LHC Entering Operation: An Overview of the LHC Programme

SUSY 2009
Northeastern University, Boston,
5th June 2009, Peter Jenni (CERN/ATLAS)
The Large Hadron Collider Project: A Journey to Discover the Physics Shortly After the Big Bang

A dream becoming reality
pp physics at the LHC corresponds to conditions around here
A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the ‘Higgs mechanism’ which predicts the existence of a new elementary particle, the ‘Higgs’ particle (theory 1964, P. Higgs, R. Brout and F. Englert)

Peter Higgs

The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

The LHC will have sufficient energy to produce it for sure, if it exists

Francois Englert

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Astronomers say that most of the matter in the Universe is invisible.

**Dark Matter**

‘**Supersymmetric**’ particles?

We shall look for them with the LHC.

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**Composition of the Universe**

- **Dark Energy**: 72%
- **Dark Matter**: 23%
- **Atoms**: 4.6%
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva.
pp $\sqrt{s} = 14$ TeV

10-14 TeV $L_{\text{design}} = 10^{34}$ cm$^{-2}$ s$^{-1}$ (after 2012/3)

Initial $L_{\text{initial}} < \text{few x } 10^{33}$ cm$^{-2}$ s$^{-1}$ (before)

Heavy ions (e.g. Pb-Pb at ~ 1150 TeV)

First collisions: expected in November 2009

ATLAS and CMS: general purpose

LHC 27 km ring (previously used for the LEP e$^+$e$^-$ collider)

ALICE: Heavy Ions

LHCb: B-physics, CP-violation

Plus two much smaller experiments with very forward detectors at
Point-1: LHCf
Point-5: Totem

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The full LHC accelerator complex

LHC ring is divided into 8 sectors

Linac
Booster
PS
SPS
LHC

> 50 years of CERN history still alive and operational

Start the protons out here
LHC Entering Operation
LHC Layout

- 8 arcs (sectors)
- 8 long straight sections (700 m long): IR1 to IR8
- 2 separate vacuum chambers
- Beams cross in 4 points

- IR1: ATLAS experiment
- IR2: ALICE experiment
- IR3: Collimation
- IR4: Radio frequency acceleration
- IR5: CMS experiment
- IR6: Beam dumping system
- IR7: Collimation
- IR8: LHC-B experiment
The most challenging components are the 1232 high-tech superconducting dipole magnets

Magnetic field: 8.4 T  
Operation temperature: 1.9 K (pressurized superfluid helium)  
Dipole current: 11700 A  
Stored energy: 7 MJ  
Dipole weight: 34 tons  
7600 km of Nb-Ti superconducting cable
The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities.

Note: The acceleration is not such a big issue in pp colliders (unlike in e+e- colliders), because of the $\sim 1/m^4$ behaviour of the synchrotron radiation energy losses $[\sim E^{4 \text{beam}}/Rm^4]$.

<table>
<thead>
<tr>
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<th>LHC at 7 TeV</th>
<th>LEP at 100 GeV</th>
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<tbody>
<tr>
<td>Synchrotron radiation loss</td>
<td>6.7 keV/turn</td>
<td>3 GeV/turn</td>
</tr>
<tr>
<td>Peak accelerating voltage</td>
<td>16 MV/beam</td>
<td>3600 MV/beam</td>
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Special quadrupole magnets (‘Inner Triplets’) are focusing the particle beams to reach highest densities (‘luminosity’) at their interaction point in the centre of the experiments.
10 September 2008: LHC inauguration day

First (single) beams circulating in the machine

Five CERN DGs, from conception to realization: Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar (from right to left)
First Turn! 10th September 2008

10:30 am
Two beam spots on a screen near ALICE indicate that Beam 1 has made 1 turn

10:30: Beam 1 (clockwise) around the ring (in ~ 1 hour)
15:00: Beam 2 (counter-clockwise) around the ring
22:00: Beam 2 circulates for hundreds of turns …
beam energy: 450 GeV, beam intensity: $2 \times 10^9$ protons per bunch
First LHC Single Beam on 10th September 2008 seen by the experiments

