Higgs boson measurements and searches for new phenomena with ATLAS

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MPP Project Review
19 December 2017
Outline

- Higgs boson measurements
- Dark matter searches
- Di-boson resonance search
- Searches for Supersymmetry

Dataset used for these analyses: LHC Run 2, $\sqrt{s}_{\text{pp}} = 13$ TeV, integrated luminosity of 36.1 fb.
Outline

▶ Higgs boson measurements

▶ Dark matter searches

▶ Di-boson resonance search

▶ Searches for Supersymmetry

▶ Dataset used for these analyses: LHC Run 2, $\sqrt{s_{pp}} = 13$ TeV, integrated luminosity of 36.1 fb$^{-1}$
Outline

- Higgs boson measurements
  - $ttH$ production
  - Higgs boson Mass
  - Higgs boson couplings

- Dark matter searches

- Di-boson resonance search

- Searches for Supersymmetry

- Dataset used for these analyses: LHC Run 2, $\sqrt{s}_{pp} = 13$ TeV, integrated luminosity of 36.1 fb$^{-1}$
LHC Higgs Boson Physics

- **LHC Run 1** Higgs boson legacy:
  - Observation in different production and decay channels
    - Gluon fusion and vector boson fusion production
    - $\gamma\gamma$, $ZZ$, $WW$ and $\tau\tau$ decays
    - Spin 0, CP even resonance

- **LHC Run 2** Higgs boson program:
  - Investigate quark couplings - $ttH$ production, $H \rightarrow bb$ decay
  - Higher precision of property measurements
Search for $ttH$ production

- $ttH$ production: direct test of
  \[ \lambda_t = \frac{m_t}{\langle 0 | H | 0 \rangle} \approx 1 \]

- Large backgrounds \( \Rightarrow \) need to consider several $t$ and $H$ decay channels

- MPP contributions to the $H \rightarrow bb$ channel:
  - Boosted $H \rightarrow bb$ analysis
  - Top-quark modelling studies
Search for $ttH$ production

- Numerous signal and control regions
- Machine learning based classifiers for signal discrimination
- $H \rightarrow bb$ channel: 1.4 (1.6) $\sigma$ observed (expected) signal significance

![Graph showing classification BDT output and data/prediction](chart.png)
Search for $ttH$ production

- Numerous signal and control regions
- Machine learning based classifiers for signal discrimination
- $H \to bb$ channel: 1.4 (1.6) $\sigma$ observed (expected) signal significance

![Graph showing signal significance for different channels and fits.](image)

**ATLAS** Preliminary

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$m_H = 125$ GeV

$\mu = \sigma_{th}/\sigma_{SM}$
Search for $ttH$ production

- Numerous signal and control regions
- Machine learning based classifiers for signal discrimination
- $H \rightarrow bb$ channel: $1.4 (1.6) \sigma$ observed (expected) signal significance
- Combination of $H$ decay channels: $4.2 (3.8) \sigma$ signal significance

![Graph showing search results for $ttH$ production](graph.png)

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ATLAS Higgs and BSM
Combination of di-photon and 4 lepton (e, µ) channels

MPP contributions:

- Ansatz of the $m_{4\ell}$ measurement - take into account the event-wise $m_{4\ell}$ resolution
- Muon momentum scale calibration, allowing for high precision

```
Data

ATLAS
4l → ZZ* → H
-113 TeV, 36.1 fb

Events / 2.5 GeV

0
10
20
30
40
50
60

Data = 125 GeV

Signal (m_H = 125 GeV)

Background ZZ*

Background Z+jets, t\bar{t}, t\bar{t}+W, VVV

Uncertainty
```
Higgs boson mass measurement

ATLAS-CONF-2017-046

Precision close to LHC Run 1 combination

$m_{4\ell}$ measurement:
- Uncertainty dominated by statistics
- Will dominate future $m_H$ measurements
- Measurement of Higgs boson production cross-sections using the 4 lepton decay channel
  - Also as a function of jet multiplicity and Higgs boson $p_T$
- Measuring $\sigma$ rather than $\sigma/\sigma_{SM}$: low impact of theory uncertainties
- Slight excess of 2.2 $\sigma$ in the vector boson fusion category
- MPP contributions:
  - Background estimation
  - Evaluation of systematic uncertainties
  - Interpretation

