RESULTS FROM THE LHC: ATLAS

Dark Matter Beach Ascona?

Higgs beach Florida

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Outline of the talk

- Motivation of ATLAS physics
- Machine & detector status and prospects
- SM physics at LHC: Is the SM correct?
- What did we learn in 2012 about the Higgs mechanism? → Mini-review Higgs
- What did we learn in 2012 about Dark Matter candidate searches? → Mini-review SUSY et al.
QFT is invariant under a local change of gauge

\[ \Rightarrow \text{Massless force carriers (spin 1 bosons) for the electroweak and the strong force} \]

But the W and Z bosons are massive!

Problem is solved by Higgs mechanism:

\[ \Rightarrow \text{Mass of } W \text{ and } Z \text{ only generated after transformation into a ground state of the system (electroweak symmetry breaking)} \]

Predicts observable Higgs boson with spin 0
The Standard Model: Is this it?

**Dark Matter / Dark Energy** is not explained by the Standard Model (but WIMP miracle hinting to DM at LHC energies)

**Higgs mass** suffers from unnatural fine-tuning due to quadratic quantum corrections (hierarchy or fine-tuning problem)

**Major LHC goals:**
Clarify EW symmetry breaking ➔ Higgs mechanism and Higgs particle(s)
Physics Beyond the Standard Model ➔ Supersymmetry, something else?
Improvements in last 2 years due to:
- Better beam understanding of aperture (smaller beam size $\sigma$)
- Number of bunches increased from 368 to up to 1380 (nominal 2808)
→ Bunch spacing reduced from 150 to 50 (nominal 25 ns)

2012 compared to 2011:
Luminosity increased from $3 \times 10^{33}$ to $7 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (nominal $10^{34}$)

4 TeV beam energy
LHC luminosity 2012

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The ATLAS detector

Good operational status: ~99% of channels working!
Overall data taking efficiency ~95%
~90% of data taken with all sub-detectors fully operational
Standard Model Physics
Multiple interactions

Challenge for 2012 data taking:

High rate of multiple interactions due to decreased beam size ➔ Effects modeled in Monte Carlo simulations, challenge for particle IDs

Example of $Z \rightarrow \mu\mu$ decay with 20 reconstructed vertices (shown $\pm$ 15 cm, $p_T$ (track) $>$ 0.4 GeV
SM processes: Summary from ATLAS

Precise measurements for top pairs (8%). Top quark properties, ATLAS not yet to reach Tevatron precision.

Measurements of rare processes, t-channel single top, ZZ → 4 leptons.
Remarkable agreement with theoretical models in all published channels

Let’s have a look at the searches
Standard Model Physics
The search for the SM Higgs boson
Higgs channels and their importance

Main production diagram

Analyse 2012 data: A few weeks time only

- Concentrate on cleanest channels with best signal/background ratio
- ZZ and gamma gamma

High mass Higgs: WW, ZZ, tt

Low mass Higgs: Tautau, WW, ZZ, gammagamma, bbar
Low Mass Higgs Search: $H \rightarrow \gamma \gamma$

- Small branching ratio (0.002) \( \sigma \times \text{BR} \sim 50 \text{ fb} \) \( m_H \sim 126 \text{ GeV} \)
- Higgs decays via top and W loops

Advantage: **Nice 2 photon mass peak!**

- Main background from \( \pi^0 \)'s
- Need large jet rejection factors to reduce background and to see possible signal

\[ \Rightarrow \] Photon identification is crucial! (shower shapes, no track)

- Fit background with "assumed" function (no peak in bkgr.)

**Reducible background:** \( pp \rightarrow \gamma j, jj + X \)

**Irreducible background:** \( pp \rightarrow \gamma \gamma + X \)

**ATLAS**

- Photon ID efficiency 85+-5 %
- Energy scale at Z mass known to 0.5 % (mass resolution 1.6 GeV at 125 GeV)
- Contribution to mass resolution from angular terms in negligible
Low Mass Higgs Search: $H \rightarrow \gamma \gamma$

Events subdivided in categories to increase sensitivity!

