Run-2 Physics Results from ATLAS at the LHC

Bernd Stelzer (SFU)
CAP 2019, June 3rd, 2019
We are here

- New ATLAS Inner Tracker (ITk)
- LAr Calorimeter readout electronics

sTGC for Muon New Small Wheel

LAr Calorimeter trigger electronics

See Jesse Heilman’s talk
Run-2 was clearly a game-changer...

<table>
<thead>
<tr>
<th>Process</th>
<th>13 TeV</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Bias</td>
<td>1.71</td>
<td>1.6</td>
</tr>
<tr>
<td>W</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Z</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>WZ</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.5</td>
<td>3.2</td>
</tr>
<tr>
<td>t (t-channel)</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Wt</td>
<td>3.6</td>
<td>3.4</td>
</tr>
<tr>
<td>tt</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td>H (ggF)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>H (VBF)</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**BSM (signals)**

<table>
<thead>
<tr>
<th>Process</th>
<th>13 TeV</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>XX (500 GeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>tt (700 GeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>gg (1.0 TeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>gg (1.5 TeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>W (2 TeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>ZZ (3 TeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Z (4 TeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>QBH (5 TeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>QBH (6 TeV)</td>
<td>4.4</td>
<td>8.4</td>
</tr>
<tr>
<td>gg → X(750)</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>bb → X(750)</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>qq → X(750)</td>
<td>2.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**Standard Model**

<table>
<thead>
<tr>
<th>Process</th>
<th>Min. Bias</th>
<th>W</th>
<th>Z</th>
<th>WZ</th>
<th>ZZ</th>
<th>t (t-channel)</th>
<th>Wt</th>
<th>tt</th>
<th>ttZ</th>
<th>H (ggF)</th>
<th>H (VBF)</th>
<th>WH</th>
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<td>2.0</td>
<td>2.5</td>
<td>3.2</td>
<td>3.3</td>
<td>3.6</td>
<td>2.3</td>
<td>2.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Higgs**

- XX (500 GeV):
  - 4.4

- tt (700 GeV):
  - 4.4

- gg (1.0 TeV):
  - 4.4

- gg (1.5 TeV):
  - 4.4

- W (2 TeV):
  - 4.4

- ZZ (3 TeV):
  - 4.4

- Z (4 TeV):
  - 4.4

- QBH (5 TeV):
  - 4.4

- QBH (6 TeV):
  - 4.4

- gg → X(750):
  - 4.7

- bb → X(750):
  - 5.4

- qq → X(750):
  - 2.7

**Backgrounds**

<table>
<thead>
<tr>
<th>Process</th>
<th>Min. Bias</th>
<th>W</th>
<th>Z</th>
<th>WZ</th>
<th>ZZ</th>
<th>t (t-channel)</th>
<th>Wt</th>
<th>tt</th>
<th>ttZ</th>
<th>H (ggF)</th>
<th>H (VBF)</th>
<th>WH</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>2.0</td>
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<td>3.3</td>
<td>3.6</td>
<td>2.3</td>
<td>2.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**SUSY**

