Physics at

L arge H adron C ollider

Fabiola Gianotti (CERN)
Summer Student lectures, CERN, August 2002

Outline

- Part 1 : Introduction
  What is the LHC ?
  Why the LHC ?
  Experimental challenges
  The ATLAS and CMS experiments
  Overview of the physics programme

- Part 2 : Standard Model Physics
  Measurements of the W mass and top mass
  Higgs searches

- Part 3 : Physics beyond the Standard Model
  Motivations
  Searches for SUSY
  Searches for Extra-dimensions and black holes
  (if enough time …)

Note : here only a few examples of a huge
and exciting physics programme

PART 1

LHC

- pp machine (mainly):

$\sqrt{s}$ = 14 TeV

7 times higher than present highest energy machine (Tevatron/Fermilab: $\sqrt{s}$ = 2 TeV)

→ search for new massive particles up to m ~ 5 TeV

Note : $\sqrt{s}$ limited by needed bending power.
LHC : 1232 superconducting dipoles with B = 8.4 T
working at 1.9 Kelvin (biggest cryogenic system in the world)

$$L \propto \frac{N_1 \; N_2}{\delta x \; \delta y} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

~ 10^2 larger than LEP2, Tevatron

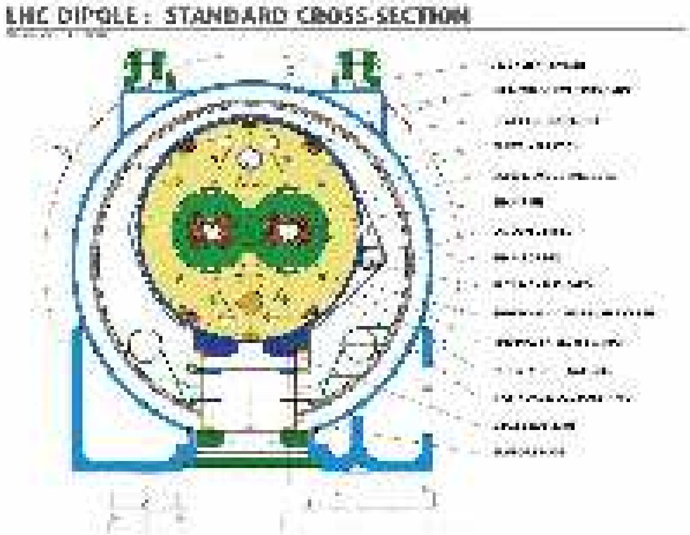
→ search for rare processes with small σ ($N = L\sigma$)

- under construction, ready 2007
- will be installed in the existing LEP tunnel
- two phases:

2007 - 2009 : $L \sim 10^{33}$ cm^{-2} s^{-1} , $\int L dt \approx 10$ fb^{-1} (1 year)
"low luminosity"

2009 - 20xx : $L \sim 10^{34}$ cm^{-2} s^{-1} , $\int L dt \approx 100$ fb^{-1} (1 year)
"high luminosity"

The machine



First full LHC cell (~ 120 m long) :
6 dipoles + 4 quads
Successful tests at nominal current (12 kA)

Four large-scale experiments:

ATLAS
CMS

general-purpose pp experiments

LHCb

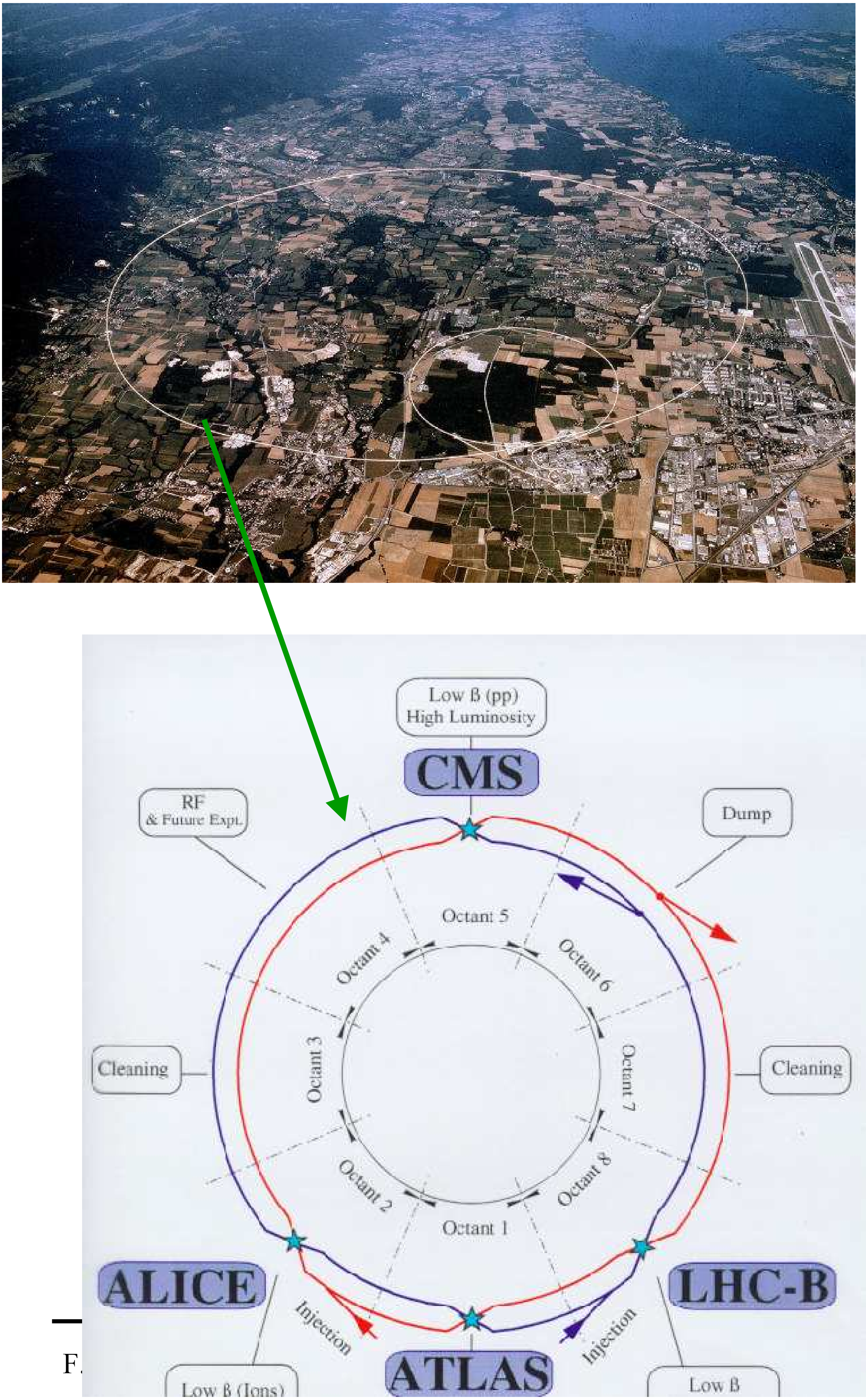
pp experiment dedicated to b-quark physics and CP-violation → see lectures by T.Nakada

ALICE

heavy-ion experiment (Pb-Pb collisions) at 5.5 TeV/nucleon → $\sqrt{s} \cong 1000$ TeV
Quark-gluon plasma studies.
→ see lectures by F. Antinori

Here : ATLAS and CMS

Note : machine discussed in O. Brüning lectures


Low ß (pp)
High Luminosity
CMS
RF
& Future Expt.
Dump
Octant 5
Octant 4
Octant 6
Octant 3
Octant 7
Octant 2
Octant 8
Octant 1
Cleaning
Cleaning
ALICE
LHC-B
Injection
Injection
ATLAS
Low ß (Ions)
Low ß

F.

LHC is unprecedented machine in terms of:

- Energy
- Luminosity
- Cost : ≈ 4000 MCHF (machine + experiments)
- Size/complexity of experiments :
  ~ 1.3-2 times bigger than present collider experiments
  ~ 10 times more complex
- Human resources : > 4000 physicists in the experiments

↓

WHY ?

Motivations for LHC

Motivation 1 : Origin of particle masses

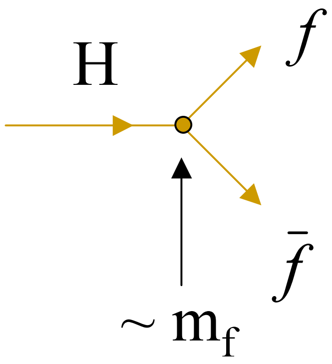
Standard Model of electroweak interactions verified with precision 10^{-3} - 10^{-4} by measurements at LEP at $\sqrt{s} \geq m_Z$ and at the Tevatron at $\sqrt{s} = 1.8$ TeV

discovery of top quark in ‘94, $m_{top} \cong 174$ GeV

However: origin of particle masses not known.

Ex. : $m_\gamma = 0$
$m_{W,Z} \approx 100$ GeV → ?

SM : Higgs mechanism gives mass to particles
(Electroweak Symmetry Breaking)



$m_H < 1$ TeV from theory

However:

-- Higgs not found yet: only missing (and essential) piece of SM

-- present limit : $m_H > 114.4$ GeV (from LEP)

-- Tevatron may go beyond (depending on L)

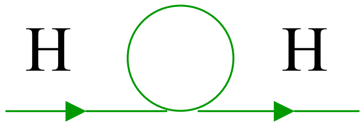
⇒ need a machine to discover/exclude Higgs from ≈ 120 GeV to 1 TeV

↓

LHC

Motivation 2 : Is SM the "ultimate theory" ?

