Exercise 2: decay chains

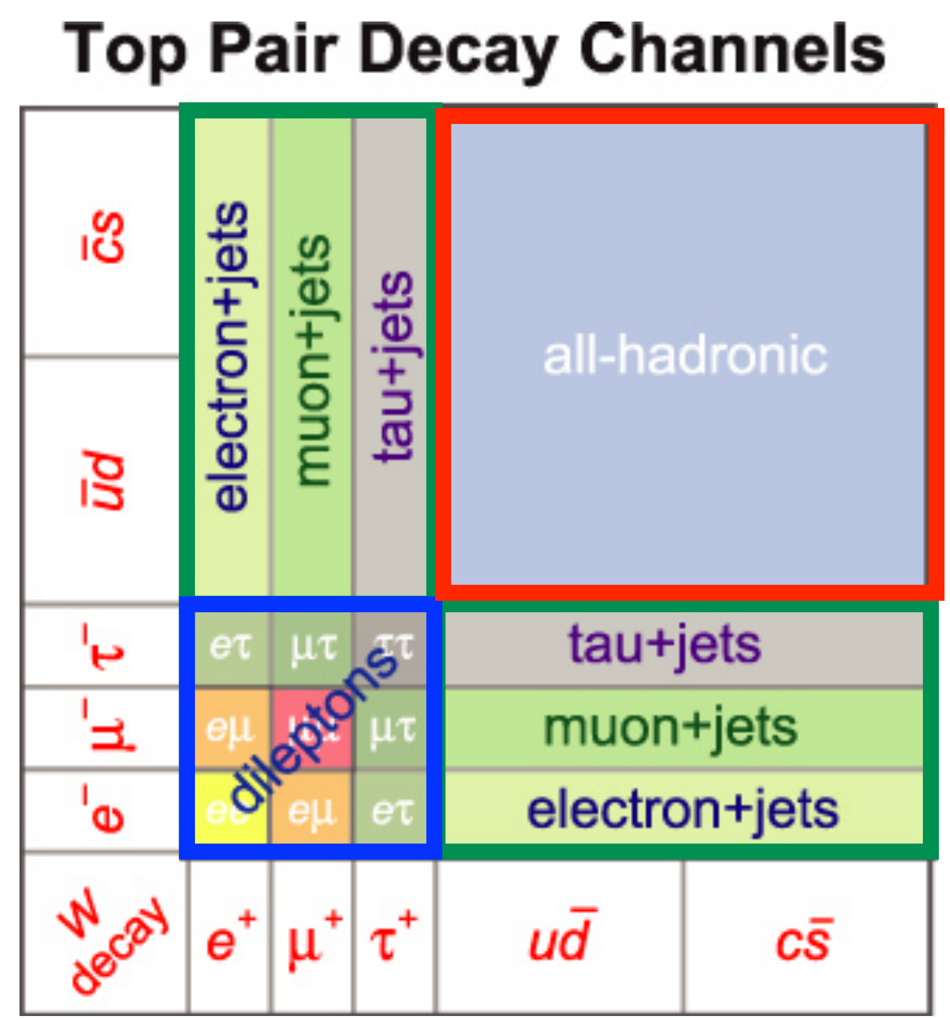
- Theory: the top quark is an unstable particle:
  - It decays: ~100% of times into b W
  - The W boson decays too:
    - 67% (2/3) of times into hadrons
    - 22% (2/9) of times into "leptons" (e-ν_e or μ-ν_μ)
    - 11% (1/9) of times into τ-ν_τ
- A decayed pair of top quarks can be classified as:
  - hadronic (both tops to hadrons)
  - semileptonic (one top to hadrons, the other to leptons)
  - dileptonic (both quarks to leptons)

Exercise 2: decay chains

- Questions:
  - How often a top pair decays hadronically/semi-leptonically/di-leptonically?
  - Learn the syntax to specify decay chains
  - Generate the code for dileptonic top decay and compute the cross-section. Compare with the case where the top does not decay (leave all parameters as default)
  - Compute the cross section for m_t=170, 175 and 180 GeV. Do you see anything strange?
  - What is the difference with `p p > l+ l- vl vl~ b b~`?

