Early Physics at the LHC

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Outline

- Lecture 1:
  Physics at proton colliders
  Status of LHC & experiments

- Lecture 2:
  Standard Model physics

- Lecture 3:
  Searches for new particles & phenomena
e.g. Higgs and SUSY
Today‘s Questions and Problems

- Are quarks and leptons really elementary? e.g. structureless, pointlike objects?
- Why are there 3 families?
- Are there additional forces and gauge bosons?
- What is the origin of the matter-antimatter asymmetry in the universe? What is the origin of CP violation?
- What is dark matter (≈ 20% of the universe) and dark energy (≈ 75%)?
- ...

- Answers to these questions need
  - experiments at high energy
  - and with high precision
Future Experiments

- Discoveries
  - Increase collision energy to explore TeV region
    - explore the allowed Higgs mass range
    - search for Supersymmetry
    - and other new physics phenomena
    - be prepared for the unexpected

→ LHC

- Precision measurements and tests of the SM
  - measure SM parameters $m_W$, $m_t$
  - measure properties of new particles (Higgs, SUSY)
  - and check consistency of the model

→ LHC & ILC
Why a proton collider like the LHC?
e\text{e}^+\text{e}^- \text{ machines like LEP are ideal machines for precision measurements:}
- e\text{e}^+/\text{e}^- \text{ are point-like, no substructure} 
  \rightarrow \text{ very clean events}
- centre-of-mass system
- event kinematics completely fixed

Events at proton collider are much more complex:
- protons are not elementary
- hard scattering of partons (quarks & gluons)
- underlying event
- use only part of the beam energy
- event kinematics only partially constraint
Problem of Electron Storage Rings

Drawback of circular electron colliders like LEP: Energy loss due to synchrotron radiation (Accelerated charge does radiate photons!)

- Radiated power $P$ (in synchrotron photons) ring with radius $R$ and energy $E$

- Energy loss per turn

- Ratio of energy loss between electrons and protons

To reach higher energies at future colliders:
  a) Linear electron-positron colliders (→ ILC)
  b) Proton colliders (→ LHC)

LHC uses existing LEP tunnel!
History of Colliders

Comparison of past and future electron and proton colliders:
The Tevatron Collider at Fermilab

Proton-Antiproton Collider

- **1992 - 1996**
  Run I with 2 experiments  
  CDF and D0  
  $\sqrt{s} = 1.8$ TeV  
  $\int L dt = 125$ pb$^{-1}$

- **1996 – 2001 Upgrade**
  - new injector, antiproton recycler  
    → higher luminosity  
  - detector improvements

- **since March 2001**
  Run II, $\sqrt{s} = 1.96$ TeV

Both experiments are running collecting & analysing data
Experiments at the Tevatron

The CDF detector

≈ 700 physicists/collaboration

The D0 detector

≈ 700 physicists/collaboration
The Large Hadron Collider (LHC) at CERN

- Proton-proton collider in the former LEP tunnel at CERN (Geneva)

- Highest ever energy per collision
  - 14 TeV in the pp-system
- Conditions as $10^{-13} - 10^{-14}$ s after the Big Bang
- 4 experiments:
  - ATLAS
  - CMS
  - LHC-B specialised on b-physics
  - ALICE specialised for heavy ion collisions
- Constructed in worldwide collaborations
- Start planned for 2008
The Large Hadron Collider LHC

CMS

ATLAS

- Total weight: 12,500t
- Overall diameter: 15.80m
- Overall length: 21.80m
- Magnetic field: 4 Tesla
Challenges for the LHC

- Superconducting dipole magnets to keep $7 \text{ TeV}$ protons on circular path ($r \approx 3 \text{ km}$)
  
  $$|B| = 8.33 \text{ Tesla}$$

- 1232 dipole magnets are needed (+ quadrupole, sextupoles etc.)
  each dipole is 15 m long

- 1.9 K operating temperature
  supraliquid He
  largest cryogenic facility in the world

- Quench protection
  stored energy in one dipole: 8 MJ
  corresponds to a 40 t truck at 50 km/h!

