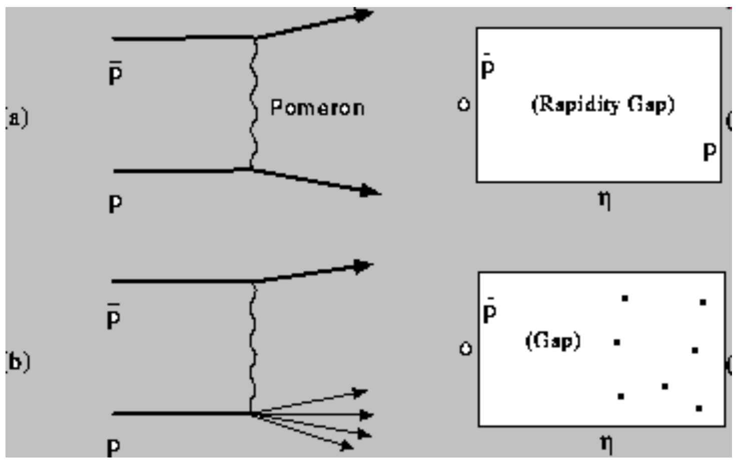
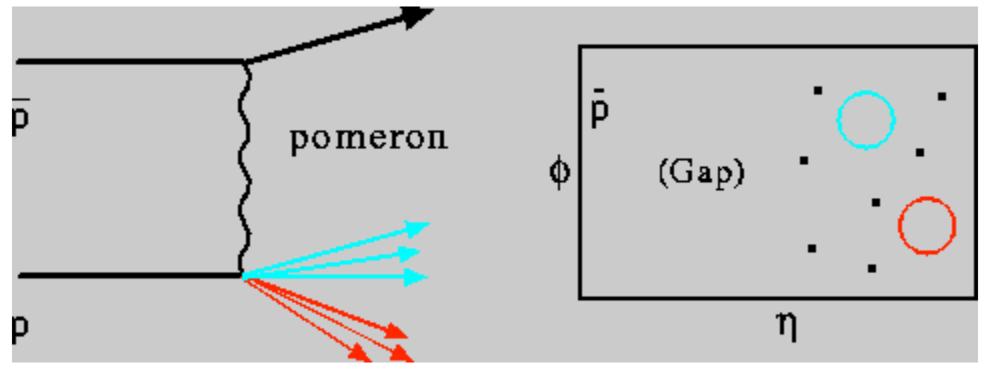
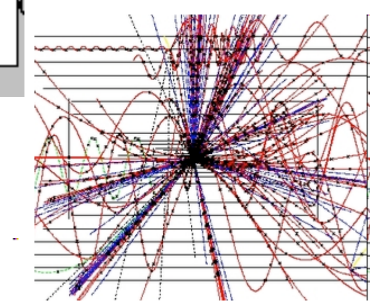
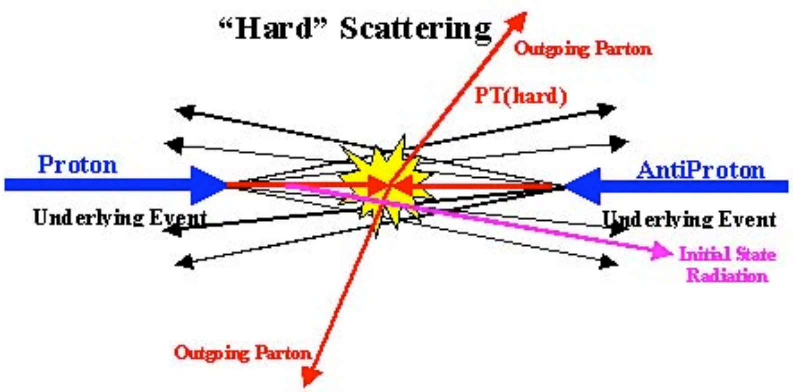
The total cross-section

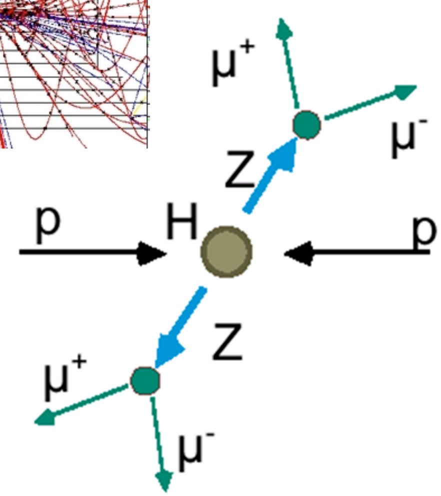
- $\sigma_{tot} = \sigma_{el} + \sigma_{diff} + \sigma_{jets} + \sigma_{EW} + \sigma_{bsm} + \ldots$

