DM simplified models at NLO

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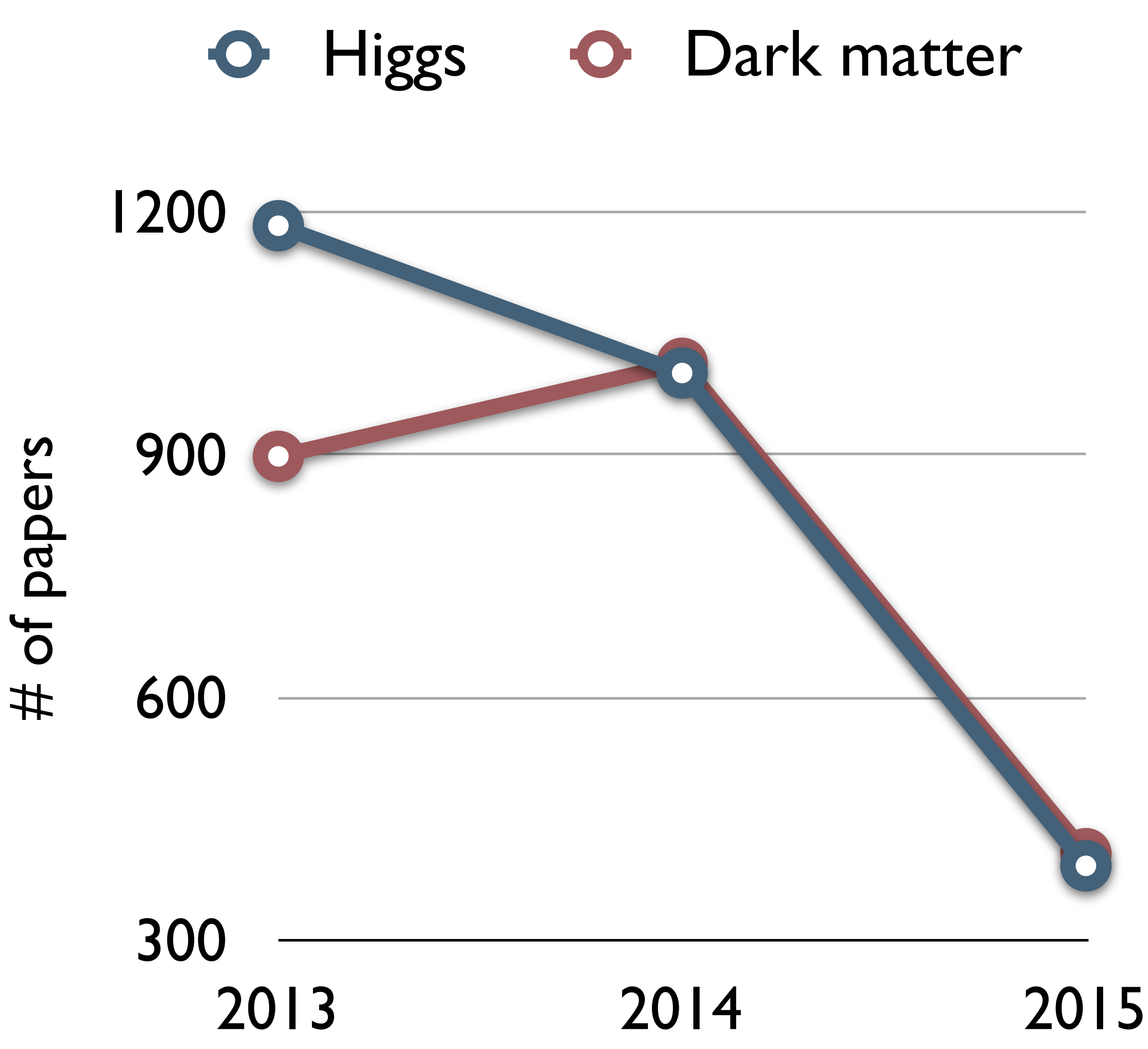
Outlines

