Physics at

LHC

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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 : Precise measurements and Higgs searches

  Measurements of the W and top masses

  Higgs searches

- Part 3 : Physics beyond the Standard Model

  Motivations

  Searches for SUSY

  Searches for Extra-dimensions

At LEP, Tevatron and LHC

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

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

~ 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"

Four large-scale experiments:

ATLAS

CMS

} general-purpose pp experiments

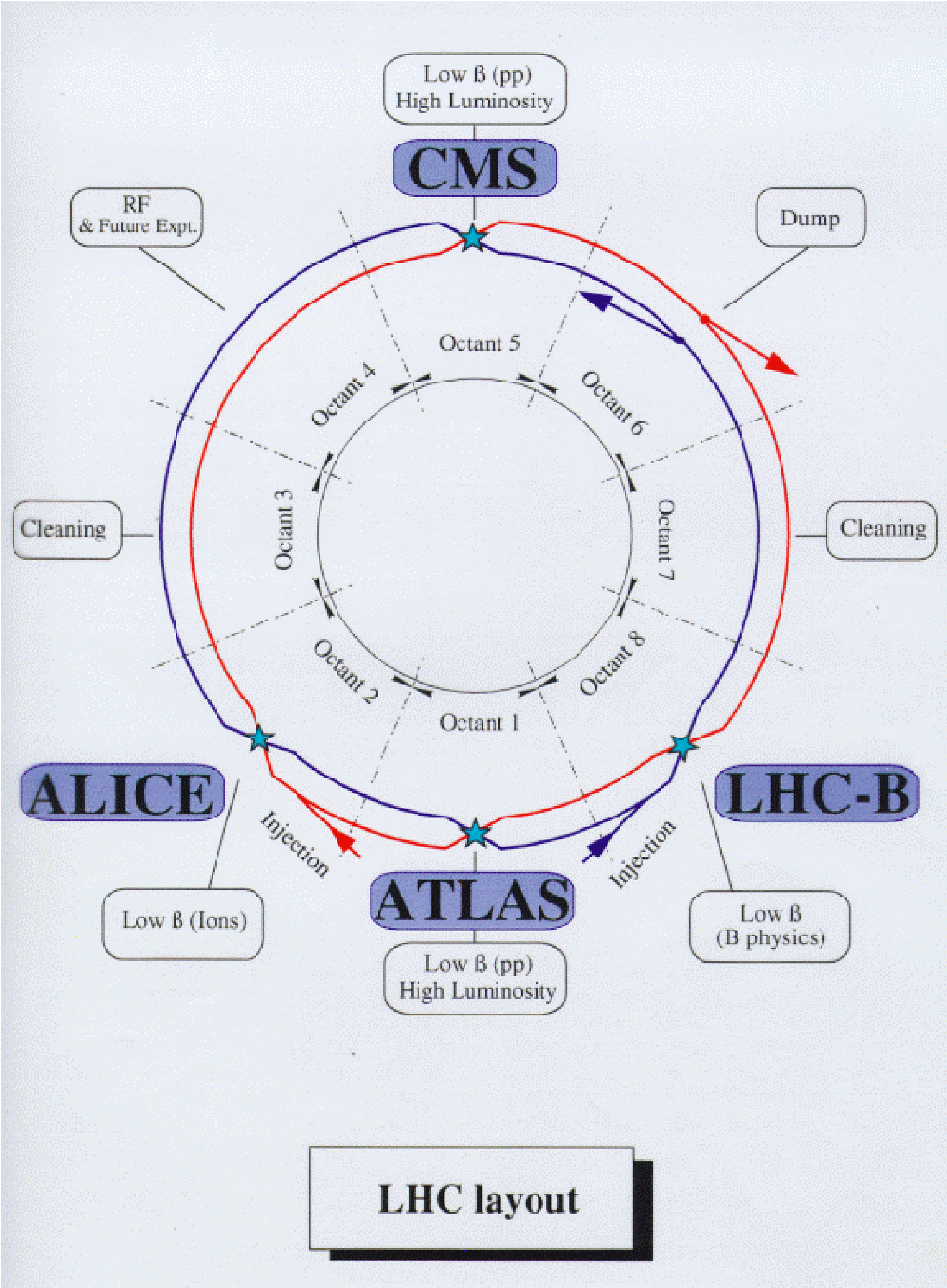
LHCb

pp experiment dedicated to b-quark physics and CP-violation. $L=10^{32}$ cm^{-2} s^{-1}

ALICE

heavy-ion experiment (Pb-Pb collisions) at 5.5 TeV/nucleon → $\sqrt{s}$ 1000 TeV
Quark-gluon plasma studies.
$L=10^{27}$ cm^{-2} s^{-1}

Here : ATLAS and CMS


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

A few machine parameters

Energy	E	[TeV]	7.0
Dipole field	B	[T]	8.4
Luminosity	L	[cm^{-2} s^{-1}]	10^{34}
Beam–beam parameter	ξ		0.0034
Total beam–beam tune spread			0.01
Injection energy	E_i	[GeV]	450
Circulating current/beam	I_{beam}	[A]	0.53
Number of bunches	k_b		2835
Harmonic number	h_{RF}		35640
Bunch spacing	τ_b	[ns]	24.95
Particles per bunch	n_b		$1.05\ 10^{11}$
Stored beam energy	E_s	[MJ]	334
Normalized transverse emittance $(\beta\gamma)\sigma^2/\beta$	ε_n	[μm.rad]	3.75
Collisions			
β-value at I.P.	β^*	[m]	0.5
r.m.s. beam radius at I.P.	σ^*	[μm]	16
r.m.s. divergence at I.P.	σ'^*	[μrad]	32
Luminosity per bunch collision	L_b	[cm^{-2}]	$3.14\ 10^{26}$
Crossing angle	ϕ	[μrad]	200
Number of events per crossing	n_c		19
Beam lifetime	τ_{beam}	[h]	22
Luminosity lifetime	τ_L	[h]	10

Limiting factor for √s : bending power needed to fit ring in 27 km circumference LEP tunnel:

$$p\ (\text{TeV}) = 0.3\ B(\text{T})\ R(\text{km})$$

= 7 TeV　　　　　　　　= 4.3 km

LHC : B=8.4 T : ~ 1300 superconducting dipoles working at 1.9 K (biggest cryogenic system in the world)

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

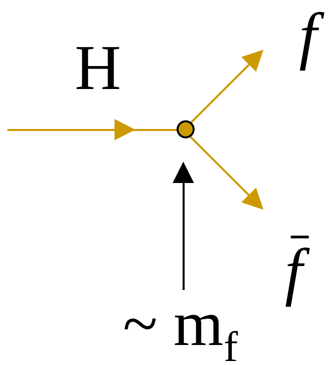
Standard Model of electroweak interactions verified with precision 10^{-3} - 10^{-4} by LEP measurements at $\sqrt{s} \geq m_Z$ and Tevatron at $\sqrt{s}$ = 1.8 TeV.

discovery of top quark in '94,
m_{top} 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

For m_H 1TeV $\Gamma_H > m_H$ and

WW scattering violates unitarity

However:

