Physics at the LHC

- high energy interactions
- luminosity, cross sections, event rates
- accelerators and colliders
- detectors
- the total cross-section
- high-pt events
- Monte Carlo simulations

High energy interactions

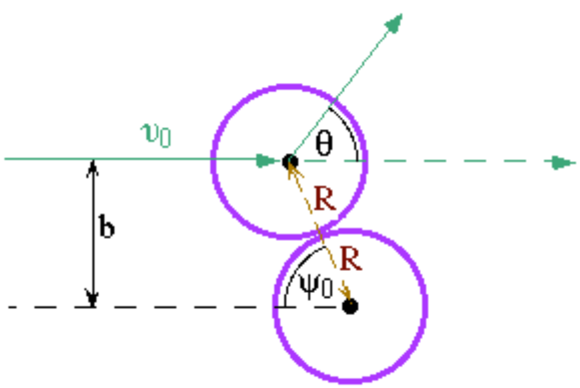
- High energy particle interactions occur naturally in many environments:
  - HE cosmic rays striking atoms in the atmosphere
  - Plasma in center of the sun
  - Energetic astrophysical systems like supernovas, rapidly spinning neutron stars, accretion around black holes
  - The hot plasma of the early universe
  - Nuclear reactors, plasma reactors (ok, not natural)
- Experiments with accelerators can measure interaction rates in a controlled environment, to study individual collisions one at a time with specified energy/momentum distribution of initial state particles (beam/target)
- Colliding beams produce large COM energies, with the COM at rest in the laboratory, surrounded by particle detectors.
- Reaction rates (cross-sections) measured as a function of E_{CM} can then be applied to natural systems of interest to work out the consequences (eg, energy production in the sun; evolution of matter, energy, space and time in the early universe; etc)

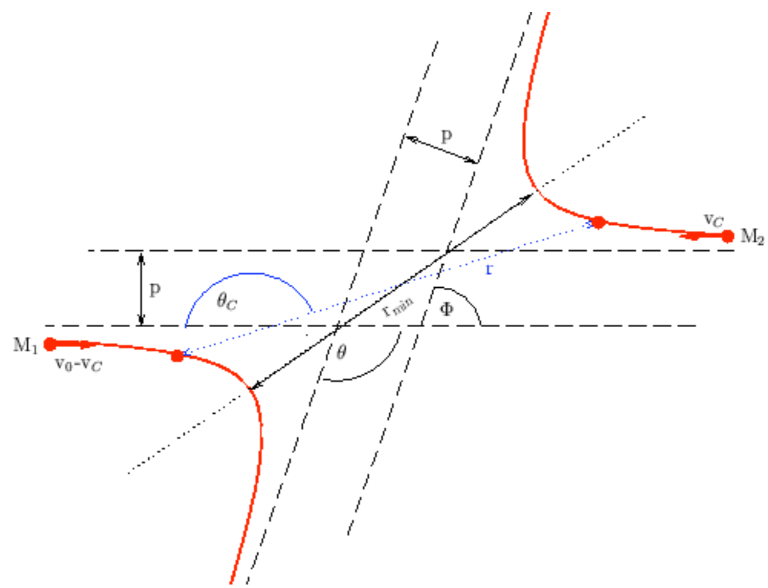
Reaction rates

- When particles interact (via collisions), one particle sees the other in "cross-section".
- Fixed target: beam particle incident on a block of matter of density ρ, atomic number A, and thickness t sees N_A ρt/A atoms (or nucleii) per unit area, (N_A = Avogadro's number, 6.02×10^{23} nucleons/gm)
- If each atom (or nucleus) has a cross-section of σ, the probability of hitting one is (N_A ρt/A) σ.
- If there is a flux of J beam particles per second, the collision rate will be $dN/dt = (JN_A\ \rho t/A)\ \sigma$
- The left hand side is measured in an experiment. The terms in the parenthesis on the right hand side (the *luminosity*) are under the experimenter's control.
- We can measure the atomic (or nuclear) cross-section σ, and compare it with microscopic theory (quantum physics of the atom or nucleus).
- At low momenta, the beam particle has a long quantum wavelength (λ~h/p) and "sees" the whole atom, *coherently*. At higher momenta (> 1 keV), the beam can "resolve" the nucleus; and at still higher momenta (> 1 GeV) the individual nucleons; higher (> 10 GeV), the quarks in the nucleons.

Scattering cross-section

- The scattering cross-section of a billiard ball of radius r is the geometric "black disk": $\sigma = \pi(2r)^2$, independent of energy.
- Ideal billiard balls scatter "*elastically*", losing no energy, so the only difference between the input asymptotic state and the output asypt. state is the scattering angle: $\sigma(\theta) \equiv d\sigma/d\theta$



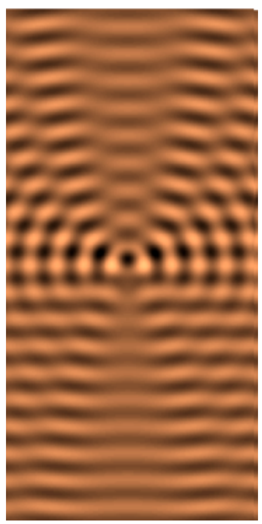


quantum scattering

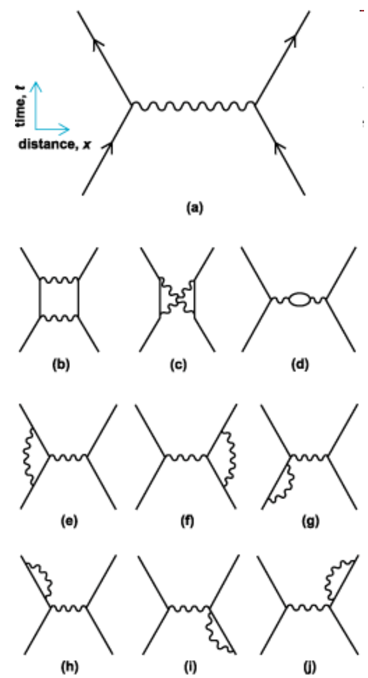
- In quantum mechanics, we calculate wave scattering; the Feynman diagram is a cartoon showing the momentum states of the outgoing quantum plane waves

wave (and quantum) scattering

incoming plane wave ψ_I



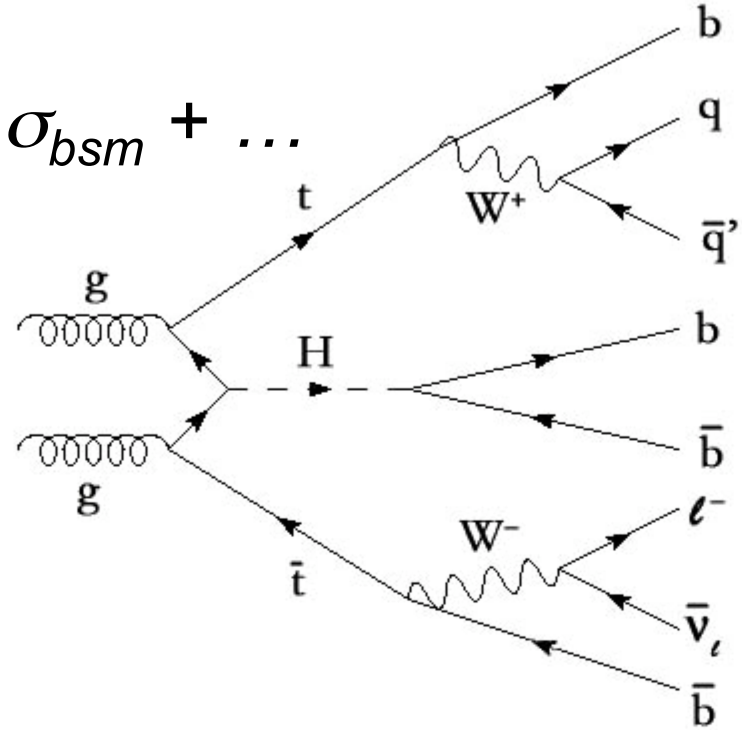
stationary state: $\psi_I + \psi_f$



same thing in Feynman diagrams, with quantum corrections

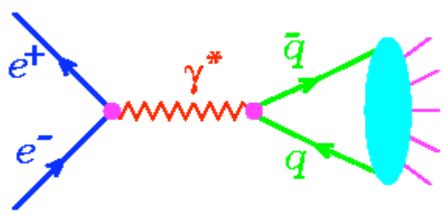
inelastic collisions

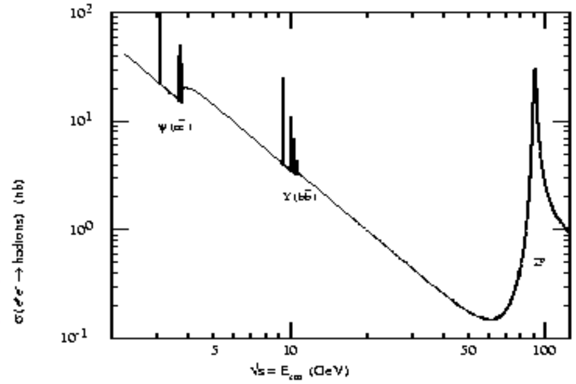
- In general, cross-sections depend on E_{cms} : $\sigma = \sigma(E_{cms})$
- At higher energies, collisions are inelastic; final state contains different particles than the initial state; and/or energy is lost (to the environment; not relevant in collider experiments).
- The inelastic cross-section can be written as the sum of many parts with different final states; depends on key (invariant) properties of the final state:
- $\sigma_{tot} = \sigma_{el} + \sigma_{diff} + \sigma_{jets} + \sigma_{EW} + \sigma_{bsm} + \ldots$



$e^+e^- \to f\bar{f}$

- Pointlike fermionic cross sections in e^+e^- collisions:





- Well below the Z^0:

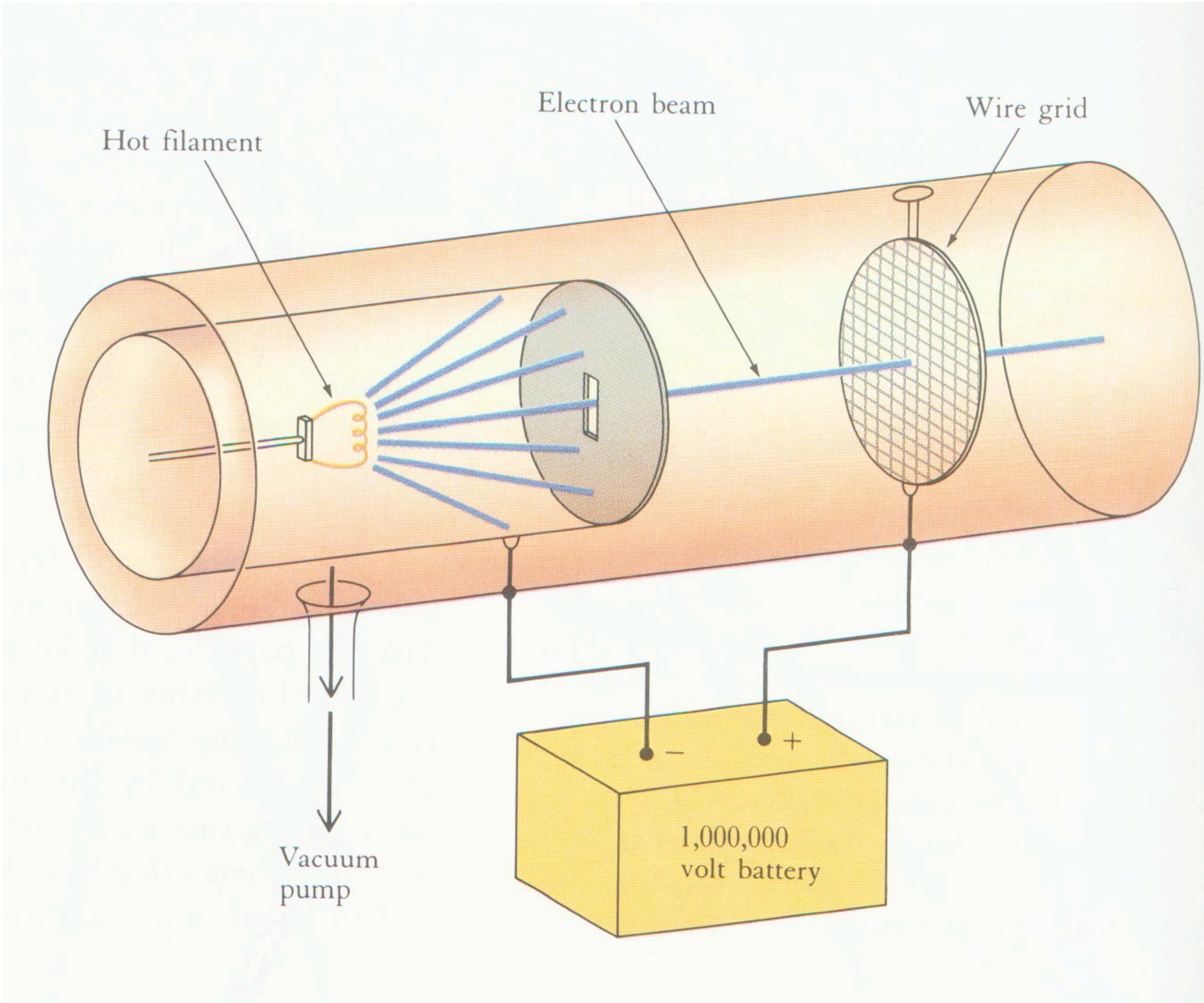
$$\sigma(e^+e^- \to f\bar{f}) = \frac{4\pi Q^2\alpha^2}{3s}\beta\left(3-\beta^2\right)$$

where $s \equiv E_{cm}^2$ and $\beta =$ velocity of final-state fermion

- analogous formulas near and at the peak of the Z^0
- Note quarkonia resonances at thresholds for $c\bar{c}$ and $b\bar{b}$.
- No such complexity for $\tau^+\tau^-$ production;
  cross section is well predicted in QED.
- B Factories operate at $E_{cm} = 10.58$ GeV, $b\bar{b}$ threshold

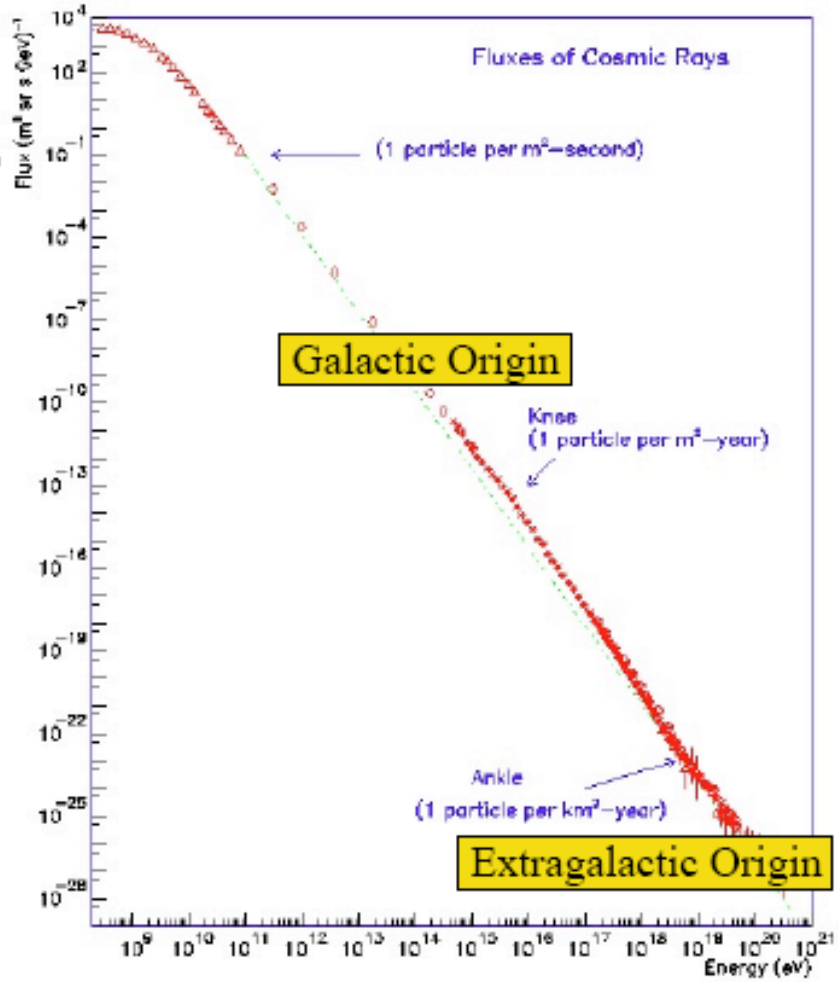
ee -> ff

Accelerators: operating principle



Cosmic Rays

- A cosmic ray "standard model:"
  - **Galactic Origin up to 10^{16} eV**
    Supernova Remnants,…
    indirect evidence (H.E.S.S.)
  - **Extragalactic origin above ~10^{18} eV**
    Active Galactic Nuclei, Gamma Ray Bursts, … -
    no evidence so far
- **W. Baade and F. Zwicky suggested in the 1930s that cosmic rays may have their origin in "stars which explode…"**

