How to perform collider studies
Part I

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How to perform collider studies

Part II:

Comparing simulations to experiment

Outline

Checklist

- Do you know all the channels leading to the signal?
  - If in doubt, put it in.
- Do you know the normalizations of the channels, and how many events in each channel to simulate to achieve the required accuracy?
- Do you want to make any trade-offs of accuracy for speed?
- Do you know the limitations of your tools?

Collider observables

What observables do we calculate from our MC data?

Colliders measure cross-sections

- Experiments quote *numbers of events* for given *delivered luminosities.*
- Number/luminosity = cross-section.
- Basic observable is σ after detector effects and kinematic cuts.
- Binned σ can be used to derive differential cross-sections.

Detector effects

- Real detectors do not have perfect acceptance.
    - Angular coverage restricted by beam pipe, support structures.
    - Identification and energy measurement of particles not perfect!
- These issues require a lot of knowledge of the specifics of the detector.
- Accurately simulating the detector is complicated, slow, and requires non-public knowledge (`ATLFAST`).
- There are public simulators that get a lot right: *e.g.* `Delphes` and `PGS`

Model → MC truth → reconstructed objects

Typical sequence is:

- Prepare model for MC (*e.g.* use `SARAH` to prepare `WHIZARD`).
- Generate events, written to a file as the *MC truth*.
- Simulate detector response to MC truth, written to a file as *reconstructed events*.
- Reconstructed events are use to calculate binned σ

Monte Carlo truth:
Les Houches Event Format files

LHEF

- Les Houches Event Format (`LHEF`) is a standard written by many generators, such as `WHIZARD`.
- `LHEF` is pseudo-`XML` detailing initial- and final-state particles, and usually intermediate decaying particles.

```
 <event>
10 0 0.21E-6 0.11E+3 0.79E-1 0.13E+0
   2 -1 0 0 502 0  0.00E+0   0.00E+0  0.16E+4 0.16E+4 0.00E+0 0. -1.
   1 -1 0 0 501 0  0.00E+0   0.00E+0 -0.90E+2 0.90E+2 0.00E+0 0. -1.
  25  2 1 2   0 0  0.27E+2   0.78E+2  0.21E+3 0.25E+3 0.12E+3 0.  0.
  24  2 3 3   0 0  0.34E+1   0.61E+2  0.13E+3 0.16E+3 0.76E+2 0.  0.
   2  1 1 2 501 0 -0.40E+1   0.33E+2 -0.60E+2 0.69E+2 0.00E+0 0. -1.
   1  1 1 2 502 0 -0.23E+2  -0.11E+3  0.13E+4 0.13E+4 0.00E+0 0. -1.
 -11  1 4 4   0 0  0.18E+2   0.18E+2  0.24E+1 0.26E+2 0.00E+0 0.  1.
  12  1 4 4   0 0 -0.13E+2   0.42E+2  0.13E+3 0.14E+3 0.00E+0 0. -1.
 -14  1 3 3   0 0 -0.19E+1   0.20E+2  0.41E+2 0.46E+2 0.00E+0 0.  1.
  13  1 3 3   0 0  0.25E+2  -0.36E+1  0.29E+2 0.39E+2 0.00E+0 0. -1.
</event>
```

An `LHEF` event `XML` element. (All decimals were truncated to fit on the slide.)

```
 <event>
10  0  0.21E-6  0.11E+3  0.79E-1  0.13E+0
   2 -1 0 0 502 0  0.00E+0  0.00E+0   0.16E+4 0.16E+4 0.00E+0 0. -1.
   1 -1 0 0 501 0  0.00E+0  0.00E+0  -0.90E+2 0.90E+2 0.00E+0 0. -1.
  25  2 1 2   0 0  0.27E+2  0.78E+2   0.21E+3 0.25E+3 0.12E+3 0.  0.
  24  2 3 3   0 0  0.34E+1  0.61E+2   0.13E+3 0.16E+3 0.76E+2 0.  0.
   2  1 1 2 501 0 -0.40E+1  0.33E+2  -0.60E+2 0.69E+2 0.00E+0 0. -1.
   1  1 1 2 502 0 -0.23E+2 -0.11E+3   0.13E+4 0.13E+4 0.00E+0 0. -1.
 -11  1 4 4   0 0  0.18E+2  0.18E+2   0.24E+1 0.26E+2 0.00E+0 0.  1.
  12  1 4 4   0 0 -0.13E+2  0.42E+2   0.13E+3 0.14E+3 0.00E+0 0. -1.
 -14  1 3 3   0 0 -0.19E+1  0.20E+2   0.41E+2 0.46E+2 0.00E+0 0.  1.
  13  1 3 3   0 0  0.25E+2 -0.36E+1   0.29E+2 0.39E+2 0.00E+0 0. -1.
</event>
```

