Preparing for physics at the LHC

Fabiola Gianotti
(CERN, PH Department)

- Machine status and schedule
- Status of experiments and preparation for physics with test beams and cosmics runs
- First physics with first data
**LHC**

- **pp** $\sqrt{s} = 14$ TeV  \( L \text{design} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) (after 2009)
- \( L \text{initial} \leq \text{few} \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) (until 2009)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s} \sim 1000$ TeV)

**TOTEM** (integrated with CMS):
- pp, cross-section, diffractive physics

**ALICE**:
- ion-ion, p-ion

**ATLAS and CMS**:
- general purpose

**27 km LEP ring**
- 1232 superconducting dipoles B=8.3 T

**LHCb**:
- pp, B-physics, CP-violation

**Here**: ATLAS and CMS

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F. Gianotti, ICHEP06, Moscow, 02/08/2006
As of this morning:
- 1154 dipoles (out of 1232) delivered at CERN
- 660 installed in the tunnel

Dipole interconnect work proceeding in 2 octants in parallel
Not only dipoles ....

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main dipoles</td>
<td>1232</td>
</tr>
<tr>
<td>Quadrupoles</td>
<td>~ 400</td>
</tr>
<tr>
<td>Sextupoles</td>
<td></td>
</tr>
<tr>
<td>Octupoles/decapoles</td>
<td>~ 6000</td>
</tr>
<tr>
<td>Other correctors</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~ 8000</td>
</tr>
</tbody>
</table>

Straight section at IP 8
First 600 m of cryoline (QRL) successfully cooled down on 14/9/2005, followed by cool-down of full cryoline sector 8-1 and pressure test of sector 4-5.
(Revised) LHC schedule
as presented to CERN Council on 23 June 2006

- Last magnet installed: March 2007
  Machine and experiments closed: 31 August 2007

- First collisions ($\sqrt{s} = 900$ GeV, $L \sim 10^{29}$ cm$^{-2}$ s$^{-1}$): November 2007
  Commissioning run at injection energy until end 2007, then shutdown (3 months?)

- First collisions at $\sqrt{s}=14$ TeV (followed by first physics run): Spring 2008

Goal: deliver integrated luminosity of few fb$^{-1}$ by end 2008

- Sectors 7-8 and 8-1 will be fully commissioned up to 7 TeV in 2006-2007.
  If we continue to commission the other sectors up to 7 TeV, we will not get circulating beam in 2007.

- The other sectors will be commissioned up to the field needed for de-Gaussing.

- Initial operation will be at 900 GeV (CM) with a static machine (no ramp, no squeeze) to debug machine and detectors.

- Full commissioning up to 7 TeV will be done in the winter 2008 shutdown
Status of ATLAS and CMS: a few examples ...

(ALICE and LHCb are also on track)
Length : ~45 m
Radius : ~12 m
Weight : ~ 7000 tons
Electronic channels : ~ 10^8
~ 3000 km of cables

- **Tracking** (|\(\eta\)|<2.5, B=2T):
  - Si pixels and strips
  - Transition Radiation Detector (e/\(\pi\) separation)

- **Calorimetry** (|\(\eta\)|<5):
  - EM: Pb-LAr with Accordion shape
  - HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

- **Muon Spectrometer** (|\(\eta\)|<2.7):
  air-core toroids with muon chambers
Barrel toroid: cool down started (this morning T~120 K), first tests of full field in Sept. End-cap toroids: will be installed in the pit end 2006-beg 2007
Barrel calorimeter (EM liquid-argon + HAD Fe/scintillator Tilecal) in final position at Z=0. Barrel cryostat cold and filled with Ar.
One end-cap calorimeter (LAr EM, LAr HAD, LAr Forward inside same cryostat, surrounded by HAD Fe/Scintillator Tilecal) being moved inside the barrel toroid
Barrel pixel detector on critical path (problems with low-mass cables), but still scheduled for installation in the pit in April 2007

F. Gianotti, ICHEP06, Moscow, 02/08/2006
Cosmics DATA taken in barrel SCT+TRT : ~ 450k events

SCT efficiency per layer

Δφ (TRT track-SCT track)

Cabling error in two modules

ATLAS preliminary
Muon Spectrometer: measurement chambers MDT, CSC (innermost forward) trigger chambers RPC (barrel), TGC (end-caps)

~50% of barrel stations installed (mostly complete end of Summer '06)

First sectors of TGC end-cap “big-wheels” installed

F. Gianotti, ICHEP06, Moscow, 02/08/2006
First cosmics have been registered in the underground cavern with barrel Muon chambers (MDT and RPC) and Level-1 \( \mu \) trigger.
Towards Physics (1): the 2004 ATLAS combined test beam

Full “vertical slice” of ATLAS tested on CERN H8 beam line May-November 2004

Geant4 simulation of test-beam set-up

- Monitored Drift Tubes
- Resistive Plate Chamber
- Monitored Drift Tubes-Cathode Strip Chamber-Thin Gap Chamber end-caps
- Tile hadronic barrel calorimeter & ext. barrel
- Liquid Argon electromagnetic calorimeter
- Transition Radiation Tracker
- SCT
- Pixel
- Magnet
- Y
- Z

O(1%) of ATLAS coverage

~ 90 million events collected (~4.5 TB of data):
- e^+, e^-, π^+, π^-, γ
- μ^+, μ^-, p
- up to 250 GeV
- up to 350 GeV
- 20-100 GeV
- B-field = 0 → 1.4 T