- LHC dipole design
  incorporates reversed field for oppositely rotating proton beam

  BTW: the stored energy in the LHC proton beams is 350 MJ enough to melt 500 kg of copper!
Status of the LHC

- Example dipoles: all 1232 dipoles built and installed
- Last dipole lowered on April 26, 2007
- All magnets prepared on schedule
  - Interconnections on-going in 6 sectors
    - sector 7-8 ready
    - closure of 4-5 and 8-1 upcoming

LHC schedule: first beam in 2008

October 2007
Status of the LHC

- Cryogenics complete

- First cooldown April 2007:
  - 1.9 K: The coldest place in the universe!
Physics at Proton Colliders

- Protons are composite, complex objects
  - partonic substructure
  - quarks and gluons

- Interesting hard scattering processes
  quark-(anti)quark
  quark-gluon
  gluon-gluon

However, hard scattering (high momentum transfer) processes are only a small fraction of the total cross section
- total inelastic cross section ≈ 70 mb (huge!)
- dominated by events with small momentum transfer
Proton-Proton Collisions

- Proton beam can be seen as beam of quarks and gluons with a wide band of energies
- The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum

The effective centre-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons

\[
\begin{align*}
  p_1 &= x_1 p_A \\
  p_2 &= x_2 p_B \\
  p_A = p_B &= 7 \text{ TeV}
\end{align*}
\]

\[
\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = x \sqrt{s}
\]

(if $x_1 = x_2 = x$)

Note:
- the component of the parton momentum parallel to the beam can vary from 0 to the proton momentum ($0 \leq x \leq 1$)
- the variation of the transverse component is much smaller (of order the proton mass)

To produce a particle of mass

<table>
<thead>
<tr>
<th>mass</th>
<th>LHC</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>$x \approx 0.007$</td>
<td>$x \approx 0.05$</td>
</tr>
<tr>
<td>5 TeV</td>
<td>$x \approx 0.36$</td>
<td>---</td>
</tr>
</tbody>
</table>
Variables in pp Collisions

Kinematics fully defined only in transverse plane

Transverse momentum $p_T$

$p_T = p \sin \theta$

Rapidity:

$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$

Differences in $y$ are invariant under Lorentz boosts

Pseudo-rapidity:

$\eta = -\ln \tan \frac{\theta}{2}$

Handy approximation, do not need to know the particle mass

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$90^\circ$</td>
<td>0</td>
</tr>
<tr>
<td>$10^\circ$</td>
<td>$\approx 2.4$</td>
</tr>
</tbody>
</table>
Rapidity and Pseudo-Rapidity

\[ R^2 = (\Delta \phi)^2 + (\Delta \eta)^2 \]

\[ \Delta \phi = \phi_1 - \phi_2 \]

\[ \Delta \eta = \eta_1 - \eta_2 \]

rotation: \( \Delta \eta = \text{constant} \)
boost: \( \Delta \phi = \text{constant} \)
Parton Density Functions

How do the distributions of the $x$-values look like? Measured at HERA in ep-scattering, e.g.:

- $u$- and $d$-quarks at large $x$-values
- Gluons dominate at small $x$
- Large uncertainties for gluons

![Graph showing the distributions of $u$, $d$, and $S$ quarks at large $x$ values](image)
Cross Section Calculation

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

- sum over initial states \( a, b \)
- \( f_i (x_i, Q^2) = \) parton density functions

**Example: W production in leading order**

\[ \sigma (pp \rightarrow W) \approx 150 \text{ nb} \approx 2 \times 10^{-6} \sigma_{\text{tot}} \]
Parton Density Functions at the LHC

LHC is a proton-proton collider
But fundamental processes are the scattering of
- Quark – antiquark
- Quark – gluon
- Gluon – gluon

Examples:
- $q\bar{q} \rightarrow W \rightarrow l\nu$
- $gg \rightarrow H$

$\Rightarrow$ need precise PDF(x,Q^2) + QCD corrections (scale)
Luminosity

Rate of produced events for a given process

\[ N = \sigma L \]

- \( \sigma \) cross section \([\text{barn} = 10^{-24} \text{ cm}^2]\)
- \( L \) luminosity \([1/\text{cm}^2/\text{s}]\)

- luminosity depends on machine parameters:
  - number of protons stored, beam focus at the interaction point, …
- luminosity should be high to achieve acceptable rates for rare processes

