# EFT Hands-on Lectures

**Ilaria Brivio & Admir Greljo**

# What you need to have installed

follow instructions on the **TWiki**

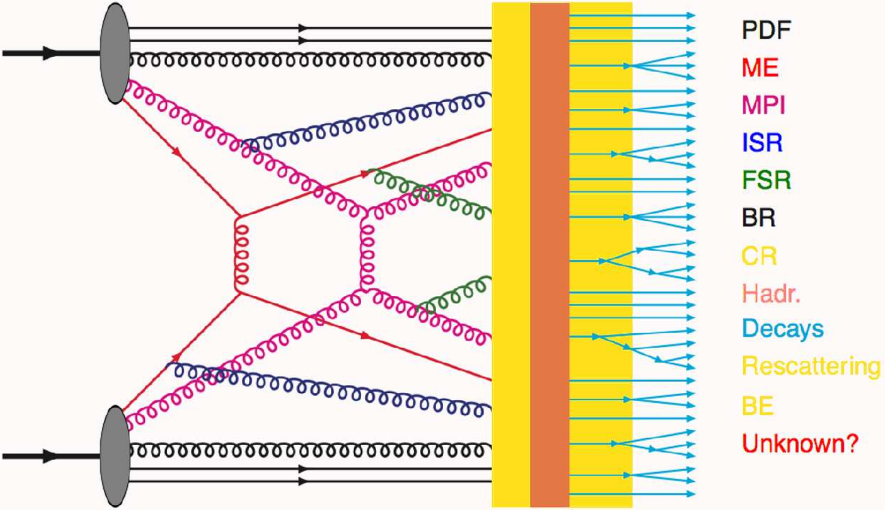
## For TODAY

- Mathematica
- FeynRules

## For TOMORROW

- VirtualBox
- the `Delphes2020.vdi` virtual machine

# The structure of a collider event




from T.Sjöstrand's slides, 2018

# From model to LHC signal

# From model to LHC signal

model

FeynRules

# From model to LHC signal

model — FeynRules

coded feynman rules — UFO format

# From model to LHC signal

| | |
|---|---|
| model | FeynRules |
| coded feynman rules | UFO format |
| parton level events | Monte Carlo MadGraph5_aMC@NLO |

Herwig, Sherpa, Powheg, Whizard, Alpgen, Comix, CompHep/CalcHep, Helac ...

# From model to LHC signal

| | |
|---|---|
| model | FeynRules |
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| parton level events | Monte Carlo MadGraph5_aMC@NLO |
| hadron level events | Parton Shower/Hadronization<br>Pythia Herwig, Sherpa ... |

# From model to LHC signal

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| model | FeynRules |
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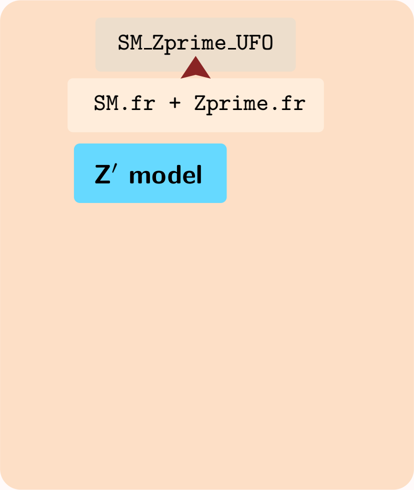
| parton level events | Monte Carlo MadGraph5_aMC@NLO |
| hadron level events | Parton Shower/Hadronization Pythia |
| detector level events | detector simulation Delphes PGS |

# From model to LHC signal

| | | | |
|---|---|---|---|
| UFO | model | ↓ | FeynRules |
| | coded feynman rules | | UFO format |
| MG/PS | parton level events | | Monte Carlo MadGraph5_aMC@NLO |
| | hadron level events | | Parton Shower/Hadronization Pythia |
| Delphes | detector level events | | detector simulation Delphes |

# Physics project for these lectures

Check the sheet on the TWiki !