All ATLAS sub-detectors (and LVL1 trigger) integrated and run together with common DAQ and monitoring, “final” electronics, slow-control, etc. Data analyzed with common ATLAS software. Gained lot of global operation experience during ~ 6 month run.
ATLAS preliminary

ATLAS @ LHC:
$\gamma$-conversion probability in tracker is $> 30\% \rightarrow$ important to develop (and validate !) efficient reconstruction tools

Inner Detector tracks extrapolated to ECAL and compared to calo clusters
• Tracking \(|\eta|<2.5, B=4T\) : Si pixels and strips

• Calorimetry \(|\eta|<5\):
  -- EM : PbWO\(_4\) crystals
  -- HAD: brass/scintillator (central+ end-cap), Fe/Quartz (fwd)

• Muon Spectrometer \(|\eta|<2.5\) : return yoke of solenoid instrumented with muon chambers

Length : \(~22\) m
Radius : \(~7\) m
Weight : \(~12500\) tons

Compact and modular:
assembled at the surface
and lowered in the cavern
piece by piece

YB0 lowering (2000t): Dec. 2006
At the surface, solenoid inserted on 14 Sept. 2005; cooled down to 4.5 K in February 2006; ramping up the current, now at 12.5 kA (2.5 T) → magnetic test/field map starting Aug./Sept. 2006 (MTCC)

<table>
<thead>
<tr>
<th>Magnetic length</th>
<th>12.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>6 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>4 T</td>
</tr>
<tr>
<td>Nominal current</td>
<td>20 kA</td>
</tr>
<tr>
<td>Stored energy</td>
<td>2.7 GJ</td>
</tr>
</tbody>
</table>
Installation of Muon chambers: ~ 90% complete in end-cap (CSC+RPC), ~ 60% in barrel (DT+RPC)

50% of RPCs installed on YE disks.

> 90% CSCs installed on YE disks.

3 out of 5 YB wheels done (DTs, RPCs)
Detailed commissioning studies with cosmic muons

Track reconstruction efficiency in MB2

are needed to see this picture.
Cosmic muon bending in the CMS return yoke, collected yesterday with 12.5kA in the solenoid (B=2.5T)
Barrel: 36 SuperModules (SM), 1700 crystals each
Total of ~ 61000 barrel crystals (85% delivered)
27 bare SM assembled, 22 equipped with electronics

Crystal delivery determines ECAL schedule: last barrel (end-cap) crystal delivered in Feb. 2007 (Jan. 2008).
Plan is to have barrel completed for commissioning run in 2007 and end-caps installed for 2008 physics run
Inner tracker:
\~ 220 m\textsuperscript{2} of Si sensors
10.6 million Si strips
65.9 million Pixels

- Assembly of all 16000 modules completed
- Integration progressing well
- Installation at Point 5 in April 2007

One TEC (9 disks) completed
Towards Physics (2): the CMS Magnet Test and Cosmic Challenge (MTCC)

Cosmics run of a ~full detector slice (few percent of CMS coverage) inside 4T field. Magnet being energized, detector closed, data taking started ...

Test: detector installation and closing; magnet commissioning and field map; combined operation of full chain detector-electronics-DAQ-trigger-DCS-software identical to final experiment; timing, calibration, alignment procedures

High muon rate: 0.5-1 kHz (run at surface)
First physics with first data

- Understand detector and Standard Model physics
- Discoveries ?

Here only a few examples .... (top, SUSY, Higgs ...)
What data samples in 2007?

30% data taking efficiency included (machine plus detector). Trigger and analysis efficiencies included.

\[ \sqrt{s} = 900 \text{ GeV}, \ L = 10^{29} \text{ cm}^{-2} \text{ s}^{-1} \]

- Jets \( p_T > 15 \text{ GeV} \)
- Jets \( p_T > 50 \text{ GeV} \)
- Jets \( p_T > 70 \text{ GeV} \)
- \( \Upsilon \rightarrow \mu \mu \)
- \( W \rightarrow e \nu, \mu \nu \)
- \( Z \rightarrow e e, \mu \mu \)

Start to commission triggers and detectors with collision data (minimum bias, jets, ..) in real LHC environment.

Maybe first physics measurements (minimum-bias, underlying event, QCD jets, ..)?

Observe a few \( W \rightarrow l \nu, \ Upsilon \rightarrow \mu \mu, J/\psi \rightarrow \mu \mu \)?
Example 1: CMS ECAL calibration
only ~ 6 SM will be tested with test beams → most/all SM will be calibrated with cosmic rays

3% calibration uniformity achievable with cosmics → improve on initial 4-5%

~ 1.5% calibration uniformity achievable in central barrel with 18 million minimum-bias (few days of data taking in 2007)

Further step toward the ~ 0.5% needed to observe a $H \rightarrow \gamma \gamma$ signal
Example 2: Measurement of the underlying event in di-jet production

Particle multiplicity of underlying event obtained from the region transverse to the leading jet.

Comparison of plateau's between LHC and Tevatron will tell if detector performance, reconstruction tools and physics are under control.

~ 15 days of data taking in 2007 enough to cover up to $p_T(\text{leading jet}) \sim 40$ GeV
With the first physics run in 2008 ($\sqrt{s} = 14$ TeV) ....

