PHYSICS

AT

LHC

Large Hadron Collider

Summer student lectures
CERN, August 2001

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Outline

- Part 1

  What is the LHC ?

  Why the LHC ?

  Experimental challenges

  The experiments

- Part 2

  The physics programme

  Example 1 : Higgs searches

- Part 3

  Example 2 : SUSY searches

  Example 3: precision measurements (W mass, top mass)

PART 1

LHC

- pp machine (mainly):

$\sqrt{s}$ = 14 TeV ~ 7 times higher than present highest energy machine (Tevatron/Fermilab: 2 TeV)

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

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

~ 10^2 larger than present machines (LEP2, Tevatron)

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

- under construction → ready 2006
- will be installed in the existing LEP tunnel
- two phases:

2006 → 2007 : $L \approx 10^{33}$ cm^{-2} s^{-1} $\int Ldt \approx 10$ fb^{-1} (1 year)
"low luminosity"

2008 → 20xx : $L = 10^{34}$ cm^{-2} s^{-1} $\int Ldt \approx 100$ fb^{-1} (1year)
"high luminosity"

Four large-scale experiments:

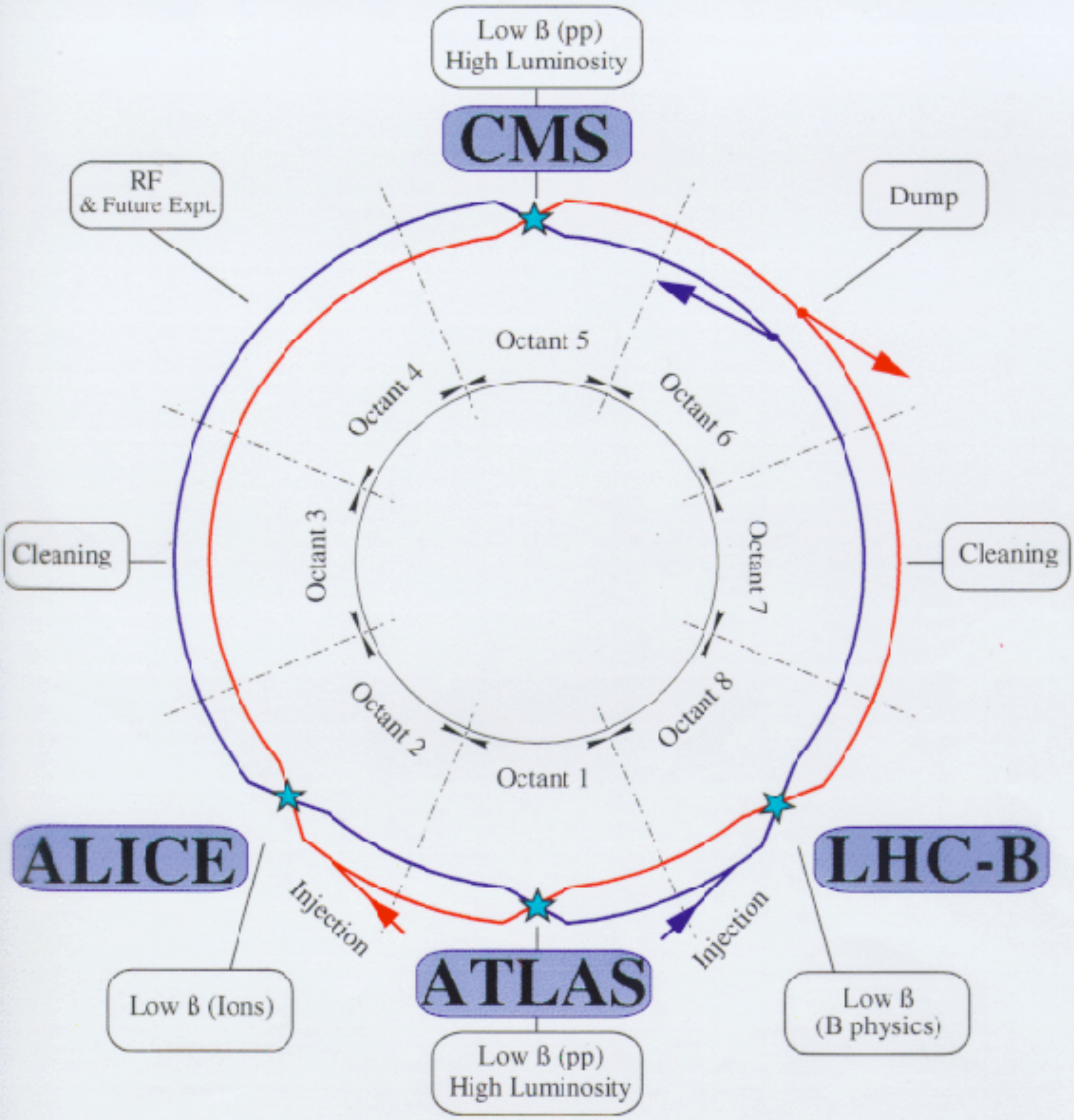
ATLAS
CMS
} general-purpose pp experiments

LHCb — pp experiment dedicated to b-quark physics and CP-violation
→ lectures of T. Nakada

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

Here : ATLAS and CMS

Note : LHC machine discussed in lectures of P. Lebrun


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

LHC layout

LHC is unprecedented machine in terms of:

- Energy ™ limited by B = 8.4 T of ~ 1300 superconducting dipoles working at 1.9 Kelvin (biggest cryogenic system in the world)

- Luminosity

- Cost : ≈ 3500 MCHF (machine + experiments)

- Size/complexity of experiments :
  ~ 1.3-2 times bigger than present collider experiments

- 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 LEP measurements at $\sqrt{s} = m_Z$ (see lectures of P. Wells) and 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 → ?

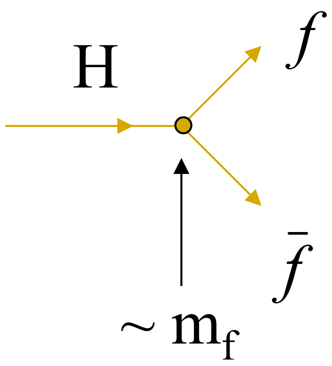
Note: particle masses determine our size

$$r \approx \frac{1}{m_e}$$

r: radius of hydrogen atom; m_e: electron mass

if m_e were 10 times larger, everything would be 10 times smaller !