- XX (500 GeV):
  - 4.4

- tt (700 GeV):
  - 4.4

- gg (1.0 TeV):
  - 4.4

- gg (1.5 TeV):
  - 4.4

- W (2 TeV):
  - 4.4

- ZZ (3 TeV):
  - 4.4

- Z (4 TeV):
  - 4.4

- QBH (5 TeV):
  - 4.4

- QBH (6 TeV):
  - 4.4

- gg → X(750):
  - 4.7

- bb → X(750):
  - 5.4

- qq → X(750):
  - 2.7

**Exotics**

- XX (500 GeV):
  - 4.4

- tt (700 GeV):
  - 4.4

- gg (1.0 TeV):
  - 4.4

- gg (1.5 TeV):
  - 4.4

- W (2 TeV):
  - 4.4

- ZZ (3 TeV):
  - 4.4

- Z (4 TeV):
  - 4.4

- QBH (5 TeV):
  - 4.4

- QBH (6 TeV):
  - 4.4

- gg → X(750):
  - 4.7

- bb → X(750):
  - 5.4

- qq → X(750):
  - 2.7

**For internal circulation only**
ATLAS & CMS: giant, ultra sophisticated general purpose particle detectors

LHC ring at CERN: 27 km circumference.
The ATLAS Experiment

Emphasis on:
- Large acceptance and hermeticity
- Excellent particle identification
- Excellent lepton and $\gamma$ resolution
- Good jet and $E_{T,\text{miss}}$ resolution
- Standalone muon measurement
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Innermost pixel layer (IBL) 3.4 cm from interaction point – added for Run2
Challenging conditions with 10-70 interactions per bunch crossing (pileup)
- High data taking efficiencies
- All subdetectors running smoothly
- Learn to live with high pileup
- 139 fb^{-1} of good data collected
- Outstanding Performance!

Data quality efficiency

**ATLAS pp data: April 25-October 24 2018**

<table>
<thead>
<tr>
<th>Inner Tracker</th>
<th>Calorimeters</th>
<th>Muon Spectrometer</th>
<th>Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>LAr</td>
<td>MDT</td>
<td>Solenoid</td>
</tr>
<tr>
<td>SCT</td>
<td>Tile</td>
<td>RPC</td>
<td>Toroid</td>
</tr>
<tr>
<td>TRT</td>
<td></td>
<td>CSC</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TGC</td>
<td></td>
</tr>
<tr>
<td>99.8</td>
<td>99.7</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>99.8</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Good for physics: 97.5% (60.1 fb^{-1})
$Z \rightarrow \mu\mu$ with 65 additionally reconstructed vertices!

- **100 MeV threshold**
- **1 GeV threshold**
- **5 GeV threshold**

Efficiency to reconstruct physics objects remains high even with pileup.
The Standard Model
of Particle Physics

\[ \mathcal{L} = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{\Psi} \slashed{D} \Psi + D_{\mu} \Phi \Phi^\dagger - V(\Phi) + \bar{\Psi}_L \gamma_5 \Phi \Psi_R + h.c. \]
ATLAS is putting the Standard Model to the test

## Standard Model Total Production Cross Section Measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>Data</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS Preliminary</td>
<td>Run 1.2 $\sqrt{s} = 7.8, 13$ TeV</td>
<td></td>
</tr>
</tbody>
</table>

### Measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>Data</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$W$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$Z$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$tt\bar{t}$-chan</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$WW$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$H$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$Wt$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$WZ$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$t_s$-chan</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$t\bar{t}W$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$WW$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
<tr>
<td>$WWZ$</td>
<td>50, $10^{-3}$</td>
<td>COMPETE HIP R17 (theory)</td>
</tr>
</tbody>
</table>

### Status: March 2019

### ATLAS cross section measurements confirm predictive power of the Standard Model

### Important to understand all backgrounds to searches for new physics

### Theory progress on NNLO calculations

### Many detailed fiducial and differential cross section measurements ongoing.
First Evidence for Three Vector Boson Production

ATLAS is reaching sensitivity to processes with very small cross sections (< 1pb)

Evidence for production of three vector bosons (WVV, V = W, Z)
- Sensitive to anomalous *triple* and *quartic* gauge couplings
- Combination of several final states (2 - 4 leptons)
- Use dijet mass and MVAs to suppress backgrounds
- First evidence with 4.0 σ observed (3.1 σ expected) significance!