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

-- present limit : $m_H > 114.1$ GeV (from LEP)

-- "hint" at LEP for $m_H \approx 115$ GeV

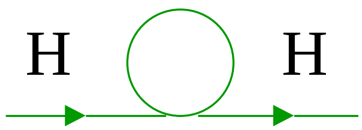
-- Tevatron may go beyond (depending on L)

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

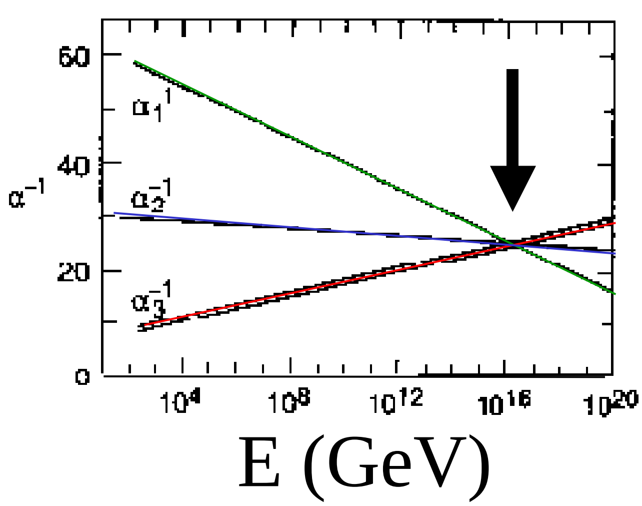


$\Delta m_H^2 \sim \Lambda^2$

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 $E \sim 10^{16}$ GeV



$\alpha_1 = \alpha_{EM} \approx 1/128$
$\alpha_2 = \alpha_{WEAK} \approx 0.03$
$\alpha_2 = \alpha_S \approx 0.12$
} $\sqrt{s} \sim 100$ GeV

Running of couplings proven experimentally

GUT: for $E > 10^{16}$ GeV 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 ($\rightarrow$ high σ) and L ($\rightarrow$ high rate)

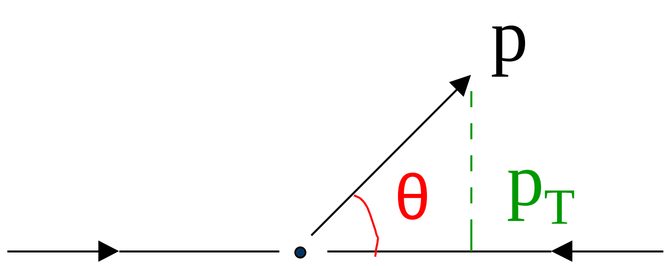
Ex. :

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

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

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:

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

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

Total inelastic cross-section:

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

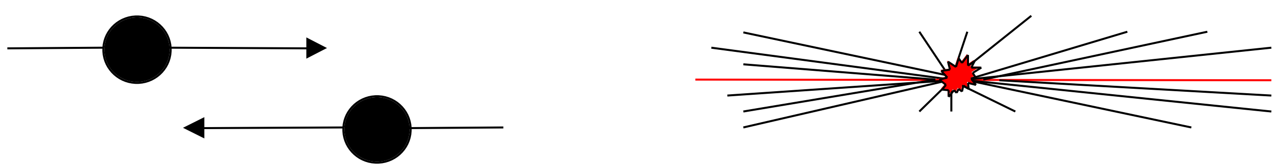
Rate = $\dfrac{\text{n. events}}{\text{second}}$ = L x σ_{tot} (pp) = 10^9 interactions/s

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

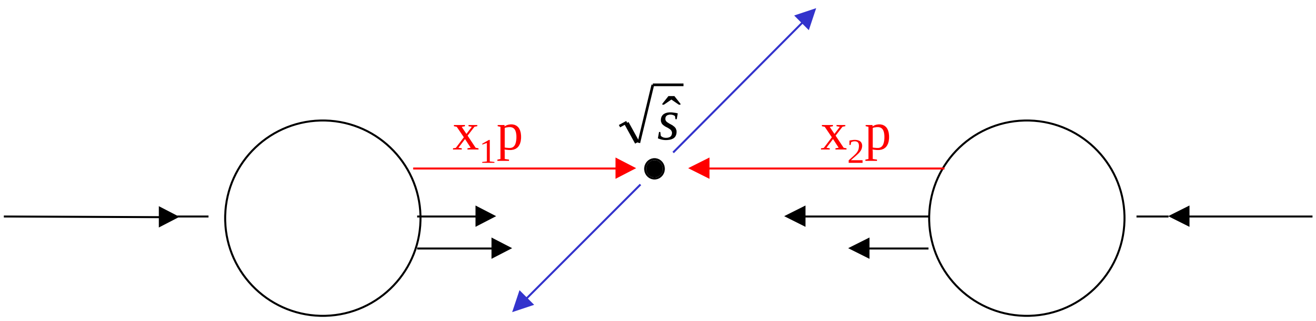
$\frac{dN}{d\eta}$ 7 charged particles uniformly distributed in φ

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.

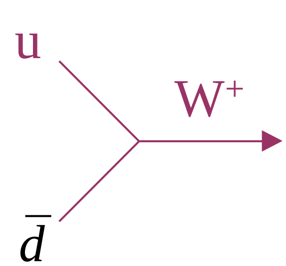


p ≡ momentum of incoming protons = 7 TeV

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

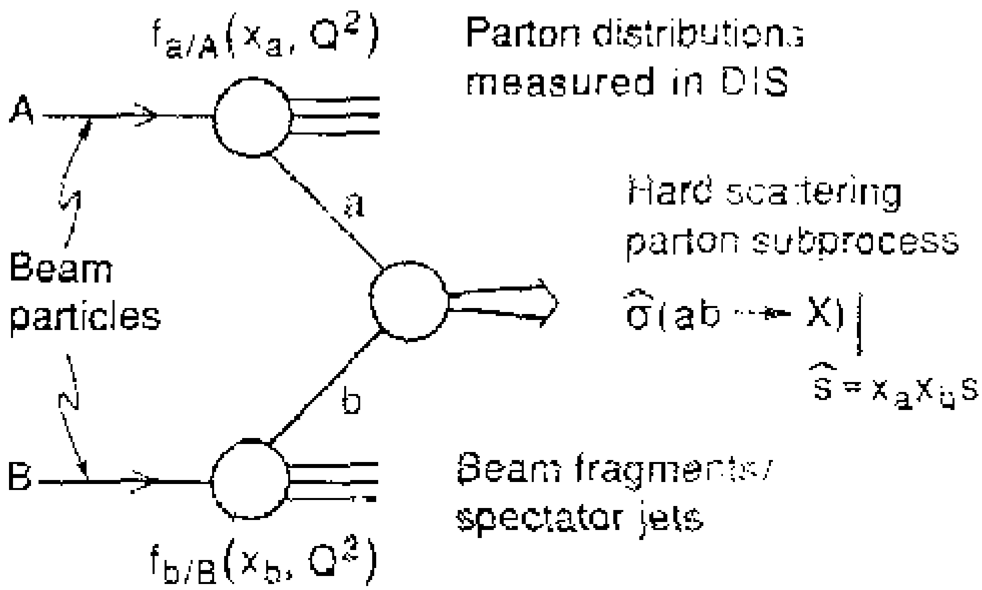
These are interesting physics events but they are rare.

