EFT tutorial

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Part I

Basic MG5_aMC use

Download models: scalarVBS.zip and UFOdim8.zip from https://twiki.cern.ch/twiki/bin/view/VBSCan/LjubljanaTrainingEvent

Unzip them in the models folder of your MG5 installation
Load the EFT model into MG5 and generate a VBS process including an EFT interaction:

```
mg5> import model UFOdim8
mg5> generate u u > w+ w+ j j QCD=0 NP=4
```

Check the diagrams with:

```
mg5> display diagrams
```

```
mg5> output dim8_same_sign
```

Try other VBS examples (w^+w^- jj, zzjj, wzjj etc)

dim-8 operators in VBS

Longitudinal

$$O_{S,0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$$
$$O_{S,1} = [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$$
$$O_{S,2} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$$

Mixed

$$O_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$O_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$O_{M,2} = \left[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$O_{M,3} = \left[\hat{B}_{\mu\nu}\hat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$O_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times \hat{B}^{\beta\nu}$$
$$O_{M,5} = \tfrac{1}{2}\left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times \hat{B}^{\beta\mu} + h.c.$$
$$O_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

Transverse

$$O_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$O_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$O_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$O_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta}$$
$$O_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \hat{B}_{\mu\beta}\hat{B}^{\alpha\nu}$$
$$O_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \hat{B}_{\beta\nu}\hat{B}^{\nu\alpha}$$
$$O_{T,8} = \hat{B}_{\mu\nu}\hat{B}^{\mu\nu} \times \hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta}$$
$$O_{T,9} = \hat{B}_{\alpha\mu}\hat{B}^{\mu\beta} \times \hat{B}_{\beta\nu}\hat{B}^{\nu\alpha},$$

How do these operators change the VBS process:

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

Coupling orders

NP=4

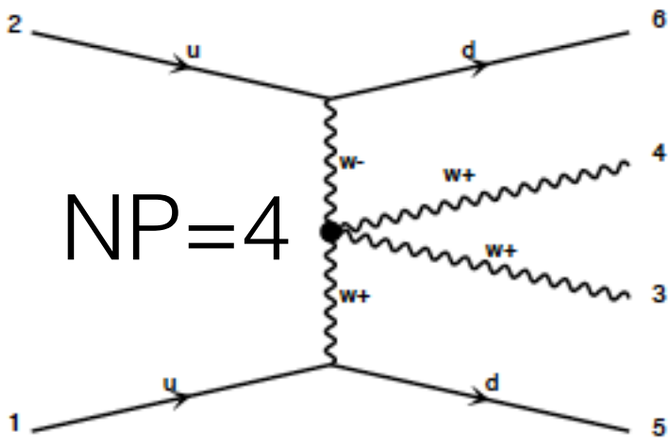

diagram 35 NP=4, QCD=0, QED=4

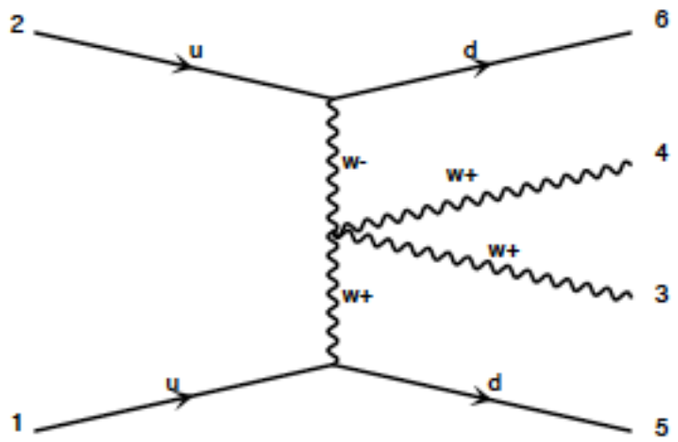

diagram 36 NP=0, QCD=0, QED=4

```
generate p p > w+ w+ j j QCD=0 NP=4
```

SM + Interference with dim-8 operator + dim-8 Squared

```
generate p p > w+ w+ j j QCD=0 NP=4 NP^2==4
```