Exercise 2: Solution

- Questions:
  - How often a top pair decays hadronically/semi-leptonically/di-leptonically?
    - Since the top always decays to Wb, look at how a pair of W decays (b's are stable)
    - Hadronically: 2/3 * 2/3 = 4/9
    - Semi-lep. (incl. τ): 2 * 1/3 * 2/3 = 4/9
    - Di-lep. (incl. τ): 1/3 * 1/3 = 1/9



Exercise 2: Solution

- Questions:
  - Learn the syntax to specify decay chains
  - > `help generate`

```
-- generate diagrams for a given process
General leading-order syntax:
 o generate INITIAL STATE > REQ S-CHANNEL > FINAL STATE $ EXCL S-CHANNEL / FORBIDDEN PARTICLES COUP1=ORDER1
COUP2^2=ORDER2 @N
 o Example: generate l+ vl > w+ > l+ vl a $ z / a h QED=3 QCD=0 @1
 > Alternative required s-channels can be separated by "|":
   b b~ > W+ W- | H+ H- > ta+ vt ta- vt~
 > If no coupling orders are given, MG5 will try to determine
   orders to ensure maximum number of QCD vertices.
 > Desired coupling orders combination can be specified directly for
   the squared matrix element by appending '^2' to the coupling name.
   For example, 'p p > j j QED^2==2 QCD^==2' selects the QED-QCD
   interference terms only. The other two operators '<=' and '>' are
   supported. Finally, a negative value COUP^2==-I refers to the
   N^(-I+1)LO term in the expansion of the COUP order.
 > To generate a second process use the "add process" command
Decay chain syntax:
 o core process, decay1, (decay2, (decay2', ...)), ...  etc
 o Example: generate p p > t~ t QED=0, (t~ > W- b~, W- > l- vl~), t > j j b @2
 > Note that identical particles will all be decayed
```

Something like this!

  - > `generate p p > t t~, (t > w+ b, w+ > l+ vl), (t~ > w- b~, w- > l- vl~)`

Exercise 2: Solution

- Questions:
  - Generate the code for dileptonic top decay and compute the cross-section. Compare with what computed in Ex.1
    - `> generate p p > t t~, (t > w+ b, w+ > l+ vl), (t~ > w- b~, w- > l- vl~)`
    - `> output myttbardecayed`
    - `> launch`
  - What do we expect? 4/81 = 25
    - Something like 505 * ~~1/9 = 56~~ pb?
  - Wait: what is `l+/l-`?
    - `> display multi particles`

```
Cross-section :   22.63 +- 0.01553 pb
Nb of events :  10000
```

last bit of discrepancy comes from more subtle things (essentially scales)

```
Multiparticle labels:
all = g u c d s u~ c~ d~ s~ a ve vm vt e- mu- ve~ vm~ vt~ e+ mu+
t b t~ b~ z w+ h w- ta- ta+
l- = e- mu-
j = g u c d s u~ c~ d~ s~
vl = ve vm vt
l+ = e+ mu+
p = g u c d s u~ c~ d~ s~
vl~ = ve~ vm~ vt~
```

Exercise 2: Solution

- Questions:
  - Compute the cross section for m_t=170, 175 and 180 GeV. Do you see anything strange?

```
launch run_170
set mt 170
done
launch run_175
set mt 175
done
launch run_180
set mt 180
done
```