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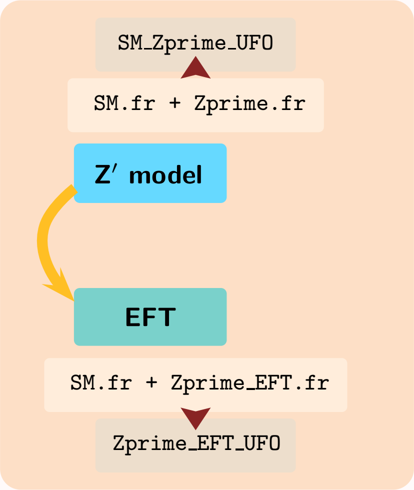

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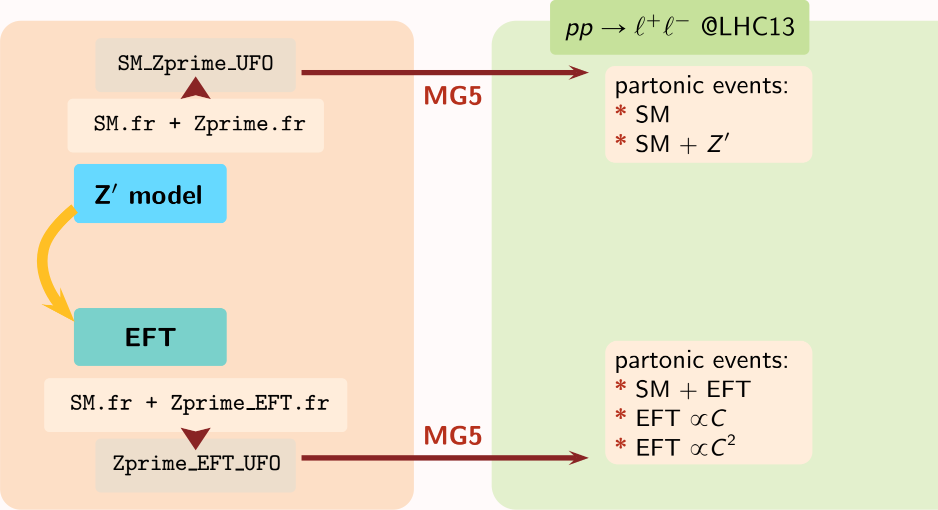


# Physics project for these lectures

Check the sheet on the TWiki !

SM_Zprime_UFO

SM.fr + Zprime.fr

**$Z'$ model**

**EFT**

SM.fr + Zprime_EFT.fr

Zprime_EFT_UFO

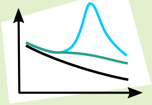
**MG5**

**MG5**

$pp \to \ell^+\ell^-$ @LHC13

partonic events:
* SM
* SM + $Z'$

compare $m_{\ell\ell}$ distributions



partonic events:
* SM + EFT
* EFT $\propto C$
* EFT $\propto C^2$

# Physics project for these lectures

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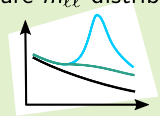

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# Physics project for these lectures

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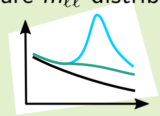
$pp \to \ell^+\ell^-$ @LHC13

partonic events:
* SM
* SM + $Z'$

**Pythia** →

showered events:
* SM
* $Z$ peak
* $Z'$ peak

compare $m_{\ell\ell}$ distributions



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* SM + EFT
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# Physics project for these lectures

Check the sheet on the TWiki !

$pp \to \ell^+\ell^-$ @LHC13

partonic events:
* SM
* SM + $Z'$

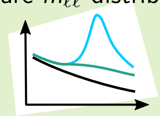
**Pythia**

showered events:
* SM
* $Z$ peak
* $Z'$ peak

detector level

Delphes hands-on

compare $m_{\ell\ell}$ distributions



partonic events:
* SM + EFT
* EFT $\propto C$
* EFT $\propto C^2$

# UFO Hands-On

# FeynRules

Alloul,Christensen,Duhr,Degrande,Fuks 1310.1921

"A Mathematica package to calculate Feynman rules"

## References

| | |
|---|---|
| website | `http://feynrules.irmp.ucl.ac.be/` |
| installation | download tarball<br>untar on your laptop |
| manual | `PDF` |
| model database | `wiki/ModelDatabaseMainPage` |

# Universal Feynrules Output – UFO

Degrande,Duhr,Fuks,Grellscheid,Mattelaer,Reiter 1108.2040

a python module containing all the model information

## References

| | |
|---|---|
| manual | `http://arxiv.org/abs/arXiv:1108.2040` |
| particle numbering scheme | http://pdg.lbl.gov/current/mc-particle-id |

# Material in the TWiki

download the tarball file UFO_HandsOn_material.tar

What it contains:

- PREFIT_HandsOn.nb: the Mathematica notebook we will use today.
- SM.fr: the predefined SM FeynRules model.
  (you should have it in your feynrules-current directory too)
- Zprime.fr, Zprime_EFT.fr, SM_Zprime_UFO.tar, Zprime_EFT_UFO are the **solutions** of today's class.
- masslessFermions.rst is a restriction file for the FeynRules models.

