Search for New Phenomena at the High Luminosity LHC with ATLAS

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Paul Glaysher
(University of Edinburgh)
On behalf of the ATLAS collaboration

Introduction

- The LHC is the primary discovery tool of our time
- The Higgs boson discovered at ATLAS and CMS was the highlight of the first LHC run
 - All evidence points to a 125 GeV Higgs boson, compatible with the Standard Model (SM)
- What will we see next, BSM physics?
- An upgrade to the LHC (**H**igh **L**uminosity-LHC) is required to fully exploit its discovery potential
- This talk covers prospects and sensitivity studies by ATLAS for discovery potential at the HL-LHC

High Luminosity LHC

<https://cds.cern.ch/record/1975962>

- **Pile up:** number of simultaneous interactions per bunch crossing
 - Increases with instantaneous luminosity
 - Degrades experimental environment
 - Primary challenge for a detector at HL-HLC

ATLAS Detector Upgrade

Phase 1 upgrades:

- Fast tracker algorithms (FTK)
- Extend muon spectrometer endcaps, New Small Wheel (NSW)
- Improve calorimeter readout

Upgrades to the ATLAS detector are essential to pursue rich physics program at the HL-LHC

- Mitigate pile up effects
- Address radiation damage to sensors

Phase 2 upgrades:

- Redesign of trigger system
- All silicon inner tracker (ITK)
- Calorimeter electronics and forward region (sFCal or Mini-Fcal)
- Muon system

Phase 0+1 FTK:

cds.cern.ch/record/1552953

Image: cds.cern.ch/record/2002880/

Phase 2 tracker simulation:

atlas.desy.de/activities/tracker_upgrade/

Simulating future ATLAS Detector

ATLAS HL studies are performed using particle level Monte Carlo

- Detector response functions based on full Geant4 simulations are applied
- Based on an upgraded ATLAS detector and takes impact of future pile up scenarios into account
 - Assumes current or even improved detector performance despite high pile up
- Scenarios with improved systematic uncertainties over today's understanding are considered

Expected improvements in b-tagging performance with the Itk upgrade compared to the current detector

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Latest HL Performance Results

Primary Vertex and b-Tagging

Number of primary vertices per bunch crossing for different pile up scenarios

Fraction of reconstructed primary vertices that are within 1mm to truth vertex

B-jet tagging vs light-jet rejection efficiency

Non-gaussian beam profile (long beamspot) is also considered...

... which increases the number PV per bunch crossing...

... and improves the vertexing performance

<http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/PLOT-UPGRADE-2014-003/>

New Phenomena

- ATLAS has conducted many studies into the prospects and discovery potential of many BSM and New Phenomena cases at the HL-LHC
- A selection is presented here:
 - Higgs sector
 - Supersymmetry
 - Gluino, squark and $\chi^\pm \chi^0$, searches
 - Di-jet resonance searches
 - Flavour Changing Neutral Currents

HL-LHC: A Higgs Boson Factory

Higgs Physics goals

- Rare decays and coupling
- Higgs pair production
- Higgs boson as a portal to new physics
 - More Higgs-like particles
 - Two Higgs doublet Model, MSSM
 - Higgs compositeness
 - Coupling to Dark Matter

125 GeV Higgs bosons at $\sqrt{s}=14$ TeV 3000 fb⁻¹

HL-LHC total	170 M
VBF	13M
ttH	1.8M
$H \rightarrow Z\gamma$	230k
$H \rightarrow \mu\mu$	37k
HH	121k

Number of event of different Higgs processes expected in the HL-LHC dataset

Higgs to SM particle couplings

Measure couplings strength in units of SM, leading order expectation $\mu = \frac{(\sigma \times \text{BR})_{\text{obs}}}{(\sigma \times \text{BR})_{\text{SM}}}$

- $m_H = 125$ GeV, narrow width approximation
- Measure couplings within 2-15% precision
 - Will be able to quantify small deviations from the SM

Outstanding SM measurements of Higgs couplings to:

- $H \rightarrow b\bar{b}$ large background
 - Expect to observe in Run 2
- $H \rightarrow \mu\mu$ low branching ratio
 - Expect to observe at HL-LHC

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ATLAS Simulation Preliminary
 $\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$

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Di-Higgs Production

- Sensitive to the Higgs self-coupling λ , this challenging measurement will provide strongest test of SM nature of the Higgs boson
- SM cross section at $\sqrt{s}=14$ TeV 40.7 fb (NNLO) suffers from destructive interference

Final states studied:

- **HH $\rightarrow$ bb $\gamma\gamma$** : 320 events expected – clean signal
- **HH $\rightarrow$ WW $\gamma\gamma$** : 30k events expected – large backgrounds
- **bbbb and bb $\tau\tau$** final states are also under consideration

HH $\rightarrow$ bb $\gamma\gamma$

- Expect 8.4 signal and ~ 47 bkg events with a $S/\sqrt{B} \sim 1.3$
- BSM models with $\lambda/\lambda_{\text{SM}} < -1.3$ & $\lambda/\lambda_{\text{SM}} > 8.7$ can be excluded with 3000 fb^{-1}
- Combination with other channels (ATLAS +CMS) likely to be sensitive to SM Higgs self-coupling

Number of signal events (red) as a function of $\lambda/\lambda_{\text{SM}}$, with projected sensitivity of the 3000 fb^{-1} dataset

- Angular cuts bring strong separation of signal and background
- ‘Others’ includes $cc\gamma\gamma$, $bb\gamma j$, $bbjj$ and $jj\gamma\gamma$, where j signifies a jet.