Comparison of colliders:
- \( 10^{31}/\text{cm}^2/\text{s} \) LEP
- \( 2 \cdot 10^{32}/\text{cm}^2/\text{s} \) Tevatron Run II design
- \( 10^{33}/\text{cm}^2/\text{s} \) LHC initial phase (\( \approx 3 \) years)
- \( 10^{34}/\text{cm}^2/\text{s} \) LHC design luminosity (> 2010)

1 experimental year is about \( 10^7 \) s
- 10 fb\(^{-1}\) per year in the initial LHC phase
- 100 fb\(^{-1}\) per year later
Proton-Proton Collisions at the LHC

- $2835 + 2835$ proton bunches separated by $7.5$ m
  - $\rightarrow$ collisions every $25$ ns
  - $= 40$ MHz crossing rate

- $10^{11}$ protons per bunch

- at $10^{34}$/cm$^2$/s
  - $\approx 35$ pp interactions per crossing pile-up

$\rightarrow \approx 10^9$ pp interactions per second !!!

- in each collision
  - $\approx 1600$ charged particles produced

enormous challenge for the detectors
⇒ Low luminosity phase
\[ 10^{33}/\text{cm}^2/\text{s} = 1/\text{nb/s} \]
approximately
- \( 10^8 \) pp interactions
- \( 10^6 \) bb events
- \( 200 \) W-bosons
- \( 50 \) Z-bosons
- \( 1 \) tt-pair
will be produced per second and
- \( 1 \) light Higgs
per minute!

The LHC is a b, W, Z, top, Higgs, …
factory!
The problem is to detect the events!
Experimental Signatures

1. Hadronic final states, e.g. quark-quark

No high $p_T$ leptons or photons in the final state

Holds for the bulk of the total cross section

2. Lepton/photons with high $p_T$, example Higgs production and decay

Important signatures for interesting events:
- leptons and photons
- missing transverse energy
Suppression of Background

- requires high granularity (many channels)
- good position, momentum and energy resolution

with 25 pile-up events

removing tracks with $p_T < 25$ GeV
Detector Design Aspects

- **good measurement of leptons** (high $p_T$)
  - muons: large and precise muon chambers
  - electrons: precise electromagnetic calorimeter and tracking

- **good measurement of photons**

- **good measurement of missing transverse energy** ($E_{T}^{\text{miss}}$)
  - requires in particular good hadronic energy measurements down to small angles, i.e. large pseudo-rapidities ($\eta \approx 5$, i.e. $\theta \approx 1^\circ$)

- **in addition identification of b-quarks and $\tau$-leptons**
  - precise vertex detectors (Si-pixel detectors)

**Very important: radiation hardness**
- e.g. flux of neutrons in forward calorimeters $10^{17} \text{n/cm}^2$ in 10 years of LHC operation
Online Trigger

Trigger of interesting events at the LHC is much more complicated than at $e^+e^-$ machines

- interaction rate: $\approx 10^9$ events/s
- max. record rate: $\approx 100$ events/s  
  event size $\approx 1$ MByte $\Rightarrow$ 1000 TByte/year of data

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

- collision rate is 25 ns (corresponds to 5 m cable delay)
- trigger decision takes $\approx$ a few $\mu$s

$\Rightarrow$ store massive amount of data in front-end pipelines while special trigger processors perform calculations
The ATLAS experiment
A Toroidal LHC ApparatuS

ATLAS in a nutshell:
- Large air toroid with $\mu$ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector
  $10^8$ channels
  15 $\mu$m resolution
Status of ATLAS

Major structures assembled underground

- all calorimeters installed

- 99% of barrel $\mu$ chambers installed

ATLAS: on track for LHC physics
Status of ATLAS

- **Magnets**
  - barrel toroid tested successfully (11/06)
  - inner solenoid:
    - tested & field map taken

- 1 endcap toroid successfully tested (03/07)
  - moved to IP1
  - 2nd followed in June
CMS in a nutshell:
- 4 T solenoid
- $\mu$ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: PbWO$_4$ crystals
- All Si-strip tracker 220 m$^2$, $10^7$ channels
- Si-pixel detector similar to ATLAS
Layout of CMS

