The total cross-section

• $\sigma_{tot} = \sigma_{el} + \sigma_{diff} + \sigma_{jets} + \sigma_{EW} + \sigma_{bsm} + \dots$



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 = Σ_{fs} ∫ σ d(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 <u>A Brief Introduction to PYTHIA 8.1</u> 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	$f_i \overline{f}_i \rightarrow \gamma^* / Z^0$	[Eic84]
+	2	$f_i \overline{f}_j \rightarrow W^+$	[Eic84]
+	- 3	$f_i \overline{f}_i \rightarrow h^0$	[Eic84]
	4	$\gamma W^+ \rightarrow W^+$	
+	5	$\dot{Z}^0 Z^0 \rightarrow h^0$	[Eic84, Cha85]
	6	$Z^0W^+ \rightarrow W^+$	
	7	$W^+W^- \rightarrow Z^0$	
+	8	$W^+W^- \rightarrow h^0$	[Eic84, Cha85]
+	10	$f_i f_j \rightarrow f_k f_l \ (QFD)$	[Ing87a]
+	11	$f_i \underline{f}_j \rightarrow f_i \underline{f}_j (QCD)$	[Com77, Ben84, Eic84]
+	12	$f_i \underline{f}_i \rightarrow f_k f_k$	[Com77, Ben84, Eic84]
+	13	$f_i f_i \rightarrow gg$	[Com77, Ben84]
+	14	$f_i f_i \rightarrow g \gamma$	[Hal78, Ben84]
+	15	$f_i \overline{f}_i \rightarrow gZ^0$	[Eic84]
+	16	$f_i \overline{f}_j \rightarrow gW^+$	[Eic84]
	17	$f_i \overline{f}_i \rightarrow gh^0$	
+	18	$f_i \bar{f}_i \rightarrow \gamma \gamma$	[Ber84]
+	19	$f_i \overline{f}_i \rightarrow \gamma Z^0$	[Eic84]
+	20	$f_i \bar{f}_j \rightarrow \gamma W^+$	[Eic84, Sam91]
	21	$f_i \tilde{f}_i \rightarrow \gamma h^0$	5 · · ·
+	22	$f_i \overline{f}_i \rightarrow Z^0 Z^0$	[Eic84, Gun86]
+	23	$f_i \overline{f}_j \rightarrow Z^0 W^+$	[Eic84, Gun86]
+	24	$f_i \overline{f}_i \rightarrow Z^0 h^0$	[Ber85]
+	25	$f_i \bar{f}_i \rightarrow W^+W^-$	[Bar94, Gun86]
+	26	$f_i \overline{f}_i \rightarrow W^+ h^0$	[Eic84]
	27	$f_i \tilde{f}_i \rightarrow h^0 h^0$	L 1
+	28	$f_i g \rightarrow f_i g$	[Com77, Ben84]
+	- 29	$f_i g \rightarrow f_i \gamma$	[Hal78, Ben84]
+	- 30	$f_i g \rightarrow f_i Z^0$	[Eic84]
+	31	$f_i g \rightarrow f_k W^+$	[Eic84]
+	32	$f_i g \rightarrow f_i h^0$	[Bar88]
+	- 33	$f_i \gamma \rightarrow f_i g$	[Duk82]
+	34	$f_i \gamma \rightarrow f_i \gamma$	[Duk82]
+	35	$f_i \gamma \rightarrow f_i Z^0$	[Gab86]
+	36	$f_i \gamma \rightarrow f_k W^+$	[Gab86]
	- 37	$t_i \gamma \rightarrow f_i h^0$	

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	<pre>ff2ff(t:gmZ), ff2ff(t:W)</pre>					
WeakSingleBoson	<pre>ffbar2gmZ, ffbar2W, ffbar2ffbar(s:gm)</pre>					
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,					
Тор	gg2ttbar, qqbar2ttbar, qq2tq(t:W),					
	<pre>ffbar2ttbar(s:gmZ), ffbar2tqbar(s:W)</pre>					
FourthBottom, Fourt	hTop, 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: $gg \rightarrow tt$

