Hands-on Tutorial
Electron Proton Colliders

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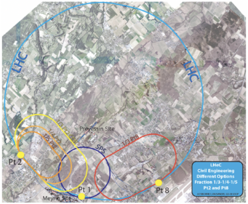
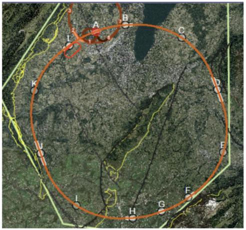
for the LHeC study group

13.10.20

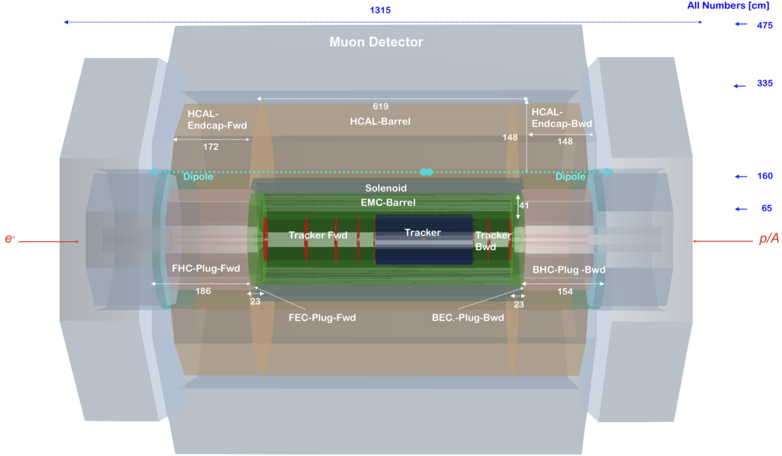
Introduction





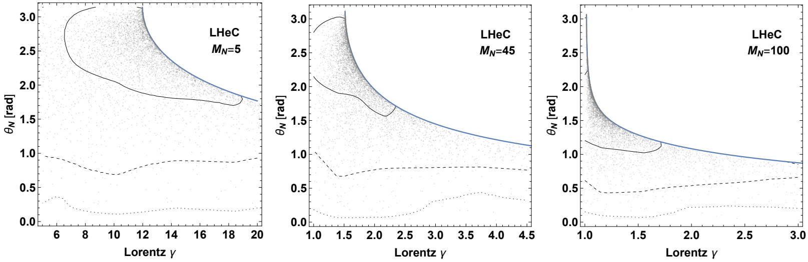
- The **L**arge **H**adron **e**lectron **C**ollider:
  - official CERN project, http://lhec.web.cern.ch/
  - Conceptual design report LHeC study group; [arXiv:1206.2913 [physics.acc-ph]]
  - Very recent update LHeC study group; [arXiv:2007.14491 [hep-ex]]
  - Part of the **F**uture **C**ircular **C**ollider: FCC-he (hadron electron)
- Working groups: PDF, Higgs, Top, Electroweak, BSM, ...
- Motivation:
  - High-resolution microscope: test **QCD** at smallest distances.
  - **PDF**: improve precision of LHC results.
  - Important **Higgs** measurements.
  - Affordable: $\sim$1.4 BCHF + one detector

The detector



Asymmetric design, “standard” HEP detector technology.

Phenomenology with asymmetric beams: **ep**



Lowscale seesaw model, `p e` $\to$ `N j` [1908.02852].

- Forward direction of detector and process must be *identical*.
- Delphes detector card: protons going forward.
  $\Rightarrow$ Process must be $p\ e$, not $e\ p$.
- Processes that 'prefer' specific momentum transfer 'fix' x.
  $\Rightarrow$ kinematics fixed (typical forward boosts of final states).
- Rule of thumb: mass $\sim$ characteristic boost.

Monte Carlo simulation tools **ep**

- MadGraph5 2.4.3 (with pythia-pgs - patched)
  - Works as you are used to.
  - MG5 3.0.X with copy&pasted patched pythia-pgs.
- Herwig7.2.1
- WHIZARD (link to version with patched PYTHIA)
  - based on the official tutorial,
  - cf. also https://whizard.hepforge.org/manual/
- Delphes
  - Existing cards for LHeC and FCC-he.
- PYTHIA does not work per default for LHeC/FCC-he
  A patch exists for PYTHIA6
- Work in progress to enable PYTHIA8 support.

WHIZARD on `login.snowmass21.io`

- Login via ssh `USER@login.snowmass21.io`
- Activate the WHIZARD module:

```
module use /local-scratch/software/modulefiles/
module load gcc-8.2.0
export LD_LIBRARY_PATH=/local-scratch/software/
ee_gen/./packages/OpenLoops/lib:$LD_LIBRARY_PATH
export PATH=/local-scratch/software/ee_gen/bin:$PATH
```

- Find scripts at `/collab/user/oliver/...`
  - `.../sindarin/ example.sin ep_1.sin ep_higgs.sin`
  - `.../plotting/ plot_P plot_Theta`
  - `.../output/ out.hist_P.dat out.hist_eta_B.dat out.plot_P_Theta.dat out.hist_Theta.dat out.hist_eta_b.dat`

