Highlight on ATLAS Physics Results

Yanwen Liu on behalf of the ATLAS Collaboration
Univ. of Science and Technology of China
8th International Conference on New Frontier Physics
Brief status of the experiment

- 156 fb⁻¹ delivered
- 147 fb⁻¹ recorded (94%)
- 139 fb⁻¹ for physics (95%)
- Luminosity precision 1.7%

[ATLAS-CONF-2019-021]
Selected topics

- **Higgs properties**
  - Higgs discovery channels
  - Higgs rare decays
  - Di-Higgs

- **SM Electroweak tests**
  - Vector Boson Scattering
  - Di-boson production
  - $t\bar{t}$ charge asymmetry
  - Direct top width measurement

- **Searches for new physics**
  - SUSY
  - New resonances ($ll, jj$)
  - Lepton + MET
  - di-boson resonances
  - Displaced signature

Produced in 139 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV:
- 12 billion W boson
- 2.8 billion Z boson
- 275 million top quark
- 7.7 million Higgs boson

Broad opportunities probing physics in Higgs, electroweak sectors and beyond the Standard Model
Higgs Production and Decay

At the LHC (13 TeV), the total Higgs production cross section is 56 pb, dominated by gluon-gluon fusion.

Diverse decay channels offer numerous possibilities of measurements.

* Cross sections and branching fractions are calculated with \( m_H = 125 \) GeV.
Higgs in di-photon

Fit extracts $6550 \pm 530$ signal candidates

Fiducial cross section:
- $65.2 \pm 7.2$ fb (measured)
- $63.6 \pm 3.3$ fb (theory)

Differential cross sections compared to the most advanced theoretical predictions
Higgs in 4-lepton

Expect $206 \pm 13$ signal events in $115 - 130$ GeV

Precision on cross section measurement $\sim 10\%$

Good agreement with theory

Categorization using jet multiplicities, kinematics and Neural Net to distinguish production modes
Combination: $\gamma\gamma$ and 4-lepton

Total cross section in good agreement with prediction
At 13 TeV, $\sigma = 55.4^{+4.3}_{-4.2} \text{ pb (measured)} / 55.6 \pm 2.5 \text{ pb (predicted)}$
Differential cross section as a function of $p_T$ well described by POWHEG NNLOPS up to 1 TeV
(K-factor of 1.1 obtained from NNNLO prediction)
The Higgs boson discovery opened a new window to probe new physics.

Higgs boson does couple to the mass!

Most couplings measured at 10-20% precision

Related talks:
Lydia Iconomidou-Fayard
ATLAS results on Higgs boson properties
Bernd Stelzer
$tth$ production
Reisaburo Tanak
Higgs couplings
Paolo Francavilla
Combination technique
Search for $H \rightarrow \mu\mu$ decay

- Challenging: $BF = 0.02\%$ in the SM, large continuum background from Drell-Yan (In mass region of $120 - 130$ GeV, $S/B = 860/0.45M = 0.2\%$)
- Events firstly categorized in jet multiplicities
- BDT in each jet-bin to distinguish signal and background (data in sidebands vs. signal MC)
- Limit: $BF < 3.8 \times 10^{-4}$, Cross section upper limit $< 1.7\sigma_{SM}$ at 95% CL
- Signal strength: $\mu = 0.5 \pm 0.7$

<table>
<thead>
<tr>
<th>Category</th>
<th>Data</th>
<th>$S_{SM}$</th>
<th>$S$</th>
<th>$B$</th>
<th>$S/\sqrt{B}$</th>
<th>$S/B$ [%]</th>
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<tr>
<td>VBF High</td>
<td>40</td>
<td>4.5</td>
<td>2.3</td>
<td>34</td>
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<td>5.5</td>
<td>2.8</td>
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<td>180000</td>
<td>0.17</td>
<td>&lt;0.1</td>
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</table>
Search for $H \rightarrow ee/e\mu$ decays

$BF < 3.6 \times 10^{-4} \ (3.5 \times 10^{-4})$ at 95% CL

In SM, $BF \sim 5 \times 10^{-9}$

$BF < 6.1 \times 10^{-5} (5.8 \times 10^{-5})$ at 95% CL

See more about Higgs rare and LFV decays in Michaela Mlynarikova’s talk
See searches for BSM in Higgs sector in Jike Wang’s talk
Higgs self-interactions

Study the Higgs self-couplings to constrain the shape of the Higgs potential near EWSB vev.

