Dark matter search at the LHC

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Outlines

- Motivations
- Simplified DM models (white board)
- 3min MadGraph5_aMC@NLO tutorial

Higgs vs. Dark matter

- inSPIRE
  - find title higgs
  - find title dark matter

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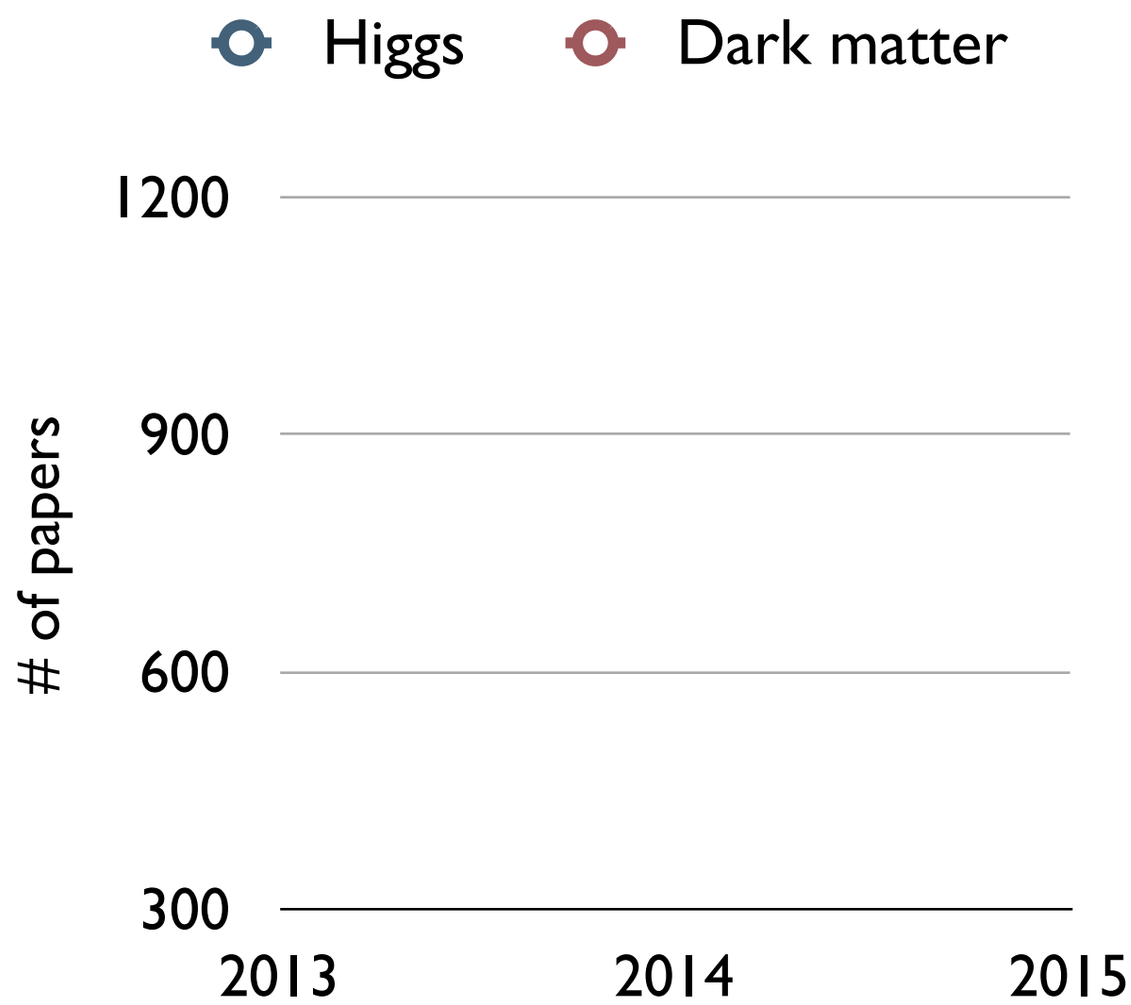

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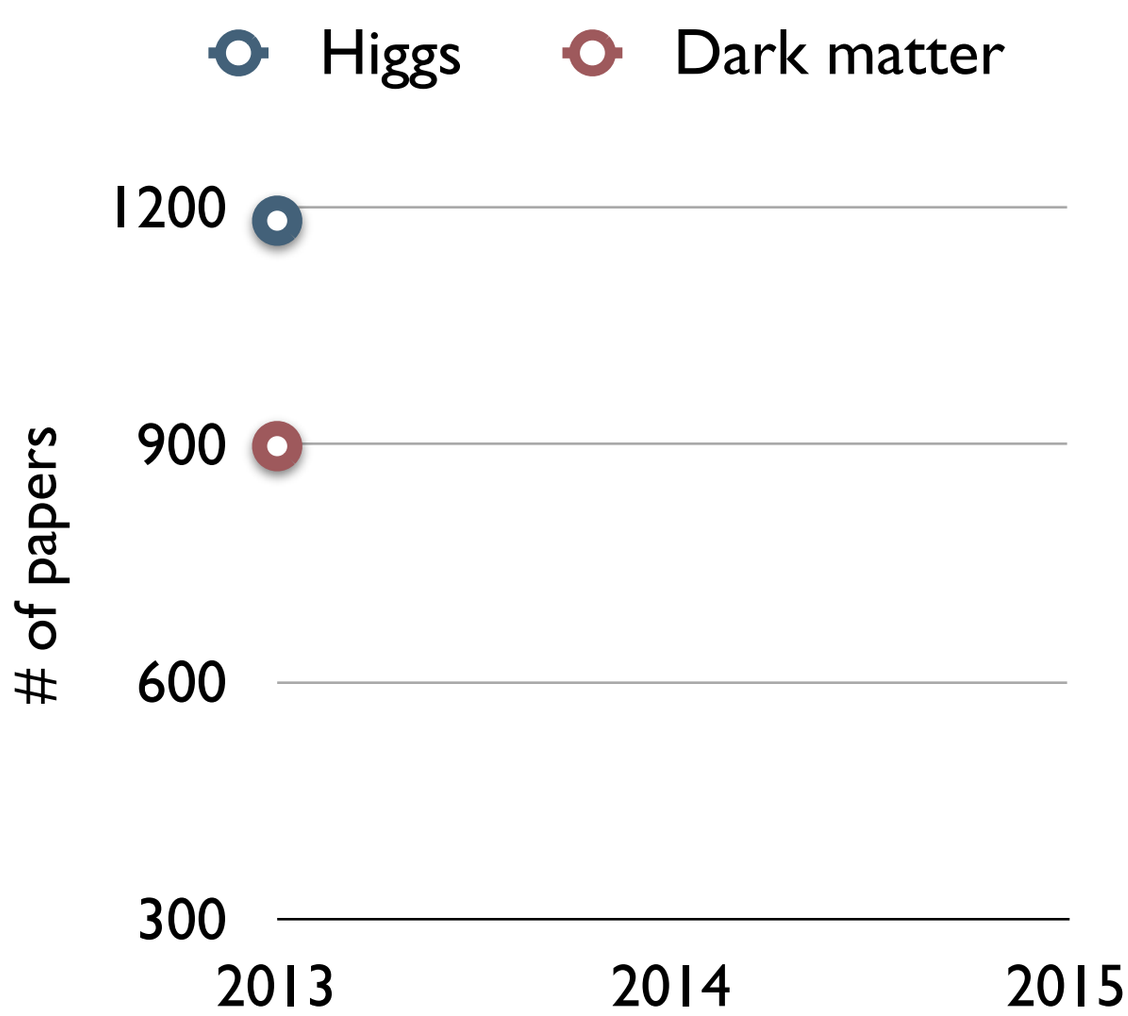