1 fb$^{-1}$ (100 pb$^{-1}$) $\equiv$ 6 months (few days) at L= $10^{32}$ cm$^{-2}$s$^{-1}$ with 50% data-taking efficiency
$\rightarrow$ may collect a few fb$^{-1}$ per experiment by end 2008

<table>
<thead>
<tr>
<th>Channels (examples ...)</th>
<th>Events to tape for 100 pb$^{-1}$ (per expt: ATLAS, CMS)</th>
<th>Total statistics from some of previous Colliders</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \mu \nu$</td>
<td>$\sim 10^4$ LEP, $\sim 10^6$ Tevatron</td>
<td>$\sim 10^6$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu \mu$</td>
<td>$\sim 10^5$</td>
<td>$\sim 10^6$ LEP, $\sim 10^5$ Tevatron</td>
</tr>
<tr>
<td>$\tilde{g} \tilde{g}$</td>
<td>$\sim 10^4$</td>
<td>$\sim 10^4$ Tevatron</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow W b W b \rightarrow \mu \nu +X$</td>
<td>$\sim 10^3$</td>
<td>$\sim 10^4$ Tevatron</td>
</tr>
<tr>
<td>QCD jets $p_T &gt; 1$ TeV</td>
<td>$\sim 50$</td>
<td>$\sim 50$</td>
</tr>
</tbody>
</table>

- Understand and calibrate detectors _in situ_ using well-known physics samples
  - e.g. - $Z \rightarrow ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $t\bar{t} \rightarrow bl b jj$ jet scale from $W \rightarrow jj$, b-tag performance, etc.

- Measure SM physics at $\sqrt{s} = 14$ TeV: $W$, $Z$, $t\bar{t}$, QCD jets ...
  (also because omnipresent backgrounds to New Physics)

$\rightarrow$ prepare the road to discovery ...... it will take time ...
Example of initial measurement: understanding detector and physics with top events

Can we observe an early top signal with limited detector performance? And use it to understand detector and physics?

\[ \sigma_{tt} \approx 250 \text{ pb for } tt \rightarrow bW bW \rightarrow blv bjj \]

- 4 jets \( p_T > 40 \text{ GeV} \)
- 2 jets \( M(jj) \sim M(W) \)
- Isolated lepton \( p_T > 20 \text{ GeV} \)
- \( E_T^{\text{miss}} > 20 \text{ GeV} \)
- \( \sum p_T \) for 3 jets

Top signal observable in early days with no b-tagging and simple analysis (100 \( \pm \) 20 evts for 50 pb\(^{-1}\)) \( \rightarrow \) measure \( \sigma_{tt} \) to 20\%, \( m \) to 10 GeV with \( \sim 100 \text{ pb}^{-1} \)?

In addition, excellent sample to:
- commission b-tagging, set jet E-scale using \( W \rightarrow jj \) peak
- understand detector performance for e, \( \mu \), jets, b-jets, missing \( E_T \), ...
- understand / constrain theory and MC generators using e.g. \( p_T \) spectra
Example of “early” discovery: Supersymmetry?

If SUSY at TeV scale → could be found “quickly” .... thanks to:

- large $\tilde{q}, \tilde{g}$ cross-section $\rightarrow \approx 10$ events/day at $10^{32}$ for
- spectacular signatures (many jets, leptons, missing $E_T$)

If SUSY at TeV scale $\rightarrow$ could be found “quickly”…. thanks to:

$m(\tilde{q}, \tilde{g}) \sim 1$ TeV

Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 (good) pb$^{-1}$ LHC could say if SUSY accessible to $\leq 1$ TeV ILC

BUT: understanding $E_T^{\text{miss}}$ spectrum (and tails from instrumental effects) is one of the most crucial and difficult experimental issue for SUSY searches at hadron colliders.
$M_{\text{eff}} (\text{GeV}) = \sum_{i=1,4} E_T^{(i)} + E_T^{\text{miss}}$

$E_T^{\text{miss}}$ spectrum contaminated by cosmics, beam-halo, machine/detector problems, etc.

Estimate physics backgrounds using data (control samples)

$R: Z(\rightarrow \nu\nu) + \text{jets}$
$B: \text{as estimated from } W(\rightarrow \mu\nu) + \text{jets}$
What about the SM Higgs boson?

Needed $\int \! L \! dt$ (fb$^{-1}$) per experiment

$\leq 1$ fb$^{-1}$ for 98% C.L. exclusion
$\leq 5$ fb$^{-1}$ for 5$\sigma$ discovery over full allowed mass range

$H \rightarrow 4l$ : narrow mass peak, small background
$H \rightarrow WW \rightarrow l\nu l\nu$ (dominant at the Tevatron): counting channel (no mass peak)

here discovery easier with gold-plated $H \rightarrow ZZ \rightarrow 4l$ → by end 2008?