	PYTHIA	Event histing	(naru proc	000,										
no	id	name	status	mot	hers	daugł	hters	co	lours	p_x	р_у	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
	End PYT	THIA Event Lis Event Listing	ting	event)										
 	End PYT PYTHIA id	THIA Event Lis Event Listing name	ting (complete status	event) mot					 	 р х			 	
 no 0	End PYT PYTHIA id 90	THIA Event Lis Event Listing name (system)	ting (complete status -11	event) mot 0	 hers 0	daugł 0	hters	 co. 0	 lours 0	p_x 0.000	р_у о.ооо	p_z 0.000	e 14000.000	m 14000.000
no 0 1	End PY PYTHIA id 90 2212	THIA Event Lis Event Listing name (system) (p+)	ting (complete status -11 -12	event) mot O O	 hers 0 0	 daugi 0 883	hters	 co. 0	lours 0 0	p_x 0.000 0.000	p_y 0.000 0.000	p_z 0.000 7000.000	e 14000.000 7000.000	 m 14000.000 0.938
no 0 1 2	End PY PYTHIA id 90 2212 2212	THIA Event Lis Event Listing name (system) (p+) (p+)	ting (complete status -11 -12 -12	event) mot O O O	 hers 0 0	 daugł 0 883 884	hters 0 0 0	 co. 0 0	lours 0 0 0	p_x 0.000 0.000 0.000	p_y 0.000 0.000 0.000	p_z 0.000 7000.000 -7000.000	e 14000.000 7000.000 7000.000	m 14000.000 0.938 0.938
no 0 1 2 3	End PY PYTHIA id 90 2212 2212 212 21	THIA Event Lis Event Listing name (system) (p+) (p+) (g)	ting (complete status -11 -12 -12 -21	event) mot 0 0 11	 hers 0 0 11	daugi 0 883 884 5	hters 0 0 0 6	 co 0 0 101	lours 0 0 102	p_x 0.000 0.000 0.000 0.000 0.000	p_y 0.000 0.000 0.000 0.000 0.000	p_z 0.000 7000.000 -7000.000 267.353	e 14000.000 7000.000 7000.000 267.353	m 14000.000 0.938 0.938 0.000
no 0 1 2 3 4	End PY PYTHIA id 90 2212 2212 21 21 21	THIA Event Lis Event Listing name (system) (p+) (p+) (g) (g)	ting (complete status -11 -12 -12 -21 -21	event) mot 0 0 11 12	 hers 0 0 11 0	 daugł 0 883 884 5 5	hters 0 0 0 6 6	 co 0 0 101 103	lours 0 0 0 102 101	p_x 0.000 0.000 0.000 0.000 0.000 0.000	p_y 0.000 0.000 0.000 0.000 0.000 0.000	p_z 0.000 7000.000 -7000.000 267.353 -111.641	e 14000.000 7000.000 7000.000 267.353 111.641	m 14000.000 0.938 0.938 0.000 0.000
no 0 1 2 3 4 5	End PY PYTHIA id 90 2212 2212 21 21 21 6	THIA Event Lis Event Listing name (system) (p+) (p+) (g) (g) (t)	ting (complete status -11 -12 -12 -21 -21 -22	event) mot 0 0 11 12 3	 chers 0 0 11 0 4	 daugł 0 883 884 5 5 13	hters 0 0 0 6 6 13	 0 0 101 103 103	lours 0 0 102 101 0	p_x 0.000 0.000 0.000 0.000 0.000 -5.871	p_y 0.000 0.000 0.000 0.000 0.000 0.000 36.280	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367	e 14000.000 7000.000 7000.000 267.353 111.641 194.164	m 14000.000 0.938 0.938 0.000 0.000 169.457
no 0 1 2 3 4 5 6	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6	THIA Event Lis Event Listing name (system) (p+) (p+) (g) (g) (t) (tbar)	ting (complete status -11 -12 -12 -21 -21 -22 -22	event) mot 0 0 11 12 3 3	 0 0 11 0 4 4	daugh 0 883 884 5 5 13 14	nters 0 0 6 6 13 14	 0 0 101 103 103 0	lours 0 0 102 101 0 102	p_x 0.000 0.000 0.000 0.000 0.000 -5.871 5.871	p_y 0.000 0.000 0.000 0.000 0.000 36.280 -36.280	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344	e 14000.000 7000.000 7000.000 267.353 111.641 194.164 184.831	m 14000.000 0.938 0.938 0.000 0.000 169.457 167.752