\[ V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \]

\[ \Rightarrow \lambda \nu^2 H^2 + \lambda \nu H^3 + \frac{\lambda}{4} H^4 \]

1-loop electroweak correction of single Higgs production involving Higgs field

Higgs production measurements are combined to constrain the self-coupling

\[-3.2 < \kappa_\lambda < 11.9 \]  
\((-6.2 < \kappa_\lambda < 14.4)\) at 95% CL
Di-Higgs overview

HH offers direct studies of Higgs self-interaction

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lumi (fb⁻¹)</th>
<th>Reference</th>
</tr>
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<tr>
<td>$b\bar{b}b\bar{b}$</td>
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<td>JHEP01(2019)030</td>
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<tr>
<td>$b\bar{b}WW$ ($b\bar{b}l\nuqq$)</td>
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<td>JHEP04(2019)092</td>
</tr>
<tr>
<td>$b\bar{b}\tau\tau$</td>
<td>36.1</td>
<td>PRL121(2018)191</td>
</tr>
<tr>
<td>$WWW$</td>
<td>36.1</td>
<td>JHEP05(2019)124</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>36.1</td>
<td>JHEP11(2018)40</td>
</tr>
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<td>$WWW\gamma\gamma$</td>
<td>36.1</td>
<td>EPJC78(2018)1007</td>
</tr>
<tr>
<td>Combination</td>
<td>36.1</td>
<td>arXiv:1906.02025</td>
</tr>
</tbody>
</table>

$\sigma_{ggF}(pp \to HH) = 33.5^{+2.4}_{-2.8}$ fb (at 13 TeV)
ATLAS combination

No observation yet $\sigma < 6.9 \sigma_{SM}$ at 95% CL
Corresponding to $-5.0 < \kappa_\lambda < 12.0$ at 95% CL
Similar to limits from single Higgs
ATLAS projection

Projection to HL-LHC: HH production can be observed at $3\sigma$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$1\sigma$ CI</th>
<th>$2\sigma$ CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainties only</td>
<td>$0.4 \leq \kappa_\lambda \leq 1.7$</td>
<td>$-0.10 \leq \kappa_\lambda \leq 2.7 \cup 5.5 \leq \kappa_\lambda \leq 6.9$</td>
</tr>
<tr>
<td>Systematic uncertainties</td>
<td>$0.25 \leq \kappa_\lambda \leq 1.9$</td>
<td>$-0.4 \leq \kappa_\lambda \leq 7.3$</td>
</tr>
</tbody>
</table>
Di-Higgs in $bbWW$

**lvlvbb** topology:
- two hemispheres
- $ll$ angular correlation
- Peak in $m_{bb}$
  deep-learning(DNN)

Cross section upper limits at 95% CL:
- $40 \times \sigma_{SM}$ (observed)
- $29^{+14}_{-9} \times \sigma_{SM}$ (expected)

Significant improvement on the limit of $300 \times \sigma_{SM}$ from 36 fb$^{-1}$ (recall p13)
VBS HH production

Trigger on b-jets since 2016

$-1.02 < C_{2V} < 2.71$ at 95% CL
CMS+ATLAS projection

Expect a significance of HH production at 4 $\sigma$
A measurement of $\kappa_\lambda$ at 50% precision

See also:
- searches for HH production and HL-LHC prospects
  by Yuta Sano and
- HL-LHC prospects
  by Francesca Pastore
Higgs in the Electroweak sector

- Higgs boson is profoundly connected to the electroweak sector
- $V_L V_L$ scattering amplitude unitarised by $H$.
- Same sign $WW$ scattering an ideal test ground since background is much reduced
- Signature: di-lepton and two forward jets, observed with a significance of 6.5 $\sigma$

Goldstone self-interaction amplitudes:

\[
\mathcal{M}(w^+ w^+ \to w^+ w^+) = \mathcal{M}(w^- w^- \to w^- w^-) = -(s/v^2)(4-3/\rho),
\]
\[
\mathcal{M}(w^+ w^- \to w^+ w^-) = -(u/v^2)(4-3/\rho),
\]
\[
\mathcal{M}(w^+ w^- \to ZZ) = s/v^2 \rho
\]
\[
\mathcal{M}(w^\pm Z \to w^\pm Z) = t/v^2 \rho, \quad \mathcal{M}(ZZ \to ZZ) = 0,
\]
VBS ZZ ($2l2\nu2j$ and $4l2j$)

- Straight cut to define signal regions
- BDT to separate electroweak production from background
- Electroweak production significance $5.5\,\sigma$
- Yield compatible with the standard model prediction