- Higgs mechanism is weakest part of the SM:
  - -- "ad hoc" mechanism, little physical justification
  - -- due to radiative corrections



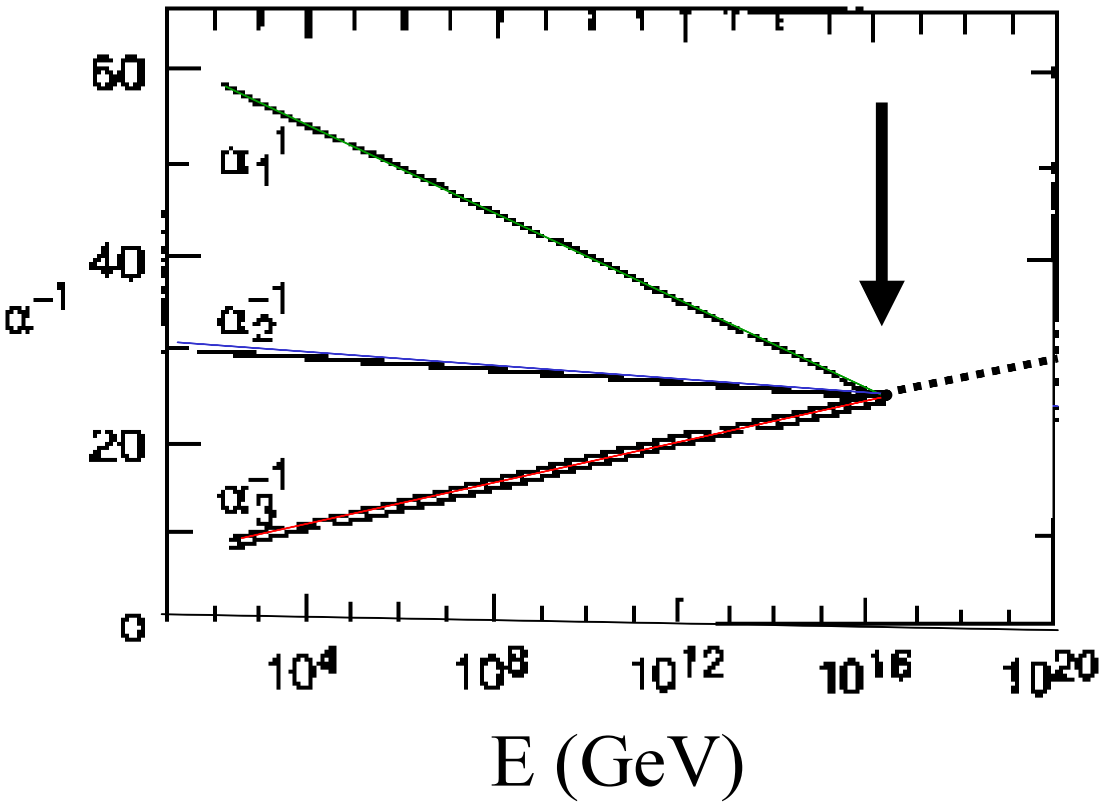
$\Delta m_H^2 \sim \Lambda^2$

Λ : energy scale
up to which SM
is valid (can be very large).

⇒ radiative corrections can be very large ("unnatural") and Higgs mass can diverge unless "fine-tuned" cancellations → " bad behaviour " of the theory

- Hints that forces could unify at high energy

$$\left.\begin{array}{l} \alpha_{EM} \equiv \alpha_1 \approx 1/128 \approx 0.008 \\ \alpha_{WEAK} \equiv \alpha_2 \approx 0.03 \\ \alpha_S \equiv \alpha_3 \approx 0.12 \end{array}\right\} \sqrt{s} = 100 \text{ GeV}$$



- E-dependence of coupling constants proven experimentally
- Grand Unified Theories: EM/Weak/Strong forces unify at E ~ 10^{16} → beyond physics become simple (one force with strength α_G)

↓

- SM is probably low-energy approximation of a more general theory

- Need a high-energy machine to look for manifestations of this theory

- e.g. Supersymmetry : $m_{SUSY} \sim$ TeV
  Many other theories predict New Physics at the TeV scale

↓

LHC

Motivation 3 : Many other open questions

- Are quarks and leptons really elementary ?
- Why 3 fermion families ?
- Are there additional families of (heavy) quarks and leptons ?
- Are there additional gauge bosons ?
- What is the origin of matter-antimatter asymmetry in the universe ?
- Can quarks and gluons be deconfined in a quark-gluon plasma as in early stage of universe ?
- …. etc. …...

Motivation 4 : The most fascinating one …

Unexpected physics ?

Motivation 5 : Precise measurements

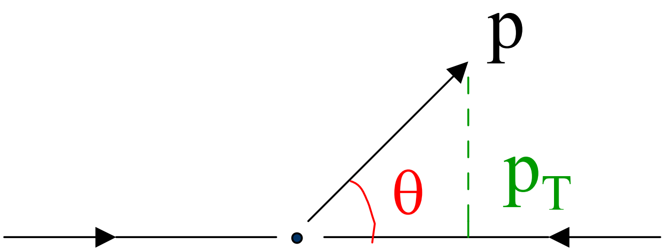
Two ways to find new physics:

-- discover new particles/phenomena

-- measure properties of known particles as precisely as possible ⇒ find deviations from SM

LHC: known particles (W, Z, b, top, …) produced with enormous rates thanks to high energy and L

Phenomenology of pp collisions



Transverse momentum (in the plane perpendicular to the beam) :

$$\boxed{p_T = p \sin\theta}$$

Rapidity:

$$\boxed{\eta = -\log\left(\mathrm{tg}\,\frac{\theta}{2}\right)}$$

$\theta = 90^o \rightarrow \eta = 0$
$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

Total inelastic cross-section:

$$\sigma_{tot}(pp) = 70 \text{ mb} \qquad \sqrt{s} = 14 \text{ TeV}$$

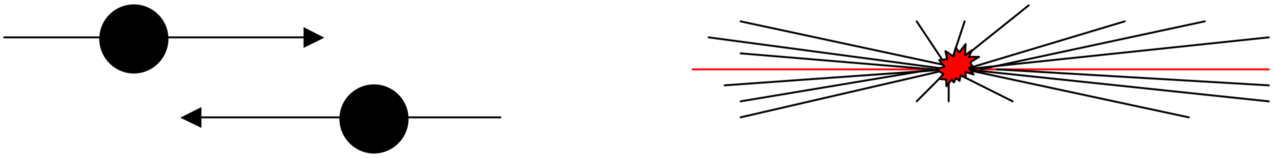
$$\text{Rate} = \frac{\text{n. events}}{\text{second}} = L \times \sigma_{tot}(pp) = 10^9 \text{ interactions/s}$$

10^{34} cm^{-2} s^{-1}

These include two classes of interactions.

Class 1:

Most interactions due to collisions at large distance between incoming protons where protons interact as “ a whole ” → small momentum transfer ($\Delta p \approx \hbar / \Delta x$) → particles in final state have large longitudinal momentum but small transverse momentum (scattering at large angle is small)



$< p_T > \approx 500$ MeV   of charged particles in final state

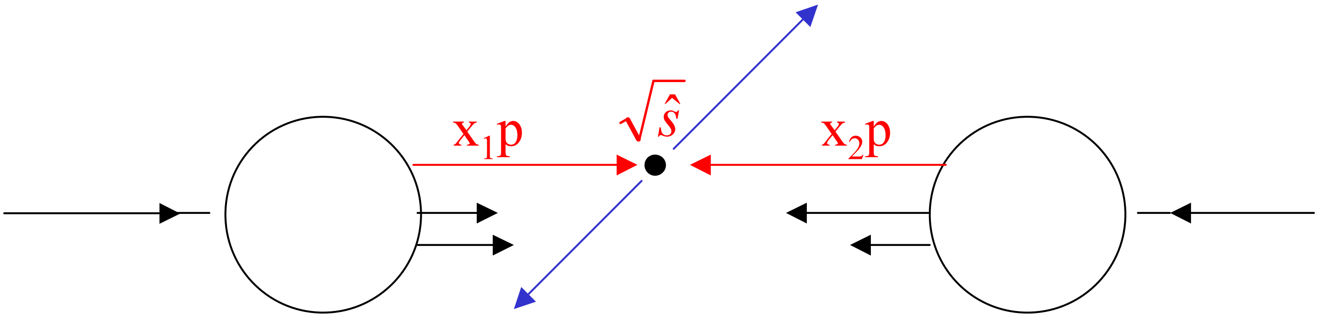
$\frac{dN}{d\eta} \approx 7$ charged particles uniformly distributed in ϕ

Most energy escapes down the beam pipe.

These are called minimum-bias events (“ soft “ events). They are the large majority but are not very interesting.

Class 2:

Monochromatic proton beam can be seen as beam of quarks and gluons with a wide band of energy. Occasionally hard scattering (“ head on”) between constituents of incoming protons occurs.

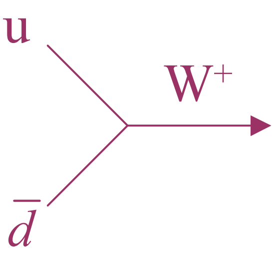


p ≡ momentum of incoming protons = 7 TeV

Interactions at <u>small distance</u> → <u>large momentum transfer</u> → massive particles and/or particles at large angle are produced.

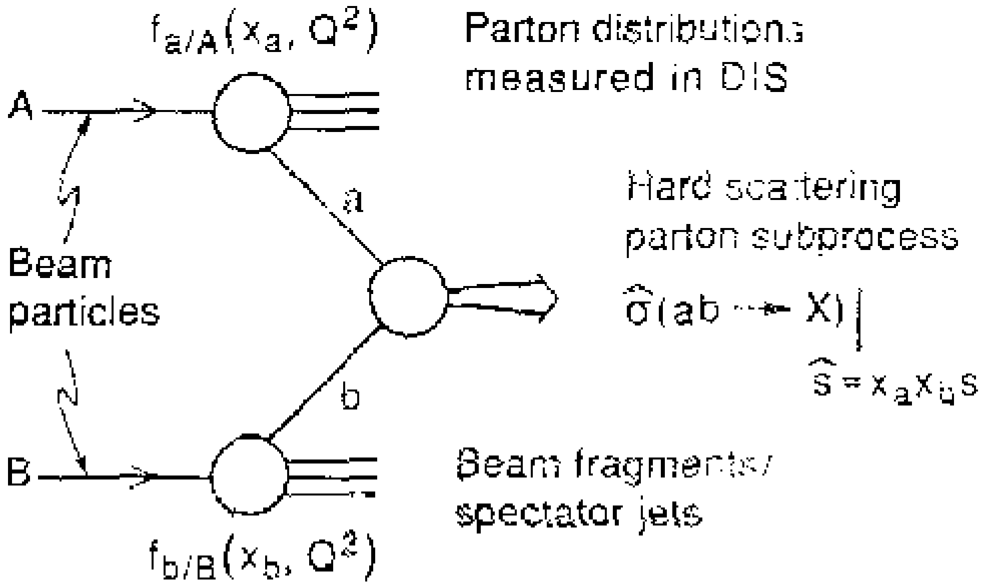
These are interesting physics events but they are rare.

