Physics Highlights of ATLAS and ALICE

$t\bar{t}H(\rightarrow \gamma\gamma)$ candidate

Xe-Xe collision events

Tancredi Carli (CERN)
LHC performance and data-set

2015-2017 data-set:
- L = 80 fb\(^{-1}\) recorded
- 13 public results

2015-2018 data-set:
- L = 108 fb\(^{-1}\) recorded

2015-2016 data-set:
- L = 36 fb\(^{-1}\)
- 88 publications on arXiv

Data taking efficiency: \(~93\%\)

We are about a factor of 2 above LHC design luminosity.
Expect L = 140 - 150 fb\(^{-1}\) for full 2015-2018 data-set.
Challenge to cope with pile-up interactions

Interactions per bunch per crossing:

Large number of additional interactions (pile-up) cause performance degradation. Powerful pile-up mitigation techniques developed. The performance loss is well described by Monte Carlo simulation.
Example: $H \rightarrow ZZ \rightarrow 4l$ channel

Higgs boson discovered in July 2012 at LHC.
Is the new particle the SM Higgs boson? → measure its properties!

Example for high purity but low branching fraction Higgs decay to four leptons $H \rightarrow ZZ \rightarrow 4l$:

$L = 4.8 \text{ fb}^{-1}$ and $5.8 \text{ fb}^{-1}$ at 7 and 8 TeV

$L = 80 \text{ fb}^{-1}$ at 13 TeV

13 events $120 < m_{4l} < 130 \text{ GeV}$

195 events for $115 < m_{4l} < 130 \text{ GeV}$


Nice peak of new fundamental scalar!
Yukawa coupling with new scalar (completely new interaction type) $ttH$, $H \rightarrow bb$ and $H \rightarrow \tau\tau$ are important!

**Higgs sector**

Gauge boson interaction with new scalar (new for scalar, but known for fermions)

Higgs potential ($\mu^2 \phi^2 + \lambda \phi^4$) (to be explored by High Lumi-LHC)

Higgs measurements at LHC test new part of SM

Describes everything experimentally confirmed before 2012

Inspired by G Salam LHCP2018
Gauge boson and Yukawa fermion coupling

Interaction with gauge bosons:

Earlier 7 and 8 TeV results:
At 7 and 8 TeV Higgs boson discovered.
Main channels: $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$

Yukawa coupling to fermions:

Recent 13 TeV results:

Only glimpse at 7 and 8 TeV (2012)
ATLAS/CMS combined $H \to \tau\tau$:
5.5σ (5.0σ) obs (exp) for 7/8/13 TeV

JHEP 08 (2016) 045

Example of mass in 1/13 signal categories
Differential cross-section using gauge boson decays

Higgs decays to gauge bosons used for differential cross-section measurements.

4 lepton channel

Differential cross-section becoming more and more precise with increasing statistics.
Data well described by recent SM predictions.

2 photon channel

New

Differential cross-section becoming more and more precise with increasing statistics.
Data well described by recent SM predictions.
Associated Higgs top quark pair production

Higgs production:

Gluon-gluon fusion (ggF)  Associated ttH production (ttH)

Yukawa coupling:

\[ y_t \approx \frac{v}{m_t \sqrt{2}} \approx 1 \]

Large top mass \( \rightarrow \) Higgs coupling is strong. Top Yukawa \( y_t \) coupling is in loop for ggF (might contain BSM contribution). but ttH production gives direct constraint on \( y_t \)

\[ \sigma(ttH) \sim 1\% \sigma(H) \]

Branching fraction:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow bb )</td>
<td>58%</td>
</tr>
<tr>
<td>( H \rightarrow WW^* )</td>
<td>21%</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>6%</td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* )</td>
<td>2.6%</td>
</tr>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

For \( H \rightarrow WW \) and \( H \rightarrow ZZ \) only leptonic decays

Evidence in December 2017 (36 fb\(^{-1}\)):

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multilepton</td>
<td>4.1(\sigma)</td>
</tr>
<tr>
<td>( H \rightarrow bb )</td>
<td>1.4(\sigma)</td>
</tr>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>0.9(\sigma)</td>
</tr>
<tr>
<td>( H \rightarrow 4\ell )</td>
<td>---</td>
</tr>
<tr>
<td>Combined</td>
<td>4.2(\sigma)</td>
</tr>
</tbody>
</table>

Observation of ttH production

June 2018 update: ttH(→γγ) and ttH(ZZ→4l) with 80 fb⁻¹

**ttH(→γγ):**

**ATLAS**

- √s = 13 TeV, 80 fb⁻¹
- m_t = 125.09 GeV

**Di-photon mass m_{γγ} [GeV]**

All channels combined:

**ATLAS**

- √s = 13 TeV, 36.1 – 80 fb⁻¹

**Analysis** | Integrated luminosity [fb⁻¹] | Expected significance | Observed significance
---|---|---|---
H → γγ | 79.8 | 3.7 σ | 4.1 σ
H → multilepton | 36.1 | 2.8 σ | 4.1 σ
H → bb | 36.1 | 1.6 σ | 1.4 σ
H → ZZ* → 4l | 79.8 | 1.2 σ | 0 σ
Combined (13 TeV) | 36.1–79.8 | 4.9 σ | 5.8 σ
Combined (7, 8, 13 TeV) | 4.5, 20.3, 36.1–79.8 | 5.1 σ | 6.3 σ

Direct observation of top Higgs coupling. Confirmation of Yukawa coupling to fermions.
June 2018 update: $\text{ttH}(\to \gamma\gamma)$ and $\text{ttH}(\to ZZ\to 4l)$ with $80 \text{ fb}^{-1}$

