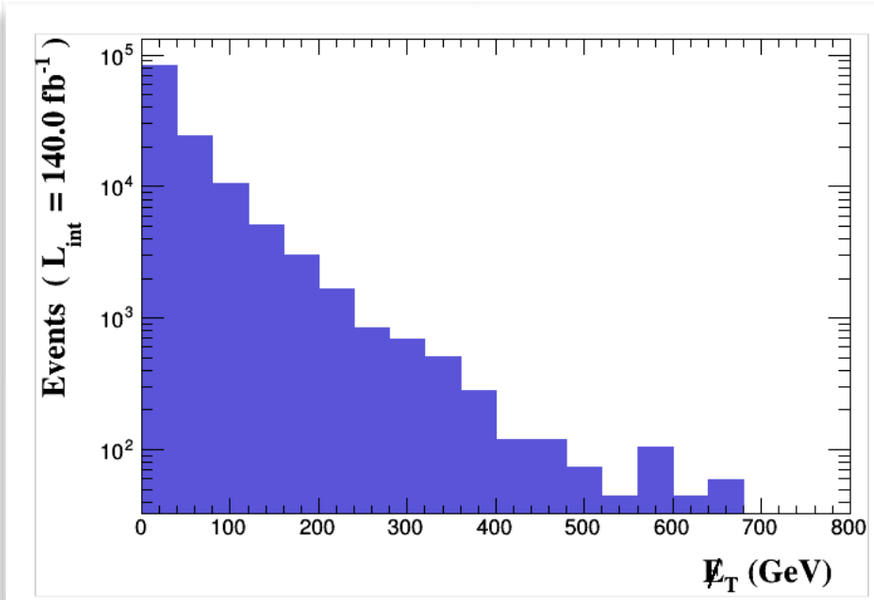
✤ Standard commands

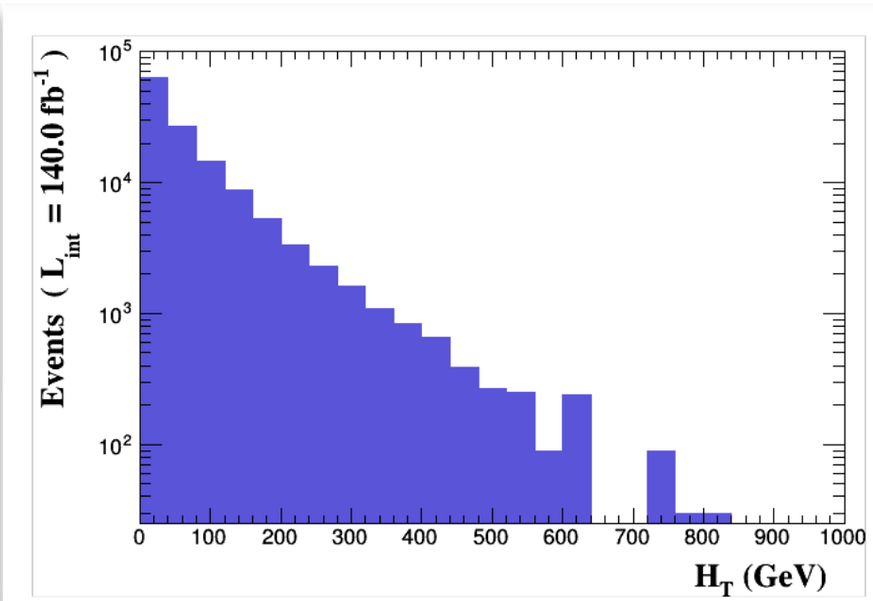
```
[ma5>import ANALYSIS_0/Output/SAF/_defaultset/lheEvents0_0/xx.reco.lhe.gz as xx
 MA5:    -> Storing the file 'xx.reco.lhe.gz' in the dataset 'xx'.
[ma5>plot MET 20 0 800 [logY]
[ma5>plot THT 25 0 1000 [logY]
[ma5>set xx.xsection = 0.927
[ma5>set main.lumi = 140
[ma5>submit
```