![Diagram of three vector bosons production](image1.png)

![Graph of data and predictions](image2.png)

Overall $\sigma_{exp} / \sigma_{SM} = 1.38^{+0.39}_{-0.37}$
First Evidence for Three Vector Boson Production

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ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, 79.8 \text{ fb}^{-1} \]

Overall \( \sigma(\text{exp}) / \sigma(\text{SM}) = 1.38^{+0.39}_{-0.37} \)
ATLAS is putting the Standard Model to the test

Rare production of processes (~ 1pb) involving top quarks: \textbf{ttW, ttZ, t\gamma and ttbb}

- Test of QCD predictions
  - Multiple energy scales involved in process
  - Matching/Merging: parton-shower vs matrix-element
- Important background for searches with multiple leptons and/or b-jets (e.g. ttH)
- Deviation of tt+X coupling from SM would indicate new physics (e.g. vector-like quarks, etc)
Measurement of $t\bar{t}$ in association with Vector Bosons

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

- Split data in lepton/charge/flavor multiplicity bins
- Differential measurements and EFT interpretations
- Fiducial measurement of $t\bar{t}+\gamma$ production

Simultaneous fit for $t\bar{t}+W$ and $t\bar{t}+Z$

$\sigma_{t\bar{t}W}/\sigma_{t\bar{t}\gamma} = 1.06 \pm 0.06$
The Higgs boson
a LHC responsibility

Higgs mechanism:
F. Englert and R. Brout, PRL 13 (1964) 321.
P.W. Higgs, PRL 13 (1964) 508.
Higgs boson production at the LHC

Gluon Fusion

Gluon Fusion

$$\sigma_{H,ggF} \sim 49 \text{ pb}$$

Higgs-Strahlung

Higgs-Strahlung

$$\sigma_{W/Z+H} \sim 1.4/0.9 \text{ pb}$$

Vector Boson Fusion

Vector Boson Fusion

$$\sigma_{VBF} \sim 3.8 \text{ pb}$$

ttH Production

ttH Production

$$\sigma_{ttH} \sim 0.5 \text{ pb}$$

Note, we typically provide experimental results in terms of:

\[
\mu = \frac{(\sigma \cdot \text{BR})_{\text{obs}}}{(\sigma \cdot \text{BR})_{\text{SM}}}
\]

$$\mu=1 \text{ (if observation agrees with Standard Model, SM)}$$
Higgs boson production at the LHC (in Run-2 numbers)

LHC = ‘Large Higgs Creator’

During Run-2, the LHC produced almost **8 million Higgs bosons**!

<table>
<thead>
<tr>
<th>Channel</th>
<th>Produced</th>
<th>Selected</th>
<th>Mass resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → γγ</td>
<td>18,200</td>
<td>6,440</td>
<td>1–2%</td>
</tr>
<tr>
<td>H → ZZ*</td>
<td>210,000</td>
<td>(→ 4ℓ)</td>
<td>210</td>
</tr>
<tr>
<td>H → WW*</td>
<td>1,680,000</td>
<td>(→ 2ℓ2ν)</td>
<td>5,880</td>
</tr>
<tr>
<td>H → ττ</td>
<td>490,000</td>
<td>2,380</td>
<td>15%</td>
</tr>
<tr>
<td>H → bb</td>
<td>4,480,000</td>
<td>9,240</td>
<td>10%</td>
</tr>
</tbody>
</table>

While this is enormous, the number of selected events is much smaller, due to:

- **Need to select final states with small backgrounds (typically require a lepton) and good resolution to measure the small Higgs signal**
- **Small branching ratios for lepton final states**
Higgs Boson Interactions

Gauge couplings: Key in Higgs discovery (ZZ, WW, $\gamma\gamma$)

Yukawa couplings: Higgs boson properties

Key Run 2 milestones accomplished - Discovery of 3\textsuperscript{rd} generation (direct) Higgs Yukawas!