Local significance: $4.5\,\sigma$

2011+2012 conclusion:
Excluded (95% CL):
112-122.5 GeV, 132-143 GeV
Expected: 110-139.5 GeV
$H \rightarrow ZZ \rightarrow 4e, 4\mu, 2e\ 2\mu$ : The Golden Channels

- **Signal**: 4 isolated lepton from common vertex
- **Fully reconstructed, Mass resolution** ~ 1.8 GeV at 130 GeV
- **Reducible Backgrounds**:
  - $t\bar{t} \rightarrow 2l2\nu2b$ ; $Z+bb$
  - Removed by Isolation & Impact parameter requirements
- **Irreducible background**: $pp \rightarrow ZZ$ Continuum
- **Event Selection**: Same Flavor, opposite charge
**H → ZZ golden channel**

**Background estimates:**
- ZZ background estimated from MC (uncertainties 10-15%)
- Z+jets and top bkg. estimated from control region
Combinations of channels

Best sensitivity by performing one combined statistical test of the SM Higgs hypothesis

⇒ Build combined likelihood with all channels

2012 gamma gamma and ZZ + all 2011 channels
Combined ATLAS Higgs results

Due to look-elsewhere effect, systematics, etc., we demand a 5-sigma deviation in both experiments. Combined signal strength consistent with SM Higgs hypothesis.

Local significance of this excess is 5.0 $\sigma$.
The search for physics beyond the Standard Model
Candidate Nr. 1: SUSY

Most studied new physics theory for several reasons:

- “Easier QFT”: Fermion and Boson loops protect the Higgs mass at large energies (reduces “fine tuning”) if SUSY mass scale is not too large (LHC)!

- SUSY is a broken symmetry and thus offers (with R-parity conservation) weakly interacting massive particles for Dark Matter with a mass of O(100) GeV

- unification of 3 coupling constants at high energy in one point (GUT scale at $10^{16}$ GeV?), SUSY breaking connected to electroweak symmetry breaking?
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Important drawback:

SUSY has not been found yet

$\Rightarrow$ some (small) fine tuning needed already in the model!

Is SUSY still candidate Nr. 1?
... more on SUSY Higgs

- Mass of the lightest MSSM Higgs boson $h^0$ must fulfill:
  \[ M(h^0) < \cos(2\beta) M_Z \]

  Weakened to $M(h^0) < 135$ GeV if radiative corrections are included.

  "Aha, SUSY predicts a low mass higgs."

Higgs of 126 GeV consistent with
a) Degenerate stops  
b) Quite heavy stops

Scenario might be
- 1\textsuperscript{st} and 2\textsuperscript{nd} gen. heavy  
- Light stop caused by naturalness  
- Somehow light gluino
Most sensitive at early LHC:
- SUSY search for squarks and gluinos

Maybe most sensitive if 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks are heavy due to 126 GeV Higgs:
- stop searches
- gluino searches
If R-Parity is conserved then SUSY particles are pair produced

LHC:
Due to strong force dominant production of squarks and gluinos (if not too heavy)
Cascade decay to lighter SUSY particles and finally the lightest SUSY particle (LSP)

Mass pattern in general SUSY unknown! Searches need to be quite general and model-parameter-independent

Similar conclusions /channels
For many other models (Universal Extra Dimension, ADD, Little Higgs, ....)
Production rate

Events in 2011

5000

500

50

$\sigma_{\text{tot}}[\text{pb}]: pp \rightarrow \text{SUSY}$

$\sqrt{S} = 7 \text{ TeV}$
Event found in signal region of jet + \( E_{\text{miss}} \) Analysis in 2010 data.
Analysis model - control regions

- Measure number of events in control selections
- Predict number of events in signal region via a fit to control regions
- Important: Test model and transfer functions
  (e.g. by alternative control regions or methods)
SUSY searches overview