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 √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 $x_a \approx x_b$

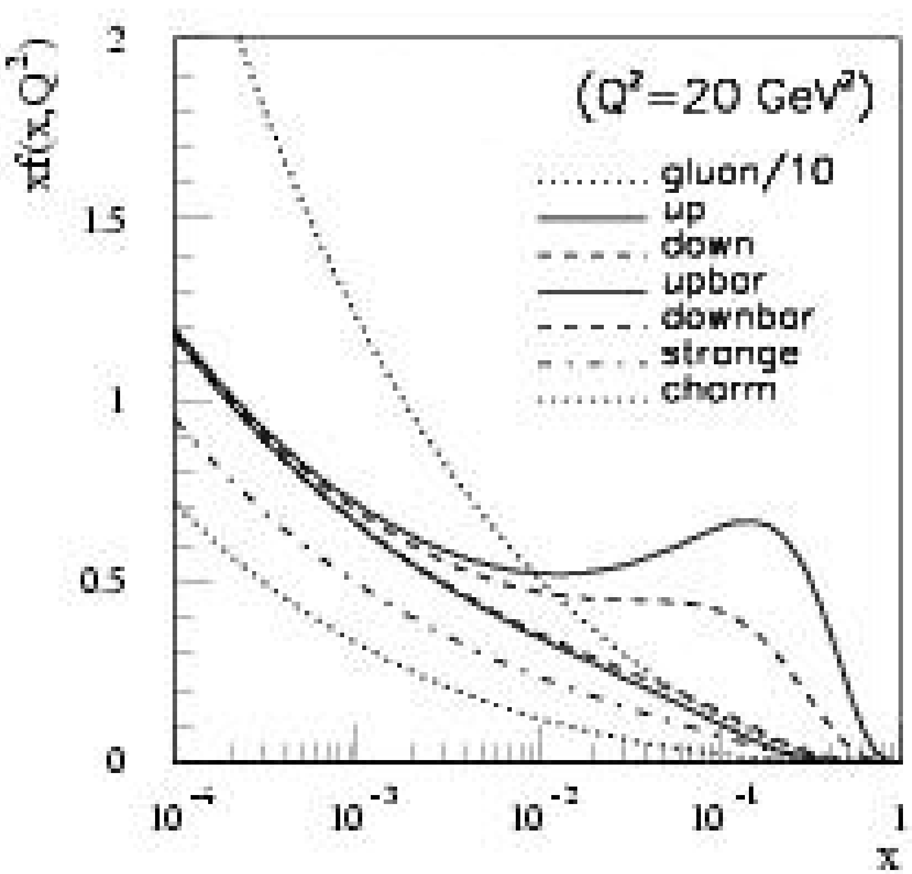
→ to produce m ≈ 100 GeV   x ~ 0.01
to produce m ≈ 5 TeV   x ~ 0.35

- cross-section :

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

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

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

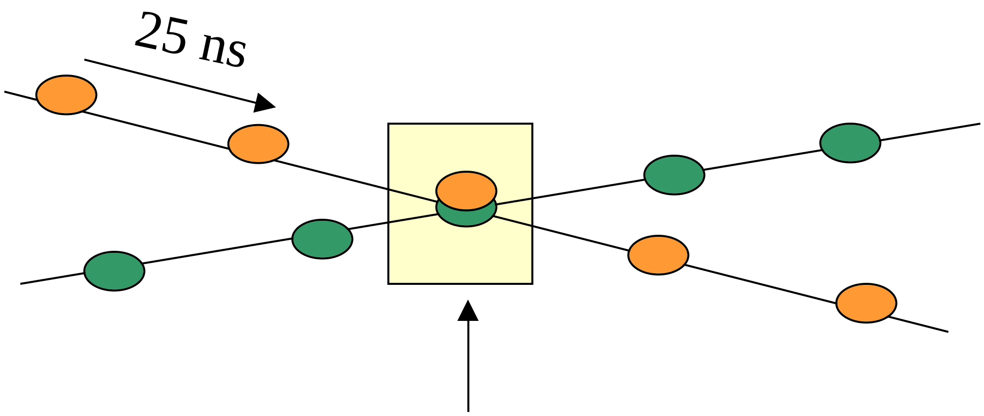


p ≡ uud

Two main difficulties

- Typical of LHC:

$R = L\sigma = 10^9$ interactions / second
Protons are grouped in bunches (of ≈ 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

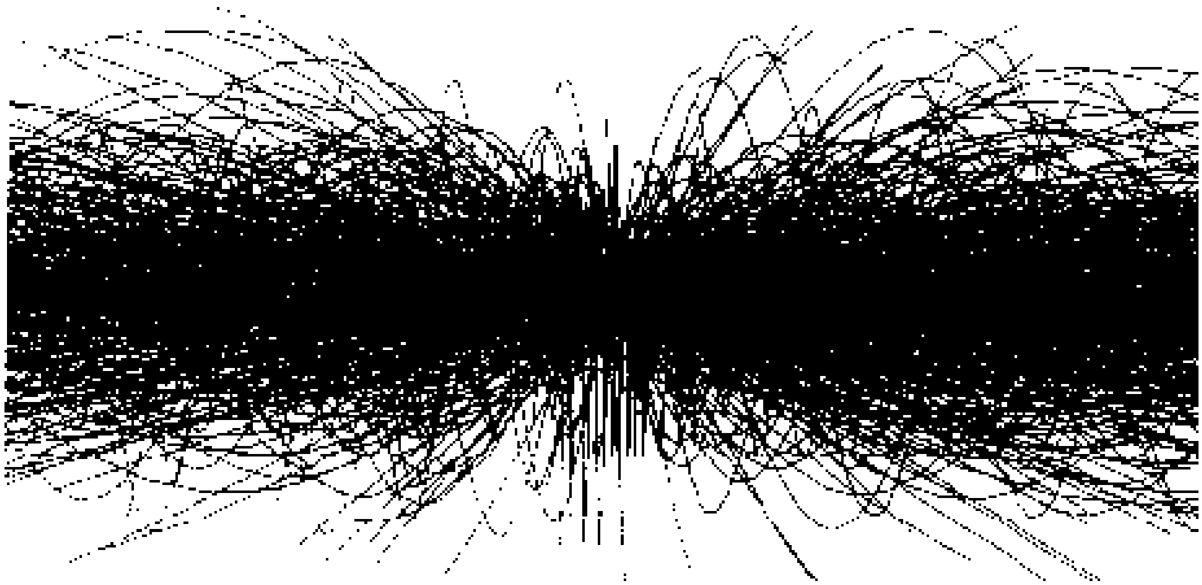
~1000 charged particles produced over $|\eta| < 2.5$ at each crossing.