**ATLAS Preliminary**

$H \rightarrow ZZ^* \rightarrow 4l$

13 TeV, 36.1 fb$^{-1}$

Stage 0 - $|y_H| < 2.5$

$\sigma BR = 1.31^{+0.28}_{-0.25} \text{[pb]}$

$(\sigma BR)_{SM} = 1.18^{+0.08}_{-0.06} \text{[pb]}$

$\sigma BR = 0.37^{+0.16}_{-0.14} \text{[pb]}$

$(\sigma BR)_{SM} = 92.8^{+2.9}_{-2.8} \text{[fb]}$

$\sigma BR < 0.20 \text{ [pb]}$

(95% CL)

$(\sigma BR)_{SM} = 52.8^{+12.6}_{-12.4} \text{[fb]}$

$\sigma BR < 0.12 \text{ [pb]}$

(95% CL)

$(\sigma BR)_{SM} = 15.4^{+1.1}_{-1.6} \text{[fb]}$
Search for non-SM couplings to gluons and W/Z bosons, both CP-even (H) and CP-odd (A)
  - Effective Field Theory approach

Taking into account lepton distributions and production rates ⇒ large sensitivity increase

Some deviation from the SM for the HVV and AVV couplings due to the VBF excess

MPP contributions:
  - coordination, strategy and implementation

\[
\begin{align*}
\kappa_{gg} & \quad \text{ggF} \\
\kappa_{VV} & \quad \text{VBF}
\end{align*}
\]
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- Higgs boson measurements
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  - Higgs boson Mass
  - Higgs boson couplings

- Dark matter searches

- Di-boson resonance search

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Dark matter searches at LHC

- Search for **WIMP pair-production**
  - Experimental signature: $X + E_{T}^{\text{miss}}$
  - Complementary searches for dijet resonances

![Diagram of dark matter pair-production and dijet resonances]

**DM Simplified Model Exclusions**

- ATLAS limits at 95% CL, direct detection limits at 90% CL

<table>
<thead>
<tr>
<th>DM Mass [GeV]</th>
<th>(DM-nucleon) $\sigma$ [cm$^2$]</th>
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<tbody>
<tr>
<td>1</td>
<td>$10^{-41}$</td>
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<tr>
<td>10</td>
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<tr>
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<td>2</td>
<td>$10^{-47}$</td>
</tr>
<tr>
<td>10</td>
<td>$10^{-48}$</td>
</tr>
</tbody>
</table>

- CRESST II
- XENON1T
- PandaX
- LUX
- ATLAS

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ATLAS Higgs and BSM
Dark matter searches at LHC

- **Search for WIMP pair-production**
  - Experimental signature: $X + E_T^{\text{miss}}$
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- **Simplified signal models**
  - E.g. a single mediator $\Phi$, different couplings
  - Assumption: at LHC energies further, heavier particles decouple

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<tr>
<td>1</td>
<td>10^{-37}</td>
<td>ATLAS Dijet</td>
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<tr>
<td>10</td>
<td>10^{-39}</td>
<td>Vector mediator, Dirac DM</td>
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Vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{\text{DM}} = 1$

ATLAS limits at 95% CL, direct detection limits at 90% CL
Dark matter searches at LHC

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ATLAS Higgs and BSM
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  - Low dark matter masses

![Graph showing DM Simplified Model Exclusions]

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ATLAS Higgs and BSM
Dark matter searches at LHC

- **Search for WIMP pair-production**
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- **Complementarity of searches at colliders**, e.g. sensitivity to
  - Low dark matter masses
  - Axial-vector couplings

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![DM Simplified Model Exclusions](image)

**ATLAS** limits at 95% CL, direct detection limits at 90% CL

Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{\text{DM}} = 1$

ATLAS limits at 95% CL, direct detection limits at 90% CL
- Associated production of dark matter and a Higgs boson $\Rightarrow$ no "ISR model", probing dark matter interactions more directly

- Aiming for $H \rightarrow bb$ decays (largest branching ratio)
» Associated production of dark matter and a Higgs boson ⇒ no "ISR model", probing dark matter interactions more directly

» Aiming for $H \rightarrow bb$ decays (largest branching ratio)

