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
• **pp** machine (mainly):

\[ \sqrt{s} = 14 \text{ TeV} \]

7 times higher than present highest energy machine (Tevatron/Fermilab: 2 TeV)

→ search for new massive particles up to \( m \sim 5 \text{ TeV} \)

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

\( \sim 10^2 \) larger than LEP2, Tevatron

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

• under construction, ready **2007**
• will be installed in the existing LEP tunnel
• two phases:
  - **2007 - 2009**: \( L \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \), \( \int Ldt \approx 10 \text{ fb}^{-1} \) (1 year)
    “low luminosity”
  - **2009 - 20xx**: \( L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \), \( \int Ldt \approx 100 \text{ fb}^{-1} \) (1 year)
    “high luminosity”

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Four large-scale experiments:

ATLAS  general-purpose pp experiments
CMS

LHCb  pp experiment dedicated to b-quark physics and CP-violation. \( L = 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)

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

Here: ATLAS and CMS
A few machine parameters

<table>
<thead>
<tr>
<th>Energy</th>
<th>E [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole field</td>
<td>B [T]</td>
</tr>
<tr>
<td>Luminosity</td>
<td>L [cm⁻² s⁻¹]</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>ξ</td>
</tr>
<tr>
<td>Total beam-beam tune spread</td>
<td>0.0034</td>
</tr>
<tr>
<td>Injection energy</td>
<td>$E_i$ [GeV]</td>
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<tr>
<td>Circulating current/beam</td>
<td>$I_{beam}$ [A]</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$k_b$</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>$n_{HF}$</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>$\tau_b$ [ns]</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$n_b$</td>
</tr>
<tr>
<td>Stored beam energy</td>
<td>$E_s$ [MJ]</td>
</tr>
<tr>
<td>Normalized transverse emittance $(\beta\gamma)\sigma^2/\beta$</td>
<td>$\varepsilon_n$ [µm rad]</td>
</tr>
<tr>
<td>Collisions</td>
<td>$\beta$-value at I.P.</td>
</tr>
<tr>
<td>r.m.s. beam radius at I.P.</td>
<td>$\beta^*$ [m]</td>
</tr>
<tr>
<td>r.m.s. divergence at I.P.</td>
<td>$\sigma^*$ [µm]</td>
</tr>
<tr>
<td>Luminosity per bunch collision</td>
<td>$L_b$ [cm⁻²]</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>$\phi$ [µrad]</td>
</tr>
<tr>
<td>Number of events per crossing</td>
<td>$n_e$</td>
</tr>
<tr>
<td>Beam lifetime</td>
<td>$\tau_{beam}$ [h]</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>$\tau_L$ [h]</td>
</tr>
</tbody>
</table>

Limiting factor for $\sqrt{s}$: bending power needed to fit ring in 27 km circumference LEP tunnel:

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

$$= 7 \text{ TeV} \quad \quad = 4.3 \text{ km}$$

LHC: $B=8.4 \text{ T}$: ~ 1300 superconducting dipoles working at 1.9 K (biggest cryogenic system in the world)
LHC is unprecedented machine in terms of:

- **Energy**

- **Luminosity**

- **Cost**: \( \approx 4000 \text{ MCHF} \) (machine + experiments)

- **Size/complexity of experiments**:  
  \( \sim 1.3-2 \text{ times bigger than present collider experiments} \)  
  \( \sim 10 \text{ times more complex} \)

- **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.

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)

\[ m_H < 1 \text{ TeV} \text{ from theory} \]
For \( m_H \sim 1 \text{ TeV} \) \( \Gamma_H > m_H \) and
WW scattering violates unitarity

\[ \sim m_f \]

However:
-- Higgs not found yet: only missing (but essential) piece of SM
-- present limit: \( m_H > 114.1 \text{ GeV} \) (from LEP)
-- “hint” at LEP for \( m_H \approx 115 \text{ GeV} \)
-- Tevatron may go beyond (depending on \( L \))
  \( \Rightarrow \) need a machine to discover/exclude
Higgs from \( \approx 120 \text{ GeV} \) to 1 TeV

\[ \downarrow \]

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

\[ \Delta m_H^2 \sim \Lambda^2 \]

\( \Lambda \): 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 \( \rightarrow \) “bad behaviour” of the theory

• Hints that forces could unify at \( E \sim 10^{16} \) GeV

\[ \begin{align*}
\alpha_1 &= \alpha_{\text{EM}} \approx 1/128 \\
\alpha_2 &= \alpha_{\text{WEAK}} \approx 0.03 \\
\alpha_3 &= \alpha_{\text{S}} \approx 0.12 \\
\sqrt{s} &\sim 100 \text{ GeV}
\end{align*} \]

Running of couplings
proven experimentally

GUT: for \( E > 10^{16} \) GeV
physics become simple
(one force with strength \( \alpha_G \))
• 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 : $m_{\text{SUSY}} \sim \text{TeV}$
  Many other theories predict New Physics at the TeV scale
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 (→ high σ) and L (→ high rate) 