★NLO cross section

★140 fb^{-1}

✤ Output in *ANALYSIS_1/Output/HTML/MadAnalysis5job_0*



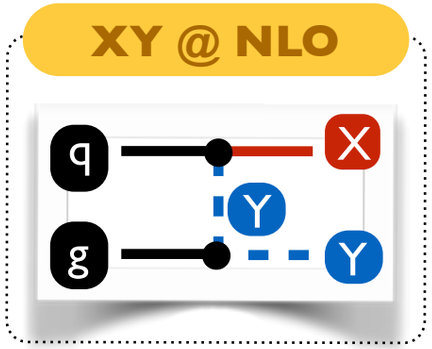


Associated production

Dark matter/mediator associated production

✦ NLO cross section calculation (no event generation yet)

- ✤ Generic model → exclusion of any irrelevant particle
- ✤ No jet cut (hard jets expected to come from Y decays)
- ✤ Reminder: m_X = 150 GeV, m_Y = 500 GeV, λ=1
  - ★ Treatment of the mediator width (not a free parameter)



✦ Working directory generated in a similar way

- ✤ Multiparticle labels

```
MadSTR > import model DMSimp_t-S3D_uR --modelname
MG5_aMC>define excluded =  a z yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 ys3qu1 ys3qu2 ys3qu3
ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 xs xc xm xv xw
Defined multiparticle excluded = a ys3qu1 ys3qu2 ys3qu3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 yf3qu1 yf3qu2 yf3qu3 yf
3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 z xs xc xv xw xm
MG5_aMC>define dm = xd xd~
Defined multiparticle dm = xd xd~
MG5_aMC>define yy = ys3u1 ys3u1~
Defined multiparticle yy = ys3u1 ys3u1~
MG5_aMC>
```

- ✤ Creation of the working directory

```
MG5_aMC>generate p p > dm yy /excluded [QCD]; output s3d_xy;
```

- ✤ Please check the output and the diagrams

Cross section calculation setup

Specificities of a cross section calculation

- The calculation is at fixed order (NLO, not NLO+PS)
- No shower, no decay (this will be changed for event generation)

```
The following switches determine which programs are run:
/============== Description ==============|============ values ============|========== other options ==========\
| 1. Type of perturbative computation      |       order = NLO              |   LO                               |
| 2. No MC@[N]LO matching / event generation | fixed_order = ON             |   OFF                              |
| 3. Shower the generated events           |      shower = OFF              |   PYTHIA6Q|PYTHIA6PT|PYTHIA8|HERWIG6 |
| 4. Decay onshell particles               |     madspin = OFF              |   ON|onshell                       |
| 5. Add weights to events for new hypp.   |    reweight = OFF              |   ON|NLO|NLO_TREE|LO             |
| 6. Run MadAnalysis5 on the events generated | madanalysis = Not Avail.    |   Please install module            |
\=========================================================================================================/
```

Parameter and run cards to be edited

- Parameter card: X and Y masses, couplings, Y width
- Run card: accuracy, no jet cuts (only 10 GeV on the p_T), parton densities

```
INFO: will run in mode: NLO
Do you want to edit a card (press enter to bypass editing)?
/-----------------------------------------------------------\
|  1. param      : param_card.dat                           |
|  2. run        : run_card.dat                             |
|  3. FO_analyse : FO_analyse_card.dat                      |
\-----------------------------------------------------------/
```

Reminder: param_card.dat

- Benchmark: m_X = 150 GeV, m_Y = 500 GeV, λ=1 & Γ_Y = Automatic

```
###################################
## INFORMATION FOR DMS3U
###################################
Block dms3u.
    1   1 1.000000e+00 # lamS3u1x1.
###################################
## INFORMATION FOR LOOP
###################################
Block loop.
    1 9.118800e+01 # MU_R.

###################################
## 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.
   52 1.000000e+09 # set of param :1*MX
*MYS3Qd3, 1*MYS3u2, 1*MYS3u3, 1*MYS3d1,
1*MYF3u1, 1*MYF3u2, 1*MYF3u3, 1*MYF3d1,
   57 1.500000e+02 # MXd.
 2000002 5.000000e+02 # MYS3u1.
```

```
###################################
## INFORMATION FOR DECAY
###################################
DECAY   6 1.470788e+00 # WT.
DECAY  23 2.415848e+00 # WZ.
DECAY  24 2.002780e+00 # WW.
DECAY  25 4.070000e-03 # WH.
DECAY  57 1.000000e-06 # WXd.
DECAY 2000002 Auto # WYS3u1.
```