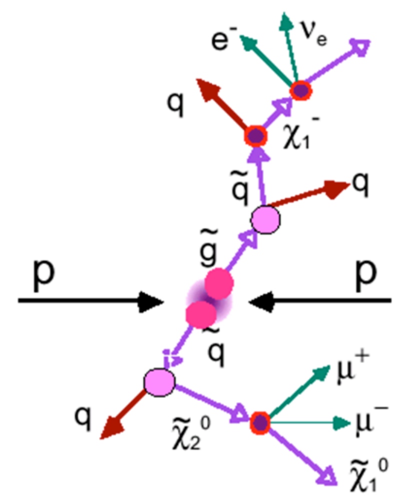












Monte Carlo simulations

- 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: $gg \to tt$

-------- 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 Tried	Selected	Accepted	sigma +- delta (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

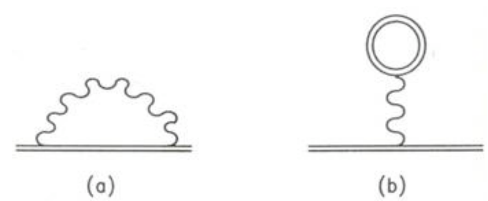
pythia example main11/out11 (Top:all; Ecm_{min} >40, pt_{min} > 20)

$\sigma = 5\times10^{-12}$ 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

What is mass?

- Newtonian inertial mass
- Newtonian gravitational mass, Equivalence principle
  $F = m_{inertial}\ a = G\ m_{grav}\ m_{source} / r^2$
- 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: $(m+i\Gamma/2)$ as dispersive/absorptive wave
  $\psi \sim \exp((imc^2-\Gamma/2)t\ /hbar)$
- QFT: mass as propagating self-energy:
  term in the Lagrangian, $L \sim m\ \psi\psi$



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

Particle decay lengths

	m (MeV)	tau (s)	Width (MeV)	<l> (m)	<l> (cm)	force	where decay
c	3.00E+08	m/s					
p	10000	MeV					
hbar	6.58E-22	MeV-s					
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"
pi	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
K	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

$\Gamma = hbar/\tau$ $\quad\quad$ $\langle l \rangle = \gamma\beta c\tau = (p/m)c\tau$

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] @ p = 10GeV
n	939.56536(8)	$pe\bar{\nu}_e$	885.7(8)	7.4×10^{-25}	3×10^{14}
μ^-	105.658367(4)	$e\nu_e\nu_\mu$	$2.197019(21)\times10^{-6}$	3×10^{-16}	6×10^6
π^-	139.57018(35)	$\mu\bar{\nu}_\mu$	$2.6033(5)\times10^{-8}$	2.5×10^{-14}	5.6×10^4
π^0	134.9766(6)	2γ	$8.4(6)\times10^{-17}$	8×10^{-6}	2×10^{-4}
ρ	775.5(3)	$\pi\pi$	4.4×10^{-24}	149	2×10^{-12}
K^-	493.677(16)	$\mu\bar{\nu}_\mu$ $\pi^-\pi^0$	$1.2380(21)\times10^{-8}$	5×10^{-14}	7×10^3
K_S	497.614(24)	$2\pi^0$ $\pi^+\pi^-$	$0.8953(5)\times10^{-10}$	7×10^{-12}	54
K_L	497.614(24)	$\pi^\pm e^\mp \nu_e$ $\pi^\pm \mu^\mp \nu_{mu}$ $3\pi^0$ $\pi^+\pi^-\pi^0$	$5.116(20)\times10^{-8}$	1.3×10^{-14}	3×10^4
τ^-	1776.84(17)	$e\bar{\nu}_e\nu_\tau$ $\mu\bar{\nu}_\mu\nu_\tau$	$290.6(1.0)\times10^{-15}$	2×10^{-9}	5×10^{-2}
D^+	1869.62(20)	$\bar{K}^0 ... + K^0 ...$	$1040(7)\times10^{-15}$	6×10^{-10}	0.17
D^{*+}	2010.27(17)	$D^0\pi^+$ $D^+\pi^0$	$\approx 7 \times 10^{-21}$	0.096(22)	10^{-9}
B^0	5279.53(33)	$K^\pm ...$	$1.530(9)\times10^{-12}$	4×10^{-10}	8.7×10^{-2}
t	$171.2(2.1)\times10^3$	bW^+	2×10^{-23}	30	4×10^{-14}
J/ψ	3096.916(11)	$[\gamma] \to$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^- $\Xi^0\pi^-$	$0.821(11)\times10^{-10}$	8×10^{-12}	14
Λ^0	1115.683(6)	$p\pi^-, n\pi^0$	$2.631(20)\times10^{-10}$	2.5×10^{-12}	70
Λ_c^+	2286.46(14)		$200(6)\times10^{-15}$	3×10^{-9}	2.6×10^{-2}
Λ_b^0	5620.2(1.6)		$1.383(-48,49)\times10^{-12}$	5×10^{-10}	7.4×10^{-2}

Thanks to Peter Mao!