The first line of each element is the header, and this header provides the forllowing information:

- 10 particles in the event.
- Process ID = 0
- The event weight is 2.1×10^{-6} .
- 110 GeV was the scale of the event.
- α_{QED} used was 0.079 .
- α_{QED} used was 0.13 .

```
 <event>
  10 0 0.21E-6 0.11E+3 0.79E-1 0.13E+0
  2  -1   0   0  502   0    0.00E+0  0.00E+0  0.16E+4 0.16E+4 0.00E+0 0. -1
  1  -1   0   0  501   0    0.00E+0  0.00E+0 -0.90E+2 0.90E+2 0.00E+0 0. -1
 25   2   1   2    0   0    0.27E+2  0.78E+2  0.21E+3 0.25E+3 0.12E+3 0.  0
 24   2   3   3    0   0    0.34E+1  0.61E+2  0.13E+3 0.16E+3 0.76E+2 0.  0
  2   1   1   2  501   0   -0.40E+1  0.33E+2 -0.60E+2 0.69E+2 0.00E+0 0. -1
  1   1   1   2  502   0   -0.23E+2 -0.11E+3  0.13E+4 0.13E+4 0.00E+0 0. -1
-11   1   4   4    0   0    0.18E+2  0.18E+2  0.24E+1 0.26E+2 0.00E+0 0.  1
 12   1   4   4    0   0   -0.13E+2  0.42E+2  0.13E+3 0.14E+3 0.00E+0 0. -1
-14   1   3   3    0   0   -0.19E+1  0.20E+2  0.41E+2 0.46E+2 0.00E+0 0.  1
 13   1   3   3    0   0    0.25E+2 -0.36E+1  0.29E+2 0.39E+2 0.00E+0 0. -1
 </event>
```

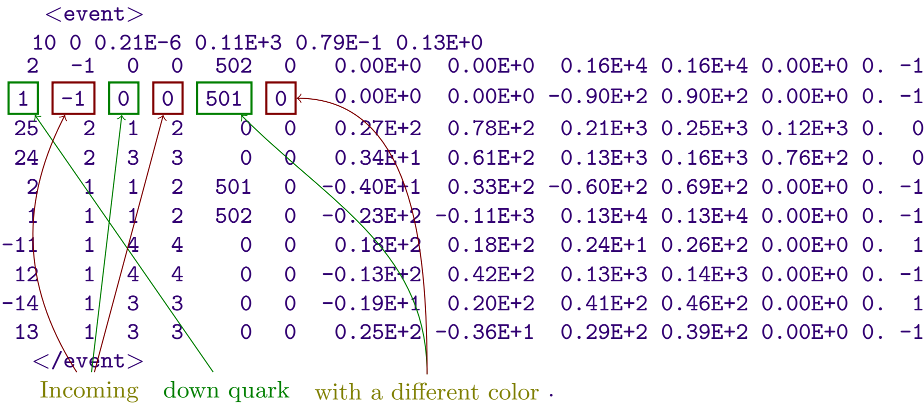
Incoming up quark with no mother particles, color code 502 , no anticolor

```
 <event>
 10 0 0.21E-6 0.11E+3 0.79E-1 0.13E+0
  2 -1 0 0 502 0   0.00E+0  0.00E+0  0.16E+4  0.16E+4  0.00E+0  0.  -1.
  1 -1 0 0 501 0   0.00E+0  0.00E+0 -0.90E+2  0.90E+2  0.00E+0  0.  -1.
 25  2 1 2   0 0   0.27E+2  0.78E+2  0.21E+3  0.25E+3  0.12E+3  0.   0.
 24  2 3 3   0 0   0.34E+1  0.61E+2  0.13E+3  0.16E+3  0.76E+2  0.   0.
  2  1 1 2 501 0  -0.40E+1  0.33E+2 -0.60E+2  0.69E+2  0.00E+0  0.  -1.
  1  1 1 2 502 0  -0.23E+2 -0.11E+3  0.13E+4  0.13E+4  0.00E+0  0.  -1.
-11  1 4 4   0 0   0.18E+2  0.18E+2  0.24E+1  0.26E+2  0.00E+0  0.   1.
 12  1 4 4   0 0  -0.13E+2  0.42E+2  0.13E+3  0.14E+3  0.00E+0  0.  -1.
-14  1 3 3   0 0  -0.19E+1  0.20E+2  0.41E+2  0.46E+2  0.00E+0  0.   1.
 13  1 3 3   0 0   0.25E+2 -0.36E+1  0.29E+2  0.39E+2  0.00E+0  0.  -1.
 </event>
```

