Physics at Hadron Colliders
1. Introduction, Particle Accelerators

1.1 Why hadron collider?

1.2 Principles on particle accelerators

1.3 The Large Hadron Collider (LHC) at CERN

1.4 The Tevatron Collider at Fermilab
1.1 Why Hadron Collider?

Key questions investigated in particle physics:

(i) Structure of matter; fundamental constituents \[ \lambda = \frac{h}{p} \]

(ii) Search for new particles, new types of matter \[ E = mc^2 \]

For the investigation of both questions, high energies and thereby particle accelerators are needed
High Energy Particle Accelerators (last 20 years):

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>type, laboratory</th>
<th>energy $\sqrt{s}$</th>
<th>years of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP-I</td>
<td>$e^+e^-$ collider, CERN</td>
<td>91 GeV</td>
<td>1989 - 1994</td>
</tr>
<tr>
<td>LEP-II</td>
<td>$e^+e^-$ collider, CERN</td>
<td>209 GeV</td>
<td>1995 - 2000</td>
</tr>
<tr>
<td>HERA-I</td>
<td>ep collider, DESY</td>
<td>$27 + 800$ GeV</td>
<td>1992 - 2000</td>
</tr>
<tr>
<td>HERA-II</td>
<td>ep collider, DESY</td>
<td>$27 + 920$ GeV</td>
<td>2002 - 2007</td>
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<tr>
<td>TeVatron Run I</td>
<td>ppbar collider, Fermilab</td>
<td>1.8 TeV</td>
<td>1987 - 1996</td>
</tr>
<tr>
<td>TeVatron Run II</td>
<td>ppbar collider, Fermilab</td>
<td>1.96 TeV</td>
<td>2002 - 2011</td>
</tr>
<tr>
<td>LHC, phase I</td>
<td>pp collider, CERN</td>
<td>7 TeV</td>
<td>2010- 2012</td>
</tr>
<tr>
<td>LHC, phase II</td>
<td>pp collider, CERN</td>
<td>14 TeV</td>
<td>2015- …….</td>
</tr>
</tbody>
</table>
Important parameters of accelerators:

- Beam energy, centre-of-mass energy $\sqrt{s}$
- Type of particles (ee, ep, or pp) and form of accelerator (circular or linear accelerator)
- Luminosity $L$, or integrated Luminosity (measured in units of cm$^{-2}$ s$^{-1}$)
Why a hadron collider?

$e^+e^-$ colliders are excellent machines for precision physics!!
- $e^+ e^-$ are point-like particles, no substructure $\rightarrow$ clean events
- complete annihilation, centre-of-mass system, kinematic fixed
Proton proton collisions are more complex
Simulation of a pp collision at the LHC:
\[ \sqrt{s} = 14 \text{ TeV}, \quad L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

Reconstruction of particles with high transverse momentum reduces the number of particles drastically
(interesting object largely kept, background from soft inelastic pp collisions rejected)
Main drawbacks of $e^+e^-$ circular accelerators:

1. Energy loss due to synchrotron radiation
   (basic electrodynamics: accelerated charges radiate, x-ray production via bremsstrahlung, synchrotron radiation…….)

   - Radiated power (synchrotron radiation):
     Ring with radius $R$ and energy $E$

   - Energy loss per turn:
     (2 GeV at LEP-II)

   - Ratio of the energy loss between protons and electrons:

\[
P = \frac{2 e^2 c}{3 R^2} \left( \frac{E}{m c^2} \right)^4
\]

\[-\Delta E \approx \frac{4 \pi e^2}{3 R} \left( \frac{E}{m c^2} \right)^4
\]

\[
\frac{\Delta E(e)}{\Delta E(p)} = \left( \frac{m_p}{m_e} \right)^4 \sim 10^{13}
\]

Future accelerators:

- pp ring accelerators (LHC, using existing LEP tunnel)

- or $e^+e^-$ linear accelerators, International Linear Collider ILC or CLIC (under study / planning)
Limiting factors:

$e^+ e^-$ accelerators:

- Energy loss is circular rings
- Acceleration gradient in linear accelerators
  (ILC design, 40 MV / m)
- Fixed centre-of-mass energy ….