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Two Higgs Doublet Models (2HDM)

- Higgs sector extended by an additional doublet, resulting in a model with five Higgs bosons:
 - one neutral-CP-odd **A** and two charged **H[±]**
 - Two neutral-CP-even: **h_{m=125 GeV}** and a **heavy H**

Indirect search for H through precision measurements of h couplings:

ATLAS **sensitive to H** via mixing with h

α mixing angle of H and h

tanβ = ratio of the vacuum expectation values of the two doublets: relative coupling strength of **H / h**

Cos(β-α) couplings and mixing term. A measure of relative coupling strength of **H→VV** over SM expectation

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Excluded regions of $\cos(\beta - \alpha)$ vs $\tan \beta$ of the type II 2HDMs by fits to the measured rates of Higgs boson production and decays.

Simplified MSSM

- A concrete example of 2HDM: Minimal Super-symmetric Model
- Simplified MSSM:
 - $\mathbf{H}$ and $\mathbf{h}$ mixing is fully determined by $\mathbf{m}_A$ and $\tan\beta$
- SM Higgs boson coupling rates K_V , K_u , K_d would be modified by $\mathbf{m}_A$
- Simplified model serves as good benchmark study
 - Particularly useful if no direct SUSY observation is made

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Regions m_A vs $\tan\beta$ expected to be excluded in a simplified MSSM model via fits to the measured rates of Higgs boson production and decays.

Minimal Composite Higgs Model

For a pseudo-Nambu-Goldstone, composite Higgs boson:

- Higgs coupling modified as a function of the compositeness f

➤ $\xi = v^2/f^2$

- **MCHM4:**

➤ $K=K_V=K_F=V(1-\xi)$

- **MCHM5:**

➤ $K_V=V(1-\xi); K_F=1-2\xi/V(1-\xi)$

Expected 95% CL lower limit on Higgs boson compositeness scale f :

Model	300 fb ⁻¹		3000 fb ⁻¹	
	All unc.	No theory unc.	All unc.	No theory unc.
MCHM4	620 GeV	810 GeV	710 GeV	980 GeV
MCHM5	780 GeV	950 GeV	1.0 TeV	1.2 TeV

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Higgs Portal to Dark Matter

- Assuming a Wimp as a DM candidate, which interacts very weakly with SM particles except for the Higgs boson
- Expected 95% CL upper limit BR ($H \rightarrow \text{invisible}$) at 3000 fb^{-1}
- $\text{BR}_{\text{inv}} < 0.13$ (0.09), nominal (improved) systematics scenario
- Run 1 VBF Higgs channel set upper limit of $\text{BR}_{\text{inv}} < 0.29$

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➤ ATLAS will provide complimentary measurement to those from dedicated DM experiments

SUSY at the HL-LHC

NLO cross-sections as a function of the average mass of the pair-produced SUSY particles.

The chargino and neutralino-2 are assumed to be wino-like.

Studies assume R-parity conserving SUSY and a stable LSP.

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- Supersymmetry is one of the best motivated and well-studied extensions of the Standard Model
- The HL-LHC will allow to probe small cross section processes

gluino pair production

- Assumes $BR(\tilde{g} \rightarrow q \tilde{\chi}_1^0) = 100\%$
- Signature:
 - No leptons, 4 jets and $E_T^{\text{missing}} > 160$ GeV
- Dominant backgrounds:
 - Z/W+jets, tt and di-boson

- 1.64 σ exclusion and 5 σ discovery contours in the $\tilde{g}-\tilde{\chi}_1^0$ mass plane
- Bands represent 1 σ uncertainty on the production cross-section

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Squark pair production

- Require 3rd generation SUSY partners to be light in order to solve the hierarchy problem
- Search for $\tilde{q}$ that exclusively decays $\tilde{q} \rightarrow q \tilde{\chi}_1^0$
- exclusion/discovery contours are shown for the $\tilde{b}-\tilde{\chi}_1^0$ and $\tilde{t}-\tilde{\chi}_1^0$ mass planes:

$\bar{\chi}_1^\pm \bar{\chi}_2^0$ production

- $\bar{\chi}_1^\pm$, $\bar{\chi}_2^0$ and $\bar{\chi}_1^0$ are expected to have masses in the few 100 GeV range
- Multivariate Analysis Techniques (MVA) increase sensitivity, using non-orthogonal cuts in a *Boosted Decision Tree*