**Inclusive ttH production cross-section**

![Graph showing inclusive ttH production cross-section](ATLAS-CONF-2018-031)

- **ATLAS**
- **Theory (NLO QCD + NLO EW)**
- **Total**
- **Combined data**
- **Stat. only**

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

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

**Already 20% precision!**

**Gluon-gluon fusion**

**Effective coupling** $\kappa_{\text{gluon}} / \kappa_{\text{top}} = 1.09 \pm 0.14$

Consistent with Higgs boson coupling as in SM. Constrains BSM contributions.
Associated VH production and $H \rightarrow bb$

$\rightarrow H \rightarrow bb$ highest branching ratio: $Br=58\%$

- $Br(H \rightarrow bb)$ constrains invisible Higgs decays
- Tests Higgs Yukawa coupling to fermions

Analysis with large background:
- Use high-$p_T$ boson region
- Multi-variate analysis in 0, 1 and 2 lepton channels
- Dijet mass analysis as cross-check

Example: One input to di-jet mass analysis global fit
Observation of H → bb

Di-jet mass analysis:

Main multi-variate analysis:

Observation of Higgs decay to beauty quarks!

VH alone: 4.9σ (4.3σ) obs (exp) (13 TeV)

Combined (7,8,13 TeV) VBF, ttH, VH: 5.4σ (5.5σ) obs (exp)
Higgs coupling measurements

Key feature:
Higgs coupling depends on the particle mass

Interaction with gauge bosons:
H → ZZ\(^*\)
Well established in run-1
H → WW\(^*\)
6.3 (5.2) σ obs (exp) (run-2 only)

Yukawa coupling to fermions:
Top-quark: \( ttH \)
6.3σ (5.1σ) obs (exp)

Beauty-quark \( H \rightarrow bb \):
5.4σ (5.5σ) obs (exp)

Tau-lepton: \( H \rightarrow \tau \tau \)
6.4σ (5.4σ) obs (exp)

Muon \( H \rightarrow \mu \mu \):
\[ \frac{\sigma_{\text{limit}}}{\sigma_{\text{SM}}} < 2.1 \text{ (obs)} \]

Charm-quark: \( H \rightarrow cc \):
\[ \frac{\sigma_{\text{limit}}}{\sigma_{\text{SM}}} < 104 \text{ (obs)} \]

All couplings to high mass particles measured. Next challenge: muon, charm-quark...
+ detailed cross-section measurements!
Higgs production modes

Associated WH or ZH production (VH)  Vector-boson fusion (VBF)  Associated ttH production (ttH)

Gluon-gluon fusion (ggF) observed since 2012 and used for precision measurements (≈10%).

Observed all major Higgs production modes! Consistent with SM.
SM Di-Higgs production

Production processes:

- New Di-Higgs production process is a direct probe of SM trilinear coupling.
- Strong destructive interference between processes.

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 27.5 - 36.1 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>obs.</th>
<th>exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b\bar{b}\tau^+\tau^-)</td>
<td>12.7</td>
<td>14.8</td>
</tr>
<tr>
<td>(b\bar{b}b\bar{b})</td>
<td>13.0</td>
<td>20.7</td>
</tr>
<tr>
<td>(b\bar{b}\gamma\gamma)</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>(W^+W^-\gamma\gamma)</td>
<td>230</td>
<td>160</td>
</tr>
</tbody>
</table>

Considerably improved \(HH \to bb \tau\tau\) result.

Limit approaching:
\[ \frac{\sigma_{\text{limit}}}{\sigma_{\text{SM}}} \approx 10 \]
Observation of same-sign WWjj

Higgs boson needed to restore unitarity of the WW scattering cross-section.
- Higgs boson leads to strong suppression via gauge cancellation of individual EW diagrams.
- Part of electroweak symmetry breaking studies.

\[ pp \rightarrow W^{+/−} W^{+/−} \text{jet jet process:} \]
- Large electroweak cross-section fraction \((\sigma_{\text{EW}}/\sigma_{\text{QCD}})\).
- and a strong background suppression.

Significance: 6.9\(\sigma\) (4.6\(\sigma\)) obs (exp)

Fiducial cross-
\[ \sigma_{\text{fid}} = 2.91^{+0.51}_{-0.47} \text{(stat.)} \pm 0.27 \text{(syst.) fb} \]
\[ \sigma_{\text{Sherpa}}^{\text{fid}} = 2.01^{+0.33}_{-0.23} \text{fb} \]
\[ \sigma_{\text{Powheg}}^{\text{fid}} = 3.08^{+0.45}_{-0.46} \text{fb} \]
WZ and WZjj production

Electroweak production of WZ boson in association with two jets pp → W⁺Z jet jet

Process sensitive to triple and quartic gauge couplings and anomalous couplings.

Differential EW cross-section:

\[ \sigma_{EW}(pp \rightarrow W^+Z \text{ jet jet}) = 0.57 \pm 0.15 \text{ fb} \]

LO (Sherpa): 0.32 \pm 0.03 \text{ fb}

Observation of electroweak W/Z jet+jet process.

Total fiducial WZ jet jet cross section:
\[ \sigma_{EW}(pp \rightarrow W^+Z \text{ jet jet}) = 0.57 \pm 0.15 \text{ fb} \]
LO (Sherpa): 0.32 \pm 0.03 \text{ fb}

Also new result on inclusive WZ production:

1) Fiducial cross-section in agreement with NNLO QCD (inclusive and differential)
2) Evidence of longitudinally W polarization (4.2\sigma)
3) Measurement of Z polarization
Measurements of electroweak parameters

**Measurement of electroweak mixing angle:**
Drell-Yan cross-section $\text{qq} \rightarrow Z \rightarrow \ell\ell$ expanded as sum of 9 harmonic polynomials (NNLO QCD). In LO QCD (Z-boson rest frame):

$$\frac{d\sigma}{dy_\ell\ell \, dm_\ell\ell \, d\cos \theta} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dy_\ell\ell \, dm_\ell\ell} \left\{ (1 + \cos^2 \theta) + A_4 \cos \theta \right\}$$

$A_4$ measured using two leptons $|\eta|<2.4$ (cc) and at least one forward electron $2.5<|\eta|<4.6$ (cf). Using 8 TeV data (2012).

