LHC detector status and early physics

David Rousseau  LAL-Orsay

- LHC accelerator status and timeline
- ATLAS and CMS:
  - Tracking
  - Calorimetry
  - Trigger and software
- Analysis activities up to first collision
- Analysis activities in 2008, the first physics year

Aspen 2007 Winter Conference « New Physics at Electroweak Scale and New Signals at Hadron Colliders »
LHC layout

- ALICE: ion-ion, p-ion
- TOTEM (integrated with CMS): Pp-cross-section, diffractive physics
- 27 km LEP ring, 1232 superconducting dipoles B=8.3 T
- ATLAS and CMS: general purpose
- ATLAS and CMS
- LHCb: pp, B-physics, CP-violation

Here: ATLAS and CMS
Status of LHC

27 Nov 2006 Arrival of the last LHC magnet at CERN

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LHC installation

- 1/8 sector ready to be cooled down early 2007
- 4/8 sectors installed
- 2/8 in progress
LHC Time Line

(from Dec 7th 2006 Lynn Evans (LHC division leader) @ LHC Machine advisory committee)

- **Commissioning**
  - Last magnet has been delivered (!) November 2006
  - Last magnet installed March 2007
  - Machine closed August 2007
  - First collisions: 450 GeVx450 GeV (injection energy, no ramp) November/December 2007

- **Shut down in winter 2008:**
  - Finish commissioning
  - Installation of last hardware equipment. On detectors side notably CMS endcap ECAL and pixel detector.

- **Physics Data taking:**
  - First collisions: 7 TeV x 7 TeV June 2008.

- **...then can estimate (not from L. Evans)**
  - Integrated luminosity in 2008 1 fb\(^{-1}\), maybe 3 fb\(^{-1}\) per experiment at \(\mathcal{L}=10^{33}\) cm\(^{-2}\)s\(^{-1}\)
  - Integrated luminosity end 2009 up to 30 fb\(^{-1}\) at \(\mathcal{L}=1-2 \times 10^{33}\) cm\(^{-2}\)s\(^{-1}\)
  - Integrated luminosity end 2012 \(\sim300\) fb\(^{-1}\) at \(\mathcal{L}=10^{34}\) cm\(^{-2}\)s\(^{-1}\) (high/design luminosity)
LHC exp. environment

- bunch spacing of 25 ns
- Luminosity
  - high-luminosity: $10^{34}\text{cm}^{-2}\text{s}^{-1}$
    - $\sim23$ minimum bias events per bunch crossing (“pile-up”)
    - $\sim1000$ low $p_T$ charged tracks per event
  - low-luminosity: $10^{33}\text{cm}^{-2}\text{s}^{-1}$ (3 years): still 2.3 min. bias event per bunch crossing and 100 charged tracks per event

  $\Rightarrow$ minimize out of time pile-up with a fast detector response (1-5 bunch crossing depending on detector)

  $\Rightarrow$ minimize in-time pile-up with high granularity

- High irradiation (electronics, pollution of sensitive material)

- Cavern background (especially ATLAS muon air toroid): “gas” of low energy neutral and charged particles that diffuses throughout the cavern and apparatus inducing high detector counting rates with no correlation with beam crossing
With and w/o pile up

$H \rightarrow bb$ event

ATLAS tracking

$H \rightarrow bb$ event @ high luminosity

Track density in jet >> pile-up

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Magnet Systems

Both detectors built around superconducting magnets that are major technical challenges:

- CMS: one solenoid* 6m diameter 13 meter long, field 4T

- ATLAS:
  - Solenoid* 2.5 m diameter 5m long, field 2T
  - Barrel toroid* 8 20m long coils
  - 2 endcap toroids 8 5m long coils

*successfully cooled and ramped!
ATLAS installation

Atlas being assembled in the cavern: « ship in the bottle »

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CMS installation

CMS 15 slices being assembled on the ground, then lowered in cavern
Lowering of YE2 12th December 2006
Tracking