<table>
<thead>
<tr>
<th>Yukawas at LHC</th>
<th>tau</th>
<th>b</th>
<th>top</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exp. Sig.</td>
<td>5.4 $\sigma$</td>
<td>5.5 $\sigma$</td>
<td>5.1 $\sigma$</td>
</tr>
<tr>
<td>Obs. Sig.</td>
<td>6.4 $\sigma$</td>
<td>5.4 $\sigma$</td>
<td>6.3 $\sigma$</td>
</tr>
<tr>
<td>mu</td>
<td>1.09 $\pm$ 0.35</td>
<td>1.01 $\pm$ 0.20</td>
<td>1.34 $\pm$ 0.21 $^*$</td>
</tr>
<tr>
<td>CMS</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Exp. Sig.</td>
<td>5.9 $\sigma$</td>
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<td>1.26 $\pm$ 0.26 $^{**}$</td>
</tr>
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*13 TeV only derived from cross section measurements
Observation of $H \rightarrow bb$ in Higgs-Strahlung Production

First observation of $H \rightarrow bb$ in WH/ZH Higgs-Strahlung (5.3σ observed, 4.8σ expected)
- Confirms the Higgs decay to $bb$ with largest branching ratio ~58%
- Challenging analysis requiring multivariate techniques to suppress background

Leptons  2 Jets  3 Jets

ATLAS

$\mu_{VH(\rightarrow bb)} = 1.01 \pm 0.20$
Observation of $H \to bb$ in Higgs-Strahlung Production

First observation of $H \to bb$ in WH/ZH Higgs-Strahlung (5.3$\sigma$ observed, 4.8$\sigma$ expected)

- Confirms the Higgs decay to bb with largest branching ratio $\sim$58%
- Challenging analysis requiring multivariate techniques to suppress background

\[ \mu_{VH(\to bb)} = 1.01 \pm 0.20 \]
Observation of ttH Production in Diphoton Decays

- Enhance purity by selecting leptonic and hadronic top decays
- Further improve purity using BDT based on lepton, jet, photon 4-vectors (trained mass-independent)

First observation of single-channel ttH \((H \rightarrow \gamma \gamma)\) with 4.9σ significance

\[
\mu_{ttH} = 1.38^{+0.41}_{-0.36} = 1.38^{+0.33}_{-0.31} \text{ (stat.)} +0.13_{-0.11} \text{ (exp.)} +0.22_{-0.14}
\]
Observation of $ttH$ Production

Consider $H \rightarrow bb$, multilepton(WW/ZZ/ττ) and $γγ$.

$ttH$ has tiny rate $\sim 1/100$ ggF.

Combining 4 Higgs decay channels: 6.3σ Observation.

Data agrees with predicted strong ($\sim 4\times$) rise in cross-section vs $\sqrt{s}$.
Observation of Higgs Boson Production Modes

Latest combination Higgs boson measurements establishes **observation of all Higgs boson production modes** (ggF, VBF, VH, ttH) - another Run 2 milestone

**Observation of Higgs Boson Production Modes**

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, 24.5 - 79.8 \text{ fb}^{-1} \]

\[ m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \]

\[ \sigma_{SM} = 76\% \]

Not including latest ttH result

---

**Cross-section normalized to SM value**

Overall \( \sigma(\text{exp}) / \sigma(\text{SM}) = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05 \) (stat.) \( +0.05^{+0.05}_{-0.04} \) (exp.) \( +0.05^{+0.05}_{-0.04} \) (sig. th.) \( \pm 0.03 \) (bkgr. th.)
Higgs Boson Coupling Measurements

Coupling modifiers ($\kappa=1$ in SM)

\[
\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}
\]

\[
k_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}
\]

Fermion vs Vector Boson Coupling

Assume: $\kappa_V = \kappa_W = \kappa_Z$

$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$

Measure “effective” couplings to photons ($\kappa_\gamma$) and gluons ($\kappa_g$) sensitive to new particles in the loops…

Model independent modifier ratios:

$\lambda_{ab} = \frac{\kappa_a}{\kappa_b}$. 