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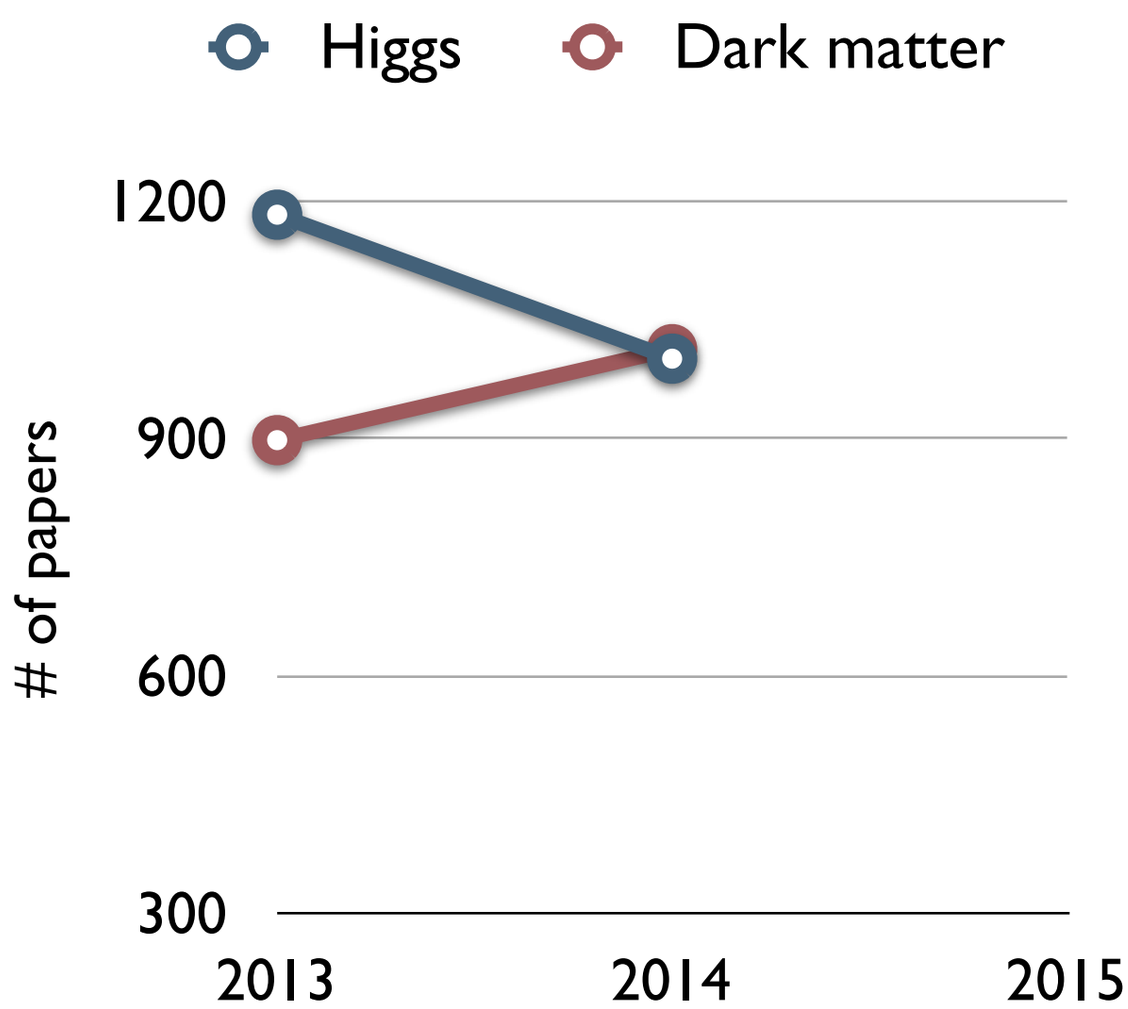

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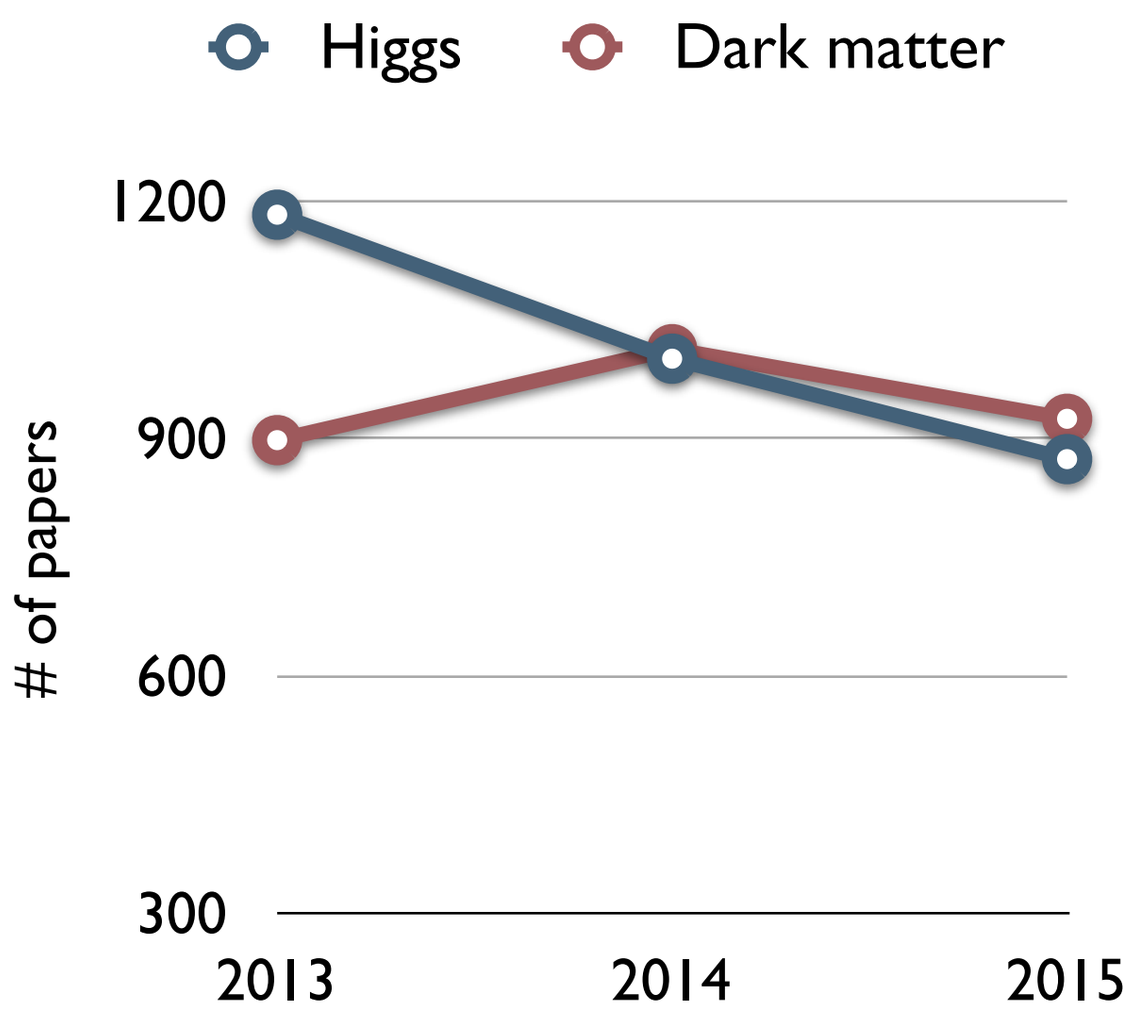

Higgs vs. Dark matter

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    + and a mawatari

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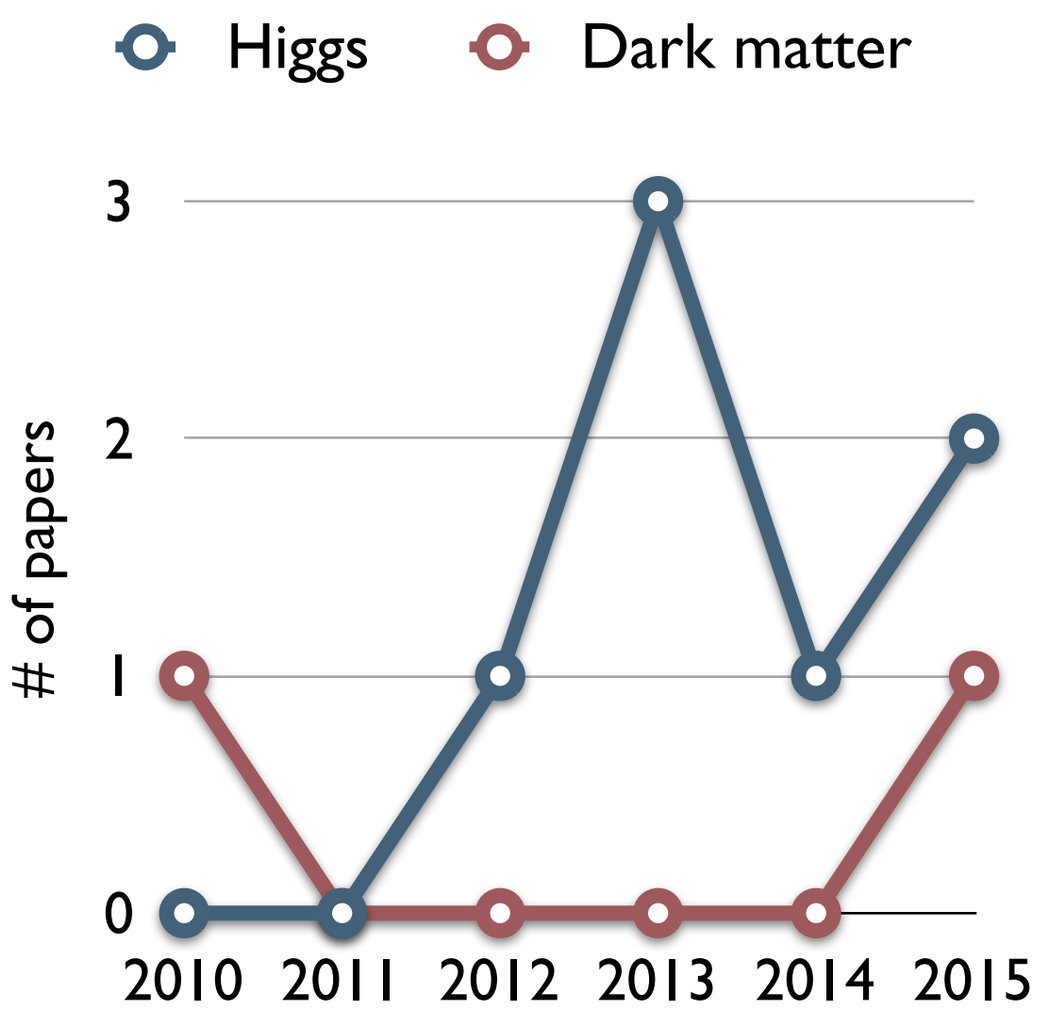