Ex. : 
\[ 5 \times 10^8 \text{ W} \rightarrow \ell \nu \]
\[ 5 \times 10^7 \text{ Z} \rightarrow \ell \ell \]
\[ 10^7 \text{ tt pairs} \]
\[ 10^{12} \text{ bb pairs} \]

→ many precision measurements possible 
thanks to large statistics (stat. error \( \sim \) \( 1/\sqrt{N} \))
→ 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 WWγ, 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:

\[ \eta = -\log (\tan \frac{\theta}{2}) \]

\[ \begin{align*}
\theta = 90^\circ & \rightarrow \eta = 0 \\
\theta = 10^\circ & \rightarrow \eta \approx 2.4 \\
\theta = 170^\circ & \rightarrow \eta \approx -2.4
\end{align*} \]

Total inelastic cross-section:

\[ \sigma_{tot} (pp) = 70 \text{ mb} \quad \sqrt{s} = 14 \text{ TeV} \]

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

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)

\[
< p_T > \approx 500 \text{ MeV}
\]
of charged particles in final state

\[
\frac{dN}{d\eta} \bigcup 7
\]
charged particles uniformly distributed in \(\phi\)

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.
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.

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

These are interesting physics events but they are rare.

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

$\sigma (pp \rightarrow W) \approx 150 \text{ nb} \approx 10^{-6} \sigma_{\text{tot}} (pp)$
Unlike at e+e- colliders

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

\[
\begin{align*}
\vec{p}_a &= x_a \vec{p}_A \\
\vec{p}_b &= x_b \vec{p}_B \\
\end{align*}
\]

\[p_A = p_B = 7 \text{ TeV} \quad \sqrt{\hat{s}} = \sqrt{x_a x_b s} \cup x \sqrt{s}
\]

if $x_a \approx x_b$

$\rightarrow$ to produce $m \approx 100 \text{ GeV}$ $x \sim 0.01$

to produce $m \approx 5 \text{ TeV}$ $x \sim 0.35$

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• cross-section:

\[
\sigma = \int_{a,b} d x_a \, d x_b \, f_a (x_a, Q^2) \, f_b (x_b, Q^2) \, \hat{\sigma}_{ab} (x_a, x_b)
\]

\[\hat{\sigma}_{ab} \equiv \text{hard scattering cross-section}\]

\[f_i (x, Q^2) \equiv \text{parton distribution function}\]

\[
\begin{array}{c}
\text{p} \equiv \text{uud}
\end{array}
\]
Two main difficulties

- Typical of LHC:

\[ R = L\sigma = 10^9 \text{ interactions / second} \]

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

\[ \Rightarrow \text{At each interaction on average} \approx 25 \text{ minimum-bias events are produced. These overlap with interesting (high } p_T \text{) physics events, giving rise to so-called } \]

\[ \text{pile-up} \]

\( \approx 1000 \) charged particles produced over \( |\eta| < 2.5 \) at each crossing.

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

\( \Rightarrow \) 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

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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. \(\gamma\) from \(H \rightarrow \gamma\gamma\) 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:

\[
\begin{align*}
\text{up to } 10^{17} \text{ n/cm}^2 & \quad \text{in 10 years of LHC operation} \\
\text{up to } 10^7 \text{ Gy} &
\end{align*}
\]

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
Common to all hadron colliders:
high-\( p_T \) events dominated by QCD jet production:

\[
\begin{align*}
q & \rightarrow \alpha_s & q \\
q & \rightarrow \alpha_s & q
\end{align*}
\]

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

Most interesting processes are rare processes:
• involve heavy particles
• have weak cross-sections (e.g. W production)
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 → ℓν) ≈ 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:

\[ e, \mu, \tau, \nu, \gamma, \text{jets, b-quarks, …} \]

⇒ “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 \( \sim 5 \text{ GeV} < p_T < \sim \text{ TeV} \) required.

- Neutrinos “detected and measured” through measurement of missing transverse energy \( E_T^{\text{miss}} \). 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:

\[ E_f, \vec{P}_f = E_i, \vec{P}_i \]

**total energy, momentum reconstructed in final state**

**total energy, momentum of initial state**

-- **e^+e^- colliders**: \( E_i = \sqrt{s}, \quad \vec{P}_i = 0 \)

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

and \( \vec{P}_f \neq 0 \) → \( \vec{P}_v = -\vec{P}_f \quad E_v = |\vec{P}_v| \)

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

However: **transverse momentum** \( \vec{P}_{Ti} = 0 \)