- Both $|\eta|<2.5$
- Both barrel/endcap geometry

Both inner tracking with 3 pixel layers (to resolve tracks despite high occupancy)

- CMS: outer tracking all Si strips (∼10 layers)
- ATLAS: outer tracking 4 Si strips layers + ∼36 transition radiation tracker (for $|\eta|<2.$)
### Tracking performance

<table>
<thead>
<tr>
<th>Selected figure-of-merit</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rec. Eff. Muons with $p_T=1\text{GeV}$</td>
<td>97%</td>
<td>97%</td>
</tr>
<tr>
<td>Rec. Eff. Pions $p_T=1\text{GeV}$</td>
<td>84%</td>
<td>80%</td>
</tr>
<tr>
<td>Rec. Eff. El. $p_T=5\text{GeV}$</td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td>$\sigma p_T$ for $p_T=1\text{GeV}$ $\eta=0$</td>
<td>1.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\sigma p_T$ for $p_T=100\text{GeV}$ $\eta=0$</td>
<td>3.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Transverse $\sigma i.p.$ for $p_T=1\text{GeV}$</td>
<td>75$\mu$m</td>
<td>90$\mu$m</td>
</tr>
<tr>
<td>Longitudinal $\sigma i.p.$ for $p_T=1\text{GeV}$</td>
<td>150$\mu$m</td>
<td>125$\mu$m</td>
</tr>
</tbody>
</table>

- CMS tracker has better momentum resolution (larger field and lever arm)
- However impact of material on efficiencies
- Similar impact parameter resolution

B tagging

- B tagging essential for:
  - ttH(bb)
  - top final states (t→Wb)

- Algorithm ranging from 2D impact parameter combination to inclusive secondary vertex reconstruction

- Key points:
  - Few GeV charged hadron reconstruction efficiency and impact parameter resolution
  - « fake » displaced tracks removal
B tagging performance

- *Impact parameter degraded by multiple scattering*
- *Lower b track efficiency*

- *More non-b tracks*
- *More fake high IP tracks*
- *B-track narrow jet*

- Algorithms getting rather sophisticated
- Also robustness and calibration on data being investigated
- $\tau$-id could have been another example

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Tracker integration

ATLAS pixel b-layer

CMS Si strip
• Electrons lose between 25% and 70% of their energy before reaching e.m. calo (damageable particularly at small R)
• Between 20% and 65% of photons convert into $e^+e^-$ pair before e.m. calo (showering may start in tracking)
• Also impact hadronic track reco efficiency
Calorimetry

- Both aim at large coverage $|\eta|<5$

- **ATLAS:**
  - e.m: Pb accordion -liquid argon, longitudinal segmentation
  - Hadronic:
    - Barrel: Fe-scintillator
    - Endcap: Cu-liquid argon

- **CMS:**
  - e.m: PbWO4 crystals, no longitudinal segmentation
  - Hadronic: brass/scintillator, Fe/Quarz (forward)
e.m calorimetry technologies
- Optimised for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow e^+e^-e^+e^-$
- Photon @ 100 GeV
  - ATLAS: 1-1.3% energy resol. (all g)
  - CMS: 0.8% energy resol. ($e_g \sim 70\%$)
- Electron @ 50 GeV
  - ATLAS: 1.3-2.3% energy resol. (use EM calor only)
  - CMS: ~ 2.0% energy resol. (combine EM calor and tracker)
- CMS intrinsic resolution better but suffer more from material
Jet energy resolution

- ATLAS better than CMS (due to hadronic energy reconstruction), but CMS expects improvement using track
Impact on supersymmetry, neutrino 2 or 3 momentum reconstruction