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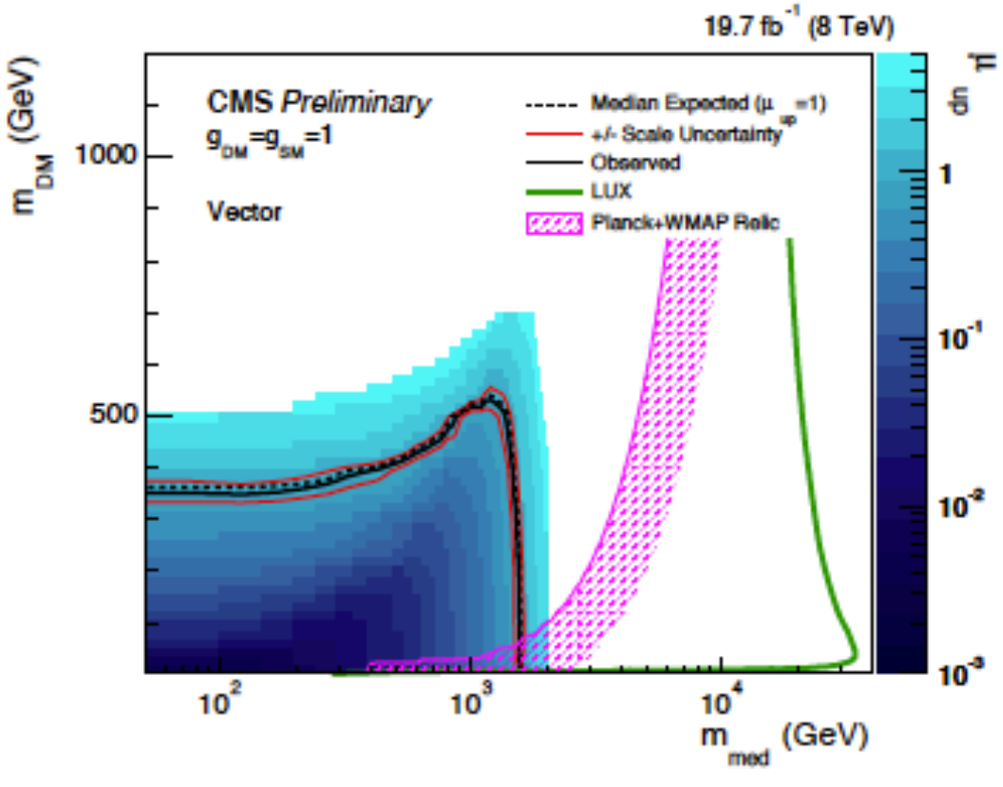
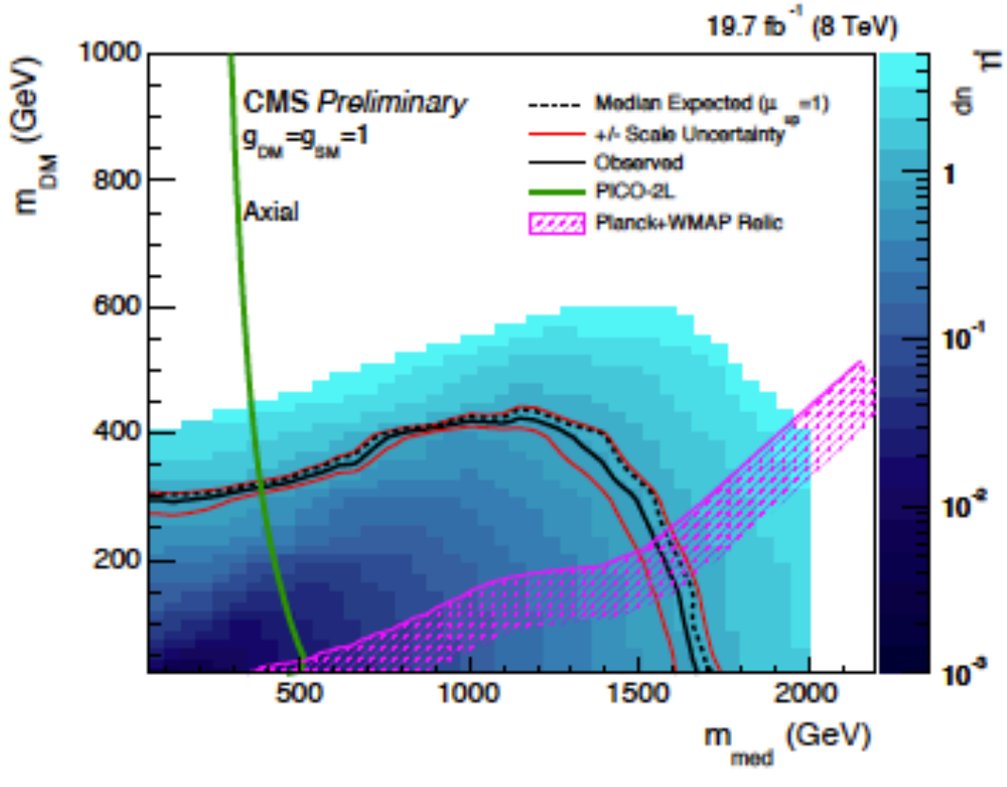
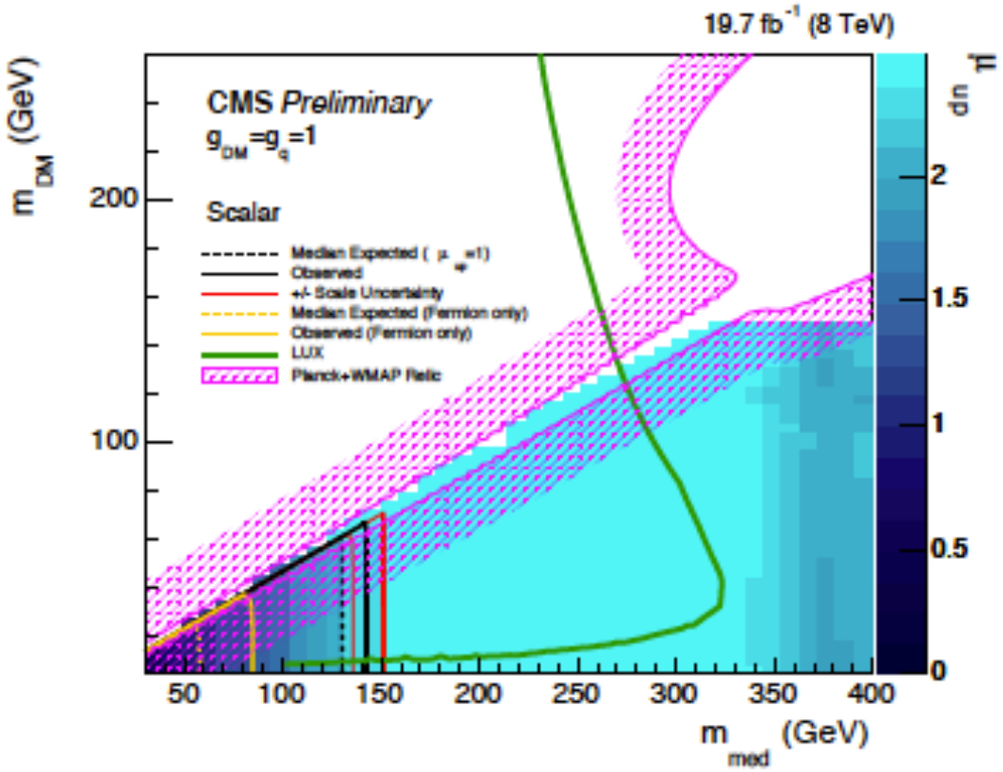