$pp$ accelerators:

- More complex interactions due to proton substructure
- Only part of the $pp$ centre-of-mass energy available in the hard scattering process (see later)
  however: higher mass values can be reached with longer running times
- Magnetic field in bending magnets (8.3 T in LHC magnets)
Accelerators at the energy frontier

**Livingston plot**

Exponential growth of $\sqrt{s}$ with time (at least in the past)

Factor 4 every 10 years

pp: discovery machines (W/Z, top, Higgs,....)

e$^+$e$^-$: precision (LEP, QCD and el.weak)

Both required!
Today’s open questions in particle physics
Key questions of particle physics

1. Mass
   - What is the origin of mass?
   - Does the Higgs particle exist?
   - Much progress in the past 2 years

2. Unification
   - Can the interactions be unified?
   - Are there new types of matter, e.g. supersymmetric particles?
   - Are they responsible for the Dark Matter in the universe?

3. Flavour
   - Why are there three generations of particles?
   - What is the origin of the matter-antimatter asymmetry (Origin of CP violation)

Answers to some of these questions are expected on the TeV energy scale, i.e. at the LHC
The role of the LHC

1. Explore the TeV mass scale
   - What is the origin of the electroweak symmetry breaking? Does the Higgs boson exist?
   - The search for “low energy” supersymmetry
     Can a link between SUSY and dark matter be established?
   - Other scenarios beyond the Standard Model
   - ……

Look for the “expected”, but we need to be open for surprises
→ perform as many searches (inclusive, exclusive…) for as many final states as possible

2. Precise tests of the Standard Model
   - There is much sensitivity to physics beyond the Standard Model in the precision area
   - Many Standard Model measurements can be used to test and to tune the detector performance
Predictions for future precision (including LHC), compared to the Standard Model and its Minimal Supersymmetric Extension (MSSM)

Ultimate test of the Standard Model: compare direct prediction of Higgs mass with direct observation
many possible theoretical models exist
experimental guidance is needed
Production Rates and Cross Sections at the LHC

- Inelastic proton-proton collisions: $10^8 / s$
- $b\bar{b}$ pairs: $5 \times 10^5 / s$
- $t\bar{t}$ pairs: $1 / s$
- $W \rightarrow e \nu$: $15 / s$
- $Z \rightarrow e^+ e^-$: $1.5 / s$
- Higgs (150 GeV): $0.02 / s$
- Gluino, Squarks (1 TeV): $0.003 / s$

Rates for the design luminosity: $\sqrt{s} = 7\, \text{TeV}$, $L = 10^{33}\, \text{cm}^{-2}\, \text{s}^{-1}$:

\[ N = \sigma \cdot L \]

\[ \frac{1}{s} = \left[ \text{cm}^2 \cdot \frac{1}{\text{cm}^2 \cdot \text{s}} \right] \]
1.2 Principles of particle accelerators
Circular accelerator principles

- **Cyclotron:** constant RF
  magnetic field radius $\rho$ increases with energy
  used for smaller machines

- **Synchrotron:**
  $\rho = \text{const}$
  $B$ increases with energy
  RF frequency adjusted slightly ($\beta = 0.999 \ldots 1.0$)

Most High Energy accelerators and all CERN ring accelerators
(PS, SPS, LEP, LHC) are of this type
Basic parameters, Lorentz Force

\[ F = q \left( E + v \times B \right) \]

charge \( q \), normally \( q = e \); \( q = Z \, e \) for ions

- Electric field \( E \) provides the acceleration or rather energy gain
- The magnetic field \( B \) keeps the particles on their path

\( \rho \) is the radius of curvature for motion perpendicular to the static magnetic field. Often called
- gyromagnetic or Larmor radius in astroparticle physics
- bending radius for accelerators
B\( \rho \) known as magnetic rigidity, units Tm

**Circular motion for**

\[ E = 0 \]
\[ v \perp B \]

\[ B = \frac{p}{q \, \rho} \]

for \( q = e \) numerically

\[ B \ [T] = p \ [\text{GeV/c}] \quad 3.336 \, \text{m} / \rho \]

High energy, \( v = c \) "\( p = E \)"

\[ E < E_H = q \, B \, \rho \] Hillas criterion

**LHC**

- Momentum \( p = 7 \, \text{TeV/c} \)
- LHC bending radius \( \rho = 2804 \, \text{m} \)
- Bending field \( B = 8.33 \, \text{Tesla} \)
- magnets at \( 1.9 \, \text{K}, \) super-fluid He