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

\[ |\vec{P}_{Tv}| = |\vec{P}_{Tf}| = E_T^{\text{miss}} \]
ATLAS

A Toroidal Lhc ApparatuS

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

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CMS
Compact Muon Solenoid

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

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<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAGNET (S)</td>
<td>Air-core toroids + solenoid in inner cavity</td>
<td>Solenoid</td>
</tr>
<tr>
<td></td>
<td>Calorimeters outside field</td>
<td>Calorimeters inside field</td>
</tr>
<tr>
<td></td>
<td>4 magnets</td>
<td>1 magnet</td>
</tr>
<tr>
<td>TRACKER</td>
<td>Si pixels + strips</td>
<td>Si pixels + strips</td>
</tr>
<tr>
<td></td>
<td>TRD → particle identification</td>
<td>No particle identification</td>
</tr>
<tr>
<td></td>
<td>B=2T</td>
<td>B=4T</td>
</tr>
<tr>
<td></td>
<td>$\sigma/p_T \sim 5 \times 10^{-4}$ p_T + 0.01</td>
<td>$\sigma/p_T \sim 1.5 \times 10^{-4}$ p_T + 0.005</td>
</tr>
<tr>
<td>EM CALO</td>
<td>Pb-liquid argon</td>
<td>PbWO_4 crystals</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \sim 10%/\sqrt{E}$ uniform</td>
<td>$\sigma/E \sim 2-5%/\sqrt{E}$ no longitudinal segm.</td>
</tr>
<tr>
<td>HAD CALO</td>
<td>Fe-scint. + Cu-liquid argon (10 $\lambda$)</td>
<td>Cu-scint. (&gt; 5.8 $\lambda$ +catcher)</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \sim 50%/\sqrt{E}$ ⨁ 0.03</td>
<td>$\sigma/E \sim 70%/\sqrt{E}$ ⨁ 0.05</td>
</tr>
<tr>
<td>MUON</td>
<td>Air $\rightarrow$ $\sigma/p_T \sim 7%$ at 1 TeV standalone</td>
<td>Fe $\rightarrow$ $\sigma/p_T \sim 5%$ at 1 TeV combining with tracker</td>
</tr>
</tbody>
</table>
ATLAS Tilecal hadronic calorimeter

ATLAS EM calo module 1

ATLAS solenoid ready

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Fabiola Gianotti, Physics at LHC

Assembly of CMS
hadronic calorimeter

Assembly of CMS
barrel magnet rings
Examples of performance requirements

- Excellent energy resolution of EM calorimeters for $e/\gamma$ and of the tracking devices for $\mu$ in order to extract a signal over the backgrounds.

Example: \[ H \rightarrow \gamma\gamma \]

![Graph showing the resolution of $H \rightarrow \gamma\gamma$](image)
• Excellent particle identification capability:
  e.g. $e/\text{jet}, \gamma/\text{jet separation}$

number and $p_T$ of hadrons in a jet have large fluctuations

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

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

$$\frac{\sigma_{jj}}{\sigma (H \, \gamma\gamma)} \sim 10^8 \quad m_{\gamma\gamma} \sim 100 \text{ GeV}$$
⇒ 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: $\sim 10^9$ events/second  
Can record $\sim 100$ events/second  
(event size $\sim$ 1 MB)

$\Rightarrow$ trigger rejection $\sim 10^7$

Trigger decision $\approx \mu s$  $\rightarrow$ larger than interaction rate of 25 ns

store massive amount of data in pipelines while trigger performs calculations

3-level trigger

`detector` $\rightarrow$ 10$^9$ evts/s  $\rightarrow$ `PIERCLINE` 10$^9$ evts/s  $\rightarrow$ `save` 10$^2$ evts/s
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** ($q/\ell$ compositness, leptoquarks, $W'/Z'$, heavy $q/\ell$, **unpredicted**? ….) up to masses of $\sim 5$ 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 $\alpha_s$

  -- etc. …. 

• Study of **phase transition** at high density from hadronic matter to plasma of deconfined quarks and gluons. Transition plasma $\rightarrow$ hadronic matter happened in universe $\sim 10^{-5}$ s after Big Bang (ALICE)
Expected event rates in ATLAS/CMS for representative (known and new) physics processes at low luminosity ($L=10^{33} \text{ cm}^{-2} \text{ s}^{-1}$)

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

High $L$: statistics 10 times larger

$\rightarrow$ 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. $e/jet \sim 10^{-3}$ Tevatron \[ p_T > 20 \text{ GeV} \]
  $e/jet \sim 10^{-5}$ LHC
How can one claim a discovery?

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

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

$N_S =$ number of signal events
$N_B =$ number of background events

$\sqrt{N_B} \equiv$ 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 $5\sigma$ : $10^{-7} \rightarrow$ discovery

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Two critical parameters to maximise $S$:

- **detector resolution:**
  if $\sigma_m$ increases by e.g. two, then need to enlarge peak region by two.

  $\rightarrow N_B$ increases by $\sim 2$
  (assuming background flat)
  $N_S$ unchanged

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

  $\Rightarrow S \approx 1 / \sqrt{\sigma_m}$
detector with better resolution has larger probability to find a signal

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

- **integrated luminosity** :

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

  $\Rightarrow S \sim \sqrt{L}$

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Summary of Part 1

• LHC:
  - pp machine (also Pb-Pb)
  - $\sqrt{s} = 14$ TeV
  - $L = 10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - 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: $\leq 5$ 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