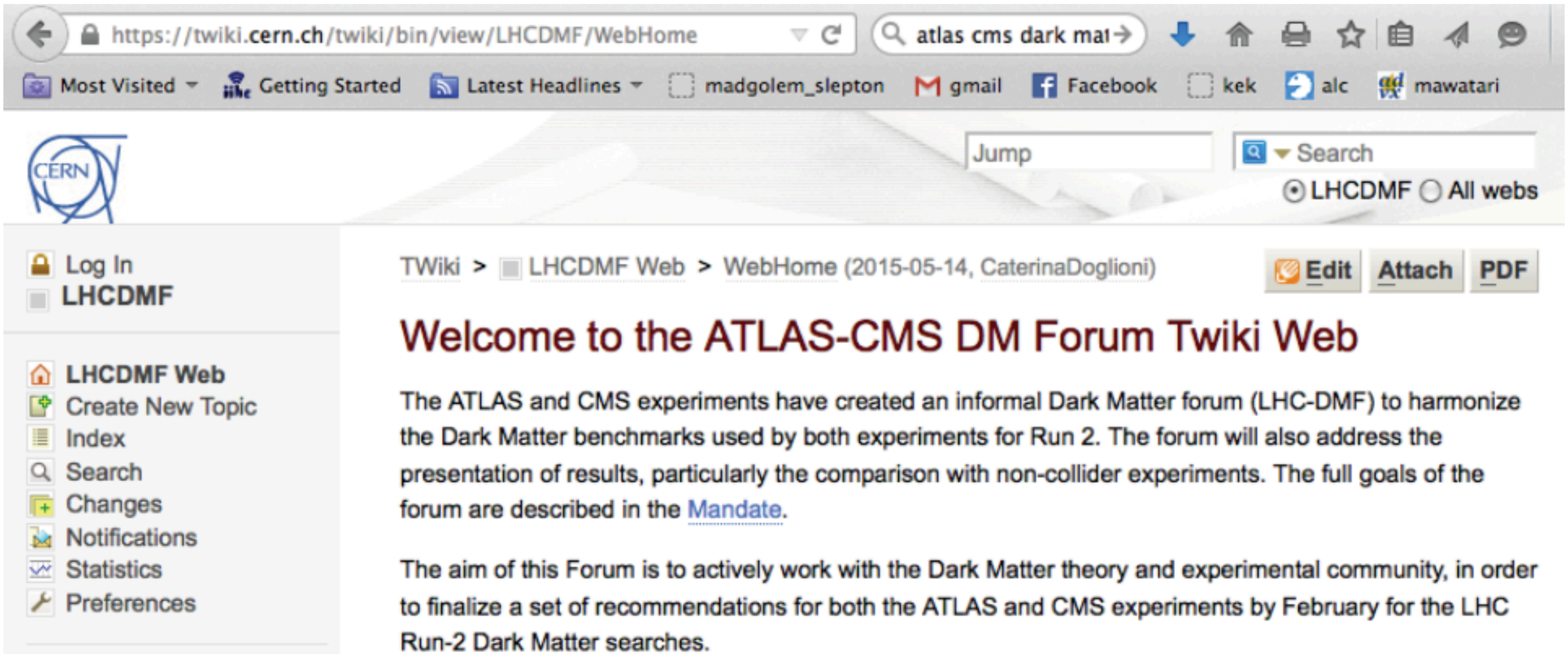
- Motivation
- Methodology
- Preliminary results

Higgs vs. Dark matter

- inSPIRE
  - find title higgs
  - find title dark matter



ATLAS-CMS DM Forum



EFT models to simplified models

- Early Run 1 searches for mono-X+MET signatures at ATLAS and CMS employed a basis of operators in effective field theories (EFTs).
- However, it has become clear that a contact interaction is often not the correct description for the signals to which the LHC is sensitive.
- While the EFT integrates out the degrees of freedom of the (heavy) intermediate particle, "simplified models" with directly-accessible mediators describe this richer phenomenology.
- Appropriate simplified models can be used both to interpret mono-X searches and to guide the design of complementary searches for additional signatures.

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ATLAS+CMS DM Forum Recommendations

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ATLAS+CMS DM Forum Recommendations

5 Recommendations for evaluation of signal theoretical uncertainties

[Comment on proper PDF sets to use, concerns about sea quark PDF in b-initiated diagrams (perhaps the latter belongs in the b-flavored DM section)]

To do **This section describes the technical details of how to vary input parameters, but it does not describe the overall strategy of what parameters to vary or by how much. (??)**

5.1 POWHEG

A comprehensive and careful assessment of theoretical uncertainties plays a much more important role for the background estimations (especially when their evaluation is non-entirely data-driven) than it does for signal simulations. Nevertheless, when using POWHEG it is possible to study scale and PDF errors for the dark matter signals. A fast reweighting machinery is available in POWHEG-BOX that allows one to add, after each event, new weights according to different scale or PDF choices, without the need to regenerate all the events from scratch.