Ex. $u + \bar{d} \rightarrow W^+$



$$\sigma\,(pp \rightarrow W) \approx 150\ \text{nb} \approx 10^{-6}\,\sigma_{tot}\,(pp)$$

Unlike at e+e- colliders



- effective centre-of-mass energy $\sqrt{\hat{s}}$ smaller than √s of colliding beams:

$$\left.\begin{aligned}\vec{p}_a &= x_a\,\vec{p}_A \\ \vec{p}_b &= x_b\,\vec{p}_B\end{aligned}\right\} \quad p_A = p_B = 7\ \text{TeV} \quad \sqrt{\hat{s}} = \sqrt{x_a x_b s} \underset{\uparrow}{\approx} x\sqrt{s}$$

if $x_a \approx x_b$

→ to produce m ≈ 100 GeV $x \sim 0.01$
to produce m ≈ 5 TeV $x \sim 0.35$

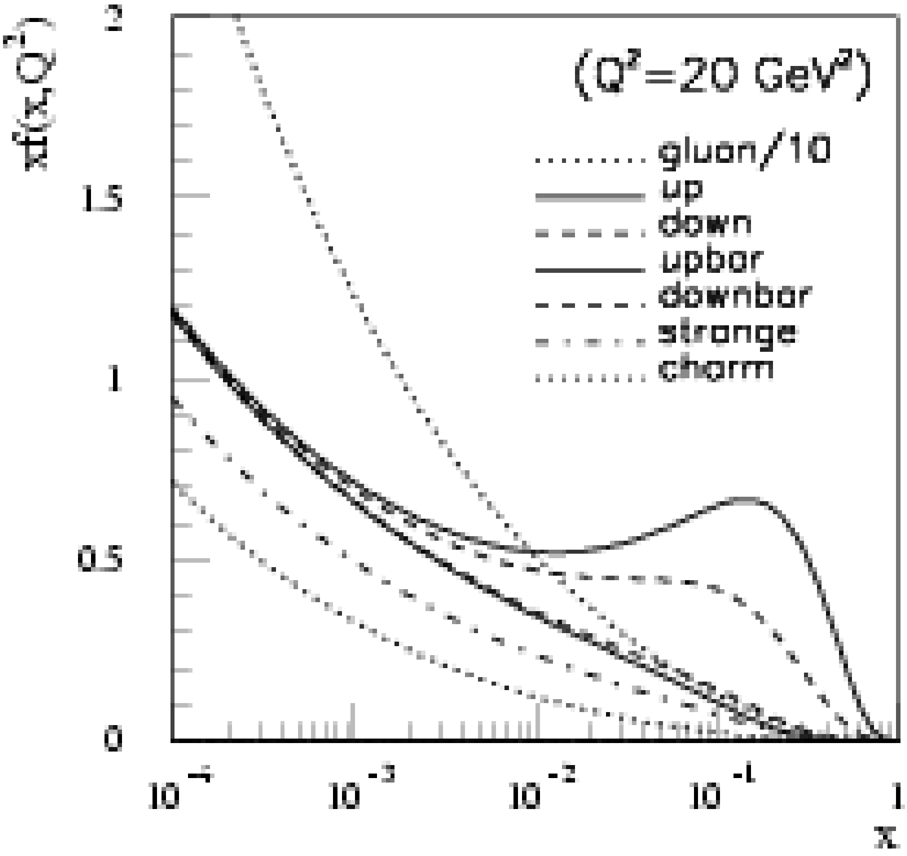
- cross-section :

$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$

$\hat{\sigma}_{ab}$ ≡ hard scattering cross-section

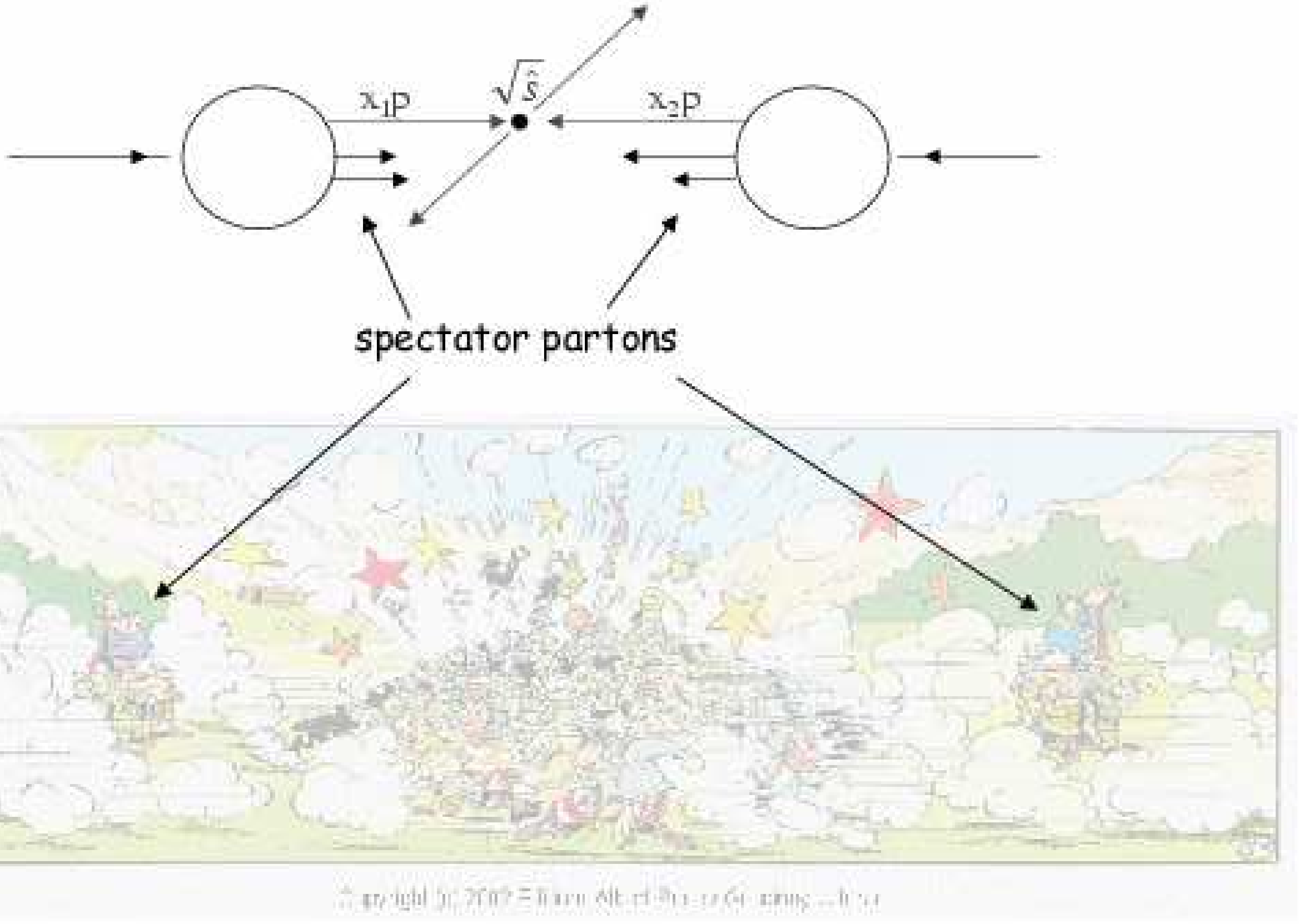
$f_i(x, Q^2) \equiv$ parton distribution function

⬇



p ≡ uud

Example of a typical LHC interaction

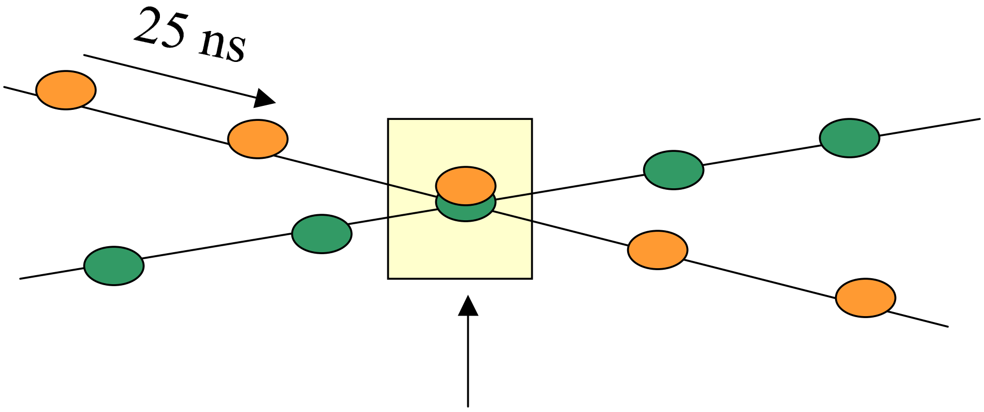


spectator partons

Two main difficulties

❶ Typical of LHC:

$R = L\sigma = 10^9$ interactions / second
Protons are grouped in bunches (of ≈ $\boxed{10^{11}}$ protons)
colliding at interaction points every 25 ns



detector

⇒ At each interaction on average ≈ 25 minimum-bias events are produced. These overlap with interesting (high p_T) physics events, giving rise to so-called

pile-up

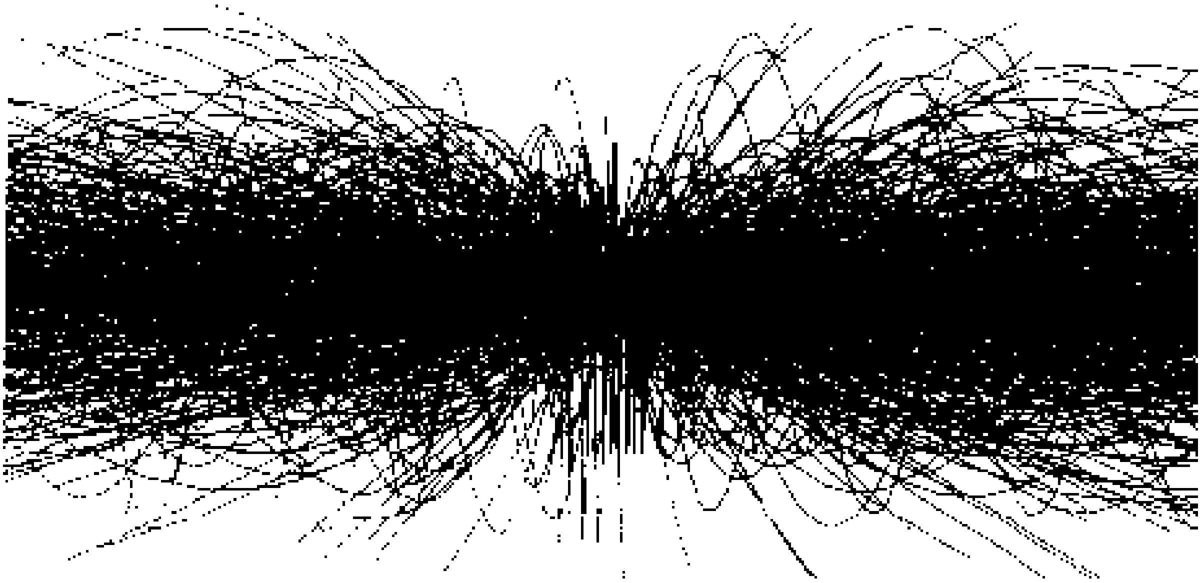
~1000 charged particles produced over $|\eta| < 2.5$ at each crossing.

However $< p_T > \approx 500$ MeV (particles from minimum-bias).

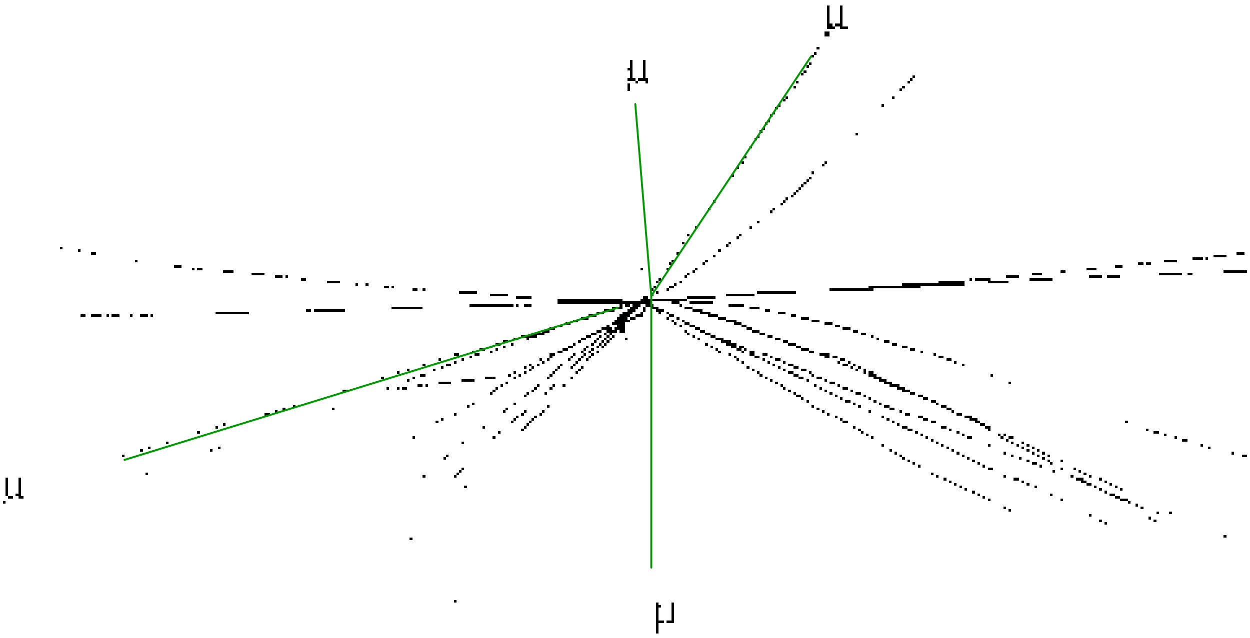
→ applying p_T cut allows extraction of interesting particles

Simulation of CMS inner detector

30 minimum bias events + $H \rightarrow ZZ \rightarrow 4\mu$



all charged particles with $|\eta| < 2.5$



reconstructed tracks with $p_t > 2.0$ GeV

Pile-up is one of the most serious experimental difficulty at LHC

Large impact on detector design:

- LHC detectors must have fast response, otherwise integrate over many bunch crossings → too large pile-up

  Typical response time : 20-50 ns

  → integrate over 1-2 bunch crossings → pile-up of 25-50 minimum bias

  ⇒ very challenging readout electronics

- LHC detectors must be highly granular to minimise probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \to \gamma\gamma$ decays)

  → large number of electronic channels

  ⇒ high cost

- LHC detectors must be radiation resistant: high flux of particles from pp collisions → high radiation environment

  E.g. in forward calorimeters:

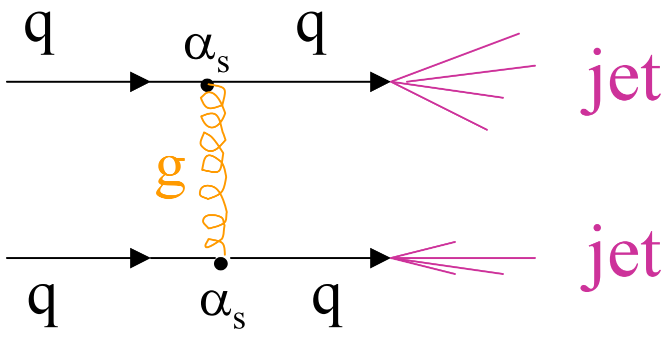
$$\left.\begin{array}{l}\text{up to } 10^{17}\ \text{n / cm}^2 \\ \text{up to } 10^{7}\ \text{Gy}\end{array}\right\} \quad \text{in 10 years of LHC operation}$$

Note : 1 Gy = unit of absorbed energy = 1 Joule/Kg

Radiation damage :

- -- decreases like d^2 from the beam → detectors nearest to beam pipe are more affected
- -- need also radiation hard electronics (military-type technology)
- -- need quality control for every piece of material
- -- detector + electronics must survive 10 years of operation

❷ Common to all hadron colliders:
high-p_T events dominated by QCD jet production:

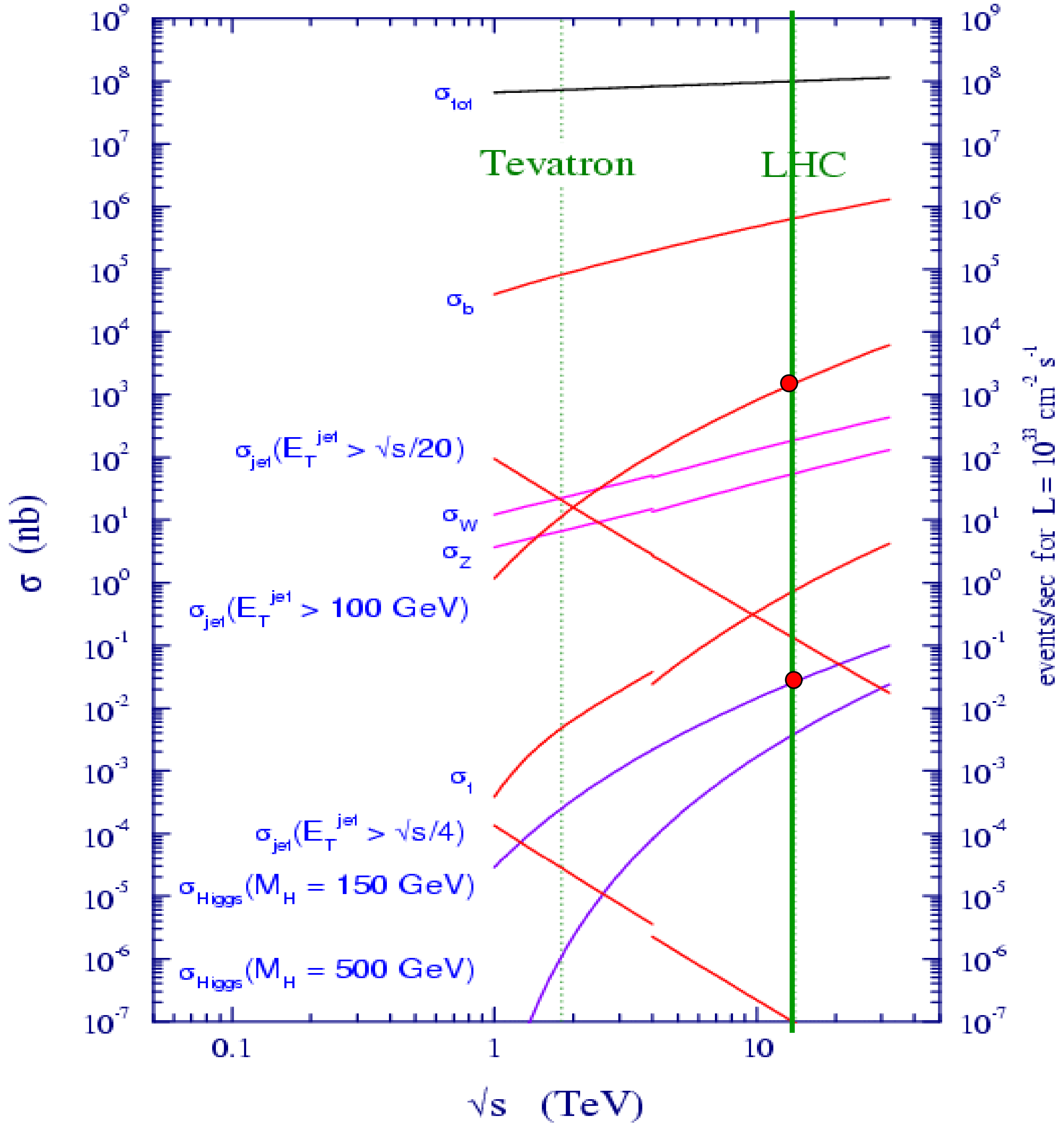


- Strong production → large cross-section
- Many diagrams contribute: qq → qq, qg → qg, gg → gg, etc.
- Called " QCD background "