WHIZARD – getting started

- Basics:
  - Evoke it with the command `whizard`.
  - Steer it via text file with ending `.sin` ("sindarin script").
  - Sindarin commands tell WHIZARD what to do.
  - Example: `printf "Hello, World"`.
  - Variables can be set: `real var = VALUE`.
  - Loops over variables and *if-then-else* constructs are possible.
- Priors:
  - Per default the complete SM and its particle content is loaded.
  - the sindarin command to define a process:
    `process NAME = PARTICLE1 PARTICLE2 => PARTICLES`
  - PARTICLE1, PARTICLE2, PARTICLES can be any particle that is contained in the model.
- Particles in the SM: leptons e1,e2,e3, neutrinos n1,n2,n3, quarks are u,d,s,c,b,t, Higgs H, gluon G, weak gauge bosons Z, Wp, Wm, photon A.
- Antiparticles are capitalized.

A basic example - I

In file ‘example.sin’

```
!Example from the WHIZARD tutorial:
process proc = "e+", "e-" => "W+", "W-"

!You can deactivate the visualization of channel history
with:
?vis_history = false

!The process is compiled into a process library with:
compile

!Set the process energy:
sqrts = 500 GeV

!Calculating the cross section for the process:
integrate (proc)
```

This will calculate the cross section of the process proc.

A basic example - II

- Execute the example:

  `whizard example.sin`

- This produces a lot of output; here is the end of it:

```
|=============================================================================|
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]   Chi2 N[It] |
|=============================================================================|
   1        864  7.2776141E+03  5.89E+01    0.81    0.24*  26.07
   2        864  7.1575556E+03  3.43E+01    0.48    0.14*  38.88
   3        776  7.2073201E+03  3.76E+01    0.52    0.15   62.61
|-----------------------------------------------------------------------------|
   3       2504  7.1954349E+03  2.33E+01    0.32    0.16   62.61    1.63   3
|-----------------------------------------------------------------------------|
   4       9888  7.2005306E+03  4.25E+00    0.06    0.06*  62.19
   5       9888  7.2005960E+03  4.17E+00    0.06    0.06*  62.16
   6       9888  7.1959794E+03  4.39E+00    0.06    0.06   62.11
|-----------------------------------------------------------------------------|
   6      29664  7.1991209E+03  2.46E+00    0.03    0.06   62.11    0.37   3
|=============================================================================|
| Time estimate for generating 10000 events: 0d:00h:00m:00s
| There were no errors and    1 warning(s).
| WHIZARD run finished.
|=============================================================================|
```

- The for us important information is:
  - Integral: cross section
  - Error: its absolute error
  - Err[%]: error in percent
  - Acc: numerical accuracy; "*" means it improved from one iteration to the next, values below 1 are excellent.

Example for electron-proton collisions - I

Use/create the file `ep_1.sin`

Then define the particles:

```
!Alias for light quark initial states:
alias parton = u:d:U:D

alias lepton = e1:E1:e2:E2:e3:E3

!Alias for the jet, including the gluon
alias j = parton:G
```

Particles are concatenated with the colon to form aliases.

Example for electron-proton collisions - II

Setup the process:

```
!Study charged current (CC) and neutral current (NC)
interaction processes
!Keep in mind that the proton beam has to come first
process pe_CC = parton, e1 => n1, j
process pe_NC = parton, e1 => e1, j
```

CC (NC) defines the process $p\, e^- \to \nu_e\, j$ ($p\, e^- \to e^-\, j$).

And the particle beams:

```
!Set up the particle beams.  Mind the ordering
beams_momentum = 7 TeV, 60 GeV
!Your choice of PDF
beams = p, "e-" => pdf_builtin, none
$pdf_builtin_set = "CT14LL"
```

Many built-in PDFs exist and external libraries can be installed.

Example for electron-proton collisions - III

Add 80% polarisation to the electron beam (if wanted):

```
beams_pol_density = @(), @(-1)
beams_pol_fraction = 0., 0.8
```

The LHeC can run with electron polarisation up to $\pm 80\%$.

Kinematic cuts on the final state

```
cuts = all 5 GeV < Pt [parton:lepton]
and all 6 > Eta [lepton:parton:n]
and all 5 GeV < abs (M) [parton, incoming parton]
```

The last cut controls the momentum transfer of the quark line.
Ensures deep inelastic scattering, can make Pt cuts redundant.

Example for electron-proton collisions - IV

Get the cross section for the two processes:

```
integrate ( pe_CC, pe_NC )
```

Numerical integration over the phase space.

Specific parameter sets in { ... } environment, e.g.

`iterations = 10:10000:"gw", 5:10000`

`mh = 126 GeV`.

Execute:

`whizard ep_1.sin`.