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

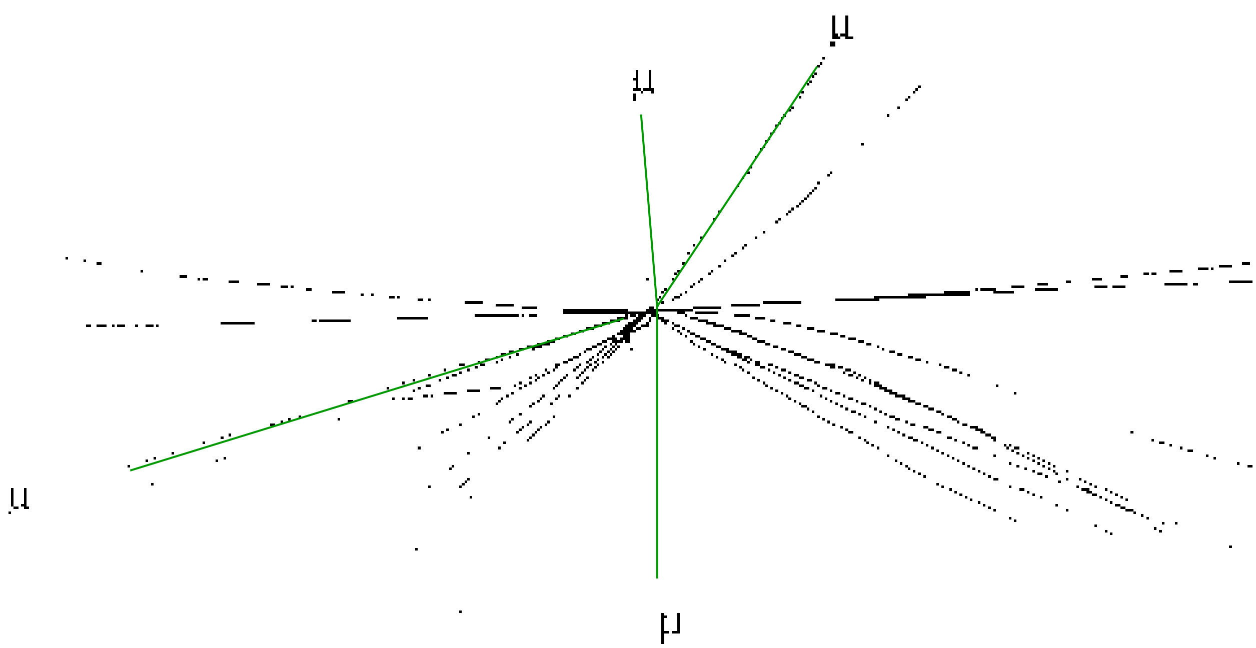
→ applying p_T cut allows extraction of interesting particles

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:

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 :

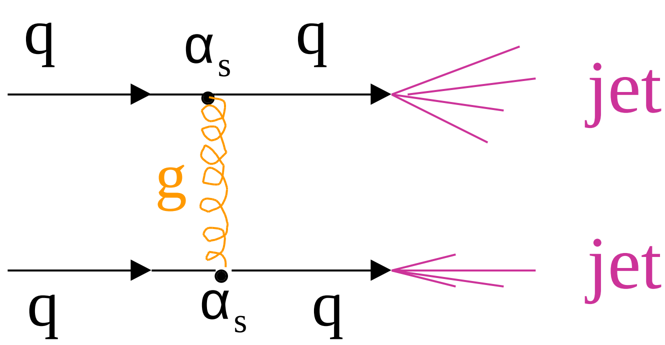
-- decreases like d^2 from the beam → detectors nearest to beam pipe are more affected

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

-- need quality control for every piece of material

-- detector + electronics must survive 10 years of operation

- <u>Common to all hadron colliders:</u>
  high-p_T events dominated by QCD jet production:

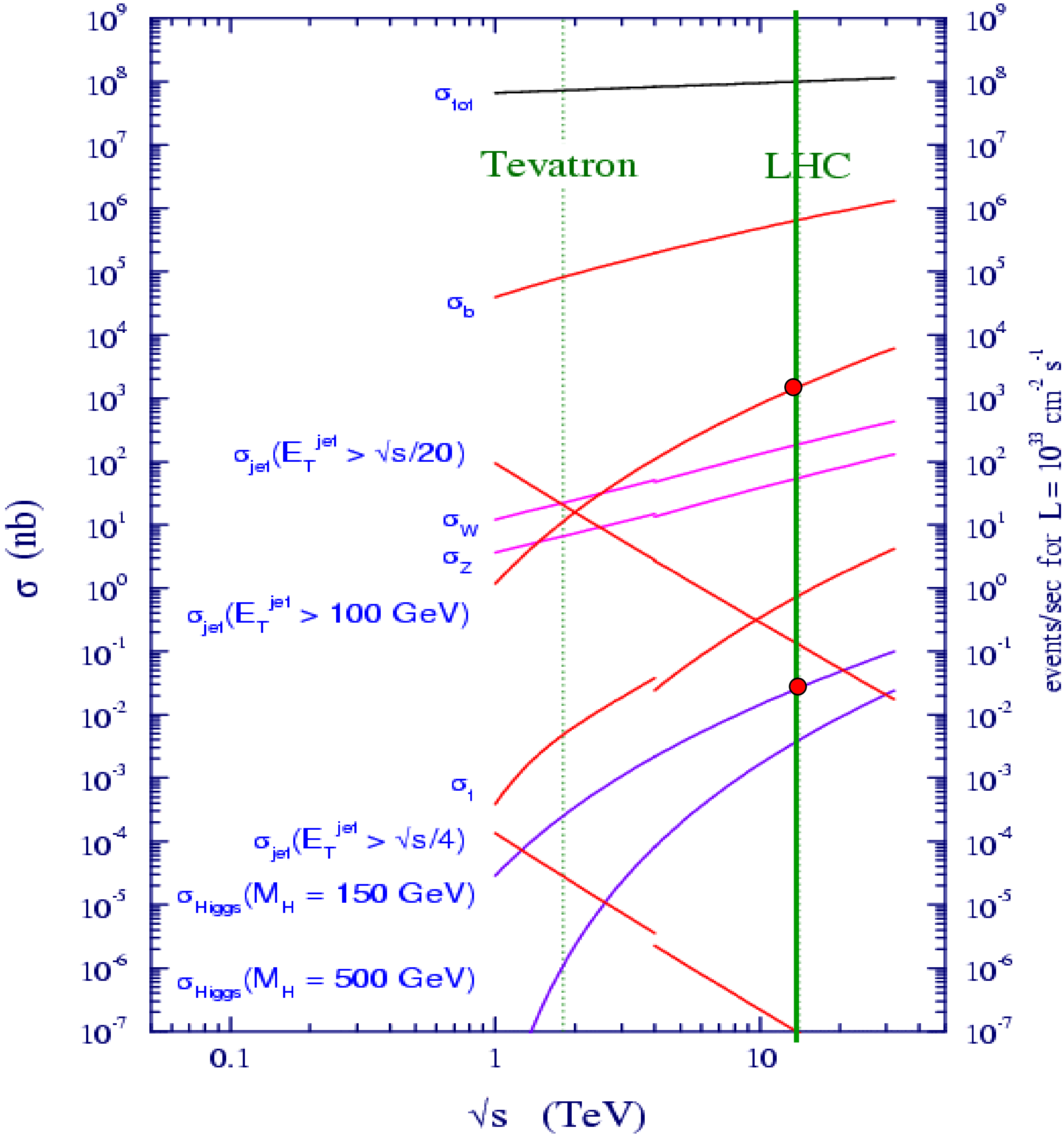


- Strong production → large cross-section
- Many diagrams contribute: qq → qq, qg → qg, gg → gg, etc.
- Called “ QCD background “

Most interesting processes are <u>rare processes</u>:

- 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. Excellent momentum and position resolution required.