Result from likelihood fit:

$$\sin^2 \theta^l_{\text{eff}} = 0.23140 \pm 0.00036$$

Uncertainty break-down:

$0.00021\,(\text{stat}) \pm 0.00024\,(PDF) \pm 0.00016\,(\text{syst})$

Main limitation knowledge initial quark direction.

**Other recent electroweak measurements:**

- **W-mass:** $80370 \pm 19$ MeV  
  [EPJ C78 (2018) 110]  
  ~0.02%
- **Higgs mass:** $124970 \pm 240$ MeV  
  [arXiv:1806.00242]  
  ~0.2%
- **Top-mass:** $172510 \pm 500$ MeV  
  [ATLAS-CONF-2017-071]  
  ~0.3%

**Precision:**

0.15% precision
Spin correlation in top pair events

Spin correlation for $pp \rightarrow tt \rightarrow e \mu b b$ measured between the top decay products and a spin axis. $\Delta \Phi(e\mu)$ is a sensitive variable.

**Example inclusive result:**

- **Template fit on $\Delta \Phi(e\mu)$:**
  - $f_{\text{SM}}$ fraction of expected cross-section under the SM spin hypothesis
  - No spin correlation template: top decay with spin correlation disabled

- Stronger spin correlations observed than expected by NLO QCD.

  Fit result: $f=1.250 \pm 0.026 \pm 0.063$
  - $3.2 \sigma$ discrepancy with NLO QCD

Previous analyses also measured stronger spin correlations (with large uncertainties).

Similar results for fiducial particle-level and comparisons of ME generators.
Search for new electro-weak boson

Very active search program (SUSY, dark matter, new Higgs models...)
In total, 62 search papers submitted (36 fb⁻¹). 8 new preliminary new physics searches with 80 fb⁻¹.

New electro-weak gauge boson (W') in context of sequential SM benchmark model.

Assuming SM coupling:

Masses below excluded at 95%CL:
5.6 TeV (80 fb⁻¹)
5.2 TeV (36 fb⁻¹)

→ Need new techniques to increase further sensitivity.

arXiv:1706.04786
High-mass Di-jet event from WW production

At high $p_t$ jets from the $W \rightarrow qq$ decay are close-by and merge in a large-R jet.

Many techniques developed to reconstruct boosted particles.

$W$-boson tagging based on large-R jet substructure.

New experimental technique: Energies from calorimeter clusters, but angles from tracks.
Di-boson resonance search

Select large $p_t$ and large radius jet with boosted W-tag

Recent improvements:
- W-boson tagging using angles from tracker and energies from calorimeter
- Tagger working point optimization at high $p_t$

Cross-section limit:
**Active SUSY Search Program**

28 publications on SUSY searches with 2015-2016 data (36 fb⁻¹).

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

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, γ, Jets</th>
<th>( L ) ([\text{fb}^{-1}])</th>
<th>Mass Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b\bar{b}, \Delta \rightarrow WW )</td>
<td>0, 2 jets</td>
<td>Yes, 36.1</td>
<td>( \tilde{g}, \tilde{t}_R \rightarrow t \tilde{t} )</td>
</tr>
<tr>
<td>( b\bar{b}, \Delta \rightarrow ZZ )</td>
<td>0, 2 jets</td>
<td>Yes, 36.1</td>
<td>Forbidden</td>
</tr>
<tr>
<td>( b\bar{b}, \Delta \rightarrow WW )</td>
<td>0, 2 jets</td>
<td>Yes, 36.1</td>
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<td>0, 2 jets</td>
<td>Yes, 36.1</td>
<td>2, 1τ</td>
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<td>2, 1τ</td>
</tr>
</tbody>
</table>

**Compressed Spectrum**

Squark degeneracy:
- squarks O(500 GeV)
- gluinos O(1 TeV)

**Longer Decay Chain**

More realistic models:
- sbottom O(700 GeV)
- stop O(500 GeV)

**Low Rate, Compressed**

- winos O(100 GeV)
- sleptons O(100 GeV)
- higgsino O(100 GeV)

**Complexity, Long-Lived**

- gluinos O(1 TeV)
- stop O(500 GeV)

Simplified signatures covered to high masses, but plenty of low mass unexplored model space.
Heavy Ion Data-set

<table>
<thead>
<tr>
<th>System</th>
<th>Year(s)</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>$L_{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Pb</td>
<td>2010-2011</td>
<td>2.76</td>
<td>$\sim 75 \mu b^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>5.02</td>
<td>$\sim 250 \mu b^{-1}$</td>
</tr>
<tr>
<td></td>
<td>by end of 2018</td>
<td>5.02</td>
<td>$\sim 1 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td>Xe-Xe</td>
<td>2017</td>
<td>5.44</td>
<td>$\sim 0.3 \mu b^{-1}$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2013</td>
<td>5.02</td>
<td>$\sim 15 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>5.02, 8.16</td>
<td>$\sim 3 \text{ nb}^{-1}, \sim 25 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2009-2013</td>
<td>0.9, 2.76, 7, 8</td>
<td>$\sim 200 \mu b^{-1}, \sim 100 \text{ nb}^{-1}, \sim 1.5 \text{ pb}^{-1}, \sim 2.5 \text{ pb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015,2017</td>
<td>5.02</td>
<td>$\sim 1.3 \text{ pb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015-2017</td>
<td>13</td>
<td>$\sim 25 \text{ pb}^{-1}$</td>
</tr>
</tbody>
</table>

Special data-sets:
p-p, Xe-Xe, p-Pb, Pb-Pb collisions.

6h Xe-Xe run in 2017

Significant increase in luminosity to study rare processes more and more precisely.
LHC scheduled: 3.5 week of Pb-Pb collision in November 2018.
Strange particle yields in pp, Xe-Xe, Pb-Pb

Alice detector with impressive particle-ID capabilities

Smooth evolution of charged particle multiplicities from small (pp), medium (Xe-Xe) to large (Pb-Pb) systems.

Increasing strange particle production with multiplicity until plateau is reached.

Confirmed by recent Xe-Xe data.
Anisotropic flow in Xe-Xe collisions

Models tuned in Pb-Pb data agree with Xe-Xe

Elliptic flow: $v_2$ (initial density profile)
Triangular flow: $v_3$ (viscosity)
(due to nucleons fluctuations in nuclei)

Models tuned in Pb-Pb data agree with Xe-Xe

Good understanding of initial density and viscosity in nucleus-nucleus collision.
D-meson suppression in Pb-Pb collisions

30-50% Pb-Pb, $|s_{NN}| = 5.02$ TeV
$|y| < 0.8$

Elliptic flow:

$\frac{dN}{d^2p_T} \propto 1 + 2v_1 \cos(\varphi - \psi_1) + 2v_2 \cos(2(\varphi - \psi_2)) + \ldots$


Charged particle spectra:
Clear increase in $\Lambda_c^+/D^0$-meson towards $p_T \sim 3$ GeV (similar to $\Lambda$/Kaon and p/π).

This specific effect in baryon formation is difficult to describe with pQCD+fragmentation.
Parton energy loss in jets

Soft-drop jet substructure grooming:

e.g.: declustering: “peel apart” the shower

(Soft Drop)

\[ z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \quad z_g > 0.1 \]

sensitive to coherence of energy loss

Result shown for dR>0.2: suppression of symmetric splittings.
Soft drop mass also used by ATLAS and CMS to characterize internal jet substructure.
Conclusions

ATLAS 13 TeV data analysis is in full swing. 13 results with 80 fb\(^{-1}\) (2015-2017 data).

Important new Higgs physics results:
- \(H \rightarrow bb\) observation. Main Higgs decays are now observed.
- Direct observation of Higgs coupling to top quark (via \(t\bar{t}H\)).
- Yukawa coupling to fermions confirmed (\(t\bar{t}H, H \rightarrow bb, H \rightarrow \tau\tau\))
- VH production observed. All major Higgs production modes observed.

Observation of electro-weak processes with dominant vector boson scattering:
- Same-sign WWjj and WZjj production.
- Important test of SM electro-weak sector.

New electro-weak mixing angle measurement with precision of 0.15%.

Top pairs: Indication for stronger top spin correlation than expected by NLO QCD.

Extensive and active search program for full run-2 (>150 fb\(^{-1}\) achievable).
New directions looking at more refined signatures.

ALICE:
Heavy-ion collisions: understanding the properties of QCD matter:
- Azimuthal anisotropies: Xe-Xe results confirm understanding of expanding QGP, viscosity
- Charm, jets probe the QGP with partons:
  Quantitative understanding of charm transport and QCD bremsstrahlung progressing.
Back-up
WZ cross-section and polarization

Electroweak production of WZ boson $pp \rightarrow W^\pm Z$:

Total fiducial cross section:

$$\sigma_{EW}(WZ) = 63.7 \pm 2.9 \text{ fb}$$

NNLO (Matrix): $61.5 \pm 1.4 \text{ fb}$

→ good agreement inclusive and differential cross-sections

Polarization measurement:

In WZ production:

1) Evidence of longitudinally $W$ polarization ($f_0^W$)
2) Measurement of $Z$ polarization

Longitudinal $W$-polarisation:

$$f_0^W = 0.26 \pm 0.06$$

$4.2\sigma \,(3.8\sigma)$ obs (exp)

Compatible with NLO QCD and LO EW (Powheg)
Identified particle spectra in Pb-Pb collisions

Alice detector with impressive particle-ID capabilities.

Particle spectra: pions, kaons, protons, Phis, Omegas, deuterons...

Increase in mean pt with centrality.

Centrality: 0-5% head-on nucleus collision (many nucleons) (central)
80-90% nucleon-nucleon collision peripheral
Hyper-triton lifetime

Hyper-triton: Hyper-nucleus formed by proton, neutron and Lambda

$^{3}_{\Lambda}H$: pn$\Lambda$ bound state

$^{3}_{\Lambda}H \rightarrow ^{3}\text{He} + \pi^-$

One of the most precise Hyper-triton lifetime measurements

Live time agrees with the free lambda live time (expected since hyper-triton is loosely bound).

Resolution of hyper-triton live time puzzle.

Heavy ion collisions as a laboratory for strange/exotic nuclei.
Tests of advanced \( tt \rightarrow WW bb \) calculation

Wt and \( tt \) processes have same final state at NLO QCD:

\[
|\mathcal{A}_{WW bb}|^2 \sim |\mathcal{A}(Wtb)|^2 + |\mathcal{A}(t\bar{t})|^2 + 2\mathcal{R}\{\mathcal{A}(Wtb)\mathcal{A}(t\bar{t})\}
\]

So far, tops produce stable and decayed (narrow width approximation)
Systematic handled \( ttbar/Wt \) interference
DR: \( tt \) removed at amplitude level
DS: \( tt \) removed at cross-section level

New calculation \( pp \rightarrow WW bb \bar{b} \)
(full matrix element)
Top final state modeling progress

Since several years ATLAS has measured fiducial cross-sections defined using the particles entering the detector. Indispensable for the tuning of modern ME(2->n)+PS MC simulations.

Total ttbb cross-section ~50% off, but shapes ~ok after tuning efforts.
### ttbb cross-section measurement

<table>
<thead>
<tr>
<th>Generator</th>
<th>Process</th>
<th>Matching</th>
<th>Tune</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Powheg-Box v2 + Pythia 8.210</strong></td>
<td>$t\bar{t}$ NLO</td>
<td>Powheg $h_{\text{damp}}=1.5$ m_t</td>
<td>A14</td>
<td>nom.</td>
</tr>
<tr>
<td><strong>MadGraph5_aMC@NLO + Pythia 8.210</strong></td>
<td>$t\bar{t} + V/H$ NLO</td>
<td>MC@NLO</td>
<td>A14</td>
<td>nom.</td>
</tr>
<tr>
<td><strong>Powheg-Box v2 + Pythia 8.210 RadLo</strong></td>
<td>$t\bar{t}$ NLO</td>
<td>Powheg $h_{\text{damp}}=1.5$ m_t</td>
<td>A14Var3cDown</td>
<td>syst.</td>
</tr>
<tr>
<td><strong>Powheg-Box v2 + Pythia 8.210 RadHi</strong></td>
<td>$t\bar{t}$ NLO</td>
<td>Powheg $h_{\text{damp}}=3.0$ m_t</td>
<td>A14Var3cUp</td>
<td>syst.</td>
</tr>
<tr>
<td><strong>Powheg-Box v2 + Herwig 7.01</strong></td>
<td>$t\bar{t}$ NLO</td>
<td>Powheg $h_{\text{damp}}=1.5$ m_t</td>
<td>H7UE</td>
<td>syst.</td>
</tr>
<tr>
<td><strong>Sherpa 2.2.1</strong></td>
<td>$t\bar{t}$ +1jet NLO +3 jets LO</td>
<td>MC@NLO</td>
<td>SHERPA</td>
<td>syst.</td>
</tr>
<tr>
<td><strong>Sherpa 2.2.1</strong></td>
<td>$t\bar{t}b\bar{b}$ NLO</td>
<td>NLO $t\bar{t}b\bar{b}$</td>
<td>SHERPA</td>
<td>comp.</td>
</tr>
<tr>
<td><strong>MadGraph5_aMC@NLO + Pythia 8.210</strong></td>
<td>$t\bar{t}$ NLO</td>
<td>MC@NLO</td>
<td>A14</td>
<td>comp.</td>
</tr>
<tr>
<td><strong>Powheg + Pythia 8.210</strong></td>
<td>$t\bar{t}b\bar{b}$ NLO</td>
<td>NLO $t\bar{t}b\bar{b}$</td>
<td>A14</td>
<td>comp.</td>
</tr>
</tbody>
</table>
Spin correlation in top pair events

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

<table>
<thead>
<tr>
<th>Generator</th>
<th>inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{SM}$ values</td>
<td></td>
</tr>
<tr>
<td>POWHEG + PYTHIA 8</td>
<td>1.25</td>
</tr>
<tr>
<td>POWHEG + PYTHIA 8 (2.0 $\mu_F$, 2.0 $\mu_R$)</td>
<td>1.29</td>
</tr>
<tr>
<td>POWHEG + PYTHIA 8 (0.5 $\mu_F$, 0.5 $\mu_R$)</td>
<td>1.18</td>
</tr>
<tr>
<td>POWHEG + PYTHIA 8 (PDF variations)</td>
<td>1.26</td>
</tr>
<tr>
<td>POWHEG + PYTHIA 8 RadLo tune</td>
<td>1.29</td>
</tr>
<tr>
<td>POWHEG + HERWIG7</td>
<td>1.32</td>
</tr>
<tr>
<td>MADGRAPH5_aMC@NLO + PYTHIA 8</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Table 3: Summary of the extracted spin correl

Fractional uncertainty size

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

Normalised cross-section

- Stat.
- Stat. $\oplus$ Syst.
- Background
- Pileup
- Jet
- Generator
- Shower
- Radiation
Measurements overview

Standard Model Total Production Cross Section Measurements

ATLAS Preliminary
Run 1,2 \( \sqrt{s} = 7, 8, 13 \) TeV

LHC pp \( \sqrt{s} = 7 \) TeV
- Data 4.5 – 4.9 fb\(^{-1}\)

LHC pp \( \sqrt{s} = 8 \) TeV
- Data 20.2 – 20.3 fb\(^{-1}\)

LHC pp \( \sqrt{s} = 13 \) TeV
- Data 3.2 – 36.1 fb\(^{-1}\)
Measurements of weak mixing angle

Polarized Drell-Yann cross-section \( pp \rightarrow Z \rightarrow ll \) can be expanded as sum of 9 harmonic polynomials

\[
\frac{d\sigma}{dp_T^l d\phi d\cos \theta} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^l d\phi d\cos \theta} \left\{ (1 + \cos^2 \theta) + \frac{1}{2} A_0 (1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi \\
+ \frac{1}{2} A_2 \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \phi \\
+ A_5 \sin^2 \theta \sin 2\phi + A_6 \sin \theta \sin \phi + A_7 \sin \theta \sin \phi \right\}.
\]

\( A_4 \) non-zero in LO
\( A_0 - A_3 \) non-zero only in NLO
\( A_5 - A_7 \) non-zero only in NNLO