no 0 1 2 3 4 5 6 7	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6 2	THIA Event Listing name (system) (p+) (g) (g) (t) (tbar) (u)	ting (complete status -11 -12 -12 -21 -21 -22 -22 -22 -21	event) mot 0 0 11 12 3 3 22	chers 0 0 11 0 4 4 22	daugh 0 883 884 5 5 13 14 9	nters 0 0 6 13 14 10	co 0 101 103 103 0 106	lours 0 102 101 0 102 0	p_x 0.000 0.000 0.000 0.000 0.000 -5.871 5.871 0.000	p_y 0.000 0.000 0.000 0.000 0.000 36.280 -36.280 0.000	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446	m 14000.000 0.938 0.938 0.000 0.000 169.457 167.752 0.000
no 0 1 2 3 4 5 6 7 8	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6 2 21	THIA Event Listing name (system) (p+) (g) (g) (t) (tbar) (u) (g)	ting (complete status -11 -12 -12 -21 -21 -22 -22 -22 -21 -21	event) mot 0 0 11 12 3 3 22 23		daugh 0 883 884 5 5 13 14 9 9	nters 0 0 6 13 14 10 10	co 0 101 103 103 0 106 107	lours 0 102 101 0 102 0 102 0 106	p_x 0.000 0.000 0.000 0.000 0.000 -5.871 5.871 0.000 0.000	p_y 0.000 0.000 0.000 0.000 0.000 36.280 -36.280 0.000 0.000	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446 -0.200	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446 0.200	m 14000.000 0.938 0.938 0.000 0.000 169.457 167.752 0.000 0.000
no 0 1 2 3 4 5 6 7 8 9	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6 2 21 21 21	THIA Event Listing name (system) (p+) (g) (g) (t) (tbar) (u) (g) (u) (u)	ting (complete status -11 -12 -21 -21 -22 -22 -22 -21 -21 -21	event) mot 0 11 12 3 22 23 7		daugh 0 883 884 5 5 13 14 9 24	nters 0 0 6 13 14 10 24	co. 0 101 103 103 0 106 107 107	lours 0 102 101 0 102 0 106 0	p_x 0.000 0.000 0.000 0.000 -5.871 5.871 0.000 0.000 -0.837	p_y 0.000 0.000 0.000 0.000 36.280 -36.280 0.000 0.000 21.543	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446 -0.200 934.764	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446 0.200 935.013	m 14000.000 0.938 0.938 0.000 169.457 167.752 0.000 0.000 0.330
no 0 1 2 3 4 5 6 7 8 9 10	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6 2 21 2 21 2 21	THIA Event List Event Listing name (system) (p+) (p+) (g) (g) (t) (tbar) (u) (g) (u) (g) (u) (gamma)	ting (complete status -11 -12 -21 -21 -22 -22 -22 -21 -21 -21	event) mot 0 11 12 3 22 23 7 7	2. hers 0 0 11 0 4 4 22 0 8 8	daugh 0 883 884 5 5 13 14 9 9 24 25	nters 0 0 6 13 14 10 24 25	co. 0 101 103 103 0 106 107 107 0	lours 0 102 101 0 102 0 106 0 0	p_x 0.000 0.000 0.000 0.000 -5.871 5.871 0.000 0.000 -0.837 0.837	p_y 0.000 0.000 0.000 0.000 36.280 -36.280 0.000 0.000 21.543 -21.543	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446 -0.200 934.764 1528.481	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446 0.200 935.013 1528.634	m 14000.000 0.938 0.938 0.000 169.457 167.752 0.000 0.000 0.330 0.000
no 0 1 2 3 4 5 6 7 8 9 10 11	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6 2 21 2 21 2 22 21	THIA Event Listing name (system) (p+) (g) (g) (t) (tbar) (u) (g) (u) (g) (u) (gamma) (g)	ting (complete status -11 -12 -21 -21 -22 -22 -22 -21 -21 -23 -23 -23 -42	event) mot 0 11 12 3 22 23 7 7 16	2. hers 0 0 11 0 4 4 22 0 8 8 0	daugh 0 883 884 5 5 13 14 9 24 25 3	nters 0 0 6 13 14 10 24 25 3	co. 0 101 103 103 0 106 107 107 0 101	lours 0 102 101 0 102 0 106 0 106 0 102	p_x 0.000 0.000 0.000 0.000 -5.871 5.871 0.000 0.000 -0.837 0.837 -0.000	p_y 0.000 0.000 0.000 0.000 36.280 -36.280 0.000 21.543 -21.543 0.000	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446 -0.200 934.764 1528.481 267.353	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446 0.200 935.013 1528.634 267.353	m 14000.000 0.938 0.938 0.000 169.457 167.752 0.000 0.000 0.330 0.000 0.000