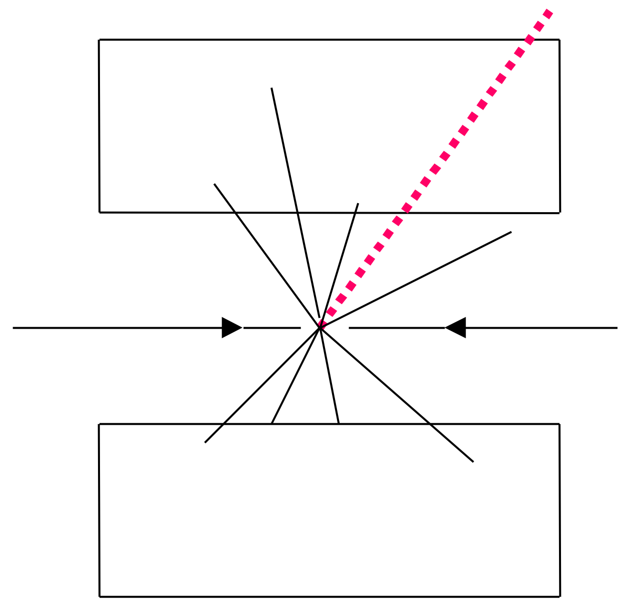
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent resolution and particle identification required.

- 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 $|\eta|<5$ needed.

Detection and measurement of neutrinos



- Neutrinos traverse the detector without interacting
  → not detected directly

- Can be detected and measured asking:

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

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 $\vec{P}_f$? 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.

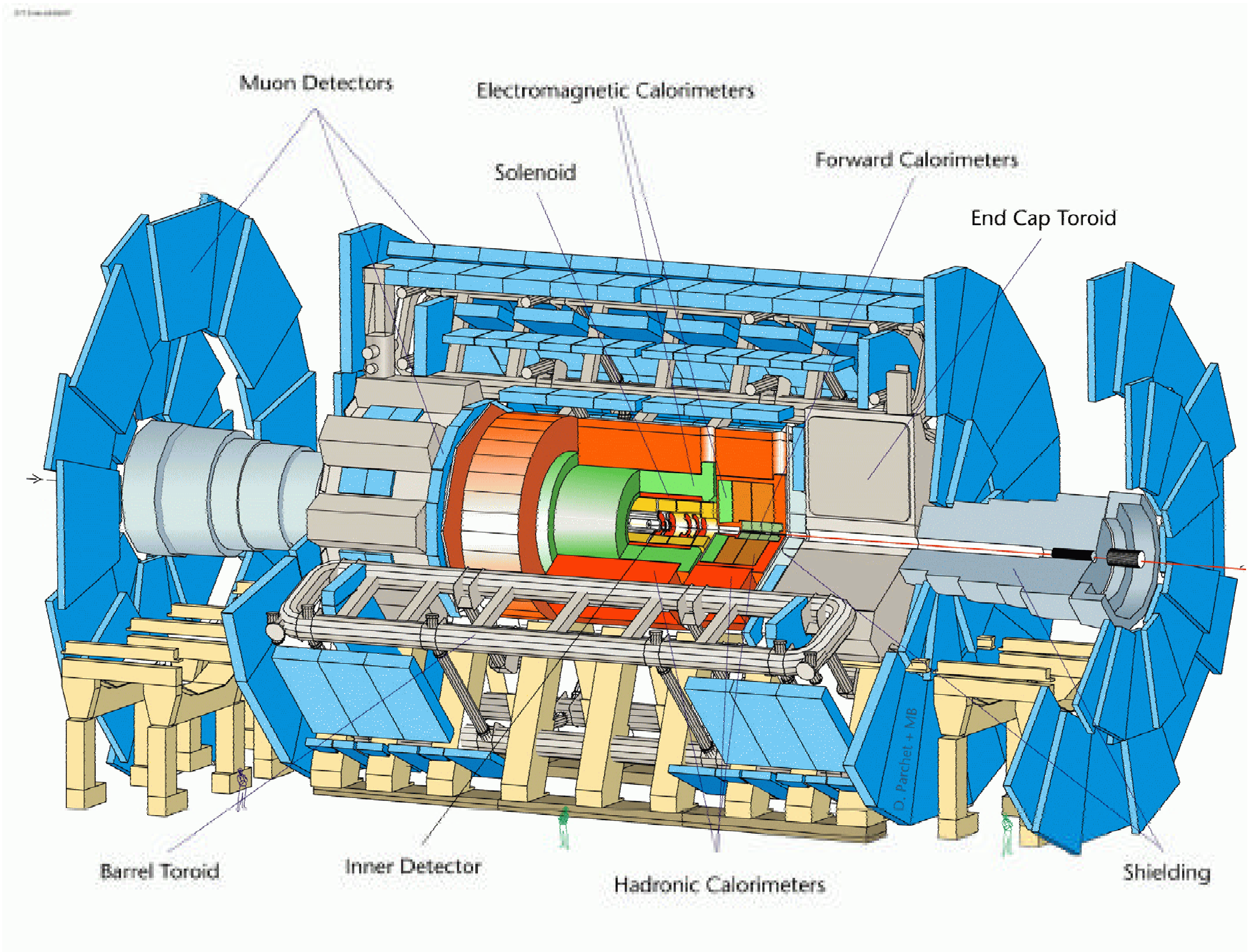
However: transverse momentum $\vec{P}_{T\,i} = 0$