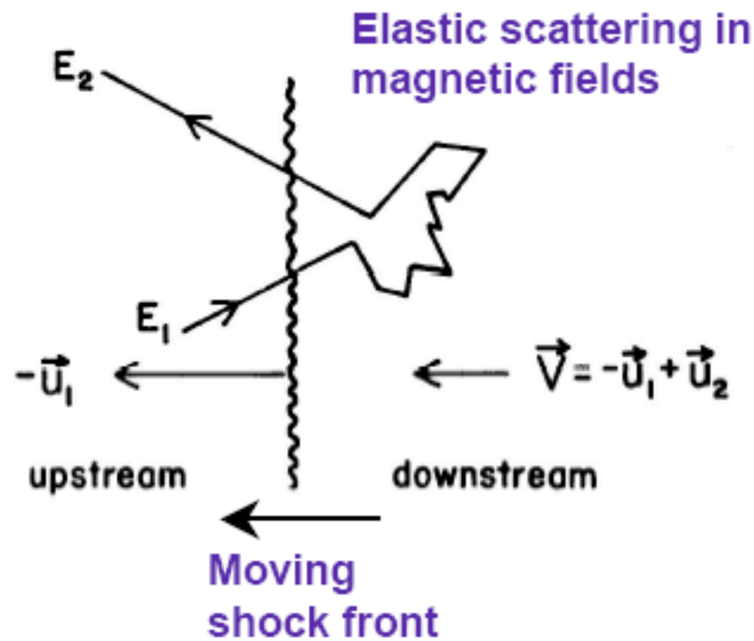


Cosmic Ray Flux vs. Energy (S. Swordy)

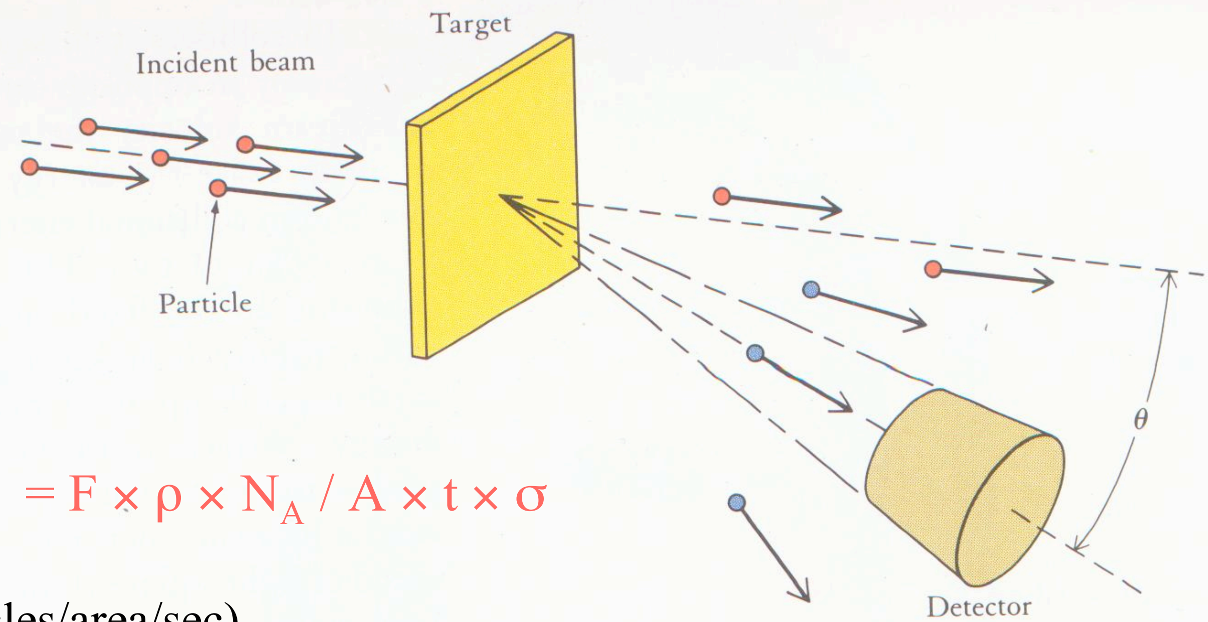
Acceleration Mechanism ?

- 1949 Enrico Fermi "On the Origin of Cosmic Radiation," Phys. Rev. 75 (1949) 1169

- In Fermi's cosmic ray "shock" accelerator, protons speed up by bouncing off moving magnetic clouds in space
- Tedious process - particles gain energy over many collisions
- Fermi acceleration "naturally" produces a power law



Fixed target scattering

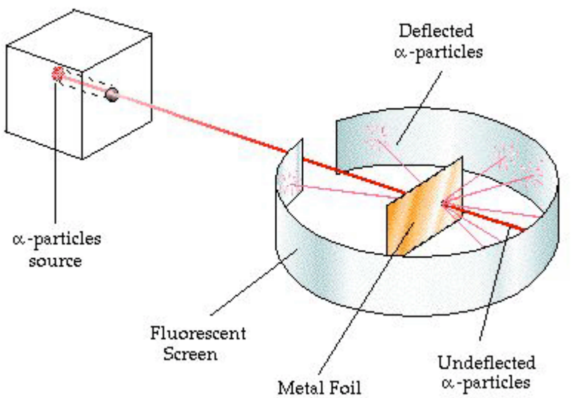


Event Rate $dN_{scatt} / dt = F \times \rho \times N_A / A \times t \times \sigma$

- F = Flux (beam particles/area/sec)
- ρ = Target density (kg/m^3)
- N_A = Avogadro's number = 6×10^{26} nucleons / kg
- A = Target atomic number (nucleons/nucleus)
- t = target thickness (m)
- σ = Beam/target (nucleus) cross-section

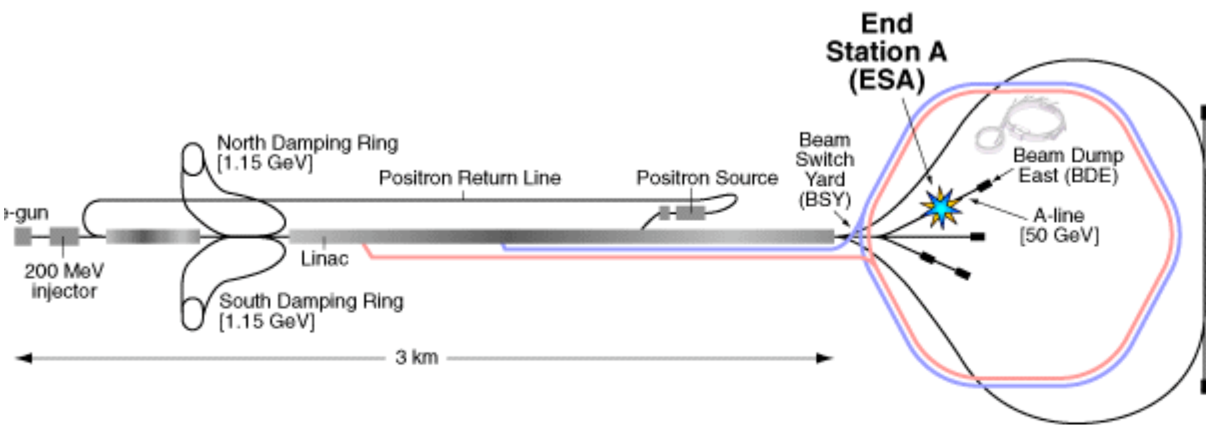
Measure "differential" cross-sections $d\sigma / d\Omega$

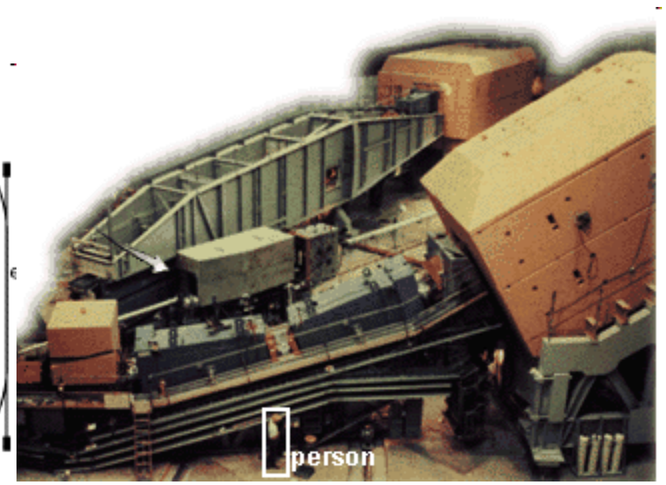
Fixed target experiments



The discovery of the nucleus
Rutherford scattering (tabletop)
(wiredchemist.com)

The discovery of partons (quarks) in the nucleus (SLAC)





Colliders

- To search for ever more massive particles, need energy in the center-of-mass to create them ($E = mc^2$)
- Fixed-target experiments "waste" a lot of energy in recoil of the system.
- To reach the highest energies, collide beams head-on; the center-of-mass is at rest in the lab, $E_{CM} = 2\ E_{beam}$ and all the beam energy is potentially available for producing massive particles.

- Event rate: $d\ N_{scat} / dt = L\ \sigma$
- Luminosity: $L = f\ N_+\ N_- / (4\ \pi\ \sigma_x\ \sigma_y)$

- Caution: don't confuse the sigmas; they're different!
- σ is the microscopic cross-section in units of area (1 barn = 1×10^{-24} cm^2)
- σ_x is the "mesoscopic" beam linear dimension (Gaussian sigma), of order 10^{-4} cm.

The Frontiers of Particle Physics

HIGH ENERGY: (LEP, LHC)

- jets, $W^{\pm}$, Z^0 production, top, Higgs/SSB
- new phenomena: SUSY, technicolor, WIMPS, 4th lepton/quark generation, leptoquarks, *etc.*

HIGH RATE: (CLEO, BaBar)

- precision measurements, rare decays, virtual heavy particles
- new phenomena: violation of conservation laws (lepton flavor, CP, *etc.*), subtle deviations from SM predictions

EXOTIC PHENOMENA: (MACRO, MINOS)

- monopoles, WIMPS, massive neutral particles, heavily or lightly ionizing particles, *etc.*, *etc.*
- new phenomena: neutrino oscillations!

Frontiers of particle physics

Luminosity, Rate, Factories

- Event rate $\dot{N} = \mathcal{L}\sigma$

$$e^+e^- \text{ collider:} \qquad \mathcal{L} = \frac{fN_+N_-}{4\pi\sigma_x\sigma_y}$$

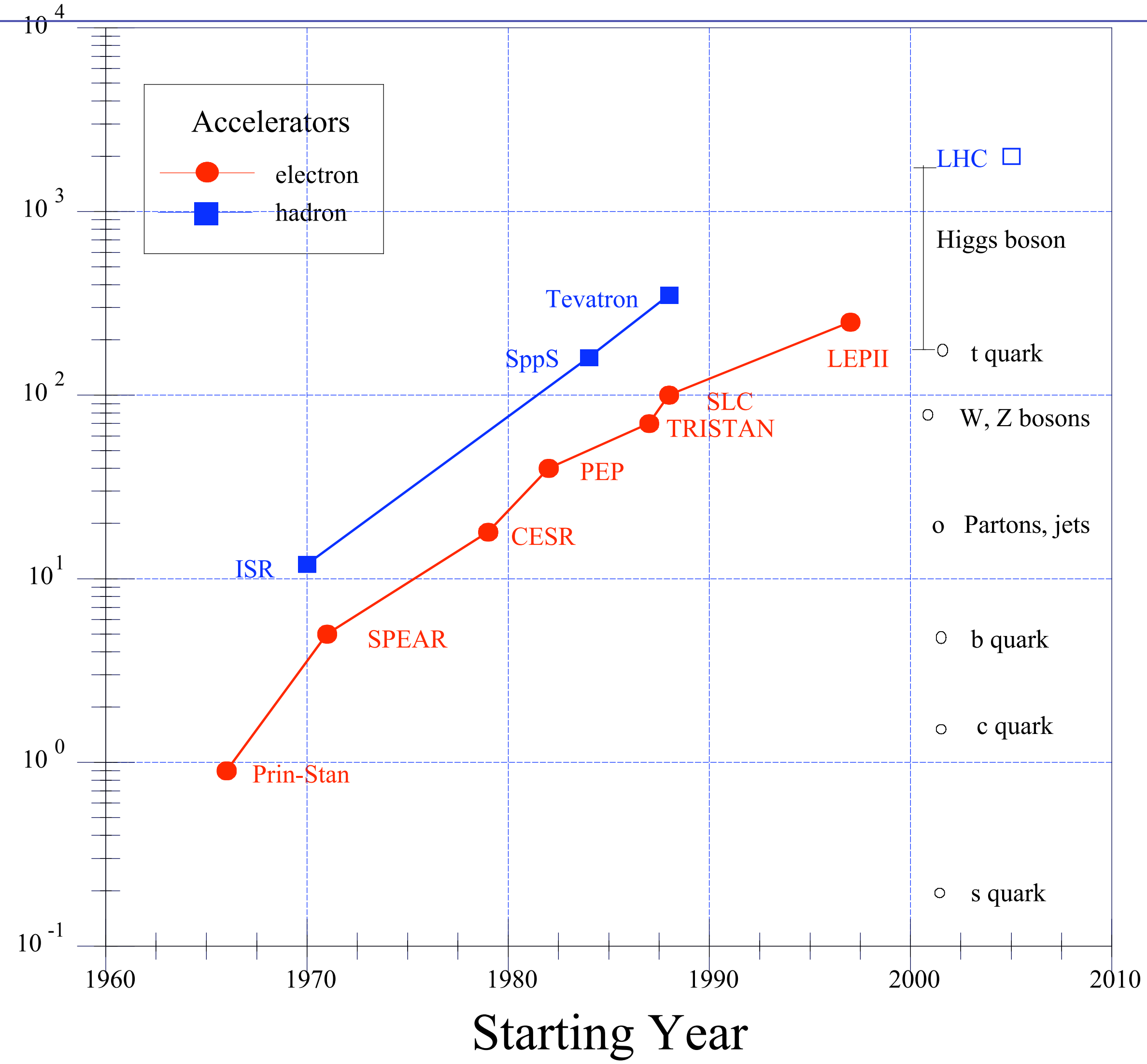
- Tune-shift limit: $\frac{N_\pm}{\sigma_x\sigma_y} < \frac{2\xi\gamma}{r_e\beta_v}$, and $\xi \lesssim 0.04$
- β_v is invariant measure of beam size; limited by size of detector, machine params
- When tune-shift limited:

$$\mathcal{L} = 2.17 \times 10^{34} \quad \frac{\xi N_b i_b E}{\beta_v} \quad \text{cm}^{-2}\text{s}^{-1}$$