SM : Higgs mechanism gives mass to particles
(electroweak symmetry breaking)



$m_H < 1$ TeV from theory

However:

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

-- present limit : $m_H > 114$ GeV (from LEP)

-- Tevatron may go beyond (depending on L)

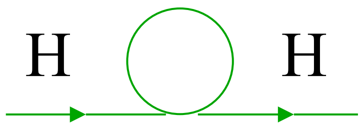
$\Rightarrow$ need a machine to discover/exclude Higgs from ≈ 120 GeV to 1 TeV

⬇

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

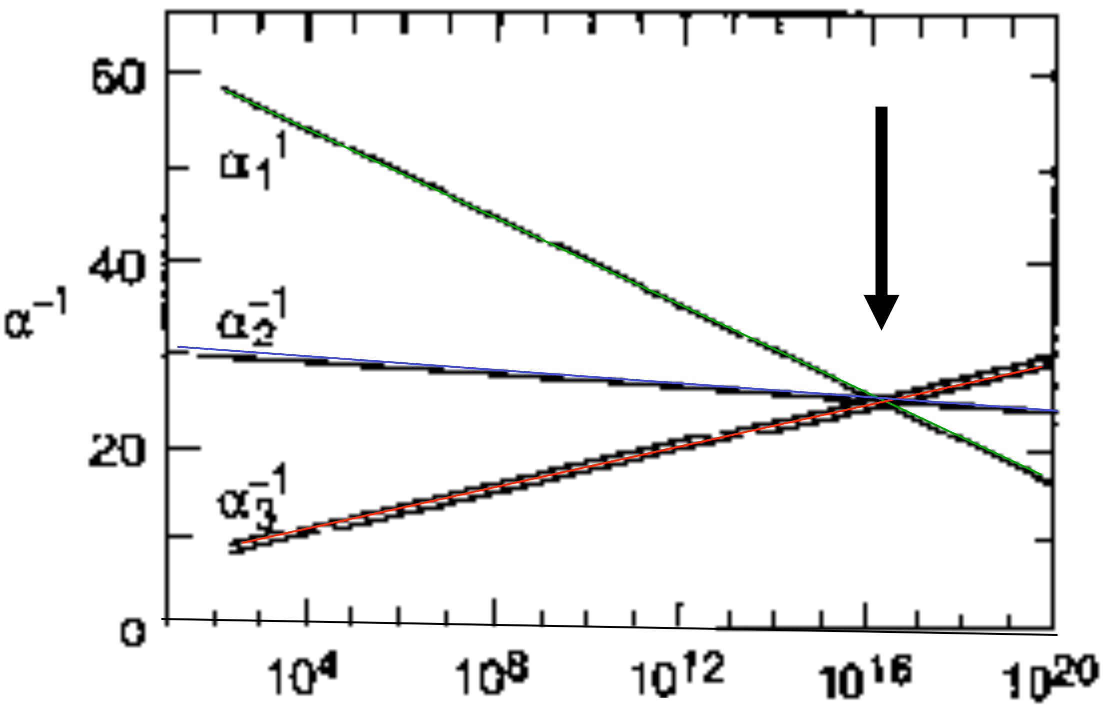
• Hints that forces could unify at high energy

$\alpha_{EM} \equiv \alpha_1 \approx 1/128 \approx 0.008$

$\alpha_{WEAK} \equiv \alpha_2 \approx 0.03$

$\alpha_S \equiv \alpha_3 \approx 0.12$

at $\sqrt{s} = 100$ GeV



E (GeV)

- E-dependence of coupling constants proven experimentally
- Grand Unified Theories: EM/Weak/Strong forces unify at $E \sim 10^{16} \rightarrow$ 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

- 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 ?
- 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 ?
- What is the nature of QCD confinement ?
- 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 $\Rightarrow$ find deviations from SM

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

Ex. :

5×10^8 $W \rightarrow \ell\nu$
5×10^7 $Z \rightarrow \ell\ell$
10^7 $t\bar{t}$ pairs
10^{12} $b\bar{b}$ pairs

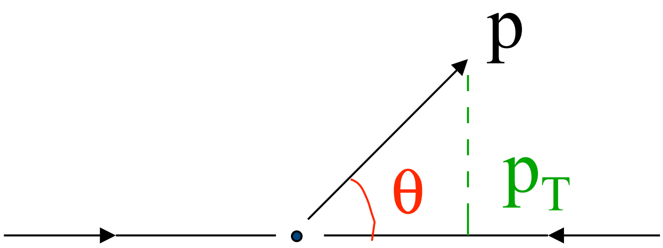
} per year at low L

$\rightarrow$ many precision measurements possible thanks to large statistics (stat. error ~ $1/\sqrt{N}$)

Note : measurements of Z parameters performed at LEP and SLD, however precision can be improved for :

-- W physics
-- Triple Gauge Couplings $WW\gamma$, WWZ
-- b-quark physics
-- top-quark physics

Phenomenology of pp collisions



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

$$p_T = p \sin\theta$$

Rapidity:

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

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

Total inelastic cross-section:

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

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

L: $10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$

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

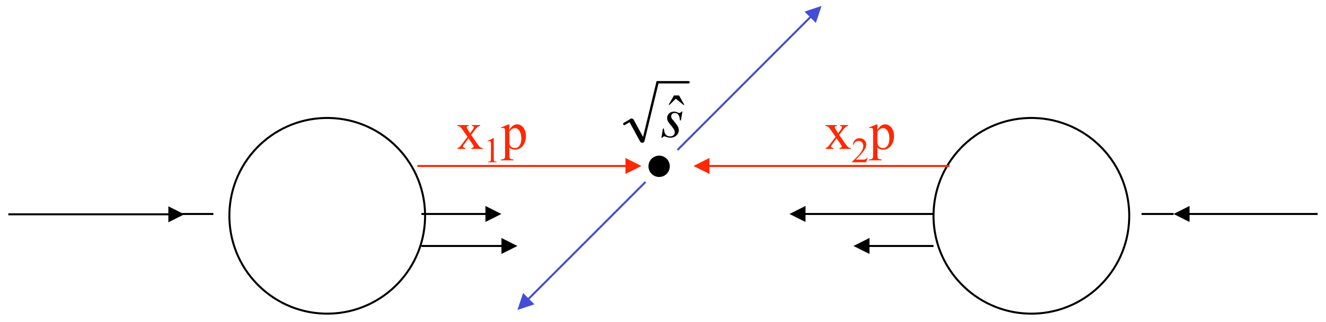
$\frac{dN}{d\eta} \approx 7$ charged particles uniformly distributed in ϕ

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.