ATLAS also better (also due to hadronic energy reconstruction)
Muon systems

- Optimised around benchmark: \(H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-\)
- Fundamental differences
  - ATLAS: separate air toroids
  - CMS: instrumented flux returned (use of inner tracking almost mandatory)
- Similar coverage Atlas \(|\eta|<2.7\), CMS \(|\eta|<2.4\)
- Resolution at \(Pt=100\) GeV, \(|\eta|=0\):
  - ATLAS standalone 3.1% combined 2.6%
  - CMS standalone 9% combined 1.2%
- Resolution at \(Pt=100\) GeV, \(|\eta|=2\):
  - ATLAS standalone 3.1% combined 2.1%
  - CMS standalone 18% combined 1.7%
- CMS better on combined resolution

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Muon backtracking

Backtracking from Muon System down to beam region through calorimeters taking into non-uniform magnetic field, account E loss, multiple scattering and E loss fluctuations

E loss from parametrization (from calo measurement possible but risk of pollution from nearby particle)

Combination with inner detector track

ATLAS (similar procedure in CMS)
Trigger

ATLAS

Calo Muon Tracking

Bunch crossing rate 40 MHz

Level 1 Trigger

< 75 (100) kHz

Regions of Interest

Level 2 Trigger

~ 1 kHz

Event Filter

~ 100 Hz

Event builder

Data recording

1 s

Full-event buffers and processor sub-farms

2.4 µs

Derandomizers

Readout drivers (RODs)

Readout buffers (ROBs)

10 ms

Pipeline memories

Hardware

Software

ATLAS

CMS

Event size ~1-2MByte ⇒ several PByte/year

Digitizers

LV1

40 MHz

Front end pipelines µs

100 kHz

Readout buffers

Switching networks

ms-s

Processor farms

100Hz

Data recording

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## Trigger menus

<table>
<thead>
<tr>
<th>Trigger type</th>
<th>ATLAS (GeV) Threshold</th>
<th>CMS (GeV) Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive isolated e/γ</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>Two electrons/Two photons</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Inclusive isolated muon</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Two muons</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Inclusive τ-jet</td>
<td>-</td>
<td>86</td>
</tr>
<tr>
<td>Two τ-jet</td>
<td>-</td>
<td>59</td>
</tr>
<tr>
<td>τ-jet and $E_T^{miss}$</td>
<td>25 and 30</td>
<td>-</td>
</tr>
<tr>
<td>1-jet, 3-jets, 4-jets</td>
<td>200, 90, 65</td>
<td>177, 86, 70</td>
</tr>
<tr>
<td>Jet and $E_T^{miss}$</td>
<td>60 and 60</td>
<td>-</td>
</tr>
<tr>
<td>Electron and Jet</td>
<td>-</td>
<td>21 and 45</td>
</tr>
<tr>
<td>Electron-Muon</td>
<td>15*10</td>
<td>-</td>
</tr>
<tr>
<td>+calibration, monitoring, etc...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Typical LVL1 menu for $L = 2.10^{33} \text{cm}^{-2} \text{s}^{-1}$
*all thresholds are adjustable
*multiple signature allow lower thresholds
*total rate $\sim 20\text{kHz}$
(allowing safety margin and deferrals)

*Typical LVL1 menu for $L = 2.10^{33} \text{cm}^{-2} \text{s}^{-1}$
*all thresholds are adjustable
*multiple signature allow lower thresholds
*total rate $\sim 20\text{kHz}$
(allowing safety margin and deferrals)
handling PBytes

ATLAS, CMS similar

• Some data for calibration and monitoring to institutes
• Calibrations flow back

Event Builder
10 GB/sec

Event Filter
~159kS/2k

T0 ~5MS/2k

Tier 0

US Regional Centre

Italian Regional Centre

Spanish Regional Centre (PIC)

UK Regional Centre (RAL)

Tier 1

≥622Mb/s

~300MB/s/T1/expt

Tier 2

Northern Tier ~200kS/2k

Tier2 Centre ~200kS/2k

Centre 40kS/2k

Centre 40kS/2k

Average Tier 2 has ~25 physicists working on one or more channels
Tier 2 do bulk of simulation

Physics data cache

100 - 1000 MB/s

Workstations

10 GB/sec

450 Mb/sec

Average Tier 2 has ~25 physicists working on one or more channels
Tier 2 do bulk of simulation

ATLAS, CMS similar

~Pb/sec

Calibration
First processing
Reprocessing
Group analysis
Analysis
Simulation
Chaos!