To enable this possibility, the variable `storeinfo_rwgt` should be set to 1 in the POWHEG input file when the events are generated for the first time[1]. After each event, a line starting with

```
#rwgt
```

is appended, containing the necessary information to generate extra weights. In order to obtain new weights, corresponding to different PDFs or scale choice, after an event file has been generated, a line

```
compute_rwgt 1
```

should be added in the input file along with the change in parameters that is desired. For instance, `renscfact` and `facscfact` allow one to study scale variations on the renormalization and factorization scales around a central value. By running the program again, a new event file will be generated, named `<OriginalName>-rwgt.lhe`, with one more line at the end of each event of the form

```
#new weight,renfact,facfact,pdf1,pdf2
```

followed by five numbers and a character string. The first of these numbers is the weight of that event with the new parameters chosen. By running in sequence the program in the reweighting mode, several weights can be added on the same file. Two remarks are in order.

- The file with new weights is always named

  ```
  <OriginalName>-rwgt.lhe
  ```

  hence care has to be taken to save it as

  ```
  <OriginalName>.lhe
  ```

  before each iteration of the reweighting procedure.
- Due to the complexity of the environment where the program is likely to be run, it is strongly suggested as a self-consistency check that the first reweighting is done keeping the initial parameters. If the new weights are not exactly the same as the original ones, then some inconsistency must have happened, or some file was probably corrupted.

It is possible to also have weights written in the version 3 Les Houches format. To do so, in the original run, at least the token

```
lhrwgt_id 'ID'
```

must be present. The reweighting procedure is the same as described above, but now each new run can be tagged by using a different value for the `lhrwgt_id` keyword. After each event, the following lines will appear:

```
<rwgt>
<wgt id='ID'>
<wgt id='ID1'>
</rwgt>
```

A more detailed explanation of what went into the computation of every single weight can be included in the <header> section of the event file by adding/changing the line

```
lhrwgt_descr 'some info'
```

in the input card, before each "reweighting" run is performed. Other useful keywords to group together different weights are `lhrwgt_group_name` and `lhrwgt_group_combine`.

More detailed information can be obtained by inspecting the document in /Docs/V2-paper.pdf under the common POWHEG-BOX-V2 directory.

5.2 MadGraph5_aMC@NLO

[1] Notice that even if the variable is not present, by default it is set to 1.

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Conclusions

Points to be made in a conclusion:

- In the case of s-channel simplified models, in particular, there is complementarity between searches for dark matter and visible particles. Thus, limits on invisible decays must be consistent with dijet and dilepton searches. In the case of the mono-top simplified model, limits on visible single-top final states must be considered.
- There are many implicit assumptions that have not been laid out entirely in our presentation. As stated earlier, the term "dark matter' in this report refers to a putative dark matter candidate. The details of a particular mono-X analysis rely on the fact that a WIMP exists, and that it is collider-stable. The observation of a signal consistent with WIMP production does can only provide indirect or confirming evidence of a dark matter particle.
- The presentation of results comparing different experimental frontiers has to be done carefully and clearly. We see the need for broader discussions on this topic.
- The experiments should aim to present limits on production cross sections corrected for acceptance when this is viable.
- The Appendix contains a presentation of some models that came out in our discussions that were not deemed a priority for early Run2 analyses. However, these should be considered in the future.

A.1 *Implementation of s-channel and t-channel models for $\not{E}_T$ +X analyses*

There are several matrix element implementations of the DM production through spin-0 and spin-1 mediators. This Appendix collects the generator recommendations and available implementations of these models for different final states, together with studies of the matching between the matrix element and the parton shower.

A.1.1 *Implementation of models for mono-jet signature*

For a spin-1 mediator, the implementation in POWHEG generates DM pair production with 1 parton at next-to-leading order (NLO), whilst MADGRAPH5_aMC@NLO and MCFM are at leading order (LO) [1]. As shown in POWHEG Ref. [HKR13], including NLO corrections result in an enhancement in the cross section as compared to LO and though this is not significant, it does lead to a substantial reduction in the dependence on the choice of the renormalization and factorization scale and hence the theoretical uncertainty on the signal prediction. Since NLO calculations are available for the process in POWHEG, we recommend to proceed with POWHEG as the generator of choice.