This u quark has a *4-momentum* given by:

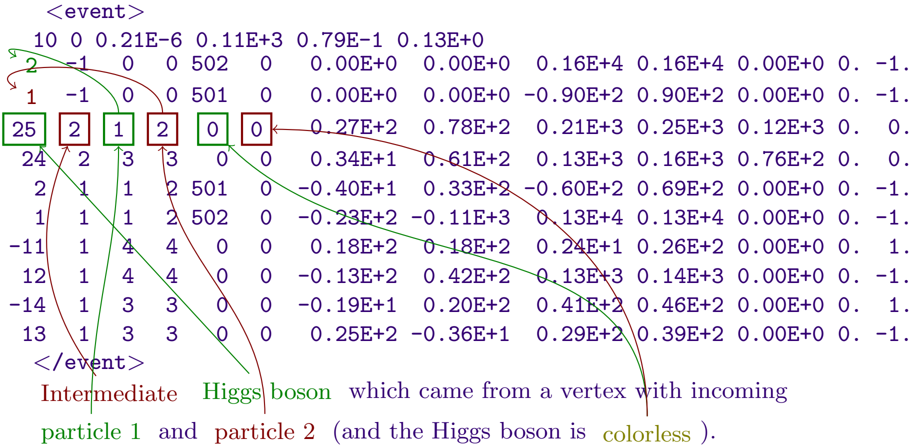
- $p_x = 0$ GeV
- $p_y = 0$ GeV
- $p_z = 1600$ GeV
- $E = 1600$ GeV

Its mass is explicitly given by $m = 0$ GeV (in case the particle had been off-shell).
This is the displacement of its decay from its production, but it's stable.
Finally, 2× helicity is given as -1 .



```
 <event>
 10 0 0.21E-6 0.11E+3 0.79E-1 0.13E+0
  2   -1   0   0   502   0    0.00E+0  0.00E+0  0.16E+4 0.16E+4 0.00E+0 0.  -1
  1   -1   0   0   501   0    0.00E+0  0.00E+0 -0.90E+2 0.90E+2 0.00E+0 0.  -1
 25    2   1   2     0   0    0.27E+2  0.78E+2  0.21E+3 0.25E+3 0.12E+3 0.   0
 24    2   3   3     0   0    0.34E+1  0.61E+2  0.13E+3 0.16E+3 0.76E+2 0.   0
  2    1   1   2   501   0   -0.40E+1  0.33E+2 -0.60E+2 0.69E+2 0.00E+0 0.  -1
  1    1   1   2   502   0   -0.23E+2 -0.11E+3  0.13E+4 0.13E+4 0.00E+0 0.  -1
-11    1   4   4     0   0    0.18E+2  0.18E+2  0.24E+1 0.26E+2 0.00E+0 0.   1
 12    1   4   4     0   0   -0.13E+2  0.42E+2  0.13E+3 0.14E+3 0.00E+0 0.  -1
-14    1   3   3     0   0   -0.19E+1  0.20E+2  0.41E+2 0.46E+2 0.00E+0 0.   1
 13    1   3   3     0   0    0.25E+2 -0.36E+1  0.29E+2 0.39E+2 0.00E+0 0.  -1
 </event>
```

Incoming down quark with a different color .