ATLAS hunts now with a twofold strategy:
- Broad inclusive searches with many signal regions
- Highly optimized dedicated searches for exclusive SUSY signals

Also various searches on R-Parity violation
Example: Jets + $E_t^{\text{miss}}$

Studies are about 15 signal regions

From monojets to $>8$ jet events
(jets from squark/gluino decay or if mass difference to LSP to low
No jets from squark/gluino decay)

From low $E_t^{\text{miss}}$ to high $E_t^{\text{miss}}$
(best cut depends on ratio of produced particle mass to neutralino mass)

From high mass to low mass
Exclusion reach not strongly sensitive to sign(\(\mu\)), tan \(\beta\) and \(A_0\).

**Simple MSSM**
- Model with light 1\(^{st}\) and 2\(^{nd}\) gen. squarks, gluinos and a massless neutralino

**Constrained MSSM Model with common Fermion and Boson Masses at the GUT scale**
- **2009 “Best fit” cMSSM fit pre-LHC**

**Jets + \(E_T^{\text{miss}}\): Results on 2011 data**
Jets + $E_T^{\text{miss}}$: LSP mass dependence

SUSY parameter space very large!

Here e.g. dependence of limits on neutralino (LSP) mass (old data)

Investigated now with projections on “relevant” parameters (simplified models)

You can make your own limit for any model with a fast det. sim..

We are providing model independent limits on $\sigma \cdot \text{BR} \cdot \text{efficiency}$ efficiencies etc. at hepdata
Stop search

- **Stop decays**
  - Stop $\rightarrow$ top neutralino (*if kinematically allowed, and no chargino...*)
  - Stop $\rightarrow$ b chargino (*if chargino is light enough and likes to couple*)
  - Stop $\rightarrow$ charm neutralino (*if stop is heavier than chargino +LSP*)
  - (also other options)

- **Possible stop production**
  - **direct production**
    - Does not depend on other parameters
      - (light gluino)
  - **produce gluinos which decay to stops**
    - Potentially large cross section
    - Easier to detect
Searching in events with 4-6 jets where 3 jets are tagged as b-jets and large missing transverse momentum

Consider, among others, models where gluino decays 100% to stop and top and stop decays to

\[ \tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \]

Gluino masses up to 1 TeV are excluded
Summary direct stop production

\( \tilde{t}_{1\,1} \) production: \( \tilde{t}_{1} \rightarrow b + \tilde{\chi}_{1}^\pm, \tilde{\chi}_{1}^\pm \rightarrow W^{\pm} + \tilde{\chi}_{1}^0 \) (BR=1, \( m_{\tilde{t}} < 200 \text{ GeV} \); \( \tilde{t}_{1} \rightarrow t + \tilde{\chi}_{1}^0 \) (BR=1, \( m_{\tilde{t}} > 200 \text{ GeV} \))

ATLAS Preliminary

\[
\int L \, dt = 4.7 \, \text{fb}^{-1} \quad \sqrt{s} = 7 \, \text{TeV}
\]

Expected limits (nominal)

All limits at 95% CLs

\( \tilde{t}_{1} \rightarrow b + \tilde{\chi}_{1}^\pm, \tilde{\chi}_{1}^\pm \rightarrow W^{\pm} + \tilde{\chi}_{1}^0 \) (\( m_{\tilde{t}} < 200 \text{ GeV} \))

- 2-lepton (\( m_{\tilde{t}} = 106 \text{ GeV} \))
- 1/2-leptons + b-jets (\( m_{\tilde{t}} = 106 \text{ GeV} \))
- 1/2-leptons + b-jets (\( m_{\tilde{t}} = 2 \times m_{\tilde{\chi}_{1}^0} \))

\( \tilde{t}_{1} \rightarrow t + \tilde{\chi}_{1}^0 \) (\( m_{\tilde{t}} > 200 \text{ GeV} \))