Beam splash events onto all four detectors

tertiary collimators 140 m
Few 100 turns

LHC Longitudinal Bunch Profile Beam2
No RF, debunching in ~ 25*10 turns, i.e. roughly 25 ms
Capture with ‘first-order’ corrected injection phasing
Capture with optimum injection phasing, correct reference
**Incident on 19th September 2008**

The LHC decided to use a few days of down-time due to a ‘standard’ power converter fault to finish work on missing powering tests in sector 3-4 (all other sectors were tested to 5.5 TeV equivalent currents)

At 8.7 kA (corresponding to ~ 5.1 TeV), a resistive zone appeared in the superconducting busbar between quadrupole Q24 and the neighboring dipole (due to a bad welding ‘splice’)
Interconnections of two magnets
Most likely, an electrical arc developed, which punctured the Helium enclosure

Large amounts of Helium gas were released into the insulating vacuum of the cryostat:

- Self actuating relief valves opened, releasing large amount of He in the tunnel, but could not handle huge pressure
- Hence, large pressure waves traveled along the accelerator both ways
- Large forces exerted on the vacuum barriers located every 2 machine cells
- These forces displaced several quadrupoles by up to ~50 cm
- Beam pipes broke as well, vacuum contaminated
Examples of collateral damage

High pressure build-up damaged the magnet interconnects and the super-insulation.

Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.
LHC repair and restart

On 30th April the last of 53 replacement/repaired magnets has been lowered back into the tunnel (16 repaired + 37 spare magnets)

- The four warm sectors have been equipped with extra pressure relief valves (PRVs) on all dipole cryostats.
- The four cold sectors are getting extra PRVs on all short straight section cryostats. This can be done with the sectors cold and is adequate for 5 TeV operation.
- The quench protection system will be upgraded everywhere to cover all busbar splices.
- The whole machine will be cold by mid August, ready for first injected beam in late September.
- The machine will run at 5 TeV until autumn 2010 after which the remaining 4 sectors will be equipped with PRVs and will be prepared for high energy operation.

Recent additional measurements of the resistances of the copper bus-bar stabilizers have been made in order to ensure the future higher energy operation of the machine.

These additional measurements, made above superconducting temperatures, have caused a slight delay (1-2 weeks) compared to the one published in February 2009, but every effort is made to regain this lost time.
In more details: what is being done

Reduce the Risk: Enhanced Quench Protection (Detection) system

• Enhanced ohmic resistance measurement - threshold trigger of 0.3mV (compared with the 1V of the system in place on 19 September 2008) will diagnose the joints before thermal runaway
• New system will be installed and tested before beam operation.

Reduce the collateral damage:
(The high impact of the Sept.19 incident was caused by collateral damage)

Vent Helium more rapidly so as to reduce the pressure increase and consequently minimize (perhaps eliminate) the damage done

• Fit additional relief valves in already existing flanges in ALL the Short Straight Sections (SSS) (cross-section increases by a factor of 8)
• Cut large ports into dipole cryostats and fit DN200 relief valves. Do it in sectors that are warm (before beam) and later on all sectors (total factor of 40)
• Strengthen the anchors in the concrete floor: of quadrupoles with vacuum barriers
Illustrating some of the preventive measures

Pressure relieve valves on dipoles

New additional anchoring system

Red: existing jacks (80 kN)

Yellow: new additional anchoring system (240 kN)
Detailed internal work planning for:
- Powering
- Injection tests
- Beam operation

Week in 2009:

September 14-20

LHC Entering Operation
### Summary of the New LHC Schedule

The plan is:

- **Machine ready for start-up operation again in October 2009**

- **Run the LHC over winter until September 2010**

- **This first physics run will be limited to 10 TeV collision energy**

- **At the end of the run, end of summer 2010, there will be also a first run with heavy ion collisions (Pb-Pb)**
Another way of summarizing the LHC Schedule...
Cross Sections and Production Rates

Rates for \( L = 10^{34} \text{ cm}^{-2}\text{ s}^{-1} \): (LHC)

- **Inelastic proton-proton reactions:** \( 10^9 / \text{s} \)
  - bb pairs \( 5 \times 10^6 / \text{s} \)
  - tt pairs \( 8 / \text{s} \)
  - \( W \rightarrow e \nu \) \( 150 / \text{s} \)
  - \( Z \rightarrow e e \) \( 15 / \text{s} \)
  - Higgs (150 GeV) \( 0.2 / \text{s} \)
  - Gluino, Squarks (1 TeV) \( 0.03 / \text{s} \)

LHC is a factory for: top-quarks, b-quarks, W, Z, …… Higgs, ……

(The challenge: you have to detect them !)


