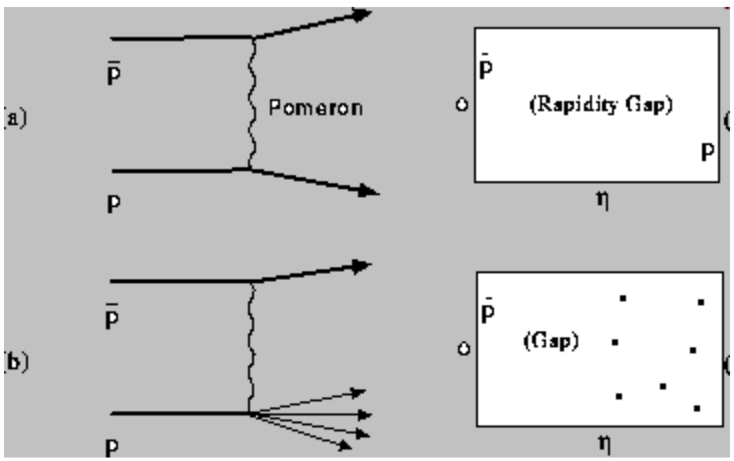
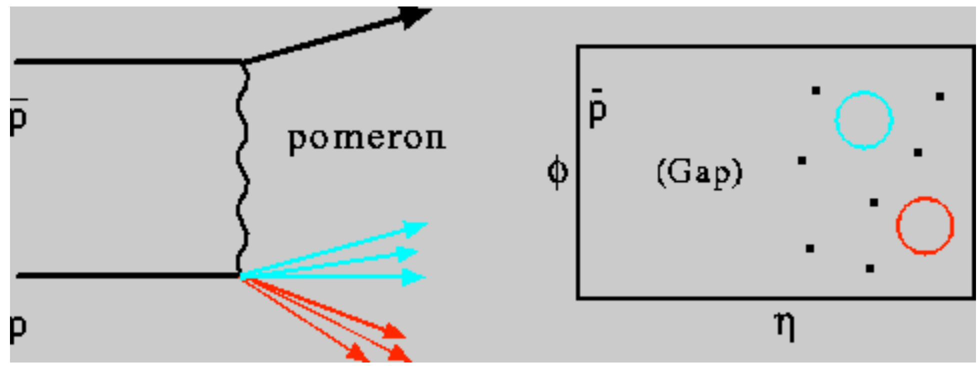
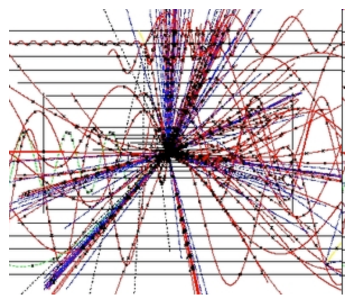
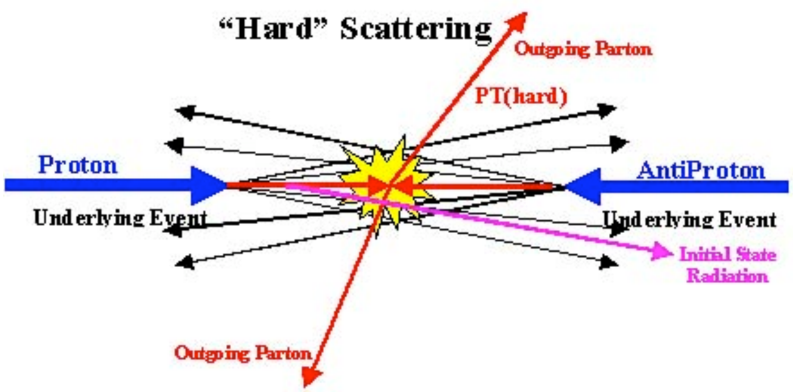
The total cross-section

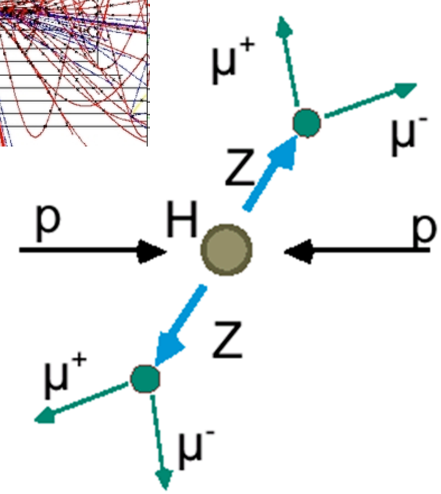
- $\sigma_{tot} = \sigma_{el} + \sigma_{diff} + \sigma_{jets} + \sigma_{EW} + \sigma_{bsm} + \ldots$