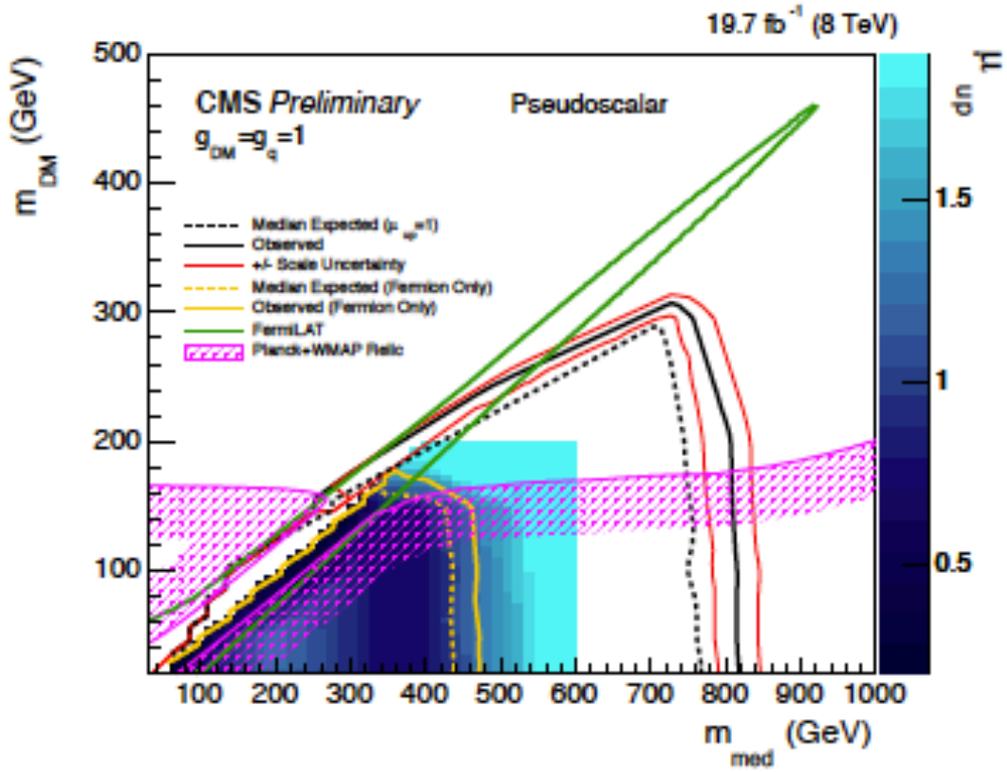
(a)



(b)



(c)



(d)

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

FeynRules/NLOCT - MG5_aMC/MadDM - MadAnalysis

DM simplified model

C. Degrande (Durham), B. Fuks (Paris)
K. Mawatari (VU Brussel/LPSC Grenoble), C. Zhang (BNL)

j+MET: spin-1 mediator

F. Maltoni, A. Martini (UC Louvain)

tt+MET: spin-0 mediator

M. Kraemer, M. Pellen (Aachen)

V+MET

M. Neubert, J. Wang (Mainz)

loop-induced

O. Mattelaer (Durham), E. Vryonidou (UC Louvain)

MadDM

C. Arian, M. Backovic, A. Martini (UC Louvain)

Analysis

B. Fuks (Paris)

DM simplified FR models

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

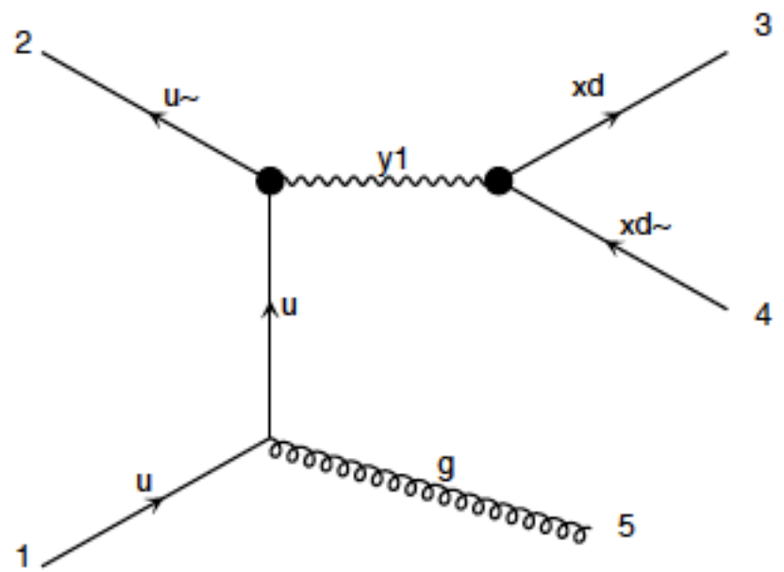
Mediator (Y):
- spin-0
- spin-1
- spin-2
- ...

1.1 Spin-0 mediator

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

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

1.2 Spin-1 mediator



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

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

3-min MadGraph5_aMC@NLO tutorial (ttY_0)

FeynRules: http://feynrules.irmp.ucl.ac.be/
MG5_aMC: https://launchpad.net/mg5amcnlo

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./bin/mg5_aMC
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☜ Start the MG5_aMC shell

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- Import the model
- Generate the process

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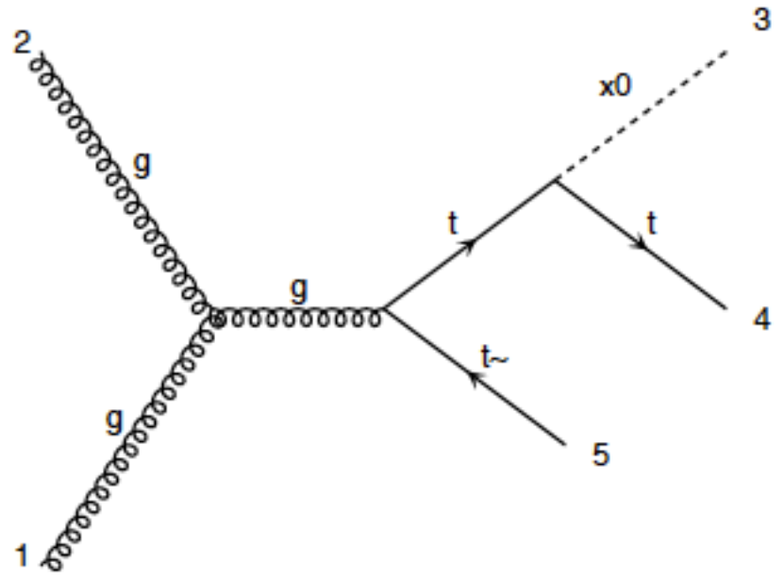
/Users/mawatari/work/tools/madgraph5/CFHEPdemo/index.html

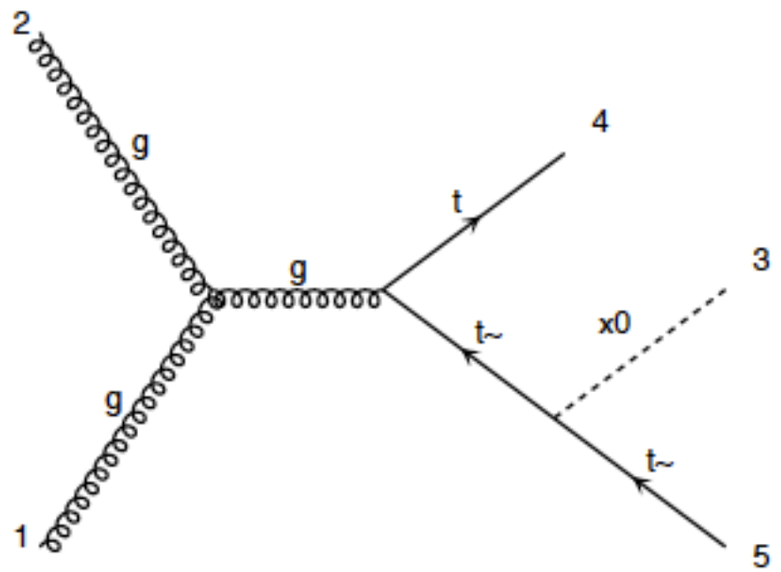
SubProcesses and Feynman diagrams

Directory	Type	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P0_gg_x0ttx	born	8	1	postscript	g g > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] WEIGHTED=1
	virt	184	1	postscript	g g > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD]
	real	50	1	postscript	g g > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	d~ g > x0 t t~ d~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [QCD]