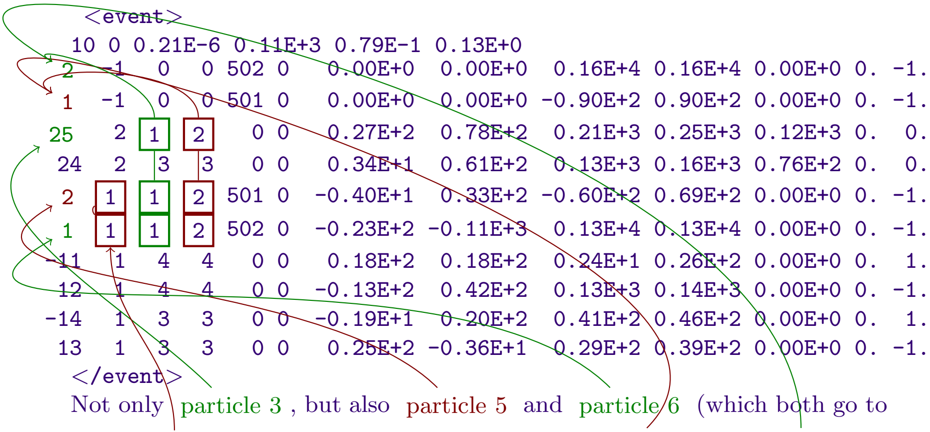


```
 <event>
 10 0 0.21E-6 0.11E+3 0.79E-1 0.13E+0
  2  -1   0   0 502   0   0.00E+0  0.00E+0  0.16E+4 0.16E+4 0.00E+0 0. -1.
  1  -1   0   0 501   0   0.00E+0  0.00E+0 -0.90E+2 0.90E+2 0.00E+0 0. -1.
 25   2   1   2   0   0   0.27E+2  0.78E+2  0.21E+3 0.25E+3 0.12E+3 0.  0.
 24   2   3   3   0   0   0.34E+1  0.61E+2  0.13E+3 0.16E+3 0.76E+2 0.  0.
  2   1   1   2 501   0  -0.40E+1  0.33E+2 -0.60E+2 0.69E+2 0.00E+0 0. -1.
  1   1   1   2 502   0  -0.23E+2 -0.11E+3  0.13E+4 0.13E+4 0.00E+0 0. -1.
-11   1   4   4   0   0   0.18E+2  0.18E+2  0.24E+1 0.26E+2 0.00E+0 0.  1.
 12   1   4   4   0   0  -0.13E+2  0.42E+2  0.13E+3 0.14E+3 0.00E+0 0. -1.
-14   1   3   3   0   0  -0.19E+1  0.20E+2  0.41E+2 0.46E+2 0.00E+0 0.  1.
 13   1   3   3   0   0   0.25E+2 -0.36E+1  0.29E+2 0.39E+2 0.00E+0 0. -1.
 </event>
```

Intermediate Higgs boson which came from a vertex with incoming particle 1 and particle 2 (and the Higgs boson is colorless).

(Particle 1 is the particle of the 1st line, even though this particle is an up quark, with code 2!)

(Likewise, the 2nd line is for particle 2, even though it begins with the number 1, which is denoting that it is a down quark!)



```
  <event>
 10 0 0.21E-6 0.11E+3 0.79E-1 0.13E+0
  2  -1   0   0 502 0   0.00E+0   0.00E+0   0.16E+4 0.16E+4 0.00E+0 0. -1.
  1  -1   0   0 501 0   0.00E+0   0.00E+0  -0.90E+2 0.90E+2 0.00E+0 0. -1.
 25   2   1   2   0 0   0.27E+2   0.78E+2   0.21E+3 0.25E+3 0.12E+3 0.  0.
 24   2   3   3   0 0   0.34E+1   0.61E+2   0.13E+3 0.16E+3 0.76E+2 0.  0.
  2   1   1   2 501 0  -0.40E+1   0.33E+2  -0.60E+2 0.69E+2 0.00E+0 0. -1.
  1   1   1   2 502 0  -0.23E+2  -0.11E+3   0.13E+4 0.13E+4 0.00E+0 0. -1.
-11   1   4   4   0 0   0.18E+2   0.18E+2   0.24E+1 0.26E+2 0.00E+0 0.  1.
 12   1   4   4   0 0  -0.13E+2   0.42E+2   0.13E+3 0.14E+3 0.00E+0 0. -1.
-14   1   3   3   0 0  -0.19E+1   0.20E+2   0.41E+2 0.46E+2 0.00E+0 0.  1.
 13   1   3   3   0 0   0.25E+2  -0.36E+1   0.29E+2 0.39E+2 0.00E+0 0. -1.
 </event>
```