**Astroparticle**

units \( 10^{-4} \, \text{T} = 1 \, \text{Gauss} \); a.u. = \( 1.5 \times 10^{11} \, \text{m} \)

Solar system \( B = 10 \, \mu \text{G} \quad E = 5 \, \text{TeV} \quad \rho = 11 \, \text{a.u.} \)

Intergalactic \( B = 1 \, \text{nG} \quad E = 5 \, \text{PeV} \) (knee)

\( \rho = 1.7 \times 10^{19} \, \text{m} \) (4 % of galaxy-radius)
Luminosity and collision rates

**Event rate** for process with cross section $\sigma$

$$\dot{n} = \mathcal{L} \sigma$$

**Luminosity** from bunch crossings at frequency $f = f_{\text{rev}} n_b$

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

for Gaussian bunches with rms sizes $\sigma_x \sigma_y$

$$A = 4 \pi \sigma_x \sigma_y$$

High luminosity:
- Large number of particles ($N_1$, $N_2$)
- Small beam dimensions ($A$) in the interaction point
- Large $f$ (large number of bunches, $\rightarrow$ small time difference between bunch crossings)

**LHC:**
- $N = 1.15 \times 10^{11}$, $n_b = 2808$ (number of bunches)
- Bunch separation: 25 ns (corresponds to 7.5 m)
- $A$: beams squeezed (using strong, large aperture quadrupoles close to the interaction region) from $\sigma = 0.2 \text{ mm}$ to $16 \mu\text{m}$
for $N = N_1 = N_2$ particles per bunch with transverse r.m.s. beam size $\sigma = \sigma_x = \sigma_y$ and frequency $f$

Accelerator physicist express this often using the transverse emittance $\varepsilon$ and the $\beta$ function:

$$L = f \frac{N_1 N_2}{4 \pi \frac{\sigma_x \sigma_y}{\beta_x \beta_y^*}}$$

where

$$\varepsilon = \frac{\pi \sigma^2}{\beta}$$

Relative beam sizes around IP1 (Atlas) in collision
Alternate gradient focusing

**Quadrupole lens focusing in x, defocusing in y or vice versa**

\[ F = e \left( v \times B \right) \]

here

\[ F = e (0, 0, v) \times (B_x, B_y, 0) = e ( -v B_y, +v B_x, 0) \]

Combine F D
Defocusing when at small amplitude
Overall focusing

Normal (light) optics:
Focal length of two lenses at distance D
\[ 1/f = 1/f_1 + 1/f_2 - D/f_1 f_2 \]
is overall focusing
with \[ 1/f = D/f^2 \]
for \[ f = f_1 = -f_2 \]

**alternate gradient focusing**

**together with bending magnets FODO lattice**

N. C. Christofilos, unpublished manuscript in 1950 and patent
Betatron motion

Equation of motion of particles in a ring (with bending fields) and quadrupoles (field gradients $\propto \partial B/\partial r$)

In both transverse planes, here written with $x$ for $x$, $y$: 

$x''(s) + k(s) x(s) = 0$ known as Hill’s equation, derived in 1801 to describe planetary motion

Generalised oscillator equation with position dependent, periodic restoring force $k(L+s) = k(s)$ given by the quadrupole gradients (+ the small weakly focusing bending term in the ring plane)

Solution: 

$$x(s) = \sqrt{\epsilon \beta(s)} \cos(\mu(s) + \phi)$$

Phase advance

$$\mu(s) = \int_0^s \frac{ds}{\beta(s)}$$

Tune # of betatron oscillations

$$Q = \frac{\mu}{2\pi}$$

$\beta(s)$ beta function, describes the focusing properties of the magnetic lattice

$\epsilon$ invariant, together with $\beta(s)$ amplitude. “single particle emittance”

Motion conveniently described in phase space $(x, x')$ with local slopes or angles $x' = p_x / p$

and linear optics elements as matrices; with simple case for $M$, applies for IP to IP

$$
\begin{pmatrix}
  x(s) \\
  x'(s)
\end{pmatrix}
= M
\begin{pmatrix}
  x(s_0) \\
  x'(s_0)
\end{pmatrix}
$$

$$M = \begin{pmatrix}
  \cos 2\pi Q & \beta \sin 2\pi Q \\
  -\frac{1}{\beta} \sin 2\pi Q & \cos 2\pi Q
\end{pmatrix}$$
Transverse beam size and emittance

consider: beam of many particles on stable orbit and
simple case: dispersion and slope $\beta' = 0$  by default at IP - relevant for experiments