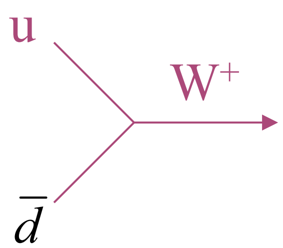


p ≡ momentum of incoming protons = 7 TeV

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

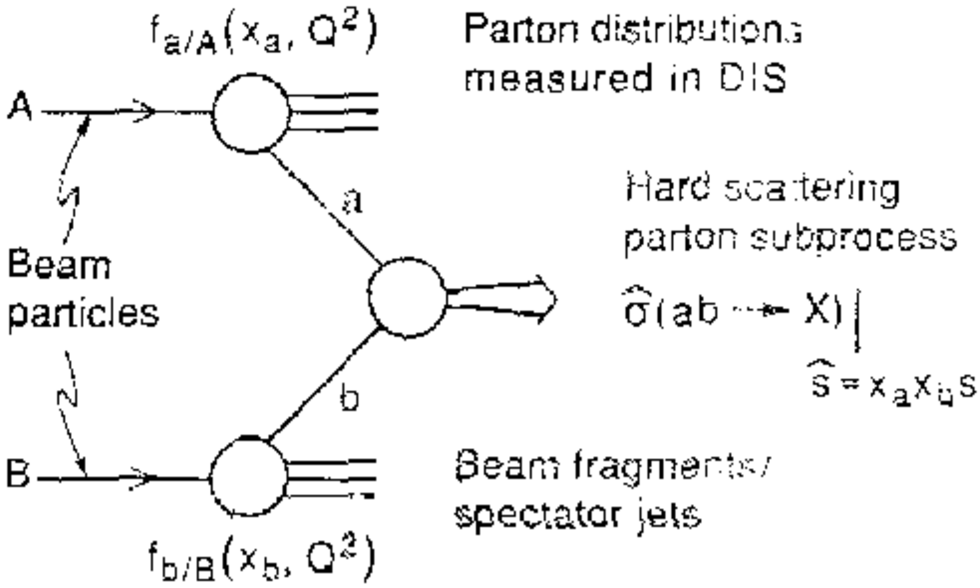
These are interesting physics events but they are rare.

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 $\sqrt{s}$ of colliding beams:

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

if $x_a \approx x_b$

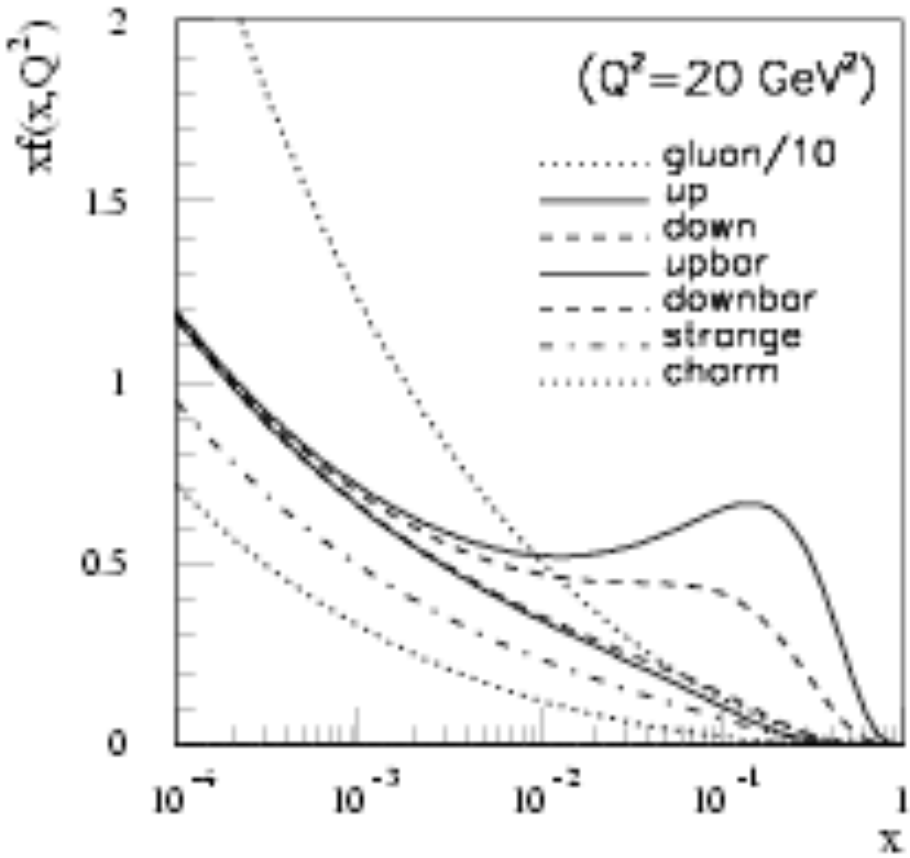
$\rightarrow$ to produce m ≈ 100 GeV $\quad x \sim 0.01$
to produce m ≈ 5 TeV $\quad x \sim 0.35$