# Z' model

SM + a neutral, massive vector boson.

$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{M_{Z'}^2}{2} Z'_\mu Z'^\mu + Z'_\mu J^\mu$$

$$J^\mu = \kappa_q\, \bar{q}_L \gamma^\mu q_L + \kappa_u\, \bar{u}_R \gamma^\mu u_R + \kappa_d\, \bar{d}_R \gamma^\mu d_R + \kappa_l\, \bar{l}_L \gamma^\mu l_L + \kappa_e\, \bar{e}_R \gamma^\mu e_R$$

- we assume a $U(3)$ symmetry for each fermion field
- we choose $q_L = (u_L, V d_L)$. convince yourself that FCNC are absent.

For $M_{Z'} > 2m_t$, the width of the $Z'$ is

$$\Gamma_{Z'} = \frac{M_{Z'}}{24\pi} \sum_f N_C^f \left[ (\kappa_{f_L}^2 + \kappa_{f_R}^2) \left( 1 - \frac{m_f^2}{M_{Z'}^2} \right) + 6 \kappa_{f_L} \kappa_{f_R} \frac{m_f^2}{M_{Z'}^2} \right] \sqrt{1 - \frac{4 m_f^2}{M_{Z'}^2}}$$

where $f = u, c, t, d, s, b, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$ and $N_C^f$ is a color factor.

# Implementing the $Z'$ model in FeynRules

Learn from `SM.fr`:

- gauge symmetries $\rightarrow$ `M$GaugeGroups`
- particles $\rightarrow$ `M$ClassesDescription`
- parameters $\rightarrow$ `M$Parameters`
- Lagrangian

Write the information for $Z'$ in `Zprime.fr`.

- define the model parameters: $M_{Z'}, \Gamma_Z, \kappa_q, \kappa_u, \kappa_d, \kappa_l, \kappa_e$.
  give $\kappa_i$ interaction order $\{$`ZPRIME,1`$\}$ and default value 0.
- define the $Z'$ field – give it $M_{Z'} = 2$TeV and $\Gamma_{Z'} = 47.7$GeV
  (check the width matches the formula!)

  –The PDG code is 32
- Write $\mathcal{L}_{Z'}$

# Z' FeynRules model

Open the Mathematica notebook `PREFIT_HandsOn.nb`

- **fix the path** and import FeynRules
- import with: `LoadModel[SM.fr, Zprime.fr]`
- do some basic checks on the Lagrangian: hermiticity, mass spectrum, quantum numbers conservation.
- printout the Feynman rules.
- export `LSM + LZprime` to UFO with the name `SM_Zprime_UFO`.

# Z' UFO model

Let's check out the product!

`cd` inside the `SM_Zprime_UFO` directory and look at the files

- `particles.py`
- `vertices.py`
- `lorentz.py`
- `couplings.py`
- `parameters.py`

# Z' UFO model

open the shell in the SM_Zprime_UFO directory and run

```
python write_param_card.py
```

a file param_card.dat will be produced. open it and set the following values:

```
0.000000e+00 # cabi

0.000000e+00 # kq
0.200000e+00 # ku
0.200000e+00 # kd
0.000000e+00 # kl
0.600000e+00 # ke

0.000000e+00 # MD / MU / MS / MC / Me / MMU / MTA            (7 lines)
0.000000e+00 # ymdo / ymup / yms / yms / yme / ymm / ymtau   (7 lines)

2.000000e+03 # MZp

auto # WZp
```

save the file as param_card_Zprime.dat.