<table>
<thead>
<tr>
<th>Property</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam size, r.m.s.</td>
<td>$\sigma(s) = \sqrt{\varepsilon \beta(s)}$</td>
</tr>
<tr>
<td>beam divergence, r.m.s.</td>
<td>$\theta(s) = \sqrt{\varepsilon / \beta(s)}$</td>
</tr>
<tr>
<td>product</td>
<td>$\varepsilon = \sigma(s) \theta(s)$</td>
</tr>
</tbody>
</table>

$\beta$ - function: local machine quantity - focusing of lattice

Emittance $\varepsilon$: beam quantity - the average action
related to phase space density or kind of beam temperature
given by initial conditions (injected beam)
or equilibrium of quantum excitation and damping - 2nd lecture
in ideal machine: $x, y, z$ motion uncoupled, 3 emittances $\varepsilon_x, \varepsilon_y, \varepsilon_z$

IP: squeeze $\beta$ to a minimum, called $\beta^*$  $\Rightarrow$ maximum of divergence, needs aperture

LHC  $\varepsilon_N = \varepsilon \beta \gamma = 3.75 \, \mu m$, at top $E_b = 7 \, TeV$: $\varepsilon = 0.503 \, nm$, $\beta^* = 0.55 \, m$, $\sigma^* = 16.63 \, \mu m$, $\theta^* = 30 \, \mu rad$
The CERN accelerator complex: injectors and transfer
1.3 The Large Hadron Collider (LHC)
Begin of a new era in particle physics
The Large Hadron Collider

... became a reality in 2008 after ~15 years of hard work

### Parameters

- **Beam energy**: 3.5 TeV (nominal)
- **SC Dipoles**: 1232, 15 m, 8.33T
- **Stored Energy**: 362 MJ/Beam
- **Bunch spacing**: 25 ns
- **Particles/Bunch**: $1.15 \times 10^{11}$
- **Design luminosity**: $10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$
- **Int. luminosity**: 10- 100 fb$^{-1}$ / year
Important components of the accelerator

- Superconducting dipole magnets
  (the largest challenge)
  - Magnetic field of 8.33 Tesla
  - in total 1232, 15 m long
  - Operation temperature of 1.9 K
    (helium cooling)

- Eight acceleration structures,
  Field gradient of 5 MV/m

- Unprecedented complexity
  (in total: ~10,000 magnets powered by
   1,700 electrical circuits, large stored
   energy, complex protection systems)
LHC dipole magnets

Two beams in one dipole magnet, 8.33 Tesla (opposite magnetic dipole fields, protons circulating in opposite directions)

15 m long, mass of 30 tons
The total stored energy of the LHC beams

Nominal LHC design: \(3 \times 10^{14}\) protons accelerated to 7 TeV circulating at 11 kHz in a SC ring

LHC: > 100 x higher stored energy and small beam size: \(~3\) orders of magnitude in energy density and damage potential. Active protection (beam loss monitors, interlocks) and collimation for machine and experiments essential. Only the specially designed beam dump can safely absorb this energy.
### Beam parameters, LHC compared to LEP

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<tr>
<th>Parameter</th>
<th>LHC</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum at collision, TeV/c</td>
<td>7</td>
<td>0.1</td>
</tr>
<tr>
<td>Nominal design Luminosity, cm⁻²s⁻¹</td>
<td>1.00E+34</td>
<td>1.00E+32</td>
</tr>
<tr>
<td>Dipole field at top energy, T</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of bunches, each beam</td>
<td>2808</td>
<td>4</td>
</tr>
<tr>
<td>Particles / bunch</td>
<td>1.15E+11</td>
<td>4.20E+11</td>
</tr>
<tr>
<td>Typical beam size in ring, μm</td>
<td>200-300</td>
<td>1800/140 (H/V)</td>
</tr>
<tr>
<td>Beam size at IP, μm</td>
<td>16</td>
<td>200/3 (H/V)</td>
</tr>
</tbody>
</table>