Run configuration [1/2]

✦ A few parameters to change in the run card (run_card.dat)

✤ The fixed-order computation accuracy: 0.1 % [reminder: no event generation]

```
#*********************************************************************
# Number of points per itegration channel (ignored for aMC@NLO runs)   *
#*********************************************************************
0.001   = req_acc_FO      ! Required accuracy (-1=ignored, and use the.
>------                  ! number of points and iter. below)
```

✤ Recent parton densities: NNPDF 3.0 NLO [default is NNPDF 2.3]

```
#*********************************************************************
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.  *
#*********************************************************************
lhapdf  = pdlabel ! PDF set
260000  = lhaid   ! If pdlabel=lhapdf, this is the lhapdf number. Only.
          ! numbers for central PDF sets are allowed. Can be a list;.
          ! PDF sets beyond the first are included via reweighting.
```

(PDF set to be downloaded)

✤ Theory error calculation

```
#*********************************************************************.
# Reweight variables for scale dependence and PDF uncertainty          *
#*********************************************************************
 1.0, 2.0, 0.5 = rw_rscale ! muR factors to be included by reweighting
 1.0, 2.0, 0.5 = rw_fscale ! muF factors to be included by reweighting
 True = reweight_scale ! Reweight to get scale variation using the.
          ! rw_rscale and rw_fscale factors. Should be a list of.
          ! booleans of equal length to dynamical_scale_choice to
          ! specify for which choice to include scale dependence.
 True  = reweight_PDF  ! Reweight to get PDF uncertainty. Should be a
          ! list booleans of equal length to lhaid to specify for
          !  which PDF set to include the uncertainties.
```

Run configuration [2/2]

✦ A few parameters to change in the run card

✤ Resonance subtraction option unchanged: istr = 2 [default]

```
#*********************************************************************
# Parameters relevant for the MasSTR plugin:                         *
# iSTR controls the strategy for the resonance treatment             *
#  istr = 1 -> DR without interferece                                *
#  istr = 2 -> DR with interferece                                   *
#  istr = 3 -> DS with reshuffling on initial state, standard BW     *
#  istr = 4 -> DS with reshuffling on initial state, running BW      *
#  istr = 5 -> DS with reshuffling on all FS particles, standard BW  *
#  istr = 6 -> DS with reshuffling on all FS particles, running BW   *
#*********************************************************************
  2 = istr ! strategy to be used to remove resonances.
           ! appearing in real emissions
 True = str_include_pdf ! compensate for PDFs when doing reshuffling
 True = str_include_flux ! compensate for flux when doing reshuffling
```

istr = 1: DR
istr = 2: DR+I
istr = 3: DS-1
istr = 4: DS-2
istr = 5: DS-3
istr = 6: DS-4
str_include_pdf: PDF reshuffling
str_include_flux: flux factor reshuffling

✤ Standard jet cuts: p_T > 10 GeV and $|\eta|$ < 5

```
#*********************************************************************
# Cuts on the jets. Jet clustering is performed by FastJet.          *
#  - When matching to a parton shower, these generation cuts should be *
#    considerably softer than the analysis cuts.                      *
#  - More specific cuts can be specified in SubProcesses/cuts.f       *
#*********************************************************************
  1.0  = jetalgo   ! FastJet jet algorithm (1=kT, 0=C/A, -1=anti-kT)
  0.7  = jetradius ! The radius parameter for the jet algorithm
 10    = ptj       ! Min jet transverse momentum
 5.0   = etaj    ! Max jet abs(pseudo-rap) (a value .lt.0 means no cut)
```