Interference with dim-8 operator

```
generate p p > w+ w+ j j QCD=0 NP=4 NP^2==8
```

dim-8 Squared

Check the diagrams for each syntax

Coupling orders

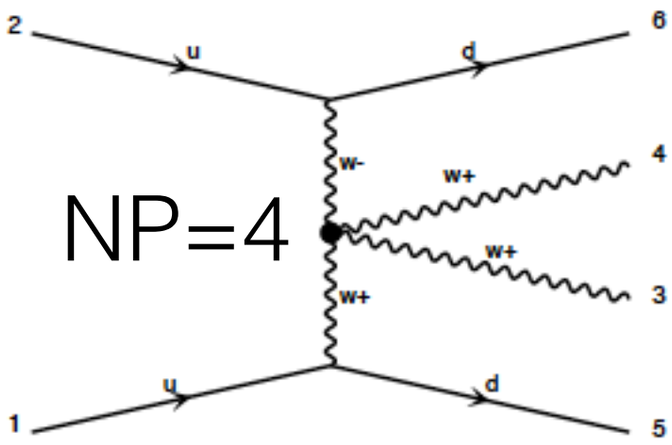

diagram 35 NP=4, QCD=0, QED=4

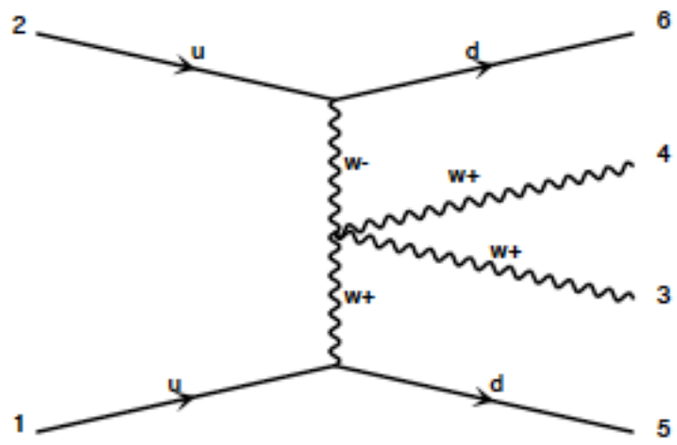

diagram 36 NP=0, QCD=0, QED=4

To generate events faster:
One partonic channel

```
generate u u > w+ w+ d d QCD=0 NP=4
output
```

This will give you: Standard Model + Interference with dim-8 operator + dim-8 Squared

EFT generation

One can set different values of the coefficients in the param_card.dat

```
BLOCK ANOINPUTS #
     1 1.000000e-10 # fs0
     2 1.000000e-10 # fs1
     3 1.000000e-10 # fs2
     4 1.000000e-10 # fm0
     5 1.000000e-10 # fm1
     6 1.000000e-10 # fm2
     7 1.000000e-10 # fm3
     8 1.000000e-10 # fm4
     9 1.000000e-10 # fm5
    10 1.000000e-10 # fm6
    11 1.000000e-10 # fm7
    12 1.000000e-10 # ft0
    13 1.000000e-10 # ft1
    14 1.000000e-10 # ft2
    15 1.000000e-10 # ft5
    16 1.000000e-10 # ft6
    17 1.000000e-10 # ft7
    18 1.000000e-10 # ft8
    19 1.000000e-10 # ft9
```

Which operators will modify the wwww vertex?

Check back in the lecture notes

dim-8 operators in VBS

How do these operators change the VBS process:

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
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$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

Generate some samples for different operators

1. Generate a small sample of 10k events for the Standard Model using the following standard VBS cuts:

20.0 = ptj
4.5 = etaj
0.4 = drjj
500.0 = mmjj
2.5 = deltaeta

2. Try non-zero values of the coefficients in the param_card.dat
    1. Generate a sample with FS0=10
    2. Generate a sample with FT0=10

Whilst waiting

Generate the diagrams for more VBS processes

Play with the coupling order constraints

Make plots

Once your samples are ready:
Plot the invariant mass of the VV pair for:

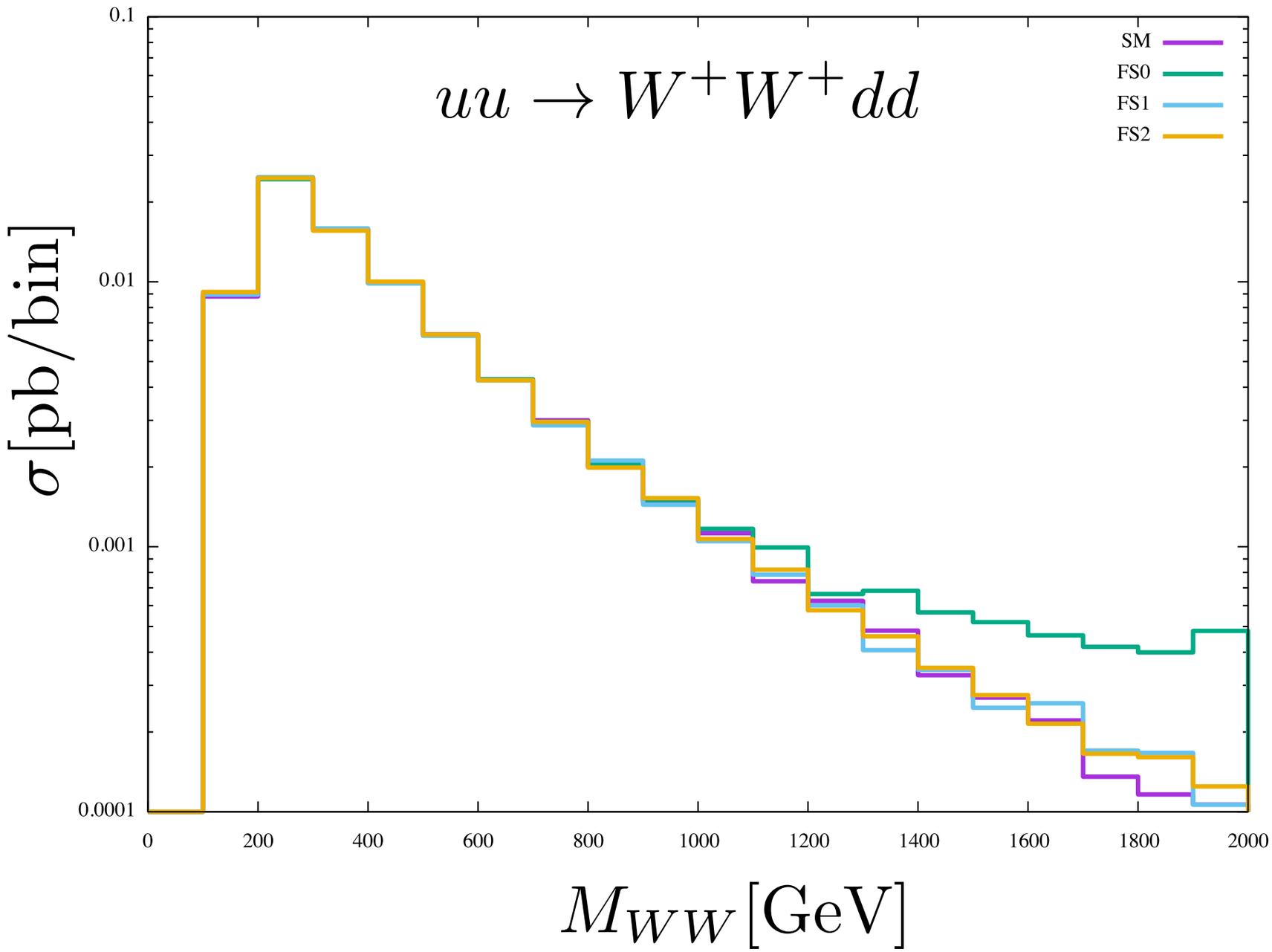
1) The SM
2) Your transverse operator sample
3) You longitudinal operator sample

Try other observables: transverse momentum of the vector bosons, the jet pT and rapidities

What is the impact of the operators?