no 0 1 2 3 4 5 6 7 8 9 10 11 12	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6 2 21 2 22 21 21 21	THIA Event Listing name (system) (p+) (p) (g) (t) (tbar) (u) (g) (u) (g) (u) (gamma) (g) (g)	ting (complete status -11 -12 -21 -21 -22 -22 -22 -21 -21 -23 -23 -23 -42 -41	event) mot 0 11 12 3 22 23 7 7 7 16 17	2.hers 0 0 11 0 4 4 22 0 8 8 0 17	daugh 0 883 884 5 13 14 9 24 25 3 15	nters 0 0 6 13 14 10 24 25 3 4	co 0 101 103 103 0 106 107 107 0 101 108	lours 0 102 101 0 102 0 106 0 102 102 101	p_x 0.000 0.000 0.000 0.000 -5.871 5.871 0.000 -0.837 0.837 -0.000 0.000	p_y 0.000 0.000 0.000 0.000 36.280 -36.280 0.000 21.543 -21.543 0.000 -0.000	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446 -0.200 934.764 1528.481 267.353 -170.759	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446 0.200 935.013 1528.634 267.353 170.759	m 14000.000 0.938 0.938 0.000 169.457 167.752 0.000 0.000 0.330 0.000 0.000 0.000
no 0 1 2 3 4 5 6 7 8 9 10 11 12 13	End PY PYTHIA id 90 2212 2212 21 21 21 6 -6 2 21 2 22 21 21 21 6	THIA Event Lis Event Listing name (system) (p+) (p+) (g) (t) (tbar) (u) (g) (u) (g) (u) (g) (u) (g) (u) (g) (t) (j) (j) (j) (j) (j) (j) (j) (j	ting (complete status -11 -12 -21 -21 -22 -22 -22 -21 -21 -23 -23 -23 -42 -41 -44	event) mot 0 11 12 3 22 23 7 7 16 17 5	2. 2. 1. 1. 0 1. 1. 0 4 4 2.2 0 8 8 8 0 1.7 5	daugh 0 883 884 5 5 13 14 9 24 25 3 15 18	nters 0 0 6 13 14 10 24 25 3 4 18	co. 0 101 103 103 0 106 107 107 0 101 108 103	lours 0 102 101 0 102 0 106 0 102 101 0 102	p_x 0.000 0.000 0.000 0.000 -5.871 5.871 0.000 -0.837 0.837 -0.000 0.000 0.000	p_y 0.000 0.000 0.000 0.000 36.280 -36.280 0.000 21.543 -21.543 0.000 -0.000 4.578	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446 -0.200 934.764 1528.481 267.353 -170.759 54.338	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446 0.200 935.013 1528.634 267.353 170.759 178.017	m 14000.000 0.938 0.938 0.000 169.457 167.752 0.000 0.330 0.000 0.330 0.000 0.000 169.457
no 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14	End PY PYTHIA id 90 2212 2212 21 21 21 2 21 22 21 21 21 6 -6 -6	THIA Event Lis Event Listing name (system) (p+) (p+) (g) (d) (tbar) (u) (g) (u) (gamma) (g) (c) (t) (tbar)	ting (complete status -11 -12 -12 -21 -21 -22 -22 -21 -21 -23 -23 -42 -41 -44 -44	event) mot 0 11 12 3 22 23 7 7 16 17 5 6	2. 2. 1. 0 0 11 0 4 4 22 0 8 8 0 17 5 6	daugh 0 883 884 5 5 13 14 9 9 24 25 3 15 18 19	nters 0 0 6 13 14 10 24 25 3 4 18 19	co. 0 101 103 103 0 106 107 107 0 101 108 103 0 0	lours 0 102 101 0 102 0 106 0 102 101 0 102 101 0 102	p_x 0.000 0.000 0.000 0.000 -5.871 5.871 0.000 -0.837 -0.837 -0.000 0.000 0.728 13.069	p_y 0.000 0.000 0.000 0.000 36.280 -36.280 0.000 21.543 -21.543 0.000 -0.000 4.578 -70.858	p_z 0.000 7000.000 -7000.000 267.353 -111.641 87.367 68.344 2463.446 -0.200 934.764 1528.481 267.353 -170.759 54.338 56.095	e 14000.000 7000.000 267.353 111.641 194.164 184.831 2463.446 0.200 935.013 1528.634 267.353 170.759 178.017 190.995	m 14000.000 0.938 0.938 0.000 169.457 167.752 0.000 0.330 0.000 0.330 0.000 0.000 169.457 167.752
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Integrated cross section in Pythia