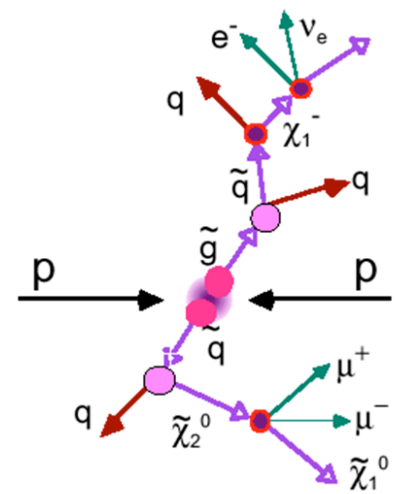












Monte Carlo simulations

- The final states of high energy collisions ("*events*") are single *samples* from the *distributions* (differential cross-sections) predicted by Quantum Field theory.
- These final states are, in general, very complex.
- So is the response of the detector to those collisions.
- It would be impossible to understand the detected events except through detailed, iterative comparisons with detailed simulations.
- The heart of these simulations is the "event loop".
- The simulations generate single events using (pseudo-)random numbers to sample the QFT predictions and fix other variables that are essentially random; hence, "Monte Carlos".
- A Monte Carlo is actually an extremely elaborate integral:

$$N = \Sigma_{fs} \int \sigma \, d(\text{phase space of final state})$$

- Phase space is all possible configuration of final state momenta, consistent with energy-momentum conservation.
- Sum over all final states that we choose to observe, consistent with all known conservation laws and dynamical laws.

Monte Carlo simulations

- Monte Carlo is in two parts: physics (event) simulation, and detector response simulation.
- The detector response is based on an elaborate and detailed program called GEANT.
  - Complete description of the detector geometry, materials, active elements
  - All the ways that particles can interact with the material: bremsstrahlung, ionization, dE/dx, hadronic showers, EM showers
- The physics simulation is based (for LHC) on Pythia (and other similar programs).
  - choice of initial state partons based on parton distribution functions in the proton
  - hard scattering sub-process
  - parton shower and fragmentation
  - hadronization
  - resonance and heavy particle decays
  - Rigorous energy-momentum conservation

Pythia

- Download from http://home.thep.lu.se/~torbjorn/Pythia.html
- Install in linux or MacOS
- Study A Brief Introduction to PYTHIA 8.1 and/or the Pythia 8.1 Intro and Tutorial
- Look at (and if you want, run through) the Pythia 8 Worksheet
- Run (all of) the examples
- Examine the results! What do events look like? What do the histograms tell us?
- What are the reported cross-sections for the different final states / processes?

From the Pythia manuals

In	No.	Subprocess	Reference
+	1	$f_i\bar{f}_i \to \gamma^*/Z^0$	[Eic84]
+	2	$f_i\bar{f}_j \to W^+$	[Eic84]
+	3	$f_i\bar{f}_i \to h^0$	[Eic84]
	4	$\gamma W^+ \to W^+$	
+	5	$Z^0Z^0 \to h^0$	[Eic84, Cha85]
	6	$Z^0W^+ \to W^+$	
	7	$W^+W^- \to Z^0$	
+	8	$W^+W^- \to h^0$	[Eic84, Cha85]
+	10	$f_if_j \to f_kf_l$ (QFD)	[Ing87a]
+	11	$f_if_j \to f_if_j$ (QCD)	[Com77, Ben84, Eic84]
+	12	$f_i\bar{f}_i \to f_k\bar{f}_k$	[Com77, Ben84, Eic84]
+	13	$f_i\bar{f}_i \to gg$	[Com77, Ben84]
+	14	$f_i\bar{f}_i \to g\gamma$	[Hal78, Ben84]
+	15	$f_i\bar{f}_i \to gZ^0$	[Eic84]
+	16	$f_i\bar{f}_j \to gW^+$	[Eic84]
	17	$f_i\bar{f}_i \to gh^0$	
+	18	$f_i\bar{f}_i \to \gamma\gamma$	[Ber84]
+	19	$f_i\bar{f}_i \to \gamma Z^0$	[Eic84]
+	20	$f_i\bar{f}_j \to \gamma W^+$	[Eic84, Sam91]
	21	$f_i\bar{f}_i \to \gamma h^0$	
+	22	$f_i\bar{f}_i \to Z^0Z^0$	[Eic84, Gun86]
+	23	$f_i\bar{f}_j \to Z^0W^+$	[Eic84, Gun86]
+	24	$f_i\bar{f}_i \to Z^0h^0$	[Ber85]
+	25	$f_i\bar{f}_i \to W^+W^-$	[Bar94, Gun86]
+	26	$f_i\bar{f}_j \to W^+h^0$	[Eic84]
	27	$f_i\bar{f}_i \to h^0h^0$	
+	28	$f_ig \to f_ig$	[Com77, Ben84]
+	29	$f_ig \to f_i\gamma$	[Hal78, Ben84]
+	30	$f_ig \to f_iZ^0$	[Eic84]
+	31	$f_ig \to f_kW^+$	[Eic84]
+	32	$f_ig \to f_ih^0$	[Bar88]
+	33	$f_i\gamma \to f_ig$	[Duk82]
+	34	$f_i\gamma \to f_i\gamma$	[Duk82]
+	35	$f_i\gamma \to f_iZ^0$	[Gab86]
+	36	$f_i\gamma \to f_kW^+$	[Gab86]
	37	$f_i\gamma \to f_ih^0$	