Ready to start the calculation

The results

- The calculation takes about 1h10 minutes on a 16-core machine
  - Decrease the precision → 2-3 minutes for a 1% precision

```
------------------------------------------------------------
   Final results and run summary:
   Process p p > dm yy /excluded [QCD]
   Run at p-p collider (6500.0 + 6500.0 GeV)
   Total cross section: 2.197e+00 +- 9.0e-03 pb
------------------------------------------------------------
   Scale variation (computed from histogram information):
       Dynamical_scale_choice -1 (envelope of 9 values):
           2.197e+00 pb  +6.0% -6.4%
   PDF variation (computed from histogram information):
       NNPDF30_nlo_as_0118 (101 members; using replicas method):
           2.197e+00 pb  +1.0% -1.0%
------------------------------------------------------------
```

$$\sigma_{\rm NLO}^{(XY)} = 2.197^{+6.0\%}_{-6.4\%} \pm 1.0\% \text{ pb}$$

Event generation

- Event generation is handled similarly (the *generate_events* command)

```
[fuks@LeMouth ~/Work/tools/madgraph/2.6.8/s3d_xy$] ./bin/generate_events
```

- Specificities of the event generation process
  - The calculation is at NLO+PS → PYTHIA 8
  - The mediator decay needs to be included → MADSPIN

```
/================ Description ================|============== values ==============|========== other options ==========\
| 1. Type of perturbative computation          |          order = NLO               |   LO                               |
| 2. No MC@[N]LO matching / event generation   |    fixed_order = OFF               |   ON                               |
| 3. Shower the generated events               |        shower = PYTHIA8            |   HERWIG6|OFF|PYTHIA6Q|PYTHIA6PT   |
| 4. Decay onshell particles                   |       madspin = ON                 |   onshell|OFF                      |
| 5. Add weights to events for new hypp.       |     reweight = OFF                 |   ON|NLO|NLO_TREE|LO               |
| 6. Run MadAnalysis5 on the events generated  |  madanalysis = Not Avail.          |   Please install module            |
\=============================================|====================================|====================================/
```

  - Need of implementing a dedicated MADSPIN card (the rest can be default)

```
 set max_weight_ps_point 400  # number of PS to estimate the maximum for each event

# specify the decay for the final state particles
decay yy > dm all
# running the actual code
launch
```

Event generation

✦ Event decay handled before showering

```
INFO: Running MadSpin
INFO: This functionality allows for the decay of resonances
INFO: in a .lhe file, keeping track of the spin correlation effets.
INFO: BE AWARE OF THE CURRENT LIMITATIONS:
INFO:   (1) Only a succession of 2 body decay are currently allowed
************************************************************
*                                                          *
*          W E L C O M E  to  M A D S P I N                *
*                                                          *
************************************************************
INFO: Extracting the banner ...
INFO: process: p p > dm yy
INFO: options: /excluded
INFO: detected model: DMSimp_t-S3D_uR. Loading...
set lhapdf to /Users/fuks/Work/tools/madgraph/MG5_aMC_v2_5_2/HEPTools/lhapdf6/bin/lhapdf-config
set ninja to /Users/fuks/Work/tools/madgraph/2.6.8/HEPTools/lib
set collier to /Users/fuks/Work/tools/madgraph/2.6.8/HEPTools/lib
set max_weight_ps_point 400  # number of PS to estimate the maximum for each event
decay yy > dm all
```

✤ A HepMC file is generated

```
INFO: MadSpin Done
INFO: Preparing MCatNLO run
INFO: Using LHAPDF v6.1.6 interface for PDFs
INFO: Compiling MCatNLO for PYTHIA8...
INFO:                       ... done
INFO: Showering events...
INFO: (Running in /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xy/MCatNLO/RUN_PYTHIA8_1)
INFO:  Idle: 0,  Running: 1,  Completed: 0 [ current time: 16h19 ]
INFO:  Idle: 0,  Running: 0,  Completed: 1 [  8m 45s  ]
INFO:  Idle: 0,  Running: 0,  Completed: 0 [ current time: 16h27 ]
INFO: The file /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xy/Events/run_01_decayed_1/events_PYTHIA8_0.hepmc.gz has been generated.
It contains showered and hadronized events in the HEPMC format obtained showering the parton-level event file /Users/fuks/Work/too
ls/madgraph/2.6.8/s3d_xy/Events/run_01_decayed_1/events.lhe.gz with PYTHIA8
INFO: Run complete
```

