Overview of datasets

139 fb\(^{-1}\) of 13 TeV proton-proton collision data collected from 2015-2018

But also special low-pileup data, 5 TeV proton-proton collision data, proton-lead, lead-lead collisions, and xenon-xenon collisions, and more!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

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A tour of ATLAS physics*

*with proton-proton collisions

- Precision measurements of the Standard Model
- Studies of top quark properties
- Studies of beauty and charm physics
- Searches for new physics
- Searches for supersymmetry
- Searches for dark matter
- Searches for unconventional signatures
- Searches for rare standard model processes
- Studies of Higgs boson properties
- Searches for exotic Higgs boson decays
- Search for supersymmetry
Higgs $\rightarrow ZZ^*$ measurements

Two same-flavour, opposite-charge lepton pairs:

$2e2\mu, 2e2e, 2\mu2\mu$

One SFOC pair close to the Z-boson mass

Four-lepton mass close to the Higgs boson mass
Overview: $H \rightarrow ZZ^* \rightarrow 4l$

Low branching ratio: only 0.17% of all Higgs boson decays!

...but a very distinct signal, and high purity in the Higgs boson mass window:

Background from SM $Z(Z^*) \rightarrow 4l$ production: simulation constrained by fitting regions outside the Higgs boson mass window

Multi-boson and $tXX$ ($X=t, V$) are estimated from simulation

Backgrounds from fake and non-prompt leptons are measured using a data-driven method
Unfolded, fiducial cross sections are measured for each channel and combined

Inclusive Higgs boson production cross section $\sigma_H$ measured using SM branching ratios

→ Overall good agreement with SM predictions

Differential cross sections for many variables, compared to different theoretical predictions, including jet-related variables and angular variables

Showing here the azimuthal angle between the two Z bosons
Improvements over the cross-section measurement:

FSR photons added to $m_{4l}$: 1% improvement in resolution

Kinematic fit used to constrain $m_{12}$ to the Z boson mass: 17% improvement in resolution

Mass constraint: $115 < m_{4l} < 130$ GeV

$316 \pm 14$ events, 66% signal

Signal lineshape dominated by detector response: $m_{4l}$ distribution is modelled with a double-sided crystal ball distribution

**ATLAS** Preliminary

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

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

Data

- Higgs (125 GeV)
- $Z(Z^*)$
- $t\bar{t}X$, VVV
- $Z$+jets, $t\bar{t}$

Uncertainty
Use the event-level resolution $\sigma_i$ instead of the average resolution $\sigma$ in the fit.

Estimate $\sigma_i$ using a quantile regression neural network:

Input individual lepton kinematics and the four-lepton momentum and its uncertainty.
Higgs boson mass: $H \rightarrow ZZ^* \rightarrow 4l$

**Measured** $m_H = 124.92^{+0.19}_{-0.19}$ (Stat.) $^{+0.09}_{-0.06}$ (Sys.) GeV

**ATLAS** Preliminary

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

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

- **Data**
- **Fit**
- **Background**

**ATLAS** Preliminary

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

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

- **Observed: Stat+Sys**
- **Observed: Sys-Only**

$124.80^{+0.29}_{-0.28}$ (Stat.) $^{+0.13}_{-0.09}$ (Sys.)

$124.95^{+0.29}_{-0.29}$ (Stat.) $^{+0.06}_{-0.04}$ (Sys.)

$125.34^{+0.48}_{-0.47}$ (Stat.) $^{+0.07}_{-0.10}$ (Sys.)

$124.59^{+0.74}_{-0.74}$ (Stat.) $^{+0.10}_{-0.09}$ (Sys.)

$124.92^{+0.19}_{-0.19}$ (Stat.) $^{+0.09}_{-0.06}$ (Sys.)
Electroweak Zjj production

Z boson decaying leptonically (2e/2µ)

Two jets
- Large rapidity separation
- Large invariant mass

No jets in the gap
We cannot directly measure vector boson fusion – there is significant interference with other diagrams of the same order in $\alpha_{\text{EW}}$, and extracting the VBF component is not a gauge invariant operation.