**Experimental Challenge**

Bunches, each containing 100 billion protons, cross 40 million times a second in the centre of each experiment

- close to 1 billion proton-proton interactions per second in ATLAS and CMS (a few orders of magnitudes less in ALICE and LHCb)

**Large Particle Fluxes**

- thousands of particles stream into the detector every 25 ns
- large number of channels (~ 100 M channels in ATLAS and CMS)
- ~ 1 MB/25ns i.e. 40 TB generated per second

**High Radiation Levels**

- radiation hard (tolerant) detectors and electronics
The LHC World of CERN

CMS
2900 Physicists
184 Institutions
38 countries
550 MCHF

CMS

LHCb
700 Physicists
52 Institutions
15 countries
75 MCHF

ATLAS
2800 Physicists
169 Institutions
37 countries
550 MCHF

ALICE
1000 Physicists
105 Institutions
30 countries
150 MCHF

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ALICE: study of quark-gluon plasma
- L3 solenoid
- Large TPC
- Si microstrip, drift and pixels detectors
- Particle identification: RICH, TRD, TOF
- PbWO₄ crystals + Pb/scintillator ecal
- Single arm forward muon system

Size: 16 x 26 meters
Weight: 10,000 tons
Installation of an ALICE TOF module May 2008
LHCb:
Study of B decays and CP Violation
(indirect search for New Physics)

- Dipole magnet (4 T.m)
- Particle Identification (2 RICH)
- 21 layer of Si microstrip vertex locator (VELO)
- Tracking: Silicon + long straw tubes
- Shashlik (Pb/scint) em calorimeter
- HCAL (Fe/scint),
- MWPC muon system
LHCb Vertex Locator (VELO)
The LHCb detector installed at Point-8
The CMS Detector

Total weight: 12500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla

Plus End
Minus End
YB0
YE-1
YE-2
YE-3
HF-

http://cms.cern.ch
Example of an Engineering Challenge: CMS Solenoid

CMS solenoid:
- Magnetic length: 12.5 m
- Diameter: 6 m
- Magnetic field: 4 T
- Nominal current: 20 kA
- Stored energy: 2.7 GJ
- Tested at full current in Summer 2006

Entering Operation
The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007

In total 15 slices were installed in this way
CMS Electron and Photon calorimeter: 76 000 PbW0₄ crystals

End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS.
ATLAS Detector

ATLAS superimposed to the 5 floors of building 40

24 m

45 m

7000 Tons

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

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The Underground Cavern at Point-1 for the ATLAS Detector

Length = 55 m
Width = 32 m
Height = 35 m
Barrel calorimeter (EM Pb/LAr + Hadron Fe/scintillator) in its final position at Z=0

November 2005

October 2004
Installation of the ATLAS barrel tracker (Aug 2006)
A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008 (the last piece was the one shown here in ATLAS side A)
Collisions at LHC

Proton-Proton
- Protons/bunch: $10^{11}$
- Beam energy: 7 TeV ($7 \times 10^{12}$ eV)
- Luminosity: $10^{34}$ cm$^{-2}$ s$^{-1}$

Event rate:
- $N = L \times \sigma (pp) \approx 10^9$ interactions/s

Mostly soft (low $p_T$) events
- Interesting hard (high-$p_T$) events are rare

Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed
As an example:
ATLAS Trigger / DAQ Data Flow

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Event data pulled:
- partial events @ ≤ 100 kHz,
- full events @ ~ 3 kHz

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Event data pushed @ ≤ 100 kHz,
1600 fragments of ~ 1 kByte each
The read-out electronics, trigger, DAQ and detector control systems have been brought into operation gradually over the past years, along with the detector commissioning with cosmics

(Examples from ATLAS)

Example of LAr calorimeter read-out electronics

Example of Level-1 Trigger electronics

In total about 300 racks with electronics in the underground counting rooms
ATLAS HLT Farms (as an example for staged implementation)