[1] Spin-0 and spin-1 mediator models will also be provided in the near future to the same precision in MADGRAPH5_aMC@NLO [A+14b].

DM simplified models

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

DM simplified models at NLO

The FeynRules/NLOCT and MG5_aMC framework

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

mono-j: spin-0 mediator
F. Maltoni, A. Martini (UC Louvain)

mono-j: spin-1 mediator
M. Kraemer, M. Pellen (Aachen)

mono-EW
M. Neubert, J. Wang (Mainz)

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

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

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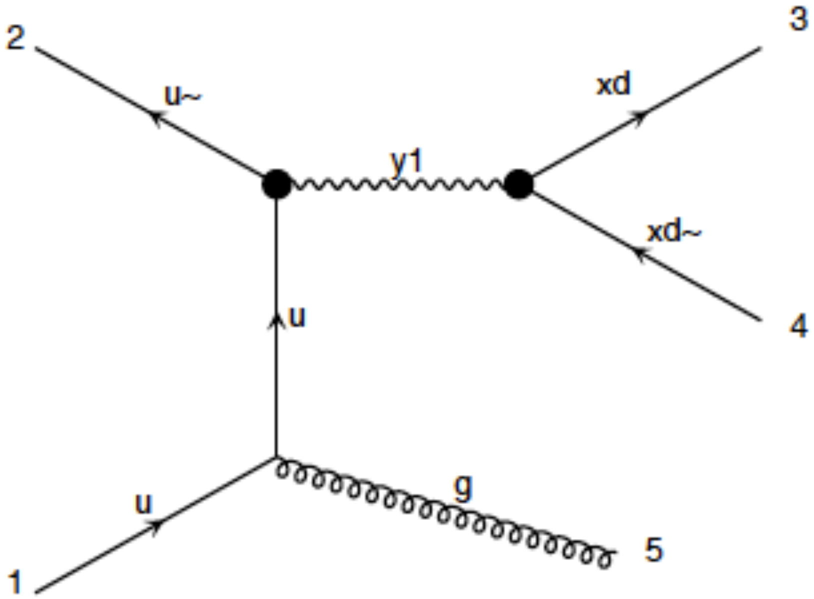
DM simplified FR models

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

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



1.1 Spin-0 mediator

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

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

1.2 Spin-1 mediator

$$\mathcal{L}^{Y_1}_{X_D} = \frac{i}{2} g^V_{X_C} (X^*_C (\partial_\mu X_C) - (\partial_\mu X^*_C) X_C) Y^\mu_1 + \overline{X}_D \gamma_\mu (g^V_{X_D} + i g^A_{X_D} \gamma_5) X_D\, Y^\mu_1$$

$$\mathcal{L}^{Y_1}_{SM} = \sum_{i,j} [\bar{d}_i \gamma_\mu (g^V_{d_{ij}} + i g^A_{d_{ij}} \gamma_5) d_j + \bar{u}_i \gamma_\mu (g^V_{u_{ij}} + i g^A_{u_{ij}} \gamma_5) u_j] Y^\mu_1$$

Validations for Dirac DM

A.1 spin-0 mediator

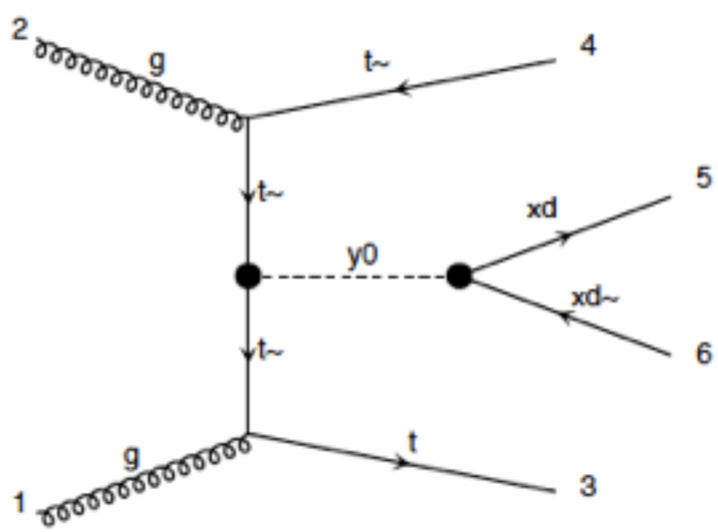
For Dirac DM:

```
> (import model loop_sm)
> generate p p > t t~ ta- ta+ / a z [QCD]
> output
> launch
```

vs.

```
> import model DM_simp_NLO_UFO
> generate p p > t t~ xd xd~ / y1 [QCD]
> output
> launch
```

with param_card_Y0.dat.