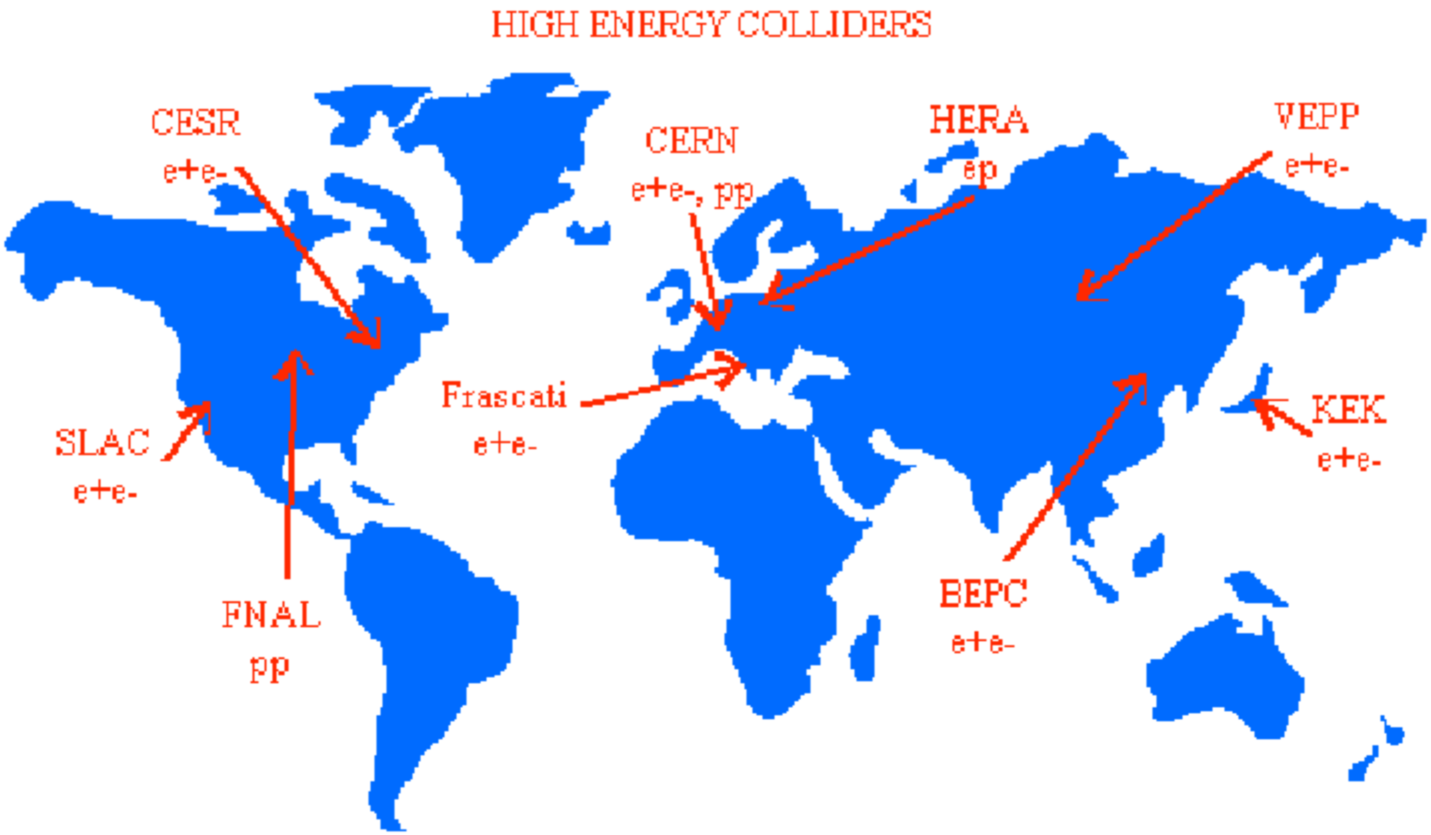
- Factory solution: instead of increasing N/bunch, increase number of bunches!

Luminosity, rate, factories

Accelerators and the energy frontier

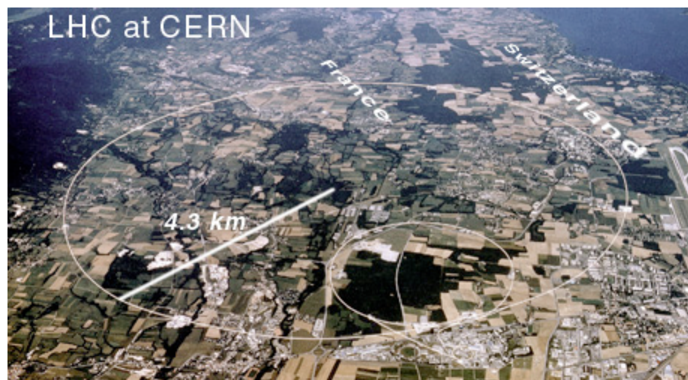


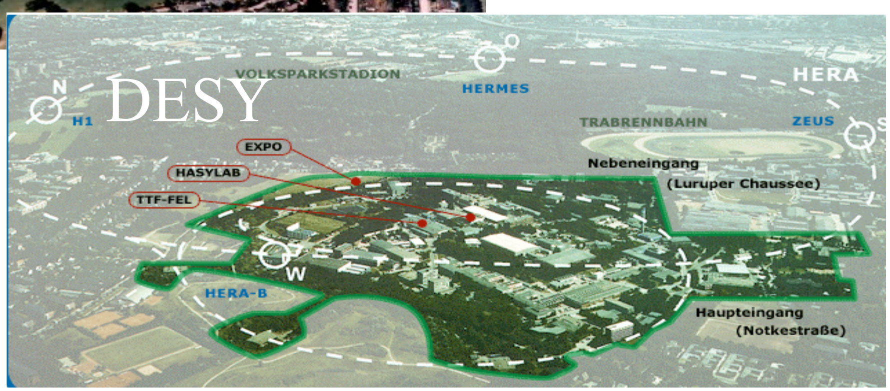
Colliders around the world

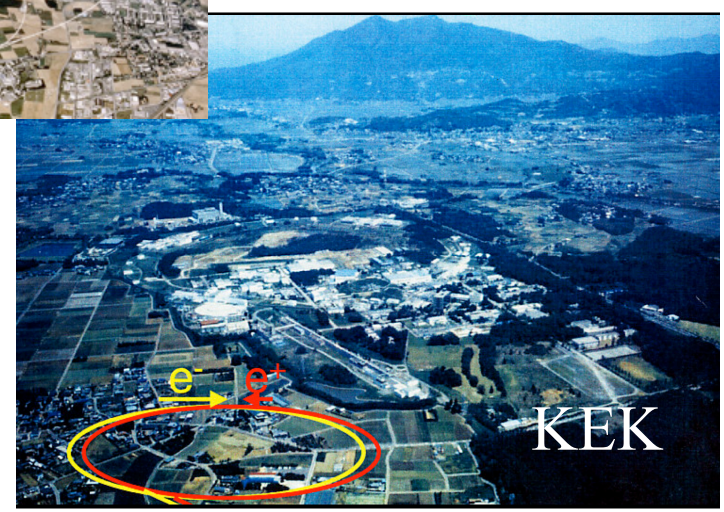


Accelerator labs around the world

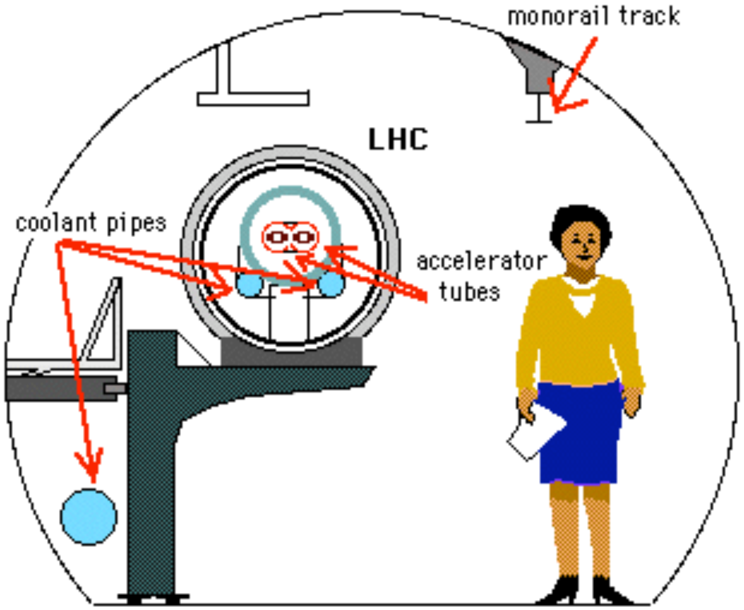
- CERN, Geneva, Switzerland (SPS, ν beams, LEP, LHC)
- Fermilab, Batavia, Illinois (Tevatron, ν beams, fixed target)
- SLAC (PEP, PEP-II, SLC)
- DESY, Hamburg, Germany (PETRA, HERA)
- KEK, Tsukuba, Japan (KEK-B, ν beams, fixed target)
- CESR/Cornell, BEPC/Beijing, DAΦNI/Frascati, VEPP (Novisibirsk), etc







LHC tunnel



Wednesday 10.09.08 theguardian

That Cern thing explained

1

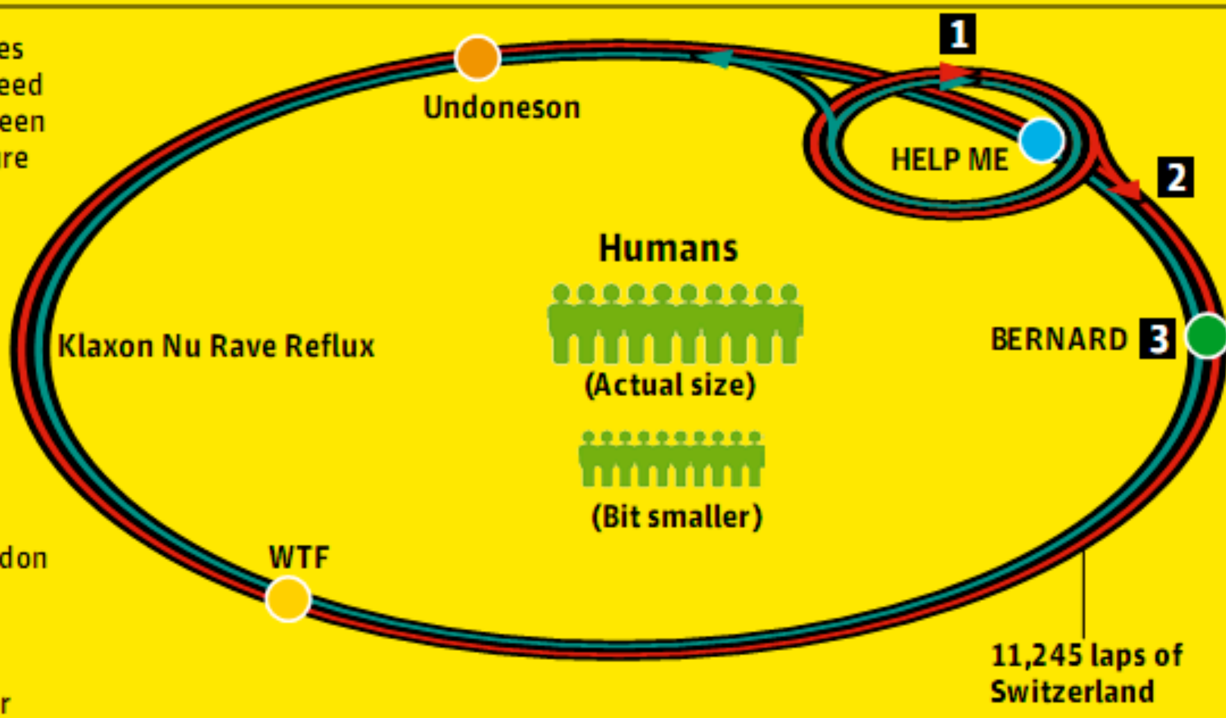
27km large haddock collider smashes barnacles together at **47** times the speed of matter, recreating conditions last seen shortly after Big Ben. Heat and pressure combine to create **Cod particle**, also known as Hog's bison. **Earth possibly engulfed by black hole**

[1] Astronomer Royal powers up the **compact muon solenoid**

[2] Hydrogen is injected into the main MPRSFPL, sending **rotator A** revolving around **rotator B** at up to a billion protons every second

[3] Time dilation unleashes forces millions of times as powerful as a London bus. Superstrong magnets assemble Irritating Jumbles of Initials (IJIs)

[4] Hadronic calorimeter tracker feeds Lembit Opik decay hole facilator



PDG section 26:

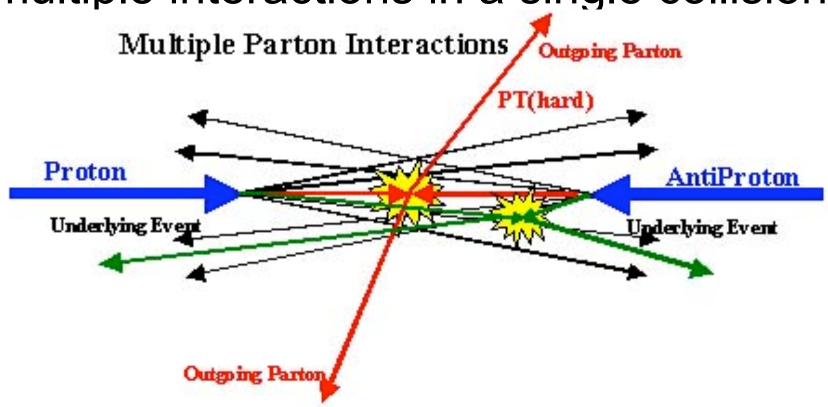
HIGH-ENERGY COLLIDER PARAMETERS: *ep*, $\bar{p}p$, *pp*, and Heavy Ion Colliders

Updated in early 2008 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). For existing (future) colliders the latest achieved (design) values are given. Quantities are, where appropriate, r.m.s.; H and V indicate horizontal and vertical directions; s.c. stands for superconducting; pk and ave denote peak and average values.

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)				LHC (CERN)	
Physics start date	1992	1987	2001	2000	2004	2002	2008	2009
Physics end date	2007	—	—				—	
Particles collided	ep	$p\bar{p}$	pp (pol.)	Au Au	Cu Cu	d Au	pp	Pb Pb
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.1 60% pol	0.1 TeV/n	0.1 TeV/n	0.1 TeV/n	7.0	2.76 TeV/n
Luminosity (10^{30} cm^{-2}s^{-1})	75	286	35 (pk) 20 (ave)	0.0030 (pk) 0.0012 (ave)	0.020 (pk) 0.0008 (ave)	0.23 (pk) 0.11 (ave)	1.0×10^4	1.0×10^{-3} $(5.4 \times 10^{-5})^\dagger$
Time between collisions (ns)	96	396	107	107	321	107	24.95	99.8 $(1347)^\dagger$
Full crossing angle (μ rad)	0	0	0				≈ 300	$\leq 100\ (0)^\dagger$
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.14	0.45	0.75	0.75	0.65	0.113	0.11
Bunch length (cm)	e: 0.83 p: 8.5	p: 50 $\bar{p}$: 45	100	30	30	25	7.55	7.94
Beam radius (10^{-6} m)	e: $280(H), 50(V)$ p: $265(H), 50(V)$	p: 28 $\bar{p}$: 16	165 (β^*=1 m)	145 (β^*=1m)	145 (β^*=0.9m)	155 (β^*=2m)	16.6	15.9 $(22.5)^\dagger$

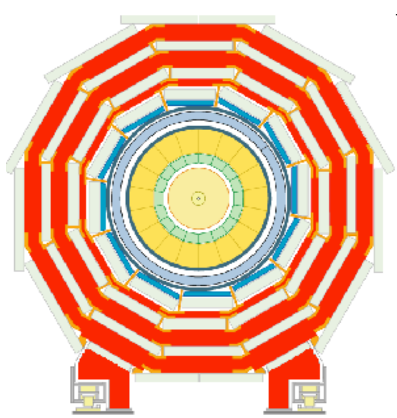
What is the interaction rate?