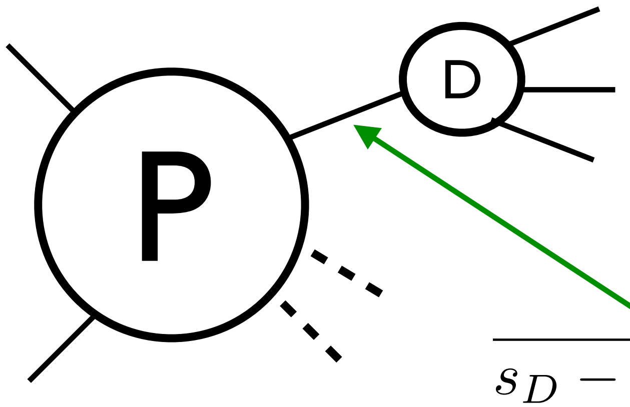
Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_170	p p 6500.0 x 6500.0 GeV	tag_1	21.83 ± 0.061	10000	parton madevent	LHE	remove run / launch detector simulation
run_175	p p 6500.0 x 6500.0 GeV	tag_1	23.41 ± 0.064	10000	parton madevent	LHE	remove run / launch detector simulation
run_180	p p 6500.0 x 6500.0 GeV	tag_1	24.92 ± 0.058	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

  - The cross section grows with m_t!?!

What is happening?



$$\sigma_{P\times D} = \int d\text{PS}\,|M_P|^2 \frac{1}{(s_D - m^2)^2 + m^2\Gamma^2}|M_D|^2$$

$$= \int d\text{PS}\,|M_P|^2 \frac{\pi}{m\Gamma}\delta(s_D - m^2)|M_D|^2 + \mathcal{O}(\Gamma^0)$$

The total width Γ depends on m and should be updated!

Exercise 2: Solution

- Questions:
  - Compute the cross section for m_t=170, 175 and 180 GeV. Do you see anything strange?

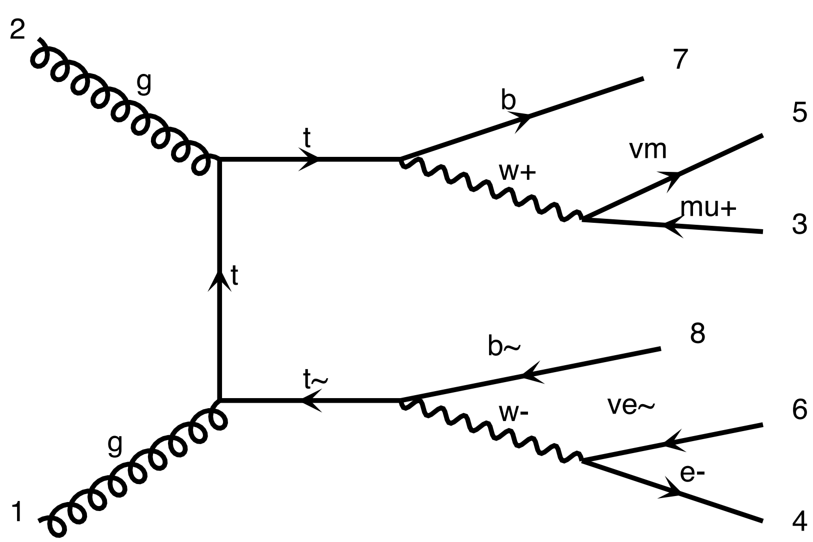
```
launch run_170_gammaok
set mt 170
set wt auto
done
launch run_175_gammaok
set mt 175
set wt auto
done
launch run_180_gammaok
set mt 180
set wt auto
done
```

run_170	p p 6500.0 x 6500.0 GeV	tag_1	21.83 ± 0.061	10000	parton madevent	LHE
run_175	p p 6500.0 x 6500.0 GeV	tag_1	23.41 ± 0.064	10000	parton madevent	LHE
run_180	p p 6500.0 x 6500.0 GeV	tag_1	24.92 ± 0.058	10000	parton madevent	LHE
run_170_gammaok	p p 6500.0 x 6500.0 GeV	tag_1	24.71 ± 0.071	10000	parton madevent	LHE
run_175_gammaok	p p 6500.0 x 6500.0 GeV	tag_1	21.54 ± 0.064	10000	parton madevent	LHE
run_180_gammaok	p p 6500.0 x 6500.0 GeV	tag_1	18.8 ± 0.05	10000	parton madevent	LHE