⇒ Measure electroweak production of $Zjj$
**Electroweak Zjj production**

**Electroweak Vjj production**  
\[ \sigma(\alpha_{EW}) = 3 \]

**Strong Vjj production**  
\[ \sigma(\alpha_{EW}) = 1, \sigma(\alpha_{S}) = 2 \]

Strong production has the same final state and a higher cross-section
Electroweak $Zjj$ production

ATLAS Preliminary $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$, $Zjj \rightarrow lljj$

- Strong $Zjj$ (SHERPA)
- EW $Zjj$ (POWHEG+PY8)
- Strong $Zjj$ (MG5+PY8)
- EW $Zjj$ (HERWIG+VBFNLO)$'$
- Strong $Zjj$ (MG5 NLO+PY8)$'$ (HERWIG+VBFNLO)$'$
- EW $Zjj$ (SHERPA)
- $ZV$, Other $VV$, top

Strong $Zjj$ is the largest background across the spectrum

Monte Carlo modelling of both strong electroweak $Zjj$ shows discrepancies between generators

Modelling of strong $Zjj$ is especially poor, particularly in the high-$m_{jj}$ signal-enriched region
## Data-driven background modelling

### Analysis

<table>
<thead>
<tr>
<th>$N_{\text{gap jets}}$</th>
<th>Strong $Z\ell\ell$ enhanced</th>
<th>Strong $Z\ell\ell$ enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1$</td>
<td>CRa</td>
<td>CRb</td>
</tr>
<tr>
<td>$= 0$</td>
<td>SR</td>
<td>CRc</td>
</tr>
</tbody>
</table>

### Variables
- **Number of jets** between the leading and subleading jets
- **Centrality** of the reconstructed $Z$ boson:
  \[
  \xi_Z = \left| y_{\ell\ell} - 0.5(y_{j1} + y_{j2}) \right| / |\Delta y_{jj}|
  \]

- Three background-enhanced regions and one signal region fit to reduce dependence on mismodelling.
Extract the electroweak $Zjj$ signal once for each of the three strong $Zjj$ MC generators:

result is the midpoint of the envelope

Signal and control regions are unfolded for both electroweak and inclusive $Zjj$ yields:
Effective field theory interpretation

\[ \sigma_{EFT} = \sigma_{SM} + \sum \frac{c_j}{\Lambda^3} \sigma_{SM,j}^{\text{interf.}} + \sum_j \frac{c_j^2}{\Lambda^6} \sigma_{j}^{\text{NP}} + \sum_{j \neq k} \frac{c_j c_k}{\Lambda^6} \sigma_{j,k}^{\text{NP - interf.}} \]

Two CP-even and two CP-odd operators were tested

\[ \rightarrow \text{sensitivity to CP-odd operators through the parity-odd observable} \]
\[ \Delta \varphi_{jj} = \varphi_{\text{higher rapidity jet}} - \varphi_{\text{lower rapidity jet}}, \]
where \( jj \) = the two leading jets
**Effective field theory interpretation**

**ATLAS Preliminary**

Fit to $\text{llj EW } \Delta \phi(j_1, j_2)$ spectrum

\[ \frac{\Delta \phi(j_1, j_2)}{\lambda^2} = -0.10 \text{ TeV}^2 \]

-99% CL
-95% CL
-68% CL

Ratio to SM

- SM
- SM + $|M_{SM}|^2$
- SM + $2 \text{Re}(M_{SM}^* M_{d6})$
- SM + $M_{d6}^2$

Measurements
Pulled measurements

\[ \Delta \phi(j_1, j_2) \]
VBF di-Higgs searches

Four central $b$-tagged jets

Two jets
- Large rapidity separation
- Opposite sides of the detector
- Large invariant mass
Two Higgs bosons decay into four $b$-jets:

Criteria based on pairs of $b$-jets, forming Higgs boson candidates

Pair of pairs with minimum $D_{HH}$ is chosen:
- correct 83% of the time for SM non-resonant HH
- correct 91% of the time for broad BSM resonance $\rightarrow$ HH
VBF di-Higgs – results

Observed 95% CL upper limit of 1450 fb on SM VBF HH production ($\sigma_{SM} = 1.73$ fb)

Not shown: limits also set on narrow and broad BSM $X \rightarrow HH$ resonances

Sensitivity to HHVV coupling ($\kappa_{2V}$) unique to VBF HH searches
Universality of lepton couplings in W boson decays

- tt events: two $b$-jets
- One leptonically decaying W ($e/\mu$) as a tag
- Second opposite-sign leptonically decaying W ($\mu\nu$ or $\tau\nu \rightarrow \mu\nu\nu\nu$)
- Z mass veto

Tag the event

Probe what happens here!
In the SM, gauge boson decays exhibit lepton flavour universality

Measure the ratio of tau decays to muon decays: Only previous measurement is from LEP, which shows a $2.7\sigma$ discrepancy from the SM

Use $\tau \to \mu$ decays to have the muon final state for both lepton flavours ($W \to \tau\nu_\tau \to \mu\nu_\mu \nu_\tau \nu_\tau$)

Properties of muons from $W \to \mu\nu$ vs. $W \to \tau\nu$ differ: form templates for each decay channel and fit to data
LFU in W boson decays