# Integrating out the Z' → EFT

At $E \ll M_{Z'}$ the $Z'$ decouples and the physics is described by an EFT

**"Integrating out" the $Z'$**

1. write the $Z'$ Equation of Motion:

$$\partial^\mu Z'_{\mu\nu} = M^2_{Z'} Z_\nu + J_\nu$$

2. solve expanding in $p^2/M^2_{Z'} \ll 1$:

$$Z'_\mu = \left[ (\Box - M^2_{Z'})\, g^{\mu\nu} - \partial^\mu \partial^\nu \right]^{-1} J_\nu = -\frac{J_\mu}{M^2_{Z'}} \left[ 1 + \mathcal{O}(p^2/M^2_{Z'}) \right]$$

3. replace the solution in $\mathcal{L}_{Z'}$:

$$\mathcal{L} \to \frac{M^2_{Z'}}{2} \frac{1}{M^4_{Z'}} J_\mu J^\mu - \frac{1}{M^2_{Z'}} J_\mu J^\mu + \mathcal{O}(M_{Z'}^{-4}) =$$

$$= -\frac{1}{2M^2_{Z'}} J_\mu J^\mu + \mathcal{O}(M_{Z'}^{-4})$$

# Matching the EFT on the Warsaw basis

Replacing the expression for $J_\mu$ in $\mathcal{L}_6 = -\frac{1}{2M_{Z'}^2} J_\mu J^\mu$ we find $\mathcal{L}_6 = \sum C_{ij}\mathcal{O}_{ij}$ with $i,j = q,u,d,l,e$.

The operators generated are

$$
\begin{aligned}
\mathcal{O}_{ll} &= (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l) & \mathcal{O}_{qq}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) & \mathcal{O}_{ql}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{l}\gamma^\mu l) \\
\mathcal{O}_{uu} &= (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u) & \mathcal{O}_{dd} &= (\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d) & \mathcal{O}_{ee} &= (\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e) \\
\mathcal{O}_{qu}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u) & \mathcal{O}_{qd}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d) & \mathcal{O}_{qe} &= (\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e) \\
\mathcal{O}_{lu} &= (\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u) & \mathcal{O}_{ld} &= (\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d) & \mathcal{O}_{le} &= (\bar{l}\gamma_\mu l)(\bar{e}\gamma^\mu e) \\
\mathcal{O}_{eu} &= (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u) & \mathcal{O}_{ed} &= (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d) & \mathcal{O}_{ud}^{(1)} &= (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)
\end{aligned}
$$

with coefficients

$$C_{ij} = -\frac{2-\delta_{ij}}{2M_{Z'}^2}\kappa_i\kappa_j$$

# Implementing the EFT in FeynRules / UFO

Create a file `Zprime_EFT.fr` and implement the EFT.

- define the EFT coefficients and give them interaction order {`EFT,1`}.
  set them to 0 by default.
- define the operators and the dimension-6 Lagrangian
  (needed for later: $\mathcal{O}_{eu}, \mathcal{O}_{ed}$)

Import the model in Mathematica (!! requires `Quit[]` and re-load FeynRules).

- do some checks on the Lagrangian
- output the Feynman rules: which operator contributes to which interaction?
- export to UFO and call it `Zprime_EFT_UFO`.

Produce a `param_card.dat` in the UFO.

- set all the parameters to match those we fixed in the $Z'$ model benchmark.
  What values should the Wilson coefficients take?
- save it as `param_card_EFT.dat`

# MadGraph Hands-On

# MadGraph_aMC@NLO

Alwall et al. 1405.0301, Frederix et al. 1804.10017

A parton level Monte Carlo generator, up to NLO QCD

| | |
|---|---|
| website | `https://launchpad.net/mg5amcnlo` |
| on-line guide | `wiki/ManualAndHelp` |
| forum | `https://answers.launchpad.net/mg5amcnlo` |

**MadAnalysis**: analysis framework embedded in MadGraph

`https://madanalysis.irmp.ucl.ac.be/`

**LHE format**: standard format for event files

`https://arxiv.org/pdf/hep-ph/0609017.pdf`

# Set up the Virtual Machine

open VirtualBox and start the VirtualMachine `Delphes2020.vdi`

- go in the directory `MG5_aMC_v2_7_0/models/`
- here, download the UFOs we produced yesterday.
  You can upload your own to a server (dropbox) and download it here.