Final size for max L1 rate \((TDR)\)

\(~ 500 \text{ PCs for L2} + \sim 1800 \text{ PCs for EF}\)
(multi-core technology)

For 2008: 850 PCs installed
\textit{total of 27 XPU racks} = 35\% \text{ of final system}

\((1 \text{ rack} = 31 \text{ PCs})\)
\((\text{XPU} = \text{can be connected to L2 or EF})\)

- \(x 8 \text{ cores}\)
- \(\text{CPU: 2} \times \text{Intel Harpertown quad-core 2.5 GHz}\)
- \(\text{RAM: 2 GB / core, i.e. 16 GB}\)

Final system: \textit{total of 17 L2 + 62 EF racks}
of which \(28 \text{ (of 79) racks as XPU}\)
Worldwide LHC Computing Grid (wLCG)

WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project’s size.

GRID computing developed to solve problem of data storage and analysis.

LHC data volume per year: 10-15 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = 10^9 MB = 10^{15} Byte

(Note: the WWW is from CERN... )
The Worldwide LHC Computing Grid (wLCG)

Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis

Tier-2 (federations of ~130 centres):
- Simulation
- End-user analysis
Site Reliability: CERN + Tier 1s

Tier 2 Reliabilities

Number of jobs/month

wLCG performances
10th September 2008 in the CMS Control room
Beam “splash” in CMS from ~ 2x10^9 protons on collimators ~ 150 m upstream of the experiment in Point-5

> 80% channels fired

100-1000 TeV energy deposits

Pink=EM calo
Blue=Had calo
Green=Muon chambers
Event splash recorded on 10 September at 9:54

Correlation between the energies measured in the barrel EM and in the barrel HAD calorimeters in beam splash events.

CMS preliminary

17 events:

\[ \langle HB \rangle = 1000 \text{ TeV} \]

\[ \langle EB \rangle = 150 \text{ TeV} \]
Excitement in the ATLAS Detector Control Room:
The first LHC events on 10th September 2008
The very first beam-splash event from the LHC in ATLAS at 10:19, on 10th September 2008
A busy beam-halo event with tracks bent in the Toroids from the start-up day
Contrary to what one wishes for the future, the splashes were highly desired events!

**Allowed to commissioning**

- Software and hardware communication interfaces with LHC
- Monitoring of LHC instrumentation and beam conditions

**Run 33062:**

6 events with ~50 tracks/event

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**First LHCb events from LHC beam injection on collimator** (Aug 2008)

Difference between inferred positions from software alignment and lab metrology ~3 microns!

If testbeam resolution can be achieved expect $\sigma \sim 7\mu$m at inner radius (in-situ so far 9 $\mu$m, work ongoing)

Determine primary vertex < 10 $\mu$m
First beam 10th September in ALICE

V0 hits on 10.9.2008, shortly after 9 am

SPD hits on 10.9.2008, shortly after 9 am
First ‘Interactions’ in ALICE on 11th September

ITS tracks on 12.9.2008
7 reconstructed tracks, common vertex

Circulating beam 2:
stray particle causing an interaction in the ITS
**Strategy toward physics**

**Before data taking starts:**
- Strict quality controls of detector construction to meet physics requirements
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation)
- Detailed simulations of realistic detector “as built and as installed” (including misalignments, material non-uniformities, dead channels, etc.) → test and validate calibration/alignment strategies
- Experiment commissioning with cosmics in the underground cavern

**With the first data:**
- Commission/calibrate detector/trigger in situ with physics (min.bias, Z→ll, …)
- “Rediscover” Standard Model, measure it at $\sqrt{s} = 10$ TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

Prepare the road to discoveries …

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**Example: ATLAS LAr em Accordion Calorimeter**

**Construction quality**
Thickness of Pb plates must be uniform to 0.5% (~10 μm)

End-cap: 1536 plates

< > ~ 2.2 mm
σ ≈ 9 μm

Absorber thickness (mm)

1 barrel module:
Δη \times Δφ = 1.4 \times 0.4
≈ 3000 channels

**Test-beam measurements**
4 (out of 32) barrel modules and 3 (out of 16) end-cap (EMEC) modules tested with beams

Scans with 120-245 GeV electrons (all 7 tested modules)

Overall uniformity: ~0.54%

Normalized energies

- All Barrel Modules: 0.43%
- All EMEC: 0.62%

1 barrel module:
Δη \times Δφ = 1.4 \times 0.4
≈ 3000 channels

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Continuous Operation of CMS

CRAFT: ‘Cosmics Run at Four Tesla’

CMS ran for 6 weeks (Oct/Nov 08) continuously to gain operational experience

Collected 300M cosmic events with tracking detectors and field (≈ 70% live-time). About 400 TB of data distributed widely.

