The Large Hadron Collider LHC
A New Era in Particle Physics

Joachim Mnich
DESY

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Outline

- The Large Hadron Collider
- The Experiments
- LHC physics
- First beams & collisions
- 2010 results*
- Plans & prospects

*results mostly from open LHCC session Nov 17, 2010
The Large Hadron Collider (LHC)
The Large Hadron Collider (LHC)

- Proton-proton collider in the former LEP tunnel
- The LHC uniquely combines the two most important virtues of HEP experiments:
  1. Highest ever energy per collision
      up to 14 TeV in the pp-system
cf. Tevatron at 2 TeV
  2. High luminosity
      up to $10^{34}$/cm$^2$/s
- 4 experiments:
  - **ATLAS**: large multi-purpose detector
  - **CMS**: large multi-purpose detector
  - **LHCb**: specialised on b-physics
  - **ALICE**: specialised for heavy ion collisions
The Large Hadron Collider (LHC)

LHC time table:

- Early 1980’s: first ideas about a multi-TeV proton collider at CERN
- Oct 1990: ECFA workshop on LHC in Aachen
- 16 Dec 1994: CERN council approves the LHC
- Feb 1996: approval of ATLAS and CMS
- Apr 1998: start civil engineering
- 7 Mar 2005: first dipole magnet installed
- 26 Apr 2007: last dipole installed
- 10 Sep 2008: first circulating beams
- Oct 2009: first pp-collisions
- Mar 2010: first collisions at 7 TeV
The LHC Project: Dipoles

- First dipole prototype reached 8.73 Tesla on April 14, 1994

- Last of 1232 dipoles lowered on April 26, 2007
The LHC Today
First Beams & Collisions

- First circulating beams on September 10, 2008
Beam Splash Events

- Beam on closed collimators
- Important to commission detectors, e.g. timing
The Accident

- Major set-back on September 19, 2008
  - bad connection between two magnets
  - thermal runaway
  - light arc between magnets destroyed a He vessel
  - shock wave in tunnel

- Consequences:
  - delayed first collisions by 1 year
  - max. beam energy 3.5 TeV
  - 1 year shutdown needed to stabilize magnet interconnects

53 magnets to be repaired & reinstalled
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
CMS in a nutshell:
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: PbWO₄ crystals
- All Si-strip tracker 220 m², 10⁷ channels
- Si-pixel detector similar to ATLAS
CMS: Compact Muon Solenoid
LHCb

- Forward spectrometer for B-physics
- addressing the question of matter-antimatter asymmetry
ALICE

- Experiment addresses new state of matter: the quark-gluon plasma

- Heavy ion collisions, eg. Pb-Pb
- Using L3 magnet
Challenges for LHC Detectors

- Protons are composite particles
  - Bags filled with quarks and gluons
  - Quark-quark and gluon-gluon collisions are the fundamental processes
  - Screened by interactions of other quarks & gluons

- LHC is filled with $2835 + 2835$ proton bunches
  - Collisions every $25$ ns, i.e. $40$ MHz crossing rate

- $10^{11}$ protons per bunch
  - $25$ pp interactions per crossing (pile-up)
  - Each bunch collision produces $\approx 1600$ charged particles
A Collision Producing a Higgs Boson

- Identify each track requires a highly granular detector
- Reconstruct every track takes a lot computing power

- with 25 pile-up interactions
- Remove low energy tracks ($p_T < 25$ GeV)
- $H \rightarrow ZZ \rightarrow 4$ muons

Reconstructed tracks with $pt > 25$ GeV
Progress in theory and experiment over the past decades

**Standard Model of Particle Physics**

- Matter particles: Quarks and Leptons
- Force carriers: Gauge Bosons

Excellent theory tested down to $10^{-18}$ m

However

- Missing corner stone: Higgs-Boson
- Many open questions to be addressed at the Terascale
- Standard Model valid only for about 5% of the universe

Experimental and theoretical evidence for new physics at scale of 1 TeV

→ LHC

- Mystery of Dark Matter
  - What is the universe made of?
  - Particles produced copiously at the big bang?
  - Supersymmetry provides a candidate for Dark Matter to be discovered at the LHC
Origin of Mass and Supersymmetry

- **Higgs Particle**
  - What is the origin of mass?
  - Do fundamental particles acquire their mass through the Higgs mechanism?
  - Is space filled with an omnipresent energy field?
  - If so it can be studied at the Terascale
  - If not new phenomena must appear