CMS, $H \rightarrow e\mu e\mu$

$\int \! L = 5.8$ fb$^{-1}$
Light Higgs: more difficult …

\[ m_H \sim 115 \text{ GeV} \quad 10 \text{ fb}^{-1} : \quad S/\sqrt{B} \approx 4 \quad \text{ATLAS} \]

K-factors \( \equiv \sigma(\text{NLO})/\sigma(\text{LO}) \approx 2 \) for \( H \rightarrow \gamma \gamma \) NOT included (conservative)

3 (complementary) channels with similar (small) significances:

- \( H \rightarrow \gamma \gamma \)
- \( t\bar{t}H \rightarrow t\bar{t}bb \rightarrow b\nu b j j b \)
- \( q\bar{q}H \rightarrow q\bar{q}\tau \tau \)

\[ S=130, \quad B=4300, \quad S/\sqrt{B}=2 \]
\[ S=15, \quad B=45, \quad S/\sqrt{B}=2.2 \]
\[ S=10, \quad B=10, \quad S/\sqrt{B}=2.7 \]

- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - ECAL crucial for \( H \rightarrow \gamma \gamma \) (in particular response uniformity): \( \sigma/m \sim 1\% \) needed
  - b-tagging crucial for \( t\bar{t}H \): 4 b-tagged jets needed to reduce combinatorics
  - efficient jet reconstruction over \(|\eta| < 5\) crucial for \( q\bar{q}H \rightarrow q\bar{q}\tau \tau \):
    forward jet tag and central jet veto needed against background

All three channels require very good understanding of detector performance and background control to 1-10% → convincing evidence likely to come later than 2008 ...

Note: \( WH \rightarrow l\nu b b \) (dominant at the Tevatron) provides less sensitivity than \( t\bar{t}H \) at LHC

F. Gianotti, ICHEP06, Moscow, 02/08/2006
Those of you who have bet for ATLAS can still hope to make money out of it....
Conclusions

- Impressive achievements in the machine construction over last months:
  - >50% dipoles installed, problems with cryoline solved, better understanding of commissioning and operation, etc.
- New LHC schedule:
  - machine and experiments closed 31 August 2007
  - commissioning run at $\sqrt{s}=900$ GeV end 2007
  - first physics run at 14 TeV starting in Spring 2008
- Experiments (huge progress as well!) on track to meet above schedule. Test-beam and cosmics results indicate they work as expected.
- All efforts now to continue installation and commissioning of machine and detectors of unprecedented complexity, technology and performance
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%?
  (Expect >$10^3$ events with $E_T(j) > 1$ TeV with 100 pb$^{-1}$)
• Measure $W$, $Z$ cross-sections to 10% with 100 pb$^{-1}$?
• Observe a top signal with ~ 30 pb$^{-1}$
• Measure $t\bar{t}$ cross-section to 20% and $m(top)$ to 7-10 GeV with 100 pb$^{-1}$?
• Improve knowledge of PDF (low-x gluons !) with $W/Z$ with $O(100)$ pb$^{-1}$?
• First tuning of MC (minimum-bias, underlying event, $t\bar{t}$, $W/Z$+jets, QCD jets, …)

And, more ambitiously:
■ Discover SUSY up to gluino masses of ~ 1.3 TeV ?
■ Discover a Z' up to masses of ~ 1.3 TeV ?
■ Surprises ?

With the first collision data (1-100 pb$^{-1}$) at 14 TeV
And, later on ....

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 will 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 likely tell us which are the right questions to ask, and how to go on
Many thanks to:

Back-up slides
What about the comparison with the Tevatron?

**CDF+DO sensitivity**

<table>
<thead>
<tr>
<th>L (fb⁻¹)/exp.</th>
<th>CDF+DO sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs Sensitivity Study ('03)</td>
<td>Statistical power only (no systematics)</td>
</tr>
<tr>
<td>SUSY/Higgs Workshop ('98-'99)</td>
<td></td>
</tr>
<tr>
<td>LEP Excluded</td>
<td></td>
</tr>
<tr>
<td>PRELIMINARY</td>
<td></td>
</tr>
</tbody>
</table>

**Today:** ~ 1.3 fb⁻¹ /exp. on tape

**Projections for end 2009:**
- 4 fb⁻¹: present machine performance
- 8 fb⁻¹: electron cooling of pbar and other improvements

With 4 (8) fb⁻¹:
- ~no 5σ sensitivity
- 3σ evidence up to 120 (130) GeV
- 95% C.L. exclusion up to ~ 130 (180) GeV

**Tevatron vs LHC after kin. cuts**

<table>
<thead>
<tr>
<th></th>
<th>WH → lν bb (m_H=120 GeV)</th>
<th>H → WW(*) (m_H = 160 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (14 TeV/ 2 TeV)</td>
<td>≈ 5</td>
<td>≈ 17</td>
</tr>
<tr>
<td>B (14 TeV/ 2 TeV)</td>
<td>≈ 25</td>
<td>≈ 6</td>
</tr>
<tr>
<td>S/B (14 TeV/ 2 TeV)</td>
<td>≈ 0.2</td>
<td>≈ 3</td>
</tr>
<tr>
<td>S/√B (14 TeV/ 2 TeV)</td>
<td>≈ 1</td>
<td>≈ 7</td>
</tr>
</tbody>
</table>

`Assuming same integrated luminosity and same detector performance at Tevatron and LHC`

Competition between Tevatron and LHC in 2008-2009 if m_H < 190 GeV?
LSS installation
QRL installation
QRL consolidation after pressure test
Cryo-magnet transport
Interconnection phase 1
LSS installation
End of 1st interconnect activity
Pressure test
Cryostat closure – Interconnect consolidation
Insulation // Interconnect phase 1
Beam pipes & bake-out
ELQA at warm
Cool-down
Power tests
Machine check-out
Beam at 450 GeV/C
LHC operation cycle

- Ramp down: ≈ 18 mins
- Pre-injection plateau: 15 mins
- Injection: ≈ 15 mins
- Ramp: ≈ 28 mins
- Squeeze: < 5 mins
- Prepare physics: ≈ 10 mins
- Physics: 10-20 hours
Distribution Feed Box
Staged commissioning plan for protons