- 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

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

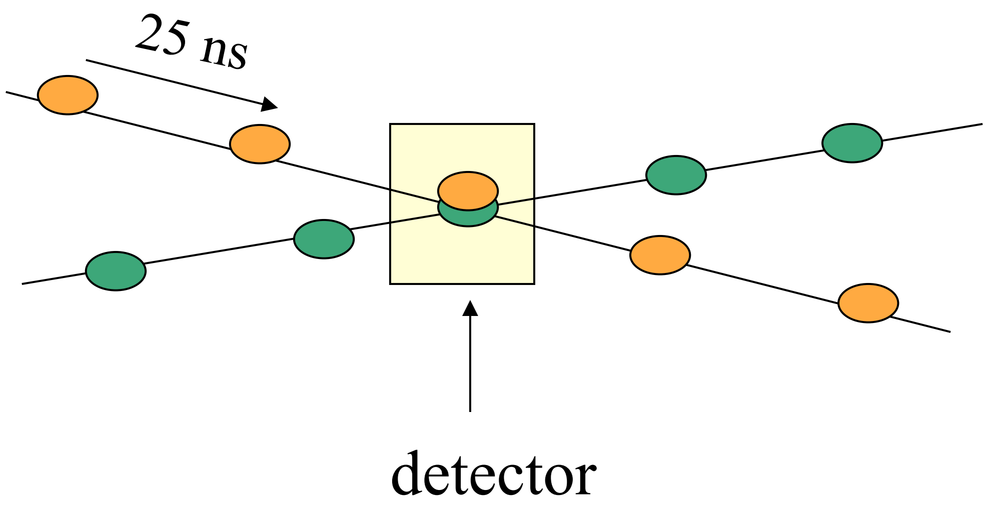


p ≡ uud

Two main difficulties

❶ $R = L\sigma = 10^9$ interactions / second

Protons are grouped in bunches (of $\approx 10^{11}$ protons) colliding at interaction points every 25 ns



⇒ 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.

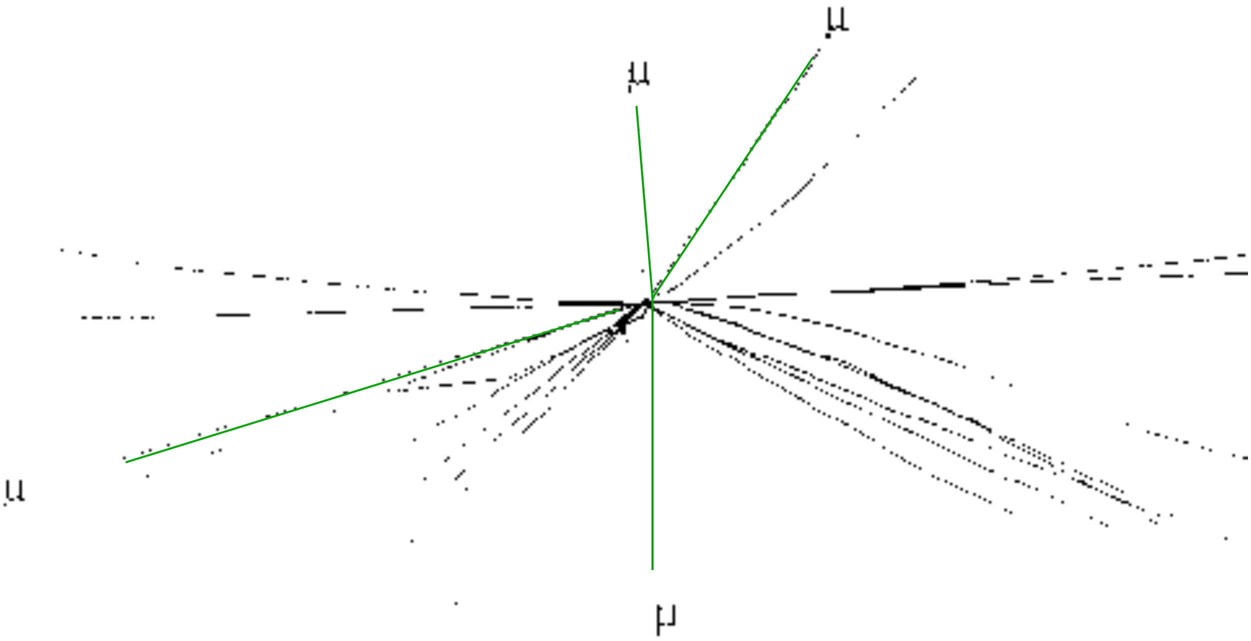
However $< p_T > \approx 500$ MeV (particles from minimum-bias).

→ 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:

  up to 10^{17} n / cm^2
  up to 10^7 Gy
  } in 10 years of LHC operation

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

Radiation damage :

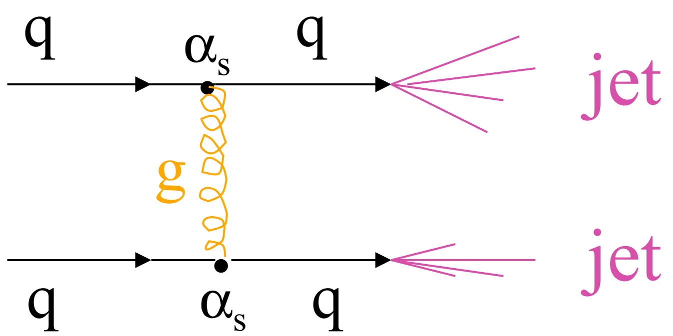
-- decreases like d^2 from the beam $\rightarrow$ detectors nearest to beam pipe are more affected

-- need also radiation hard electronics (military-type technology)