See talks about VBS by Ondrej Penc, precision electroweak measurements by Maarten Boonekamp, electroweak probe of pQCD by Vasiliki Kouskoura
$Z\gamma$ differential cross section

- Prediction at NNLO describes data well
- NLO inadequate (discrepancies in both shape and normalizations)

See measurements of multiboson production in Jessica Metcalfe’s talk
See Paul Glaysher’s talk about $ttW/Z$ production
Top quark

- Top quark is the unique quark that decays before hadronization – easy to measure
- Produced in abundance at the LHC – ideal test ground of the SM and for BSM search
- Many nice measurements

See talks about top quark physics by Nello Bruscino,
tt cross section measurements by Adam James Bozson
and measurement of $m_t$ by Jiri Hejbal
Direct measurement of top width

- NNLO theory prediction 1.322 GeV uncertainty ~ 1% (6% incl. experimental uncertainties of related parameters: \(m_t, G_F, v_{tb}\))
- The most precise (0.1%) indirect measurement, assuming \(\Gamma(t \rightarrow Wb)\) [PLB736(2014)33]
- NEW: Template fit of \(m_{lb}\) (leptons paired the closest b-jet)
- Significant improvement from 8 TeV results (limited by syst. uncertainty of 0.7-0.8 GeV)

**Result:** \(\Gamma(t) = 1.9 \pm 0.5\) GeV \((m_t = 172.5\) GeV)
Charge asymmetry

“forward – central” charge asymmetry a subtle effect: in $q\bar{q} \rightarrow t\bar{t}, qg \rightarrow t\bar{t}g$
$t$ more forward than $\bar{t}$

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

Bayesian statistical inference

$A_C = 0.0060 \pm 0.0015$
$A_C = 0$ ruled out at 4 σ level
### ATLAS SUSY Searches* - 95% CL Lower Limits

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, cf. refs. for the assumptions made.

#### Model

<table>
<thead>
<tr>
<th>Model</th>
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<th>[\mathcal{L} dt [\text{fb}^{-1}]]</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td>(\tilde{\chi}_1^0, \tilde{\chi}_1^0)</td>
<td>0 e, \mu, mono-jet 2-6 jets</td>
<td>36.1</td>
<td>(m(\tilde{\chi}_1^0) = 100 \text{ GeV})</td>
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<td>(\tilde{\chi}_1^0)</td>
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<td>6.0</td>
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<td>(\tilde{\chi}_3^0)</td>
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<td>(\tilde{\chi}_4^0)</td>
<td>(m(\tilde{\chi}_4^0) = 500 \text{ GeV})</td>
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#### Inclusive Searches

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#### EW direct

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#### RPV

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#### Reference

- ATLAS Preliminary
- \(\sqrt{s} = 13 \text{ TeV}\)
- **July 2019**

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

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, cf. refs. for the assumptions made.
Electroweakino pair production

$N_{\text{lepton}}$ | SR-LM | SR-MM | SR-HM
---|---|---|---
$p_T^\ell$ [GeV] | $= 1$ | $> 7(6)$ for $e(\mu)$ | 
$N_\text{jet}$ | $= 2$ or 3 | 
$N_\text{p-jet}$ | $= 2$ | 
$E_T^{\text{miss}}$ [GeV] | $> 240$ | 
$m_{bb}$ [GeV] | $\in [100, 140]$ | 
$m(\ell, b_1)$ [GeV] | $> 120$ | 
$m_T$ [GeV](excl.) | $\in [100, 160]$, $\in [160, 240]$ | $> 240$ | 
$m_{CT}$ [GeV](excl.) | $\{\in [180, 230], \in [230, 280], > 280\}$ | 
$m_T$ [GeV](disc.) | $> 100$, $> 160$, $> 240$ | 
$m_{CT}$ [GeV](disc.) | $> 180$ | 

$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}} (1 - \cos[\Delta \phi(p_T^\ell, p_T^{\text{miss}})])}$

$W + j$ and $t\bar{t}$ upper bound at $m_W$

$m_{CT} = \sqrt{2p_T^{b_1} p_T^{b_2} (1 + \cos \Delta \phi_{bb})}$

t$\bar{t}$ upper bound at $\sim 180$ GeV [JHEP 0804(2008)034]

See more about search for the electroweak production of SUSY particles in Joaquin Poveda’s talk.
squark, gluino pair production