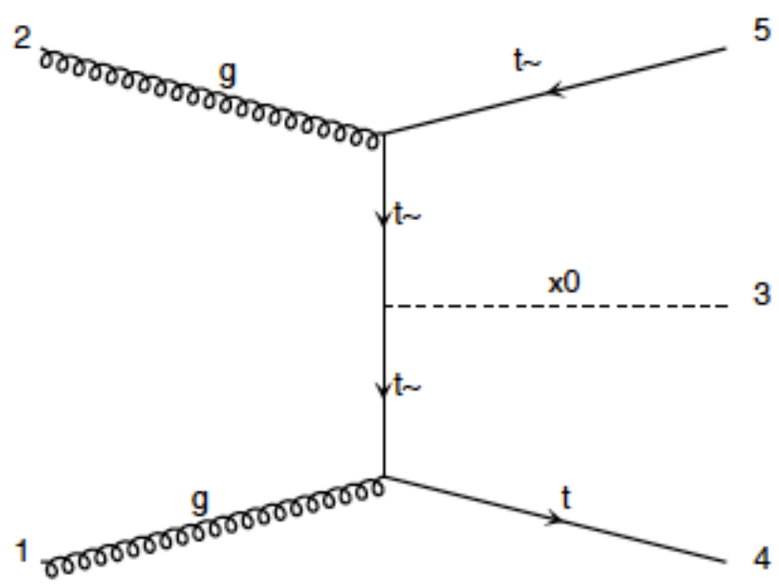
born (ttY_0)



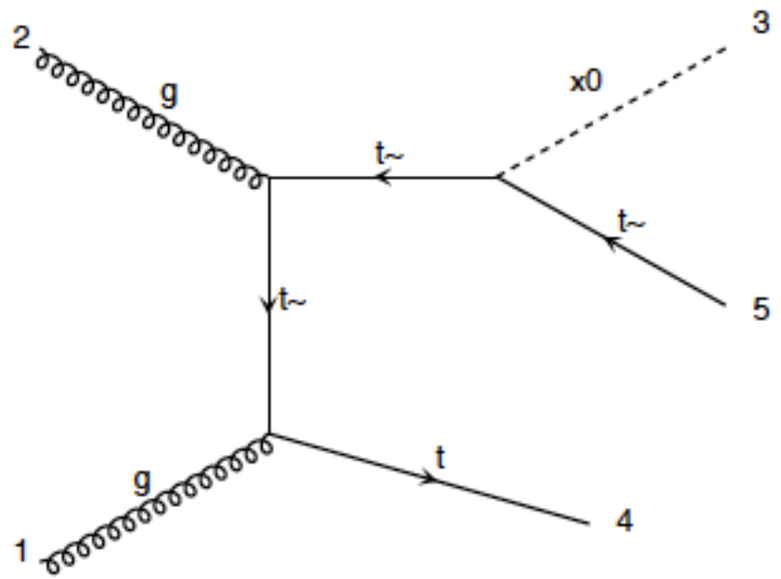
born diagram 1 QCD=2, QED=1, QNP=0



born diagram 2 QCD=2, QED=1, QNP=0



born diagram 3 QCD=2, QED=1, QNP=0



born diagram 4 QCD=2, QED=1, QNP=0

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	real	12	4	postscript	d~ g > x0 t t~ d~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	d g > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [QCD] , u g > x0 t t~ u XGLU=1 WEIGHTED=5 QNP=1 [QCD] , s g > x0 t t~ s XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c g > x0 t t~ c XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	g d~ > x0 t t~ d~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g u~ > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g s~ > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g c~ > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	g d > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g u > x0 t t~ u XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g s > x0 t t~ s XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g c > x0 t t~ c XGLU=1 WEIGHTED=5 QNP=1 [QCD]
P0_uux_x0ttx	born	2	4	postscript	u u~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] , c c~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] , d d~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] , s s~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD]
	virt	41	4	postscript	u u~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD] , c c~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD] , d d~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD] , s s~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD]
	real	12	4	postscript	u u~ > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c c~ > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [QCD] ,

virtual (ttY_0)