-- need quality control for every piece of material

-- detector + electronics must survive 10 years of operation

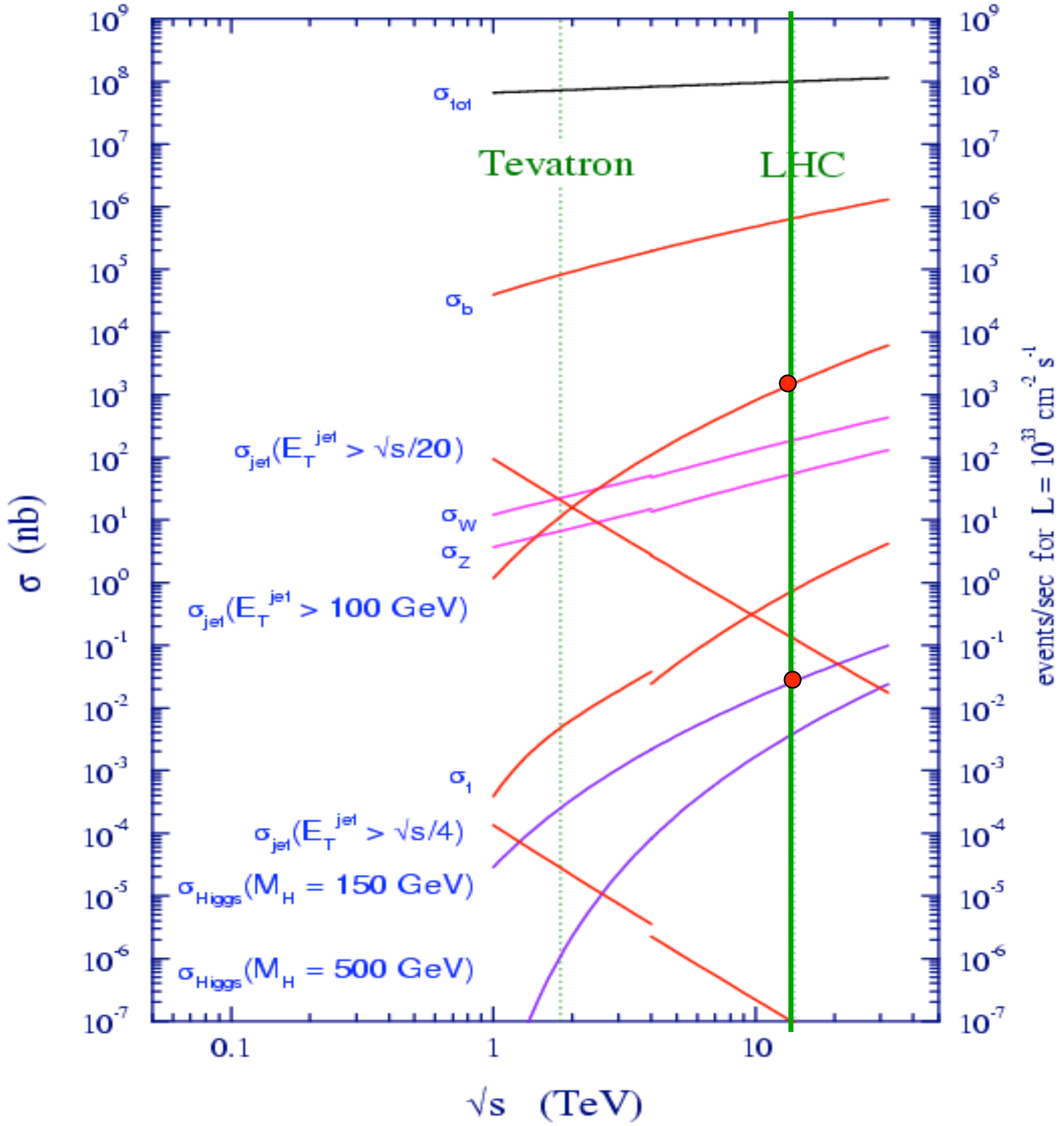
❷ High-p_T events dominated by QCD jet production:



- 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 → jet jet) ≈ 70%
BR (W → $\ell\nu$) ≈ 30%

ATLAS and CMS detectors

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

$e, \mu, \tau, \nu, \gamma$, jets, b-quarks, ….

⇒ " multi-purpose" experiments.

- Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) are measured in central tracker (Silicon layers plus gas detectors).

- Energy and positions of electrons and photons measured in electromagnetic calorimeters.

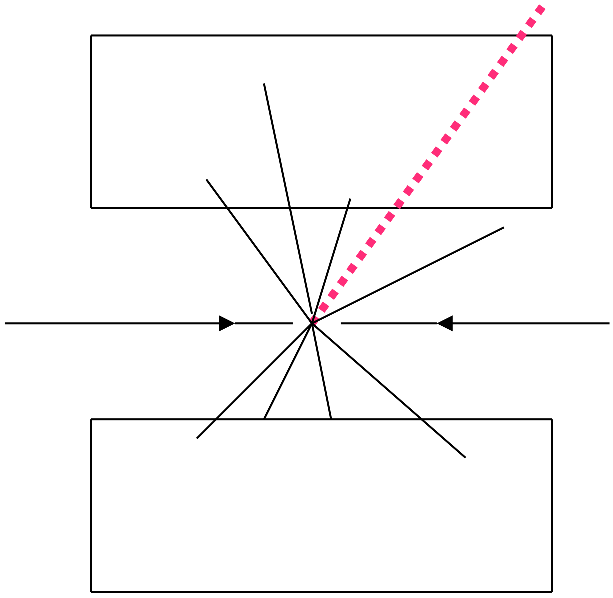
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters.

- Muons identified and momentum measured in external muon spectrometer (+ central tracker).

- Neutrinos "detected and measured" through measurement of missing transverse energy (E_T^{miss}) in calorimeters.

Detection and measurement of neutrinos

- Neutrinos traverse the detector without interacting
  $\rightarrow$ not detected directly



- Can be detected and measured asking:

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

total energy, momentum reconstructed in final state (for $E_f, \vec{P}_f$)

total energy, momentum of initial state (for $E_i, \vec{P}_i$)