~0.1s/event

~10s/event

~400s/event

100 - 1000 MB/s

Workstations

10 GB/sec

450 Mb/sec

Average Tier 2 has ~25 physicists working on one or more channels
Tier 2 do bulk of simulation
on grid..

- Processing needs cannot be handled by one or two supercomputing centers:
  - Typical HEP job is « process n events »: can be easily parallelised
- grid ⇔ more than a super-batch machine
- ~$10^5$ CPU distributed worldwide in computing centers (not on your desktop)
- Mixture of operating systems and CPU’s:
  - => unified job description/submission language
  - Remote software installation procedure (do not rely on computing center managers)
- Job submitted to « the grid » (actually different grid flavours but some interoperability) automatically dispatched to where the input data is replicated
- Automatic job splitting/merging to process/analyse full data sets
- Recent progress on bringing this power from experts to λ-physicist fingertips
- THE challenge (IMHO): reliability of data handling/replicating. One good day for one experiment (as being done these days):
  - 10000 jobs run
  - ⇔ 500,000 simulated events produced or 10 million events reconstructed
  - ⇔ 1 to 5 TeraBytes of data produced
Activities up to first collision
Long history of test-beam in both experiments since early R&D up to production detectors

Primary goal was to allow technology choice and validate production processes

But still on-going activity:
- Detailed understanding and robustness of signal reconstruction
- Testing and tuning detailed Monte Carlo simulation
- Combined detector analysis
- Understanding and possibly correct for potential sources of distortions (mechanics, electronics, calibration procedure, etc...)

Feed into:
- Signal reconstruction procedure
- Calibration strategy
- Global detector simulation
- Reconstruction software robustness
e.m. Calorimetry test beam

Atlas e.m. barrel uniformity

CMS ECAL test beam
Resolution in 3x3 crystals
18 crystal response curves

Energy (GeV)

Mean energy (GeV)

Middle η index

Energy (GeV)

M10

$E = 245.7 \text{ GeV}$
RMS/E = 0.49%

P13

$E = 245.6 \text{ GeV}$
RMS/E = 0.43%

$\sigma/E = 2.9\% / \sqrt{E} \oplus 0.125/E \oplus 0.30\%$

P15

$E = 245.8 \text{ GeV}$
RMS/E = 0.41%

With correction

Without correction

3x3 crystals

Fit results:
$m = 120.0 \text{ GeV}$
$\sigma = 0.60 \text{ GeV}$
$\sigma / m = 0.50\%$
ATLAS Combined Tbeam 2004

SCT

Pixel

Muon

γ → ee

μon

ATLAS

SCT

Pixel

SCT

Pixel

Magnet

transition radiation tracker

Liquid argon electromagnetic calorimeter

Tile hadronic barrel calorimeter & ext. barrel

Monitored drift tubes & resistive plate chamber

Monitored drift tubes-cathode strip chamber-thin gap chamber end-cap

γ → ee

Cell Phi

Cell Eta

Log Scale

10^8

10^7

10^6

10^5

10^4

10^3

10^2

10^1

10^0

10^-1

10^-2

10^-3

10^-4

10^-5

10^-6

10^-7

10^-8
CMS Ecal + Hcal Tbeam 2006

A phi slice of CMS HCAL

HB: 2 wedges
   8 φ segm
   Δφ = 40deg

HE: 4 φ segm
   Δφ = 20 deg

HO: Ring 0, 1 Δ

ECAL: SM9
Cosmics commissioning

- Since early 2006 data taking taking place with dedicated cosmic trigger
  - either underground with detectors in place (ATLAS, muon and calo)
  - either at the surface (CMS, ATLAS tracking)
Cosmic muon with B

also calorimeter
Beam gas

Simulation

Expect $\sim 10^8$ events
Beam halo event

Few weeks of circulating beam before first collision @ 900 GeV

Expect $\sim 10^7$ events

Simulation
900 GeV running

- Mostly inclusive jets + minimum bias
- debugging, debugging, debugging,...