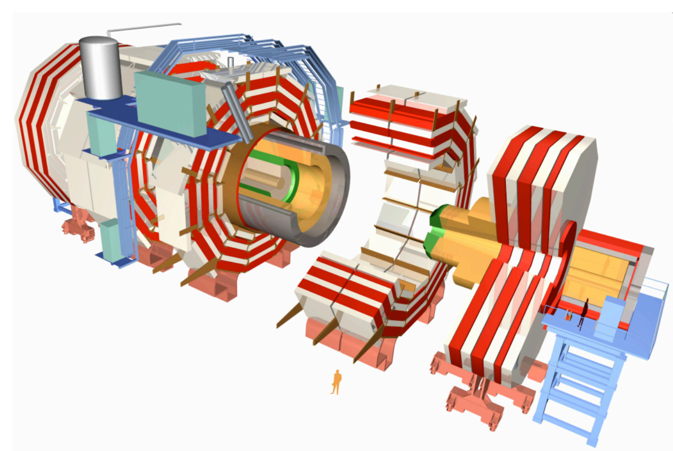
- At the LHC, there are 2808 bunches of 10^{11} protons, spaced ~7.5 m apart (and ~30 cm long) around the 17 km circumference
- They collide every 25 ns ($\Delta t = \Delta x/c$), that is, $f = 4 \times 10^7$ /s
- Design luminosity is $L = fN_1N_2 / (4\pi\sigma_x\sigma_y) \sim 1 \times 10^{34}$ /cm^2/s
- total pp cross-section is close to geometric black disk with r = 1 fm: $\sigma = \pi(2r_p)^2 \approx 0.1 \times 10^{-24}$ cm^2 = 0.1 barn = 100 mb
- Interaction rate is $dN/dt = L\,\sigma = 10^9$/s = 1/ns
- So there are on order of 25 interactions per collision!
- This is unique to the LHC; all previous colliders had << 1 interaction per beam collision
- Most interactions are "soft" (low-p_t), leaving little energy in the detector (elastic, diffractive)
- Hard (high-pt, interesting) interactions are rare in a single beam collision
- The detector must be capable of distinguishing different beam collisions (25 ns apart!), and multiple interactions in a single collision



Particle detectors

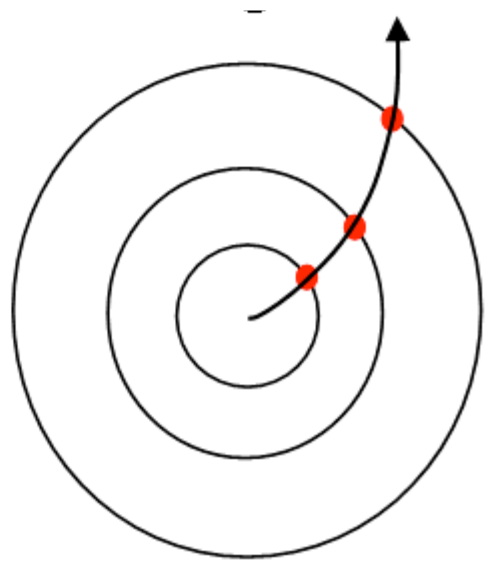
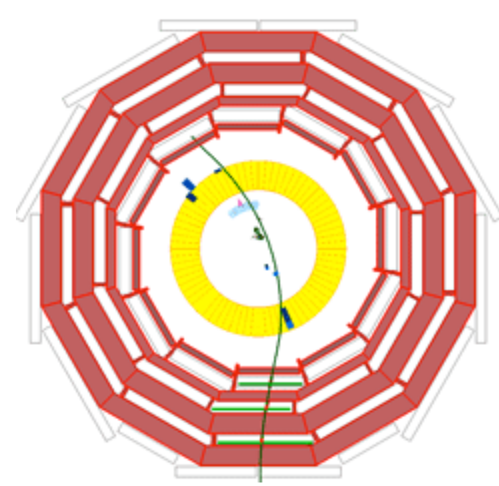
- Surround the collision with detector systems to catch and measure the properties of the final state particles
- Collider detectors must cover (almost) the full 4π solid angle, leaving smallest hole for the beampipe and cables
- and have many (sometimes 10^6 or more) individual elements (with associated readout electronics) capable of locating a particle in space, time, momentum, energy.
- Most built as concentric cylindrical layers (plus endcaps) to respond to different particles.





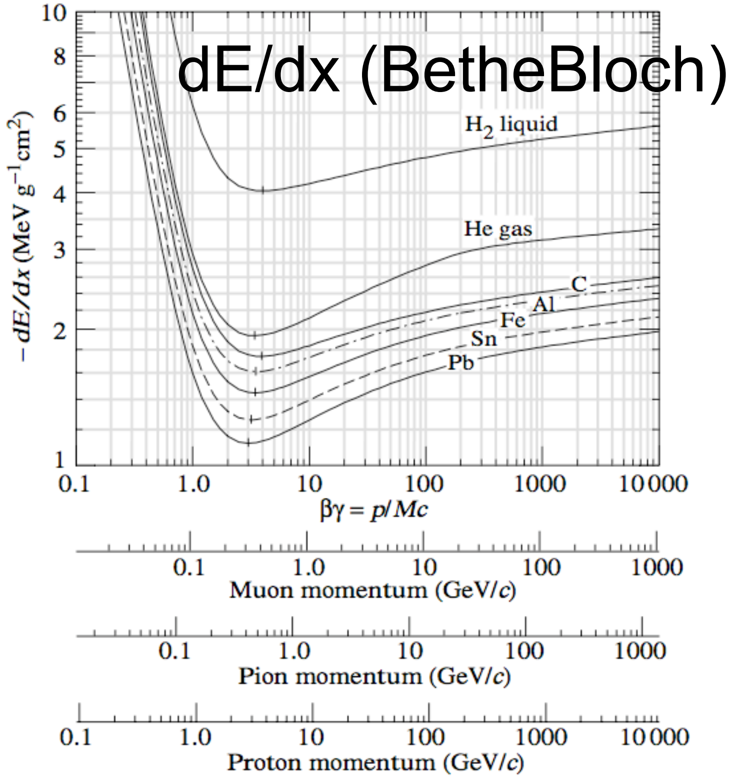
solenoidal trackers

- Most collider detectors are spectrometers that measure the momentum of charged particles moving in a central solenoidal magnet, with high B field (4 Tesla in CMS) along beam axis, to bend the paths of the particles in the plane perp. to beam axis (a helix in 3D).
- Lorentz magnetic force gives:
  $p_t = 0.3\ q\ B\ R_c$

Interactions of high energy particles with material (detectors)

- Particle decay ($\pi^0 \rightarrow \gamma\gamma$, $\mu \rightarrow e\nu\nu$, $\pi \rightarrow \mu\nu$, $K \rightarrow \pi\pi$ …)
  decay length $\langle L \rangle = \gamma\beta c\tau = (p/m)\, c\tau$
- High-p charged particles ($e^\pm$,$\mu^\pm$,$\pi^\pm$,$K^\pm$,$p^\pm$):
  ionization (dE/dx energy loss: Bethe-Bloch)
- Charged particles: Multiple scattering, range-out
- Light particles (γ, $e^\pm$): Bremsstrahlung, pair-production
  $\Rightarrow$ electromagnetic showers
- Fast charged particles ($e^\pm$,$\mu^\pm$,$\pi^\pm$,$K^\pm$,$p^\pm$, with $v > c/n$):
  Cerenkov radiation
- Hadronic particles ($\pi^\pm$,$K^\pm$,K^0_L, n^0, $p^\pm$):
  inelastic nuclear collisions $\Rightarrow$ hadronic showers



Multiple coulomb scattering

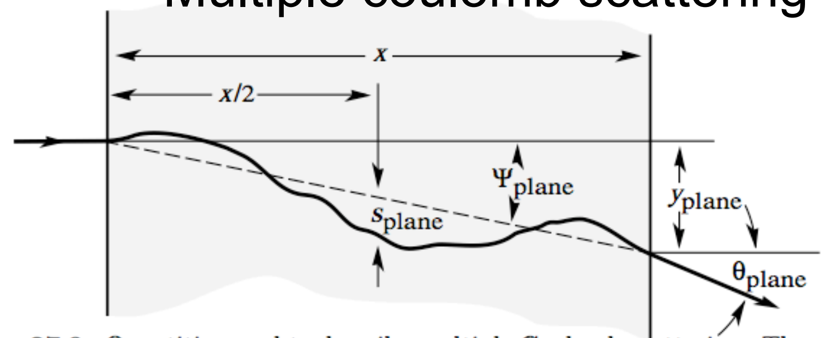
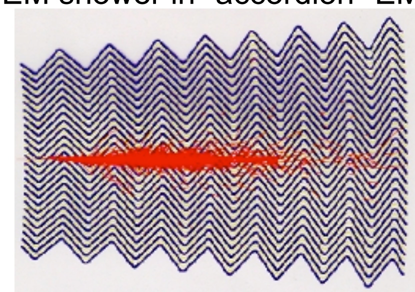
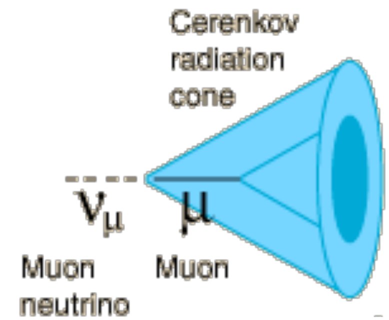
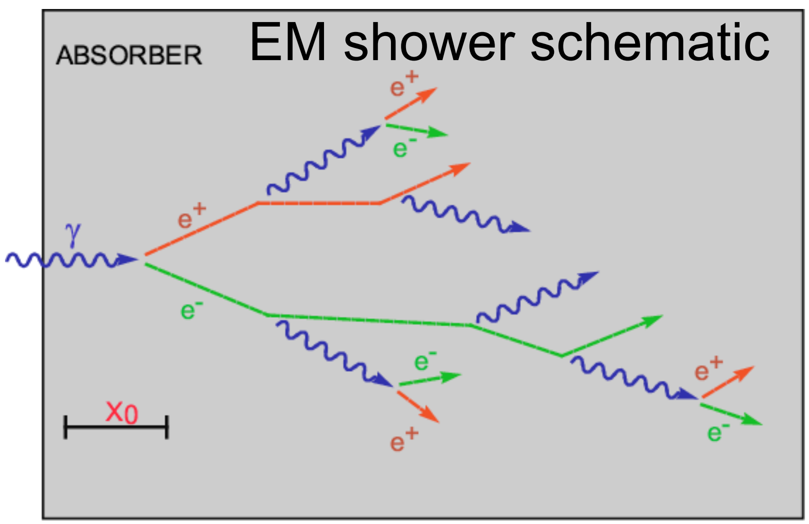


Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

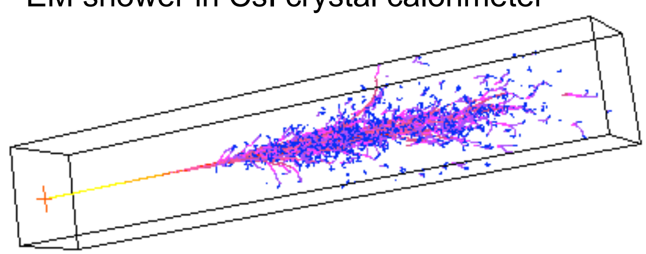
EM shower in "accordion" EM calorimeter



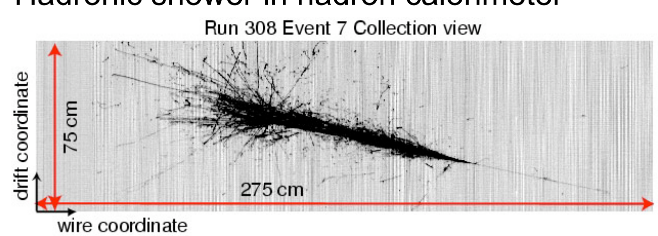




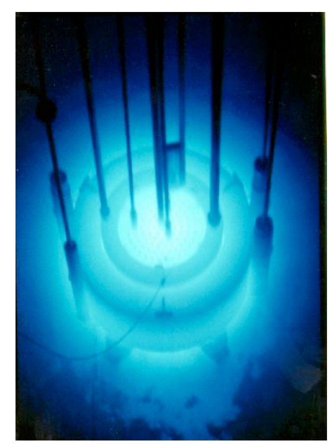
EM shower in CsI crystal calorimeter



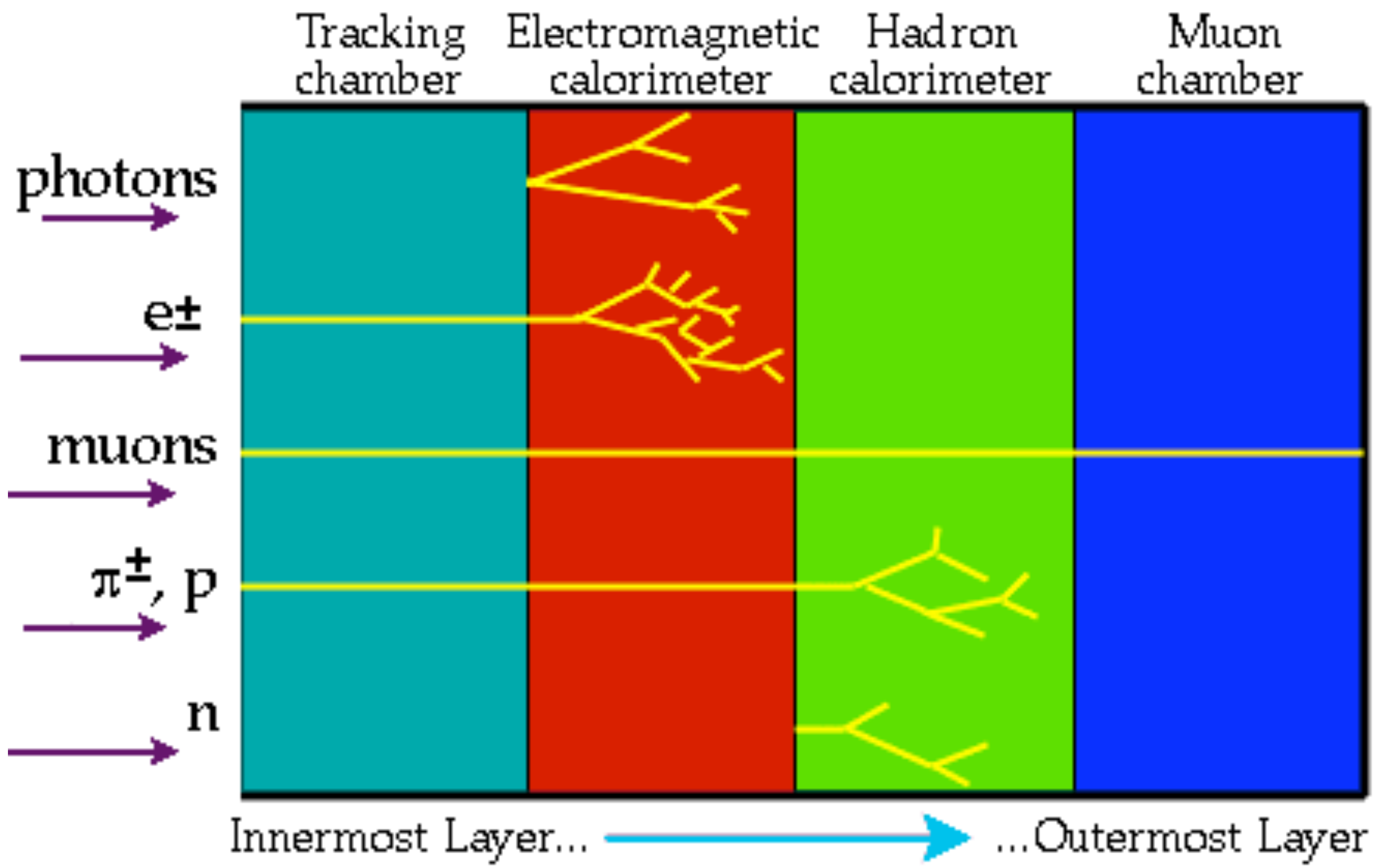
Hadronic shower in hadron calorimeter

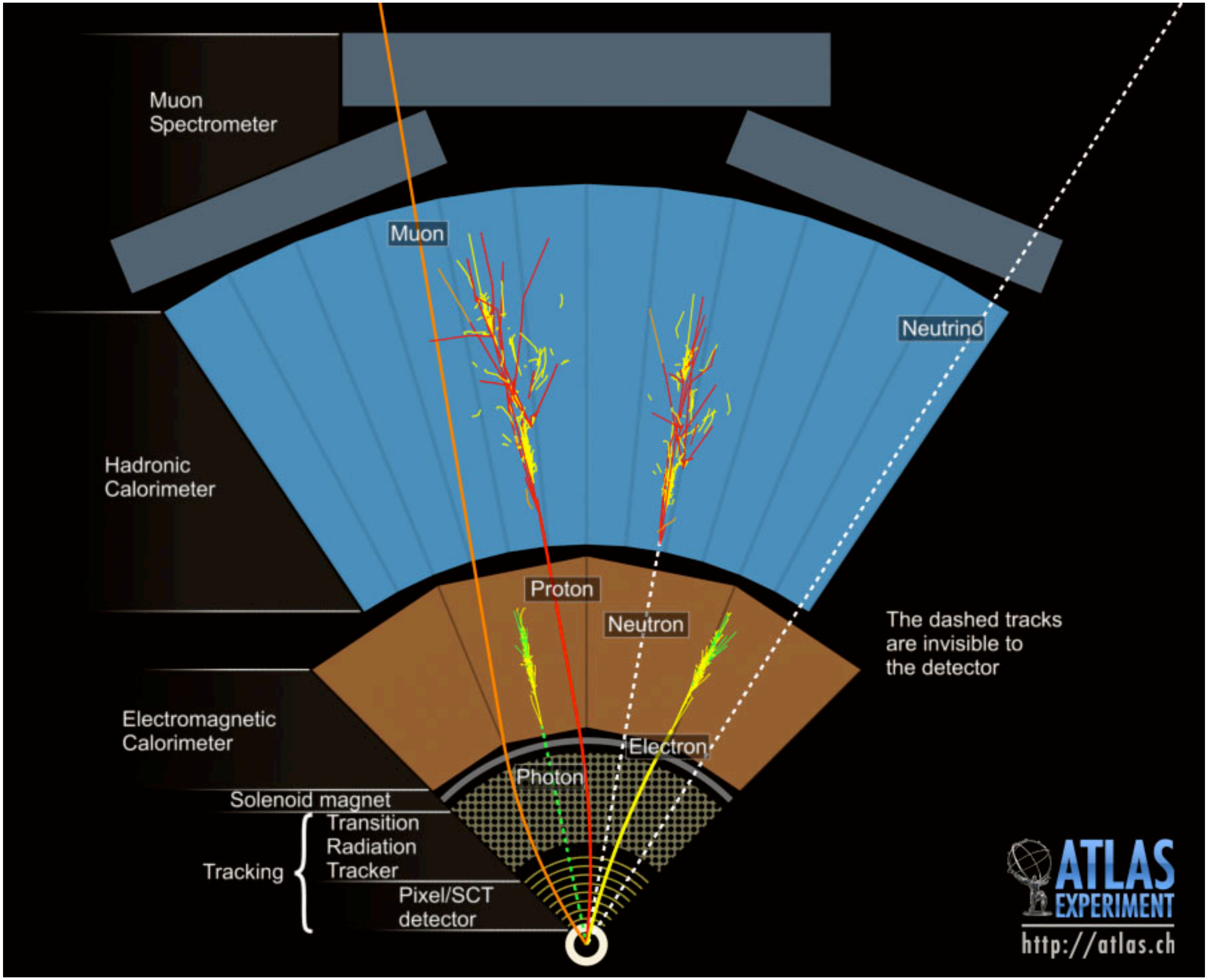


Č radiation
in nuclear reactor



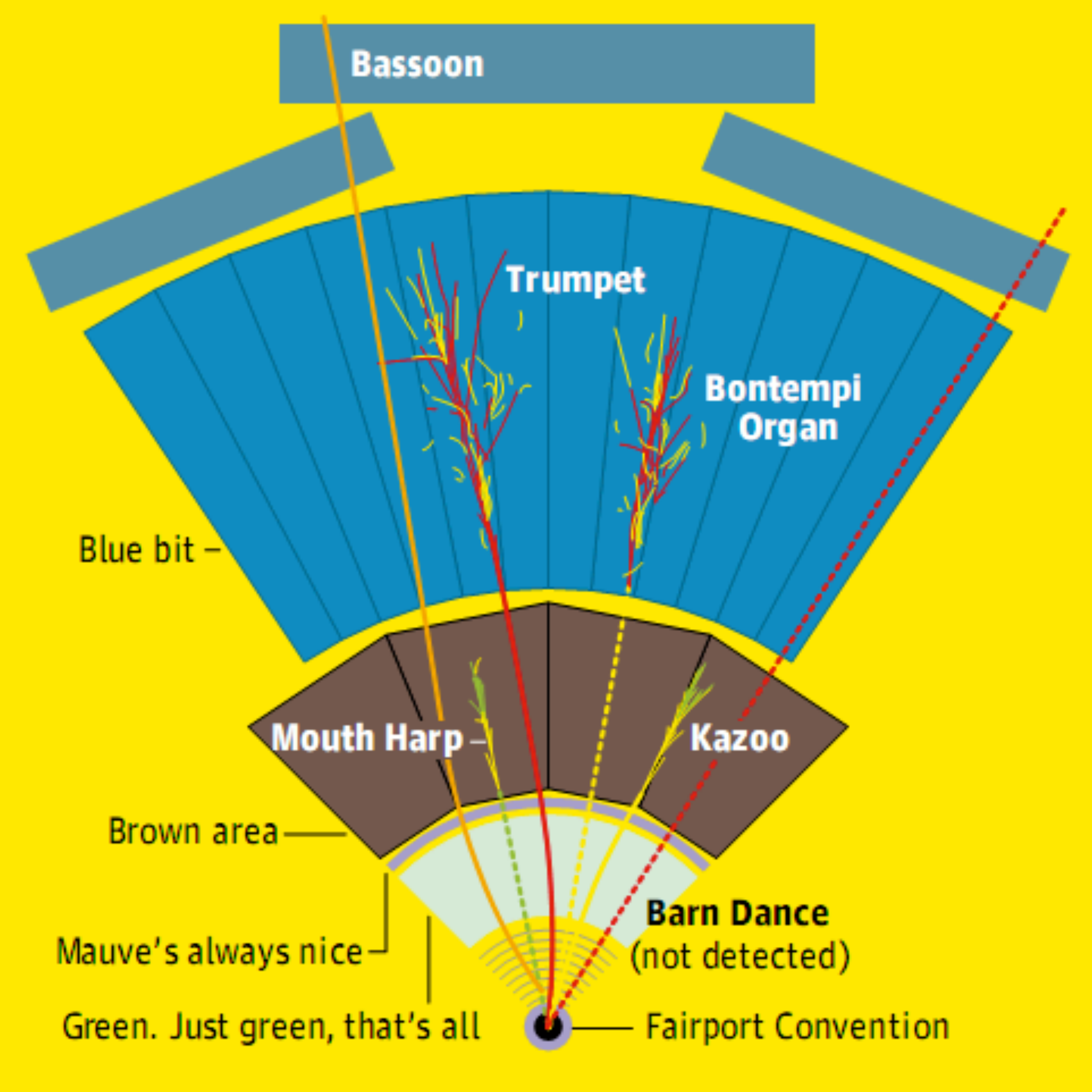
Particles in a detector





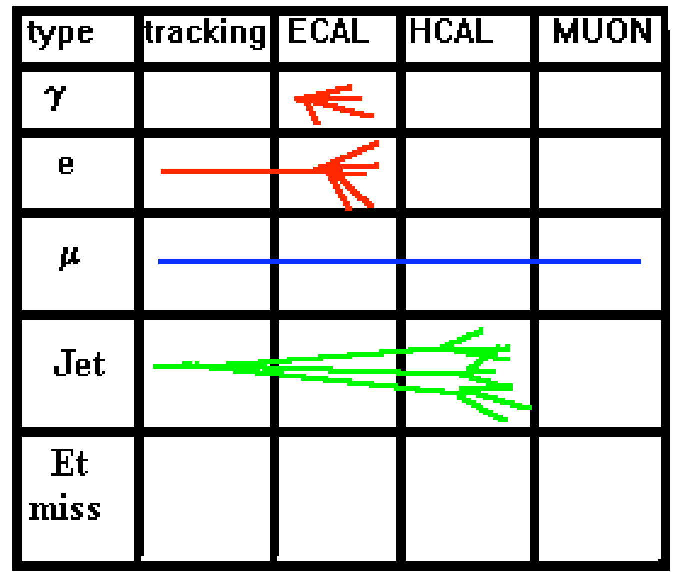
Muon Spectrometer
Muon
Hadronic Calorimeter
Neutrino
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

B Explainer: what figure 4 means

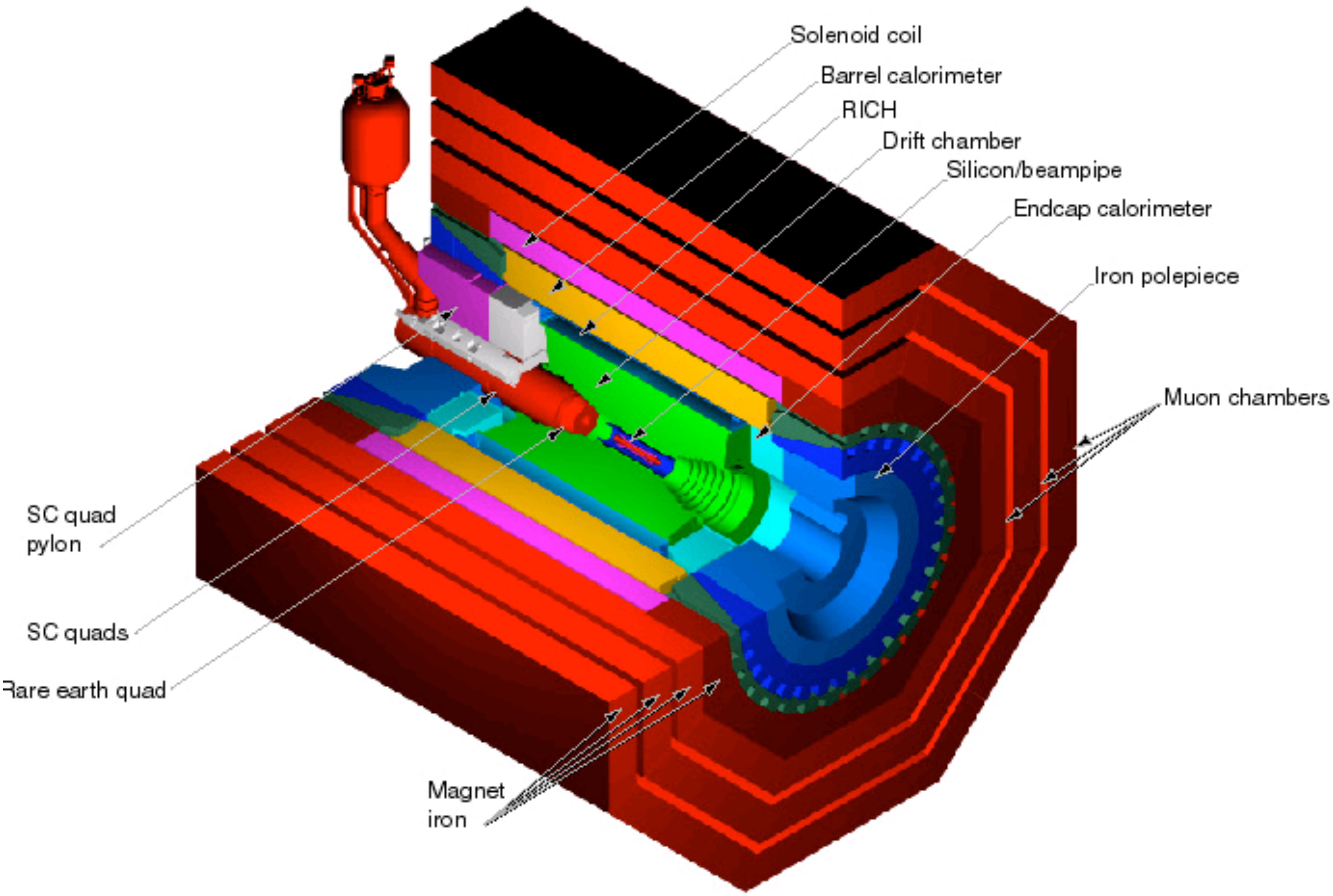


Particles in a detector

SM Fundamental Particle	Appears As
γ	γ (ECAL shower, no track)
e	e (ECAL shower, with track)
μ	μ (ionization only)
g	Jet in ECAL+ HCAL
q = u, d, s	Jet (narrow) in ECAL+HCAL
q = c, b	Jet (narrow) + Decay Vertex
t $\rightarrow$ W +b	W + b
$\nu_e \nu_\mu \nu_\tau$	E_t missing in ECAL+HCAL
$\tau \rightarrow l + \nu_\tau + \nu_l$	E_t missing + charged lepton
$W \rightarrow l + \nu_l$	E_t missing + charged lepton, E_t ~M/2
$Z \rightarrow l^+ + l^-$	charged lepton pair
$\rightarrow \nu_l + \nu_l$	E_t missing in ECAL+HCAL