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

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

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

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

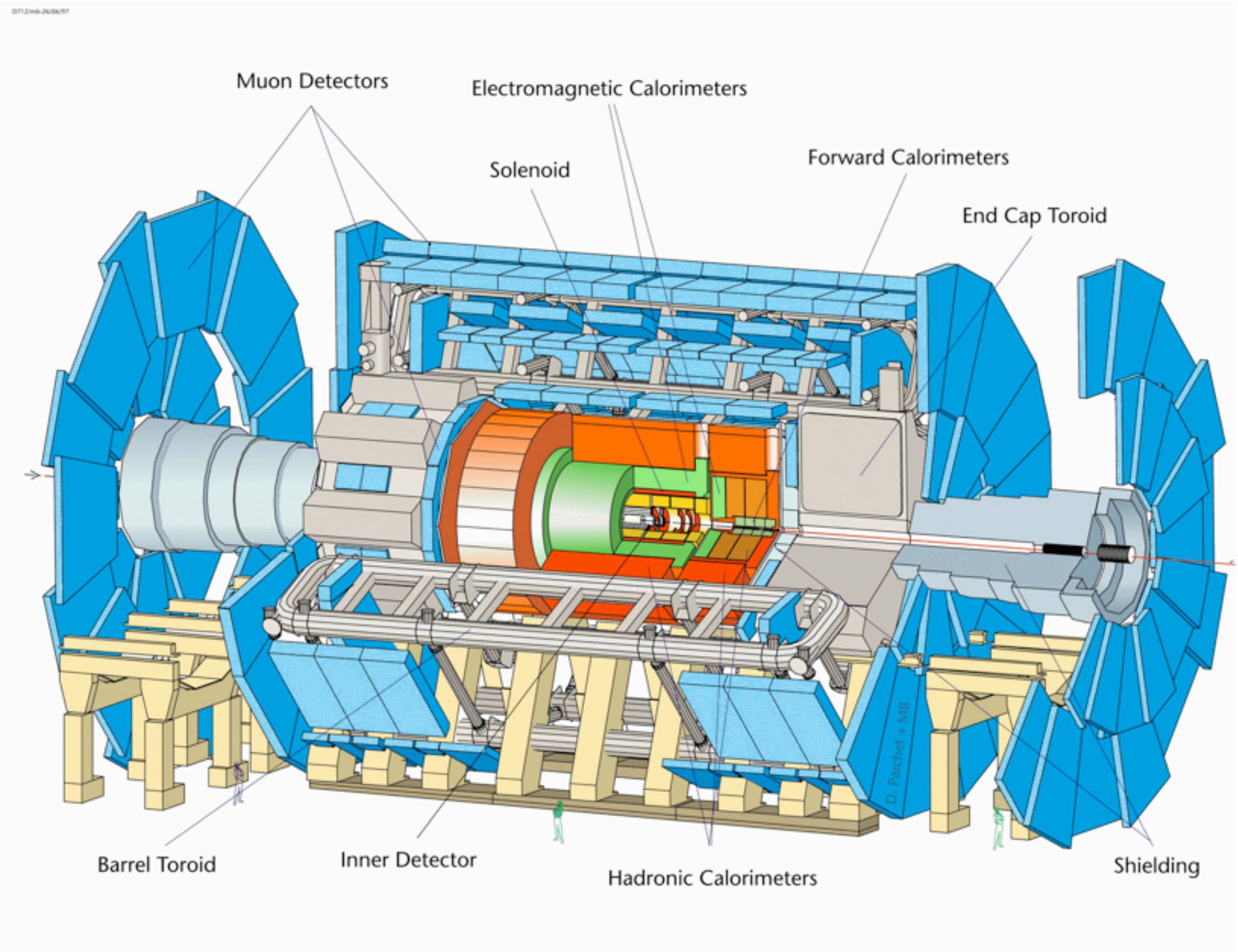
However: transverse momentum $\vec{P}_{Ti} = 0$

$\rightarrow$ if a neutrino produced $\vec{P}_{Tf} \neq 0$ ($\rightarrow$ missing transverse momentum) and

