ATLAS status and plans for physics with first LHC data

Fabiola Gianotti (CERN, PH Department)

- Introduction, machine status
- Experimental challenges at the TeV scale
- ATLAS detector and installation status
- Toward physics: test-beam and cosmics runs
- First physics with first data (examples ...)

Fabiola Gianotti (CERN, PH Department)
LHC

- **pp**, $\sqrt{s} = 14$ TeV
  - $L_{\text{design}} = 10^{34}$ cm$^{-2}$ s$^{-1}$ (after 2010)
  - $L_{\text{initial}}$ up to few $\times 10^{33}$ cm$^{-2}$ s$^{-1}$ (before 2010)

  Note: $\sqrt{s}$ is x7 Tevatron, $L_{\text{design}}$ is x100 Tevatron

- Heavy ions (e.g. Pb-Pb at $\sqrt{s} \sim 1000$ TeV)

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**ATLAS general purpose**

**ALICE, heavy ions**

**CMS general purpose**

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

**CERN main site**

**Geneva Airport**

**French-Swiss border**

**LHC 27 km ring** (previously used for LEP)
Machine most challenging component:
1232 high-tech superconducting dipole magnets

Dipole field: 8.4 T
Operation temperature: 1.9 K
Dipole current: 11700 A
Dipole weight: 34 tons
7600 km of Nb-Ti superconducting cable

Dipole installation completed
The first one of eight sectors (sector 7-8) was cooled down to 1.9 K in the first half of 2007. Cool-down of sector 4-5 started.

One sector: 3.3 km, 154 dipoles
Not only dipoles ....

<table>
<thead>
<tr>
<th>Correction</th>
<th>Count</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>~ 7000</td>
</tr>
<tr>
<td>Other correctors</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~ 9000</td>
</tr>
</tbody>
</table>

Focusing inner-triplet quadrupoles being repaired

Straight section at IP 8
Main parameters of the machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Dipole field</td>
<td>8.4 T</td>
</tr>
<tr>
<td>Dipole current</td>
<td>11700 A</td>
</tr>
<tr>
<td>Instantaneous luminosity L</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Integrated luminosity/year</td>
<td>$\sim 100$ fb$^{-1}$</td>
</tr>
<tr>
<td>Circulating current/beam</td>
<td>0.53 A</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>R.m.s. beam radius at IP1/5</td>
<td>16 µm</td>
</tr>
<tr>
<td>R.m.s. bunch length</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>Stored beam energy</td>
<td>360 MJ</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>300 µrad</td>
</tr>
<tr>
<td>Number of events per crossing</td>
<td>$\sim 20$</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>10 hours</td>
</tr>
</tbody>
</table>

Design operation

- Aircraft carrier at 12 knots

$$L = \frac{N^2 k_b f}{4 \pi \sigma_x \sigma_y}$$

- Beam size at IP ($\sigma_{x,y} = 16 \text{ µm}$)
- Number of protons per bunch
- Number of bunches
- Number of turns per second

Aircraft carrier at 12 knots
General LHC Schedule

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.
- 450 GeV operation now part of normal setting up procedure for beam commissioning to high-energy
- General schedule being reassessed, accounting for inner triplet repairs and their impact on sector commissioning
  - All technical systems commissioned to 7 TeV operation, and machine closed April 2008
  - Beam commissioning starts May 2008
  - First collisions at 14 TeV c.m. July 2008
  - Pilot run pushed to 156 bunches for reaching $10^{32}$ cm$^{-2}$ s$^{-1}$ by end 2008
- No provision in success-oriented schedule for major mishaps, e.g. additional warm-up/cooldown of sector
The various steps toward design luminosity

Beam commissioning will proceed in phases with increased complexity:

- Number of bunches and bunch intensity.
- Crossing angle (start without crossing angle!).
- Less focusing at the collision point (larger \(\beta^*\)).
- It cannot be excluded that initially the LHC will operate at 6 TeV or so due to magnet 'stability'. Experience will tell...