	* PYTHIA Process Initialization		*
	 We collide p+ with p+ at a CM energy of 1.400e+04 =	GeV	
ntegrated	 Subprocess Code	 	 Estimated
oss section	 	 	(max (mb)
	' gg->ttbar 601	i	4.481e-06
in Dirthia	q qbar -> t tbar 602	I.	6.994e-07
	q q -> t q (t-channel W+-) 603	Ι	4.295e-06
5	f fbar -> t tbar (s-channel gamma*/ZO) 604	Ι	6.022e-09
	f fbar -> t qbar (s-channel W+-) 605	Ι	1.185e-07
		Ι	1
PVTHIN Event and Cross Section Stat			

Subprocess Code I Number of events siqma +- delta Selected Tried Accepted | (estimated) (mb) First hard process: $q q \rightarrow t t bar$ 601 I 1492 152 134 I 3.505e-12 3.370e-13 229 25 18 I 4.796e-13 8.485e-14 q qbar -> t tbar 602 I 1376 59 $q q \rightarrow t q (t-channel W+-)$ 603 I 47 1 1.151e-12 1.439e-13 f fbar \rightarrow t tbar (s-channel gamma*/20) 1 Ω 0 | 0.000e+00 0.000e+00 604 | f fbar -> t gbar (s-channel W+-) 42 2 3.241e-14 3.252e-14 605 I 1 | sum 3140 238 200 I 5.168e-12 4.790e-13

