The ATLAS Experiment@LHC
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LHC physics

- test the Standard Model, hopefully find “physics beyond SM”
- find clues to the EWK symmetry breaking - Higgs(ses)?

Standard Model is a gauge theory based on the following “internal” symmetries:

$$SU(3)c \times SU(2)I \times U(1)Y$$

The SU(3) is an unbroken symmetry, it gives Quantum Chromo-Dynamics (QCD), a quantum theory of strong interactions, whose carriers (gluons) are massless, couple to color (strong force charge)

SU(2) $\times$ U(1) (quantum theory of electroweak interactions) is spontaneously broken by the Brout-Englert-Higgs mechanism; which gives mass to electroweak bosons (massive W+, W-, Z0 and a massless photon) and all fermions

In the Minimal Standard Model, the Higgs sector is the simplest possible: contains one weak isospin doublet of complex Higgs fields, which after giving masses to W+, W-, Z0 leaves a single neutral scalar Higgs particle which should be observable.
LHC physics

- Matter is built of fermions: quarks and leptons, three families of each, with corresponding antiparticles; quarks come in three colors, leptons are color singlets, do not couple to gluons.
- Bosons are carriers of interactions: 8 massless gluons, 3 heavy weak bosons (W, Z) and 1 massless photon.
- A neutral scalar Higgs field permeates the Universe and is (in some way) responsible for masses of all particles (their masses originate from couplings to Higgs field).
- SINGLE NEUTRAL HIGGS SCALAR - THE ONLY PARTICLE MISSING IN SM
7 anni di costruzione nel tunnel gia’ utilizzato da LEP: 1989-2000

Tunnel LHC:
27 km di circonferenza
The key parameters of an accelerator are the c.m.s. energy ($\sqrt{s}$) and the number of collisions that can be generated ($\mathcal{L}$).

Higher energy means possibility to generate with larger cross-section particles high mass particles.

High luminosity gives the opportunity to access to rare (small cross-sections) events.

- $N_x = \int \sigma_x \mathcal{L}(t) \, dt$

LHC pp collider, designed for $\sqrt{s} = 14$ TeV and Maximum design luminosity at 14 TeV $\mathcal{L}_{\text{max}} = 10^{34}$ cm$^2$ s$^{-1}$

✓ Run at $\sqrt{s} = 7$ TeV in 2010 and 2011, and at $\sqrt{s} = 8$ TeV in 2012 and $\mathcal{L}_{\text{max}} = 8 \times 10^{33}$ cm$^2$ s$^{-1}$

- Upgrading at $\sqrt{s} = 13$ TeV in 2015
A collider particle detector

- Tracking systems to reconstruct trajectories and momenta of charged particles
- EM/hadronic calorimeters to measure energy of particles and missing energy
- Muon Spectrometers to precisely measure muon momenta
- Efficient Trigger system to reduce the huge collision rate
The ATLAS Detector

Muon Spectrometer: air-core toroids with gas-based muon chambers. Trigger and meas. with momentum resolution < 10% up to E(μ) ~ 1 TeV

Solenoid magnet (2T)

Toroid magnets (0.5-2T)

EM Calorimeter: |η|<3.2
Pb-LAr Accordion
σ(E)/E = 10% √E + 0.7%

Inner Detector |η|<2.5
Precise tracking and vertexing, e/p separation, momentum resolution:
σ(p)/p ~ 0.04% p (GeV) + 1.5%

More than 20 years of history
- 1989: R&D starts
- 1997: construction starts
- 2008: installation completed
- 2009-2013: data taking
- 2013-2015: First long shutdown

http://www.atlas.ch/multimedia/atlas-built-1-minute.html

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Pixel Detector

- 1744 pixel modules in the detector.
  - 2 End-caps (16% of the detector) built in US.
  - 3 cylindrical barrel Layers built in Europe (half in Genova)
The interesting events are only few hundreds every second out of the 20 MHz of interactions frequency.

It would be impossible to transfer out of the detector such a huge amount of data (each event is ~ few MB)

The trigger system is designed to select the interesting events, based on their signatures, in a short time.

The ATLAS trigger system has a 3-levels structure:

Each level analysis only events accepted by the previous step, the algorithms being more and more complex, requiring more information and more time to take a decision.
LHC $pp$ phase 1 ended (2010-2012), now preparing for phase 2 from 2015

ATLAS recorded:
- 45 pb$^{-1}$ in 2010 ($\sqrt{s} = 7$ TeV, max lumi $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$)
- 5.3 fb$^{-1}$ in 2011 ($\sqrt{s} = 7$ TeV, max lumi $3.6 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$)
- 22 fb$^{-1}$ in 2012 ($\sqrt{s} = 8$ TeV, max lumi $7.7 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$)

excellent acquisition efficiency ($>90\%$) and detector performance

% of not operative channels typically 0.5%, max 4%
Typical run conditions ...