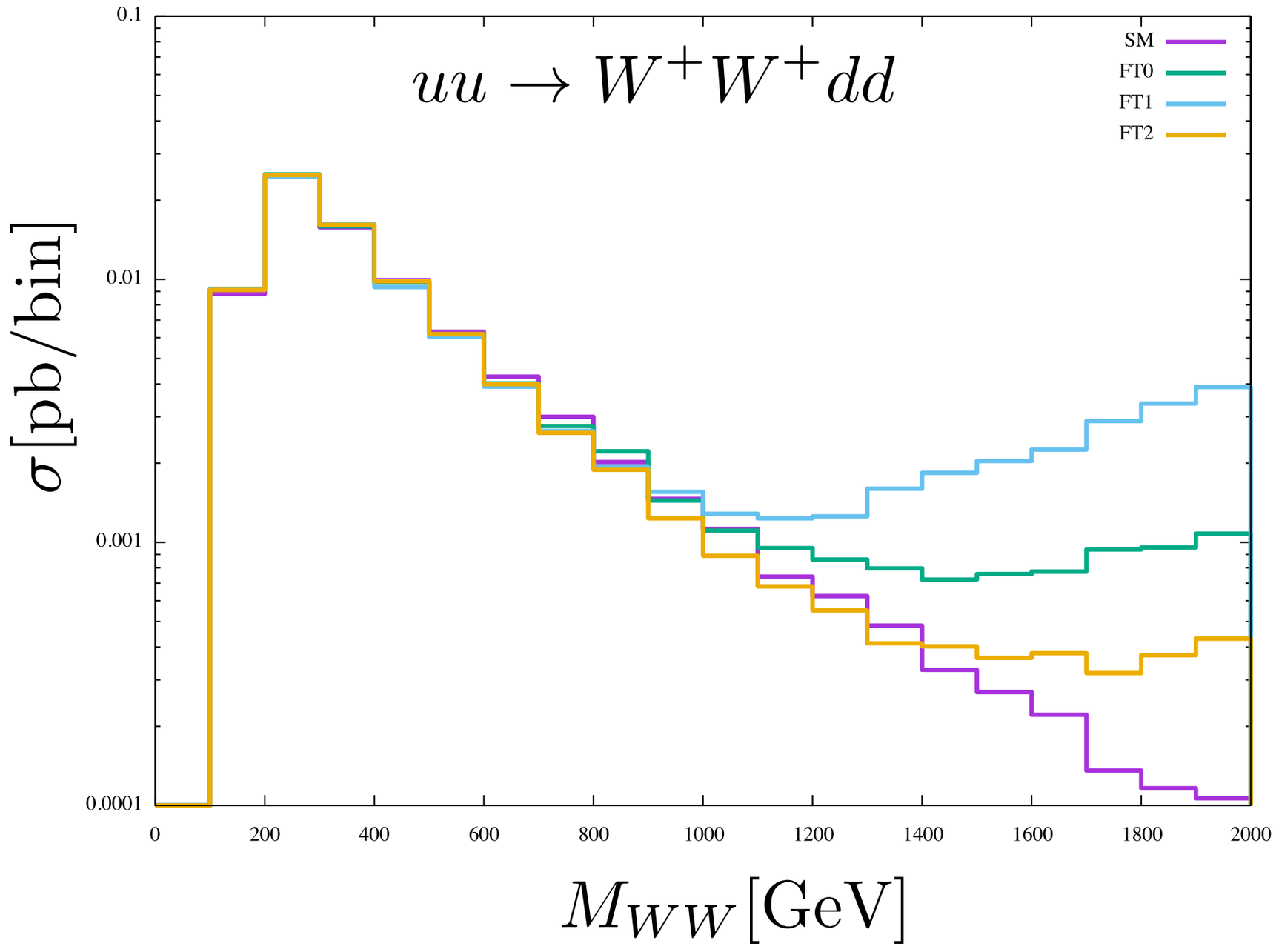
Example: same sign W

Distributions for dim-8: Longitudinal operators



Example: same sign W

Distributions for dim-8: Transverse operators



Reweighting

You can obtain results for different values of the coefficients by using reweighting

Follow the instructions in Cards/reweight_card_default.dat
Example: Adding the following to the reweight_card.dat