\( A_3 \) and \( A_4 \) depend on vector and axial couplings to Z-boson \( \sim \) sensitive to \( \sin \theta_W \)

\( A_4 \) sensitive to weak mixing angle \( 3/8 A_4 \sim \sin^2 \theta_W \)

Measurement for \( |\eta|<2.4 \) (cc) and with one electron in forward region \( 2.5<|\eta|<4.6 \) (cf)

\( A_4 \) is parity violating, best sensitivity at Z-pole

Limitation by radiation of initial state quarks \( \rightarrow \) large systematics from PDFs

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{PDF set} & \text{CT10} & \text{CT14} & \text{MMHT14} & \text{NNPDF31} \\
\hline
\text{Central value} & 0.23118 & 0.23141 & 0.23140 & 0.23146 \\
\hline
\text{Uncertainties in measurements} & & & & \\
\text{Total} & 40 & 37 & 36 & 38 \\
\text{Stat.} & 21 & 21 & 21 & 21 \\
\text{Syst.} & 32 & 31 & 29 & 31 \\
\hline
\end{array}
\]

Final uncertainty from PDF spread
Compatibly weak mixing measurements

Z-boson rapidity bins

Result also compatible with reinterpretation of recent triple-differential Drell-Yan cross-section measurement.

Final uncertainty from PDF spread.
CT10 considered since it fits best the 7 TeV Drell-Yan data.
Search for dark matter at LHC

Particle physics relevant for understanding of early universe. DM model require new stable particle beyond SM. Coupling to SM particle via mediator $(A)$. 

Two strategies:

1) Events only visible if strong boost by radiation 
Signature: Mono-X, $X=$jet, photon, $Z/W$ etc.

2) Look for mediator decay to SM particles.

LHC is sensitive to some models (not too heavy, sizable couplings)
Search for dark matter at LHC

Complementarity to direct detection experiments

Production at LHC

Example for $g_q = 0.25, g_\chi = 1$ for vector mediator:

Vector mediator, Dirac DM

$g_q = 0.25, g_t = 0, g_{DM} = 1$

ATLAS limits at 95% CL, direct detection limits at 90% CL
Dijet resonance search limited by trigger $p_{t,jet}$ threshold. In sub-TeV regime need to do analysis on trigger level overcoming bandwidth limitations by writing only small amount of trigger jet information. Need full jet calibration for trigger-level jets.

Example coupling limits for DM axial vector mediator:

![Graph showing dijet mass vs. dijet resonance search](image)

**ATLAS**

$\sqrt{s} = 13$ TeV, 29.3 fb$^{-1}$

$|y^*| < 0.6$

Large gain at low mass

- Trigger-level jets
- Offline jets, single-jet triggers
- Offline jets, single-jet triggers, prescale-corrected

**ATLAS Preliminary April 2018**

$\sqrt{s} = 13$ TeV, 3.6-37.0 fb$^{-1}$

95% CL upper limits
- Observed
- Expected

Large-$R$ jet + ISR, 36.1 fb$^{-1}$

Dijet + ISR ($\gamma$, 15.5 fb$^{-1}$

ATLAS-CONF-2015-070

Dijet + ISR (jet), 15.5 fb$^{-1}$

ATLAS-CONF-2015-070

Dijet TLA, 3.6-29.7 fb$^{-1}$

arXiv: 1804.03496

Dijet, 37.0 fb$^{-1}$


Axial vector mediator

Dirac Dark Matter

$\overline{\chi}_{DM} = 10$ TeV

$|y^*| < 0.3$

$|y^*| < 0.6$
Search for electroweak SUSY particles

2\ell compressed
Soft $p_T^{e,\mu} > 4.5, 4$ GeV

Disappearing track
IBL+Pixel tracklets

ATLAS Simulation

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

All limits at 95% CL
- Observed limits
- Expected limits

[1712.08119]
[PHYS-PUB-2017-019]
[CONF-2017-081]
ttH event candidate
ttH event candidate

Run: 331742
Event: 1873900334
2017-08-04 21:48:42 CEST
Event display of the 4μ VH-Had candidate with the with BDTVH-Had = 0.47. The invariant mass of the 4-lepton system is 128.2 GeV, the muons are indicated by red tracks (pT = 103.7, 16.9, 16.4 and 15.4 GeV). The two jets, with an invariant mass of 96.2 GeV, are marked with purple cones (pT,j1 = 64.9 GeV and pT,j2 = 37.9 GeV).
Two $Z\rightarrow\mu\mu$ events superimposed. With high LHC luminosity starts to matter even for rare processes.

<table>
<thead>
<tr>
<th>Final state</th>
<th>Number of observed events</th>
<th>Number of expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-e^+e^-$</td>
<td>2</td>
<td>2.1</td>
</tr>
<tr>
<td>$\mu^+\mu^-e^+e^-$</td>
<td>6</td>
<td>6.6</td>
</tr>
<tr>
<td>$\mu^+\mu^-\mu^+\mu^-$</td>
<td>5</td>
<td>5.4</td>
</tr>
<tr>
<td>Sum over all channels</td>
<td>13</td>
<td>14.1</td>
</tr>
</tbody>
</table>
Coupling fits in $H \rightarrow bb$ analysis

**ATLAS** Preliminary

$\sqrt{s} = 7$ TeV, 8 TeV, and 13 TeV
4.7 fb$^{-1}$, 20.3 fb$^{-1}$, and 24.5-79.8 fb$^{-1}$