  Alternatively, use the solutions:

```
wget https://www.dropbox.com/s/51d9j1tnje8583o/SM_Zprime_UFO.tar
wget https://www.dropbox.com/s/4owbj8k5wk97s2m/Zprime_EFT_UFO.tar
```

- go back to the home and create a working directory. `cd` here.

# Material in the TWiki

in the working directory:

download the tarball file MG_HandsOn_material.tar

```
wget https://twiki.cern.ch/twiki/pub/VBSCan/PREFIT20/MG_HandsOn_material.tar
```

What it contains:

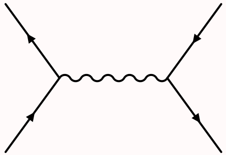
- `param_card_Zprime.dat`, `param_card_EFT.dat` are the same cards produced yesterday.
- `run_card.dat`, `madanalysis5_parton_card.dat` contain additional settings for the runs.
- `lhe_analyzer.py`, `plot_histos.py` are python scripts needed to analyze the events generated and make a plot.

# The process: $pp \to l^+ l^-$

We are interested in the $m_{ll}$ spectrum at $E \simeq M_{Z'} = 2$ TeV

## in the Z' model

we expect to see a resonance with the width computed yesterday



## in the EFT

$$|\mathcal{A}_{SM} + \mathcal{A}_6|^2 = |\mathcal{A}_{SM}|^2 + 2\,\mathrm{Re}\,\mathcal{A}_{SM}\mathcal{A}_6^\dagger + |\mathcal{A}_6|^2$$

SM

interference $\propto C_i \sim M_{Z'}^{-2}$

quadratic $\propto C_i C_j \sim M_{Z'}^{-4}$

at $m_{ll} \ll M_{Z'}$ the EFT should reproduce the resonance tail

as $m_{ll} \to M_{Z'}$ the expansion breaks down $\to$ the resonance is not reproduced!

# Generate $pp \to l^+ l^-$ diagrams in $Z'$ model

open MadGraph with

```
../MG5_aMC_v2_7_0/bin/mg5_aMC
```

now do:

```
import model SM_Zprime_UFO

generate p p > l+ l- ZPRIME=0
output pp_ll_SM

generate p p > l+ l- ZPRIME=2
output pp_ll_SM_Zp

quit
```

now open `pp_ll_SM_Zp/index.html`.

Check the diagrams that have been included.

# Generate $pp \to l^+ l^-$ events in $Z'$ model

Let us first look at the run_card.dat and madanalysis5_parton_card.dat from the material. What do these fix?

copy the 3 cards into the generated process folder.

Change the parameter card name into param_card.dat!

```
cp param_card_Zprime.dat WORKINGDIR/pp_ll_SM_Zp/Cards/ param_card.dat

cp run_card.dat WORKINGDIR/pp_ll_SM_Zp/Cards/

cp madanalysis5_parton_card.dat WORKINGDIR/pp_ll_SM_Zp/Cards/
```

and the same with pp_ll_SM_Zp → pp_ll_SM

# Generate $pp \to l^+ l^-$ events in $Z'$ model

go into the working directory and run

```
./pp_ll_SM_Zp/bin/generate_events
```

make sure the screen gives `analysis = MadAnalysis5` and the rest all `OFF` or `Not Avail.` Confirm all questions.

When finished, a Firefox window automatically opens
(ignore the errors in the shell!)

- Click on MA5_report_analysis1 to see first plots you produced!
- Go back to the shell and do

  ```
  gunzip pp_ll_SM_Zp/Events/run_01/unweighted_events.lhe.gz
  ```

  open the .lhe file with Firefox and let's look at it!
- open the param_card inside the process folder. Is it the same we copied in?

repeat the event generation for `pp_ll_SM`

# Generate $pp \to l^+ l^-$ diagrams in the EFT

In MadGraph:

```
import model Zprime_EFT_UFO

generate p p > l+ l- EFT=1
output pp_ll_EFT_all

generate p p > l+ l- EFT=1 EFT^2==1
output pp_ll_EFT_int

generate p p > l+ l- EFT=1 EFT^2==2
output pp_ll_EFT_sq

quit
```

now open `pp_ll_EFT_all/index.html`.
Check the diagrams that have been included.

do the same with `pp_ll_EFT_sq/index.html`.
Any difference? Why?