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

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

ATLAS

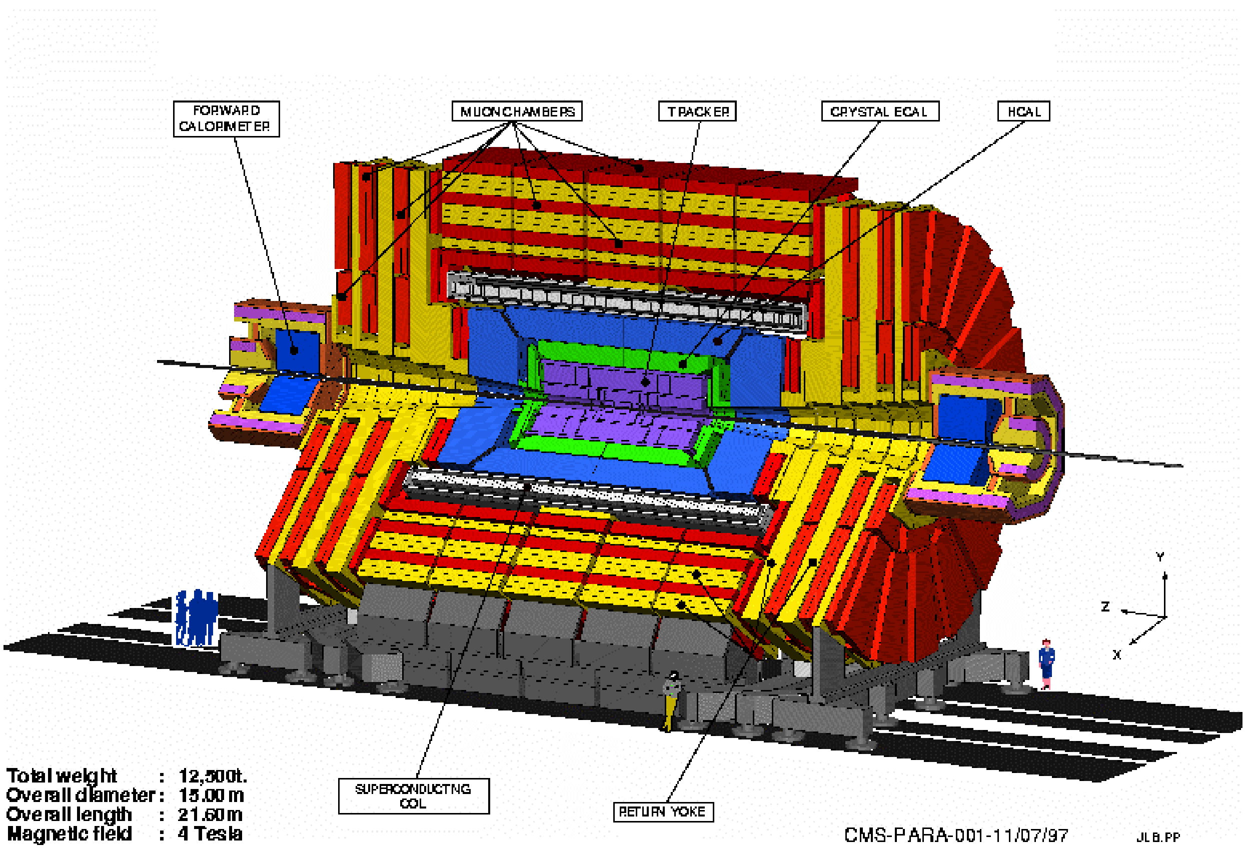
A Toroidal Lhc ApparatuS



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

CMS

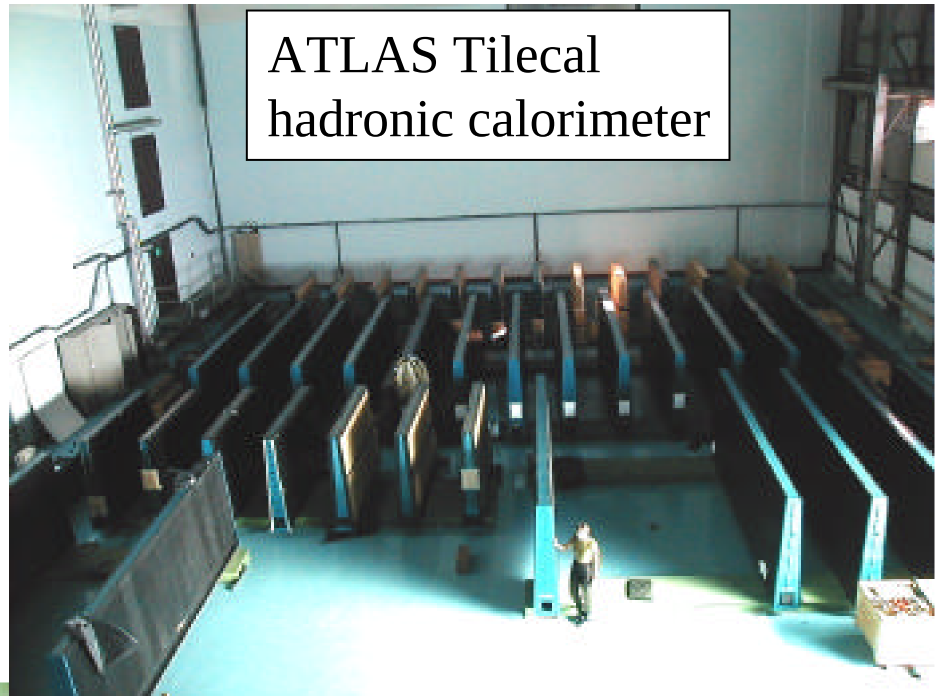
Compact Muon Solenoid

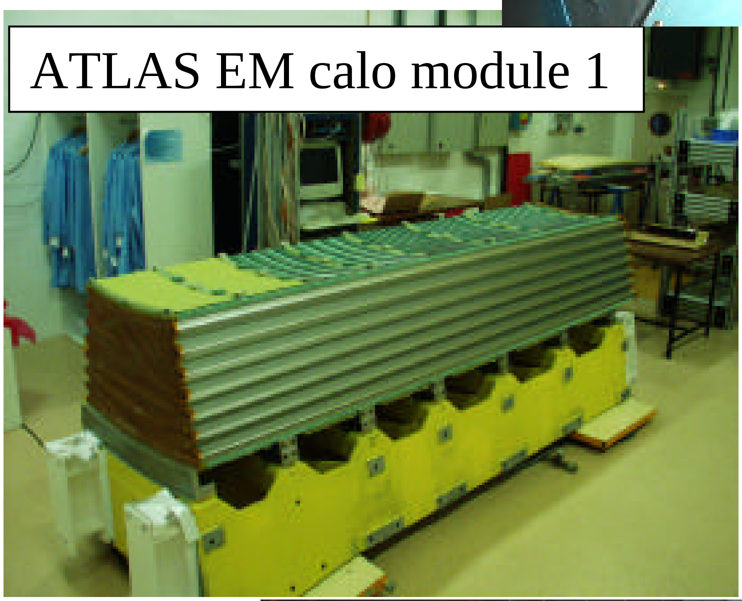


Length : 20 m
Radius : 7 m
Weight : 14000 tons
Electronics channels : 10^8

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRD → particle identification B=2T $\sigma/p_T \sim 5x10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5x10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 70\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7\ \%$ at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