See Kazuki Todome’s talk about searches for squarks and gluinos
See searches for new phenomena in Francesco Guescini’s talk, searches for dark matter in Edoardo Maria Farina’s talk.
Search for di-lepton resonances

Model independent approach:
- Functional form fit to the mass spectrum
- Generic signal shape (Breit-Wigner convoluted with Gaus)
- Proven effectiveness for $Z'$

See Deshan Kavinshka Abhayasinghe’s talk about searches for new phenomena in di-lepton final state
Search for $W' \rightarrow l\nu$

$W'$ predicted by many BSM models, SSM as benchmark. Mass below 6.0 (5.1) TeV excluded for electron (muon) channel.
Search in di-jet events

$q^*$ below 6.7 TeV excluded at 95% CL

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- Data
- Background fit
- BumpHunter interval

$q^*$, $m_{q^*} = 4.0$ TeV
$q^*$, $m_{q^*} = 5.0$ TeV

$q^*$, $\sigma \times 0.1$
$p$-value = 0.8
Fit Range: 1.1 - 8.1 TeV
$|y^*| < 0.6$
Search in di-bjets

SSM Z’ below 2.7 TeV is excluded at 95% CL

See Tadej Novak’s talk about searches with leptons and jets
Search for di-boson resonance

- Heavy particles such as $W'$, $Z'$, gravitons ($M > 1.3$ TeV) decaying to $WW$, $WZ$ or $ZZ$
- $W$ and $Z$ are boosted and reconstructed in fat jets

$W/Z + j$ control region
$W/Z$ jet mass resolution : 10-20%

For $g_V = 1$, $1.3 - 3.5$ TeV mass range excluded at 95% CL

See Trine Poulsen’s talk about searches with hadronic final states
Search for heavy neutral leptons

Right-handed, Majorana neutrinos give rise to type-I see-saw mechanism and leptogenesis, address neutrino masses and provide dark matter candidates

Signature: lepton number conserved / violated decays
prompt / displaced leptons

[PRD29(1984)2539]
Search for long-lived particle

Many extensions to SM include a “dark sector” that couples very weakly to SM.

FRVZ model: Higgs as a portal to the dark sector and dark photon mixing with normal photon

\[ L_{\text{gauge mixing}} = \frac{\epsilon}{2} B_{\mu\nu} B^{\mu\nu} \]

Cascade decays lead to

- collimated and displaced leptons
- collimated and displaced hadrons

**Benchmark settings**

<table>
<thead>
<tr>
<th>Sample</th>
<th>( m_H ) [GeV]</th>
<th>( m_{\delta_0} ) [GeV]</th>
<th>( m_{\text{HLSP}} ) [GeV]</th>
<th>( m_{\gamma_d} ) [GeV]</th>
<th>( m_{\gamma_d} ) [GeV]</th>
<th>( c\tau ) [mm]</th>
</tr>
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<tbody>
<tr>
<td>( H \to 2\gamma_d + X )</td>
<td>125</td>
<td>5.0</td>
<td>2.0</td>
<td>—</td>
<td>0.4</td>
<td>49.23</td>
</tr>
<tr>
<td>( H \to 4\gamma_d + X )</td>
<td>125</td>
<td>5.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.4</td>
<td>82.40</td>
</tr>
<tr>
<td>( H \to 2\gamma_d + X )</td>
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<td>5.0</td>
<td>2.0</td>
<td>—</td>
<td>0.4</td>
<td>11.76</td>
</tr>
<tr>
<td>( H \to 4\gamma_d + X )</td>
<td>800</td>
<td>5.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.4</td>
<td>21.04</td>
</tr>
</tbody>
</table>

See Lawrence Lee JR’s talk about searches for long-lived particles
Summary

- Higgs studies entering precision era
- Higgs rare decays sensitive to BSM
- Higgs Self-Interaction direct observation challenging
- SM tested by unprecedented data from ATLAS
- Broad program in searches for new physics

Not mentioned: quarkonia and heavy flavor production (see Tatiana Lyubushkina’s talk)
diphoton process in HI collisions (see Martin Spousta’s talk)
measurement of the weak mixing phase $\varphi_s$ (see Vladimir Nikolaenko’s talk)
BACK-UP starts
H self-interactions affect single-H production
squark, gluino pair production

$m_{\text{eff}}$: scalar pT sum of all objects added to MET

See Kazuki Todome’s talk about searches for squarks and gluinos
Lower limits for masses reaching 1.6 TeV for gluinos and 750 GeV for bottom and top squarks