I. Pilot physics run
   - First collisions
   - 43 bunches, no crossing angle, no squeeze, moderate intensities
   - Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
     - Performance limit $10^{32}$ cm$^{-2}$ s$^{-1}$ (event pileup)

II. 75ns operation
   - Establish multi-bunch operation, moderate intensities
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
   - Performance limit $10^{32}$ cm$^{-2}$ s$^{-1}$ (event pileup)

III. 25ns operation I
   - Nominal crossing angle
   - Push squeeze
   - Increase intensity to 50% nominal
   - Performance limit $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

IV. 25ns operation II
   - Push towards nominal performance

Note: dates and integrated luminosities are MY interpretation
<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>4 magnets</td>
<td>Only 1 magnet</td>
</tr>
<tr>
<td></td>
<td>Calorimeters in field-free region</td>
<td>Calorimeters inside field</td>
</tr>
<tr>
<td>TRACKER</td>
<td>Si pixels + strips</td>
<td>Si pixels + strips</td>
</tr>
<tr>
<td></td>
<td>TRT → 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>$\sigma/p_T \sim 5 \times 10^{-4}$</td>
<td>$\sigma/p_T \sim 1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$p_T \oplus 0.01$</td>
<td>$p_T \oplus 0.005$</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>$\sigma/E \sim 2-5%/\sqrt{E}$</td>
</tr>
<tr>
<td></td>
<td>longitudinal segmentation</td>
<td>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>$\sigma/E \sim 50%/\sqrt{E}$ $\oplus 0.03$</td>
<td>$\sigma/E \sim 100%/\sqrt{E}$ $\oplus 0.05$</td>
</tr>
<tr>
<td>MUON</td>
<td>Air → $\sigma/p_T \sim 7%$ at 1 TeV standalone</td>
<td>Fe → $\sigma/p_T \sim 5%$ at 1 TeV combining with tracker</td>
</tr>
</tbody>
</table>
CMS Magnet Test and Cosmic Challenge (MTCC)

Ramping up of the magnet to nominal field started. A combined test of a slice of CMS will then be performed with cosmics.
Commissioning ECAL with cosmics (first studies...)

- check calorimeter timing to < 1 ns --> input to optimal filtering in electronics
- check calorimeter position in $\eta$ / $\phi$ wrt other sub-detectors to < 1 mm
- check response uniformity vs $\eta$: $\approx$ 0.5% precision could be achieved

Test-beam data

Barrel middle compartment

S($\mu$)/N $\approx$ 7

Test-beam data

Muons
E$\sim$300 MeV
$\sigma_t \sim$ 6 ns

$\sigma_t = 1.62$ ns/E (GeV) $\pm$ 19 ps (from calibration)
Commissioning ID with cosmics and beam gas (some ideas)

**Cosmics:** O (1Hz) tracks in Pixels+SCT+TRT
- useful statistics for debugging readout, maps of dead modules, etc.
- check relative position Pixels/SCT/TRT and of ID wrt ECAL and Muon Spectrometer
- first alignment: may achieve statistical precision of ~10 \( \mu \text{m} \) in parts of Pixels/SCT, 50 \( \mu \text{m} \) in TRT
- first calibration of \( t_0 \) and R-t relation in straws

**Beam-gas:**
- \( \sim 25 \) Hz of reconstructed tracks with \( p_T > 1 \text{ GeV} \) and \( |z| < 20 \text{ cm} \)
- >10\(^7\) tracks (similar to LHC events) in 2 months
- enough statistics for alignment in “relaxed” environment --> exceed initial survey precision of \( \sim 100 \mu \text{m} \)

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F. Gianotti, ICHEP06, Moscow, 02/08/2006
Which detector performance on day one?

A few examples and educated guesses based on detector construction quality, test-beam results, cosmics, and simulation studies.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Expected performance day 1</th>
<th>Physics samples to improve (examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL</td>
<td>~ 1% (ATLAS), 3% (CMS) ~ 2%</td>
<td>Minimum-bias, Z→ ee Z→ ee</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCAL</td>
<td>~ 3 %</td>
<td>Single pions, QCD jets Z (→ ll) +1j, W→ jj in tt events</td>
</tr>
<tr>
<td>Jet scale</td>
<td>&lt; 10%</td>
<td></td>
</tr>
<tr>
<td>Tracking alignment</td>
<td>20-200 μm in Rφ ?</td>
<td>Generic tracks, isolated μ, Z→μμ</td>
</tr>
</tbody>
</table>

Ultimate statistical precision achievable after few weeks of operation. Then face systematics. E.g.: tracker alignment: 100 μm (1 month) → 10 μm (6 months) → 5 μm (1 year)?
• No hope to observe light objects (W, Z, H ?) in fully-hadronic final states $\rightarrow$ rely on l, $\gamma$
• Fully-hadronic final states (e.g. $q^* \rightarrow qg$) can be extracted from backgrounds only with hard $O(100 \text{ GeV})$ $p_T$ cuts $\rightarrow$ works only for heavy objects
• Mass resolutions of $\sim 1\%$ ($10\%$) needed for l, $\gamma$ (jets) to extract tiny signals from backgrounds, and excellent particle identification (e.g. $e$/jet separation)
• $S$ (EW) /$B$ (QCD) larger at Tevatron than at LHC
How many events per experiment at the beginning?