<table>
<thead>
<tr>
<th>$\lambda_g$</th>
<th>$\lambda_\gamma Z$</th>
<th>$\lambda_{\tau Z}$</th>
<th>$\lambda_{b Z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.10^{+0.15}_{-0.14}$</td>
<td>$0.94 \pm 0.07$</td>
<td>$0.95 \pm 0.13$</td>
<td>$0.93^{+0.15}_{-0.13}$</td>
</tr>
</tbody>
</table>
Coupling scale factors for the coupling strengths to W, Z, t, b, τ and μ treated independently.

Assume SM structure of loop processes.
Summary of Higgs Boson Status

Mass: Run-1 (ATLAS & CMS): 125.09 ± 0.24 GeV | confirmed by ATLAS and CMS with Run-2 data

Spin / CP: Spin 1, 2 excluded with high significance | CP-even, but CP-odd admixtures possible

BR(H → invisible): < 26% (assuming SM production)

Differential cross section measurements ($p_T(H)$, $y(H)$, $N_{jets}$, ...): performed in most channels
There are many big questions beyond the SM to be answered at TeV scale

Big Ideas are constrained from theory and observed phenomena
Searches for New Phenomena (Exotics)

3 Searches with full Run-2 dataset

I.e. You get to see the “Final word” on those (until 2021)
Searches for New Resonances
Searches for New Resonances

Neutral
- Dilepton
- Dijet
- Top

Charged
- Dilepton
- Dijet
- Top
- DiPhoton
- Diboson
- Zy
Searches for Di-Jet Resonances (Full Run-2 dataset)

Hadronic resonances are sensitivity to highest energy scales at the LHC

**Benchmark**: Excited quarks $q^*$

No anomaly seen in this search

Limit on $M_{q^*} > 6.7$ TeV at 95% CL
Searches for New Resonances

Highest Mass Event: $m_{JJ} = 8.02$ TeV
Dilepton Resonance Searches (Full Run-2 dataset)

Highest mass dilepton candidate: $m_{\text{ee}} = 4.06 \text{ TeV}$

ATLAS has excluded Z' bosons with SM couplings up to 5.1 TeV at 95% CL

See Etienne Dreyer’s talk
Di-Boson Resonance Search

Use large radius $R=1.0$ jets as input to $W/Z$ Tagger to reconstruct boosted $W/Z$ bosons

- Substructure analysis based on Track-CalocClusters
- Consider spin-0, 1, 2 benchmark models

$1.3 \, \text{TeV} < M_G^- < 1.6 \, \text{TeV}$ at 95% CL (bulk RS model)

$m(JJ) = 4.4 \, \text{TeV}$

$\chi^2/\text{DOF} = 8.1/4$

Fitted $W/Z+$jet events: $17112 \pm 777$

$s_{\text{Tag}} = 0.92 \pm 0.04$
Search for Supersymmetry

“naturalness”
Searches for New Phenomena (SuperSymmetry)

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>( \text{LB} ) (fb^{-1})</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. ( \tilde{g} \rightarrow q\bar{q}\tilde{t} )</td>
<td>0, 3, ( \tilde{t} \text{ mono-jet} )</td>
<td>96.1</td>
<td>( \tilde{t} \text{ f.f. (sign)} )</td>
</tr>
<tr>
<td>0. ( \tilde{g} \rightarrow q\bar{q}\tilde{b} )</td>
<td>0, 3, ( \tilde{b} \text{ mono-jet} )</td>
<td>96.1</td>
<td>( \tilde{b} \text{ f.f. (sign)} )</td>
</tr>
<tr>
<td>0. ( \tilde{g} \rightarrow q\bar{q}\tilde{t} )</td>
<td>0, 3, ( \tilde{t} \text{ tri-jet} )</td>
<td>96.1</td>
<td>( \tilde{t} \text{ f.f. (sign)} )</td>
</tr>
<tr>
<td>0. ( \tilde{g} \rightarrow q\bar{q}\tilde{b} )</td>
<td>0, 3, ( \tilde{b} \text{ tri-jet} )</td>
<td>96.1</td>
<td>( \tilde{b} \text{ f.f. (sign)} )</td>
</tr>
</tbody>
</table>

4 Searches with full Run-2 dataset
Search for long lived Top Squarks (Full Run-2 dataset)

What if SUSY particles are long lived?