Table 1
Currently implemented processes, complete with respect to groups, but with some individual processes missing for lack of space (represented by "..."). In the names, a "2" separates initial and final state, an "(s:X)", "(t:X)" or "(l:X)" occasionally appends info on an s- or t-channel- or loop-exchanged particle X.

ProcessGroup	ProcessName
SoftQCD	minBias,elastic, singleDiffractive, doubleDiffractive
HardQCD	gg2gg, gg2qqbar, qg2qg, qq2qq, qqbar2gg, qqbar2qqbarNew, gg2ccbar, qqbar2ccbar, gg2bbbar, qqbar2bbbar
PromptPhoton	qg2qgamma, qqbar2ggamma, gg2ggamma, ffbar2gammagamma, gg2gammagamma
WeakBosonExchange	ff2ff(t:gmZ), ff2ff(t:W)
WeakSingleBoson	ffbar2gmZ, ffbar2W, ffbar2ffbar(s:gm)
WeakDoubleBoson	ffbar2gmZgmZ, ffbar2ZW, ffbar2WW
WeakBosonAndParton	qqbar2gmZg, qg2gmZq, ffbar2gmZgm, fgm2gmZf qqbar2Wg, qg2Wq, ffbar2Wgm, fgm2Wf
Charmonium	gg2QQbar[3S1(1)]g, qg2QQbar[3PJ(8)]q, ...
Bottomonium	gg2QQbar[3S1(1)]g, gg2QQbar[3P2(1)]g, ...
Top	gg2ttbar, qqbar2ttbar, qq2tq(t:W), ffbar2ttbar(s:gmZ), ffbar2tqbar(s:W)
FourthBottom, FourthTop, FourthPair (fourth generation)	
HiggsSM	ffbar2H, gg2H, ffbar2HZ, ff2Hff(t:WW), ...
HiggsBSM	h, H and A as above, charged Higgs, pairs
SUSY	qqbar2chi0chi0 (not yet completed)
NewGaugeBoson	ffbar2gmZZprime, ffbar2Wprime, ffbar2R0
LeftRightSymmmetry	ffbar2ZR, ffbar2WR, ffbar2HLHL, ...
LeptoQuark	ql2LQ, qg2LQl, gg2LQLQbar, qqbar2LQLQbar
ExcitedFermion	dg2dStar, qq2uStarq, qqbar2muStarmu, ...
ExtraDimensionsG*	gg2G*, qqbar2G*, ...