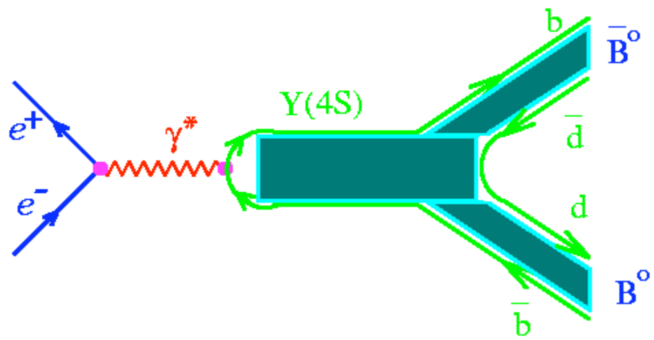


The CLEO III detector

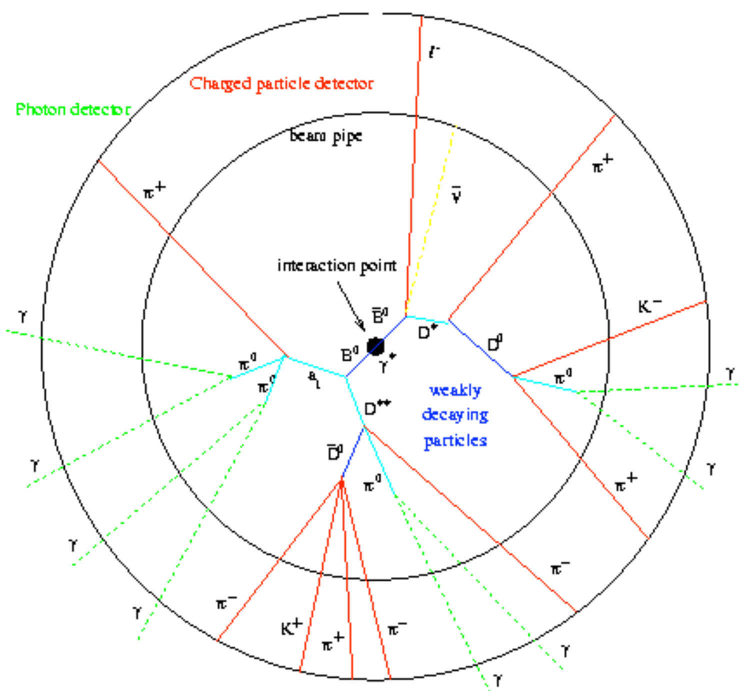


$e^+e^- \to B\bar{B}$ Production and decay

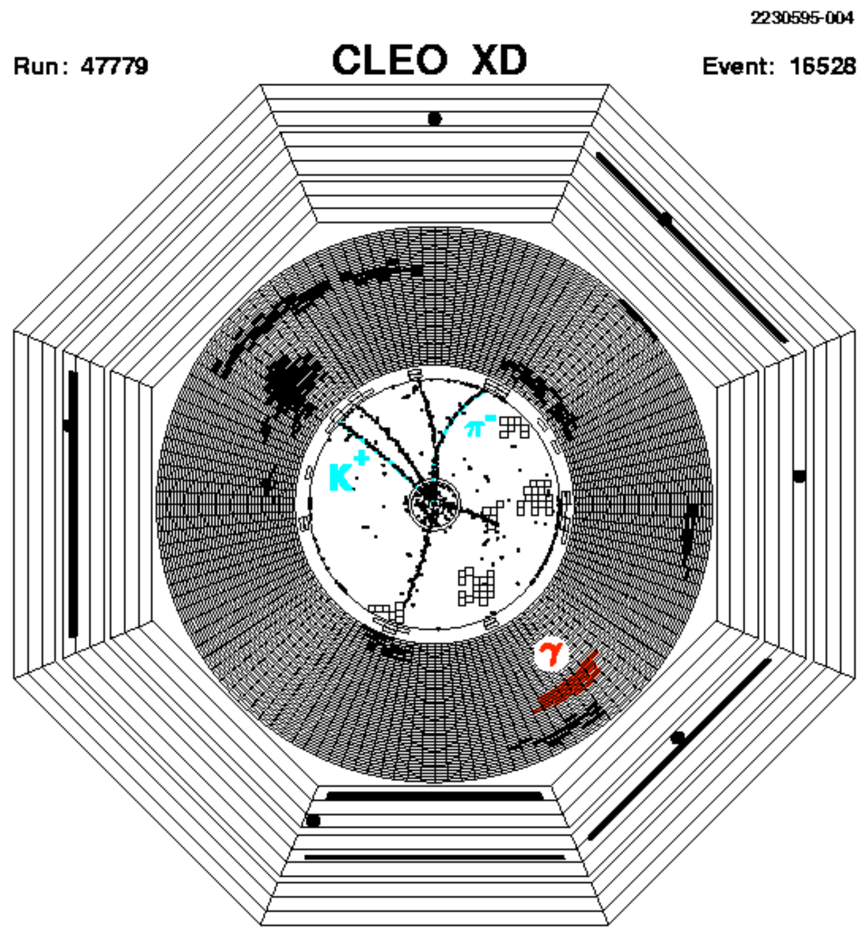
Production:



Decay:



What does an event in the detector look like?

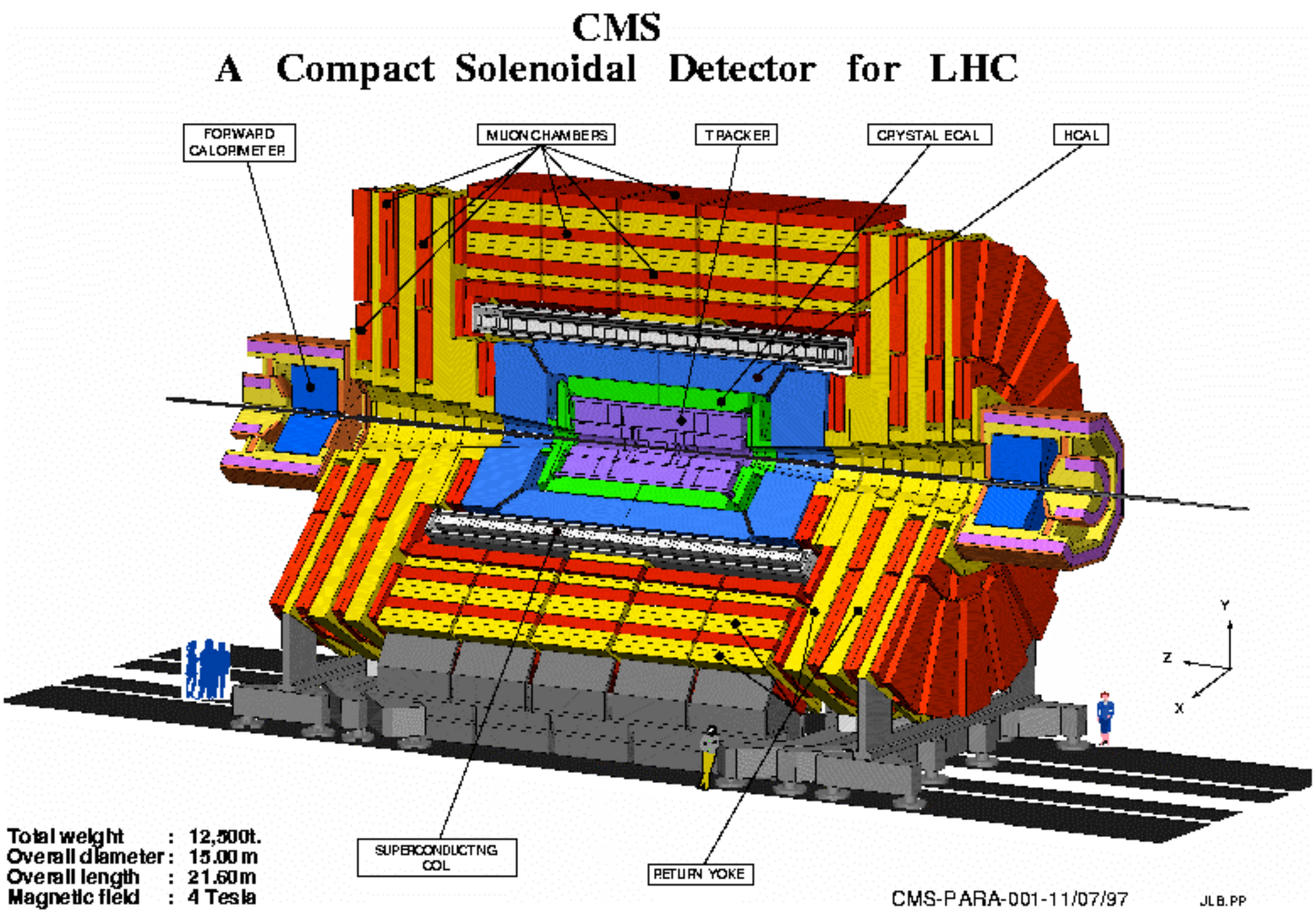


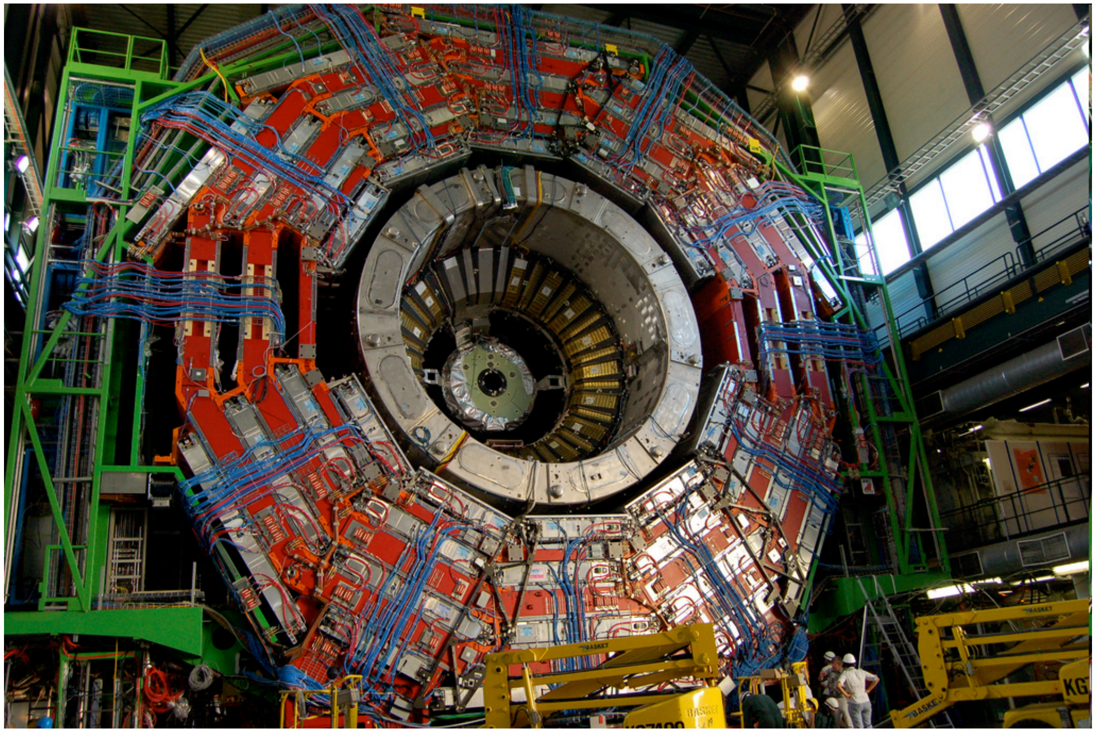
$B^0 \to K^{*0}\gamma$, $\quad K^{*0} \to K^+\pi^-$

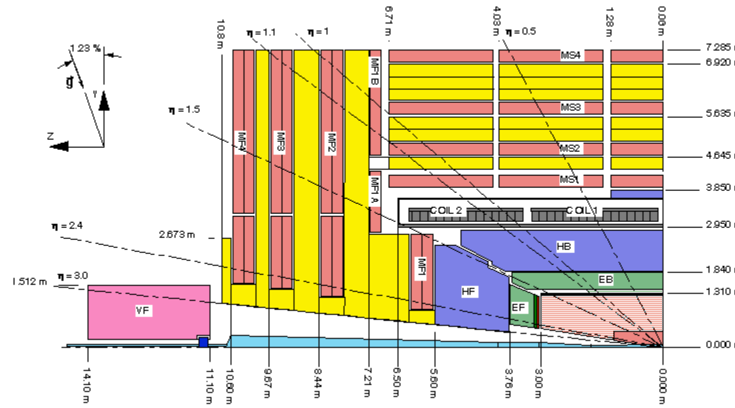
$\bar{B}^0 \to D^+\rho^-$, $\quad \rho^- \to \pi^-\pi^0$, $\quad D^+ \to K^-\pi^+\pi^+$