It will most likely take YEARS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k ) / no. bunches</td>
<td>43-156</td>
<td>936</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>2021-566</td>
<td>75</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>(N ) (10^{11} protons)</td>
<td>0.4-0.9</td>
<td>0.4-0.9</td>
<td>0.5</td>
<td>1.15</td>
</tr>
<tr>
<td>Crossing angle ((\mu)rad)</td>
<td>0</td>
<td>250</td>
<td>280</td>
<td>280</td>
</tr>
<tr>
<td>(\sqrt{\beta^<em>/\beta^</em>_{\text{nom}}})</td>
<td>2</td>
<td>(\sqrt{2})</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(\sigma^* ) ((\mu)m, IR1&amp;5)</td>
<td>32</td>
<td>22</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>(L ) (cm^{-2}s^{-1})</td>
<td>(6 \times 10^{30})-(10^{32})</td>
<td>(10^{32})-(10^{33})</td>
<td>(1-2)(10^{33})</td>
<td>(10^{34})</td>
</tr>
<tr>
<td>Year (?)</td>
<td>2008</td>
<td>2009</td>
<td>2009-2010</td>
<td>&gt; 2010</td>
</tr>
</tbody>
</table>

My guess: total integrated luminosity \(\int L dt\) \(O(100\text{ pb}^{-1})\) in 2008? \(\int L dt \sim \text{ few fb}^{-1}\) in 2009?
Main experimental challenges to be faced in order to explore the TeV scale
• **No hope to observe light objects** (W, Z, H?) in fully-hadronic final states → rely on l, γ
• **Mass resolutions of ~ 1% (10%)** needed for l, γ (jets) to extract tiny signals from backgrounds, and excellent particle identification (e.g. e/jet separation)
• **Fully-hadronic final states** (e.g. q* → qg) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects
• **Signal (EW) /Background (QCD)** larger at Tevatron than at LHC
Event rate and pile-up (consequence of machine high luminosity ...)

Event rate in ATLAS, CMS:
\[ N = L \times \sigma_{\text{inelastic}} (\text{pp}) \approx 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \times 70 \text{ mb} \]
\[ \approx 10^9 \text{ interactions/s} \]

Proton bunch spacing: 25 ns
Protons per bunch: \(10^{11}\)

\[ \sim 20 \text{ inelastic (low-}\not{p}_T\text{) events ("minimum bias") produced simultaneously in the detectors at each bunch crossing} \rightarrow \text{pile-up} \]
Impact of pile-up on detector requirements and performance:

- Fast response: ~50 ns
- Granularity: >10^8 channels
- Radiation resistance (up to 10^{16} n/cm^2/year in forward calorimeters)
- Event reconstruction much more challenging than at previous colliders

At each crossing: \~1000 charged particles produced over |\eta| < 2.5 (10^0 < \theta < 170^0)
However: \langle p_T \rangle \approx 500 \text{ MeV}

\rightarrow applying p_T cuts allows extraction of interesting events

\eta = -\ln \tan \frac{\theta}{2}
3 Powerful high-performance experiments

Don’t know how New Physics will manifest → detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, .... → ATLAS and CMS are general-purpose experiments.

Excellent performance over unprecedented energy range:
Few GeV → few TeV

tt → bW bW → blν bjj event from CDF data

b-tagging (secondary vertices)
τ (b-hadrons) ~ 1.5 ps → decay at few mm from primary vertex → detected with high-granularity Si detectors
Examples of detector performance requirements:

Lepton measurement: \( p_T \approx \text{GeV} \rightarrow 5 \text{ TeV} \) (b \( \rightarrow \) l+X, W'/Z', ...)

Mass resolutions:
\( \approx 1\% \) decays into leptons or photons
(Higgs, new resonances)
\( \approx 10\% \) W \( \rightarrow \) jj, H \( \rightarrow \) bb
(top physics, Higgs, ...)