# Generate $pp \to l^+ l^-$ events in the EFT

copy the 3 cards into the generated process folder. Remember to use the **EFT** parameter card, and to change its name into `param_card.dat`!

```
cp param_card_EFT.dat WORKINGDIR/pp_ll_EFT_all/Cards/param_card.dat

cp run_card.dat WORKINGDIR/pp_ll_EFT_all/Cards/

cp madanalysis5_parton_card.dat WORKINGDIR/pp_ll_EFT_all/Cards/
```

go into the working directory and run

```
./pp_ll_EFT_all/bin/generate_events
```

make sure the screen gives `analysis = MadAnalysis5` and the rest all `OFF` or `Not Avail.` Confirm all questions.

repeat everything for `pp_ll_EFT_int` and `pp_ll_EFT_sq`

`gunzip` the events for all 3 processes.

# Analyze events and plot the $m_{ll}$ distribution

Use the two python scripts in the materials folder:

- `lhe_analyzer.py` takes an .lhe file, creates a ROOT histogram of the dilepton invariant mass, fills it and stores it in a .root output file.
  Place it in the working directory and run it on each sample:

```
python lhe_analyzer.py pp_ll_SM/Events/run_01/unweighted_events.lhe events_SM.root
python lhe_analyzer.py pp_ll_SM_Zp/Events/run_01/unweighted_events.lhe events_Zp.root
python lhe_analyzer.py pp_ll_EFT_all/Events/run_01/unweighted_events.lhe events_EFT_all.root
python lhe_analyzer.py pp_ll_EFT_int/Events/run_01/unweighted_events.lhe events_EFT_int.root
python lhe_analyzer.py pp_ll_EFT_sq/Events/run_01/unweighted_events.lhe events_EFT_sq.root
```

- open `plot_histos.py` and fix the main directory path to match your working directory. also adjust the root file names if you have different ones. then make the plot with:

```
python plot_histos.py
```

  the output will be stored in `plot_ll_mass.pdf`.

  Let's look at it!

# Pythia

Sjöstrand,Mrenna,Skands 0710.3820

a library of hard processes, models for initial- and final-state parton showers, matching and merging methods between hard processes and parton showers, multiparton interactions, beam remnants, string fragmentation and particle decays.

## References

| | |
|---|---|
| website | `http://home.thep.lu.se/~torbjorn/Pythia.html` |
| on-line guide | `pythia82html/Welcome.html` |
| manual | `pdfdoc/pythia8200.pdf` |

# Shower $Z'$ and SM dilepton events

We will produce 4 showered samples to be used in the Delphes session:

1. repeat the event generation in `pp_ll_SM_Zp` with

   ```
   ./pp_ll_SM_Zp/bin/generate_events
   ```

   - when prompted the first options screen, hit **1** to switch on `Pythia8` as shower
   - when prompted with the second options ("do you want to edit a card?") write

     ```
     set nevents 30000
     ```

   - then hit **3** to open the `pythia8_card`.
     go to the bottom and remove the ! from `!partonlevel:mpi = off`

   Open the Madanalysis report for the `run_02` events.
   Compare them with `run_01`. Is the effect of the parton shower visible?

2. Do the same with `pp_ll_SM`

# Showered dilepton samples

3. in `pp_ll_SM/Cards`, modify the `run_card.dat` changing:

```
40.0 = mmll
120.0 = mmllmax
```

and the `madanalysis5_parton_card.dat` changing the plot lines into

```
plot M(l+[1] l-[1]) 20 40 120 [logY]
plot M(l+[1] l-[1]) 20 70 110 [logY]
plot M(l+[1] l-[1]) 20 40 120
plot M(l+[1] l-[1]) 20 70 110
```

generate events switching on `Pythia8` and giving `set nevents 30000`

# Showered dilepton samples

4. in Madgraph load the `SM_Zprime_UFO` and generate dilepton without the SM background:

```
generate p p > l+ l- ZPRIME==2
output pp_ll_Zp
```

- copy the benchmark `param_card`, `run_card` and `madanalysis5_parton_card` to `pp_ll_Zp/Cards` and generate events.
- generate events switching on `Pythia8` and giving `set nevents 30000`

# Backup slides

# The Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$ |

# The Warsaw basis

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| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$ | | |