ATLAS preliminary \( \sqrt{s} = 900 \text{ GeV}, L = 10^{29} \text{ cm}^{-2} \text{ s}^{-1} \)

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

Number of events in ATLAS after all cuts

Number of days of data taking

- 30 nb\(^{-1}\)
- 100 nb\(^{-1}\)
CMS Ecal calibration

~ 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

Energy deposition of traversing cosmic rays vs eta

3% calibration uniformity achievable with cosmics → improve on initial 4-5%
Activities in 2008 the first physics year
## Detector performance

<table>
<thead>
<tr>
<th></th>
<th>Expected Day 0</th>
<th>Goals for Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ECAL uniformity</strong></td>
<td>~ 1% ATLAS</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td></td>
<td>~ 4% CMS</td>
<td></td>
</tr>
<tr>
<td><strong>Lepton energy scale</strong></td>
<td>0.5—2%</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>HCAL uniformity</strong></td>
<td>2—3%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td><strong>Jet energy scale</strong></td>
<td>&lt;10%</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Tracker alignment</strong></td>
<td>20—200 μm in Rφ</td>
<td>O(10 μm)</td>
</tr>
</tbody>
</table>
Data samples for calib

- **Standard model processes:**
  - $Z \rightarrow ee$ ($\sim 6 \times 10^4$ evts/day after cuts): ECAL inter-calibration, absolute E-scale, etc.
  - $Z \rightarrow \mu\mu$ ($\sim 6 \times 10^4$ evts/day after cuts): p-scale in tracker and Muon Spectrometer, etc.
  - $tt\rightarrow b\bar{b}n\ bjj$ ($\sim 1 \times 10^4$ evts/day after cuts): absolute jet-scale from $W\rightarrow jj$, b-tag performance, reconstruction of complex final states (for $ttH$), etc.

- **Inclusive processes (dedicated prescaled trigger):**
  - Minimum-bias events: pp interaction properties, MC tuning, LVL1 efficiency, timing, radiation background in Muon chambers, etc.
  - QCD: QCD cross-sections and MC tuning, trigger efficiency, calorimeter inter-calibration, jet algorithms, background to Higgs, SUSY, etc.
  - Inclusive $e^{\pm}$ $p_T > 10$ GeV: trigger efficiency, ECAL calibration, ID alignment, $E/p$, $e^\pm$ reconstruction at low-$p_T$, etc.
  - Inclusive $\mu^{\pm}$ $p_T > 6$ GeV: trigger efficiency, $\mu^{\pm}$ reconstruction at low-$p_T$, E-loss in calorimeters, ID alignment, etc.
First physics

- A few selected examples (e.g. omitted B phys, extra dim) of physics analysis doable with first year statistics
- Very brief: much more in this conference
- THE challenge:
  - One month worth of data certainly does not mean one month to have publication ready analysis
  - Thriving to minimize the delay
  - The LHC community is listening to Tevatron experience
ATLAS recent studies

- ATLAS performance and physics TDR was published in 1999
- ...getting somewhat obsolete by now...
- Continued studies to converge in spring 2007 with a large set of consistent « CSC notes »
  - Most up to date « as-built » simulation (with distortions, mis-calibrations, « final » material,...)
    Large samples being produced since last November
  - Revised and enriched reconstruction algorithms.
    Production starting now.
  - Up-to-date generators (Tevatron calibration of SM processes, recent cross-section calculations (next or next-to-next to leading order)
Minimum bias