Most interesting processes are rare processes:

- involve heavy particles
- have weak cross-sections (e.g. W production)

Proton - (anti) proton cross-section



To extract signal over QCD jet background must look at decays to photons and leptons → pay a prize in branching ratio

Ex. BR (W $\rightarrow$ jet jet) $\approx$ 70%

BR (W $\rightarrow \ell\nu$) $\approx$ 30%

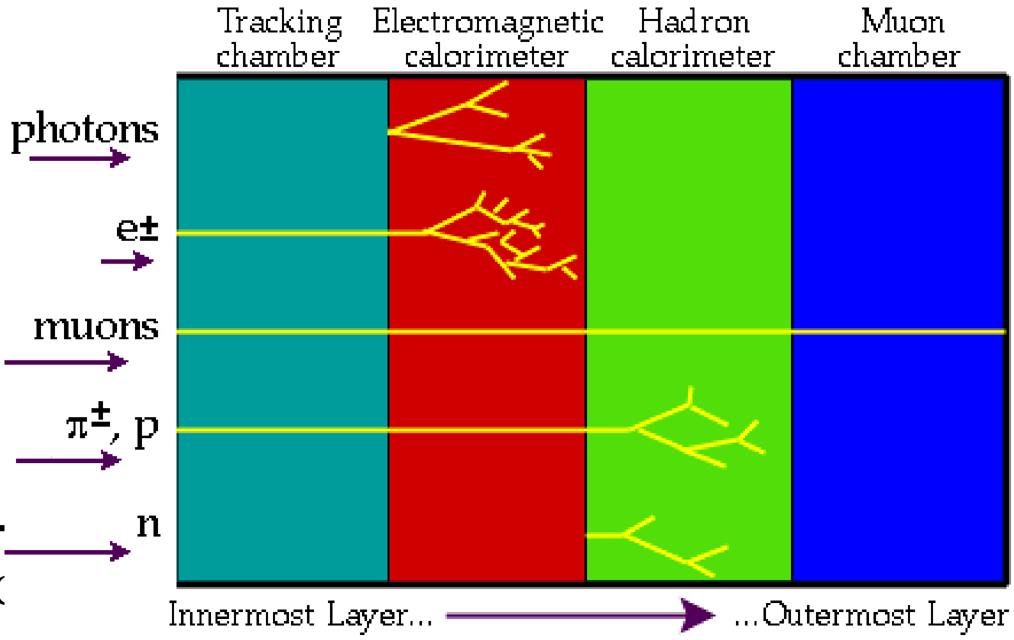
ATLAS and CMS detectors

(see C. Joram's lectures)

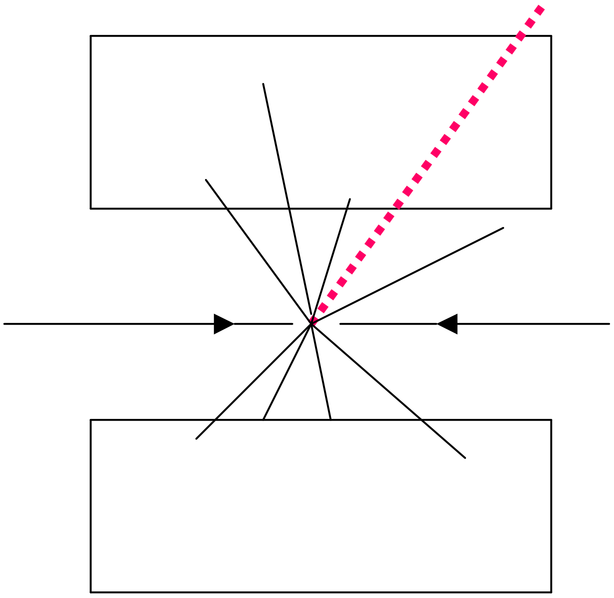
Don' t know how New Physics will manifest → detectors must be able to detect as many particles and signatures as possible:

e, μ, τ, ν, γ, jets, b-quarks, ….
→ " multi-purpose" experiments.

- Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) measured in central tracker. Excellent momentum and position resolution required.
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent resolution and particle identification required.
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters. Good coverage and granularity are required.
- Muons identified and momentum measured in external muon spectrometer (+ central tracker). Excellent resolution over ~ 5 GeV < p_T < ~ TeV required.
- Neutrinos "detected and measured" through measurement of missing transverse energy E_T^{miss}. Calorimeter coverage over | η |<5 needed.



Detection and measurement of neutrinos



- Neutrinos traverse the detector without interacting
  → not detected directly

- Can be detected and measured asking:

$$E_f, \vec{P}_f \;=\; E_i, \vec{P}_i$$

total energy, momentum reconstructed in final state

total energy, momentum of initial state

-- e^+e^- colliders: $E_i = \sqrt{s}$, $\vec{P}_i = 0$

→ if a neutrino produced, then $E_f < E_i$ (→ missing energy)

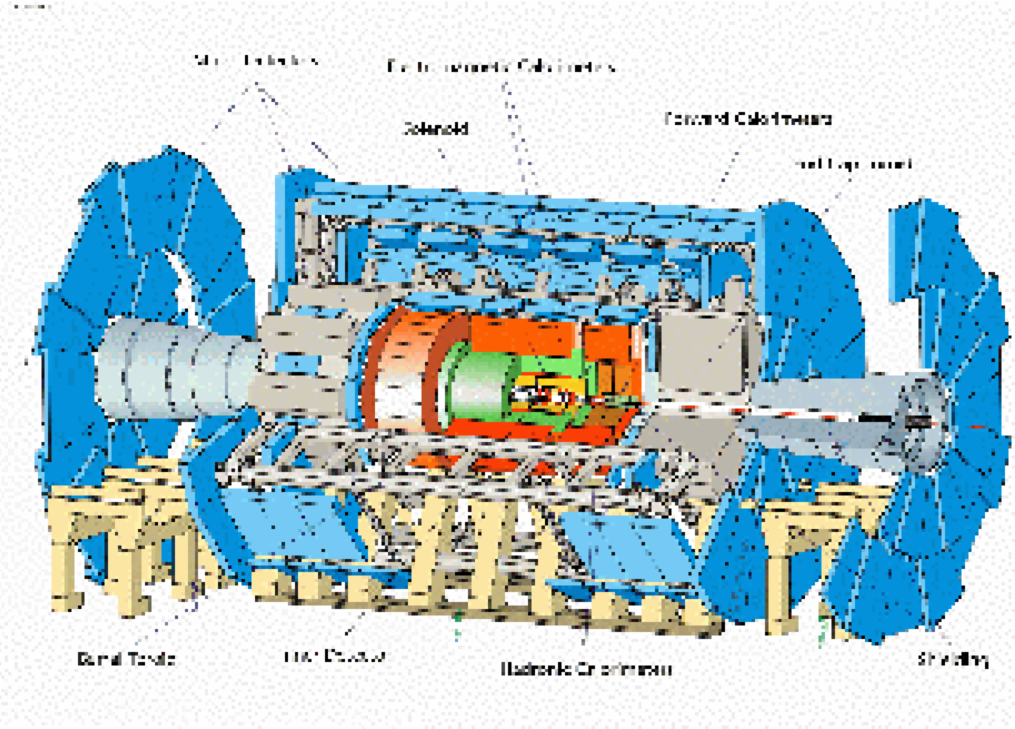
and $\vec{P}_f \neq 0$ → $\vec{P}_\nu = -\vec{P}_f$ $E_\nu = |\vec{P}_\nu|$

-- hadron colliders: energy and momentum of initial state (energy and momentum of interacting partons) not known.

However: transverse momentum $\vec{P}_{T\,i} = 0$

→ if a neutrino produced $\vec{P}_{T\,f} \neq 0$ (→ missing transverse momentum) and

$$|\vec{P}_{T\,\nu}| = |\vec{P}_{T\,f}| = E_T^{\text{miss}}$$



ATLAS

A Toroidal Lhc ApparatuS

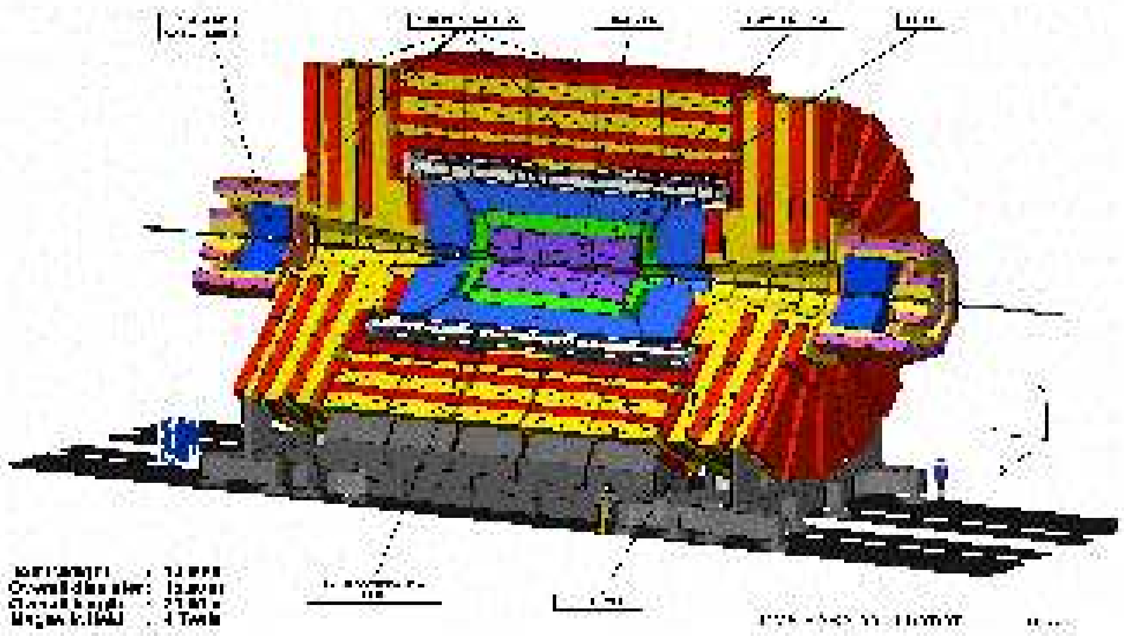
Length : ~40 m
Radius : ~10 m
Weight : ~ 7000 tons
Electronics channels : 10^8

... and 3000 km of cables ...