A.2 spin-1 mediator

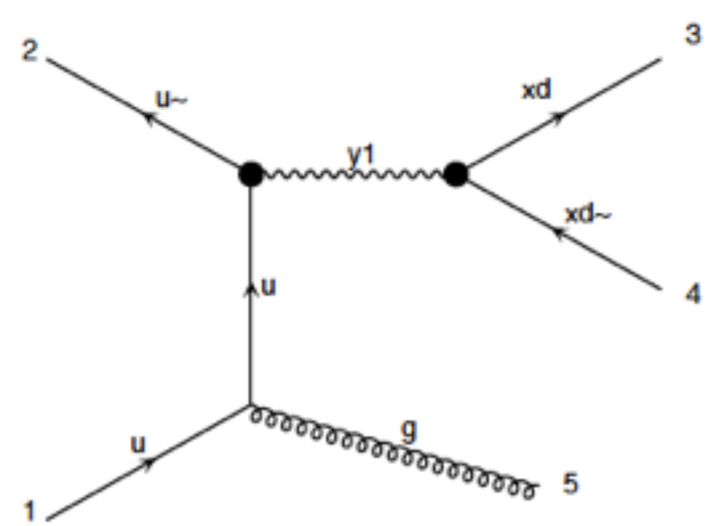
For Dirac DM:

```
> (import model loop_sm)
> generate p p > ta- ta+ j / a [QCD]
> output
> launch
```

vs.

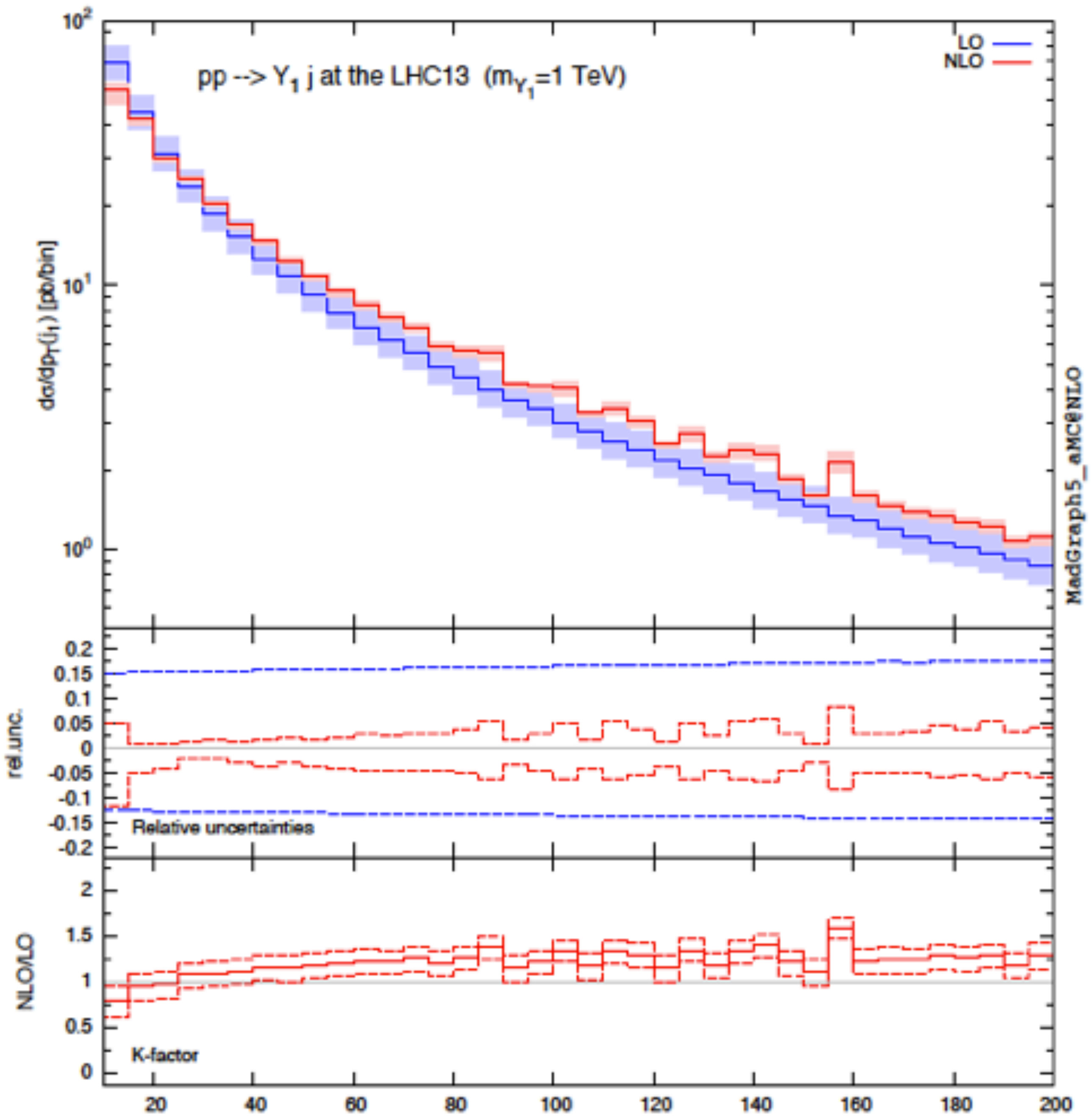
```
> import model DM_simp_NLO_UFO
> generate p p > xd xd~ j / y0 [QCD]
> output
> launch
```