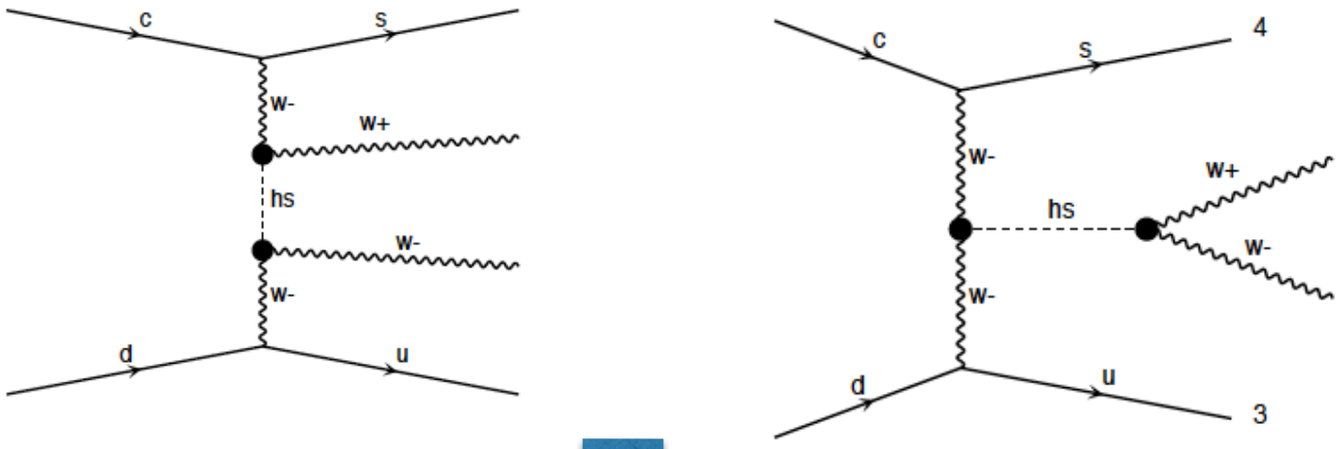
launch
set ft0 10.0
launch
set fm0 10.0

Reweight your SM sample. Compare with the results you got with separate samples.

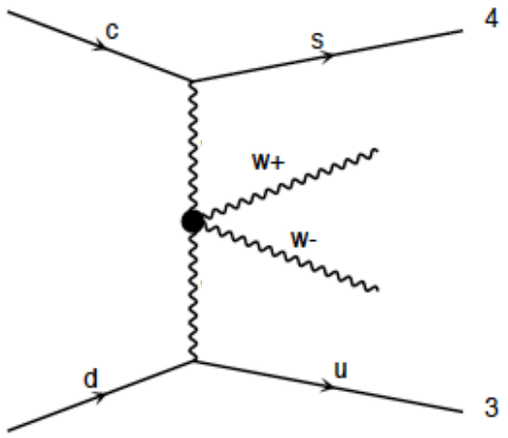
Part II

Matching example

A scalar resonance:



If M>>E we can match



$$F_{S,1} = \frac{a_H^2}{2M_S^2}\Lambda^4$$

$$F_{T,0} = \frac{\bar{a}_W^2}{2M_S^2}\Lambda^4$$

$$F_{T,5} = \frac{\bar{a}_W \bar{a}_B}{M_S^2}\Lambda^4$$

$$F_{T,8} = \frac{\bar{a}_B^2}{2M_S^2}\Lambda^4$$

$$F_{M,0} = \frac{a_H \bar{a}_W}{M_S^2}\Lambda^4$$

$$F_{M,2} = \frac{a_H \bar{a}_B}{M_S^2}\Lambda^4$$

Matching conditions

$$\bar{a}_W = -2g^{-2}a_W$$

$$\bar{a}_B = -4g'^{-2}a_B$$

Resonance vs EFT

We will try to compare EFT and resonance description

1. Import the resonance model and generate the same process as before

```
import model scalarVBS
generate u u > w+ w+ j j QCD=0 NP=2
output reson_same_signW
```

Block bsminputs
  1 1.000000e-10 # aH
  2 0.0400000e-01 # aW ⟶ Coupling of the resonance
  3 1.000000e-10 # aB
Block mass
 10025 4.0000e+03 # MHS ⟶ Mass of the resonance

Check the diagrams

Matching

Example 1: aw = 0.00002
MS = 4000 GeV

Example 2: aw = 0.00001
MS = 2000 GeV

Example 3: aw = 0.00005
MS = 10000 GeV

Assume:
g’ = 0.358
g=0.648

1. Use the matching relations to extract the operator coefficients.
2. Generate the 4 samples: EFT, resonance 1-3
3. To make the comparison easier generate only the resonant/EFT diagrams

Generating specific diagrams

1. Use the matching relations to extract the operator coefficients.
2. Generate the 4 samples: EFT, resonance 1-3
3. To make the comparison easier generate only the resonant/EFT diagrams: Use the squared syntax

```
import model scalarVBS
generate u u > w+ w+ j j QCD=0 NP=2 NP^2==4
output res_only
```

```
import model UFOdim8
generate u u > w+ w+ j j QCD=0 NP=4 NP^2==8
output dim8squared
```

4. Compare the mWW distribution

Comparison of EFT and resonance

Try to obtain this result: