Searches for squarks and gluinos with the ATLAS detector

WIN2019
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Introduction

- Supersymmetry at weak scale motivated by:
  - unification of forces
  - hierarchy problem
  - nature of Dark Matter
- Potential to discover partners for all Standard Model (SM) particles
- Light 3rd generation squarks motivated by naturalness
  - motivates also not too heavy gluinos
- High cross sections of strong production (depending on mass)

![Graph showing cross-sections for different SUSY processes](image)

3rd generation squarks
(stop/sbottom)

“strong production”: gluinos, 1st & 2nd generation squarks

Based on calculations in EPJC 74 (2014) 12
The ATLAS detector

- ATLAS is a multi-layer general-purpose detector at the LHC
- LHC Run 2 finished in 2018
- 139 fb\(^{-1}\) of proton-proton collisions at a center-of-mass energy of 13 TeV ready to be analysed
Object reconstruction

"SUSY candidate"

Typical SUSY signatures:

- hadronic jets initiated by quarks or gluons; $b$-jets can be identified due to long lifetime of B-mesons
- sometimes leptons (only electrons and muons in this presentation)
- missing transverse energy ($E_T^{\text{miss}}$) as indicator for invisible particles
### Strong production search program

<table>
<thead>
<tr>
<th>Channel</th>
<th>Published</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>0l + 2-4j</td>
<td>PRD 97 (2018) 112001</td>
<td>36 fb⁻¹</td>
</tr>
<tr>
<td>0l + 7-11j</td>
<td>JHEP12 (2017) 034</td>
<td>36 fb⁻¹</td>
</tr>
<tr>
<td><strong>multi-b</strong></td>
<td>ATLAS-CONF-2018-041</td>
<td>80 fb⁻¹</td>
</tr>
<tr>
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</tr>
<tr>
<td>SFOS 2l</td>
<td>EPJC 78 (2018) 625</td>
<td>36 fb⁻¹</td>
</tr>
<tr>
<td><strong>SS/3L</strong></td>
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</tr>
<tr>
<td>γ + jets</td>
<td>PRD 97 (2018) 092006</td>
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</tr>
<tr>
<td>τ + jets</td>
<td>PRD 99 (2019) 012009</td>
<td>36 fb⁻¹</td>
</tr>
</tbody>
</table>

+ more dedicated searches for R-parity violating scenarios (not in this presentation)
+ dedicated search program for 3\(^{rd}\) generation squarks (more later)
Strong multi-b

Decay channels:
\[ \tilde{g} \rightarrow t \bar{t} + \tilde{\chi}^0_1 \] via off-shell/on-shell
\[ \tilde{g} \rightarrow b \bar{b} + \tilde{\chi}^0_1 \] 3rd generation squark
\[ \tilde{g} \rightarrow t \bar{b} + \tilde{\chi}^0_1 \] via 3rd gen. squark & chargino

Final state:
- \( \geq 3 \) \( b \)-jets, up to 12 jets, \( E_T^{\text{miss}} \)
- 0 or 1 lepton

Dominant background: \( t \bar{t} \)

Cut-and-count and multi-bin signal regions dependent on jet and lepton multiplicity

1-lepton control regions with low \( m_T \) to normalise background to data (background-only fit), validation regions close to signal regions as cross check

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

Events passing the 1-l preselection
Strong multi-b

ATLAS-CONF-2018-041

on-shell stop
Gtb interpretation is new!

- No excess observed
- Interpretation based on different assumptions for $\tilde{g}, \tilde{t}/\tilde{b}, \tilde{\chi}_1^0, \tilde{\chi}_1^\pm$
- Exclusion limits based on multi-bin signal regions
Decay channels:
\[
\tilde{b}_1 \rightarrow t \ W + \tilde{\chi}_1^0 \\
\tilde{g} \rightarrow t \ \bar{t} + \tilde{\chi}_1^0 \\
\tilde{g} \rightarrow q \ \bar{q} \ W \ Z + \tilde{\chi}_1^0
\]

Final state:
- \( \geq 2 \) same-sign leptons, \( \geq 6 \) jets, \((E_T^{\text{miss}})\)

Challenging backgrounds: \( WZ + \text{jets}, t \ \bar{t} + W / Z \)
- high theory uncertainties

Data-driven estimates for
- fake/non-prompt leptons: matrix method
- charge-flip electrons: weighted OS data
More channels:

- **R-parity violating:**
  
  \[
  \tilde{g} \rightarrow t \bar{t} \tilde{\chi}^0_{1}, \tilde{\chi}^0_{1} \rightarrow 3q
  \]
  
  \[
  \tilde{g} \rightarrow q \bar{q} \tilde{\chi}^0_{1}, \tilde{\chi}^0_{1} \rightarrow qq' l
  \]
  
  \[
  \tilde{g} \rightarrow t \tilde{t}^*_{1}, \tilde{t}^*_{1} \rightarrow qq'
  \]

- **3L:**
  
  \[
  \tilde{t} \rightarrow t W^\pm (W^*) \tilde{\chi}^0_{1}
  \]

---

<table>
<thead>
<tr>
<th>SR</th>
<th>(N_{t})</th>
<th>(N_{b,jets})</th>
<th>(N_{jets})</th>
<th>(p_T^{jets} [GeV])</th>
<th>(E_{miss}^{miss} [GeV])</th>
<th>(m_{eff} [GeV])</th>
<th>(E_{miss}^{miss} / m_{eff})</th>
<th>Targeted Model</th>
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</thead>
<tbody>
<tr>
<td>Rpc2L1b</td>
<td>(\geq 2)</td>
<td>(\geq 1)</td>
<td>(\geq 6)</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>(&gt; 0.25)</td>
<td>(\tilde{b}<em>1 \rightarrow t \tilde{\chi}^-</em>{1})</td>
</tr>
<tr>
<td>Rpc2L2b</td>
<td>(\geq 2)</td>
<td>(\geq 2)</td>
<td>(\geq 6)</td>
<td>25</td>
<td>(&gt; 300)</td>
<td>(&gt; 1400)</td>
<td>(&gt; 0.14)</td>
<td>(\tilde{b}<em>1 \rightarrow t \tilde{\chi}^-</em>{1}) (\tilde{g} \rightarrow t \tilde{\chi}^0_{1} / t \tilde{b} \tilde{\chi}^-_{1})</td>
</tr>
<tr>
<td>Rpc2L0b</td>
<td>(\geq 2)</td>
<td>(= 0)</td>
<td>(\geq 6)</td>
<td>40</td>
<td>(&gt; 200)</td>
<td>(&gt; 1000)</td>
<td>(&gt; 0.2)</td>
<td>(\tilde{g} \rightarrow q \bar{q}' WZ \tilde{\chi}^0_{1})</td>
</tr>
<tr>
<td>Rpc3LSS1b</td>
<td>(\geq 3) (SS)</td>
<td>(\geq 1)</td>
<td>no cut but veto (81 &lt; m_{e^+ e^-} &lt; 101) GeV</td>
<td>(&gt; 0.14)</td>
<td>(\tilde{t}<em>1 \rightarrow t W^\pm (W^*) \tilde{\chi}^0</em>{1})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rpv2L</td>
<td>(\geq 2)</td>
<td>(\geq 0)</td>
<td>(\geq 6)</td>
<td>40</td>
<td>-</td>
<td>(&gt; 2600)</td>
<td>-</td>
<td>(\tilde{g} \rightarrow t \tilde{t}^<em>_{1}, \tilde{t}^</em><em>{1} \rightarrow qq' (\chi'' \neq 0)) (\tilde{g} \rightarrow q q \tilde{\chi}^0</em>{1}, \tilde{\chi}^0_{1} \rightarrow qq' \ell (\chi' \neq 0)) (\tilde{g} \rightarrow t \tilde{\chi}^0_{1} \tilde{\chi}^-_{1} \rightarrow 3q (\chi'' \neq 0))</td>
</tr>
</tbody>
</table>
ATLAS-CONF-2019-015

- No excess observed
- Limits for multiple scenarios including also 3rd generation squarks
New updated summary plots coming soon!
All results and summary plots on:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
### 3\textsuperscript{rd} generation search program

<table>
<thead>
<tr>
<th>Channel</th>
<th>Published</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop 0l</td>
<td>JHEP 12 (2017) 085</td>
<td>36 fb(^{-1})</td>
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<tr>
<td>Stop 1l</td>
<td>JHEP 06 (2018) 108 / ATLAS-CONF-2019-017</td>
<td>36 fb(^{-1}) / 139 fb(^{-1})</td>
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<tr>
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<td>PRD 97 (2018) 032003</td>
<td>36 fb(^{-1})</td>
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<tr>
<td>Stop to charm</td>
<td>JHEP 09 (2018) 050</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Stop to stau</td>
<td>PRD 98 (2018) 032008</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Stop to Z/h</td>
<td>ATLAS-CONF-2019-016</td>
<td>139 fb(^{-1})</td>
</tr>
<tr>
<td>Sbottom</td>
<td>EPJC 76 (2016) 547</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Sbottom with h</td>
<td>ATLAS-CONF-2019-011</td>
<td>139 fb(^{-1})</td>
</tr>
<tr>
<td>DM + HF</td>
<td>EPJC 78 (2018) 18</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>tt spin correlation</td>
<td>arXiv:1903.07570</td>
<td>36 fb(^{-1})</td>
</tr>
</tbody>
</table>

+ more dedicated searches for R-parity violating scenarios (not in this presentation)
Spin correlation

- Challenging region $m(\tilde{t}) \sim m(t)$:
  - stop pair hardly distinguishable from top pair
- Top lifetime shorter than decorrelation time
  - spin correlated for top pair but not for decay products of stop pair
  - make use of angular variables between leptons

arXiv:1903.07570

Graphs showing data and theoretical predictions for $m(\tilde{t})$ and $m(t)$, with comparisons to background and expected limits.
Sbottom with Higgs

ATLAS-CONF-2019-011

- Two scenarios considered:
  - fixed $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV
  - fixed $m(\tilde{\chi}_1^0) = 60$ GeV
- Final state: $\geq 4$ jets, $\geq 3$ $b$-jets, $E_T^{\text{miss}}$
- Methods:
  - associate $b$-jets to Higgs candidates
  - if not possible, use $E_T^{\text{miss}}$ significance:
    new method calculating significance of $E_T^{\text{miss}}$ with uncertainties of all objects:
    ATLAS-CONF-2018-038
- Main backgrounds: $t\bar{t}$, $Z +$ jets
  - normalised to data in 1-lepton / 2-lepton control regions
Sbottom with Higgs

- 3 signal regions
  - SRA: “bulk” region, bins in $m_{\text{eff}}$
  - SRB: ISR selection
  - SRC: bins in $E_T^{\text{miss}}$ significance
- No excess observed
- New exclusion limits for both scenarios
Stop to Z/h

- Two scenarios considered:
  - Final state:
    - ≥ 3 leptons, 2 same-flavor opposite sign with $m_{ll} \sim m(Z)$
    - ≥ 3 jets, $E_T^{miss}$
  - 2 signal regions for each scenario
    - targeting high/low $\Delta m(\chi_2^0, \tilde{\chi}_1^0)$ and $\Delta m(\tilde{t}_2, \tilde{\chi}_1^0)$
  - Main backgrounds: $t\bar{t} + Z$, multi-boson
    - normalised to data in low-$E_T^{miss}$ control regions
    - leading systematic uncertainty
  - Fake and non-prompt lepton estimated with matrix method
  - Validation regions for all backgrounds
Stop to Z/h

- Multi-bin signal regions
- No excess found
- New limits in both scenarios
3-body stop

- Targeting region $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$
- Final state:
  - $\geq 4$ jets, $\geq 1$ $b$-jet, $E_T^{\text{miss}}$
  - 1 lepton
- Neural network (NN) design to distinguish from background:
  - jet 4-vectors + 12 other variables
  - trained with truth-smeared signal samples for larger statistics
- Main background: $t\bar{t}$ (di-leptonic with missed lepton)
- Control region for background normalisation and validation region both orthogonal in NN discriminator
3-body stop

No excess observed

10-bin fit in SR

Large improvement of exclusion limits in $\tilde{t}_1 - \tilde{\chi}_0^1$ plane
3rd generation summary plots

New updated summary plots coming soon!
All results and summary plots on:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
Conclusion

- Broad search program for squarks and gluinos @ATLAS
  First results with full Run 2 dataset public!
  - updated results of previous searches
  - new scenarios in difficult phase space / longer decay-chains considered
  - new methods used
- No excess above Standard Model expectation observed
- New exclusion limits
- In simplified models, e.g.:
  - gluinos (into top/bottom pair) up to 2.2 TeV
  - sbottoms (with Higgs) up to 1.45 TeV
  - stops (3-body decay) up to 720 GeV
- And more incoming, stay tuned!
### Dominant systematic uncertainties varying in each signal bin:

- **Jet energy scale**: 0.5% - 15%
- **Jet energy resolution**: 1% - 19%
- **b-tagging efficiency / mis-tagging rate**: 1% - 7%
- **single-top modelling uncertainties**: 4-35%
- **W/Z+jets factorisation and renormalisation**: 0-50%
Strong multi-b – exclusions

- Different visualisation methods in multi-parameter phase space
Systematics:
- cross section uncertainty of $VV, t \bar{t} + W/Z/H$ processes
- factorisation and renormalisation scales from generator-provided up/down weights
- modelling uncertainties obtained by comparing with alternative generators/same generator with different event tune
- overall: 35-45% $t \bar{t} + W$, 25-45% $t \bar{t} + Z$, 40-45% $WZ$

Matrix method:
- F/NP leptons usually filtered out by lepton isolation criteria
- Loosen criteria, measure how many leptons pass this and the nominal (tight) lepton selection
- Obtain probabilities from MC events
- 30-80% uncertainty on probability

$$
\begin{pmatrix}
N^u \\
N^{\bar{u}} \\
N^t \\
N^{\bar{t}}
\end{pmatrix} =
\begin{pmatrix}
 r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\
 r_1 \bar{r}_2 & r_1 \bar{f}_2 & \bar{f}_1 r_2 & \bar{f}_1 f_2 \\
 \bar{r}_1 r_2 & \bar{r}_1 f_2 & \bar{f}_1 r_2 & \bar{f}_1 f_2 \\
 \bar{r}_1 \bar{r}_2 & \bar{r}_1 \bar{f}_2 & \bar{f}_1 \bar{r}_2 & \bar{f}_1 \bar{f}_2
\end{pmatrix}
\begin{pmatrix}
 N^{tt} / (r_1 r_2) \\
 N^{t\bar{t}} / (r_1 f_2) \\
 N^{tt} / (f_1 r_2) \\
 N^{t\bar{t}} / (f_1 f_2)
\end{pmatrix}
$$

$t$: passes tight criteria, $\bar{t}$: does not pass tight criteria
$r$: real lepton, $f$: fake lepton
Spin correlation

- Selection:
  - inclusive: 2 OFOS leptons, ≥ 2 jets, ≥ 1 b-jet

- Unfolding procedure: Background-subtracted data are corrected for detector acceptance and resolution effects.

- Systematic uncertainties:
  - $t\,\bar{t}$ modelling: matrix-element generator, hadronisation and parton-shower model, amount of ISR/FSR, choice of PDF set
  - normalisation of other backgrounds
  - only small detector uncertainties
Sbottom with Higgs

- Decay hierarchy predicted in MSSM, when: is lightest neutral boson, LSP is bino-like, $\tilde{\chi}_2^0$ is wino-higgsino mixture

- “bulk” region
  - all objects high $p_T$ and resolved
  - *max-min* method: remove b-jets most likely from sbottoms (pair with max $\Delta R$), then find Higgs candidate (pair with min $\Delta R$)
  - use lower bound on invariant mass of Higgs candidate

- “compressed” region, small $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$, $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV
  - soft b-jets from sbottoms
  - use ISR-like selection
  - reconstruct two Higgs candidates with high $\Delta R$
  - use mass window around Higgs mass for avg. cand. mass

- “compressed” region, small $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 60$ GeV
  - soft b-jets from sbottoms
  - require lower b-multiplicity
  - visible and invisible hemisphere
  - more $Z+\text{jets}$ background
Sbottom with Higgs

- Dominating systematic uncertainties:
  - experimental: jet energy scale & jet energy resolution, \( b \)-tagging efficiency and mis-tagging (dominant in SRC)
  - theoretical: top quark pair and Z+jets modelling

<table>
<thead>
<tr>
<th>Region</th>
<th>SRA</th>
<th>SRB</th>
<th>SRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background expectation</td>
<td>17.1</td>
<td>3.3</td>
<td>37.9</td>
</tr>
<tr>
<td>Total background error</td>
<td>2.8 (16%)</td>
<td>0.9 (27%)</td>
<td>6.2 (16%)</td>
</tr>
<tr>
<td>Systematic, experimental</td>
<td>1.4 (8%)</td>
<td>0.3 (10%)</td>
<td>3.0 (8%)</td>
</tr>
<tr>
<td>Systematic, theoretical</td>
<td>2.3 (13%)</td>
<td>0.6 (18%)</td>
<td>3.2 (8%)</td>
</tr>
<tr>
<td>Statistical, MC samples</td>
<td>0.7 (4%)</td>
<td>0.4 (12%)</td>
<td>2.0 (5%)</td>
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</tbody>
</table>
Stop to Z/h

<table>
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<tr>
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<th>SR_{2A}</th>
<th>SR_{1B}</th>
<th>SR_{1A}</th>
<th>SR_{2B}</th>
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<tbody>
<tr>
<td>Total systematic uncertainty (%)</td>
<td>13</td>
<td>13</td>
<td>29</td>
<td>15</td>
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<tr>
<td>Diboson theoretical uncertainties (%)</td>
<td>2</td>
<td>3</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>ttZ theoretical uncertainties (%)</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Other theoretical uncertainties (%)</td>
<td>6</td>
<td>9</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>MC and FNP statistical uncertainties (%)</td>
<td>6</td>
<td>&lt;1</td>
<td>14</td>
<td>7</td>
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<tr>
<td>Diboson fitted normalisation (%)</td>
<td>2</td>
<td>3</td>
<td>11</td>
<td>6</td>
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<tr>
<td>ttZ fitted normalisation (%)</td>
<td>5</td>
<td>9</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Fake/non-prompt leptons efficiency (%)</td>
<td>4</td>
<td>&lt;1</td>
<td>14</td>
<td>2</td>
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<tr>
<td>Jet energy resolution (%)</td>
<td>4</td>
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<td>4</td>
<td>&lt;1</td>
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<tr>
<td>b-tagging (%)</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>
3-body stop

Jet 4-vectors (up to 8) \rightarrow \text{Recurrent neural network (RNN)}

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>Missing transverse energy</td>
</tr>
<tr>
<td>$\phi(p_T^{\text{miss}})$</td>
<td>Azimuthal angle of the $p_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$m_T$</td>
<td>Transverse mass</td>
</tr>
<tr>
<td>$\Delta \phi(l, p_T^{\text{miss}})$</td>
<td>Azimuthal angle between $p_T^{\text{miss}}$ and lepton</td>
</tr>
<tr>
<td>$m_{bl}$</td>
<td>Invariant mass of leading b-tagged jet and lepton</td>
</tr>
<tr>
<td>$p_{T_{bl}}$</td>
<td>Transverse momentum of the leading b-tagged jet</td>
</tr>
<tr>
<td>$n_{\text{jet}}$</td>
<td>Jet multiplicity</td>
</tr>
<tr>
<td>$n_{b-\text{tag}}$</td>
<td>Number of b-tagged jets ( @ 77% )</td>
</tr>
<tr>
<td>$p_T(\ell)$</td>
<td>Transverse momentum of lepton</td>
</tr>
<tr>
<td>$\eta(\ell)$</td>
<td>Pseudorapidity of lepton</td>
</tr>
<tr>
<td>$\phi(\ell)$</td>
<td>Azimuthal angle of lepton</td>
</tr>
<tr>
<td>$E(\ell)$</td>
<td>Energy of lepton</td>
</tr>
</tbody>
</table>

Dominant systematic uncertainty: \( t \bar{t} \) hadronisation/fragmentation (16\%)
## MC samples

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator + fragmentation/hadronization</th>
<th>Tune</th>
<th>PDF set</th>
<th>Cross-section order</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G\bar{b}/G\bar{t}/G\bar{t}$</td>
<td>MadGraph5_aMC@NLO-2.2.2 + Pythia v8.186</td>
<td>A14</td>
<td>NNPDF2.3</td>
<td>NLO+NLL [30,31,32,33,34,35]</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>Powheg-Box v2 + Pythia-8.230</td>
<td>A14</td>
<td>NNPDF3.0</td>
<td>NNLO+NNLL [36]</td>
</tr>
<tr>
<td>Single top</td>
<td>Powheg-Box v1 (v2) + Pythia-6.428 (-8.230)</td>
<td>PERUGIA2012</td>
<td>CT10</td>
<td>NNLO+NNLL [37,38,39]</td>
</tr>
<tr>
<td>Wt-channel (s/t)</td>
<td>MadGraph5_aMC@NLO-2.2.2 + Pythia-8.186</td>
<td>A14</td>
<td>NNPDF2.3</td>
<td>NLO [40]</td>
</tr>
<tr>
<td>$ttW/ttZ$</td>
<td>MadGraph5_aMC@NLO-2.2.2 + Pythia-8.186</td>
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<td>NNPDF2.3</td>
<td>NLO [40]</td>
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<td>4-tops</td>
<td>MadGraph2.2.2 + Pythia-8.186</td>
<td>A14</td>
<td>NNPDF2.3</td>
<td>NLO [40]</td>
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<tr>
<td>$ttH$</td>
<td>MadGraph5_aMC@NLO-2.2.1 + HERWIG++-2.7.1</td>
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<td>CT10</td>
<td>NLO [41]</td>
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<tr>
<td>Dibosons</td>
<td>Sherpa-2.2.1</td>
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<td>NNPDF3.0</td>
<td>NLO [42,43]</td>
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<td>$WW$, $WZ$, $ZZ$</td>
<td>Sherpa-2.2.1</td>
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<td>NNPDF3.0</td>
<td>NNLO [44]</td>
</tr>
<tr>
<td>$W/Z+$jets</td>
<td>Sherpa-2.2.1</td>
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<td>NNPDF3.0</td>
<td>NNLO [44]</td>
</tr>
</tbody>
</table>

### Table: Physics processes

<table>
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<tr>
<th>Physics process</th>
<th>Generator</th>
<th>Parton shower</th>
<th>Cross-section normalisation</th>
<th>PDF set</th>
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<tr>
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<td>Pythia 8.212 [32]</td>
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<td>A14 [39]</td>
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<tr>
<td>$ttZ$, $ttW$</td>
<td>MG5_aMC@NLO 2.3.3</td>
<td>Pythia 8.210</td>
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<td>Dibosons</td>
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<td>Generator NLO</td>
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<td>Sherpa default</td>
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<td>$t\bar{t}$</td>
<td>Powheg v2 [42]</td>
<td>Pythia 8.186</td>
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<tr>
<td>$W\bar{h}$, $Zh$</td>
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<td>Pythia 8.186</td>
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<td>$t\bar{t}WW$, $t\bar{t}t$</td>
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<td>Pythia 8.186</td>
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<tr>
<td>$t\bar{t}t$</td>
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<td>LO</td>
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<tr>
<td>$t\bar{t}Z$</td>
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<tr>
<td>Tribosons</td>
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<td>Sherpa 2.2.2</td>
<td>Generator NLO</td>
<td>NNPDF2.3LO</td>
<td>Sherpa default</td>
</tr>
</tbody>
</table>

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**Notes:**

- squarks and gluinos @ATLAS
- strong multi-b
- stop with Z
Detector uncertainties

- Jet energy scale (top left), jet energy resolution (top right) and $b$-tagging efficiencies.