Particle identification:
• b/jet separation : \( \varepsilon (b) \approx 50\% \) R(jet) \( \approx 100 \)
  (H \( \rightarrow \) bb, SUSY, 3rd generation !!)
• \( \tau \)/jet separation : \( \varepsilon (\tau) \approx 50\% \) R(jet) \( \approx 100 \)
  (A/H \( \rightarrow \) \( \tau \)\( \tau \), SUSY, 3rd generation !!)
• \( \gamma \)/jet separation : \( \varepsilon (\gamma) \approx 80\% \) R(jet) \( > 10^3 \)
  (H \( \rightarrow \) \( \gamma \gamma \))
• e/jet separation : \( \varepsilon (e) > 70\% \) R(jet) \( > 10^5 \)
  (inclusive electron sample)
Trigger: one of the biggest challenges

Must reduce rate from 40 MHz (interaction rate) to ~ 200 Hz (affordable rate to storage)
Must be very selective and efficient: e.g. 1 H → 4e event every $10^{13}$ interactions
⇒ multi-level trigger systems

ATLAS 3-level Trigger/DAQ system

 LEVEL 1 TRIGGER
• Hardware-Based (FPGAs ASICs)
• Coarse granularity from calorimeter & muon systems
• 2 µs latency (2.5 µs pipelines)

 LEVEL 2 TRIGGER
• Regions-of-Interest “seeds”
• Full granularity for all subdetector systems
• Fast Rejection “steering”
• O(10 ms) processing time

 EVENT FILTER
• “Seeded” by Level 2 result
• Potential full event access
• Offline-like Algorithms
• O(1 s) processing time

High Level Trigger

RATES

<table>
<thead>
<tr>
<th></th>
<th>40 MHz</th>
<th>75 kHz</th>
<th>2 kHz</th>
<th>200 Hz</th>
</tr>
</thead>
</table>

More in S. Dasu’s talk
Finally, need massive (distributed) computing resources (CPU, storage)

The LHC experiments will produce 10-15 PB of data per year: corresponds to ~ 20 million CD (a 20 km stack ...)

Data analysis requires computing power equivalent to \(\sim 10^5\) today’s fastest PC processors

The experiment Collaborations are spread all over the world

→ Computing resources must be distributed.

The Grid provides seamless access to computing power and data storage capacity distributed over the globe.

A map of the worldwide LHC Computing Grid infrastructure provided by EGEE and OSG

~120 computing centers
~ 40 countries
The ATLAS experiment:
- detector
- installation status
- expected performance

- Construction: finished
- Installation in underground cavern: almost completed
- Commissioning with cosmics: ongoing
Length : ~ 46 m  
Radius : ~ 12 m  
Weight : ~ 7000 tons  
~$10^8$ electronic channels  
~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  
  -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

• Muon Spectrometer ($|\eta|<2.7$) :  
  air-core toroids with muon chambers

And … 1900 physicists from  
165 Institutions from 35 countries  
from 5 continents

F. Gianotti, CERN Theory Institute, 23/8/2007
<table>
<thead>
<tr>
<th></th>
<th>ATLAS ≡ A Toroidal LHC ApparatuS</th>
<th>CMS ≡ Compact Muon Solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAGNET (S)</strong></td>
<td>Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region</td>
<td>Solenoid Only 1 magnet Calorimeters inside field</td>
</tr>
<tr>
<td><strong>TRACKER</strong></td>
<td>Si pixels+ strips TRT → particle identification $B=2T$ $\sigma/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$</td>
<td>Si pixels + strips No particle identification $B=4T$ $\sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$</td>
</tr>
<tr>
<td><strong>EM CALO</strong></td>
<td>Pb-liquid argon $\sigma/E \sim 10%/\sqrt{E}$ uniform longitudinal segmentation</td>
<td>PbWO$_4$ crystals $\sigma/E \sim 2-5%/\sqrt{E}$ no longitudinal segm.</td>
</tr>
<tr>
<td><strong>HAD CALO</strong></td>
<td>Fe-scint. + Cu-liquid argon ($10 \lambda$) $\sigma/E \sim 50%/\sqrt{E} \oplus 0.03$</td>
<td>Cu-scint. ($&gt;5.8 \lambda$ +catcher) $\sigma/E \sim 100%/\sqrt{E} \oplus 0.05$</td>
</tr>
<tr>
<td><strong>MUON</strong></td>
<td>Air $\rightarrow \sigma/p_T \sim 7%$ at 1 TeV standalone</td>
<td>Fe $\rightarrow \sigma/p_T \sim 5%$ at 1 TeV only combining with tracker</td>
</tr>
</tbody>
</table>
Barrel toroid system (eight 25m-long, 100 tons superconducting coils): tested at full field (20 kA current) in November 2006.
Calorimeters