Fabiola Gianotti, Physics at LHC, Pisa, April 2002


ATLAS Tilecal
hadronic calorimeter


ATLAS EM calo module 1


ATLAS solenoid ready

Assembly of CMS hadronic calorimeter

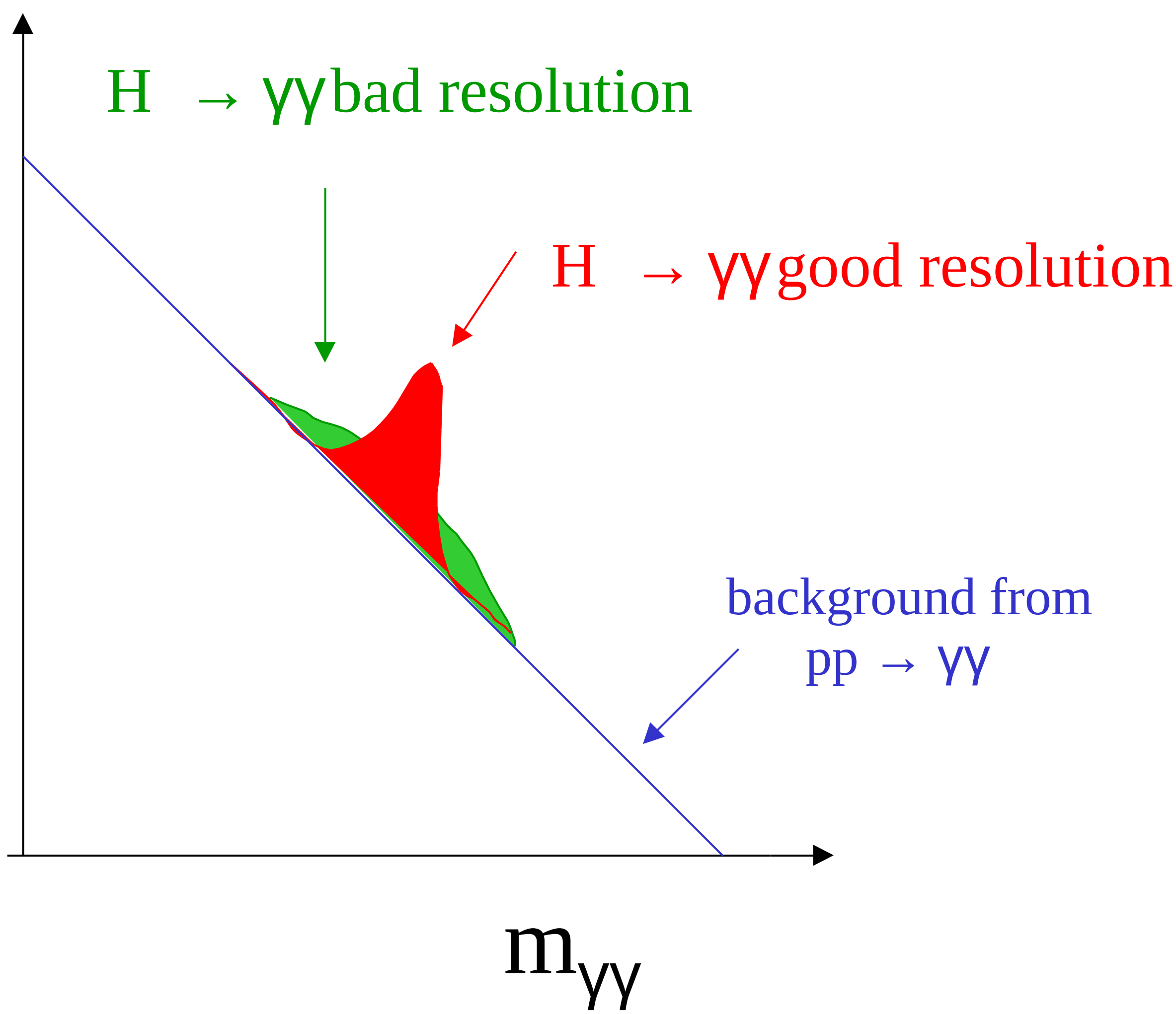
Assembly of CMS barrel magnet rings


the Large Hadron Collider accelerator
String 2
the Large Hadron Collider accelerator
String 2
up to nominal current

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.

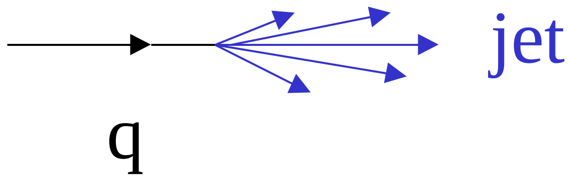
Example : $H \rightarrow \gamma\gamma$



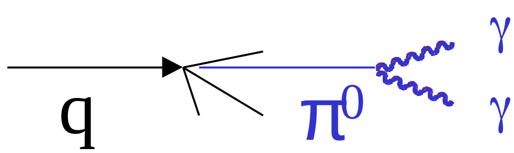
… see later ...

- Excellent particle identification capability:

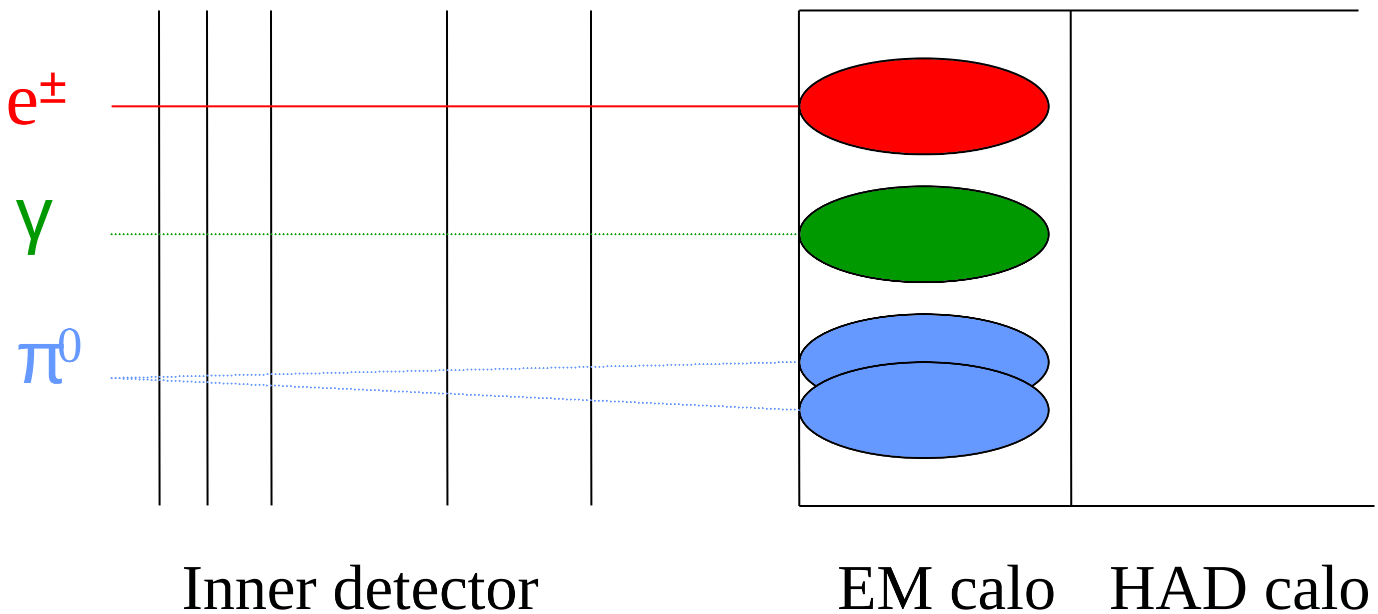
  e.g. e/jet , γ/jet separation



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:

$$\frac{\sigma_{jj}}{\sigma\,(H \to \gamma\gamma)} \sim 10^8$$

$m_{\gamma\gamma} \sim 100$ GeV

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

ATLAS EM calorimeter : 4 mm strips in first compartment

Title:
/u5/zp/gianotti/dice/ana/ntuple/paw.metafile
Creator:
HIGZ Version 1.21/10
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