- LHC providing very stable beam conditions for several hours, ATLAS recording and use on average ~ 90% of the delivered luminosity.
- Bunch spacing 50 ns (vs 25 ns nominal) and p/bunch up to $1.7 \times 10^{11}$ (vs $\sim 1.1 \times 10^{11}$ nominal).

Inefficiencies in data taking, mainly synchronizations.
The Challenge in 2012: Pileup

Collision Event at 7 TeV with 2 Pile Up Vertices

Event in ATLAS with 2 reconstructed vertices in 2011 at 7 TeV: Display with track pT threshold of 0.4 GeV and all tracks are required to have at least 3 Pixel and 6 SCT hits

The Challenge in 2012: Pileup

- Running with 50 ns bunch spacing (rather than 25 ns) results in 2x larger pile-up for the same luminosity
  - On average ~20 interactions per bunch-crossing
  - Up to 40 interactions at peak luminosity
- Huge effort to minimize physics impact
  - Biggest impact for calorimeter, trigger rates and computing.

ATLAS Online Luminosity

Event size linear with pile-up

| p0   | 1076 ± 10.56 |
| p1   | 13.25 ± 0.4529 |

| p0   | 1100 ± 16.56 |
| p1   | 15.96 ± 0.6713 |

| p0   | 1099 ± 15.41 |
| p1   | 15.14 ± 0.6695 |

Mean Number of Interactions per Crossing

nominal@25ns

28/5/2013
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Physics observables

Data selection and analysis are based on large on physics observables in the final state; they are introduced in the next slides:

- Leptons: electrons, muons
- Hadrons (jets)
- Taus
- Neutrinos (missing energy)
Electrons and photons are selected at L1 based on energy deposit in Trigger towers (large granularity).

Following trigger levels use the full calorimeters granularity and depth and the tracker information.

According to the EM shower shape, to the association to a track, and to a secondary vertex, calorimeters deposits are associated to electrons, photons or converted photons.

Rejection wrt hadronic jet achieved mainly using the shower shape and leakage in the hadronic calo.
Discriminating variables

Identification criteria include calorimetric cuts using the information from the different layers of the EM calorimeter, leakage in the hadronic calorimeter, track quality variables and cluster-track matching. 

$R_\eta$ variable: ratio of energies of middle cells in $\Delta \eta \times \Delta \phi = 3 \times 7$ over $7 \times 7$. For electrons and photons it peaks close to 1.

Clear difference between isolated electrons/photons and jets. Need to use multiple variables to get a powerful rejection.
Several algorithms to identify muons, exploiting all the detectors to get the maximum coverage.

- Main algorithm combines tracker and muon spectrometer.

- Momentum resolution is highly improved at low momentum by using the Tracker information.

- Muons required to be isolated to suppress background in many analyses.

Required Standalone Momentum resolution:

\[ \sigma / p_T < 10\% \text{ up to } 1 \text{ TeV} \]

Acceptance: \(|\eta| < 2.7\)

\[
\sigma(p) = p_0^{MS} + p_1^{MS} + p_2^{MS} \frac{1}{p} 
\]

\[
\sigma(p) = p_1^{ID} + p_2^{ID} \frac{1}{p_T} 
\]

Main contributions and results for barrel:

<table>
<thead>
<tr>
<th>Energy losses in calorimeters</th>
<th>Multiple scattering</th>
<th>Intrinsic resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>1.60 ± 0.32</td>
<td>0.49 ± 0.04</td>
</tr>
<tr>
<td>MS</td>
<td>0.23 ± 0.01</td>
<td>3.75 ± 0.10</td>
</tr>
</tbody>
</table>

\[ \text{Dominant at low } p \] \[ \text{Dominant at high } p \]
Jet

✓ Jets are generated by the hadronization of quarks and gluons.

✓ Calorimeters are heavily sensitive to pile-up
  • In-time PU estimated via the number of primary vertices
  • Out-of-time PU (as read-out time is rather long)
    • Seed: \(|E_{cell}| > 4 \sigma_{noise}
    • Neighbours: \(|E_{cell}| > 2 \sigma_{noise}
    \text{Perimeter cells: } \sum_{i} E_{cell} > 0
    \text{where: } \sigma_{noise} = \sqrt{\sigma_{noise\, electronic}^2 + (\sigma_{noise\, pile-up})^2}

✓ The energy deposits are measured starting from Topo-Clusters: Group of calorimeter cells topologically connected optimized for electronic noise and pile-up suppression.
**b-jet**