CLEO event

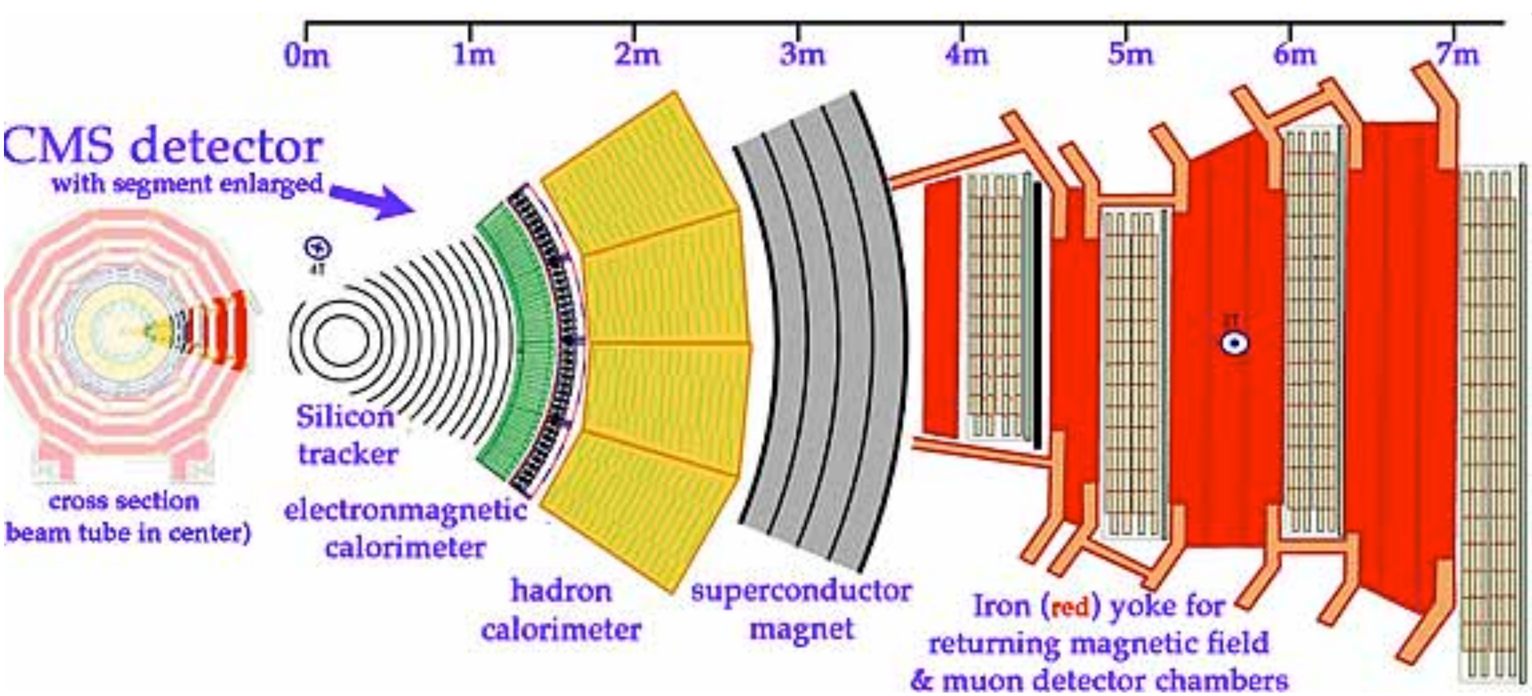
The CMS detector





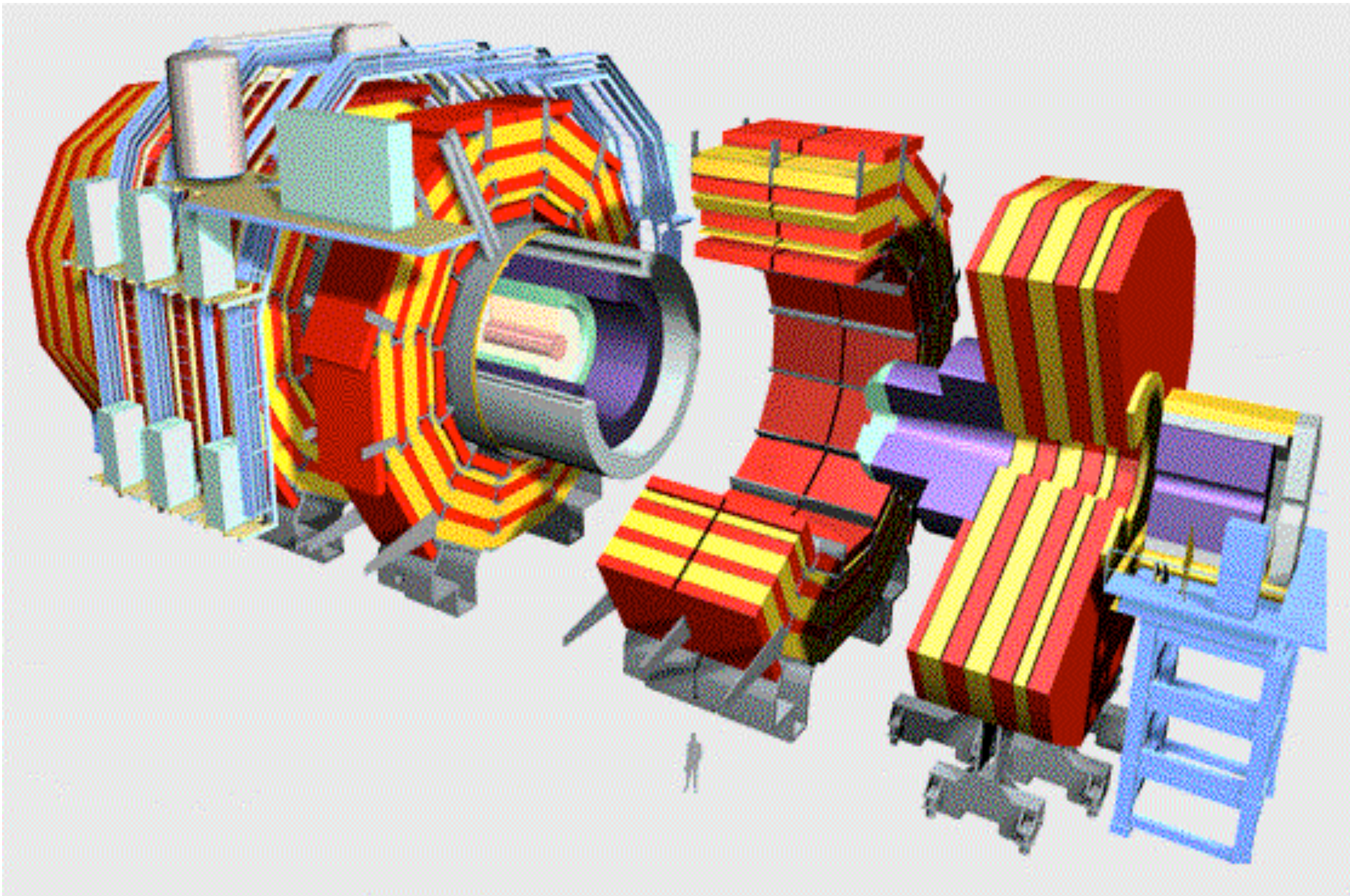


MS4
MS3
MS2
MS1
COIL 2
COIL 1
HB
EB
HF
EF
VF
7.285 m
6.920 m
5.635 m
4.645 m
3.850 m
2.950 m
1.840 m
1.310 m
0.000 m

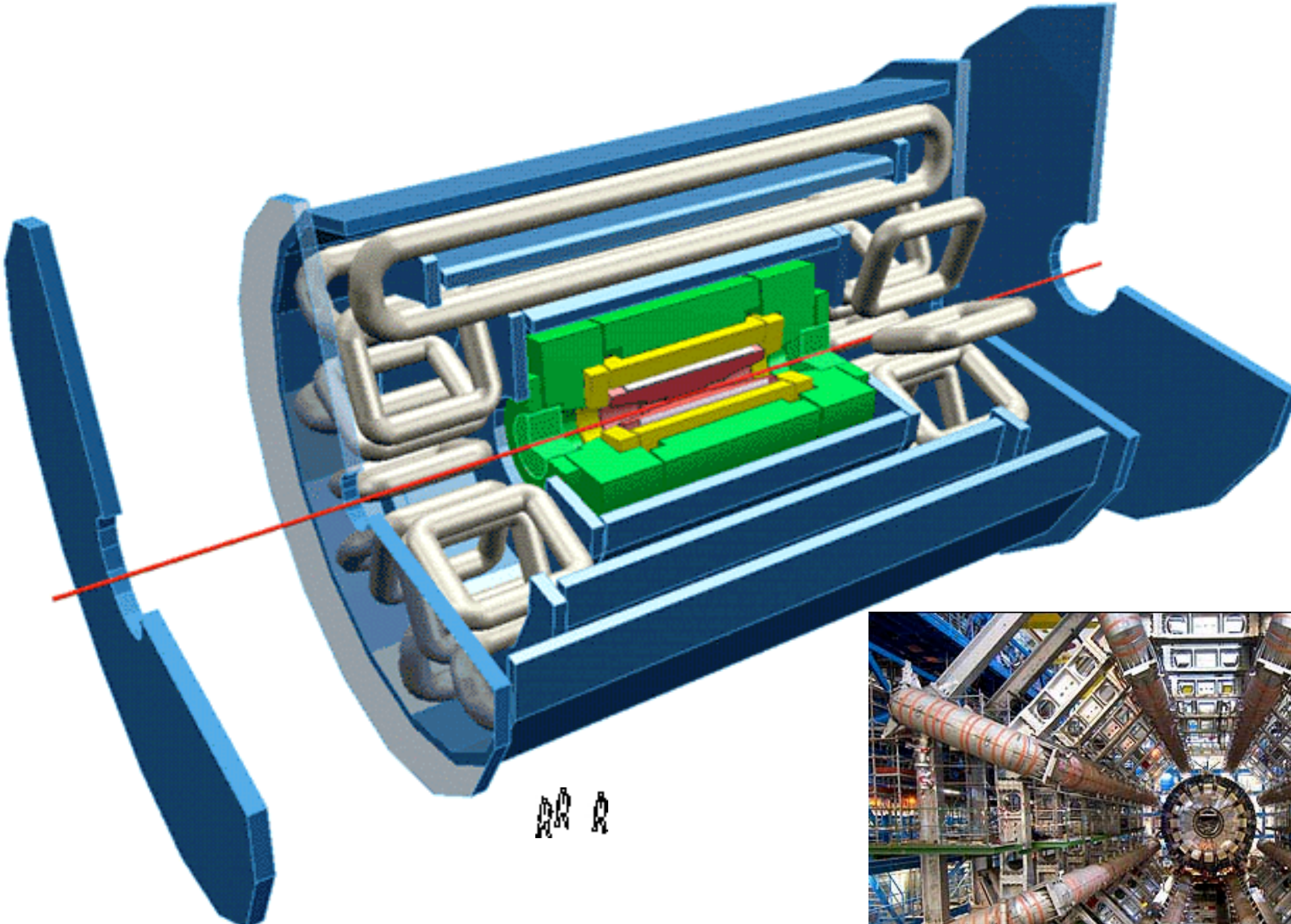


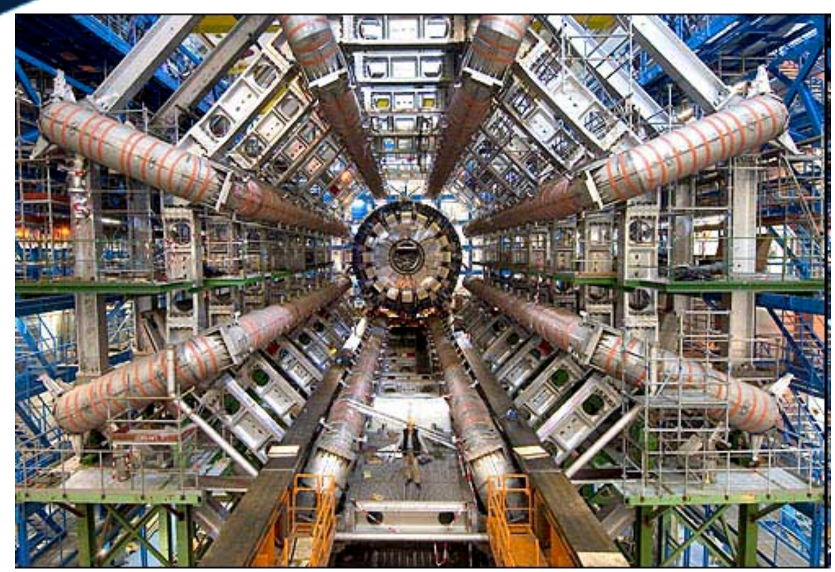
0m
1m
2m
3m
4m
5m
6m
7m
CMS detector
with segment enlarged
cross section
beam tube in center)
Silicon
tracker
electronmagnetic
calorimeter
hadron
calorimeter
superconductor
magnet
Iron (red) yoke for
returning magnetic field
& muon detector chambers