$(m_{\bar{\chi}_1^\pm} = m_{\bar{\chi}_2^0} \text{ vs } m_{\bar{\chi}_1^0})$ exclusion/discovery limits for *count and count* and MVA analysis

W,h mediated 2b, 1lep channel

BDT output for training on main backgrounds and given signal masses

Exotics: Di-jet resonance searches

A number of new phenomena are expected to modify the di-jet mass distribution, creating a bump on the smooth QCD continuum

- For example **excited quarks q^*** or **quantum black holes QBH** which decay into two high momentum hadronic jets
- Assumes $q^* \rightarrow q + \text{gauge bosons}$ decays
- QBH decays to all allowed two-body final states, simulated using the BlackMax generator [see Phys. Rev. D 77 \(2008\) 076007](#)

Expected limits Limits are calculated from projected sensitivity and theoretical expectation on $\sigma \times \text{BR}$:

integrated luminosity [fb^{-1}]	m_{q^*} [TeV]	m_{QBH} [TeV]
0.1	4.0	8.2
1	5.0	8.9
5	5.9	9.2
25	6.6	9.7
300	7.4	10.0
3000	8.0	10.1

Equivalent to current
20.3 fb^{-1} 8 TeV limits

cds.cern.ch/record/2002136

Flavour Changing Neutral Currents

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- FCNC are allowed but highly suppressed in SM loop diagrams, expected to have $BR \sim 10^{-12}$ $\rightarrow$ inaccessible even at HL-LHC
- Therefore any observation would be a strong sign of new physics

- BSM enhancement of the BR could be seen in top decays
 - $t \rightarrow q\gamma$ and $t \rightarrow qZ$ are considered, where q is either an u or c quark
- Sensitivity is evaluated from model independent effective Lagrangian
- *Sequential*: extrapolate results from 7 TeV data
- *Discriminant*: 14 TeV MC analysis, using a likelihood discriminant

Conclusion

- With the discovery of the Higgs boson at LHC-Run 1 we enter a new era of particle physics
- Unprecedented collision energy of 14 TeV in Run 2 will vastly increase the scope of New Physics and precision Higgs studies
- The HL-LHC with 10x more luminosity will offer unique opportunities to explore the Higgs sector and probe for high scale New Physics
 - the 3000 fb⁻¹ dataset at 14 TeV will allow large gains in precision, discovery potential, and will make important, low cross-section measurements possible
- Upgrades to the ATLAS detector are foreseen to ensure optimal performance in harsh experimental environment
- All prospects studies shown are a conservative projection, likely to see significant improvements in analysis techniques

Stay tuned for exciting results to come!

Backup slides

Detailed LHC schedule

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in **2019** $\Rightarrow$ **24** months + 3 months BC
 LS3 LHC: starting in **2024** $\Rightarrow$ **30** months + 3 months BC
 Injectors: in **2025** $\Rightarrow$ **13** months + 3 months BC

<http://lhccommissioning.web.cern.ch/> (June 2015)

Detailed LHC schedule

LHC roadmap: according to MTP 2016-2020 V2

LS2 starting in **2019** $\Rightarrow$ **24** months + 3 months BC
 LS3 LHC: starting in 2024 $\Rightarrow$ **30** months + 3 months BC
 Injectors: in 2025 $\Rightarrow$ **13** months + 3 months BC

<http://lh-commissioning.web.cern.ch/> (June 2015)

Bottom-squark pair production

- Require 3rd generation SUSY partners to be light in order to solve the hierarchy problem
- Search for $\tilde{b}$ that exclusively decays $\tilde{b} \rightarrow b \tilde{\chi}_1^0$
- Event selection based on *boost corrected contrasverse mass*, $m_{CT} \rightarrow$ powerful $t\bar{t}$ veto

See [arXiv:1308.2631](https://arxiv.org/abs/1308.2631) and [arXiv:0802.2879](https://arxiv.org/abs/0802.2879)

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$\bar{\chi}_1^\pm \bar{\chi}_2^0$ production

- $\bar{\chi}_1^\pm$ and $\bar{\chi}_2^0$ are wino-like, $\bar{\chi}_1^0$ is bino-like

Missing transverse momentum spectrum for main backgrounds and signal with different mass assumptions

Arrows indicate different signal regions, optimized for exclusion or discovery

1.64 σ exclusion & 5 σ discovery contours for $(m_{\bar{\chi}_1^\pm} = m_{\bar{\chi}_2^0} \text{ vs } m_{\bar{\chi}_1^0})$

Here, W,Z mediated 3 lepton channel

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New heavy gauge boson

- $Z' \rightarrow \ell\ell$ resonances search (older study)
- For di-electron or di-muon events, only consider dominant Drell-Yan background
- Assumes a Sequential SM (SSM) Z'_{SSM} with SM fermionic couplings

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Limits are calculated from projected sensitivity and theoretical expectation on $\sigma \times \text{BR}$

model	300 fb ⁻¹	1000 fb ⁻¹	3000 fb ⁻¹
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6

Expected limits on mass of Z'_{SSM} in TeV