» 2 topologies, depending on the Higgs boson momentum
  » Pair of separated jets
- Associated production of dark matter and a Higgs boson $\Rightarrow$ no “ISR model”, probing dark matter interactions more directly

- Aiming for $H \rightarrow bb$ decays (largest branching ratio)

- 2 topologies, depending on the Higgs boson momentum
  - Pair of separated jets
  - Single large-Radius jet
Discriminating variables: 
di-jet or large-R jet mass, $E_T^{\text{miss}}$

Mass limits for new mediators, most stringent to date

Also search for dark matter in $W/Z+\text{MET}$ channel, paper in preparation

MPP contributions:
- Analysis coordination
- Background estimation
- Interpretation

**Excluded**

$E_T^{\text{miss}} > 500 \text{ GeV}$

2 b-tags

**Observed limit**

$\sigma = 3.75 \text{ fb}$

**Expected limit**

$\sigma = 1.4 \text{ TeV, } m_A = 0.6 \text{ TeV}$

$\chi = 0.8, m_Z = 1, g_{\beta \tan} = 300 \text{ GeV} ± H = m_H m$

**Pre-fit Background**

$\sigma_{\text{Signal}} = 3.75 \text{ fb}$

$\text{SR (Merged)} : 0 \text{ lepton}$

$\gamma = 1$, $g_{\gamma} = 100 \text{ GeV}$

$\text{m}_{\gamma} = 300 \text{ GeV}$

$\text{h} + E_T^{\text{miss}}, \text{ all limits at 95\% CL}$

$\gamma = 13 \text{ TeV, } 3.2 \text{ fb}^{-1}$

$\gamma = 13 \text{ TeV, } 36.1 \text{ fb}^{-1}$

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Di-boson resonance searches

- Previous excitement: local excess in di-photon mass spectrum, 2015 data
- Despite this excess having vanished: SM extensions predicting new, heavy mediators coupling to pairs of bosons (e.g. 2 Higgs-doublet or composite Higgs models)
- Interpretation in terms of simplified models
Search for new, heavy mediators coupling to $WH$ or $ZH$.

Aim for leptonic $W/Z$ decays (lower background) and $H \rightarrow bb$ decays (larger statistics).

- Again, resolved and merged double $b$-jet topologies, depending on the Higgs boson momentum.

Search for a localised excess in $VH$ mass spectra, only small model dependence.
Setting cross-section limits down to $O(1 \text{ fb})$, exclude model parameters like mediator masses

- **MPP contributions:**
  - Background estimation
  - $H \rightarrow bb$ tagging as a future improvement, under development: Higgs boson reconstruction based on large-R jet mass, substructure and $b$-tagging
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- Searches for Supersymmetry
  - top-quark partners and Jets + MET final states
  - 4 lepton final states
  - Long lived particle search
Theoretical preference for sparticle mass scale $\lesssim 1$ TeV

Many LHC Run 1 SUSY limits beyond 1 TeV, except for top partners

**ATLAS SUSY Searches** - 95% CL Lower Limits

- $\sqrt{s} = 7, 8$ TeV
- $\sqrt{s} = 13$ TeV

**Model**
- MSUGRA/CMSSM
- $\tilde{g} \rightarrow q\bar{q}$, $\tilde{g} \rightarrow q\bar{q}X_i$ (compressed)
- $\tilde{g} \rightarrow q\bar{q}X_i^c$
- $\tilde{g} \rightarrow q\bar{q}X_i^c$ (compressed)

**Jets**
- 0-3 jets, 1-2 $\tau$
- 0-3 $e$, $\mu$, $\tau$, $\gamma$
- 1-2 mono-jet, 0-2 $e$, $\mu$, $\tau$, $\gamma$
- 0-3 jets, 1-2 $\tau$

**$E_{\text{miss}}$**
- $L$, $d [(fb^{-1})$]
- $3 \text{rd}$ gen. squarks
- $3 \text{rd}$ gen. slepton

**Mass limit**
- 1.85 TeV
- 1.57 TeV
- 1.825 TeV
- 1.79 TeV
- 1.65 TeV
- 1.65 TeV
- 1.37 TeV
- 1.8 TeV
- 1.37 TeV
- 0.91 TeV
- 0.865 GeV
- 0.81 TeV
- 0.81 TeV