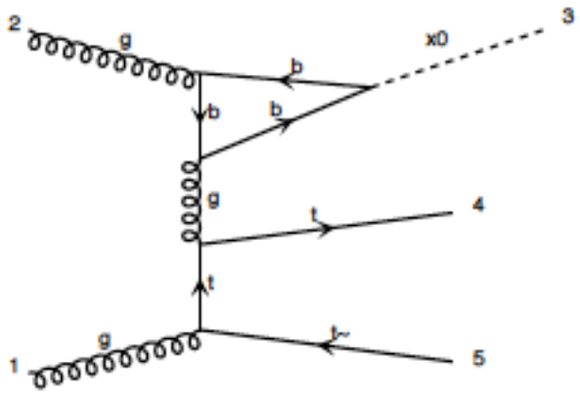


diagram 31 QCD=4, QED=1, QNP=0

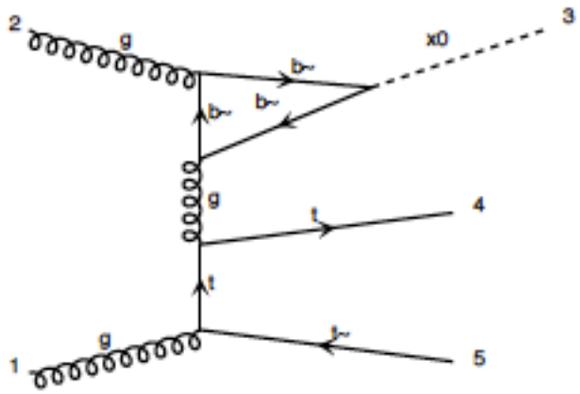


diagram 32 QCD=4, QED=1, QNP=0

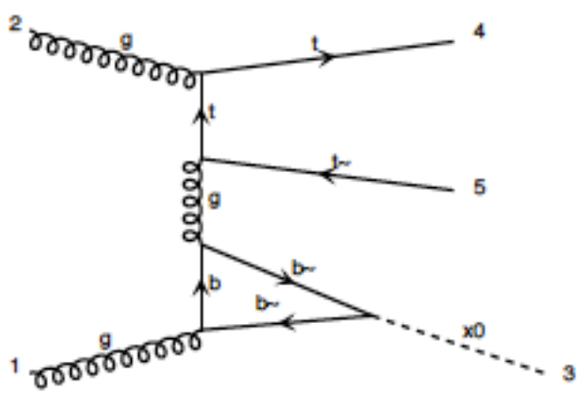


diagram 33 QCD=4, QED=1, QNP=0

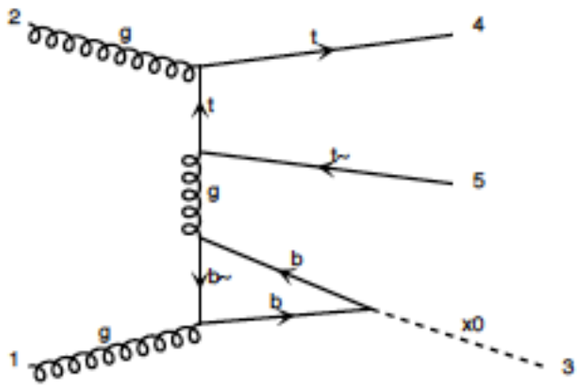


diagram 34 QCD=4, QED=1, QNP=0

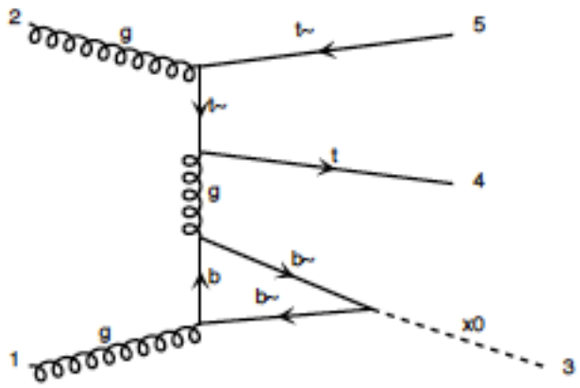


diagram 35 QCD=4, QED=1, QNP=0

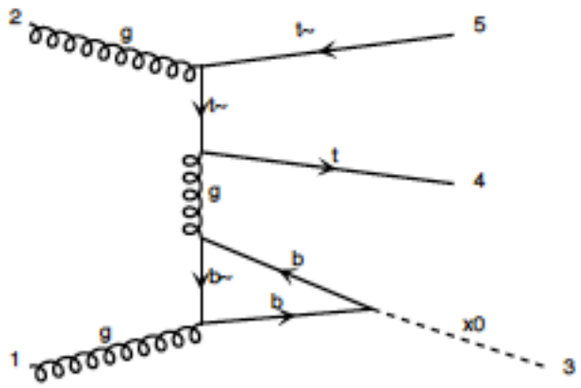


diagram 36 QCD=4, QED=1, QNP=0

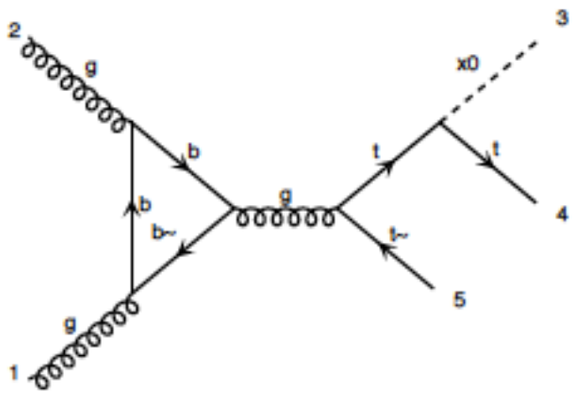


diagram 37 QCD=4, QED=1, QNP=0

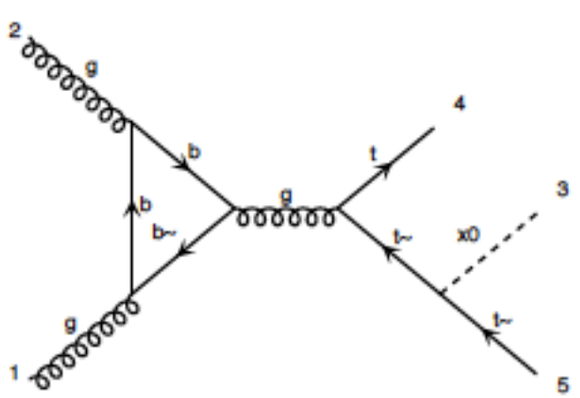


diagram 38 QCD=4, QED=1, QNP=0

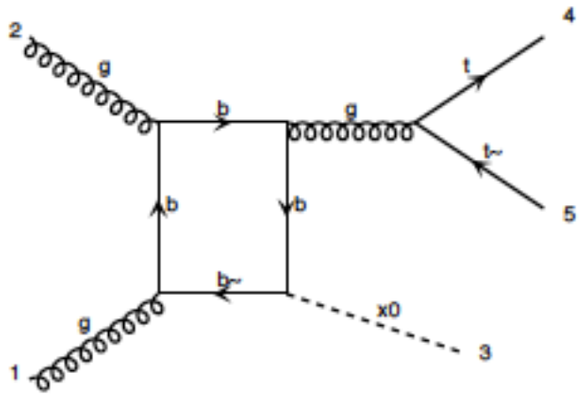
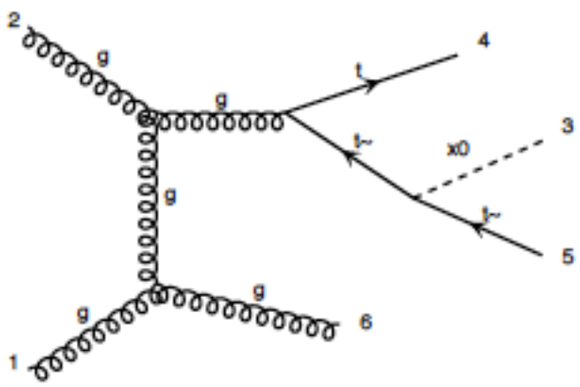
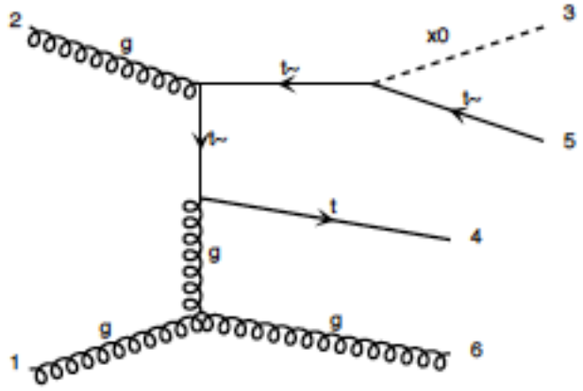


diagram 39 QCD=4, QED=1, QNP=0

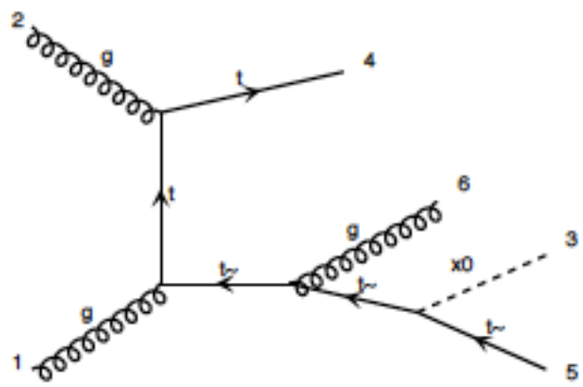
real (ttY_0)



real diagram 31 QCD=3, QED=1, QNP=0



real diagram 32 QCD=3, QED=1, QNP=0



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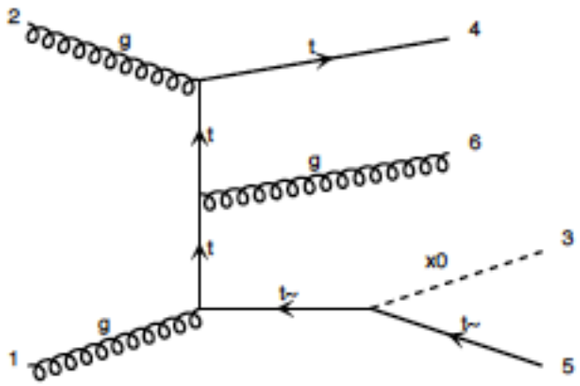
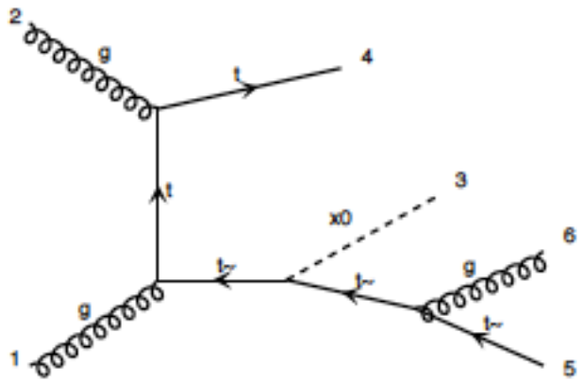
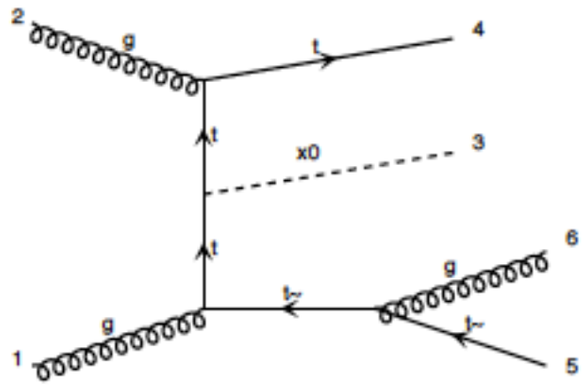