Not only particle 3 , but also particle 5 and particle 6 (which both go to the final state) came from the interaction of particle 2 and particle 1 .

```
 <event>
10 0 0.21E-6 0.11E+3 0.79E-1 0.13E+0
  2 -1   0   0 502 0   0.00E+0  0.00E+0  0.16E+4 0.16E+4 0.00E+0 0. -1.
  1 -1   0   0 501 0   0.00E+0  0.00E+0 -0.90E+2 0.90E+2 0.00E+0 0. -1.
 25  2   1   2   0 0   0.27E+2  0.78E+2  0.21E+3 0.25E+3 0.12E+3 0.  0.
 24  2   3   3   0 0   0.34E+1  0.61E+2  0.13E+3 0.16E+3 0.76E+2 0.  0.
  2  1   1   2 501 0  -0.40E+1  0.33E+2 -0.60E+2 0.69E+2 0.00E+0 0. -1.
  1  1   1   2 502 0  -0.23E+2 -0.11E+3  0.13E+4 0.13E+4 0.00E+0 0. -1.
-11  1   4   4   0 0   0.18E+2  0.18E+2  0.24E+1 0.26E+2 0.00E+0 0.  1.
 12  1   4   4   0 0  -0.13E+2  0.42E+2  0.13E+3 0.14E+3 0.00E+0 0. -1.
-14  1   3   3   0 0  -0.19E+1  0.20E+2  0.41E+2 0.46E+2 0.00E+0 0.  1.
 13  1   3   3   0 0   0.25E+2 -0.36E+1  0.29E+2 0.39E+2 0.00E+0 0. -1.
</event>
```

Particle 4 is an intermediate W^+ boson which came from a vertex with just particle 3 incoming (*i.e.* from the decay of the Higgs boson).

The decay of the Higgs boson also resulted in a final-state *anti-*(muon) neutrino ($\bar{\nu}_\mu$) and muon (μ^-)

The W^+ decays to a final-state anti-electron (e^+) and a final-state (electron) neutrino ν_e.

SM particle codes

down ($d^{-1/3}$)	1
up ($u^{+2/3}$)	2
strange ($s^{-1/3}$)	3
charm ($c^{+2/3}$)	4
bottom ($b^{-1/3}$)	5
top ($t^{+2/3}$)	6

electron (e^-)	11
ν_e	12
muon (μ^-)	13
ν_μ	14
tau lepton (τ^-)	15
ν_τ	16

gluon	21
photon	22
Z boson	23
W^+ boson	24
Higgs boson	25

and negative codes for charge-conjugates
(*e.g.* -24 for W^-, there is no -21, -22, -23, or -25)

+ many codes for mesons and hadrons, + many extra codes for SUSY particles, + many other codes with no organization for other models

... + proposal for consistent particle code scheme in `arXiv:1206.4563`.

`LHEF` summary

`LHEF` details MC truth:

- All initial-state and final-state, and, depending on the calculator, usually most intermediate particles given.
- Each particle is specified with its nature and 4-momentum.
- Very useful to check what processes might be important to features of the signal!
- *Not* what is measured by the experiment!

Reconstructed events: LHC Olympics files

`LHCO`

- LHC Olympics format (`LHCO`) is a (not-so-widespread) standard for writing reconstructed events, but is at least readable and portable, unlike `HEPMC`...
- Both widespread "generic LHC detector" simulators `PGS` and `Delphes` support output in `LHCO`.

```
0         1  3635
1 1  0.122 0.776  25.06 0.00  1.0  0.0  0.00 0.0 0.0
2 2  0.995 6.141  26.40 0.11 -1.0  4.0  0.08 0.0 0.0
3 3 -1.340 1.542  31.88 0.00  3.0  0.0 19.36 0.0 0.0
4 4  3.143 4.497 119.02 9.49  0.0  0.0  1.56 0.0 0.0
5 6  0.000 1.817  67.14 0.00  0.0  0.0  0.00 0.0 0.0
0         2  3969
1 0 -0.393 2.686  48.64 0.00  0.0  0.0  0.02 0.0 0.0
2 0  0.424 0.518  82.84 0.00  0.0  0.0  0.00 0.0 0.0
3 4  1.161 4.124  91.13 2.59  5.0  0.0  2.19 0.0 0.0
4 4 -2.090 0.455  26.28 2.99  5.0  0.0 45.65 0.0 0.0
5 6  0.000 2.348   2.18 0.00  0.0  0.0  0.00 0.0 0.0
```