87% have a standalone muon track reconstructed

3% have a global muon track with strip tracker hits (~7M trks)

3-4 x 10^{-4} have a track with pixel hits (~70k trks)
CMS CRAFT Results: Some Examples

Alignment in Inner Tracker
Distn of Mean Residuals

Muon Chambers
Point Resolution

Energy deposited by muons

Si Trkr
TOB 10μm

BPix
PXB 14μm

TOB
dE/dx (MeV cm²/g)

Energy deposition

DCAL

Points- data

σ ~ 250μm

ECAL

radiative

T. Virdee
RRB28
Apr09 70

MB1

MB2

MB3

MB4

CMS Preliminary
After the LHC incident, a huge amount of cosmic ray triggers are recorded, in total (left) as well as tracks also in the smallest volume detector, the Pixels (below).
A cosmic muon through the whole ATLAS detector...
ATLAS RPC track impact points projected to the surface

The two installation shafts and the two elevator shafts are nicely visible…

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Correlation between measurements in the ATLAS Inner Detector and Muon Spectrometer

Difference between the muon momentum measured in the ID and in the MS for tracks in the bottom part of the detector (~3 GeV energy loss in the calorimeter)

Muon momentum (data with B-field on)
Two examples of inner detector commissioning results from ATLAS

Turn-on of the transition radiation effect for high-momentum muons

Alignment of pixel modules, performed using cosmics tracks and an iterative procedure that minimizes the hit residuals globally

\~ 36000 degrees of freedom: 6000 detector modules x 6 unknown (3 position coordinates + 3 rotation angles per module)

Achieved in best illuminated modules: \~ 25 \(\mu\)m

Pixels alignment with cosmics data

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LHC Entering Operation
An example from ALICE: TPC Performance

- First preliminary results from cosmics
  - $dE/dx$ resolution (goal: ~ 5.5%)
    - < 6%
  - $p_t$ resolution (goal: ~ 5% @ 10 GeV)
    - < 7% @ 10 GeV partial calibration
Strategy toward physics

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Prepare the road to discoveries …

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**LHC physics goals**

- Search for the Standard Model Higgs boson over $115 < m_H < 1000$ GeV.
- Explore the highly-motivated TeV-scale, looking for physics beyond the SM (Supersymmetry, Extra-dimensions, q/l compositness, leptoquarks, W’/Z’, heavy q/l,..)
- Measure CP-violation in B-decays
- Measure transition from hadronic matter to quark-gluon plasma

What is the origin of the particle masses ?

What is the nature of the Universe dark matter ?

What is the origin of the Universe matter-antimatter asymmetry ?

What were the constituents of the Universe primordial plasma $\sim 10 \mu s$ after the Big Bang ?

What happened in the first instants of the Universe life ($10^{-10}$ s after the Big Bang) ?

Etc. etc.
ATLAS and CMS early “signals”: \( J/\psi, W, Z, \) top, the so-called “candles”

\( Z \rightarrow ee, 14 \text{ TeV}, 50 \text{ pb}^{-1} \)

\( \sqrt{s} = 10 \text{ TeV}, \) after cuts:
\(~ 200 Z \rightarrow ee, \mu\mu \) per day at \( L = 10^{31} \)
\(~ 40000 \) events \( 50 \text{ pb}^{-1} \)

→ Muon Spectrometer alignment, EM calo uniformity, energy/momentum scale of full detector, lepton trigger and reconstruction efficiency, …

\( \sqrt{s} = 10 \text{ TeV}, \) after simple cuts:
\(~ 1200 \) events \( 100 \text{ pb}^{-1} \)