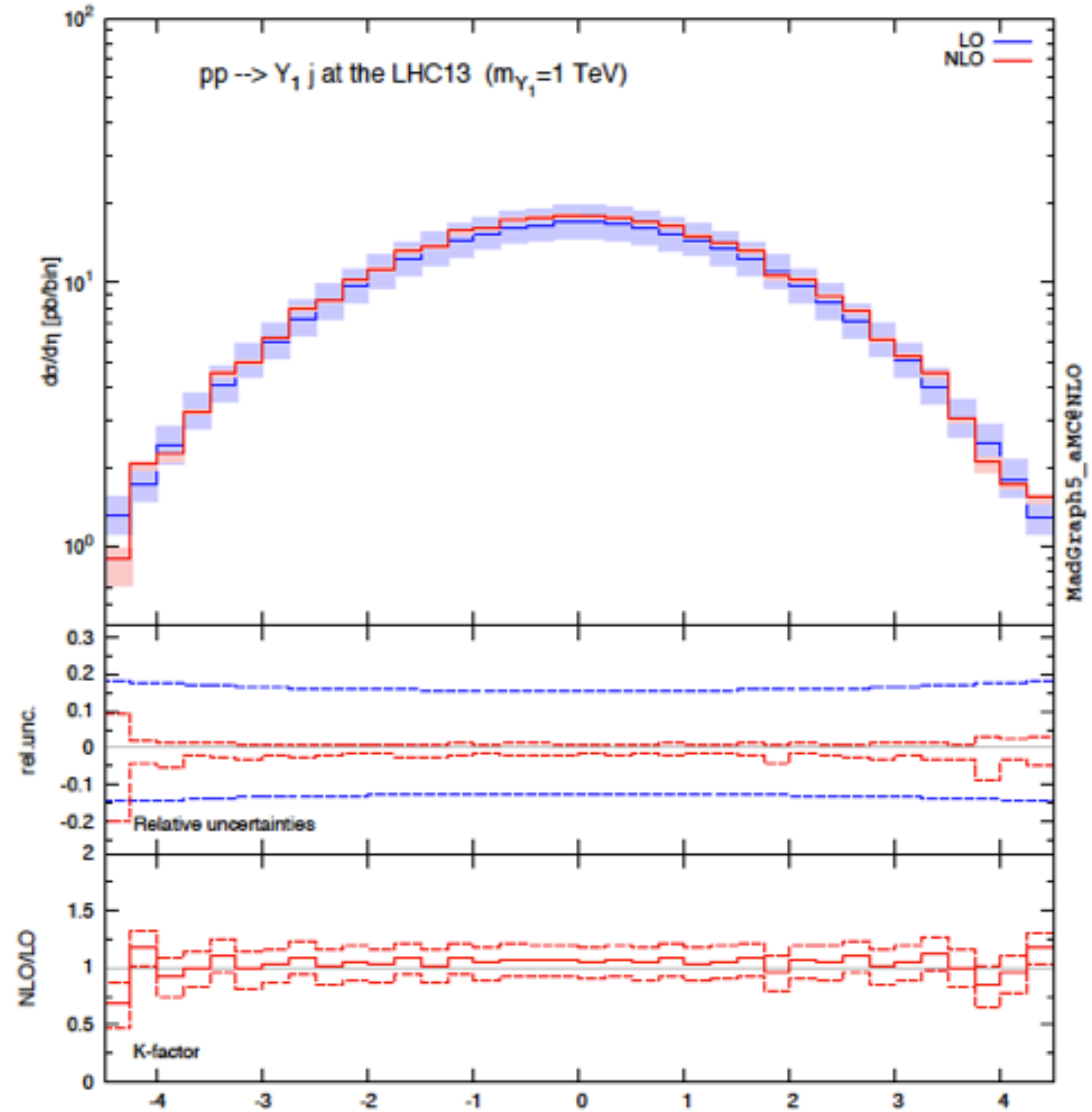
with param_card_Y1.dat.




```
##################################
## INFORMATION FOR DMINPUTS
##################################
Block DMINPUTS
    1 1.000000e+04 # Lambda
    2 1.000000e+00 # gSXr
    3 1.000000e+00 # gSXc
    4 1.000000e+00 # gSXd
    5 0.000000e+00 # gPXd
    6 1.000000e+00 # gSd11
    7 1.000000e+00 # gSu11
    8 1.000000e+00 # gSd22
    9 1.000000e+00 # gSu22
   10 1.000000e+00 # gSd33
   11 1.000000e+00 # gSu33
   12 0.000000e+00 # gPd11
   13 0.000000e+00 # gPu11
   14 0.000000e+00 # gPd22
   15 0.000000e+00 # gPu22
   16 0.000000e+00 # gPd33
   17 0.000000e+00 # gPu33
   18 0.000000e+00 # gSg
   19 0.000000e+00 # gPg
   20 1.000000e+00 # gVXc
   21 2.055722003e-2 # gVXd
   22 -1.851770197e-01 # gAXd
   23 1.303037531e-01 # gVd11
   24 -7.543048658e-02 # gVu11
   25 1.303037531e-01 # gVd22
   26 -7.543048658e-02 # gVu22
   27 0.1303037531e+00 # gVd33
   28 -0.07543048658e+00 # gVu33
   29 -1.851770197e-01 # gAd11
   30 1.851770197e-01 # gAu11
   31 -1.851770197e-01 # gAd22
   32 1.851770197e-01 # gAu22
   33 -0.1851770197e+00 # gAd33
   34 0.1851770197e+00 # gAu33
```