- 11 slices: 5 barrel and 2*3 endcaps
Lowering of CMS

- Crane installed
- Lowering starts in autumn 2006
Status of CMS

CMS: major structures assembled on surface
- solenoid successfully operated at 4 Tesla (11/06), field map
- lowering of central magnet slice (YB0) on February 28th
- 5/13 heavy pieces still to be lowered but all of known type
- 2nd endcap cabled, tested & commissioned on surface

Cosmic from magnet test
- most μ chambers installed
Status of CMS

- Silicon tracker ready
  - under test at surface
  - to be installed in August 2007

- Pixel detector:
  - 2/3 of modules produced
  - ready for installation end 2007

CMS tracker:
- ≈ 220 m² of Si sensors
- 10.6 million Si strips
- 65.9 million Si pixel

CMS: on track for LHC physics
Comparison of ATLAS and CMS

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>≈ 46 m</td>
<td>≈ 22 m</td>
</tr>
<tr>
<td>diameter</td>
<td>≈ 25 m</td>
<td>≈ 15 m</td>
</tr>
<tr>
<td>weight</td>
<td>≈ 7000 t</td>
<td>≈ 12000 t</td>
</tr>
</tbody>
</table>
Comparison of ATLAS and CMS

Physics performance:
comparison in terms of mass resolutions

<table>
<thead>
<tr>
<th></th>
<th>ATLAS (GeV $c^{-2}$)</th>
<th>CMS (GeV $c^{-2}$)</th>
<th>LHCb (GeV $c^{-2}$)</th>
<th>ALICE (GeV $c^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \pi\pi$</td>
<td>0.070</td>
<td>0.031</td>
<td>0.017</td>
<td>—</td>
</tr>
<tr>
<td>$B \rightarrow J/\psi K_S^0$</td>
<td>0.019</td>
<td>0.016</td>
<td>0.010</td>
<td>—</td>
</tr>
<tr>
<td>$Y \rightarrow \mu\mu$</td>
<td>0.152</td>
<td>0.050</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$H(130\text{GeV} c^{-2}) \rightarrow \gamma\gamma$</td>
<td>1.55</td>
<td>0.90</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$H(150\text{GeV} c^{-2}) \rightarrow ZZ^* \rightarrow 4\mu$</td>
<td>1.60</td>
<td>1.35</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\Lambda(500\text{GeV} c^{-2}) \rightarrow \tau\tau$</td>
<td>50.0</td>
<td>75.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$W \rightarrow$ jet jet</td>
<td>8.0</td>
<td>10.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$Z'(3\text{TeV} c^{-2}) \rightarrow \mu\mu$</td>
<td>240</td>
<td>170</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$Z'(1\text{TeV} c^{-2}) \rightarrow ee$</td>
<td>7.0</td>
<td>5.0</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Trigger & DAQ system

Similar design for ATLAS & CMS

Example CMS:
Collision rate 40 MHz
Level-1 max. trigger rate 100 kHz†
Average event size ≈ 1 Mbyte
† 50 kHz at startup (DAQ staging)

Filter farm:
- approx. 2000 CPUs
- easily scaleable
- staged (lower lumi & saves money)
- uses offline software
The longest journey starts with the first step…

- Cosmic data taking with assembled detector components…

December 2005
Cosmic Muons in CMS

August 2006:
cosmic with magnet on
Possible LHC Schedule

- **2008 first physics year**
  - machine closure April
  - first collisions in summer at 7 TeV proton energy
  - try to reach $10^{32}/\text{cm}^2/\text{s}$
    $$\int Ldt \leq 1 \text{ fb}^{-1}$$

- **2009 – 2010/11 two or three years at 1 - 2 \cdot 10^{33}/\text{cm}^2/\text{s}**
  - $\geq 30 \text{ fb}^{-1}$ in total
  - important for precision physics and discoveries

- **≥ 2011 high luminosity running at 10^{34}/\text{cm}^2/\text{s}**
  - 100 fb\(^{-1}\) per year

- **2015 Upgrade to Super LHC 10^{35}/\text{cm}^2/\text{s}**
  - under discussion
  - requires major machine and detector upgrades
End of Lecture 1