\( tt \rightarrow bW bW \rightarrow bl\nu bjj \)

3 jets \( p_T > 40 \text{ GeV} \)
1 jets \( p_T > 20 \text{ GeV} \)
1 lepton \( p_T > 20 \text{ GeV} \)
\( E_T^{\text{miss}} > 20 \text{ GeV} \)

contain most physics objects: leptons, jets, \( E_T^{\text{miss}} \), b-jets
background to ~ all searches
→ when top measured, experiment is ready for discovery phase
Example of early LHCb physics: $B_s$-$\bar{B}_s$ mixing phase $\phi_s$

Sensitive to New Physics effects in box diagrams

- $\phi_s = \phi_{s(SM)} + \phi_{s(NP)}$
- $\phi_{s(SM)} = -2\beta_s = -2\lambda^2\eta \sim -0.04$

\[ \phi_{s(NP)} \]

\[ \beta_s = -2\lambda^2 \eta \]

\[ \sim -0.04 \]

\[ (2\beta_s = 0.0368) \]

$B^0 \to W^+ W^-$

With $\sim 0.3 \text{ fb}^{-1}$ LHCb should improve on expected Tevatron limit, similarly also for the rare decay $B_s \to \mu\mu$
Heavy-ion physics with ALICE

There schedule foresees a nominal PbPb@4TeV run at the end of 2010

- **fully commissioned detector & trigger**
  - alignment, calibration available from pp
- **first 10^5 events**: global event properties
  - multiplicity, rapidity density
  - elliptic flow
- **first 10^6 events**: source characteristics
  - particle spectra, resonances
  - differential flow analysis
  - interferometry
- **first 10^7 events**: high-p_t, heavy flavours
  - jet quenching, heavy-flavour energy loss
  - charmonium production
- **yield bulk properties of created medium**
  - energy density, temperature, pressure
  - heat capacity/entropy, viscosity, sound velocity, opacity
  - susceptibilities, order of phase transition
Example of an early surprise with ATLAS and CMS:

$Z' \rightarrow e^+ e^-$ with SM-like couplings ($Z_{SSM}$)

![Graph showing results of ATLAS and CMS experiments](image_url)
First discoveries: Supersymmetry?

If it is at the TeV mass scale, it should be found “quickly” .... thanks to:

- **Huge production rate for** $\tilde{q}, \tilde{g}$ production
  
  For $m(\tilde{q}, \tilde{g}) \sim 1$ TeV
  
  expect 1 event/day at $L=10^{31}$ cm$^{-2}$ s$^{-1}$

- **Spectacular final states** (many jets, leptons, missing transverse energy)

This particle (lightest neutralino) is stable, neutral and weakly interacting $\rightarrow$ escapes detection (like $\nu$) $\rightarrow$ apparent missing energy in the final state

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Obviously a main topic for the coming days here at SUSY2009
The Higgs Hunt

Higgs production cross sections at LHC

\( \sigma(pp \rightarrow H+X) \)
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ m_t = 175 \text{ GeV} \]

CTEQ4M

M. Spira et al.
NLO QCD

\[ \sigma_{gg\rightarrow H} \]
\[ \sigma_{q\bar{q}\rightarrow H} \]
\[ \sigma_{gg,q\bar{q}\rightarrow H^{\pm}} \]
\[ \sigma_{gg,q\bar{q}\rightarrow H^{0}} \]

events for \( 10^5 \text{ pb}^{-1} \)

\( M_H \) (GeV)

0

10

100

1000

10^2

10^3

10^4

10^5

10^6

10^7

WW, ZZ fusion

W, Z bremsstrahlung

W, Z

q, \bar{q}

\( H^0 \)

\( H^0 \)

\( H^0 \)
Higgs decay modes

Remember: light fully-hadronic final states cannot be extracted from QCD background at hadron colliders

\( m_H < 130 \text{ GeV} \): \( H \rightarrow bb, \tau\tau \) dominate
→ best search channels at the LHC: \( qqH \rightarrow qq \tau\tau, ttH \rightarrow bb l+X (\text{?}) \)
\( H \rightarrow \gamma\gamma \) (rare decay mode)
This is the most difficult region (S/B <<1)!