2 example `LHCO` events.

```
0         1  3635
 1 1  0.122 0.776  25.06 0.00  1.0  0.0  0.00 0.0 0.0
 2 2  0.995 6.141  26.40 0.11 -1.0  4.0  0.08 0.0 0.0
 3 3 -1.340 1.542  31.88 0.00  3.0  0.0 19.36 0.0 0.0
 4 4  3.143 4.497 119.02 9.49  0.0  0.0  1.56 0.0 0.0
 5 6  0.000 1.817  67.14 0.00  0.0  0.0  0.00 0.0 0.0
0         2  3969
 1 0 -0.393 2.686  48.64 0.00  0.0  0.0  0.02 0.0 0.0
 2 0  0.424 0.518  82.84 0.00  0.0  0.0  0.00 0.0 0.0
 3 4  1.161 4.124  91.13 2.59  5.0  0.0  2.19 0.0 0.0
 4 4 -2.090 0.455  26.28 2.99  5.0  0.0 45.65 0.0 0.0
 5 6  0.000 2.348   2.18 0.00  0.0  0.0  0.00 0.0 0.0
```

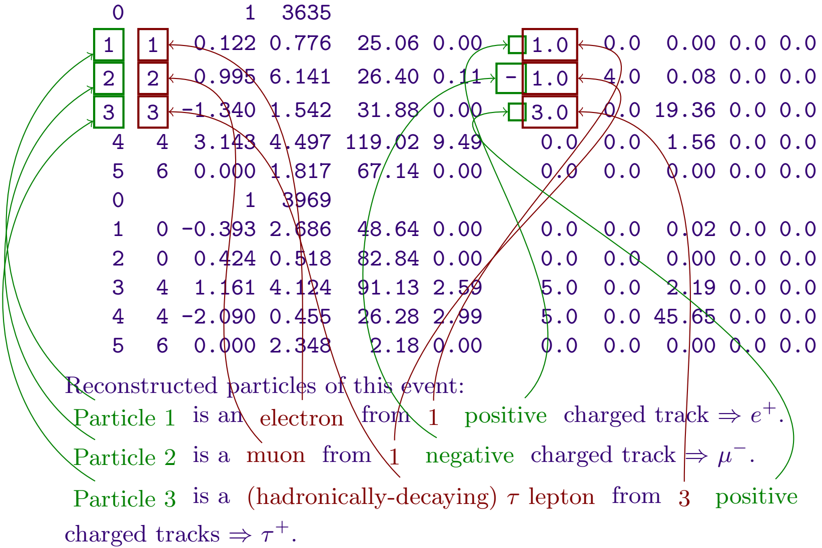
Lines beginning with 0 are the header lines for each event, and provide the event number and trigger code .

```
 0          1   3635
 1   1  0.122  0.776   25.06  0.00  1.0  0.0  0.00 0.0 0.0
 2   2  0.995  6.141   26.40  0.11 -1.0  4.0  0.08 0.0 0.0
 3   3 -1.340  1.542   31.88  0.00  3.0  0.0 19.36 0.0 0.0
 4   4  3.143  4.497  119.02  9.49  0.0  0.0  1.56 0.0 0.0
 5   6  0.000  1.817   67.14  0.00  0.0  0.0  0.00 0.0 0.0
 0          1   3969
 1   0 -0.393  2.686   48.64  0.00  0.0  0.0  0.02 0.0 0.0
 2   0  0.424  0.518   82.84  0.00  0.0  0.0  0.00 0.0 0.0
 3   4  1.161  4.124   91.13  2.59  5.0  0.0  2.19 0.0 0.0
 4   4 -2.090  0.455   26.28  2.99  5.0  0.0 45.65 0.0 0.0
 5   6  0.000  2.348    2.18  0.00  0.0  0.0  0.00 0.0 0.0
```

Particle 1 of this event is a reconstructed photon with

- pseudorapidity $= -0.393$
- azimuthal angle $= 2.686$
- transverse momentum $= 48.64$ GeV
- invariant mass $= 0.0$ GeV

These will be discussed in a few slides.



```
0        1  3635
1  1  0.122 0.776  25.06 0.00   1.0  0.0  0.00 0.0 0.0
2  2  0.995 6.141  26.40 0.11  -1.0  4.0  0.08 0.0 0.0
3  3 -1.340 1.542  31.88 0.00   3.0  0.0 19.36 0.0 0.0
4  4  3.143 4.497 119.02 9.49   0.0  0.0  1.56 0.0 0.0
5  6  0.000 1.817  67.14 0.00   0.0  0.0  0.00 0.0 0.0
0        1  3969
1  0 -0.393 2.686  48.64 0.00   0.0  0.0  0.02 0.0 0.0
2  0  0.424 0.518  82.84 0.00   0.0  0.0  0.00 0.0 0.0
3  4  1.161 4.124  91.13 2.59   5.0  0.0  2.19 0.0 0.0
4  4 -2.090 0.455  26.28 2.99   5.0  0.0 45.65 0.0 0.0
5  6  0.000 2.348   2.18 0.00   0.0  0.0  0.00 0.0 0.0
```