- Tracking ($|\eta|<2.5$, B=2T) :
  - -- Si pixels and strips
  - -- Transition Radiation Detector (e/π separation)
- Calorimetry ($|\eta|<5$) :
  - -- EM : Pb-LAr
  - -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- Muon Spectrometer ($|\eta|<2.7$) :
  air-core toroids with muon chambers

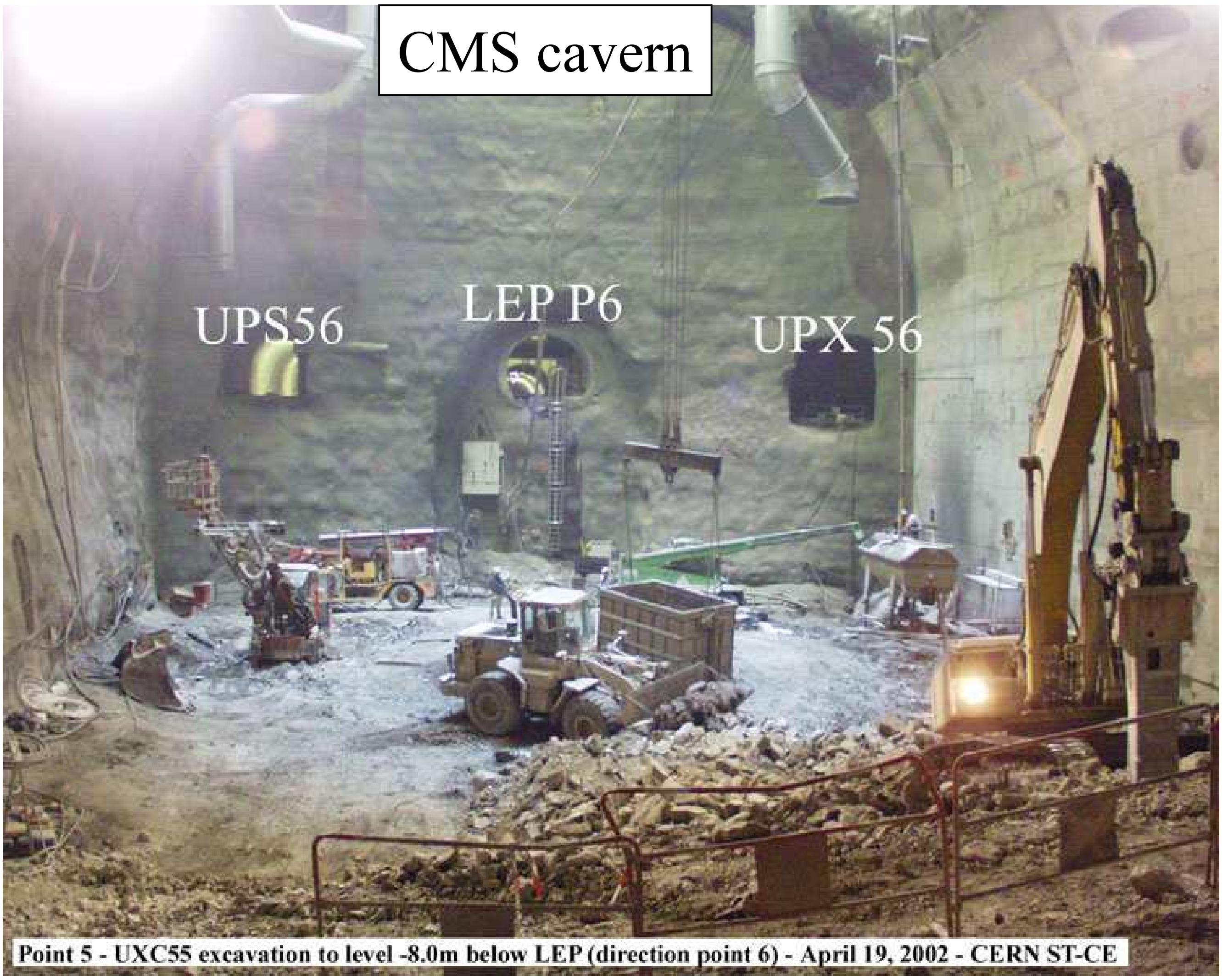
CMS

Compact Muon Solenoid

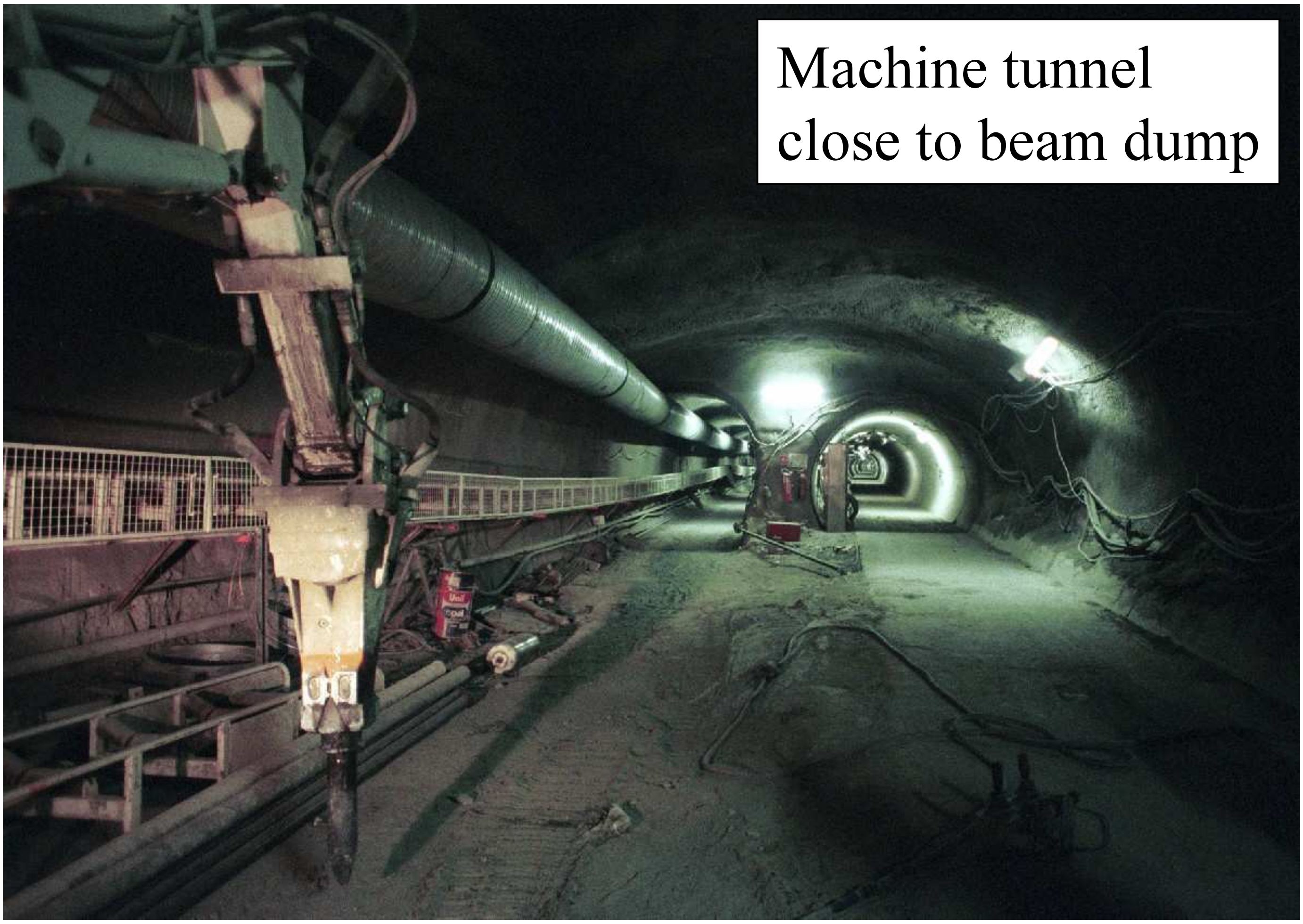


Length : ~20 m
Radius : ~7 m
Weight : ~ 13000 tons
Electronics channels : 10^8

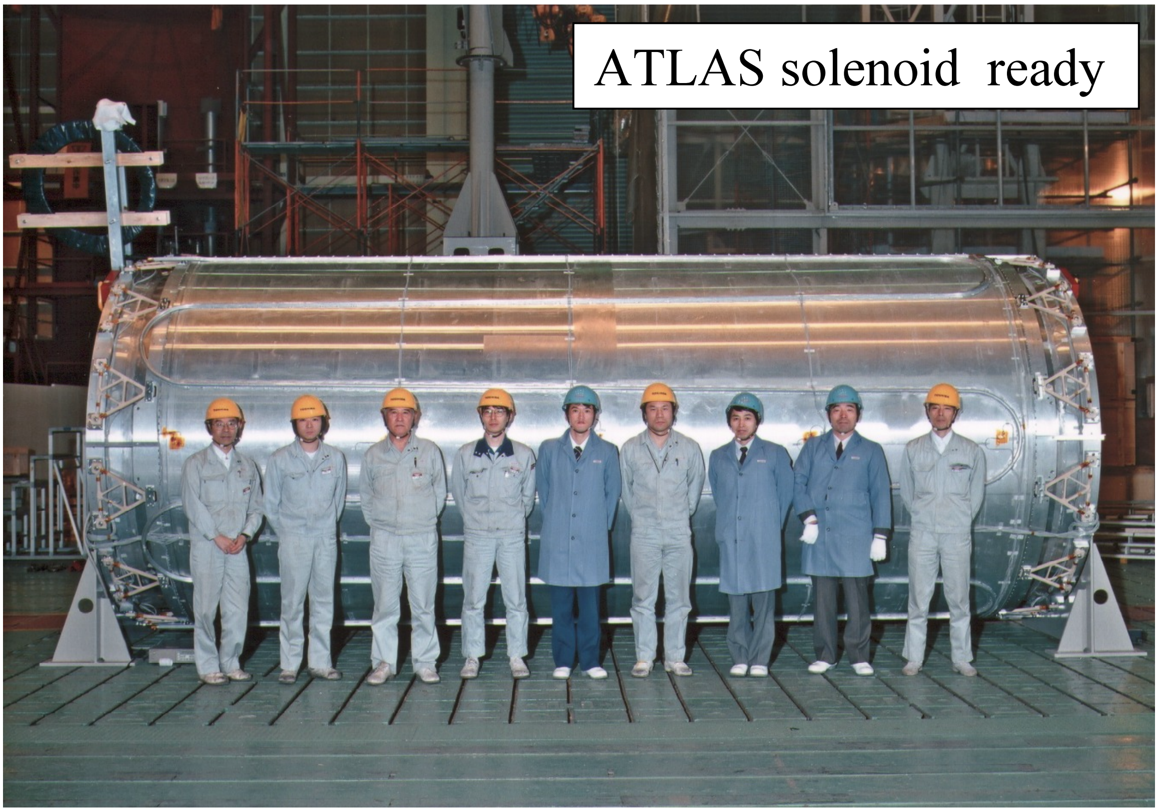
- Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: Cu/scintillator (central+ end-cap), Fe/Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers



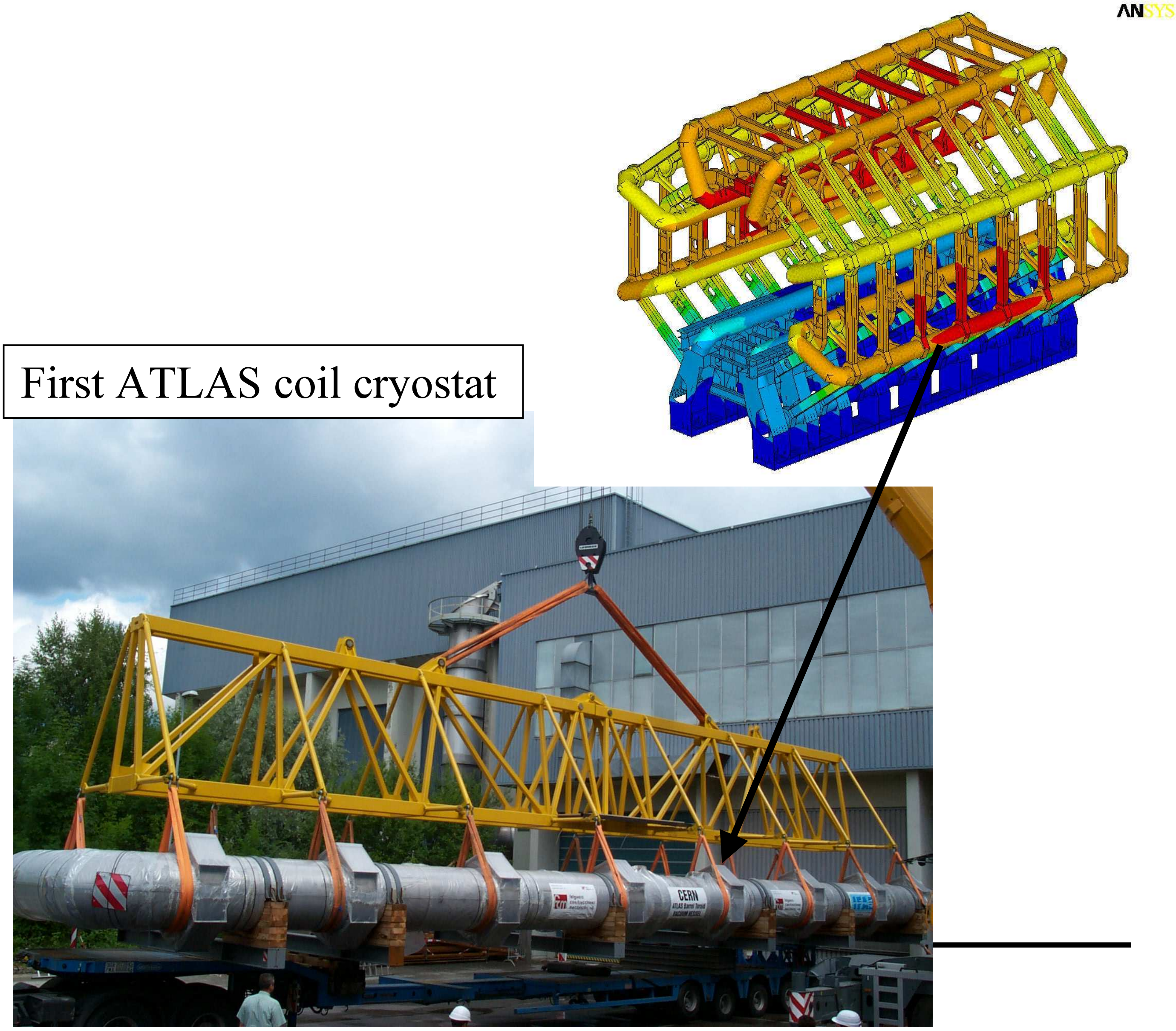
CMS cavern



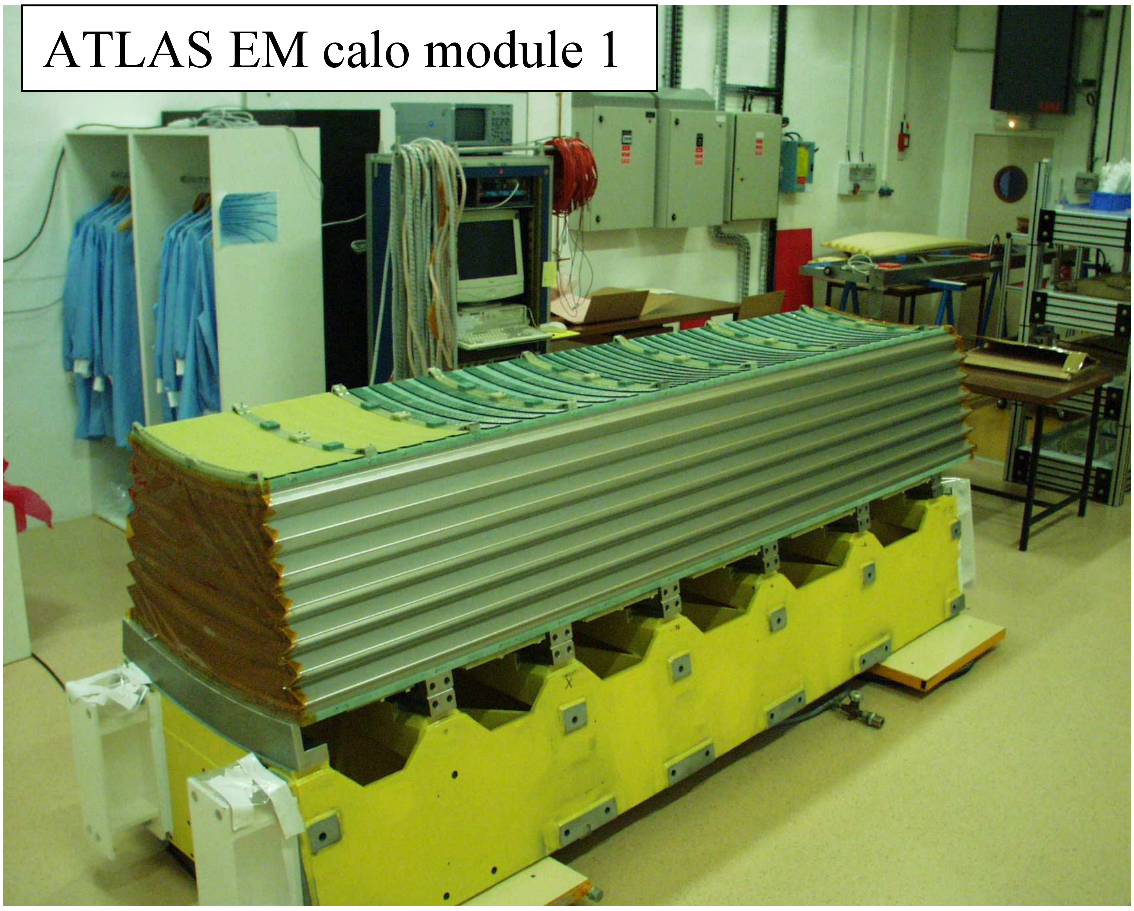
Machine tunnel close to beam dump



ATLAS solenoid ready



First ATLAS coil cryostat



ATLAS EM calo module 1

Assembly of ATLAS barrel calorimeter

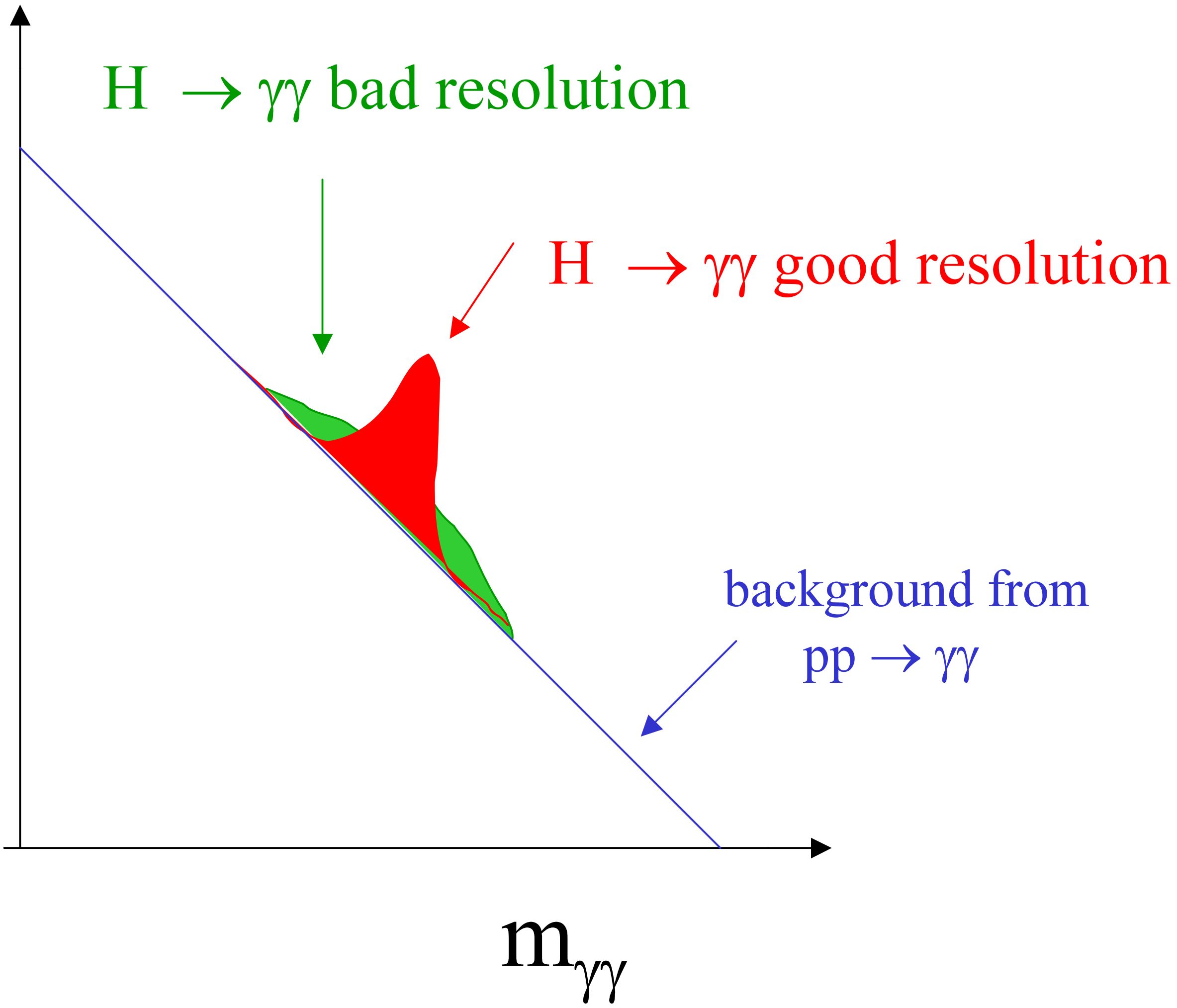
Assembly of CMS hadronic calorimeter

CMS magnet yoke ready

Examples of performance requirements

- Excellent energy resolution of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.

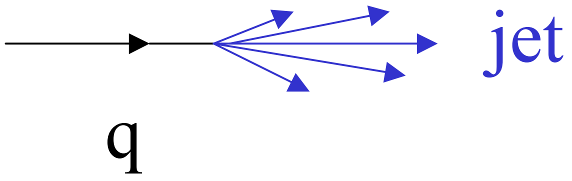
Example : $H \rightarrow \gamma\gamma$



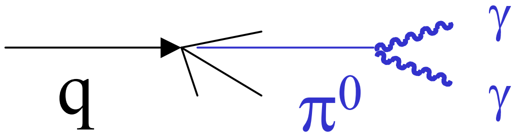
… see later ...

- Excellent particle identification capability:

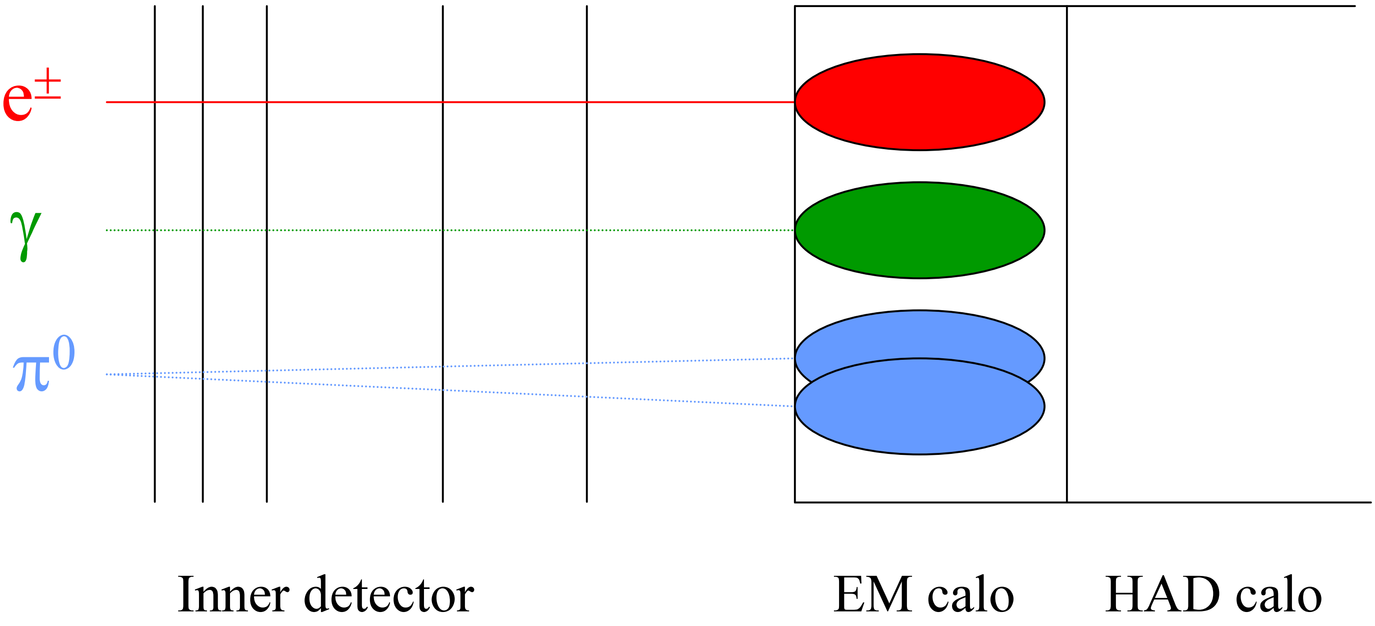
  e.g. e/jet , γ/jet separation



number and p_T of hadrons in a jet have large fluctuations



in some cases: one high-p_T π^0; all other particles too soft to be detected



d (γγ) < 10 mm in calorimeter → QCD jets can mimic photons. Rare cases, however:

$$\frac{\sigma_{jj}}{\sigma(H \to \gamma\gamma)} \sim 10^8 \qquad m_{\gamma\gamma} \sim 100 \text{ GeV}$$

⇒ need detector (calorimeter) with fine granularity to separate overlapping photons from single photons

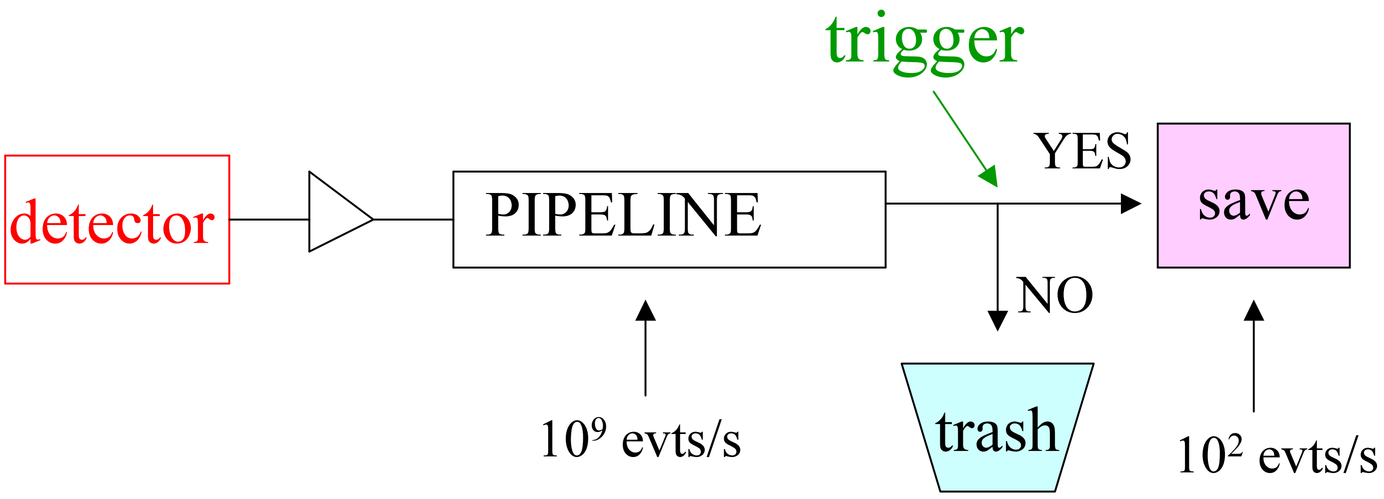