\( m_H > 130 \text{ GeV} \): \( H \rightarrow WW(\text{?}), ZZ(\text{?}) \) dominate
→ best search channels at the LHC: \( H \rightarrow ZZ(\text{?}) \rightarrow 4l \) (gold-plated)
\( H \rightarrow WW(\text{?}) \rightarrow l\nu l\nu \\

Especially in the region \( m_H < 130 \text{ GeV} \), excellent detector performance needed to suppress the huge backgrounds: b-tag, l/\gamma E-resolution, \gamma/j separation, missing \( E_T \) resolution, forward jet tag, etc.
→ Higgs searches used as benchmarks for ATLAS and CMS detector design
SM Higgs in CMS

H → γγ

H → ZZ* → 4 ℓ ±

H → ZZ → ℓℓ jj

Events / 500 MeV for 100 fb⁻¹

M_{γγ} (GeV)

M_{4 ℓ ±} (GeV)

M_{ℓℓ jj} (GeV)

Higgs signal

LHC Entering Operation

SUSY2009, Northeastern
5-June-09, P Jenni (CERN)
Simulation of a 130 GeV mass $H \rightarrow \mu\mu$ ee event in ATLAS
Summary of Higgs discovery potential at the LHC

Needed $\int Ldt$ per experiment (fb$^{-1}$)

With
1 fb$^{-1}$: 95% C.L. exclusion
5 fb$^{-1}$: 5$\sigma$ discovery over full allowed mass range
Final word about Higgs mechanism by end 2012?

Higgs

Most difficult region

With 200 pb$^{-1}$, reach current Tevatron sensitivity for Higgs

SUSY2009, Northeastern 5-June-09, P Jenni (CERN)
LHC Entering Operation
The first “Higgs” events observed jointly in CMS and ATLAS … (April 2008)

somewhat later, even in ALICE…
The LHC is one of the most ambitious, challenging and motivated projects in science ever.

After a very successful inauguration of the accelerator and experiments on 10 September 2008, operation has been interrupted by an incident provoked by a faulty electrical connection between two magnets.

Repairs are progressing well and the revised schedule foresees first collisions in November 2009 leading into a first physics run at 10 TeV extending to end summer 2010.

Commissioning of the experiments in the underground caverns with cosmics has been going on since a long time. It has demonstrated excellent detector quality and has allowed first alignment, calibration and timing studies to be made in situ with the final detectors. → experiments are ready to do good physics with first collision data.
With the first collision data (100-200 pb⁻¹) at 10 TeV

Understand detector performance in situ in the LHC environment, and perform first physics measurements:
• Measure particle multiplicity in minimum bias (a few hours of data taking …)
• Measure QCD jet cross-section to ~ 30% ?
• Measure W, Z cross-sections to 10% with 100 pb⁻¹?
• Observe a top signal with ~ 50 pb⁻¹
• Measure tt cross-section to 20% and m_t to 10 GeV with 100 pb⁻¹ ?
• Improve knowledge of PDF with W/Z with O(100) pb⁻¹ ?
• First tuning of MC (minimum-bias, underlying event, tt, W/Z+jets, QCD jets,…)

And, more ambitiously:
■ Discover SUSY up to gluino masses of ~ 1 TeV ?
■ Discover a Z’ up to masses of ~ 1 TeV ?
■ Surprises ?
The LHC will explore in detail the highly-motivated TeV-scale with a direct discovery potential up to $m \approx 5-6$ TeV

→ if New Physics is there, the LHC should find it

→ it will say the final word about the SM Higgs mechanism and many TeV-scale predictions

→ it may add crucial pieces to our knowledge of fundamental physics → impact also on astroparticle physics and cosmology

→ most importantly: it will most likely tell us which are the right questions to ask, and how to go on
Susy 2009, Northeastern 5-6 June 09, P Jenni (CERN) LHC

Entering Operation

"Hard" Scattering

proton

outgoing parton

final-state radiation

underlying event

initial-state radiation

outgoing parton

proton
"Hard" Scattering

proton
underlying event
outgoing parton

initial-state radiation
final-state radiation

SUSY

SUSY2009, Northeastern, June 09, PJenni (CERN)
Entering Operation
Thank you for your attention!