~ 12 m long, 4.3 m radius

LAr/Pb electromagnetic

Fe/scintillator hadronic Tilecal

LAr/Cu hadronic

LAr/W forward
Barrel calorimeter (EM Pb/LAr + Hadron Fe/scintillator) in its final position at Z=0. Cryostat is filled with LAr and cold (87 K)

November 2005

October 2004
**Inner tracker**

3 sub-systems:
- Silicon pixels: $0.8 \times 10^8$ channels
- Silicon strips (SCT): $6 \times 10^6$ channels
- Transition Radiation Tracker (TRT): straw tubes filled with gas, $4 \times 10^5$ channels

**Cosmic muon** recorded in the barrel TRT (in the assembly surface room)

February 2006
SCT + TRT in place, May 2007

Inner Detector installation in underground cavern completed

Pixels (+ beam pipe) insertion June 2007
The core of ATLAS: the Pixel detector

- 3 layers at ~5cm, 10cm, 13cm from the beam line
- made of ~80 million high-tech Si pixels 50\(\mu\)m wide, 400\(\mu\)m long, 250\(\mu\)m thick

Each one of these modules contains ~45000 pixel sensors

High detector granularity needed in very dense track environment around the beam
Installation of barrel muon chambers (~ 700 stations) started in December 2005 and is ~ completed.
Forward muon spectrometer: 6 out of 8 big wheels installed in the cavern
The two end-cap toroid magnets installed in June-July 2007
Spectacular operations ...
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

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.

O(1%) of ATLAS coverage

~ 90 million events collected (~4.5 TB of data):
- $e^\pm$, $\pi^\pm$ → 250 GeV
- $\mu^\pm$, $\pi^\pm$, $p$ up to 350 GeV
- $\gamma$ 20-100 GeV
- B-field = 0 → 1.4 T
$\gamma$→e$^+e^-$ in the tracker material → important to develop (and validate !) efficient reconstruction tools.
Towards Physics (2) : detector commissioning with cosmics in the underground cavern (the first real data in situ !)

Very useful to:

■ Run an increasingly more complete detector with final trigger, data acquisition and monitoring systems. Data analyzed with final software
■ Shake-down and debug the experiment in its final position → fix problems
■ Gain global operation experience in situ before collisions start
Simulated cosmics flux in the ATLAS cavern

Cosmics data: muon impact points extrapolated to surface as measured by Muon Trigger chambers (RPC)

Rate ~100 m below ground: ~ O(10 Hz)
A cosmic muon in LAr EM calorimeter and Tile calorimeter

Cosmics Muon spectrum in bottom part of Tilecal

A cosmic muon in Muon Spectrometer
Expected performance: muon measurement

Combining the information from Inner Detector and Muon Spectrometer

\( \sigma/p < 10\% \) for \( E_\mu \sim 1 \text{ TeV} \) needed to observe a possible new resonance \( X \rightarrow \mu\mu \) as “narrow” peak

**ATLAS Muon momentum resolution**

ATLAS Muon Spectrometer:

\( E_\mu \sim 1 \text{ TeV} \Rightarrow \Delta \sim 500 \text{ \( \mu \)m} \)

- \( \sigma/p \sim 10\% \Rightarrow \delta \Delta \sim 50 \text{ \( \mu \)m} \)
- alignment accuracy to ~20 \( \mu \)m

<table>
<thead>
<tr>
<th>( p_T (\text{GeV}) )</th>
<th>STACO (%)</th>
<th>Muon Spectrometer</th>
<th>Combined</th>
<th>Inner Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

GEANT simulation
Expected performance: electron measurement

Electron $E$-resolution measured in beam tests of ATLAS EM calorimeter (Pb/LAr)

$\sigma / E \sim 9.4\% / \sqrt{E} \oplus 0.1\%$

1 TeV $\mu^\pm : \sigma (p)/p \sim 5\%$
1 TeV $e^\pm : \sigma (E)/E \sim 0.5\%$
→ heavy narrow resonances will likely be observed first in the $X \rightarrow ee$ channel

$\mu^+ \mu^-$
$e^+ e^-$

$2000 \rightarrow 8000$
$m(l^+ l^-) \text{ GeV}$
First physics with first data
a few examples ...