- **VBF+ggF Run1**: $\mu = 0.78$, $\sigma = 2.26$, $\mu_{\text{Stat.}} = -0.78$ (+1.59, +1.60)
- **VBF+ggF Run2**: $\mu = 2.47$, $\sigma = 1.38$, $\mu_{\text{Stat.}} = 2.47$ (+1.30, +0.46)
- **ttH Run1**: $\mu = 1.50$, $\sigma = 1.22$, $\mu_{\text{Stat.}} = 1.50$ (+0.73, +0.98)
- **ttH Run2**: $\mu = 0.85$, $\sigma = 0.63$, $\mu_{\text{Stat.}} = 0.85$ (+0.30, +0.56)
- **VH Run1**: $\mu = 0.51$, $\sigma = 0.40$, $\mu_{\text{Stat.}} = 0.51$ (+0.31, +0.25)
- **VH Run2**: $\mu = 1.15$, $\sigma = 0.27$, $\mu_{\text{Stat.}} = 1.15$ (+0.16, +0.21)
- **Comb.**: $\mu = 1.01$, $\sigma = 0.20$, $\mu_{\text{Stat.}} = 1.01$ (+0.12, +0.16)
June 2018 update: \( ttH \to \gamma\gamma \) and \( tt(ZZ \to 4l) \) with \( 80 \text{ fb}^{-1} \)

**ttH production cross-section**

**Inclusive ttH production cross-section**

**ttH cross-section per production modes**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \)

- \( ttH (H \to \tau\tau) \):
  - \( \sigma = 1.36 \pm 0.19 \) (stat) \( \pm 0.89 \) (syst)
- \( ttH (H \to b\bar{b}) \):
  - \( \sigma = 0.83 \pm 0.61 \) (stat) \( \pm 0.30 \) (syst)
- \( ttH (H \to VV) \):
  - \( \sigma = 1.50 \pm 0.63 \) (stat) \( \pm 0.45 \) (syst)
- \( ttH (H \to \gamma\gamma) \):
  - \( \sigma = 1.41 \pm 0.48 \) (stat) \( \pm 0.42 \) (syst)
- **Combined**: \( \sigma = 1.32 \pm 0.26 \) (stat) \( \pm 0.18 \) (syst)

**ttH cross-section**

- At 8 TeV: \( \sigma_{ttH} = 220 \pm 100 \) (stat) \( \pm 70 \) (syst)
- At 13 TeV: \( \sigma_{ttH} = 670 \pm 90 \) (stat) \( \pm 105 \) (syst)

Already 20% precision!
### Coupling ratios in Kappa-framework

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition in terms of $\kappa$ modifiers</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{gZ}$</td>
<td>$\kappa_g \kappa_Z / \kappa_H$</td>
<td>$1.06 \pm 0.07$</td>
</tr>
<tr>
<td>$\lambda_{tZ}$</td>
<td>$\kappa_t / \kappa_g$</td>
<td>$1.09^{+0.14}_{-0.14}$</td>
</tr>
<tr>
<td>$\lambda_{Zg}$</td>
<td>$\kappa_Z / \kappa_g$</td>
<td>$1.06^{+0.14}_{-0.13}$</td>
</tr>
<tr>
<td>$\lambda_{WZ}$</td>
<td>$\kappa_W / \kappa_Z$</td>
<td>$0.99^{+0.09}_{-0.08}$</td>
</tr>
<tr>
<td>$\lambda_{YZ}$</td>
<td>$\kappa_Y / \kappa_Z$</td>
<td>$0.95^{+0.08}_{-0.07}$</td>
</tr>
<tr>
<td>$\lambda_{rZ}$</td>
<td>$\kappa_r / \kappa_Z$</td>
<td>$0.95 \pm 0.13$</td>
</tr>
<tr>
<td>$\lambda_{bZ}$</td>
<td>$\kappa_b / \kappa_Z$</td>
<td>$0.91^{+0.17}_{-0.16}$</td>
</tr>
</tbody>
</table>
$H \rightarrow WW$

**ATLAS Preliminary**

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$, $N_{jet} \leq 1$

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

$\mu_{ggF} = 1.21^{+0.12}_{-0.11} (stat.)^{+0.18}_{-0.17} (sys.) = 1.21^{+0.22}_{-0.21}$

$\mu_{VBF} = 0.62^{+0.30}_{-0.28} (stat.) \pm 0.22 (sys.) = 0.62^{+0.37}_{-0.36}$. 
Cross-section measurement for H->ττ
Mass distributions in H-\(\tau\tau\) VBF categories
Mass distributions in H-$\tau\tau$ boosted categories
### Search summary