- **Supersymmetry**
  - Symmetry between forces and matter?
  - Mirror world of new supersymmetric particles?
  - New shadow world like antimatter?
  - Supersymmetry as key to resolve clash between Einstein’s general relativity and quantum mechanics, i.e. the worlds of large and small scales?
  - Experiments at the LHC will provide answers
Extra Dimensions and Grand Unification

- **Extra Space Dimensions:**
  - Mystery of vastly different scales of electroweak force (0.1 TeV) and gravity ($10^{16}$ TeV)
  - Gravity scale lowered through extra spatial dimensions to 1 TeV? Curled up on small distances?
  - Particles living in extra dimensions could be detected at the LHC

- **Grand Unification:**
  - Why are there three different fundamental interactions?
  - Only one truly fundamental interaction of universal strength?
  - Insight to be gained at the LHC
LHC: The Start of the Experimental Programme

- 23 November 2009: First Collisions at 900 GeV
- Followed by collisions at 2.36 TeV (world record)
2010: Collisions at 7 TeV

March 30, 2010
LHC Operation in 2010

- About 200 days of very successful machine commissioning and pp-running
  - Steady increase of luminosity
  - Bunch trains with 150 ns bunch spacing
  - Up to 348 colling bunches
  - Nominal bunch charge
- Peak luminosity of $2 \times 10^{32}/\text{cm}^2/\text{s}$ achieved
  - exceeding goal for 2010 by factor 2
- 50 pb$^{-1}$ integrated luminosity per experiment
LHC Stored Energy

- LHC pushes the limits of particle accelerators

[Graph showing LHC stored energy compared to other accelerators, with key points labeled: LHC Injection, LHC Goal ’10/’11, LHC Oct. ’10, LHC Sep. ’10, ISR, SPS, HERA, RHIC, Tevatron.]
Performance of the Experiments

- All experiments are extremely well prepared
  - DAQ efficiencies >> 90%
  - Already well aligned & calibrated
  - Performance often already close to design

Example: LHCb sub-detector efficiencies
The LHC Computing Grid

- Computing Grid jobs (example from ATLAS)

- Working very reliably
- Pre-requisite for LHC data analysis
- Important role of GridKa
A few first physics results of 2010
First LHC Results

- The re-discovery of the Standard Model

\[ \text{pp} \rightarrow \mu^+\mu^- + X \]

CMS Preliminary

\[ \sqrt{s} = 7 \, \text{TeV}, \quad L_{\text{int}} = 40 \, \text{pb}^{-1} \]
LHCb: Exclusive B-Decays

- Important milestone in LHCb physics programme
QCD and Jets

- Inclusive jet rates
- Combination of various triggers
- Good understanding over 9 orders of magnitude in rate
- Highest $p_T$ jet observed: 1.3 TeV
Highest $p_T$ jet

$p_T$ jet 1 = 1.3 TeV
$p_T$ jet 2 = 1.2 TeV
$m_{jj} = 2.6$ TeV
Di-jet Events

**ATLAS Preliminary**
\[ \sqrt{s} = 7 \text{ TeV} \]

- Highest di-jet mass 3.7 TeV

- For comparison:
  Tevatron result:
  - Highest di-jet mass 3.7 TeV

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MC (Pythia LO + Parton Shower, normalised to data)
Statistical errors only

- Anti-k, R=0.6
- |y^{jet}|<2.8
Highest mass di-jet

$p_{T}$ jet1 = 670 GeV
$p_{T}$ jet2 = 610 GeV
$m_{jj} = 3.7$ TeV
Soft QCD

- Long range two-particle correlations in pp collisions at 7 TeV

- Two-particle correlation function \( R \)
- Same side correlation (ridge structure) observed for high multiplicity events at \( \Delta \Phi = 0 \)
- Most evident in intermediate \( p_T \) range
- Resembles features seen in Heavy Ion collisions
Top Quark Physics

- CMS: di-lepton channel

$\sigma(pp \rightarrow t\bar{t}) = 194 \pm 72{\text{(stat.)}} \pm 24{\text{(syst.)}} \pm 21{\text{(lumi.)}} \text{ pb}$
Top Di-lepton Candidate

\[ pp \rightarrow WW \, bb \, + \, X \]

\[ \mu^+ \, \nu \, \mu^- \, \bar{\nu} \]
Top Quark Physics

- ATLAS: Lepton + jets channel

- Lepton + jets:

- Requiring 1 b-tag:

![Graphs showing ATLAS preliminary results for lepton + jets channel with data, single top, Z + jets, W + jets, and QCD contributions.](image-url)
Top-pair Cross Section at 7 TeV

- Based on $\approx 3 \text{ pb}^{-1}$
- Good agreement with expectation

ATLAS: $\sigma_{tt} = 145 \pm 31^{+42}_{-27} \text{ pb}$
Electroweak Physics

- W and Z bosons
  - \( \approx 250k \) W-events
  - \( \approx 25k \) Z-events per experiment
- CMS results based on 35 pb\(^{-1}\)
\[ p_T(\mu) = 18 \text{ GeV} \]
\[ p_T^{\text{vis}}(\tau_h) = 26 \text{ GeV} \]
\[ m_{\text{vis}}(\mu,\tau_h) = 47 \text{ GeV} \]
\[ m_T(\mu, E_T^{\text{miss}}) = 8 \text{ GeV} \]
\[ E_T^{\text{miss}} = 7 \text{ GeV} \]

**Z \rightarrow \tau\tau**

Candidate in 7 TeV Collisions

3-prong hadronic tau decay
**W → τν and Z → ττ observation**

- **ATLAS observation of** $W → τν$ based on 550 nb$^{-1}$ (1% of total statistics)
- **78 events with hadronic τ decay candidates**
- **23 background events**

- **CMS Z → ττ candidates**

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**Graphs:**

1. **ATLAS:**
   - Integrated Luminosity 546 nb$^{-1}$
   - 78 events with hadronic τ decay candidates
   - 23 background events

2. **CMS:**
   - CMS Preliminary 2010
   - $L_{int} = 1.7$ pb$^{-1}$, $\sqrt{s} = 7$ TeV
   - Z → ττ candidates

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A Beautiful ZZ Event

Invariant Masses

\[ \mu_0 + \mu_1: 92.15 \text{ GeV (total } Z \text{ p}_T 26.5 \text{ GeV, } \phi -3.03), \]
\[ \mu_2 + \mu_3: 92.24 \text{ GeV (total } Z \text{ p}_T 29.4 \text{ GeV, } \phi +.06), \]
\[ \mu_0 + \mu_2: 70.12 \text{ GeV (total } p_T 27 \text{ GeV),} \]
\[ \mu_3 + \mu_1: 83.1 \text{ GeV (total } p_T 26.1 \text{ GeV).} \]

Invariant Mass of 4\mu: 201 \text{ GeV}
Candidate for $ZZ \rightarrow \mu\mu\nu\nu$

- $m_{\mu\mu} = 94$ GeV, $E_T^{\text{miss}} = 161$ GeV

Candidate Event with a $Z \rightarrow \mu\mu$ and missing $E_T$
Searches for New Physics

- Search for pair produced Lepto-Quarks decaying $\beta$ % in $\mu+\text{jet}$

Final discriminant variable

$$S_T = \sum_{\mu_{1,2}} p_t^{\mu} + \sum_{\text{Jet}_{1,2}} p_t^{\text{jet}}$$

As a function of $\beta$

$m_{LQ} > 330 \text{ GeV}$

For $\beta=1$
ATLAS: Di-jet Mass & Angular Distribution

excluded:
$0.50 < m(q^*) < 1.53 \text{ TeV} @ 95\% \text{ CL}$

Quark contact interactions with
scale $\Lambda < 3.4 \text{ TeV} @ 95\% \text{ CL}$

Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC, Phys. Rev. Lett. 105, 161801 with 315 nb$^{-1}$

Search for Quark Contact Interactions in Dijet Angular Distributions in in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC, Accepted by PLB
CMS: Limits on Stopped Gluinos

Search for decays of stopped long lived R-hadrons (gluino-meson, gluino-baryon, gluino-gluon bound states) during time intervals without LHC crossing.
Heavy Ion Collisions

- 4 weeks of Pb-Pb running in Nov/Dec 2010
- Up to 10,000 tracks per event observed
Luminosity in Heavy Ion Run

- Steady progress
- \( \approx 8 \, \mu b^{-1} \) per experiment delivered
Detector Performance in Pb-Pb Collisions