$$|\vec{P}_{T\nu}| = |\vec{P}_{Tf}| = E_T^{miss}$$

ATLAS

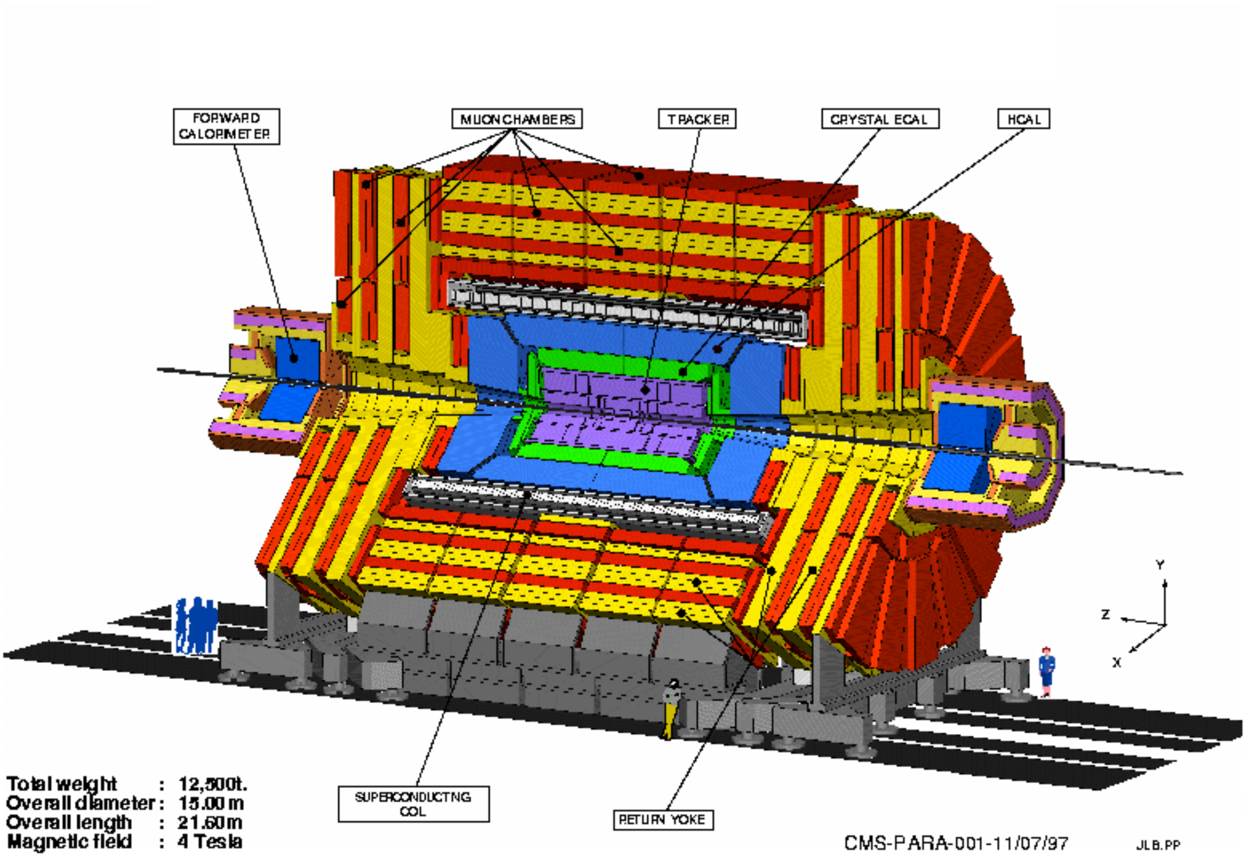
A Toroidal Lhc ApparatuS



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

CMS

Compact Muon Solenoid

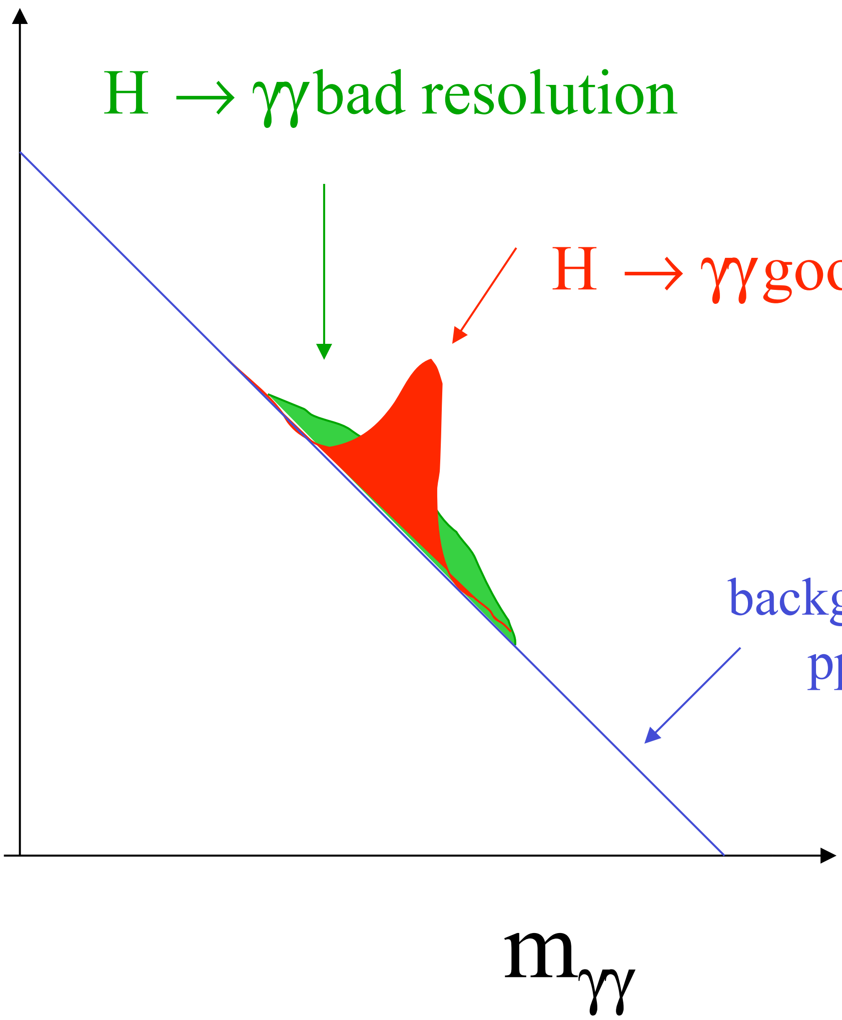


Length : 20 m Radius : 7 m Weight : 14000 tons Electronics channels : 10^8

Examples of performance requirements

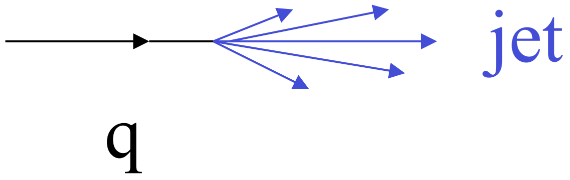
- Excellent energy resolution of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.

Example : $H \to \gamma\gamma$

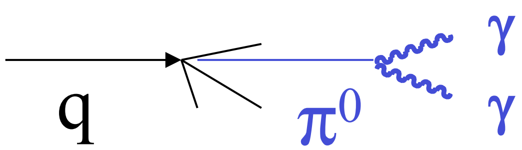


… see later ...

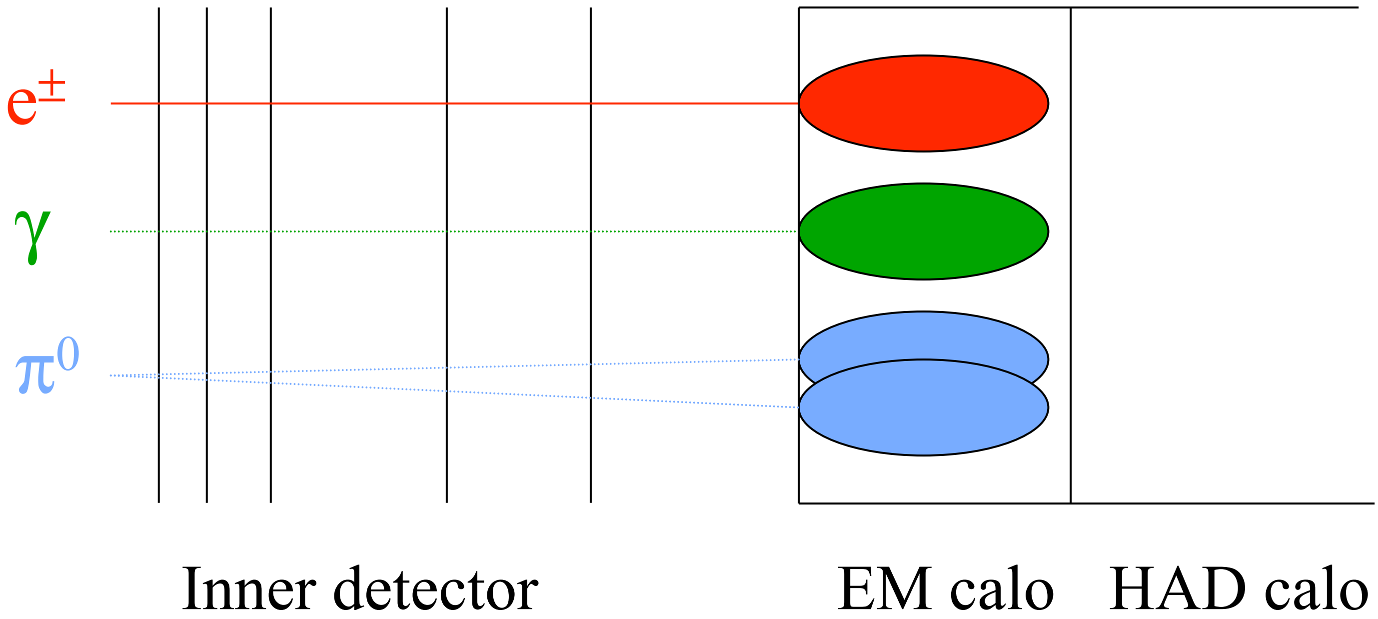
- Excellent particle identification capability:
  e.g. e/jet , γ/jet separation