- Energy stored in the magnet system: 10 GJoule
- Energy stored in one (of 8) dipole circuit: 1.1 GJ
- **Energy stored in one beam:** 362 MJ
- Energy to heat and melt one kg of copper: 0.7 MJ

The LEP2 total stored beam energy was about 0.03 MJ
LHC: From first ideas to realisation

- 1982: First studies for the LHC project
- 1983: Z discovered at SPS proton antiproton collider
- 1989: Start of LEP operation ~ 92 GeV, Z-factory
- 1994: Approval of the LHC by the CERN Council
- 1996: Final decision to start the LHC construction
- 1996: LEP2 operation towards ~ 200 GeV, W+W-
- 2000: End of LEP operation
- 2002: LEP equipment removed
- 2003: Start of the LHC installation - infrastructure
- 2005: Start of Magnet installation in LHC tunnel
- 2007: Installation complete, starting cooldown
- 2008: Commissioning with beam and first collisions
Proton-proton collisions at the LHC

Proton–proton:

2808 x 2808 bunches
Separation: 7.5 m (25 ns)

$10^{11}$ protons / bunch
crossing rate of p bunches: 40 Mio / s
Luminosity: $L = 10^{34}$ cm$^{-2}$ s$^{-1}$

$\sim 10^9$ pp collisions / s
(superposition of $> 20$ pp interactions per crossing: pile-up)

$\sim 1600$ charged particles in the detector

$\Rightarrow$ high particle densities,
high requirements on detectors
Incident on 19th Sep. 2008, repair, comeback.....

- A resistive zone developed in an electrical bus bar connection
- Electrical arc → punctured the helium enclosure
- Helium release under high pressure
- Relief discs unable to maintain the pressure rise below 0.15 MPa → large pressure forces

- Lot of repair work during 2009
  (14 quadrupole and 39 dipole magnets replaced, electrical interconnections repaired, larger helium pressure release ports installed,.....)

- A very successful re-start in Nov. 2009
LHC re-start in Nov. 2009

Protons, $E_{\text{beam}} = 0.45$ TeV
The first signals in the ATLAS experiment, 20. Nov 2009
Scientists at Cern in Geneva have restarted the Large Hadron Collider (LHC) experiment, which hopes to shed light on the origins of the universe.
First results on detector performance after only a few days / weeks

First publications of physics results in Feb/March 2010
Since 30. March 2010: collisions at 7 TeV
(.... first interesting results appeared soon)

- High energy jets (scattered quarks, gluons)
- Energy: ~0.5 TeV
A six-jet event at 7 TeV

**ATLAS** Preliminary
\[ \sqrt{s} = 7 \text{ TeV} \]
anti-\( k_t \) jets \( R=0.6 \)
\[ p_T^{\text{jet}} > 30 \text{ GeV} \quad \text{and} \quad \eta^{\text{jet}} < 2.8 \]

- Data \( \int L dt = 1 \text{ nb}^{-1} \)
- PYTHIA

6 Jet Event in 7 TeV Collisions
Production of W and Z bosons

- Hochenergetisches Elektron
- Fehlende Energie

W→ev candidate in 7 TeV collisions

$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV
Production of the first top quarks in Europe

The fragmentation products of b-quarks (B-Hadrons) have a life time of 1.5 ps

= decay distance of ~2.5 mm
Collected data in 2010:

~40 pb\(^{-1}\) recorded
~36 pb\(^{-1}\) used in analysis (good quality)

Running again since a few weeks

collected so far: > 100 pb\(^{-1}\)
expected for 2011: 1 – 2 fb\(^{-1}\)

World record in instantaneous luminosity on 22. April 2011: \(4.67 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\)
so far: Tevatron record: \(4.02 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\)
Data taking in 2011/2012

- Excellent LHC performance in 2011 and 2012 (far beyond expectations)
- Peak luminosity seen by ATLAS: \(7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\) (world record, 2012)
- Excellent performance of the experiments in recording the data (efficiency \(\sim 93.5\%\), working detector channels >99%, speed of data analysis,...)