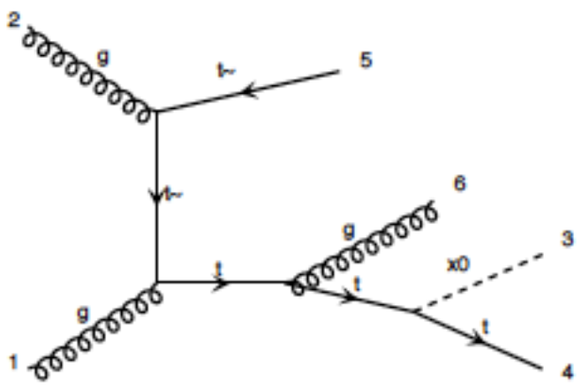
real diagram 34 QCD=3, QED=1, QNP=0



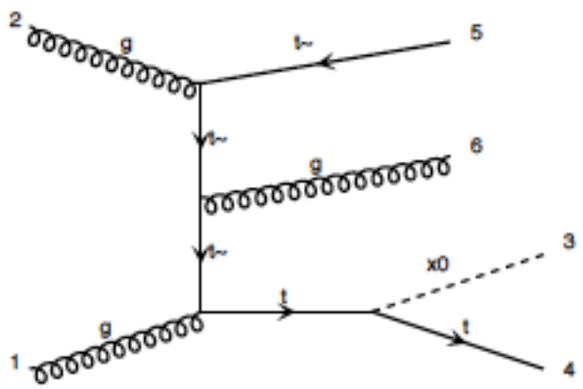
real diagram 35 QCD=3, QED=1, QNP=0



real diagram 36 QCD=3, QED=1, QNP=0



real diagram 37 QCD=3, QED=1, QNP=0



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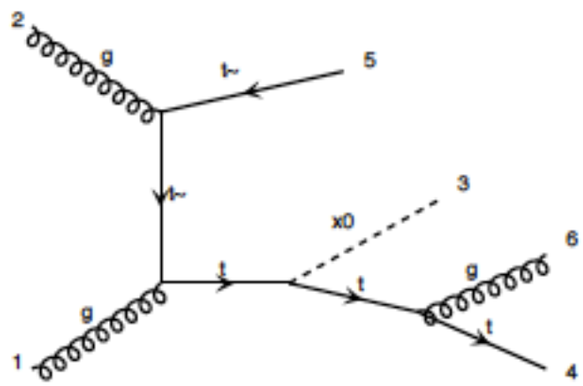

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- Import the model
- Generate the process
- Write the code (including html)
- Generate the LO/NLO events

```
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=ON
  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, ... ]
>
```

MadSpin: Artoisenet, Frederix, Mattelaer, Rietkert [arxiv:1212.3460]

- allows one to decay narrow resonances in Les Houches Monte Carlo events.
- preserves both spin correlation and finite width effects.

3-min MadGraph5_aMC@NLO tutorial (ttY_0)

```
Do you want to edit a card (press enter to bypass editing)?
  1 / param      : param_card.dat
  2 / run        : run_card.dat
  3 / madspin    : madspin_card.dat
  4 / shower     : shower_card.dat
 [0, done, 1, param, 2, run, 3, madspin, 4, enter path, ... ]
>
```

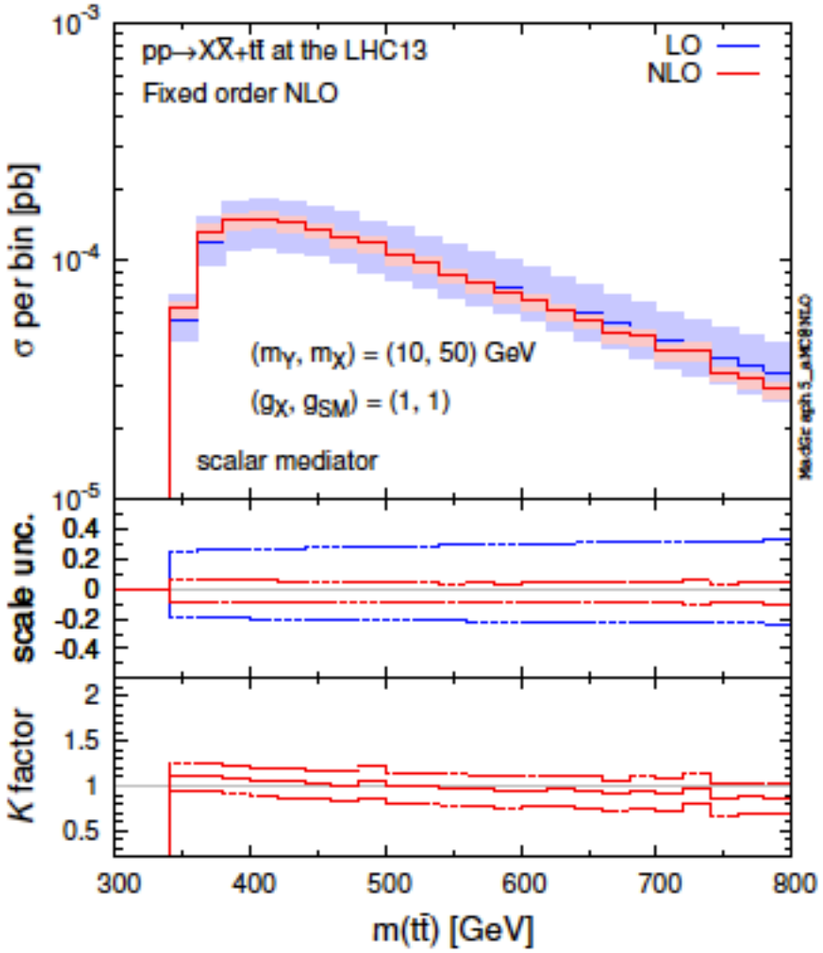
param_card.dat

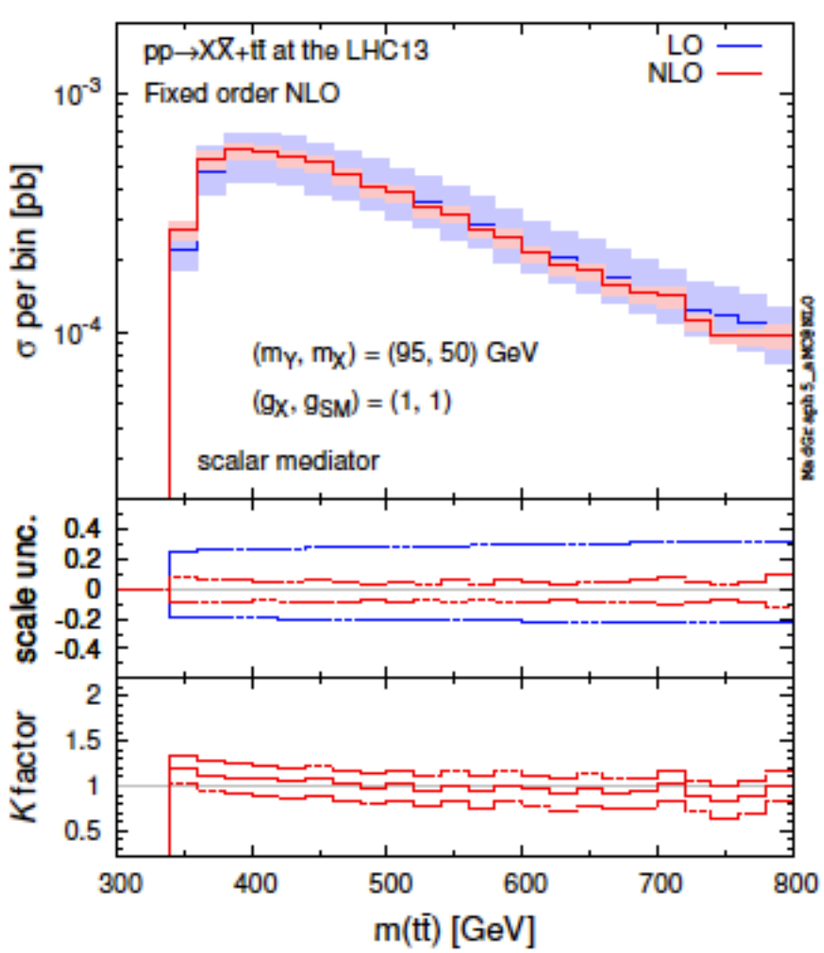
```
###################################
## INFORMATION FOR DMINPUTS
###################################
Block dminputs
    1 1.000000e+04 # Lambda
    2 1.000000e+00 # gSXr
    3 1.000000e+00 # gSXc
    4 1.000000e+00 # gSXd
    5 0.000000e+00 # gPXd
    6 0.000000e+00 # gSd11
    7 0.000000e+00 # gSu11
    8 0.000000e+00 # gSd22
    9 0.000000e+00 # gSu22
   10 0.000000e+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
```