Distributions





Dark Matter production in loop induced processes

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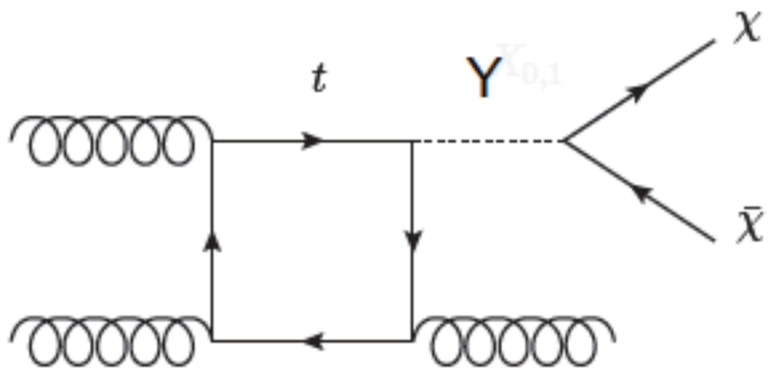
25/5/15

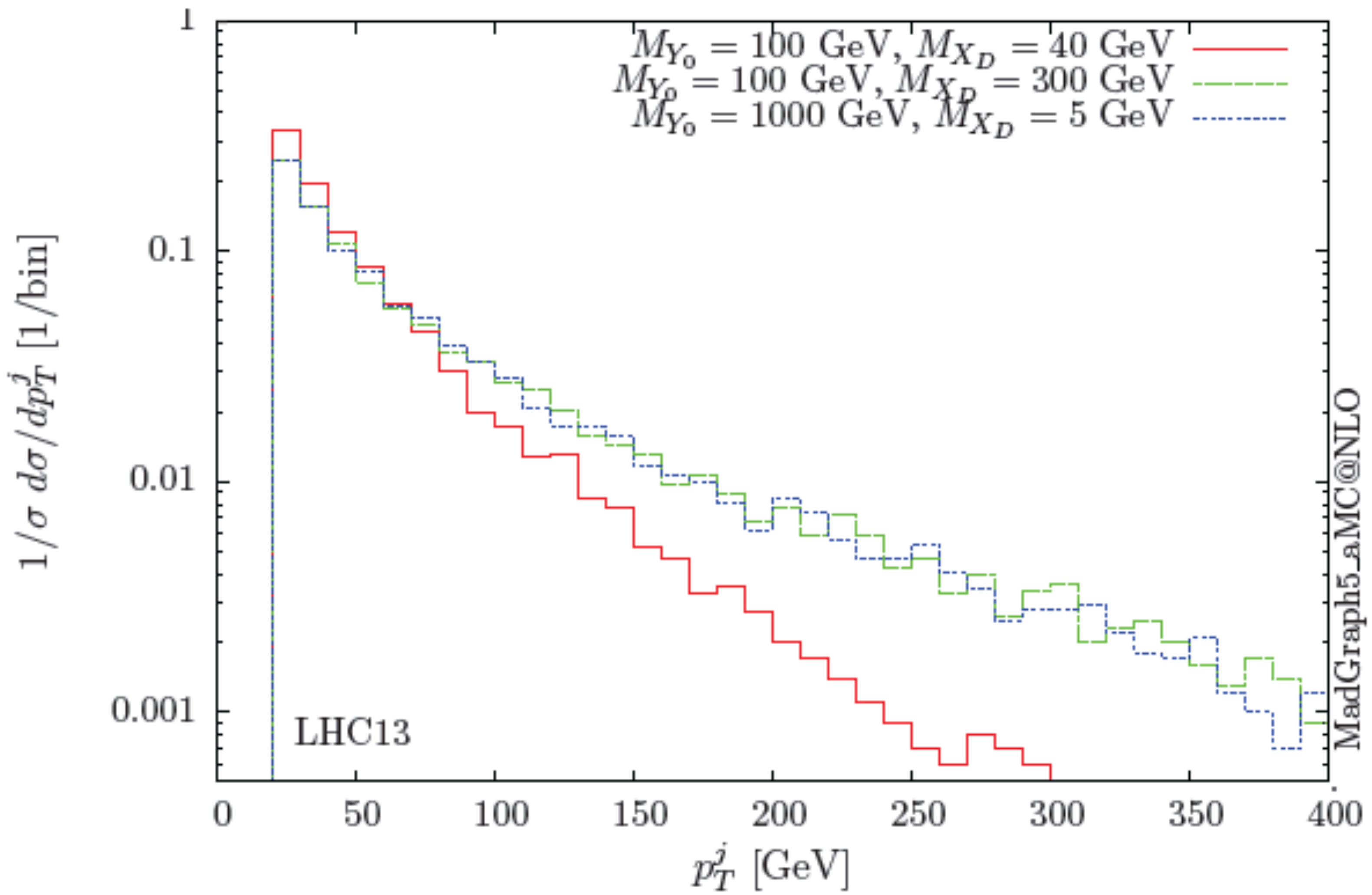


Restrict card to remove light quark interactions

Loop-induced process means the event generation is significantly slower

Reweighting still the fastest/more efficient option?
Use tree-level EFT to generate the events and reweight using the ratio $|M|^2_{exact}/|M|^2_{EFT}$

Dark Matter example: monojet signal



g g → χ χ j

Spin-0 mediator:
scalar couplings to both top and Dirac spinor DM

Shape comparison:
Normalised to 1

Mediator width:
Calculated automatically with MG5_aMC@NLO

Similar shapes for 1) very light DM particle and very heavy mediator
2) heavy DM particle and relatively light mediator