pythia example main11/out11 (Top:all; $Ecm_{min} > 40$, $pt_{min} > 20$) $\sigma = 5 \times 10^{-12}$ mb, L = 1×10³⁴ /cm²/s, dN/dt = 5×10⁻⁵/s $\sigma = 5 \times 10^{-6}$ mb, L = 1×10³⁴ /cm²/s, dN/dt = 50/s

What is mass?

- Newtonian inertial mass
- Newtonian gravitational mass, Equivalence principle
 F = m_{inertial} a = G m_{grav} m_{source} / r²
- Special relativity: conservation of matter-energy
- GR: mass-energy as source of curvature
- QM: Binding energy as mass; defining mass for quarks
- QM: mass-energy as dispersive wave e^{iEt/hbar}
- QM: (m+i Γ /2) as dispersive/absorptive wave $\psi \sim \exp((imc^2-\Gamma/2)t/hbar)$
- QFT: mass as propagating self-energy: term in the Lagrangian, L ~ m $\psi\psi$



- QFT: mass as coupling to Higgs ether L ~ $\langle \phi \rangle \psi \psi$
- Cosmological baryogenesis (matter/antimatter asymmetry)

Particle decay lengths

С	3.00E+08	m/s					
р	10000	MeV					
hbar	6.58E-22	MeV-s					
	m (MeV)	tau (s)	Width (MeV)	<l> (m)</l>	<l> (cm)</l>	force	where decay
n	939.56	8.86E+02	7.43E-25	2.83E+12	2.83E+14	weak	"stable"
mu	105.66	2.20E-06	3.00E-16	6.24E+04	6.24E+06	weak	"stable"
рі	139.57	2.60E-08	2.53E-14	5.60E+02	5.60E+04	weak	"stable"
pi0	134.98	8.40E-17	7.84E-06	1.87E-06	1.87E-04	EM	very short
rho	770	4.41E-21	1.49E-01	1.72E-11	1.72E-09	strong	very short
К	493.68	1.24E-08	5.31E-14	7.54E+01	7.54E+03	weak	"stable"
KS	497.61	8.95E-11	7.35E-12	5.40E-01	5.40E+01	weak	"Vee"
KL	497.61	5.12E-08	1.29E-14	3.08E+02	3.08E+04	weak	"Vee"
tau	1776.84	2.91E-13	2.26E-09	4.91E-04	4.91E-02	weak	sep vertex
D+	1869.62	1.04E-12	6.33E-10	1.67E-03	1.67E-01	weak	sep vertex
D*+	2010.27	6.86E-21	9.60E-02	1.02E-11	1.02E-09	strong	very short
B0	5279.53	1.53E-12	4.30E-10	8.69E-04	8.69E-02	weak	sep vertex
top	171200	2.19E-23	3.01E+01	3.83E-16	3.83E-14	weak	very short
J/psi	3096.92	7.06E-21	9.32E-02	6.84E-12	6.84E-10	strong, EM	very short
ups(1S)	9460.3	1.22E-20	5.40E-02	3.87E-12	3.87E-10	strong, EM	very short
Omega-	1672.45	8.21E-11	8.02E-12	1.47E-01	1.47E+01	weak	"Vee"
Lambda0	1115.68	2.63E-10	2.50E-12	7.07E-01	7.07E+01	weak	"Vee"
Lambdac+	2286.46	2.00E-13	3.29E-09	2.62E-04	2.62E-02	weak	sep vertex
Lambdab0	5620.2	1.38E-12	4.77E-10	7.37E-04	7.37E-02	weak	sep vertex