48-bin fit (3 muon $p_T$ bins, 8 muon $d_0$ bins, two tag-lepton channels) to extract two parameters:

$R(\tau/\mu)$: parameter of interest, applied to $\tau \rightarrow \mu$ (top) component

$k(tt)$: normalization applied to both tt and Wt

$R(\tau/\mu) = 0.992 \pm 0.013$

$[\pm 0.007 \text{ (stat)} \pm 0.011 \text{ (syst)}]$}

Most precise value to-date!
LFU in W boson decays

\[ \text{BR}(W \rightarrow \mu \nu) \]
\[ \text{BR}(W \rightarrow e \nu) \]

\[ \text{BR}(W \rightarrow \tau \nu) \]
\[ \text{BR}(W \rightarrow e \nu) \]

- \text{UA1, } Z\text{Phys. C44 (1989) 15-61}
- \text{UA2, } PLB. 280 (1992) 137-145
- \text{D0, } PRL. 75 (1995) 1456, PRL. 84 (2000) 5710
- \text{LHCb, } JHEP 10 (2016) 030
- \text{LEP, } Phys.Rept. 522 (2013) 119
- \text{ATLAS, } EPJC. 77 (2017) 367
- PDG averages

\[ \text{ATLAS} \text{- this result} \]

- \text{Statistical Error}
- \text{Systematic Error}
- \text{Total Error}

\[ \sqrt{s} = 13 \text{ TeV, 139 fb}^{-1} \]
Searches for Dark Matter

Many, many possibilities!
Dark matter could be produced in many, many ways at the LHC:
Dark matter summary

Important to understand how ATLAS compare to other experiments:

ATLAS Vector $Z'$
Vector mediator, Dirac DM
$g_q = 0.25, g = 0, g_\chi = 1$
Preliminary ATLAS-CONF-2016-070
JHEP 01 (2018) 126
PLB 776 (2017) 318
JHEP 10 (2018) 180

ATLAS $Z'$ baryonic
$Z'$ baryonic, Dirac DM
$\sin\theta = 0.3, g_q = 1/3, g_\chi = 1$

ATLAS Scalar
Scalar mediator, Dirac DM
$g_q = 1, g_\chi = 1$

Important to understand how ATLAS compare to other experiments:
Important to understand how searches in different channels are complementary, and what areas of phase space we still need to focus on:

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

- **Observed**
- **Expected**

2HDM+a, Dirac DM
\[ m_\chi = 10 \text{ GeV}, \ g_\chi = 1 \]
\[ m_A = m_H = m_{H^\pm} = 600 \text{ GeV} \]
\[ \sin \theta = 0.35 \]

\[ \tan \beta = 1 \]
\[ \Gamma/m_g > 20\% \]
In the SM, the Higgs boson decays invisibly 0.12% of the time

*Previous best fit measurement:*  
< 26% at 95% CL  

PRL 122, 231801 (2019)

Full Run 2 preliminary result has limited this to < 13% at 95% CL!

**Strong $BR_{\text{invisibles}}$ limit can be interpreted as strong constraints on Higgs portal DM:**
ATLAS has a hugely diverse physics program

Many results using the full Run 2 dataset are already complete

I’ve only shown a small handful of what we have:
- Higgs → ZZ* → 4l
- VBF HH
- VBF Z
- R(τ/mu) in W decays
- Dark matter searches

...and many more interesting results are still to come!
The ATLAS detector
Detecting particles with ATLAS

- Electrons
- Photons
- Neutrinos
- Muons
- Hadrons
Detecting particles with ATLAS
For $\kappa_{2V}$ values deviating from the SM prediction, growing non-cancellation effects result in a harder $m_{HH}$ spectrum, and thereby higher-$p_T$ $b$-jets, which in turn lead to increased signal acceptance times efficiency as shown in Figure 2.

This search is therefore not sensitive to the region close to the SM prediction, corresponding to $\kappa_{2V} = 1$"
Extracting the EW $Zjj$ signal

Binned maximum likelihood fit is performed to reduce dependence on MC mismodelling, with \(3 \times N_{\text{bins}} + 2\) free parameters:

1. bin-by-bin weights for strong $Zjj$, separate for low and high centrality but linked between $N_{\text{jets}}^{\text{gap}} \geq 1$ and $N_{\text{jets}}^{\text{gap}} = 0$

2. linear $f(x)$ applied to strong $Zjj$ to correct for residual $N_{\text{jets}}^{\text{gap}}$ dependence

3. bin-by-bin electroweak $Zjj$ signal strengths (same in all regions)
Perform fit again with alternative generators for strong $Zjj$ component