- 0-lepton
- 1-lepton
- 2-lepton
DM production in SUSY decays

Summary of current limits, mostly on the production of Squarks and Gluinos

→ Strong constrains on SUSY models

Limit 1 TeV strong interacting particles

Limit 300-400 GeV stop particles

Also limits on WEAK INTERACTIONS now
Monojets/Monophotons

Looking for a jet from initial state Radiation to search for WIMP WIMP Events

- Signal is a Monojet/monophoton event!
- Missing momentum distribution

Assuming coupling ATLAS monojet searches can give bounds on WIMP-nucleon spin dependent cross section (assuming heavy mediator with free coupling) Collider limit competitive if WIMP couple only via D11 (gg) coupling and for very low WIMP masses
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Limit converted to limit on WIMP-nucleon cross section
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No SUSY? ➔ Are there ways out ...

- Maybe SUSY is hidden?
  - Close the gaps, e.g. low mass splittings, long decay chains
  - Search for a initial state radiation + NOTHING ➔ Monojets

- Or SUSY is a bit heavier?
  - For electroweak symmetry breaking not all SUSY particles have to be close to the 1 TeV scale, light stop and heavy 1\text{st} and 2\text{nd} gen. fermions
  - If the Higgs is around 125 GeV, usually stop heavier, also other SUSY particles expected to be >1 TeV?

- Or SUSY looks a bit different?
  - Extend searches to non-standard SUSY scenarios
- Opened the door to real understanding of EW symmetry breaking:
  Is this signal the SM Higgs? Or a BSM Higgs?
- Where is SUSY hidden?
  Are we closing all “gaps”?
- Is new physics hidden in an unexpected place?
INTERMEZZO: Higgs limit plots...

Previous 95% CL limits from LEP (<114 GeV) and Tevatron (156-177 GeV)
Monojets/Monophotons

Looking for a jet from initial state radiation to search for WIMP WIMP events!
- Signal is a Monojet event!
- Missing momentum distribution as measured by ATLAS

Assuming coupling ATLAS monojet searches can give bounds on WIMP-nucleon spin averaged cross section (assuming Z’ mediator with free coupling)
Combined results: consistency of the global picture

Are the 4l and γγ observations consistent?

From 2-dim likelihood fit to signal mass and strength curves show approximate 68% (full) and 95% (dashed) CL contours.

Best-fit signal strengths, normalized to the SM expectations, for all studied channels, at $m_H = 126.5$ GeV.
Intermediate mass: Higgs $\rightarrow$ WW$\rightarrow$ llvv

- $H \rightarrow WW \rightarrow llvv$ most sensitive $130 < m_H < 200$ GeV
  
  ($H \rightarrow WW \rightarrow jjlv$ less sensitive, but also taken into account into combination)

- ... but challenging: complete reconstruction of the invariant mass not possible

- Largest background is irreducible WW SM production

- But also Drell-Yan and top process when looking to final states associated to one jet channel

- Select events with two high-\(p_T\) opposite sign leptons and large transverse missing energy

- Subdivide into 0,1 and 2 jet channel

$\rightarrow$ Channel not ready yet
Status of ATLAS searches ... until this morning

Results on the full 7 TeV dataset submitted for publication

\[ \int L dt = 4.6 - 4.9 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

Combination of 12 channels:
- H → WW
- W/ZH → W/Z bb (3 final states)
- H → ZZ (3 final states)
- H → ZZ(*) → 4l
- H → WW(*) → lvlv
- H → ZZ → llqq
- H → ZZ → llvv
- H → WW → lvqq

Excluded at 95% CL
- \( 111.4 < m_H < 122.1 \text{ GeV} \) (except 116.6-119.4)
- \( 129.2 < m_H < 541 \text{ GeV} \)

Excluded at 99% CL
- \( 130.7 < m_H < 506 \text{ GeV} \)

Expected if no signal: \( 120 - 560 \text{ GeV} \)