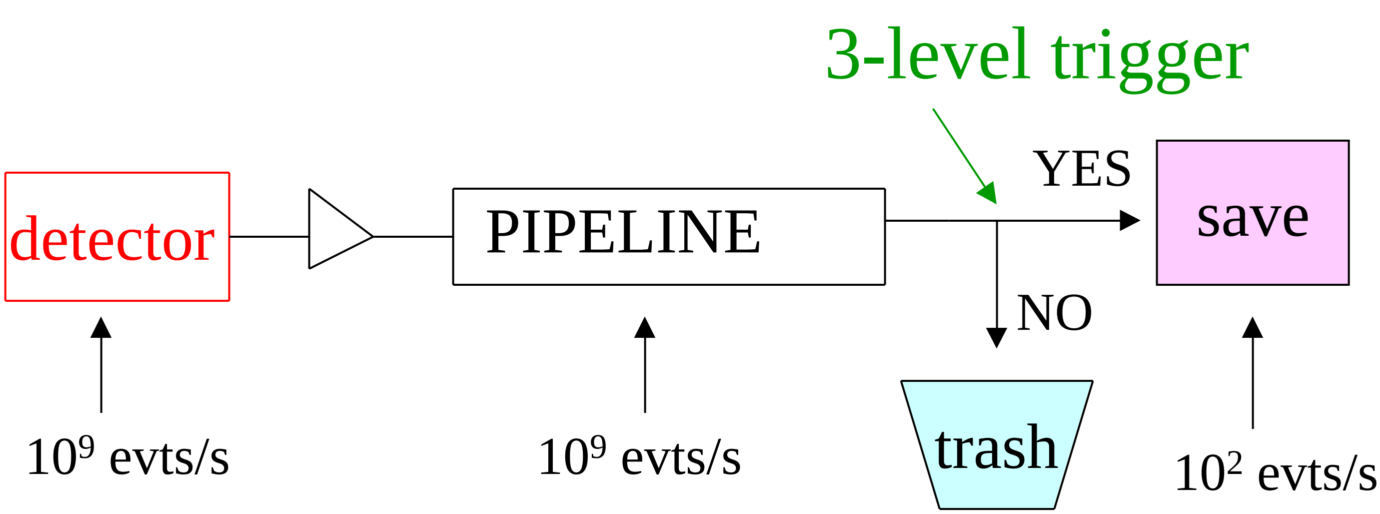
- Trigger : much more difficult than at e^+e^- machines

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



The LHC physics programme

- Search for Standard Model Higgs boson over $\sim 120 < m_H < 1000$ GeV.

- Search for Supersymmetry and other physics beyond the SM (q/ℓ compositness, leptoquarks, W'/Z', heavy q/ℓ, unpredicted ? ….) up to masses of ~ 5 TeV

- Precise measurements :
  - -- W mass
  - -- WWγ, WWZ Triple Gauge Couplings
  - -- top mass, couplings and decay properties
  - -- Higgs mass, spin, couplings (if Higgs found)
  - -- B-physics: CP violation, rare decays, B^0 oscillations (ATLAS, CMS, LHCb)
  - -- QCD jet cross-section and α_s
  - -- etc. ….

- Study of phase transition at high density from hadronic matter to plasma of deconfined quarks and gluons. Transition plasma → hadronic matter happened in universe ~ 10^{-5} s after Big Bang (ALICE)

Keyword: large event statistics

Expected event rates in ATLAS/CMS for representative (known and new) physics processes at low luminosity ($L=10^{33}$ cm^{-2} s^{-1})

Process	Events/s	Events/year	Other machines
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tev.
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^5 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
QCD jets $p_T > 200$ GeV	10^2	10^9	10^7

High L : statistics 10 times larger

→ LHC is a B-factory, top factory, W/Z factory Higgs factory, SUSY factory, etc.

Physics rates are the strongest point in favour of LHC. What about weaknesses ?

w.r.t. e^+e^- machines:

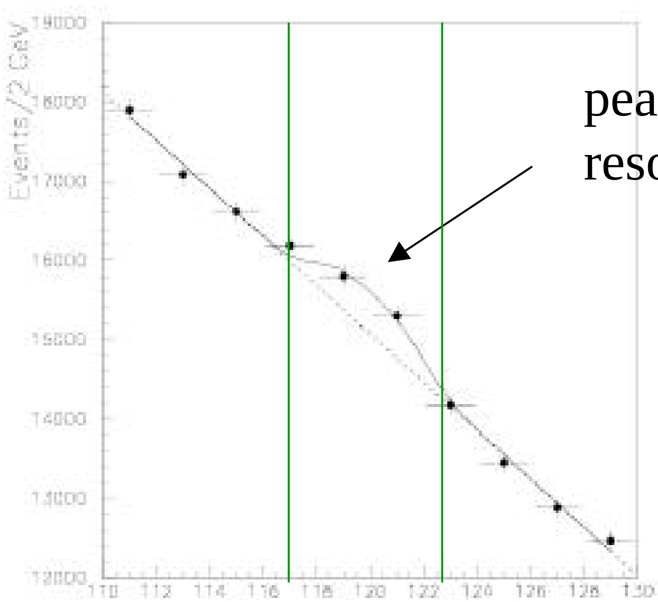
-- backgrounds (QCD) are much larger
-- trigger is much more difficult
-- centre-of-mass energy is not known
→ less kinematic constraints in final state
-- underlying event and pile-up make final state complex
-- etc. ...

w.r.t. Tevatron:

-- pile-up due to higher L
-- QCD processes grow faster with energy than electroweak processes
e.g. e/jet ~ 10^{-3} Tevatron
e/jet ~ 10^{-5} LHC
} $p_T > 20$ GeV

How can one claim a discovery ?

Suppose a new narrow particle $X \rightarrow \gamma\gamma$ is produced:



peak width due to detector resolution

$m_{\gamma\gamma}$

Signal significance :

$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S = number of signal events
N_B = number of background events
} in peak region

$\sqrt{N_B} \equiv$ error on number of background events

$S > 5$: signal is larger than 5 times error on background.
Probability that background fluctuates up by more than 5σ : 10^{-7} → discovery

Two critical parameters to maximise S:

- detector resolution:
  if σ_m increases by e.g. two, then need to enlarge peak region by two.

→ N_B increases by ~ 2
(assuming background flat)

N_S unchanged

} $S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$

$$S \approx 1/\sqrt{\sigma_m}$$

detector with better resolution has larger probability to find a signal

Note: only valid if $\Gamma_x << \sigma_m$. If new particle is broad, then detector resolution is not relevant.

- integrated luminosity :

$N_S \sim L$
$N_B \sim L$

} $S \sim \sqrt{L}$

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 lecture ...

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