CMS exploded

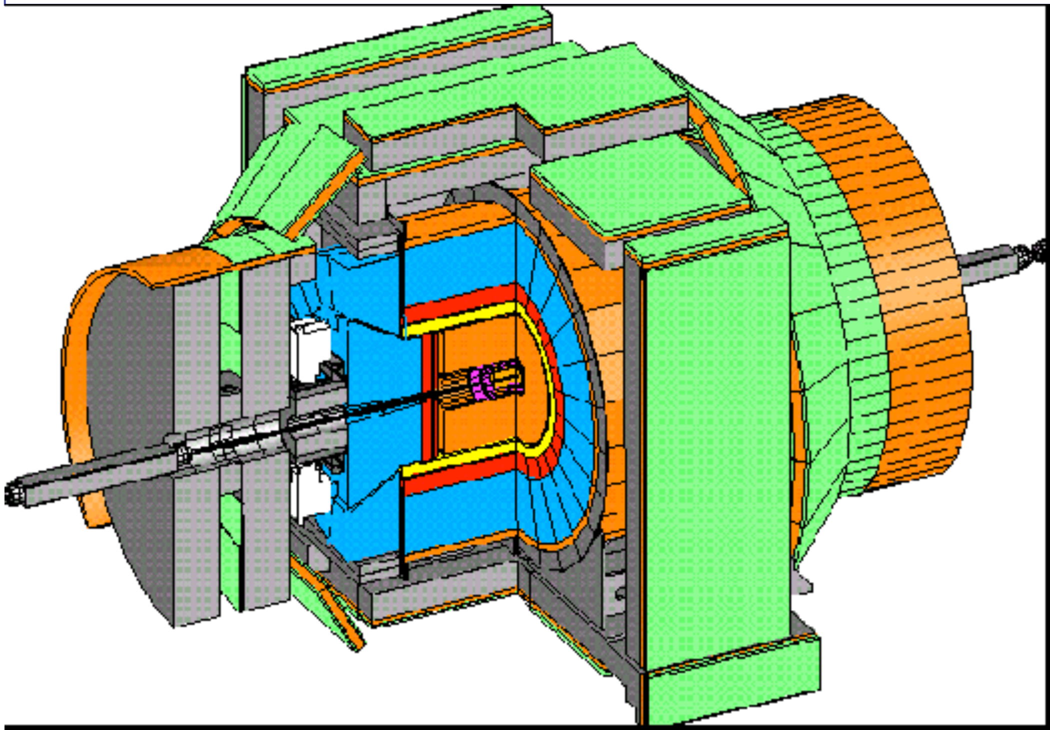


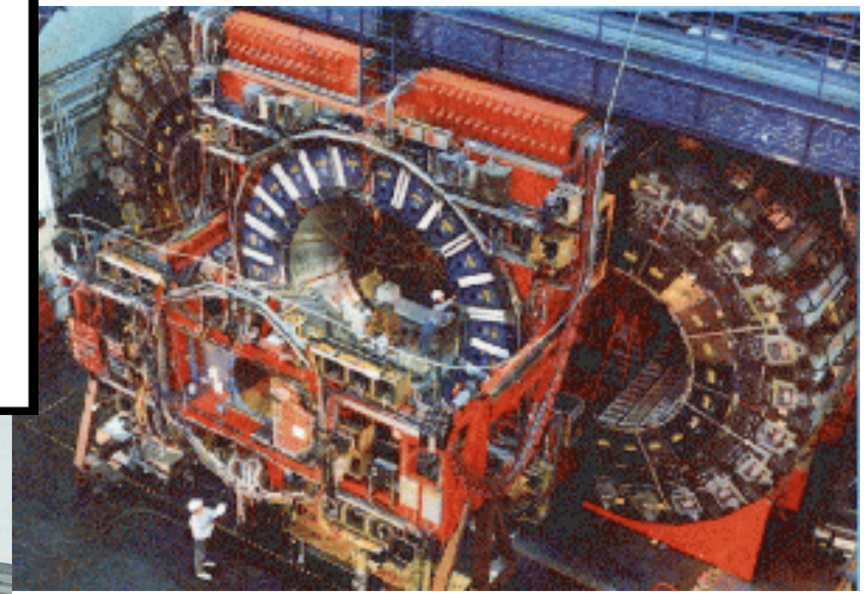
Atlas at LHC

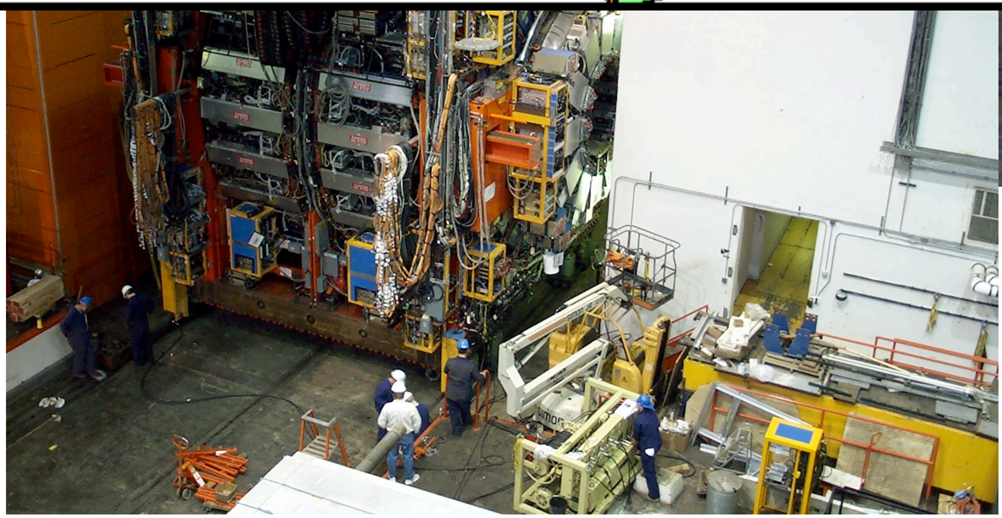




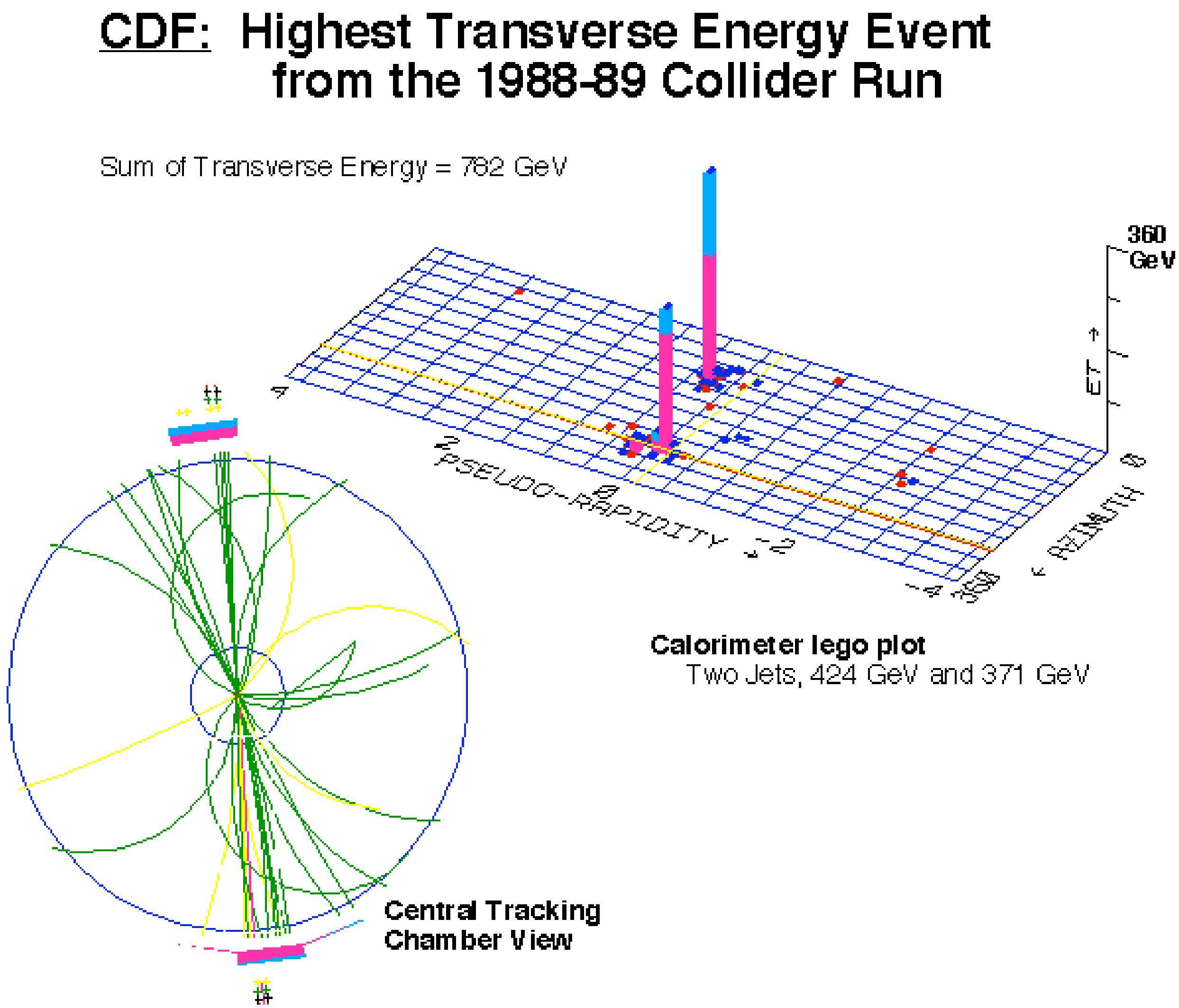
CDF Detector at Fermilab Tevatron







CDF high Et event



CDF 4-jet event

e + 4 jet event

40758_44414

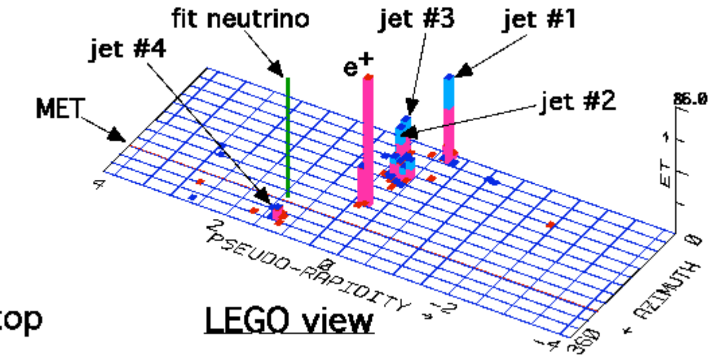
24-September, 1992

TWO jets tagged by SVX

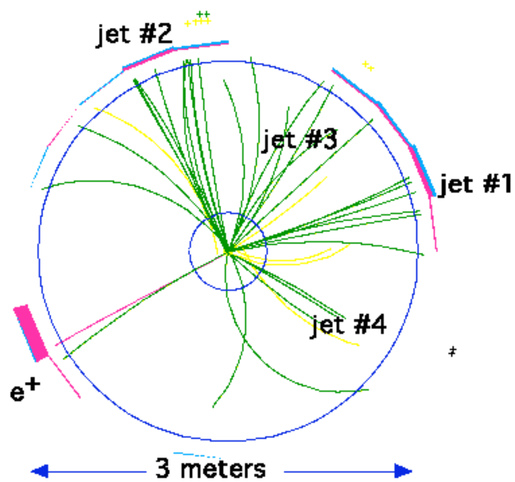
fit top mass is 170 +- 10 GeV

e^+, Missing E_t, jet #4 from top

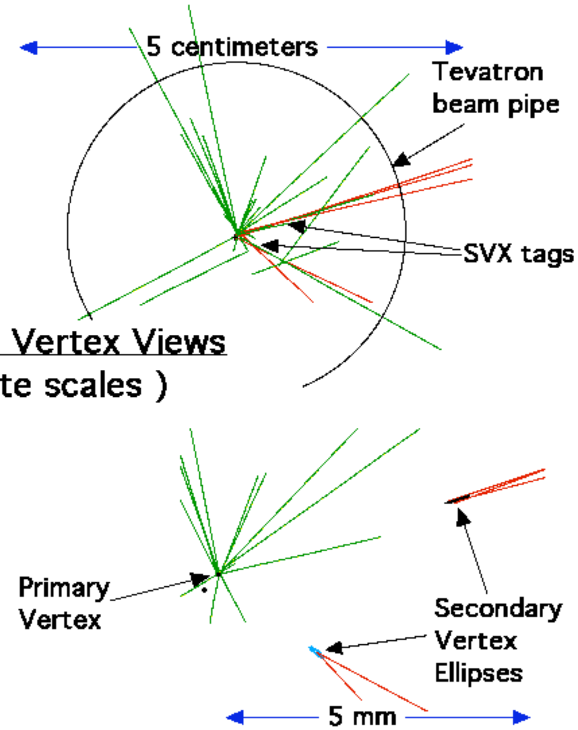
jets 1,2,3 from top (2&3 from W)



LEGO view

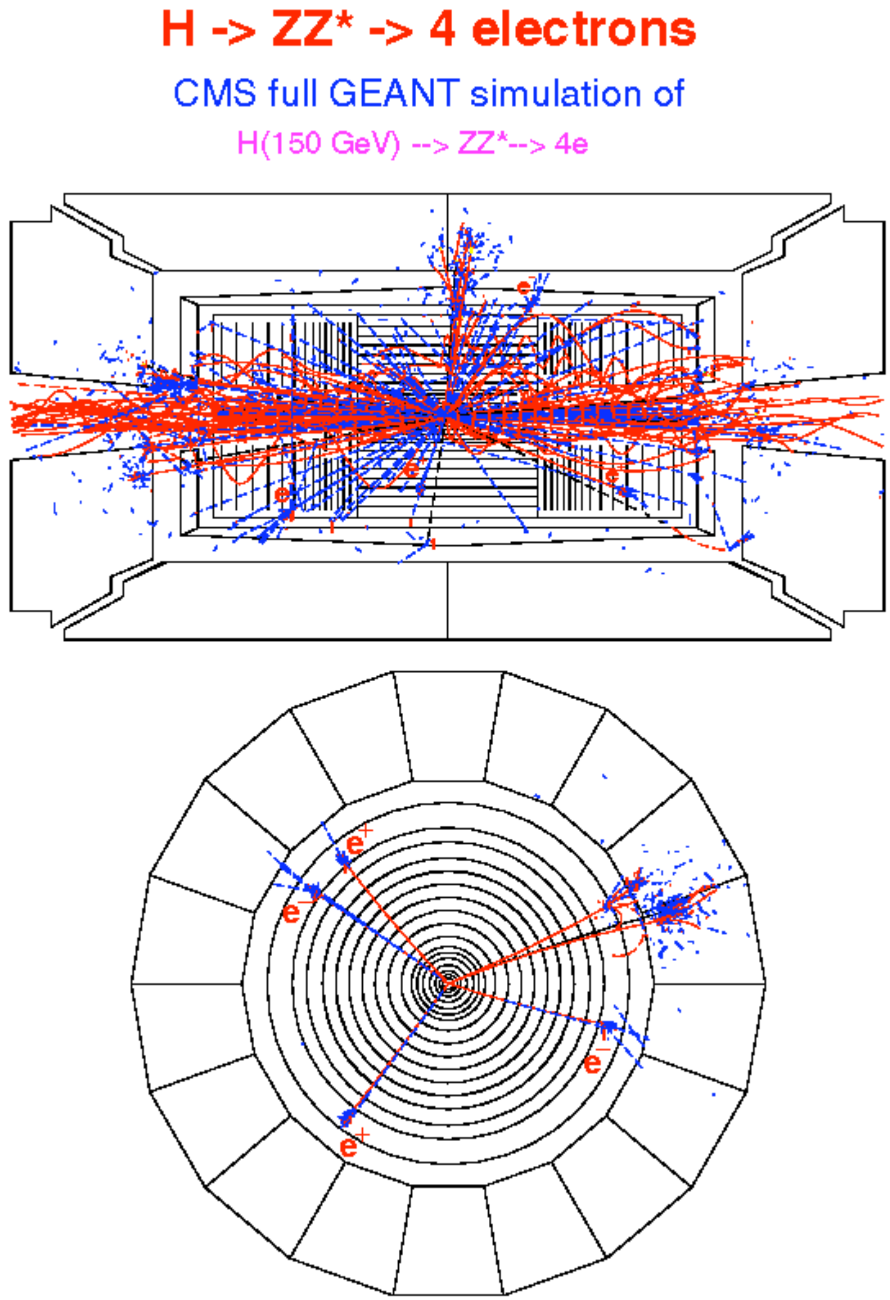


Tracking View



Two Vertex Views

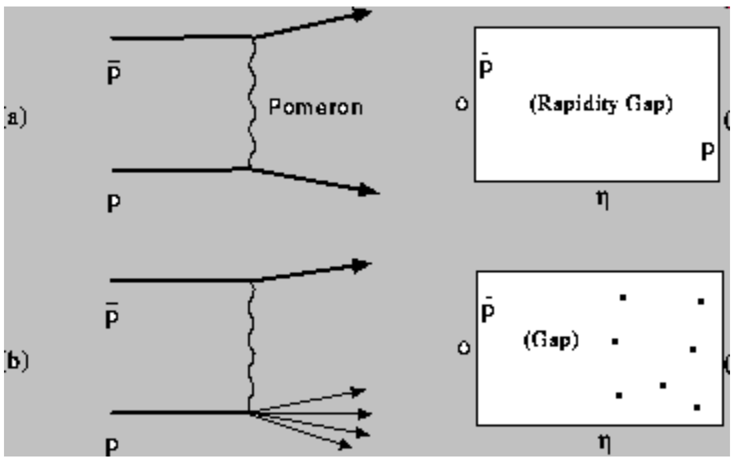
(note scales)

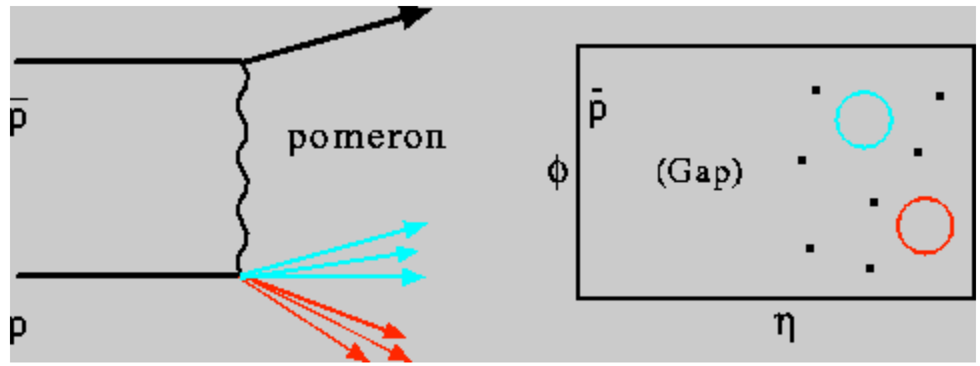

H -> ZZ* -> 4 electrons
CMS full GEANT simulation of
H(150 GeV) --> ZZ*--> 4e
e+
e−
e−
e+

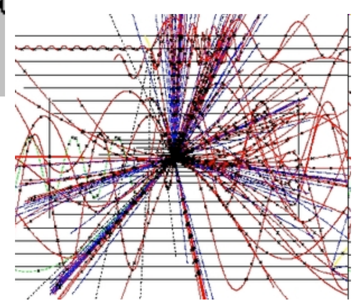
CMS
H→4e

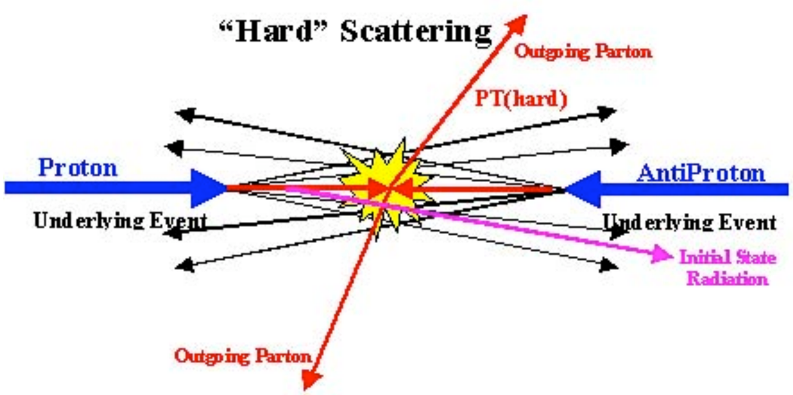
The total cross-section

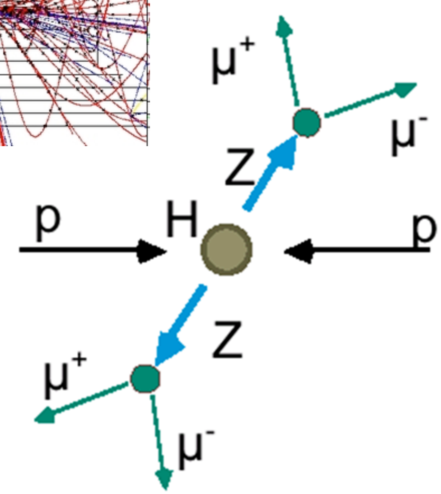
- $\sigma_{tot} = \sigma_{el} + \sigma_{diff} + \sigma_{jets} + \sigma_{EW} + \sigma_{bsm} + \ldots$

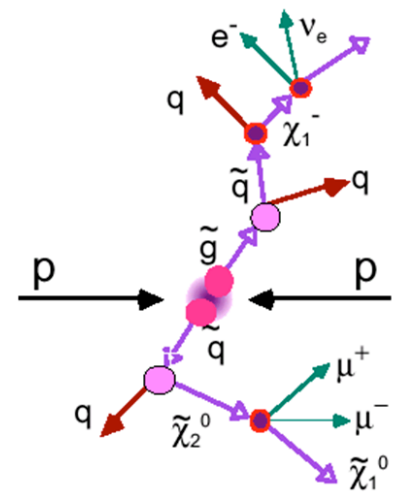












Monte Carlo simulations

- 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?

a single pythia event: gg $\rightarrow$ 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