Reconstructed particles of this event:
Particle 1 is an electron from 1 positive charged track ⇒ e^+.
Particle 2 is a muon from 1 negative charged track ⇒ μ^-.
Particle 3 is a (hadronically-decaying) τ lepton from 3 positive charged tracks ⇒ τ^+.

```
0          1  3635
1  1  0.122 0.776  25.06 0.00  1.0   0.0   0.00 0.0 0.0
2  2  0.995 6.141  26.40 0.11 -1.0   4.0   0.08 0.0 0.0
3  3 -1.340 1.542  31.88 0.00  3.0   0.0  19.36 0.0 0.0
4  4  3.143 4.497 119.02 9.49  0.0   0.0   1.56 0.0 0.0
5  6  0.000 1.817  67.14 0.00  0.0   0.0   0.00 0.0 0.0
0          1  3969
1  0 -0.393 2.686  48.64 0.00  0.0   0.0   0.02 0.0 0.0
2  0  0.424 0.518  82.84 0.00  0.0   0.0   0.00 0.0 0.0
3  4  1.161 4.124  91.13 2.59  5.0   0.0   2.19 0.0 0.0
4  4 -2.090 0.455  26.28 2.99  5.0   0.0  45.65 0.0 0.0
5  6  0.000 2.348   2.18 0.00  0.0   0.0   0.00 0.0 0.0
```

Particle 3 of this event is a reconstructed jet from 5 charged tracks, which deposited a calorimeter energy ratio of 2.19 times as much hadronic energy as electromagnetic energy.

This column is the *b*-tag of a jet (1.0 or 2.0 for a jet tagged as having a bottom quark), but for a muon, it gives the line number of the nearest jet to it.

```
0          1  3635
1  1  0.122 0.776  25.06 0.00  1.0  0.0  0.00 0.0 0.0
2  2  0.995 6.141  26.40 0.11 -1.0  4.0  0.08 0.0 0.0
3  3 -1.340 1.542  31.88 0.00  3.0  0.0 19.36 0.0 0.0
4  4  3.143 4.497 119.02 9.49  0.0  0.0  1.56 0.0 0.0
5  6  0.000 1.817  67.14 0.00  0.0  0.0  0.00 0.0 0.0
0          1  3969
1  0 -0.393 2.686  48.64 0.00  0.0  0.0  0.02 0.0 0.0
2  0  0.424 0.518  82.84 0.00  0.0  0.0  0.00 0.0 0.0
3  4  1.161 4.124  91.13 2.59  5.0  0.0  2.19 0.0 0.0
4  4 -2.090 0.455  26.28 2.99  5.0  0.0 45.65 0.0 0.0
5  6  0.000 2.348   2.18 0.00  0.0  0.0  0.00 0.0 0.0
```

The last “particle” of each event is the *missing transverse momentum* .

The *missing transverse momentum* (MET) is the negative of the vector sum of all the transverse momenta of the detected particles. Ideally it is the transverse component of the sum of the momenta of the invisible particles. Since momenta cannot be measured perfectly, there is always some MET even if there were no invisible particles.

```
0        1  3635
1 1  0.122 0.776  25.06 0.00  1.0  0.0  0.00 0.0 0.0
2 2  0.995 6.141  26.40 0.11 -1.0  4.0  0.08 0.0 0.0
3 3 -1.340 1.542  31.88 0.00  3.0  0.0 19.36 0.0 0.0
4 4  3.143 4.497 119.02 9.49  0.0  0.0  1.56 0.0 0.0
5 6  0.000 1.817  67.14 0.00  0.0  0.0  0.00 0.0 0.0
0        2  3969
1 0 -0.393 2.686  48.64 0.00  0.0  0.0  0.02 0.0 0.0
2 0  0.424 0.518  82.84 0.00  0.0  0.0  0.00 0.0 0.0
3 4  1.161 4.124  91.13 2.59  5.0  0.0  2.19 0.0 0.0
4 4 -2.090 0.455  26.28 2.99  5.0  0.0 45.65 0.0 0.0
5 6  0.000 2.348   2.18 0.00  0.0  0.0  0.00 0.0 0.0
```

1st event taken from `LHCO` file based on `LHEF` file with MC truth of only ever final state of 2 jets, 1 μ^-, 1 $\bar{\nu}_\mu$, 1 e^+, 1 ν_e: μ^-, e^+ present, $\bar{\nu}, \nu$ present as MET, but 1 jet seems to have faked a τ^+!