**ATLAS Preliminary**
- $\sqrt{s} = 7, 8, 13$ TeV

**Searches**
- Inclusive Searches
- Direct searches
- $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^{0}$
- $\tilde{t}_2 \rightarrow t\tilde{\chi}_2^{0}$
- $\tilde{t}_3 \rightarrow t\tilde{\chi}_3^{0}$

**Phenomena**
- Produced and long-lived
- Produced and stable, stopped
- Produced and stable, NLSP

**Mass scale**
- [GeV]
- $90-440$
- $250-700$
- $410$
- $590$
- $635$
- $710$
- $760$
- $950$
- $1.0$ TeV
- $1.14$ TeV
- $1.65$ TeV

**Other**
- Phenomena is shown. Many of the limits are based on...
Considering **top-squark pair production** in different scenarios

Aiming for **hadronic top-quark decays**

- $E_T^{\text{miss}}$ caused only by neutralino
- Complete top-quark reconstruction, including boosted topologies

**Complexity of final states** ⇒ comprehensive background estimations using control regions (single lepton, di-lepton, $tt\gamma$)
- Set limits on top-squark and neutralino masses
- Significant sensitivity increase due to luminosity increase and analysis improvements
- MPP contributions: signal and control region design, event selection implementation
Set limits on top-squark and neutralino masses

Significant sensitivity increase due to luminosity increase and analysis improvements

MPP contributions: signal and control region design, event selection implementation

Top squark pair production, $B(\tilde{t}_1 \to t^{(*)} \tilde{\chi}_1^0) = 100\%$

Observed limit ($\pm 1 \sigma_{\text{SUSY}}$)

Expected limit ($\pm 1 \sigma_{\text{exp}}$)

ATLAS $20 \text{ fb}^{-1}, \sqrt{s}=8 \text{ TeV}$

Limits at 95% CL

$\sqrt{s}=13 \text{ TeV, 36.1 fb}^{-1}$

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ATLAS Higgs and BSM
Additional interpretation for the same final state: dark matter production with a new scalar mediator

- Compared to SUSY: slightly softer $p_T$ spectra

- Setting limits on the dark matter - nucleon cross-section and the dark matter mass within the scalar mediator model

ATLAS
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Excluded by ATLAS

$\sigma_{SI}(\chi\text{-nucleon})$ [cm$^2$]

All limits at 90% CL

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ATLAS Higgs and BSM
No SUSY signals yet ⇒ extend searches to more complicated scenarios

- R-parity violation (RPV): $\tilde{\chi}_1^0 \rightarrow \ell^+\ell^−\nu$

- Using 4 lepton final states, almost independent of the $\tilde{\chi}_1^0$ production mechanism

MPP contributions:
  - Analysis coordination: driven by MPP since Run 1
  - Model development
  - Background estimates
  - Preparing update with 36 fb$^{-1}$ testing more models, including $\tau$ leptons
Alternative RPV scenario: small coupling $\lambda \Rightarrow$ long-lived $\tilde{\chi}^0_1$

Signature: displaced vertices with two associated charged leptons in the inner detector

Sensitivity to particles with lifetimes of order ps to ns

MPP contributions:
  ▶ Analysis leadership since Run 1

ATLAS
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

ee/\mu\mu channels
RPV Model
$\tilde{g} \rightarrow q\bar{q}[\tilde{\chi}^0_1 \rightarrow e\mu\nu / e\mu\nu]$ 95% CL limit

Cross-section [fb]

$\tilde{g}$ gluino production
$\tilde{q}$ gluino production

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ATLAS Higgs and BSM
Summary

- Leading and visible contributions of the MPP group to high priority studies of limitations of the Standard Model, in spite of the competitive research environment
  - Higgs precision measurements, Higgs physics as a portal to new phenomena
  - Searches for dark matter particle production and heavy di-boson resonances
  - Searches for SUSY particles in uncharted regions of the parameter space
- Analyses of Run 2 data in full speed - dataset increase to 120 fb$^{-1}$ until the end of 2018
- Future prospects: Run 3 going to $\sqrt{s_{pp}} = 14$ TeV, followed by High-Luminosity LHC - dataset increase of about a factor of 100 compared to now
- Plan to stay at the collider energy frontier