Event reconstruction / plots

✦ Run of FastJet through MadAnalysis 5

```
[ma5>set main.fastsim.package = fastjet
[ma5>set main.fastsim.algorithm = antikt
[ma5>set main.fastsim.radius = 0.4
[ma5>set main.outputfile = xy.reco.lhe.gz
[ma5>define invisible = invisible 57 -57
 MA5-WARNING: Particle/Multiparticle labelled 'invisible' is already defined.
 MA5-WARNING: Would you like to overwrite the previous definition ? (Y/N)
[Answer: y
[ma5>import /Users/fuks/Work/tools/madgraph/2.6.8/s3d_xy/Events/run_01_decayed_1/events_PYTHIA8_0.hepmc.gz
 MA5:    -> Storing the file 'events_PYTHIA8_0.hepmc.gz' in the dataset 'defaultset'.
[ma5>submit
```

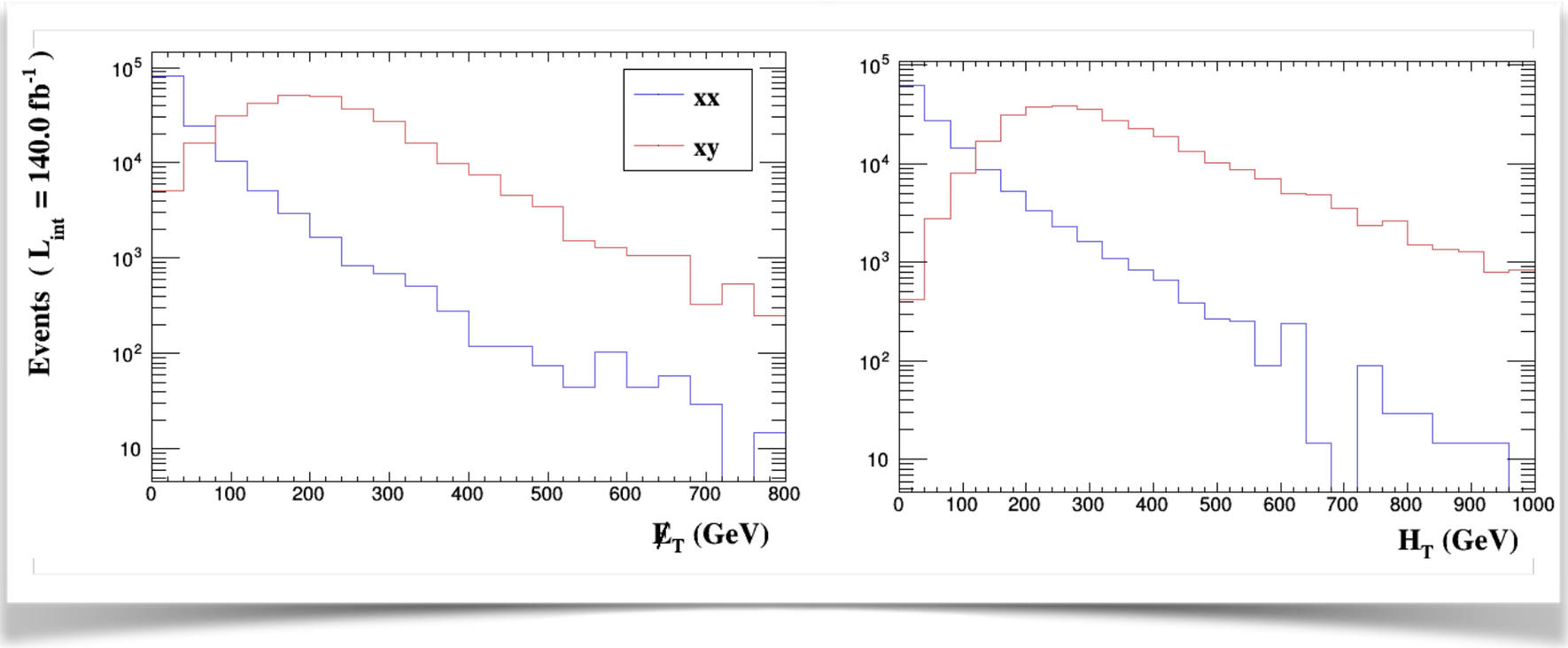
✦ Plots (superimposing both XX and XY)

```
[ma5>import ANALYSIS_0/Output/SAF/_defaultset/lheEvents0_0/xx.reco.lhe.gz as xx
MA5:    -> Storing the file 'xx.reco.lhe.gz' in the dataset 'xx'.
[ma5>import ANALYSIS_2/Output/SAF/_defaultset/lheEvents0_0/xy.reco.lhe.gz as xy
MA5:    -> Storing the file 'xy.reco.lhe.gz' in the dataset 'xy'.
[ma5>set xx.xsection = 0.927
[ma5>set xy.xsection = 2.197
[ma5>set main.lumi = 140
[ma5>set main.stacking_method = superimpose
[ma5>plot MET 20 0 800 [logY]
[ma5>plot THT 25 0 1000 [logY]
[ma5>submit
```