Jump immediately into
a new territory ...

QCD Jet cross-sections

LHC

Tevatron
With the first physics data in 2008 ....

1 fb⁻¹ (100 pb⁻¹) ≡ 6 months (few days) at \( L = 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) with 50% data-taking efficiency
→ may collect \( O(100 \text{ pb}^{-1}) \) 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 10^6 ) ( \sim 10^5 ) ( \sim 10^4 ) ( &gt; 10^3 ) ( \sim 50 )</td>
<td>( \sim 10^4 \text{ LEP}, \sim 10^6 \text{ Tevatron} ) ( \sim 10^6 \text{ LEP}, \sim 10^5 \text{ Tevatron} ) ( \sim 10^4 \text{ Tevatron} ) --- ---</td>
</tr>
<tr>
<td>( Z \rightarrow \mu \mu )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau \tau \rightarrow W b W b \rightarrow \mu \nu +X )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD jets ( p_T &gt; 1 \text{ TeV} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tilde{g}\tilde{g} ) ( m = 1 \text{ TeV} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With these data:

- **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.
  - \( \tau \tau \rightarrow bl\nu bjj \) jet scale from \( W \rightarrow jj, b\)-tag performance, etc.

- “Rediscover” and measure SM physics at \( \sqrt{s} = 14 \text{ TeV} \): \( W, Z, \tau \tau, \text{QCD jets} \) ...
  (also because omnipresent backgrounds to New Physics)

→ prepare the road to discoveries ...... it will take time ...
Example of initial measurement: the first top quarks in Europe ...

A top signal can be observed quickly, even with limited detector performance and simple analysis .... and then used to “calibrate” the detector and understand physics

\[ \sigma_{\text{tt}} \approx 250 \, \text{pb} \text{ for } \text{tt} \rightarrow bW bW \rightarrow b\nu bjj \]

Top signal observable in early days with no b-tagging and simple analysis

(100 ± 20 evts for 50 pb\(^{-1}\)) \rightarrow with ~100 pb\(^{-1}\) measure \( \sigma_{\text{tt}} \) to 20%, \( m_t \) to 10 GeV ? Note: ultimate LHC precision on \( m_t \) is ~ 1 GeV

In addition, excellent sample to:

• understand detector performance for e, µ, jets, b-jets, missing \( E_T \), ...
• understand / constrain theory and MC generators using e.g. \( p_T \) spectra
One of the best candidates for an early discovery:
a narrow resonance with mass ~ 1 TeV decaying into $e^+e^-$

<table>
<thead>
<tr>
<th>Mass</th>
<th>Expected events for 1 fb$^{-1}$ (after all analysis cuts)</th>
<th>Integrated luminosity needed for discovery (corresponds to 10 observed evts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 TeV</td>
<td>~ 160</td>
<td>~ 70 fb$^{-1}$</td>
</tr>
<tr>
<td>1.5 TeV</td>
<td>~ 30</td>
<td>~ 300 fb$^{-1}$</td>
</tr>
<tr>
<td>2 TeV</td>
<td>~ 7</td>
<td>~ 1.5 fb$^{-1}$</td>
</tr>
</tbody>
</table>

- large enough signal for discovery with ~100 pb$^{-1}$ up to $m > 1$ TeV
- small well-known SM background (Drell-Yan)
- signal is (narrow) mass peak on top of background

Ultimate ATLAS reach (300 fb$^{-1}$): ~ 5 TeV

F. Gianotti, CERN Theory Institute, 23/8/2007
Is it a $Z'$ or a Randall-Sundrum Graviton?

Look at $e^\pm$ angular distributions to disentangle $G$ (s=2) from $Z'$ (S=1)
Need more integrated luminosity ...