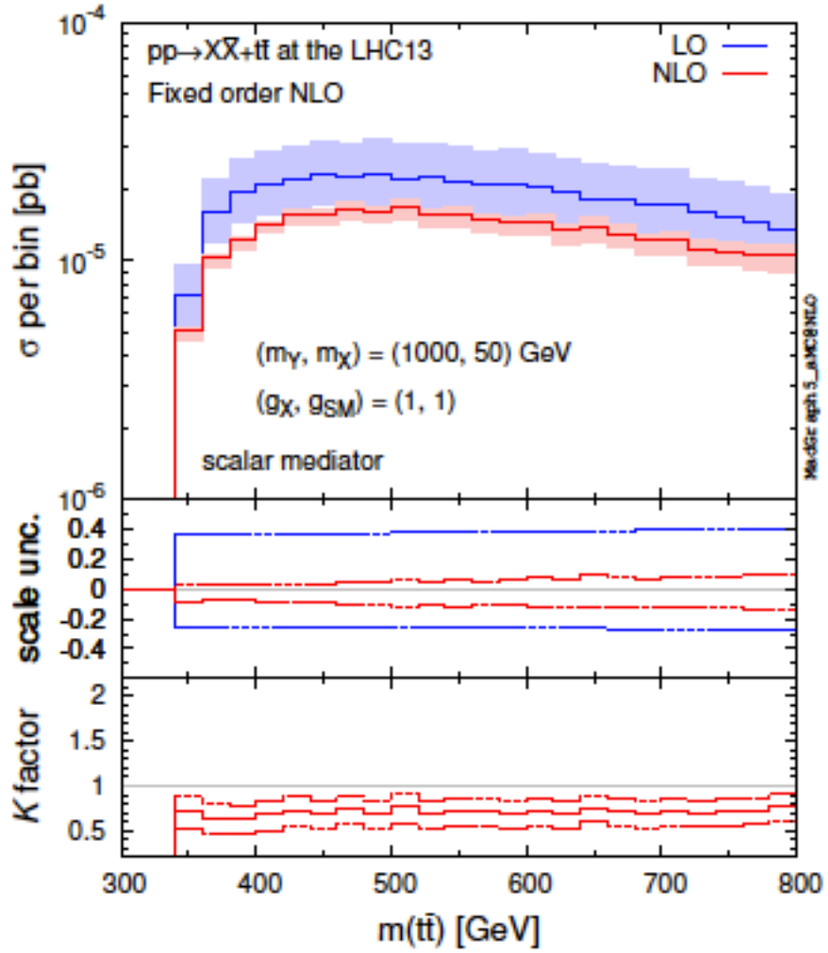
run_card.dat

```
#*********************************************************************
# Collider type and energy                                           *
#*********************************************************************
    1   = lpp1    ! beam 1 type (0 = no PDF)
    1   = lpp2    ! beam 2 type (0 = no PDF)
 6500   = ebeam1  ! beam 1 energy in GeV
 6500   = ebeam2  ! beam 2 energy in GeV
#*********************************************************************
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.  *
#*********************************************************************
 nn23nlo    = pdlabel   ! PDF set
 230000     = lhaid     ! if pdlabel=lhapdf, this is the lhapdf number
#*********************************************************************
# Include the NLO Monte Carlo subtr. terms for the following parton    *
# shower (HERWIG6 | HERWIGPP | PYTHIA6Q | PYTHIA6PT | PYTHIA8)         *
# WARNING: PYTHIA6PT works only for processes without FSR!!!!         *
#*********************************************************************
  HERWIG6    = parton_shower
```

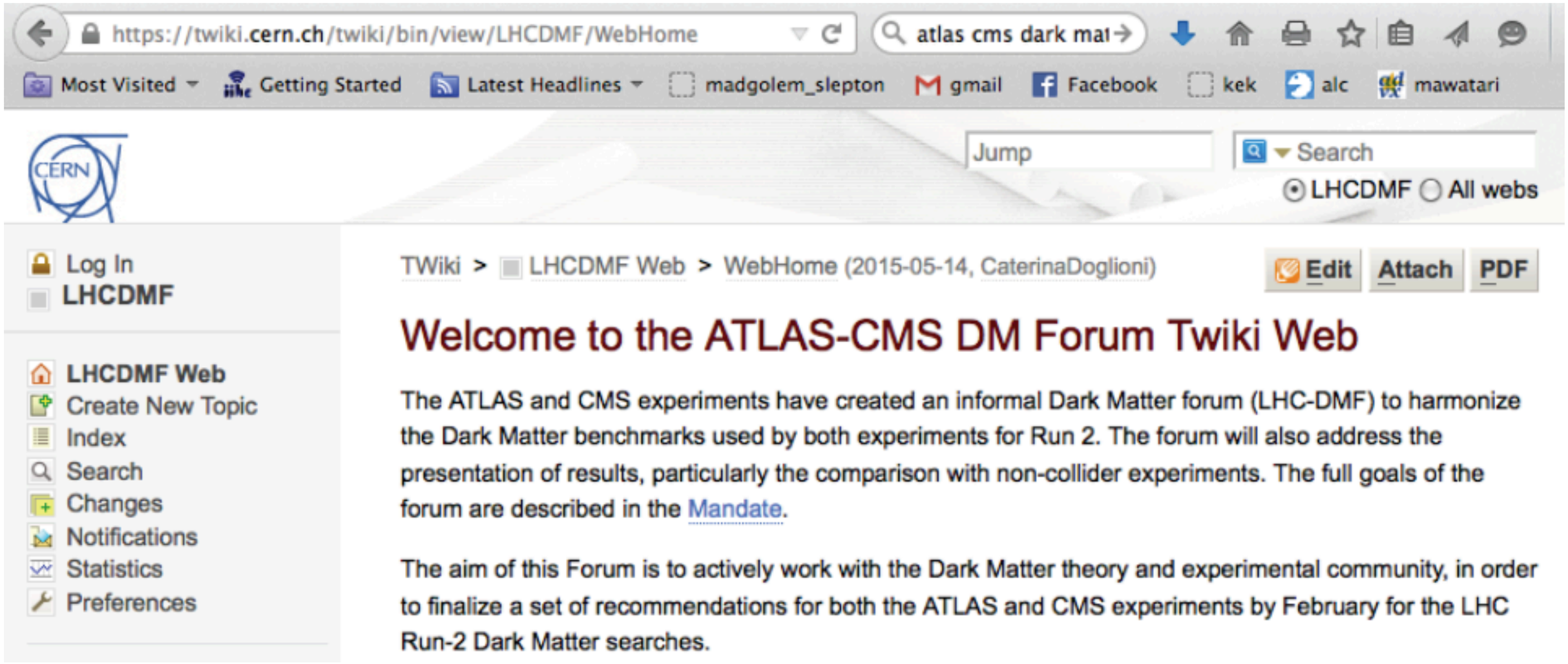
Distributions with scale unc.







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.

Validations for Dirac DM

A.1 spin-0 mediator

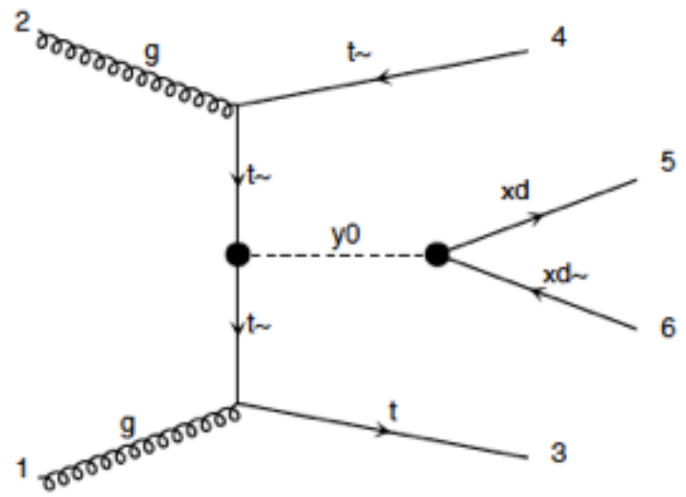
For Dirac DM:

```
> (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

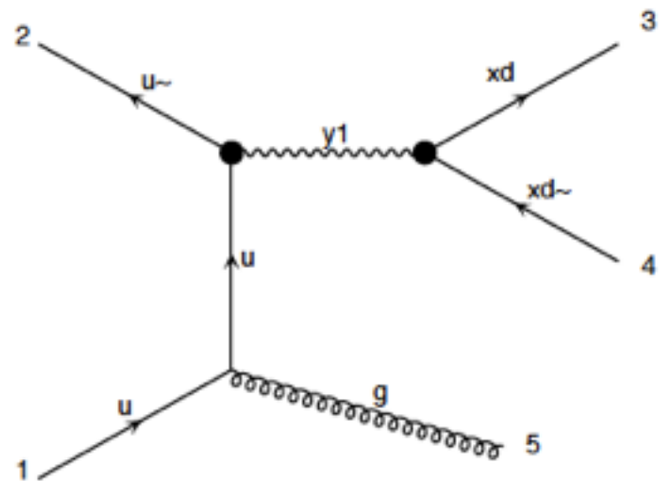
For Dirac DM:

```
> (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
```