F. Gianotti, ICHEP06, Moscow, 02/08/2006

\[ \sim 10^5 J/\Psi \rightarrow \mu \mu + Y \rightarrow \mu \mu, \text{ee} \]

Assumed selection efficiency:
\[ W \rightarrow l\nu, Z \rightarrow ll: 20\% \]
\[ t\bar{t} \rightarrow l\nu + X: 1.5\% \text{ (no b-tag, inside mass bin)} \]

+ lots of minimum-bias and jets (\(10^7\) events in 2 weeks of data taking if 20% of trigger bandwidth allocated)

\[ 10 \text{ pb}^{-1} \equiv 1 \text{ month at } 10^{30} \text{ and } < 2 \text{ weeks at } 10^{31}, \varepsilon=50\% \]

\[ 100 \text{ pb}^{-1} \equiv \text{few days at } 10^{32}, \varepsilon=50\% \]

\[ 1 \text{ fb}^{-1} \equiv 6 \text{ month at } 10^{32}, \varepsilon=50\% \]

\[ 5 \text{ fb}^{-1} \equiv 3 \text{ month at } 10^{32} \text{ and 3 month at } 10^{33}, \varepsilon=50\% \]
Knowledge of SM physics on day 1?

- W, Z cross-sections: to 3-4% (NNLO calculation → dominated by PDF)
- $tt$ cross-section to ~7% (NLO+PDF)

Lot of progress with NLO matrix element
MC interfaced to parton shower MC (MC@ NLO, AlpGen,.. )

$\langle N_{ch} \rangle$ at $\eta=0$ for generic pp collisions (minimum bias)

Candidate to very early measurement:
few $10^4$ events enough to get $dN_{ch}/d\eta$, $dN_{ch}/dp_T$
→ tuning of MC models
→ understand basics of pp collisions, occupancy, pile-up, ...

LHC?
B-physics with 100pb-1 - statistics in dominant inclusive, exclusive channels

<table>
<thead>
<tr>
<th></th>
<th>10 pb-1</th>
<th>100 pb-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp → μ6 X</td>
<td>60 \times 10^6</td>
<td>600 \times 10^6</td>
</tr>
<tr>
<td>bb → μ6 X</td>
<td>40 \times 10^6</td>
<td>400 \times 10^6</td>
</tr>
<tr>
<td>cc → μ6 X</td>
<td>20 \times 10^6</td>
<td>200 \times 10^6</td>
</tr>
<tr>
<td>bb → μ6 μ3 X</td>
<td>2 \times 10^6</td>
<td>20 \times 10^6</td>
</tr>
<tr>
<td>pp → J/ψ(μ6μ3)</td>
<td>2.8 \times 10^5</td>
<td>2.8 \times 10^6</td>
</tr>
<tr>
<td>Y (μ6μ3)</td>
<td>0.9 \times 10^5</td>
<td>0.9 \times 10^6</td>
</tr>
<tr>
<td>B^+ → J/ψ K^+</td>
<td>1700</td>
<td>17000</td>
</tr>
<tr>
<td>B^0 → J/ψ K^{0*}</td>
<td>870</td>
<td>8700</td>
</tr>
</tbody>
</table>
B-physics with 100 pb-1 measurements in control channels at 14 TeV

**Sensitive tests of understanding of detector properties with strong impact on selected B-physics measurements: masses, lifetimes**

<table>
<thead>
<tr>
<th>B-photon Channel</th>
<th>Statistics 100 pb-1</th>
<th>Statistical error on Lifetime</th>
<th>World today (stat + syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B^+</td>
<td>B^+ → J/ψ K^+</td>
<td>17000</td>
<td>1.5 %</td>
</tr>
<tr>
<td>B^0</td>
<td>B^0 → J/ψ K^{0*}</td>
<td>8700</td>
<td>2.2 %</td>
</tr>
<tr>
<td>B_s</td>
<td>B_s → J/ψ φ</td>
<td>900</td>
<td>6 %</td>
</tr>
<tr>
<td>Λ_b</td>
<td>Λ_b → J/ψ Λ</td>
<td>260</td>
<td>8 %</td>
</tr>
</tbody>
</table>
ATLAS sensitivity in discovery channel
\[ \text{Br}(B^0_s \rightarrow \mu^+\mu^-) \]
sensitive to SUSY with 100 pb\(^{-1}\) and later

<table>
<thead>
<tr>
<th>Integral LHC Luminosity</th>
<th>Signal ev. after cuts</th>
<th>BG ev. after cuts</th>
<th>ATLAS upper limit at 90% CL</th>
<th>CDF&amp;D0 upper limit at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 pb(^{-1})</td>
<td>(~ 0)</td>
<td>(~ 0.2)</td>
<td>(6.4 \times 10^{-8})</td>
<td></td>
</tr>
<tr>
<td>10 fb(^{-1})</td>
<td>(~ 7)</td>
<td>(~ 20)</td>
<td>(7.0 \times 10^{-9})</td>
<td>(8 \times 10^{-8})</td>
</tr>
<tr>
<td>30 fb(^{-1})</td>
<td>(~ 21)</td>
<td>(~ 60)</td>
<td>(6.6 \times 10^{-9})</td>
<td></td>
</tr>
</tbody>
</table>
Constraining PDF with early ATLAS data using $W \to l\nu$ angular distributions

$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm y) \Rightarrow W$ production over $|y| < 2.5$ at LHC
involves $10^{-4} < x_{1,2} < 0.1$
⇒ region dominated by $g \to q\bar{q}$