• New search for long-lived top squarks
• For small couplings $\lambda$, lifetime of top squark is long enough to give rise to displaced vertex (DV)

Search for heavy displaced vertex (DV) + muon
Simulated Signal Event
Top Squark Pair Production

\[ m(\tilde{t}) = 1.5 \text{ TeV}, \ \tau(\tilde{t}) = 1 \text{ ns} \]

\[ \tilde{t} \rightarrow \mu j \]
Looking to the Future

We are here

- New ATLAS Inner Tracker (ITk)
- LAr Calorimeter trigger electronics

- sTGC for Muon New Small Wheel
- LAr Calorimeter readout electronics

See Jesse Heilman’s talk
Expected integrated luminosity of LHC and HL-LHC

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\mathcal{L}_{\text{inst}}$ [$10^{34} \text{cm}^{-2} \text{s}^{-1}$]</th>
<th>$\langle \mu \rangle$</th>
<th>$\int \mathcal{L}$ per year [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>5</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>Ultimate</td>
<td>7.5</td>
<td>200</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

Target is 3000 fb$^{-1}$ possibly up to 4000 fb$^{-1}$
New ATLAS Inner Tracker (ITk) for the HL-LHC

Challenges for the ITk upgrade:

- Higher occupancies and pile-up ➔ Finer segmentation
- Higher particle fluences ➔ Increase radiation tolerance

Canada is building approximately 2.5 endcap disks

- 6 endcap discs
- ~180 m² of silicon
- 4 barrel cylinders

New Inner Tracker: 80M ➔ ~5G channels

Rapidity coverage: |η| < 2.5 ➔ |η| < 4
HL-LHC inclusive Higgs sample will be 23 times larger (30 times for 4000 fb\(^{-1}\)) than that of the full Run-2 dataset (~140 fb\(^{-1}\) at 13 TeV)

With 3000 fb\(^{-1}\): **190 million H** and **120 thousand HH** (ggF) will be produced

Target is 3000 fb\(^{-1}\) possibly up to 4000 fb\(^{-1}\)
Higgs Boson Coupling Measurements at the HL-LHC

**ATLAS** Preliminary

Projection from Run 2 data

$\sqrt{s}=14$TeV, 3000 fb$^{-1}$

- Combined 68% CL
- Combined 95% CL

SM prediction
Higgs Boson Coupling Measurements at the HL-LHC

Measurement of the couplings properties of the Higgs boson - in this case assuming no BSM in the Higgs width

### ATLAS - CMS Run 1 combination

<table>
<thead>
<tr>
<th>Coupling</th>
<th>ATLAS Run 2</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\gamma$</td>
<td>9%</td>
<td>1.8%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>8.6%</td>
<td>1.7%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>7.2%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>11%</td>
<td>2.5%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>14%</td>
<td>3.4%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>18%</td>
<td>3.7%</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>14%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

### ATLAS and CMS HL-LHC Projection

<table>
<thead>
<tr>
<th>Coupling</th>
<th>ATLAS-CONF-2019-04</th>
<th>HL-LHC YR 1902.00134</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\gamma$</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>1.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>1.5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>2.5%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>3.4%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>3.7%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>1.9%</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

Uncertainty [%]

<table>
<thead>
<tr>
<th></th>
<th>Tot</th>
<th>Stat</th>
<th>Exp</th>
<th>Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\gamma$</td>
<td>1.8</td>
<td>0.8</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>1.7</td>
<td>0.8</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>1.5</td>
<td>0.7</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>2.5</td>
<td>0.9</td>
<td>0.8</td>
<td>2.1</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>3.4</td>
<td>0.9</td>
<td>1.1</td>
<td>3.1</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>3.7</td>
<td>1.3</td>
<td>1.3</td>
<td>3.2</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>1.9</td>
<td>0.9</td>
<td>0.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Improved TH and PDF uncertainties by a factor of 2 w.r.t. current (motivated from current PDF studies and current TH uncertainties assumptions)
SM Higgs pair production is small (33.5 fb at 13 TeV)
• Destructive interference between two diagrams
• Allows to directly probe Higgs self-coupling $\lambda$
• Combination of several channels and lots of data (+MVAs)
Higgs Boson Pair Production (Di-Higgs) \(\rightarrow\) HL-LHC Prospects