★NLO cross section

★140 fb^{-1}

Results for the two distributions



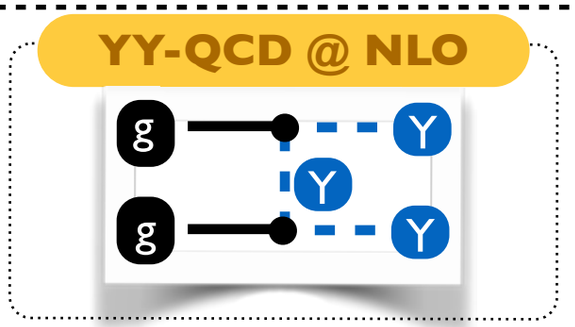
Mediator pair-production

Mediator pair production: 3 separate runs

✦ QCD contributions: normal MG5_aMC, no MADSTR

→ Resonant contributions are not pure QCD processes

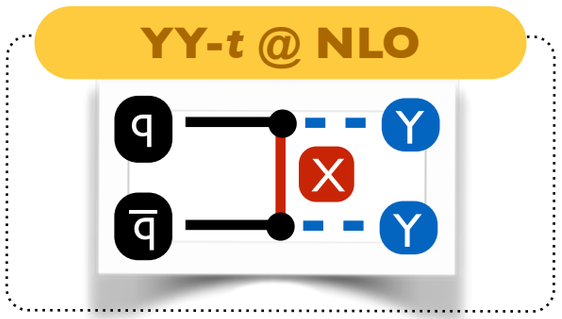
→ MADSPIN card: both mediator/anti-mediator decays




```
MG5_aMC>define excluded =  a z yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 ys3qu1 ys3qu2 ys3qu3
ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 xs xc xm xv xw
Defined multiparticle excluded = a ys3qu1 ys3qu2 ys3qu3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 yf3qu1 yf3qu2 yf3qu3 yf
3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 z xs xc xv xw xm
MG5_aMC>define dm = xd xd~
Defined multiparticle dm = xd xd~
MG5_aMC>generate p p > ys3u1 ys3u1~ /excluded [QCD]; output s3d_yy_qcd;
```

✦ *t*-channel contributions: MADSTR needed

→ MADSPIN card: both mediator/anti-mediator decays




```
MadSTR > import model DMSimp_t-S3D_uR --modelname
INFO: Restrict model DMSimp_t with file models/DMSimp_t/restrict_S3D_uR.dat .
MG5_aMC>define dm = xd xd~
Defined multiparticle dm = xd xd~
MG5_aMC>define excluded =  a z yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 ys3qu1 ys3qu2 ys3qu3
ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 xs xc xm xv xw
Defined multiparticle excluded = a ys3qu1 ys3qu2 ys3qu3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 yf3qu1 yf3qu2 yf3qu3 yf
3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 z xs xc xv xw xm
MG5_aMC>generate p p > ys3u1 ys3u1~ DMT=2 QED=0 QCD=0 / excluded [QCD]; output s3d_yy_t;
```

✦ Interferences: LO simulations

```
MG5_aMC>generate p p > ys3u1 ys3u1~ DMT^2==2 / excluded; output s3d_yy_int;
```

Results

✦ Cross sections (1% numerical precision; 1-10 minutes each run)

YY-QCD @ NLO

```
------------------------------------------------------------
  Final results and run summary:
  Process p p > ys3u1 ys3u1~ /excluded [QCD]
  Run at p-p collider (6500.0 + 6500.0 GeV)
  Total cross section: 4.849e-01 +- 3.0e-03 pb
------------------------------------------------------------
  Scale variation (computed from histogram information):
      Dynamical_scale_choice -1 (envelope of 9 values):
          4.849e-01 pb  +10.6% -12.3%
  PDF variation (computed from histogram information):
      NNPDF30_nlo_as_0118 (101 members; using replicas method):
          4.849e-01 pb  +3.4% -3.4%
------------------------------------------------------------
```