- Trigger : much more difficult than at e^+e^- machines

Interaction rate: ~ 10^9 events/second
Can record ~ 100 events/second
(event size 1 MB)

⇒ trigger rejection ~ 10^7

Trigger decision ≈ µs → larger than interaction rate of 25 ns

↳ store massive amount of data in pipelines while trigger performs calculations


trigger

detector

PIPELINE

YES

save

NO

trash

10^9 evts/s

10^2 evts/s

Summary of Part1

- LHC:

  pp machine (also Pb-Pb)
  $\sqrt{s} = 14$ TeV
  $L = 10^{33}$-10^{34} cm^{-2} s^{-1}
  Start-up : 2007

- Four large-scale experiments:

ATLAS, CMS	pp multi-purpose
LHCb	pp B-physics
ALICE	Pb-Pb

- Very broad physics programme thanks to high energy and luminosity: mass reach : ≤ 5 TeV

Few examples in next two lectures ...

Very difficult environment:

-- pile-up : ~ 25 soft events produced at each crossing.
Overlap with interesting high-p_T events.
-- large background from QCD processes (jet production): typical of hadron colliders

↓

Very challenging, highly-performing and expensive detectors:

- -- radiation hard
- -- fast
- -- granular
- -- excellent energy resolution and particle identification capability
- -- complicated trigger

End of Part 1