Combination of ATLAS and CMS data (projection)

- ATLAS includes \(bbbb, bb\tau\tau\) and \(bb\gamma\gamma\)
- CMS includes \(bbbb, bb\tau\tau, bb\gamma\gamma, bbVV\) (2-lepton) and \(bbZZ\) (4-lepton)

<table>
<thead>
<tr>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td><strong>CMS</strong></td>
</tr>
<tr>
<td>(HH \rightarrow bbb)</td>
<td>1.4</td>
</tr>
<tr>
<td>(HH \rightarrow bb\tau\tau)</td>
<td>2.5</td>
</tr>
<tr>
<td>(HH \rightarrow bb\gamma\gamma)</td>
<td>2.1</td>
</tr>
<tr>
<td>(HH \rightarrow bbVV) ((ll\nu\nu))</td>
<td>-</td>
</tr>
<tr>
<td>(HH \rightarrow bbZZ) ((4l))</td>
<td>-</td>
</tr>
<tr>
<td><strong>combined</strong></td>
<td>3.5</td>
</tr>
</tbody>
</table>

\[\text{Combined} \quad 4.5 \quad \text{Combined} \quad 4.0\]

- Expected **HH signal significance** \(4\sigma\)
- Expected precision on signal strength \(\mu_{HH}\) is estimate to be \(\Delta \mu_{HH} = 25\%\)

Scale HL-LHC (14 TeV) to HE-LHC (27 TeV)
- Cross section \(x4\)
- Dataset size 15 ab\(^{-1}\)

Note: Not all projected channels optimized yet to measure \(\kappa_\lambda\)

- \(0.5 < \kappa_\lambda < 1.5\) (incl sys) at HL-LHC (50%)
- \(0.8 < \kappa_\lambda < 1.2\) (incl sys) at HE-LHC (20%)
Going to 14 TeV proton–proton centre-of-mass energy

14 TeV / 13 TeV inclusive pp cross-section ratio

- Minimum bias: 1.02
- W: 1.08
- Z: 1.09
- ZZ: 1.11
- t (s-channel): 1.10
- t (t-channel): 1.14
- Wt: 1.18
- WH: 1.10
- H (ggF): 1.13
- H (VBF): 1.13
- HH: 1.19
- tt: 1.18
- ttZ: 1.20
- ttH: 1.21
- stop pair (0.9 TeV): 1.37
- gluino pair (2.0 TeV): 1.73
- Z' SSM (4 TeV): 1.40
- q* (6 Tev): 2.0
- QBH (9 TeV, n=6): 5.3

Modest increase in cross sections for Higgs boson production, larger for BSM
Particle physics at the energy frontier is extensively probing TeV scale physics.

Contrary to the Fermi (electroweak) scale, we do not know the next new physics scale. Naturalness suggests $\mathcal{O}(\text{TeV})$ but it is challenged by LHC results.

We have observed the Higgs boson – none of its properties can be taken for granted.

Nice progress during Run-2 – detailed measurements is the responsibility of the LHC.

Run-3 promises more interesting advances (2nd generation Yukawas, BSM, etc).

Looking into the future

Upgrades for the HL-LHC are underway

HL-LHC Higgs physics shows impressive goals

Leave no stone unturned (e.g. lifetime frontier, unconventional signatures, etc)

More new ideas are needed to further push the frontiers of particle physics at LHC.
More Information:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

Thank you!