- The b-tagging is the capability to identify jets coming from b-quark fragmentation. It is based on the relatively long lifetime of b-hadrons ($\tau \approx 1.5$ ps, $\beta\gamma c\tau \approx 3$ mm for $p_T \approx 50$ GeV).
- Several b-tagging algorithms, exploiting: tracks impact parameters (JetProb, IP3D), reconstruction of the secondary vertex (SV1), topological structure of b and c-hadron decays inside the jet (JetFitter).
- Different algorithm combinations for improved performance, quantified in light jet rejection vs b-tagging efficiency: IP3D+SV1, JetFitterCOMBNN, MV1.
**Tau leptons**

- Hadronic decay of tau: 65%
- Reconstruction is seeded by jets
  - Requiring combined information from calorimeter and tracking
  - Input to multivariate algorithms

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![Pie chart showing hadronic and leptonic modes of tau decay](image)

- **Hadronic mode**
  - $3\pi^\pm 1\pi^0 \nu$: 8%
  - $3\pi^\pm$: 14%
  - $2\pi^\pm 1\pi^0 \nu$: 39%
  - $1\pi^\pm 2\pi^0 \nu$: 14%
  - $1\pi^\pm 1\pi^0 \nu$: 35%
  - $1\pi^\pm$: 65%
  - Others: 17%

- **Leptonic mode**
  - $3\pi^\pm 1\pi^0 \nu$: 7%

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![Diagram showing jet of hadrons](image)

- **Core cone**
  - $\Delta R < 0.2$

- **Isolation cone**
  - $0.2 < \Delta R < 0.4$
**Tau leptons**

✓ Tau’s are identified thanks to some peculiar characteristics:

• collimated decay products, leading charged hadron, no gluon radiation, low invariant mass, lifetime (discrimination against jets);

• EM energy fraction, Em component from pi0, transition radiation (discrimination against electrons)
Missing energy

✓ To detect particles that escape detection (mainly $\nu$’s, but also beyond SM low interacting particles), a balance of the event energy is done.

✓ Missing Transverse momentum is a complex event quantity:
  • Adding significant signals from all detectors
  • Asking for momentum conservation in the transverse plane

✓ ETmiss (in particular its resolution) is highly affected by pile-up.

✓ Using tracks not associated to physics objects and matched to PV to provide a reliable estimate of pile conditions and correct for it (Soft term vertex fraction).
ATLAS Trigger and Computing

- Trigger menu optimized for a luminosity of $8 \times 10^{33}$ cm$^{-2}$s$^{-1}$
  - Peak Level-1 rate $\sim 70$ kHz
  - Peak Event Filter rate $\sim 1$ kHz
- Streaming at Event Filter
  - Average (prompt) physics output rate $\sim 400$ Hz
  - In addition $\sim 200$ Hz of delayed physics events
  - Delayed events reconstructed during shutdown
- Grid used for analysis and simulation

**Average Stream Rates in 2012**

**ATLAS Trigger Operation 2012**

- L1: $\sim 65$ kHz
- L2: $\sim 5$ kHz
- EF: $\sim 400$ Hz

Additional / looser Missing-$E_T$, tau and VBF triggers added to increase sensitivity for 125 GeV Higgs decays to $b\bar{b}$ and $\tau\tau$ final states.
Spares
The Insertable B-Layer (IBL) will be built around a new beam pipe and slipped inside the present detector in situ or, if the pixel package is removed to replace the services, this operation can be carried out on the surface.

IBL will have

- \(<r_{sens}> = 33 \text{ mm} \text{ vs present } 50.5 \text{ mm} \rightarrow \text{ smaller beam pipe radius (29} \rightarrow 25 \text{ mm}).\)
Insertable B-Layer: Layout

✓ The Insertable B-Layer (IBL) will be built around a new beam pipe and slipped inside the present detector in situ or, if the pixel package is removed to replace the services, this operation can be carried out on the surface.

✓ IBL will have

- \(< r_{\text{sens}} > = 33 \text{ mm vs present 50.5 mm} \rightarrow \text{smaller beam pipe radius (29\rightarrow 25 \text{ mm})}
- \text{Coverage: } z = 60 \text{ cm, } |\eta| < 2.5
- 14 staves with \(\phi\) overlap
- No \(\eta\) overlap possible due to clearance
  - \(\rightarrow\) minimize modules edge:
    - Mixed scenario with 3D and slim edge planar envelope

PHASE 0 Upgrades 2013-2014 – Running 2014-2018

27/3/2012

C. Gemme, ATLAS Upgrades
Typical run conditions ...
Photon identification efficiency measured using $Z\rightarrow ll\gamma$ events or MC/data mixed procedures. Electron identification efficiency measured with tag&probe method on $Z$, $W$ and $J/\psi$ (low $p_T$).

Various levels of identification:
- $e$: loose (eff=90%, Rej=500), medium, tight (eff=60%, $R=10^5$)
- $\gamma$: loose, tight (eff=85%, Rej=5 $10^3$)