  - With "set wt auto" the top width is re-computed from the param_card parameters

Exercise 2: Solution

- Questions:
  - What is the difference with `p p > l+ l- vl vl~ b b~`?
    - It is a much more complex process (will not run in 10s on a laptop)
      - Each subprocess has O(100) diagrams rather than O(1)
    - This process 'contains' $t\bar{t}$ decayed, but also other things



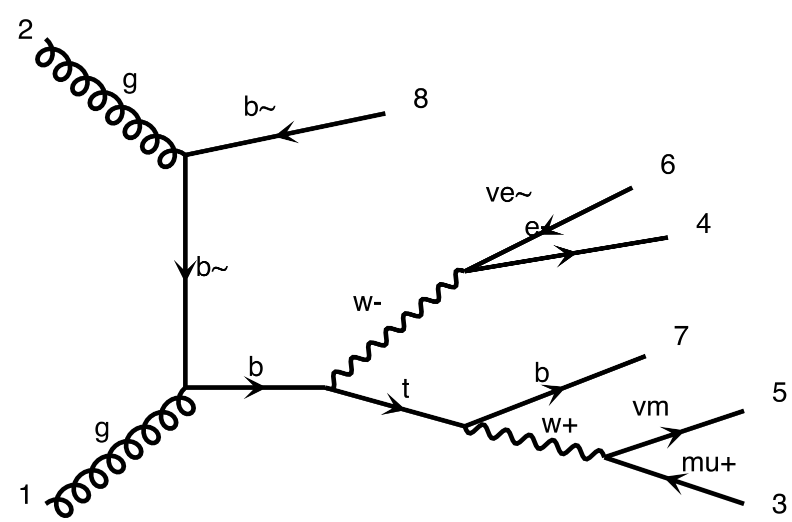


diagram 81 QCD=2, QED=4

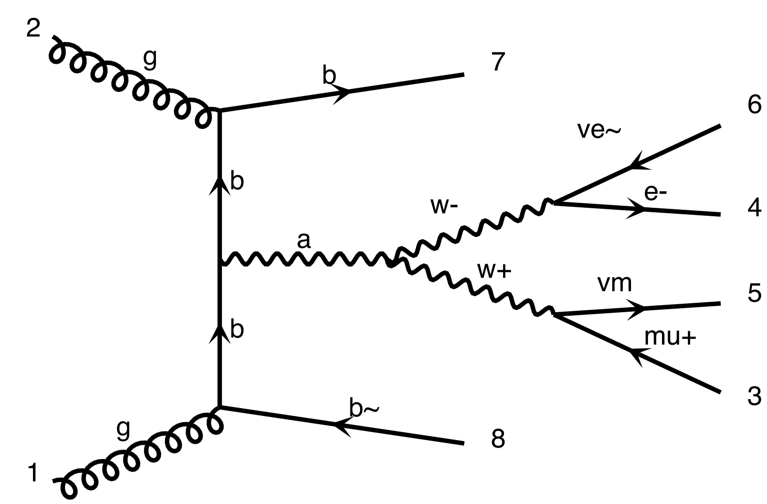


diagram 46 QCD=2, QED=4

Exercise 2: Solution

- Questions:
  - What is the difference with `p p > l+ l- vl vl~ b b~`?
    - It is a much more complex process (will not run in 10s on a laptop)
      - Each subprocess has O(100) diagrams rather than O(1)
    - This process 'contains' $t\bar{t}$ decayed, but also other things
  - Which one is correct?
    - Strictly speaking $t\bar{t}$ decayed, is correct only in the limit Γ_t=0 i.e. when tops are on-shell
    - If one searches for (on-shell) top-pair production (e.g.imposing cuts on l, v, b mass), the full process will give little extra contribution
    - If one wants to look away from the resonant region, then the full

Exercise 2: Solution

- Questions:
  - What is the difference with `p p > l+ l- vl vl~ b b~`?
  - Have a look at single-top production (Papanastasiou et al. arXiv:1305.7088)