a single pythia event: gg → tt

-------- PYTHIA Event Listing (hard process) --------

no	id	name	status	mothers		daughters		colours		p_x	p_y	p_z	e	m
0	90	(system)	-11	0	0	0	0	0	0	0.000	0.000	0.000	14000.000	14000.000
1	2212	(p+)	-12	0	0	3	0	0	0	0.000	0.000	7000.000	7000.000	0.938
2	2212	(p+)	-12	0	0	4	0	0	0	0.000	0.000	-7000.000	7000.000	0.938
3	21	(g)	-21	1	0	5	6	101	102	0.000	0.000	267.353	267.353	0.000
4	21	(g)	-21	2	0	5	6	103	101	0.000	0.000	-111.641	111.641	0.000
5	6	(t)	-22	3	4	11	12	103	0	-5.871	36.280	87.367	194.164	169.457
6	-6	(tbar)	-22	3	4	13	14	0	102	5.871	-36.280	68.344	184.831	167.752
7	2	(u)	-21	1	0	9	10	106	0	0.000	0.000	2463.446	2463.446	0.000
8	21	(g)	-21	2	0	9	10	107	106	0.000	0.000	-0.200	0.200	0.000
9	2	u	23	7	8	0	0	107	0	-0.837	21.543	934.764	935.013	0.330
10	22	gamma	23	7	8	0	0	0	0	0.837	-21.543	1528.481	1528.634	0.000
11	24	(W+)	-22	5	0	15	16	0	0	42.629	8.698	101.674	136.365	79.780
12	5	b	23	5	0	0	0	103	0	-48.500	27.582	-14.307	57.799	4.800
13	-24	(W-)	-22	6	0	17	18	0	0	16.544	9.702	98.824	128.436	79.761
14	-5	bbar	23	6	0	0	0	0	102	-10.673	-45.982	-30.480	56.394	4.800
15	-1	dbar	23	11	0	0	0	0	104	0.911	-6.926	-12.213	14.074	0.330
16	2	u	23	11	0	0	0	104	0	41.718	15.624	113.888	122.291	0.330
17	1	d	23	13	0	0	0	105	0	-10.230	-31.329	42.560	53.830	0.330
18	-2	ubar	23	13	0	0	0	0	105	26.774	41.031	56.264	74.606	0.330
			Charge sum:	0.667			Momentum sum:			0.000	0.000	2618.957	2842.640	1105.291

-------- End PYTHIA Event Listing --------

-------- PYTHIA Event Listing (complete event) --------

no	id	name	status	mothers		daughters		colours		p_x	p_y	p_z	e	m
0	90	(system)	-11	0	0	0	0	0	0	0.000	0.000	0.000	14000.000	14000.000
1	2212	(p+)	-12	0	0	883	0	0	0	0.000	0.000	7000.000	7000.000	0.938
2	2212	(p+)	-12	0	0	884	0	0	0	0.000	0.000	-7000.000	7000.000	0.938
3	21	(g)	-21	11	11	5	6	101	102	0.000	0.000	267.353	267.353	0.000
4	21	(g)	-21	12	0	5	6	103	101	0.000	0.000	-111.641	111.641	0.000
5	6	(t)	-22	3	4	13	13	103	0	-5.871	36.280	87.367	194.164	169.457
6	-6	(tbar)	-22	3	4	14	14	0	102	5.871	-36.280	68.344	184.831	167.752
7	2	(u)	-21	22	22	9	10	106	0	0.000	0.000	2463.446	2463.446	0.000
8	21	(g)	-21	23	0	9	10	107	106	0.000	0.000	-0.200	0.200	0.000
9	2	(u)	-23	7	8	24	24	107	0	-0.837	21.543	934.764	935.013	0.330
10	22	(gamma)	-23	7	8	25	25	0	0	0.837	-21.543	1528.481	1528.634	0.000
11	21	(g)	-42	16	0	3	3	101	102	-0.000	0.000	267.353	267.353	0.000
12	21	(g)	-41	17	17	15	4	108	101	0.000	-0.000	-170.759	170.759	0.000
13	6	(t)	-44	5	5	18	18	103	0	0.728	4.578	54.338	178.017	169.457
14	-6	(tbar)	-44	6	6	19	19	0	102	13.069	-70.858	56.095	190.995	167.752
15	21	(g)	-43	12	0	20	20	108	103	-13.797	66.279	-13.840	69.100	0.000
16	21	(g)	-41	29	29	21	11	109	102	-0.000	-0.000	359.391	359.391	0.000