 $\Gamma = hbar/\tau$ <l> = $\gamma\beta c\tau = (p/m)c\tau$

Notes to previous table

- "stable" well, stable enough to traverse the detector without decaying
- "Vee" can decay in the detector, often to two charged particles that form a "V"
- Sep vertex: decays before exiting the beampipe, but long enough to be measurable (as a "separated vertex") by precision detectors just outside the beampipe that track the daughter charged particles
- Very short: decays strongly, traveling un unmeasurably short distance. Instead, "width" is measured by forming distribution of invariant mass of decay products.
- The quarkonia (J/psi and Upsilon) decay strongly, but the decays are suppressed (the heavy quark pair must annihilate), so the width is narrow and EM decays can compete.

particle	mass [MeV]	major decay modes	lifetime [s]	width $[MeV]$	distance [cm] \square n = 10CeV
n	939.56536(8)	$pe\bar{\nu}_{e}$	885.7(8)	7.4×10^{-25}	3×10^{14}
μ^{-}	105.658367(4)	$e V_e V_{\mu}$	$2.197019(21) \times 10^{-6}$	3×10^{-16}	6×10^{6}
π^{-}	139.57018(35)	$\mu \bar{\nu}_{\mu}$	$2.6033(5) \times 10^{-8}$	2.5×10^{-14}	5.6×10^{4}
π^0	134.9766(6)	$\frac{2\gamma}{2\gamma}$	$8.4(6) \times 10^{-17}$	8×10^{-6}	2×10^{-4}
ρ	775.5(3)	$\pi\pi$	4.4×10^{-24}	149	2×10^{-12}
K^{-}	493.677(16)	$\mu \bar{ u}_{\mu}$	$1.2380(21)\!\times\!10^{-8}$	$5 imes 10^{-14}$	7×10^3
K_S	497.614(24)	$\pi^{-}\pi^{0}$ $2\pi^{0}$ $-\pm -=$	$0.8953(5) {\times} 10^{-10}$	7×10^{-12}	54
K_L	497.614(24)	$\pi^+\pi^- \pi^\pm e^\mp \nu_e$	$5.116(20){\times}10^{-8}$	1.3×10^{-14}	$3 imes 10^4$
		$ \begin{array}{c} \pi \mu^+ \nu_{mu} \\ 3\pi^0 \\ \pi^+ \pi^- \pi^0 \end{array} $	200.0(1.0) 10-15	0 10-9	x 10-2
$ au^-$	1776.84(17)	$e\overline{\nu}_e\nu_{\tau}$	$290.6(1.0) \times 10^{-15}$	2×10^{-9}	5×10^{-2}
D^+	1869.62(20)	$\bar{K}^{0}+K^{0}$	$1040(7) \times 10^{-15}$	6×10^{-10}	0.17
D^{*+}	2010.27(17)	$D^0\pi^+$	$\approx 7 \times 10^{-21}$	0.096(22)	10^{-9}
		$D^+\pi^0$			
B^0	5279.53(33)	K^{\pm}	$1.530(9) \times 10^{-12}$	4×10^{-10}	8.7×10^{-2}
t	$171.2(2.1) \times 10^3$	bW^+	2×10^{-23}	30	4×10^{-14}
J/ψ	3096.916(11)	$[\gamma] \rightarrow \text{hadrons}$	$\approx 7 \times 10^{-21}$	0.0932(21)	7×10^{-10}
Y(1S)	9460.30(26)	$l^+l^-?$	$\approx 1 \times 10^{-20}$	0.05402(125)	4×10^{-12}
Ω^{-}	1672.45(29)	ΛK^{-}	$0.821(11) \times 10^{-10}$	8×10^{-12}	14
Λ^0	1115.683(6)	$\Xi^{\circ}\pi^{-}$, $n\pi^{0}$	$2.631(20) \times 10^{-10}$	2.5×10^{-12}	70
Λ^+_{-}	2286.46(14)	r	$200(6) \times 10^{-15}$	3×10^{-9}	2.6×10^{-2}
Λ_{h}^{0}	5620.2(1.6)		$1.383(-48,49) \times 10^{-12}$	5×10^{-10}	7.4×10^{-2}

Thanks to Peter Mao!