#### ATLAS Exotics Searches - 95% CL Upper Exclusion Limits

**Status:** July 2017  
\[ \int L \, dt = (3.2 - 37.0) \, fb^{-1} \]

\[ \sqrt{s} = 8, 13 \, TeV \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets†</th>
<th>( E_{\text{miss}} )</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
</table>
| ADD \( G_{\text{KX}} + e/q \) | 0, e, \( \mu \) | 1–4 | | \( M_{\text{D}} \) | \[ 7.75 \, TeV \]
| ADD non-resonant \( g \gamma \) | 2 \( \gamma \) | | | \( M_{\text{S}} \) | \[ 8.6 \, TeV \]
| ADD Q\( \bar{b} \) | | | | \( M_{\text{Q\( \bar{b} \)}} \) | \[ 8.9 \, TeV \]
| ADD BH \( \sum pt \) | \( \geq 1 \), e, \( \mu \) | 2–2 | | \( M_{\text{BH}} \) | \[ 8.2 \, TeV \]
| ADD BH multijet | \( \geq 3 \) | | | \( M_{\text{BH multijet}} \) | \[ 9.55 \, TeV \]
| RS1 \( G_{\text{KX}} \) | 2 \( \gamma \) | 2–2 | | \( M_{\text{GKX mass}} \) | \[ 2.67 \, TeV \]
| Bulk RS \( G_{\text{KX}} \) \( \to WW \) \( \to qqf \) | 1, e, \( \mu \) | 1 | Yes | \( M_{\text{Gk mass}} \) | \[ 1.75 \, TeV \]
| 2UED \( G_{\text{KX}} \) | 1, e, \( \mu \) | 2, b, b, b, J, J | Yes | \( M_{\text{KK mass}} \) | \[ 1.37 \, TeV \]
| SSM \( Z \to \ell \ell \) | 2, e, \( \mu \) | 2–2 | | \( M_{\text{Z mass}} \) | \[ 2.4 \, TeV \]
| SSM \( Z \to \tau \tau \) | 2 \( \tau \) | 2–2 | | \( M_{\text{Z mass}} \) | \[ 1.5 \, TeV \]
| Leptophobic \( Z' \to bb \) | | 2 \( b \) | | \( M_{\text{Z mass}} \) | \[ 2.0 \, TeV \]
| Leptophobic \( Z' \to tt \) | | 1, e, \( \mu \) | \( \geq 1 \), \( \leq 2 \) | | \[ 5.1 \, TeV \]
| HVT \( V \to WW \to qqq \) \( \text{model B} \) | 0 \( e, \mu \) | 2 \( J \) | | \( M_{\text{V mass}} \) | \[ 3.5 \, TeV \]
| HVT \( V \to WH/ZZH \) \( \text{model B} \) | | 2 \( e, \mu \) | | \( M_{\text{V mass}} \) | \[ 2.93 \, TeV \]
| LRSM \( W_{\ell} \to tb \) | 1, e, \( \mu \) | 2, b, 0–1 | Yes | \( M_{\text{W mass}} \) | \[ 1.92 \, TeV \]
| LRSM \( W_{\nu} \to tb \) | 0, e, \( \mu \) | 1, b, b, J | Yes | \( M_{\text{W mass}} \) | \[ 1.76 \, TeV \]
| CI \( qq \) | | | | | \[ 21.8 \, TeV \]
| CI \( \gamma \gamma \) | | | | \( \eta_{\ell\ell} \) | \[ 40.1 \, TeV \]
| CI \( uu \) | \( 2, SS/3 \, \mu, e \) | | | | \[ 4.9 \, TeV \]
| DM \( \gamma \gamma \) | | | | | \[ \eta_{\ell\ell} = 1 \]
| DM \( \gamma \gamma \) | | | | | \[ \eta_{\ell\ell} = 1 \]
| Scalar \( Q_1 \) \( 1st \) \( q \) | 2, \( e, \mu \) | 2–2 | | \( M_{\text{Q mass}} \) | \[ 700 \, GeV \]
| Scalar \( Q_2 \) \( 2nd \) \( q \) | 2, \( e, \mu \) | 1, b, b, J | Yes | \( M_{\text{Q mass}} \) | \[ 640 \, GeV \]
| Heavy quark \( T \to H + X \) | \( 0 \) or 1 \( e, \mu \) | 2, b, b, b, J | Yes | \( M_{\text{T mass}} \) | \[ 1.2 \, TeV \]
| Heavy quark \( T \to Z + X \) | | | | | \[ 1.16 \, TeV \]
| Heavy quark \( T \to Wb + X \) | | | | | \[ 1.35 \, TeV \]
| Heavy quark \( Bb + X \) | | | | | \[ 700 \, GeV \]
| Heavy quark \( Bb + Zb + X \) | | | | | \[ 790 \, GeV \]
| Heavy quark \( Bb + Wb + X \) | | | | | \[ 1.25 \, TeV \]
| Excited quark \( q' \to q \) | | | | | \[ 6.0 \, TeV \]
| Excited quark \( q' \to q \) | | | | | \[ 5.3 \, TeV \]
| Excited quark \( b' \to bg \) | | | | | \[ 2.3 \, TeV \]
| Excited quark \( b' \to Wt \) | | | | | \[ 1.5 \, TeV \]
| Excited top \( t' \) | | | | | \[ 3.0 \, TeV \]
| Excited top \( v' \) | | | | | \[ 1.5 \, TeV \]
| Other | | | | | \[ m(W_{\ell}) = 2.4 \, TeV, \text{no mixing} \]

*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter \( J \).
Vector-like Quark summary

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

- **Exp. exclusion**
- **Obs. exclusion**

- **ATLAS** Preliminary

<table>
<thead>
<tr>
<th>( m_T ) (GeV)</th>
<th>BR(( T \rightarrow Ht ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0.8</td>
</tr>
<tr>
<td>900</td>
<td>0.6</td>
</tr>
<tr>
<td>950</td>
<td>0.4</td>
</tr>
<tr>
<td>1000</td>
<td>0.2</td>
</tr>
<tr>
<td>1050</td>
<td>0.8</td>
</tr>
<tr>
<td>1100</td>
<td>0.6</td>
</tr>
<tr>
<td>1150</td>
<td>0.4</td>
</tr>
<tr>
<td>1200</td>
<td>0.2</td>
</tr>
<tr>
<td>1300</td>
<td>0.8</td>
</tr>
<tr>
<td>1400</td>
<td>0.6</td>
</tr>
</tbody>
</table>

- **SU(2) doublet**
- **SU(2) singlet**

- \( W(lV)b+X \) [arXiv:1707.03947]
- \( H(bb)+X \) [arXiv:1803.09678]
- \( Z(\nu\overline{\nu})t+X \) [arXiv:1705.10751]
- \( Z(l\overline{l})t+b+X \) [arXiv:1806.10555]
- All-had (CERN-EP-2018-176)