Uncertainties on present PDF: 4-8%

--> ATLAS measurements of $e^\pm$ angular distributions provide discrimination between different PDF if experimental precision ~ 3-5%

Tricoli et al., ATL-PHYS-CONF-2005-008

HERWIG + NLO K-factor
CTEQ61
MRST01
ZEUS-S
Effect of including ATLAS data on PDF fits

Sample of $10^6 \ W \rightarrow \ e \nu$ generated with CTEQ6.1 and ATLAS fast simulation
Statistics corresponds to $\sim 100 \ pb^{-1}$
4% systematic error included by hand (statistical error negligible)

Central value of ZEUS-PDF prediction shifts and uncertainties is reduced
Error on low-$x$ gluon shape parameter $\lambda$ ($xg(x) \sim x^{-\lambda}$) reduced by 35%

Systematics (e.g. $e^{\pm}$ acceptance vs $\eta$) can be controlled to few percent with $Z \rightarrow ee$
($\sim 30000 \ events \ for \ 100 \ pb^{-1}$)
An “easy case” : $Z'$ of mass $\sim 1$ TeV with SM-like couplings

$Z' \rightarrow ee$, SSM

<table>
<thead>
<tr>
<th>Mass</th>
<th>Expected events for 1 fb$^{-1}$ (after all cuts)</th>
<th>$\int L , dt$ needed for discovery (corresponds to 10 observed evts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 TeV</td>
<td>$\sim 160$</td>
<td>$\sim 70$ pb$^{-1}$</td>
</tr>
<tr>
<td>1.5 TeV</td>
<td>$\sim 30$</td>
<td>$\sim 300$ pb$^{-1}$</td>
</tr>
<tr>
<td>2 TeV</td>
<td>$\sim 7$</td>
<td>$\sim 1.5$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

- large enough signal sample with $\int L \, dt \sim 100$ pb$^{-1}$ up to $m \approx 1$ TeV if “reasonable” $Z'ee$ couplings
- dominant Drell-Yan background small ($< 0.2$ events in the region 1400-1600 GeV, 100 pb$^{-1}$)
- signal as mass peak on top of background

$Z \rightarrow ll +$jet samples and DY needed for E-calibration and determination of lepton efficiency

---

F. Gianotti, ICHEP06, Moscow, 02/08/2006
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
SUSY inclusive search

**Effective mass**

0-lepton mode, $L=1fb^{-1}$

![Effective mass plot](image)

**Correct**

30% over-estimate

30% under-estimate

Result with fast simulation.

*only scale is changed (slope is same).*

**Important to understand background scale and slope.**

F. Gianotti, ICHEP06, Moscow, 02/08/2006
LHC Kinematic regime

Kinematic regime for LHC much broader than currently explored

Test of QCD:
- Test DGLAP evolution at small $x$:
  - Is NLO DGLAP evolution sufficient at so small $x$?
  - Are higher orders $\sim \alpha_s^n \log^m x$ important?
- Improve information of high $x$ gluon distribution

At TeV scale New Physics cross section predictions are dominated by high-$x$ gluon uncertainty (not sufficiently well constrained by PDF fits)

At the EW scale theoretical predictions for LHC are dominated by low-$x$ gluon uncertainty (i.e. W and Z masses) => see later slides

How can we constrain PDF’s at LHC?

\[ x_{i,2} = \frac{M}{\sqrt{s}} \exp(\pm y) \quad Q = M \quad y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \]
PDF scenario at LHC start up (2007) might be different

- In most of the relevant x regions accessible at LHC, HERA data are most important source of information in PDF determinations (low-x sea and gluon PDFs)

- HERA now in second stage of operation (HERA-II)
  - substantial increase in luminosity
  - possibilities for new measurements

HERA-II projection shows significant improvement to high-x PDF uncertainties
⇒ relevant for high-scale physics at the LHC
→ where we expect new physics !!

- significant improvement to valence-quark uncertainties over all-x
- significant improvement to sea and gluon uncertainties at mid-to-high-x
- little visible improvement to sea and gluon uncertainties at low-x
Missing ET resolution can be studied in 2007 (plot made with 35k minimum-bias events)
-- HLT/DAQ deferrals limit available networking and computing for HLT → limit LVL1 output rate
-- Large uncertainties on LVL1 affordable rate vs money (component cost, software performance, etc.)

<table>
<thead>
<tr>
<th>Selections (examples ...)</th>
<th>LVL1 rate (kHz)</th>
<th>LVL1 rate (kHz)</th>
<th>LVL1 rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L = 1 x 10^{33}</td>
<td>L = 2 x 10^{33}</td>
<td>L = 2 x 10^{33}</td>
</tr>
<tr>
<td></td>
<td>no deferrals</td>
<td>no deferrals</td>
<td>with deferrals</td>
</tr>
<tr>
<td>Real thresholds set for</td>
<td></td>
<td></td>
<td>An example for</td>
</tr>
<tr>
<td>95% efficiency at these</td>
<td></td>
<td></td>
<td>illustration...</td>
</tr>
<tr>
<td>E_T</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MU6,8,20</td>
<td>23</td>
<td>→ 19</td>
<td>→ 0.8</td>
</tr>
<tr>
<td>2MU6</td>
<td>---</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>EM20i,25,25</td>
<td>11</td>
<td>→ 12</td>
<td>12</td>
</tr>
<tr>
<td>2EM15i,15,15</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>J180,200,200</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>3J75,90,90</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>4J55,65,65</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>J50+xE50,60,60</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>TAU20,25,25 +xE30</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>MU10+EM15i</td>
<td>---</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Others (pre-scaled, etc.)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>~ 44</td>
<td>~ 43</td>
<td>~ 25</td>
</tr>
</tbody>
</table>

LVL1 designed for 75 kHz → room for factor ~ 2 safety
Likely max affordable rate, no room for safety factor
### Which data samples?