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

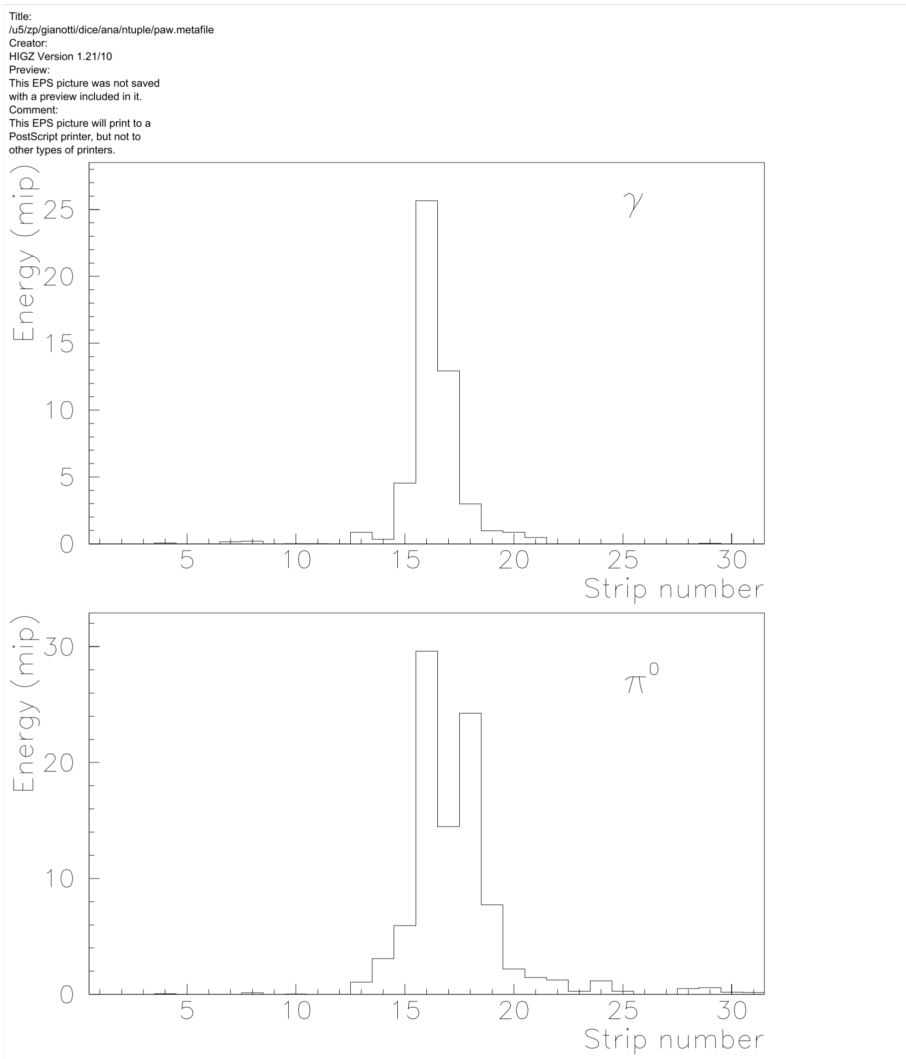


d ($\gamma\gamma$) < 10 mm in calorimeter → QCD jets can mimic photons. Rare cases, however:

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

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

ATLAS EM calorimeter : 4 mm strips in first compartment



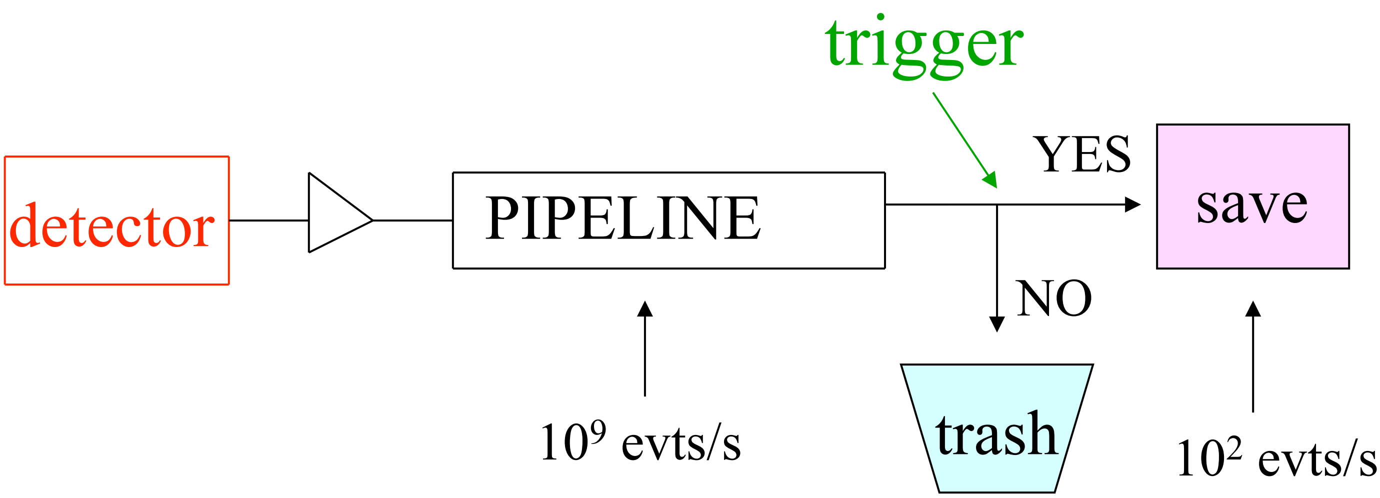
• Trigger : much more difficult than at e^+e^- machines

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



Summary of Part1

- LHC:
  pp machine (also Pb-Pb)
  $\sqrt{s}$ = 14 TeV
  $L = 10^{33}\text{-}10^{34}\ cm^{-2}\ s^{-1}$
  Start-up : 2006

- 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