ATLAS, 100 fb$^{-1}$, $m_G=1.5$ TeV

Allanach et al., JHEP 0009 (2000) 019
Another possible “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 $E_T$)

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

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 a $\leq 1$ 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.
Main backgrounds to SUSY searches in jets + $E_{T}^{\text{miss}}$ topology (one of the most “dirty” signatures ...):

- $W/Z + \text{jets}$ with $Z \rightarrow \nu\nu$, $W \rightarrow \tau\nu$; $tt$; etc.
- QCD multijet events with fake $E_{T}^{\text{miss}}$ from jet mis-measurements (calorimeter resolution and non-compensation, cracks, ...)
- cosmics, beam-halo, detector problems overlapped with high-$p_T$ triggers, ...

Estimate backgrounds using as much as possible data (control samples) and MC

Understanding $E_{T}^{\text{miss}}$ spectrum (and tails from instrumental effects) is one of most crucial and difficult experimental issues for SUSY searches at hadron colliders. Note: can also use final states with leptons (cleaner ...)

<table>
<thead>
<tr>
<th>Background process (examples ....)</th>
<th>Control samples (examples ....)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z (\rightarrow \nu\nu) + \text{jets}$</td>
<td>$Z (\rightarrow ee, \mu\mu) + \text{jets}$</td>
</tr>
<tr>
<td>$W (\rightarrow \tau\nu) + \text{jets}$</td>
<td>$W (\rightarrow e\nu, \mu\nu) + \text{jets}$</td>
</tr>
<tr>
<td>$tt \rightarrow blvbjj$</td>
<td>$tt \rightarrow blv blv$</td>
</tr>
<tr>
<td>QCD multijets</td>
<td>lower $E_{T}$ sample</td>
</tr>
</tbody>
</table>
A more difficult case: a light Higgs ($m_H \sim 115-150$ GeV)...

$m_H < 130$ GeV: $H \rightarrow bb, \tau\tau$ dominate
→ best search channels at the LHC: $qqH \rightarrow qq \tau\tau$, $H \rightarrow \gamma\gamma$, $ttH \rightarrow lbbX$

$m_H > 130$ GeV: $H \rightarrow WW^{(*)}, ZZ^{(*)}$ dominate
→ best search channels at the LHC: $H \rightarrow ZZ^{(*)} \rightarrow 4l$ (gold-plated) $H \rightarrow WW^{(*)} \rightarrow l\nu\nu$
Summary of Higgs discovery potential

If Higgs found, mass can be measured to 0.1%, couplings to ~ 10-20% → useful insight into EWSB

Most difficult region: need to combine many channels with small S/B

Here discovery easier with gold-plated \( H \rightarrow ZZ \rightarrow 4l \) narrow mass peak, small background

\[ \text{Needed } \int L dt \,(\text{fb}^{-1}) \text{ per experiment} \]

\[ \leq 1 \text{ fb}^{-1} \text{ for } 95\% \text{ C.L. exclusion} \]

\[ \leq 5 \text{ fb}^{-1} \text{ for } 5\sigma \text{ discovery} \]

over full allowed mass range

Final word about Higgs mechanism by 2009?

\[ \text{ATLAS (2003) } + \text{ CMS preliminary} \]

\[ \text{ATLAS (2003) } + \text{ CMS preliminary} \]

J.J. Blaising et al, input to Eur. Strategy workshop

\[ \int L dt = 30 \text{ fb}^{-1} \]

(no K-factors)

ATLAS

\[ m_H (\text{GeV}) \]

\[ \text{Events/7.5 GeV } \]

ATLAS 10 fb\(^{-1}\)

\[ \text{2003} \]

\[ H \rightarrow ZZ \rightarrow 4l \]
The most difficult low-mass region:

**ATLAS**: $m_H \sim 115$ GeV  
10 fb$^{-1}$ : $S/\sqrt{B} \approx 4-5.6$

range comes from $H \rightarrow \gamma\gamma$: LO vs NLO cross-section, cuts vs likelihood analysis

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

- **$H \rightarrow \gamma\gamma$**
  - S=130, B=4300, $S/\sqrt{B}=2 - 4.4$

- **$ttH \rightarrow ttbb \rightarrow bl\nu bjbb$**
  - S=15, B=45, $S/\sqrt{B}=2.2$ being re-evaluated

- **$qqH \rightarrow qq\tau\tau$**
  - S=10, B=10, $S/\sqrt{B}=2.7$

- 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 $ttH$: 4 b-tagged jets needed to reduce combinatorics (background being re-evaluated)
  -- efficient jet reconstruction over $|\eta| < 5$ crucial for $qqH \rightarrow qq\tau\tau$:
    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% \(ightarrow\) convincing evidence likely to come mid-end 2009...
What about the Tevatron?

Today: ~ 3 fb\(^{-1}\) /experiment
2009: expect 6-7 fb\(^{-1}\) /experiment
Tevatron operation in 2010 being discussed

With 4 (8) fb\(^{-1}\):
~no 5\(\sigma\) sensitivity
3\(\sigma\) evidence up to 120 (130) GeV
95\% C.L. exclusion up to ~ 130 (180) GeV

competition between Tevatron and LHC in 2009 if \(m_H < 130\) GeV?
With more time and more data, LHC can discover:

- Large number of scenarios studied
- Main conclusions:
  - LHC direct discovery reach up to $m \sim 5-6$ TeV
  - Demonstrated detector sensitivity to many signatures
  - Robustness, ability to cope with unexpected scenarios

**Excited quarks** $q^* \rightarrow \gamma q$: up to $m \approx 6$ TeV

**Leptoquarks**: up to $m \approx 1.5$ TeV

**Monopoles** $pp \rightarrow \gamma \gamma pp$: up to $m \approx 20$ TeV

**Compositeness**: up to $\Lambda \approx 40$ TeV

$Z' \rightarrow ll, jj$: up to $m \approx 5$ TeV

$W' \rightarrow l\nu$: up to $m \approx 6$ TeV

etc.... etc....
Conclusions
Impressive achievements on the machine side over last months:
e.g. magnet installation completed, one full sector cooled down to 1.9 K,
many components tested, inner triplets repair progressing,
machine commissioning and operation plan better understood, etc.

Revised LHC schedule foresees first collisions at 14 TeV in Summer 2008
(L. Evans: “no provision in success-oriented schedule for major mishaps”)

Luminosity projections: $6 \times 10^{30} - 10^{32}$ in 2008 $\rightarrow O(100 \text{ pb}^{-1})$?
$10^{32} - 10^{33}$ in 2009 $\rightarrow$ few fb$^{-1}$?
ATLAS detector installation in the underground cavern is almost completed → ATLAS ready to close the beam pipe in April 2008 (as requested by the LHC schedule)

An intense test-beam campaign over the last decade has demonstrated that the detector behaves as expected. These studies have also allowed validation and improvements of the software tools (simulation, reconstruction, etc.) with real data

Cosmics data taking has started with the detector in its final position in the underground cavern → this commissioning effort will allow us to save time when first collisions will become available.

A re-evaluation of the experiment's physics potential will be completed by the end of the year and documented in ATLAS notes. The huge number of channels and scenarios studied demonstrate the detector sensitivity to many signatures → robustness, ability to cope with unexpected scenarios
Understand ATLAS 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 $\sim 30\%$ ?
  (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 $\sim 30$ pb$^{-1}$
• Measure $t\bar{t}$ cross-section to 20% and $m(\text{top})$ 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 $\sim 1.3$ TeV ?
■ Discover a $Z'$ up to masses of $\sim 1.3$ TeV ?
■ Surprises ?
With more time and more data ....

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 likely tell us which are the right questions to ask, and how to go on

This will be the best reward for 20 years of efforts to conceive and build a machine and detectors of unprecedented performance, complexity and technology