Cross sections:

- CC: 2.1510746E+05 $\pm$ 5.85E+02 [fb], $\sigma/\delta\sigma = 0.27$ [%], accuracy 0.47
- NC: 8.1468338E+07 $\pm$ 3.71E+06 [fb], $\sigma/\delta\sigma = 4.55$ [%], accuracy 7.80

Now for an interesting process

Higgs production in electron proton collisions - I

- File: `ep_higgs.sin`
- Processes:

  `parton, eq => j, H, n1` (CC)

  `parton, eq => j, H, e1` (NC)
- New features:
  - Data display with `histogram` and `plot`
  - `simulate ( processes ) {n_events = VALUE record HISTOGRAMS/PLOTS}`
  - `analysis = record HISTOGRAM (eval OBSERVABLE [ PARTICLES ])`
- Generates: 10k-event files in WHIZARD format (`.evx`).
- Output: P and θ of H as histograms and data file.

Higgs production in electron proton collisions - II

Higgs boson decay automatically according to the SM:

```
unstable H () { ?auto_decays = true }
```

This will essentially only produce *bb* final states in the SM.

One can manually control the decay channel:

```
!process higgsdecay = H => b, B
...
!unstable H ( higgsdecay )
```

Higgs decays into vectors: add `h => Wp, e1:e2:e3, N1:N2:N3`
For decays into gluons, gammas, muons, use the model: `SM_Higgs`.

Higgs production in electron proton collisions - III

Data visualisation with histograms and plots; definition:

```
histogram hist_P (0 GeV, 4000 GeV) { n_bins = 20 }
...
plot plot_P_Theta
```

Histograms are filled with a single variable.
Plots can be filled with up to four variables.

Simulation produces per default `process.evx` event files:

```
simulate ( ep_higgs_NC, ep_higgs_CC ){
n_events = 10000
...
}
```

The analysis goes into "...".

Higgs production in electron proton collisions - IV

Analysis of simulated event data:

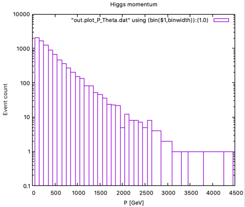
```
analysis = record hist_P (eval P [ b+B ]);
...
record plot_P_Theta (eval P [b+B], eval Theta [b+B] )
```

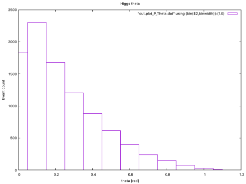
Consult the WHIZARD manual for the list of observables.

Write the analysis results to output files:

```
write_analysis (hist_P)  $out_file = "out.hist_P.dat"
...
```

Quick visualisation with gnuplot - I



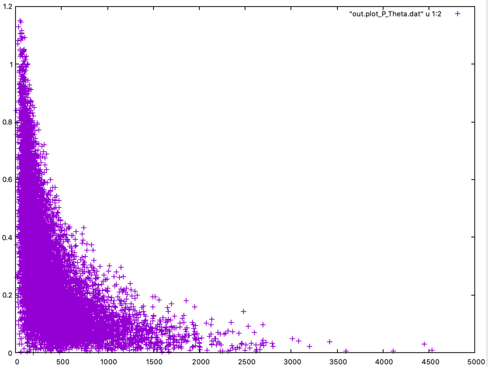


- Histogram of Higgs candidate momentum (the `b+B` pair): Execute gnuplot + `p "../out.hist_P.dat" u 1:2`.
- Can be obtained from the `plot` output file; `gnuplot` plus:

```
binwidth=100
bin(x,width)=width*floor(x/width)
set yrange [0.1:10000]
set log y
p "out.plot_P_Theta.dat" using
(bin($1,binwidth)):(1.0) smooth
freq with boxes
```

- Scripts: `gnuplot plot_P` or `gnuplot plot_Theta`.

Quick visualisation with gnuplot - II



- `out.plot_P_Theta.dat` also allows to visualise correlations:
  `p "out.plot_P_Theta.dat" u 1:2 w p`
- This file can be the basis of a *cut-and-count* analysis.

Hadronisation and detector simulation

- **New commands in the file** ep_higgs_pythia.sin:

```
$shower_method = "PYTHIA6"
$hadronization_method = "PYTHIA6"
sample_format = hepmc
```

- Works only with the patched version.
- Produces "hepmc" files for detector simulation.
- At present, this does not work 'out-of-the-box'.
- Call Delphes:

```
./DelphesHepMC [detector card] [outputfile.root] [inputfile.hepmc]
```

- Delphes cards for LHeC and FCC-he are in /collab/user/oliver/delphescards.

Next steps

- Run the inclusive process:
  `parton, e1 => j, e1:n1, b, B`
- Consider backgrounds:
  `parton, e1 => j, e1:n1, Z` with Z decaying
  Any others?
- Use your own UFO model:

```
! UFO file in working directory
model = MyModel (ufo)


! UFO file in user-specified directory
model = MyModel (ufo ("<my UFO path>"))
```

Last remarks

- PYTHIA6 patch available, PYTHIA8 is work in progress.
  Special WHIZARD version: available from this link
- More information on WHIZARD in the tutorial by JRR:
  https://indico.fnal.gov/event/45413/overview
- Questions on **ep**: email to me anytime!
- It is very important not to be confined in a box!

⇒ Change of reference frame:

$$\mathbf{pp} \leftrightarrow \mathbf{ee} \leftrightarrow \mathbf{ep}$$
$$\text{MG5} \leftrightarrow \text{WHIZARD} \leftrightarrow \text{Herwig.}$$