Until end 2012:

- > \(10^{15}\) pp collisions
- \(~10^{10}\) pp collisions recorded
- \(25 \times 10^6\) \(Z \rightarrow \mu\mu\) decays produced
• High efficiencies of the ATLAS and CMS experiments to collect and analyze the data
$Z \rightarrow \mu^+ \mu^-$ with 20 superimposed events
The Standard Model at the LHC

LHC pp $\sqrt{s} = 7$ TeV
- Theory
- Data 2010 (L = 35 pb$^{-1}$)
- Data 2011 (L = 1.0 - 4.7 fb$^{-1}$)

LHC pp $\sqrt{s} = 8$ TeV
- Theory
- Data 2012 (L = 5.8 fb$^{-1}$)

$H \rightarrow ZZ$ (0.5 pb)

H (20 pb)

July 2012
Discovery of a Higgs-like particle
Higgs-Teilchen offenbar entdeckt

tagesschau 04.07.2012
From the editorial:

The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers.
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

ATLAS Collaboration*
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

CMS Collaboration*
This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away, in recognition of their many contributions to the achievement of this observation.

Decay observed into particles with same spin and electric charge sum = 0 → a new neutral boson has been discovered
Constraints on the Higgs boson mass (before LHC)

- $m_H > 114.4 \text{ GeV/c}^2$ from direct searches at LEP
- $m_H < 156 \text{ GeV/c}^2$ or $m_H > 177 \text{ GeV/c}^2$ from direct searches at the Tevatron
- $m_H = 92^{+34}_{-26} \text{ GeV/c}^2$ (95% C.L.)

Indirect constraints from precision measurements (quantum corrections)
Constraints on the Higgs boson mass (before LHC)

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Indirect constraints from precision measurements (quantum corrections)

\[ m_H = 92^{+34}_{-26} \text{ GeV/c}^2 \]
\[ m_H < 161 \text{ GeV/c}^2 \] (95 % C.L.)
1.4 The Fermilab Tevatron collider
The Tevatron Collider at Fermilab

- Proton antiproton collider
  - 6.5 km circumference
  - Beam energy 0.98 TeV, $\sqrt{s} = 1.96$ TeV
  - 36 bunches, 396 ns separation (time between crossings)

- 2 Experiments: CDF and DØ

- Main challenges:
  - Antiproton production and storage
    → luminosity, stability of operation

Collider is running in so called Run II (since 2001)
[Run I from 1990 – 1996, int. luminosity: 0.125 fb\(^{-1}\), Top quark discovery]

- March 2001 – Feb 2006: Run II a, $\int L \, dt = 1.2$ fb\(^{-1}\)
- July 2006 - 2011: Run II b, $\int L \, dt = 10 - 12$ fb\(^{-1}\)
Tevatron performance

Peak luminosities of the machine as a function of time

- Peak luminosity of $4 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Corresponds to $\sim 10$ interactions per bunch crossing
  (superposition of minimum bias events on hard collision)
The integrated Tevatron luminosity (until April 2011)

- After a slow start-up (2001 – 2003), the Tevatron accelerator has reached an excellent performance
- Today, Tevatron delivers a data set equal to Run I (~100 pb\(^{-1}\)) every 2 weeks
- Integrated luminosity delivered to the experiments so far ~ 10.8 fb\(^{-1}\)
- Anticipate an int. luminosity of ~12 fb\(^{-1}\) until end of 2011.

Data corresponding to an int. luminosity of up to ~8 fb\(^{-1}\) analyzed…
Challenges with high luminosity

Min. bias pileup at the Tevatron, at $0.6 \cdot 10^{32}$ cm$^2$s$^{-1}$ ... and at $2.4 \cdot 10^{32}$ cm$^2$s$^{-1}$

Average number of interactions:

- **LHC**: initial “low” luminosity run
  - ($L=2 \cdot 10^{33}$ cm$^2$s$^{-1}$): $\langle N \rangle = 3.5$

- **TeV**: ($L=3 \cdot 10^{32}$ cm$^2$s$^{-1}$): $\langle N \rangle = 10$
Comparison of the LHC and Tevatron machine parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC (design)</th>
<th>Tevatron (achieved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>14 TeV</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>36</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
<td>396 ns</td>
</tr>
<tr>
<td>Energy stored in beam</td>
<td>360 MJ</td>
<td>1 MJ</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$10^{33-34}$ cm$^{-2}$s$^{-1}$</td>
<td>$3.5 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Integrated Luminosity / year</td>
<td>10-100 fb$^{-1}$</td>
<td>$\sim 2$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

- 7 times more energy (after initial 3.5 TeV phase)
- Factor 3-30 times more luminosity
- Physics cross sections factor 10-100 larger