- Particle ID by ALICE

A single Pb-Pb collision!
Event-by-event PID

\[ \sigma_{\text{tot}} = \sqrt{\sigma^2_{\text{TOF}} + \sigma^2_{t_{\text{zero}}}} \]

\[ 1.0 < p < 1.4 \text{ GeV/c} \]

TOF

\[ \sigma_{\text{tot}} = 83 \text{ ps} \]
\[ \sigma_{t_{\text{zero}}} = 35 \text{ ps} \]
\[ \sigma_{\text{TOF}} = 75 \text{ ps} \]

<80 ps (design) resolution seems within reach!
Di-jet Candidate in PbPb

Cog-wheel effect due to projection of structure of fwd calo

~220 GeV  ~220 GeV
Jet-Quenching

- Jets are expected to lose momentum traversing dense colore medium
- Asymmetric jets if produced at the edge

- Many events with asymmetric di-jets observed
Charged Track Multiplicity

- **ALICE:**
  \[ \frac{dN_{ch}}{d\eta} = 1584 \pm 4 \; (\text{stat.}) \pm 76 \; (\text{syst.}) \]

- Increase by factor 1.9 wrt pp collisions at same energy
- Increase by factor 2.2 wrt RHIC Au-Au at 200 GeV
Outlook for 2011

- LHC will resume in February after the technical stop
- 200 days pp physics plus 4 weeks heavy ion scheduled
- Goal:
  
  $1 \text{ fb}^{-1}$ per experiment at 7 TeV

- Based on very positive experience in 2010 goals might be revised
  - increase cms energy to 8 TeV
  - peak lumi $\approx 6 \times 10^{32}/\text{cm}^2/\text{s}$ resulting in integrated lumi of $\approx 2 \text{ fb}^{-1}$
  - LHC running in 2012?

  more news early February

- Opens bright perspective for the Higgs particle hunt in 2011/12
The Hunt for the SM Higgs

- ATLAS simulation at 7 TeV

- 5 fb\(^{-1}\) enough to close gap with LEP
- Expected 3\(\sigma\) observation from 123 to 550 GeV
The Hunt for the SM Higgs

- CMS simulations at 7 TeV and 8 TeV

With 5 fb\(^{-1}\) can exclude or have 3 \(\sigma\) evidence from 114 to 600 GeV

![Graph showing projected 95% CL limit on \(\sigma/\sigma_{SM}\) and significance of observation](image)
Search for Supersymmetry

<table>
<thead>
<tr>
<th>M (TeV)</th>
<th>1 fb⁻¹</th>
<th>2 fb⁻¹</th>
<th>5 fb⁻¹</th>
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</thead>
<tbody>
<tr>
<td>√s=7 TeV</td>
<td>0.7</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>√s=8 TeV</td>
<td>0.8</td>
<td>0.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Tevatron exclusion reach: ~ 450 GeV
Outlook beyond 2011

Long term planning

- **2012:**
  - shutdown to repair might be postponed to 2013

- **2013 – 2020:**
  - running at 14 TeV
  - two years running interleaved with 1 year shutdown
  - push luminosity to $10^{34}$/cm$^2$/s
  - collect $\approx 300$ fb$^{-1}$ per experiment

- **2020+:**
  - plans to upgrade the luminosity (High-lumi LHC) to $\approx 5 \times 10^{34}$/cm$^2$/s
  - major upgrades of detector
Search for the Higgs Boson at the LHC

Combine all search channels and determine expected significance as function of the luminosity and Higgs mass:

10 fb\(^{-1}\) sufficient for 5 \( \sigma \) discovery of the Higgs. LHC will definitely tell if there is a Higgs or not.
SUSY Search at LHC

Example: discovery reach as function of luminosity and model parameters which fix the mass scale of SUSY parameters

- achievable limits exploiting $E_T^{\text{miss}}$ signatures
- requires very good understanding of detectors

Conclusion:
- LHC will eclipse today’s limits on SUSY particles and parameters
- or discover SUSY if it exists at the TeV scale
Summary

- Phantastic start of the LHC physics programme
  - very good performance of the machine
  - and of the detectors
  - Successful stress tests of computing, analysis tools etc.

- Excellent prospects
  - many SM measurements on top quarks, W/Z bosons and others
  - entering uncharted territory next year
  - extending mass regions for SUSY and other particles
  - the hunt for the Higgs will start

- LHC will revolutionize the understanding of our world

Very exciting times are ahead of us!