Integrated cross section in Pythia

```
*-------  PYTHIA Process Initialization  --------------------------*
|                                                                  |
| We collide p+ with p+ at a CM energy of 1.400e+04 GeV            |
|                                                                  |
|------------------------------------------------------------------|
|                                                    |             |
| Subprocess                                   Code |   Estimated |
|                                                    |    max (mb) |
|                                                    |             |
|------------------------------------------------------------------|
|                                                    |             |
| g g -> t tbar                                 601 |   4.481e-06 |
| q qbar -> t tbar                              602 |   6.994e-07 |
| q q -> t q (t-channel W+-)                    603 |   4.295e-06 |
| f fbar -> t tbar (s-channel gamma*/Z0)        604 |   6.022e-09 |
| f fbar -> t qbar (s-channel W+-)              605 |   1.185e-07 |
|                                                    |             |
|------------------------------------------------------------------|
```

```
*-------  PYTHIA Event and Cross Section Statistics  -------------------------------------------------------*
|                                                                                                           |
| Subprocess                                    Code |      Number of events           |    sigma +- delta    |
|                                                    |    Tried   Selected   Accepted |  (estimated) (mb)    |
|                                                    |                                 |                      |
|-----------------------------------------------------------------------------------------------------------|
|                                                    |                                 |                      |
| First hard process:                                |                                 |                      |
|                                                    |                                 |                      |
| g g -> t tbar                                  601 |     1492        152        134 | 3.505e-12  3.370e-13 |
| q qbar -> t tbar                               602 |      229         25         18 | 4.796e-13  8.485e-14 |
| q q -> t q (t-channel W+-)                     603 |     1376         59         47 | 1.151e-12  1.439e-13 |
| f fbar -> t tbar (s-channel gamma*/Z0)         604 |        1          0          0 | 0.000e+00  0.000e+00 |
| f fbar -> t qbar (s-channel W+-)               605 |       42          2          1 | 3.241e-14  3.252e-14 |
|                                                    |                                 |                      |
| sum                                                |     3140        238        200 | 5.168e-12  4.790e-13 |
|                                                    |                                 |                      |
|-----------------------------------------------------------------------------------------------------------|
```

pythia example main11/out11 (Top:all; Ecm_{min} >40, pt_{min} > 20)

$\sigma = 5\times10^{-12}$ mb, $L = 1\times10^{34}$ /cm^2/s, $dN/dt = 5\times10^{-5}$/s

$\sigma = 5\times10^{-6}$ mb, $L = 1\times10^{34}$ /cm^2/s, $dN/dt = 50$/s

Fun with Pythia

- Run Pythia and understand the output.
  - a. Download from http://home.thep.lu.se/~torbjorn/Pythia.html
  - b. Install, compile and build it in linux or MacOS, following the instructions on that web page.
  - c. Study A Brief Introduction to PYTHIA 8.1 and/or the Pythia 8.1 Intro and Tutorial
  - d. Look at (and if you want, run through) the Pythia 8 Worksheet
  - e. Run (all of) the examples (by typing "./runmains"). Not all of the programs will run; some require additional infrastructure.
  - f. Examine the results! What do events look like? Trace through and diagram the chain from parent to child, from the initial hard scatter, through the parton shower, the hadronization, and decay to final state particles. Doing this for one whole event is maybe too big a job; try to follow one branch of the parton shower all the way to the end.
  - g. Look at the output of ALL the jobs that ran through (some won't run). For each job, write down the hard scattering process, the initial cross-section estimate, and the final computer cross-section with error. Jot down the histograms that were made and note their overall shape. Try to construct a "total cross-section".
  - h. What are the reported cross-sections for the different final states / processes?
  - i. How does the program simulate the detector response?
  - j. What do the histograms tell us? Look at the output of a bunch of jobs, at the resulting histograms. How were these histograms made?
- Try to modify the code for one of the jobs, to make one or two additional histograms of quantities of interest.

A good first exercise

- Use Pythia to answer the question: what threshold do I need to place on "missing E_T" before a SUSY signal stands out over the QCD background?
- SUSY with "R-parity" has a "lightest supersymmetric particle" (LSP) which is a neutral, weakly-interacting massive particle (a "neutralino").
- The LSP is a perfect candidate for the dark matter! (This is a very significant observation; we will explore it later).
- So processes in which supersymmetric particles are produced (especially strongly interacting ones, like gluinos or squarks) lead to a decay chain which ultimately ends in a pair of LSPs exiting the detector, carrying away momentum and energy, undetected. This is the missing energy signature for SUSY at the LHC.
- Because it is difficult to measure energy flow along the beamline (so much energy escapes undetected at small angles), LHC detectors are best at measuring momentum flow transverse to the beampipe (p_t).
- If all final state (~stable) particles are observed (ie, no neutrinos or neutralinos), Pythia will report Sum(p_x) = 0, Sum(p_y) = 0. VERIFY THIS.
- If there are neutrinos or neutralinos in the final state, they leave no trace in the detector; p_x and p_y will be unbalanced, and there will be "missing E_t"
  MET = sqrt($(\text{Sum}(p_x))^2 + (\text{Sum}(p_y))^2$).
- HISTOGRAM THIS, for "HardQCD:all" (background) and SUSY:all (signal).
- Now normalize the histograms by cross-section, to $d\sigma/d(\text{MET})$, and superimpose them (on a semilogy scale!).
- Try to answer the above question.