YY-*t* @ NLO

```
------------------------------------------------------------
Final results and run summary:
Process p p > ys3u1 ys3u1~ DMT=2 QED=0 QCD=0 / excluded [QCD]
Run at p-p collider (6500.0 + 6500.0 GeV)
Total cross section: 3.175e-01 +- 1.7e-03 pb
------------------------------------------------------------
Scale variation (computed from histogram information):
    Dynamical_scale_choice -1 (envelope of 9 values):
        3.175e-01 pb  +2.5% -2.6%
PDF variation (computed from histogram information):
    NNPDF30_nlo_as_0118 (101 members; using replicas method):
        3.175e-01 pb  +2.5% -2.5%
```

Interference @ LO

```
== Results Summary for run: run_01 tag: tag_1

 Cross-section :   -0.1008 +- 0.0001797 pb
 Nb of events :  10000
```

✦ Event generation (20-25 minutes each run)

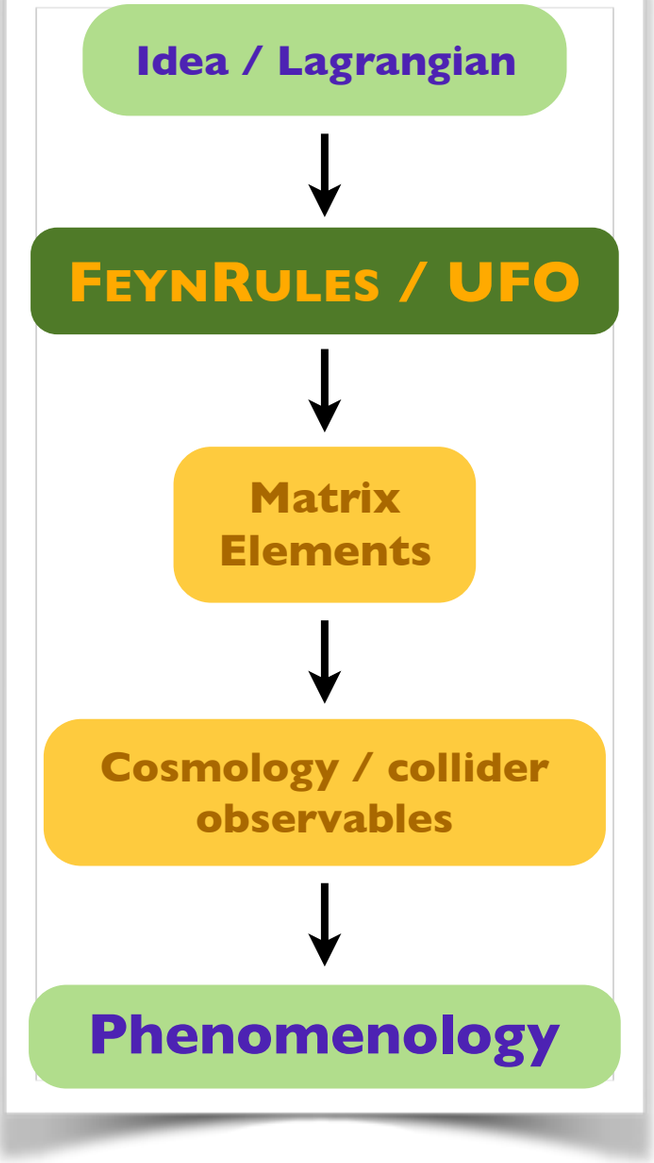
Outline

1. A short overview of the model

2. The tutorial example: the S3D model

3. **Summary**

Summary- outlook



✦ The Über UFO is available

- ✤ LO calculations straightforward (collider + cosmo)
- ✤ NLO @ colliders → not so straightforward;
  → Follow the guidelines
- ✤ More information:
  - ★ See the paper (2001.05024)
  - ★ Web: http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt

✦ Validation

- ✤ Comparison with the literature
  - ★ Cosmological observables (Chiara's and Luca's talks)
  - ★ SUSY cross sections