Total trigger rate to storage at $2 \times 10^{33}$ reduced from ~ 540 Hz (HLT/DAQ TP, 2000) to ~ 200 Hz (now)

**High-Level-Trigger output**

<table>
<thead>
<tr>
<th>Selection (examples …)</th>
<th>Rate to storage at $2 \times 10^{33}$ (Hz)</th>
<th>Physics motivations (examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e$^{25}$i, 2e$^{15}$i</td>
<td>~ 40  (55% W/b/c $\rightarrow$ eX)</td>
<td>Low-mass Higgs (ttH, H $\rightarrow$ 4ℓ, qqW, Z, top, New Physics ?)</td>
</tr>
<tr>
<td>μ$^{20}$i, 2μ$^{10}$</td>
<td>~ 40  (85% W/b/c $\rightarrow$ μX)</td>
<td>H $\rightarrow$ γγ, New Physics</td>
</tr>
<tr>
<td>γ$^{60}$i, 2γ$^{20}$i</td>
<td>~ 40  (57% prompt γ)</td>
<td>(e.g. X $\rightarrow$ γγ, m_X~ 500 GeV)</td>
</tr>
<tr>
<td>j$^{40}$, 3j$^{165}$, 4j$^{110}$</td>
<td>~ 25</td>
<td>Overlap with Tevatron for new X $\rightarrow$ jj in danger …</td>
</tr>
<tr>
<td>j$^{70}$ + xE$^{70}$</td>
<td>~ 20</td>
<td>SUSY : ~ 400 GeV squarks/glu</td>
</tr>
<tr>
<td>τ$^{35}$ + xE$^{45}$</td>
<td>~ 5</td>
<td>MSSM Higgs, New Physics</td>
</tr>
<tr>
<td>2μ$^{6}$ (+ $m_B$)</td>
<td>~ 10</td>
<td>(3rd family !) ? More difficult</td>
</tr>
<tr>
<td>Others (pre-scaled, exclusive, …)</td>
<td>~ 20</td>
<td>Rare decays B $\rightarrow$ μμX</td>
</tr>
<tr>
<td>Total</td>
<td>~ 200</td>
<td>Only 10% of total !</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Signal” (W, γ, etc.) : ~ 100</td>
</tr>
</tbody>
</table>

Best use of spare capacity when $L < 2 \times 10^{33}$ being investigated
ALICE Experimental Layout

L3 magnet
$B \leq 0.5 \, \text{T}$

Muon Forward Spectrometer
$2.4 < \eta < 4$

Total weight: 9,800 tons
Overall diameter: 16 m
Overall length: 26 m
130 MCHF CORE
MUON spectrometer set-up

- 5 stations of high granularity pad tracking chambers, over 1 million channels
- 0.7 T, bending power 3 Tm
- 4 MW power, 800 tons
- World’s largest warm dipole

Complex absorber/small angle shield system (∼10 λ) to minimize background (90 cm from vertex)

RPC Trigger Chambers
LHCb detector at IP8
**Compact Muon Solenoid (CMS)**

- **Strong Field 4T**
- **Compact design**
- **Solenoid for Muon $P_t$ trigger in transverse plane**
- **Redundancy**: 4 muon stations with 32 r-phi measurements
- $\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)
Muon Reconstruction (Momentum Res.)

CMS
Muon System

Reduced RE system $|\eta| < 1.6$
ECAL: PbWO₄ Crystals

Material | PbWO₄ | Pb | Fe  
--- | --- | --- | ---  
Density (g/cm³) | 8.3 | 11.3 | 7.9  
X₀ (mm) | 8.9 | 5.6 | 17.6  

Radiation Resistance: 10⁵ Gy (10 Mrad)
Inner Tracker

Bpix: 3 layers  Fpix: 2 disks  Pixel size 150\(\mu\)m; Resol \(~~~20\mu\)m
TIB: 4 layers  TID: 3 disks  Pitch: 80\(\mu\)m to 200\(\mu\)m
TOB: 6 layers  TEC: 9 disks  Resol: 20\(\mu\)m to 50\(\mu\)m
Laser Alignment System proves

NB: diffraction patterns from strips

TID and Pixel not in LAS!

Laser profile in all 9 disks (laser at “full” gain to illuminate all disks)
Hadronic Calorimeter: HCAL

- Had Barrel: HB
- Had Endcaps: HE
- Had Forward: HF
- Had Outer: HO
The low mass cable problem

- The barrel Al cables are made of 100 μm wire for signal and 300 μm for power (21 wires in a bundle), both wire-bonded on a small printed board + mini connector (~1m, module → PP0).
- The initial interpretation was that the cable was stressed during manipulation and strain relief and better practice should solve the problem.
- Visual inspection and electrical tests after stress on all production started and found that ~50% of the 2000 cable produced are bad or likely to evolve bad.
- Indeed the insulation was found to have cracks and, being the insulator much stronger than a 100 μm Al wire, any stress would concentrate on the wire thus breaking it (sooner or later), this is not true for the thicker power wires.