2nd event taken from `LHCO` file based on `LHEF` file with MC truth of only ever final state of 2 jets, 2 photons, no invisible particles: all present, but non-zero MET.

Kinematic cuts

How do we bin our MC data?

Event binning process

- Particles of event are *preselected*.
- Event is vetoed or accepted based on kinematics of preselected particles.
- Accepted event is binned based on kinematics of preselected particles.

Definitions of kinematic quantities

Selection/veto at LHC usually based on

- Transverse momentum p_T: spatial momentum perpendicular to beam axis.
- Pseudorapidity η: $\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}|+p^z}{|\mathbf{p}|-p^z} \right)$.
- Separation in η, ϕ, where ϕ is the azimuthal angle of the momentum around the beam axis.

and Lorentz-invariant combinations of momenta, such as

- $m_{AB} = \sqrt{(p_A + p_B)^2}$.
- $m_{ABC} = \sqrt{(p_A + p_B + p_C)^2}$.
- and so forth...

Preselection

- Detectors usually have a threshold for effectiveness: they don't see particles that are too soft, usually.
- Detectors tuned for very soft particles would have a lot of noise.
- Detectors close to the beam thus at large η also suffer from lots of noise.
- Very soft particles and those close to the beam are usually just ignored.
- Event recording usually only triggers on certain combinations of “hard-enough” particles

- Typically soft e, μ, jets ignored if $p_T < 10$ GeV – 20 GeV, depending on analysis.
- Typically η must be less than ~ 2.5 for e, μ or up to ~ 5 for jets.
- e, μ usually ignored if part of a jet.

Atlas Higgs search example

ATLAS looked for $h \rightarrow W^+W^-$ in `arXiv:1206.0756`. Some of the results just cannot be accounted for by a lone grad student with an MC generator, but plenty can be done with for example an `LHCO` file of simulated reconstructed events.

Atlas Higgs search example: preselection

- $|\eta_\mu| < 2.4$, $|\eta_e| < 2.47$, except $1.37 < |\eta| < 1.52$
  - *e.g.* an electron with $\eta = -3.1$ would be ignored for the purposes of looking for exactly $1e^+$ and $1e^-$ in the event.
- Leptons with $p_T < 15$ GeV are ignored.
- Jets with $|\eta| > 4.5$ or $p_T < 25$ GeV (or both) are ignored.
- Jets with $2.75 < |\eta| < 3.25$ and $p_T < 30$ GeV are ignored also.

Atlas Higgs search example: event selection

Once the leptons and jets have been preselected, the event is kept unless rejected by any of the following vetos:

- The hardest lepton must have $p_T > 25$ GeV.
- There must be exactly 1 preselected ℓ^+ and exactly 1 preselected ℓ^-.
- $m_{\mu\mu}, m_{ee} > 12$ GeV or $m_{e\mu} > 10$ GeV.
- $|m_{\ell\ell} - m_Z| > 15$ GeV if not $e\mu$.
- MET (also written $\not\!\!E_T$) > 45 GeV if not $e\mu$ or > 25 GeV if $e\mu$.
- $\Delta\phi_{\ell\ell} > 1.8$
- $m_{\ell\ell} > 50$ GeV unless there are 2 preselected jets, then $m_{\ell\ell} > 80$ GeV.

In code

Computer code can easily be written to read each event, and, for each event, to:

- Filter out any particles that do not pass the preselection cuts.
- Accept or reject the event based on the kinematics of the preselected particles.
- Record the cumulative sum of weights of the accepted events.

and the sum of the weights of the events can be compared to the total weight of the sample, and scaled to the total cross-section of the sample.

- You can get `LHPC` from `HepForge` to read events in `LHEF` and `LHCO` into `C++` (also reads in `SLHA` files).

Summary

Summary

- LHC analysis typically requires MC.
- MC should be planned: appropriate programs should be chosen based on required features.
- Trade-offs of accuracy for speed and better statistics should be thought through.
- Parton level MC truth $\neq$ detector-level reconstructed events.
- Usually final number is sum of cross-section weights of events that pass a full set of yes/no conditions on easily-calculated kinematic quantities.

That's all, folks.