- Minimum bias particle density drives detector global occupancy even at « low » \( \mathcal{L}=10^{33}\text{cm}^{-2}\text{s}^{-1} \)
- Uncertainties up to 30% from extrapolation from lower energies
- Can be measured in a few days, but should always be kept in mind when defining startup scenarios (occupancies, rates...) 
- (similar issue about underlying event)
Top Mass

- Reconstructed in $tt\to W(l\nu)bW(qq)b$
  - Most important background: $W+4$ jets

- Selection without $b$ tag at the beginning (pending tracker alignment):
  - Isolated lepton with $P_T > 20$ GeV
  - Exactly 4 jets ($\Delta R = 0.4$) with $P_T > 40$ GeV
  - Reconstruction:
    - Select 3 jets with maximal resulting $P_T$
    - Identify $W$ peak (also useful for jet energy scale calibration)
    - Select highest $p_T$ 2 jet combination
  - $W$ and Top peaks visible with $30 \text{ pb}^{-1}$
  - $\sigma(M_{\text{top}}) \sim 3.2$ GeV with $30 \text{ pb}^{-1}$

- With $b$ tag: $\sigma(M_{\text{top}}) \sim 0.8$ GeV with $150 \text{ pb}^{-1}$
\[ Z' \rightarrow e^+e^-/\mu^+\mu^- \text{ search} \]

Search for high mass dilepton resonance

\[ Z' \rightarrow \mu^+\mu^- : 5\sigma \text{ significance curves} \]
SUSY Searches

Typical SUSY event at LHC:

- Strongly interacting sparticles (squarks, gluinos) dominate production
  - Can have high cross-sections $\Rightarrow$ good candidate for early discovery
- sleptons, gauginos etc. $\tilde{g}$ cascade decays to LSP.
- Long decay chains and large mass differences between SUSY states
  - Many high $p_T$ objects observed (leptons, jets, b-jets).
- If R-Parity conserved LSP stable and sparticles pair produced.
  - Large $E_T\text{miss}$ signature
- Closest equivalent SM signature $t \rightarrow Wb$ with $W \rightarrow l \nu$

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Susy reach

\[ \tan \beta = 10, \ A_0 = 0, \ \mu > 0 \]
with systematics

- \( m_h = 120 \text{ GeV} \)
- \( m_{\chi} = 103 \text{ GeV} \)
- \( m_h = 114 \text{ GeV} \)

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SM Higgs search

- Higgs search combination of different channels
- $m_H > 150$ GeV could be visible in 2008
- Lower (more probable?) masses need more luminosity

$\sqrt{s} \ L dt = 30 \ fb^{-1}$ (no K-factors)

ATLAS

Signal significance

- $H \rightarrow \gamma\gamma$
- $tth (H \rightarrow bb)$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$
- $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$
- $qqH \rightarrow qq WW^{(*)}$
- $qqH \rightarrow qq \tau\tau$
- Total significance

$5\sigma$ @ 3 fb$^{-1}$

$5\sigma$ @ 30 fb$^{-1}$

$5\sigma$ @ 30 fb$^{-1}$

$m_H$ (GeV)

$M_h$ up to 1 TeV also covered

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The end of the beginning...

- 1984: first studies
- 1990: Aachen workshop
- Summer 1992: Evian workshop
- End 1992: ATLAS and CMS Letters Of Intent
- No very significative change of detector design since
Conclusion

- LHC accelerator and ATLAS/CMS on track for 14 TeV p-p collisions in 2008
- Continuous understanding/ debugging/ calibrating effort since several years:
  - Test beams → Cosmics → beam gas/halo → 900 GeV collision
  - In addition to « as-built » large scale simulation
- Data collected in year 2008 can bring first physics results (standard model) even discoveries (SuSy, heavy gauge bosons, maybe non-light Higgs)
- However this will only be possible with continued work on understanding the detector with ever increasing accuracy and level of details

- Many thanks to long list of people from both experiments who helped me prepare this talk

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